Searches for Dark Matter at the LHC

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Rabat, Morocco
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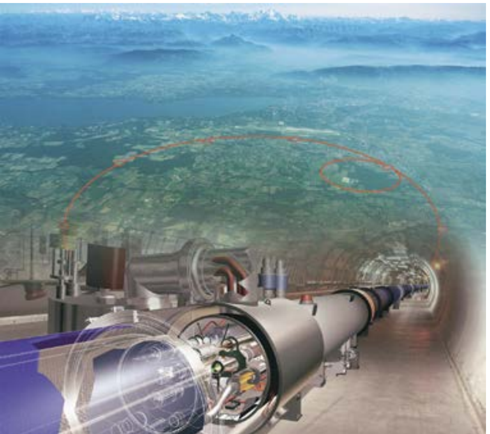
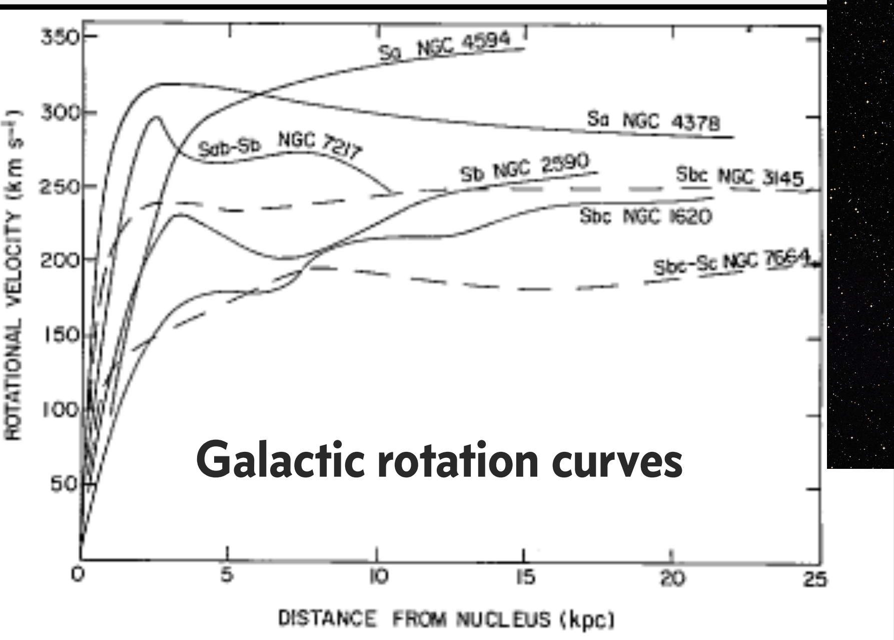
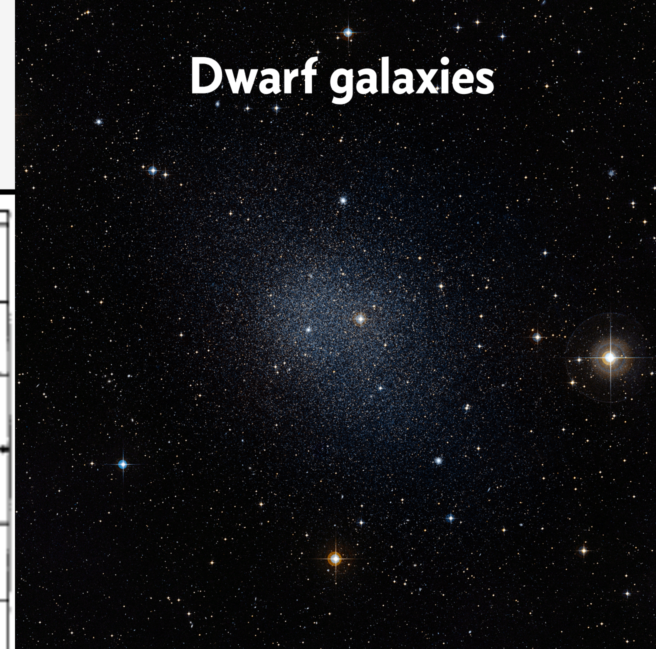
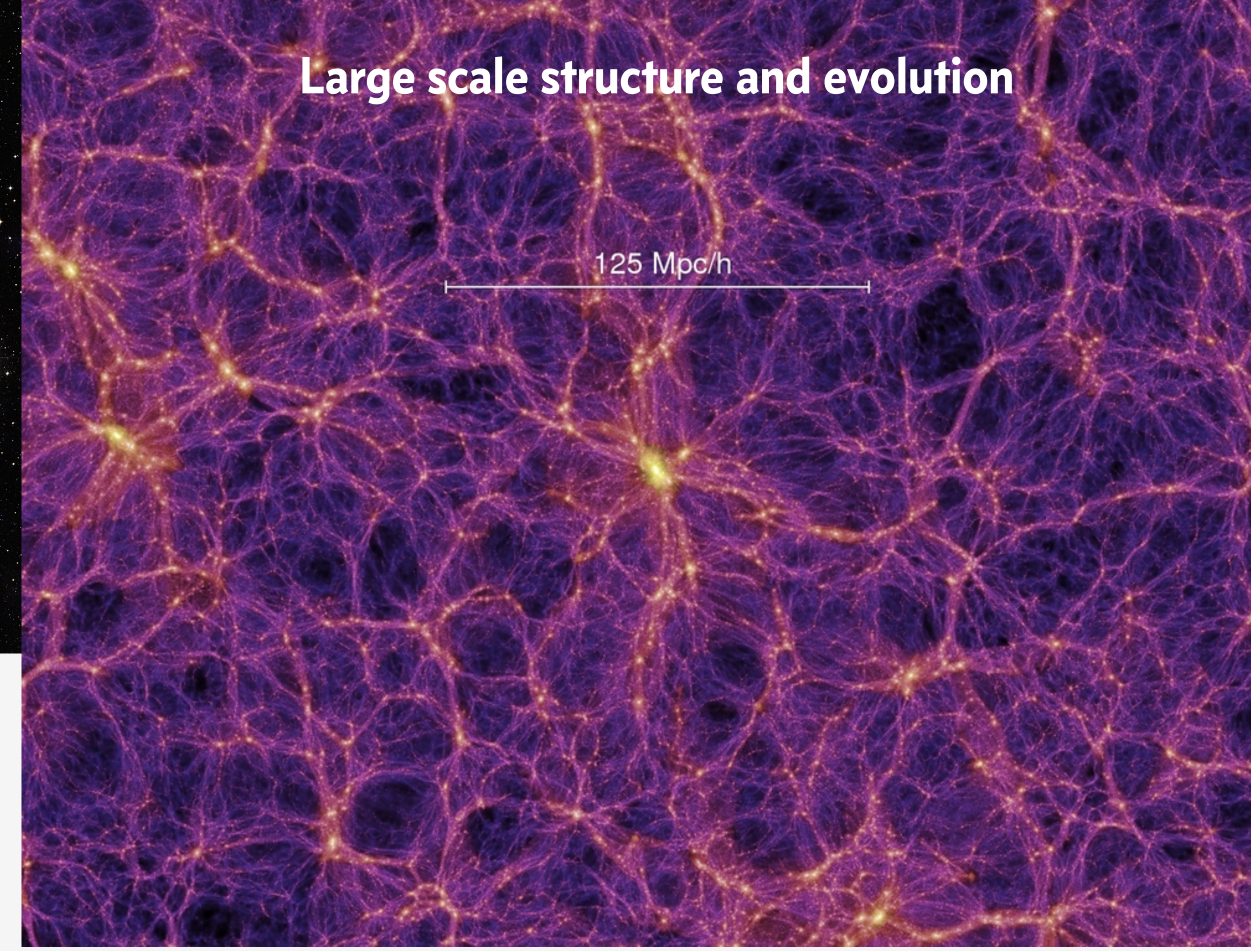


Evidence for Dark Matter

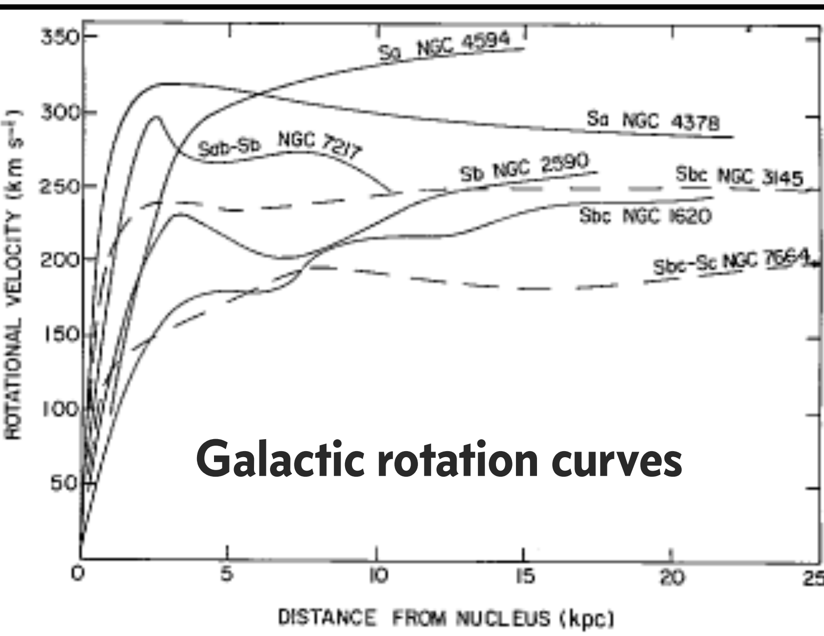






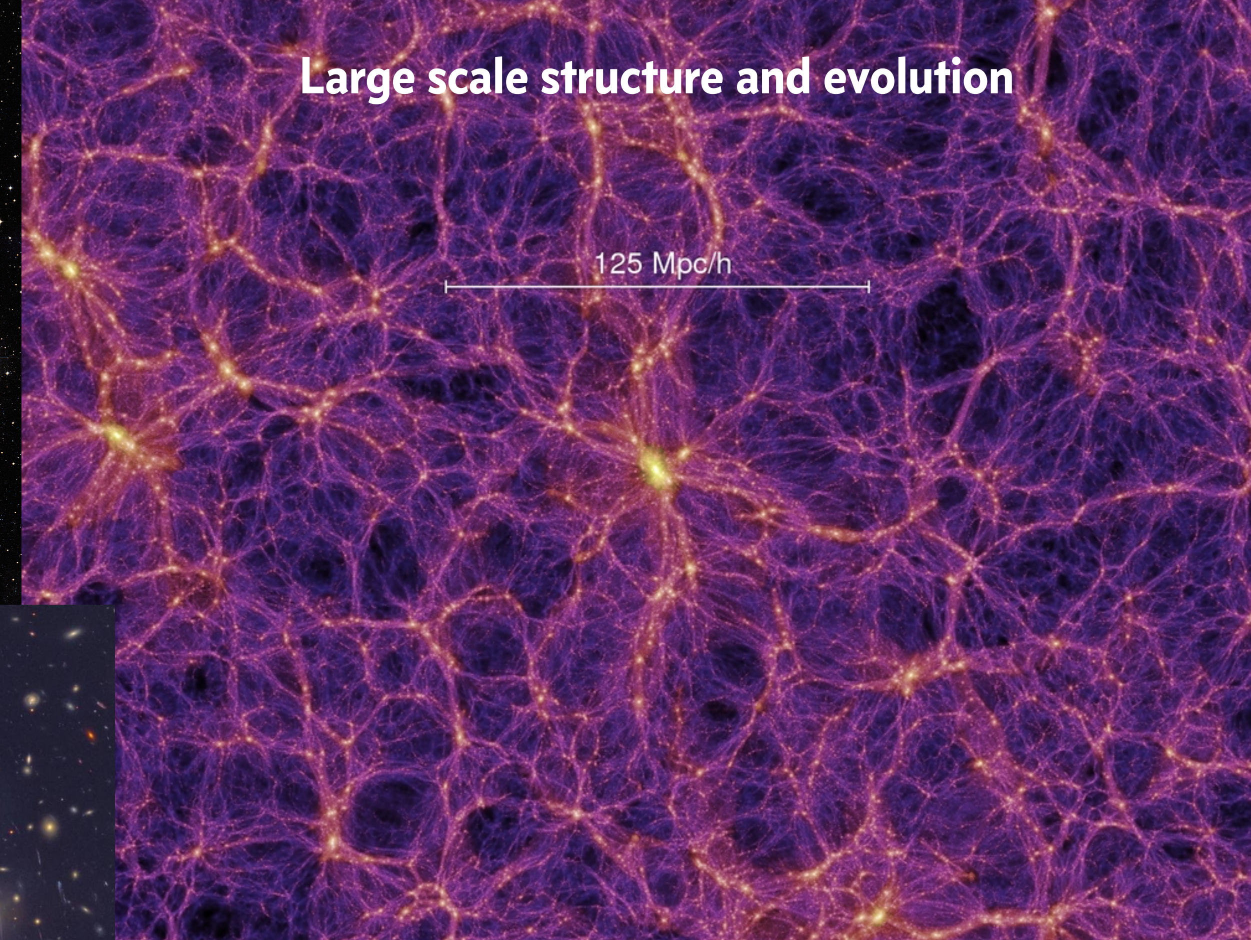
Cluster collisions

Evidence for Dark Matter



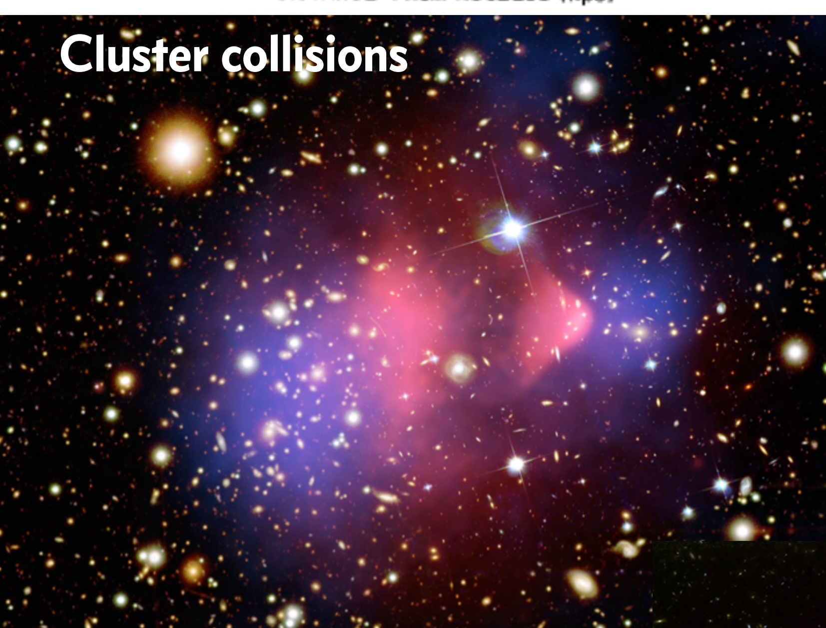
Galactic rotation curves

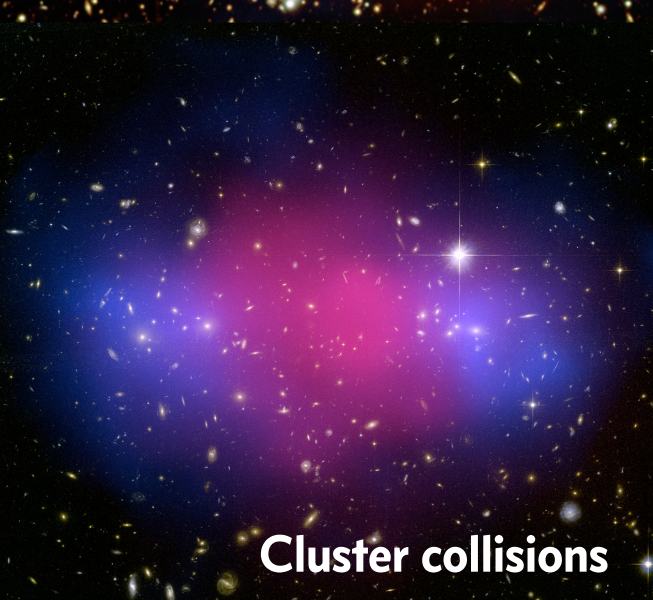

Dwarf galaxies



Large scale structure and evolution

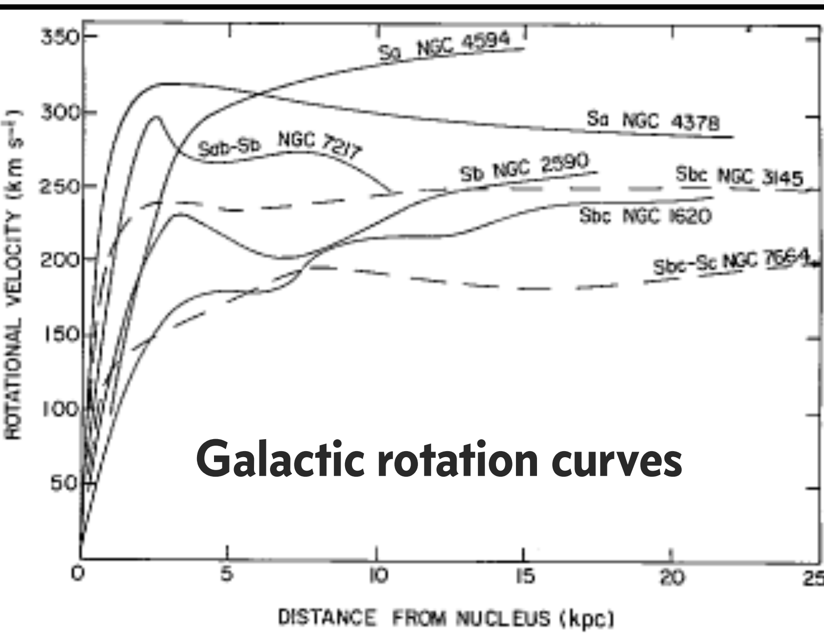

Gravitational lensing

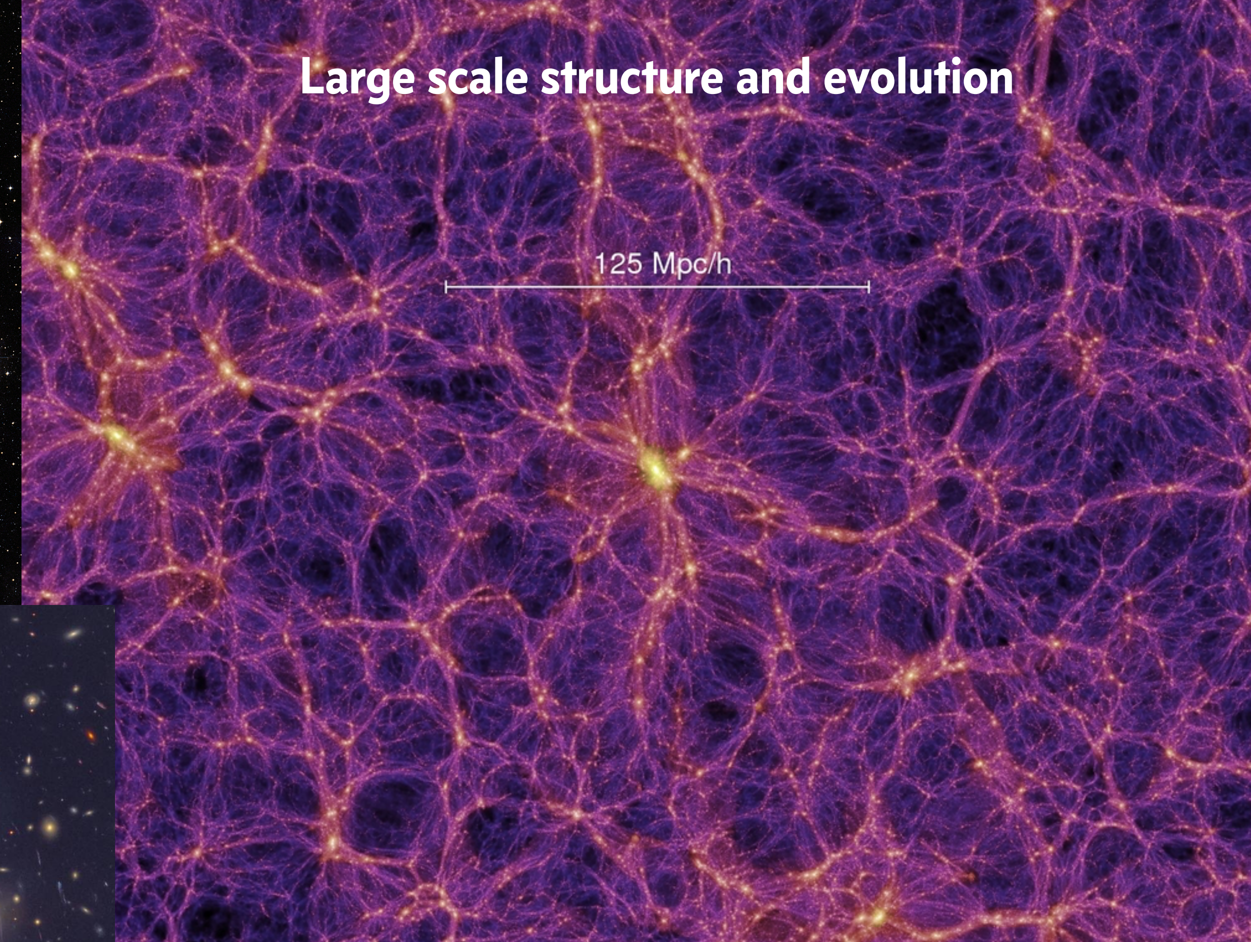

Cluster collisions

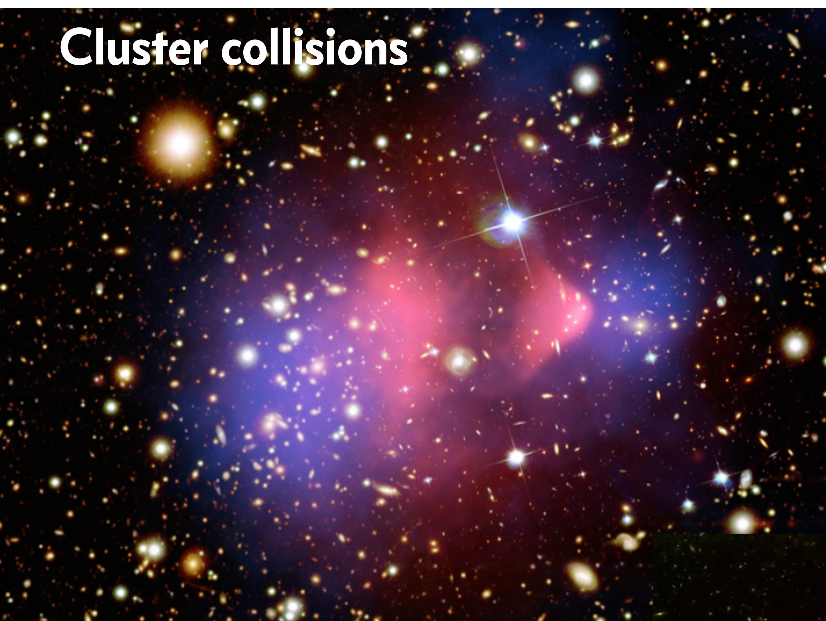

Cluster collisions

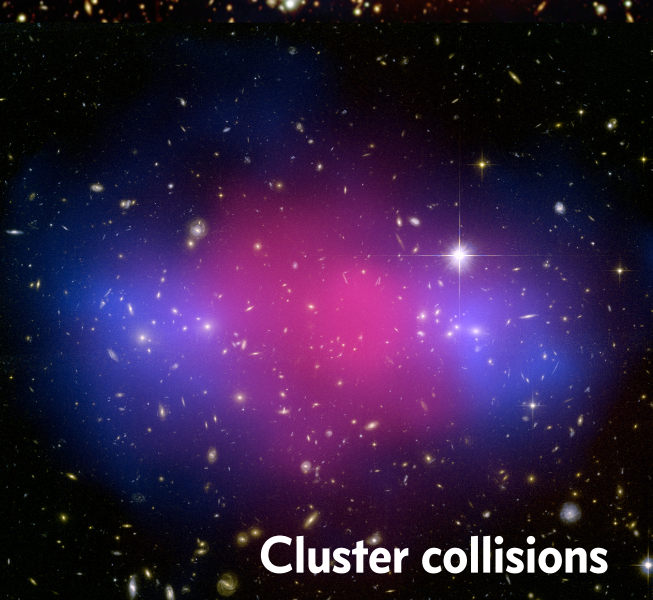

Gas in x-rays

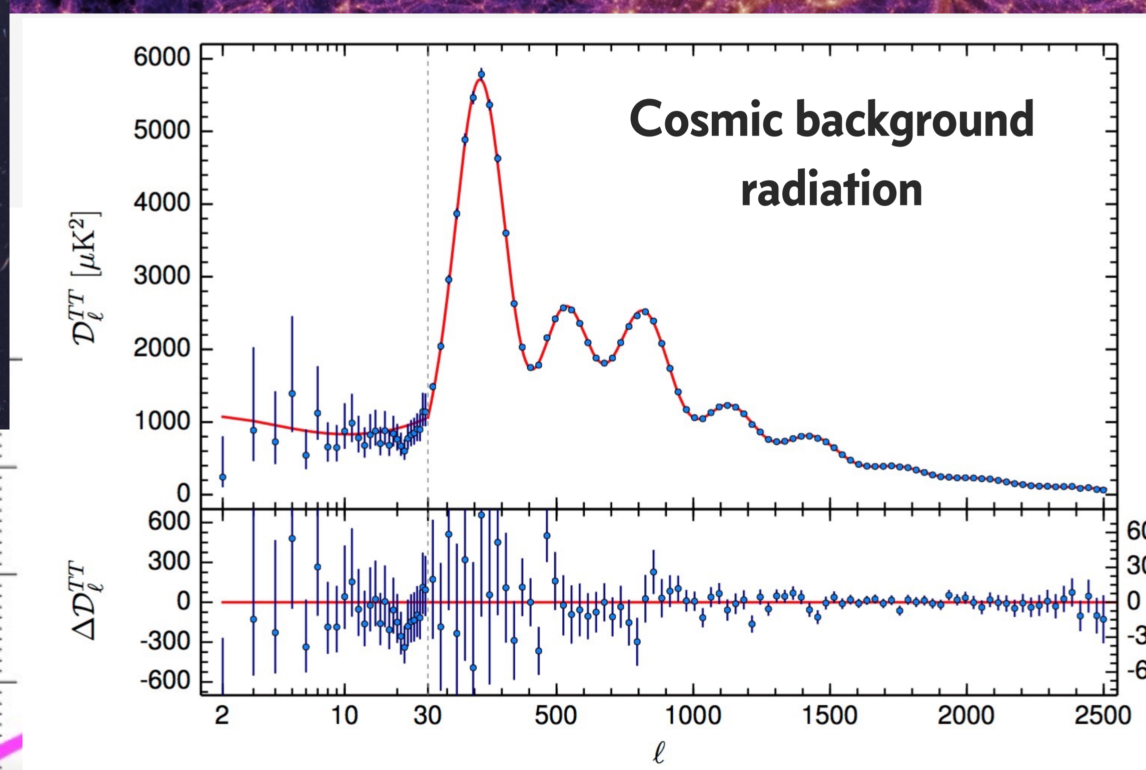
Evidence for Dark Matter

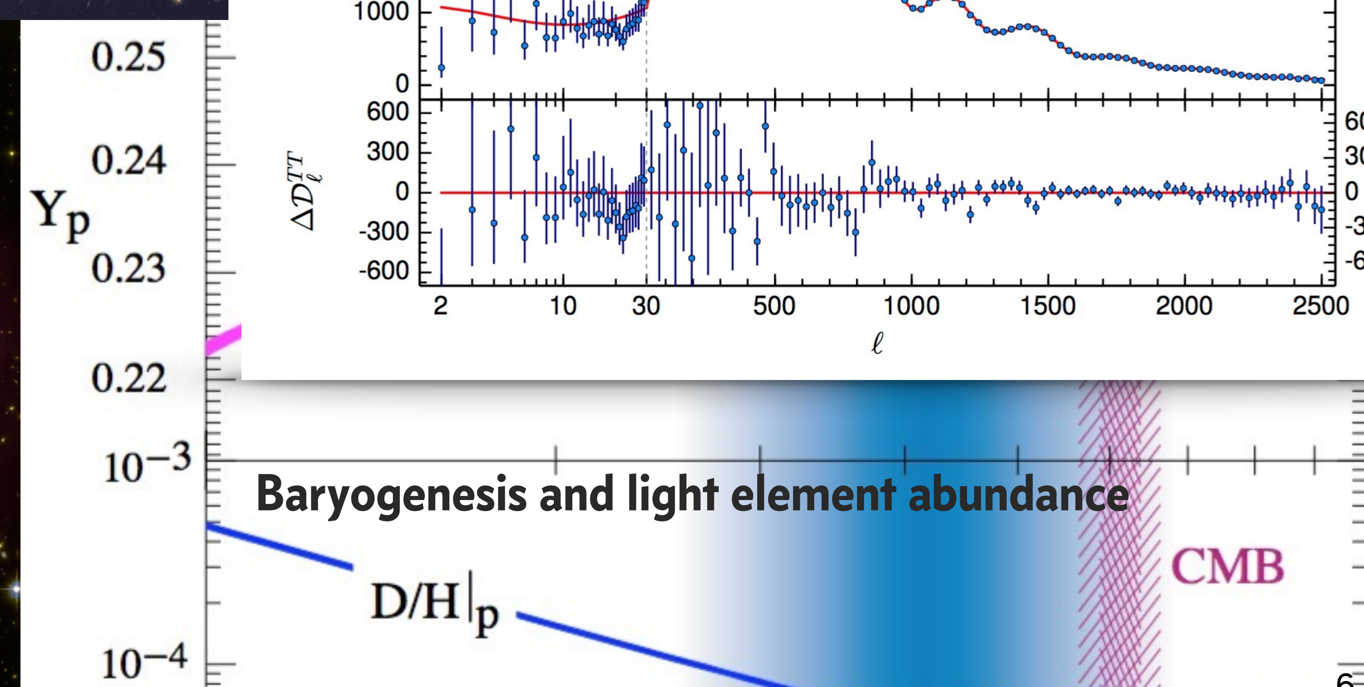












Properties of dark matter

Interacts gravitationally

Properties of dark matter

Interacts gravitationally

Dark

(other effective couplings to SM are zero or small)

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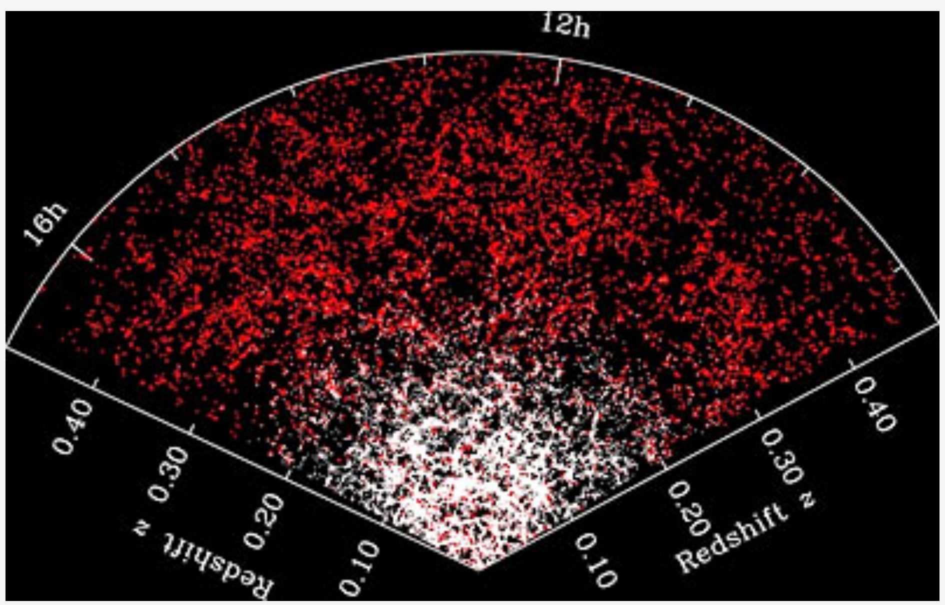
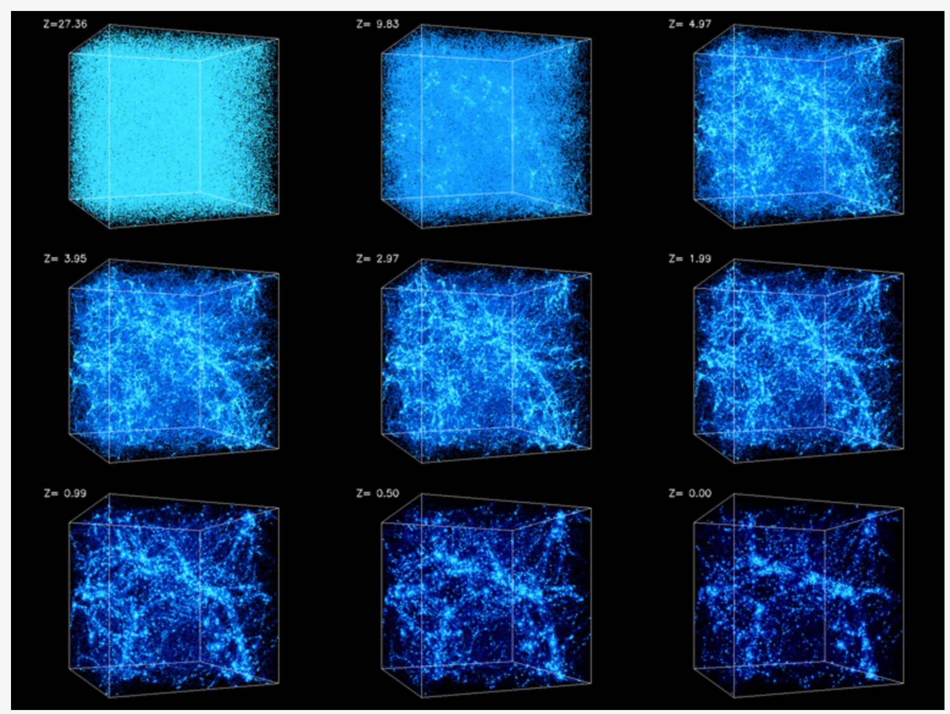


Cosmologically stable

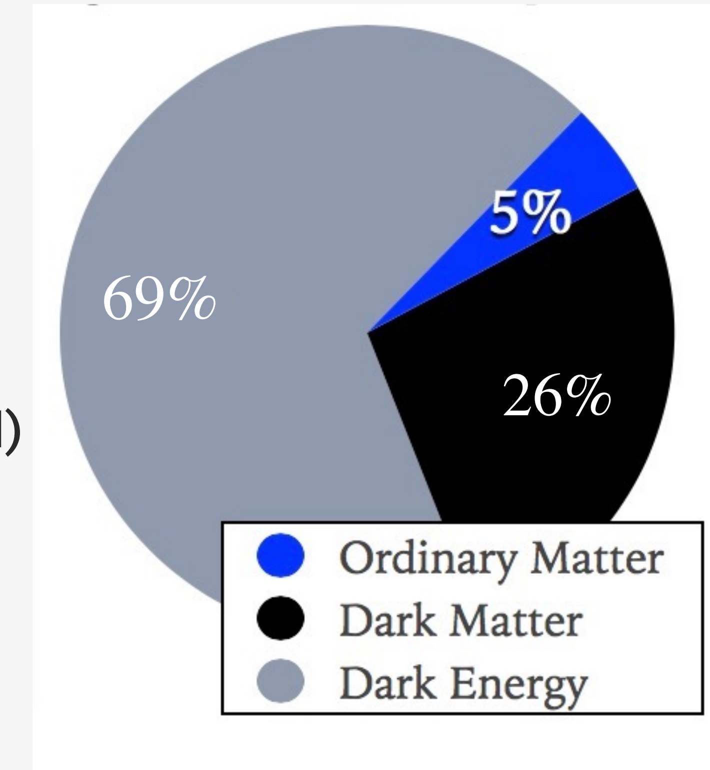


Approximately Cold / non-relativistic

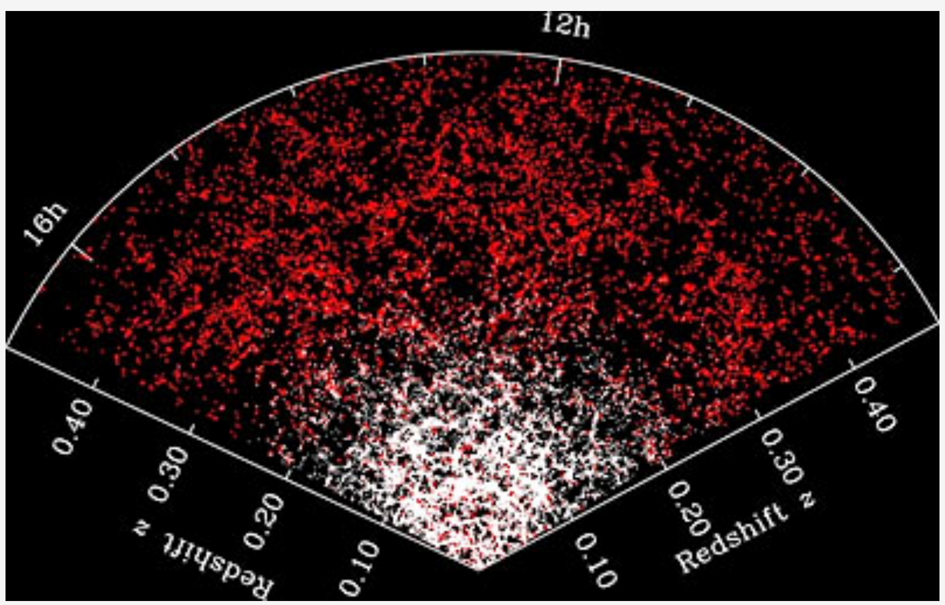
Properties of dark matter

Interacts gravitationally

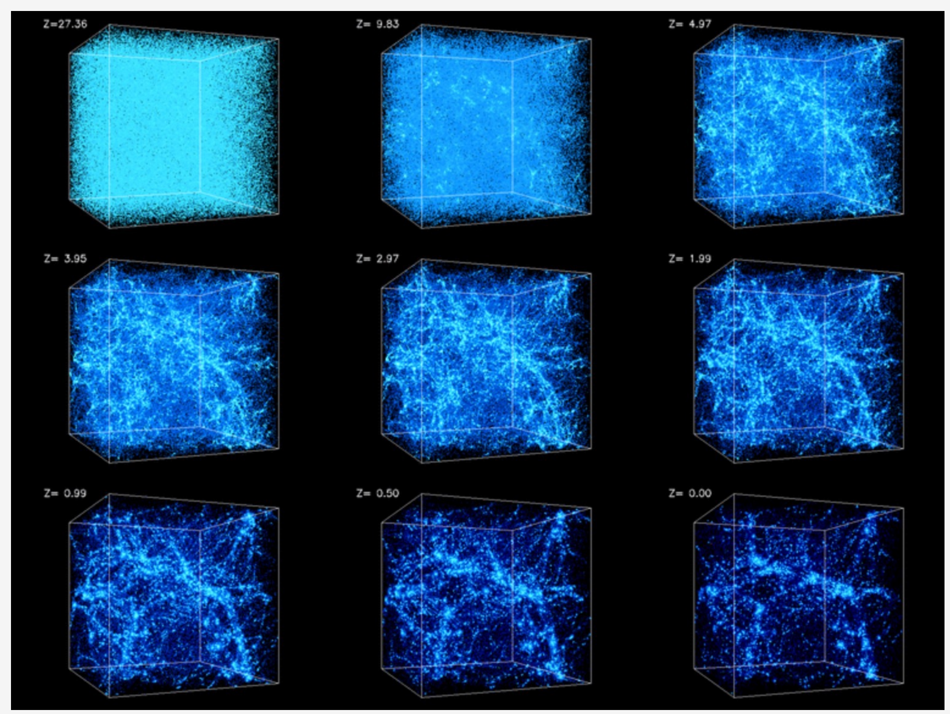
Dark
(other effective couplings to SM are zero or small)



5x as much DM as SM



Cosmologically stable



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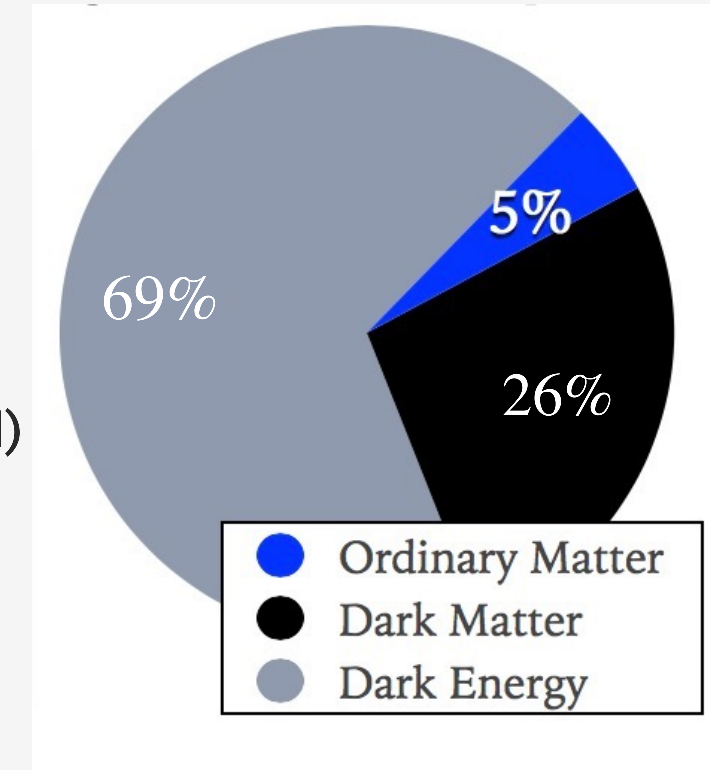

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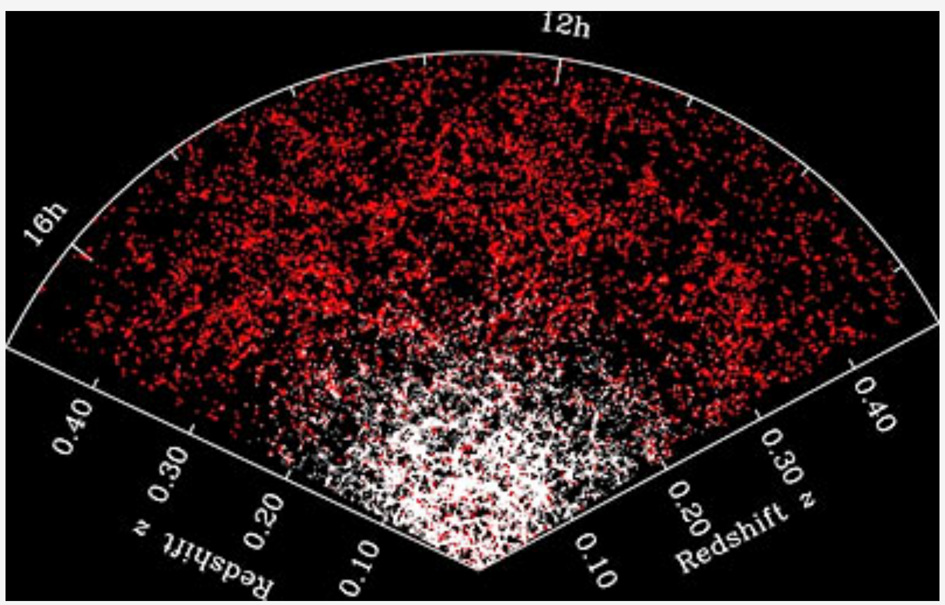
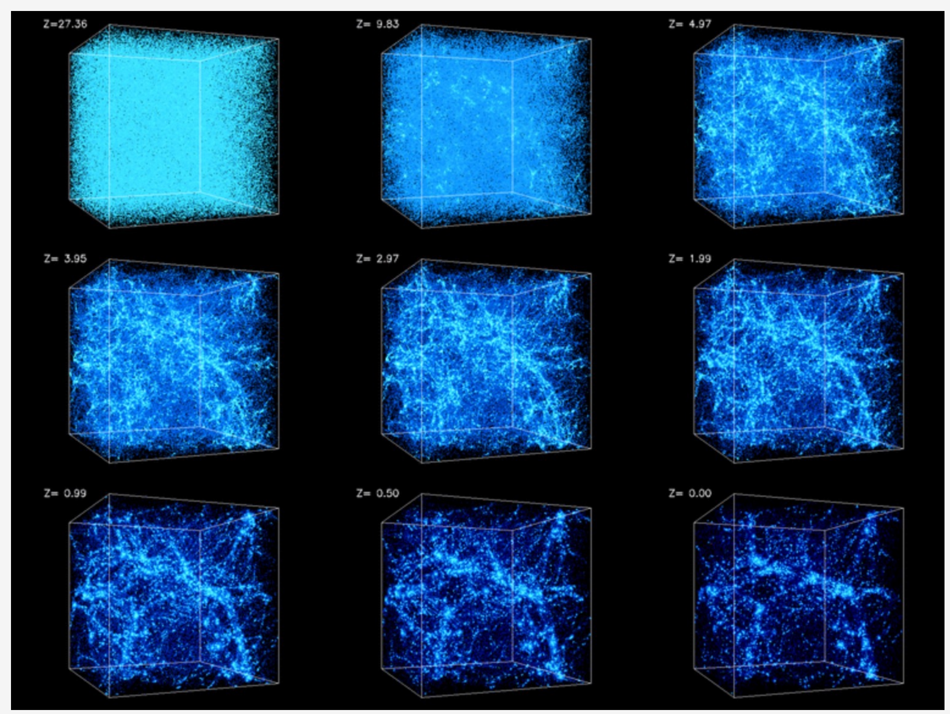


Cosmologically stable

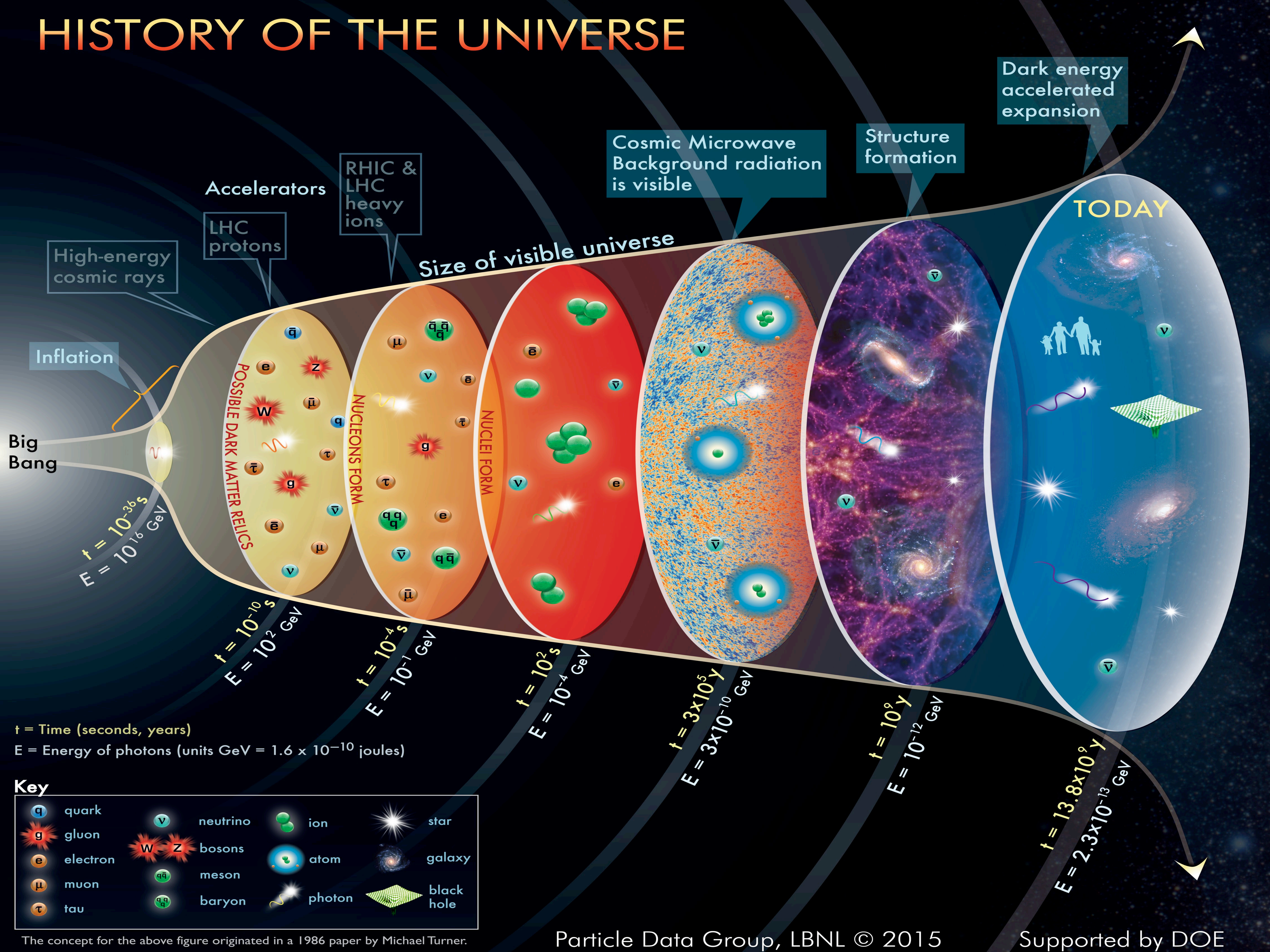


Approximately Cold / non-relativistic

Modified gravity difficult and lacks other evidence

Massive AstrophysiCal Halo Objects (MACHOs) cannot account for observed density

Particle dark matter: but properties inconsistent with any Standard Model particle



