Overview of Dark Matter Searches by the ATLAS Experiment

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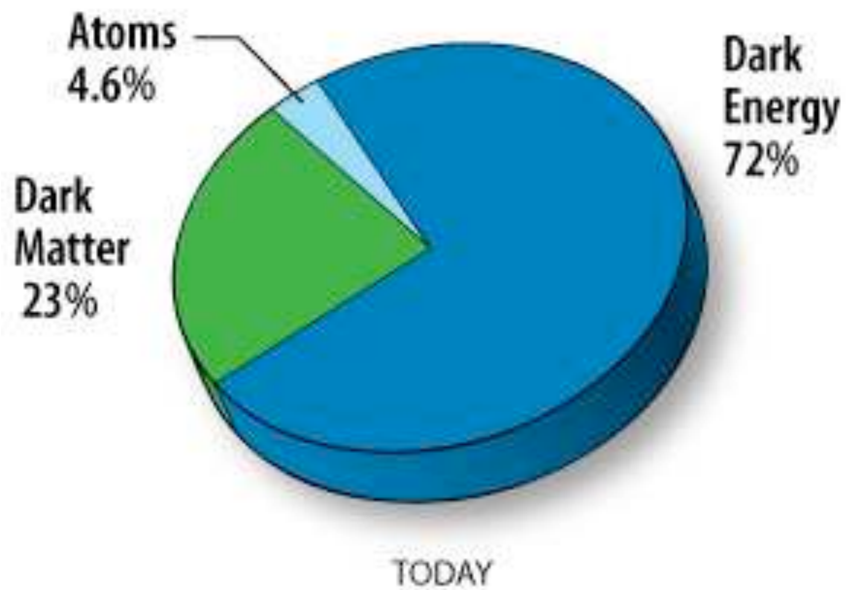
Canadian Association of Physicists Congress, June 4, 2019

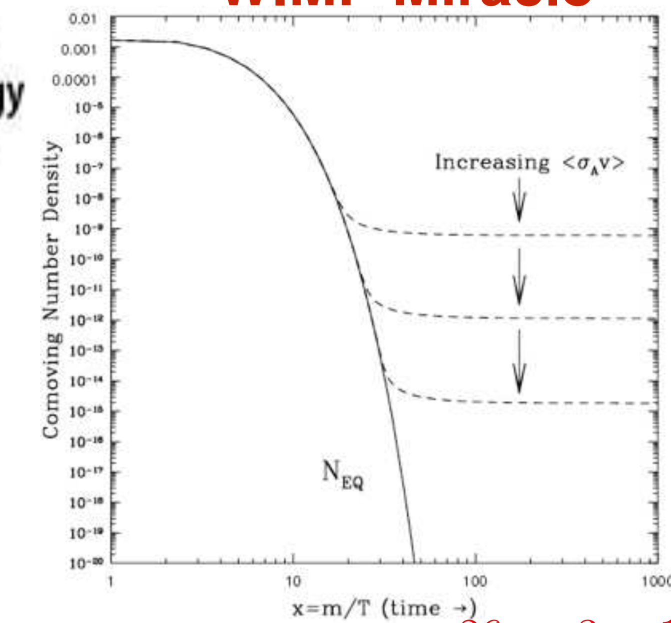
Evidence for Dark Matter

Abundance of astrophysical evidence for the existence of non-baryonic, dark matter (DM):

Galaxy Rotation Curves

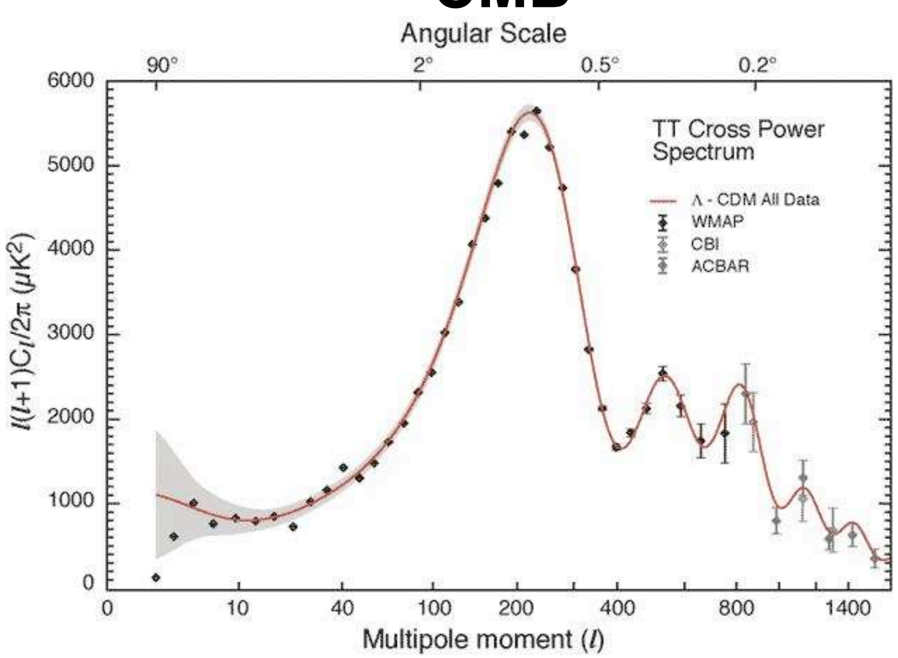


WIMP Miracle

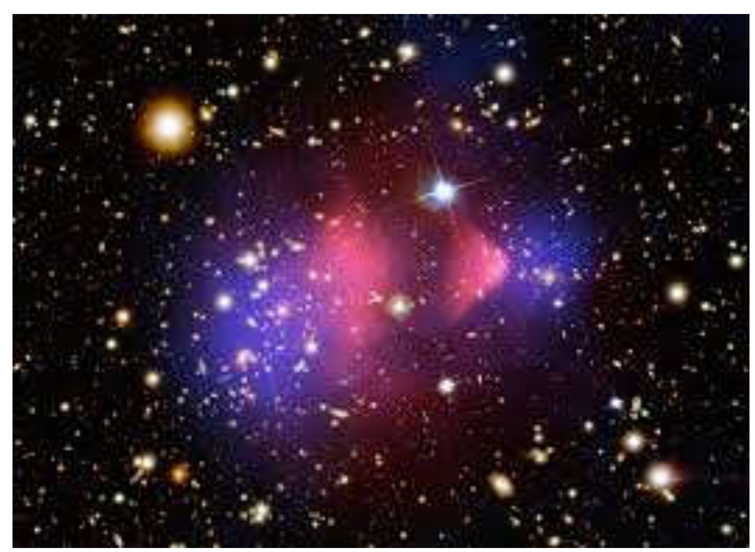


$$< \sigma v > \simeq 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

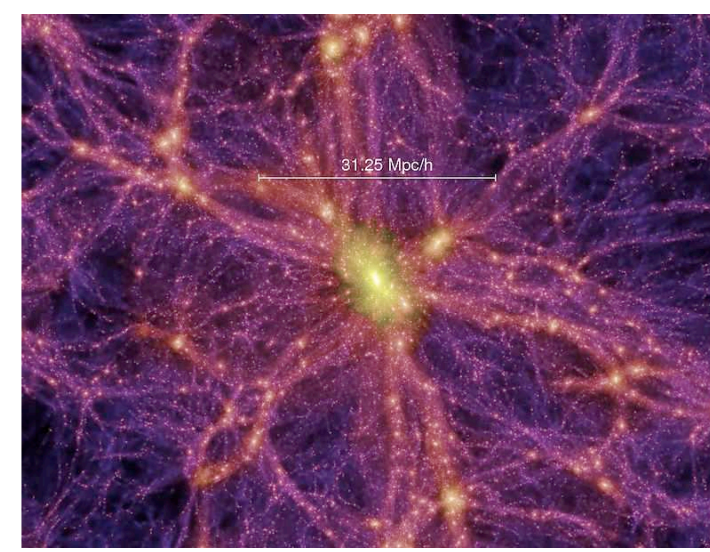
CMB



Gravitational Lensing

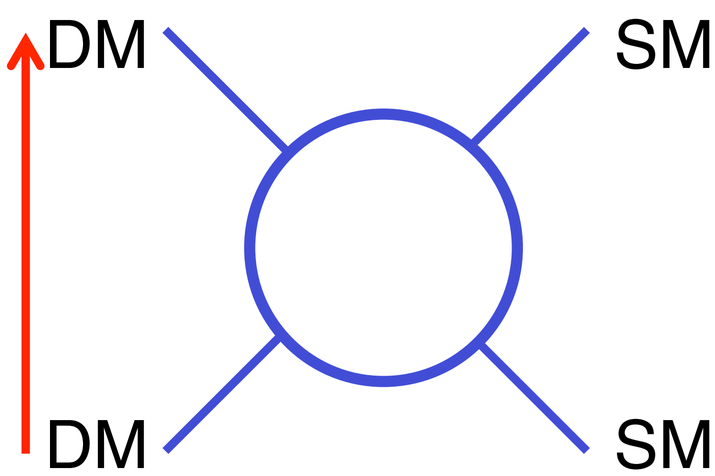


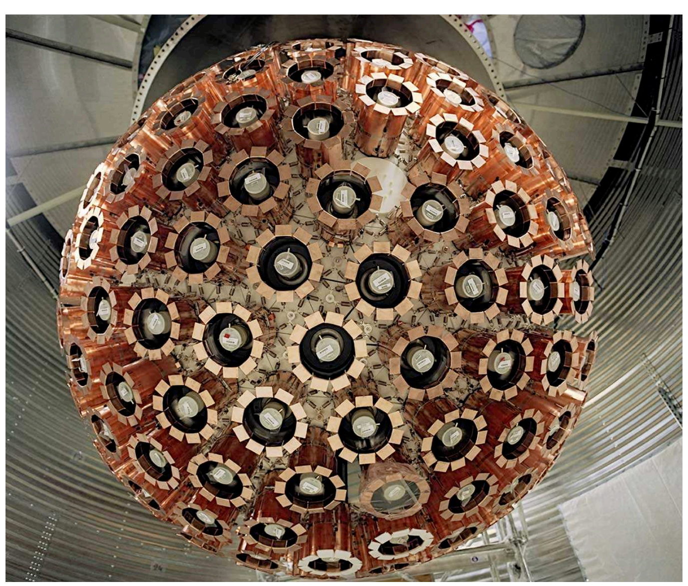
Structure Formation



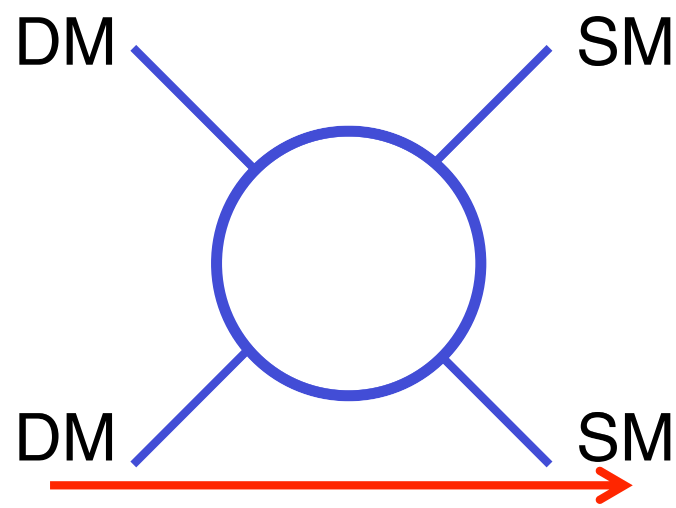
Detection Methods

Direct Detection

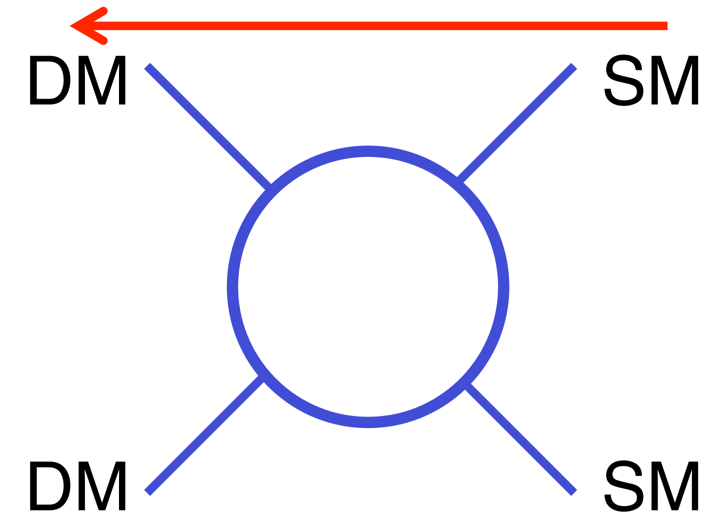


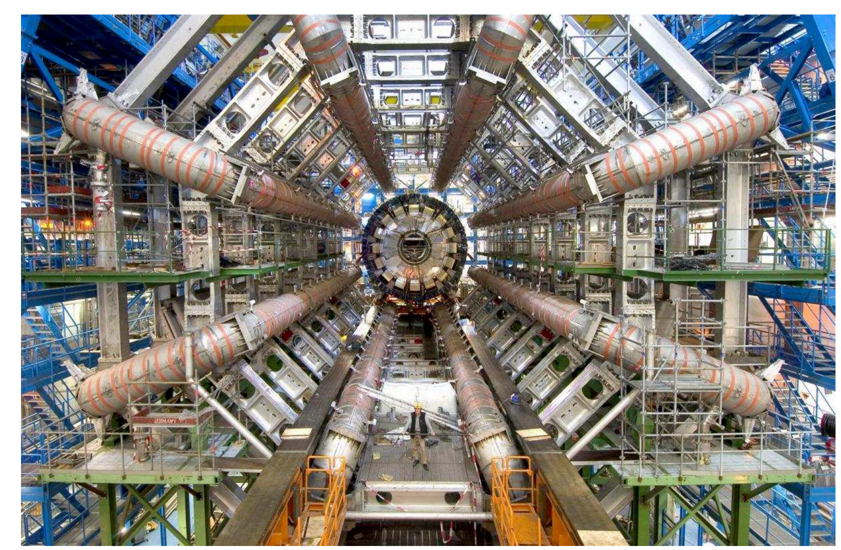


Indirect Detection

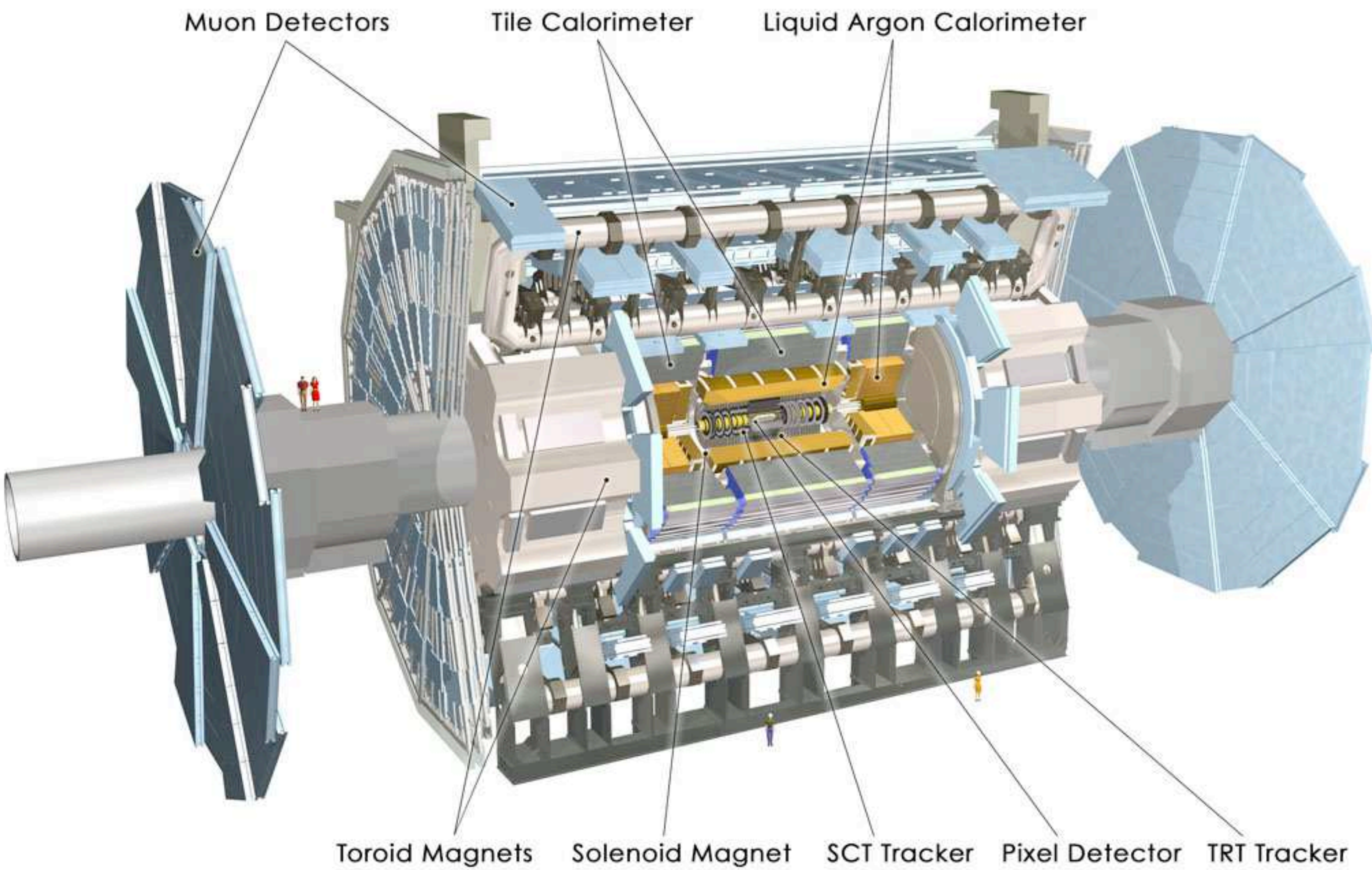


Collider Production





ATLAS Experiment



Over 20 DM Searches at ATLAS!

