Second HEP Graduate Workshop
University of Mohamed Boudiaf
M'sila – Algeria, 03-05 April 2021

Dark Matter Searches at Colliders

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Academia Sinica, Taiwan

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ACADEMIA SINICA

ATLAS EXPERIMENT

Outline: part-II

- Production at Colliders
- DM Signatures and Searches
- Dark Sector at the LHC
- Future Prospects

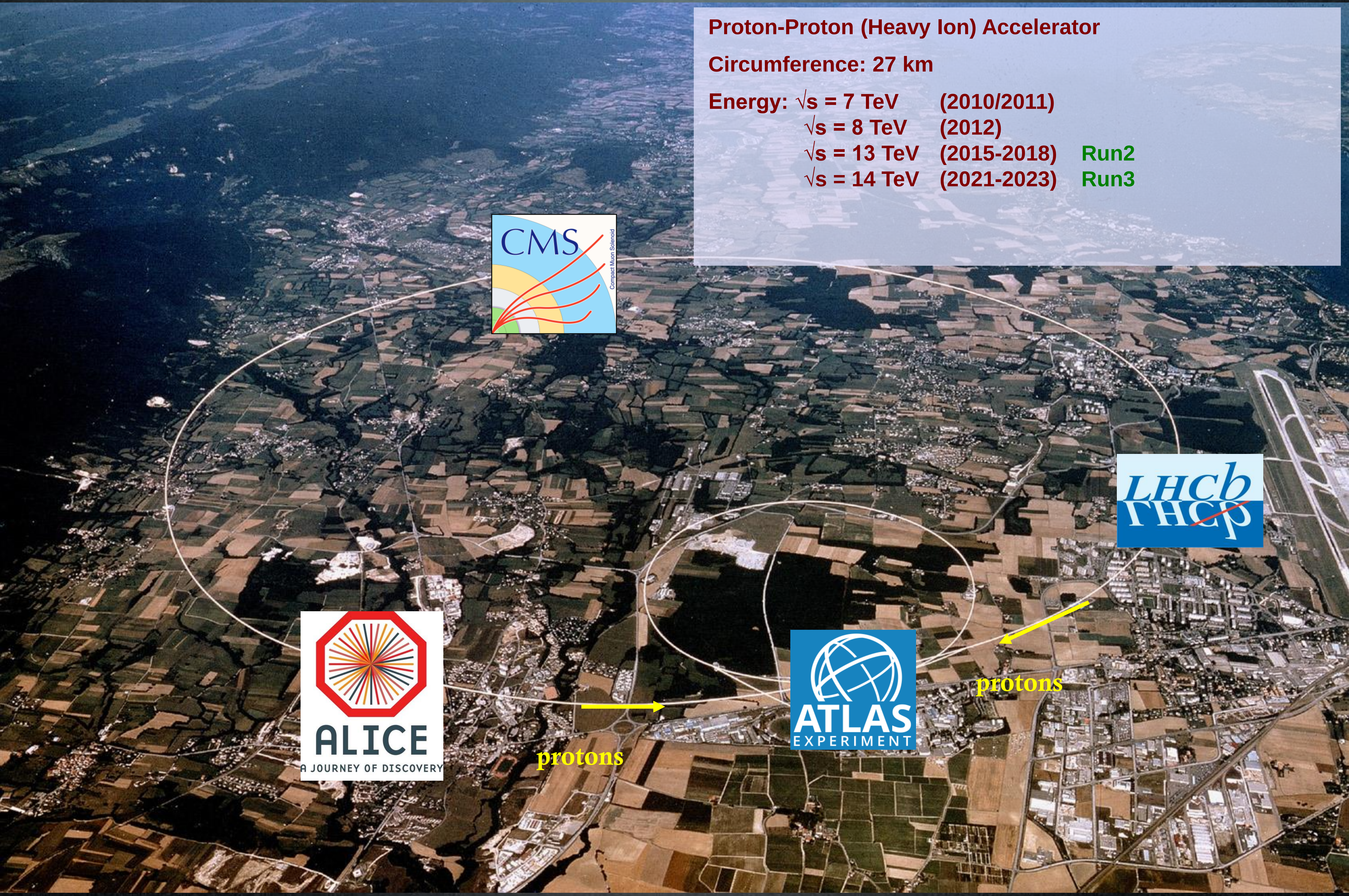
Production at colliders

Proton-Proton (Heavy Ion) Accelerator

Circumference: 27 km

Energy:

$\sqrt{s}$ = 7 TeV	(2010/2011)	
$\sqrt{s}$ = 8 TeV	(2012)	
$\sqrt{s}$ = 13 TeV	(2015-2018)	Run2
$\sqrt{s}$ = 14 TeV	(2021-2023)	Run3



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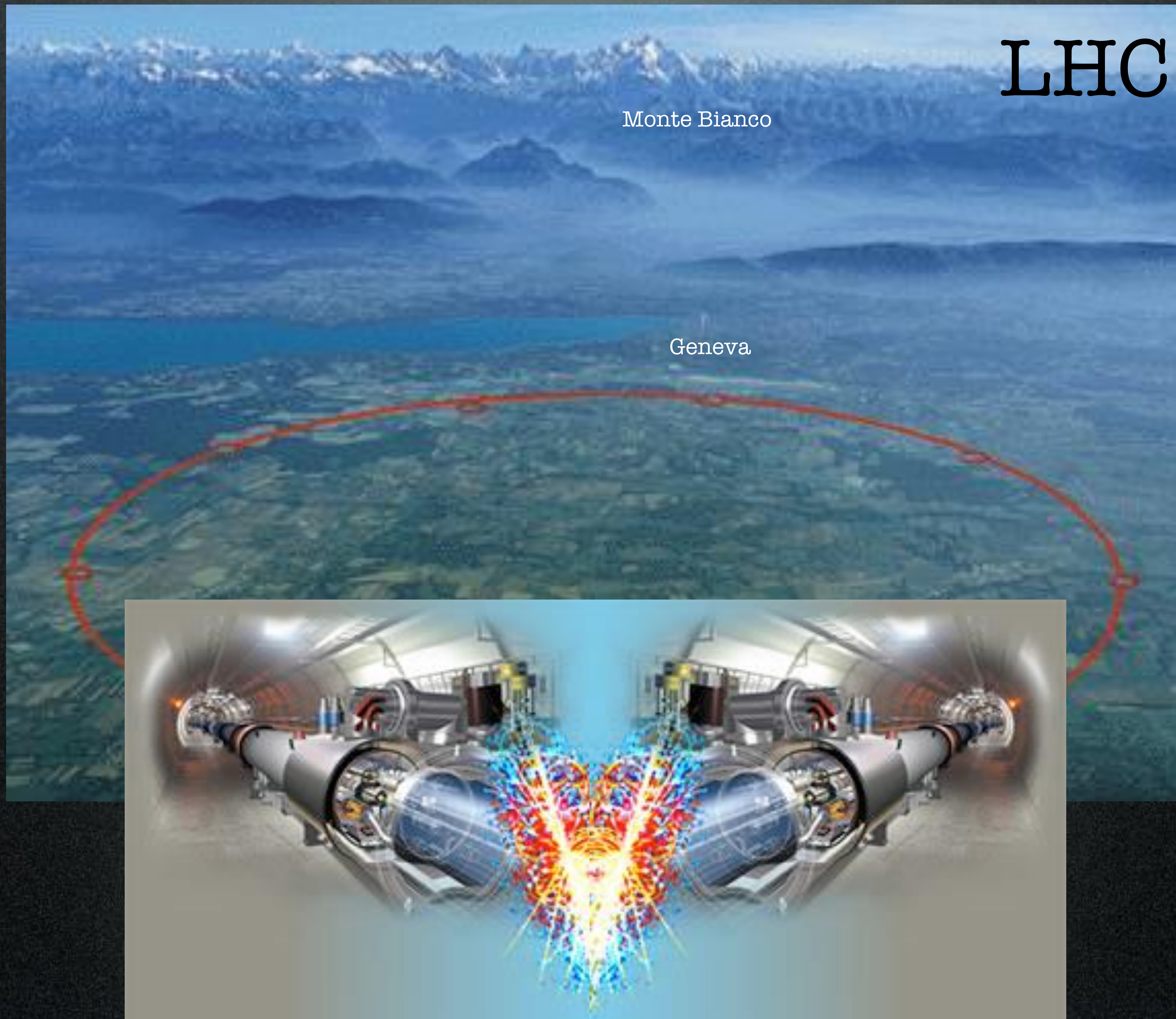

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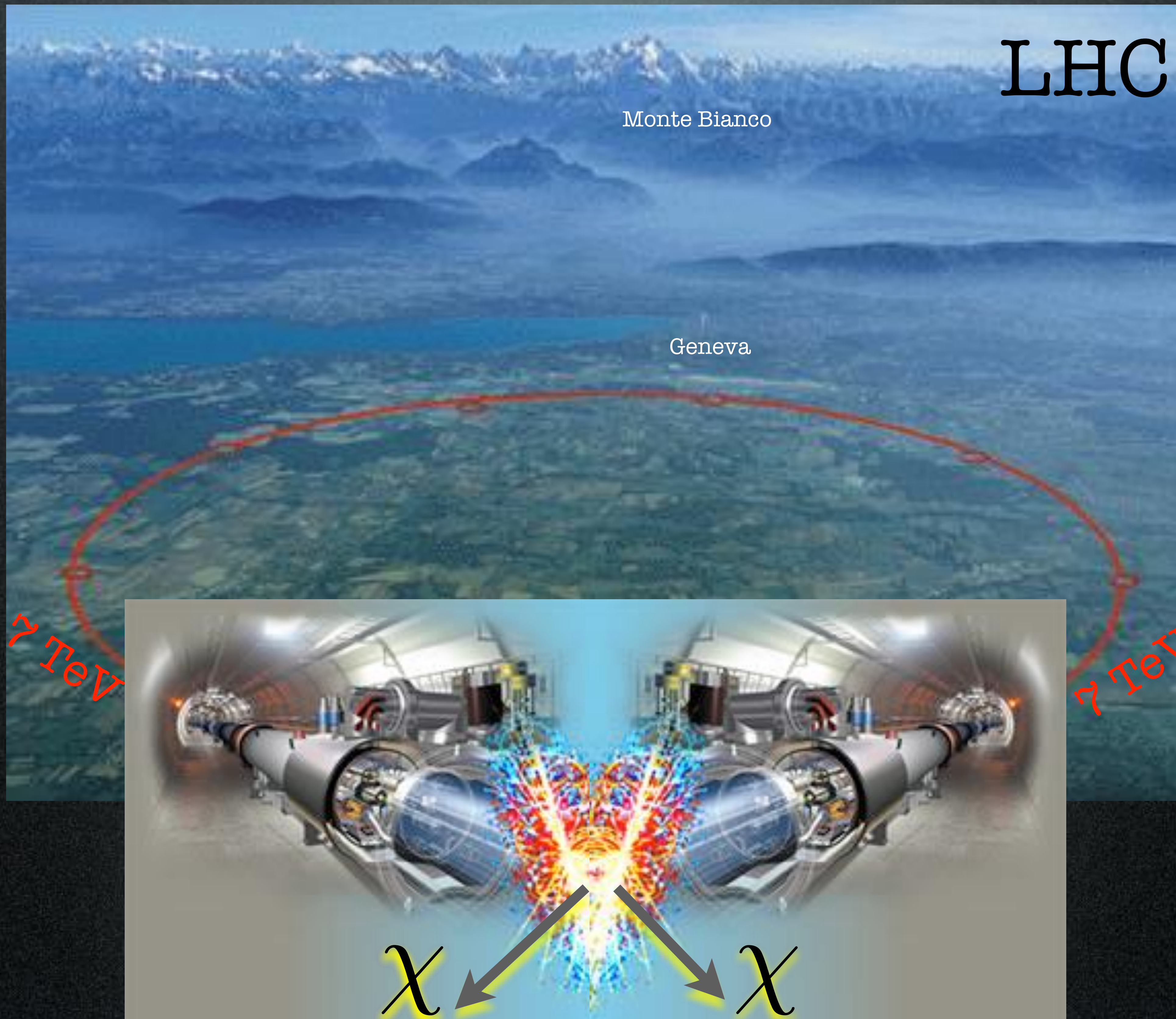

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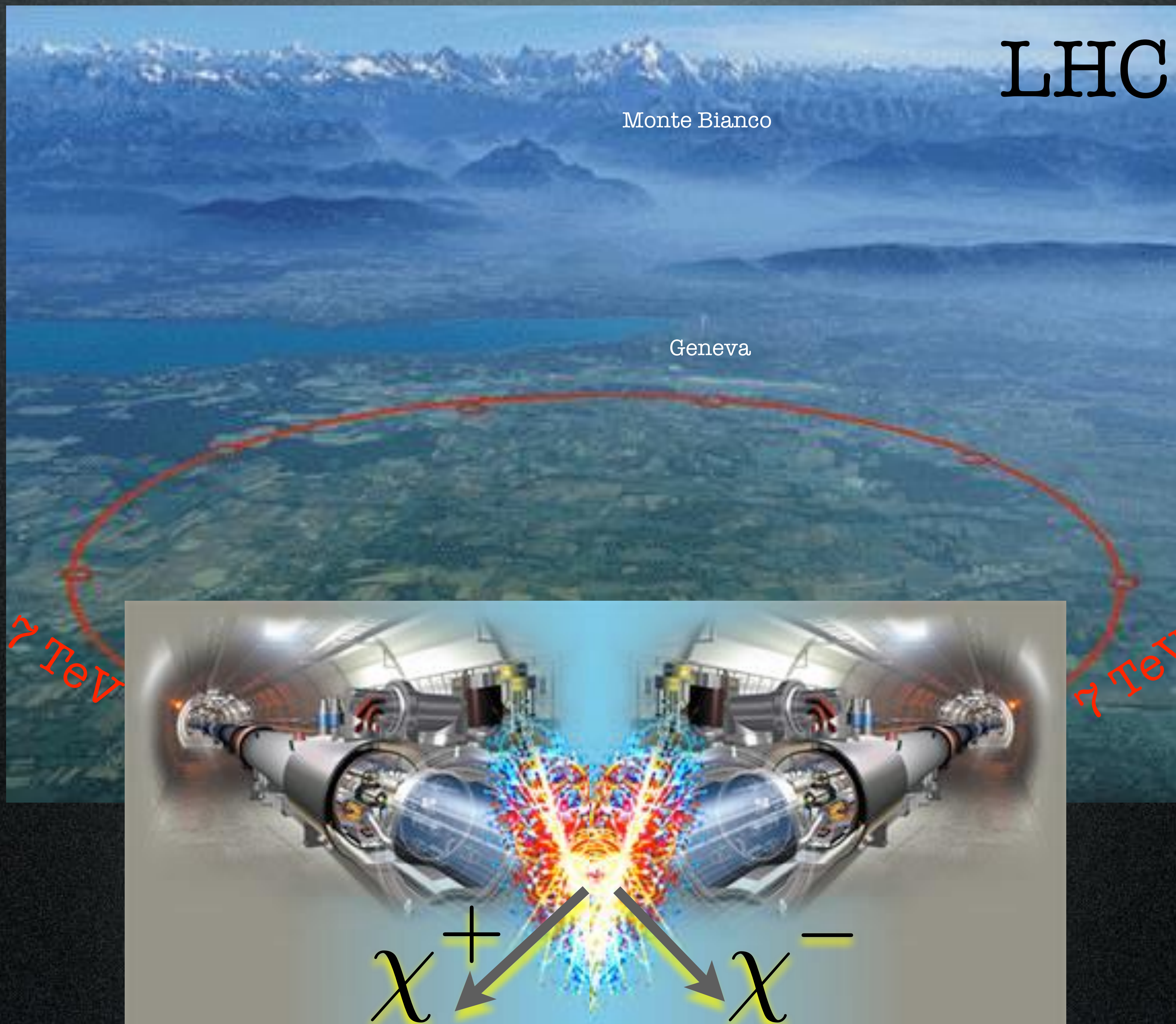

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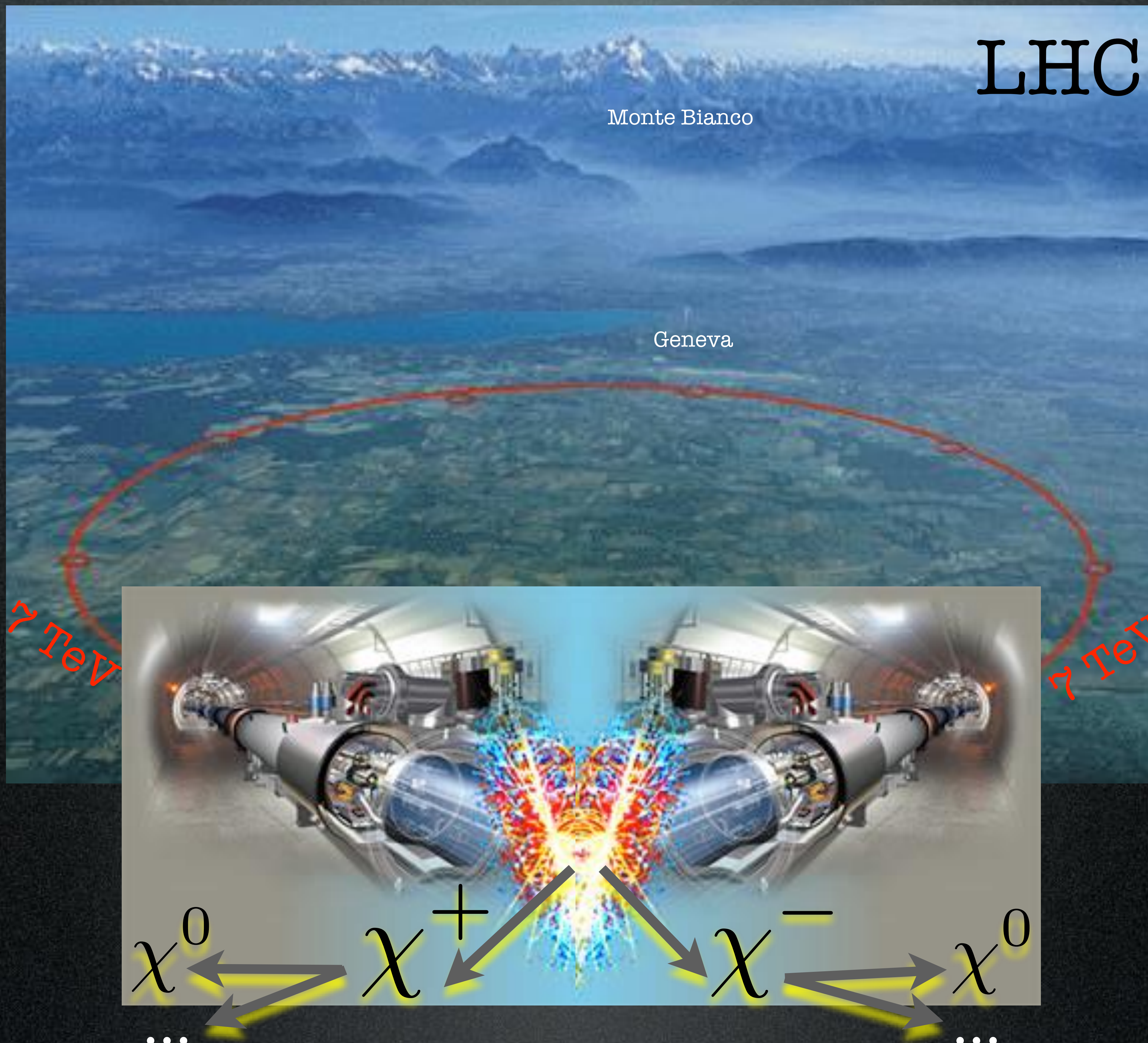

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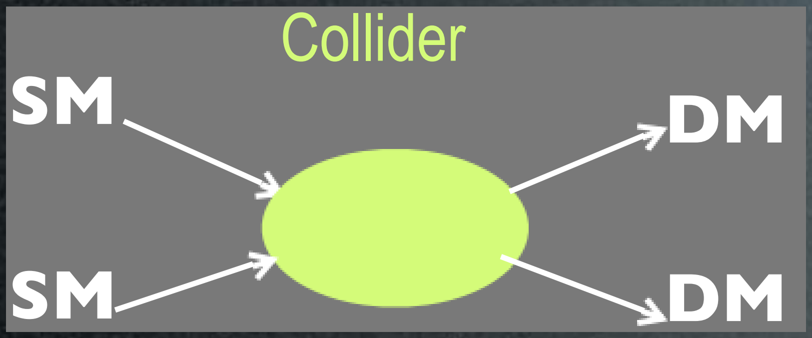
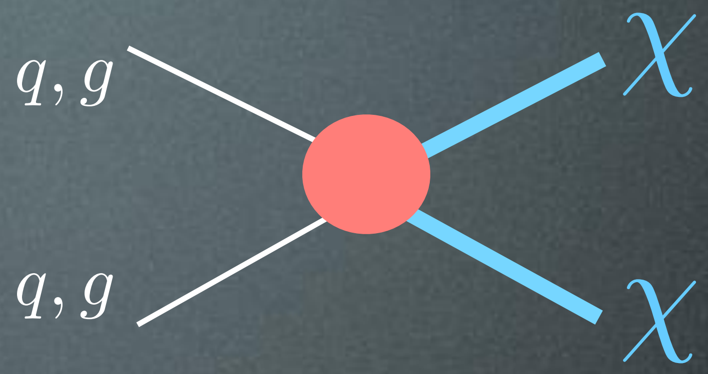


At LHC:



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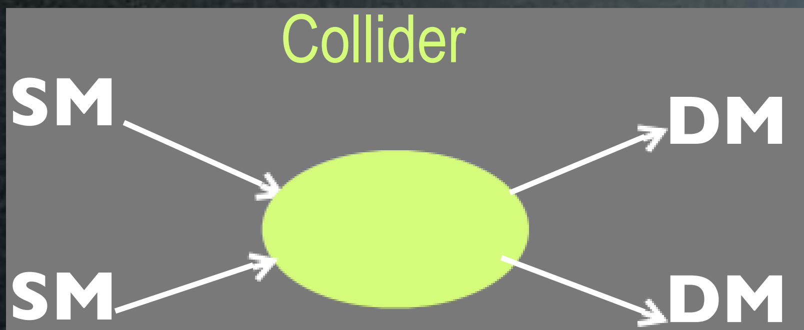

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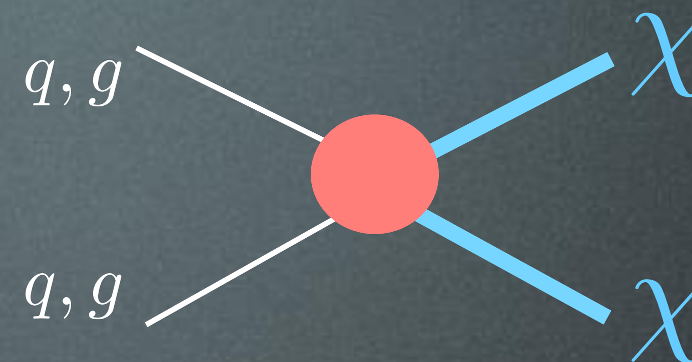
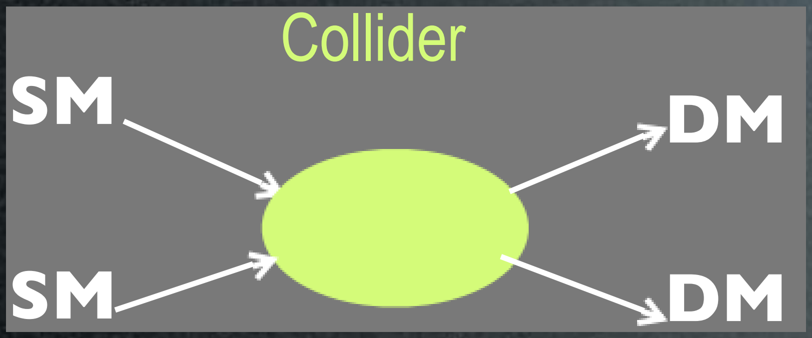


'Problem' is: DM flies away

Production at colliders



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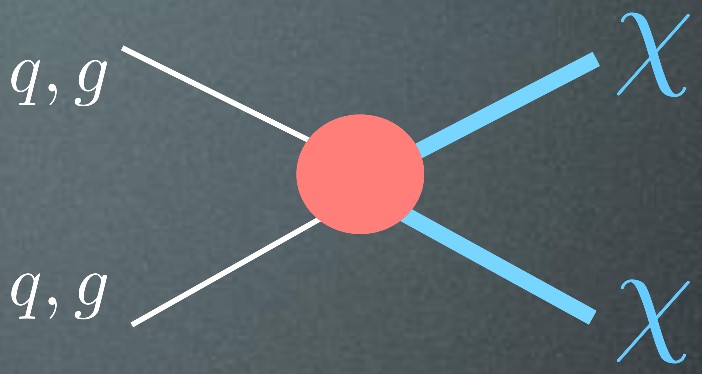
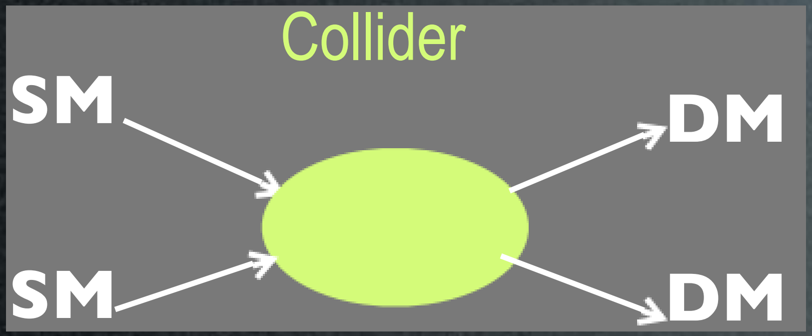


'Problem' is: DM flies away

Signature is: missing energy

Production at colliders



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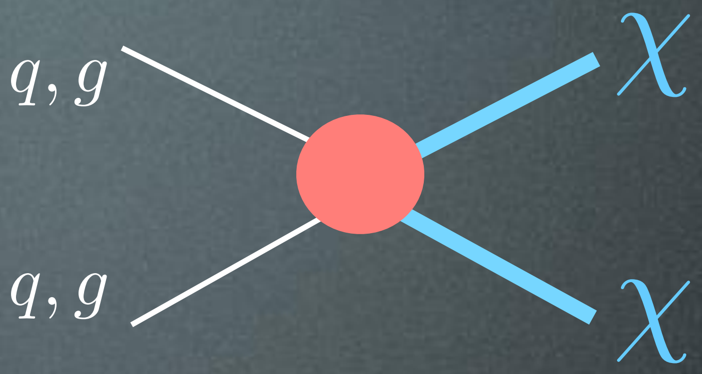

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transverse

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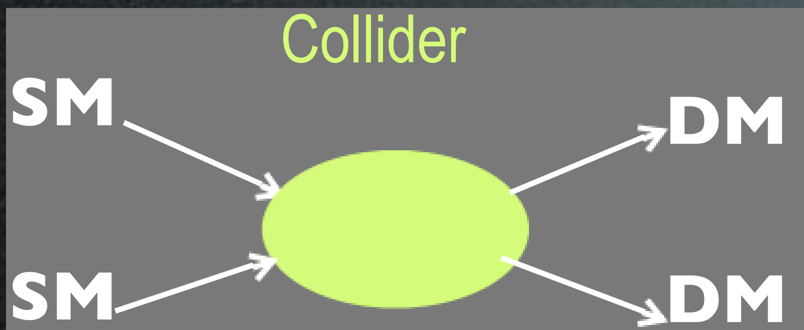

