

# Searches for dark matter with the ATLAS detector

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LABORATÓRIO DE INSTRUMENTAÇÃO  
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

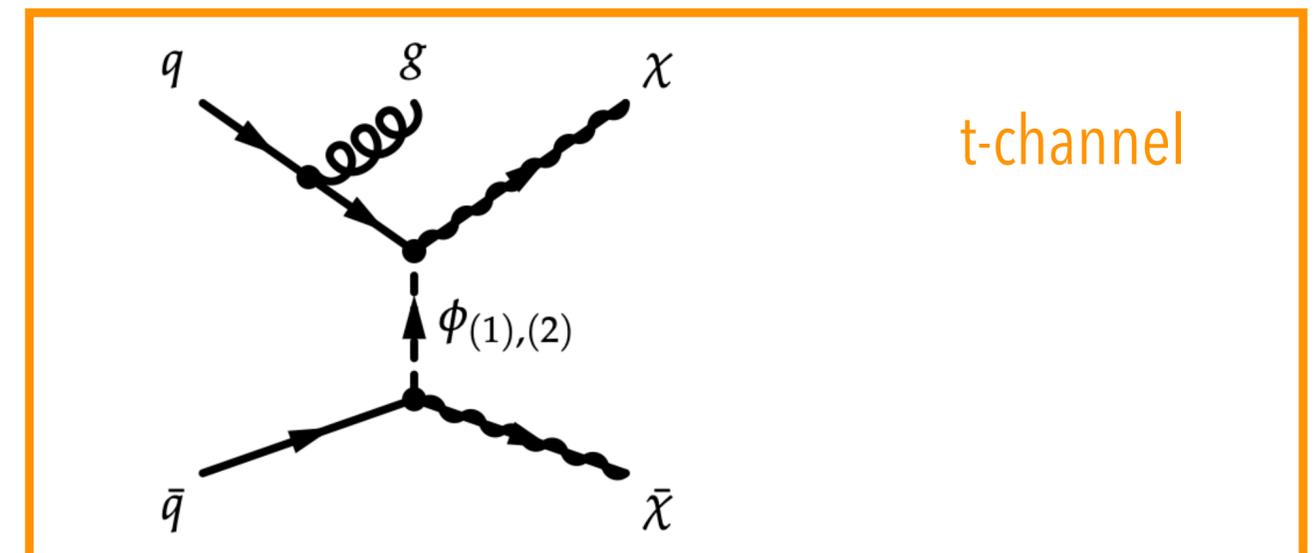
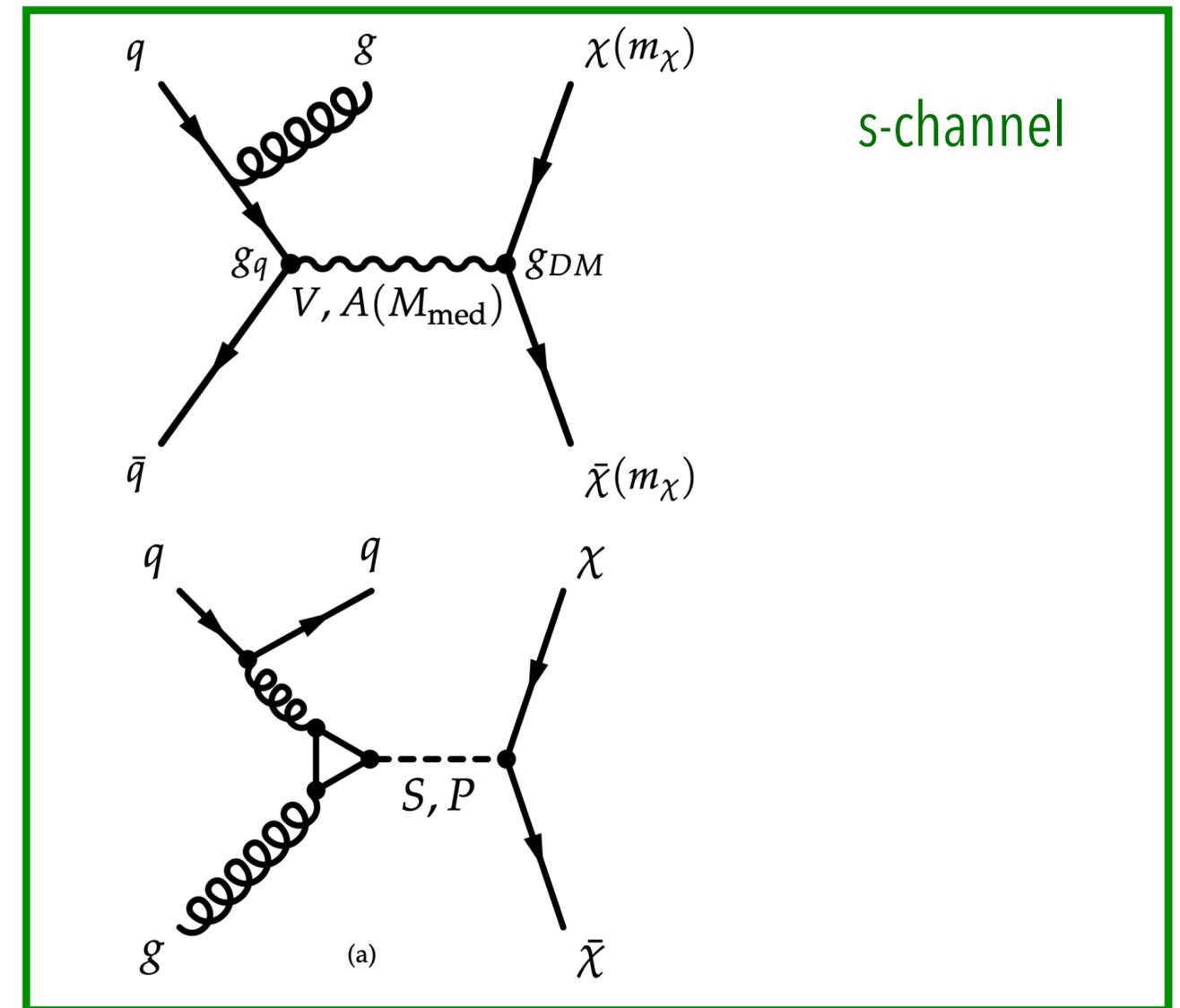
# Dark Matter searches at ATLAS/LHC

- Dark Matter (DM) is an important part of the LHC search program
  - ▶ Complementary to direct/indirect DM detection
- DM production at colliders yield final states with undetected particles
- Searches framed by the Simplified Benchmark DM and (extended) Higgs sector models
  - ▶ Mediator coupling DM particle to SM matter
  - ▶ Mono-X topologies, mediator resonance
- Searches for exotic Higgs decays (Victoria's talk) and other dark sector particles (Binbin's talk)

# Simplified DM models

CMS/ATLAS DM Forum [arxiv:1507.00966](https://arxiv.org/abs/1507.00966)

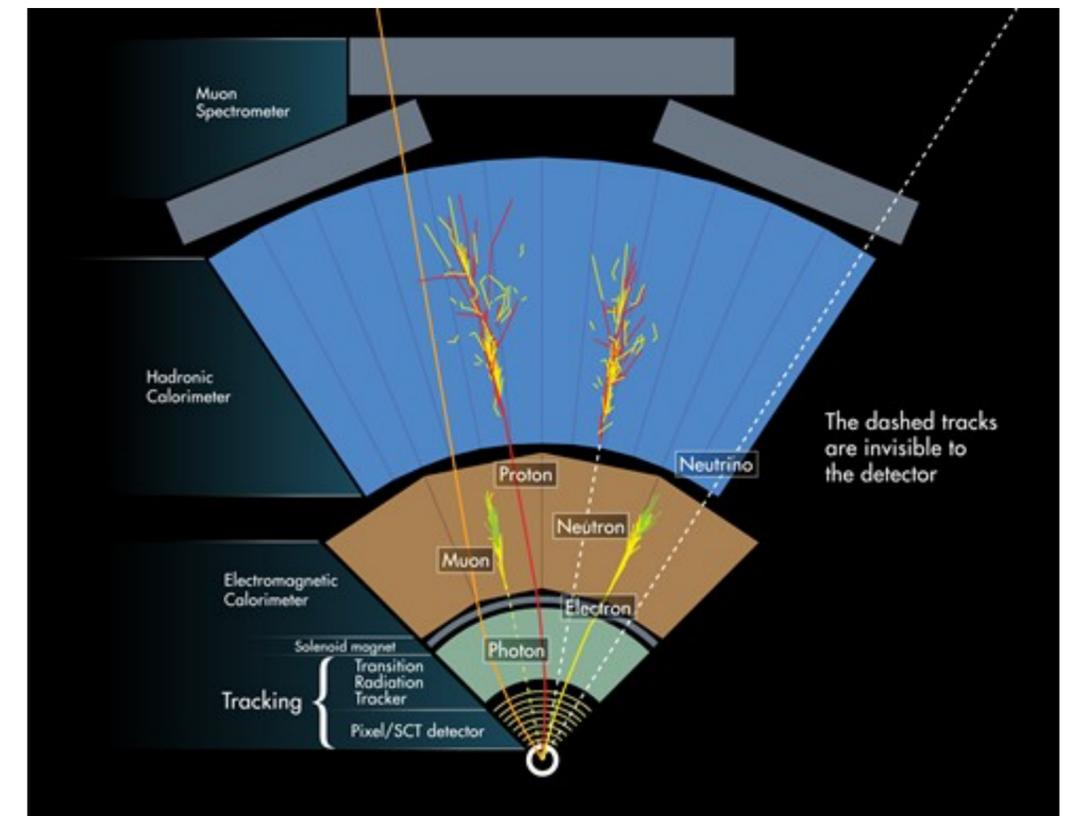
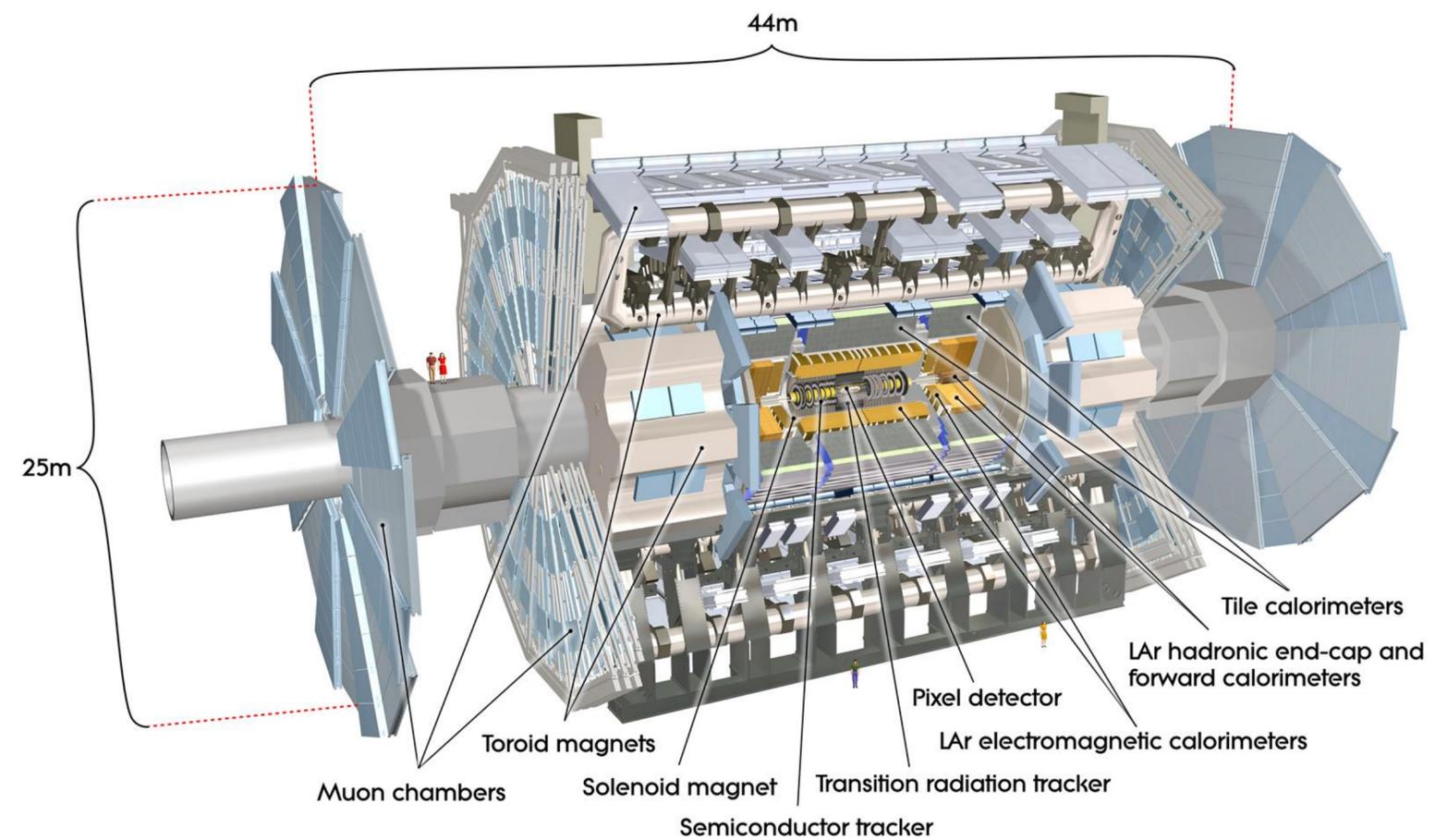
- Dark matter assumed to be a Dirac fermion WIMP  $\chi$
- New particle mediating coupling between  $\chi$  and SM
  - ▶ Spin 1: vector (V) / axial-vector (A)
  - ▶ Spin 0: scalar (S) / pseudoscalar (P)
  - ▶ Collider advantage: characterize the mediator
- Minimal set of parameters:  
 $\{M_{med}, m_\chi, g_\chi, g_q, g_\ell\}$



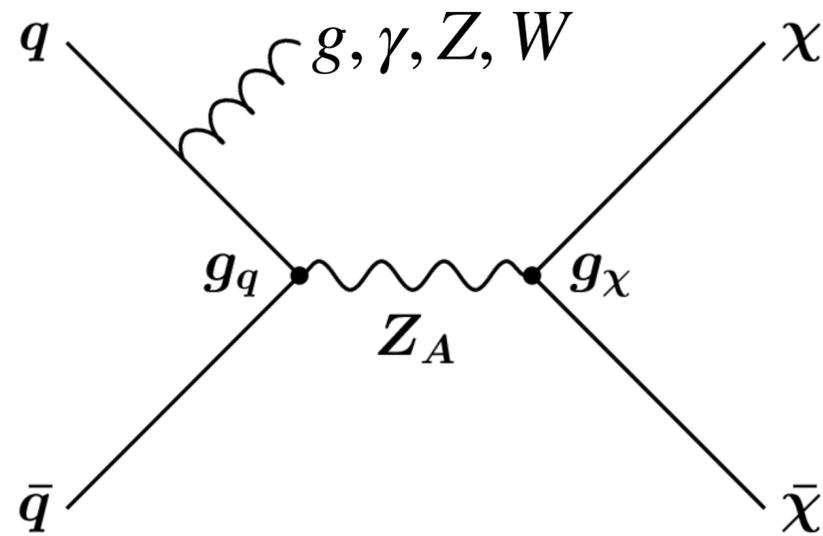
# ATLAS/LHC Experiment

- 27 km  $pp$  circular collider,  $\sqrt{s} = 13$  TeV
- ATLAS is one of the detectors
- Combination of different technologies
  - ▶ Measure and identify collision final state particles
- WIMP assumed stable, does not interact with the detector
  - ▶ Signatures with large missing energy  $E_T$

$$E_T = \left| - \sum \vec{p}_{T,i} \right|$$

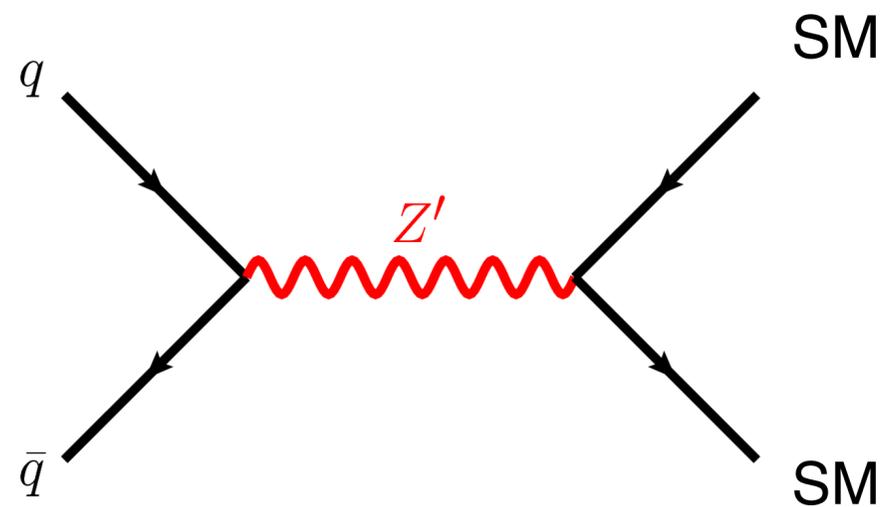


# DM search strategies at ATLAS/LHC



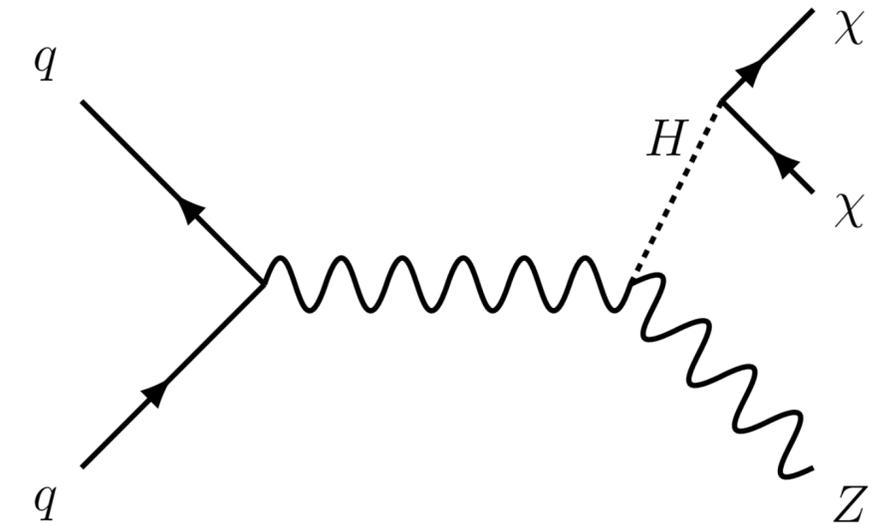
$\cancel{E}_T + X$  ("Mono-X")

