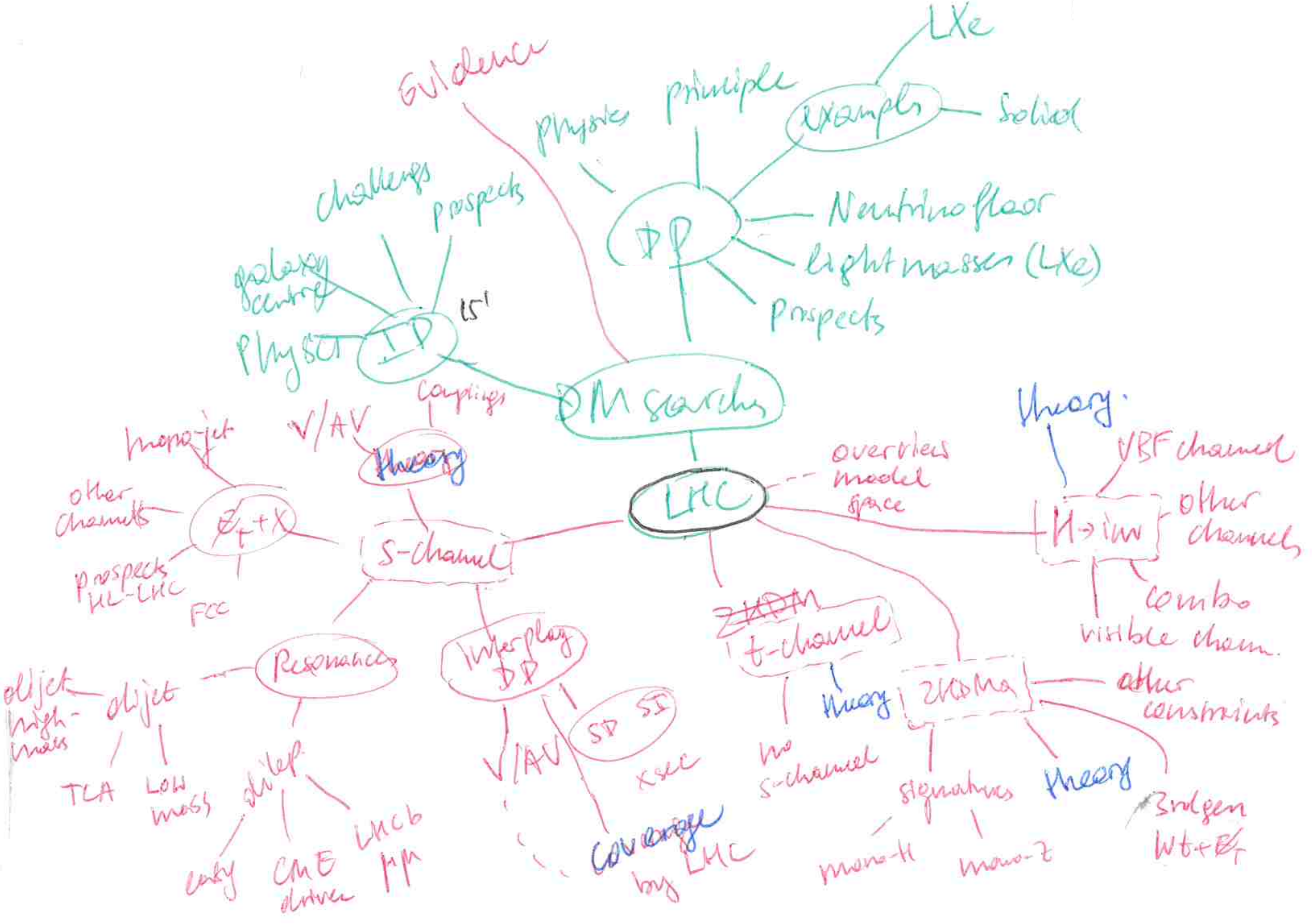
Hunting for Dark Matter using proton-proton collisions at the LHC

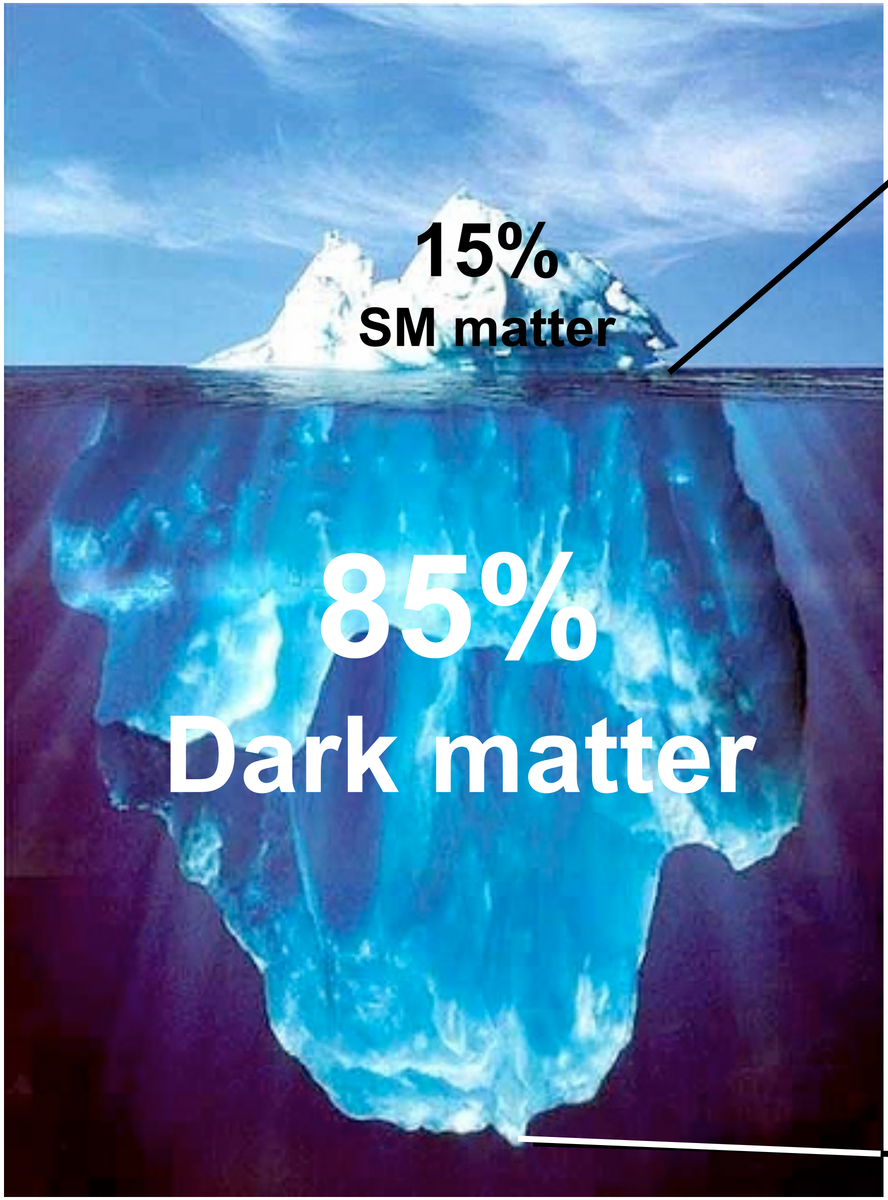
UNIVERSITY OF CAMBRIDGE

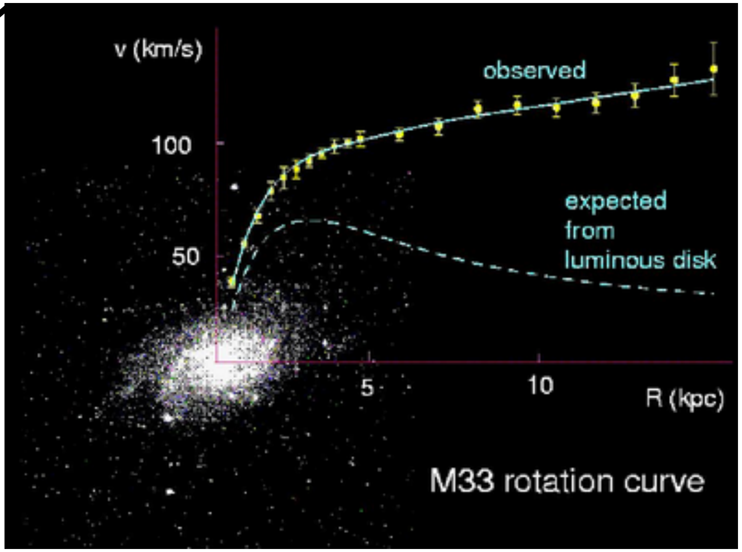
OLEG BRANDT

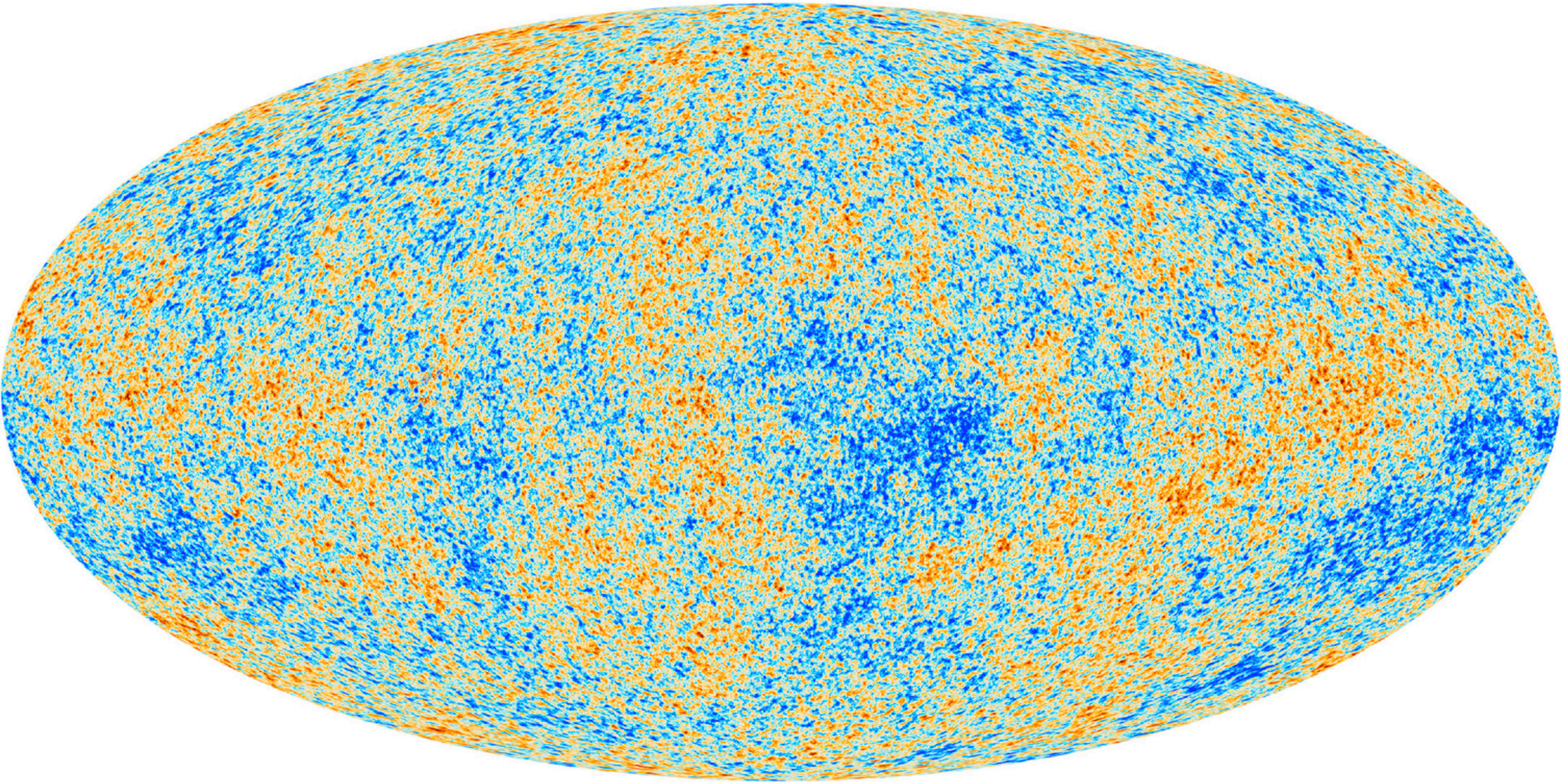
16/11/2020


DM searches
Evidence
DD
Physics
principle
examples
LXe
Solid
Neutrino floor
light masses (LXe)
Prospects
ID
challenges
prospects
galaxy centre
PhysSCI
15'
LHC
overview model space
Couplings
V/AV
theory
mono-jet
other channels
$\not{E}_T$+X
prospects HL-LHC
FCC
s-channel
Resonances
object
object high-mass
TLA
Low mass
dilep
early
CME driven
LHCb
μμ
Interplay DD
V/AV
SD SI
xsec
coverage by LHC
t-channel
theory
no s-channel
2HDMa
signatures
mono-H
mono-Z
theory
other constraints
3rd gen
Wt+$\not{E}_T$
theory
VBF channel
H→inv
other channels
combo
visible chan.

Just a brief reminder about the evidence for DM
after Matthias' overview lecture…

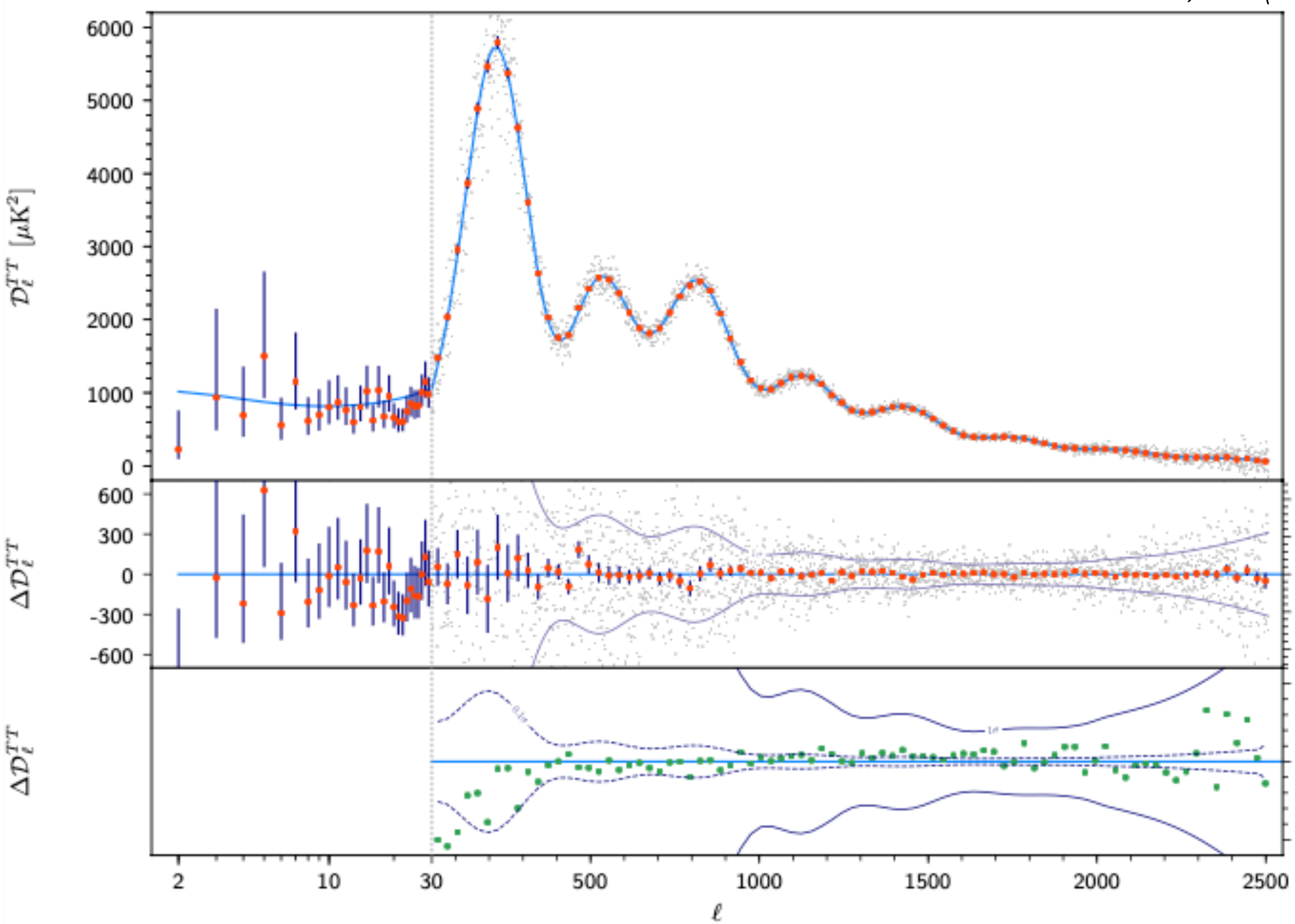

15%
SM matter
85%
Dark matter

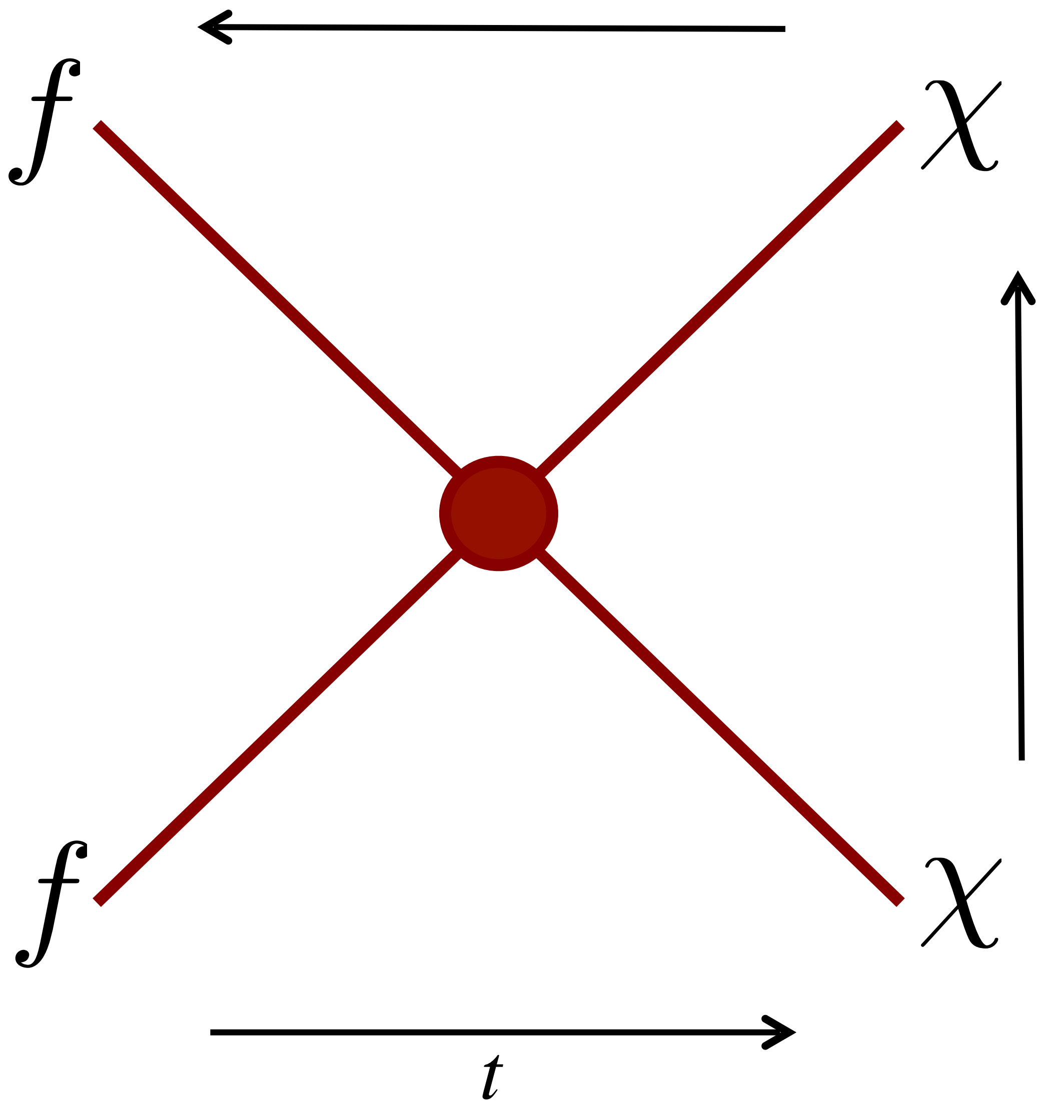

v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

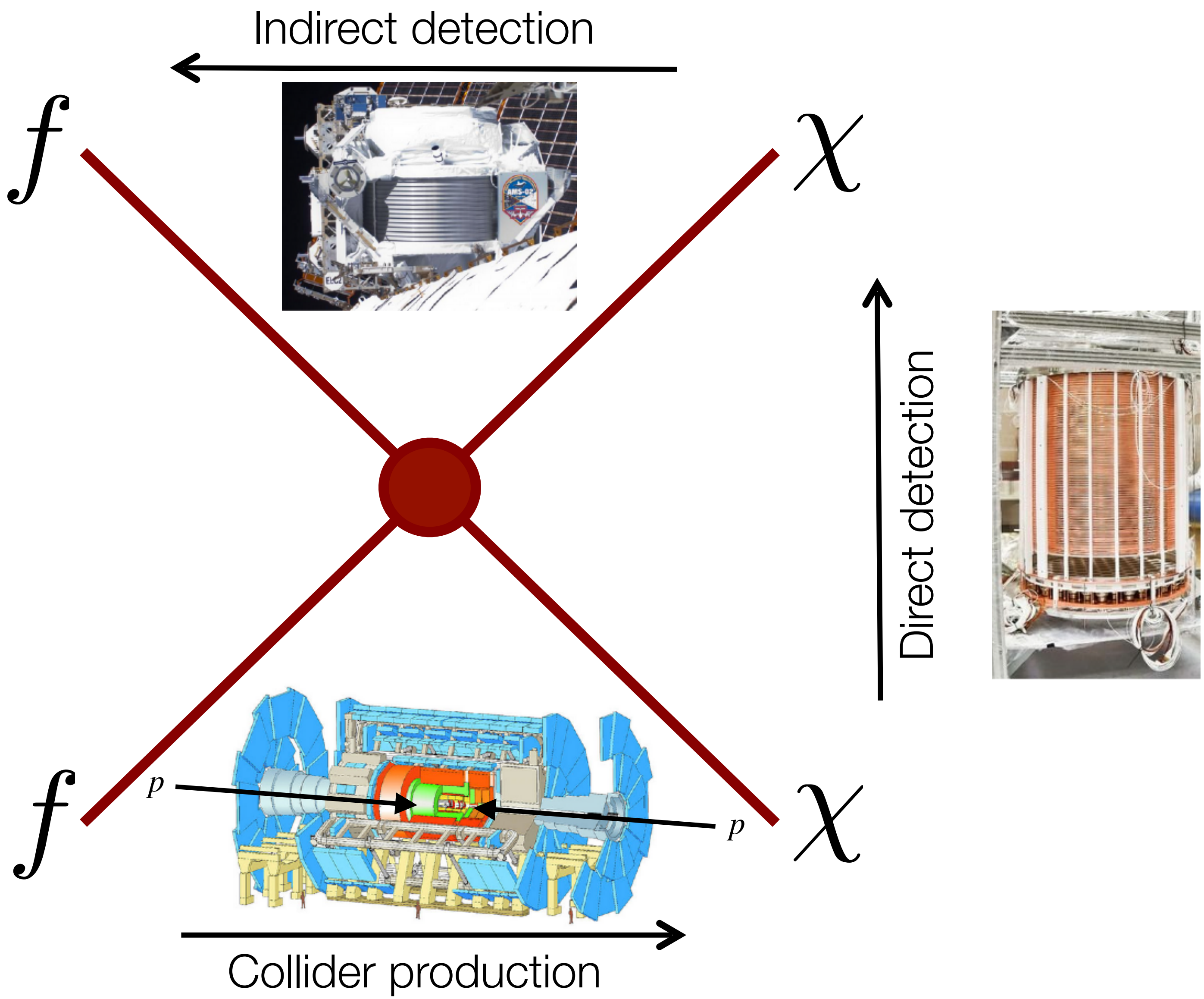


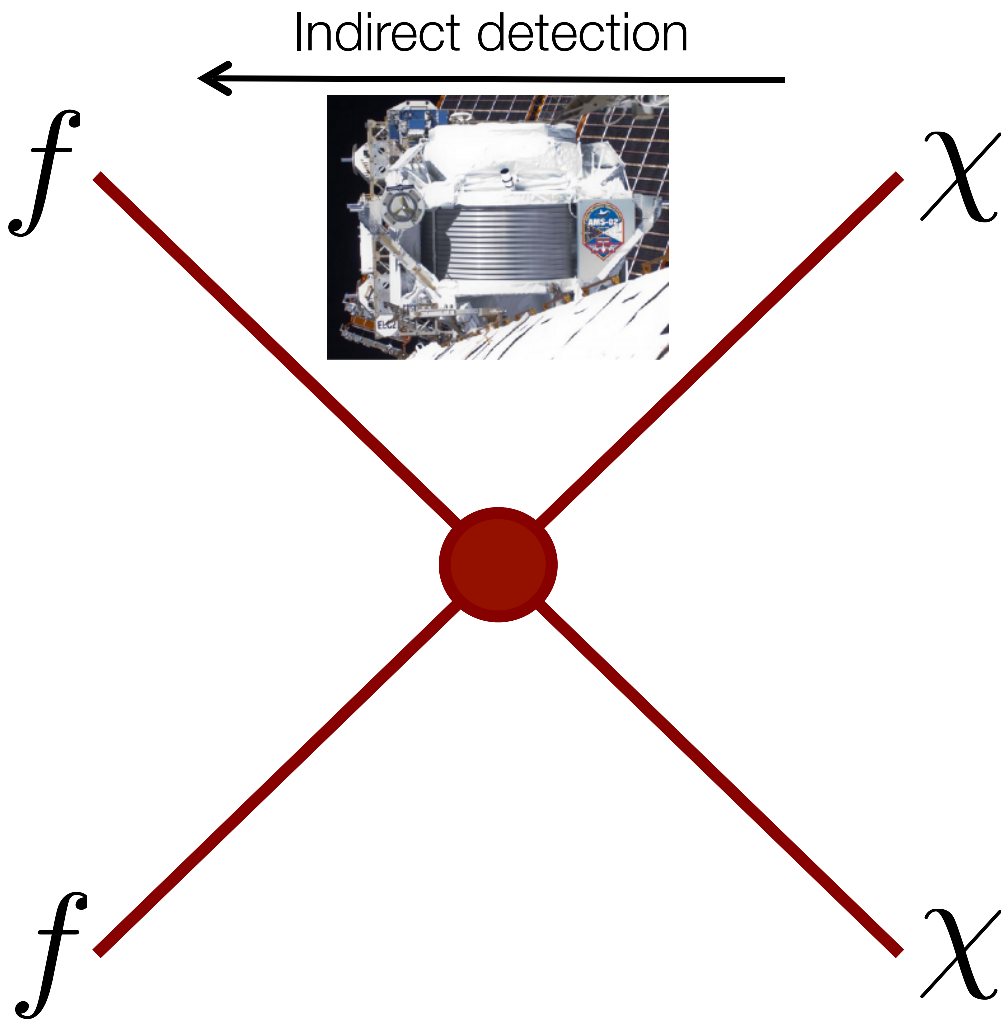
Dark Matter evidence

A&A 641, A5 (2020)



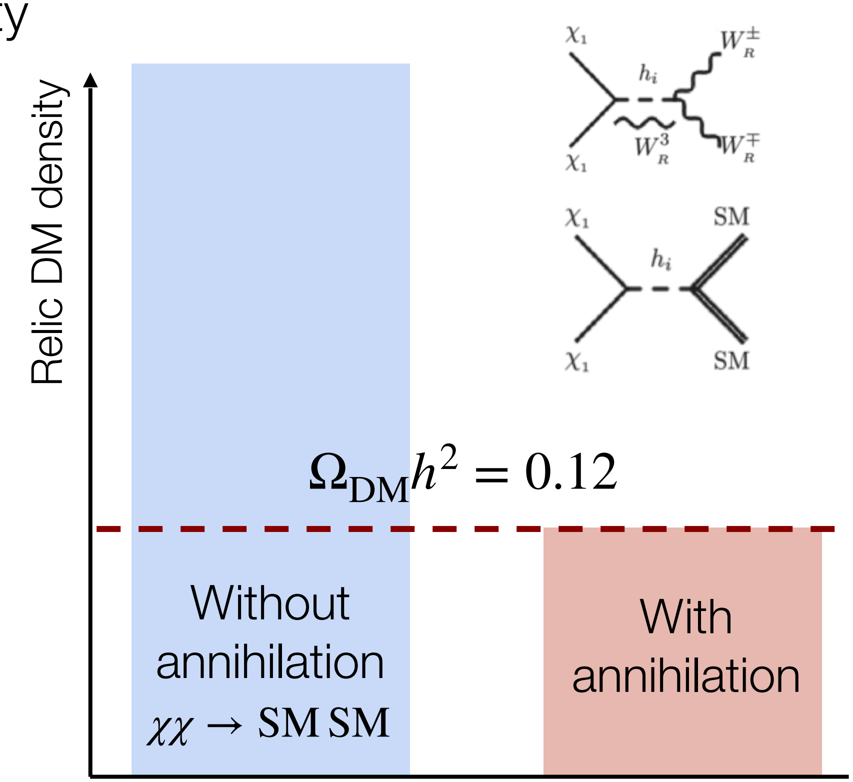

f
χ
f
χ
t


Indirect detection
f
χ
Direct detection
f
p
p
χ
Collider production


Indirect detection
f
χ
f
χ

- DM annihilation into SM particles:
  - Need high DM density for observation!
    - a) Shortly after big bang (BB)
    - b) Today in gravitational wells

- a) DM annihilation after BB:
  - Indirect constraint from relic DM density
  - May need effective mechanism to deplete DM density if too high
    - Constraint very model-specific!



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  - Need high DM density for observation!
    - a) Shortly after big bang (BB)
    - b) Today in gravitational wells

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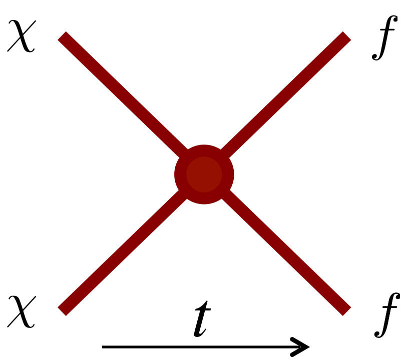
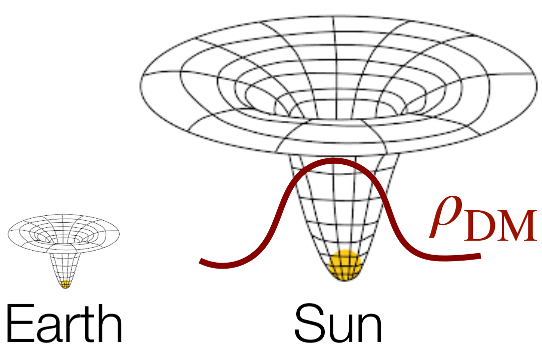
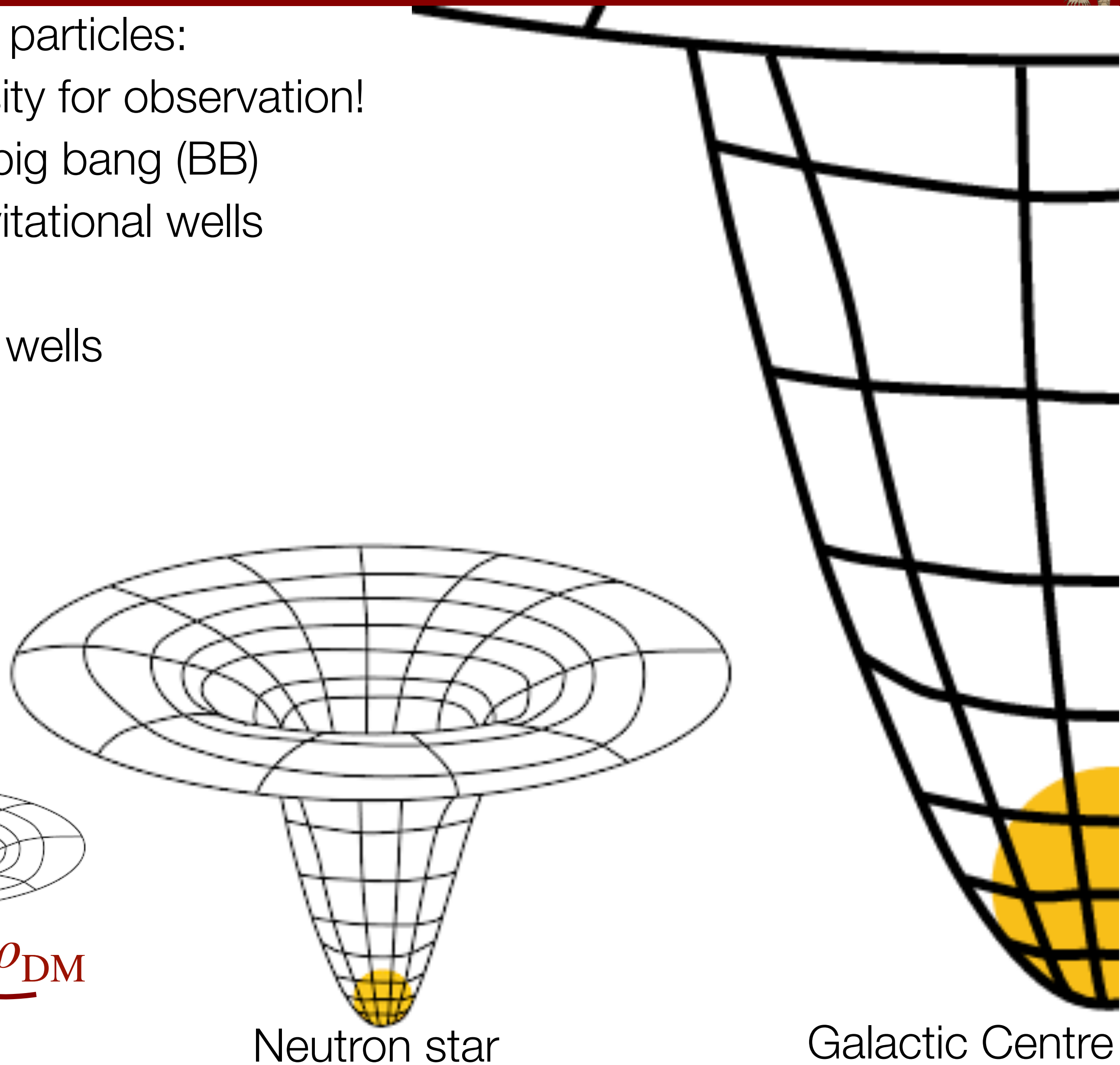
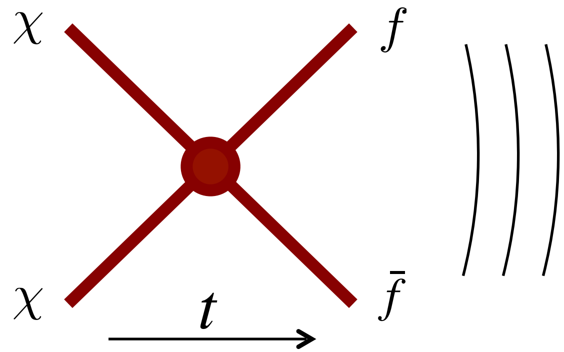








a.k.a. J-factor

$$\overbrace{\frac{d\Phi}{d\Omega dE}}^{Diff.Flux} = \frac{\overbrace{\sigma v}^{Anni.Cross\ Section}}{8\pi m_\chi^2} \times \underbrace{\frac{dN}{dE}}_{Energy\ Spectrum} \times \int_{l.o.s} ds \underbrace{\rho^2(\vec{r}(s,\Omega))}_{Dark\ Matter\ Distribution}$$

Measurement

Model assumption,
Colliders (fragmentation etc)

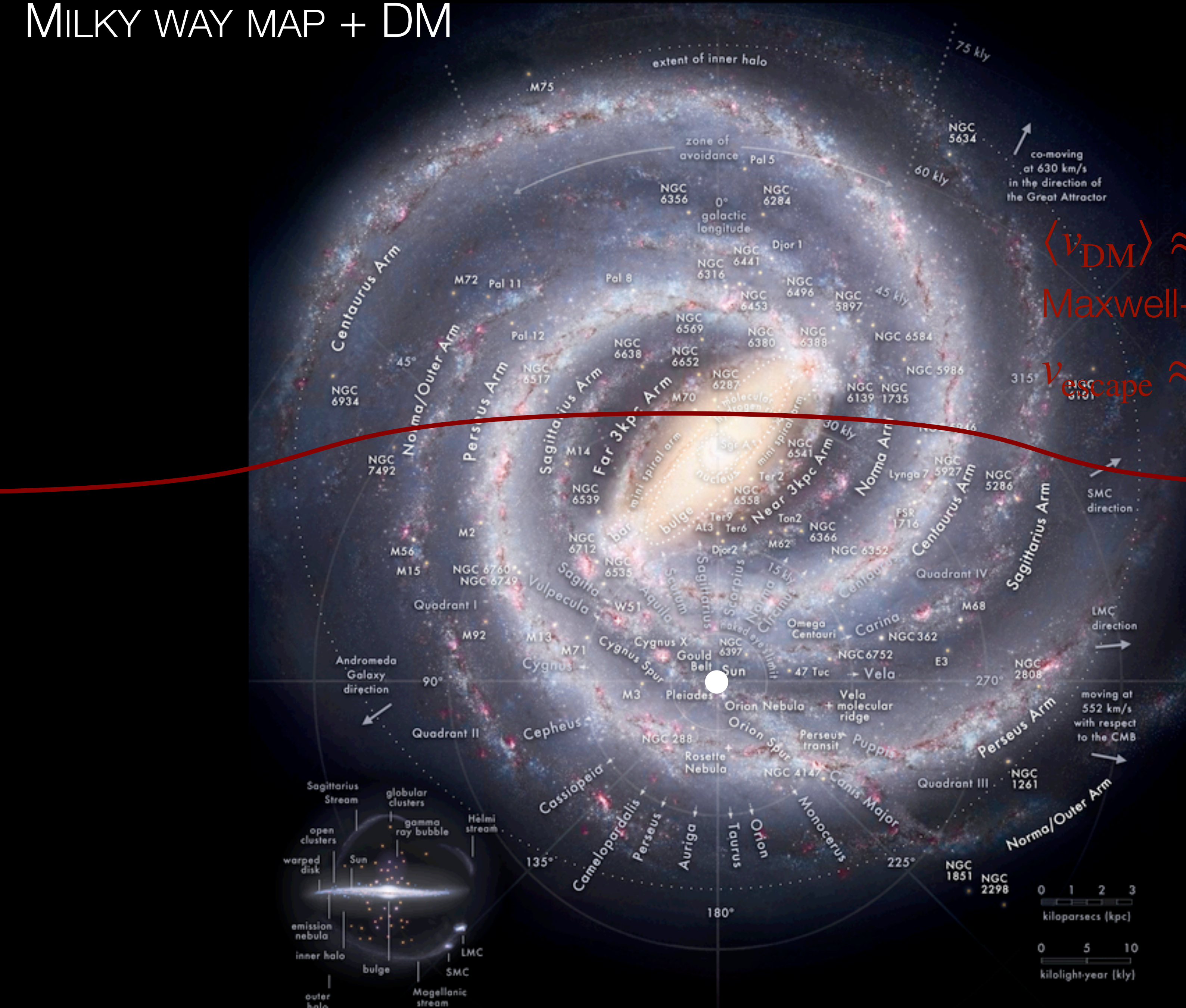
Cosmology

σv: Interpretation (final observable)

m_χ: model assumption

1605.08788

MILKY WAY MAP + DM



$\langle v_{\rm DM} \rangle \approx 200$ km/s

Maxwell-distributed

$v_{\rm escape} \approx 600$ km/s

$\rho_{\rm DM}$

- Cosmology input matters [1]:

2001.06193

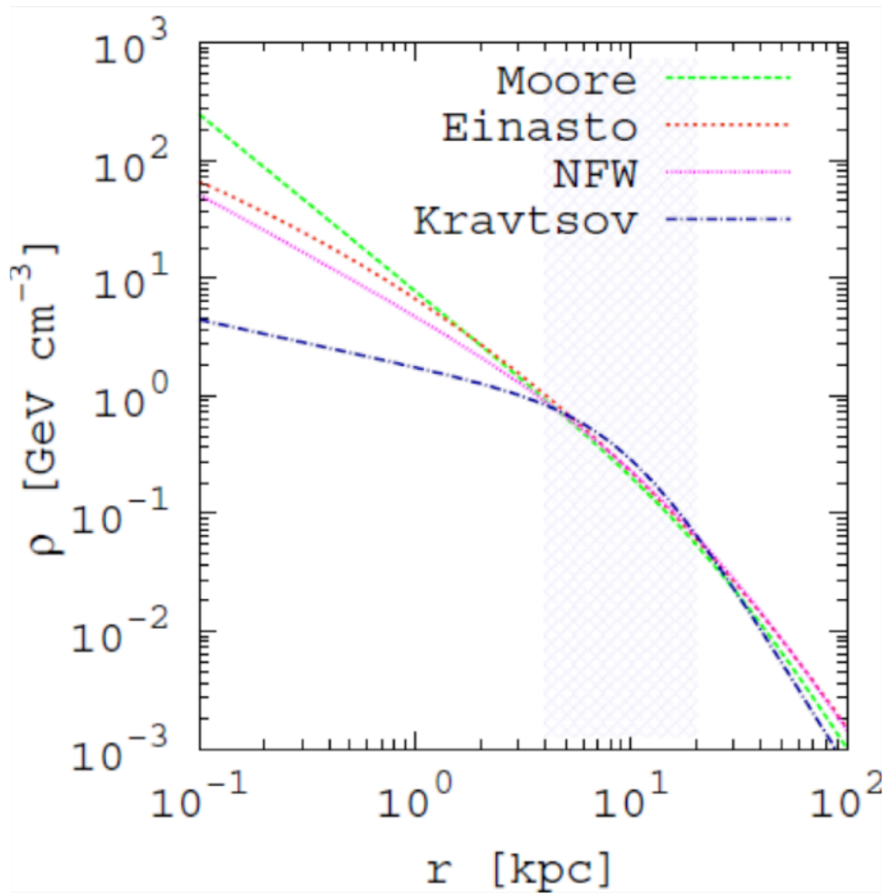
  - Navarro-Frenk-White profile:

$$\rho(r) \propto \frac{r_s}{r[1 + r/r_s]^2}$$

$$\alpha \simeq 0.17$$
$$r_s \simeq 20 \text{ kpc}$$

  - Einasto profile:

$$\rho(r) \propto exp\left[\frac{-2.0}{\alpha}\left((r/r_s)^{\alpha} - 1\right)\right]$$



[1] other profiles, typically: $\frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^{\gamma} \cdot \left(1 + \left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\beta-\gamma)/\alpha}}$

- Cosmology input matters [1]:

2001.06193

  - Navarro-Frenk-White profile:

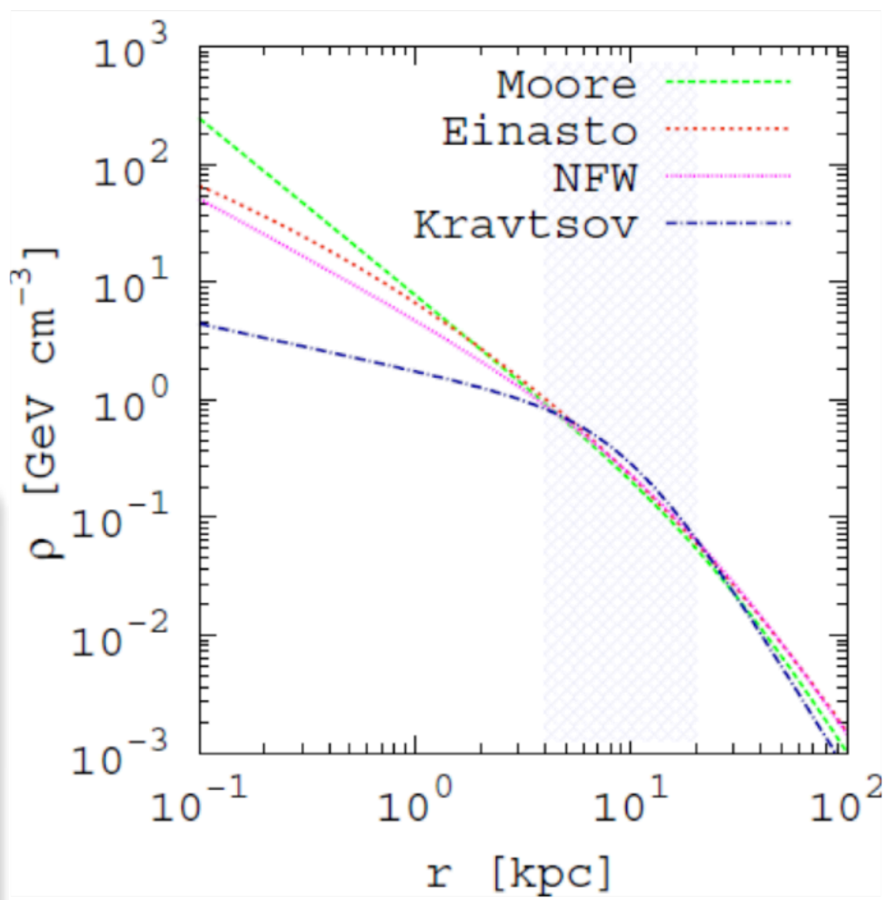
$$\rho(r) \propto \frac{r_s}{r[1 + r/r_s]^2}$$

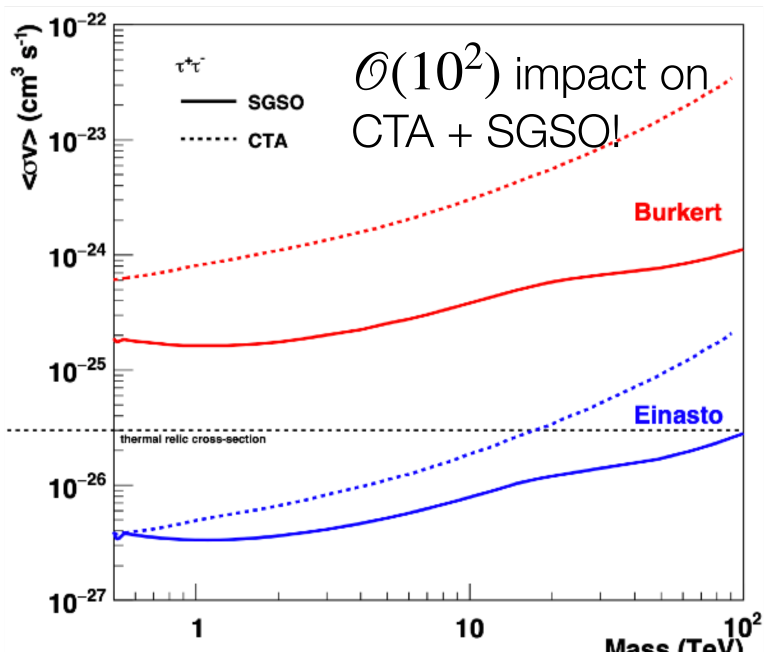
  - Einasto profile:

$$\rho(r) \propto exp\left[\frac{-2.0}{\alpha}\left(\left(r/r_s\right)^{\alpha} - 1\right)\right]$$

$\alpha \simeq 0.17$

$r_s \simeq 20$ kpc

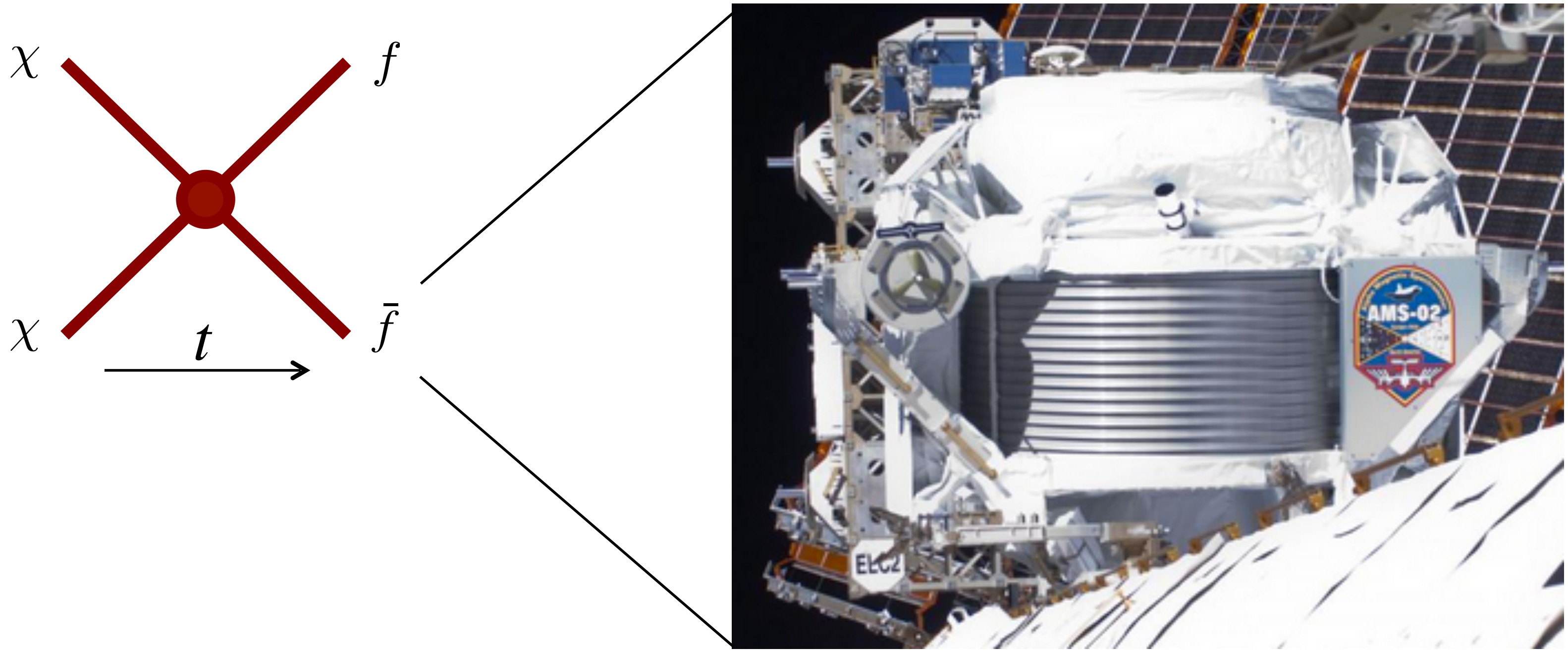




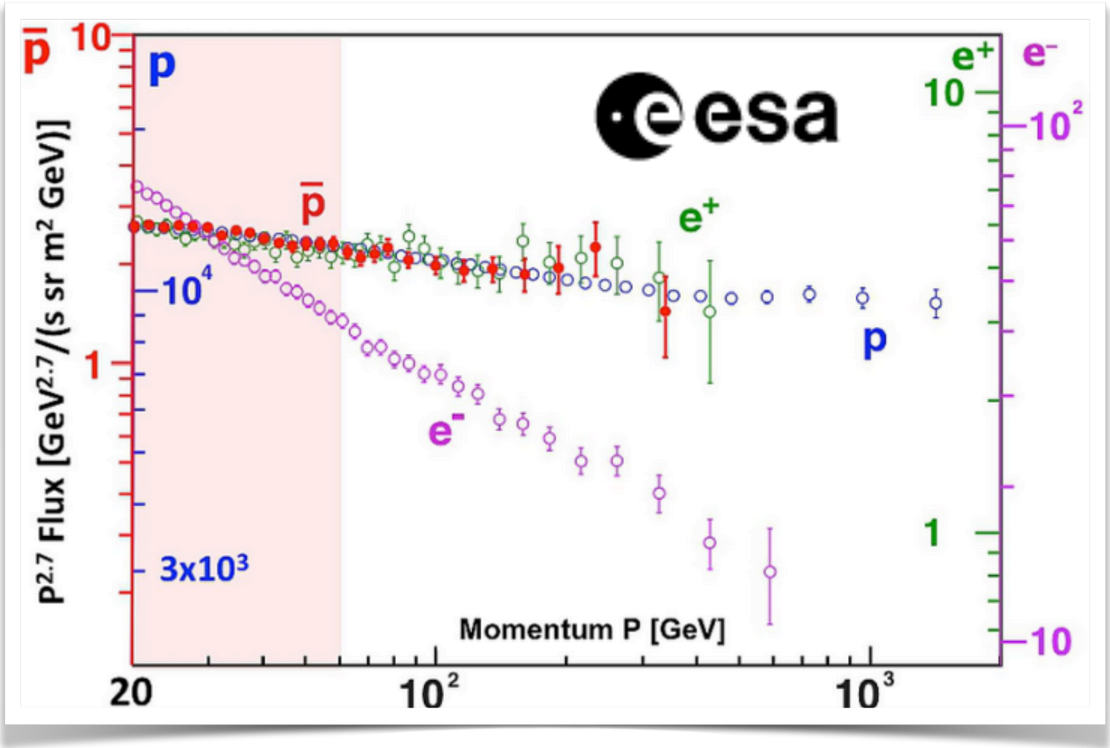
$\mathcal{O}(10^2)$ impact on CTA + SGSO!

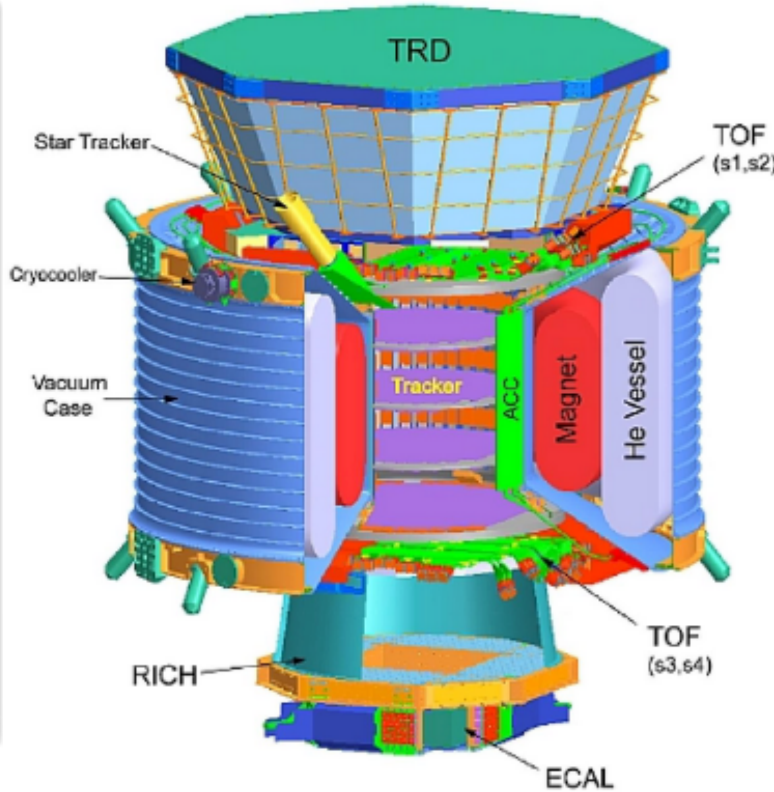
INDIRECT DETECTION SIGNATURE: EXCESS OF $\bar{f}_{\mathrm{SM}}$

Alpha Magnetic Spectrometer (AMS-02)

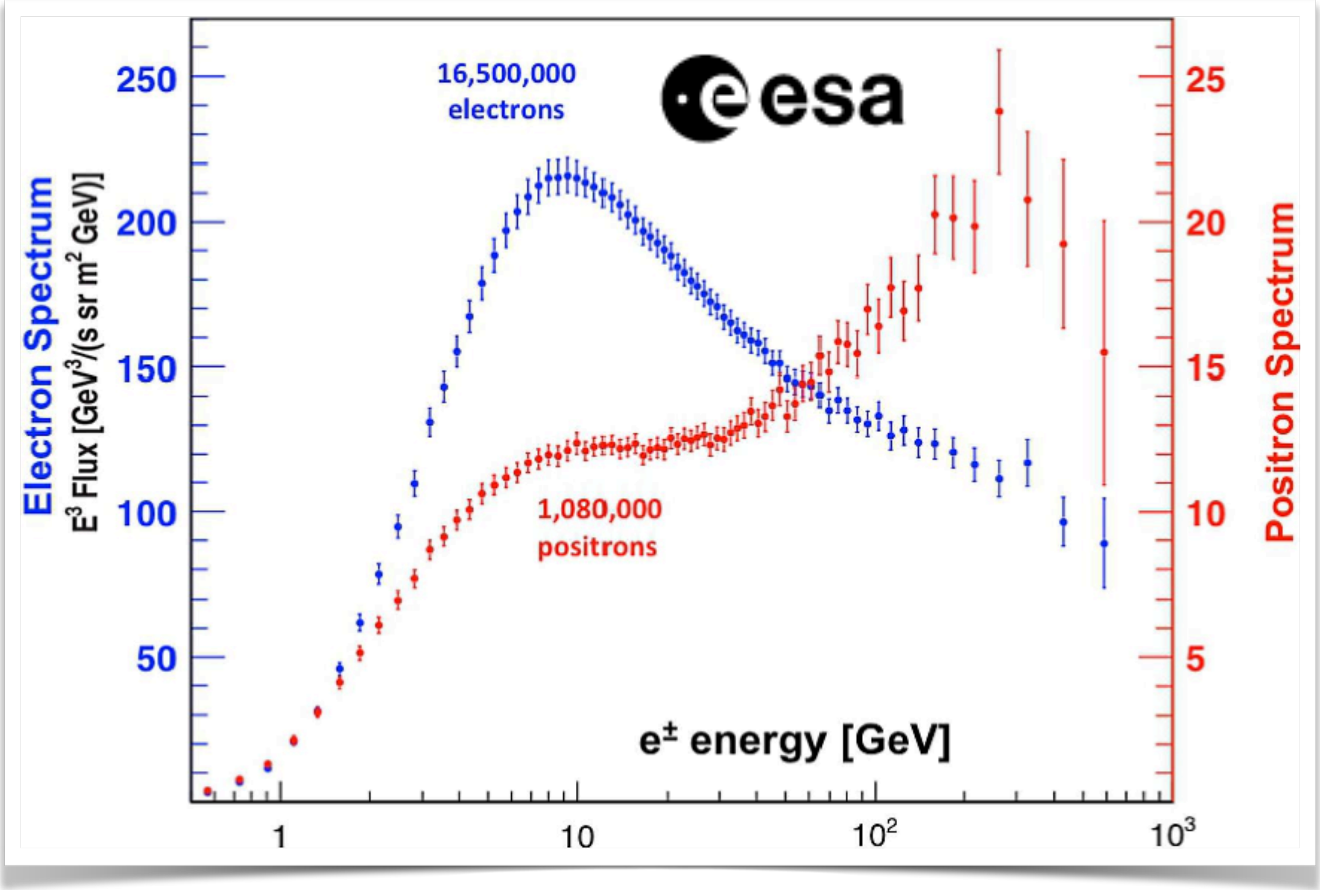


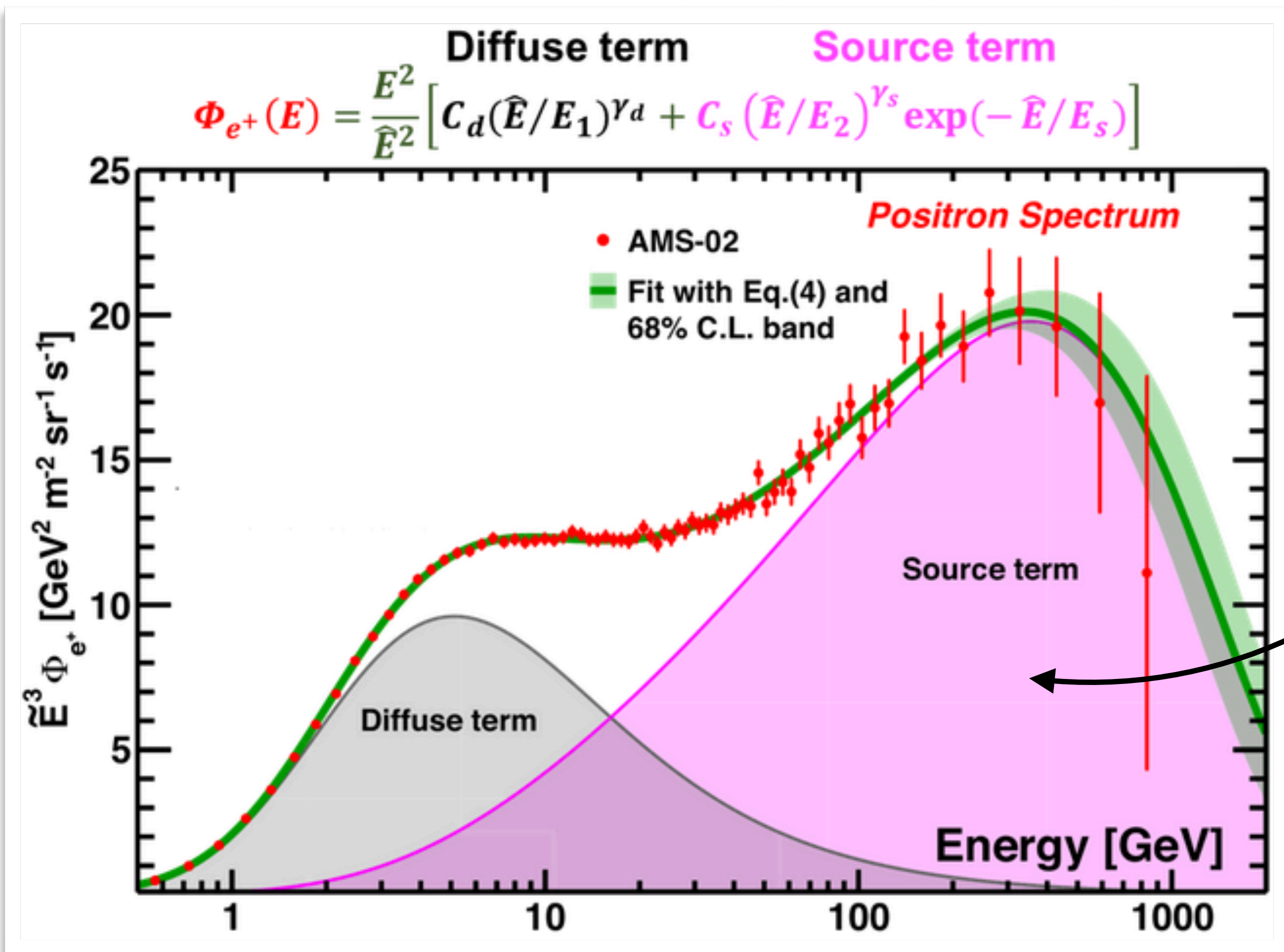
Also: PAMELA, Fermi-LAT, etc.


p̄
10
p
esa
e+
e-
10
10²
p̄
e+
10⁴
1
p
e-
1
3x10³
Momentum P [GeV]
10
20
10²
10³
p^2.7 Flux [GeV^2.7/(s sr m² GeV)]

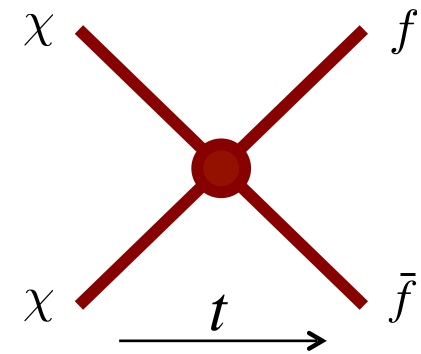

TRD
Star Tracker
TOF
(s1,s2)
Cryocooler
Vacuum
Case
Tracker
ACC
Magnet
He Vessel
TOF
(s3,s4)
RICH
ECAL

Electron and positron spectra ($\times E^3$)





PRL 122, 041102 (2019)

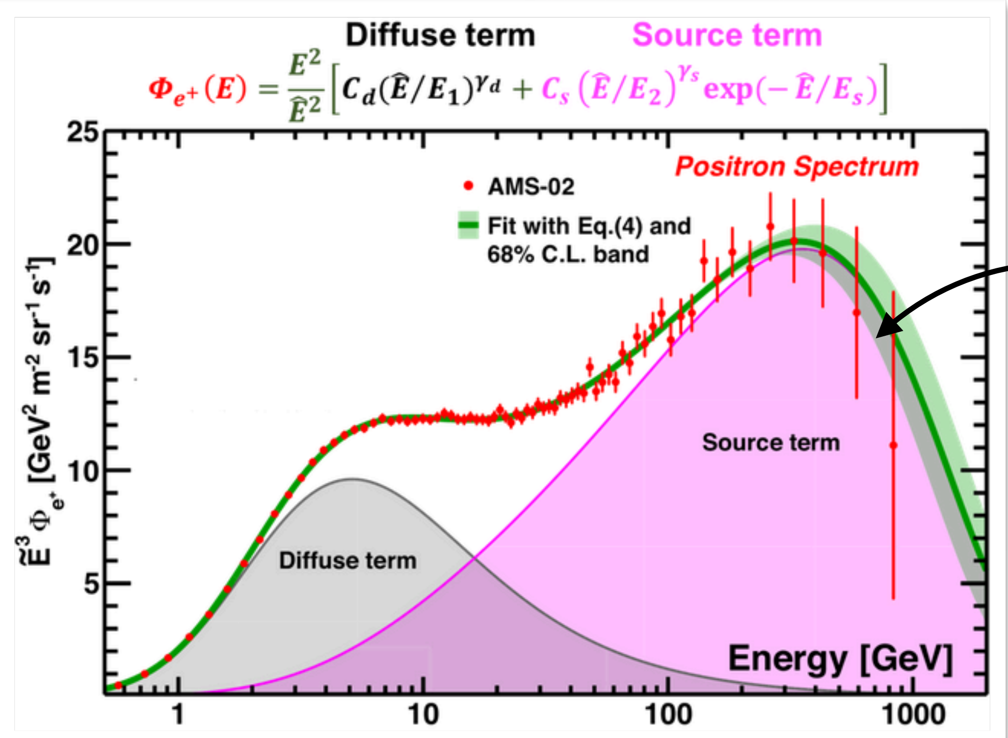


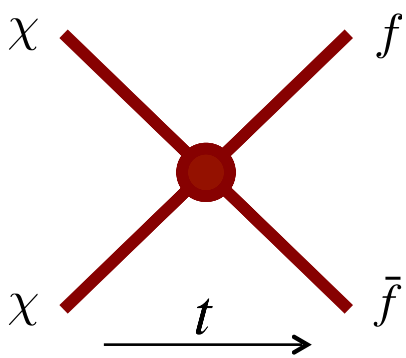
$m_\chi \simeq 1$ TeV?

Also proposed:

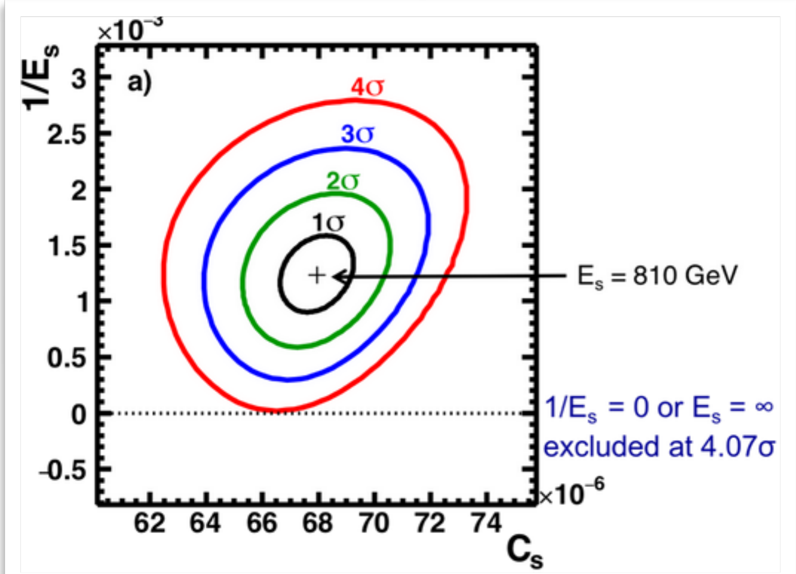
- pulsars
- quasars
- …

why cut-off at 1 TeV?



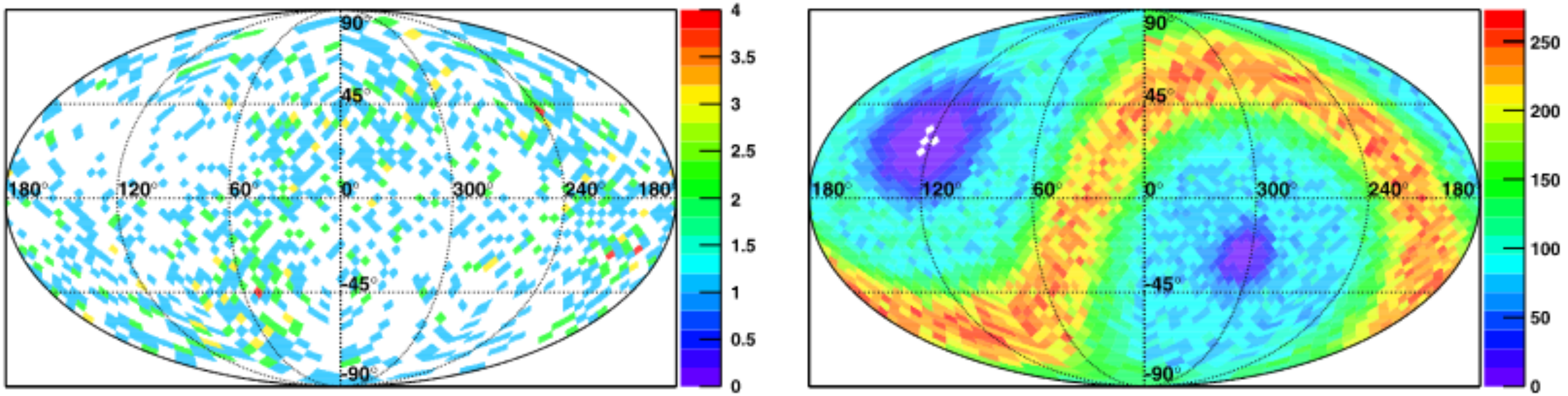


Significance of cut-off



PRL 122, 041102 (2019)

PAMELA maps: APJ, 811:21 (2015)



(a) Positrons (b) Protons

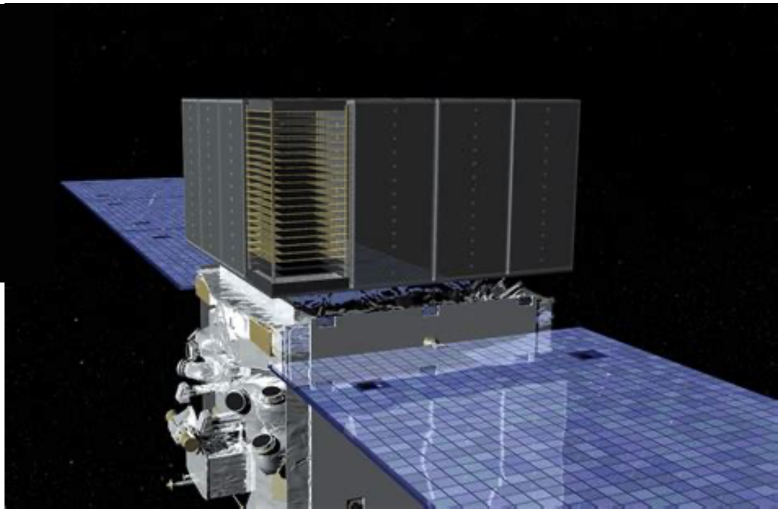
Origin of e^+ not clear:

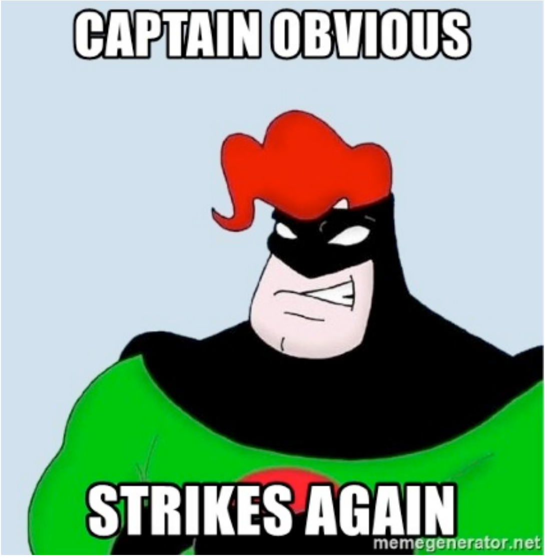
- Charged particles deflected in magnetic fields (GALPROP)
- Large uncertainties

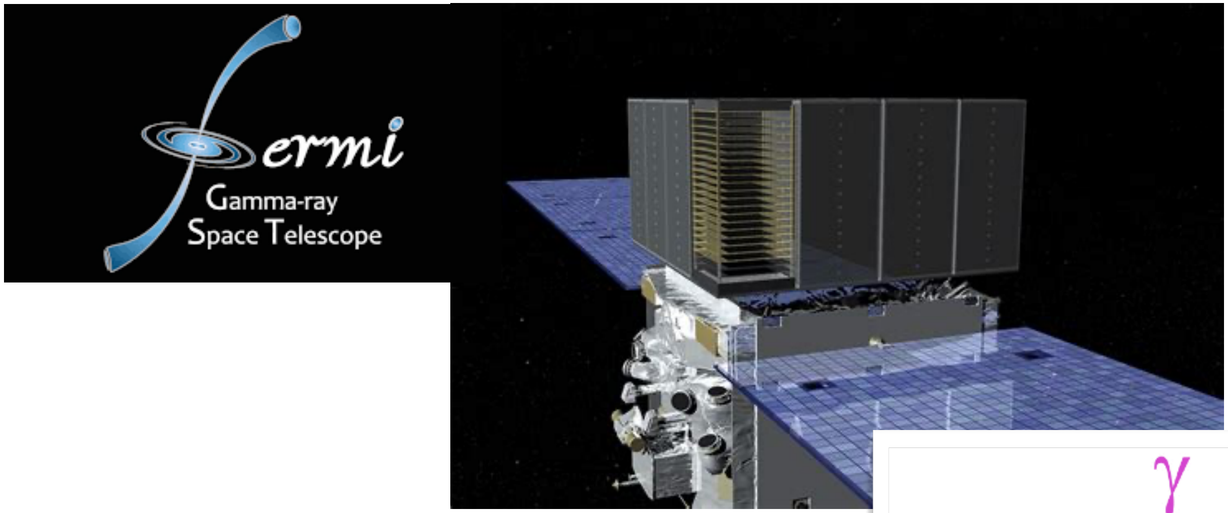
INDIRECT DETECTION: γ GALACTIC CENTRE EXCESS

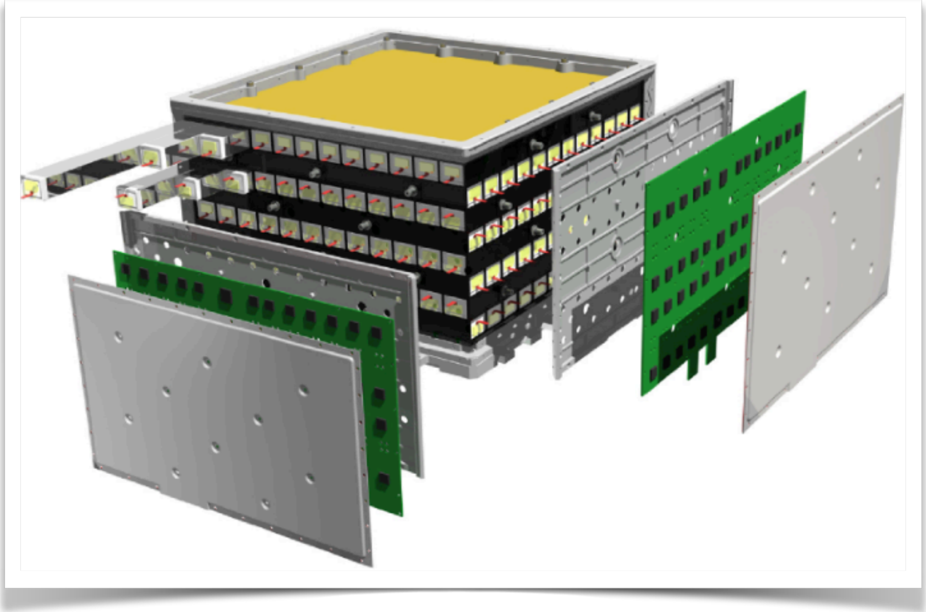
Search for energetic photons:

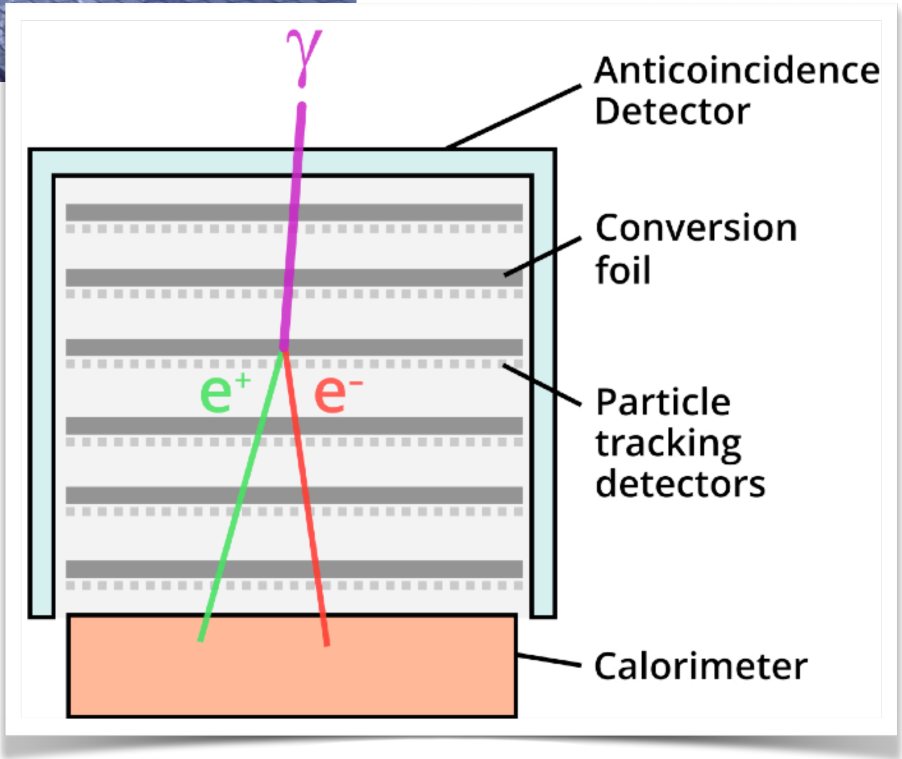
- no deflection in magnetic field
- produced in association with charged particles like e^+



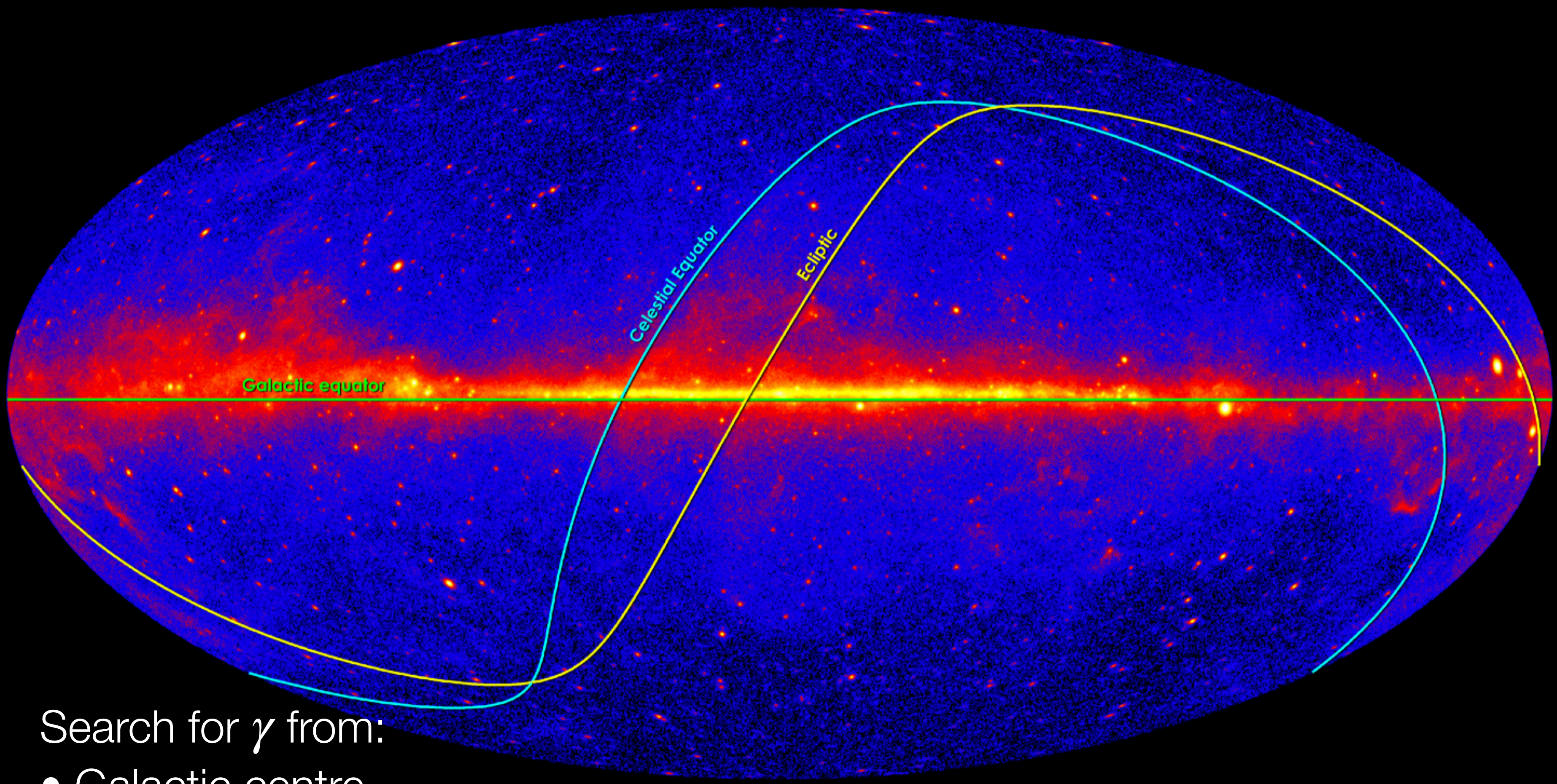



Fermi
Gamma-ray
Space Telescope




γ
Anticoincidence
Detector
Conversion
foil
e+
e−
Particle
tracking
detectors
Calorimeter

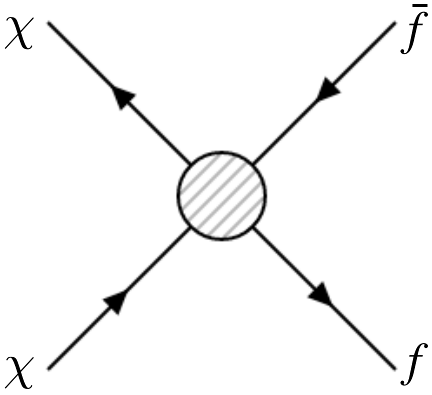
Fermi-LAT map of the γ ray sky

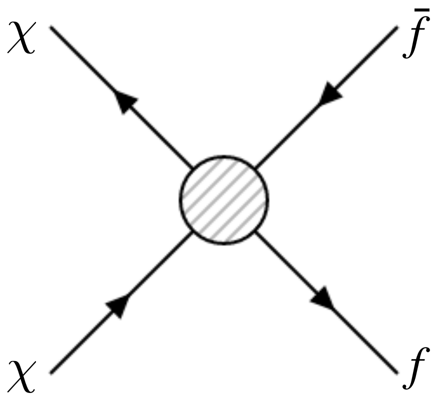


Search for γ from:

- Galactic centre
- Dwarf spheroidal galaxies

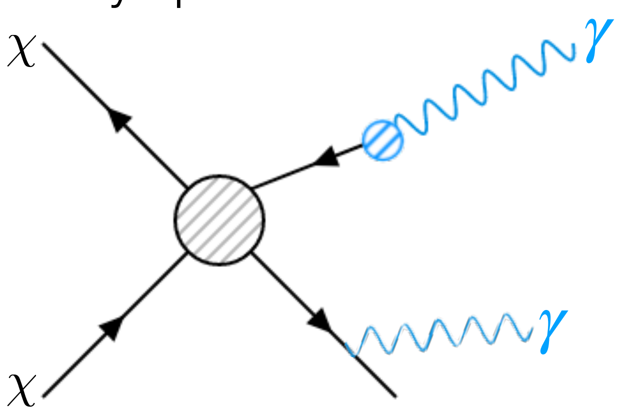
Interpret as limits on DM annihilation


χ
$\bar{f}$
χ
f



But: γ fragmentation

and γ final state radiation always possible



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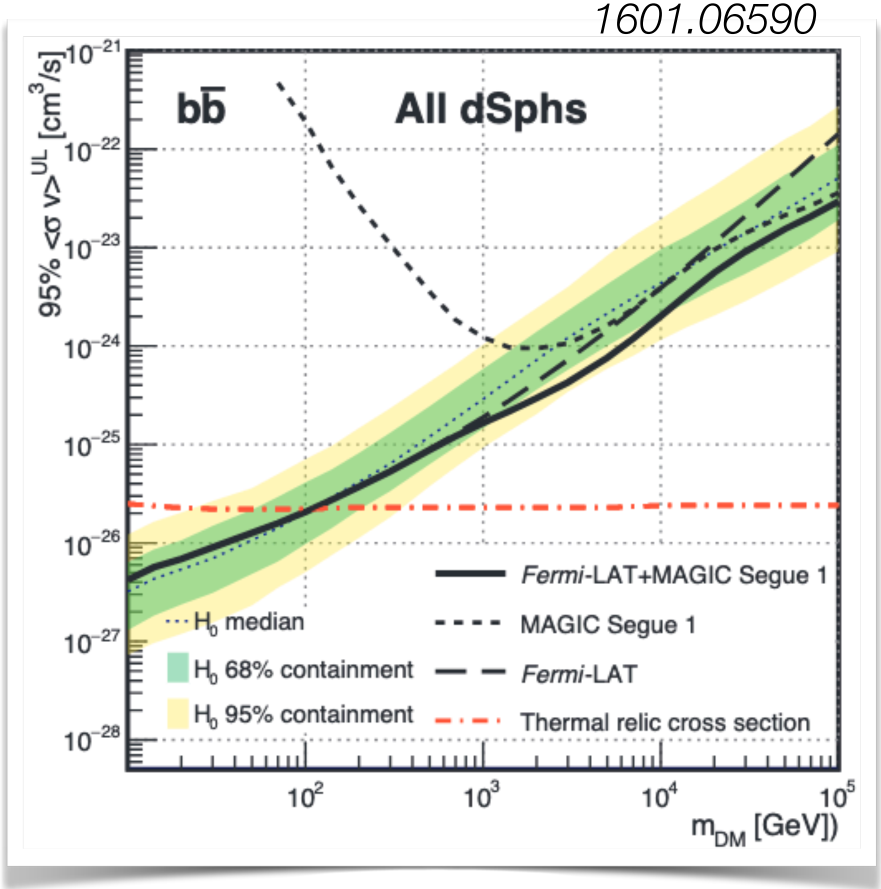
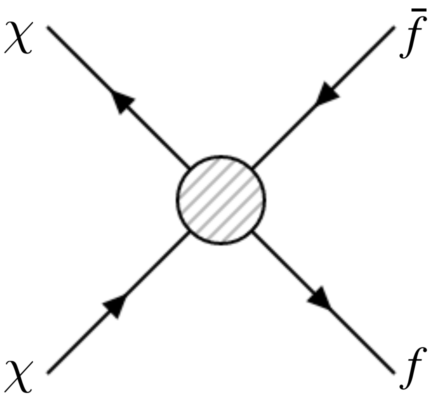


INDIRECT DETECTION: γ GALACTIC CENTRE EXCESS



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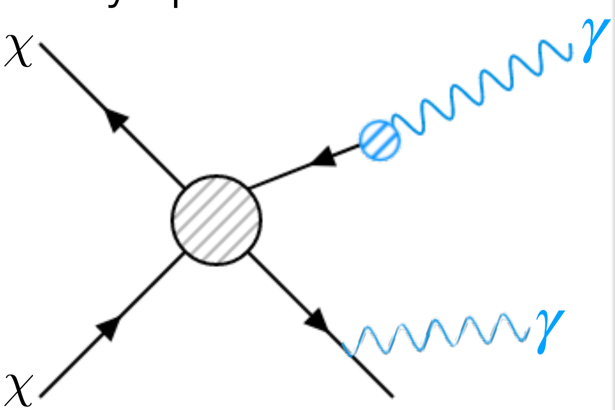

