Searches for dark matter with the ATLAS detector

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Oklahoma State Universtiy

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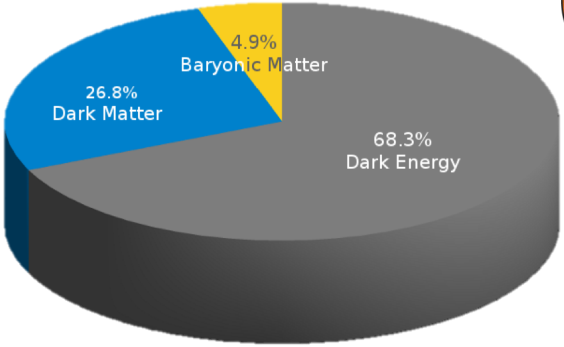
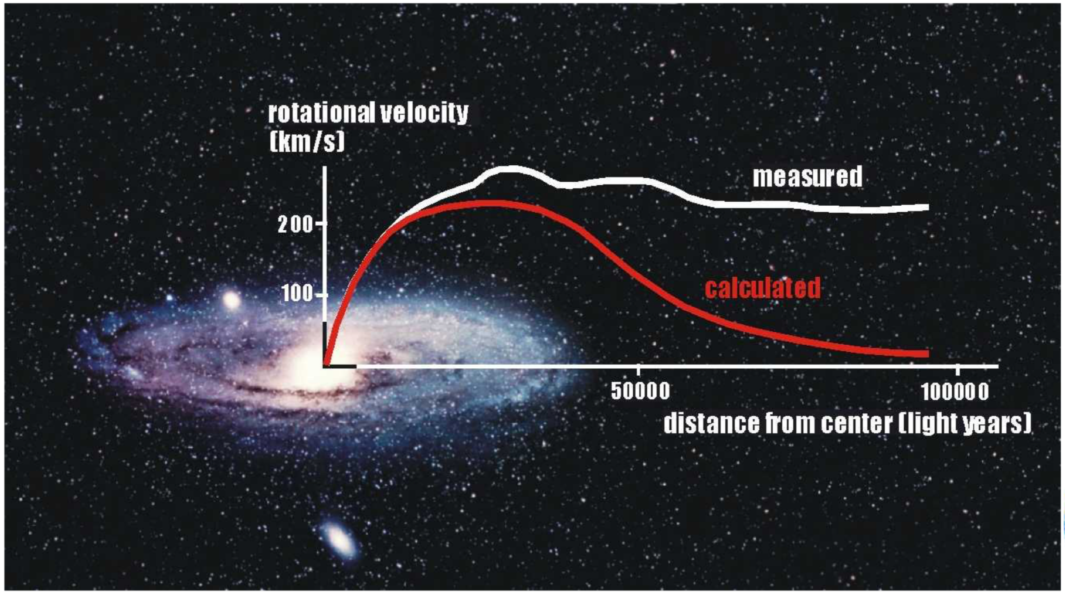
September 4

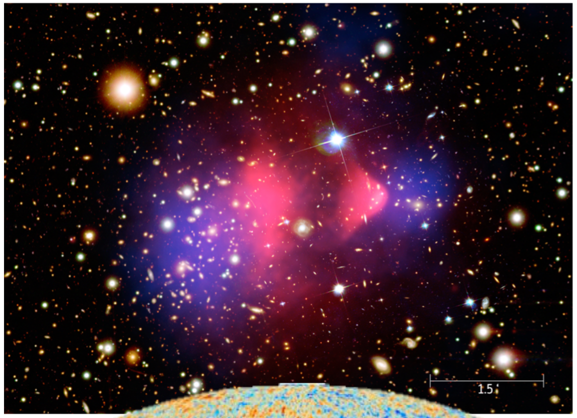
Dark Matter

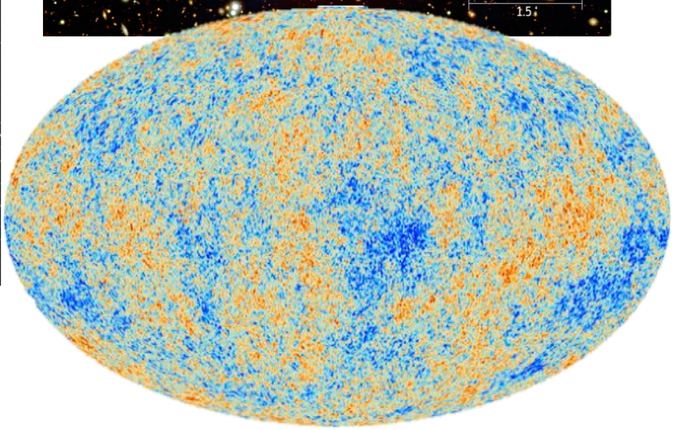


Favorite collider candidate: WIMP

- Weakly interacting, heavy, & stable
- Naturally accounts for observed relic density (WIMP Miracle)
- *Should* be produced at the LHC







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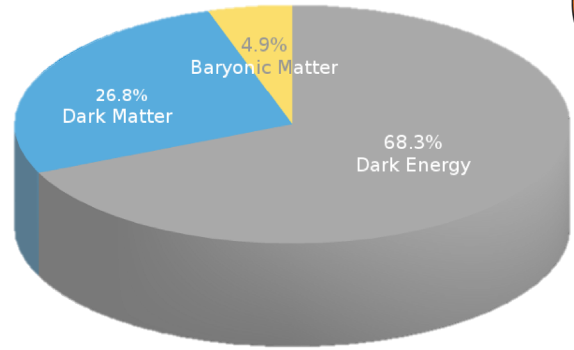

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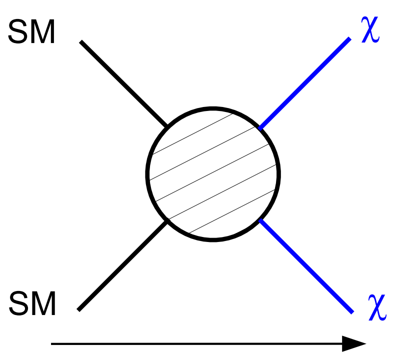
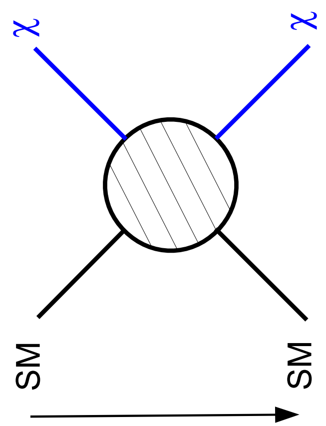
Complementary to dedicated DM experiments

"make it"



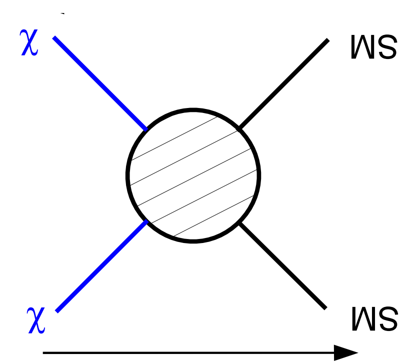
Collider

"shake it"



Direct detection

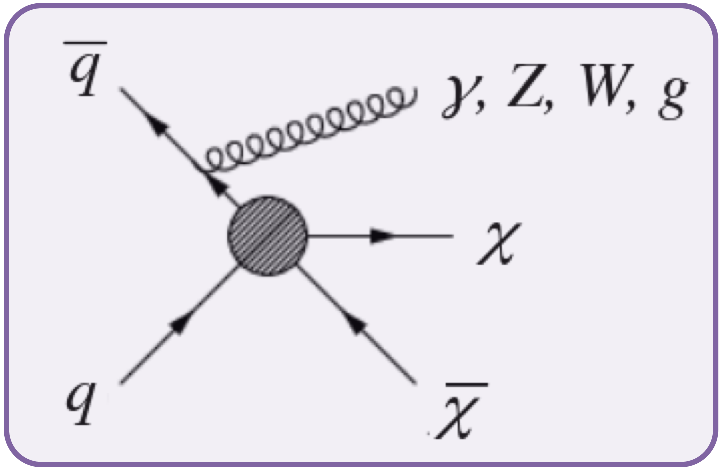
"break it"

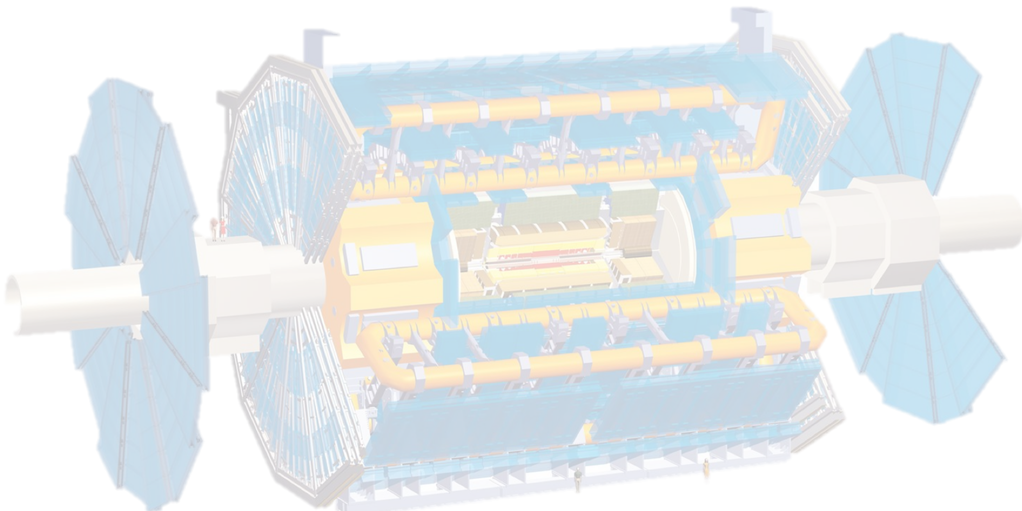


Indirect detection

General Collider Strategy

- Resonance searches: $\chi \rightarrow$jj/bb/tt/ℓℓ
- **E_T^{miss} + X**
  - DM particles escape detection
    $\Rightarrow$ $|\mathbf{p}_T^{miss}| \equiv E_T^{miss}$
  - Recoil against SM object(s)
    $\Rightarrow$ X = jet, γ, *W*, *Z*, *H*/*S*, *tt*/*bb*, *tW*, …





This talk:

- A selection of the **most recent** ATLAS dark matter searches
  $\Rightarrow$ **E_T^{miss} + X**
- All results using the full Run 2 dataset
  $\Rightarrow$ 139 fb^{-1} of *pp* collisions at $\sqrt{s}$ = 13 TeV

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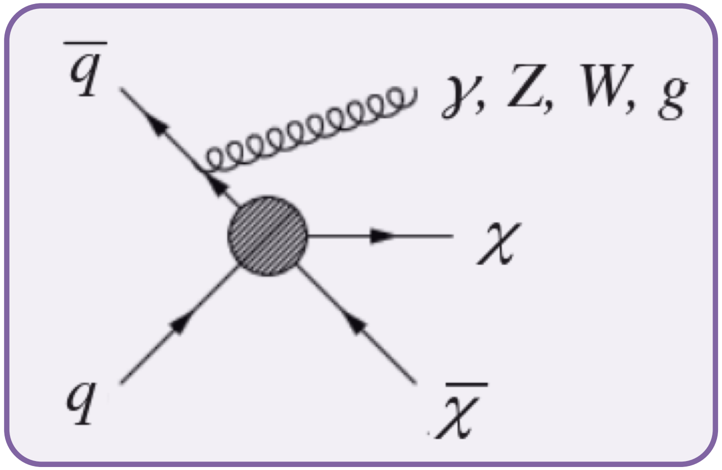