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
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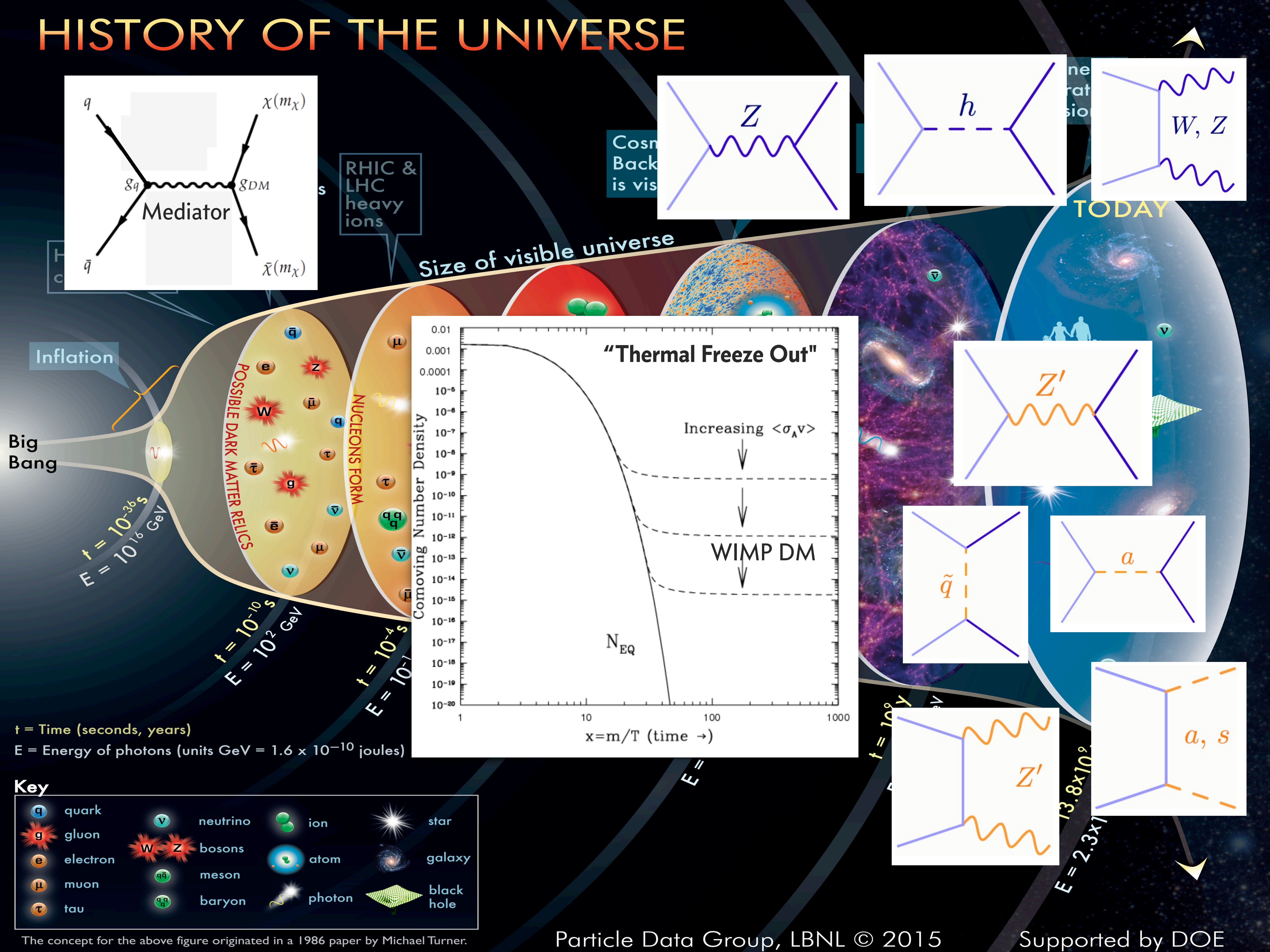

HISTORY OF THE UNIVERSE
Mediator
q
$\bar{q}$
$\chi(m_\chi)$
$\bar{\chi}(m_\chi)$
g_q
g_{DM}
RHIC & LHC heavy ions
Z
h
W, Z
TODAY
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
"Thermal Freeze Out"
Increasing $\langle\sigma_A v\rangle$
WIMP DM
N_{EQ}
Comoving Number Density
$x=m/T$ (time $\rightarrow$)
Z'
$\tilde{q}$
a
a, s
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
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The concept for the above figure originated in a 1986 paper by Michael Turner.
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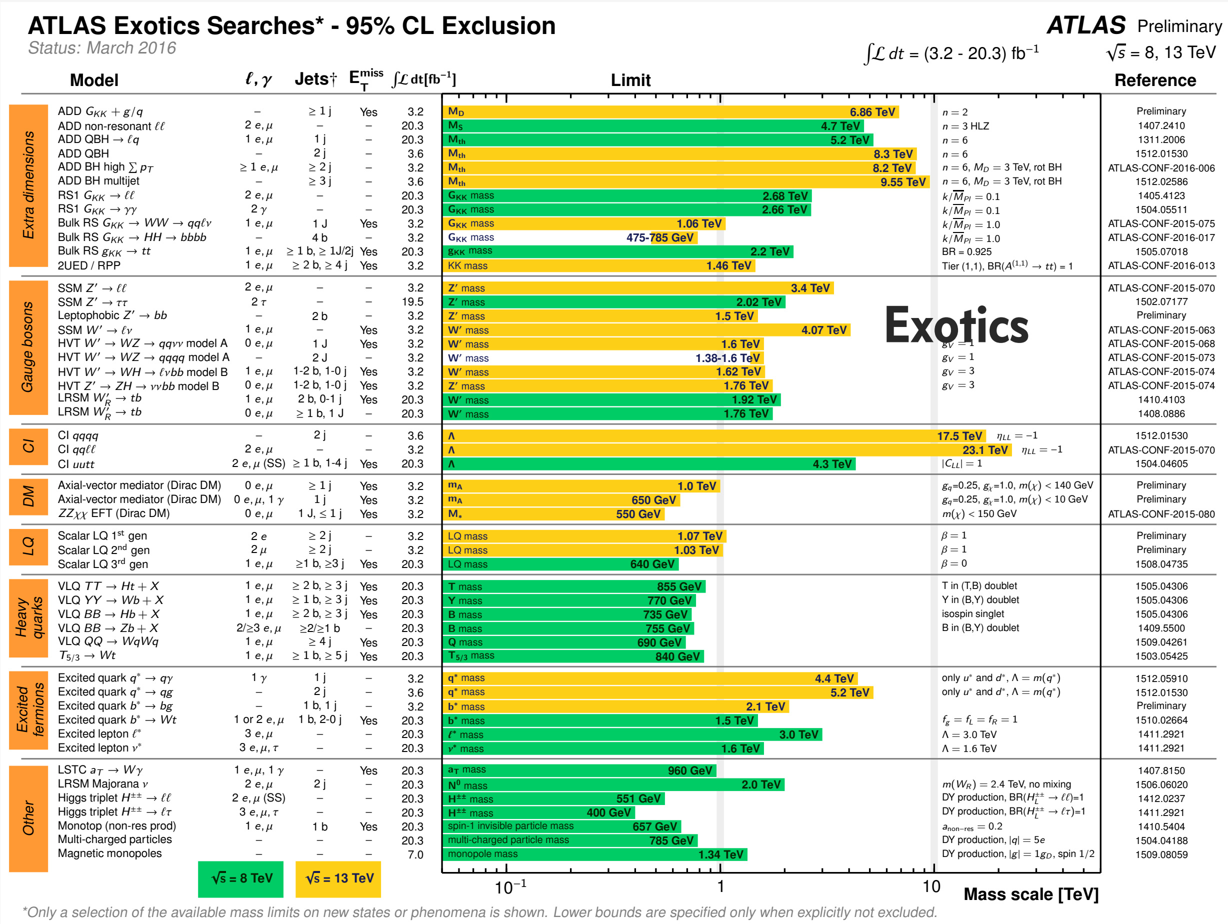
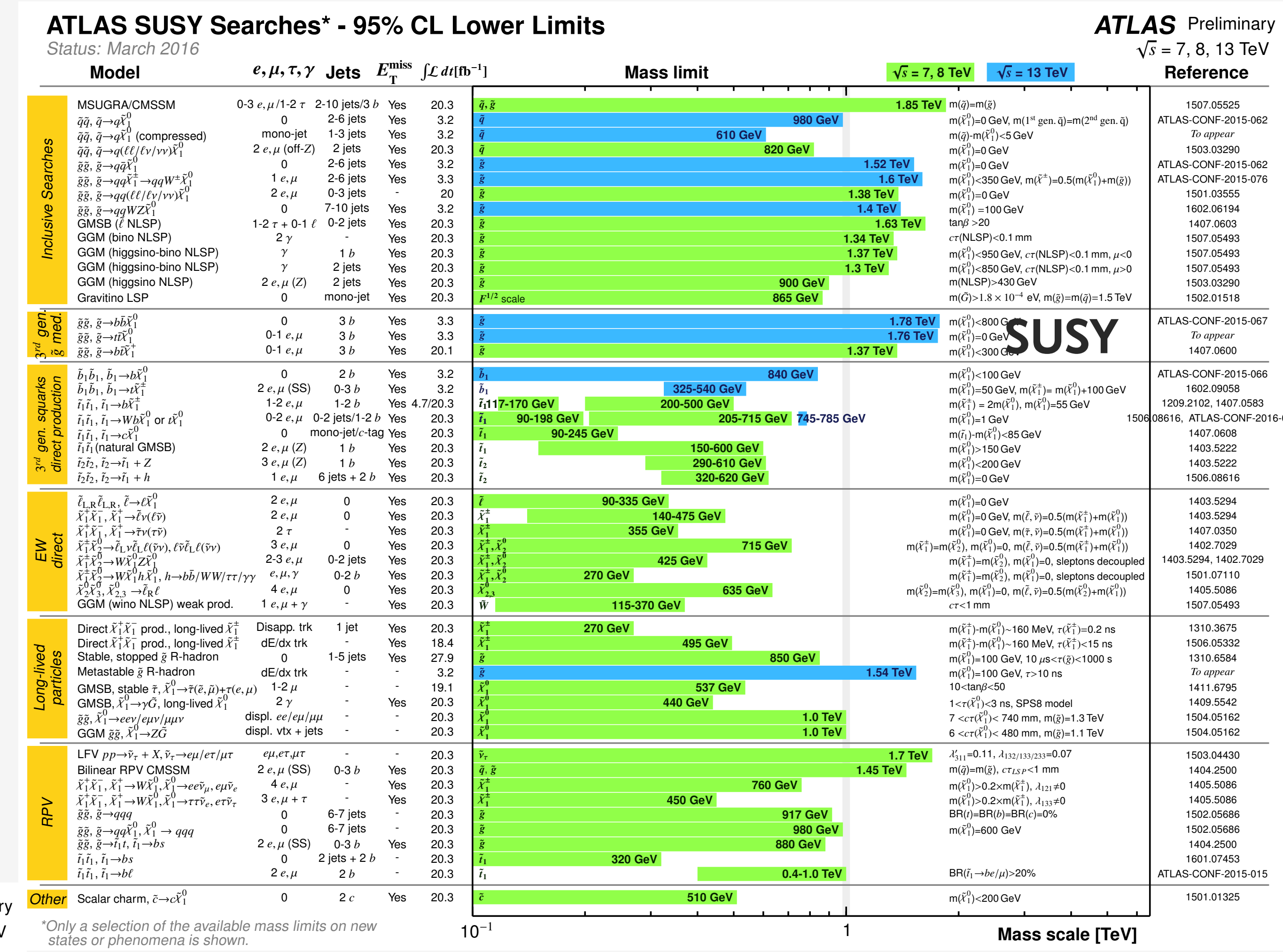
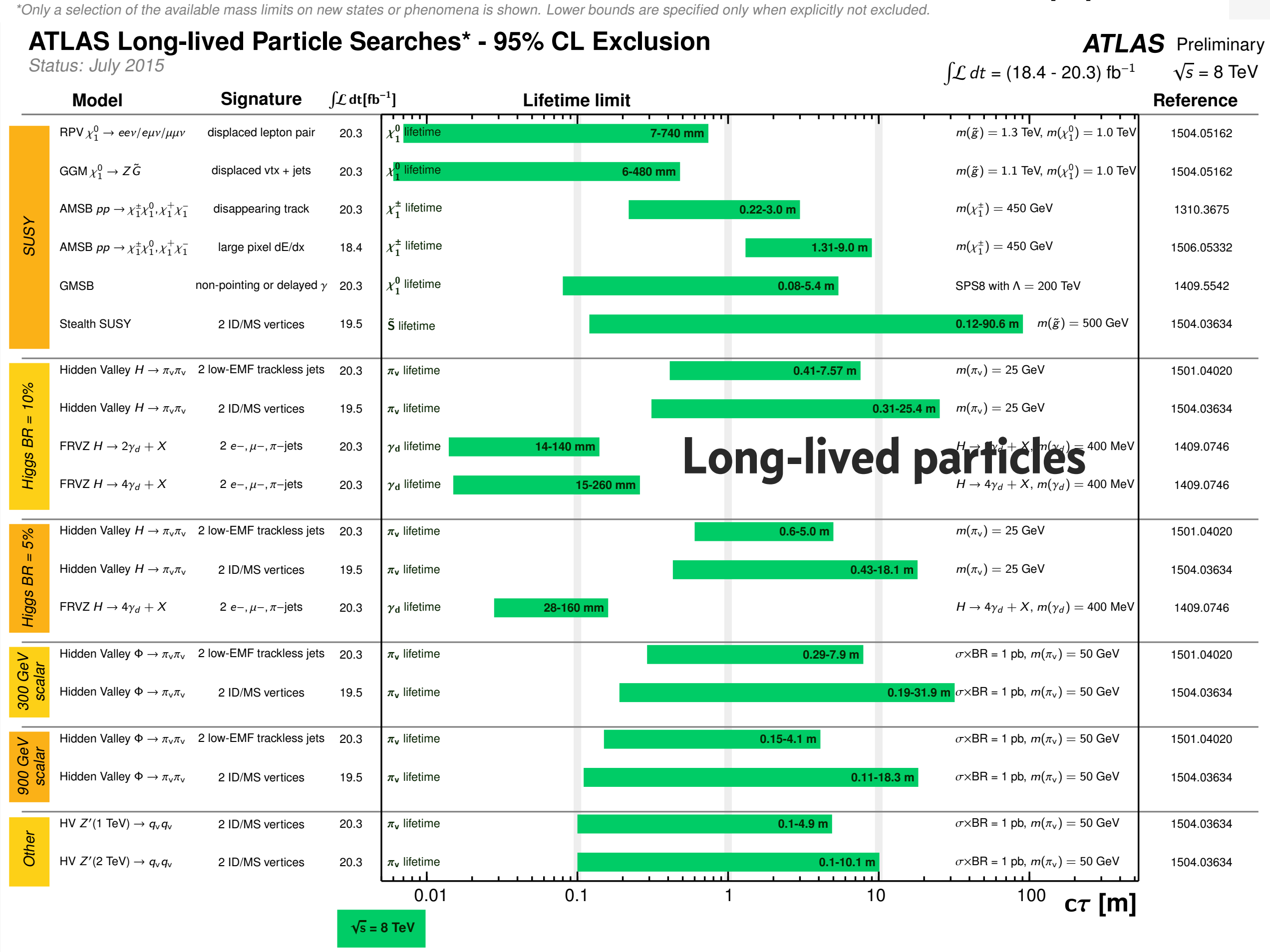
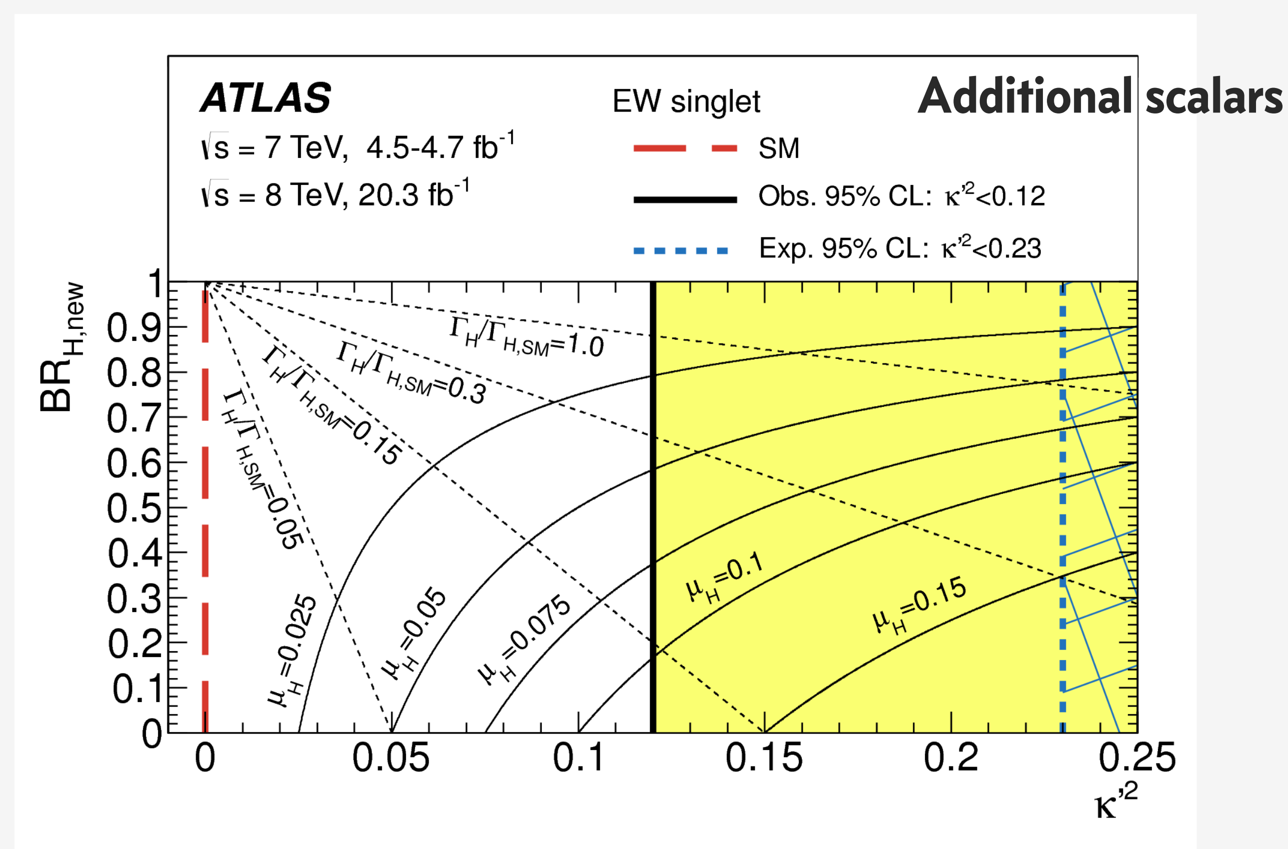
Searches for New Physics at ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

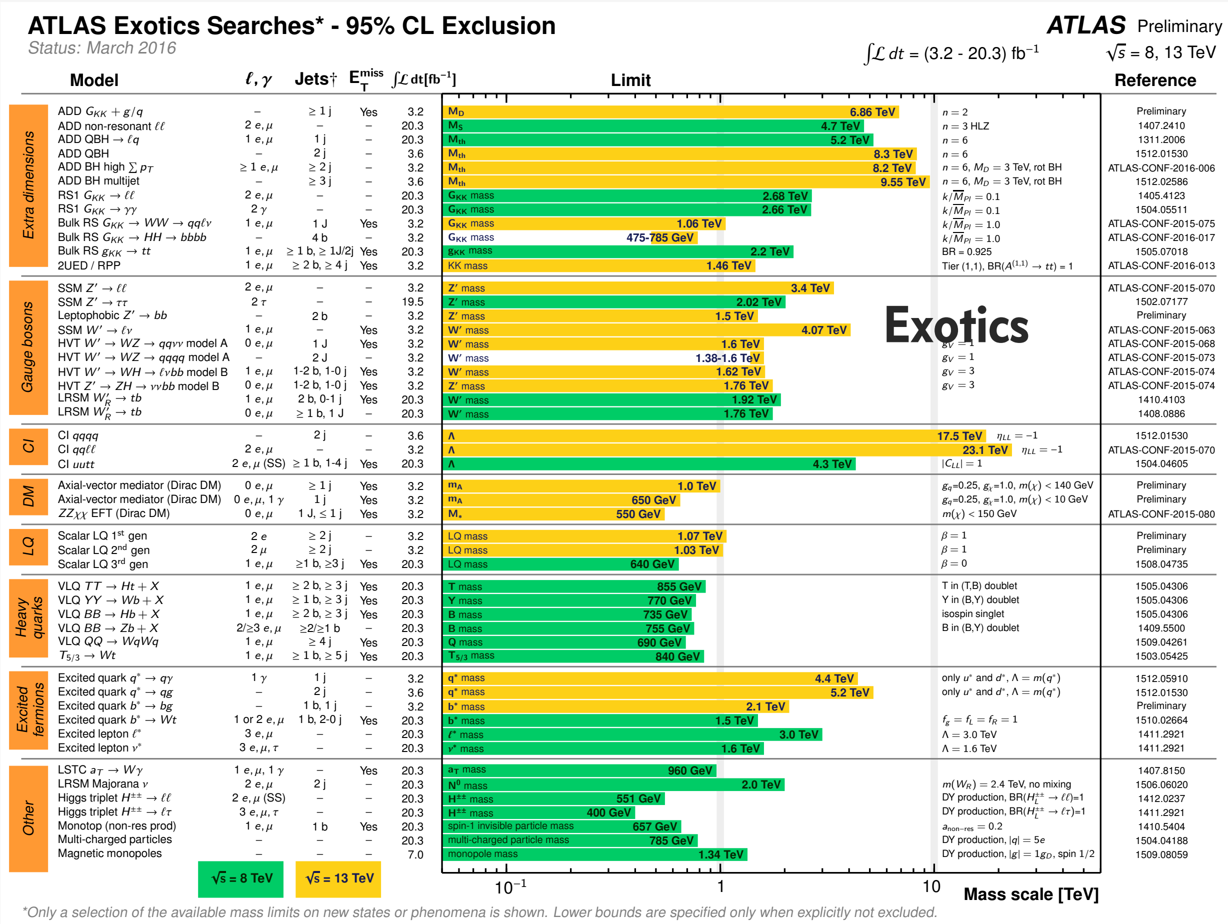


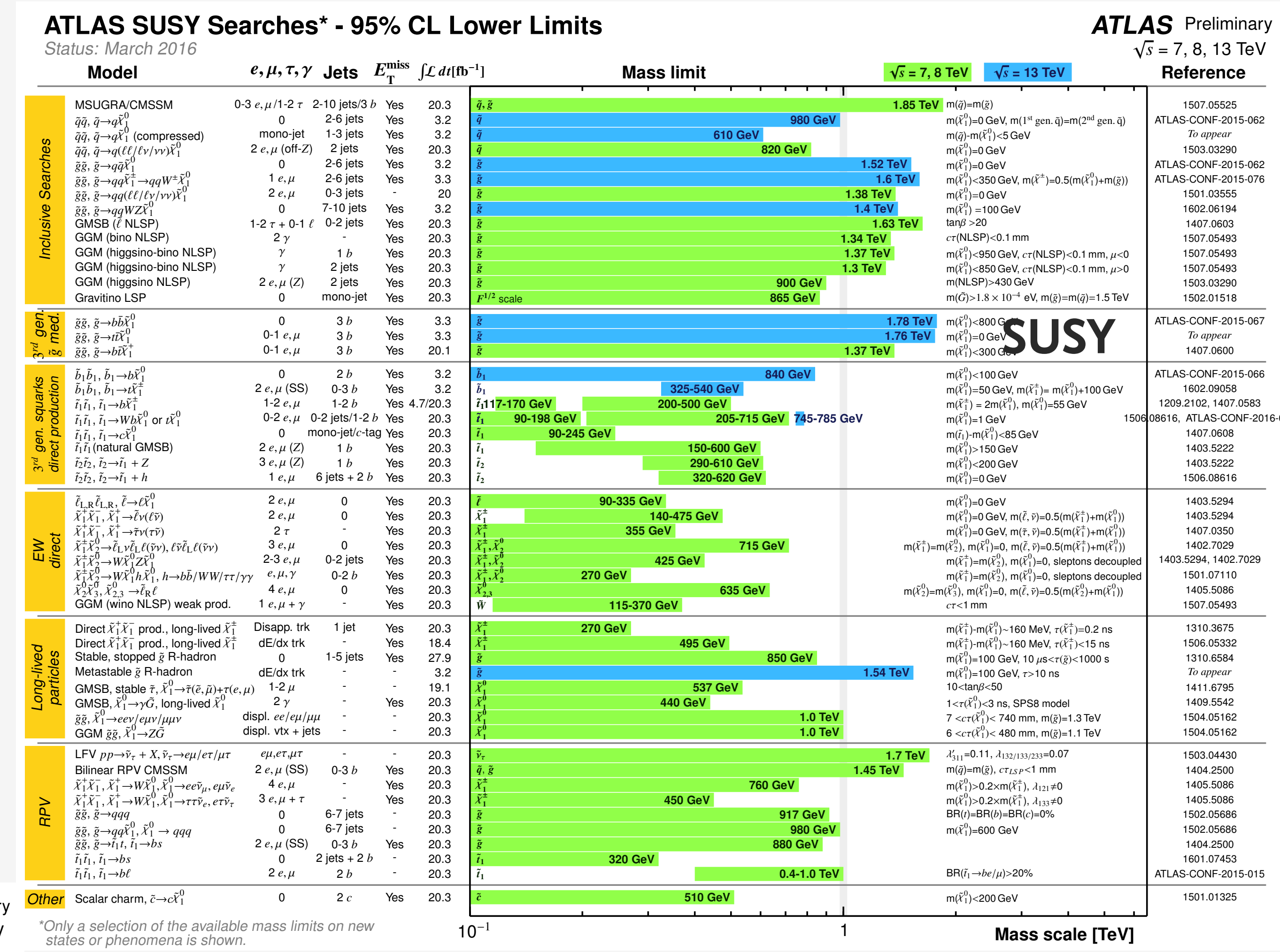


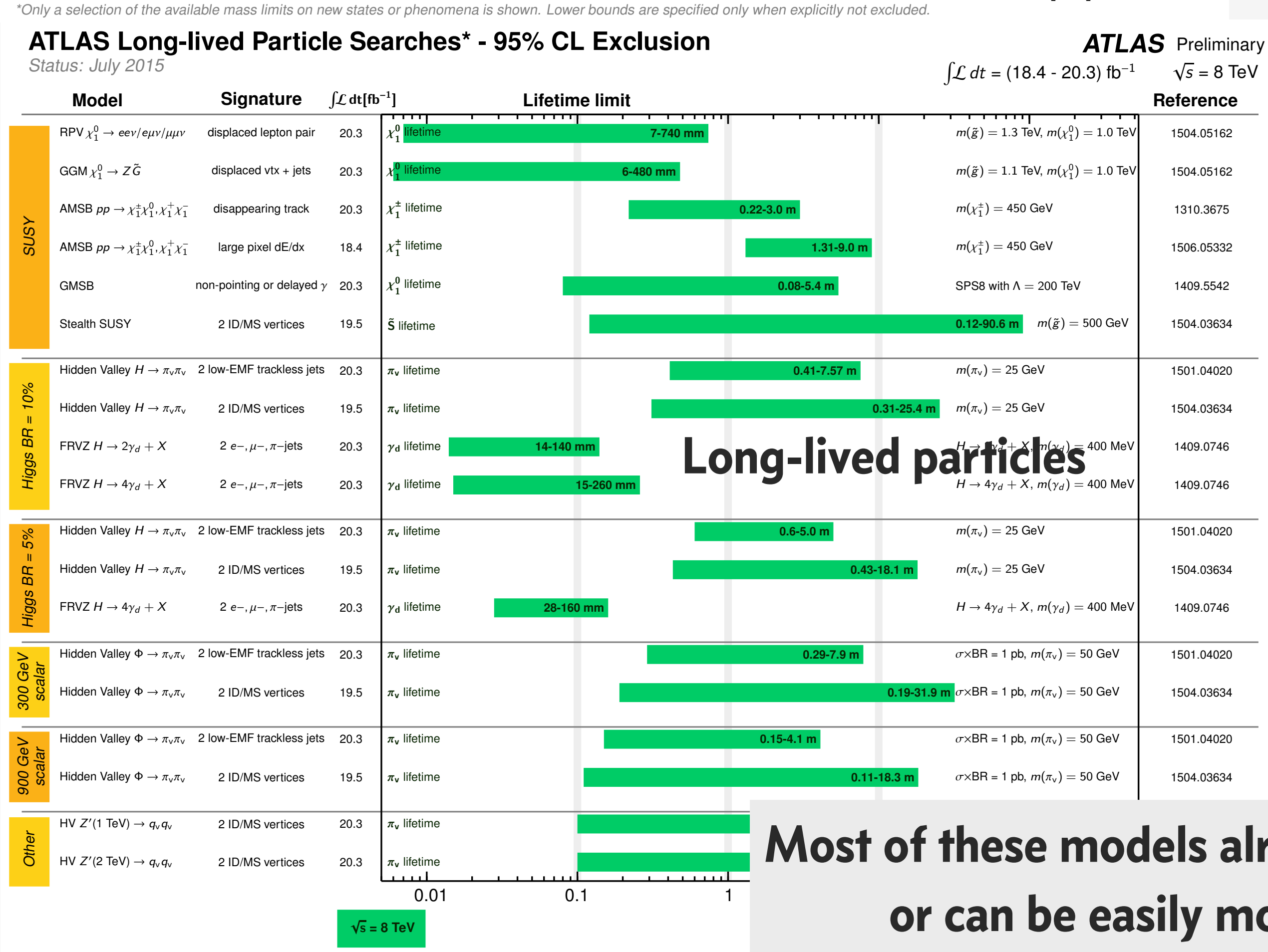


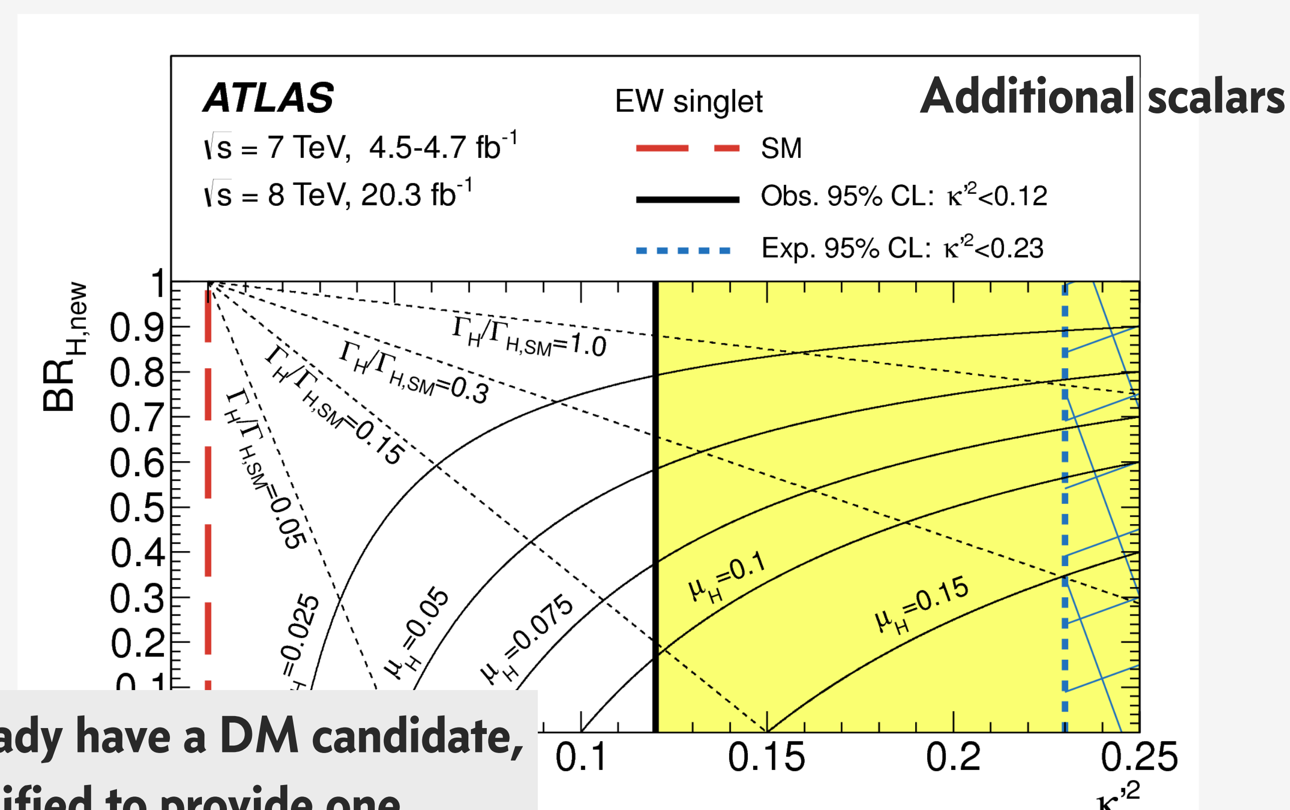


~~Searches for New Physics at ATLAS~~ Searches for Dark Matter at ATLAS









Most of these models already have a DM candidate, or can be easily modified to provide one

Models of Particle Dark Matter: General aspects

Dark matter is something with **very small effective couplings** to the SM

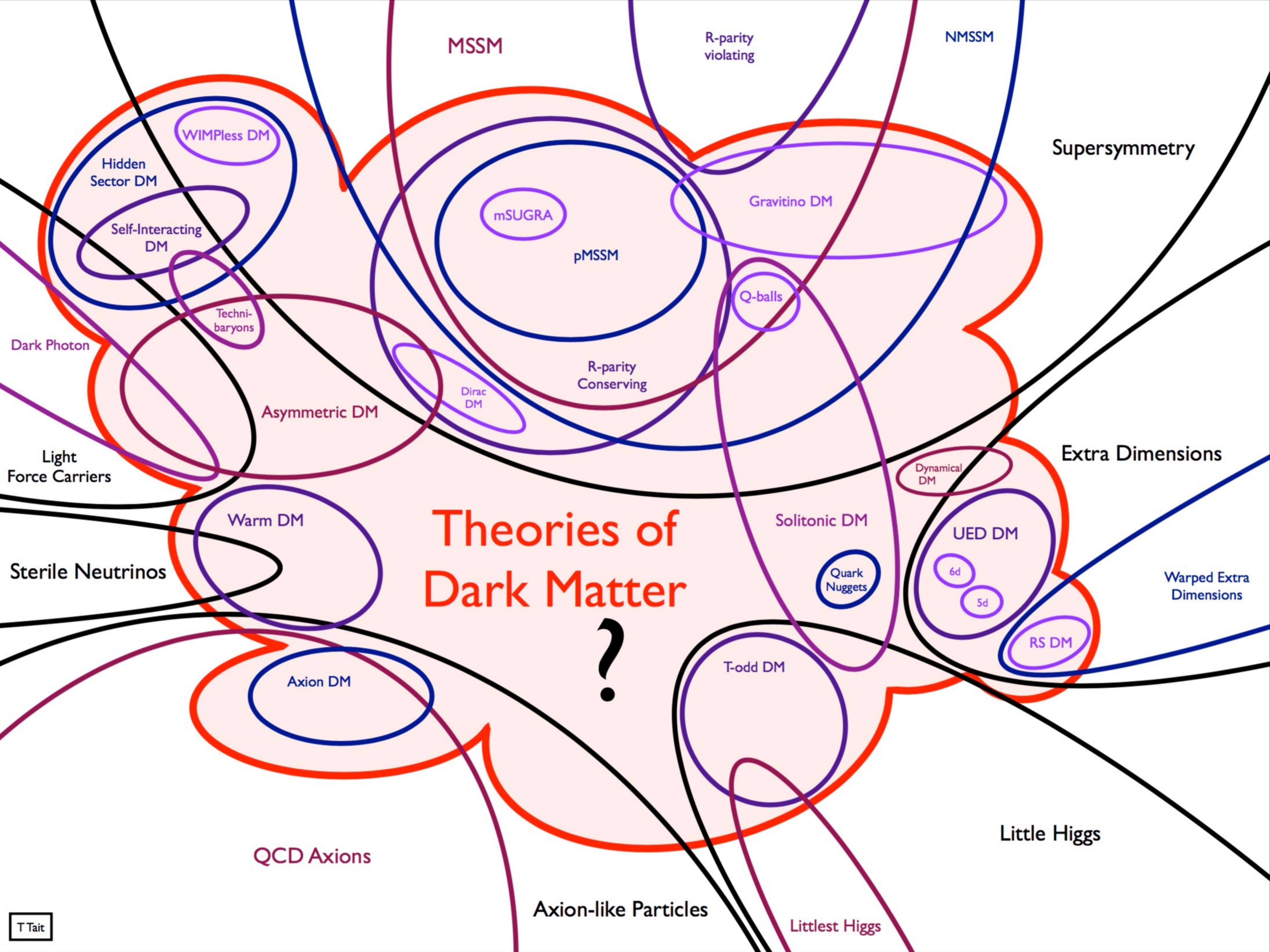
- either directly to SM particles (H, Z, …) or
- indirectly through new BSM particles (e.g. Z′)

What distinguishes searches for dark matter from general BSM searches:
what we know about it from astrophysics and astroparticle DM searches

relic density, direct detection, indirect detection

- e.g. thermal freeze out, freeze-in, “dark” freeze out, etc.
- e.g. scalar, Majorana or Dirac fermion, vector DM.

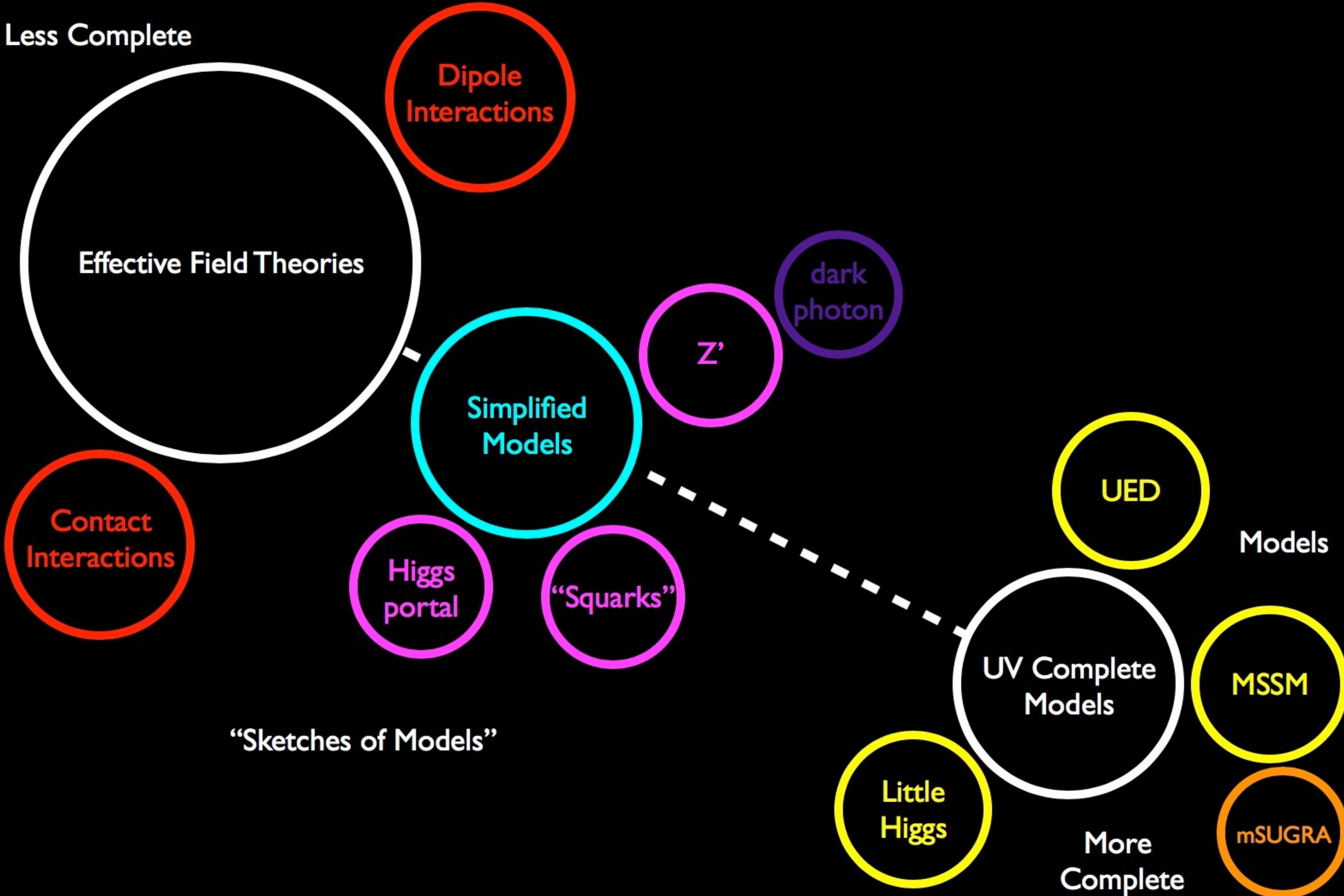
Use this information to target our effort.



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
Sterile Neutrinos
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Spectrum of Theory Space

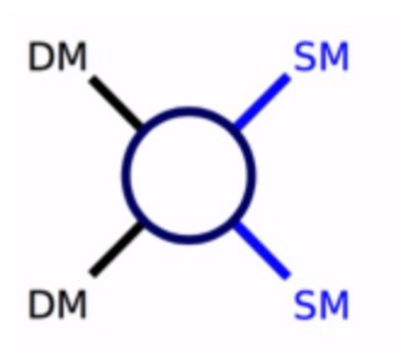
Tim M.P. Tait



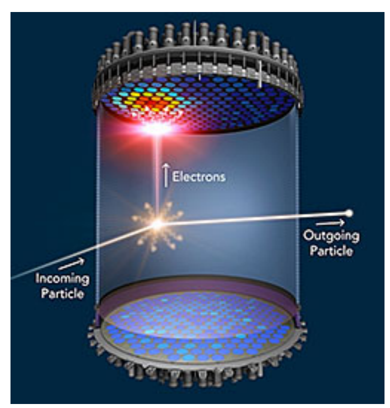
Models of Particle Dark Matter: Complementarity

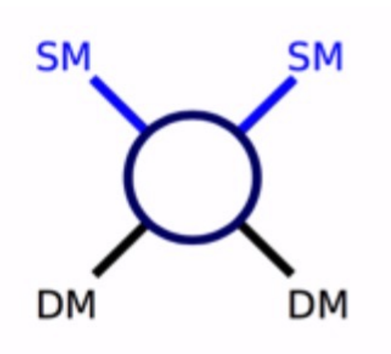
Focus on general-purpose searches for WIMP dark matter **emphasizing complementarity**

- assume dark matter has **non-gravitational interactions with the SM**
- focus on models with **effective baryon coupling**: scattering off **nuclei** and production in **pp collisions**
- **signature-based searches** applicable to broad classes of possible models
- balance between model agnosticism and using models to translate astro-physical/-particle knowledge

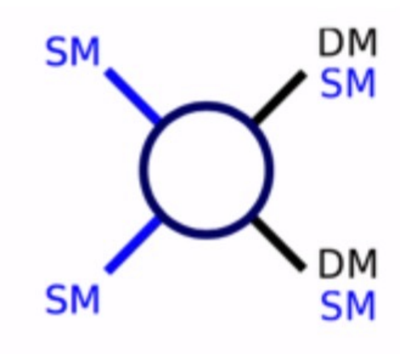


Indirect Detection

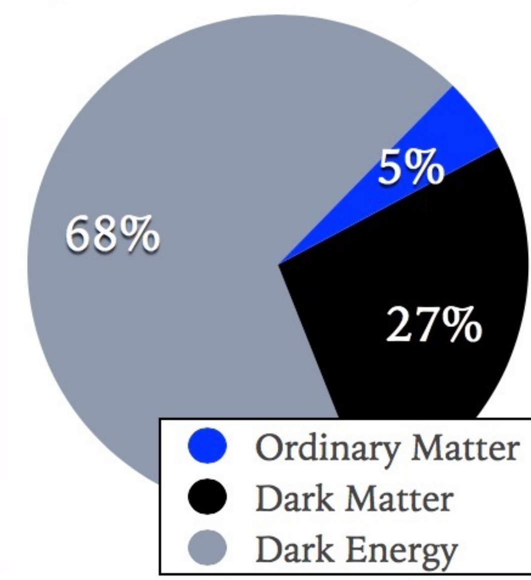




Direct Detection



Colliders



Require some model, to translate what we know from astrophysics and non-collider DM,
vs. taking the model too seriously (it's probably wrong)

The Optimistic Possibility: Dark Matter can be studied in many complementary experiments

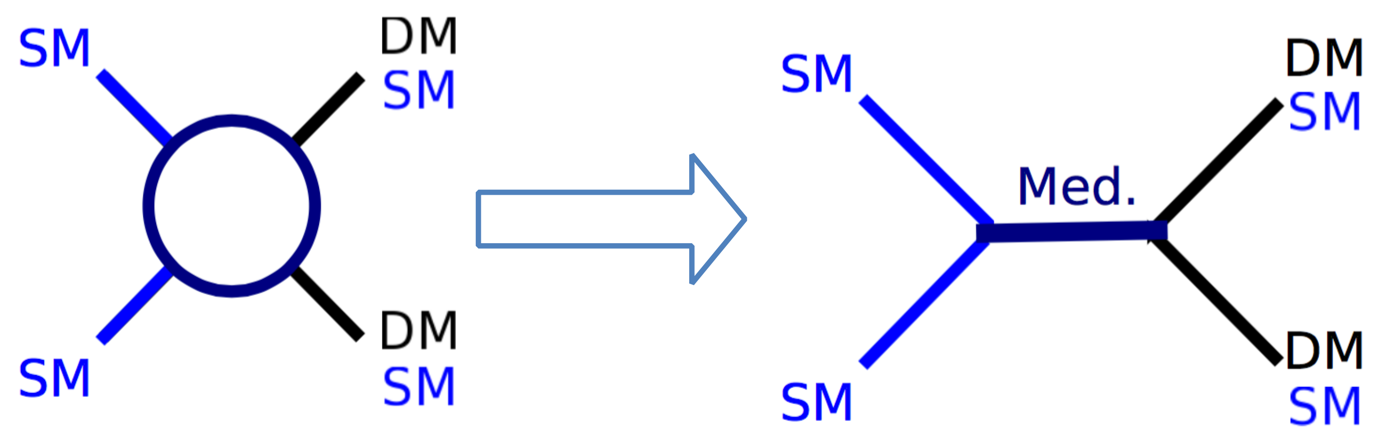
Standard Model Particles interact with **Dark Matter**

insert known particle(s) here

insert new particle(s) here

through

insert mediator of new SM/DM interaction



Colliders
(Contact interaction)

Colliders
(Simplified Models)

The Optimistic Possibility: Dark Matter can be studied in many complementary experiments

Standard Model Particles interact with **Dark Matter**

insert known particle(s) here

insert new particle(s) here

through **W and Z bosons**

insert mediator of new SM/DM interaction

strongly constrained

The Optimistic Possibility: Dark Matter can be studied in many complementary experiments

Standard Model Particles interact with **Dark Matter**

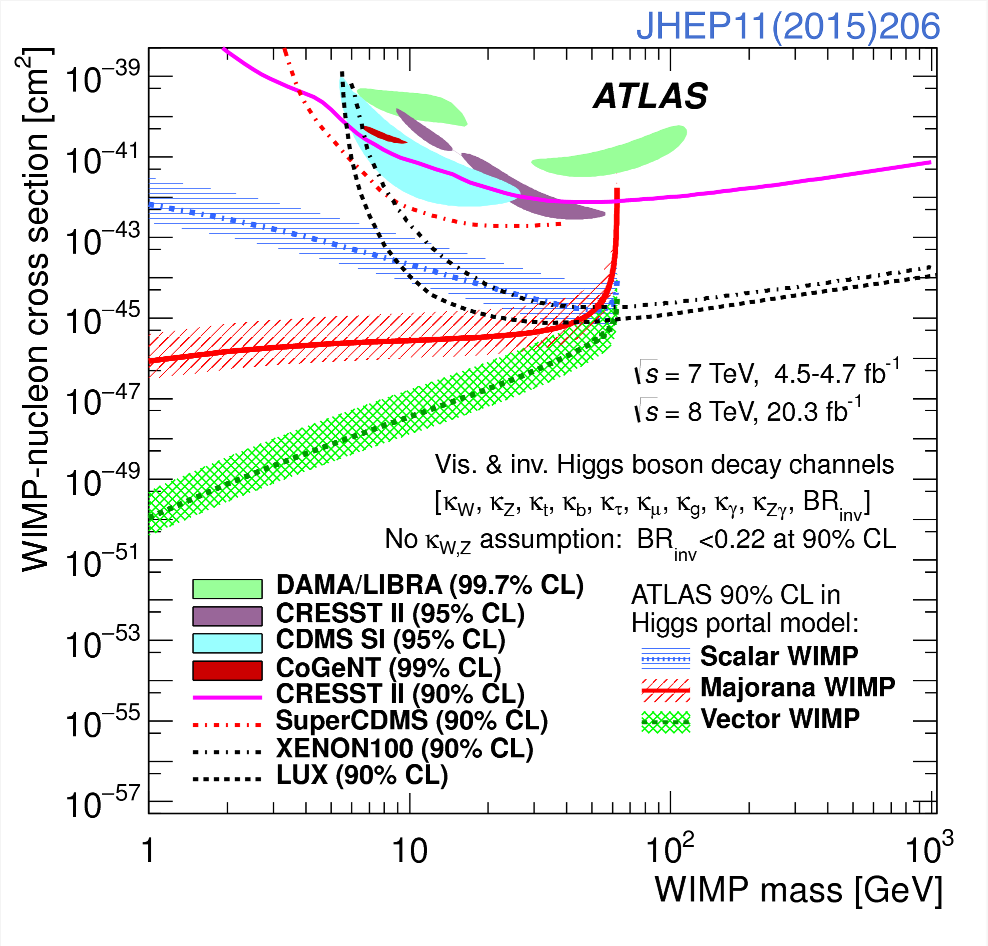
insert known particle(s) here

insert new particle(s) here

through **the Higgs boson**

insert mediator of new SM/DM interaction

probing since 2012



The Optimistic Possibility: Dark Matter can be studied in many complementary experiments

Standard Model Particles interact with **Dark Matter**

insert known particle(s) here

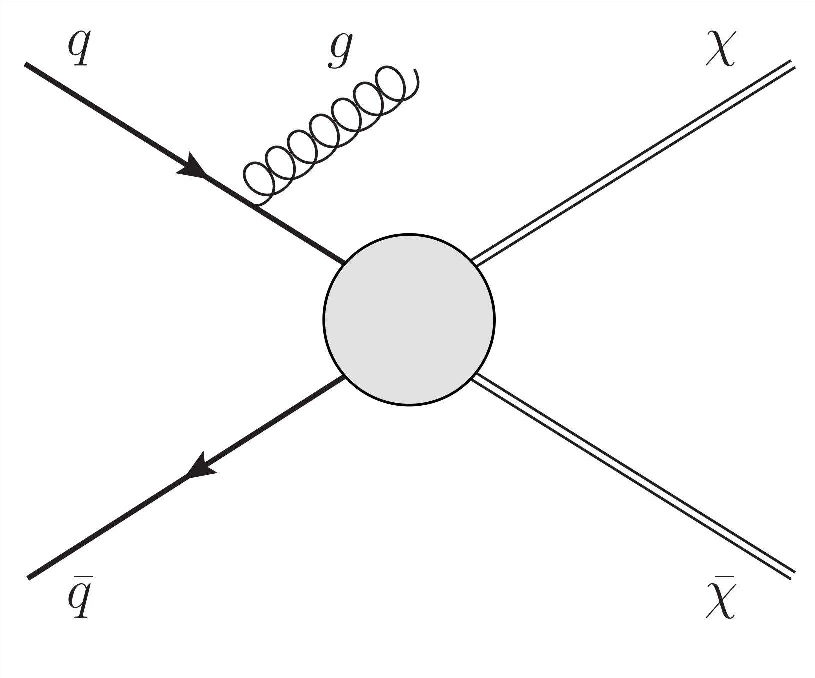
insert new particle(s) here

through **BSM particles**

insert mediator of new SM/DM interaction

lots of possibilities!