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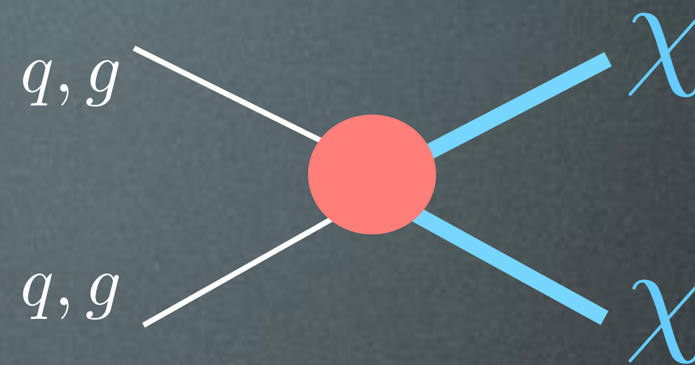

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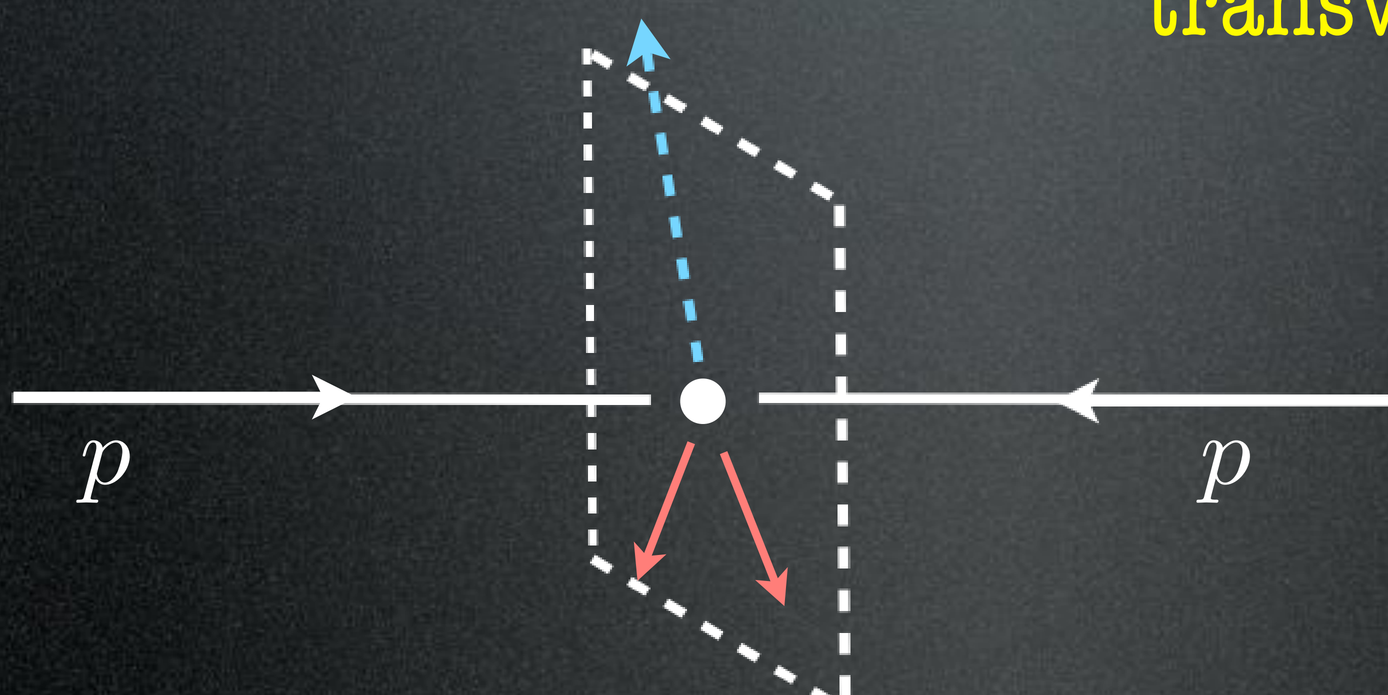


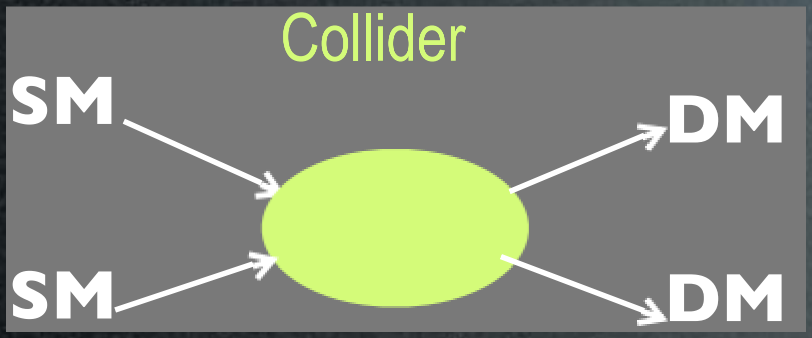
Before collision: $\vec{P}_T^{\rm tot} \equiv 0$

(NB: $\vec{P}_L^{\rm tot} \neq 0$ in general)

After collision: $\vec{P}_T^{\rm vis} \stackrel{?}{=} 0$

If $\neq$, then 'MET'

Production at colliders



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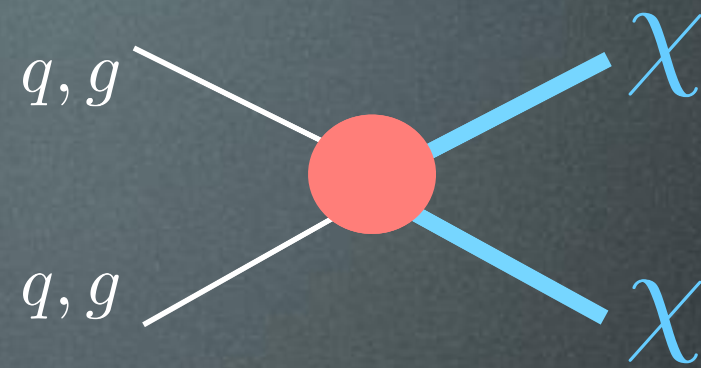

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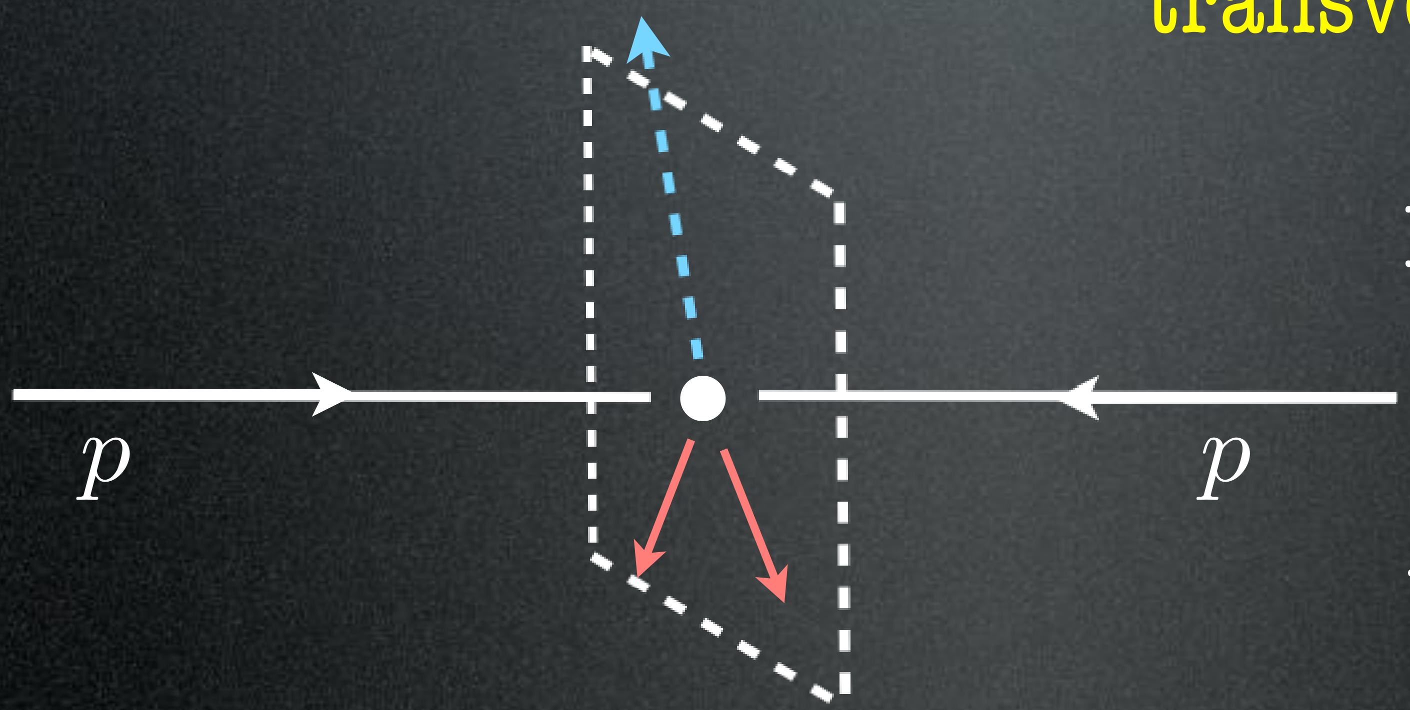

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If ≠, then 'MET'

Background: neutrinos (e.g. W⟶eν)

- model your background and look for anomalies
- construct kinematic variables sensitive to χ mass

Production at colliders

OK, MET is the crucial signature. Then what else?

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the bare minimum — lots of things

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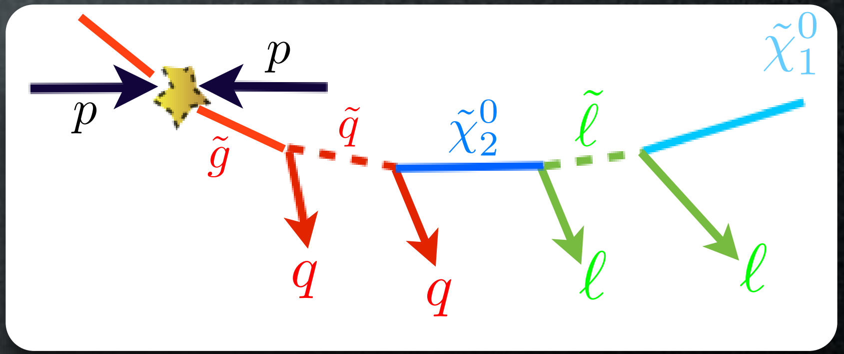

'trigger on 4j+4l+MET...'

huge literature

- well studied (M_{T}^{2}...)
- model dependent

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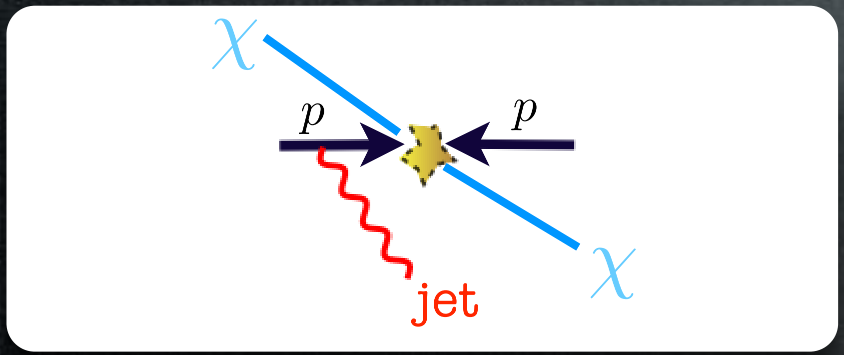
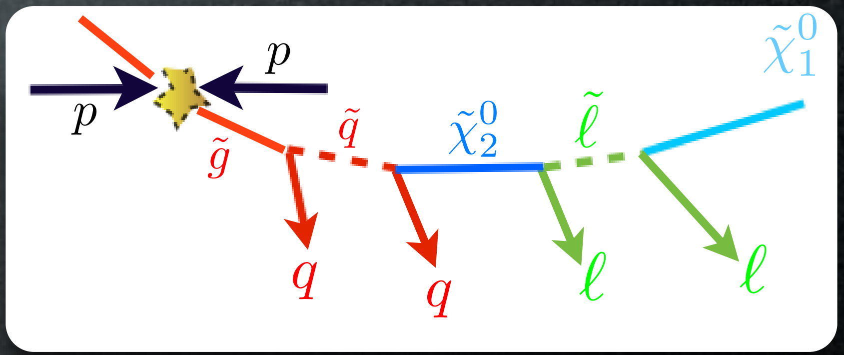


'mono-jet'

'started' by J.Goodman et al., 1008.1783

- 'new'
- model independent



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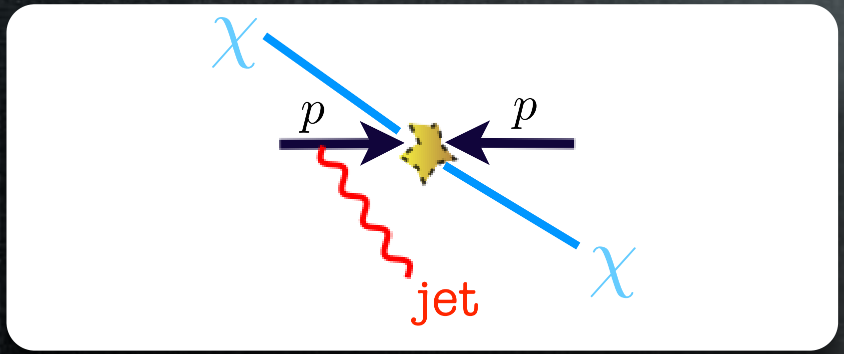

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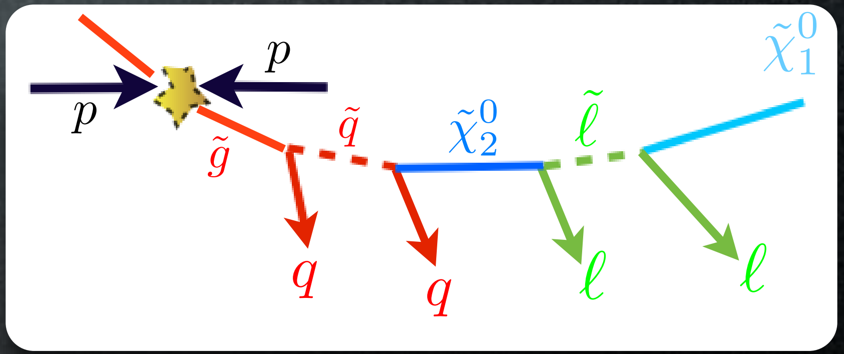

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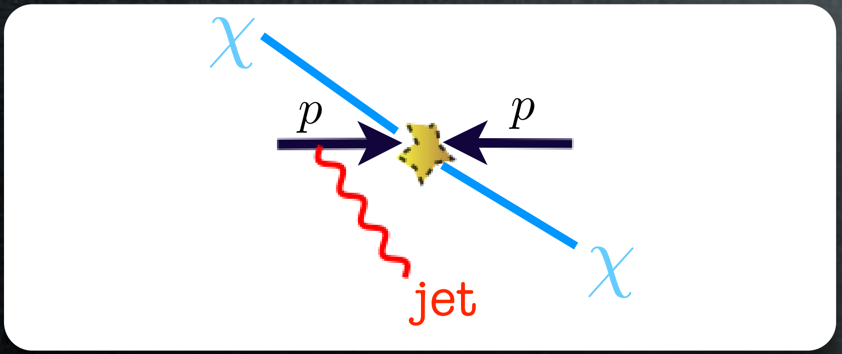

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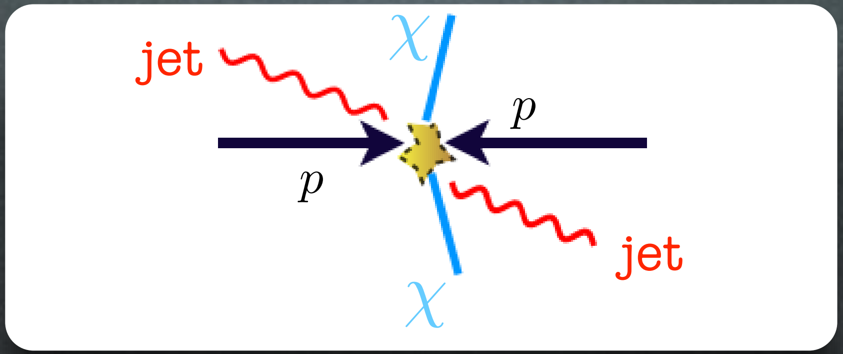

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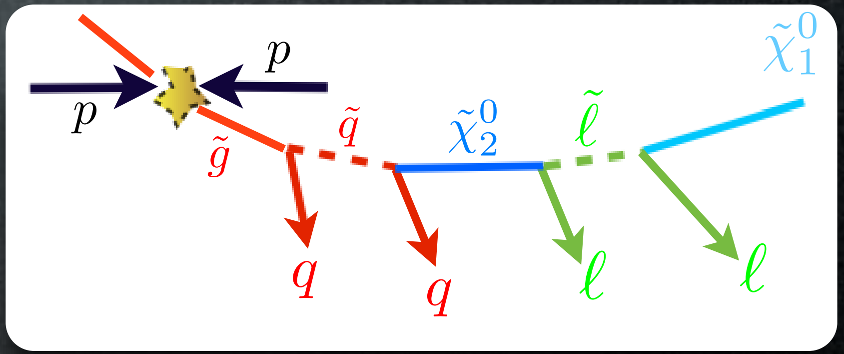

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⇓

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‘(forward) di-jets’

- ‘clean’ topology
- flexible interpretation (see later)

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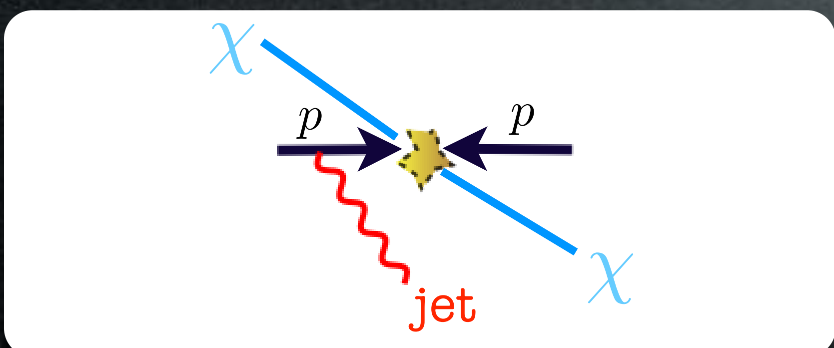

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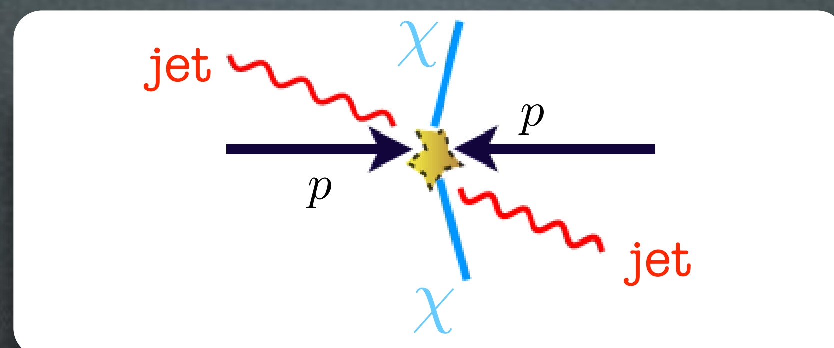

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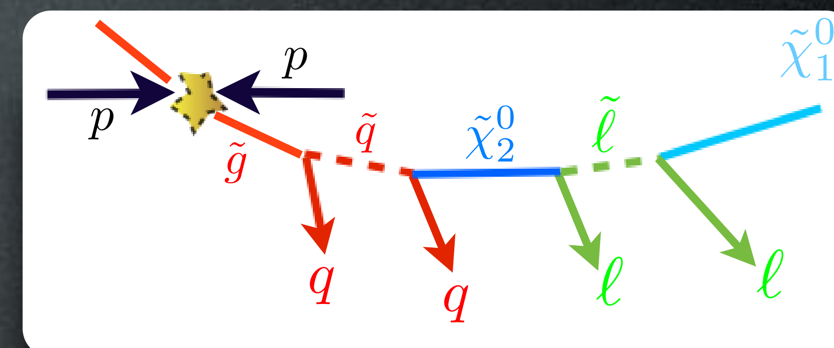

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NB: not an exhaustive list

Production at colliders

OK, given what we (do not) see, how do we interpret?

effectively	simplified models	a simple model	a full theory

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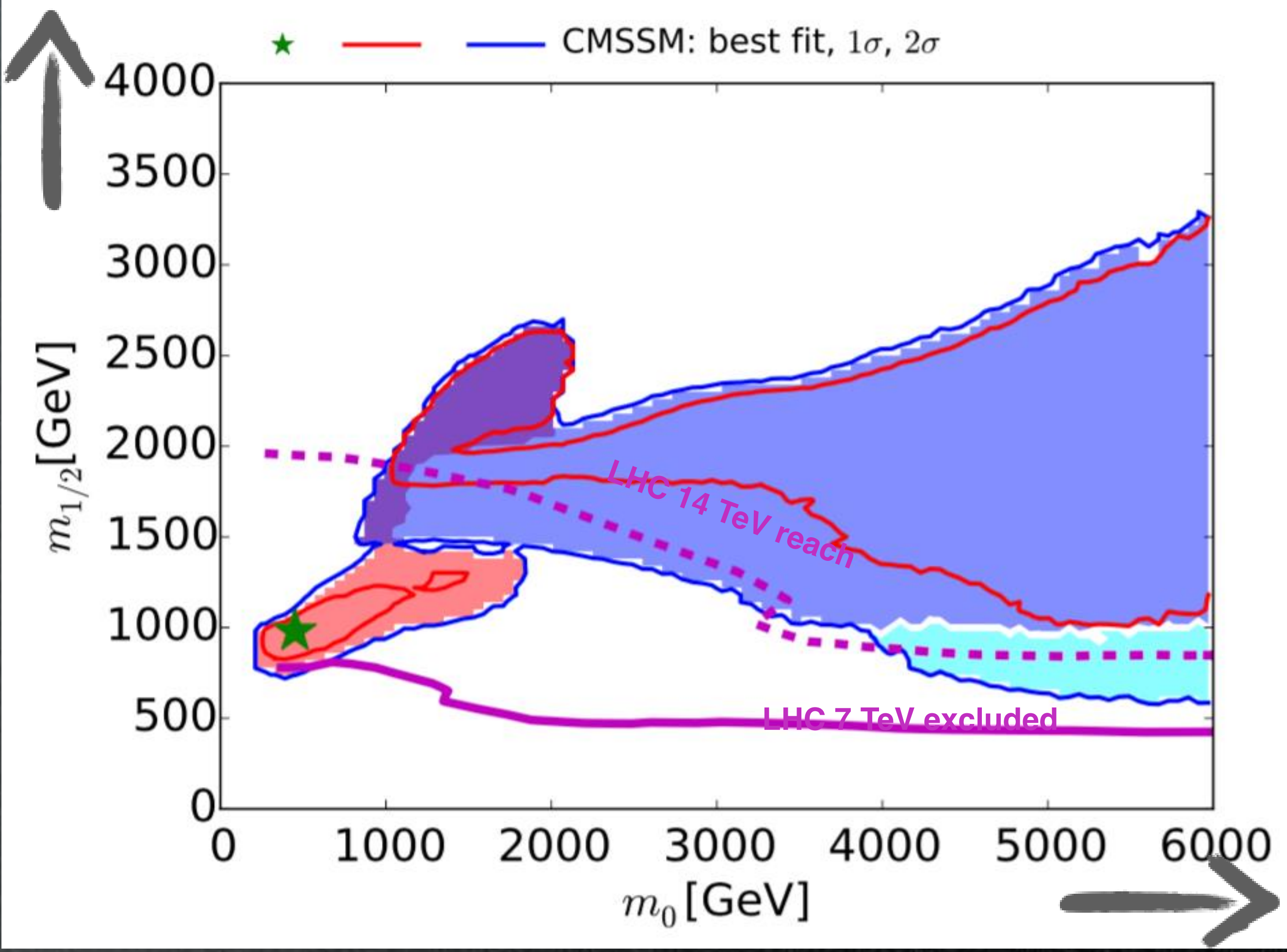
E.g. SUSY: cMSSM, pMSSM...

parameters: tens (or even hundreds!)

the glorious m_0 /$m_{1/2}$ plane:



filled areas get Ω_{DM} right due to:

stau coann.	hybrid	stop coann.
A/H funnel	$\tilde{\chi}_1^{\pm}$ coann.	focus point

Bagnaschi, Buchmuller, Ellis, Heinemeyer, Olive, Weiglein... 1508.01173

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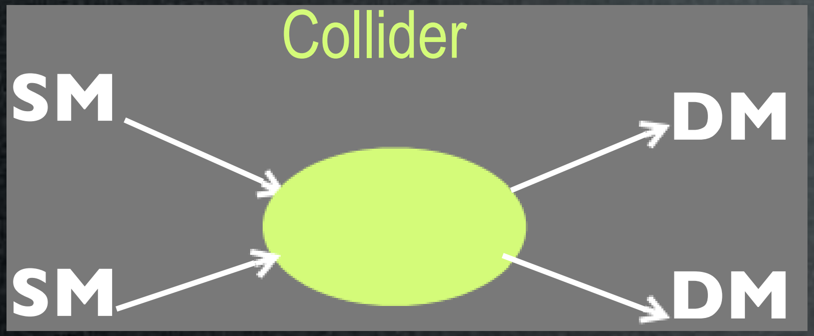

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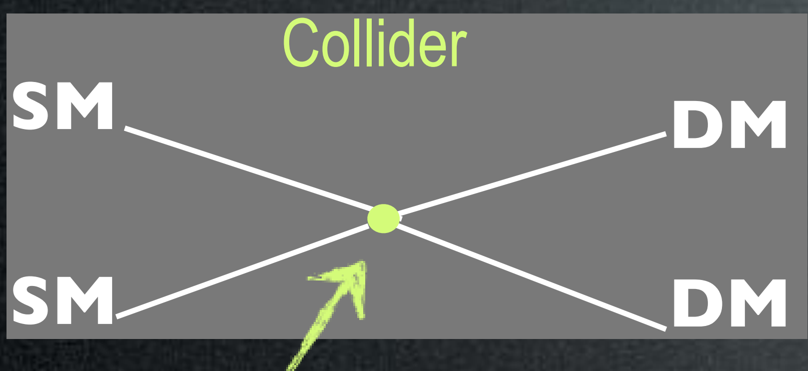

$$\frac{g}{\Lambda^n}$$

$$\frac{1}{\Lambda_1^2}[q\bar{q}][\chi\bar{\chi}]$$

$$\frac{1}{\Lambda_2^2}[q\gamma_\mu\bar{q}][\chi\gamma^\mu\bar{\chi}]$$

parameters: Λ (assuming $g \simeq 1$)