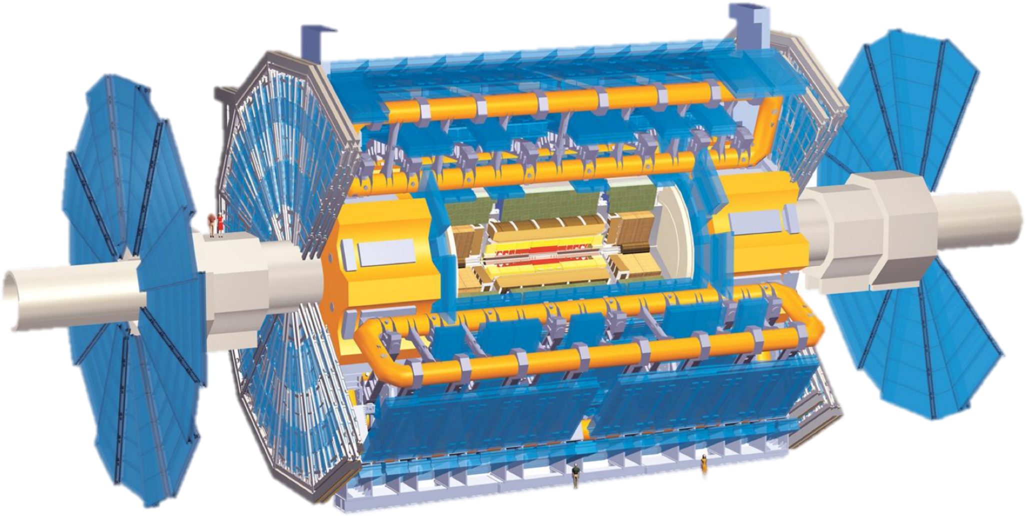

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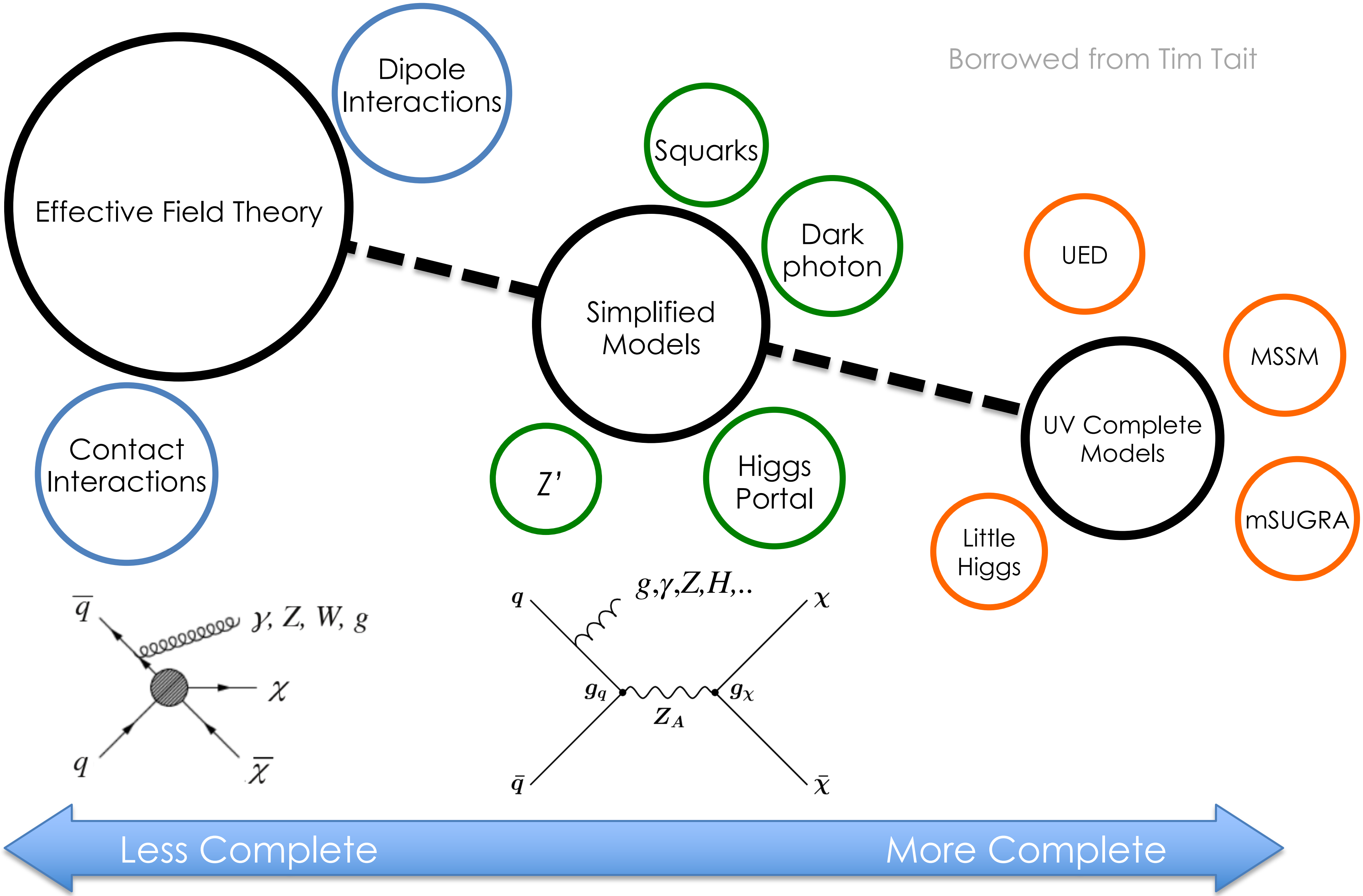
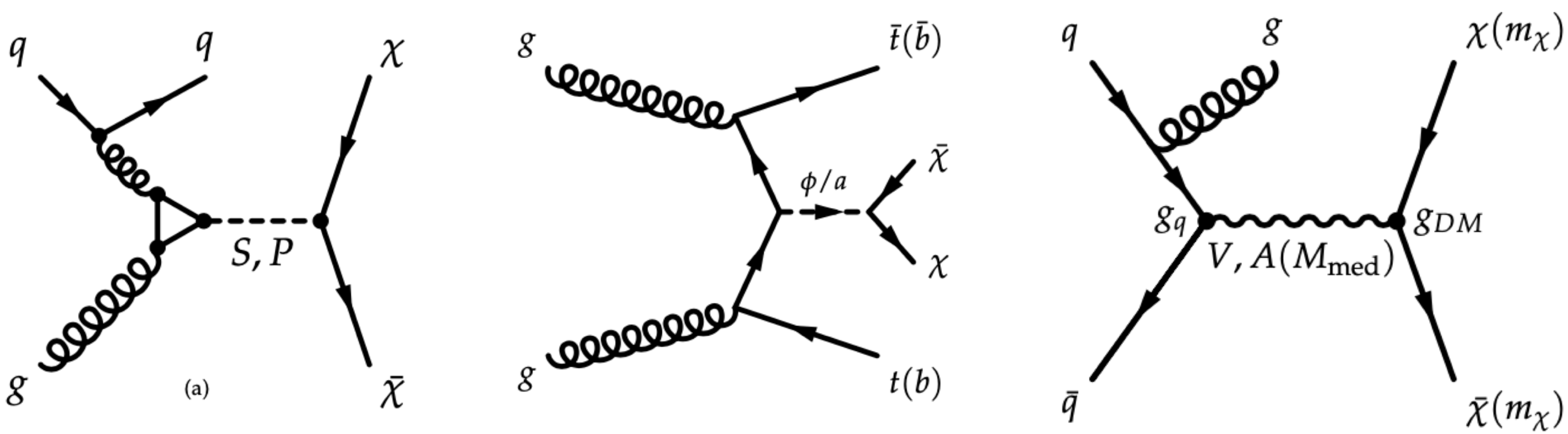
Interpreting DM Production



Simplified DM Models

Benchmark models defined in CMS/ATLAS Dark Matter Forum
[Physics of the Dark Universe 27 (2020) 100371]

- Dark matter assumed to be a Dirac fermion WIMP: χ
- Boson mediator between SM and DM
  - Spin-0: Scalar (*S*) or pseudo-scalar (*P*/*a*)
  - Spin-1: Vector (*V*/*Z'*) or axial-vector (*A*)
- Minimal set of parameters: M_χ , M_{med} , g_χ , g_q , g_ℓ



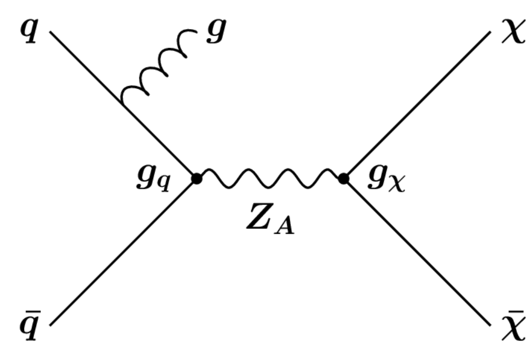
[Phys. Rev. D 103, 112006 (2021)](#)

E_T^{miss} + jet

Sensitive to Pseudo-scalar and Axial-vector mediators

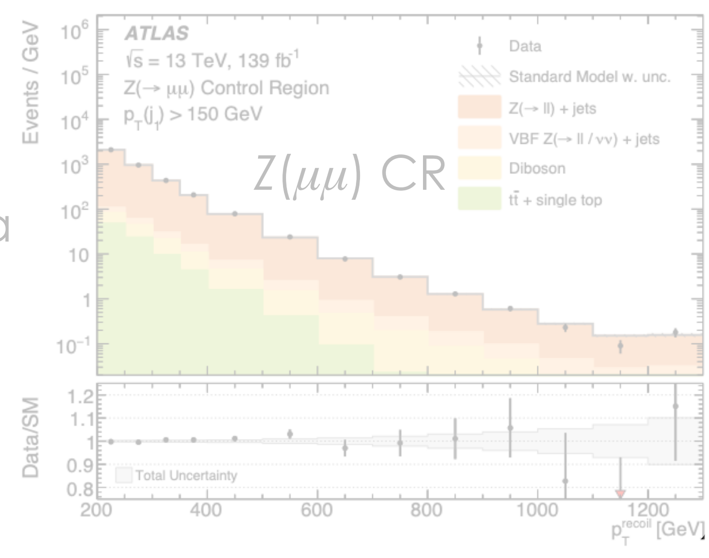
Select events with:

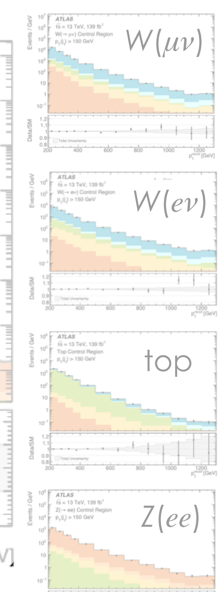
- Large missing momentum: E_T^{miss} > 200 GeV
- High-p_T jet from initial state radiation: p_T^{jet} > 150 GeV
- Veto events with e, μ, τ, γ



Main backgrounds from W/Z+jets (90%), plus top

- Shapes modeled by state-of-the-art Monte Carlo simulation
  - NNLO QCD + NLO EW
- Normalization determined from data
  - Four W/Z+jets Control Regions (CRs) enriched in $W(e\nu)$, $W(\mu\nu)$, $Z(ee)$, $Z(\mu\mu)$
  - One top CR enriched in $t\bar{t}$ + single top





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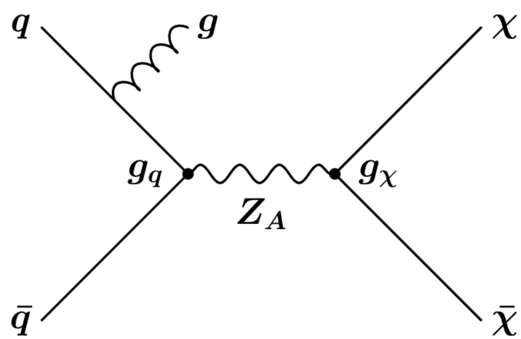

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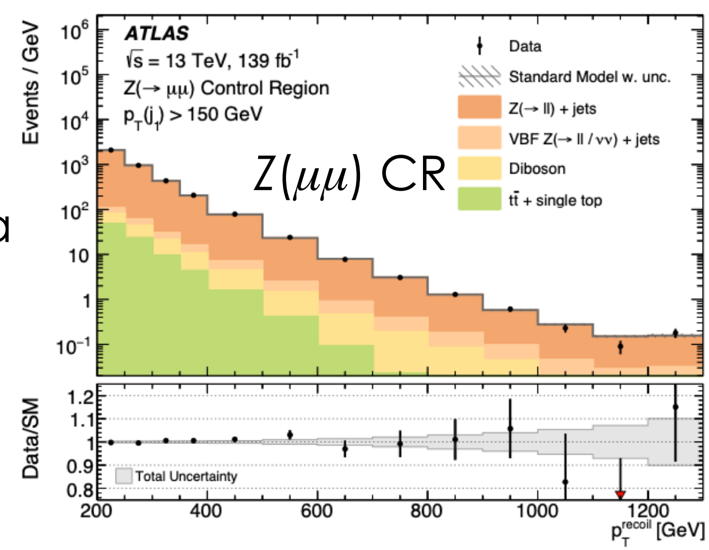
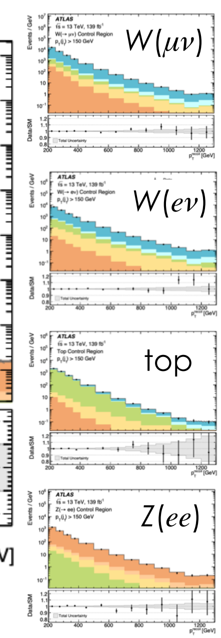




Phys. Rev. D 103, 112006 (2021)

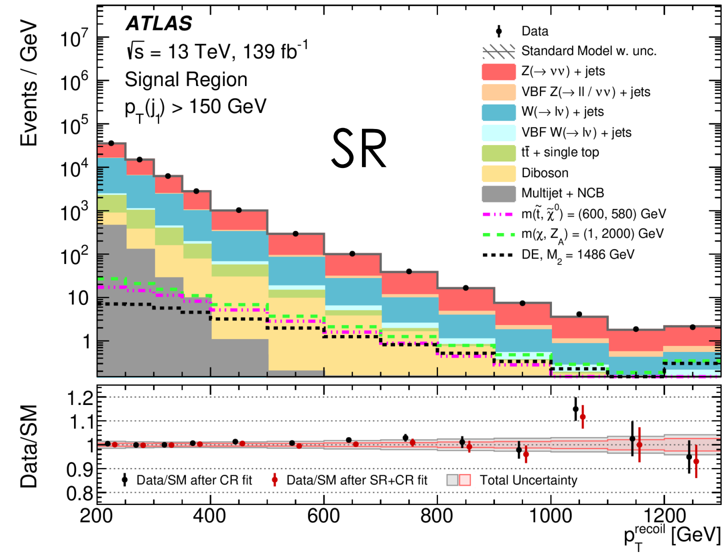
E_T^{miss} + jet

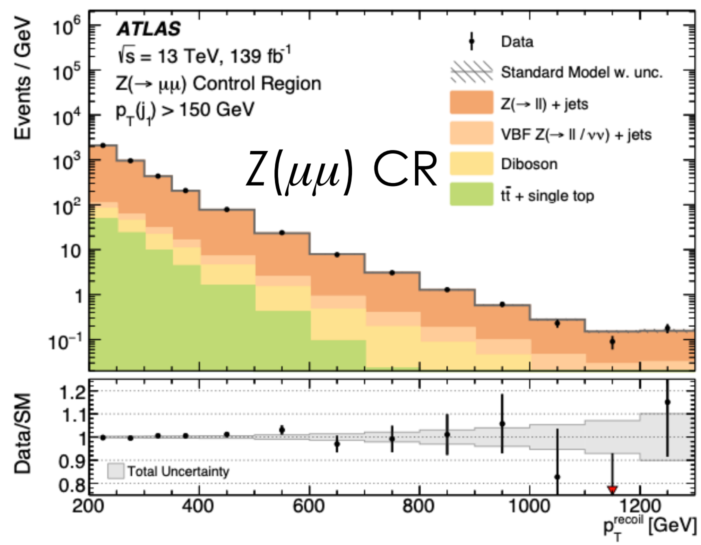
Perform profile likelihood fit

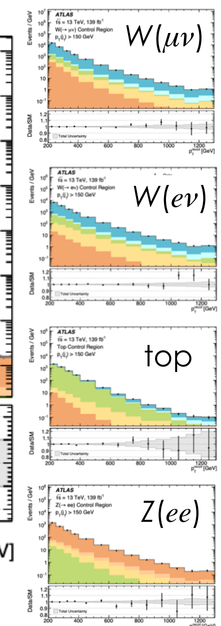
- Simultaneous fit in five CRs and one Signal Region (SR)
- Fit p_T^{recoil} = | $\mathbf{p}_T$ | of system recoiling against hadronic activity
  (In SR: $p_T^{recoil} \equiv E_T^{miss}$)
- 1.5-4.2% total uncertainty on background prediction

• Fit consistent with SM

⇒ Set limits on DM production cross-section and parameters







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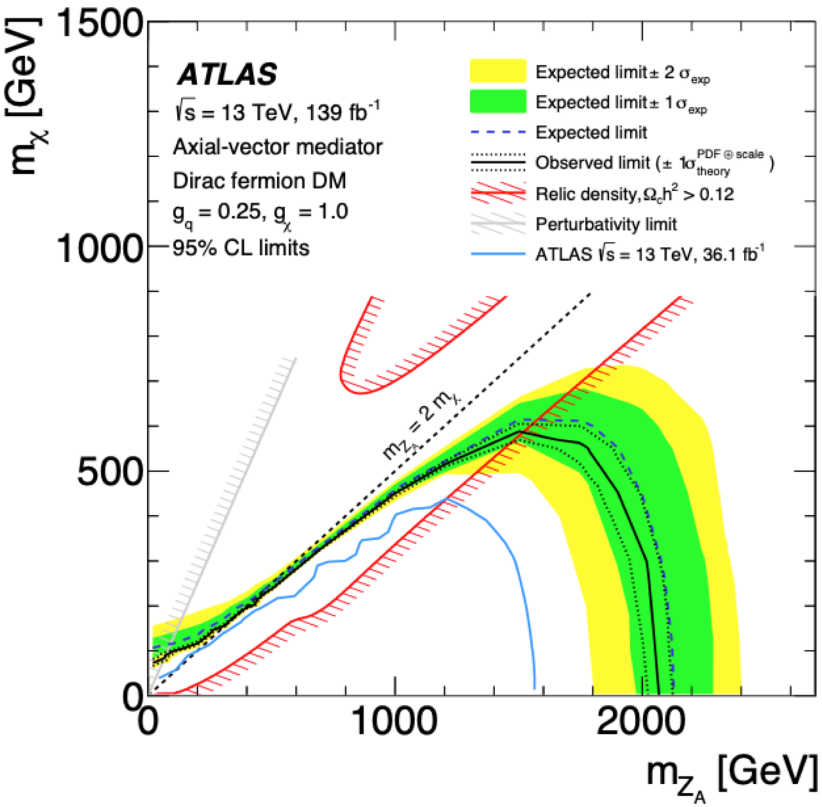
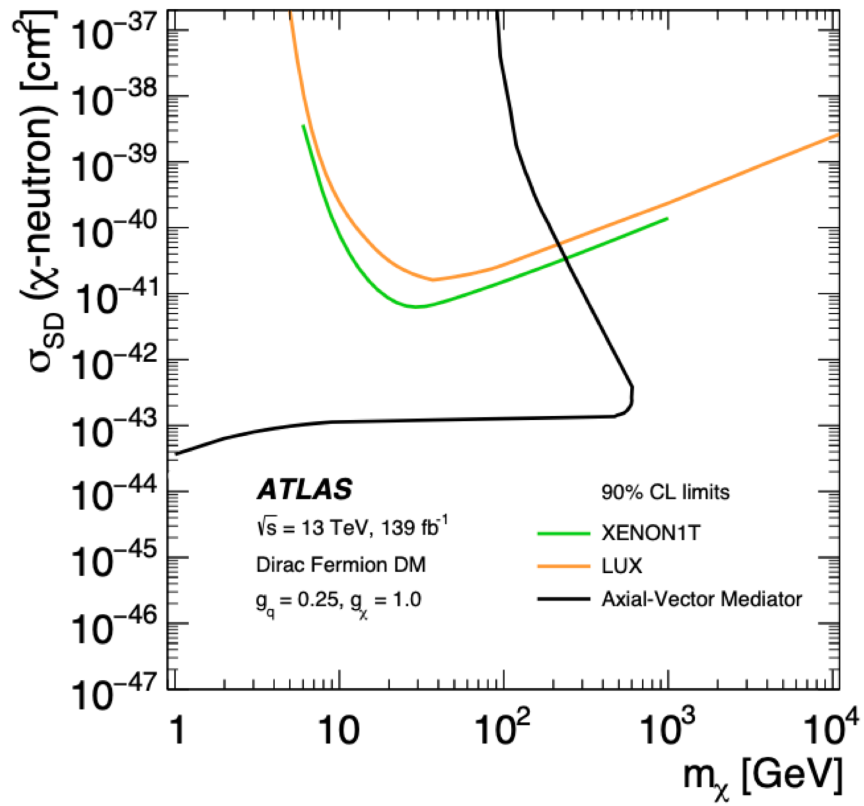
E_T^{miss} + jet