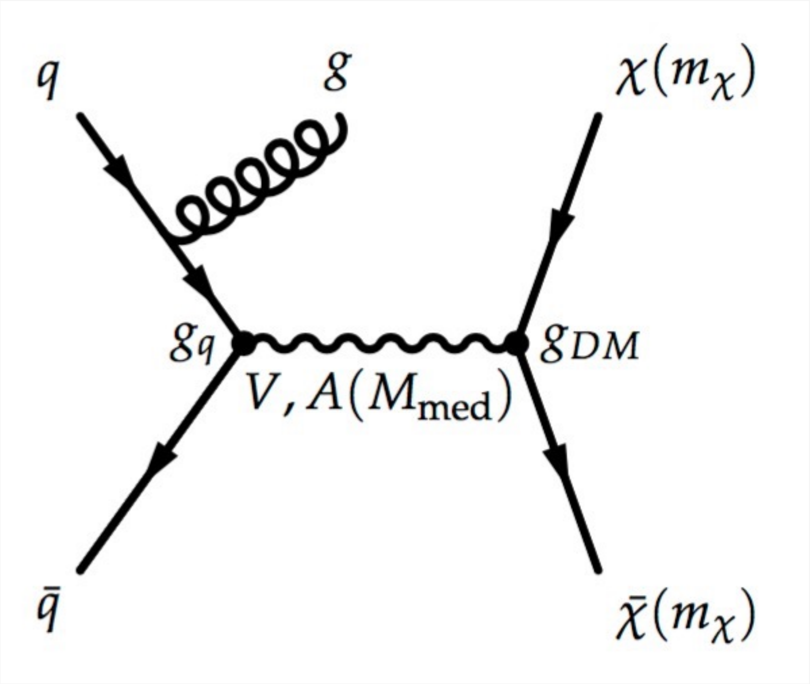
Contact Interaction Theory



1. DM must be pair produced
2. MET+proton remnants is indistinguishable from backgrounds
3. We need to “tag” the collision with high p_T ISR
4. The Standard Model predicts what ISR occurs most often…

➠ do a mono-jet or “mono-X” search

Simplified Models



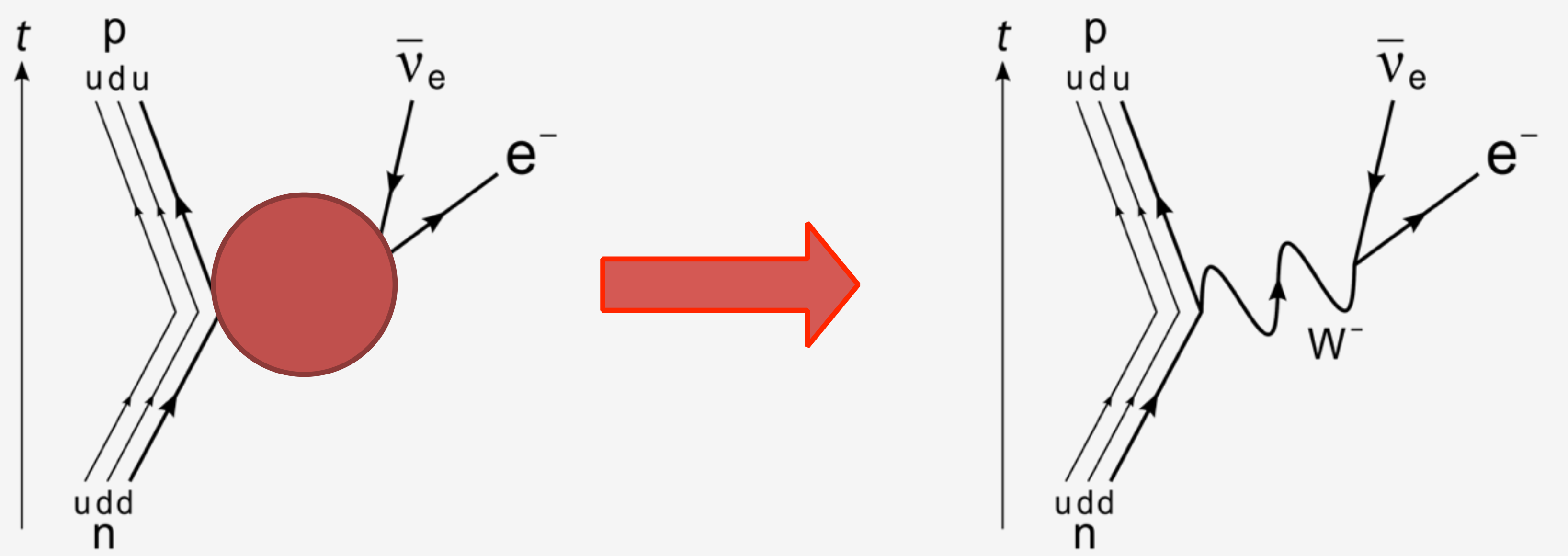
LHC can resolve the interaction between DM and the SM—additional kinematic features and new signatures

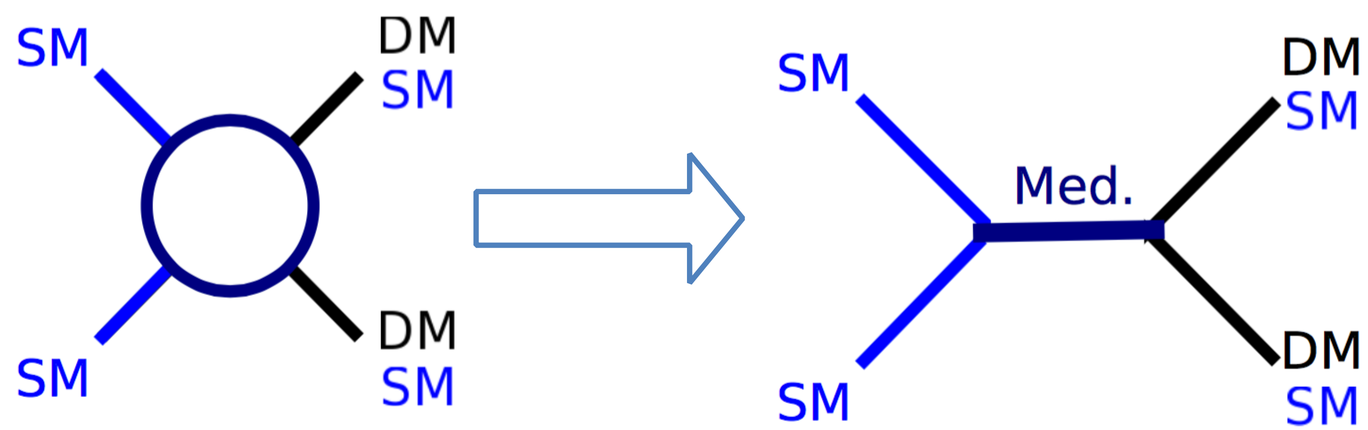
There is at one least more particle to discover: the ‘mediator’ of the interaction

Discovery of dark matter interactions, involving the phenomenology of a larger framework of new particles (new resonances, cascade decays, …)

A Crucial Advantage of Collider Searches

LHC probes high energy scales with respect to other dark matter searches
Discovery and characterization of the interaction with dark matter

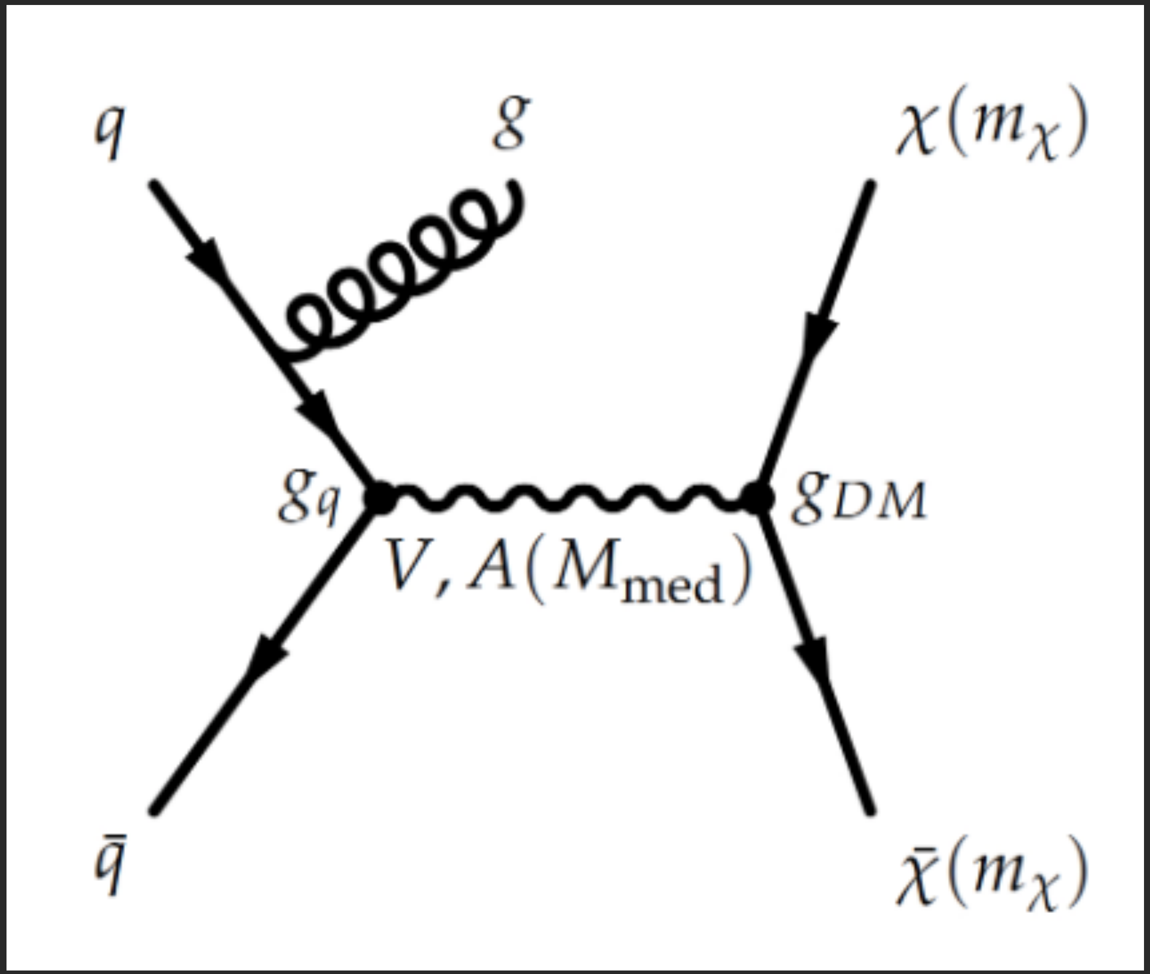




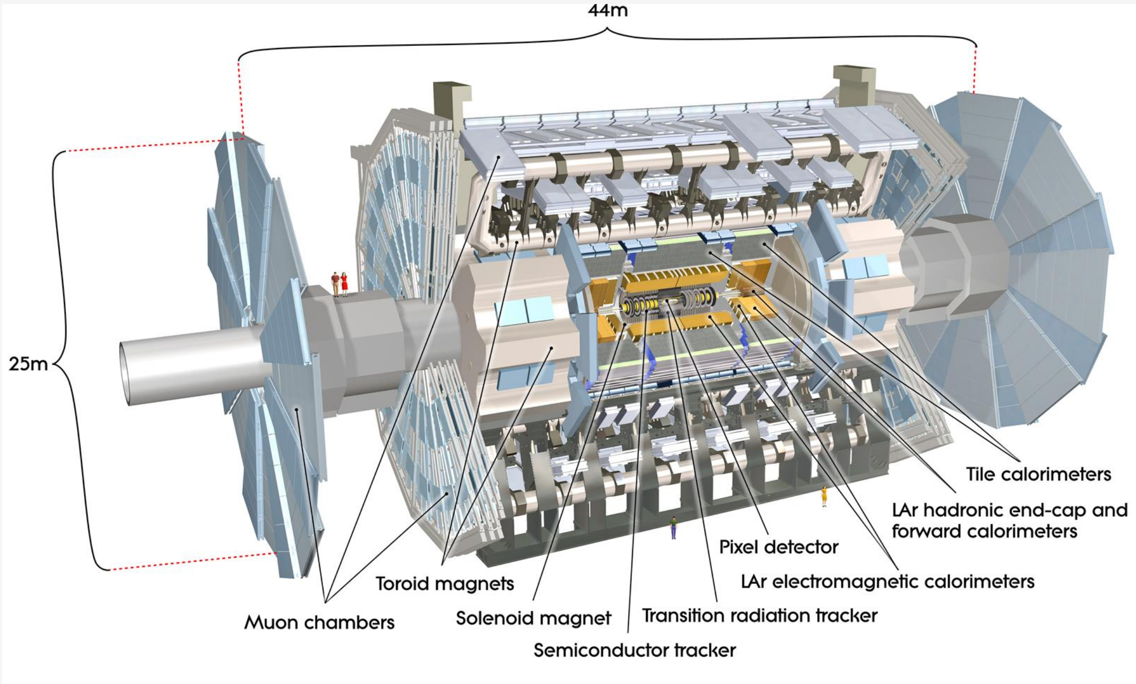
Colliders
(Contact interaction)

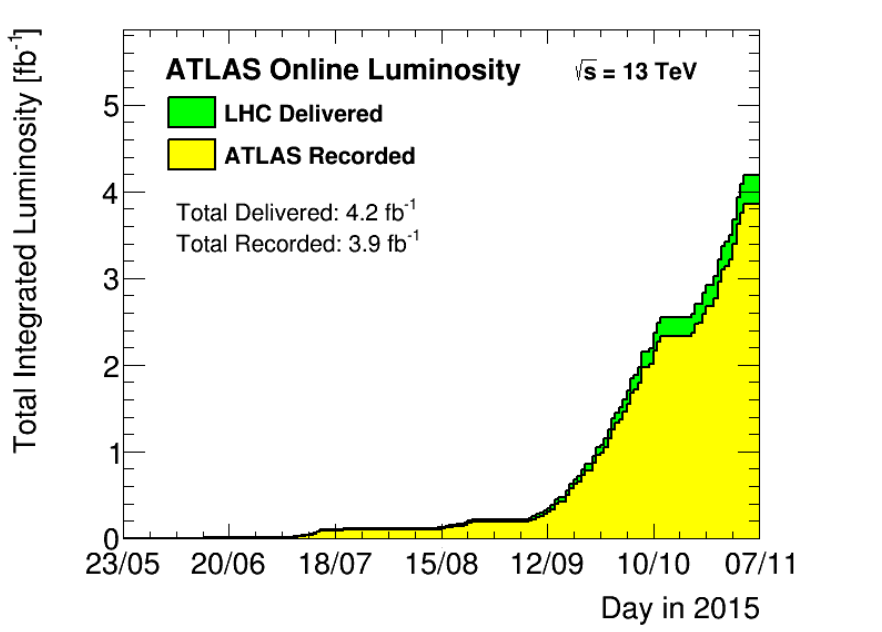
Colliders
(Simplified Models)

Searching for Dark Matter Production



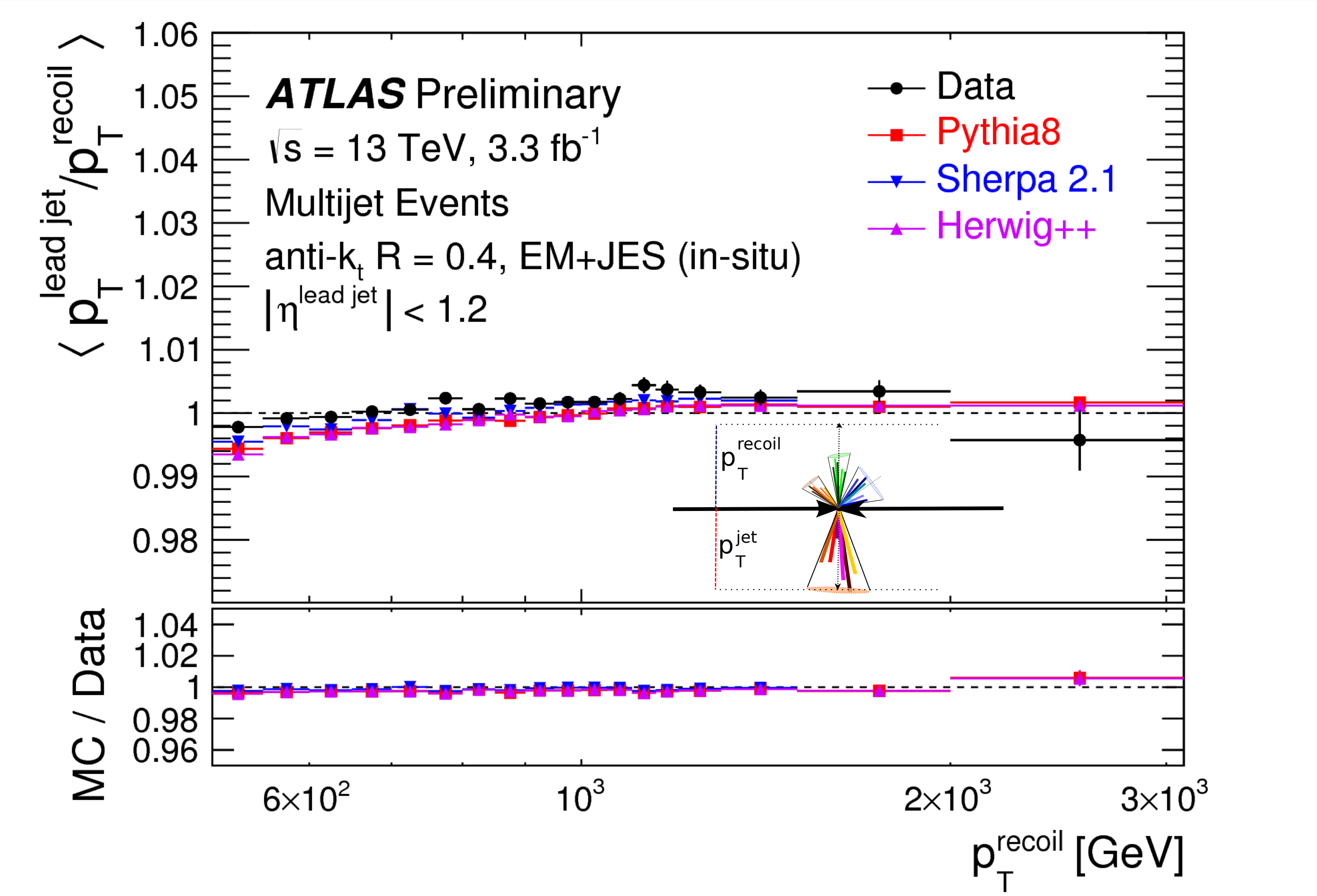
Experimental performance for DM signatures in ATLAS



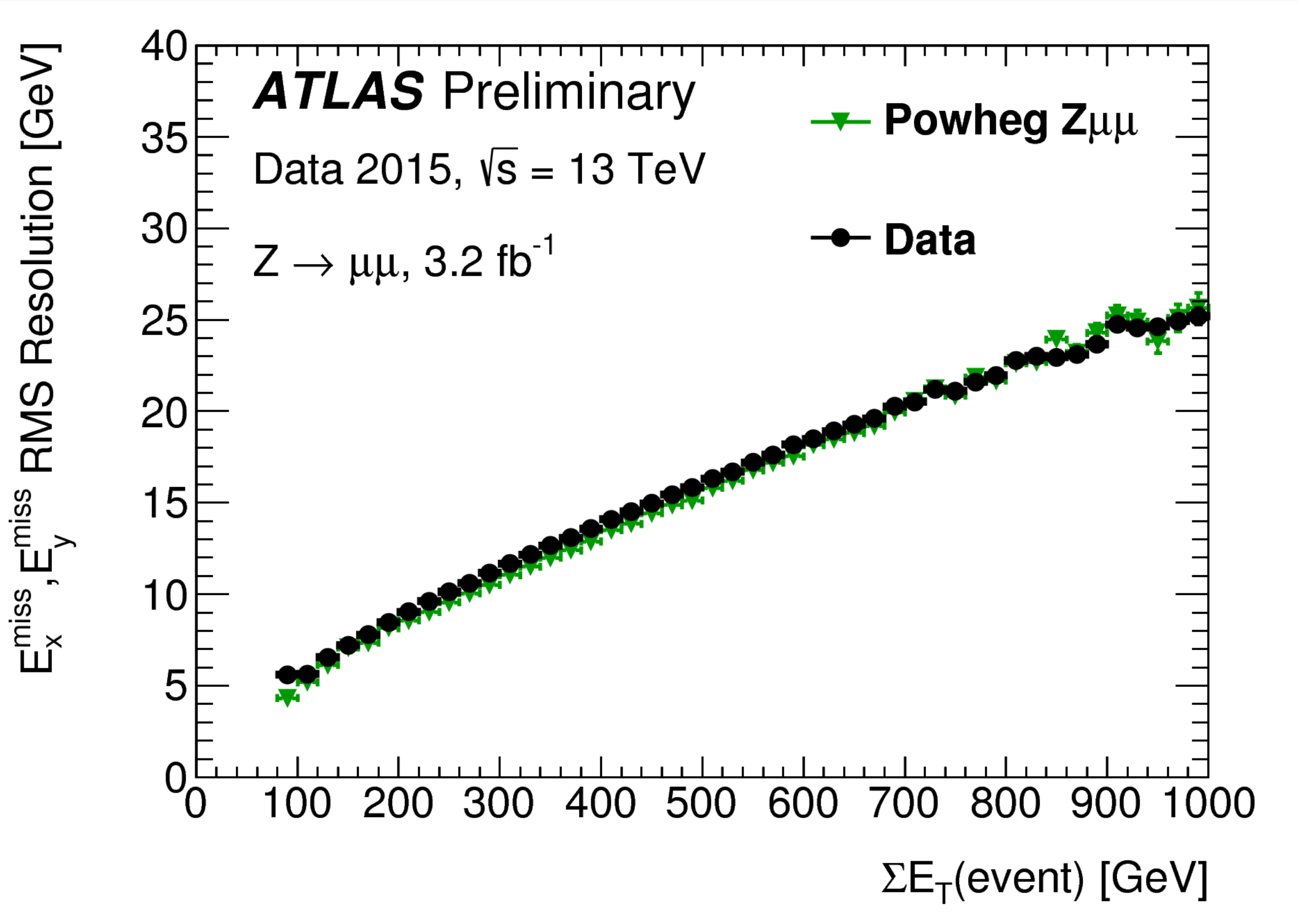


Event selection (trigger) → Object reconstruction and calibration → Dark Matter search

Jet calibration well understood up to multi-TeV scale

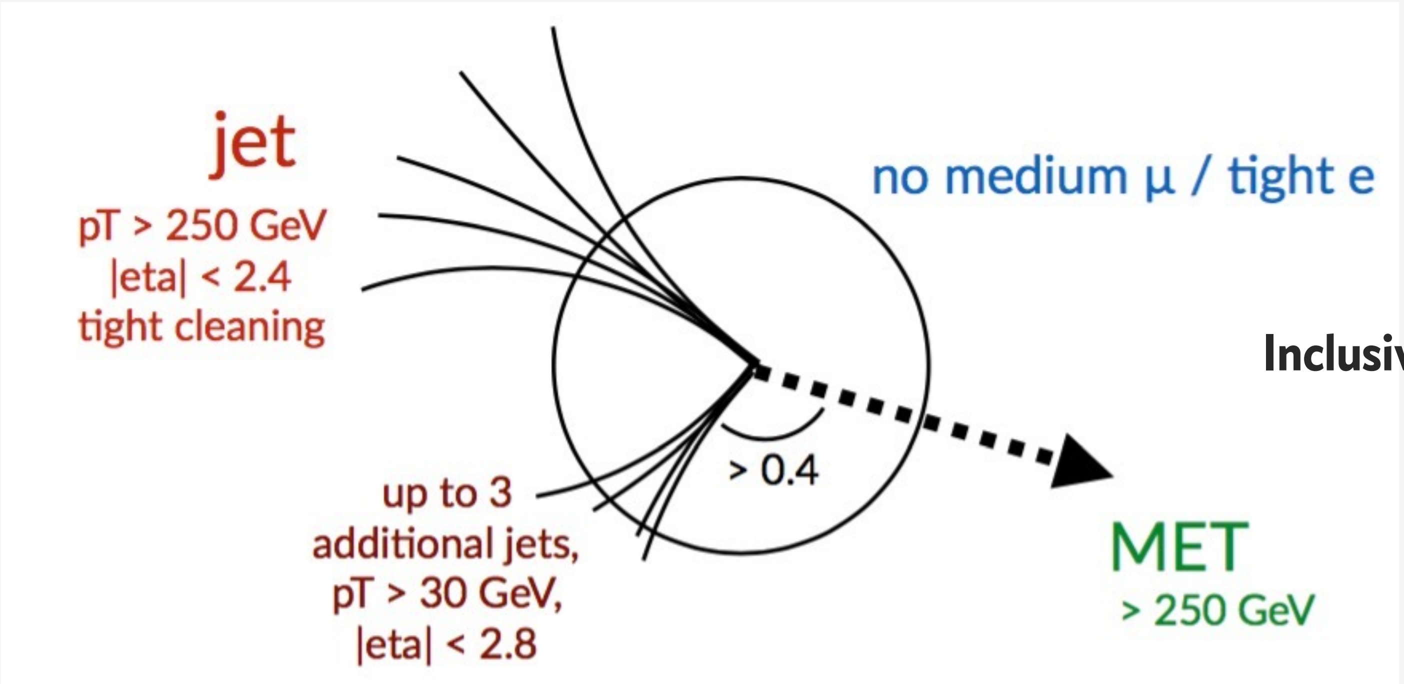


Excellent MET performance



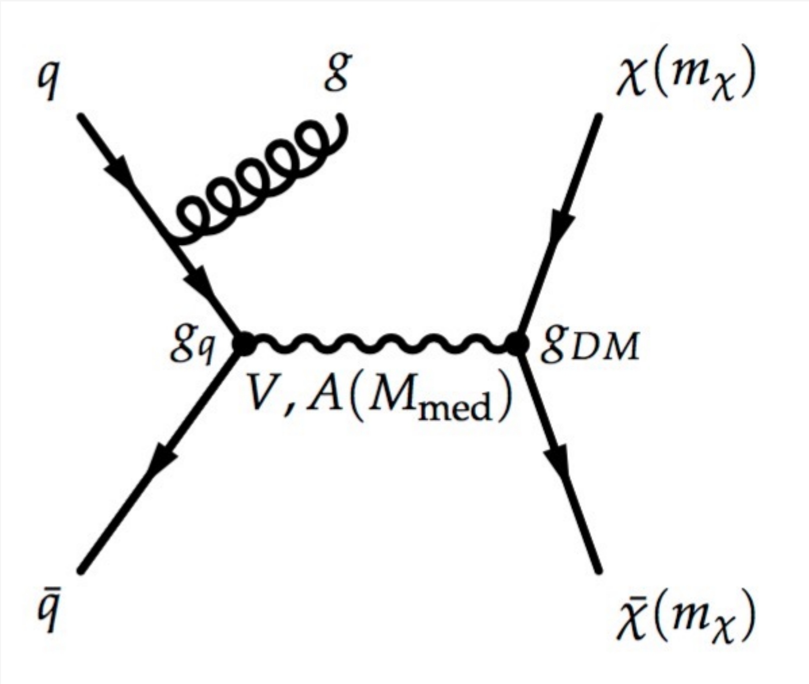
MET+X searches, or "mono-X"

New at 13 TeV: to appear

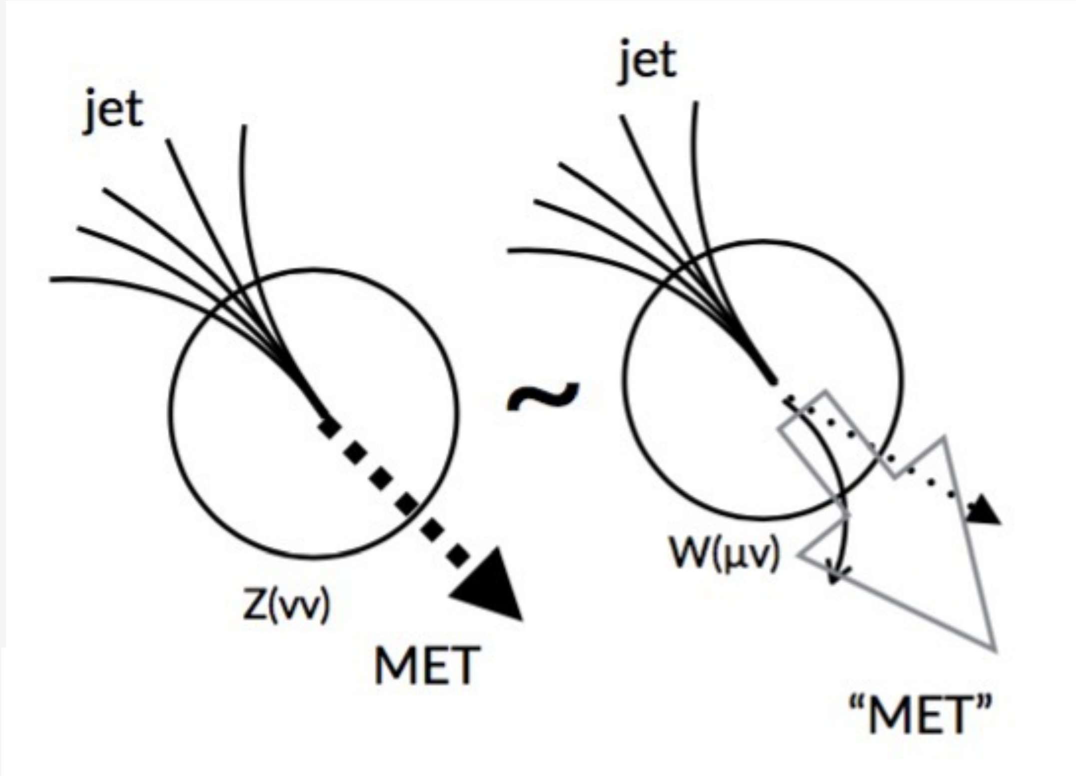


Inclusive and Exclusive signal regions with successively larger MET requirements

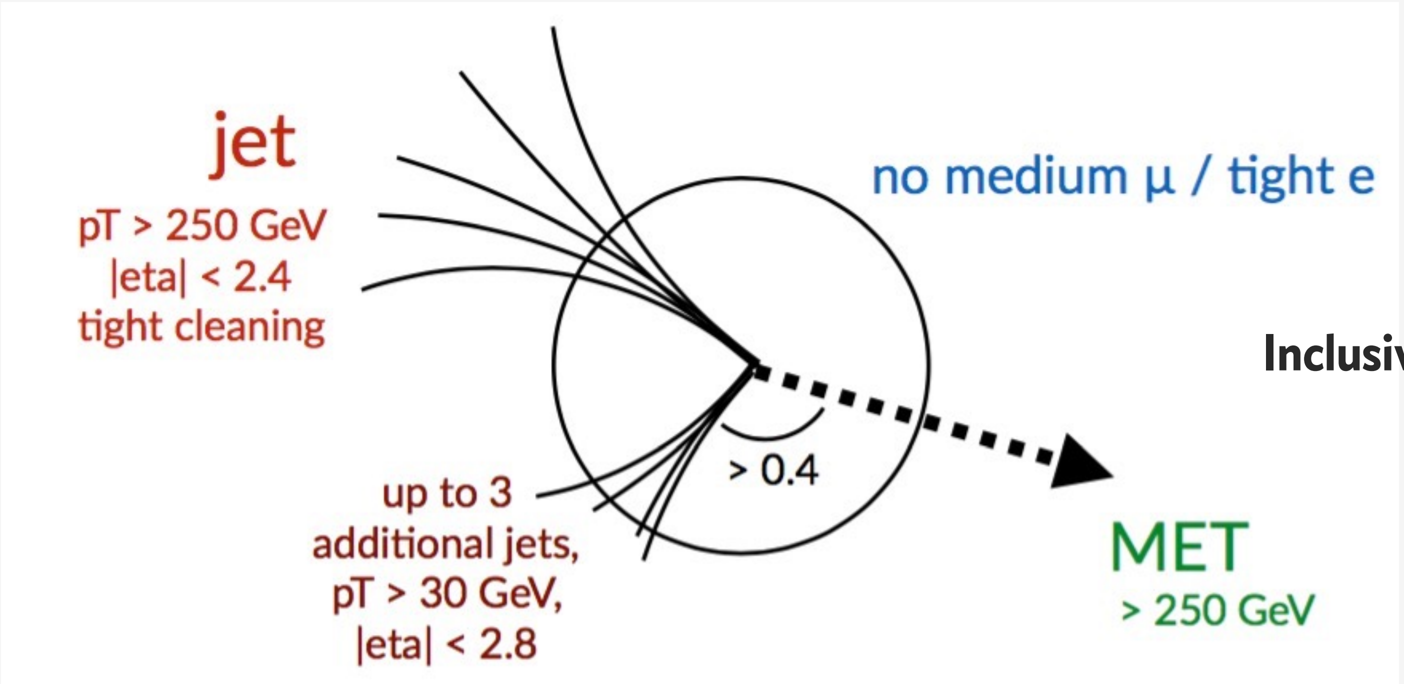
Signal



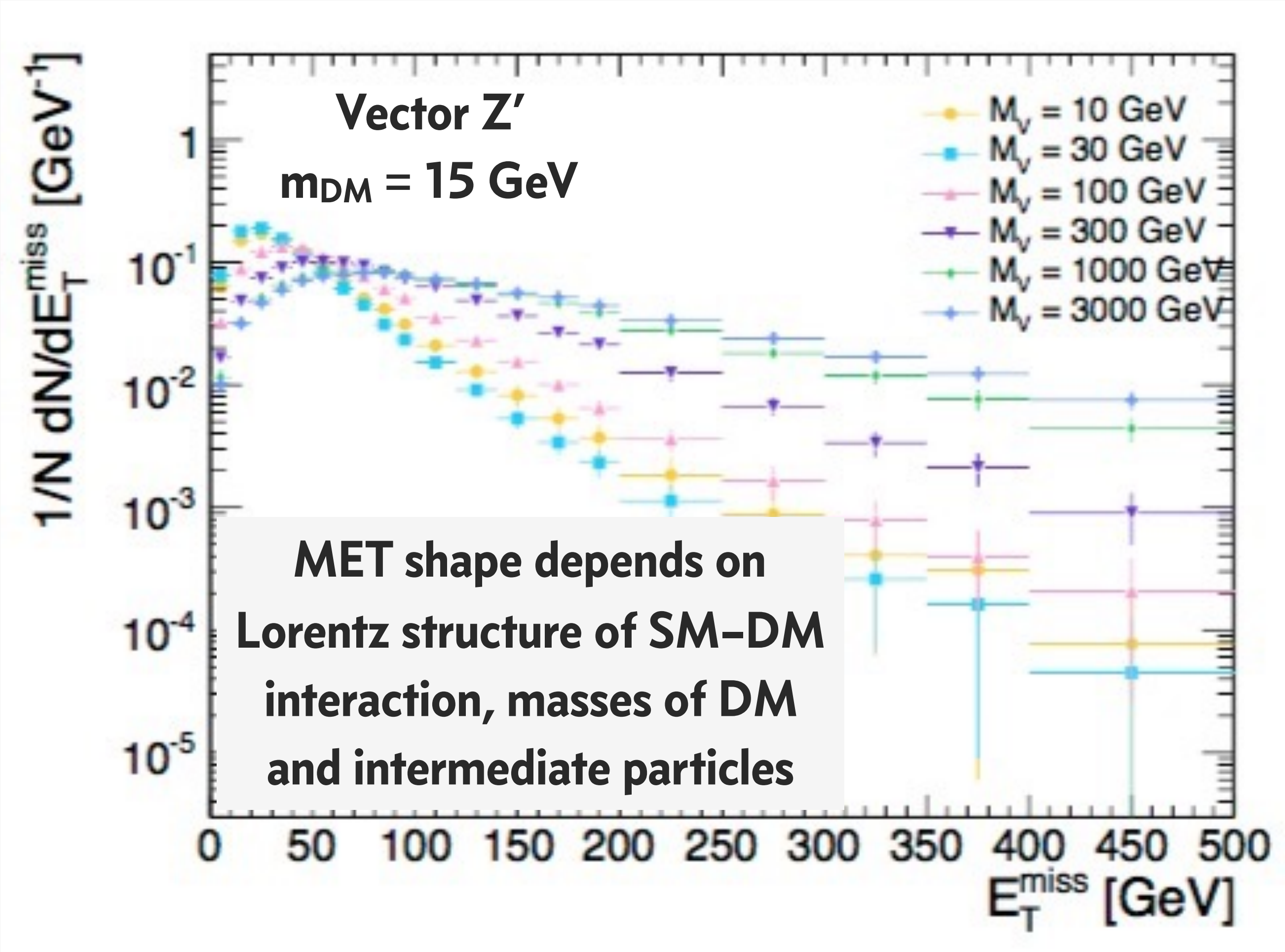
Backgrounds



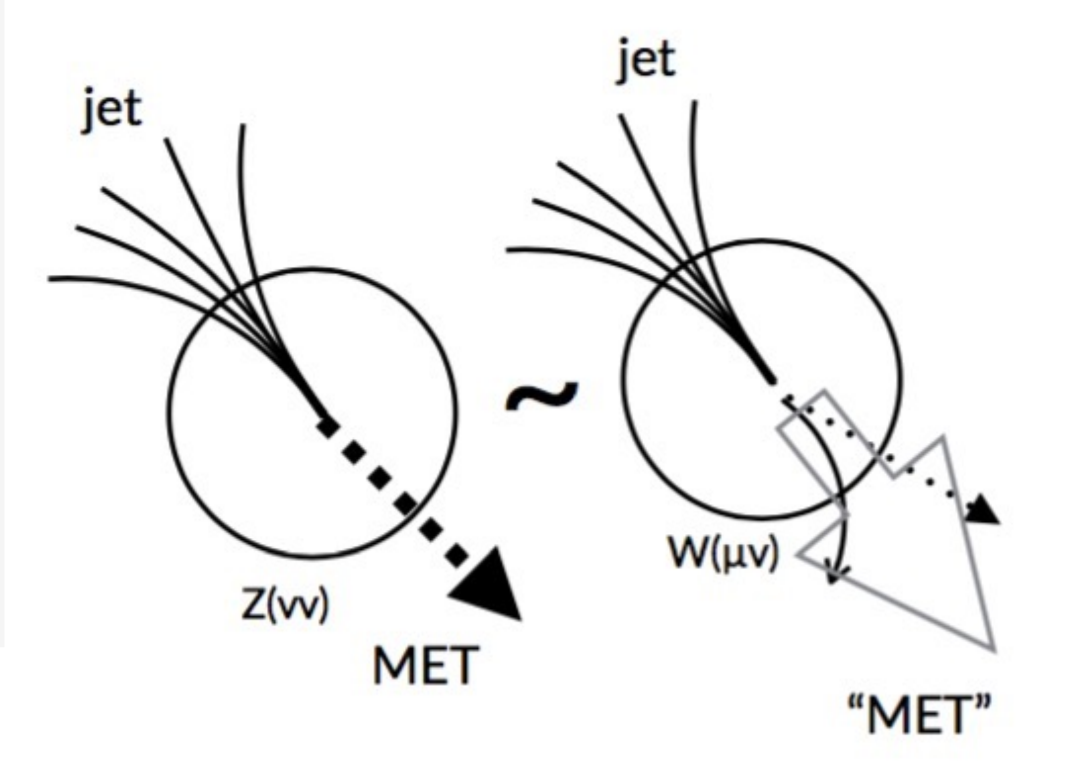
MET+X searches, or "mono-X"



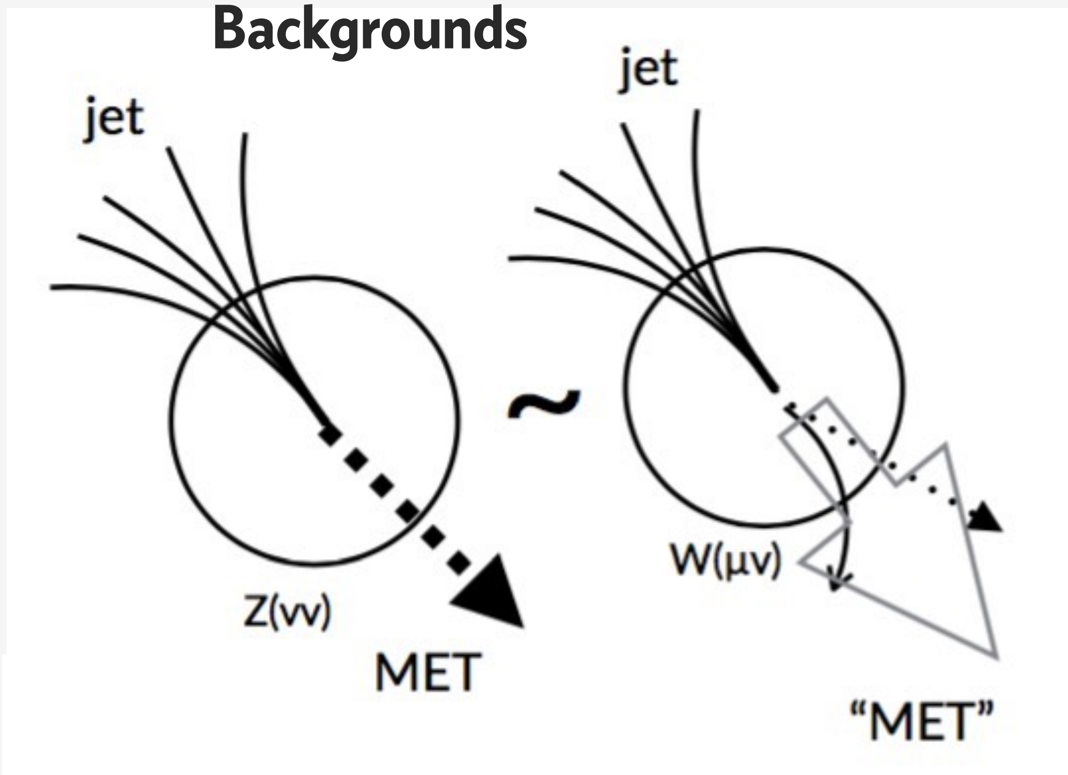
Inclusive and Exclusive signal regions with successively larger MET requirements



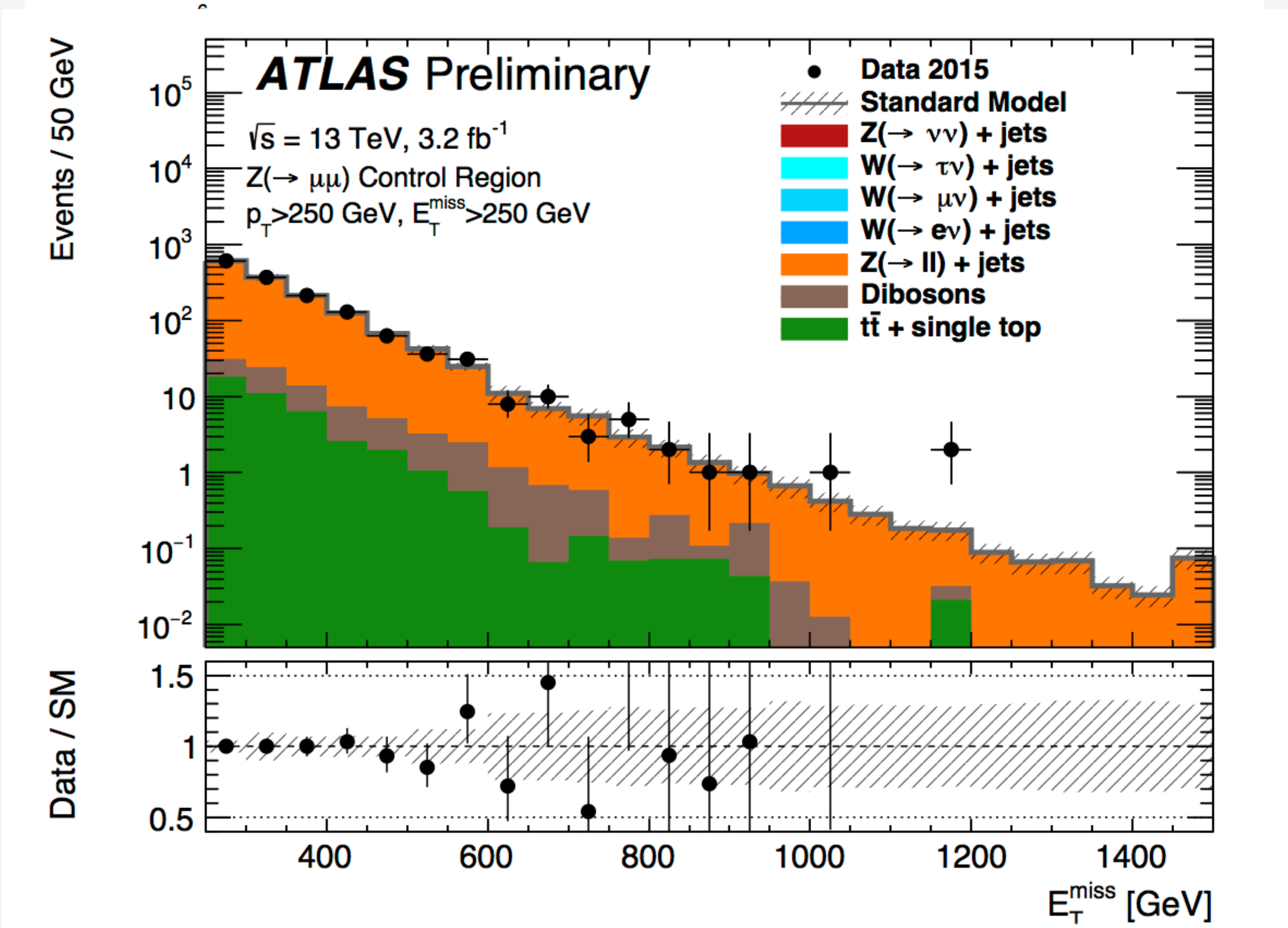
Backgrounds



MET+X searches, or "mono-X"