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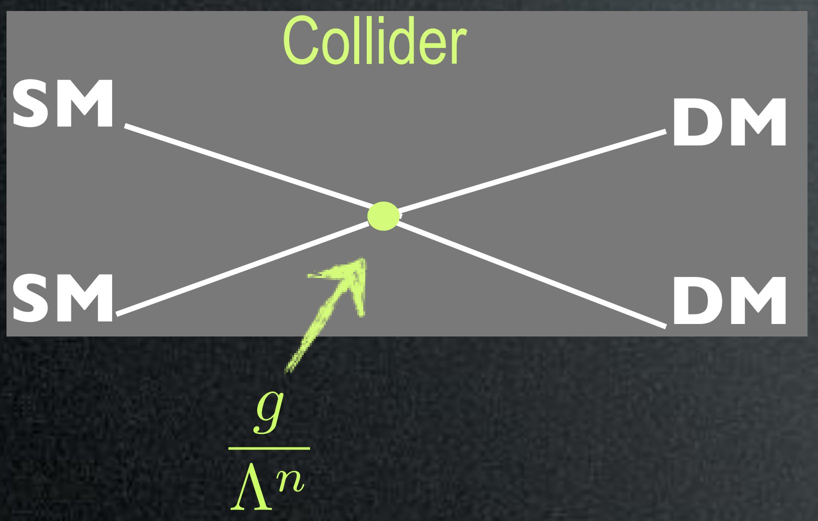

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar\chi\chi\bar q q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar\chi\gamma^5\chi\bar q q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar\chi\chi\bar q\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar\chi\gamma^5\chi\bar q\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\gamma^5\chi\bar q\sigma_{\mu\nu}q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar\chi\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar\chi\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar\chi\chi G^{\mu\nu}\tilde G_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar\chi\gamma^5\chi G^{\mu\nu}\tilde G_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar q q$	6	SI
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar q\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar q\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar q\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde G_{\mu\nu}$	6	N/A

Tim Tait, 2010+

and many **many** **many** others

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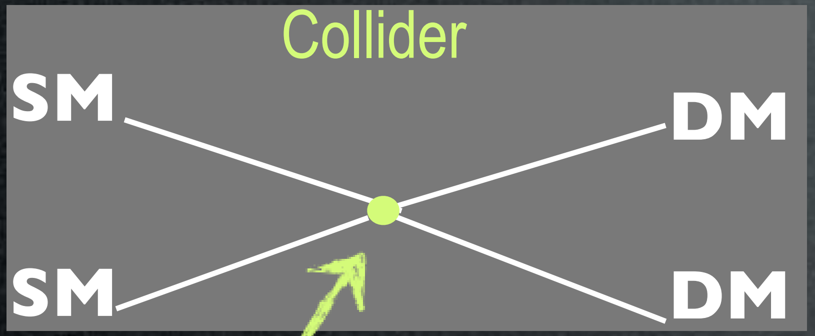
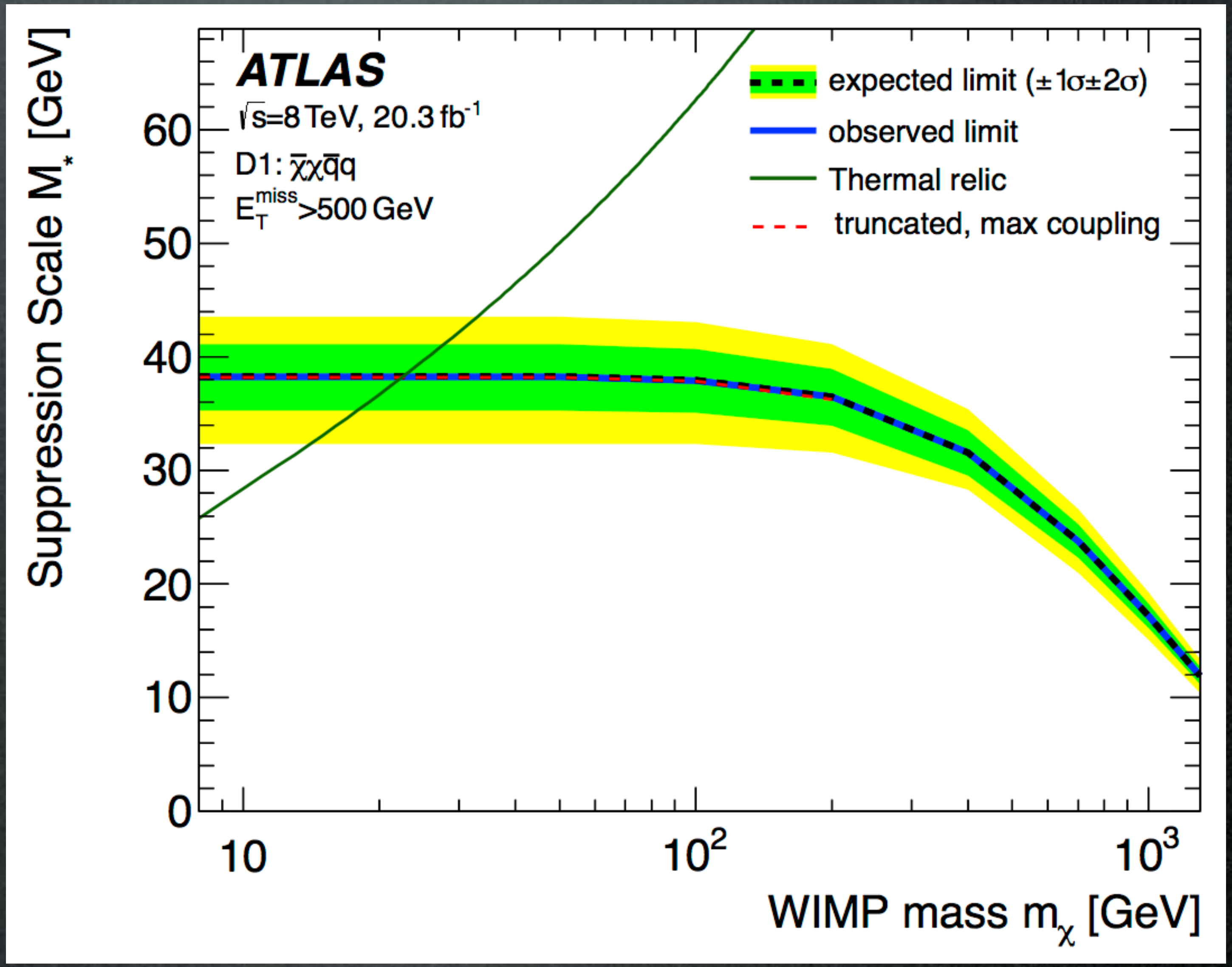


$\frac{g}{\Lambda^n}$

limits on Λ



ATLAS, 1502.01518

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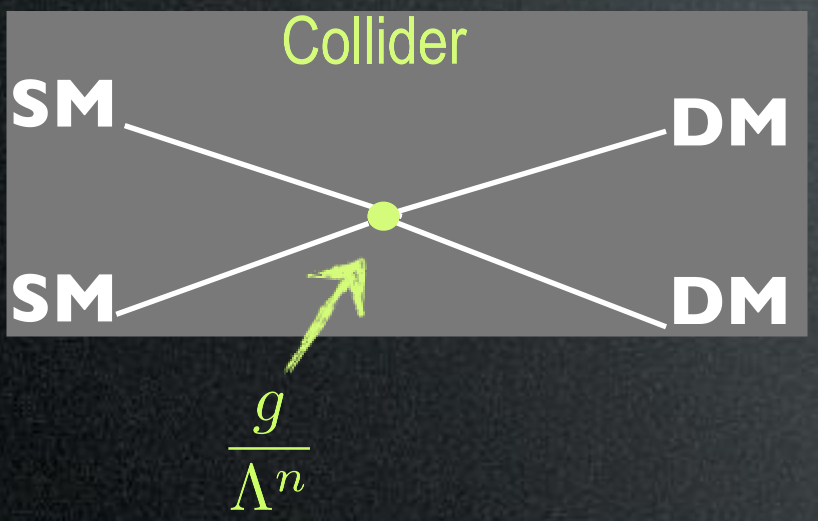

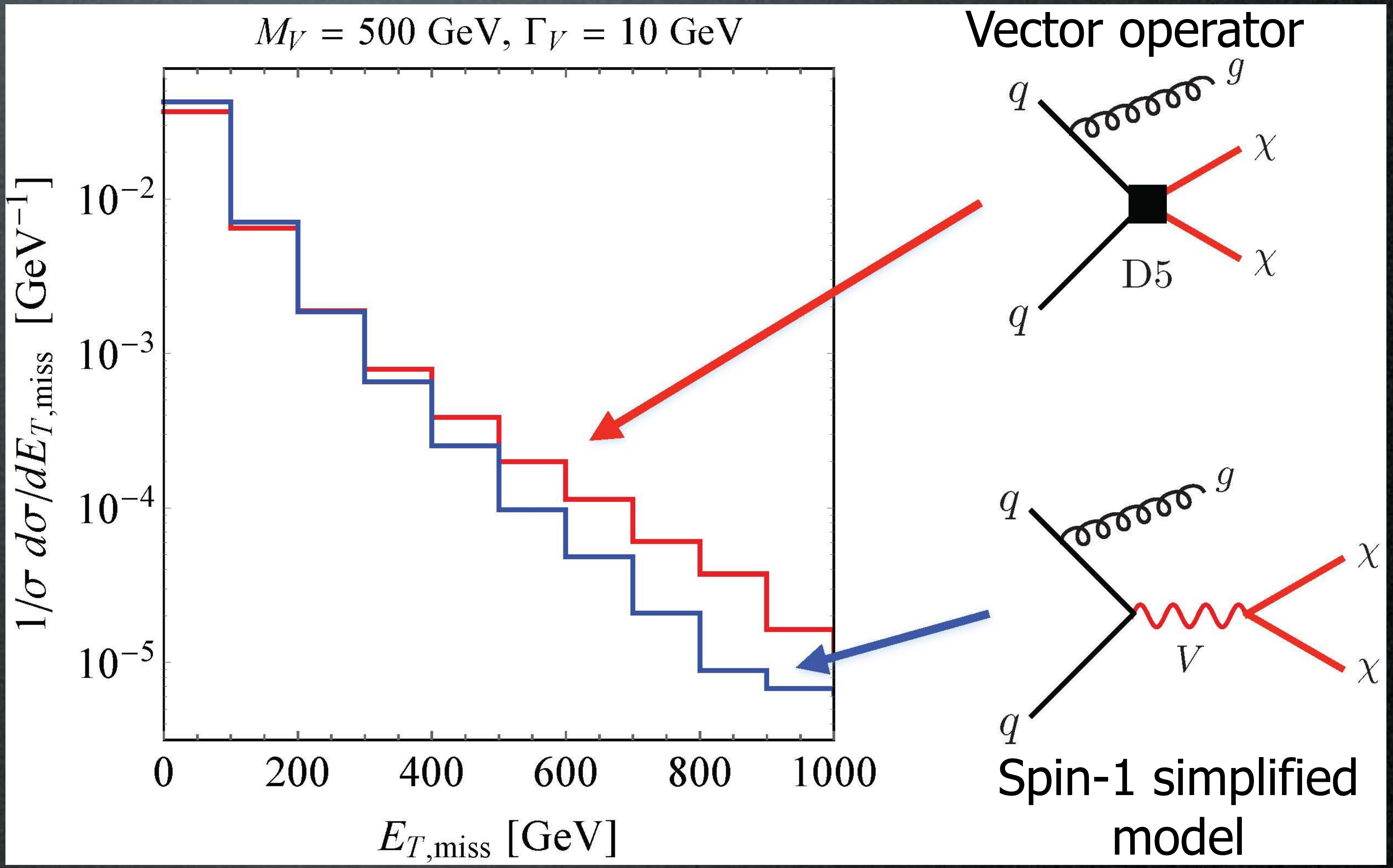

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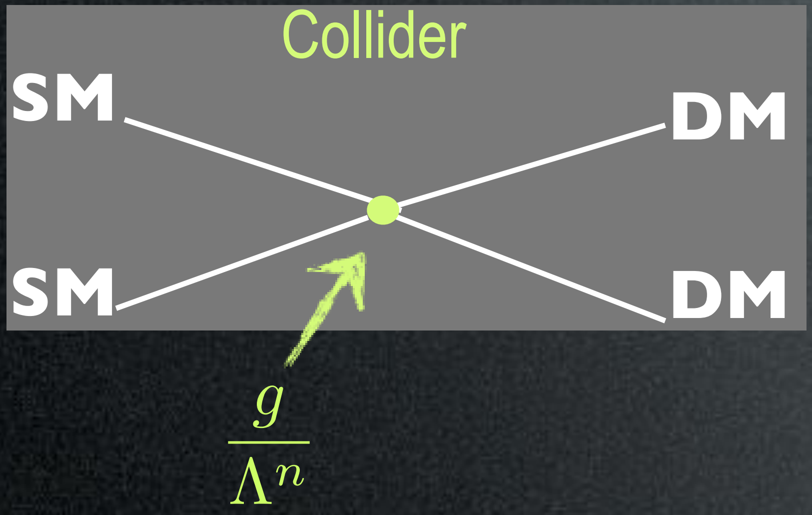

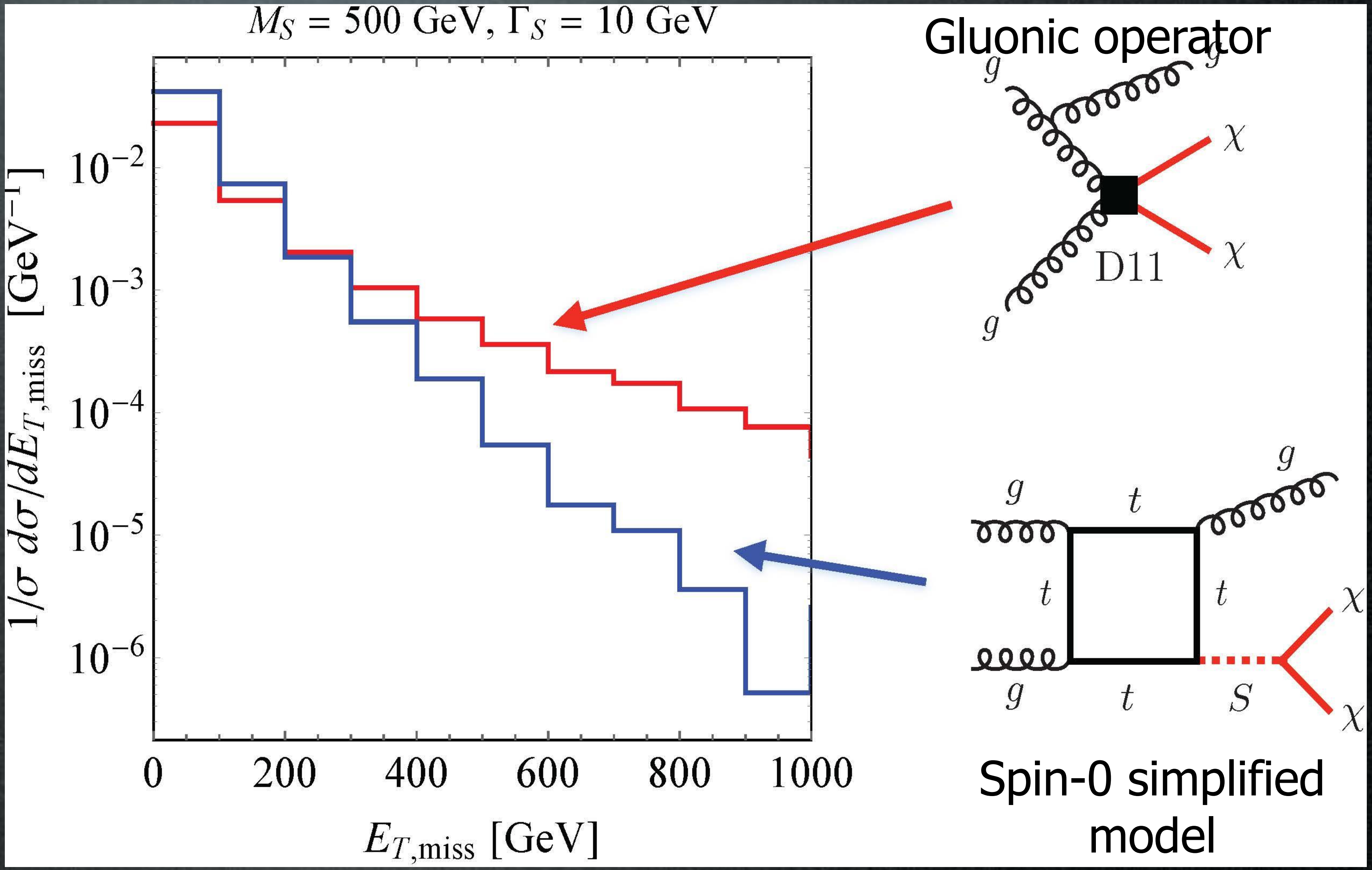

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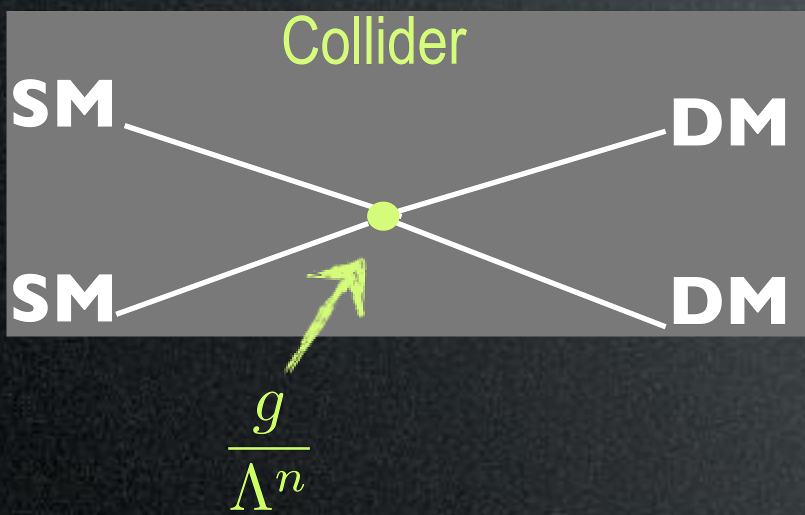
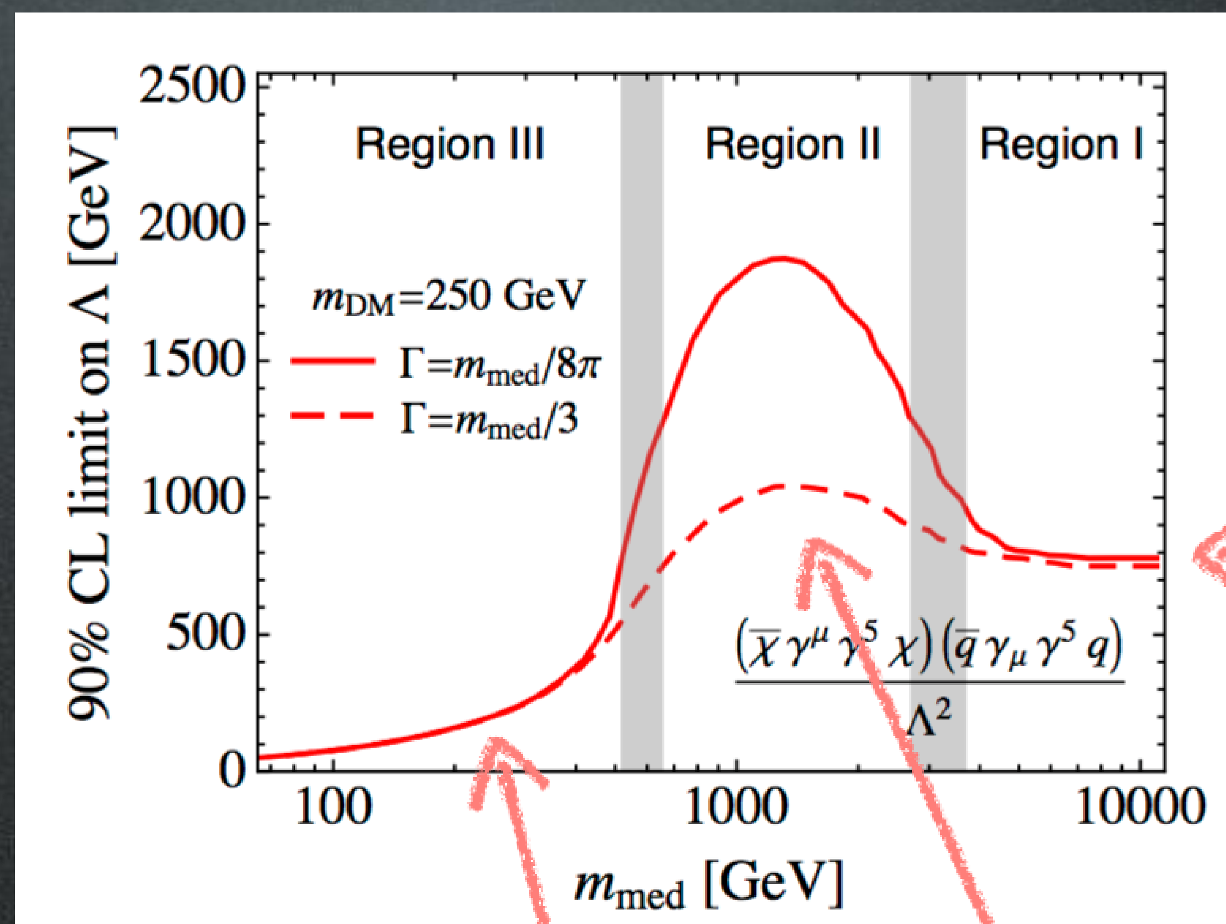


but how 'sensible' are they?



Buchmuller, Dolan, McCabe 1308.6799

EFT puts bounds on Λ

but Λ is actually $\Lambda = \frac{m_{med}}{\sqrt{g_q\, g_\chi}}$

at large m_{med}, the two agree

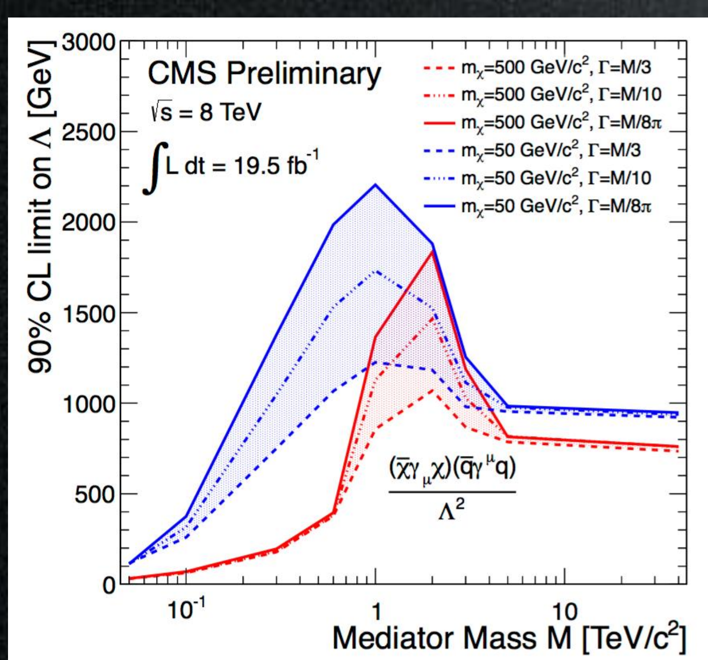
resolving, at small m_{med}, what is the discrepancy?

i.e. what is the limit deduced on Λ, defined as above?

limits agree

EFT bound is much larger

EFT underestimates bound by some % up to factor 2 or more



CMS, CMS PAS EXO-12-048

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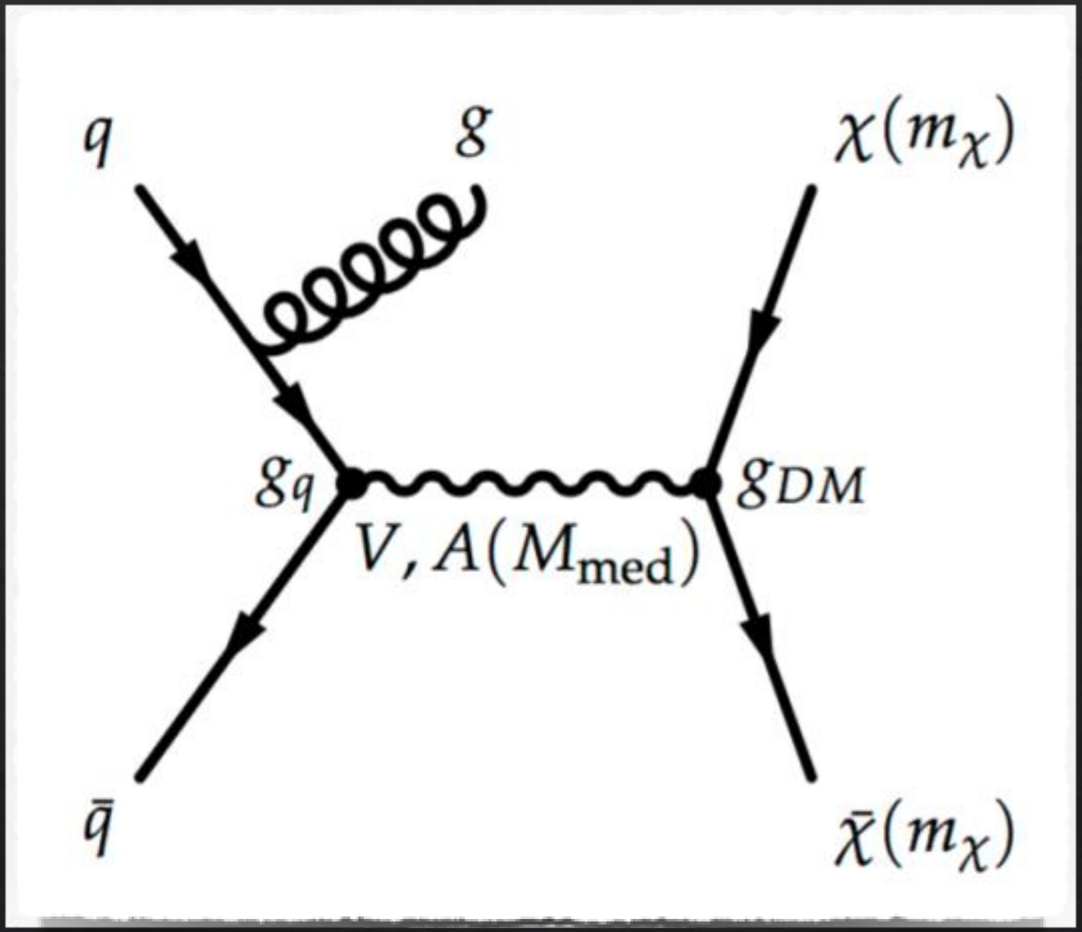
ATLAS+CMS DM forum, 1507.00966



parameters:

$m_\chi, m_{\text{med}}, g_q, g_{\text{DM}}$

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

$$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi.$$

(and similarly for t-channel, scalar mediator, scalar DM etc...)

