Searches for Dark Matter

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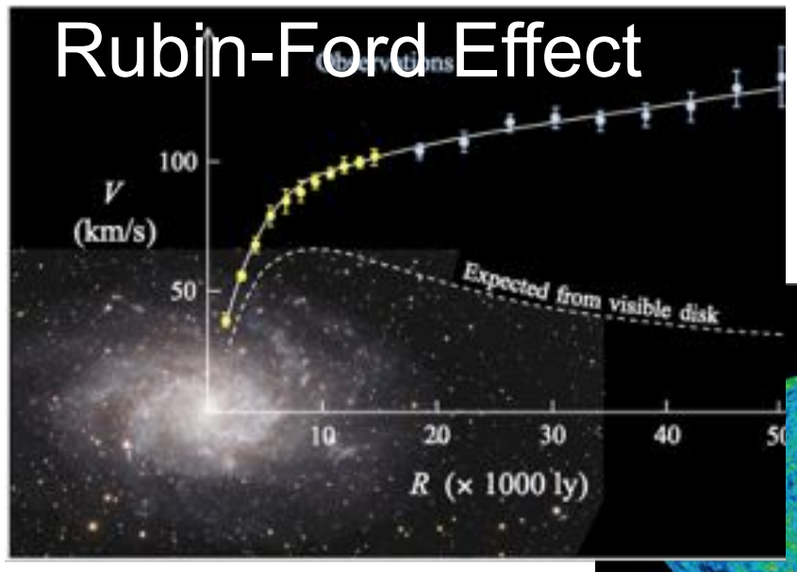
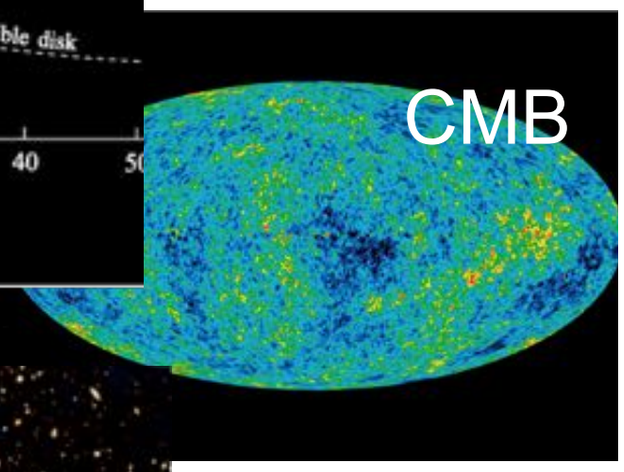
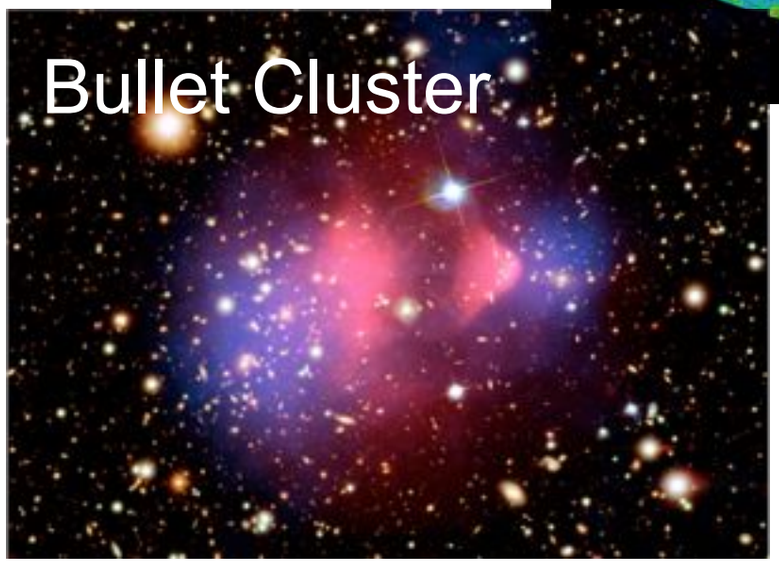
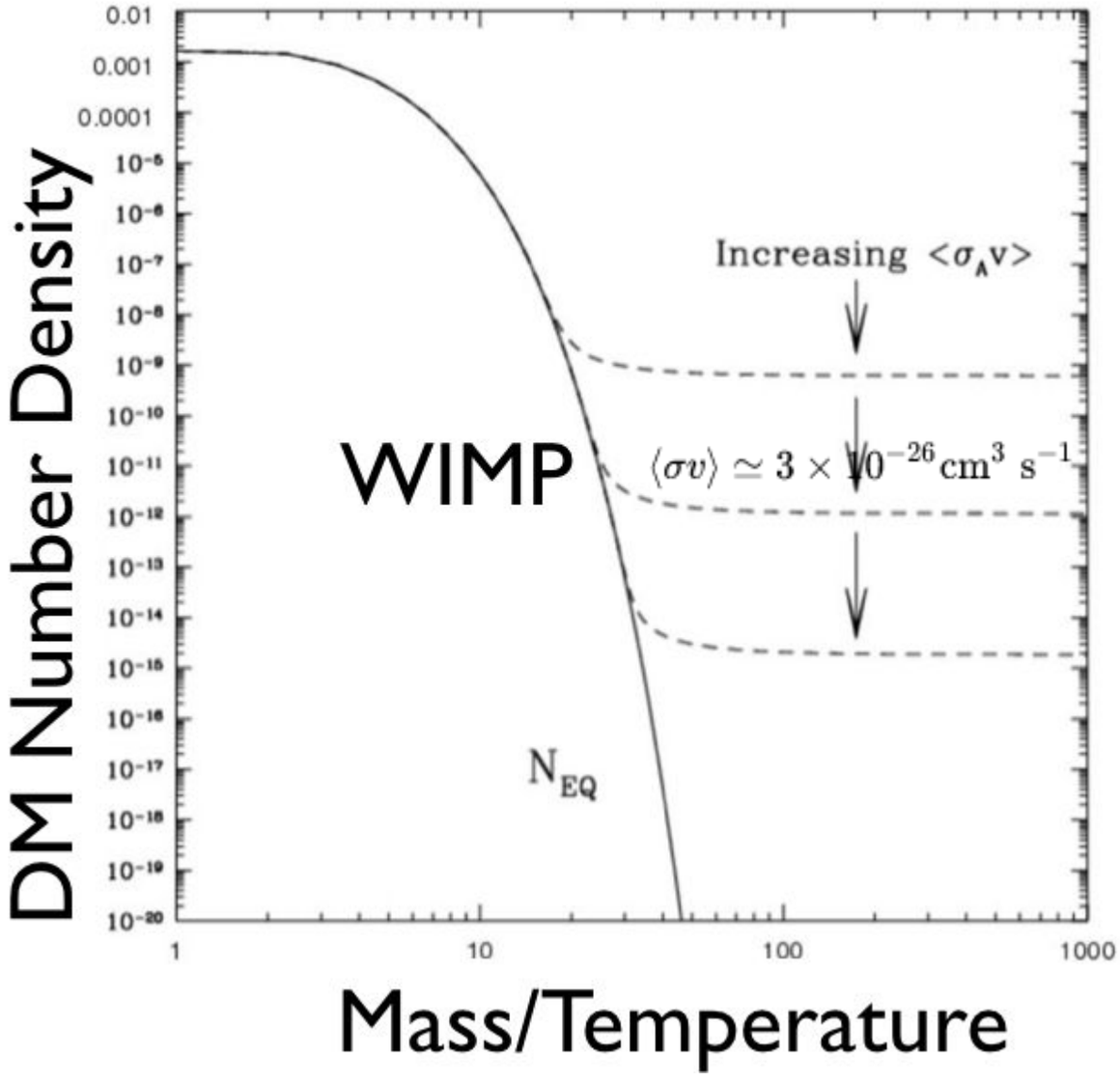
Dark Matter & WIMPs

- Particle nature of dark matter (DM) strongly suggested by gravitational anomaly observations
- Weakly Interacting Massive Particles (WIMPs) - attract DM candidates with properties consistent to thermal relics (a **WIMP miracle!**)



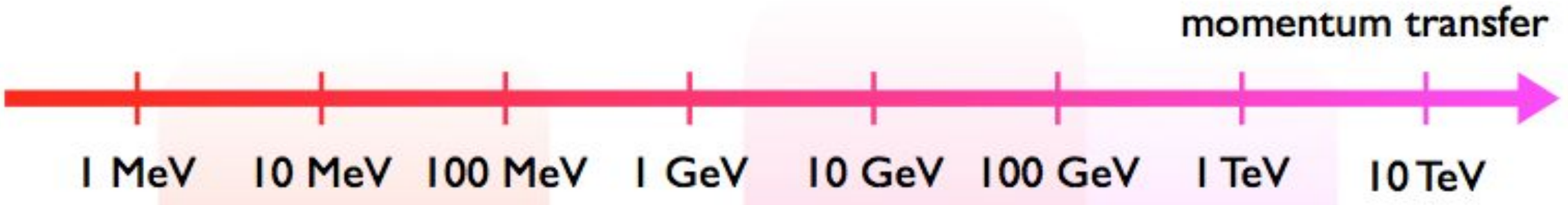


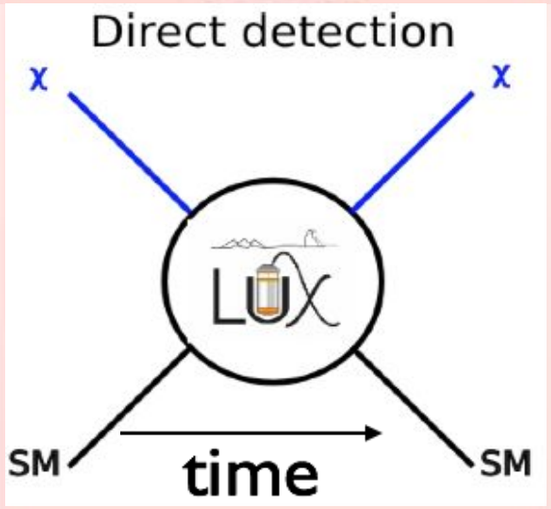


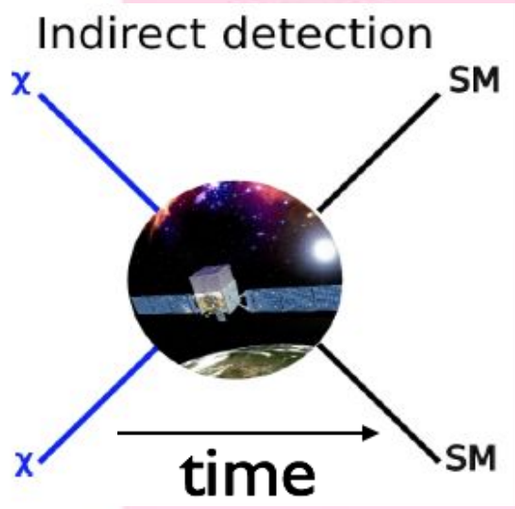


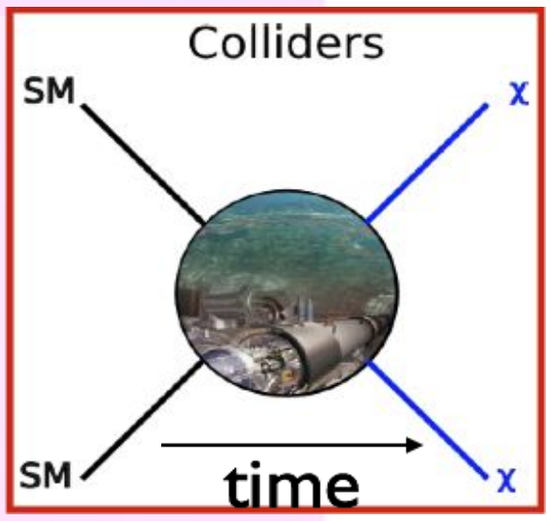
WIMPs Detection

- **WIMPs** may be produced through proton-proton collisions at the **LHC**!
- **Collider searches** are complementary to **Direct Detections** and **Indirect Detections**.



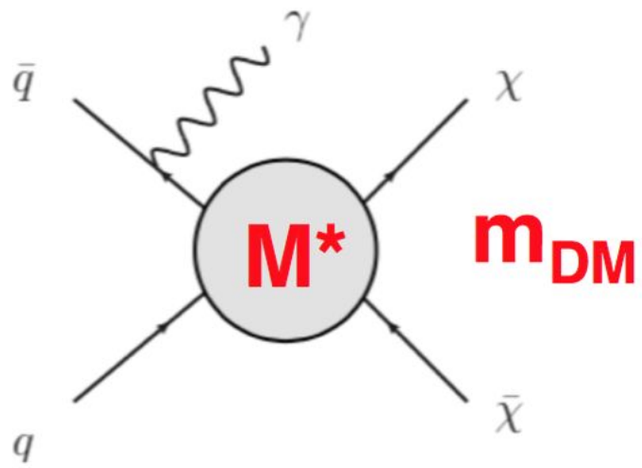




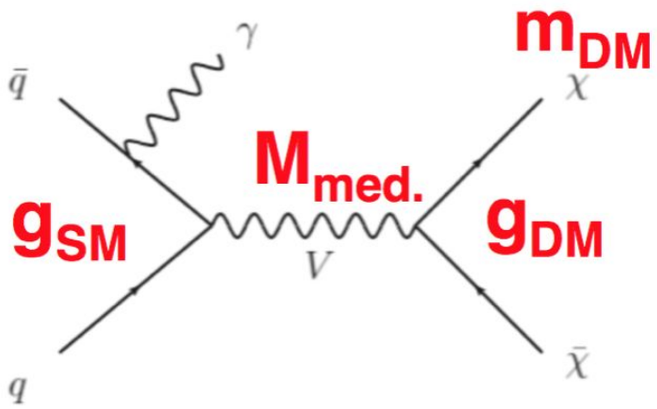


Dark Matter Models

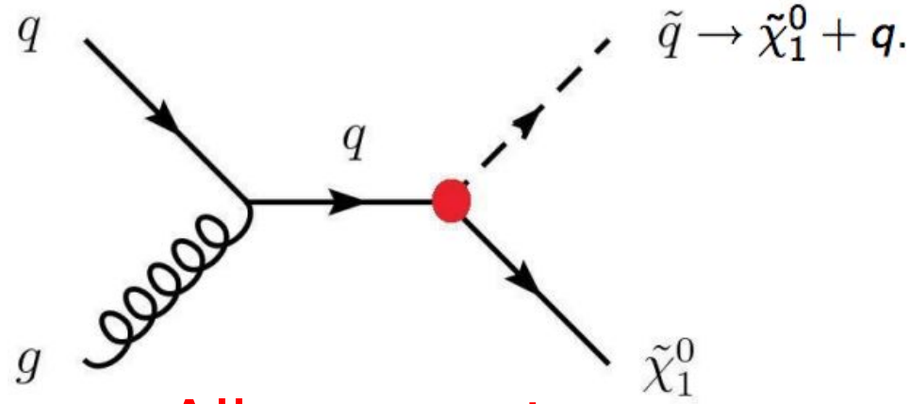
Effective Field Theories



Simplified Models



Complete Models
(e.g. Supersymmetry)



