Searches for Dark Matter with the ATLAS Detector

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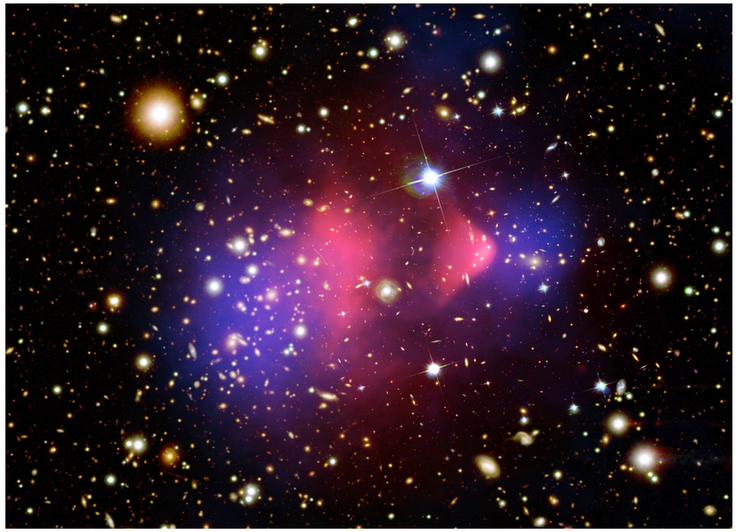
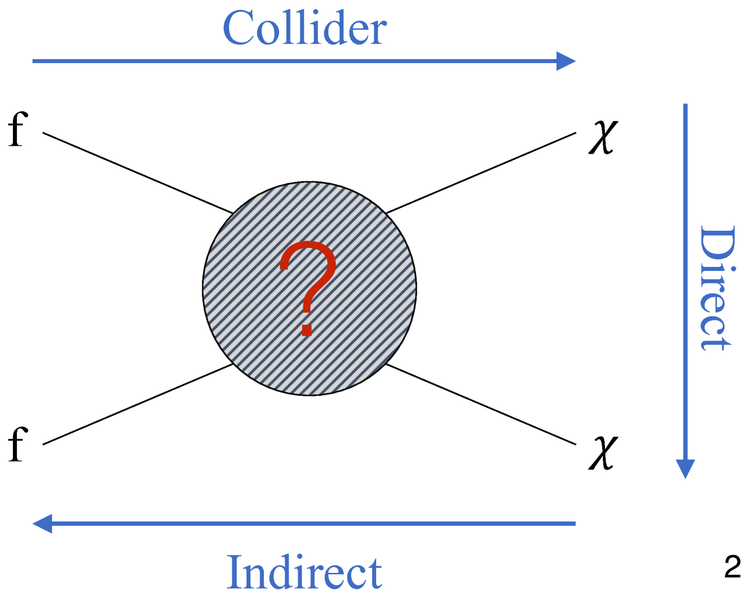
on behalf of the *ATLAS* collaboration

3/30/23

Introduction

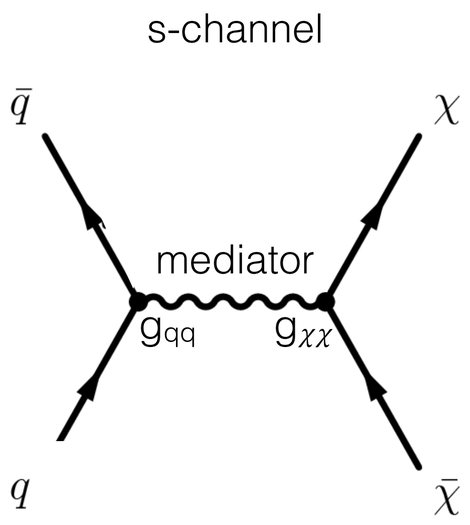
- Evidence for Dark Matter (DM) from a variety of astrophysical sources
  - Galactic cluster velocity dispersion
  - Galactic rotation curves
  - Cosmic microwave background
  - Gravitational lensing
- If DM is particle-like and has non-gravitational interactions, can be probed at the LHC
  - Complementarity with direct and indirect detection
- WIMP Miracle
  - Assuming thermal production and subsequent freeze out, correct relic abundance obtained for weak scale DM mass and coupling

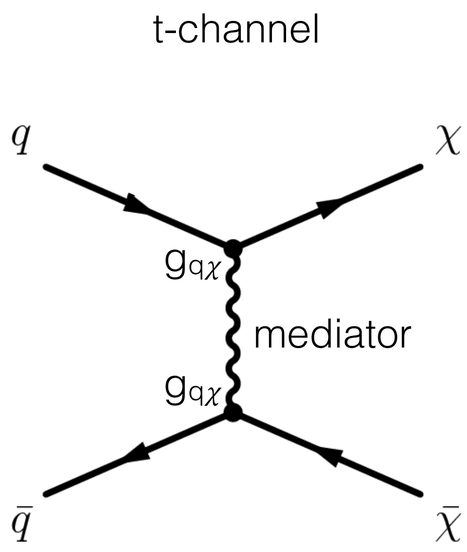




Overview

- If DM can be produced at the LHC, there must be some mediator which couples DM to SM
  - Mediator could be BSM or SM (Z or H)
- DM is invisible to ATLAS





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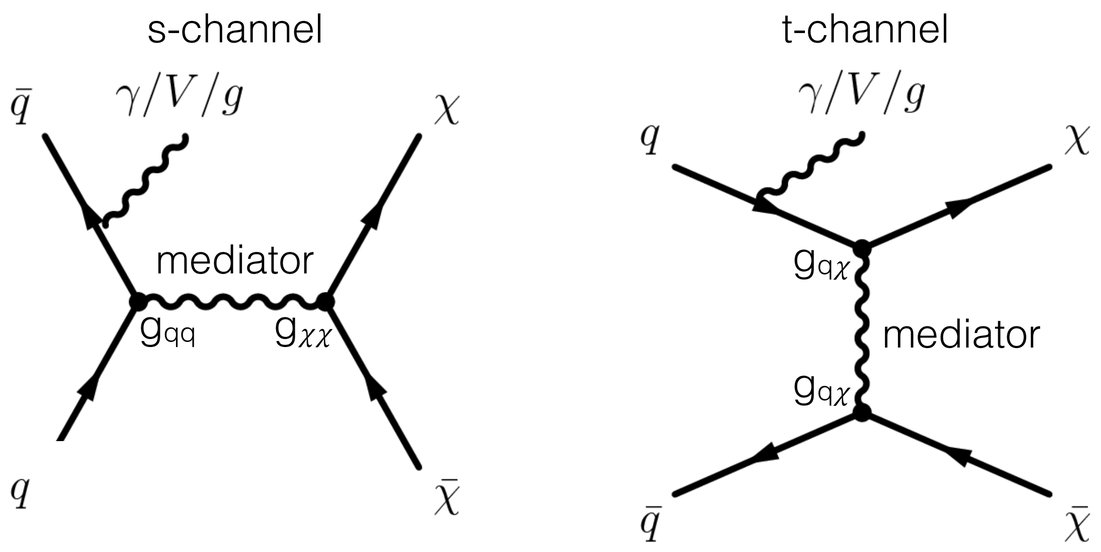
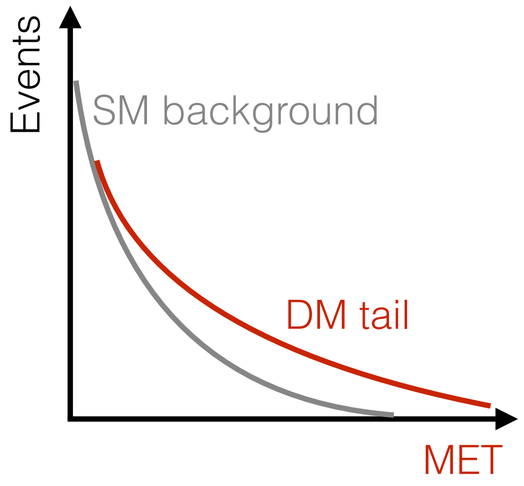
  - 2 complementary search strategies:
    - Search for DM recoiling against visible particles → broad MET excess





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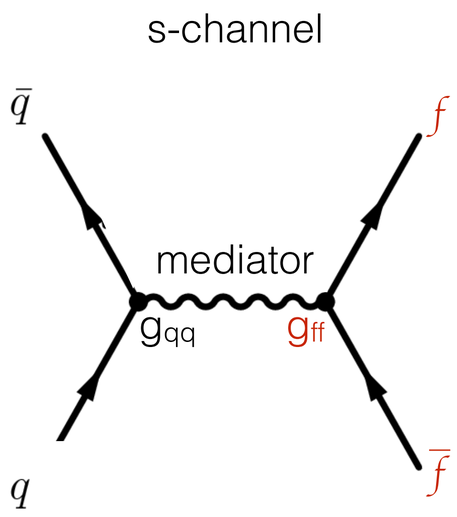
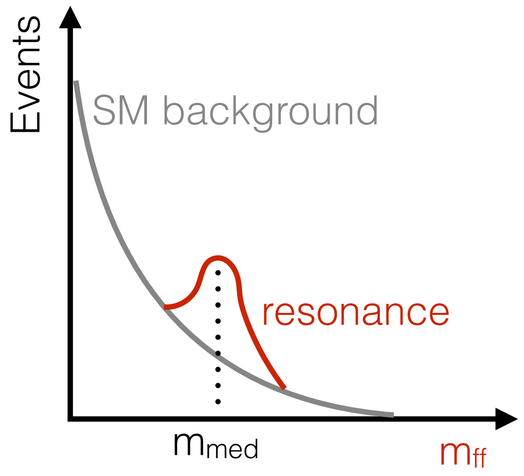
    - Search for DM recoiling against visible particles → broad MET excess
    - Search for decays of mediator to SM → resonance at mediator mass



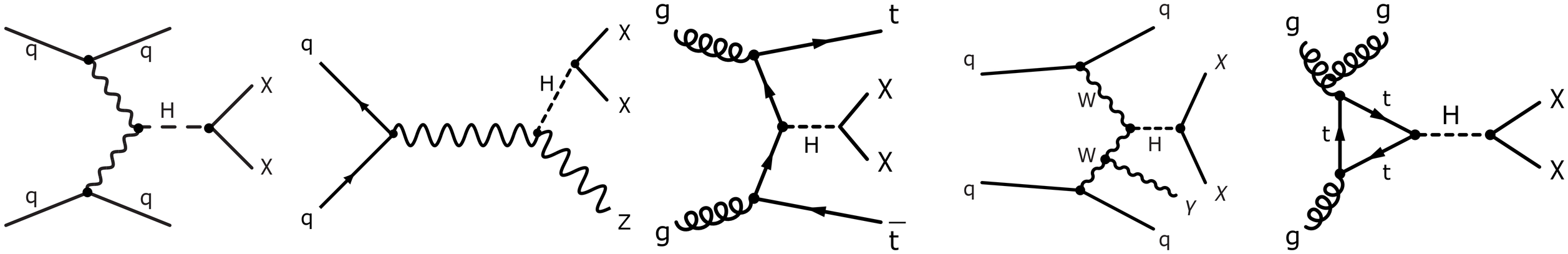


Higgs Portal

Higgs → Invisible

- $B_{SM}(h \to ZZ^* \to 4\nu) \approx 0.1\%$
- If $m_\chi < m_h/2$, $h \to \chi\chi$ is allowed
- Global fit of visible decay modes: $B(h \to inv) < 13\%$ [Nature 607, 52–59 (2022)]
- Many production modes to probe:

VBF	JHEP 08 (2022) 104
Z(ℓℓ)h	PLB 829 (2021) 137066
tth	ATLAS-CONF-2022-007
VBF+γ	EPJC 82 (2021) 105
ggF	PRD 103 (2021) 112006
combo	2301.10731

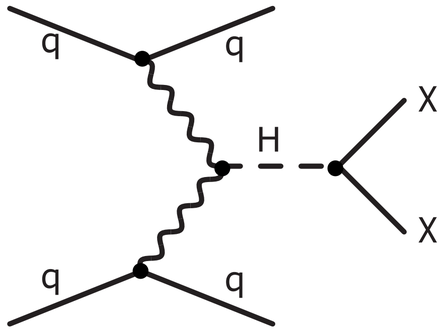


[JHEP 08 (2022) 104]

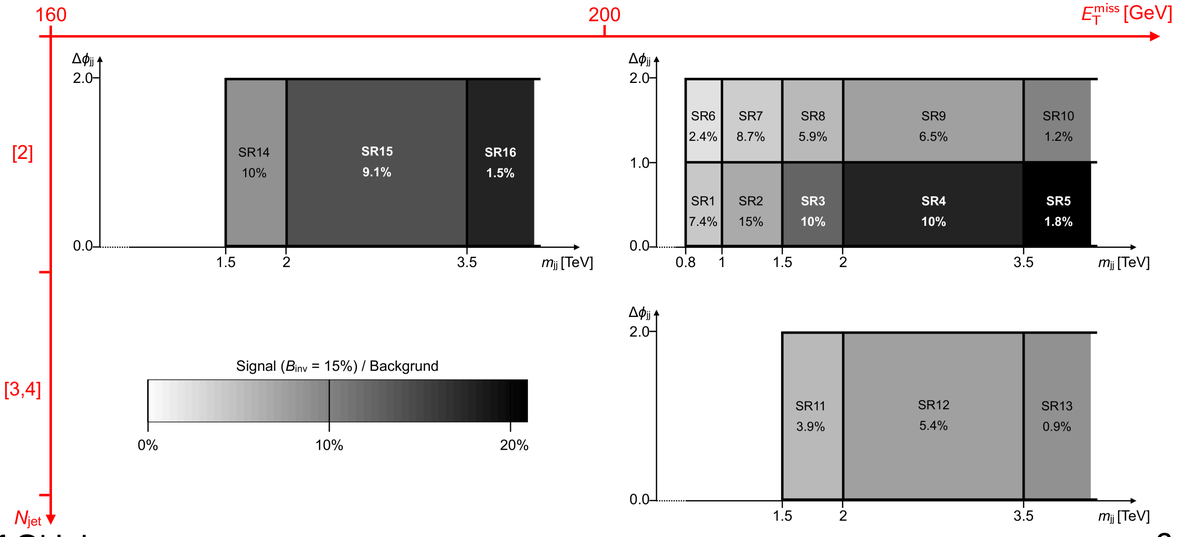
Higgs → Invisible: VBF

- Distinctive topology - pair of highly-energetic forward jets with:
  - Wide pseudorapidity gap ($\Delta\eta_{jj}$)
  - Large invariant mass (m_{jj})
- Reject QCD by requiring large MET
  - Dominant background: Z(νν)+jets
- Background-enriched control regions (CRs) defined for Z(ℓℓ), W(ℓν), and QCD multijet backgrounds*
- Simultaneous likelihood fit in signal region (SR) and CRs to constrain backgrounds, test for presence of signal
  - W and Z have similar mass/couplings/spin → σ_W/σ_Z constrained to SM prediction (NLO QCD/EWK)
  - Validated in events with $2 < \Delta\phi_{jj} < 2.5$
- SR (and CRs) categorized in 16 bins of varying signal purity

*MET calculated by excluding charged leptons ("MET" = V p_T)