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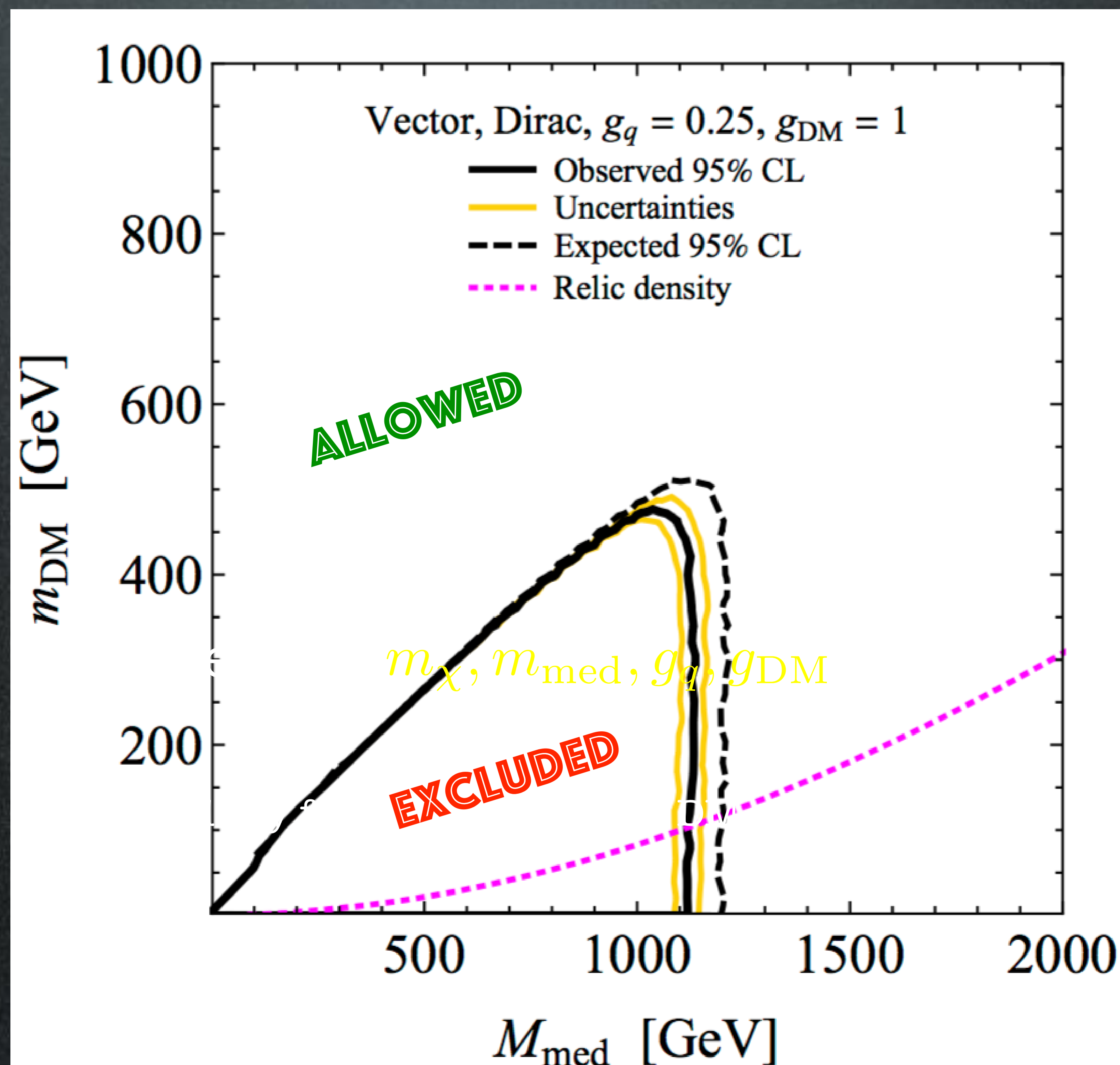
mock plot:



LHCDMWG, 1603.04156

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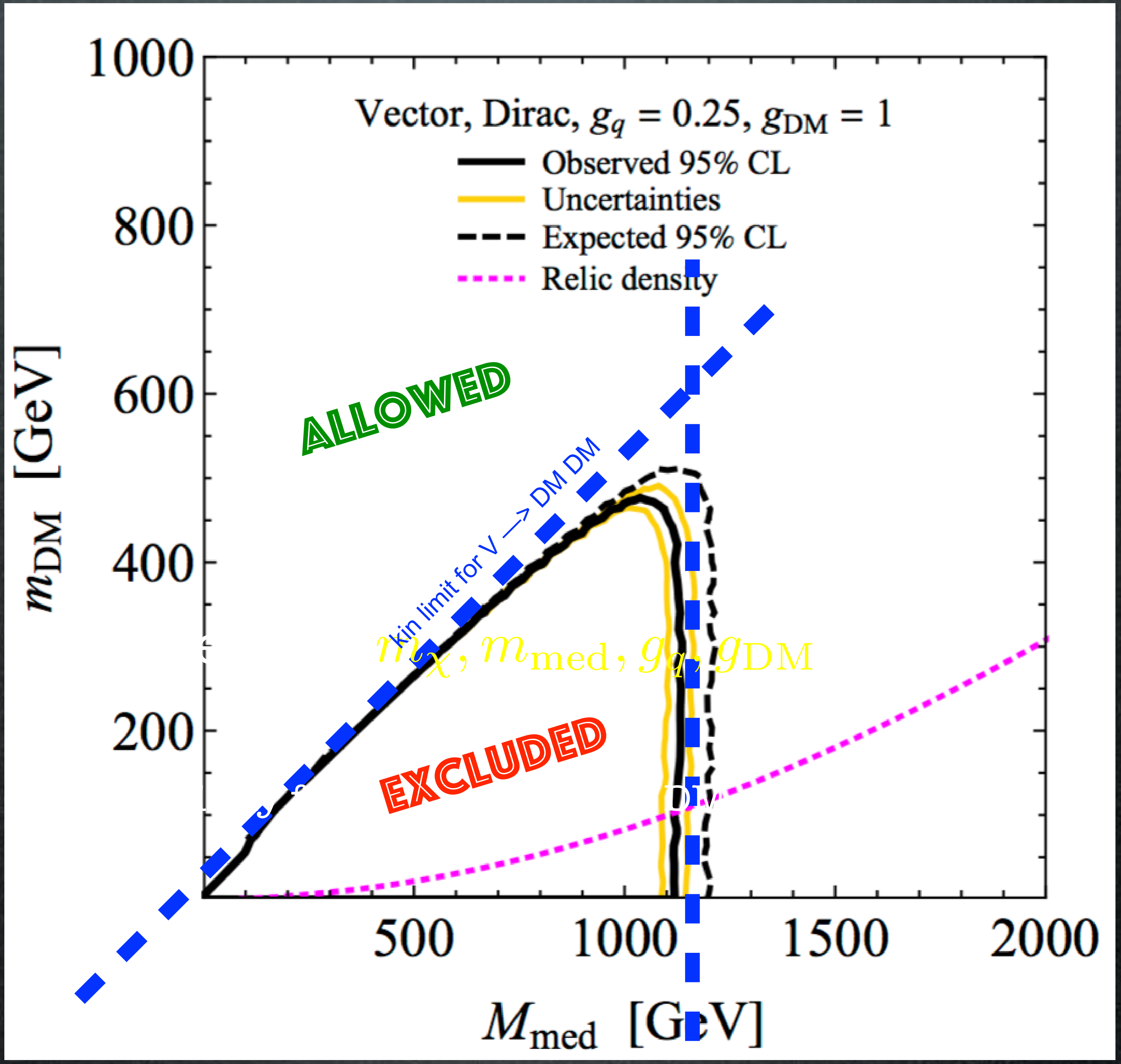

LHCDMWG, 1603.04156

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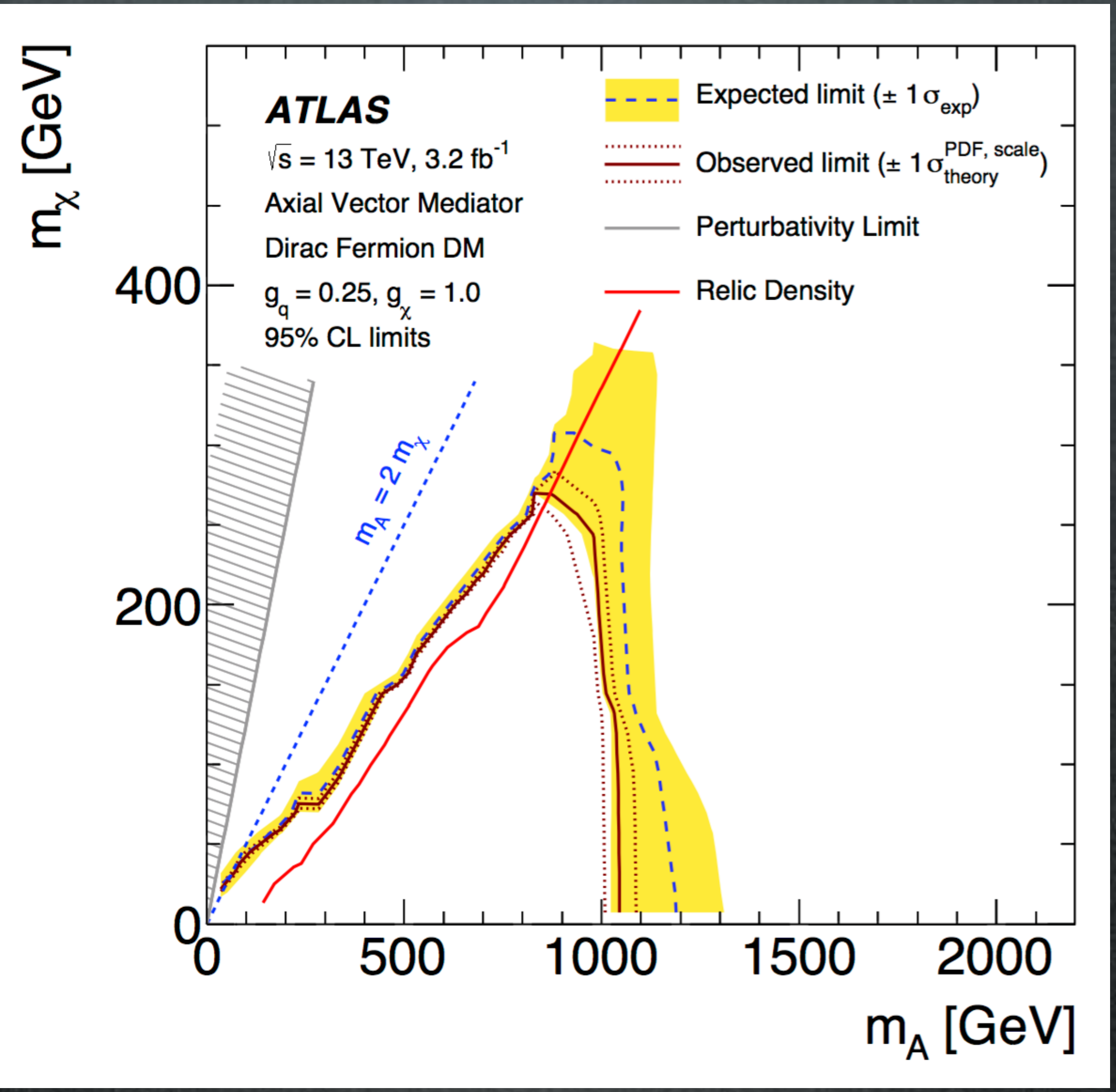
effectively — simplified models — a simple model — a full theory

actual plots:

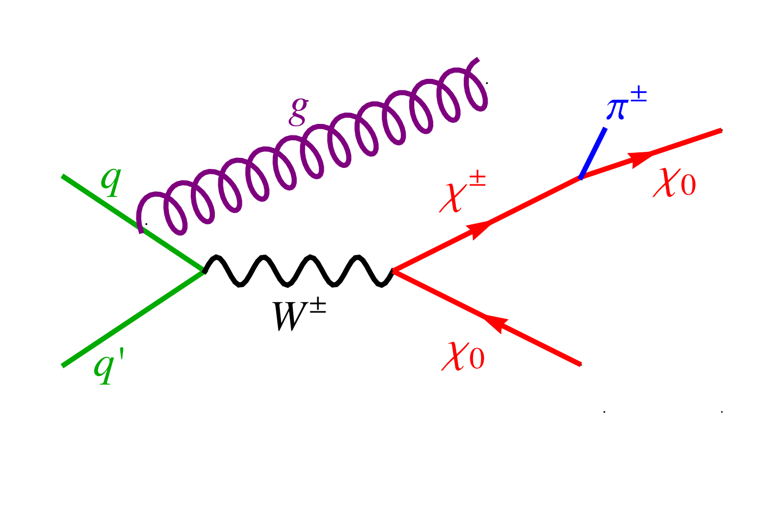


Production at colliders

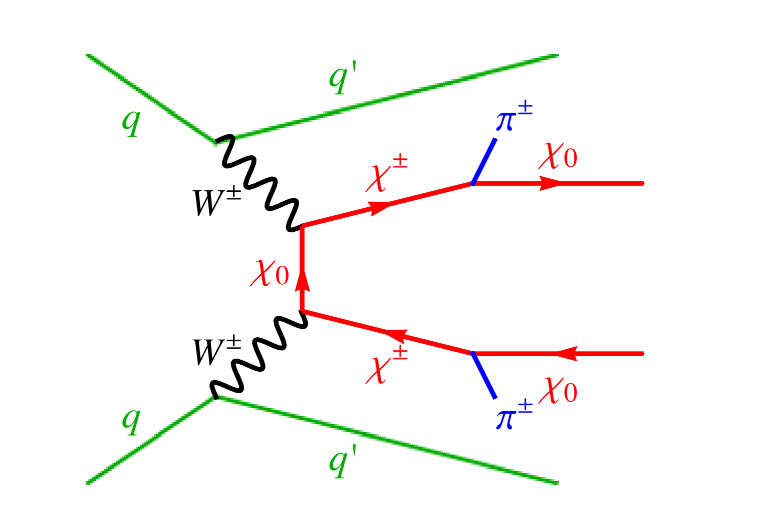
OK, given what we (do not) see, how do we interpret?

effectively — *simplified models* — *a simple model* — *a full theory*

e.g. pure WIMP model (a.k.a. 'Minimal DM')



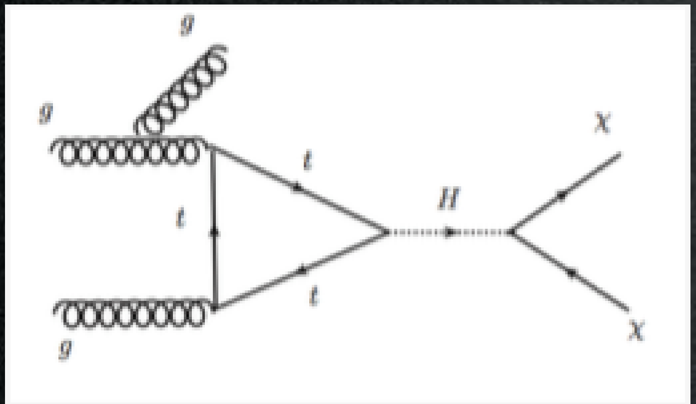
mono-jet



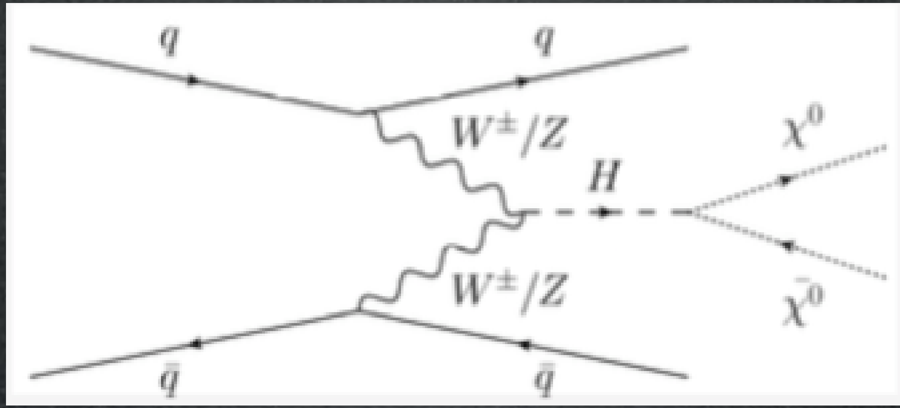
Vector Boson Fusion (VBF)

parameters: $M_{\rm DM}$

e.g. higgs portal models



mono-jet

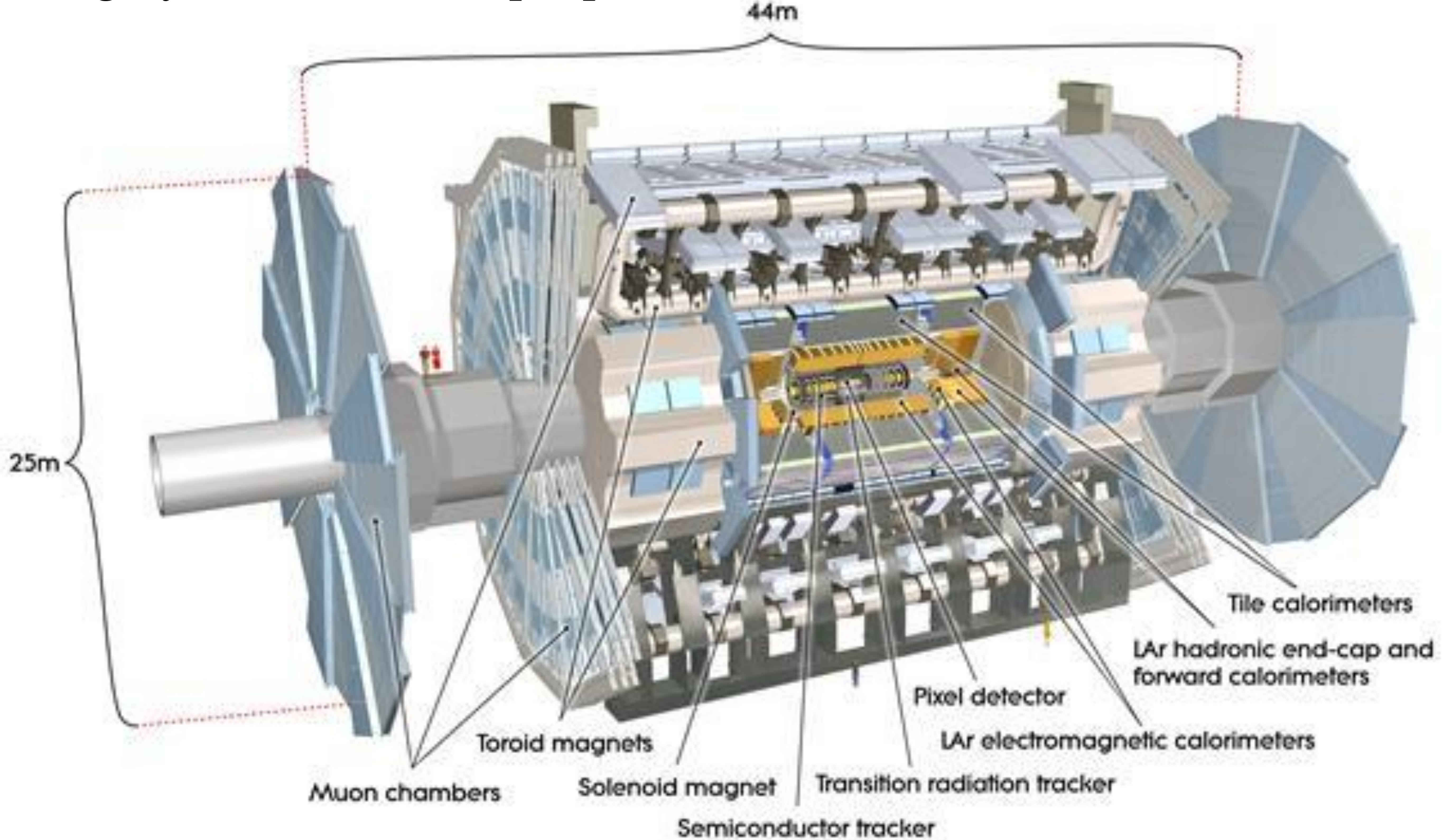


Vector Boson Fusion (VBF)

parameters: $g_{h\chi}$

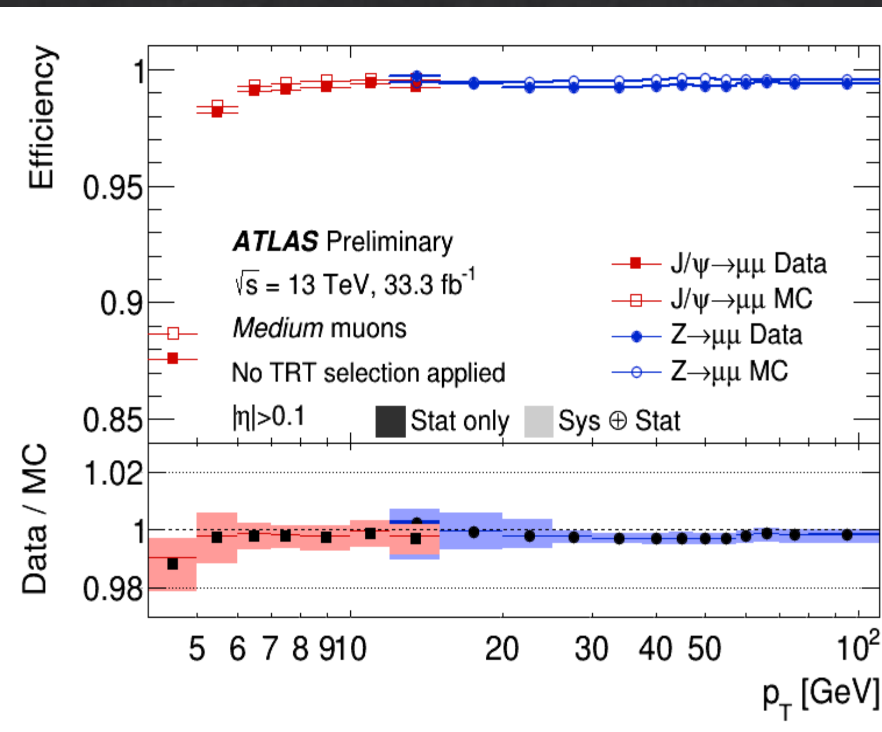
The ATLAS Detector

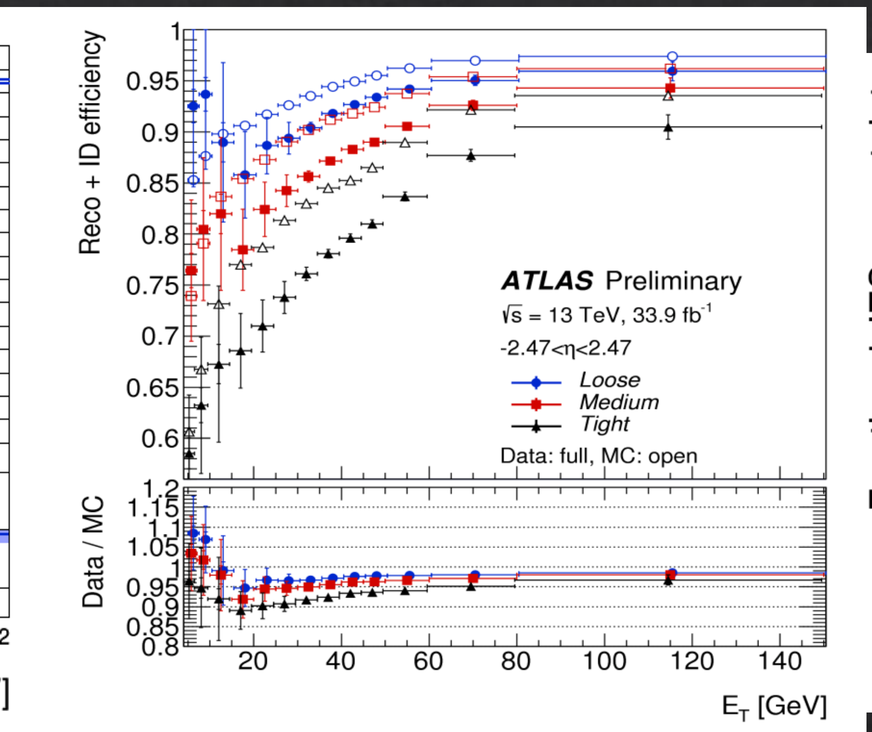
A highly efficient multi-purpose detector

