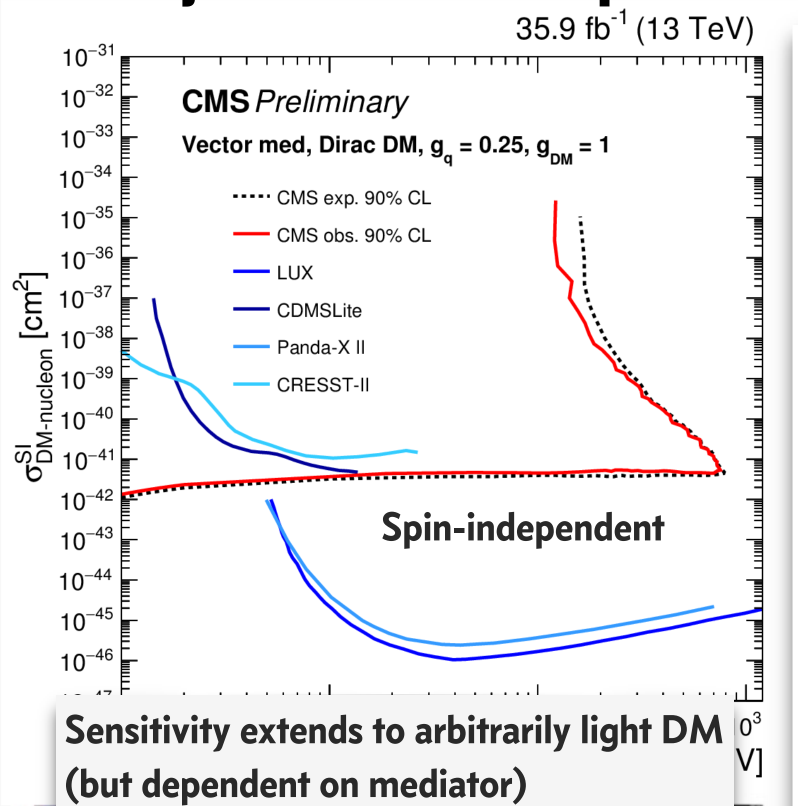
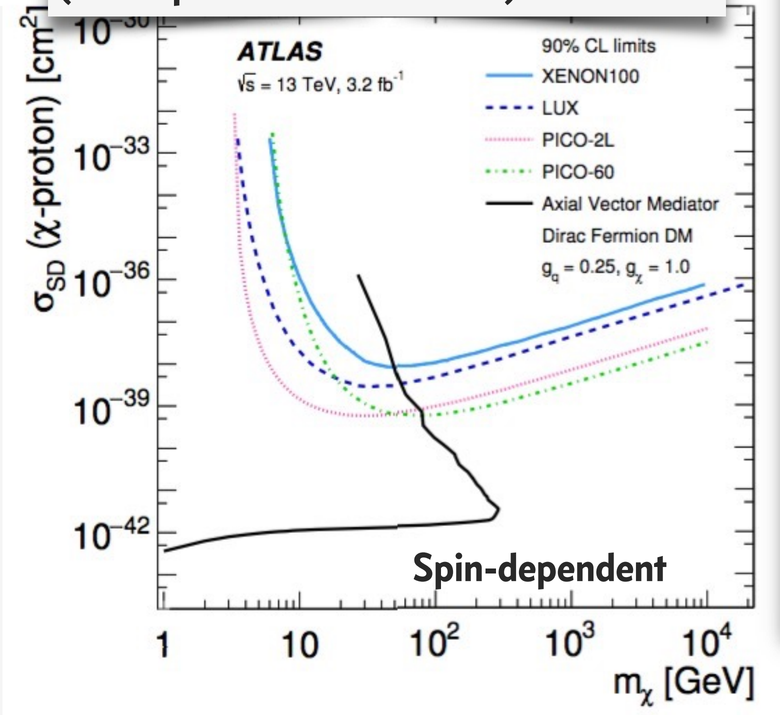
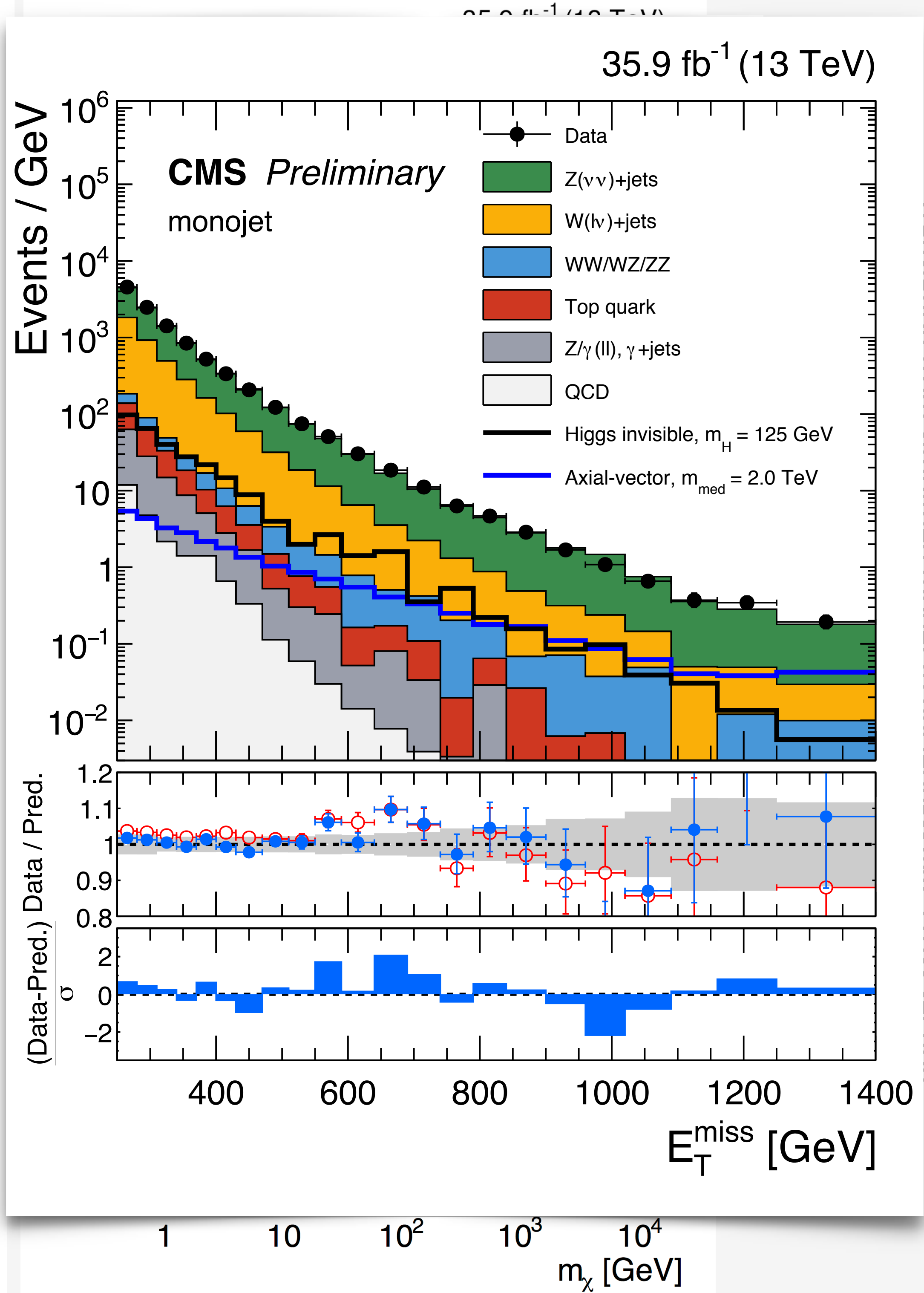
13 TeV mono-jet results with simplified models



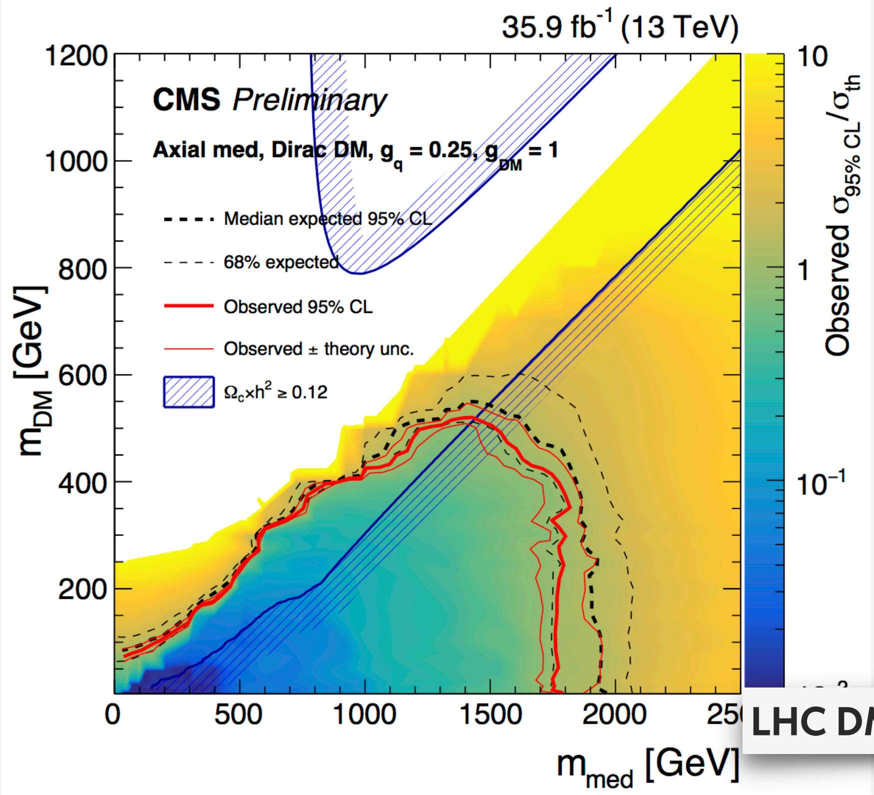
Sensitivity extends to arbitrarily light DM (but dependent on mediator)



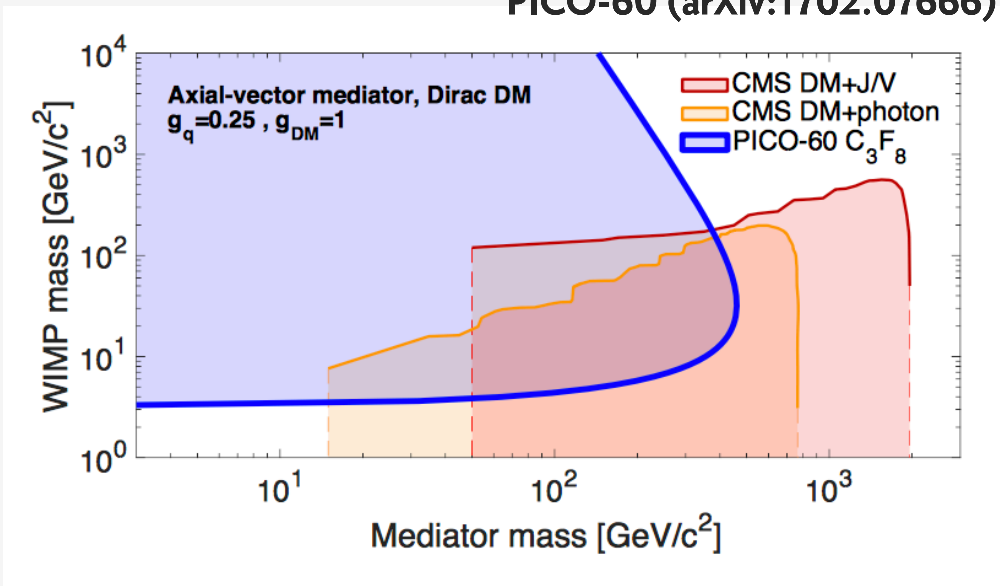


Translation from simplified model to nucleon-WIMP cross section

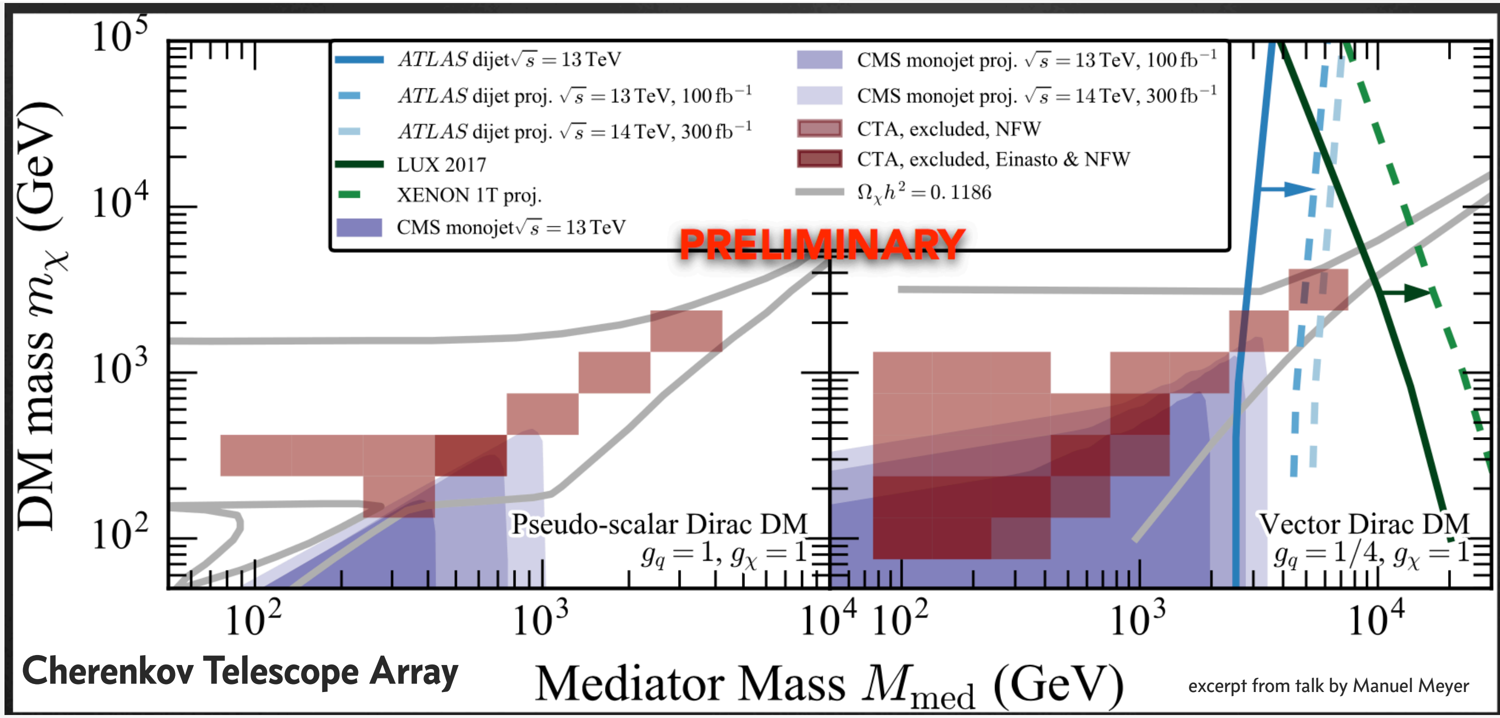
Comparison to Non-collider searches for Dark Matter



PICO-60 (arXiv:1702.07666)



LHC DMF simplified model language being adopted by non-collider DM searches



CMS monojet: Sirunyan et el., arXiv: 1703.01651
LHC projection: Collider Reach Tool
ATLAS dijet: ATLAS-CONF-2016-069
LUX: Akerib et al. arXiv: 1608.07648
Xenon 1T: Aprile et al., arXiv: 1512.07501

Already Many MET+X Searches Done with 13 TeV Data by Last Summer

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

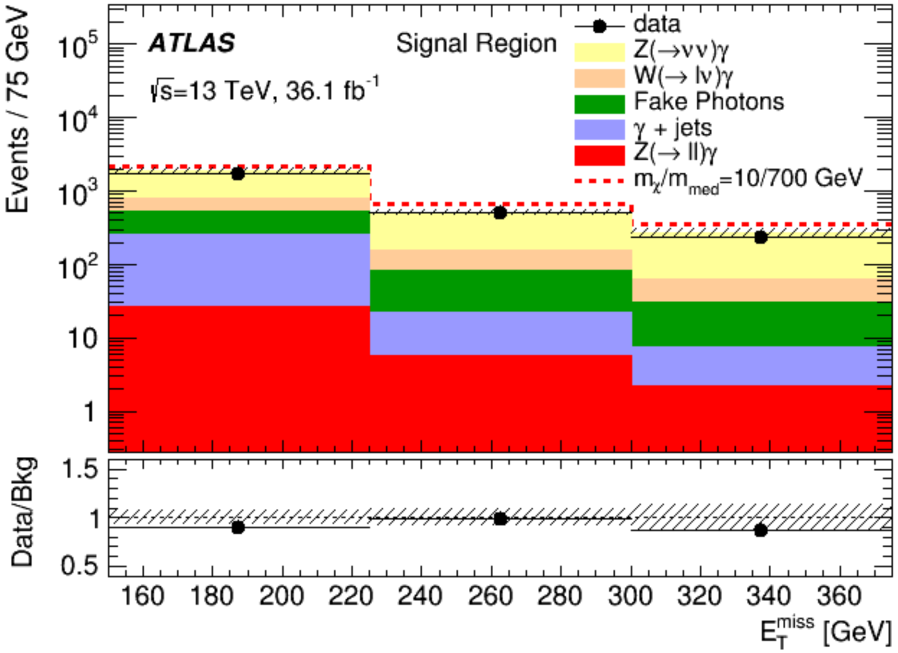
Eiko Yu

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

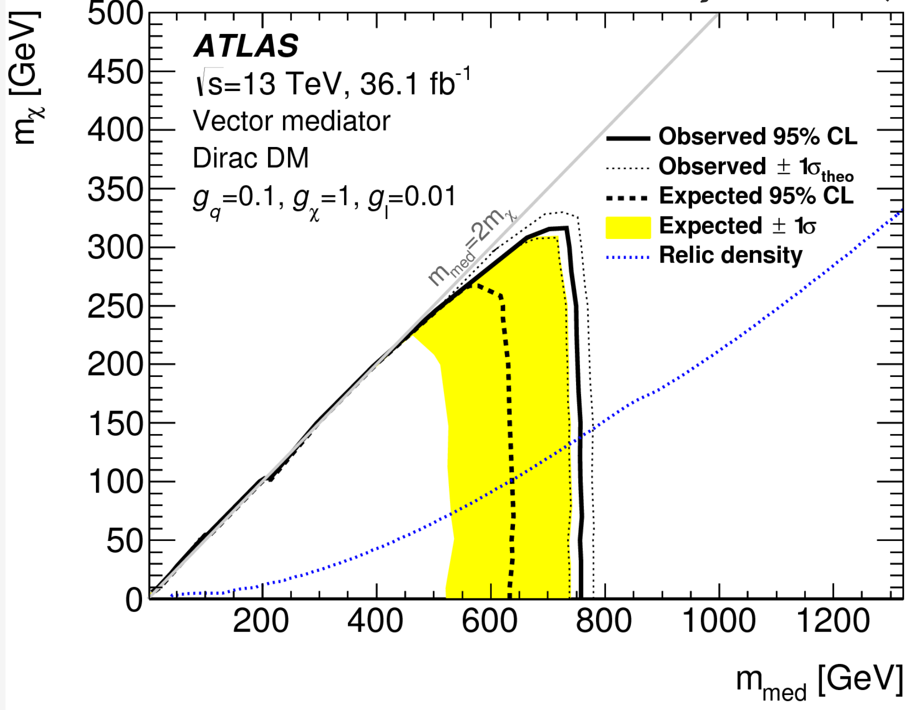
Steven Schramm

Publishing Results with 36/fb...