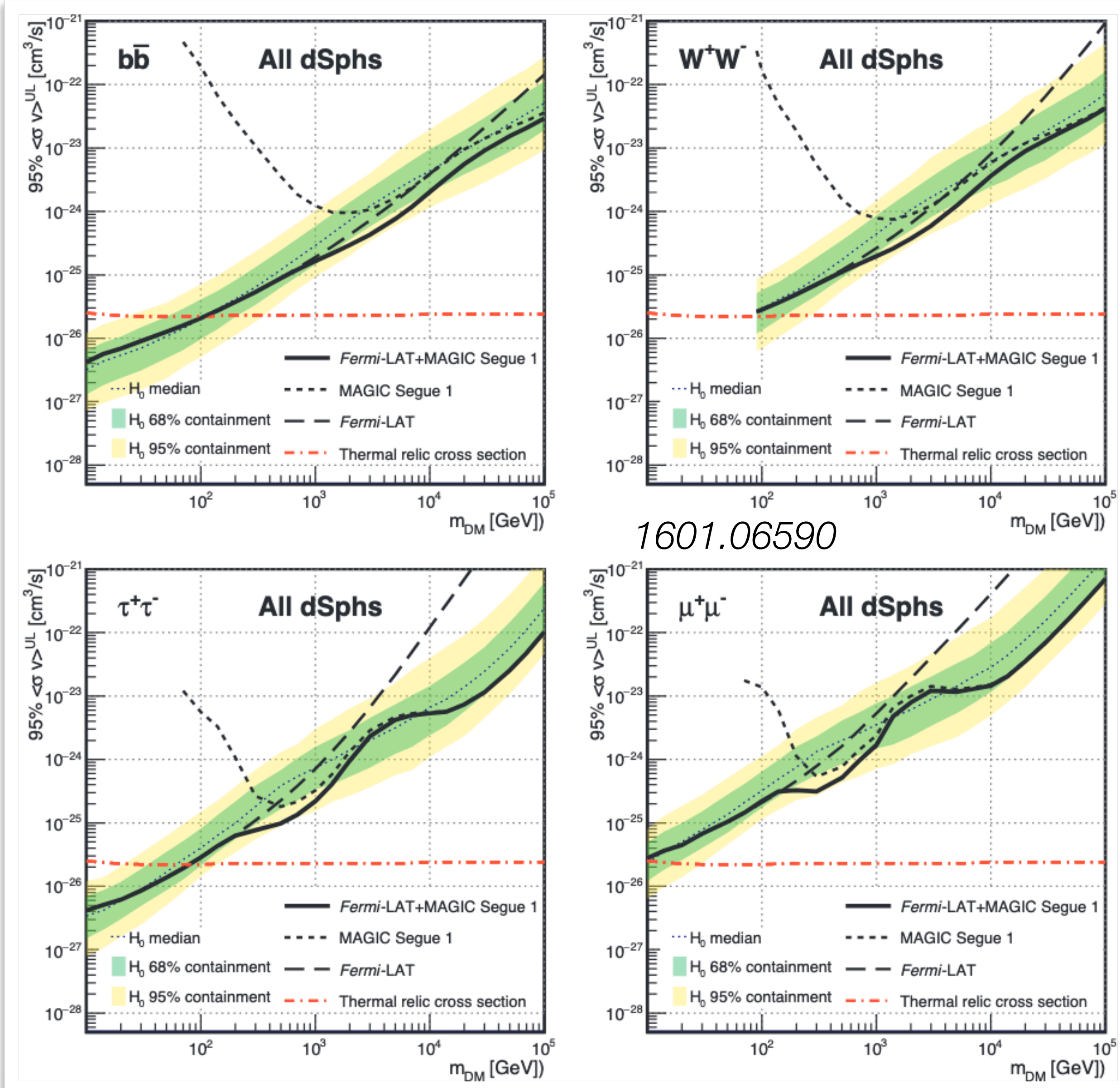

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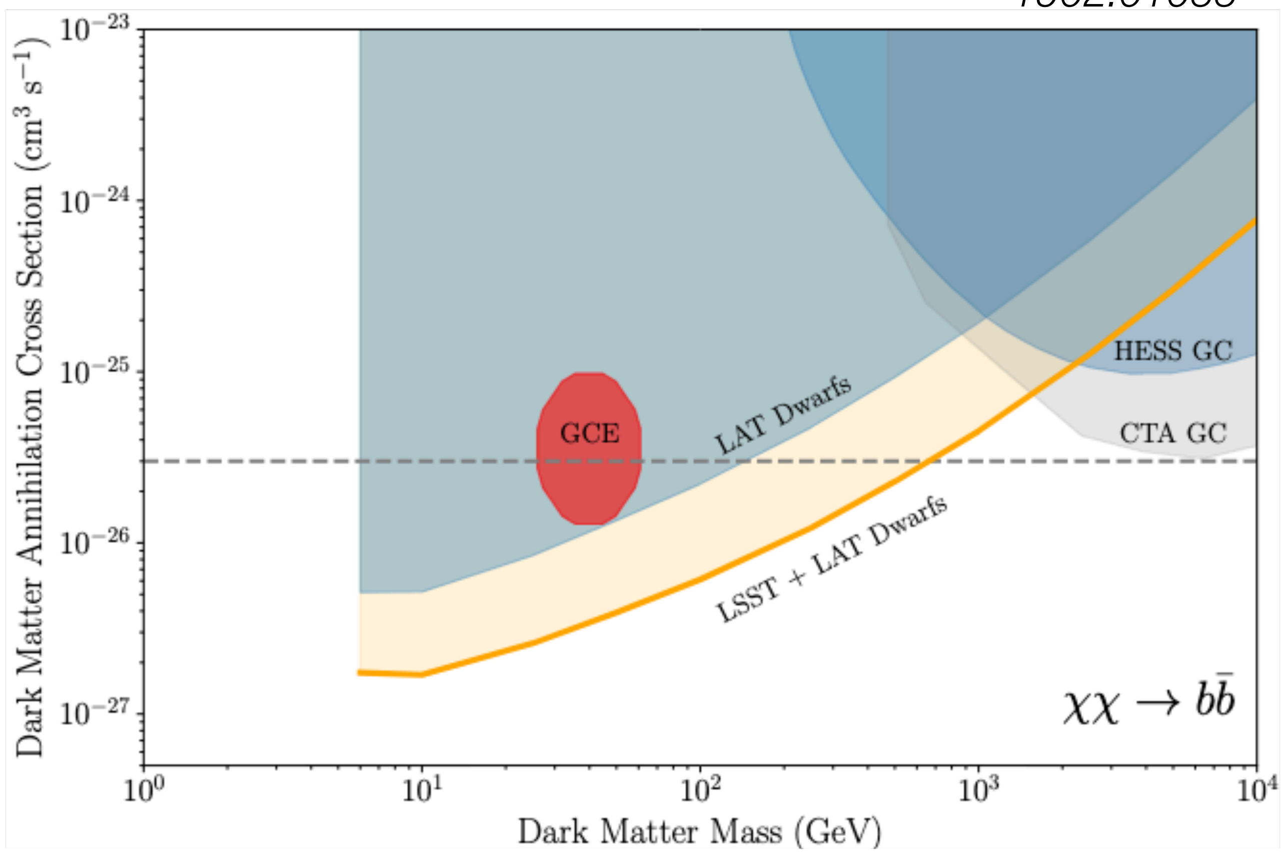
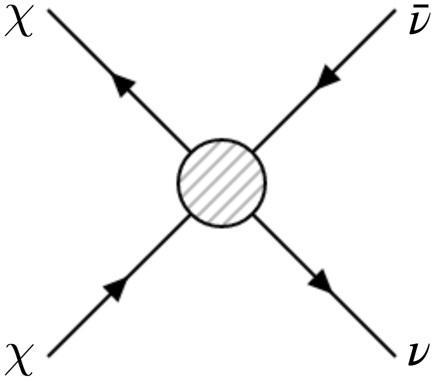
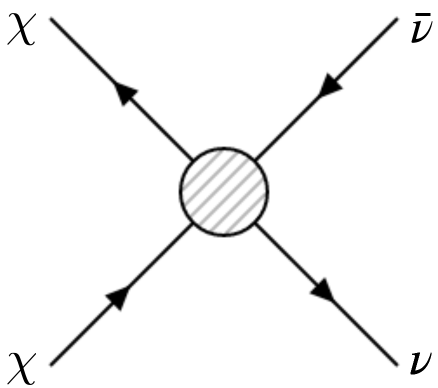
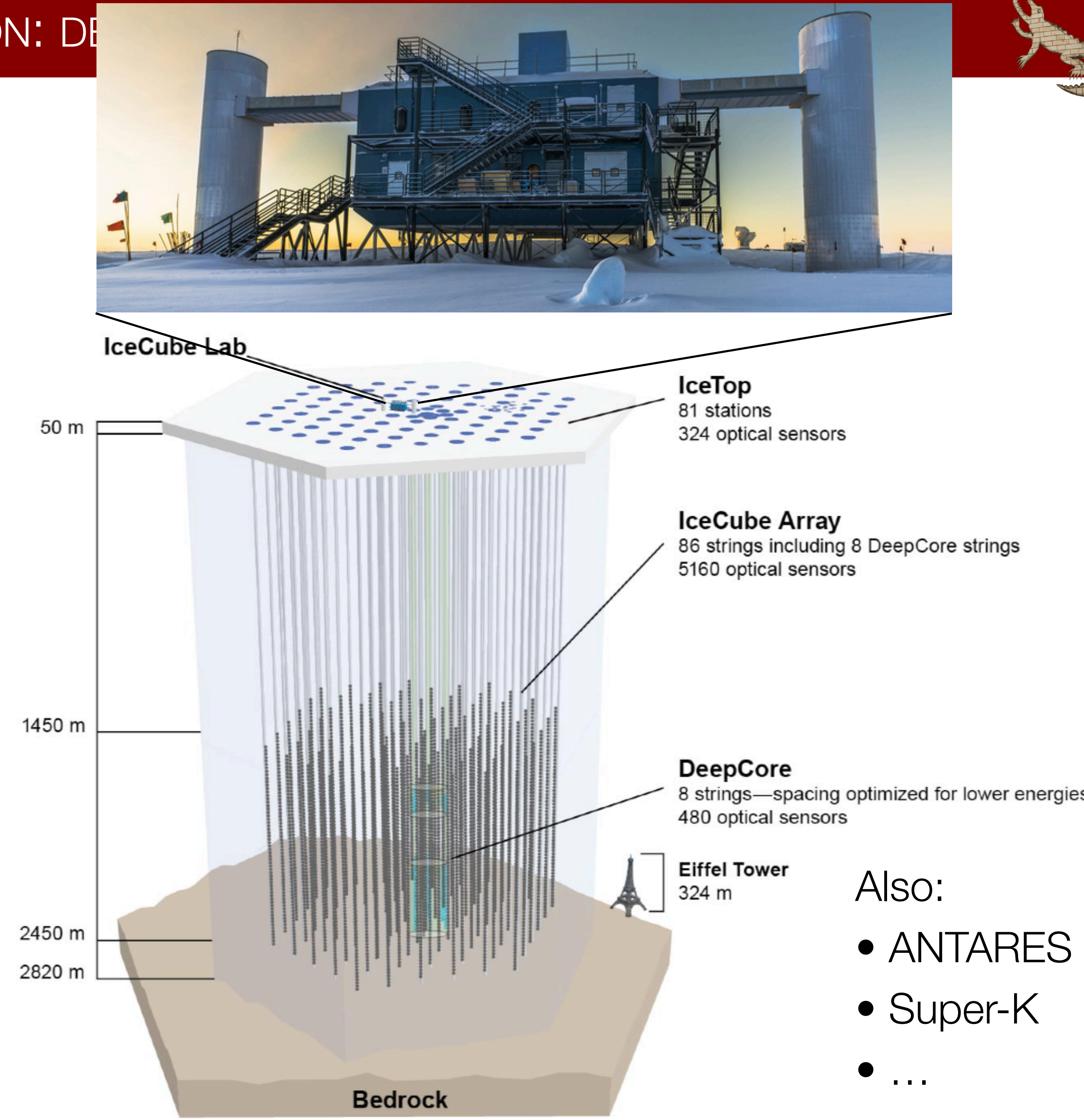


Stay tuned…

INDIRECT DETECTION: DECAYS TO SM NEUTRINOS

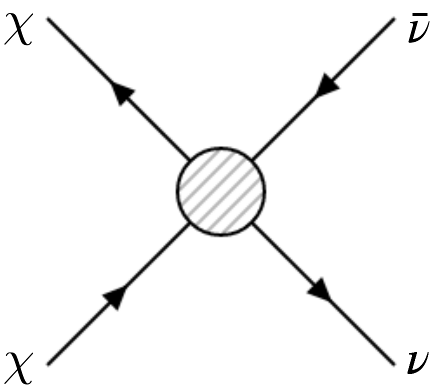


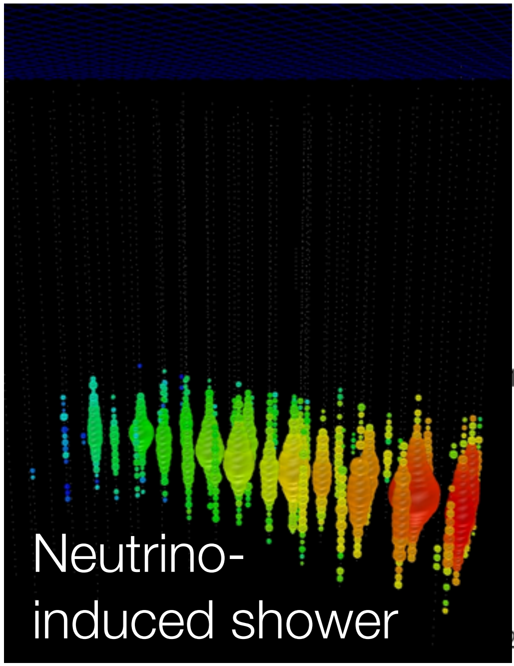


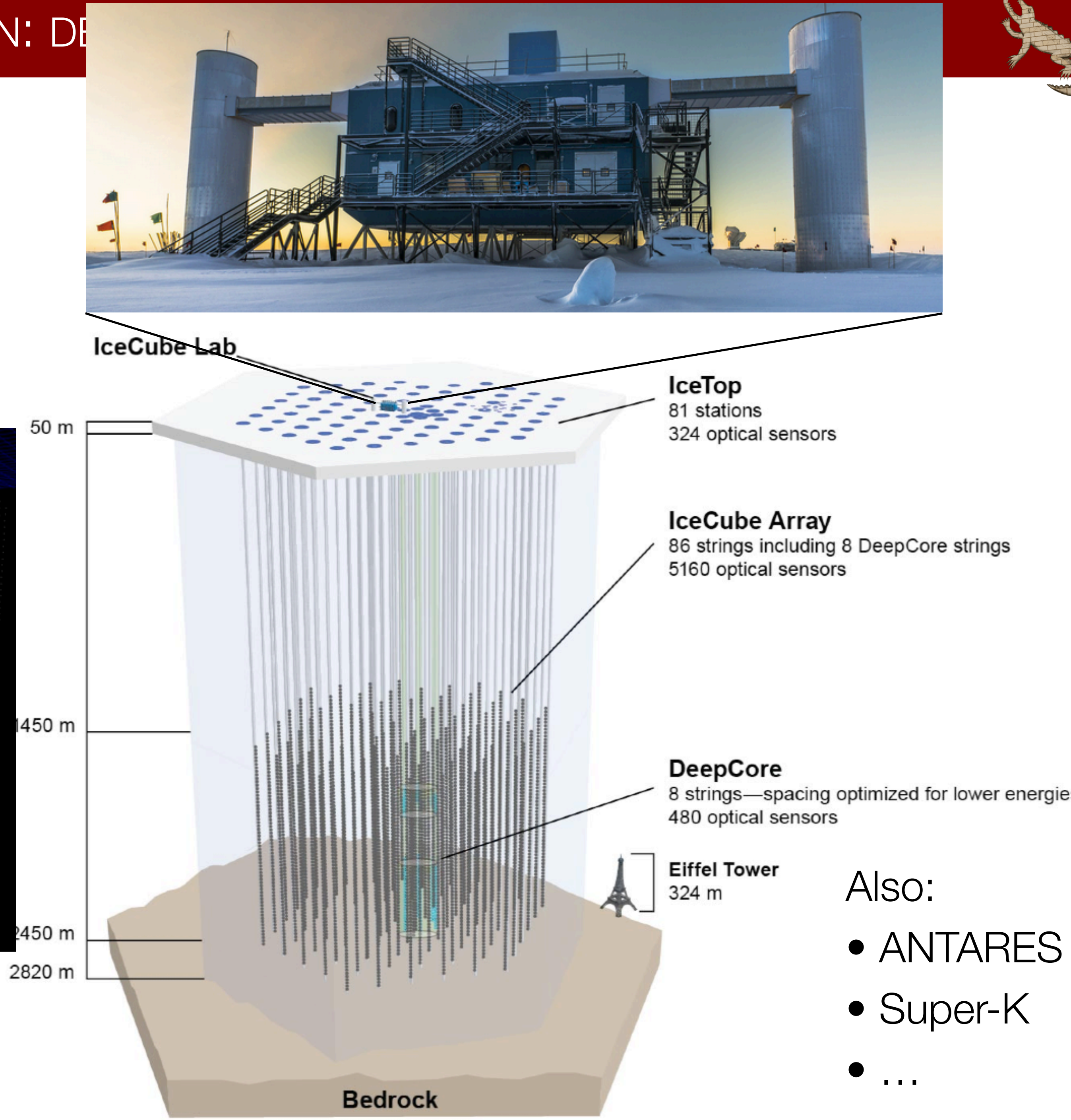


Also:

- ANTARES
- Super-K
- …

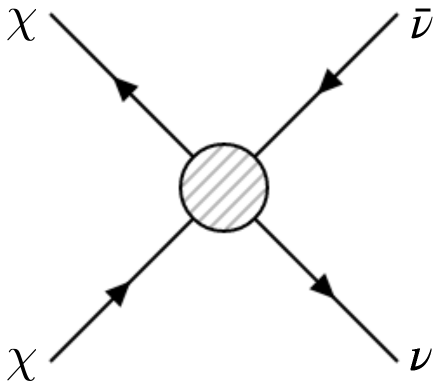




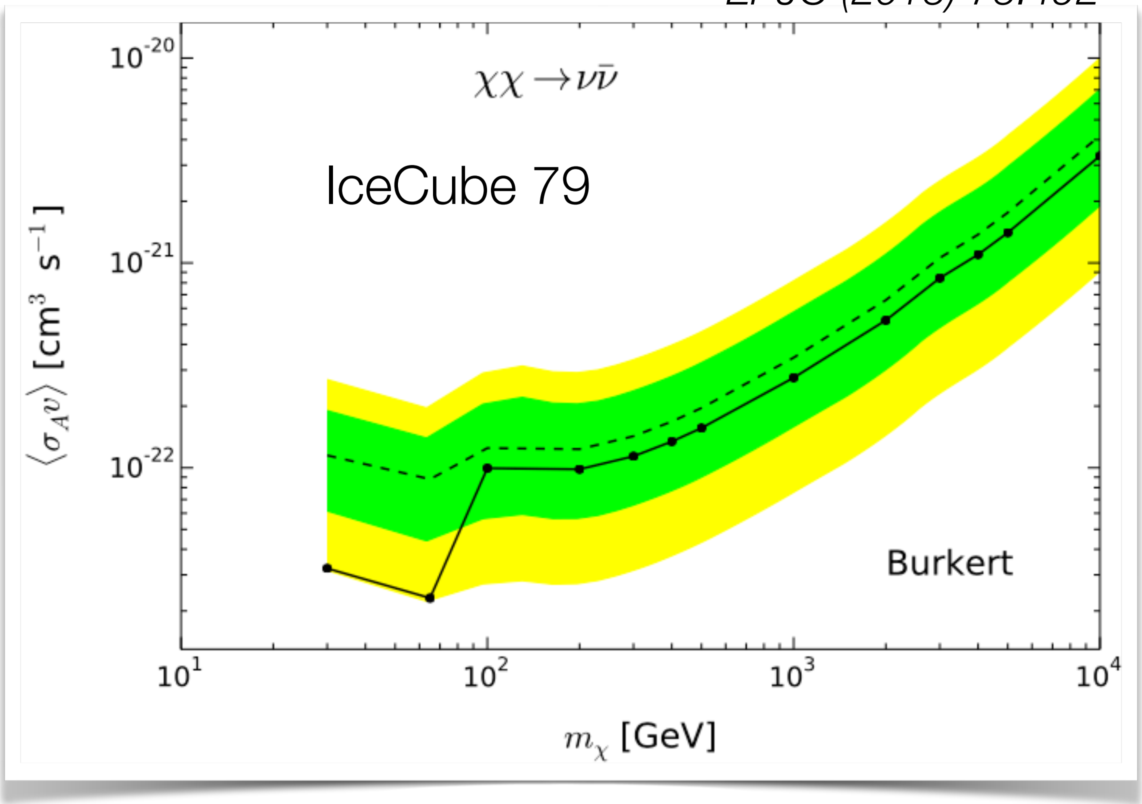


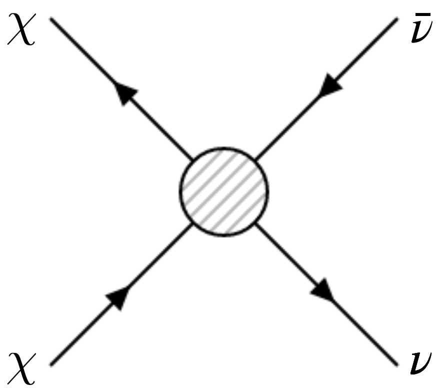
Also:

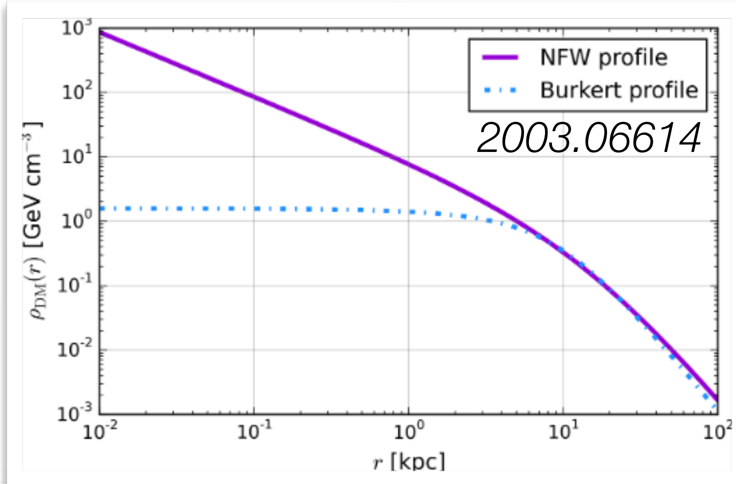
- ANTARES
- Super-K
- …

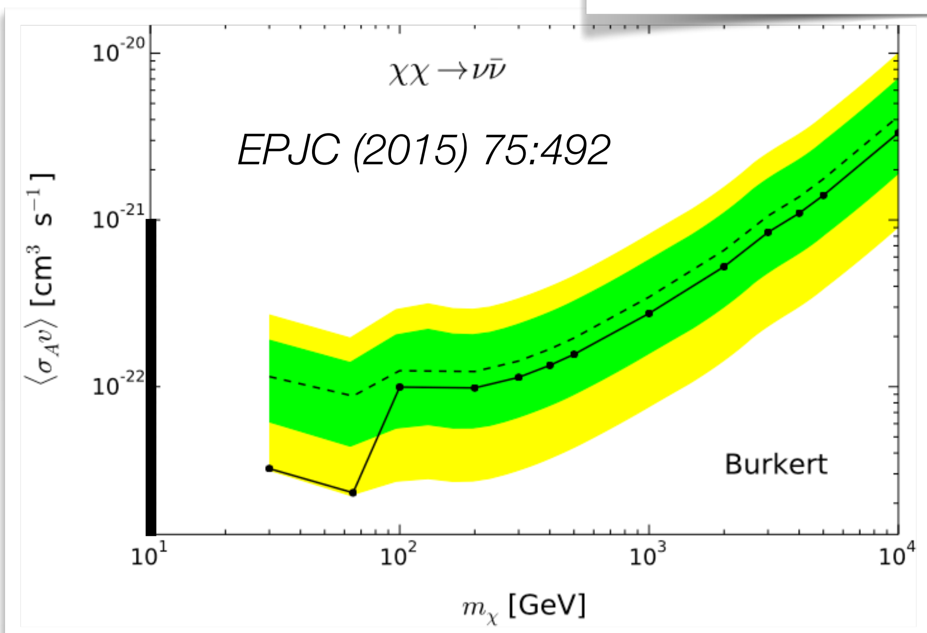


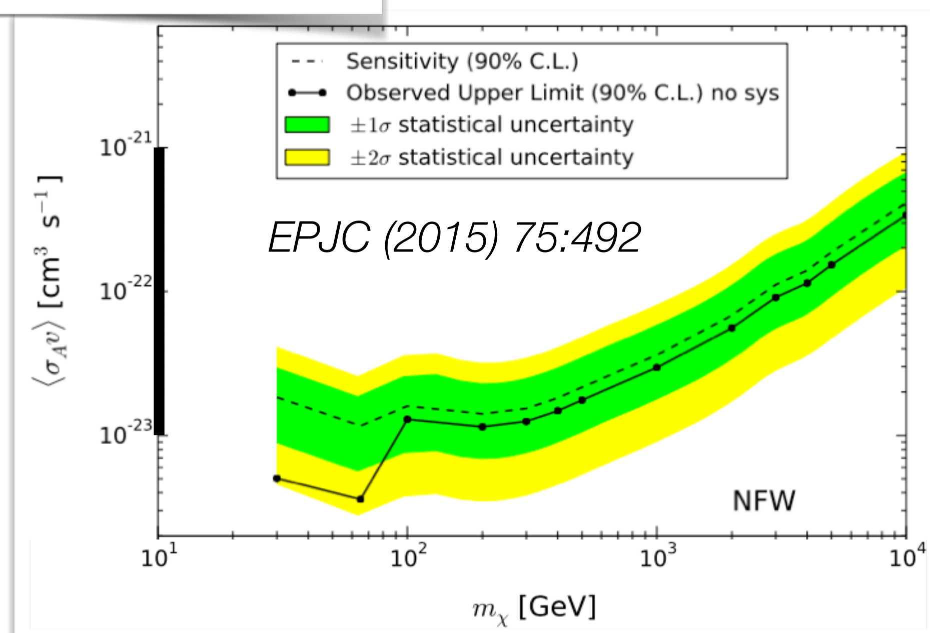
EPJC (2015) 75:492



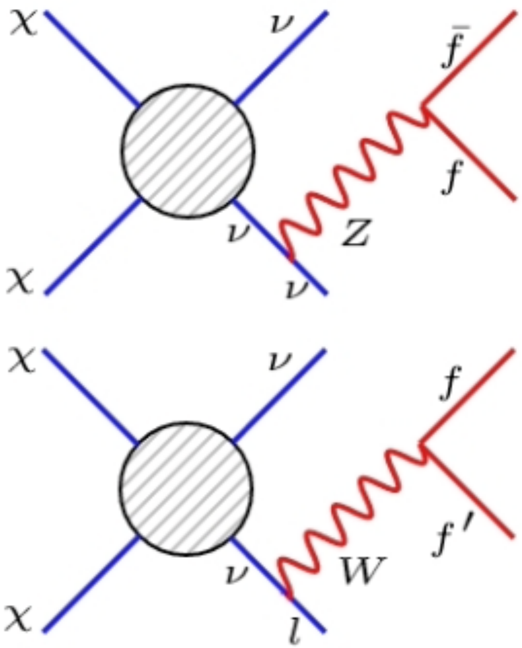








- Big impact from $\rho_{\rm DM}(r)$



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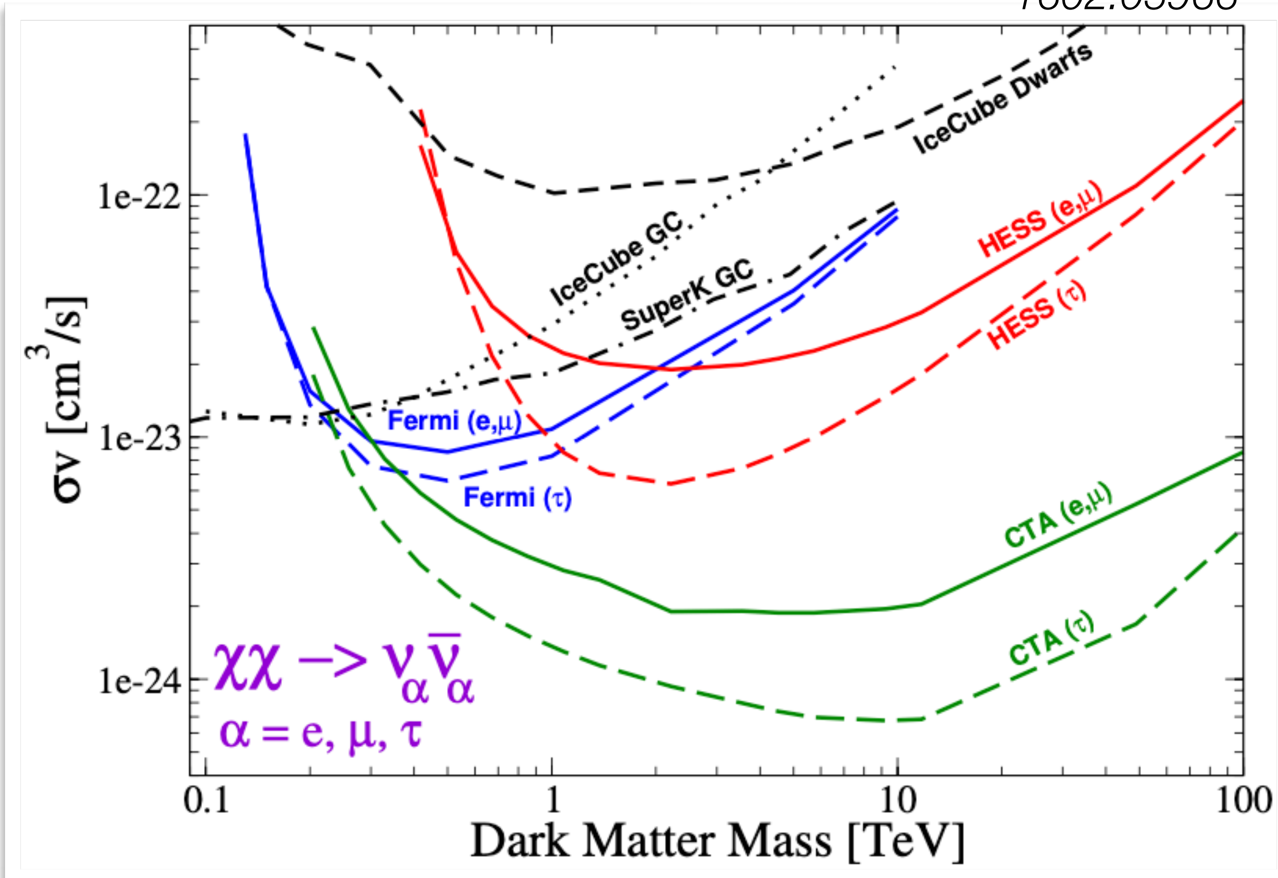
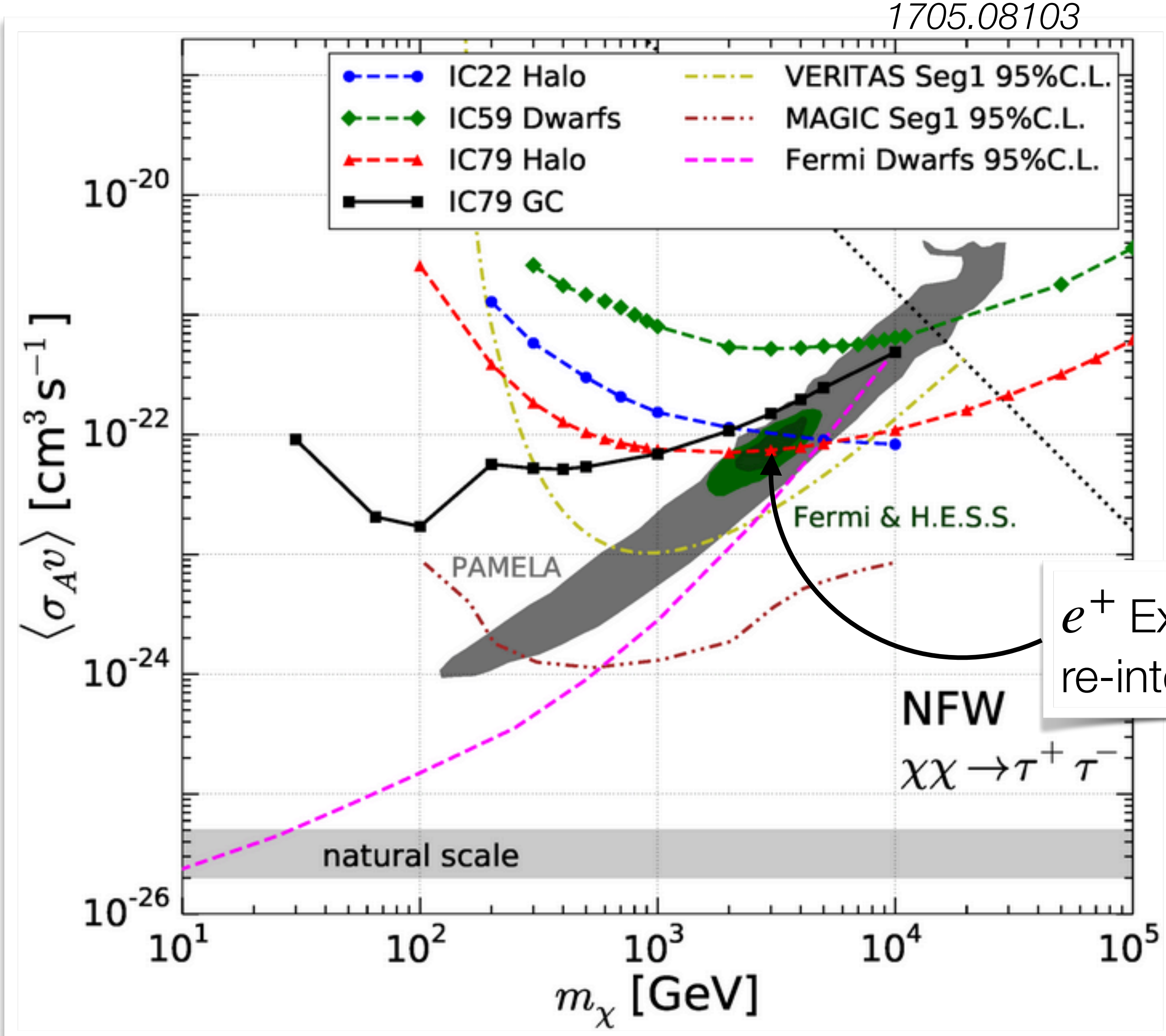


- Best limits for $m_{\mathrm{DM}} > 200$ GeV from Fermi-LAT + HESS
- Neutrino telescope confirmation indispensable

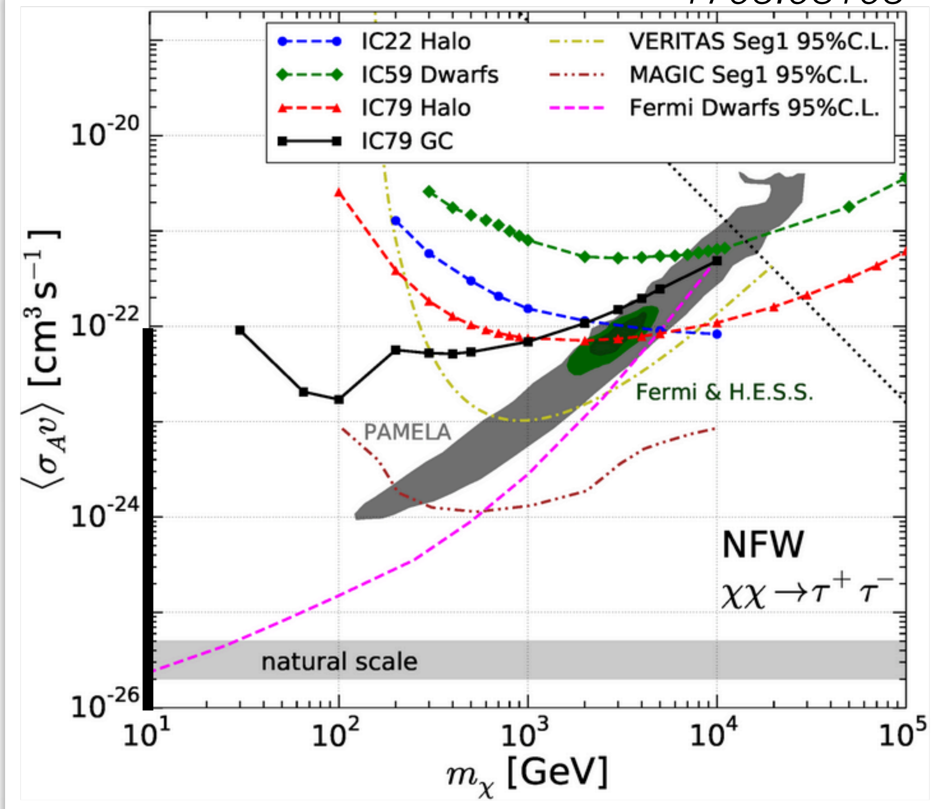
INDIRECT DETECTION: $\gamma + \nu$ AS PROBES

1705.08103

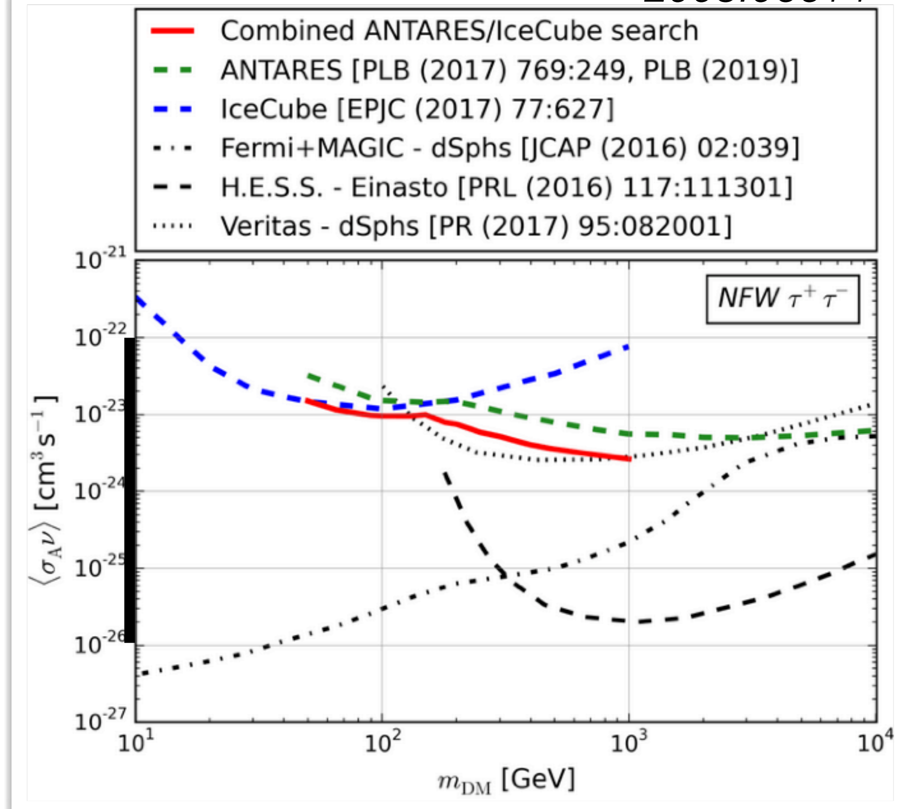


e^+ Excess re-interpretation

1705.08103



2003.06614



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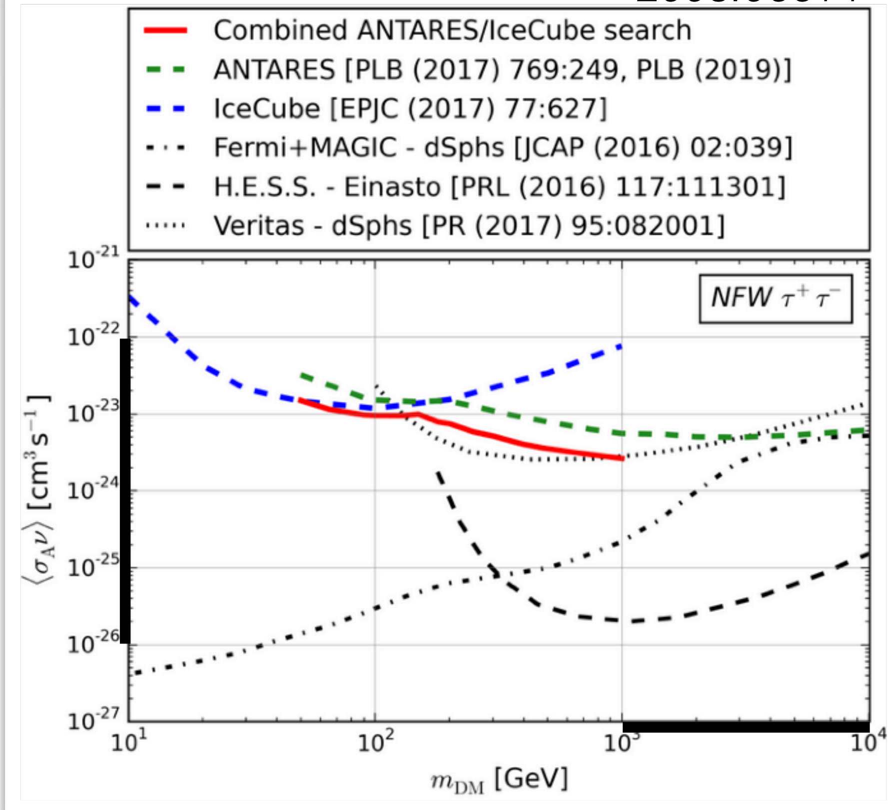
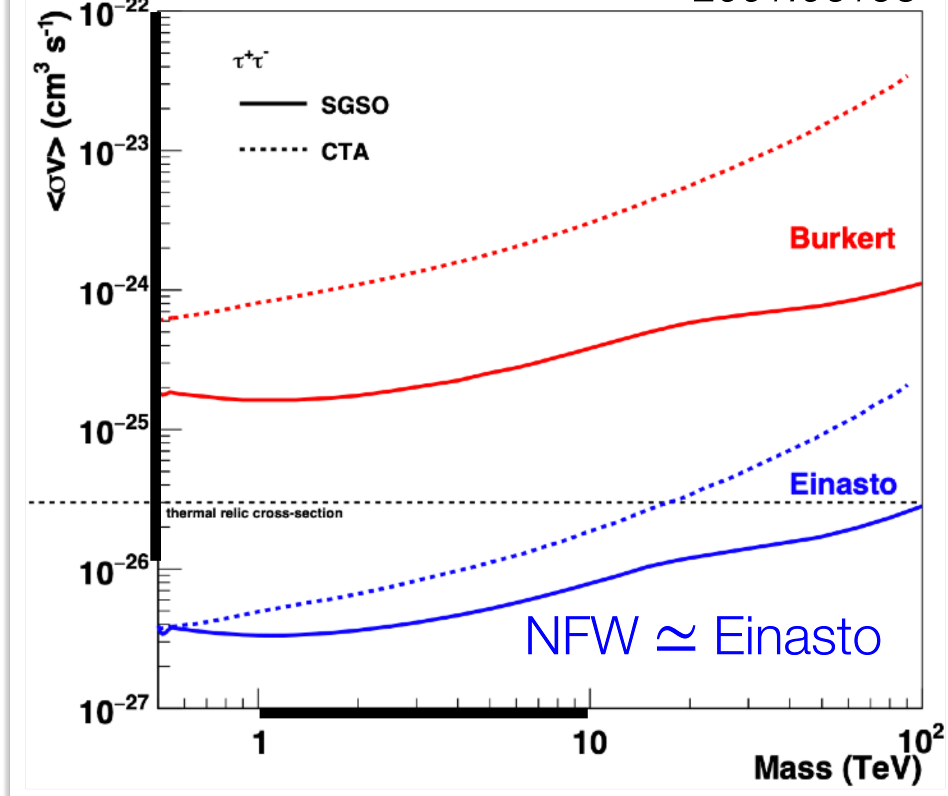
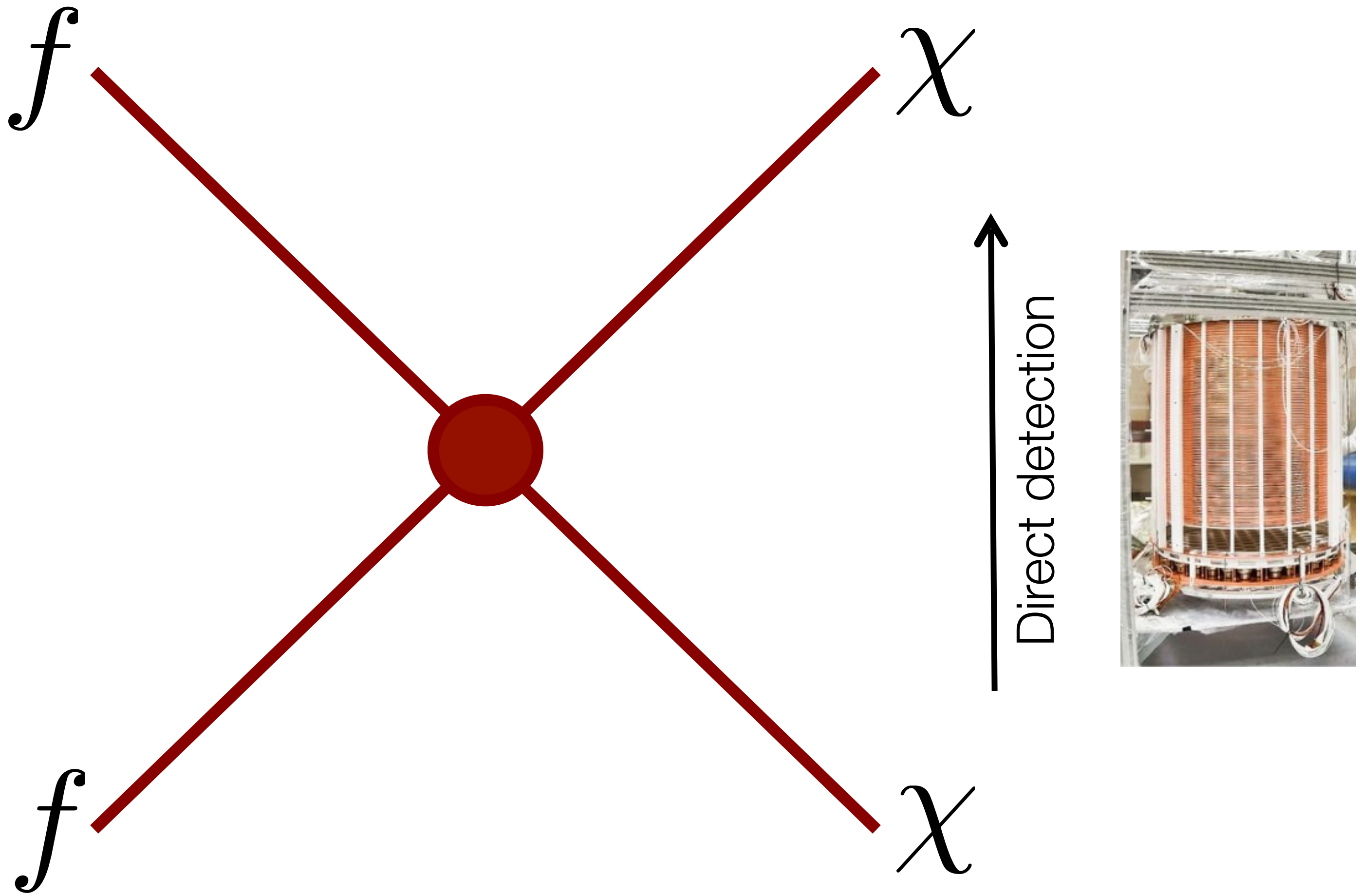
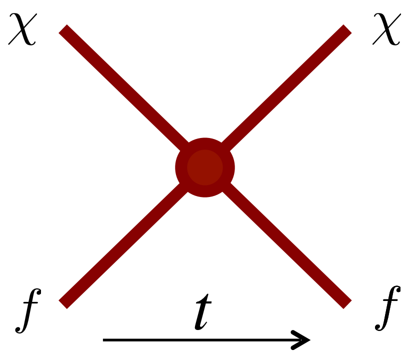


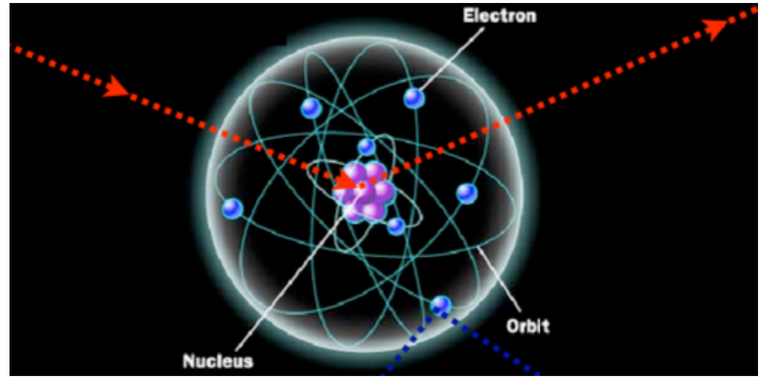
2001.06193



Exciting years ahead: CTA entering construction phase, James Webb etc…


f
χ
Direct detection
f
χ





$$\overbrace{\frac{dR}{dE}}^{Scatt.\ Rate}(E,t) = \underbrace{N_T}_{Target\ dependence} \overbrace{\frac{\rho_\chi}{m_\chi}}^{Number\ density} \int_{v_{min}} \underbrace{\frac{d\sigma}{dE}(v,E)}_{Diff.\ Cross\ Section} v \overbrace{f_E(\vec{v},t)}^{veloc.\ distribution} d^3\vec{v}$$

Measurement

Colliders, nuclear

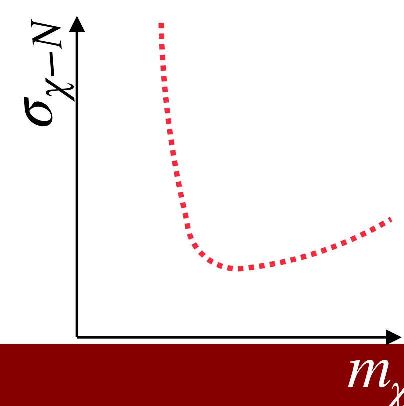
ρ: Cosmology

m_χ: model

σ: Interpretation

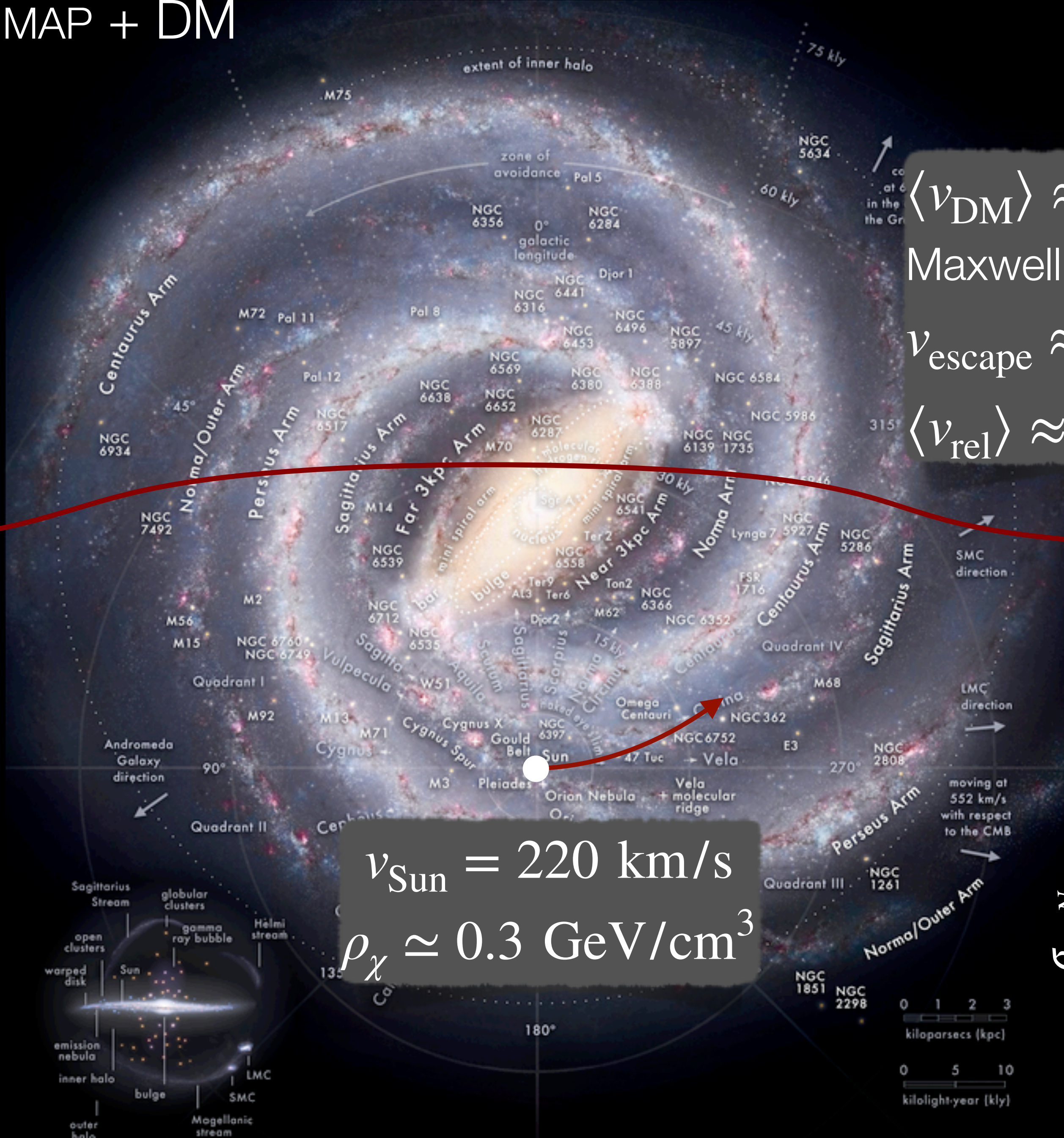
m_N: experimental handle

Cosmology



1605.08788

Milky way map + DM



$\langle v_{\rm DM}\rangle \approx 200$ km/s

Maxwell-Boltzmann

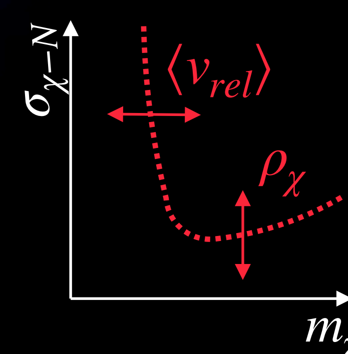
$v_{\rm escape} \approx 600$ km/s

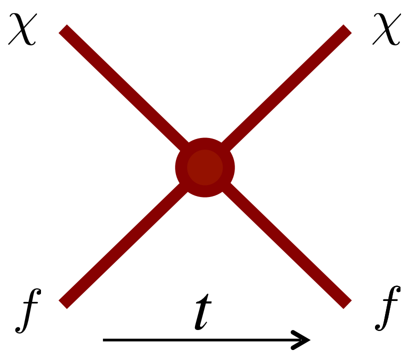
$\langle v_{\rm rel}\rangle \approx 250$ km/s

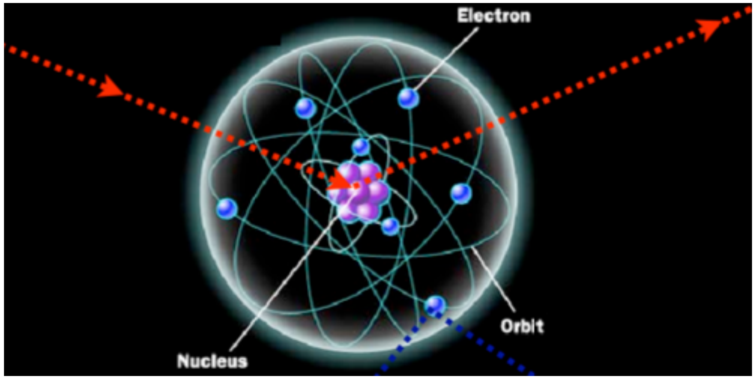
$\rho_{\rm DM}$

$v_{\rm Sun} = 220$ km/s

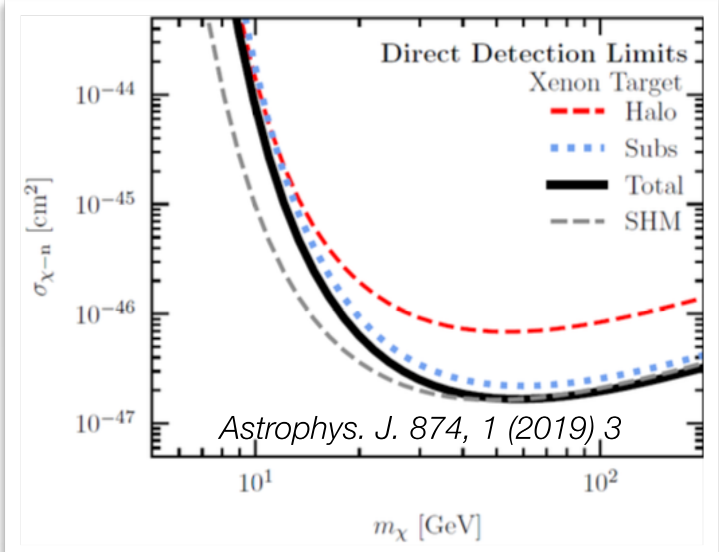
$\rho_\chi \simeq 0.3$ GeV/cm^3







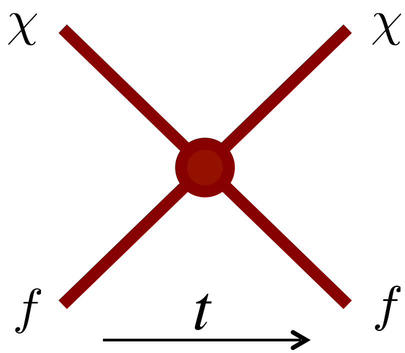
$$\overbrace{\frac{dR}{dE}(E,t)}^{Scatt.\ Rate} = \underbrace{N_T}_{Target\ dependence} \overbrace{\frac{\rho_\chi}{m_\chi}}^{Number\ density} \int_{v_{min}} \underbrace{\frac{d\sigma}{dE}(v,E)}_{Diff.\ Cross\ Section} \, v \, \overbrace{f_E(\vec{v},t)}^{veloc.\ distribution} \, d^3\vec{v}$$

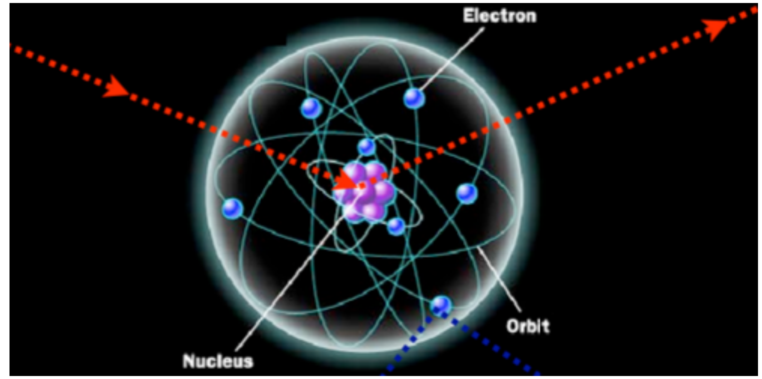


1605.08788

Benchmark for ρ_χ impact:

- background-free Xe target
- 1 kton x year
- $E_{\rm recoil}$ threshold 4.9 keV
- spin-independent scattering
- Maxwell-Boltzmann (SHM) vs. Gaia+SDSS data (Total)





$$\overbrace{\frac{dR}{dE}(E,t)}^{\text{Scatt. Rate}} = \underbrace{N_T}_{\text{Target dependence}} \overbrace{\frac{\rho_\chi}{m_\chi}}^{\text{Number density}} \int_{v_{min}} \underbrace{\frac{d\sigma}{dE}(v,E)}_{\text{Diff. Cross Section}} \, v \, \overbrace{f_E(\vec{v},t)}^{\text{veloc. distribution}} \, d^3\vec{v}$$

Measurement

Colliders, nuclear

ρ: Cosmology

m_χ: model

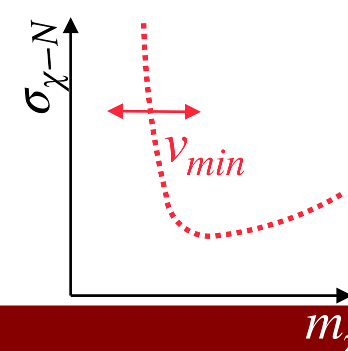
σ: Interpretation

m_N: experimental handle

Cosmology

$$v_{min} = \sqrt{\frac{m_N E}{2\mu^2}}, \; \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

min velocity for detectable recoil



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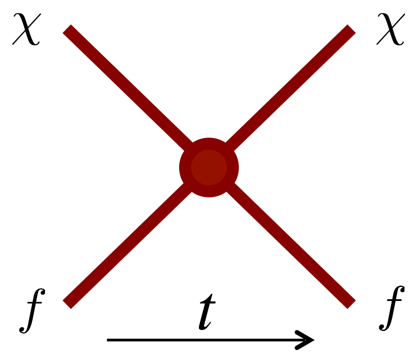

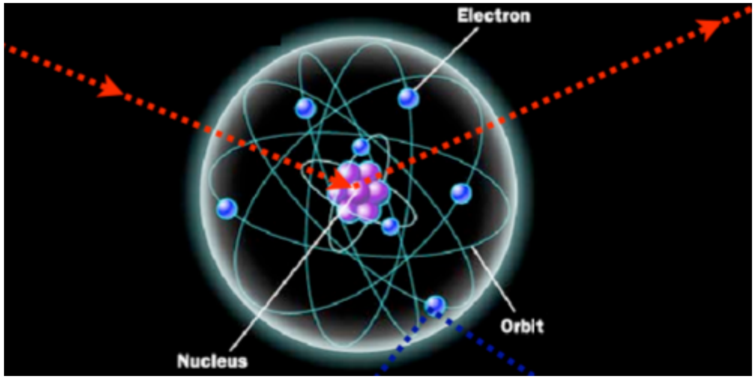

$$\overbrace{\frac{dR}{dE}(E,t)}^{Scatt.\ Rate} = \underbrace{N_T}_{Target\ dependence} \overbrace{\frac{\rho_\chi}{m_\chi}}^{Number\ density} \int_{v_{min}} \underbrace{\frac{d\sigma}{dE}(v,E)}_{Diff.\ Cross\ Section} \; v \; \overbrace{f_E(\vec{v},t)}^{veloc.\ distribution} \; d^3\vec{v}$$

Measurement

Colliders, nuclear

ρ: Cosmology

m_χ: model

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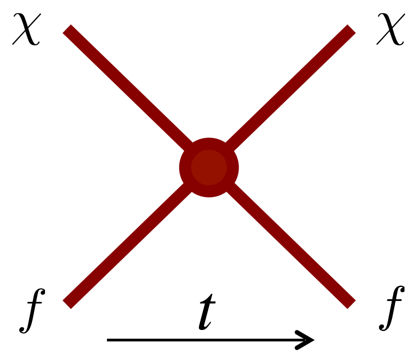
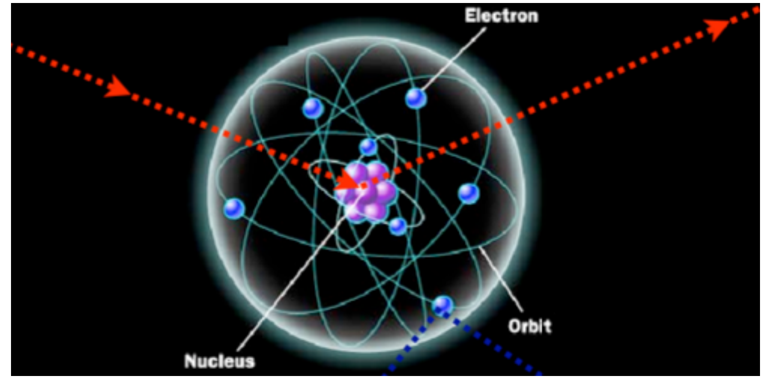
m_N: experimental handle

Cosmology

$$\frac{d\sigma}{dE} = \frac{m_N}{2\mu^2 v^2}(\sigma_{SI} F^2(q) + \sigma_{SD} S(q))$$

1605.08788





$$\frac{d\sigma}{dE} = \frac{m_N}{2\mu^2 v^2}(\sigma_{SI}F^2(q) + \sigma_{SD}S(q))$$

Target choice: the ONLY experimental handle!

Spin-independent:
- vector coupling
- scalar coupling

P

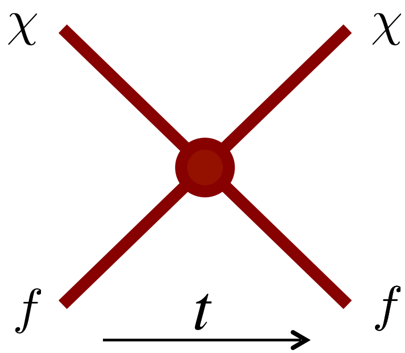
DM interaction with:
any nucleon in nucleus
→ enhancement $\propto A^2$

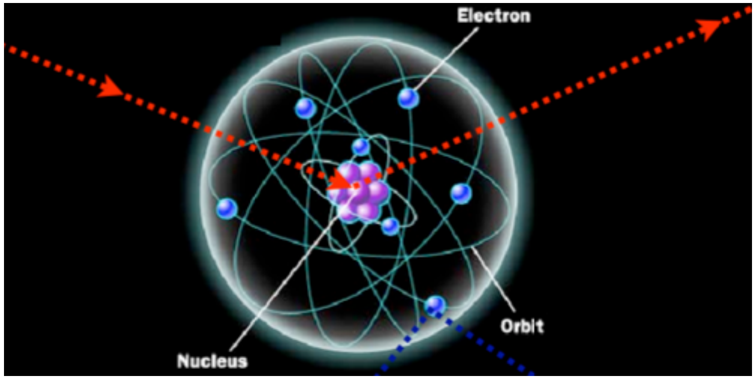
Spin-dependent:
- axial-vector coupling
- pseudoscalar coupling

$\not{P}$

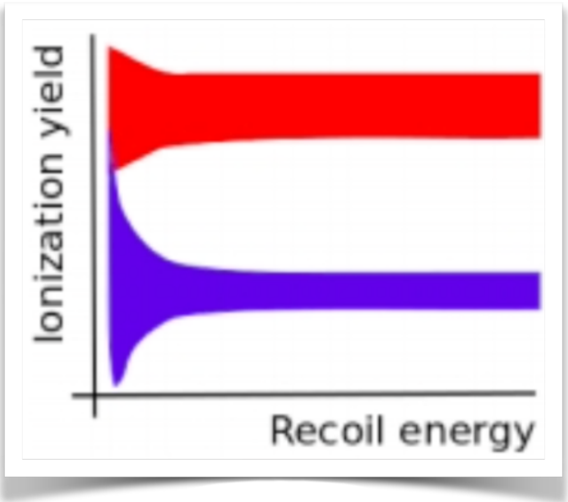
DM interaction with:
spin of unpaired p or n
→ optimise for u or d, $\propto A$

1605.08788

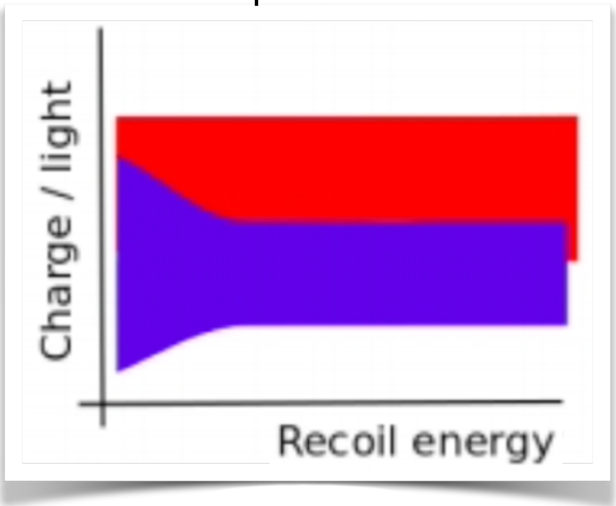




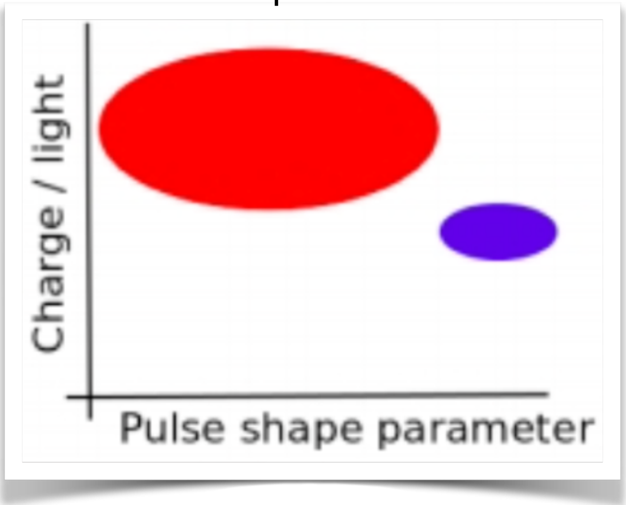
Germanium



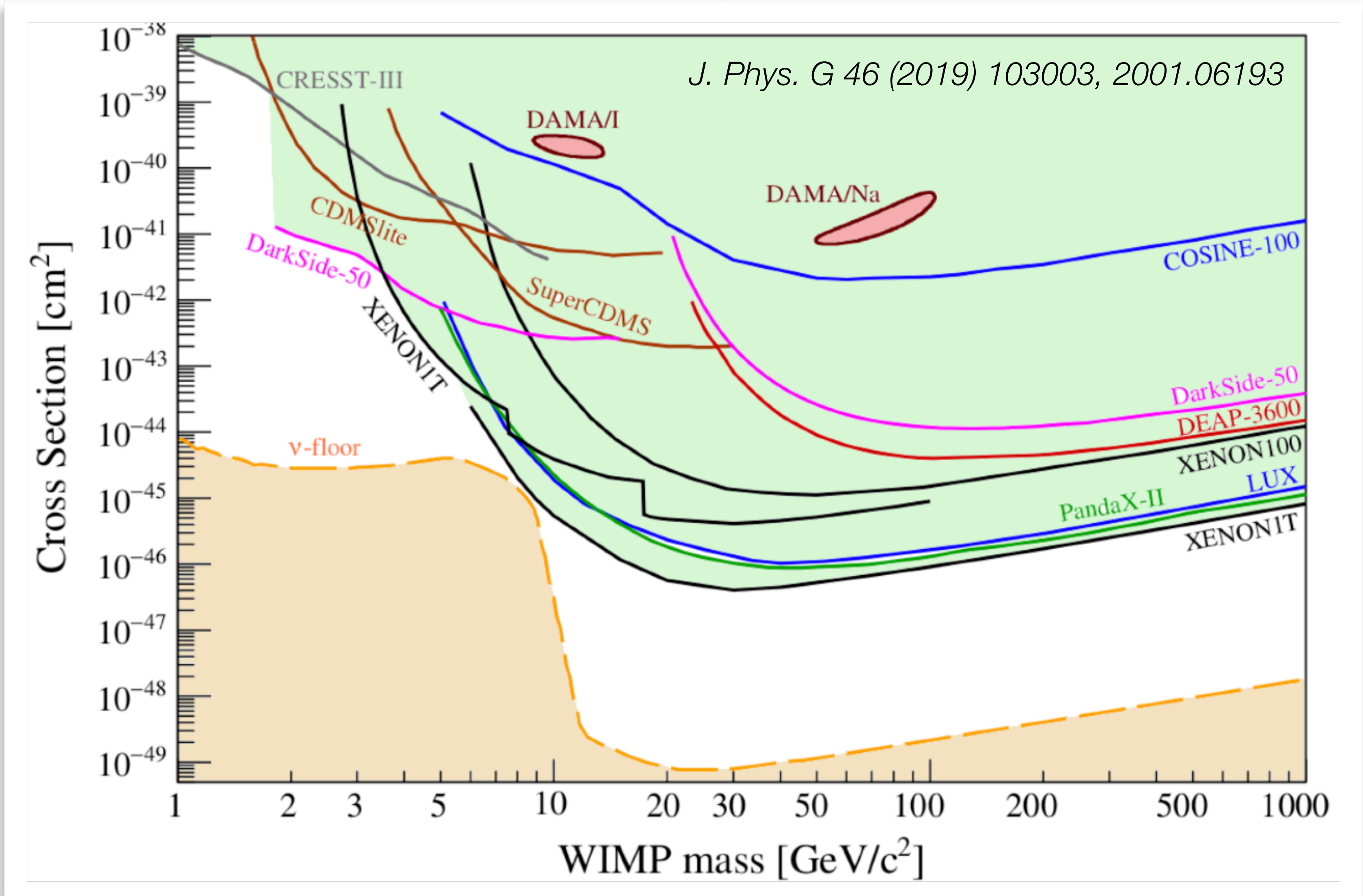
Liquid Xe

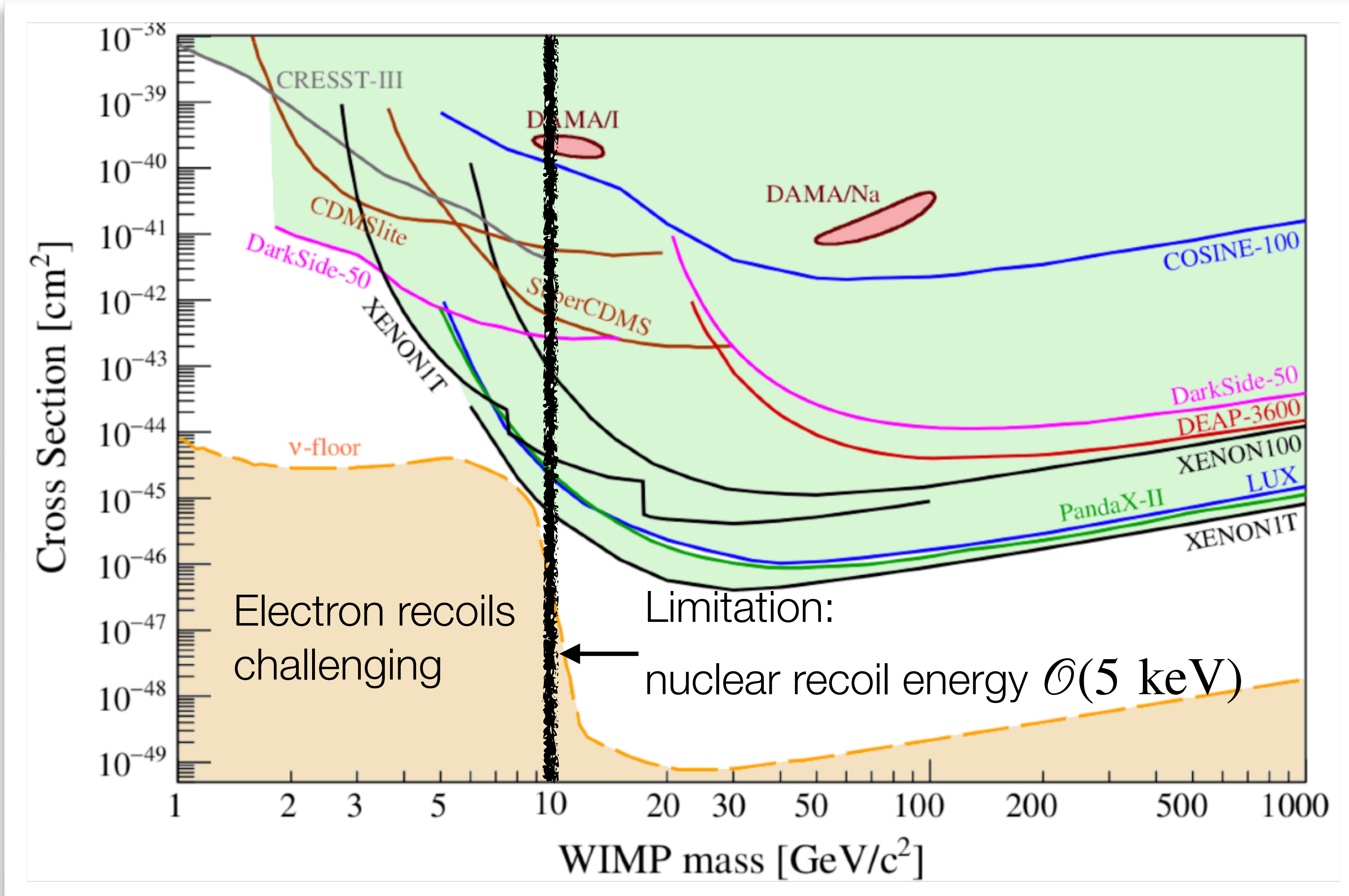


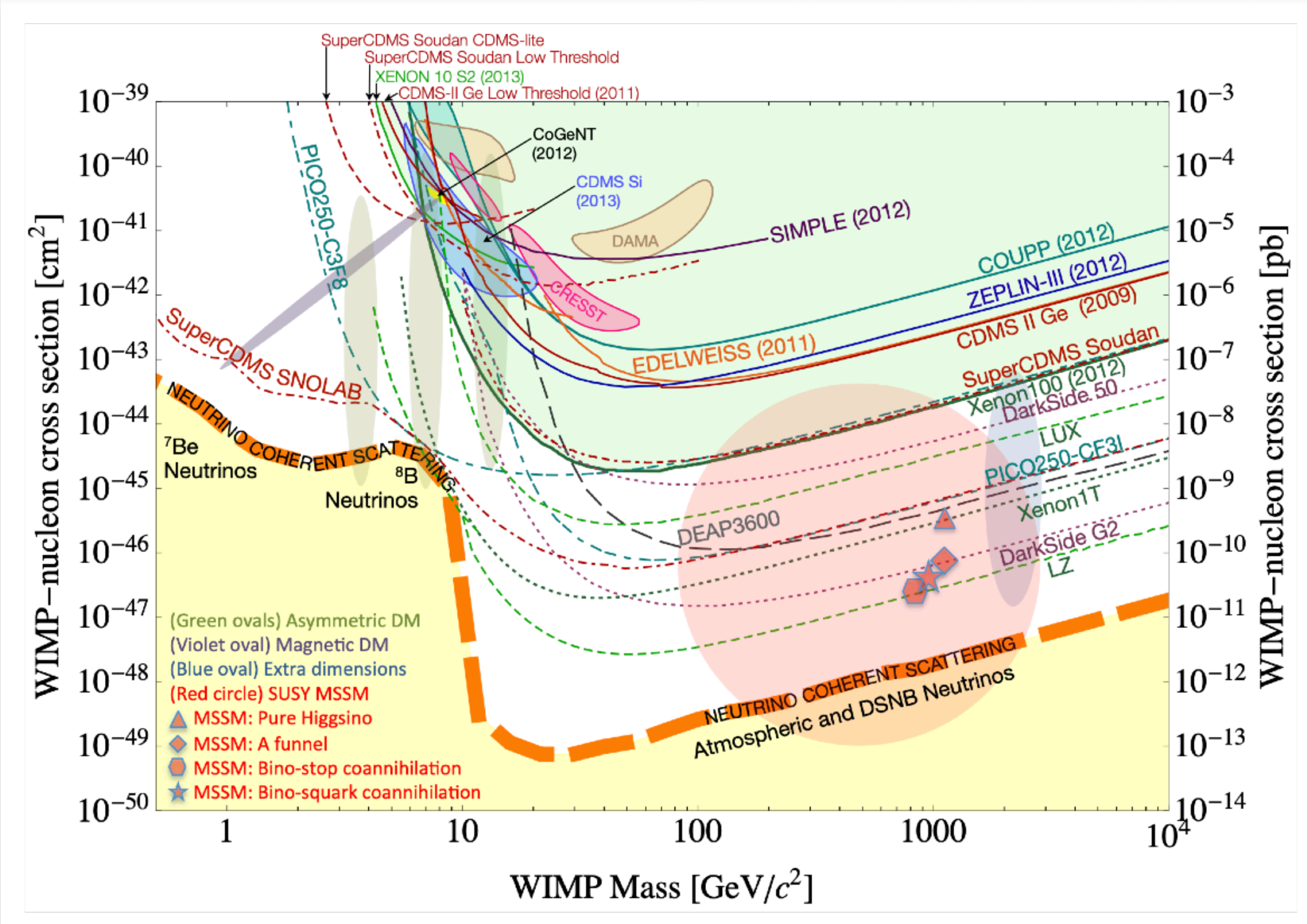
Liquid Ar



1605.08788


J. Phys. G 46 (2019) 103003, 2001.06193
Cross Section [cm²]
WIMP mass [GeV/c²]
CRESST-III
DAMA/I
DAMA/Na
CDMSlite
DarkSide-50
SuperCDMS
XENON1T
COSINE-100
DarkSide-50
DEAP-3600
XENON100
LUX
PandaX-II
XENON1T
ν-floor


Cross Section [cm^2]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
1
2
3
5
10
20
30
50
100
200
500
1000
WIMP mass [GeV/c^2]
CRESST-III
DAMA/I
DAMA/Na
CDMSlite
DarkSide-50
XENON1T
SuperCDMS
COSINE-100
DarkSide-50
DEAP-3600
XENON100
LUX
PandaX-II
XENON1T
ν-floor
Electron recoils challenging
Limitation:
nuclear recoil energy $\mathcal{O}(5\ \text{keV})$



The next decade will be very exciting!

(in the standard single WIMP paradigm)

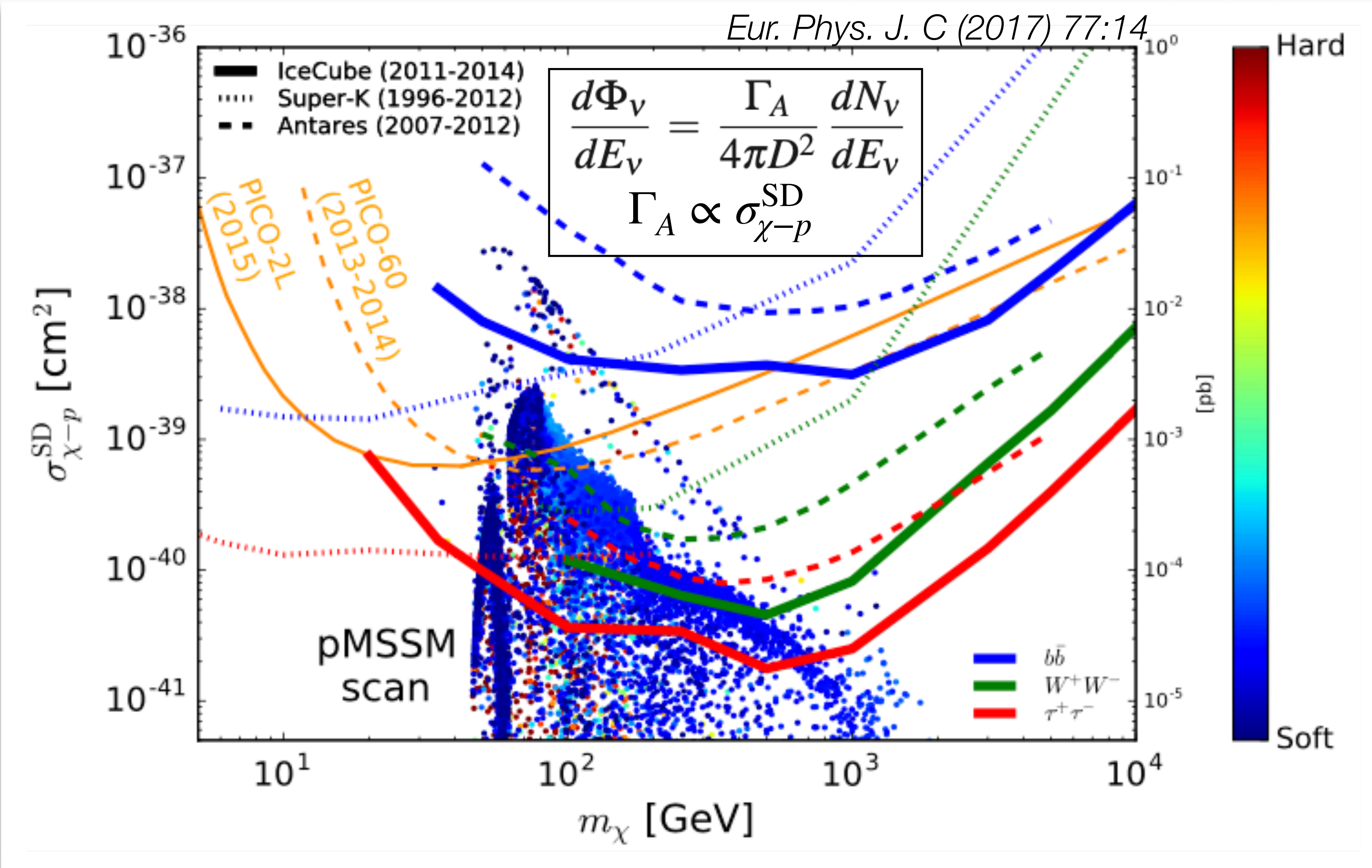
- DM annihilation in Sun, e.g., $\chi\chi \to b\bar{b}, \tau\bar{\tau}, W^+W^-$
  - *Only* neutrinos as probe
    - Almost background-free: $E_\nu > 1\ \mathrm{GeV}$
  - Neutrino telescopes: ANTARES, Ice Cube, Super-K, etc.
    - Look for neutrino-induced showers from the Sun
  - Equilibrium: DM annihilation rate $\Gamma_A \leftrightarrow$ DM capture rate

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi D^2}\frac{dN_\nu}{dE_\nu} \quad \text{and} \quad \Gamma_A \propto \sigma^{\mathrm{SD}}_{\chi-p}$$

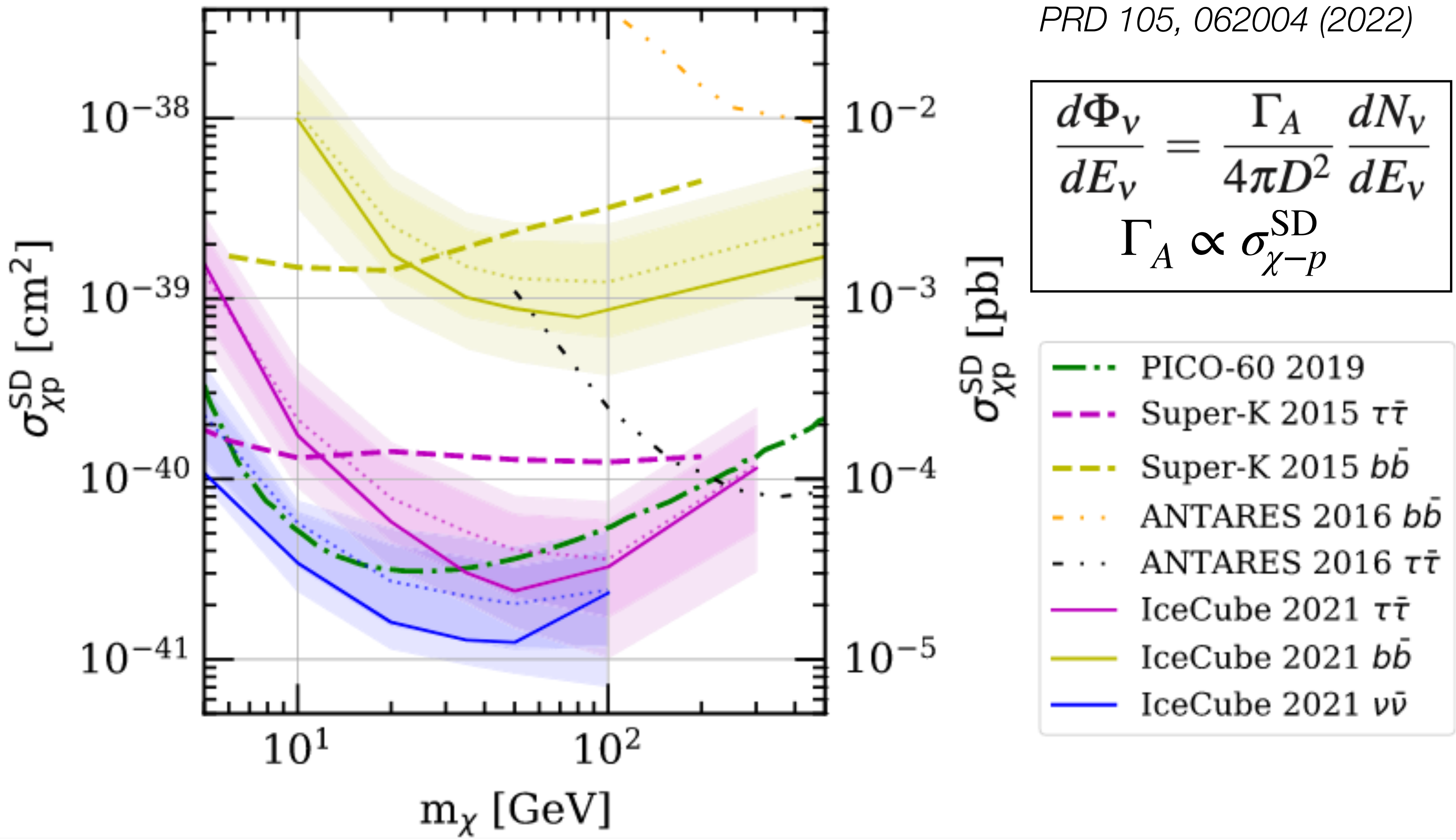
Why $\sigma^{\mathrm{SD}}_{\chi-p}$?

  - *Aside*: similar approach possible for the Earth
    - challenge: equilibrium assumption breaks down
    - $\to$ constrain σ^{SI} for a given $\sigma^{\chi\ \mathrm{ann.}}$

Why σ^{SI}?

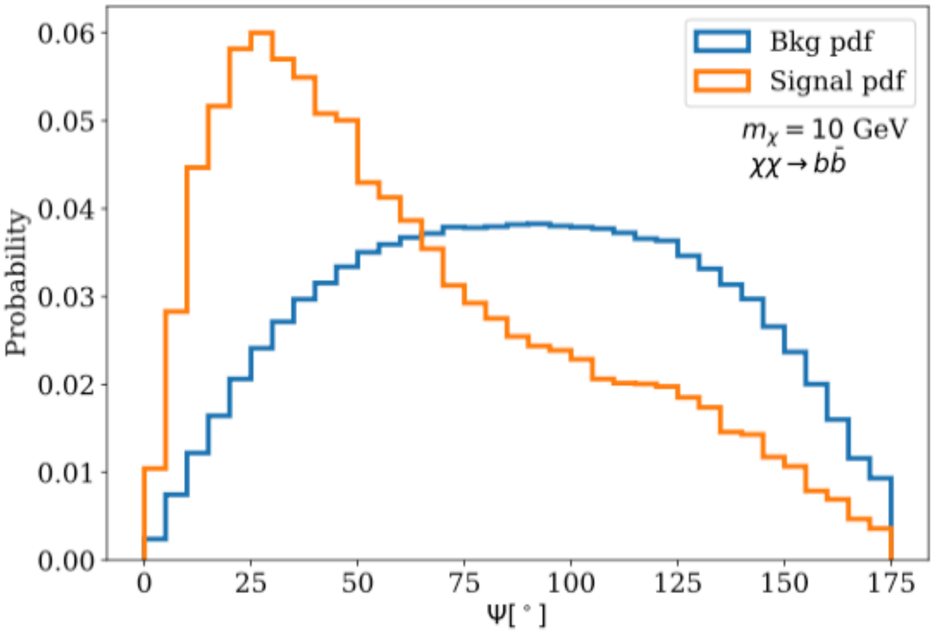

Eur. Phys. J. C (2017) 77:14
IceCube (2011-2014)
Super-K (1996-2012)
Antares (2007-2012)
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi D^2}\frac{dN_\nu}{dE_\nu}$$
$$\Gamma_A \propto \sigma^{SD}_{\chi-p}$$
PICO-2L (2015)
PICO-60 (2013-2014)
pMSSM scan
$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
Hard
Soft
[pb]
$\sigma^{SD}_{\chi-p}$ [cm^2]
m_χ [GeV]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^1
10^2
10^3
10^4
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

PRD 105, 062004 (2022)



$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi D^2}\frac{dN_\nu}{dE_\nu}$$

$$\Gamma_A \propto \sigma^{SD}_{\chi-p}$$



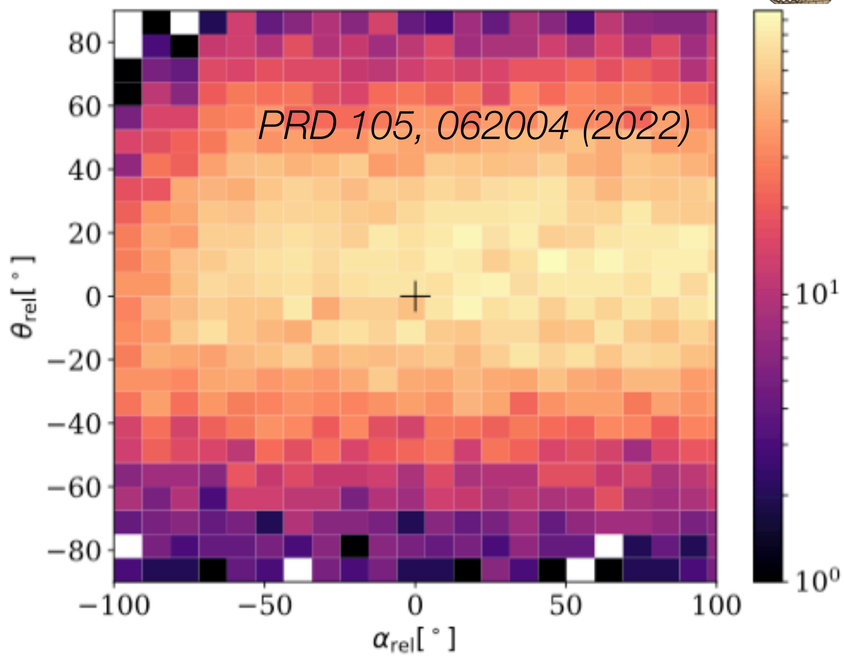
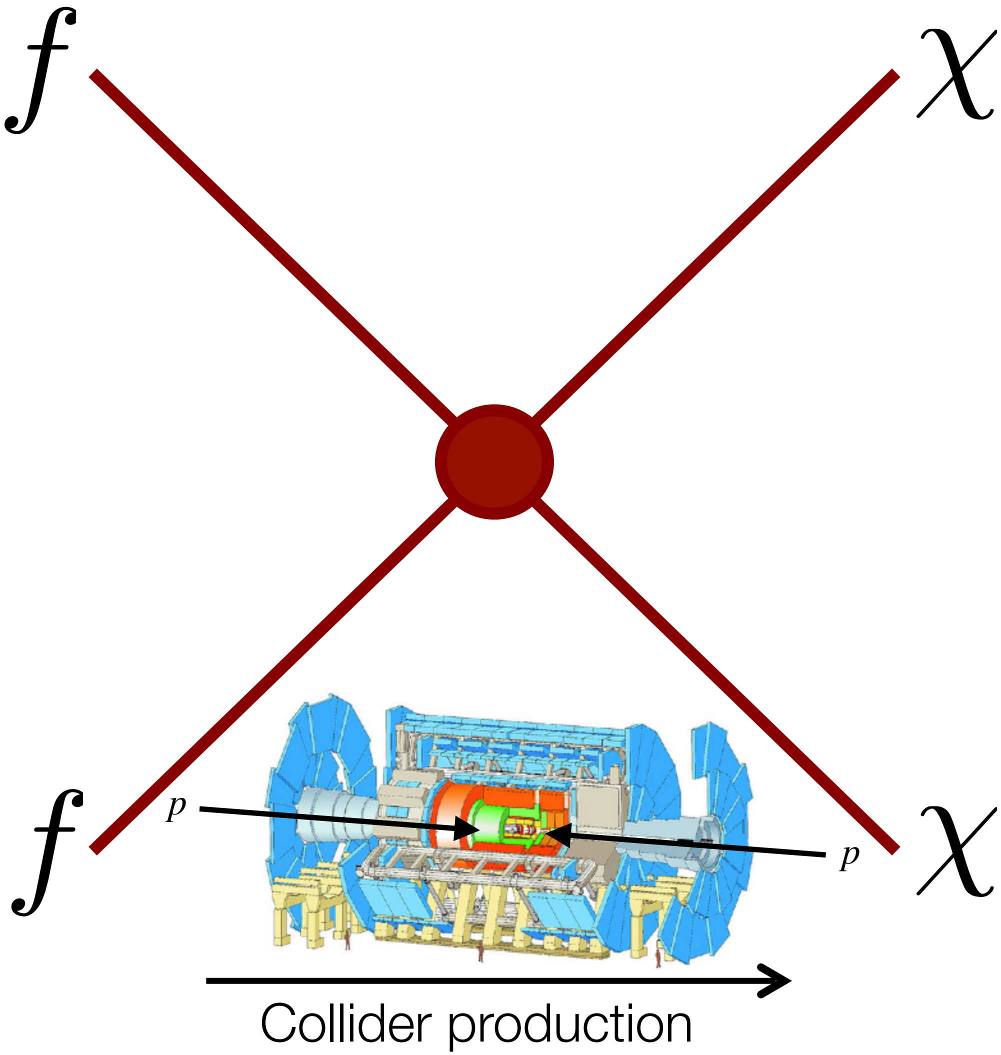


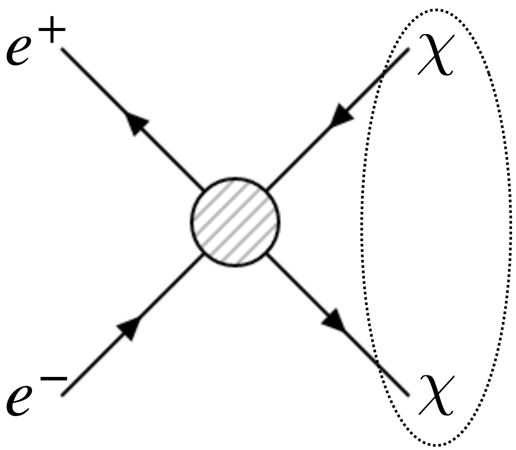
TABLE I. The reconstructed energy ranges of neutrinos used in the search for each WIMP mass and channel. The median energy of neutrinos in each range is shown in parentheses.