Limits on Axial-Vector Mediator:



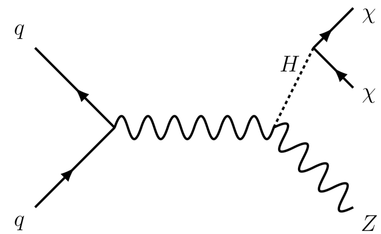


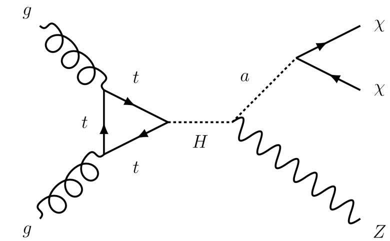
See paper for additional limits on pseudo-scalar model, squark production, large extra-dimensions, and invisible Higgs

Phys. Lett. B 829 (2022) 137066

$E_T^{miss} + Z(\ell\ell)$

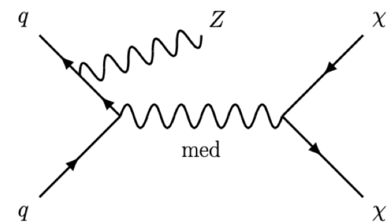
Interpreted in H➞invisible, 2HDM+*a*, and simplified DM models





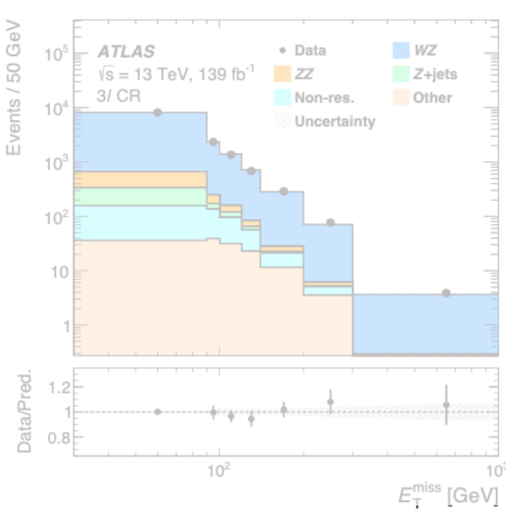
Select Signal Region (SR) with:

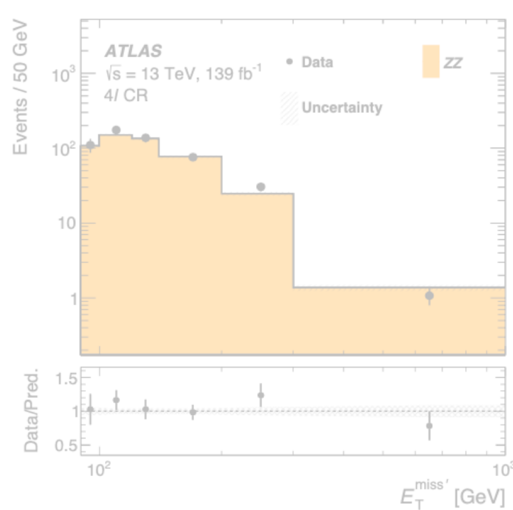
- Two opposite-charge leptons (e^+e^-, $\mu^+\mu^-$)
- $m_{\ell\ell} \in [76,106]$ GeV, $\Delta R_{\ell\ell} < 1.8$
- $E_T^{miss} > 90$ GeV, E_T^{miss} signif. > 9

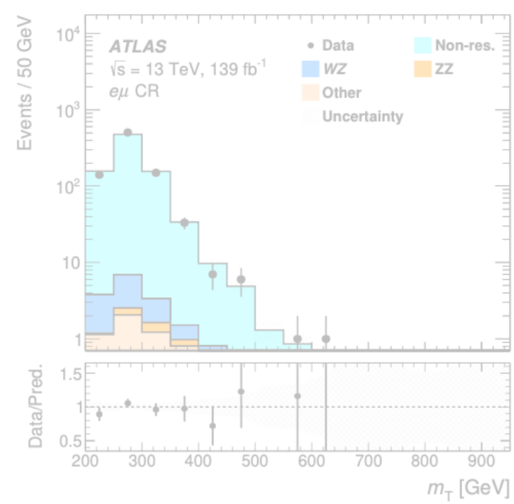


Dominant backgrounds from *ZZ* and *WZ*

- Constrained using three Control Regions (CRs):







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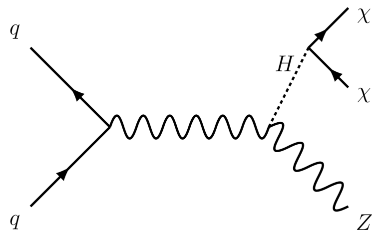

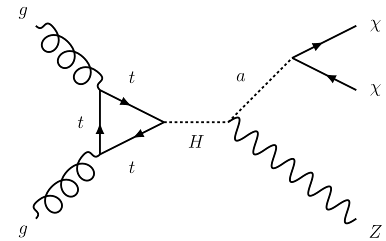

Interpreted in H→invisible, 2HDM+a, and simplified DM models

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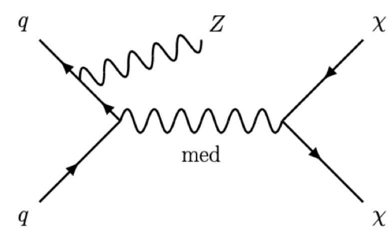

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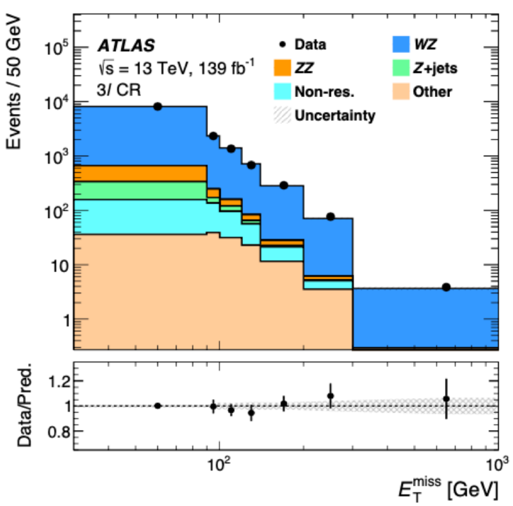

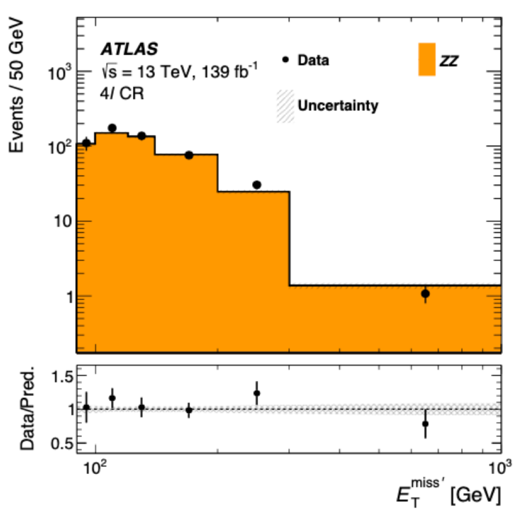

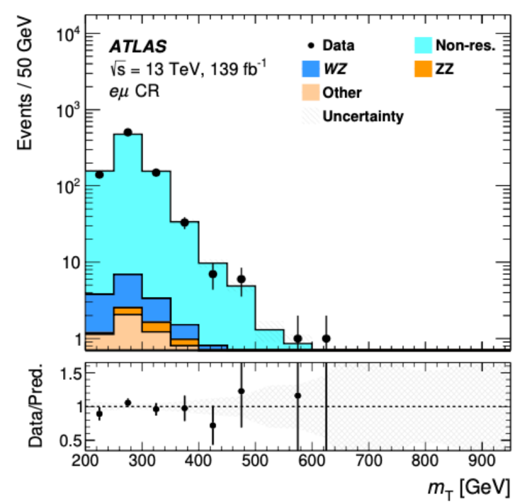

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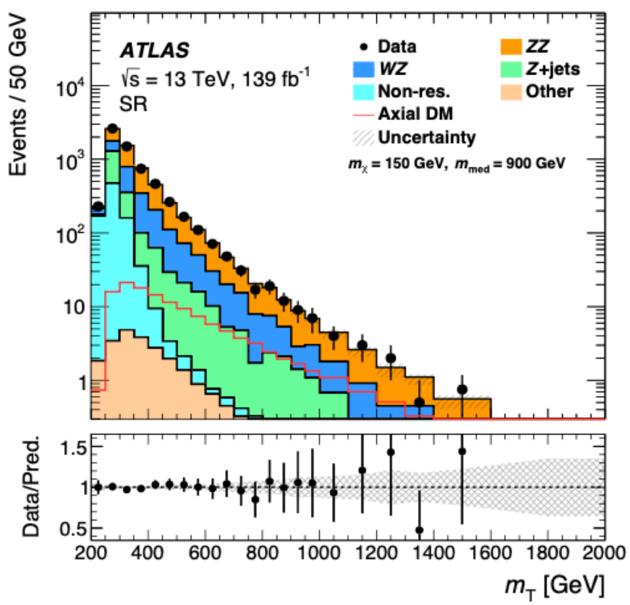
$E_T^{\text{miss}} + Z(\ell\ell)$

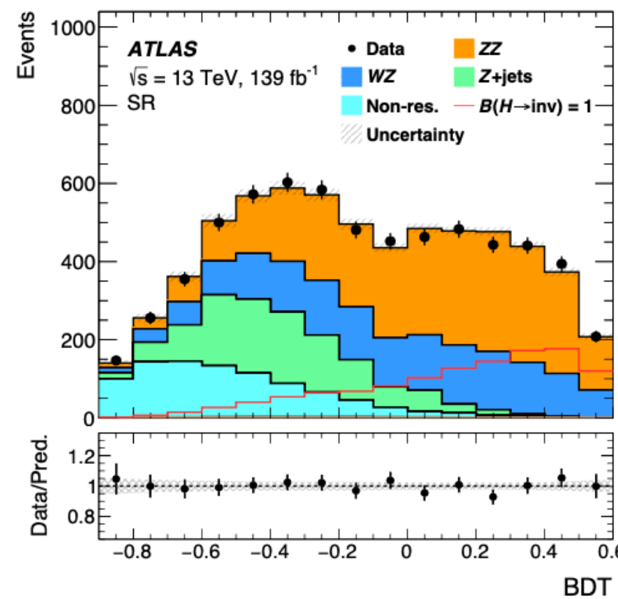
Simultaneous profile likelihood fit in SR and three CRs

- Simplified DM and 2HDM+*a* model use m_T distribution



$$m_T = \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2}\right]^2 - \left[\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right]^2}$$

- $H\rightarrow$inv. uses Boosted Decision Tree discriminant



Good agreement with SM prediction :-(

⇒ Set limits on model parameters

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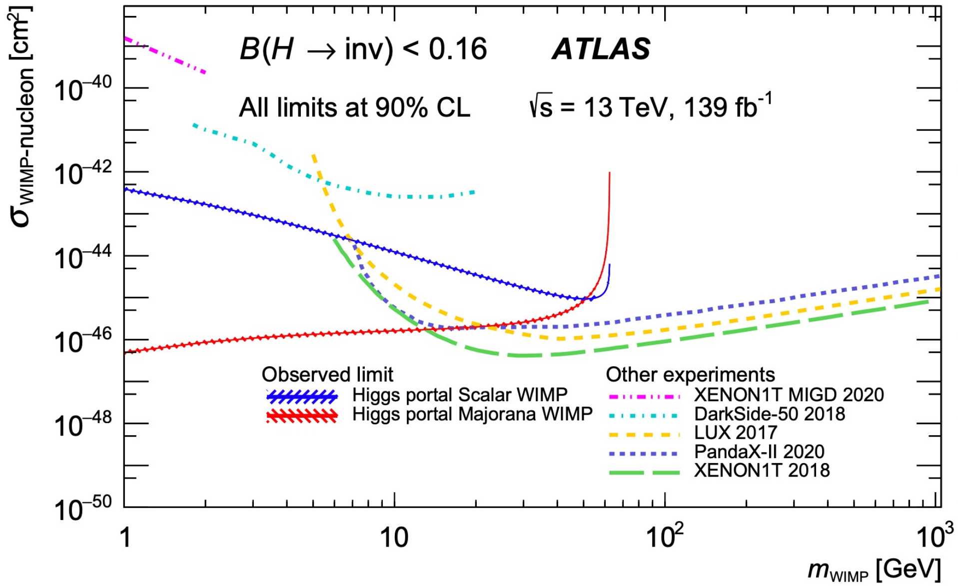
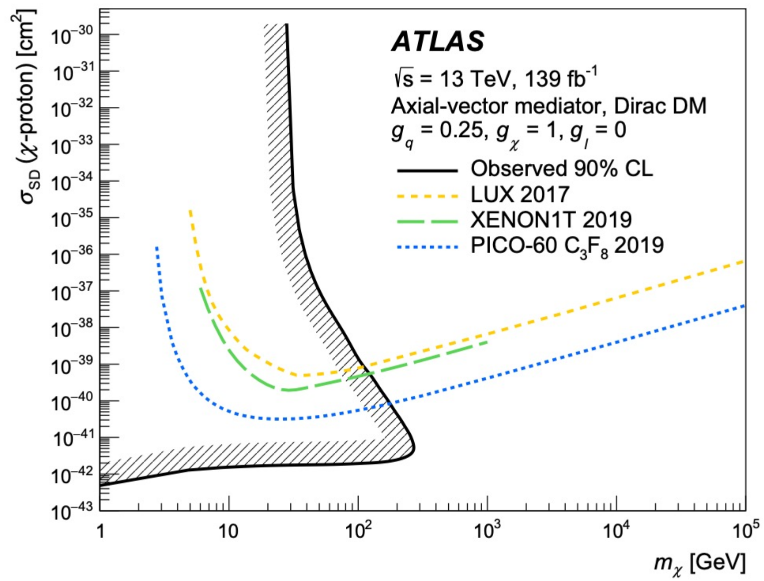
$E_T^{miss} + Z(\ell\ell)$

Limits on WIMP-nucleon cross-section complementary to direct detection





Interpreted as SM Higgs ➞ invisible: BR(H➞inv.) = 0.003 ± 0.09

- 45% better sensitivity beyond increase in luminosity!
- Competitive with VBF H➞invisible

Also interpreted in 2HDM+a and simplified DM models

See also talk by Will Fawcett with more H➞inv. and Higgs as a portal to dark sector.

