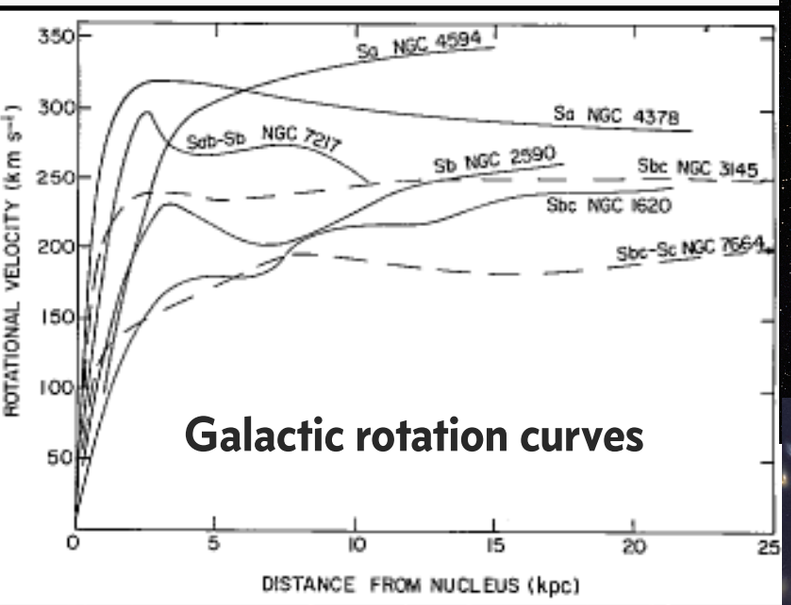
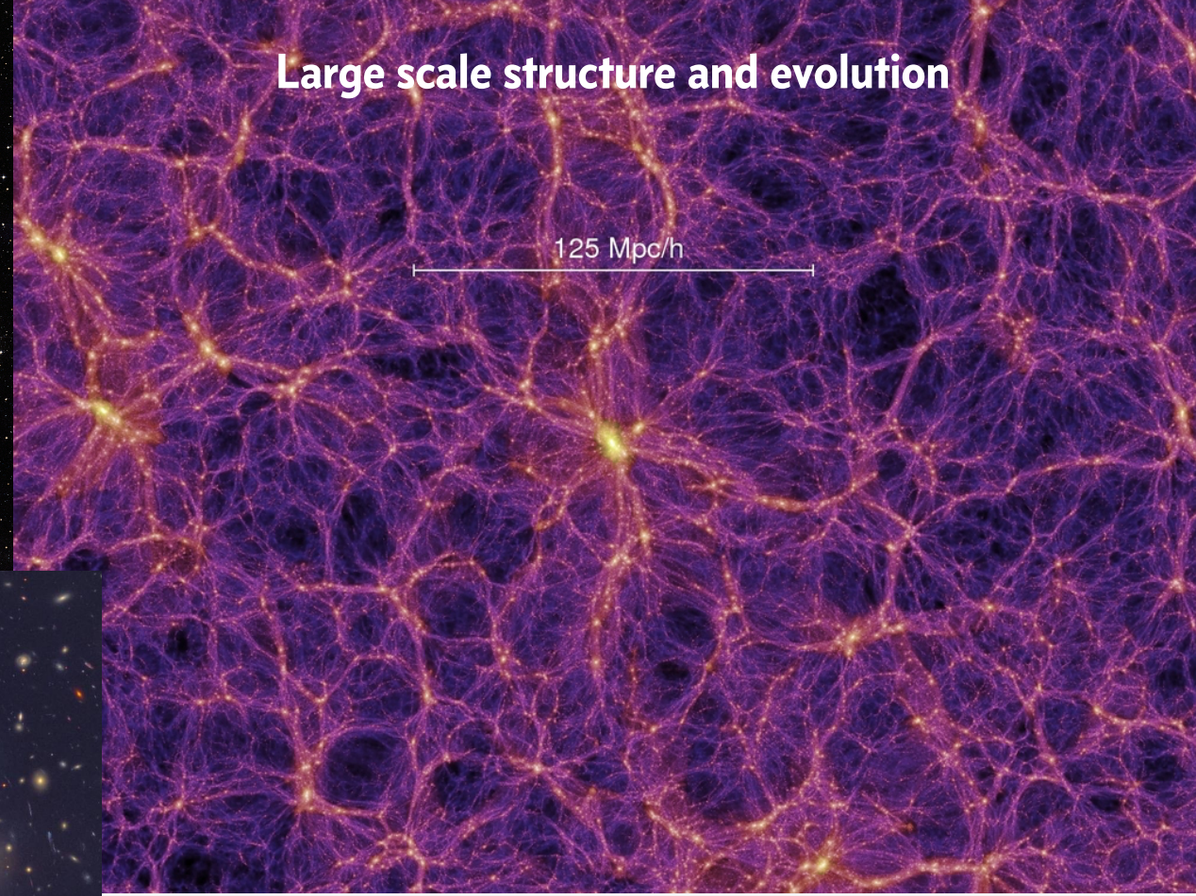
Dark Matter Searches at the LHC

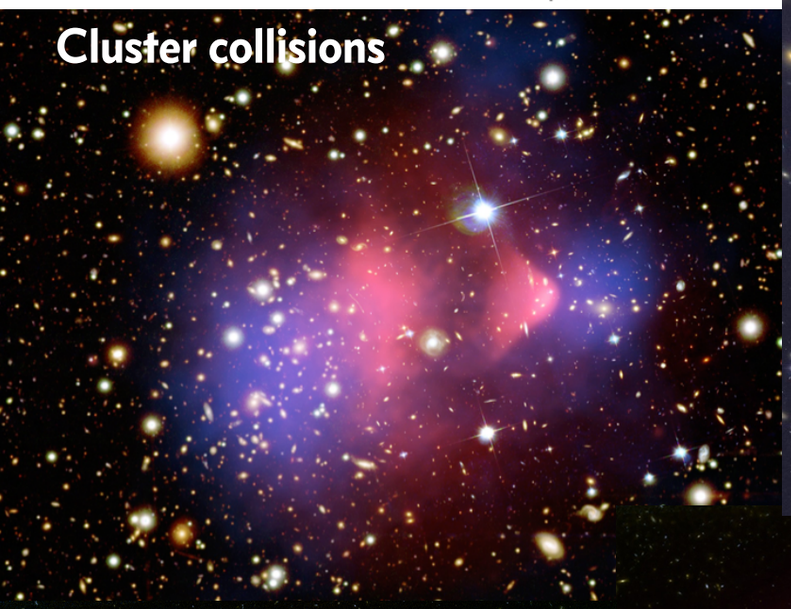
Antonio Boveia (Ohio State University)

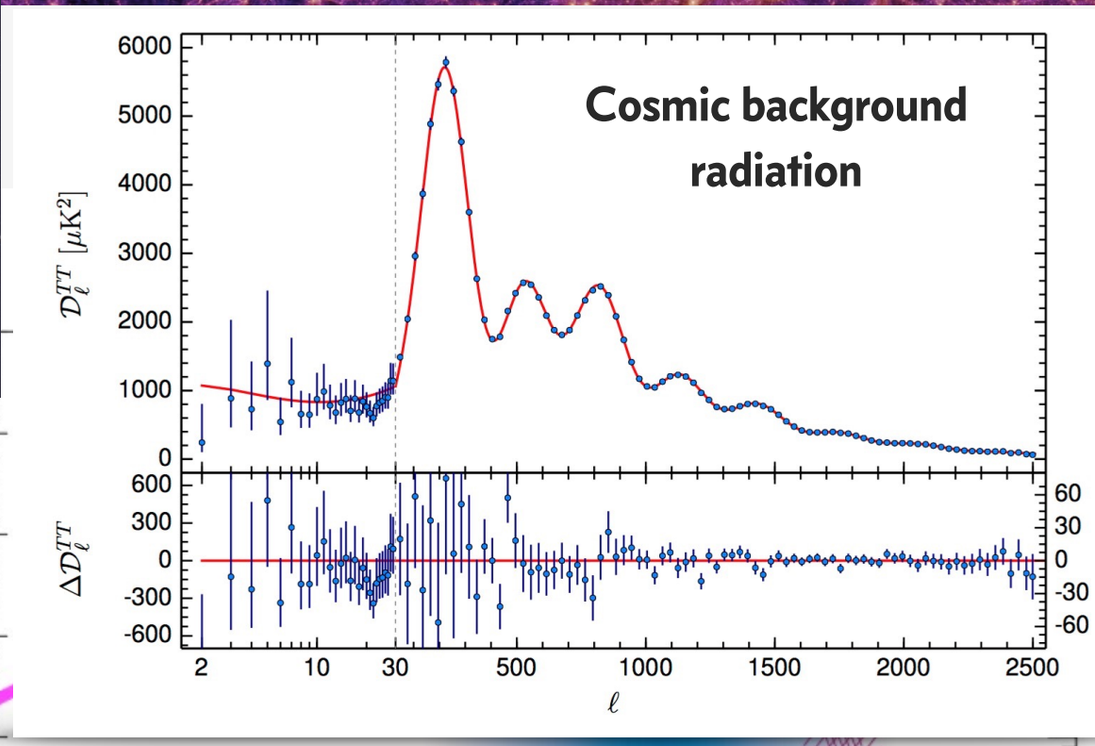
(my personal view)

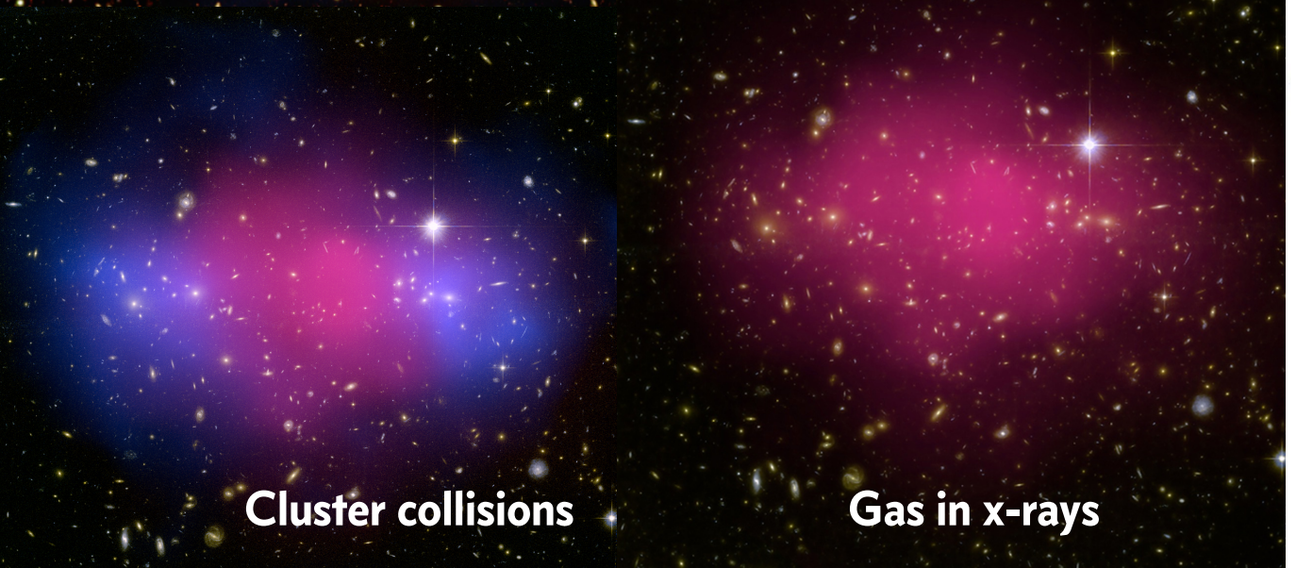
Experimental Evidence

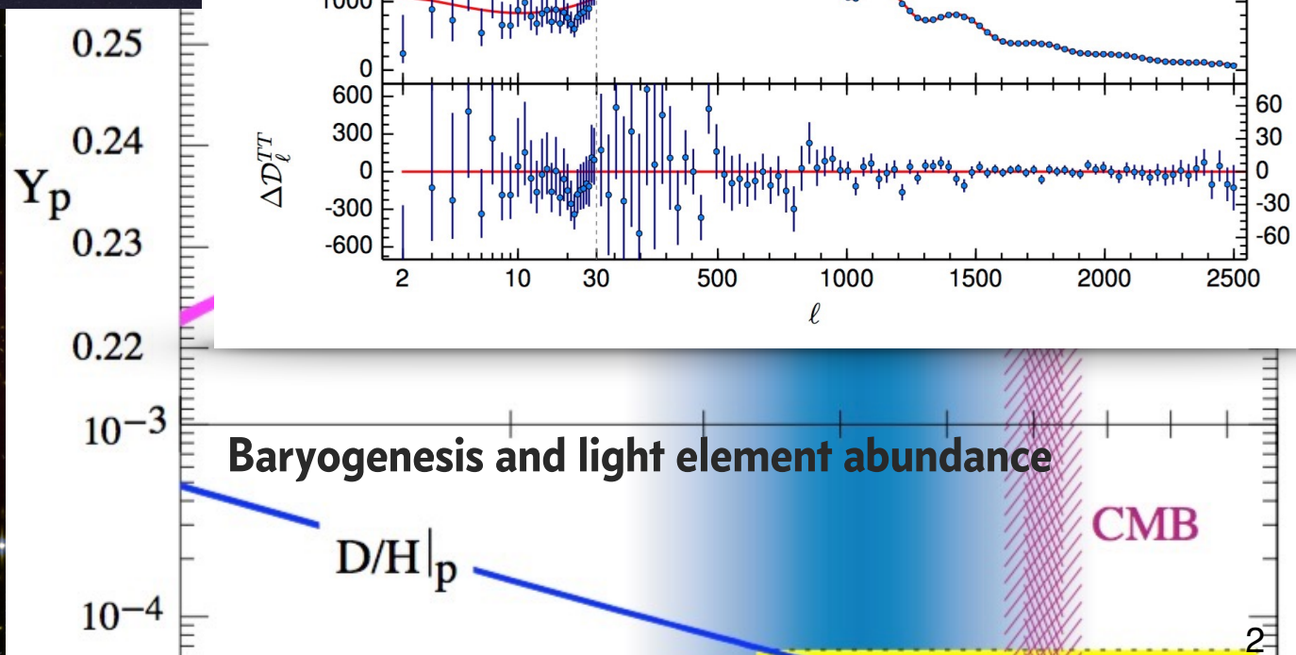




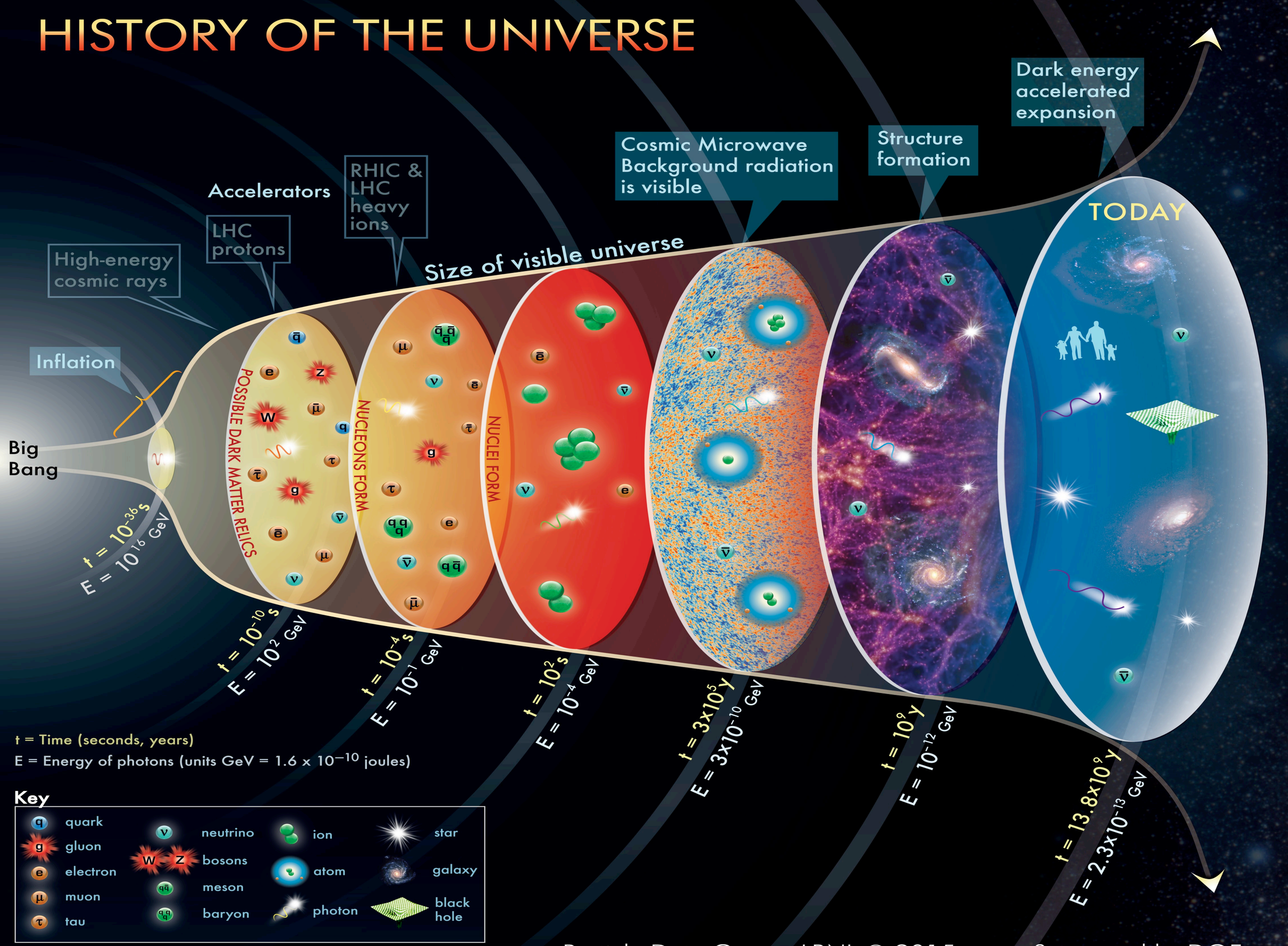








HISTORY OF THE UNIVERSE



The concept for the above figure originated in a 1986 paper by Michael Turner.

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HISTORY OF THE UNIVERSE

Dark energy accelerated expansion

Cosmic Microwave Background radiation is visible

Structure formation

Accelerators

RHIC & LHC heavy ions

LHC protons

High-energy cosmic rays

Size of visible universe

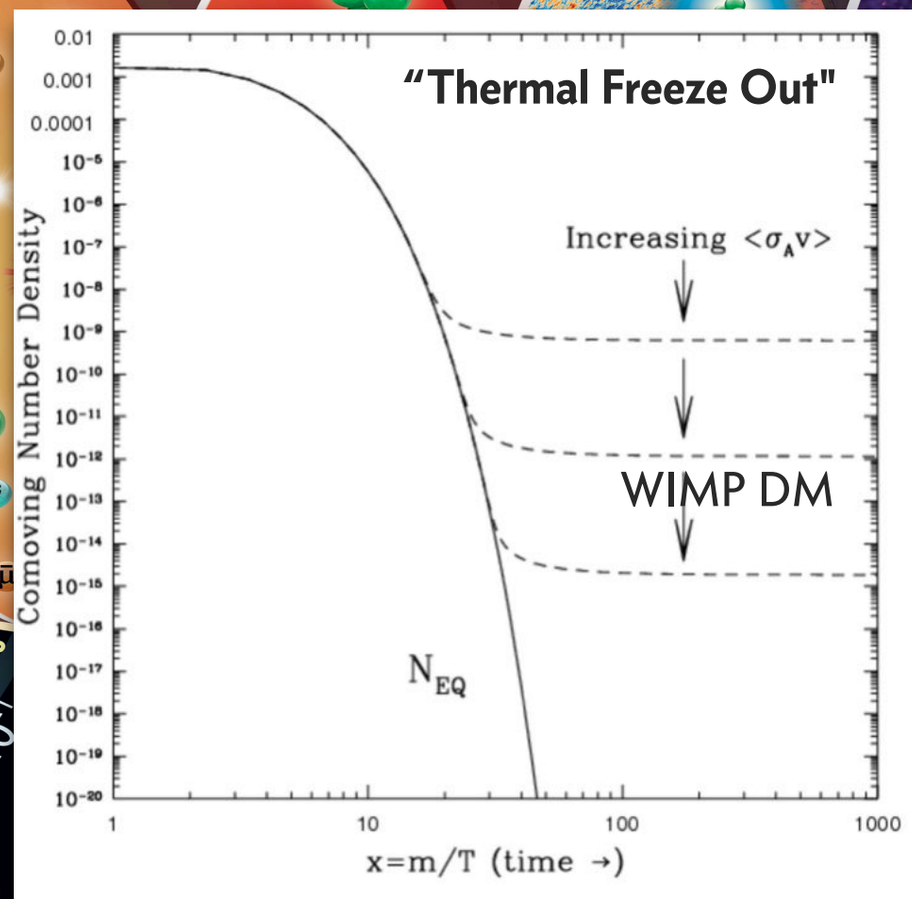
TODAY

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

$t = 10^{-4}$ s
$E = 10^{-1}$

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

Key

q	quark	ν	neutrino		ion		star
g	gluon	W Z	bosons		atom		galaxy
e	electron	qq̄	meson		photon		black hole
μ	muon	q q q	baryon				
τ	tau						

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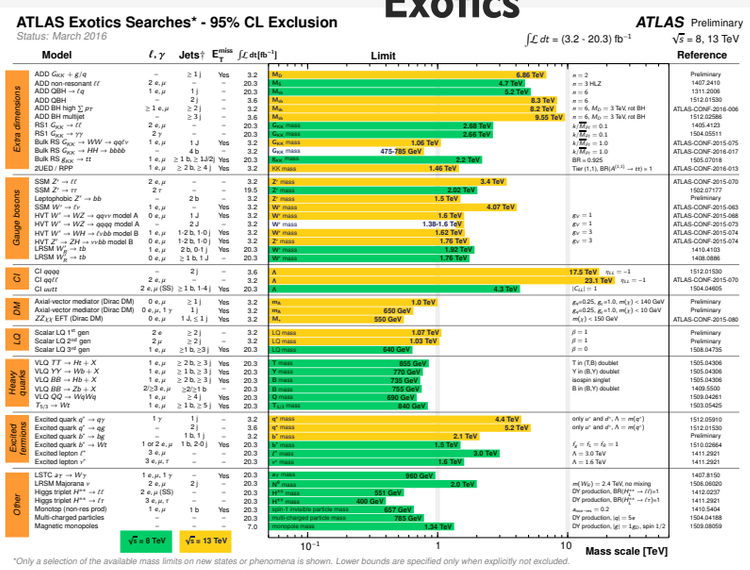
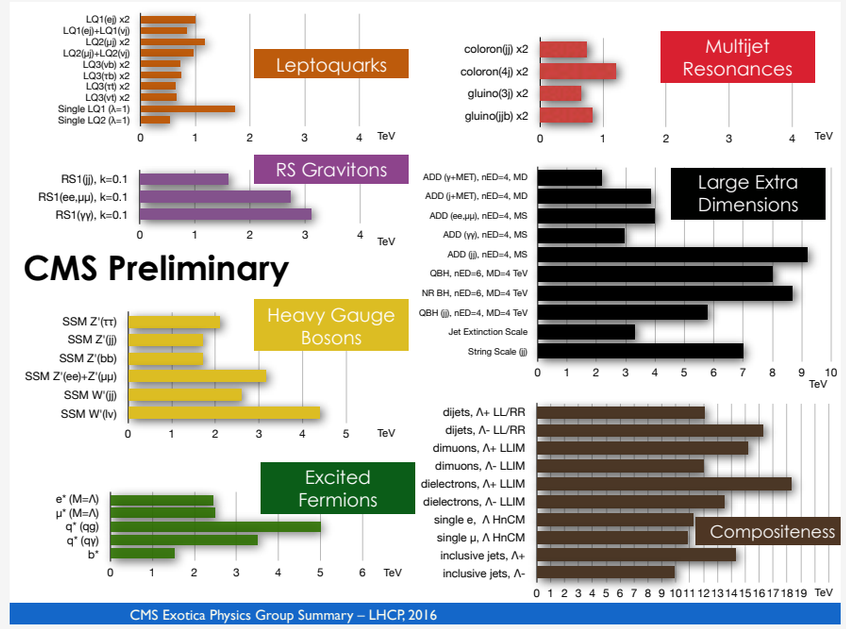
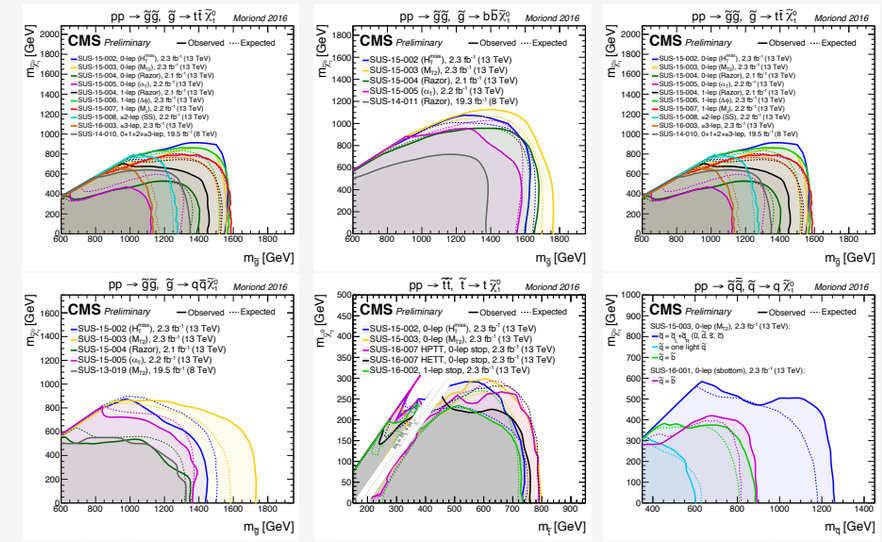
Searches for New Physics