WIMP Mass (GeV)	$\tau^+\tau^-$ E_{reco} (GeV)	$\nu\bar{\nu}$ E_{reco} (GeV)	$b\bar{b}$ E_{reco} (GeV)
5	<9 (7)	2–11 (8)	–
10	1–16 (10)	<23 (13)	0–11 (8)
20	3–30 (15)	13–39 (23)	<18 (11)
35	8–50 (21)	25–70 (38)	<27 (14)
50	15–69 (29)	42–86 (55)	3–38 (17)
100	30–128 (47)	83–167 (107)	6–70 (22)

	$b\bar{b}$		
Mass (GeV)	σ_{SI} [cm^2] $\times 10^{-41}$	σ_{SD} [cm^2] $\times 10^{-39}$	σ_{SD}^{Exp} [cm^2] $\times 10^{-39}$
5	...	...	...
10	16.6	8.39	10.8
20	1.54	1.57	2.53
35	0.54	0.93	1.50
50	0.34	0.80	1.29
100	0.29	1.12	1.23

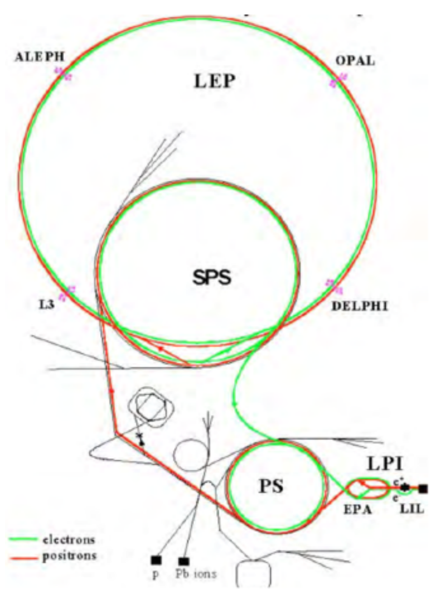
Translation: *Phys.Rept.* 267 (1996) 195


f
χ
f
χ
p
p
Collider production

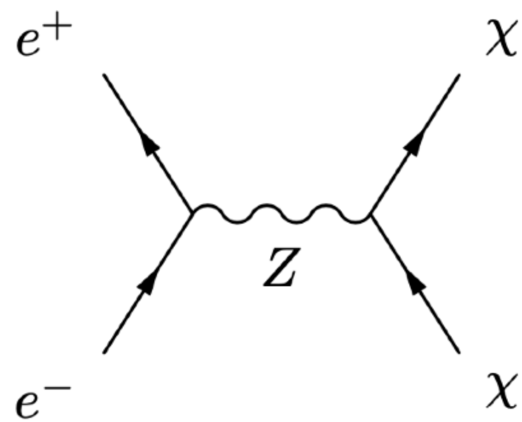


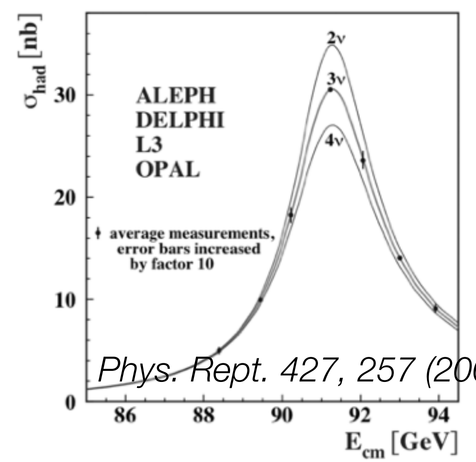
Signature:
missing 4-momentum
(initial state known)

Collider production
(controlled experimental environment!)



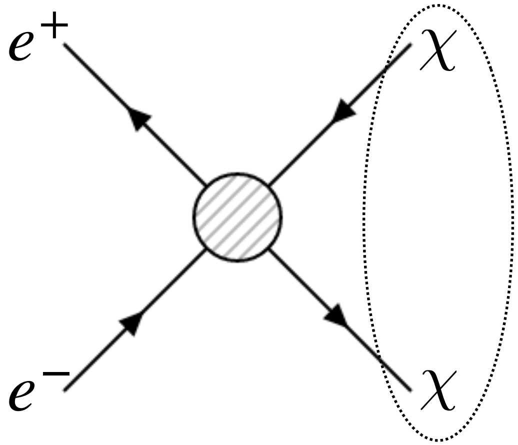
Solid limits for WIMPs coupling through Z:





Phys. Rept. 427, 257 (2006)

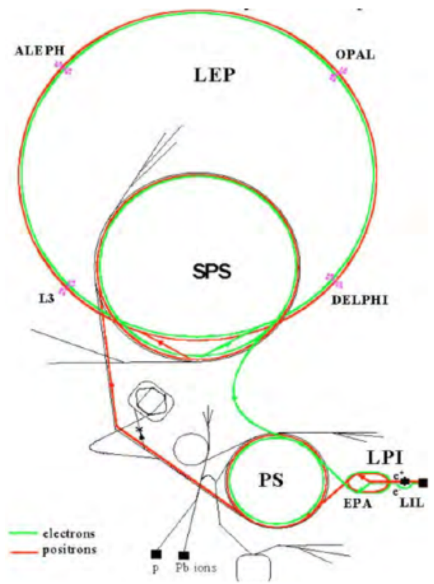
$$m_\chi < \frac{m_Z}{2} = 45\ \text{GeV excluded}$$

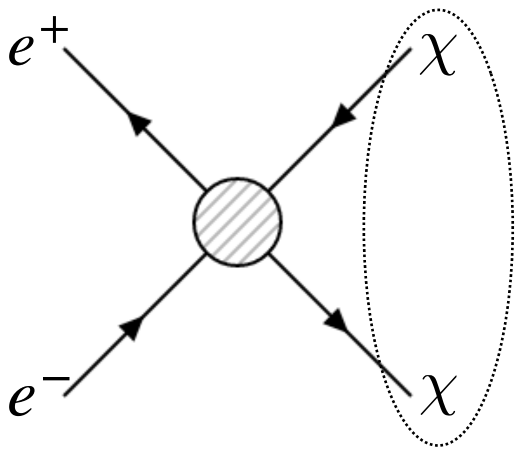


Signature:
missing 4-momentum
(initial state known)

Collider production
(controlled experimental environment!)

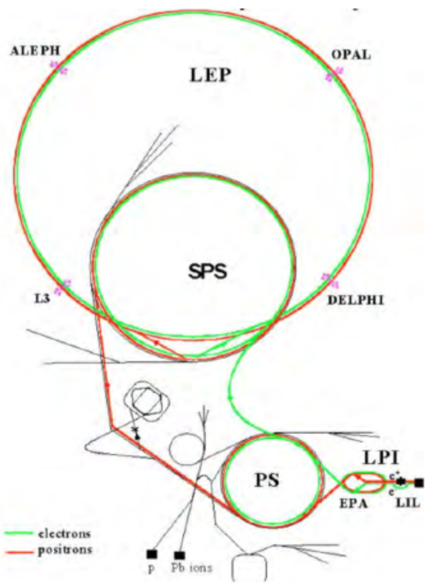
Go above the Z pole ???



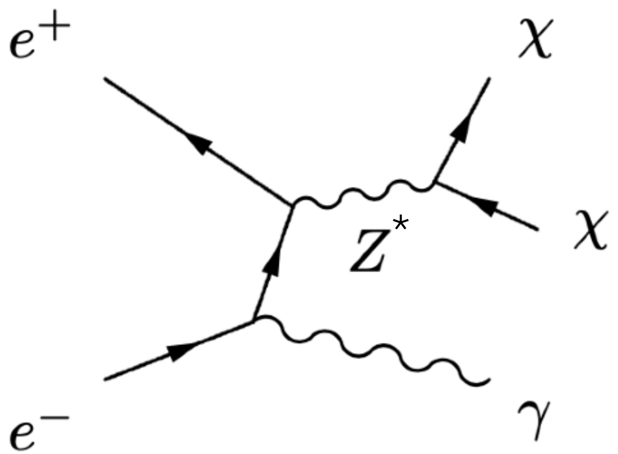


Signature:
missing 4-momentum
(initial state known)

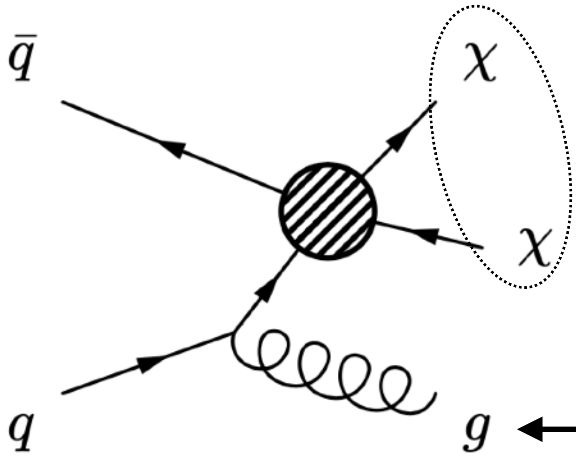
Collider production
(controlled experimental environment!)



Go above the Z pole: *initial state radiation (ISR)*



[large hit from α_{EM}, but hey…]

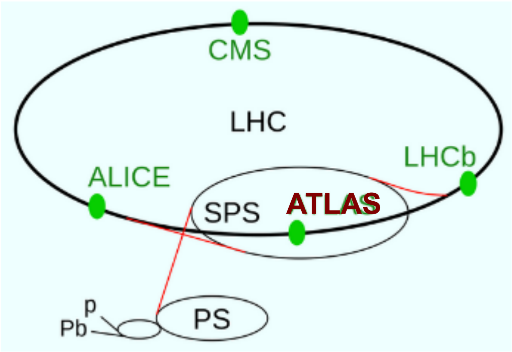


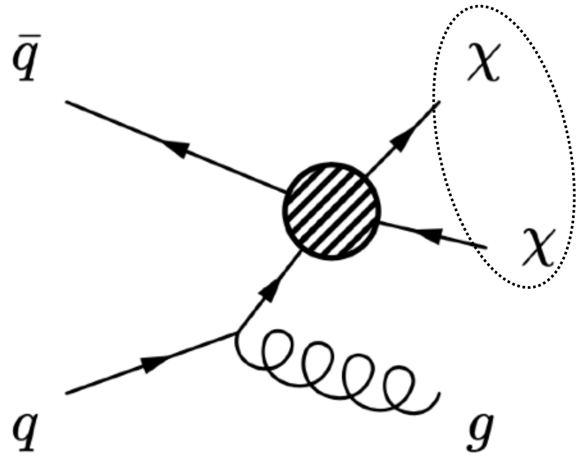
Signature:

missing transverse momentum

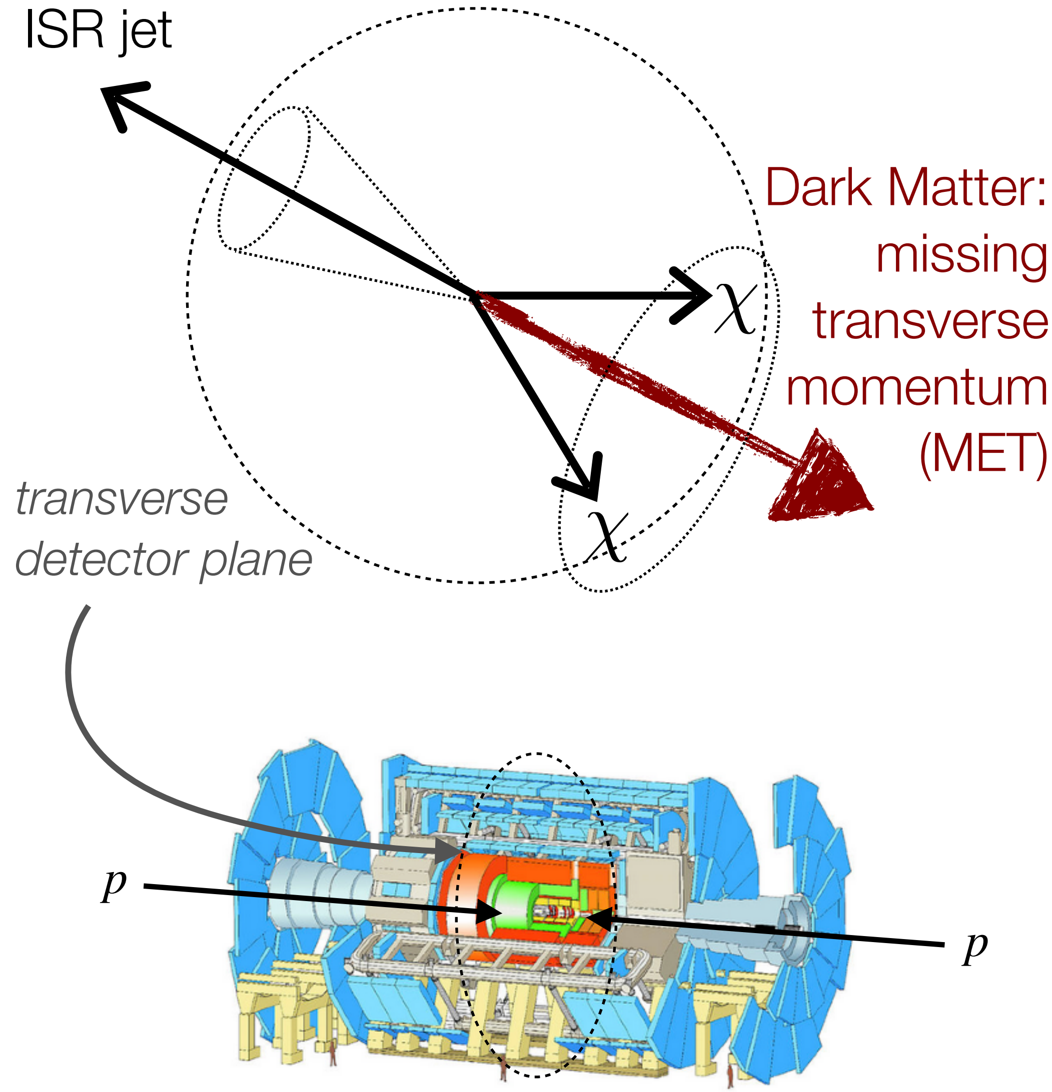
(initial state p_z not known)

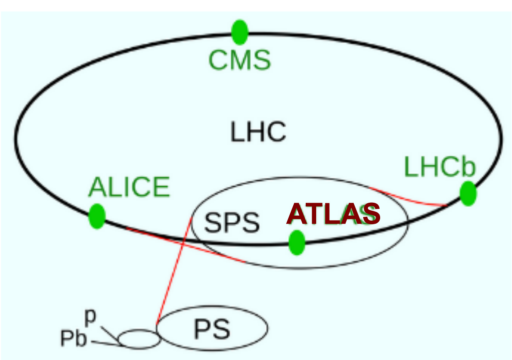
← jet

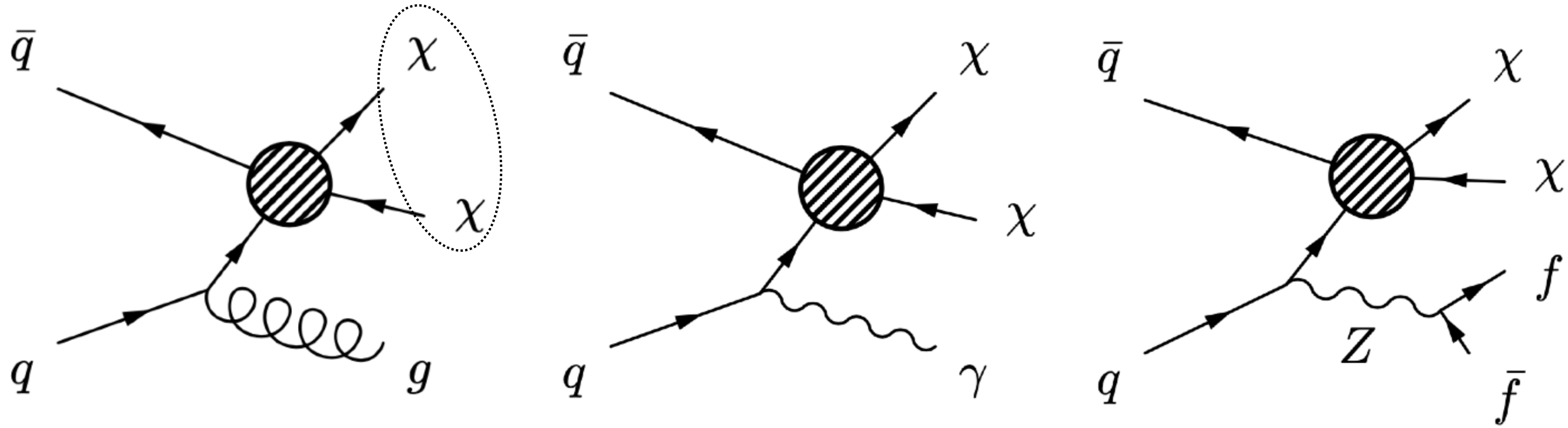




Collider production
(controlled experimental environment!)

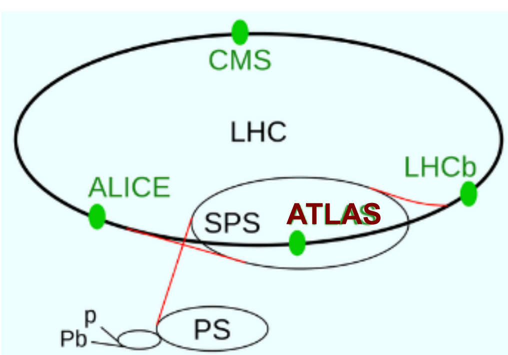


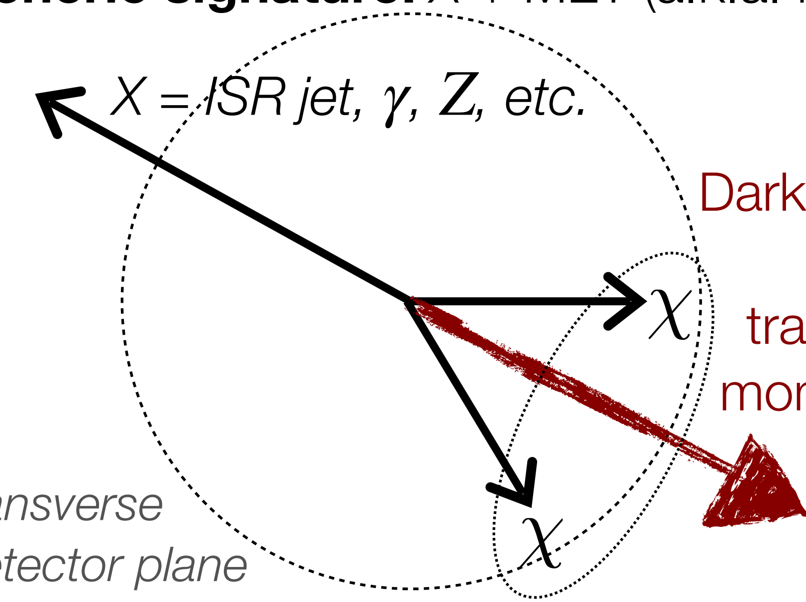




Collider production
(controlled experimental environment!)

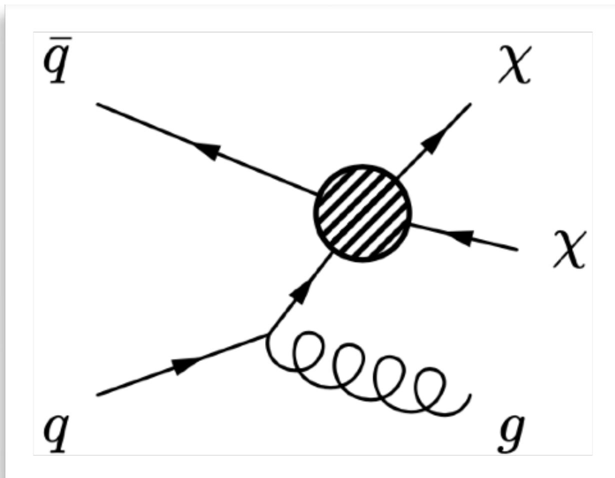
Generic signature: *X* + MET (a.k.a. mono-*X*)





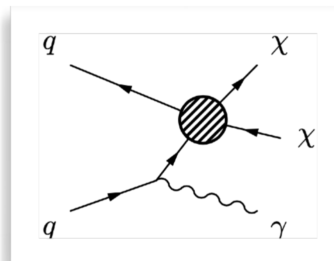
DM @ LHC: Mono-X with X from ISR

Mono-jet



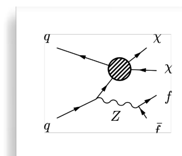
[not-so-large hit from α_s]

Mono-γ



$$\frac{\sigma_{\chi\chi\gamma}}{\sigma_{\chi\chi j}} \approx \frac{\alpha}{\alpha_s}\frac{Q_q^2}{C_F} \approx \frac{1}{40}$$

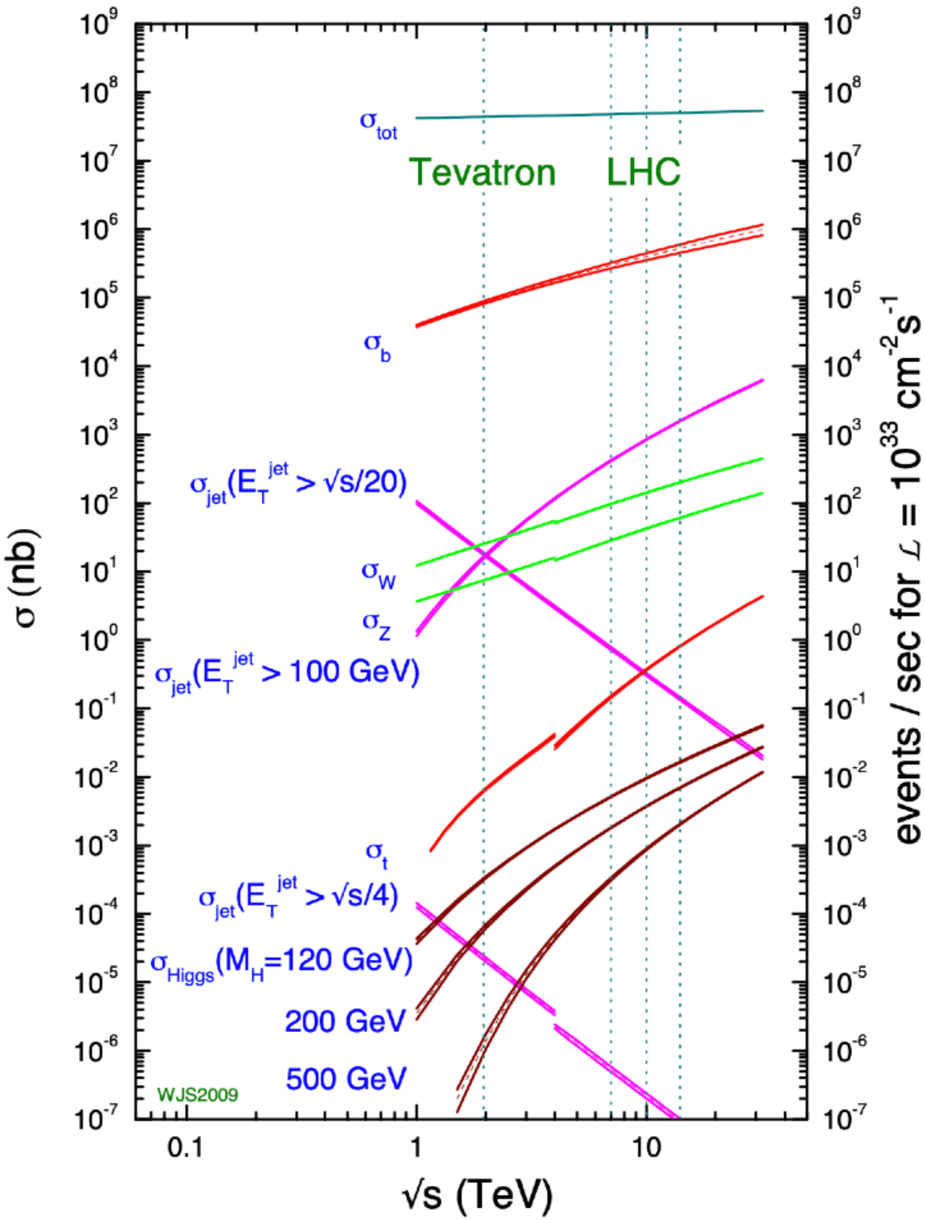
Mono-$Z(\rightarrow \mu\mu)$



$$\frac{\sigma_{\chi\chi\mu\mu}}{\sigma_{\chi\chi j}} \approx \frac{1}{4000}$$

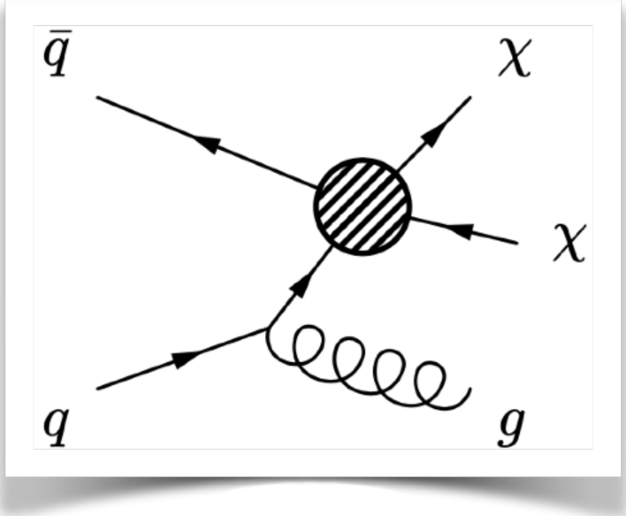
$$\approx \frac{\alpha}{\alpha_s}\frac{Q_q^2\, s_w^2}{C_F}\,\mathrm{BR}(Z \rightarrow \mu\mu)$$

1705.01987

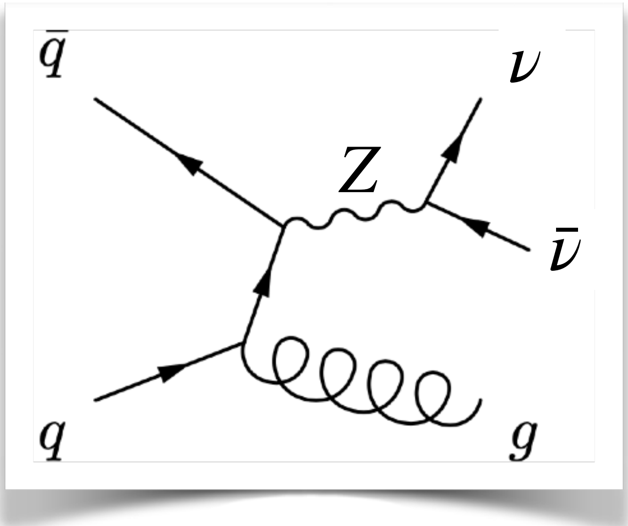


Rept. Prog. Phys. 70, 89 (2007)

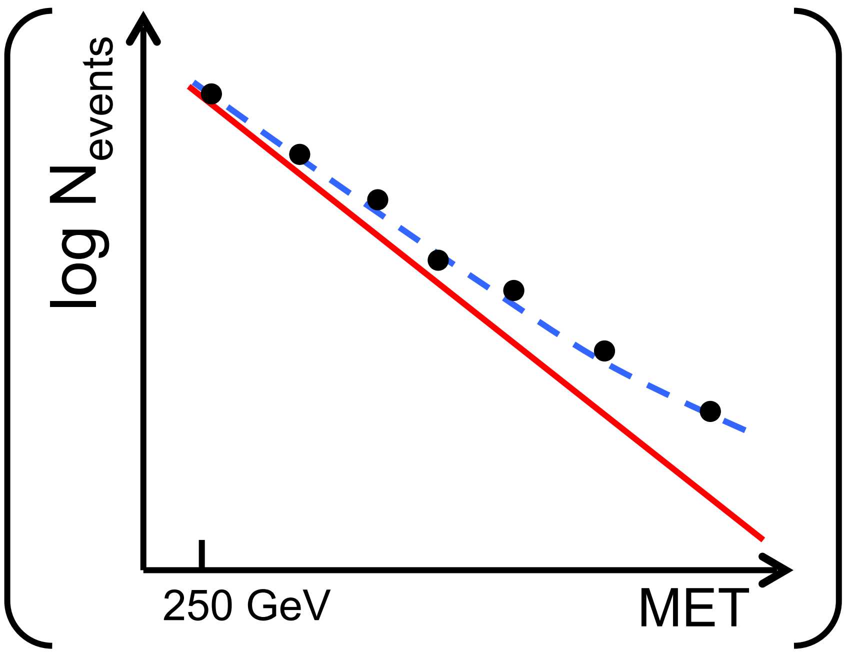
Mono-jet



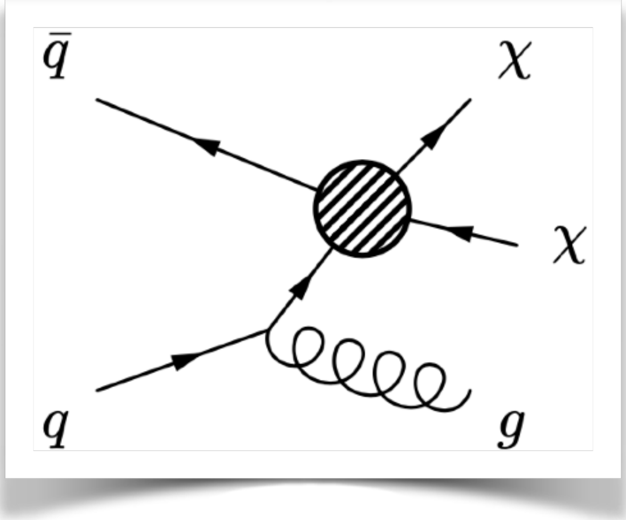
$Z(\rightarrow \nu\bar{\nu})$ + jets

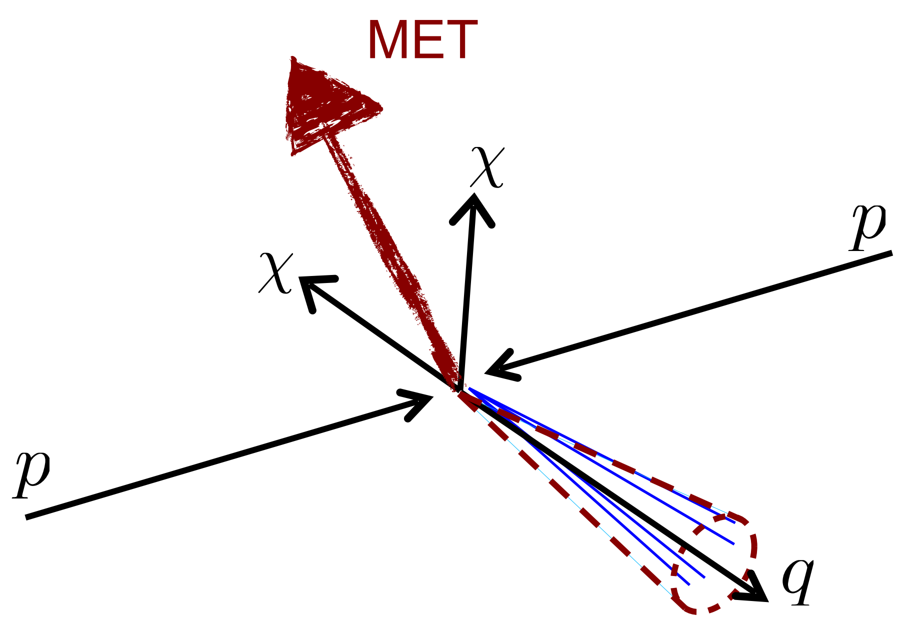


- **Analysis strategy:**
  - Require MET > 200 GeV
  - Require jet with p_T > 150 GeV
  - Up to 3 extra jets
  - Look for excess in MET:

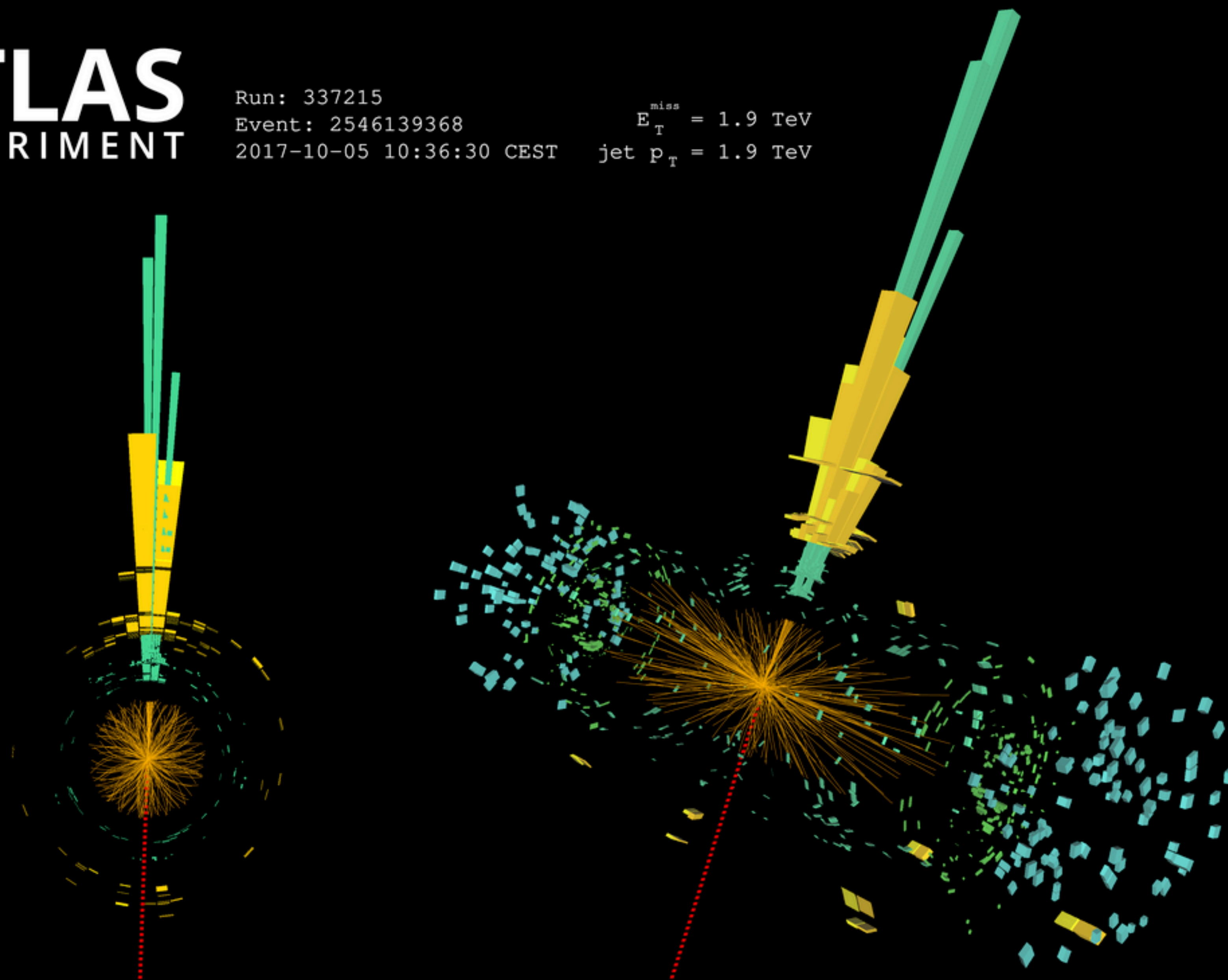


Shape fit: 13 bins in MET



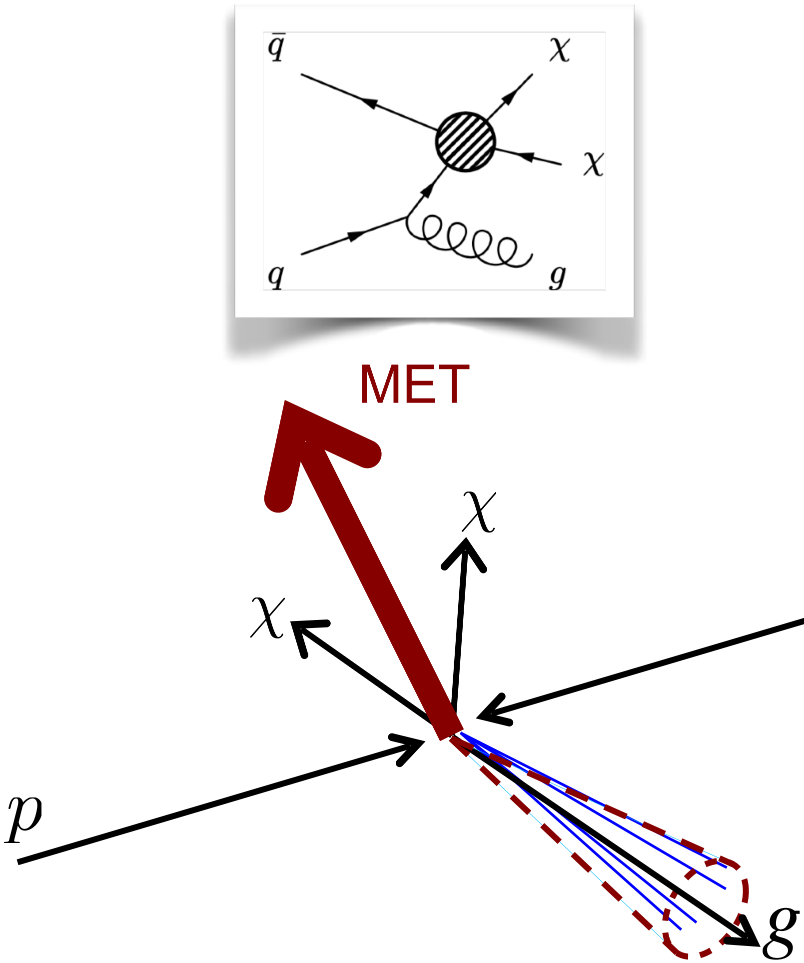


PRD 103 (2021) 112006

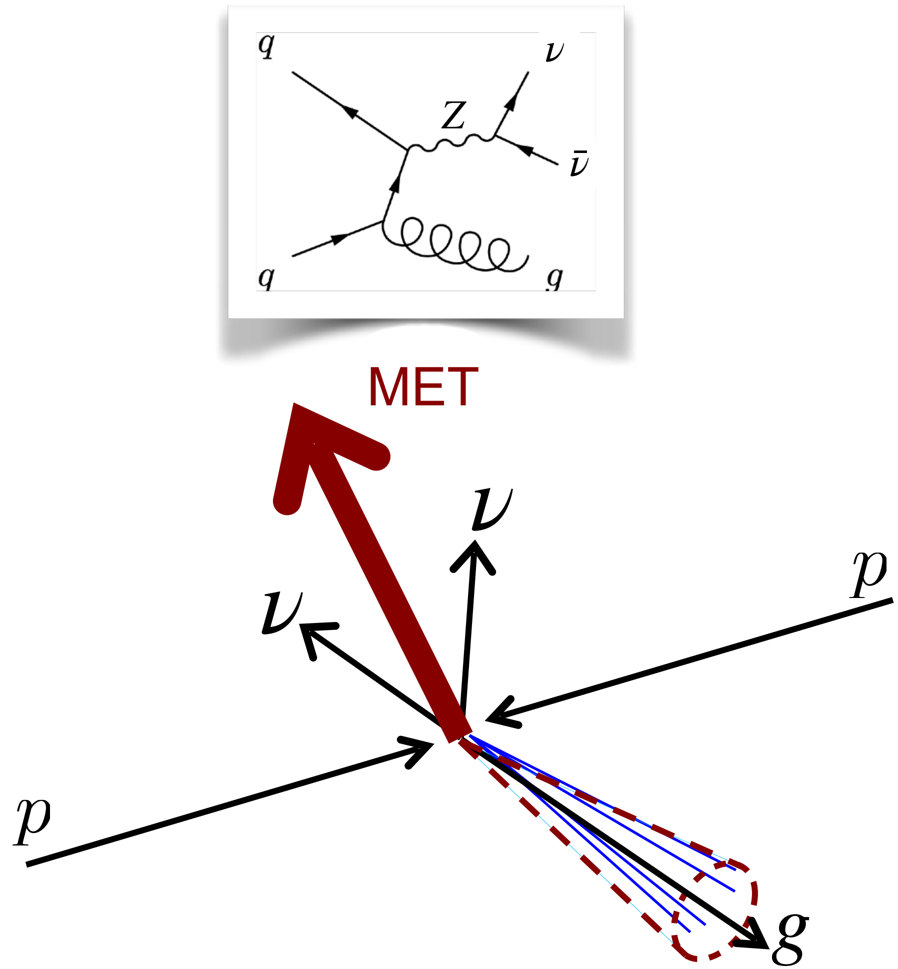

ATLAS EXPERIMENT
Run: 337215
Event: 2546139368
2017-10-05 10:36:30 CEST
E_T^{miss} = 1.9 TeV
jet p_T = 1.9 TeV

- **Backgrounds:** *PRD 103 (2021) 112006, web*
  - SM Z(νν)+jets (dominant + irreducible), W+jets, Diboson, tt, rest

Signal



Background (Z+jets)



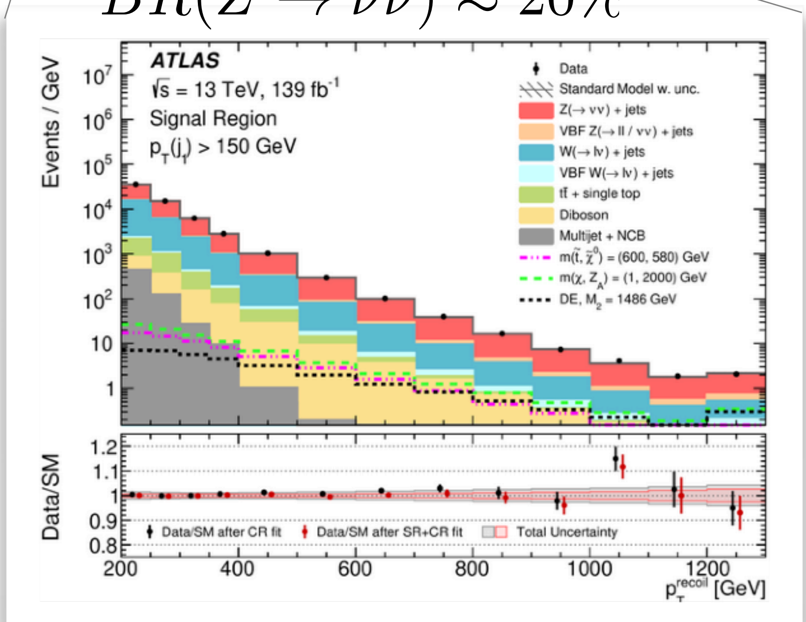
PRD 103 (2021) 112006

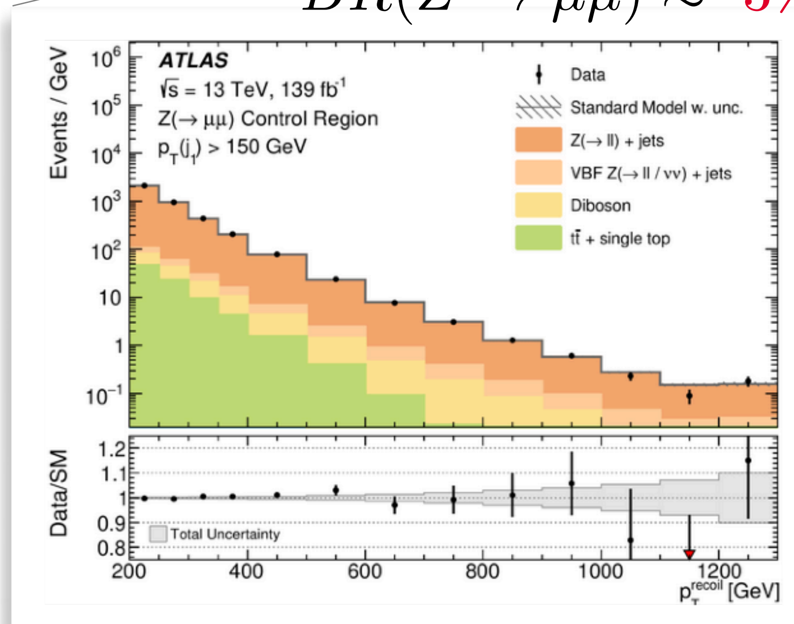
- **Backgrounds:**
  - SM Z(νν)+jets (dominant), W+jets, Diboson, tt + rest
- **Strategy:**
  - Constrain major backgrounds:

0 lepton signal region	1 lepton control region	2 lepton control region
Signal	Constrain W(ℓv)+jets and Z(vv)+jets	Constrain Z(vv)+jets using Z(ℓℓ)+jets

$$BR(Z \to \nu\nu) \approx 20\%$$

$$BR(Z \to \mu\mu) \approx 3\%$$





PRD 103 (2021) 112006

- **Backgrounds:**
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- **Strategy:**
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0 lepton signal region	1 lepton control region	2 lepton control region
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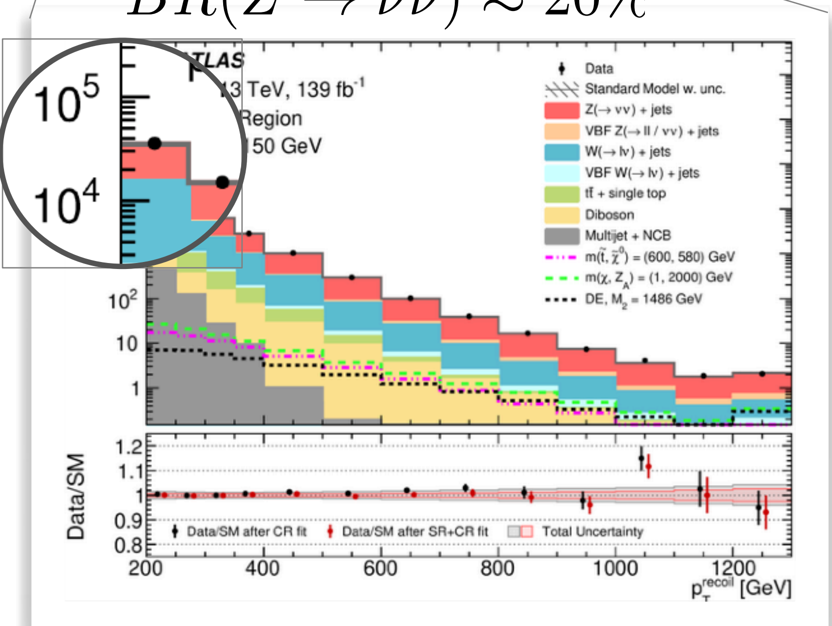
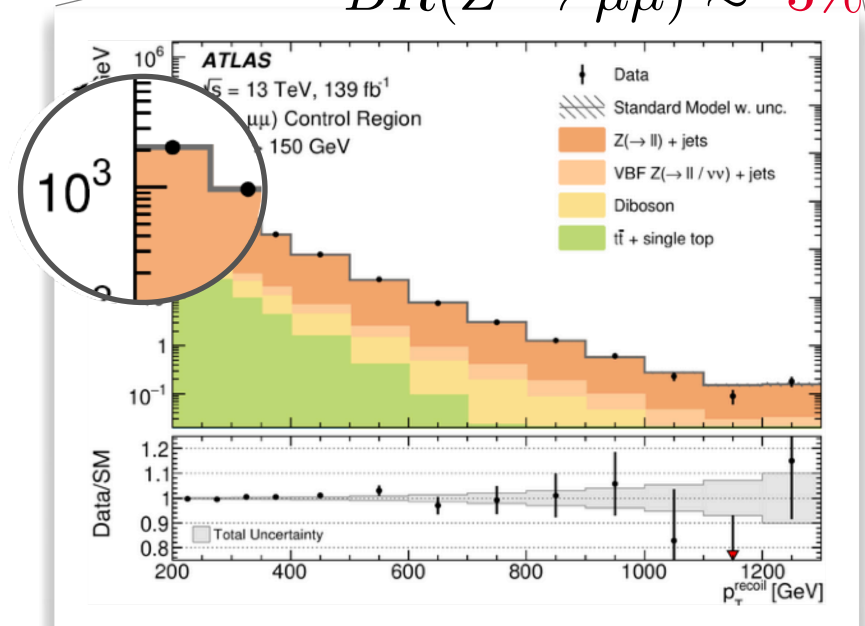
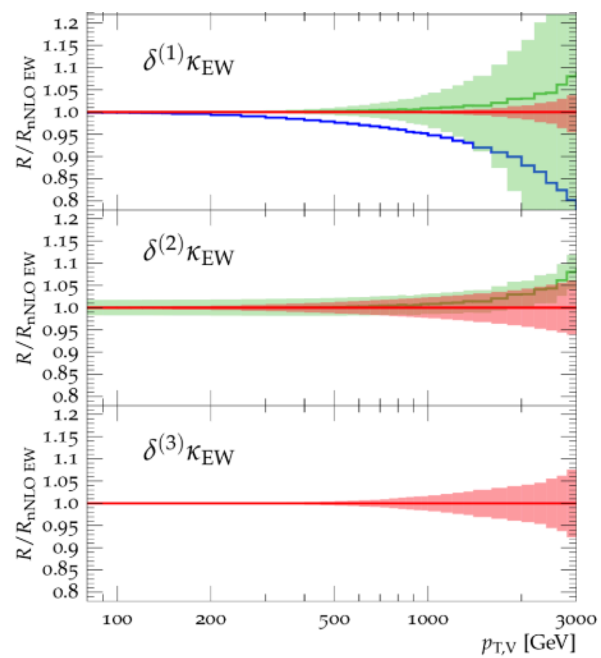


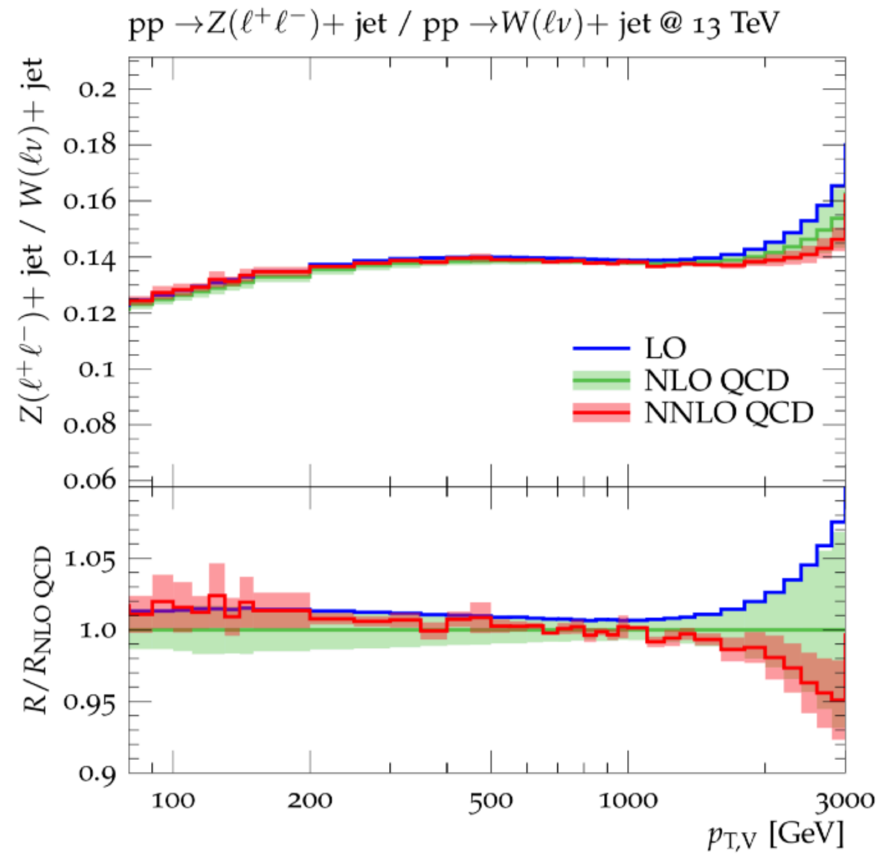
$BR(Z \to \mu\mu) \approx 3\%$



CERN-LPCC-2017-002 (LHC DM WG report)

- **Ansatz:**
  - Constrain Z(νν)+jets using W+jets!
  - Benefit: $BR(W \to \mu\nu) \approx\ 10\%\ |\times 2\ (e\nu)$
- **Challenge:**
  - Z+jets and W+jets related, but different!
- **Solution:**
  - Calculate Z+jets vs W+jets difference at NNLO($\boldsymbol{\alpha}_S$)+NNLL($\boldsymbol{\alpha}_S$), NLO($\boldsymbol{\alpha}_{EW}$)

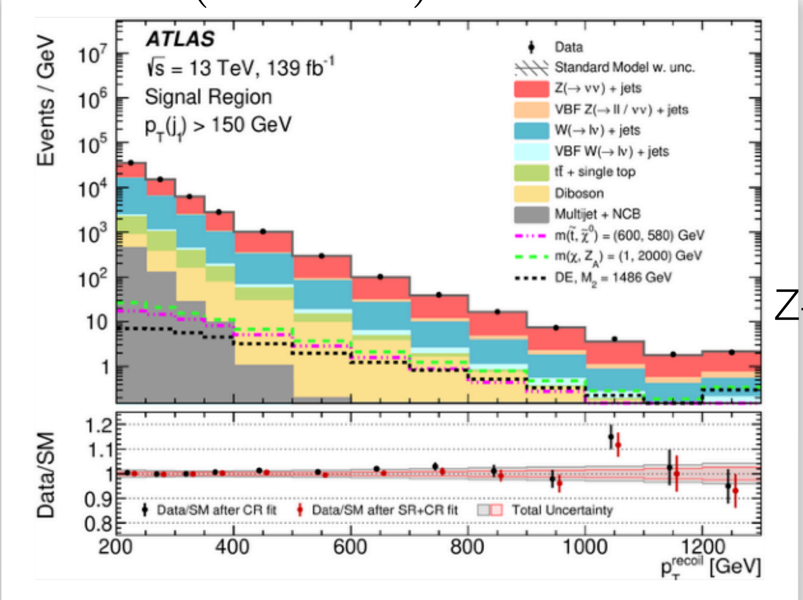




- **Backgrounds:** *PRD 103 (2021) 112006*
  - SM Z(νν)+jets (dominant), W+jets, Diboson, tt + rest
- **Strategy:**
  - Constrain major backgrounds:

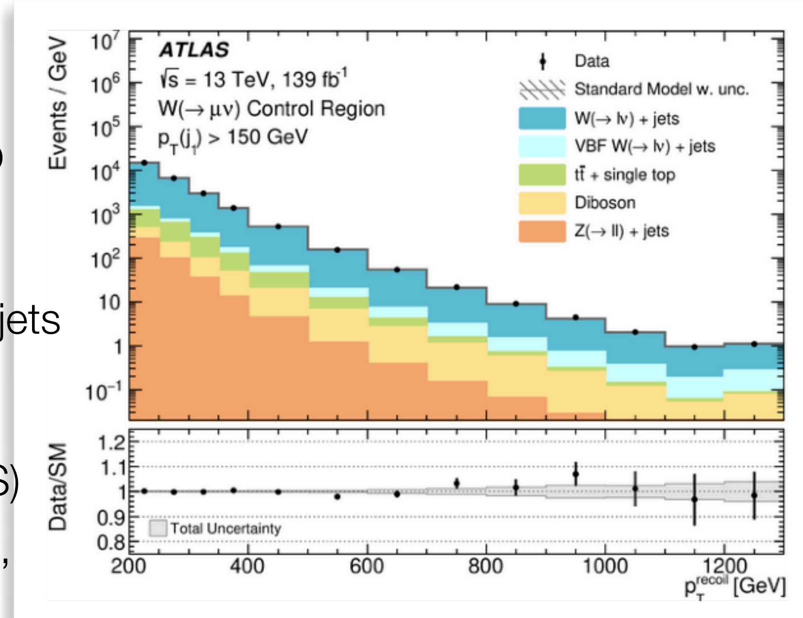
0 lepton signal region	1 lepton control region	2 lepton control region
Signal	Constrain W(ℓν)+jets **and Z(νν)+jets**	Constrain Z(νν)+jets using Z(ℓℓ)+jets

$$BR(Z \to \nu\nu) \approx 20\%$$



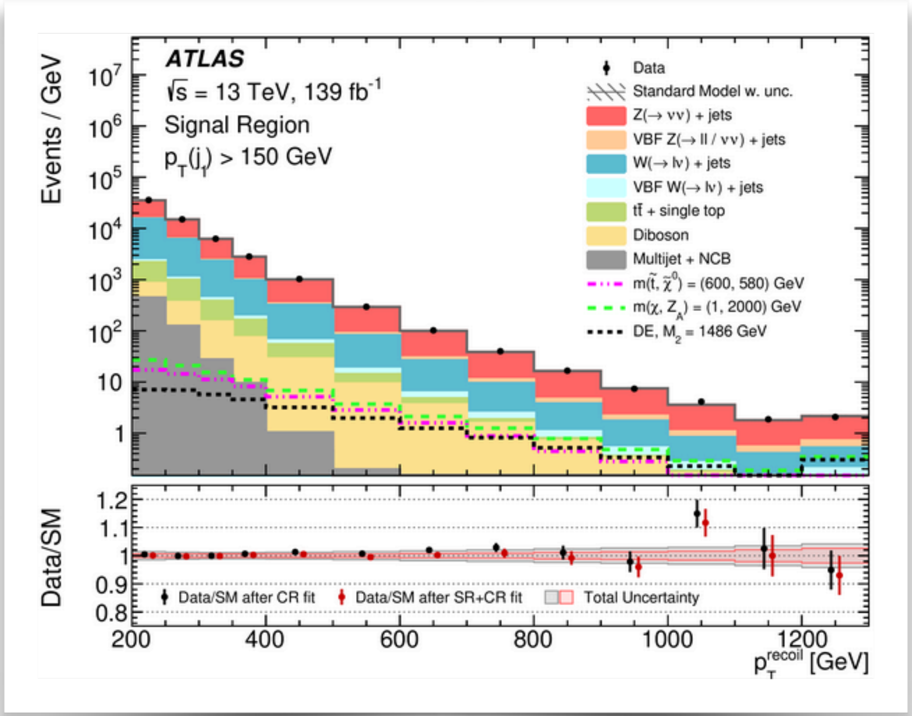
$\times \varepsilon_{\text{anti-ID}}$

Z+jets vs. W+jets difference calculated at NNLO(αS) +NNLL(αS), NLO(αEW)



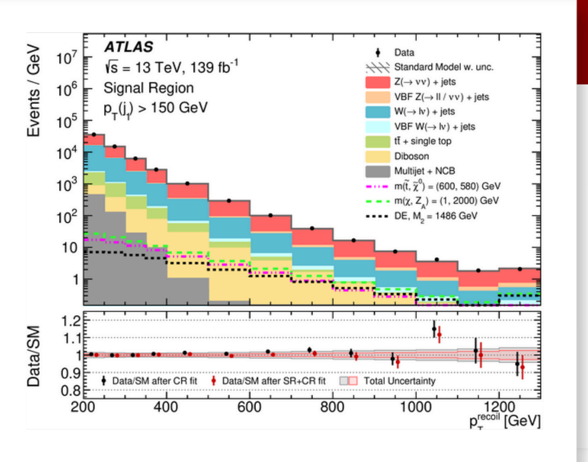
EPJC 77 (2017) 829

PRD 103 (2021) 112006



How to interpret this fantastic, incredibly precise result?

DM @ LHC: INTERPRETATION?



PRD 103 (2021) 112006

Model-independent limits!

Selection	$\langle\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}
$p_T^{\text{recoil}} > 200$ GeV	736	102 274	$83\,000^{+22\,000}_{-23\,000}$
$p_T^{\text{recoil}} > 250$ GeV	296	41 158	$33\,800^{+11\,300}_{-9400}$
$p_T^{\text{recoil}} > 300$ GeV	150	20 893	$15\,400^{+5900}_{-4300}$
$p_T^{\text{recoil}} > 350$ GeV	86	11 937	8300^{+3100}_{-2300}
$p_T^{\text{recoil}} > 400$ GeV	52	7214	4700^{+1800}_{-1300}
$p_T^{\text{recoil}} > 500$ GeV	21	2918	1930^{+730}_{-540}
$p_T^{\text{recoil}} > 600$ GeV	10	1391	940^{+360}_{-260}
$p_T^{\text{recoil}} > 700$ GeV	4.1	574	490^{+190}_{-140}
$p_T^{\text{recoil}} > 800$ GeV	2.1	298	277^{+106}_{-77}
$p_T^{\text{recoil}} > 900$ GeV	1.2	164	168^{+65}_{-47}
$p_T^{\text{recoil}} > 1000$ GeV	1.3	186	119^{+45}_{-33}
$p_T^{\text{recoil}} > 1100$ GeV	0.5	73	75^{+28}_{-21}
$p_T^{\text{recoil}} > 1200$ GeV	0.3	40	49^{+19}_{-14}

PRD 103 (2021) 112006

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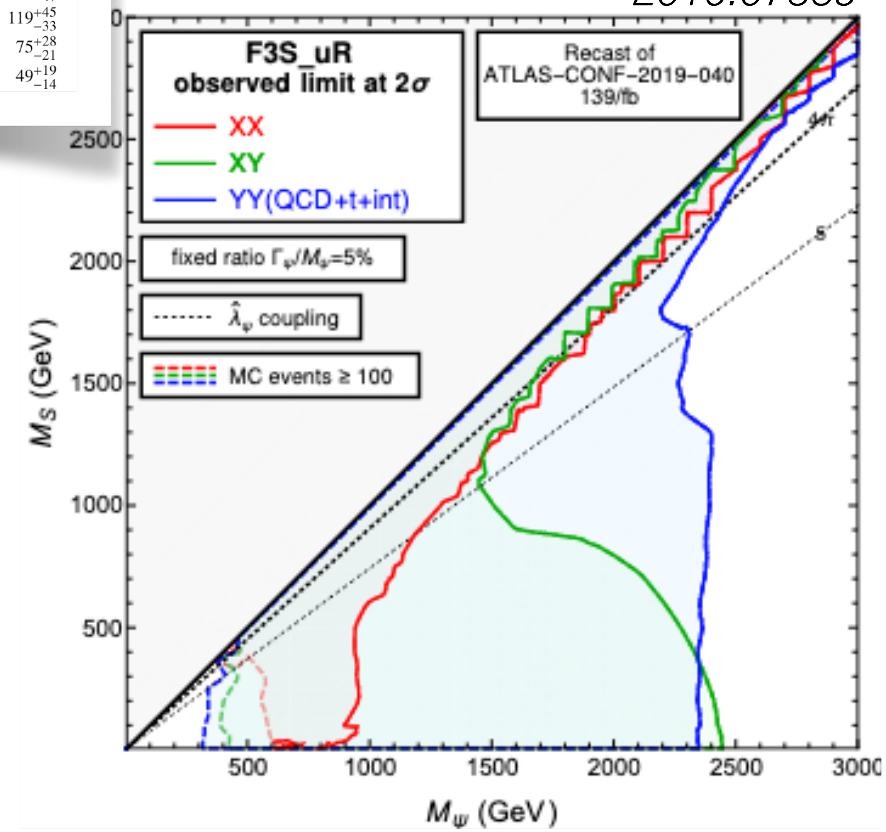
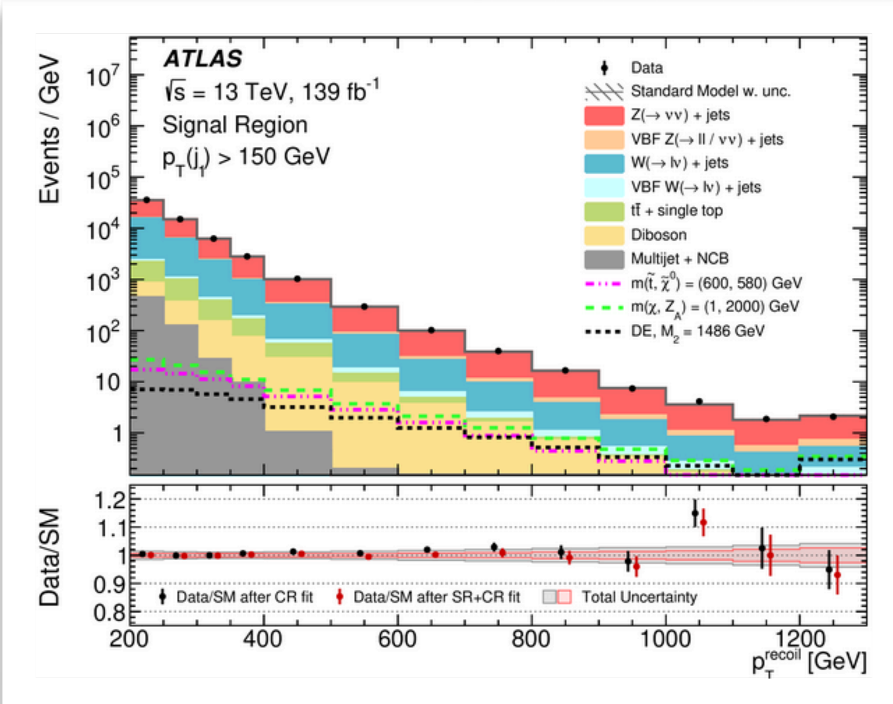
$p_T^{\text{recoil}} > 1200$ GeV	0.3	40	49^{+19}_{-14}

Extremely useful to theorists to test their favourite model

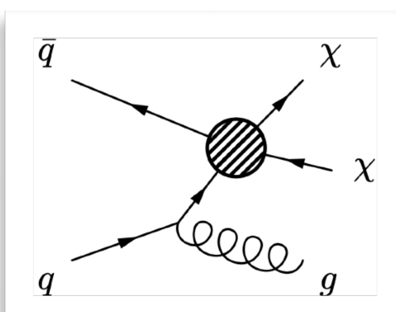
2010.07559



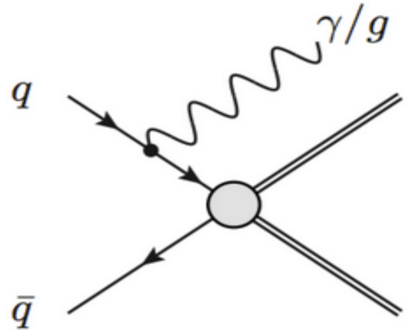
PRD 103 (2021) 112006

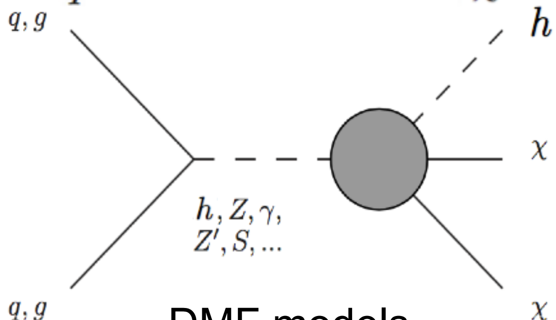


What can we say about dark matter?



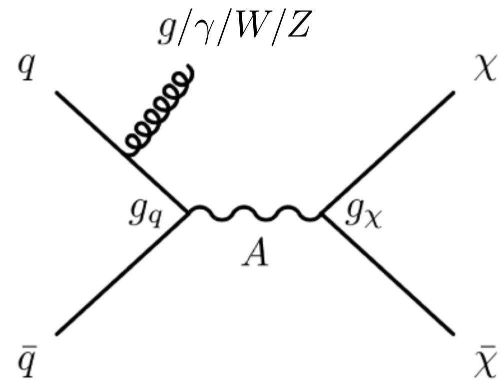
Models for DM searches @ LHC





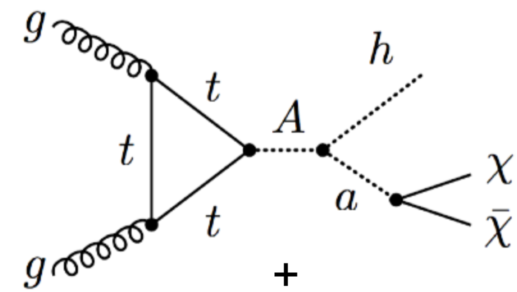
DMF models
1507.00966

1) Effective field theory



s-channel mediators
1507.00966
1603.04156
1703.05703
t-channel mediators
1507.00966

2) Simplified models



+
many other signatures

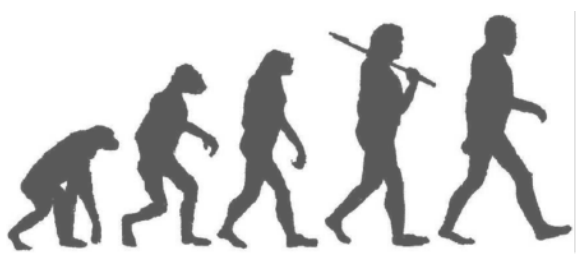
2HDM+a model
JHEP 05 (2017) 138
1810.09420

Dark Higgs model
JHEP 04(2017)143

3) Simplified, consistent, & UV-complete models

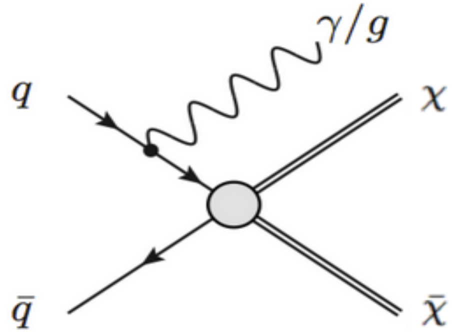
Supersymmetry
DM candidate: lightest super-symmetric particle

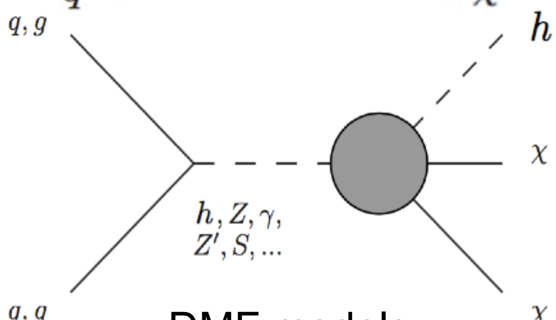
4) complete models



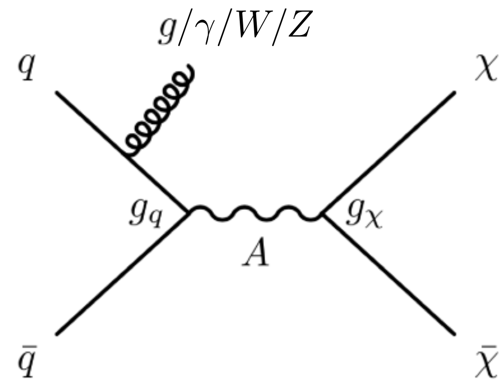
Richer kinematics + phenomenology

MODELS FOR DM SEARCHES @ LHC





DMF models
1507.00966



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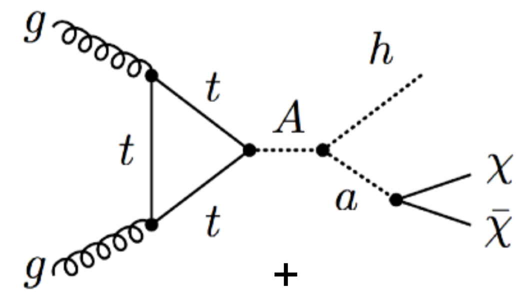

\+
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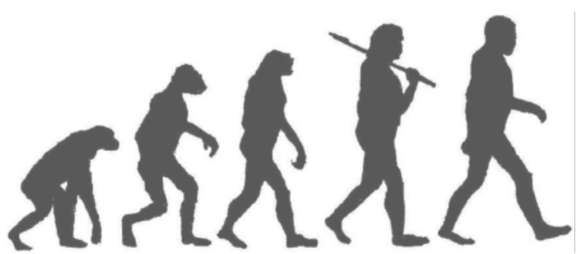
2HDM+a model
JHEP 05 (2017) 138
1810.09420

Dark Higgs model
JHEP 04(2017)143

Supersymmetry
DM candidate: lightest super-symmetric particle

1) Effective field theory **2) Simplified models** **3) Simplified, consistent, & UV-complete models** **4) complete models**

White Papers of [*LHC DM WG/DMF*]



Richer kinematics + phenomenology

No EFT model interpretations for DM searches at the LHC:

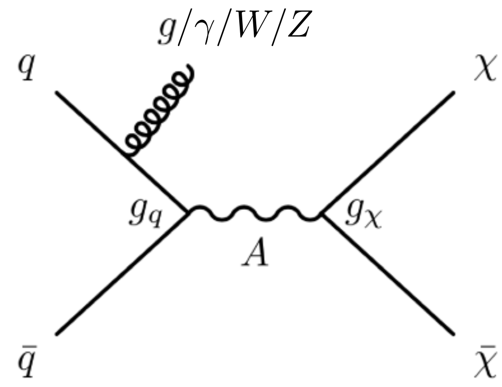
$$Q^2 \gtrsim \Lambda$$

→ Need models with a resolved mediator

DMF models
1507.00966

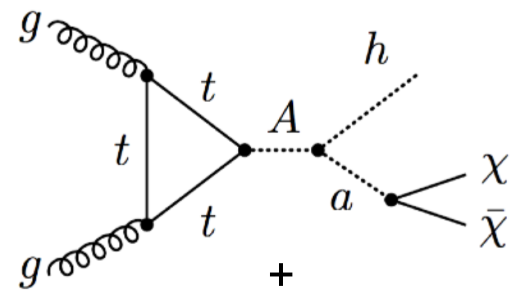
Exception:
Higgs portal models
(why?)

1) Effective field theory



s-channel mediators
1507.00966
1603.04156
1703.05703
t-channel mediators
1507.00966

2) Simplified models



+
many other signatures

2HDM+a model
JHEP 05 (2017) 138
1810.09420

Dark Higgs model
JHEP 04(2017)143

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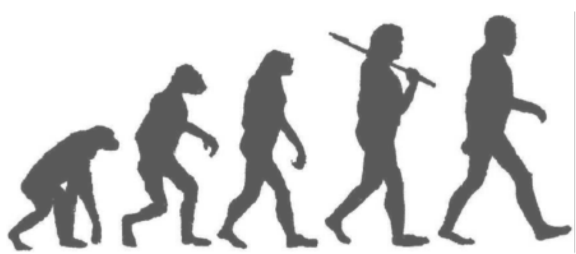
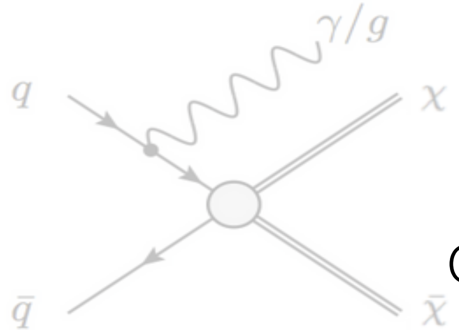
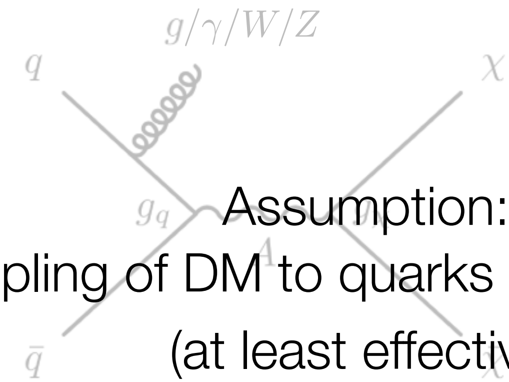
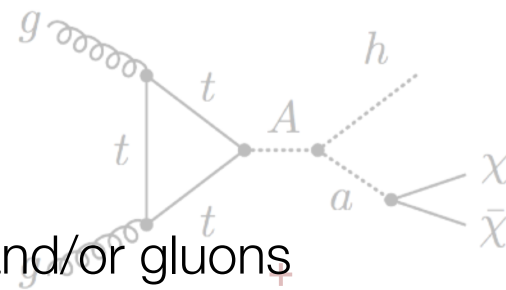


Richer kinematics + phenomenology

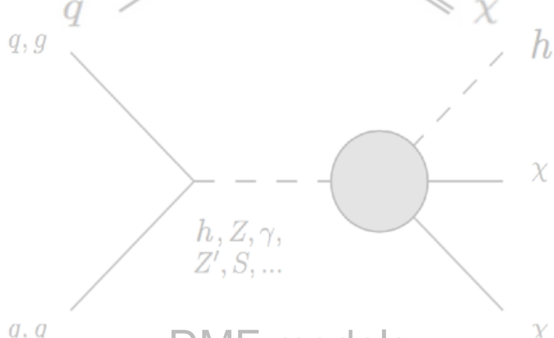






Assumption:
Coupling of DM to quarks and/or gluons
(at least effective)

+ *many other signatures*



DMF models
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Supersymmetry
DM candidate: lightest super-symmetric particle

1) Effective field theory

2) Simplified models

3) Simplified, consistent, & UV-complete models

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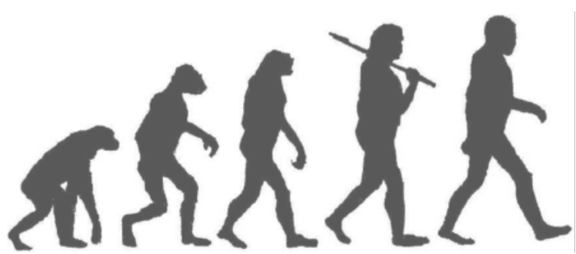
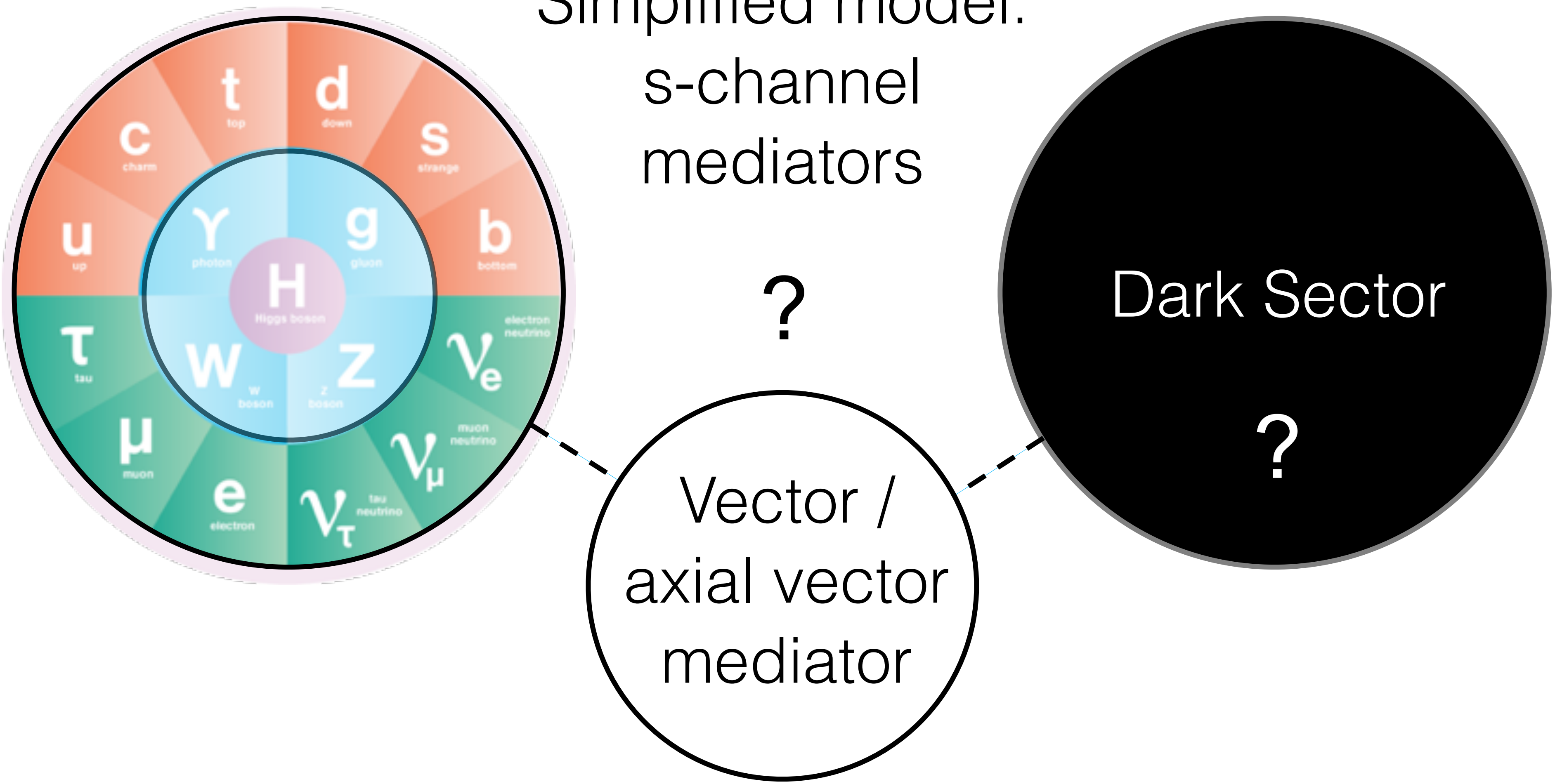


Richer kinematics + phenomenology

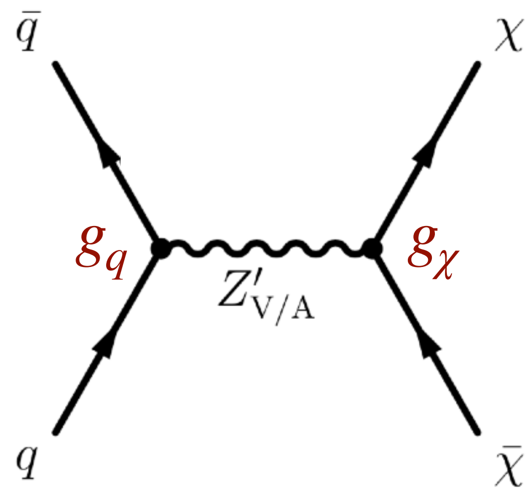
Simplified model:
s-channel
mediators



Motivation: 1) Mediator that couples to SM and to Dark Sector particles
2) Generic signatures that are present in complete models
3) minimal assumptions about dark sector (one DM particle)

DM @ LHC: S-CHANNEL MEDIATOR

1603.04156



U(1) symmetry

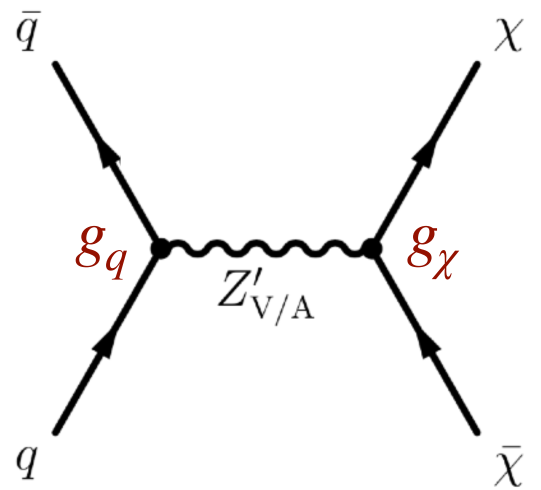
Dirac DM

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q\,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q$$

Minimal flavour violation (g_q universal) → avoid flavour physics constraints

Minimal assumptions about the dark sector (additional DOF integrated out)



1603.04156

$z_{\mathrm{DM},q} = m^2_{\mathrm{DM},q}/M^2_{\mathrm{med}}$

U(1) symmetry

Dirac DM

$$\mathcal{L}_{\mathrm{vector}} = -g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q\,,$$

$$\mathcal{L}_{\mathrm{axial\text{-}vector}} = -g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q$$

$$\Gamma^{\chi\bar{\chi}}_{\mathrm{vector}} = \frac{g^2_{\mathrm{DM}} M_{\mathrm{med}}}{12\pi}(1-4z_{\mathrm{DM}})^{1/2}(1+2z_{\mathrm{DM}})$$

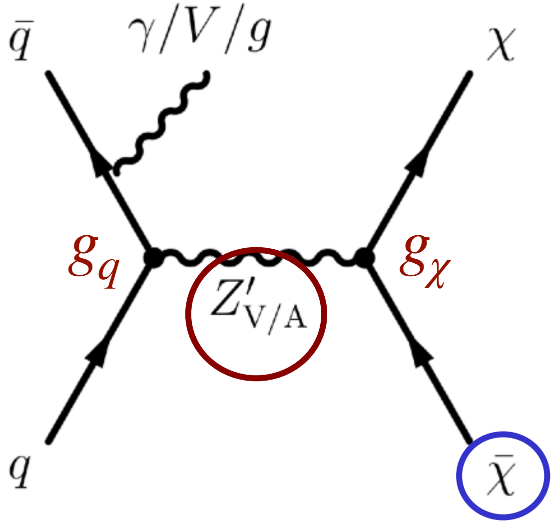
$$\Gamma^{q\bar{q}}_{\mathrm{vector}} = \frac{g^2_q M_{\mathrm{med}}}{4\pi}(1-4z_q)^{1/2}(1+2z_q)\,,$$

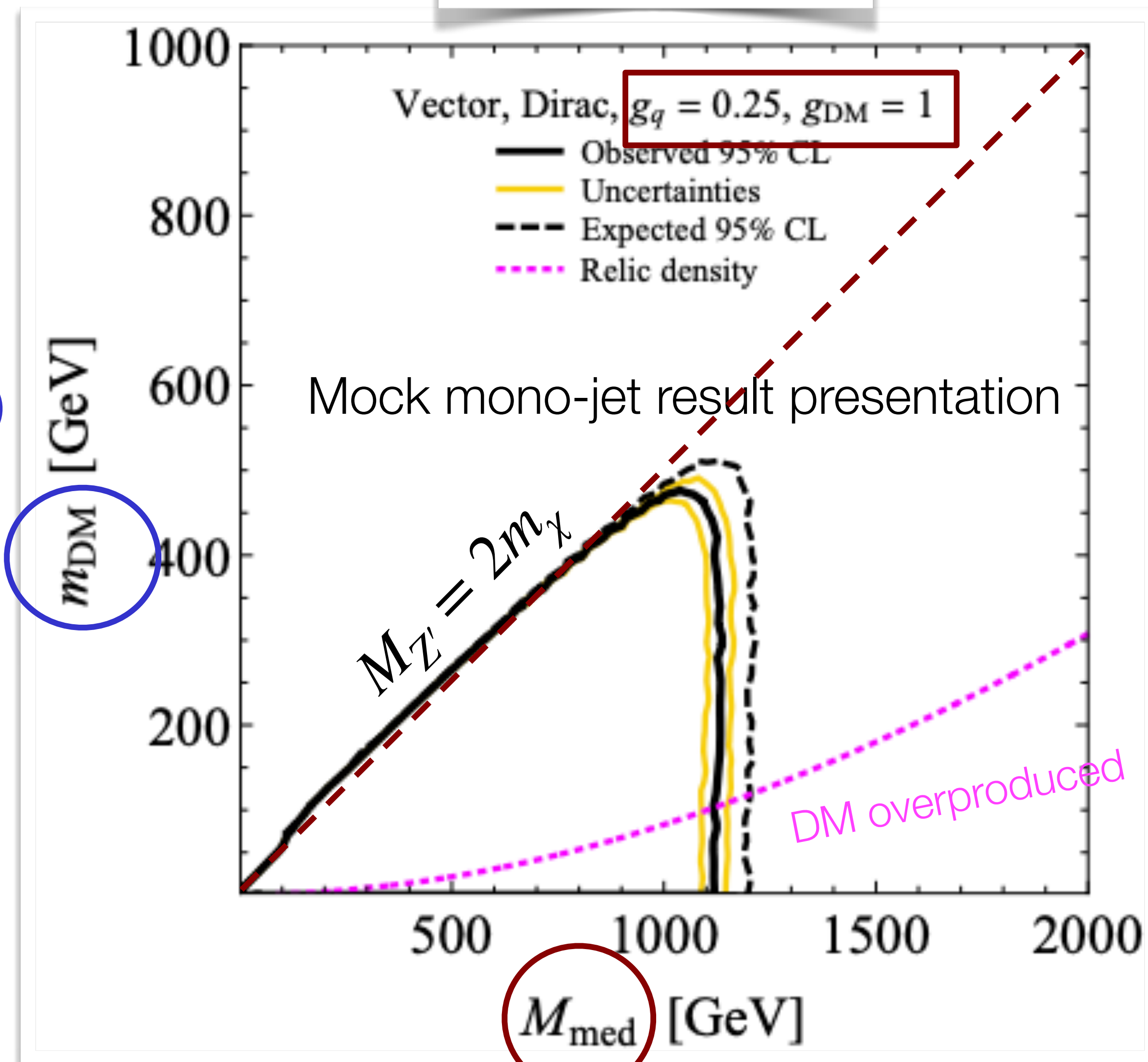
$$\Gamma^{\chi\bar{\chi}}_{\mathrm{axial\text{-}vector}} = \frac{g^2_{\mathrm{DM}} M_{\mathrm{med}}}{12\pi}(1-4z_{\mathrm{DM}})^{3/2}$$

$$\Gamma^{q\bar{q}}_{\mathrm{axial\text{-}vector}} = \frac{g^2_q M_{\mathrm{med}}}{4\pi}(1-4z_q)^{3/2}\,.$$

Assume g_q, g_χ [1]

1603.04156





[1] values recommended by LHC DM WG

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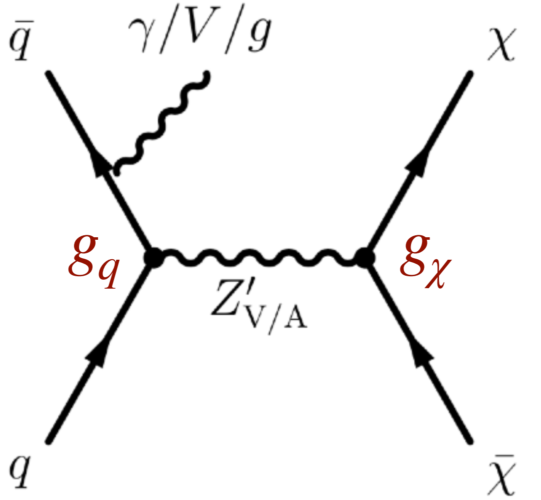

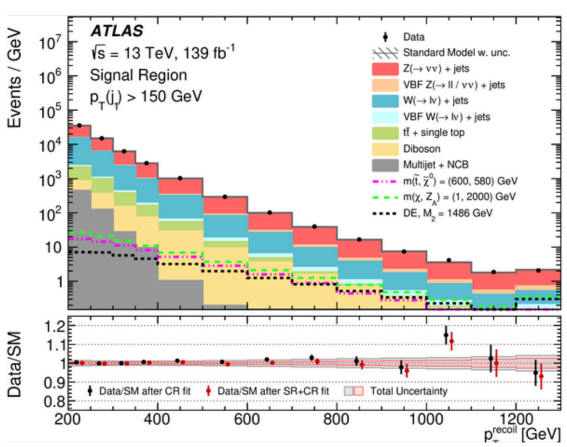

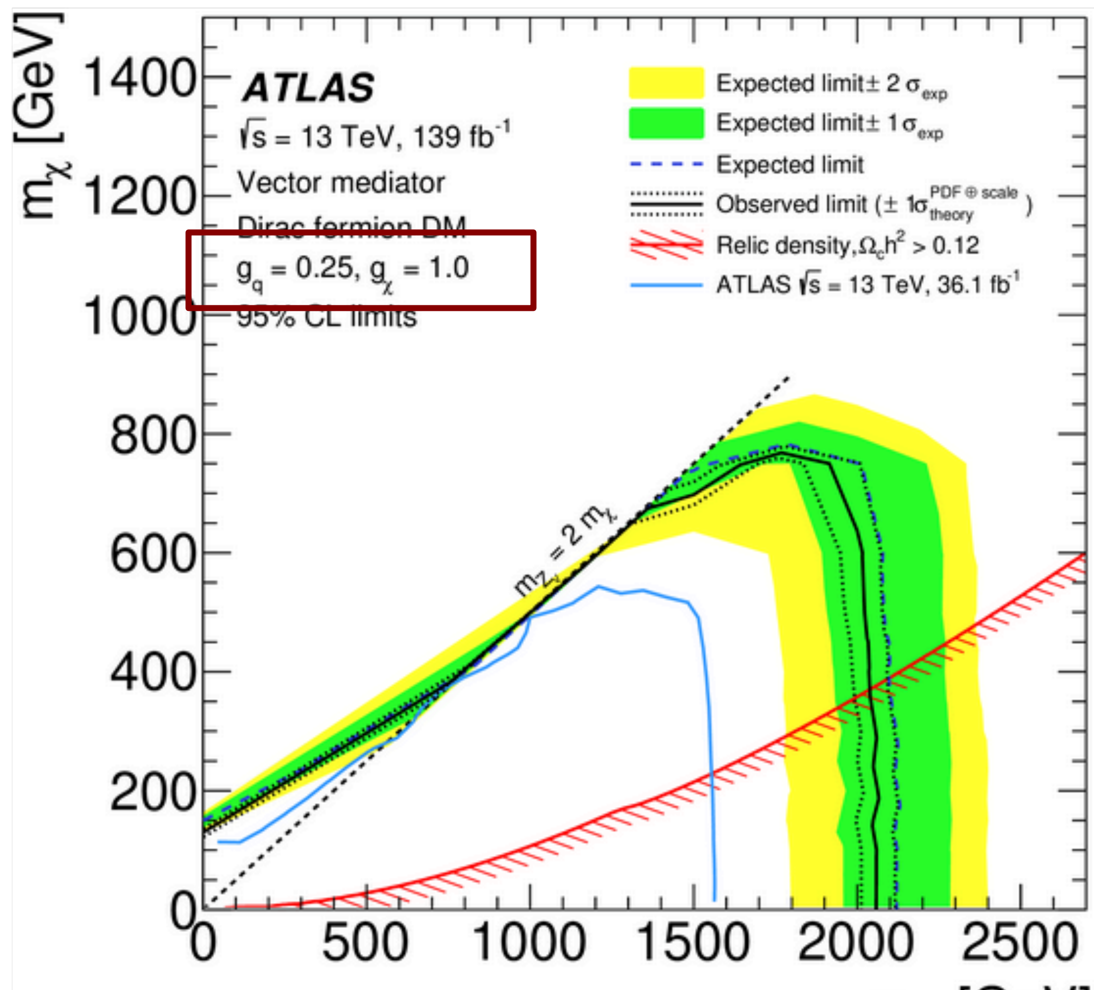

Vector mediator

DM @ LHC: S-CHANNEL MEDIATOR

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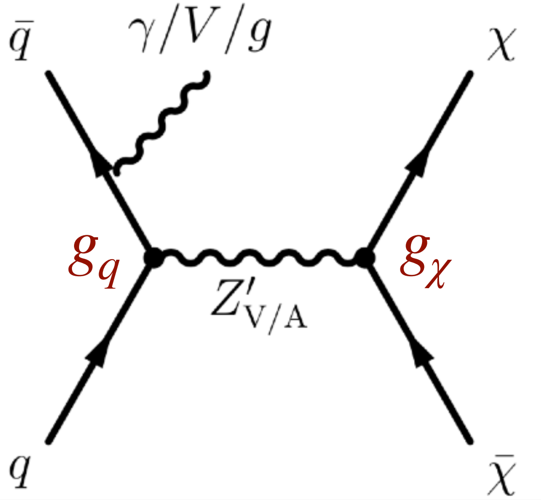
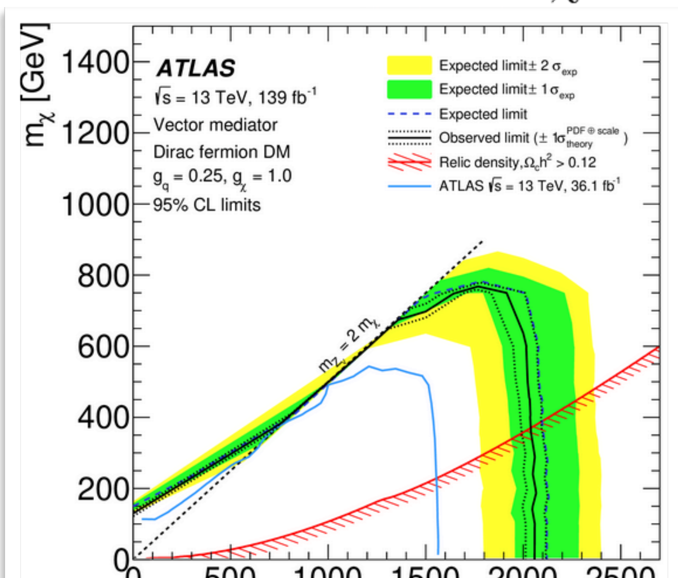
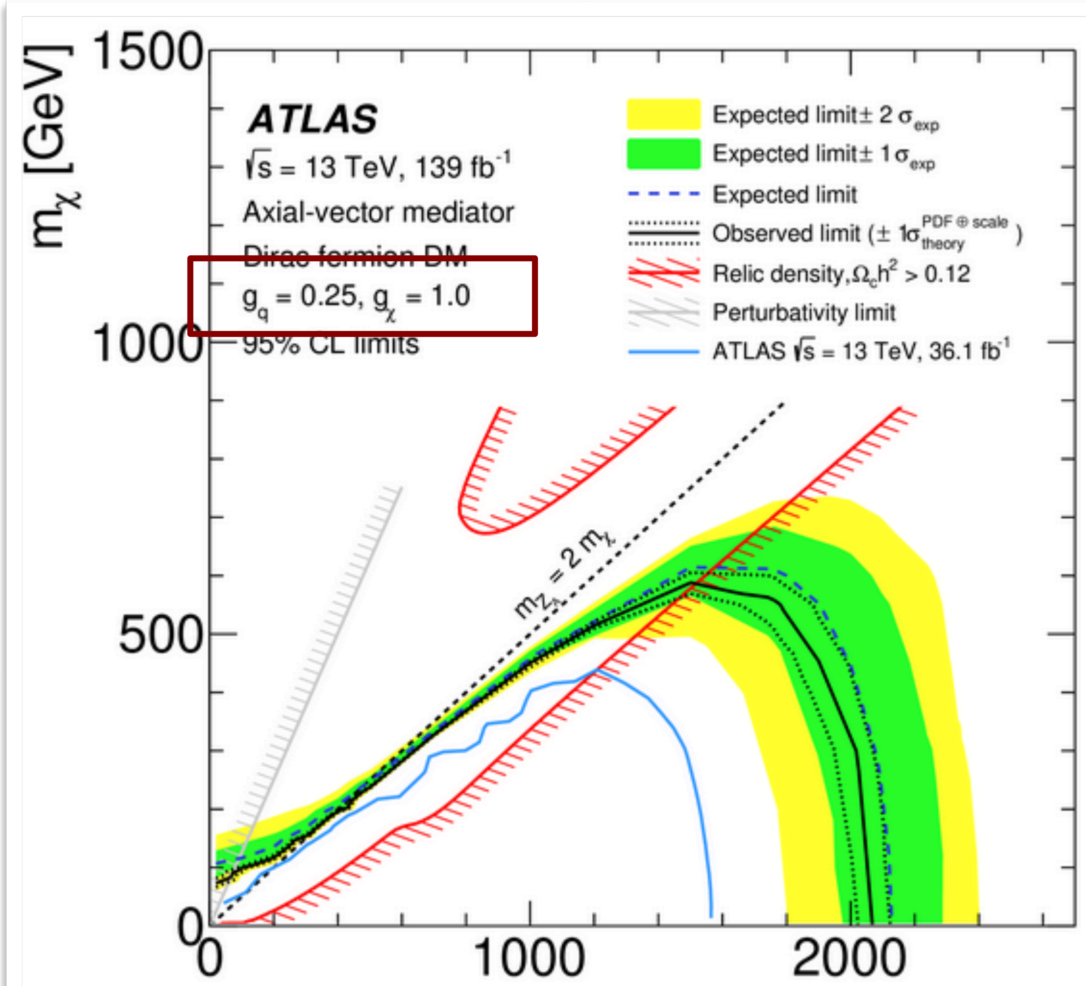
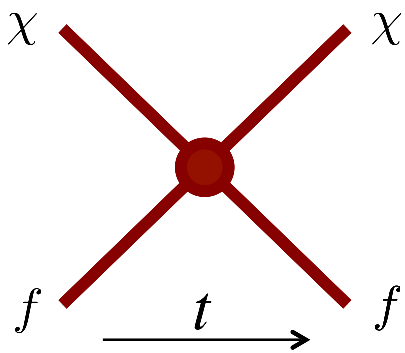


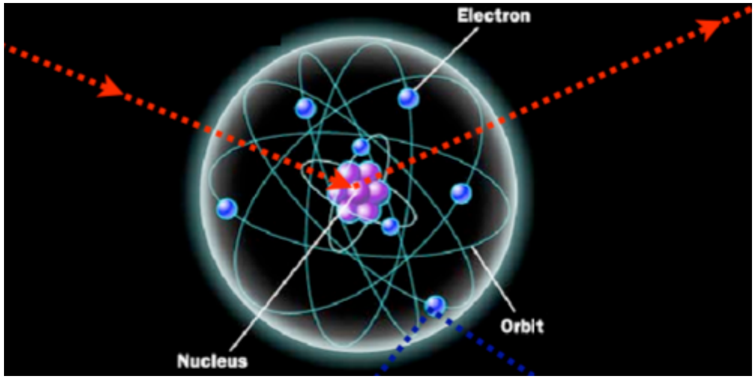


Vector mediator



Axial vector mediator





$$\frac{d\sigma}{dE} = \frac{m_N}{2\mu^2 v^2}\left(\sigma_{SI} F^2(q) + \sigma_{SD} S(q)\right)$$

Target choice: the ONLY experimental handle!