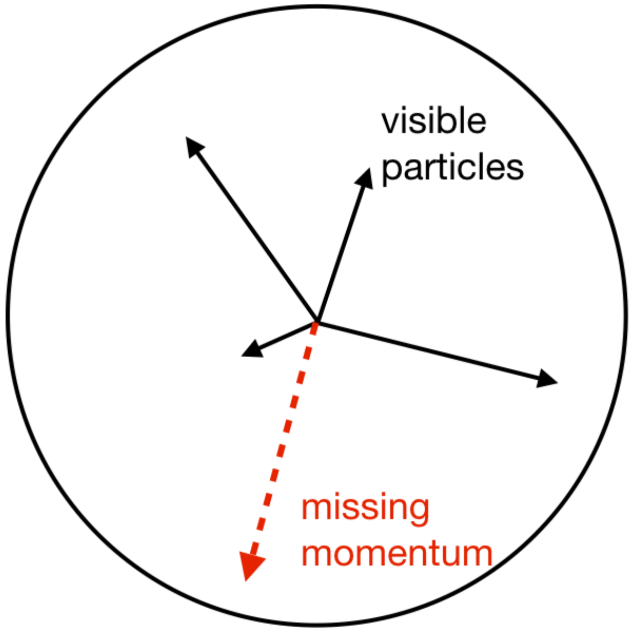
- **13 TeV** Proton-Proton collisions collected by the ATLAS detector during 2015-2016 of LHC Run-2.
- Collected events correspond to an integrated luminosity of **37 fb**$^{-1}$.

Mono-X Searches

Infer DM from the presence of missing transverse momentum (**E_T^{miss}**) in the detector:

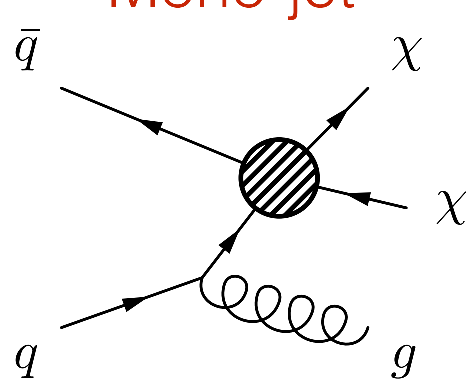
E_T^{miss} $= -\Sigma \overrightarrow{p_T}$ All Reconstructed Objects

Neutrinos produce **E_T^{miss}** , and are one of the main background sources.

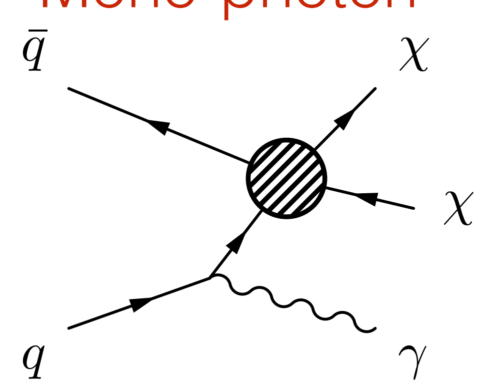


P_T imbalance requires the DM production to be recoiled against a visible particle, X. Where X can be a quark, gluon, a photon, a heavy gauge boson, or a Higgs. These are the so called Mono-X searches.

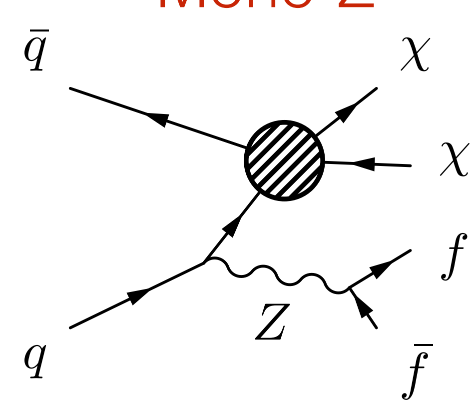
Mono-jet



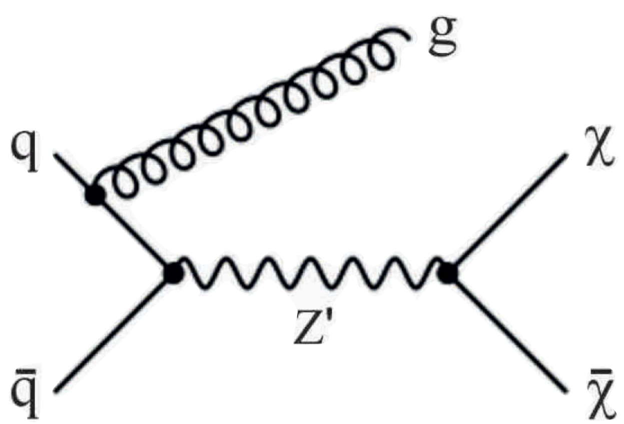
Mono-photon



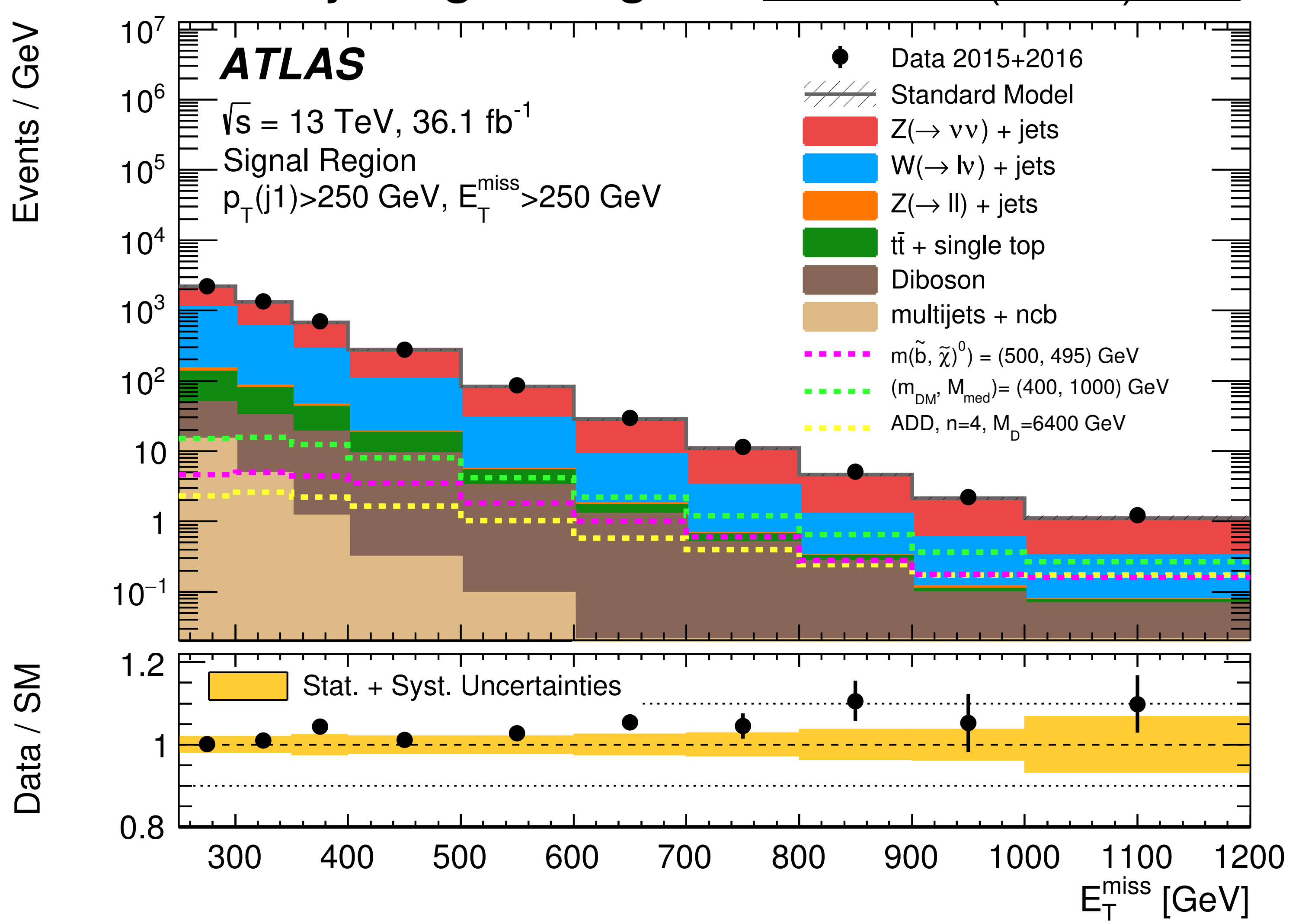
Mono-Z



Analysis Strategy



Mono-jet Signal Region JHEP-01 (2018) 126



Analysis Overview

- Estimate signal through Monte Carlo simulation. (including detector response)
- Estimate Background through Monte Carlo and Data Driven Methods
- Optimize Selection Cuts for maximal Signal over Background
- Bin Events by Discriminating Variable
- Calculate Systematic Uncertainties
- Unblind Data
- Binned Likelihoods used for Discovery Significance and Exclusion Limits (95% CL)

Evolution of DM Models

Effective Field Theories

Basic model, different operators can be placed in the Effective Lagrangian

EFTs have an associated energy scale, model is only valid if reaction energy is well below

Simplified Models

Introduce spin-0 or spin-1 mediators

Describes DM production kinematics with a minimal number of free parameters

Not a complete theory

More Complete Models

I.e. Super Symmetry or Extended Higgs Sector

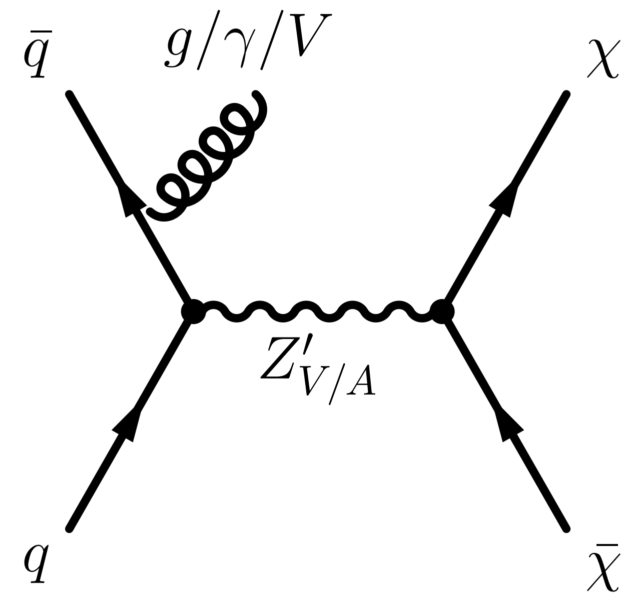
UV Complete, Renormalizable

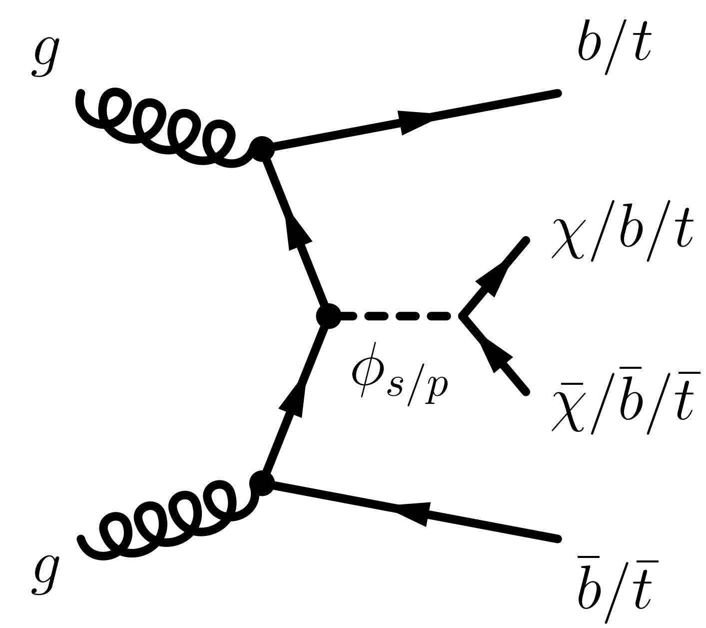
Larger number of free parameters leading to richer phenomenology

Simplified Models

s-channel mediators:

- **Vector** } Spin-1
- **Axial-vector**
- **Scalar** } Spin-0
- **Pseudoscalar**





DM simplified models have 5 free parameters:

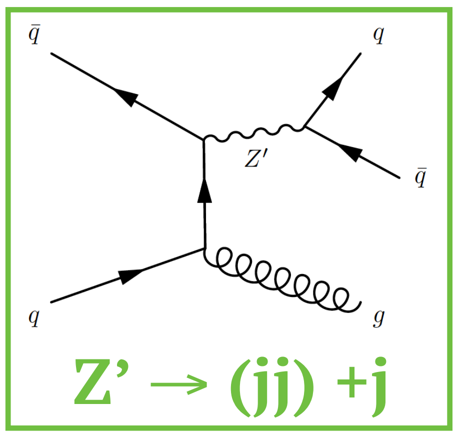
- $\mathbf{g_q}$ - mediator coupling to quarks
- $\mathbf{g_\ell}$ - mediator coupling to leptons
- $\mathbf{g_\chi}$ - mediator coupling to DM
- $\mathbf{M_\chi}$ - DM mass
- $\mathbf{M_{med}}$ - Mediator mass

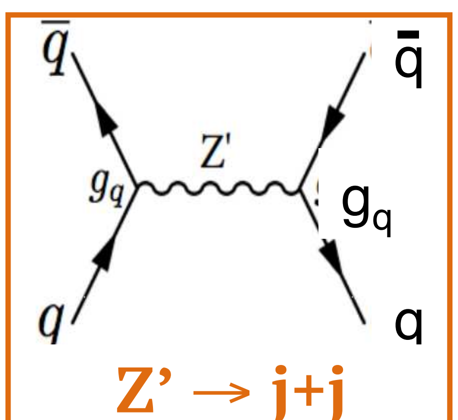
Mediator width, $\mathbf{\Gamma_{med}}$, is set set to minimal width formula.