- ▶ DM produced with SM particle X
- ▶ Search for SM particle recoiling against the undetected system
- ▶  $\cancel{E}_T + \text{jet}$ : most sensitive



Resonant search

- ▶ Mediator decay to SM particles
- ▶ Look for resonances in the invariant mass spectrum of the decay system
- ▶ Di-jet: most sensitive

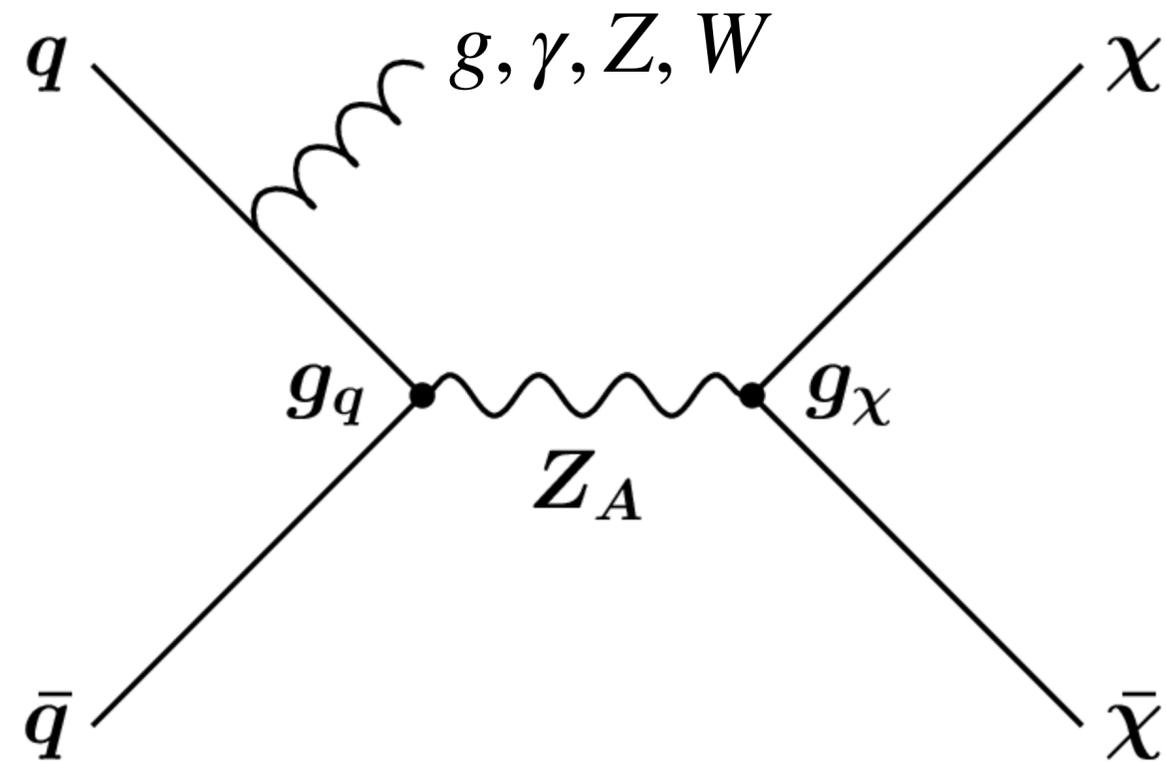


Higgs Sector

- ▶ DM production through couplings to Higgs (extended) sector
- ▶  $H \rightarrow \text{invisible}$
- ▶ 2HDM+a LHC benchmark [arXiv:1810.09420](https://arxiv.org/abs/1810.09420)

**This talk:** present a few specific analyses of full Run 2 data + ATLAS Dark Matter summary results  
 ([ATL-PHYS-PUB-2022-036](https://arxiv.org/abs/2203.036) [ATL-PHYS-PUB-2021-045](https://arxiv.org/abs/2104.045) [ATLAS-CONF-2020-052](https://arxiv.org/abs/2005.052))

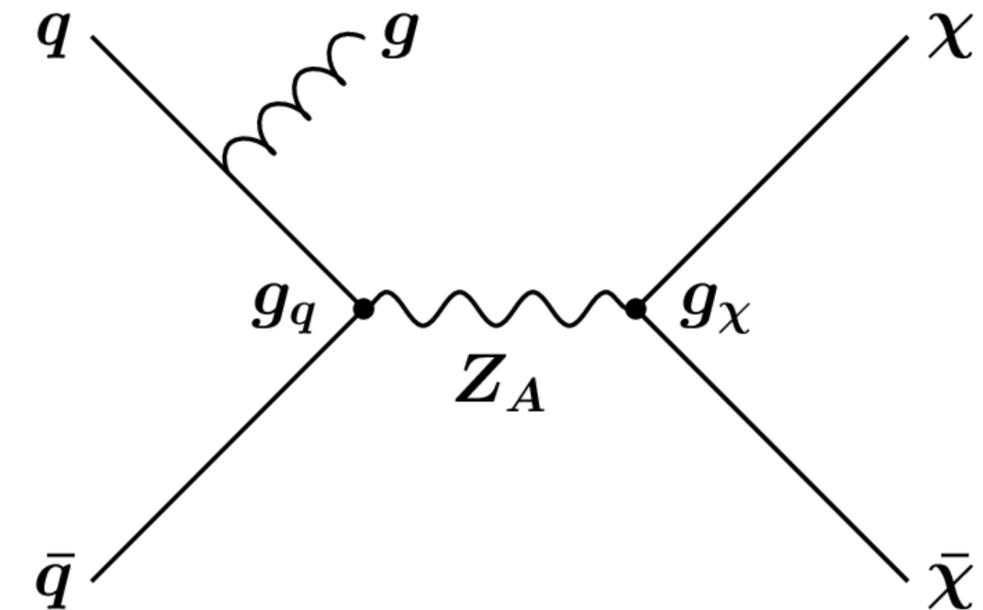
# $E_T + X$ searches



# $\cancel{E}_T + jet$

[Phys. Rev. D 103, 112006 \(2021\)](#)

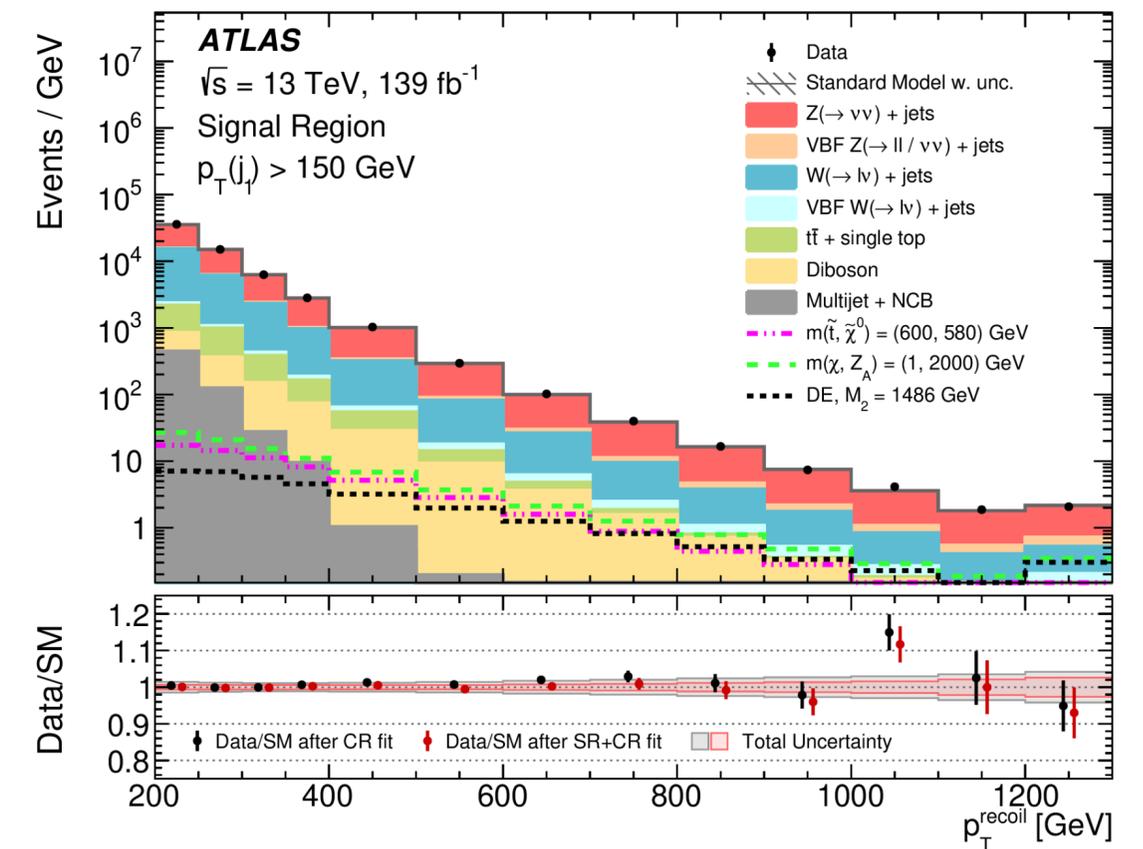
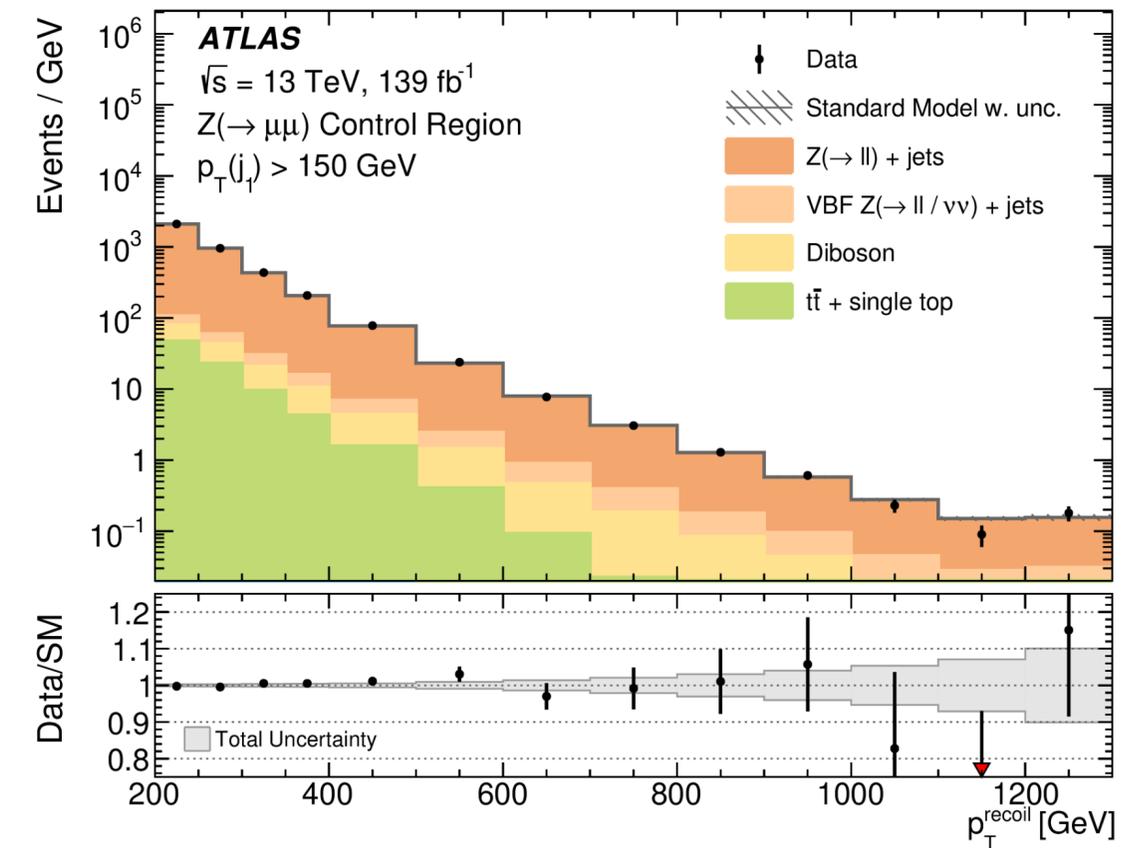
- Sensitive to spin 0 (pseudoscalar) 1 (axial-vector) mediators
- Experimental signature:
  - ▶ Large  $\cancel{E}_T$  ( $> 200$  GeV) from mediator decay to  $\chi\bar{\chi}$
  - ▶ Jet from initial state radiation ( $p_T > 150$  GeV)
  - ▶ Events with leptons ( $e, \mu, \tau$ ) or photons are vetoed
- Main SM backgrounds (90%):
  - ▶  $Z(\nu\nu)+jets$ , irreducible
  - ▶  $W(\ell\nu)+jets$ , when the charged lepton is not detected



# $E_T + jet$

[Phys. Rev. D 103, 112006 \(2021\)](#)

- Background estimate from MC normalized to data in 5 dedicated control regions (CRs):
  - $W(\ell\nu)$  and  $Z(\nu\nu)$  main backgrounds simultaneously constrained with 4 CRs enriched in  $W(e\nu)$ ,  $W(\mu\nu)$ ,  $Z(ee)$ ,  $Z(\mu\mu)$
  - Dedicated  $t\bar{t} + t$ -quark enriched samples (b-jet requirement)
- $W/Z$ +jets modeled with state-of-the-art theory predictions at NNLO QCD and NLO EW
- Signal hypothesis tested with simultaneous profile likelihood fit
  - Fit  $p_T$  of the system recoiling against the hadronic activity
  - 2% uncertainty on SM prediction