Visible Z Control Regions, Post-Fit

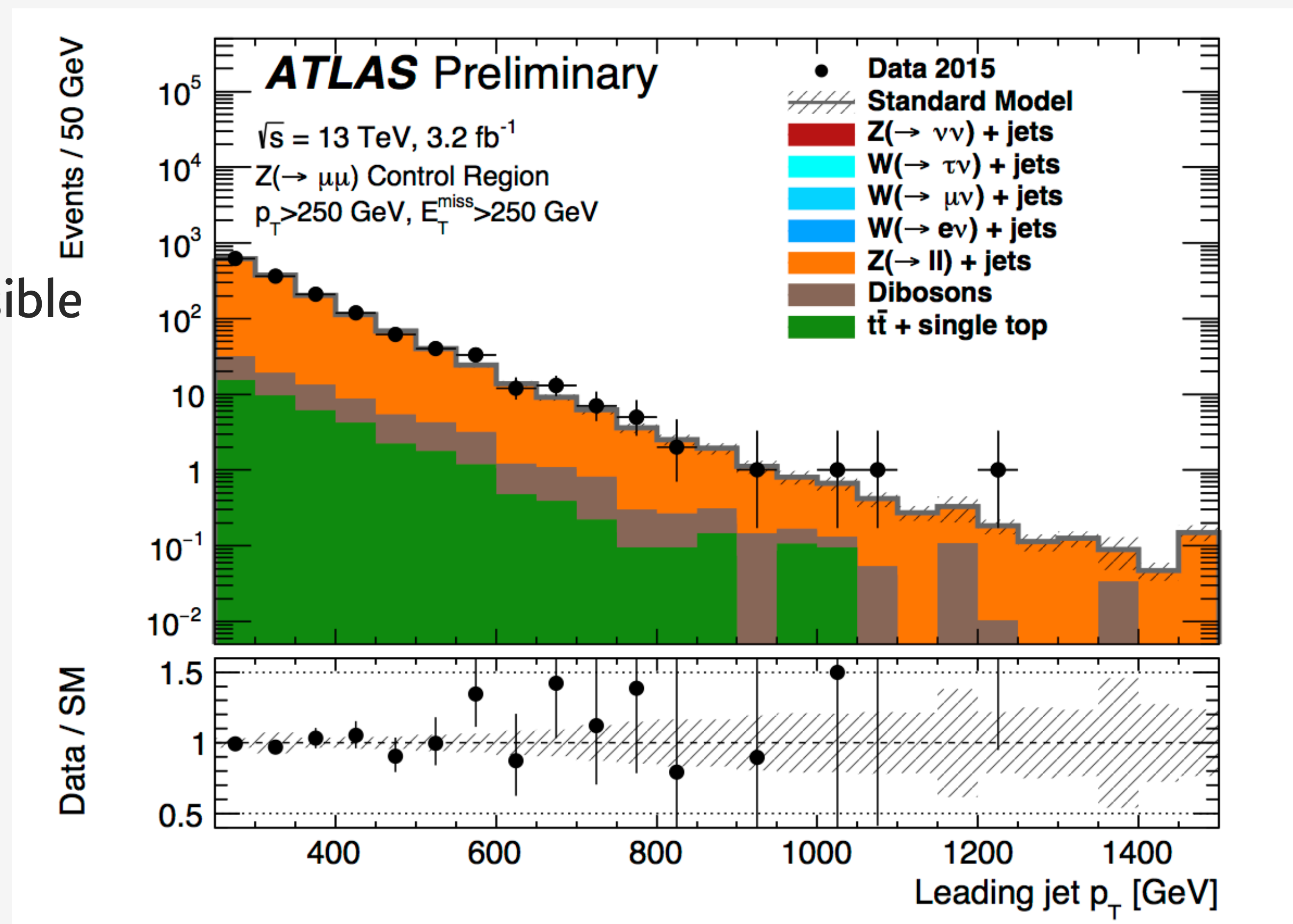


One key challenge of the mono-jet analysis is modeling

Z+jets and W+jets background at very high boson p_T

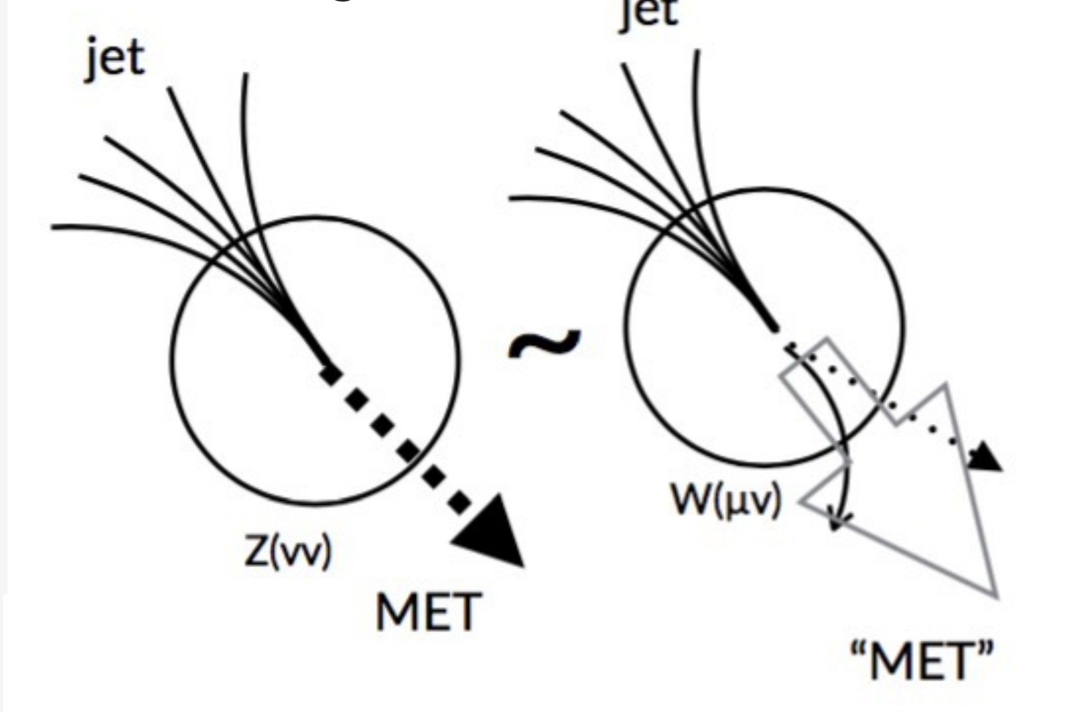
Check with visible W and Z decays, but

invisible decays of the Z occurs 6x more often than visible



MET+X searches, or "mono-X"

Backgrounds



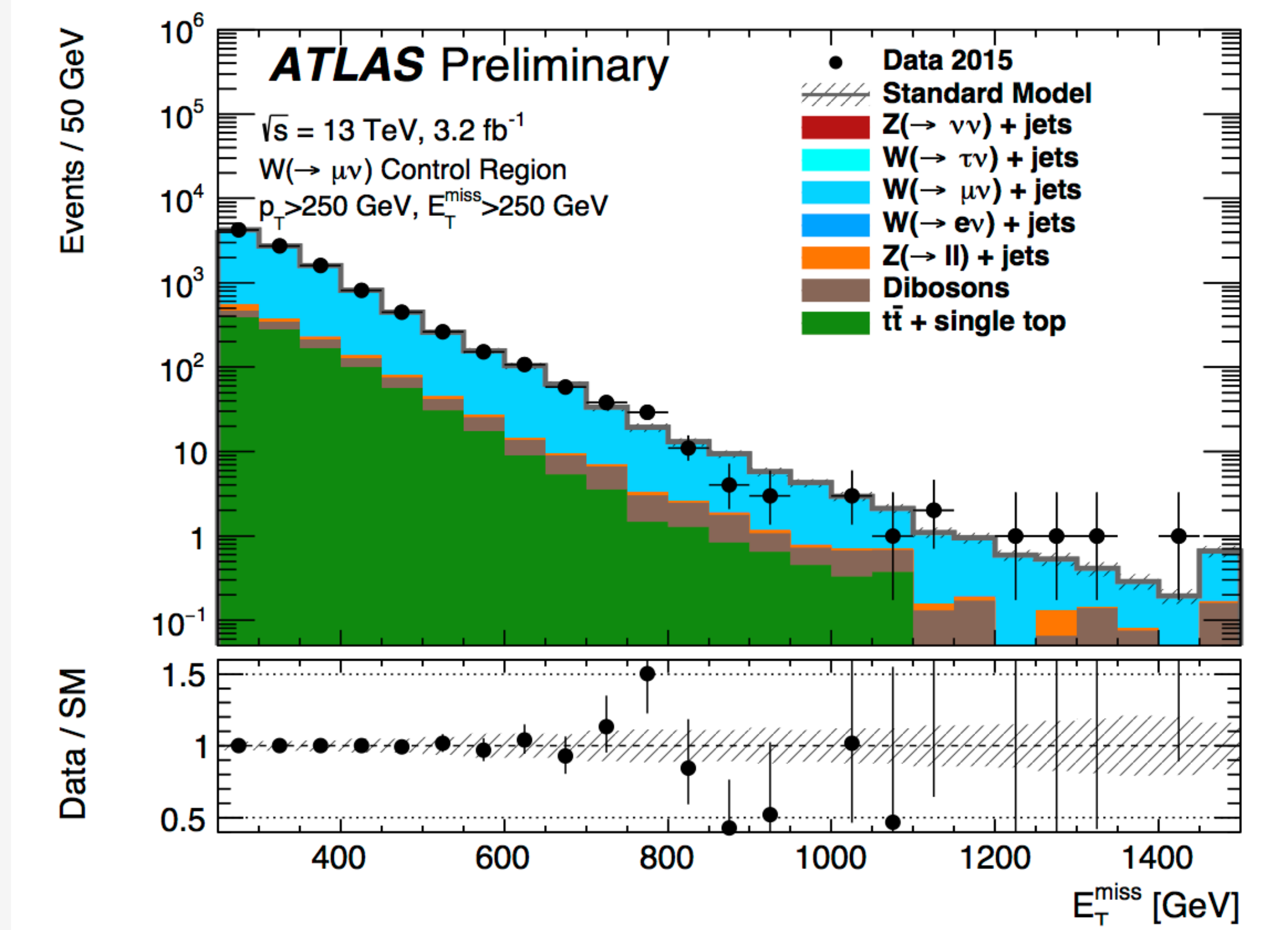
One key challenge of the mono-jet analysis is modeling
Z+jets and W+jets background at very high boson p_T

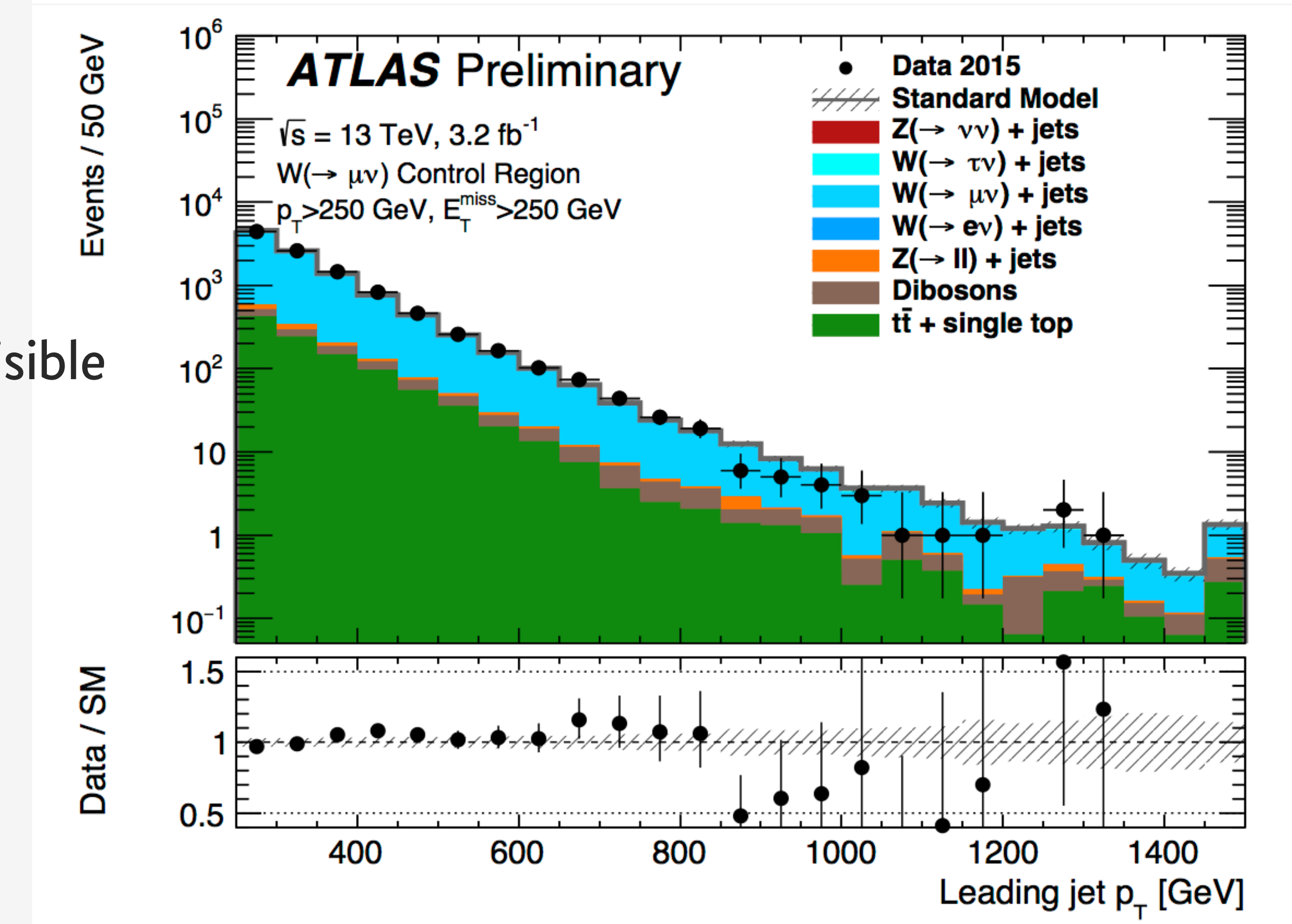
Check with visible W and Z decays, but
invisible decays of the Z occurs 6x more often than visible
Also W decays

Constrain predictions for **$Z(\rightarrow \nu\bar{\nu})$+jets, W+jets**
and decays with missed leptons from SHERPA 2.1
+ ATLAS simulation and control regions with
visible decays

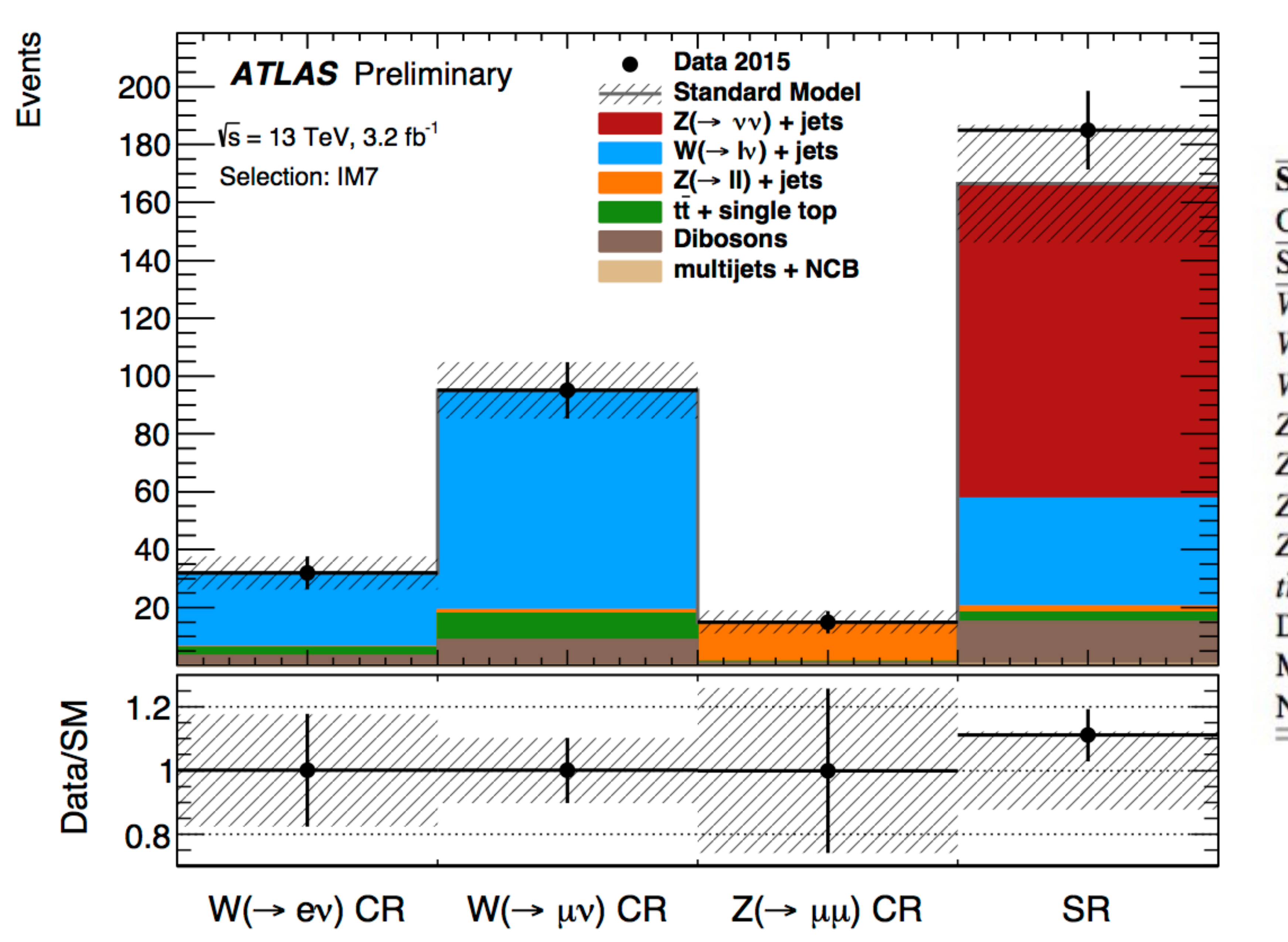
$$N^{Z(\rightarrow\nu\bar{\nu})}_{\text{signal}} = (N^{\text{data}}_{W(\rightarrow\mu\nu),\text{control}} - N^{\text{non}-W}_{W(\rightarrow\mu\nu),\text{control}}) \times \frac{N^{\text{MC}(Z(\rightarrow\nu\bar{\nu}))}_{\text{signal}}}{N^{\text{MC}}_{W(\rightarrow\mu\nu),\text{control}}}$$

Visible W Control Regions, Post-Fit





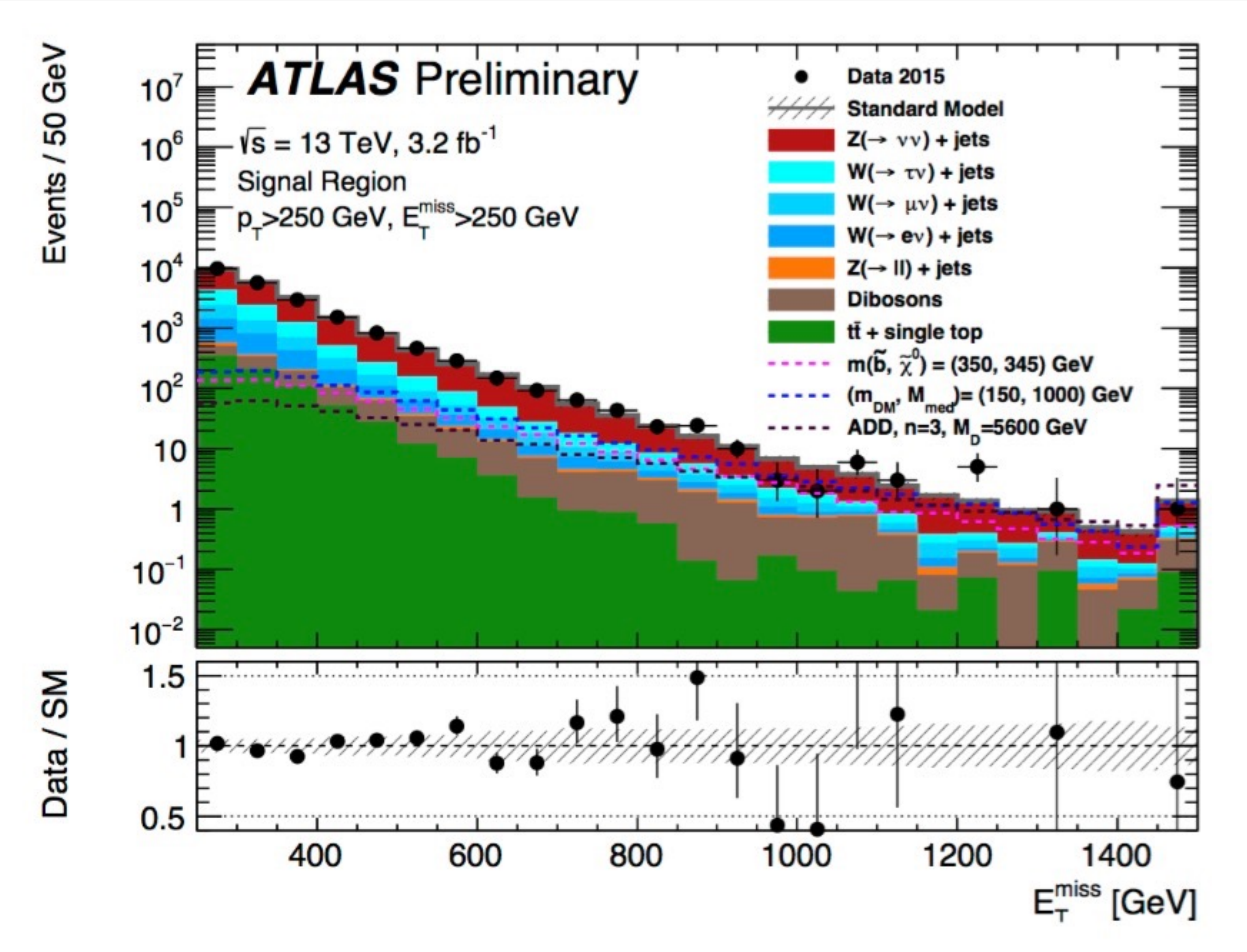
Control and Signal Region Composition for MET>700 GeV



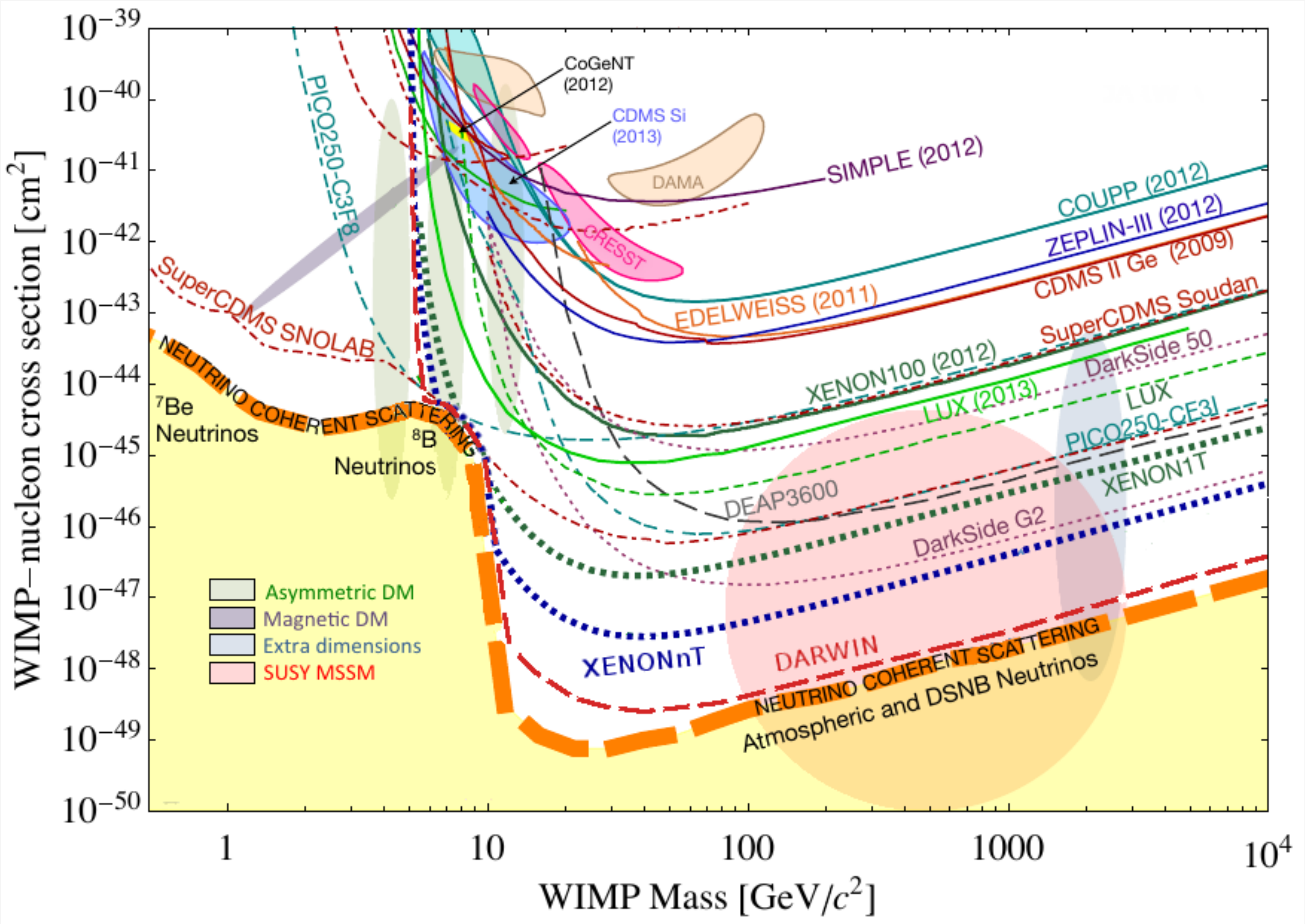
Signal Region	IM7
Observed events (3.2 fb^{-1})	185
SM prediction	167 ± 20
$W(\to e\nu)$	7 ± 2
$W(\to \mu\nu)$	11 ± 2
$W(\to \tau\nu)$	19 ± 4
$Z/\gamma^*(\to e^+e^-)$	–
$Z/\gamma^*(\to \mu^+\mu^-)$	2 ± 1
$Z/\gamma^*(\to \tau^+\tau^-)$	0.2 ± 0.1
$Z(\to \nu\bar{\nu})$	109 ± 18
$t\bar{t}$, single top	3 ± 1
Dibosons	15 ± 2
Multijets	0.4 ± 0.4
Non-collision background	–

Analysis quickly becomes systematics-limited:
precise high p_T Z background estimates crucial for further progress

Monojet results

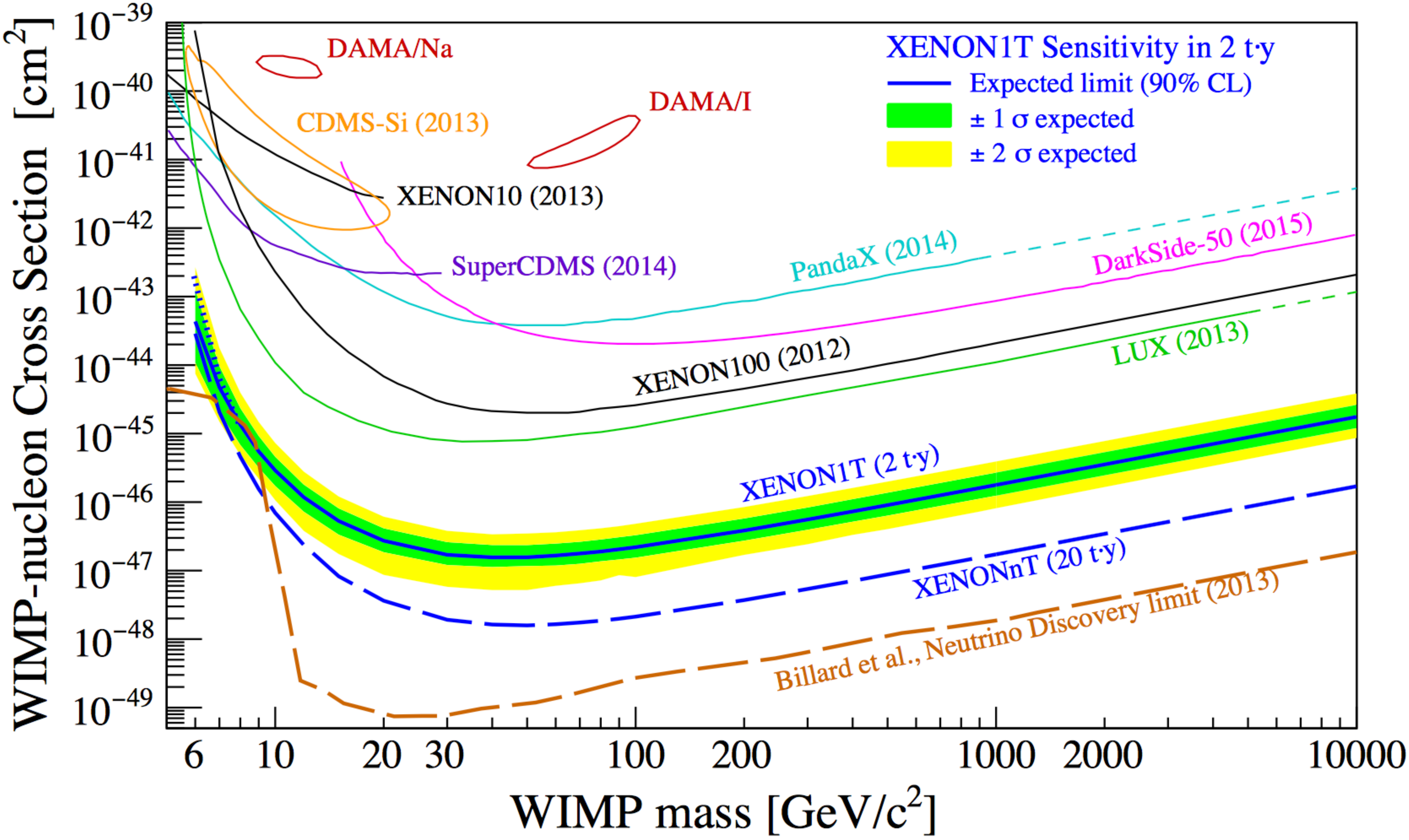


Present and Future of Direct Detection Searches

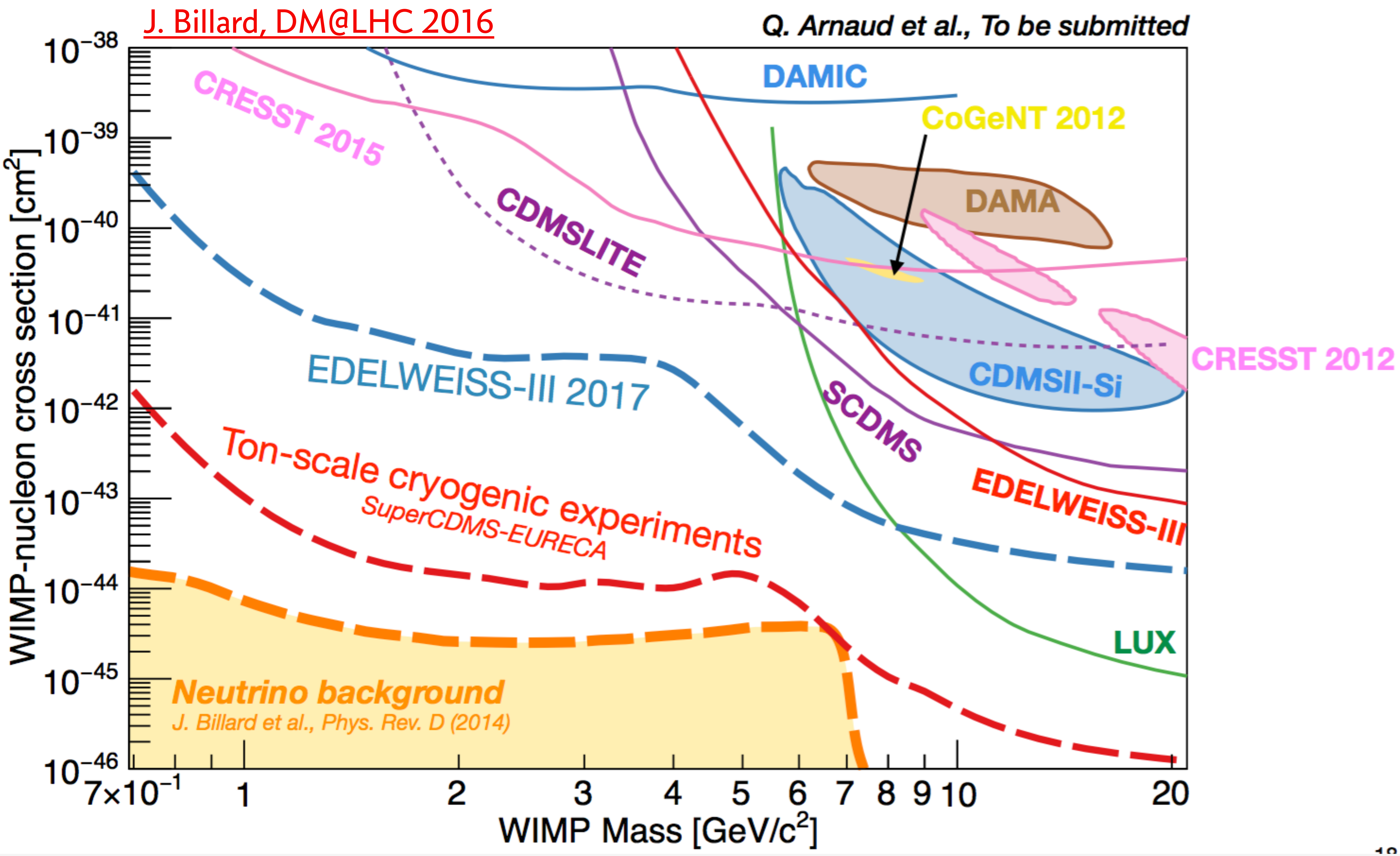


Present and Future of Direct Detection Searches

arXiv:1512.07501



Present and Future of Direct Detection Searches



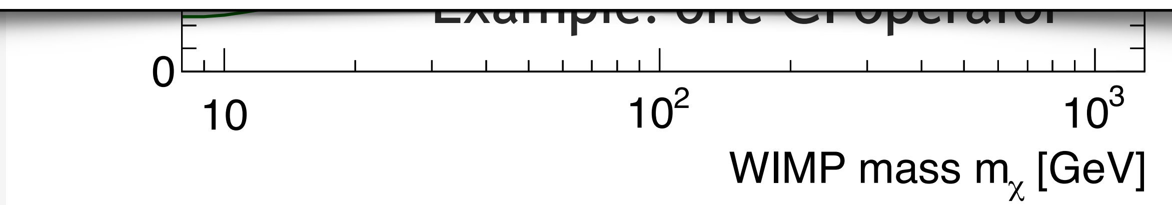
Eur. Phys. J. C (2015) 75:299

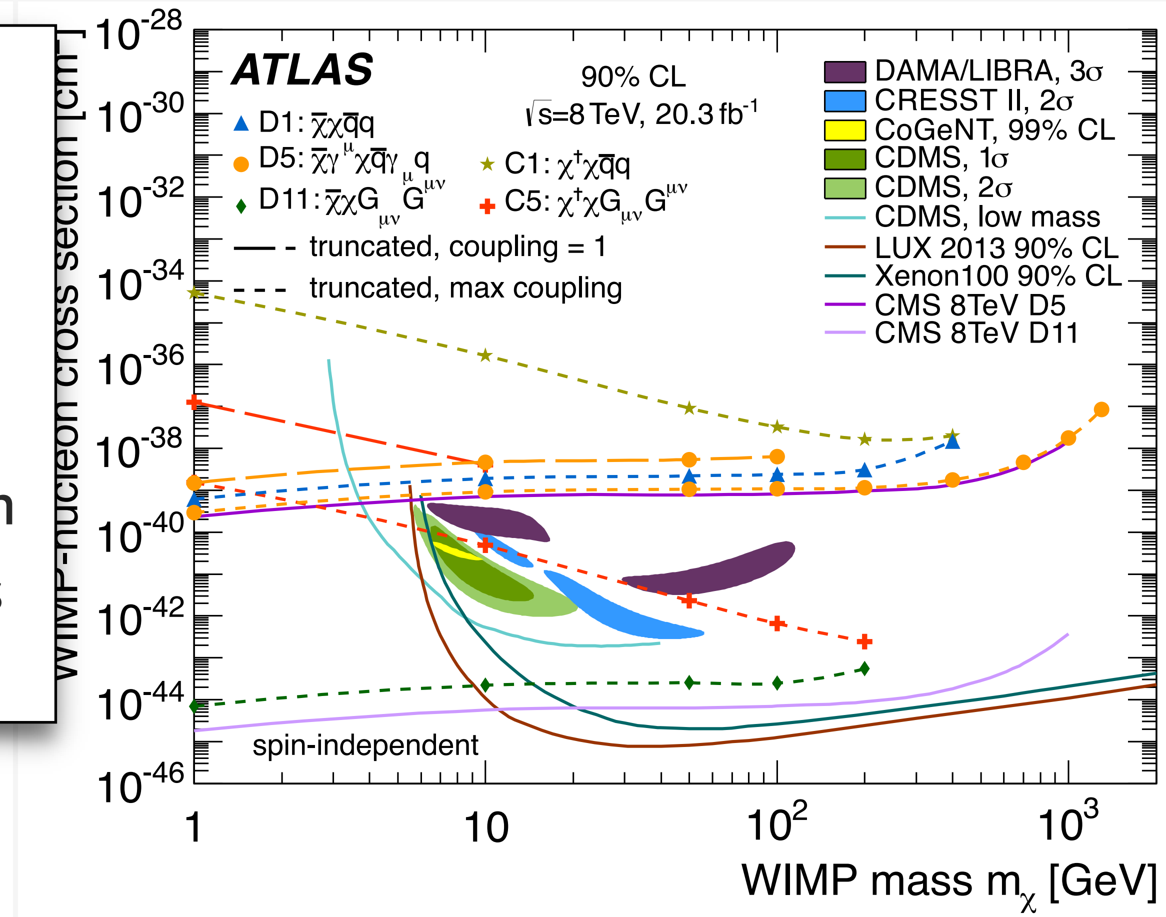
8 TeV Mono-jet Result: Connecting EFT limits to Non-collider WIMP Searches

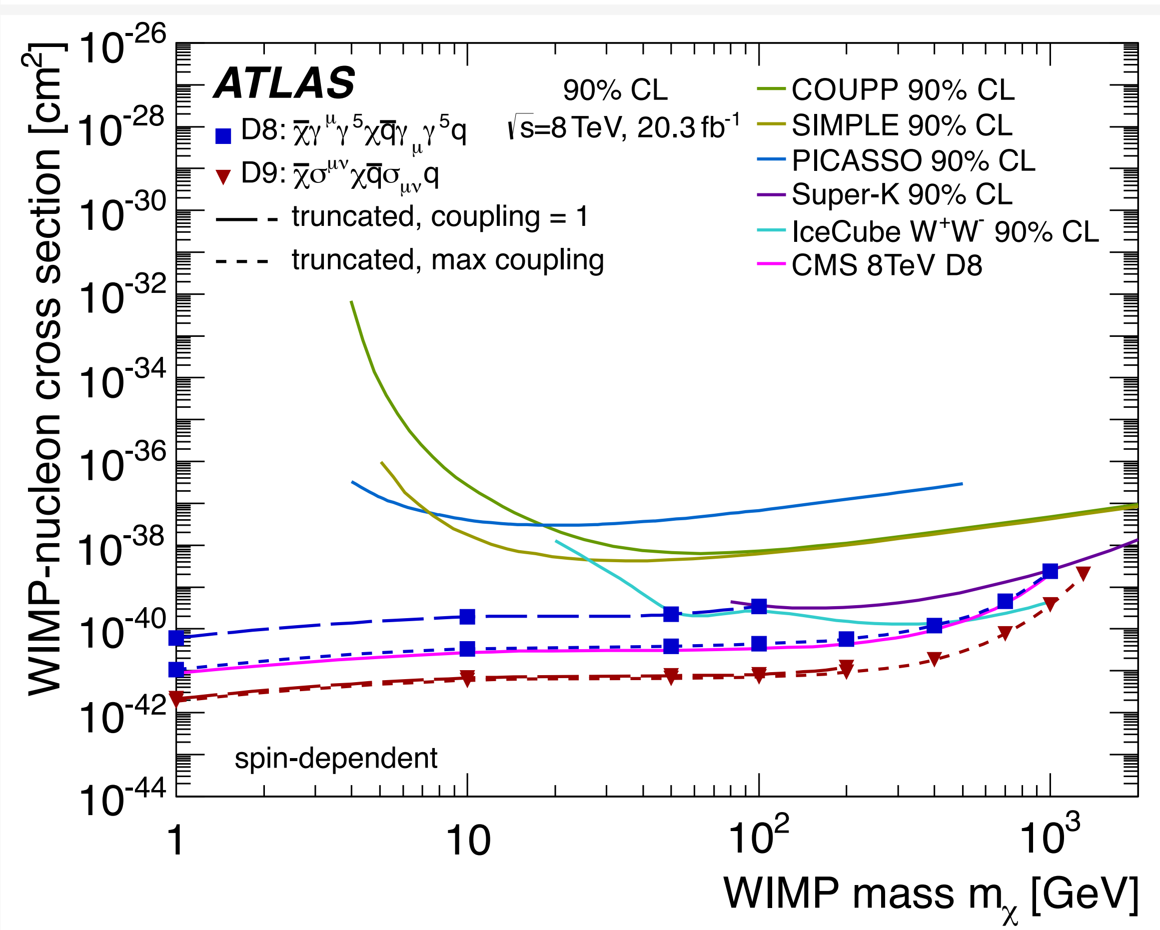
Some lessons:

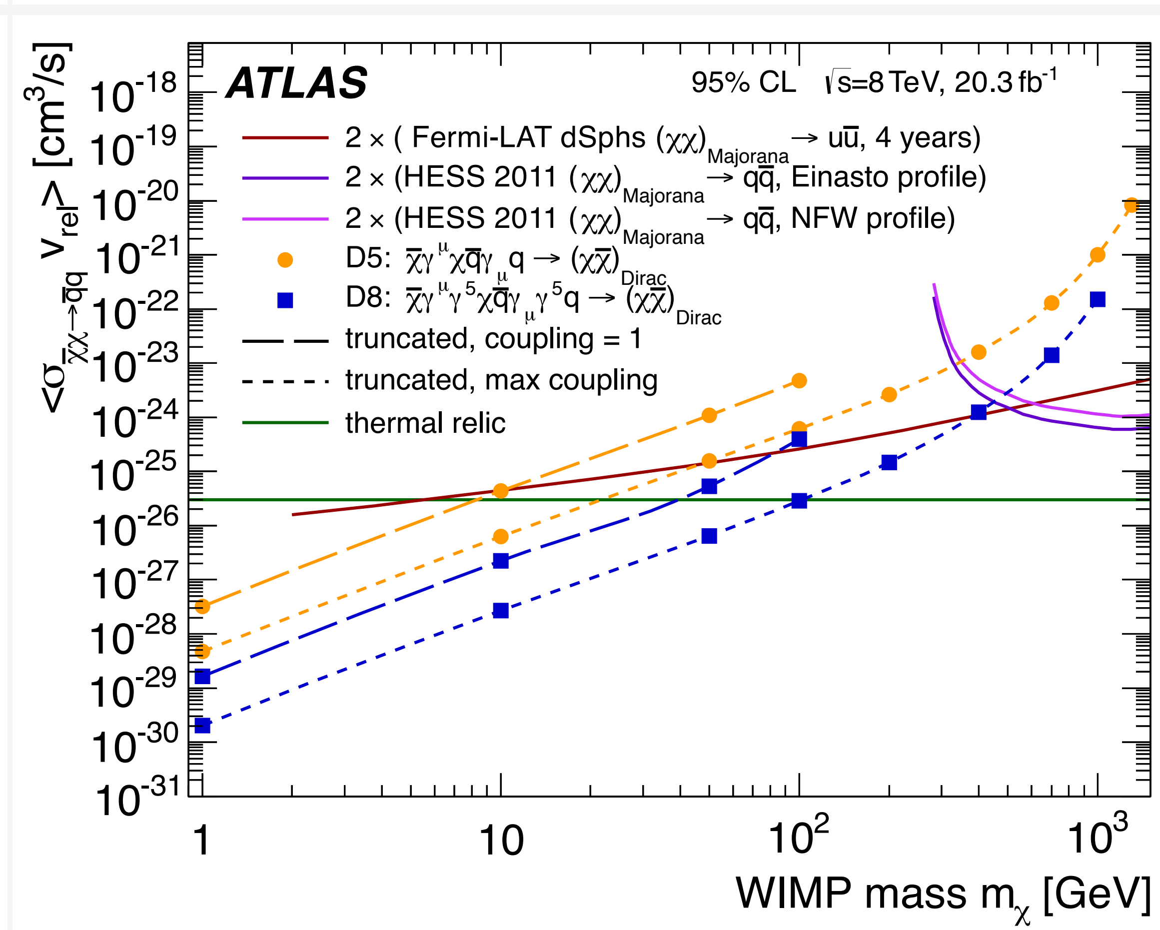
- Once the WIMP is light enough (below the scales of the cuts on MET and jet p_T), **colllider searches are insensitive to the WIMP mass**—can continue the ~same limit below 1 GeV
- The mono-jet search is **insensitive** to differences in Lorentz structure, unlike direct-detection searches

These nicely **complement the non-collider searches**





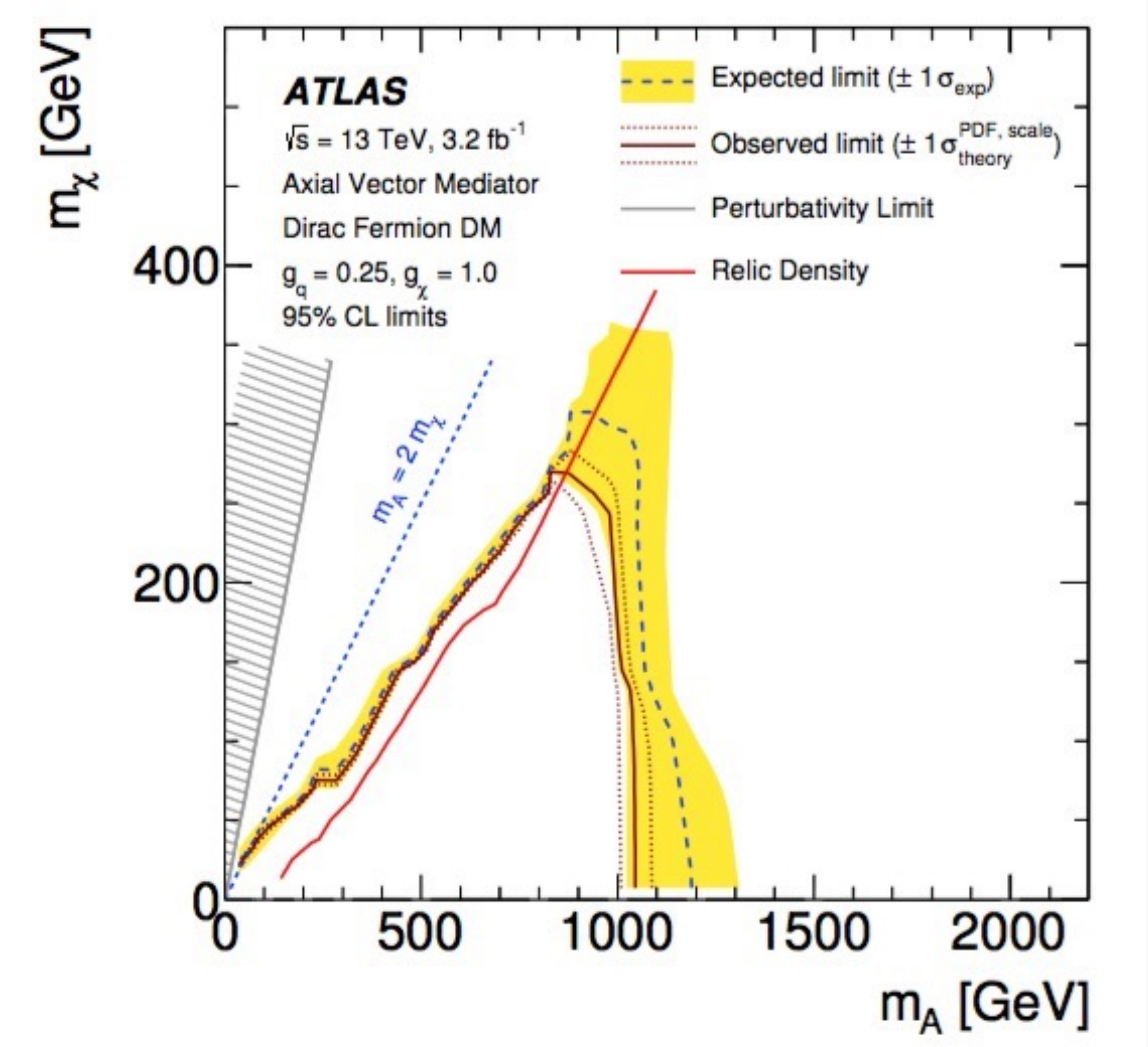




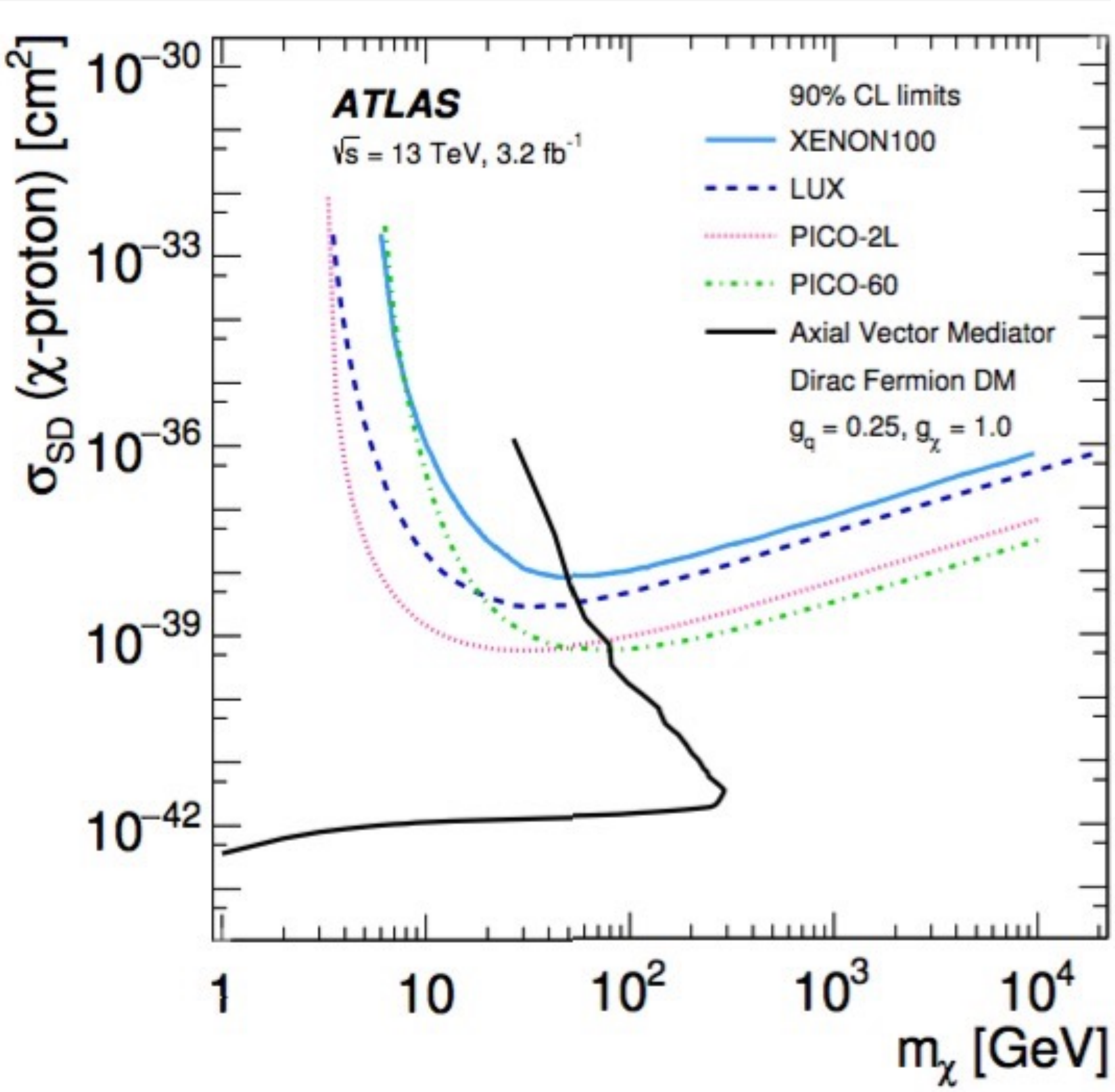
First 13 TeV Monojet results: Constraint on DM Simplified Model