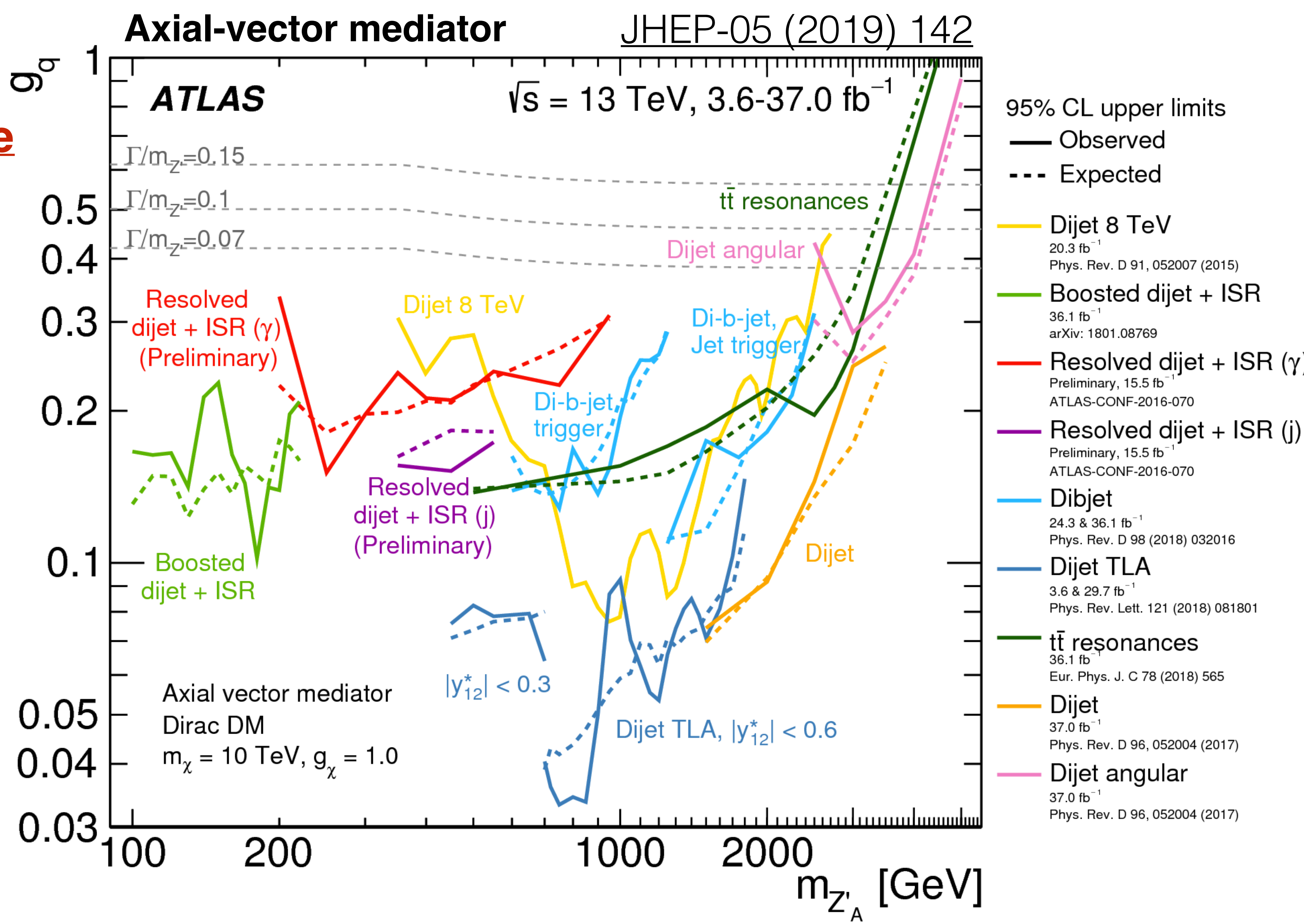
Resonance Searches

Since the mediators couple to quarks, they can also decay to dijet final states.

LHC is a Mediator Machine



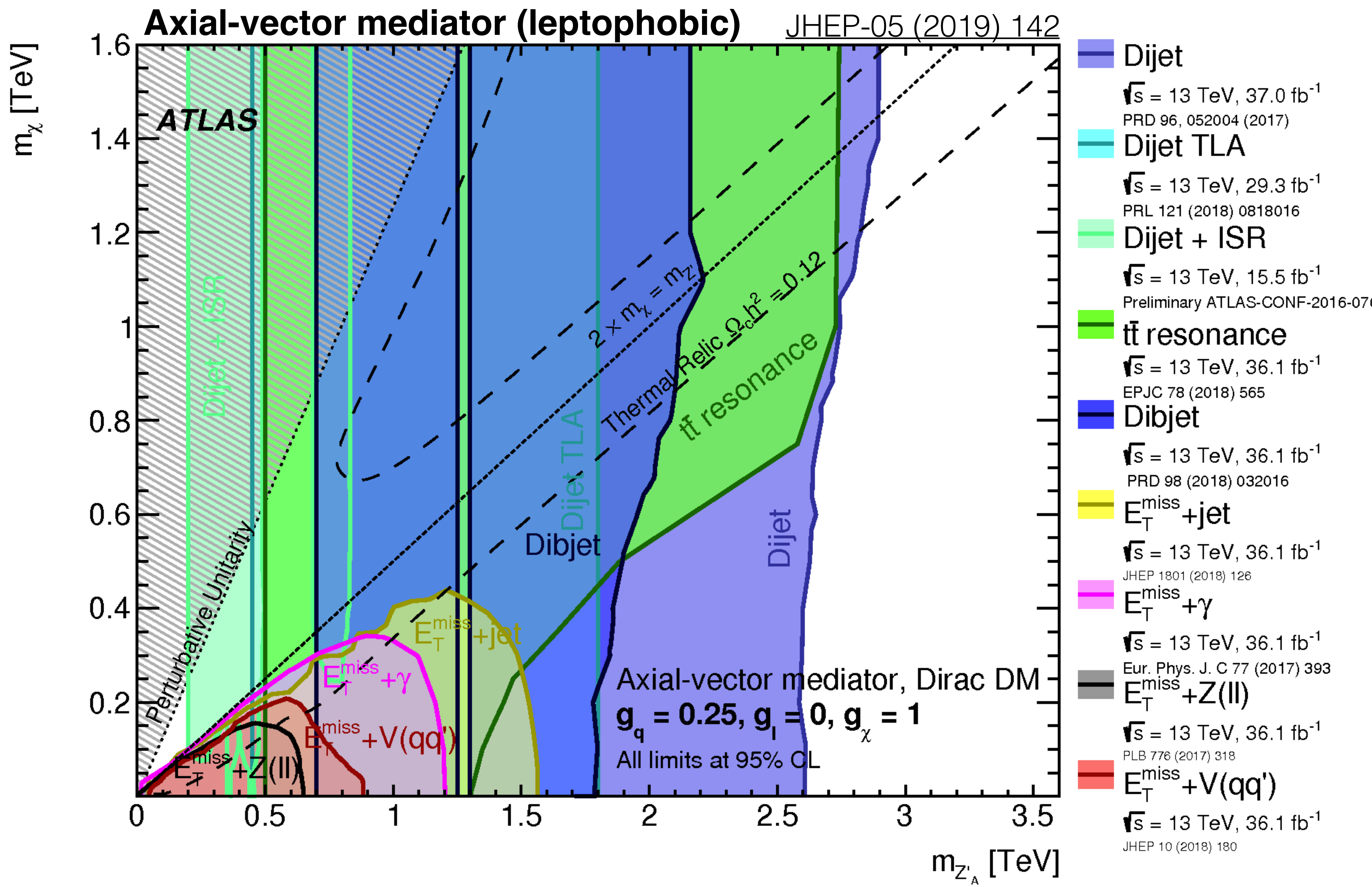




Vector and Axial-Vector Mediators

Compare sensitivity of the different **Mono-X** signatures. (Mono-Jet dominates)

- Results shown as 2D exclusion plots in **M_{med} : M_{χ}**



Vector and Axial-Vector Mediators

Following recommendations of LHC DM Working Group, ATLAS and CMS use two sets of coupling values:

- **Leptophobic** couplings for the AV/V models, **(g_q=0.25 , g_ℓ=0 , g_χ=1)**.
- **Leptophilic** couplings for Axial-vector **(g_q=0.1 , g_ℓ=0.1 , g_χ=1),** and Vector **(g_q=0.1 , g_ℓ=0.01 , g_χ=1)** models.

- Acceptance and kinematics are largely independent of the coupling values and mediator type (AV/V), it is the cross sections that are affected.

Vector model (leptophobic)

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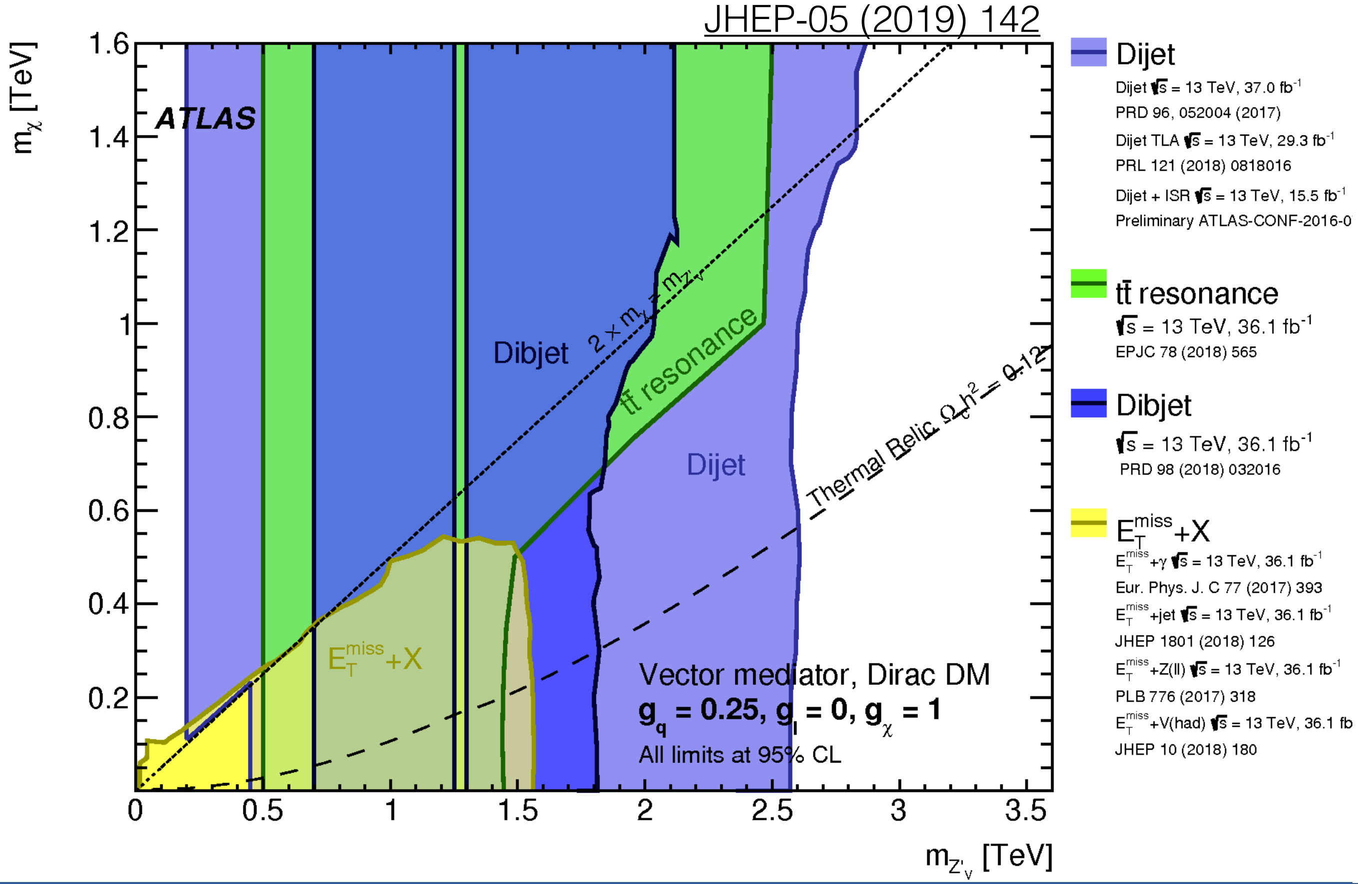

Vector model (leptophilic)

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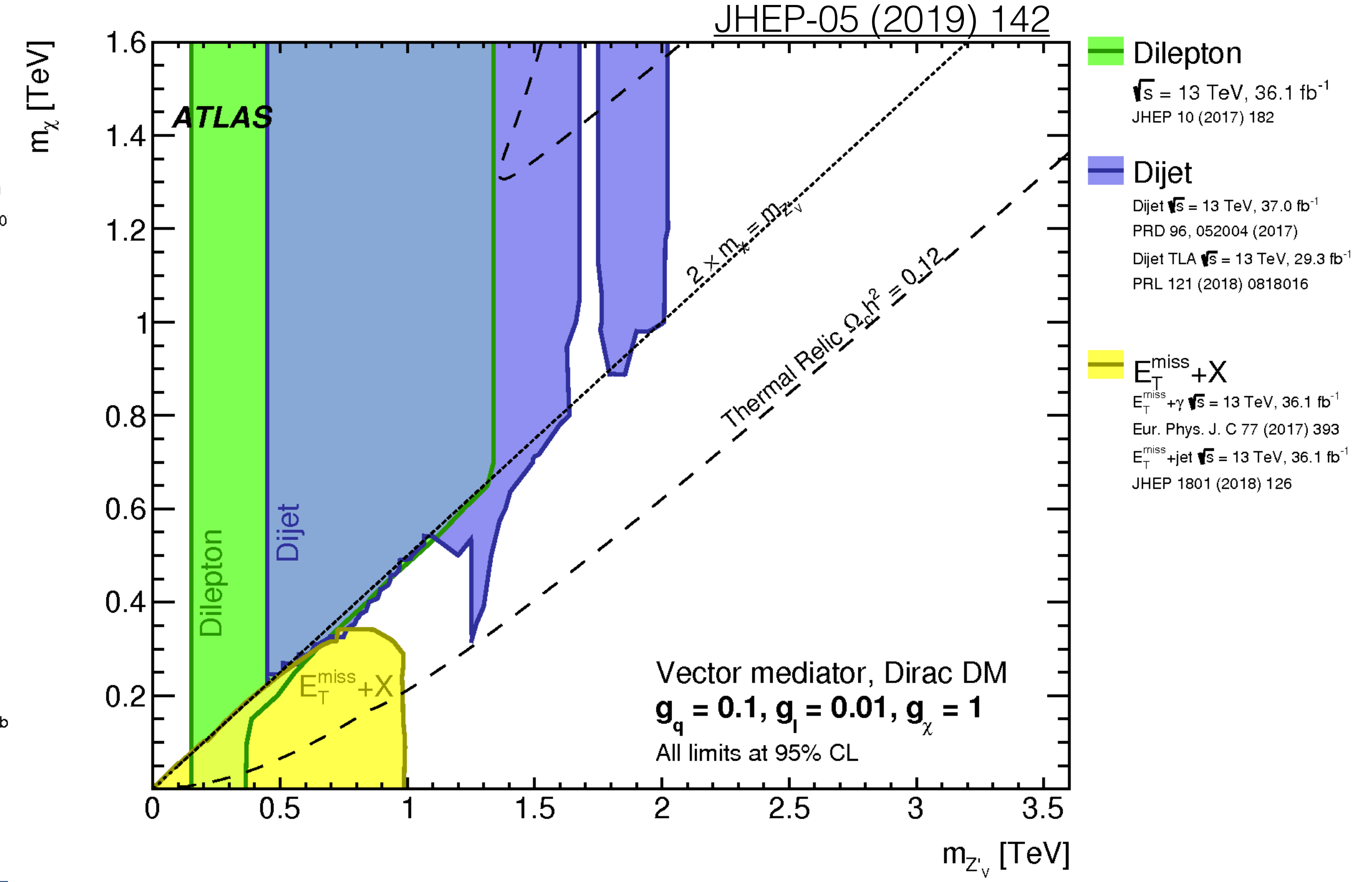
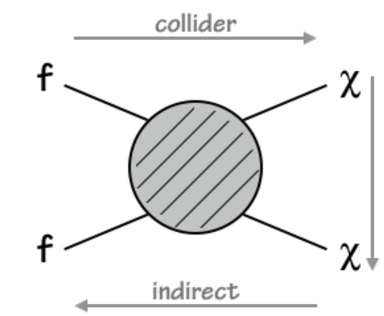


Comparison to Direct Detection

Simplified models allow for comparison between direct detection and collider experiments.