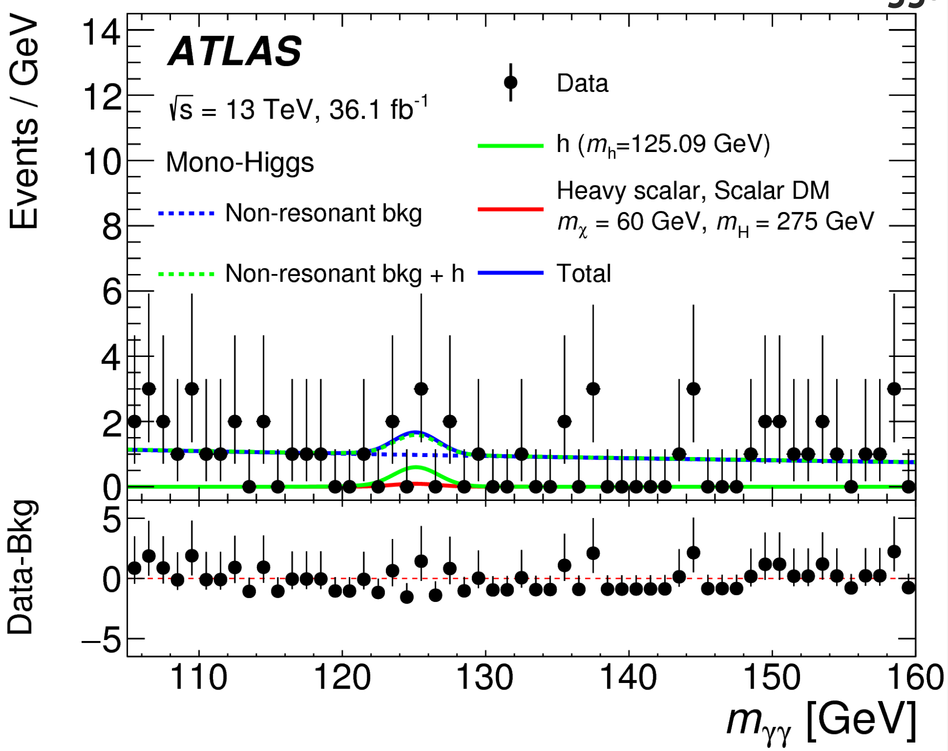
MET+Photon



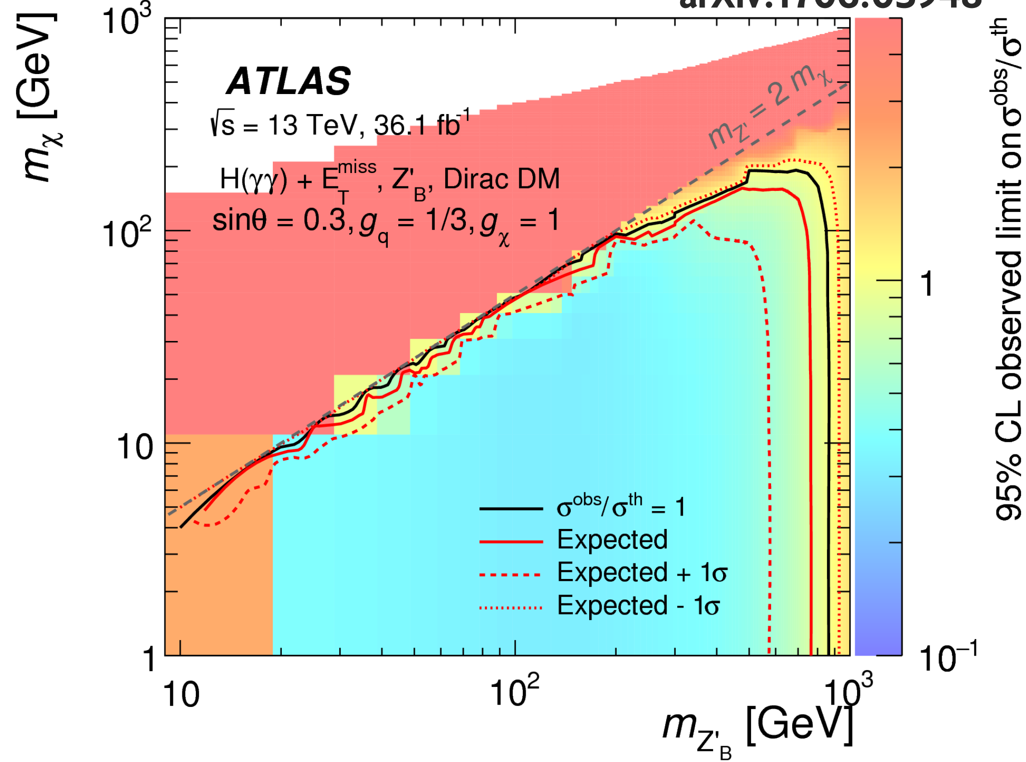
Eur. Phys. J. C 77 (2017) 393



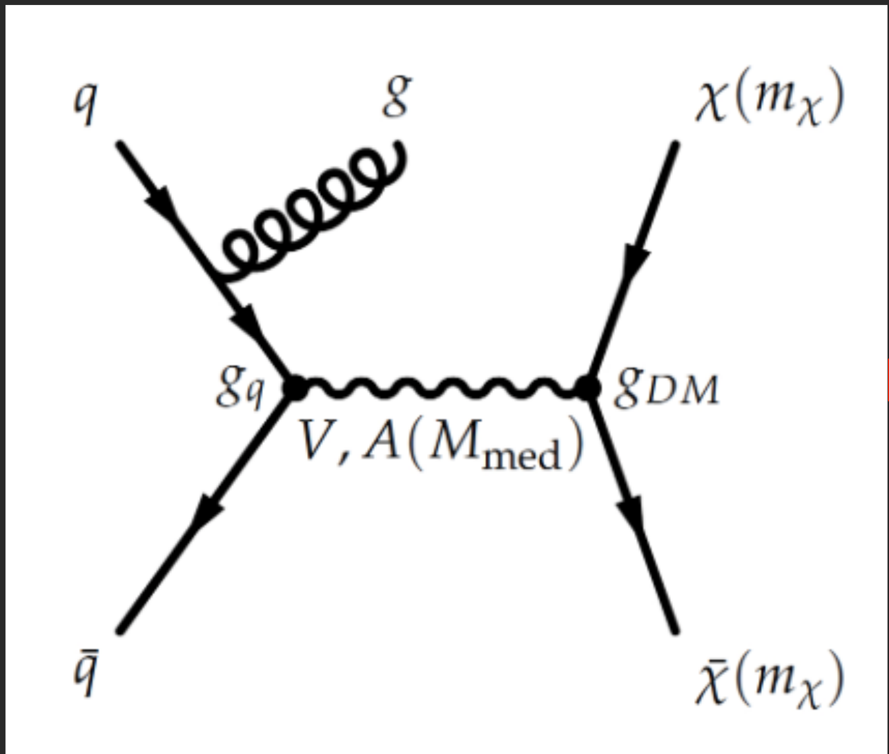
MET+Higgs

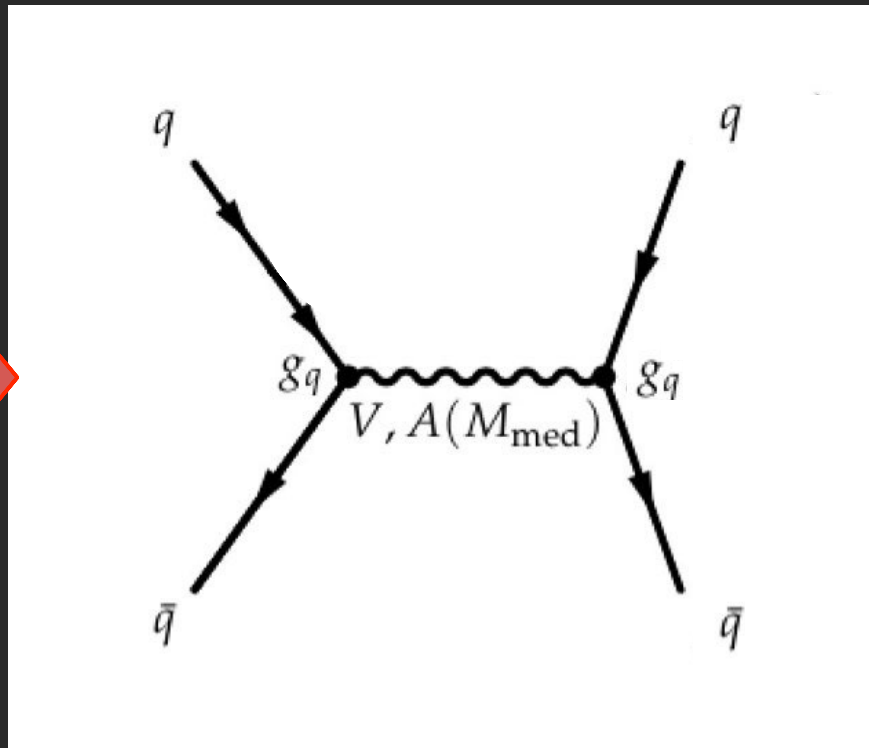


arXiv:1706.03948



Searching for Dark Sector Interactions





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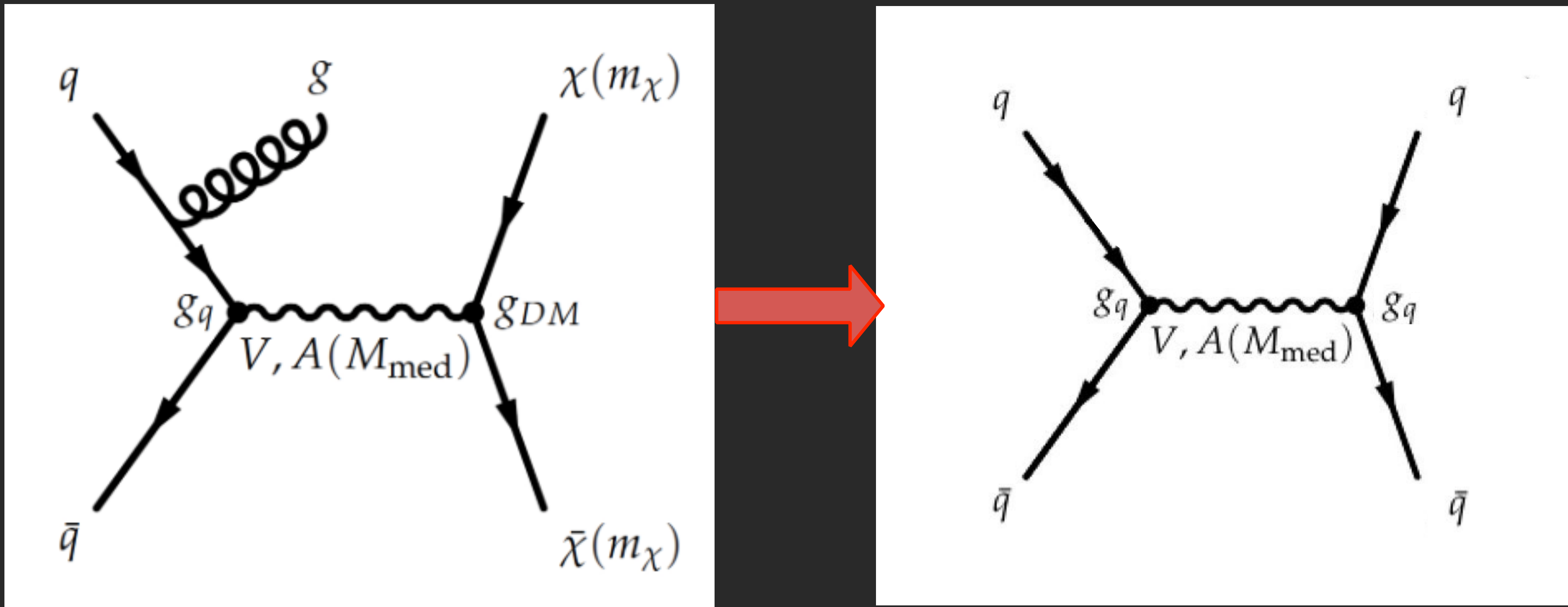
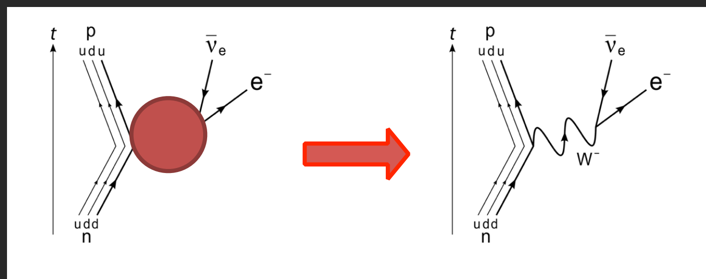
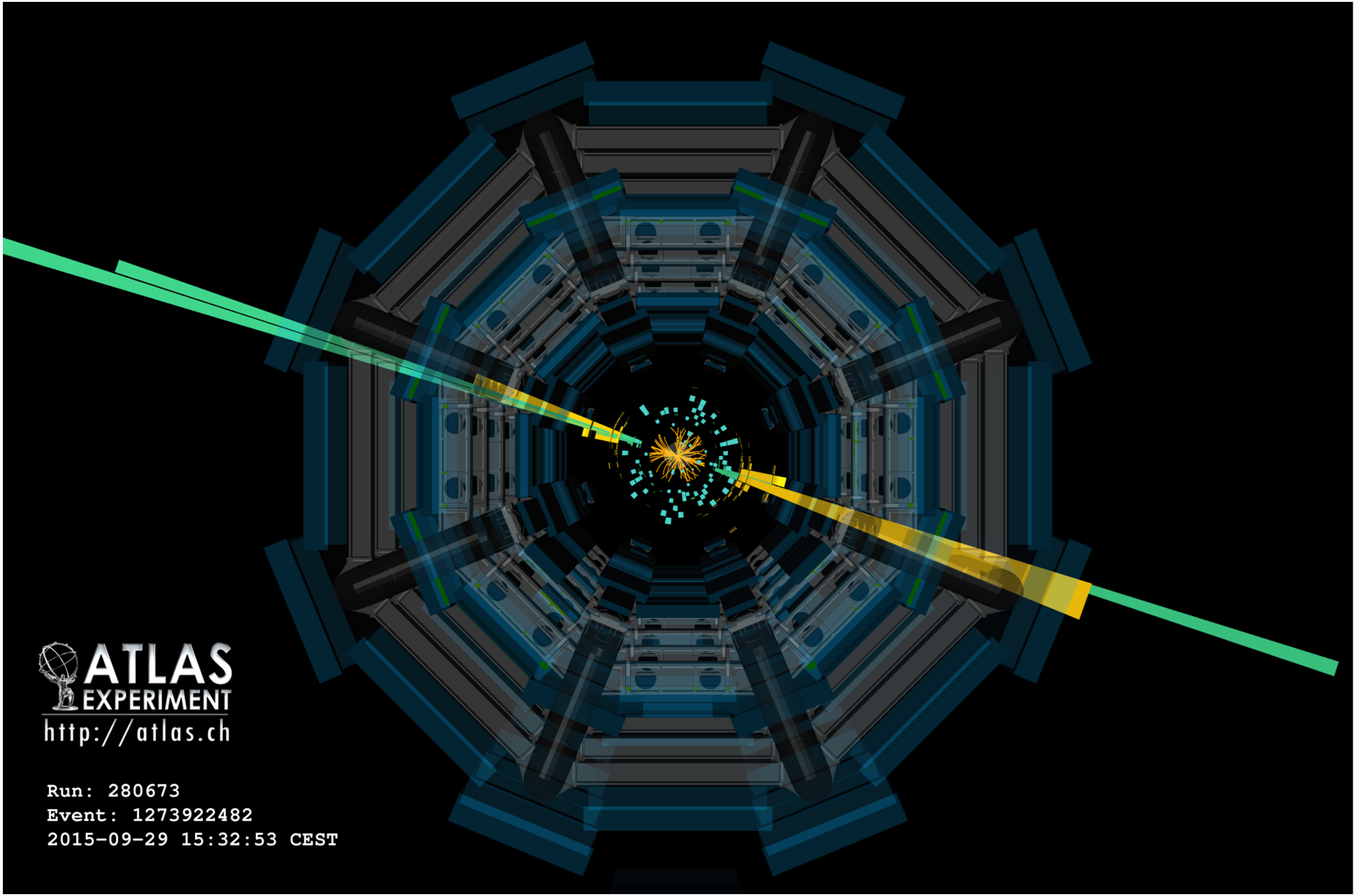
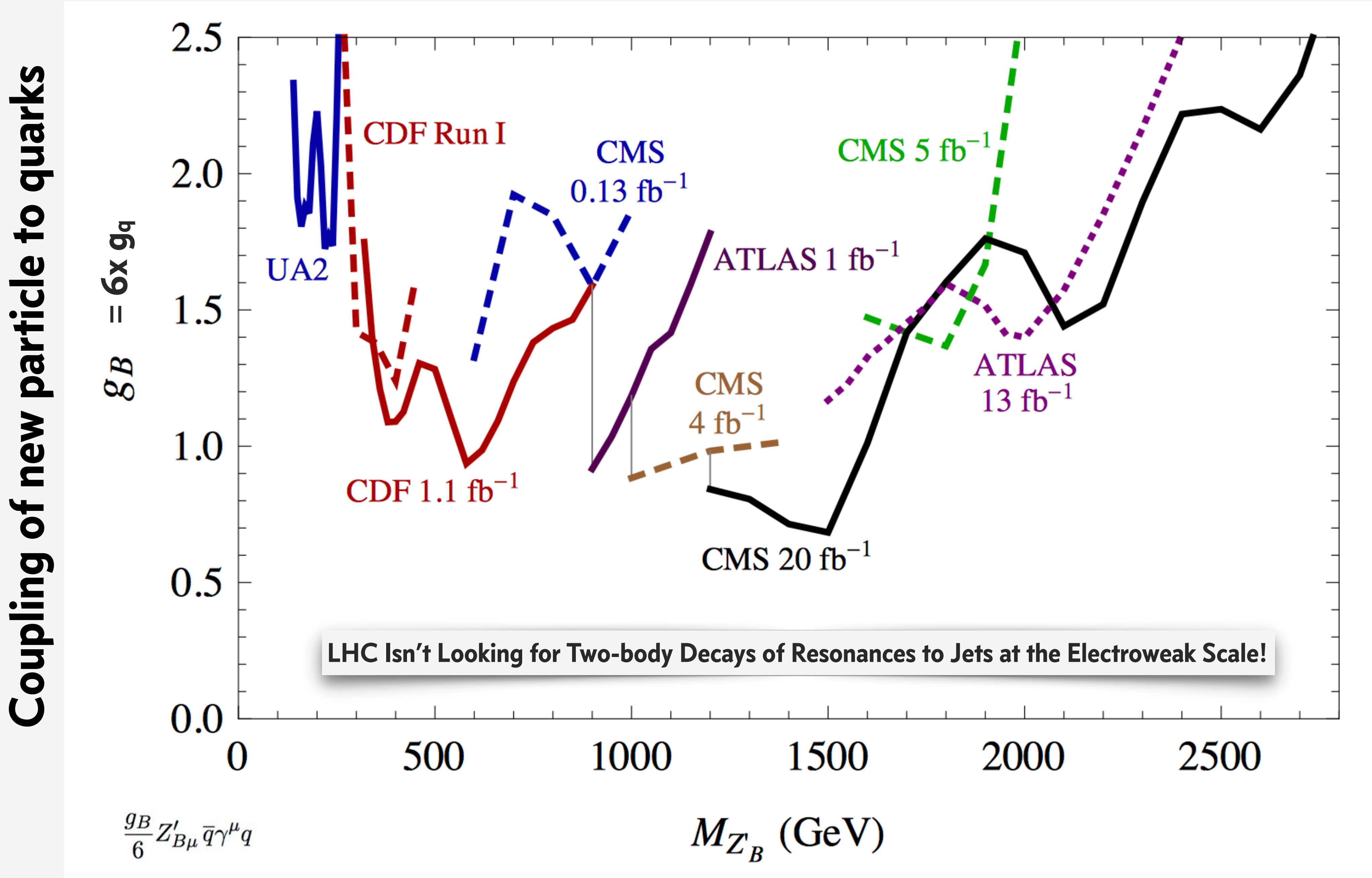





ATLAS
EXPERIMENT
http://atlas.ch
Run: 280673
Event: 1273922482
2015-09-29 15:32:53 CEST

Dijet Resonance Searches circa 2013

Dobrescu, Yu Phys Rev D 88 035021 (2013)



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

DM interactions are rare because coupling is tiny

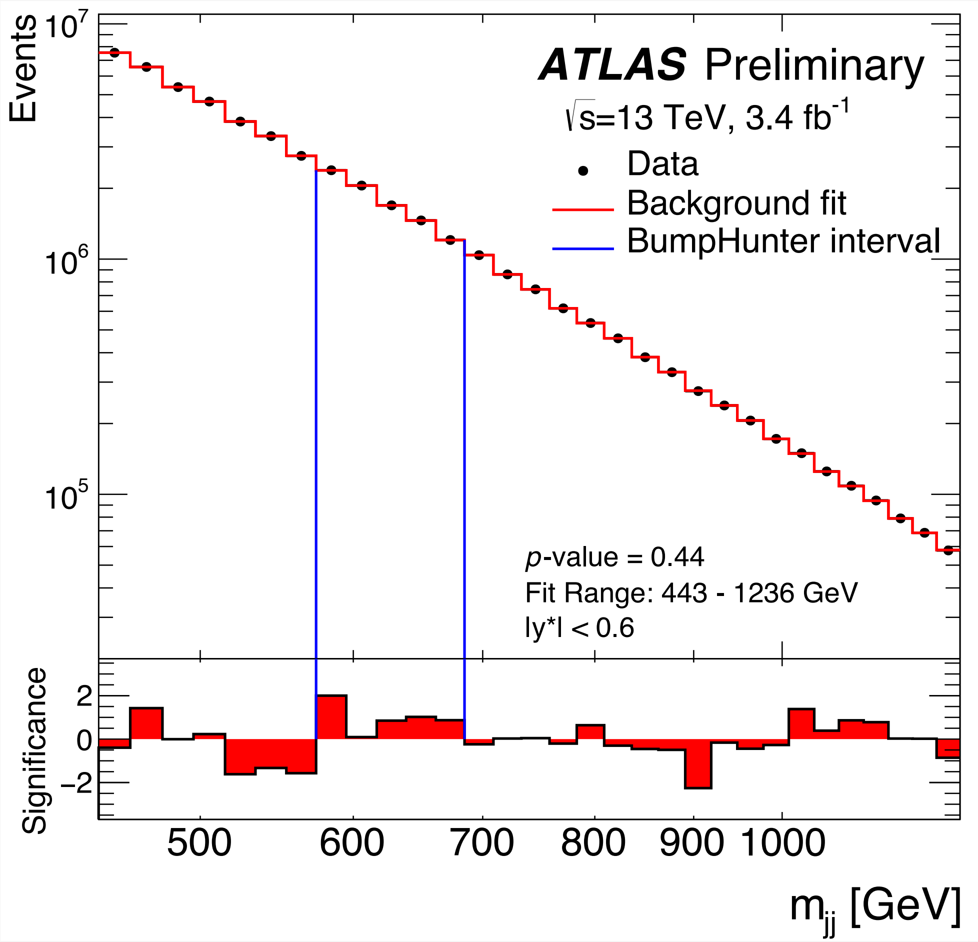
Usual collider detector readout: record everything for a collision   Bandwidth = Rate * Event Size

