Searches for Dark Matter with the ATLAS Experiment at the LHC

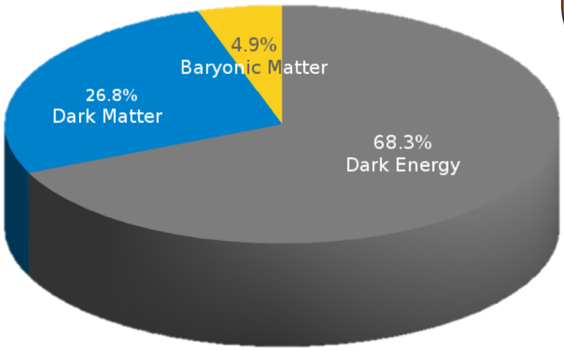
Joe Haley
Oklahoma State U.

HEP2023

Valparaíso, Chile
January 9-13, 2023

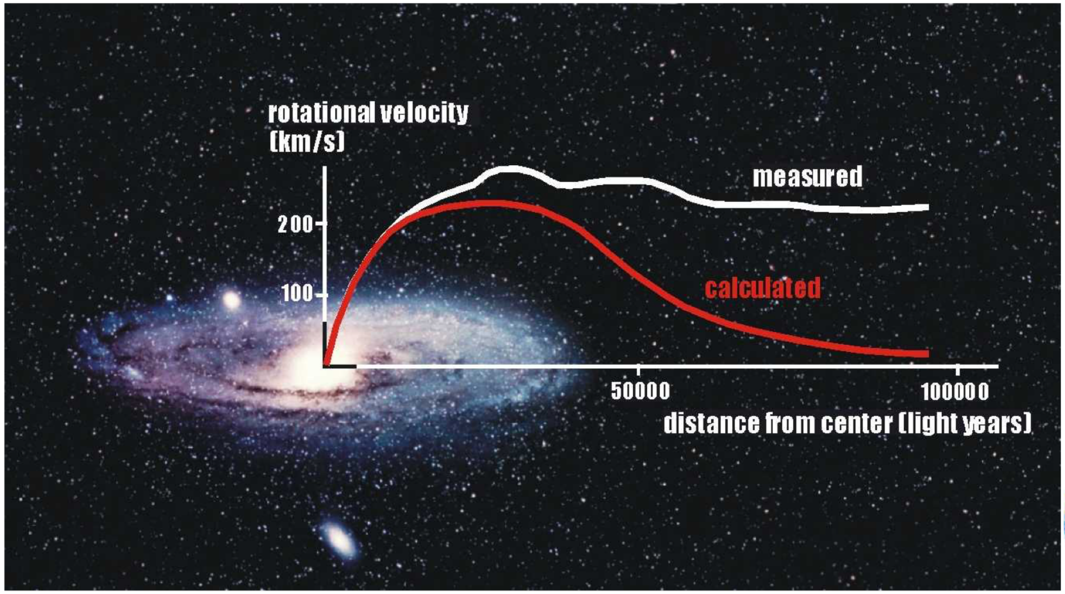
Supported by the U.S. Department of Energy

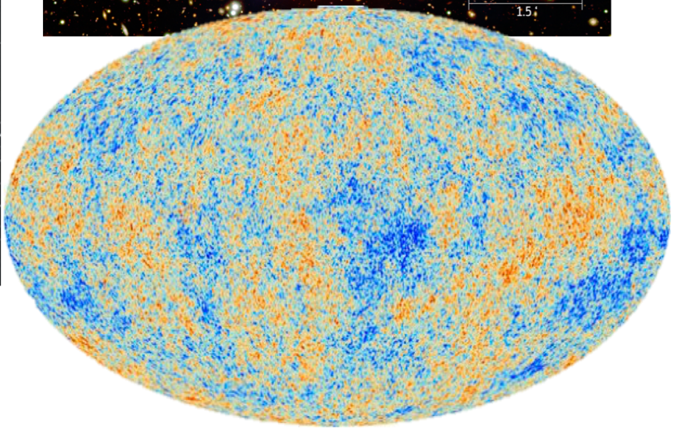
Dark Matter



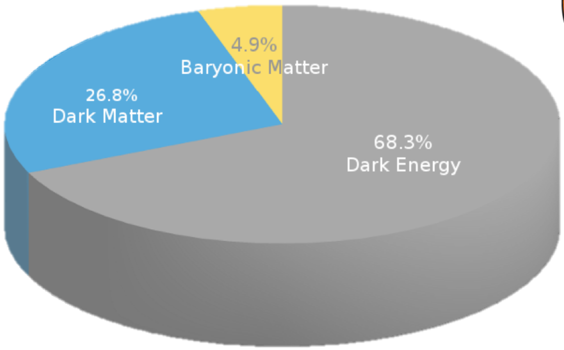
Favorite collider candidate: WIMP

- Heavy, stable, & couples to SM
- Naturally accounts for observed relic density (WIMP Miracle)
- *Should* be produced at the LHC





Dark Matter

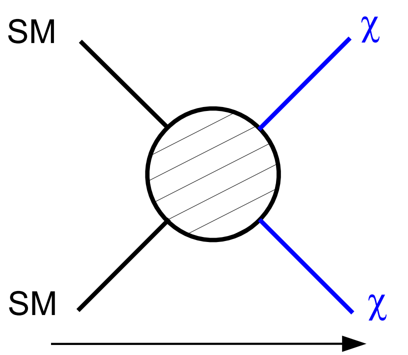


Favorite collider candidate: WIMP

- Heavy, stable, & couples to SM
- Naturally accounts for observed relic density (WIMP Miracle)
- *Should* be produced at the LHC

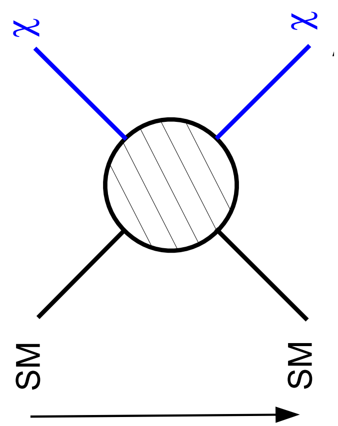
Complementary to dedicated DM experiments

"make it"



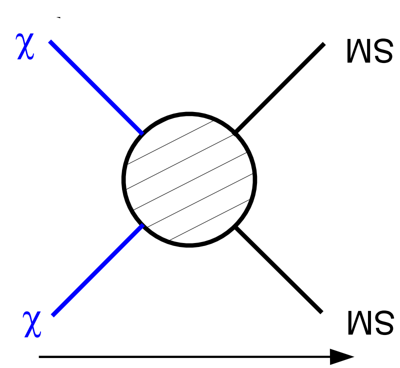
Collider

"shake it"