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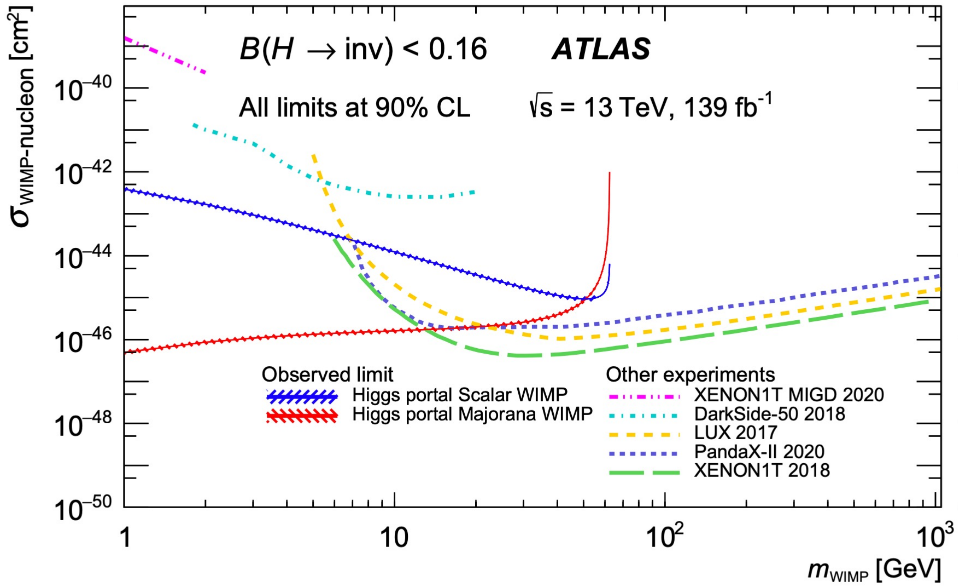

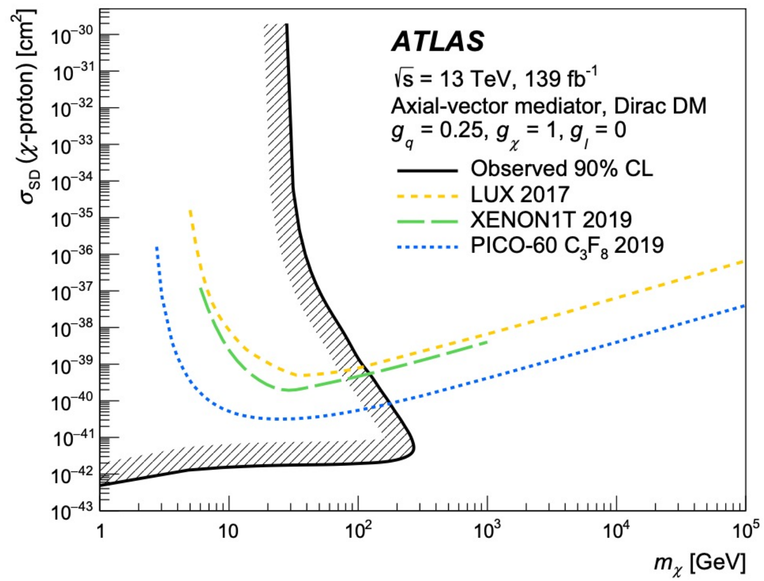

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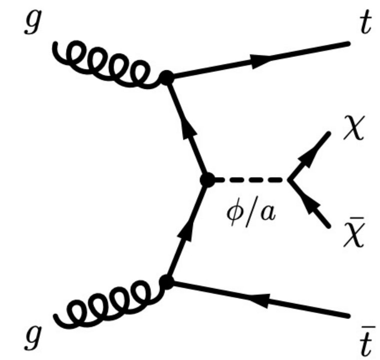
E_T^{miss} + tt (tW,tq)

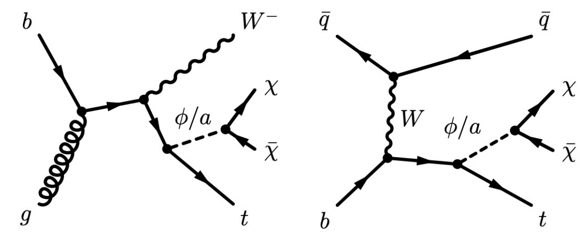


Focus on DM with spin-0 mediator

- Important in models with Min. Flavor Violation
- Yukawa-like coupling to mediator $\propto m_f$

Combination of 0, 1, & 2 lepton searches

Eur. Phys. J. C 80 (2020) 737, JHEP 04 (2020) 174, JHEP 04 (2021) 165



- Set limits on $\sigma/\sigma_{\text{theory}}$ vs. $m_{\phi(a)}$

  ⇒ Exclude m_ϕ up to 370 GeV
- Interpreted as $H\rightarrow$invisible

Analysis	Best fit $\mathcal{B}_{H\rightarrow\text{inv}}$	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	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$
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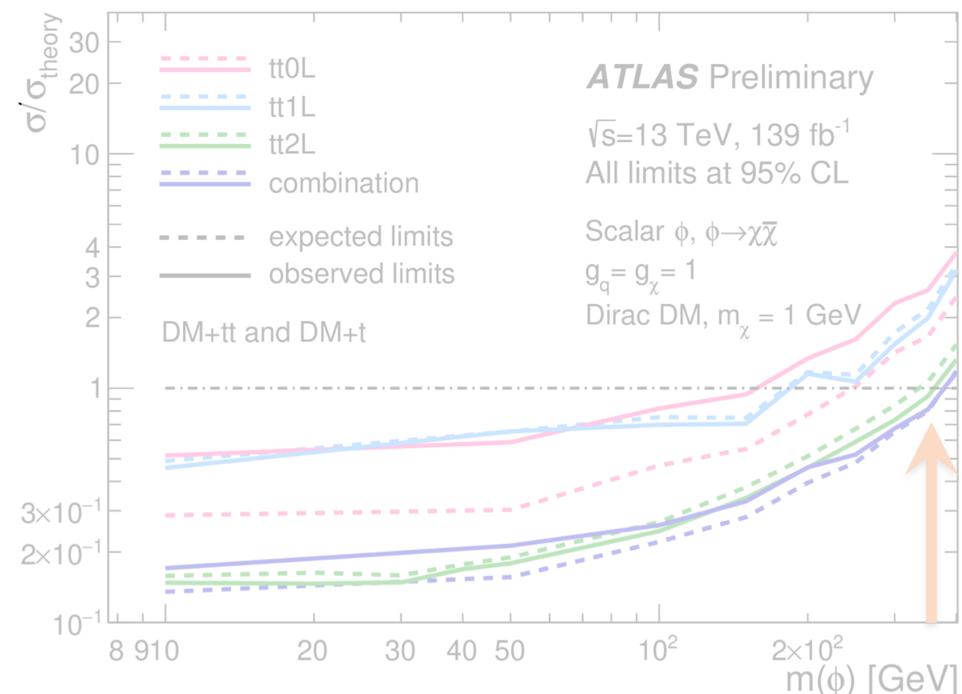
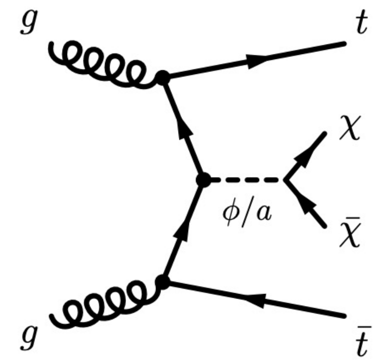
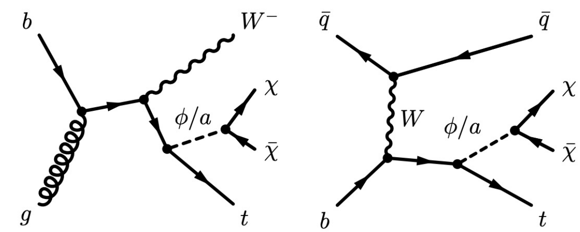


ATLAS-CONF-2022-007

E_T^{miss} + tt (tW,tq)





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- Yukawa-like coupling to mediator ∝ m_f

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Eur. Phys. J. C 80 (2020) 737, JHEP 04 (2020) 174, JHEP 04 (2021) 165

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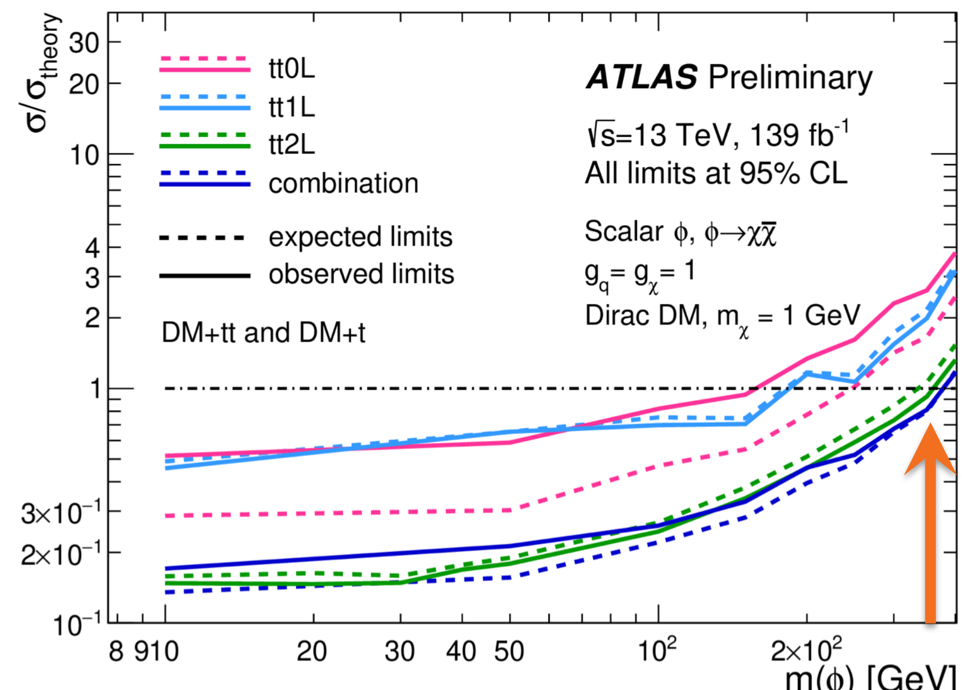

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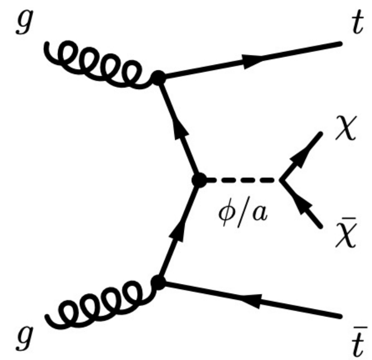

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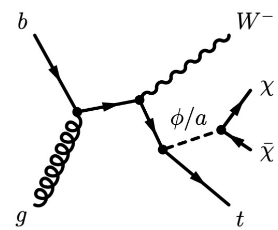
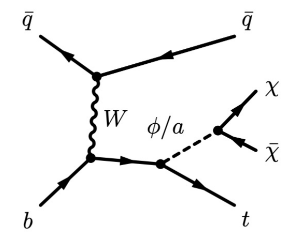




Combination of 0, 1, & 2 lepton searches

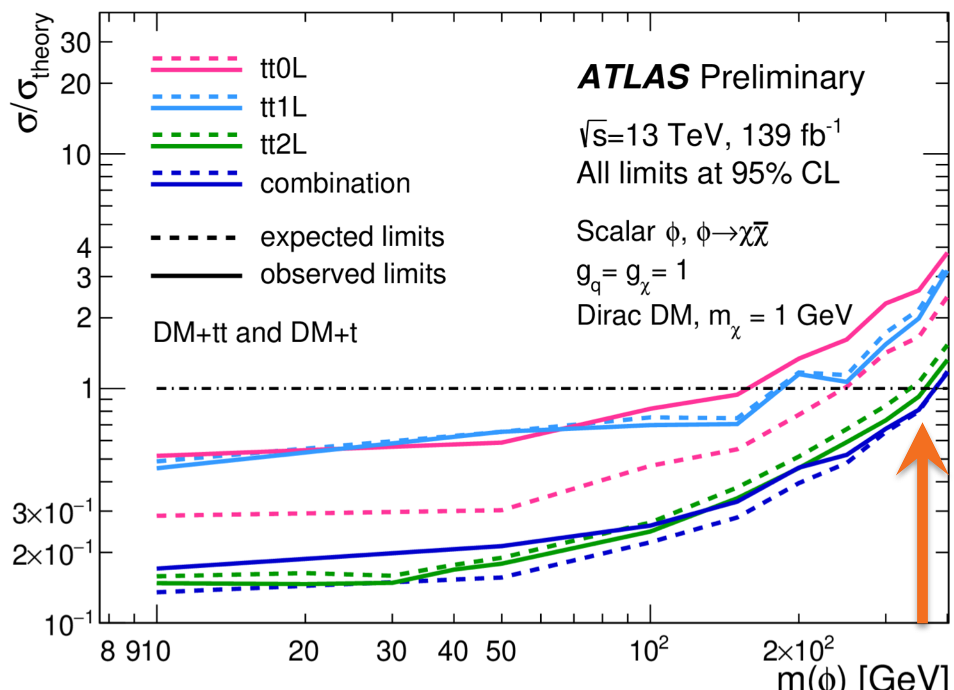
Eur. Phys. J. C 80 (2020) 737, JHEP 04 (2020) 174, JHEP 04 (2021) 165

- Set limits on $\sigma/\sigma_{\text{theory}}$ vs. $m_{\phi(a)}$

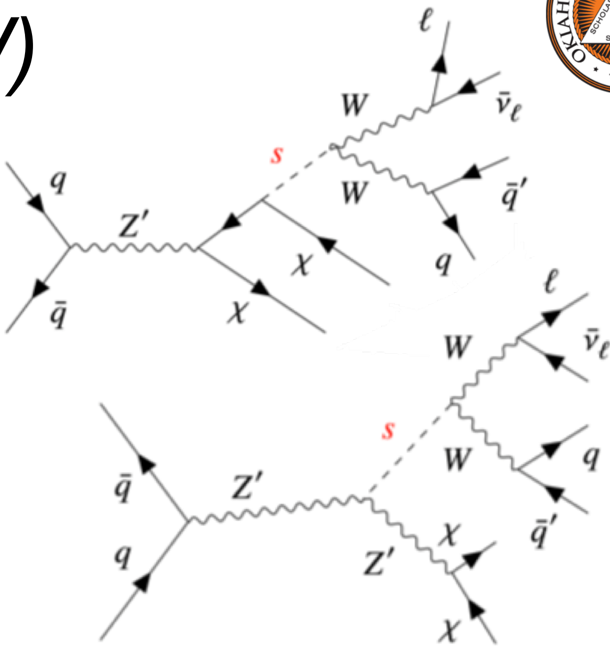
  ⇒ Exclude m_ϕ up to 370 GeV

- Interpreted as $H\rightarrow$invisible

Analysis	Best fit $\mathcal{B}_{H\rightarrow\text{inv}}$	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	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$



$E_T^{miss} + S(WW)$

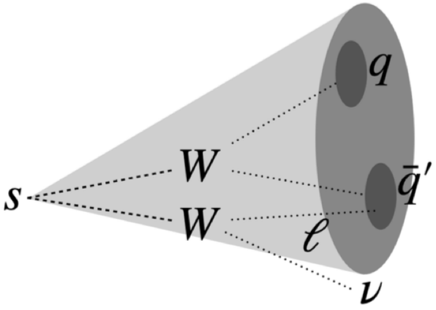


Dark Higgs decaying to $WW(qq\ell\nu)$

- Interpreted in two-mediator model with vector $Z' \to \chi\chi$ and scalar $S \to WW$

Select events with

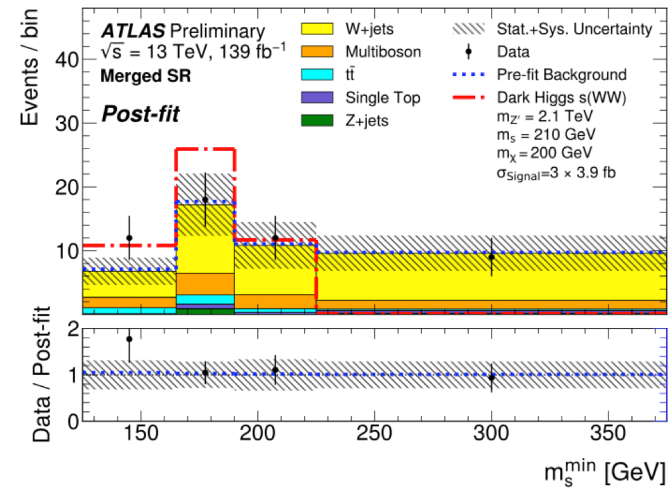
- $E_T^{miss} > 200$ GeV
- 1 high-p_T lepton (e/μ)
- Two categories for $W \to qq$
  - Merged: large-R jet with 2-prong substructure
    - Use "track-assisted reclustering" (TAR) to remove overlapping leptons
  - Resolved: two small-R jets
- CRs to constrain dominate W+jets and tt backgrounds