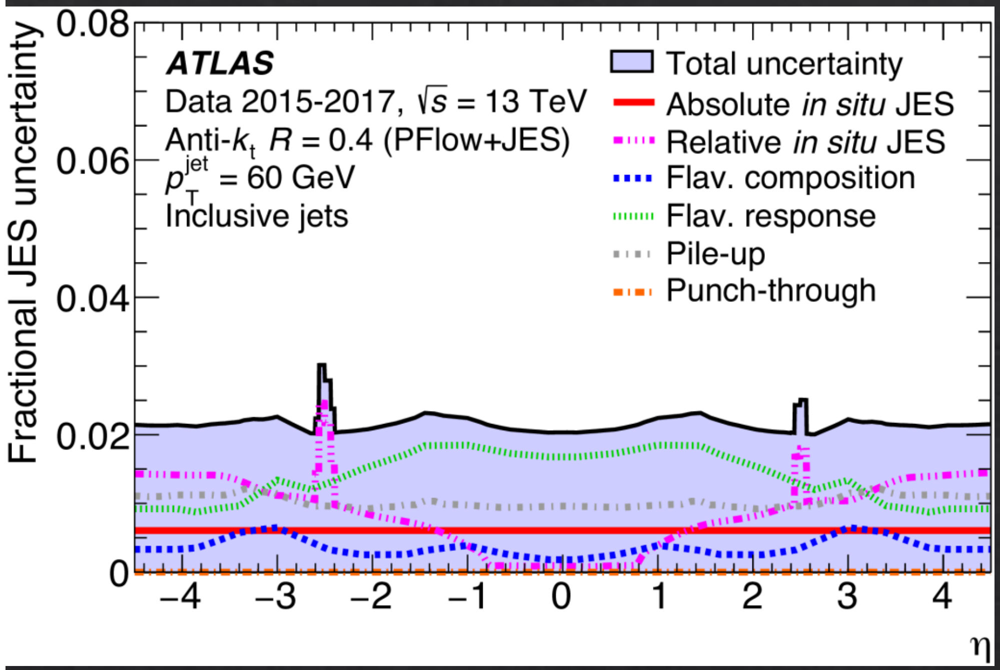


The ATLAS Detector

Example of measurements with the ATLAS detector



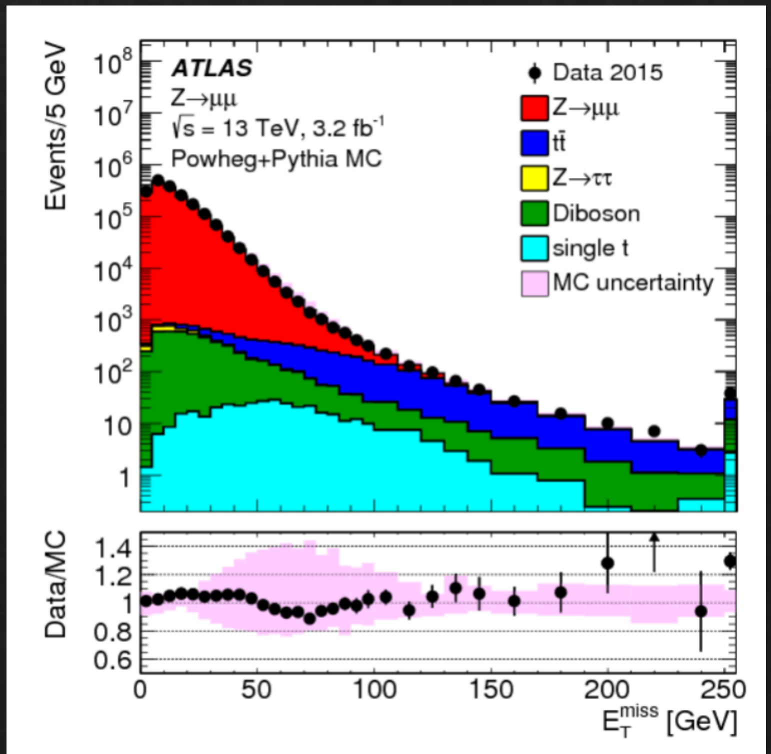




Electrons | Muons | Jets

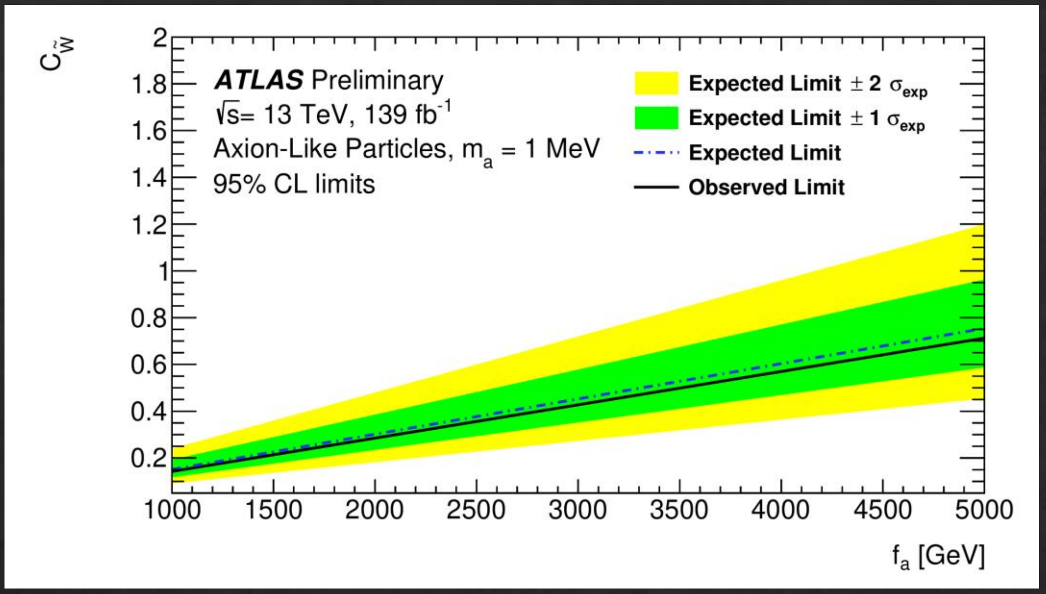
Missing Transverse Momentum

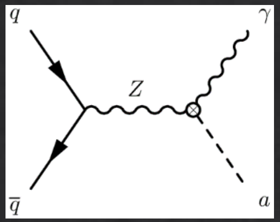
$$E_{x(y)}^{\text{miss}} = - \sum_{i \in \{\text{hard objects}\}} p_{x(y),i} - \sum_{j \in \{\text{soft signals}\}} p_{x(y),j} \, .$$

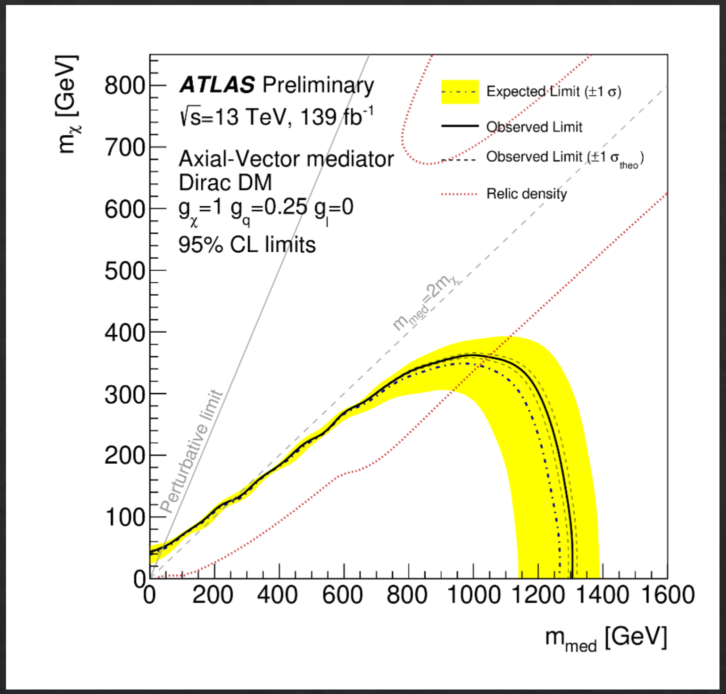


Mono-X searches

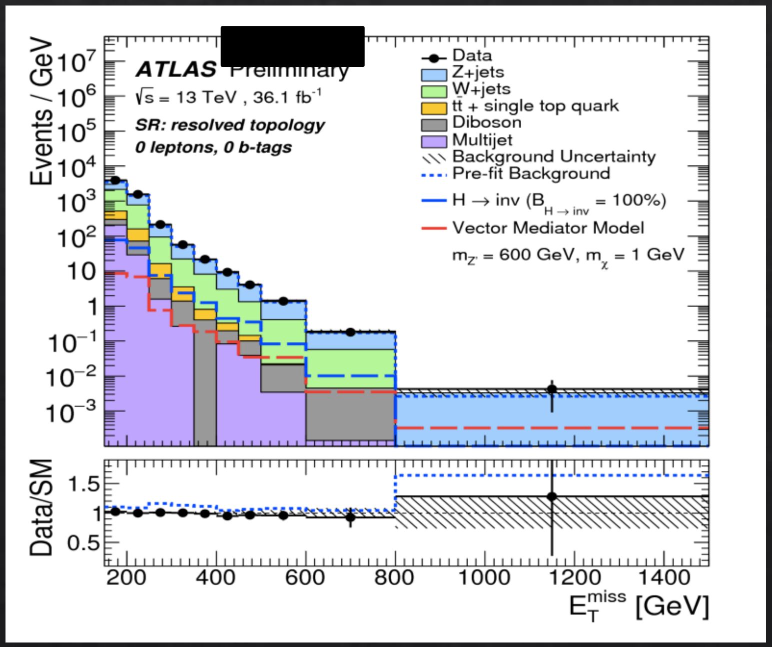
- Mono-photon searches:

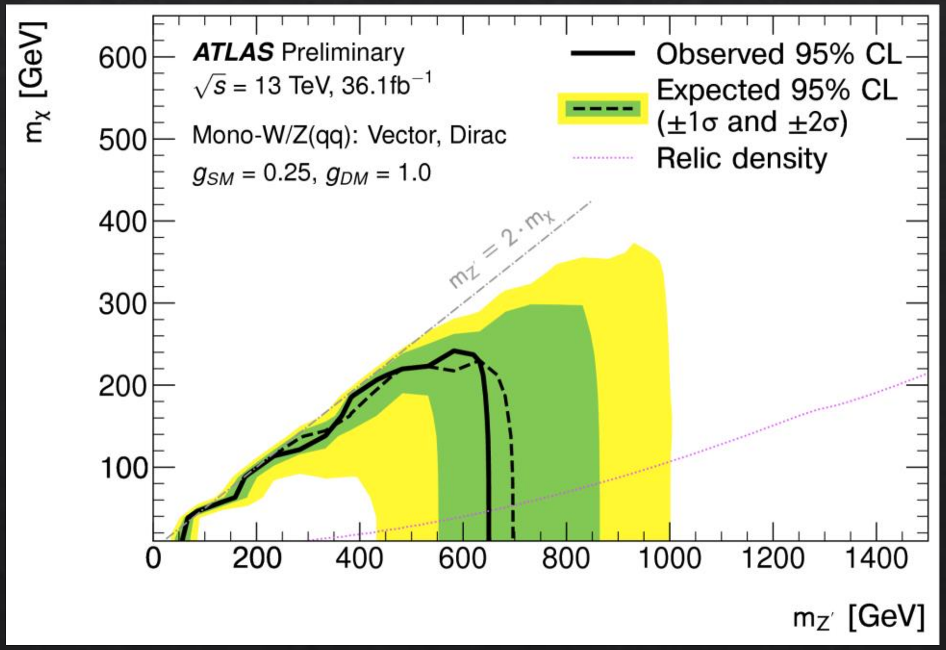






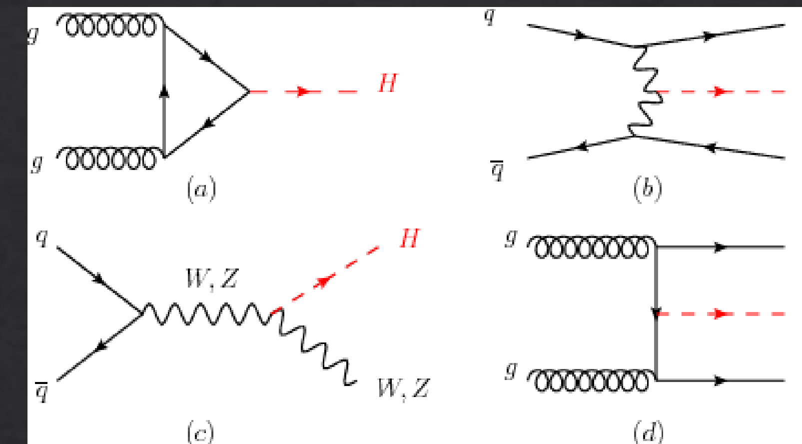
- Mono-W/Z searches:



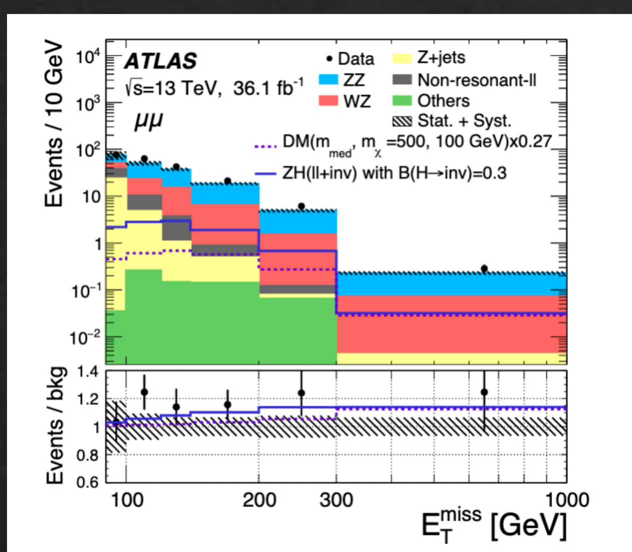


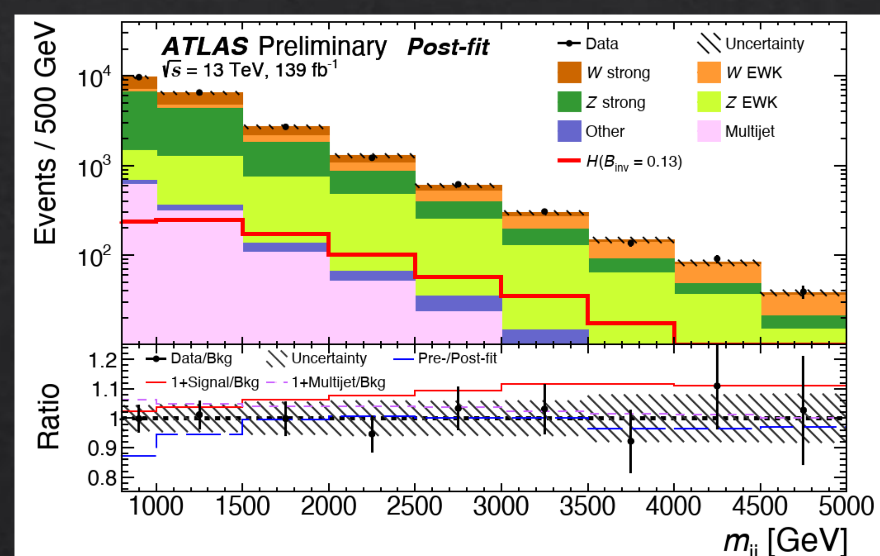
- Many other Mono-X sigatures being searched at the LHC

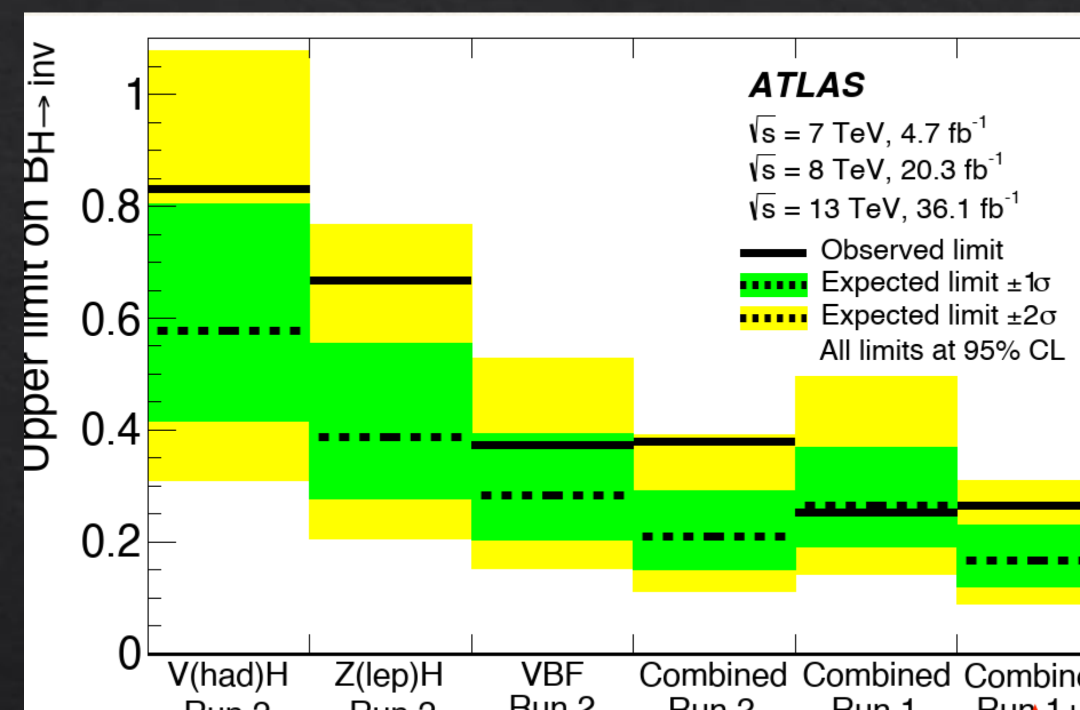
Higgs Portal



- Up-to-date measurements at the LHC
  - 20% BR possible for new physics
  - We can investigates unknown (invisible) decays
- Searches done in ZH, ttH and VBF modes:



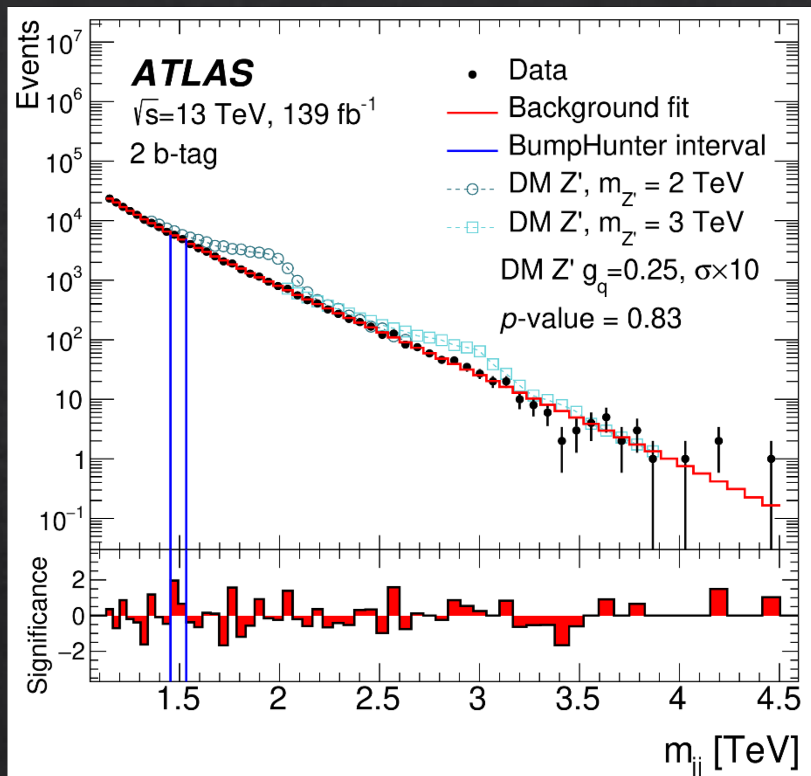


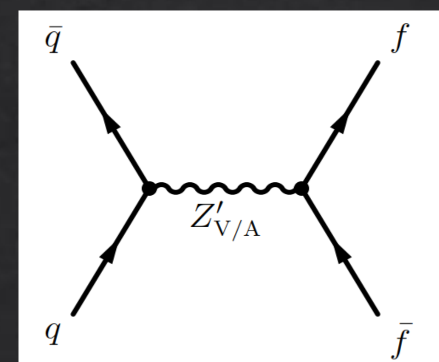


- Best limit achieved with ATLAS VBF
  - BR (H→χχ) < 13%

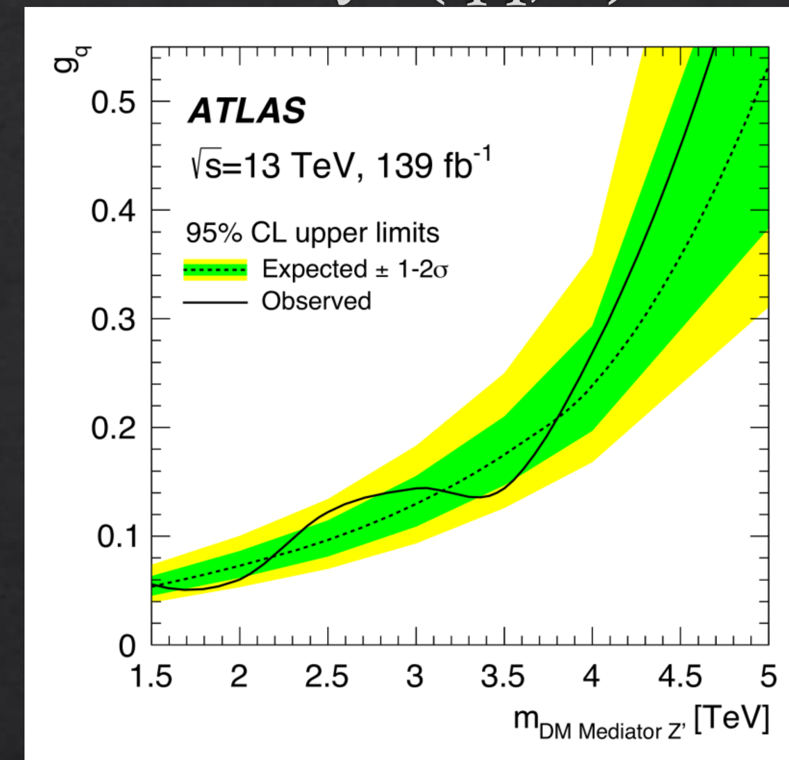
Other Signatures

◈ Mediator searches: look for resonnances in visible decays (qq, ll)