Collider limits are coupling dependent.



$$\sigma^0_{\mathrm{SI}} \approx 1.1 \times 10^{-39}\ \mathrm{cm}^2 \cdot \left(\frac{g_{\mathrm{DM}}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

$$\sigma^0_{\mathrm{SD}} \approx 4.6 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_{\mathrm{DM}}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

Vector model (leptophobic)

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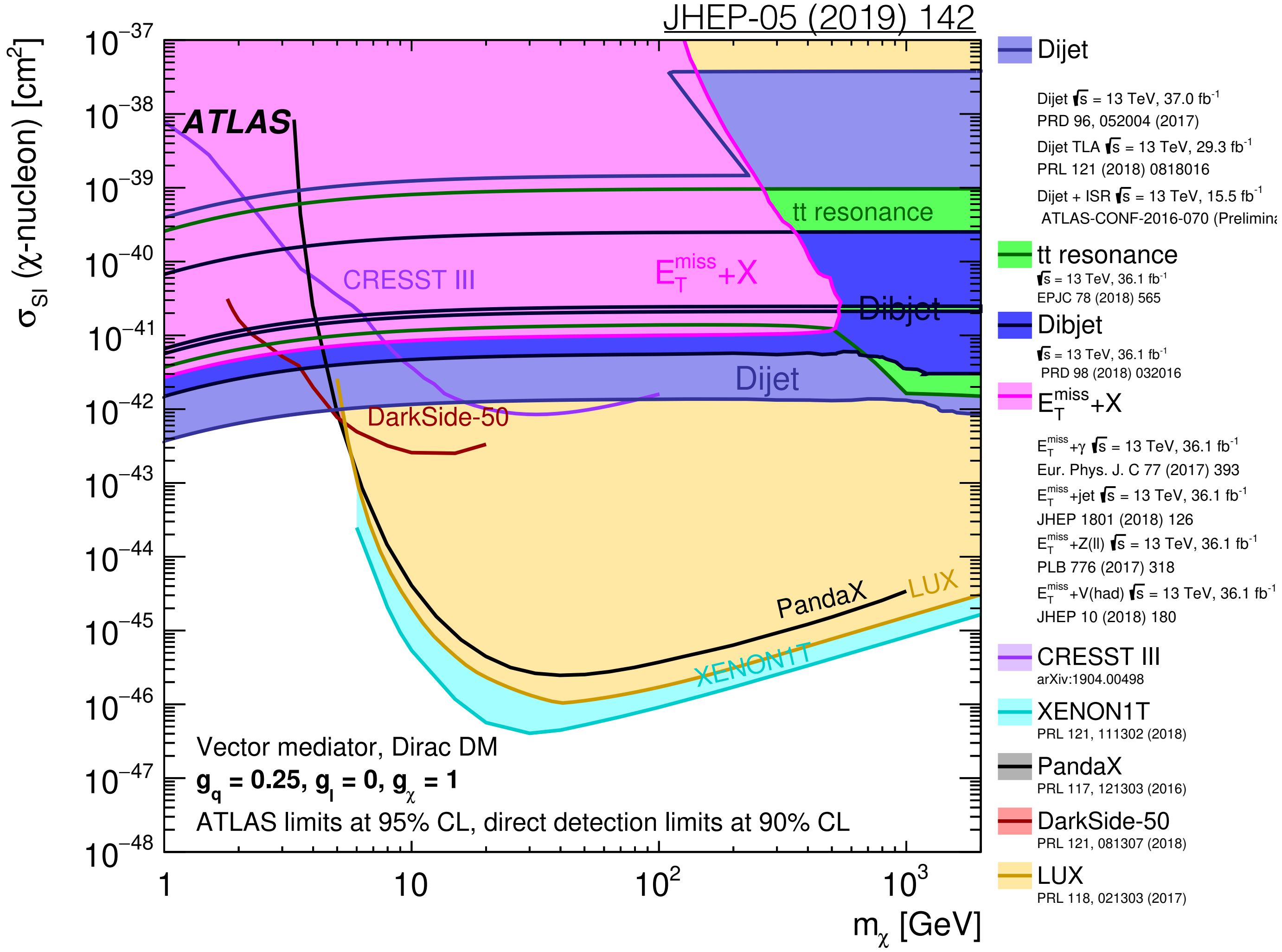

Axial-vector model (leptophilic)

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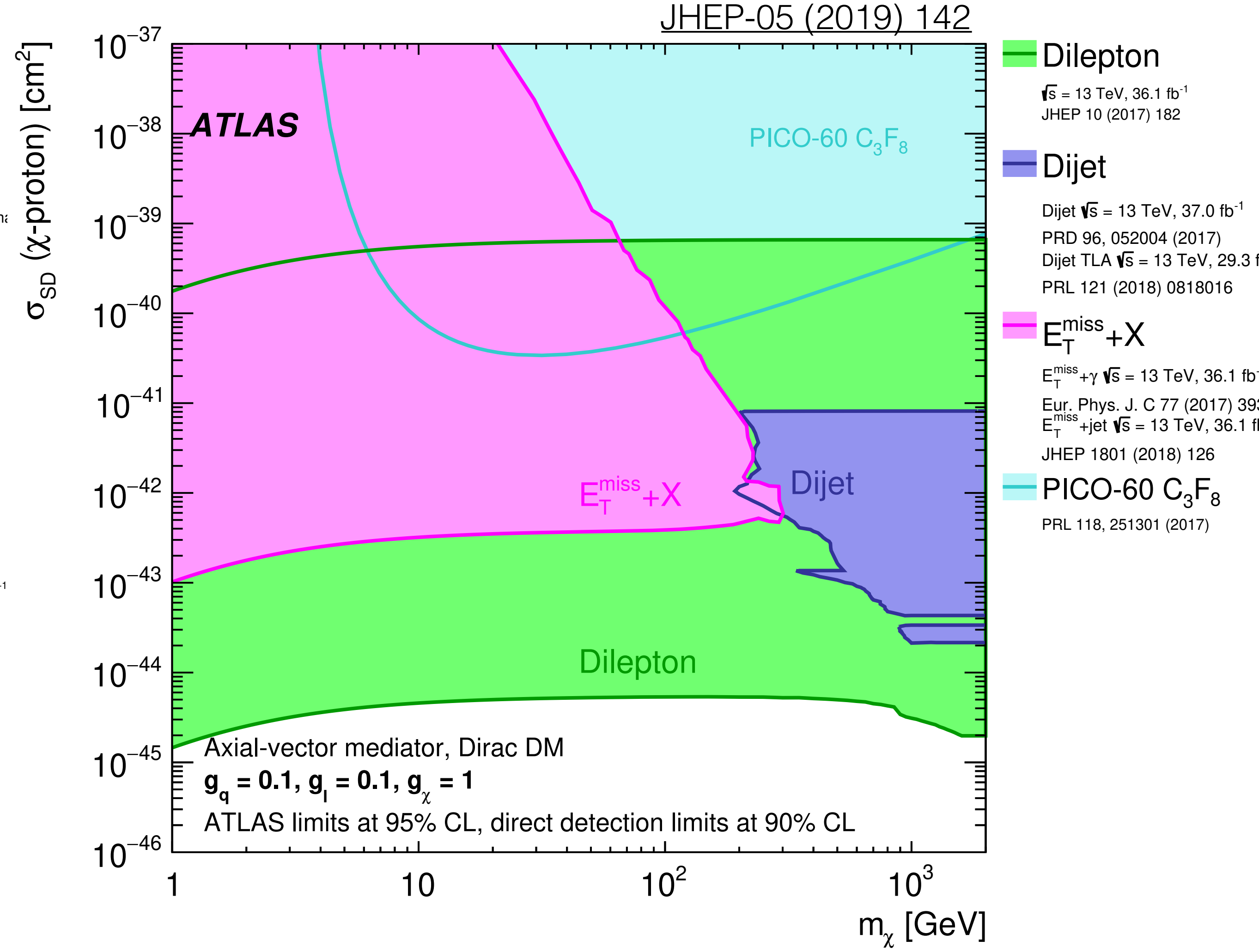


ATLAS limits are at 95% CL while detector limits are at 90% CL

Extended Higgs Sector (2HDM+a)

Extended Higgs Sector

Type-II Two Higgs Doublet Model (2HDM): Bosons (A, H, $H^{\pm}$, h)

Work in alignment limit, $\cos(\beta - \alpha) = 0$. Light scalar, h, associated with SM Higgs.

Free Parameters

M_A=M_H=$M_{H\pm}$: mass of heavy pseudoscalar A, heavy scalar H, and charged scalar, $H^{\pm}$.

M_a: mass of pseudoscalar mediator

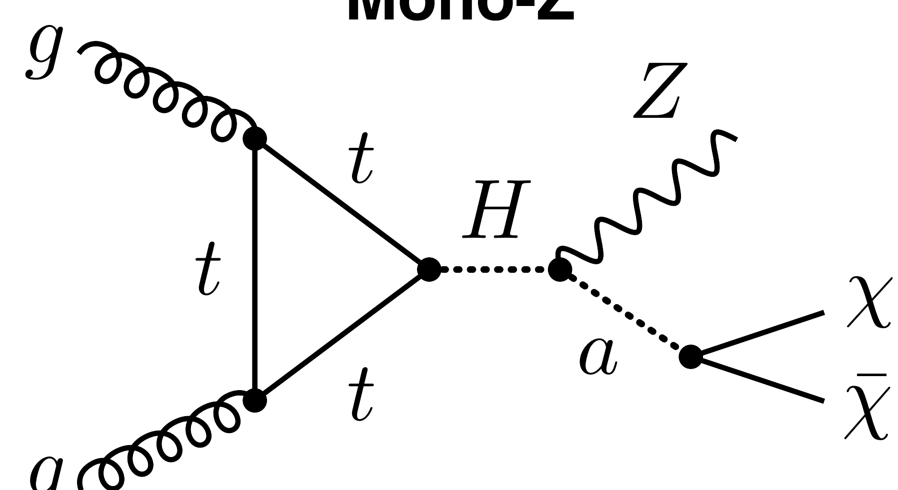
sinθ: mixing angle between a and A, both couple to DM.

tanβ: ratio of VEVs of Higgs doublets

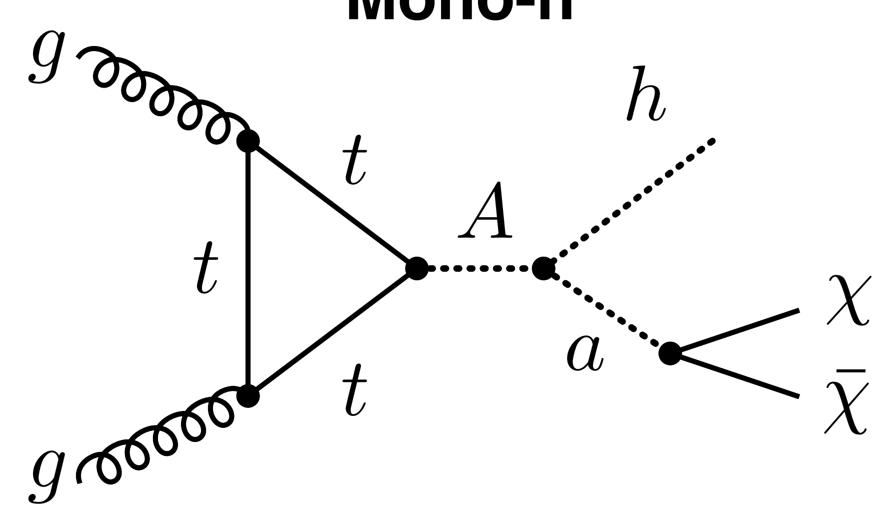
M_χ: DM mass

- Both **a** and **A** couple to DM
- Resonant enhancement of h/Z + E_T^{miss} signatures