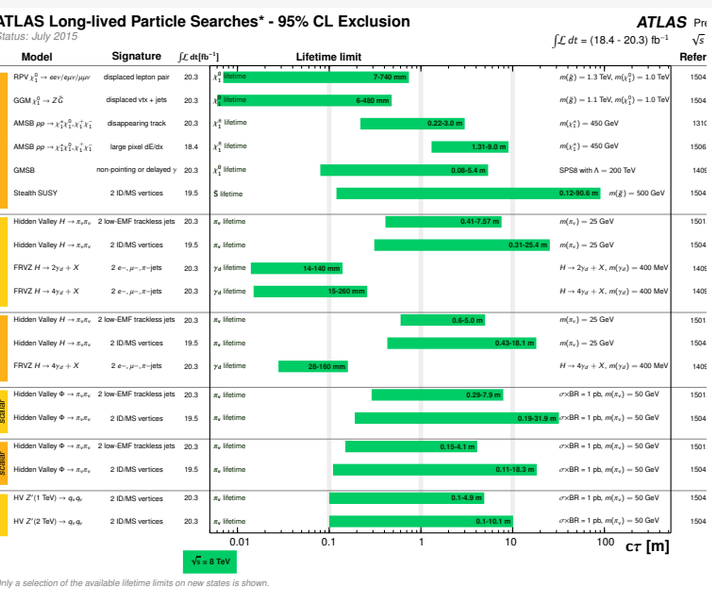
Exotics

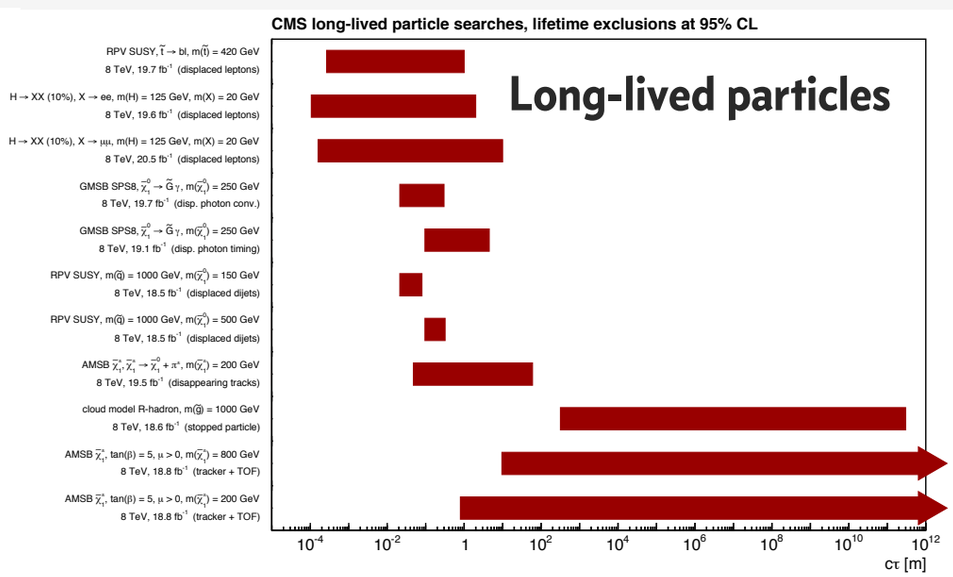


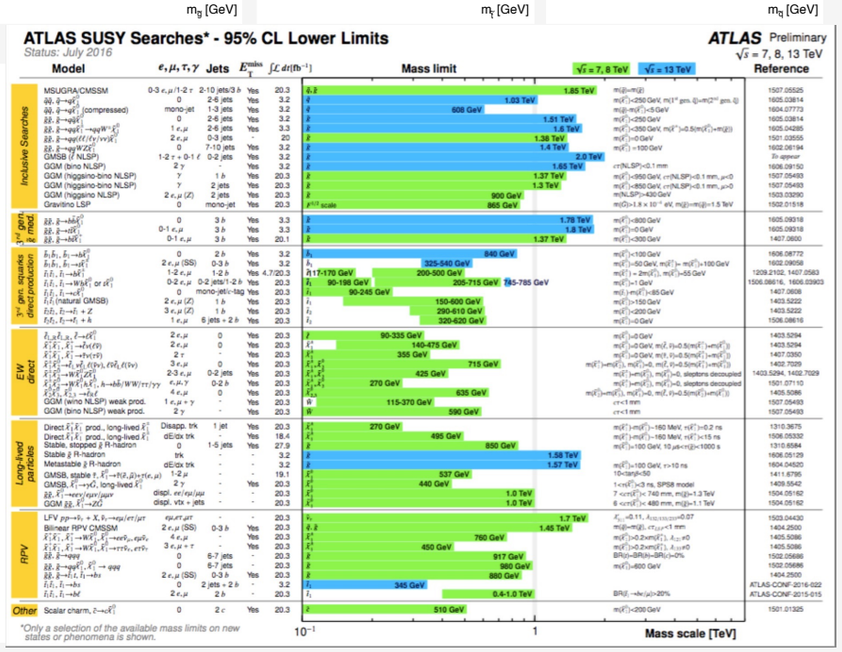


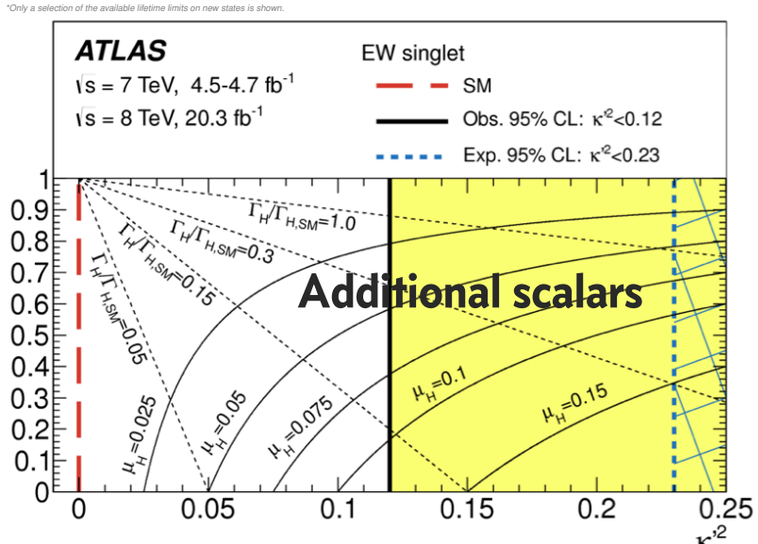
SUSY











ATLAS Summary Plots

CMS Summary Plots

Properties of dark matter

Interacts gravitationally

Properties of dark matter

Interacts gravitationally

Dark, cosmologically stable

(other effective couplings to SM are zero or small)

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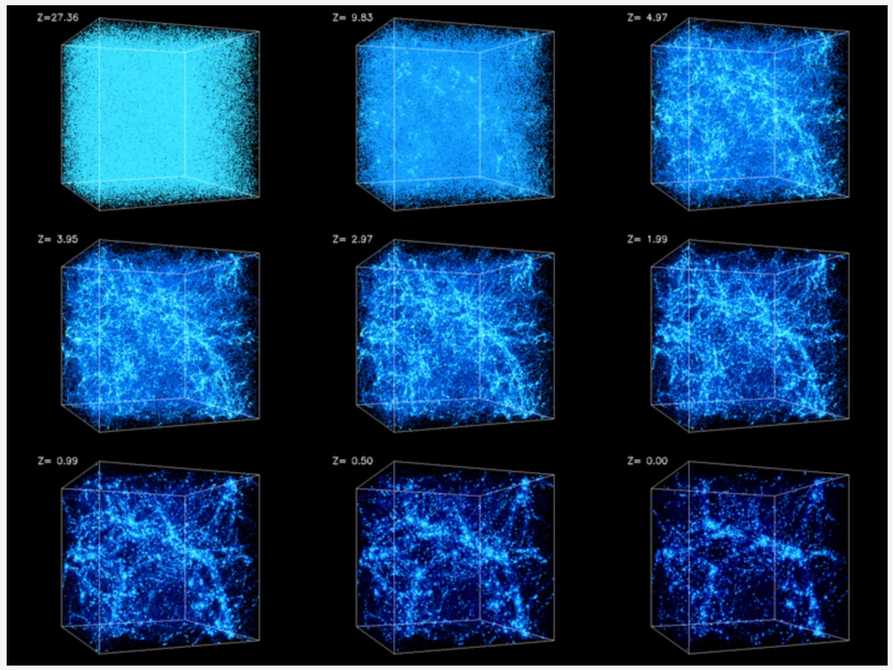


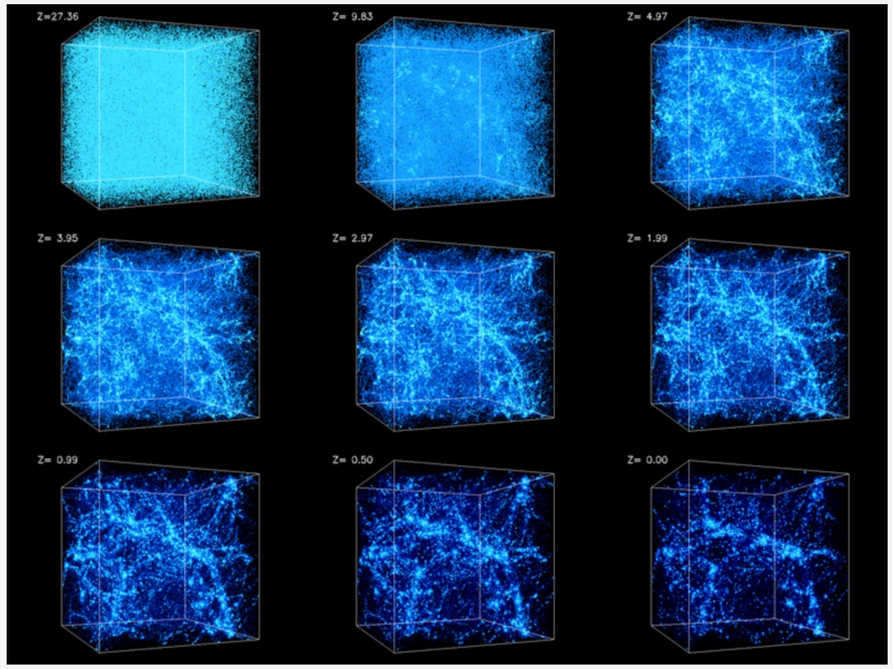
Approximately Cold / non-relativistic

Properties of dark matter

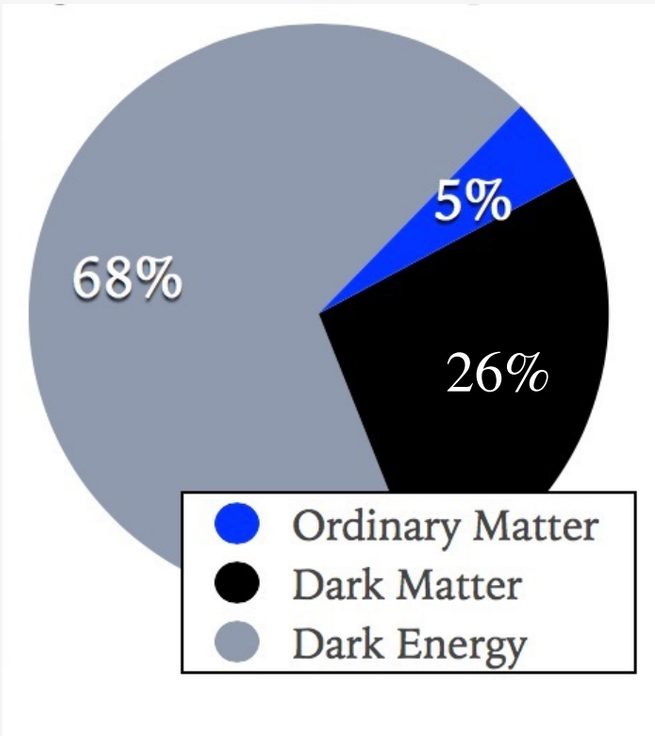
Interacts gravitationally

Dark, cosmologically stable

(other effective couplings to SM are zero or small)



Approximately Cold / non-relativistic

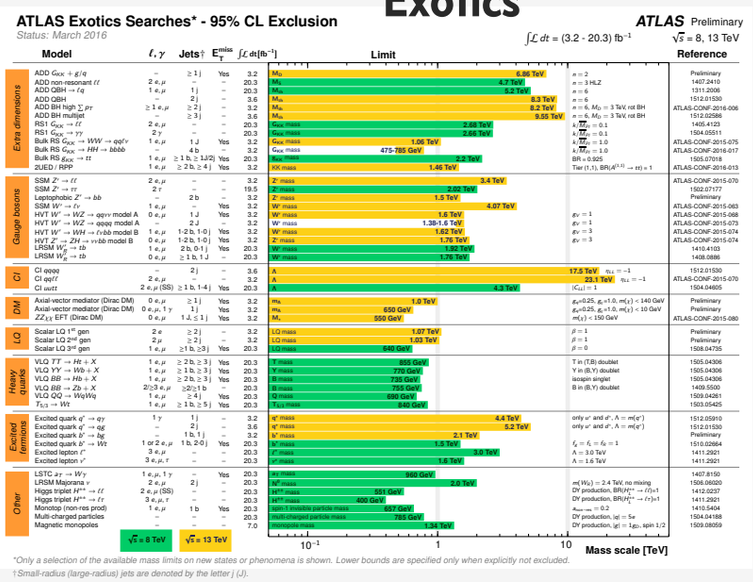


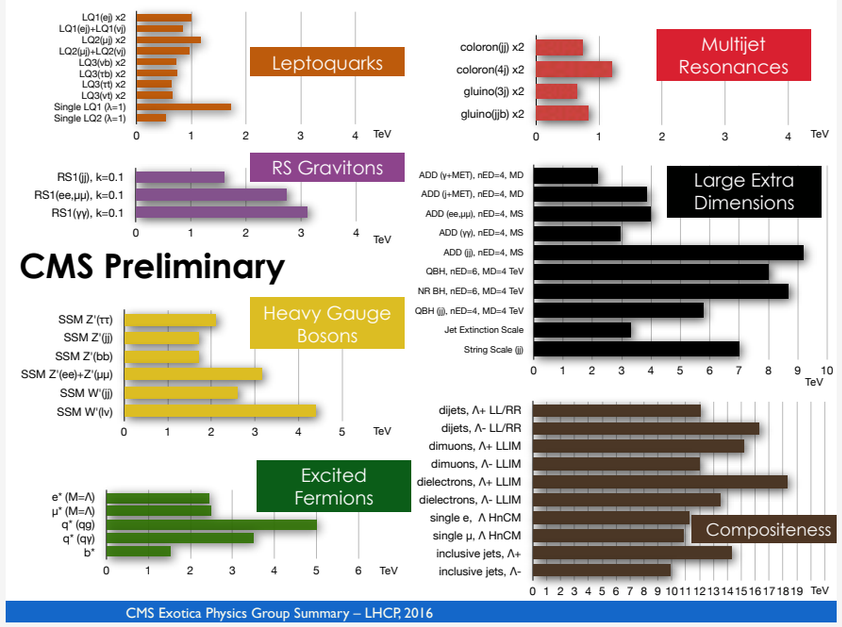
5x as much DM as SM

Searches for New Physics

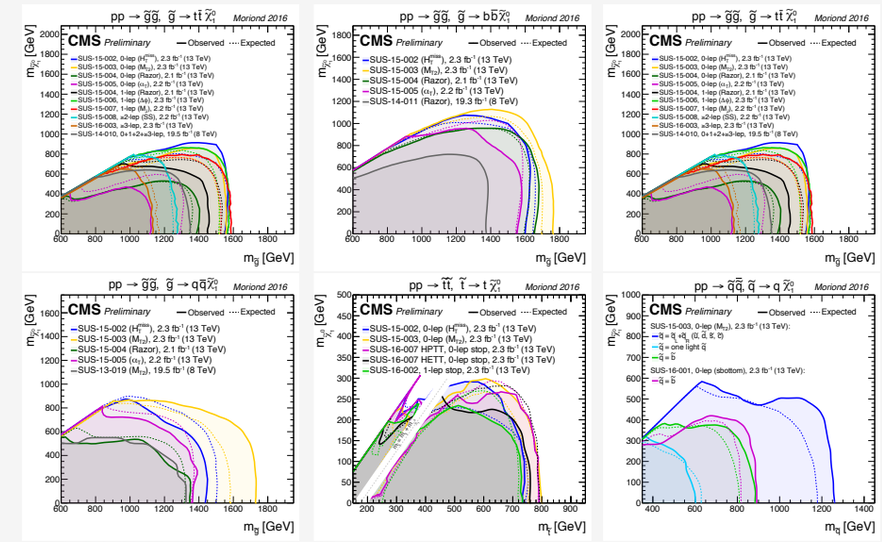
Searches for Dark Matter

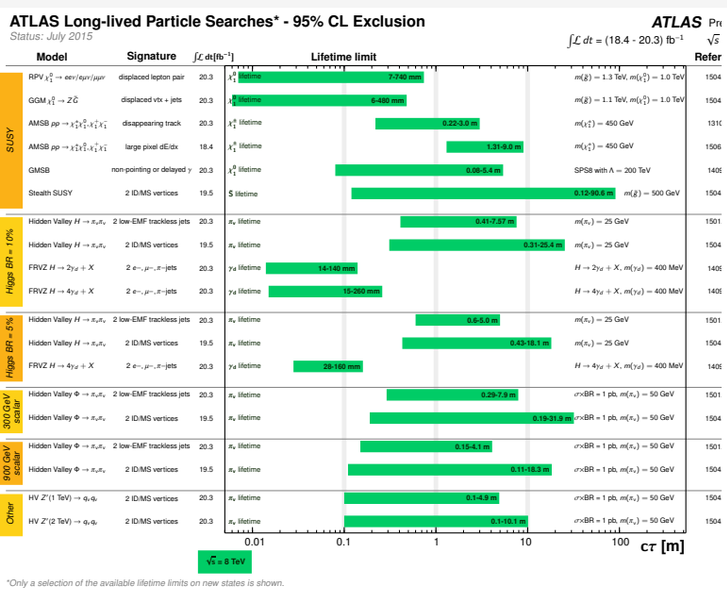
Exotics

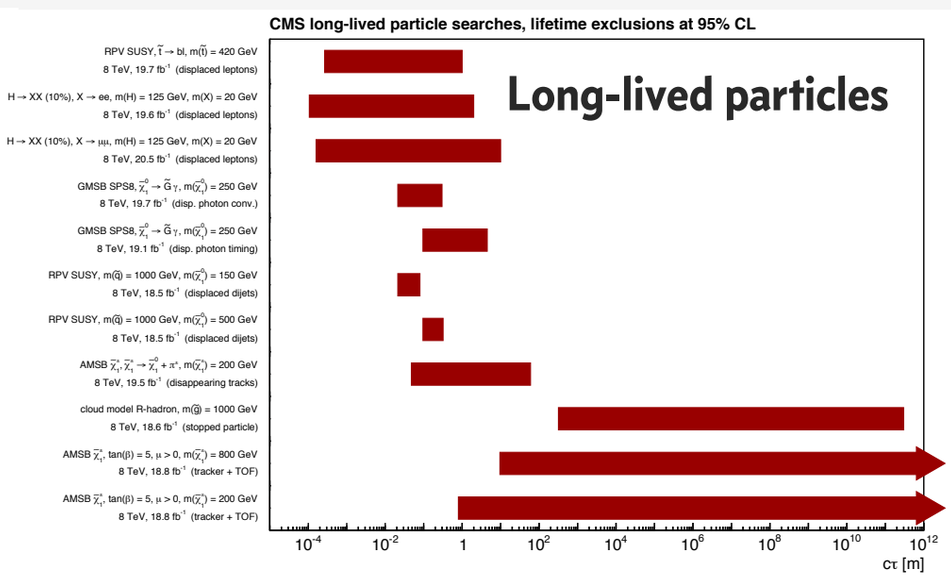


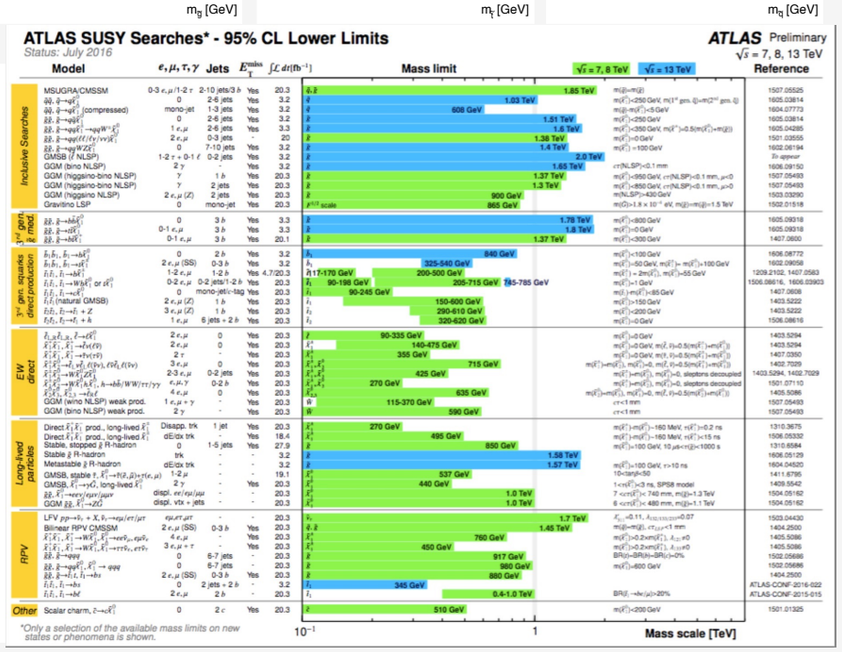


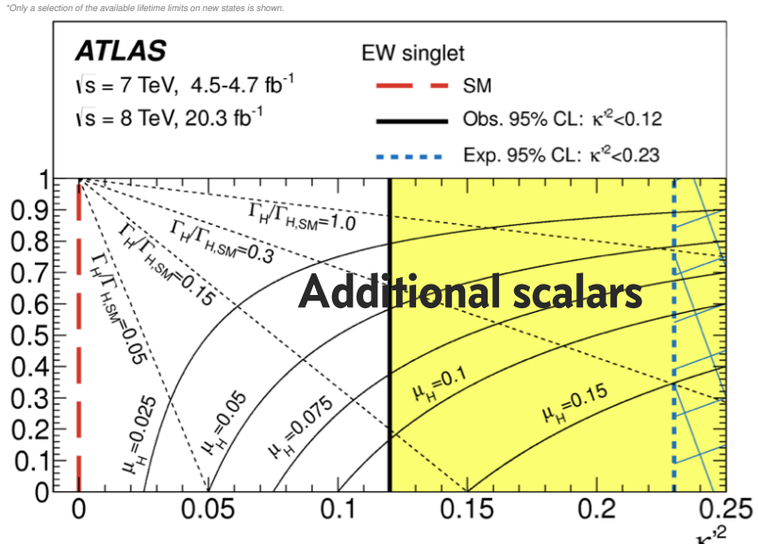
SUSY











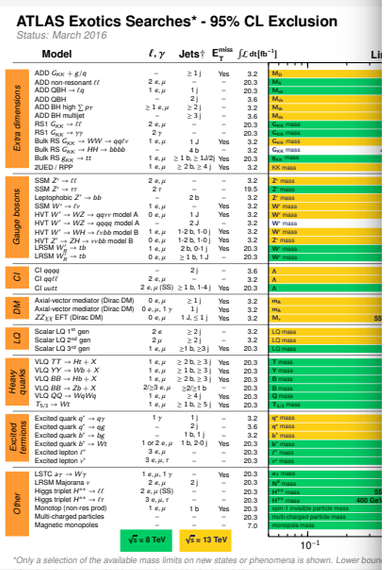
ATLAS Summary Plots

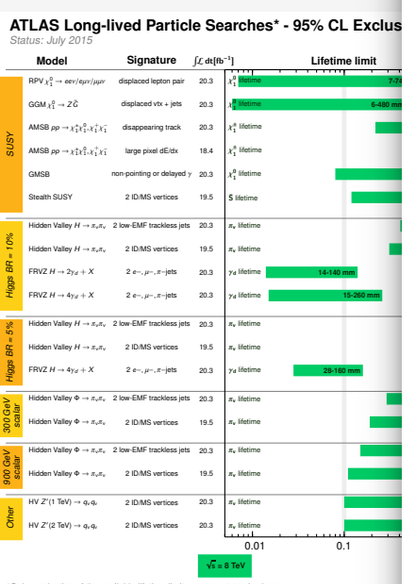
CMS Summary Plots

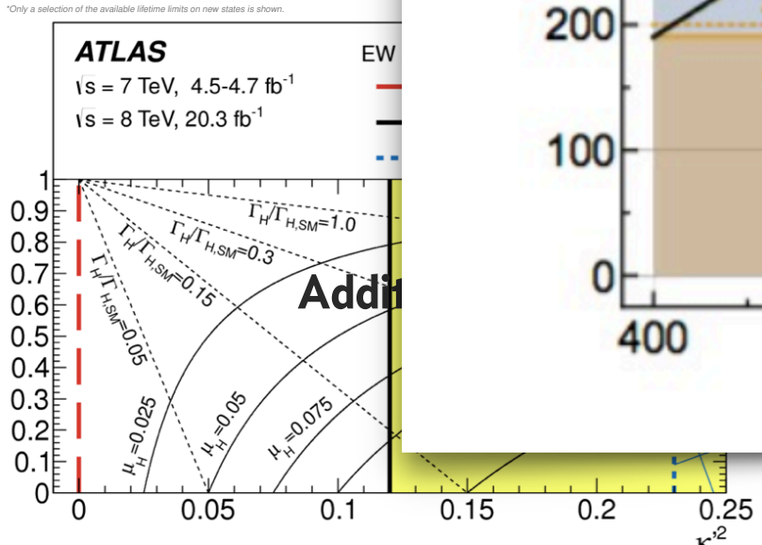
Most of these models already have a DM candidate, or can be easily modified to provide one

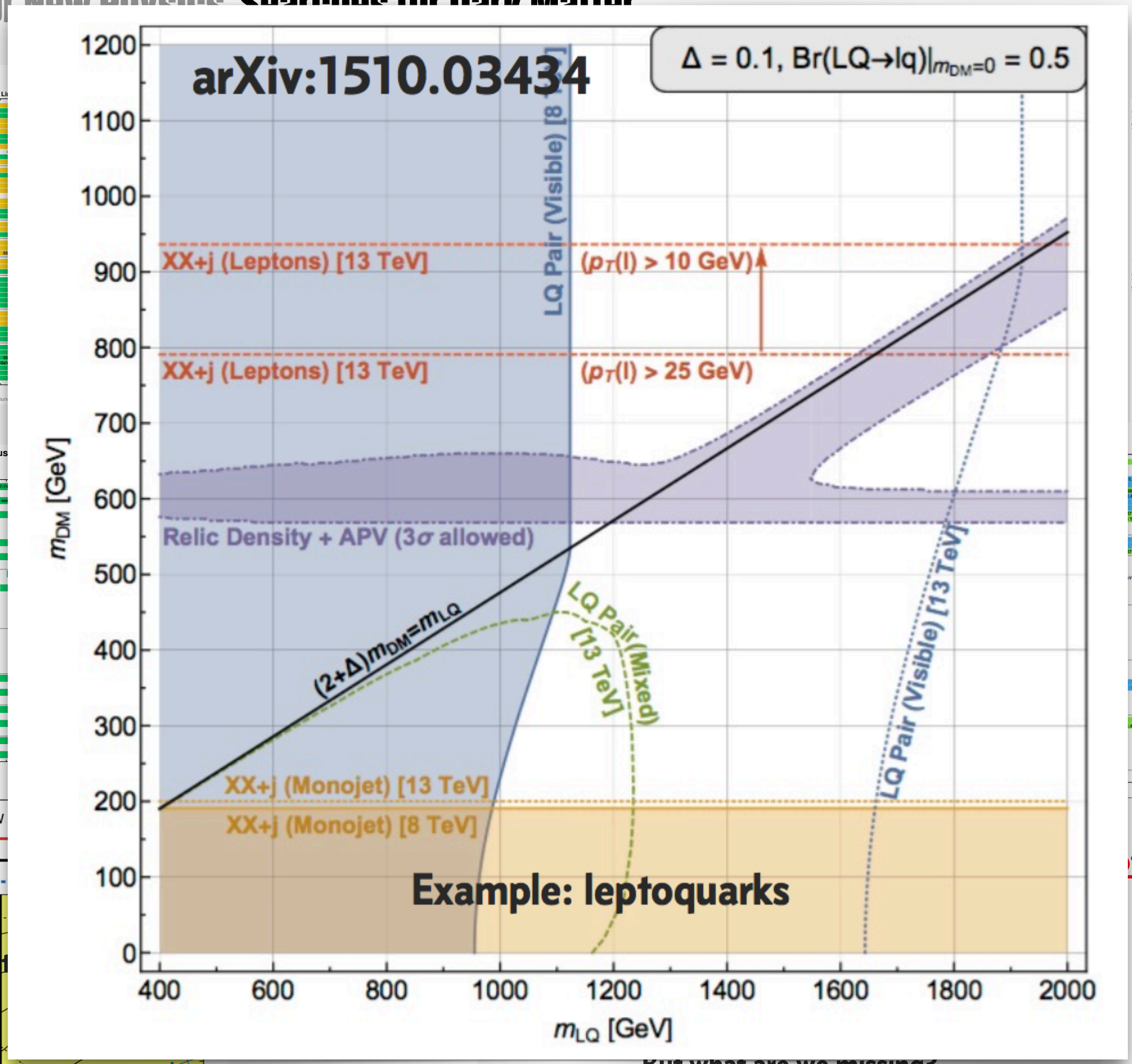
But what are we missing?