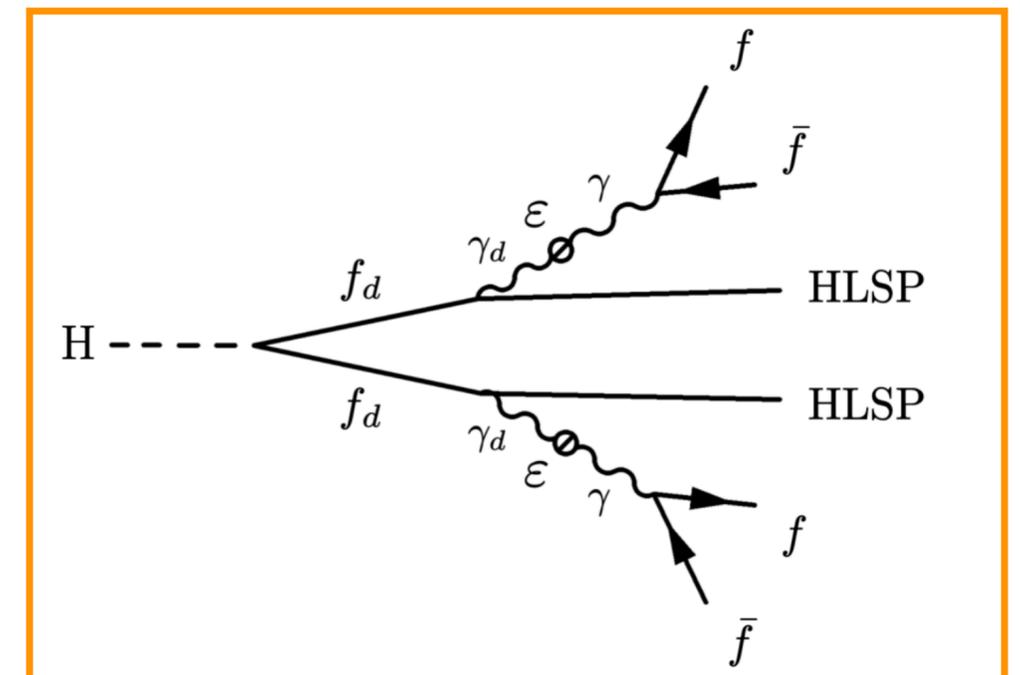
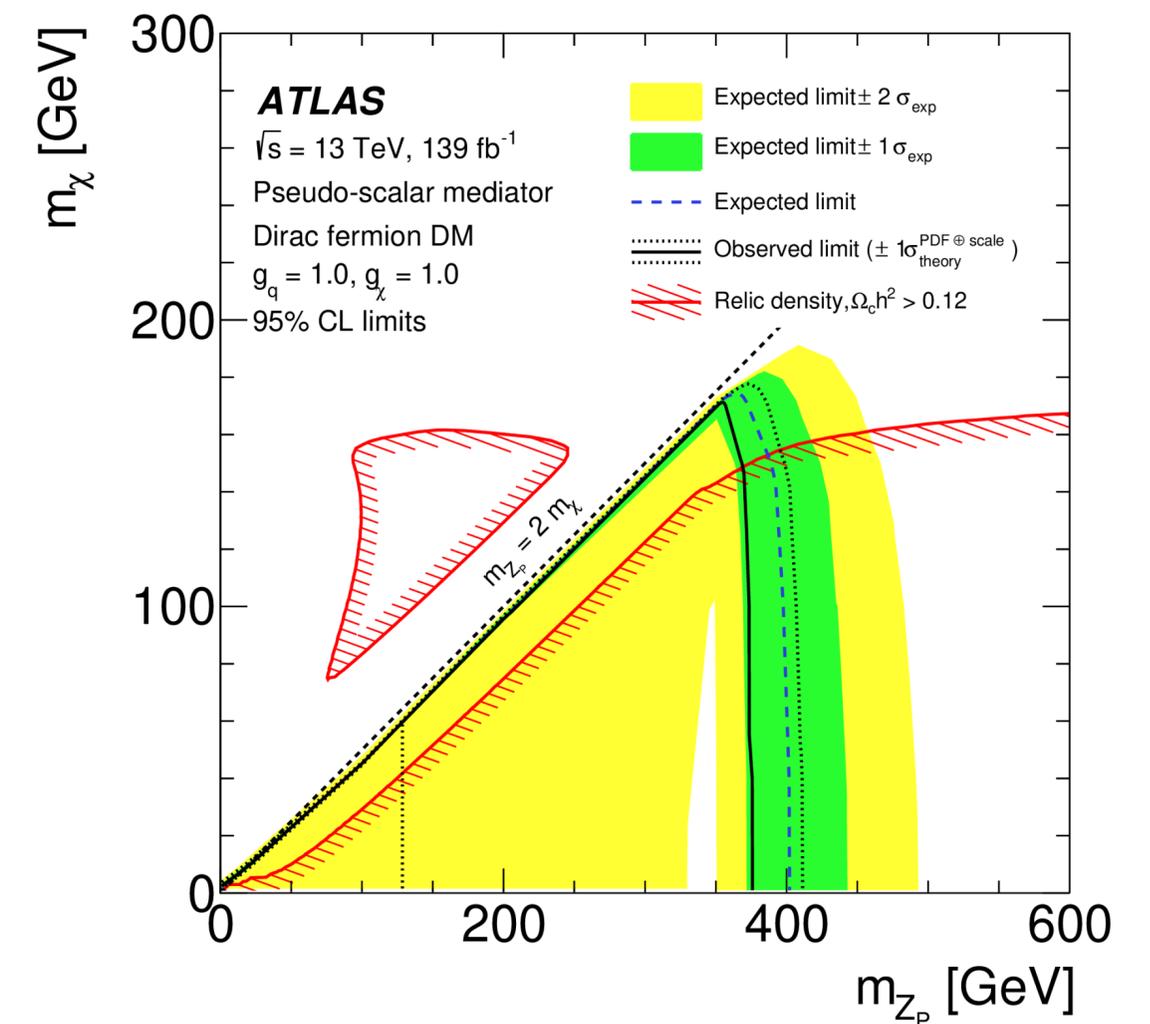


# $E_T + jet$

[Phys. Rev. D 103, 112006 \(2021\)](#)

- No signal observed
- Exclusion limits set on the  $m_\chi$  vs  $m_{med}$  parameter plane
  - ▶ Eg. pseudoscalar mass  $< 380$  GeV excluded for light WIMP
    - Sensitivity for the first time
  - ▶ More results on the ATLAS DM summary plots: [ATL-PHYS-PUB-2022-036](#)

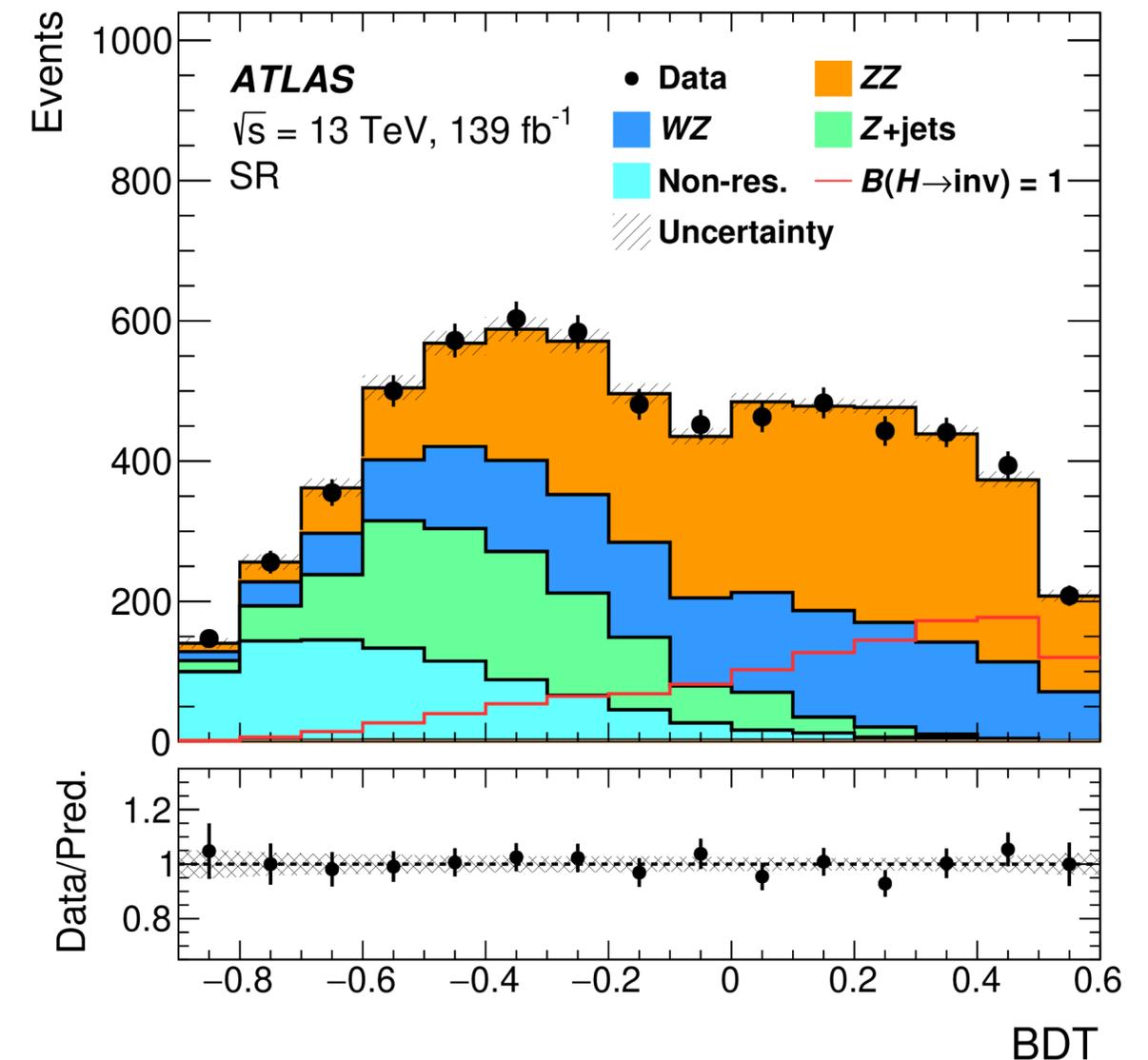
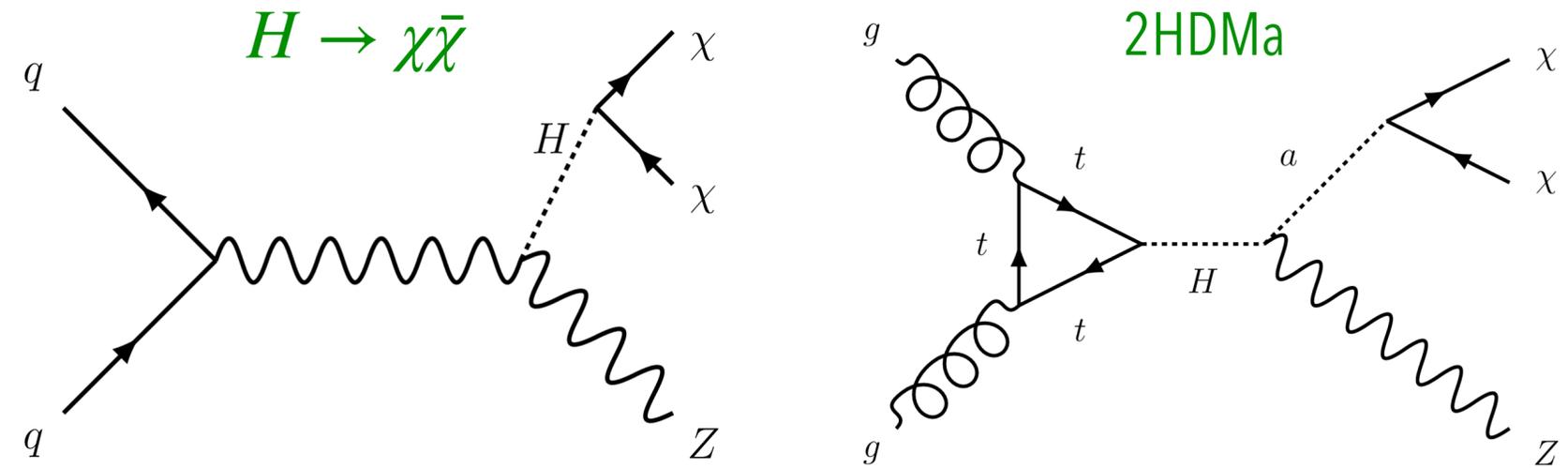
- Re-interpretation of results in dark sector models with long-lived non-charged particles (eg. dark photon): [ATL-PHYS-PUB-2021-020](#)



# $\cancel{E}_T + Z(\ell\ell)$

[Phys. Lett. B 829 \(2022\) 137066](#)

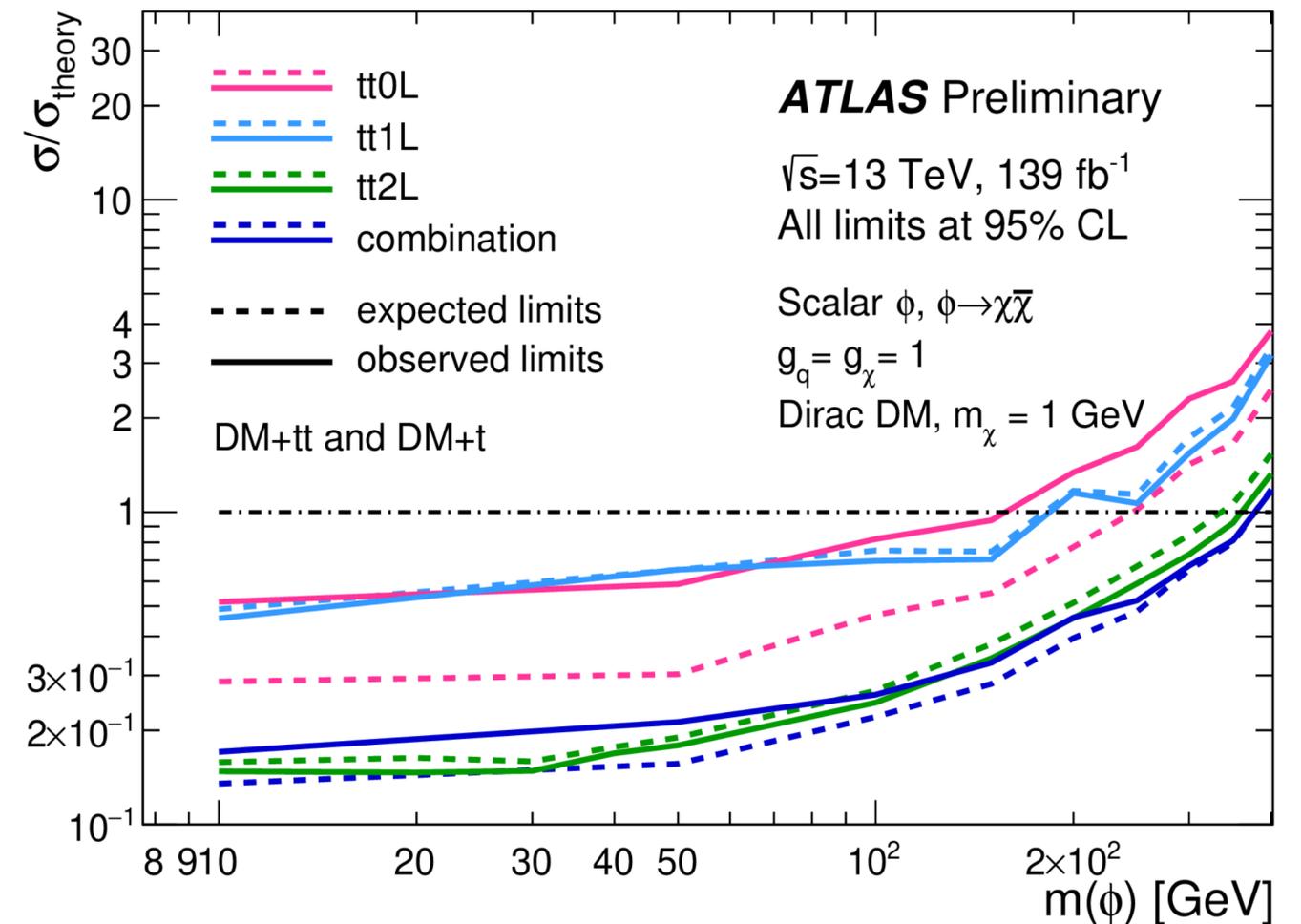
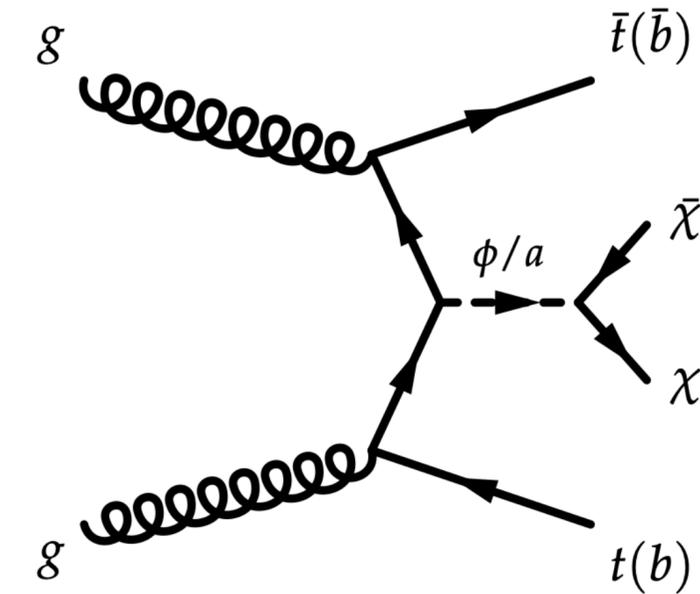
- Large  $\cancel{E}_T$  and oppositely charged electrons/muons from  $Z$
- Sensitive to
  - ▶ V/AV decays to  $\chi\bar{\chi}$  in the DM simplified model
  - ▶ Higgs portal signals (eg.  $H \rightarrow \chi\bar{\chi}$  and 2HDM+a)
- Boosted Decision Tree discriminate  $H \rightarrow \chi\bar{\chi}$  ( $m_T(\cancel{E}_T + \ell\ell)$  for 2HDMa)
- Main SM backgrounds
  - ▶ Non-resonant  $t\bar{t}$ , diboson ( $WW, WZ, ZZ$ ),  $Z$ +jets
  - ▶ Constrained with control samples in a combined fit
- Input to the 2HDM+a interpretation (along with eg.  $\cancel{E}_T + H(bb)$ )
  - ▶ [ATLAS-CONF-2021-036](#)



# $\cancel{E}_T + t\bar{t}/b\bar{b}$

[JHEP 05 \(2021\) 093](#) [EPJC 80 \(2020\) 737](#) [JHEP 04 \(2021\) 174](#) [JHEP 04 \(2021\) 165](#)

- Spin 0 mediators produced in association with pairs of  $t/b$ -quarks
- Important in models with Minimum Flavour Violation
  - Mediator has Yukawa-like couplings,  $\propto m_f$
- Search for  $H \rightarrow inv$  decays
  - With b-quark pairs
  - 0, 1 or 2 charged leptons from the  $t\bar{t}$  decay
- [ATLAS-CONF-2022-007](#) Combination of  $\cancel{E}_T + t\bar{t}$ 
  - Limits set on the DM production  $\sigma$  for  $m_{\phi(a)}$  up to 370 (300) GeV



# Summary Results on Scalar/Pseudoscalar DM Mediator

[ATL-PHYS-PUB-2022-036](#)