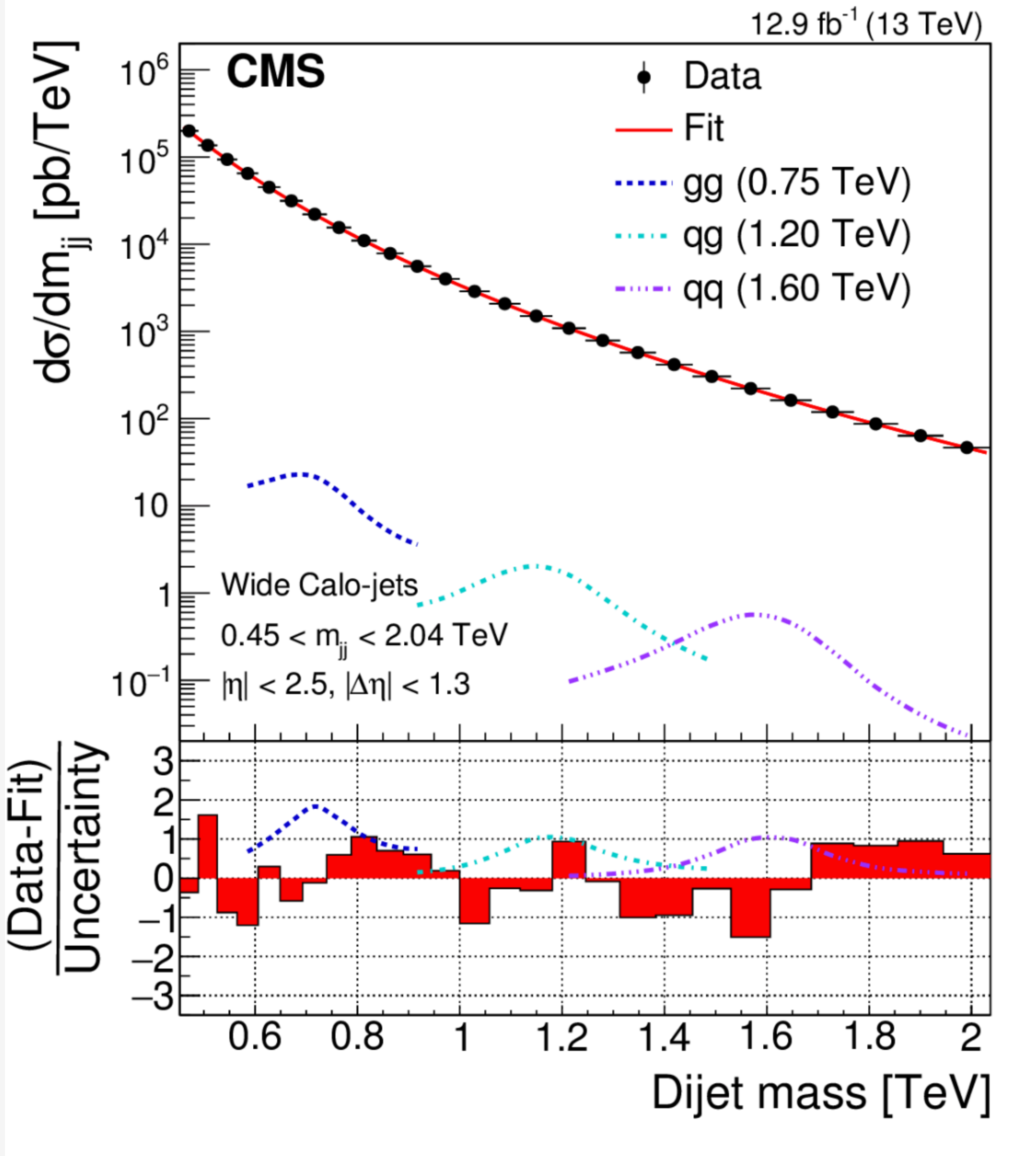
For signals buried in huge background, **reduce data size/complexity to increase rate of recorded data**

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

arXiv:1611.03568

ATLAS-CONF-2016-029





Physics Letters B 754 (2016) 302–322
arXiv:1703.09127

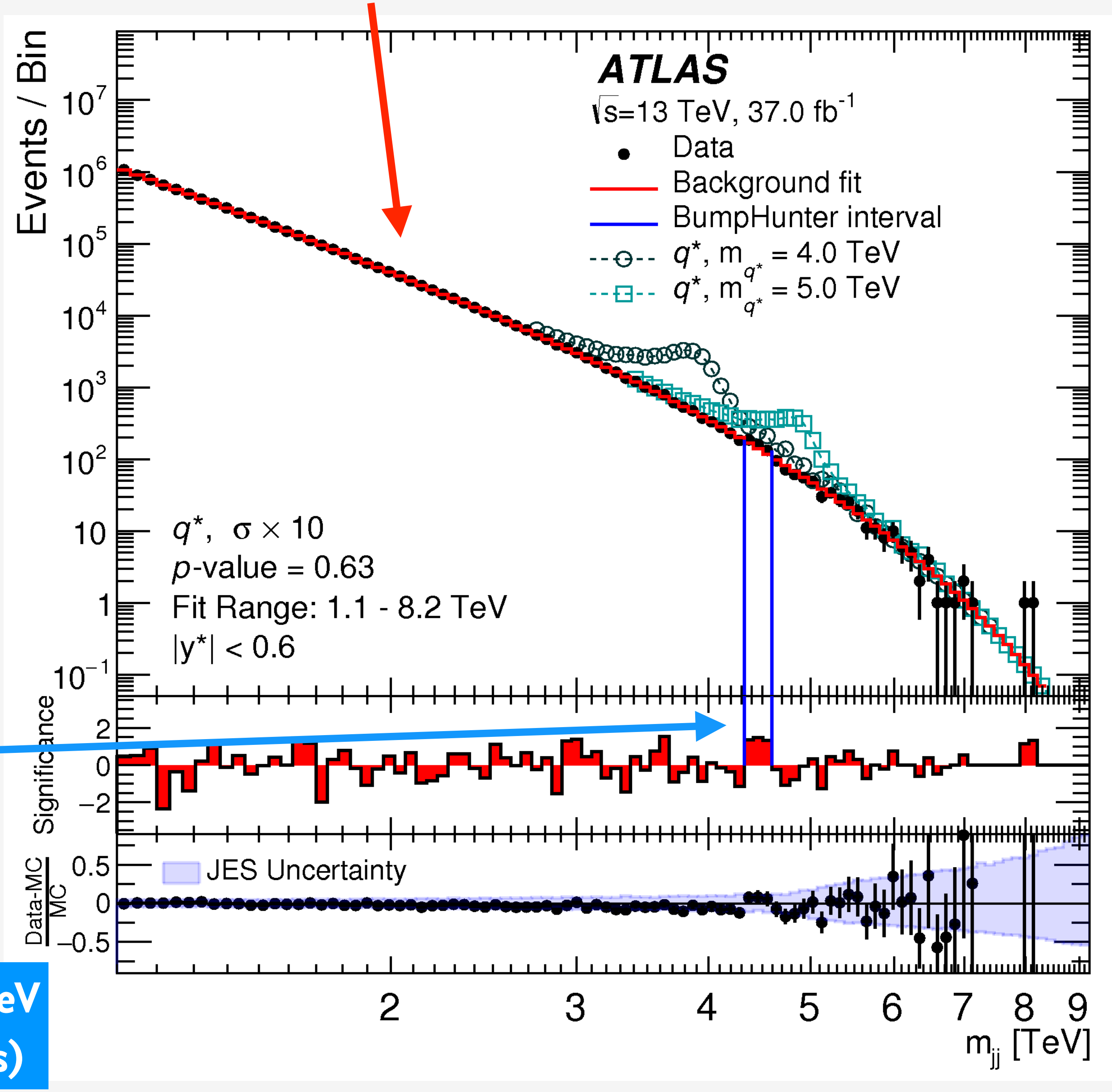
Data-driven background fit

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

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 0.63)

Model: DM interactions are rare because resonance is heavy

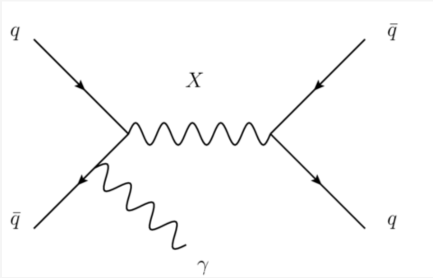
Only probing above M ~ 1 TeV (single jet trigger thresholds)

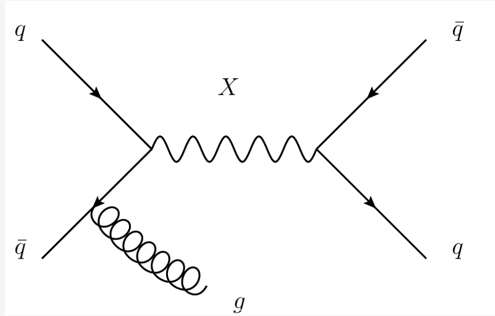
ATLAS Photon+Dijet and Jet + Dijet

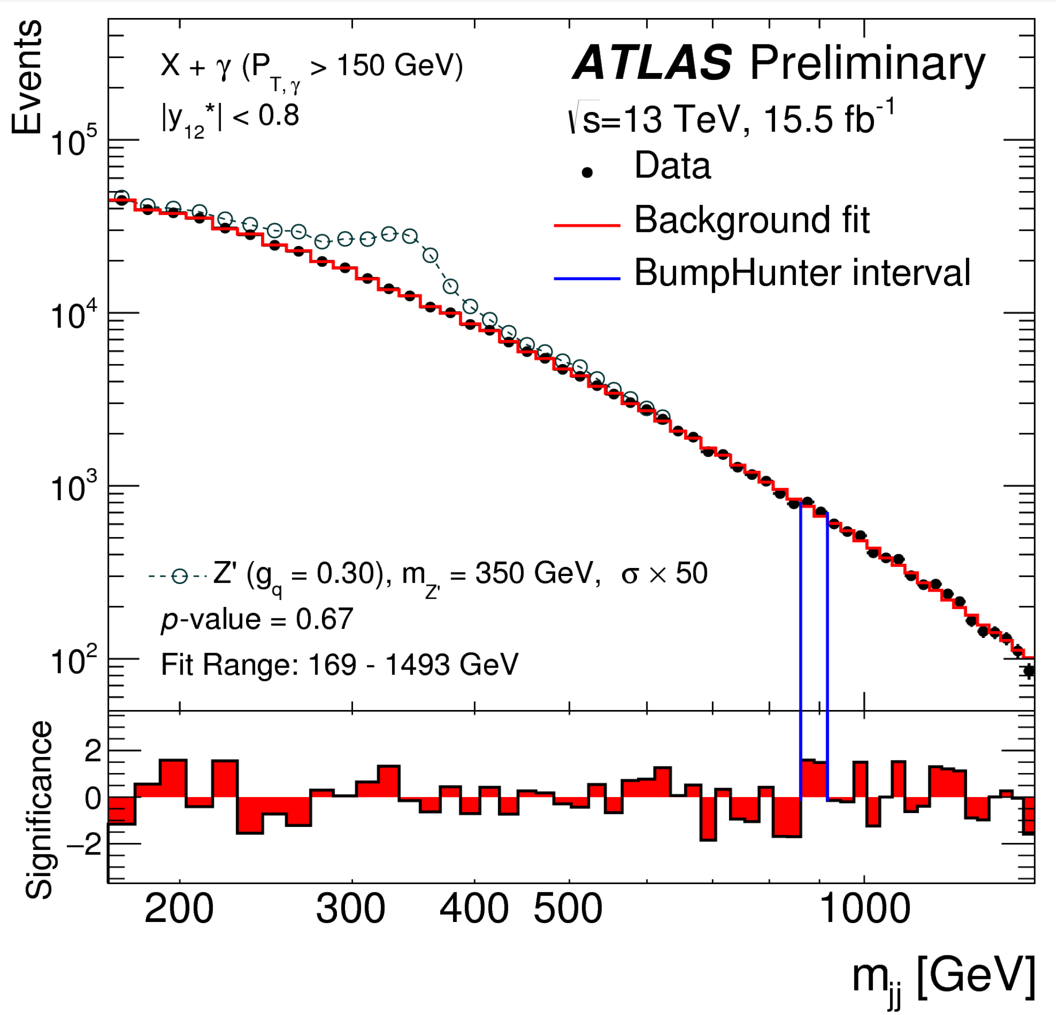
ATLAS-CONF-2016-070

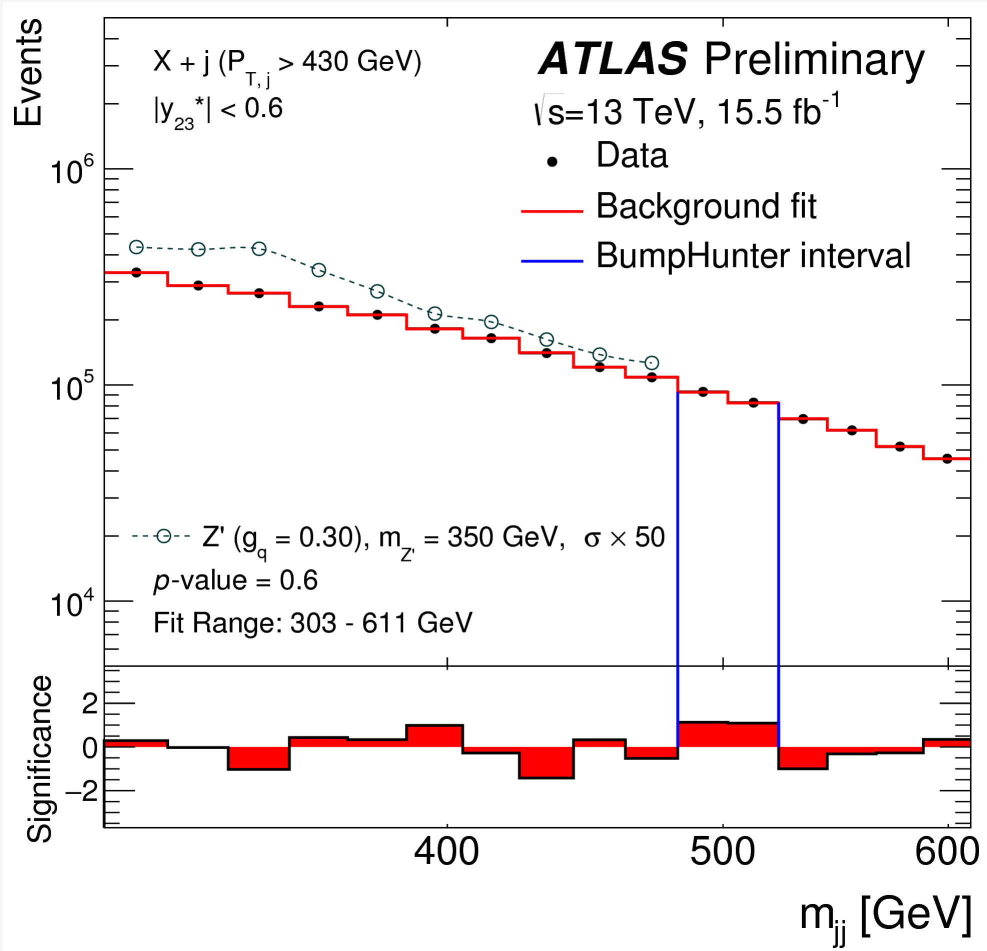
DM interactions are rare because coupling is tiny

