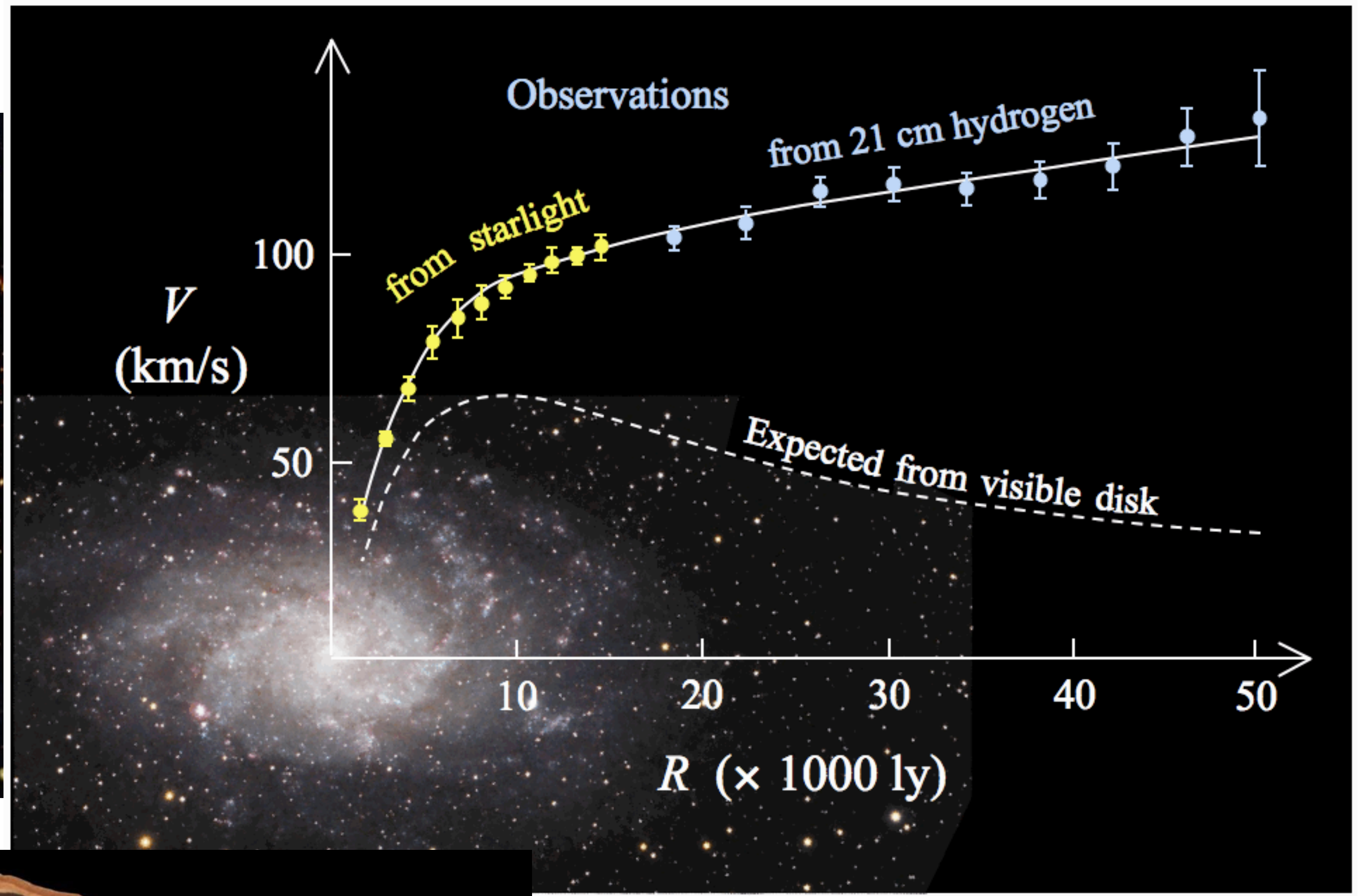
Status of Searches for Dark Matter at the LHC

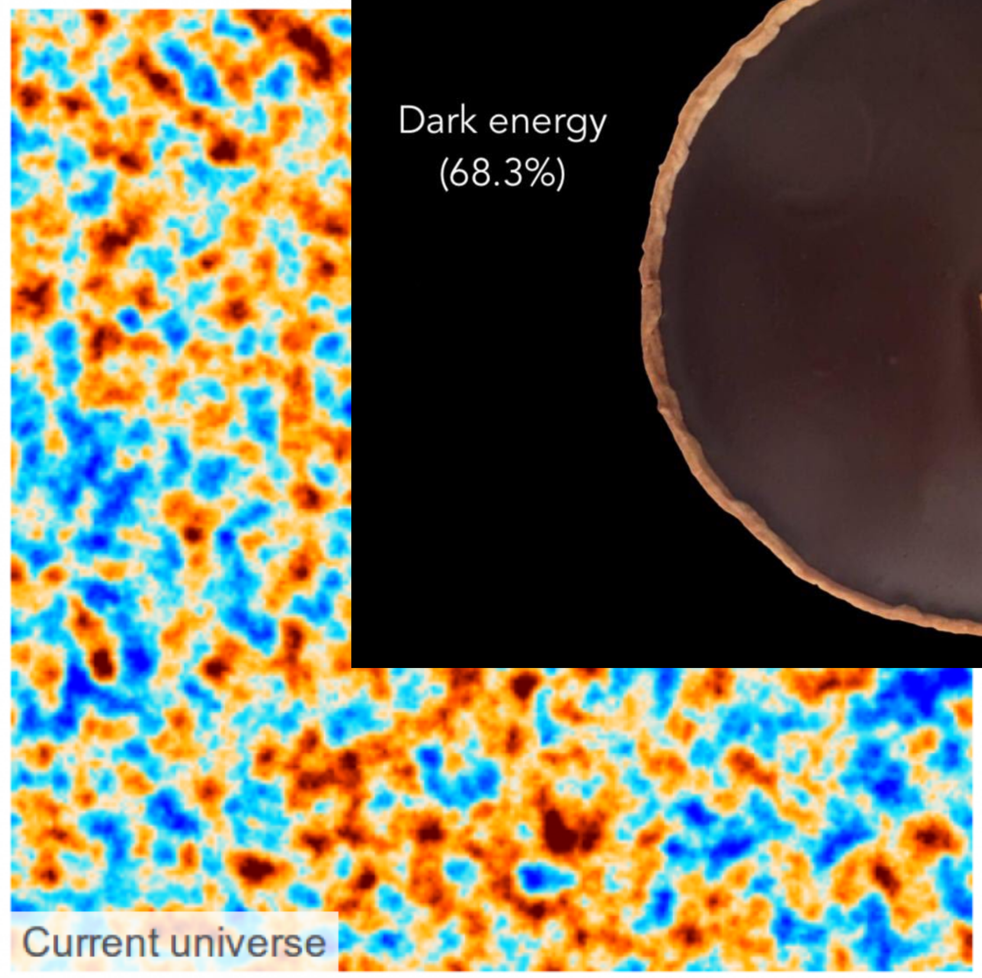
Alex Tapper for the ATLAS and CMS collaborations

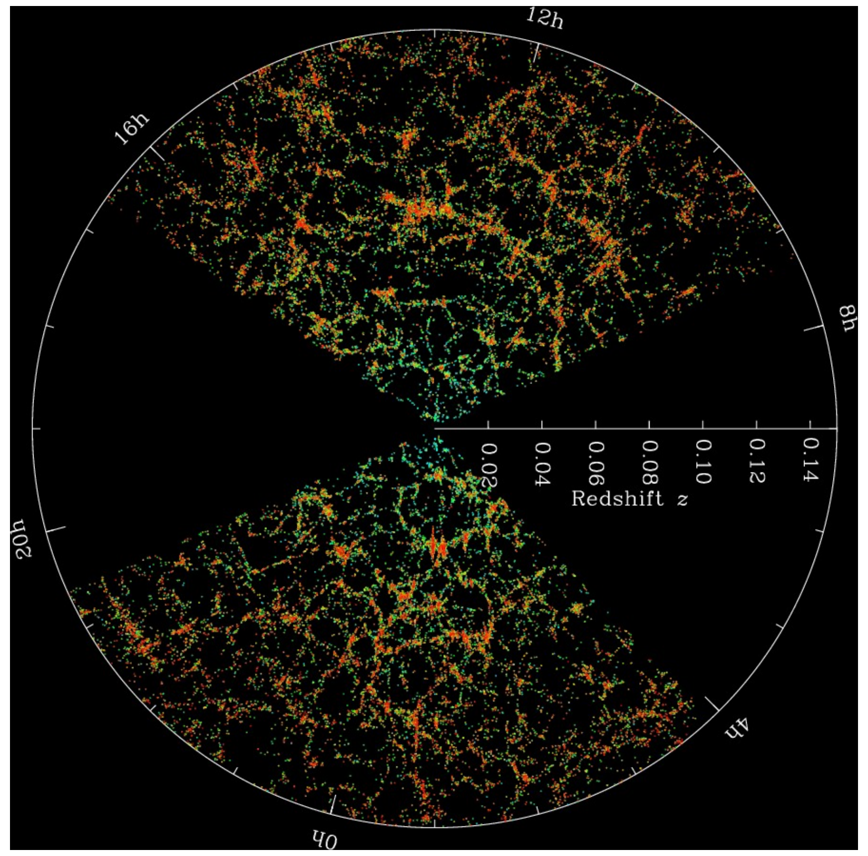
Why Dark Matter?

- Empirical evidence from astronomical observations

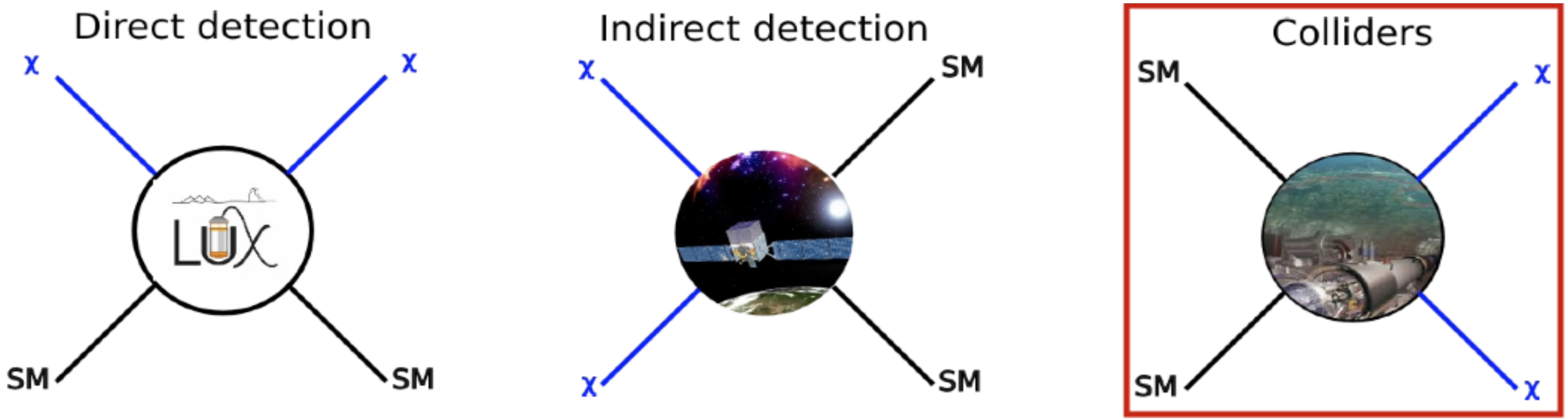
- What do we know?
  - Interacts gravitationally, electrically and colour neutral and long lived
  - We assume it interacts weakly with the Standard Model
  - Most studied class of theories is weakly interacting massive particle







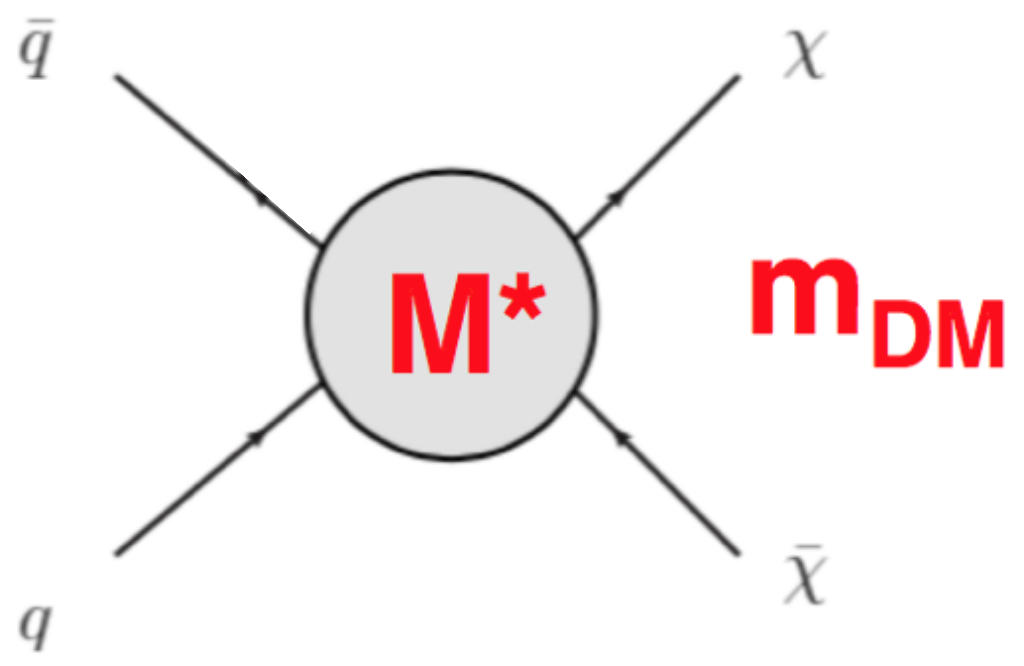
Detecting Dark Matter



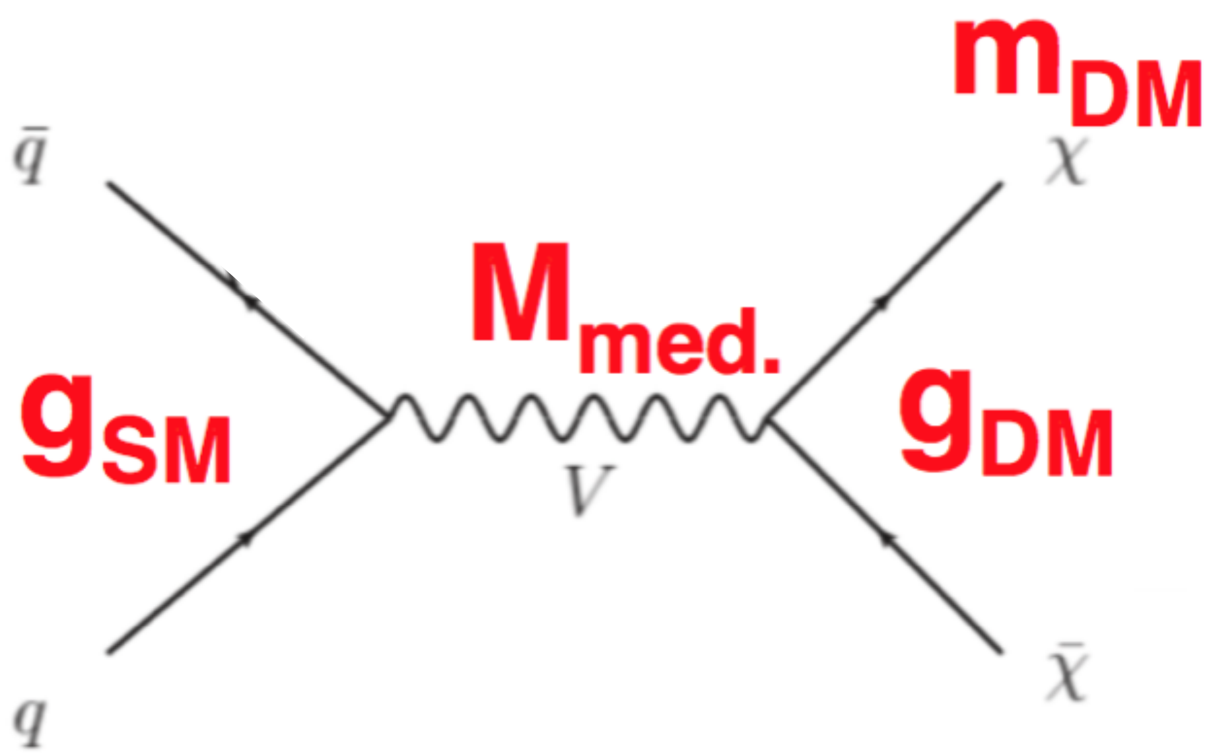
- Complementary ways to search for Dark Matter
- Same particles .. very different energy scales .. common theory framework?

Intermezzo: Interpretation

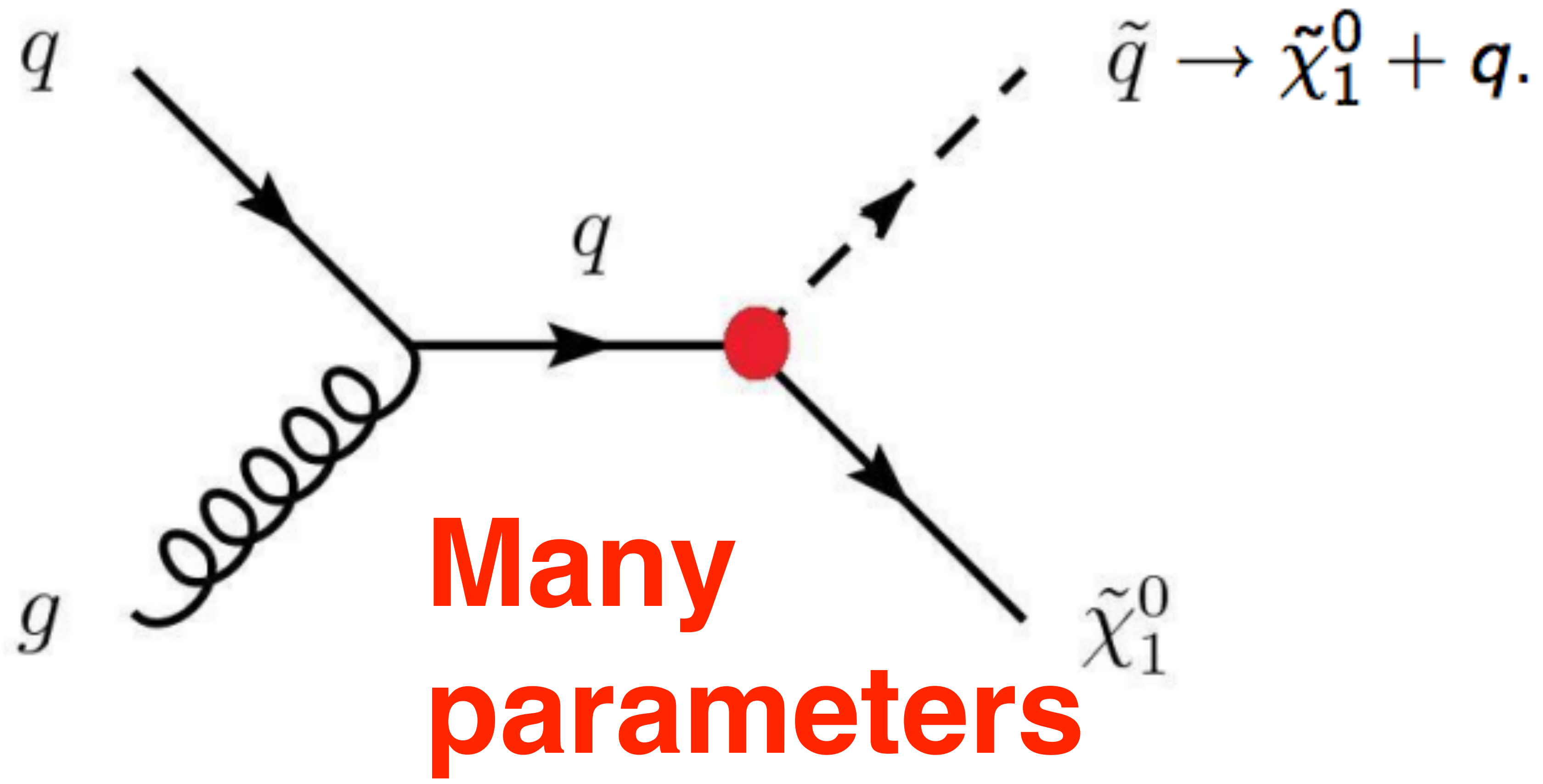
Effective field theory



Simplified Models



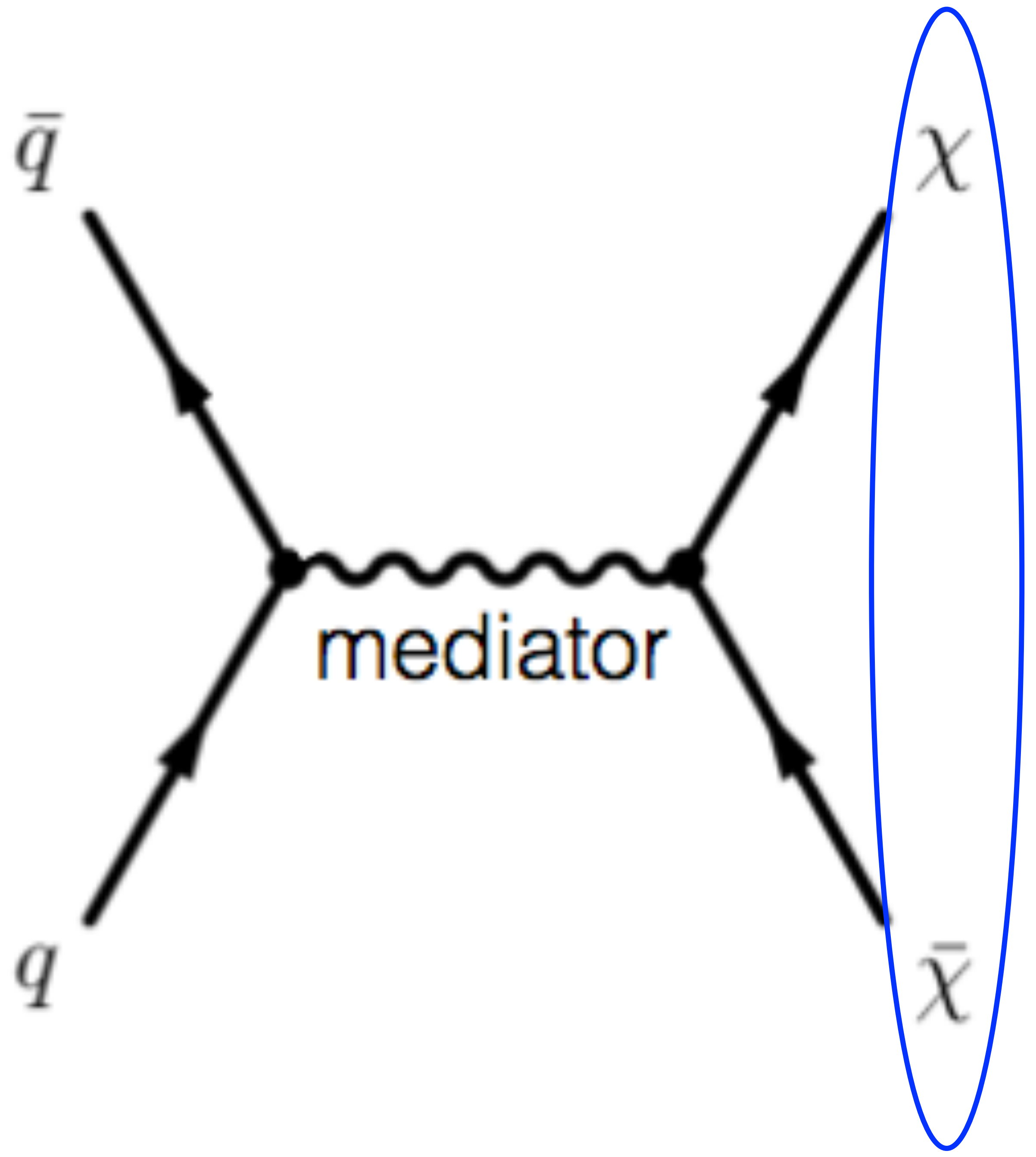
Complete theory



- **Simplified Models** (à la SUSY) focus of LHC community
  - Avoid validity concerns of EFT @ LHC
  - Capture generic signatures common to many complete theories
  - Express results in terms of couplings g_{DM} and g_{SM}, M_{med}, and m_{DM}