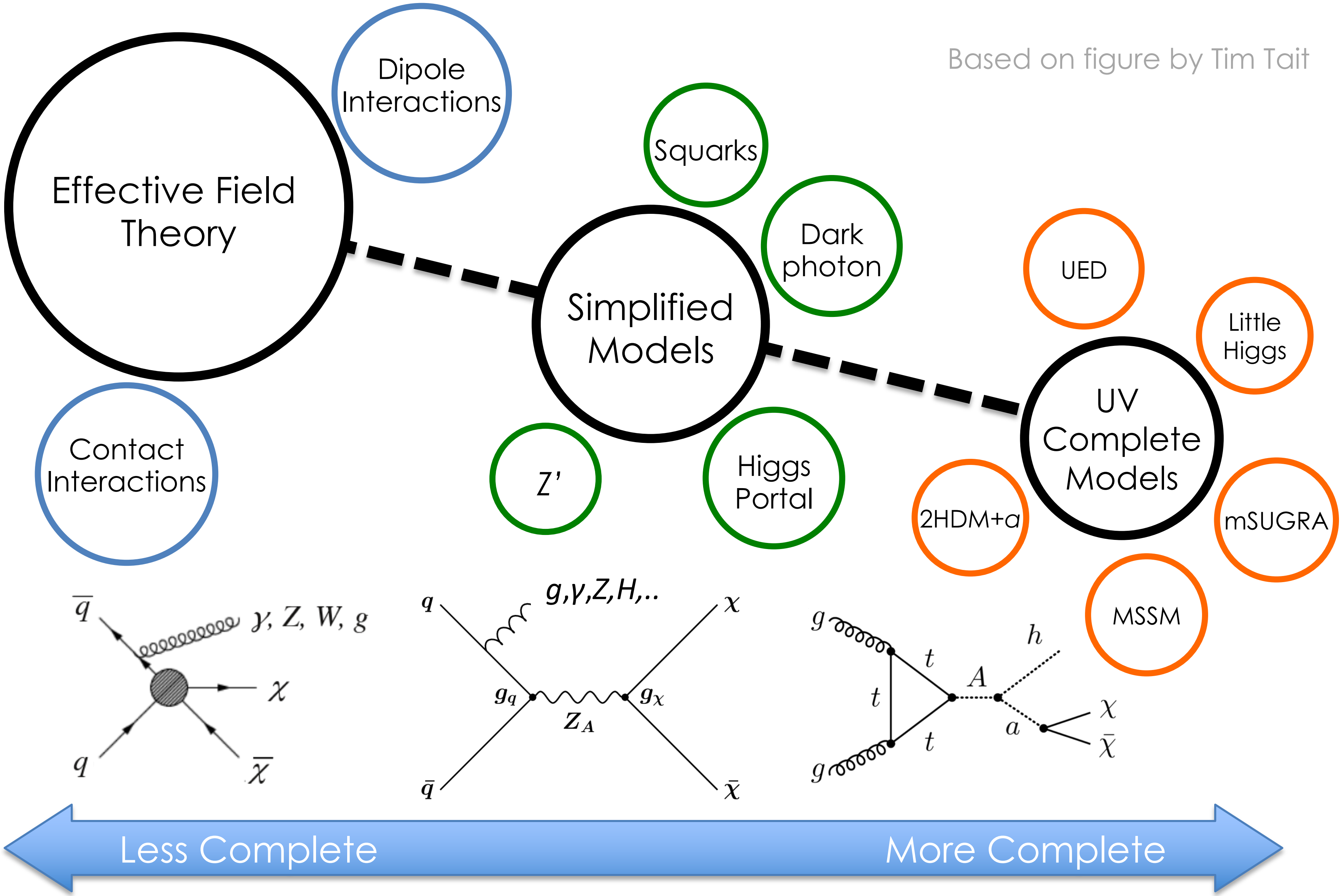
Direct detection

"break it"



Indirect detection

Interpreting DM Production

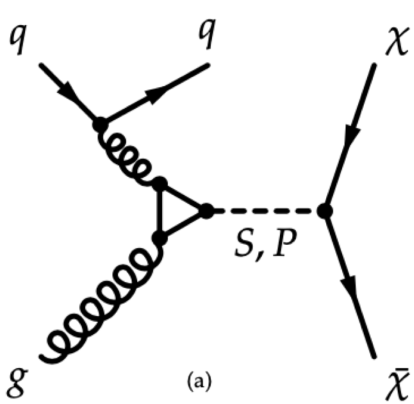


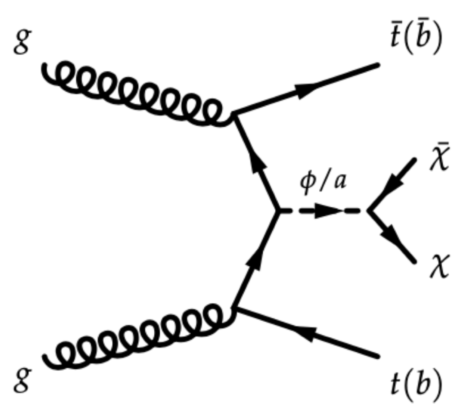
Simplified DM Models

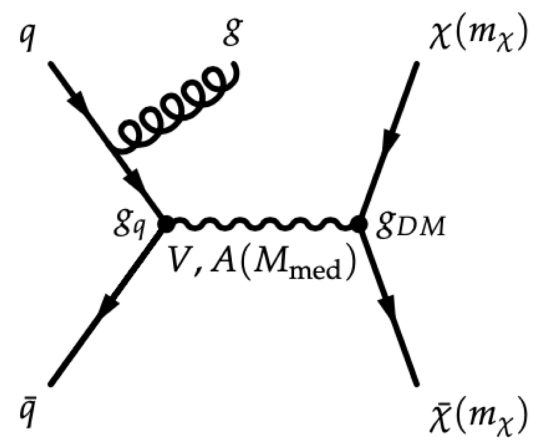
Benchmark models defined in
CMS/ATLAS Dark Matter Forum

[Physics of the Dark Universe 27 (2020) 100371]

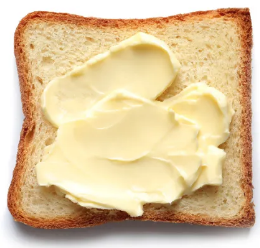
- Dark matter assumed to be a Dirac fermion WIMP: χ
- Boson mediator between SM and DM
  - Spin-0: Scalar (*S*) or pseudo-scalar (*P/a*)
  - Spin-1: Vector (*V/Z'*) or axial-vector (*A*)
- Minimal set of parameters: M_χ , M_{med} , g_χ , g_q , g_ℓ







This Talk



- **E_T^{miss} + X**
  - Z + E_T^{miss}
  - tt + E_T^{miss}
  - Summary Plots

- **H→invisible**
  - VBF + E_T^{miss}
  - Combination

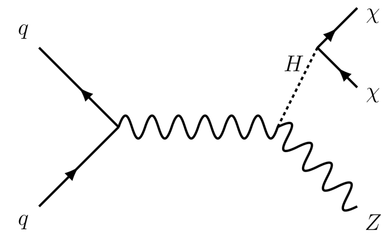
- **Novel search for semi-visible jets**

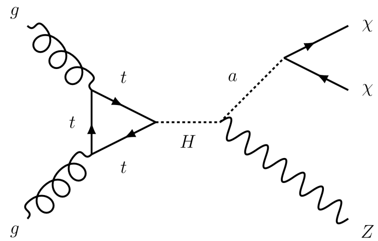
- ***Briefly* advertise**
  - SUSY Electroweakinos
  - Dark Higgs
  - 2HDM+a $H\rightarrow\tau\tau$

[Phys. Lett. B 829 (2022) 137066](https://doi.org/10.1016/j.physletb.2022.137066)

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

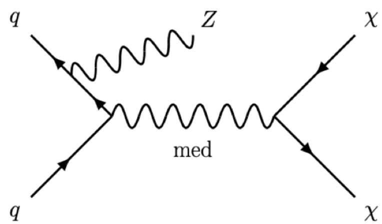
Interpreted in simplified DM models, 2HDM+a, and H→invisible





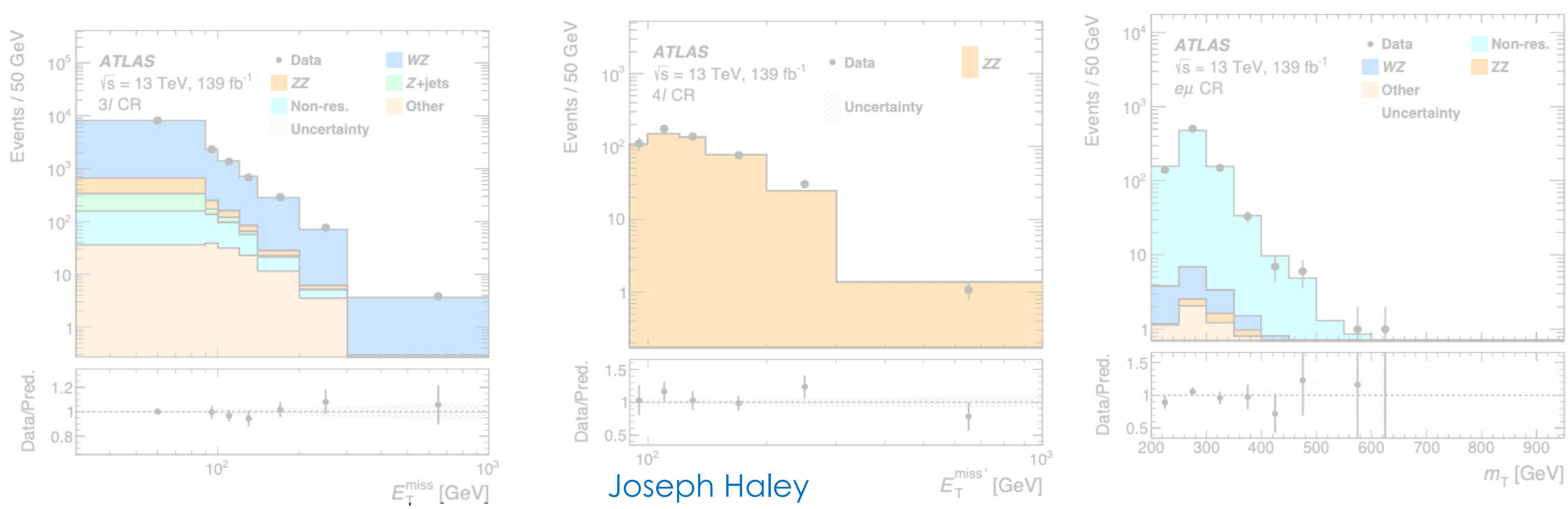
Select Signal Region (SR) with:

- 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):



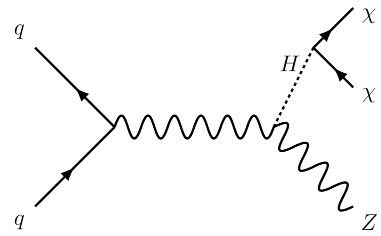
Phys. Lett. B 829 (2022) 137066

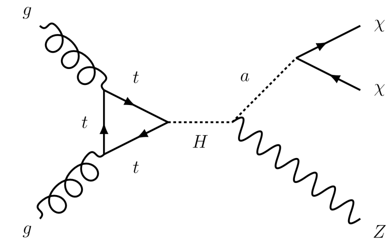
$Z(\ell\ell) + E_T^{miss}$

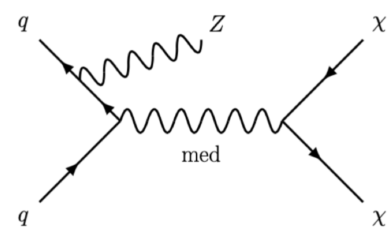
Interpreted in simplified DM models, 2HDM+a, and $H\rightarrow$invisible

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

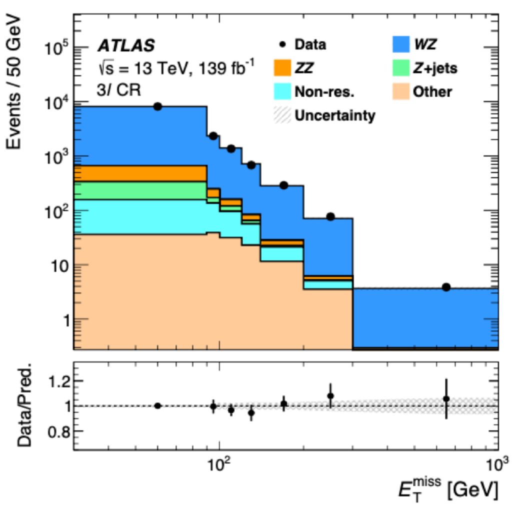


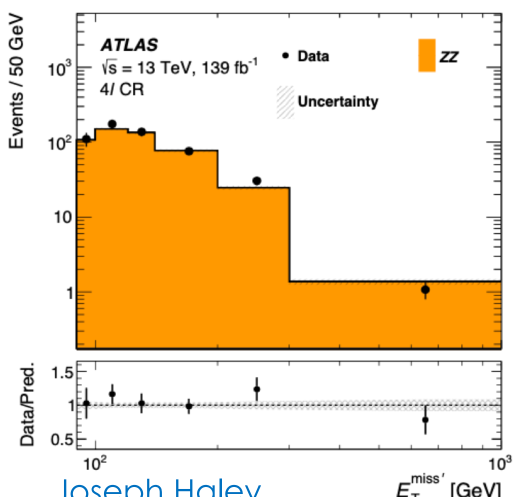


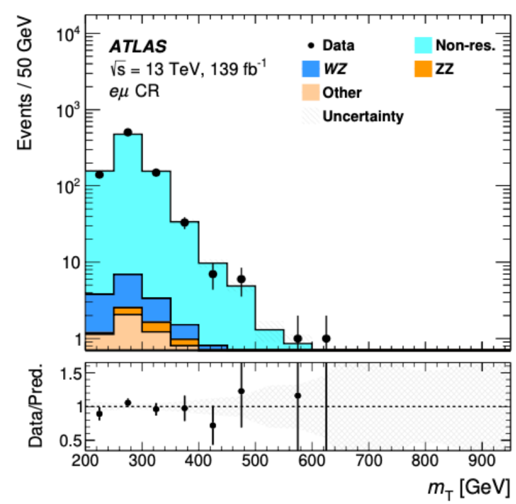


Dominant backgrounds from ZZ and WZ

- Constrained using three Control Regions (CRs):



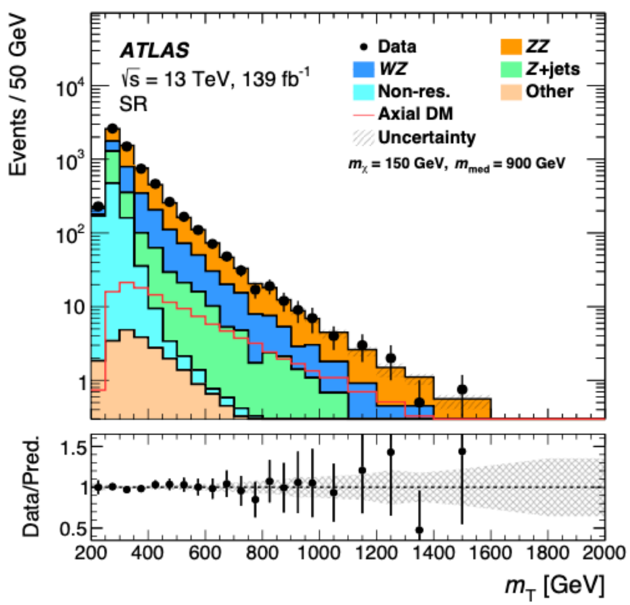


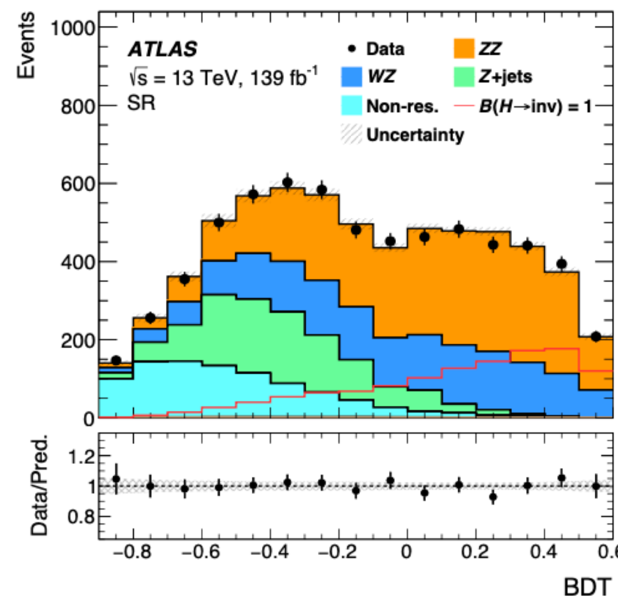


$Z(\ell\ell) + E_T^{miss}$

Simultaneous profile likelihood fit in SR and three CRs

- Simplified DM and 2HDM+a model use m_T distribution
- $H \rightarrow$inv. uses Boosted Decision Tree discriminant