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



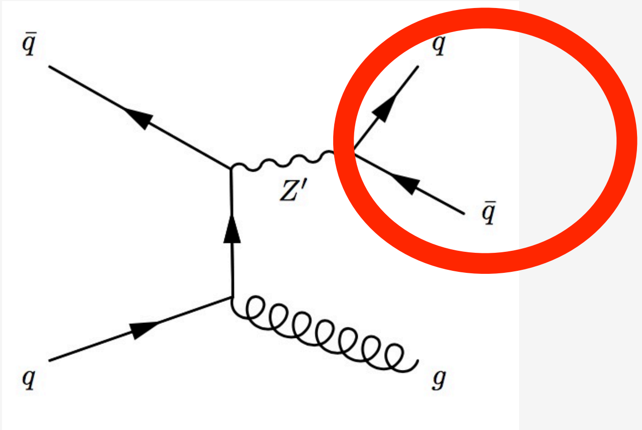




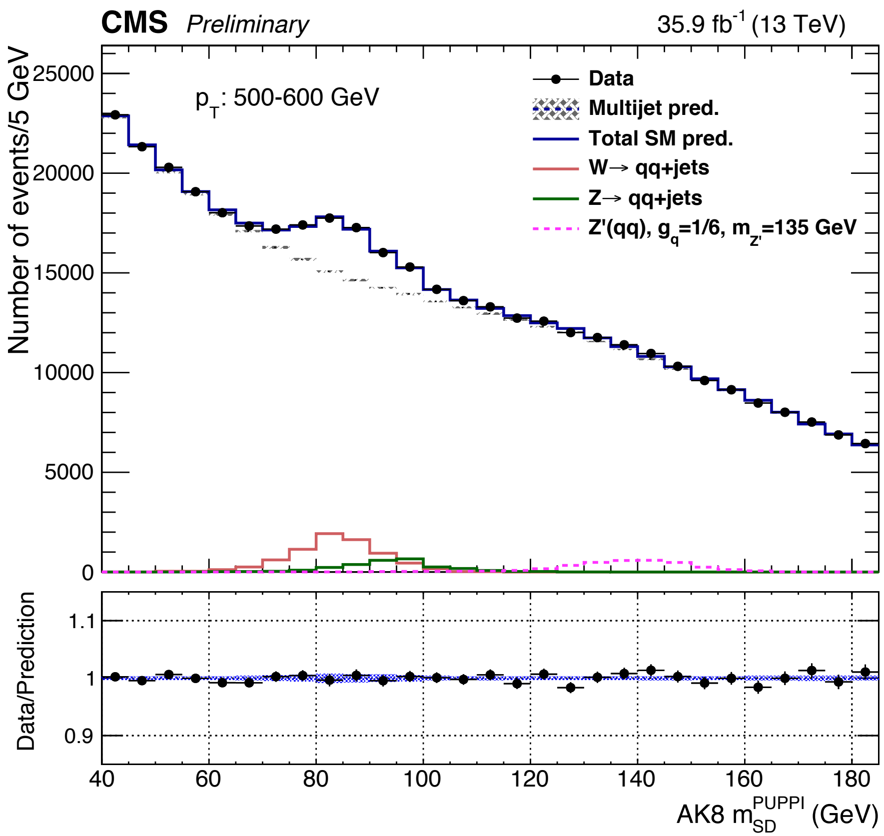


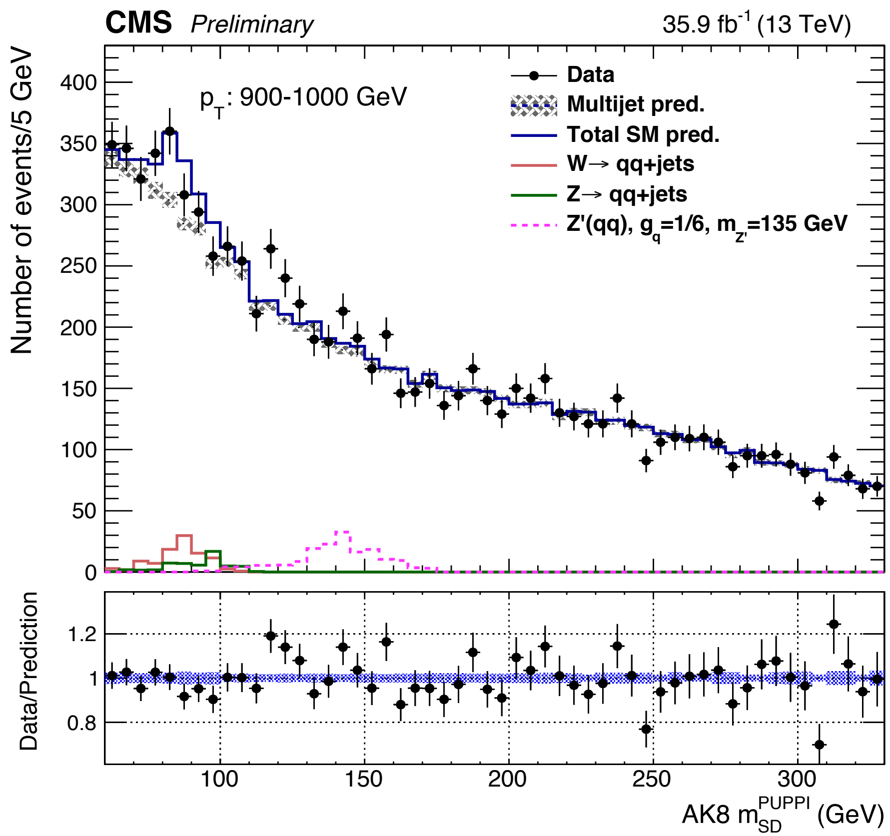
CMS Jet + Highly-boosted Dijet

CMS PAS EXO-17-001



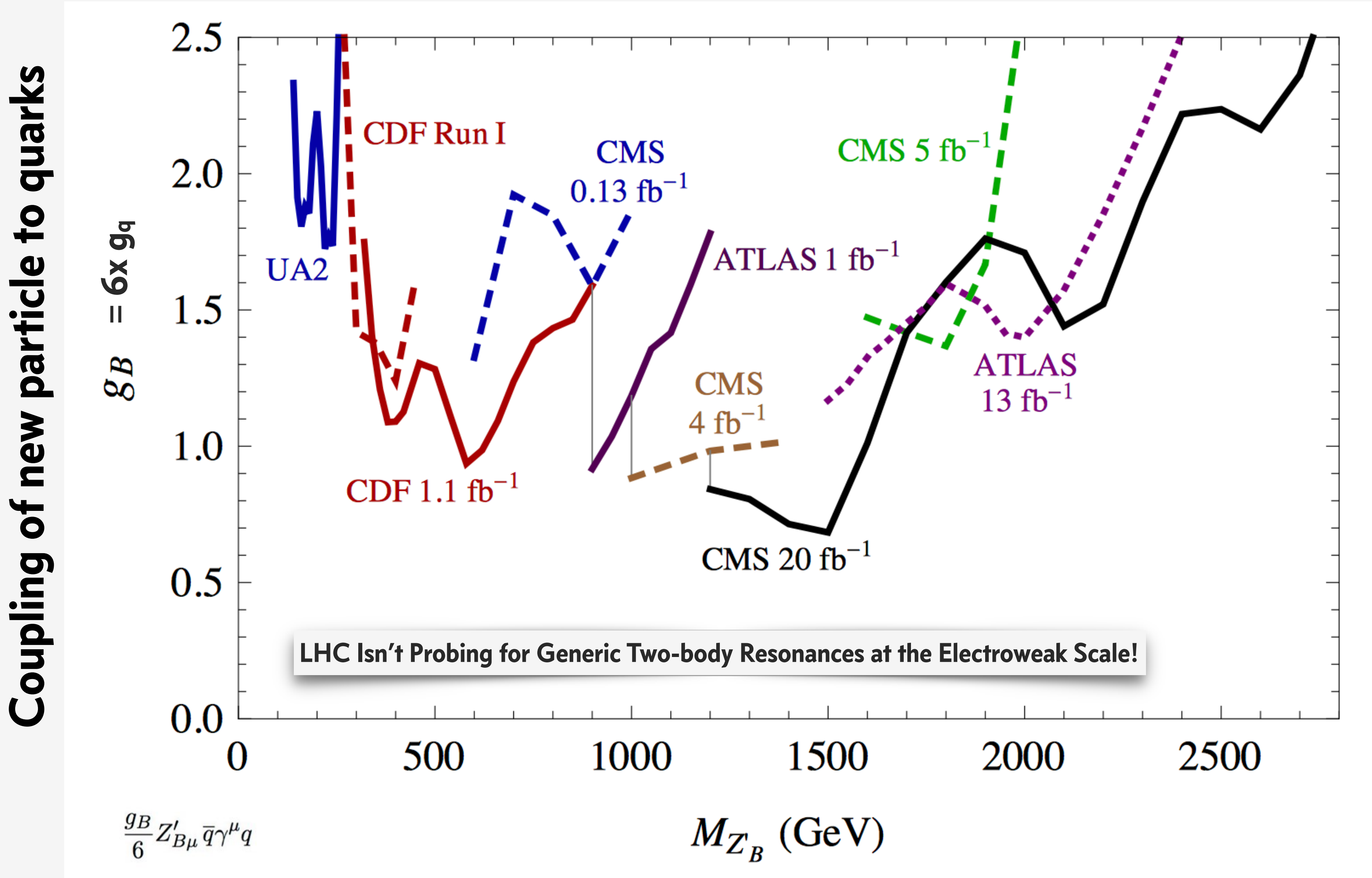
Collimated into single jet



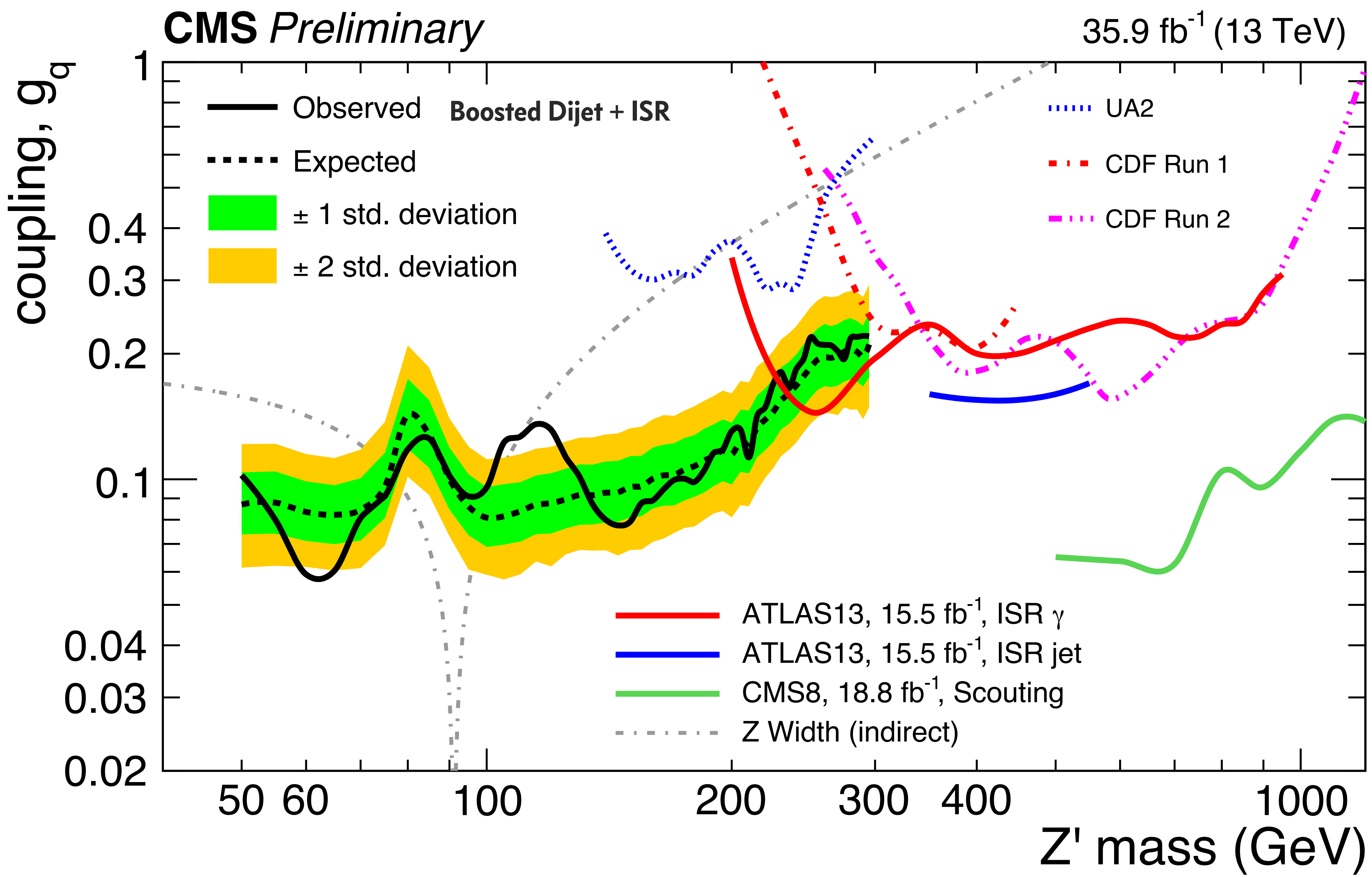


ATLAS Dijet Resonance Searches

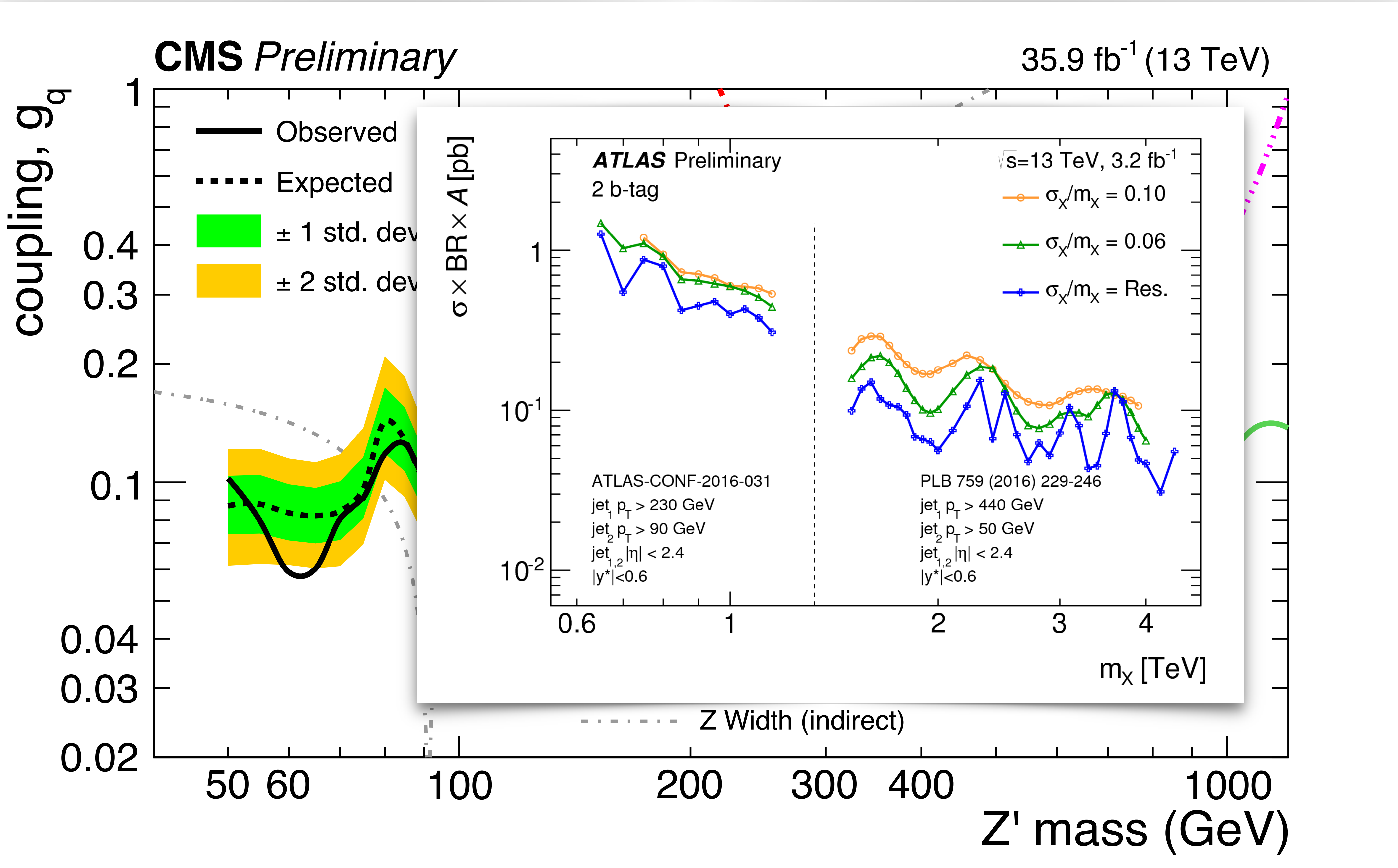
Dobrescu, Yu Phys Rev D 88 035021 (2013)



Latest Dijet Resonance Searches...

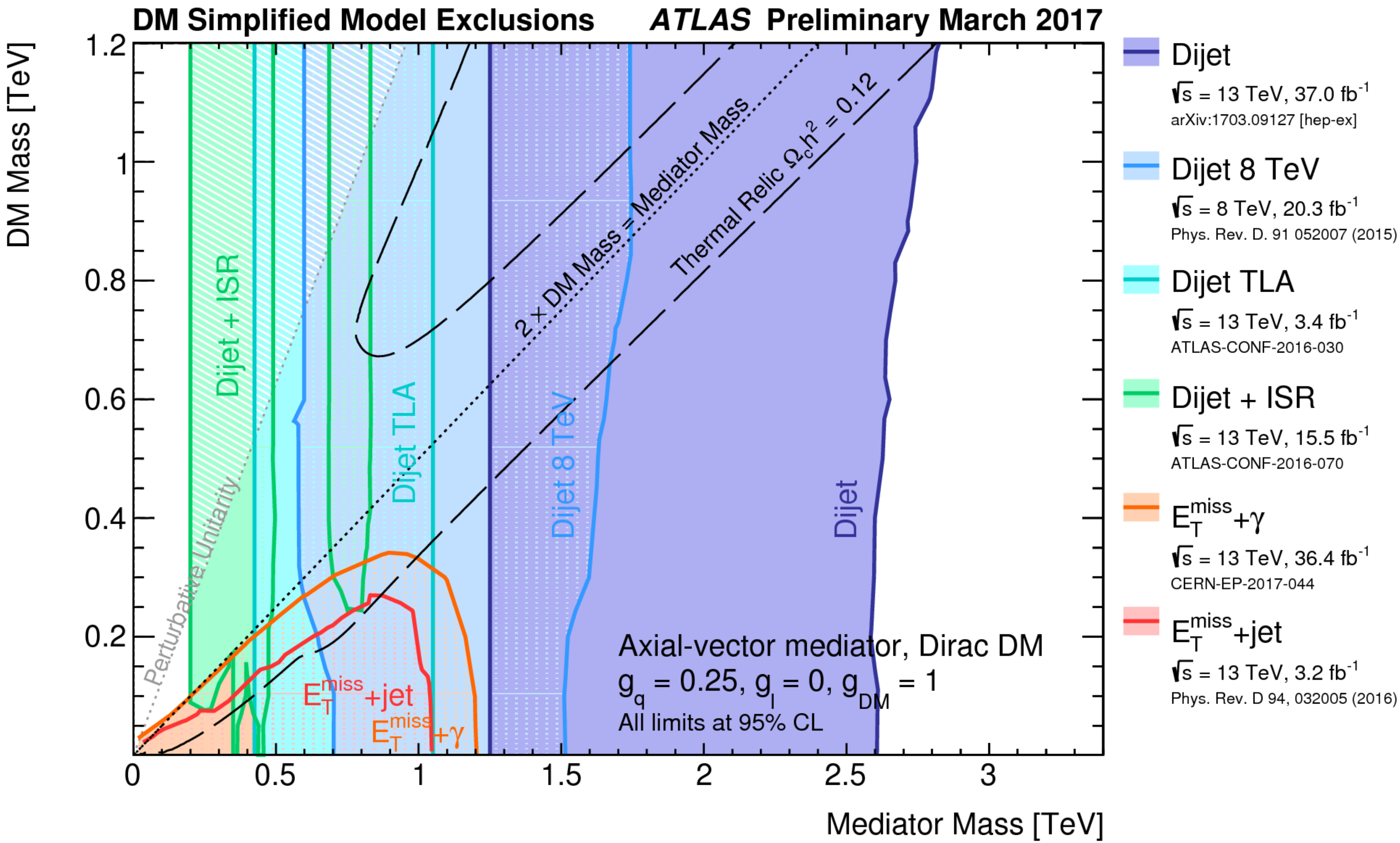


Latest Dijet Resonance Searches...