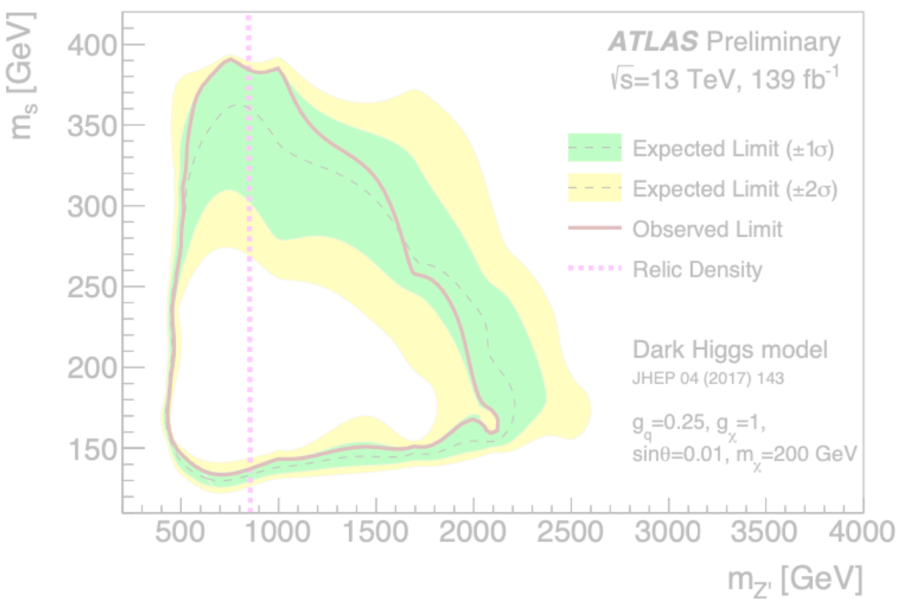


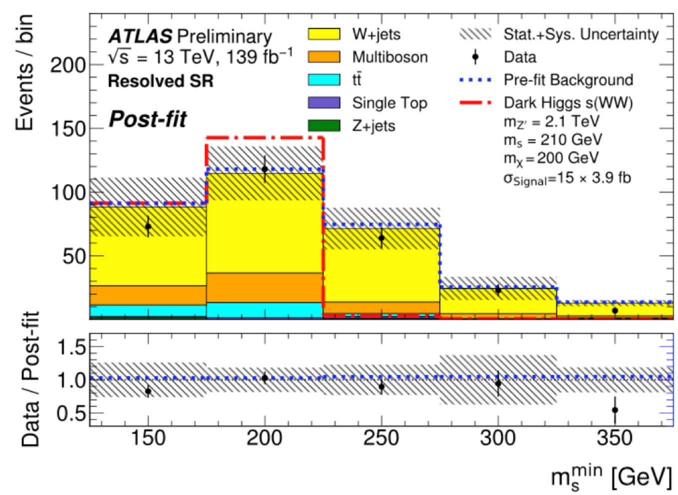
Also see talk by Christian Weber on searches for exotic Higgs decays.

$E_T^{miss} + S(WW)$

- Reconstruct $S \to WW \to qq\ell\nu$ up to ambiguity from missing neutrino
- Fit m_S^{min} distribution in Merged and Resolved SRs
- No significant excess
  $\Rightarrow$ Set limits on mediator masses







$E_T^{miss} + S(WW)$

- Reconstruct $S \rightarrow WW \rightarrow qq\ell\nu$ up to ambiguity from missing neutrino
- Fit m_S^{min} distribution in Merged and Resolved SRs
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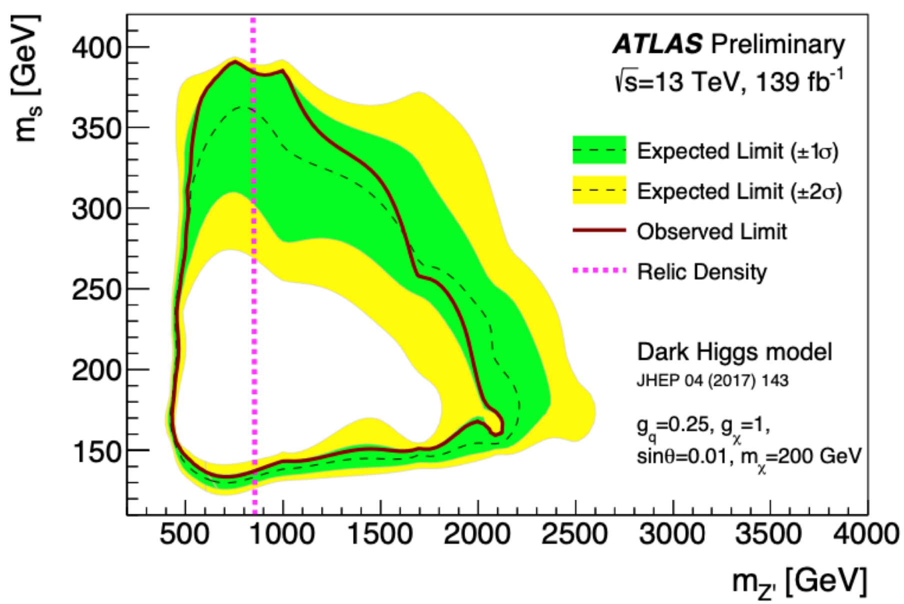
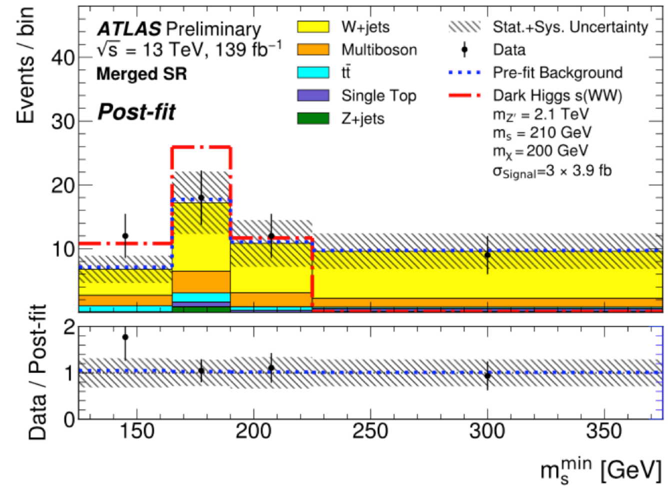
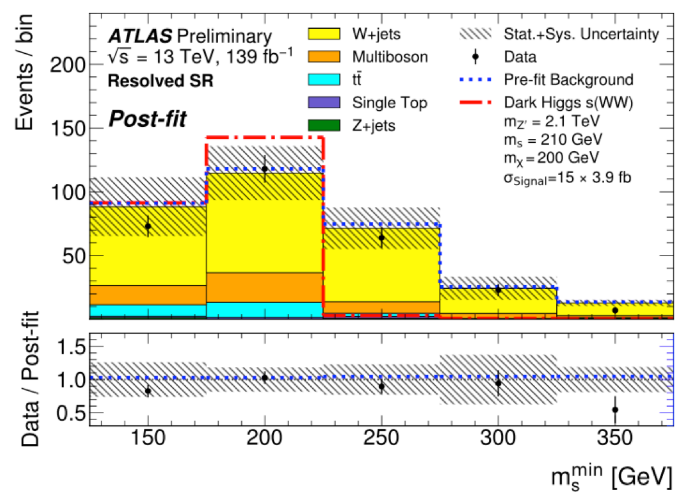
  ⇒ Set limits on mediator masses