Searches for New Physics Searches for Dark Matter









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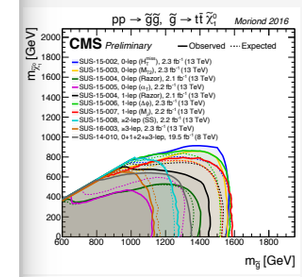
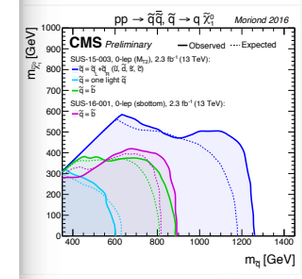
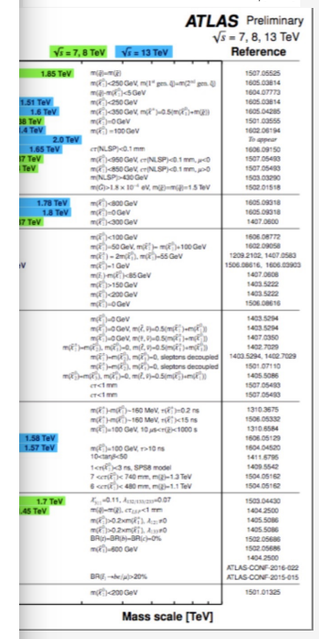






ts

But what are we missing?

What can the LHC do to look for Dark Matter

Searches targeting a full model that provides a DM candidate

- e.g. classic SUSY, leptoquarks, etc.

Searches for direct WIMP pair production through heavy mediators
(DM pair-produced with SM-scale couplings)

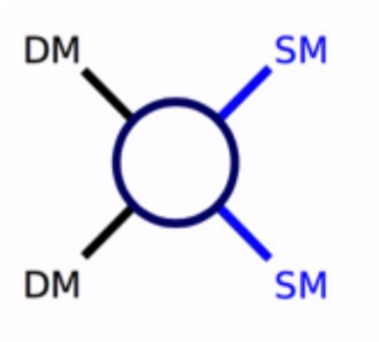
Searches for light mediators (with very small couplings)
See talks by Ted, Andrea, Wei, Savannah…

Is this the end of the list????

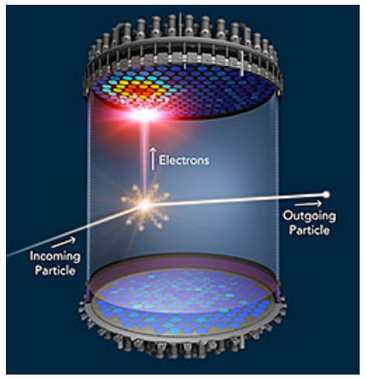
Models of Particle Dark Matter: Complementarity

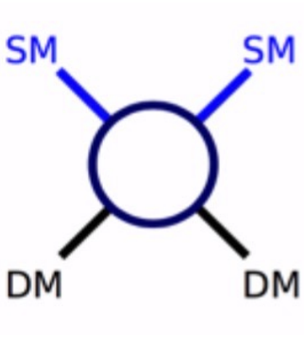
Collider searches have many advantages, but

- dark matter must have **non-gravitational interactions with the SM** to produce it
- a MET signal != astrophysical DM
- the results cannot be related to other knowledge of DM without a model (and, for DM, we know very little)

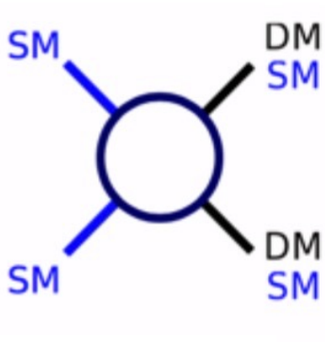


Indirect Detection

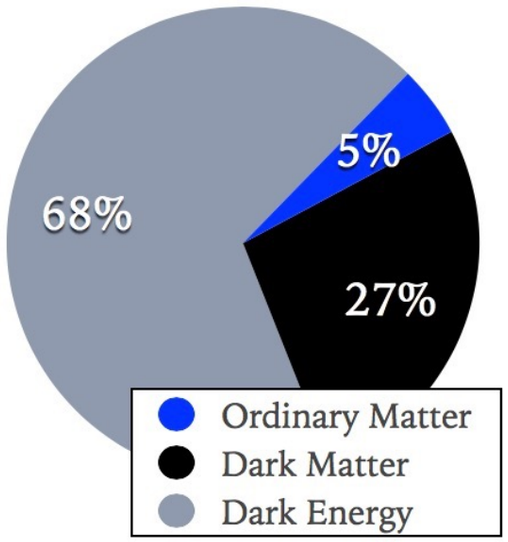




Direct Detection



Colliders



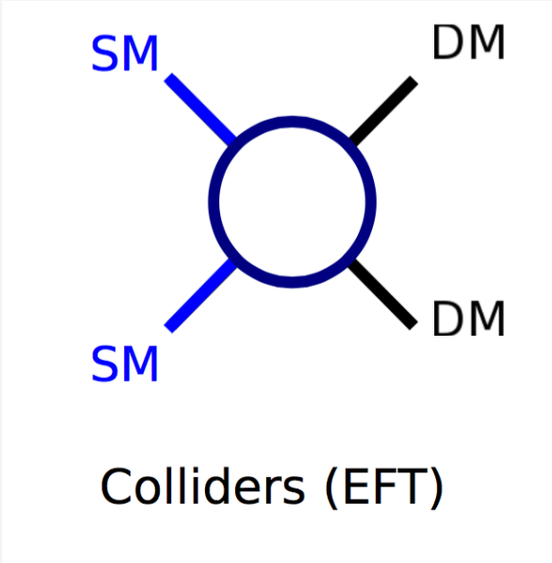
During Run 1, general purpose WIMP searches focused on contact-interaction models **emphasizing complementarity**

- 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

PHYSICAL REVIEW D **82,** 116010 (2010)

TABLE I. Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars, respectively.

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



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D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
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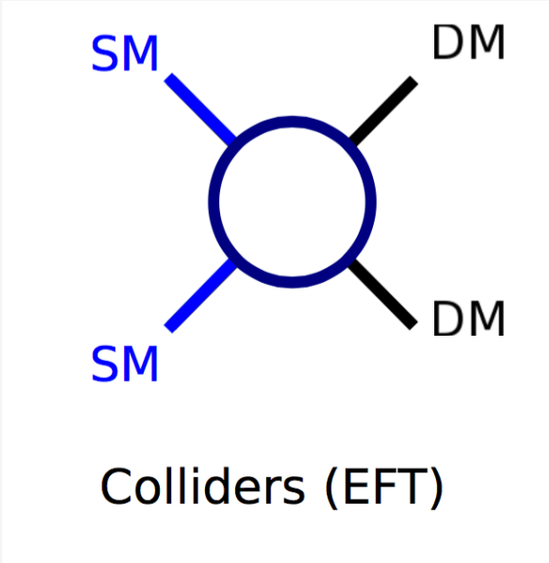
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



Problem:

In typical completions, the inaccessible physics must be too strongly coupled to produce observable signals

e.g. s-channel mediator: rate depends on

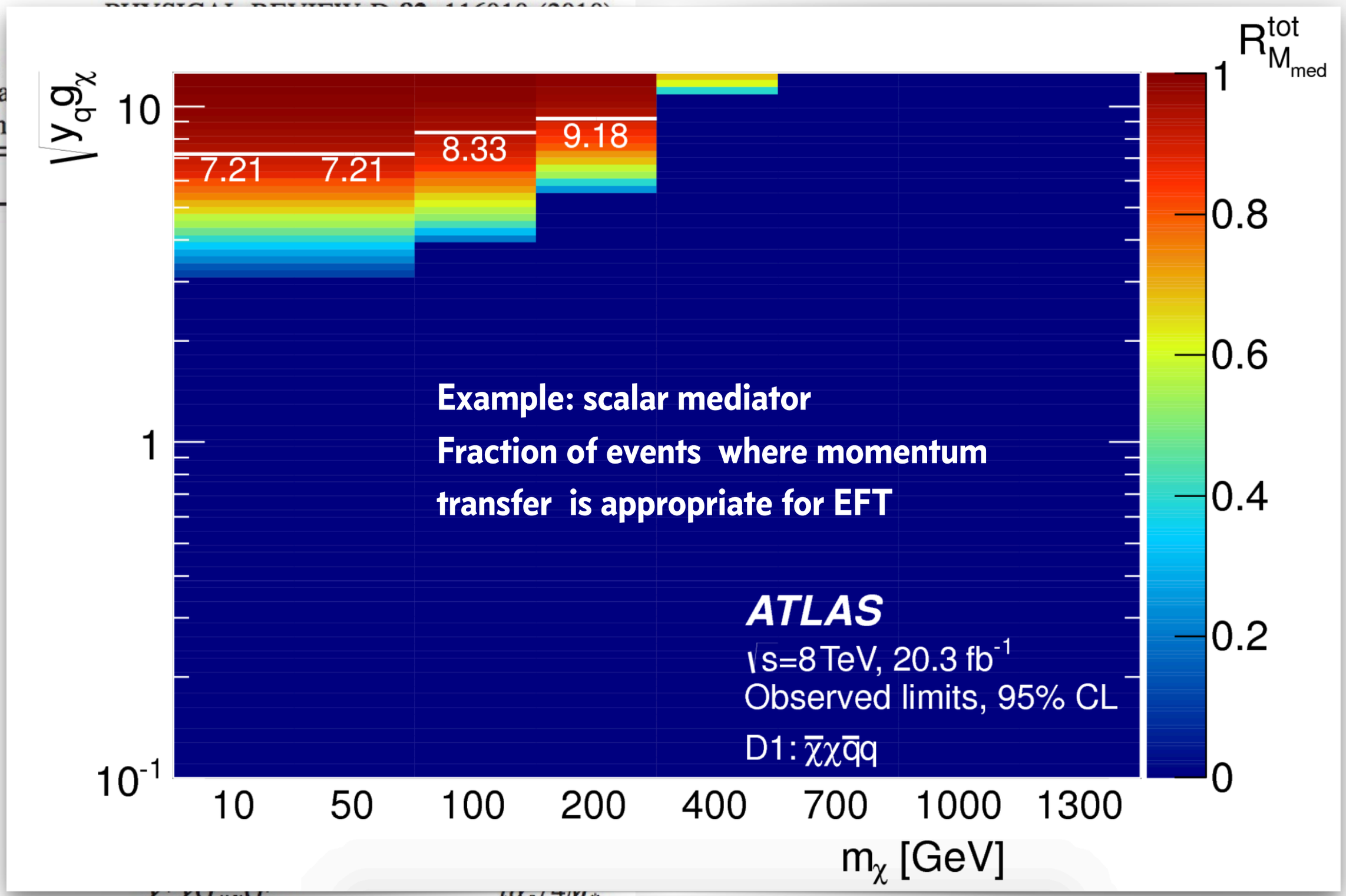
$$M_\star = M_{\rm med}/\sqrt{g_q\, g_\chi}$$

High enough rate implies either:

- heavy mediator, non-perturbative couplings
- light mediator (EFT incorrect theory)

TABLE I.
operator na
Dirac ferm

Name		
D1		
D2		
D3		
D4		
D5		
D6		
D7		
D8		
D9		
D10		
D11		
D12		
D13		
D14		
C1		
C2		
C3		
C4		
C5		
C6	$\chi^2\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



- heavy mediator, non-perturbative couplings
- light mediator (EFT incorrect theory)

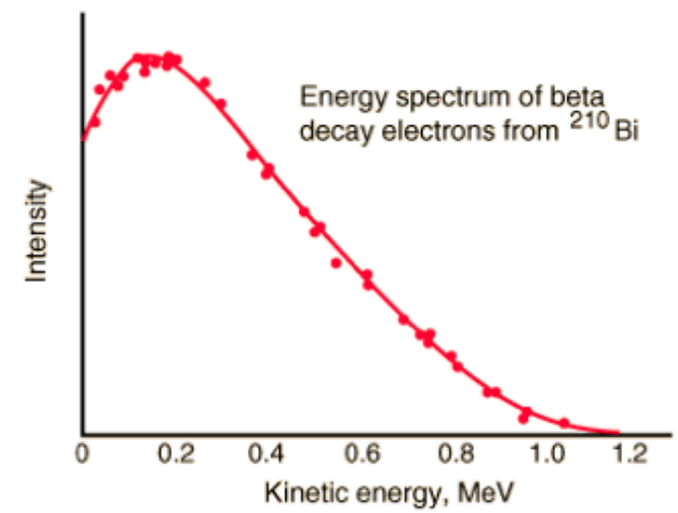
Is this a problem?

Brian's talk yesterday

History lesson - 1930s:

- Back then, the "Standard Model" was photon, electron, nucleons
- Beta decay: $n \to p + e^-$

Continuous spectrum!

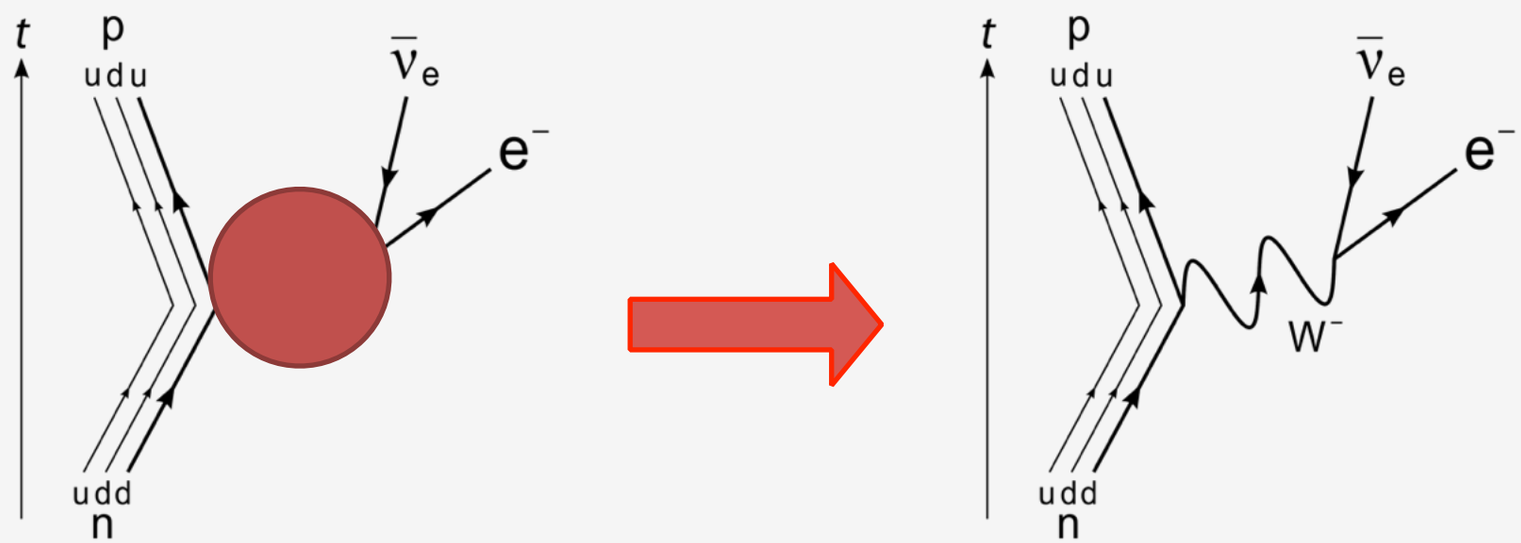


- Pauli proposes a radical solution - the neutrino!

$$n \to p + e^- + \bar{\nu}$$

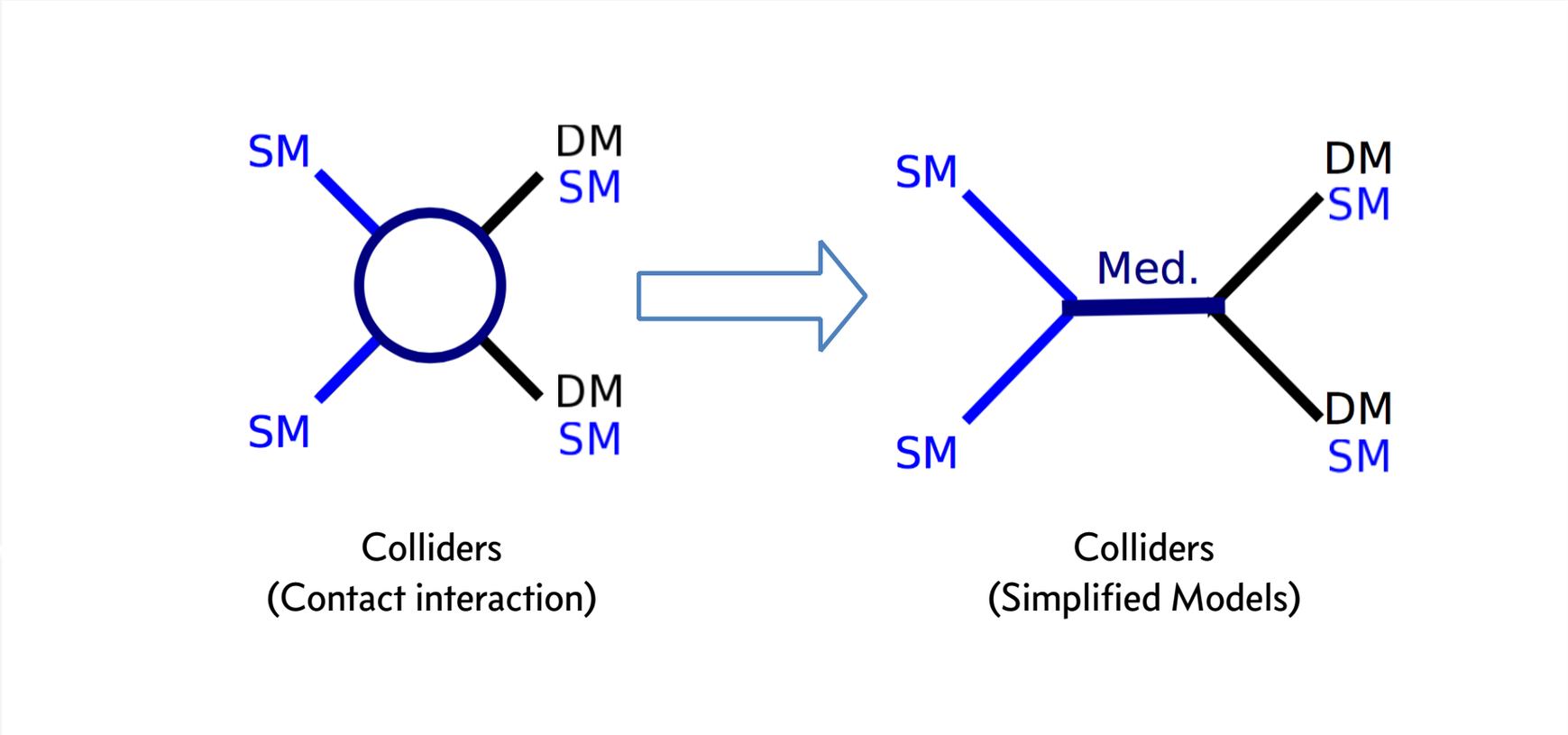
- **Perfect example of a hidden sector!**
  - neutrino is electrically neutral (QED gauge singlet)
  - very weakly interacting and light
  - interacts with "Standard Model" through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

Is this a problem?



LHC probes 'high' energy scales
If 'high' is high enough, it can discovery and characterize the interactions between normal and dark matter

Is this a problem?



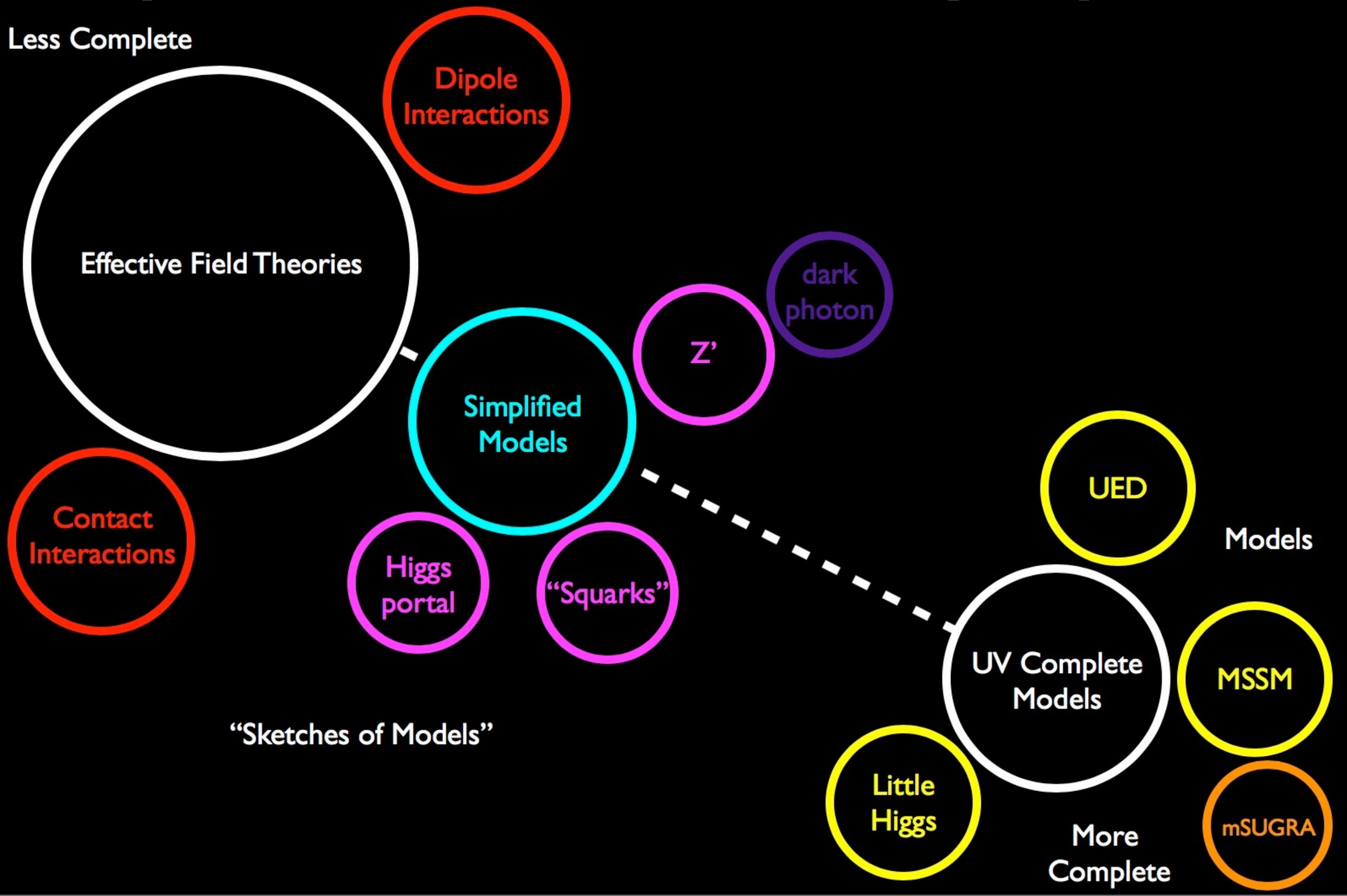
LHC probes 'high' energy scales
If 'high' is high enough, it can discovery and characterize the interactions between normal and dark matter

Requires more model assumptions (and parameters)

Take-away: LHC results are highly sensitive to model

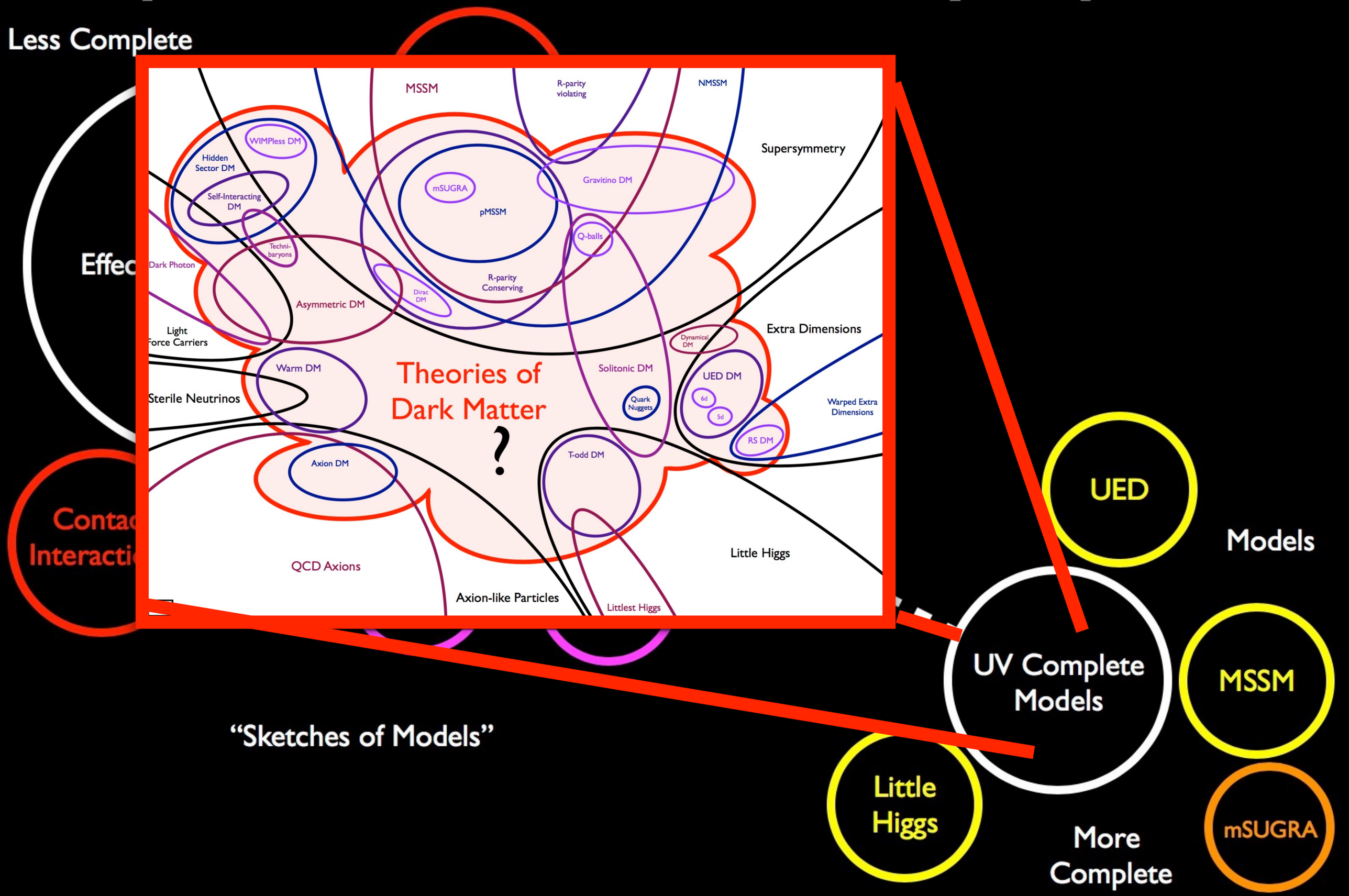
Tim M.P. Tait

Spectrum of Theory Space



Tim M.P. Tait

Spectrum of Theory Space



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We gratefully acknowledge support from the Simons Foundation and member institutions

High Energy Physics - Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

Subjects: **High Energy Physics - Experiment (hep-e** (hep-ph)
Cite as: **arXiv:1507.00966 [hep-ex]**
(or **arXiv:1507.00966v1 [hep-ex]** for this v

Submission history
From: Antonio Boveia [view email]
[v1] Fri, 3 Jul 2015 16:54:32 GMT (3860kb,D)

Which authors of this paper are endorsers? | Disable MathJax (What is MathJax?)