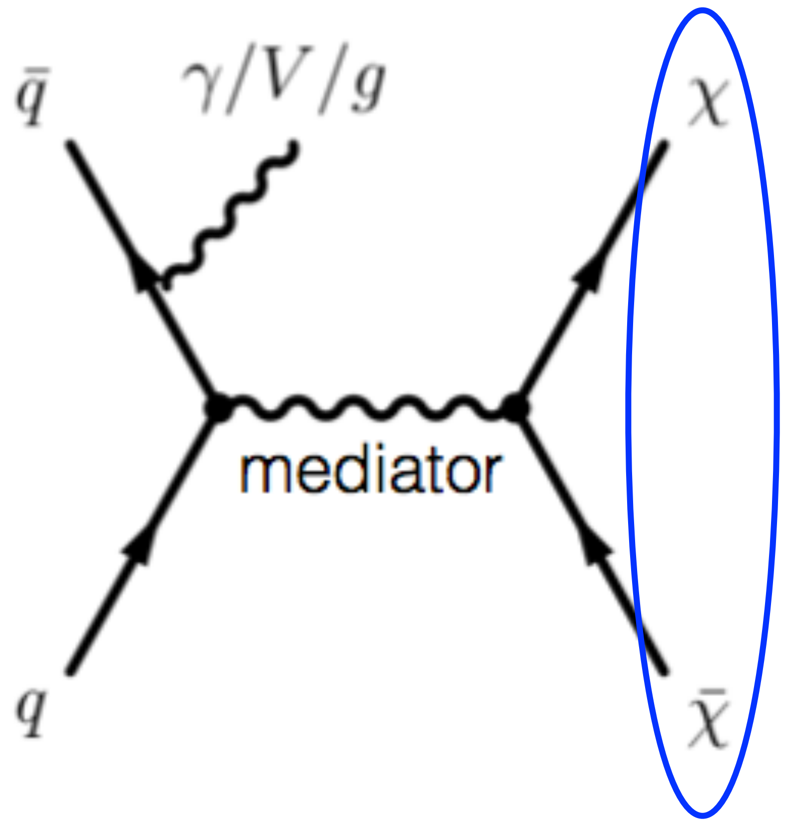
arXiv:1603.04156
arXiv:1703.05703

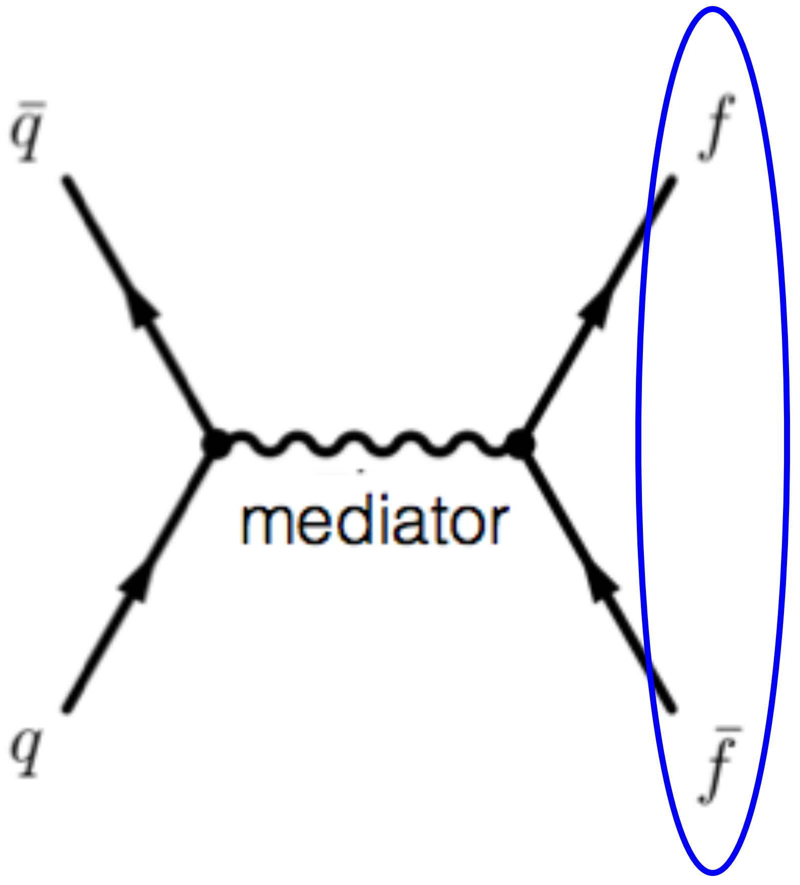
Detecting Dark Matter @ LHC



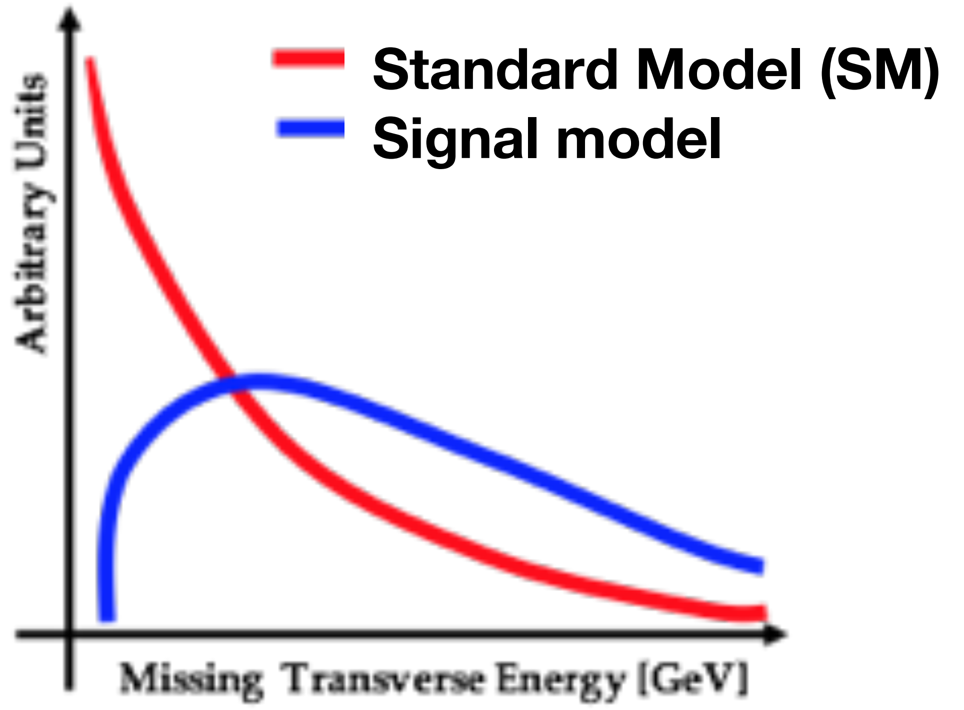
Dark Matter does not interact in detectors

Invisible searches

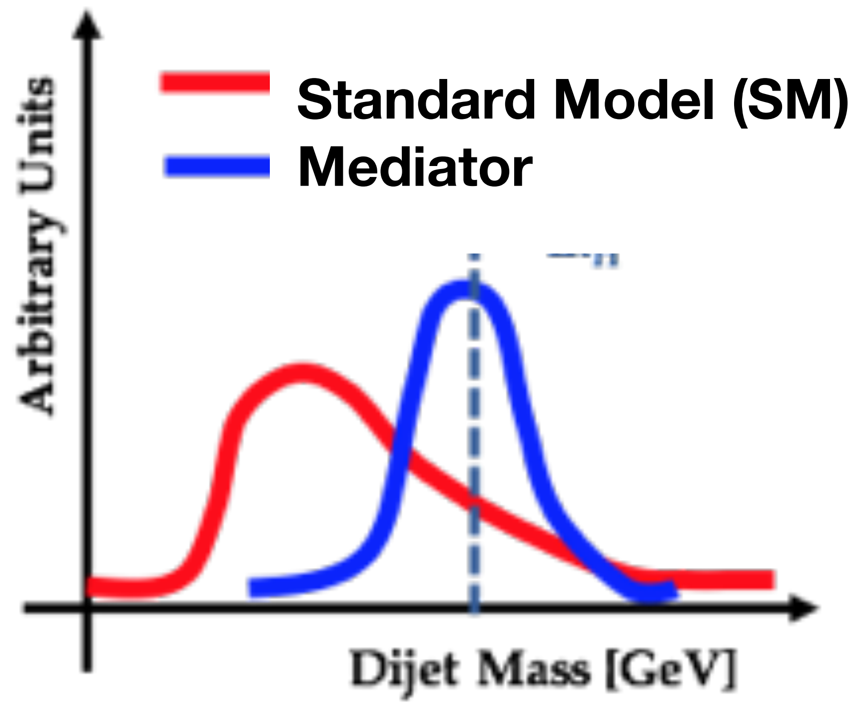




Visible searches



Tails of distributions



Bump hunt

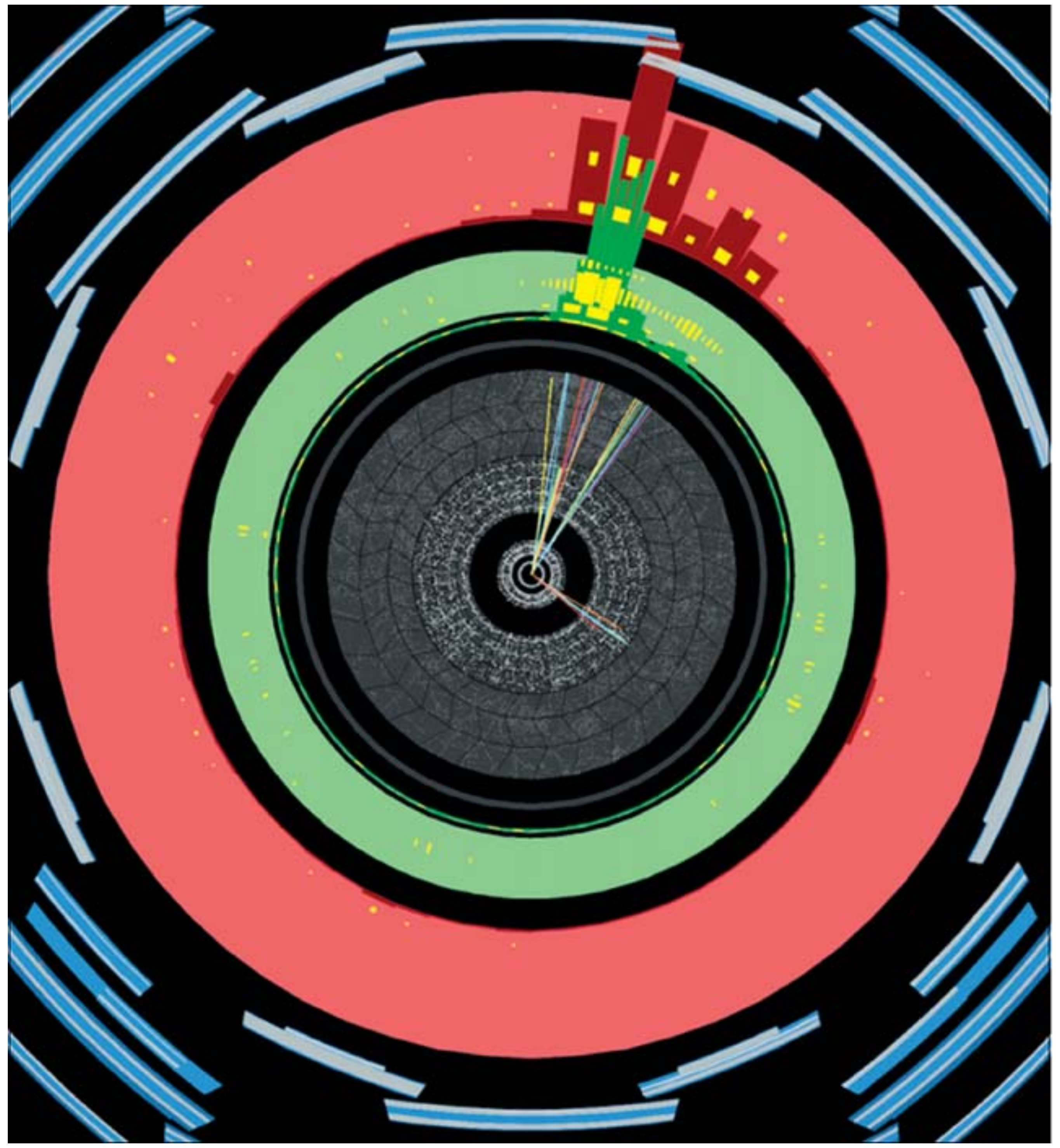
Detecting Dark Matter @ LHC

- Key variables:
  - Missing energy from invisible Dark Matter particles

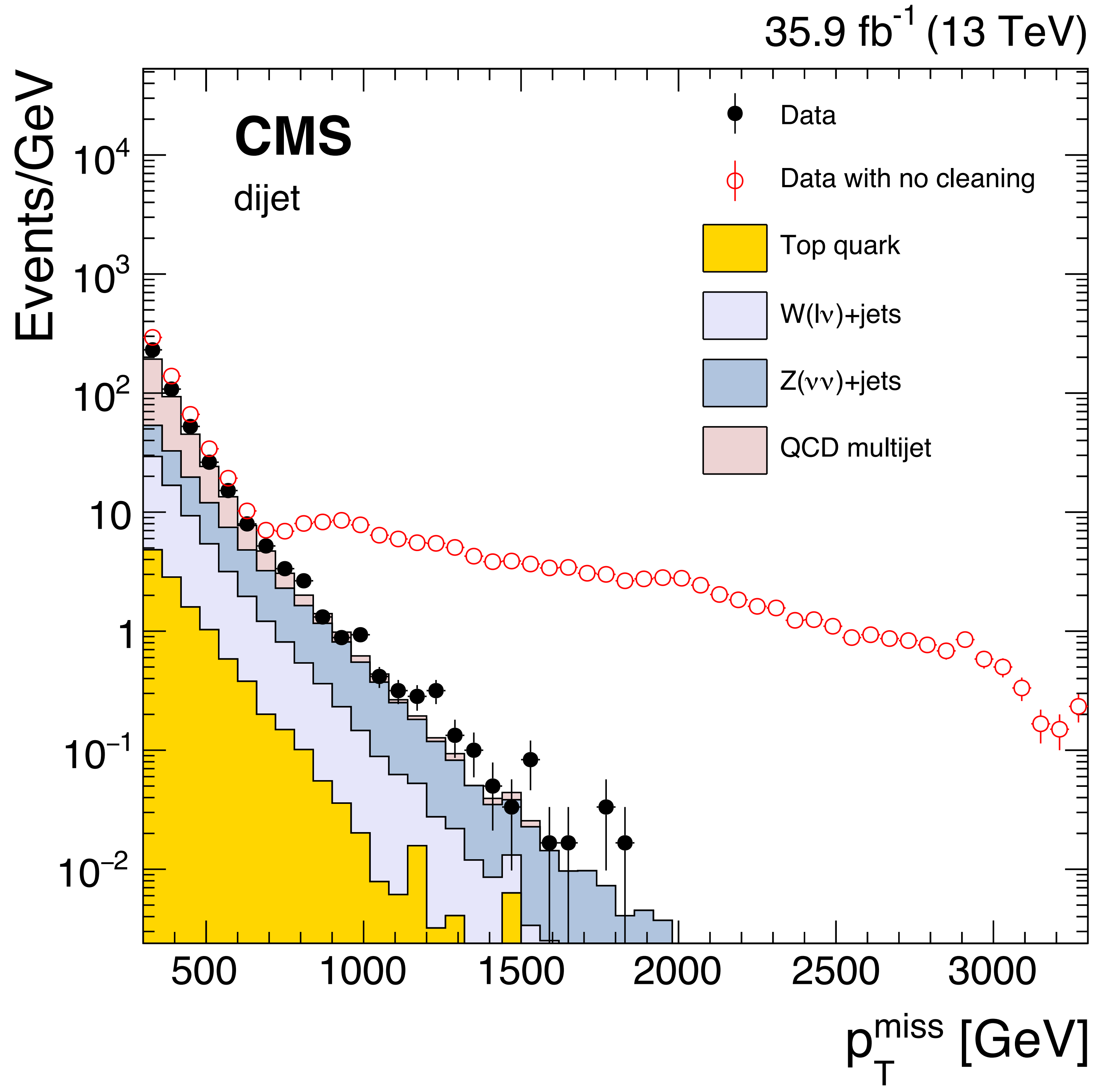
$$p_T^{miss} = |\Sigma_i \vec{p_i}|$$

  - Invariant mass for resonant production of mediator particles

$$M_{12} = \sqrt{(E_1 + E_2)^2 - |\vec{p_1} + \vec{p_2}|^2}$$

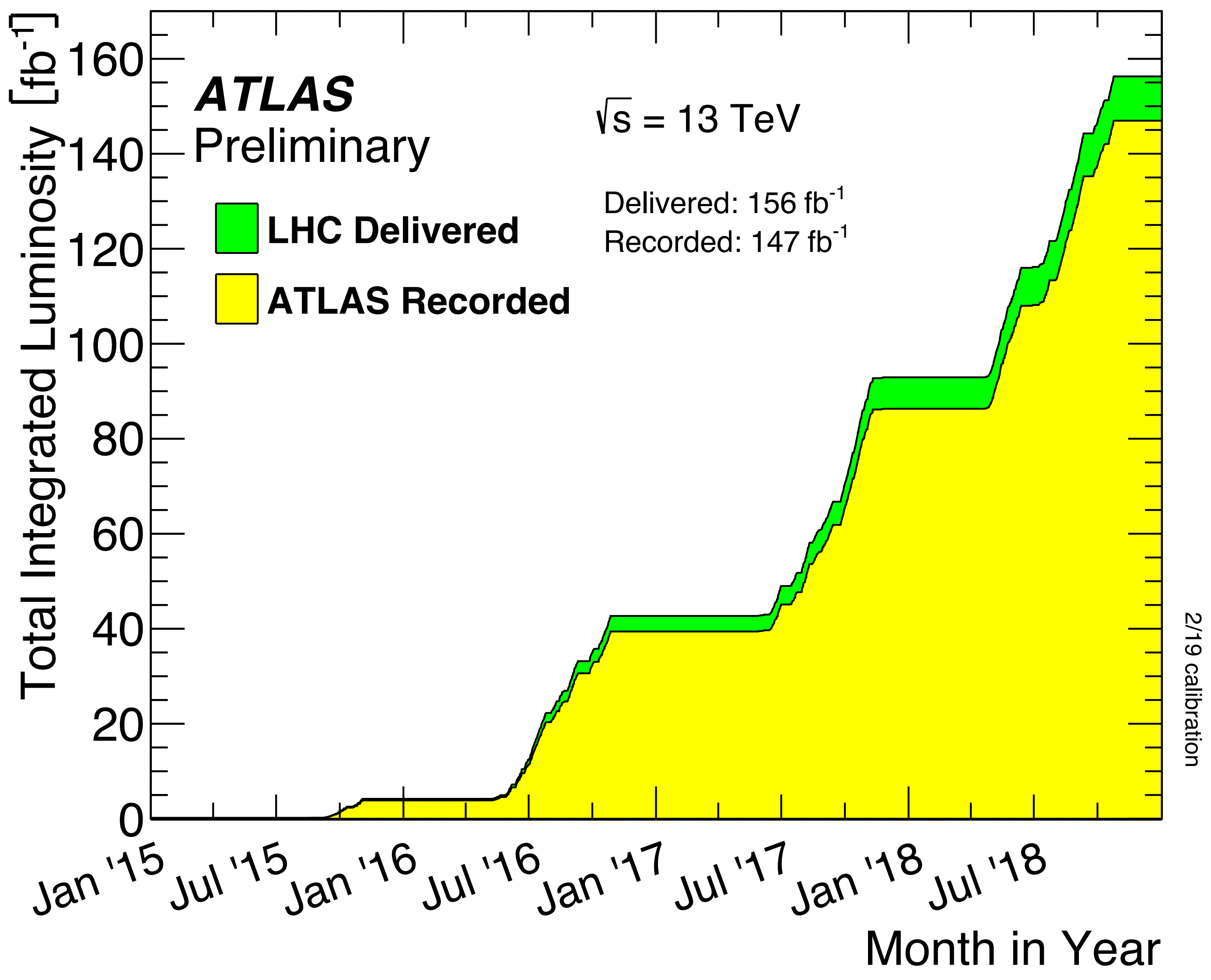


- Missing energy a challenge!
- Excellent detector calibration and understanding of noise and backgrounds necessary



Dark Matter signatures @ LHC

- Wide range of signatures probed for hints of Dark Matter…
  - Invisible/mono-objects: jet, γ, Z/W, h, b, t(t)….
  - Visible/mediator: dijets, boosted jets, leptoquarks…
  - Long-lived particles (see talk of J. Alimena)
  - SUSY decay chains (see talk of M. Wielers)
  - Hidden sector particles (see talk of J. Alimena)



- Crucial to cover all possible signatures
- Most analyses on 2015/16 data → 36 fb^{-1}
- <u>Cover selection of representative/new results</u>