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

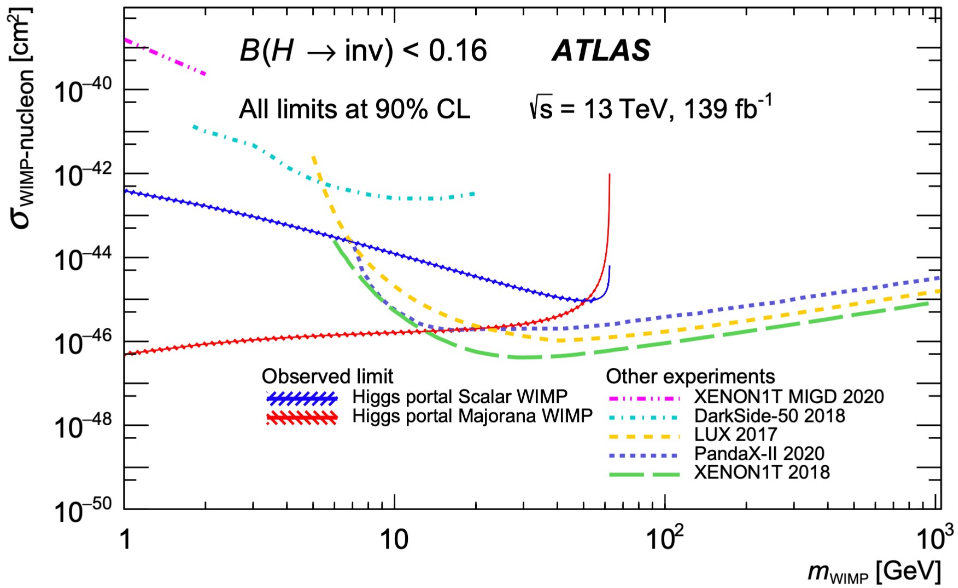
Good agreement with SM prediction :-(

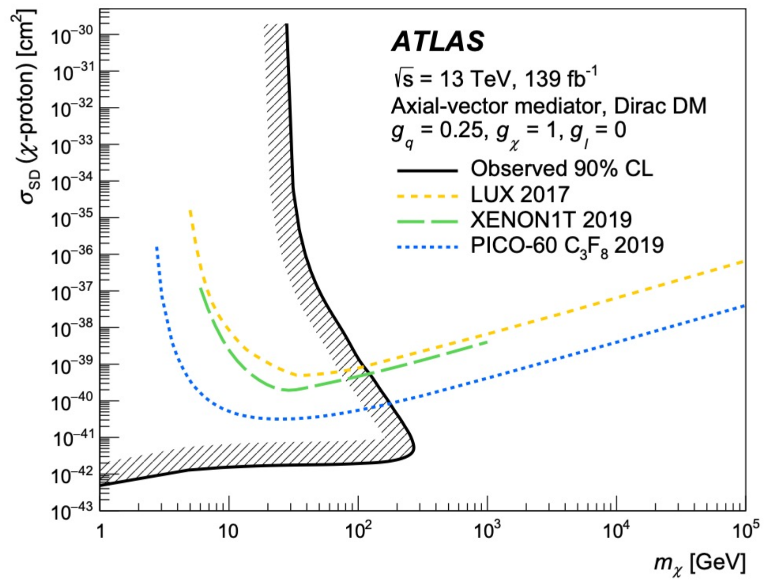
⇒ Set limits on model parameters

Phys. Lett. B 829 (2022) 137066

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

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





Interpreting as SM Higgs → invisible: BR(H→inv.) = 0.003 ± 0.09

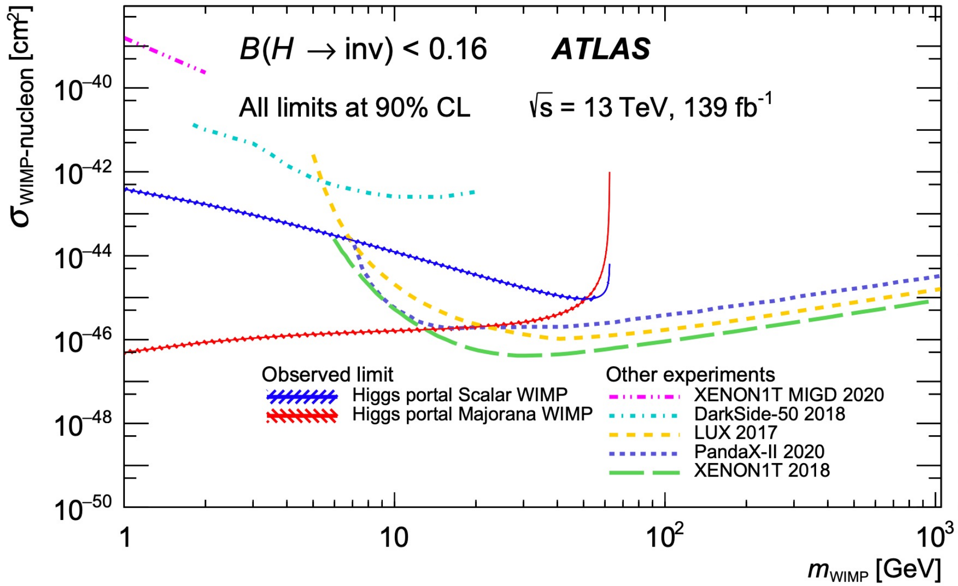
- 45% better sensitivity beyond increase in luminosity!
- Competitive with VBF H→invisible

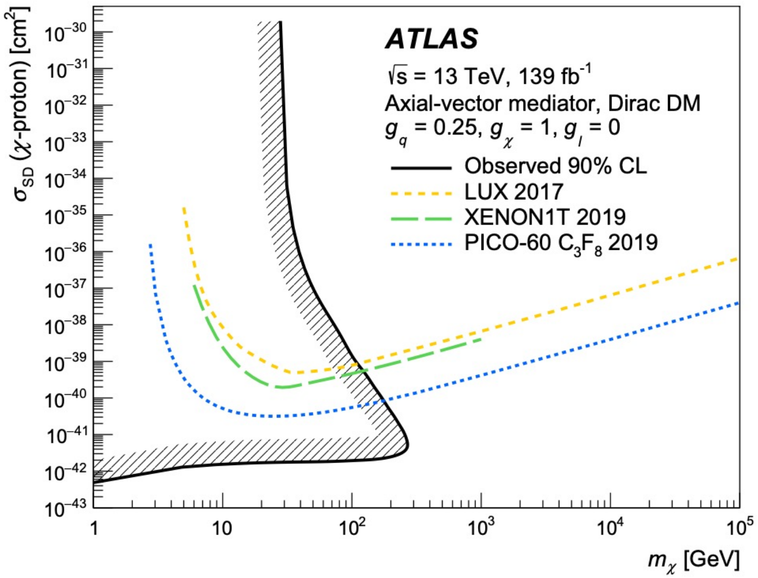
(Also interpreted in 2HDM+a and simplified DM parameters)

Phys. Lett. B 829 (2022) 137066

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

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





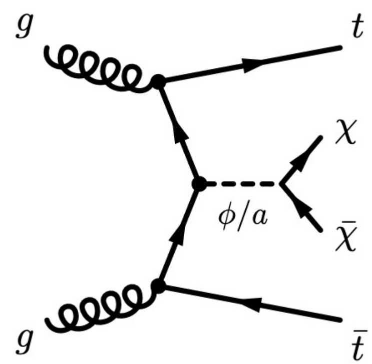
Interpreting as SM Higgs → invisible: BR(H→inv.) = 0.003 ± 0.09

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

(Also interpreted in 2HDM+a and simplified DM parameters)

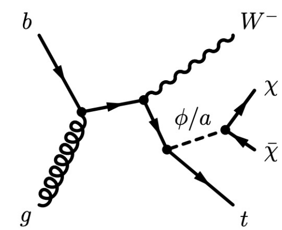
[2211.05426](Submitted to EPJC)

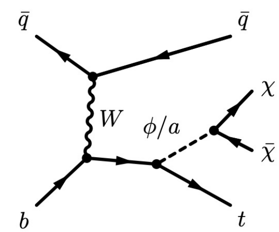
$tt\ (tW, tq) + E_T^{miss}$



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

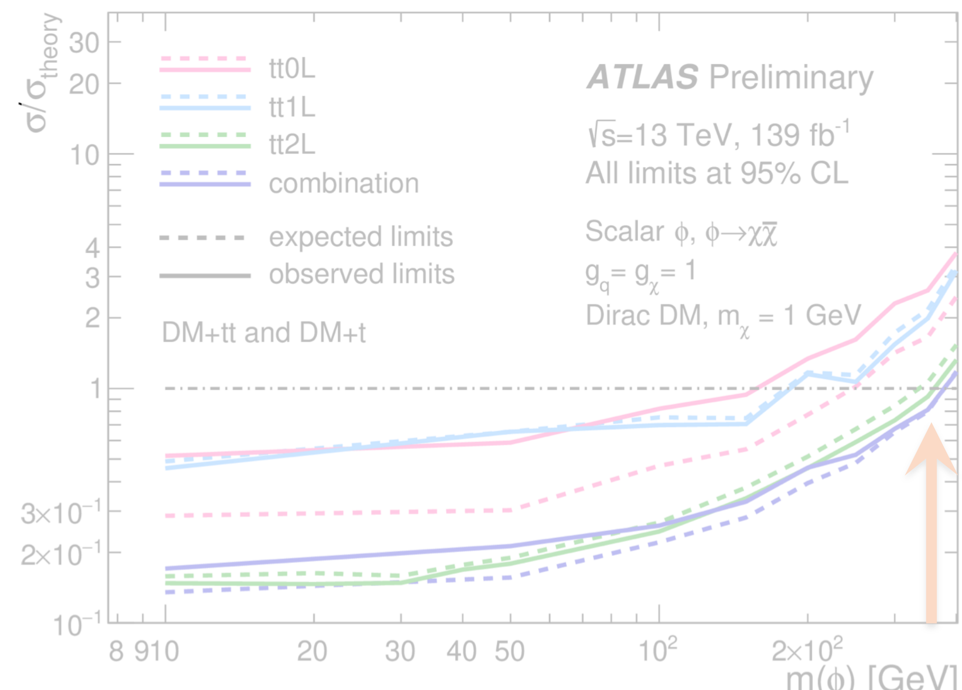
Eur. Phys. J. C 80 (2020) 737, JHEP 04 (2020) 174, JHEP 04 (2021) 165