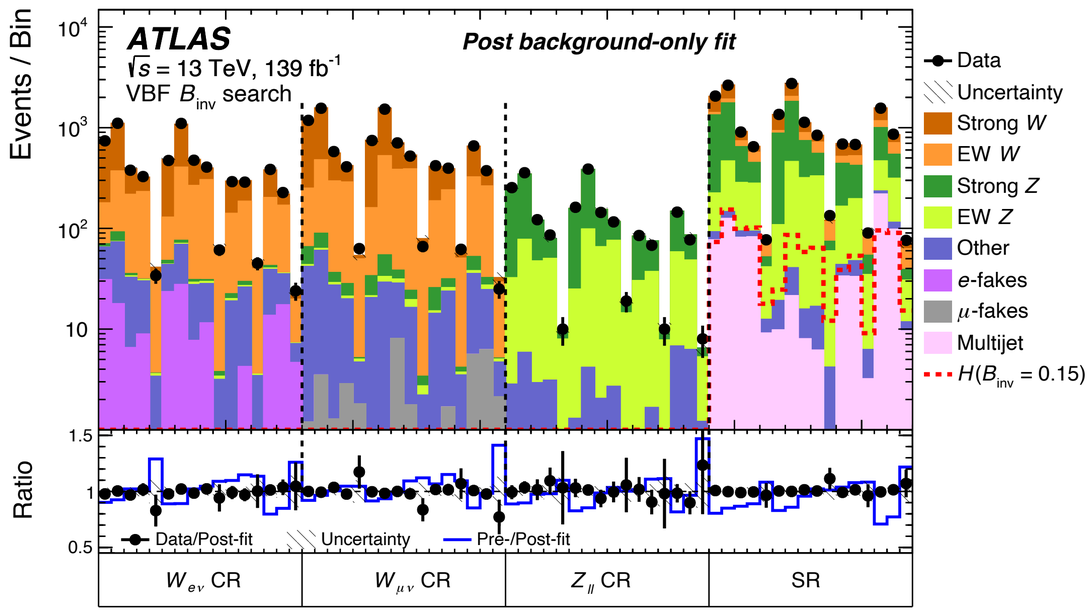
	SR	W(ℓν)	Z(ℓℓ)
N_ℓ	0	1	2
N_j	2-4		
$p_T(j_1)$	> 80 GeV		
$p_T(j_2)$	> 50 GeV		
$\eta_{j1} \cdot \eta_{j2}$	< 0		
MET	> 160 GeV		
$\Delta\eta_{jj}$	> 3.8		
$\Delta\phi_{jj}$	< 2		
m_j	> 800 GeV		



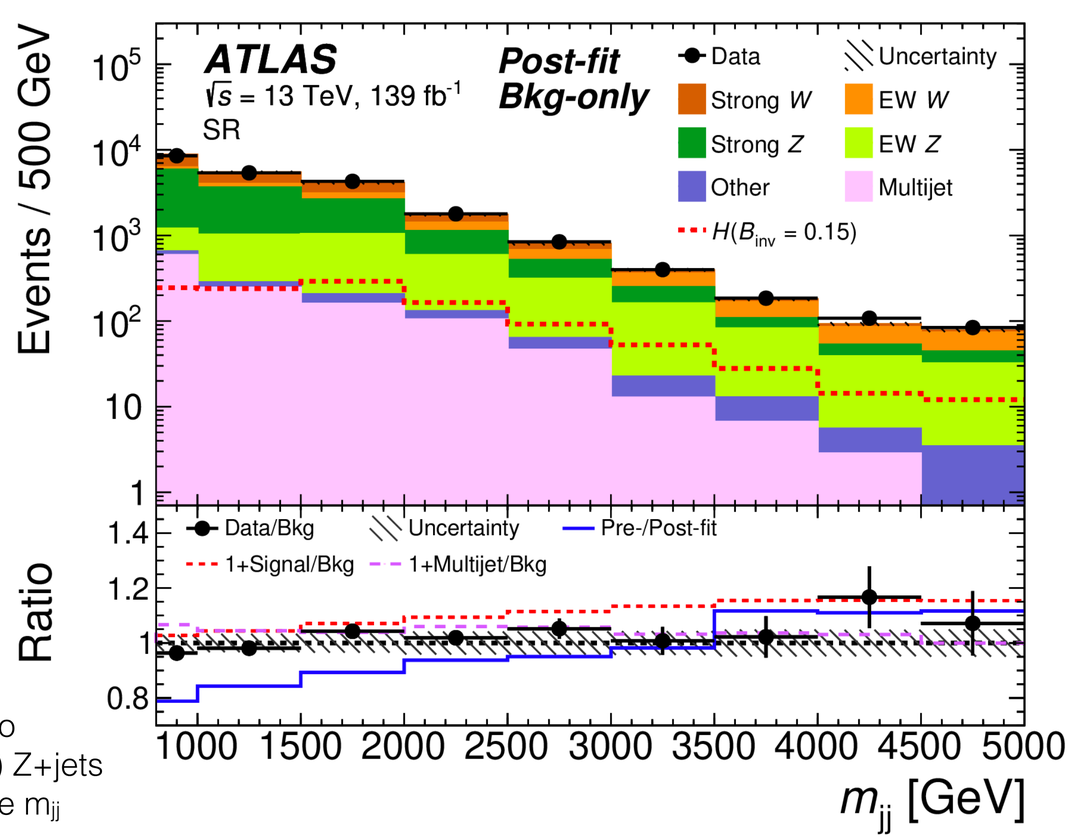
[JHEP 08 (2022) 104]

Higgs → Invisible: VBF

background-only fit



inclusive signal region



Sherpa tends to overestimate (strong) Z+jets production at large m_{jj}

uncertainties

Source	Contribution to $\pm 1\sigma$ (= 0.052)
Data stats.	0.029
V+jets data stats.	0.022
MC stats.	0.014
Multijet	0.021
μ/e-fakes	0.019
Lepton	0.017
(Lepton – muon only)	0.0049
(Lepton – electron only)	0.016
JER	0.015
JES	0.011
Remaining	0.012
V+jets – theory	0.015
Signal – theory	0.0056

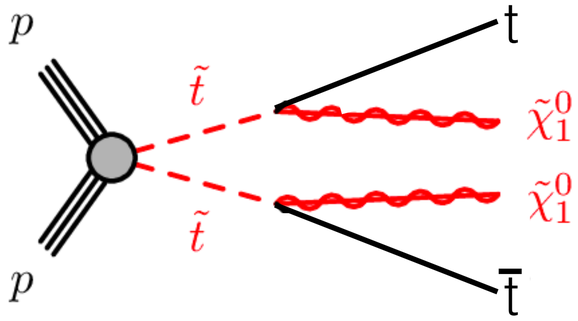
95% CL uppler limit on B(h→inv)

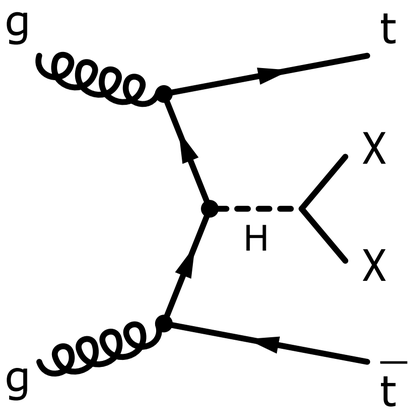
Observed	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.145	0.103	0.144	0.075	0.196	0.055

[2211.05426]

Higgs → Invisible: tth

- Adapted from a stop search [EPJC 80 (2020) 737] See Francesco's talk (next)
- Consider 0,1, and 2ℓ final states
  - Includes a new 0ℓ, low-p_T channel
  - Further subdivided into 25 SRs
- Dominant backgrounds: tt, ttZ(νν), and Z+jets
  - Constrained in dedicated CRs
- Triggers: MET, b jet, lepton
- Reclusters R = 0.4 jets into large-R jets for top tagging

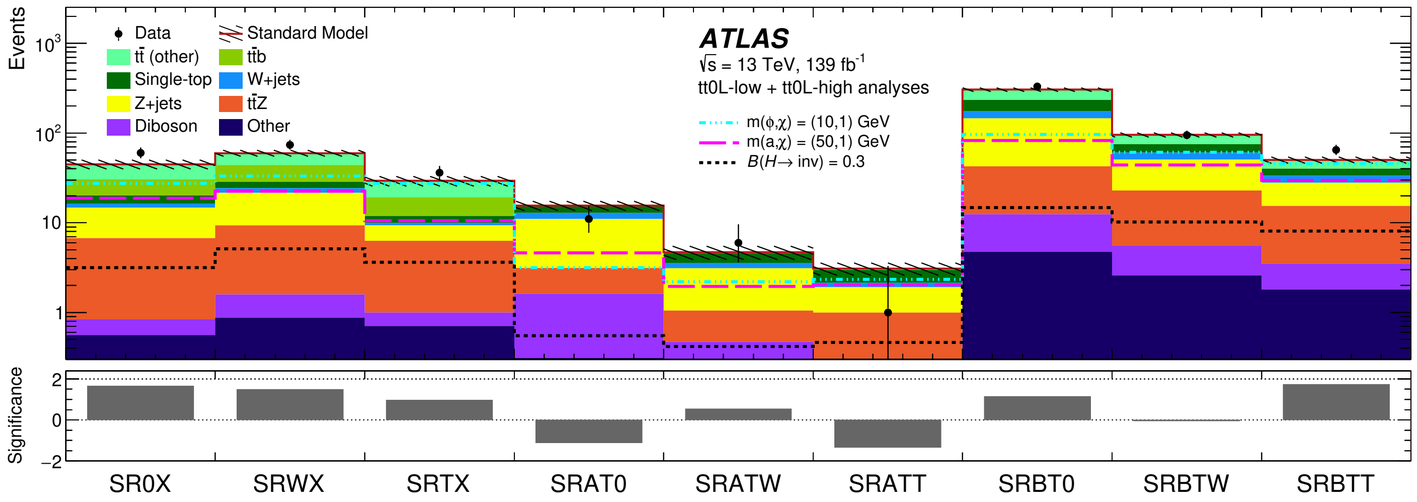


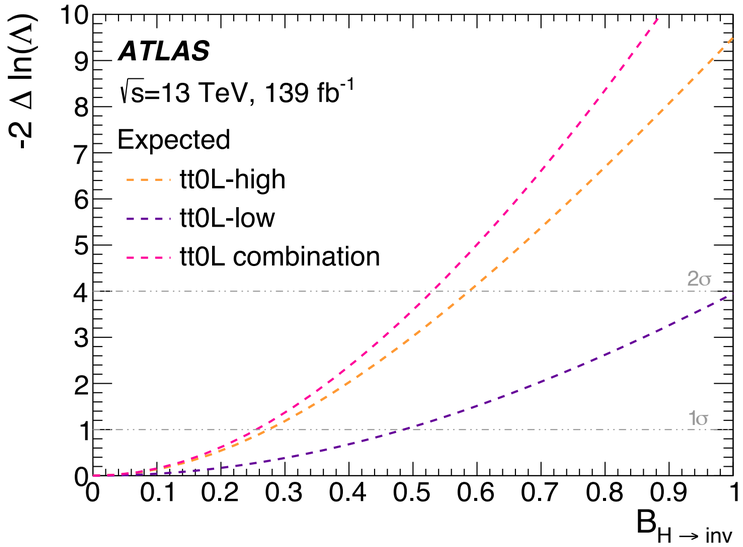


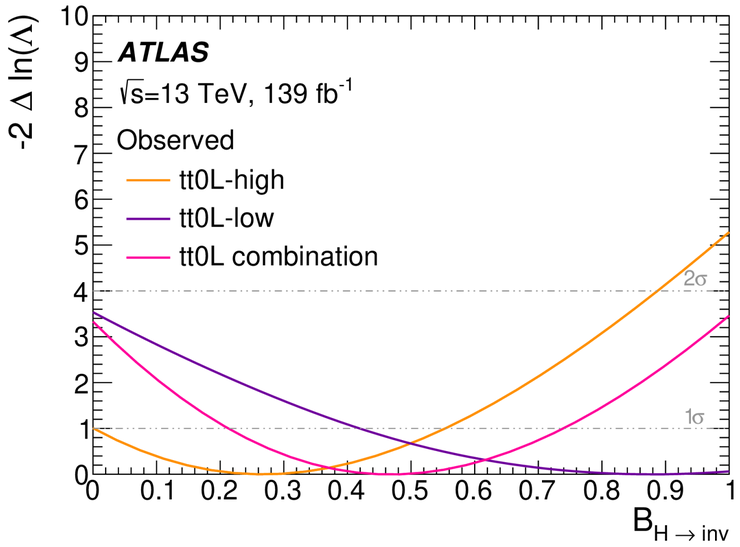
[2211.05426]

Higgs → Invisible: tth

- 0ℓ final state
  - Low-p_T channel (new)
    - MET>160 GeV, $S = \frac{E_T^{miss}}{\sqrt{\sigma_L\left(1-\rho_{LT}^2\right)}} > 10$
    - Categorize events based on presence/mass of leading jet (p_T > 200 GeV)





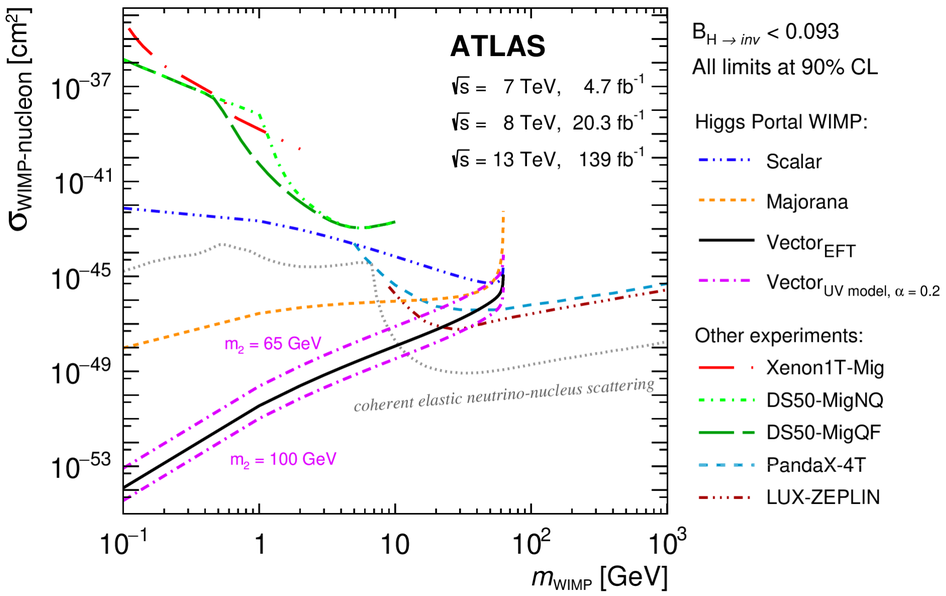


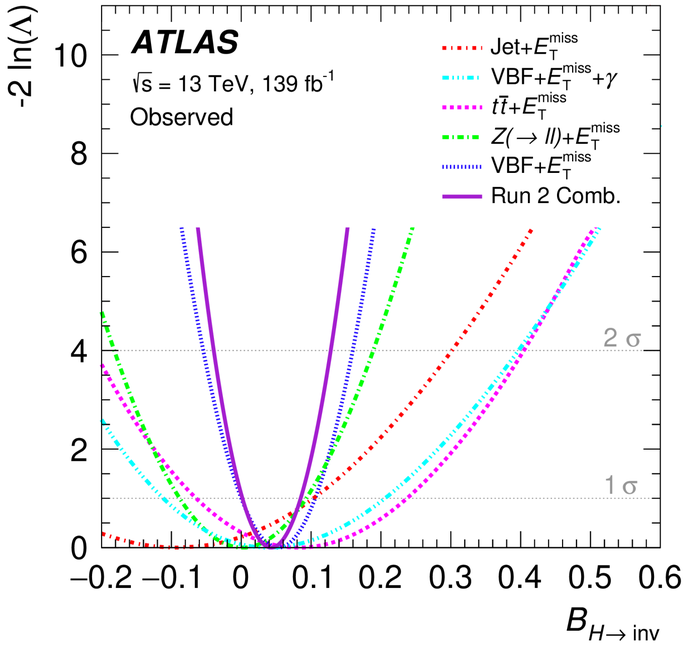
Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.08^{+0.20}_{-0.19}$	0.36	$0.40^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$