Invisible (mono-object) searches

P_T^{miss}+jet

Couplings fixed to standard values
g_q=0.25 g_{DM}=1.0

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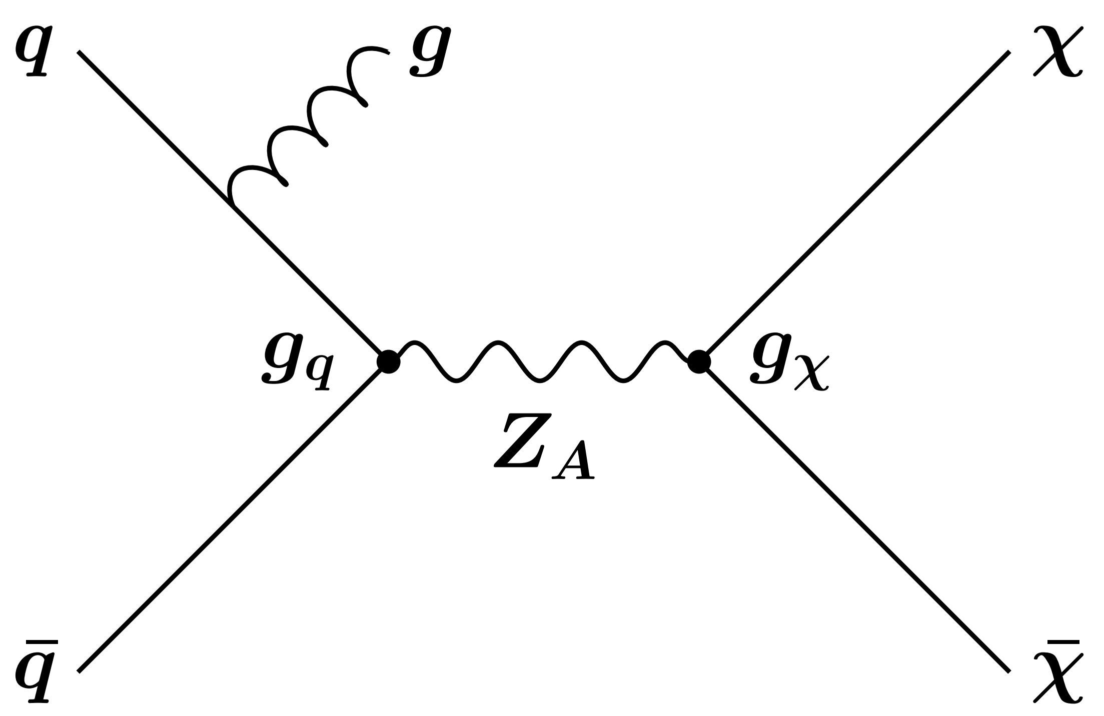
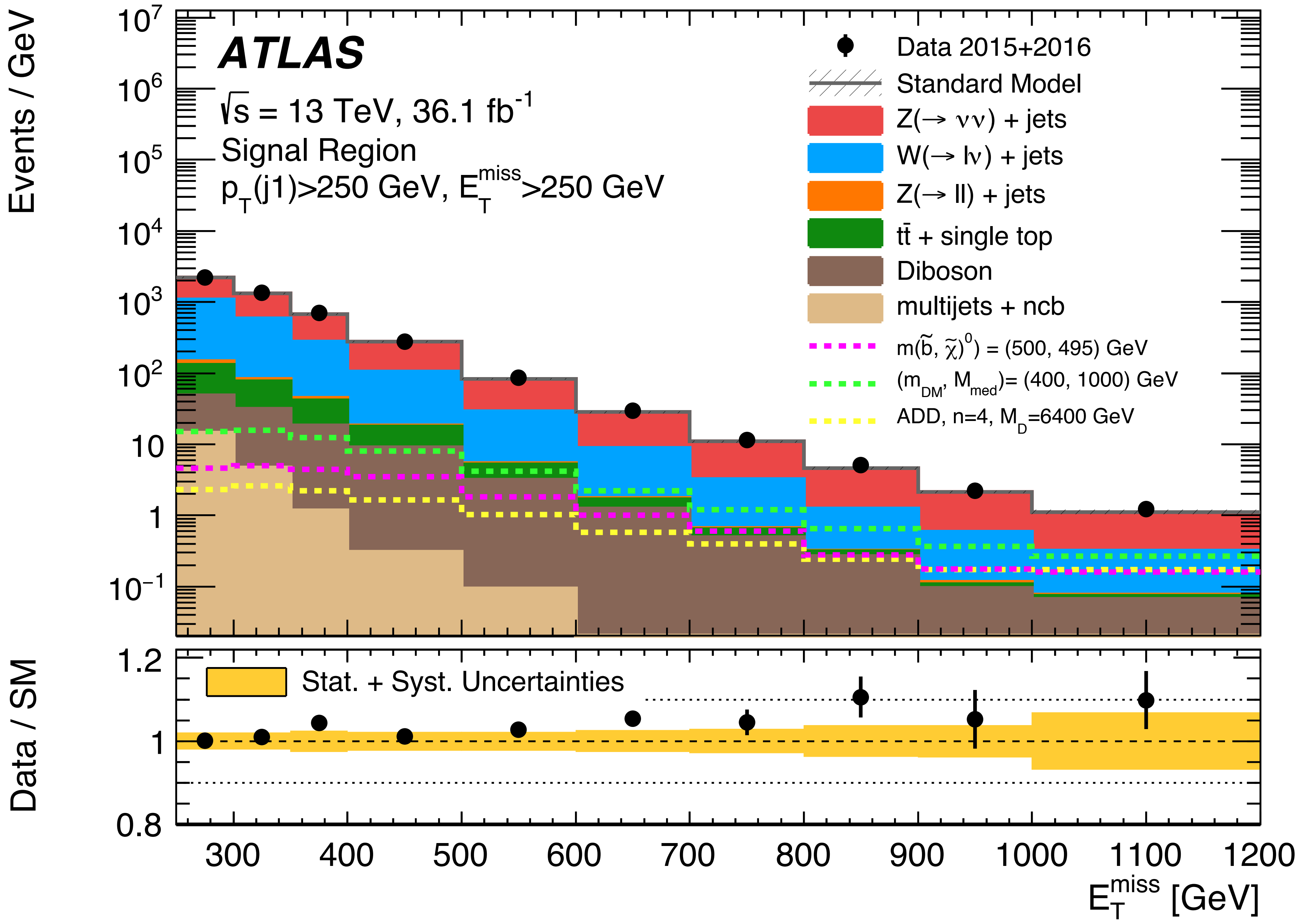
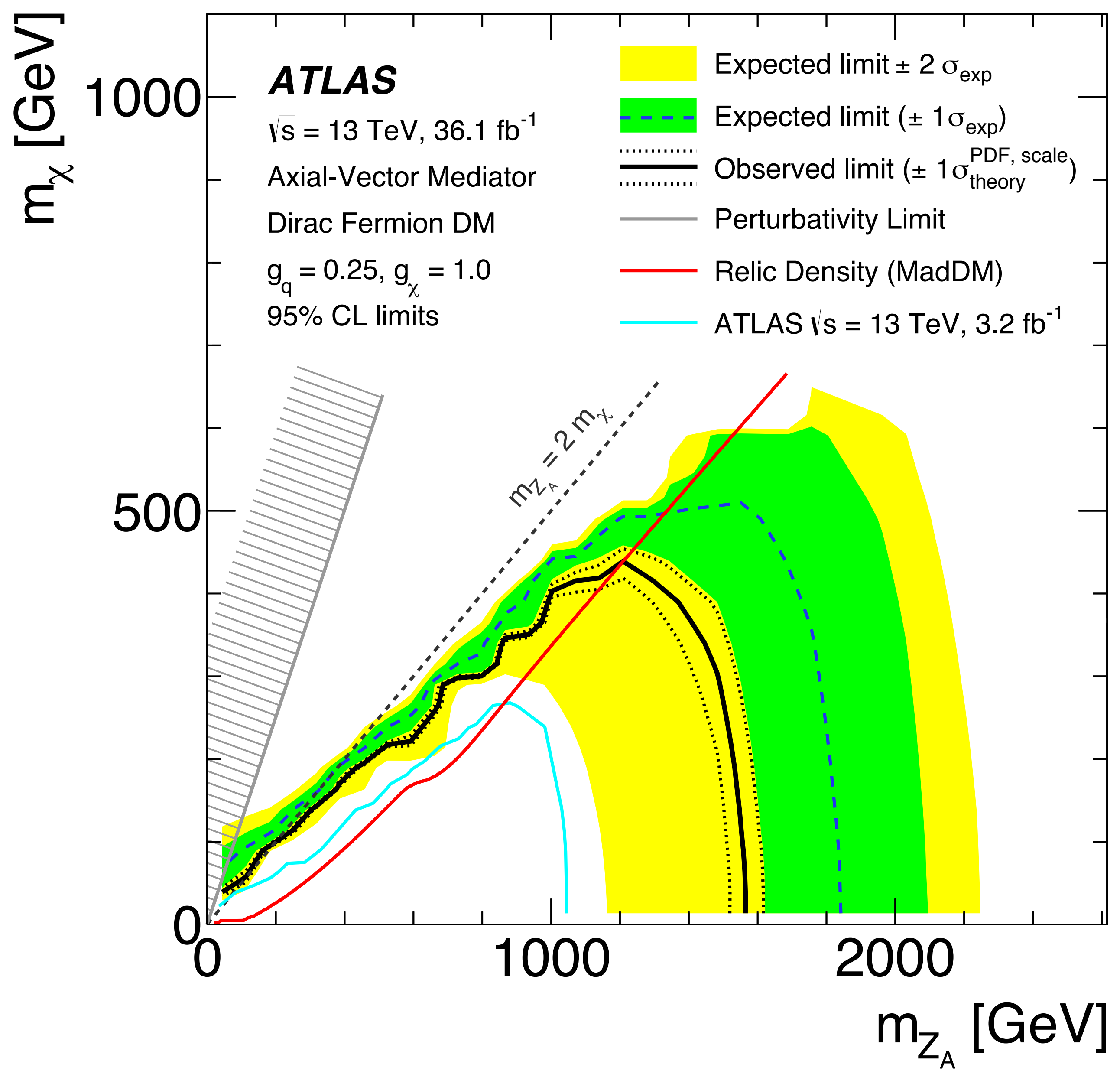
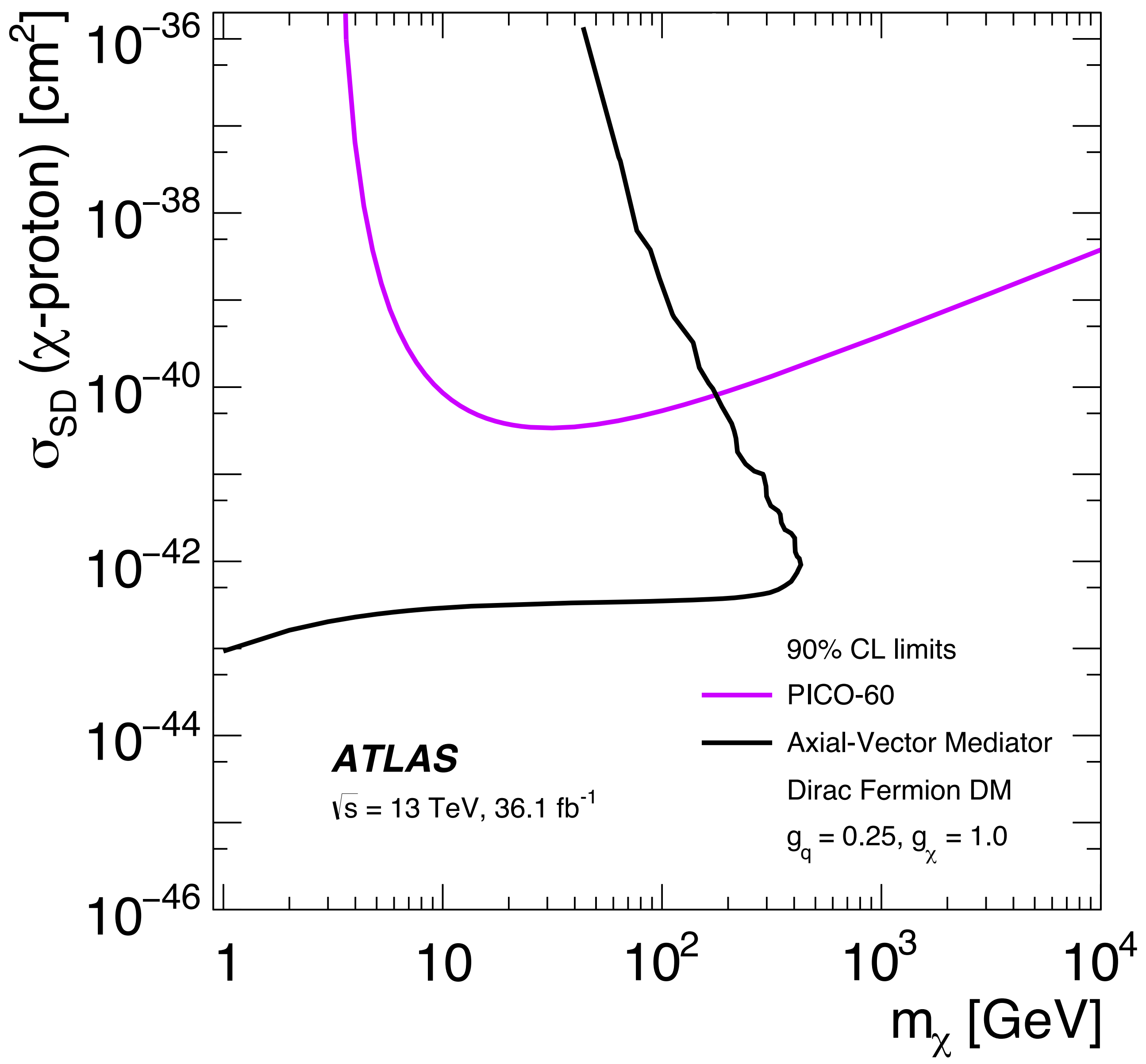








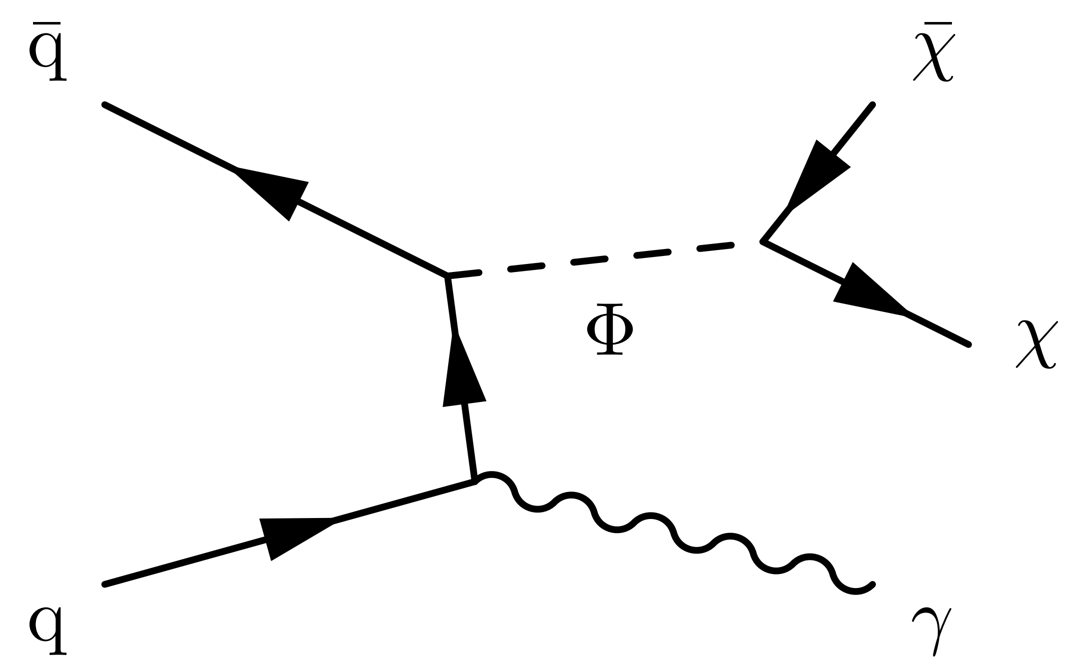
- Initial State gluon Radiation (also W/Z…)
- Irreducible background Z → νν (~60%)
- Sophisticated set of control regions to constrain backgrounds
- 5-10% uncertainties — modelling p_T of Z is largest uncertainty

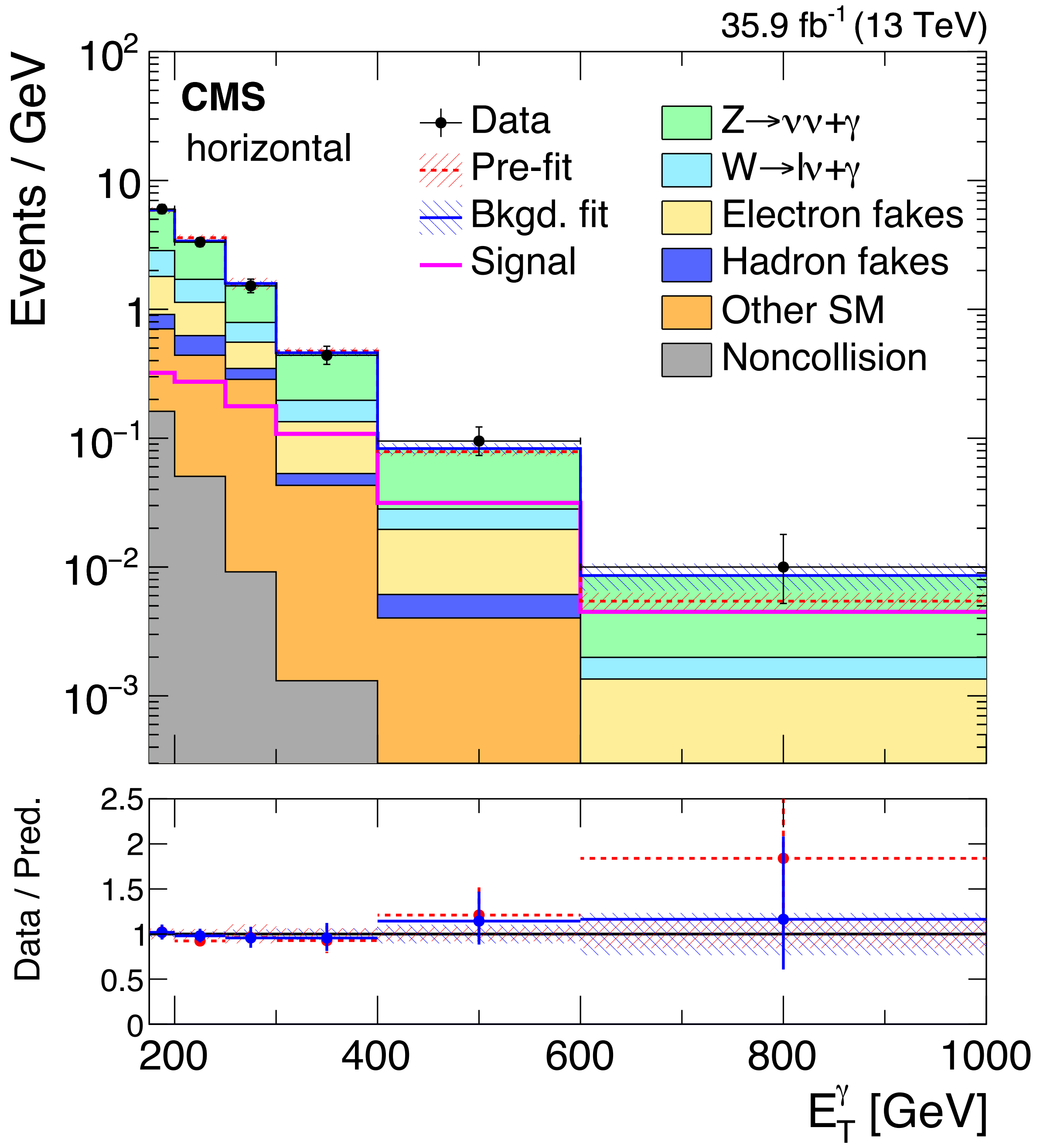
$$\sigma_{SD} \propto \left(g_q g_\chi \frac{m_\chi}{(m_{Z_A})^2} \right)^2$$