- Different final states

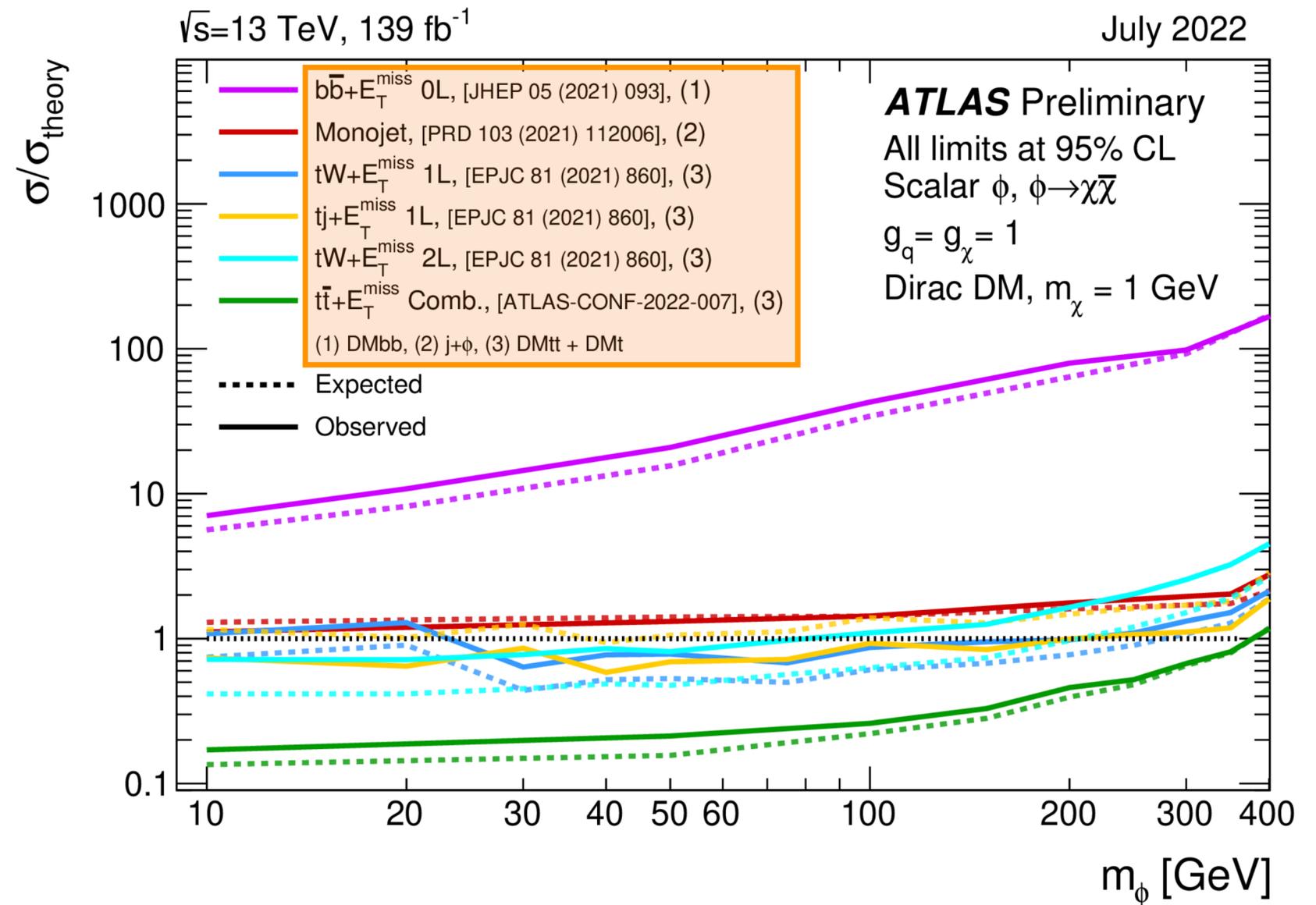
- New results not mentioned

- ▶ [EPJC 81 \(2021\) 860](#)  $E_T + Wt$  (jet, 1/2 leptons)

- Exclusion of  $m_\phi < 370$  GeV

- ▶ Assume  $g_{\chi/q} = 1$  and  $m_\chi = 1$  GeV

- Similar results for the pseudoscalar mediator

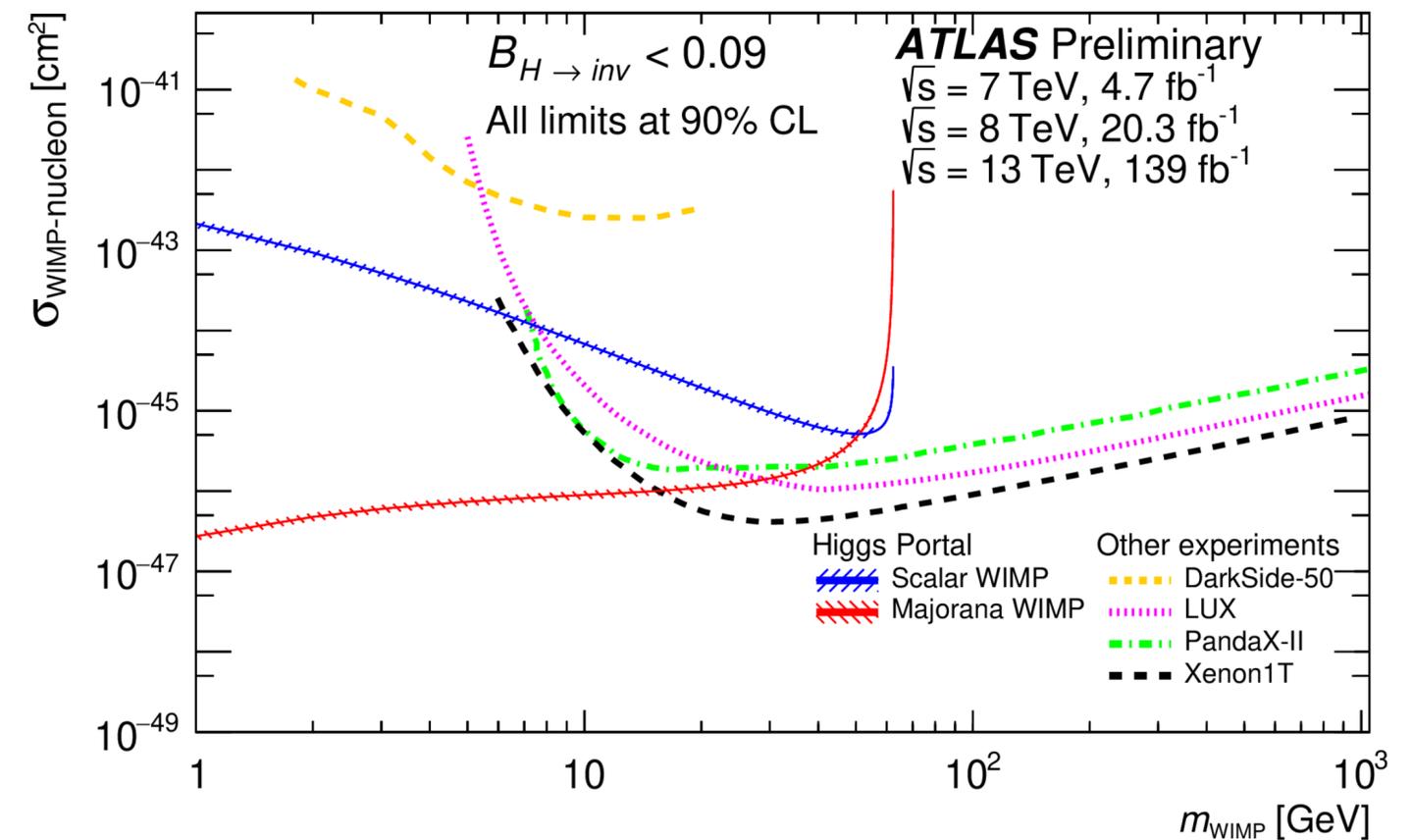
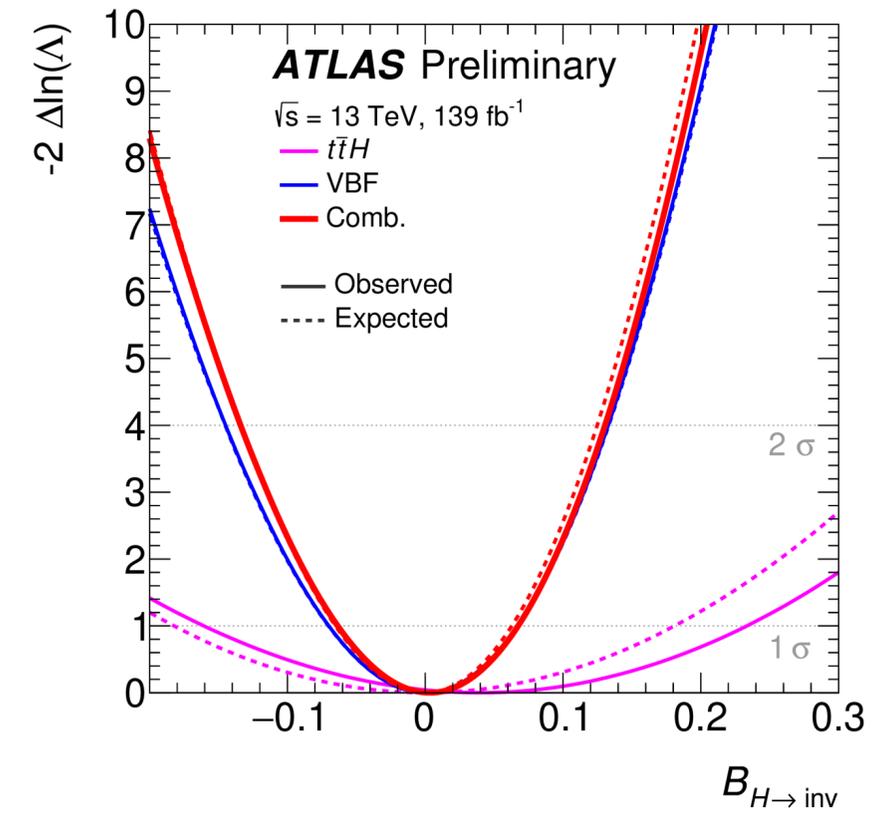


# Preliminary combination of searches for $H \rightarrow inv$

[ATLAS-CONF-2020-052](#)

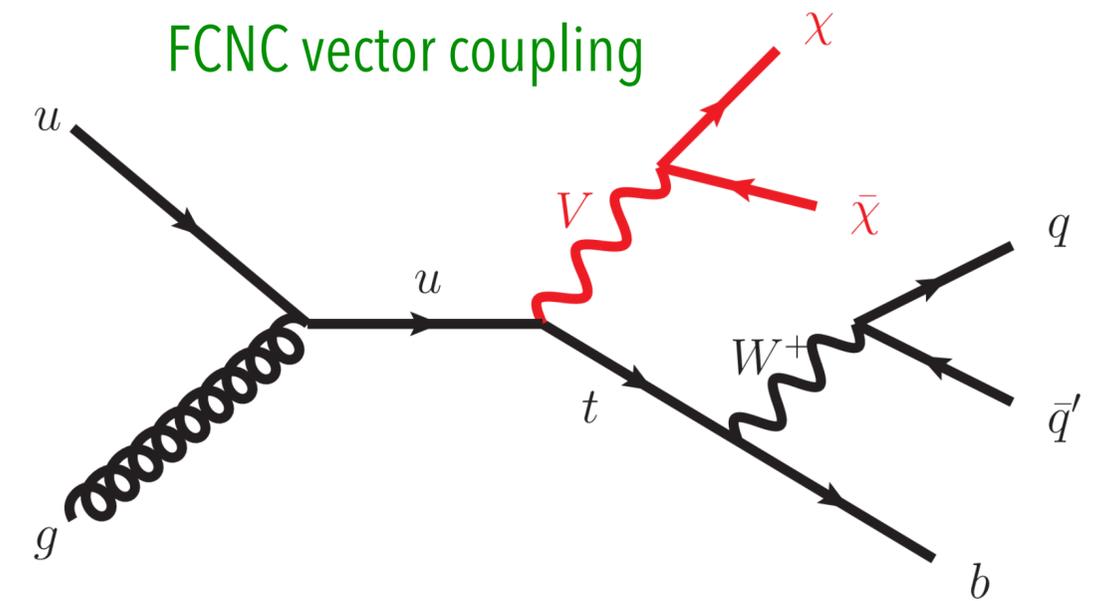
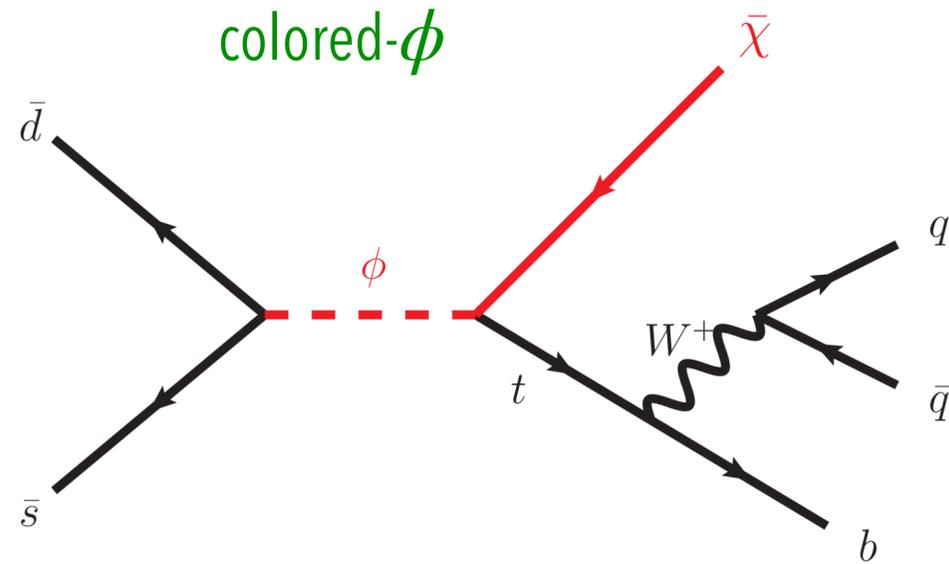
- Combination of different Higgs production mechanisms
  - ▶ Vector-boson-Fusion (most sensitive)
  - ▶  $t\bar{t}H$  (0, 2 leptons)
  - ▶ Run 1 results
  - ▶ Others topologies being included (eg.  $\cancel{E}_T + Z(\ell\ell), \dots$ )
- SM:  $H \rightarrow ZZ \rightarrow 4\nu(inv)$ , BR = 0.1% for  $m_H = 125$  GeV
- 95% CL upper limit (Run 1+Run 2): BR( $H \rightarrow inv$ ) < 11%
- Translated into nucleon scattering  $\sigma$ 
  - ▶ Assuming and effective coupling in the Higgs Portal model

Run 2 combination

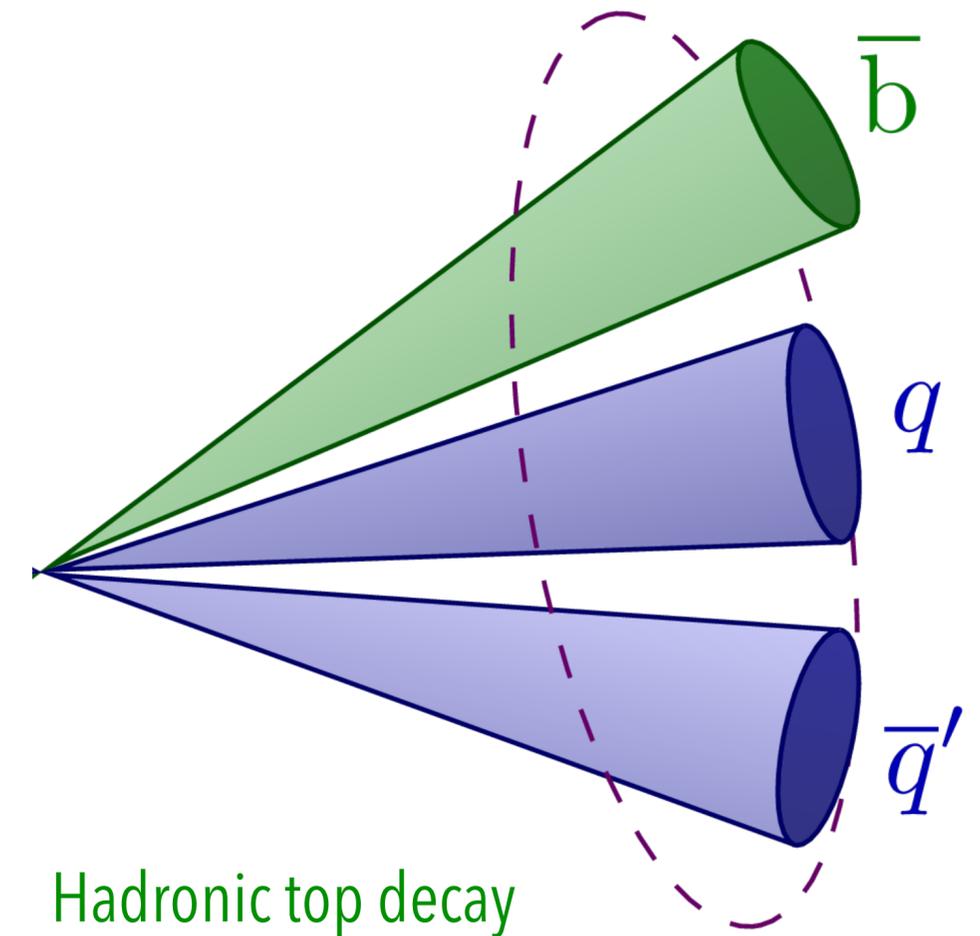


# $\cancel{E}_T + t(\text{had})$

[ATLAS-CONF-2022-036](#)