- Set limits on σ/σ_{theory} vs. $m_{\phi(a)}$

  ⇒ Exclude m_ϕ up to 370 GeV

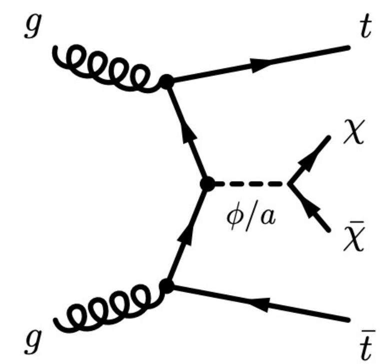
- Interpreting as $H \rightarrow$ invisible

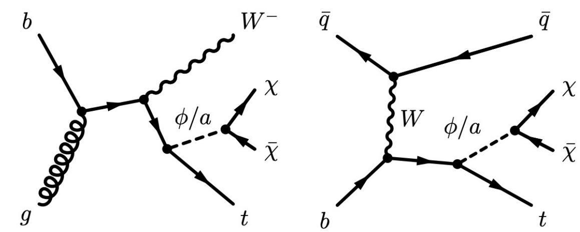
Analysis	Best fit $\mathcal{B}_{H\rightarrow inv}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$



2211.05426 (Submitted to EPJC)

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





Focus on DM with spin-0 mediator

- Important in models with Min. Flavor Violation
- Yukawa-like coupling to mediator ∝ m_f

Combination of 0, 1, & 2 lepton searches

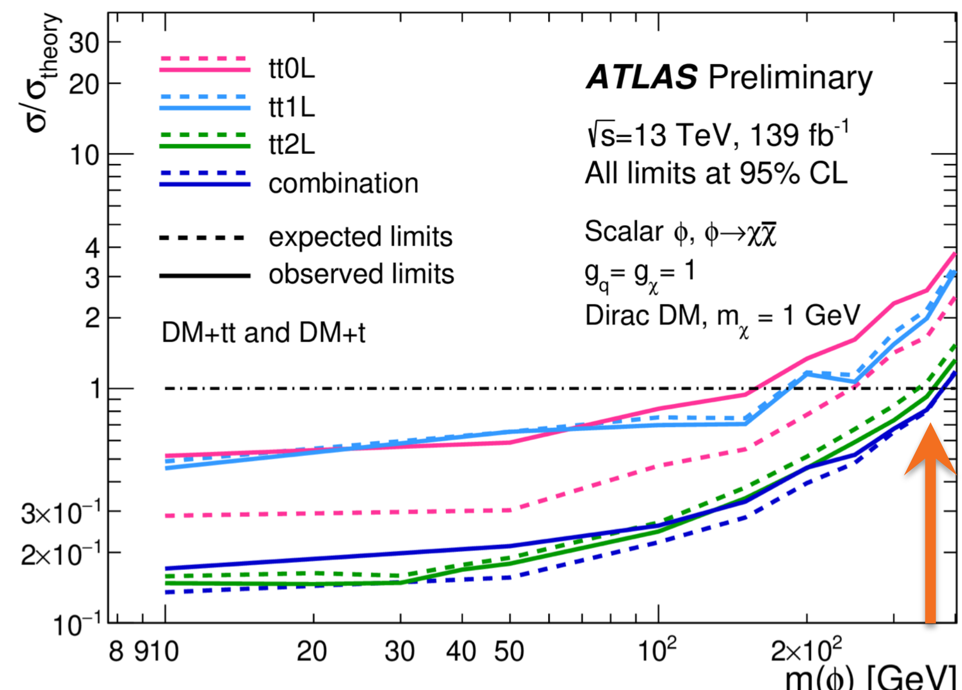
Eur. Phys. J. C 80 (2020) 737, JHEP 04 (2020) 174, JHEP 04 (2021) 165

- Set limits on σ/σ_{theory} vs. $m_{\phi(a)}$

  ⇒ Exclude m_ϕ up to 370 GeV

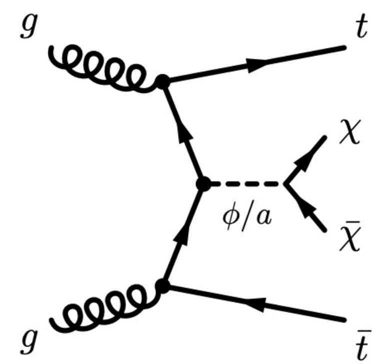
- Interpreting as $H\rightarrow$invisible

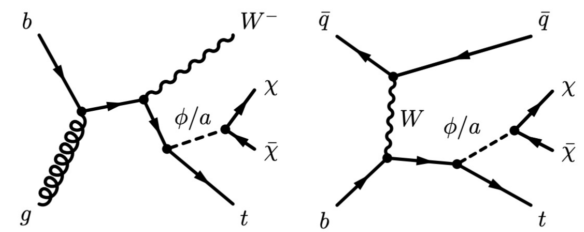
Analysis	Best fit $\mathcal{B}_{H\rightarrow inv}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$



2211.05426 (Submitted to EPJC)

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





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

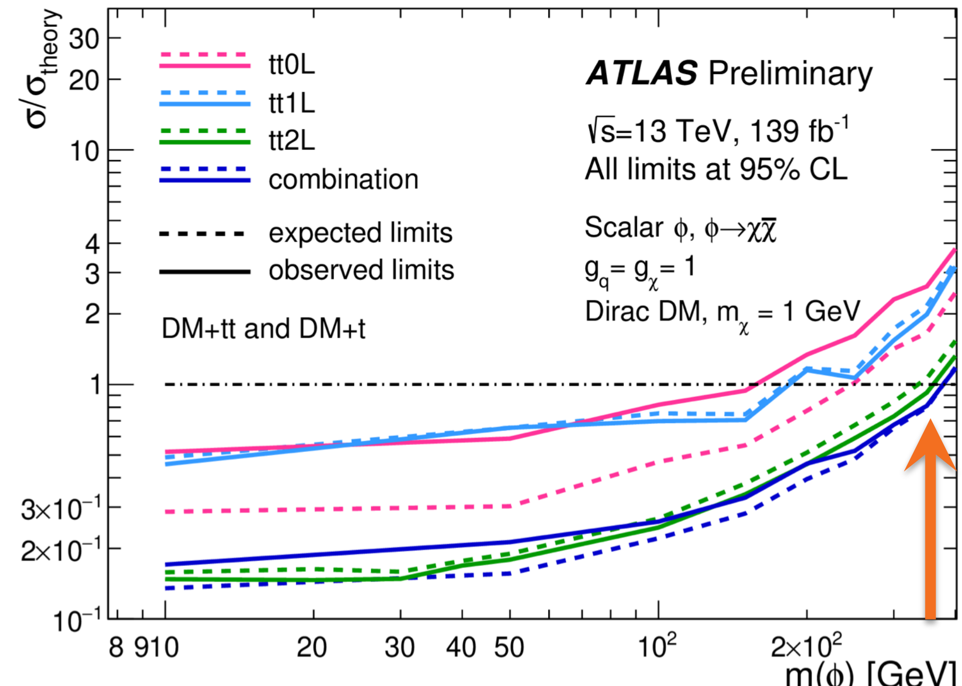
Eur. Phys. J. C 80 (2020) 737, JHEP 04 (2020) 174, JHEP 04 (2021) 165