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References & Citations
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- NASA ADS

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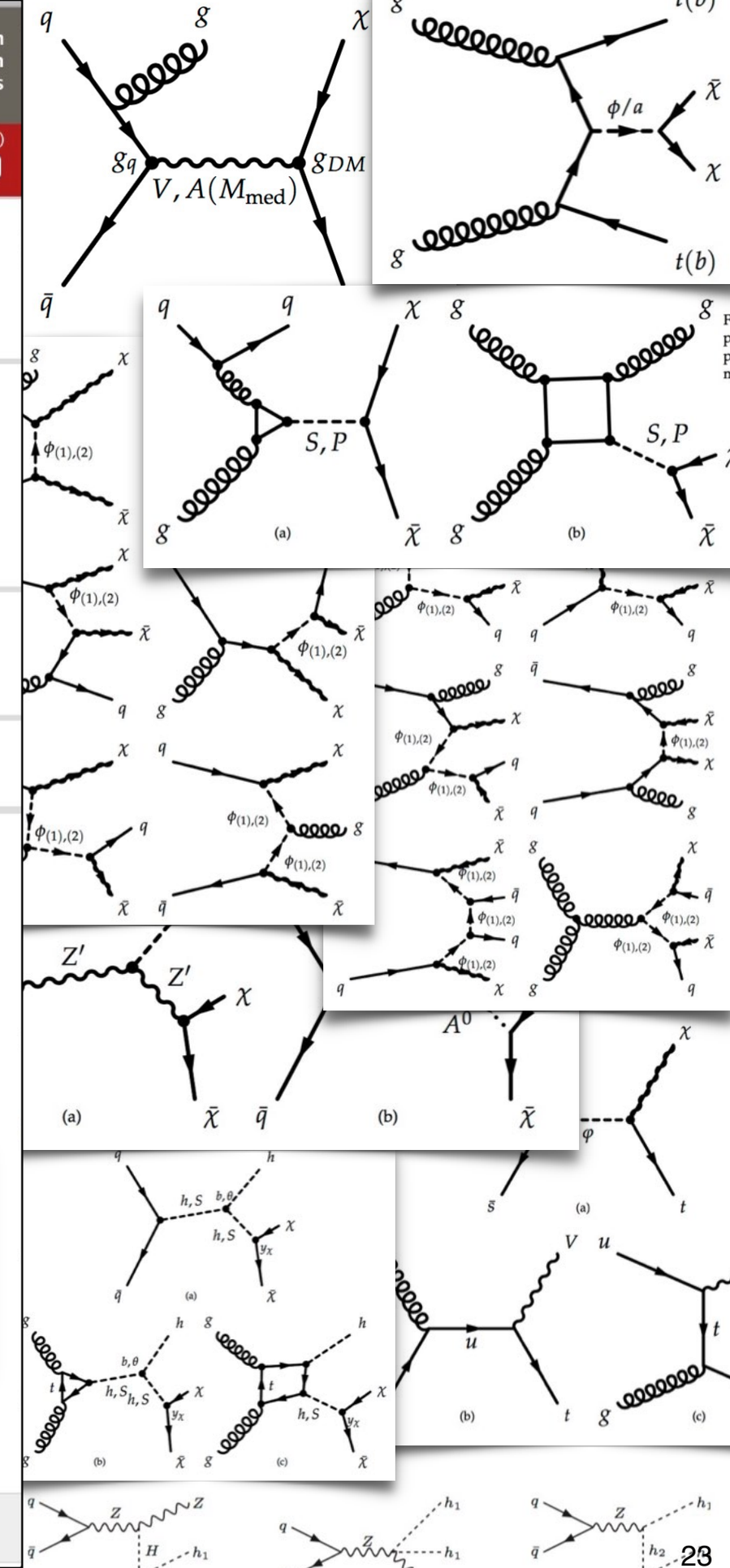
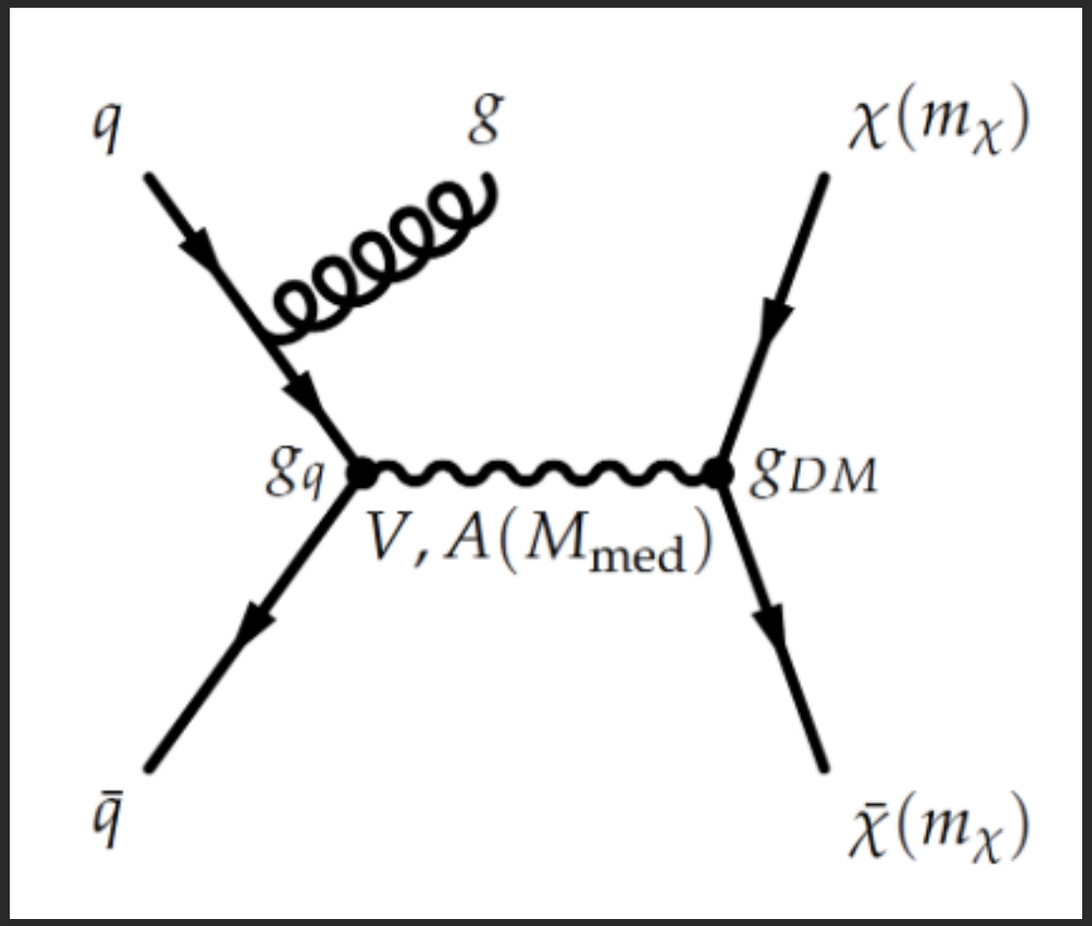
Dirac WIMP mediators:
t- and s-channel exchange
vector/axial-vector/scalar/pseudo-scalar (MFV)
MET+heavy flavor, W, Z, and Higgs

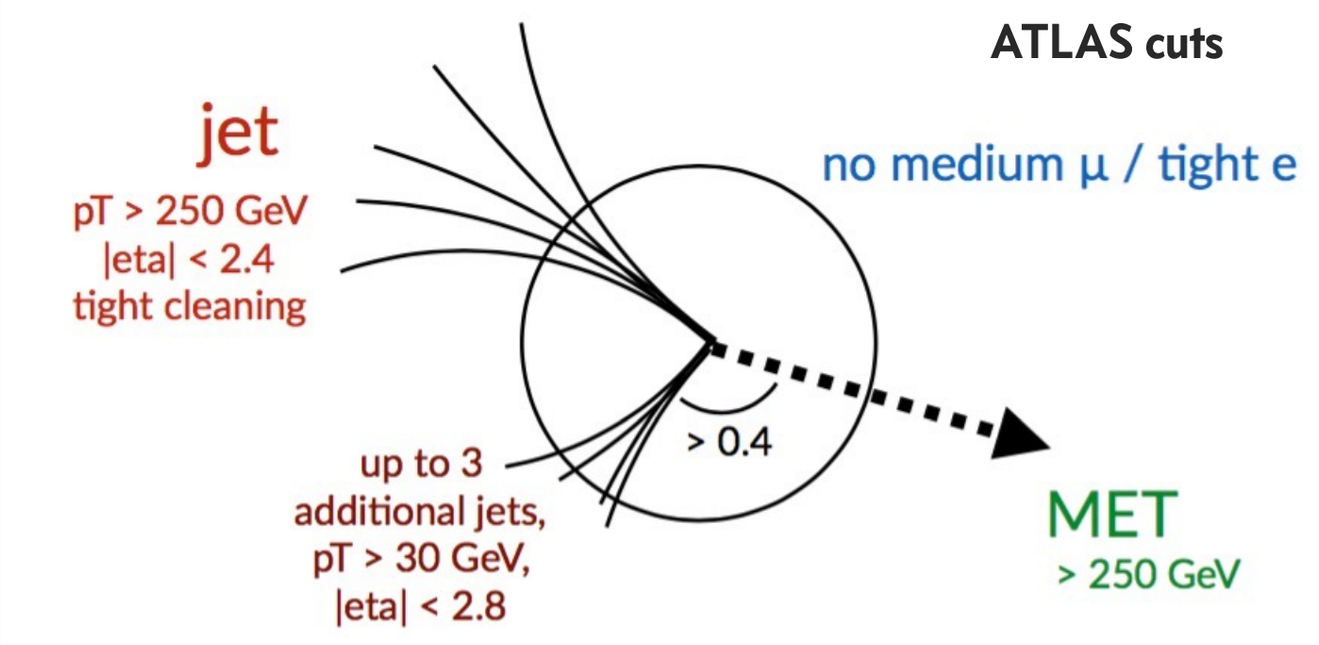


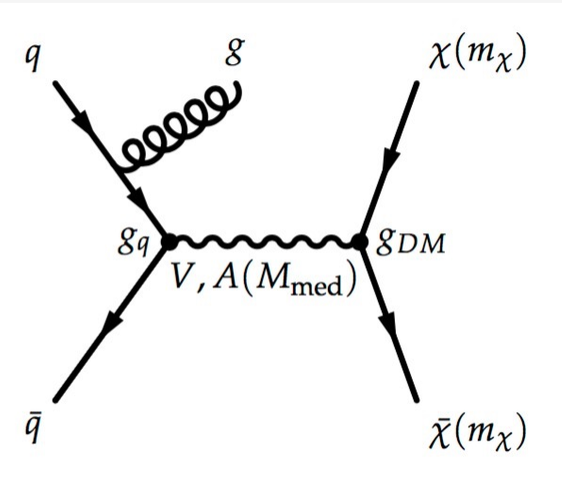
Searching for Dark Matter Production

(or: collider-stable weakly-interacting particles)

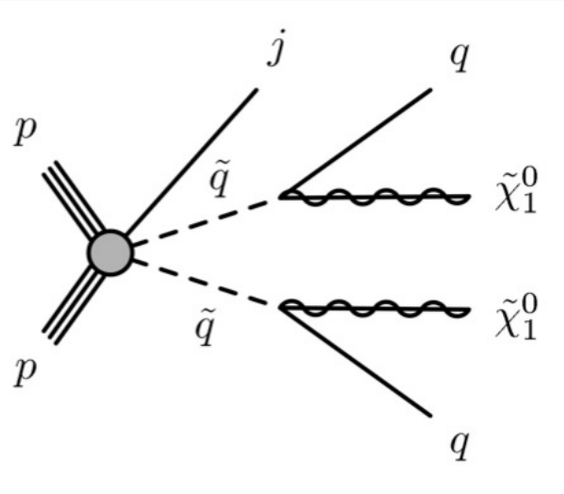


MET+X searches, or “mono-X”

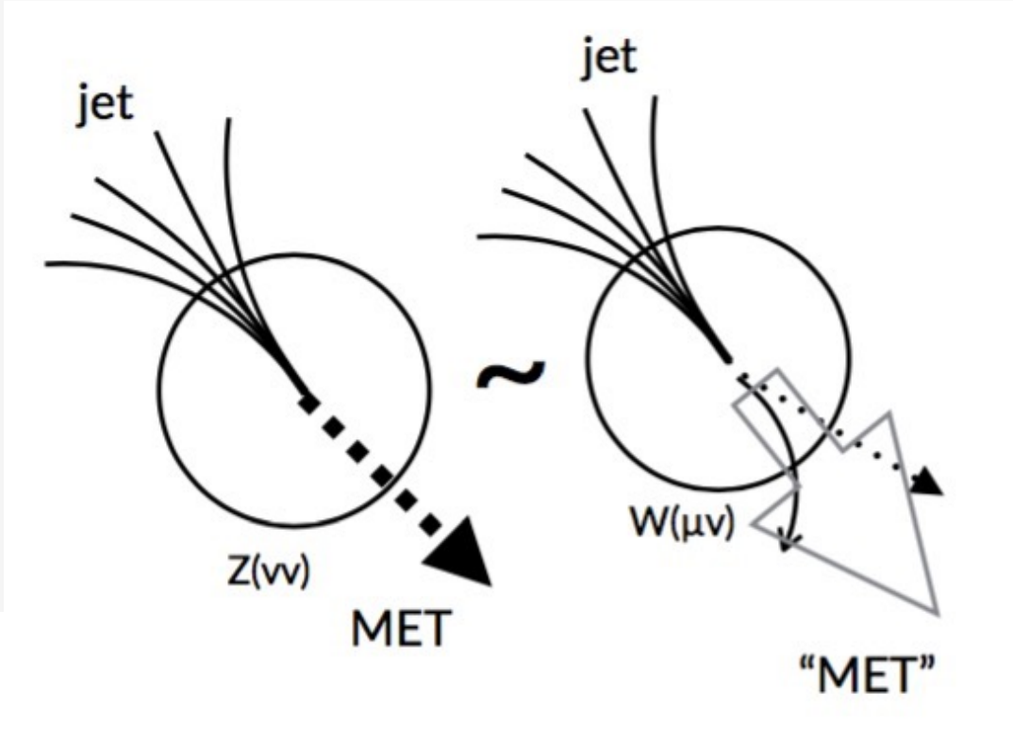




Signals



Backgrounds



+…

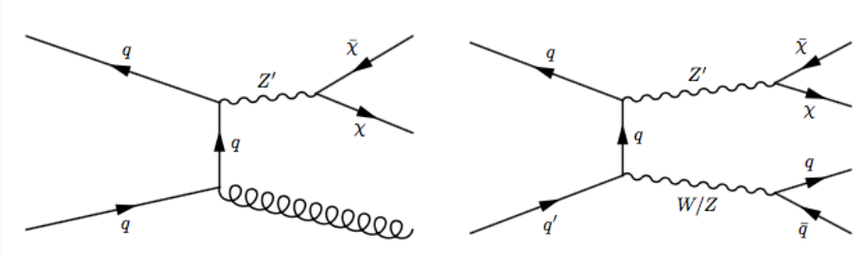
CMS Mono-W/Z/jet

CMS PAS EXO-16-037

Look for large MET and ≥1 high p_T jet; veto e, μ, tau, γ, b-jet

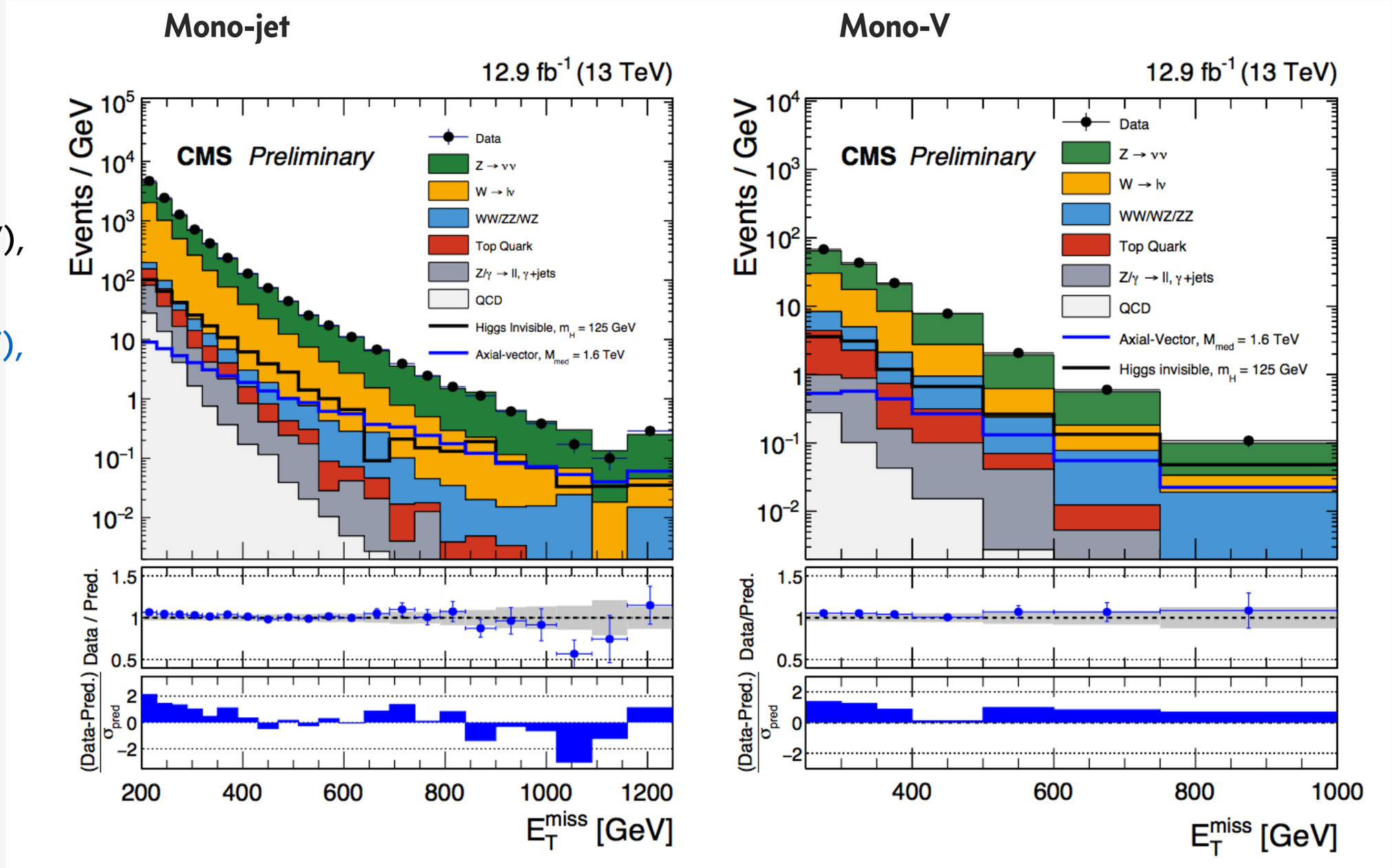
- Mono-V: p_{Tj1}^{AK8}, MET > 250 GeV, mass 65-105 GeV, tau21 < 0.6
- Mono-jet: remaining events p_{Tj1}^{AK4} > 100 GeV, MET > 200 GeV

Fit background and signal predictions to MET control regions (ee/μμ/e/μ/γ+jets)