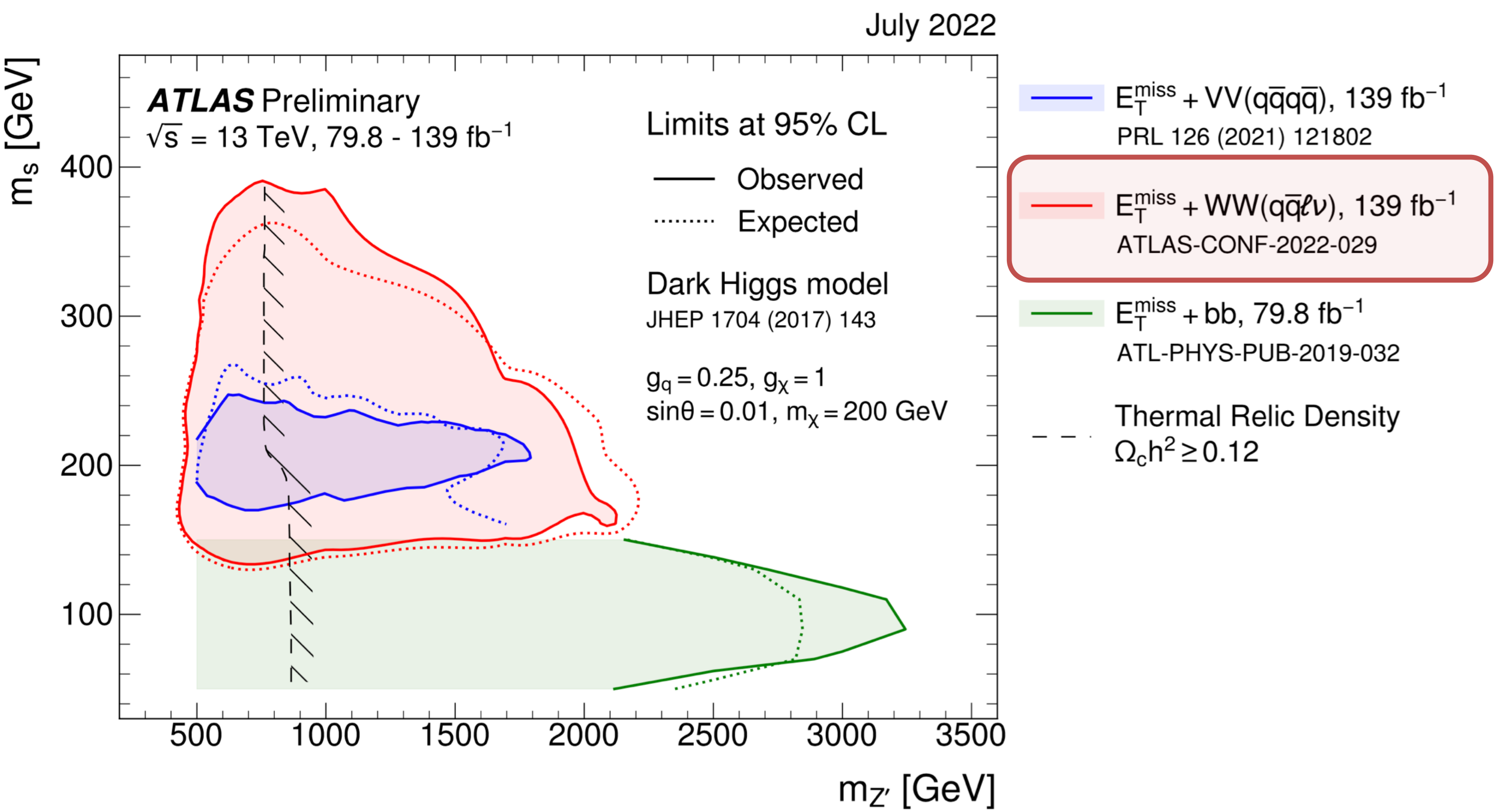






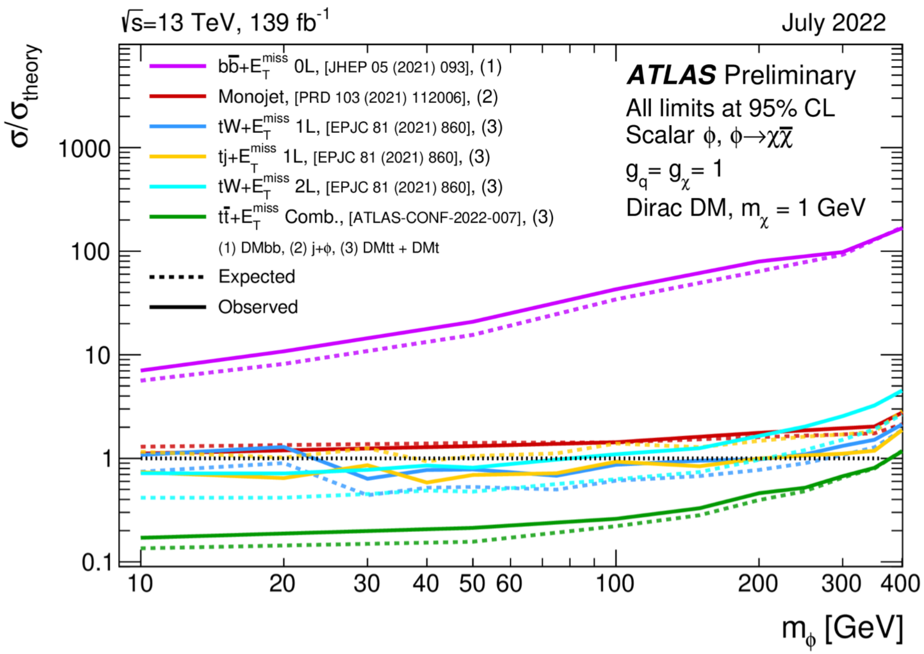
ATL-PHYS-PUB-2022-036

Summary Plot: Dark Higgs



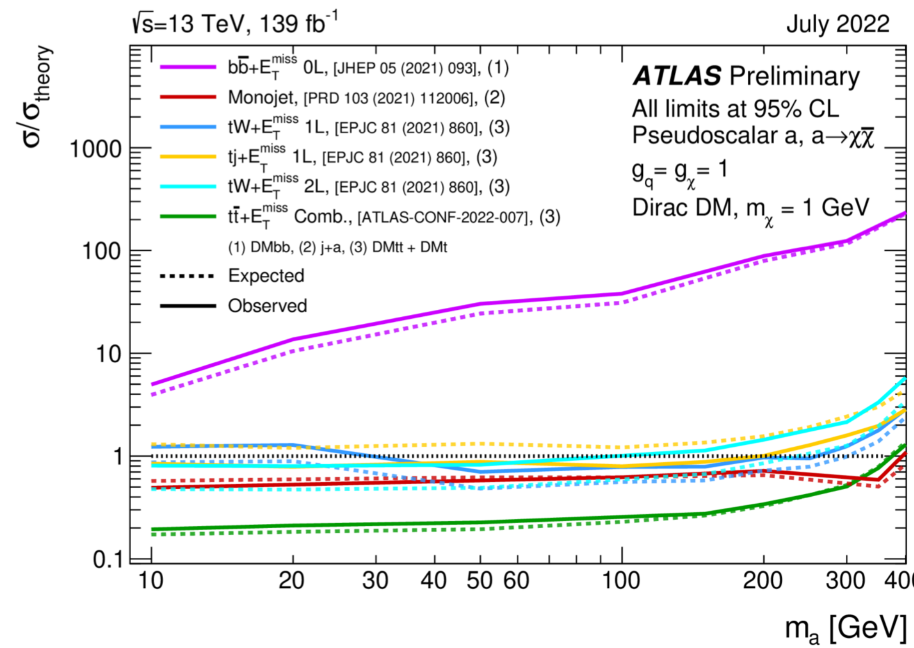
Summary Plots: Spin-0 Mediators

Limit on σ/σ_{theory} assuming $g_\chi = g_q = 1$, $m_\chi = 1$ GeV



Scalar mediator

⇒ Exclude $m_\phi < 370$ GeV



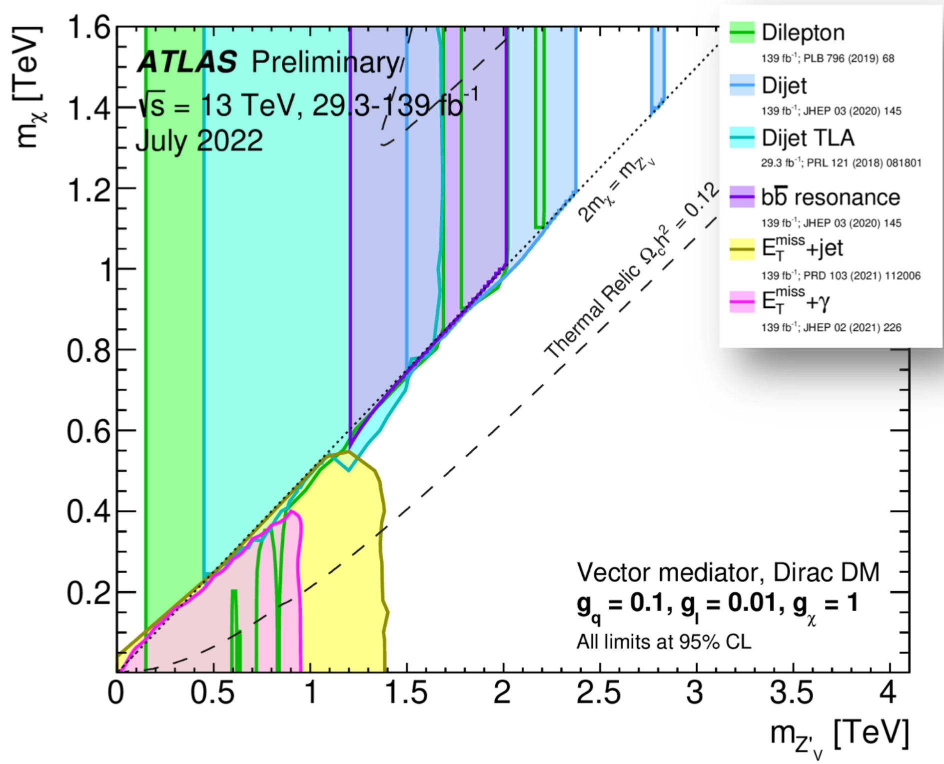
Pseudoscalar mediator

⇒ Exclude $m_a < 376$ GeV

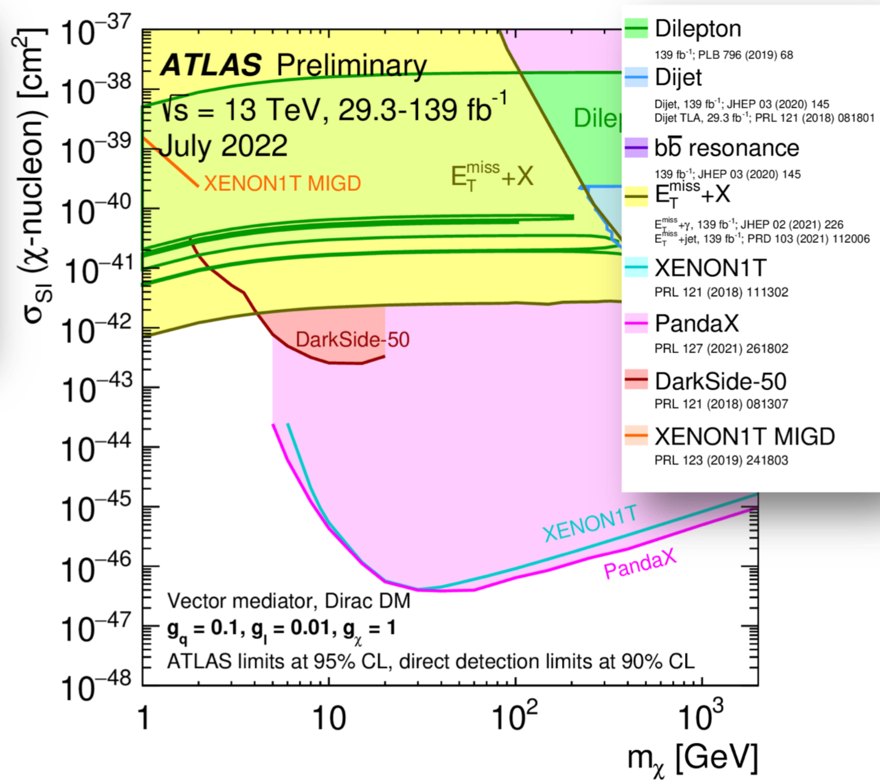
Summary Plots: Spin-1 Mediators

Leptophilic Vector mediator assuming g_q=0.1, g_ℓ=0.01, g_χ=1

95% CL limits on m_χ vs. $m_{V(A)}$



90% CL limits on WIMP-nucleon cross-sction vs. m_χ



- Similar results for Axial-Vector
- Also results for leptophobic couplings g_q=0.25, g_ℓ=0, g_χ=1

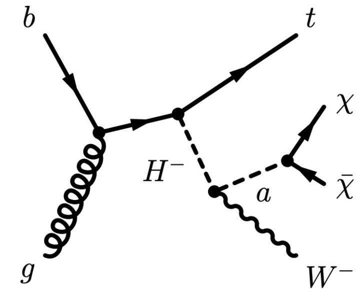
ATLAS-CONF-2022-012

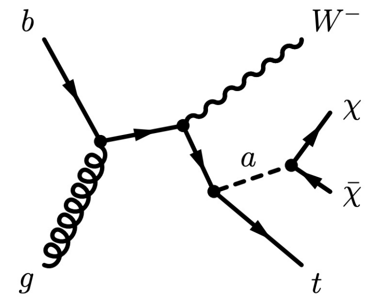
E_T^{miss} + tW

Dominant single-top final state for 2HDM+a

Target events with 0 or 1 lepton from top decay and hadronic W decay

- W-tagged large-R jet or two small-R jets
- Combined with previous 2 lepton analysis

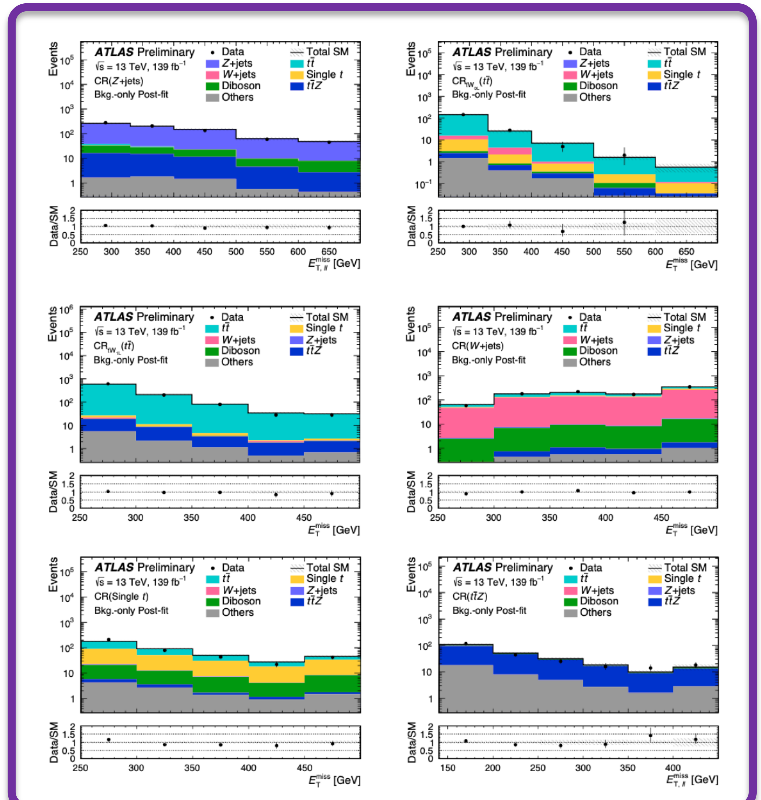




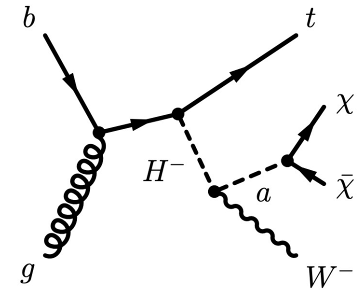
- Six CRs to constrain main backgrounds (t, tt, W/Z+jets, ttZ)
- Three SRs (binned in E_T^{miss})
  - $t\,W$ ➞ had had / had lep / lep had

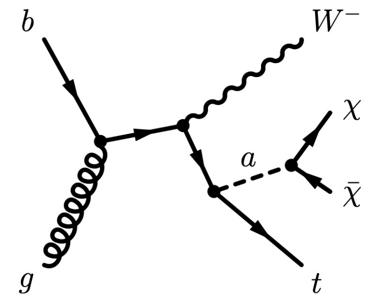
Interpret in 2HDM+a model

- Set **limits on $m_{H\pm}$ vs. m_a** and tanβ
- Also other 2HDM+a results in summary note (ATL-PHYS-PUB-2022-036)



E_T^{miss} + tW





Dominant single-top final state for 2HDM+*a*

Target events with 0 or 1 lepton from top decay and hadronic *W* decay

- *W*-tagged large-*R* jet or two small-*R* jets
- Combined with previous 2 lepton analysis

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Interpret in 2HDM+*a* model

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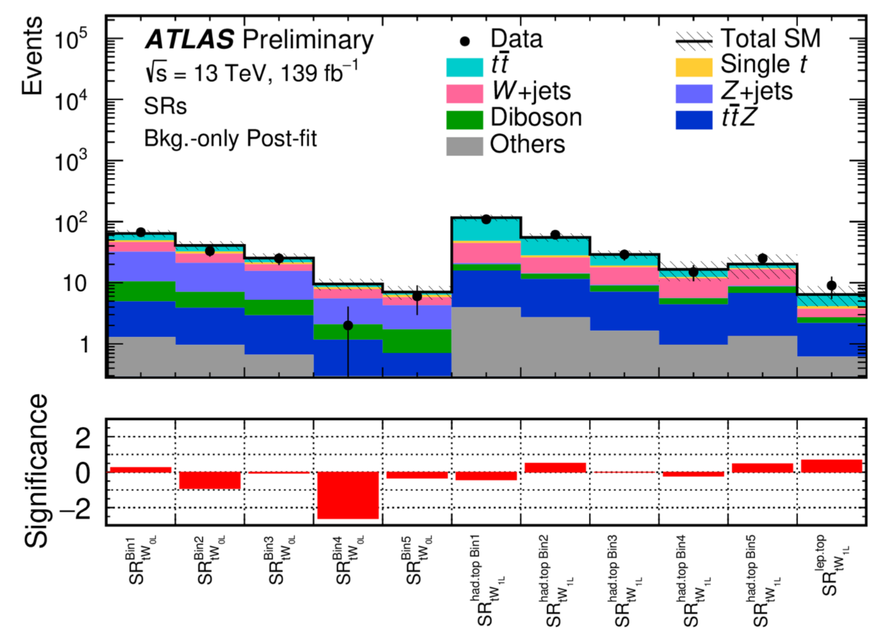
- Also other 2HDM+*a* results in summary note (ATL-PHYS-PUB-2022-036)



ATLAS-CONF-2022-012

E_T^{miss} + tW

Dominant single-top final state for 2HDM+*a*

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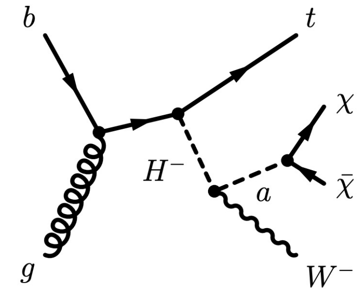

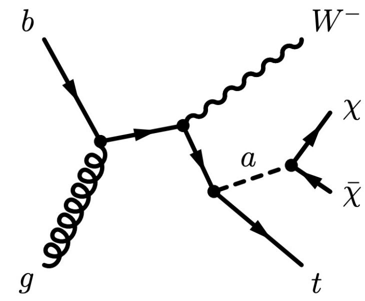

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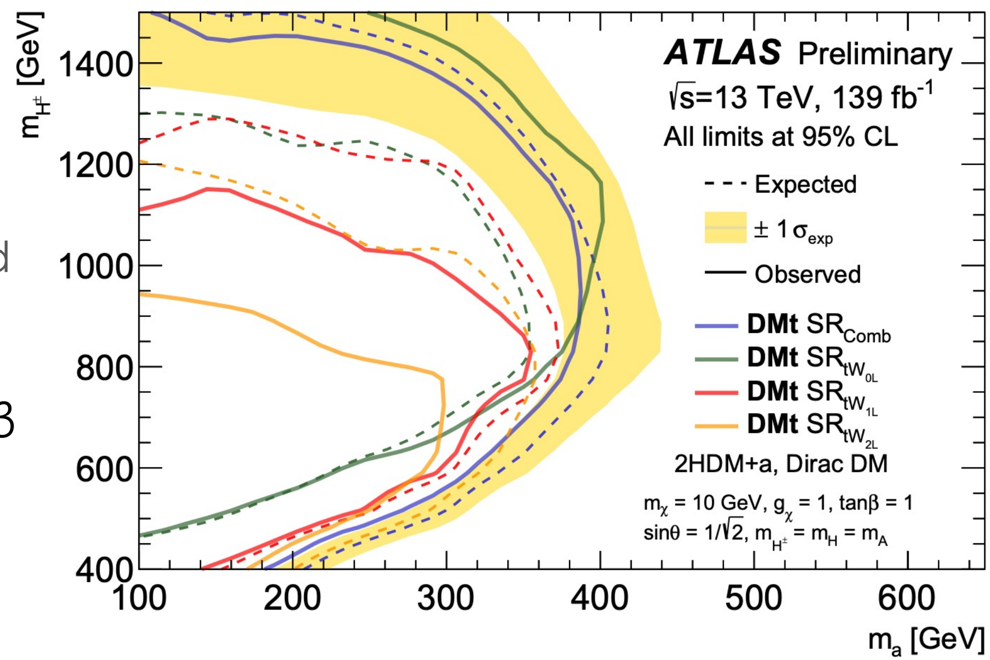
- Also other 2HDM+*a* results in summary note (ATL-PHYS-PUB-2022-036)

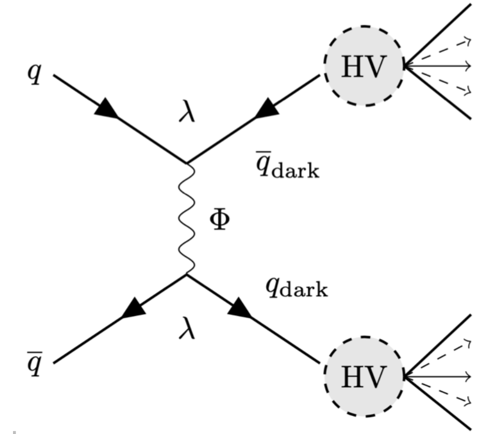


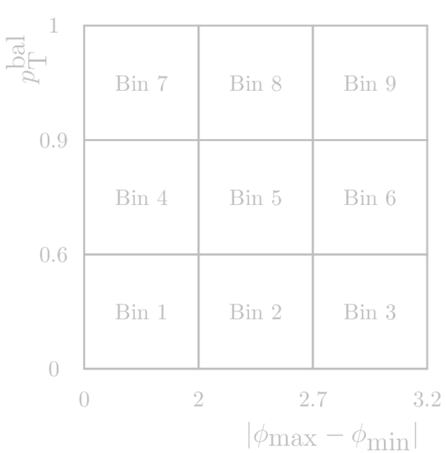
Another recent E_T^{miss}+*t* analysis (ATLAS-CONF-2022-036) presented by Evan Van de Wall.