Spin-independent:
- vector coupling
- scalar coupling

P

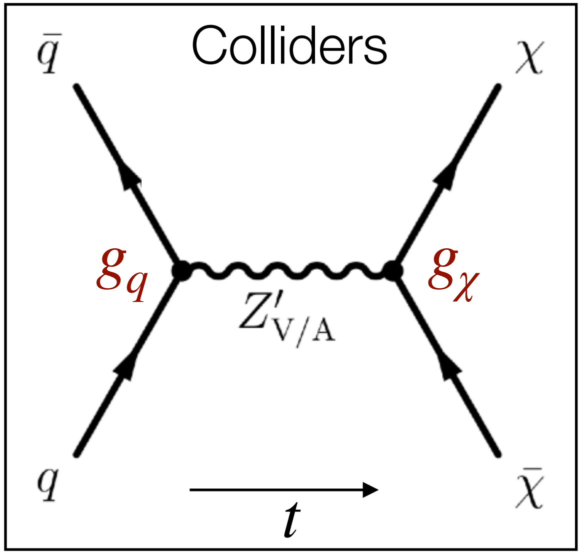
DM interaction with:
any nucleon in nucleus
→ enhancement $\propto A^2$

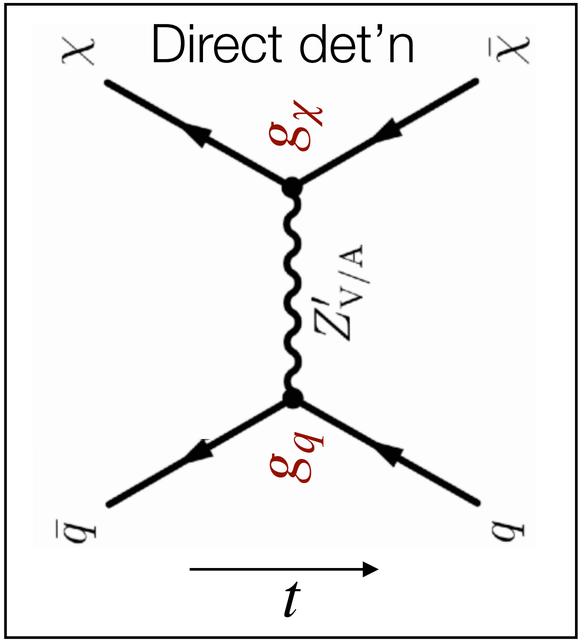
Spin-dependent:
- axial-vector coupling
- pseudoscalar coupling

$\not{P}$

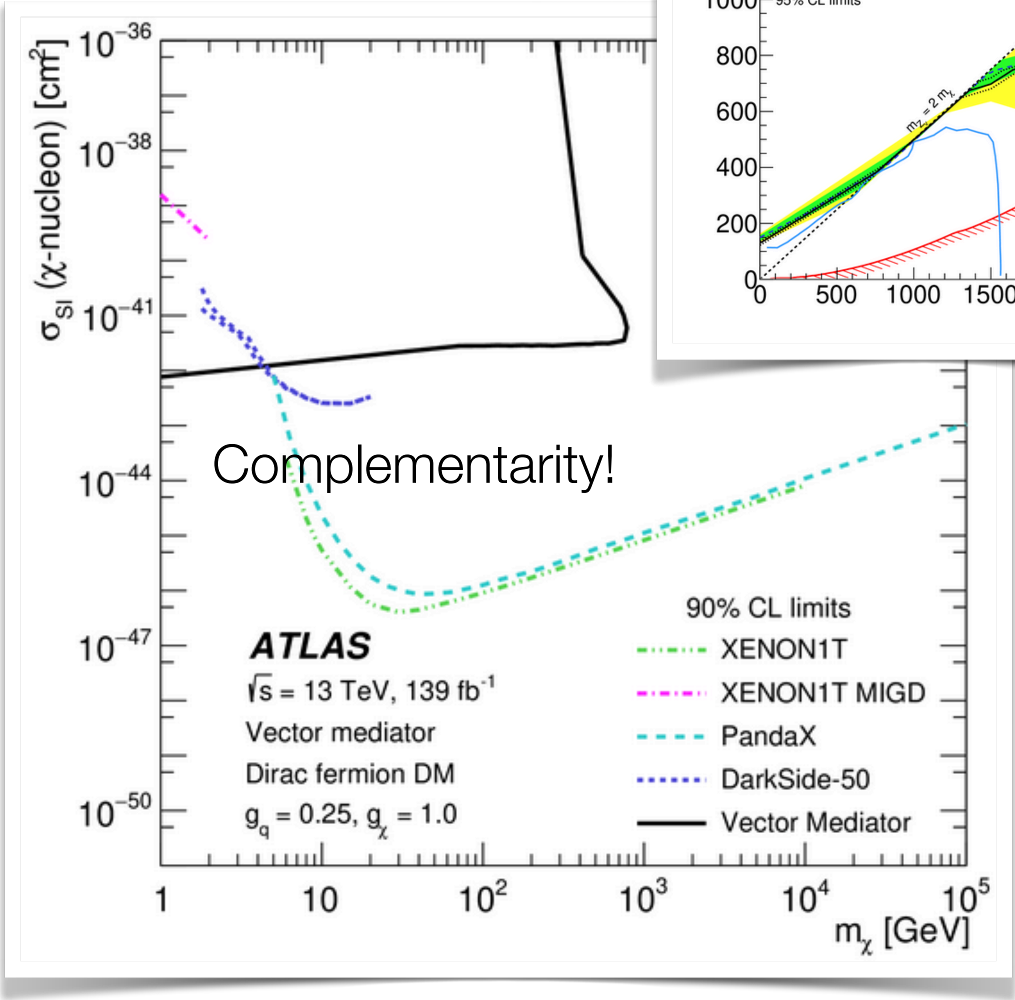
DM interaction with:
spin of unpaired p or n
→ optimise for u or d, $\propto A$

1605.08788





Vector mediator



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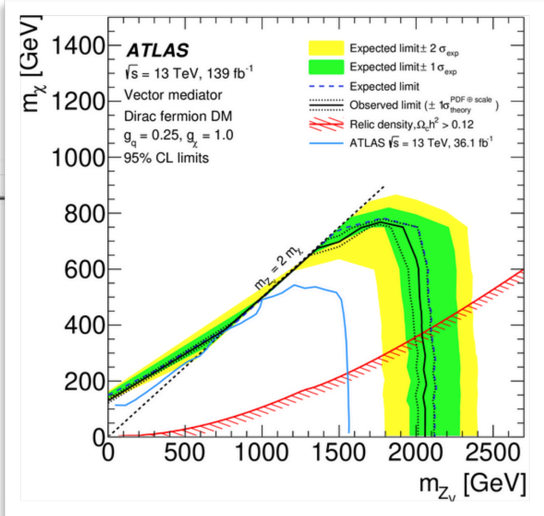

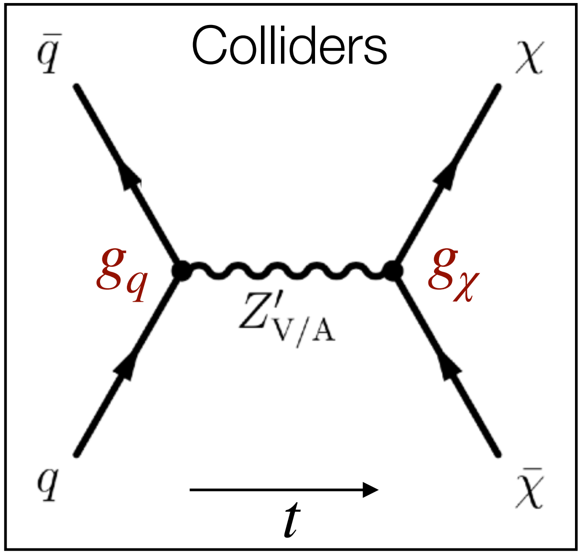

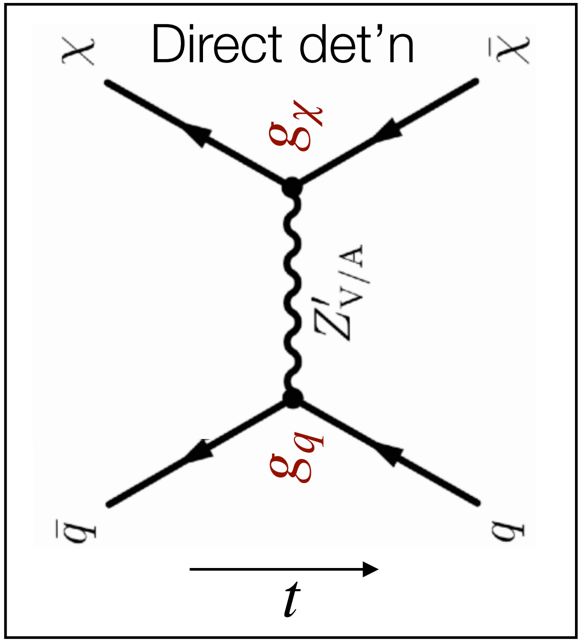

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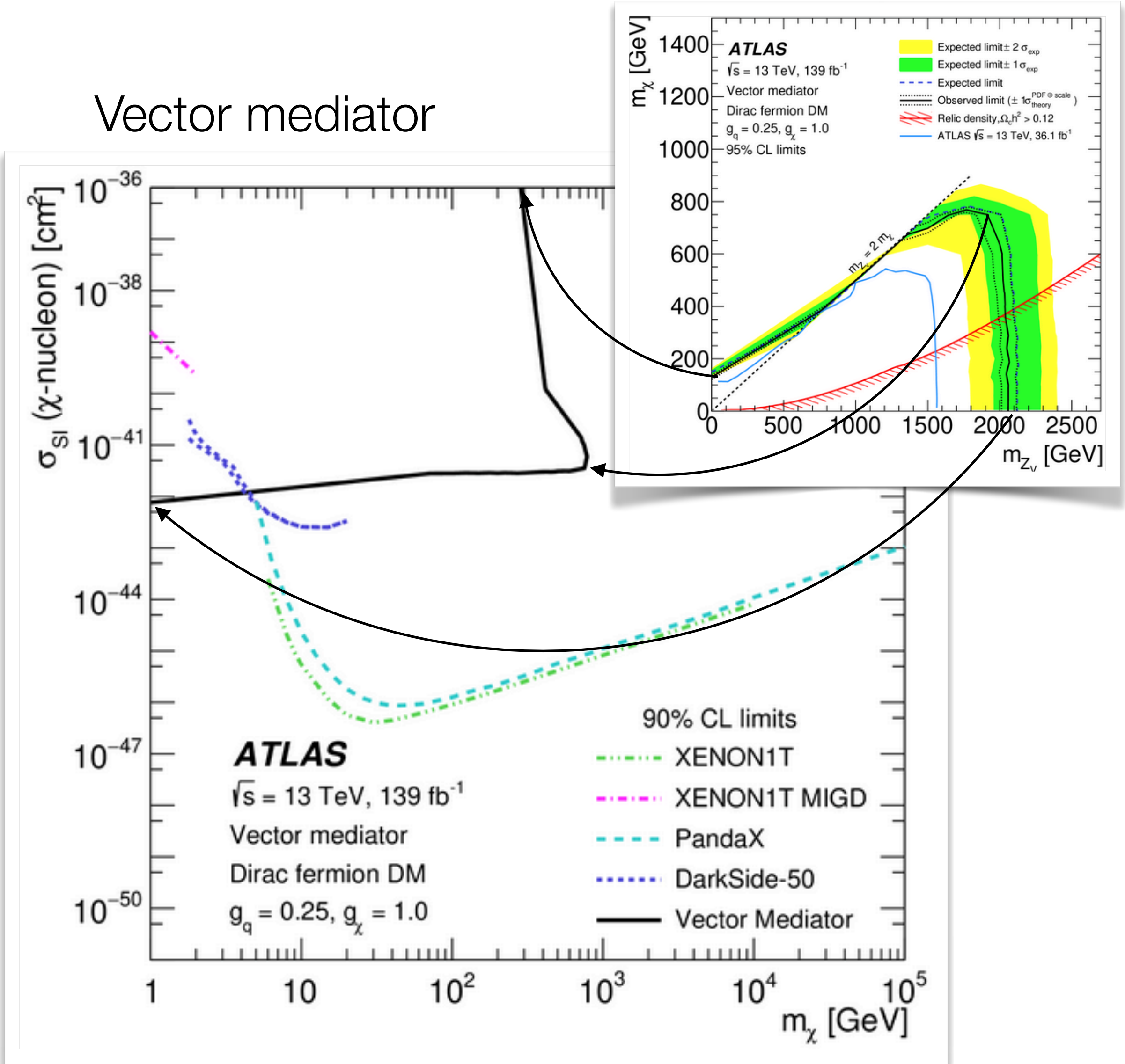
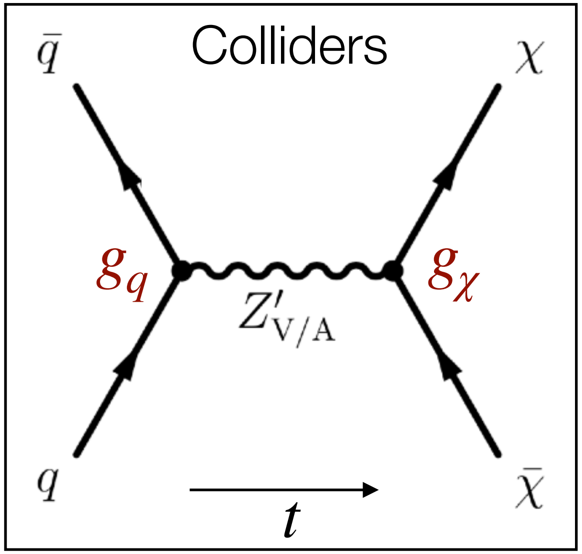
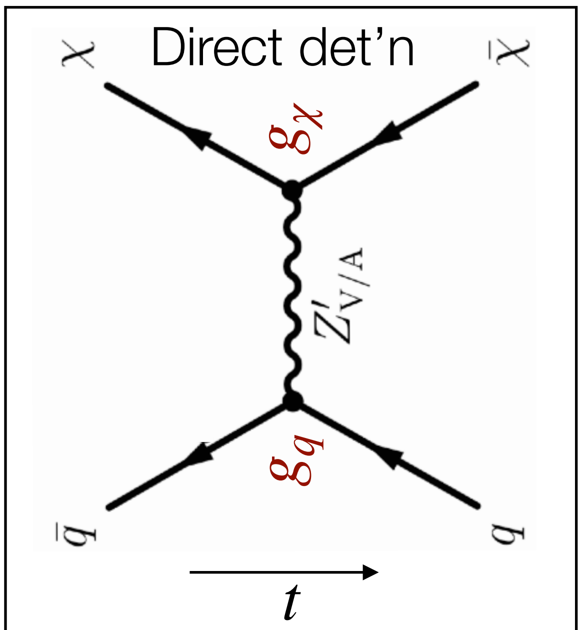
Vector mediator







Axial vector mediator

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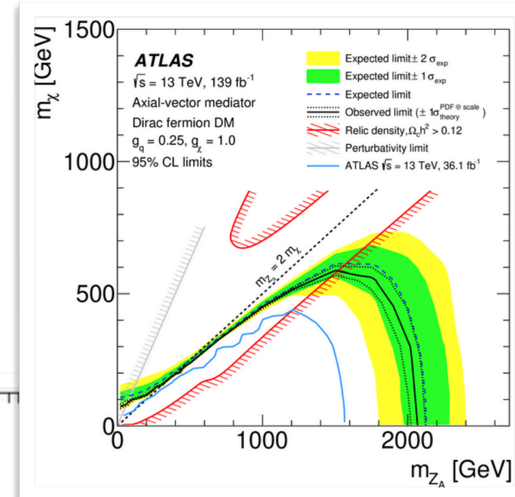

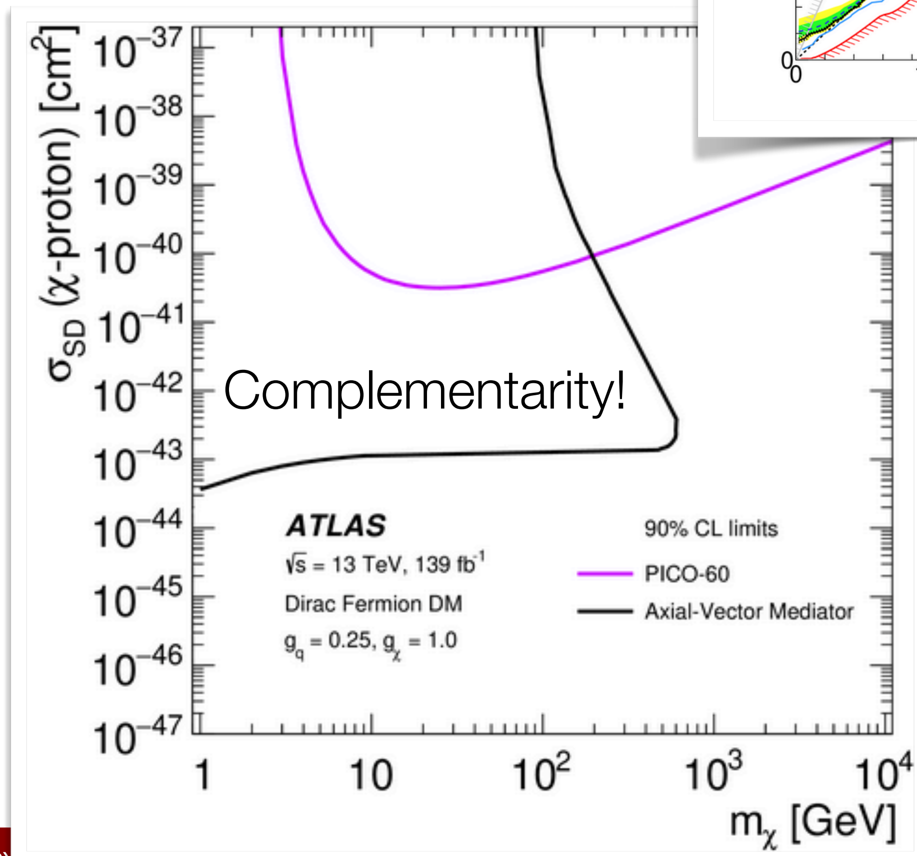

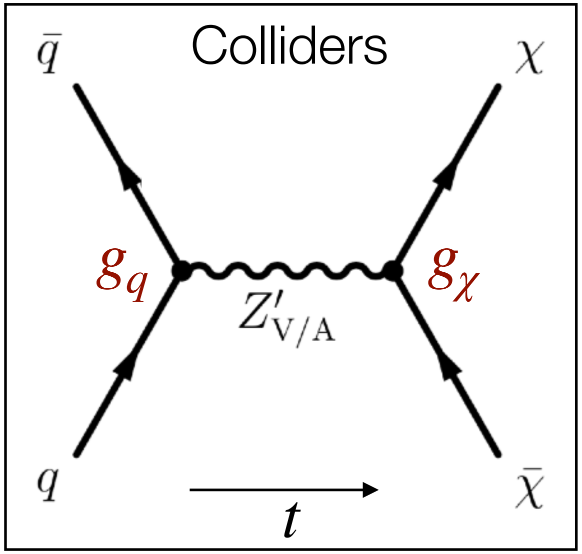

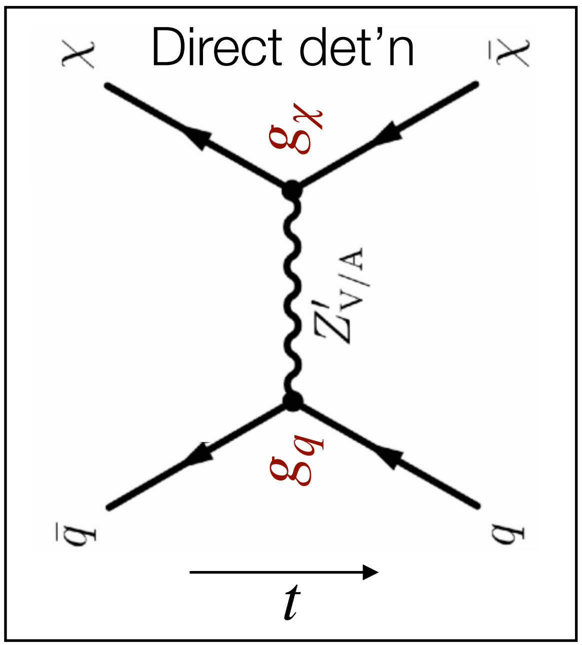

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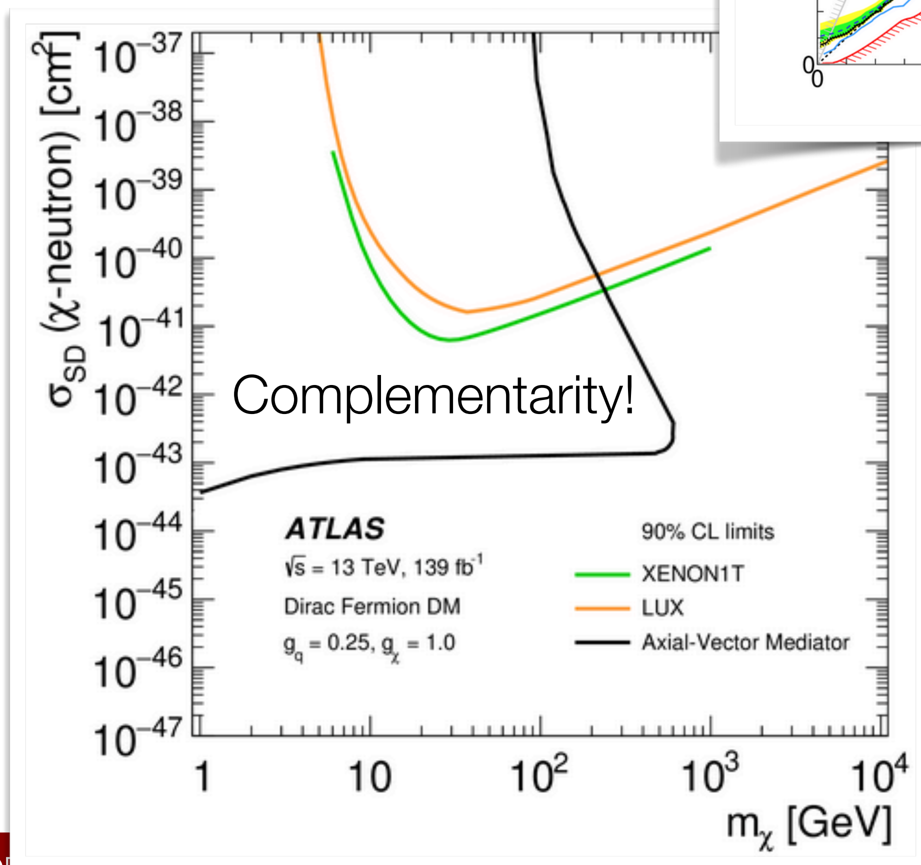
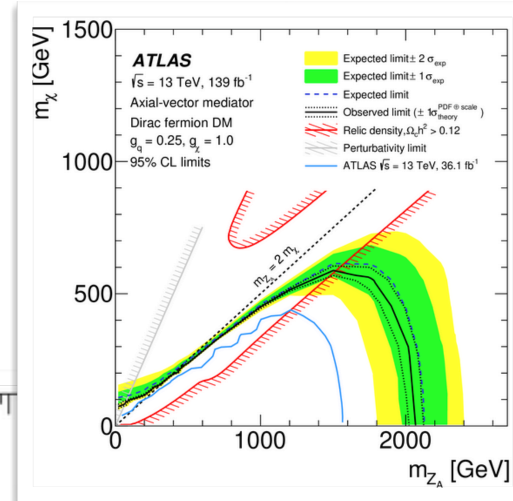
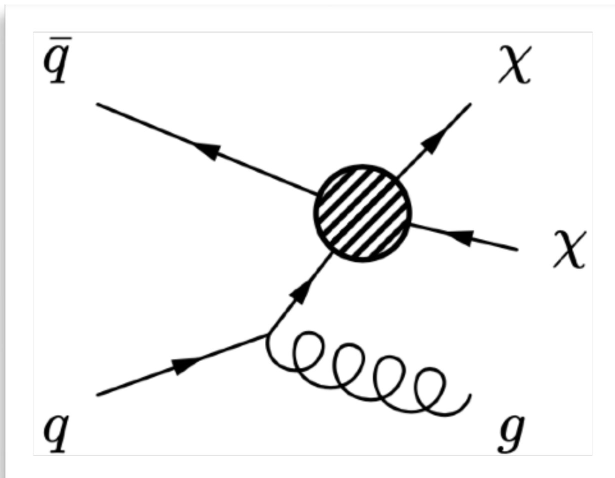
Axial vector mediator



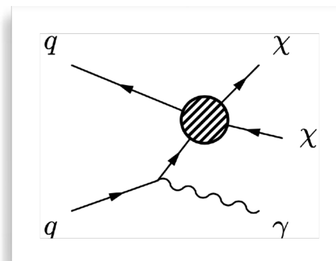


Mono-jet



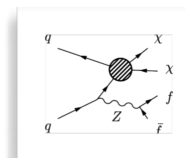
[not-so-large hit from α_s]

Mono-γ



$$\frac{\sigma_{\chi\chi\gamma}}{\sigma_{\chi\chi j}} \approx \frac{\alpha}{\alpha_s}\frac{Q_q^2}{C_F} \approx \frac{1}{40}$$

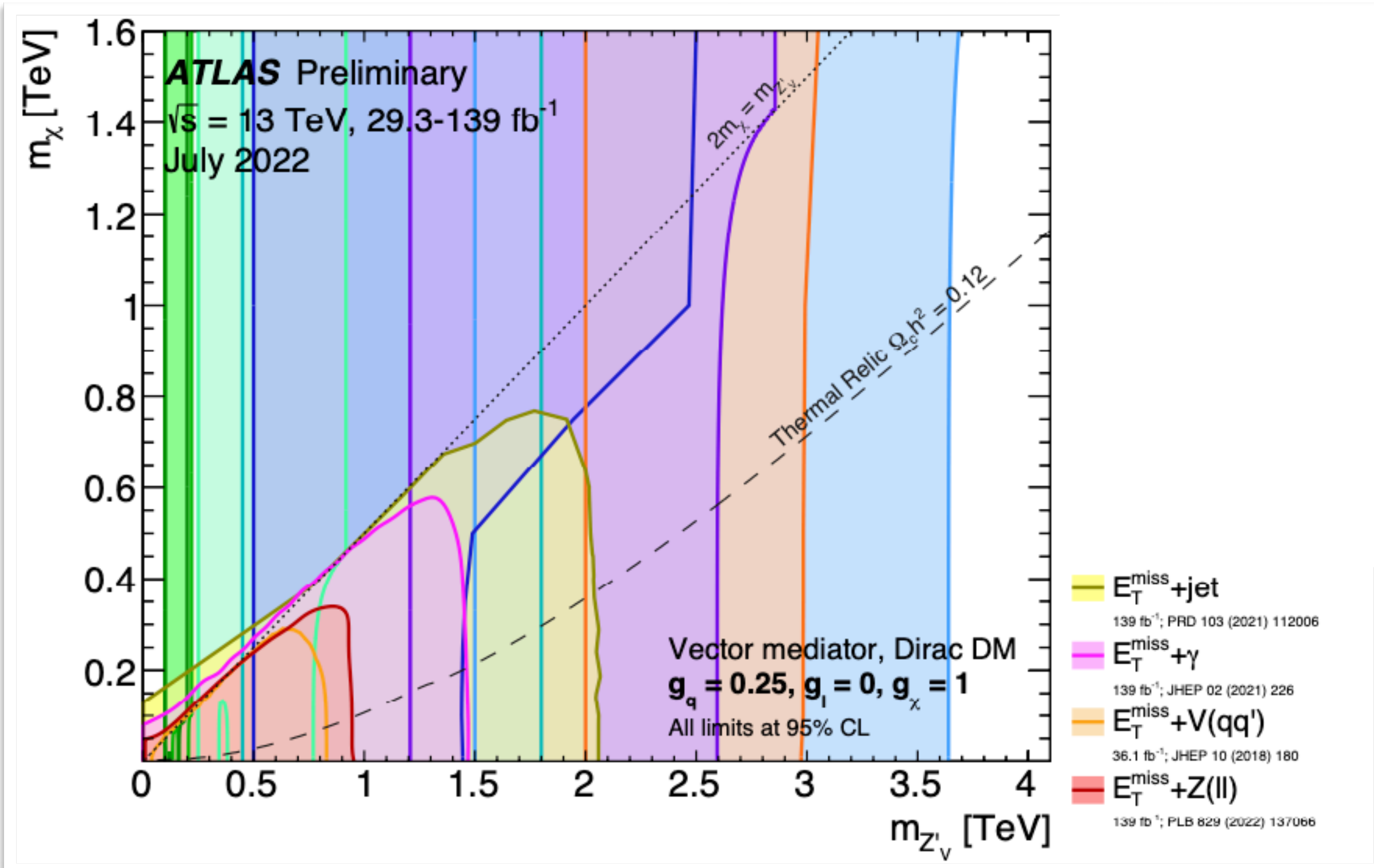
Mono-$Z(\rightarrow \mu\mu)$

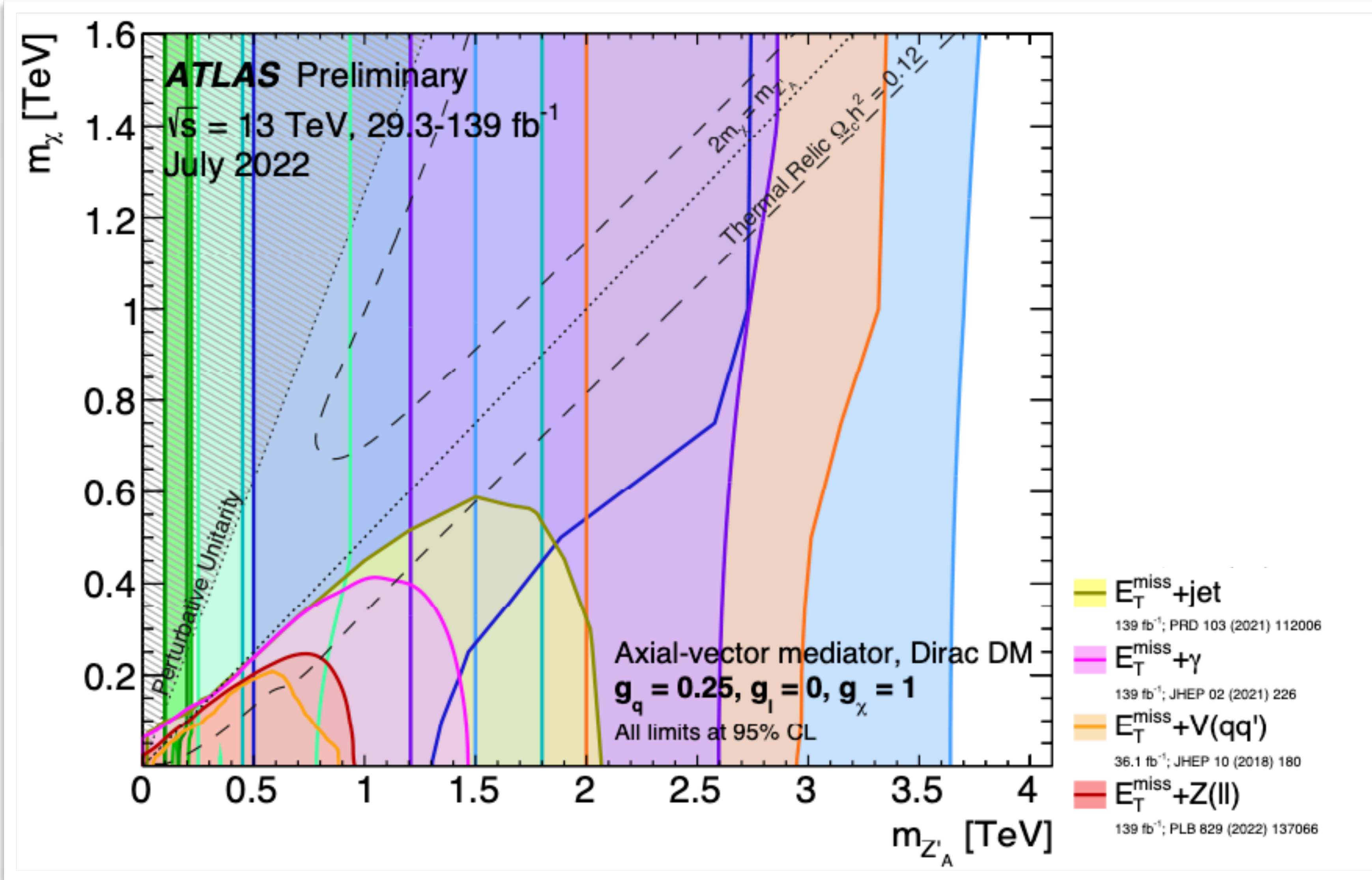


$$\frac{\sigma_{\chi\chi\mu\mu}}{\sigma_{\chi\chi j}} \approx \frac{1}{4000}$$

$$\approx \frac{\alpha}{\alpha_s}\frac{Q_q^2\, s_w^2}{C_F}\,\mathbf{BR}(Z\rightarrow\mu\mu)$$

1705.01987

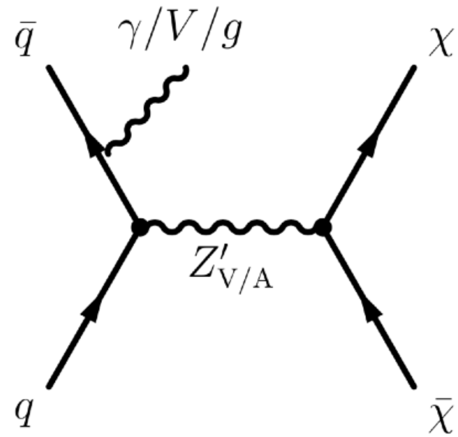

ATLAS Preliminary
√s = 13 TeV, 29.3-139 fb⁻¹
July 2022
m_χ [TeV]
$m_{Z'_V}$ [TeV]
$2m_\chi = m_{Z'_V}$
Thermal Relic $\Omega_c h^2 = 0.12$
Vector mediator, Dirac DM
$g_q = 0.25, g_l = 0, g_\chi = 1$
All limits at 95% CL
E_T^{miss}+jet
139 fb⁻¹; PRD 103 (2021) 112006
$E_T^{miss}+\gamma$
139 fb⁻¹; JHEP 02 (2021) 226
E_T^{miss}+V(qq')
36.1 fb⁻¹; JHEP 10 (2018) 180
E_T^{miss}+Z(ll)
139 fb⁻¹; PLB 829 (2022) 137066

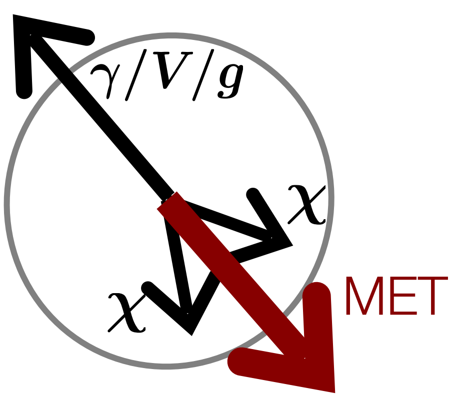


ATLAS Preliminary
√s = 13 TeV, 29.3-139 fb⁻¹
July 2022
m_χ [TeV]
$m_{Z'_A}$ [TeV]
Perturbative Unitarity
$2m_\chi = m_{Z'_A}$
Thermal Relic $\Omega_c h^2 = 0.12$
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_\chi = 1$
All limits at 95% CL
E_T^{miss}+jet
139 fb⁻¹; PRD 103 (2021) 112006
E_T^{miss}+γ
139 fb⁻¹; JHEP 02 (2021) 226
E_T^{miss}+V(qq')
36.1 fb⁻¹; JHEP 10 (2018) 180
E_T^{miss}+Z(ll)
139 fb⁻¹; PLB 829 (2022) 137066

Exciting interplay between signatures:

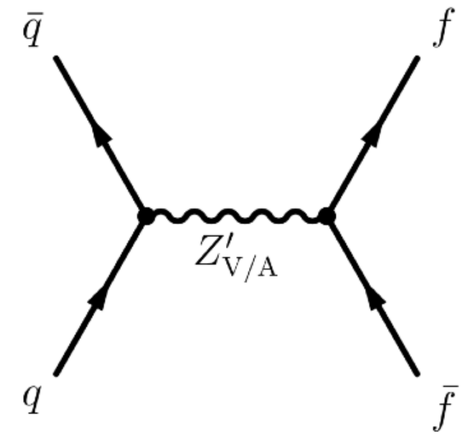
X+MET

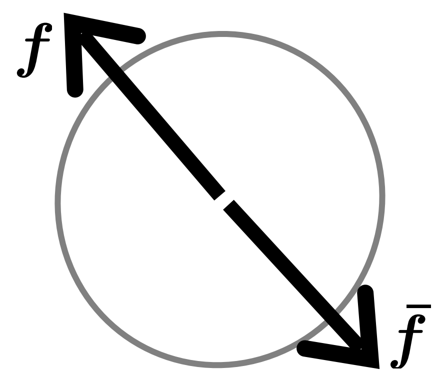




Smoking gun DM signature

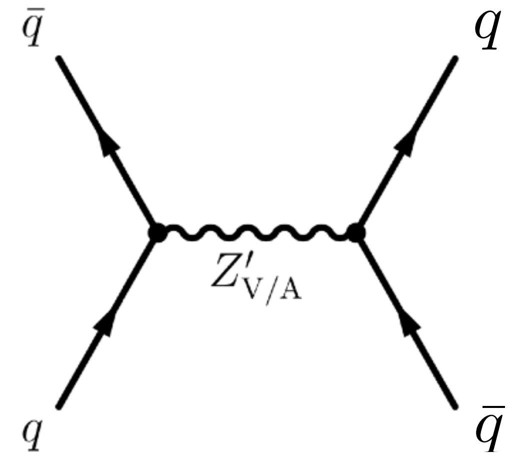
Resonances

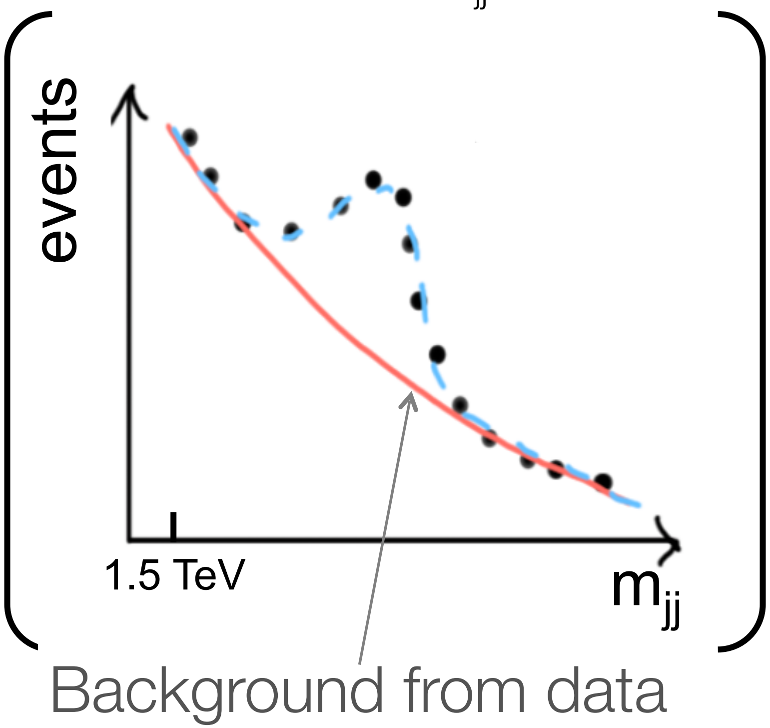


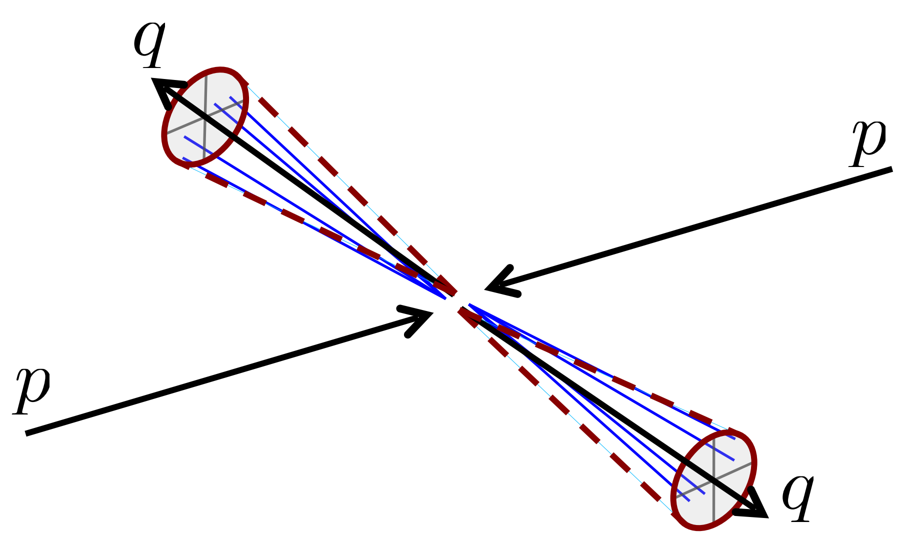


arXiv:1507.00966 (DMF report)
arXiv:1603.04156, arXiv:1703.05703 (White Papers of LHC DM WG)

- **Analysis strategy:**
  - Require ≥2 of jets + jet triggers
  - Include initial state radiation jets if $\Delta R < 1.1$
  - Reduce SM *t*-channel dijets:
    - $|\Delta\eta| < 1.1$ (SR), $1.1 < |\Delta\eta| < 2.6$ (CR)
  - Look for excess in m_{jj} distribution:

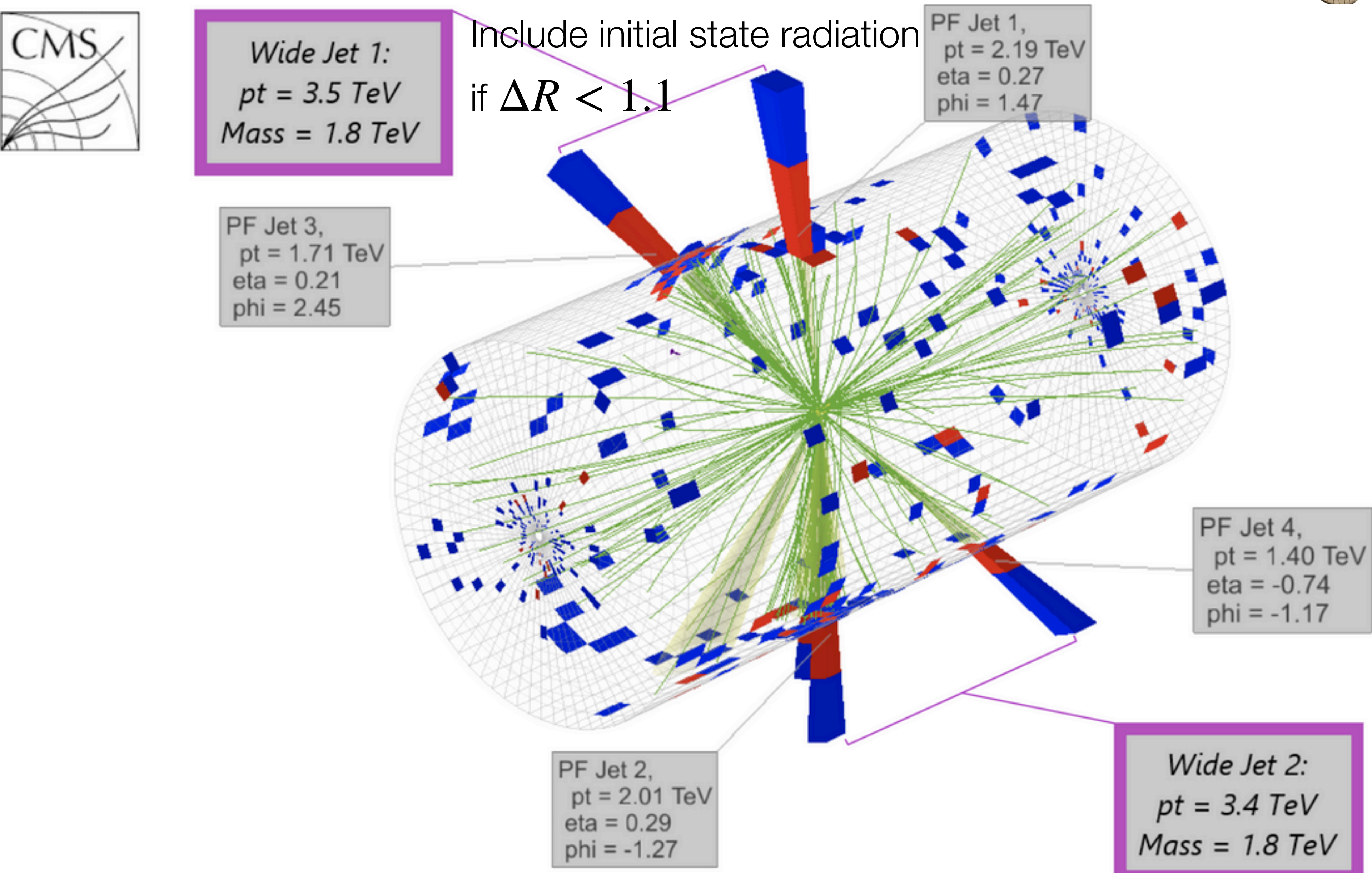


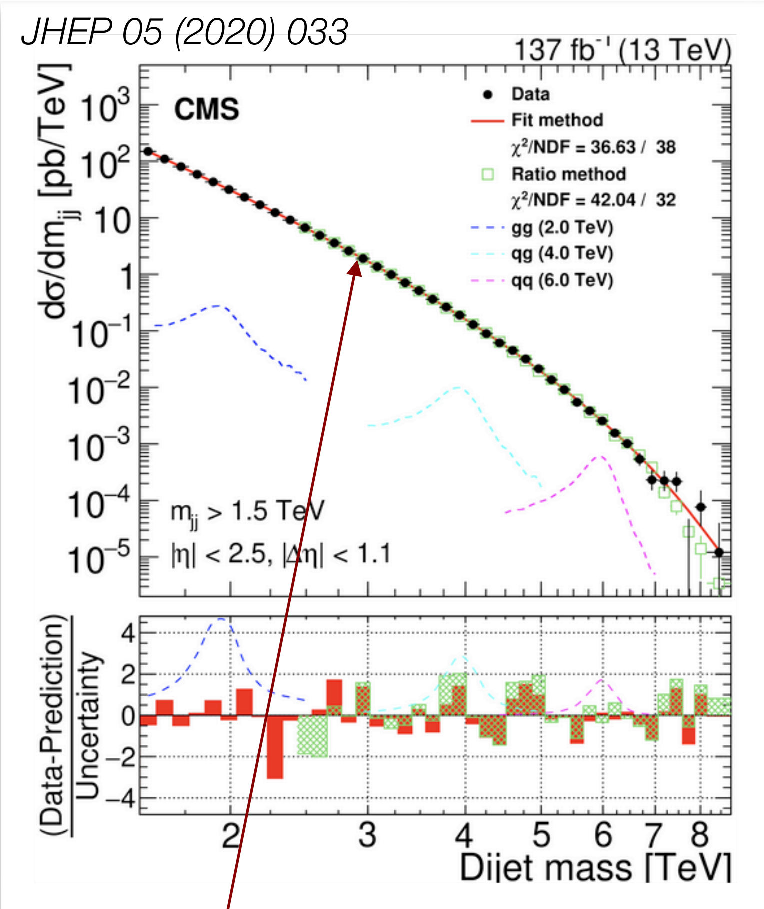


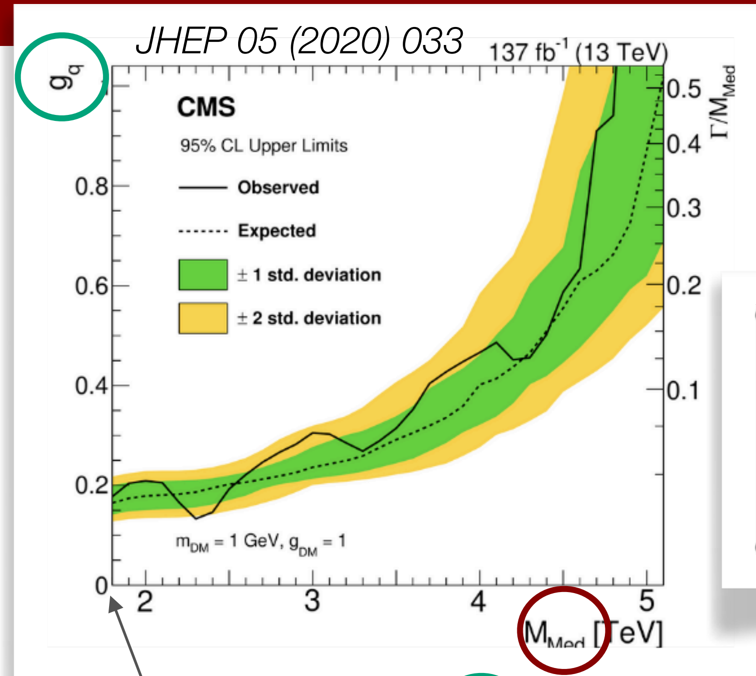


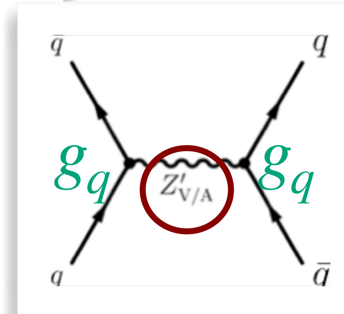
JHEP 05 (2020) 033

Include initial state radiation if $\Delta R < 1.1$



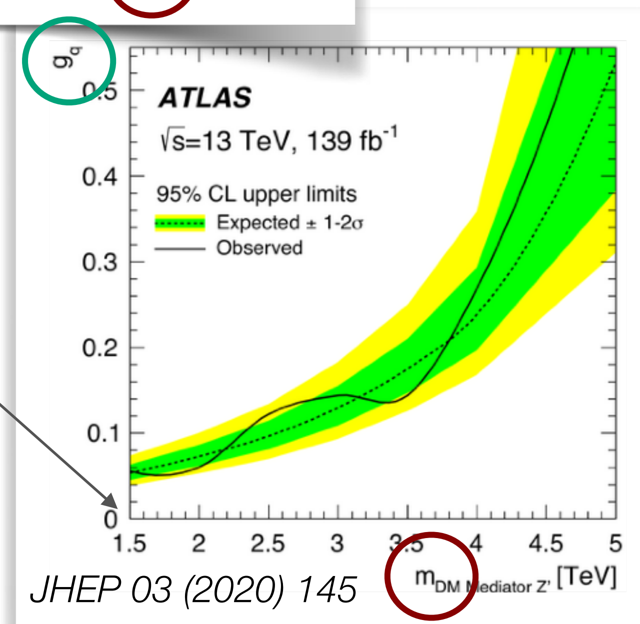






Challenge:

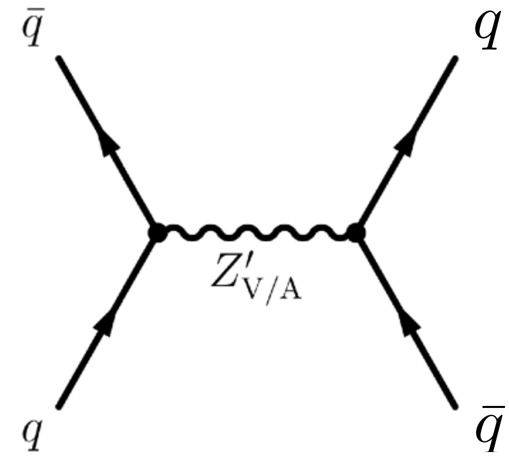
trigger threshold

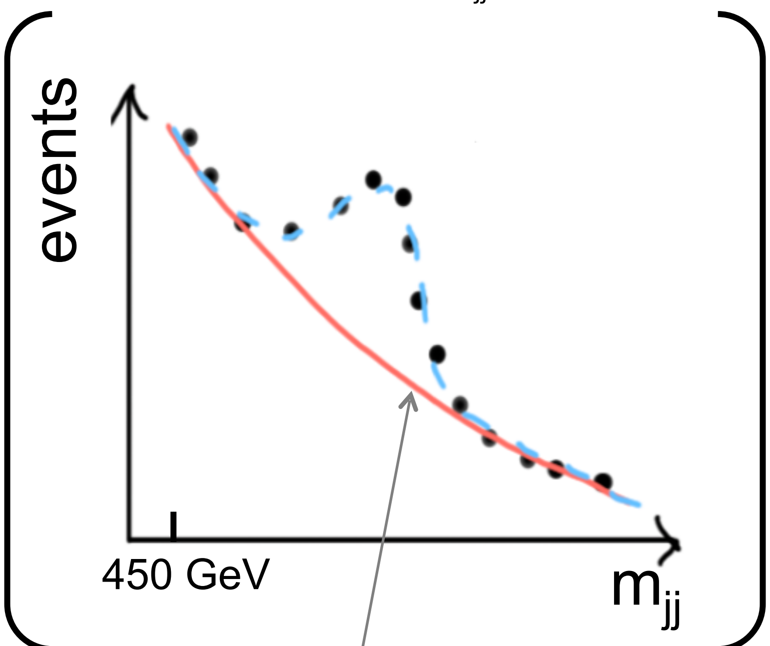


Background fit + alternative bgr. estimation (not shown)

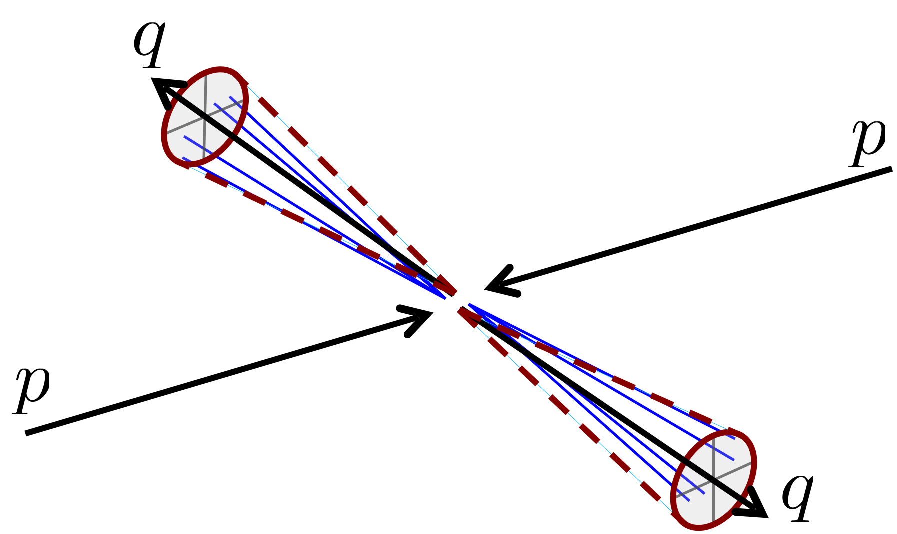
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}} \qquad x \equiv m_{jj}/\sqrt{s}$$

- **Analysis strategy:**
  - Jets reconstructed by high-level trigger
  - Require ≥2 of jets with $p_T \gtrsim 220$ GeV
  - $|y^*| = \frac{1}{2}|y_1 - y_2| < 0.6$ (also 0.3)
  - $M_{jj} > 450$ GeV
  - Look for excess in m_{jj} distribution:





Background from data

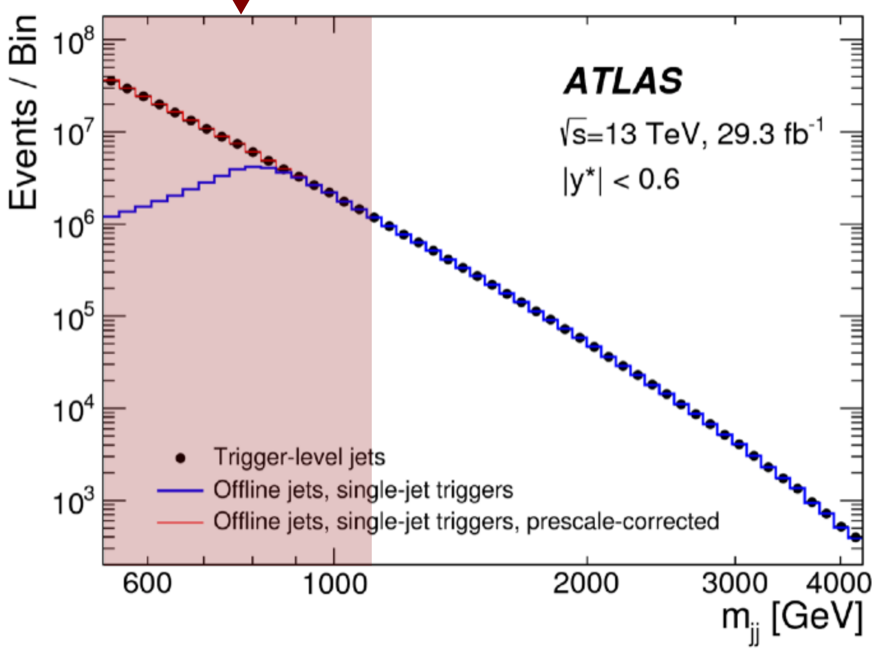


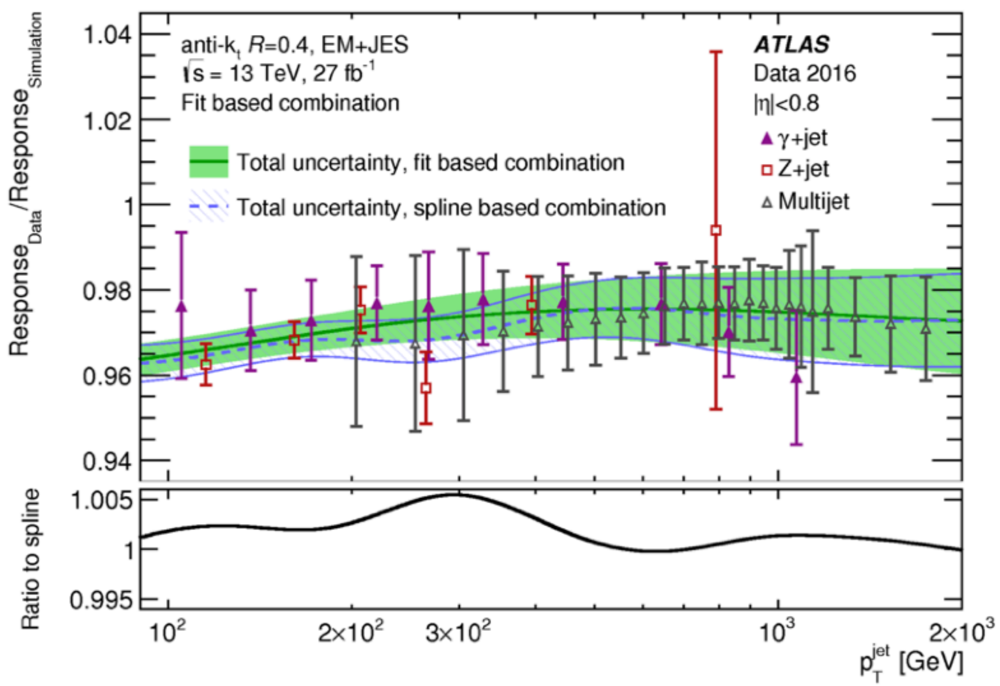
PRL 121 (2018) 081801

TRIGGER LEVEL DIJET RESONANCES: STRATEGY

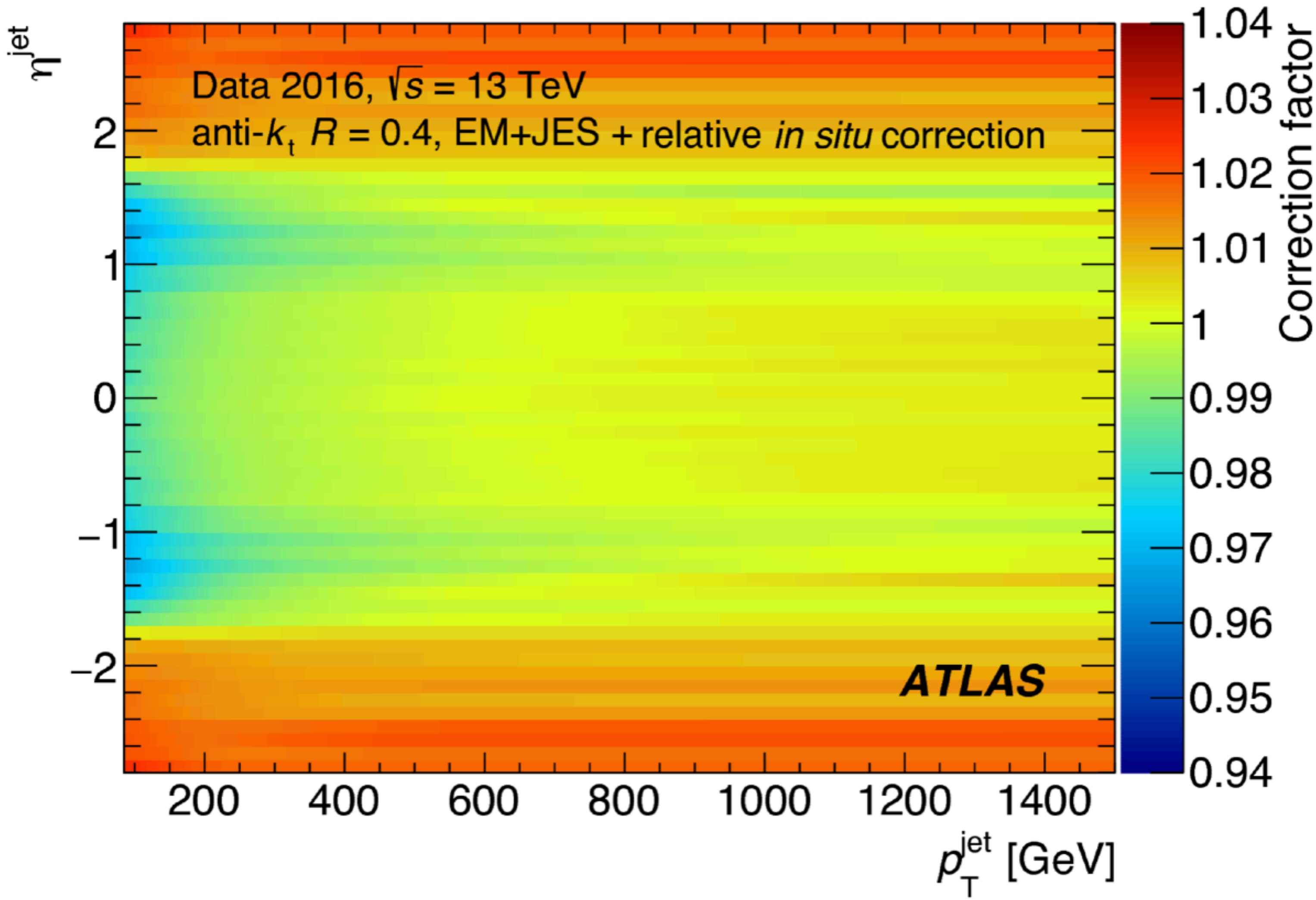
- **Ansatz:**
  - Reconstruct jets using High Level Trigger
  - Storage: one 4-vector per jet → larger bandwidth!
- **Challenge:**
  - Calibration of jets in High Level Trigger:

Trigger level analysis

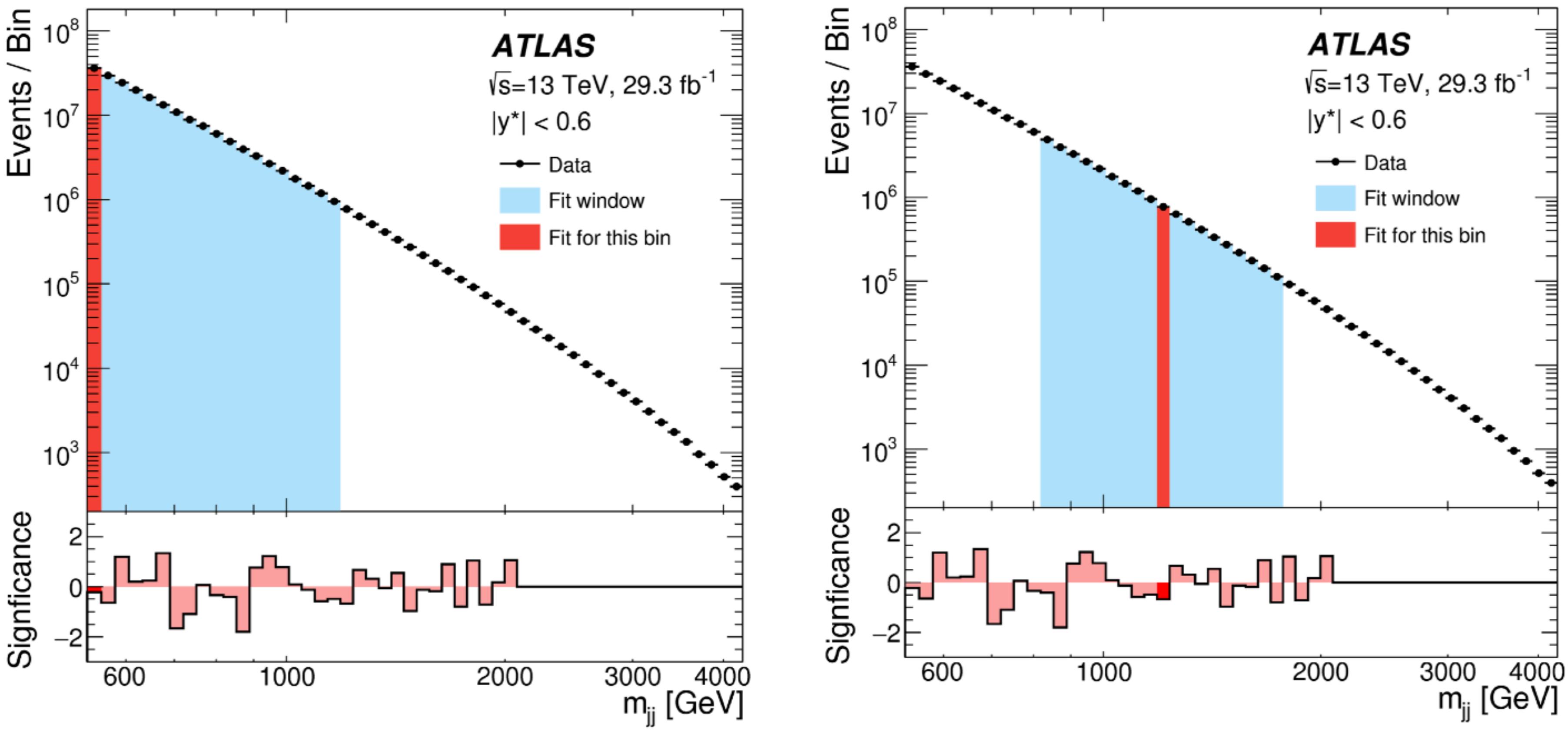




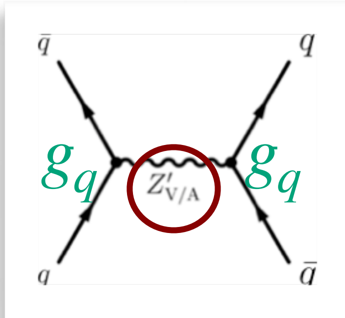
PRL 121 (2018) 081801

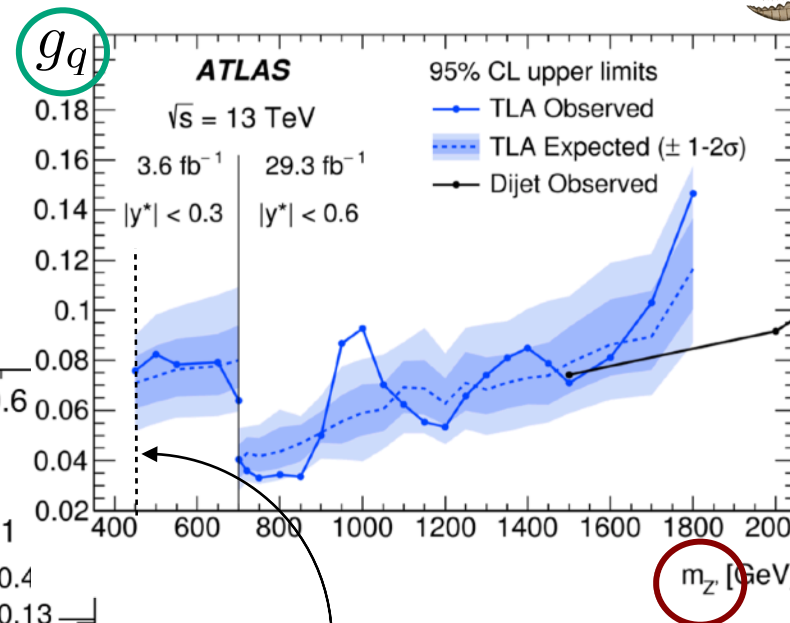


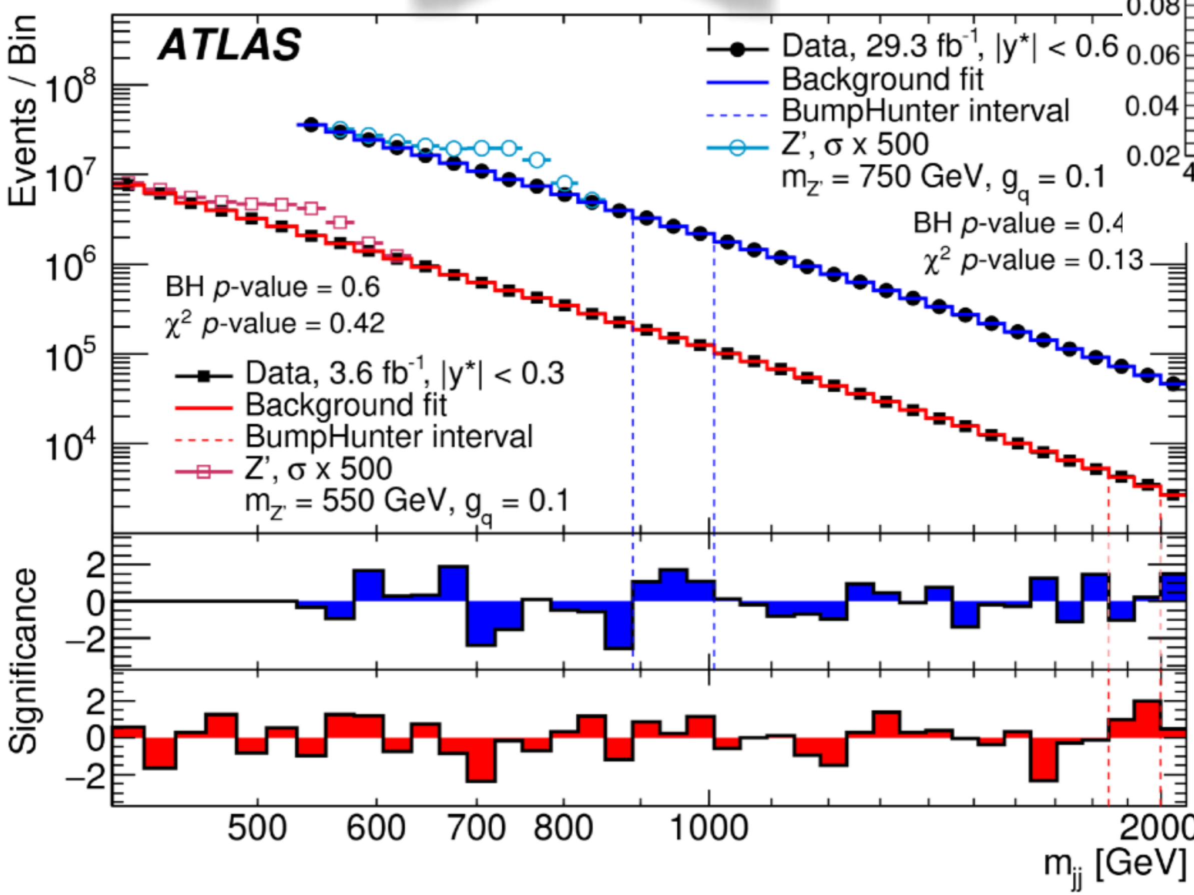
PRL 121 (2018) 081801



PRL 121 (2018) 081801





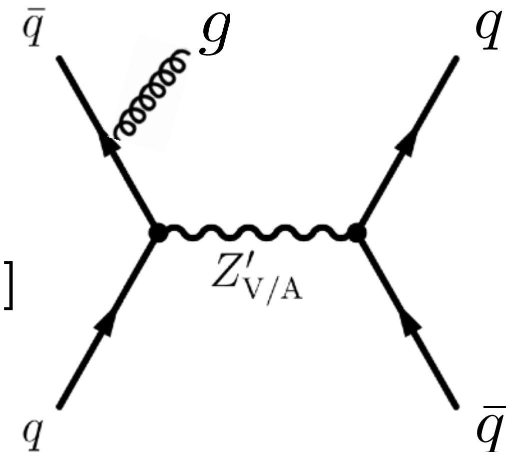


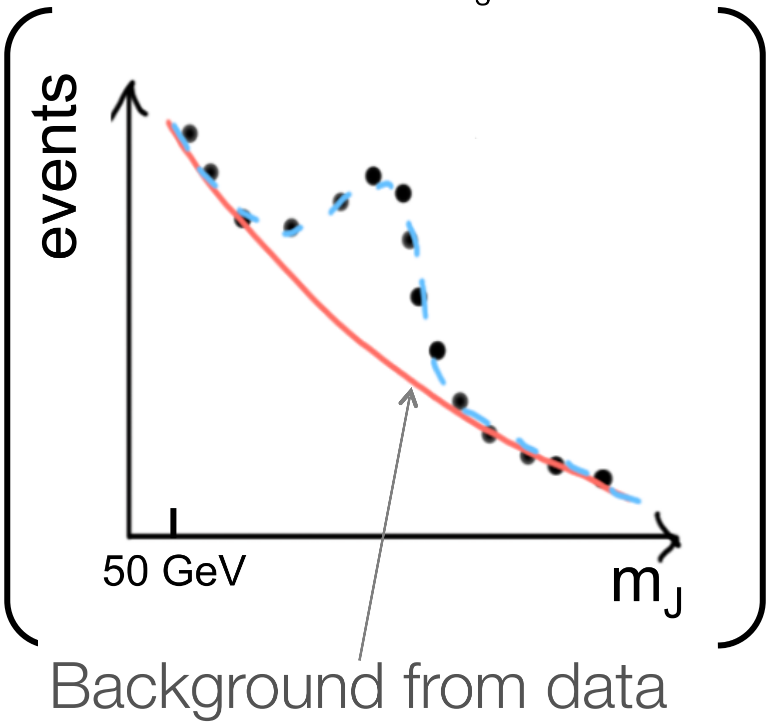
Push further down to

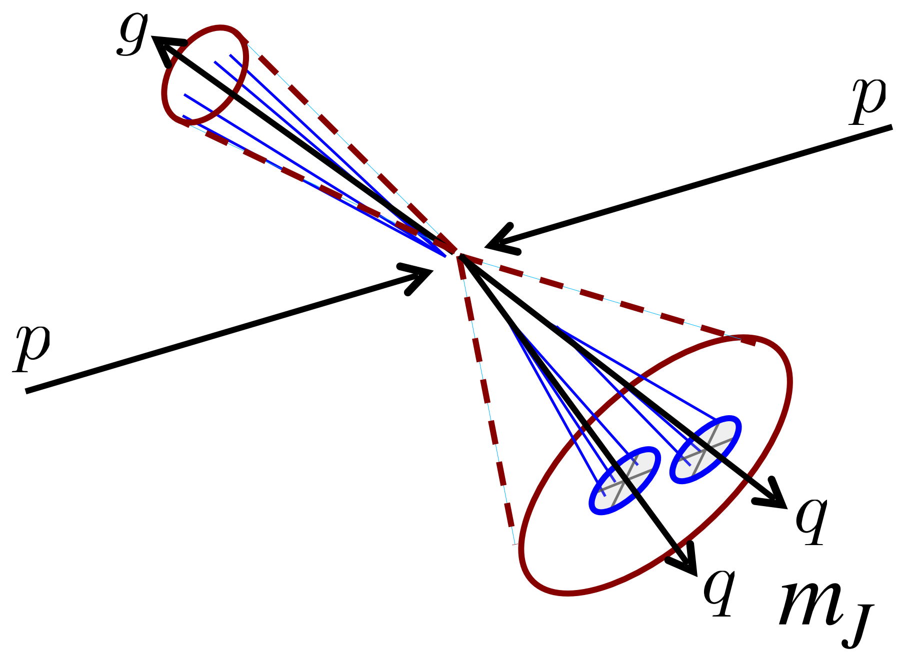
$m_{Z'} < 450$ GeV?

PRL 121 (2018) 081801

- **Analysis strategy:**
  - Capture resonance as large-R jet (2-prong)
    - R=0.8 anti-kt jet ($m_{Z'} < 220$ GeV) [1]
    - R=1.5 C/A jet ($220 < m_{Z'} < 450$ GeV) [1]
  - Initial state gluon radiation for *trigger*
  - Look for excess in m_J distribution:



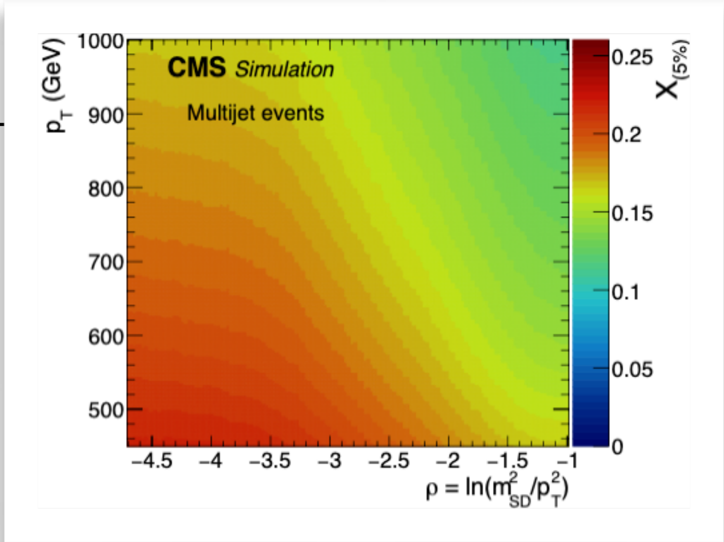




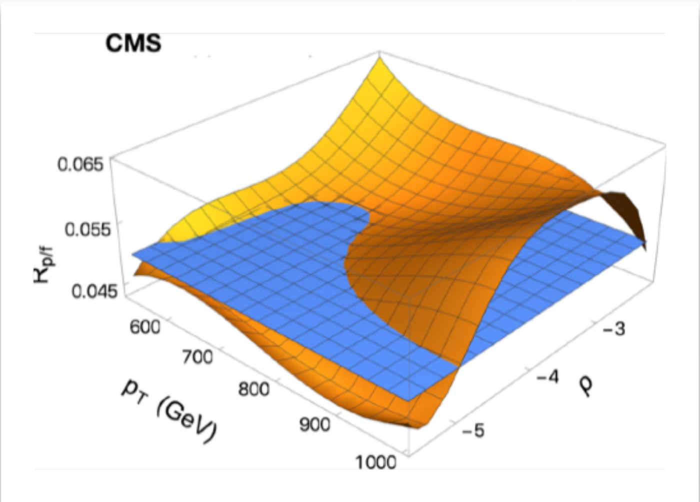
PRD 100 (2019) 112007

[1] JHEP 04 (2008) 005

- **Signal jet discriminants:**
  - Jet mass $m_J \equiv m_{Z'}$
  - Ratio of energy correlation functions $N_2^{1,\mathrm{DDT}}$
    - DDT: de-correlated from m_J and $p_{T,J}$
      - QCD jets: $\rho \equiv \ln(m_J^2/p_{T,J}^2)$ irrespective of $p_{T,J}$

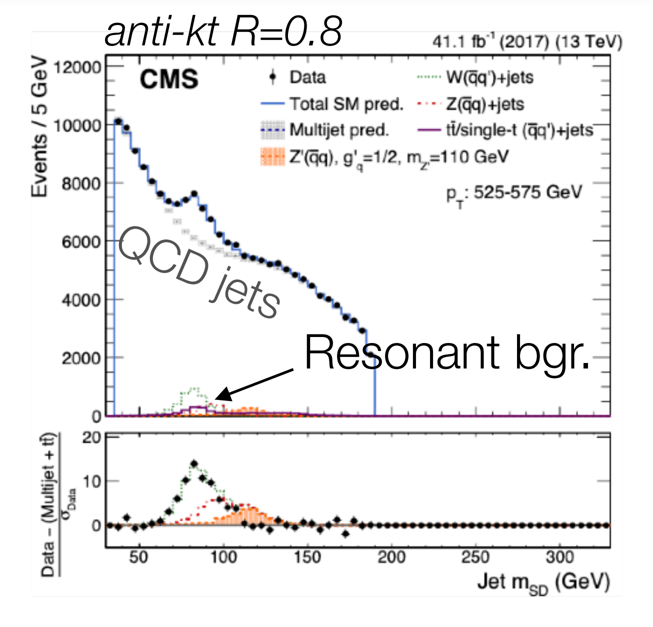


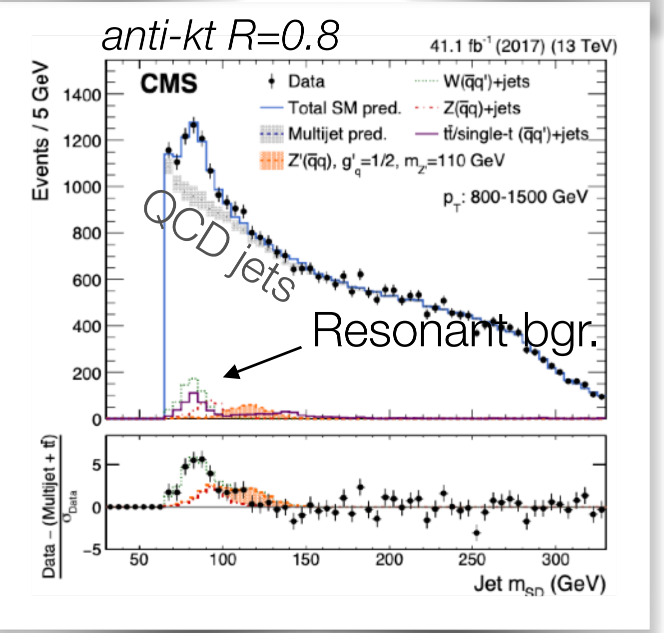
- **Background Estimate:**
  - From CR in data with $\varepsilon = 95\%$ for QCD jets:
    - $N_2^{1,\mathrm{DDT}} > 0$
  - Extrapolate to SR ($N_2^{1,\mathrm{DDT}} < 0$) using
    - $n_{\mathrm{pass}}^{\mathrm{QCD}} = R_{\mathrm{p/f}}\, n_{\mathrm{fail}}^{\mathrm{QCD}}$ + fit of $R_{\mathrm{p/f}}$

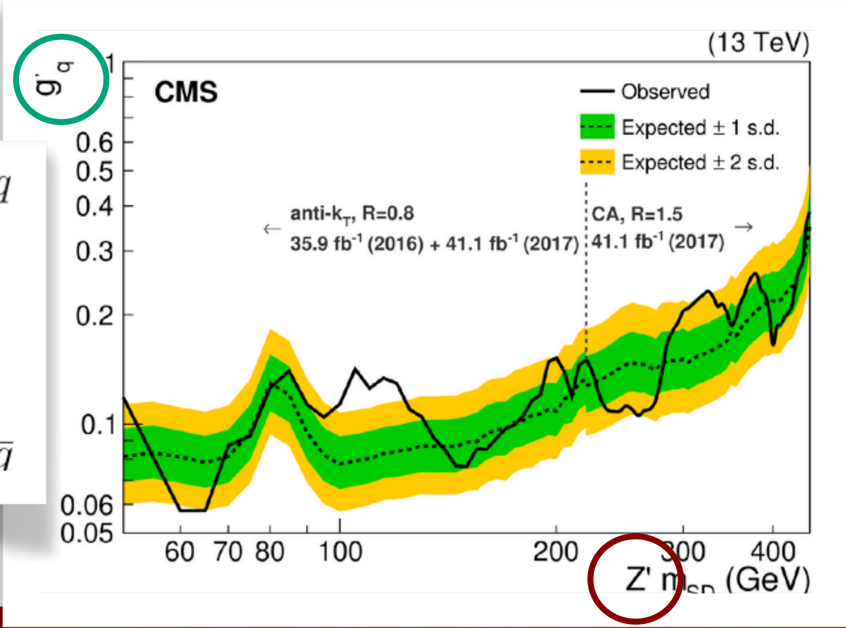


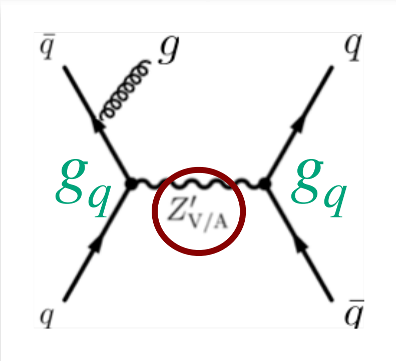
JHEP 05 (2020) 033

- **Signal jet discriminants:** *JHEP 05 (2020) 033*
  - Jet mass $m_J \equiv m_{Z'}$
  - Ratio of energy correlation functions $N_2^{1,\text{DDT}}$ [1]
    - DDT: decorrelated from m_J and $p_{T,J}$
- **Background Estimate:**
  - From CR in data with $\varepsilon = 95\%$ for QCD jets:
    - $N_2^{1,\text{DDT}} > 0$



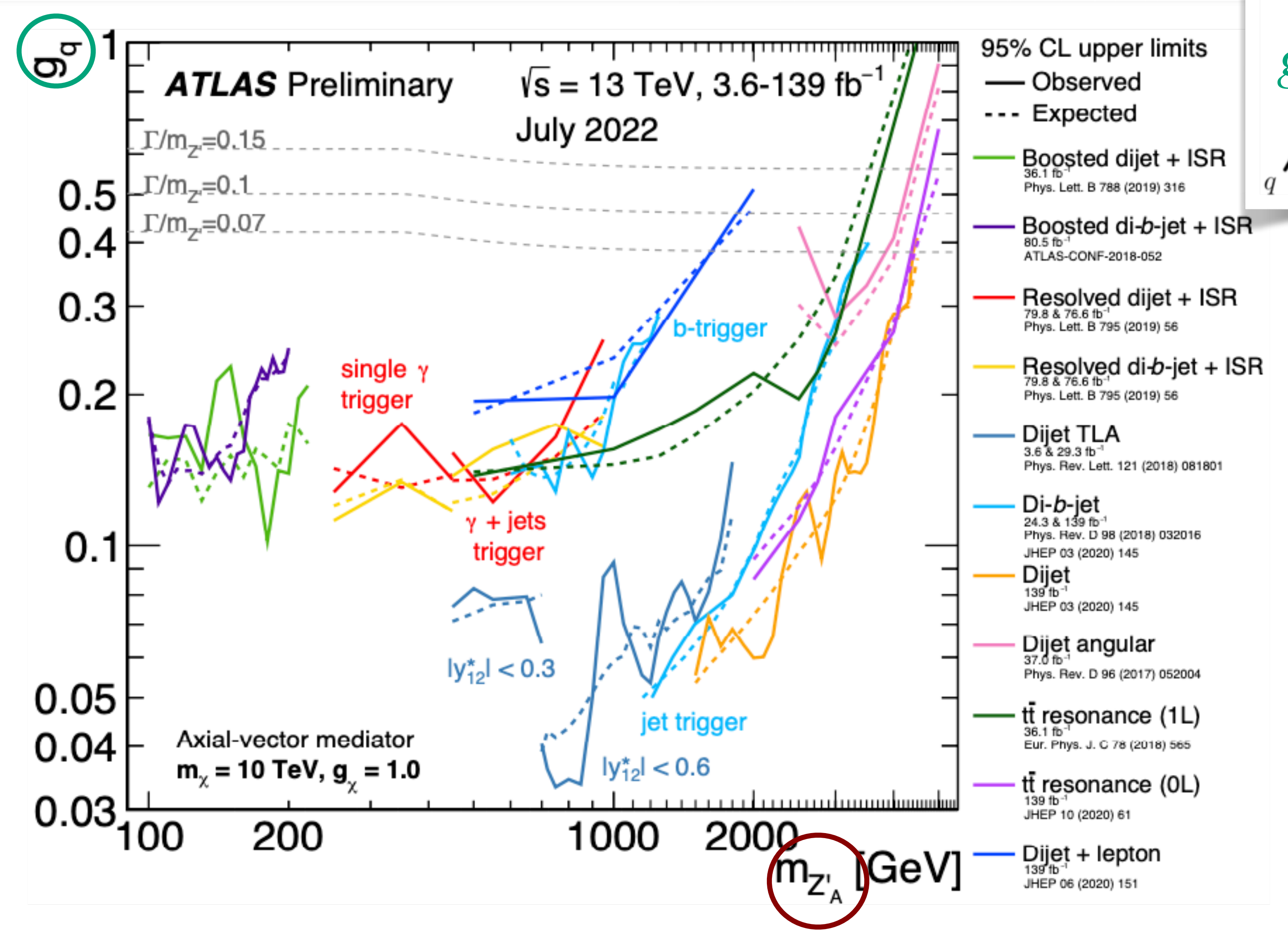


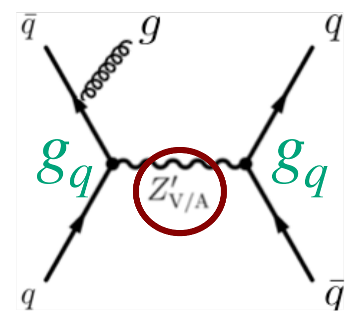




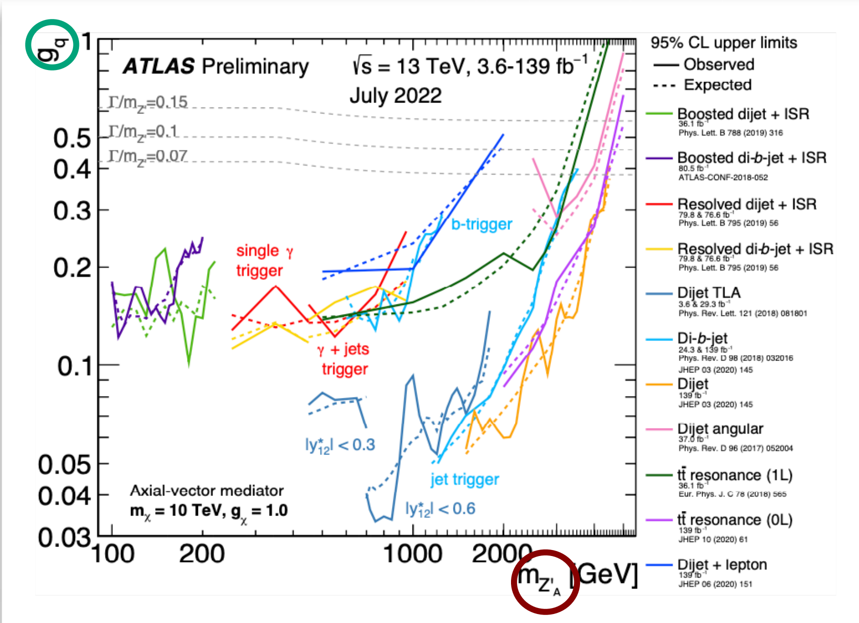
DARK MATTER V/AV MODEL: PIECE IT ALL TOGETHER

All DM summary plots: ATLAS / CMS





DM @ LHC: S-CHANNEL V/AV: RESONANCES



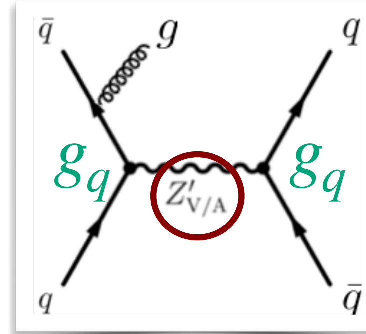
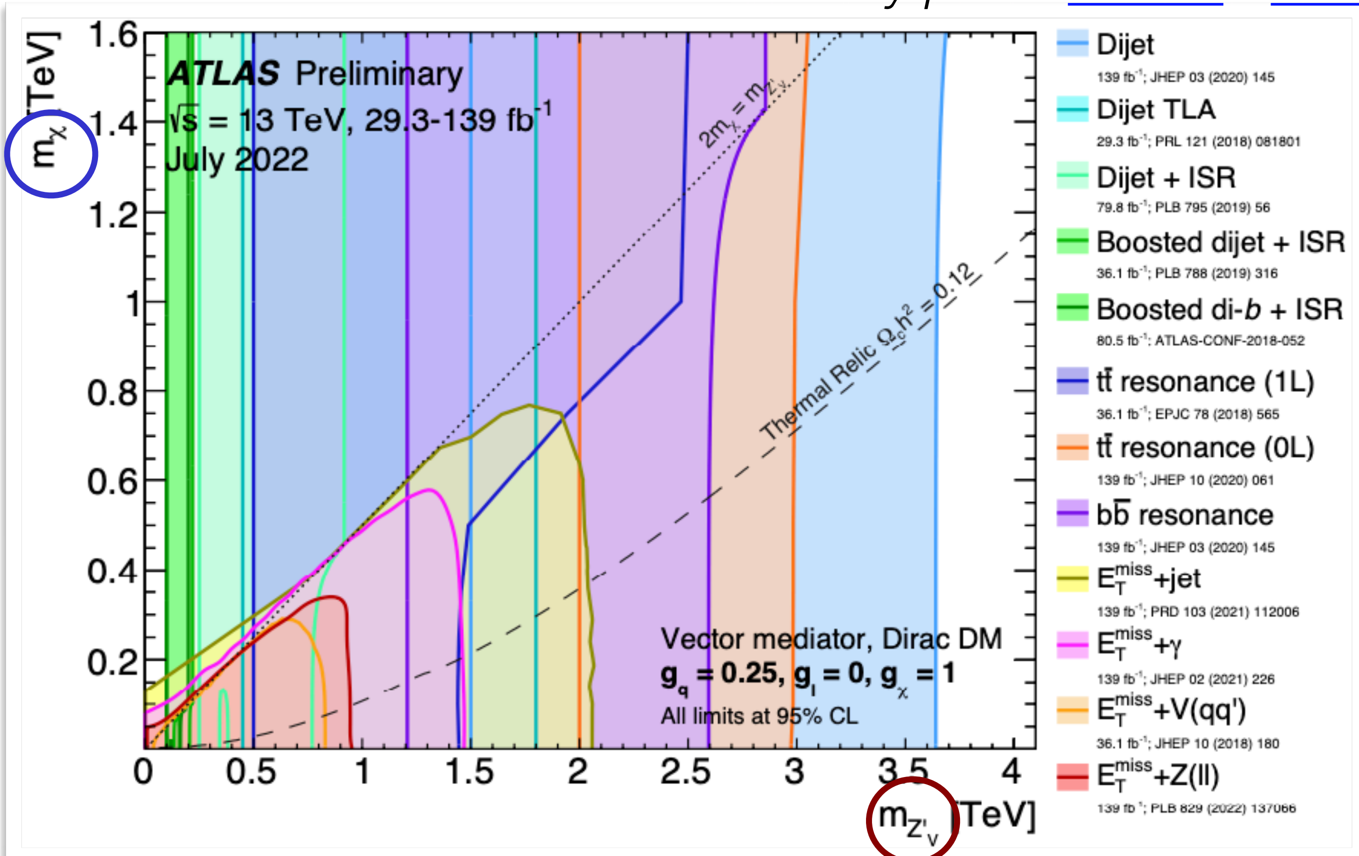
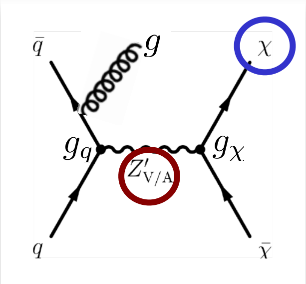


Figure 15: Hadronic resonance search contours for 95% CL upper limits on the coupling g_q as a function of the resonance mass $m_{Z'_A}$ for the leptophilic axial-vector mediator simplified model. The expected limits from each search are indicated by dotted lines. The TLA dijet analysis has two parts, employing different datasets with different selections in the rapidity difference y^* as indicated. The dijet+ISR (γ) analysis also has two parts, each using a different trigger strategy, and each further studied in inclusive and b-tagged channels. Two lines are also shown for the di-b-jet search. These are from separate analyses, one which used b-jet triggers and provides the limit at lower mass, and one which used inclusive jet triggers and provides the high mass limit. Coupling values above the solid lines are excluded, as long as the signals are narrow enough to be detected using these searches. The TLA dijet search with $|y^*| < 0.6$ is sensitive up to $\Gamma/m_{Z'} = 7\%$, the TLA dijet with $|y^*| < 0.3$ and dijet + ISR searches are sensitive up to $\Gamma/m_{Z'} = 10\%$, and the dijet and di-b-jet searches are sensitive up to $\Gamma/m_{Z'} = 15\%$. The dijet angular analysis is sensitive up to $\Gamma/m_{Z'} = 50\%$. No limitation in sensitivity arises from large width resonances in the $t\bar{t}$ resonance analysis. Benchmark width lines are indicated in the canvas. $\Gamma/m_{Z'} = 50\%$ lies beyond the canvas borders.