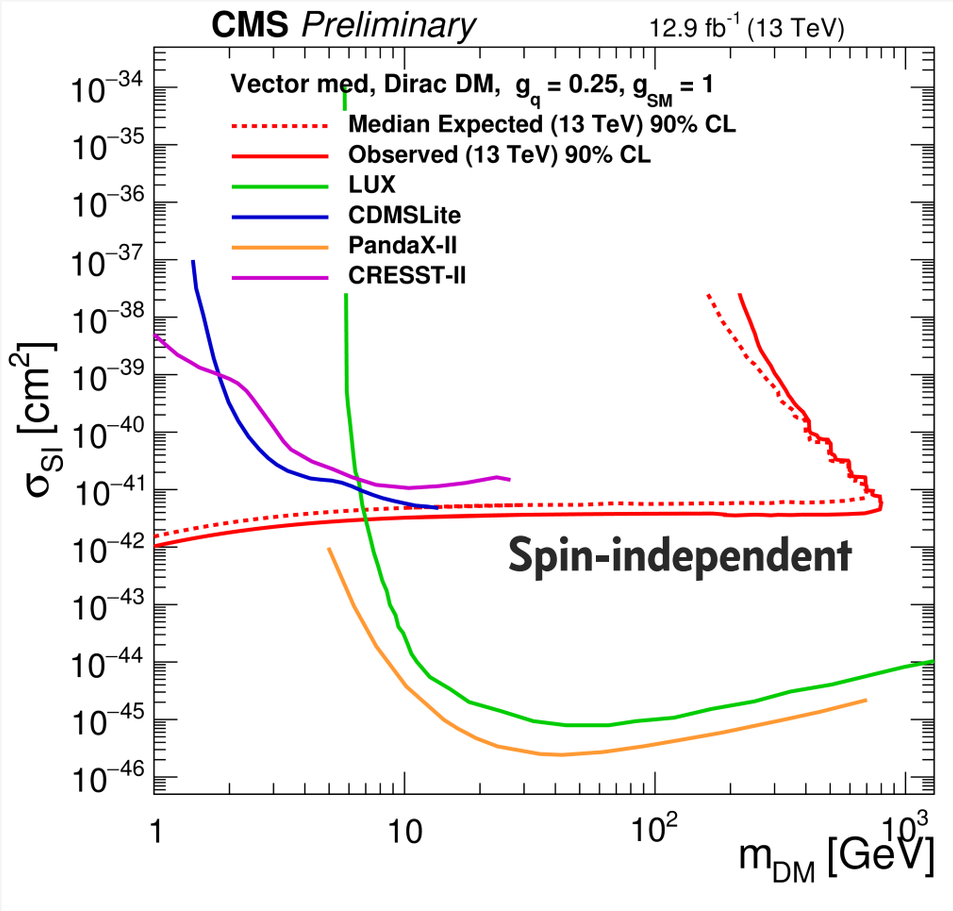


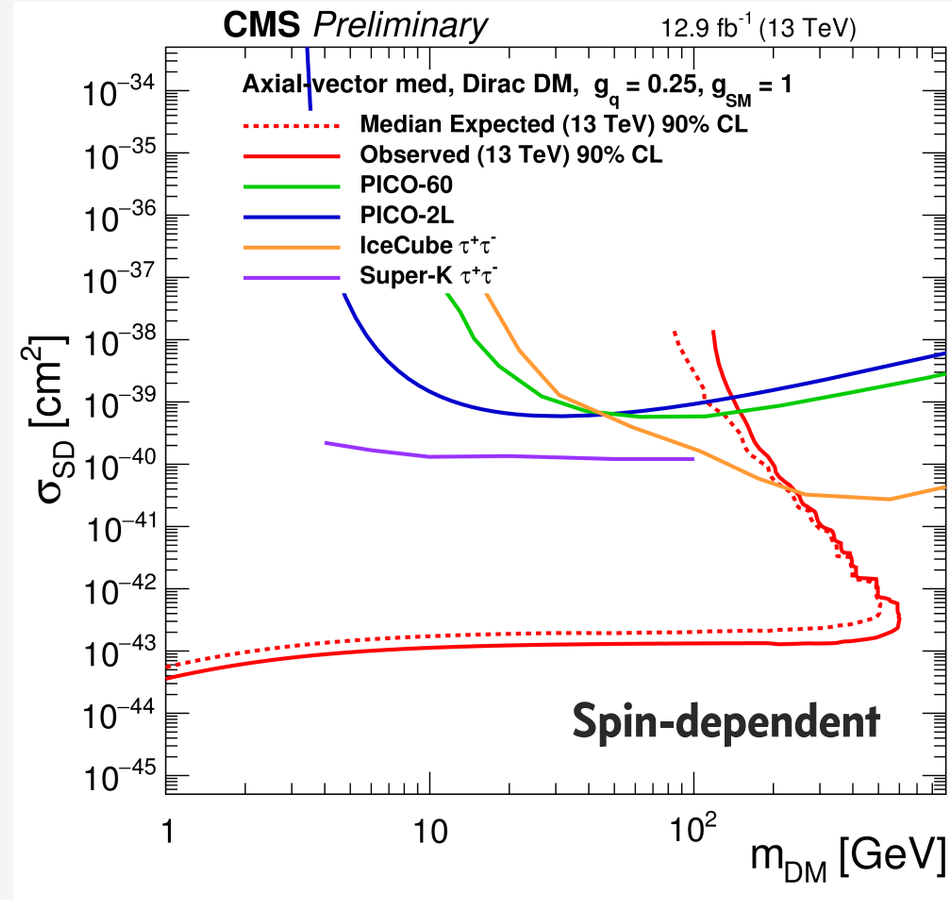
Light mediator (125 GeV), Light DM

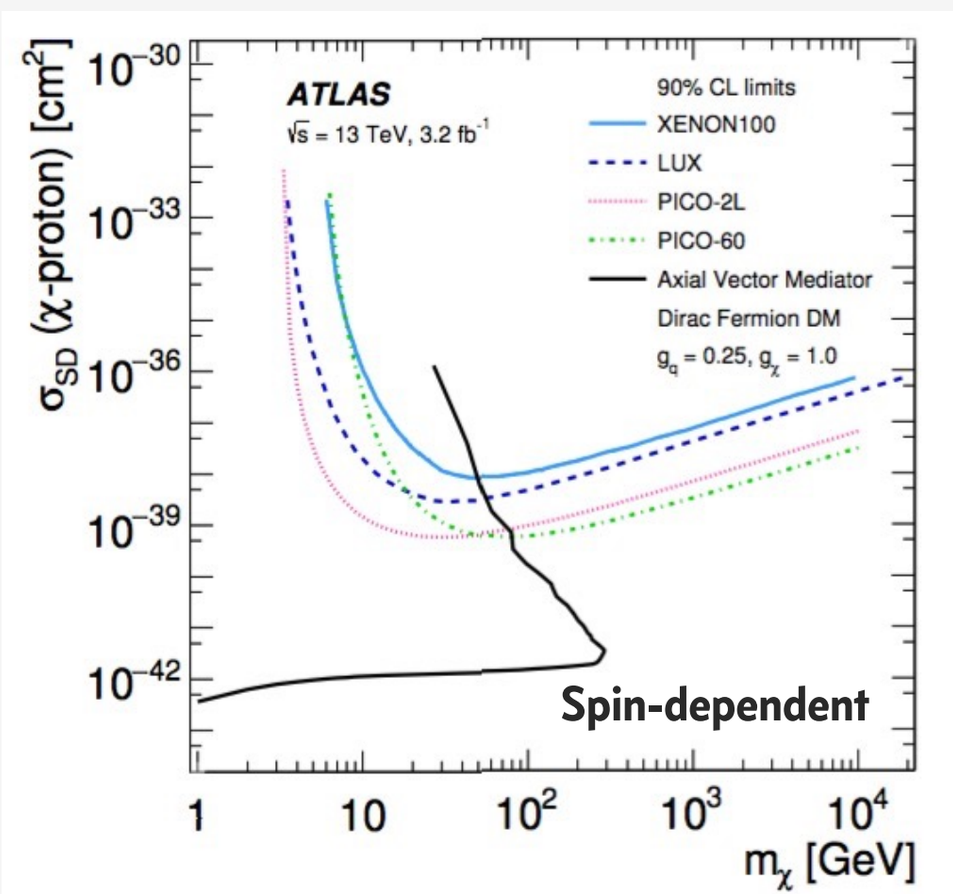
Heavy mediator (1.6 TeV), Light DM

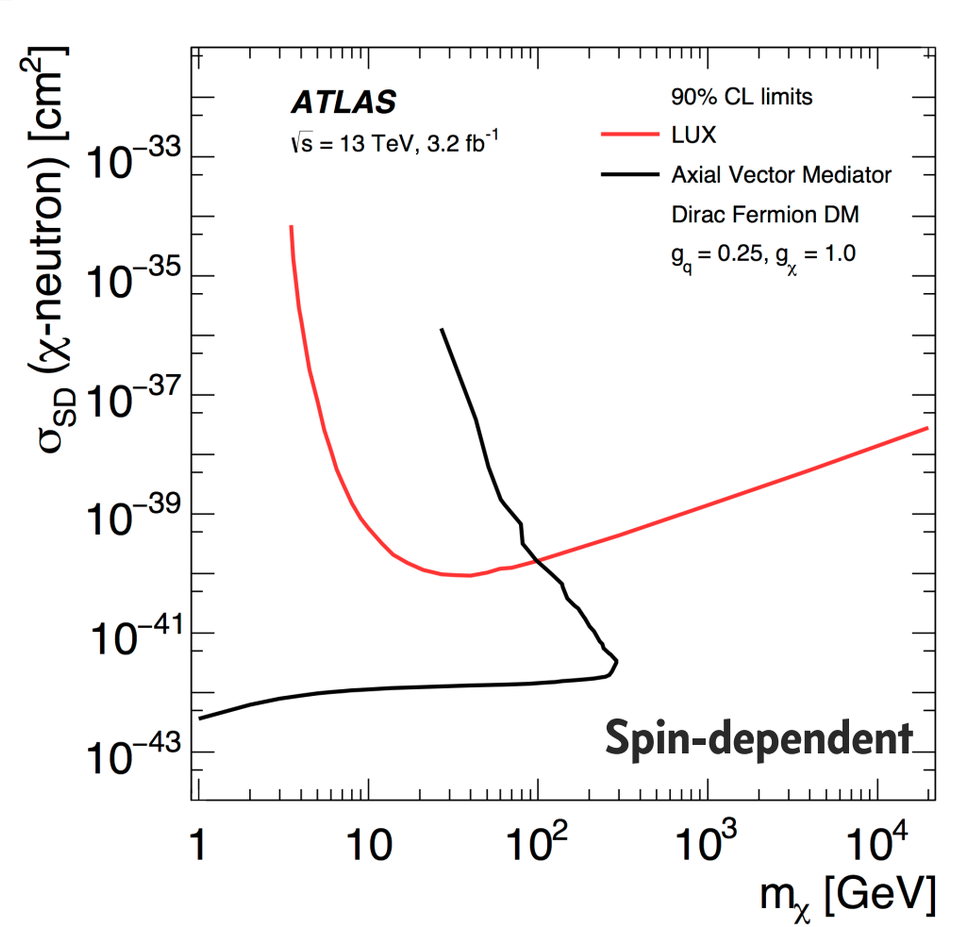


13 TeV mono-jet results with simplified models



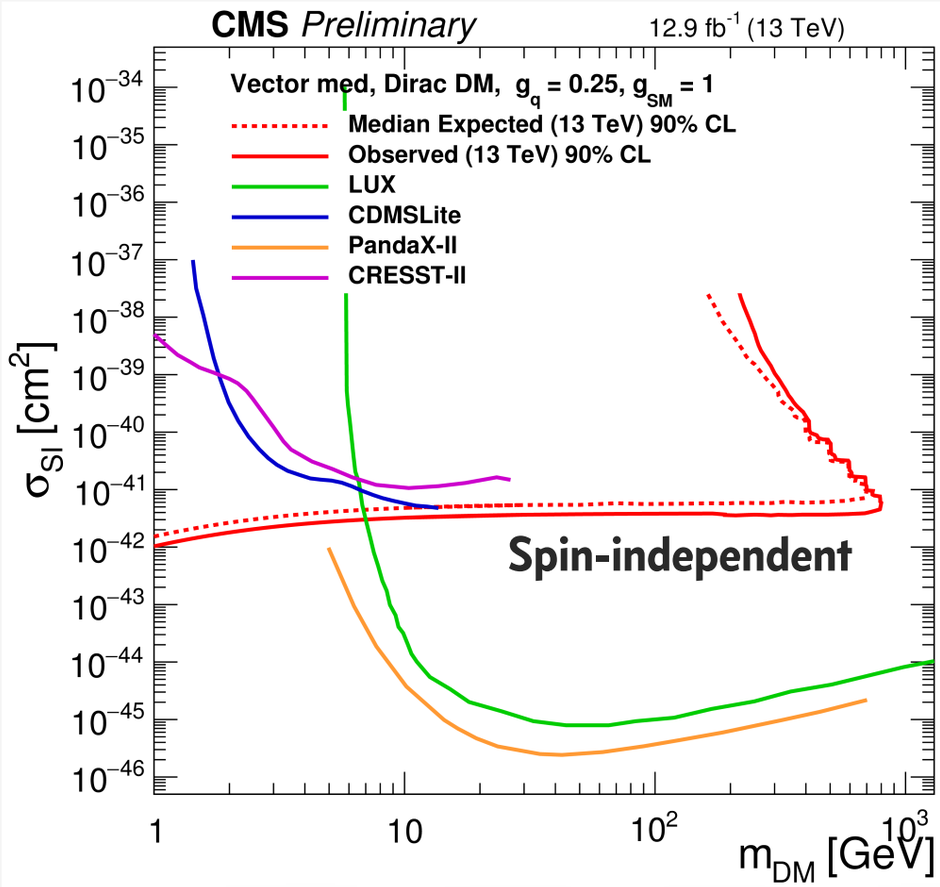




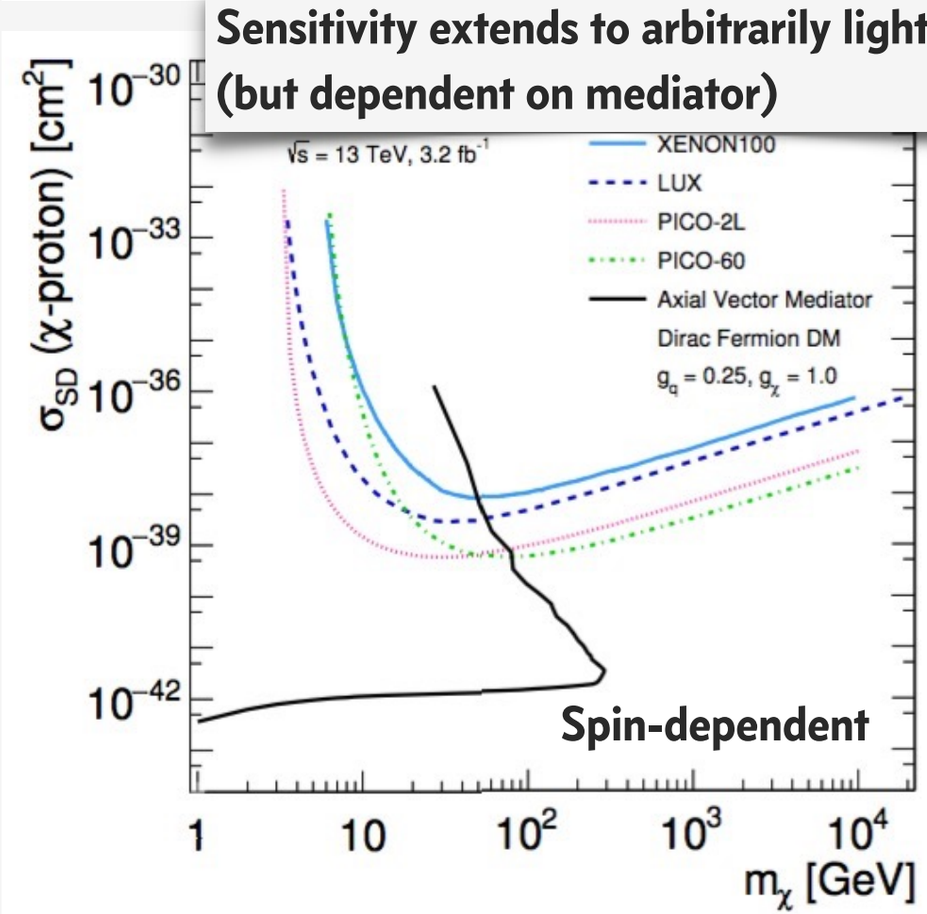


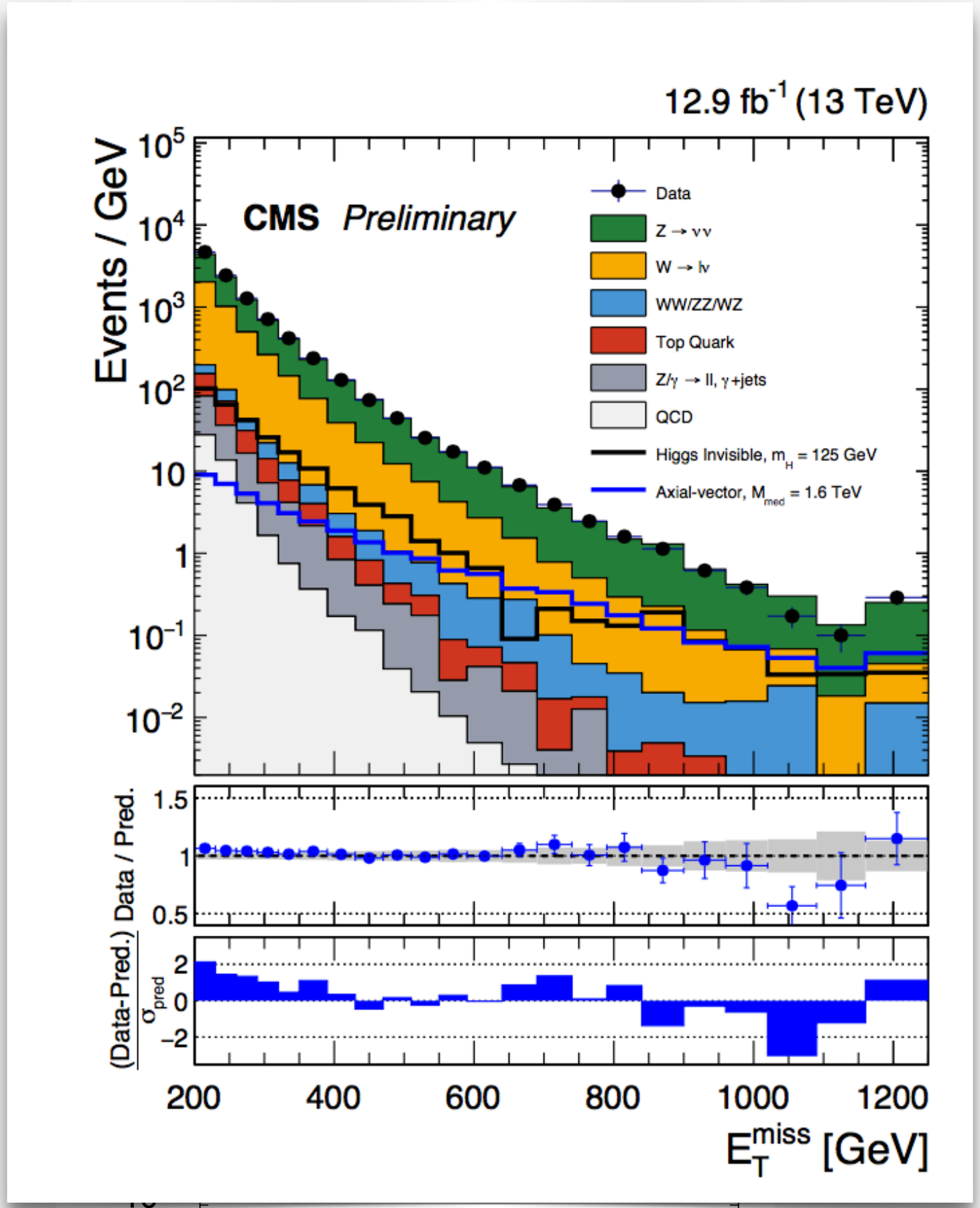
Translation from simplified model to nucleon-WIMP cross section described in arXiv:1603.04156

13 TeV mono-jet results with simplified models



Sensitivity extends to arbitrarily light DM (but dependent on mediator)





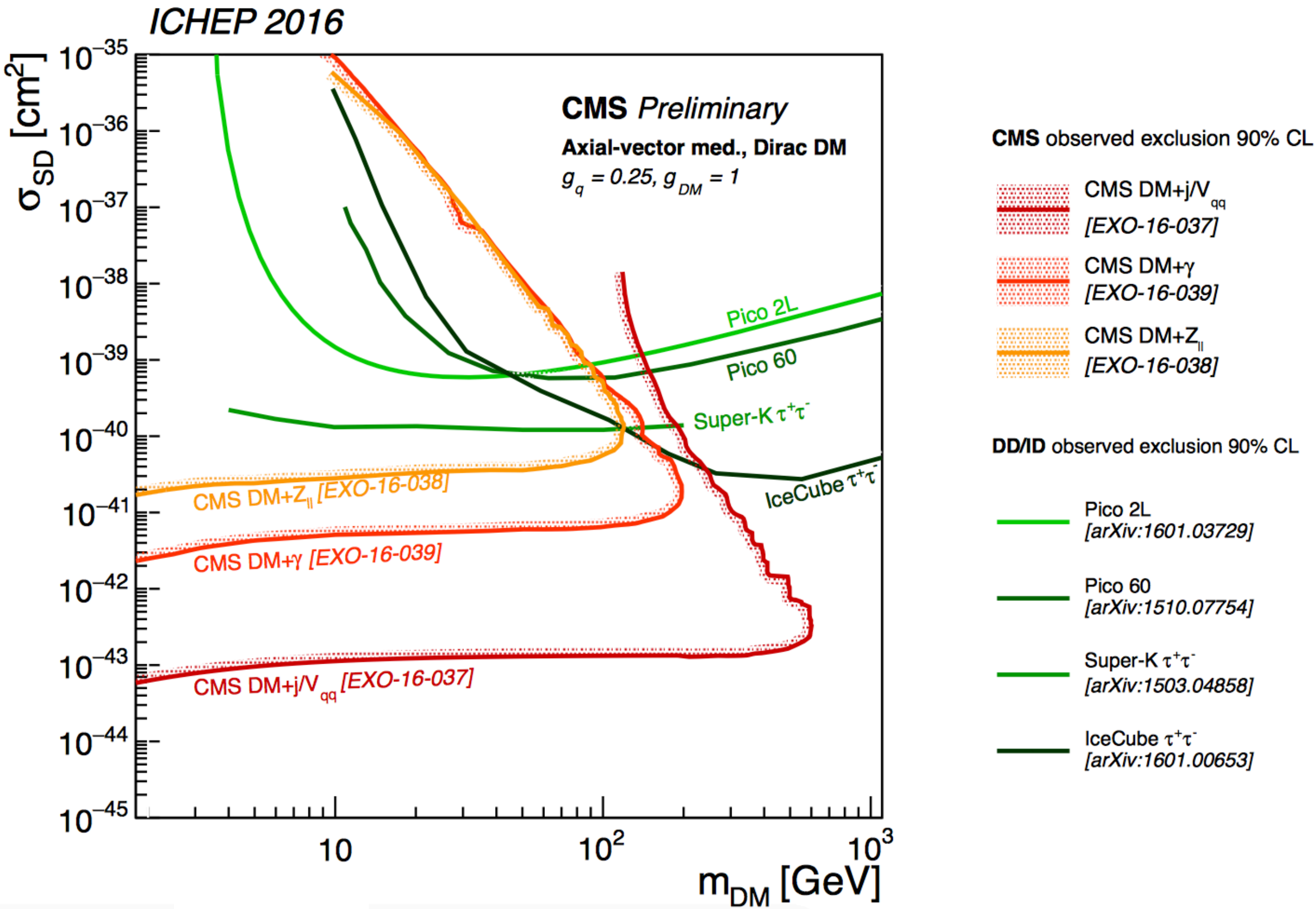
Already Many MET+X Searches Done with 13 TeV Data and Shown at ICHEP

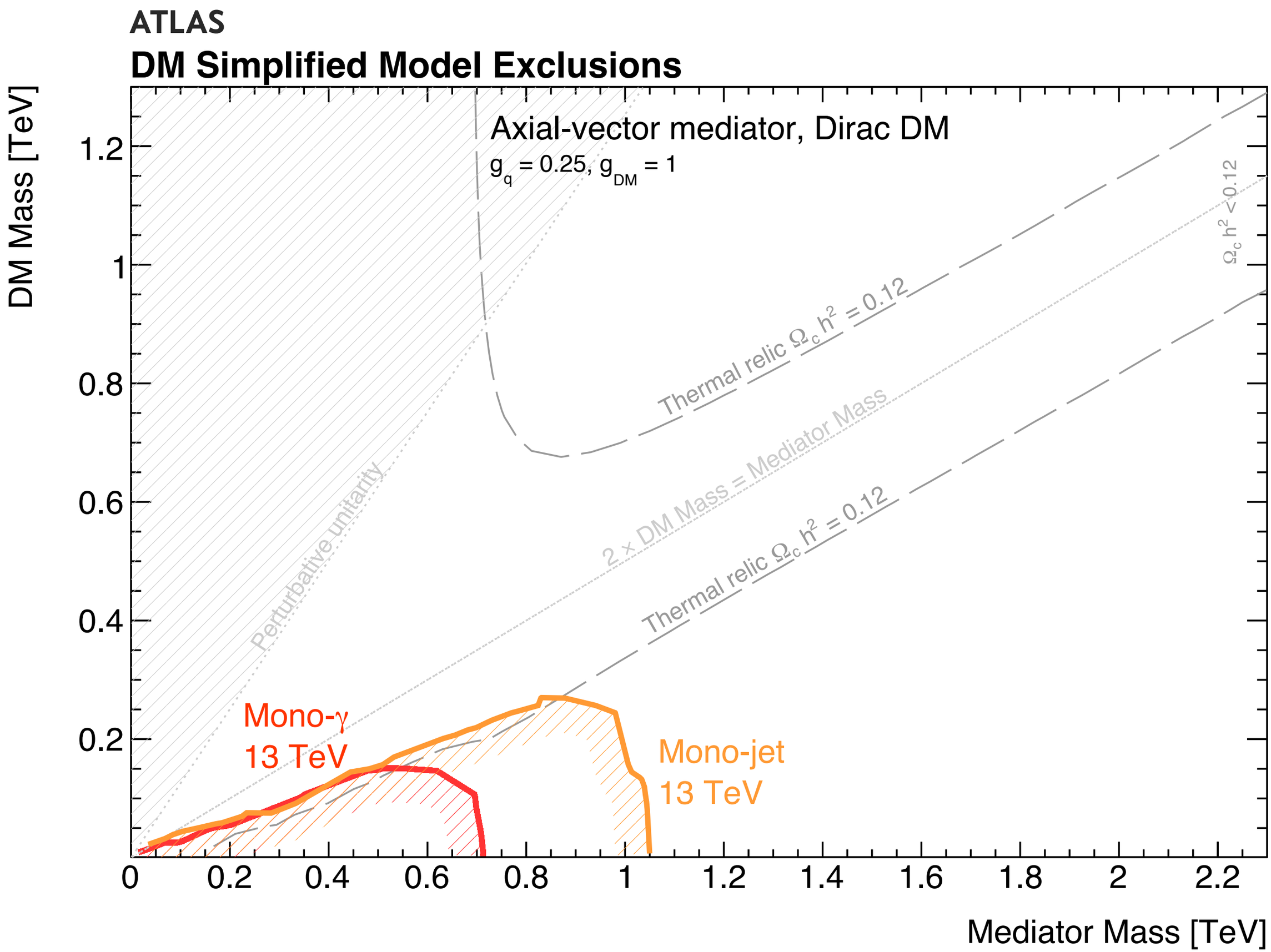
X	Dataset	CMS Documentation
jet or V (hadronic)	2016, 12.9 fb	EXO-16-037
photon	2016, 12.9 fb	EXO-16-039
Z (ll)	2015, 2.3 fb	EXO-16-010
Z (ll)	2016, 12.9 fb	EXO-16-038
Higgs (bb)	2015, 2.3 fb	EXO-16-012
Higgs (γγ)	2015, 2.3 fb	EXO-16-011
tt (semilep+had)	2015, 2.2 fb	EXO-16-005
t (hadronic)	2016, 12.9 fb	EXO-16-040

Eiko Yu

Analysis	Dataset	Public link
Production search:		
E_T^{miss}+jet	2015	Paper: EXOT-2015-03
$E_T^{miss}+\gamma$	2015	Paper: EXOT-2015-05
$E_T^{miss}+Z(\to \ell\ell)$	2015+2016	Note: ATLAS-CONF-2016-056
$E_T^{miss}+W/Z(\to qq)$	2015	Paper: EXOT-2015-08
$E_T^{miss}+H(\to bb)$	2015	Note: ATLAS-CONF-2016-019
$E_T^{miss}+H(\to \gamma\gamma)$	2015+2016	Note: ATLAS-CONF-2016-087
$E_T^{miss}+H(\to \ell\ell\ell\ell)$	2015	Note: ATLAS-CONF-2015-059
E_T^{miss}+b-jets	2015+2016	Note: ATLAS-CONF-2016-086
$E_T^{miss}+t\bar{t}$ (0ℓ)	2015+2016	Note: ATLAS-CONF-2016-077
$E_T^{miss}+t\bar{t}$ (1ℓ)	2015+2016	Note: ATLAS-CONF-2016-050
$E_T^{miss}+t\bar{t}$ (2ℓ)	2015+2016	Note: ATLAS-CONF-2016-076