[2301.10731]

Higgs → Invisible: Combination

- Statistical combination of all searches
- Searches for h→invisible are largely orthogonal
  - Overlapping data (signal MC) events between ggF and VBF: 0.2% (1.5%)
    - Negligible impact of limit





Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + E_T^{miss}	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + E_T^{miss} + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + E_T^{miss}	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell)$ + E_T^{miss}	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + E_T^{miss}	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

B(h→inv) < 13% from visible channels

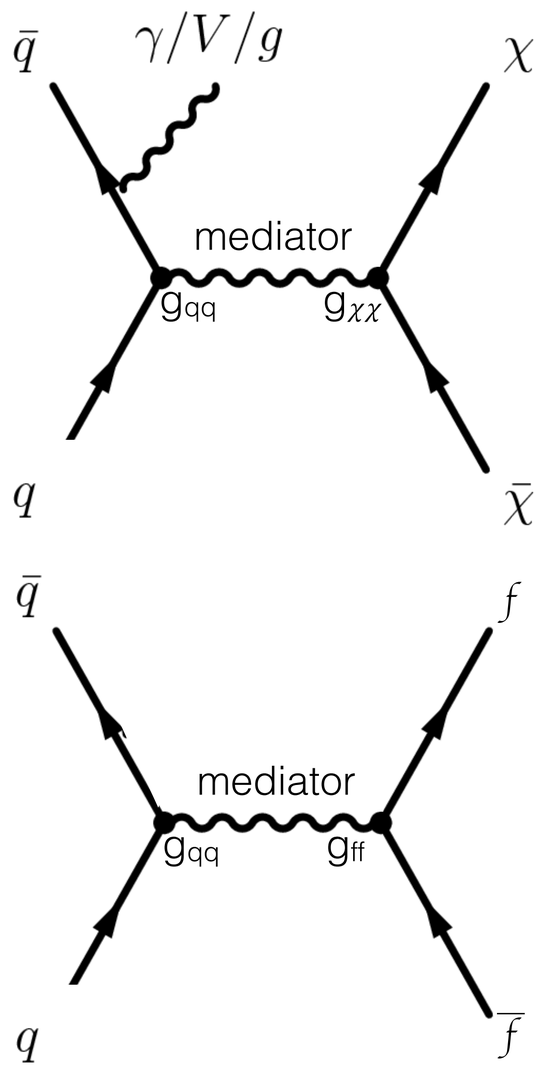
uncertainties

Source of uncertainty	Run2	Run1+2
Luminosity / pile up	0.005	0.005
Leptons / Photons	0.014	0.013
Jets	0.013	0.013
Flavour tagging	0.002	0.001
E_T^{miss}	0.004	0.003
MC statistics	0.013	0.012
All experimental	0.024	0.023
V+jets modelling	0.019	0.018
Other background Modelling	0.014	0.014
Data-driven Backgrounds	0.011	0.010
Signal Modelling	0.002	0.003
All theory	0.025	0.024
Total systematic uncertainty	0.037	0.035
Data statistics	0.011	0.011
Background normalization	0.012	0.012
Total statistical uncertainty	0.017	0.016
Total uncertainty	0.041	0.039

S-Channel Simplified Models

Simplified Models

- Assume DM is a Dirac fermion
- Consider CP-even and CP-odd mediators
  - Spin-1: flavor-independent couplings to SM
  - Spin-0: Yukawa-like couplings to SM (minimal flavor violation scenario)
- MET- and resonance-based searches → probe different regions of high-dimensional phase space

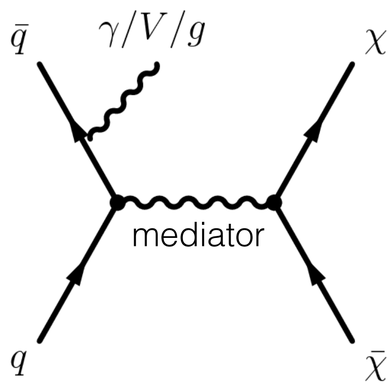


[PRD 103 (2021) 112006]

MET-Based Searches

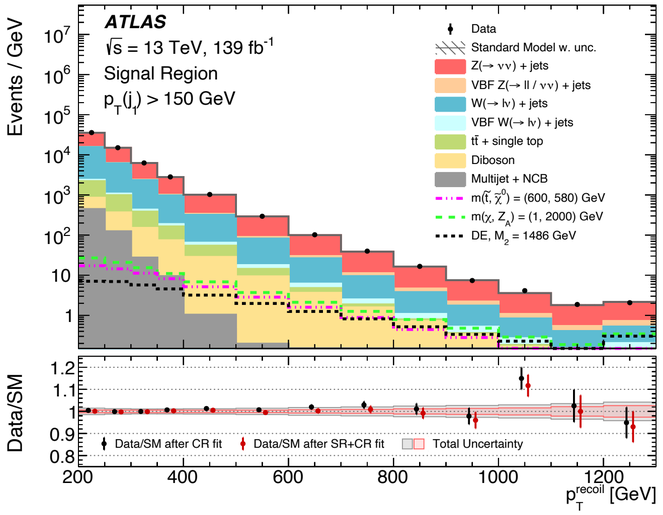
- ISR is dictated by SM → model-independent
- Systematics limited → precise background estimates vital

mono-j	PRD 103 (2021) 112006
mono-γ	JHEP 02 (2021) 226
mono-Z($\ell\ell$)	PLB 829 (2022) 137066

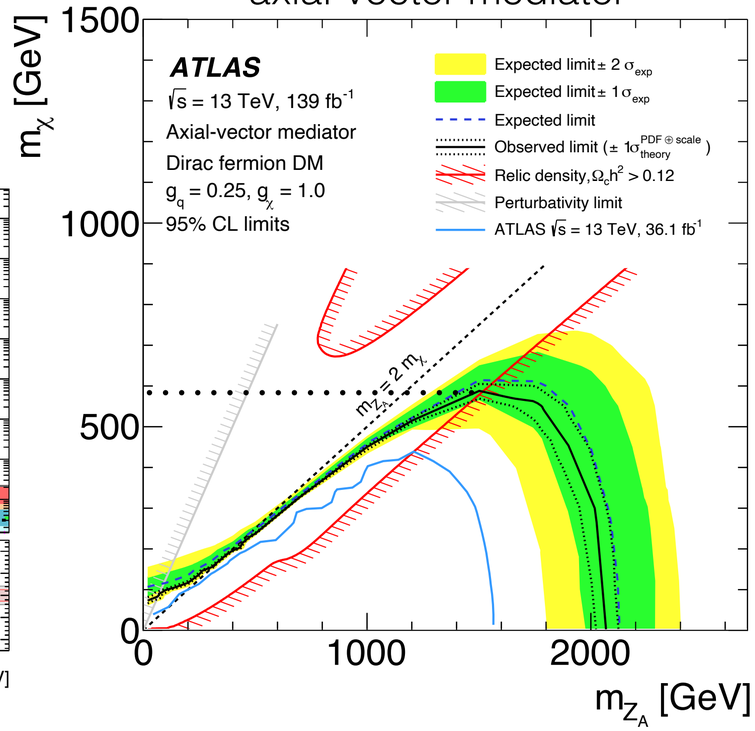


- Mono-jet
  - σ_W/σ_Z constrained to SM prediction (NLO QCD/EWK)
  - Simultaneous likelihood fit in SR and CRs used to constrain dominant Z→νν background

Requirement	SR	$W \to \mu\nu$	$Z \to \mu\mu$	$W \to e\nu$	$Z \to ee$	Top
Primary vertex	at least one with ≥ 2 associated tracks with $p_T > 500$ MeV					
Trigger	E_T^{miss}			single-electron		E_T^{miss}, single-electron
p_T^{recoil} cut	$E_T^{miss} >$ 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu) \rvert >$ 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu\mu) \rvert >$ 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(e) \rvert >$ 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(ee) \rvert >$ 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu) \rvert >$ 200 GeV or $\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(e) \rvert >$ 200 GeV
Jets	up to 4 with $p_T > 30$ GeV, $\lvert\eta\rvert < 2.8$					
$\lvert\Delta\phi(\text{jets}, \mathbf{p}_T^{recoil})\rvert$	> 0.4 (> 0.6 if 200 GeV $< E_T^{miss} \leq 250$ GeV)					
Leading jet	$p_T > 150$ GeV, $\lvert\eta\rvert < 2.4$, $f_{ch}/f_{max} > 0.1$					



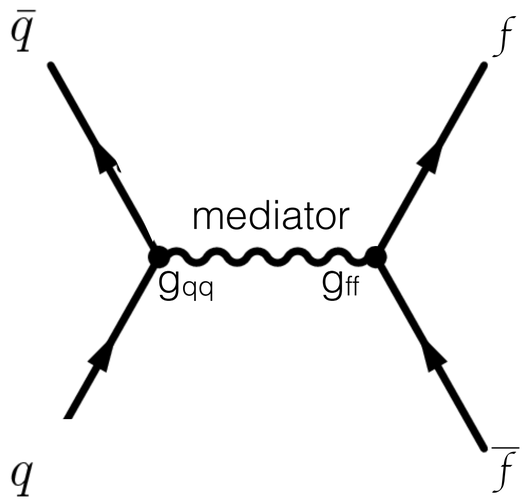
axial-vector mediator

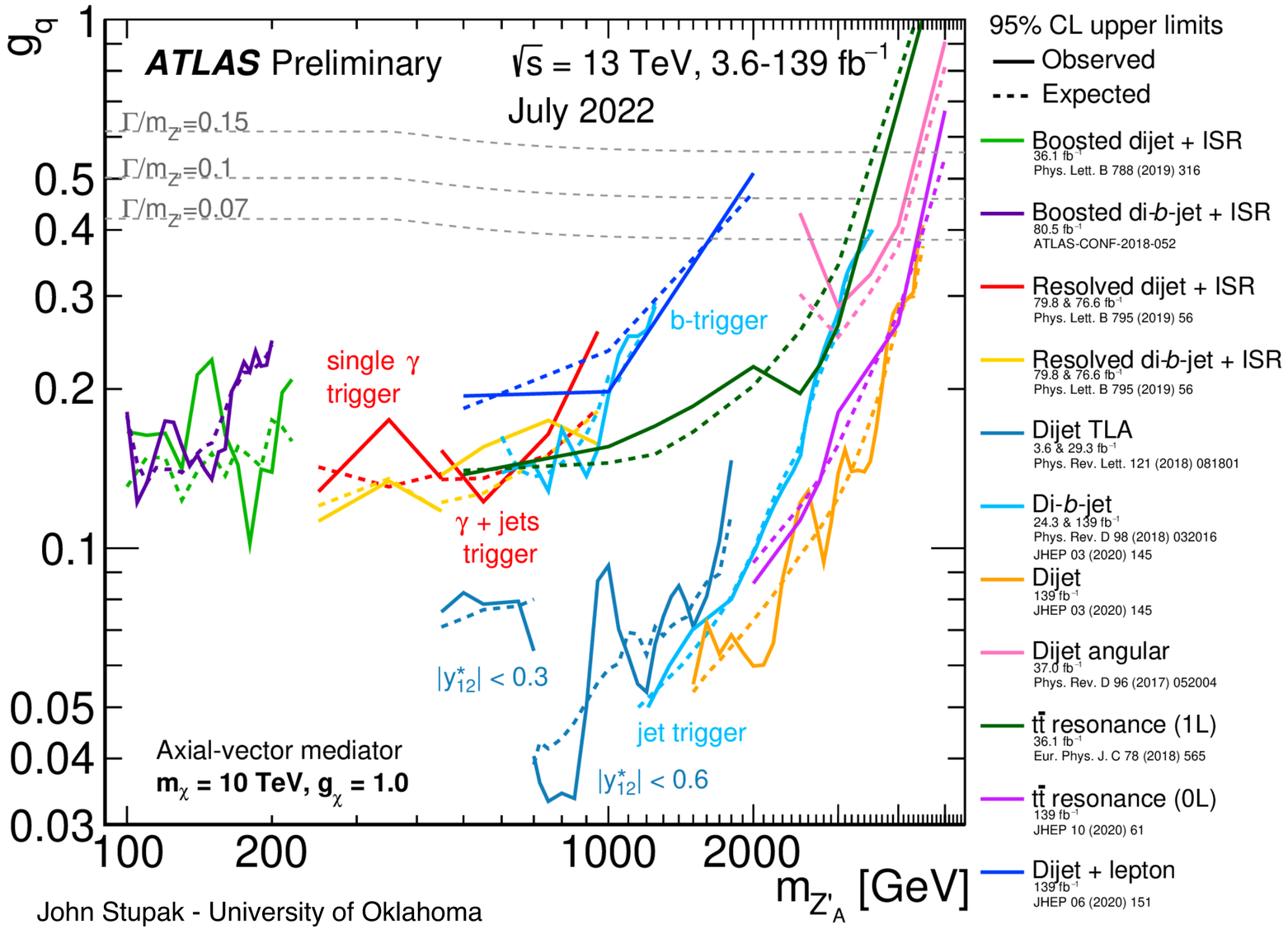


[ATL-PHYS-PUB-2022-036]