All DM summary plots: ATLAS / CMS





arXiv:1703.05703

LHC DM WG recommendation:
Explore complementarity between X+MET & resonance searches in 4 representative scenarios!

Coupl.	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
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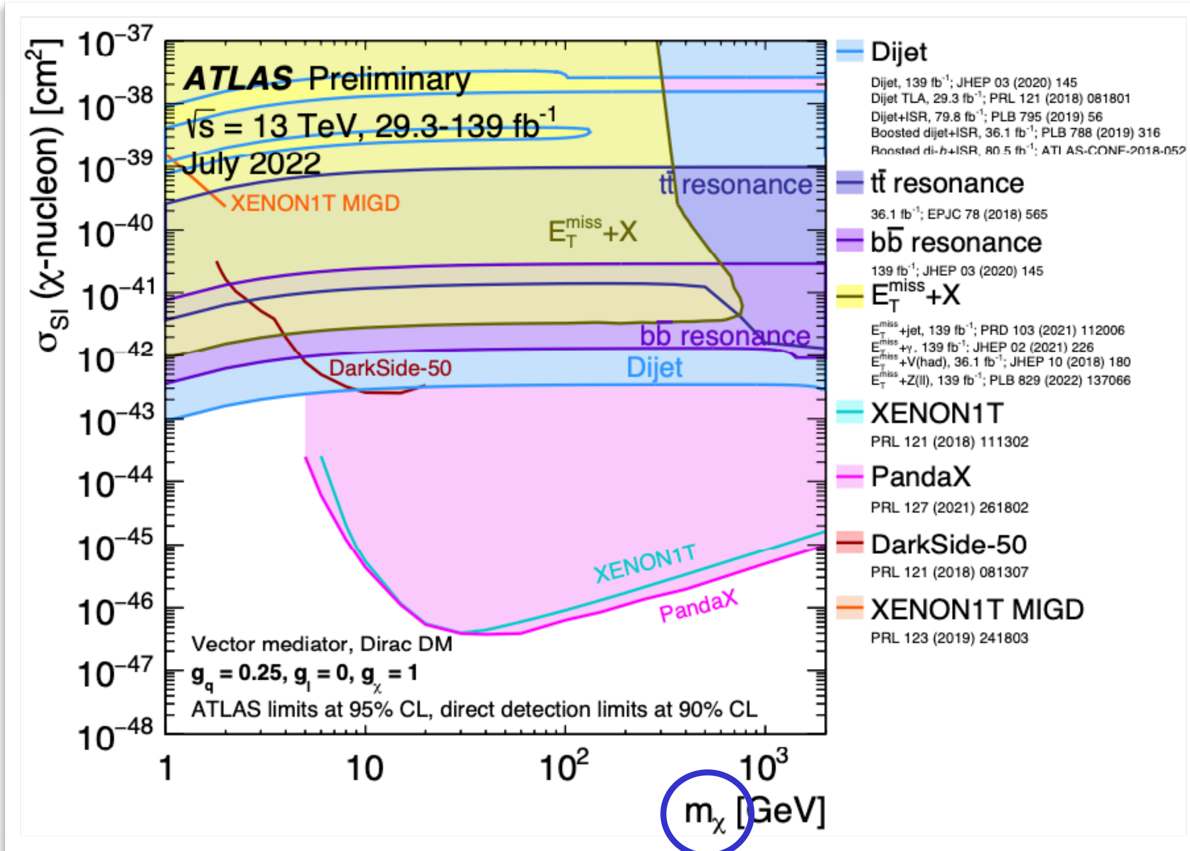
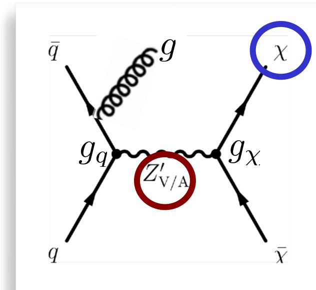
g_χ	1	1	1	1

All DM summary plots: ATLAS / CMS





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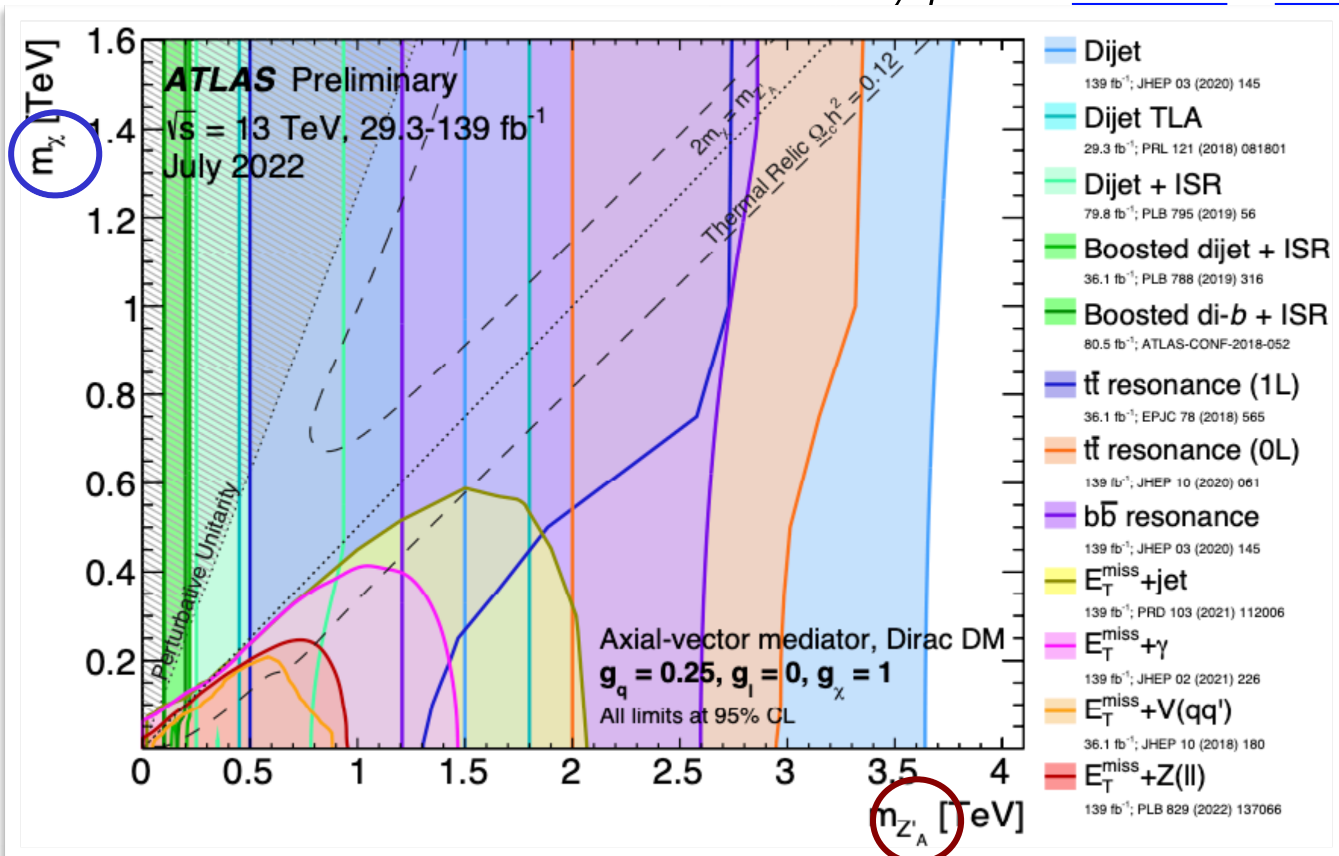

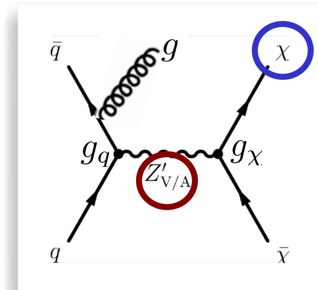

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DM @ LHC: s-channel V/AV: X+MET vs resonances

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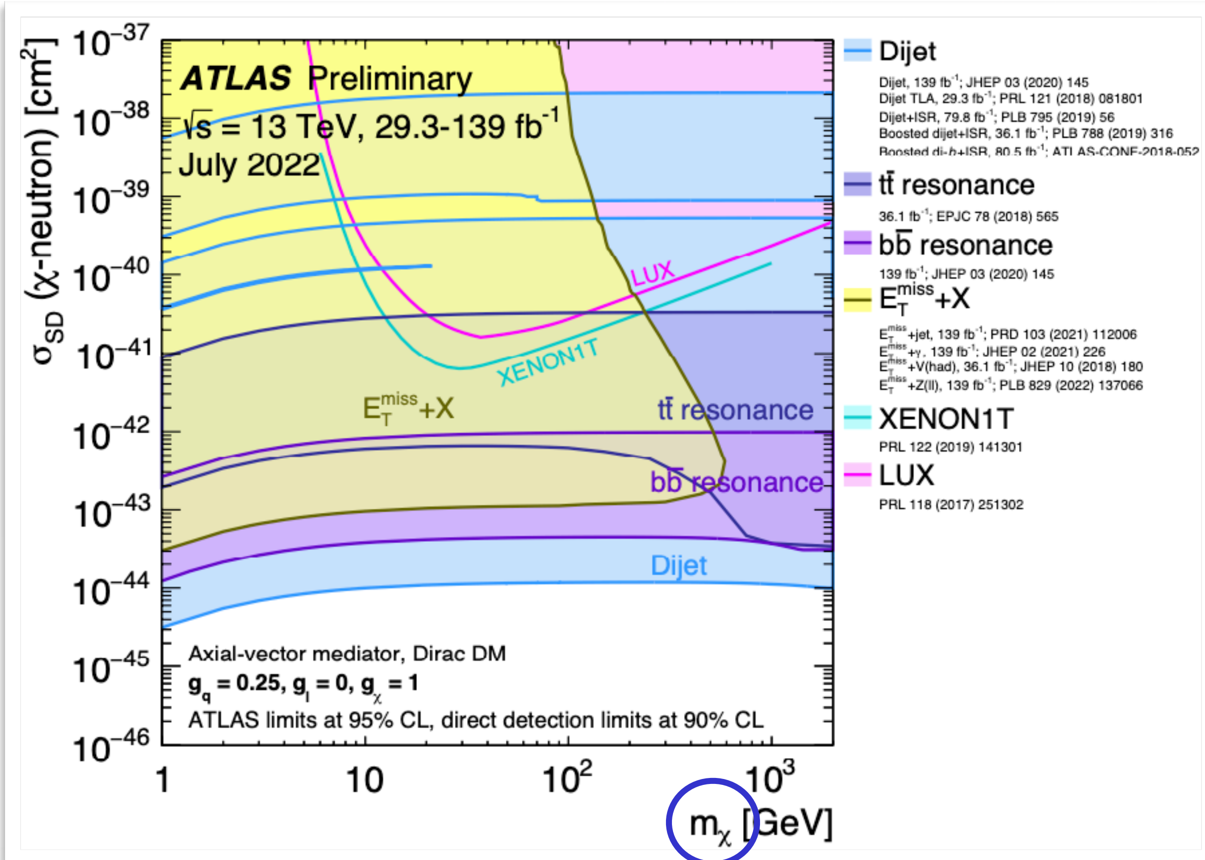

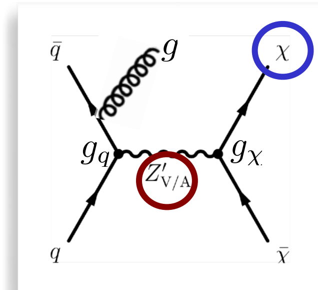

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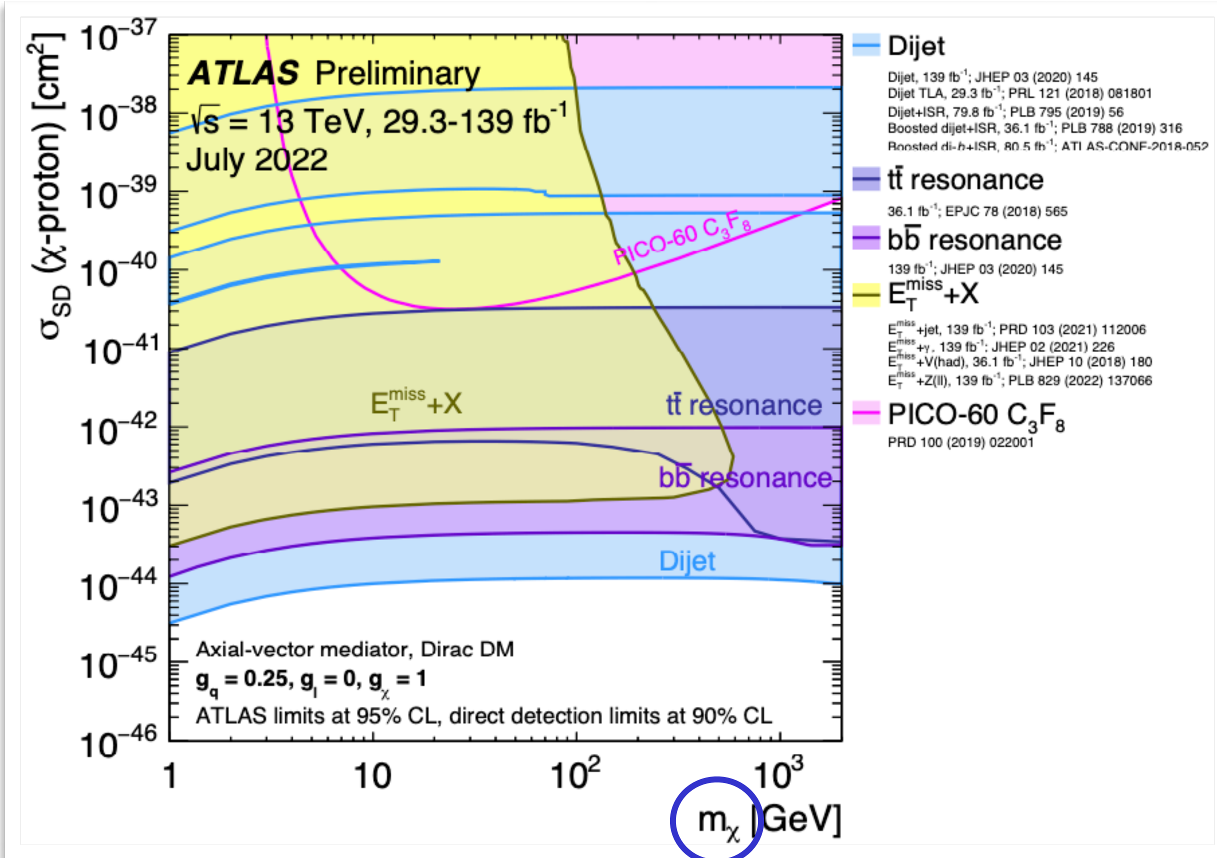

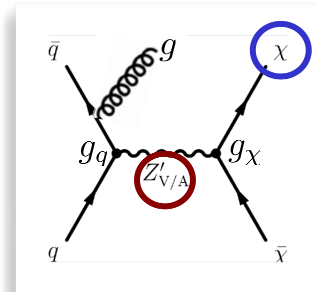

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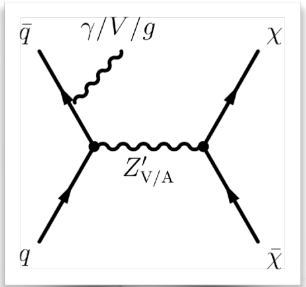

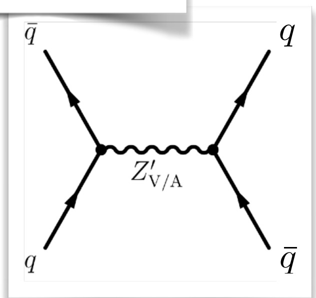

1703.05703

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g_χ	1	1	1	1

Why those benchmarks?

- $g_\chi = 1$: sizeable coupling to DM through $Z'\chi\bar{\chi}$ vertex!
- $g_q = 0.25$: mediator coupling to SM quarks ensures $\Gamma_{Z'}/m_{Z'} < 10\,\%$
  - Narrow width approximation + interpretation as *resonance* searches
- $g_\ell = 0.01$: effective coupling to leptons through Z'-Z mixing via loops
  - natural for $g_\ell/g_q = \mathcal{O}(0.1)$ [1], since $g_q = 0.25$
- $g_\ell = 0.1$: scenario with $g_\ell = g_q = 0.1$: prevalence of leptonic channels

[1] 1606.07609

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu\ell\,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu\gamma_5 q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu\gamma_5\ell\,.$$

$$\Gamma^{\chi\bar{\chi}}_{\text{vector}} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi}\,(1-4z_{\text{DM}})^{1/2}\,(1+2z_{\text{DM}})$$

$$\Gamma^{q\bar{q}}_{\text{vector}} = \frac{g^2_q M_{\text{med}}}{4\pi}\,(1-4z_q)^{1/2}\,(1+2z_q)\,,$$

$$\Gamma^{\ell\bar{\ell}}_{\text{vector}} = \frac{g^2_\ell M_{\text{med}}}{12\pi}\,(1-4z_\ell)^{1/2}\,(1+2z_\ell)\,,$$

$$\Gamma^{\nu\bar{\nu}}_{\text{vector}} = \frac{g^2_\ell}{24\pi} M_{\text{med}}\,,$$

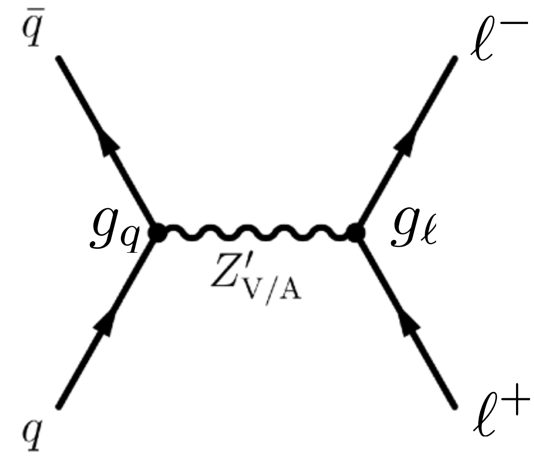
$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi}\,(1-4z_{\text{DM}})^{3/2}$$

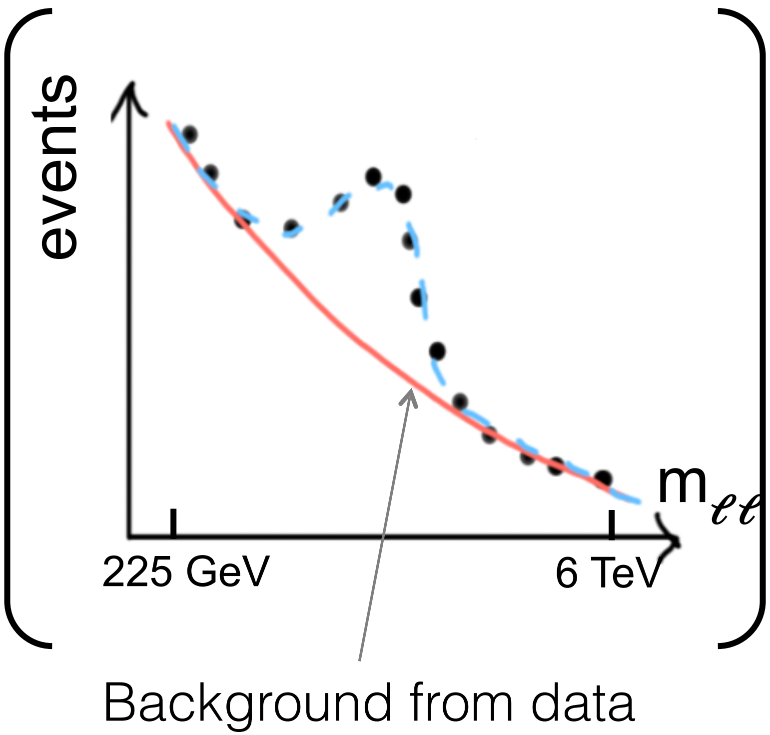
$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g^2_q M_{\text{med}}}{4\pi}\,(1-4z_q)^{3/2}\,,$$

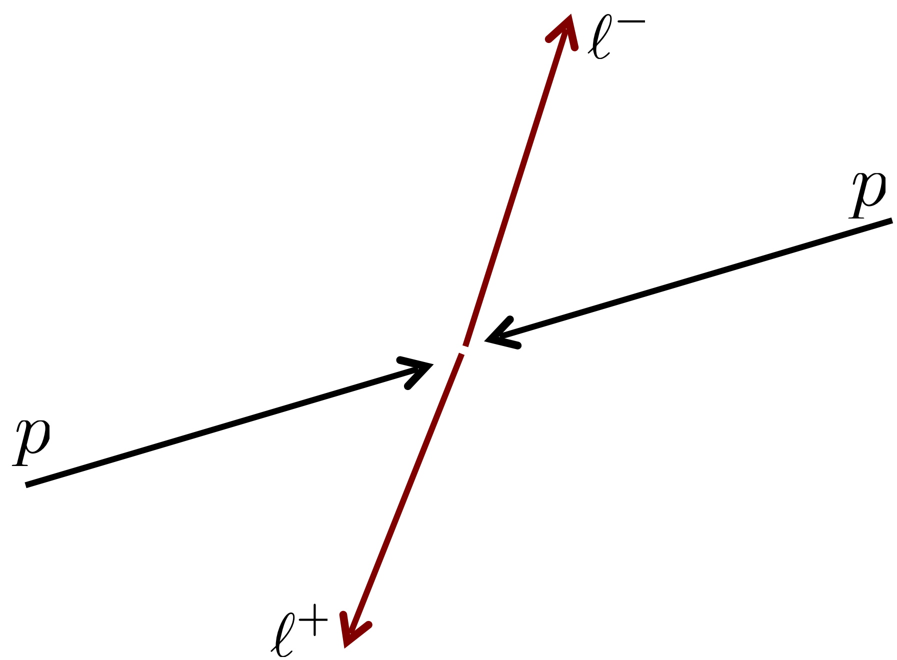
$$\Gamma^{\ell\bar{\ell}}_{\text{axial-vector}} = \frac{g^2_\ell M_{\text{med}}}{12\pi}\,(1-4z_\ell)^{3/2}\,,$$

$$\Gamma^{\nu\bar{\nu}}_{\text{axial-vector}} = \frac{g^2_\ell}{24\pi} M_{\text{med}}\,.$$

- **Analysis strategy:**
  - Require ee or $\mu\mu$ pair with $p_T \gtrsim 220$ GeV
  - $m_{\ell\ell} > 225$ GeV
  - Look for excess in $m_{\ell\ell}$ distribution:



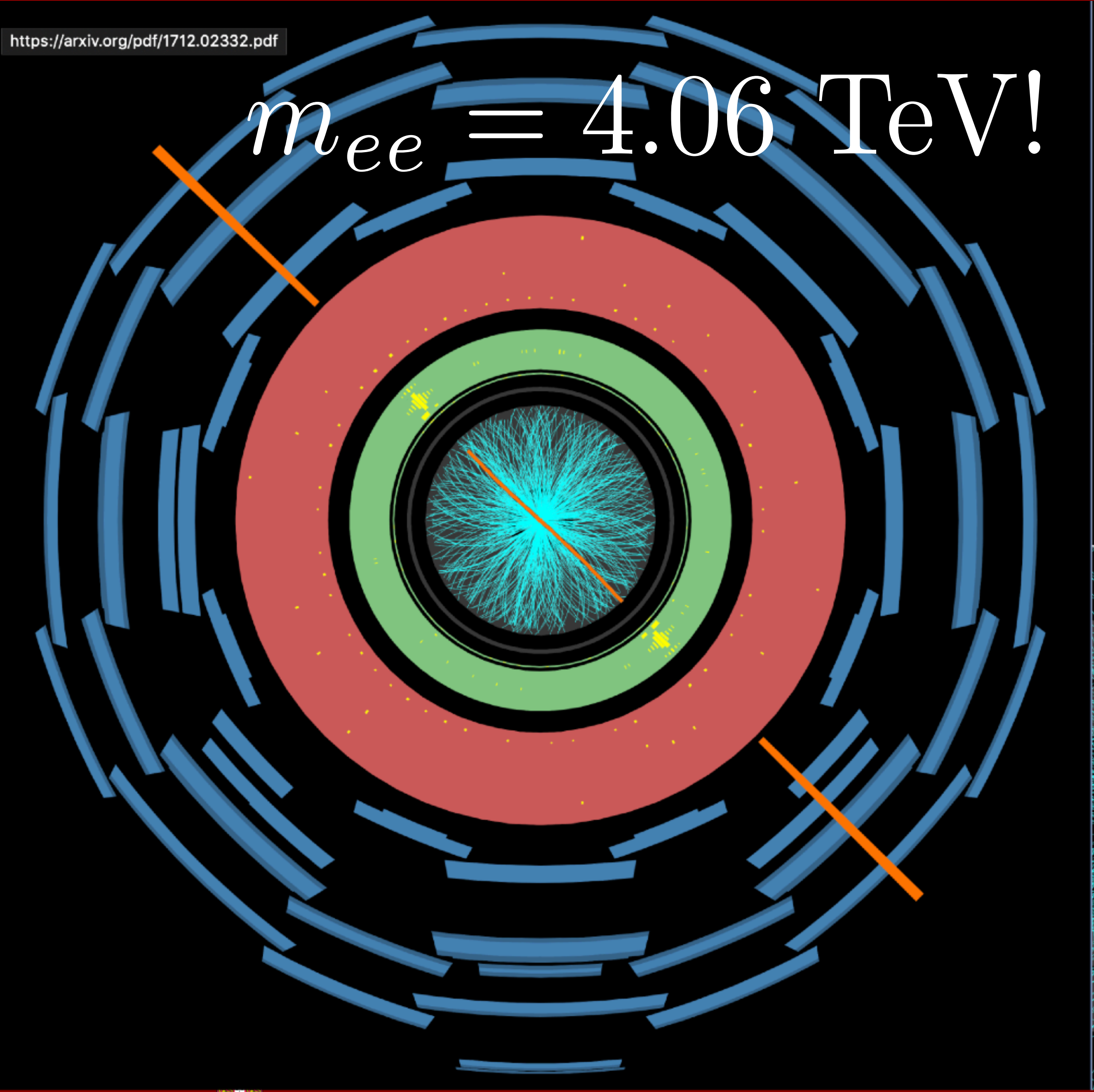




1903.06248

https://arxiv.org/pdf/1712.02332.pdf

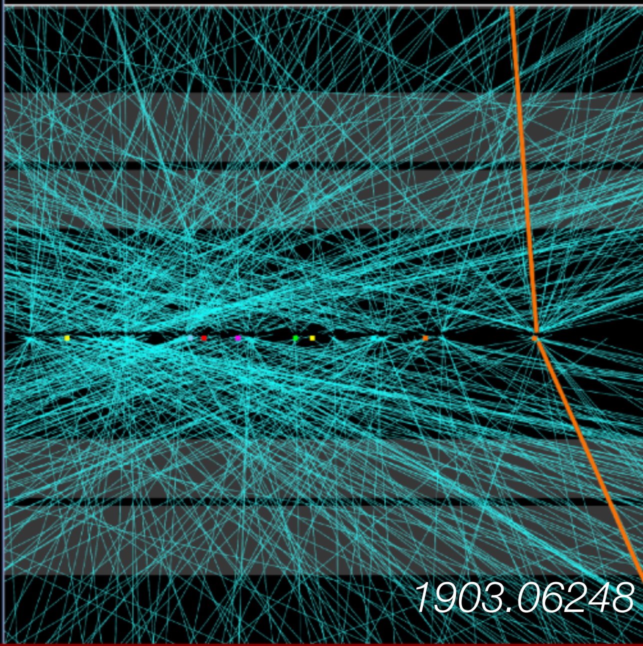
$$m_{ee} = 4.06 \text{ TeV!}$$



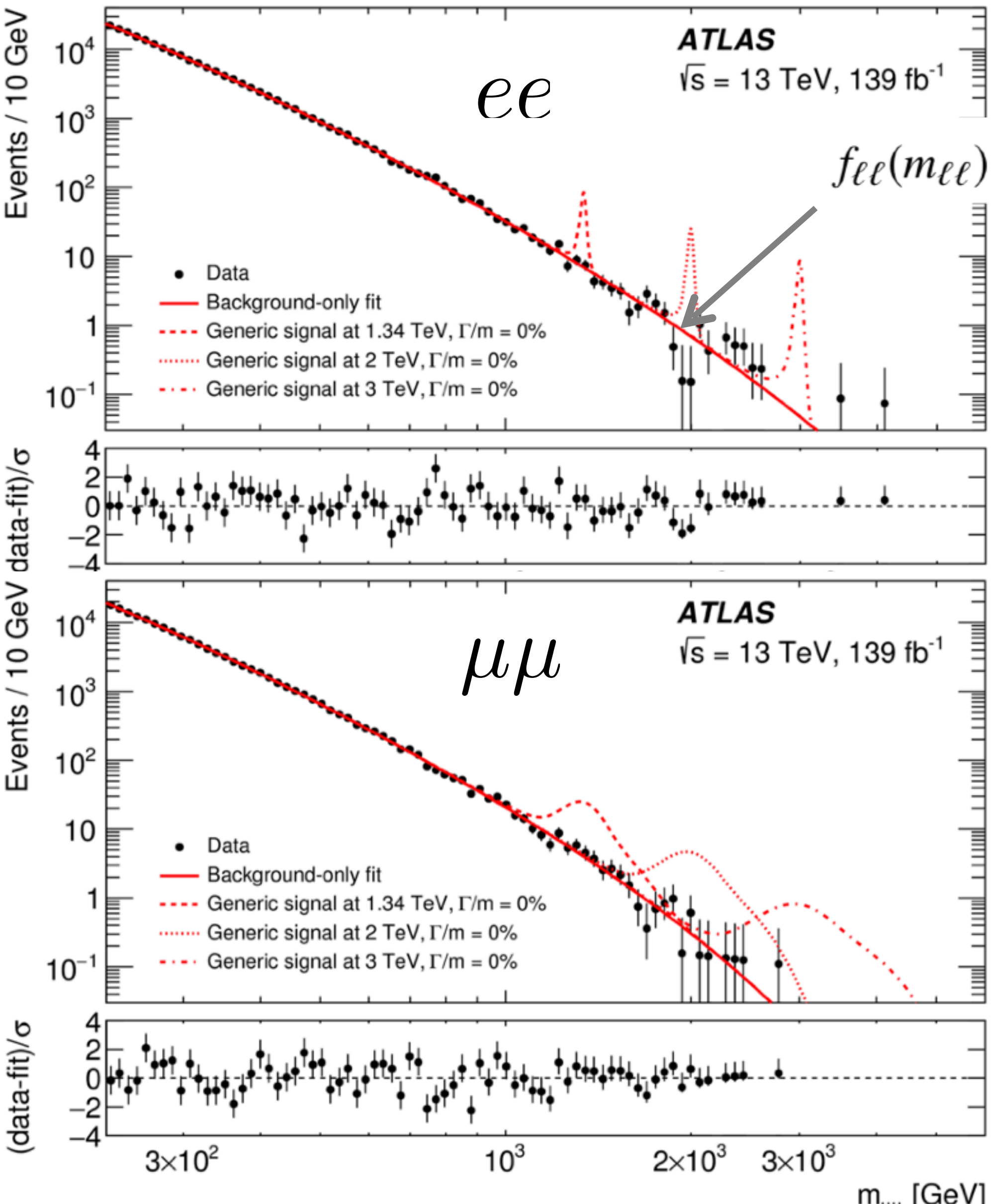
ATLAS EXPERIMENT

Run Number: 336852, Event Number: 1440436043

Date: 2017-09-29 11:44:35 CEST



1903.06248

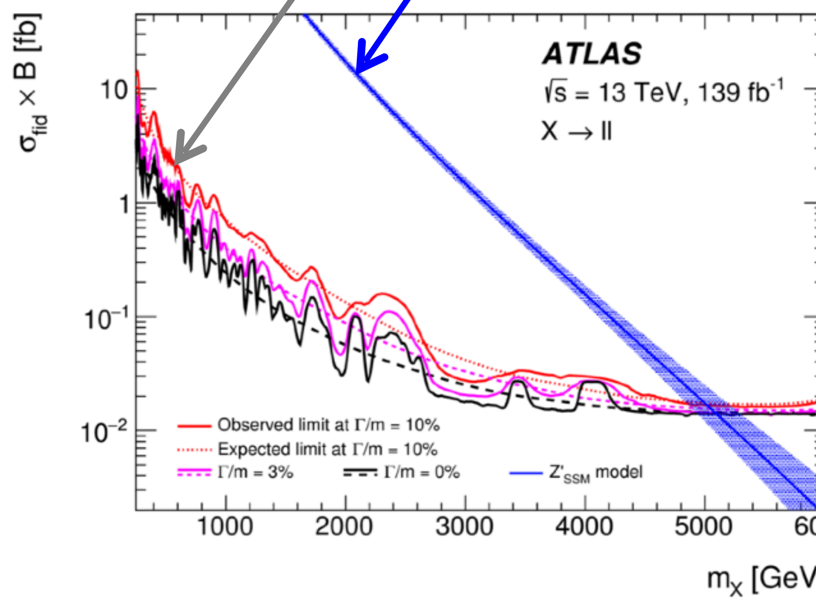


Background parametrisation:

$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i},$$

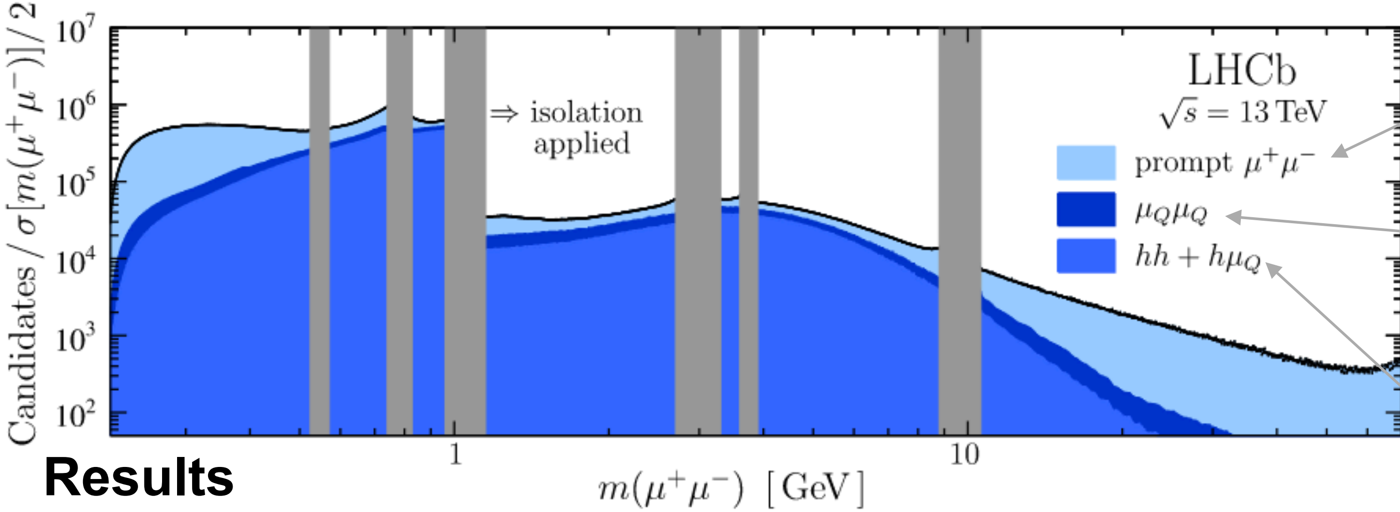
Generic resonance limits for Breit-Wigner ⊗ resolution

Z'_{SSM} $(\Gamma/m = 3.0\%)$



1903.06248

- **Analysis strategy:**
  - Capture resonance decaying into $\mu^+\mu^-$ + dedicated dimuon triggers
    - Reduce Drell-Yann via k_t-cone isolation

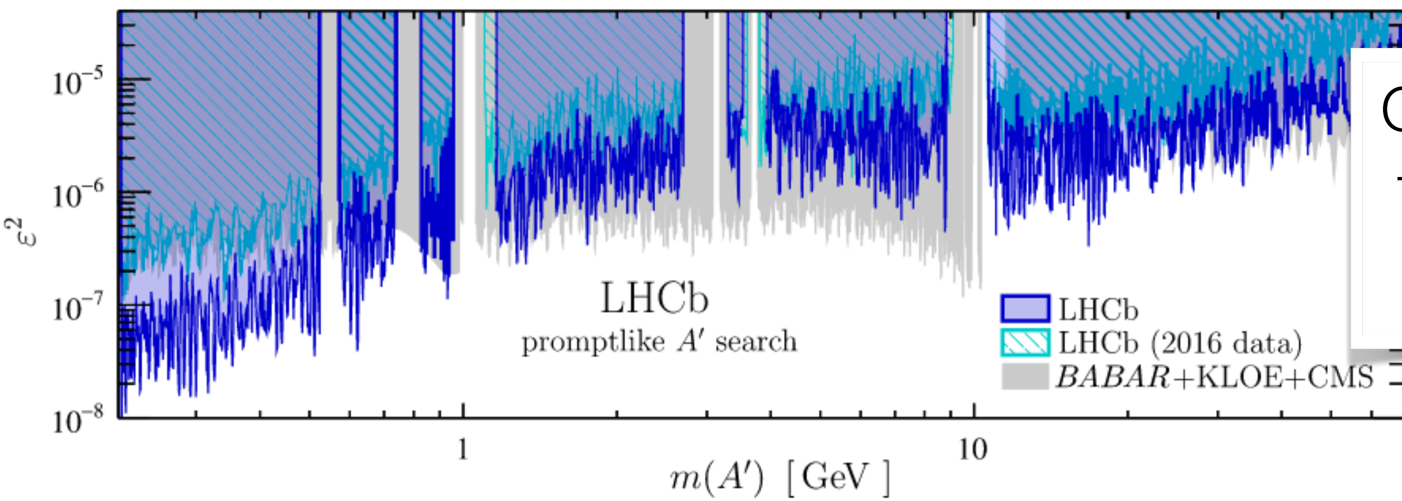


Drell-Yann dominant for $m_{\mu\mu} > 1.1$ GeV

non-prompt muons from HF decays

misidentified hadrons + mixed

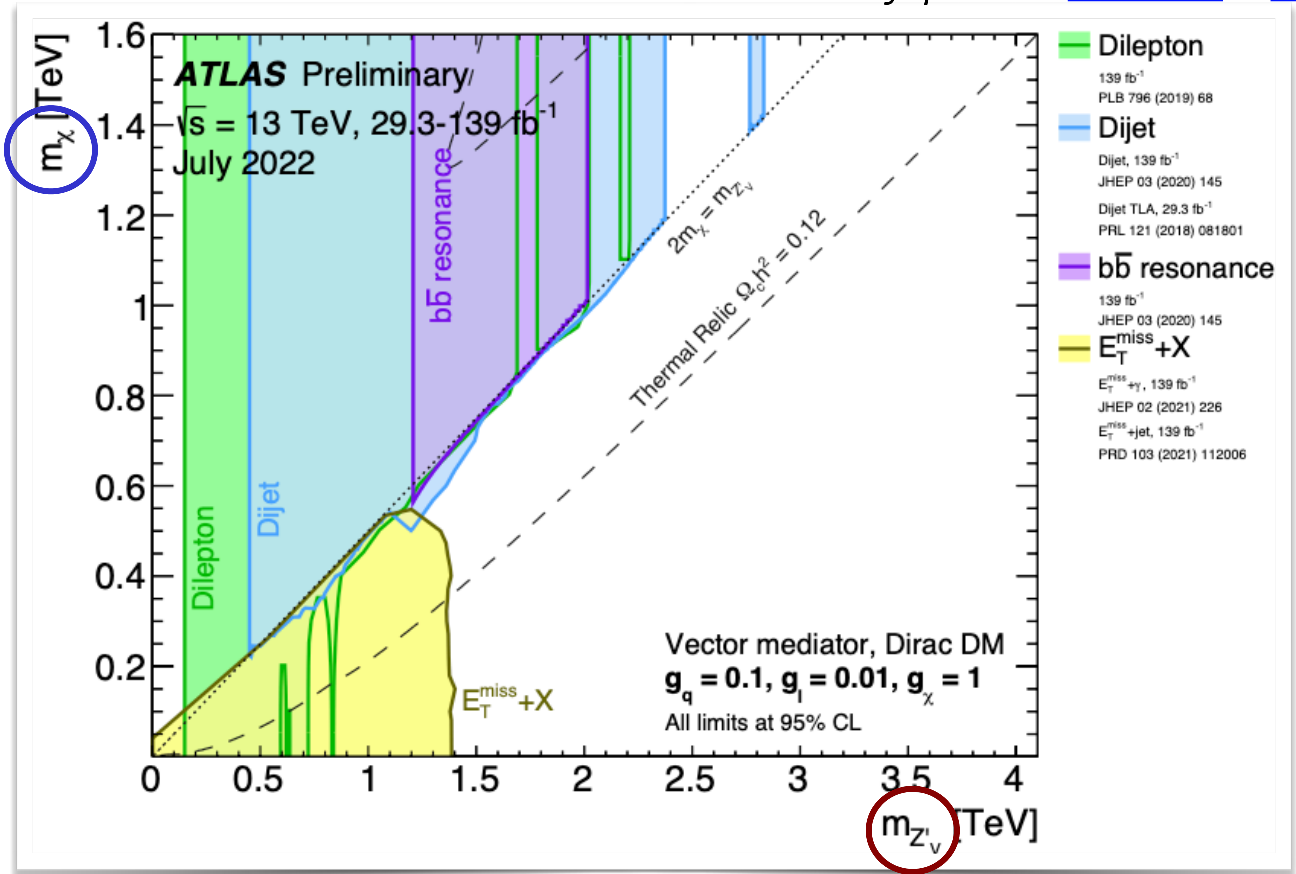
- **Results**

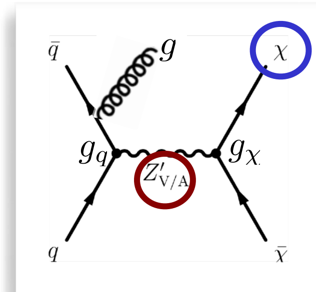


Complementarity to ATLAS+CMS at low $m_{\mu\mu}$!

PRL 124 (2020) 041801

All DM summary plots: ATLAS / CMS





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DM @ LHC: s-channel V/AV: X+MET vs resonances

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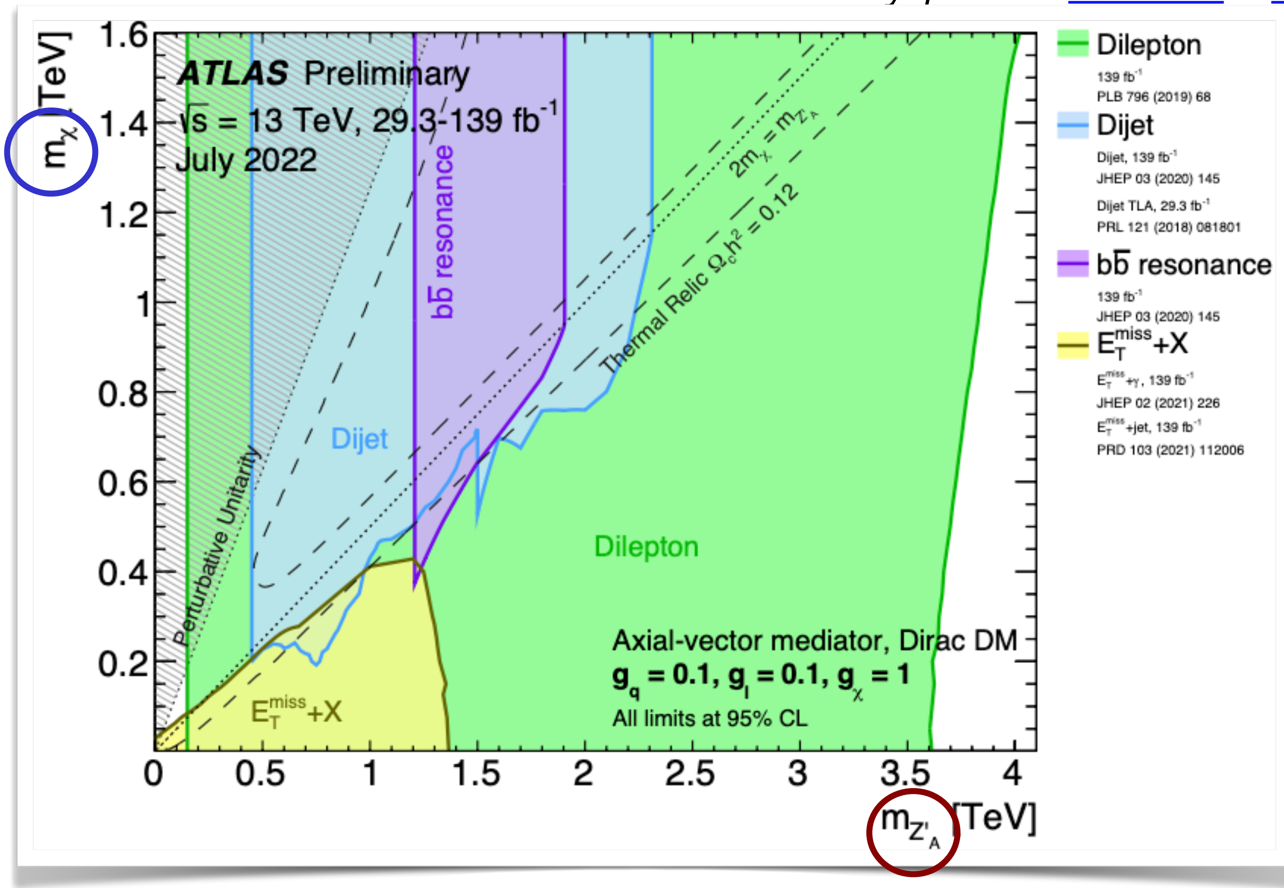

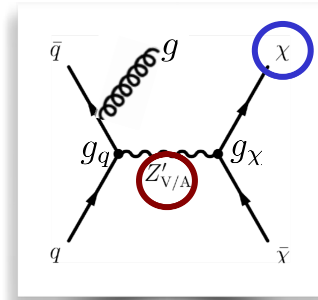

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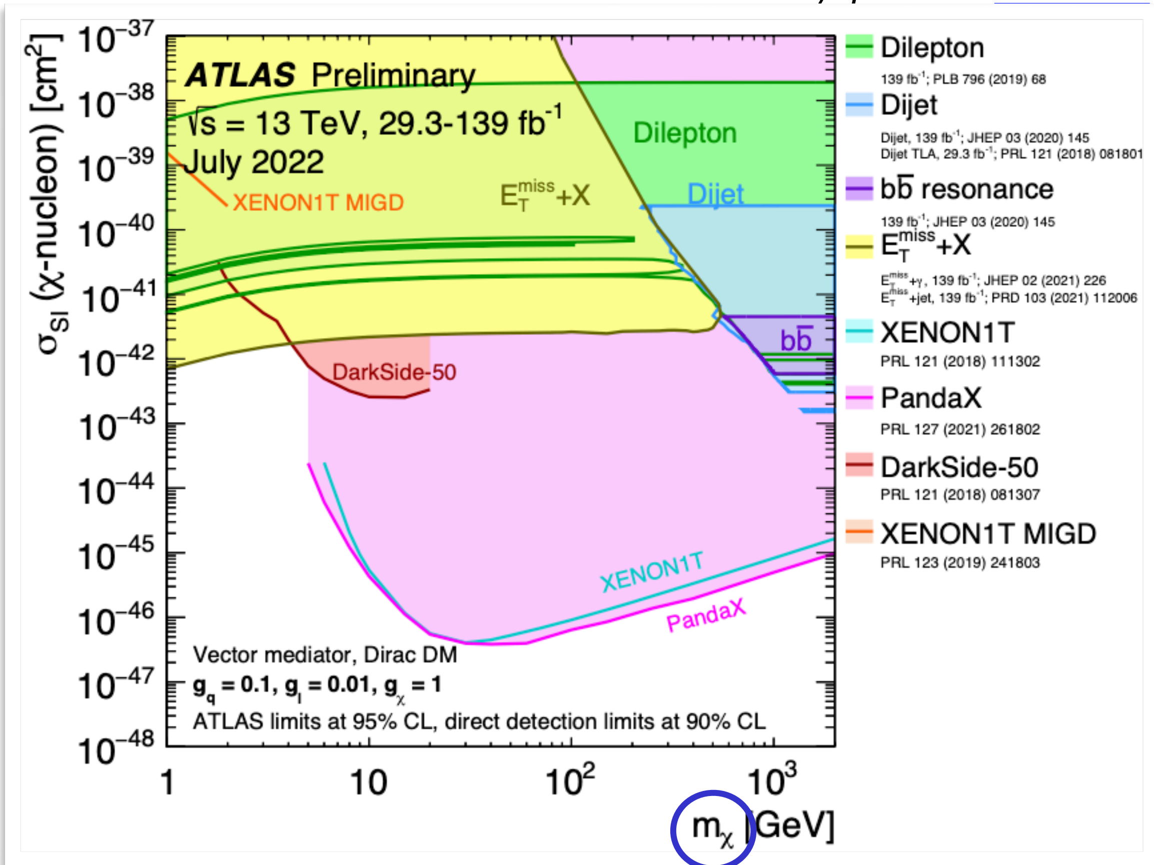

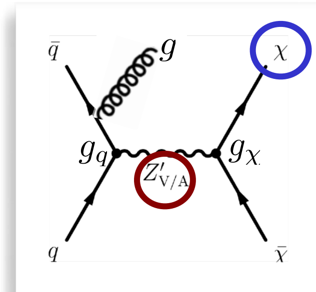

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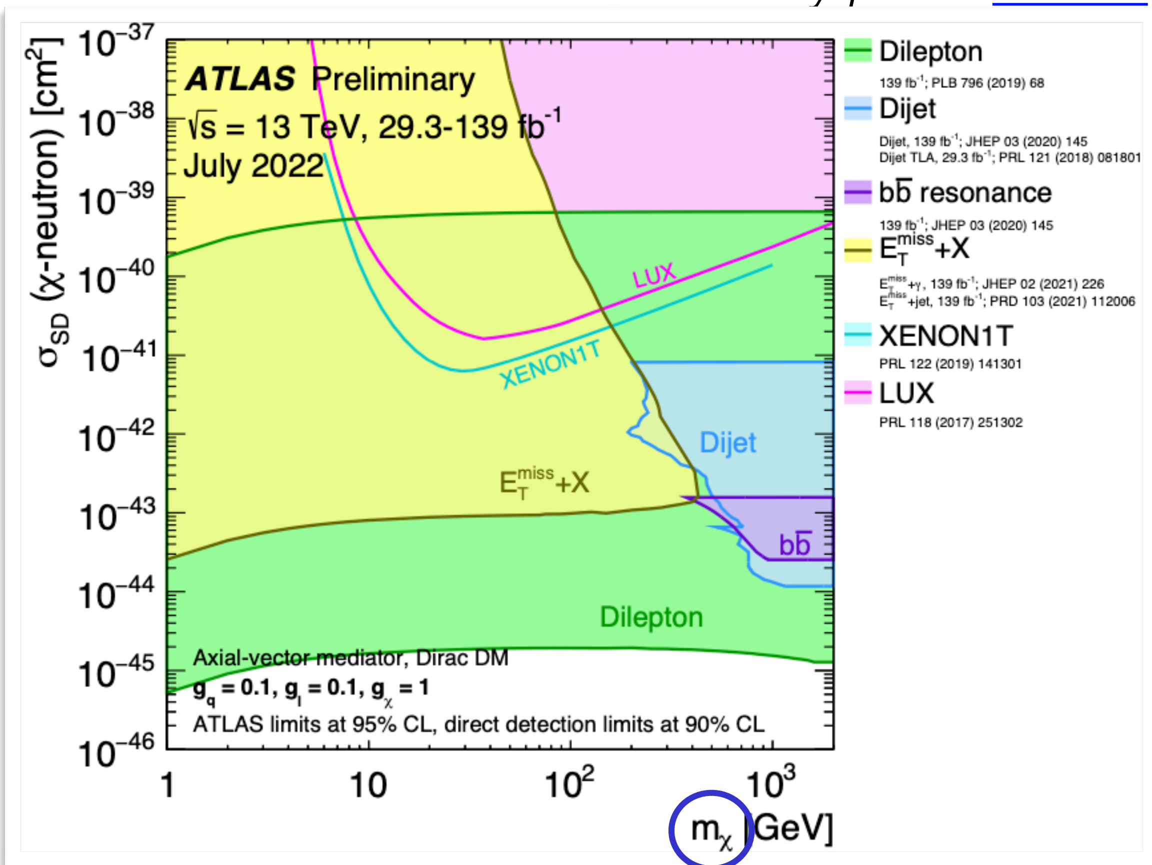

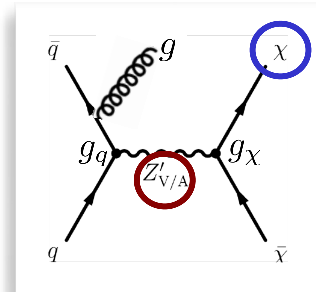

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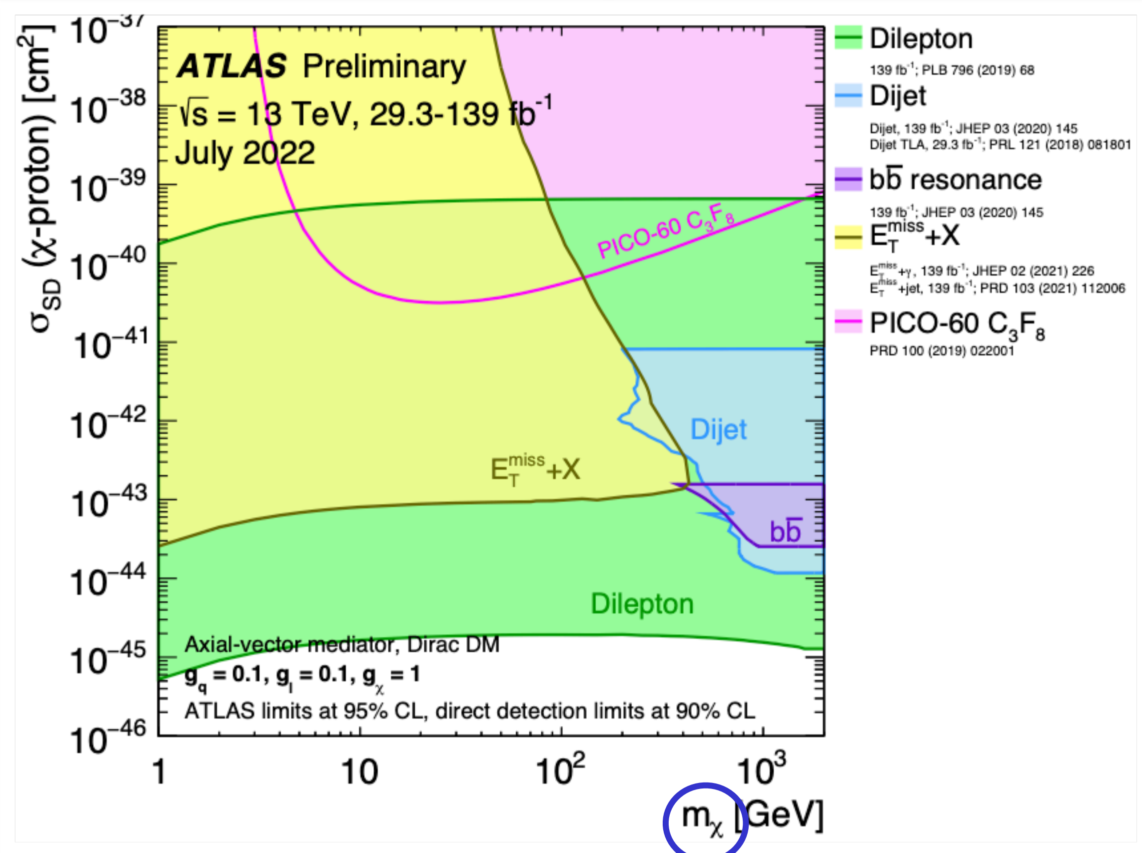

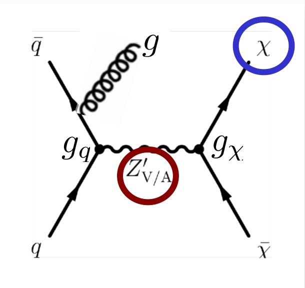

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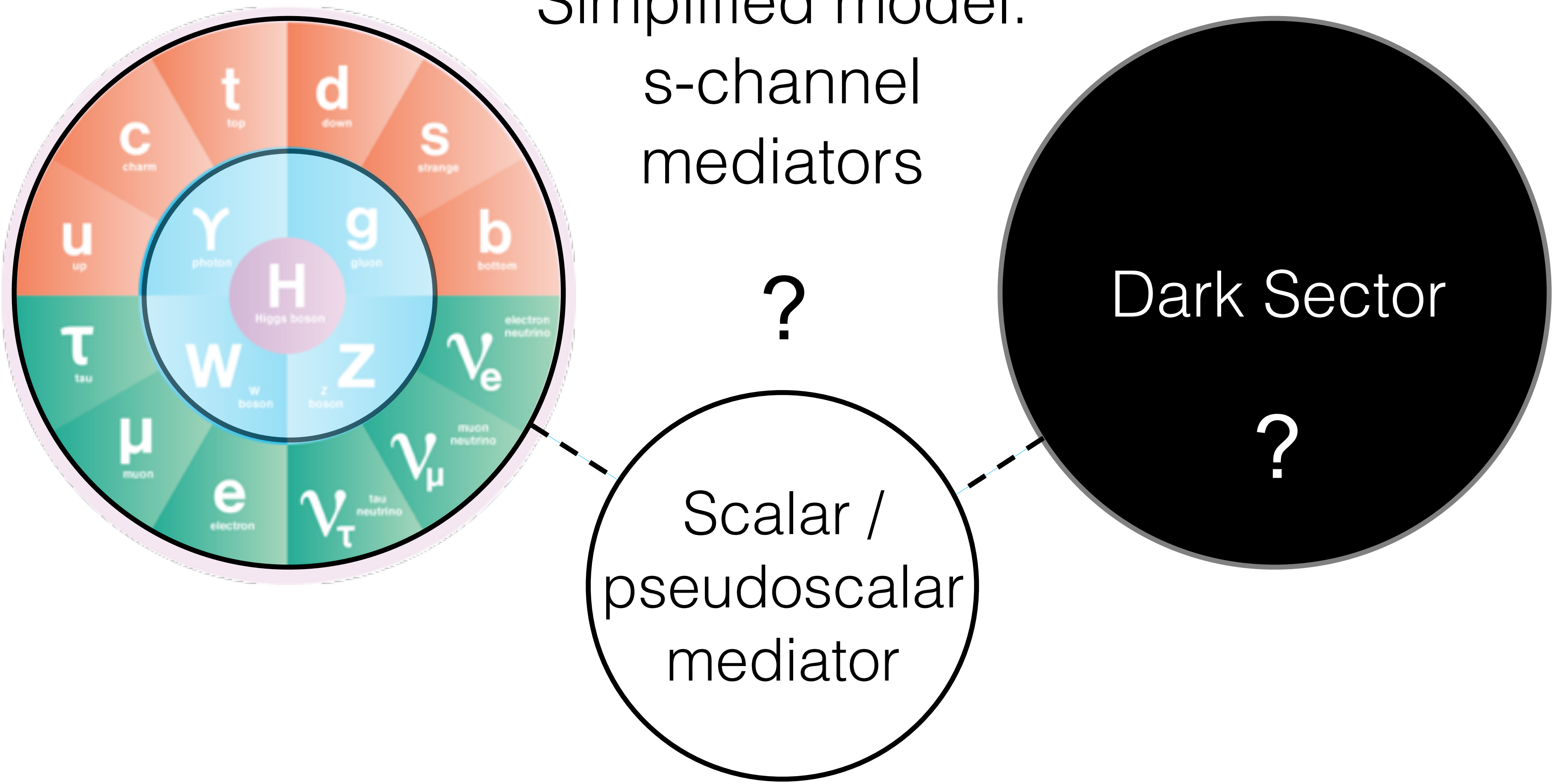
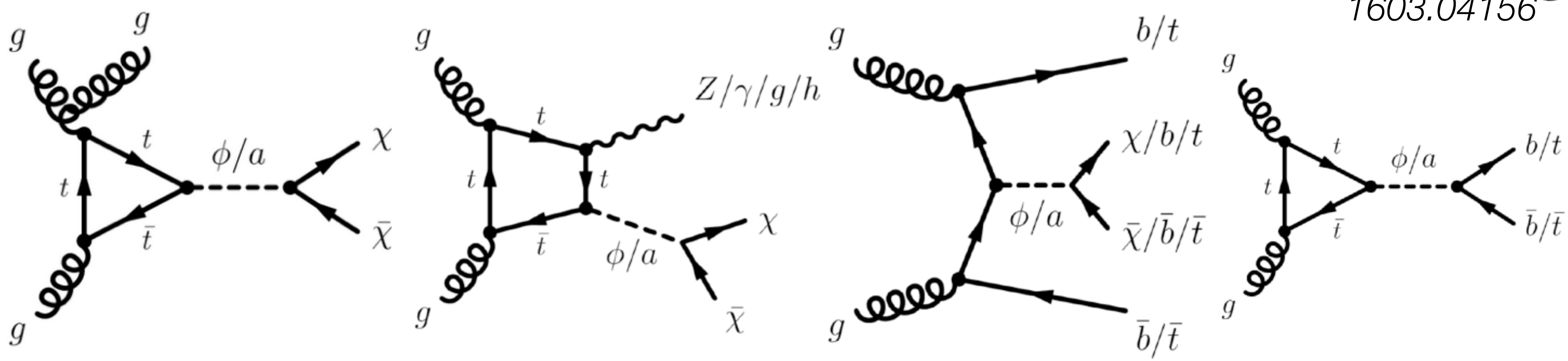
Simplified model:
s-channel
mediators



Motivation: 1) Mediator that couples to SM and to Dark Sector particles
2) Generic signatures that are present in complete models
3) minimal assumptions about dark sector (one DM particle)

DM @ LHC: S-CHANNEL: (PSEUDO-) SCALAR MEDIATOR

1603.04156



$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\,\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}q \,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -ig_{\text{DM}}\,\phi\bar{\chi}\gamma_5\chi - ig_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q$$

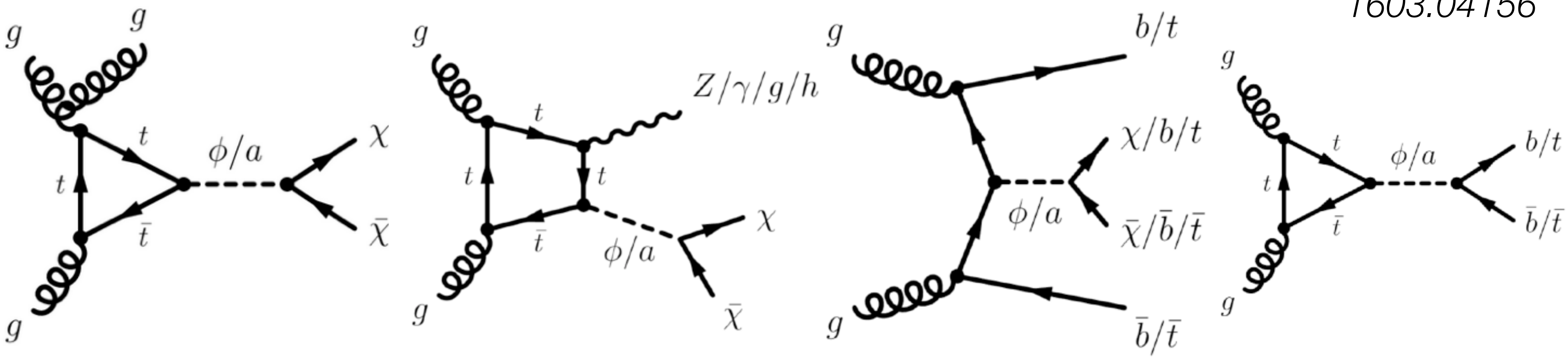
Yukawa-like coupling to SM fermions: $y_q = \sqrt{2}m_q/v, v = 246\ \text{GeV}$

Minimal flavour violation (g_q universal) → avoid flavour physics constraints

Minimal assumptions about the dark sector (additional DOF integrated out)

DM @ LHC: S-CHANNEL: (PSEUDO-) SCALAR MEDIATOR

1603.04156



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$$\Gamma^{\chi\bar{\chi}}_{\text{scalar}} = \frac{g^2_{\text{DM}}M_{\text{med}}}{8\pi}\left(1-4z^2_{\text{DM}}\right)^{3/2}$$

$$\Gamma^{q\bar{q}}_{\text{scalar}} = \frac{3g^2_q y^2_q M_{\text{med}}}{16\pi}\left(1-4z^2_q\right)^{3/2}$$

$$\Gamma^{gg}_{\text{scalar}} = \frac{\alpha^2_s g^2_q M^3_{\text{med}}}{32\pi^3 v^2}\left|f_{\text{scalar}}(4z_t)\right|^2,$$

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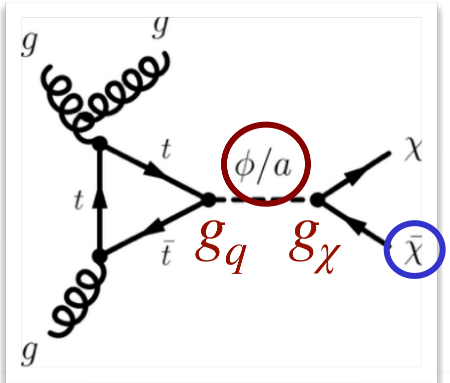
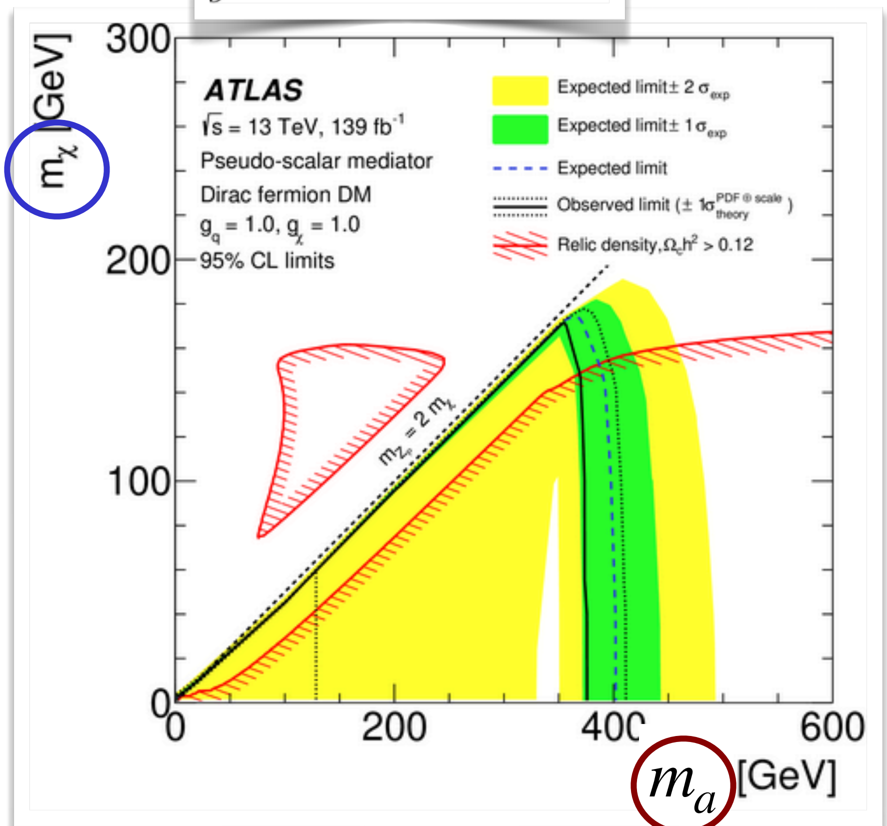
PRD 103 (2021) 112006, web

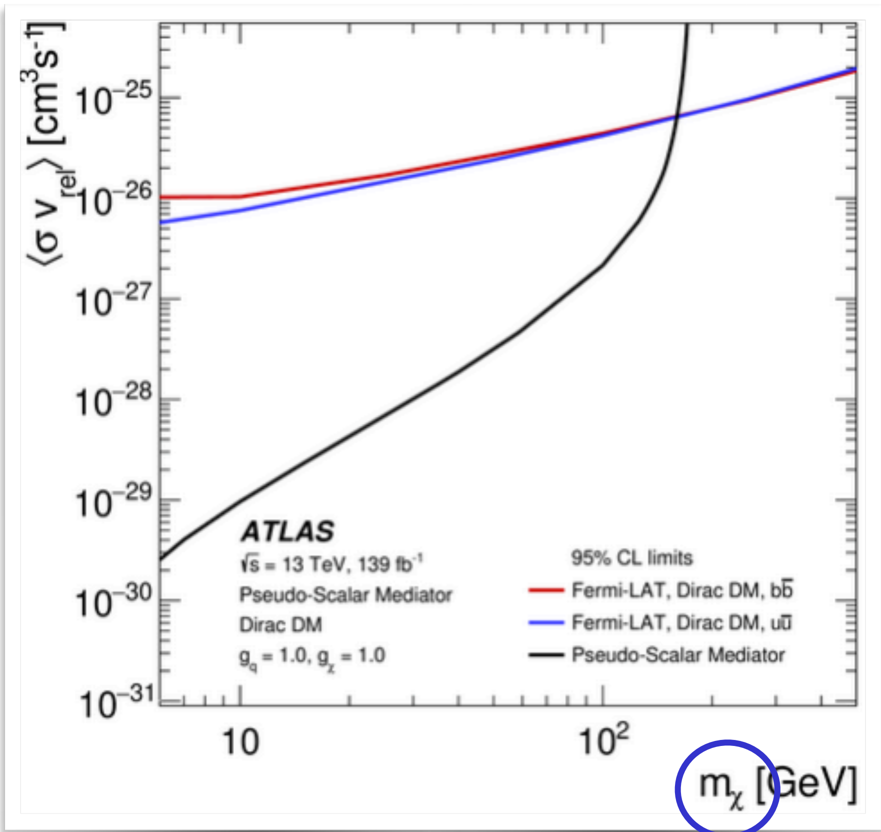


Direct detection sensitivity to DM strongly velocity-suppressed

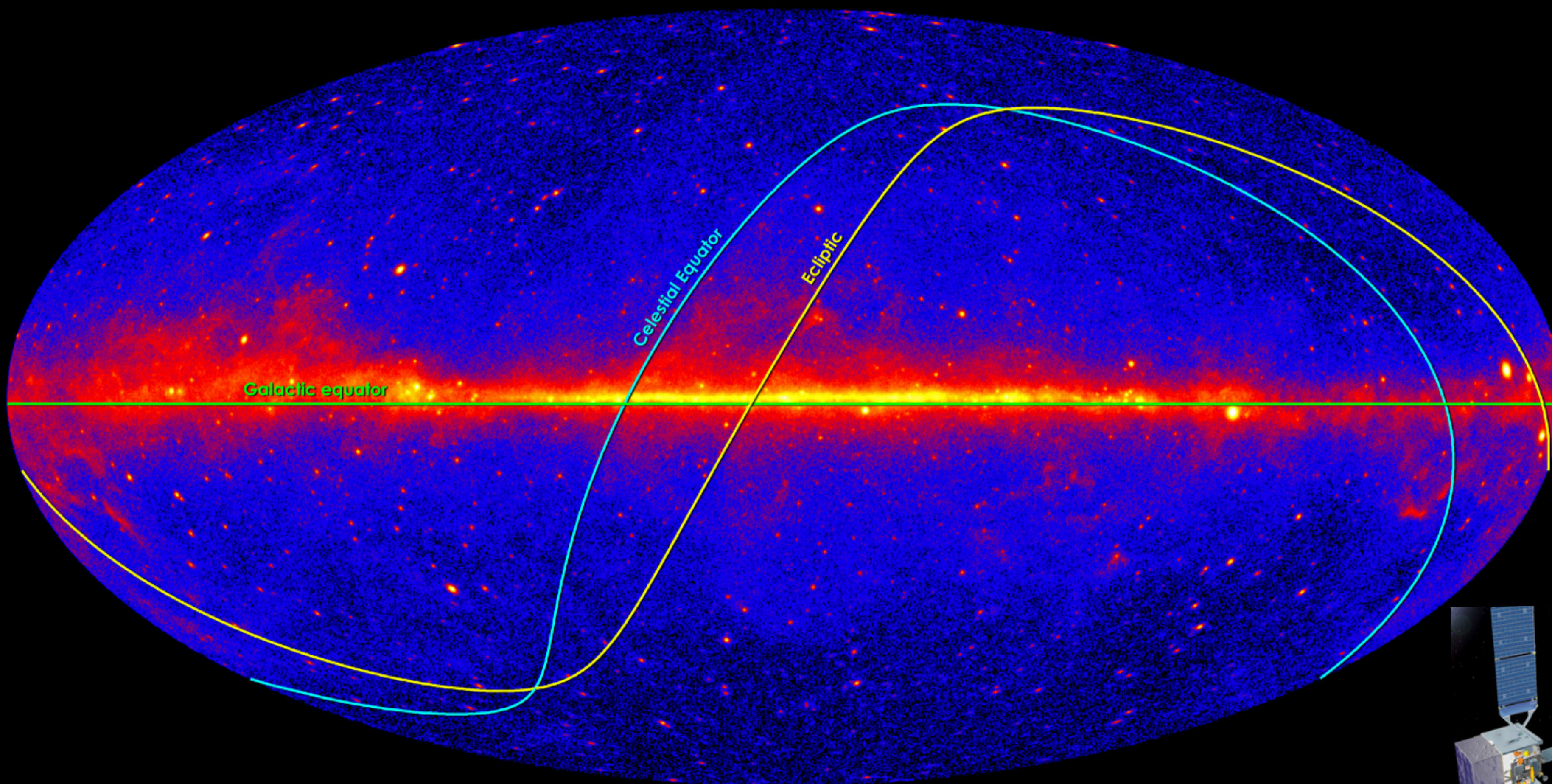
→ indirect detection interpretation

→ compare to Fermi-LAT





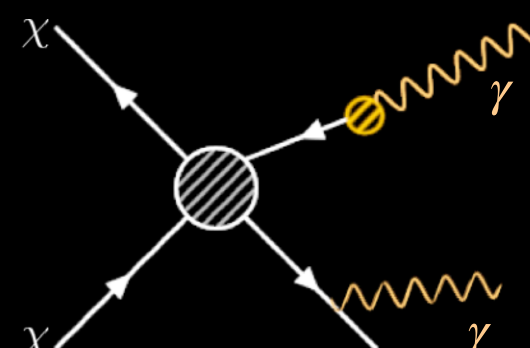
FERMI-LAT MAP OF THE γ RAY SKY



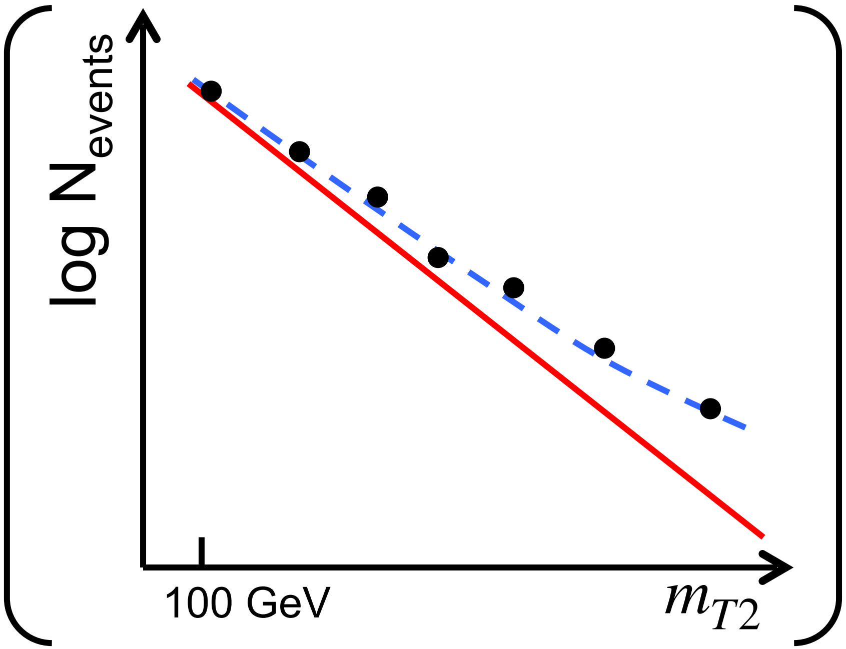
Search for γ from:

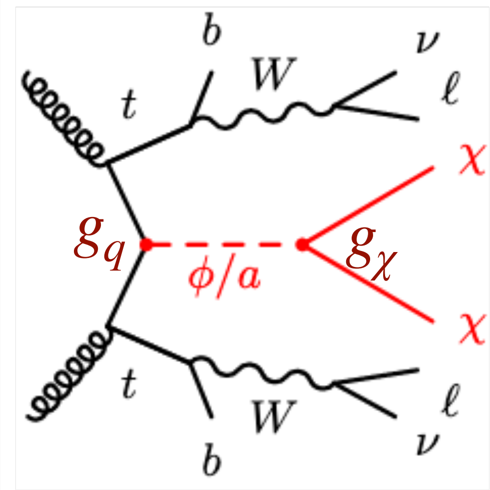
- Galactic centre
- Dwarf spheroidal galaxies

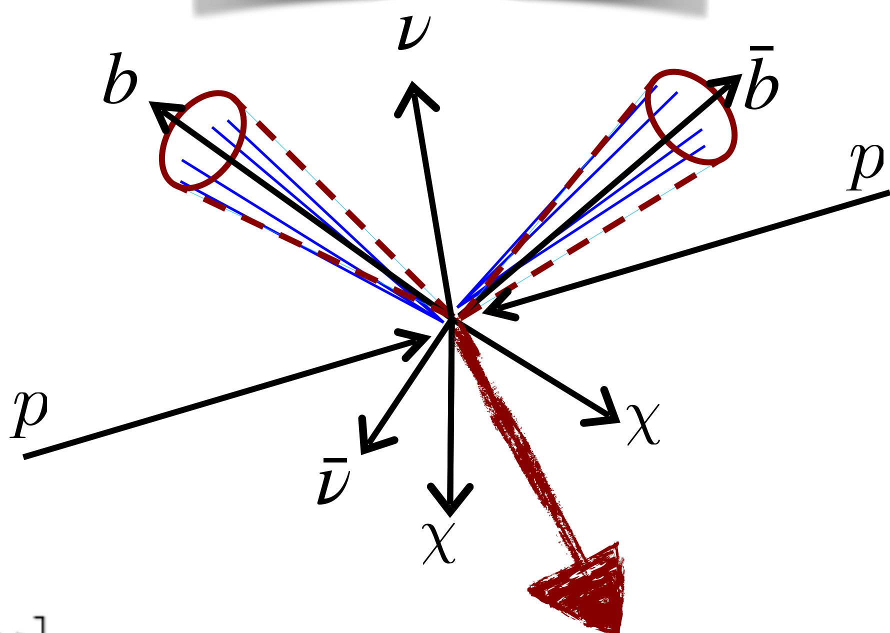
Interpret as limits on DM annihilation



- **Analysis strategy:**
  - Dilepton channel, single lepton trigger
  - Require ≥1 b-tagged jet
  - Significant MET
  - $|m_{\ell\ell} - m_Z| > 20$ GeV
  - Look for excess in m_{T2} distribution:







$$m_{\tilde{l}}^2 \geq M_{T2}^2 \equiv \min_{\not{\mathbf{p}}_1 + \not{\mathbf{p}}_2 = \not{\mathbf{p}}_T} \left[\max \{ m_T^2(\mathbf{p}_{Tl^-}, \not{\mathbf{p}}_1), m_T^2(\mathbf{p}_{Tl^+}, \not{\mathbf{p}}_2) \} \right]$$

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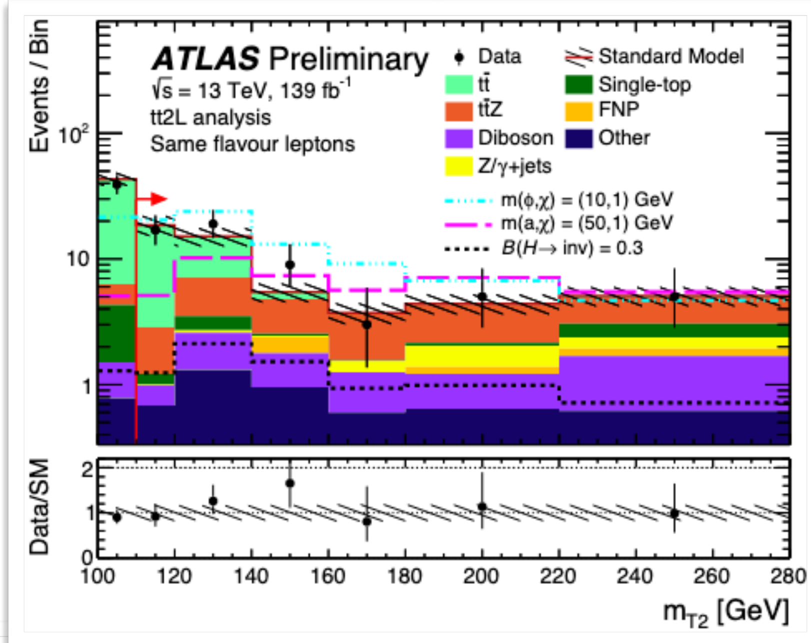
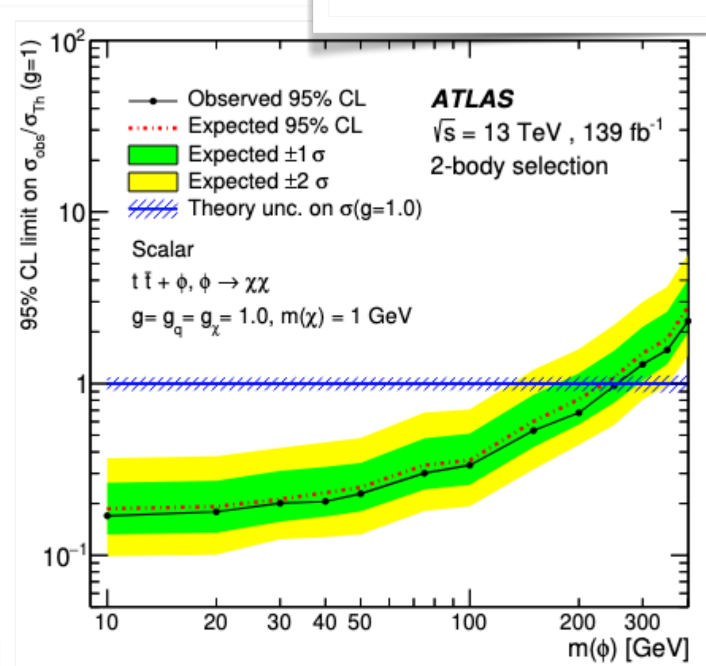
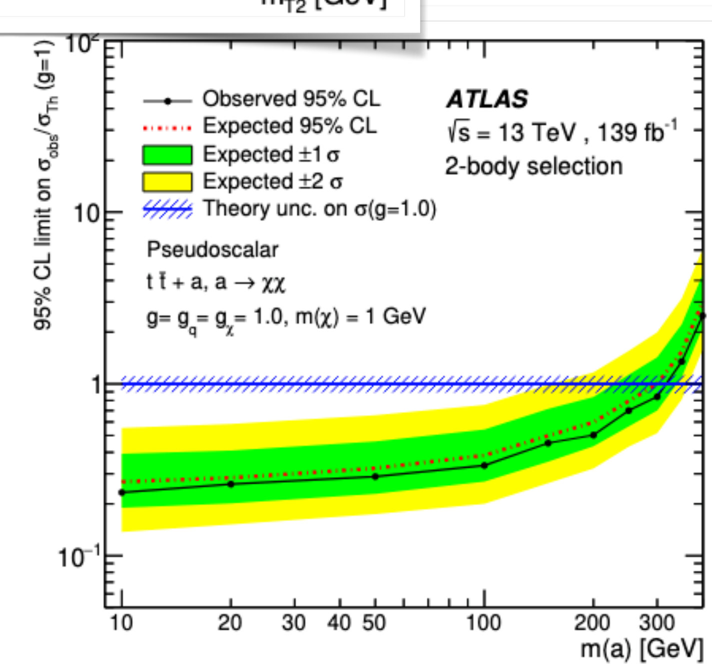
$t\bar{t} + \chi\bar{\chi}$: (PSEUDO-) SCALAR MEDIATORS