Mono-Z



Mono-h



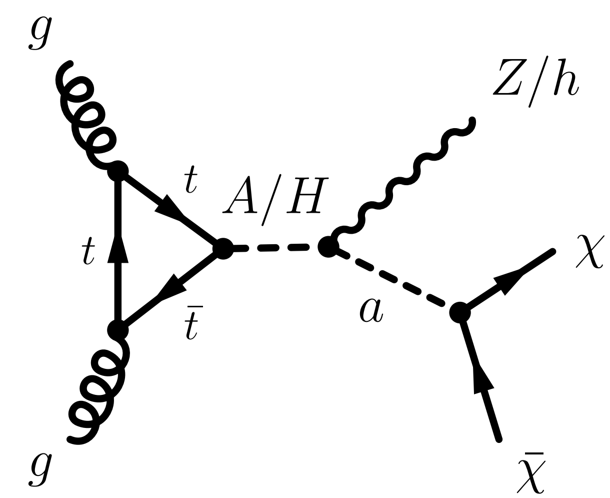
Model Description: arXiv.1701.07427

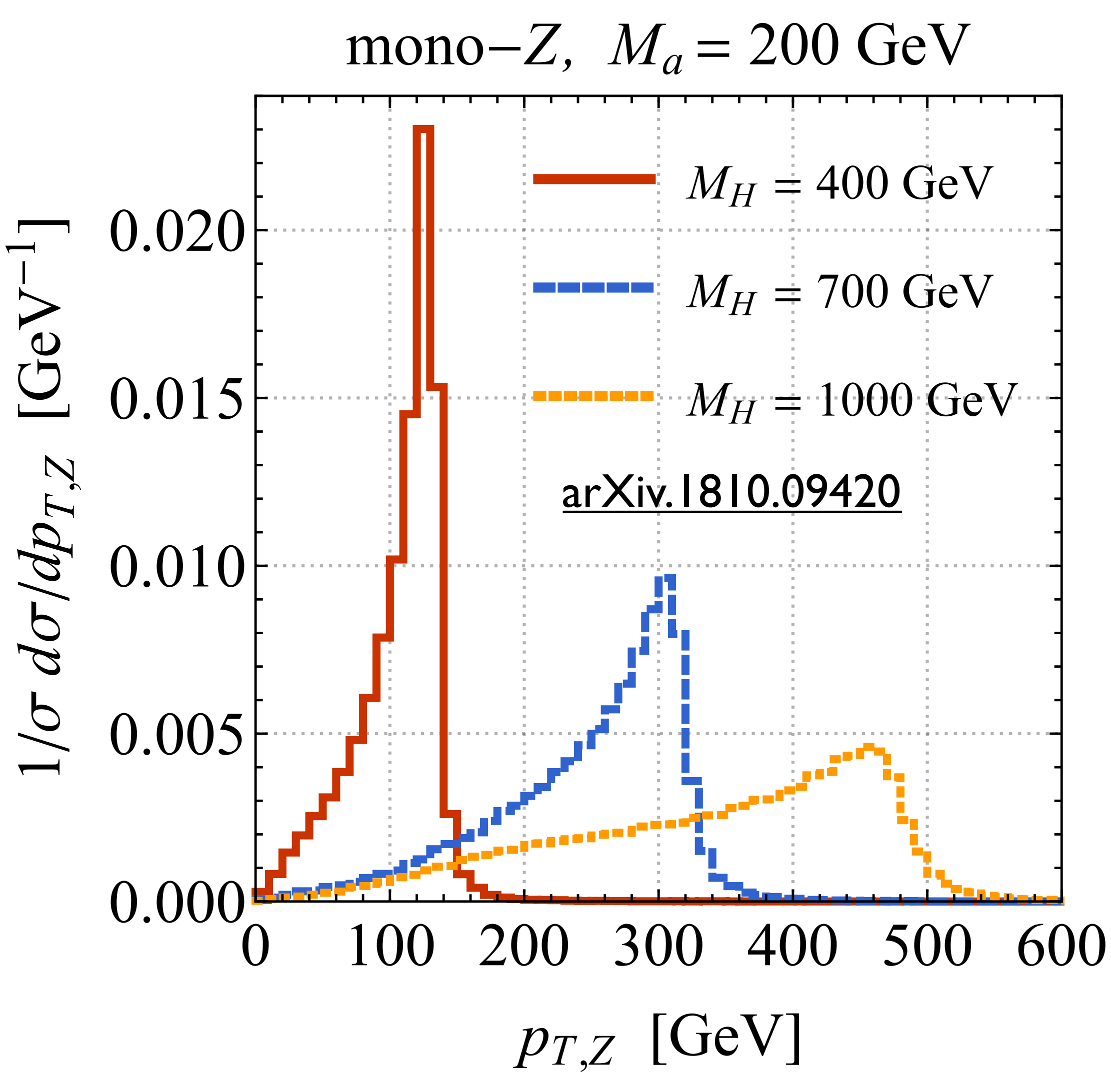
2HDM+a Kinematics

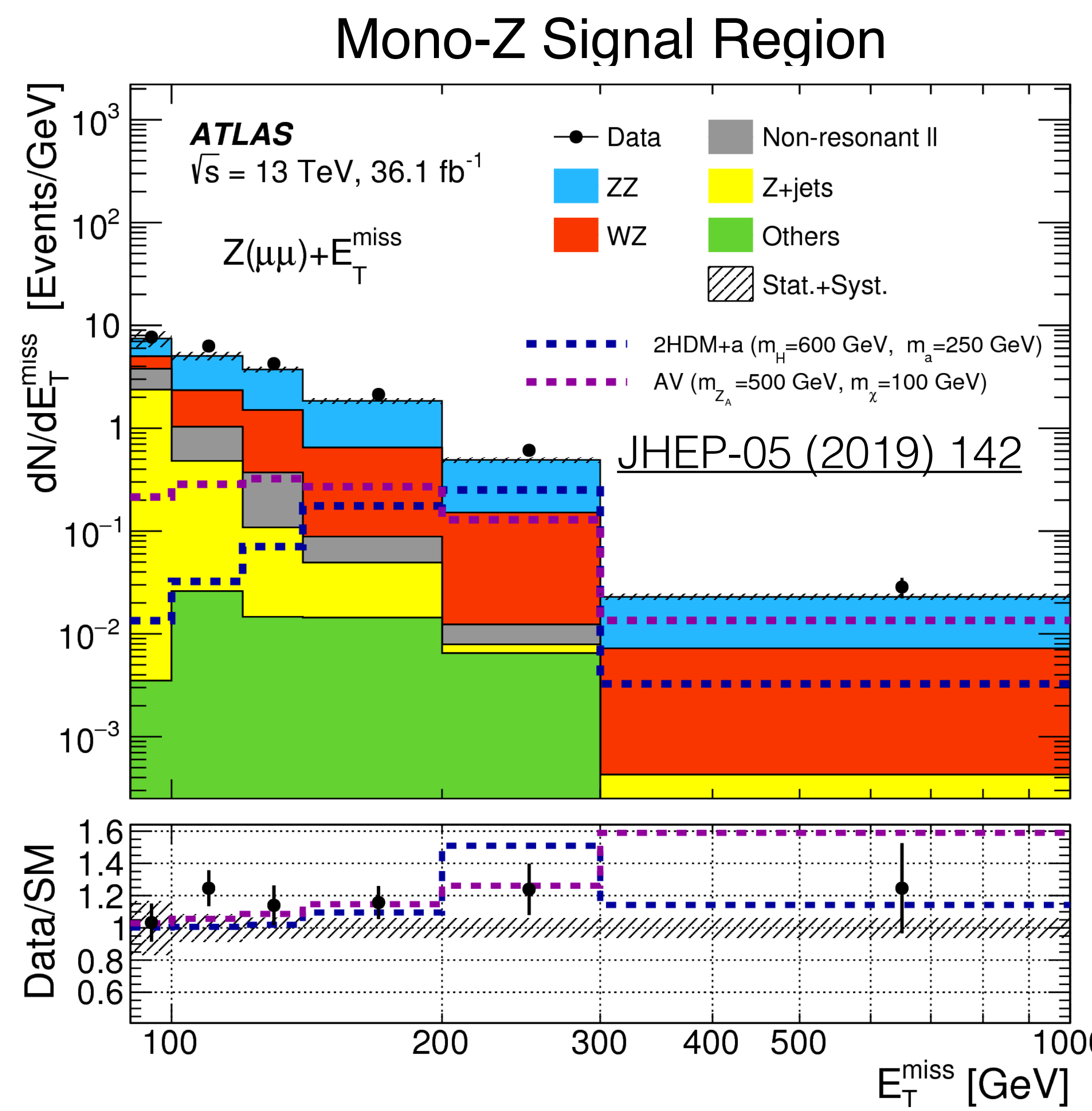
- For resonantly enhanced signatures, the MET spectrum has a *Jacobian* peak.

$$p_{T,Z}^{\max} \simeq \frac{\lambda^{1/2}(M_H, M_Z, M_a)}{2M_H}$$

$$\lambda(m_A, m_B, m_C) = (m_A^2 - m_B^2 - m_C^2)^2 - 4m_B^2 m_C^2$$



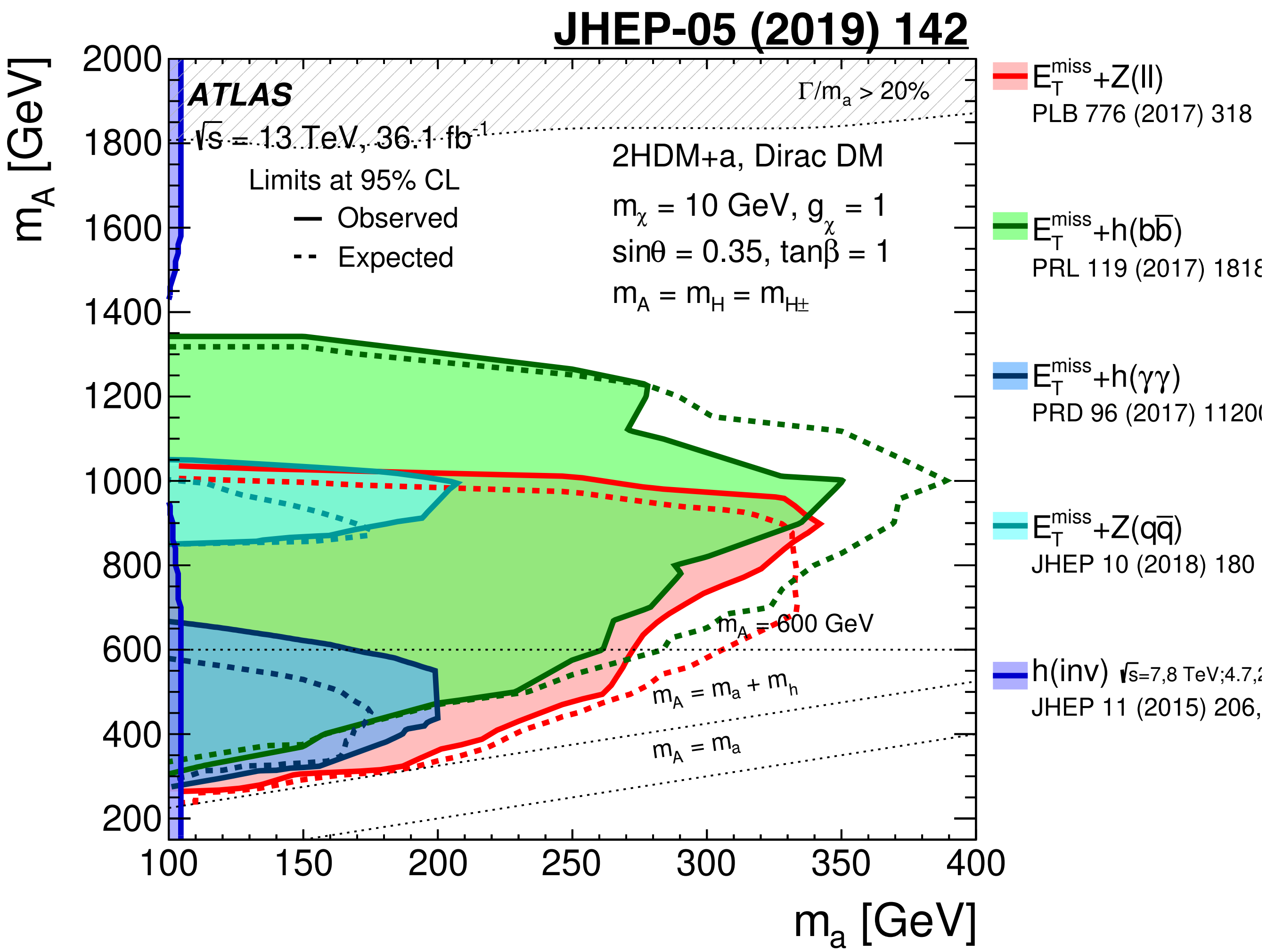




2HDM+a Limits

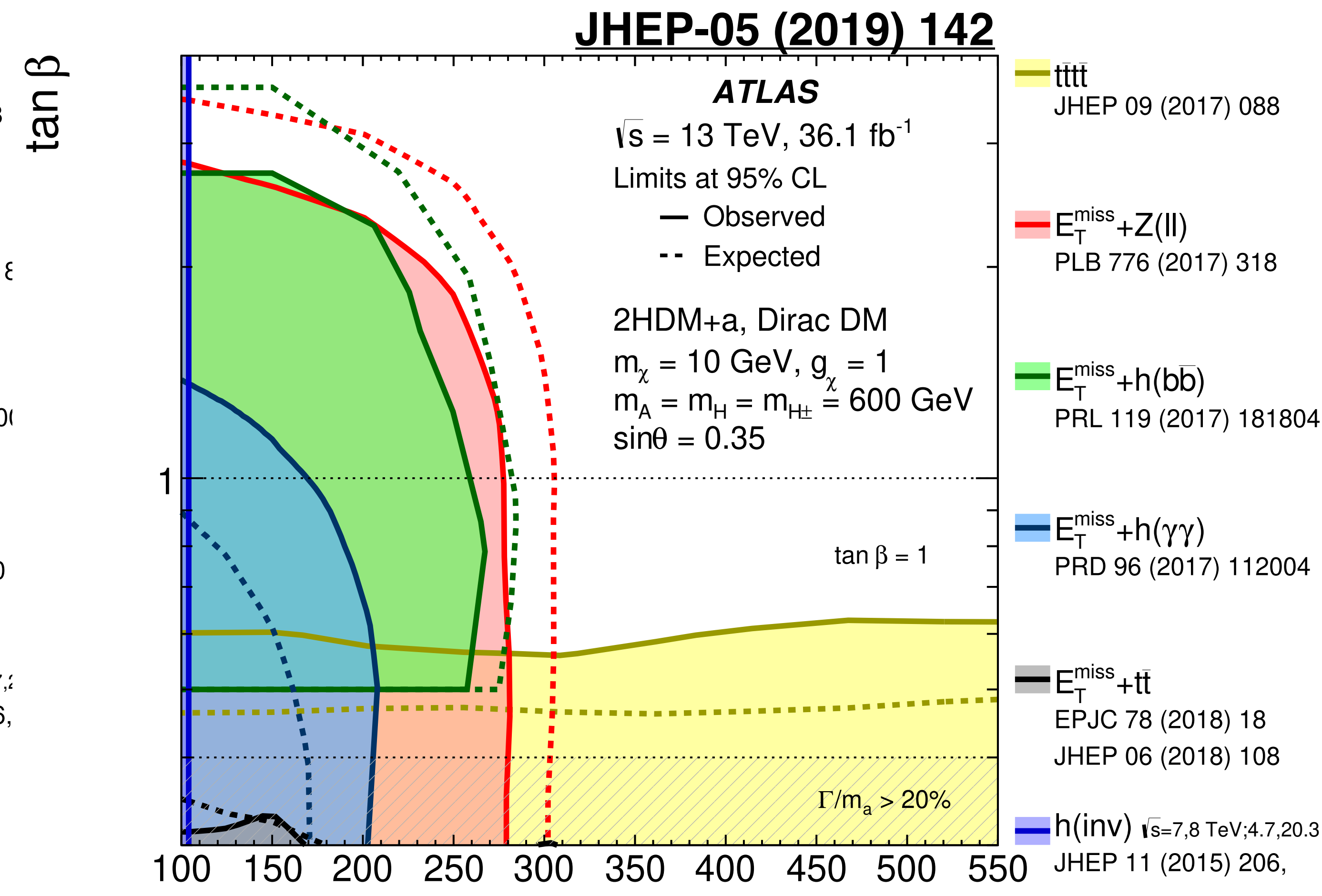
M_A-M_a Scan

($\sin\theta = 0.35$, $\tan\beta = 1.0$, $M_\chi = 10$ GeV)



tanβ-M_a Scan

($\sin\theta = 0.35$, $M_H = 600$ GeV, $M_\chi = 10$ GeV)



*Only gg fusion production considered

Pseudoscalar+2HDM limits are set for 4 benchmarks described in the White Paper. Scans are chosen to highlight the complementarity of the different signatures.

*Shaded grey region corresponds to parameter space with Γ/m > 20%. Included to show ttbar limits.

DM mass Scan

Relic density has a strong dependence on m_χ:

- Density is depleted for resonant enhancement $\chi\chi$-> a/A->SM. ($m_\chi = 1/2 * m_{a/A}$)
- For $m_\chi > m_t$ annihilation to fermions becomes favored leading to an under-abundance of DM.