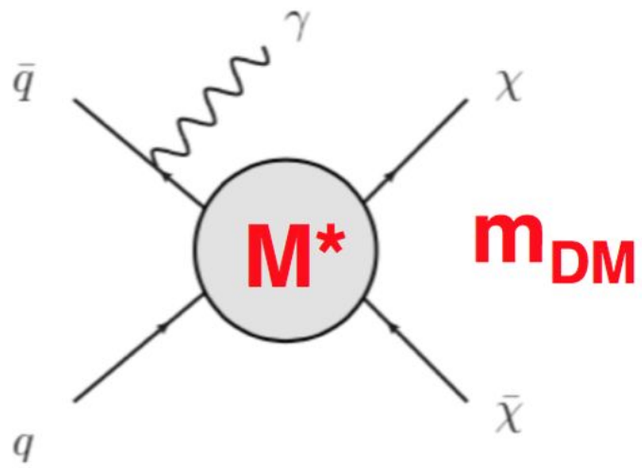
All parameters

Simple

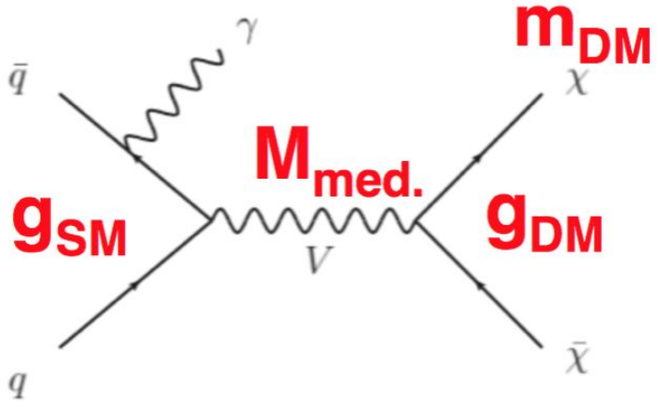
Complex

Dark Matter Models

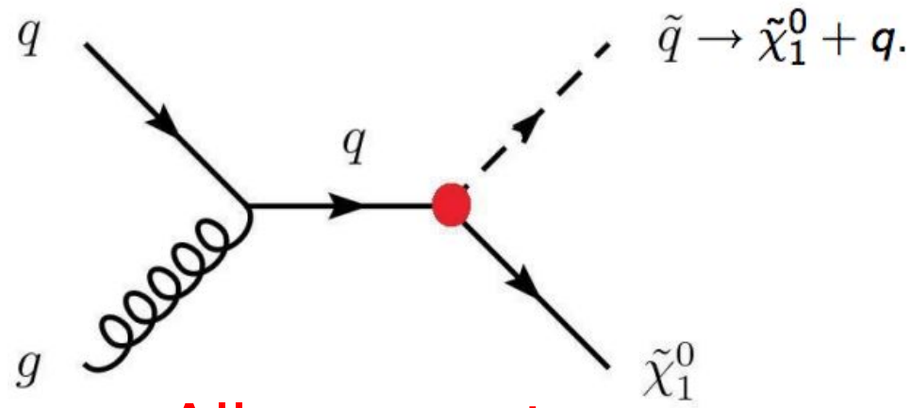
Effective Field Theories



Simplified Models



Complete Models



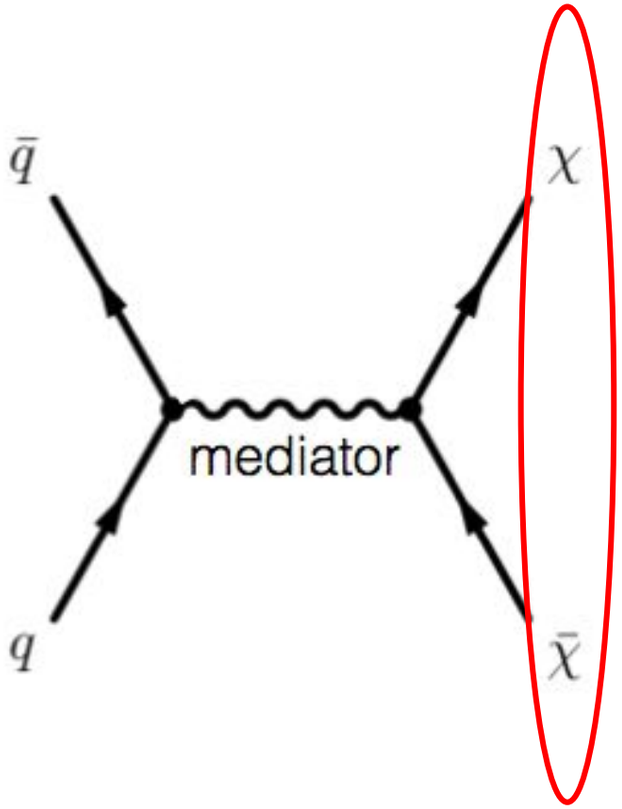
All parameters

Simple ⟷ Complex

Simplified Models being the primary focus at the LHC DM community:

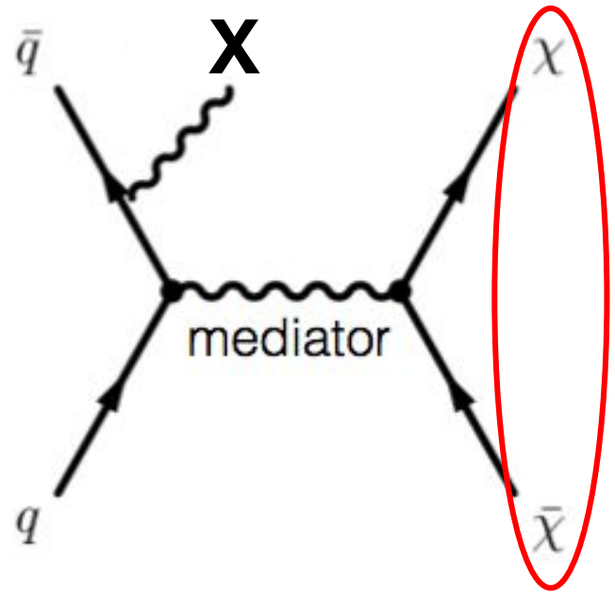
- Avoid EFT validity concerns
- Capture generic signatures arised in a variety of complete models

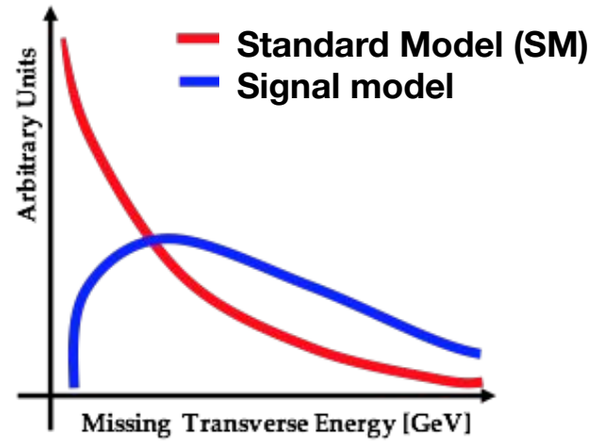
Dark Matter Detection at the LHC



DM (χ) has NO interactions with detectors.

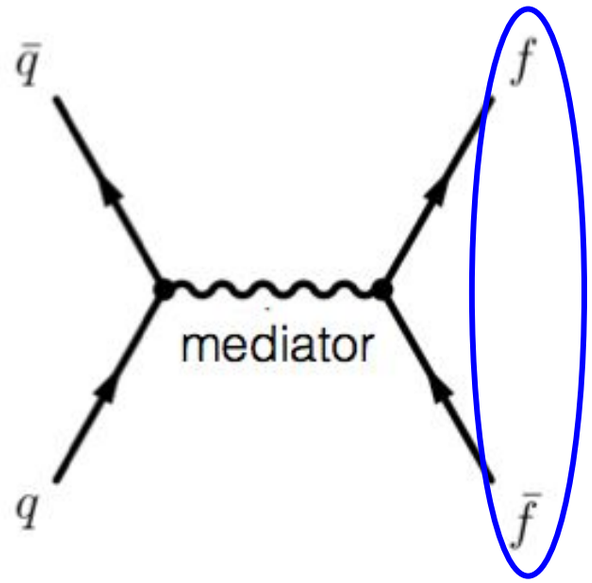
1. $\mathbf{X+E_T^{miss}}$ searches (**X**= SM particles)

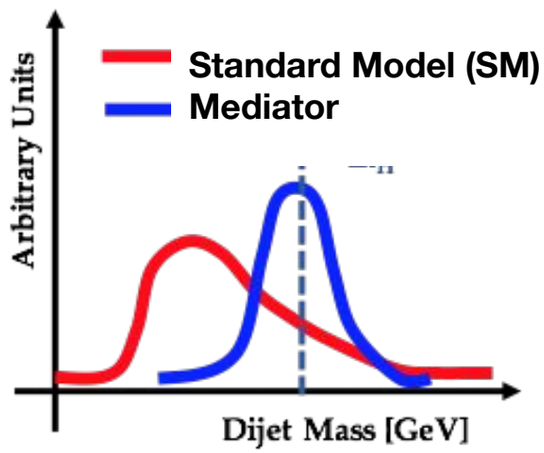




Tail distribution

2. **Mediator searches**

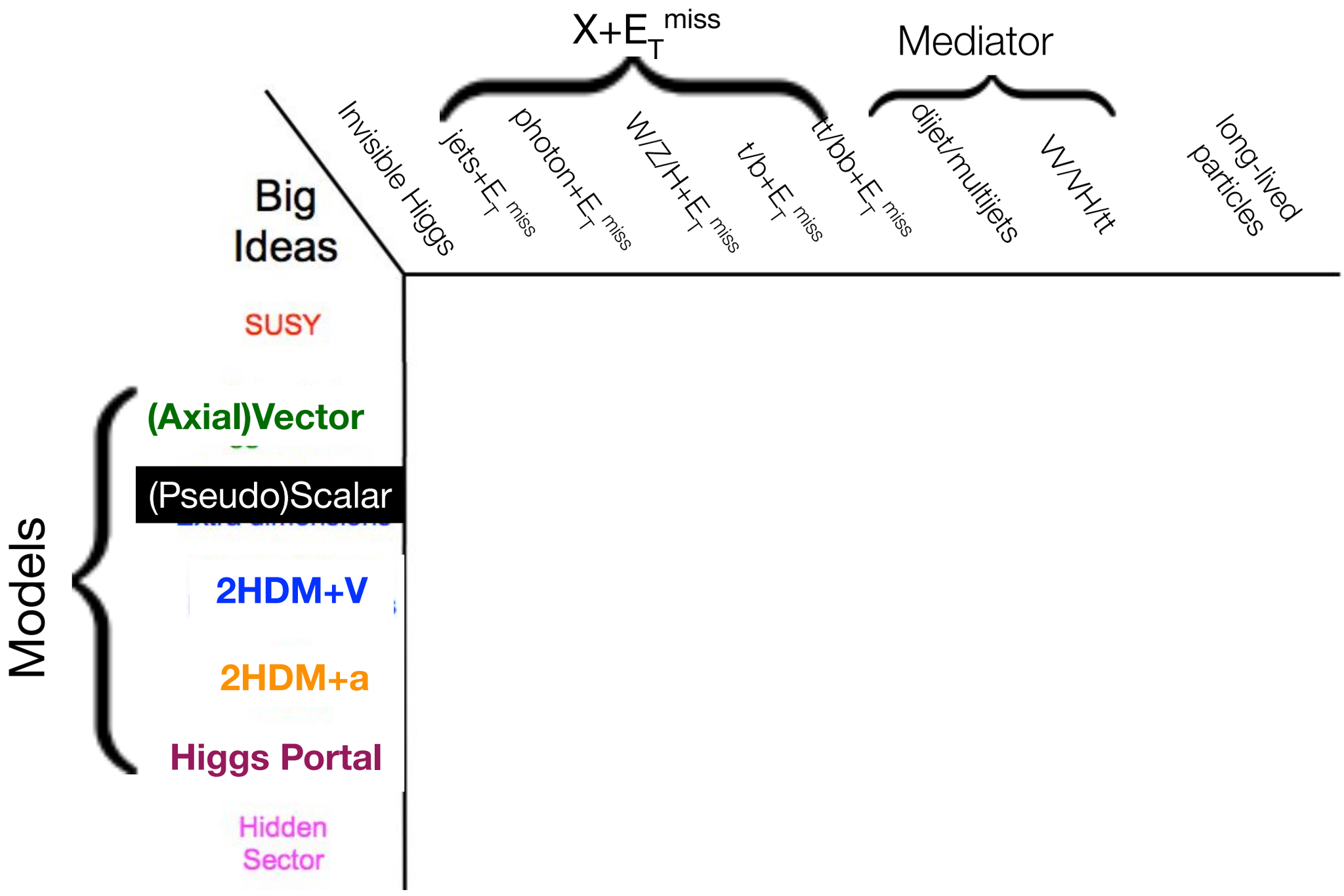




Bump hunting

Broad Search Program

- Quite often the same big idea probed by different signatures
  - It's crucial to search all complementary signatures



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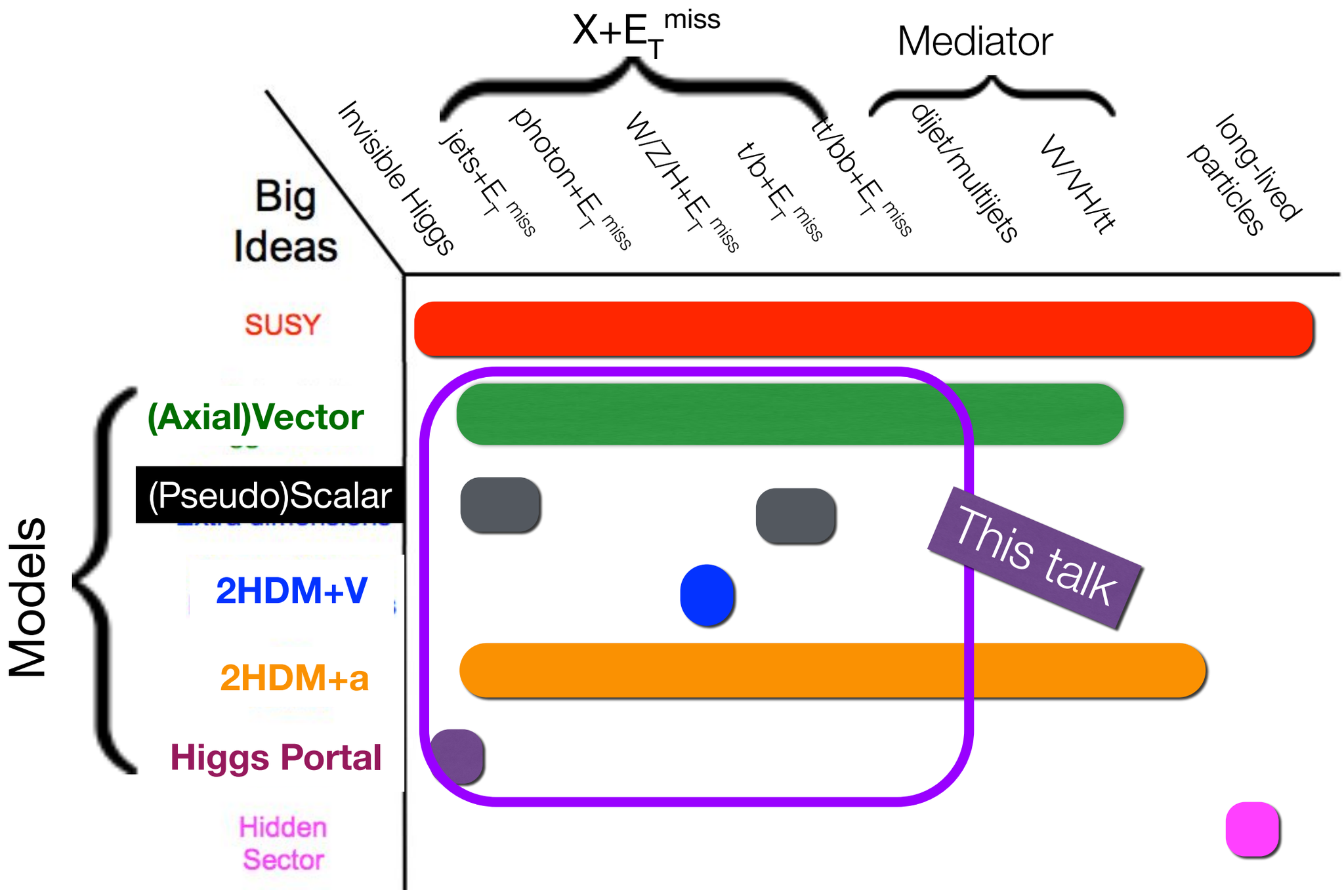