Resonance-Based Searches

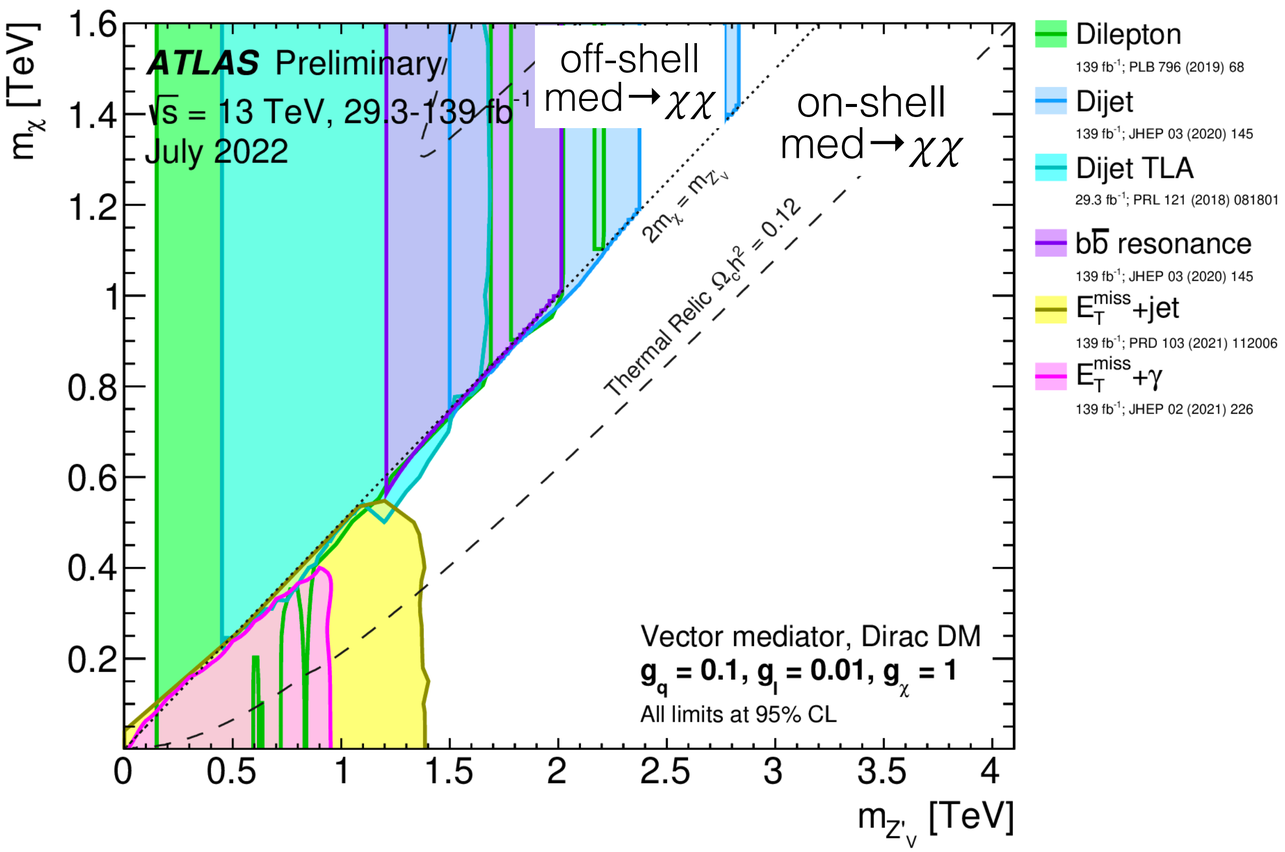
- Resonance searches can be interpreted in DM simplified models
  - High mass: limited by small cross section
  - Low mass: limited by trigger and background rejection

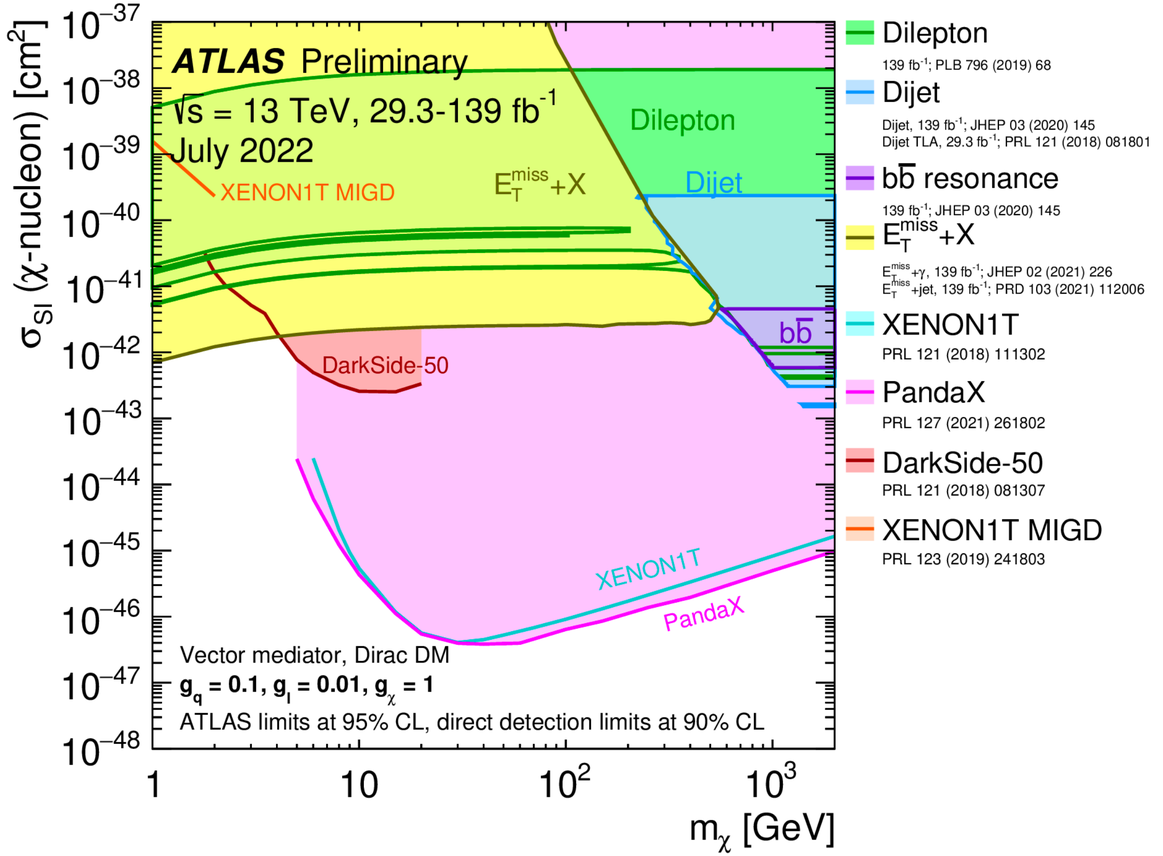




[ATL-PHYS-PUB-2022-036]

Summary

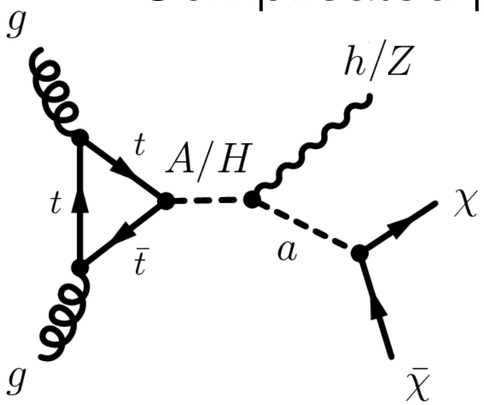




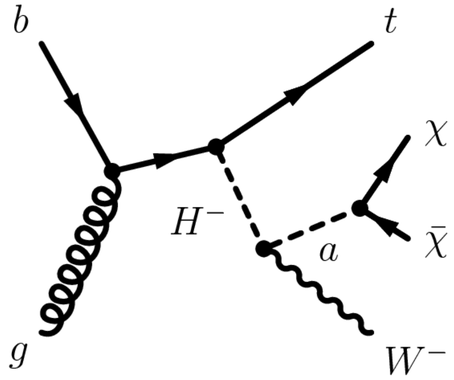
2HDM + a

2HDM+a Model

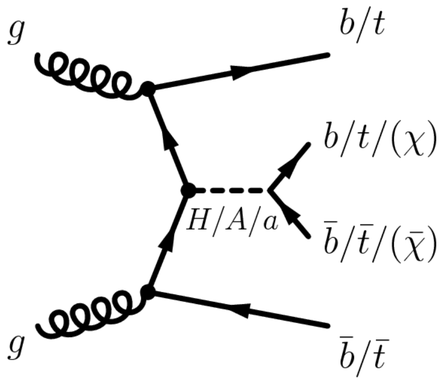
- CP conserving type-2 2HDM (in the alignment and decoupling limit) with additional pseudoscalar
  - Gauge invariant, renormalizable, UV complete
- Mixing between *A* and *a* couples SM to DM
- 14 parameters → 5 (assumptions)
  - Complicated phenomenology with additional signatures:



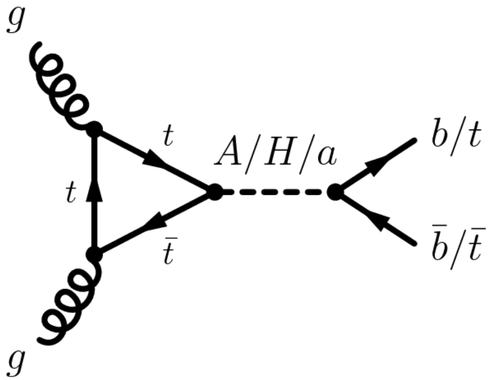
mono-h/Z



tW + MET



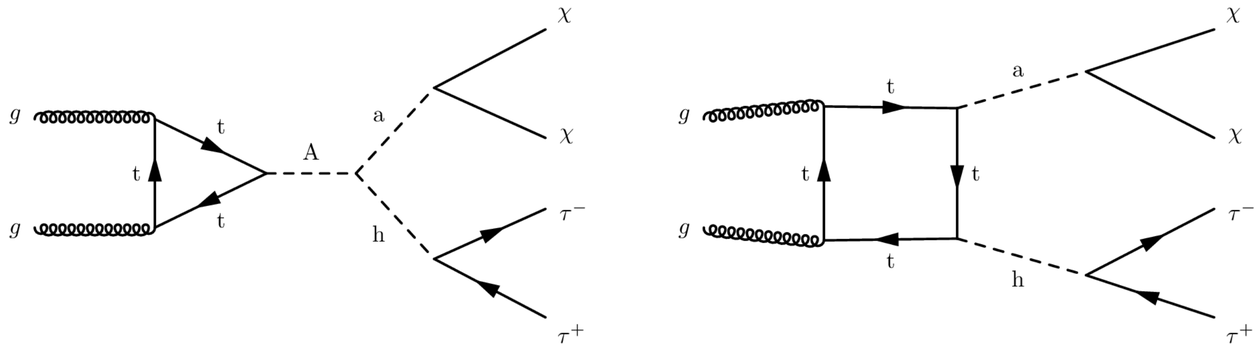
tt/bb + MET
4 t/b



t/b resonance

[ATLAS-CONF-2022-069]

Mono-h($\tau\tau$)



mono-h(bb)	JHEP11(2021) 209
mono-h($\gamma\gamma$)	JHEP10(2021) 013
mono-h($\tau\tau$)	ATLAS-CONF-2022-069

- Search for h→$\tau_h\tau_h$ in association with MET
  - Optimized separately for low- and high-mass *A*
- Di-τ_{had} + MET trigger allows reduced MET threshold (150 GeV)
- "Fake factor" method used to model background with fake τ_h
  - Assumption: N_{tight}/N_{loose} = f(p_T, η, N_{track}, g/q initiated)
  - Measure N_{tight}/N_{loose} in fake-enriched CR
  - Apply this ratio to loose τ candidates to obtain fake tau contribution
- Backgrounds with real τ_h (Z+jets, ttbar) normalized to data in CRs
  - Modeling checked in 4 VRs

	Common SR Preselection
$\Delta R(\tau_1, \tau_2)$	< 2
m_T^{tot}	> 50 GeV
$m_{vis}(\tau_1, \tau_2)$	$\in [40, 125]$ GeV
$m_T^{\tau_1} + m_T^{\tau_2}$	> 100 GeV
Charge(τ_1, τ_2)	$q(\tau_1) \times q(\tau_2) = -1$
$N_{b\text{-jet}}$	0

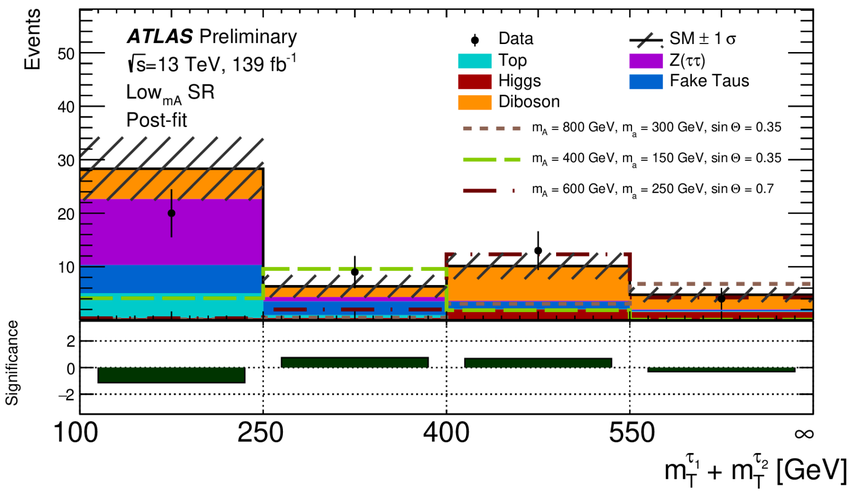
	Low_{m_A} SR	High_{m_A} SR
$\Delta R(\tau_1, \tau_2)$	$\in [0.6, 1.9]$	< 2
m_T^{tot}	-	> 400 GeV
$m_T^{\tau_1}$	> 50 GeV	-
$m_T^{\tau_2}$	> 25 GeV	-
$m_{vis}(\tau_1, \tau_2)$	> 75 GeV	$\in [40, 125]$ GeV
$m_T^{\tau_1} + m_T^{\tau_2}$ Binning	$[100, 250, 400, 550, \infty]$ GeV	$[400, 750, \infty]$ GeV

$$m_T^{tot} = \sqrt{(p_T(\tau_1) + p_T(\tau_2) + p_T^{miss})^2 - (p_x(\tau_1) + p_x(\tau_2) + p_x^{miss})^2 - (p_y(\tau_1) + p_y(\tau_2) + p_y^{miss})^2}$$

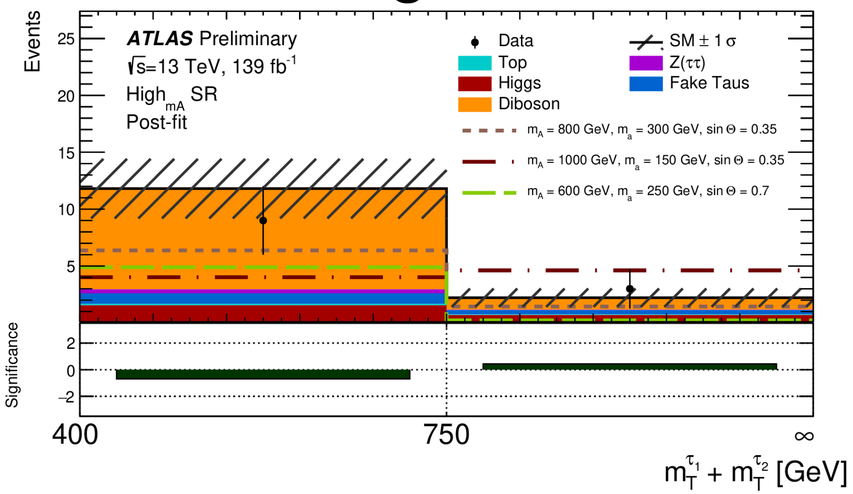
[ATLAS-CONF-2022-069]