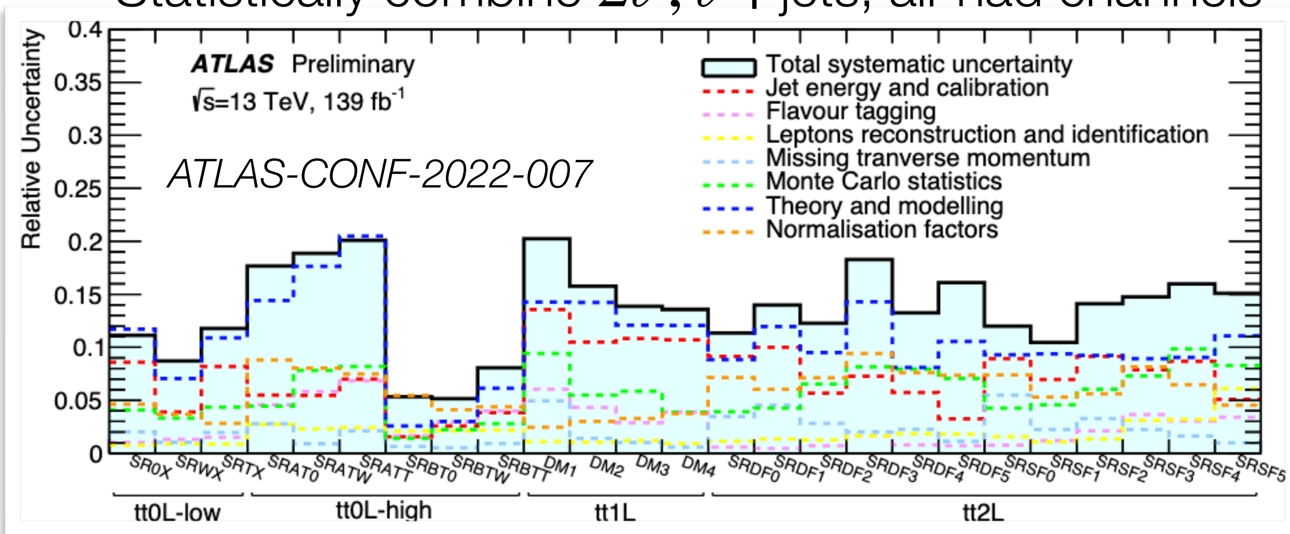
JHEP 04 (2021) 165



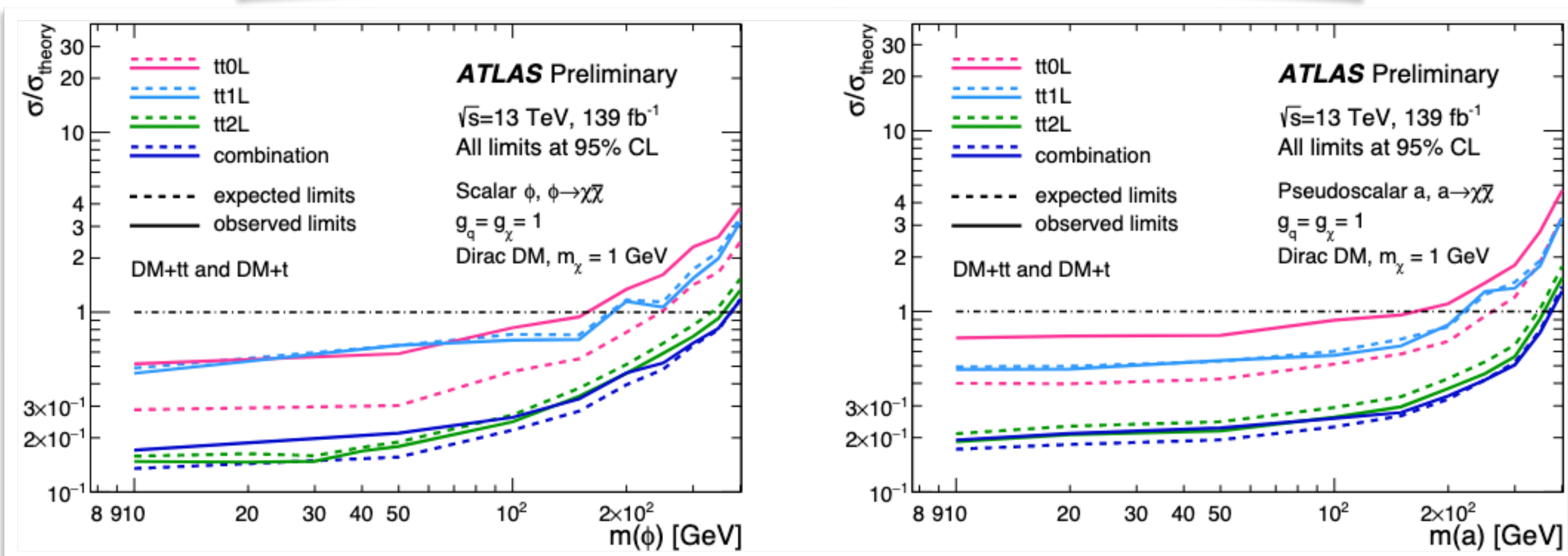


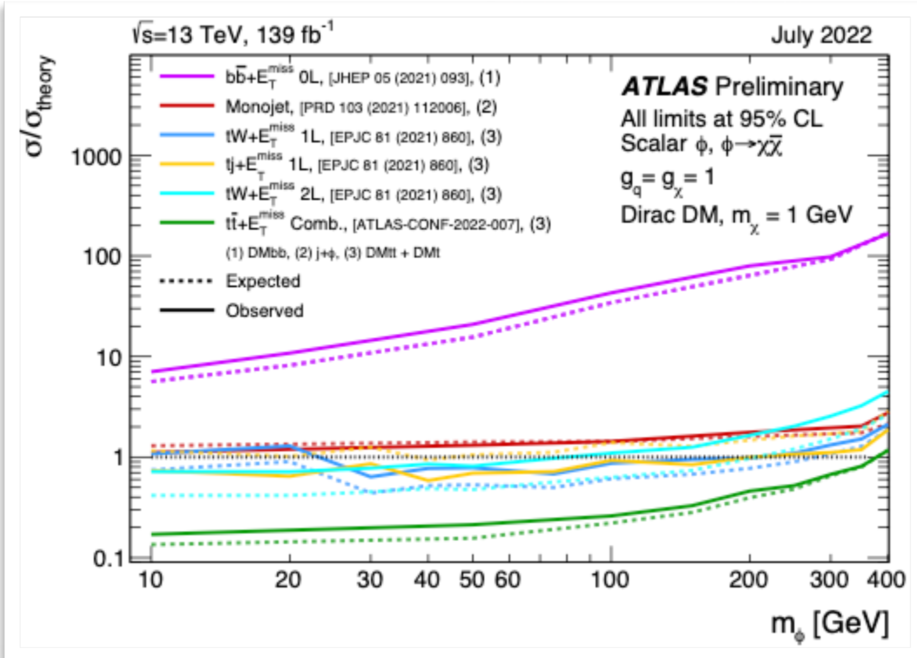


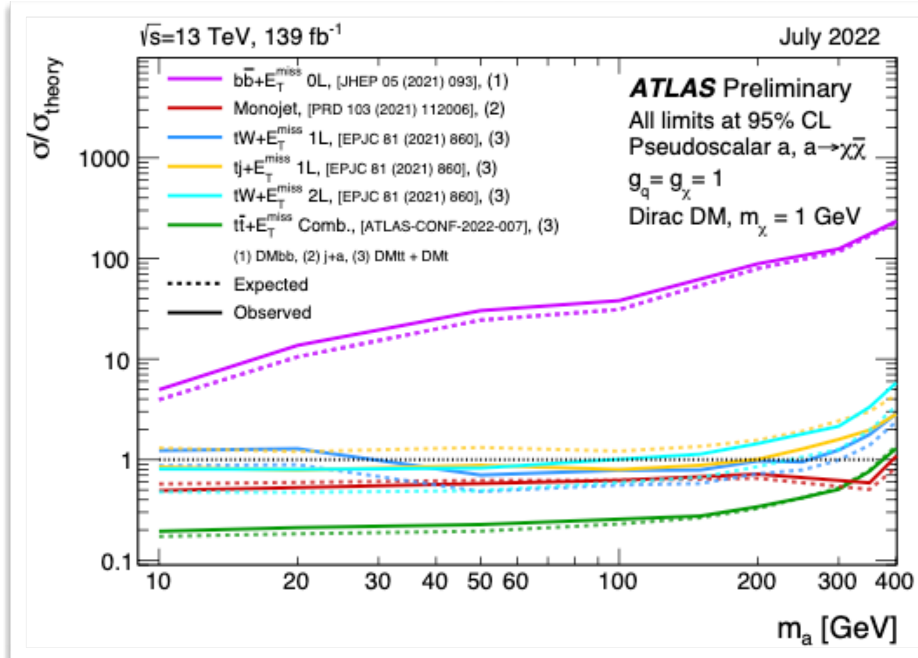
Statistically combine 2ℓ, ℓ+jets, all-had channels



ATLAS-CONF-2022-007







$b\bar{b}+E_T^{miss}$ 0L, [JHEP 05 (2021) 093], (1)

Monojet, [PRD 103 (2021) 112006], (2)

$tW+E_T^{miss}$ 1L, [EPJC 81 (2021) 860], (3)

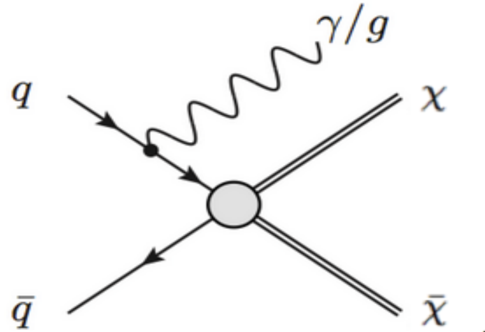
$tj+E_T^{miss}$ 1L, [EPJC 81 (2021) 860], (3)

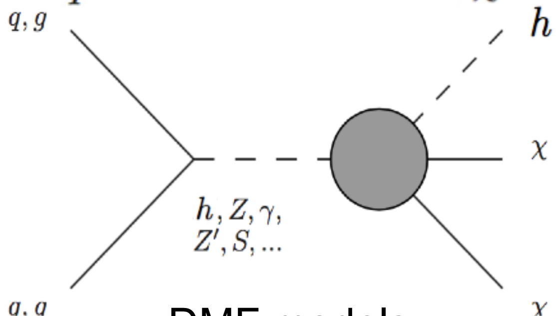
$tW+E_T^{miss}$ 2L, [EPJC 81 (2021) 860], (3)

$t\bar{t}+E_T^{miss}$ Comb., [ATLAS-CONF-2022-007], (3)

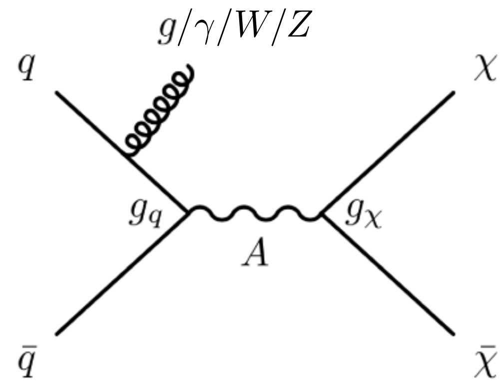
(1) DMbb, (2) j+a, (3) DMtt + DMt

MODELS FOR DM SEARCHES @ LHC

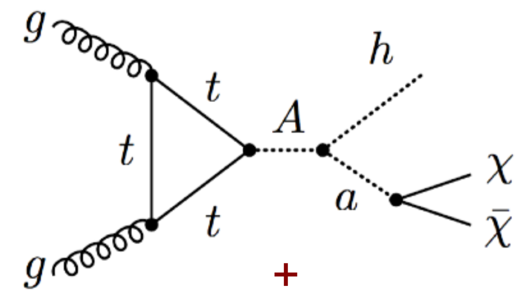




DMF models
1507.00966



s-channel mediators
1507.00966
1603.04156
1703.05703
t-channel mediators
1507.00966



\+
many other signatures

2HDM+a model
JHEP 05 (2017) 138
1810.09420

Dark Higgs model
JHEP 04(2017)143

Supersymmetry
DM candidate: lightest super-symmetric particle

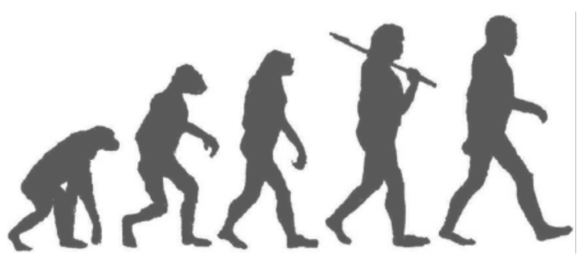
1) Effective field theory

2) Simplified models

3) Simplified, consistent, & UV-complete models

4) complete models

White Papers of
LHC DM WG/DMF



Richer kinematics + phenomenology

- **Role:**
  - Provide **open, collaborative, and friendly** environment for:
    - Discuss new Dark Matter signatures
    - Devise future searches for Dark Matter
    - Provide recommendations for interpretation of Dark Matter searches
  - **Your** ideas very welcome:
    - E.g. t-channel mediators, dark photon models, you name it!
      - Suggestions for future topics you would like to tackle very welcome!
  - **Facilitate exchange of ideas** through meetings etc:
    - http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors

LHC Dark Matter Working Group:

- Raison d'être & rôle:
  - Coordinate discussion about DM searches at the LHC between theory and experiment
  - Provide advice about searches & parameter spaces of simplified models
  - Defining benchmark models and interpretations for DM searches
  - Facilitate collaboration across the LHC experiments and theory
  - Open and topical meetings, with O(100) interested physicists participating
  - Facilitate development of higher-precision calculations for backgrounds
  - Interface to direct and indirect detection communities

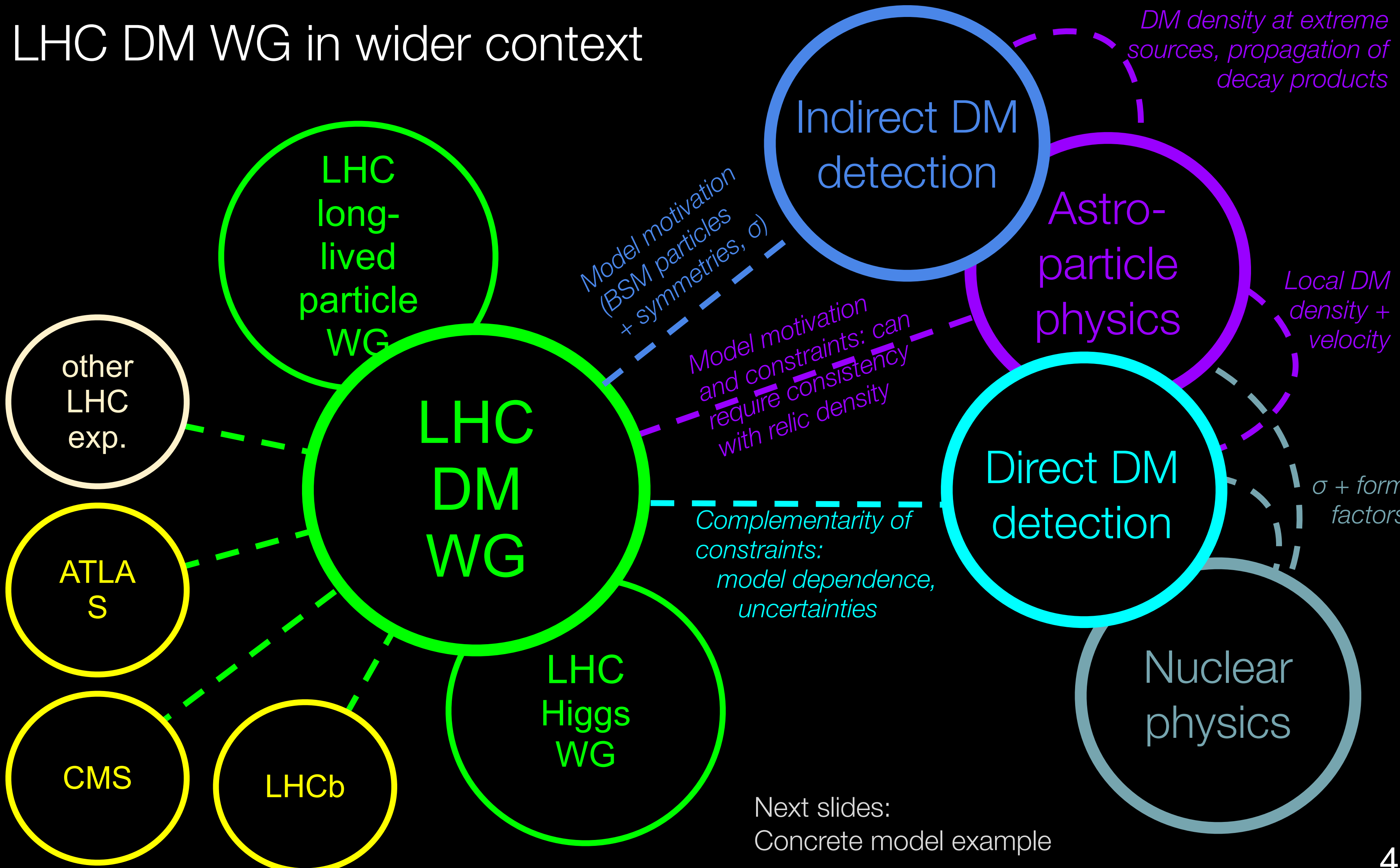
LHC DM WG context

Open to newcomers!
Easy to contribute!

- Logistics:
  - Website
  - Indico agenda space
  - Mailing list for discussion/questions (everyone subscribed can post):
    - lhc-dmwg-contributors@cern.ch, subscribe
  - Mailing list for t-channel studies (everyone subscribed can post)
    - lhc-dmwg-contributors-tchannel@cern.ch, subscribe
  - Mailing list for announcements (restricted posting, write to organisers)
    - lhc-dmwg@cern.ch, subscribe
  - Mailing list DM WG organisers:
    - lhc-dmwg-admin@cern.ch

- LHC DM WG organisers (email us):
  - ATLAS: Spyros, James Frost
  - CMS: Matteo Cremonesi
  - LHCb: Xabier Cid Vidal
  - Theory: Uli Haisch, Tim Tait

LHC DM WG in wider context



Next slides:
Concrete model example

LHC DM WG ecosystem in theory space

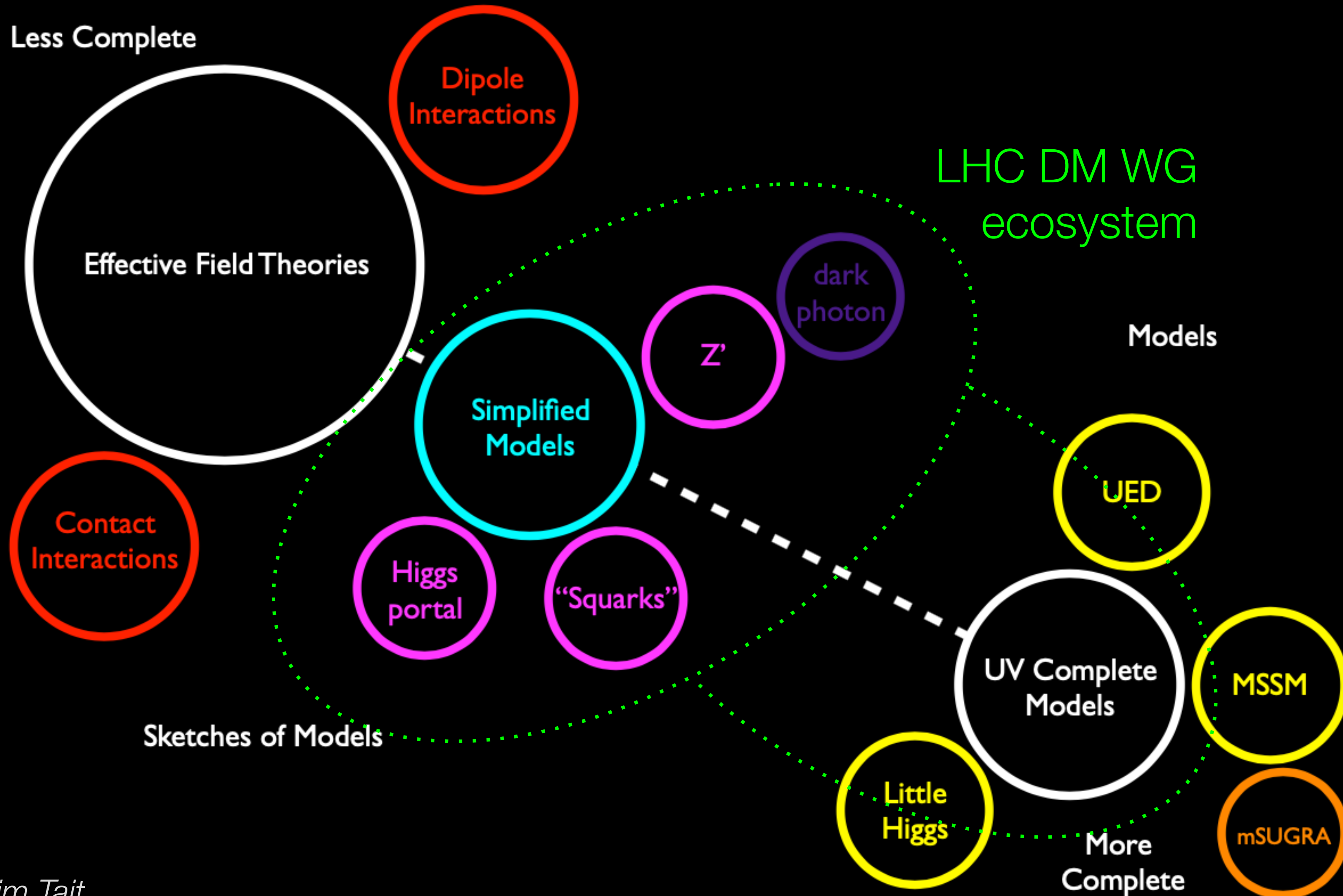
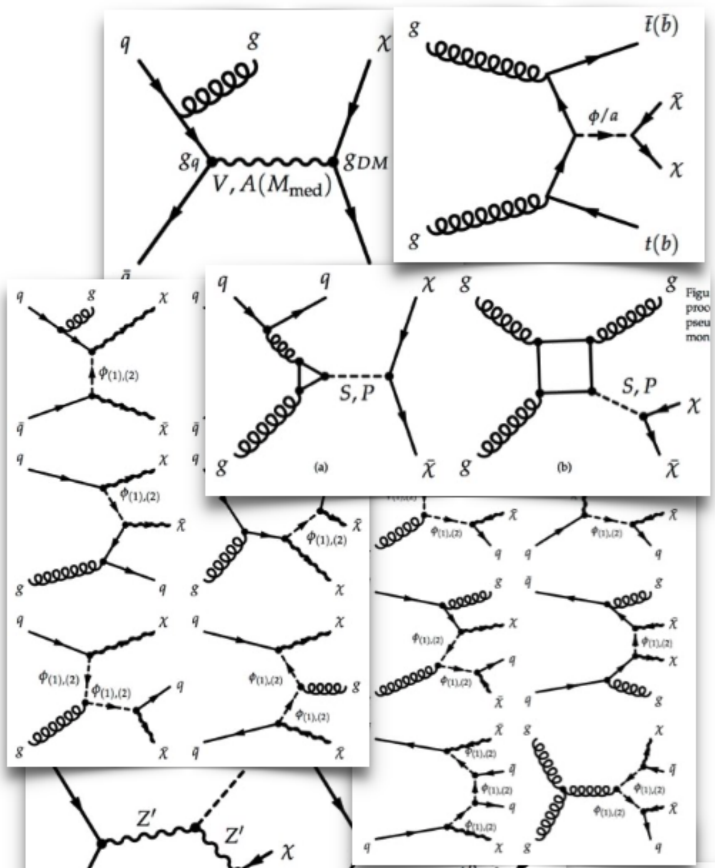


Figure: Tim Tait

LHC DM WG: past activities

- Series of White Papers published in Phys. Dark Univ.



5.62
CiteScore

5.66
Impact Factor

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum
August 8, 2016
Phys. Dark Univ. 26 (2020) 100371

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter
Phys. Dark Univ. 27 (2020) 100365

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels
Phys. Dark Univ. 26 (2019) 100377

LHC Dark Matter Working Group: Next-generation spin-0 dark matter models
Phys. Dark Univ. 27 (2020) 100351

Next White Paper
t-channel mediator models

Navigating (DM) theory space

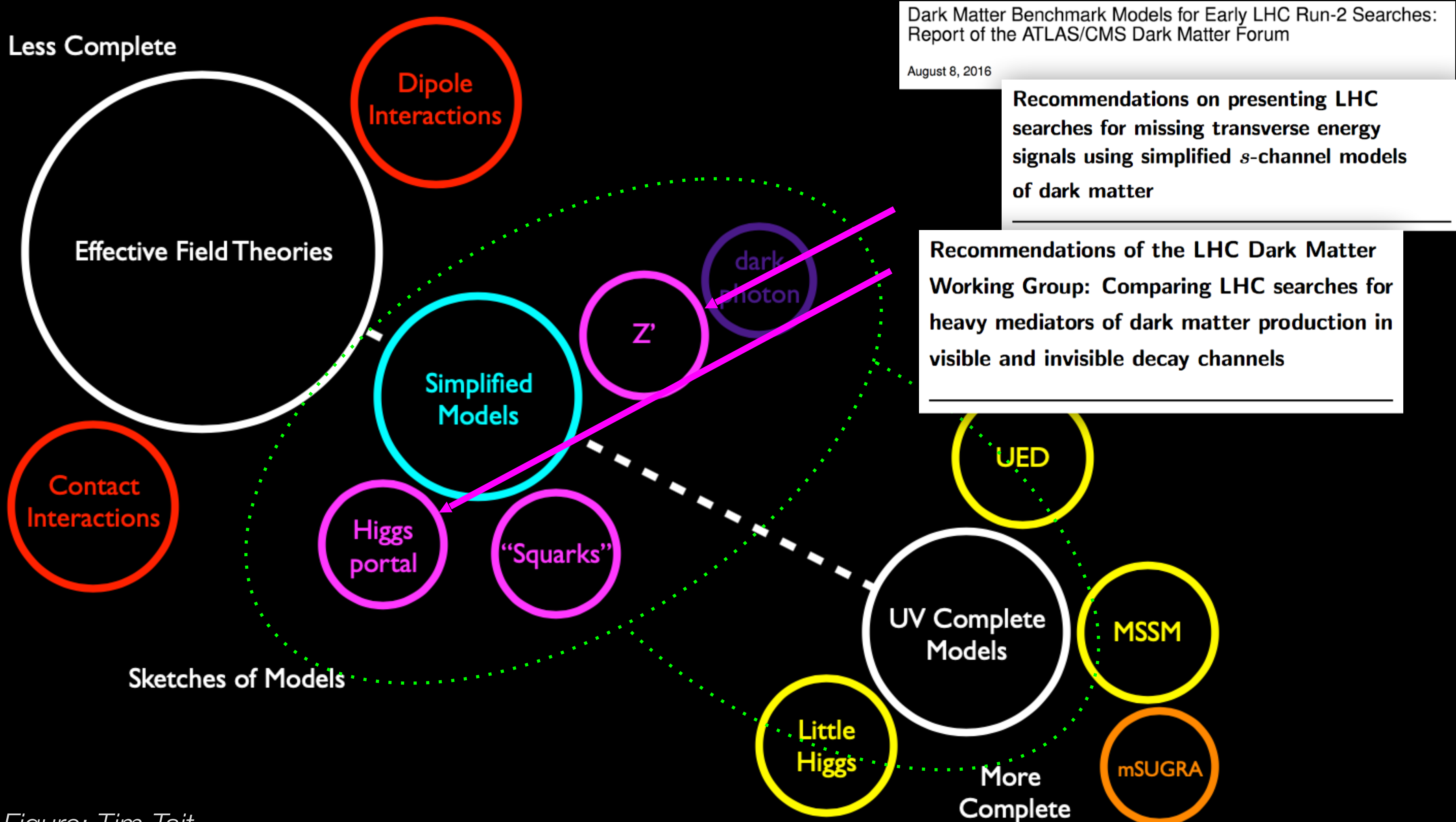
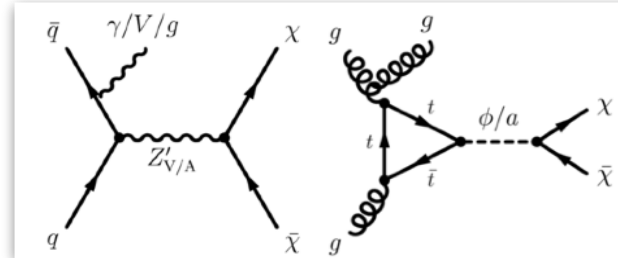
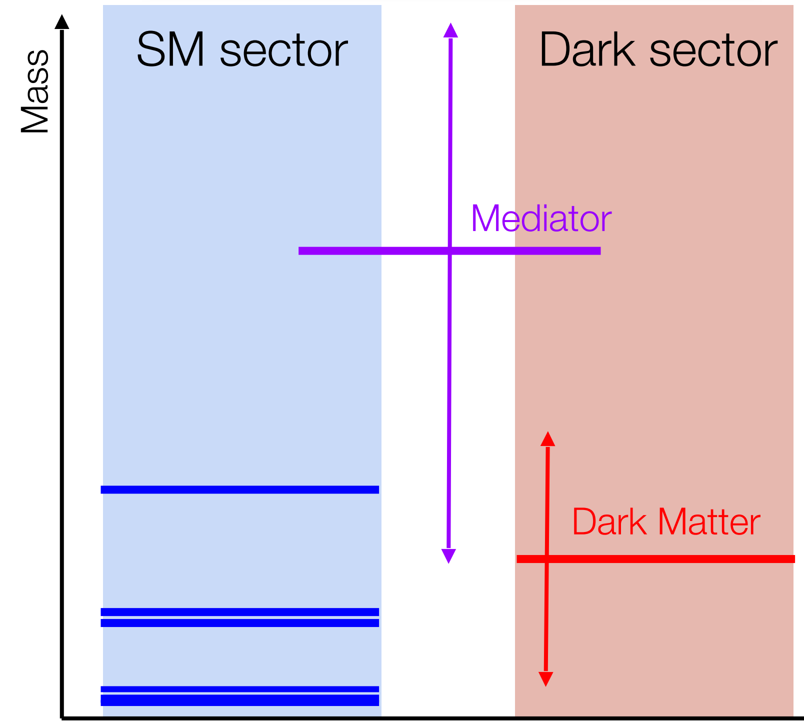


Figure: Tim Tait

s-channel mediator models

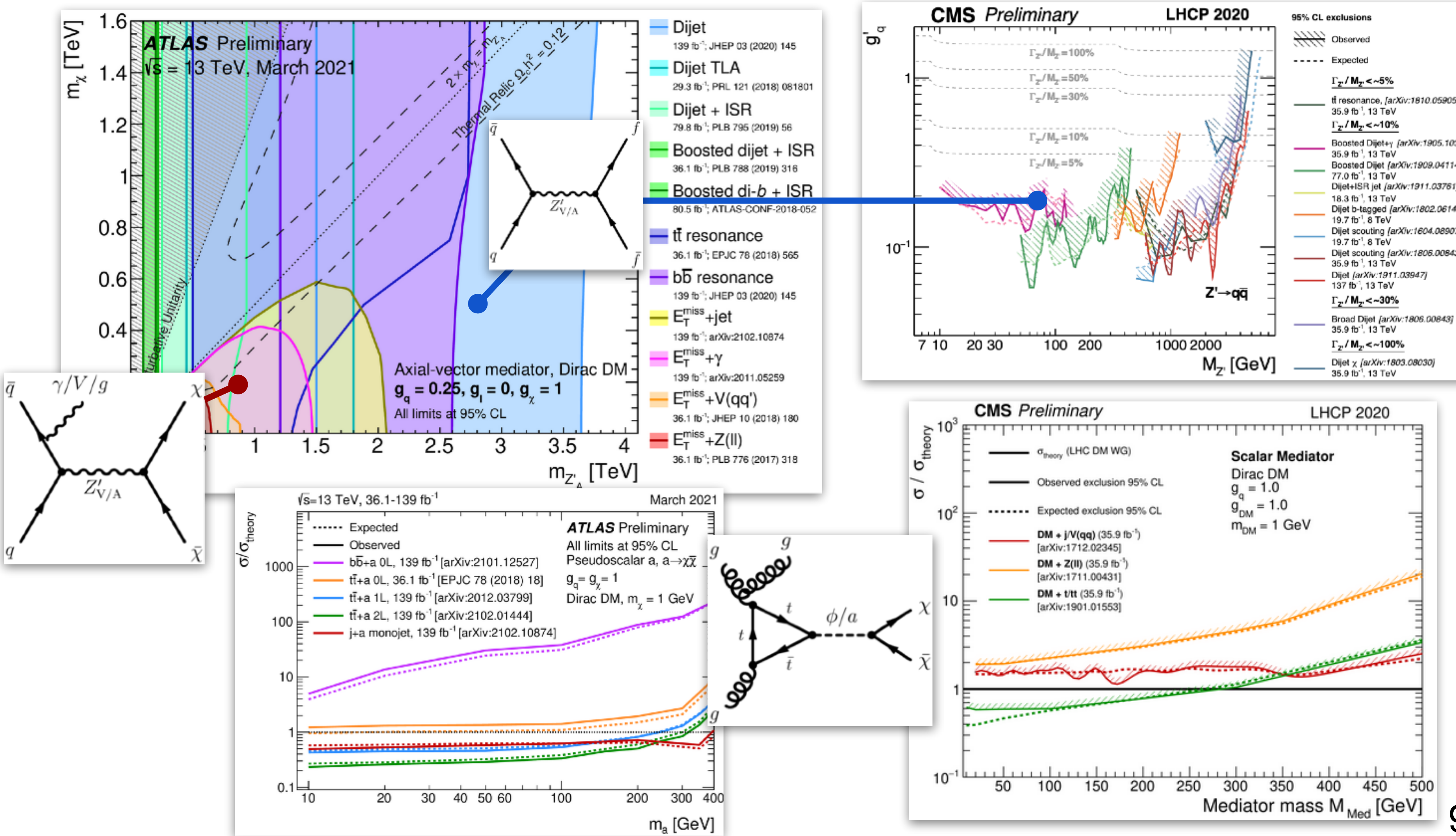
- Strong motivation (as strong as t-channel)
- Ansatz:
  - DM-mediator interaction
  - SM fermions-mediator interaction
- Mediator can be a vector vs scalar
  - (gauge vs Yukawa type of couplings)
  - Chiral structure (LH, RH) for SM fermions can be important
- Complementary signatures:
  - X+MET final states, X+ISR
  - resonance searches



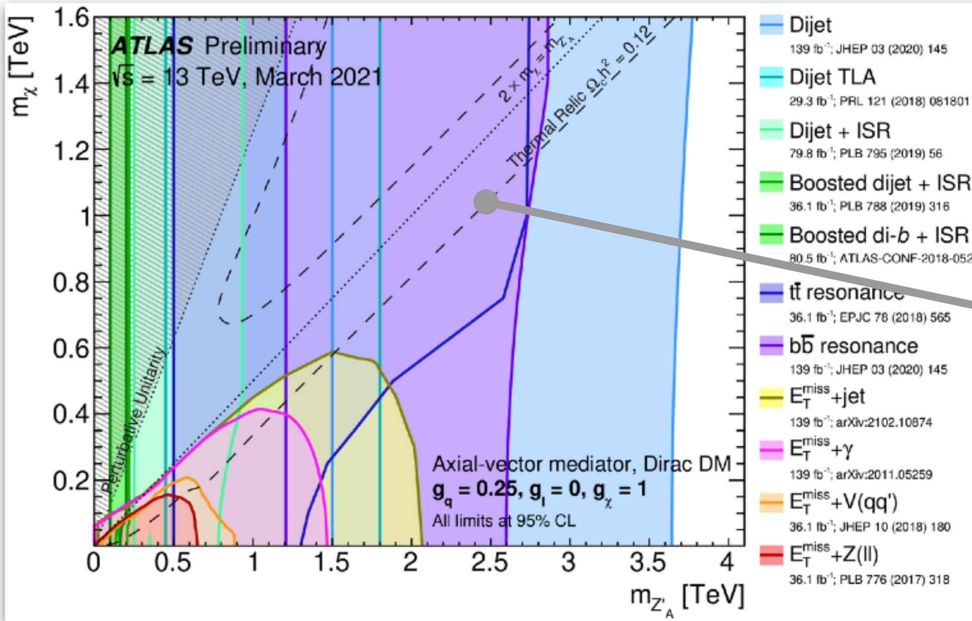


Phys. Dark Univ. 26 (2020) 100371
Phys. Dark Univ. 27 (2020) 100365
Phys. Dark Univ. 26 (2019) 100377

s-channel mediator models



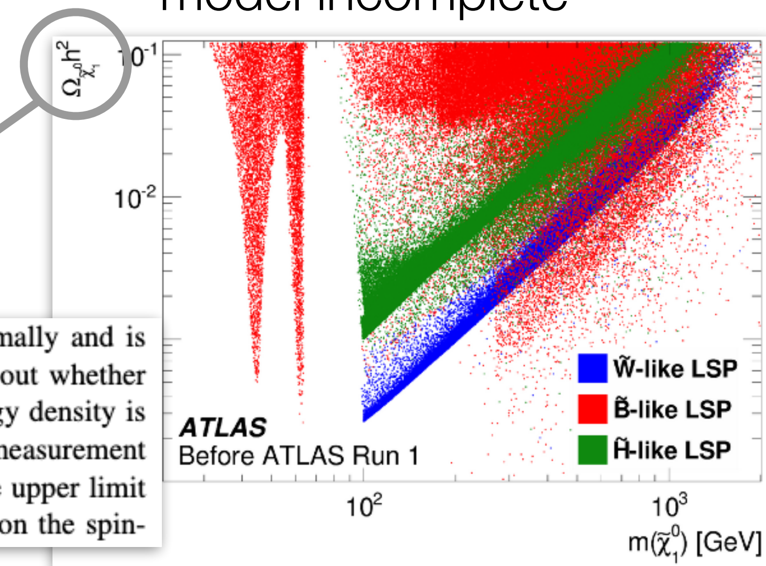
s-channel connections: relic density



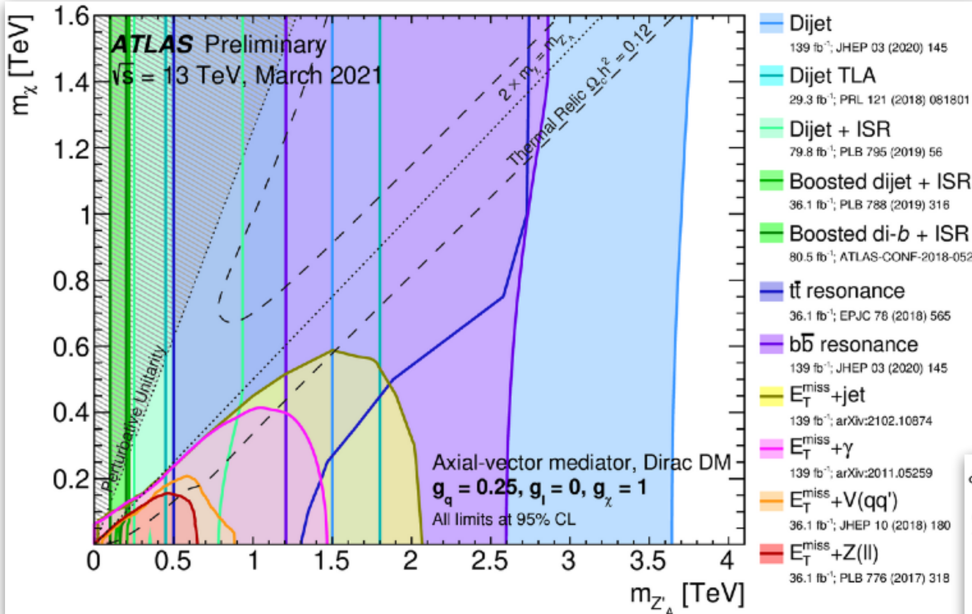
Relic density input:

- from astroparticle physics (Planck / WMAP)
- In simplified models, use relic density to *guide* searches
  - No constraint: simplified model incomplete
- In complete models (e.g. SUSY), use relic density to *constrain* searches

zero cosmological abundance. It is assumed that the LSP abundance is determined thermally and is not diluted by other processes e.g. late-time entropy addition. No assumption is made about whether the LSP is the sole constituent of dark matter. As a result, the total cold dark matter energy density is used as an upper limit on the LSP abundance. The limit is based on the latest combined measurement from the Planck Collaboration of $\Omega_{CDM}h^2 = 0.1188 \pm 0.0010$ (Table 4 of Ref. [97]).[2] The upper limit is set to the observed central value plus double the experimental uncertainty. The limit on the spin-



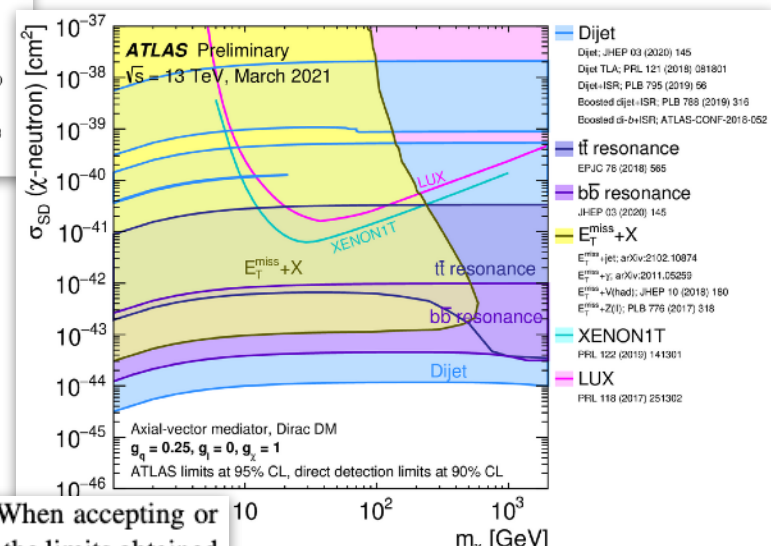
s-channel connections: direct detection



Direct detection input:

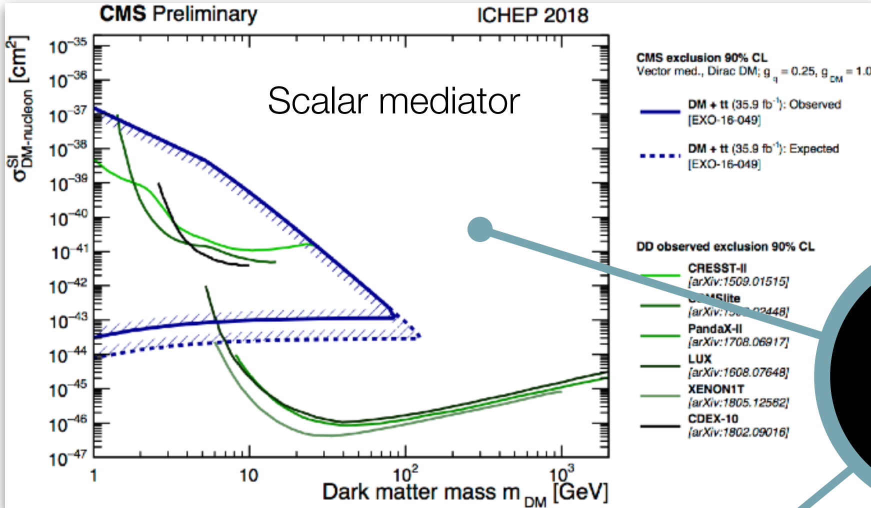
- *WIMP assumption* + *local DM density* + type of interaction
- In simplified models, highlight complementarity between colliders and direct detection

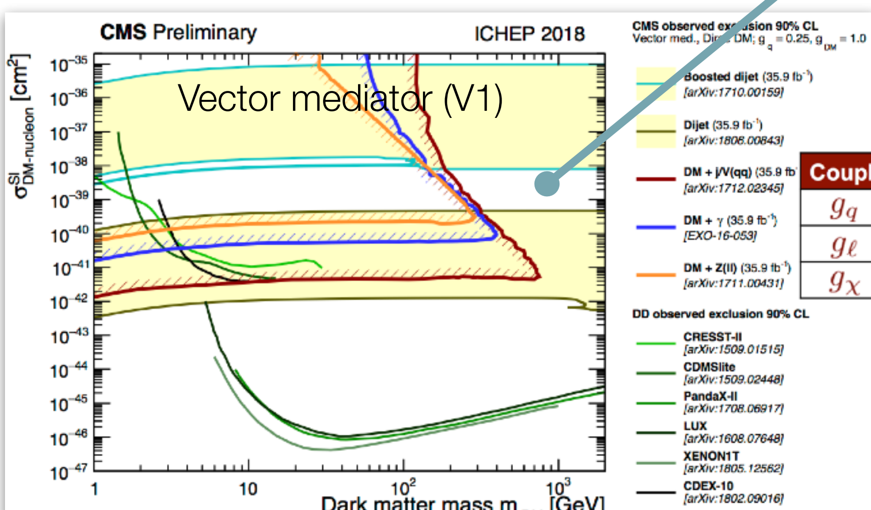
- Challenges:
  - uncertainties on direct det.?
    (so far: 4x, 10x)
    → constrain complete models:



the remaining non-LSP dark matter is invisible to the direct detection experiments. When accepting or rejecting models, the calculated value is allowed to be up to a factor of four higher than the limits obtained by the experiments, to account for nucleon form-factor uncertainties [33].

s-channel connections: direct detection



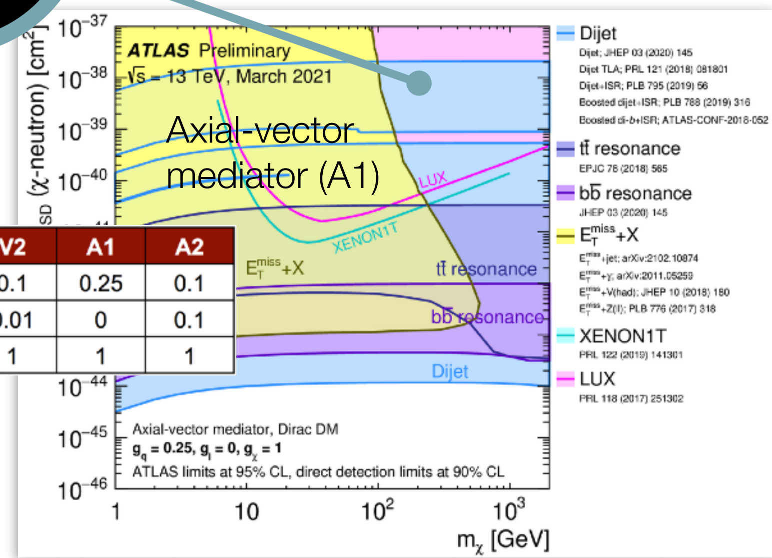


Nuclear physics: Form Factor

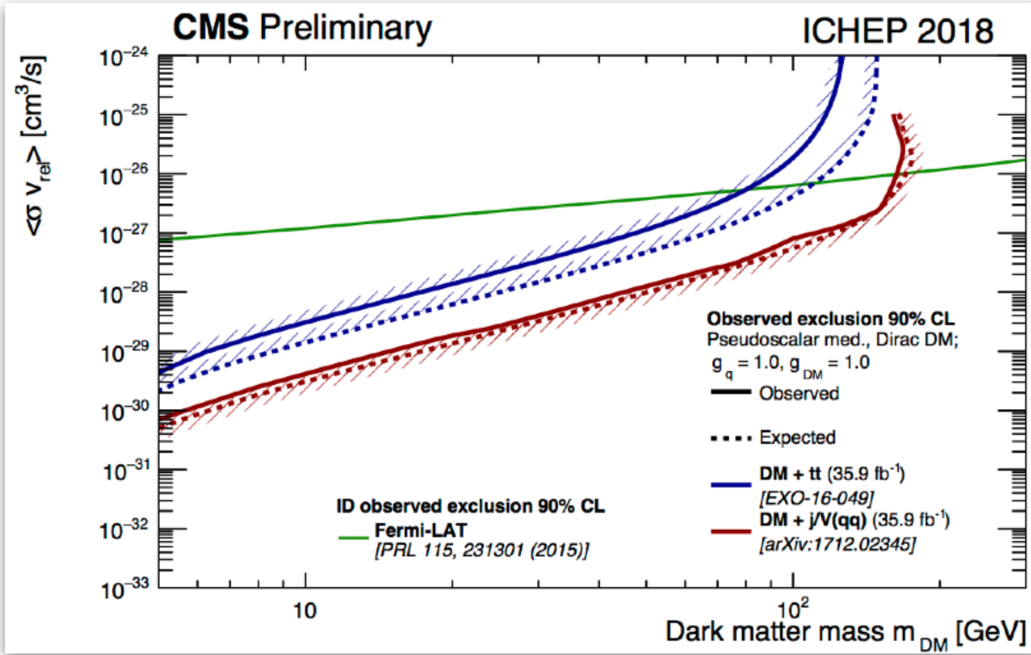
Direct detection input:

- WIMP assumption + local DM density + *type of interaction*
- Study impact of mediator + coupling assumptions (even within the same model)

Coupl.	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1



s-channel connections: direct detection



Indirect detection input:

- WIMP assumption + DM density at extreme sources + type of interaction + (inter-)galactic propagation
- Use constraints to *guide* searches

- Challenges:
  - uncertainties on indirect detection?

Navigating (DM) theory space

Next White Paper?
t-channel mediator models

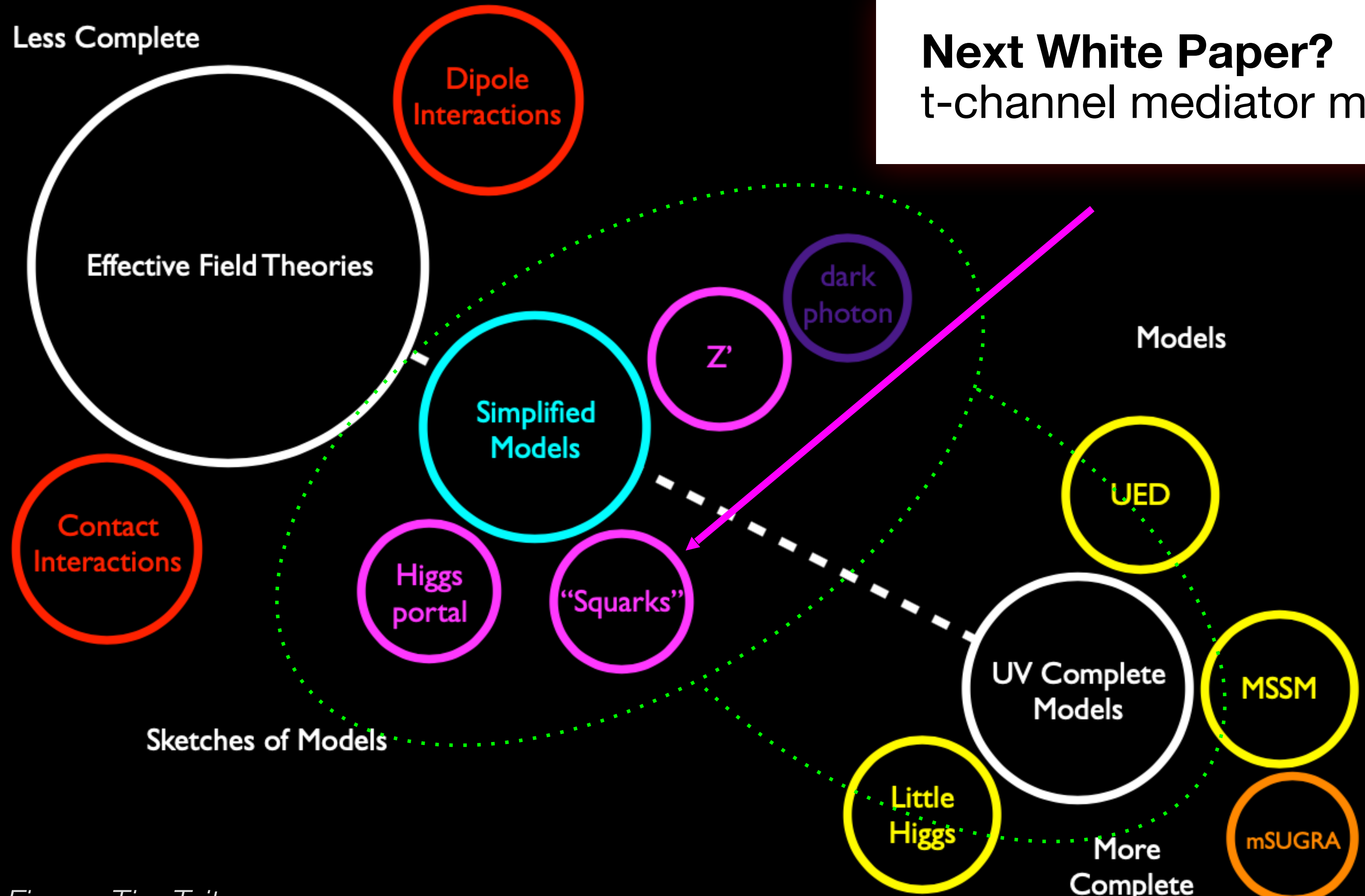
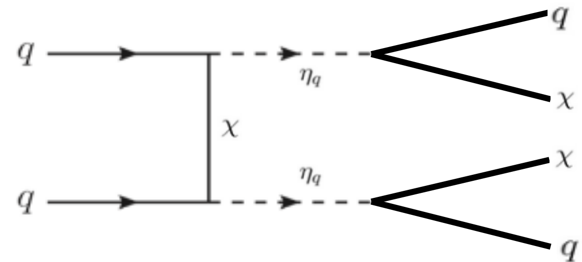
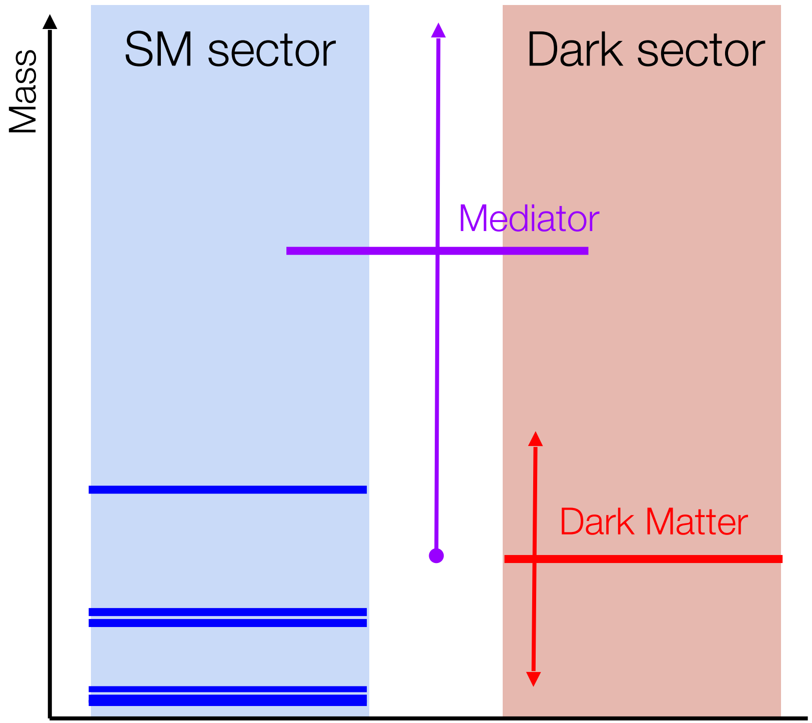


Figure: Tim Tait

t-channel mediator models

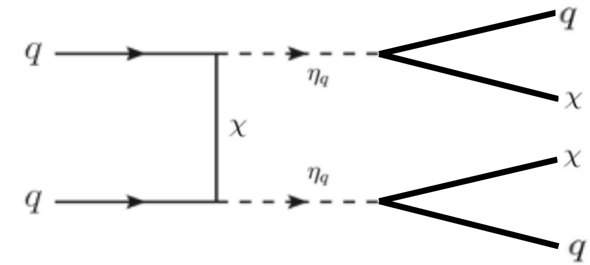
- Strong motivation (as strong as s-channel)
- Ansatz:
  - DM interacting with SM fermions and a mediator
- Corollary:
  - SM mediators must carry charge (since SM particles carry charge)
  - mediator shares the symmetry that stabilises DM
    → $m_{Mediator} > m_{DM}$
  - Different possibilities for DM and mediator spin QN, but one must be a fermion, and the other a boson

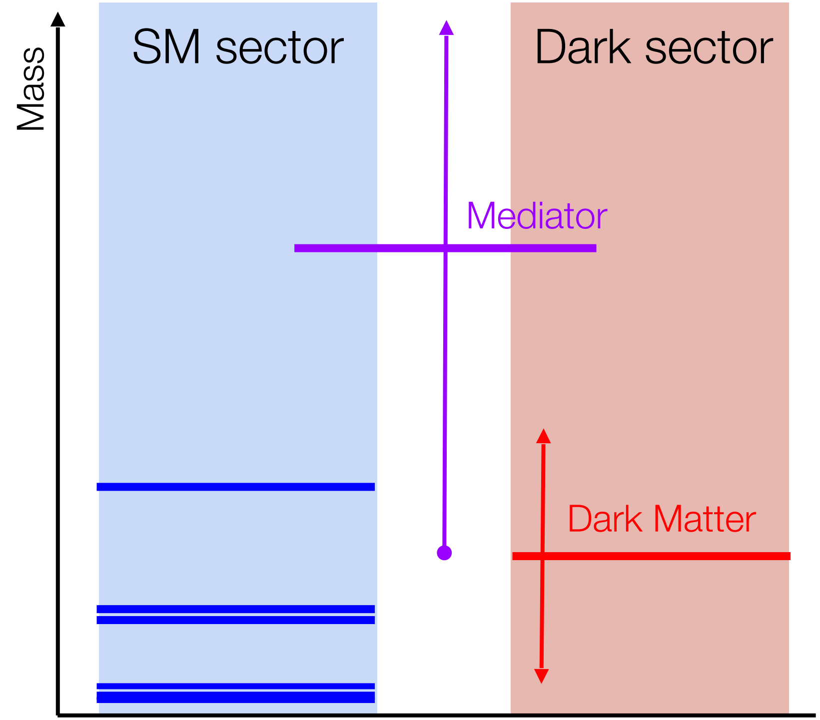




t-channel mediator models

- Self-consistent mediator-SM pairing:
  - LH quarks
  - RH up-type quarks
  - RH down-type quarks
  - leptons
- Signatures:
  - No restriction across families
    - can have interesting flavour dependence beyond MFV
  - No resonant mediator searches!
    - MET ubiquitous!
  - Possible long-lived particle signatures



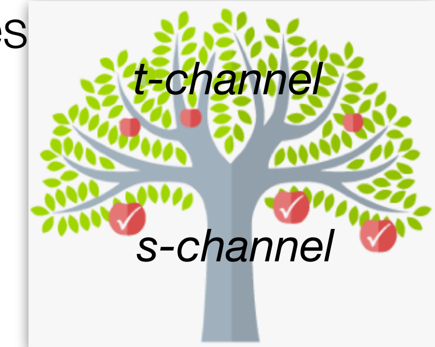


Basic signatures

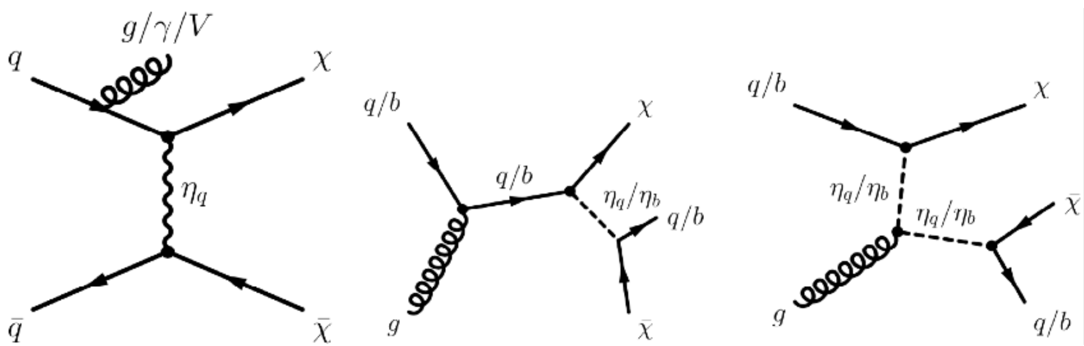
- Example Lagrangian for Dirac DM coupling to 1&2nd families

$$\mathcal{L} \supset g_{q\chi} \sum_{i=1,2} (\bar{Q}_{L,i}\eta_{L,q_i} + \bar{u}_{R,i}\eta_{R,u_i} + \bar{d}_{R,i}\eta_{R,d_i})\chi + \text{h.c.}$$

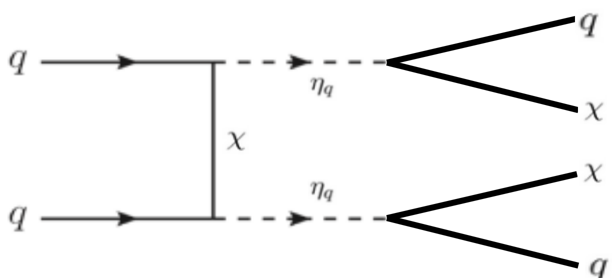
quark-DM coupling — LH quarks — LH mediators — RH up- and down-type quarks — **Dirac** fermion DM

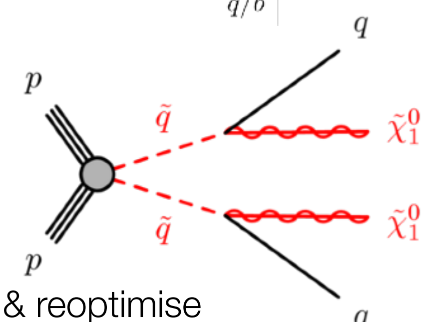


Jet + MET:



Di-jet + MET:





Reinterpret & reoptimise

Going beyond

- Study impact of spin of DM particles
  - Majorana DM has more diagrams
  - Quantify effect on which phase-space regions are relevant?
- Study DM properties:
  - Dirac/Majorana fermion
  - Scalar
  - Vector

↑ cf. Chiara's talk for details

✦ 18 restrictions with 3 parameters each

Name	DM	Mediators	Parameters
S3M_uni	$\tilde{\chi}$	$\varphi_{Q_f}, \varphi_{u_f}, \varphi_{d_f}$	$M_\varphi, M_\chi, \lambda_\varphi$
S3D_uni	χ		
S3M_3rd	$\tilde{\chi}$	$\varphi_{Q_3}, \varphi_{u_3}, \varphi_{d_3}$	
S3D_3rd	χ		
S3M_uR	$\tilde{\chi}$	φ_{u_1}	
S3D_uR	χ		
F3S_uni	$\tilde{S}$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	$M_S, M_\psi, \hat{\lambda}_\psi$
F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	$M_V, M_\psi, \hat{\lambda}_\psi$
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	
F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
F3W_uR	V_μ		

✤ Universal models (uni):
- ★ 1 dark matter particle
- ★ 12 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

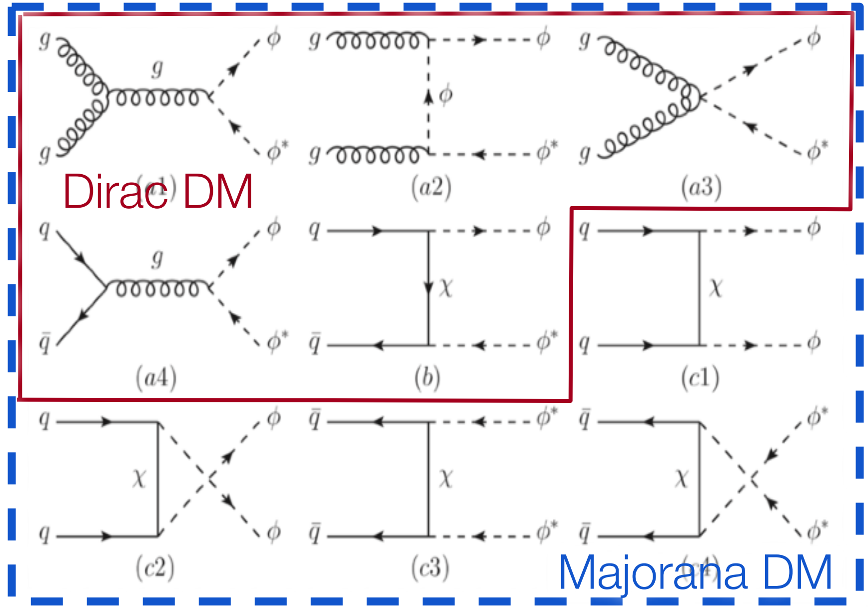
$$\mathcal{L}_{X\_uni}(X) = \sum_{F=Q,u,d} \sum_{f=1}^{3} \left[\lambda_\varphi \bar{X} F_f \varphi^\dagger_{F_f} + \text{h.c.}\right]$$

✤ 3rd generation models (3rd):
- ★ 1 dark matter particle
- ★ 4 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

$$\mathcal{L}_{X\_3rd}(X) = \sum_{F=Q,u,d} \left[\lambda_\varphi \bar{X} F_3 \varphi^\dagger_{F_3} + \text{h.c.}\right]$$

✤ uR models (uR):
- ★ 1 dark matter particle
- ★ 1 mediator
- ★ Coupling to the right-handed up-quark

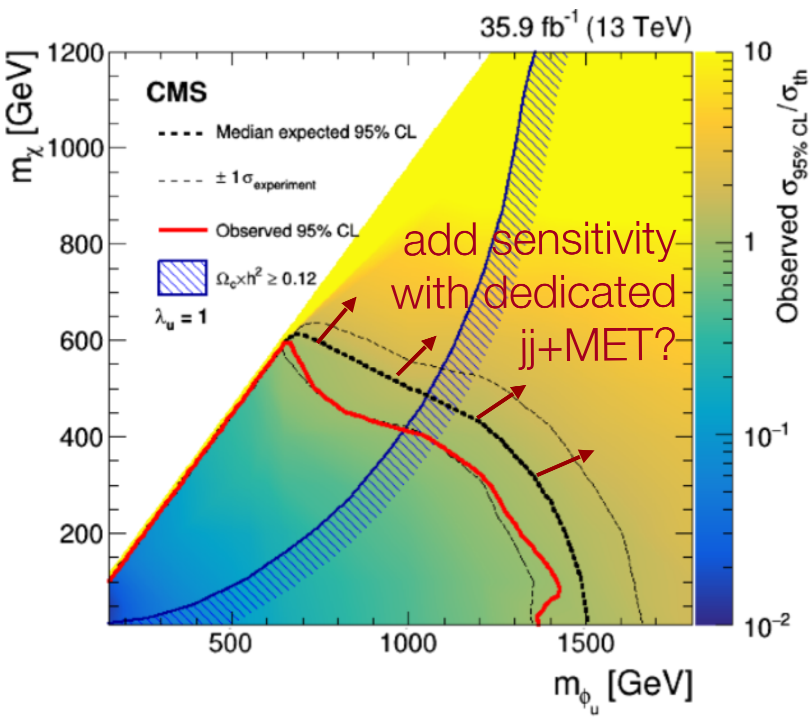
$$\mathcal{L}_{X\_uR}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\right]$$

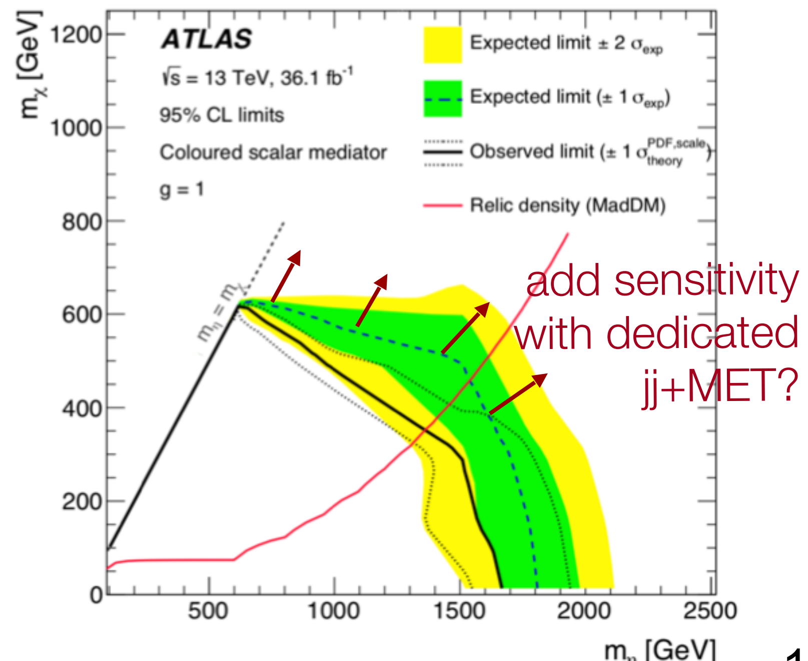


- Important step forward:
  - New Über-UFO [1,2,3] available
    - can do all DM spin hypotheses
  - über-UFO validated against few existing implementations

Previous work

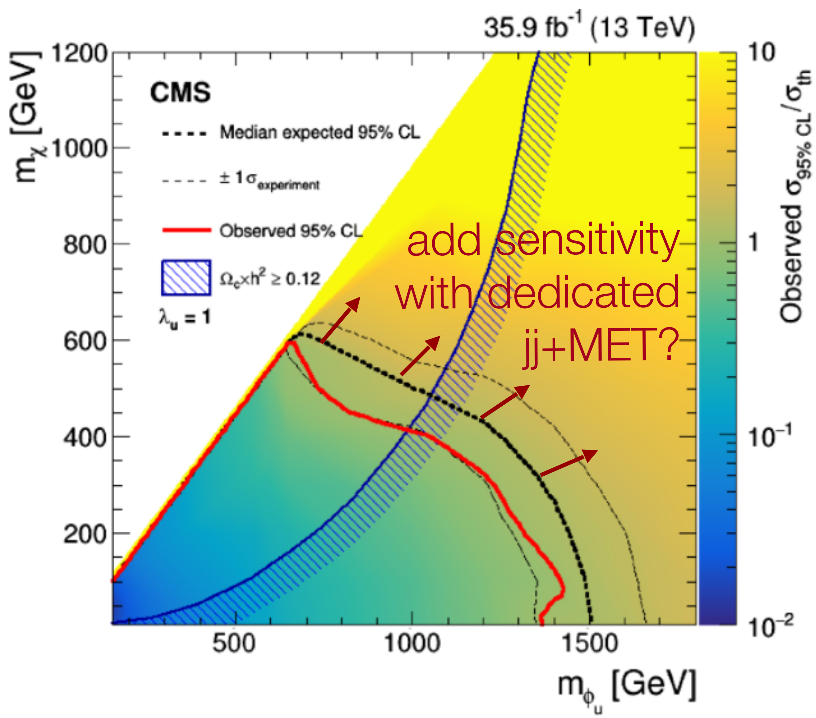
- Fermion portal DM [1,2]
  - CMS monojet
  - Coincides with S3D_uR restriction for Über-UFO
  - Previous results reproduced [1]
- Scalar color-charged model [1,2]
  - ATLAS monojet
  - LH coupling 1st gen. restriction for Über-UFO worked out
  - Previous results reproduced

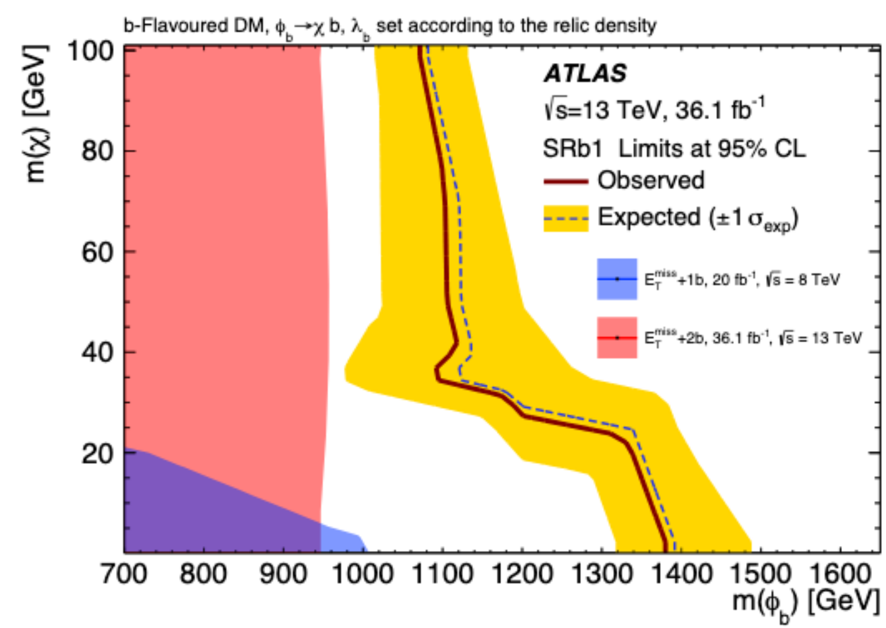




Previous work

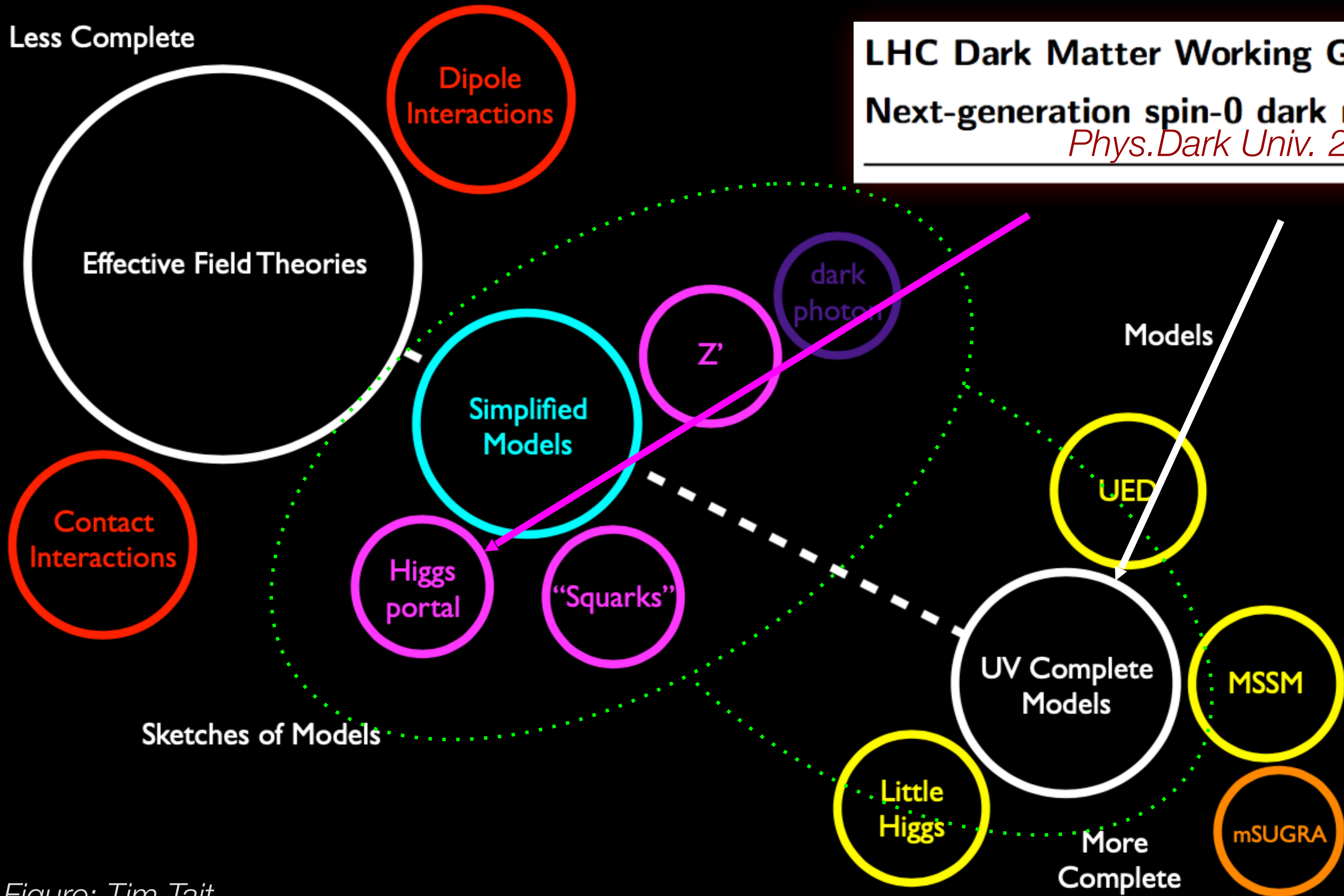
- Fermion portal DM [1,2]
  - CMS monojet
  - Coincides with S3D_uR restriction for über-UFO
  - Previous results reproduced [1]
- Scalar color-charged b model [2,3]
  - ATLAS mono-b-jet
  - RH coupling 3rd generation
  - qualitatively similar kinematic behaviour to 1st gen case





Navigating (DM) theory space

LHC Dark Matter Working Group



LHC Dark Matter Working Group:

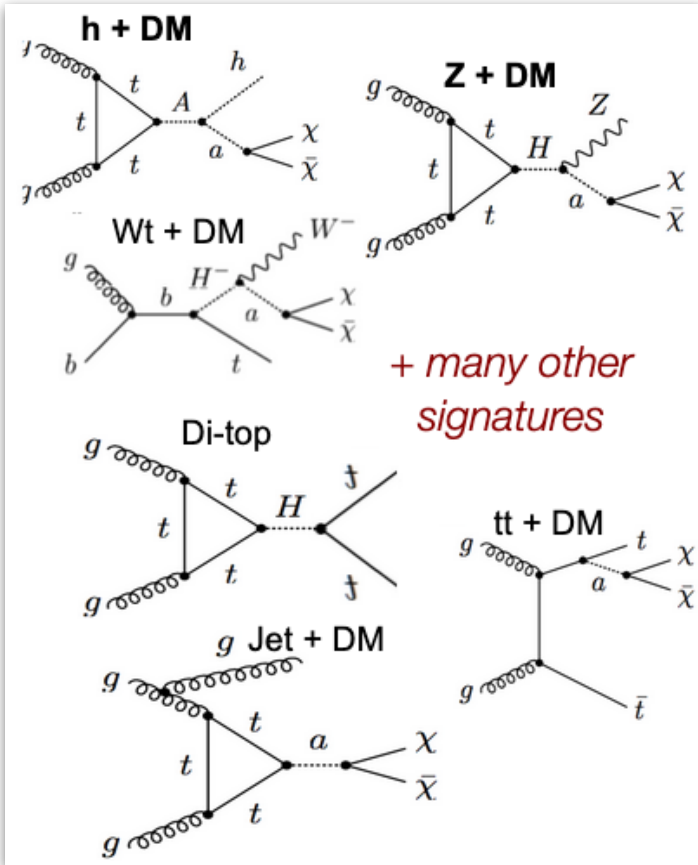
Next-generation spin-0 dark matter models

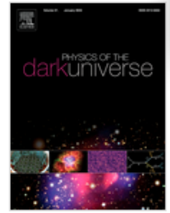
Phys.Dark Univ. 27 (2020) 100351

Figure: Tim Tait

LHC DM WG: past activities

- Series of White Papers published in Phys. Dark Univ.





5.62
CiteScore

5.66
Impact Factor

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum
August 8, 2016
Phys. Dark Univ. 26 (2020) 100371

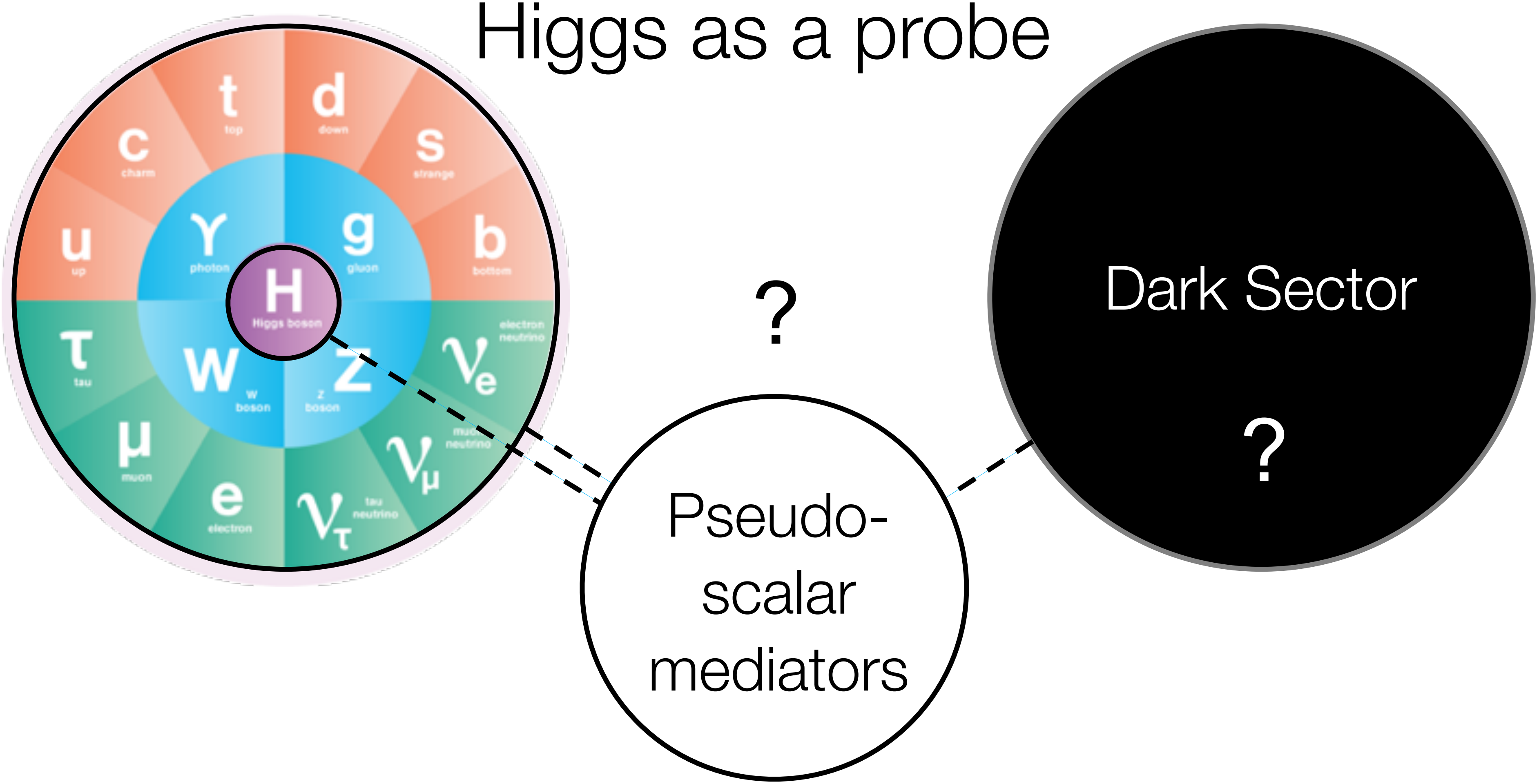
Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter
Phys. Dark Univ. 27 (2020) 100365

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels
Phys. Dark Univ. 26 (2019) 100377

LHC Dark Matter Working Group: Next-generation spin-0 dark matter models
Phys. Dark Univ. 27 (2020) 100351

Next White Paper
t-channel mediator models

Higgs as a probe



Motivation: 1) Mediator that couples to Higgs, SM and Dark Sector
typically: Higgs sector extension, 2HDM
2) Higgs coupling to new particles (hierarchy problem)

For further details…

Review

Collider Searches for Dark Matter through the Higgs Lens

Spyros Argyropoulos [1], **Oleg Brandt** [2,*] and **Ulrich Haisch** [3]

Symmetry 13(12) (2021) 2406
2109.13597

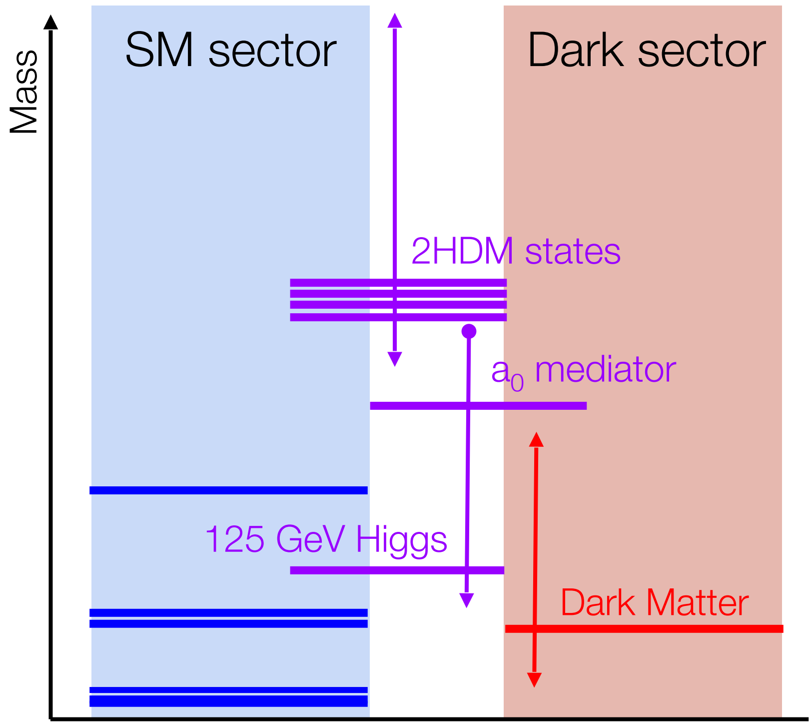
[1] Physikalisches Institut, Albert-Ludwigs Universität Freiburg; spyros.argyropoulos@cern.ch
[2] Cavendish Laboratory, University of Cambridge; obrandt@hep.phy.cam.ac.uk
[3] Max Planck Institut für Physik in München; haisch@mpp.mpg.de
* Corresponding author

Abstract: Despite the fact that dark matter constitutes one of the cornerstones of the standard cosmological paradigm, its existence has so far only been inferred from astronomical observations and its microscopic nature remains elusive. Theoretical arguments suggest that dark matter might be connected to the symmetry-breaking mechanism of the electroweak interactions or of other symmetries extending the Standard Model of particle physics. The resulting Higgs bosons, including the 125 GeV spin-0 particle discovered recently at the Large Hadron Collider therefore represent a unique tool to search for dark matter candidates at collider experiments. This article reviews some of the relevant theoretical models as well as the results from the searches for dark matter in signatures that involve a Higgs-like particle at the Large Hadron Collider.

Keywords: dark matter; Higgs; LHC

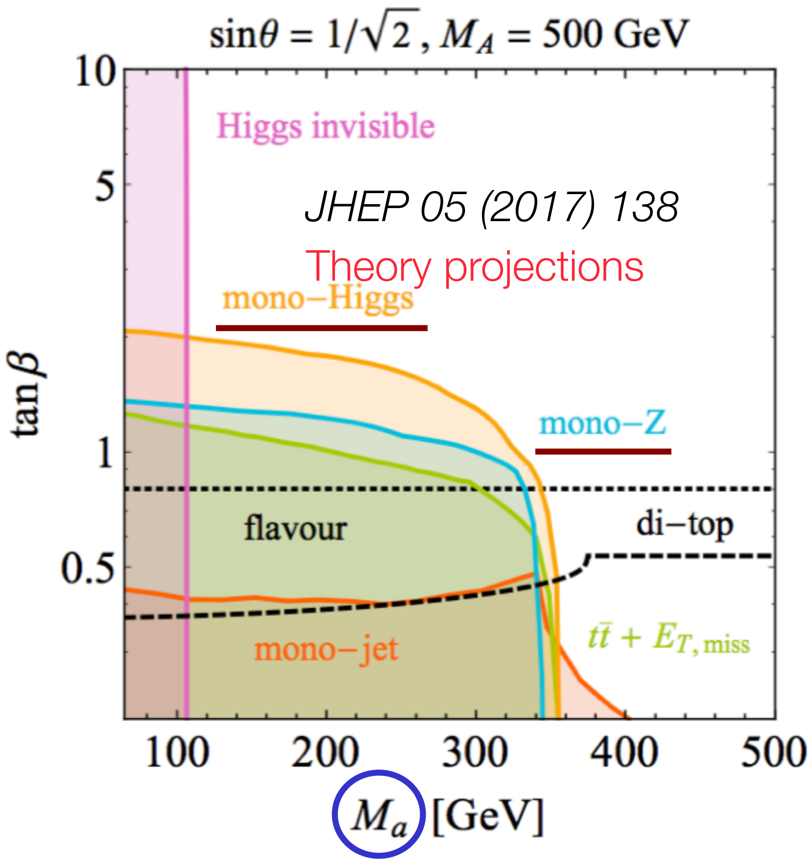
2HDM+a: SIGNATURES @ LHC

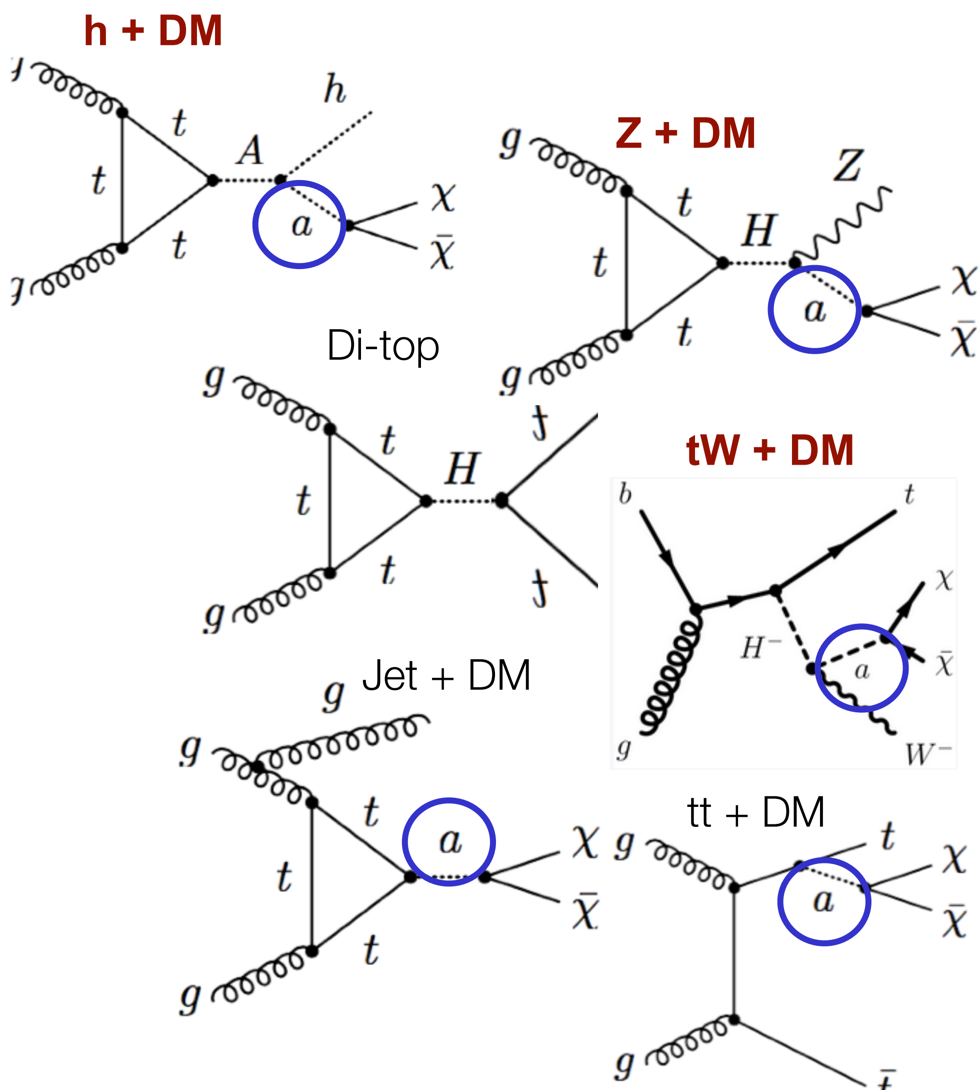
- 2HDM+a model [JHEP 05 (2017) 138, LHC DM WG: PDU 27 (2020) 100351]
  - Simplified, but UV-complete
- Ansatz: Extended Higgs sector
  - 2HDM as simple UV-complete
    Higgs sector extension: $H^{\pm}, H, A_0, h$
  - a_0: portal to DM
  - $A_0 - a_0$ mixing into A, a physical states
    $\rightarrow$ interesting SM - dark sector interplay
- Complementary signatures:
  - Prominence of h+MET, Z+MET, Wt+MET (not in other models)
  - non-resonant, e.g., jet+MET
  - resonant visible channels, e.g., $t\bar{t}$



2HDM+a: SIGNATURES @ LHC

- 2HDM+a model [JHEP 05 (2017) 138, LHC DM WG: PDU 27 (2020) 100351]
  - Simplified, but UV-complete
- Diverse palette of signatures
  - Experimentally exciting interplay!