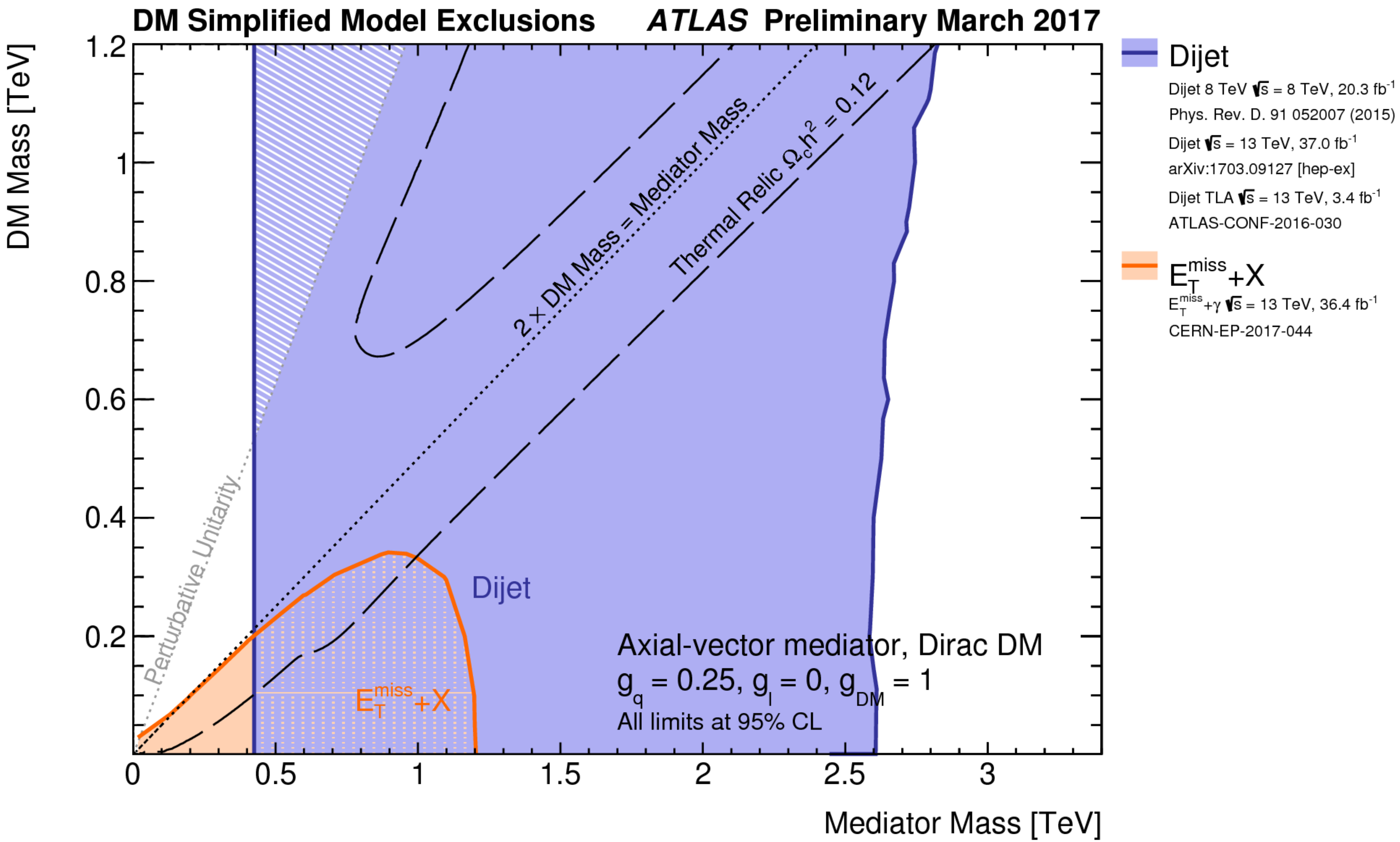
ATLAS MET+X and Dijet Searches

Benchmark model points: LHC DM WG, arXiv:1703.05703

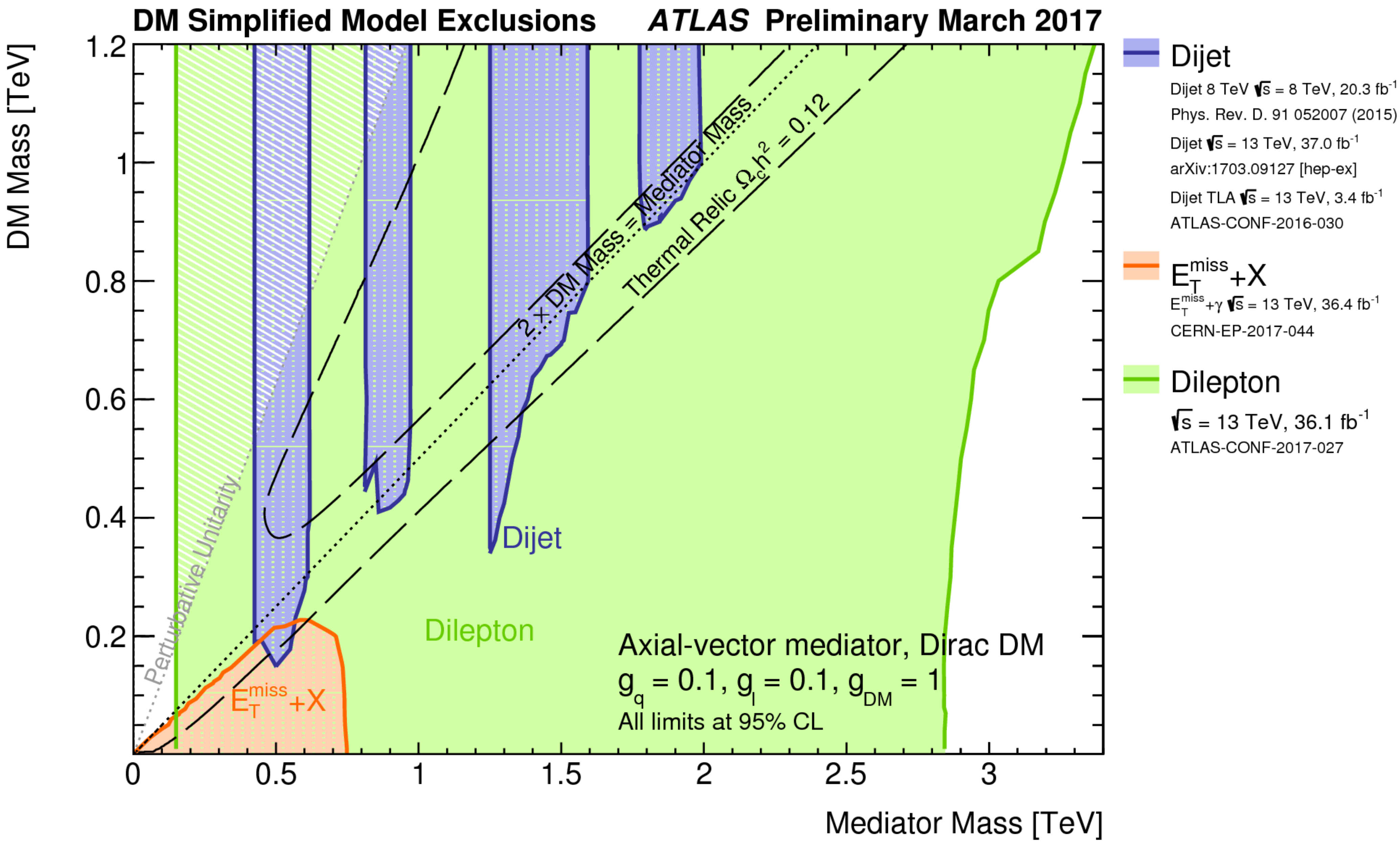


ATLAS MET+X and Dijet Searches

Benchmark model points: LHC DM WG, arXiv:1703.05703



Benchmark model points: LHC DM WG, arXiv:1703.05703



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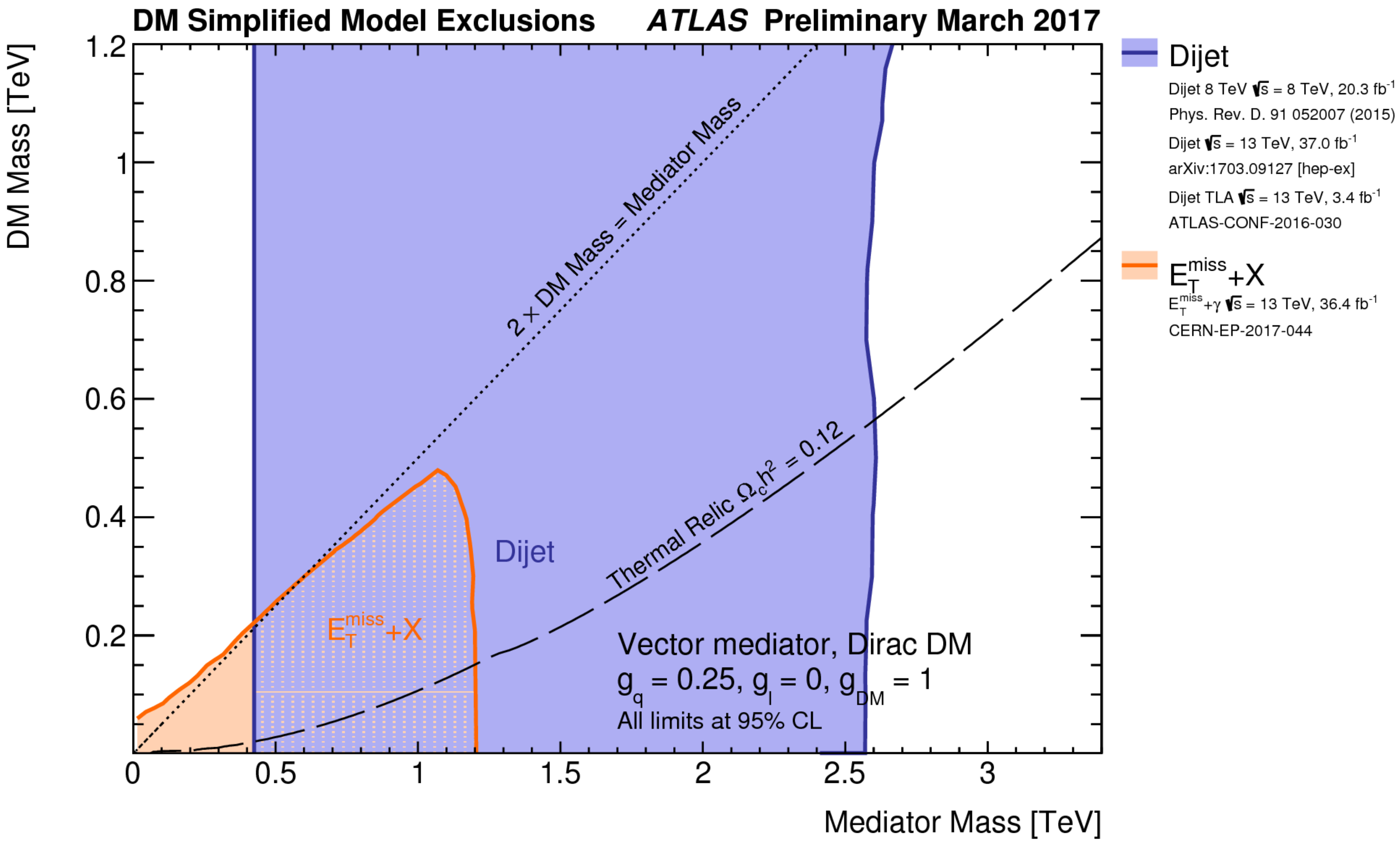

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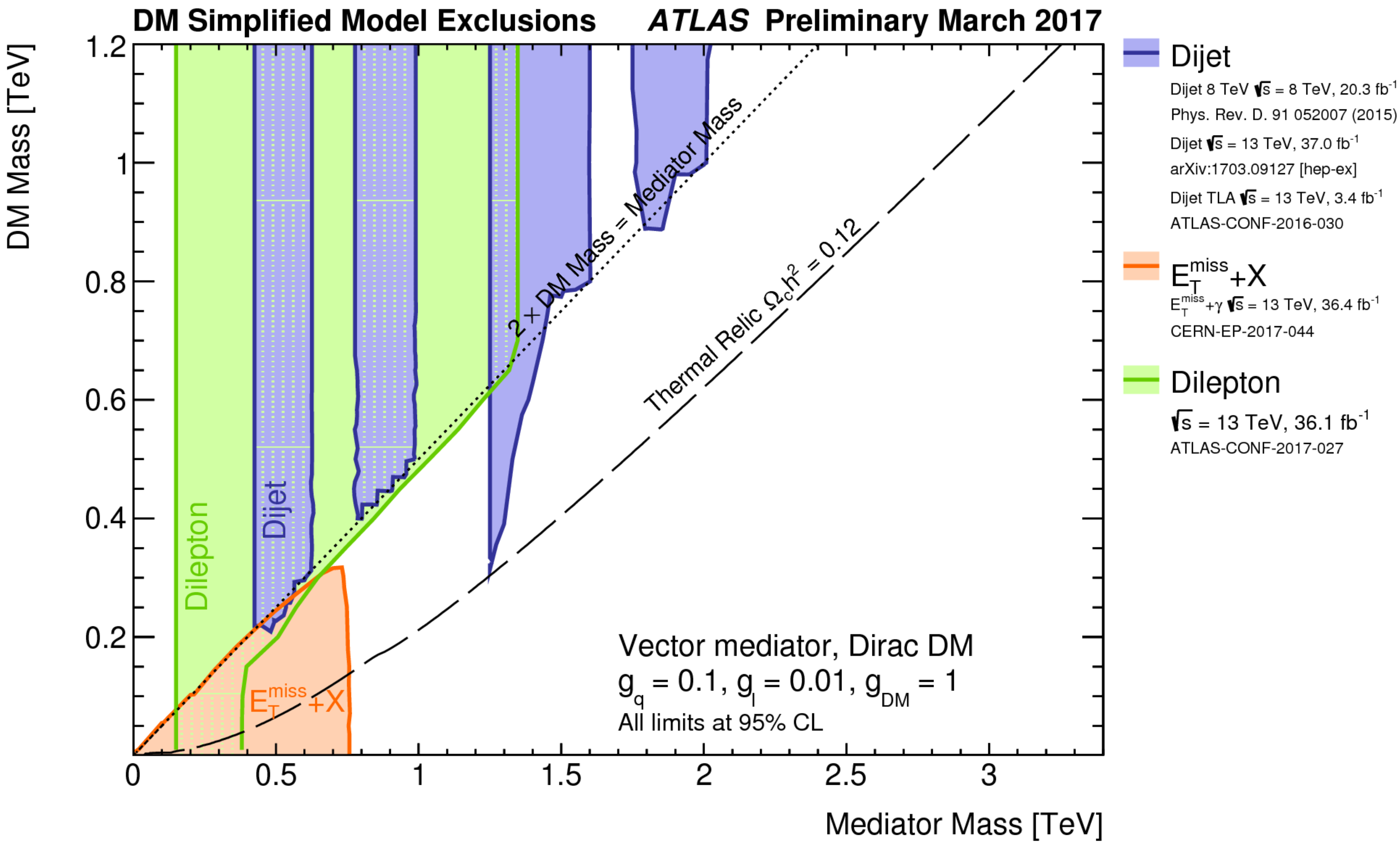
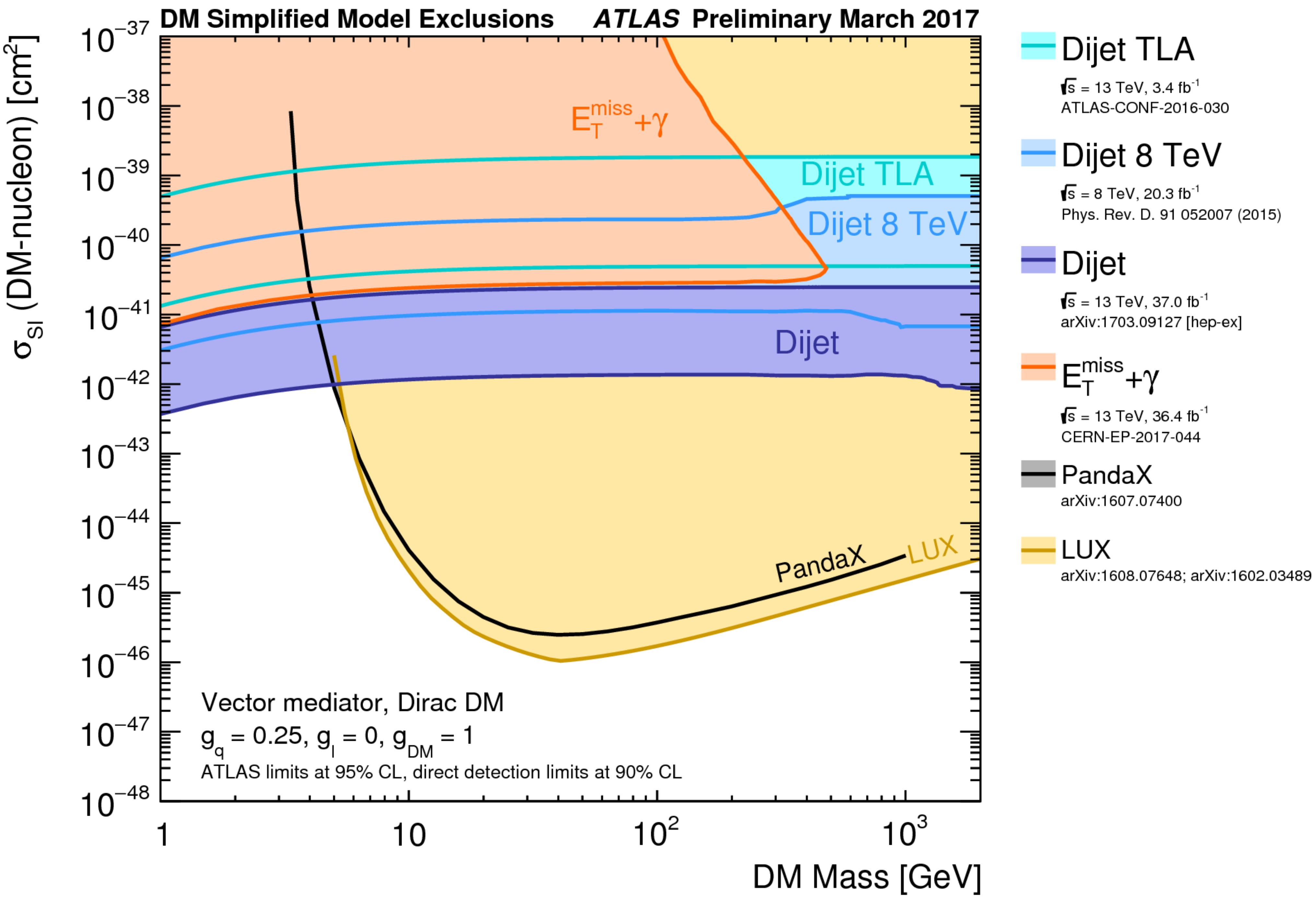
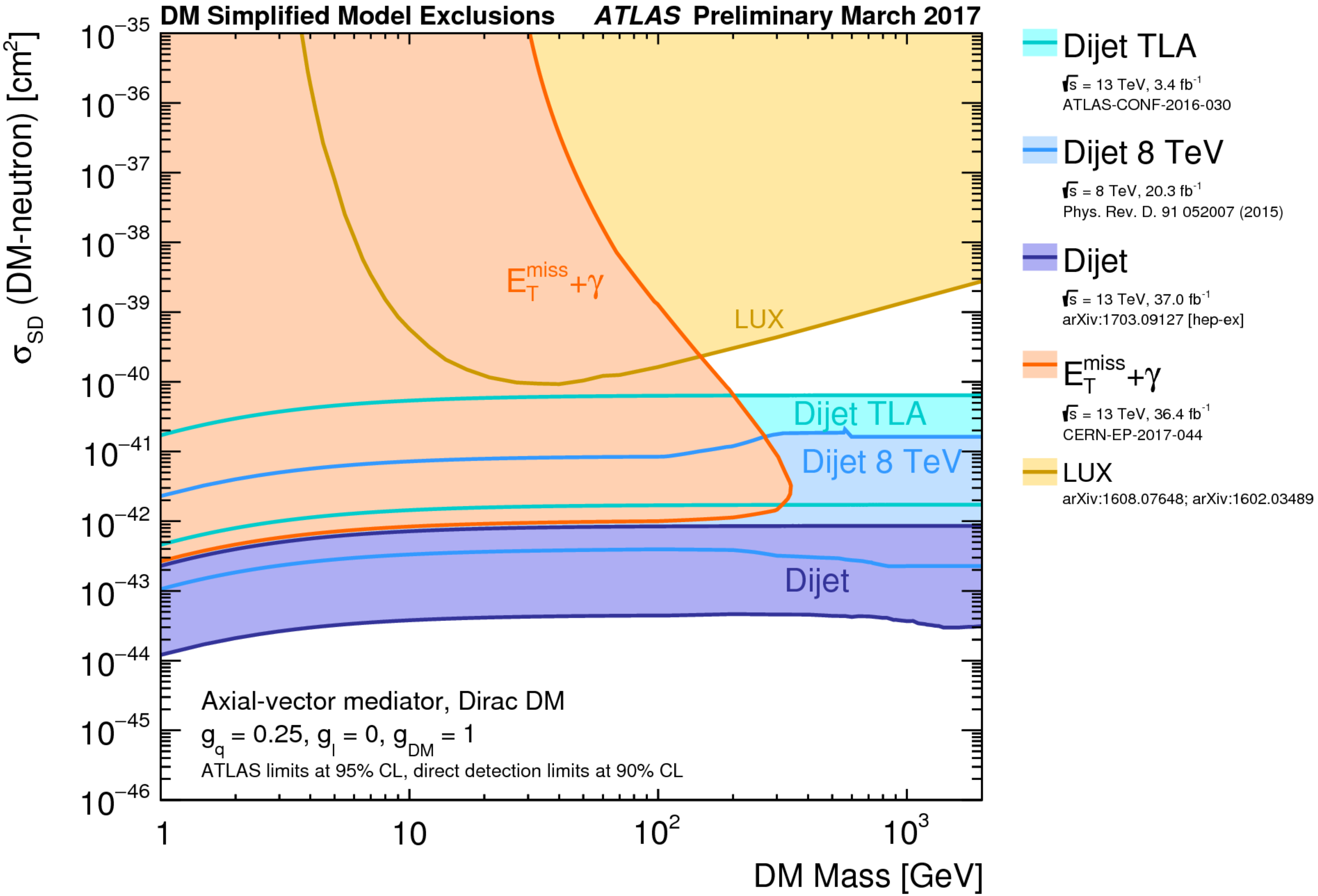


Benchmark model points: LHC DM WG, arXiv:1703.05703



Benchmark model points: LHC DM WG, arXiv:1703.05703



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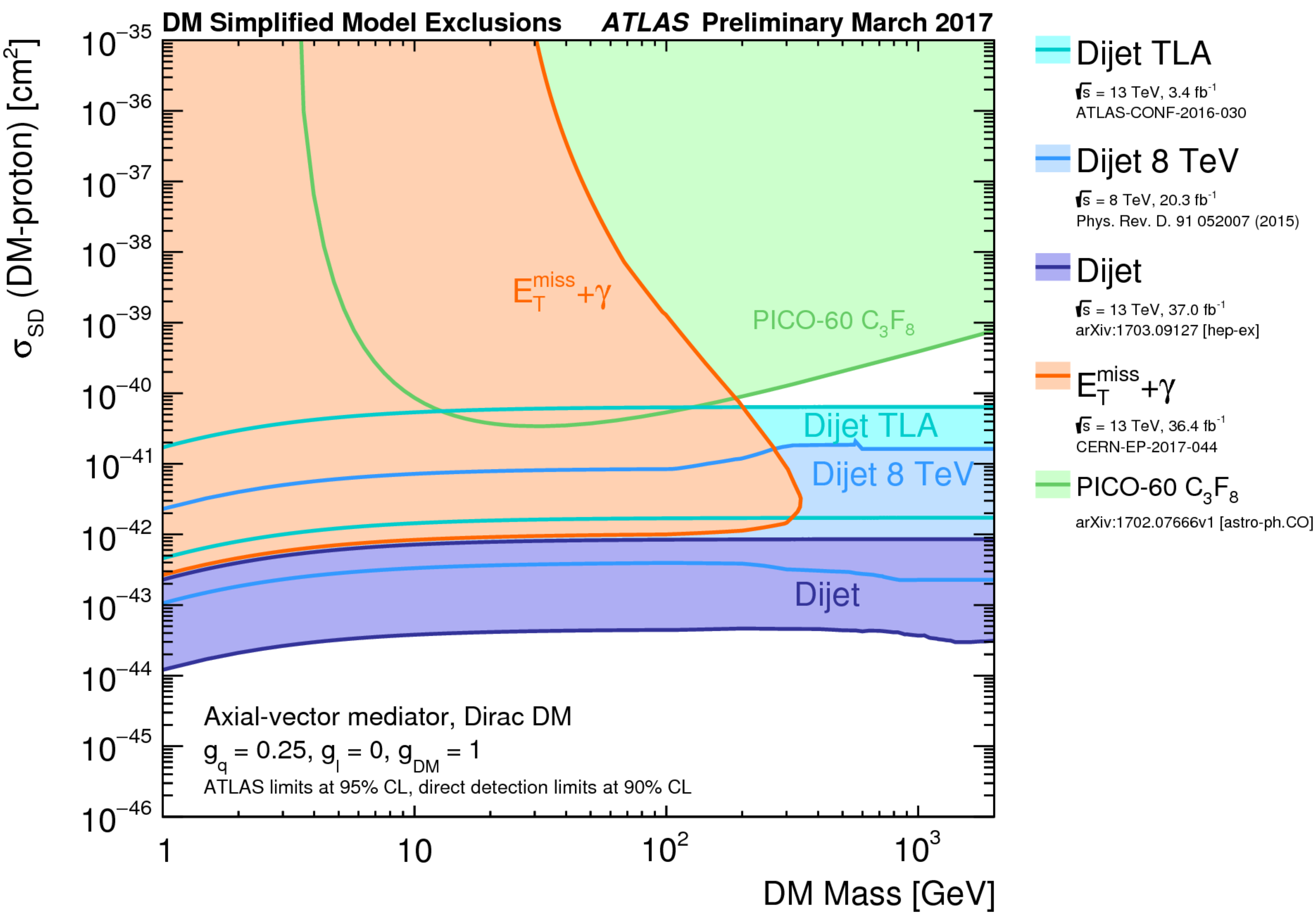

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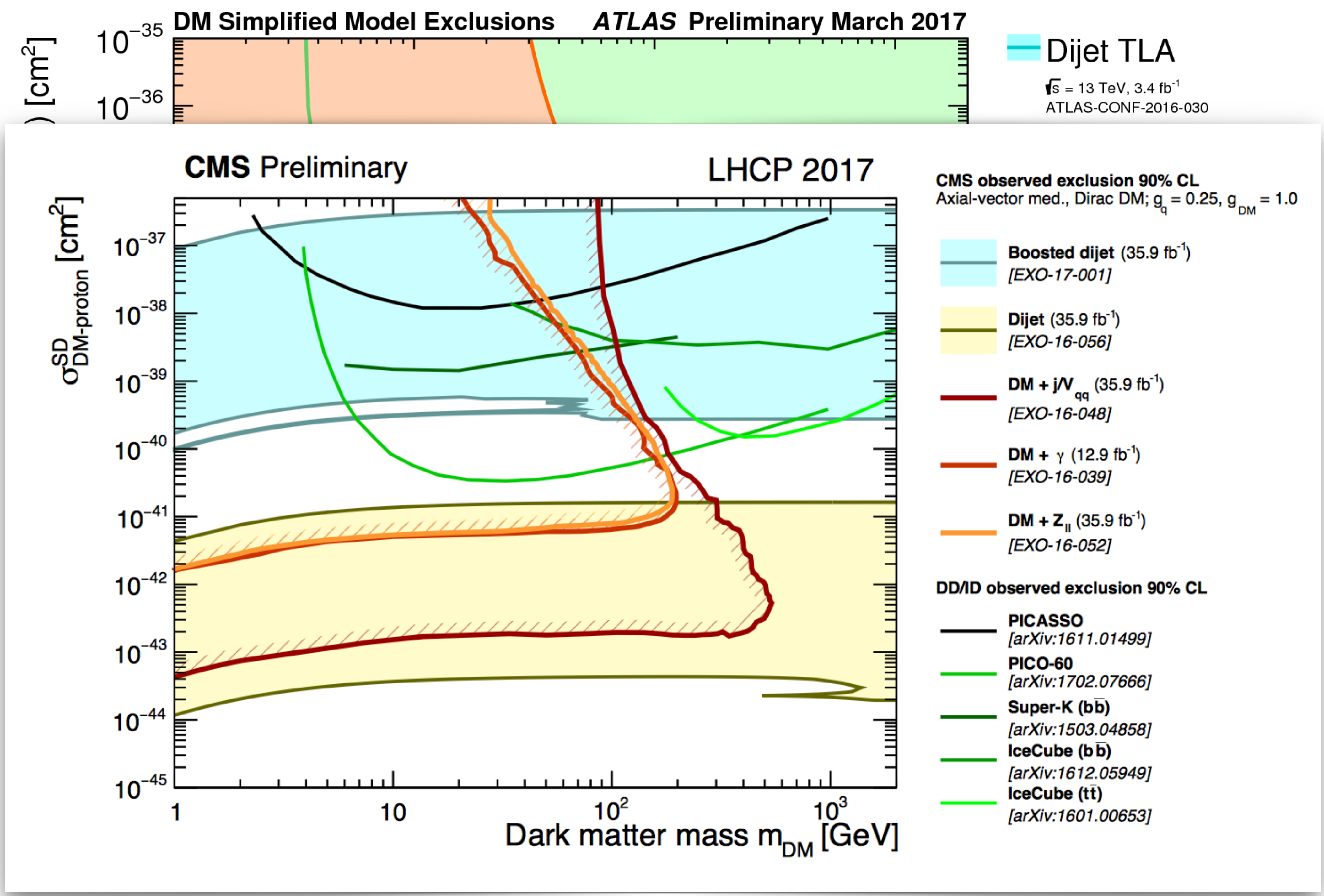