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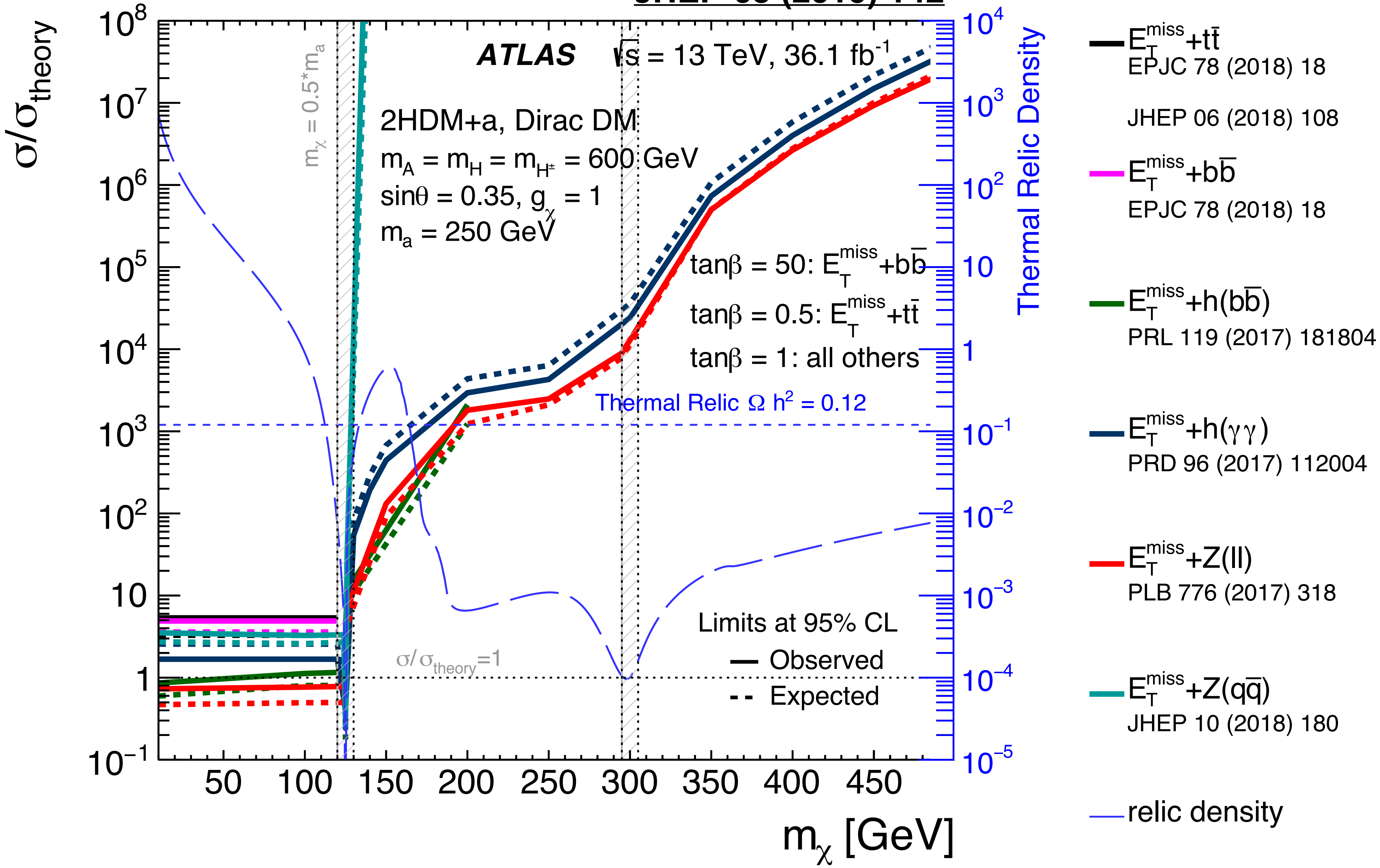


More Dark Matter Models!

This talk covers many, but not all, of the DM models. Additional DM models as well as the current ATLAS limits can be found in the recent DM Summary paper.

	Short description	Acronym	Symbol	CP	Charge	Signatures	Results	
★	Vector/axial-vector mediator	V/AV	Z'_V/Z'_A	$1^{\pm}$	-	jet/$\gamma/W/Z$+$E_{\mathrm{T}}^{\mathrm{miss}}$, di-fermion resonance	Sec.7.1.1	Simplified Models
	Vector baryon-charged mediator	VBC	Z'_B	1^{+}	baryon-number	$h+E_{\mathrm{T}}^{\mathrm{miss}}$	Sec.7.1.2	
	Vector flavour-changing mediator	VFC	Z'_{VFC}	1^{+}	flavour	tt, $t+E_{\mathrm{T}}^{\mathrm{miss}}$	Sec.7.1.3	
	Scalar/pseudo-scalar mediator	S/PS	ϕ_s/ϕ_p	$0^{\pm}$	-	jet+$E_{\mathrm{T}}^{\mathrm{miss}}$, $t\bar{t}/b\bar{b}$+$E_{\mathrm{T}}^{\mathrm{miss}}$	Sec.7.2.1	
	Scalar colour-charged mediator	SCC	$\eta_{q/b/t}$	0^{+}	colour, 2/3 electric-charge	jet+$E_{\mathrm{T}}^{\mathrm{miss}}$, $b+E_{\mathrm{T}}^{\mathrm{miss}}$, $t+E_{\mathrm{T}}^{\mathrm{miss}}$	Sec.7.2.2	
	Two-Higgs-doublet plus vector mediator	2HDM+Z'_V	Z'_V	1^{+}	-	$h+E_{\mathrm{T}}^{\mathrm{miss}}$	Sec.7.3.1	Extended Higgs Sector
★	Two-Higgs-doublet plus pseudo-scalar mediator	2HDM+ϕ_p	ϕ_p	0^{-}	-	$W/Z/h+E_{\mathrm{T}}^{\mathrm{miss}}$, $t\bar{t}/b\bar{b}$+$E_{\mathrm{T}}^{\mathrm{miss}}$, h(inv), $t\bar{t}t\bar{t}$	Sec.7.3.2	

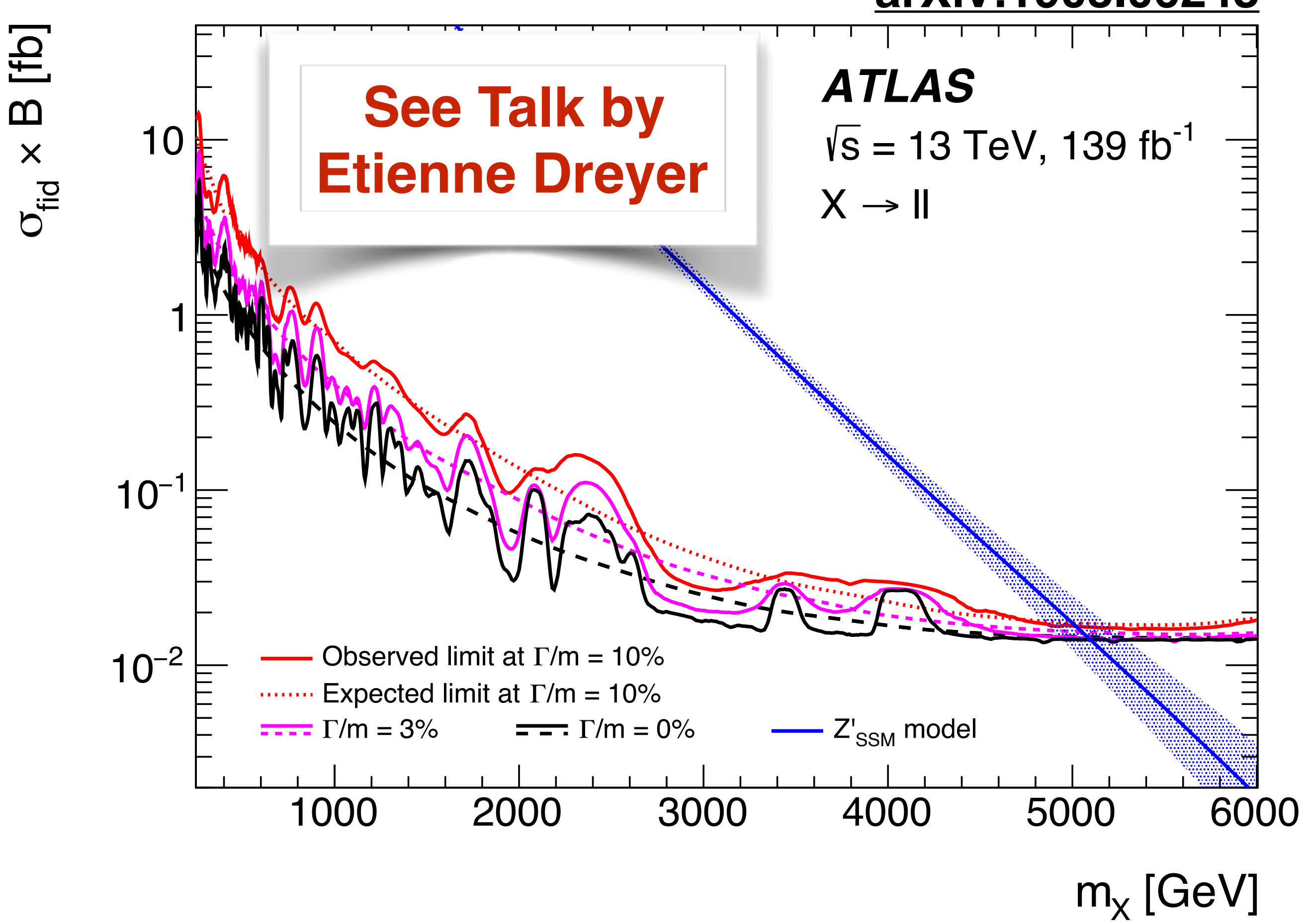
Conclusion

- A robust search program at ATLAS has set stringent limits on a variety of DM models.
- Multiple collider signatures studied, comparisons to direct detection experiments made, and relic densities calculated.
- Significant improvements expected with analysis of full Run-2 data (139 fb^{-1}):

NEW

Limits on Dilepton Resonances (139 fb^{-1})

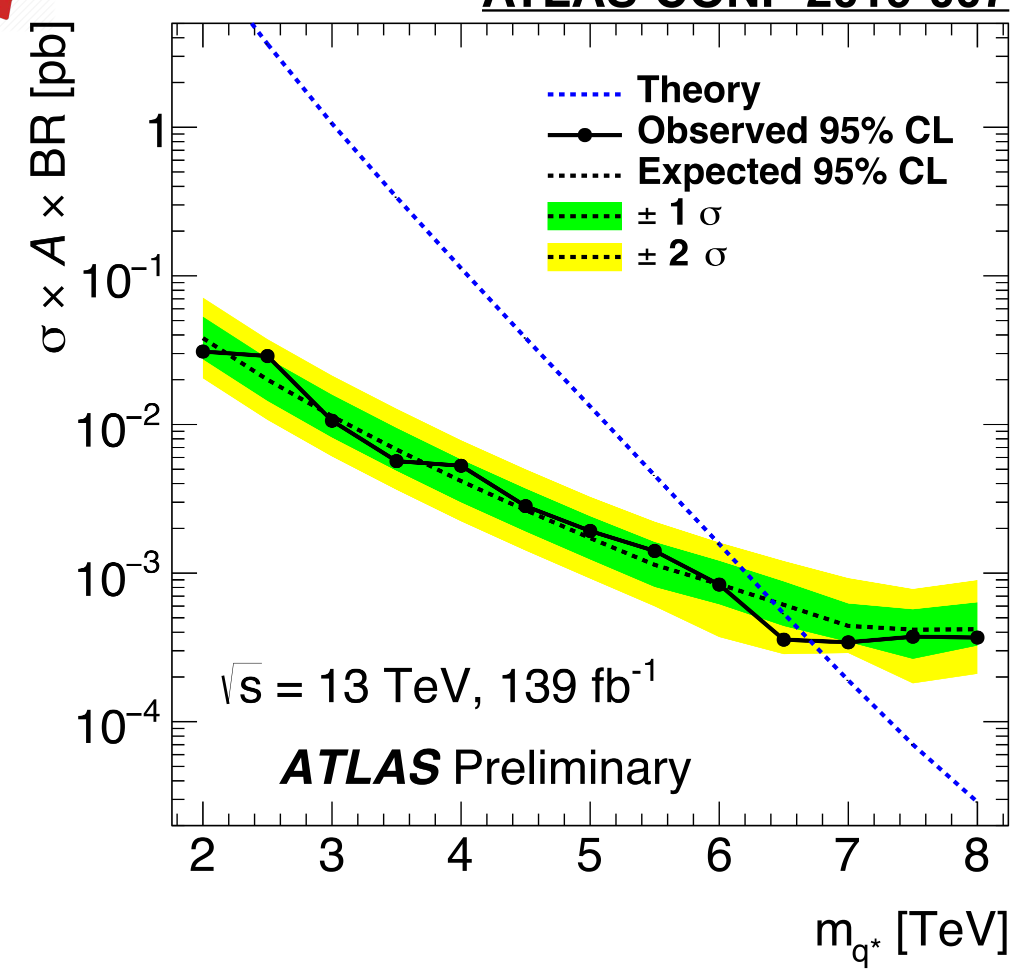
arXiv:1903.06248



NEW

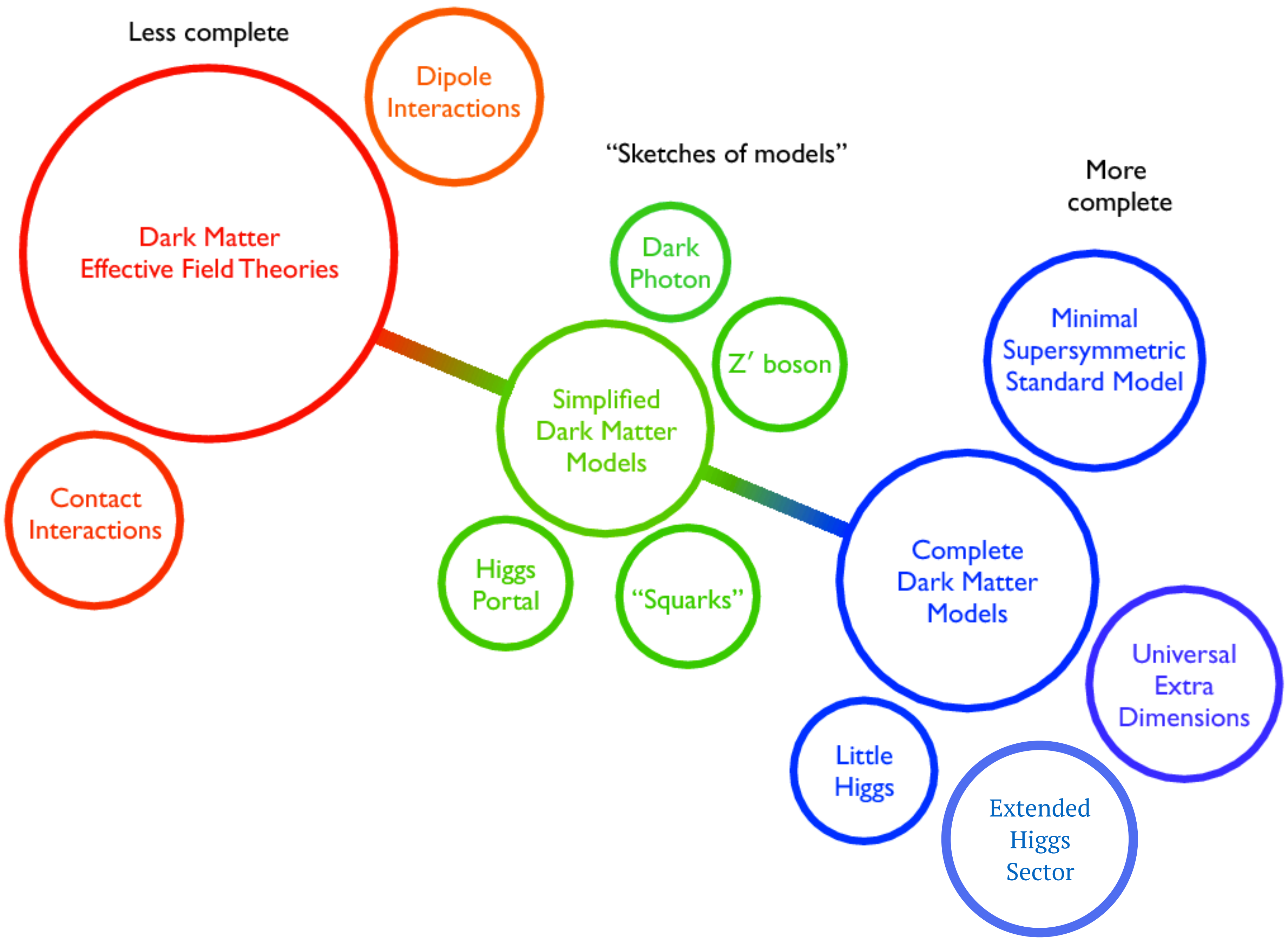
Limits on Dijet Resonances (139 fb^{-1})