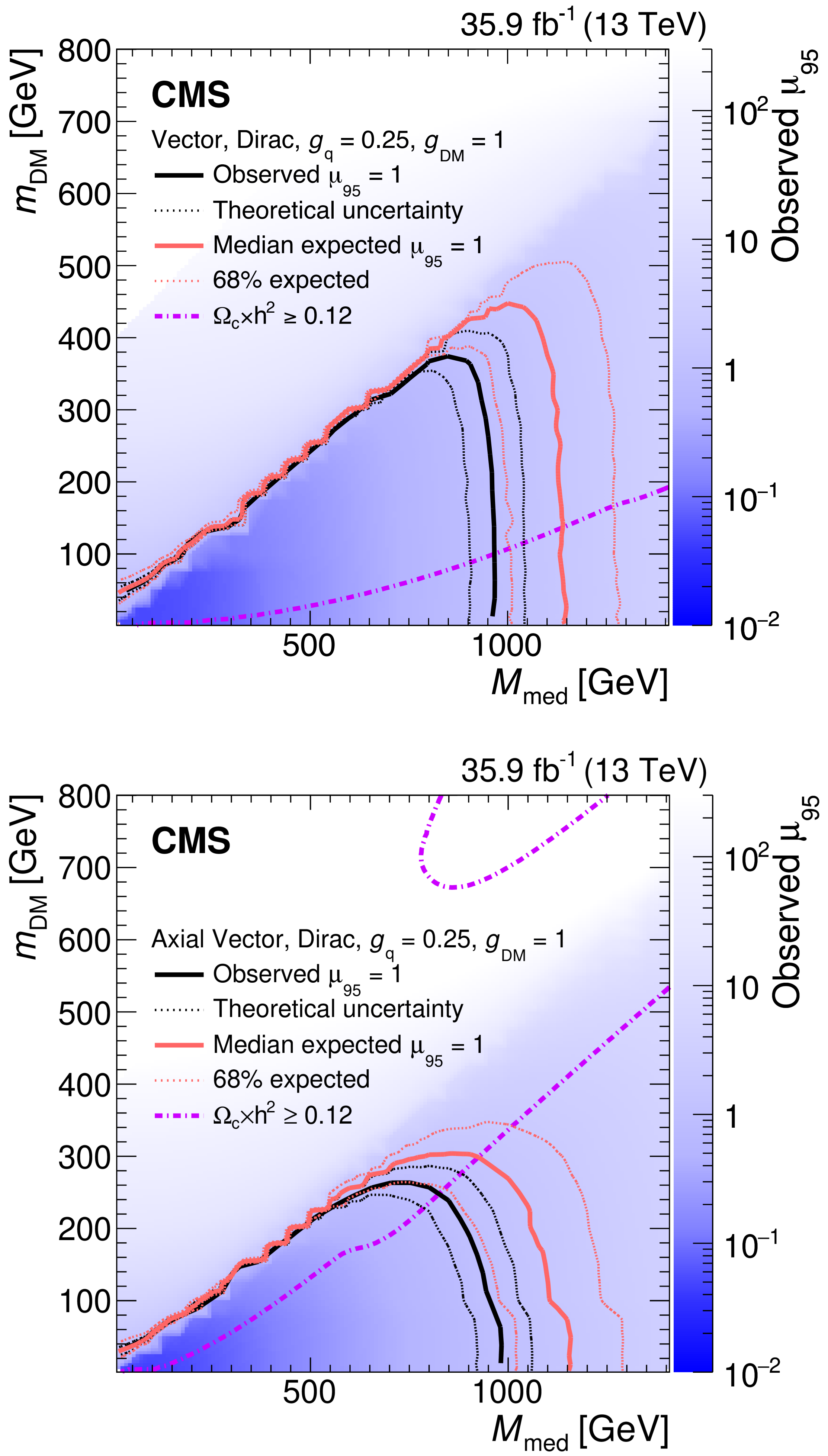
CMS Phys. Rev. D 97 (2018) 092005

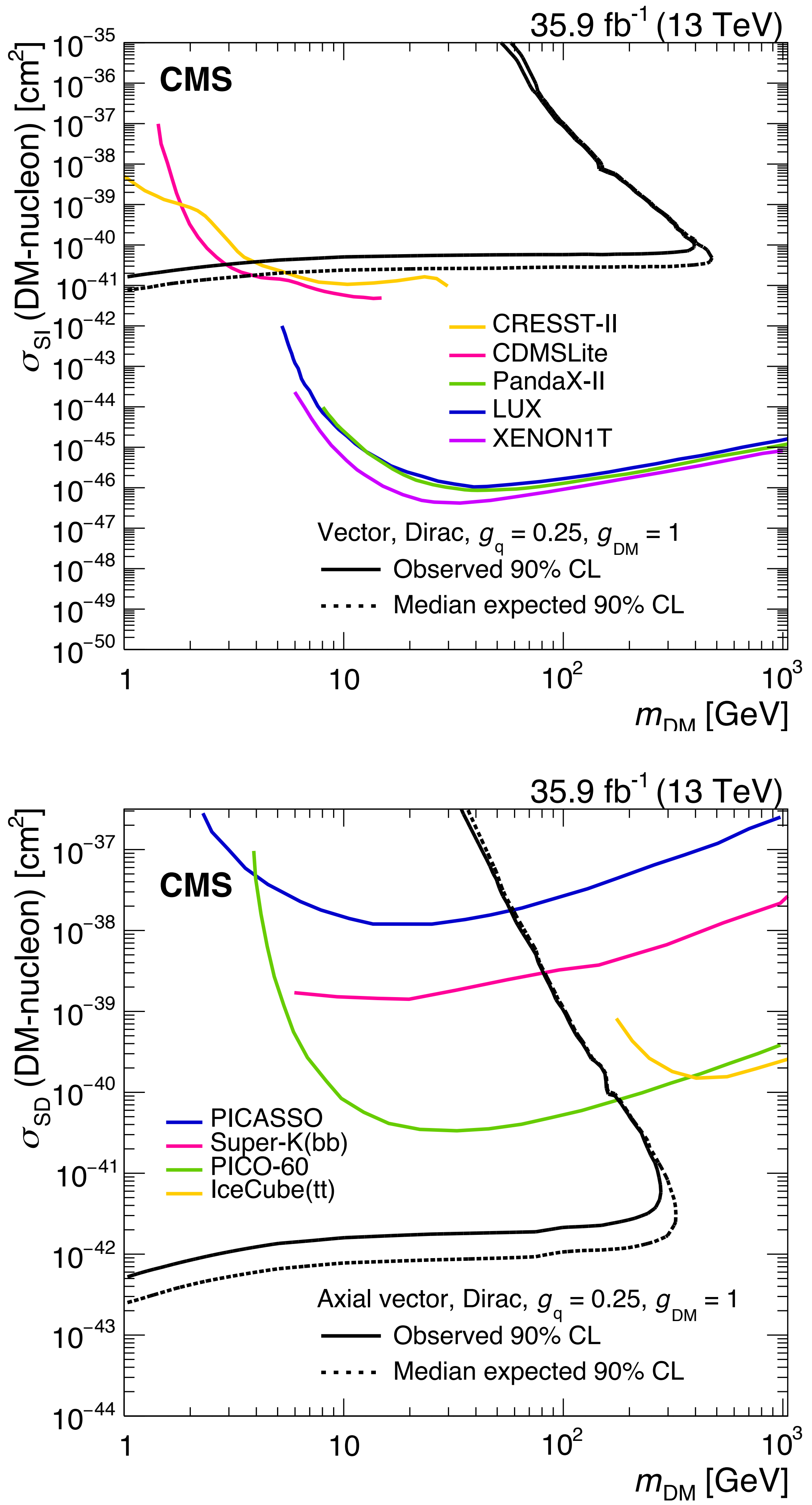
P_T^{miss}+γ

JHEP 02 (2019) 074



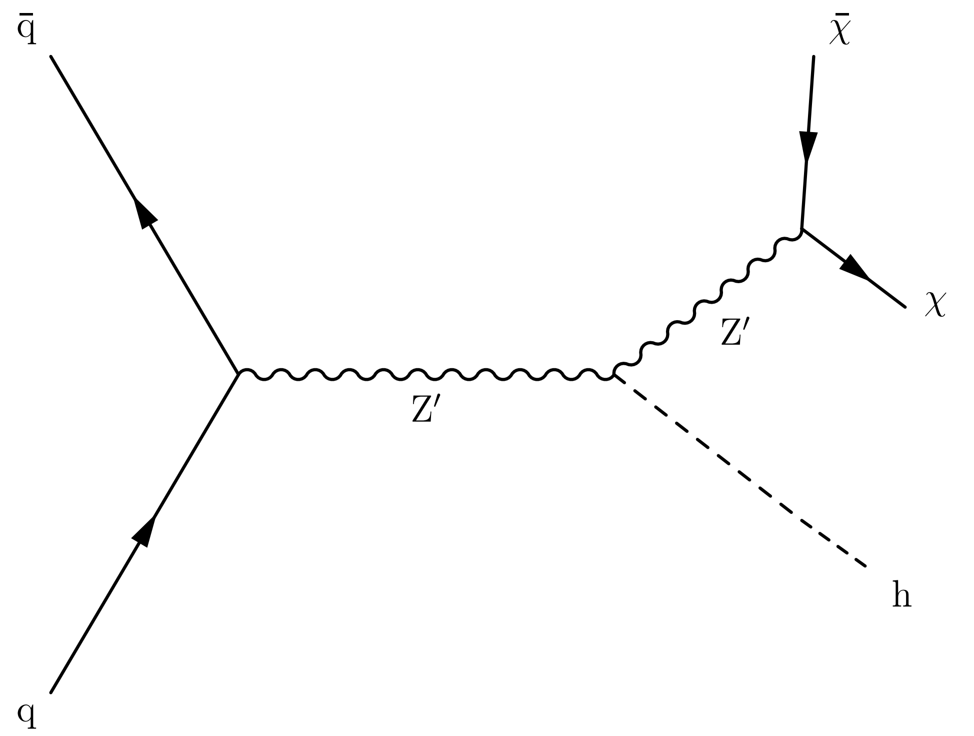






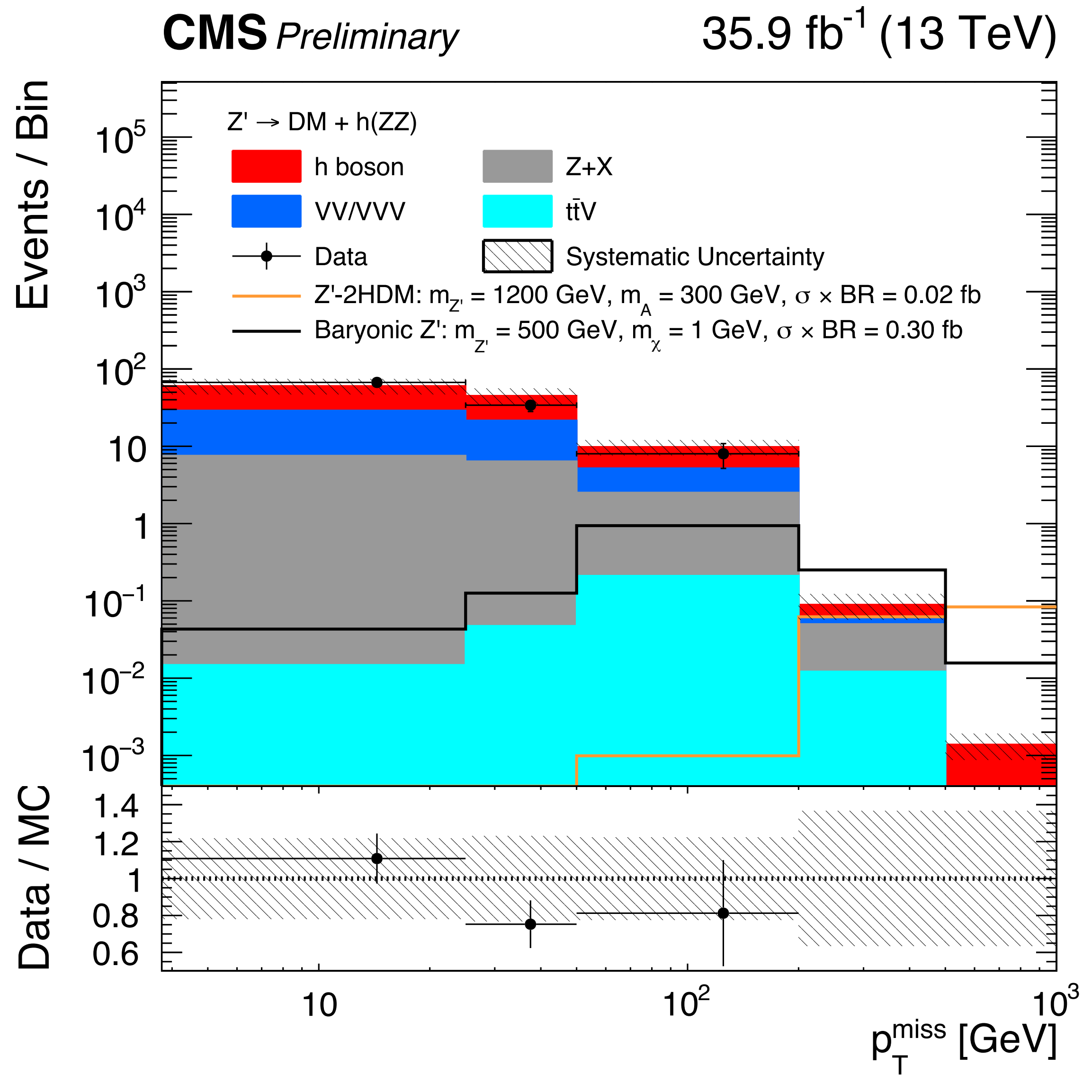
ATLAS Eur. Phys. J. C 77 (2017) 393

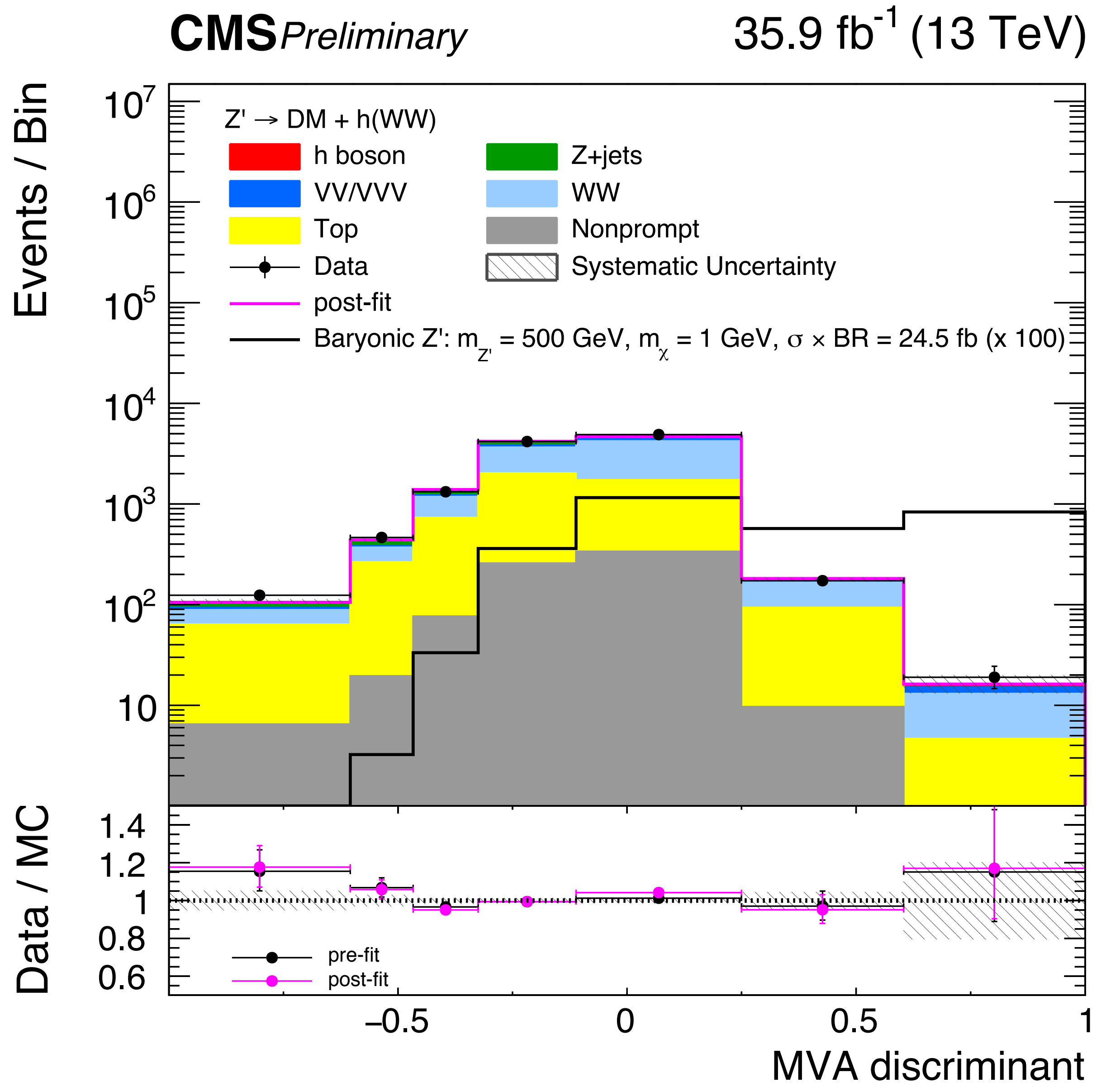
P_T^{miss}+Higgs

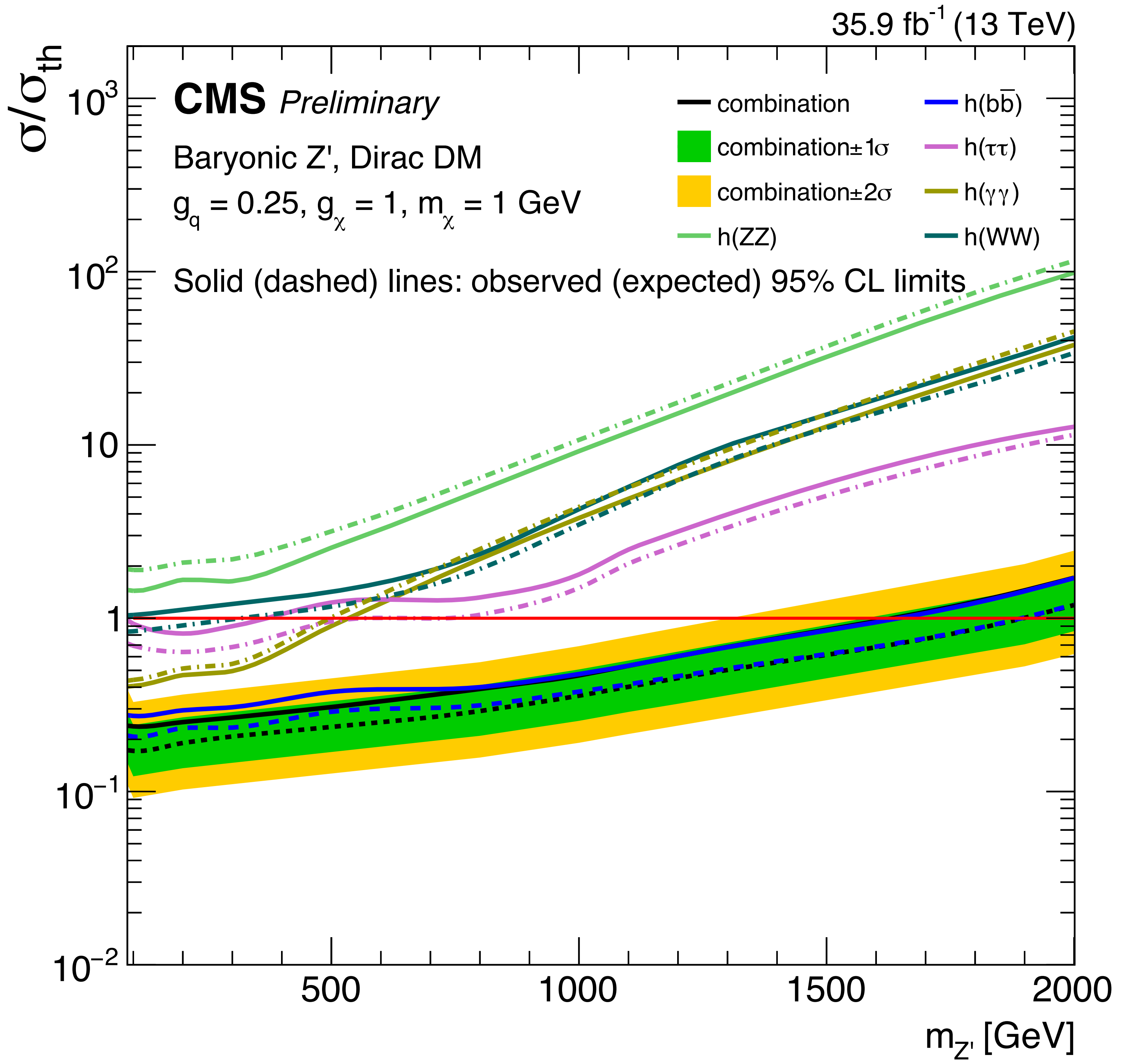


- Combination of Higgs channels (ττ, bb, γγ, WW, ZZ)
- MVA discriminant for WW channel
- Sensitivity driven by bb channel (prel. result with 80 fb^{-1} ATLAS-CONF-2018-039)
- Probe of DM mediator — Higgs coupling
- Also interpretation in 2HDM+a

CMS-EXO-18-011







P_T^{miss}+(t)t

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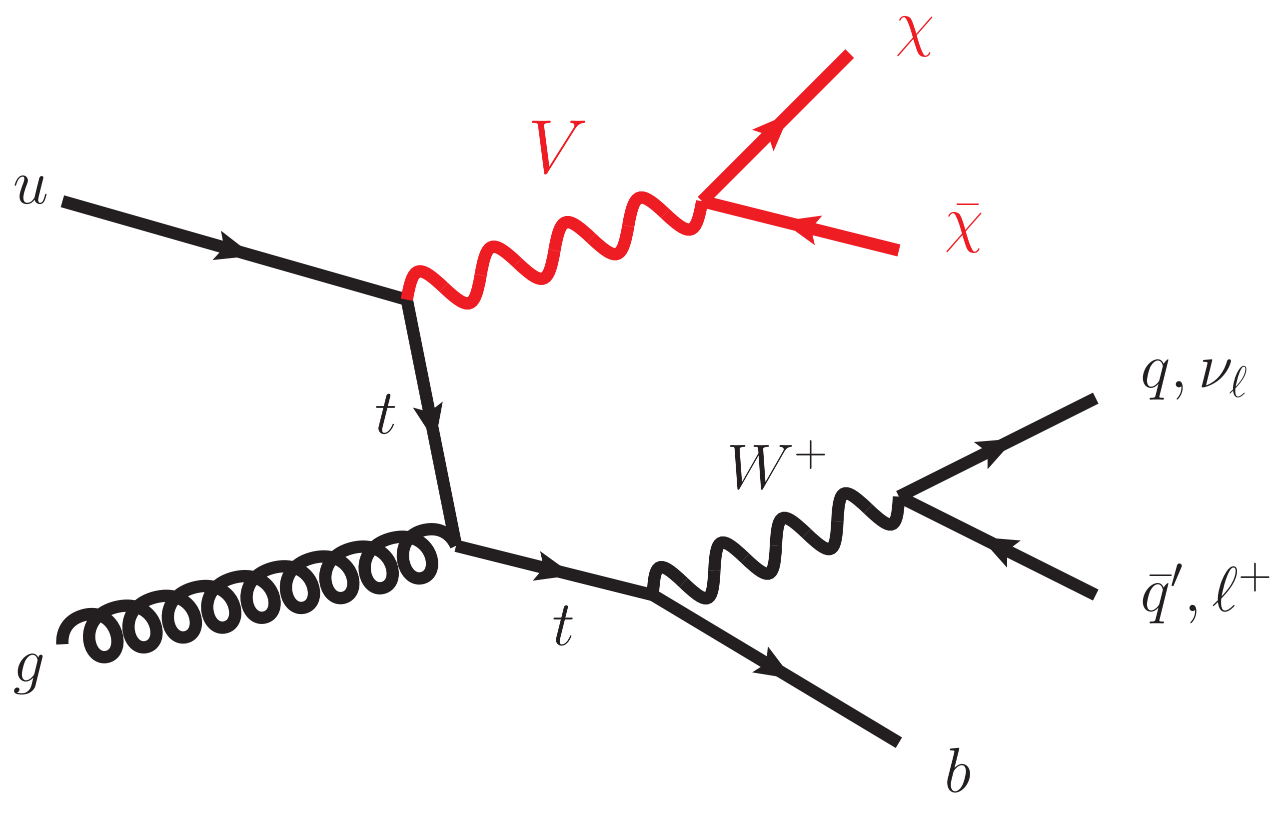