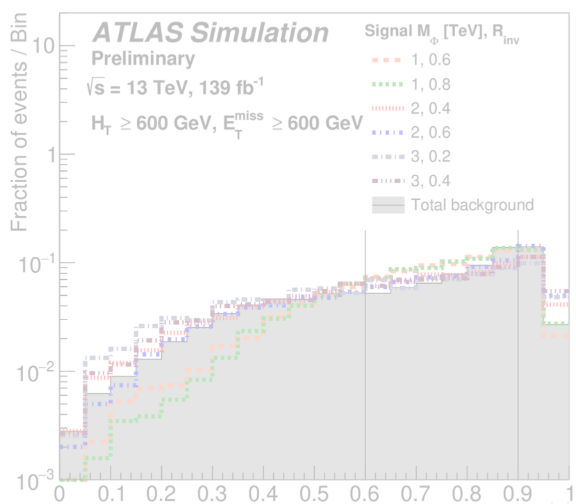
ATLAS-CONF-2022-038

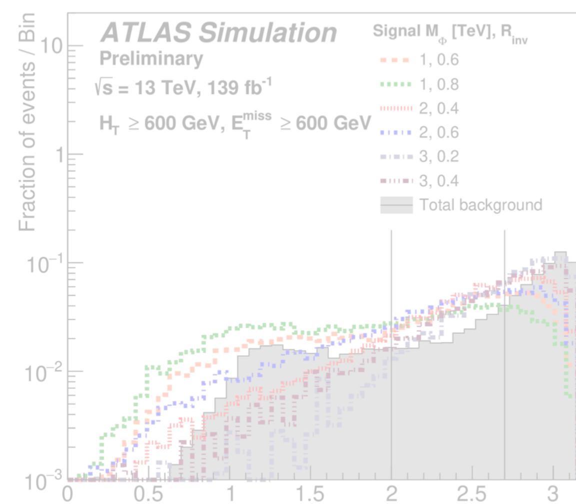
Dark matter to semi-visible jets

- Sensitive to strongly coupled dark sector
  - Scalar mediator (Φ) acts as portal
  - Focus on t-channel (can probe high masses)
- Signal: 2 semi-visible jets (SVJs)
  - High $H_T = \Sigma_{jets} p_T$ and high E_T^{miss} close to a jet
  - ≥1 additional jet to suppress dominant multijet background
  - Veto e, μ, and ≥2 b-tags to suppress other backgrounds
- Fit 9-bin distribution of two discriminating variables



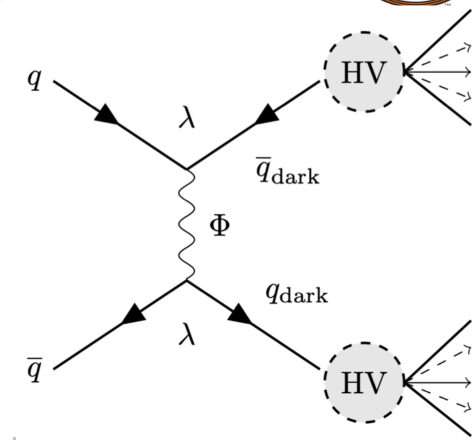






ATLAS-CONF-2022-038

Dark matter to semi-visible jets

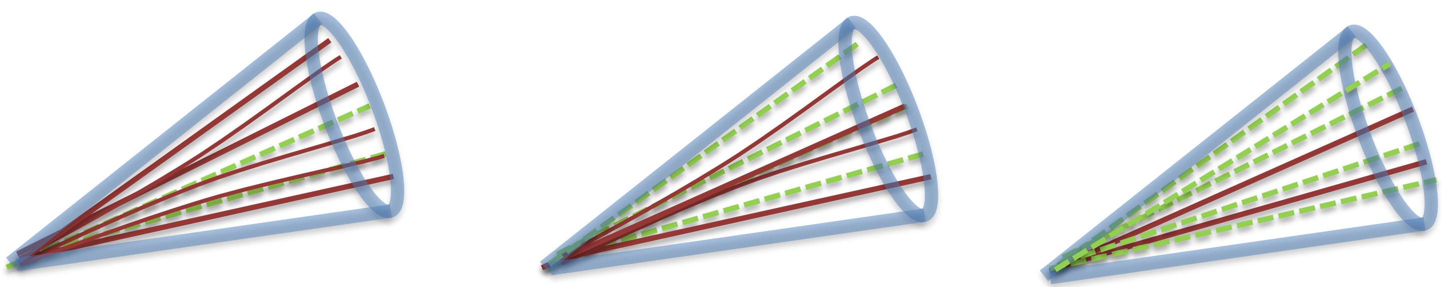


Sensitive to strongly coupled dark sector

- Scalar mediator (Φ) acts as portal
- Focus on t-channel (can probe high masses)

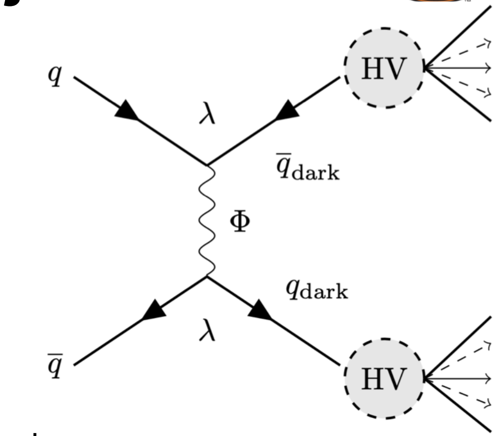
Signal: 2 semi-visible jets (SVJs)

- High $H_T = \Sigma_{\text{jets}} p_T$ and high E_T^{miss} close to a jet
- ≥1 additional jet to suppress dominant multijet background



$$R_{\text{inv}} = \frac{\text{stable dark hadrons}}{\text{all stable hadrons}}$$

Dark matter to semi-visible jets



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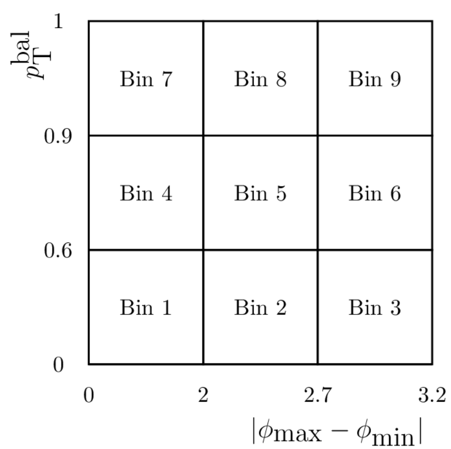
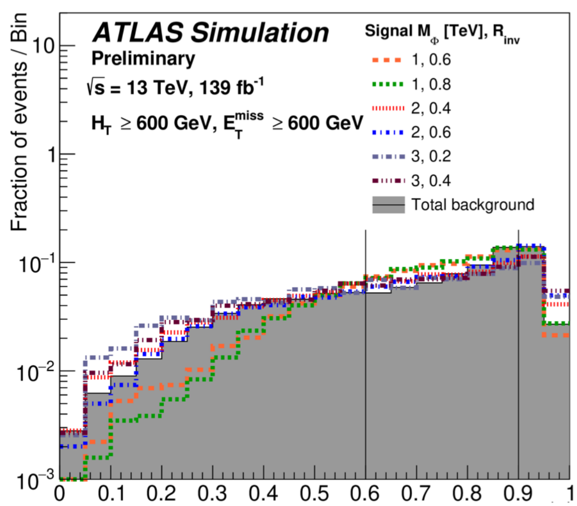
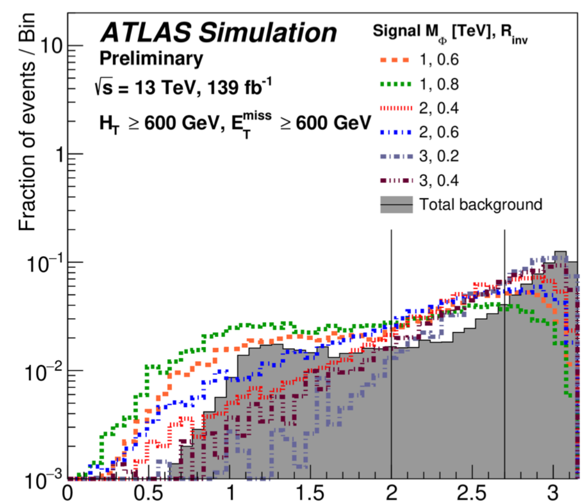
• Fit 9-bin distribution of two discriminating variables



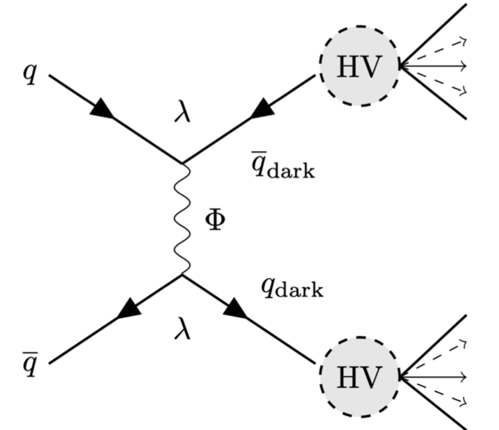


$$p_T^{bal} = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}$$



$$|\phi_{max} - \phi_{min}|$$

Dark matter to semi-visible jets



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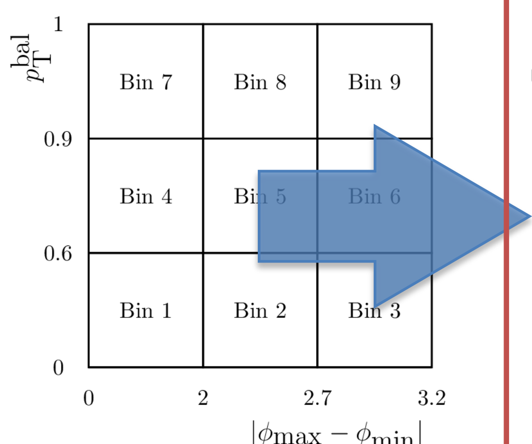
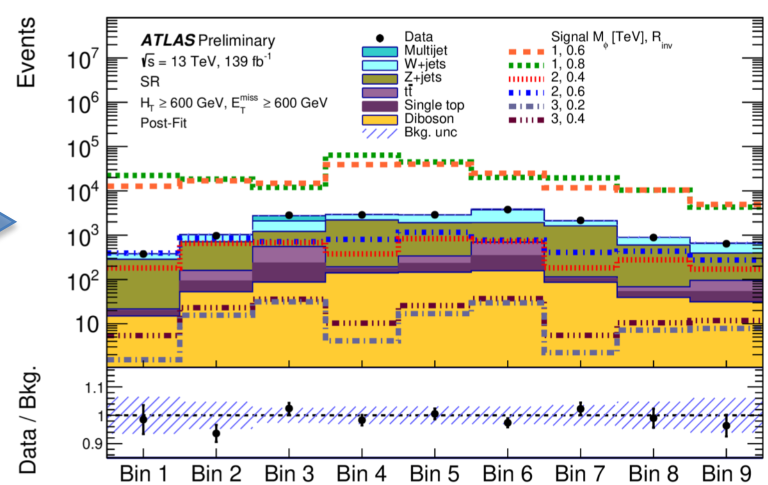
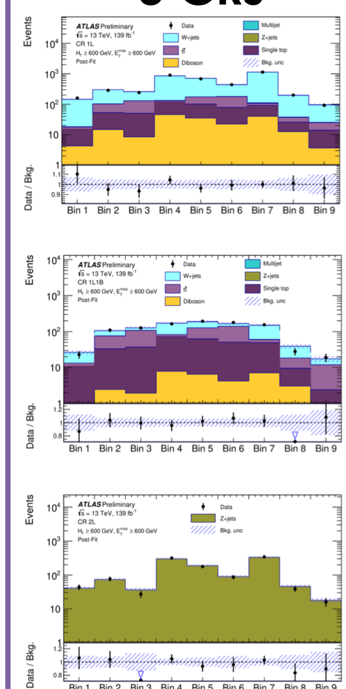


SR

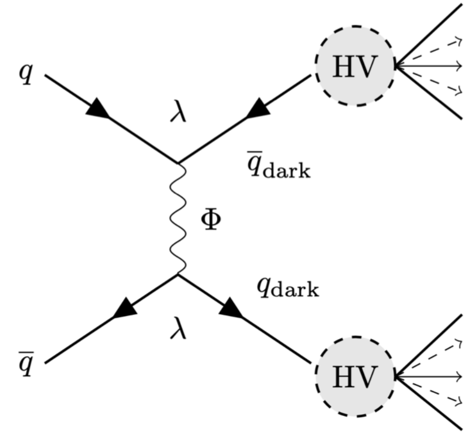


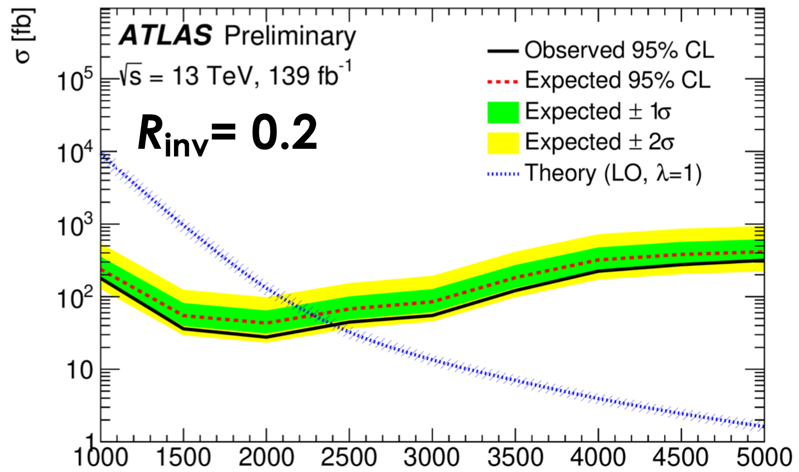
3 CRs

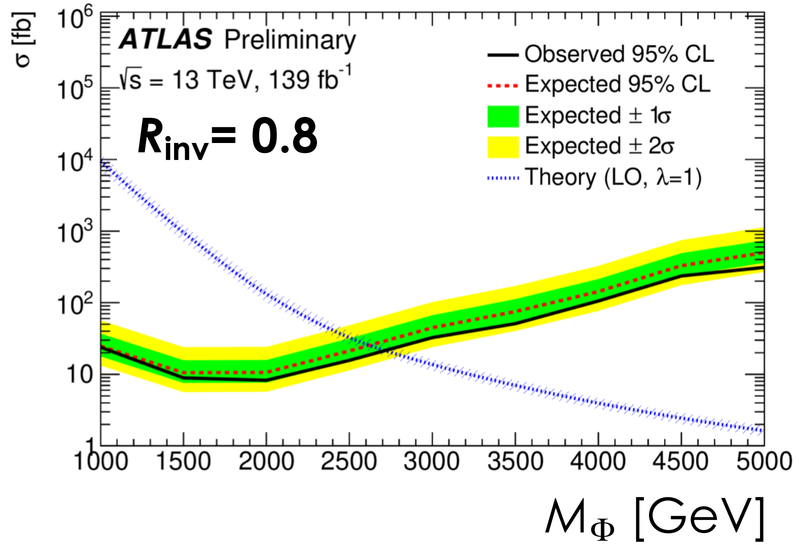


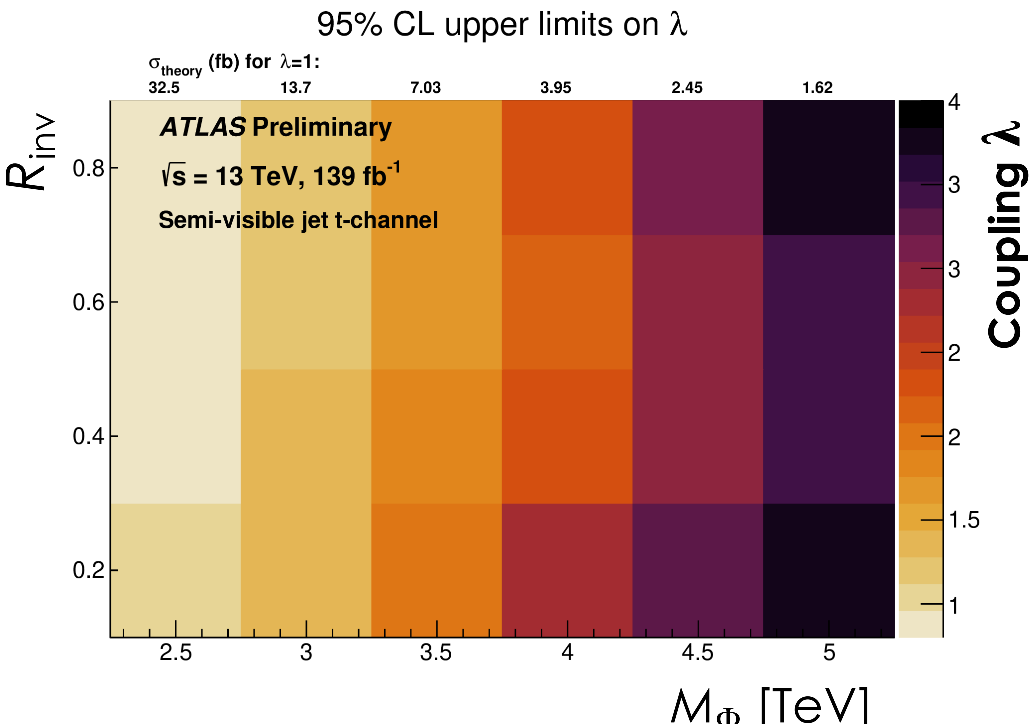
Dark matter to semi-visible jets

Set limits on cross-section and coupling vs. M_Φ and R_{inv}





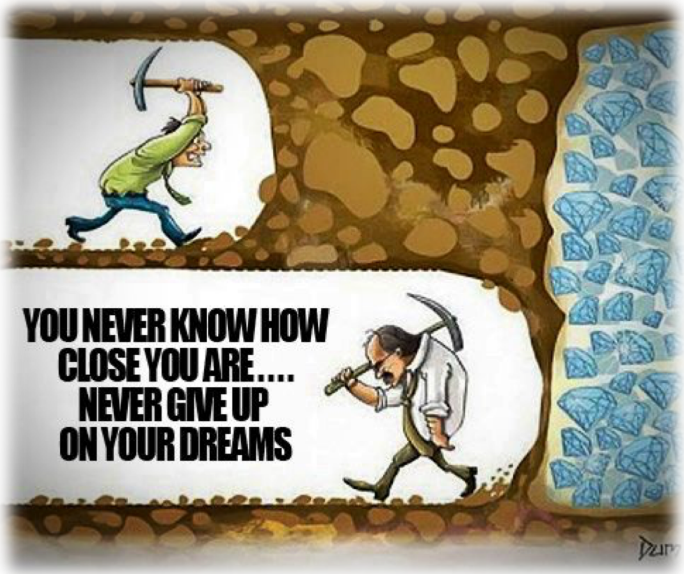




Conclusion

Many recent DM results from ATLAS

- Complementary to direct and indirect detection experiments
- Probing a wide range of final states and models
  - Complete list of ATLAS dark matter results (many more not shown today): https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - Also see related talks by Will Fawcett, Christian Weber, and Evan Van de Wall
- Significant gains from previous results
  - Larger data set + improved analysis tools + re-optimized selections + improved background modeling