ATLAS-CONF-2019-007



Backup Slides

Dark Matter Models



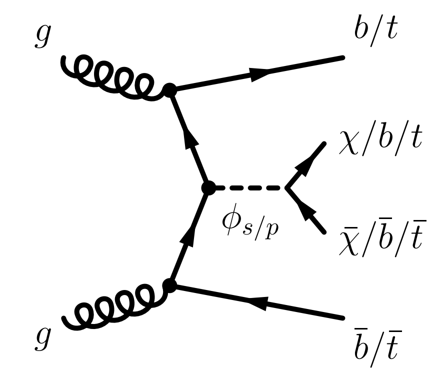
Experimental Signatures

Multiple visible and invisible (E_T^{miss}) final states probe the described DM models:

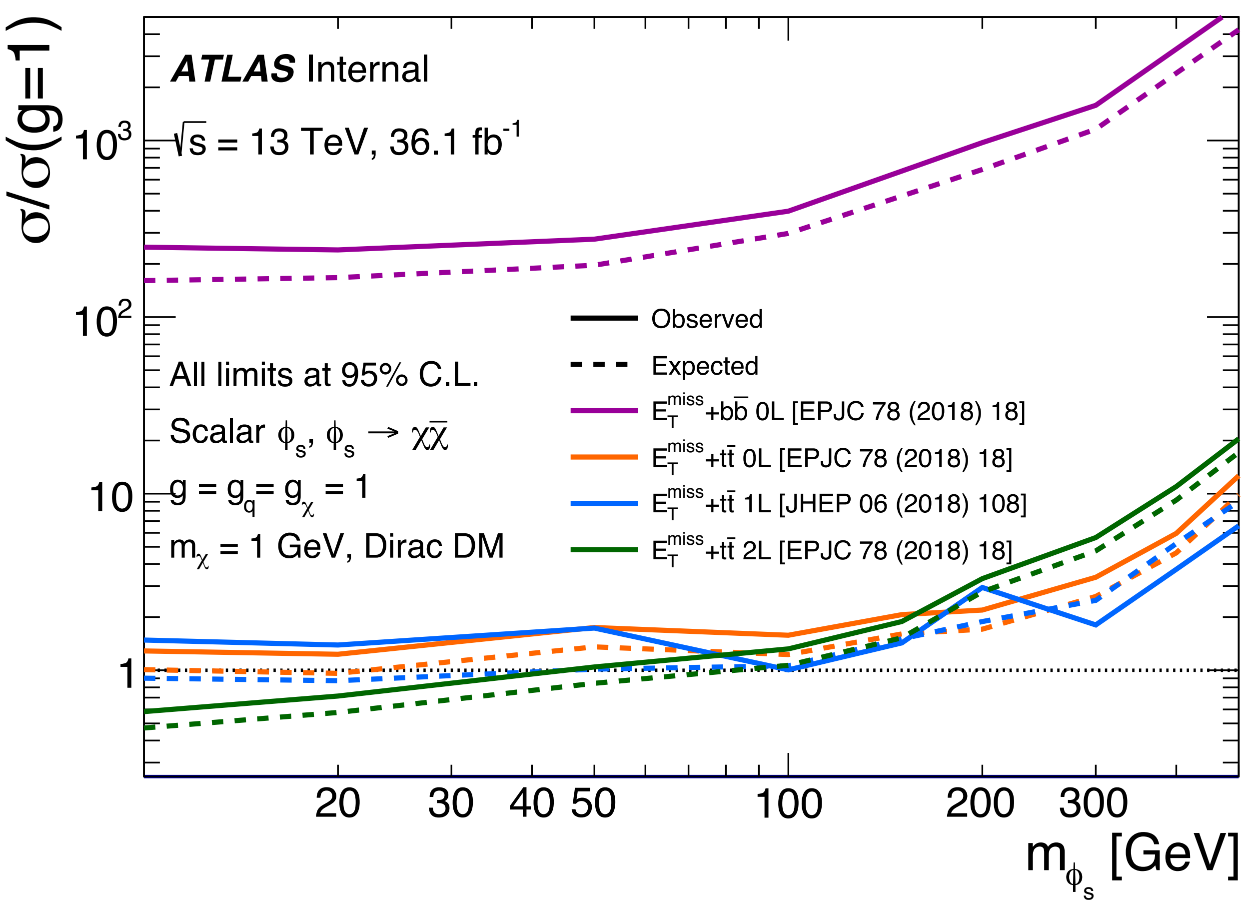
Visible Final States	Invisible Final States
Dijet : PRD-96 (2017) 052004	**Jet + E_T^{miss}** : JHEP-01 (2018) 126
TLA dijet: arXiv:1804.03496	**h(inv)** : JHEP-11 (2015) 206 (7+8 TeV)
Resolved dijet+ISR :ATLAS-CONF-2016-070	**γ + E_T^{miss}** EuroPhys(2018) 77:393
Boosted dijet +ISR : arXiv.1801.08769	**h(bb) + E_T^{miss}** : PRL-119 (2017) 181804
Dibjet : arXiv.1805.09299	**h(γγ) + E_T^{miss}** : PRD-96 (2017) 112004
Dilepton : JHEP-10 (2017) 182	**Z(ll) + E_T^{miss}** : PLB 776 (2017) 318
Same-sign tt: arXiv.1807.11883	**V(qq) + E_T^{miss}**: arXiv.1807.11471
tt tt : JHEP-09 (2017) 088	**tt /bb + E_T^{miss}**: EurPhys (2018) 78:18
tt resonance : arXiv.1804.10823	**tt (1L) + E_T^{miss}** : arXiv.1711.11520

Scalar and Pseudoscalar Mediators

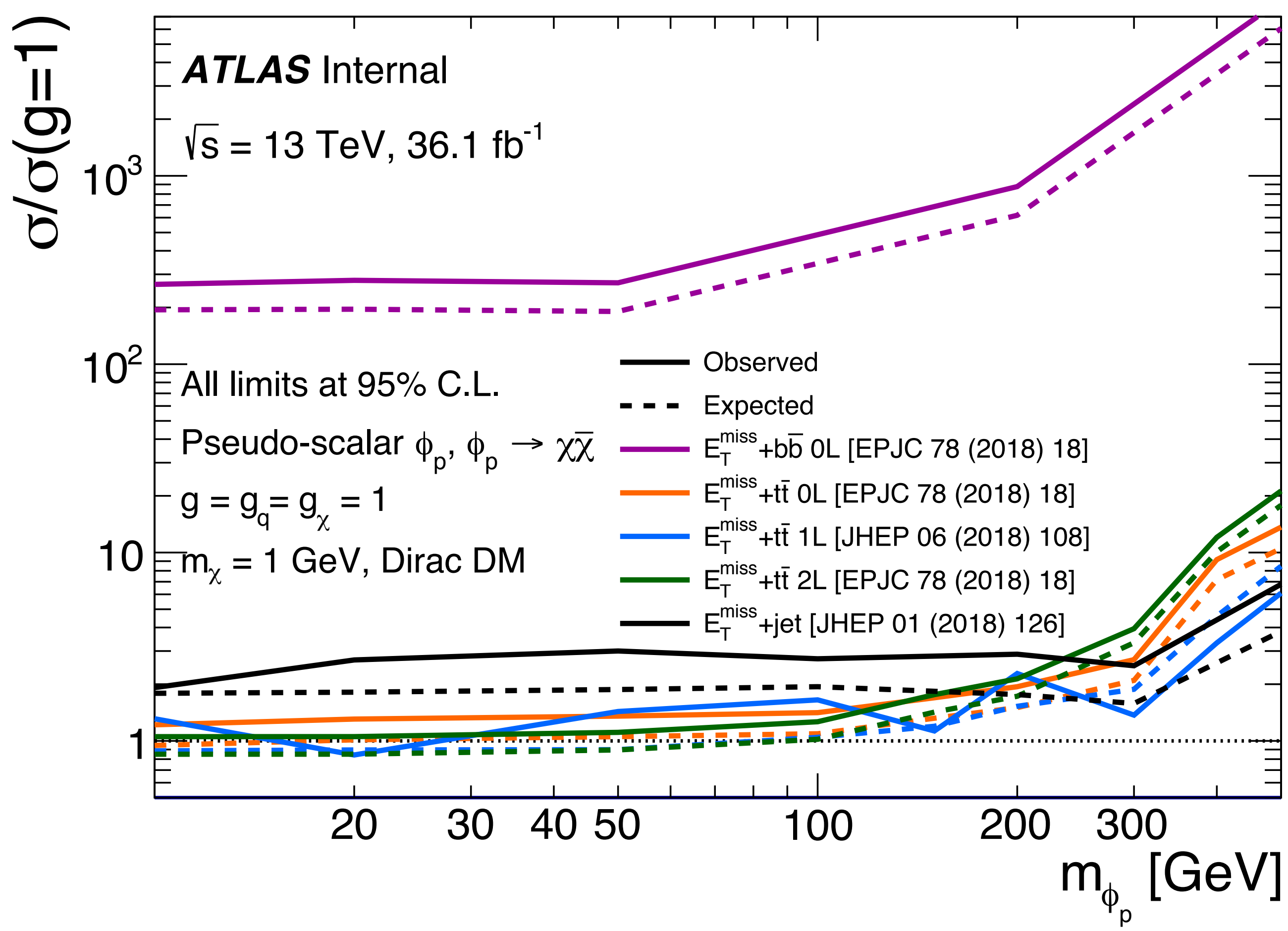
- For Scalar and Pseudoscalar models **$g_q = g_\chi = g = 1$.**
- **$M_\chi = 1$ GeV.** S/PS mediators have similar off-shell cutoff as the AV/V mediators.
- For spin-0 mediators strongest limits are placed by tt+E_T^{miss} final state. Jet+E_T^{miss} becomes important for the higher mediator masses.



Scalar



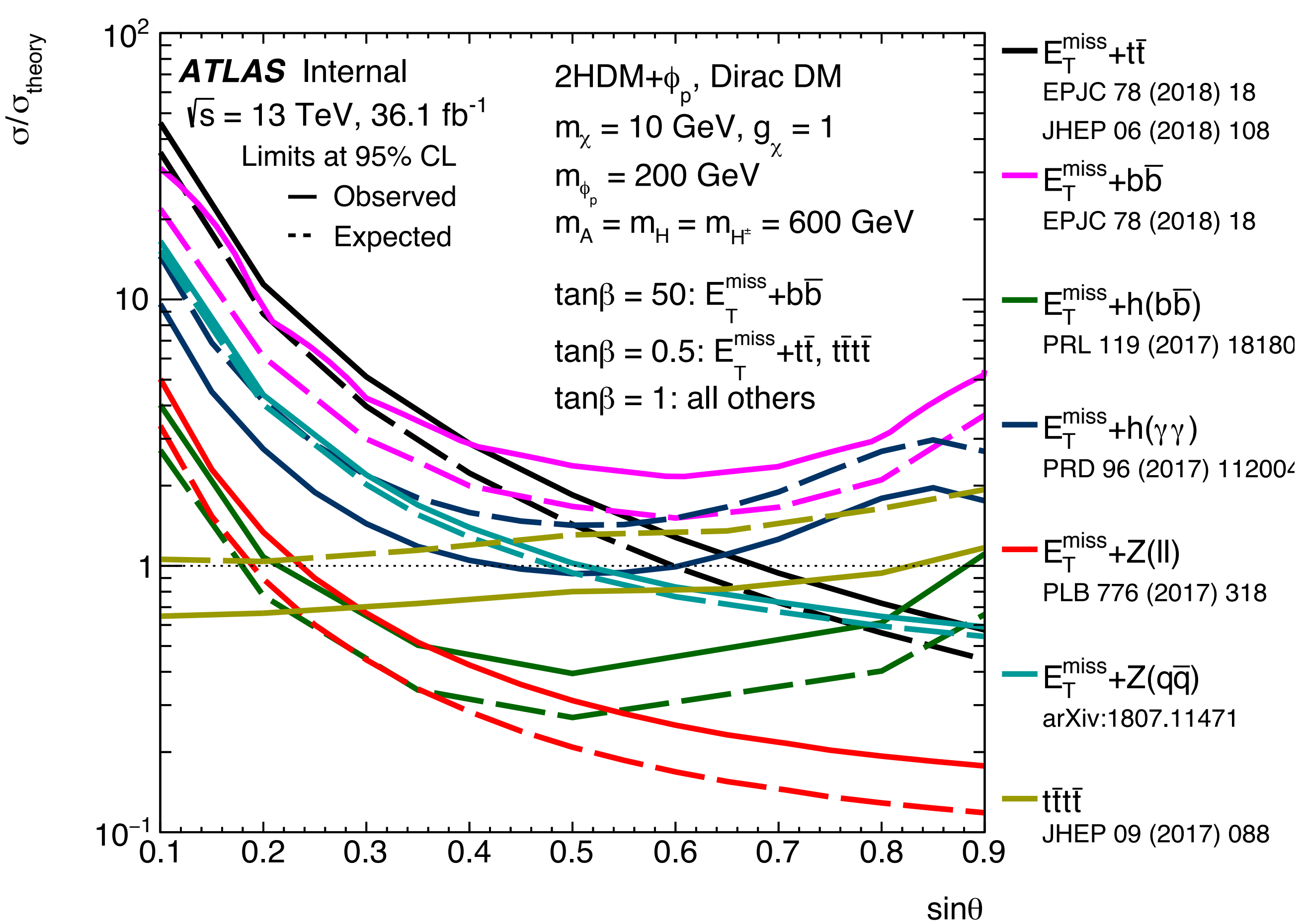
Pseudoscalar



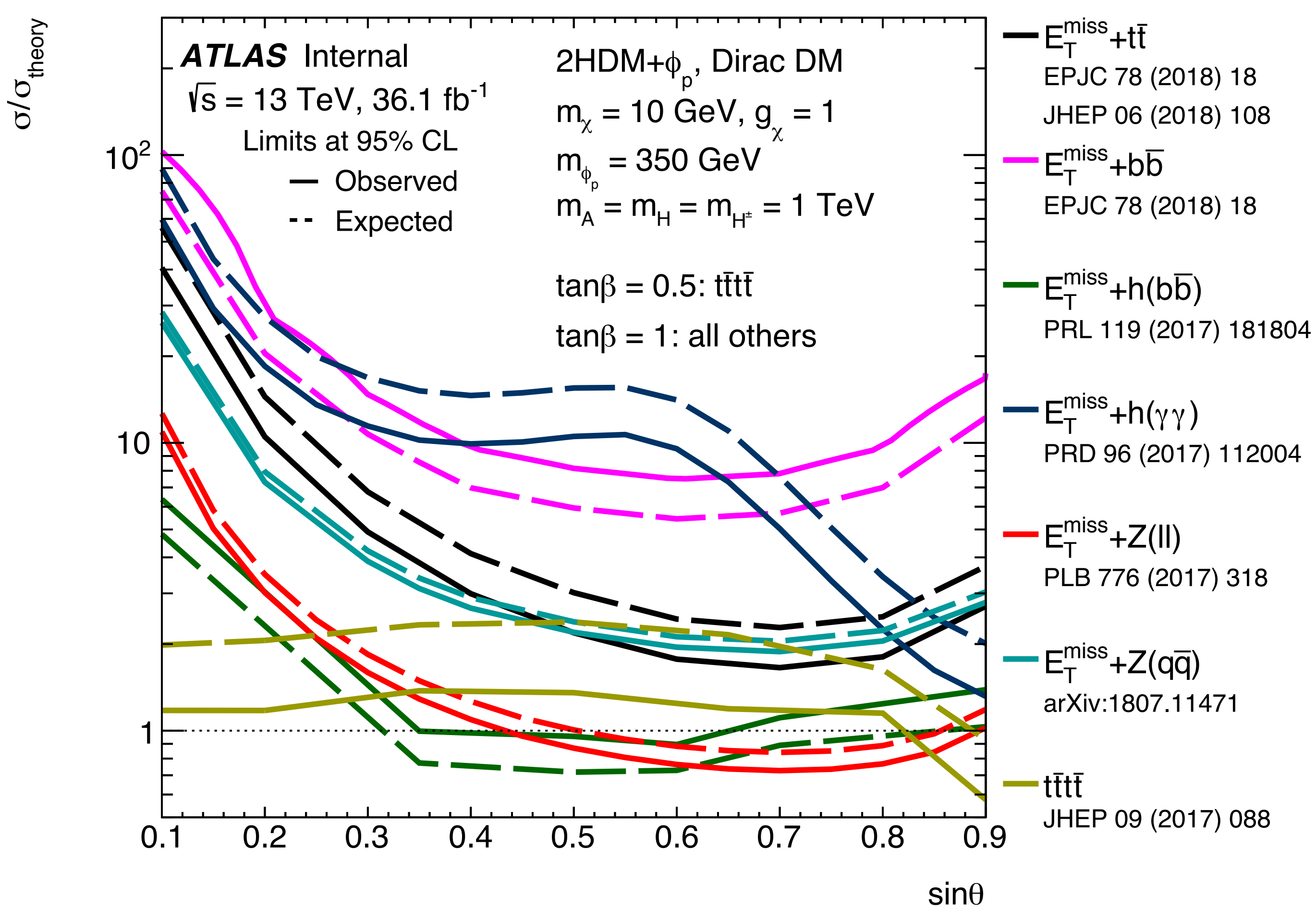
2HDM+a: sinθ scan

- sinθ is the mixing angle between A and a. For low values of sinθ, main decay is a->χχ, for high values main is a->tt (if kinematically possible).
- Two sinθ scans are performed, one for $m_a < m_{tt}$ and one for m_a greater.