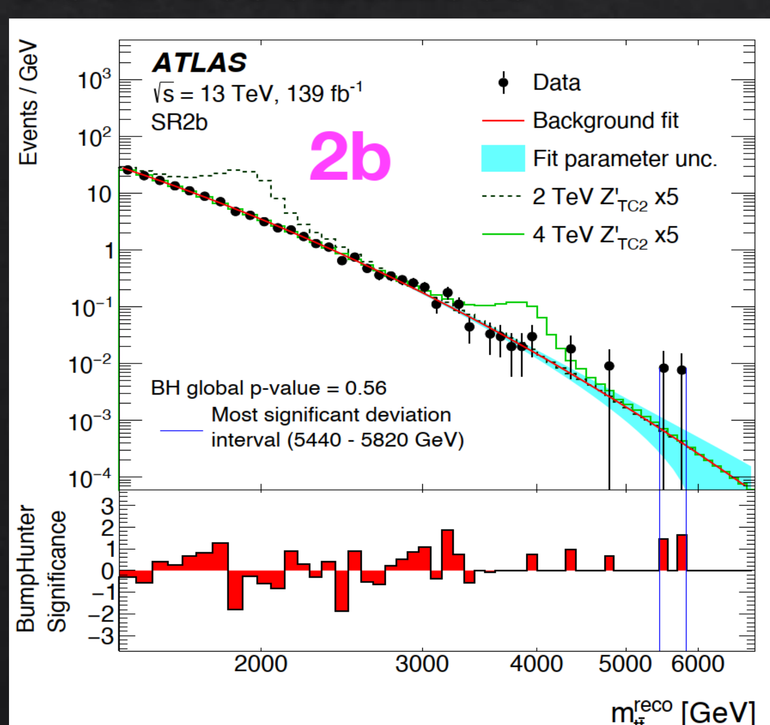


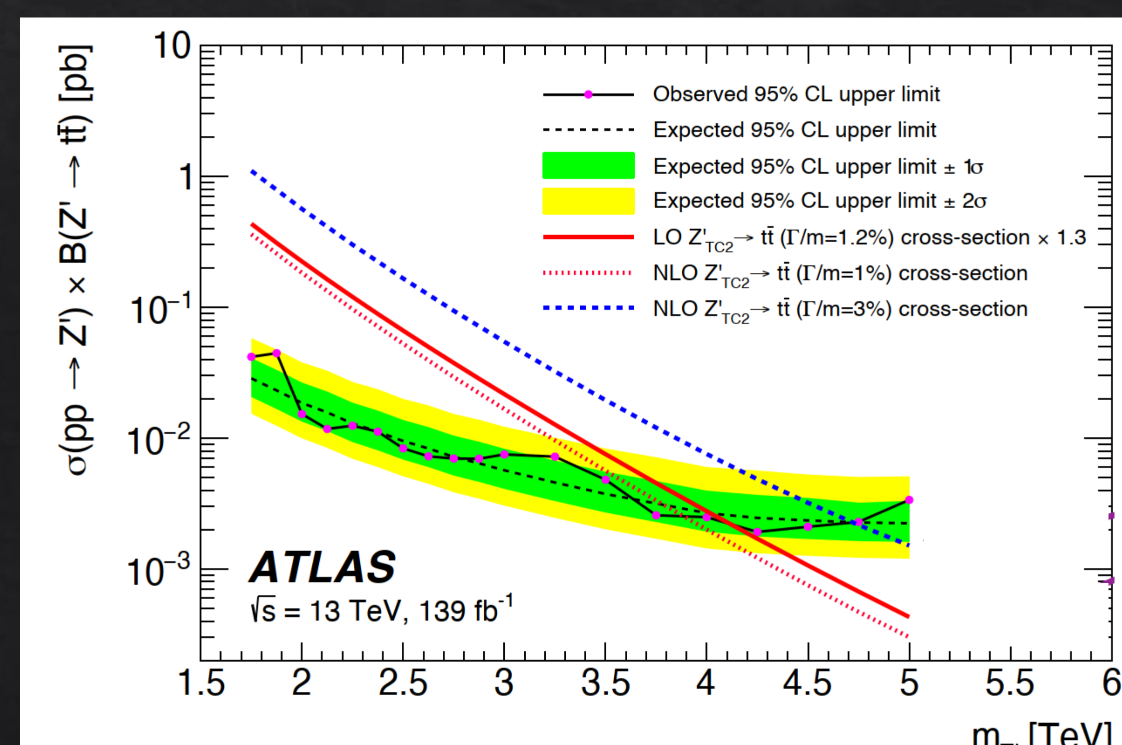


Leptophilic or
Leptophobic Z’,
Low mass resonances



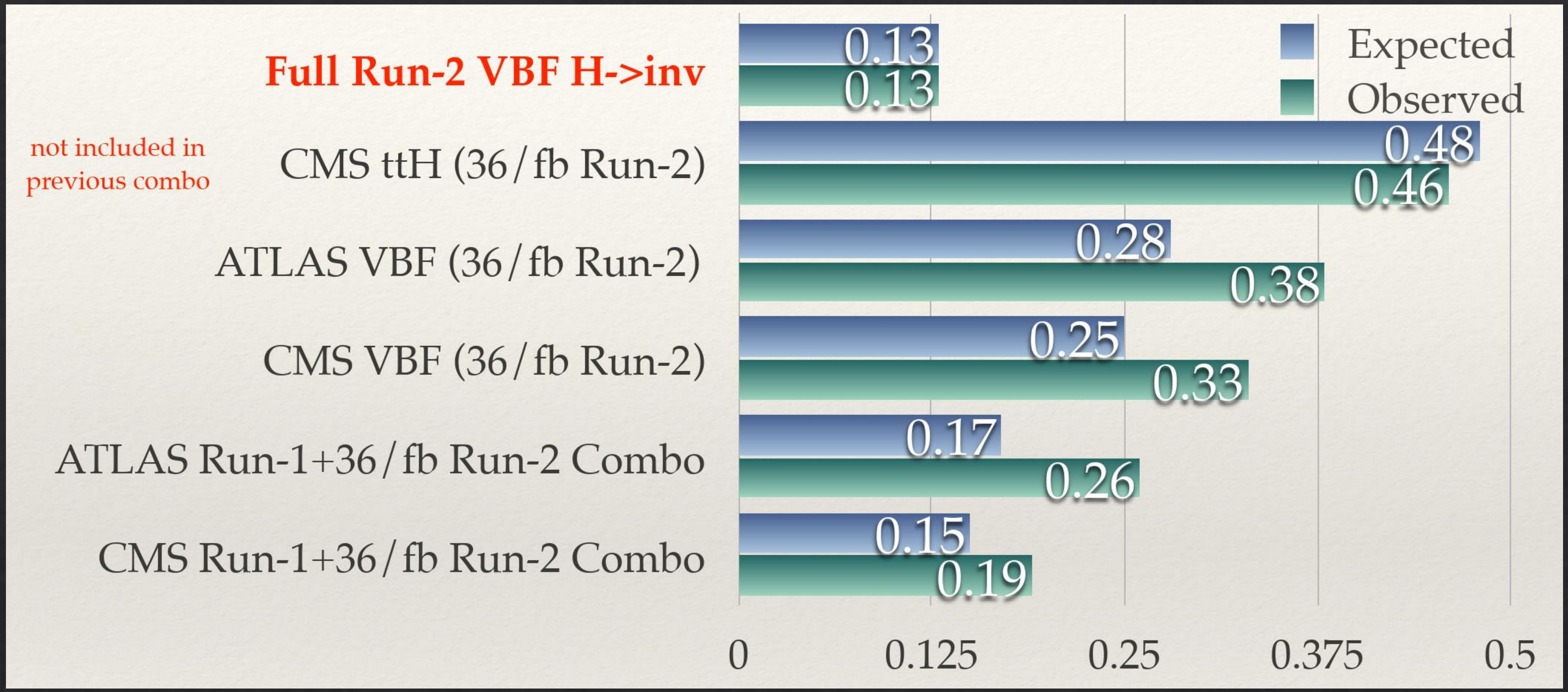
◈ ttbar resonances



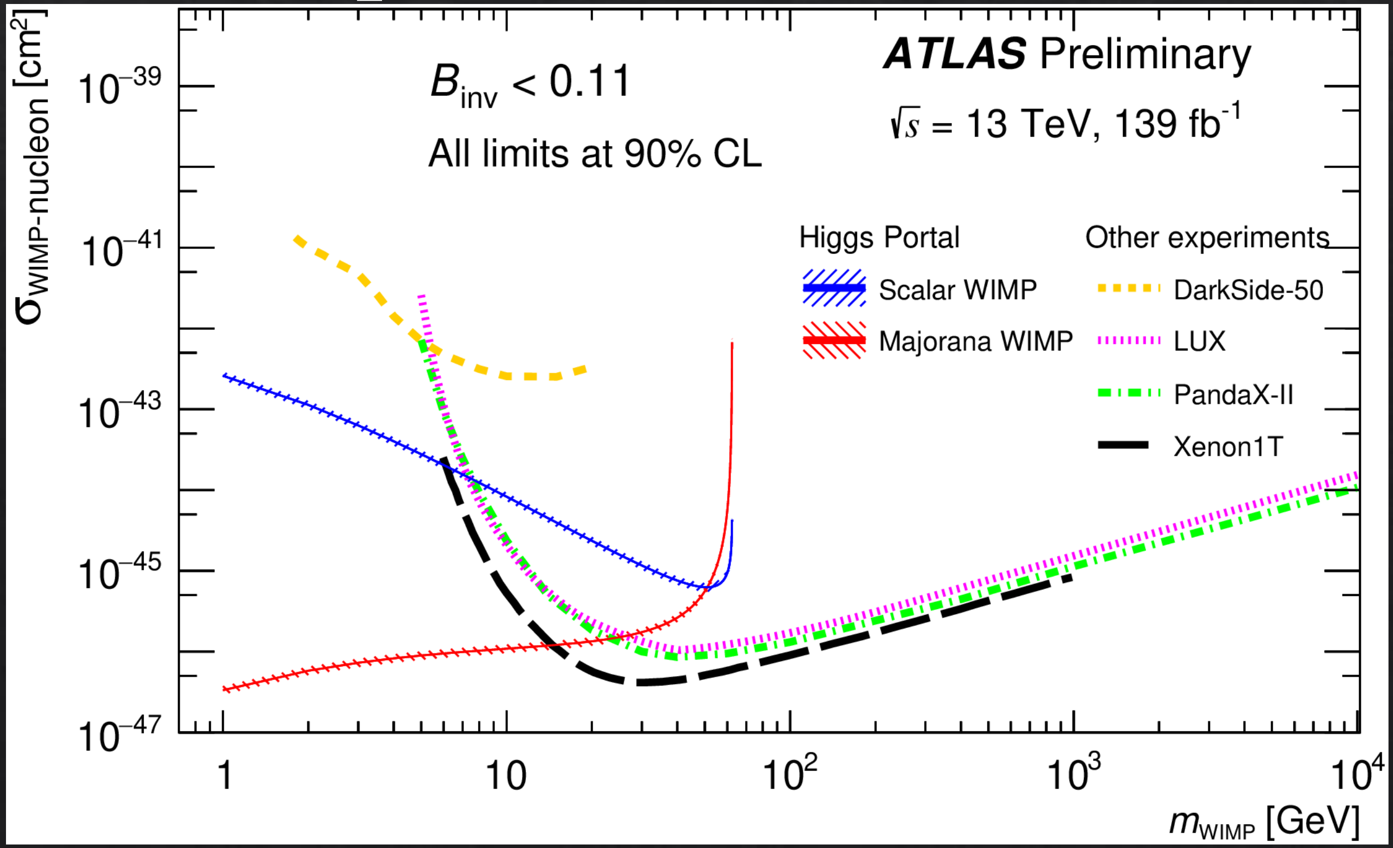


Higgs Portal

- Combined results:

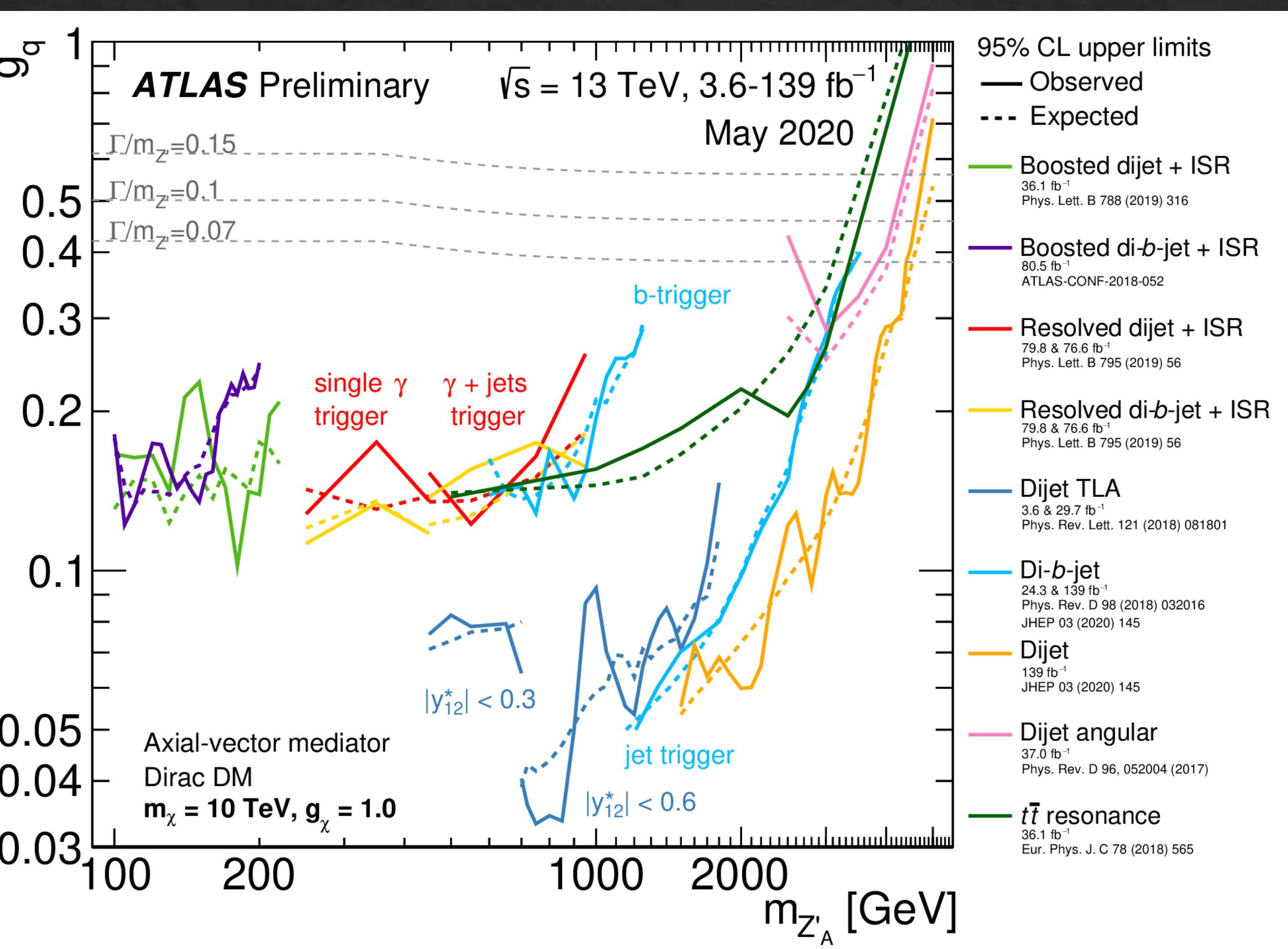


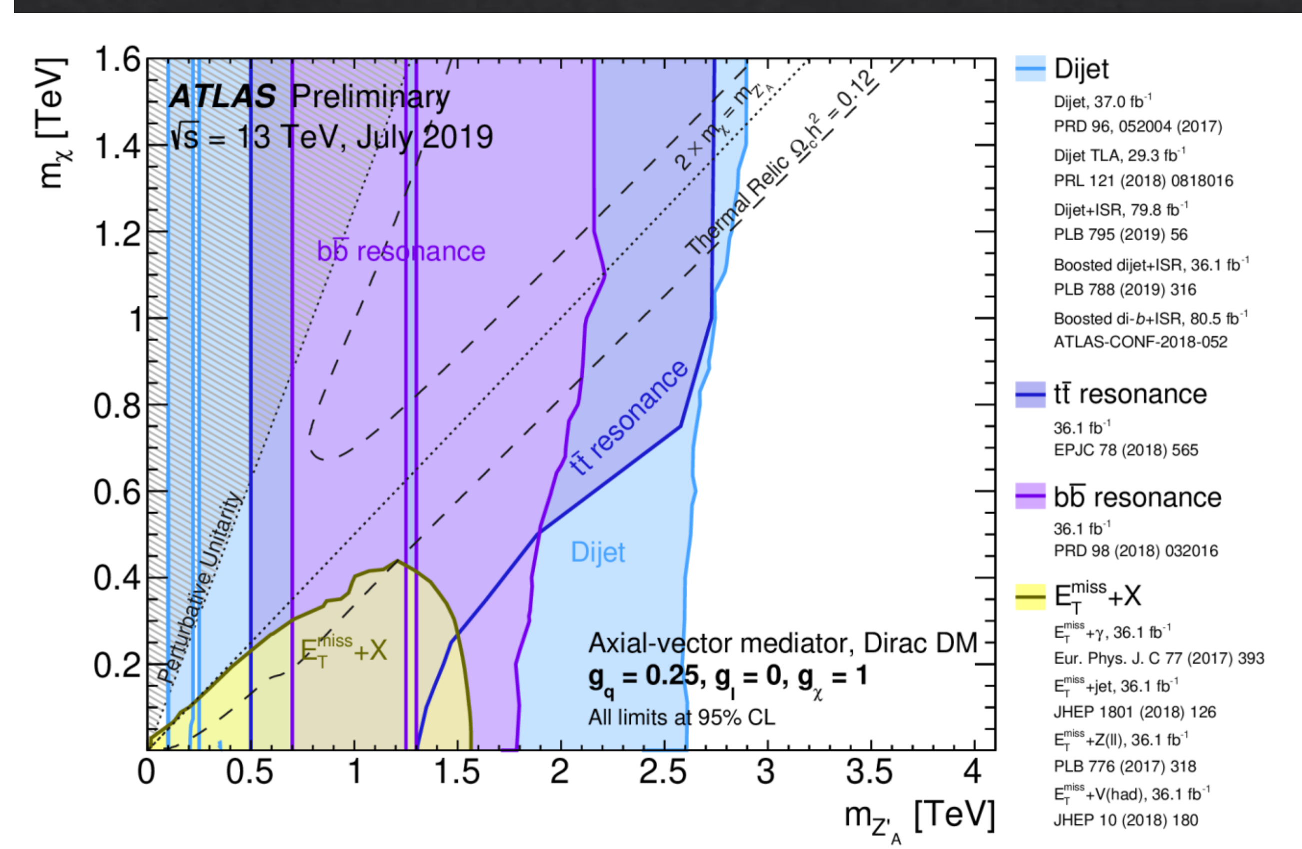
- Comparison to DD experiments:



Combinations

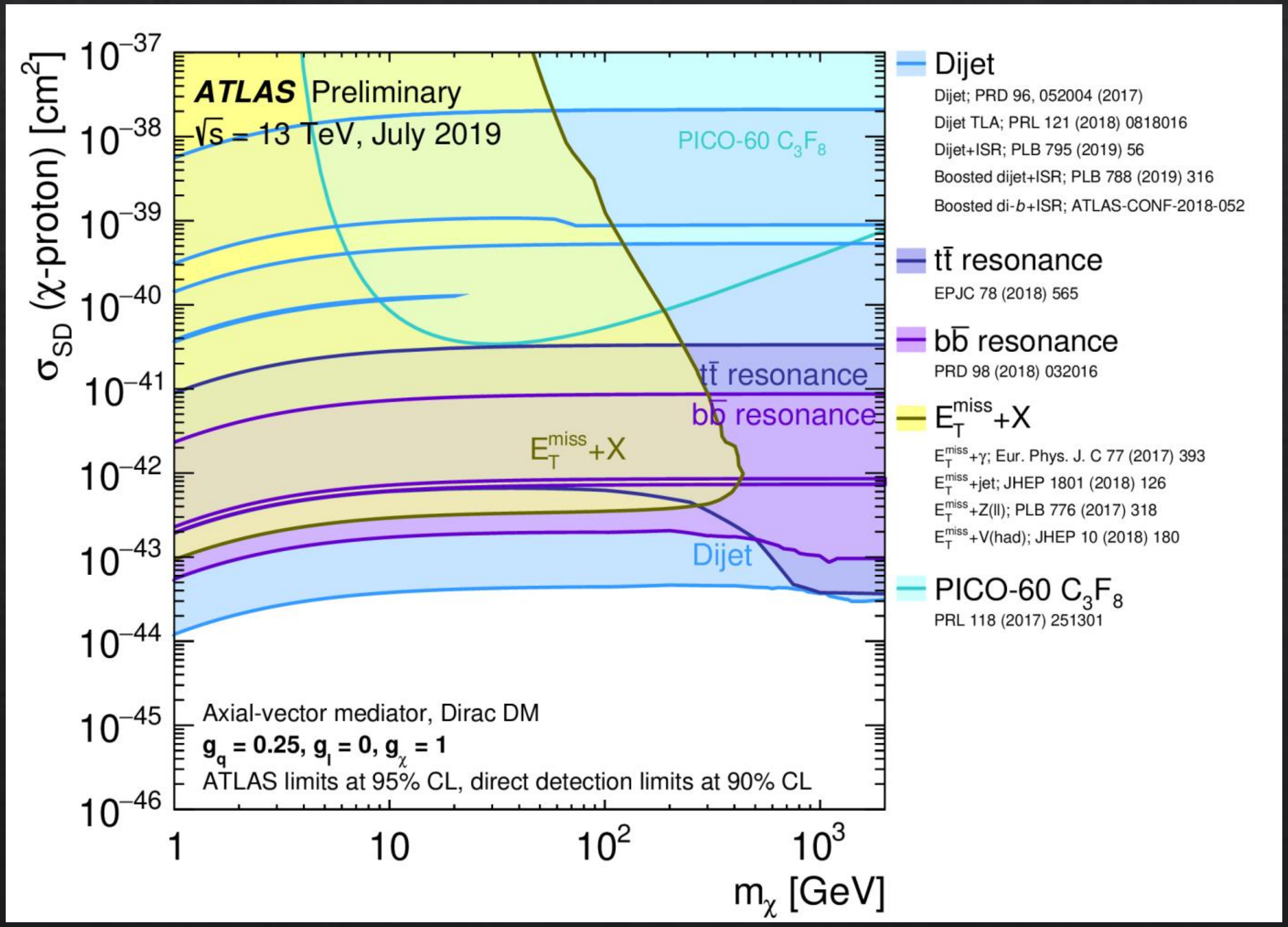
- Extensive work to combine ATLAS results within Simplified Models interpretation

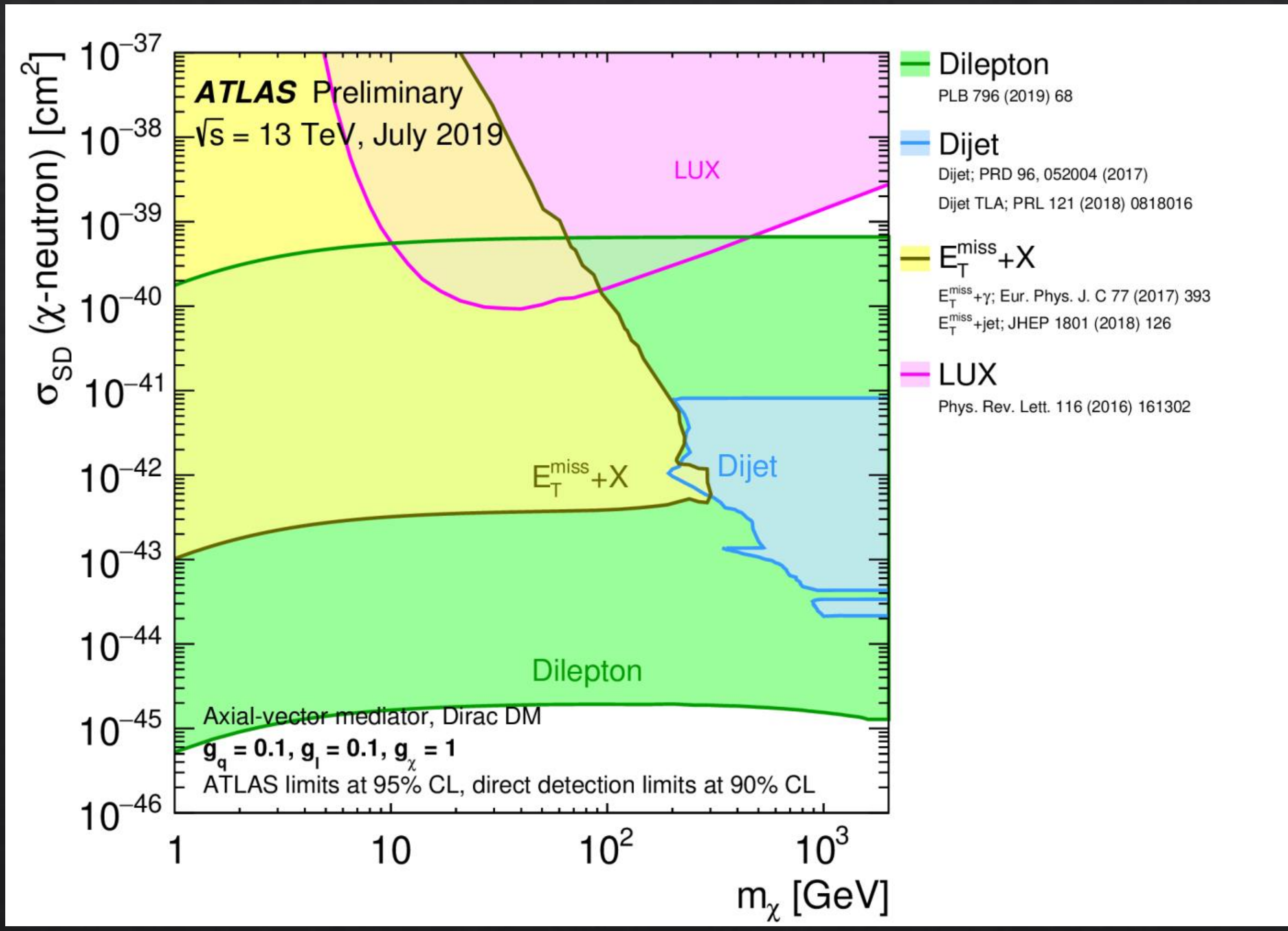




Combinations

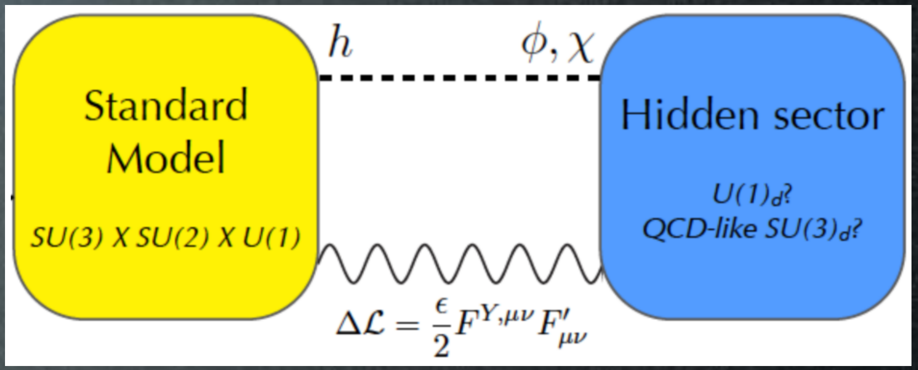
- Extensive work to combine ATLAS results within Simplified Models interpretation and comparison to DD experiments:





What about the Dark Sector

- The "dark sector" consists of particles that do not couple to known SM fields, but interact through a mediator:
  - Dark photons (vector portal), dark scalars (Higgs portal), ALPs (axion), sterile neutrinos…
- Mediators can provide "portal" to DM candidates or be candidates themselves.



- Exotics decays of Higgs boson are predicted in many BSM models to explain g-2 discrepancy or positron excesses

But there physics laws or constraints that SM – Dark Sector interactions must respect

$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j$$

Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal [Patt & Wilczek]

Neutrino portal

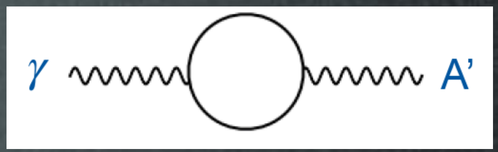
$$+ \frac{1}{f_a} \left(\mathrm{tr}(G\tilde{G}) + c_F F\tilde{F} \right) a + \mathcal{O}(\dim \geq 5)$$

Axion portal [Weinberg, Wilczek, KSVZ, DFSZ]

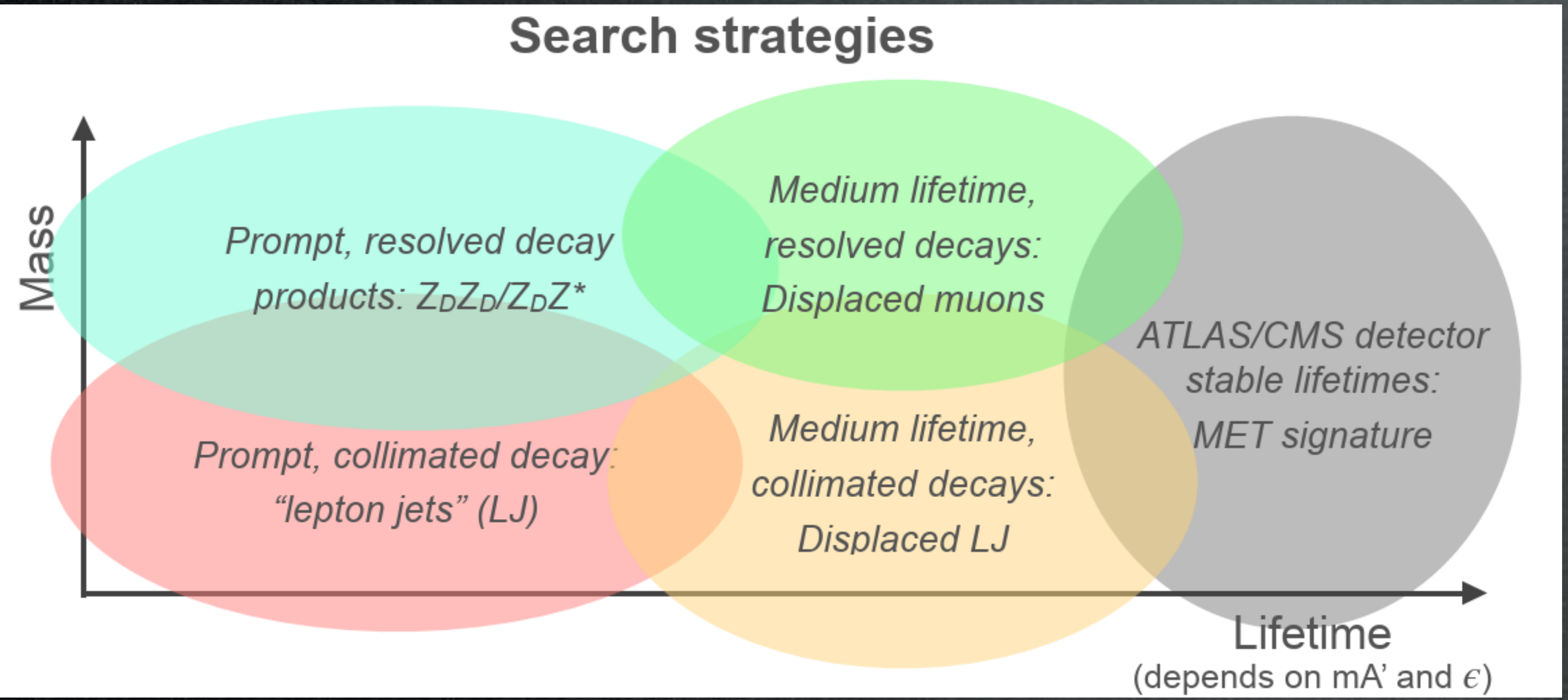
Vector Portal:
Min. Lagrangian = SM Lagrangian
\+ Dark QED
\+ "Kinetic Mixing (e)"

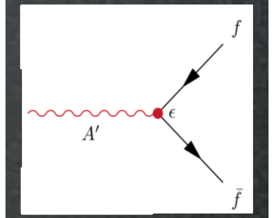
Dark Photon

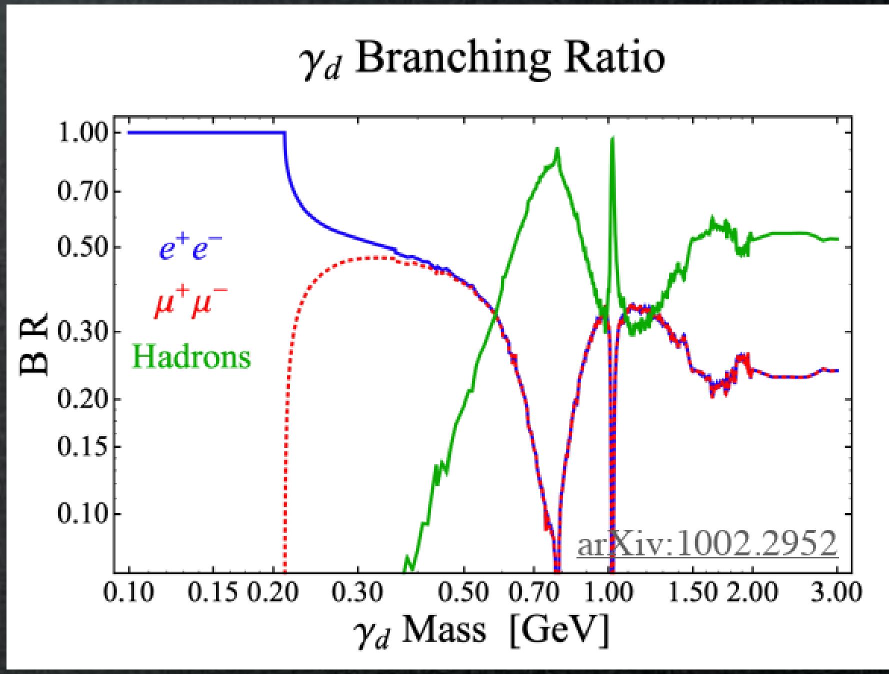
- Add a U(1)D where massive dark gauge boson ($A'/Z_D/\gamma_D$) kinetically mix with SM photon
  - Parameters: kinetic mixing term, ϵ. and $m_{A'}$



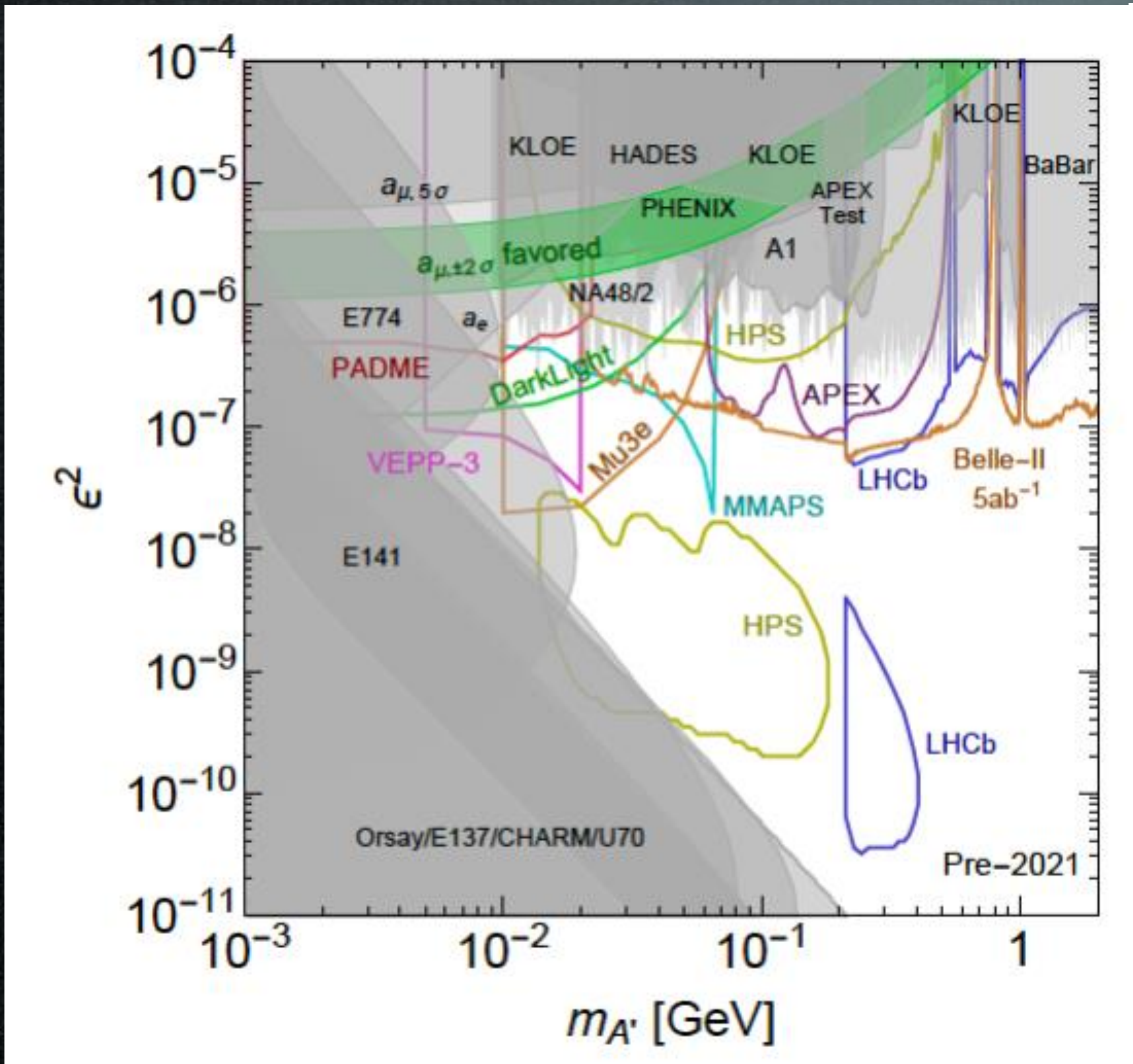
- Dark photon decay can be:
  - Minimal: via same mixing as production
  - Generic: not ϵ-suppressed, dominant in cases where $m_\chi < m_{A'}$ with either χ stable & invisible, or χ decays to SM particles, $A' \rightarrow > 2$ charged partciles.