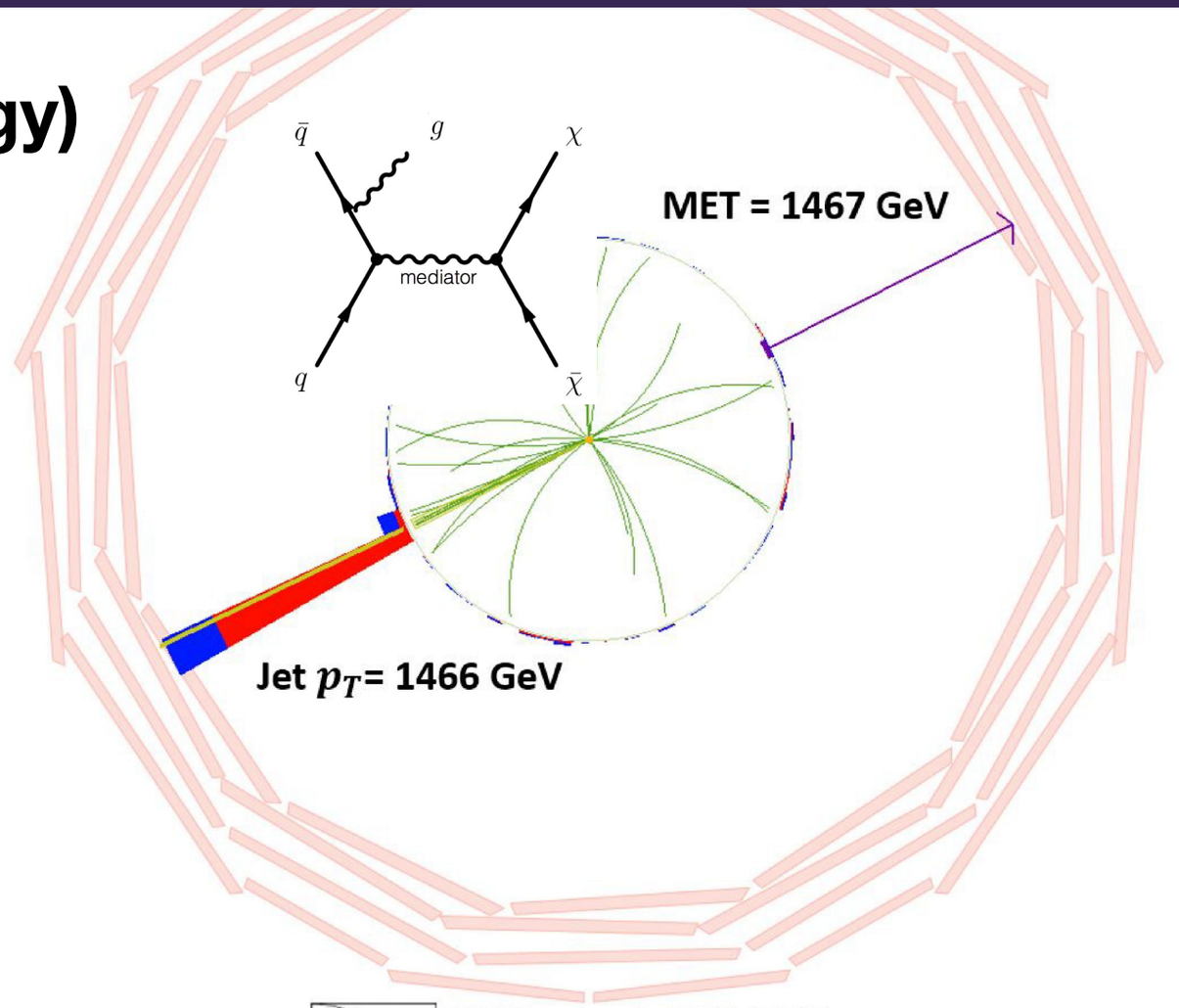
Key Experiment Observables

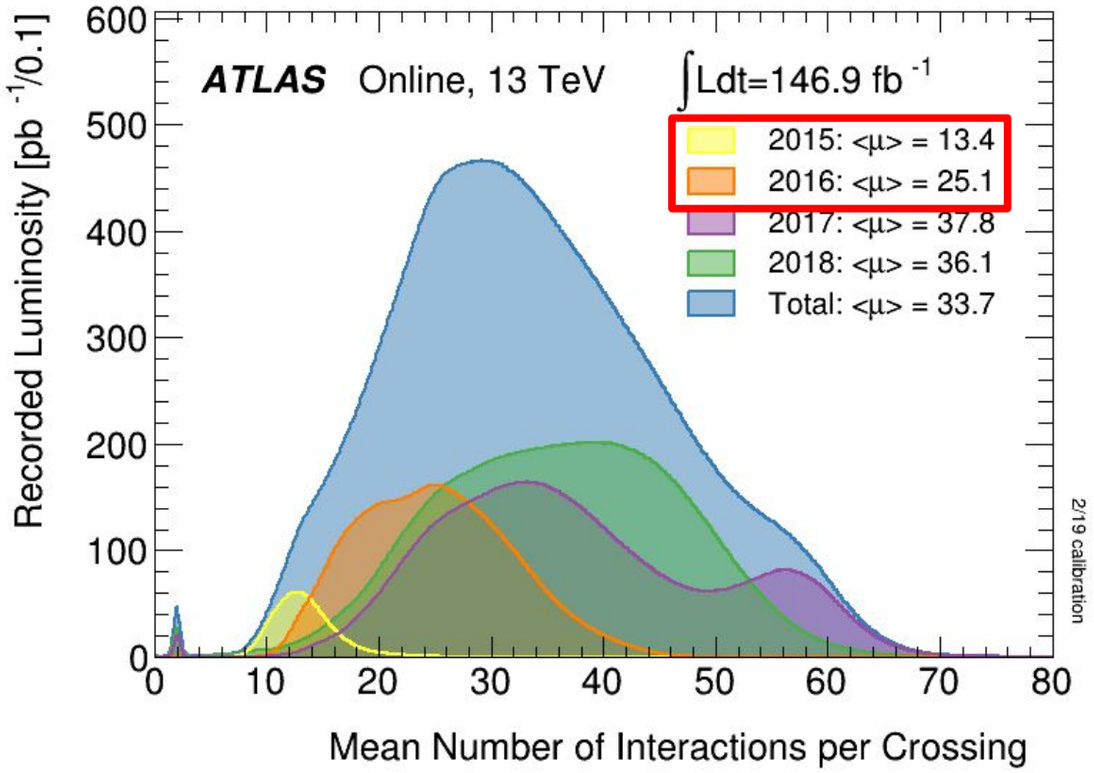
Missing transverse momentum (energy)

- Transverse momentum balanced with initial transverse momenta = 0!

$$\Delta\phi\left(p_T^{miss}, X\right) \sim \pi$$

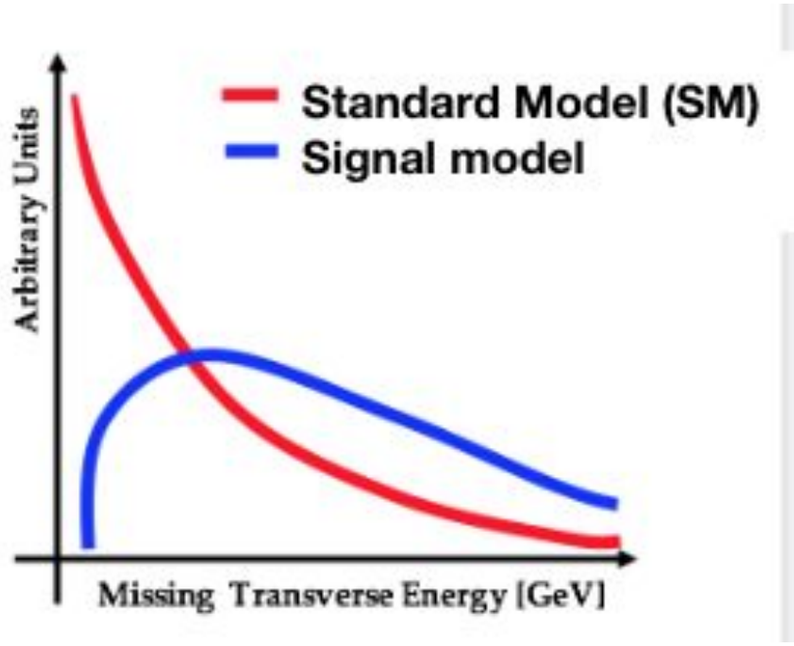
$$p_T^{miss} \sim p_T^X(E_T^{miss})$$





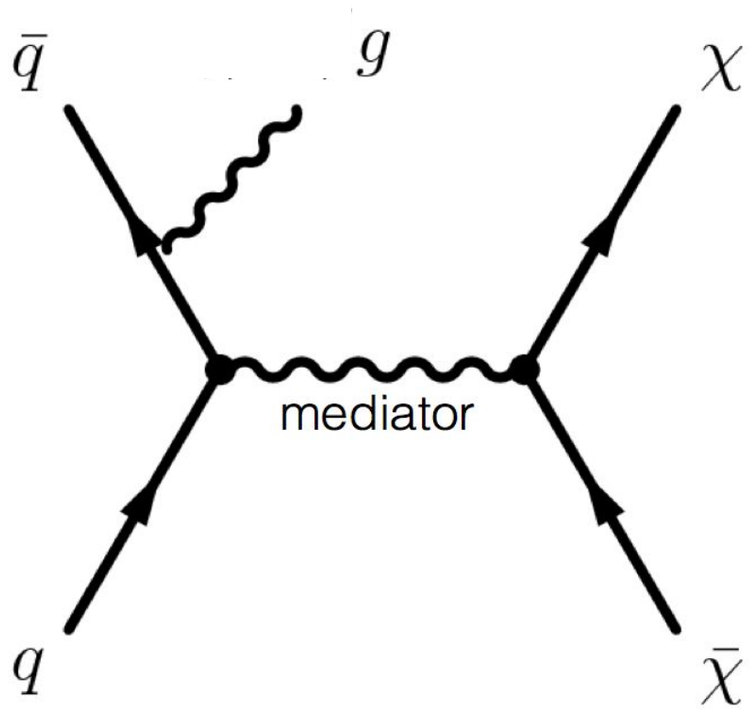
- Understanding E_T^{miss} is crucial for dark matter searches at collider, and challenging due to high pileup events.
- Most of results in this talk exploit **2015+2016** data.

X+E_T^{miss} Searches



Jet+E_T^{miss}

- Initial State Radiation (ISR) of SM particles



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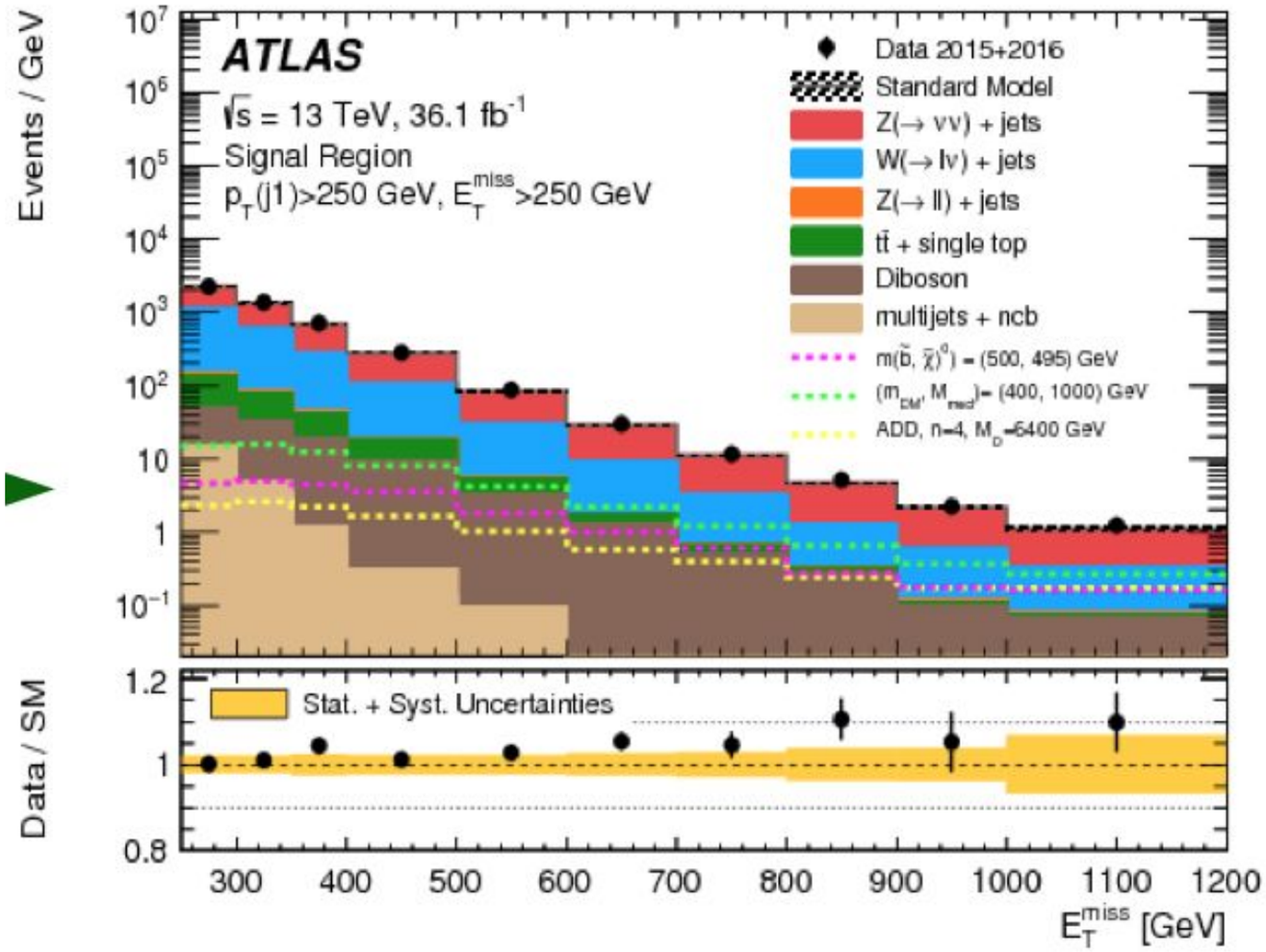
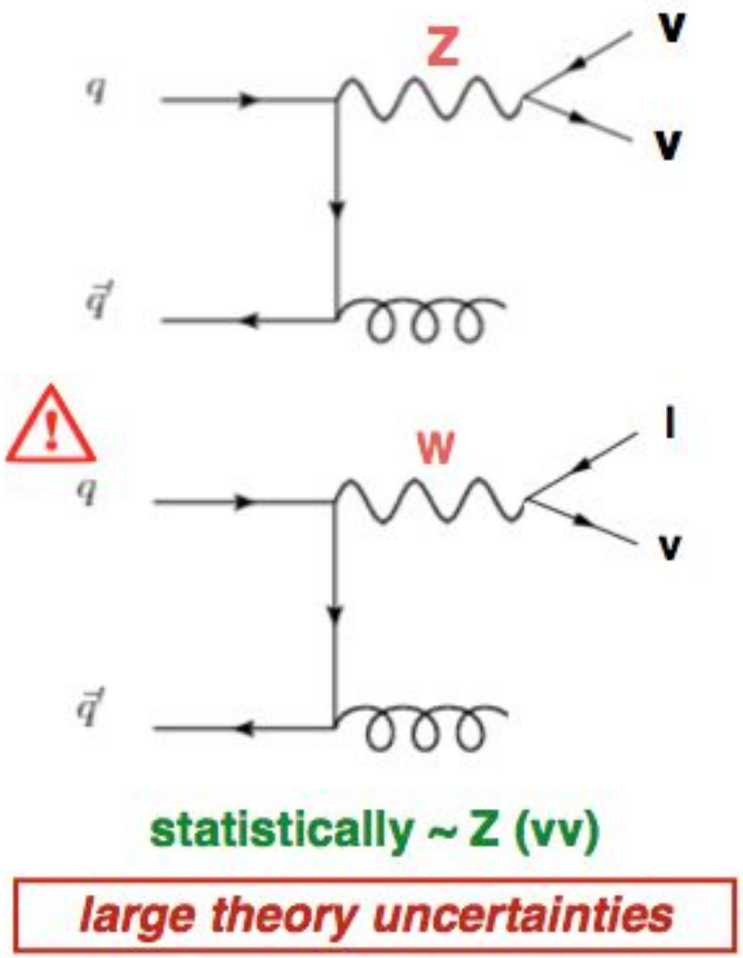
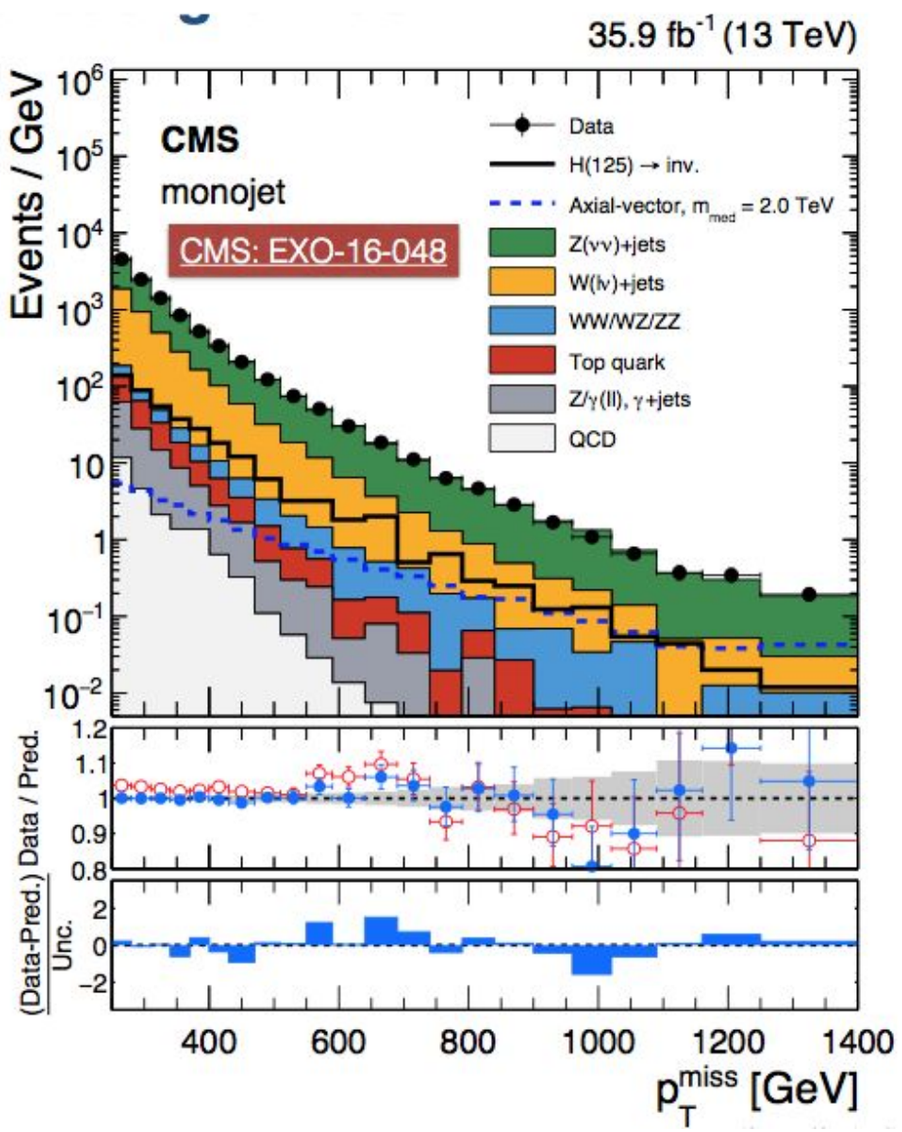