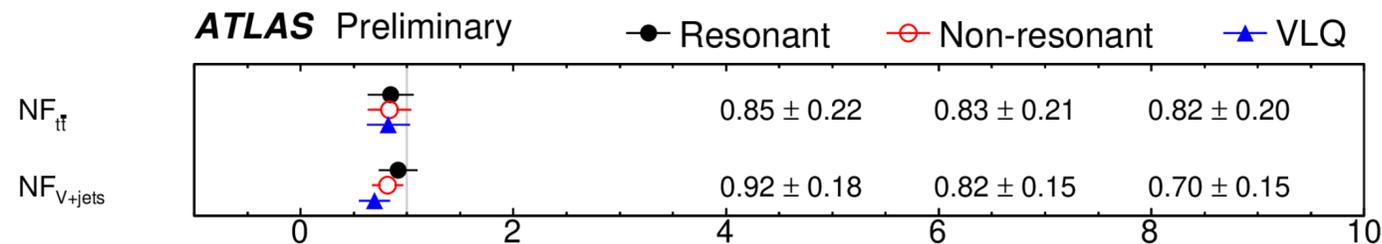
- Topology arises in models predicting baryon number violation or flavour-changing neutral currents:
  - ▶ Colored scalar mediator  $\phi$  decay to top+DM fermion
  - ▶ Vector mediator with FCNC coupling to the SM
- Events with  $\cancel{E}_T > 250$  GeV
- high- $p_T$  top reconstructed as large radius jet ( $p_T > 350$  GeV)



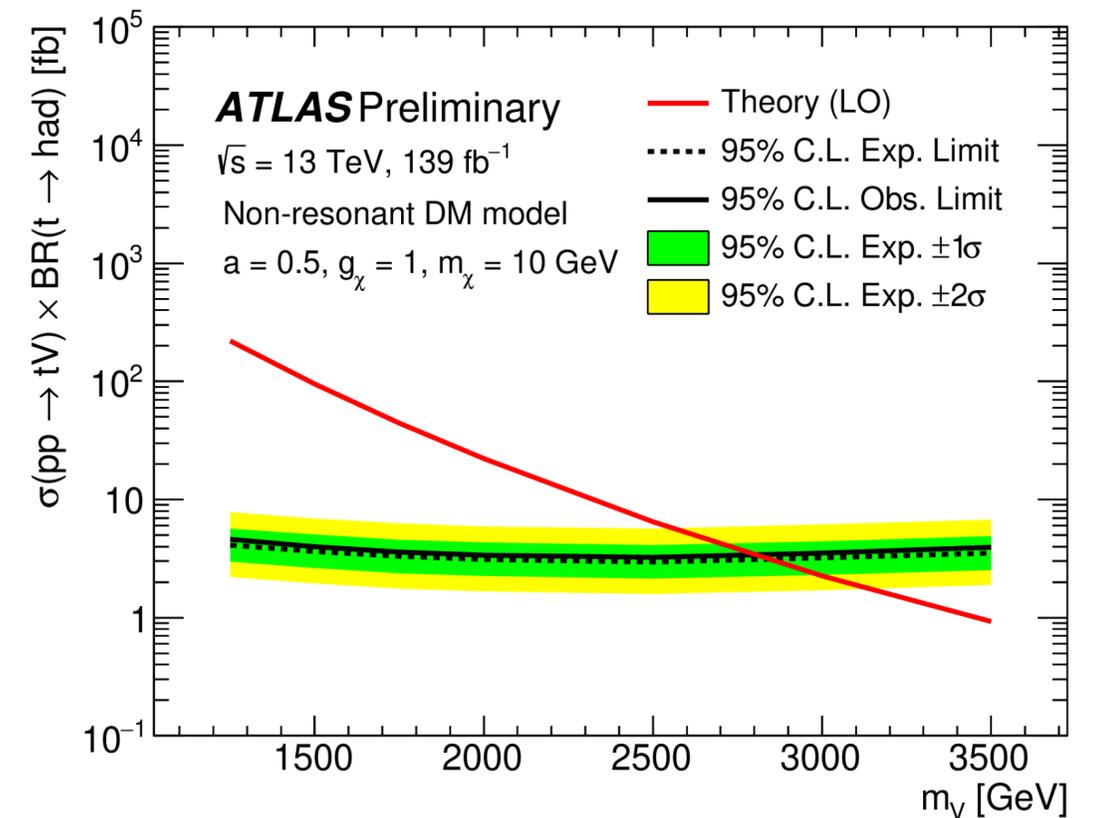
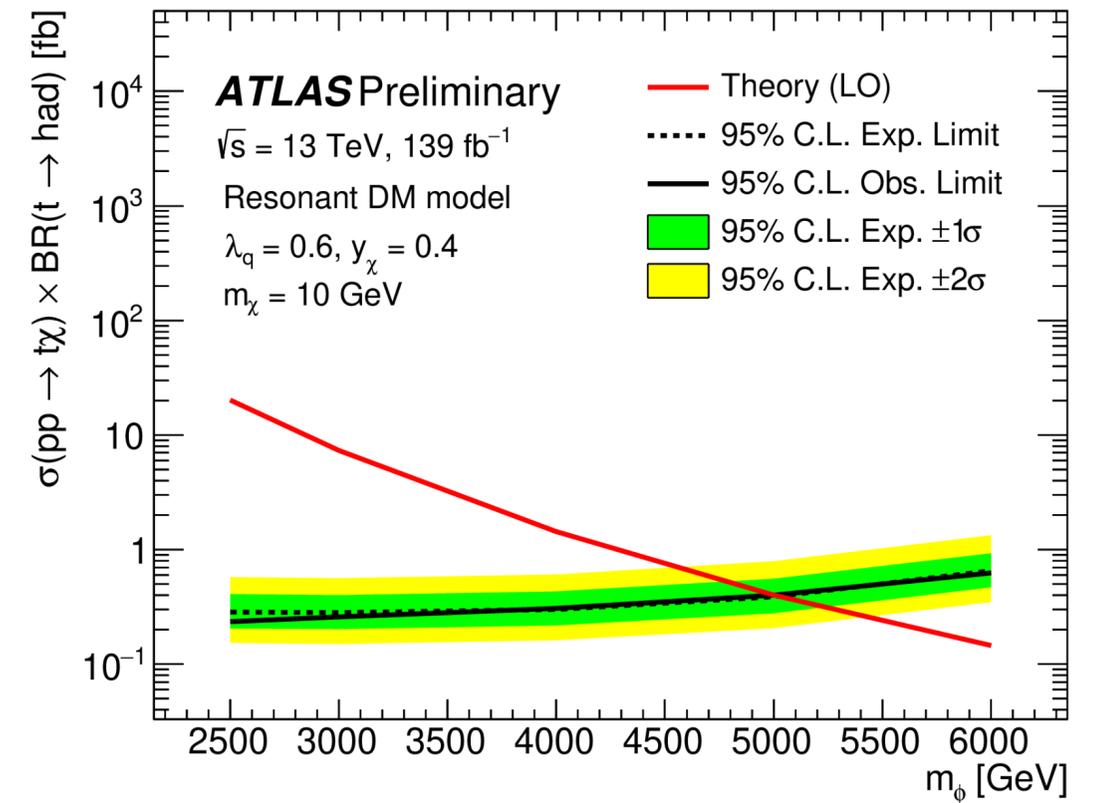
# $E_T + t(had)$

**ATLAS-CONF-2022-036**

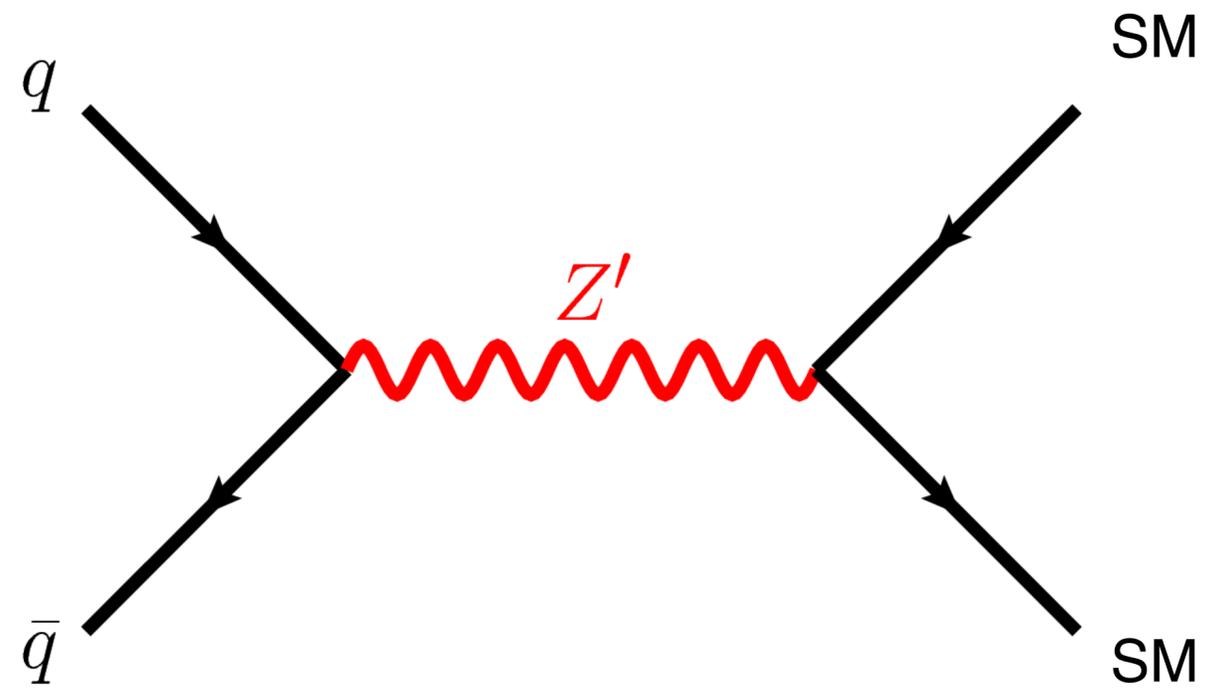
- Boostered Decision Tree used as signal discriminant and fit observable
- Normalization of main backgrounds ( $t\bar{t}$  and  $W/Z$ +jets) constrained with real data (and cross-checked in validation regions)



- 95% CL Upper limits on the signal cross-section versus the mediator mass
  - $m_\phi > 5 \text{ TeV}, m_V > 2.8 \text{ TeV}$
  - Assuming specific couplings,  $m_\chi = 10 \text{ GeV}$



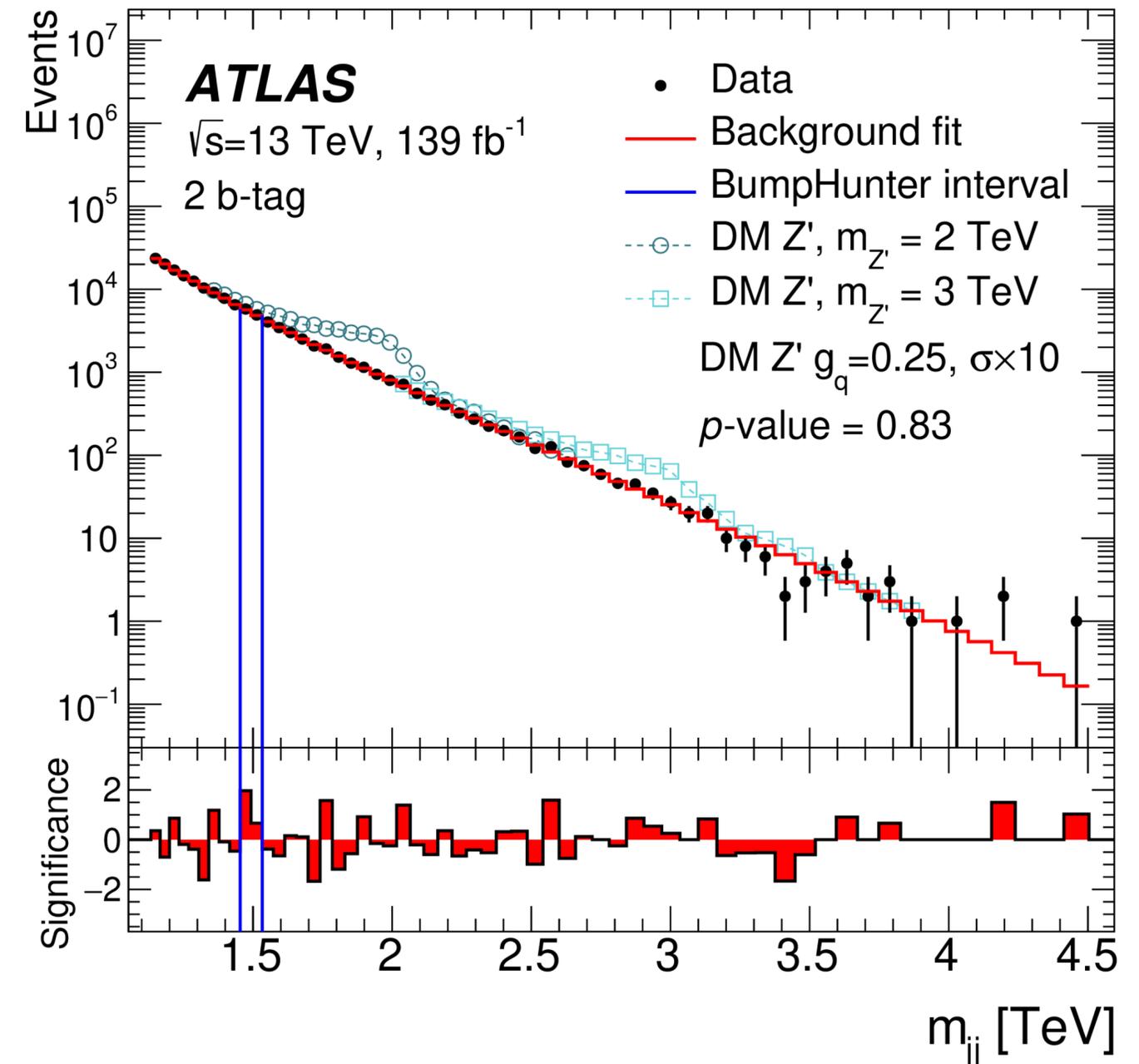
# Mediator searches



# Di-jet ( $jj, bb$ )

[JHEP 03 \(2020\) 145](#)

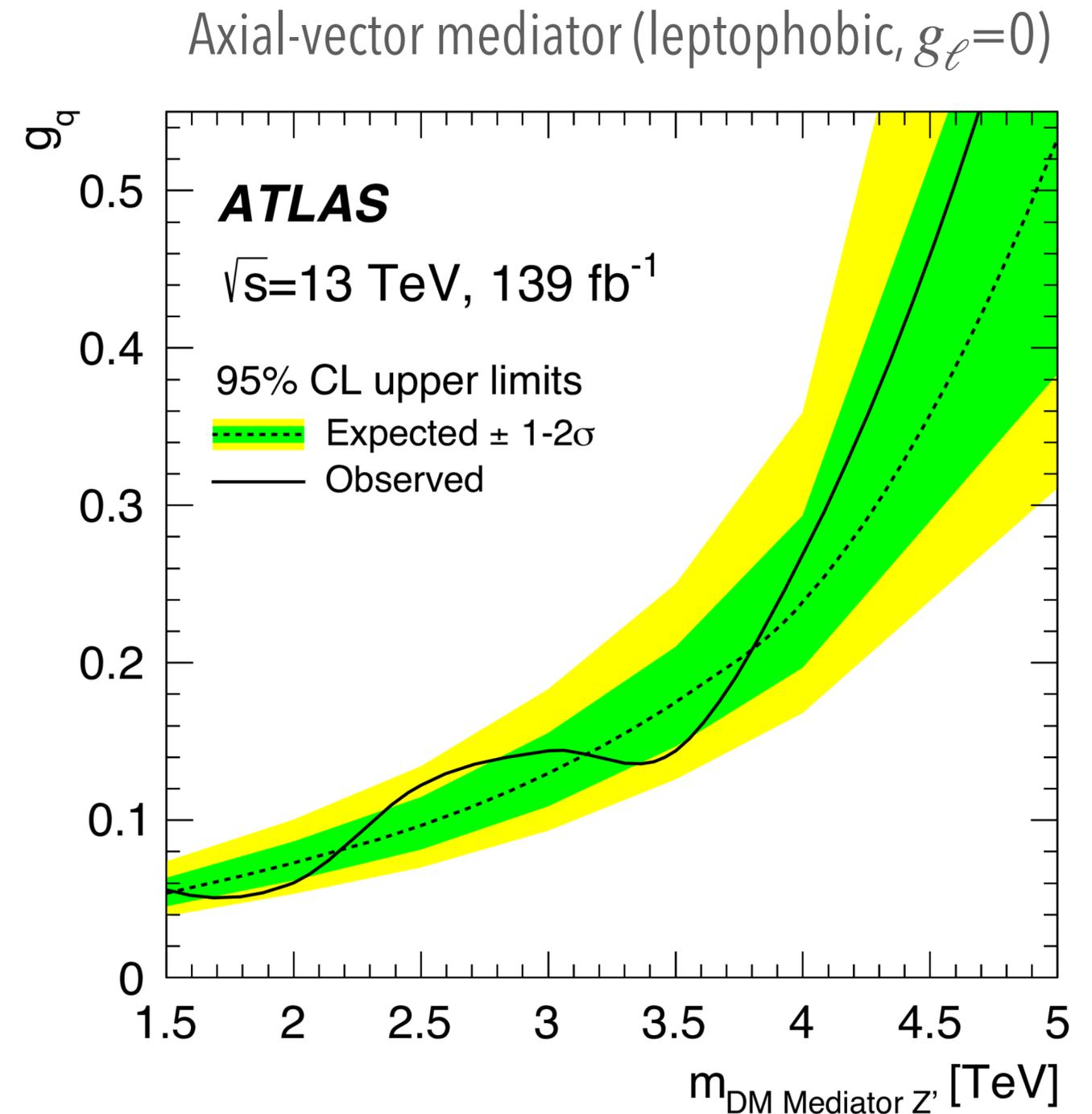
- Search for resonant excess in the  $m_{jj}$  spectrum
  - Most energetic di-jet pair, jet  $p_T > 420, 150$  GeV
  - Probe masses from 1.1 to 8 TeV
- QCD background with smoothly falling  $m_{jj}$ 
  - Estimated by fitting real data, validated with MC
- Split in  $jj$  and  $bb$  categories
  - Sensitivity to mediator coupling to b-quarks
- Additional low- $m_{jj}$  search with trigger-level jets
  - [Phys. Rev. Lett. 121, 081801 \(2018\)](#)