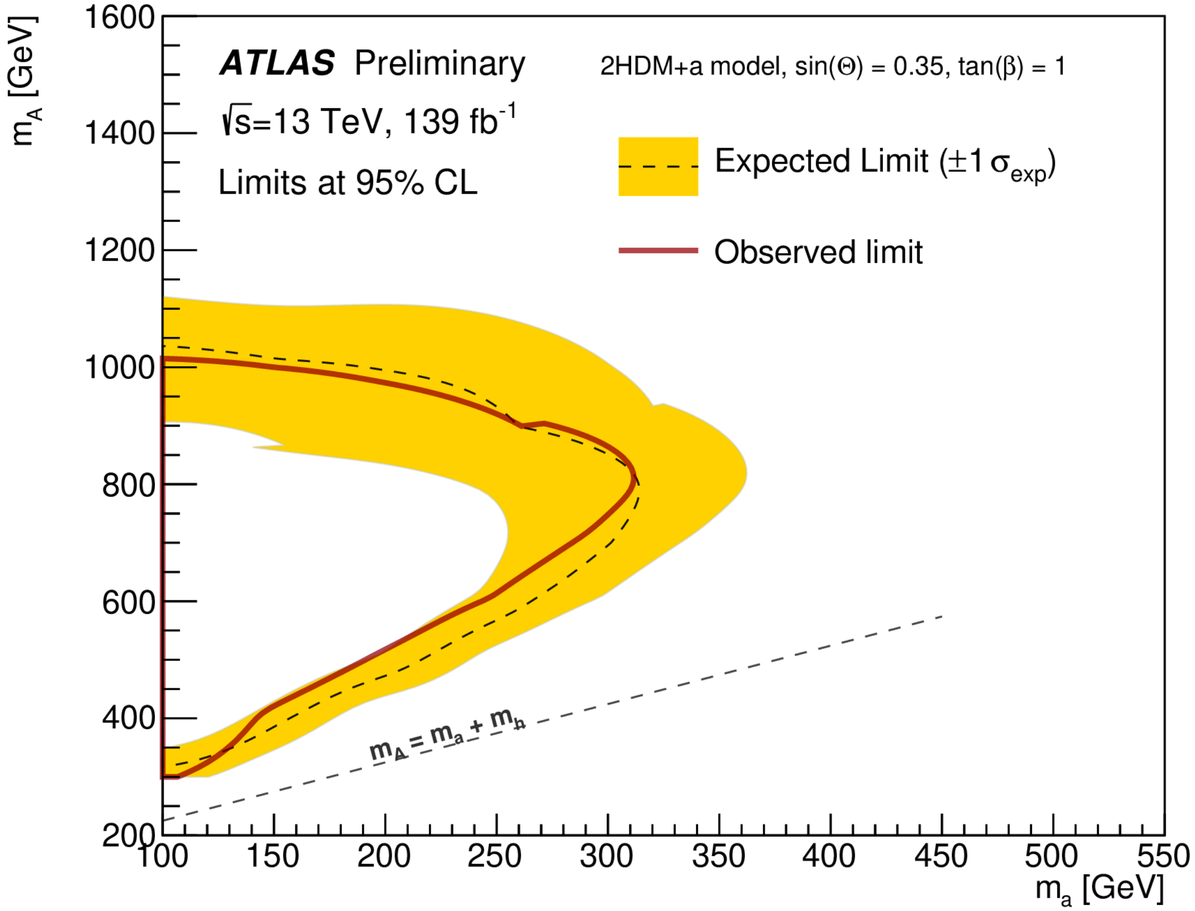
Mono-h($\tau\tau$)

low m_A



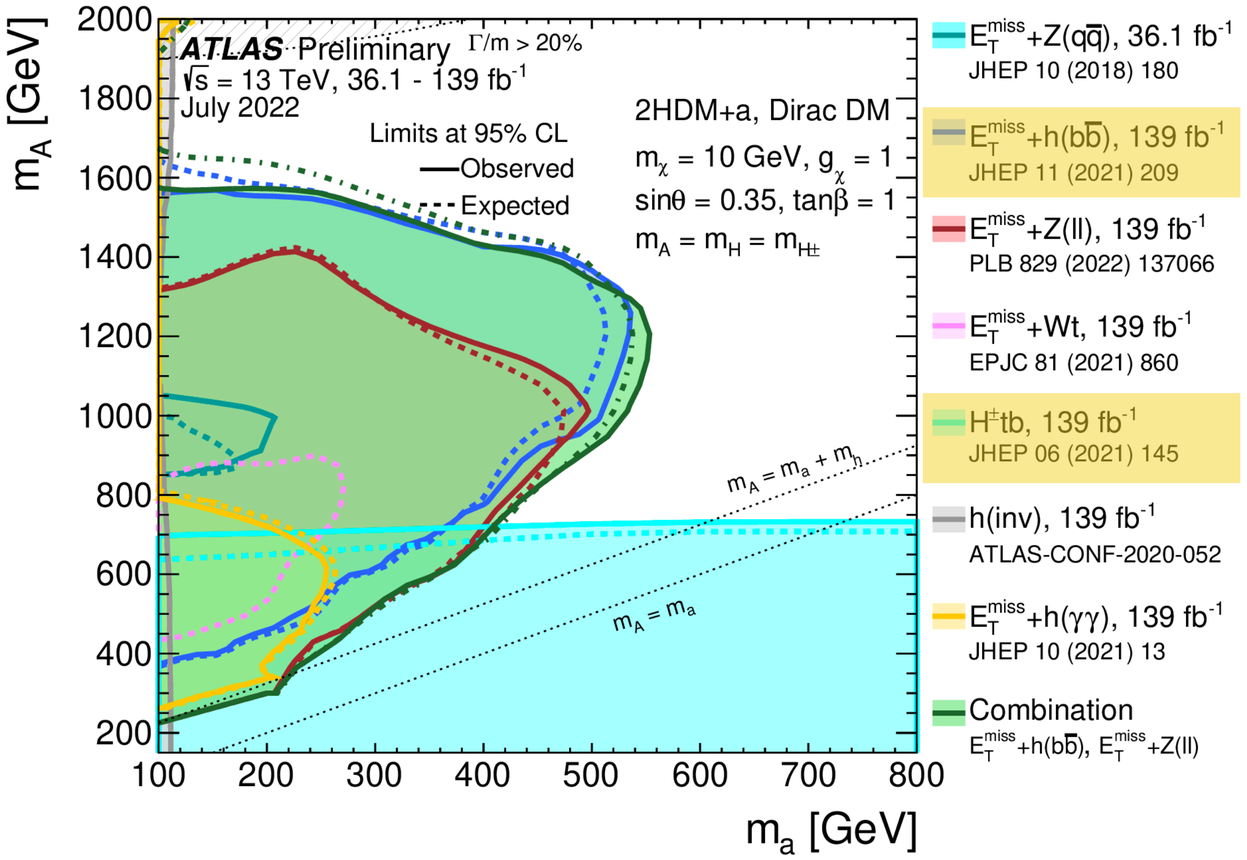
high m_A

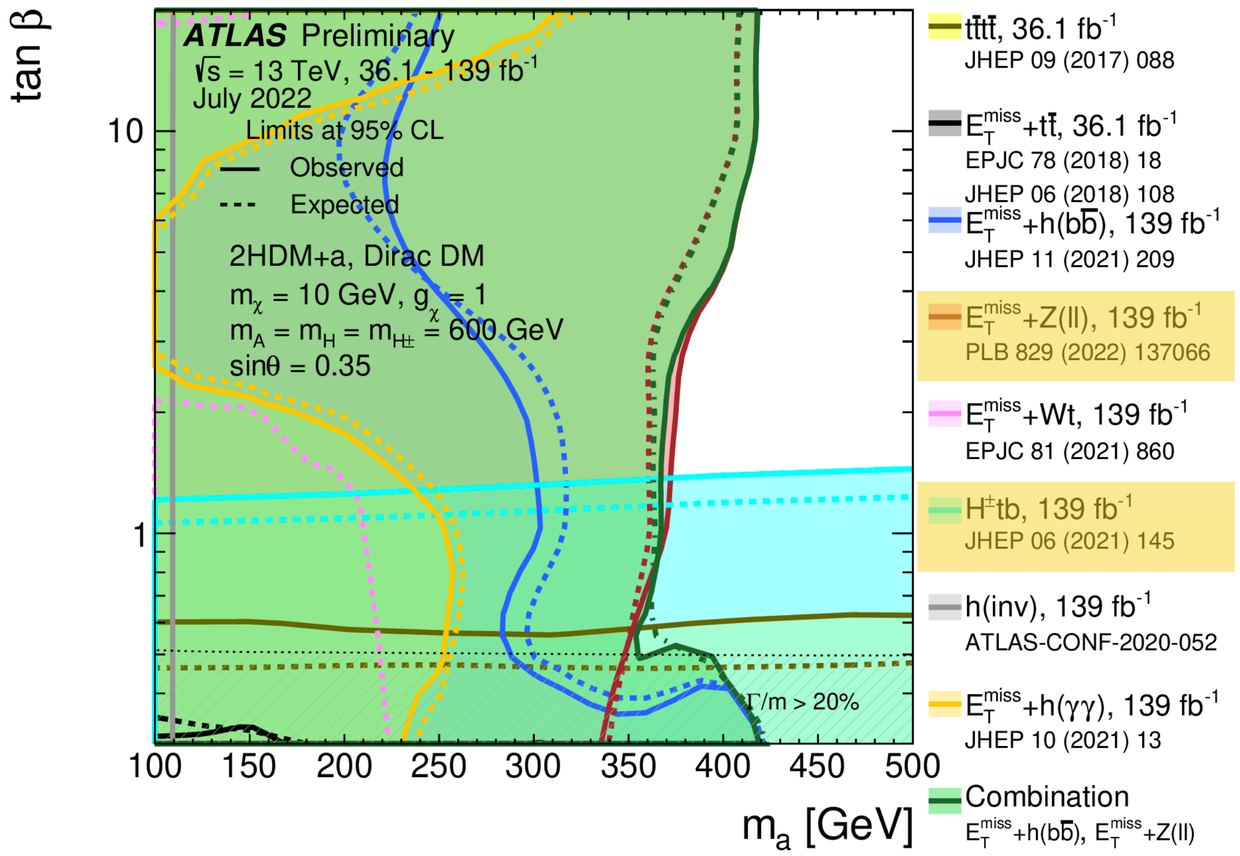




[ATL-PHYS-PUB-2022-036]