Unfortunately, still no signs of dark matter at the LHC

... But much more data coming in Run 3!!!

Thank you!

And special thanks to:

DOE for supporting this research

The ATLAS Collaboration

- **Complete list of ATLAS exotic results:** **twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults**

The CIPANP 2022 Organizers!

Stillwater, OK

Bonus Material

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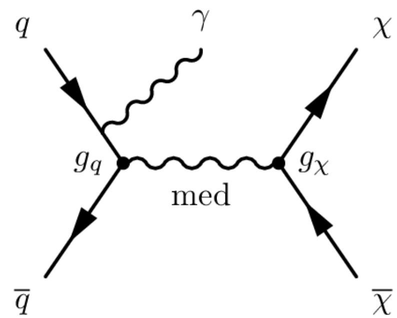
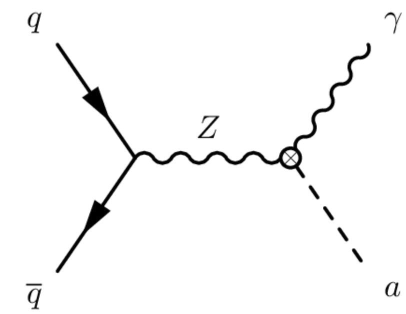
$E_T^{miss} + \gamma$



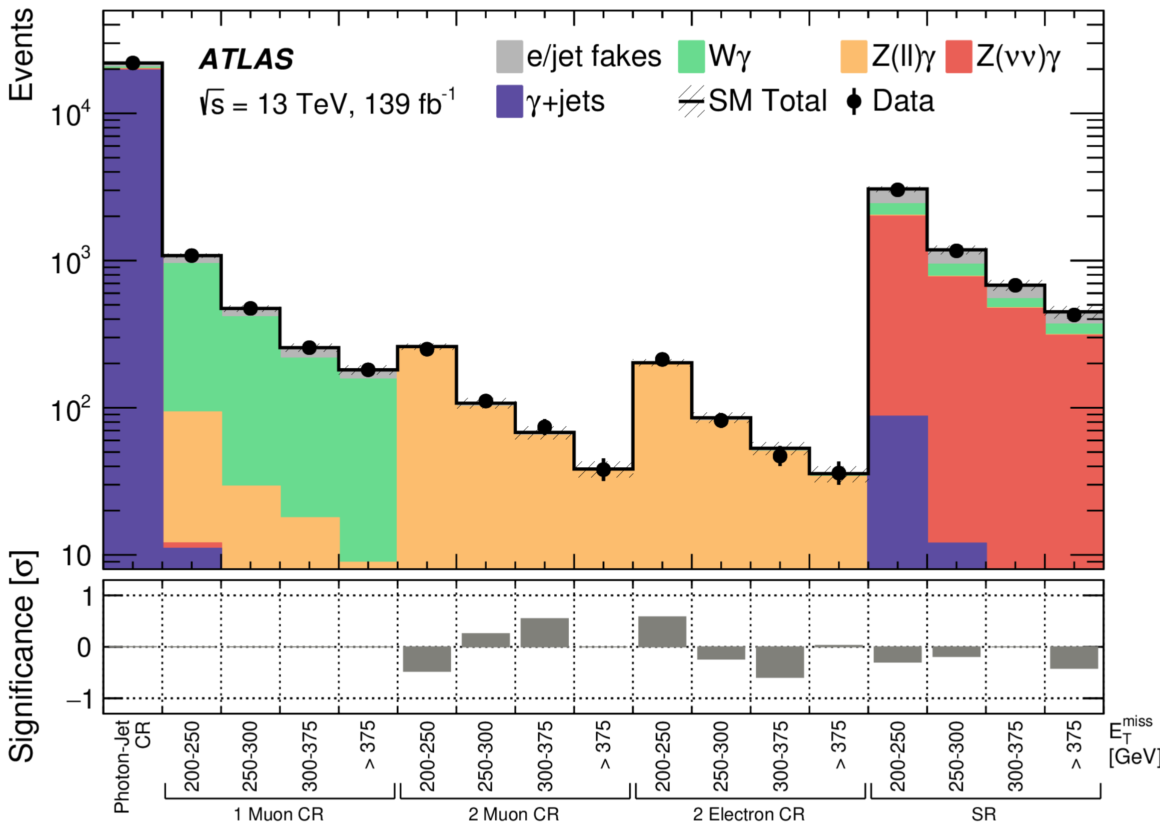


Select events with

- Isolated photon, p_T^γ > 150 GeV
- E_T^{miss} > 200 GeV, E_T^{miss} signif. > 8.5
- No leptons
- Up to one jet

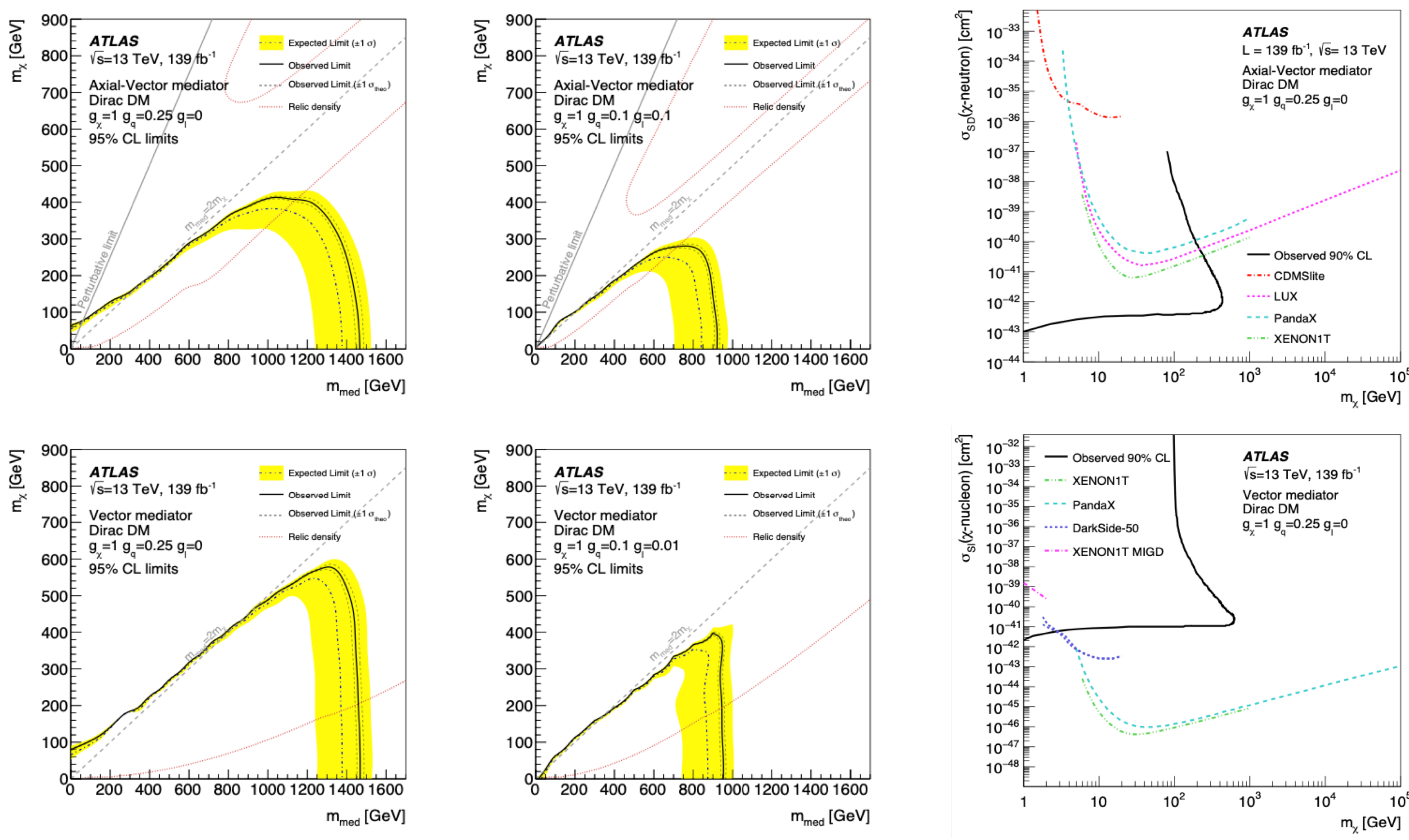
Fit SR and 4 CRs in bins of E_T^{miss}

- Normalization of main backgrounds from fit to data



JHEP 02 (2021) 226

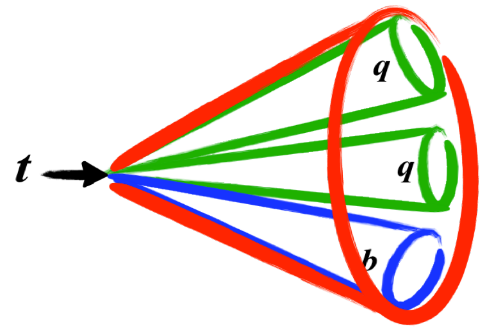
$\gamma + E_T^{miss}$



top-tagging

Identify high-p_T **top** quarks ("boosted-tops")

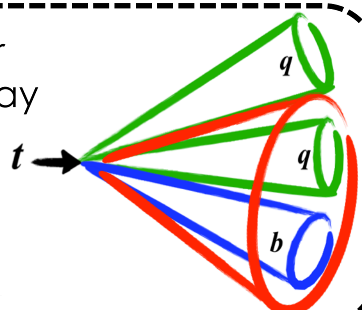
- Large-radius jet with highly collimated sub-jets, including one b-jet

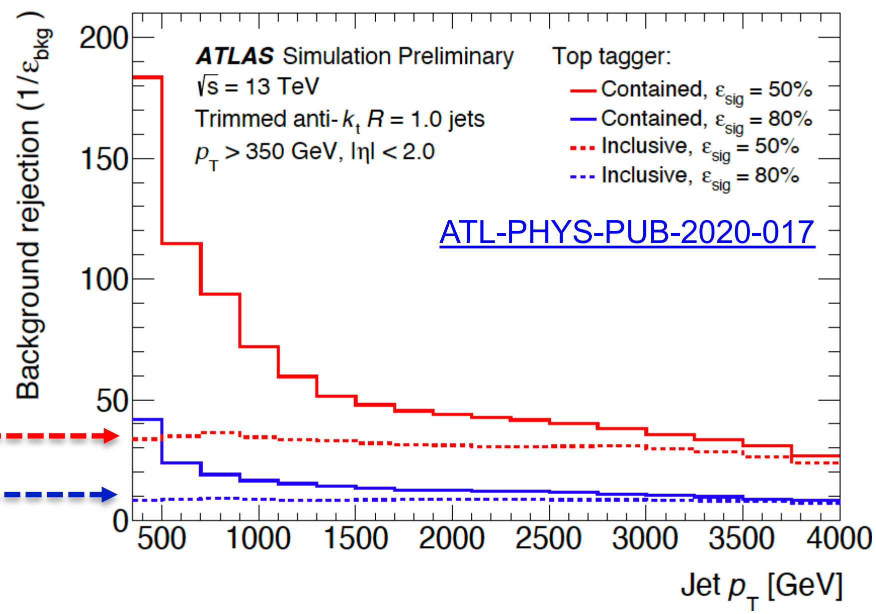


⇒ Deep Neural Network top-tagger

- Uses kinematics (jet mass, p_T, etc.) and dispersion of jet constituents (N-subjettiness, splitting scales, and energy correlation functions)

Inclusive top-tagger allows some of decay productions to fall outside large-R jet

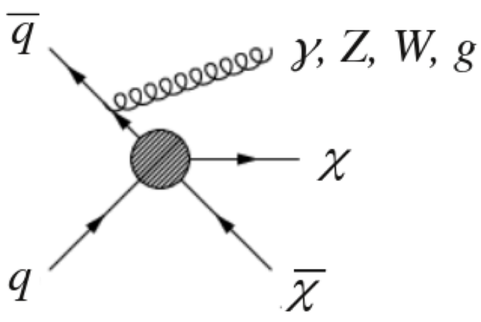




(Some analyses define their own custom taggers, but idea is the same)

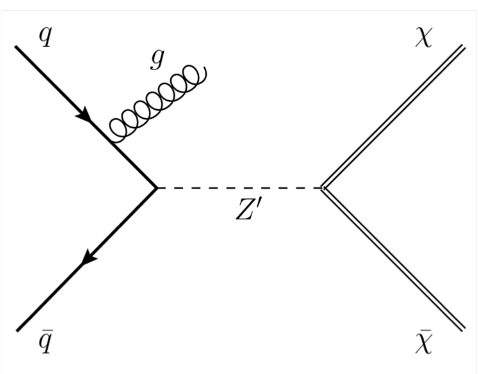
Interpreting DM Production

Effective field theory (EFT)



Name	Operator	Type of interaction
D1	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$	Scalar, WIMP-quark
D5	$\frac{1}{M_*^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	Vector
D8	$\frac{1}{M_*^2}\bar{\chi}\gamma^{\mu}\gamma^5\chi\bar{q}\gamma_{\mu}\gamma^5 q$	Axial-vector
D9	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	Tensor
D11	$\frac{\alpha_s}{(4M_*)^3}\bar{\chi}\chi G_{\mu\nu}\tilde{G}_{\mu\nu}$	Scalar, WIMP-gluon
C1	$\frac{m_q}{M_*^2}\chi^{\dagger}\chi\bar{q}q$	Scalar, WIMP-quark
C5	$\frac{\alpha_s}{4M_*^2}\chi^{\dagger}\chi G_{\mu\nu}\tilde{G}_{\mu\nu}$	Scalar, WIMP-gluon

- Only two parameters: DM mass (m_χ) & interaction scale (M_* or Λ)
- Good approximation if momentum transfer is less than mediator mass (m_V)



Simplified models

- Valid for higher momentum transfer
- But more parameters: m_χ, m_V, g_q, g_χ, Γ