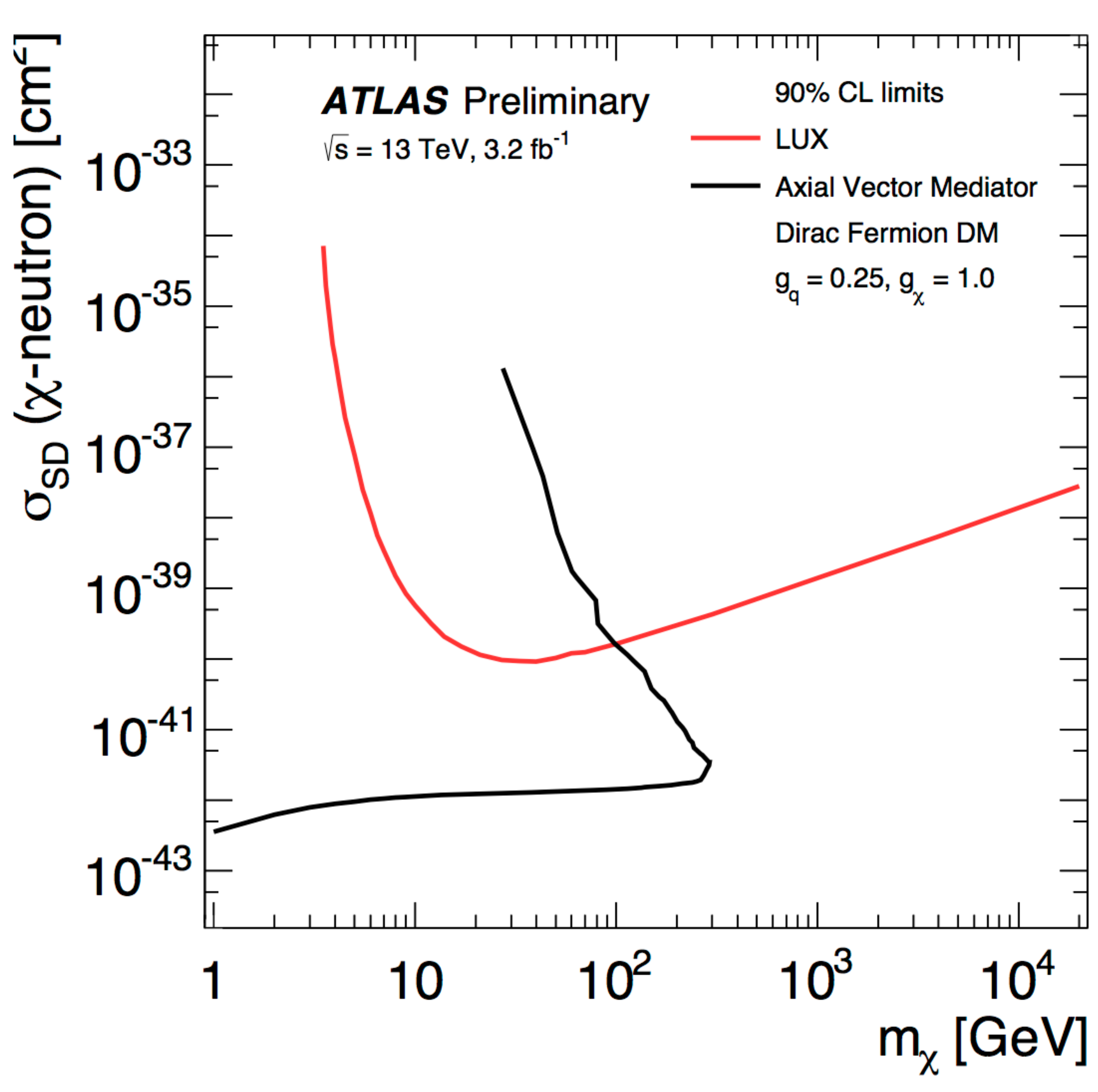
Axial-vector simplifed model:

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



First 13 TeV Monojet results

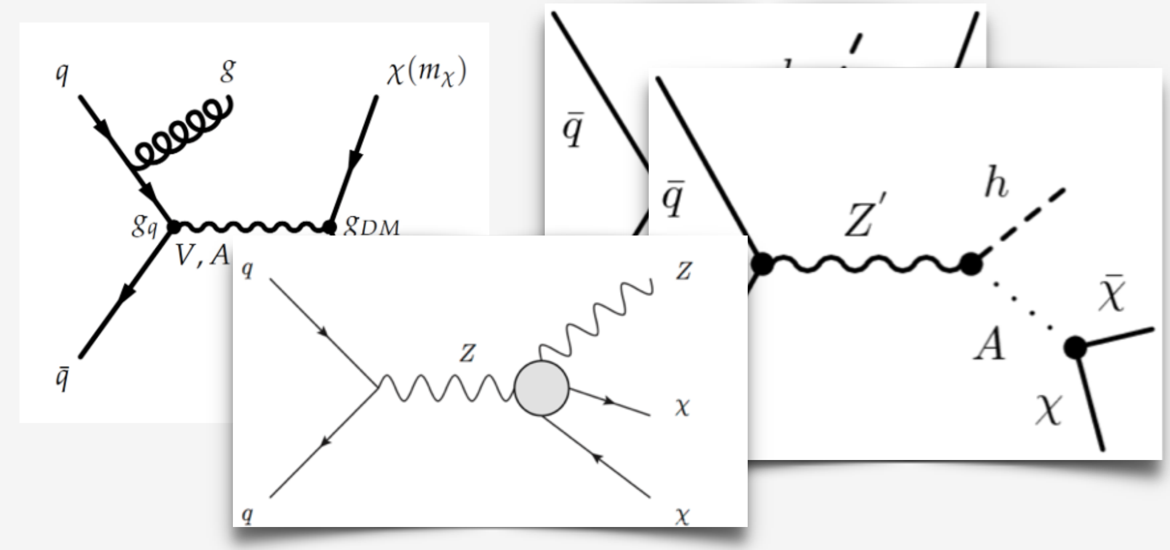




Searches for Dark Matter Production Beyond Mono-jets

Substitute any other boson for the ISR gluon or directly involve the SM particles in the interaction

ATLAS: systematic search program in many final states



Standard Model Particles interact with **Dark Matter**

insert known particle(s) here — insert new particle(s) here

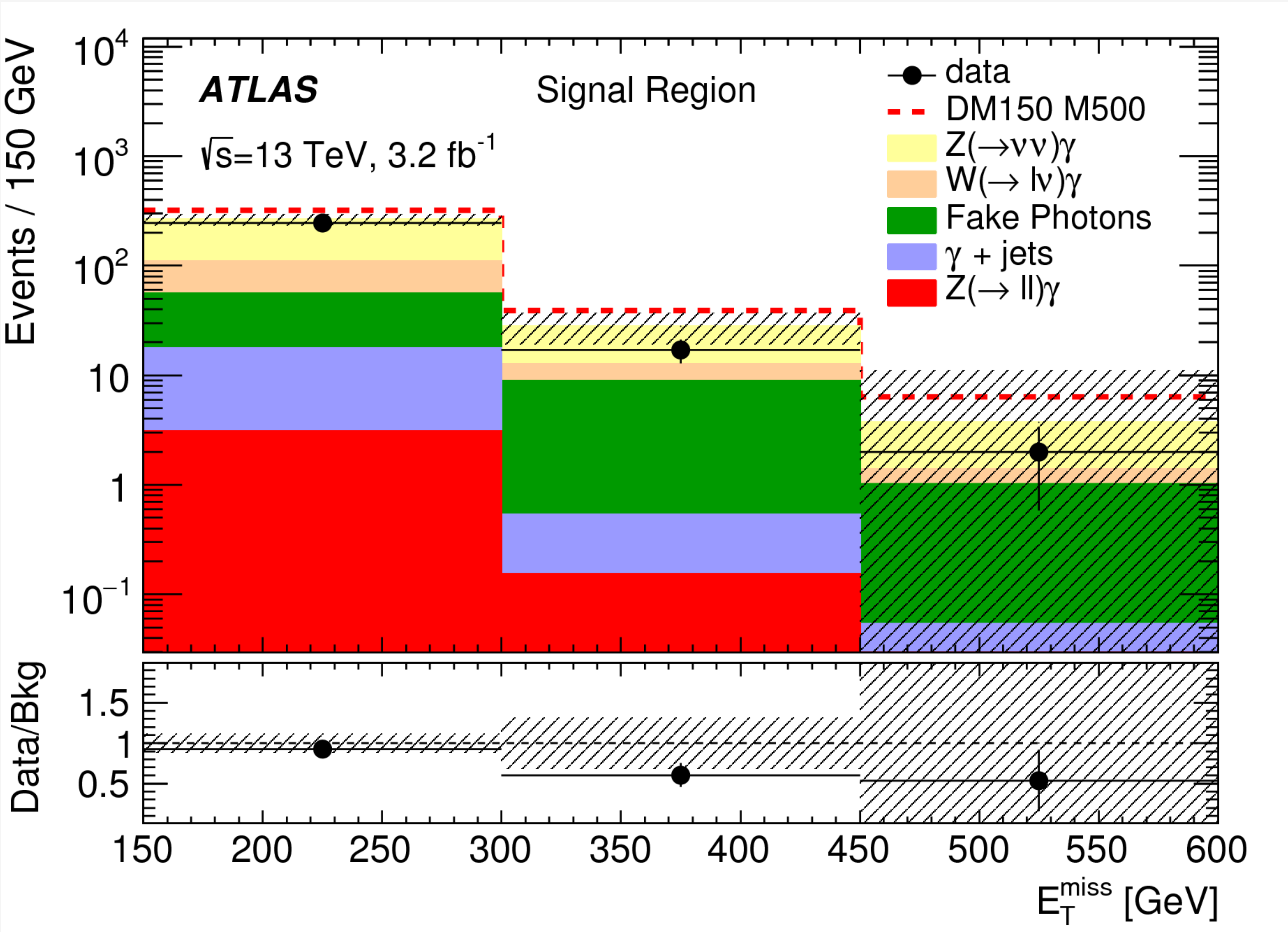
in signatures including

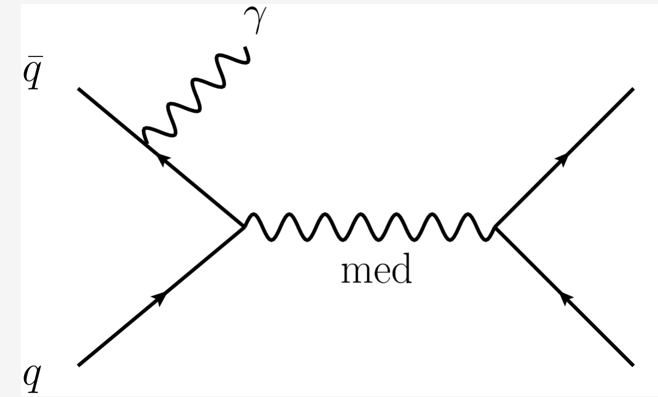
insert ISR/FSR boson, or additional particles

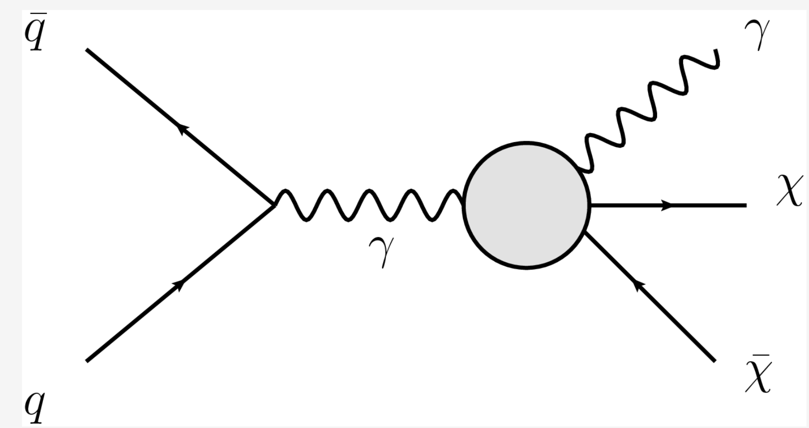
Photons	http://arxiv.org/abs/1604.01306 (13 TeV) Phys. Rev. D 91, 012008 (8 TeV)	
Heavy flavour quarks	Eur. Phys. J. C (2015) 75:92 (8 TeV)	
W and Z bosons	Hadronic decays: ATLAS-CONF-2015-080 (13 TeV) Phys. Rev. Lett 112, 041802 (8 TeV)	Leptonic W decays: JHEP09 (2014) 037 (8 TeV) Leptonic Z decays: PRD 90, 012004 (8 TeV)
Higgs bosons	H→bb: ATLAS-CONF-2016-019 (13 TeV) Phys. Rev. D 93, 072007 (8 TeV)	H→γγ: ATLAS-CONF-2016-011 (13 TeV) Phys. Rev. Lett. 115, 131801 (8 TeV)

Mono-photon

New at 13 TeV: arXiv:1604.01306







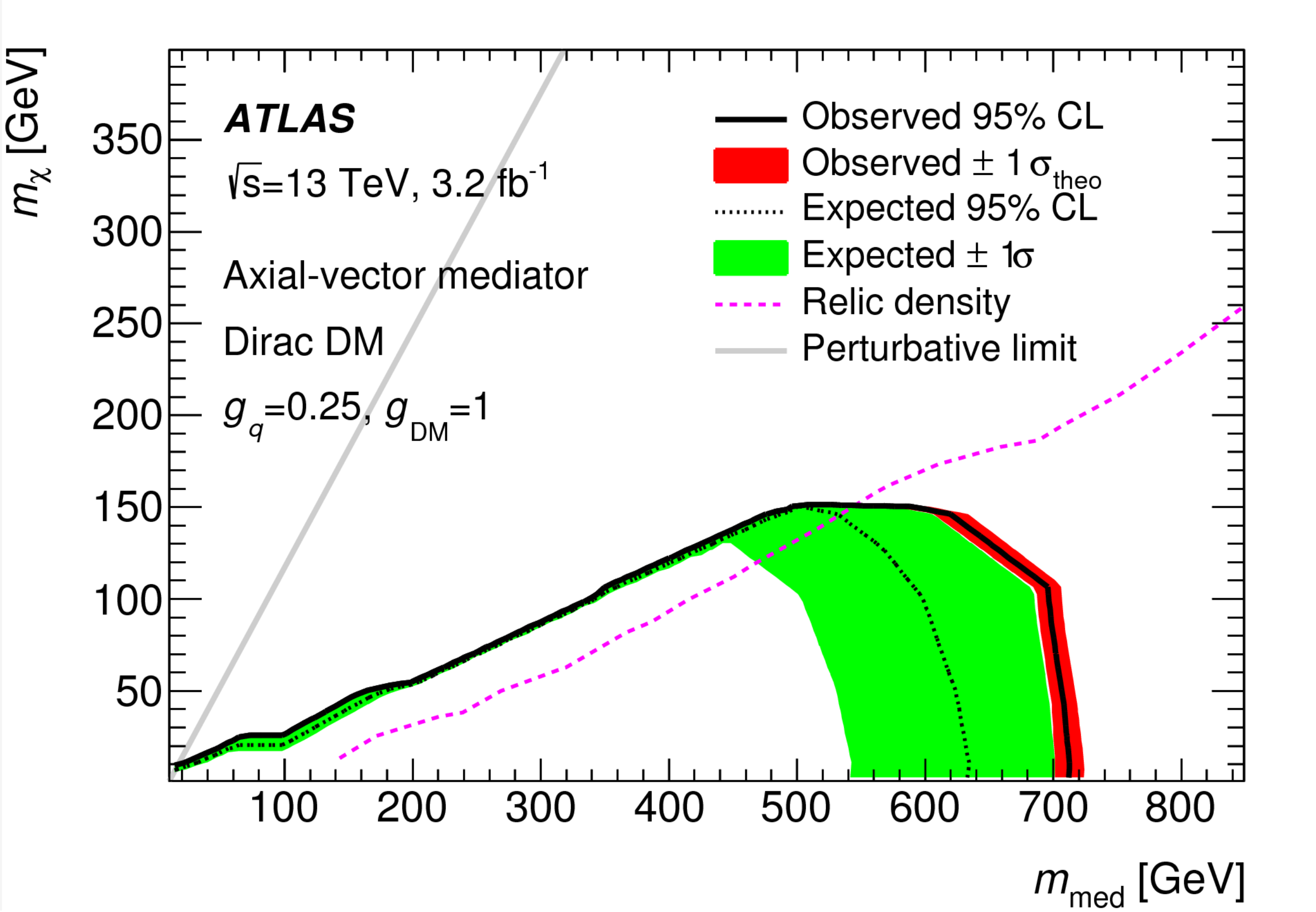
	SR	1muCR	2muCR	2eleCR	PhJetCR
Observed events	264	145	29	20	214
Fitted Background	295±34	145±12	27±4	23±3	214±15
$Z(\to \nu\nu)\gamma$	171±29	0.15±0.03	0.00±0.00	0.00±0.00	8.6±1.4
$W(\to \ell\nu)\gamma$	58±9	119±17	0.14±0.04	0.11±0.03	22±4
$Z(\to \ell\ell)\gamma$	3.3±0.6	7.9±1.3	26±4	20±3	1.2±0.2
$\gamma +$ jets	15±4	0.7±0.5	0.00±0.00	0.03±0.03	166±17
Fake photons from electrons	22±18	1.7±1.5	0.05±0.05	0.00±0.00	5.8±5.1
Fake photons from jets	26±12	16±11	1.1±0.8	2.5±1.3	9.9±3.1
Pre-fit background	249±29	105±14	23±2	19±2	209±50

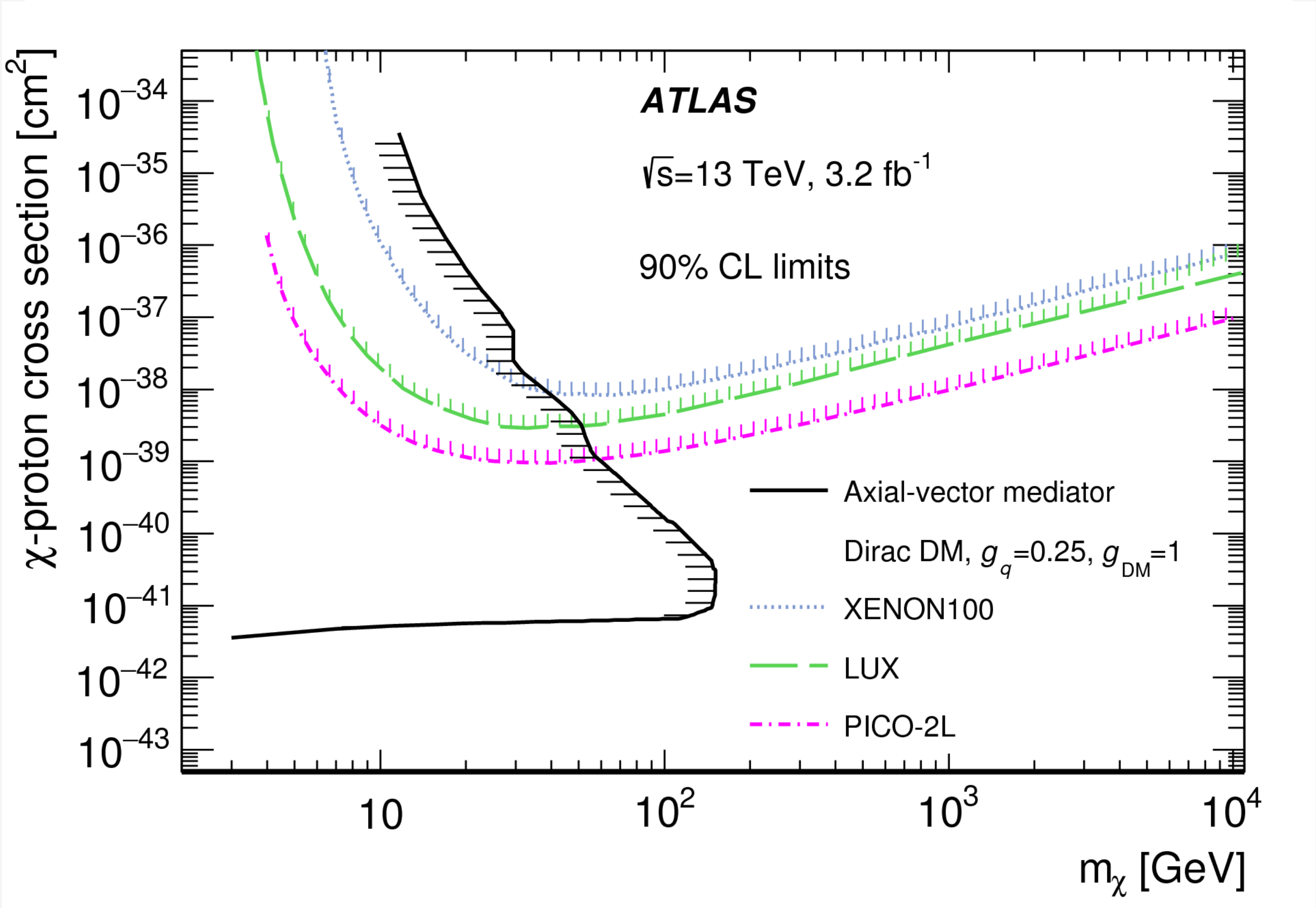
Stat. error: 9%

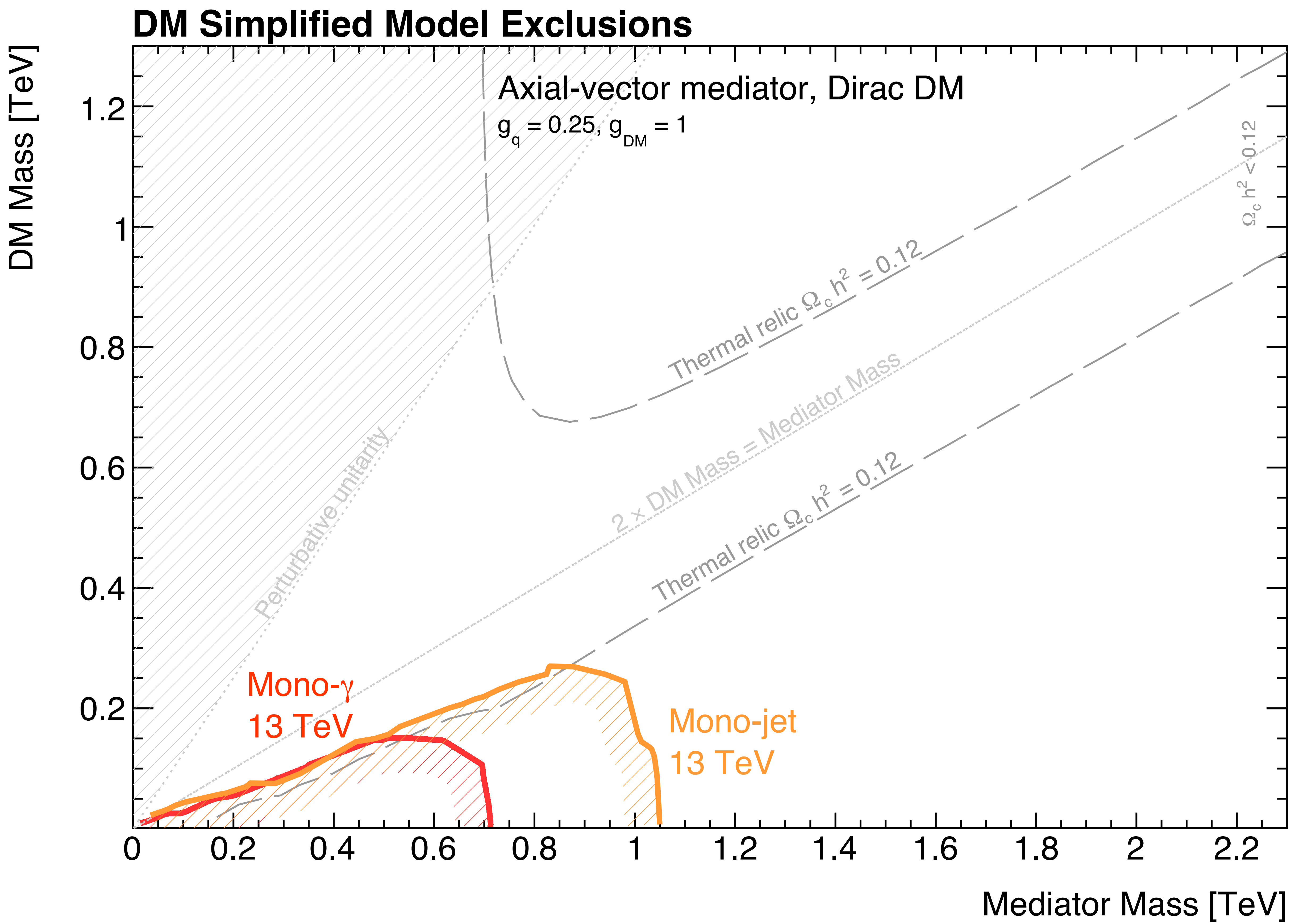
Total error: 11%

(rate for electrons and jets faking photons)

13 TeV Mono-Photon Results

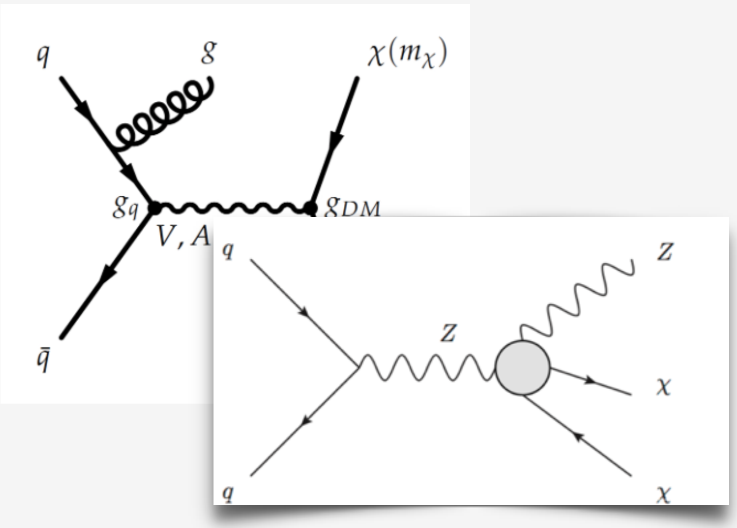


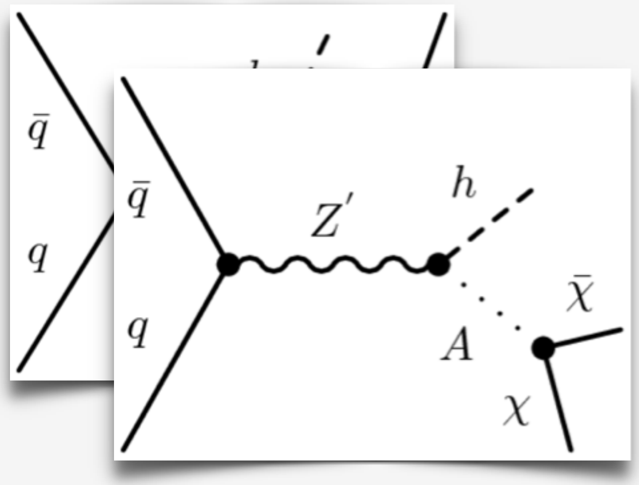


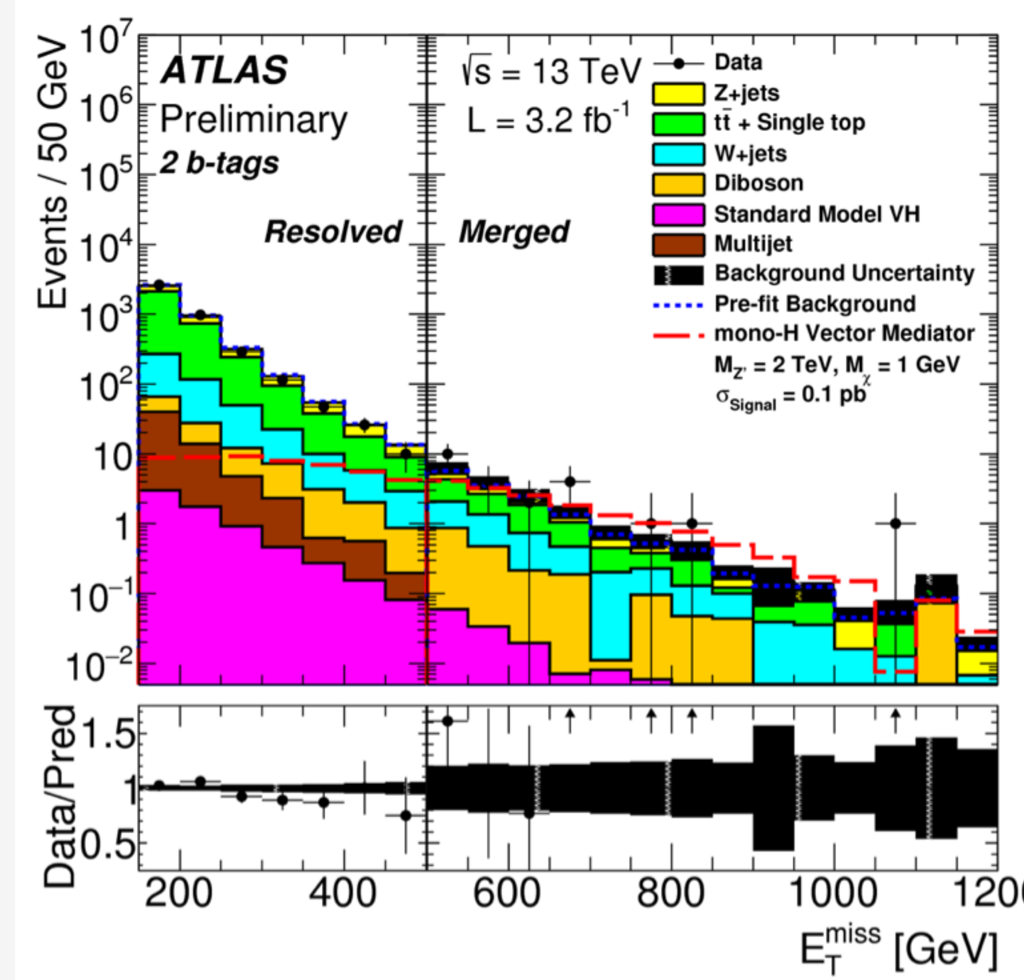

DM Simplified Model Exclusions
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_{DM} = 1$
Thermal relic $\Omega_c h^2 = 0.12$
2 × DM Mass = Mediator Mass
Thermal relic $\Omega_c h^2 = 0.12$
$\Omega_c h^2 < 0.12$
Perturbative unitarity
Mono-γ
13 TeV
Mono-jet
13 TeV
DM Mass [TeV]
Mediator Mass [TeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2

Searches for Dark Matter Production Beyond Mono-jets

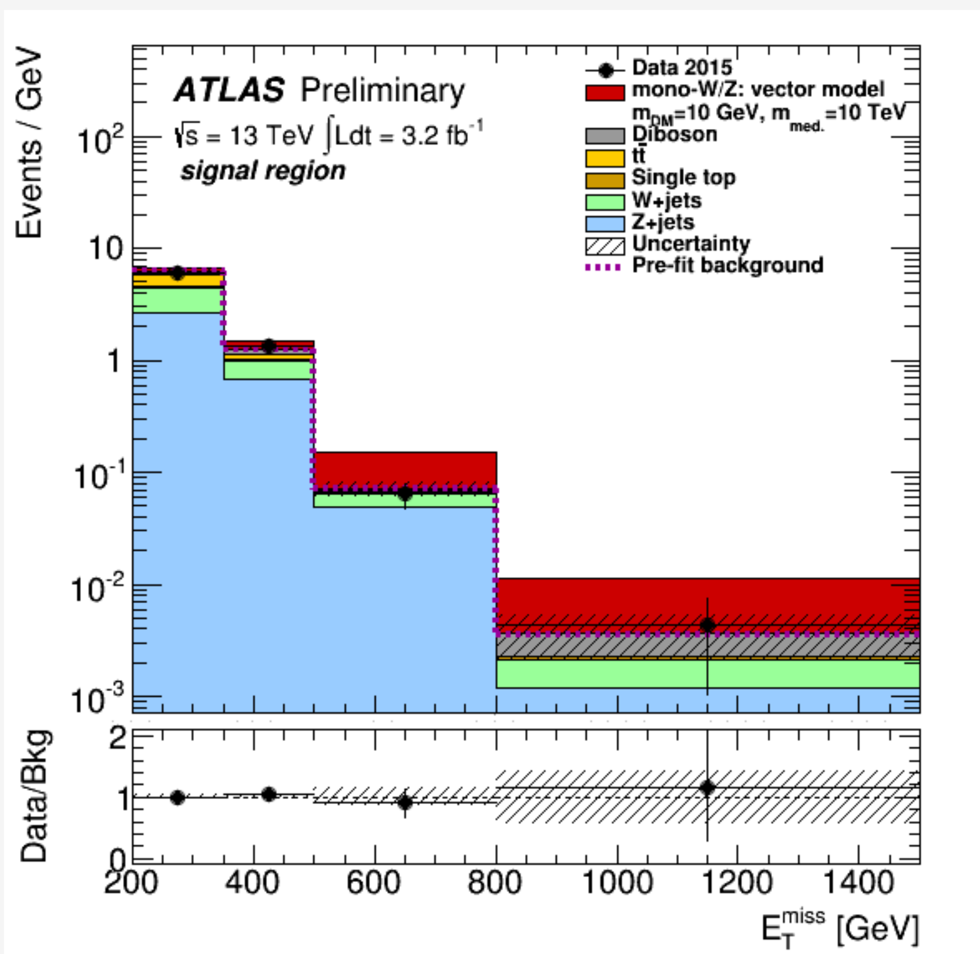
Substitute any other boson for the ISR gluon or directly involve the SM particles in the interaction



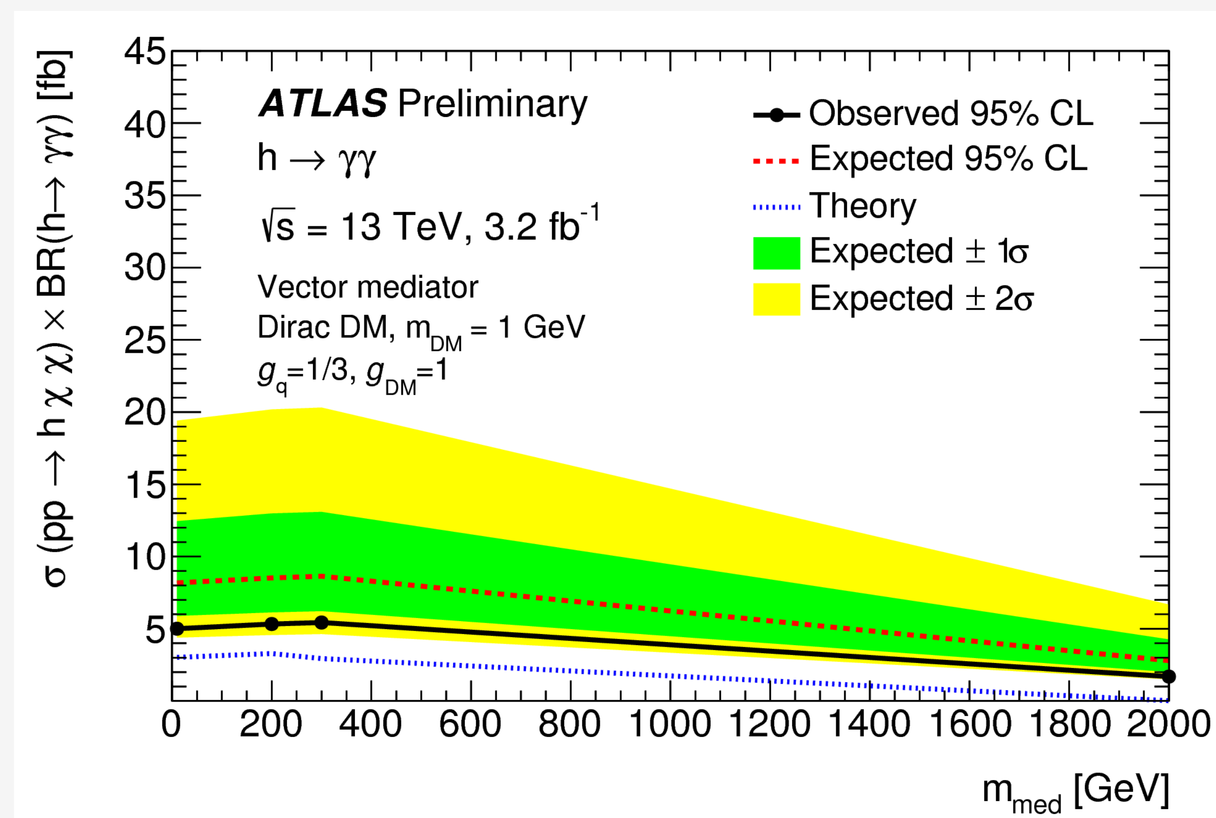




Higgs boson decaying to b quarks



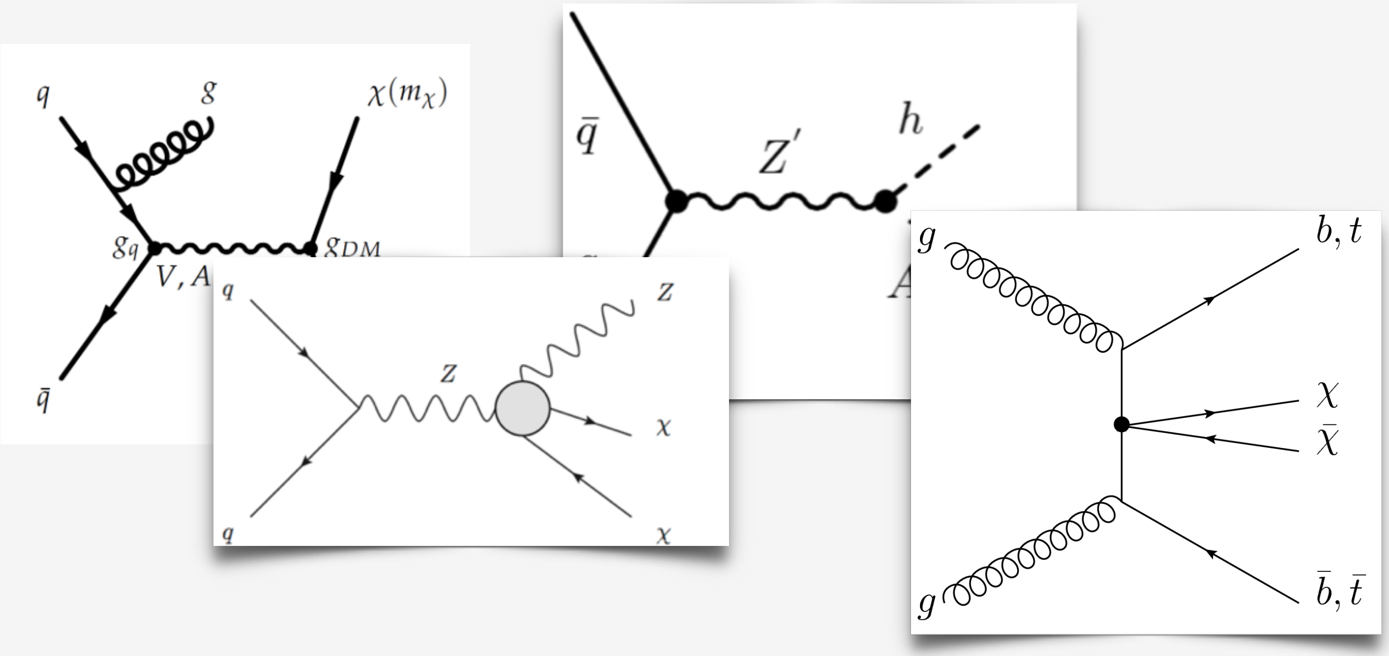
W/Z boson, decaying hadronically

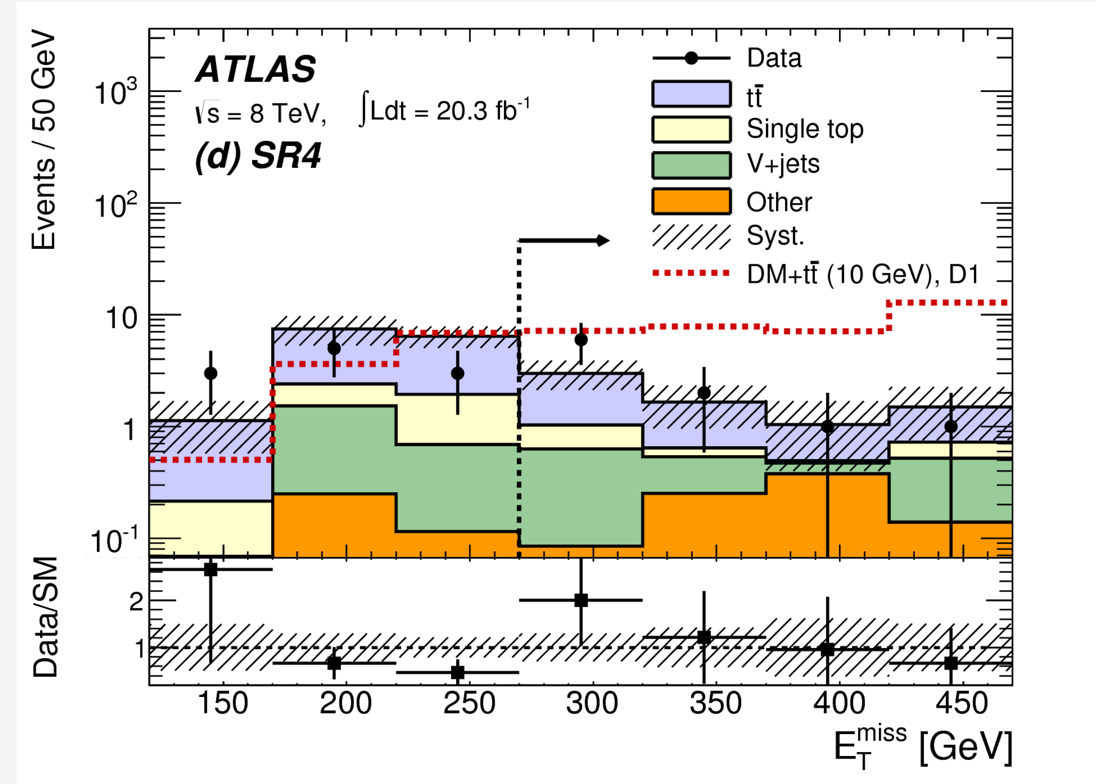


Higgs boson decaying to photons

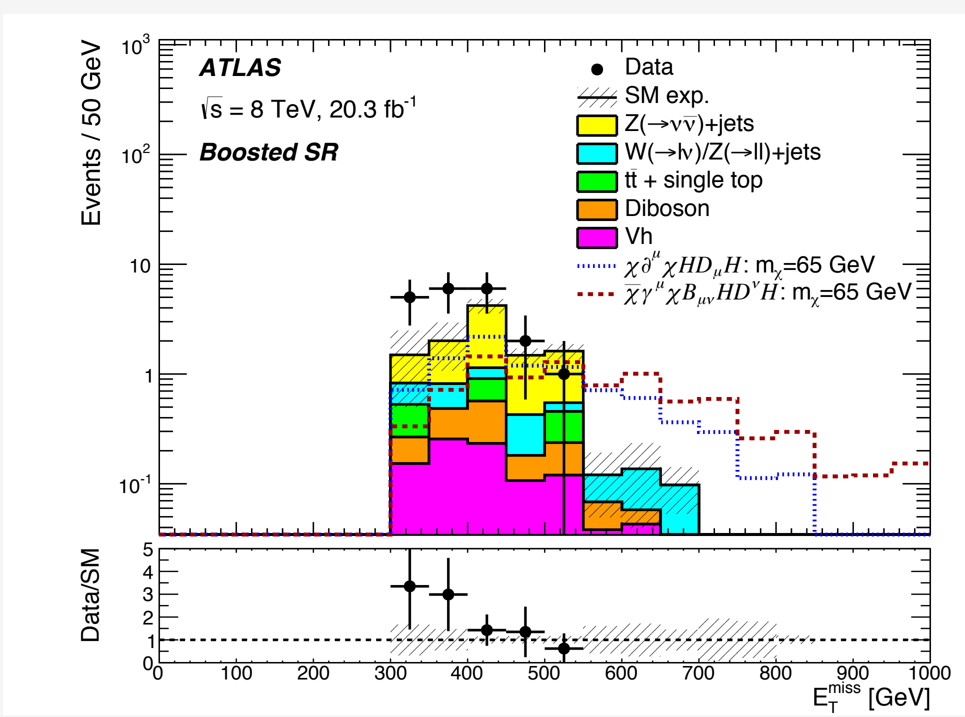
Searches for Dark Matter Production Beyond Mono-jets

Substitute any other boson for the ISR gluon or directly involve the SM particles in the interaction