$p_T(V)$ dramatically reduced modelling uncertainties in collaboration with theorists 2%~10%. (arXiv:1705.04664)

Jet+E_T^{miss}: Background Estimate

- Irreducible background: Z($\nu\bar{\nu}$)+jets

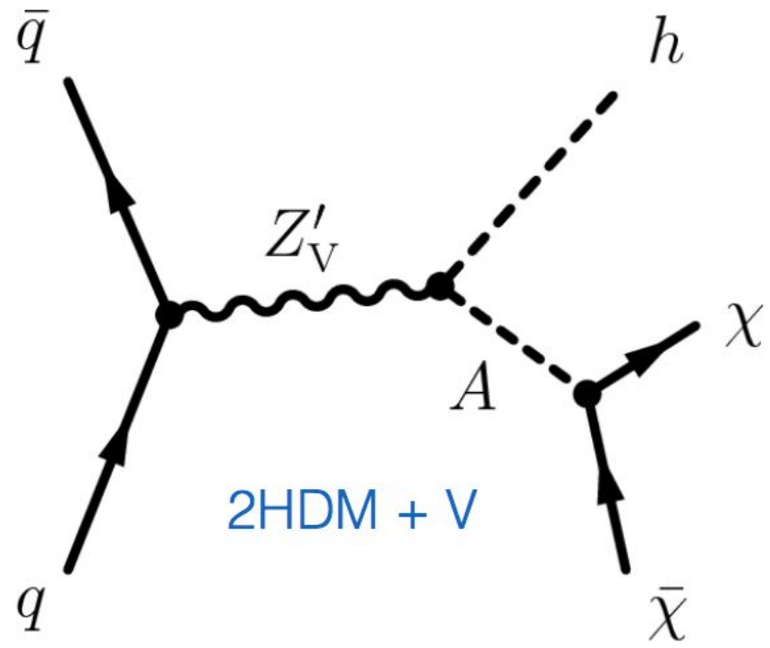


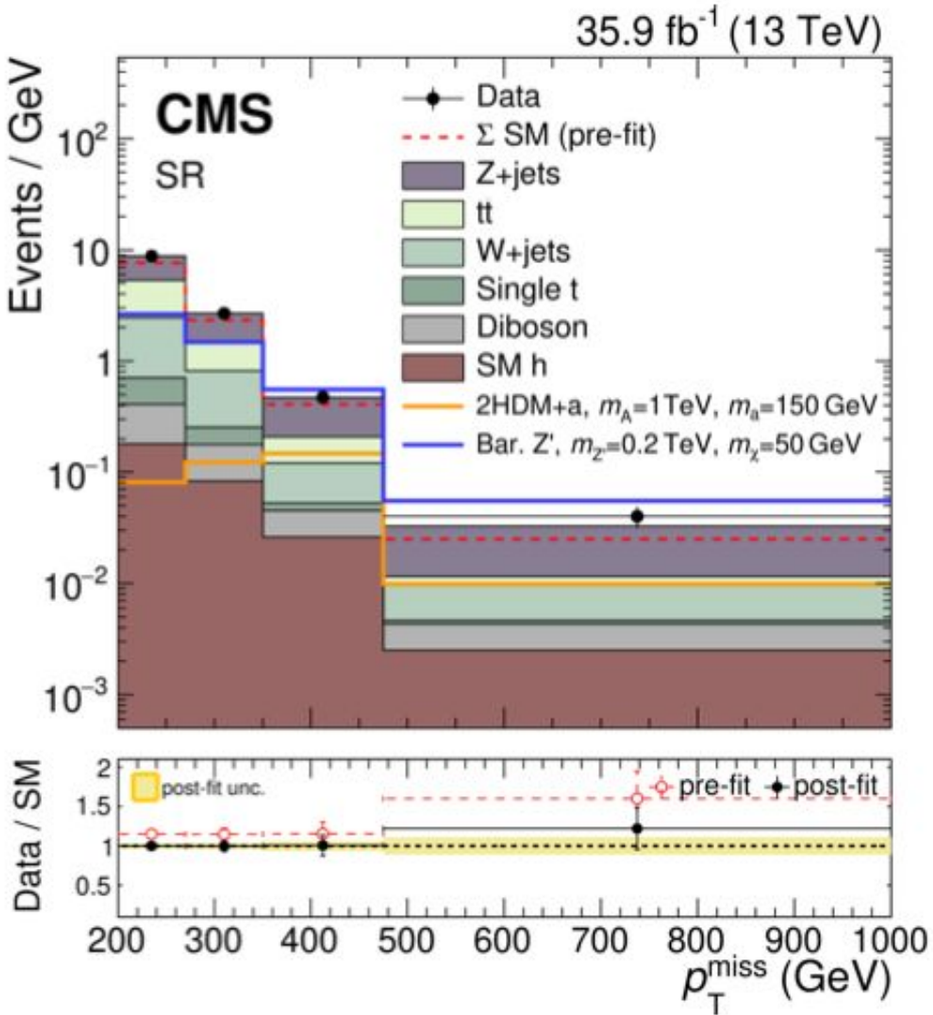


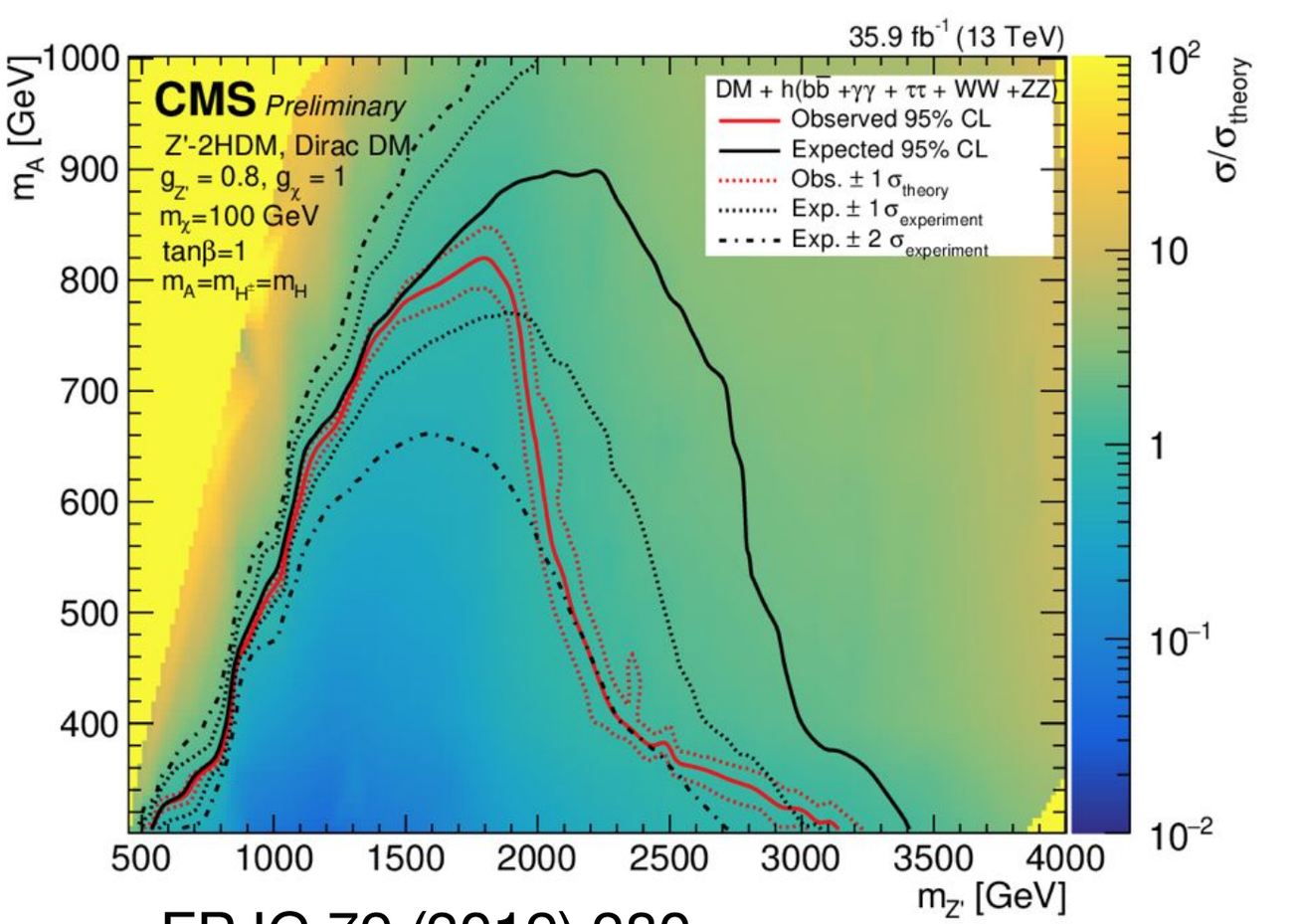
- Z+jets could also be dominant background to other X+E_T^{miss}
  - jets might be mis-reconstructed as b-jets, γ, W, Z, h, top.
  - Theory uncertainty of p_T(V) is a limiting factor for high-pT search in Run 3

Higgs+E_T^{miss}

- ISR process strongly suppressed
  It's a direct probe of couplings between DM mediators and Higgs.
- New combinations of 5 Higgs channels carried out by CMS
  - bb + τ τ + γ γ + WW + ZZ
- Sensitivity driven by bb







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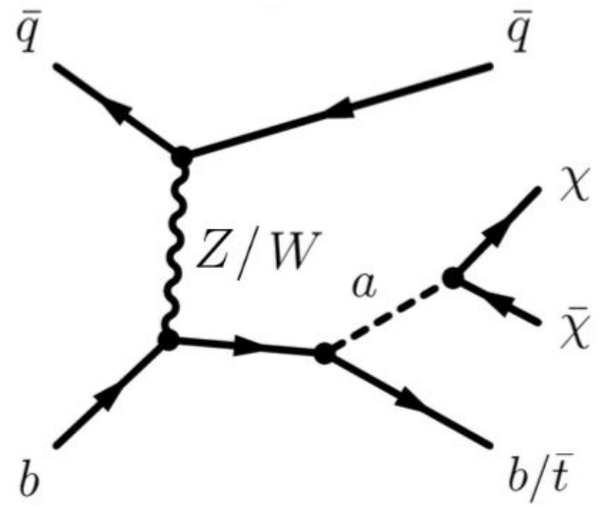
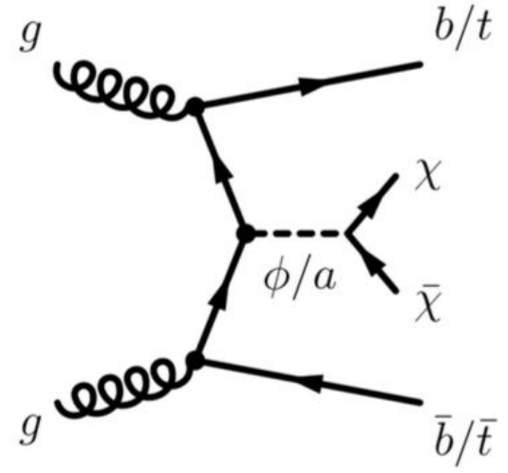
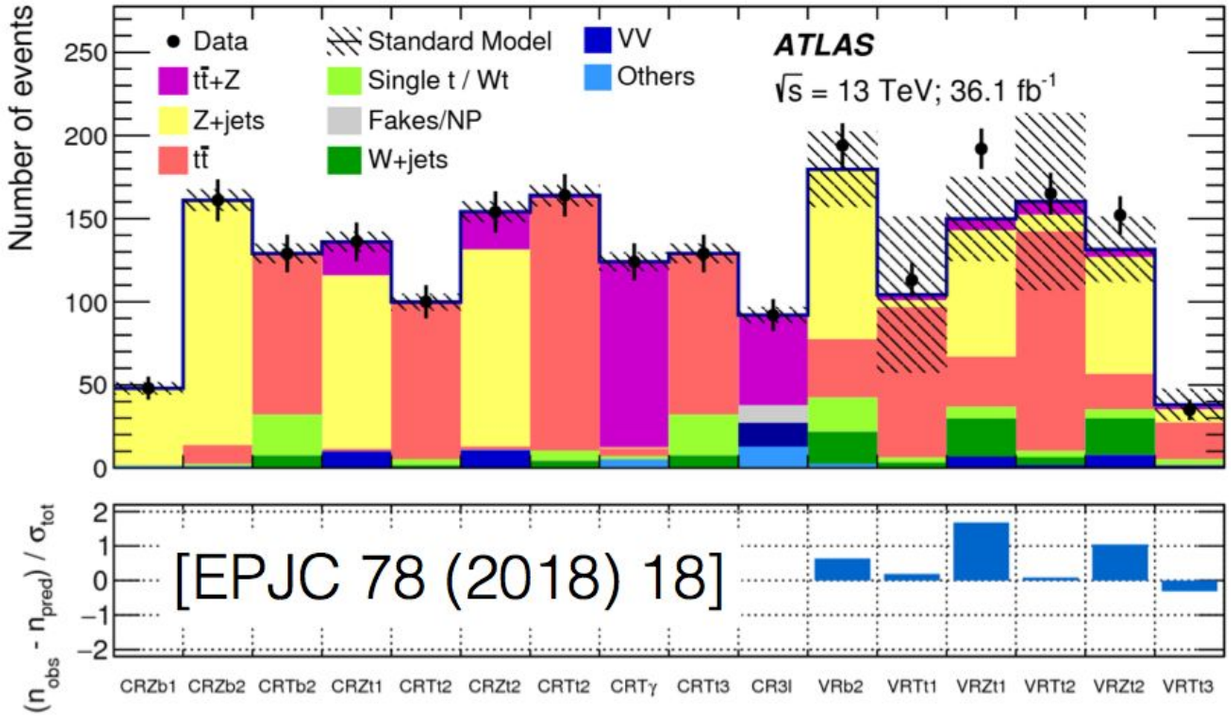
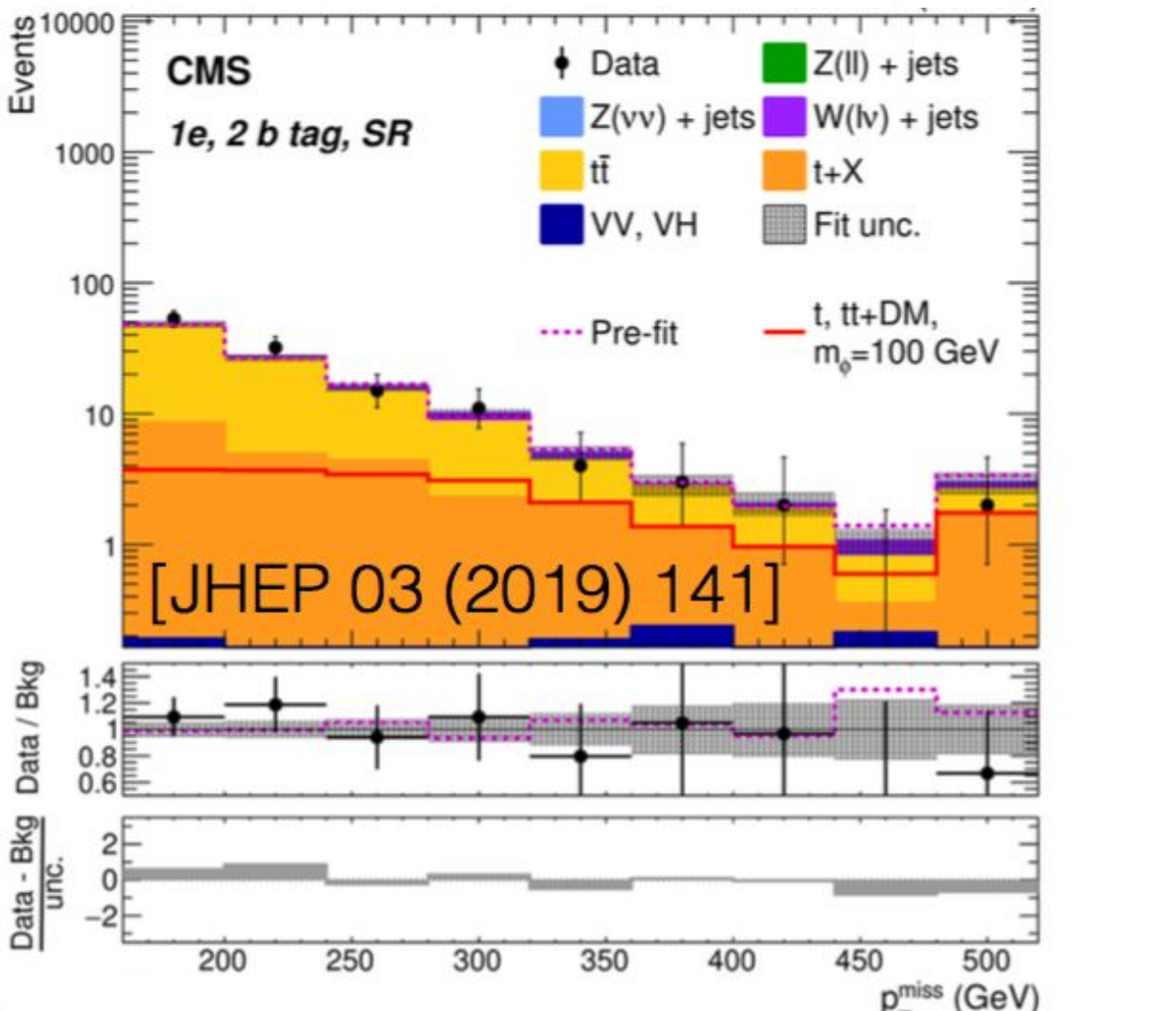
Heavy Flavor (t/b/tt/bb)+E_T^{miss}