+ *other signatures*

2HDM+a: SIGNATURES @ LHC

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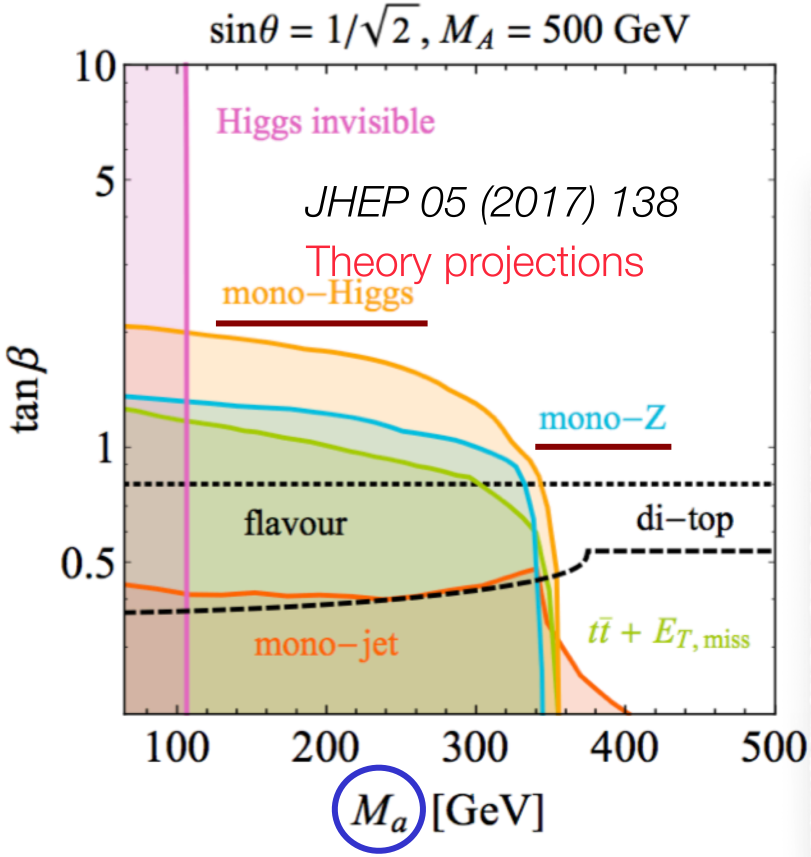

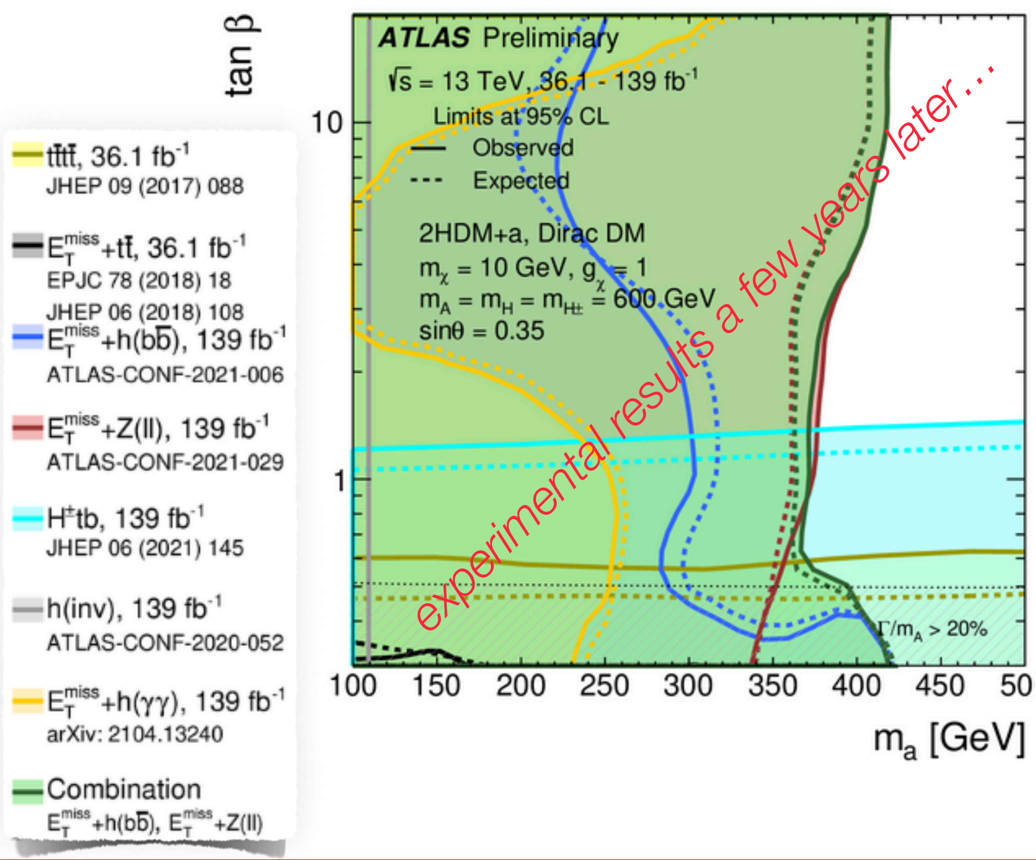

2HDM+a: SIGNATURES @ LHC

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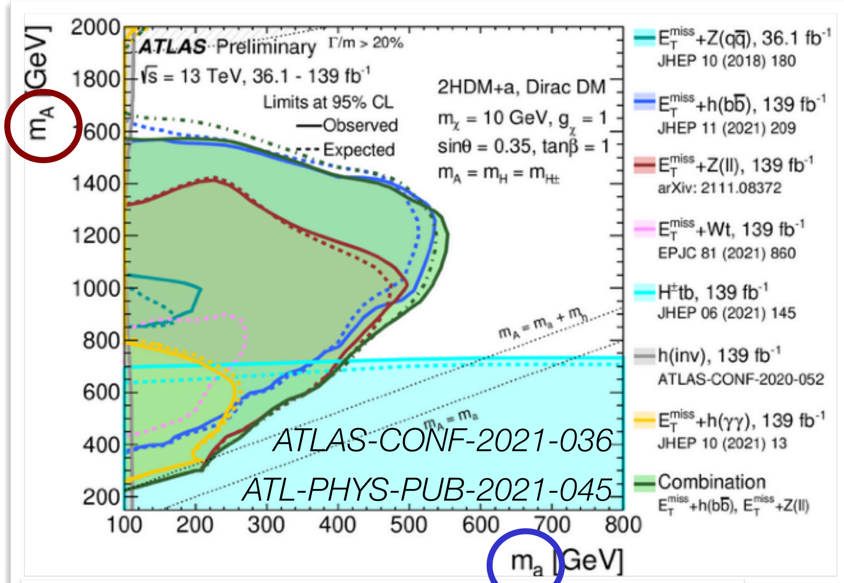
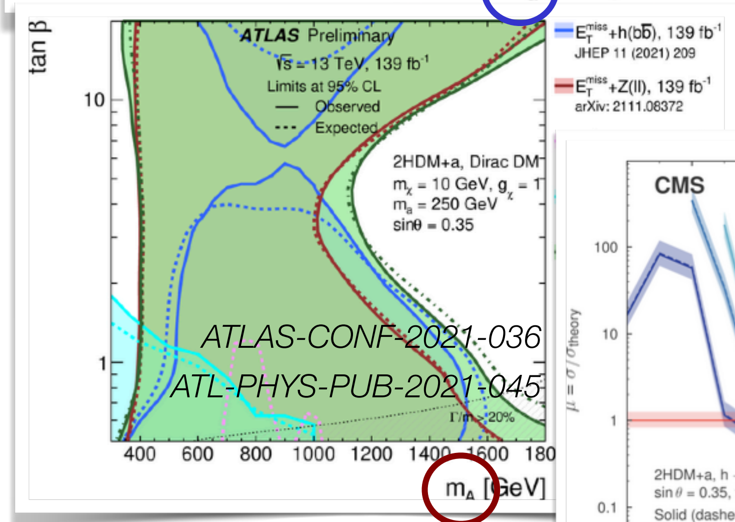
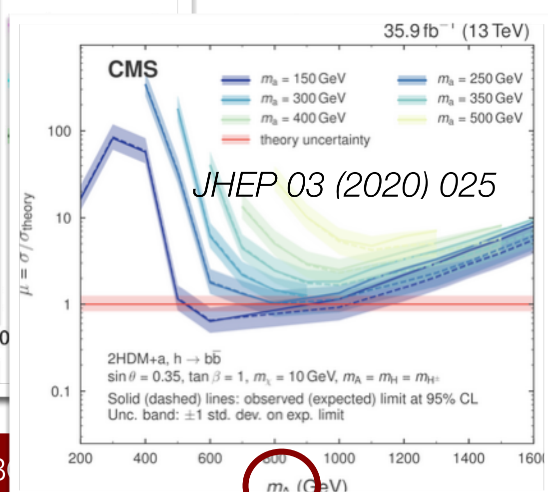
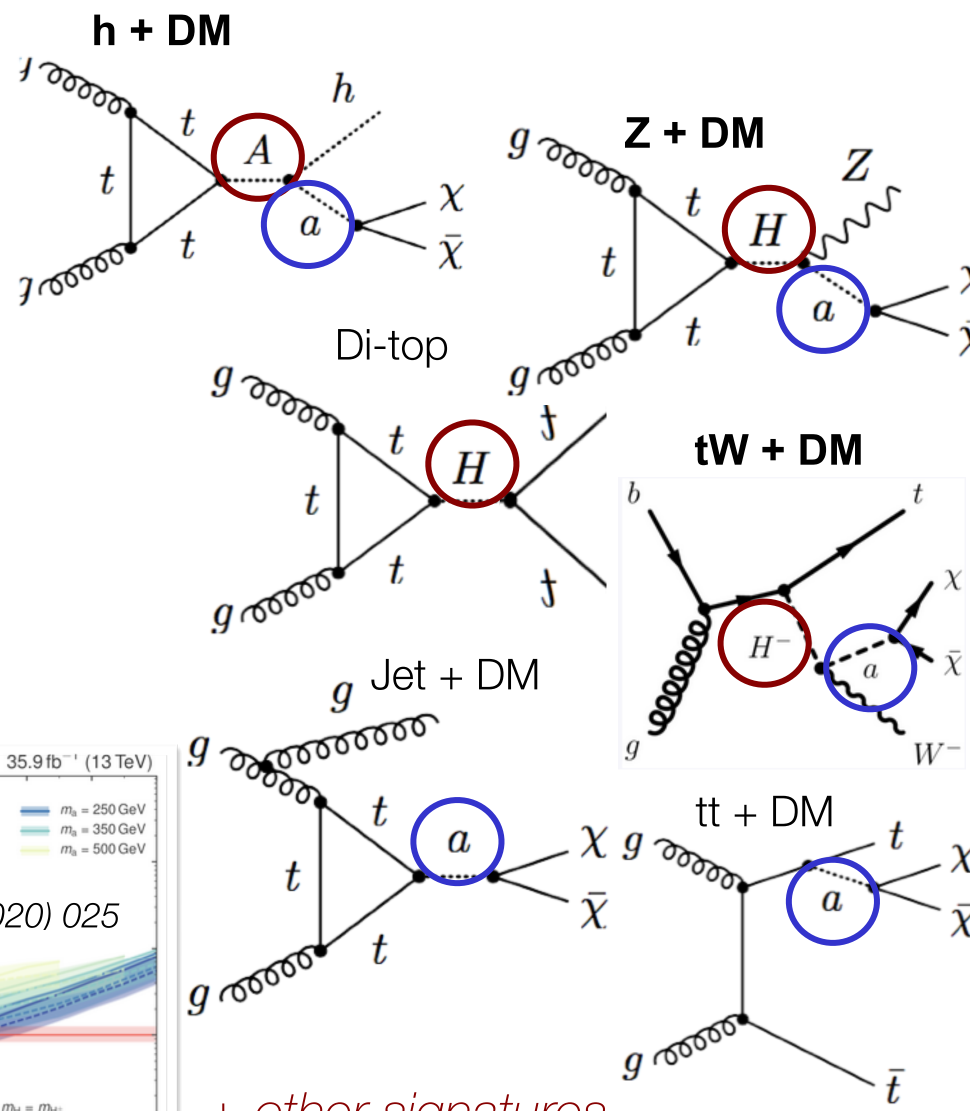








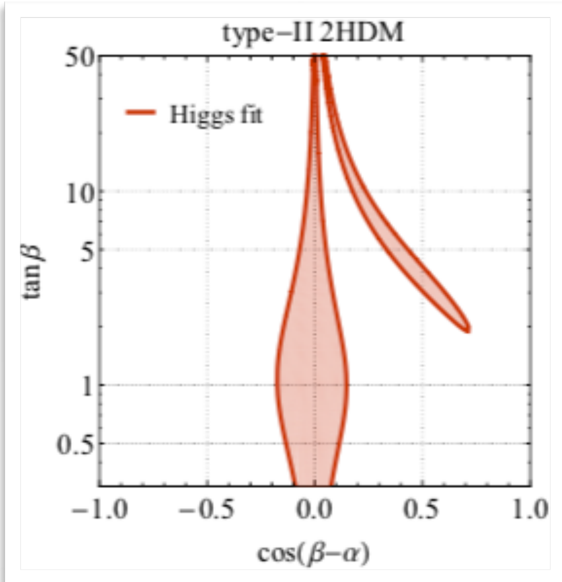
+ *other signatures*

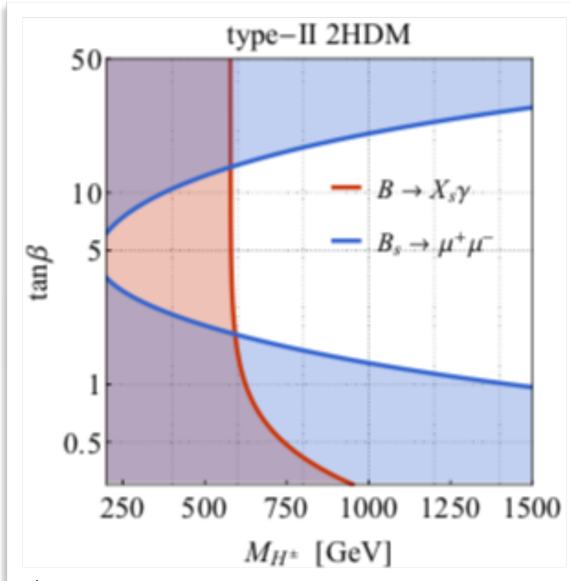
CERN-LPCC-2018-02

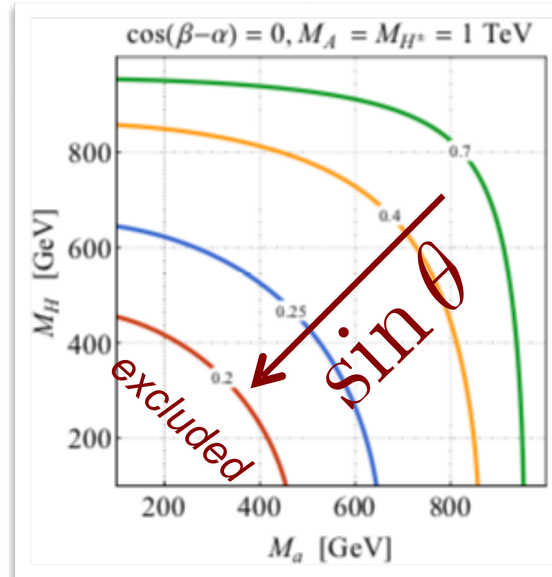
LHC Dark Matter Working Group: Next-generation spin-0 dark matter models

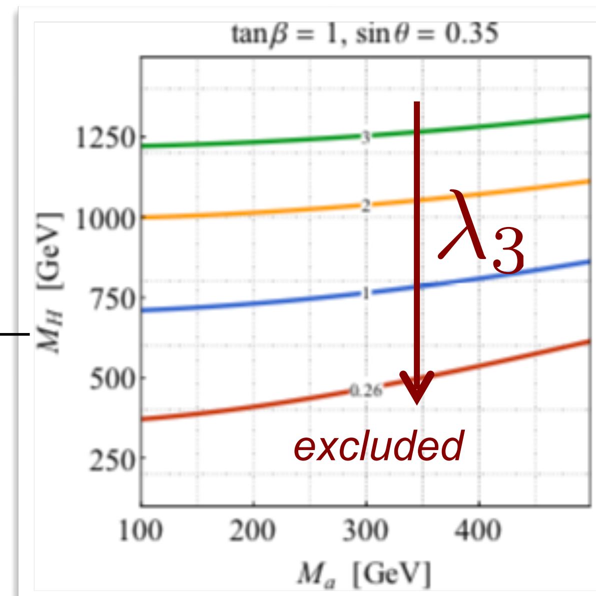
arXiv:1810.09420v2 [hep-ex]

Abstract. Dark matter (DM) simplified models are by now commonly used by the ATLAS and CMS Collaborations to interpret searches for missing transverse energy (E_T^{miss}). The coherent use of these models sharpened the LHC DM search program, especially in the presentation of its results and their comparison to DM direct-detection (DD) and indirect-detection (ID) experiments. However, the community has been aware of the limitations of the DM simplified models, in particular the lack of theoretical consistency of some of them and their restricted phenomenology leading to the relevance of only a small subset of E_T^{miss} signatures. This document from the LHC Dark Matter Working Group identifies an example of a next-generation DM model, called 2HDM+a, that provides the simplest theoretically consistent extension of the DM pseudoscalar simplified model. A comprehensive study of the phenomenology of the 2HDM+a model is presented, including a discussion of the rich and intricate pattern of mono-X signatures and the relevance of other DM as well as non-DM experiments. Based on our discussions, a set of recommended scans are proposed to explore the parameter space of the 2HDM+a model through LHC searches. The exclusion limits obtained from the proposed scans can be consistently compared to the constraints on the 2HDM+a model that derive from DD, ID and the DM relic density.









$$M_H = M_A = M_{H^\pm}\,, \quad m_\chi = 10\,\text{GeV}\,,$$

$$\cos(\beta-\alpha) = 0\,, \quad \tan\beta = 1\,, \quad \sin\theta = 0.35\,,$$

$$y_\chi = 1\,, \quad \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3\,.$$

Convenience

Resonant enhancement

- ~~Executive~~ Experimental summary on model pheno:
  - 14 parameters to start with
    - 7 parameters fixed:
      - symmetry, EW-precision measurements, Higgs properties,...
    - 7 "free" parameters:

More details in talk by Johanna Gramling
https://indico.cern.ch/event/665524/sessions/260090/

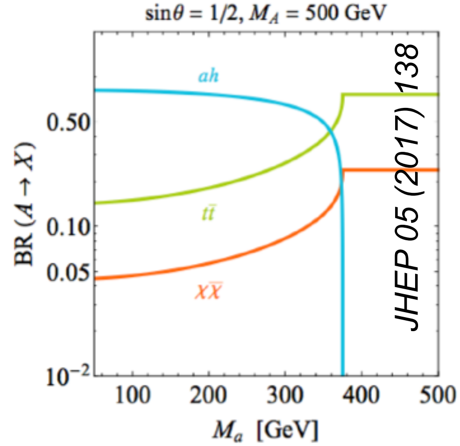
- **4 affect MET shape:**
  - m_a
  - m_A
  - m_H
  - $\sin(\theta)$ ← *couplings*

  (m_a, m_A, m_H: *kinematics & channels*)

- **3 only affect total cross-section:**
  - $\tan(\beta)$ [1]
  - m_χ [2]
  - y_χ ← *Yukawa*

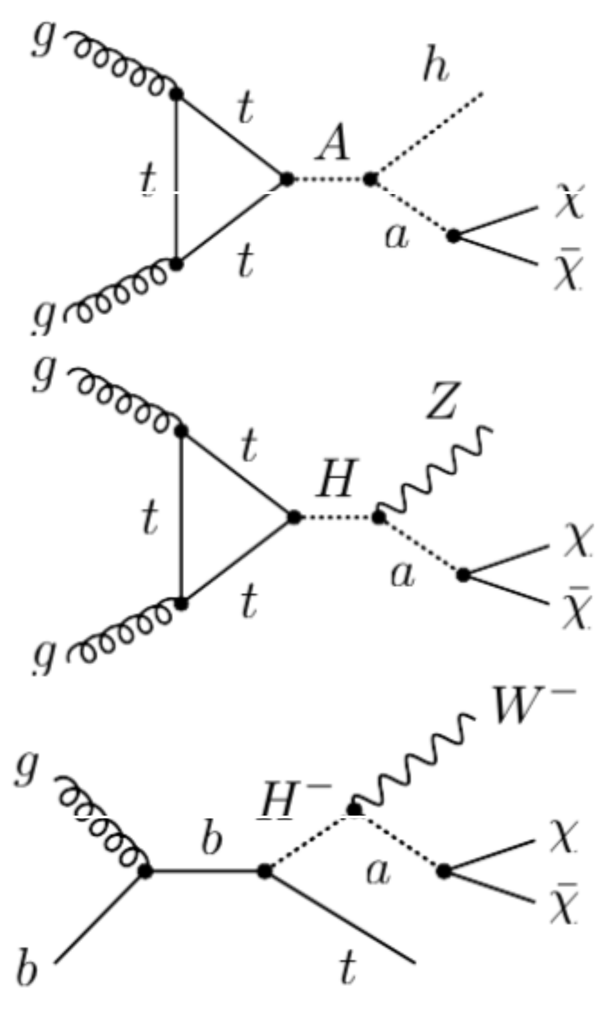
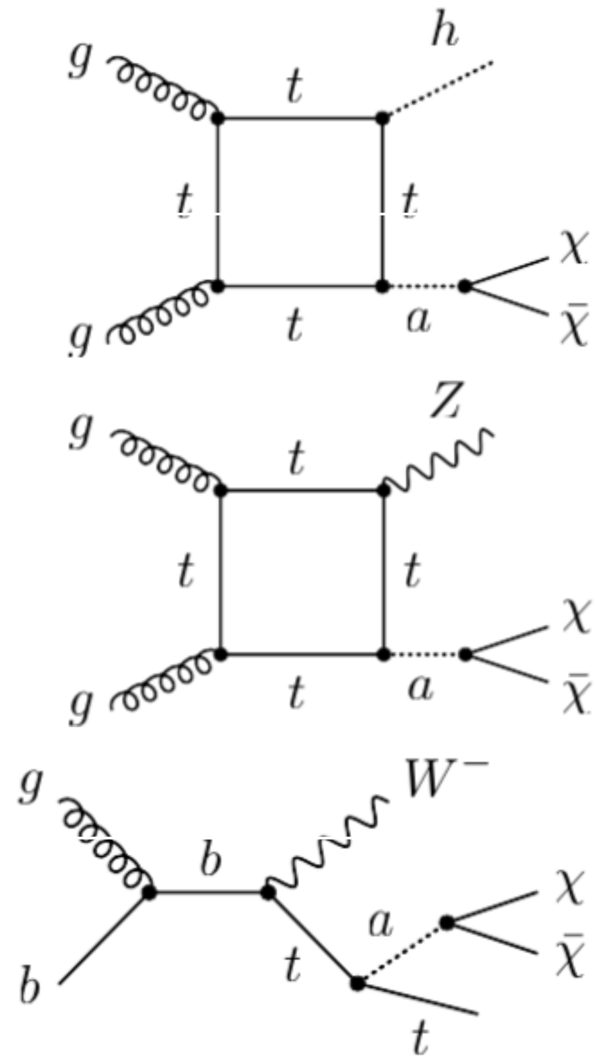
- A/a mixing angle $\sin\theta$ important, e.g.:

$$\Gamma(A \to \chi\chi) \propto \sin^2\theta \qquad \Gamma(a \to \chi\chi) \propto \cos^2\theta$$
$$\Gamma(A \to ff) \propto \cos^2\theta \qquad \Gamma(a \to ff) \propto \sin^2\theta$$
$$\Gamma(A \to ah) \propto \sin\theta\cos\theta$$



JHEP 05 (2017) 138

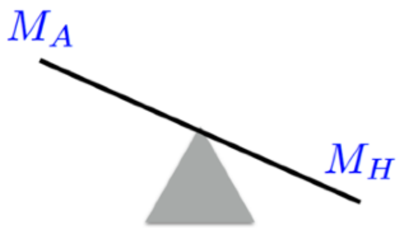
[1] can change shapes if u/d-type couplings process-relevant
[2] statement true if decay mediator on-shell

Resonant	Non-Resonant
	

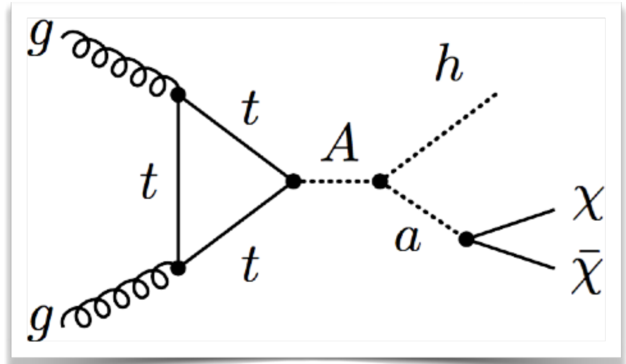
+ many other signatures

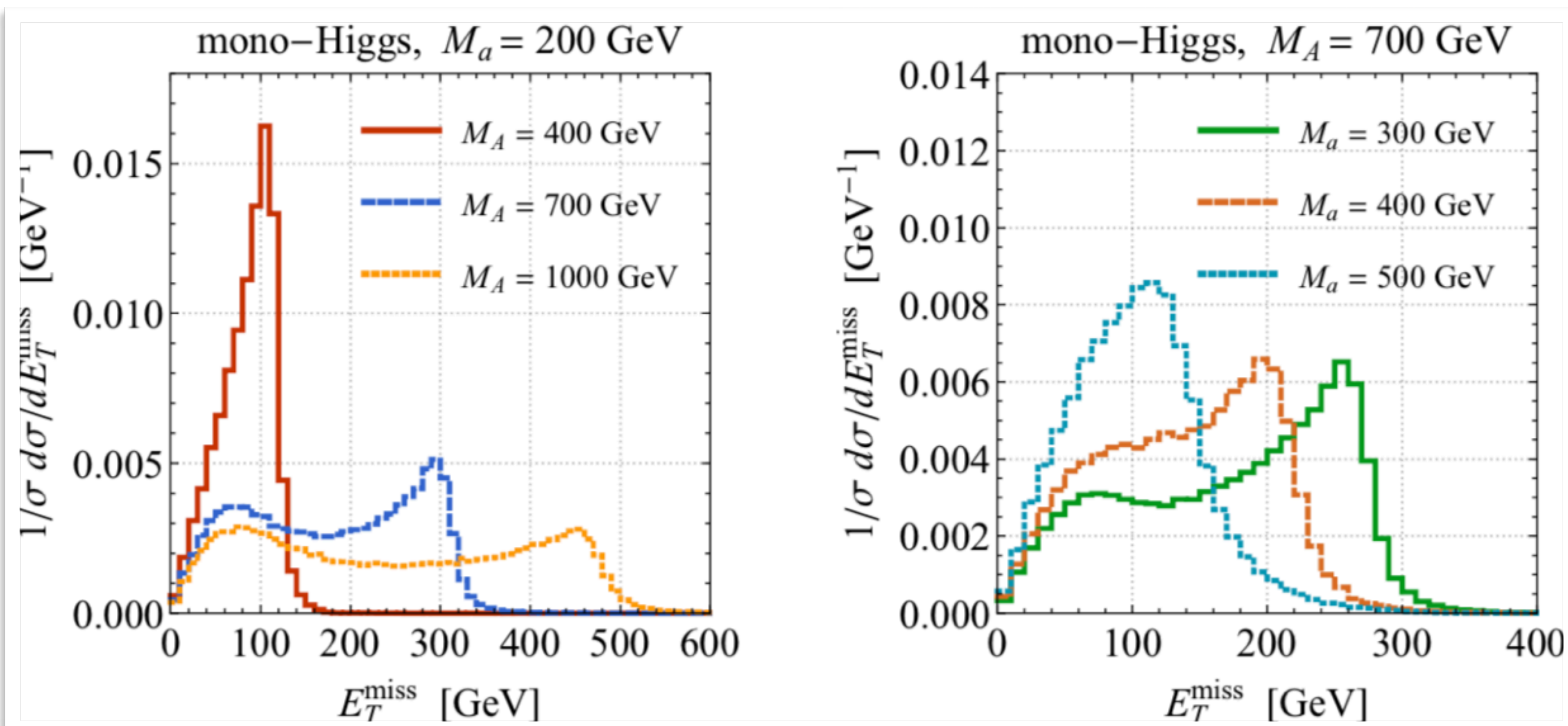
2HDM+*a*: *h* + DM

- Can be resonantly enhanced
    - → driving sensitivity for 2HDM+a
- h+MET dominant over Z+MET if $M_H > M_A$



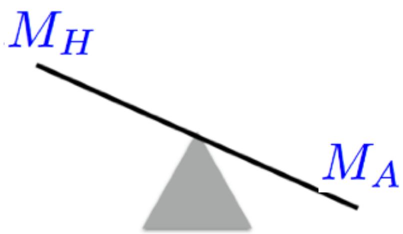
$$\Rightarrow M_H = M_{H^\pm} = M_A$$



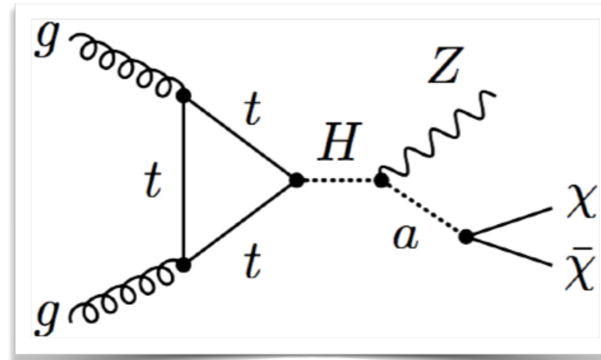


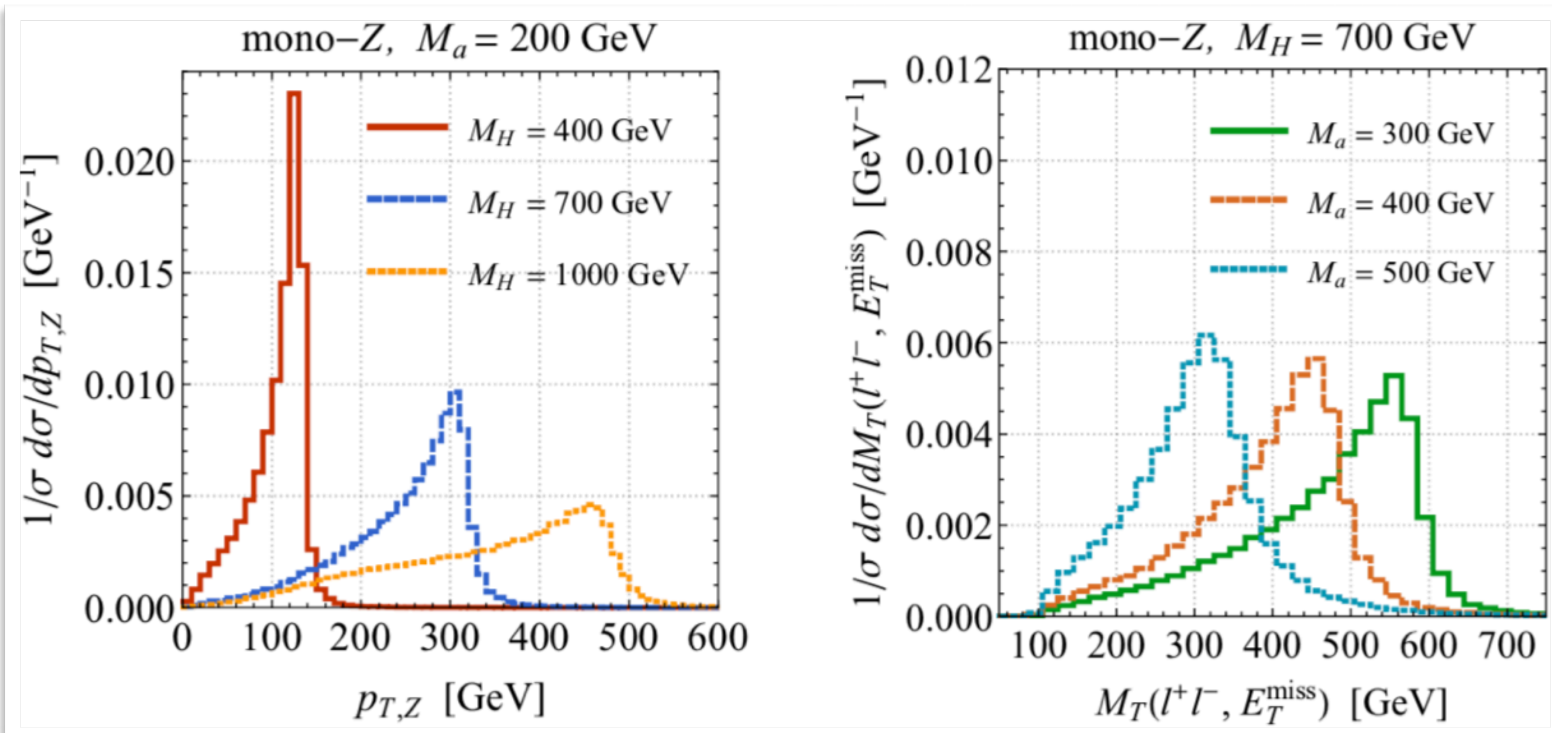
2HDM+a: Z + DM

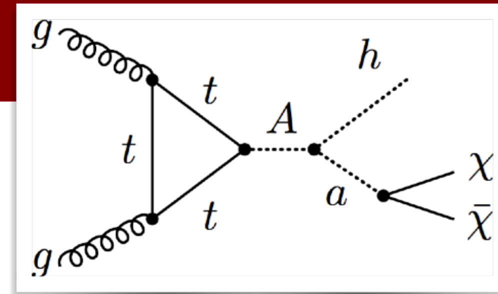
- Can be resonantly enhanced
  - → driving sensitivity for 2HDM+a
- Z+MET dominant over h+MET if $M_A > M_H$



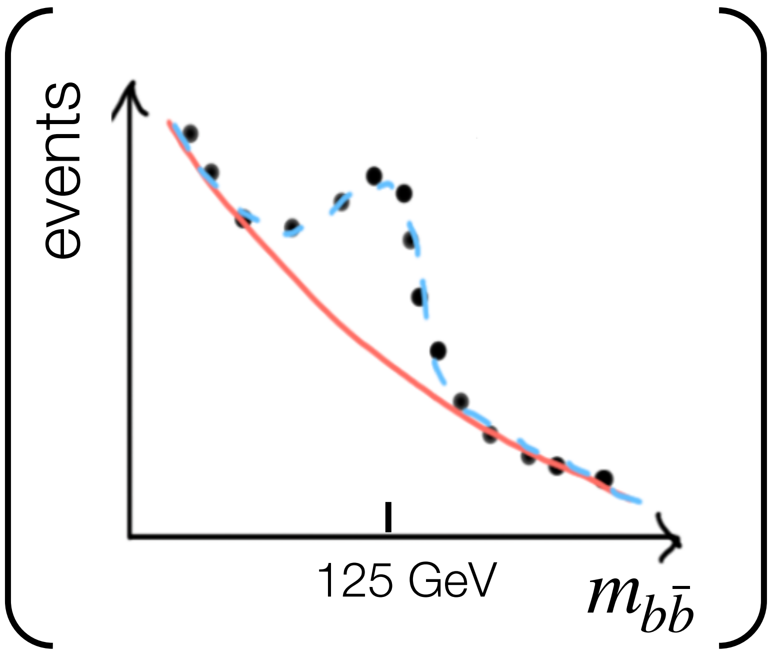
$$\Rightarrow M_H = M_{H^\pm} = M_A$$

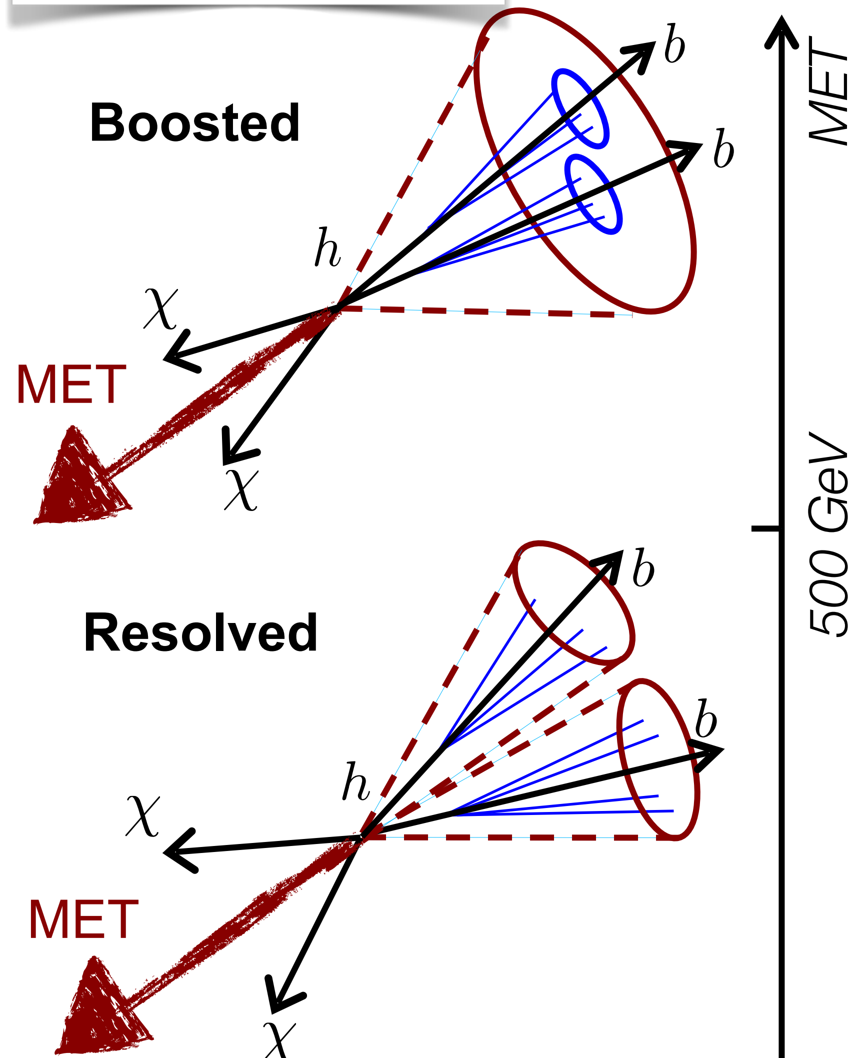






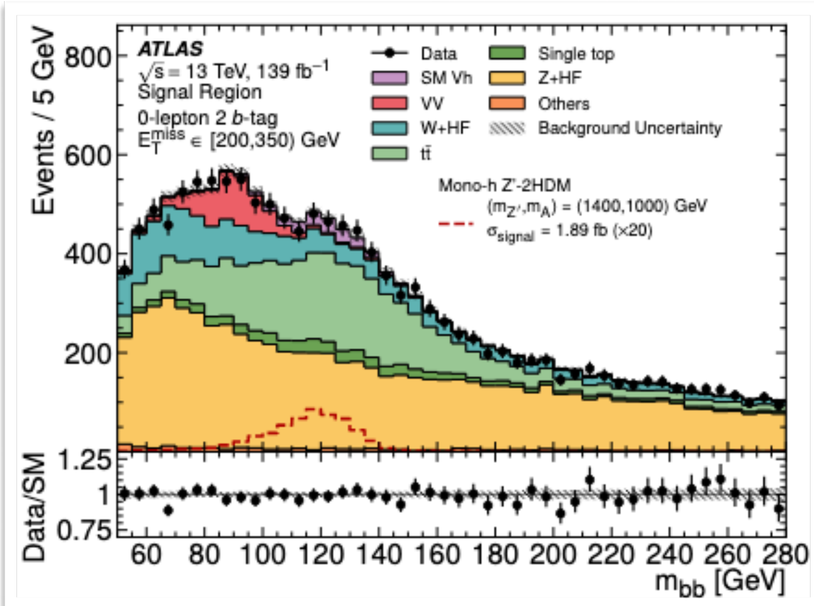
- **Analysis strategy:**
  - MET > 150 GeV from DM particles
  - 2 or 3+ b-tagged jets
  - Higgs → $b\bar{b}$ candidate decay
  - Constrain W,Z+HF with 1μ,2ℓ CRs
  - Look for localised excess in $m_{b\bar{b}}$

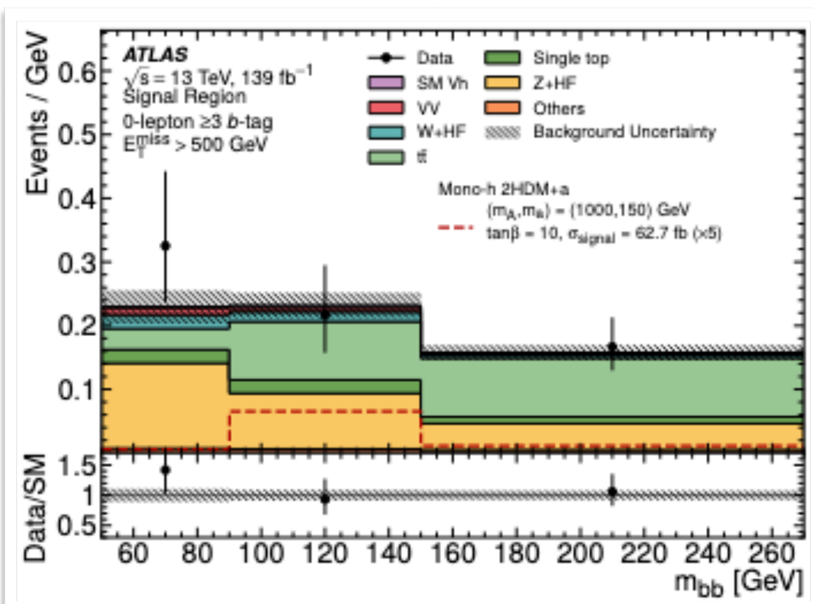


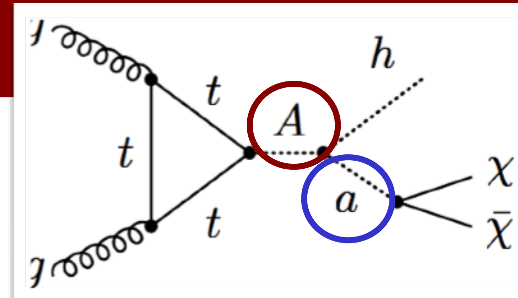


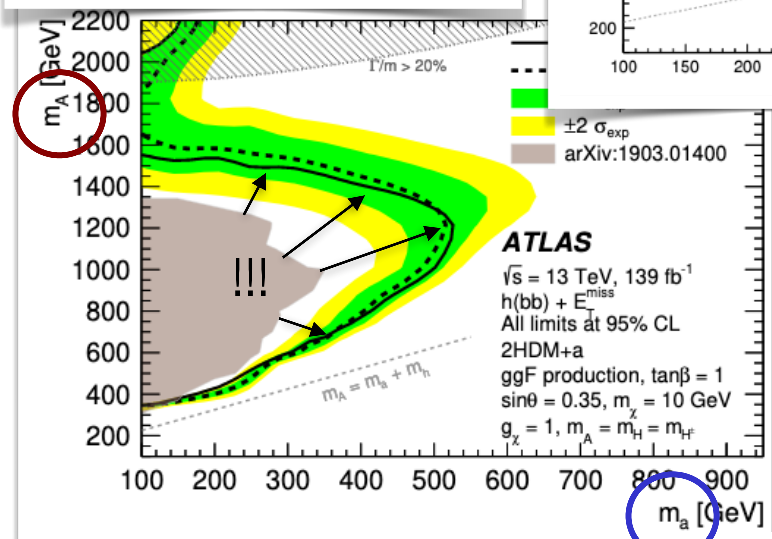
JHEP 11 (2021) 209

2HDM+a: Higgs($b\bar{b}$)+DM

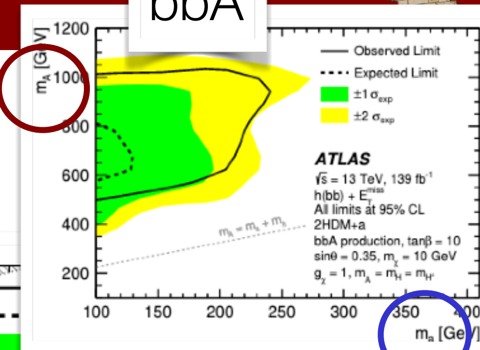




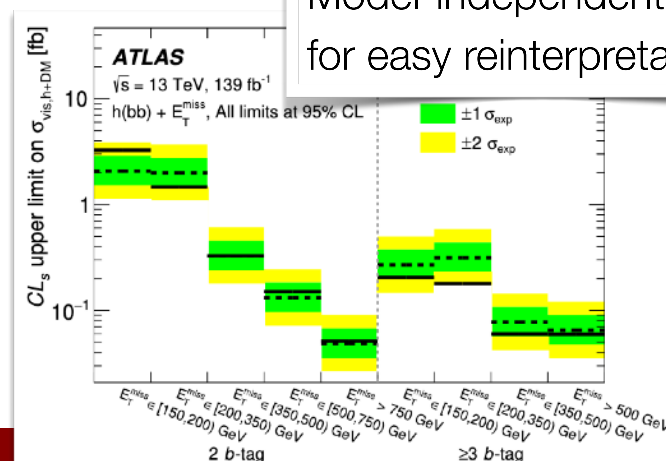




bbA



Model-independent limits for easy reinterpretation!



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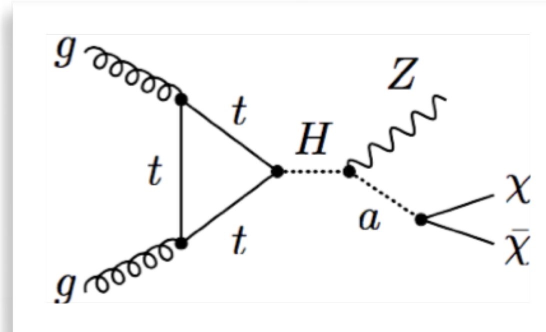
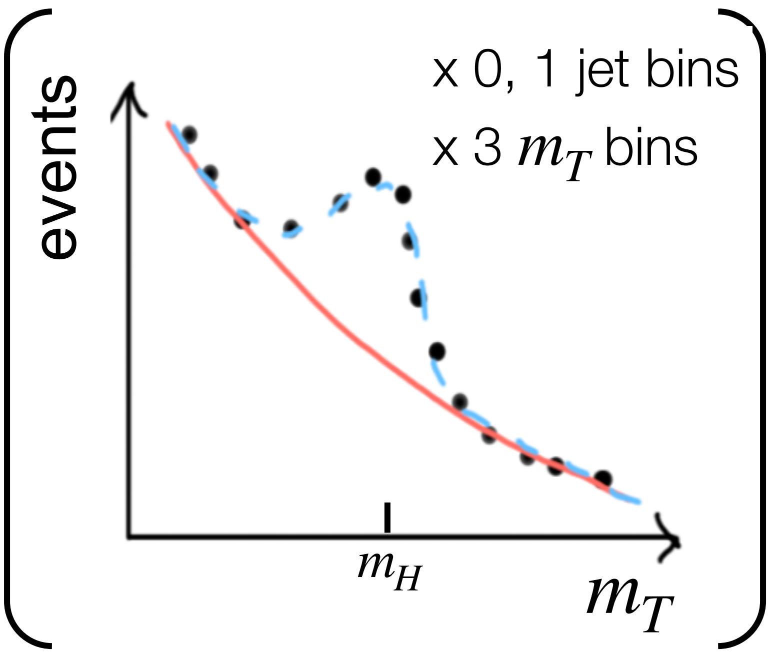
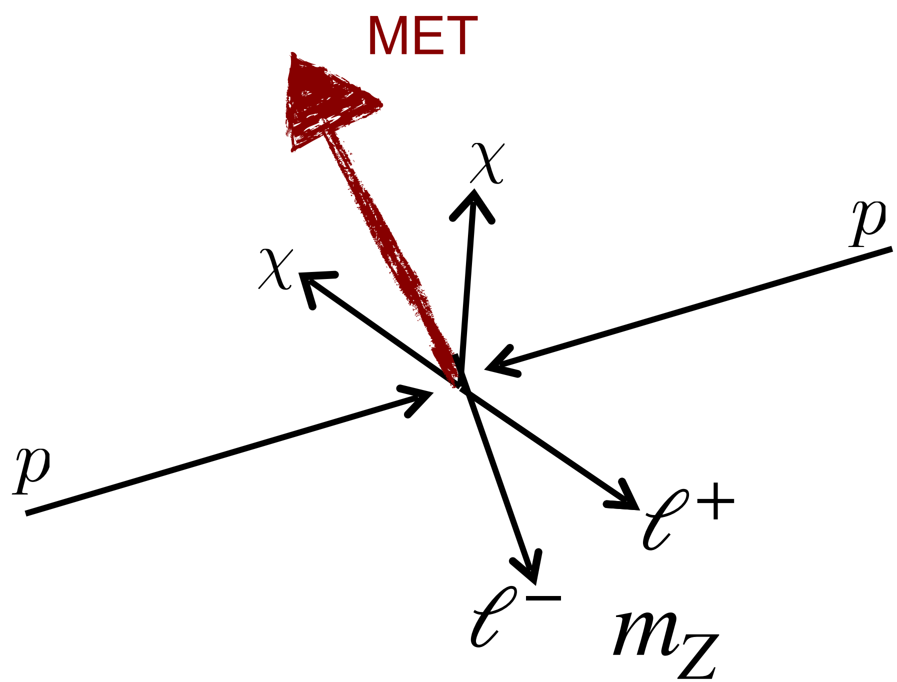
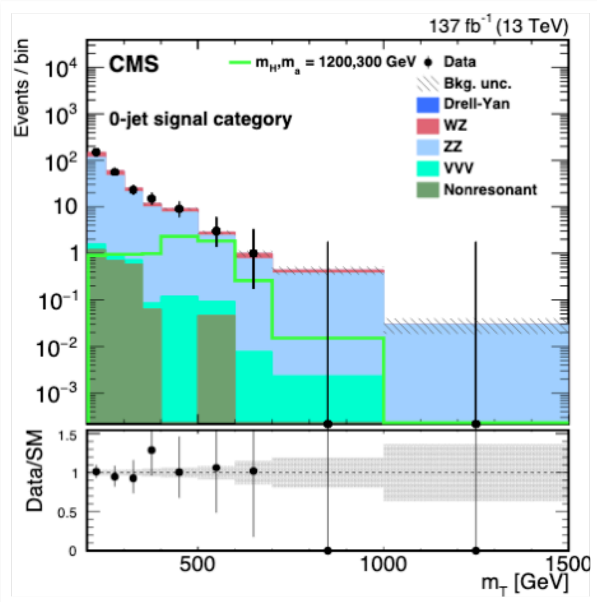
- **Analysis strategy:**
  - Significant MET from DM particles
  - $Z \to \ell\ell$ candidate decay
  - $\leq$1 extra jet, $|p_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\ell\ell}|/p_{\mathrm{T}}^{\ell\ell} < 0.4$
  - Constrain WZ, ZZ with $3\ell, 4\ell$ CRs
  - Look for excess in m_T distribution:

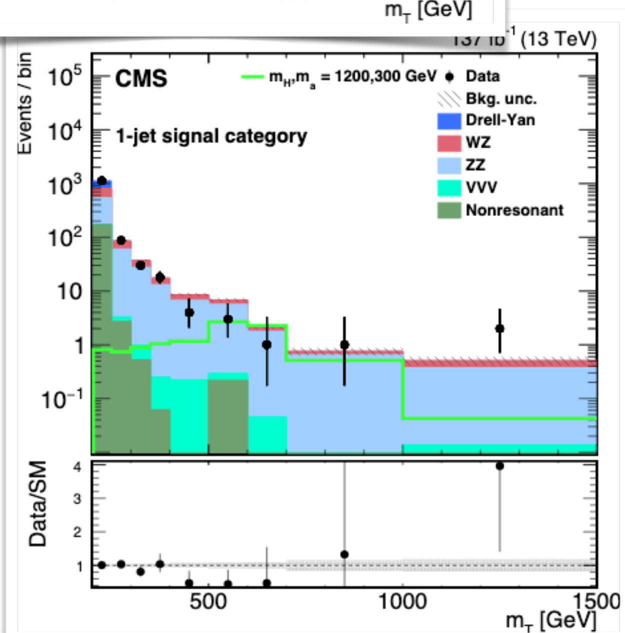


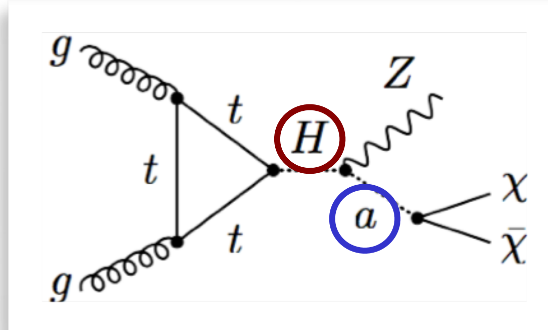




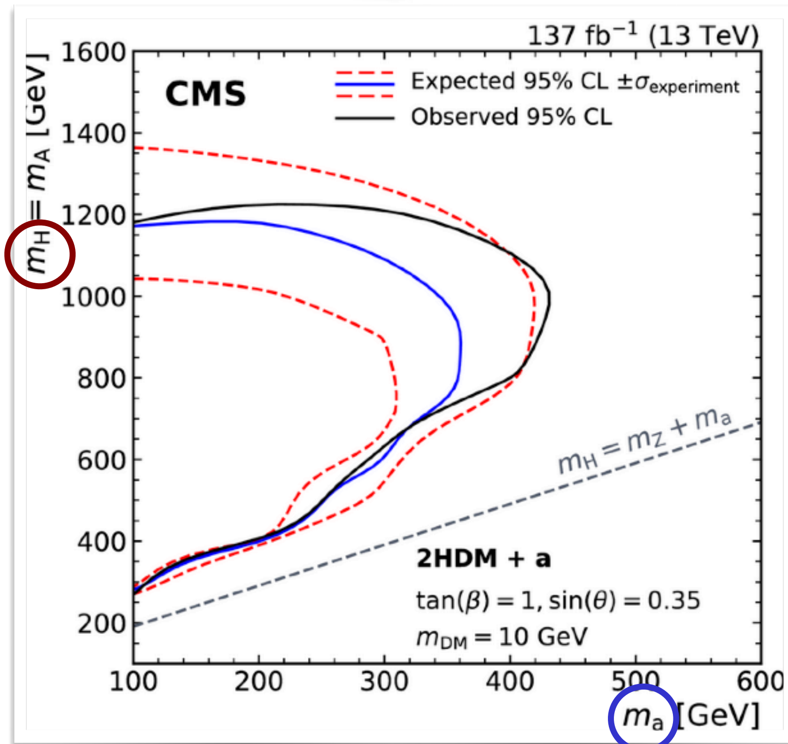
EPJC 81 (2021) 13







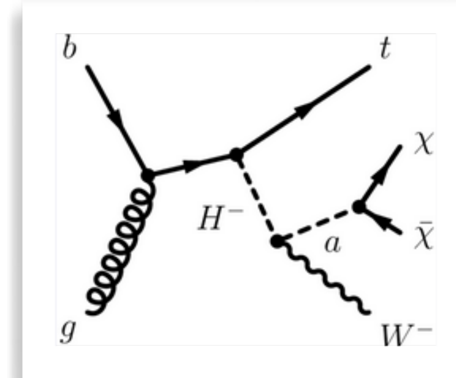
Significant improvement w/r/t 36/fb results!



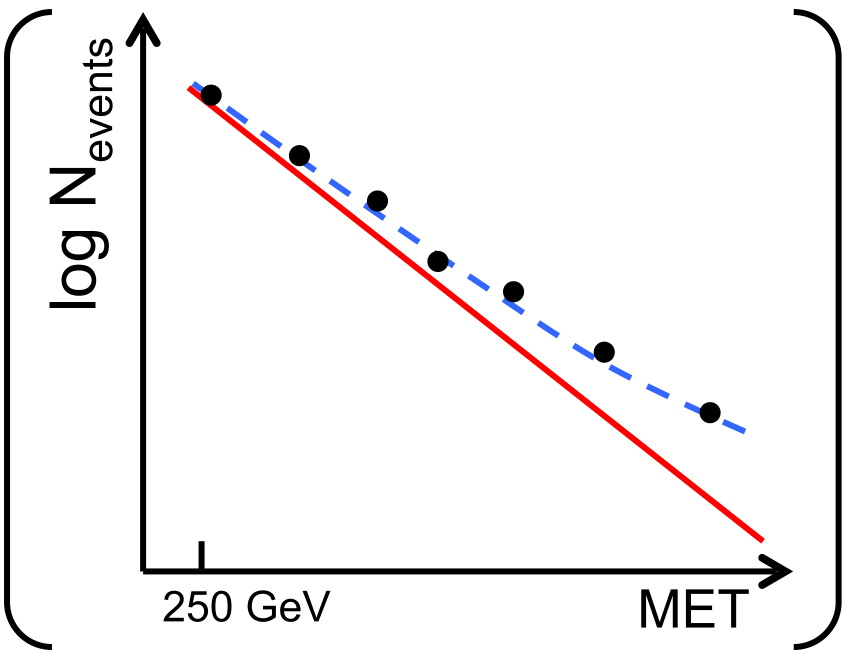
EPJC 81 (2021) 13

2HDM+a: tW + DM

- **Analysis strategy:**
  - Large MET (>250 GeV) from DM particles
  - t candidate, W candidate from $H^{\pm} \to Wa$
  - 1,2 leptons for tW+DM, 1 lepton for tq+DM
  - ≥ 1 b-tagged jet
  - Constrain tt+V with CRs
  - Look for excesses in MET + other distributions:



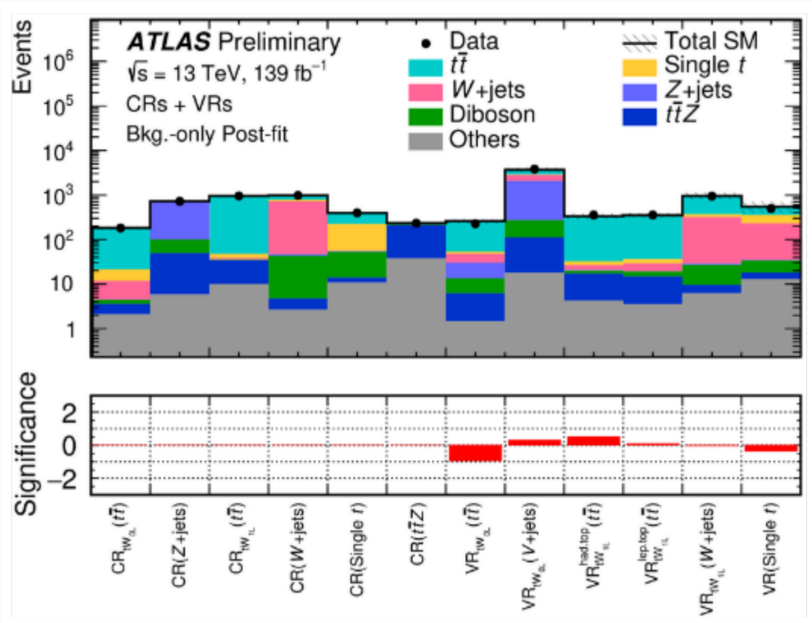
$\sin(\theta) = 1/\sqrt{2}$ enhances resonant $H^{\pm}$

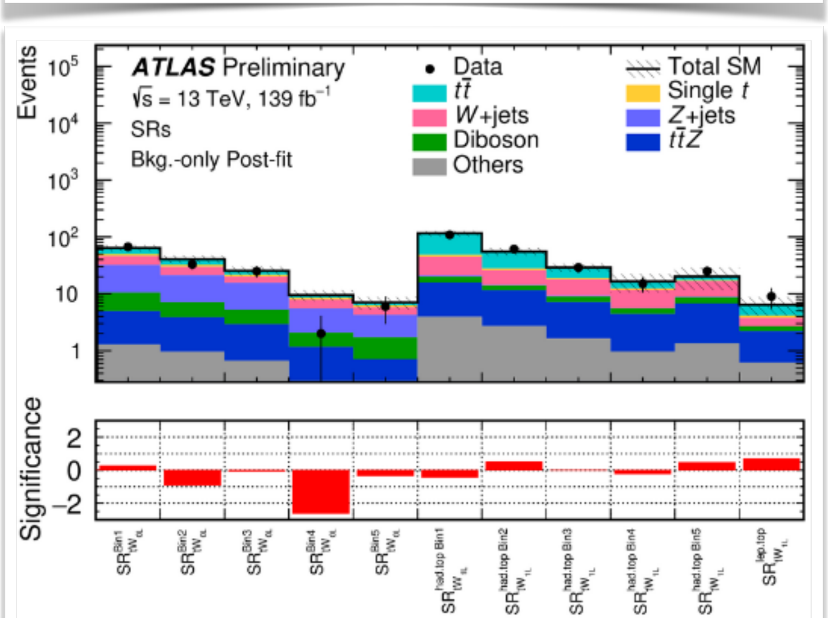


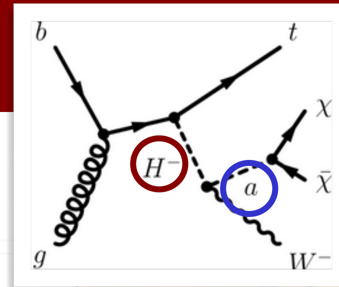
First-time experimental search for this process!

ATLAS-CONF-2022-012, ATLAS-CONF-2020-034

2HDM+a: tW + DM







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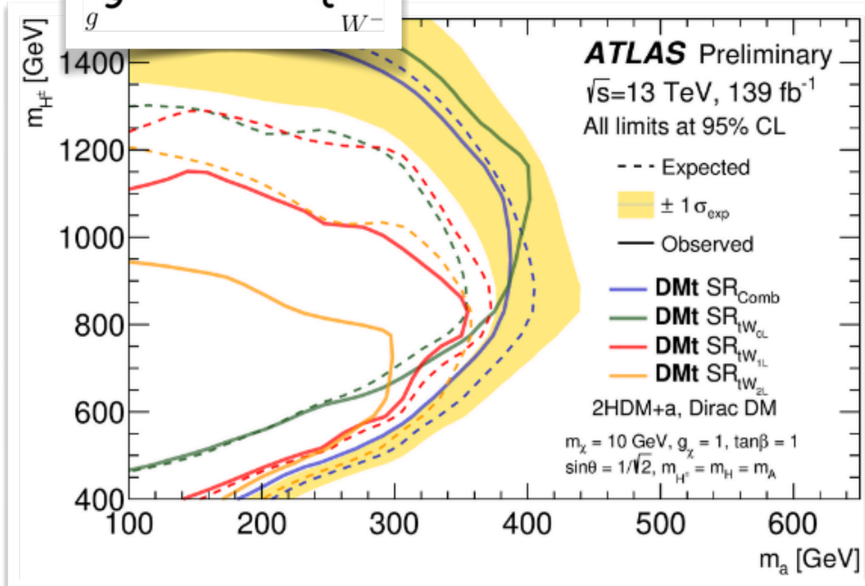
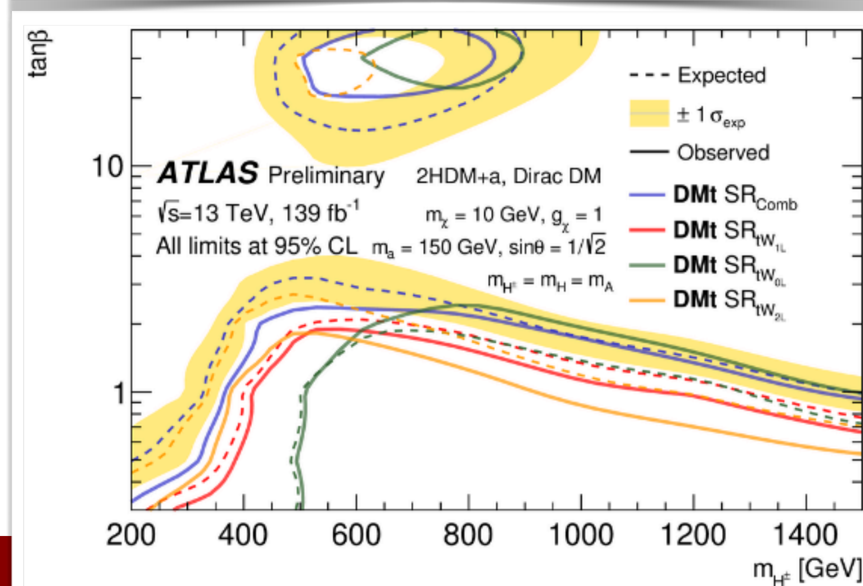
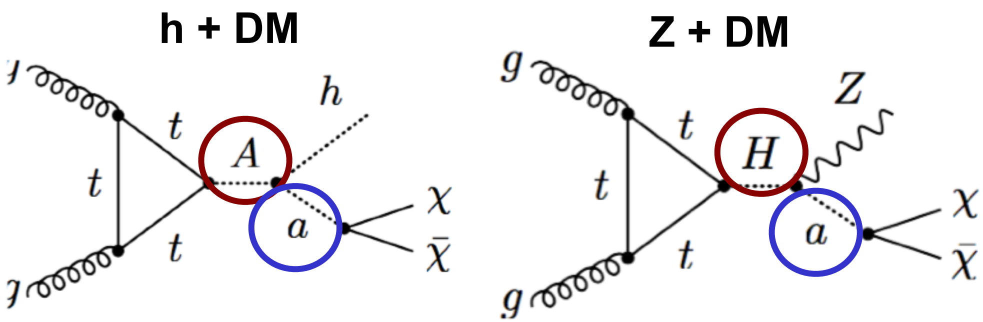
enhances resonant $H^{\pm}$

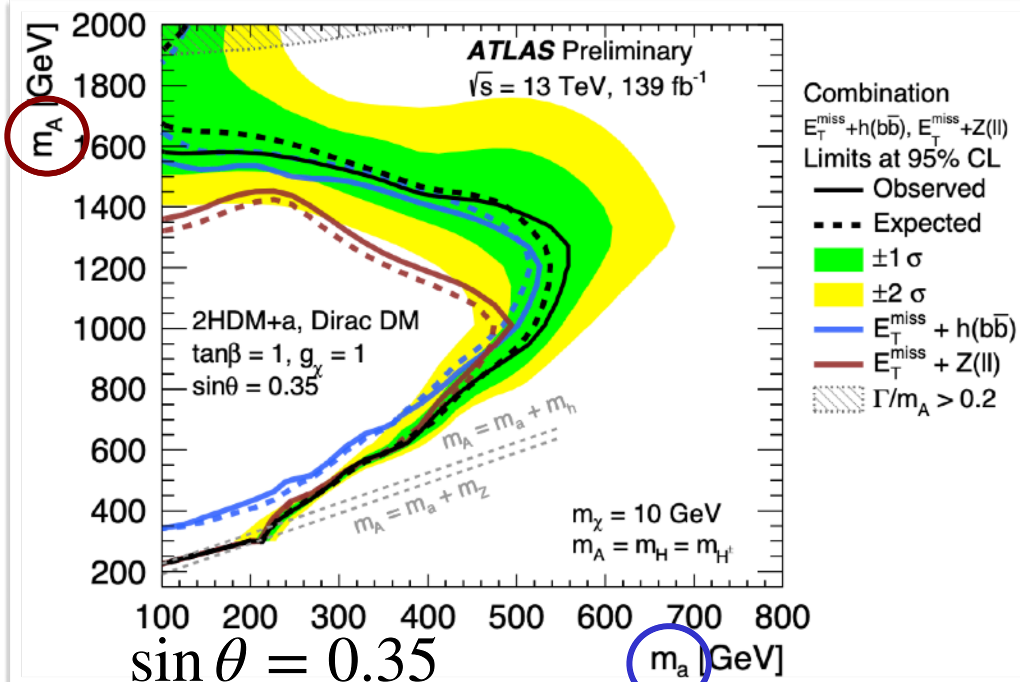




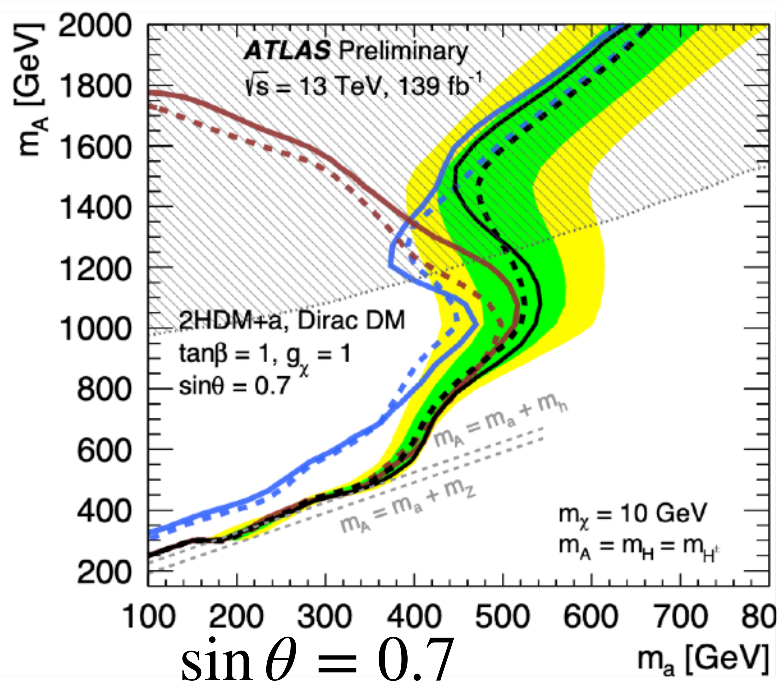
ATLAS-CONF-2022-012

ATLAS-CONF-2021-036





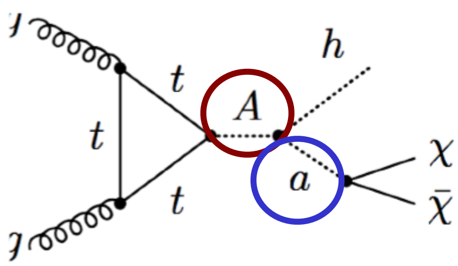
$\sin\theta = 0.35$

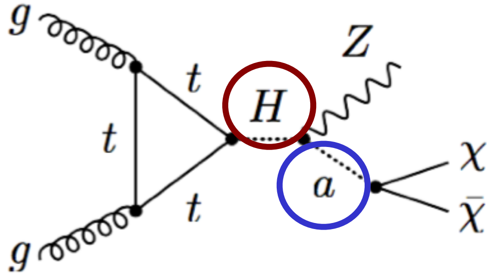


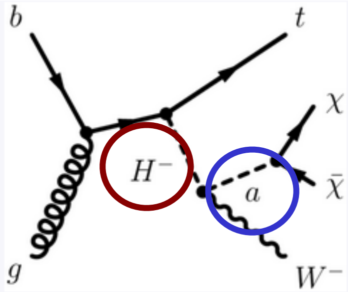
$\sin\theta = 0.7$

ATLAS-CONF-2021-036, ATL-PHYS-PUB-2022-036

h + DM **Z + DM** **tW + DM**

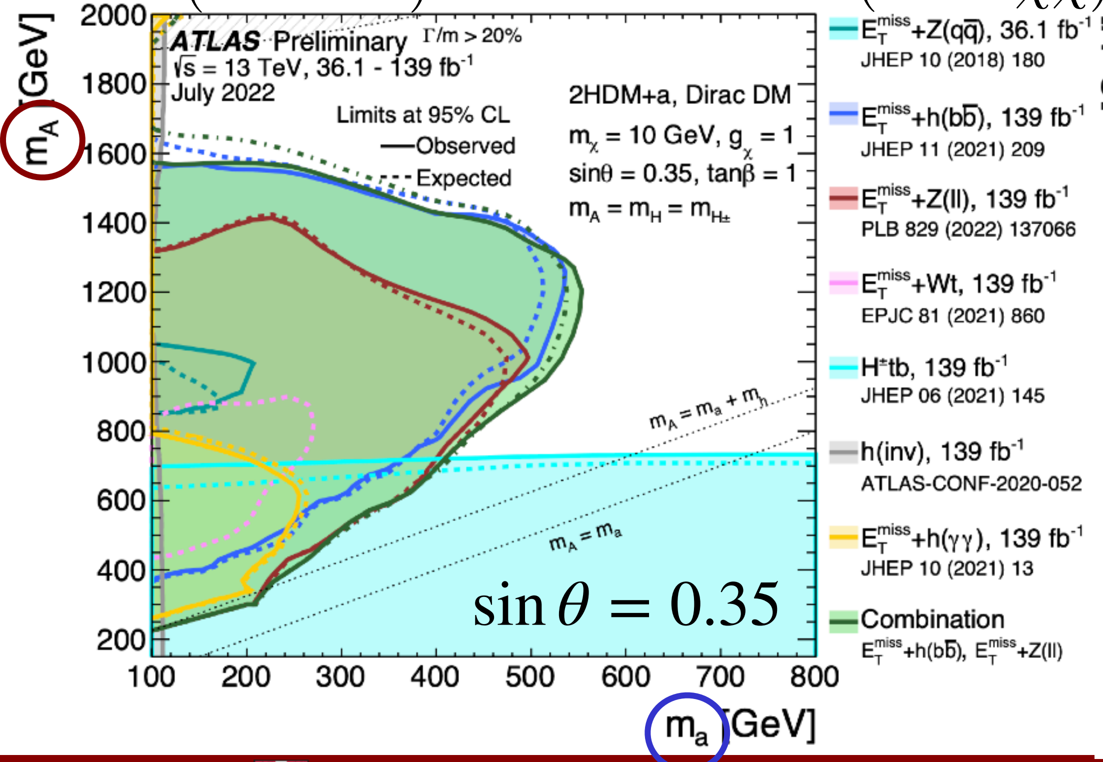


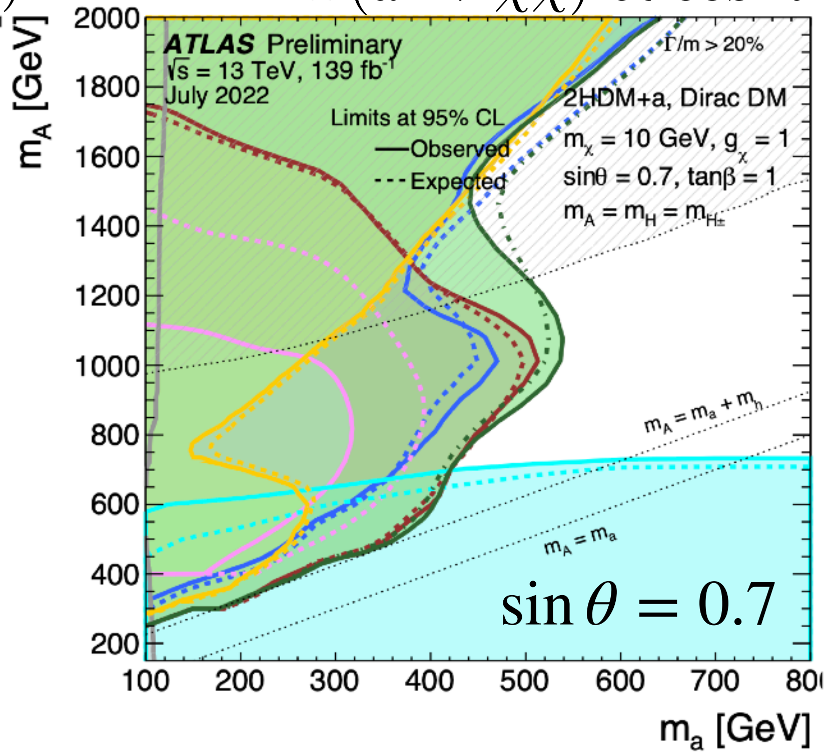




...

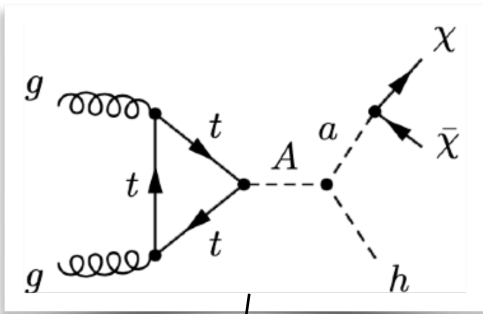
$$\Gamma(A \to ah) \propto \sin\theta\cos\theta \qquad \Gamma(A \to \chi\chi) \propto \sin^2\theta \qquad \Gamma(a \to \chi\chi) \propto \cos^2\theta$$

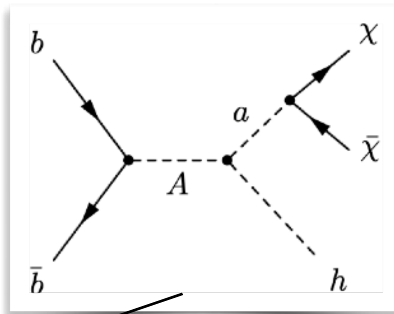


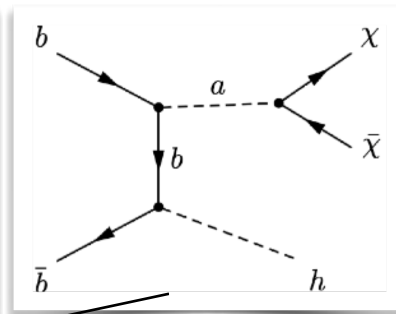


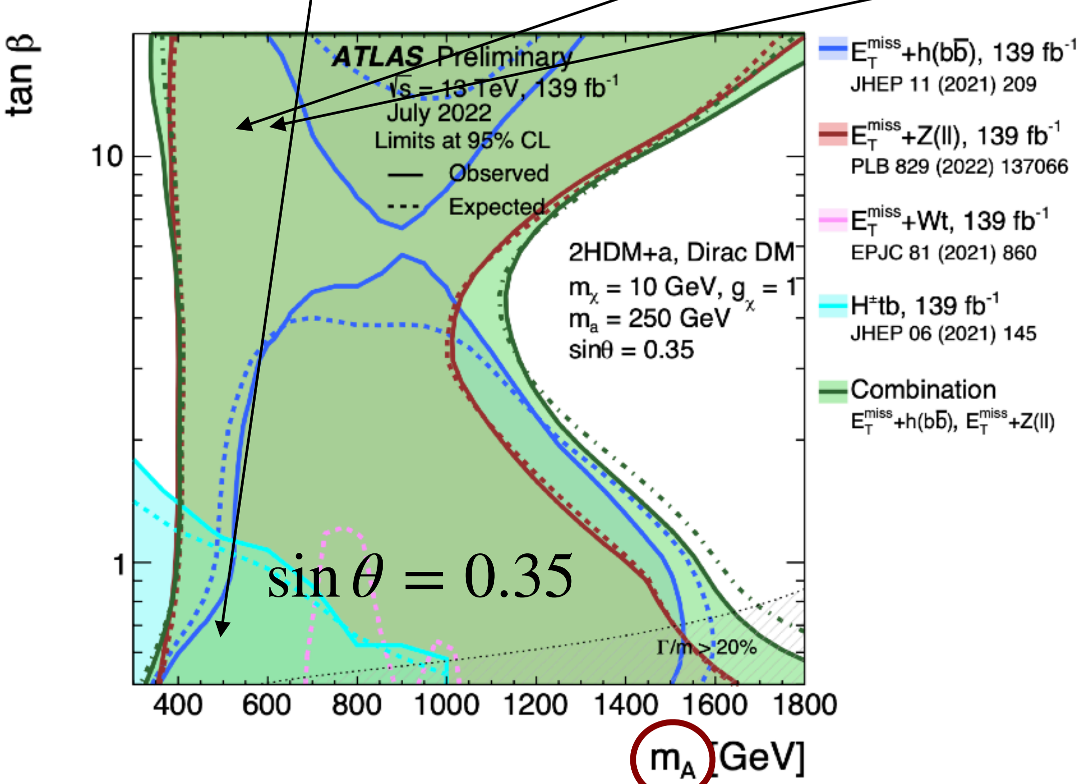
2HDM+a: SENSITIVITY IN ALL CHANNELS

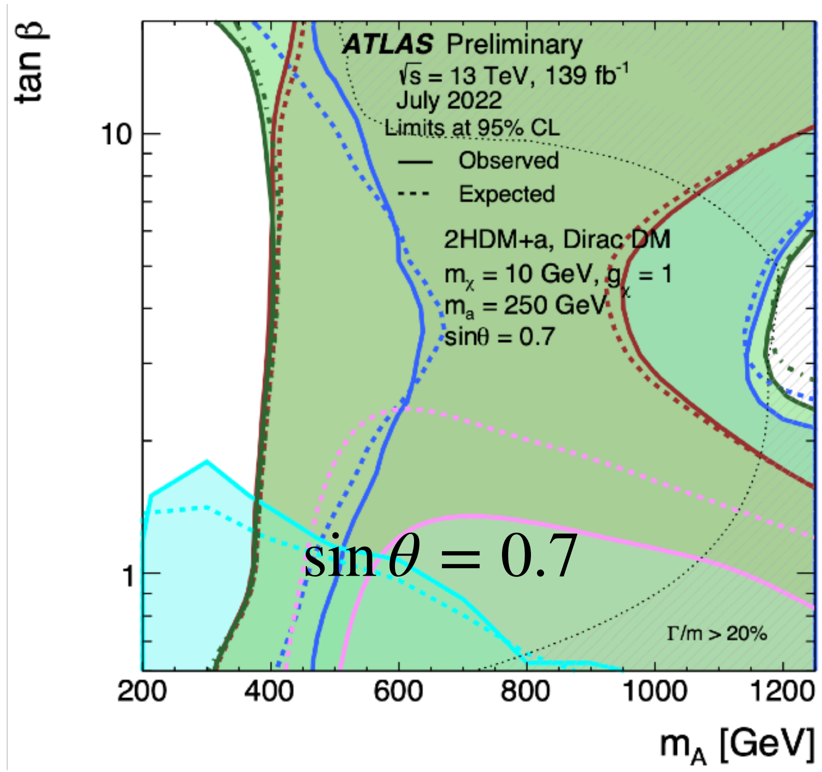
ATLAS-CONF-2021-036, ATL-PHYS-PUB-2022-036







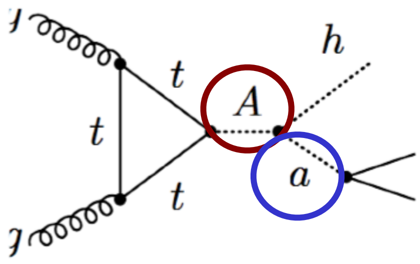




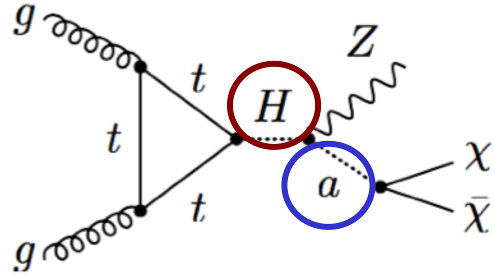
2HDM+a: SENSITIVITY IN ALL CHANNELS

ATLAS-CONF-2021-036, ATL-PHYS-PUB-2022-036

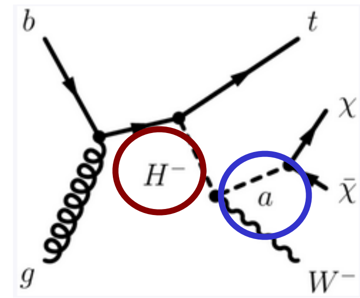
h + DM



Z + DM

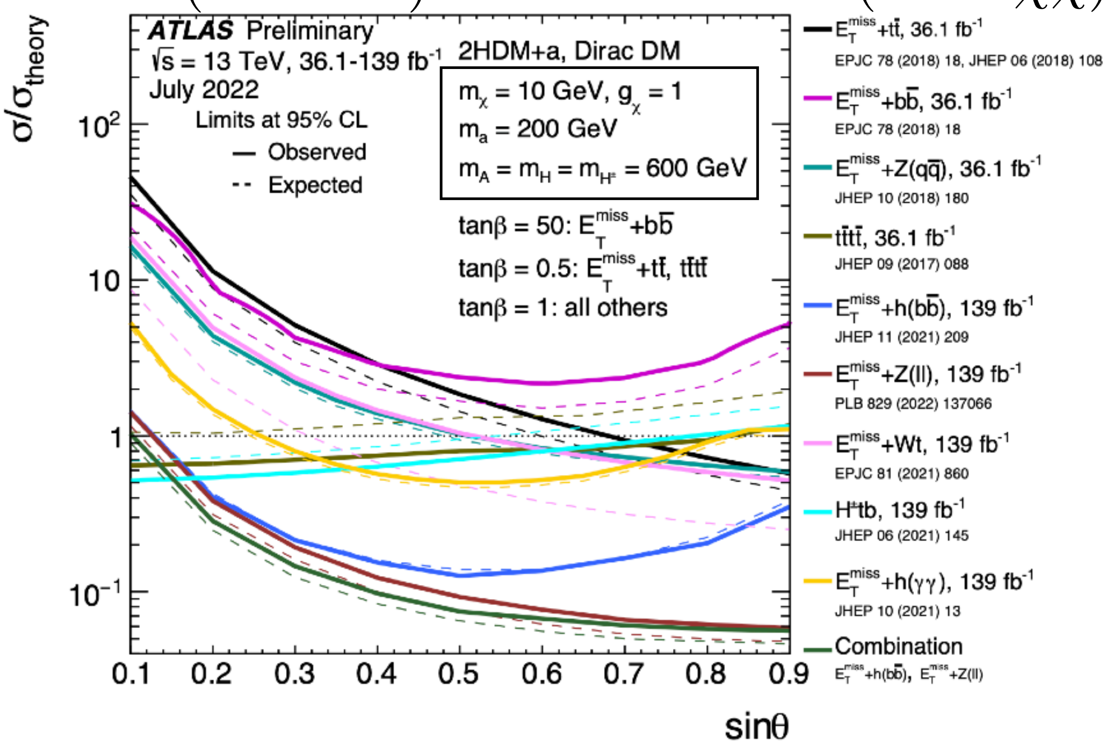


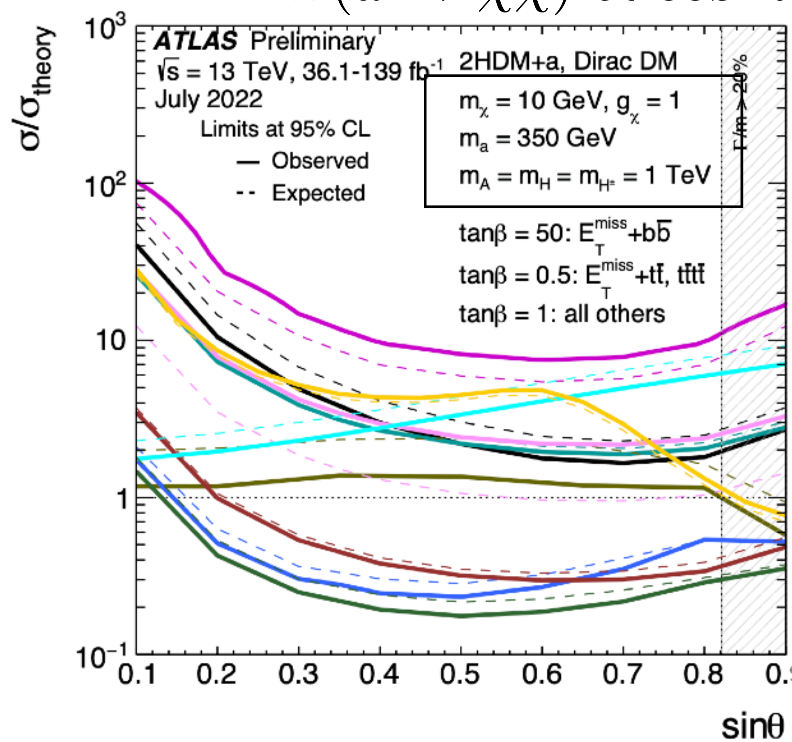
tW + DM



. . .

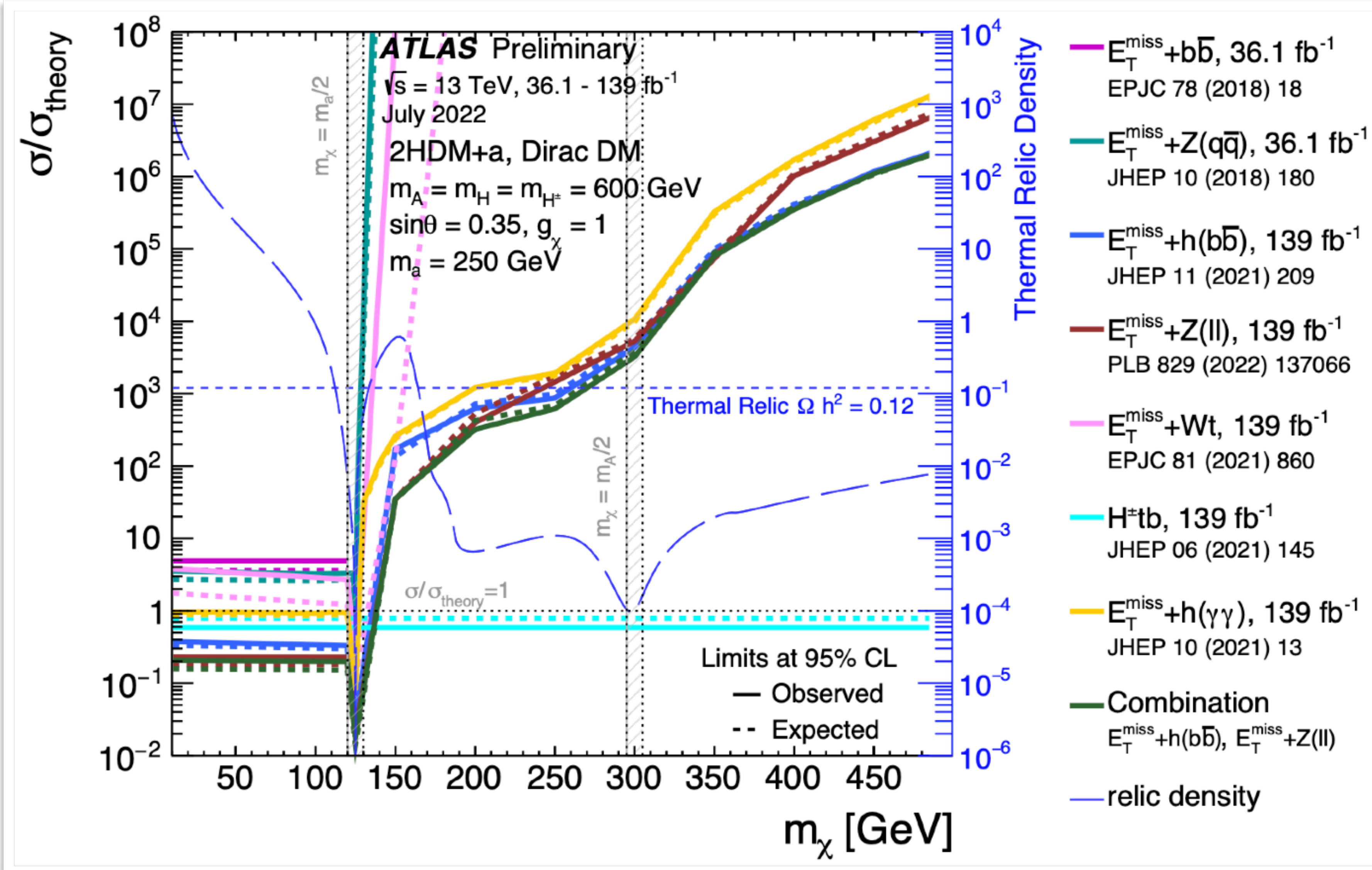
$\Gamma(A \to ah) \propto \sin\theta\cos\theta$ $\Gamma(A \to \chi\chi) \propto \sin^2\theta$ $\Gamma(a \to \chi\chi) \propto \cos^2\theta$



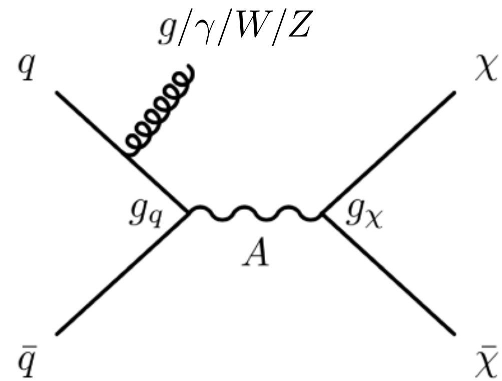


2HDM+a: SENSITIVITY IN ALL CHANNELS

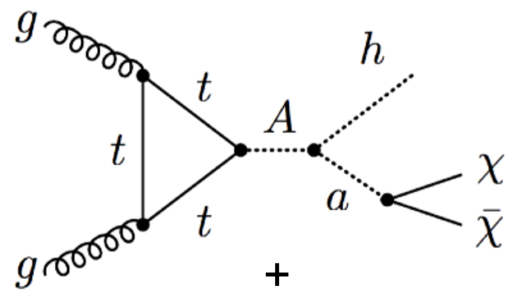
ATLAS-CONF-2021-036, ATL-PHYS-PUB-2022-036



DMF recommendations
arXiv:1507.00966



Scalar mediator model
V/AV mediator model
arXiv:1507.00966



+
many other signatures

2HDM+a model
JHEP 05 (2017) 138
arXiv:1507.00966

Dark Higgs model
JHEP 04(2017)143

Supersymmetry

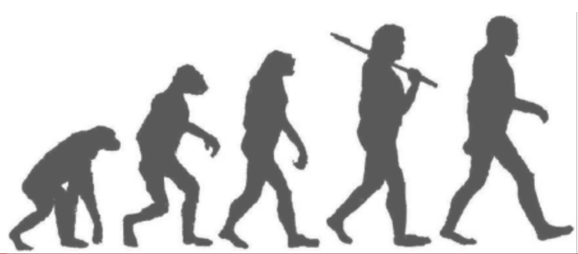
1) Effective field theory

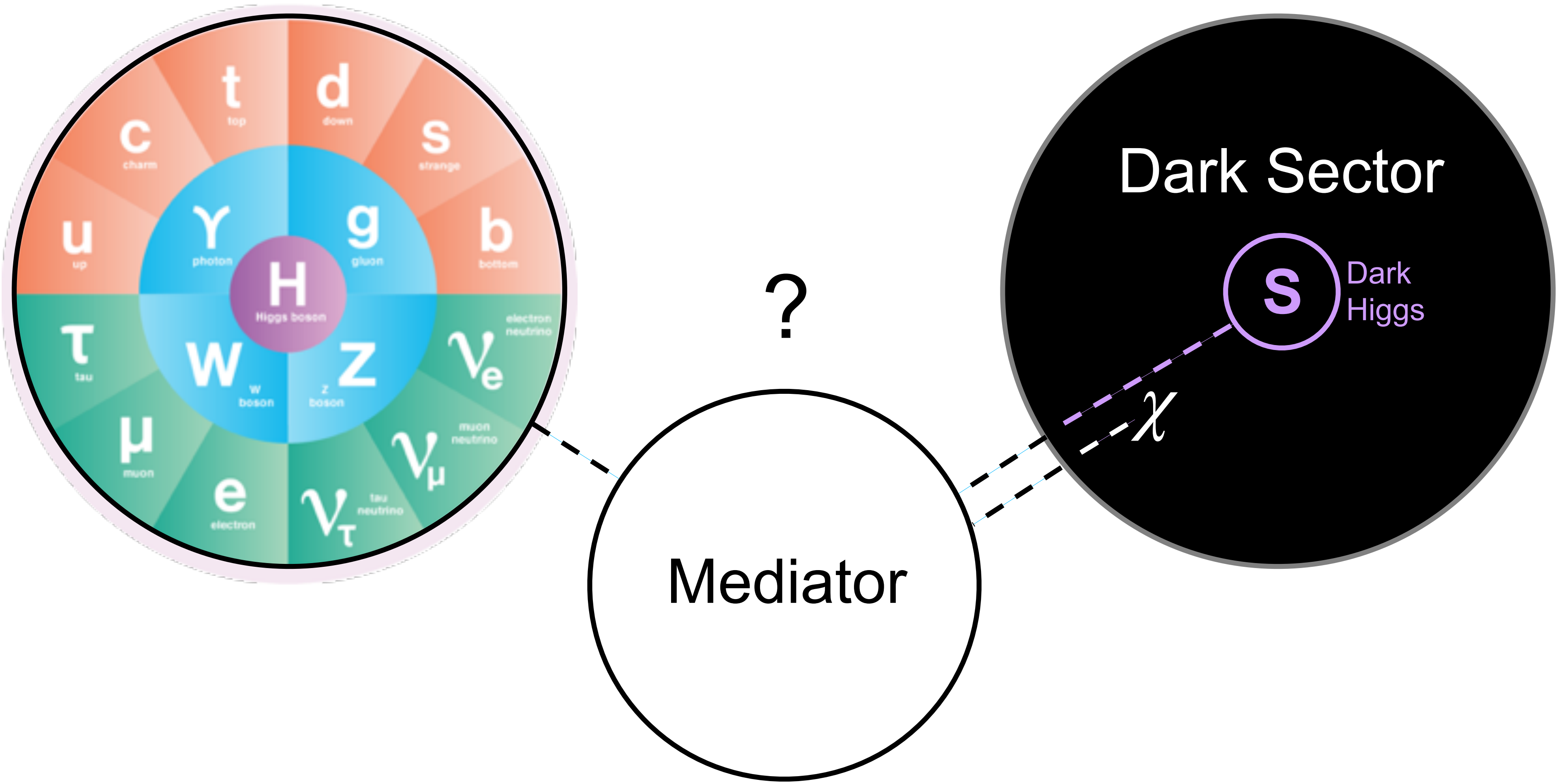
2) Simplified models

3) Simplified, consistent, & UV-complete models

4) complete models

Richer kinematics + phenomenology





Motivation: 1) Dark Higgs mechanism to give mass to DM particles χ

2) Mediator that couples to SM and to Dark Higgs (S) and χ

3) Generic signatures that are present in complete models

FOR FURTHER DETAILS…

Review

Collider Searches for Dark Matter through the Higgs Lens

Spyros Argyropoulos [1], **Oleg Brandt** [2,*] **and Ulrich Haisch** [3]

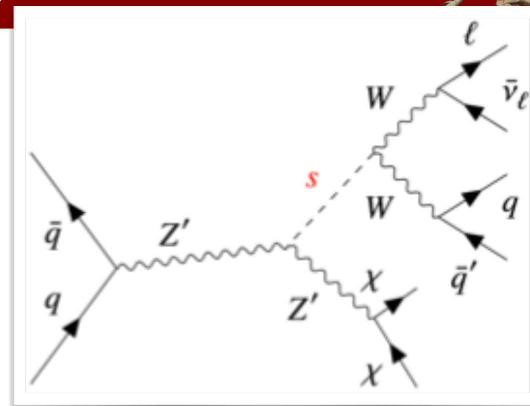
Symmetry 13(12) (2021) 2406
2109.13597

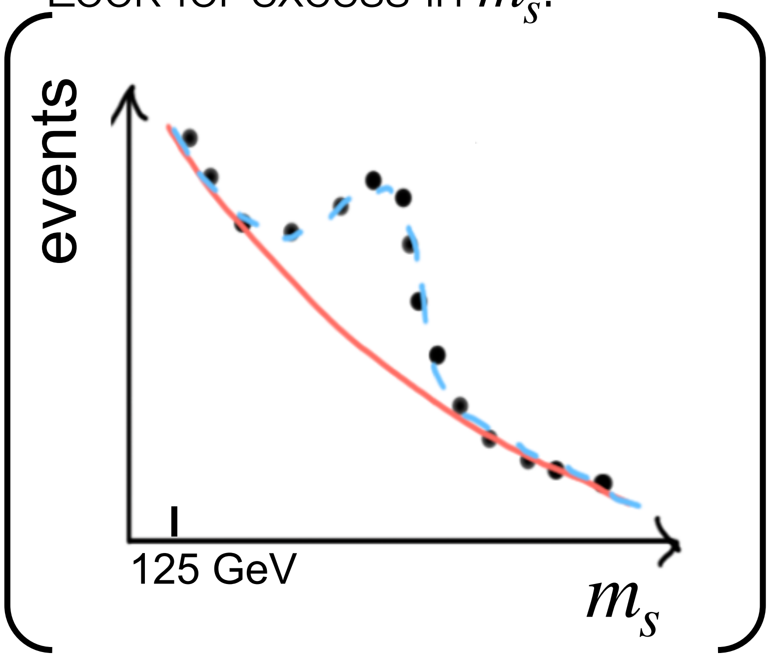
[1] Physikalisches Institut, Albert-Ludwigs Universität Freiburg; spyros.argyropoulos@cern.ch
[2] Cavendish Laboratory, University of Cambridge; obrandt@hep.phy.cam.ac.uk
[3] Max Planck Institut für Physik in München; haisch@mpp.mpg.de
* Corresponding author

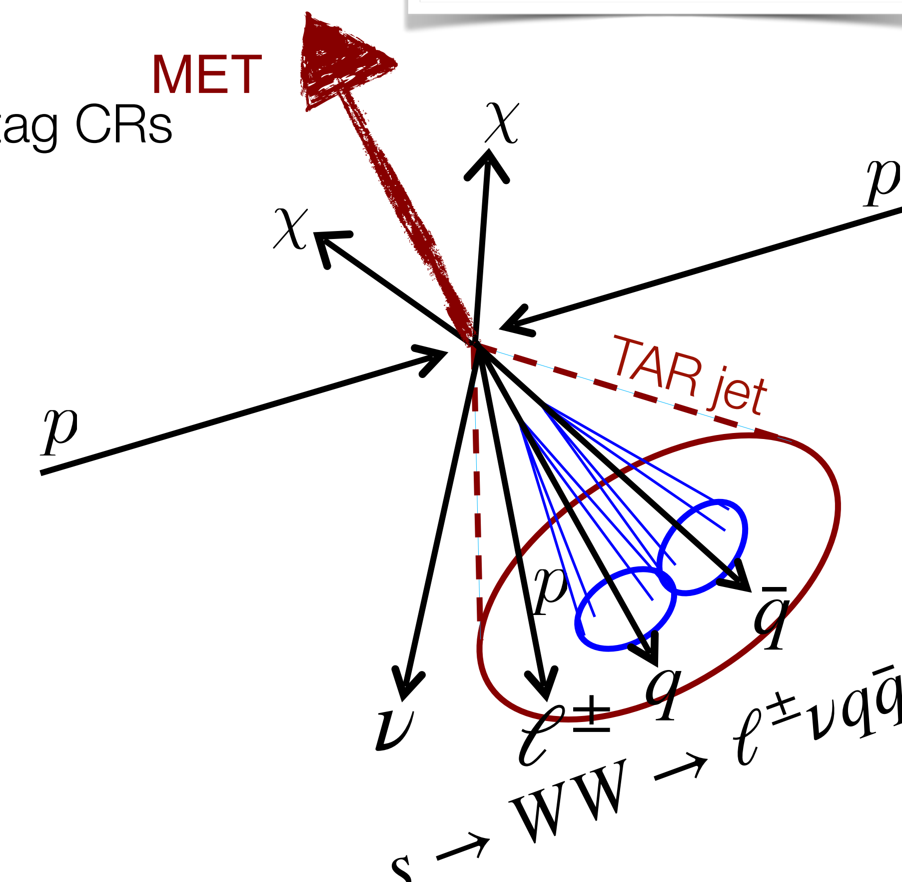
Abstract: Despite the fact that dark matter constitutes one of the cornerstones of the standard cosmological paradigm, its existence has so far only been inferred from astronomical observations and its microscopic nature remains elusive. Theoretical arguments suggest that dark matter might be connected to the symmetry-breaking mechanism of the electroweak interactions or of other symmetries extending the Standard Model of particle physics. The resulting Higgs bosons, including the 125 GeV spin-0 particle discovered recently at the Large Hadron Collider therefore represent a unique tool to search for dark matter candidates at collider experiments. This article reviews some of the relevant theoretical models as well as the results from the searches for dark matter in signatures that involve a Higgs-like particle at the Large Hadron Collider.