Low Mass



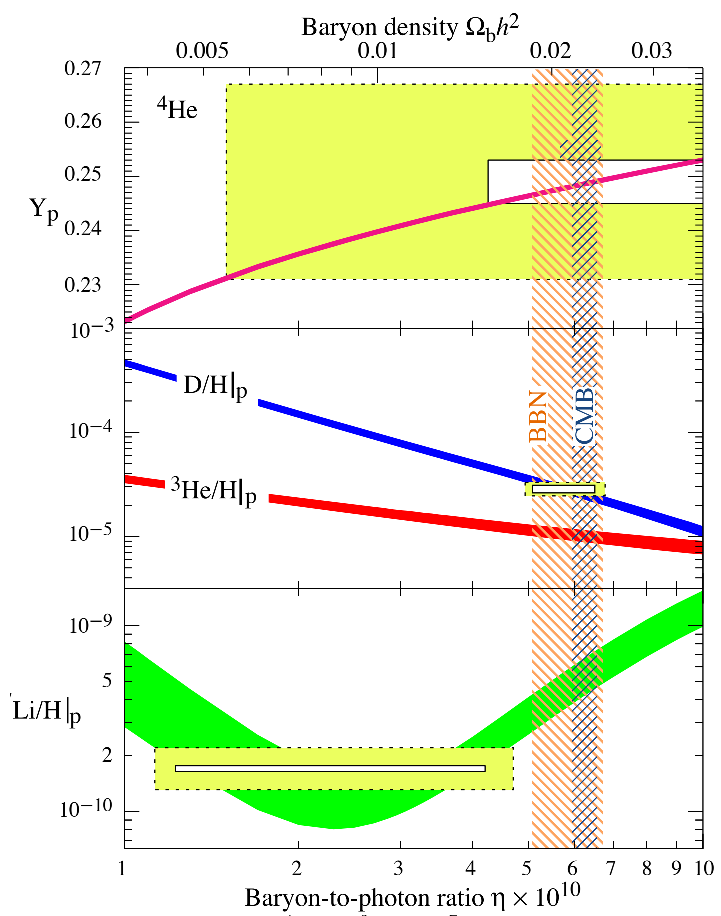
High Mass

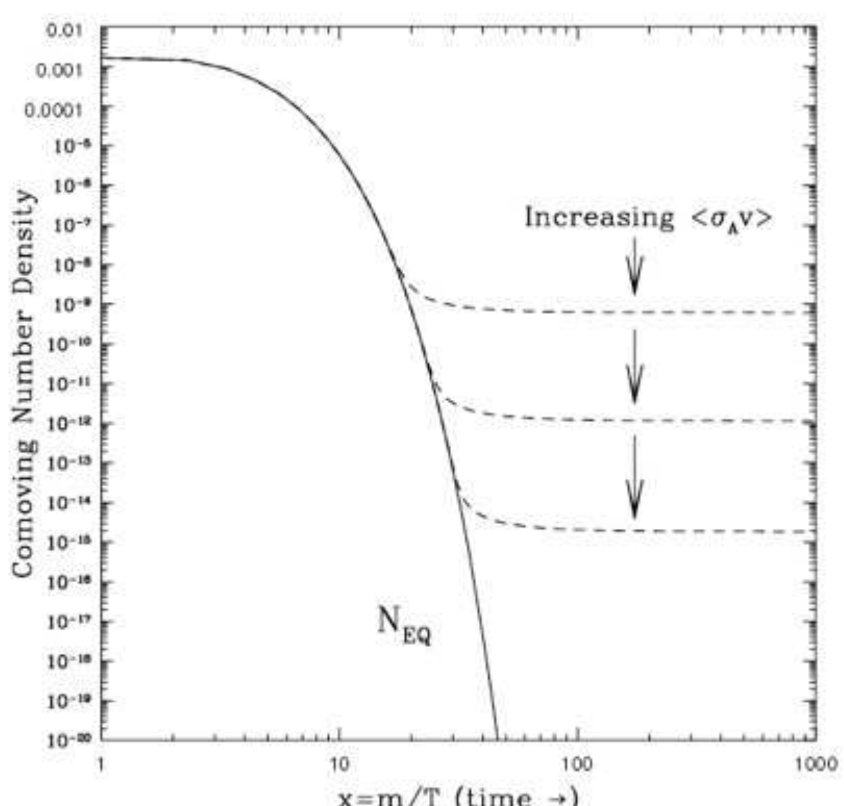


Particle Dark Matter

Dark matter cannot be explained by Standard Model (SM) particles.

- CMB and Big Bang Nucleosynthesis measure the baryon fraction and rule out ordinary dark baryons.
- Supporting a new, Beyond the Standard Model (BSM) particle, WIMP miracle predicts a weakly interacting particle will freeze out with correct relic abundance to account for current dark matter density.





$$< \sigma v > \simeq 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

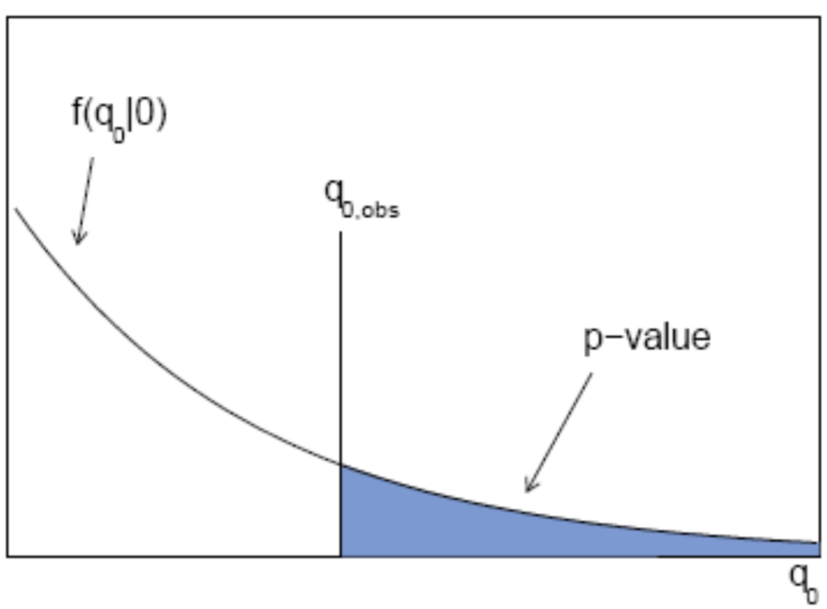
Likelihood Profile

Likelihood for observed number of events following a Poisson distribution. Product over nbins.

$$\mathcal{L}(\mu) = \prod_{i=1}^{nbins} \text{Pois}(x_i | \mu \cdot s_i(\theta) + b_i(\theta)) \times P_n(\theta)$$

Signal → $s_i(\theta)$; **Estimated Background** → $b_i(\theta)$; **Observed Events** → x_i; **Strength Parameter** → μ; **Nuisance Parameters** → θ

Significances and limits are calculated using a likelihood profile test statistic, q_μ. From Wilk's theorem, test statistic behaves asymptotically as a $\chi 2$ distribution.



$$q_\mu = -2 \ln \frac{\mathcal{L}(\mu, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

$\mathcal{L}(\mu, \hat{\hat{\theta}})$ ⟵ maximizes likelihood for specific μ

$\mathcal{L}(\hat{\mu}, \hat{\theta})$ ⟵ global maximum likelihood

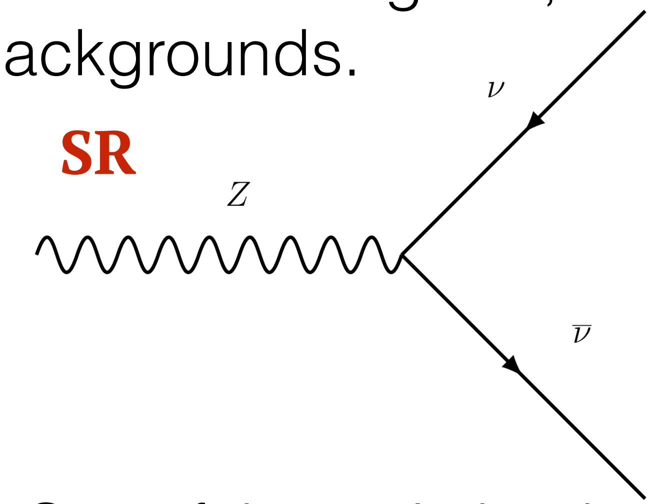
From the distribution, $\chi 2$, get p-value for specific q. Can convert p-value into equivalent significance.

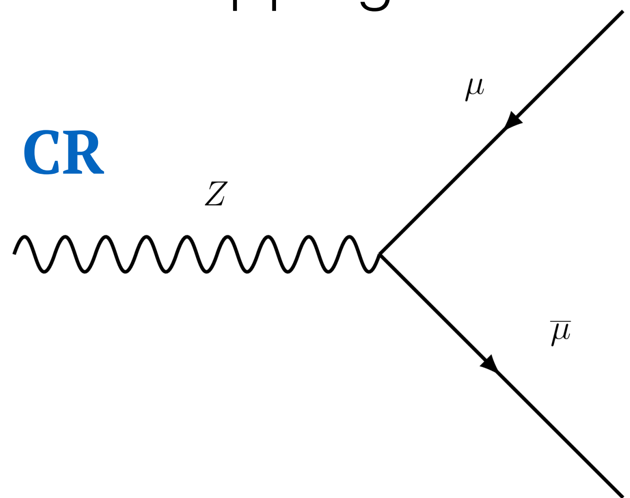
$$Z = \Phi^{-1}(1 - p)$$

Φ^{-1} ⟵ Inverse Gaussian CDF

Data Driven Estimates

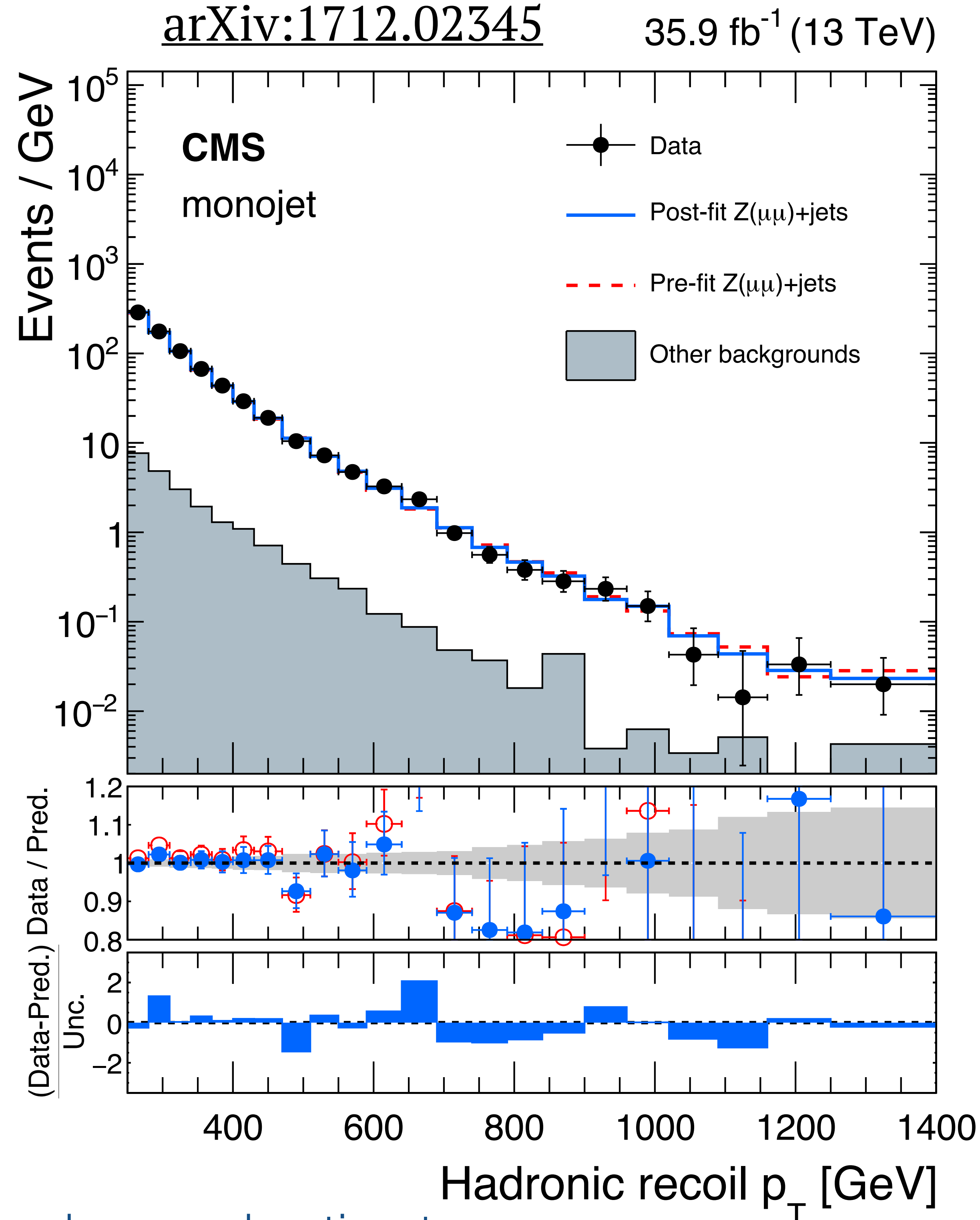
Data control regions, non-overlapping with the signal region, are leveraged to estimate backgrounds.





- One of the main backgrounds for Mono-Jet is Z(νν) + jets.
- Dimuon control region is same as signal region, but with inverted lepton veto and requirement of muon pair consistent with Z-boson decay.
- Simulated transfer factors account for branching fractions and different selection efficiencies, multiply control region Z(μμ) to estimate Z(νν) background in the signal region.
- Five control regions used for final estimate of Z(νν) + jets and W(ℓν) + jets backgrounds, fit to maximum likelihood.

arXiv:1712.02345



Control regions also used to validate simulated background estimates.