- Analysis regions categorized by number of leptons, b-jets and jets
- Simultaneous fit across all regions to extract signal yields.

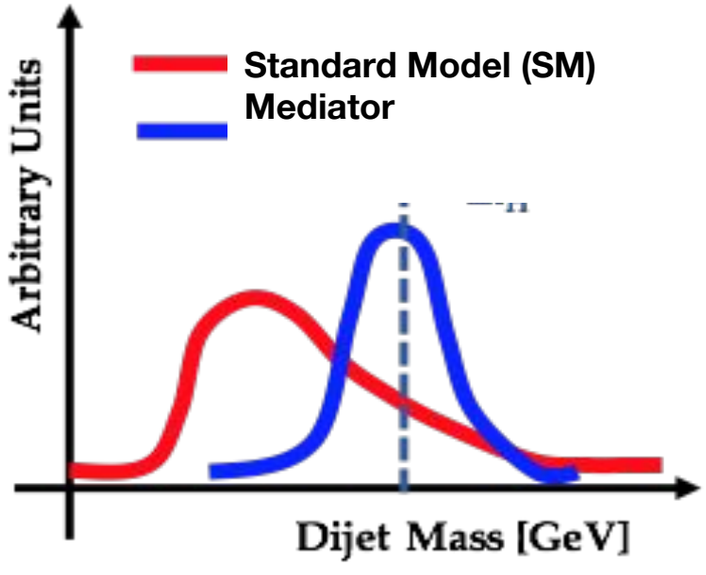






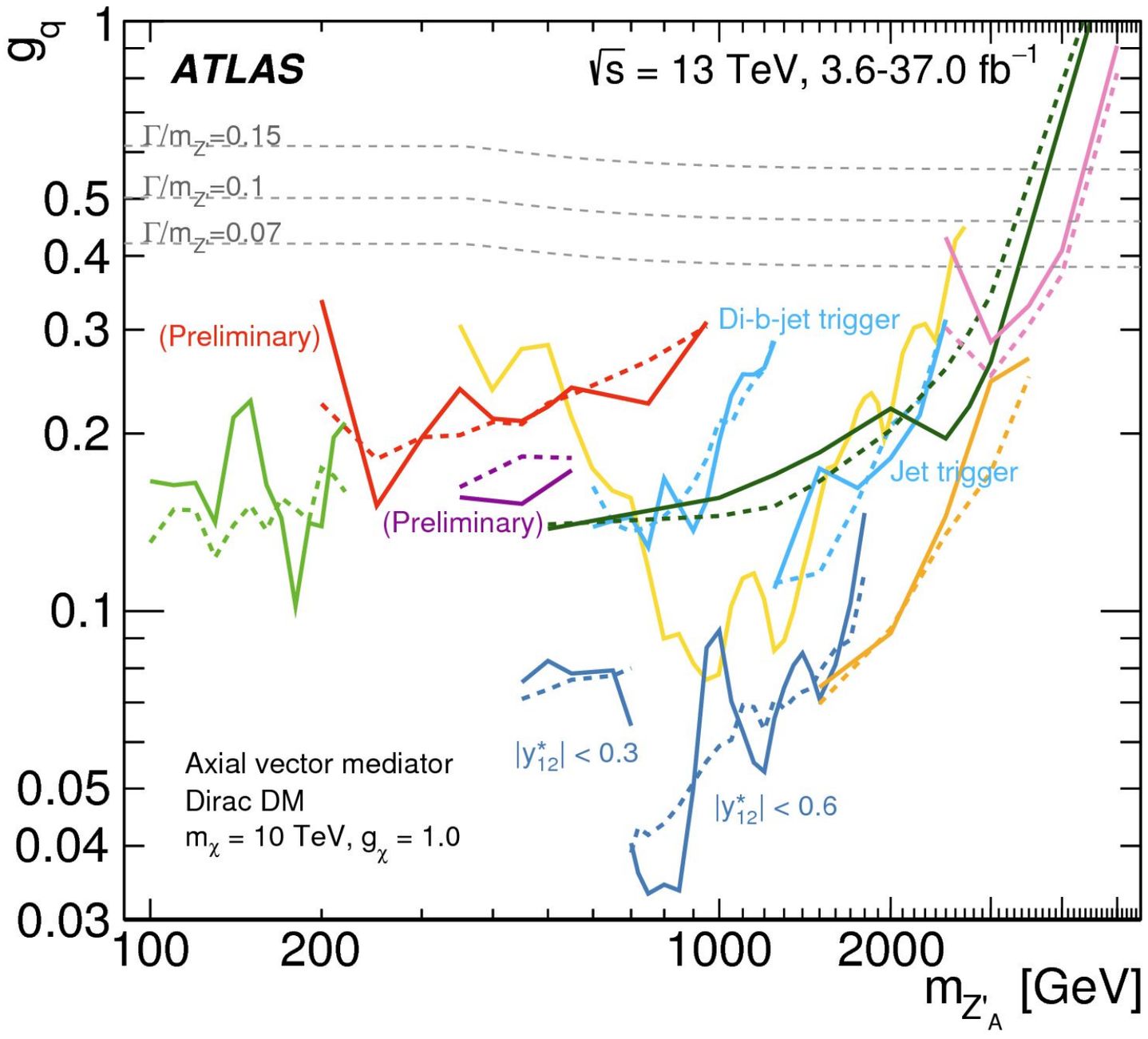


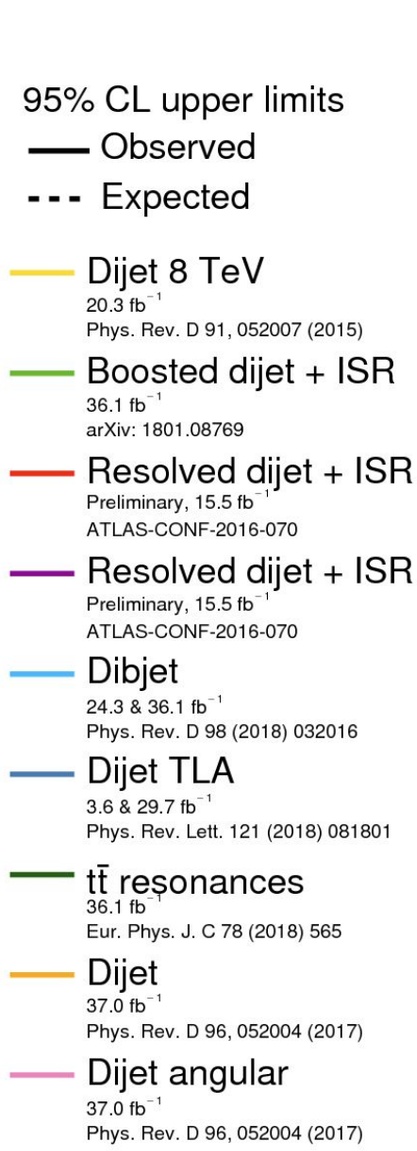
Mediator Search

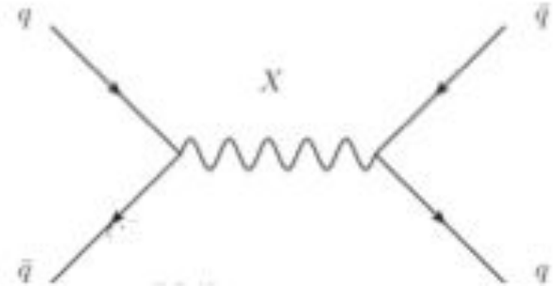


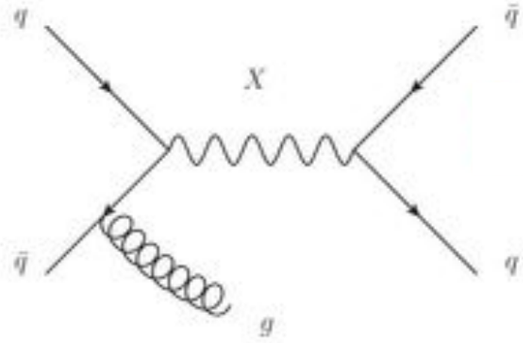
Dijet resonance search

- Complementary searches for dark matter
  - Dark matter may be too heavy to be produced directly, or weakly coupled to mediator





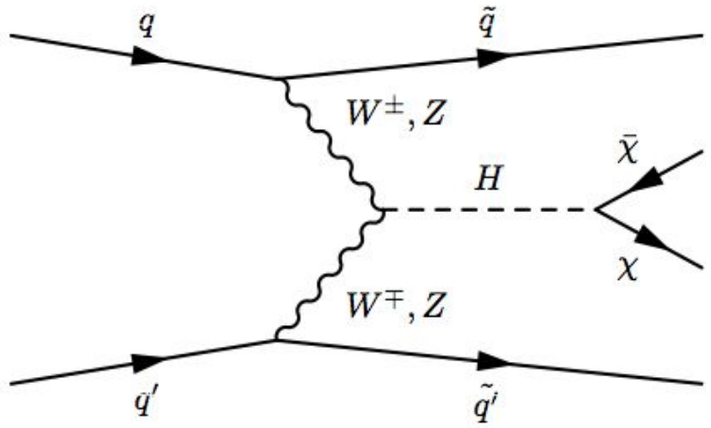


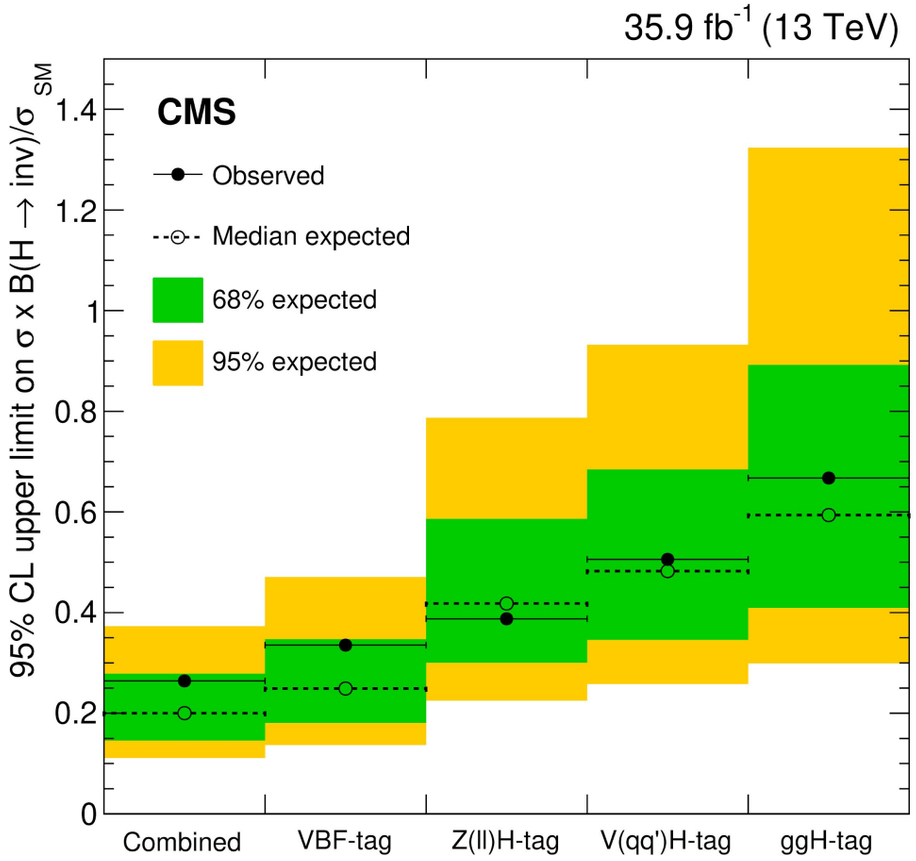


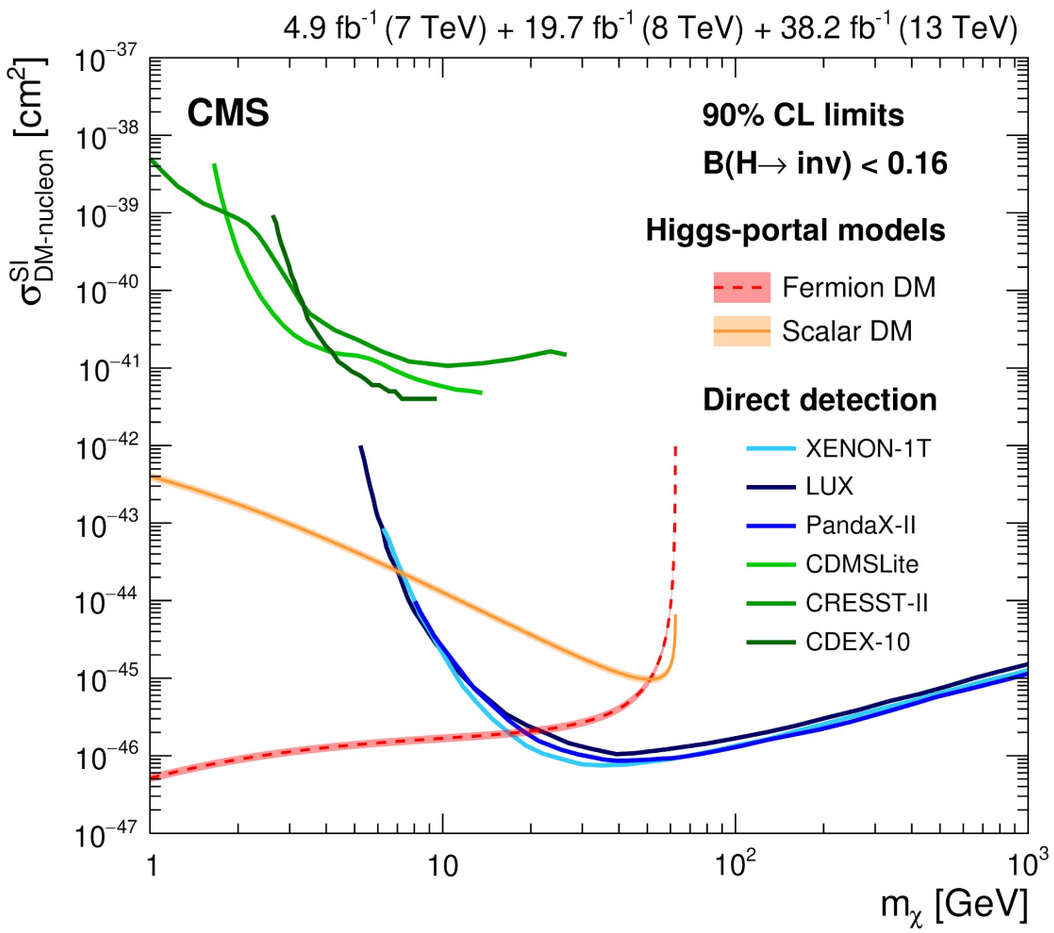
Higgs Invisible

arXiv:1809.05937

- SM prediction is small BR(H → ZZ → 4ν) ~ 0.1%
- A direct probe of coupling between DM and the Higgs with mass of DM lighter than 62 GeV.
- VBF production is the most sensitive channel