# Di-jet ( $jj, bb$ )

[JHEP 03 \(2020\) 145](#)

- Bump hunter scan of  $m_{jj}$  binned distribution
- No significant data excess
- Upper limits on the simplified DM model couplings to quarks
  - ▶ Fixed  $m_\chi = 10$  TeV and  $g_\chi = 1.5$
  - ▶  $m_{Z'} > 3.8$  (4.6) TeV for  $g_q = 0.2$  (0.5)

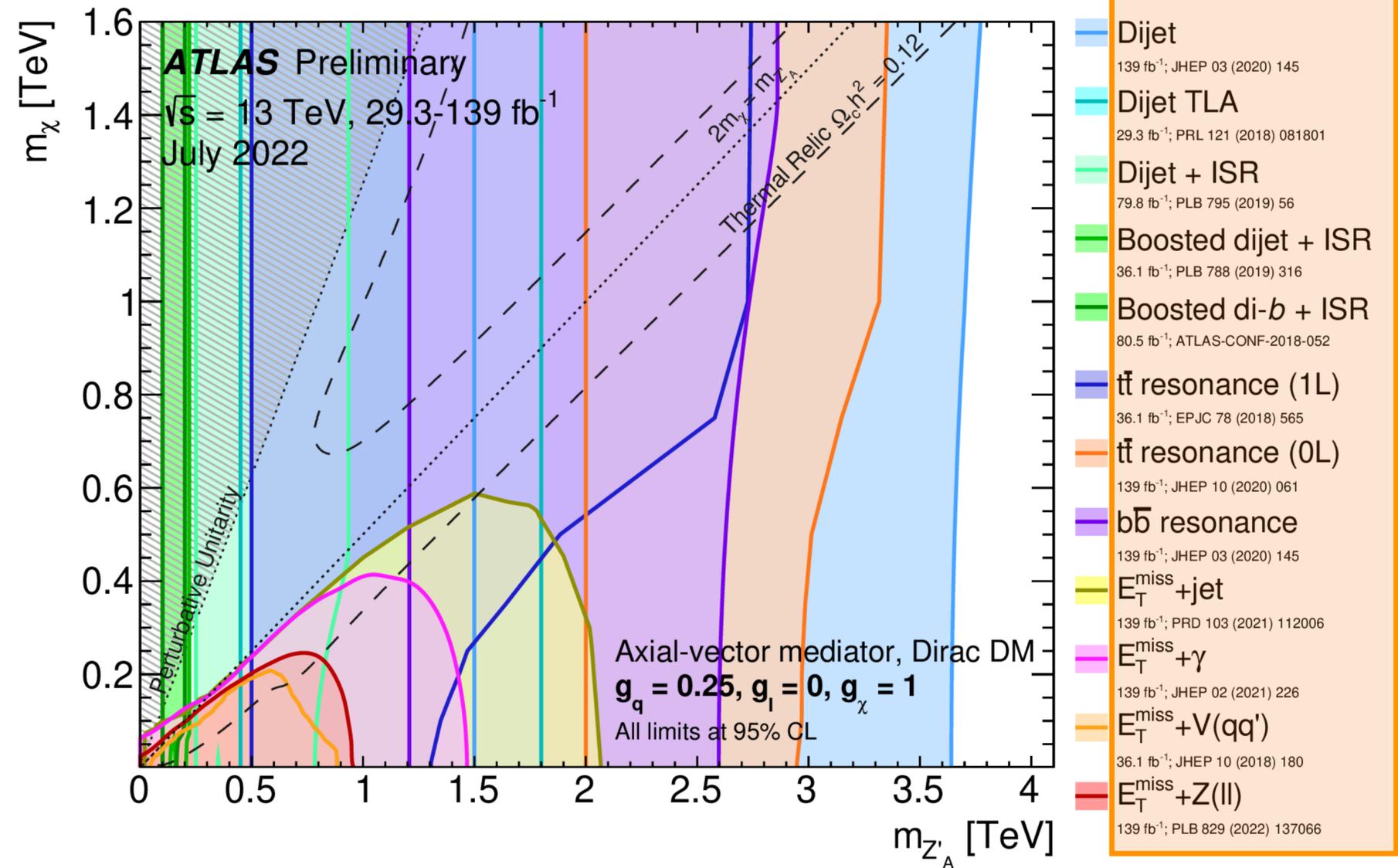


# Summary Results on Vector/Axial-vector DM Mediator

[ATL-PHYS-PUB-2022-036](#)

Summary results

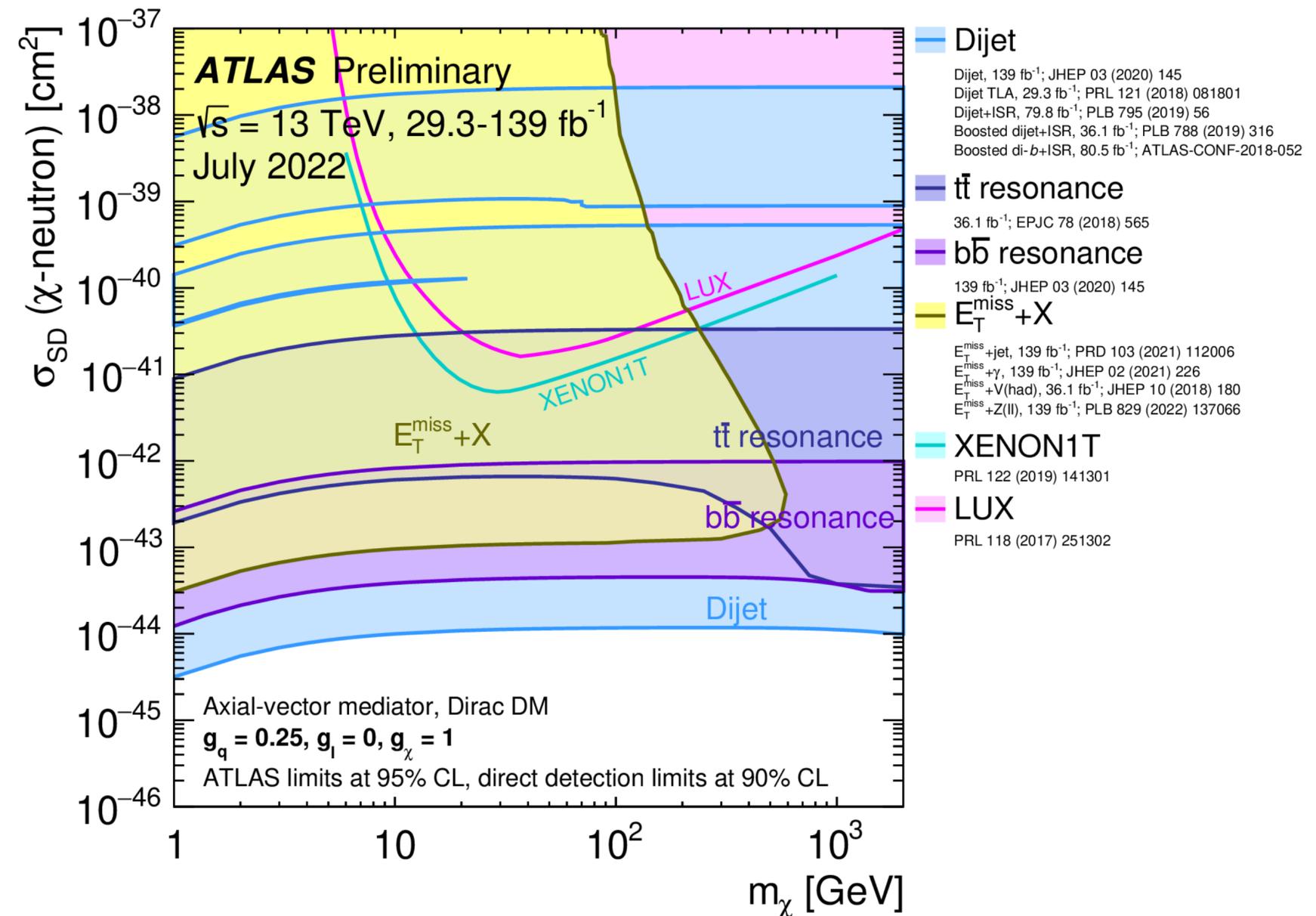
- 95% exclusion contours on the  $m_{A/AV} \times m_\chi$  plane
- Axial-vector
  - $E_T+X$  searches exclude mass up to 2.1 TeV for very light DM mass
  - Resonant searches exclude mass up to 3.5 TeV
- Similar results for vector mediator
  - Leptophilic scenarios less constrained



# Exclusion of equivalent nucleon scattering $\sigma$ vs $m_\chi$

[ATL-PHYS-PUB-2022-036](#)

- Comparison with constraints from direct detection
  - Very model/parameter dependent
- Complementary exclusion limits
- Better constrains in large region of the phase space
  - Similarly for the equivalent proton cross-section (wrt PICO-60 C3 F8)
- Direct detection has better exclusion limits for the spin-independent nucleon cross-section



# Wrap-up

- Wealth of results on DM from the ATLAS/LHC Run 2 analyses
  - ▶ DM simplified models
  - ▶ Higgs portal
  - ▶ Extended Higgs/gauge sectors (eg. 2HDM+a), ...
- No evidence of DM so far, across a wide range of signatures
- LHC Run 3 just started, hopefully will shed light to the DM puzzle

# Thank you



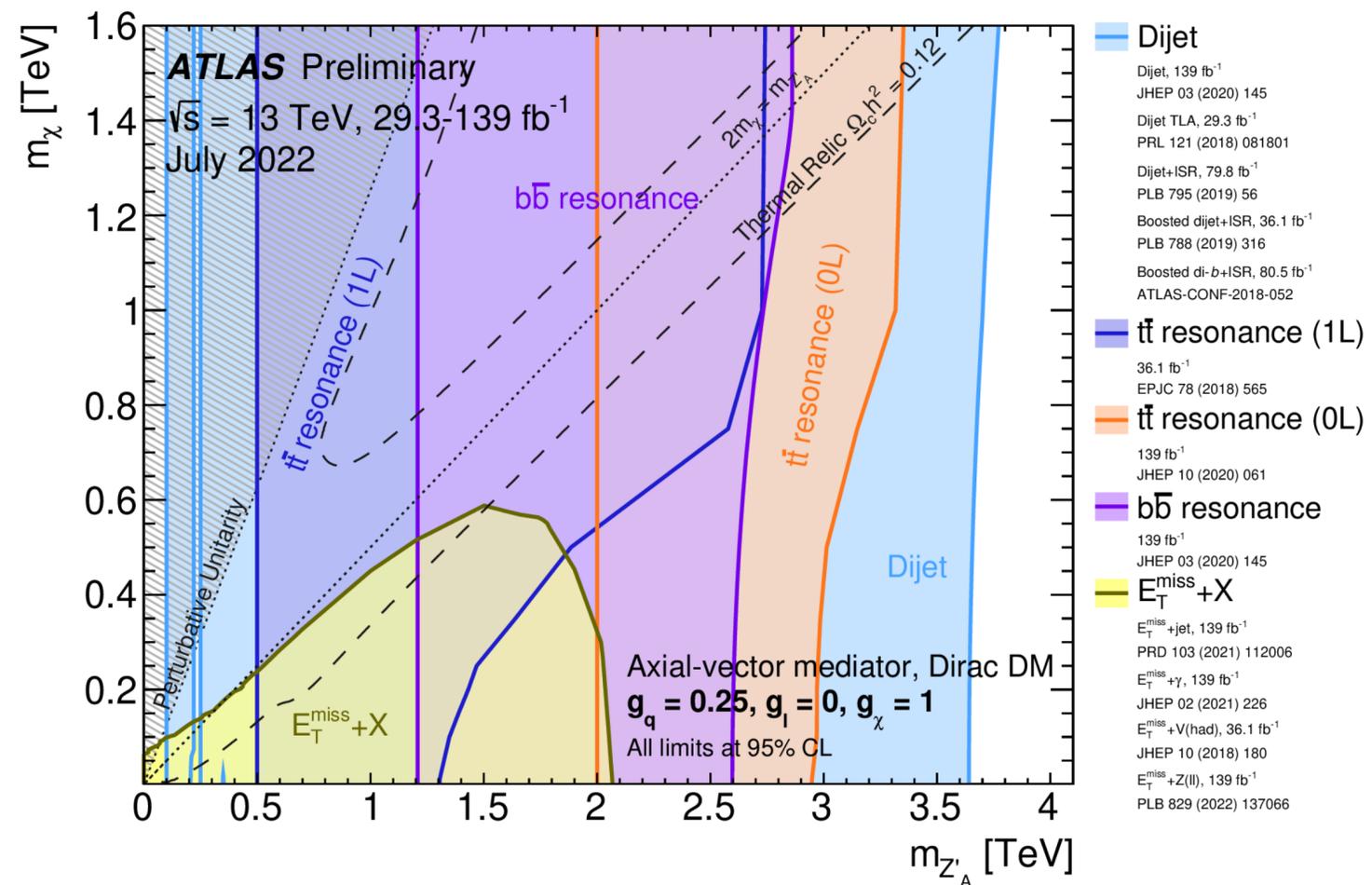
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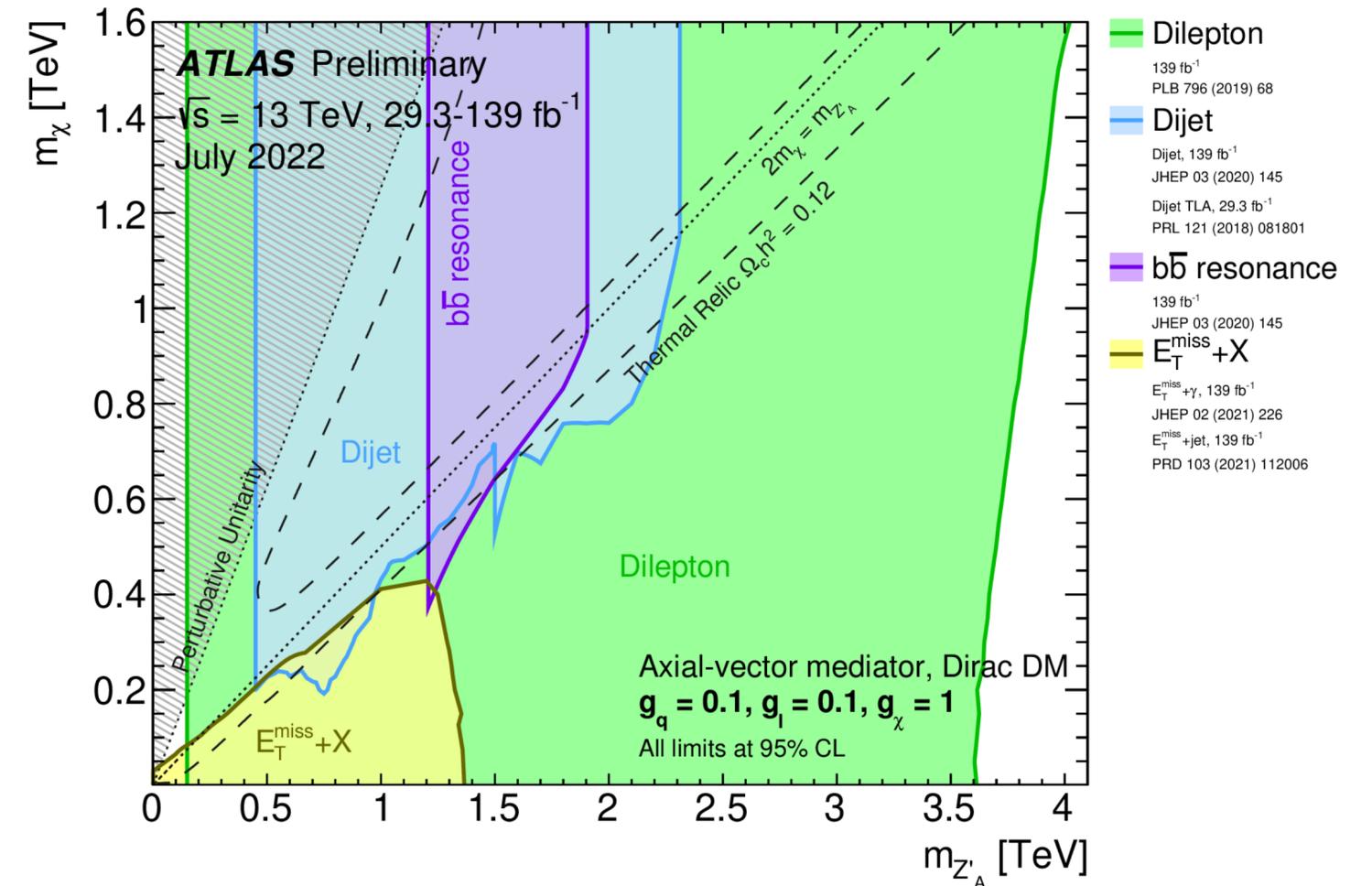
**FCT** Fundação  
para a Ciência  
e a Tecnologia