Future: Extended Scalar Sectors

The DMF report recommended several types of scalar sector models:

mono-jet-like models (intentionally simplistic)

- scalar/pseudo-scalar 's-channel' models — not gauge invariant

and three examples of **more complex sectors with mono-V/H signatures**:

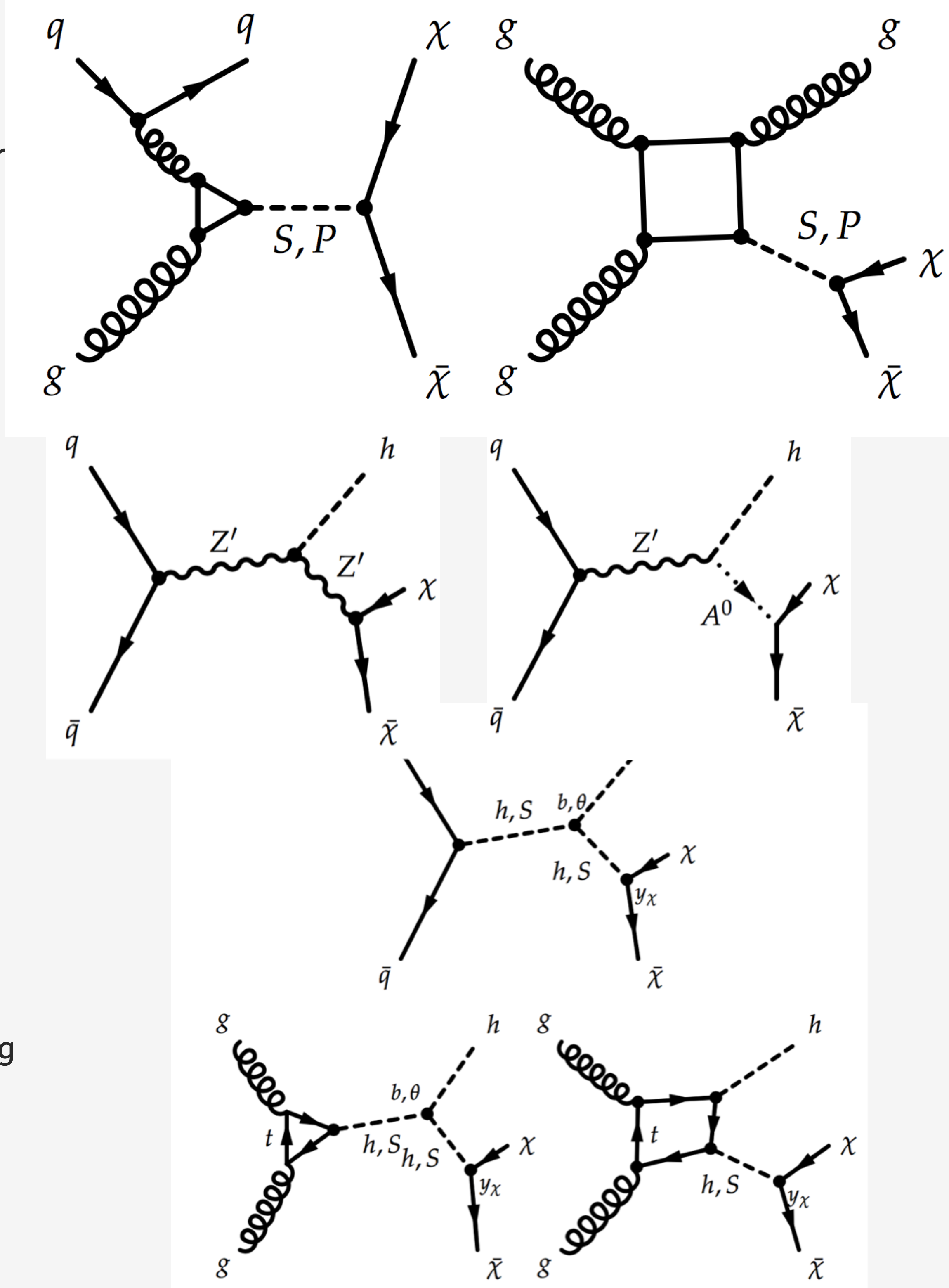
- Z'→ DM DM with h
- singlet S→DM DM with mixing to h
- 2HDM+Z' (A_0→DM DM)

Since the DMF report, the community has produced more coherent surveys of these kinds of models and some proposals to replace the above.

- Add mixing with Higgs sector ($SU(2)_L$) (=> at least two scalars)
- Forces VV coupling of DM mediator, through mixing with Higgs

  => Mono-Higgs, Mono-W/Z

  => diboson decays



Scalar singlet mixing with SM Higgs, +DM

$$V = V_{Higgs,SM} - \frac{1}{2}M_{SS}^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \frac{1}{2}\lambda_{HS}\Phi^\dagger\Phi S^2$$

- Mixing angle small due to combination of H→invisible, precision Higgs constraints, direct detection

$$L_{int,s-h} = -(h\cos\epsilon - s\sin\epsilon)\sum_f \frac{m_i}{v}\bar{f}_i f_i - y_{DM}(s\cos\epsilon + h\sin\epsilon)\bar{\chi}\chi$$

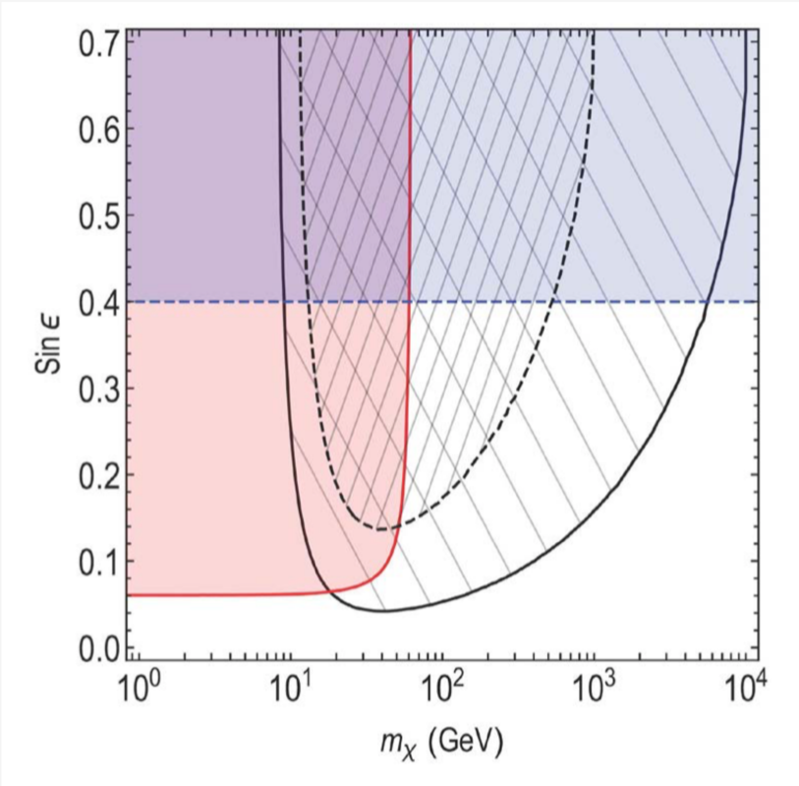
=> small cross sections (small ε)

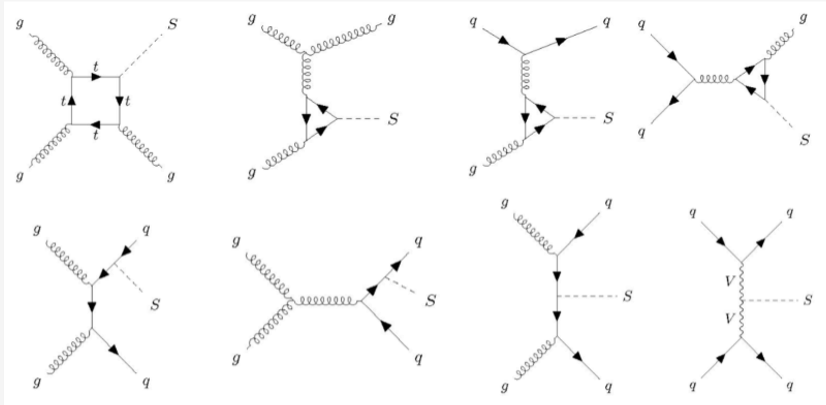
Exceptions:

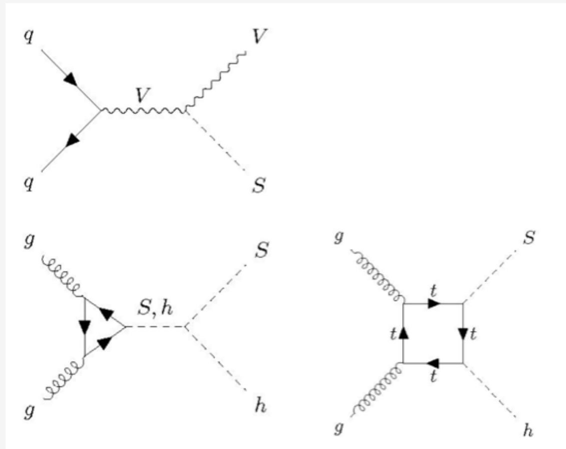
$$\Gamma(h \to \bar{\chi}\chi) = \frac{y_\chi^2 \sin^2\epsilon}{8\pi} M_h \left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{3/2}$$

- weak bounds for DM >~O(1 TeV)

- gap in constraints for $m_S \sim m_H$ and DM>O(10's GeV)







—— m_S = 1 TeV
- - - - m_s = 150 GeV

SI DD

Red – excluded by Higgs invisible width
Blue – excluded by EW constraints

Scalar singlet mixing with SM Higgs, +DM

$$V = V_{Higgs,SM} - \frac{1}{2}M_{SS}^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \frac{1}{2}\lambda_{HS}\Phi^\dagger\Phi S^2$$

- Mixing angle small due to combination of H→invisible, precision Higgs constraints, direct detection

$$L_{int,s-h} = -(h\cos\epsilon - s\sin\epsilon)\sum_f \frac{m_i}{v}\bar{f}_i f_i - y_{DM}(s\cos\epsilon + h\sin\epsilon)\bar{\chi}\chi$$

=> small cross sections (small ε)

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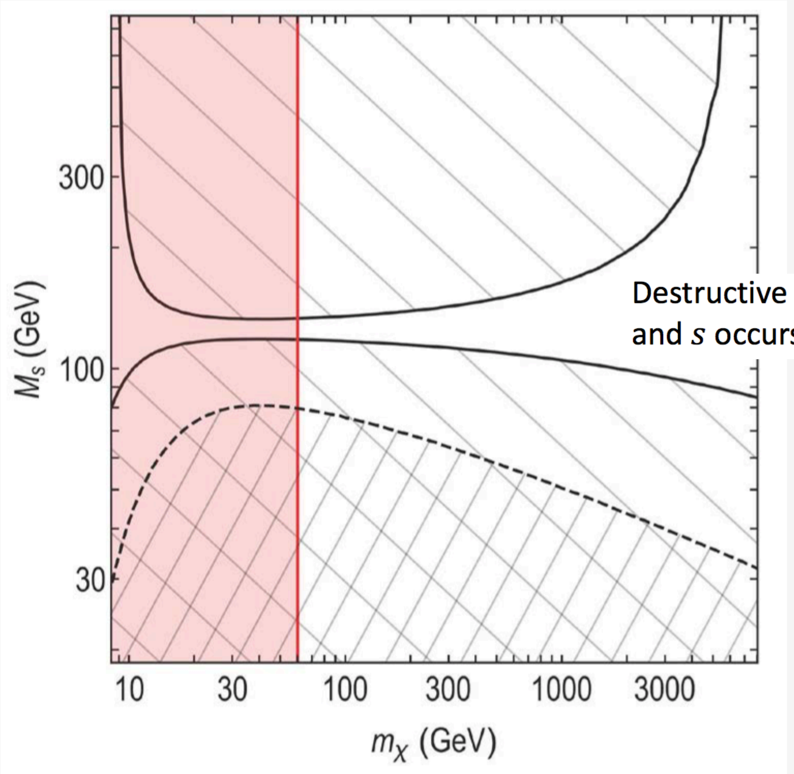
Exceptions:

- weak bounds for DM >~O(1 TeV)

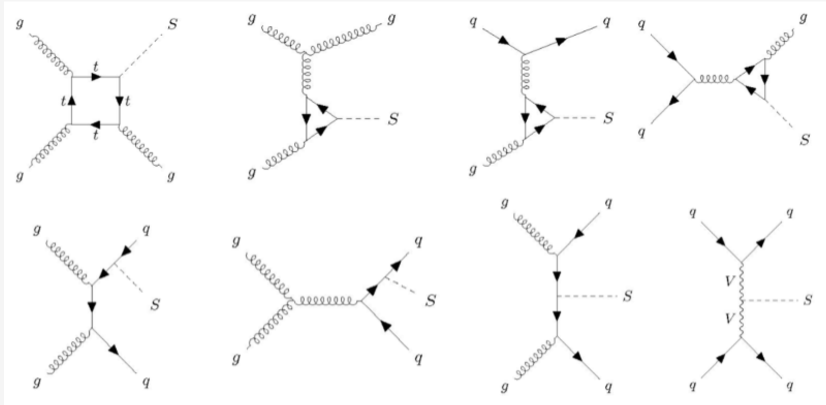
- gap in constraints for $m_S \sim m_H$ and DM>O(10's GeV)

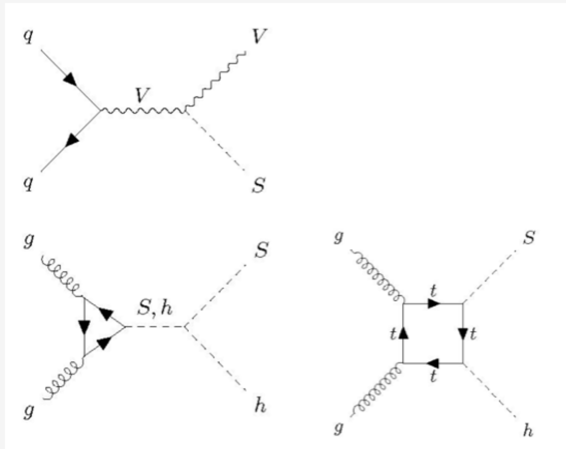


Destructive interference of h and s occurs when $m_s \sim m_h$

—— $\sin\epsilon = 0.4$
- - - - $\sin\epsilon = 0.03$ SI DD

Red – For $\sin\epsilon = 0.4$, this region excluded by Higgs invisible width.
No corresponding bound for $\sin\epsilon = 0.03$.





Extended Higgs sector and singlet (2HDM+S)

Introduce an additional Higgs doublet and a separate scalar

- generalization of scalar singlet mixing model

- one doublet to be SM-like (alignment limit)

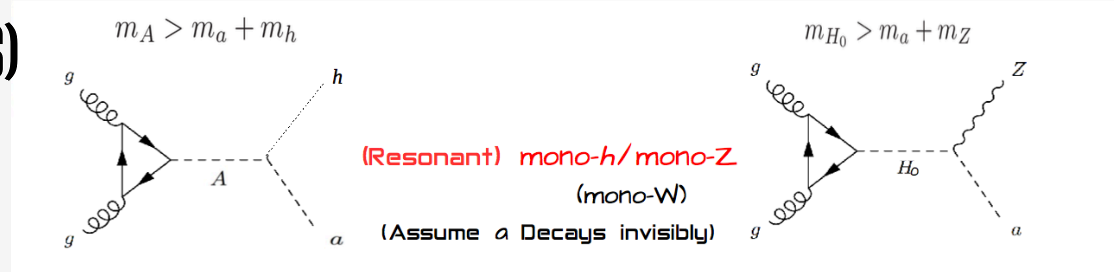
- mix the additional doublet with a singlet to mediate DM interactions

=> h, H, S in Bell et al, or h, H_0, H+-, A, a_0 in No et al., etc.

Substantial mono-h, mono-Z, and VBF+invisible signatures

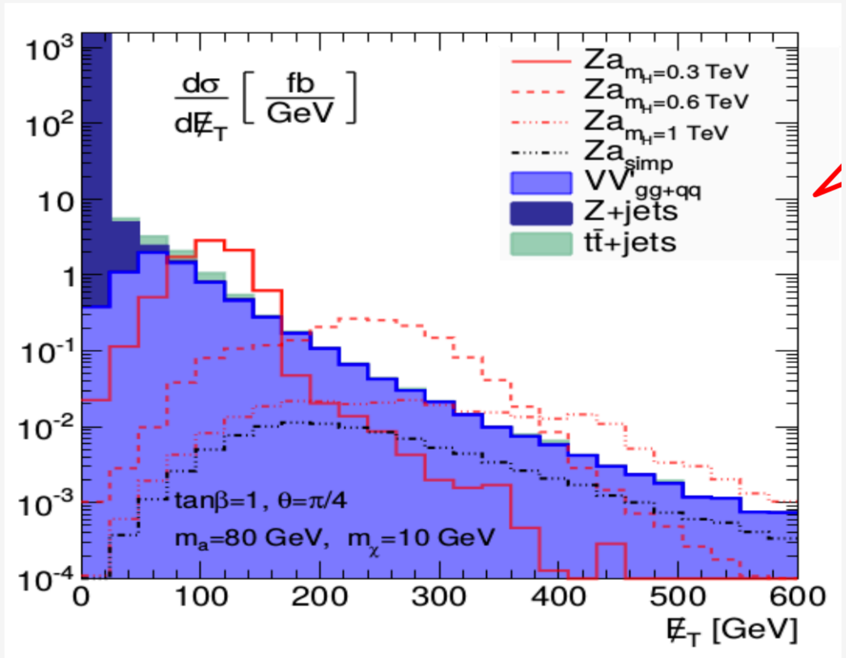
- **lots of different pheno**, depending on hierarchy of scalar masses

e.g. **resonantly-enhanced (Jacobian) mono-h, mono-Z (mono-W)**



$$\not{E}_T^{\max} \sim \frac{1}{2m_A}\sqrt{(m_A^2 - m_h^2 - m_a^2)^2 - 4m_h^2 m_a^2}$$

$$\not{E}_T^{\max} \sim \frac{1}{2m_{H_0}}\sqrt{(m_{H_0}^2 - m_Z^2 - m_a^2)^2 - 4m_Z^2 m_a^2}$$



Representation in Bauer, No, YR4, etc.

$$m_h, M_H, M_A, M_{H^\pm}, M_a$$
$$v, \tan\beta, \cos(\beta-\alpha), \sin\theta$$
$$m_f, y_\chi, \lambda_3$$

Many variations

Two scalar doublets means

- additional constraints from Higgs measurements, precision EW observables, flavor physics….
- lots of parameters → requires careful evaluation of constraints to understand 1) where colliders are uniquely sensitive 2) how to simplify parameter space

Coupling of DM and SM fermions to scalars of similar form to H+S model, but

- couplings not subject to Higgs invisible width constraints on the mixing angle

(can even get tan beta enhancement)

- interference effects possible for m1, m2 very different to h

=> gaps in direct detection coverage at low mDM

- more freedom in Yukawa couplings for fermions (u,d,lepton)

but needs more care to avoid substantial flavor-changing interactions

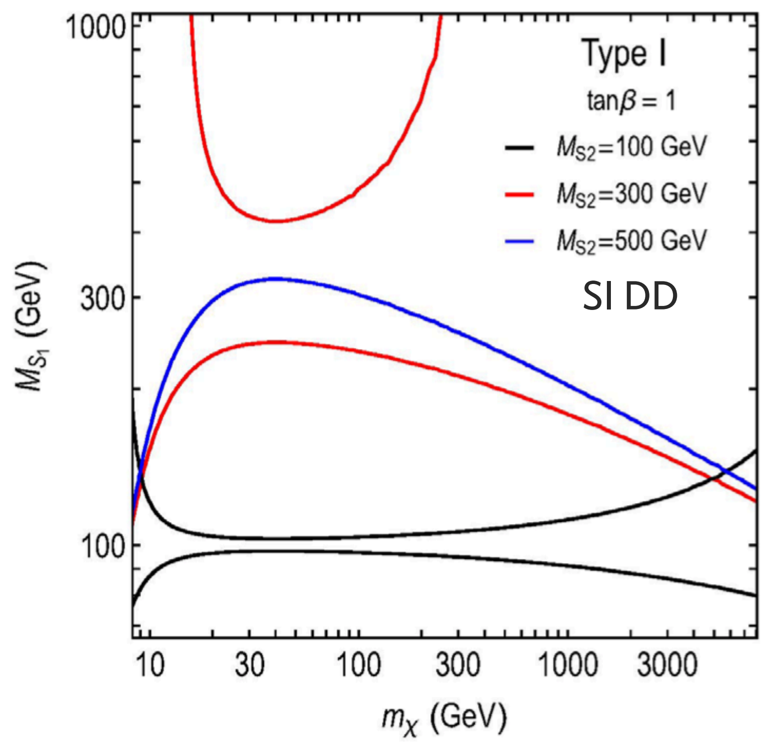
Type I, II, X and Y, with Natural Flavour Conservation (NFC):