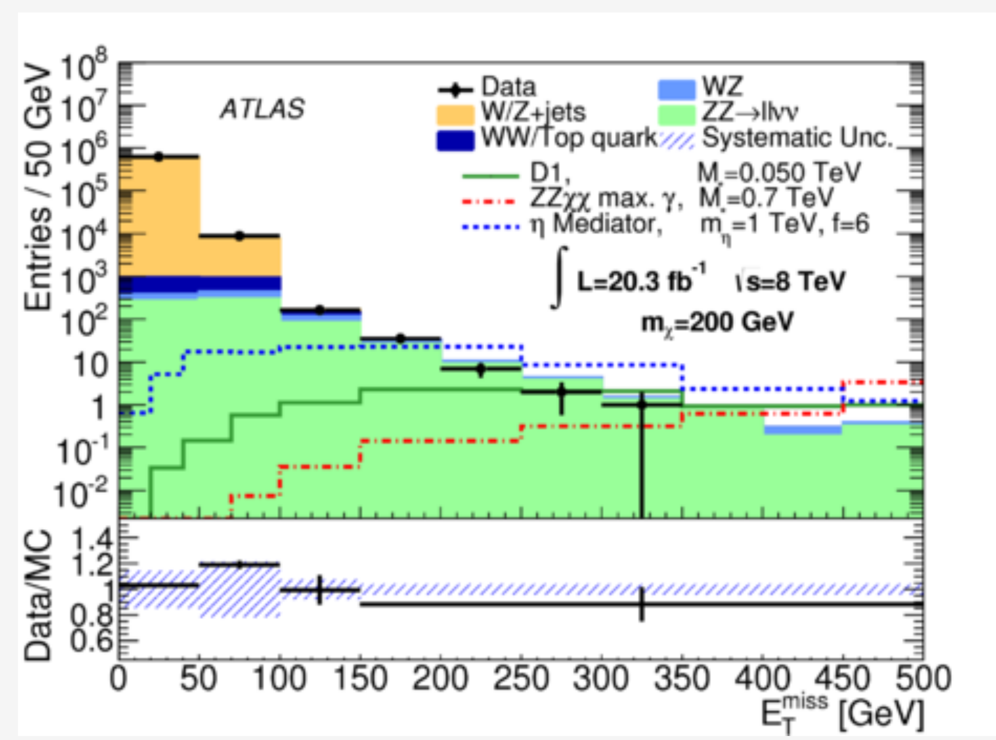




DM produced in association with heavy quarks

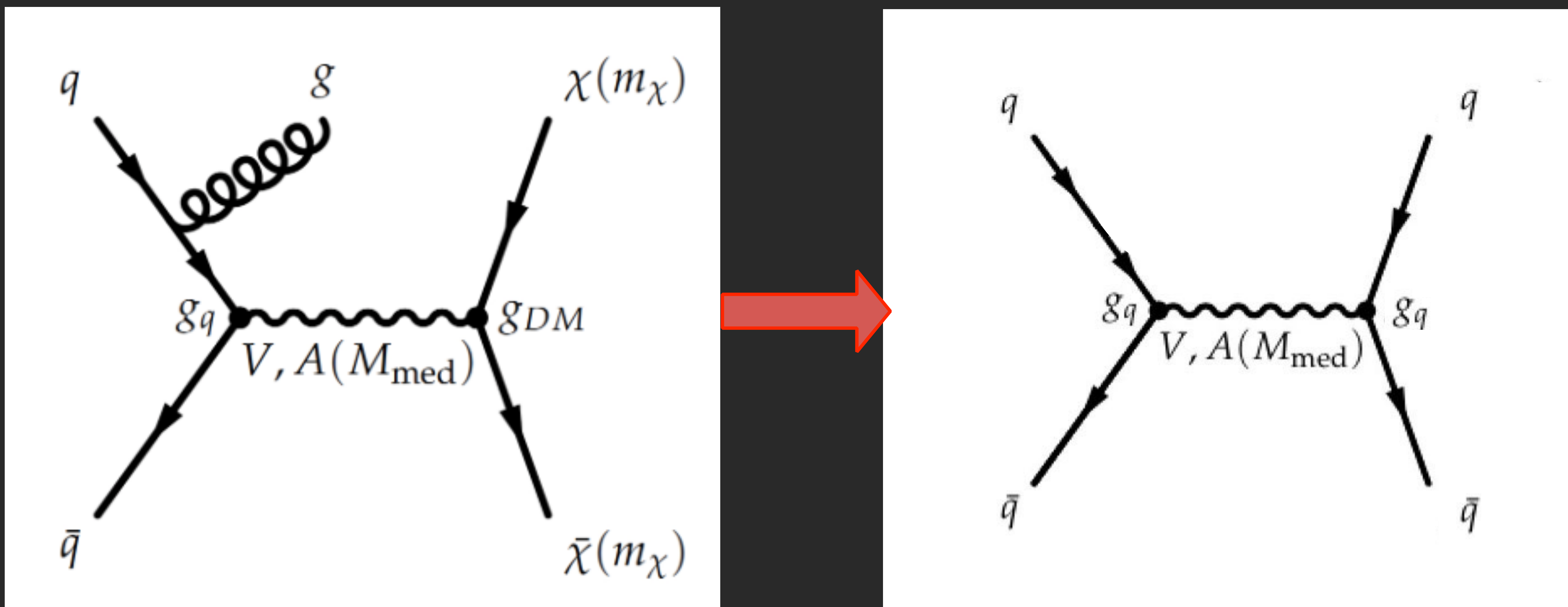


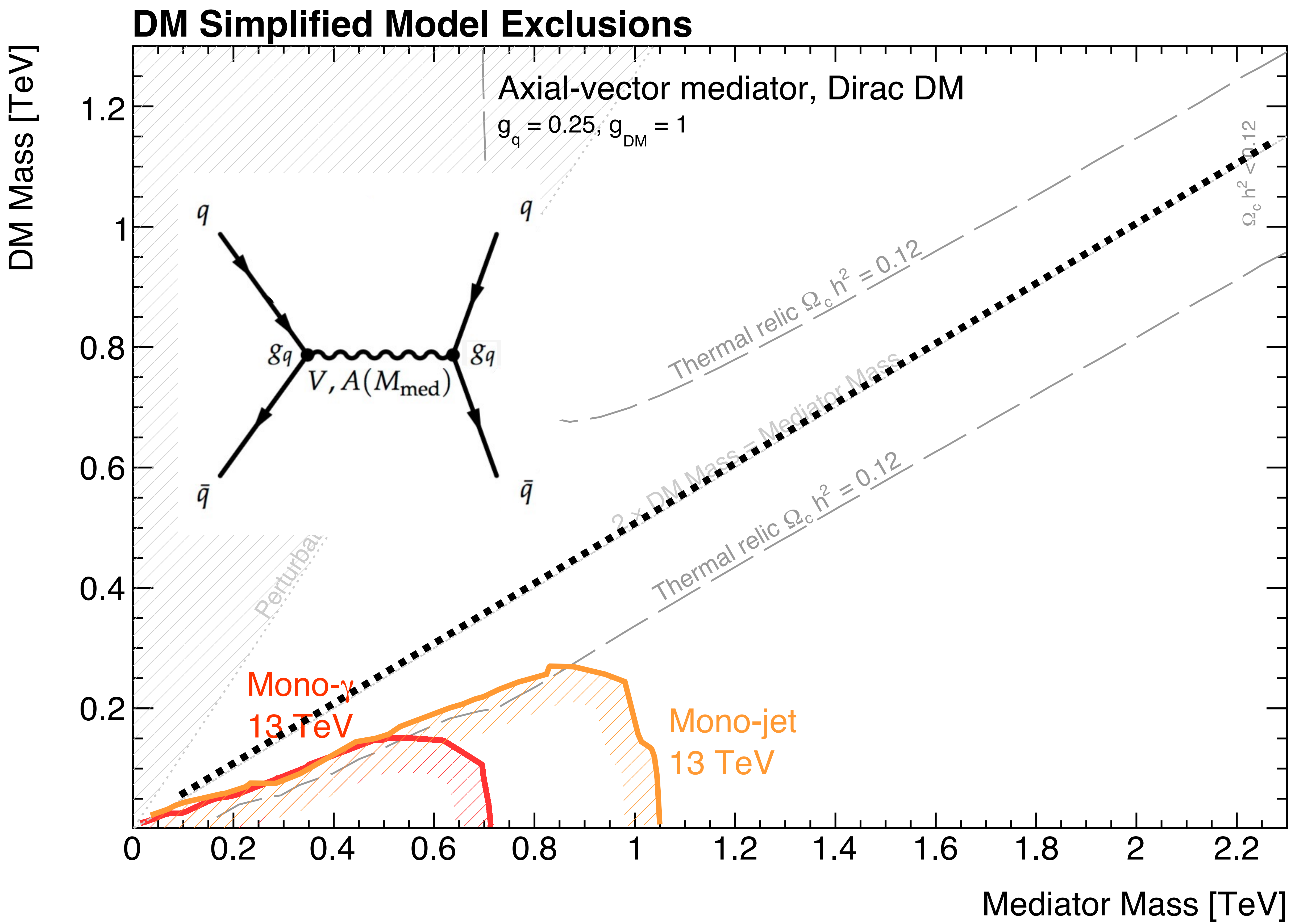
Mono-Higgs→bb



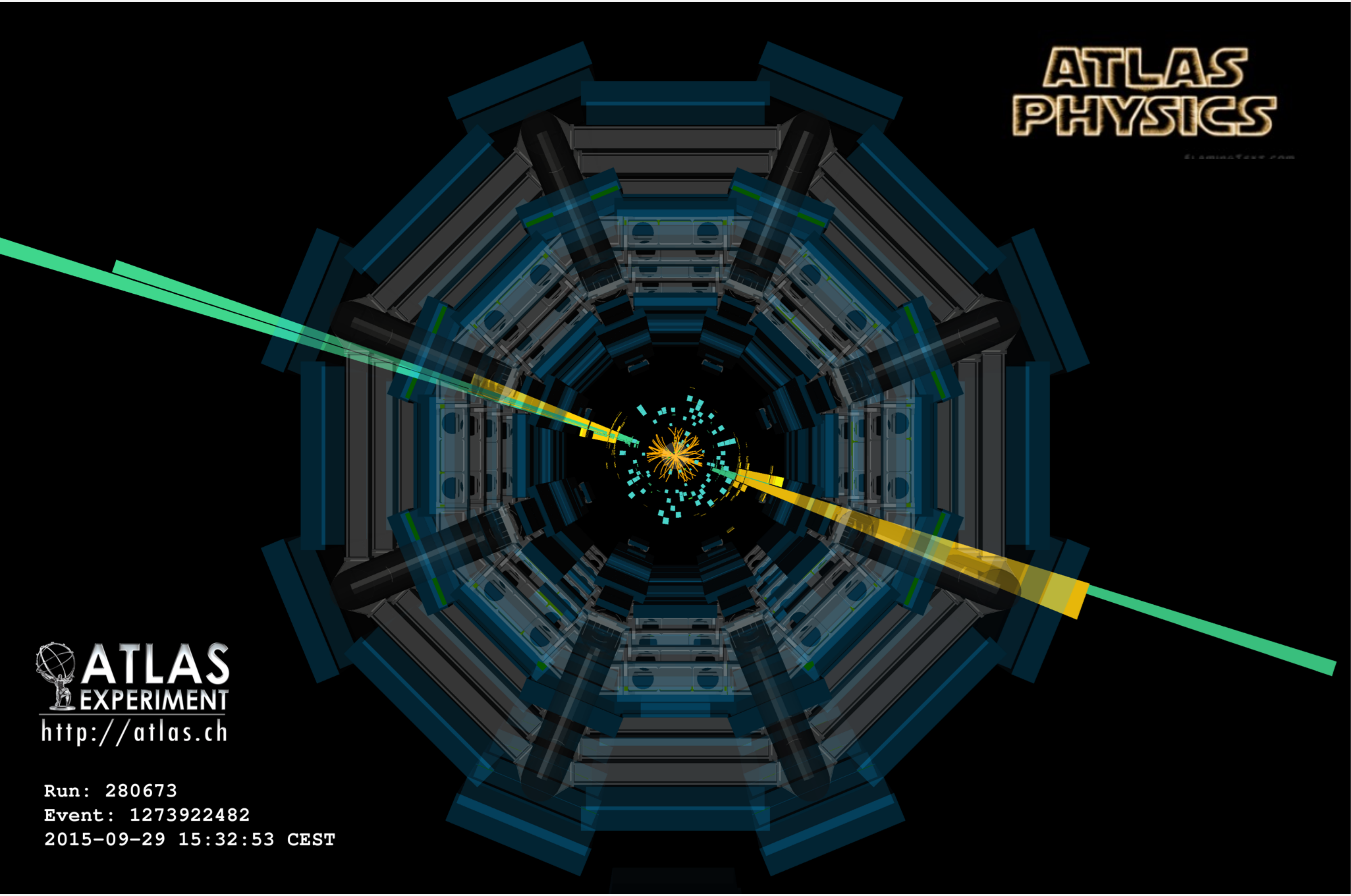
Z boson, decaying leptonically

Searching for Dark Sector Interactions





DM Simplified Model Exclusions
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_{DM} = 1$
q
q
g_q
g_q
$V, A(M_{med})$
$\bar{q}$
$\bar{q}$
Thermal relic $\Omega_c h^2 = 0.12$
2 × DM Mass = Mediator Mass
Thermal relic $\Omega_c h^2 = 0.12$
$\Omega_c h^2 < 0.12$
Mono-γ
13 TeV
Mono-jet
13 TeV
DM Mass [TeV]
Mediator Mass [TeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2


ATLAS
PHYSICS
ATLAS
EXPERIMENT
http://atlas.ch
Run: 280673
Event: 1273922482
2015-09-29 15:32:53 CEST

ATLAS Dijets Searches at 13 TeV

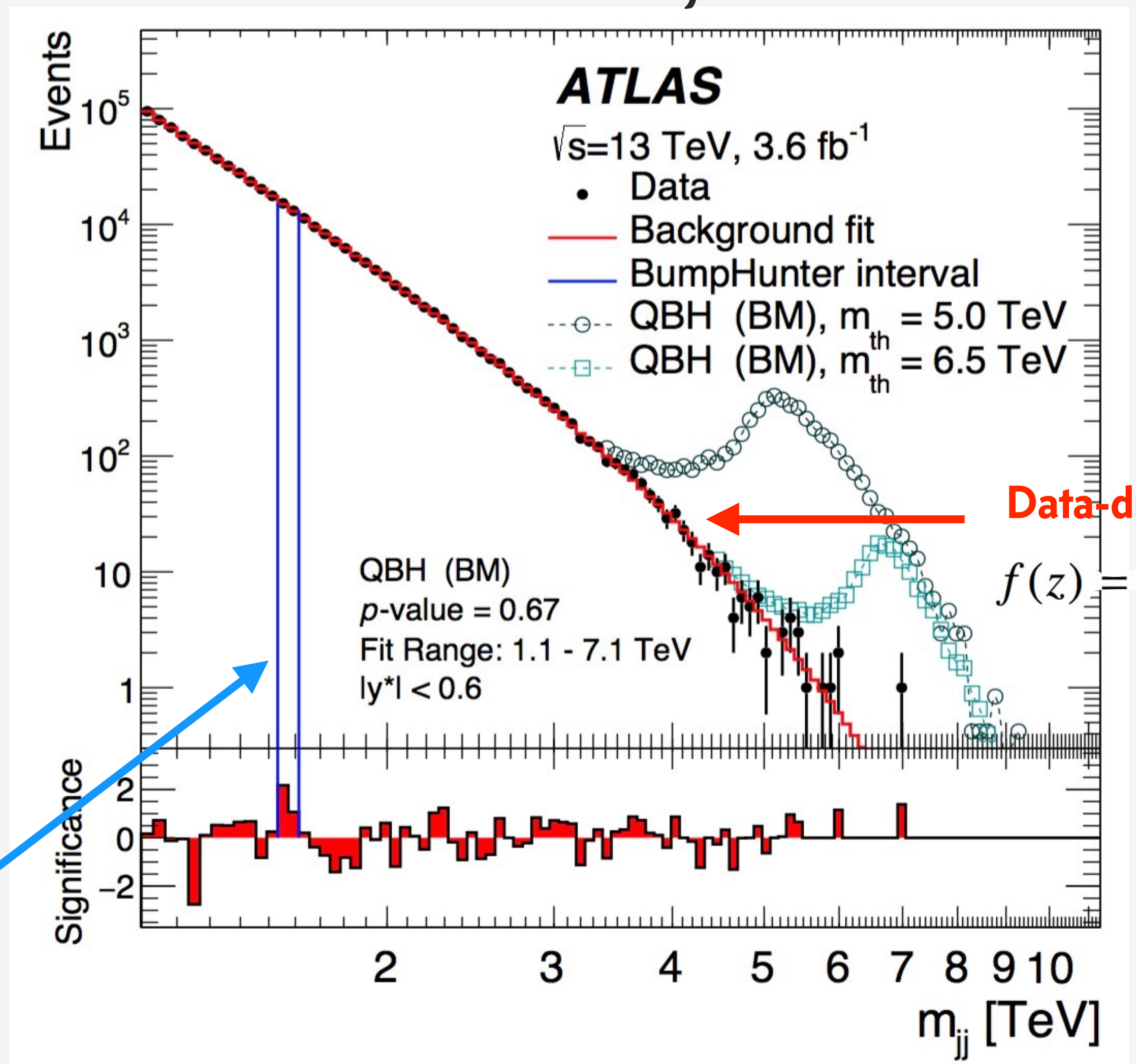
Physics Letters B 754 (2016) 302–322

Jet p_T > 440, 50 GeV

$|y^*| = |y_1 - y_2|/2 < 0.6$
(rejects forward-peaking t-channel QCD processes)

m_{jj} > 1.1 TeV

Resonant analysis

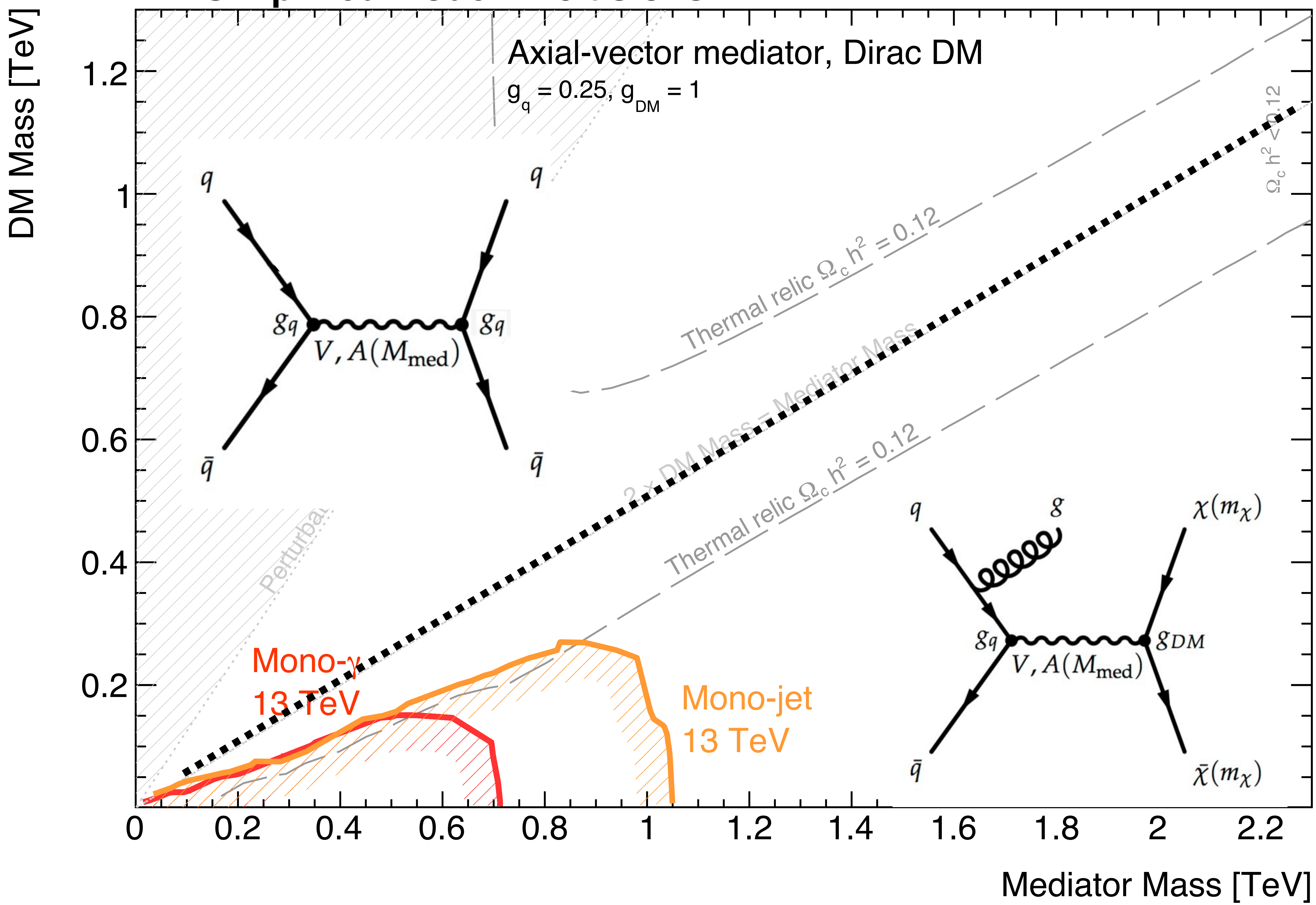


Data-driven background fit

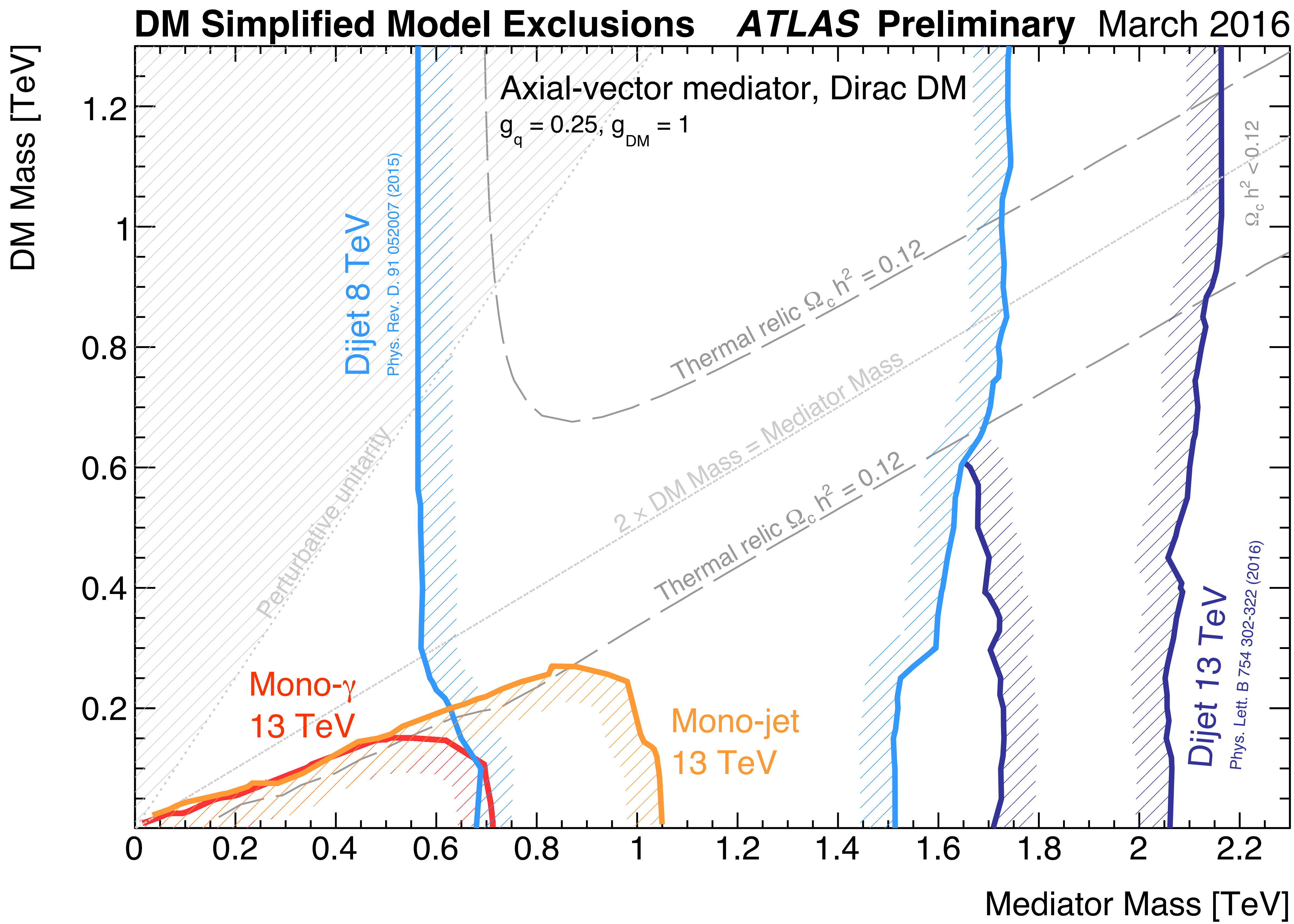
$$f(z) = p_1(1-z)^{p_2} z^{p_3+\cancel{p_4 \log z}}$$

Most discrepant region
1.53-1.61 TeV
(p-value 0.67)

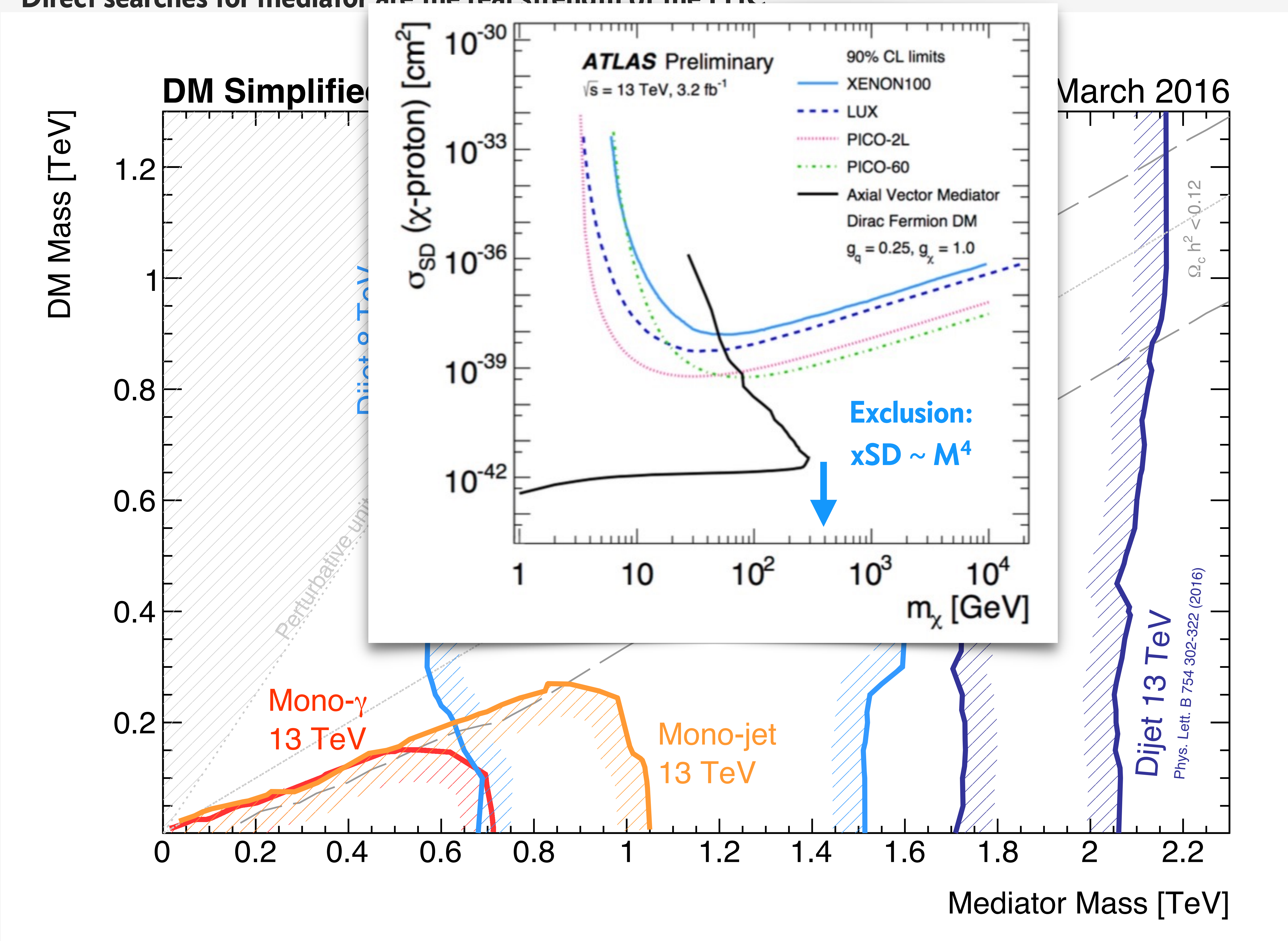
DM Simplified Model Exclusions



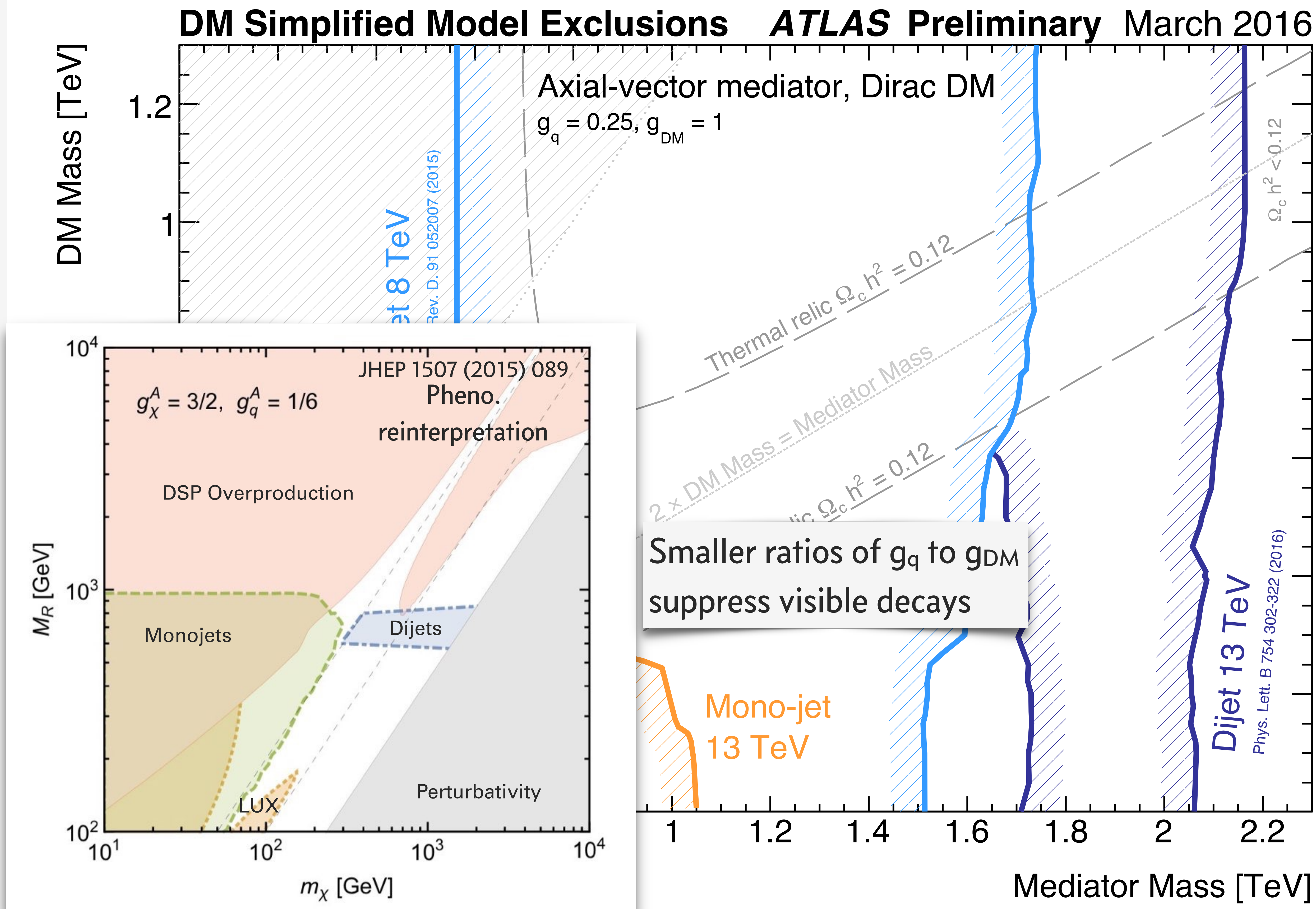
Direct searches for mediator are the real strength of the LHC



Direct searches for mediator are the real strength of the LHC

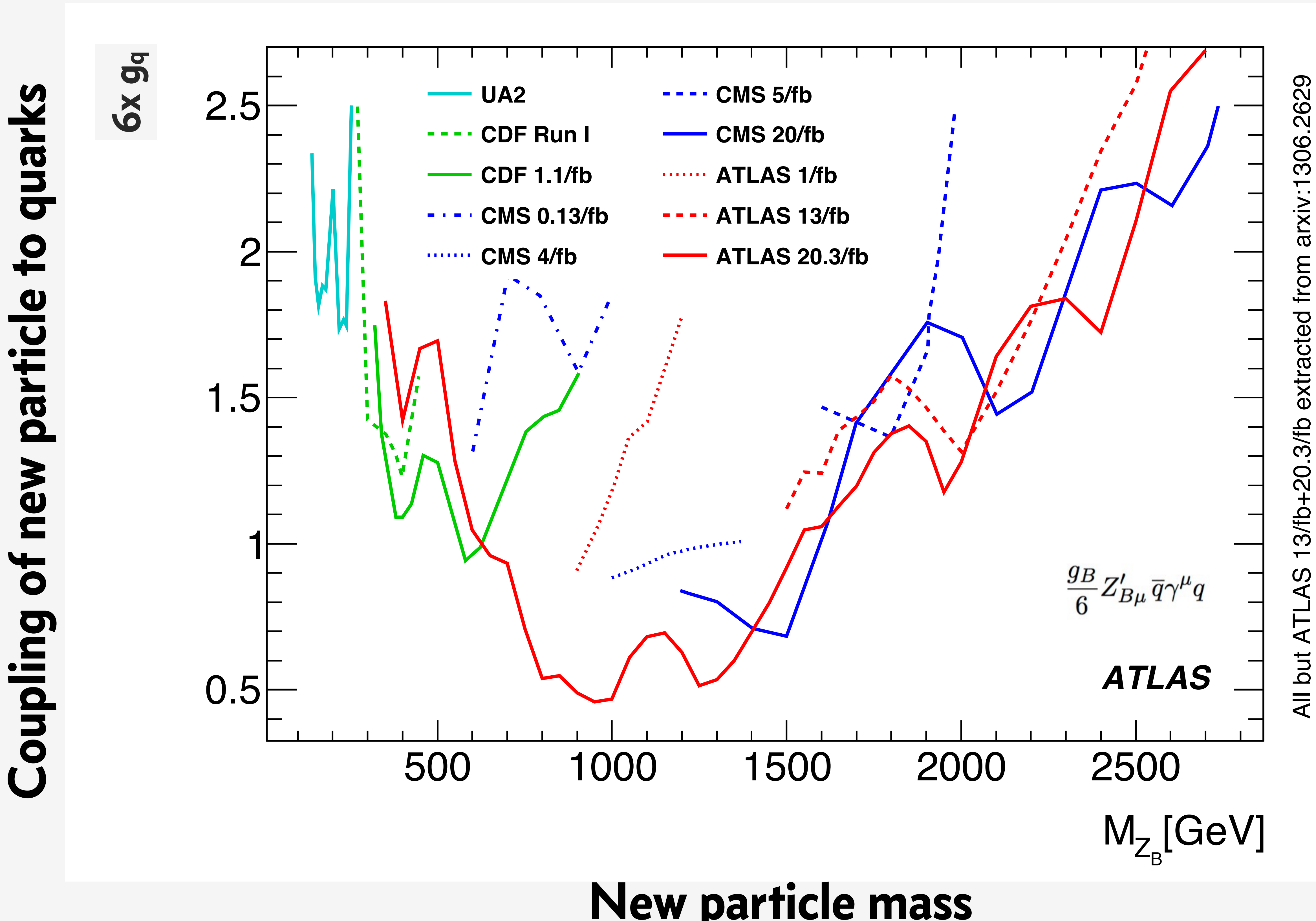


Direct searches for mediator are the strength of the LHC



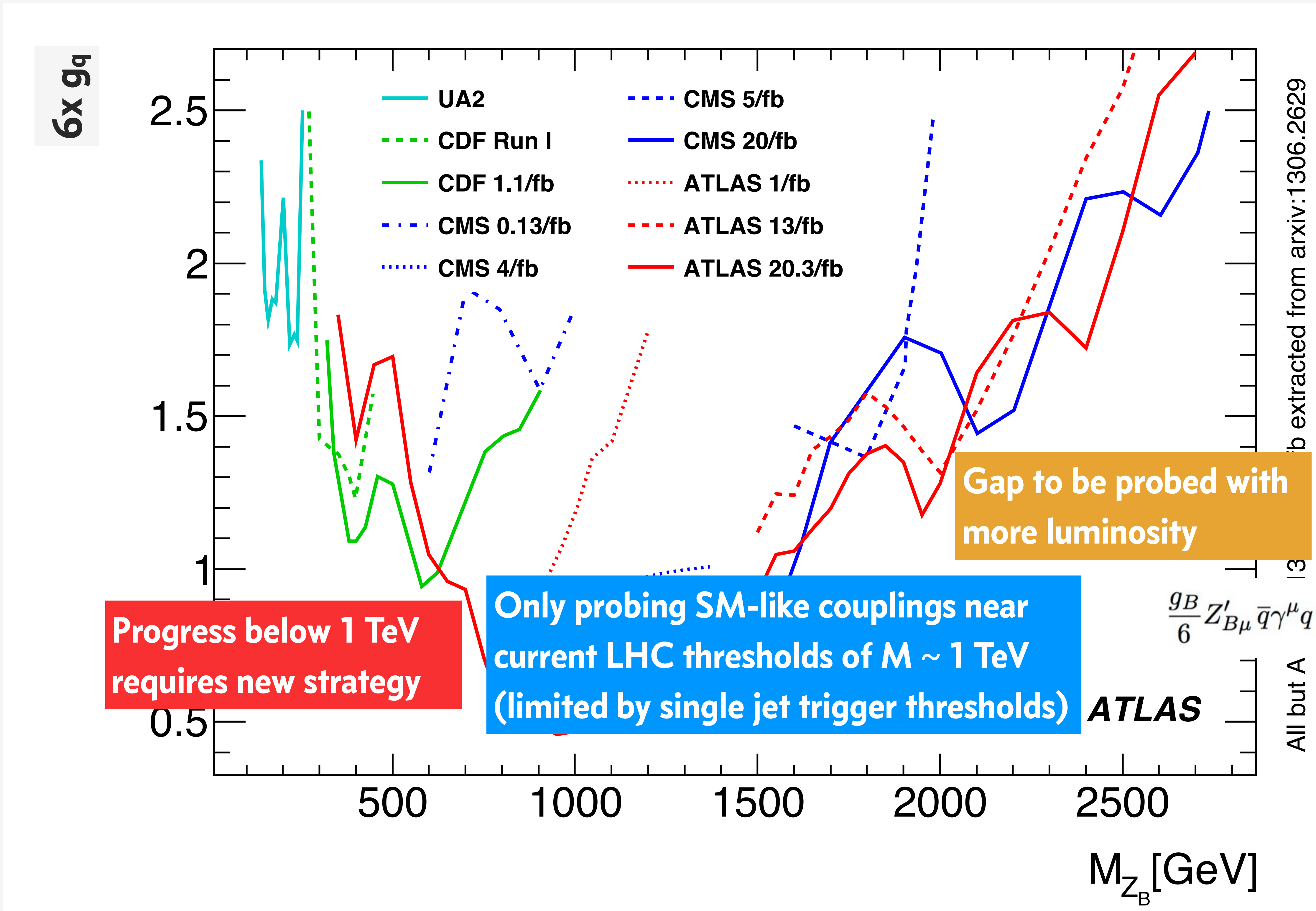
Smaller ratios of g_q to g_{DM} suppress visible decays

Run 1 Results: Dijet Resonances in Heavy DM Limit



Run 1 Results: Dijet Resonances in Heavy DM Limit

Coupling of new particle to quarks



New particle mass

Community-wide Discussion of LHC Dark Matter Searches

LHC Dark Matter Working Group (2015–)

http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

The LHC Dark Matter Working Group (LHC DM WG) brings together **theorists** and **experimentalists** to define **guidelines and recommendations for the benchmark models**, **interpretation**, and **characterisation** necessary for **broad and systematic searches for dark matter at the LHC**.

The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order to help **verify and constrain particle physics models** of **astrophysical excesses**, to understand how collider searches and non-collider experiments **complement** one another, and to help build a **comprehensive understanding** of viable dark matter **models**.

arXiv:1603.04156

arXiv:1603.04156v1 [hep-ex] 14 Mar 2016

CERN-LPCC-2016-001

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

*Editor
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[4]UC, Santa Cruz and UC, Santa Cruz, Inst. Part. Phys., USA
[5]Antwerp University, B2610 Wilrijk, Belgium
[6]SISSA and INFN Sezione di Trieste, via Bonomea 265, I-34136 Trieste, Italy
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[8]LPSC, Universite Grenoble-Alpes, CNRS/IN2P3, France
[9]Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA
[10]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, OX1 3PN, United Kingdom

Pilot effort: translation of LHC simplified model results into DM-nucleon cross-section plane (DD/ID)

Summary

A broad set of searches for dark matter are an important part of the ATLAS BSM search program —healthy Run 1 program is fully underway and evolving at 13 TeV

LHC (ATLAS/CMS/theory) is a key player in the search for dark matter

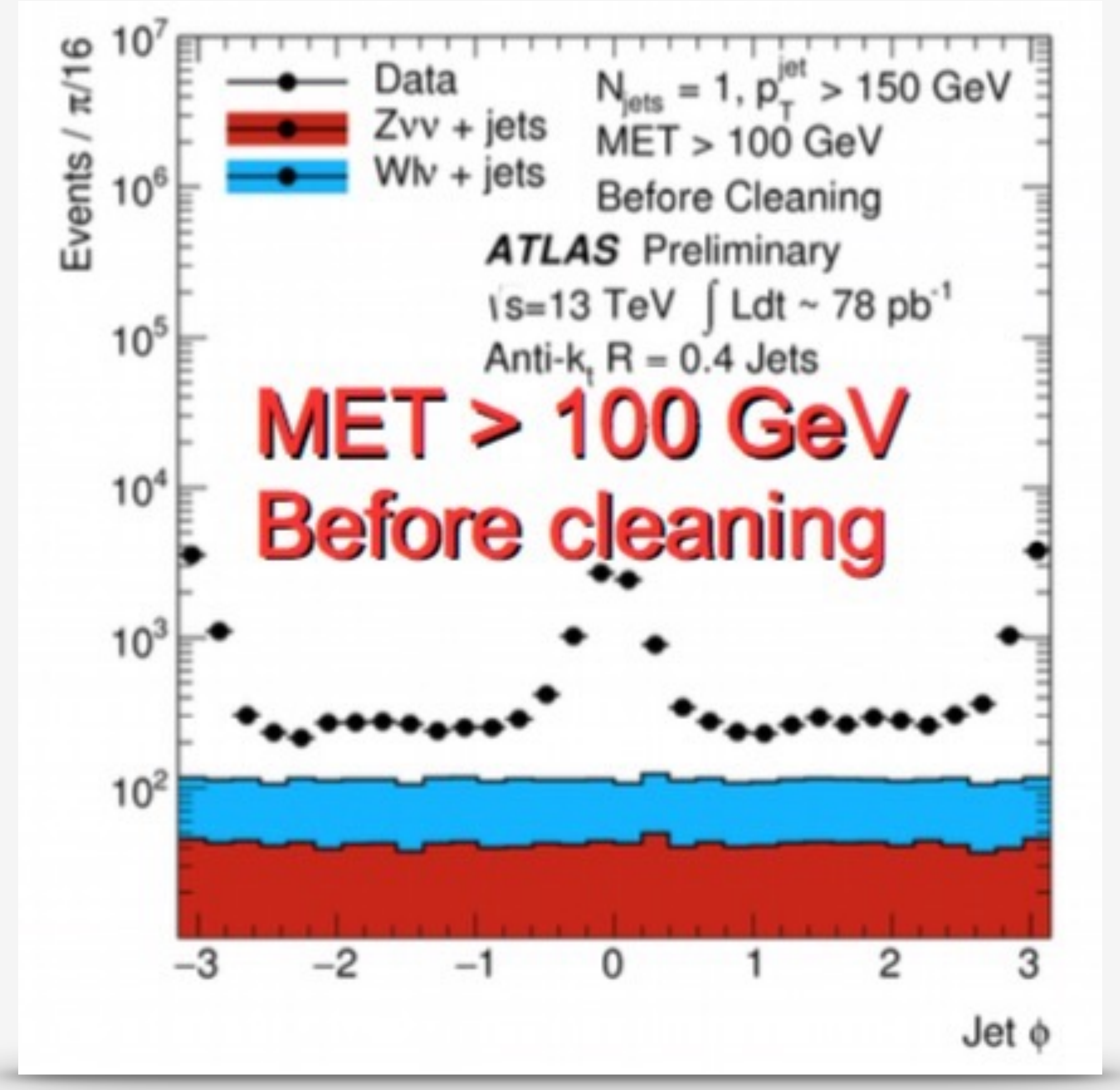
- LHC-wide WIMP benchmark models (Dark Matter Forum)
- LHC Dark Matter Working Group

New ATLAS results with 2015+2016 dataset

* Searches for invisible DM particles
  * monojet, monophoton, mono-W/Z, mono-Higgs
* Searches for visible DM mediators
  * dijets (heavy and light resonances)

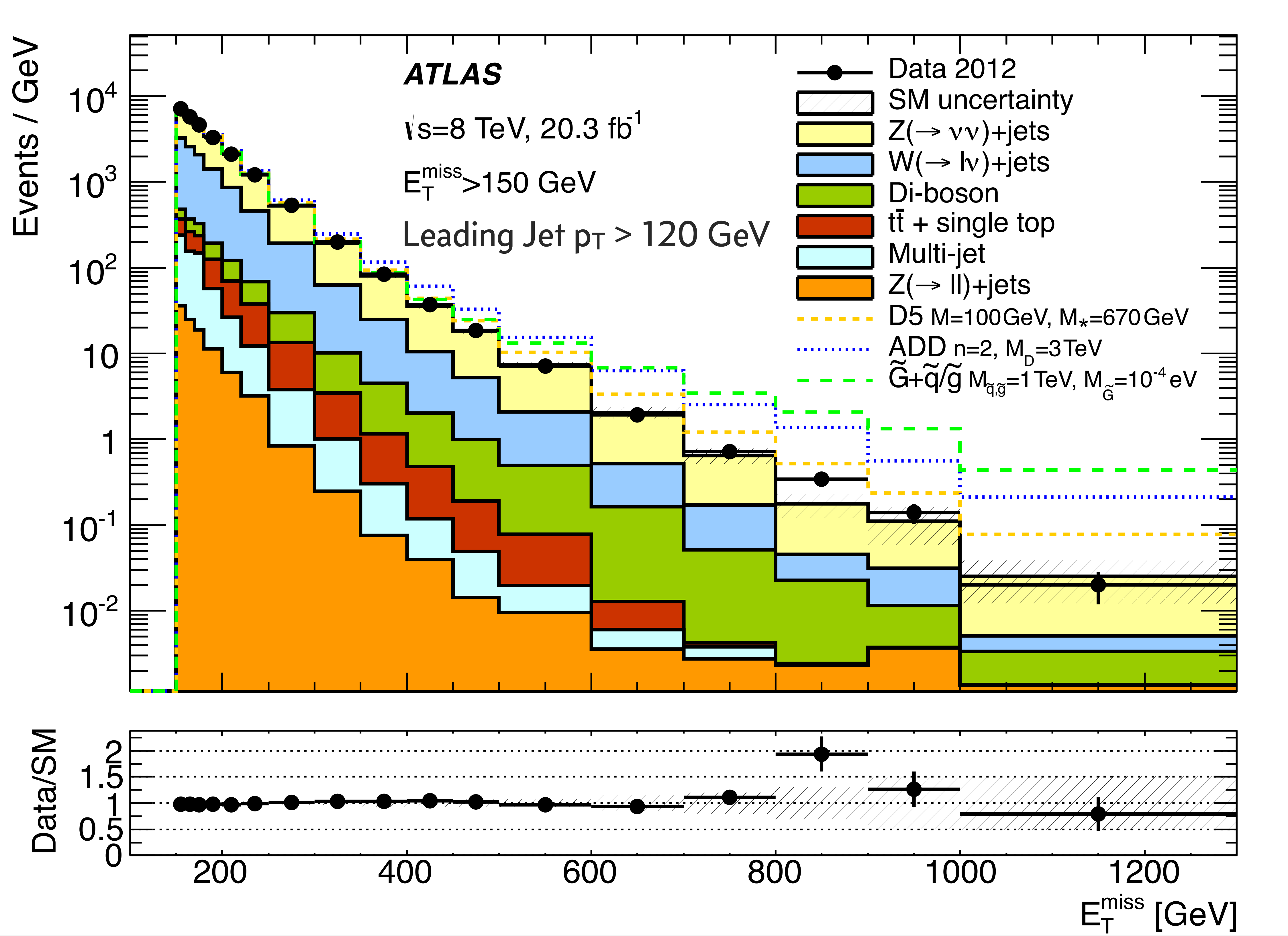
The landscape of Dark Matter at the LHC is just starting to be explored… More to come!

Back-up Slides


Events / π/16
Data
Zνν + jets
Wlν + jets
N_jets = 1, p_T^jet > 150 GeV
MET > 100 GeV
Before Cleaning
ATLAS Preliminary
√s=13 TeV ∫ Ldt ~ 78 pb^-1
Anti-k_t R = 0.4 Jets
MET > 100 GeV
Before cleaning
Jet φ

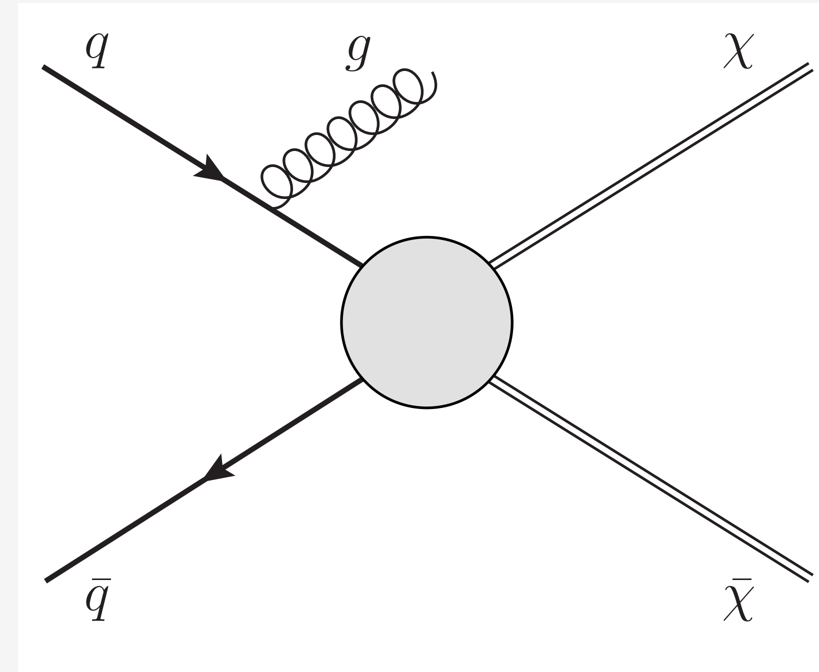
Mono-jet Search: Results

Eur. Phys. J. C (2015) 75:299

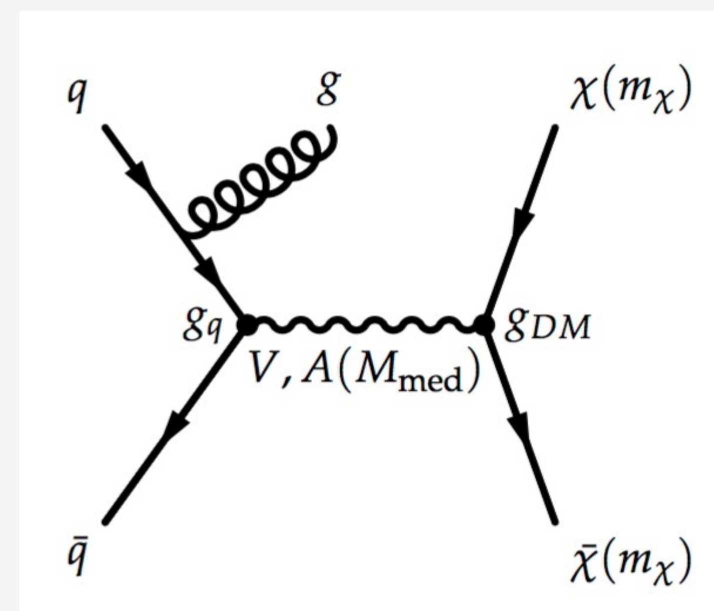


Background uncertainty dominated by theory knowledge

Options for very general dark matter models involving BSM mediators



- **Contact interaction**: ~no information about kinematics.
  Single parameter controls rate
  Discovery can't learn much:
  rate ←→ astroparticle cross sections
  Little sensitivity to DM mass or the interaction



- **Simplified models**: describe only LHC-energy phenomenology
  Strength of the LHC:
  Study properties of interaction: couplings, width—consistent with other results, relic density
  heavy mediators: Z′, additional scalar, graviton, squark,…
  light mediators: can have tiny couplings, displaced decays
  Can be much more powerful than MET search

- Exhaustive catalogs:
  attempts to capture all possible phenomenology
  e.g. co-annihilation codex: ~200 models
  or: full UV-complete theory: MSSM, etc.