# Backup

# Results: Axial-vector DM Mediator



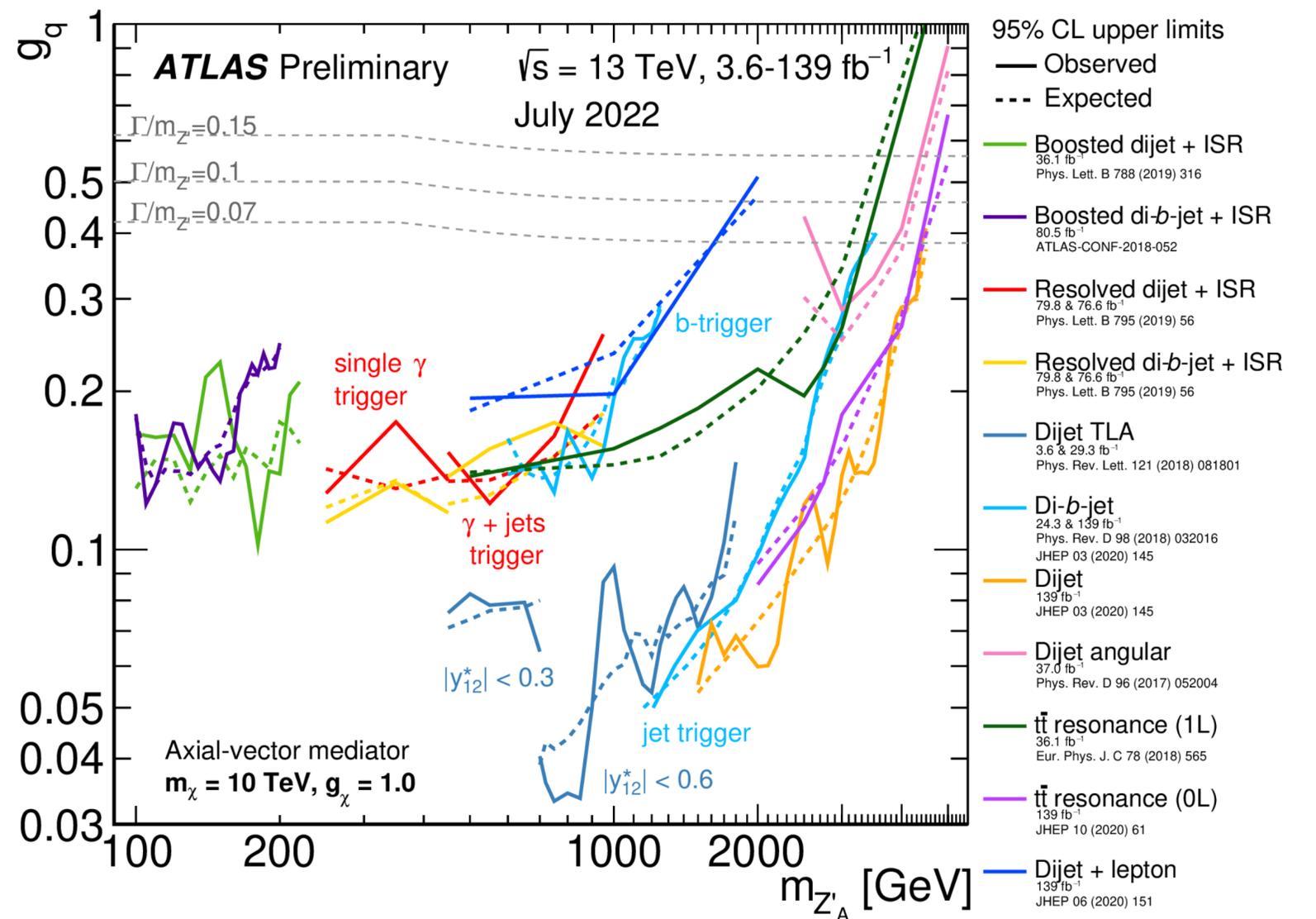
Leptophobic,  $g_\ell = 0$



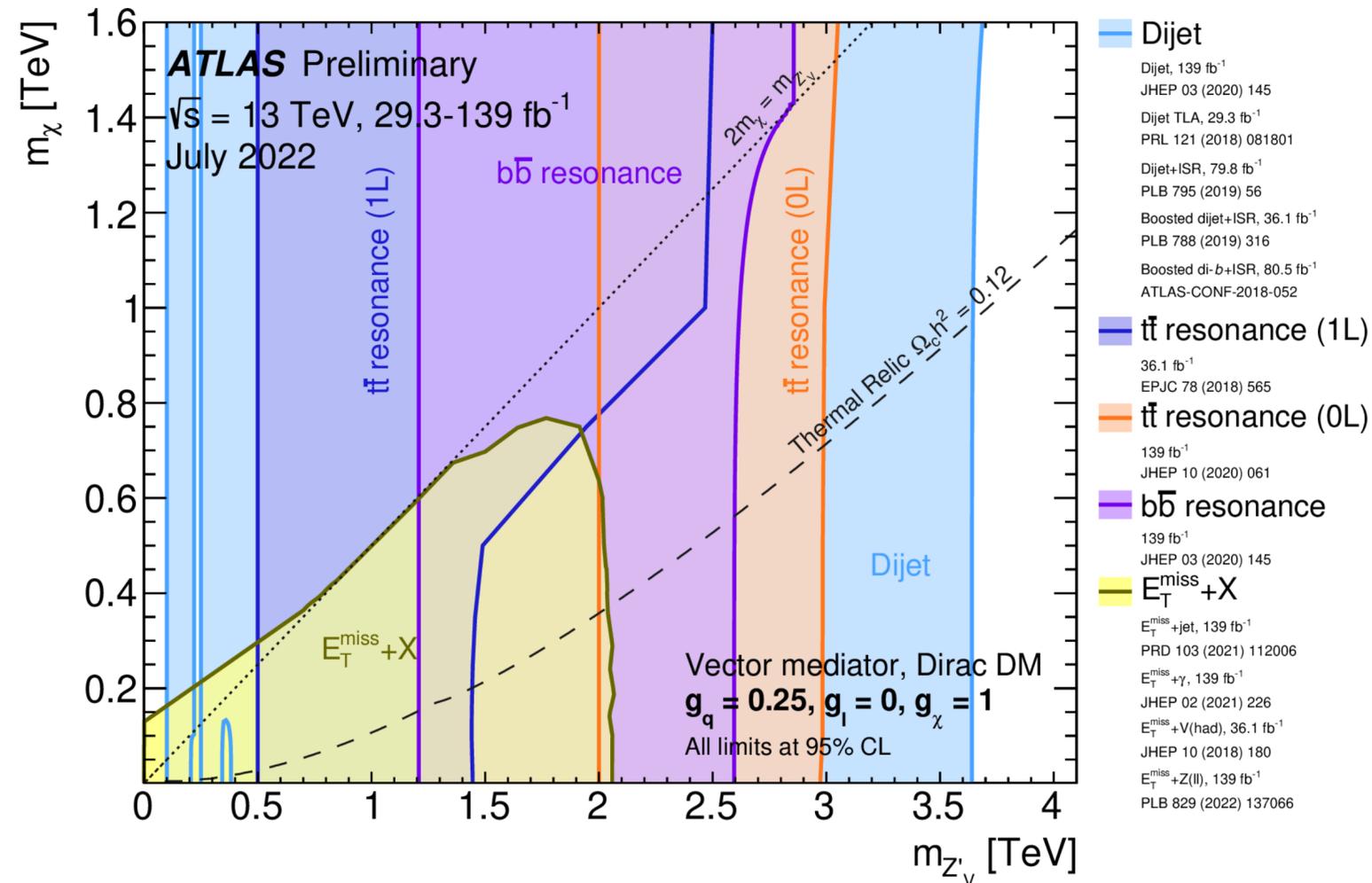
Leptophilic,  $g_\ell = 0.1$

# Axial-vector DM Mediator Coupling

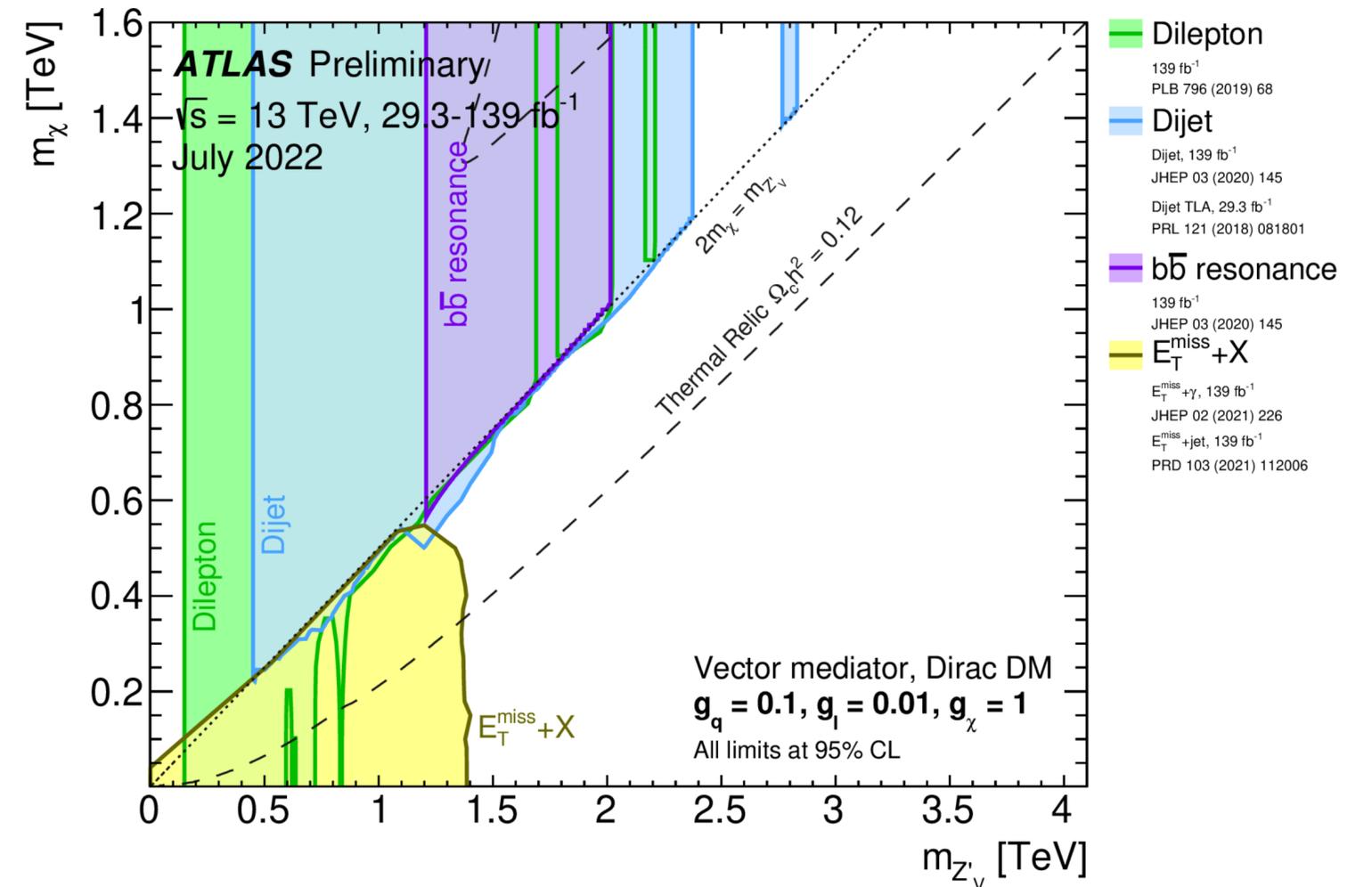
- 95% upper limits on the coupling  $g_q$  versus the AV mediator mass