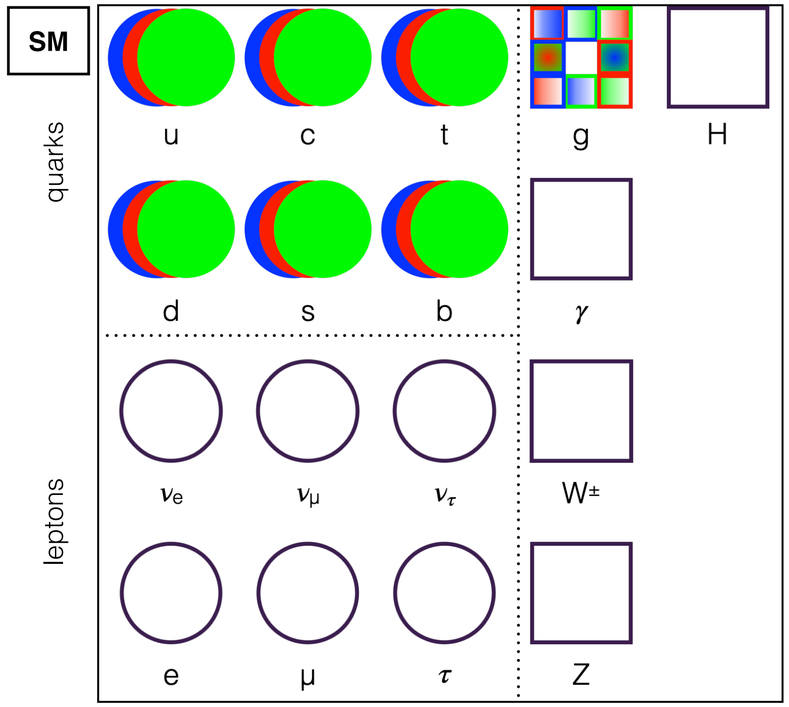
Summary

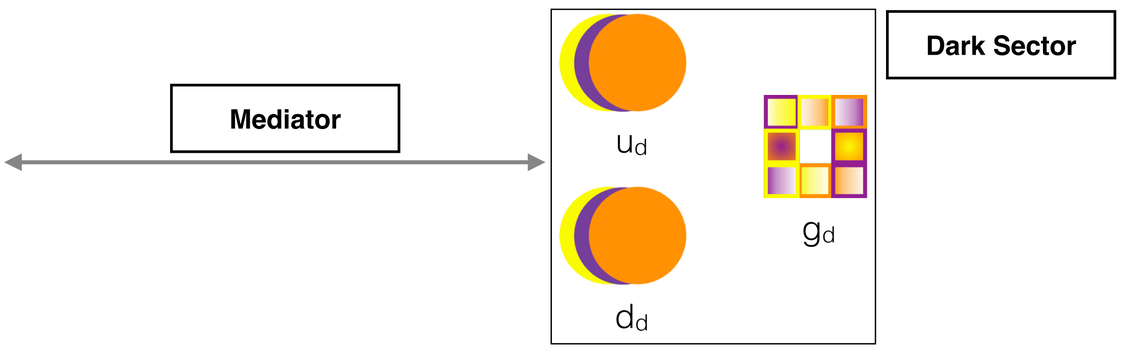


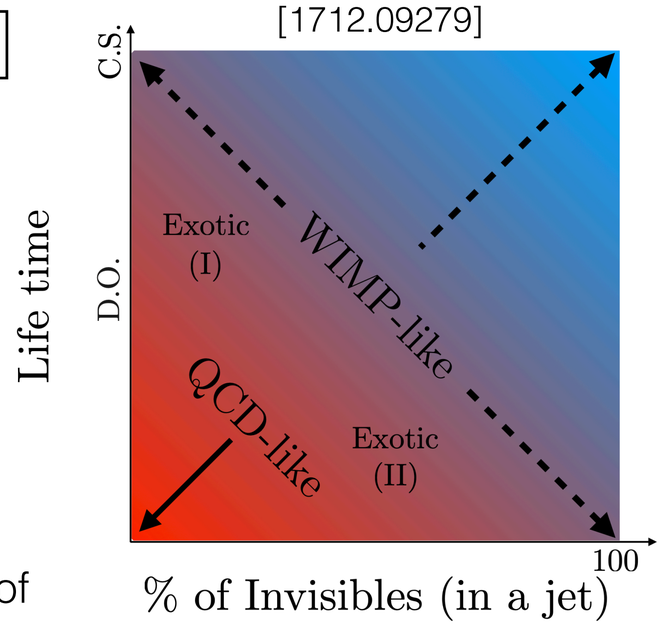


Strongly-Interacting DM

Dark QCD

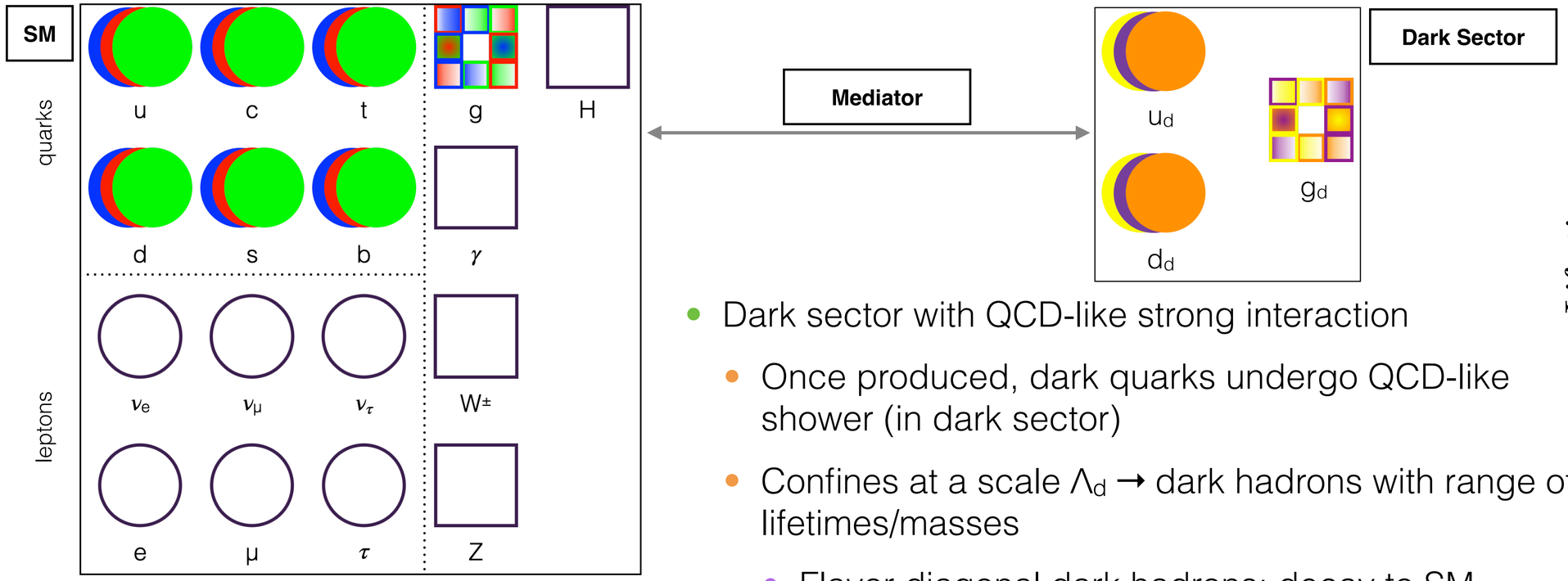


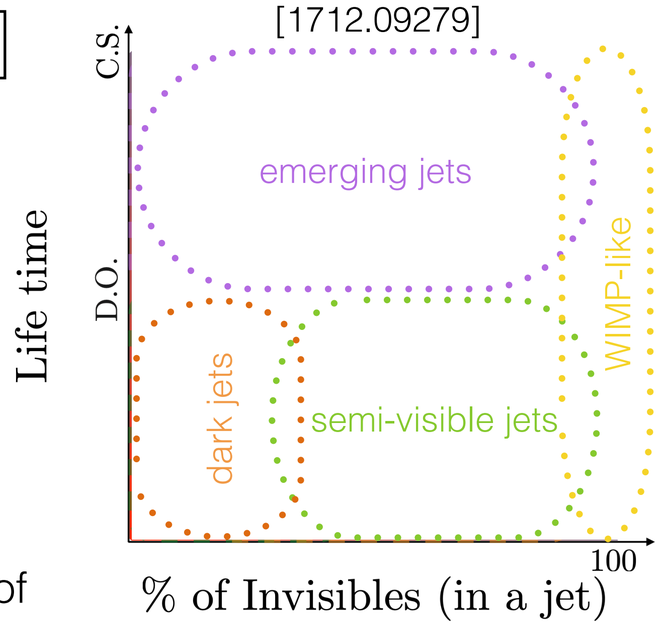




- Dark sector with QCD-like strong interaction
  - Once produced, dark quarks undergo QCD-like shower (in dark sector)
  - Confines at a scale Λ_d → dark hadrons with range of lifetimes/masses
    - Flavor diagonal dark hadrons: decay to SM
    - Flavor off-diagonal dark hadrons: invisible
- Modeling of non-perturbative dark shower is complicated
  - Bottom up approach: ignore underlying physics and parameterize shower in terms of lifetime and $R_{\rm inv} \equiv \left\langle \frac{\text{number of stable dark hadrons}}{\text{total number of hadrons}} \right\rangle$

Dark QCD





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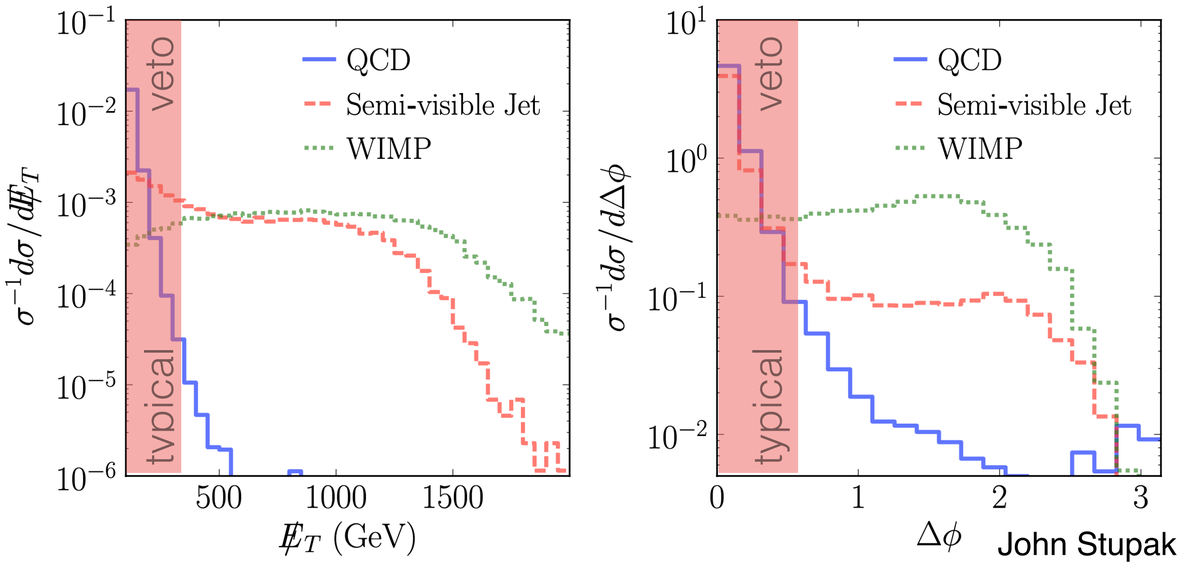
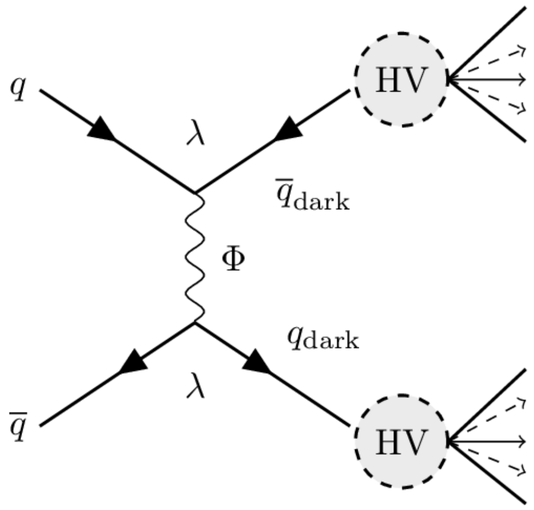
[ATLAS-CONF-2022-038]

Semi-Visible Jets

- Search for (prompt) semi-visible jets produced through a *t*-channel mediator
  - Large MET, aligned with jet
    - DM searches typically veto small Δϕ(j,MET) to reject QCD

[1712.09279]



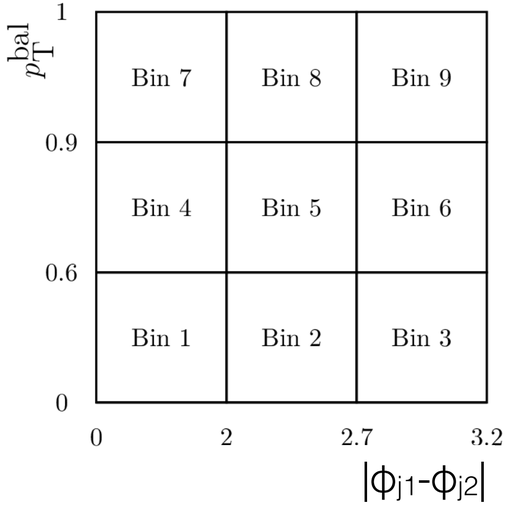


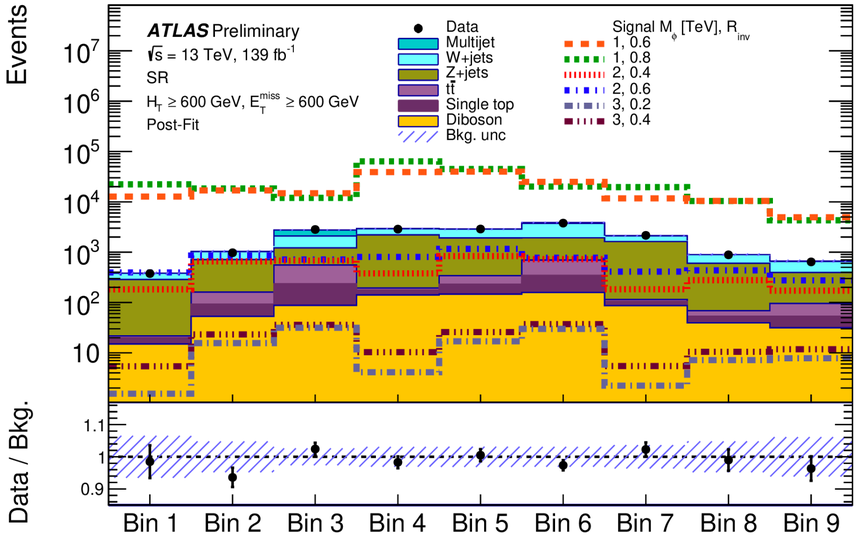
- SR:
  - H_T > 600 GeV
  - MET > 600 GeV
  - ≥2 jets
    - ≤1 b-tag
  - Δϕ(MET,jet) < 2
  - 0 leptons
- CRs for W+jets (1μ/0b), top (1μ/1b), and Z+jets (2μ/0b)
- VRs with reduced MET

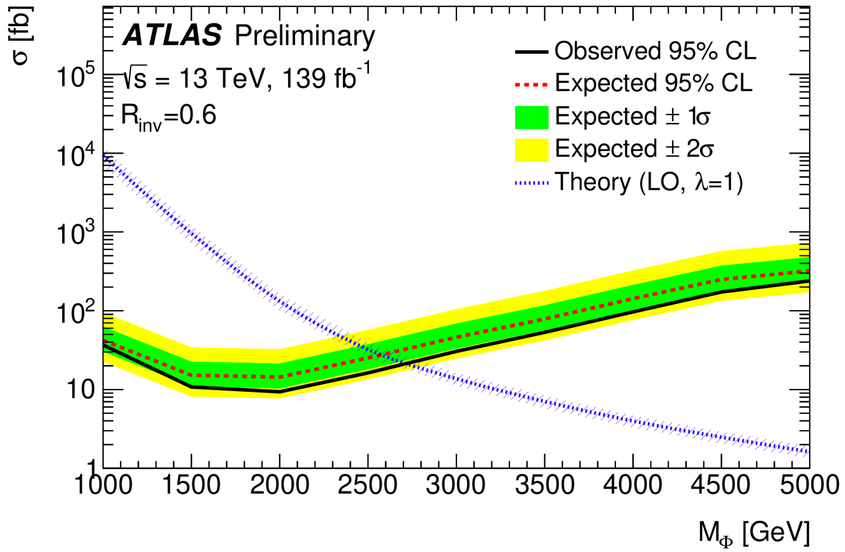
[ATLAS-CONF-2022-038]

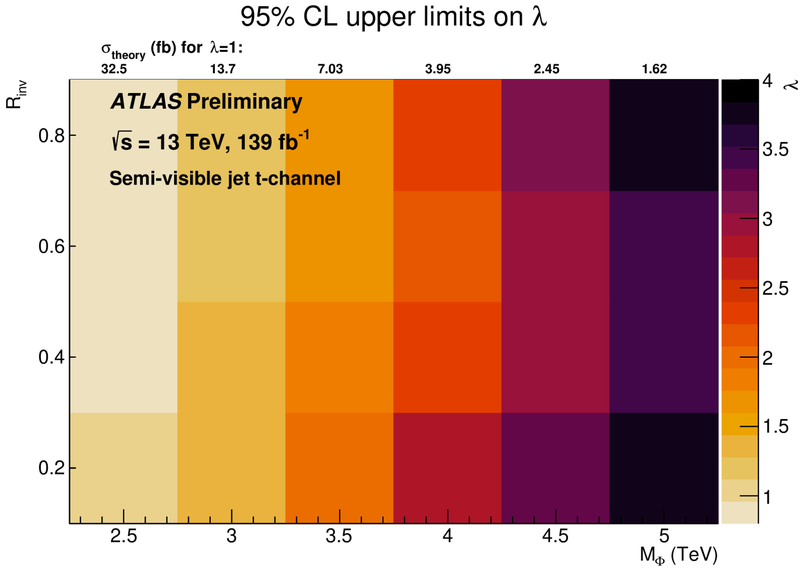
Semi-Visible Jets

- SR binned in terms of $|\phi_{j1}-\phi_{j2}|$ and $p_T^{bal} = \frac{|\vec{p}_T(j_1)+\vec{p}_T(j_2)|}{|\vec{p}_T(j_1)|+|\vec{p}_T(j_2)|}$
- No excess over SM
  - Excludes mediator masses >2.4–2.7 TeV for $0.2<R_{inv}<0.8$ (λ =1)









Conclusion

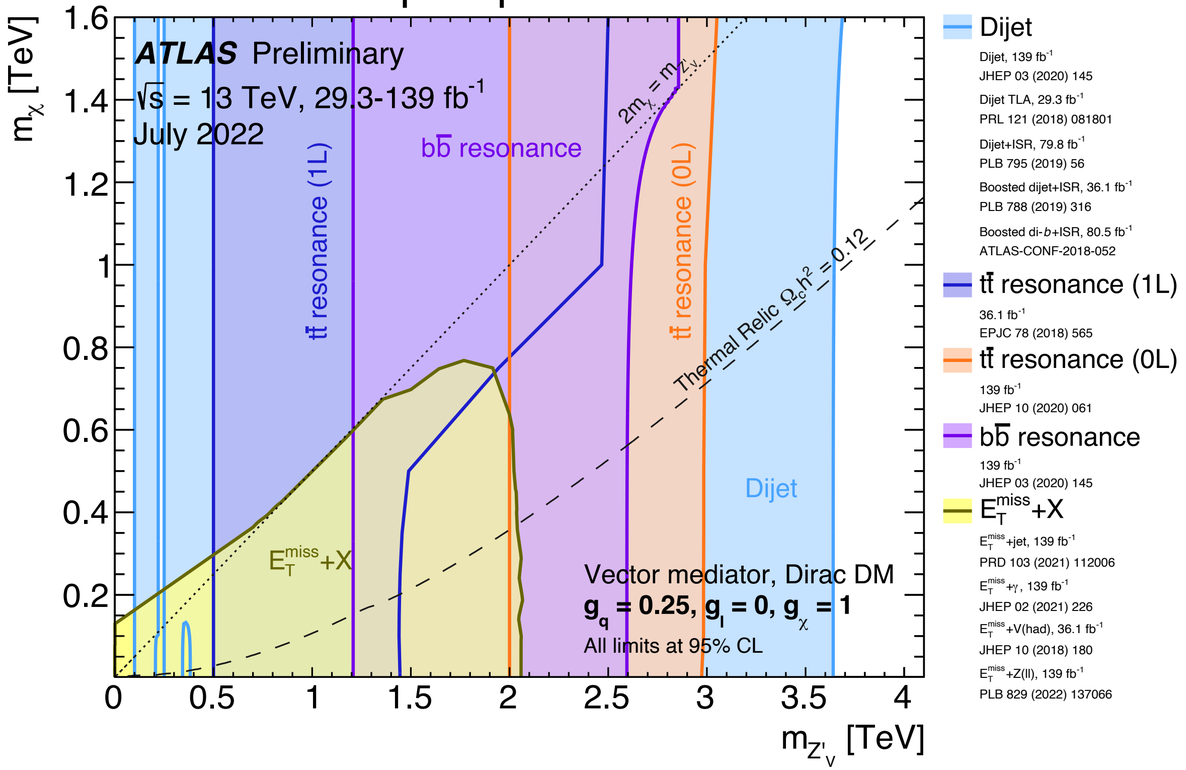
- ATLAS has a strong DM search program
  - Wide range of models/signatures probed
- Complementarity between:
  - Colliders and direct/indirect detection experiment
  - Visible and MET-based searches
  - Various visible final states
- No significant evidence for DM yet
  - Results shown here are based on ≲5% of the anticipated LHC luminosity
    - Stay tuned!