CMS BR(H→ inv) < 19% (15% exp.) @95% CL

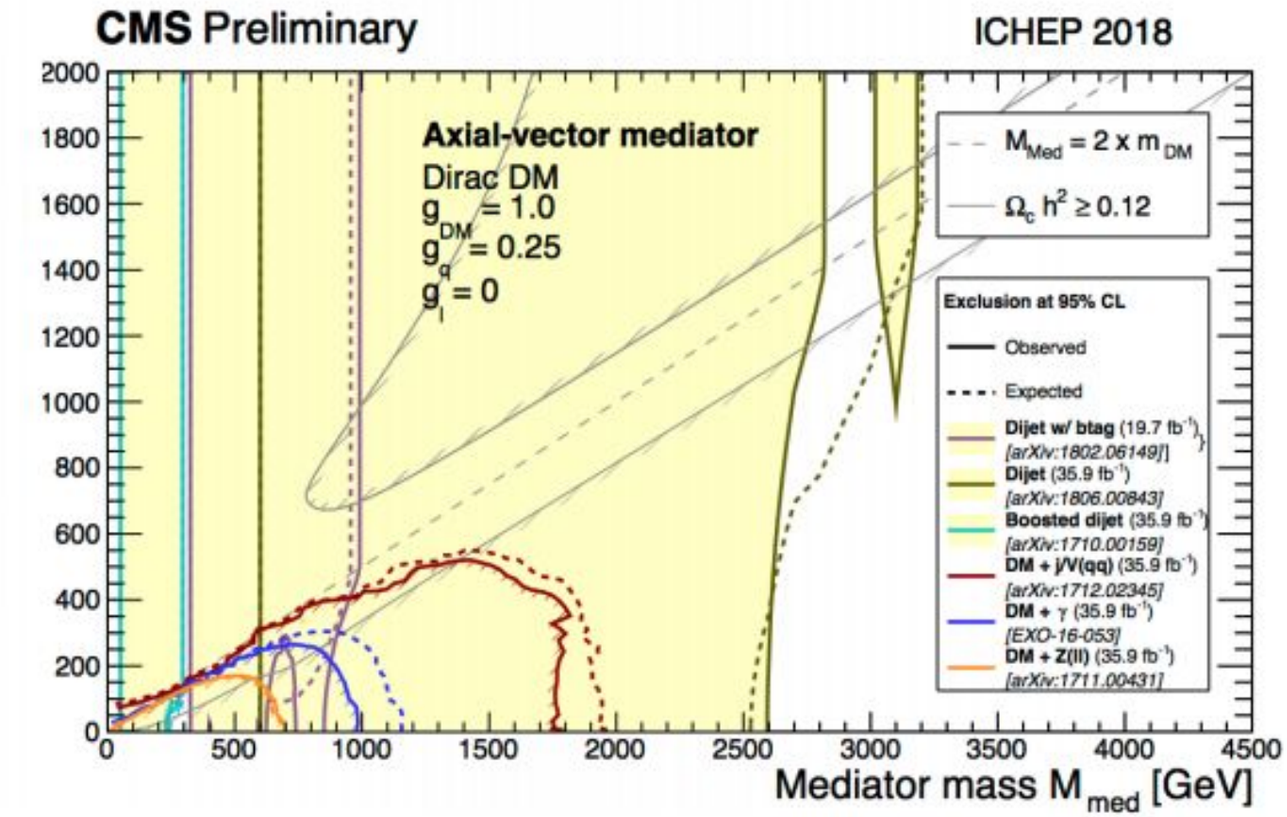
ATLAS BR(H→ inv) < 26% (17% exp.) @95% CL [arXiv: 1904.05105]

Joint Interpretations

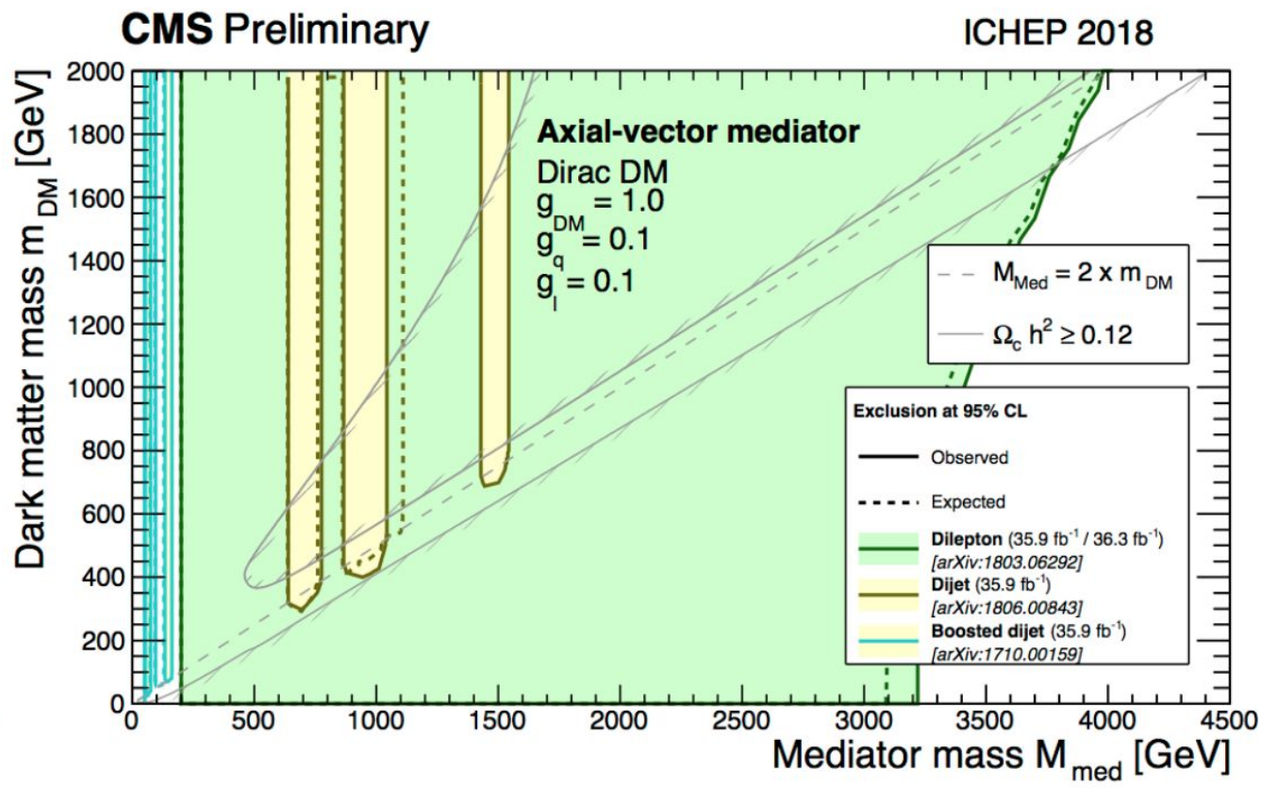
DM Interpretations with Mediator Searches

- Complementary searches for **X+E_T^{miss}** and **mediator searches**
  - Dijet searches cover a broad mediator mass range
  - Results highly depend on choice of coupling parameters

g_q=0.25 g_l=0 g_{DM}=1



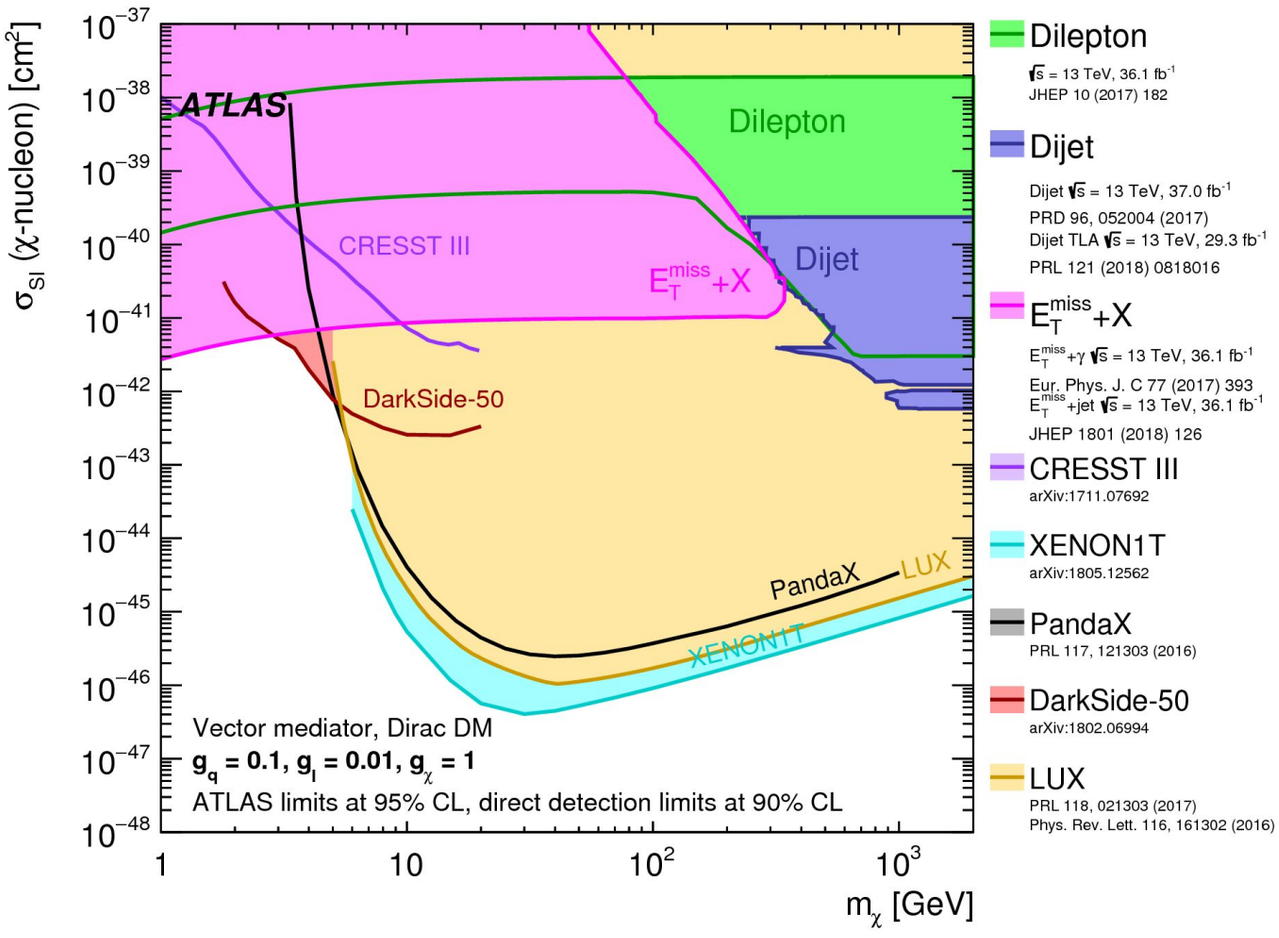
g_q=0.1 g_l=0.1 g_{DM}=1



Comparison to Direct Detections

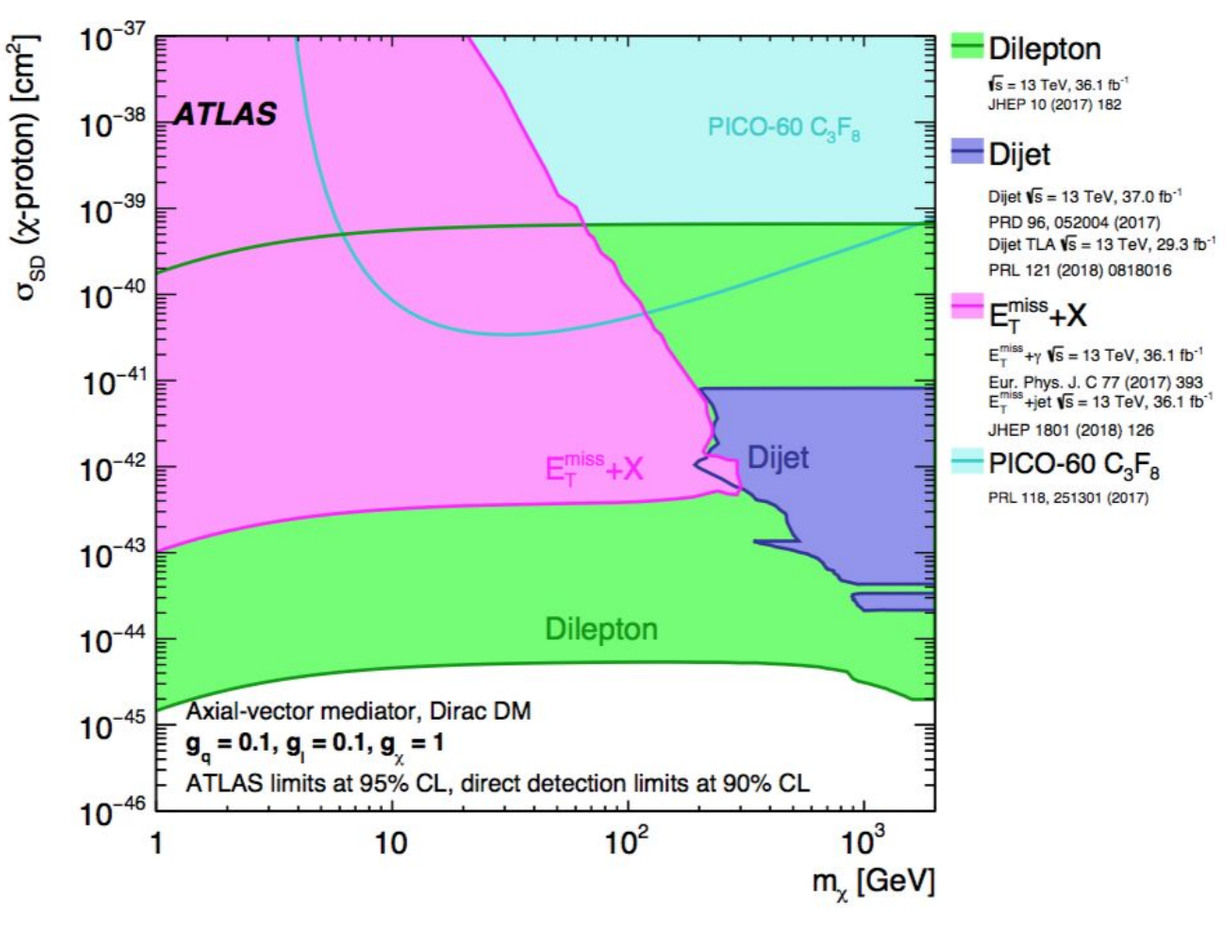
- Complementary searches for **Direct Detections** and **Collider Searches**
  - The results are re-interpreted in terms of DM-nucleon scattering [arXiv:1603.04156].
  - Caveats: comparisons are model dependent.