- Set limits on σ/σ_{theory} vs. $m_{\phi(a)}$

  ⇒ Exclude m_ϕ up to 370 GeV

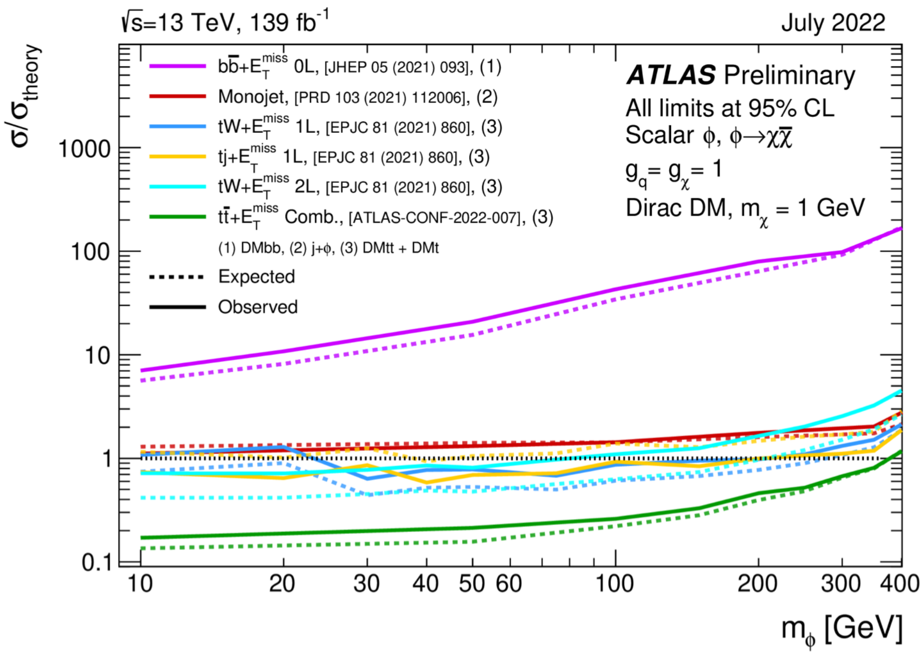
- Interpreting as $H\to$invisible

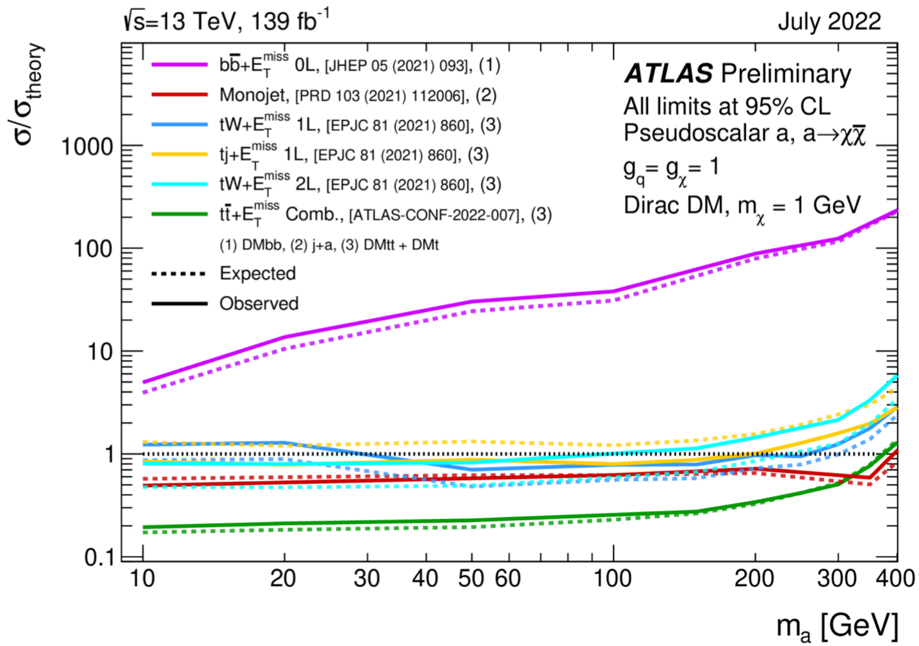
Analysis	Best fit $\mathcal{B}_{H\to inv}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$



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

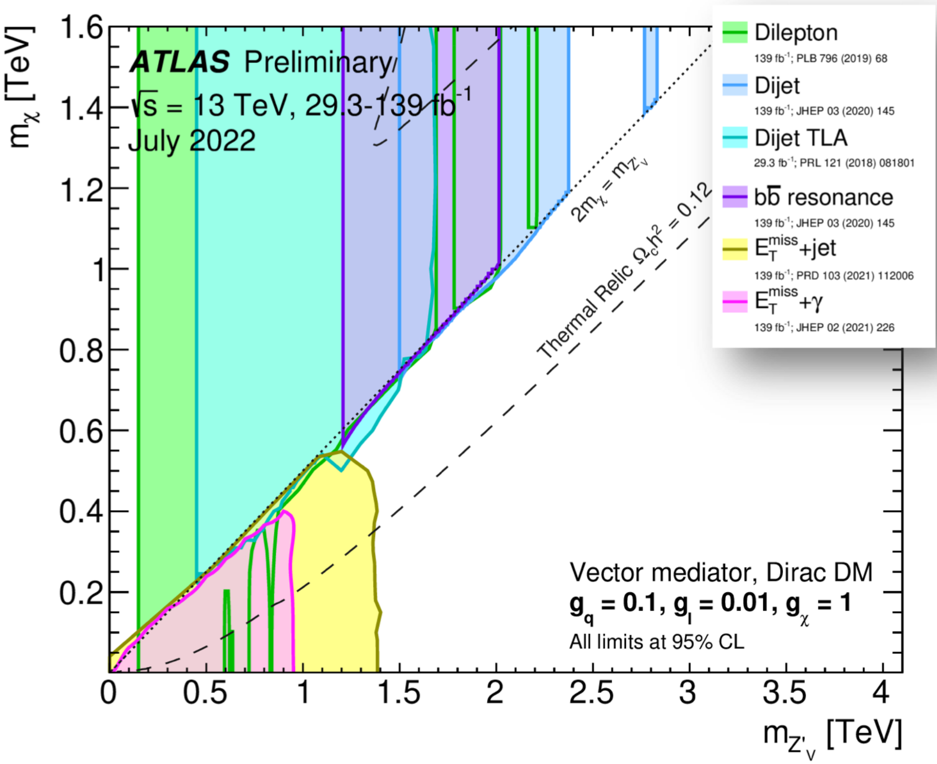
⇒ Exclude $m_a < 376$ GeV

ATL-PHYS-PUB-2022-036

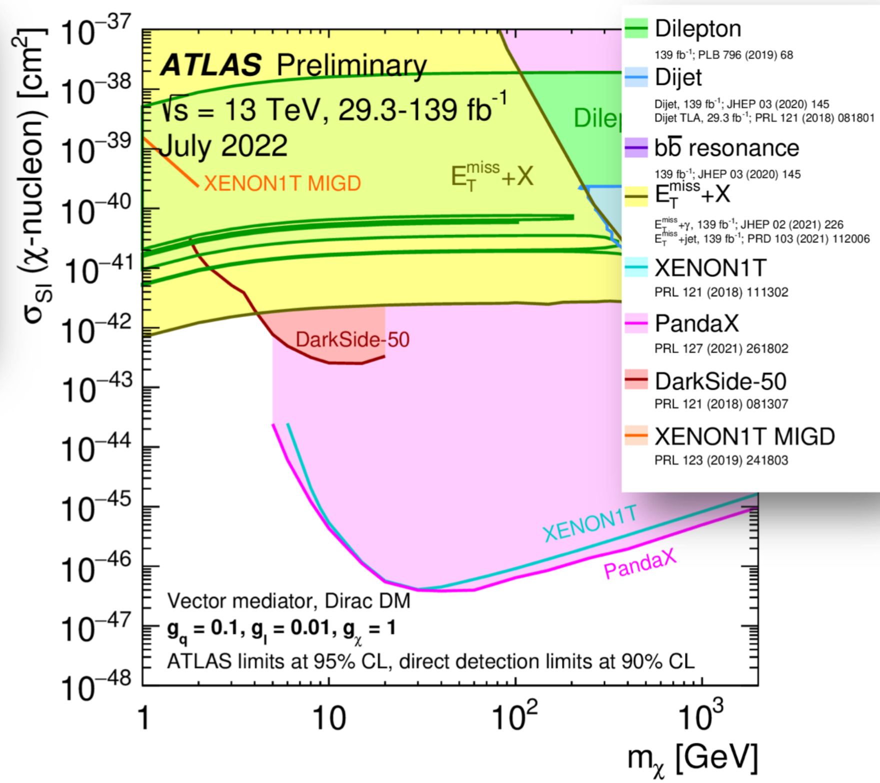
Summary Plots: Spin-1 Mediators

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

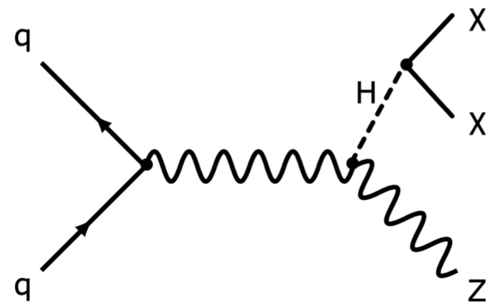


- Similar results for Axial-Vector
- Also results for leptophobic couplings g_q=0.25, g_ℓ=0, g_χ=1

New $H \rightarrow$ invisible Combination

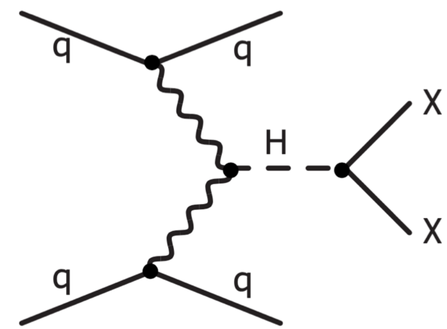
Assume SM production cross sections, but $H \rightarrow E_T^{miss}$