Steven Schramm

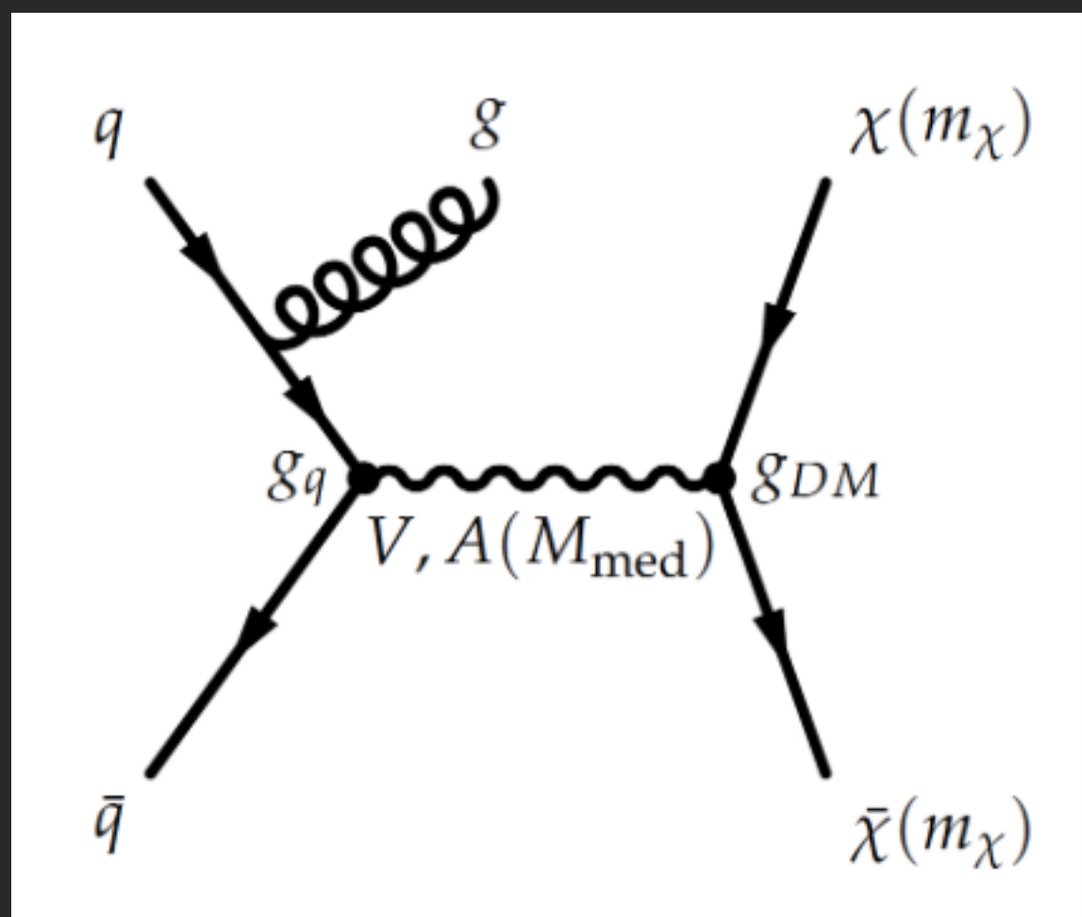

ICHEP 2016
CMS Preliminary
Axial-vector med., Dirac DM
$g_q = 0.25$, $g_{DM} = 1$
σ_{SD} [cm^2]
m_{DM} [GeV]
Pico 2L
Pico 60
Super-K $\tau^+\tau^-$
IceCube $\tau^+\tau^-$
CMS DM+Z_{ll} [EXO-16-038]
CMS DM+γ [EXO-16-039]
CMS DM+j/V_{qq} [EXO-16-037]
CMS observed exclusion 90% CL
CMS DM+j/V_{qq} [EXO-16-037]
CMS DM+γ [EXO-16-039]
CMS DM+Z_{ll} [EXO-16-038]
DD/ID observed exclusion 90% CL
Pico 2L [arXiv:1601.03729]
Pico 60 [arXiv:1510.07754]
Super-K $\tau^+\tau^-$ [arXiv:1503.04858]
IceCube $\tau^+\tau^-$ [arXiv:1601.00653]

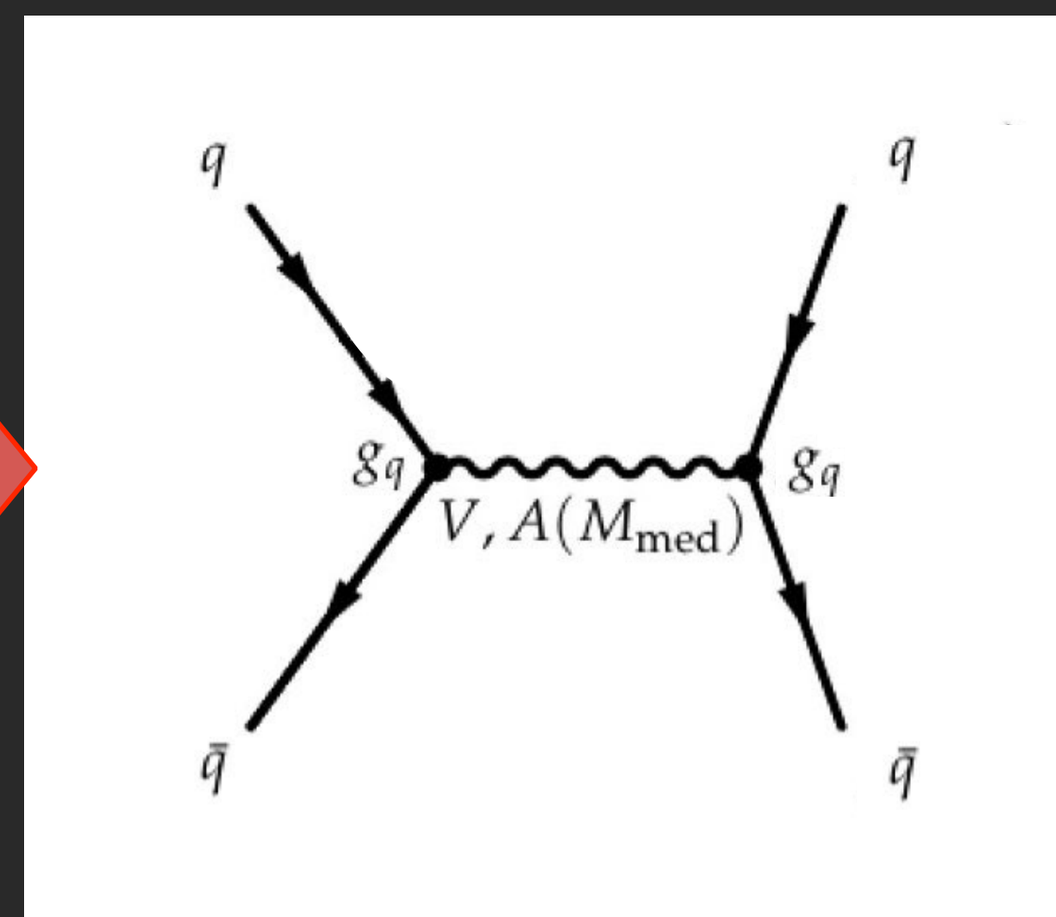

ATLAS
DM Simplified Model Exclusions
Axial-vector mediator, Dirac DM
g_q = 0.25, g_{DM} = 1
Thermal relic $\Omega_c h^2$ = 0.12
Thermal relic $\Omega_c h^2$ = 0.12
$\Omega_c h^2$ < 0.12
2 × DM Mass = Mediator Mass
Perturbative unitarity
Mono-γ
13 TeV
Mono-jet
13 TeV
DM Mass [TeV]
Mediator Mass [TeV]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

Take-away: easy to find situations where mono-X searches can nicely complement DD sensitivity

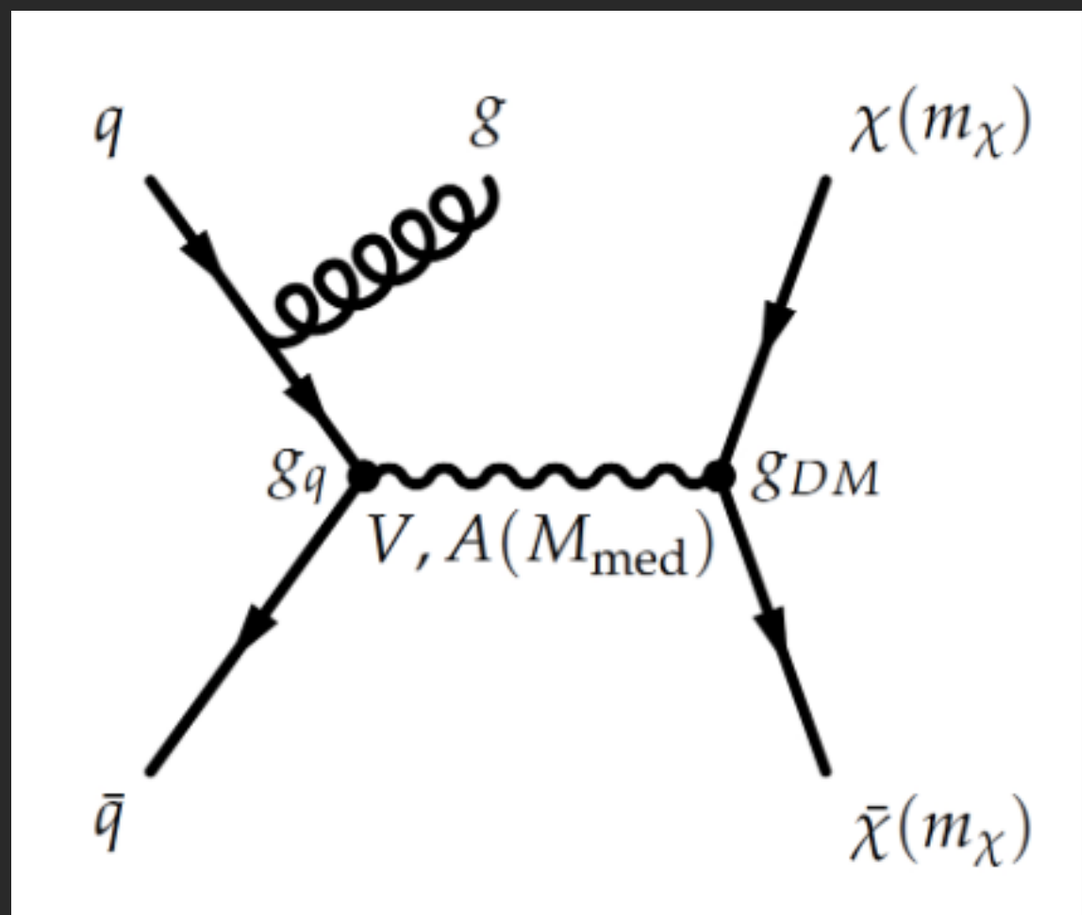
but comparison between the two requires a model

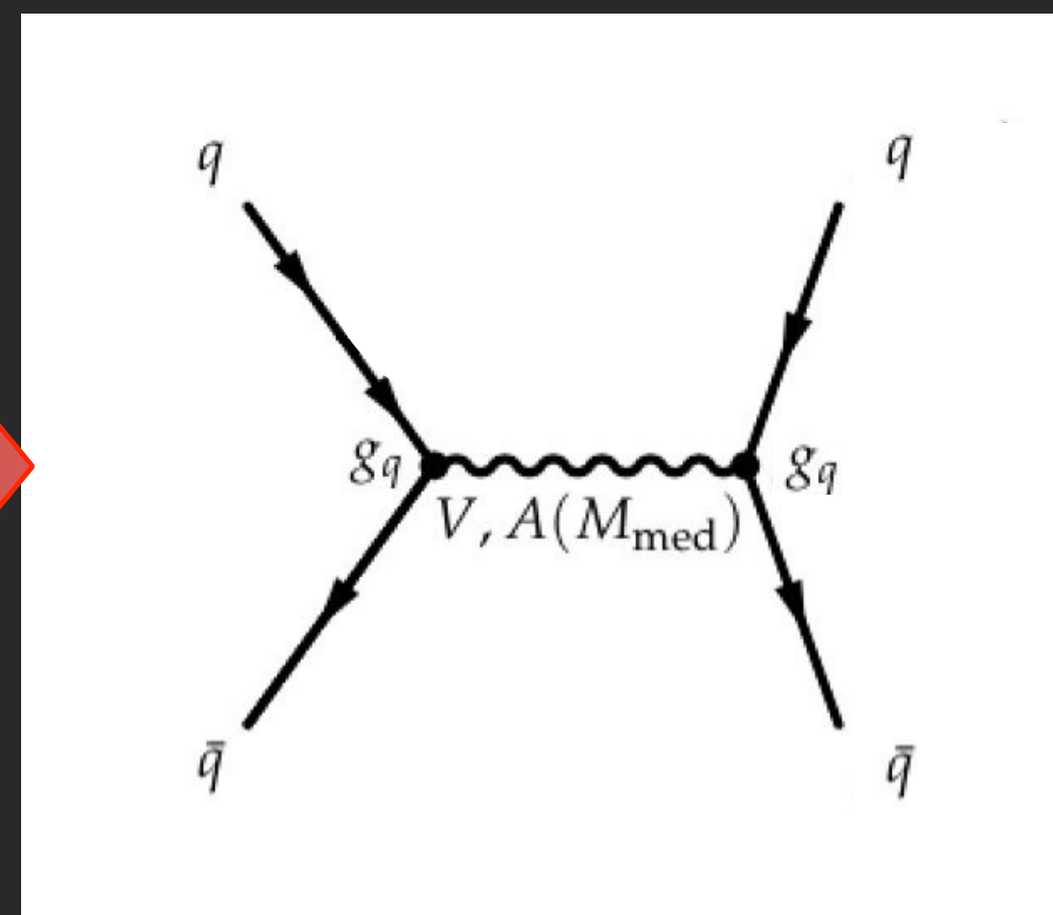
Searching for Dark Sector Interactions

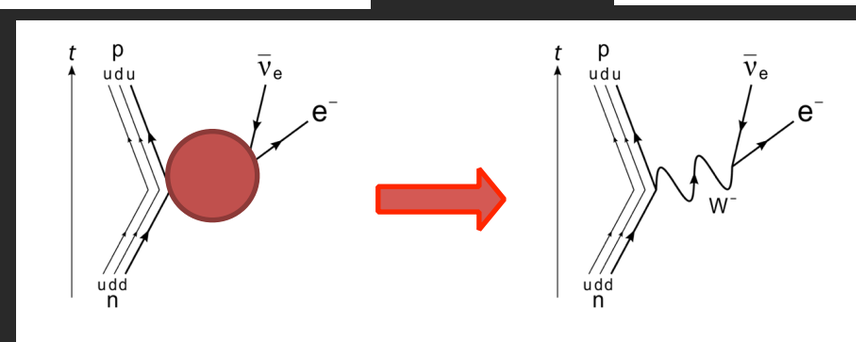


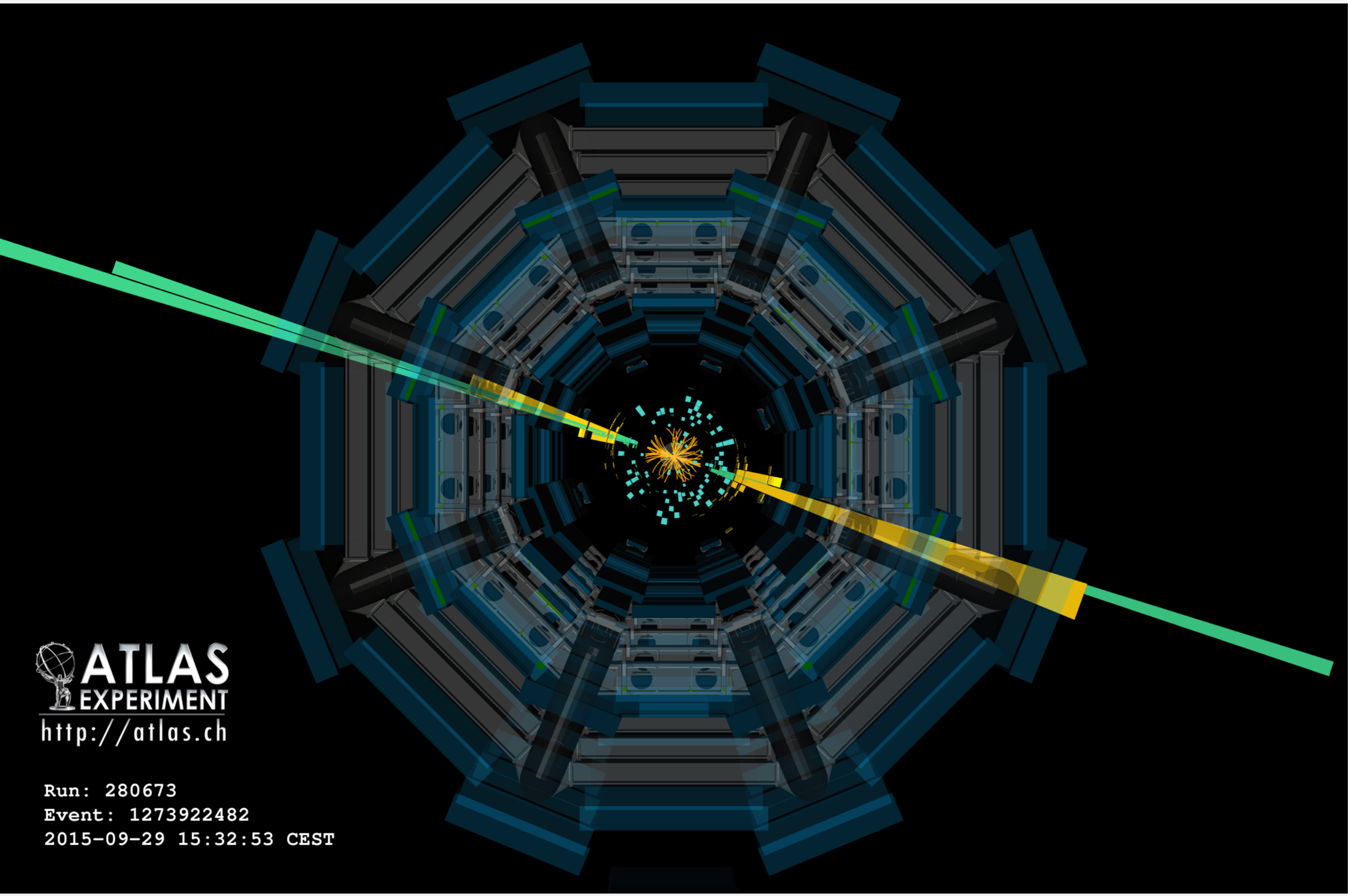


Searching for Dark Sector Interactions








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

ATLAS Dijet Resonance Search at 13 TeV

Physics Letters B 754 (2016) 302–322
ATLAS-CONF-2016-069

Model: DM interactions are rare because resonance is heavy

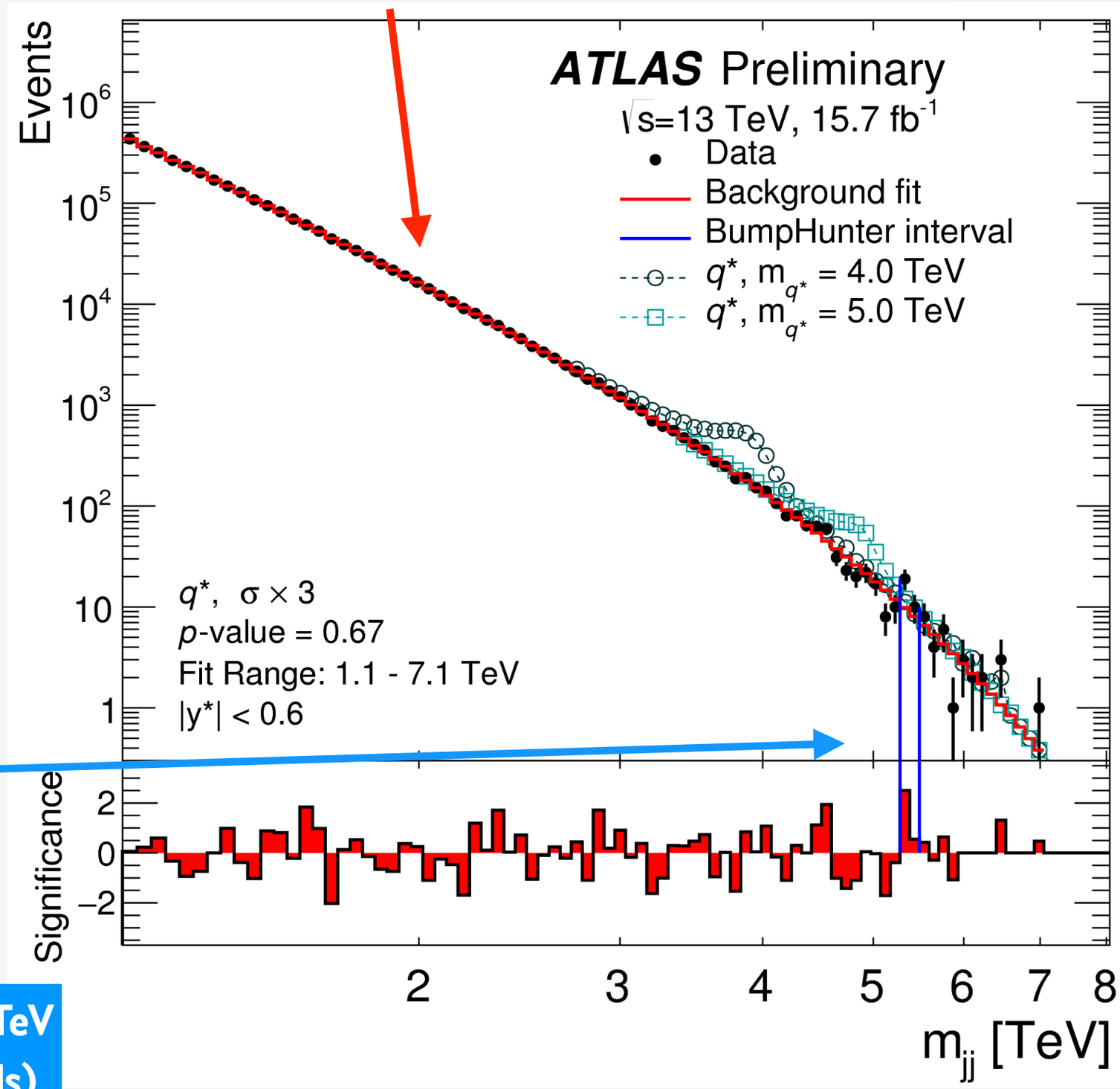
Data-driven background fit

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

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



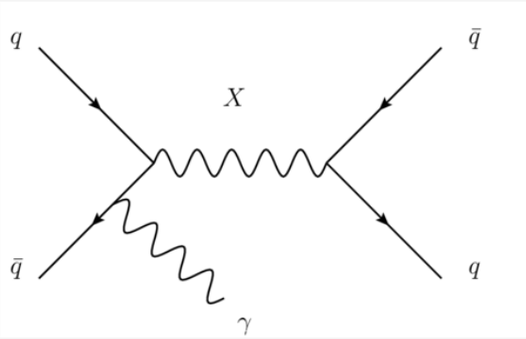
Most discrepant region (p-value 0.67)

Only probing above M ~ 1 TeV (single jet trigger thresholds)