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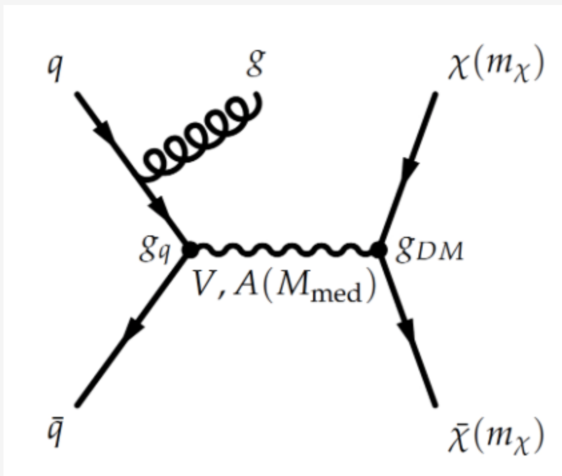
Category (# of models)	New fields	New couplings
Hybrid (7)	DM, X	DM-X-SM_3
s-channel (49)	DM, X, M_s	DM-X-M_s M_s-SM_1-SM_2
t-channel (105)	DM, X, M_t	DM-M_t-SM_1 M_t-X-SM_2

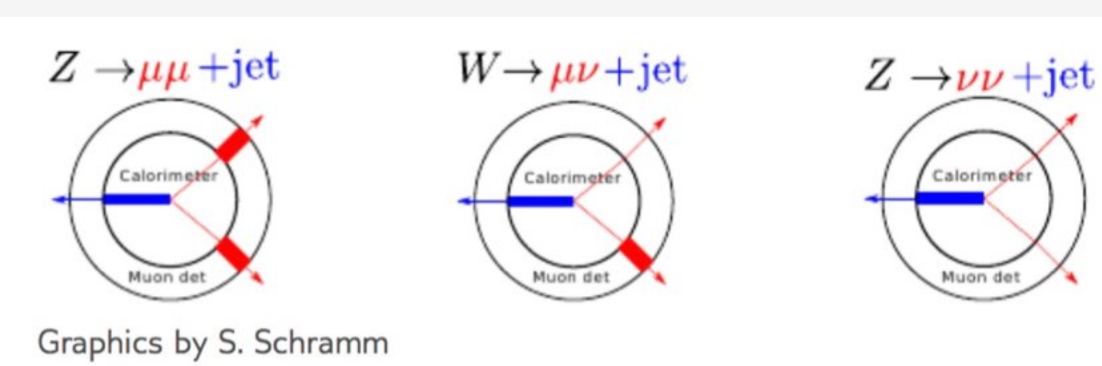
Missing Transverse Energy Signals in the Mono-jet Analysis

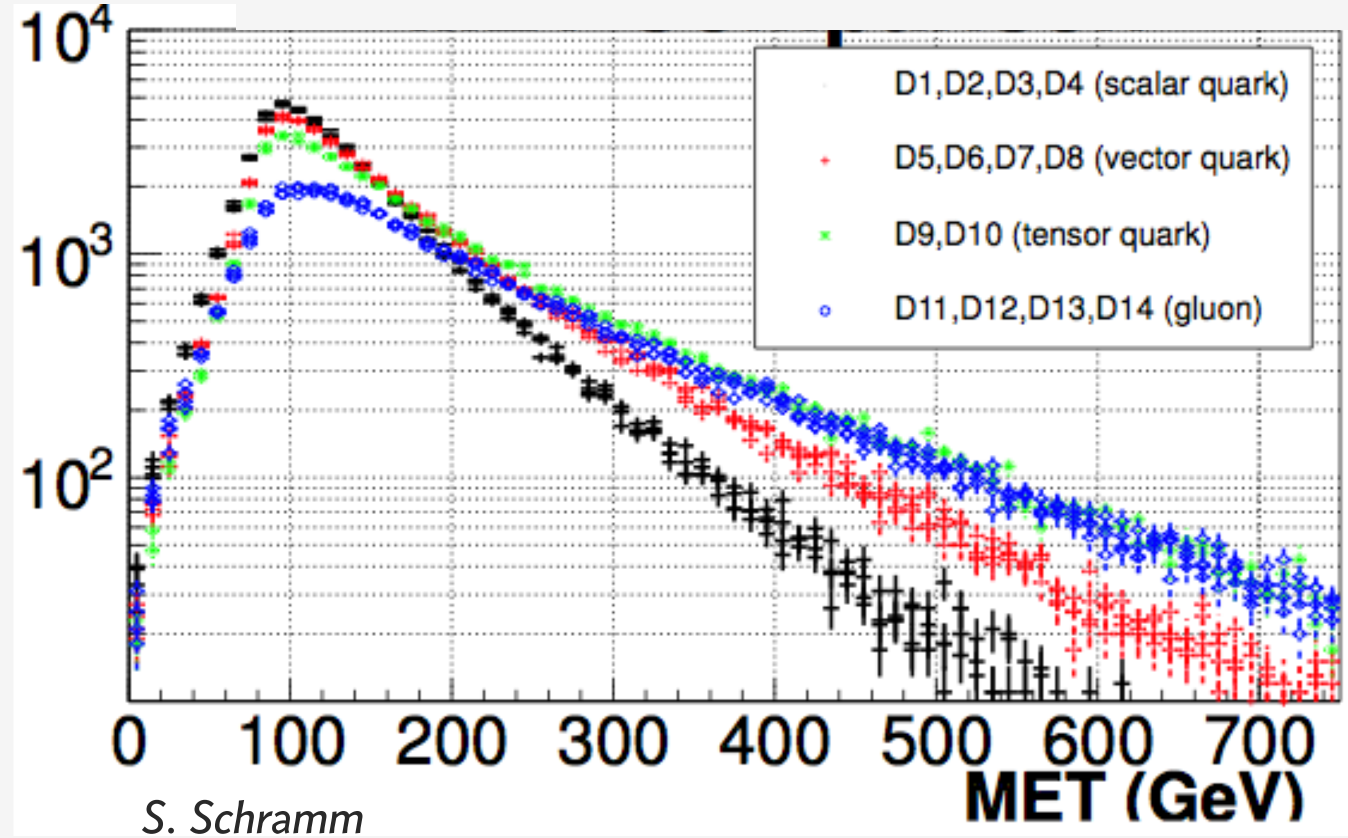
DM signals: invisible particles + initial state radiation → Missing transverse energy + jet

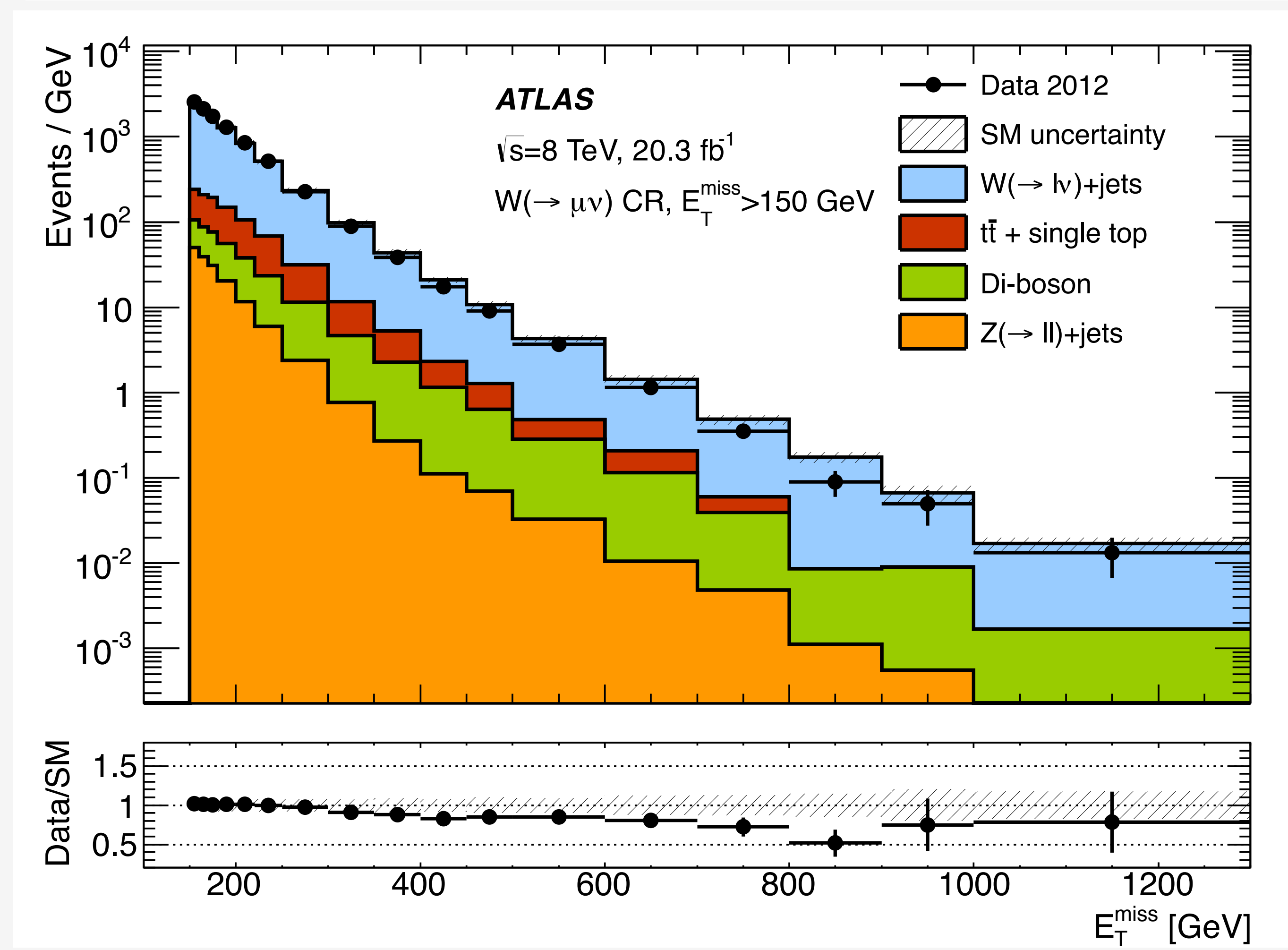


SM background: Z boson decaying to neutrinos in association with jets → Missing transverse energy + jet

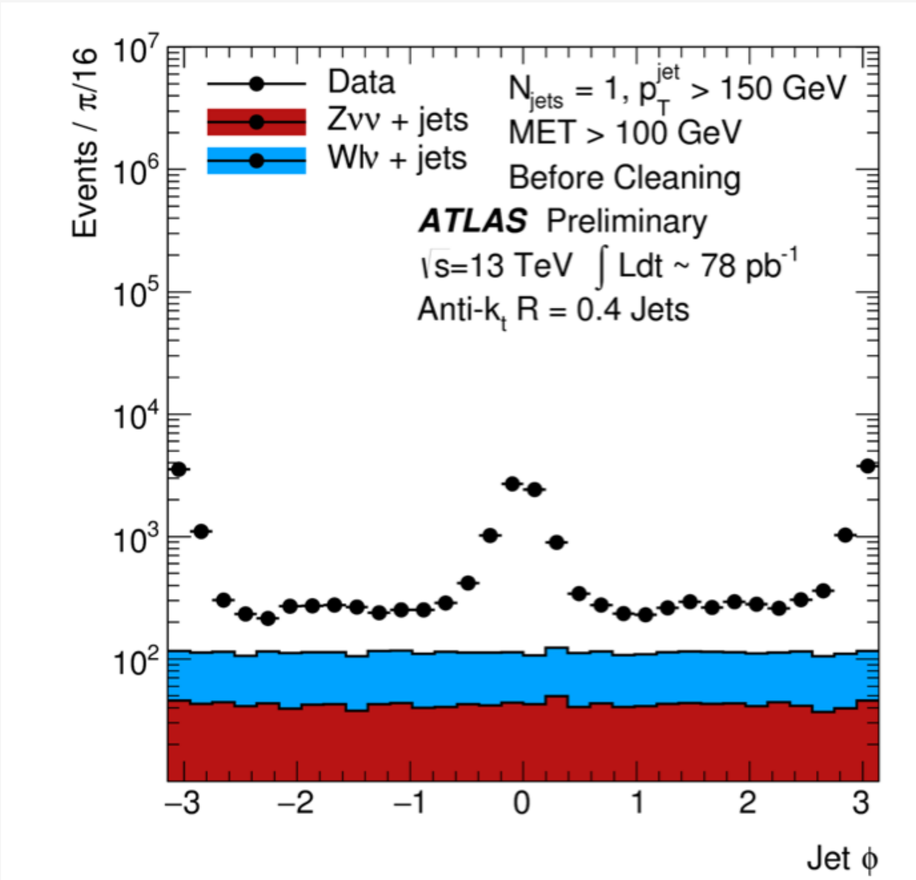
Background estimation:
Use known processes to derive background rates directly from data

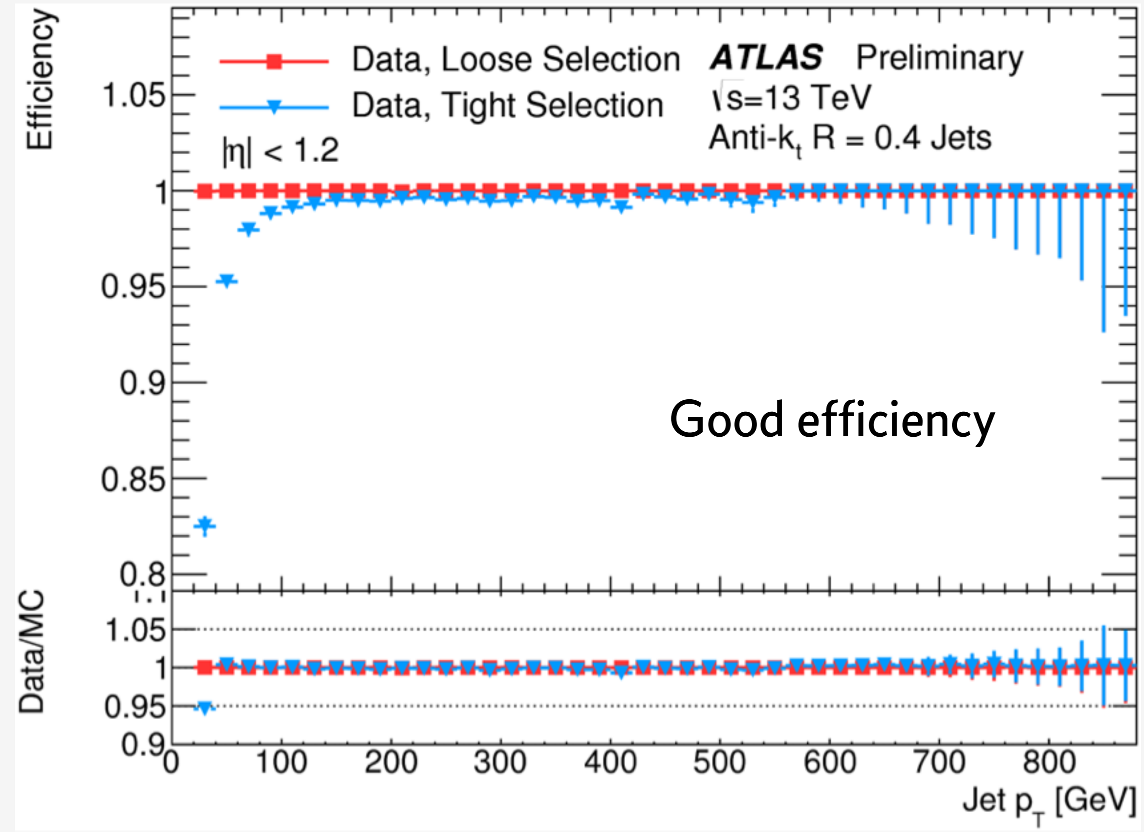




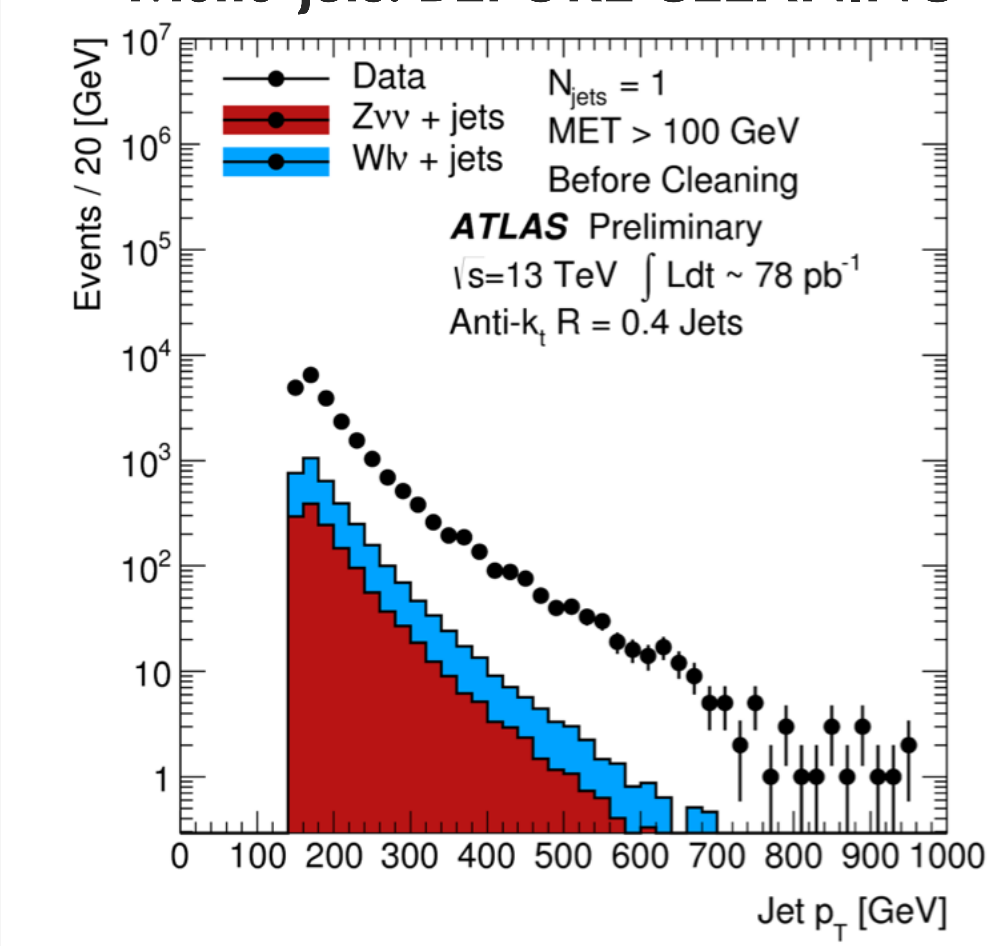


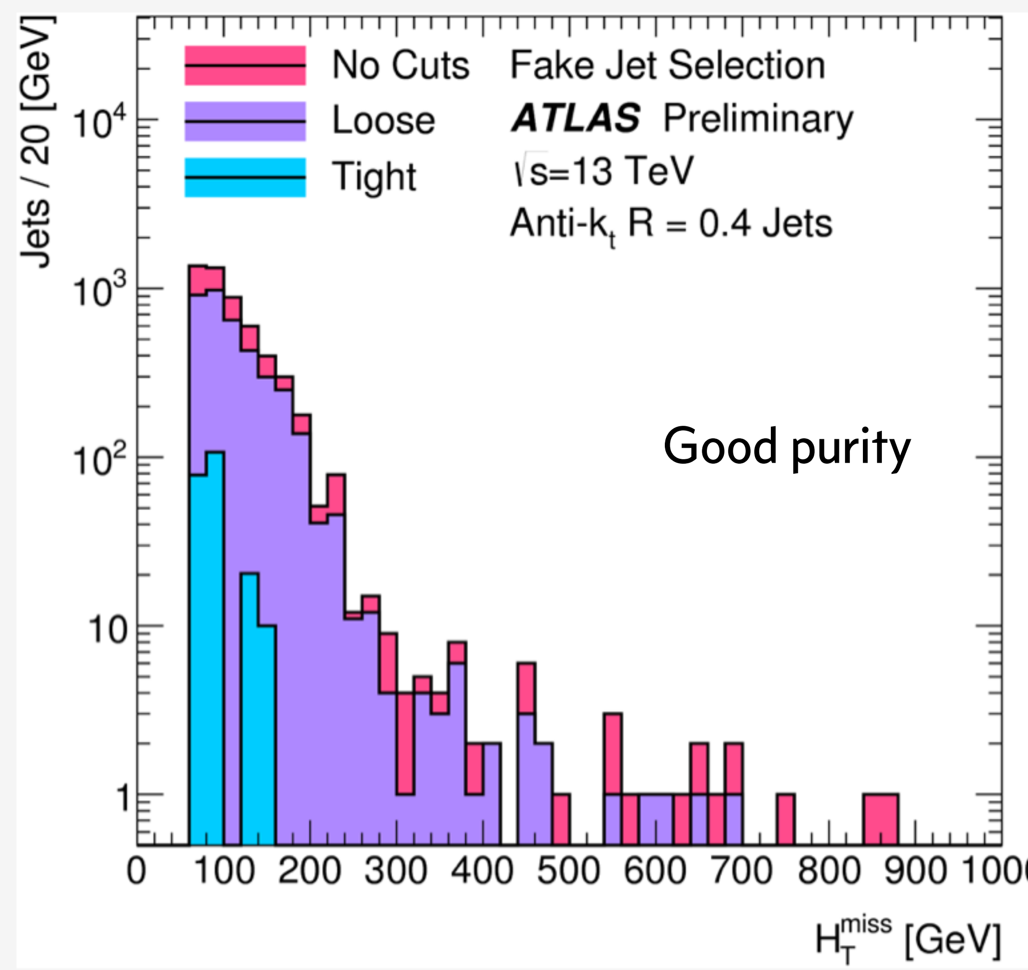
Rejection of fake jets is crucial





Mono-jets: BEFORE CLEANING





Kinematics of Two-Parton Scattering

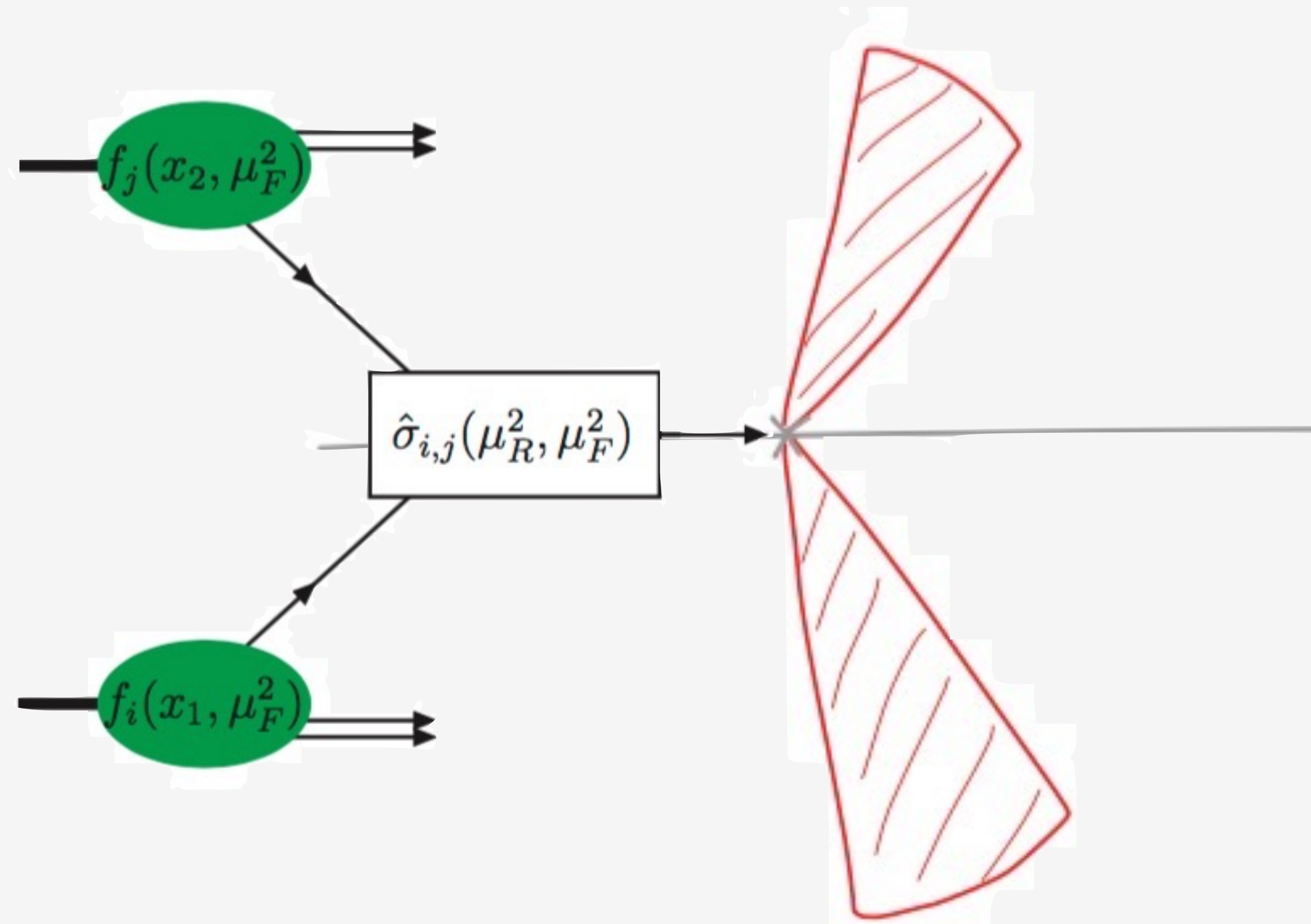
$$M^2 = \hat{s} = x_1 x_2 s$$

$$\hat{t} = -\frac{1}{2}\hat{s}\left(1-\cos\theta^*\right), \quad \hat{u} = -\frac{1}{2}\hat{s}\left(1+\cos\theta^*\right)$$

$$\hat{s} = 4p_T^2\cosh^2 y^*$$

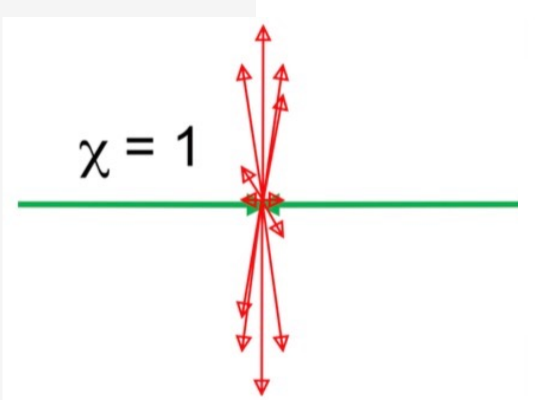
$$\cos\theta^* = \tanh y^*$$

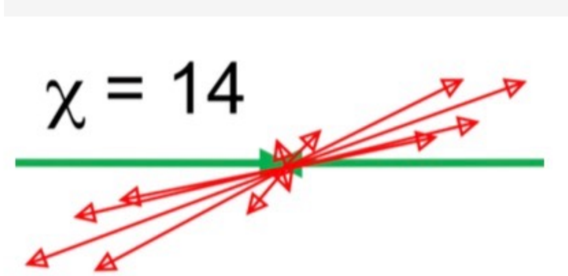
y_B $$\bar{y} = \frac{y_3+y_4}{2}, \quad y^* = \frac{y_3-y_4}{2}$$

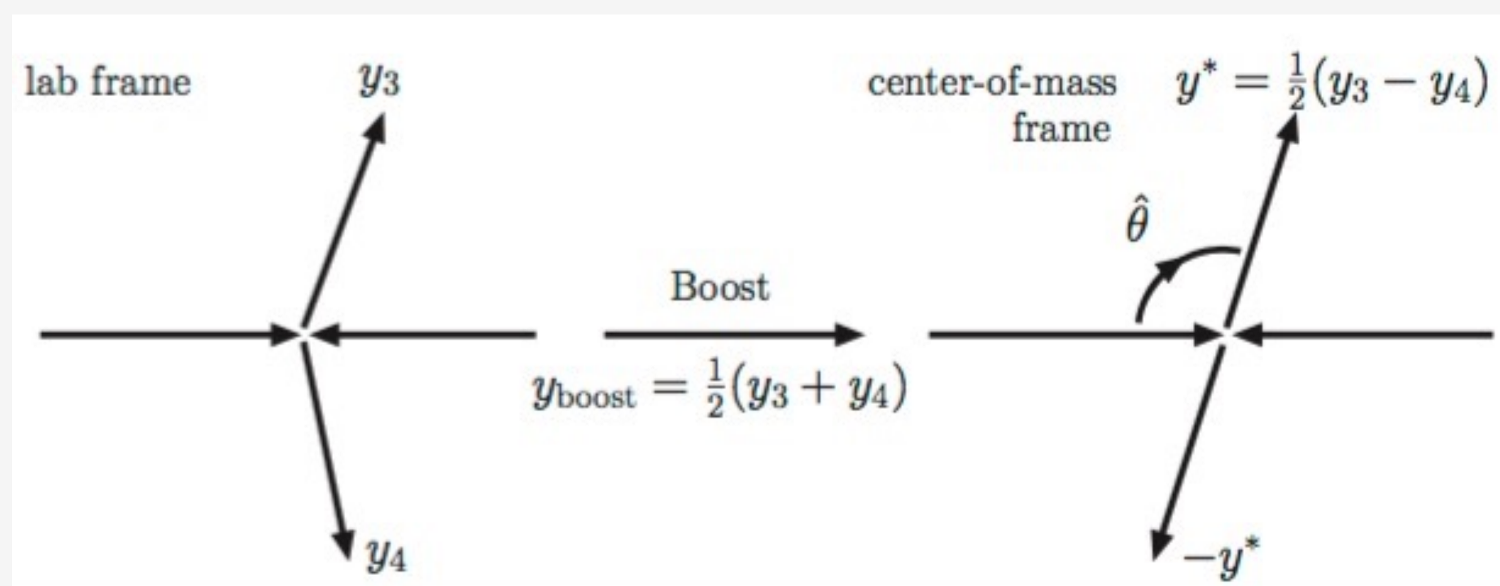


$$x_1 = \frac{2p_T}{\sqrt{s}}\cosh y^* e^{\bar{y}}, \quad x_2 = \frac{2p_T}{\sqrt{s}}\cosh y^* e^{-\bar{y}}$$

$$\chi = e^{2|y^*|}$$







QCD Matrix Elements for Dijet Processes

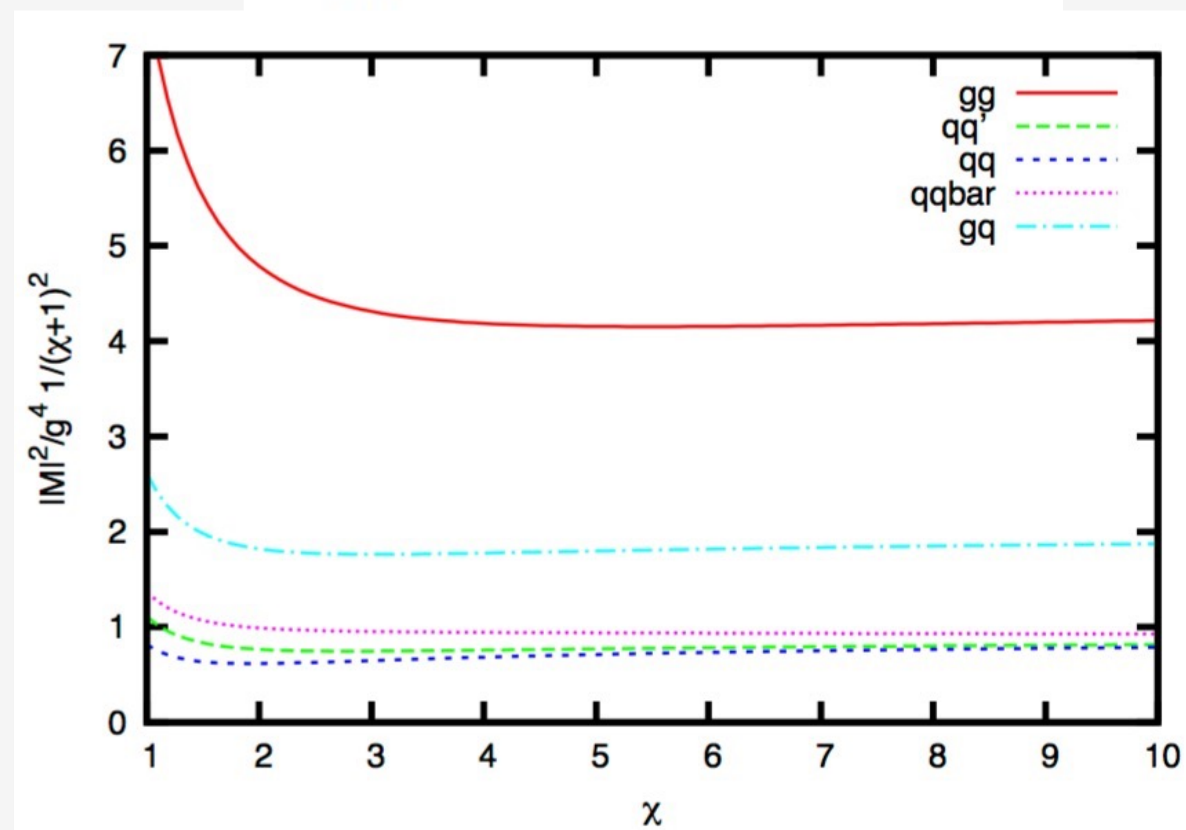
Subprocess	$\mathcal{S}(ij \to kl) = \frac{\hat{s}^2}{\pi \alpha_s^2} \frac{d\hat{\sigma}}{d\hat{t}}(ij \to kl)$
$q_1 q_2 \to q_1 q_2$	$\frac{4}{9} \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$q_1 \bar{q}_2 \to q_1 \bar{q}_2$	$\frac{4}{9} \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right) - \frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$
$q_1 \bar{q}_1 \to q_2 \bar{q}_2$	$\frac{4}{9} \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right) - \frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$gq \to gq$	$-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}} + \frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$
$gg \to gg$	$\frac{9}{2}\left(3 - \frac{\hat{t}\hat{u}}{\hat{s}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

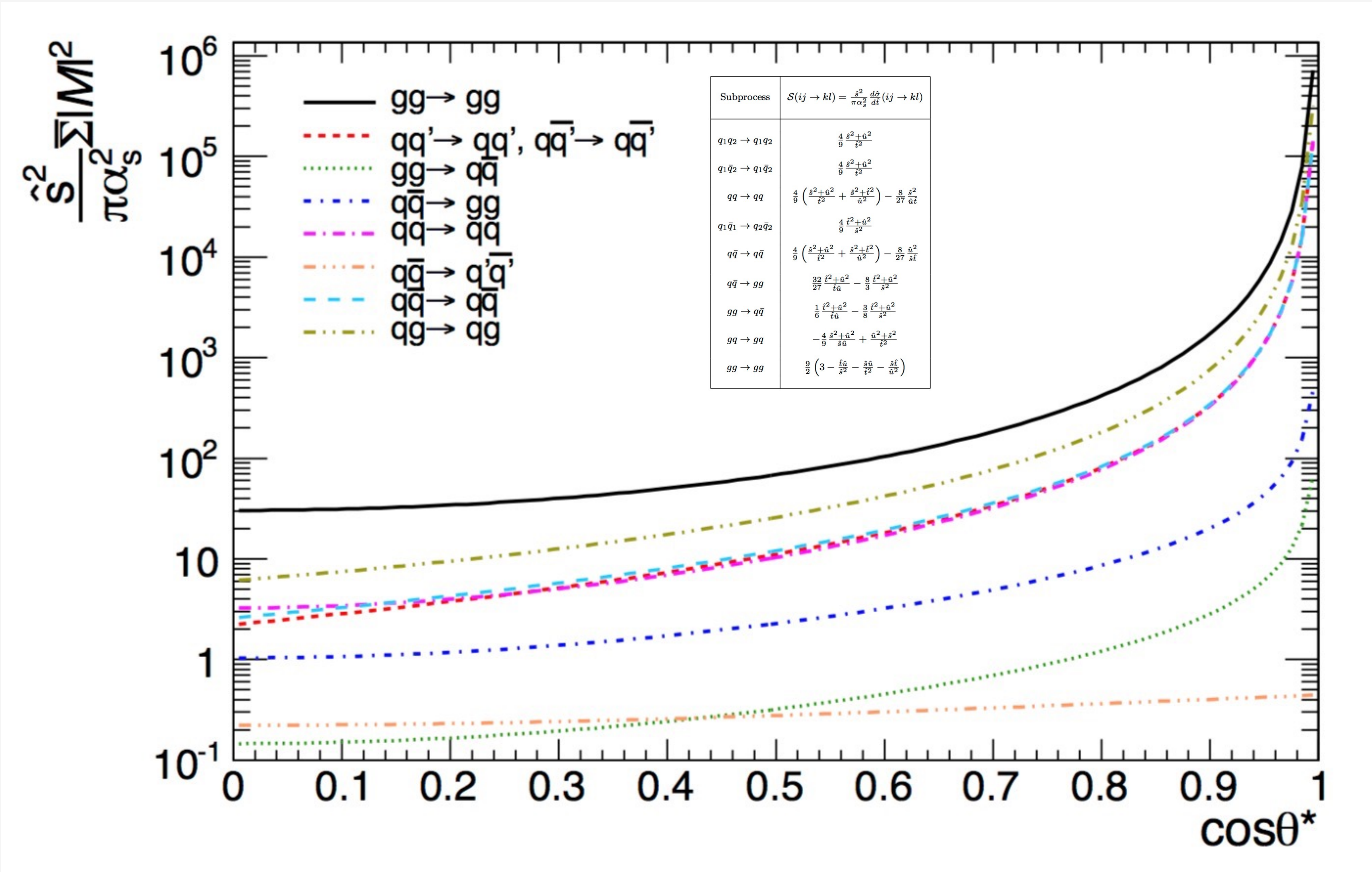
$$\frac{d\hat{\sigma}}{d\hat{t}} \propto \frac{\alpha_s^2}{\hat{t}^2}$$

$$\chi = \frac{1+|\cos\hat{\theta}|}{1-|\cos\hat{\theta}|} \sim \frac{1}{1-|\cos\hat{\theta}|} \propto \frac{\hat{s}}{\hat{t}}$$

$$\hat{t} \to 0, \qquad \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} \approx \frac{\hat{s}^2}{\hat{t}^2}$$

$$\frac{d\hat{\sigma}}{d\chi} \propto \frac{\alpha_s^2}{\hat{s}} \quad (\hat{s}\ \text{fixed})$$

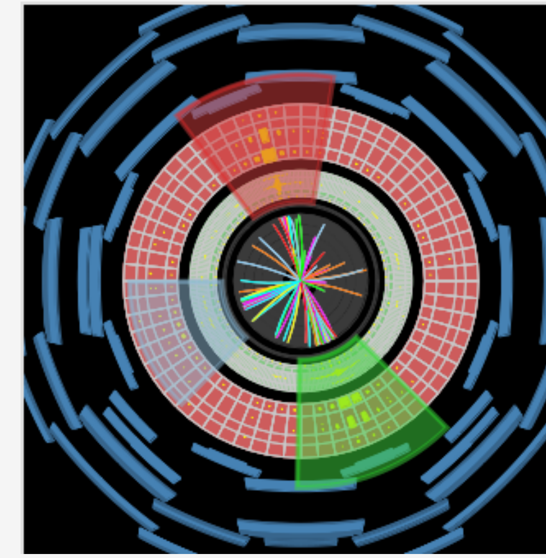


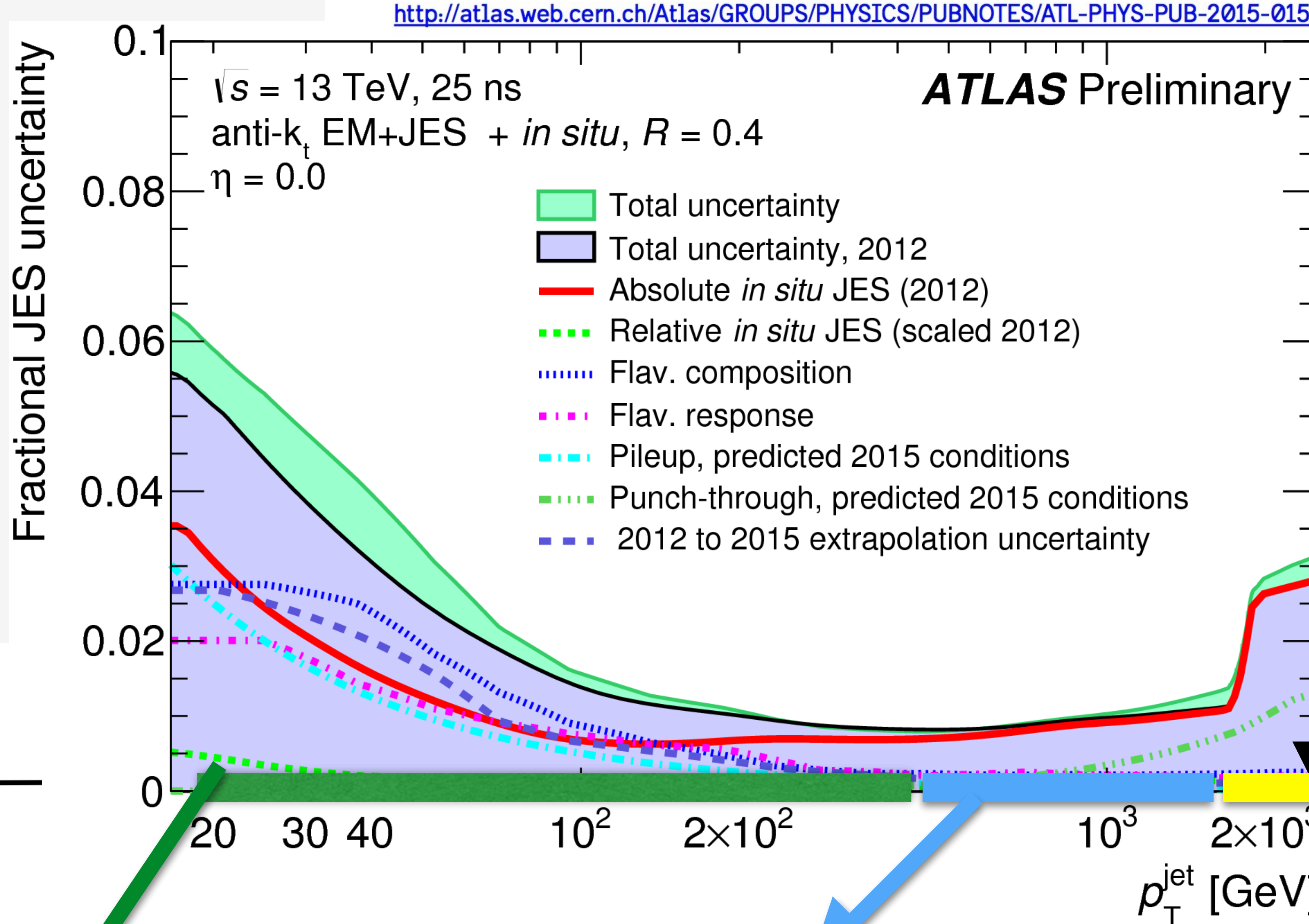


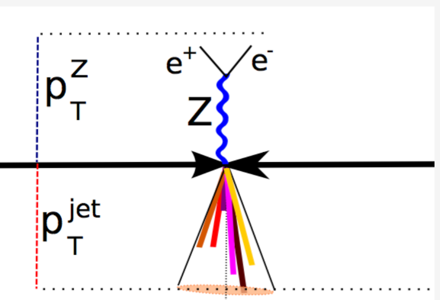
Subprocess	$\mathcal{S}(ij \to kl) = \frac{\hat{s}^2}{\pi\alpha_s^2}\frac{d\hat{\sigma}}{d\hat{t}}(ij \to kl)$
$q_1q_2 \to q_1q_2$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$q_1\bar{q}_2 \to q_1\bar{q}_2$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$
$q_1\bar{q}_1 \to q_2\bar{q}_2$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$gq \to gq$	$-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$
$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

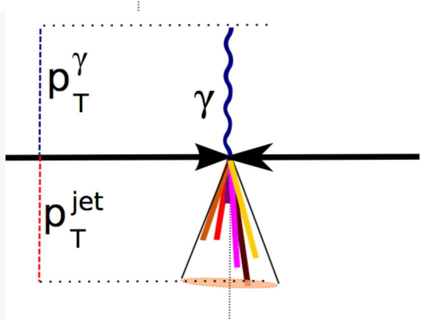
Jet calibration and uncertainty

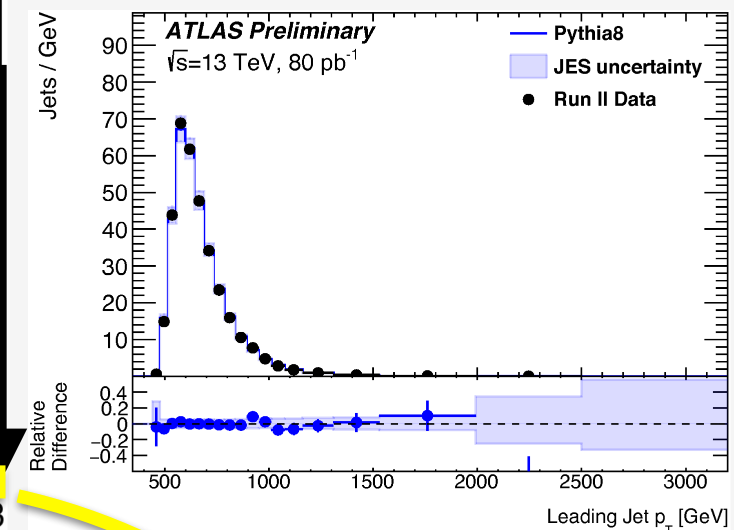
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2015-015/



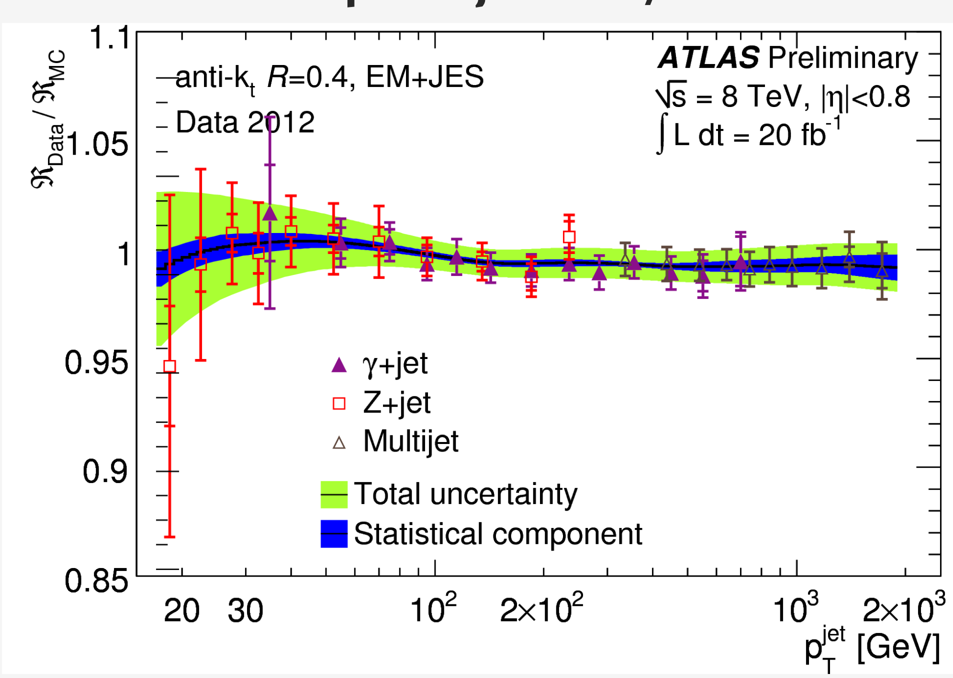




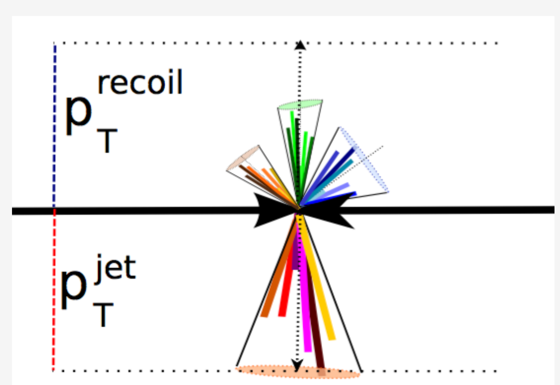




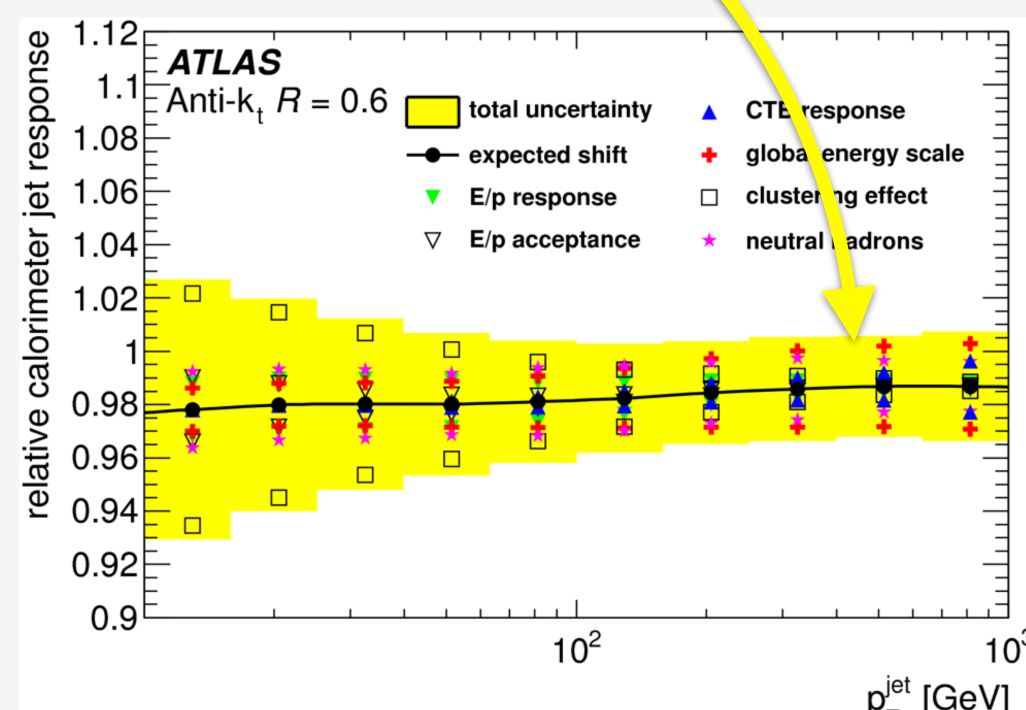
Well-calibrated object vs probe jet: data/MC



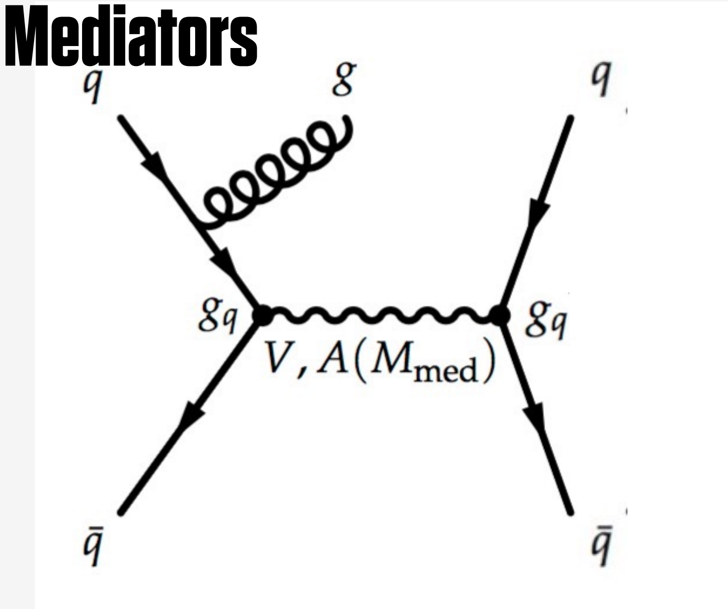
Balance of high-pT jet with calibrated low-pT recoil system