Look in main production topologies



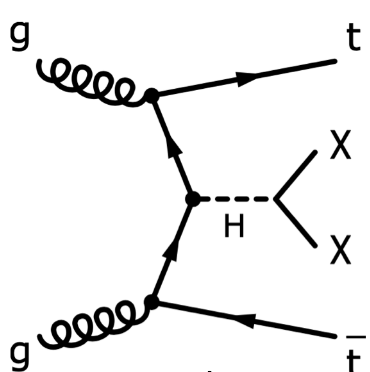
✓ ***Z* + E_T^{miss}**

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



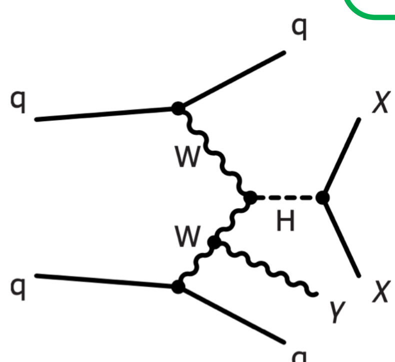
VBF + E_T^{miss}

[JHEP 08 (2022) 104]



✓ ***tt* + E_T^{miss}**

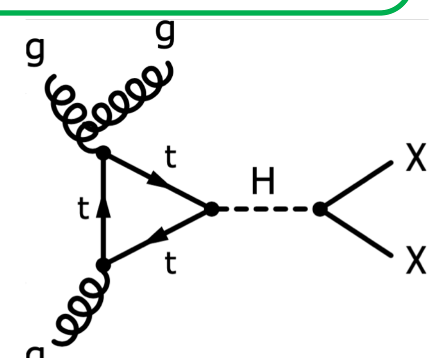
[2211.05426]



VBF + γ + E_T^{miss}

[Eur. Phys. J. C82 (2022) 105]

(see backup slides)



jet + E_T^{miss}

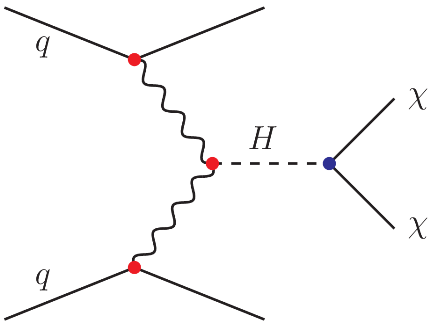
[Phys. Rev. D 103, 112006 (2021)]

(see backup slides)

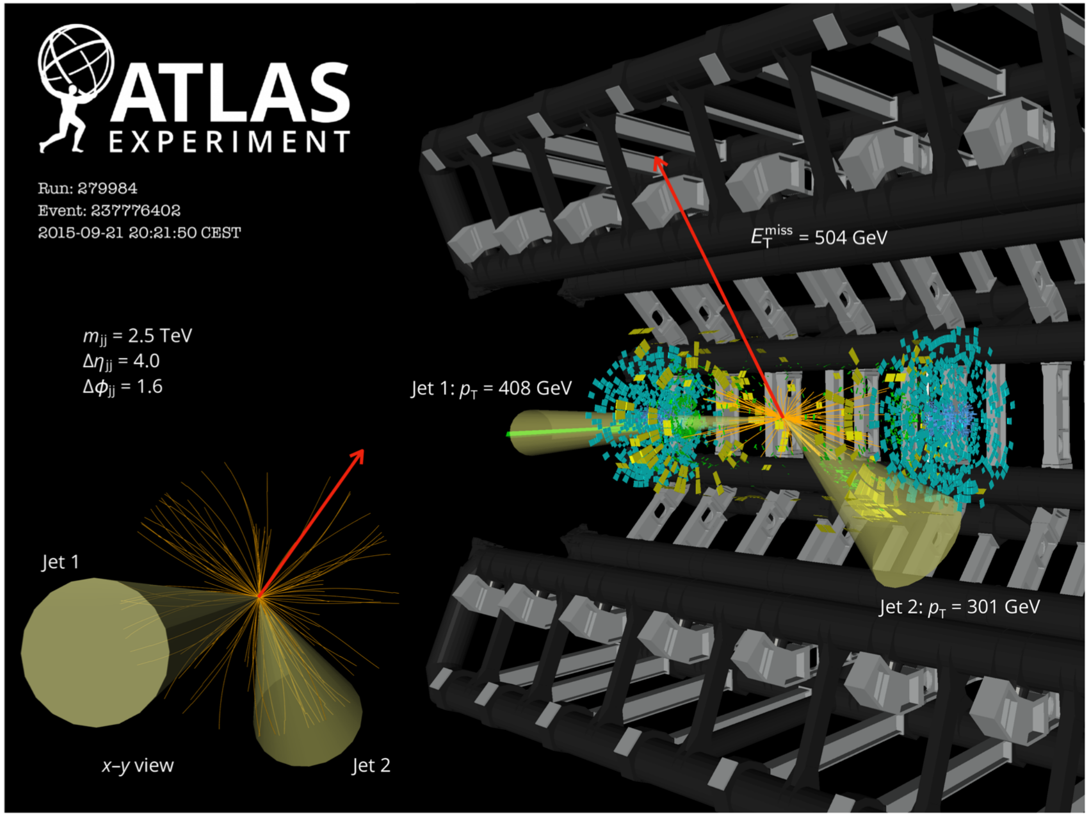
JHEP 08 (2022) 104

VBF + E_T^{miss}

Second highest rate and unique signature
⇒ most sensitive channel



- E_T^{miss} + two forward jets in opposite hemisphere
  - Large E_T^{miss} > 160 GeV
  - Large $\Delta\eta_{jj}$ > 3.8
  - Large m_{jj} > 800 GeV
  - $\Delta\phi$ < 2.0
    ⇒ Reduce multijet
  - Veto e, μ, γ
    ⇒ Reduce other backgrounds
  - Allow up 3rd and 4th jet
    if compatible with VBF FSR