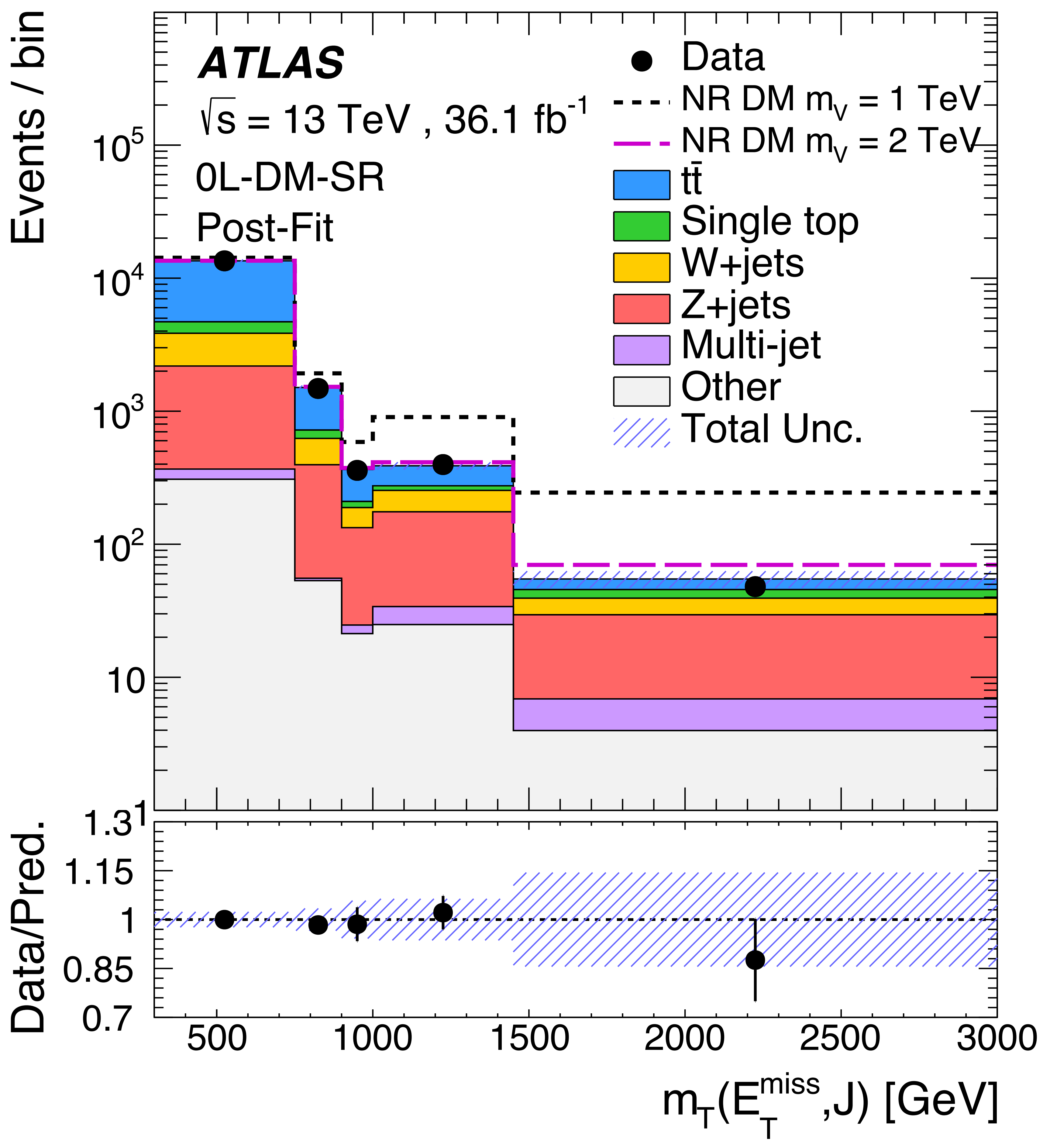

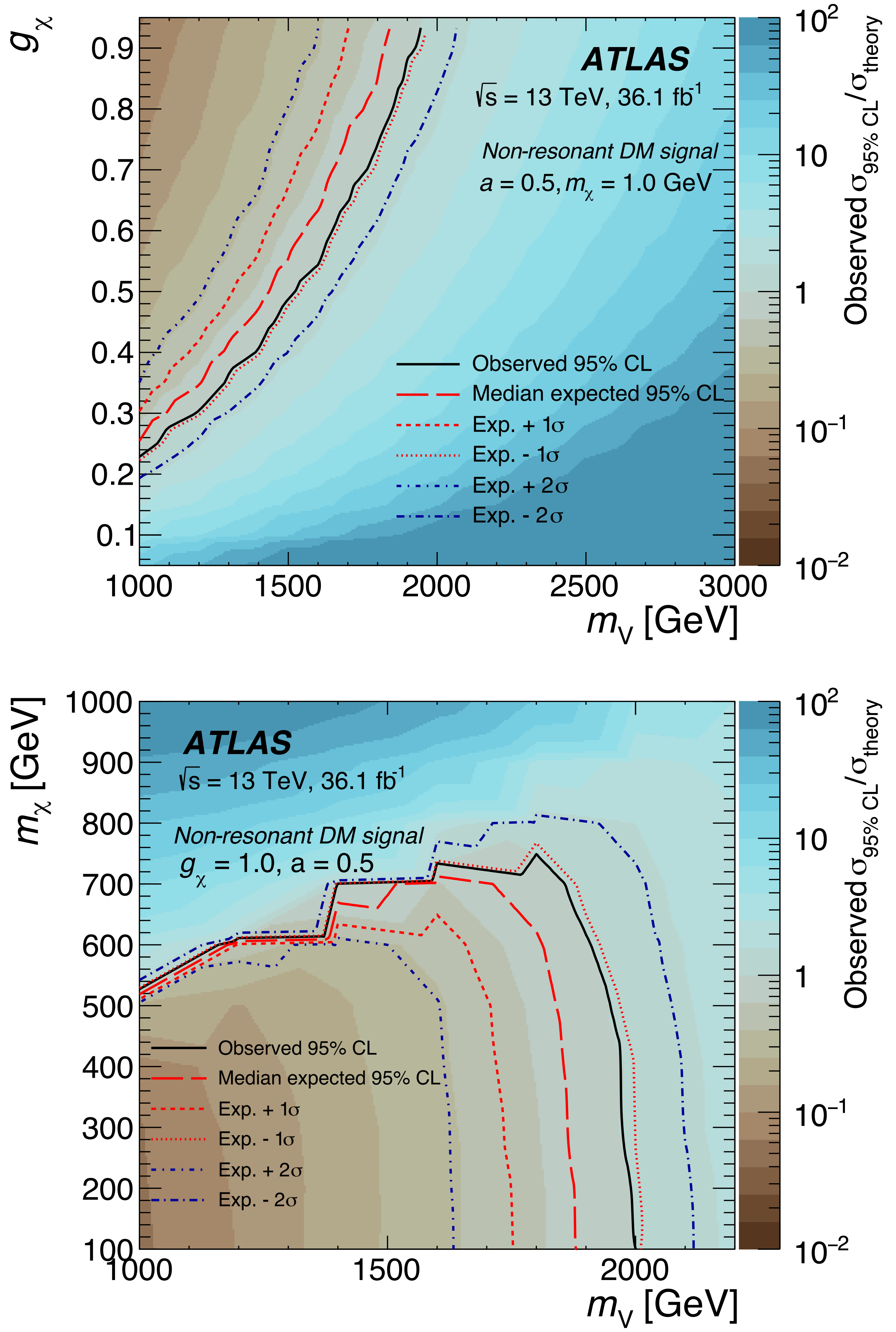

- Probe of DM mediator — top coupling

P_T^{miss}+tt

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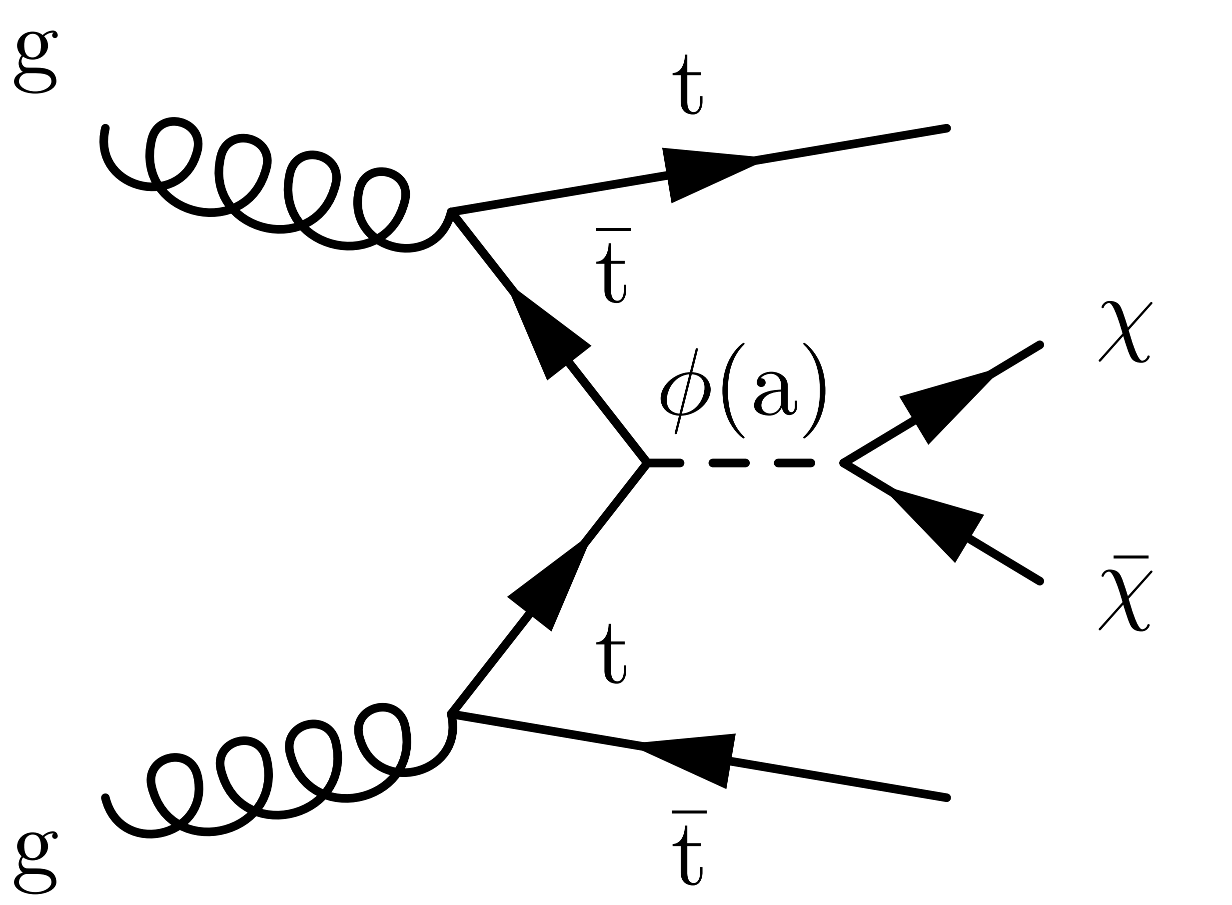
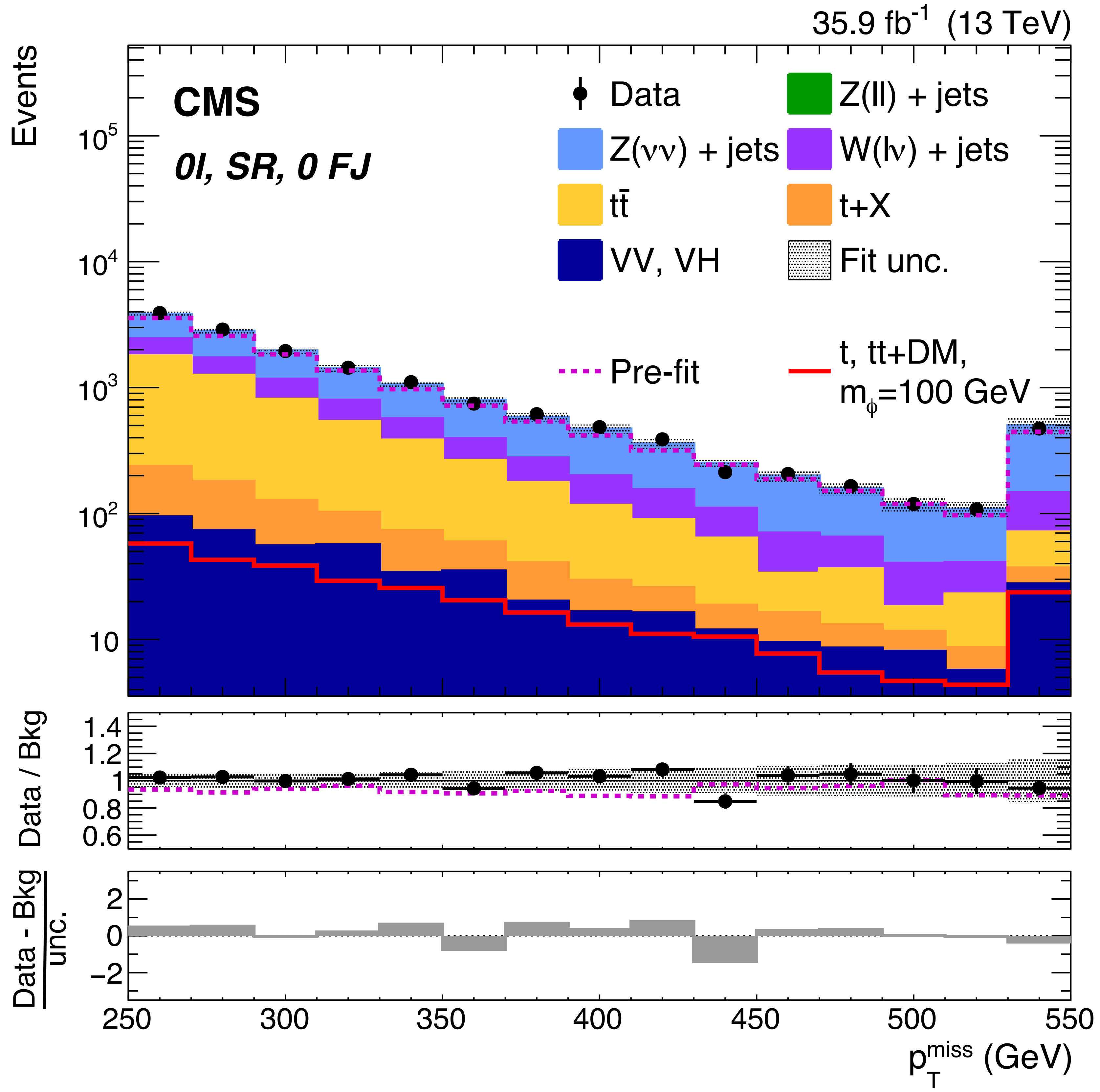
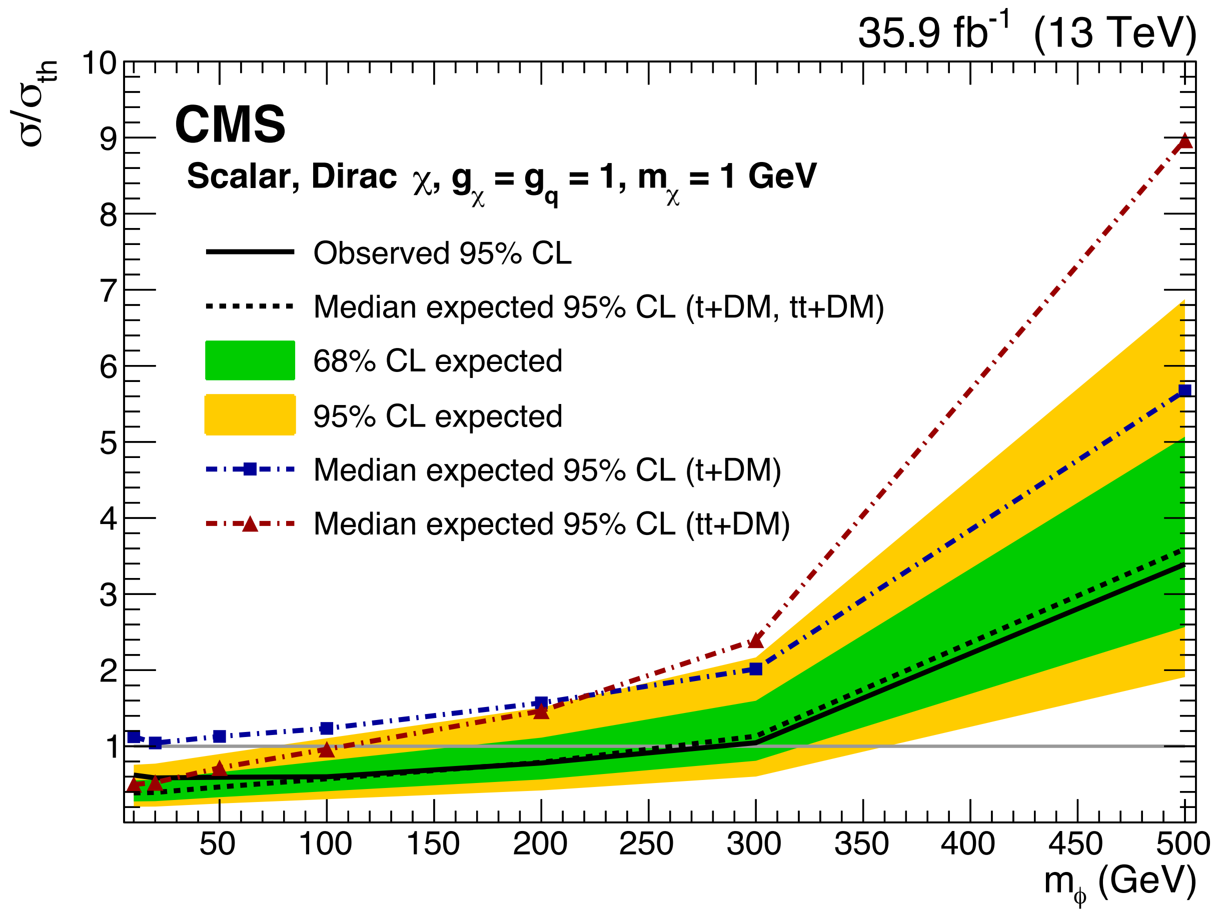
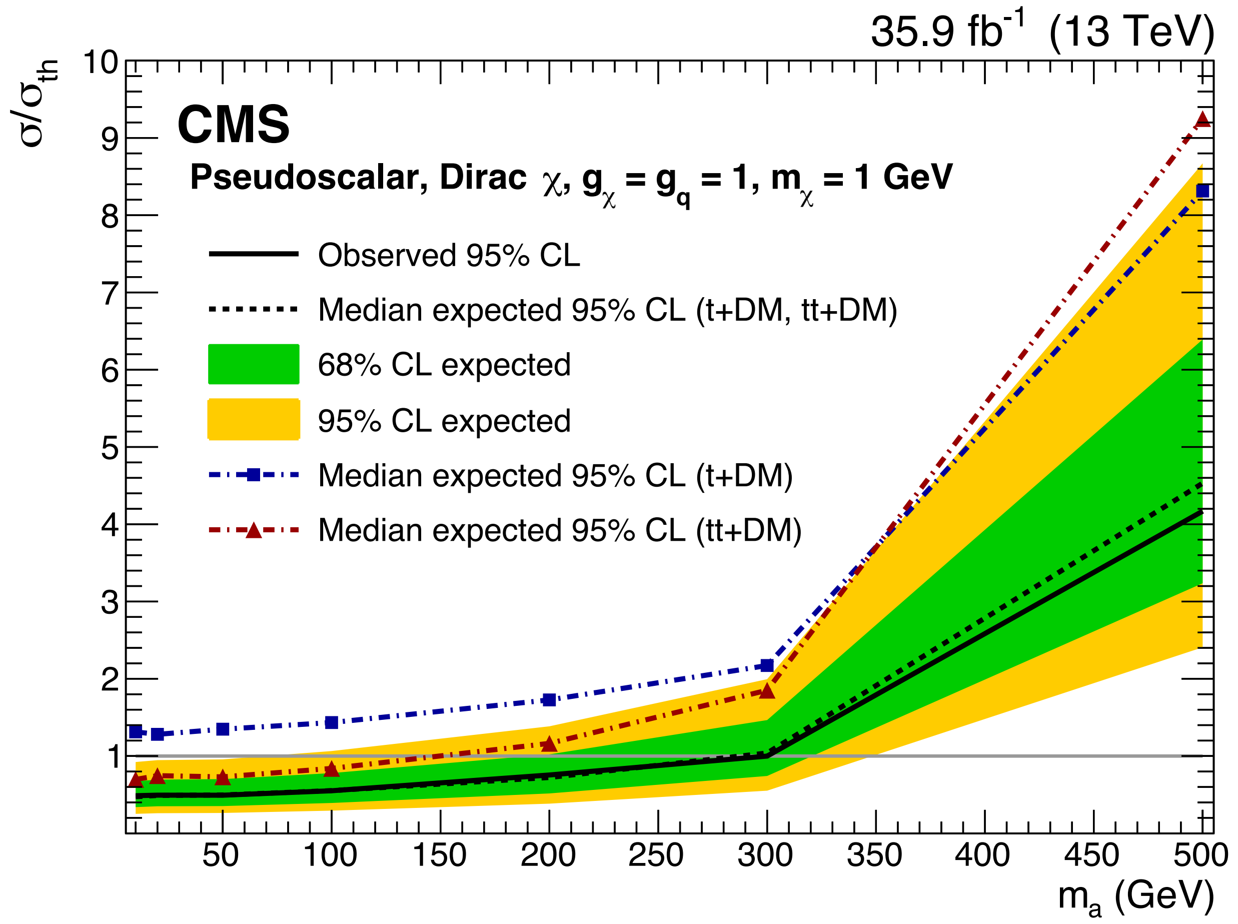




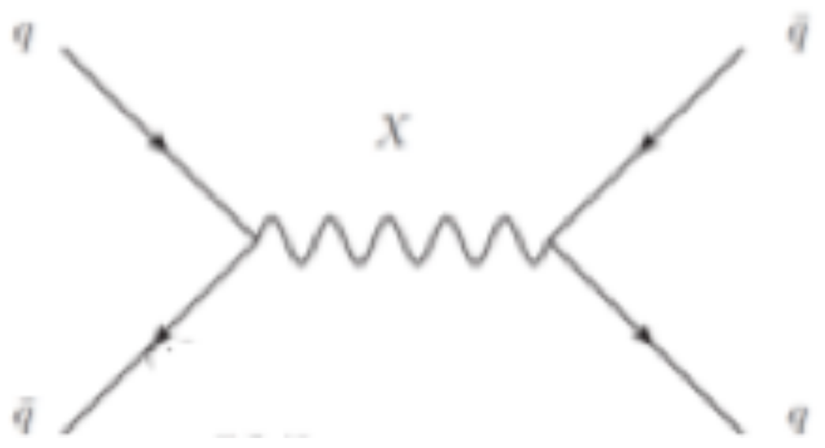


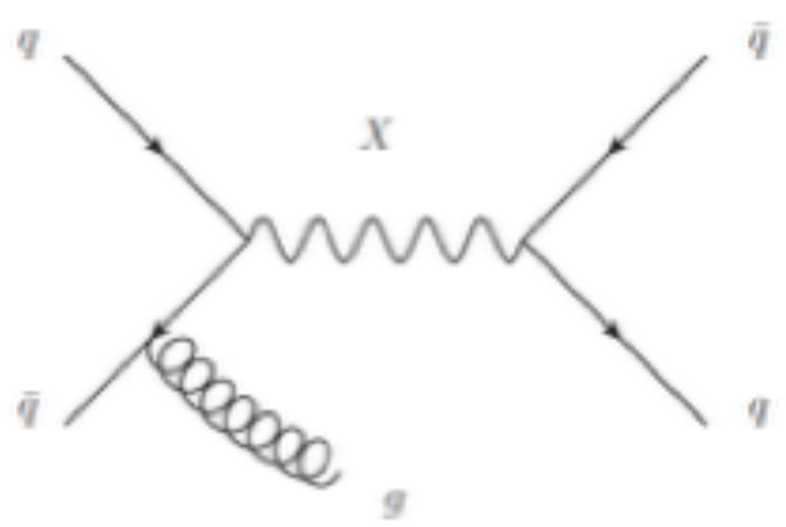


- Leptonic and hadronic top decay channels included
- Combination for limit

Mediator searches

Dijets





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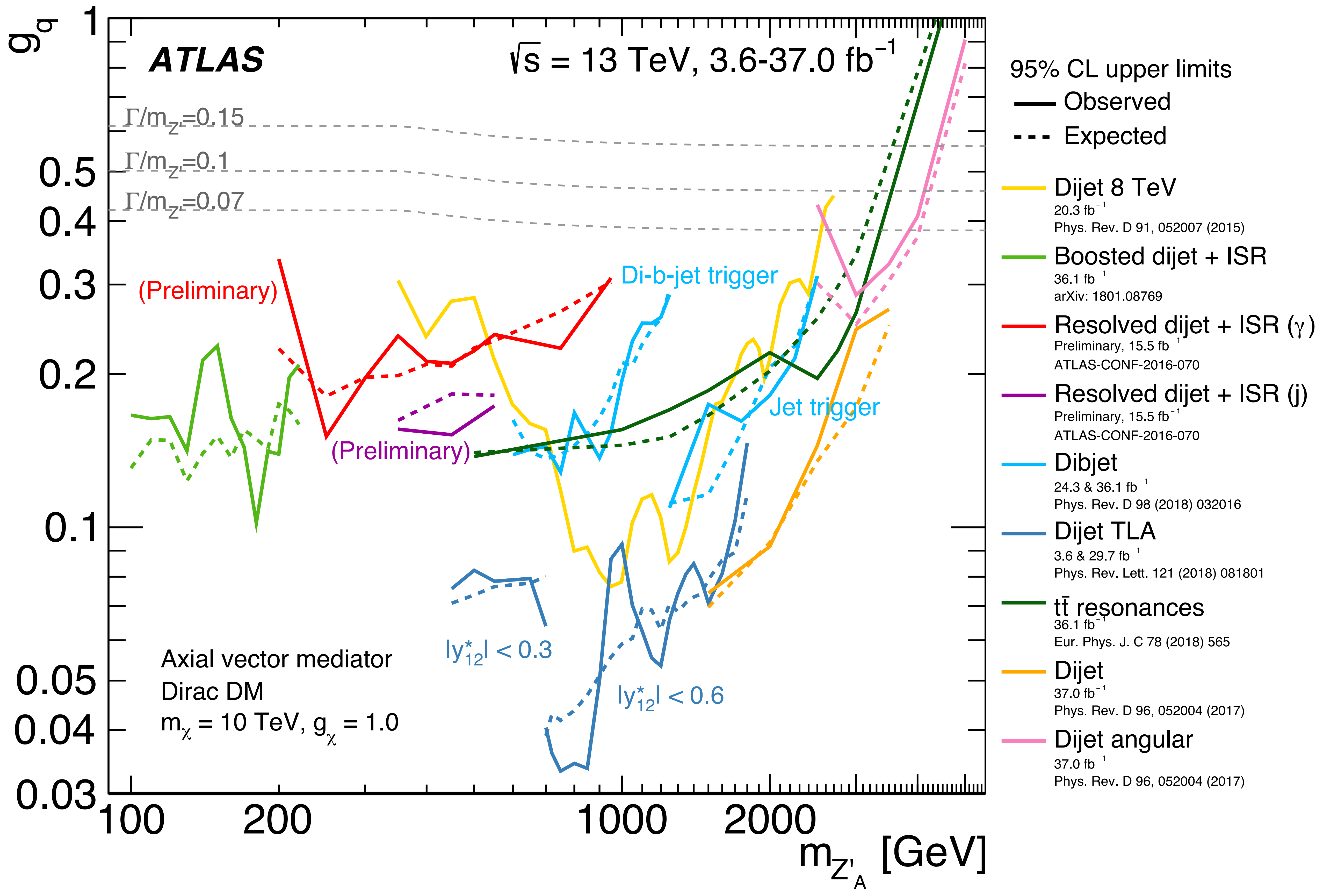
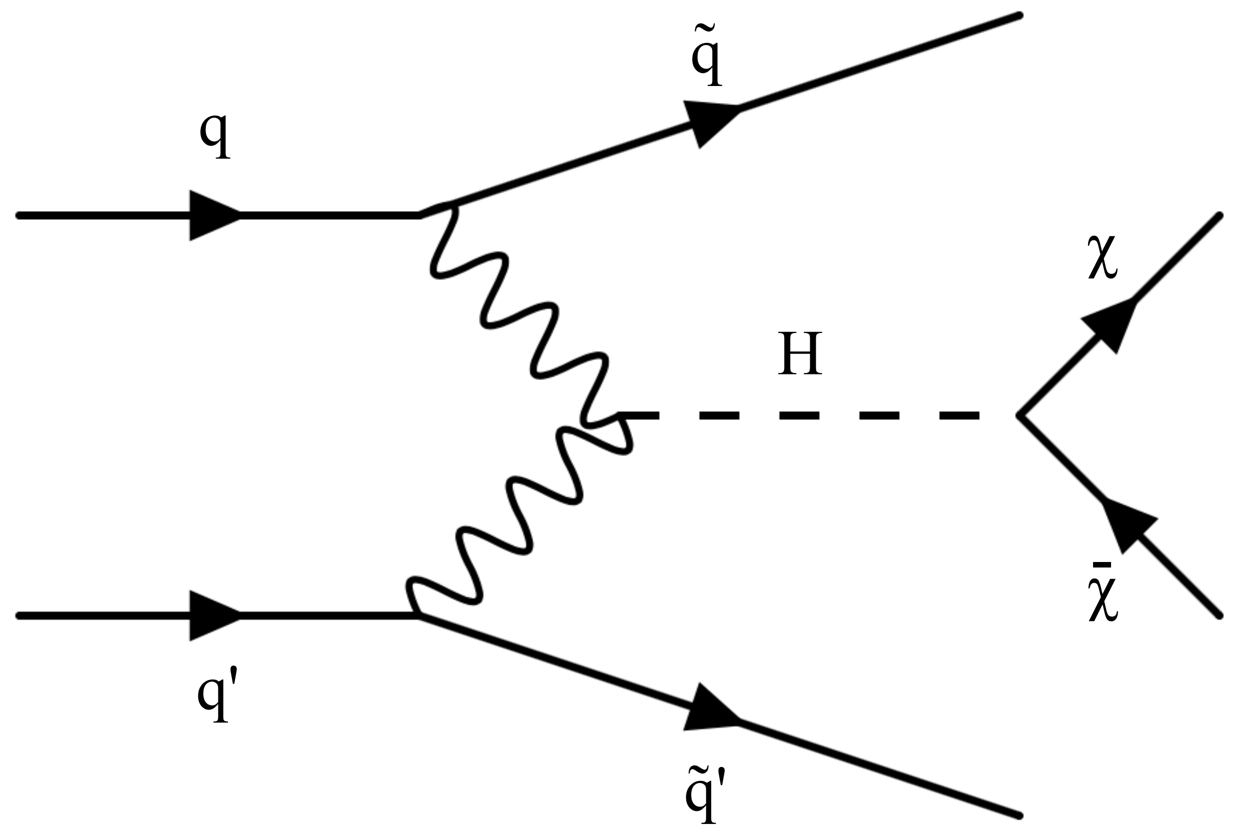


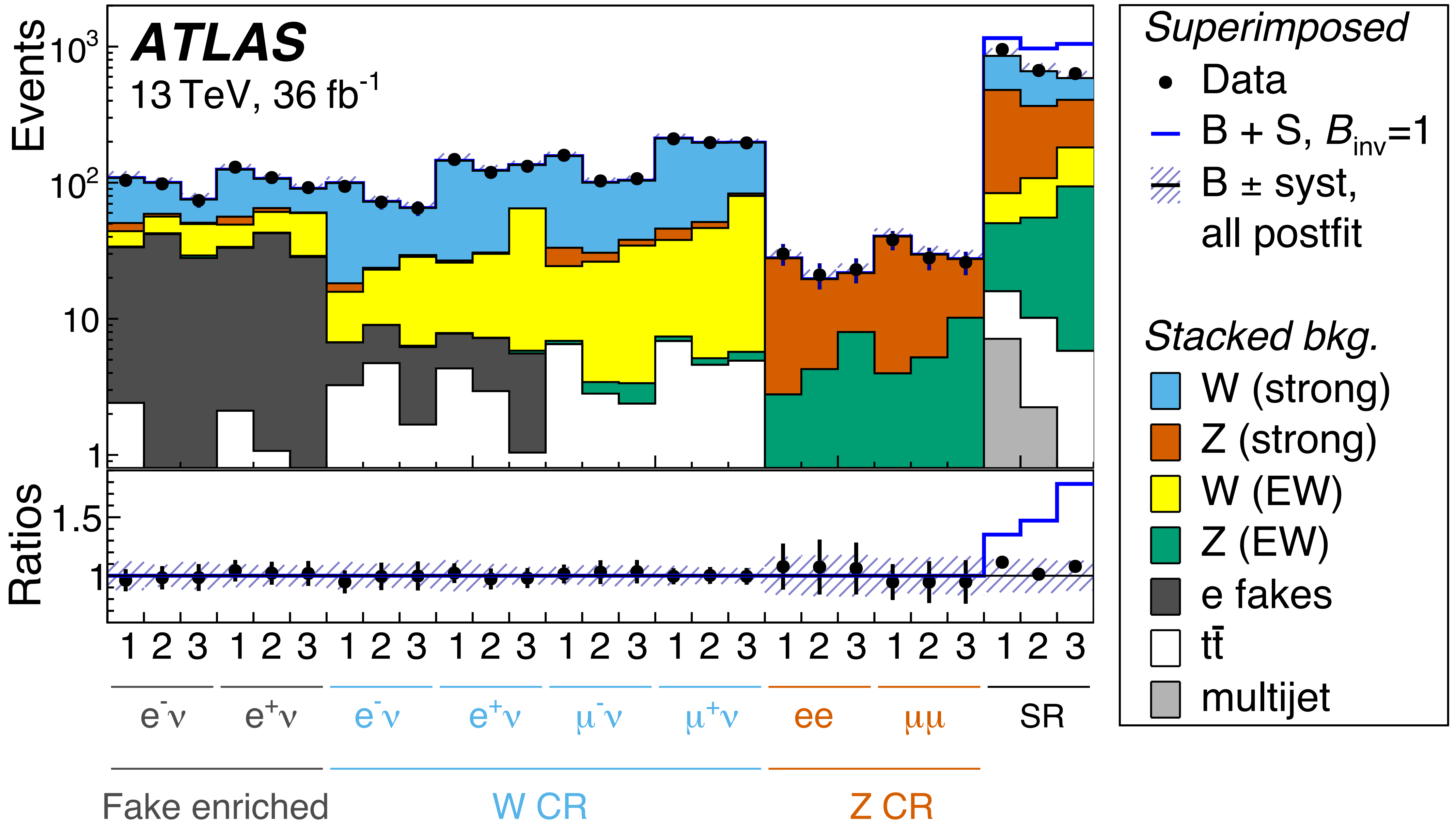
- Complementary to the mono-object searches
- Experimentally cleaner and easier
  - Higher sensitivity than invisible searches
- Dark Matter too heavy to produce or weak coupling to mediator
- Include wide variety of channels
  - Dijet, dijet + ISR (γ, jet), tt resonance…