# Results: Vector DM Mediator

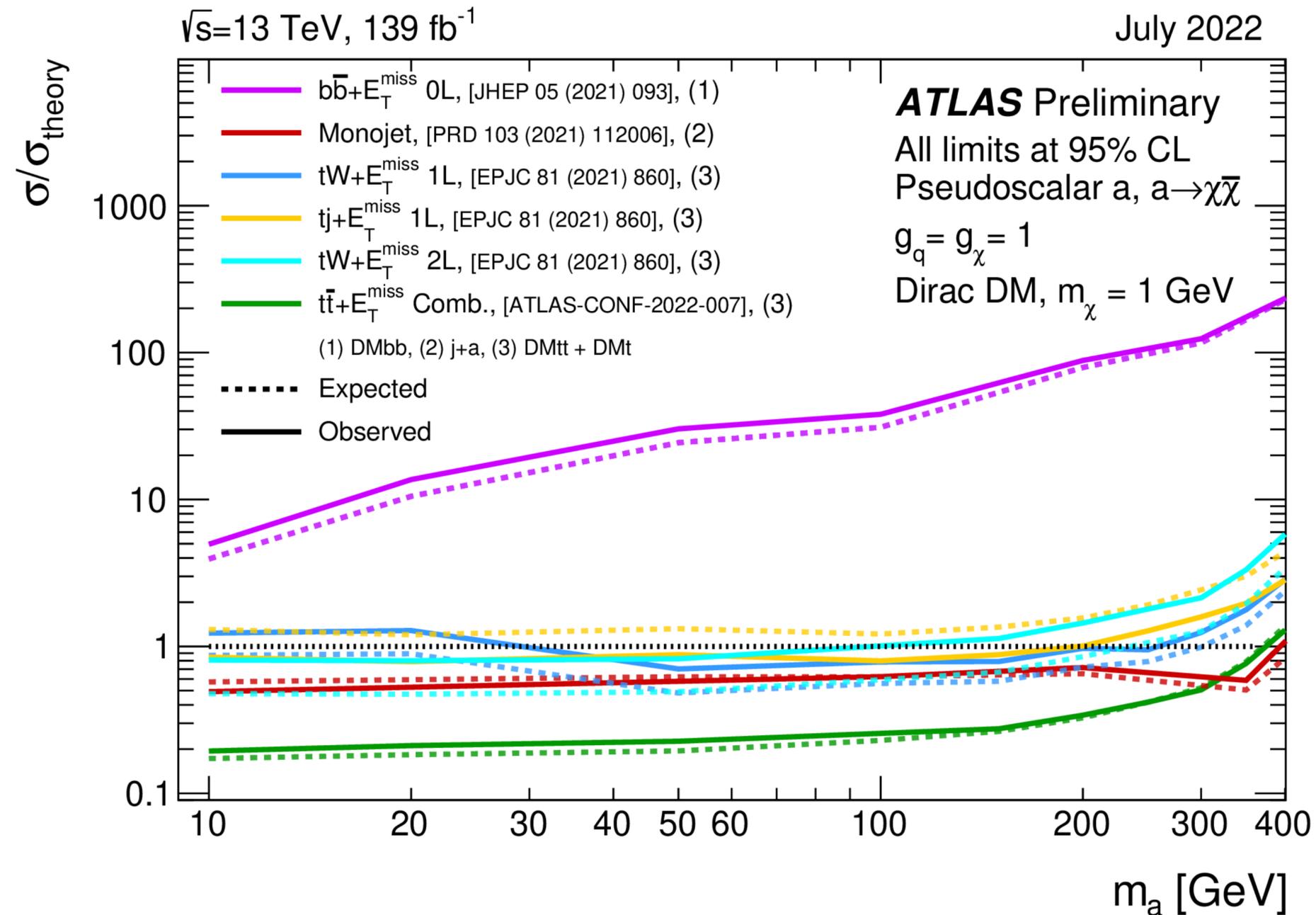


Leptophobic,  $g_\ell = 0$



Leptophilic,  $g_\ell = 0.01$

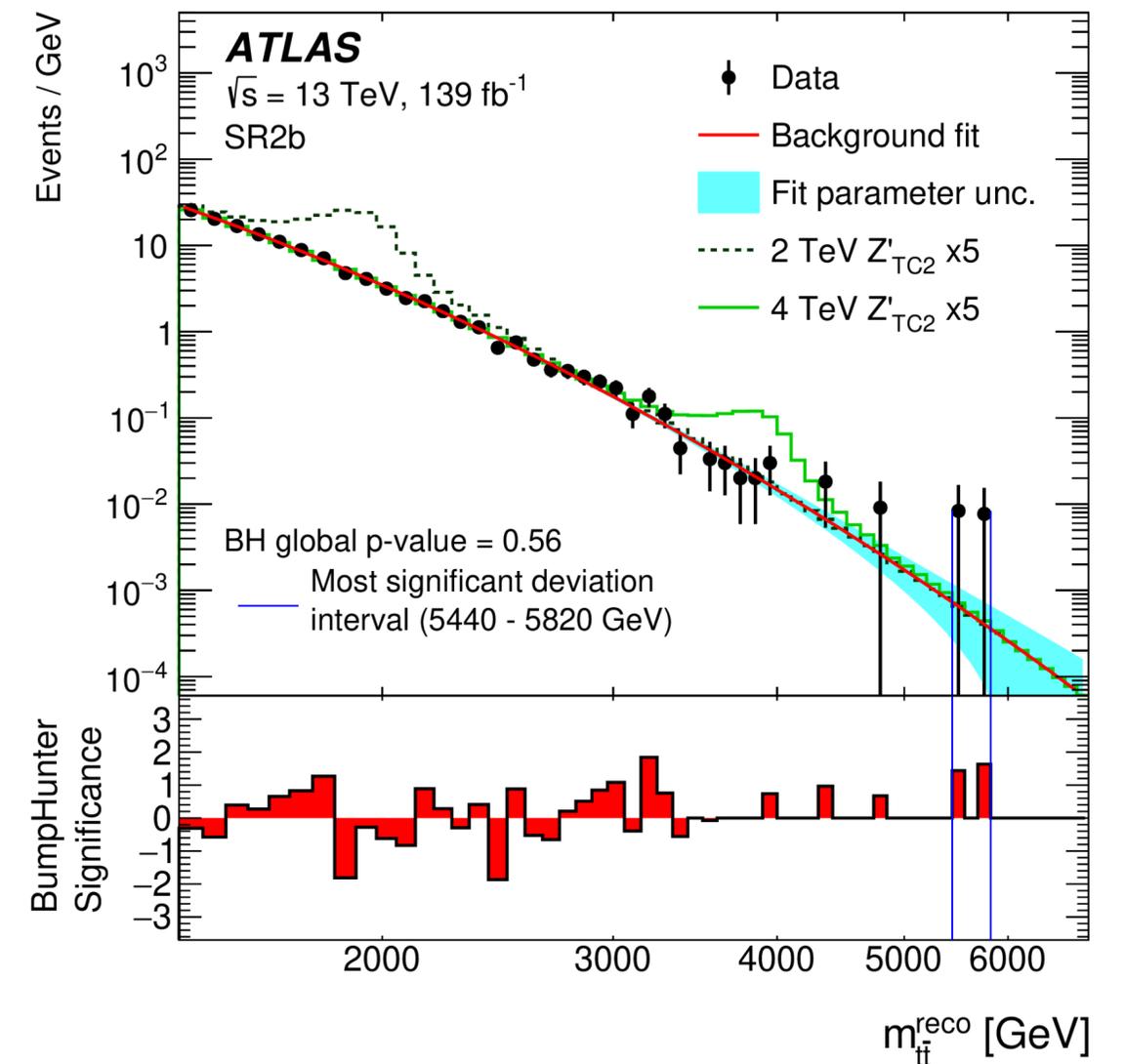
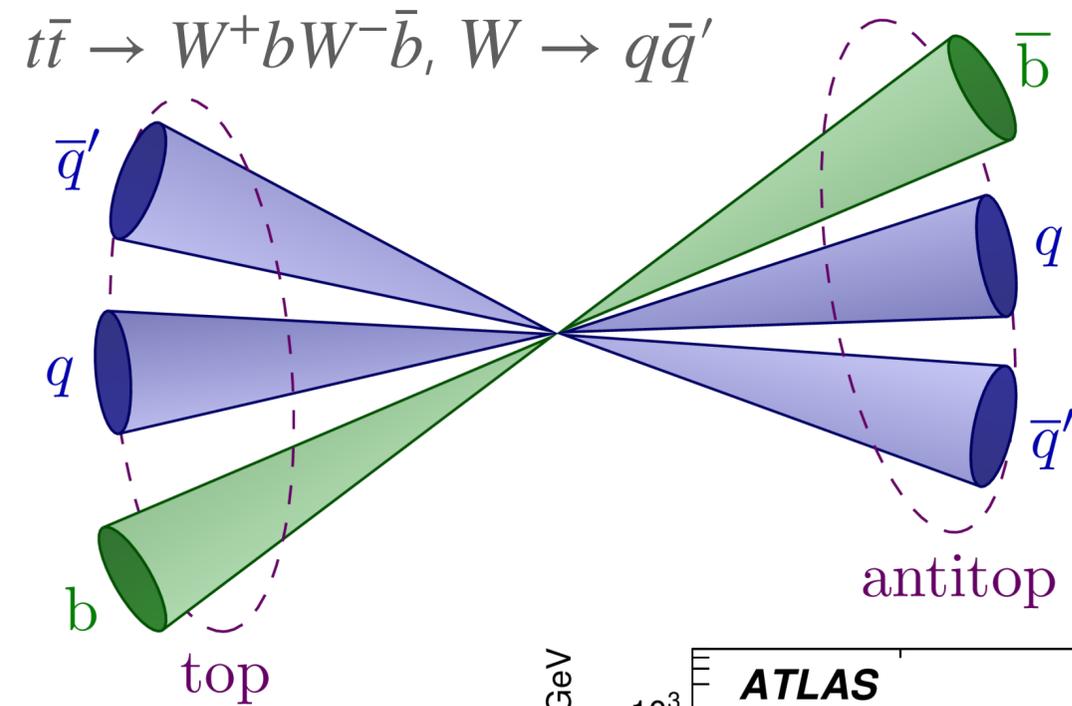
# Results: Pseudoscalar DM Mediator



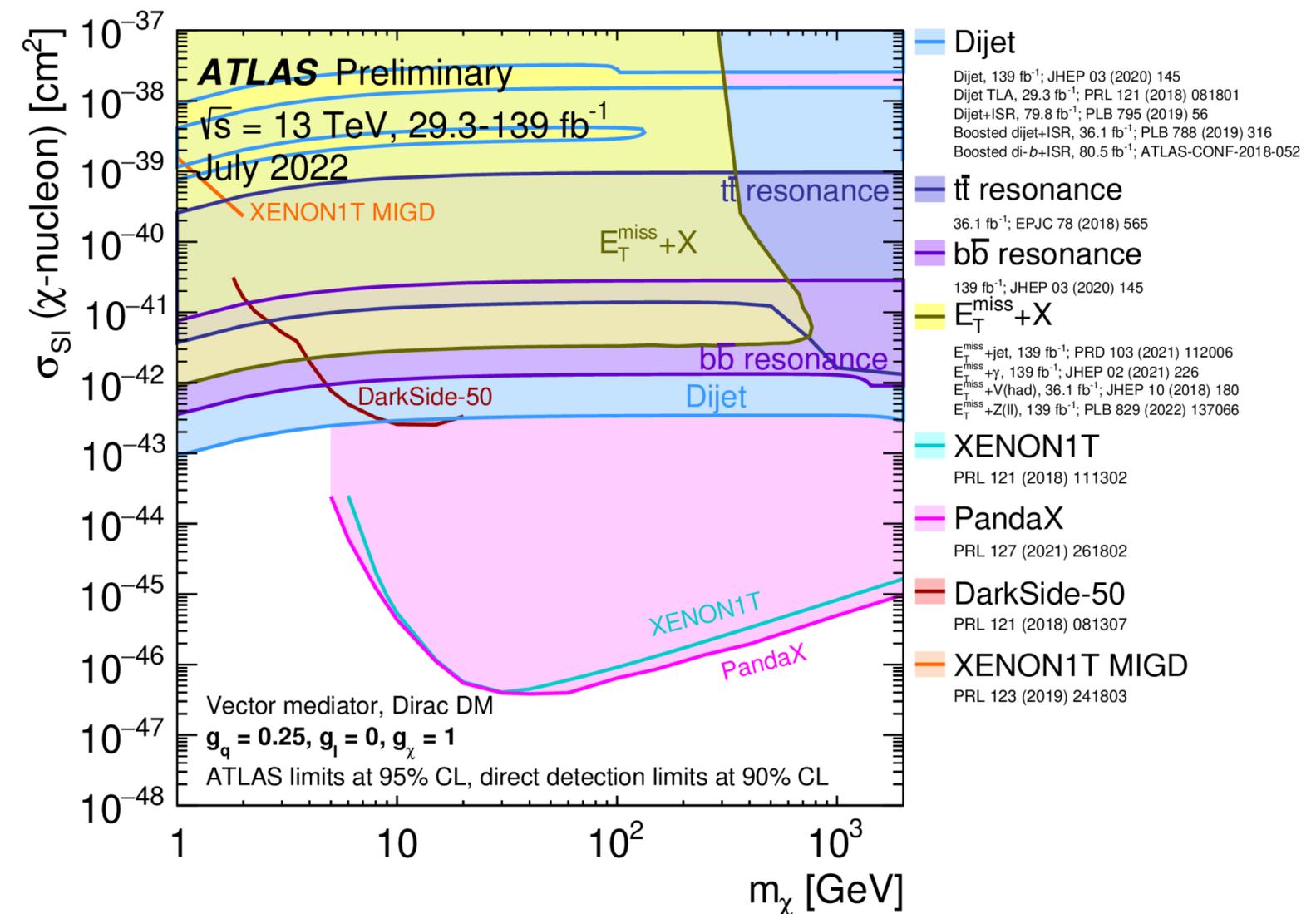
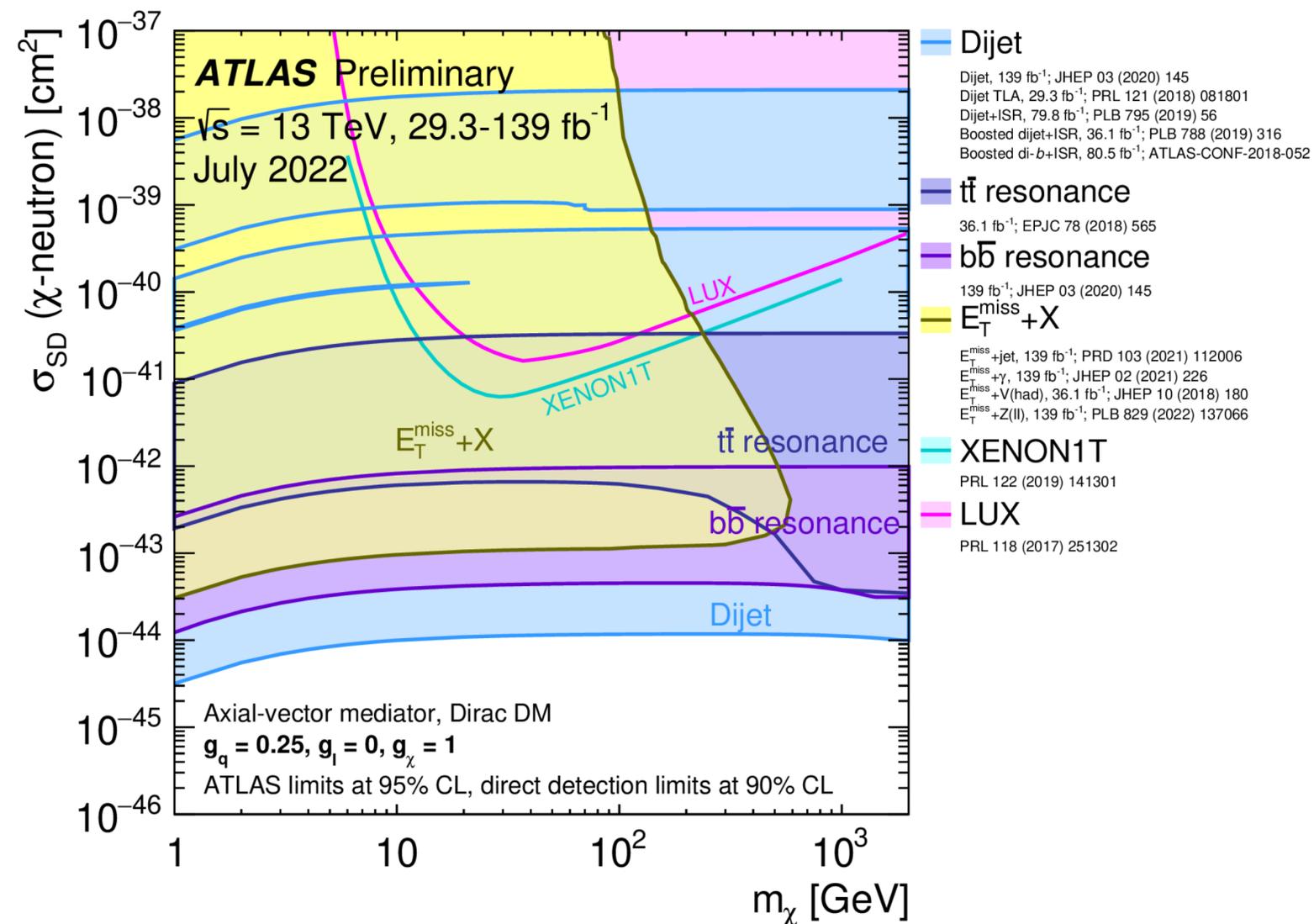
# $t\bar{t}$ (hadronic decays)

[JHEP 10 \(2020\) 061](#)

- Look for heavy resonant production of  $t\bar{t}$ 
  - ▶ Fully hadronic final states
  - ▶ 2 high- $p_T$  tops reconstructed as large radius jet ( $p_T > 500$  (350) GeV)
  - ▶ Top identification with Deep Learning based on internal substructure
- No data excess
  - ▶ Exclusion limits shown in the summary results



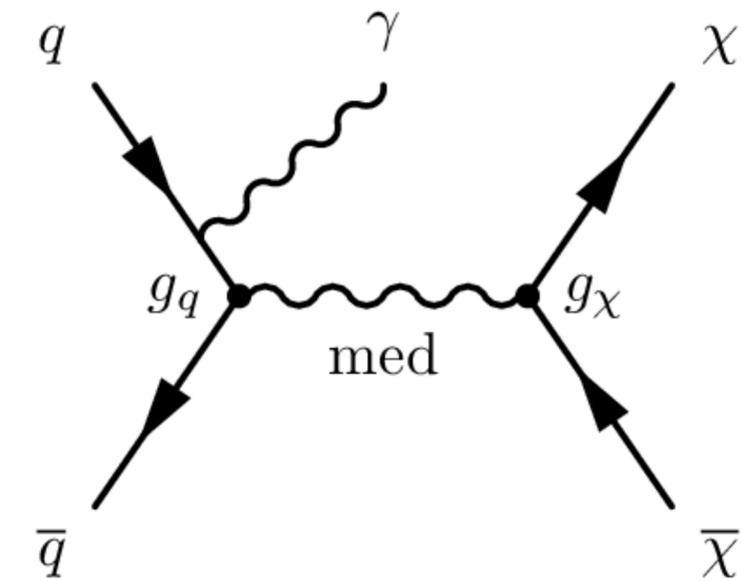
# Results: Exclusion of equivalent neutron $\sigma$ vs $m_\chi$



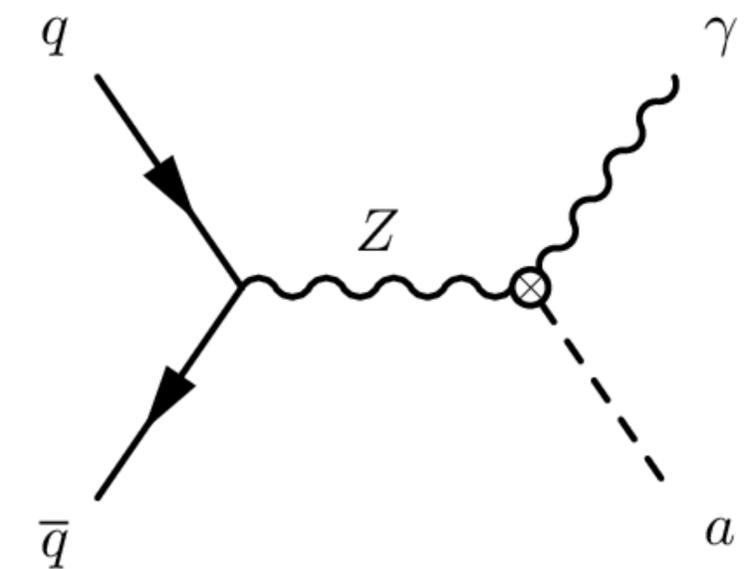
# $\cancel{E}_T + \gamma$

[JHEP 02 \(2021\) 226](#)

- Probes DM simplified model with V/AV mediator
  - ▶ Also includes an interpretation for an Axion-like Particle with Effective coupling to the SM (not discussed here)
- Event selection:
  - ▶  $\cancel{E}_T > 200$  GeV and isolated energetic photon ( $E_T > 150$  GeV)
  - ▶ No charged leptons



Simplified DM model



ALP model

# $E_T + \gamma$

[JHEP 02 \(2021\) 226](#)

- Simultaneous fit of expected and observed events in different  $E_T$  ranges
- Two background sources in processes with:
  - ▶ Fake  $\gamma$  (jets/electrons mis-classification)
  - ▶ Real  $\gamma$  and energetic neutrinos (dominant  $Z(\nu\nu)\gamma$ +jets)
- Significance of data excess  $< 0.5 \sigma$ 
  - ▶ V/ AV mediator mass excluded up to  $\sim 1.5\text{TeV}$  (leptophobic mediator,  $g_\ell=0$ )
  - ▶ DM mass excluded up to 580 GeV, depending on mediator and couplings