Backup

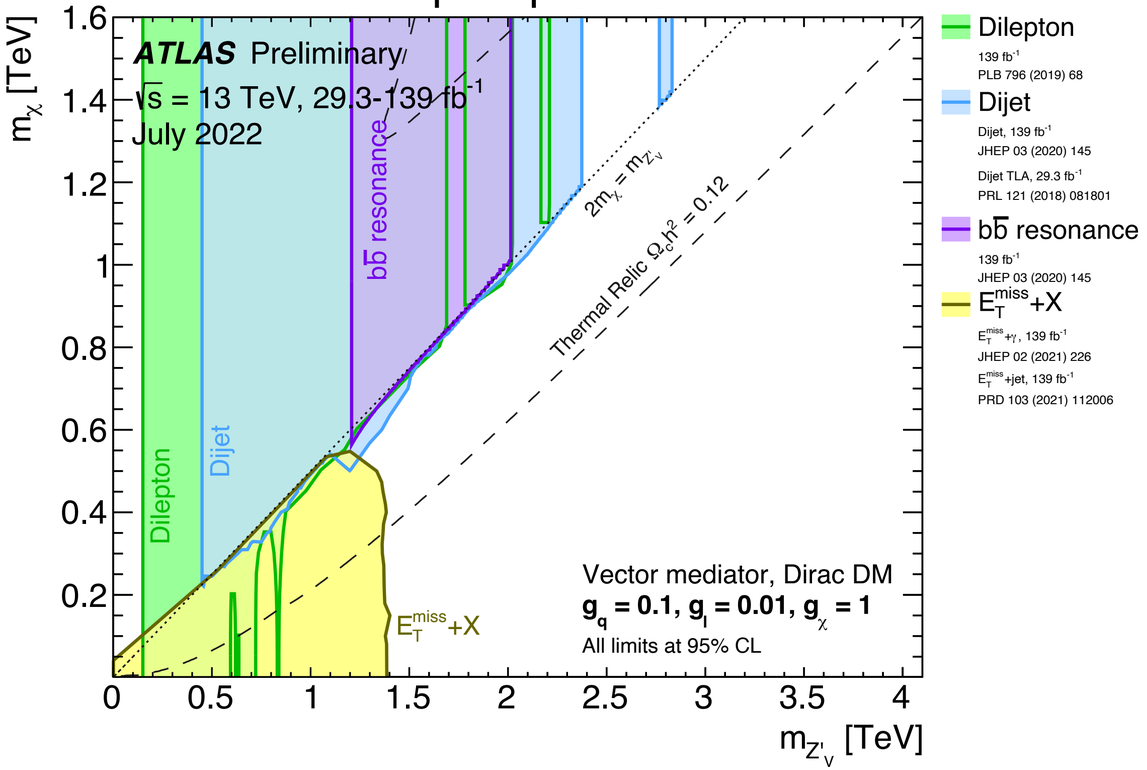
[ATL-PHYS-PUB-2022-036]

Vector Mediator

leptophobic



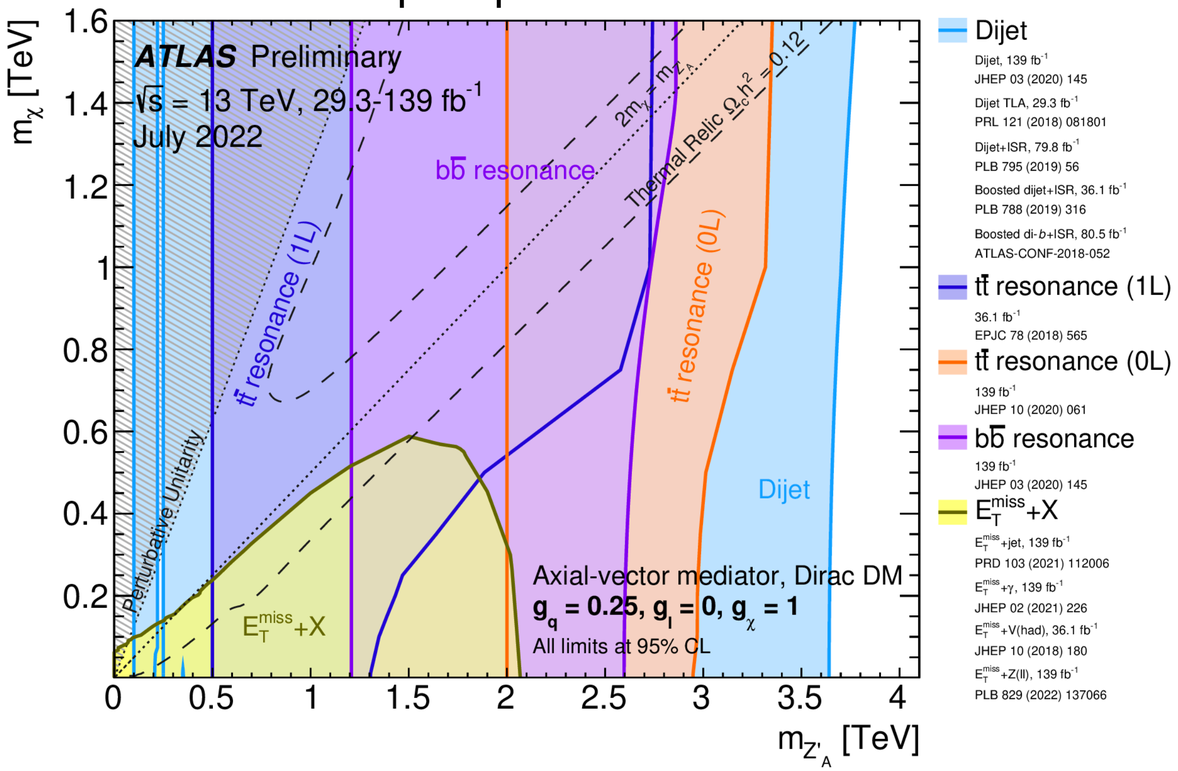
leptophilic



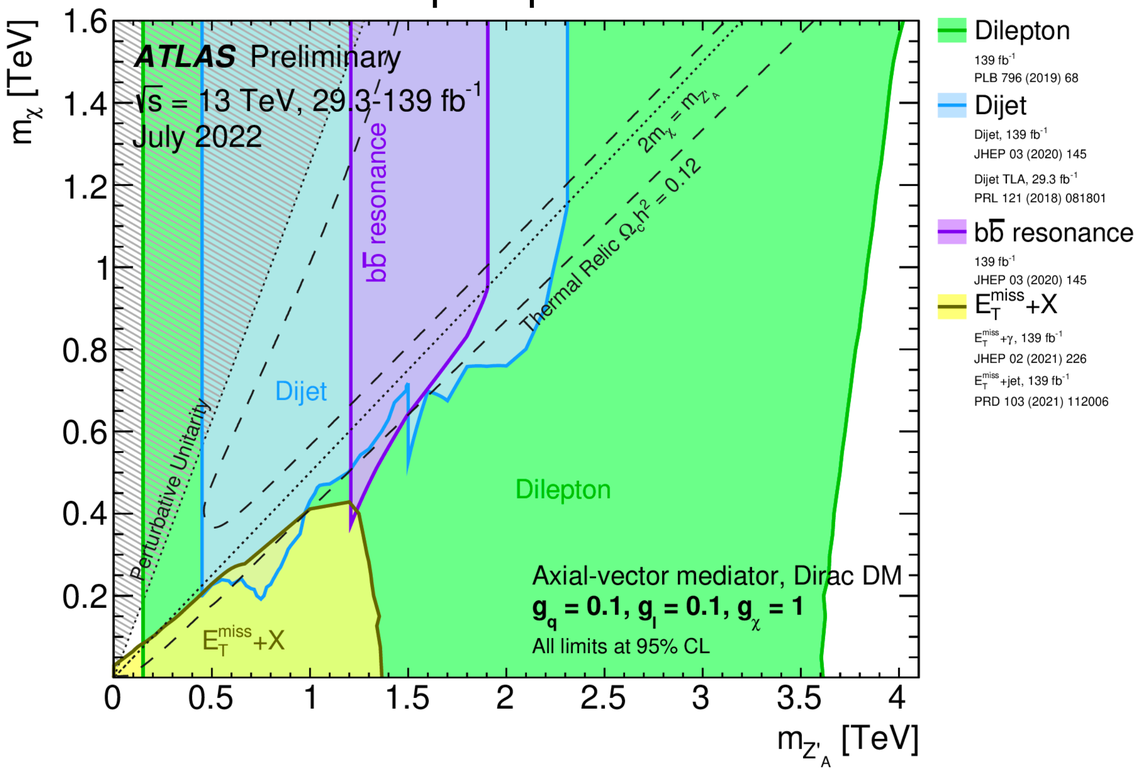
[ATL-PHYS-PUB-2022-036]

Axial-Vector Mediator

leptophobic



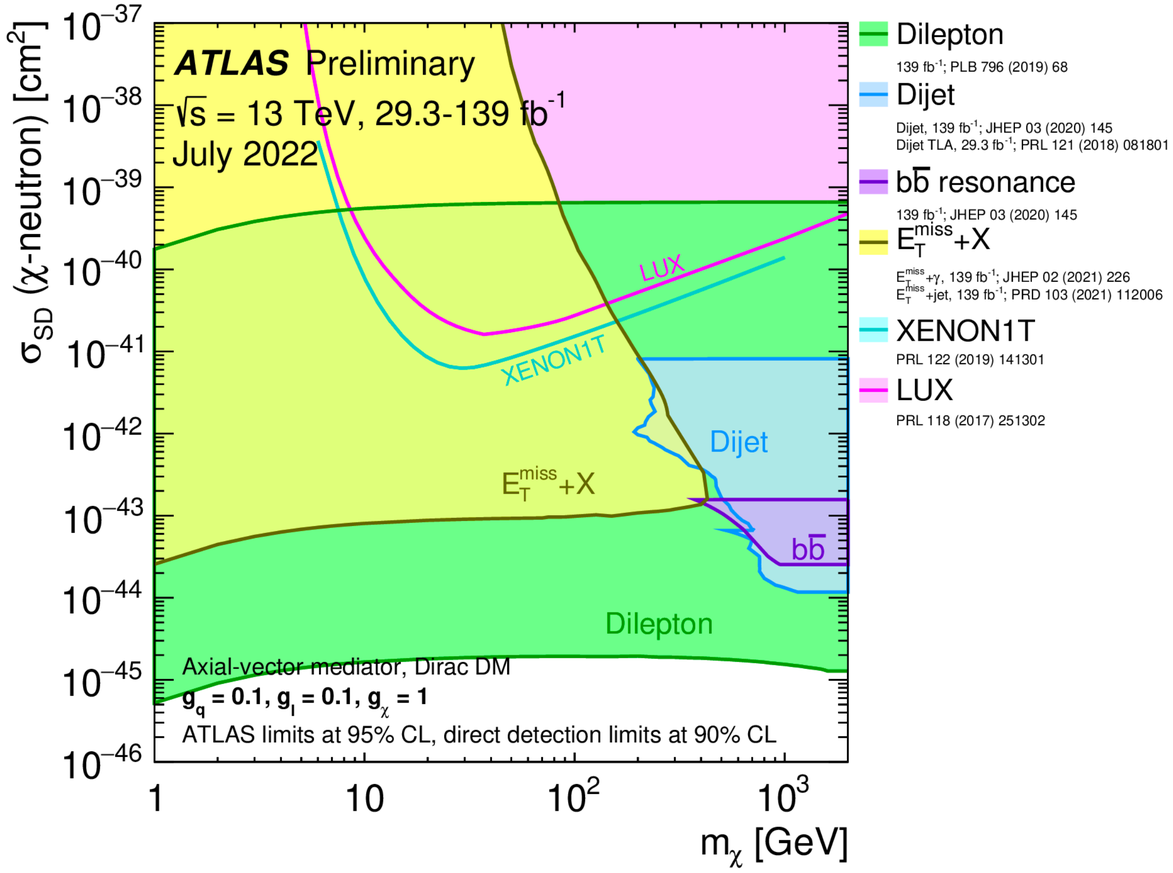
leptophilic



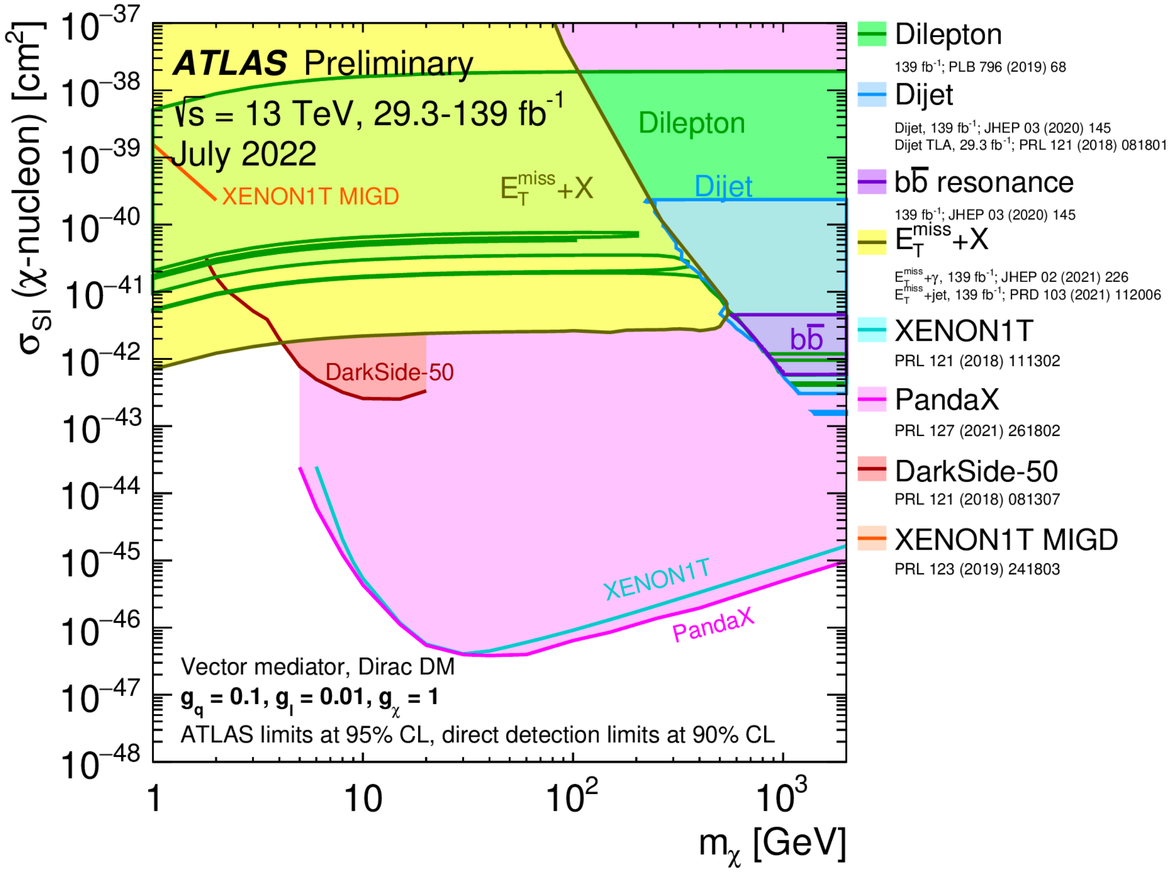
[ATL-PHYS-PUB-2022-036]