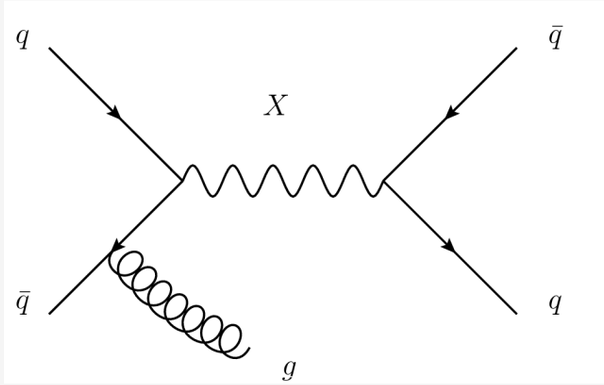
ATLAS Photon+Dijet and Jet + Dijet

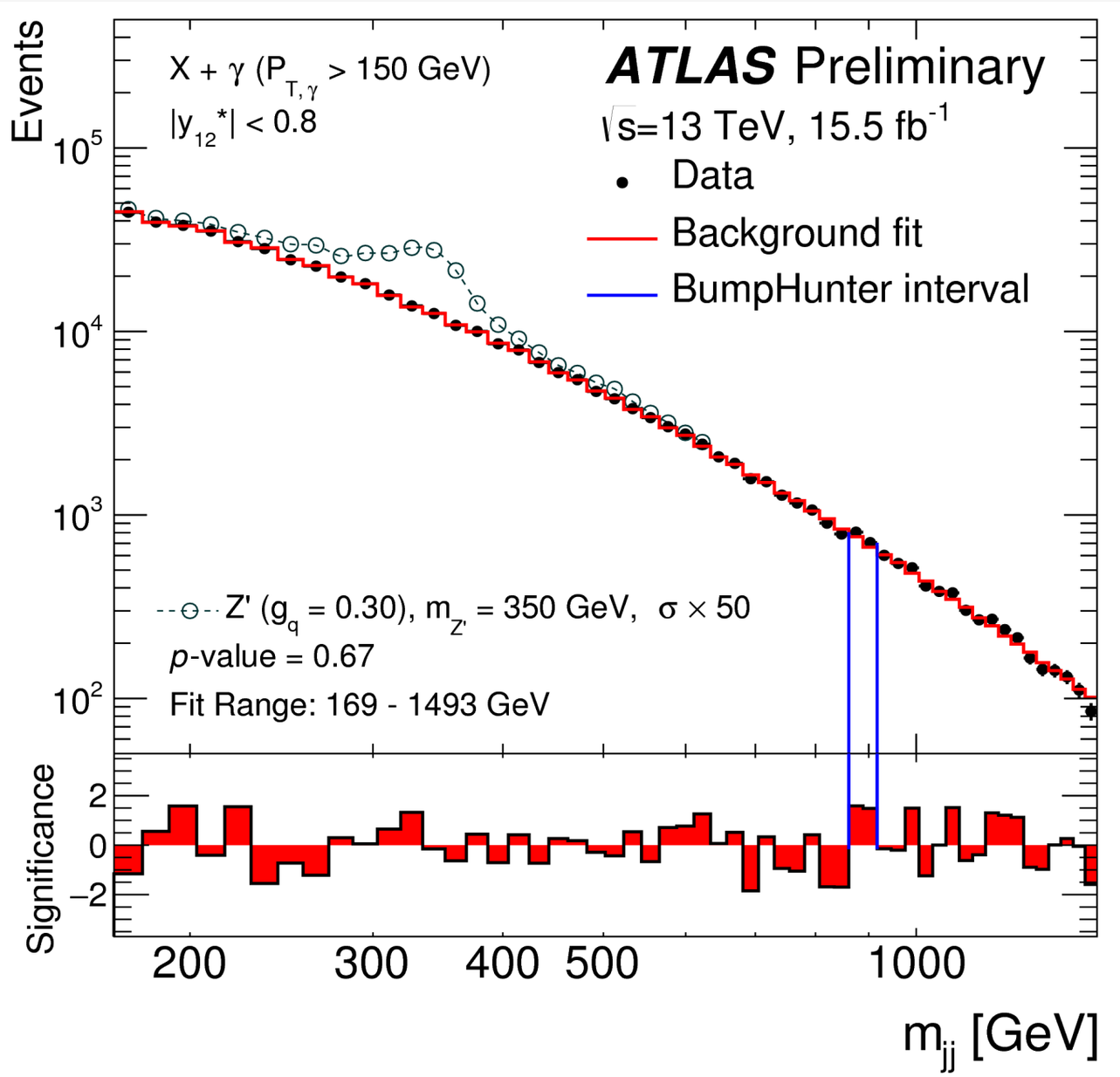
ATLAS-CONF-2016-070

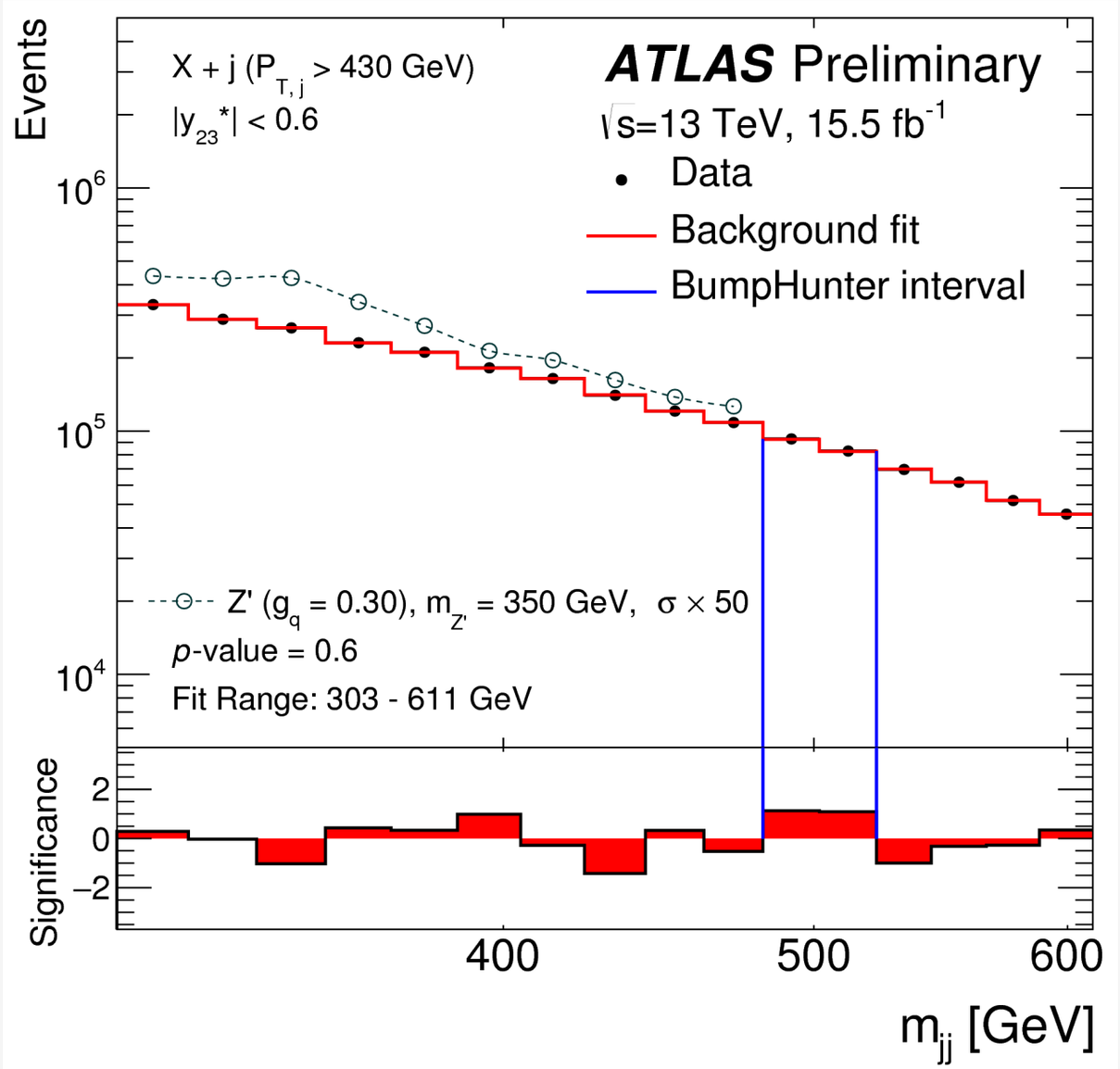
Trigger on an ISR photon to avoid the high thresholds of the jet triggers



DM interactions are rare because coupling is tiny

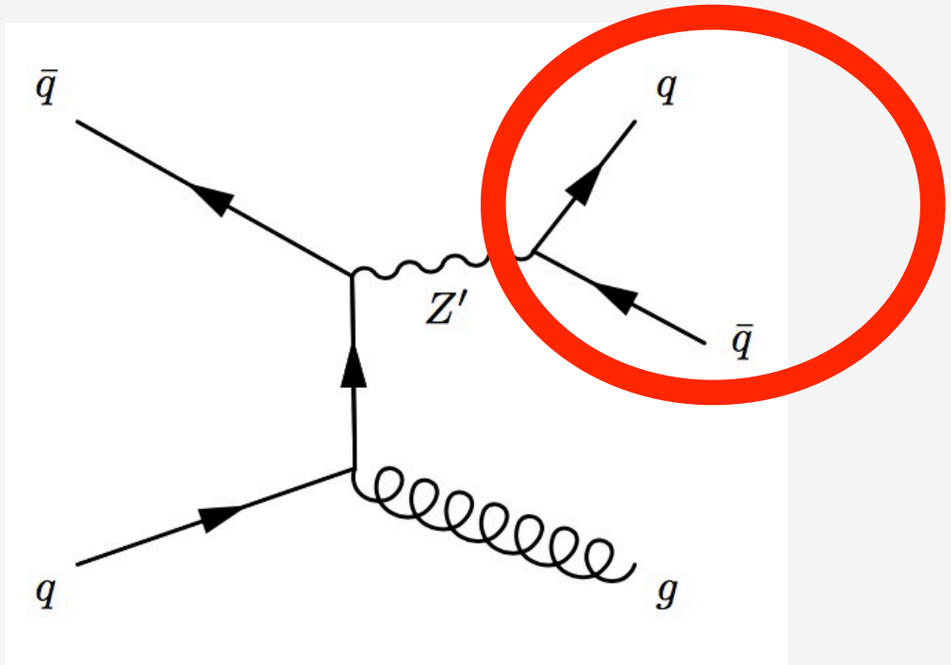






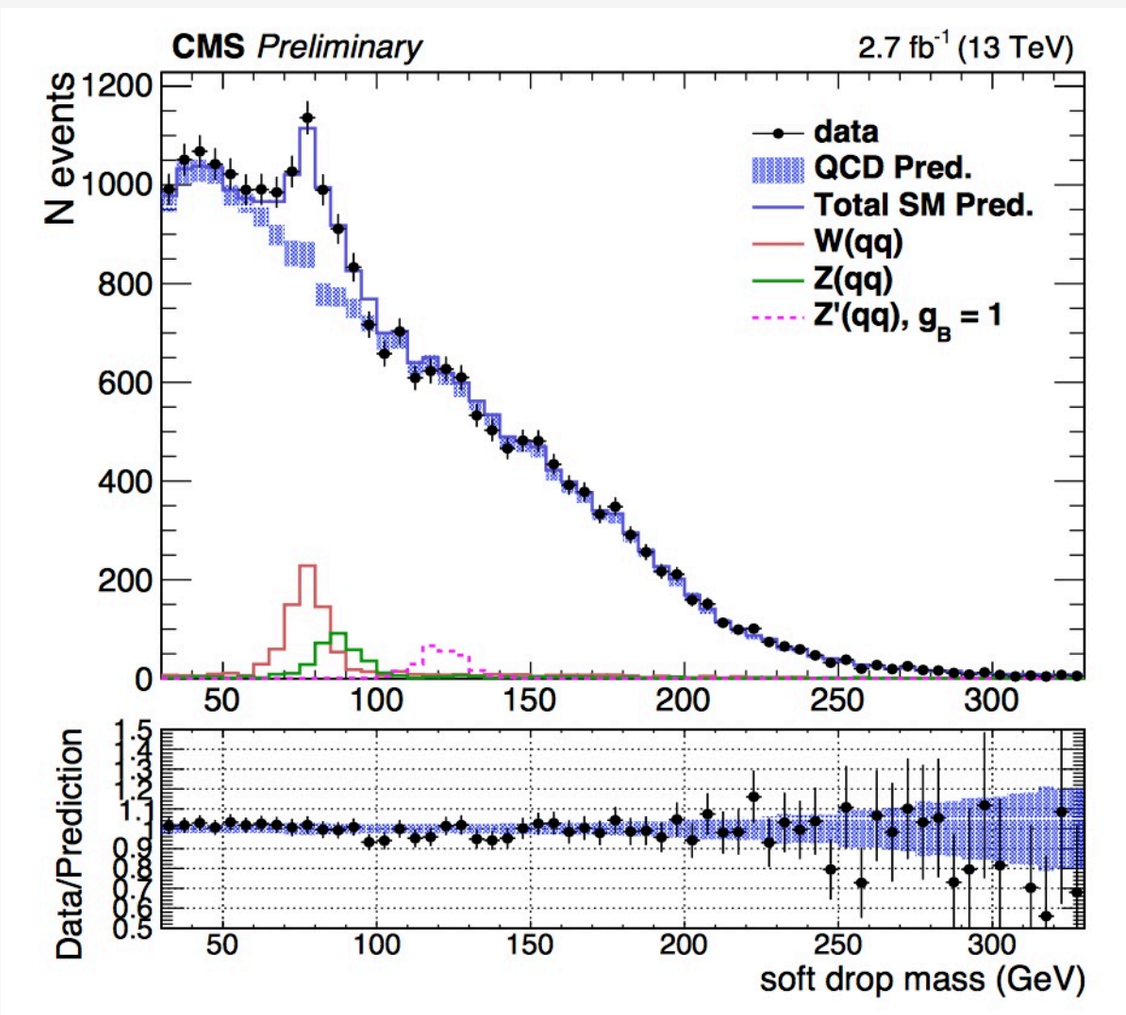
CMS Jet + Highly-boosted Dijet

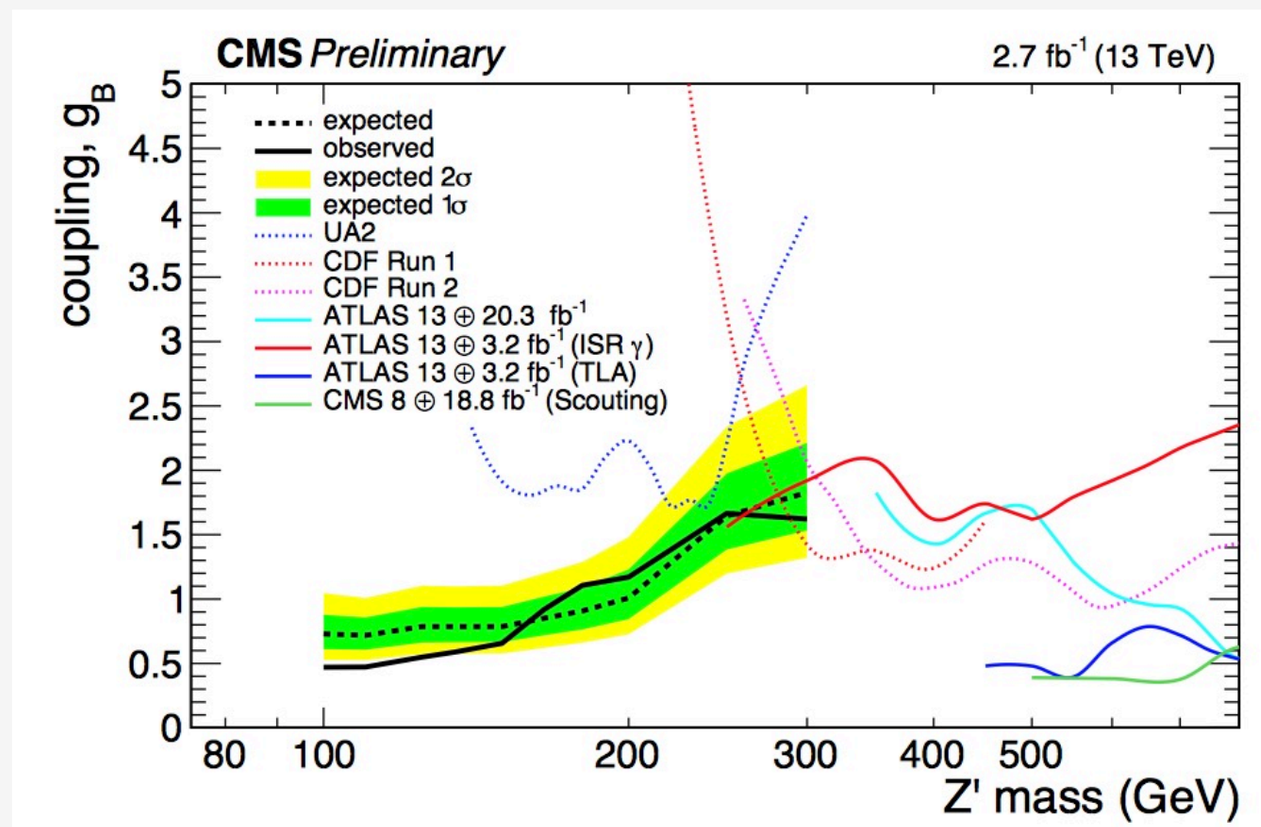
CMS PAS EXO 16 030



Collimated into single jet

DM interactions are rare because coupling is tiny





Data Scouting, Trigger-Level, and Real-time analysis

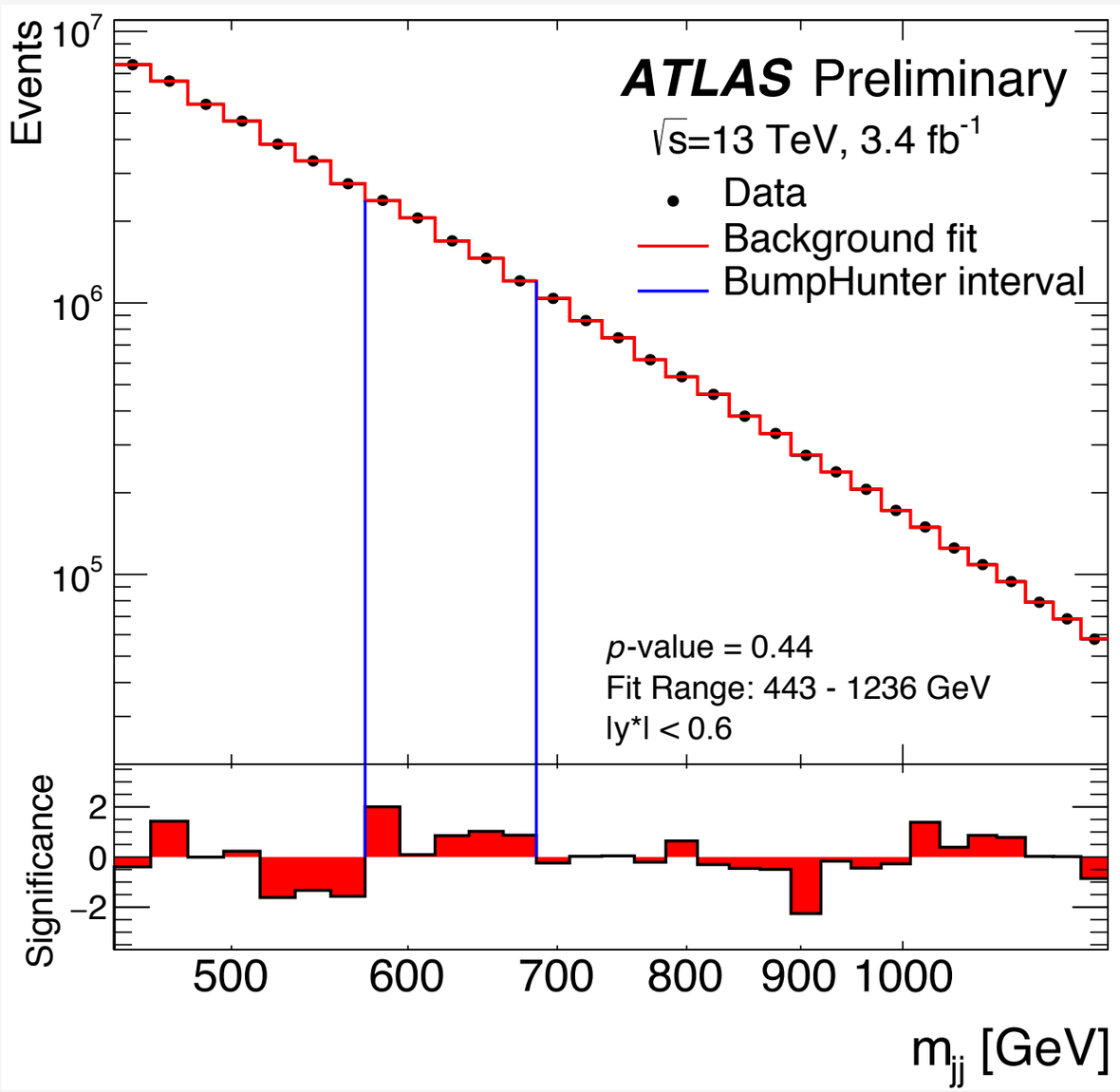
DM interactions are rare because coupling is tiny

Usual collider detector readout: record everything for a collision Bandwidth = Rate * Event Size

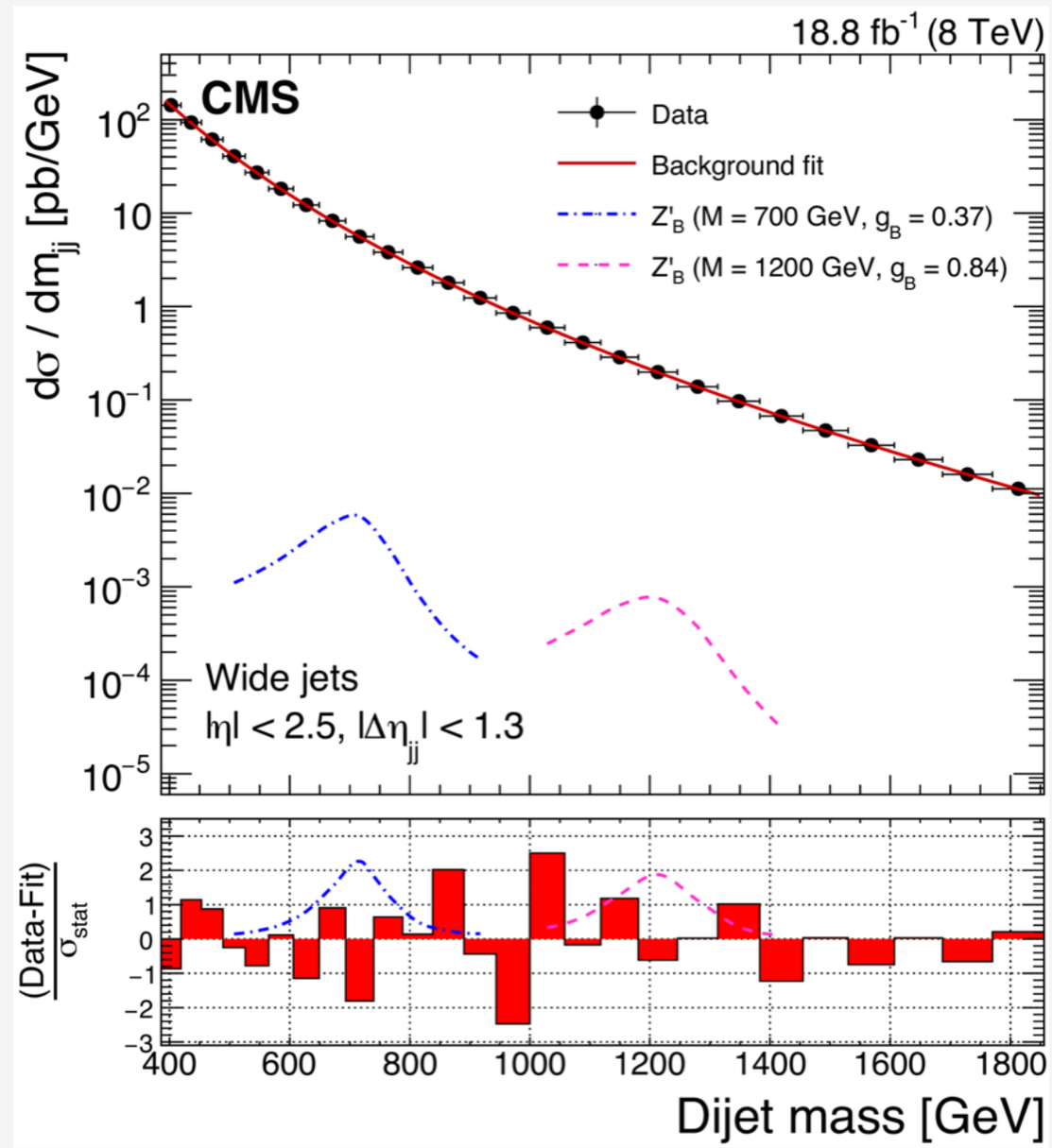
For signals buried in huge background, **reduce data size/complexity to increase rate of recorded data**