Vector



Spin Independent

Axial-Vector

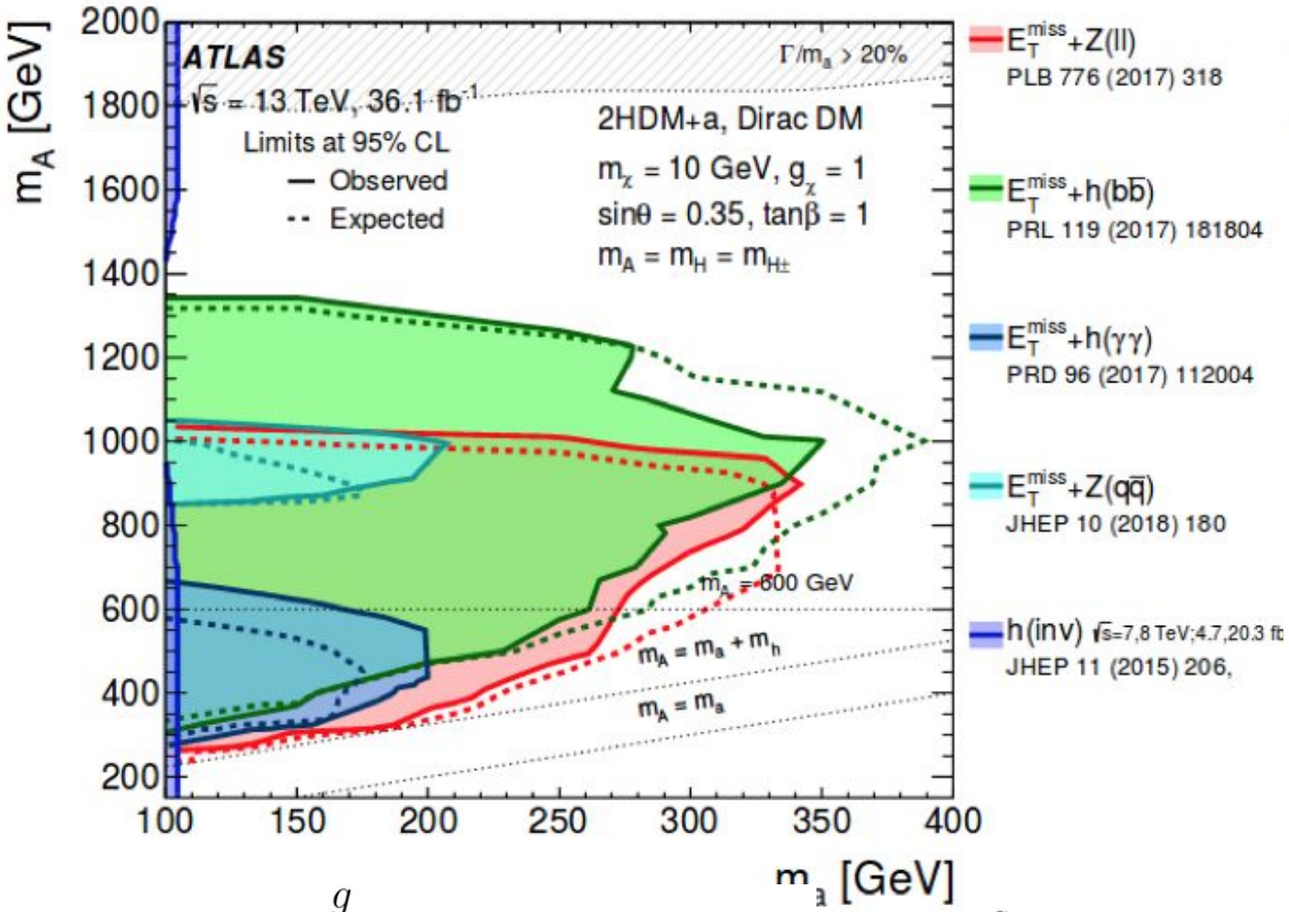


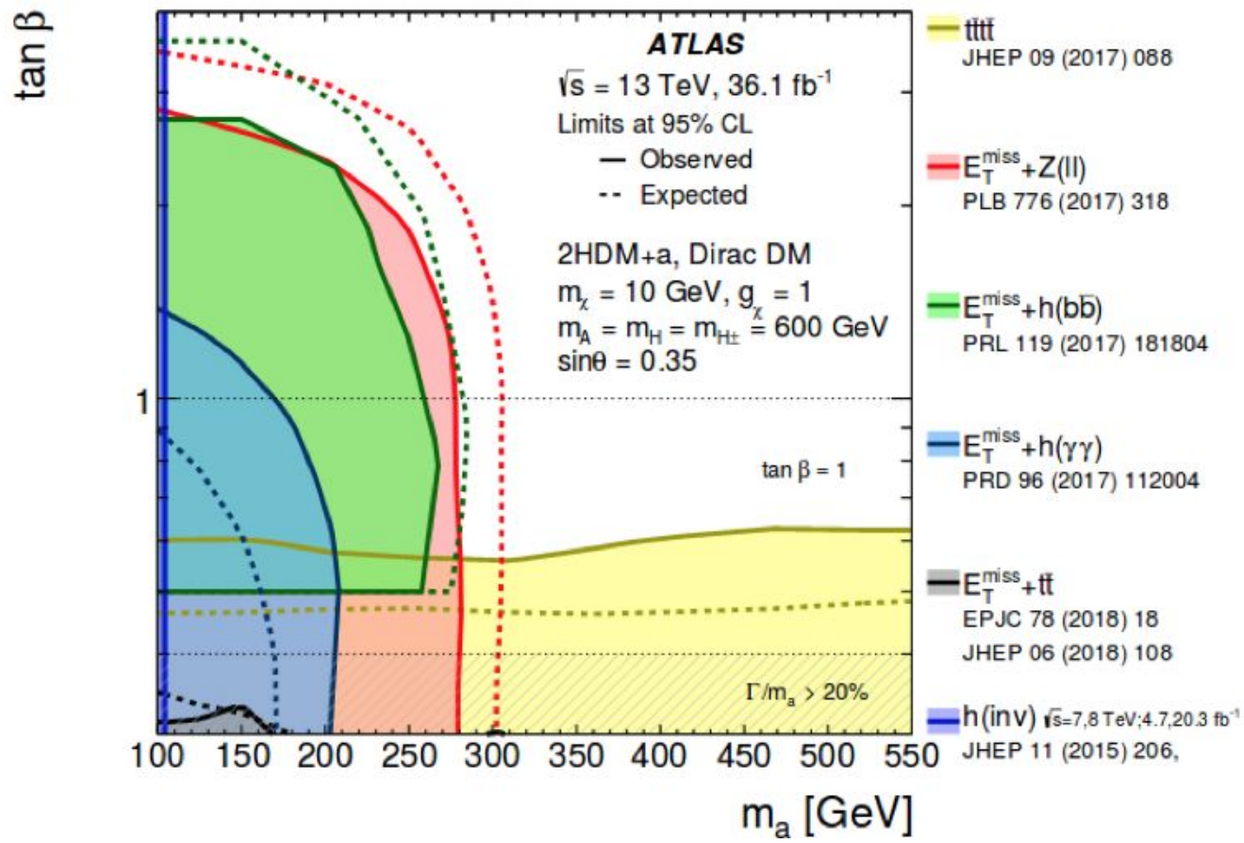
Spin Dependent

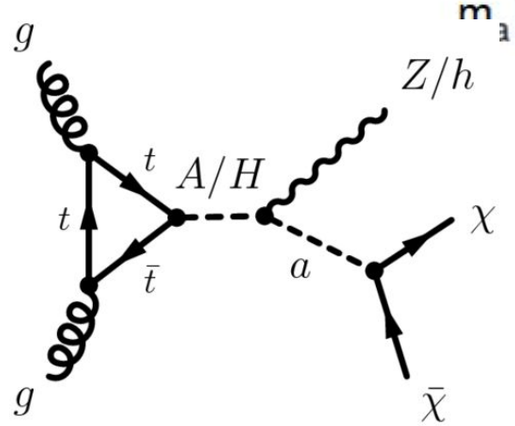
2HDM+a

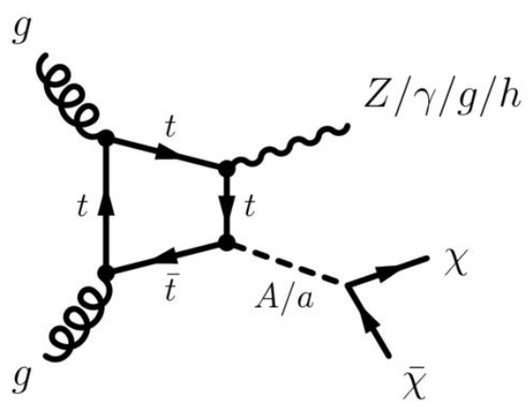
arXiv:1903.01400

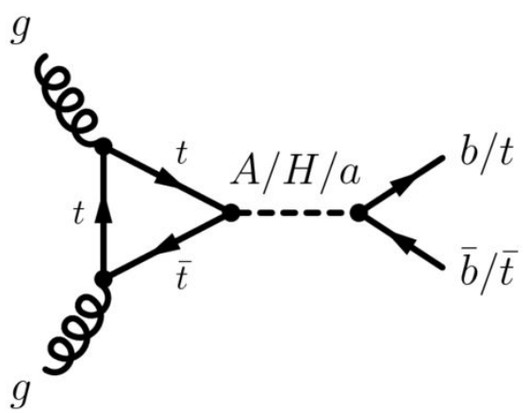
- Rich phenomenology in Two Higgs Doublet Model with additional pseudo-scalar which couples to dark matter:
  - 3 new physical scalars (H, H+, H-), and 2 new pseudo-scalars (a, A)











Summary

- **Broad dark matter search program from ATLAS and CMS presented**
  - No significant discrepancies from SM predictions
  - See more details from parallel talks by William Kalderon (ATLAS), Alison Hall (CMS)

- **Complementarity between mono-X searches, mediator searches, and direct detections**
  - New summary papers are exploiting joint information with less models
  - **Caveats**: results highly depend on choice of coupling parameters

- **Large sets of results still based on 2015/2016 (~36 fb^{-1}) data**
  - Full Run 2 analyses (140 fb^{-1}) are actively on-going.
  - Precision searches!

Backup

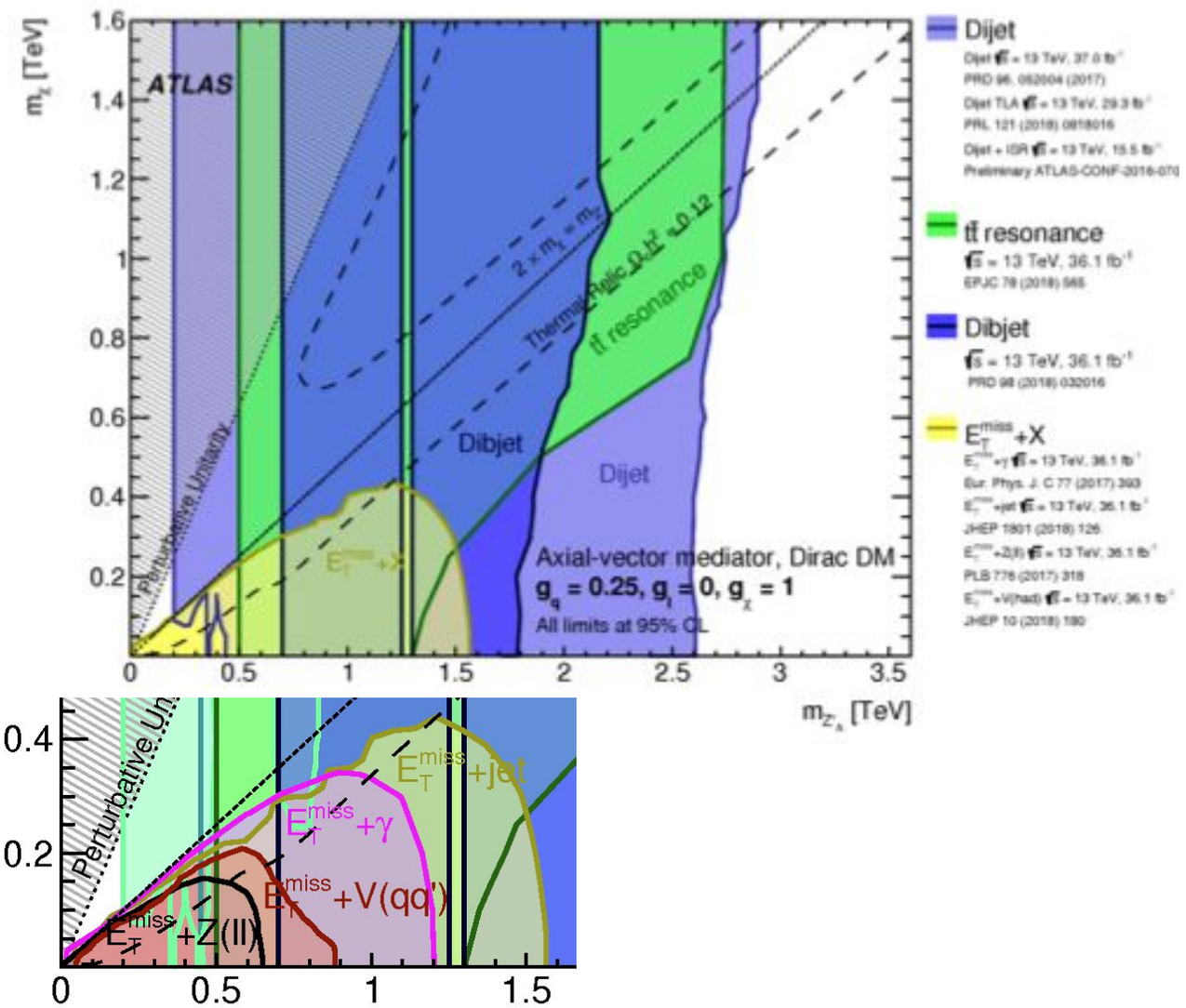
References

	ATLAS	CMS
Mono-jet	JHEP 01 (2018) 126	PRD 97 (2018) 092005
mono-γ	EPJC (2017) 77:393	JHEP 02 (2019) 074
mono-Z(ll)	EPJC 78 (2018) 291	EPJC 78 (2018) 291
mono-V(had)	JHEP 10 (2018) 180	PRD 97 (2018) 092005
mono-h(bb)	ATLAS-CONF-2018-039	EPJC 79 (2019) 280
mono-h($\gamma\gamma$)	PRD 96 (2017) 112004	JHEP 09 (2018) 046
mono-h($\tau\tau$)	-	JHEP 09 (2018) 046
mono-h(WW,ZZ)	-	CMS PAS EXO-18-011 (new)
Mono-top	1812.09743	JHEP 03 (2019) 141
tt+MET	EPJC 78 (2018) 18	JHEP 03 (2019) 141
mono-Bottom	EPJC 78 (2018) 18	-
b+MET	EPJC 78 (2018) 18	-
Higgs Invisibl	**arXiv:1904.05105**	arXiv:1809.05937