Direct Detection Comparison

spin-dependent cross section
axial-vector mediator



spin-independent cross section
vector mediator

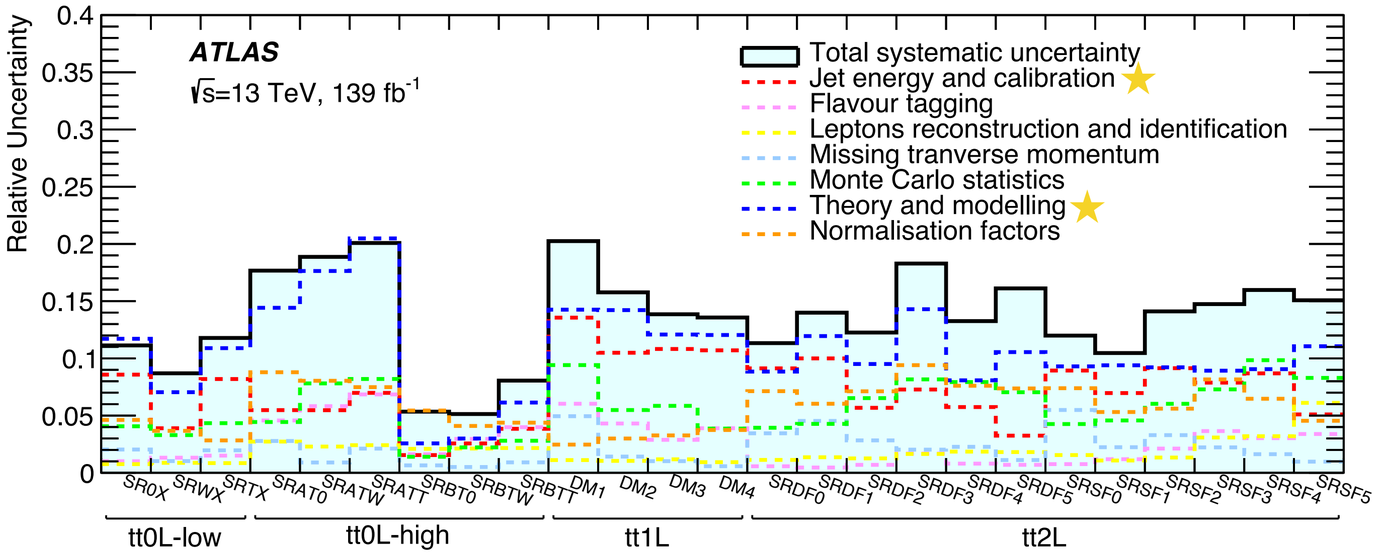


[ATLAS-CONF-2022-007]

Higgs → Invisible: tth

- 0ℓ final state
  - ≥4 jets (2 b-tagged)
  - High-p_T channel
    - MET>250 GeV, $\mathcal{S} = \frac{E_T^{miss}}{\sqrt{\sigma_L^2 (1-\rho_{LT}^2)}} > 14$
    - $p_{T,j2}$ > 80 GeV
    - ≥1 top tag (m>120 GeV)
    - Categorize events based on mass of subleading jet and m_{T2,χ^2}
  - Low-p_T channel (new)
    - MET>160 GeV, $\mathcal{S} > 10$
    - Categorize events based on presence/ mass of leading jet (p_T > 200 GeV)

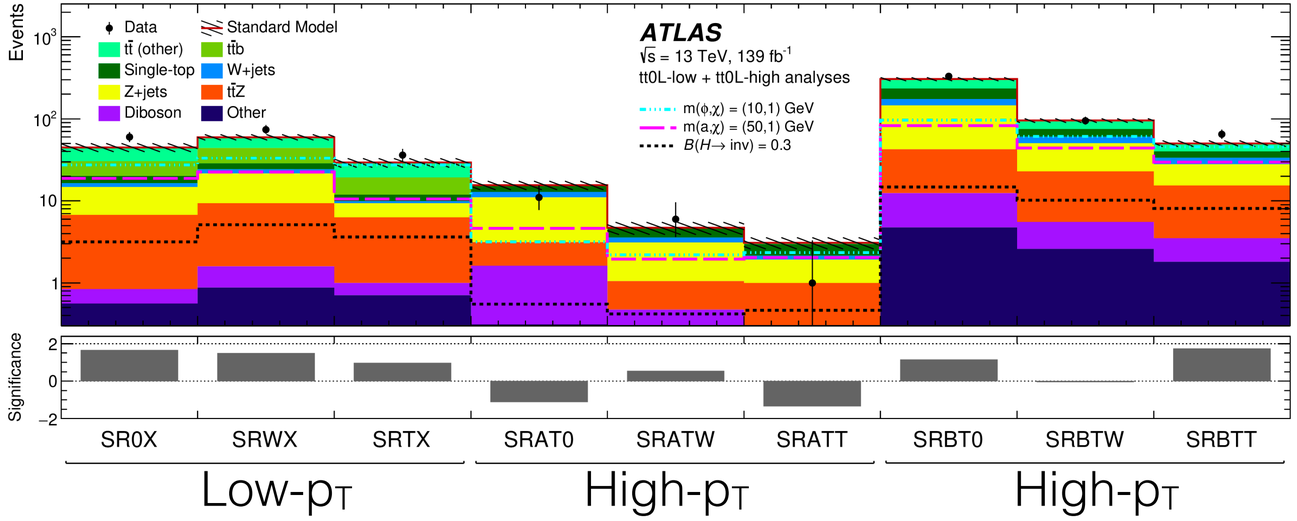
	Variables	SR0X	SRWX	SRTX
	N_{lepton}	= 0		
	Orthogonalisation	$E_T^{miss} < 250$ GeV or $\mathcal{S} < 14$ or $m^{R=1.2}_{\text{large-radius jet}} < 120$ GeV		
	E_T^{miss} [GeV]	> 160 < 250, when passing b-jet triggers		
	$\mathcal{S}$	> 10		
QCD	$\Delta\phi_{min}(\boldsymbol{p}_{T,1\text{-}4}, \boldsymbol{p}_T^{miss})$	> 1.0	> 0.5	
g→bb	$\Delta R(b_1, b_2)$	> 1.2		
	$N_{\text{large-radius jet}}$	= 0	> 0	
	$m_{\text{large-radius jet}}$ [GeV]	—	(40, 130)	≥ 130
	ΔR_{min}(large-radius jet, b-tagged jets)	—		< 1.2
tt	$\cosh_{max}$	< 0.5	< 0.6	< 0.7
	$\chi^2_{t\bar{t},\text{had}}$	< 4	< 6	< 8
	$p_T^{t\bar{t}}/E_T^{miss}$	(0.7, 1.2)	(0.5, 1.2)	



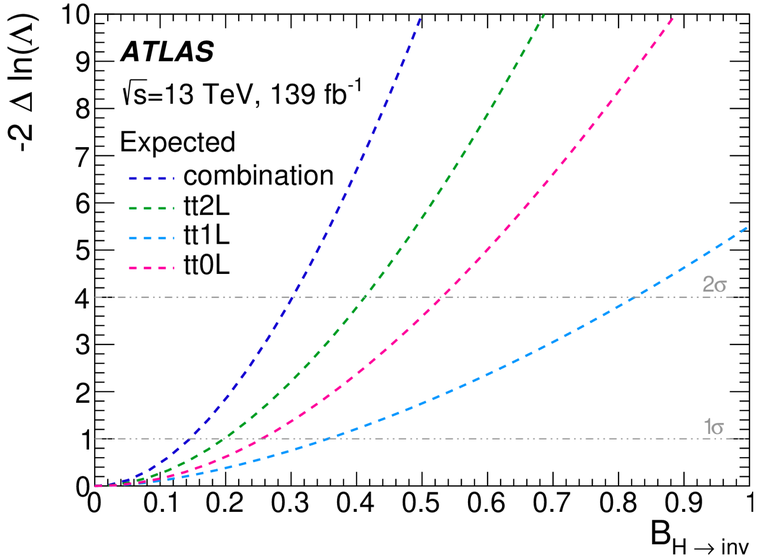
[ATLAS-CONF-2022-007]

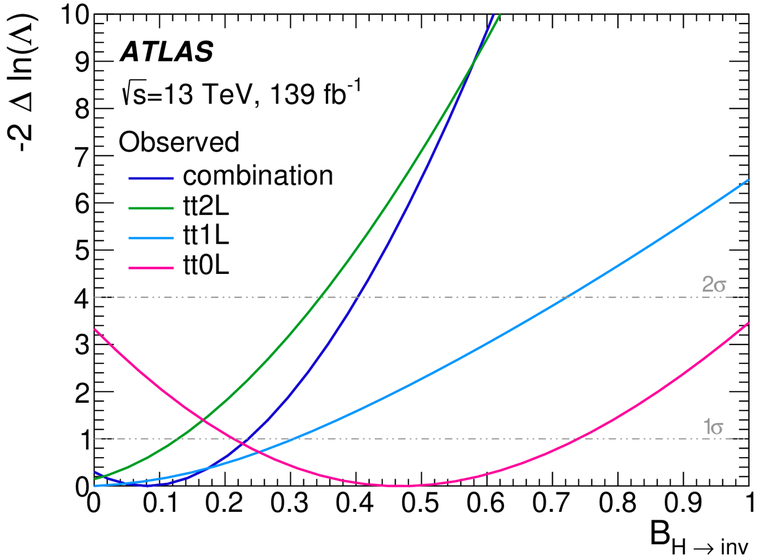
Higgs → Invisible: tth

- No excess over SM
  - B(h→inv) < 0.38 at 95%



Low-p_T | High-p_T $m_{T2,\chi^2} > 450$ GeV | High-p_T $m_{T2,\chi^2} < 450$ GeV



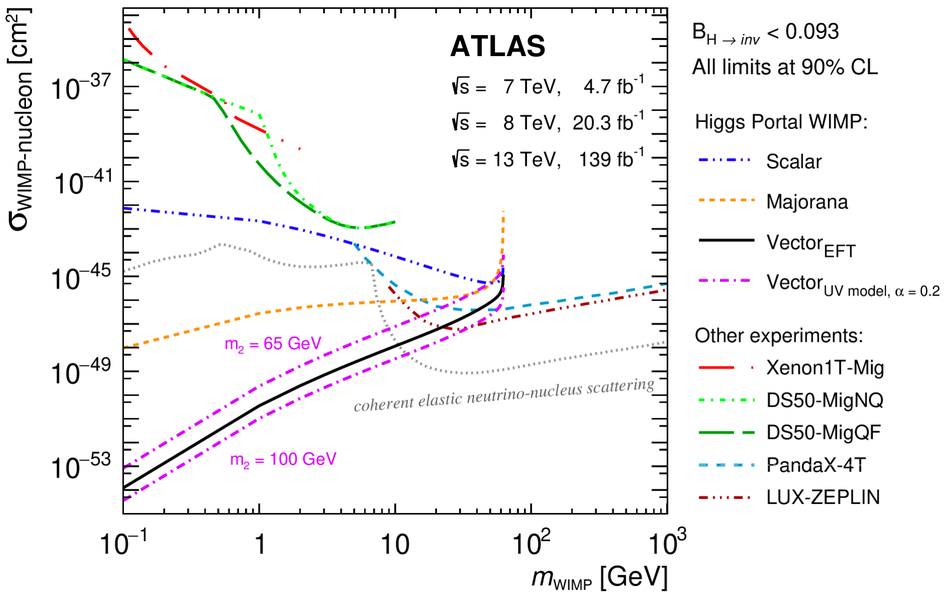


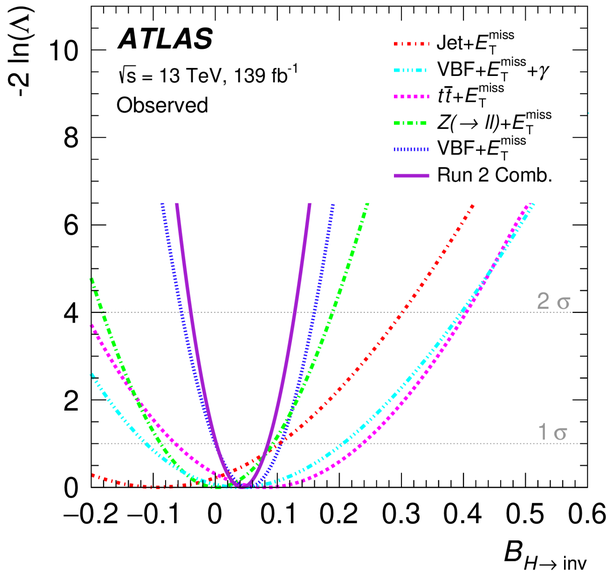
Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.08^{+0.20}_{-0.19}$	0.36	$0.40^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$

[2301.10731]

Higgs → Invisible: Combination

- Statistical combination of all searches
- Searches for h→invisible are largely orthogonal
  - Overlapping data (signal MC) events between ggF and VBF: 0.2% (1.5%)
    - Negligible impact of limit





Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + E_T^{miss}	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + E_T^{miss} + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + E_T^{miss}	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell)$ + E_T^{miss}	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + E_T^{miss}	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

Systematics:

Source of uncertainty	Run2
Luminosity / pile up	0.005
Leptons / Photons	0.014
Jets	0.013
Flavour tagging	0.002
E_T^{miss}	0.004
MC statistics	0.013
All experimental	0.024
V+jets modelling	0.019
Other background Modelling	0.014
Data-driven Backgrounds	0.011
Signal Modelling	0.002
All theory	0.025
Total systematic uncertainty	0.037
Data statistics	0.011
Background normalization	0.012
Total statistical uncertainty	0.017
Total uncertainty	0.041