ATLAS: factor O(100x) increase in event rates

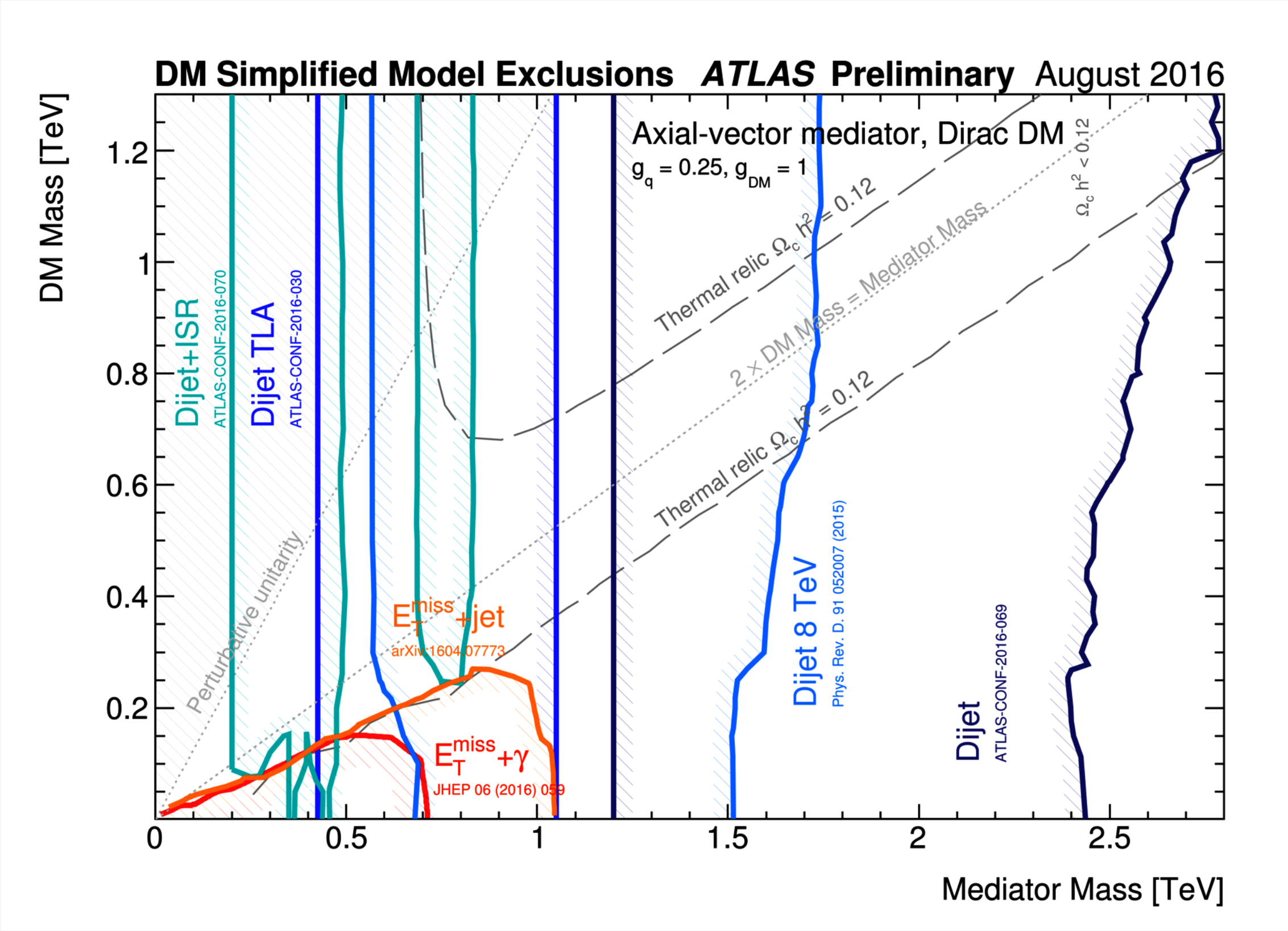
ATLAS-CONF-2016-029



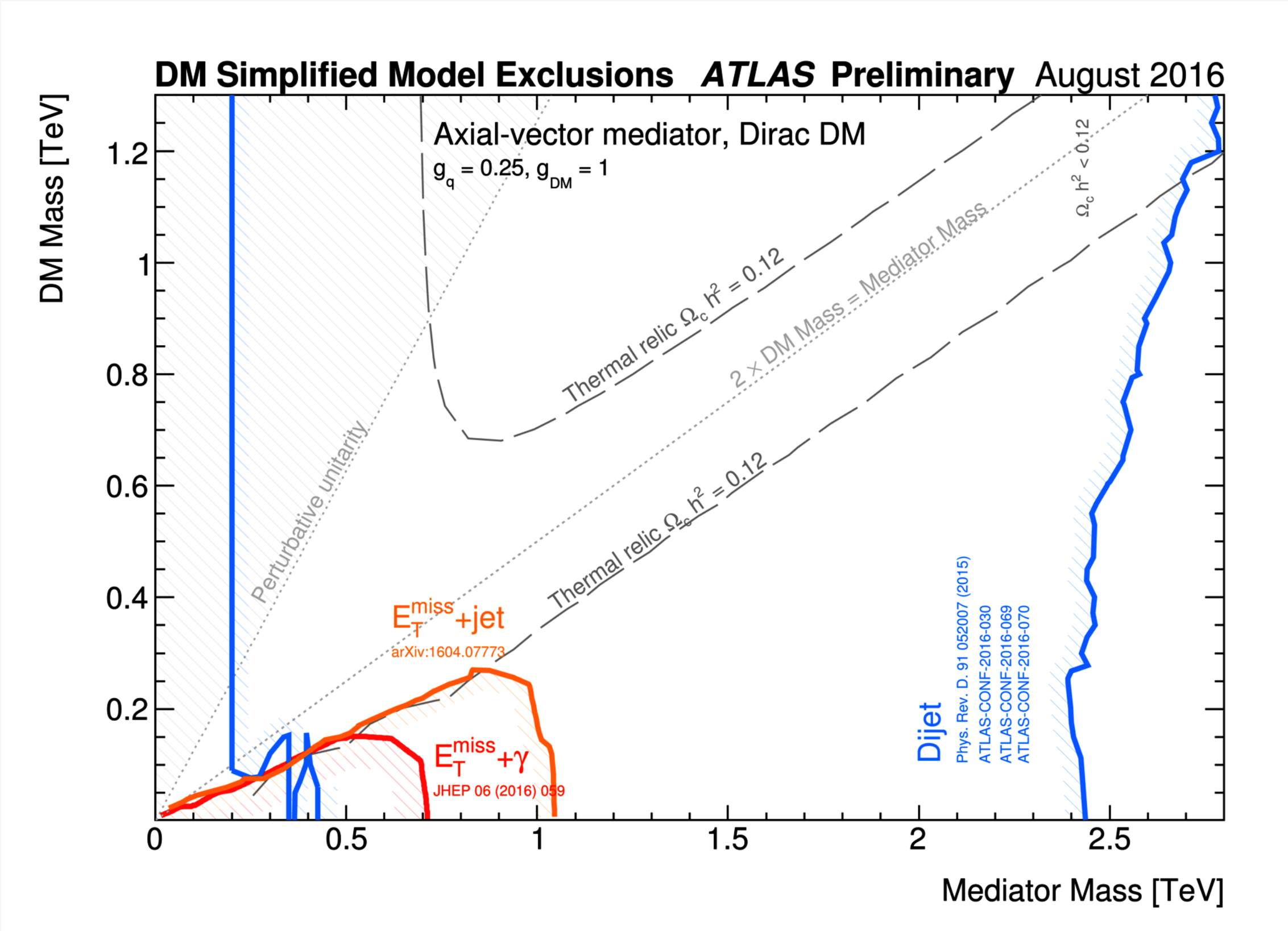
arXiv:1604.08907



ATLAS MET+X and Dijet Searches



ATLAS MET+X and Dijet Searches: Z'–quark coupling of 0.25



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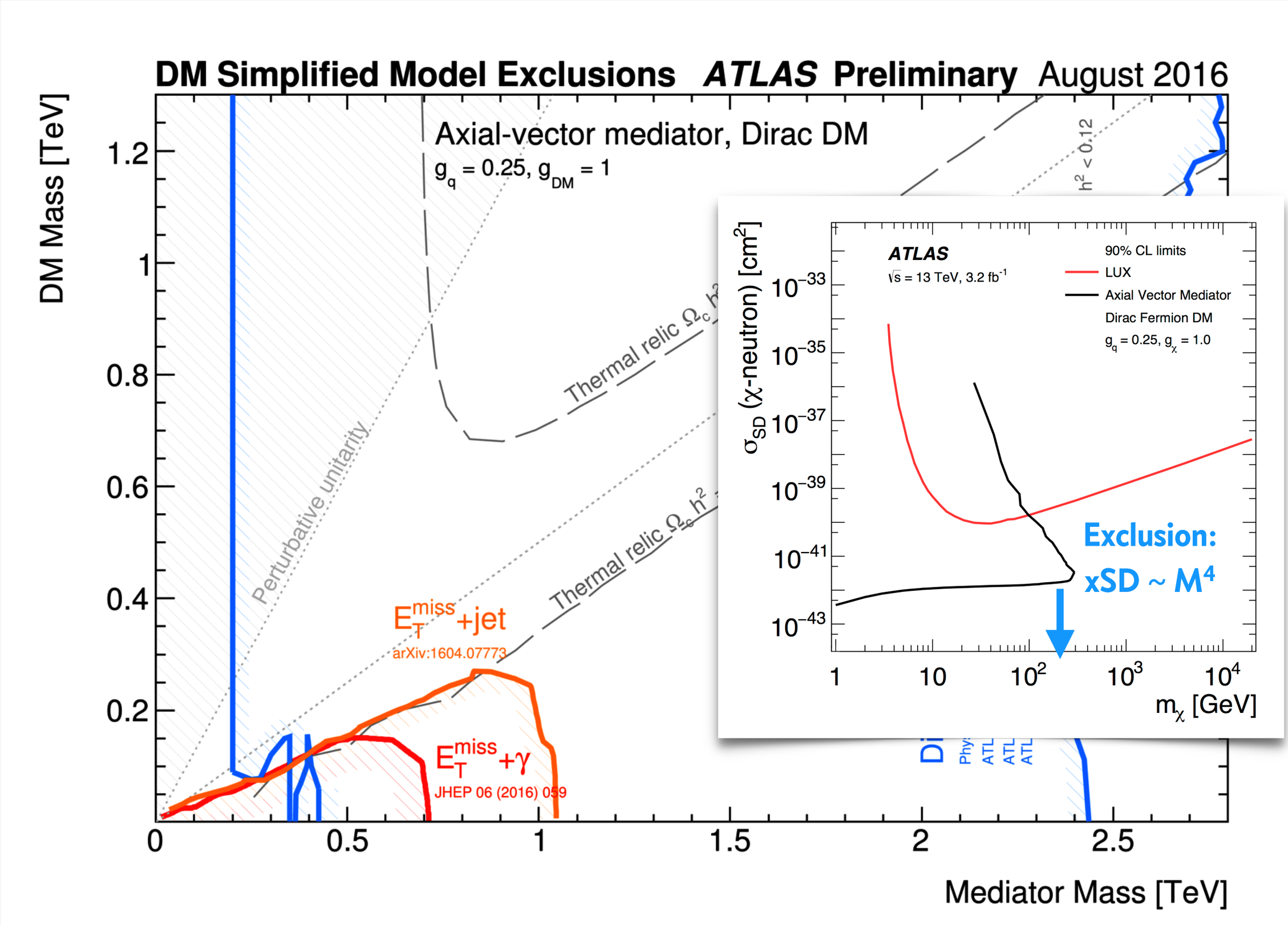
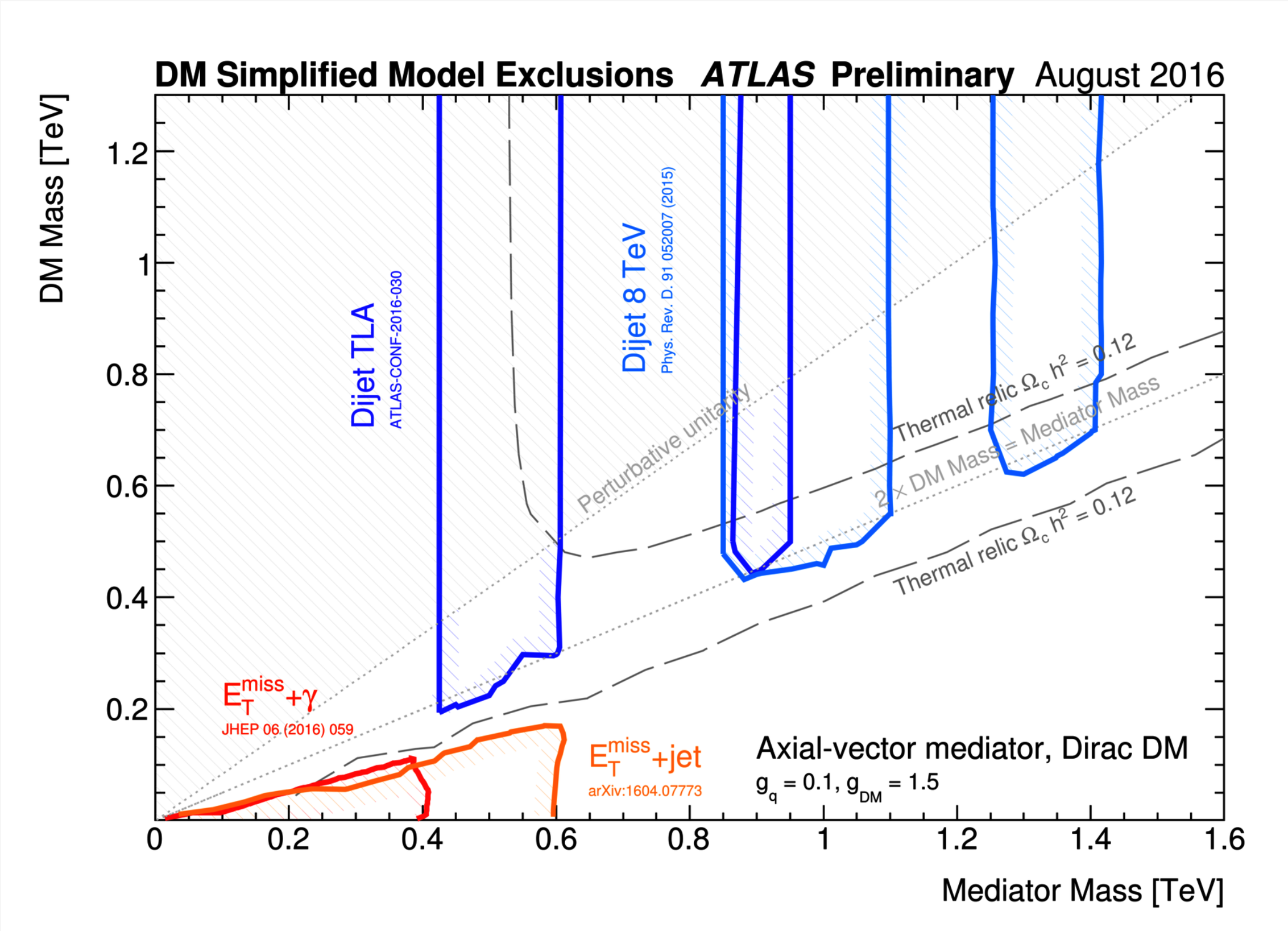


ATLAS MET+X and Dijet Searches: Z'–quark coupling of 0.1



Take-away: LHC searches for dark interactions can be much more sensitive than searches for WIMP production alone

Broadening the LHC Dark Matter Search Program

LHC Dark Matter Forum / Working Group (2014–)
http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

Why?

Complement diverse (but not very systematic) chance collaborations between experiment and theory

Make the most of what little we know of DM

Pay attention to great ideas from theory and help make things happen inside the collaborations

Is the current program the best we can do?

arXiv:1507.00966

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August 8, 2016

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arXiv:1603.04156

CERN-LPCC-2016-001

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

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Broadening the LHC Dark Matter Search Program

LHC Dark Matter Forum / Working Group (2014–)

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:1507.00966

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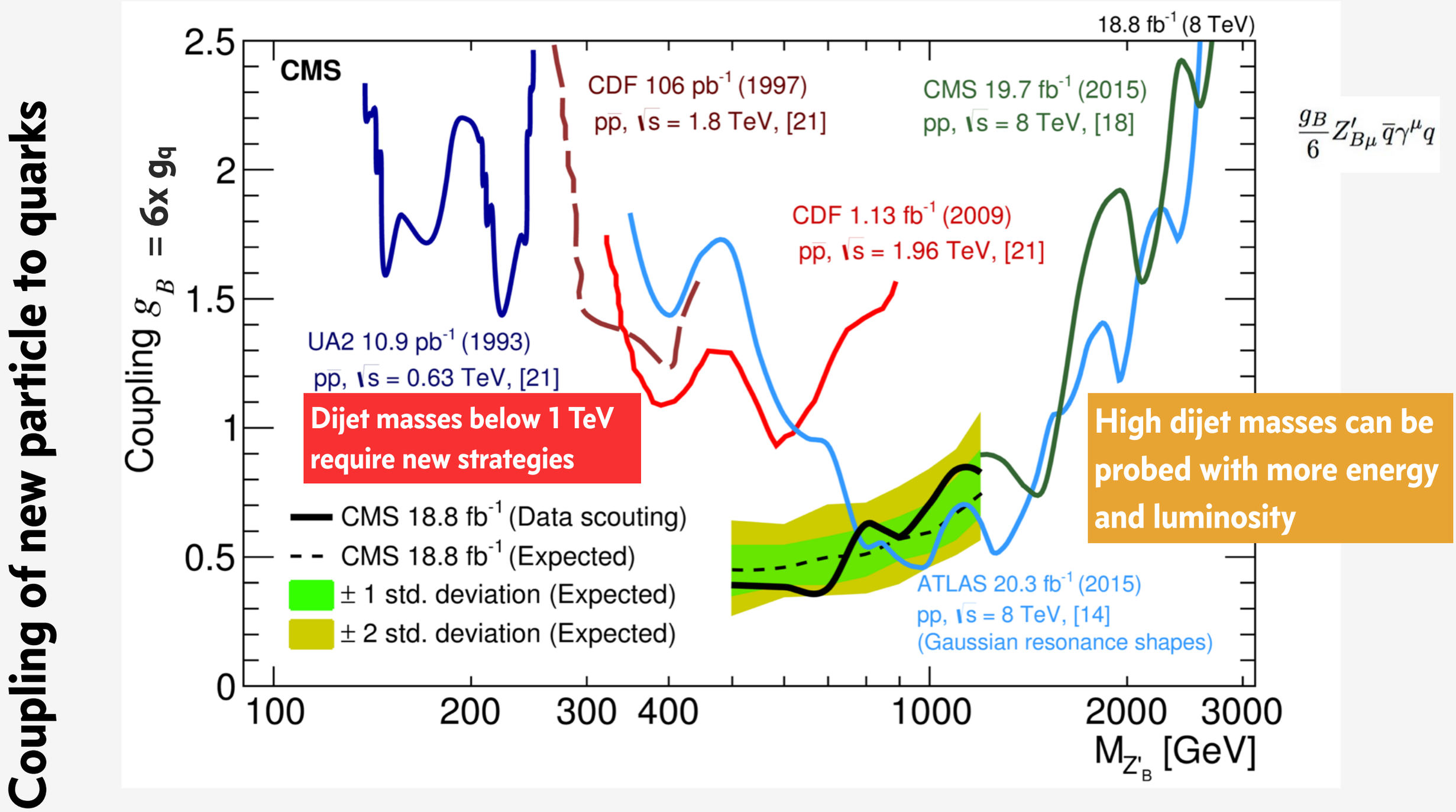
Additional Slides

Run 1 Results: Dijet Resonances in Heavy DM Limit

arXiv:1604.08907

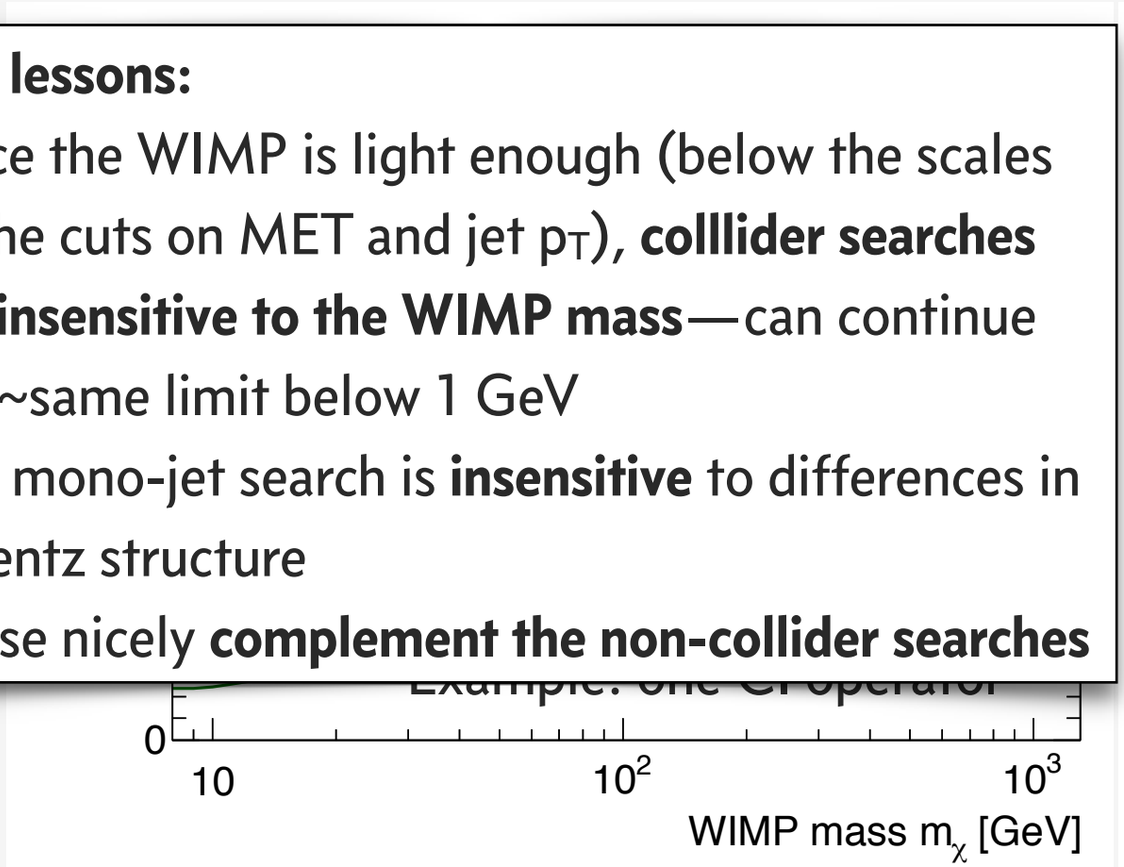
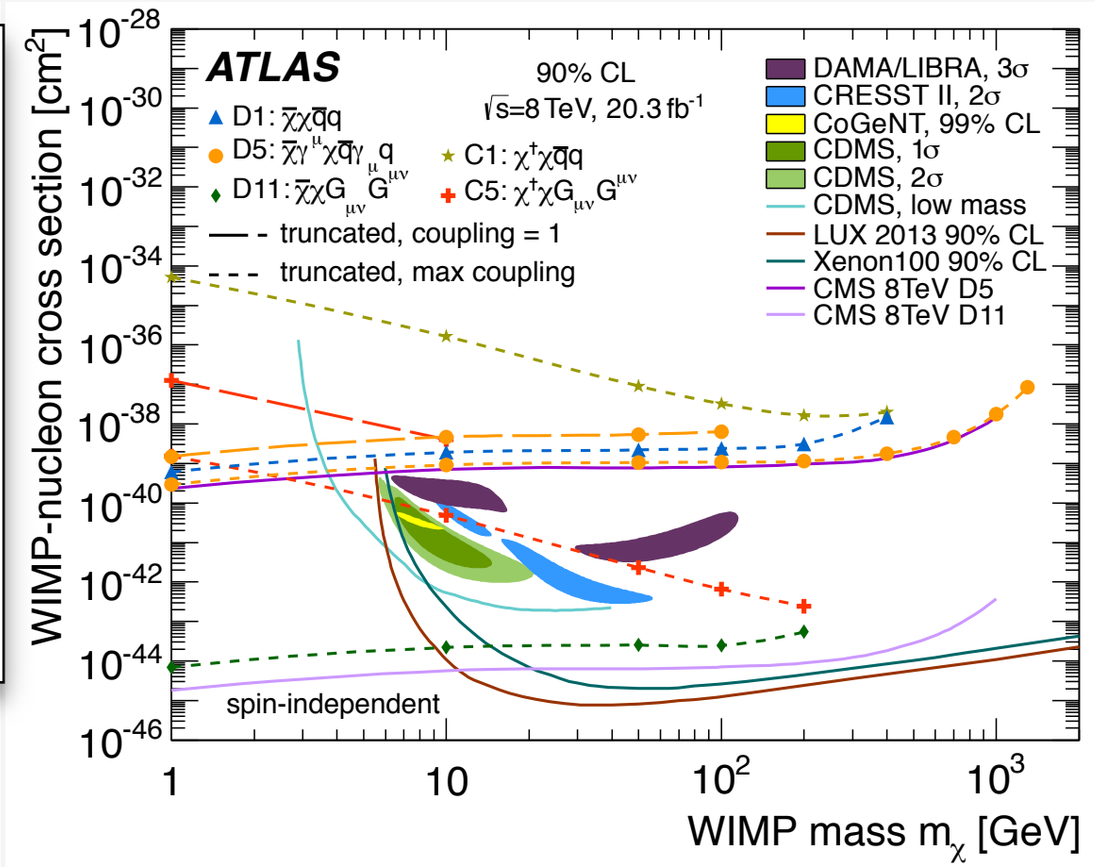
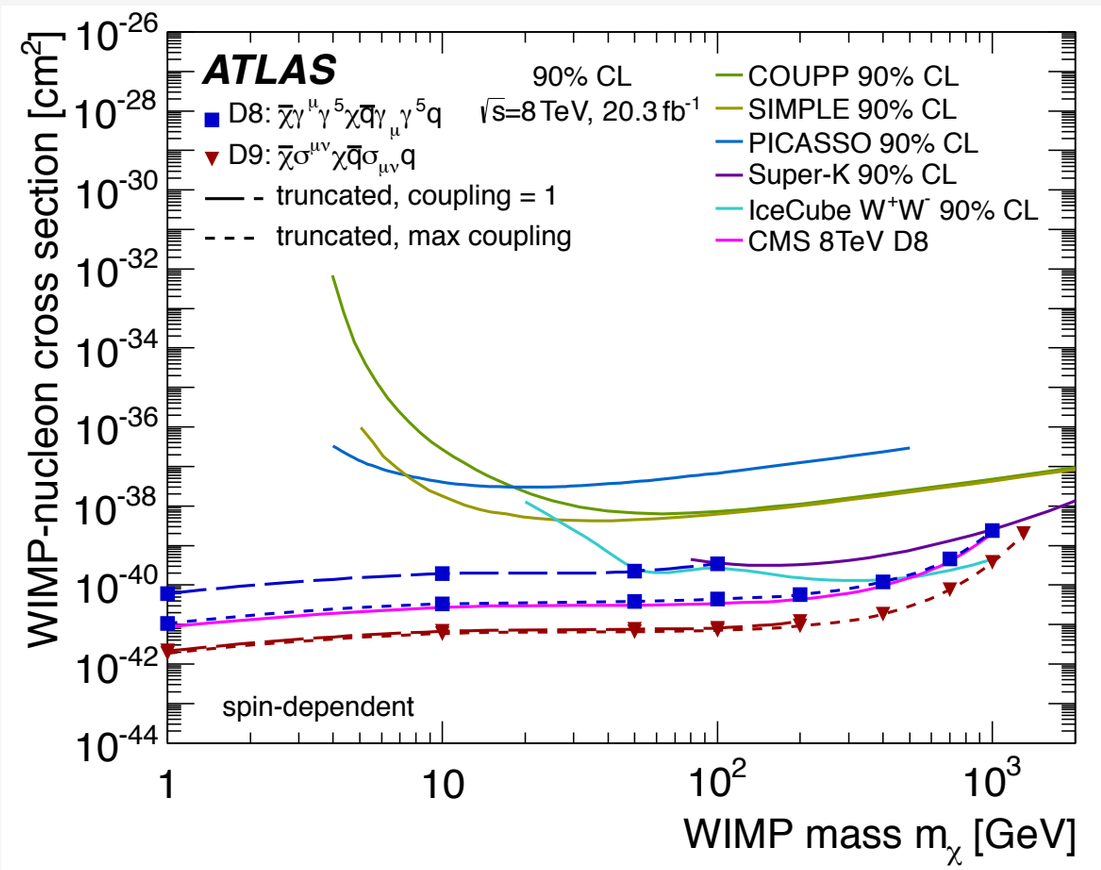
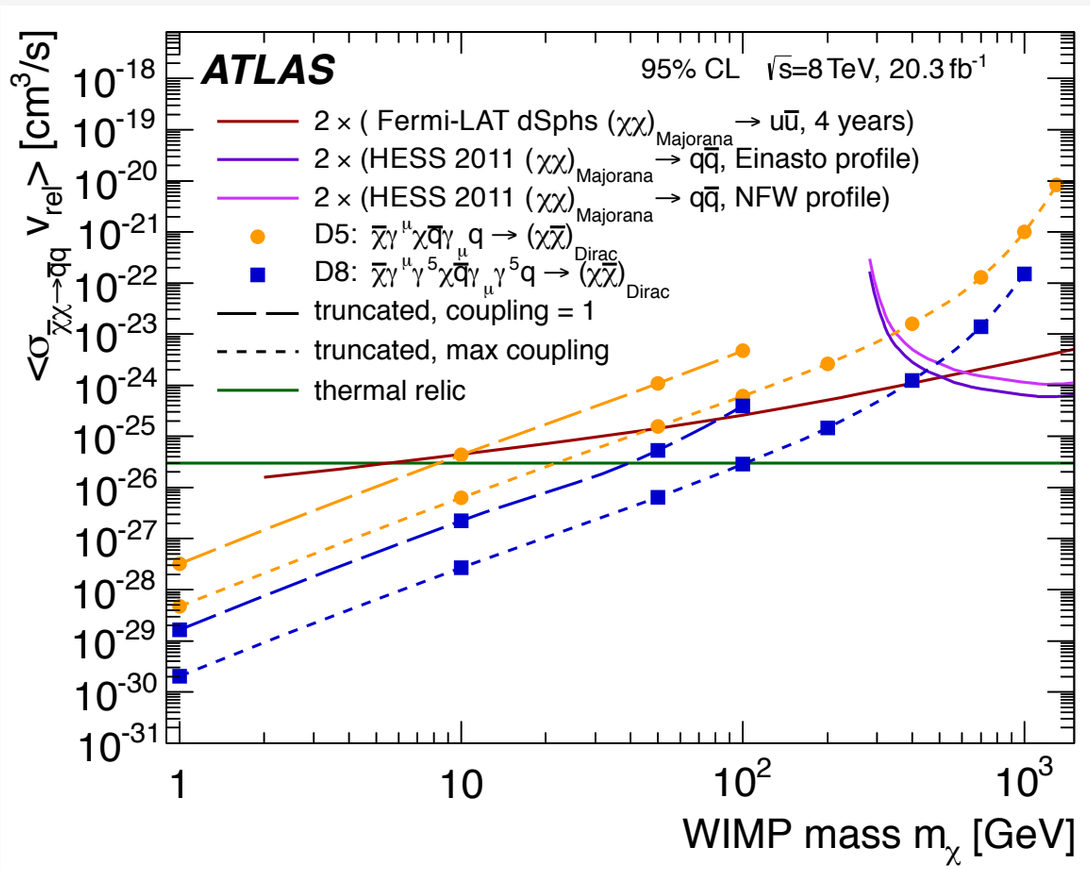


New particle mass

Only probing SM-like couplings near current LHC thresholds of M ~ 1 TeV (limited by single jet trigger thresholds)

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

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