Model	ϵ_d	ϵ_u	ϵ_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
X (lepton specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Y (flipped)	$-\tan\beta$	$\cot\beta$	$\cot\beta$

Type III models, with Minimal Flavour Violation (MFV):

- **Yukawa Aligned model**
- **2-generation model**

Type I, $\tan\beta = 1$ (the "plain vanilla" case)



Many variations

Two scalar doublets means

- additional constraints from Higgs measurements, precision EW observables, flavor physics….
- lots of parameters → requires careful evaluation of constraints to understand 1) where colliders are uniquely sensitive 2) how to simplify parameter space

Coupling of DM and SM fermions to scalars of similar form to H+S model, but

- couplings not subject to Higgs invisible width constraints on the mixing angle

(can even get tan beta enhancement)

- interference effects possible for m1, m2 very different to h

=> gaps in direct detection coverage at low mDM

- more freedom in Yukawa couplings for fermions (u,d,lepton)

but needs more care to avoid substantial flavor-changing interactions

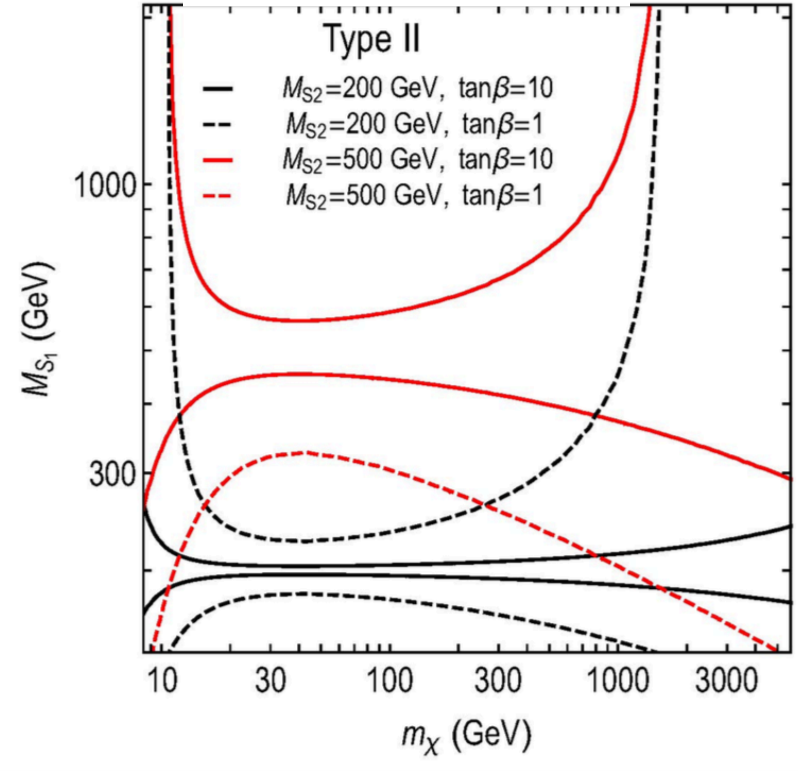
Type I, II, X and Y, with Natural Flavour Conservation (NFC):

Model	ϵ_d	ϵ_u	ϵ_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
X (lepton specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Y (flipped)	$-\tan\beta$	$\cot\beta$	$\cot\beta$

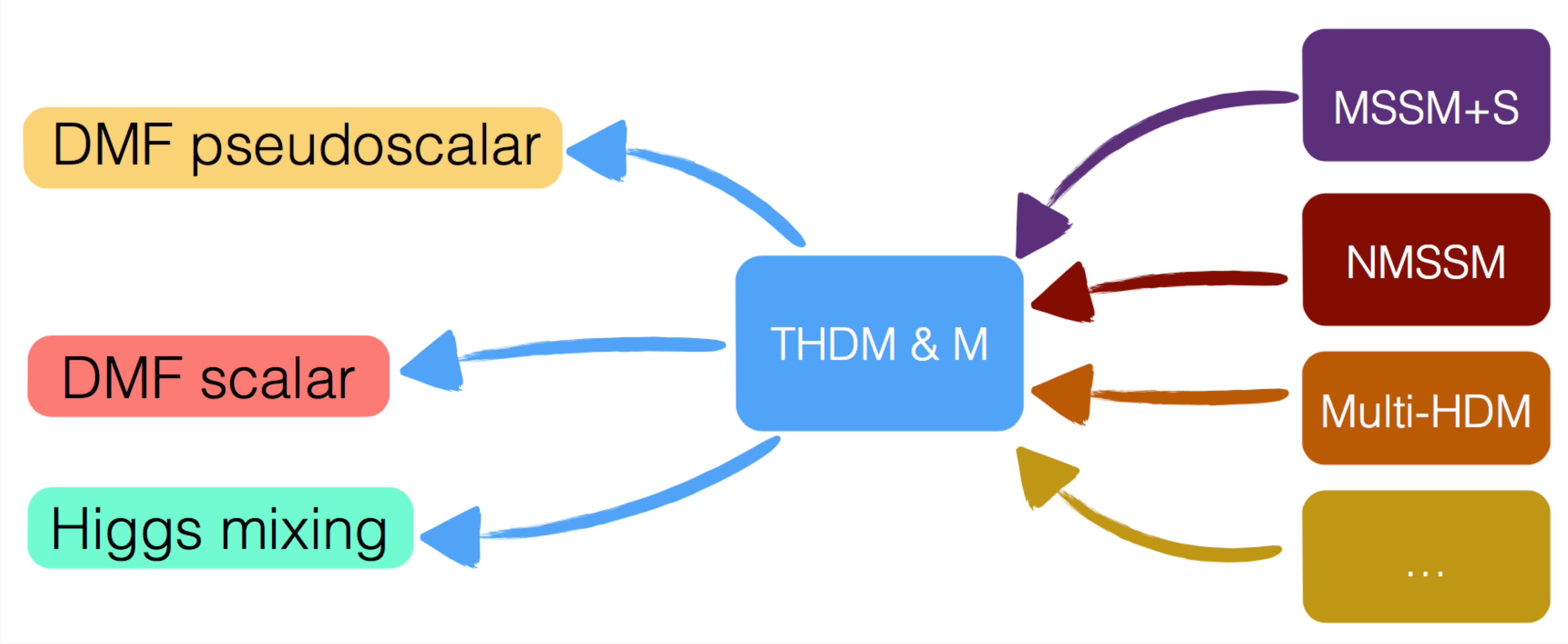
Type III models, with Minimal Flavour Violation (MFV):

- **Yukawa Aligned model**
- **2-generation model**

Type II, $tan\ \beta = 1, 10$



The bigger picture



arXiv:1701.07427


Simplified dark matter models with two Higgs doublets: I. Pseudoscalar mediators

Martin Bauer, Ulrich Haisch, Felix Kahlhoefer

(Submitted on 25 Jan 2017 (v1), last revised 8 Feb 2017 (this version, v2))

+ ??

Searches for long-lived particles

Dark matter very weakly-coupled to the SM through **light, long-lived particles**

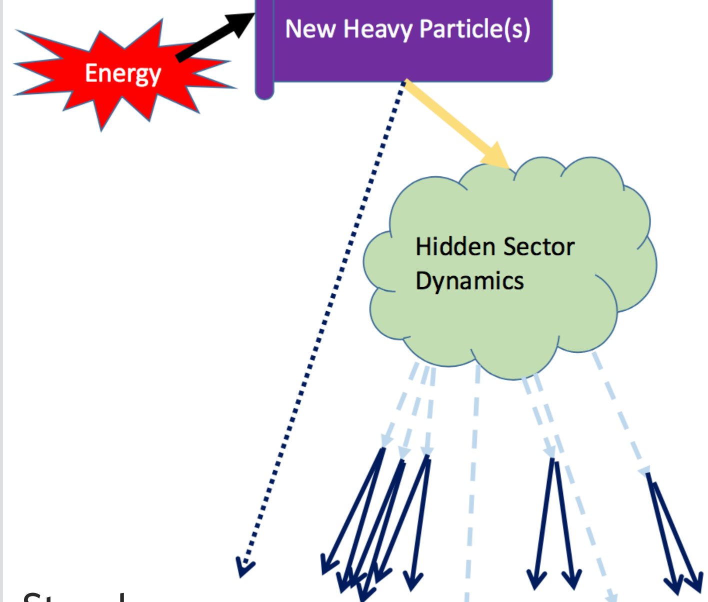
- Displaced decays (e.g. displaced / emerging jets)
- Collimated decay products (lepton jets)

Current detectors not designed for

- reconstruction of very odd physics objects
- triggering on displaced decays of neutral long-lived particles
- triggering on ‘low’ energy physics

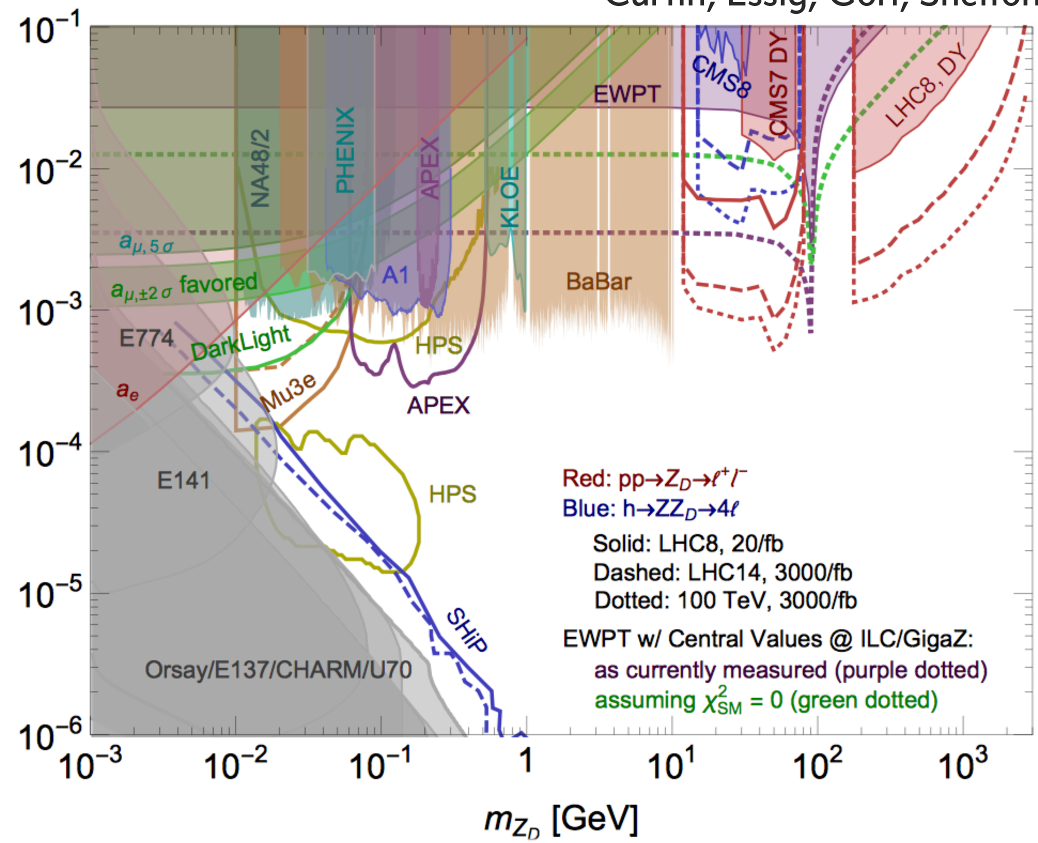
Partial wish list

- Better online reconstruction capability
- Timing information and dE/dx
- Detector design for very displaced objects cases (e.g. disappearing tracks)

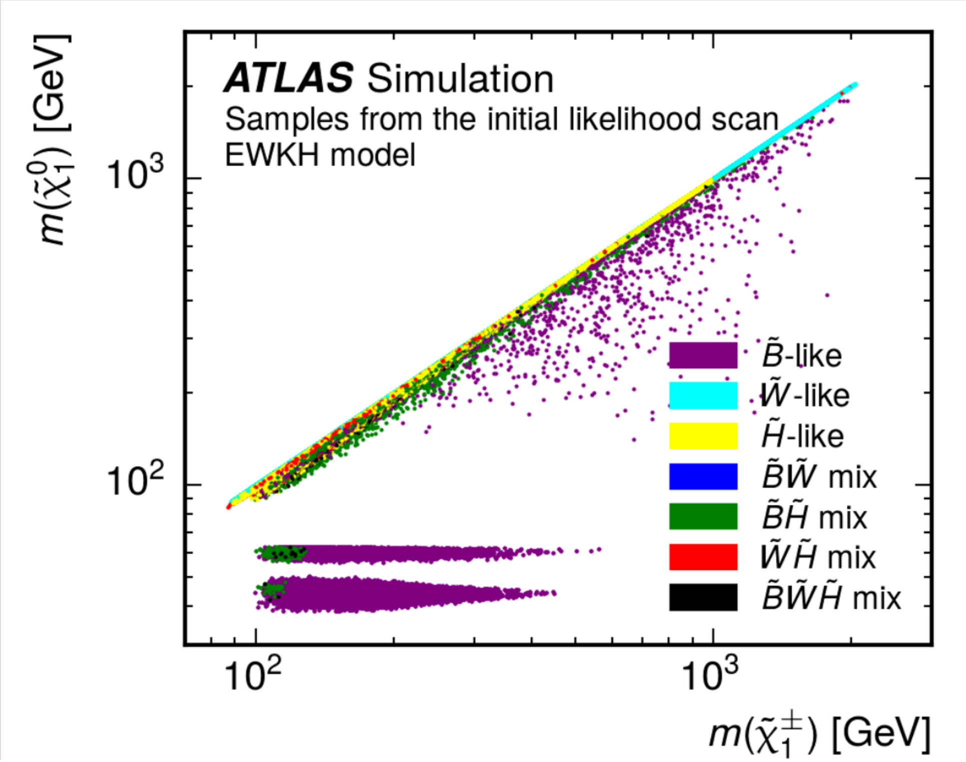


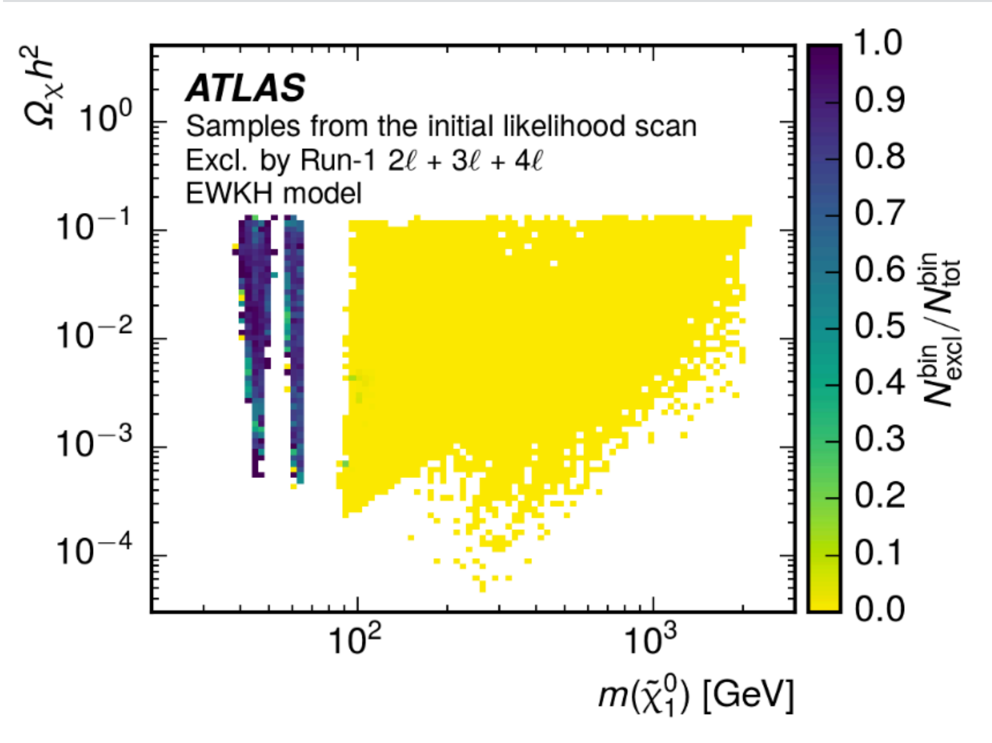
Strassler

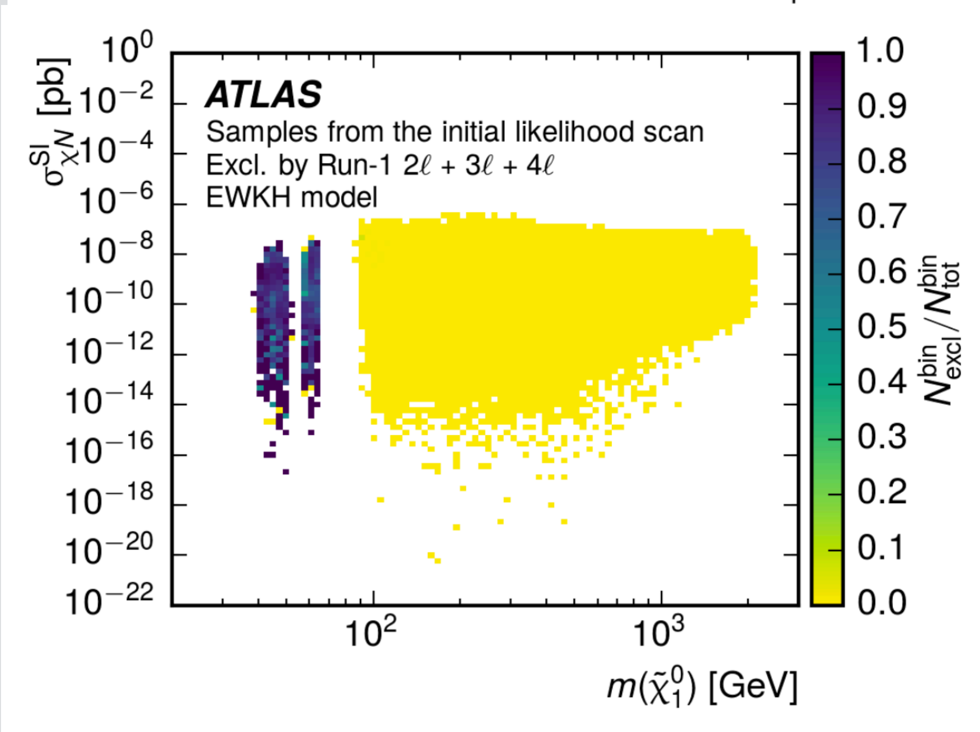
Curtin, Essig, Gori, Shelton

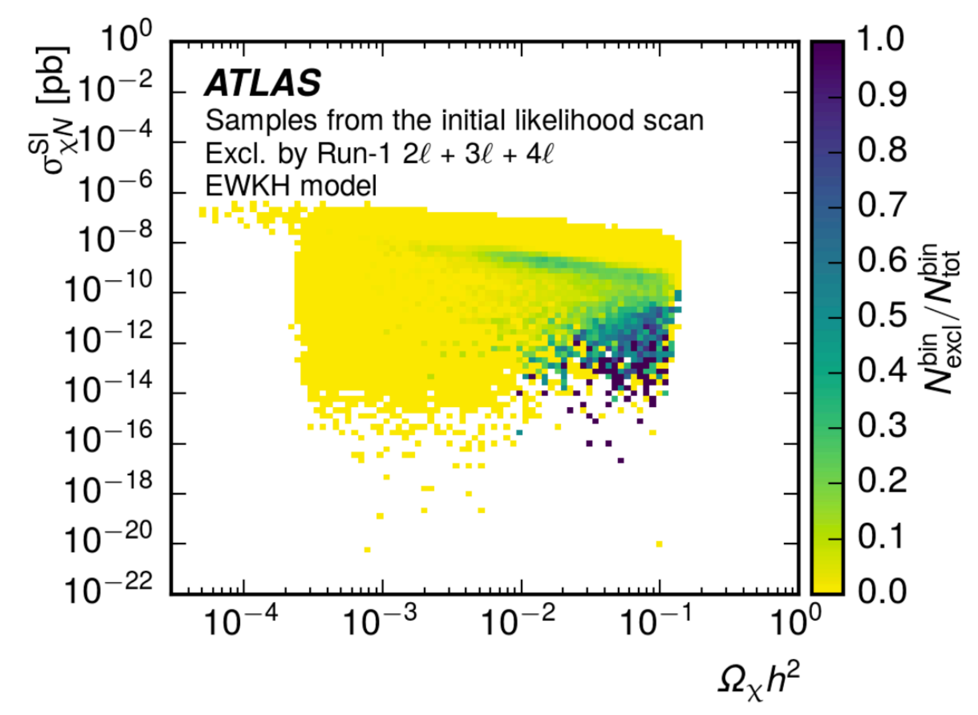


JHEP09 (2016) 175 — Dark matter interpretations of ATLAS searches for EW SUSY at 8 TeV