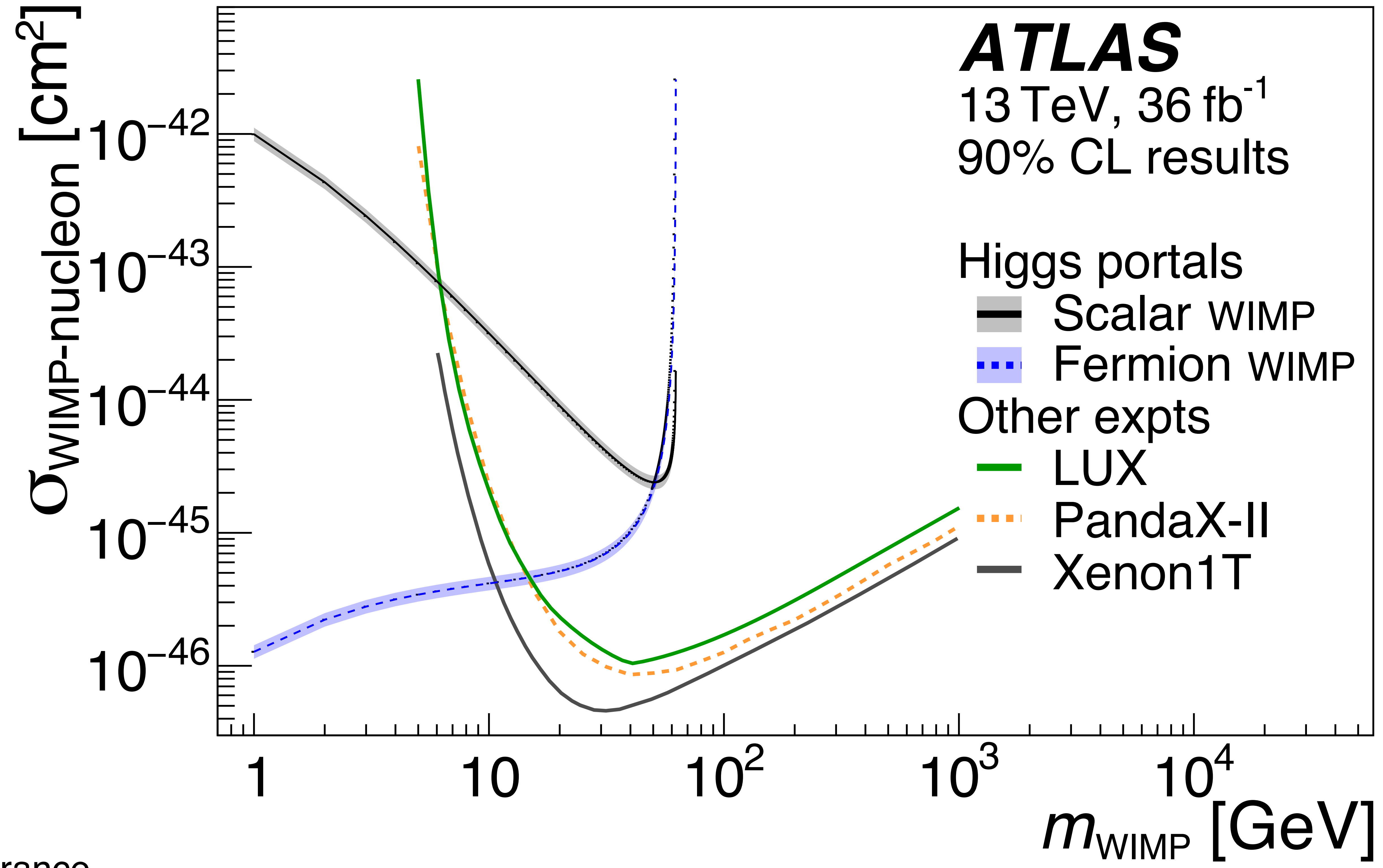
P_T^{miss}+VBF



- SM BR < 0.1% (via ZZ → 4ν)
- Probe DM coupling to Higgs
- Signal extraction using M_{jj} distribution with central jet veto
- BR (H → invs.) < 0.26 (0.17 exp.) combination (driven by VBF channel)

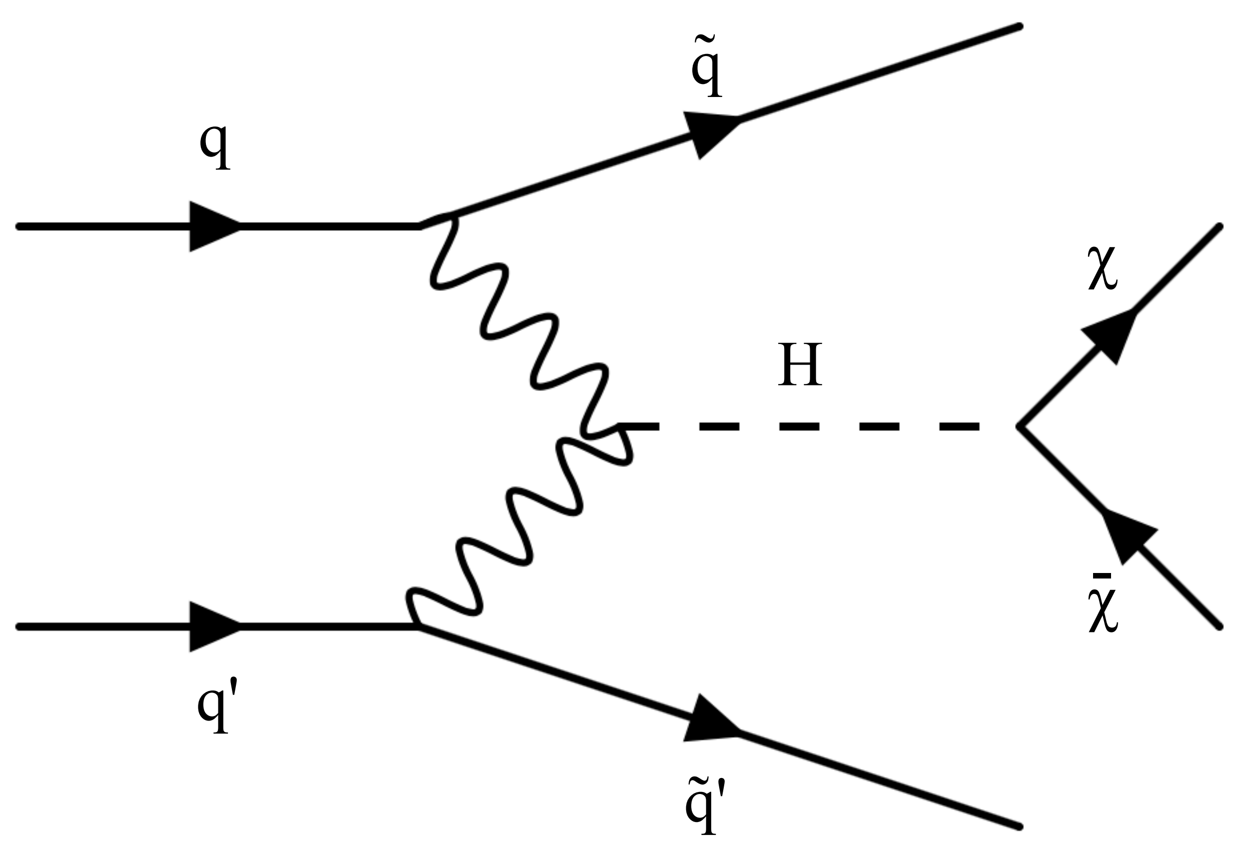
arXiv:1809.06682
arXiv:1904.0510

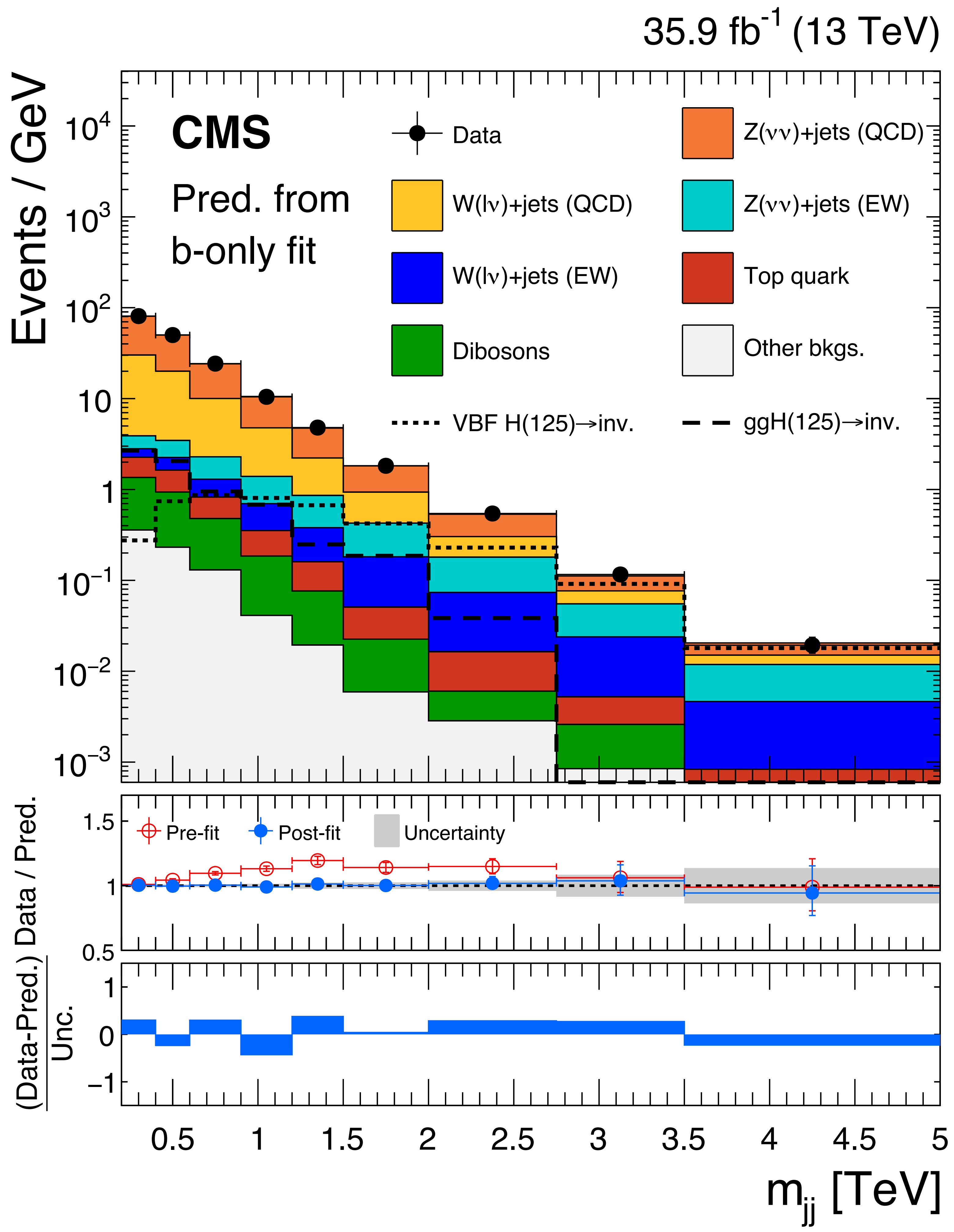


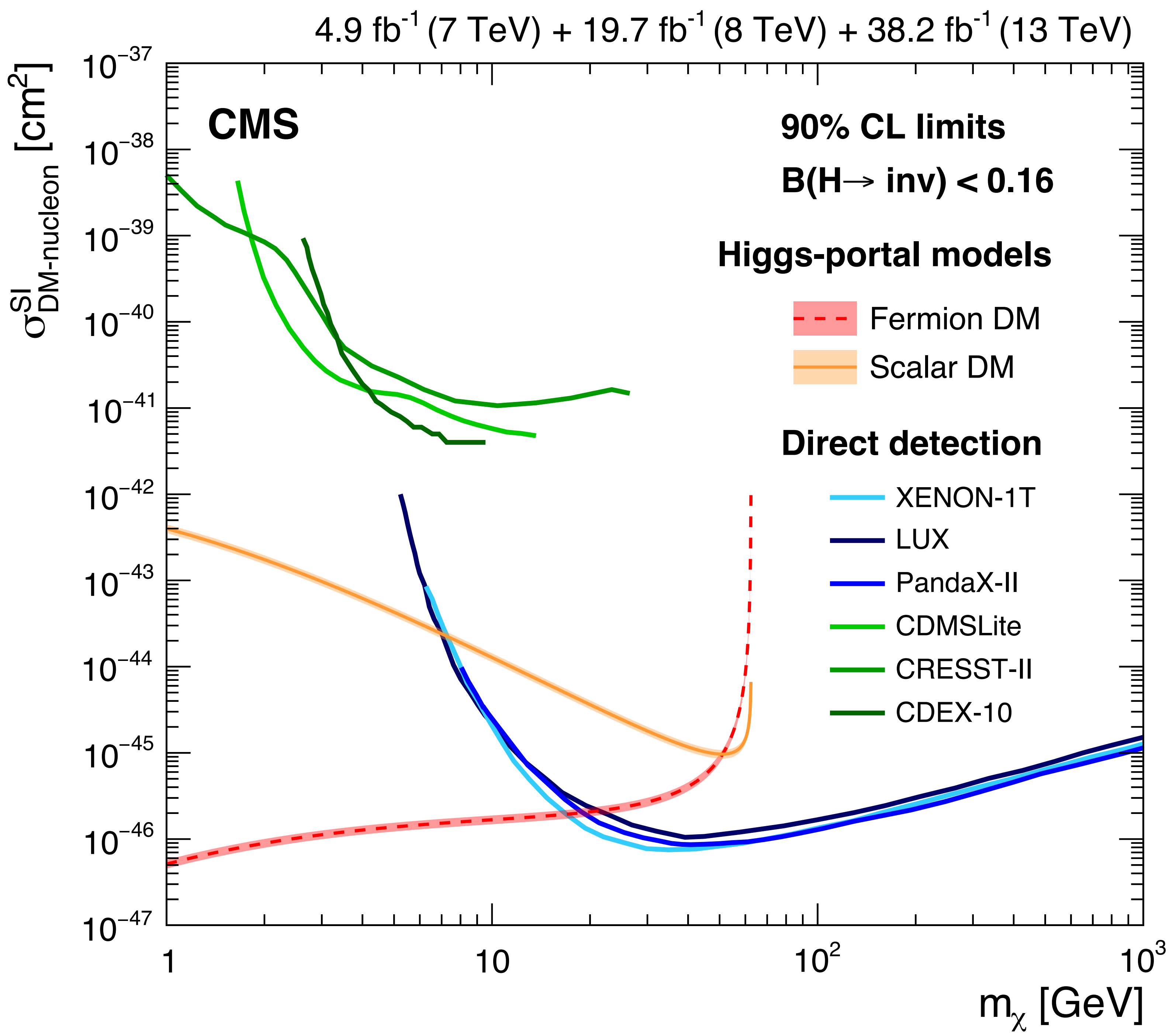


P_T^{miss}+VBF

arXiv:1809.05937







- BR (H → invs.) < 0.19 (0.15 exp.) combination

Putting it all together…

Combined limits

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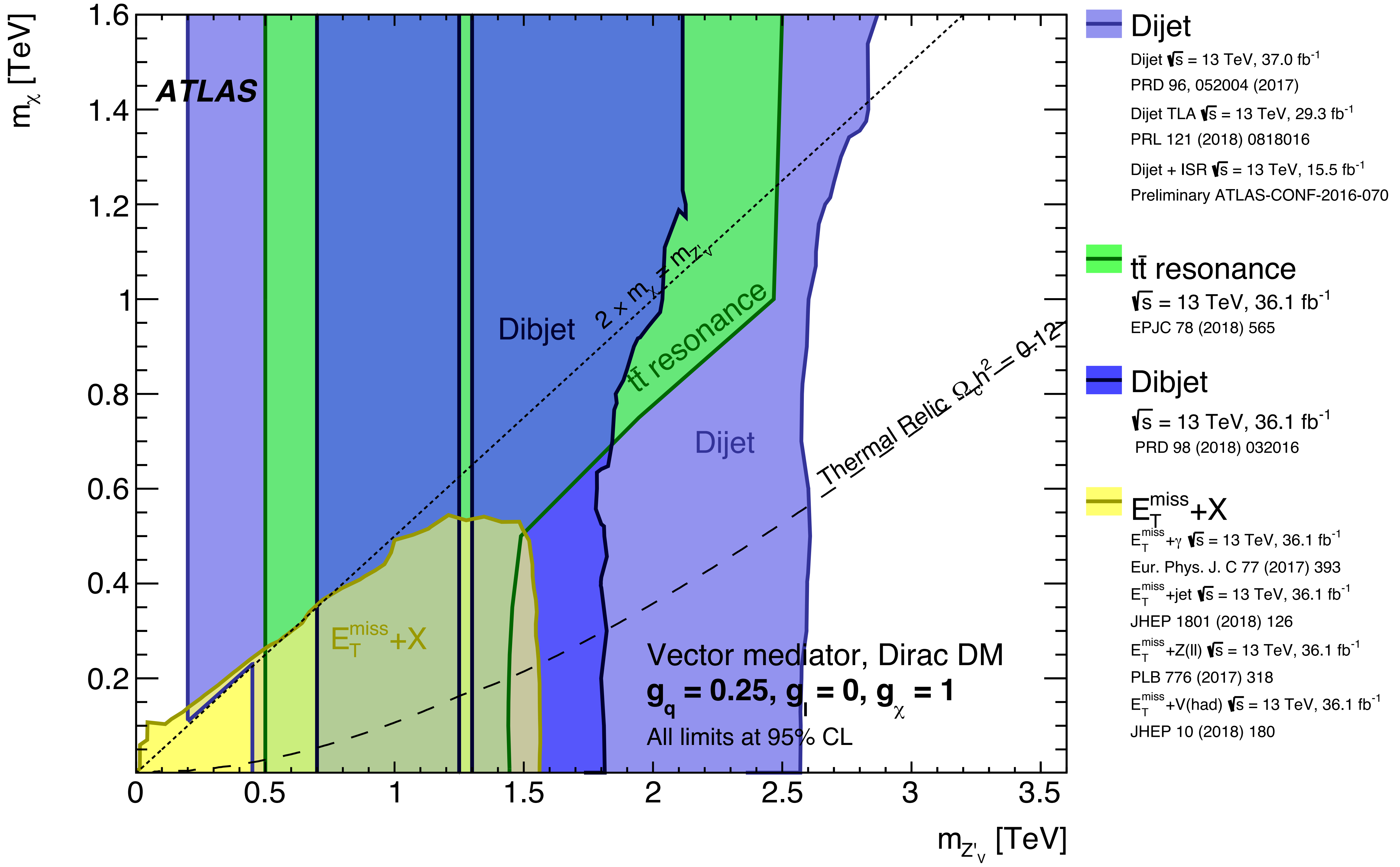

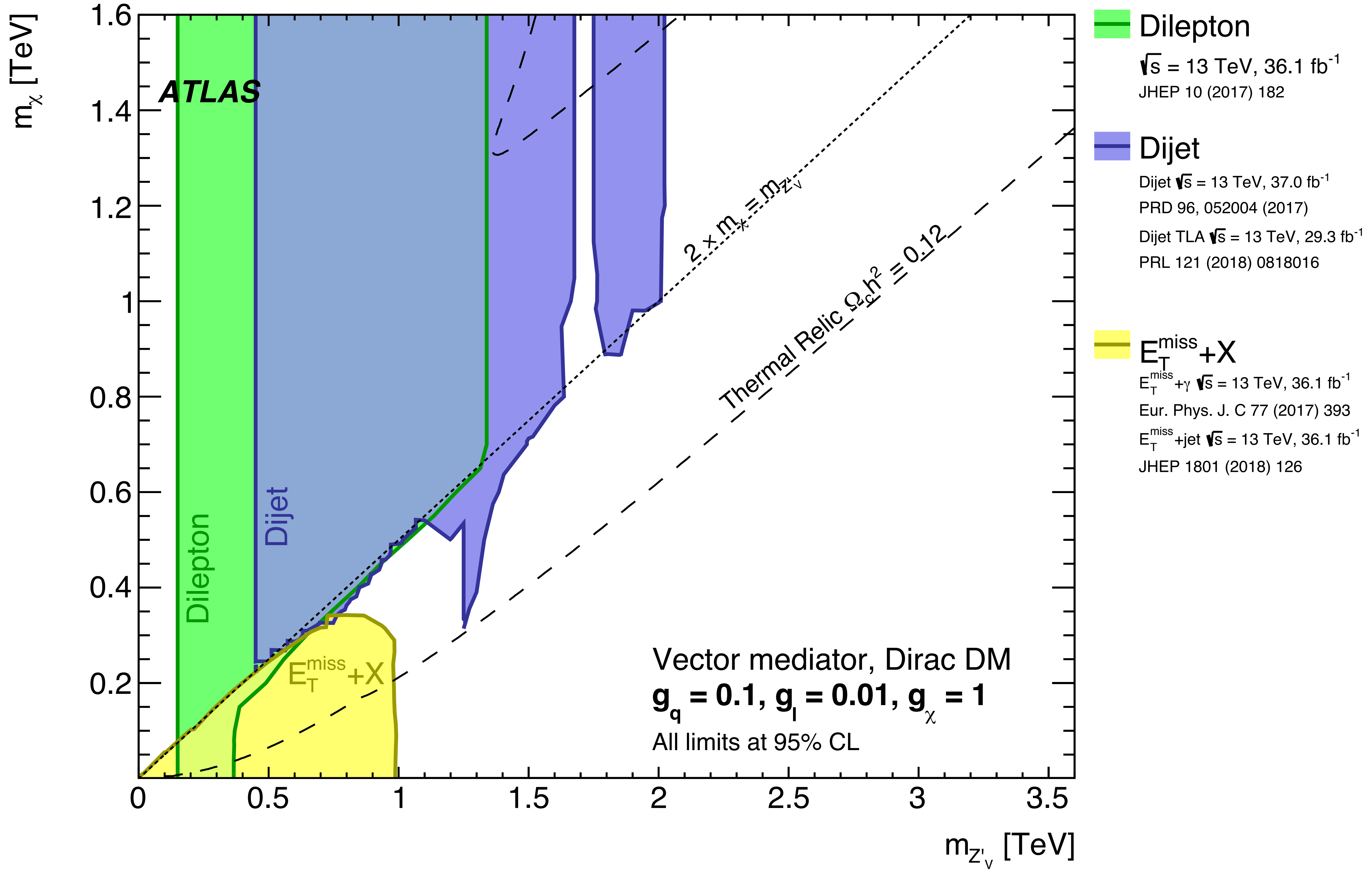

- Combine the mono-object and **vector** mediator searches
- Complementary sensitivity in m_χ — m_{med} space
- Impact of di-lepton constraints

Combined limits

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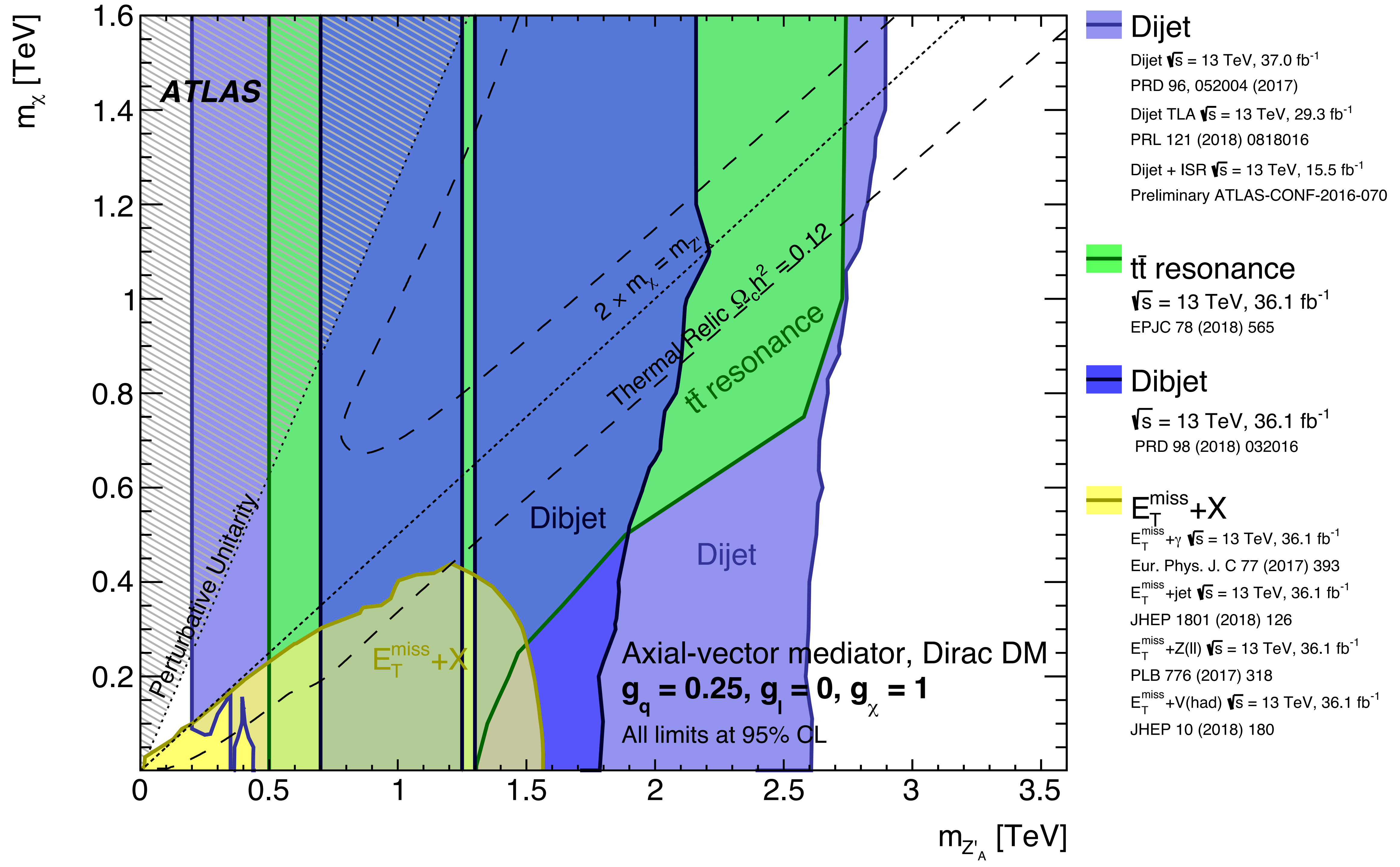