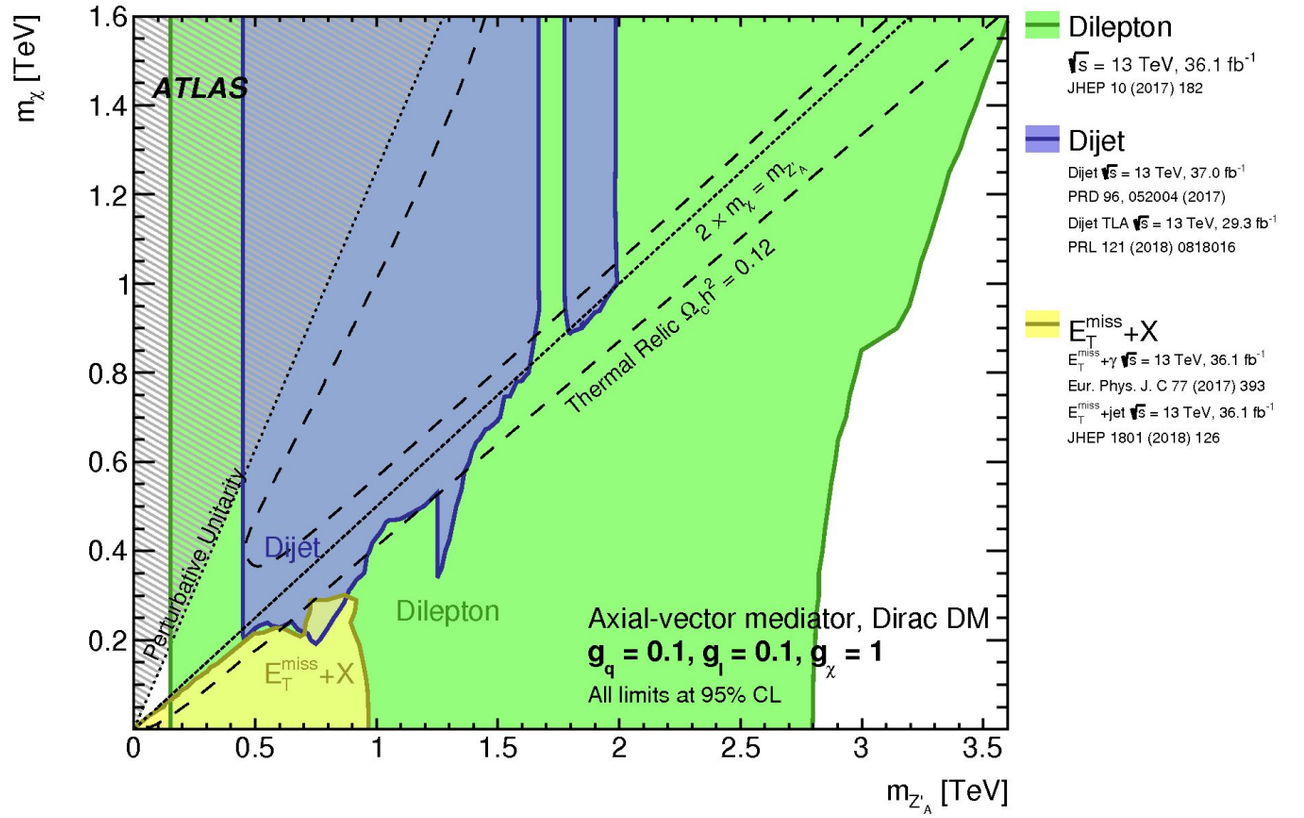
DM Interpretation with mediator searches

- Complementary searches by **mono-X** and **mediator searches**
  - Dijet searches cover a broad mediator mass range
  - Results highly depend on choice of coupling parameters

g_q=0.25 g_l=0 g_{DM}=1



g_q=0.1 g_l=0.1 g_{DM}=1

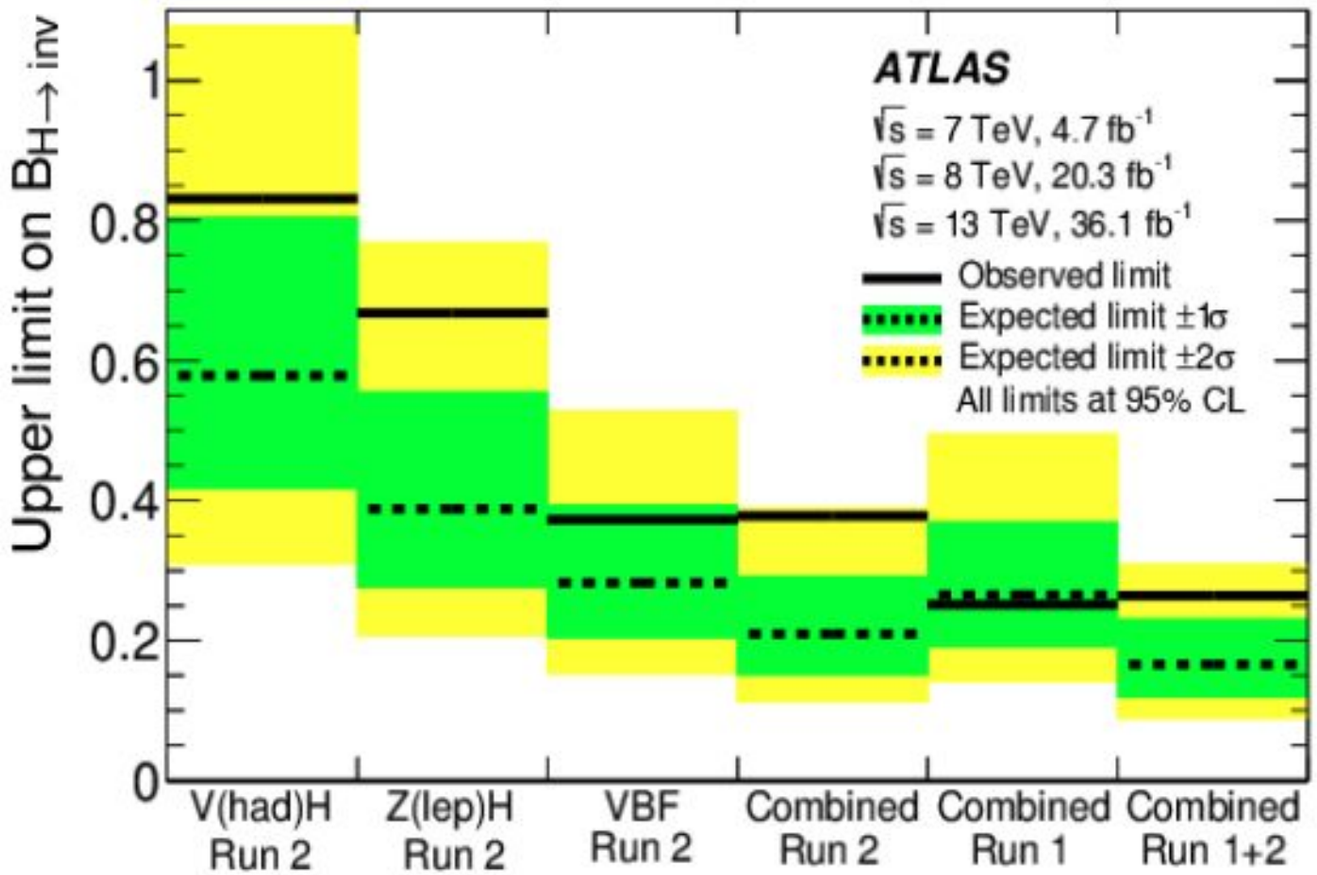


arXiv:1903.01400

ATLAS Higgs Invisible

BR(H inv) < 26% → (17 % expected)

Constraints weaker than Run 1 due to excesses in every Run 2 channel.



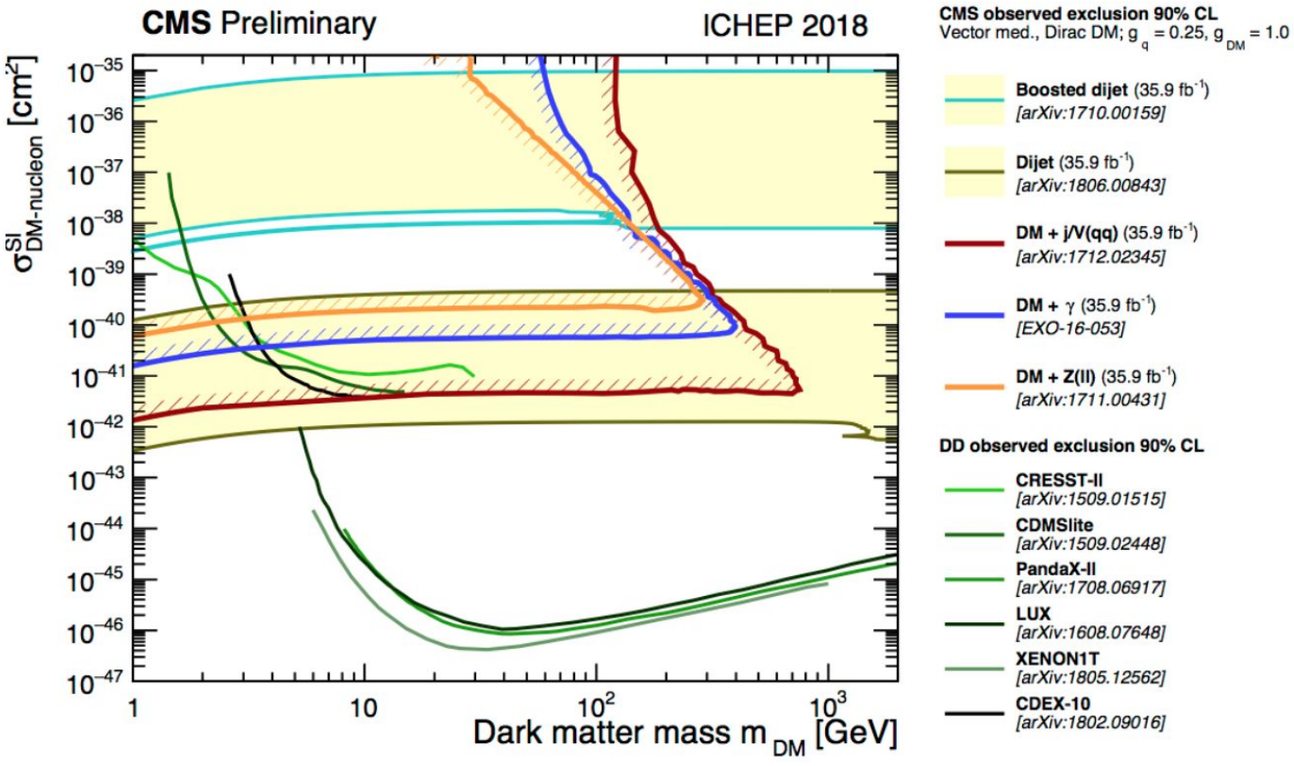
CMS Higgs Invisible Interpretations

The results are re-interpreted in terms of DM- nucleon scattering [arXiv:1603.04156].

Good complementarity between • LHC and direct detection experiments

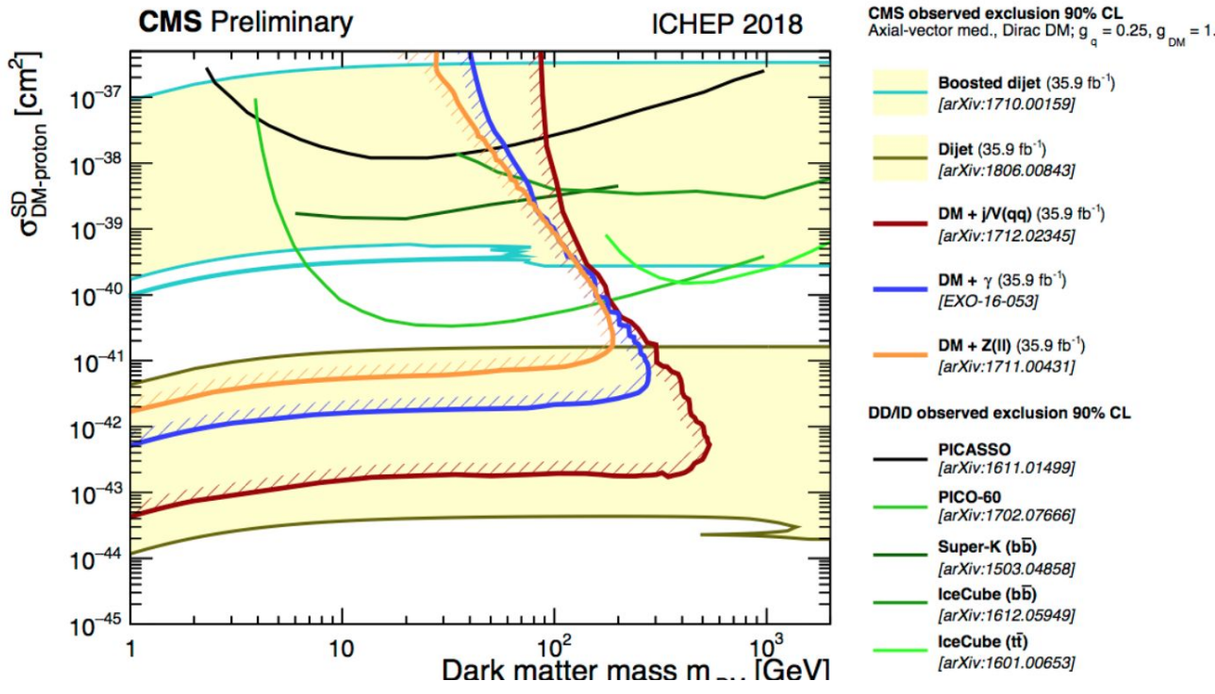
Vector

$g_{SM} = 0.25, g_l = 0, g_{DM} = 1$



Axial-Vector

$g_{SM} = 0.1, g_l = 0.1, g_{DM} = 1$



Spin Independent

Spin Dependent

2HDM+a Phenomenology

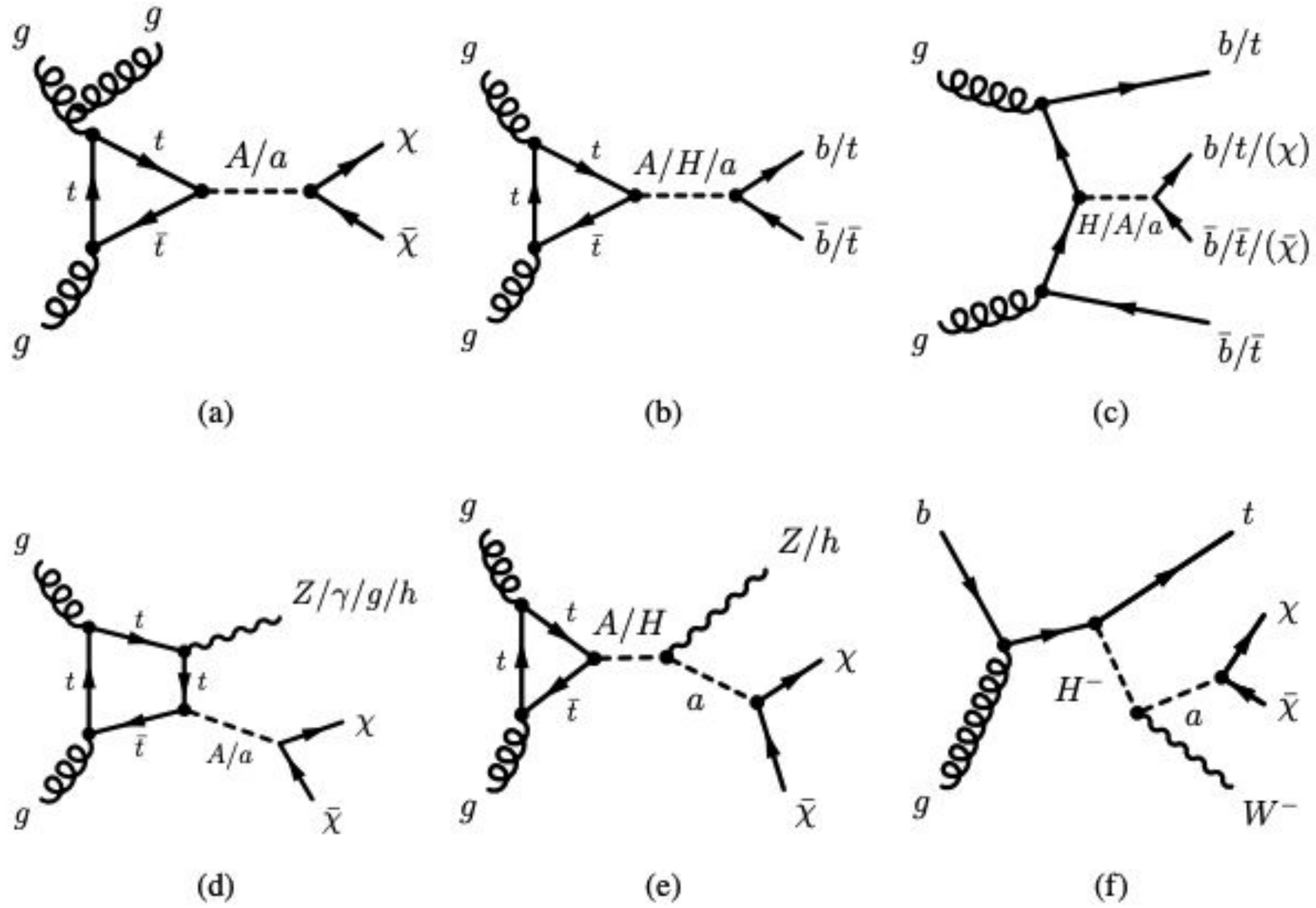


Figure 6: Schematic representation of the dominant production and decay modes for the 2HDM+a model.