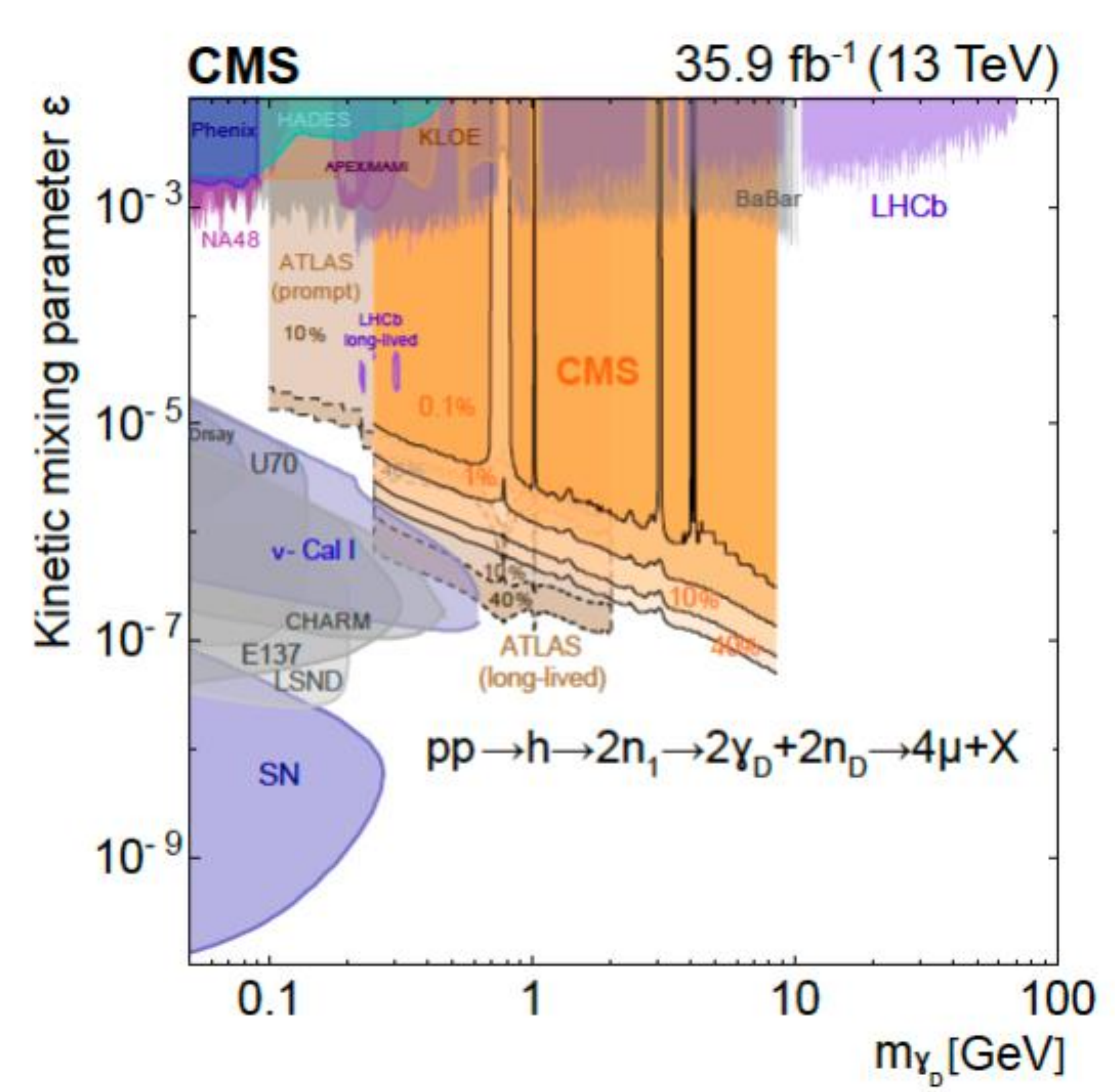




Kinetic mixing in A’→*ll*



arXiV:1608.08632



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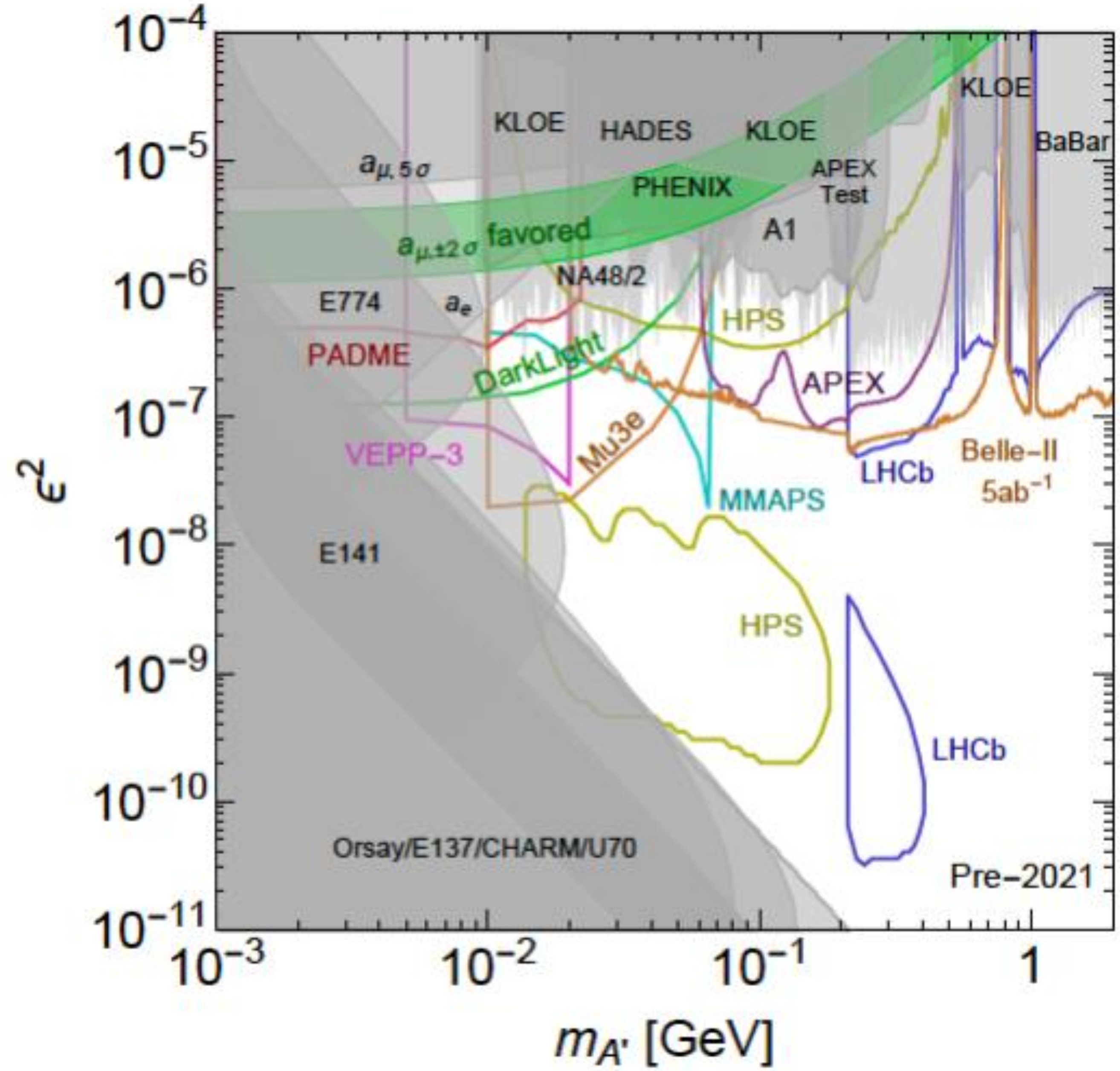
Kinetic mixing in A’→*ll*



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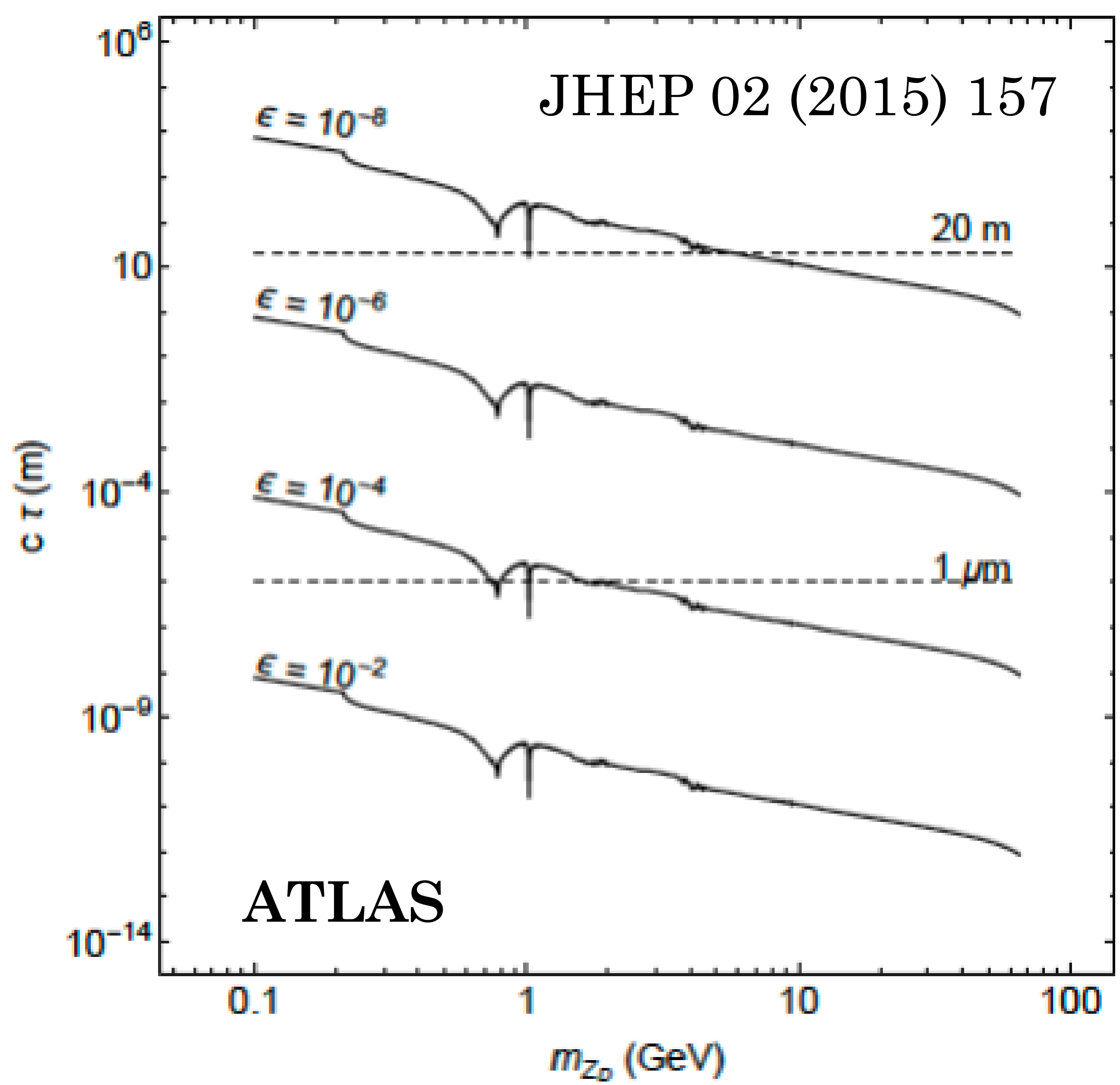
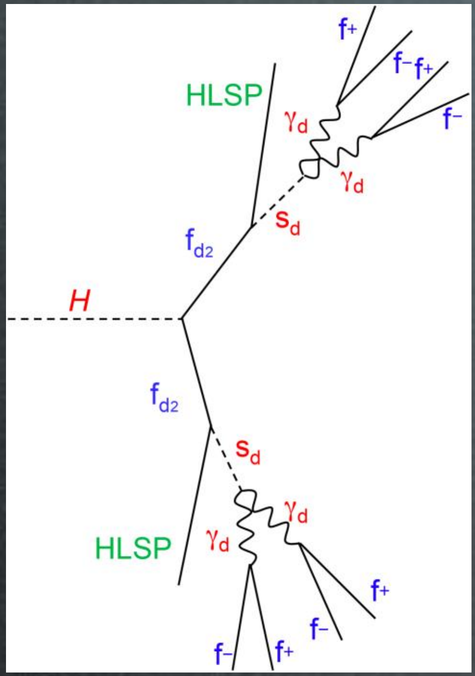
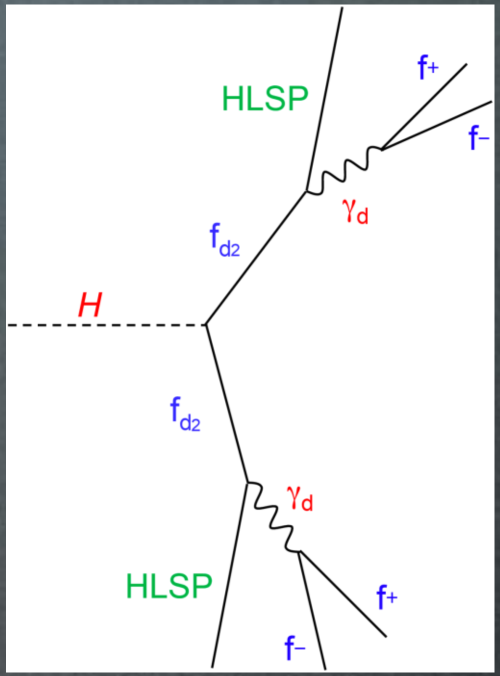


Dark Photon may be prompt or long lived depending of e and its mass

Lepton jets

- Search for collimated production of leptons: “lepton jets”.
- Dark fermions (fd2) produced in H decays, which decay to γD (via dark scalar, sd) and HLSP





HLSP = hidden lightest stable particle (fermion)

- Different experimental signatures depending on lifetime of dark photon.
  - Mean life time

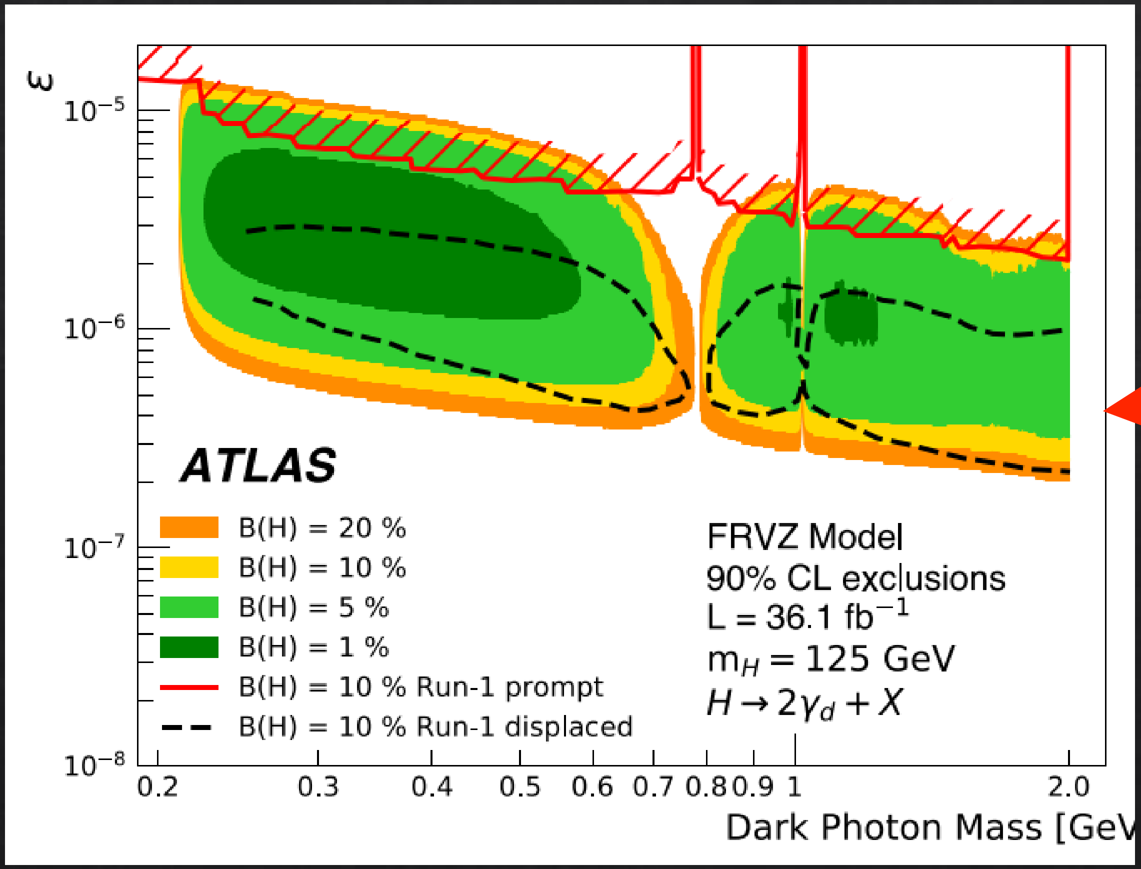
$$\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma_d}}\right)$$

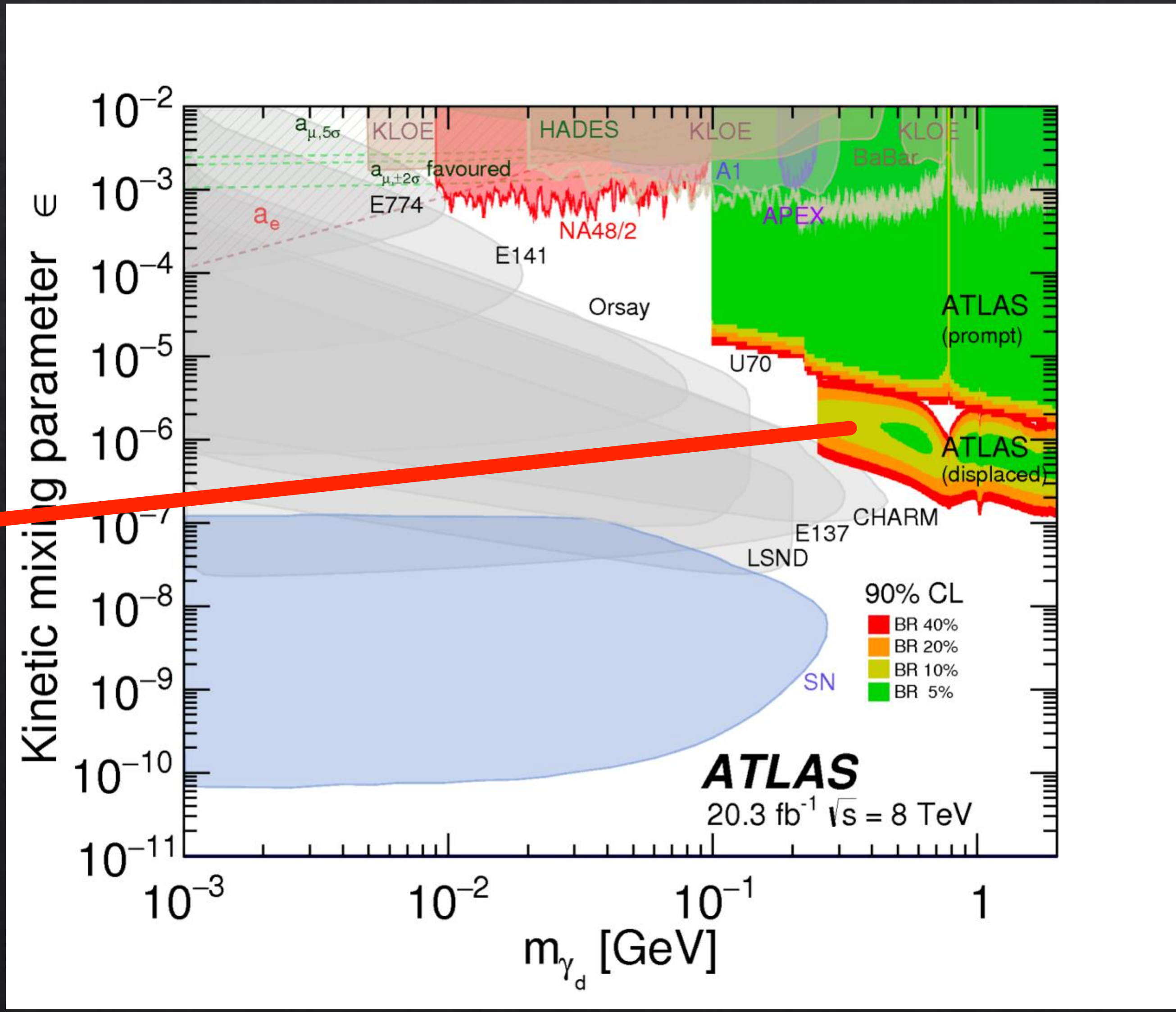
  - Prompt and displaced lepton jet signatures

Lepton jets

- Interpreted in terms of limits on the kinetic mixing parameter, ε, and $m_{A'}$

- Limits are shown for $B(h \to 2\gamma_D + X)$ in range 1–20%.