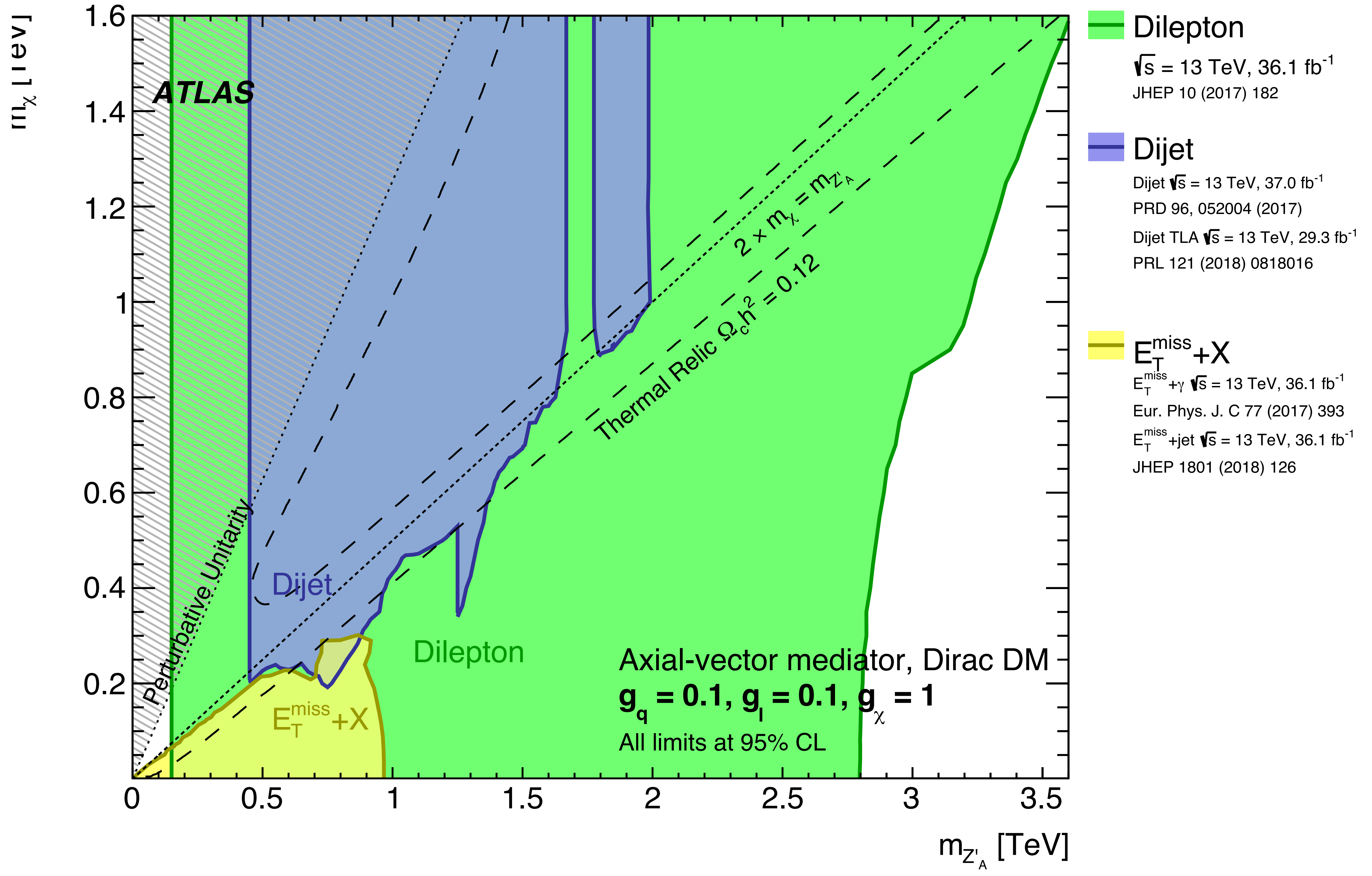

- Combine the mono-object and **axial-vector** mediator searches
- Complementary sensitivity in m_χ — m_{med} space
- Impact of di-lepton constraints

Combined limits

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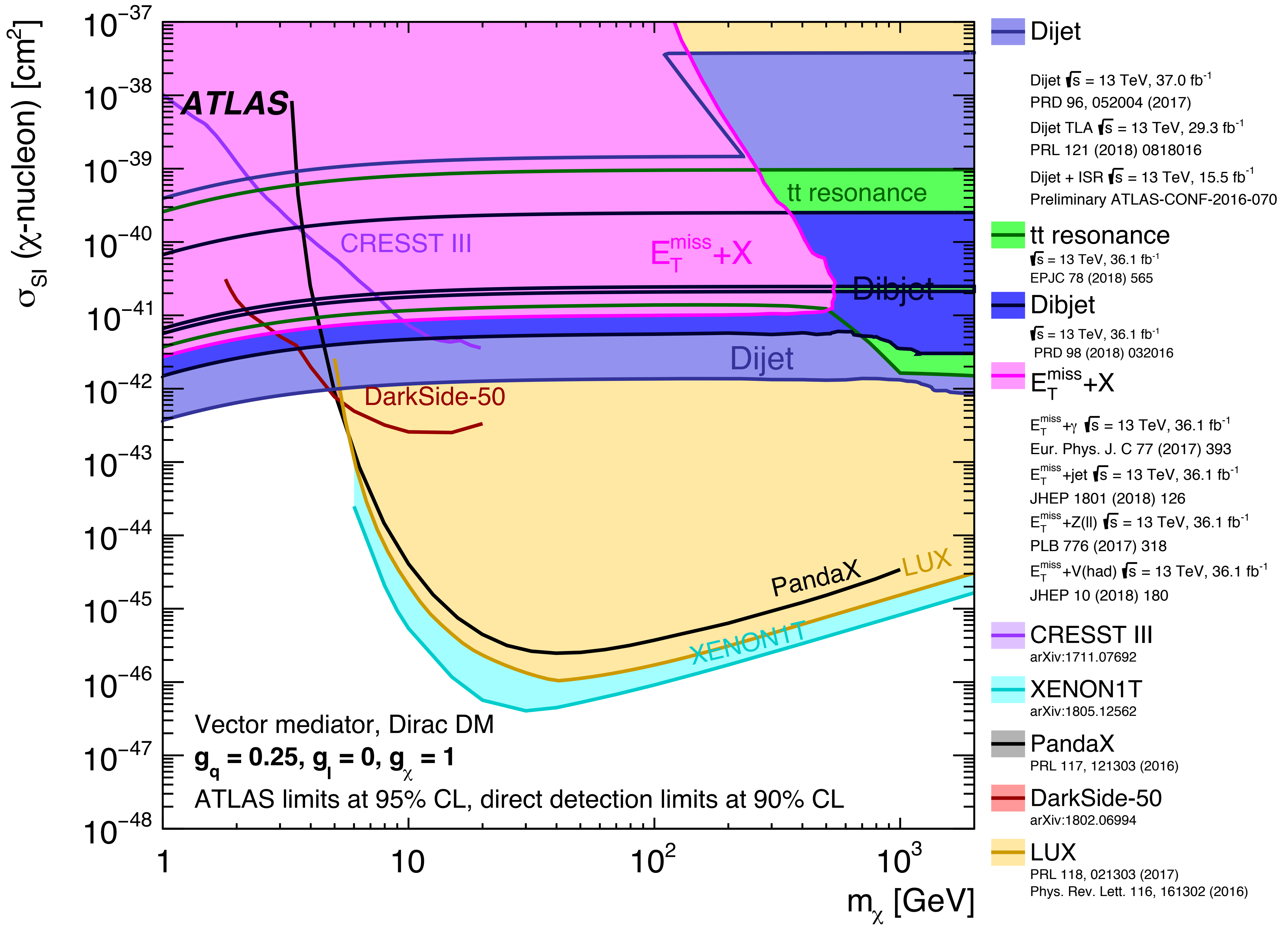
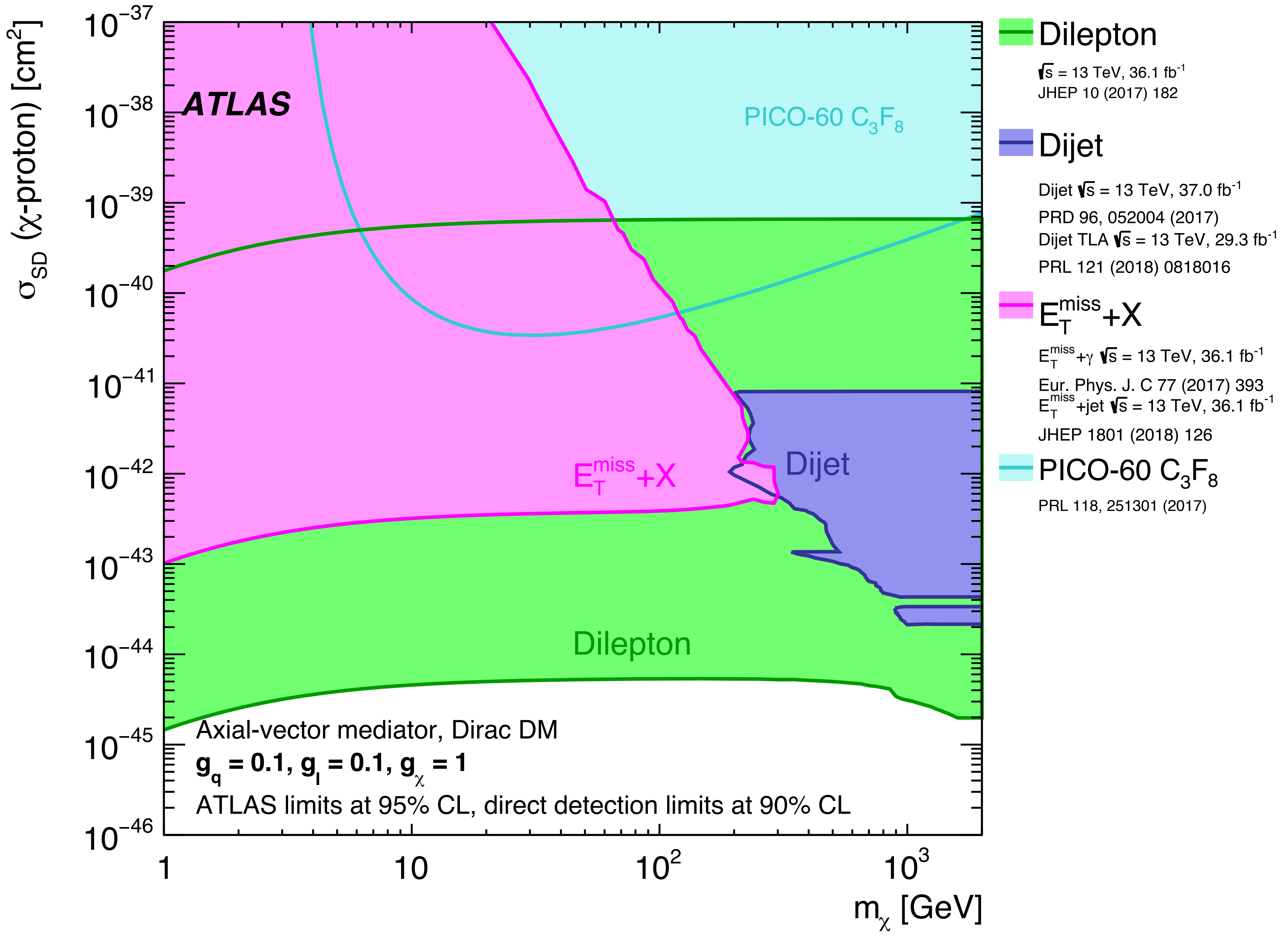


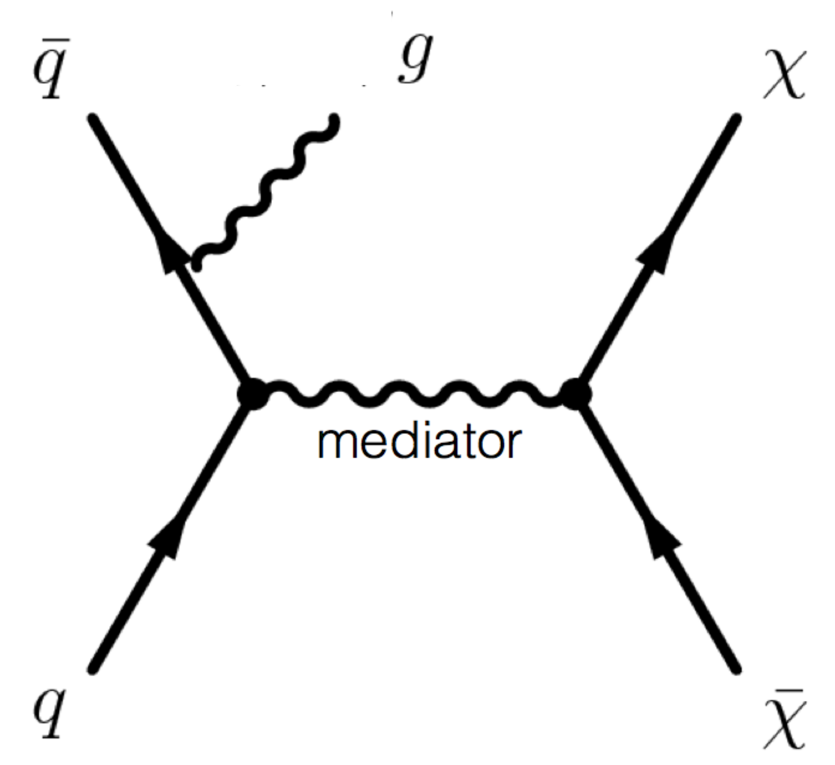


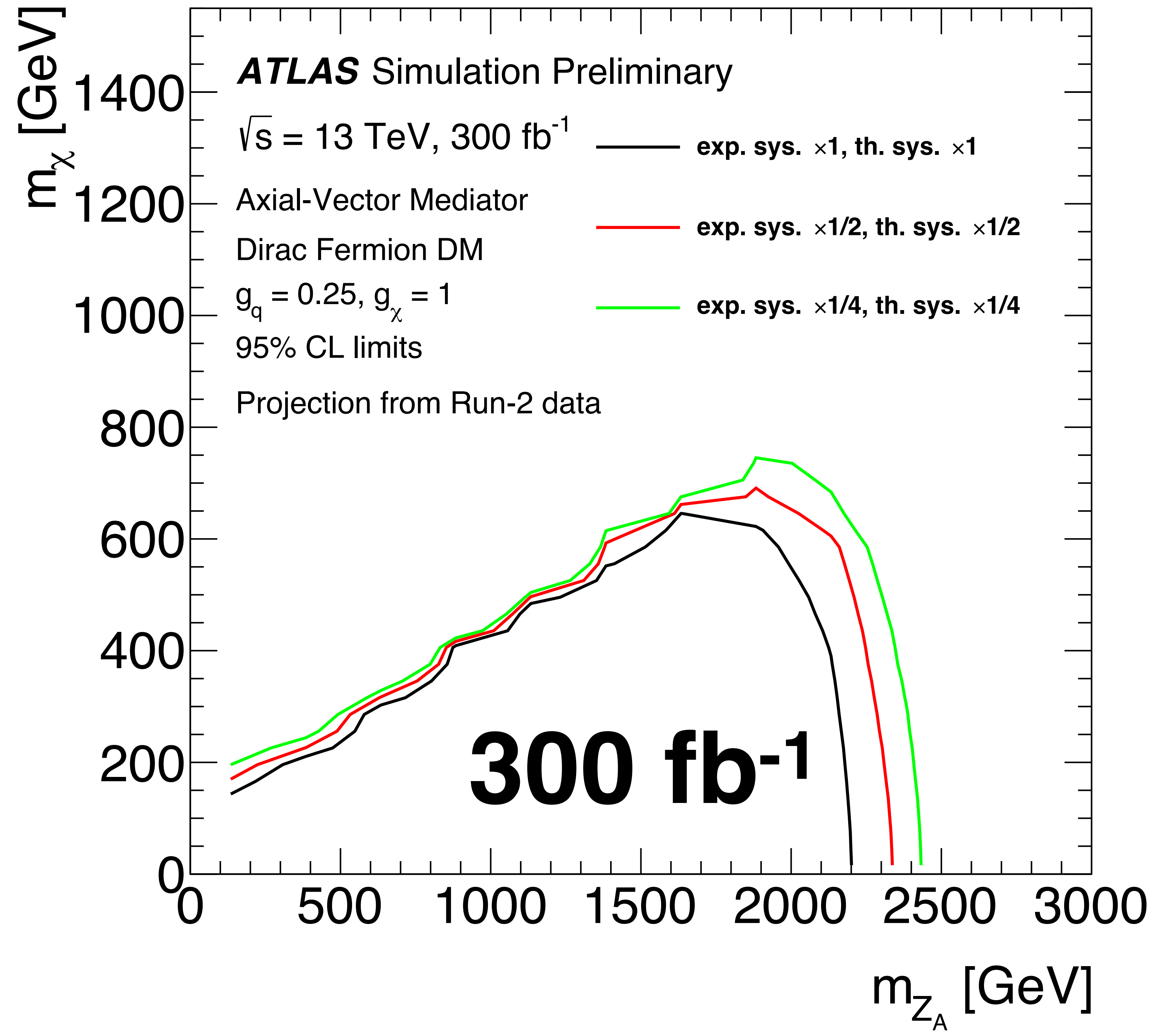
- Cross section limits for **vector** and **axial-vector** mediator searches
- Comparison of collider and direct detection limits

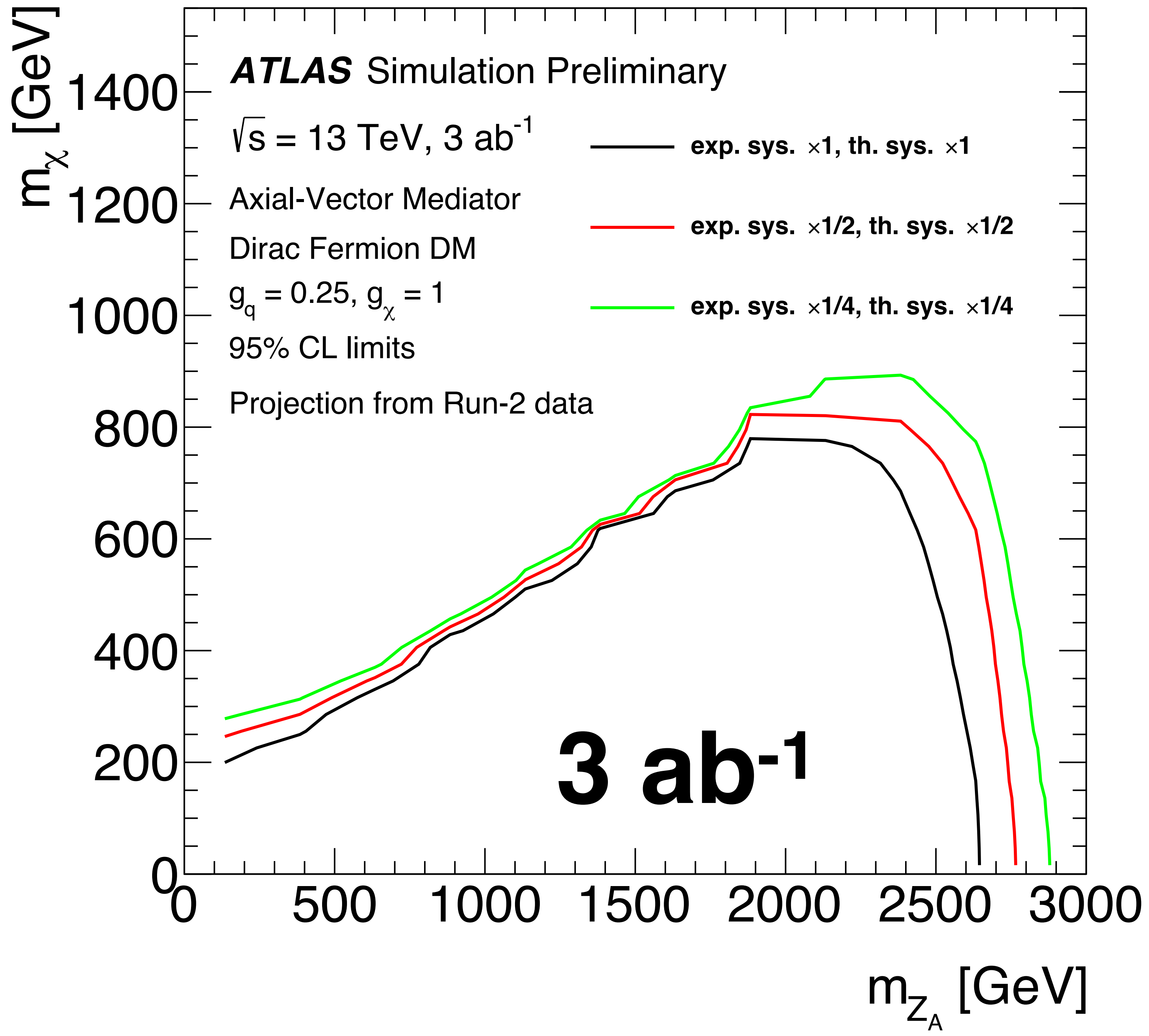
Future prospects

P_T^{miss}+jet

ATL-PHYS-PUB-2018-043



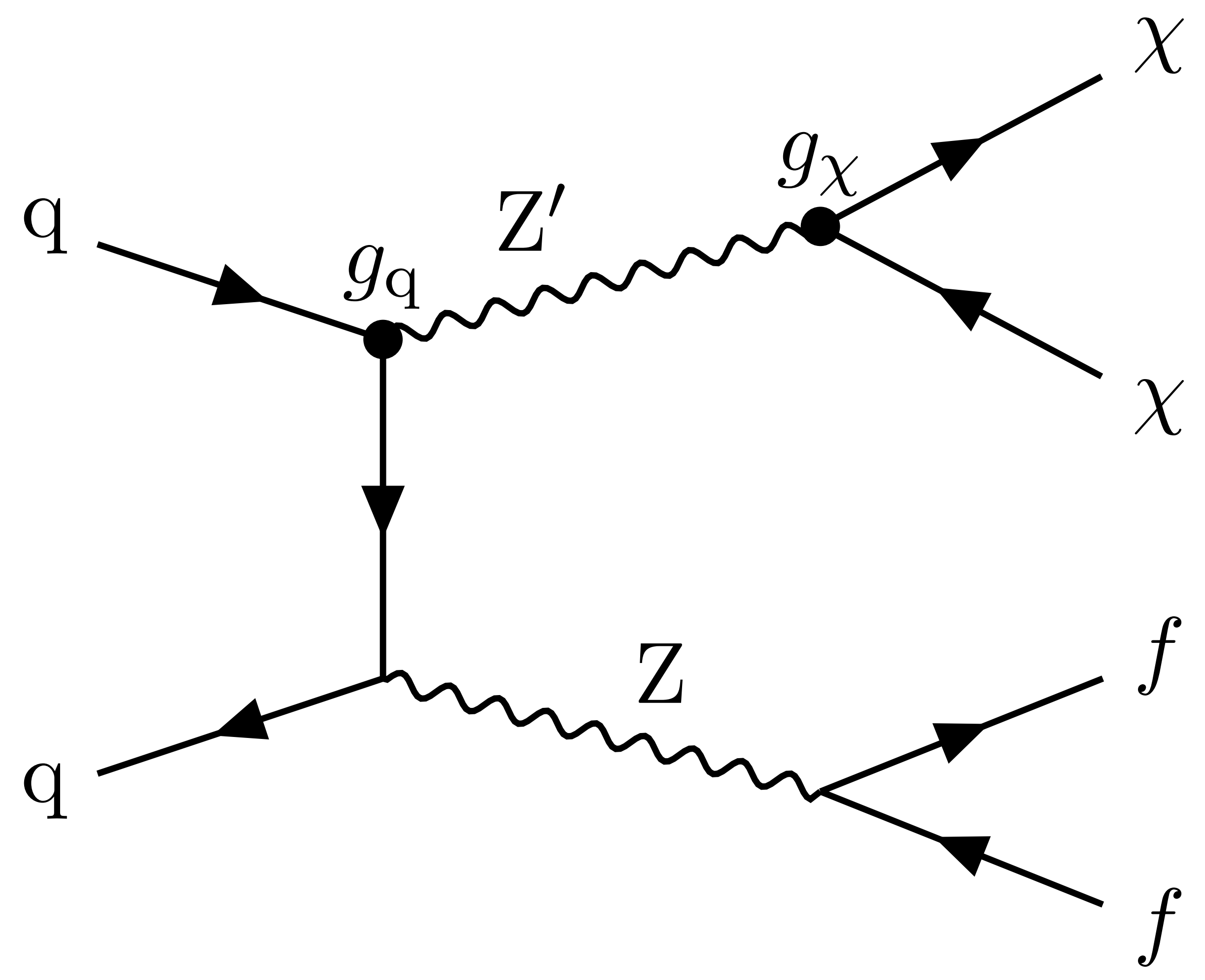




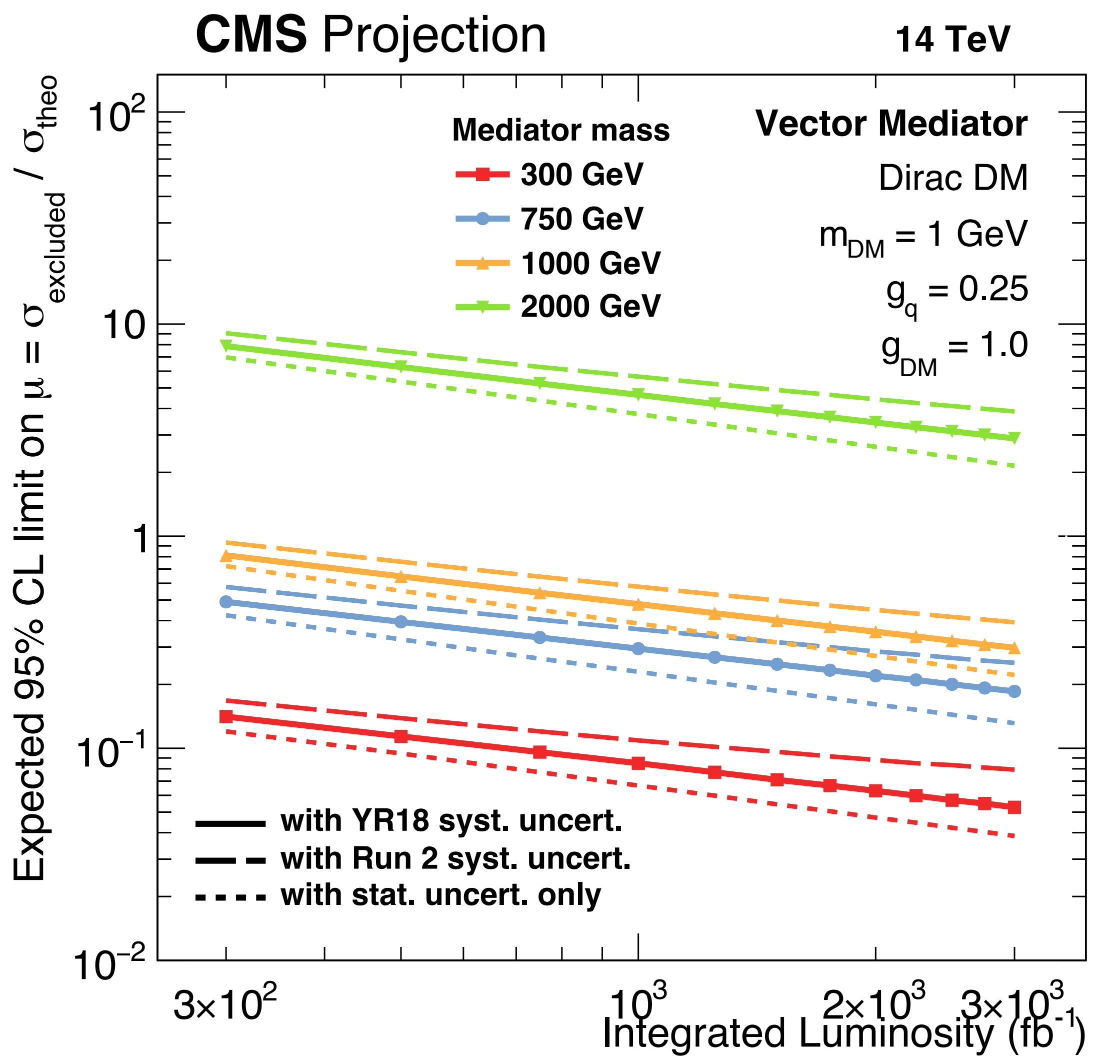
- Projections for future data samples
  - Run 1-3: 300 fb^{-1}
  - HL-LHC: 3 ab^{-1}
- Systematics will play a role in sensitivity