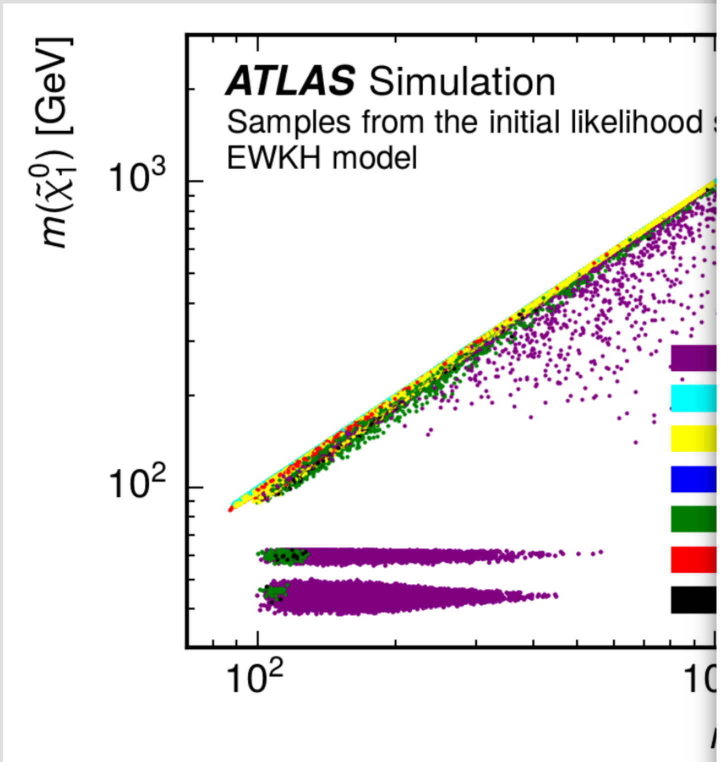


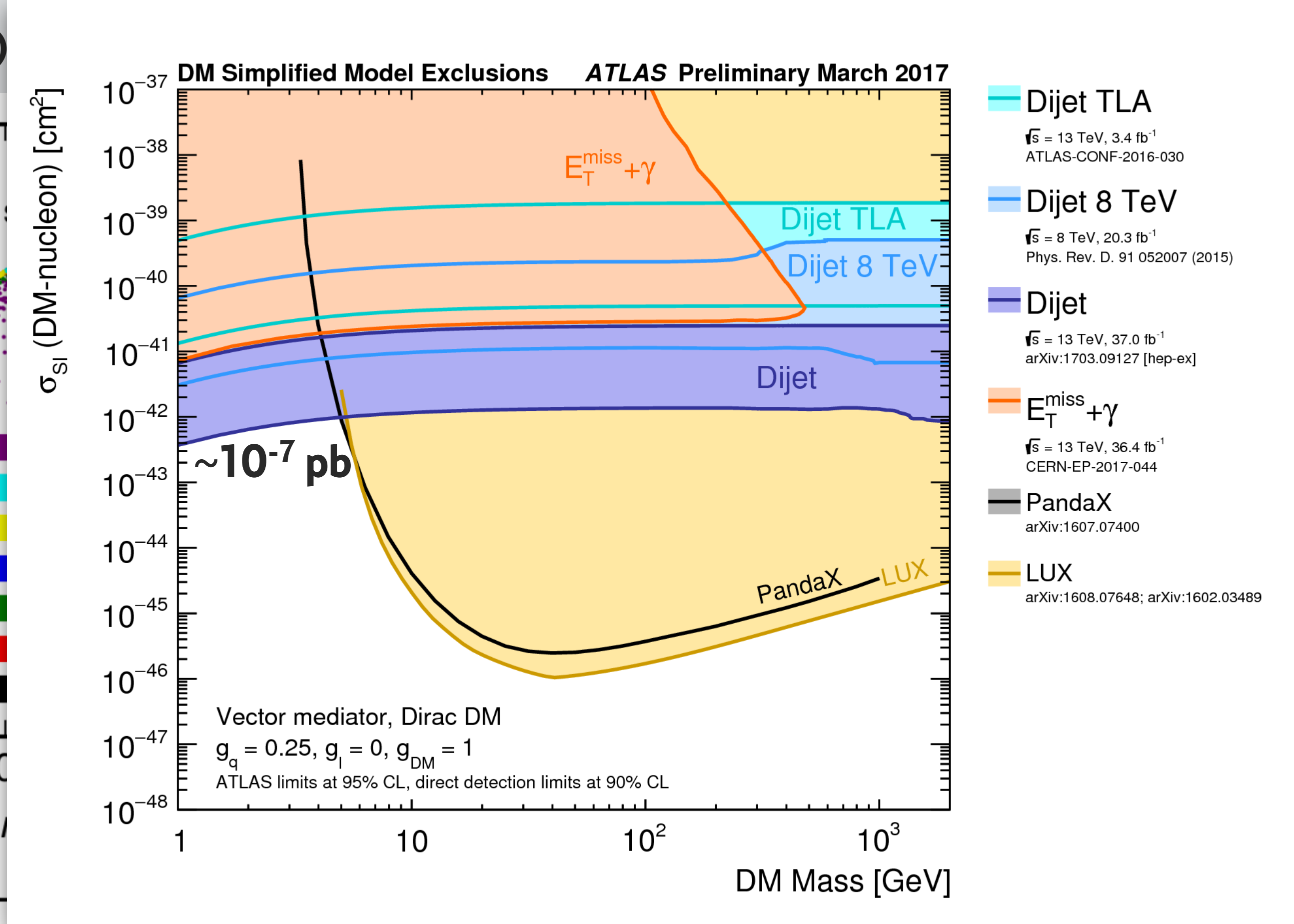


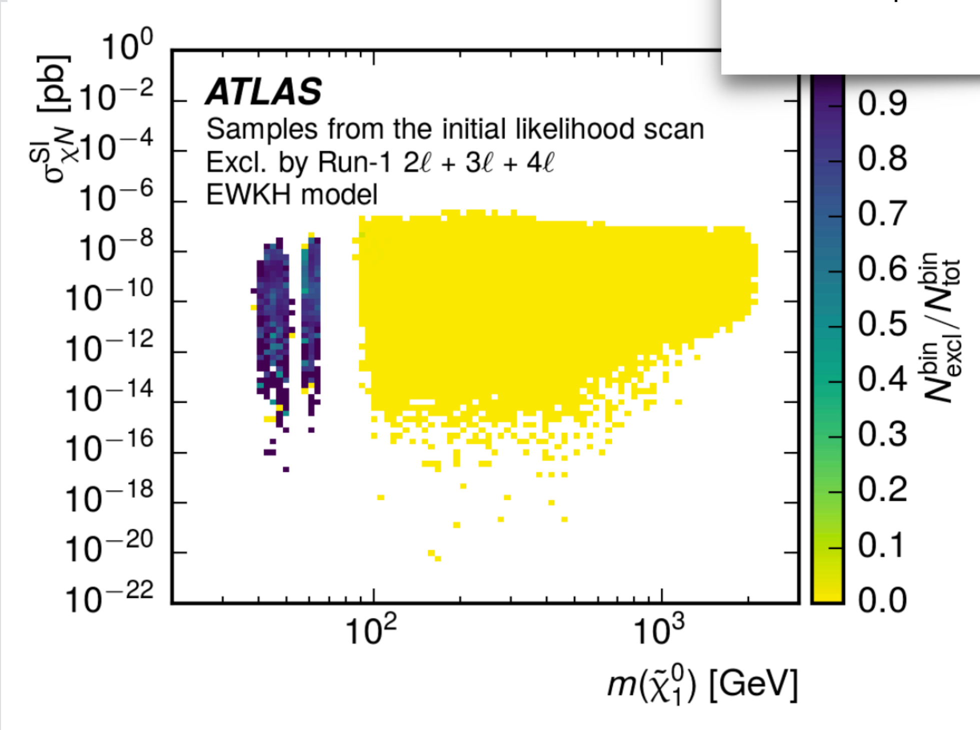


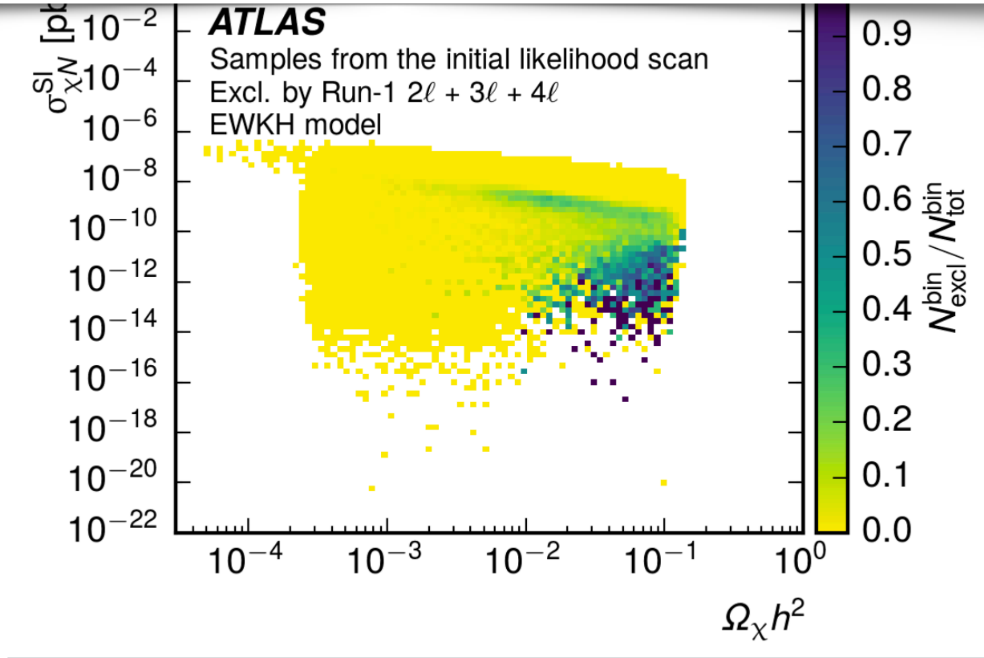
SUSY Dark Matter

JHEP09 (2016)









Summary

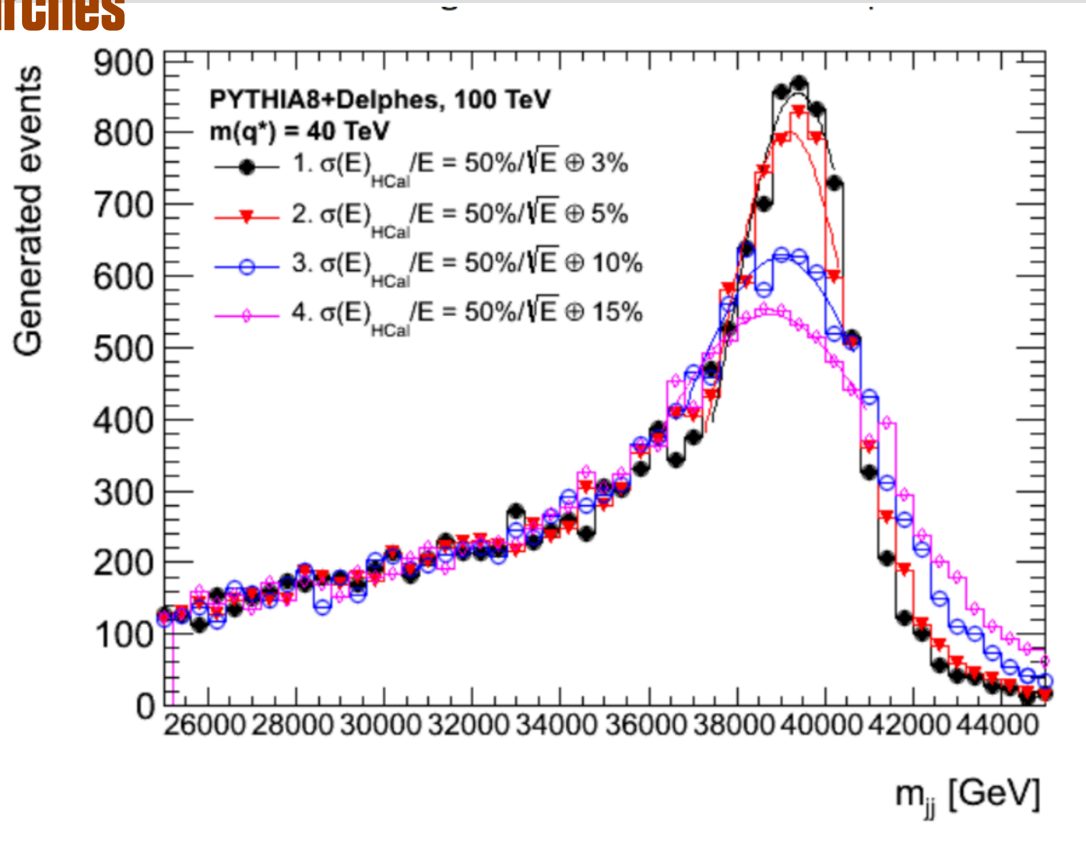
Additional Slides

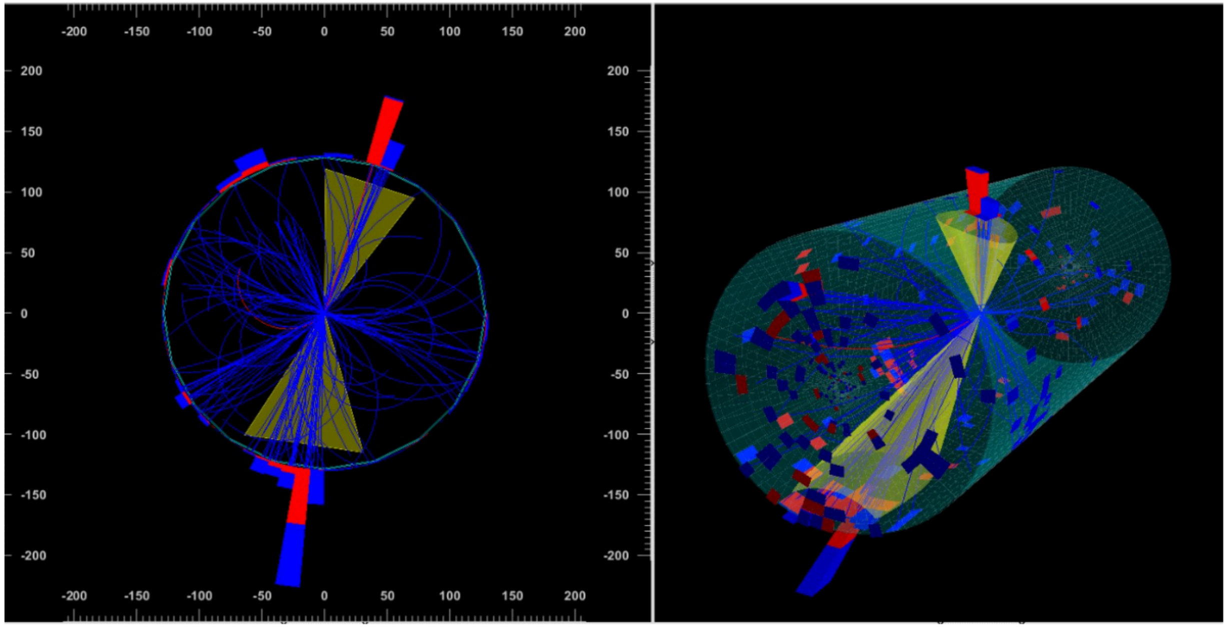
Detector performance in MET+X and di-X searches

Consider narrow mediators decaying to dijets

Sensitvity depends on **mass resolution** (=peak sharpness), which in turn depends on

- Jet algorithm (see "jetography": http://arxiv.org/abs/0810.1304)
- Calorimeter resolution
- Calorimeter depth (leakage)





Delphes Sim.

Boosted objects needed for scalars (everything from the ttbar system merges)

Ultimate calorimeter granularity required

Substructure techniques

How to trigger?

LHC / HL-LHC Plan

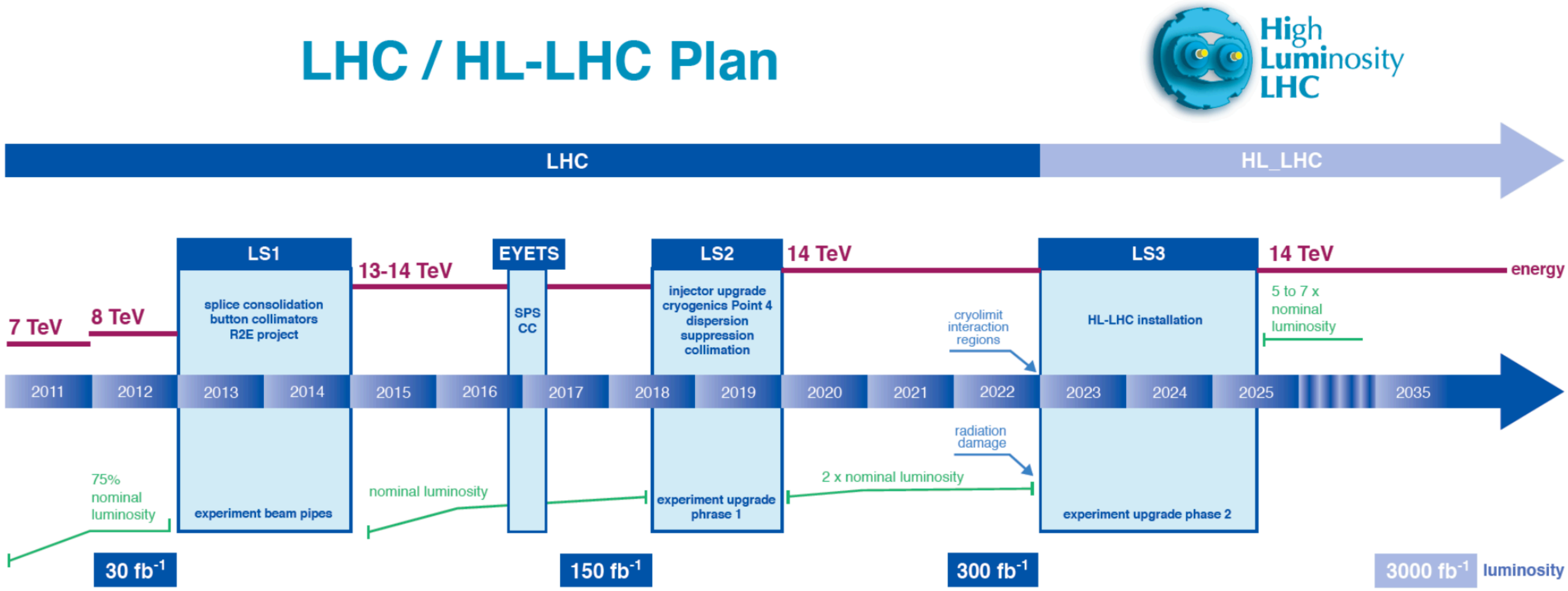
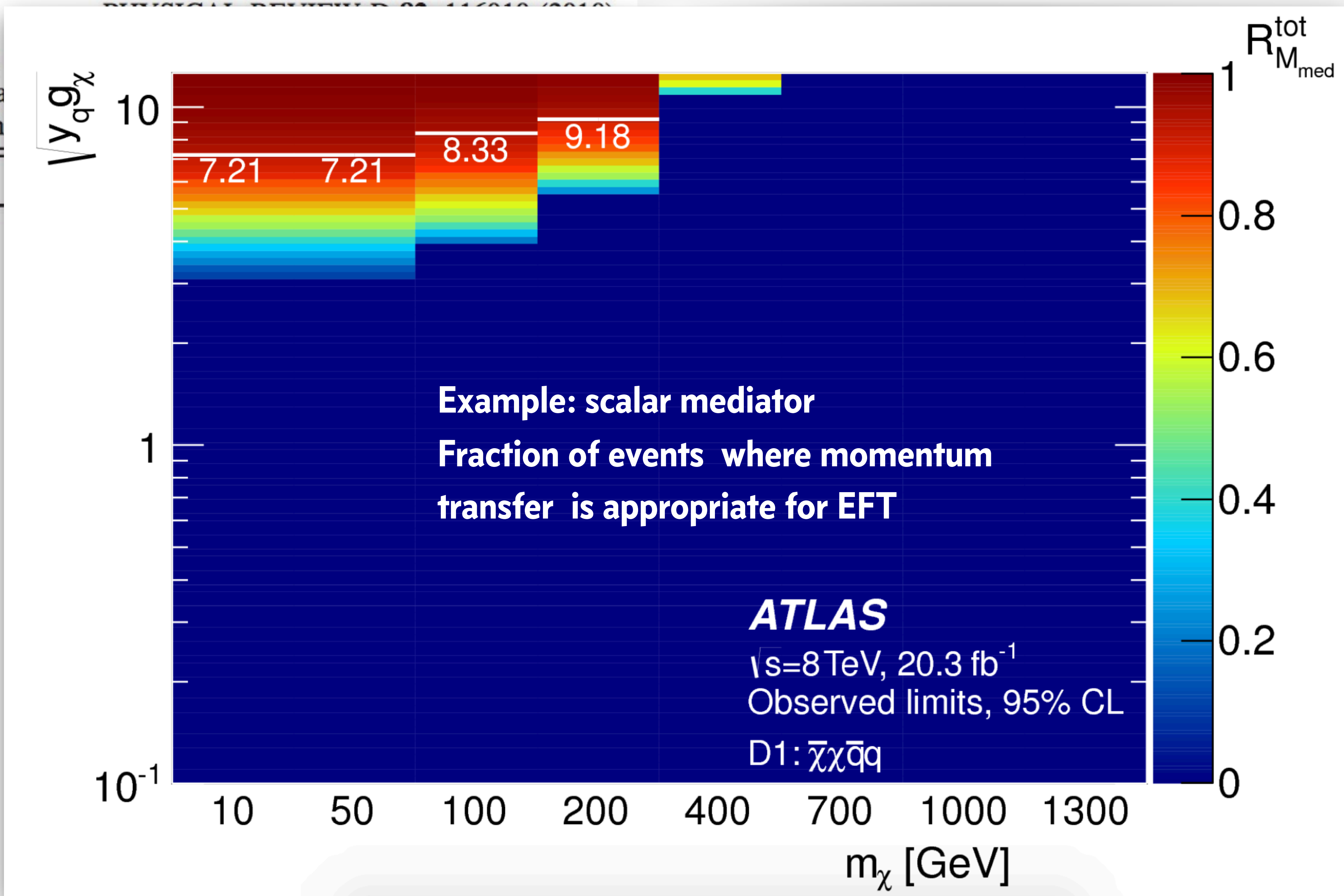


TABLE I. operator na... Dirac ferm...

Name		
D1		
D2		
D3		
D4		
D5		
D6		
D7		
D8		
D9		
D10		
D11		
D12		
D13		
D14		
C1		
C2		
C3		
C4		
C5		
C6		
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)

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**