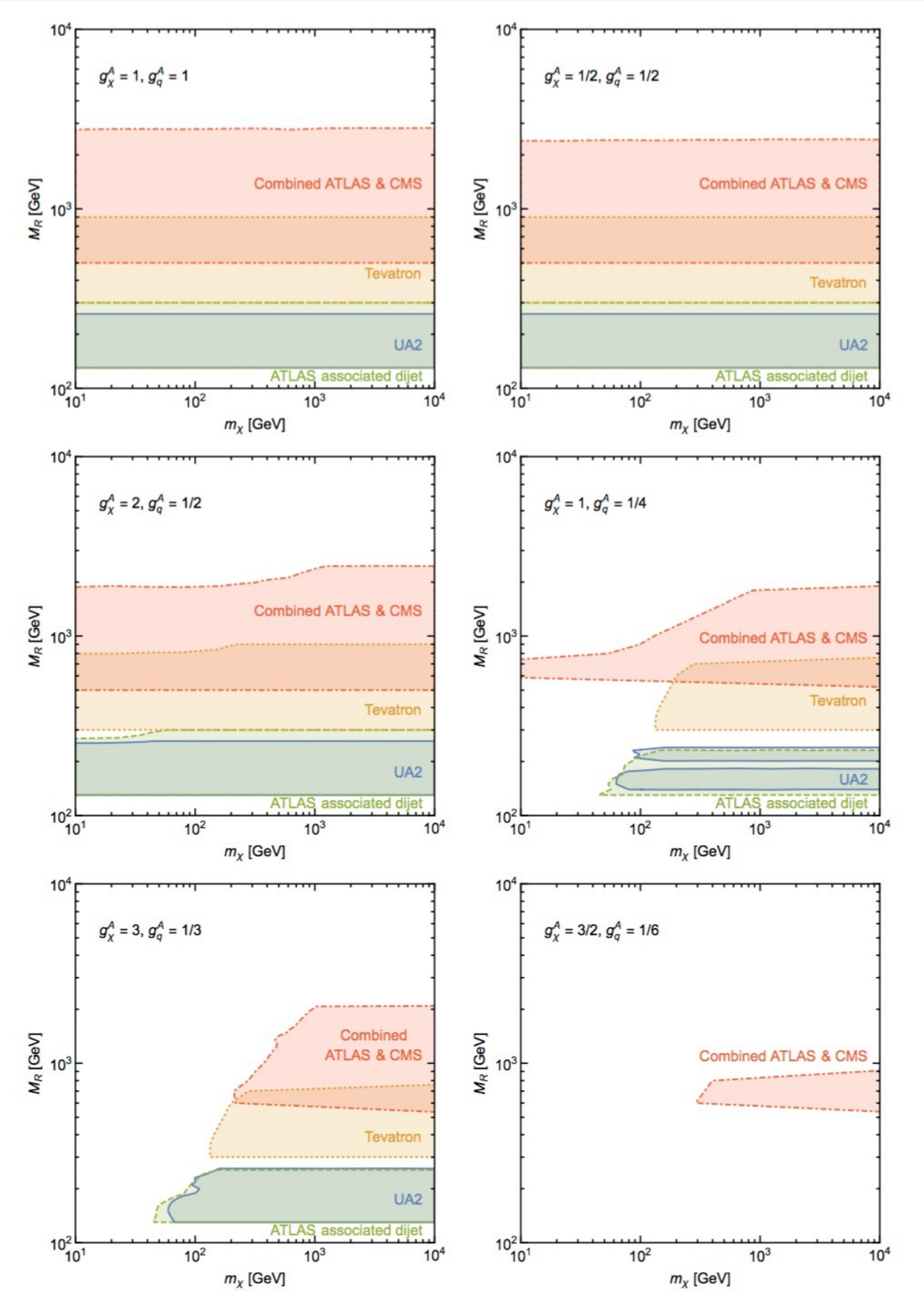
Propagation of single particle uncertainties to jets



Benefits of ATLAS/CMS Agreement on Models: Dijet Implications for SM-DM Mediators

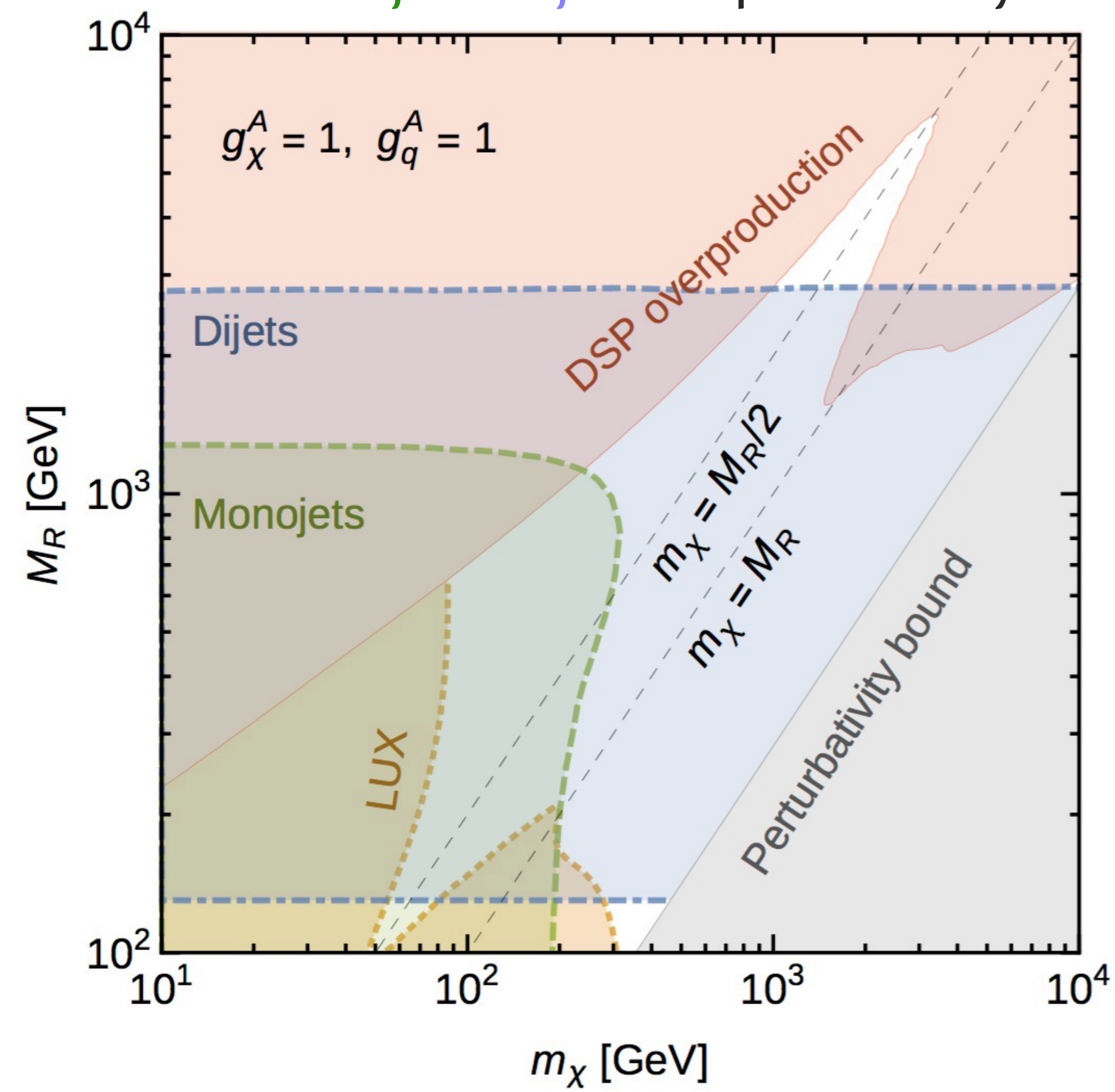


Axial-Vector Z′ Mass

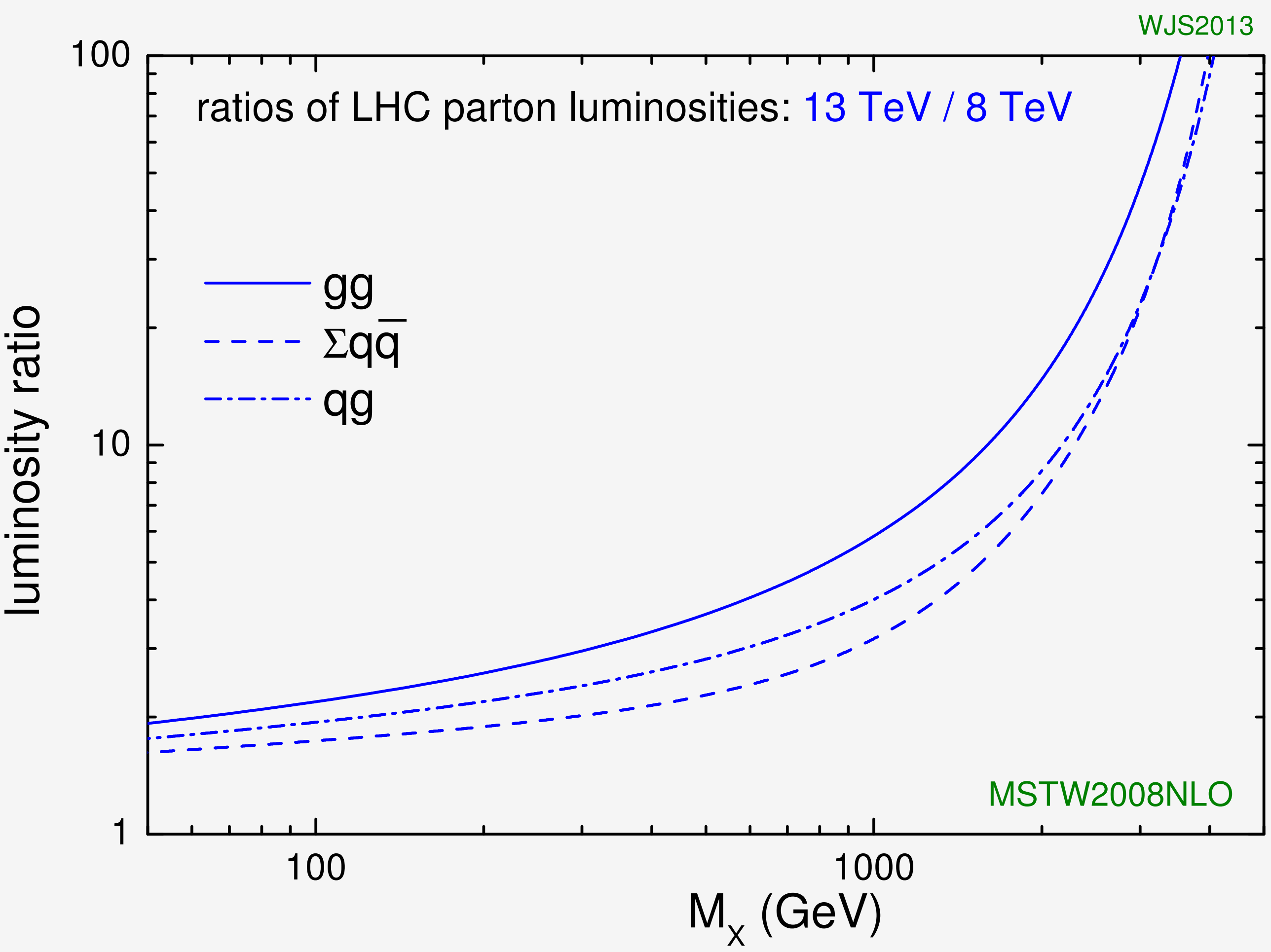


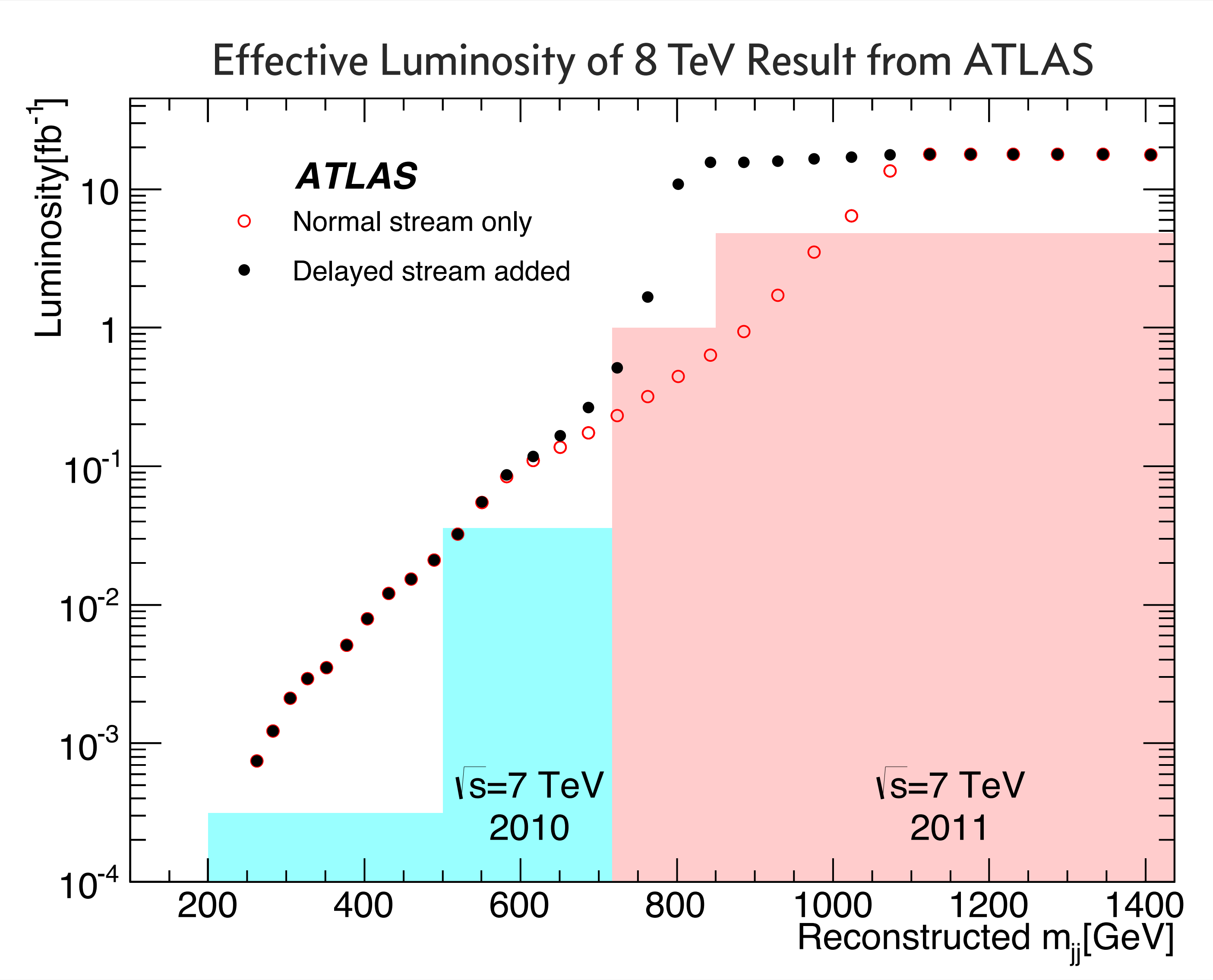
DM Mass

Mono-jet + Dijet Complementarity



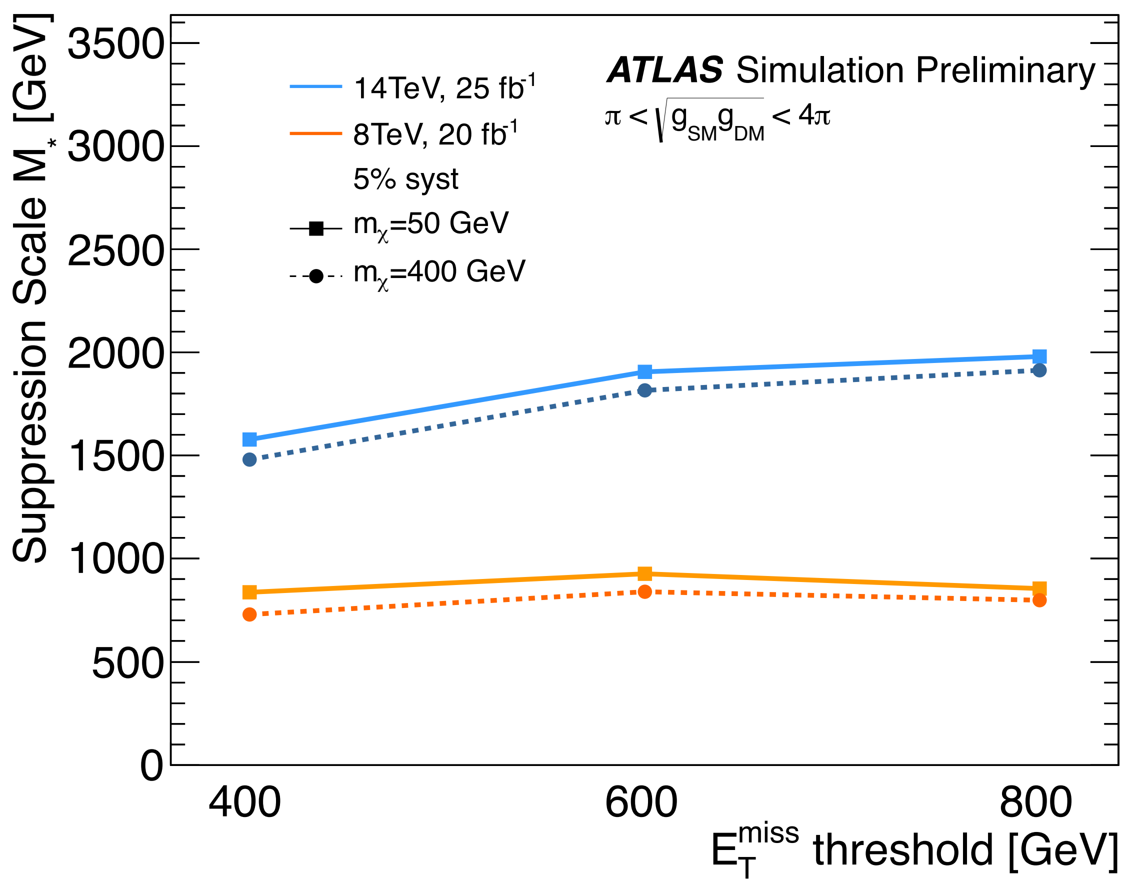
Light Resonances at 13 TeV

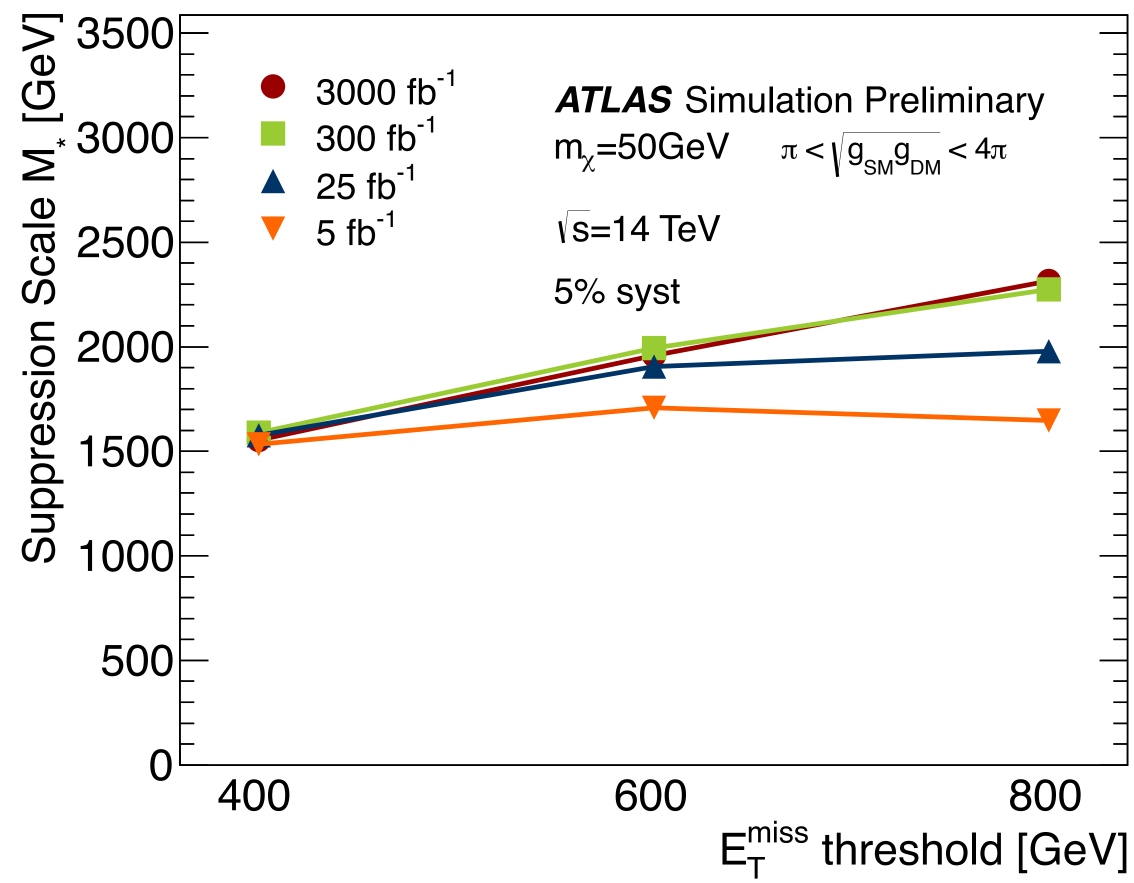


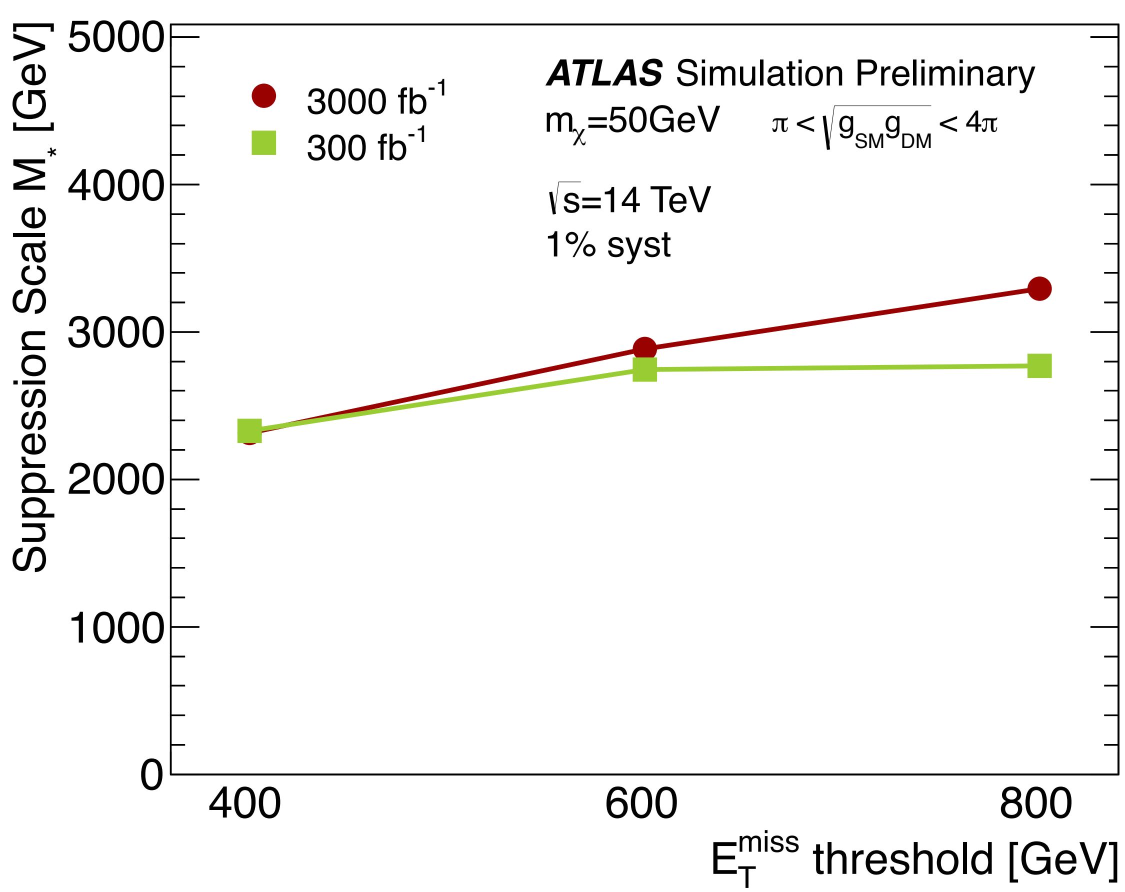


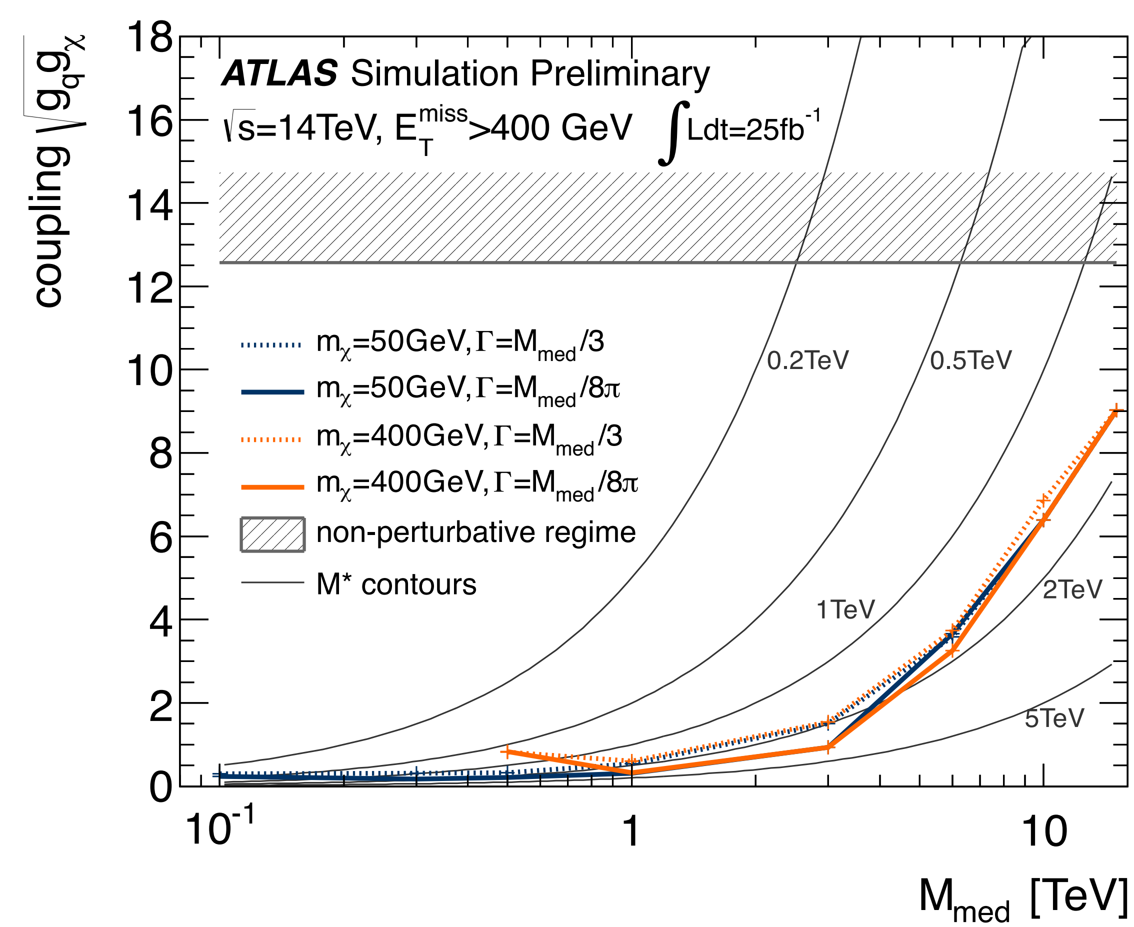
Early Mono-jet Sensitivity Projections (14 TeV)

ATL-PHYS-PUB-2014-007









Run 1 equivalent roughly follows the 1 TeV contour

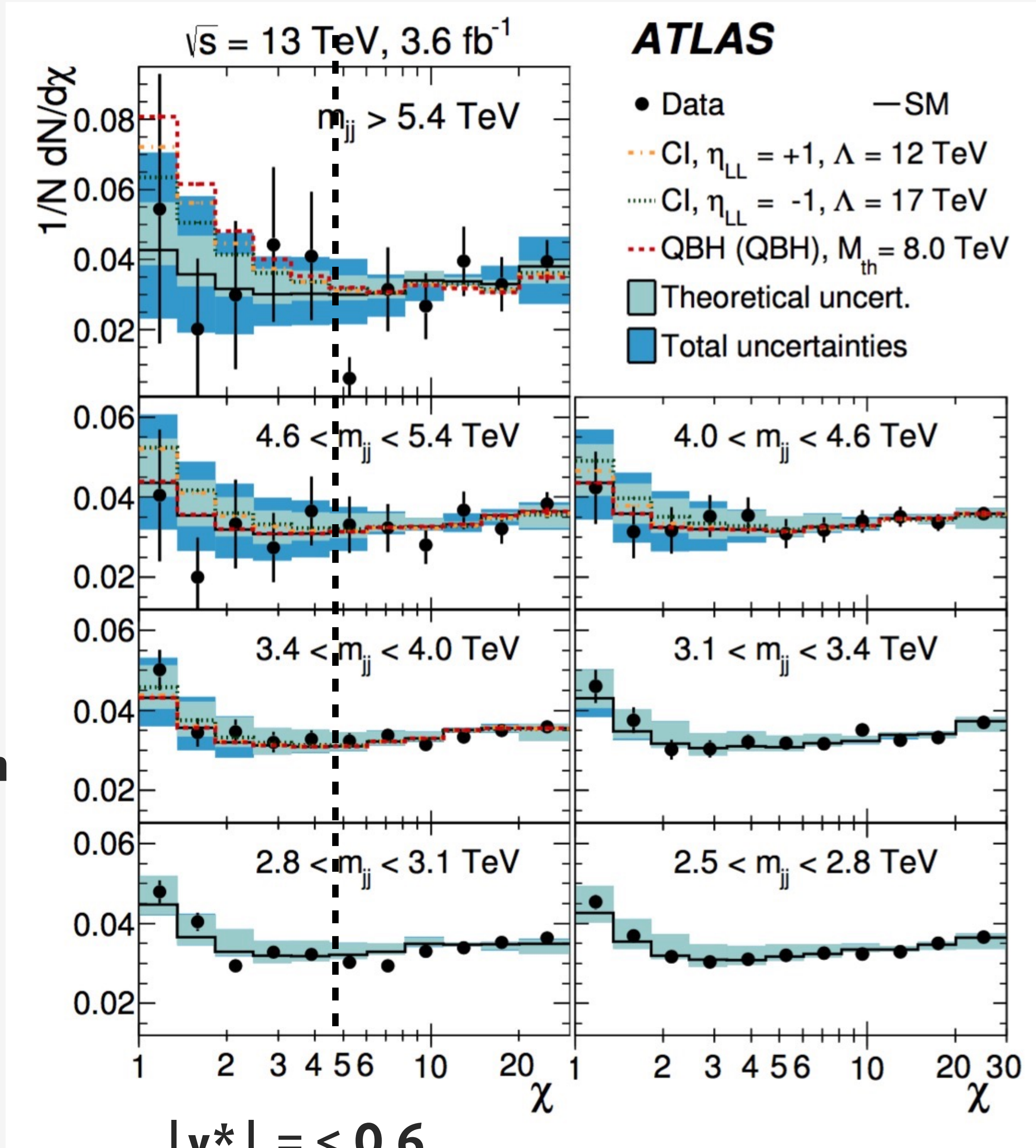
ATLAS Dijets Searches at 13 TeV

Physics Letters B 754 (2016) 302–322

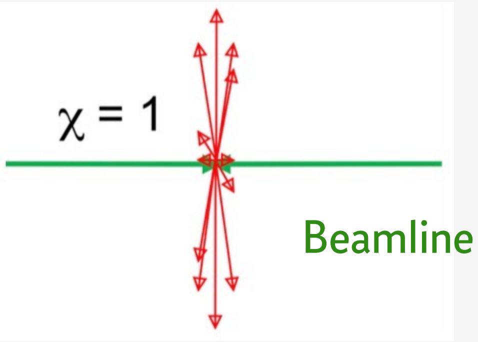
Jet p_T > 440, 50 GeV
$|y^*| = |y_1 - y_2|/2 < 1.7$
$|y_B| = |y_1 + y_2|/2 < 1.1$
m_{jj} > 2.5 TeV

Shape comparison uses **high y* region to confirm and normalize background prediction** with forward-peaking t-channel QCD processes

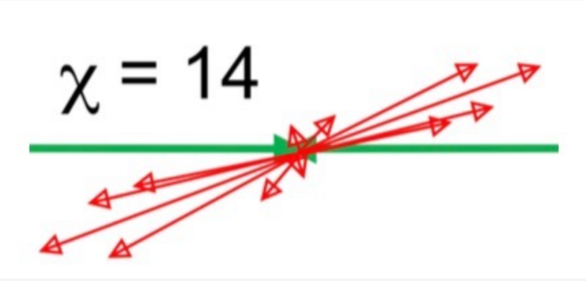
"Non-resonant" analysis



$|y^*|$ = < 0.6



Signal



Background-dominated

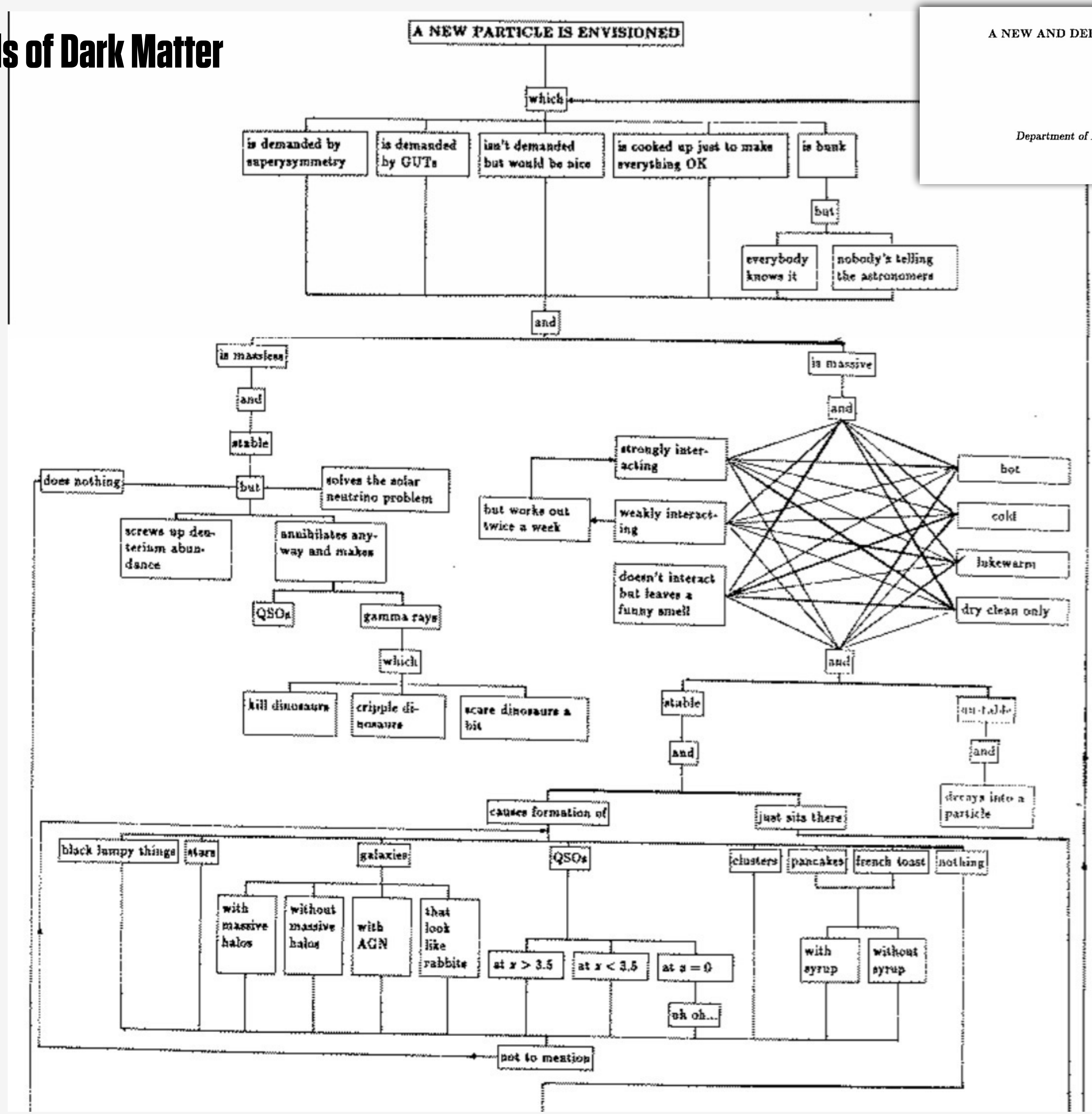
Background shape from NLOJet++ / Pythia 8 with electroweak corrections

$$k(\chi, m_{jj}) = \frac{\sigma_{\mathrm{NLO}}(\chi, m_{jj})^{\mathrm{NLOJET++}}}{\sigma_{\mathrm{LO+shower}}(\chi, m_{jj})^{\mathrm{Pythia\ 8}}}$$

At high mass, low chi:
NLO: up to 15%
EW: up to 3%

chi^2 probability. 0.35

Models of Dark Matter

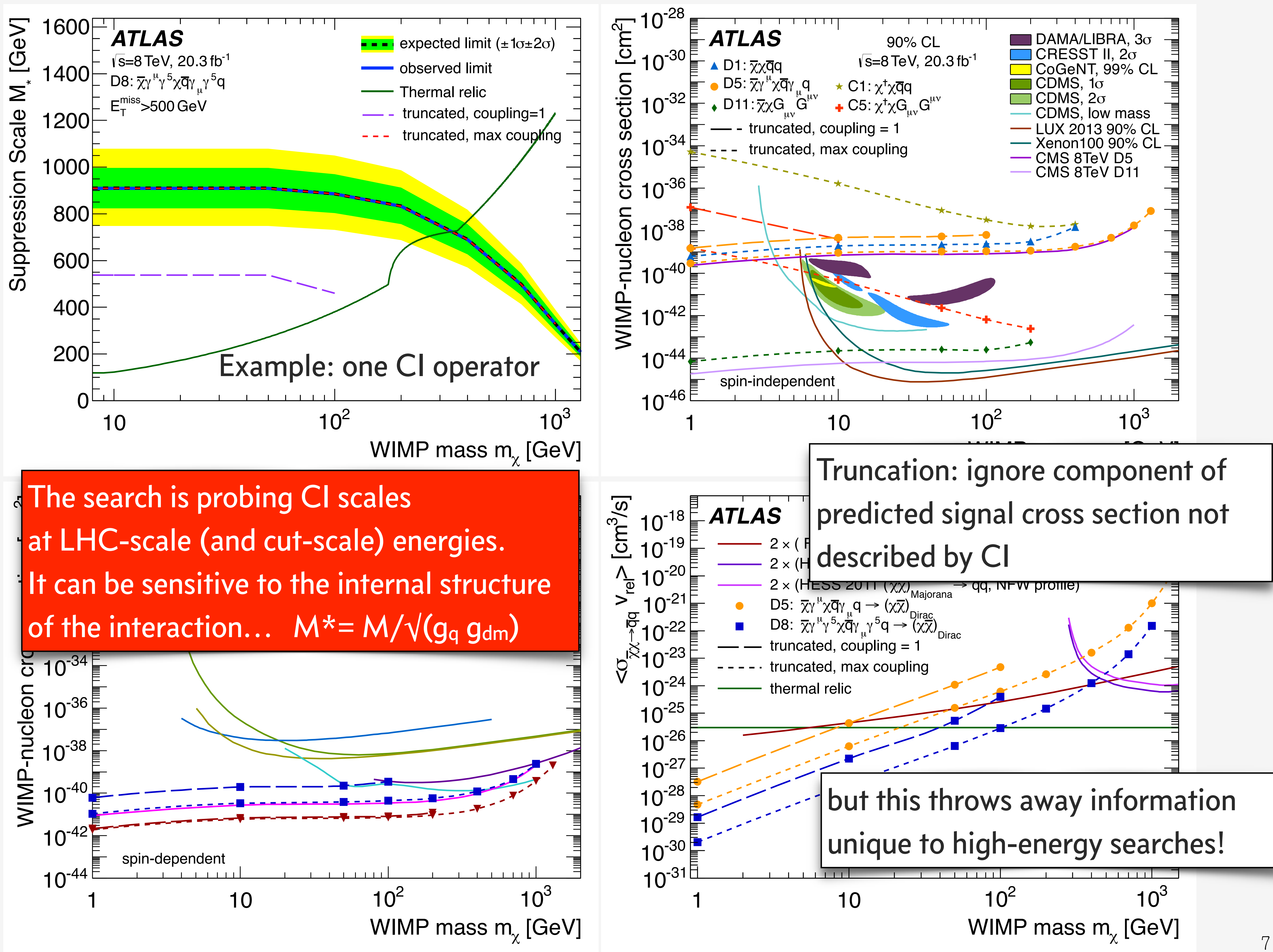


A NEW AND DEFINITIVE META-COSMOLOGY THEORY

T. R. Lauer
T. S. Statler
B. S. Ryden
D. H. Weinberg

Department of Astrophysical Sciences, Princeton University

8 TeV Mono-jet Result: Connecting EFT limits to Non-collider WIMP Searches

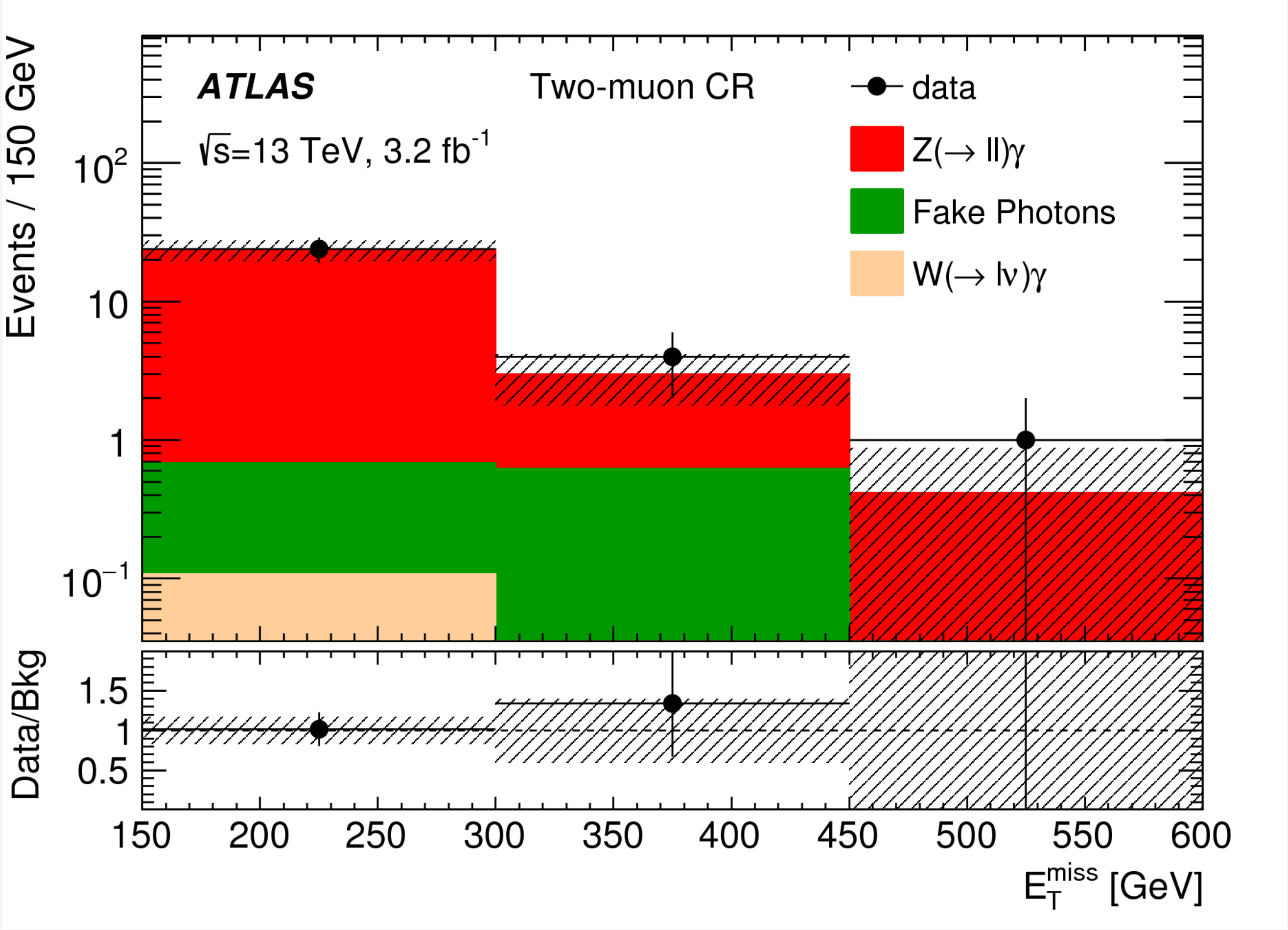


The search is probing CI scales at LHC-scale (and cut-scale) energies. It can be sensitive to the internal structure of the interaction… $M^* = M/\sqrt{(g_q\, g_{dm})}$

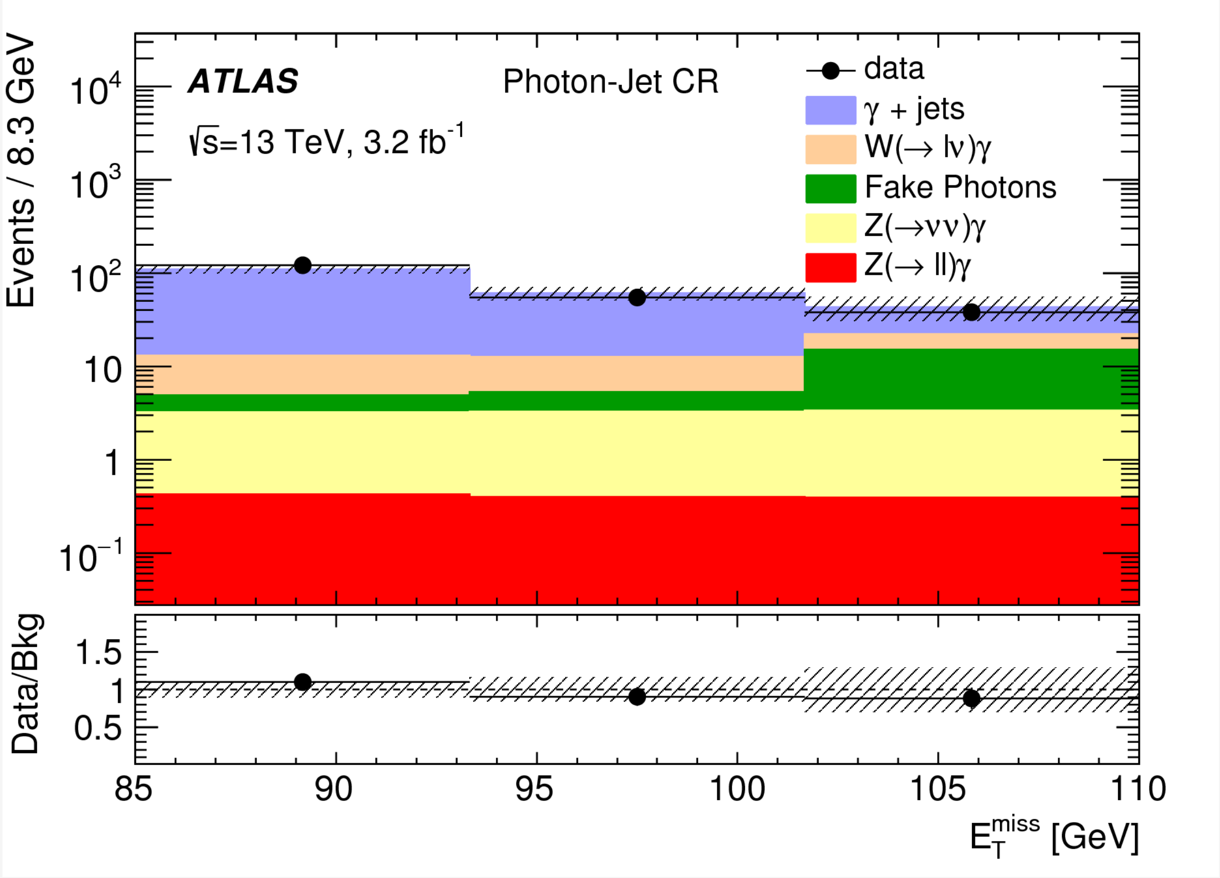
Truncation: ignore component of predicted signal cross section not described by CI

but this throws away information unique to high-energy searches!

Mono-photon



ATLAS
Two-muon CR
√s=13 TeV, 3.2 fb-1
data
Z(→ ll)γ
Fake Photons
W(→ lν)γ
Events / 150 GeV
Data/Bkg
E_T^miss [GeV]



ATLAS
Photon-Jet CR
√s=13 TeV, 3.2 fb-1
data
γ + jets
W(→ lν)γ
Fake Photons
Z(→νν)γ
Z(→ ll)γ
Events / 8.3 GeV
Data/Bkg
E_T^miss [GeV]