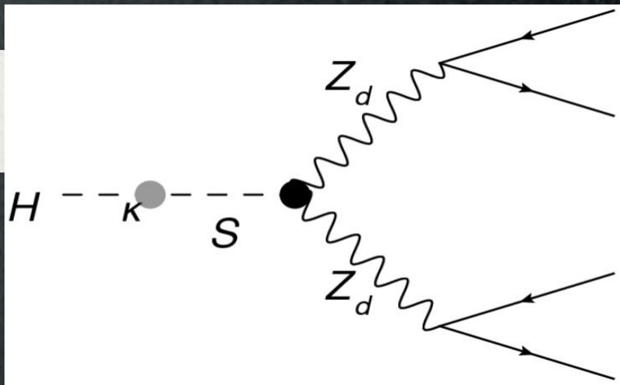




Higgs Portal

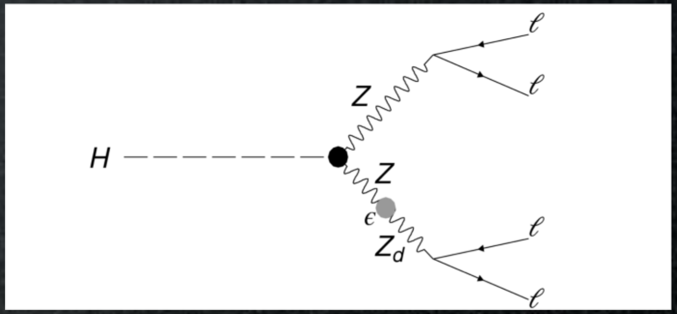
- There may be a dark Higgs boson; then there could also be a mixing between the SM Higgs boson (H) and the dark sector Higgs boson (S).

$$\epsilon_h \, |h|^2 |\phi|^2$$



- The mixing parameter κ between H and S, can be extracted from $H \rightarrow Z_d Z_d \rightarrow 4l$, a unique channel to access this parameter

- In addition to kinetic mixing, there could be also a mass mixing between SM Z and Z_d

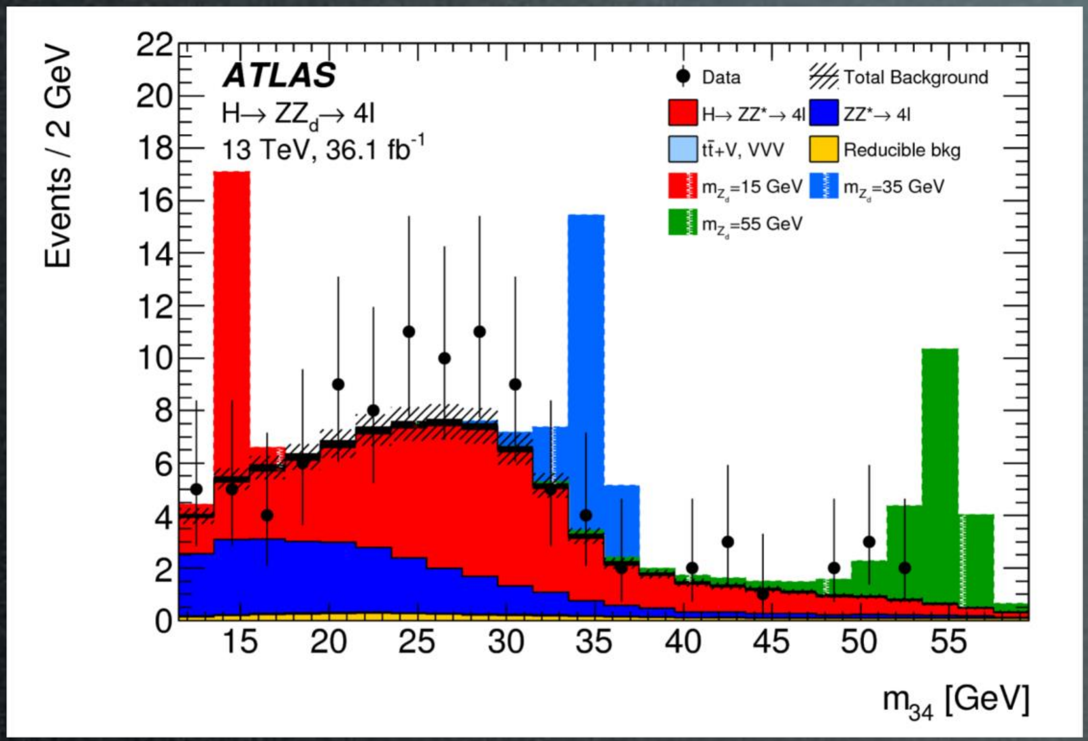


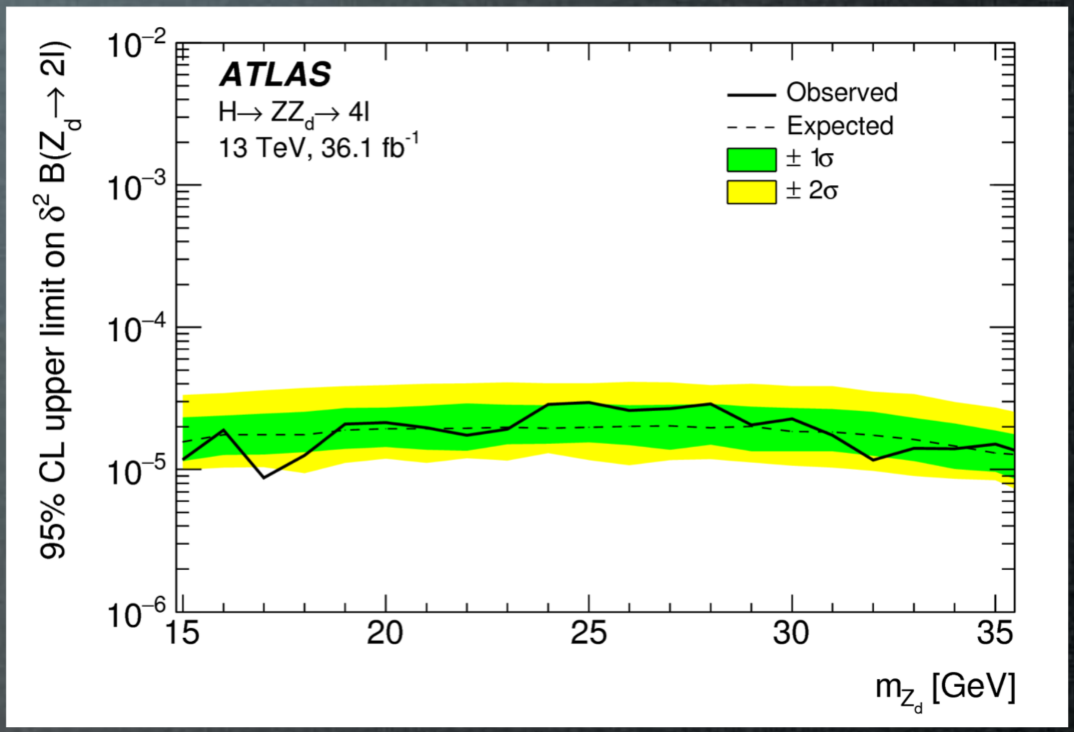
$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z} \delta ,$$

- $H \rightarrow Z Z_d \rightarrow 4l$ is sensitive to the kinetic mixing parameter ε, and to Z-Z_d mixing parameter δ. Unique channel to extract δ

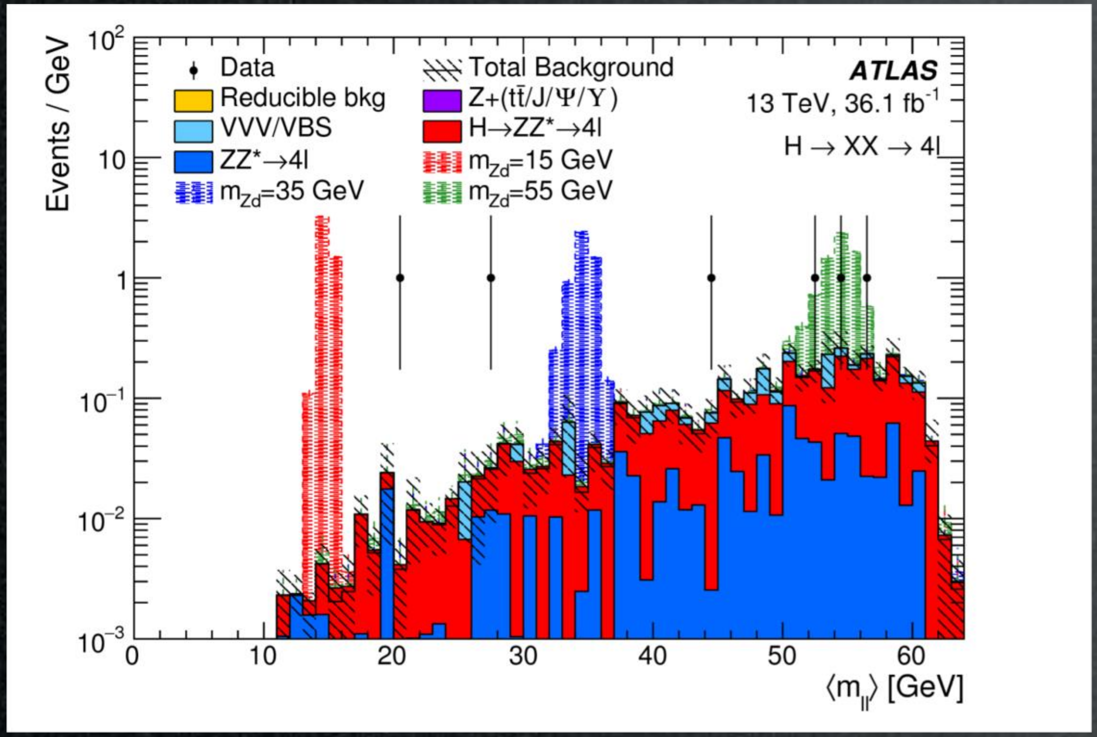
Higgs Portal

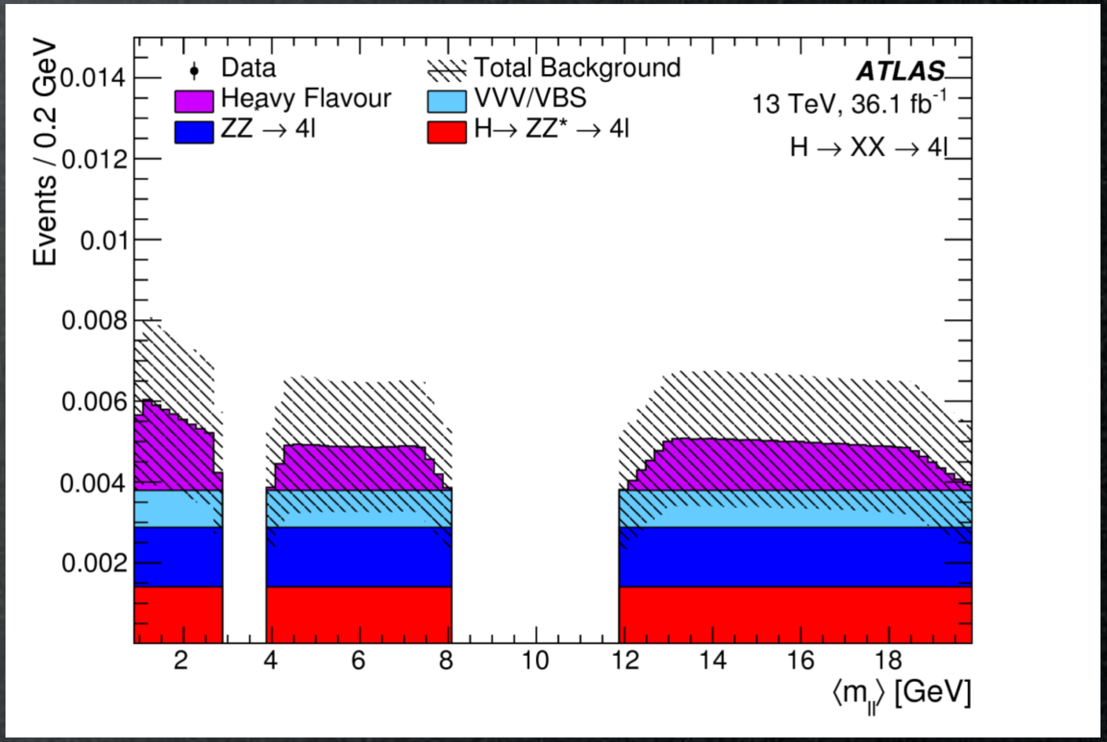
- $H \to Z\, Z_d \to 4l$. No exess of events. Bound on ε (loose) and δ





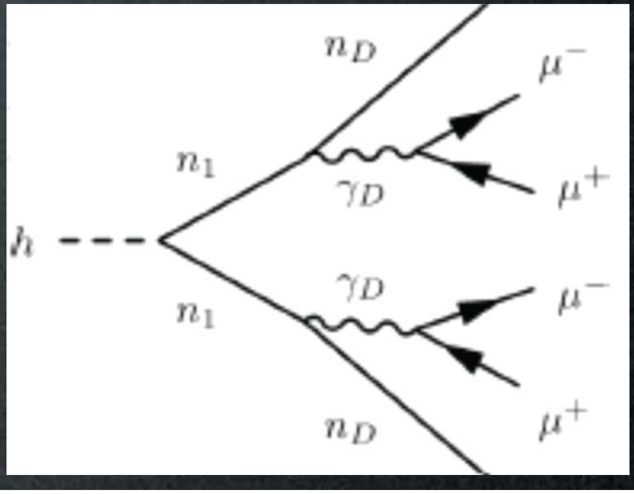
- $H \to Z_d\, Z_d \to 4l$. No excess of events. Searches for higher masses.



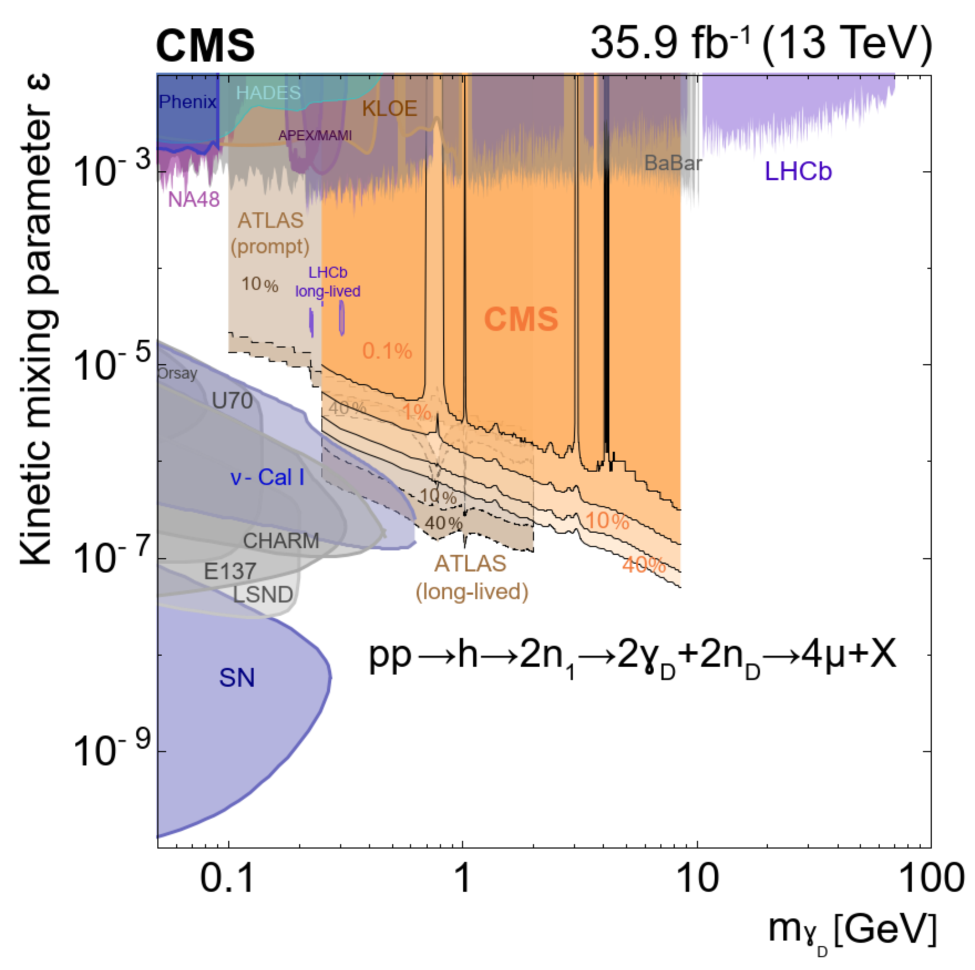


Higgs Portal

- Search for with dark SUSY benchmark model:
  - η_1 = lightest non-dark neutralino, and η_D = a dark neutralino that is undetected.



- Signal region defined by: $m(\mu\mu)_1 \sim m(\mu\mu)_2$
  $|m(\mu\mu)_1 - m(\mu\mu)_2| < 5\sigma(m_{\mu\mu})$

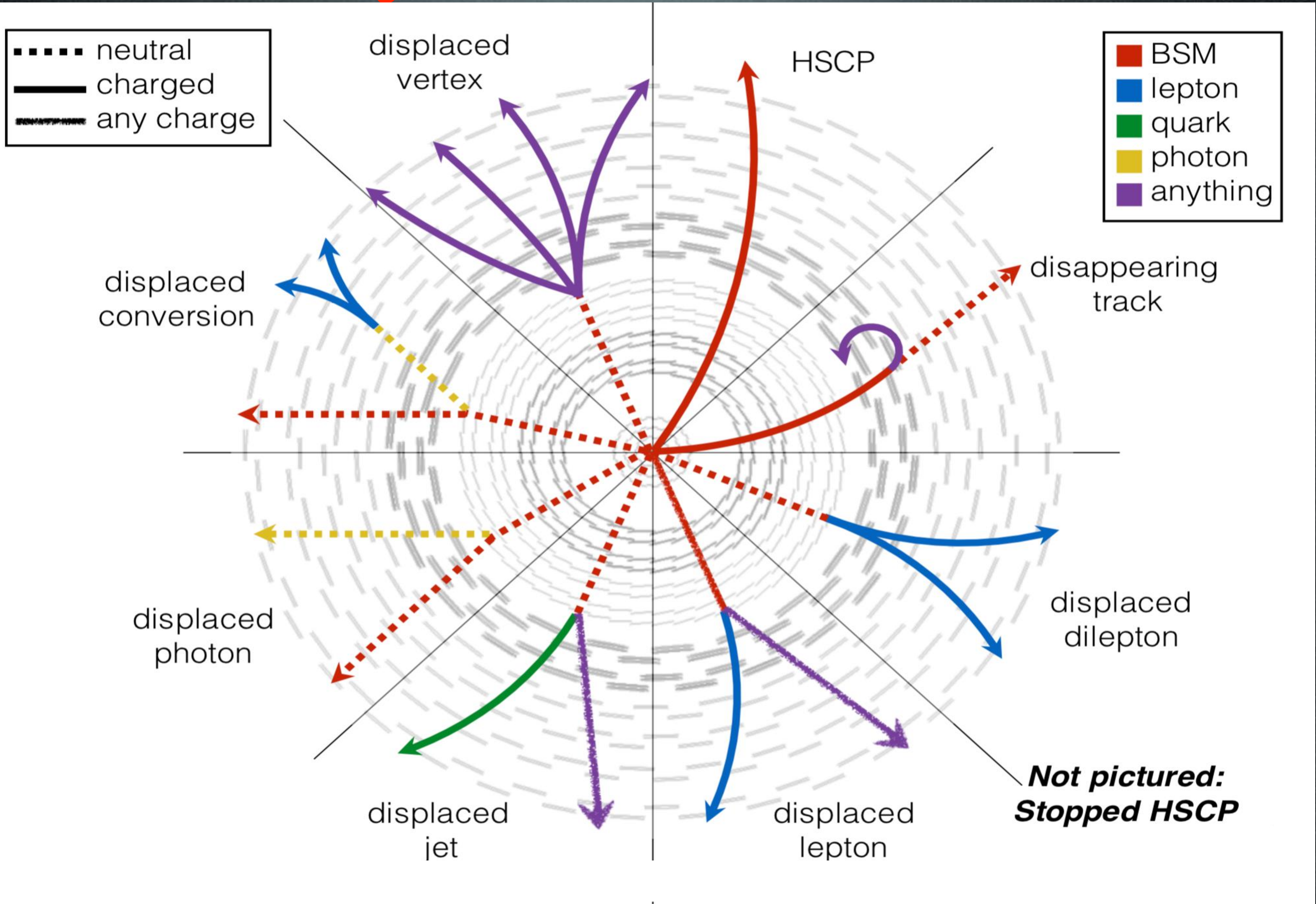


- Upper limits set on product of H production cross section and BR of Higgs boson (cascade) decay to a pair of dark photons:

$$\sigma(pp \to h \to 2\eta_1 \to 2\gamma_D + 2\,\eta_D) \times B(\gamma_D \to 2\mu)$$

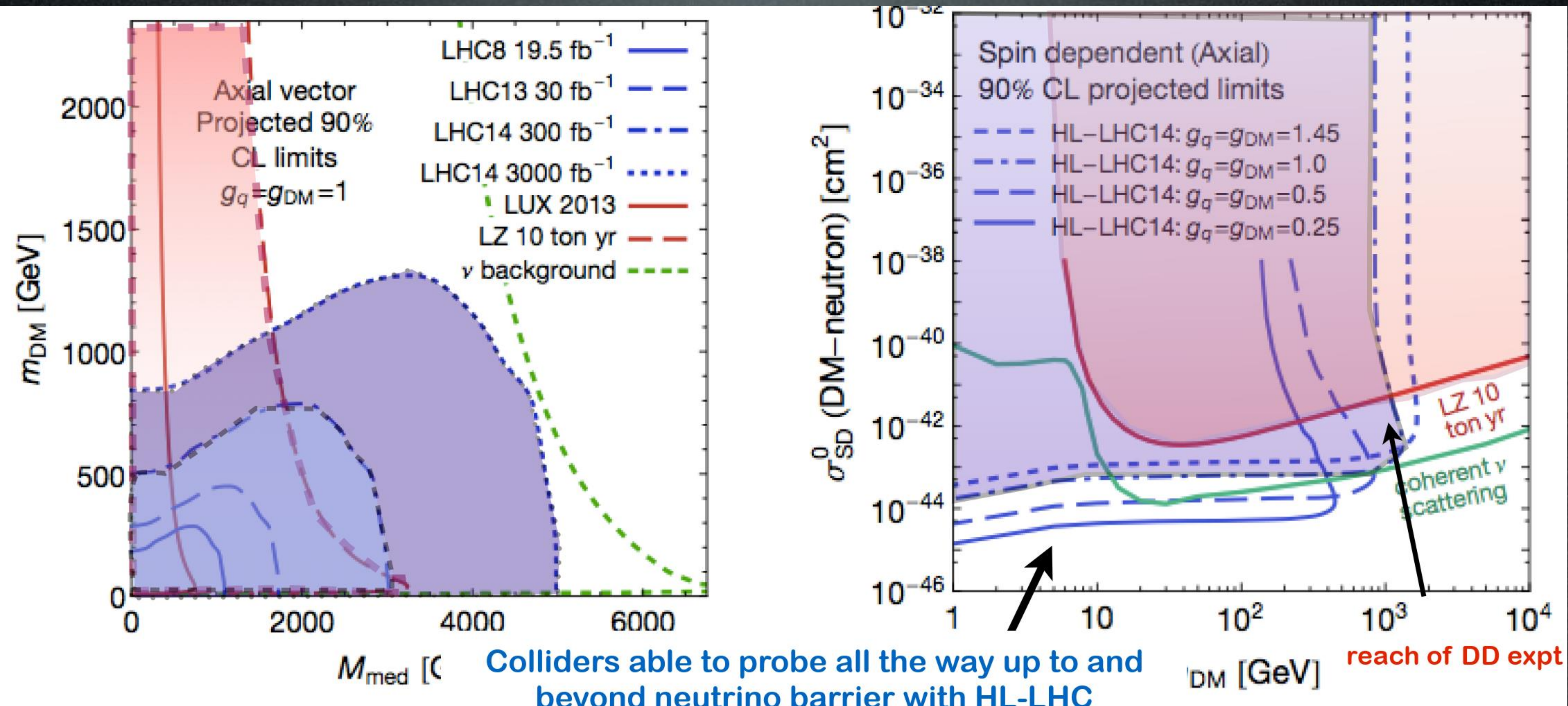
- Limits on $B(h \to 2\gamma_D + X)$ in the range 0.1–40%

Beyond the WIMP



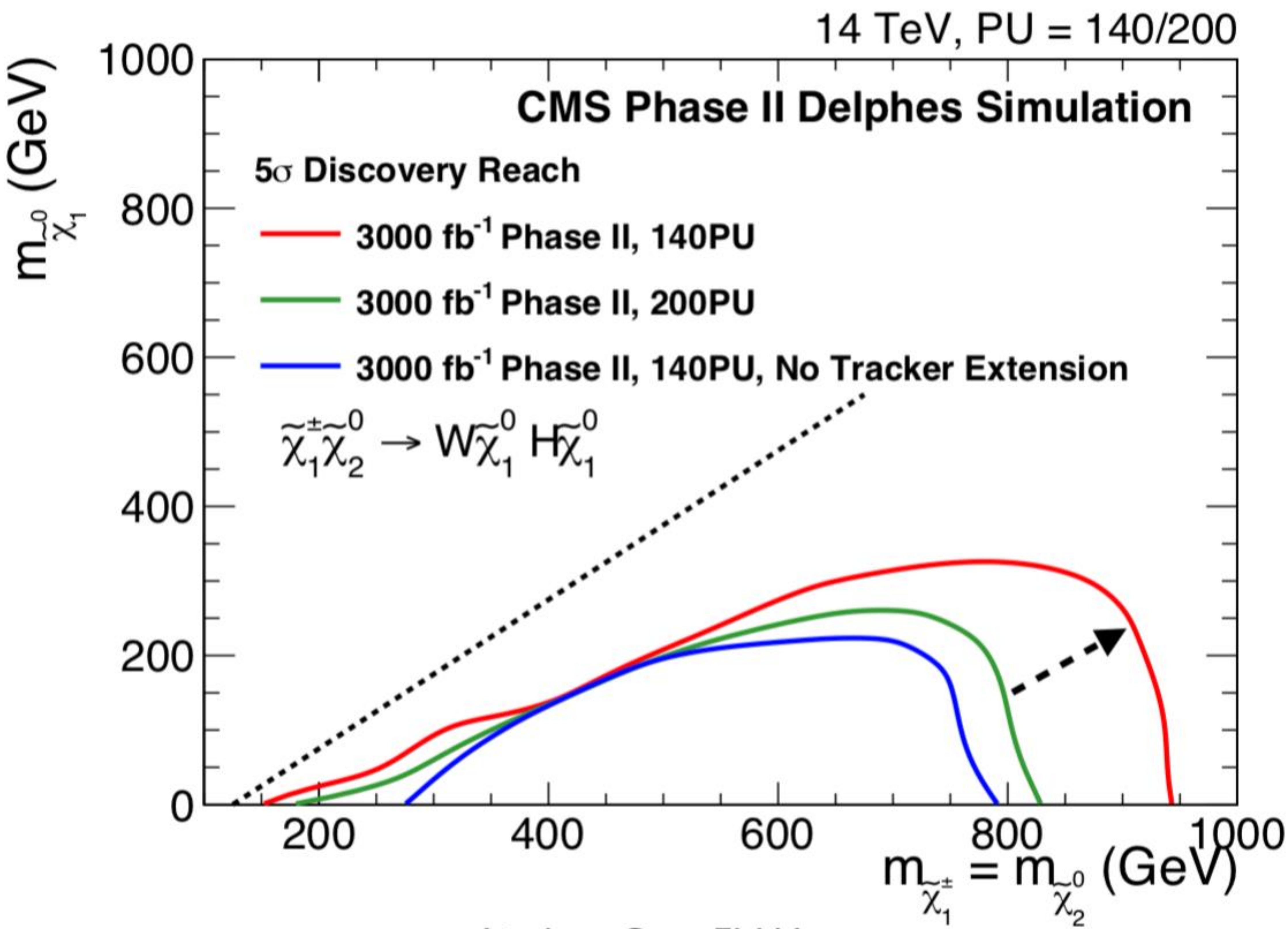
Future Prospects

- Colliders can still do more with Run2 data. Reinterpretation, models..
- Future HL-LHC very challenging
  - High pile-up, Higher MET trigger threshold. But NEW and more performant detectors
  - Control of systematic uncertainties crucial
- Better interplay with DD experiments (Axion, Dark photons…)



Future Prospects

SUSY EW Searches, with conservative systematic uncertainties



Lindsey Gray, FNAL

Summary

- DM searches is the ideal inter-disciplinay field comibining theoretical and experimental efforts from Cosmology, Astrophyics and Partcile Physics.

- Interpretation (=benchmarks) important to understand the big picture
  - But the models we use inevitably influence motivations for searches

- Outlook for LHC DM searches:
  - expanding beyond WIMP simplified models
  - less simplified models (e.g. 2HDM), dark sectors
  - More complicated signatures (LLP), dark photon…

- Futue LHC runs (Run3, HL-LHC) might open new era with higher reach in DM parameter space.
  - Significant improvement in detectors/Systematics to keep perfromance

- Only 1% of full LHC dataset analyzed so far
  - A long way to go to probe SM-DM interactions, whatever they are!