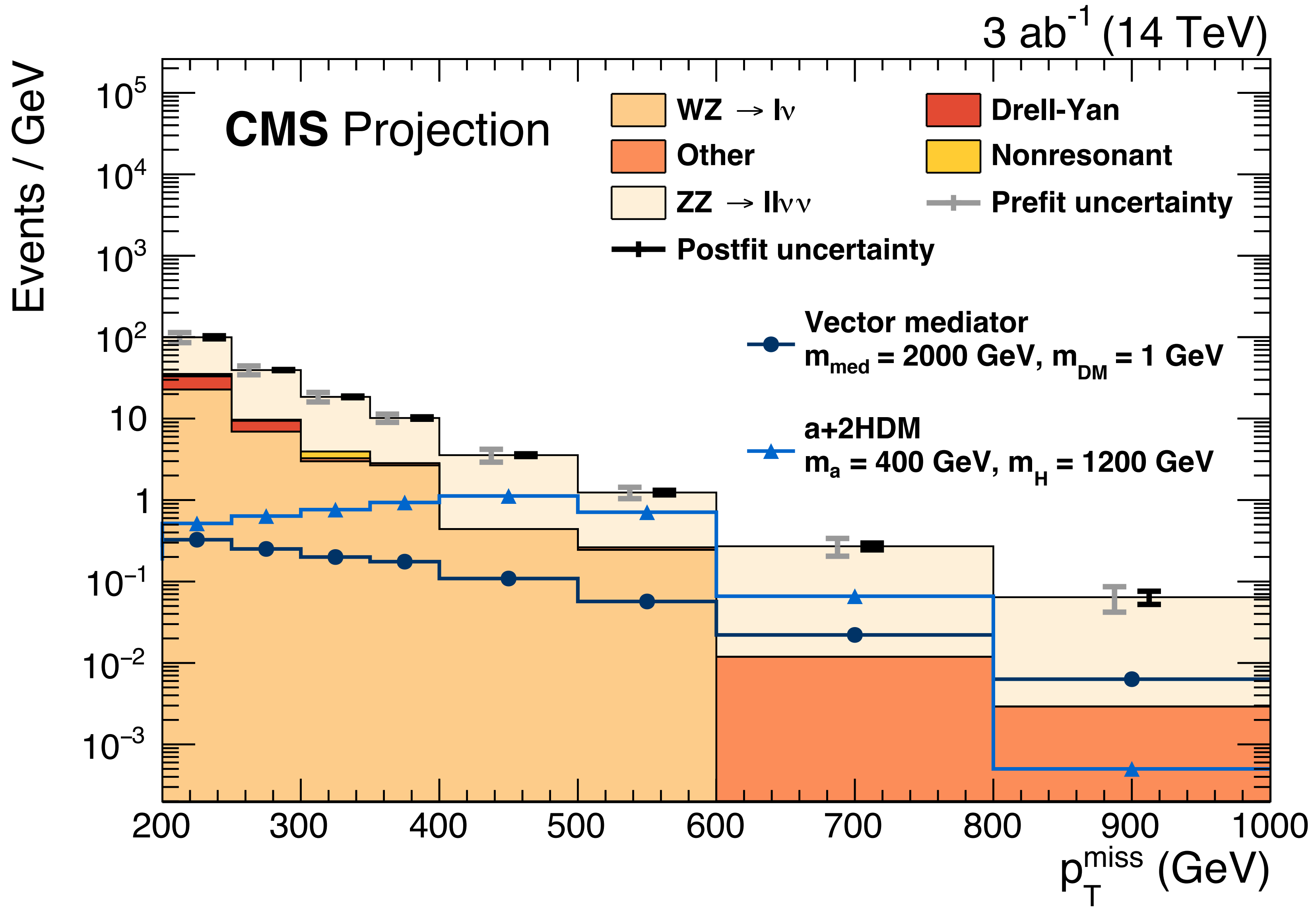
P_T^{miss}+Z

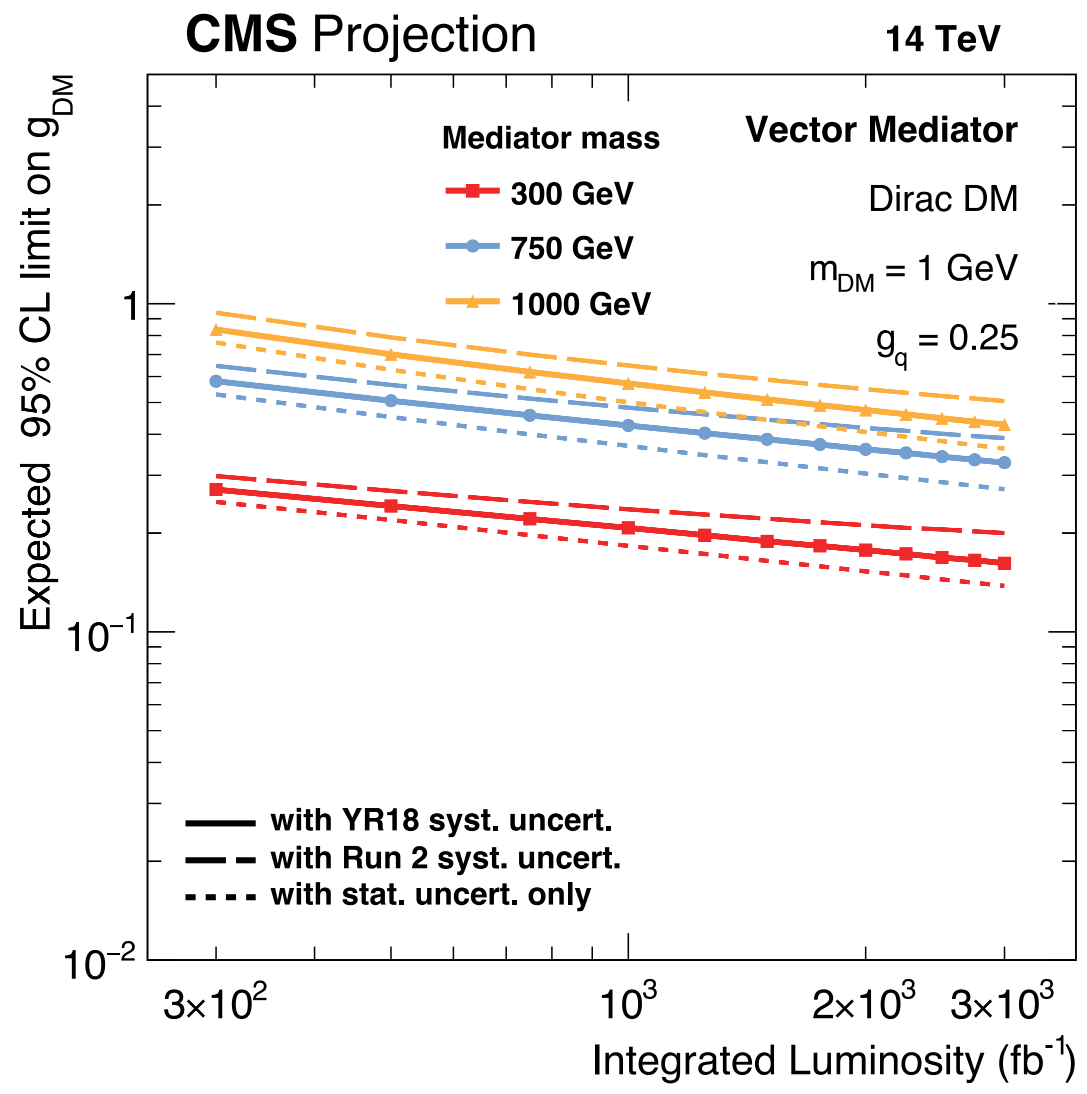
CMS-PAS-FTR-18-007

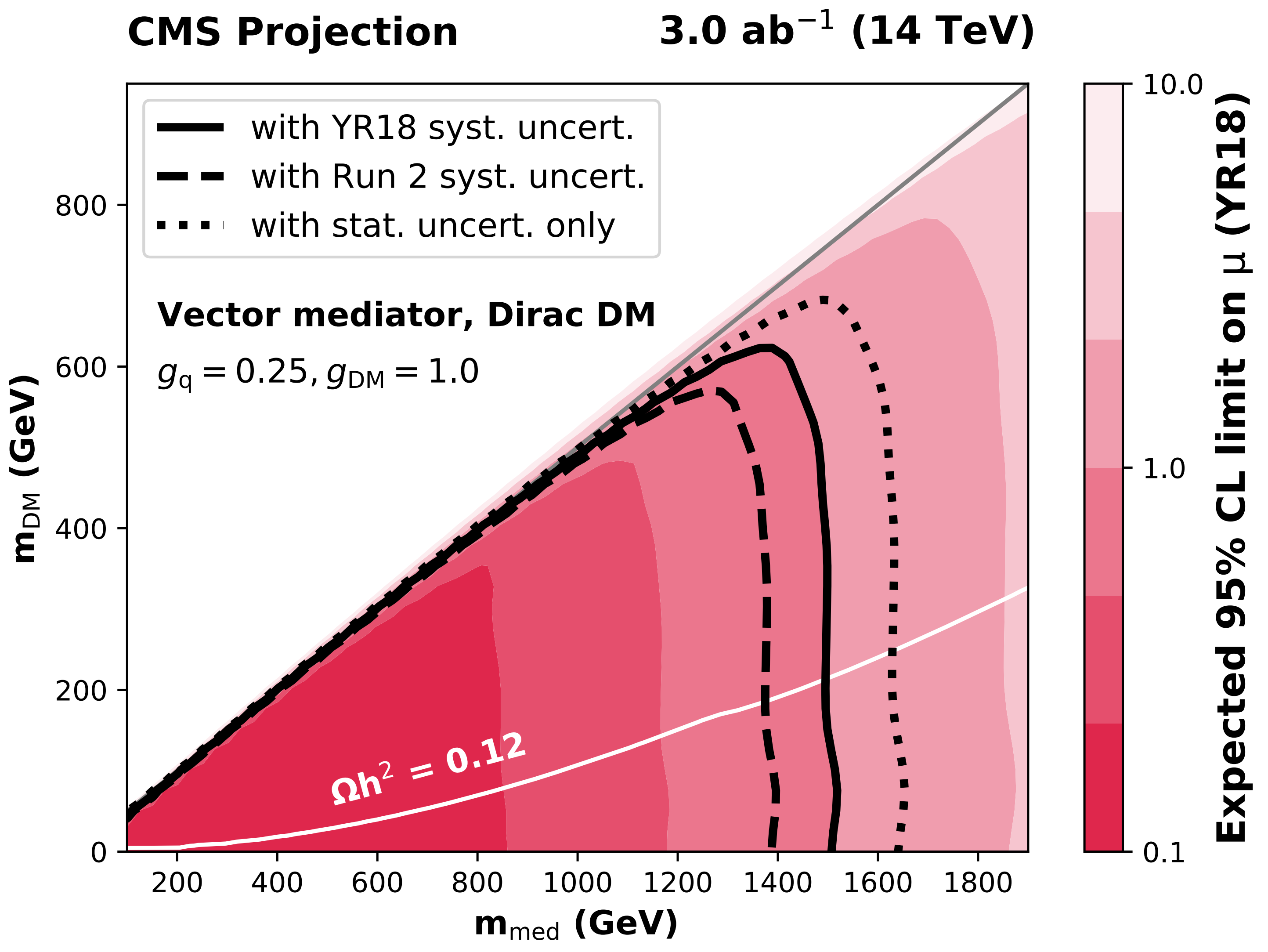


- Projections for increasing data samples
- Different mediator masses
- Systematics important









Summary

- LHC Dark Matter searches complementary to direct and indirect searches

- Broad search programme at the LHC
  - So far no significant discrepancies with Standard Model predictions
  - More analysis details in the parallel talks

- Future prospects
  - Completed analyses mainly based on 36 fb^{-1} of data
  - Full Run 2 dataset analyses based on 140 fb^{-1} in progress — plenty more to come!
  - Projections to 300 fb^{-1} and 3000 fb^{-1} studied — expect improvements in analyses too

Further information

- LPCC Dark Matter Working Group
  - http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc

- ATLAS and CMS results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/DM.html

- Acknowledgments
  - Thanks to Shih-Chieh Hsu for kind use of many useful diagrams

Backup

Reference simplified models

- Assume Dark Matter candidate is a Dirac fermion
  - (Majorana would not change kinematics)

- Meditator assumed to be a boson
  - g_{DM} = 1 g_{SM} = 0.25 for spin 1 vector or axial-vector mediator
  - g_{DM} = 1 g_{SM} = 1 for spin 0 scaler or pseudo-scaler mediator and proportional to m_f (min FV)
  - Minimum decay width calculated from couplings and mass

- Kinematics do not dependent on couplings

Comparisons of (in)direct and collider sensitivity

	Vector:	**Axial-vector:**
Spin 1 (electroweak couplings)	$g_{DM} Z'_\mu \bar{\chi} \gamma^\mu \chi$ Direct detection more sensitive than colliders except at low DM masses	$g_{DM} Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$ Direct detection and colliders equally sensitive in different regions of parameters space.
	Scaler:	**Pseudo-scalar:**
Spin 0 (Yukawa couplings)	$g_{DM} S \bar{\chi} \chi$ Direct detection and collider equally sensitive in different regions of parameter space	$g_{DM} S \bar{\chi} \gamma^5 \chi$ No limits from direct detection only indirect. Colliders provide limits similar to scalar.

2HDM

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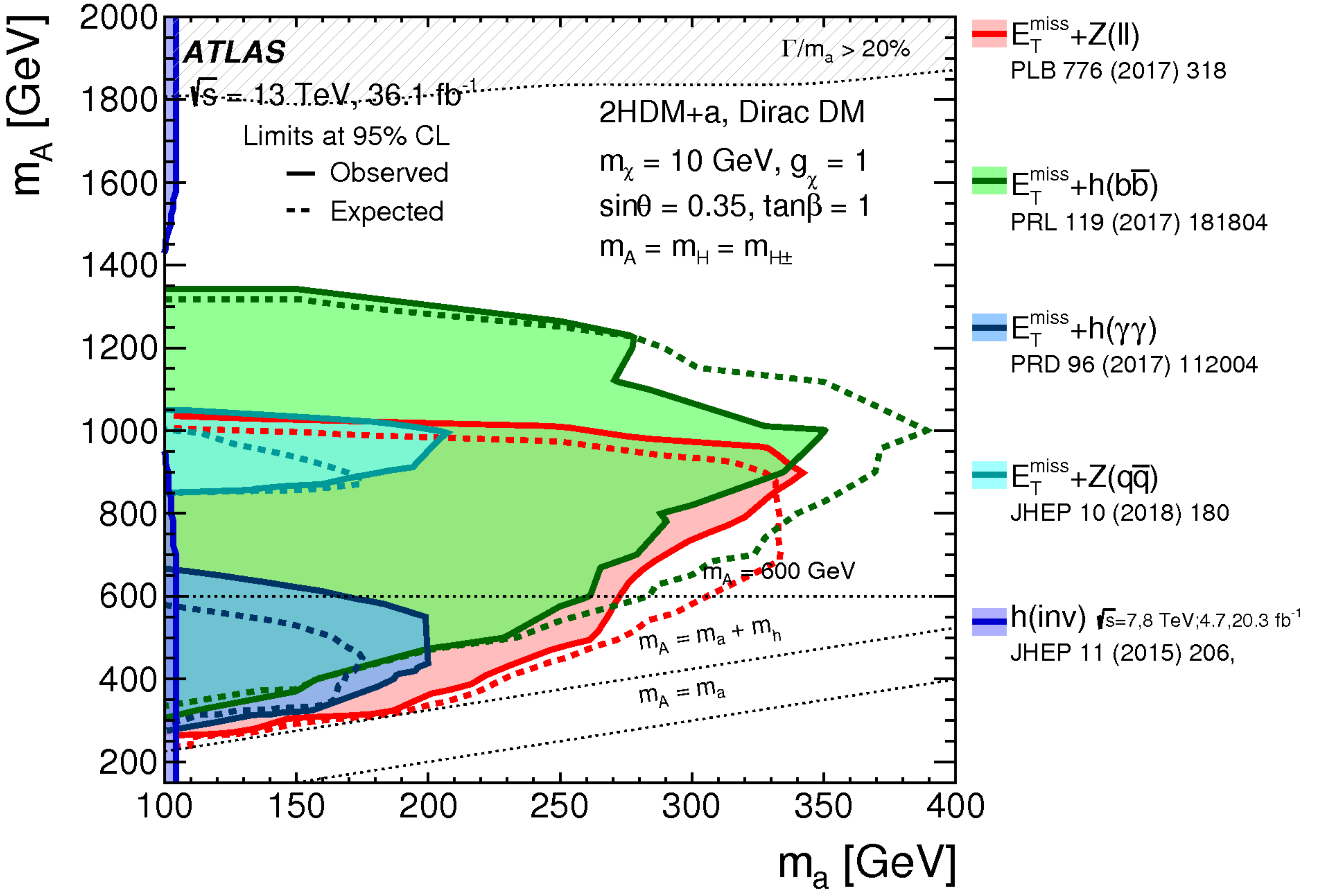
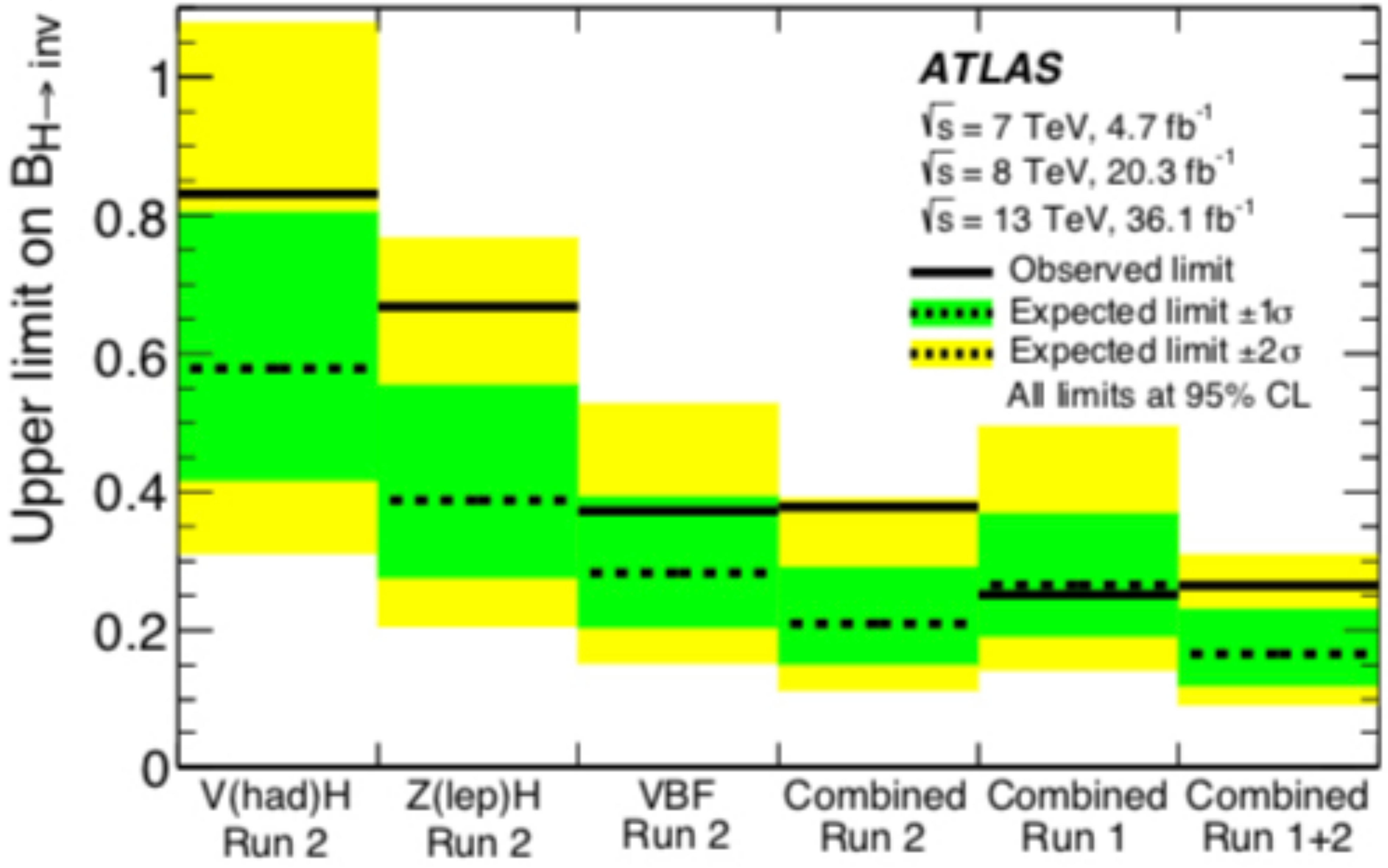
- DM couples to new spin 0 mediator and coupling to SM via mixing with Higgs
  - Satisfy constraints from LHC and achieve DM density
- 2HDM+a
  - Three new scalars (H, H+, H-)
  - Two new pseudo scalars (a,A)
  - tanβ = 1
  - A couples to DM
  - m_{DM} = 100 GeV
- Similarly for 2HDM+V



Higgs → invisible combination

arXiv:1904.0510



Analysis	$\sqrt{s}$	Int. luminosity	Observed	Expected	p_{SM}-value	Reference
Run 2 VBF	13 TeV	36.1 fb^{-1}	0.37	$0.28^{+0.11}_{-0.08}$	0.19	[36]
Run 2 Z(lep)H	13 TeV	36.1 fb^{-1}	0.67	$0.39^{+0.17}_{-0.11}$	0.06	[37]
Run 2 V(had)H	13 TeV	36.1 fb^{-1}	0.83	$0.58^{+0.23}_{-0.16}$	0.12	[38]
Run 2 Comb.	13 TeV	36.1 fb^{-1}	0.38	$0.21^{+0.08}_{-0.06}$	0.03	this Letter
Run 1 Comb.	7, 8 TeV	4.7, 20.3 fb^{-1}	0.25	$0.27^{+0.10}_{-0.08}$	—	[35]
Run 1+2 Comb.	7, 8, 13 TeV	4.7, 20.3, 36.1 fb^{-1}	0.26	$0.17^{+0.07}_{-0.05}$	0.10	this Letter