Keywords: dark matter; Higgs; LHC

- **Analysis strategy:**
  - MET > 200 GeV, m_T > 220 GeV
  - Dark Higgs candidate $s \rightarrow W(\ell\nu)W(q\bar{q})$
    - single $W(\rightarrow q\bar{q})$ TAR jet (merged)
    - two $W(\rightarrow q\bar{q})$ jets (resolved)
  - Constrain W+jets and $t\bar{t}$: 1ℓ, 2 b-tag CRs
  - Look for excess in m_s:

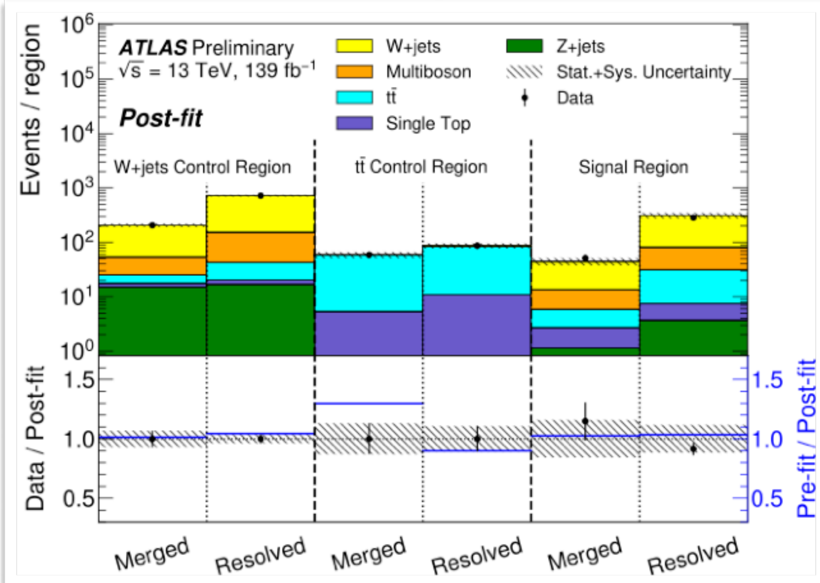


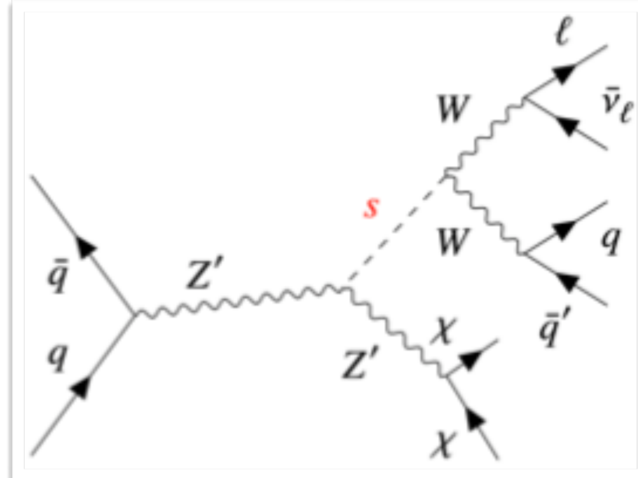


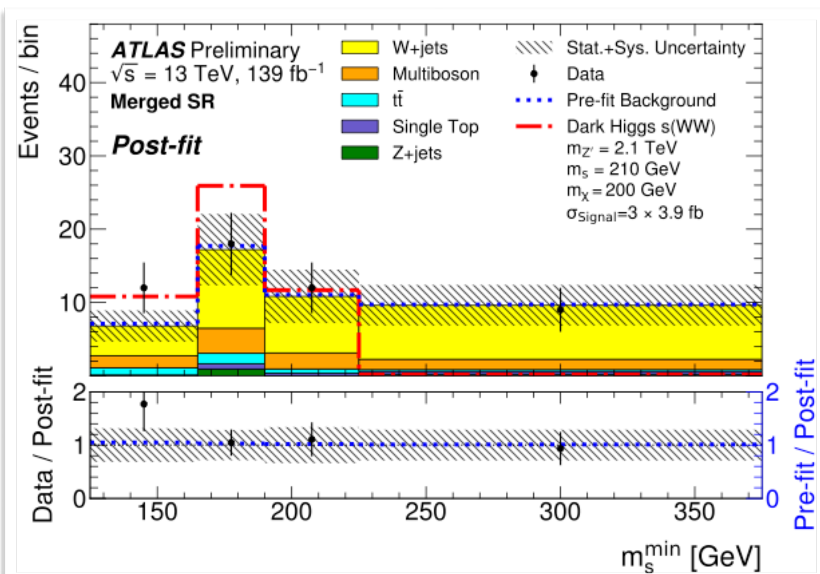


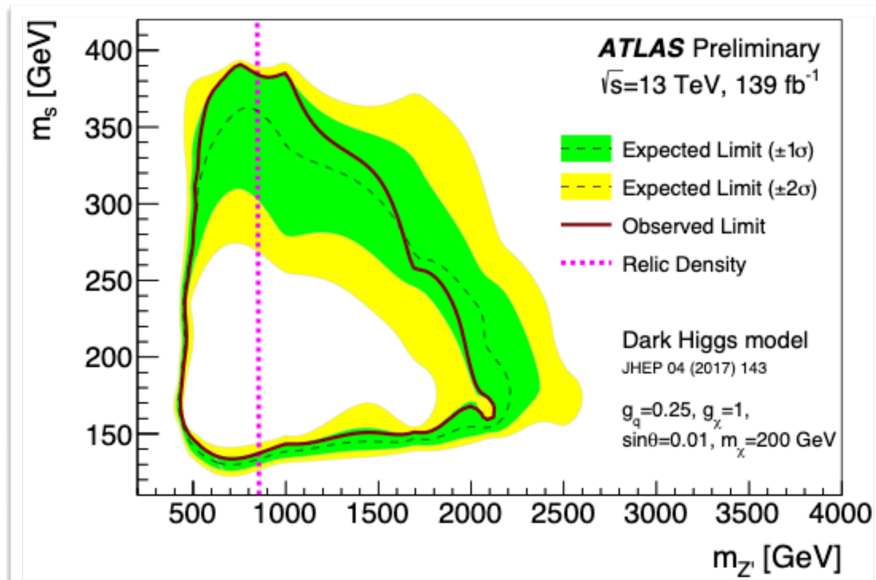
ATLAS-CONF-2022-029

DARK HIGGS + DM: RESULTS

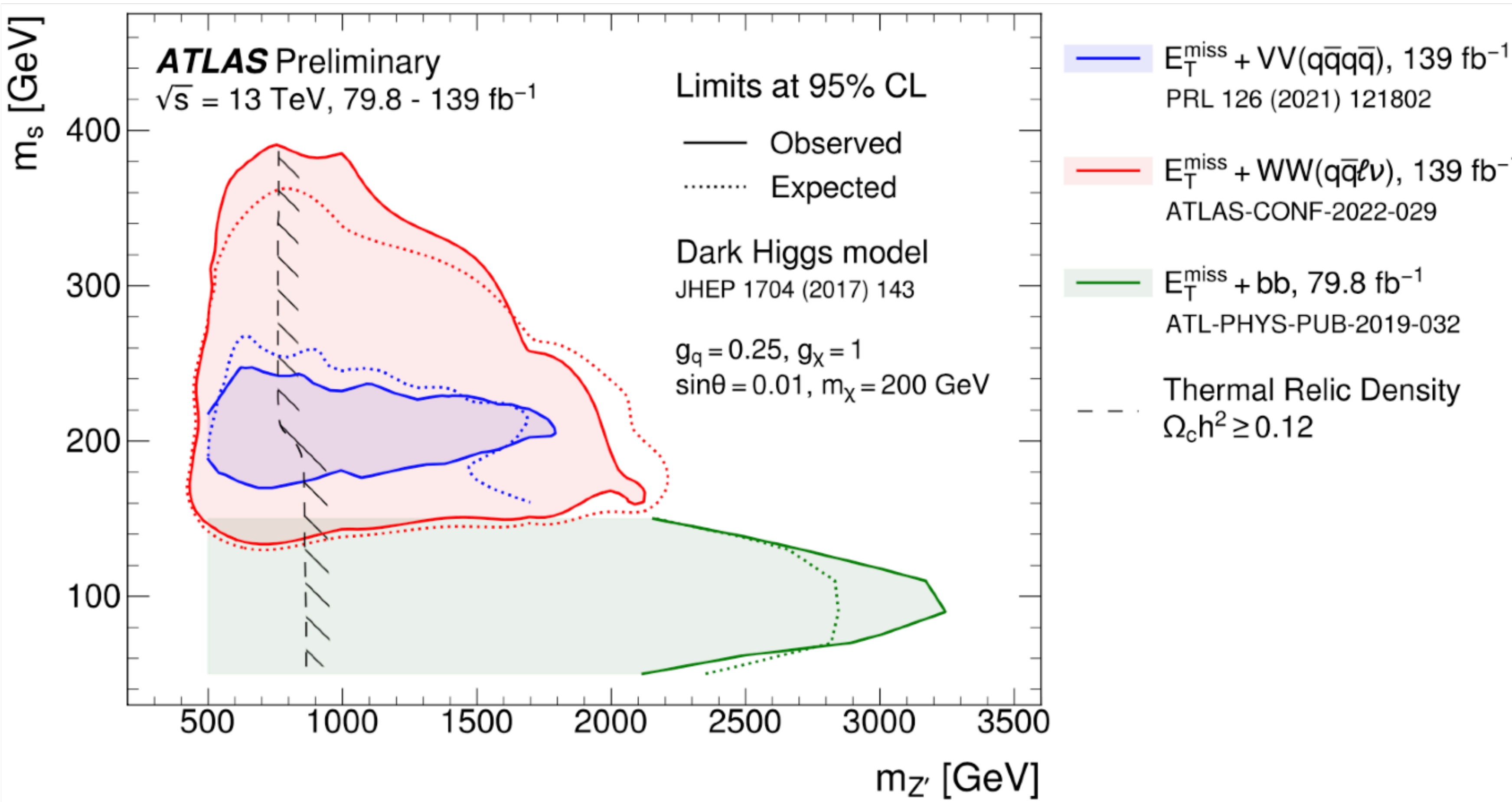






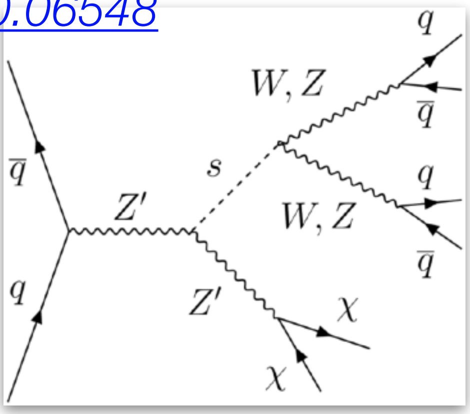


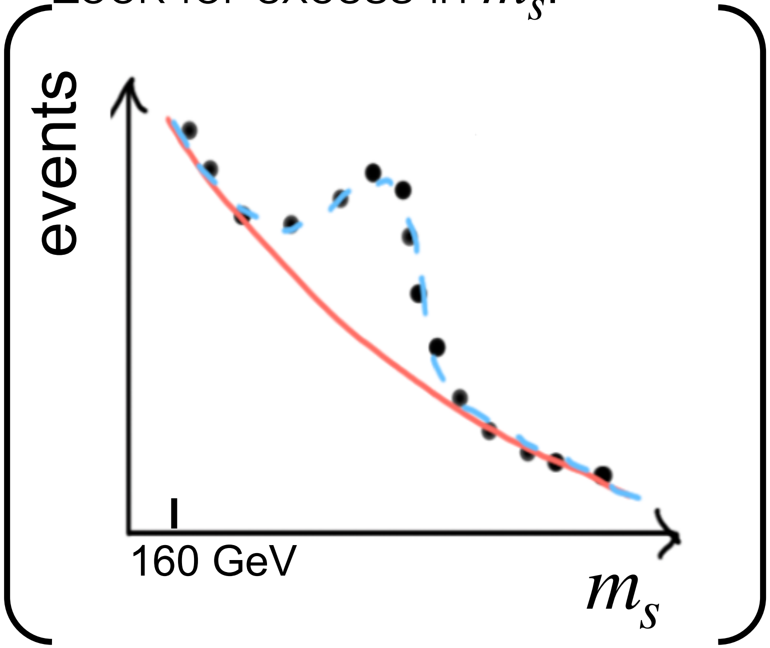
ATLAS-CONF-2022-029

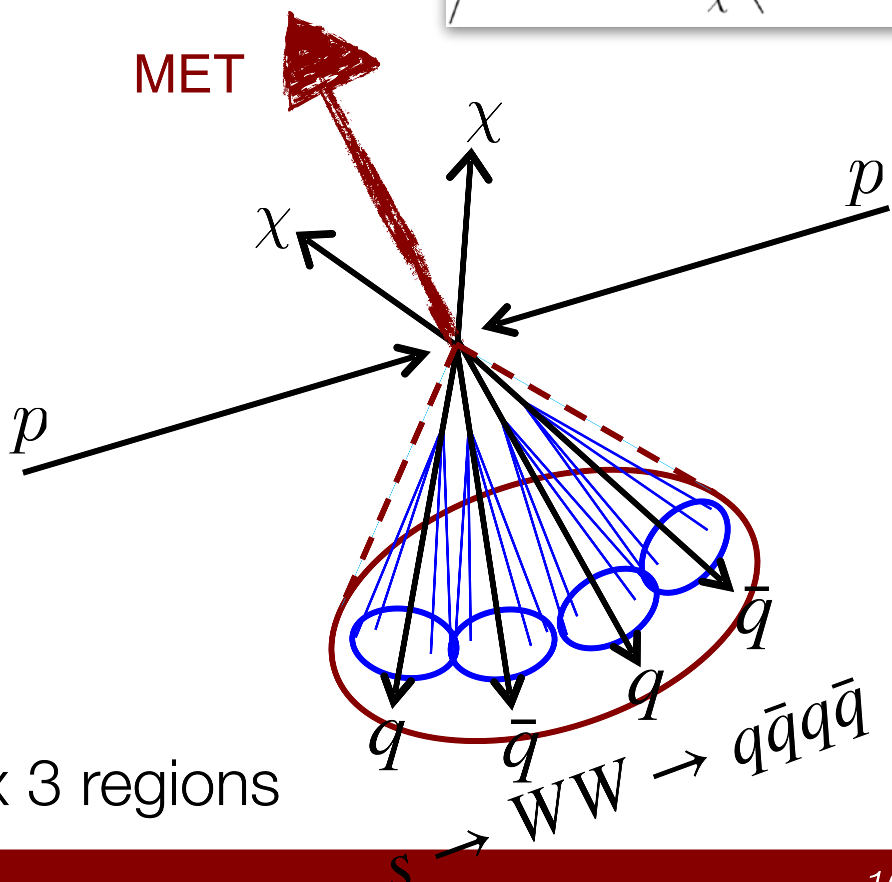


ATLAS Preliminary
√s = 13 TeV, 79.8 - 139 fb⁻¹
Limits at 95% CL
Observed
Expected
Dark Higgs model
JHEP 1704 (2017) 143
$g_q = 0.25$, $g_\chi = 1$
$\sin\theta = 0.01$, $m_\chi = 200$ GeV
$E_T^{miss} + VV(q\bar{q}q\bar{q})$, 139 fb^{-1}
PRL 126 (2021) 121802
$E_T^{miss} + WW(q\bar{q}\ell\nu)$, 139 fb^{-1}
ATLAS-CONF-2022-029
E_T^{miss} + bb, 79.8 fb^{-1}
ATL-PHYS-PUB-2019-032
Thermal Relic Density
$\Omega_c h^2 \geq 0.12$
m_s [GeV]
$m_{Z'}$ [GeV]
100
200
300
400
500
1000
1500
2000
2500
3000
3500

- **Analysis strategy:** *subm. to PRL, arXiv:2010.06548*
  - Require MET > 200 GeV
  - Require Dark Higgs candidate s
    - One $s \to WW \to q\bar{q}q\bar{q}$ jet ("merged")
    - One $W(\to q\bar{q})$ jet + extra jets ("intermediate")
  - Look for excess in m_s:

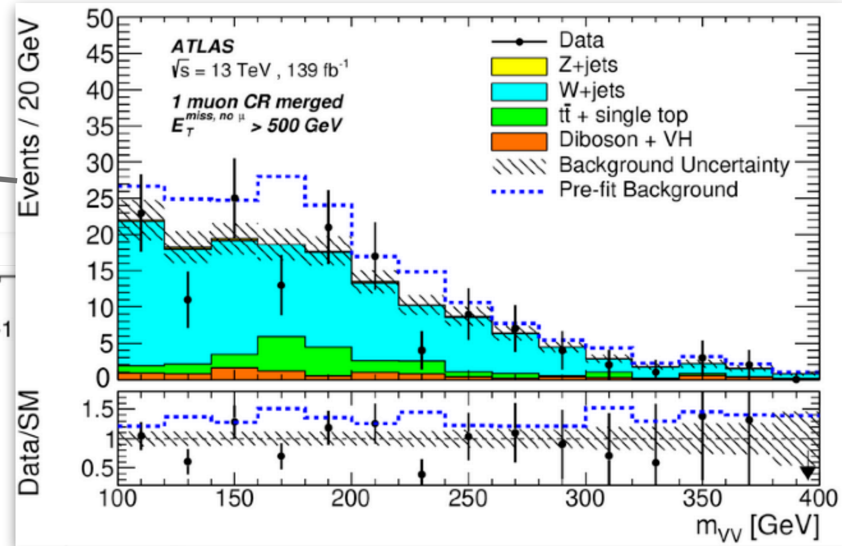


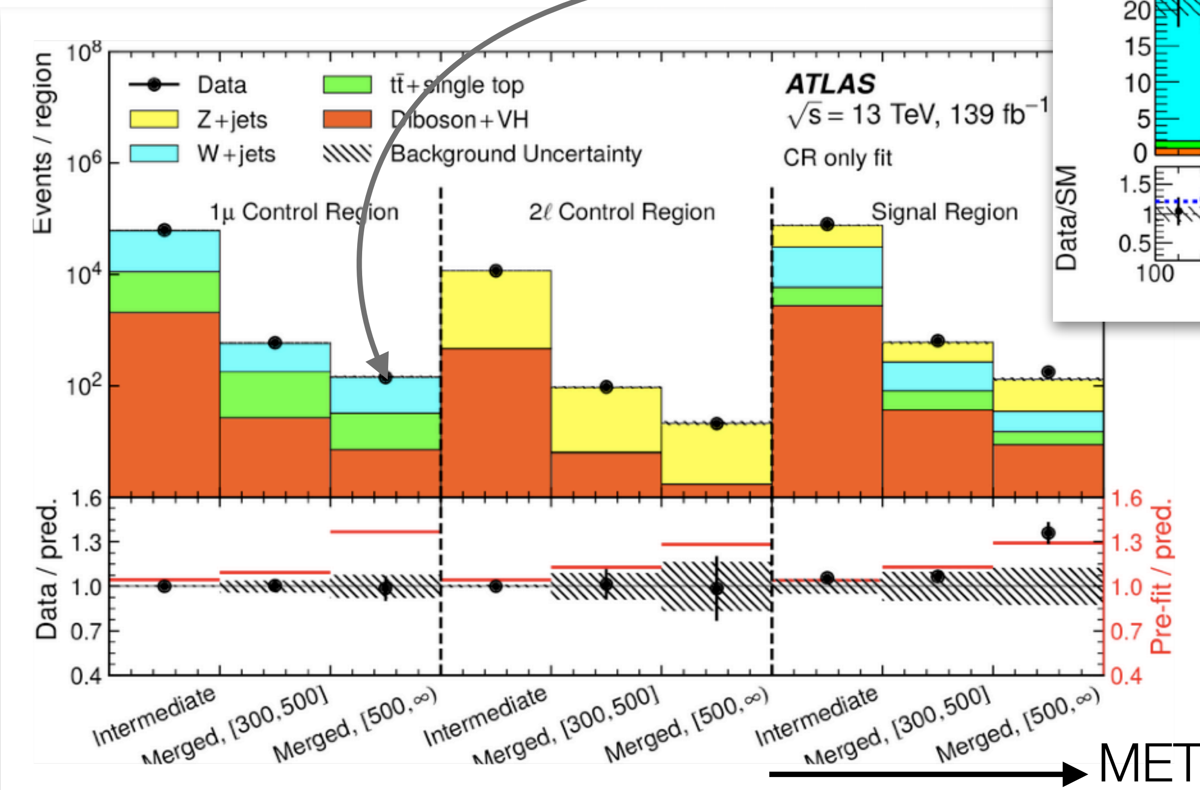




[Shape fit m_s > 160 GeV] x 3 regions

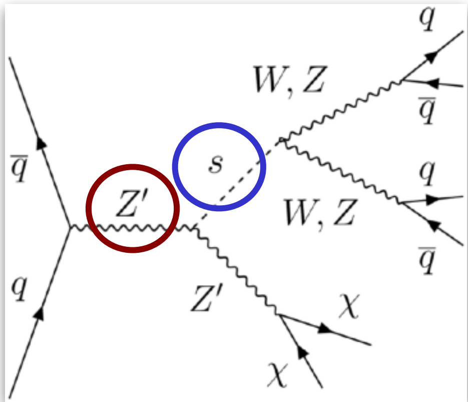
- **Backgrounds:** *subm. to PRL, arXiv:2010.06548*
  - SM Z(νν)+jets (dominant + irreducible), W+jets, Diboson, tt + rest
  - Challenge: extreme kinematic regime
- **Strategy:**
  - Constrain major backgrounds:



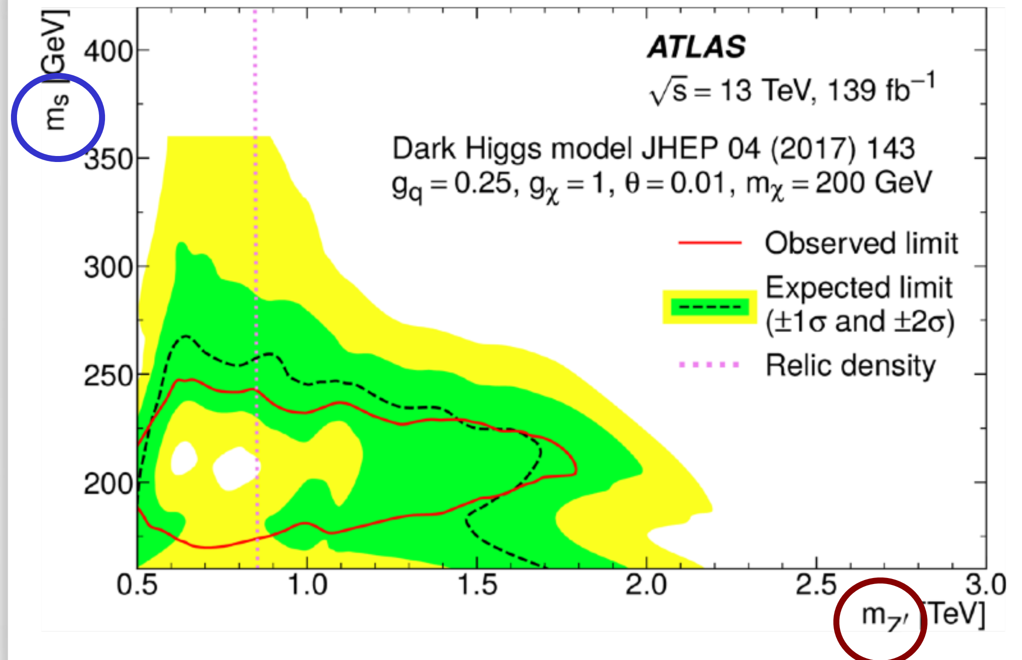


- Results:

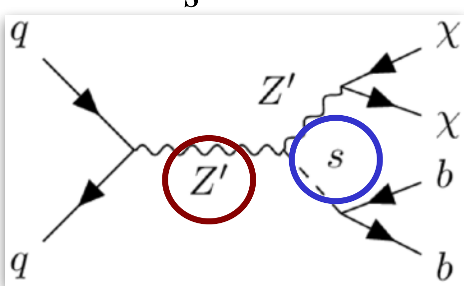
subm. to PRL, arXiv:2010.06548

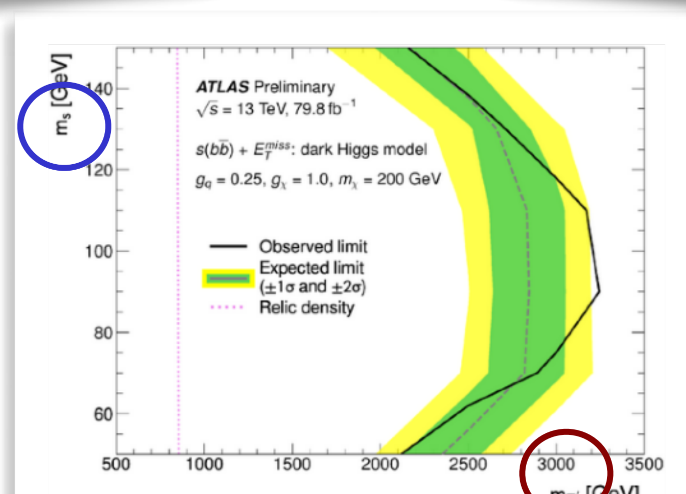


First look at this signature at the LHC!



- Results for m_s < 160 GeV:





ATL-PHYS-PUB-2019-032

No EFT model interpretations for DM searches at the LHC:

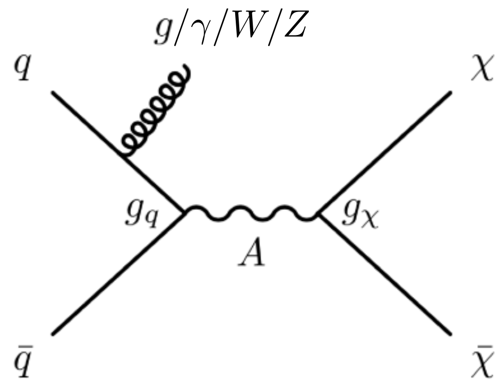
$$Q^2 \gtrsim \Lambda$$

→ Need models with a resolved mediator

DMF models 1507.00966

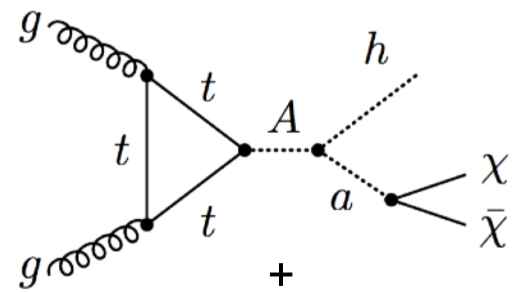
Exception:
Higgs portal models
(why?)

1) Effective field theory



s-channel mediators
1507.00966
1603.04156
1703.05703
t-channel mediators
1507.00966

2) Simplified models



\+
many other signatures

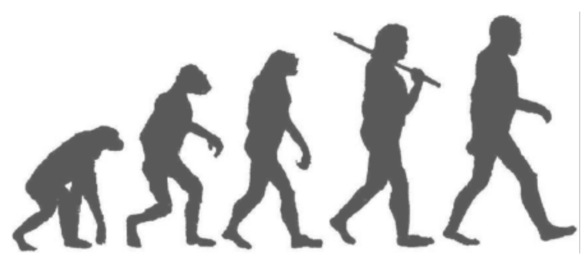
2HDM+a model
JHEP 05 (2017) 138
1810.09420

Dark Higgs model
JHEP 04(2017)143

3) Simplified, consistent, & UV-complete models

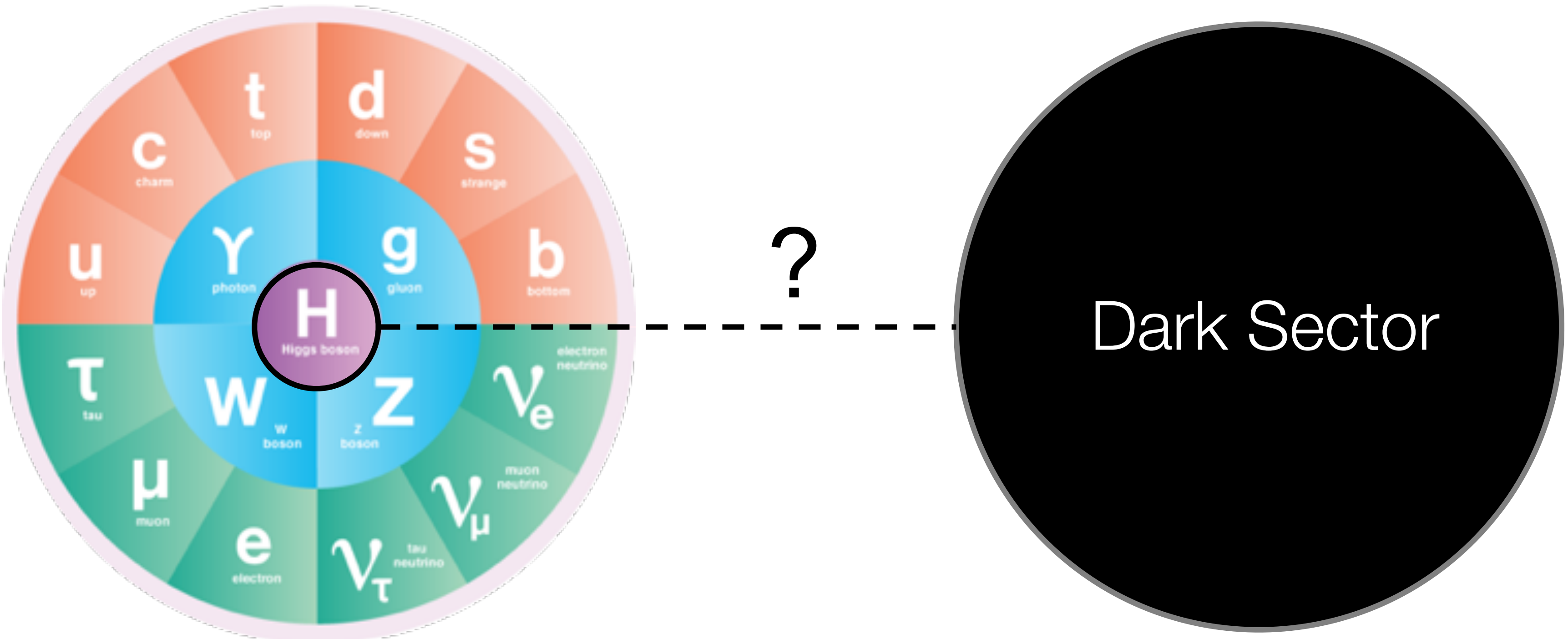
Supersymmetry
DM candidate: lightest super-symmetric particle

4) complete models



Richer kinematics + phenomenology

Higgs-portal models



Motivation: 1) Higgs Yukawa coupling to massive Dark Sector particles
2) Higgs coupling to new particles (hierarchy problem)
3) can be UV-complete
4) the only dim-4 operator to couple SM and scalar/vector DM

$$\mathcal{L}_{\phi H} = c_m \phi^2 (H^\dagger H)$$

For further details…

Review

Collider Searches for Dark Matter through the Higgs Lens

Spyros Argyropoulos [1], **Oleg Brandt** [2,*] **and Ulrich Haisch** [3]

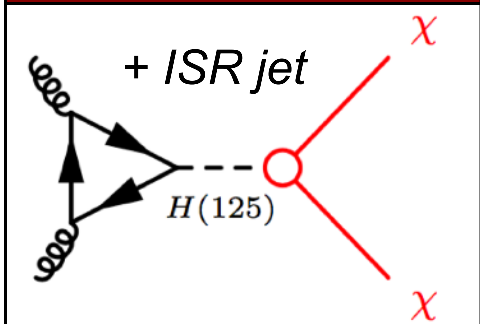
Symmetry 13(12) (2021) 2406
2109.13597

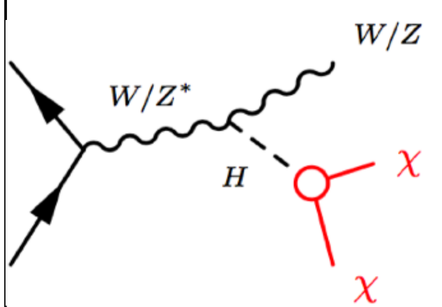
[1] Physikalisches Institut, Albert-Ludwigs Universität Freiburg; spyros.argyropoulos@cern.ch
[2] Cavendish Laboratory, University of Cambridge; obrandt@hep.phy.cam.ac.uk
[3] Max Planck Institut für Physik in München; haisch@mpp.mpg.de
* Corresponding author

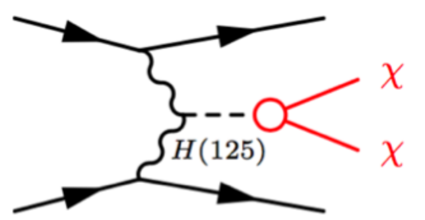
Abstract: Despite the fact that dark matter constitutes one of the cornerstones of the standard cosmological paradigm, its existence has so far only been inferred from astronomical observations and its microscopic nature remains elusive. Theoretical arguments suggest that dark matter might be connected to the symmetry-breaking mechanism of the electroweak interactions or of other symmetries extending the Standard Model of particle physics. The resulting Higgs bosons, including the 125 GeV spin-0 particle discovered recently at the Large Hadron Collider therefore represent a unique tool to search for dark matter candidates at collider experiments. This article reviews some of the relevant theoretical models as well as the results from the searches for dark matter in signatures that involve a Higgs-like particle at the Large Hadron Collider.

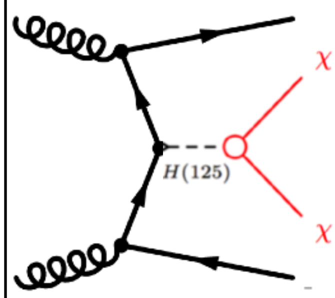
Keywords: dark matter; Higgs; LHC

ggF H [49 pb]	VH [2.3 pb]	VBF H [3.8 pb]	ttH [0.09 pb]

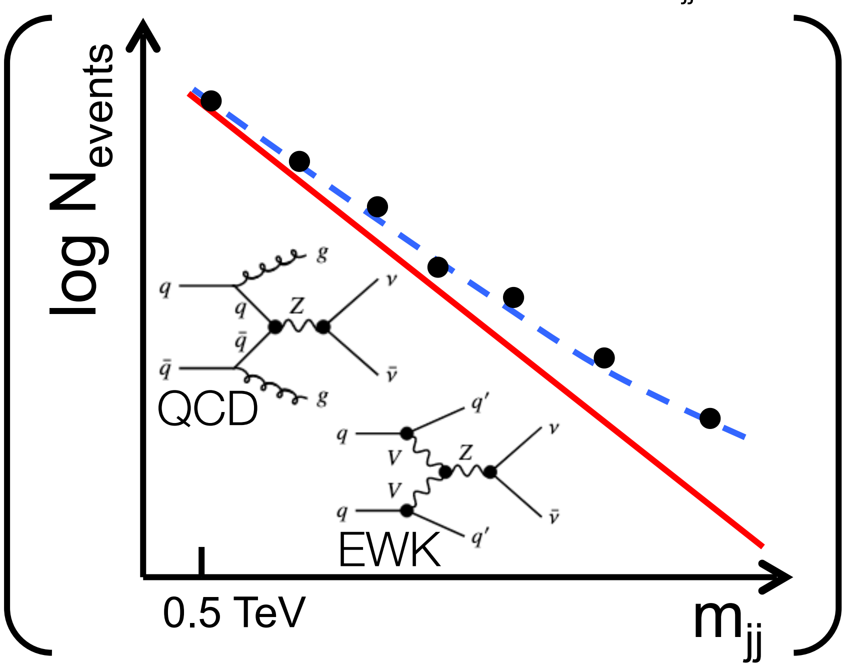


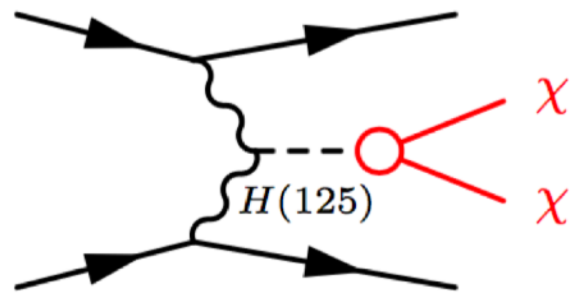


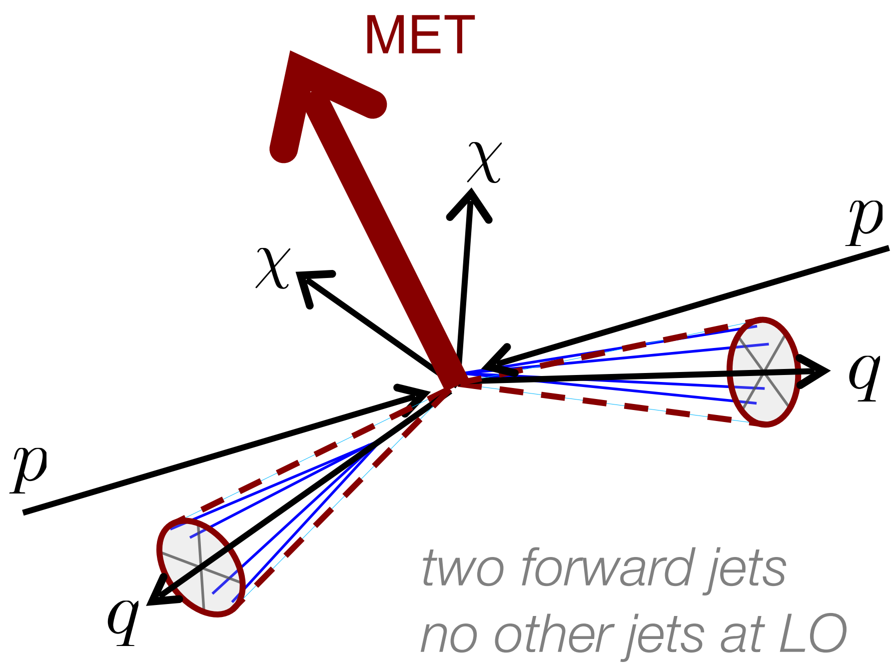




- **Analysis strategy:**
  - Require MET > 200 GeV, MHT > 180 GeV
  - Require high $|\Delta\eta_{jj}| > 3.8$
  - No 3rd or 4th jet with large impact on m_{jj}
  - Look for excess at high m_{jj}:







Shape fit $m_{jj} > 0.5$ TeV

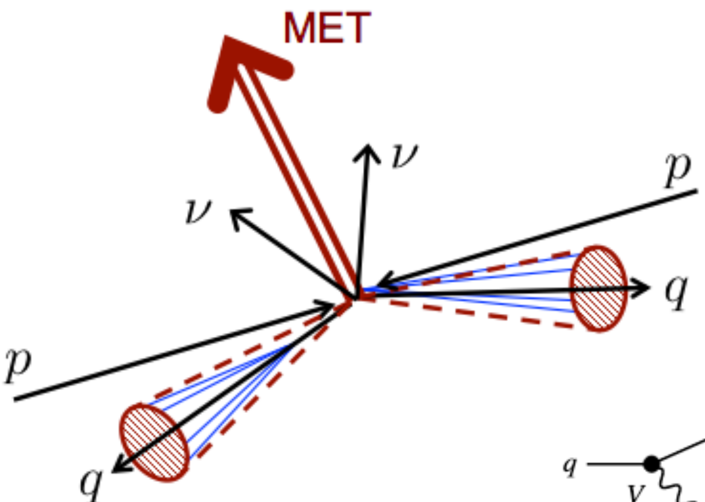
ATLAS-CONF-2020-008

VBF $H(\rightarrow inv)$: CONSTRAIN BACKGROUNDS

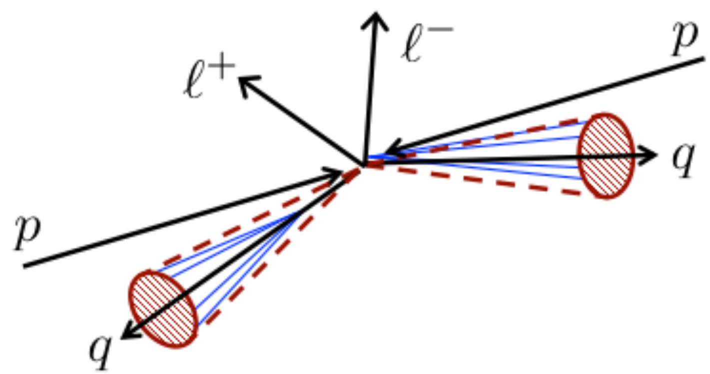
- Constrain Z(vv)+jets, W+jets in signal region (SR) using control regions (CR):

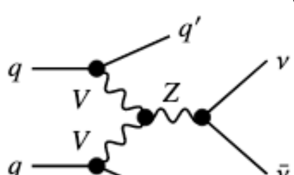
0 lepton SR	1 lepton CR	2 lepton CR
Signal + constrain Z(vv)+jets etc. at low mjj	Constrain W+jets	Constrain Z(vv)+jets using Z($\ell\ell$)+jets

Z(vv)+jets

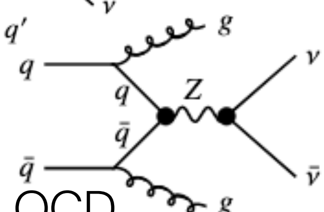


Z($\ell\ell$)+jets





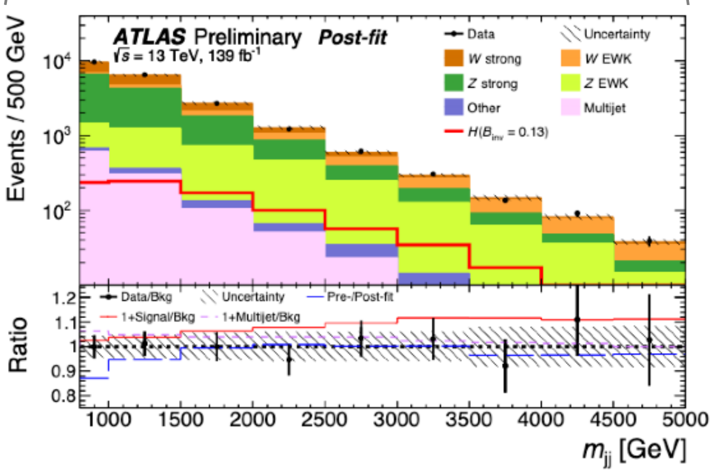
EWK

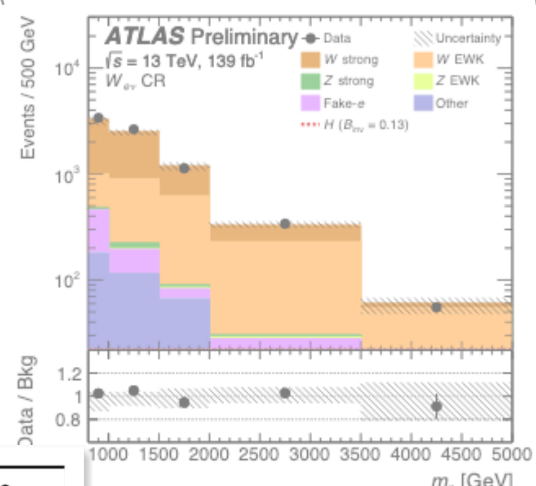


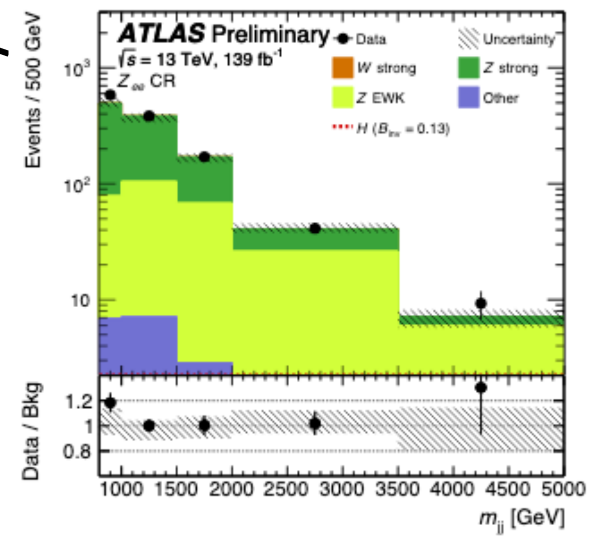
QCD

- Constrain Z(νν)+jets, W+jets in signal region (SR) using control regions (CR):

0 lepton SR	1 lepton CR	2 lepton CR
Signal + constrain Z(νν)+jets etc. at low mjj	Constrain W+jets	Constrain Z(νν)+jets using Z($\ell\ell$)+jets

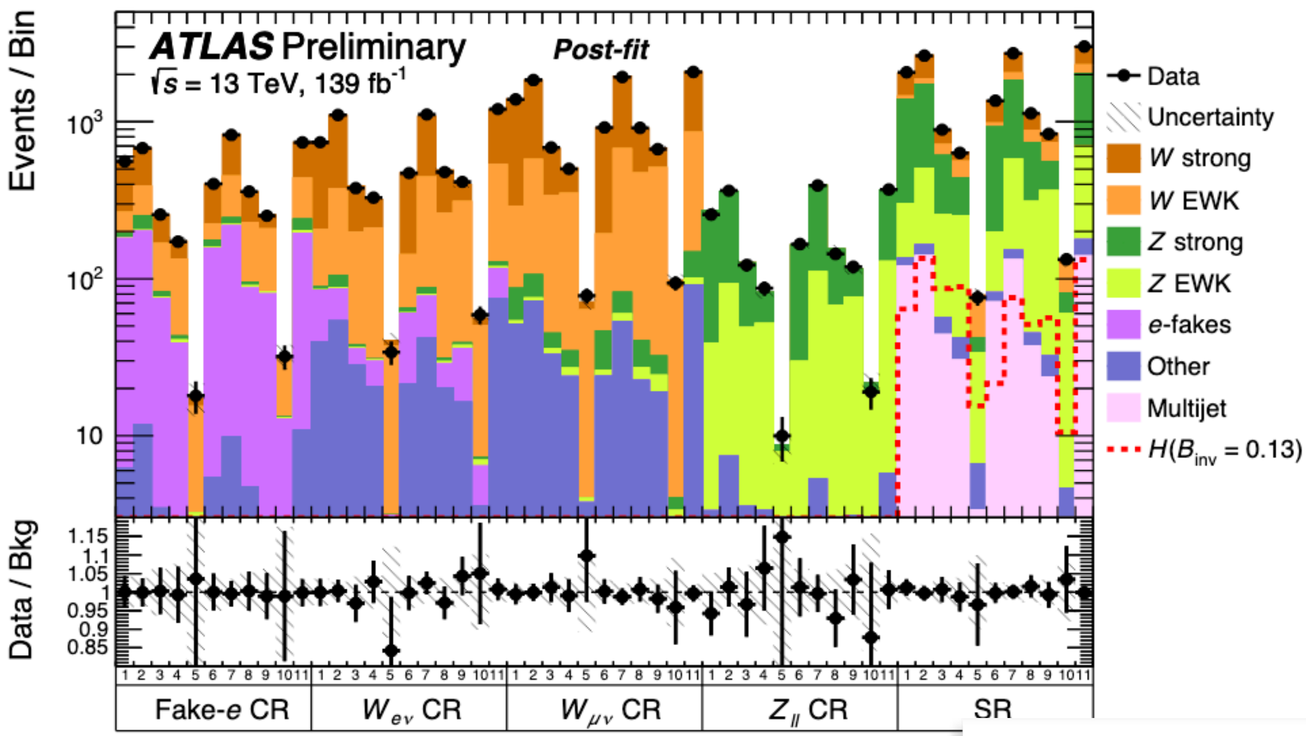






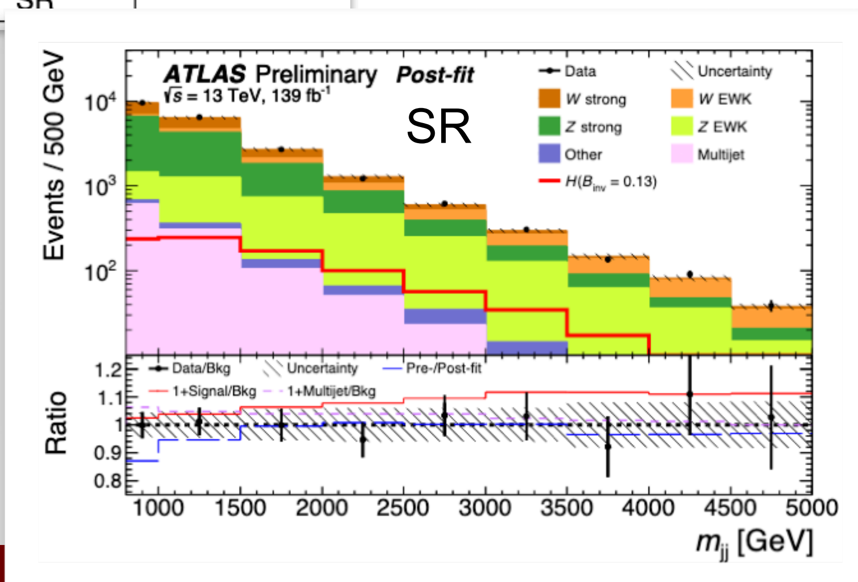
Observed	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.145	0.103	0.144	0.075	0.196	0.055

VBF $H(\to inv)$: RESULTS

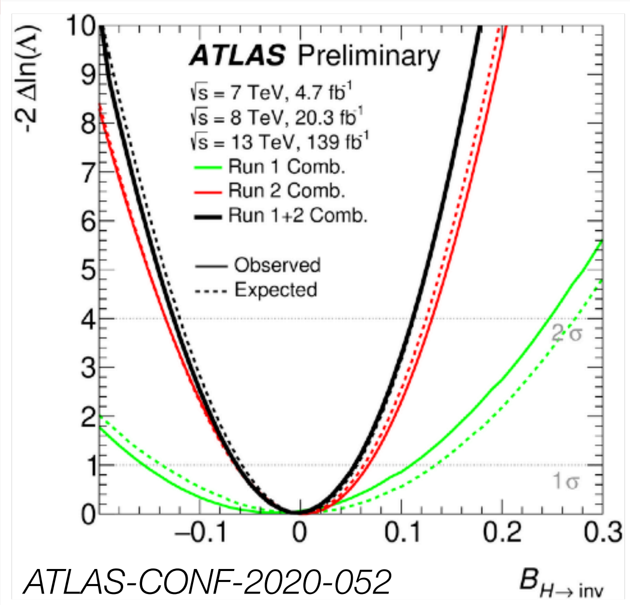


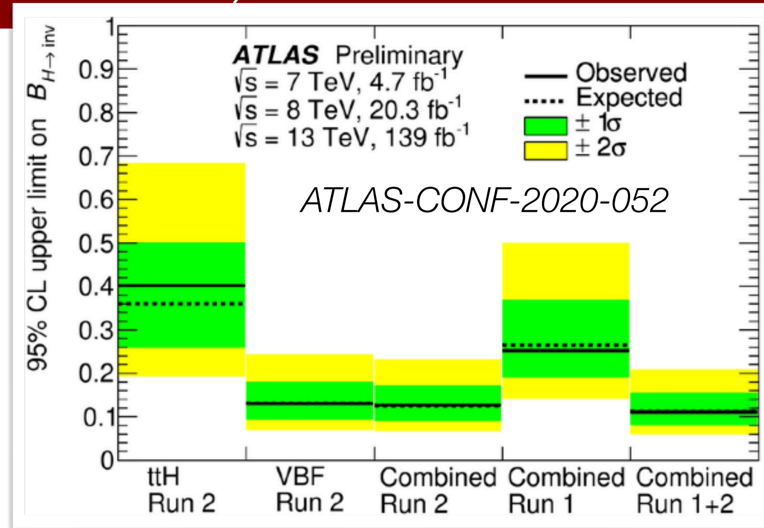
Observed	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.145	0.103	0.144	0.075	0.196	0.055

Most precise result @ LHC!



ATLAS $H(\to inv)$ COMBINATION: RUN 1+2, ALL CHANNELS





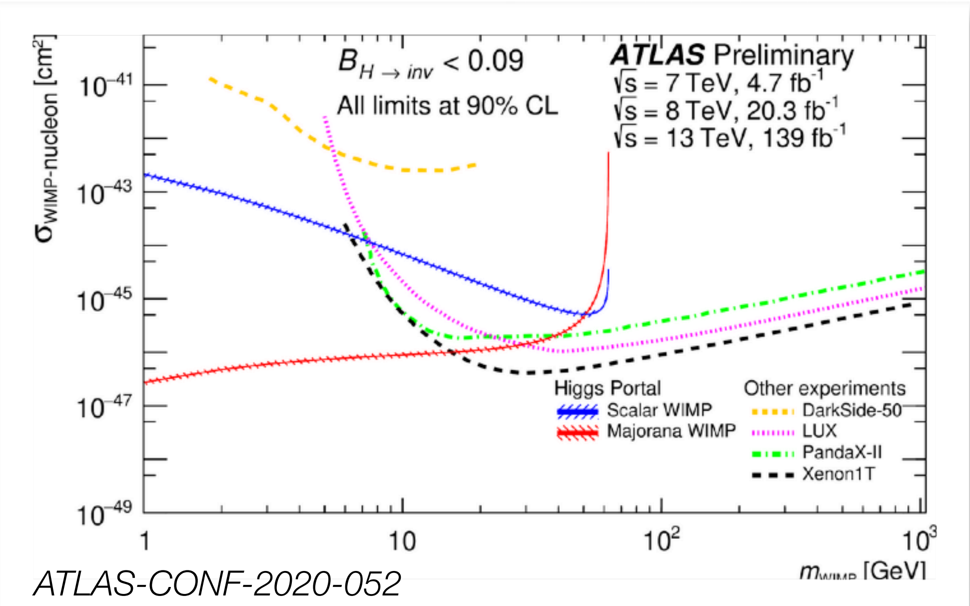
ATLAS-CONF-2020-052, all limits at 95% CL

Analysis	[TeV]	luminosity [fb^{-1}]	Best fit $\mathcal{B}_{H\to inv}$	Observed upper limit	Expected upper limit	Reference
Run 2 VBF	13	139	$0.00^{+0.07}_{-0.07}$	0.13	$0.13^{+0.05}_{-0.04}$	[42]
Run 2 $t\bar{t}H$	13	139	$0.04^{+0.20}_{-0.20}$	0.40	$0.36^{+0.15}_{-0.10}$	This document
Run 2 Comb.	13	139	$0.00^{+0.06}_{-0.07}$	0.13	$0.12^{+0.05}_{-0.04}$	This document
Run 1 Comb.	7, 8	4.7, 20.3	$-0.02^{+0.14}_{-0.13}$	0.25	$0.27^{+0.10}_{-0.08}$	[36]
Run 1+2 Comb.	7, 8, 13	4.7, 20.3, 139	$0.00^{+0.06}_{-0.06}$	0.11	$0.11^{+0.04}_{-0.03}$	This document

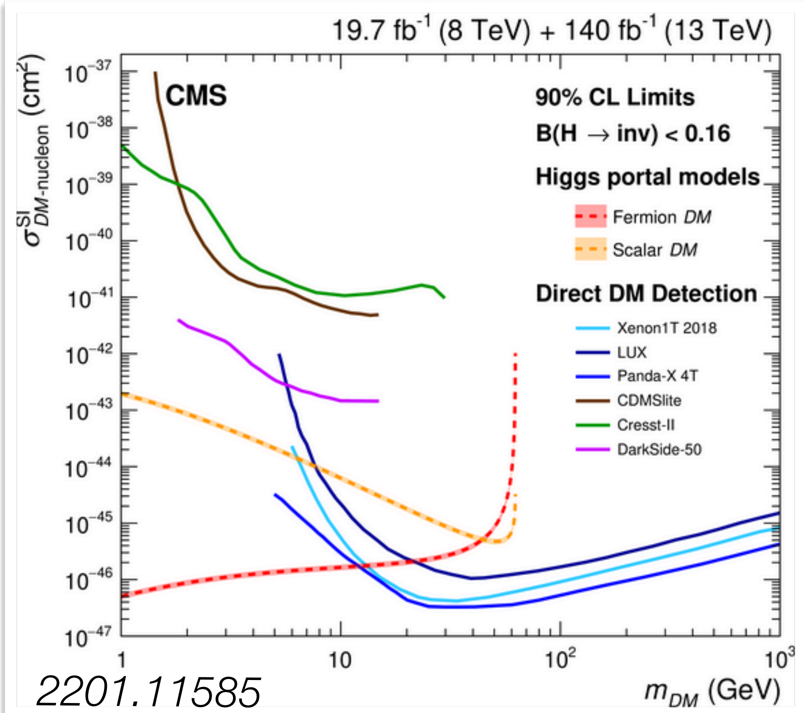
Updates since:
(to be included)

Analysis	Obs.	Expected limit	*Reference*
Run 2 VBF	0.15	$0.10^{+0.04}/_{-0.03}$	*arXiv:2202.07953*
Run 2 ZH	0.19	0.19	*PLB 829 (2022) 137066*
Run 2 ttH	0.40	$0.30^{+0.13}/_{-0.09}$	*ATLAS-CONF-2022-007*
Run 2 VBF+y	0.37	$0.34^{+0.15}/_{-0.10}$	*arXiv:2109.00925*

CONNECTION OF $H(\to inv)$ TO DIRECT DETECTION EXPERIMENTS

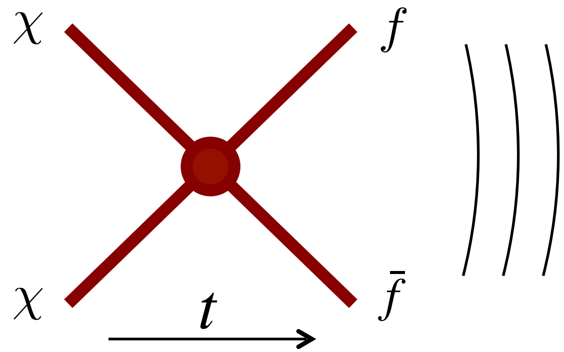


ATLAS-CONF-2020-052



2201.11585

Highlights & overview



$$\overbrace{\frac{d\Phi}{d\Omega dE}}^{Diff.Flux} = \frac{\overbrace{\sigma v}^{Anni.\,Cross\,Section}}{8\pi m_\chi^2} \times \underbrace{\frac{dN}{dE}}_{Energy\,Spectrum} \times \overbrace{\int_{l.o.s} ds \underbrace{\rho^2(\vec{r}(s,\Omega))}_{Dark\,Matter\,Distribution}}^{\text{a.k.a. J-factor}}$$

Measurement

Model assumption, Colliders (fragmentation etc)

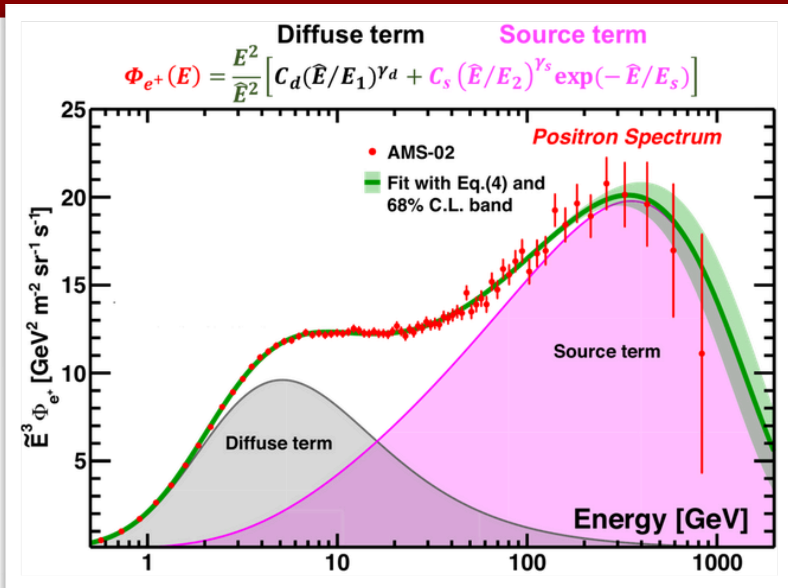
Cosmology

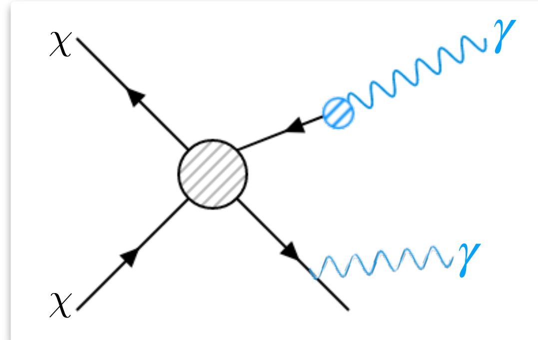
σv: Interpretation (final observable)

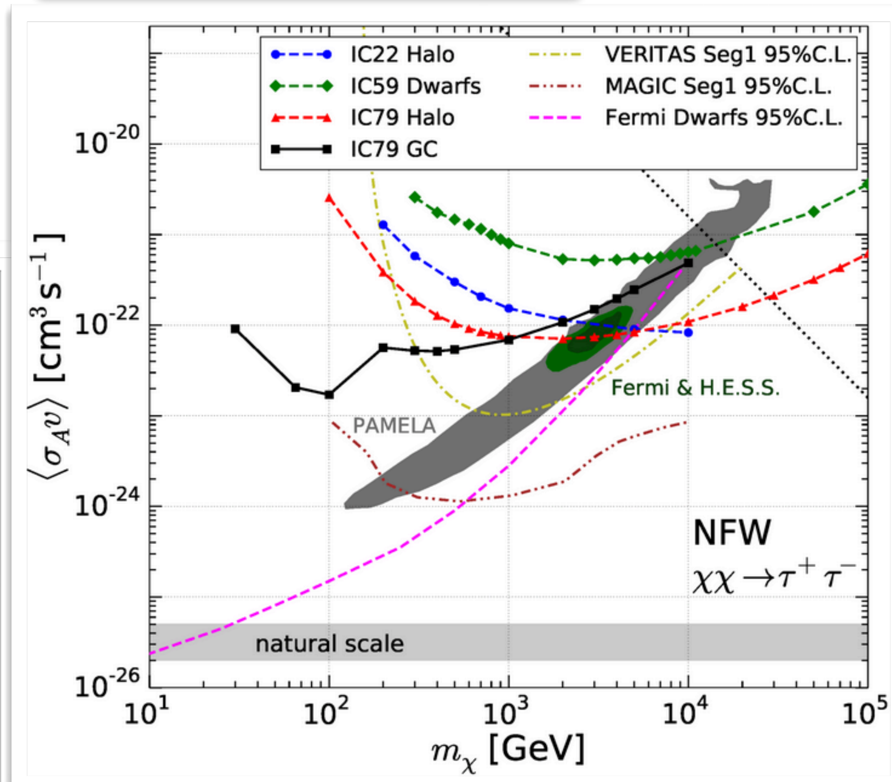
m_χ: model assumption

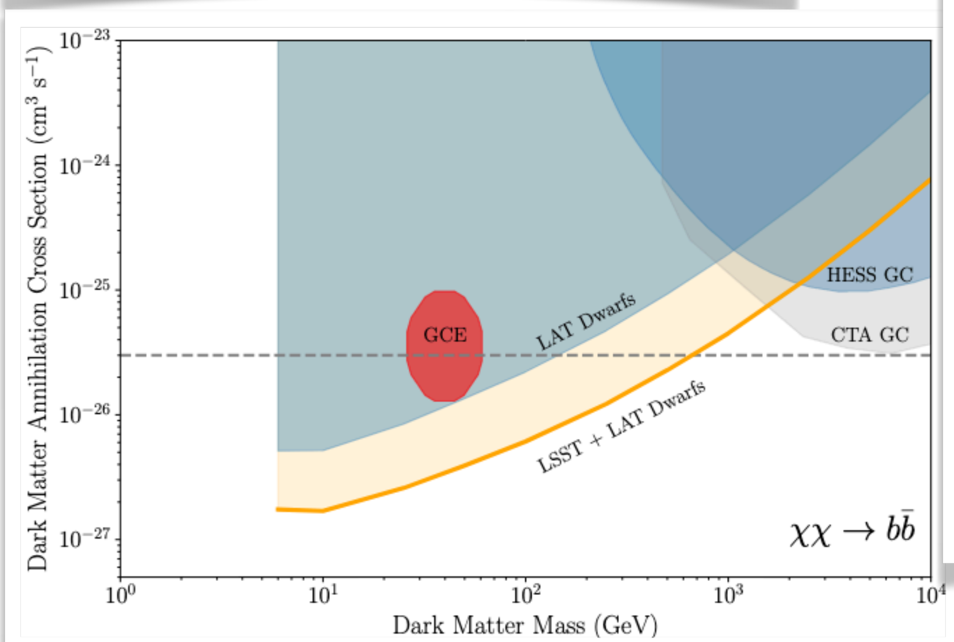
1605.08788

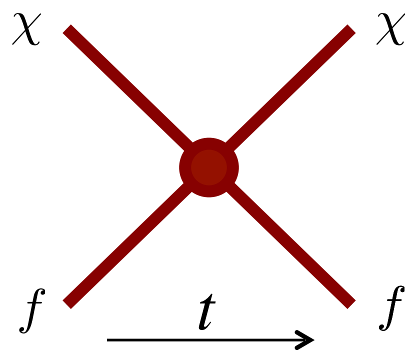
INDIRECT DETECTION - HIGHLIGHTS

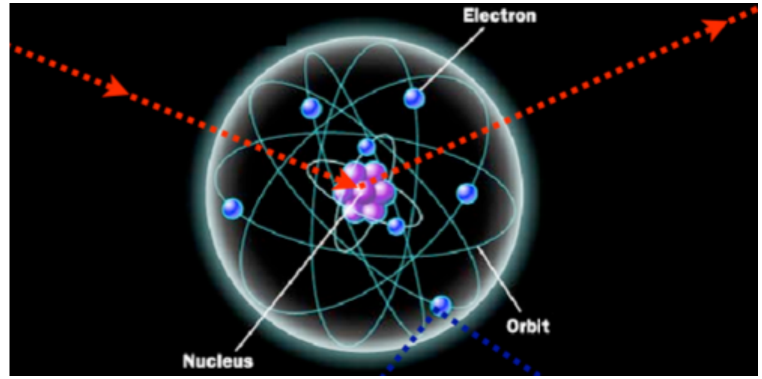












$$\overbrace{\frac{dR}{dE}(E,t)}^{Scatt.\,Rate} = \underbrace{N_T}_{Target\ dependence} \overbrace{\frac{\rho_\chi}{m_\chi}}^{Number\ density} \int_{v_{min}} \underbrace{\frac{d\sigma}{dE}(v,E)}_{Diff.\ Cross\ Section} \; v \; \overbrace{f_E(\vec{v},t)}^{veloc.\ distribution} \; d^3\vec{v}$$

Measurement

Colliders, nuclear

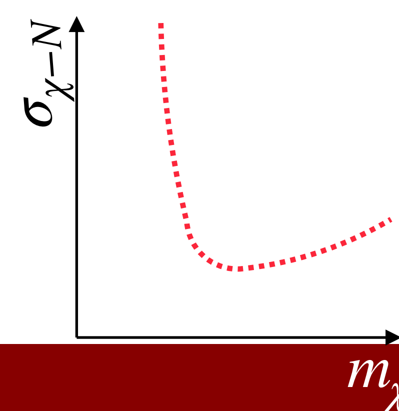
ρ: Cosmology

m_χ: model

σ: Interpretation

m_N: experimental handle

Cosmology

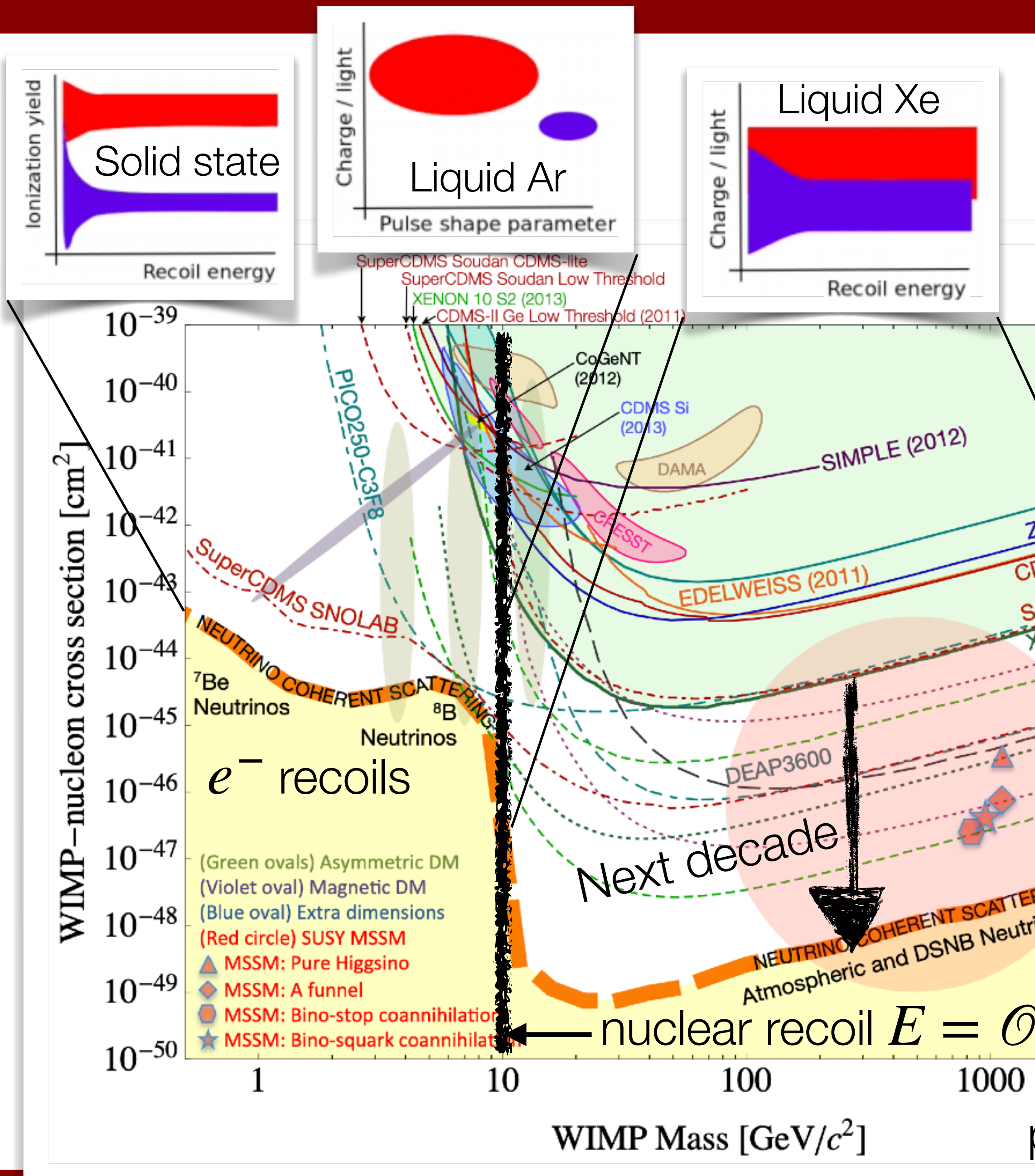


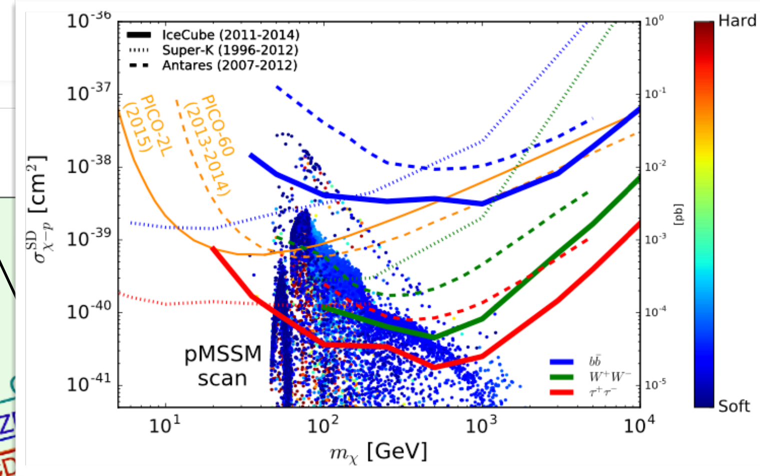
1605.08788

DIRECT DETECTION - HIGHLIGHTS

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi D^2}\frac{dN_\nu}{dE_\nu}$$

$$\Gamma_A \propto \sigma^{SD}_{\chi-p}$$

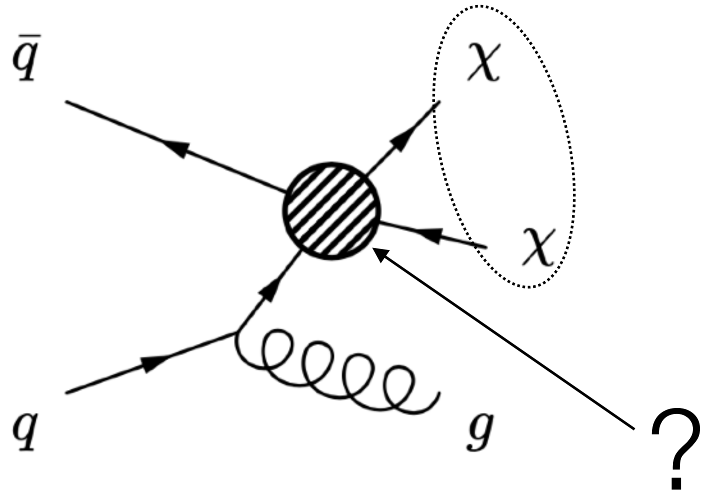




$P \to \sigma_{SI}$

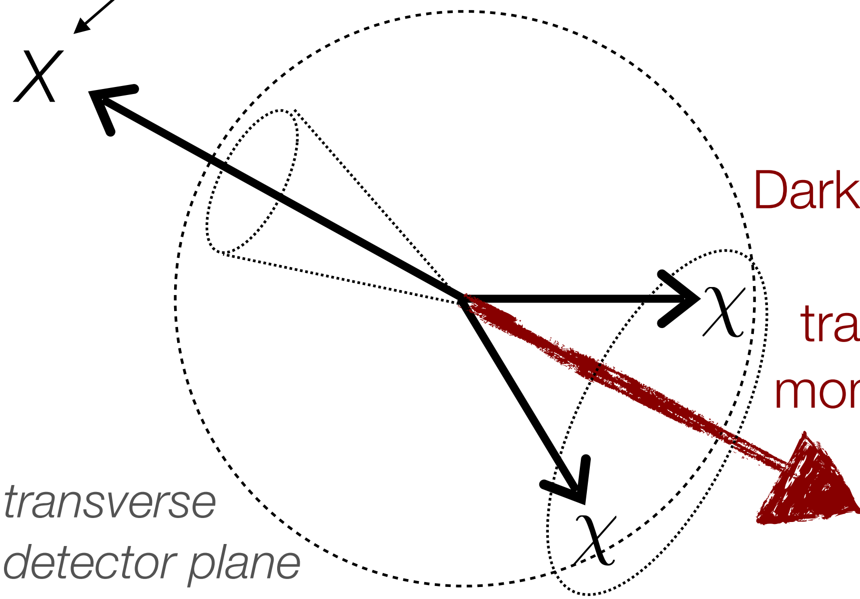
$\not{P} \to \sigma_{SD}$

pseudo-scalar mediator hopeless



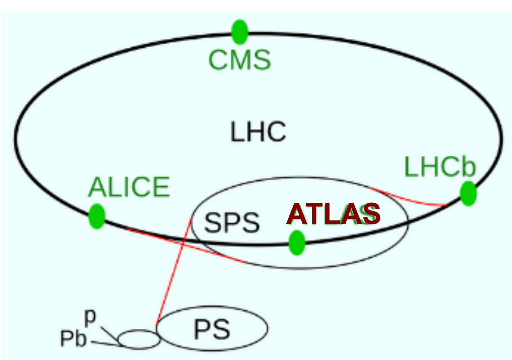
Collider production
(controlled experimental environment!)

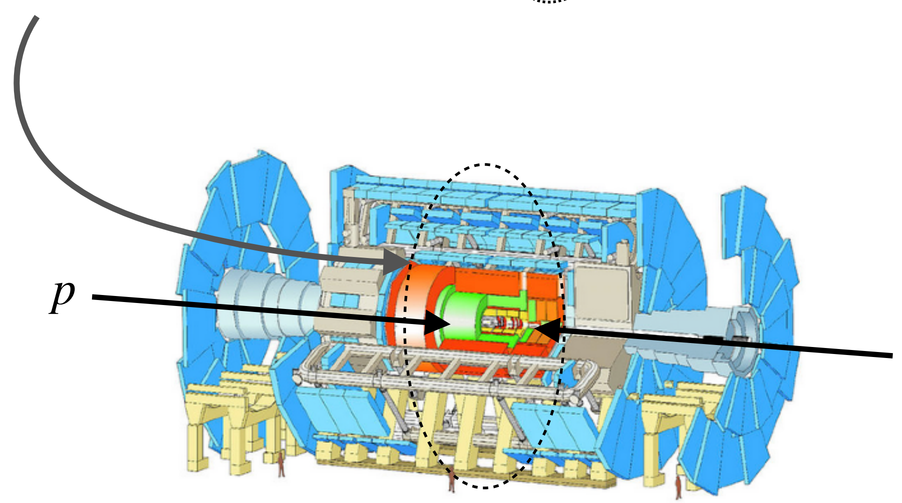
ISR(jet,γ), $Z, W, h, t, t\bar{t}, tW$, VBF etc.



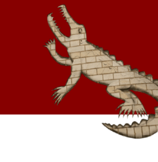
Dark Matter: missing transverse momentum (MET)

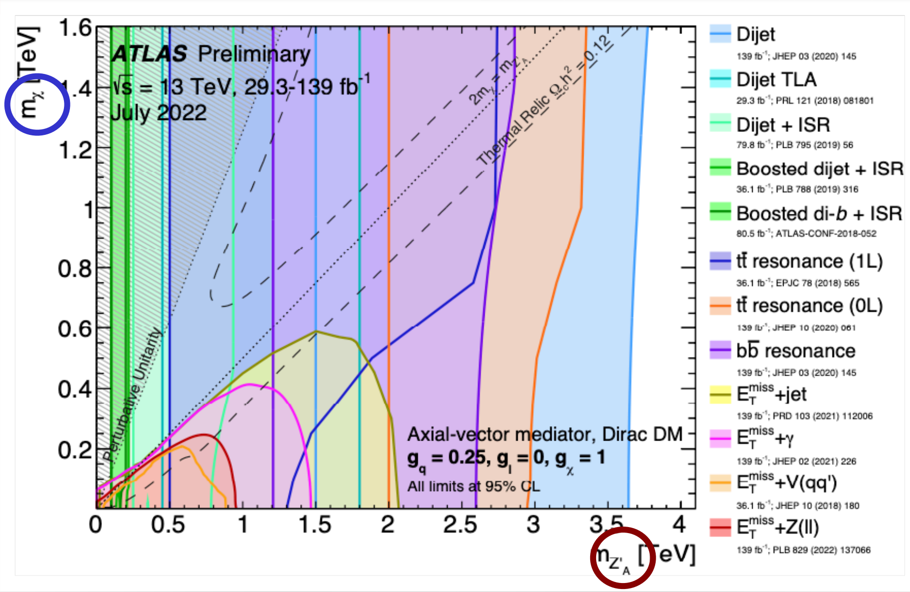
transverse detector plane

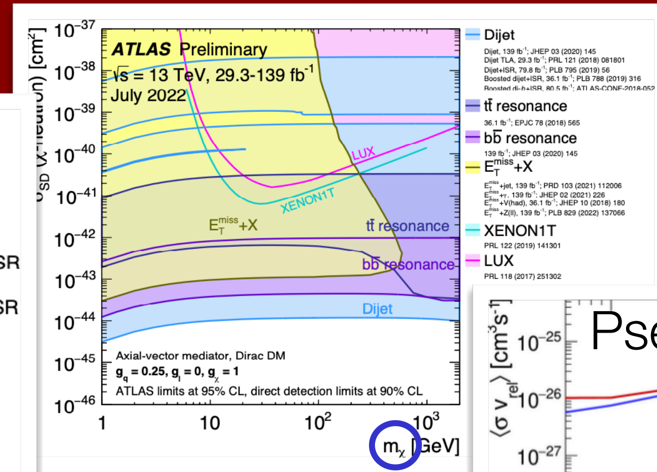


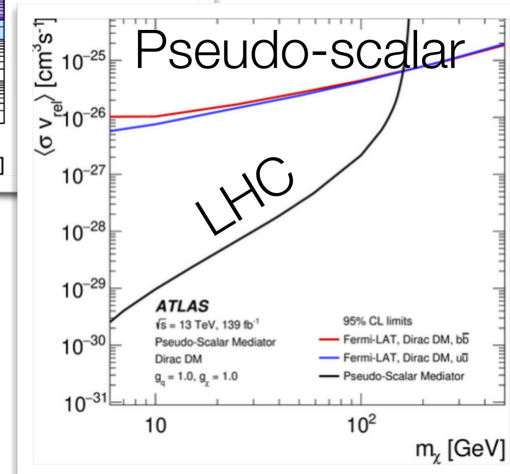


DM @ LHC: HIGHLIGHTS

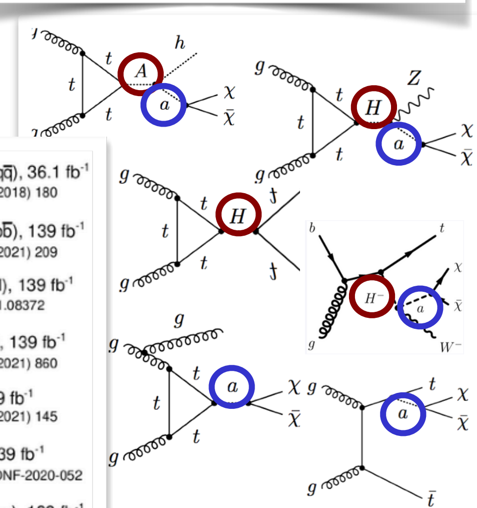


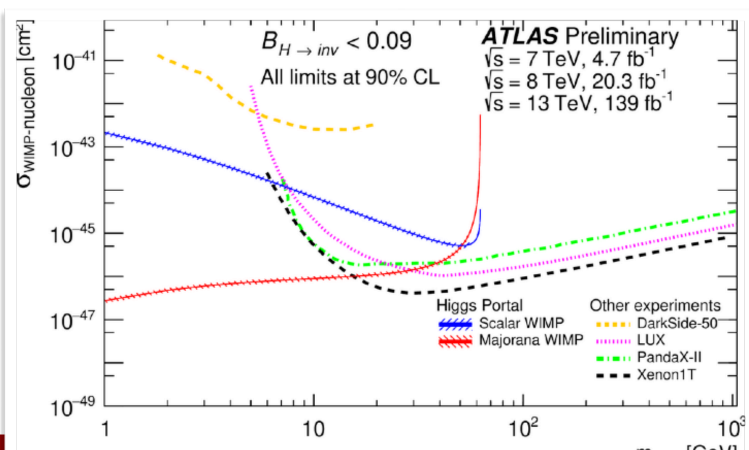


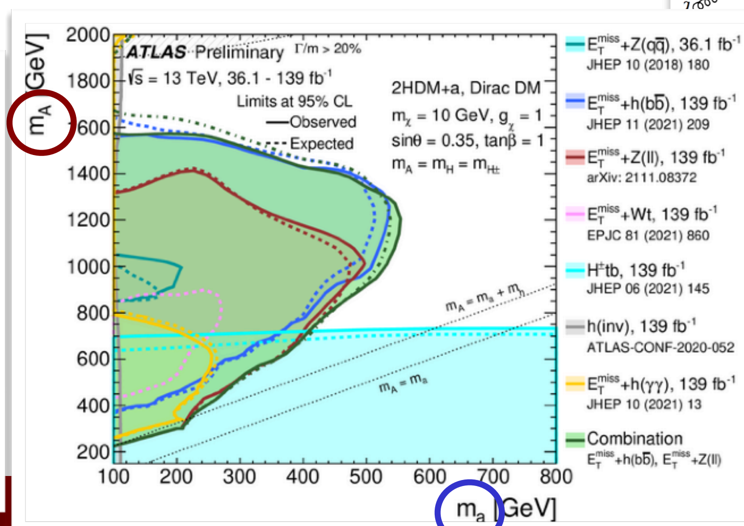




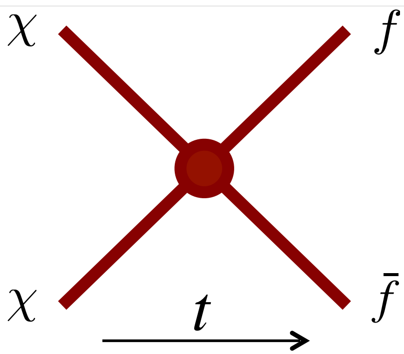
$$\mathrm{BR}(h \to \mathrm{inv}) < 0.15 \; (0.10^{+0.04}_{-0.03})$$





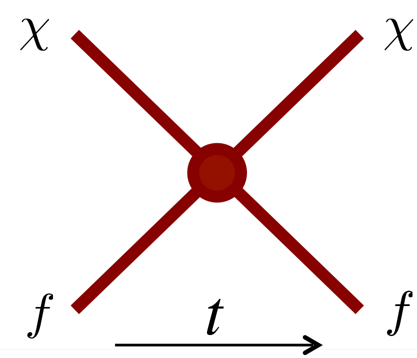


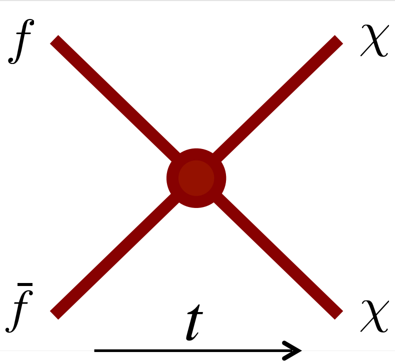
LIMITATIONS & ASSUMPTIONS



- $\langle v\sigma \rangle$: velocity profile
- $\langle v\sigma \rangle$: annihilation model $\sigma_{\mathrm{annihil}}$
- ρ_χ profile
- single DM species
- Decay channel

- velocity profile, especially at high v
- ρ_χ profile + smooth halo
- Rotation of galactic disk → DM wind
- type of interaction
- single DM species



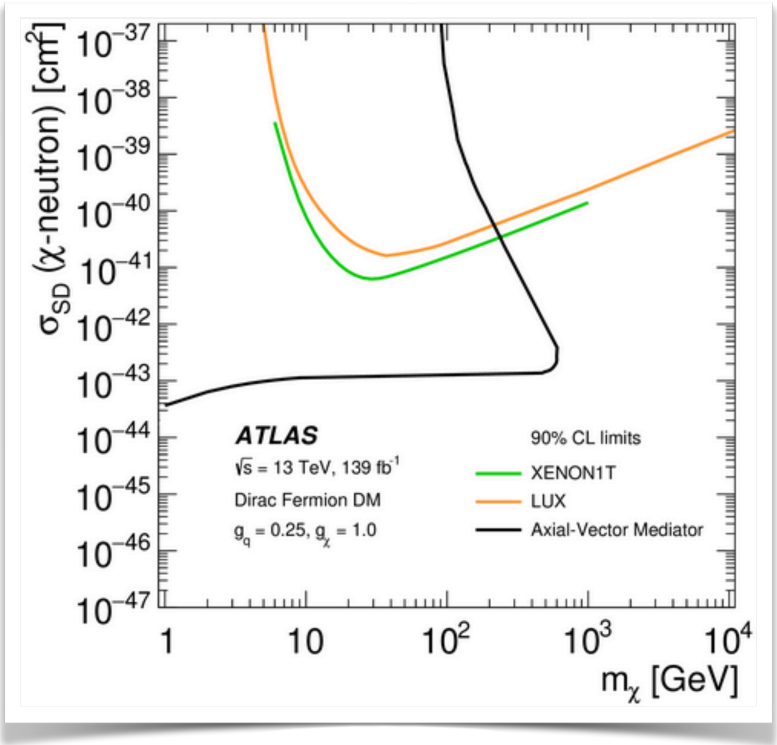


- Model for interaction
- mediator couplings + quantum numbers
- Often minimal flavour violation (flavour physics)

Single vs several DM species:

Colliders

NO change in limits or better limit (conservative)



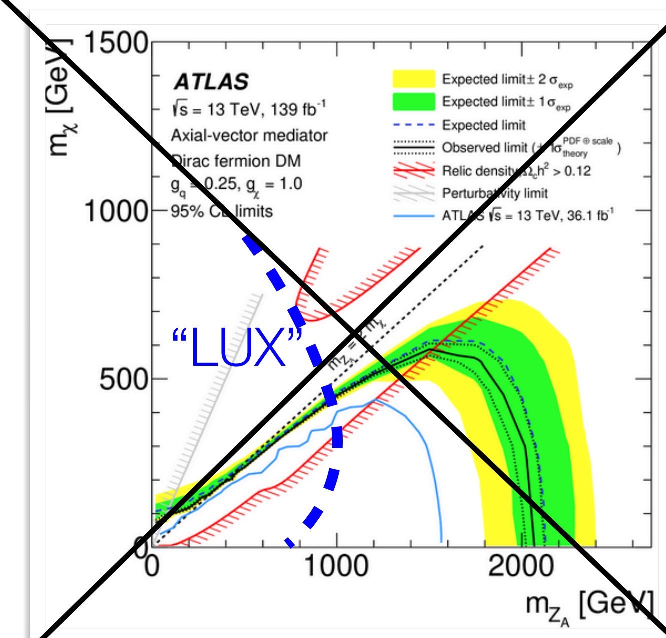
Direct detection

Limits become weaker

$$\rho_{\rm DM} = \rho_{\chi_1} + \rho_{\chi_2} + \ldots$$

(ρ_{χ_i} enters limits on $\sigma_{\chi-N}$)

EFT problems at $Q^2 \gtrsim 0.5$ TeV



Thank you!