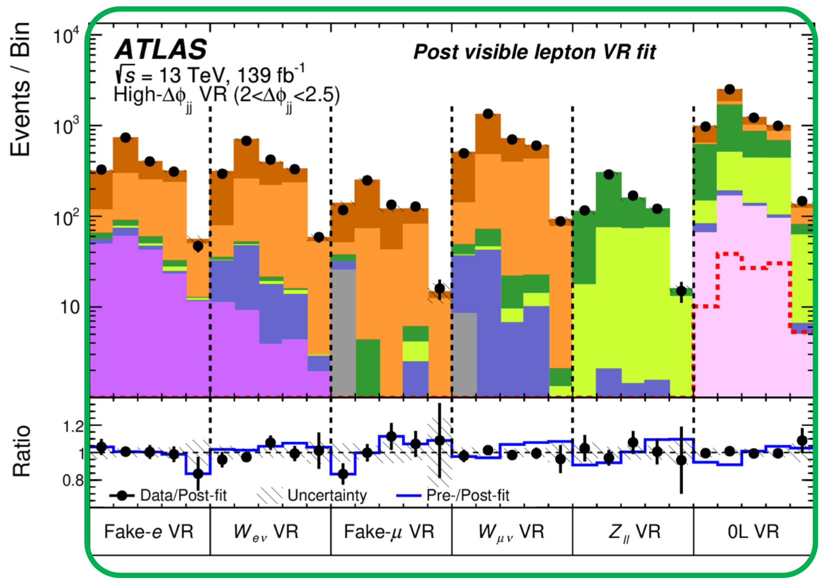


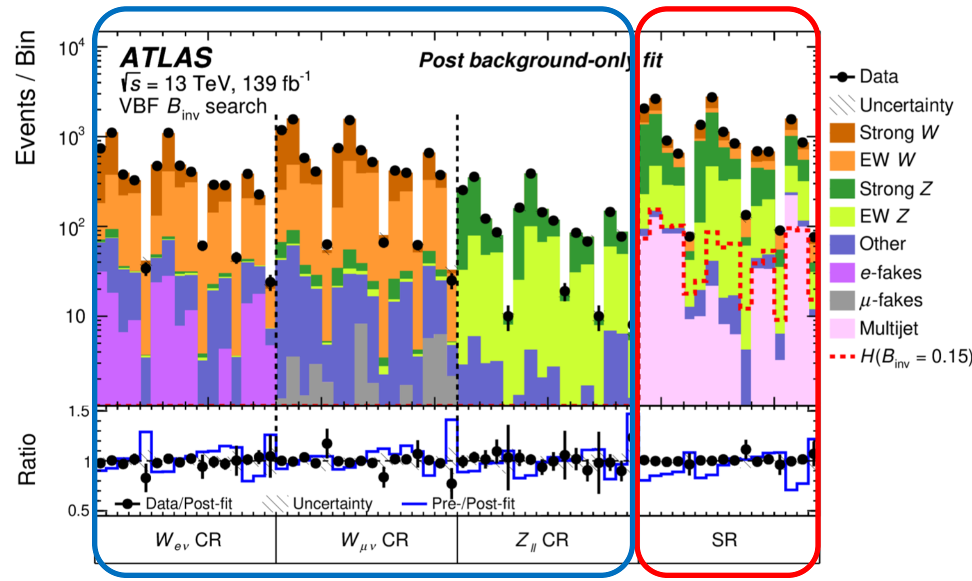
JHEP 08 (2022) 104

VBF + E_T^{miss}

Dedicated VRs and CRs to validate and constrain backgrounds

16 SRs of varying purity and composition





Data consistent with SM ⇒ Set limit @ 95%CL

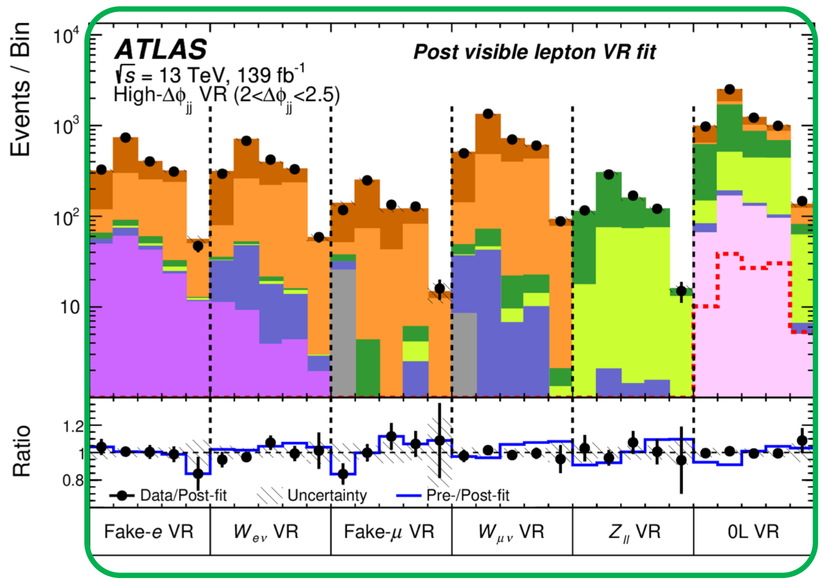
- **Observed: $B(H \rightarrow \text{inv}) < 0.145$**
- Expected: $B(H \rightarrow \text{inv}) < 0.103$

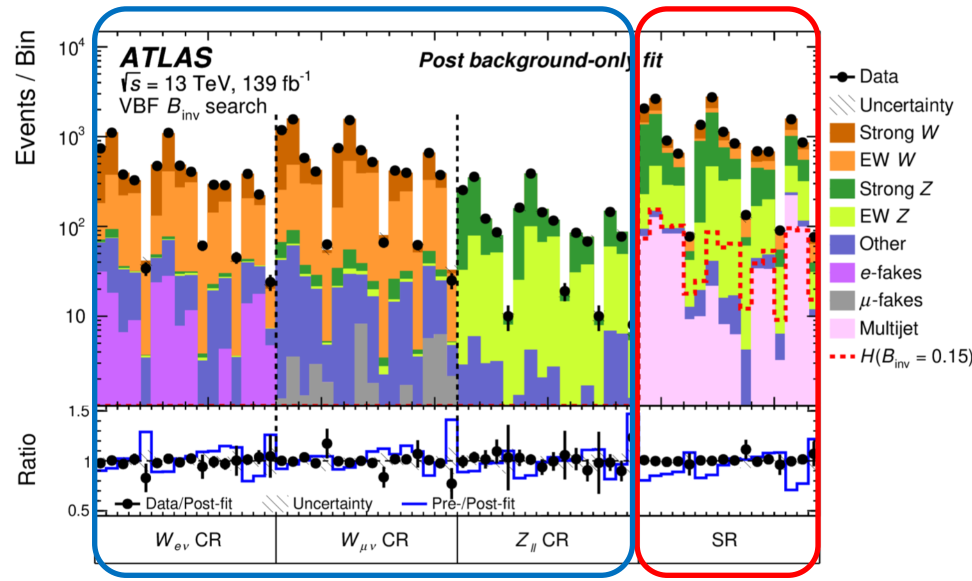
⇒ **Combine** with other Run 2 searches, plus previous Run 1 combination…

VBF + E_T^{miss}

Dedicated VRs and CRs to validate and constrain backgrounds

16 SRs of varying purity and composition





Data consistent with SM ⇒ Set limit @ 95%CL

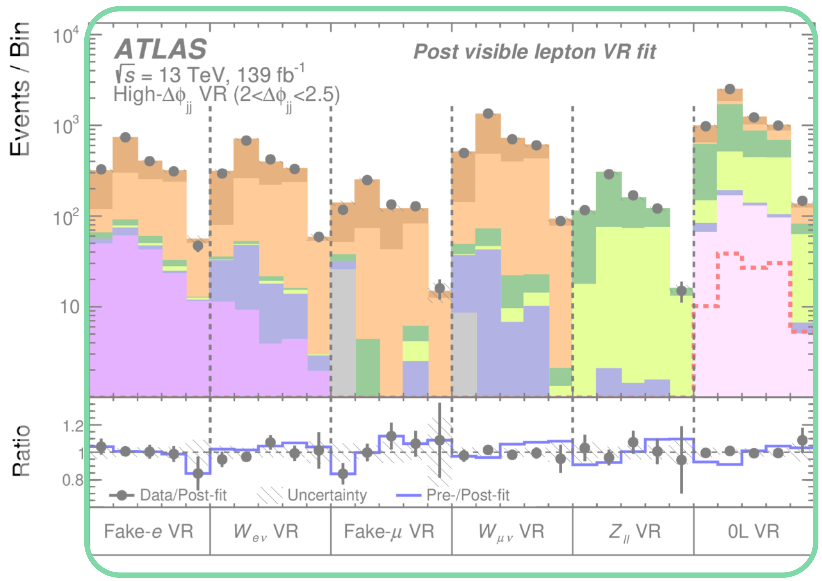
- **Observed: $B(H \rightarrow \text{inv}) < 0.145$**
- Expected: $B(H \rightarrow \text{inv}) < 0.103$

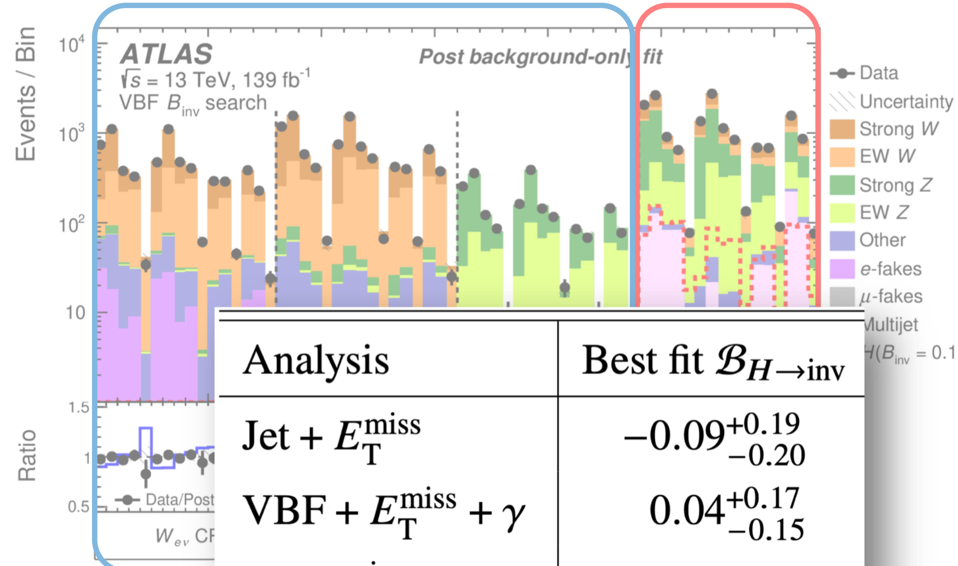
⇒ **Combine** with other Run 2 searches, plus previous Run 1 combination…

VBF + E_T^{miss}

Dedicated VRs and CRs to validate and constrain backgrounds

16 SRs of varying purity and composition





Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$
Jet + E_T^{miss}	$-0.09^{+0.19}_{-0.20}$
VBF + E_T^{miss} + γ	$0.04^{+0.17}_{-0.15}$
$t\bar{t}$ + E_T^{miss}	0.08 ± 0.15
$Z(\to \ell\ell)$ + E_T^{miss}	0.00 ± 0.09
VBF + E_T^{miss}	0.05 ± 0.05
Run 2 Comb.	0.04 ± 0.04
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$
Run 1+2 Comb.	0.04 ± 0.04

Data consistent with SM ⇒ Set limit @ 95%CL

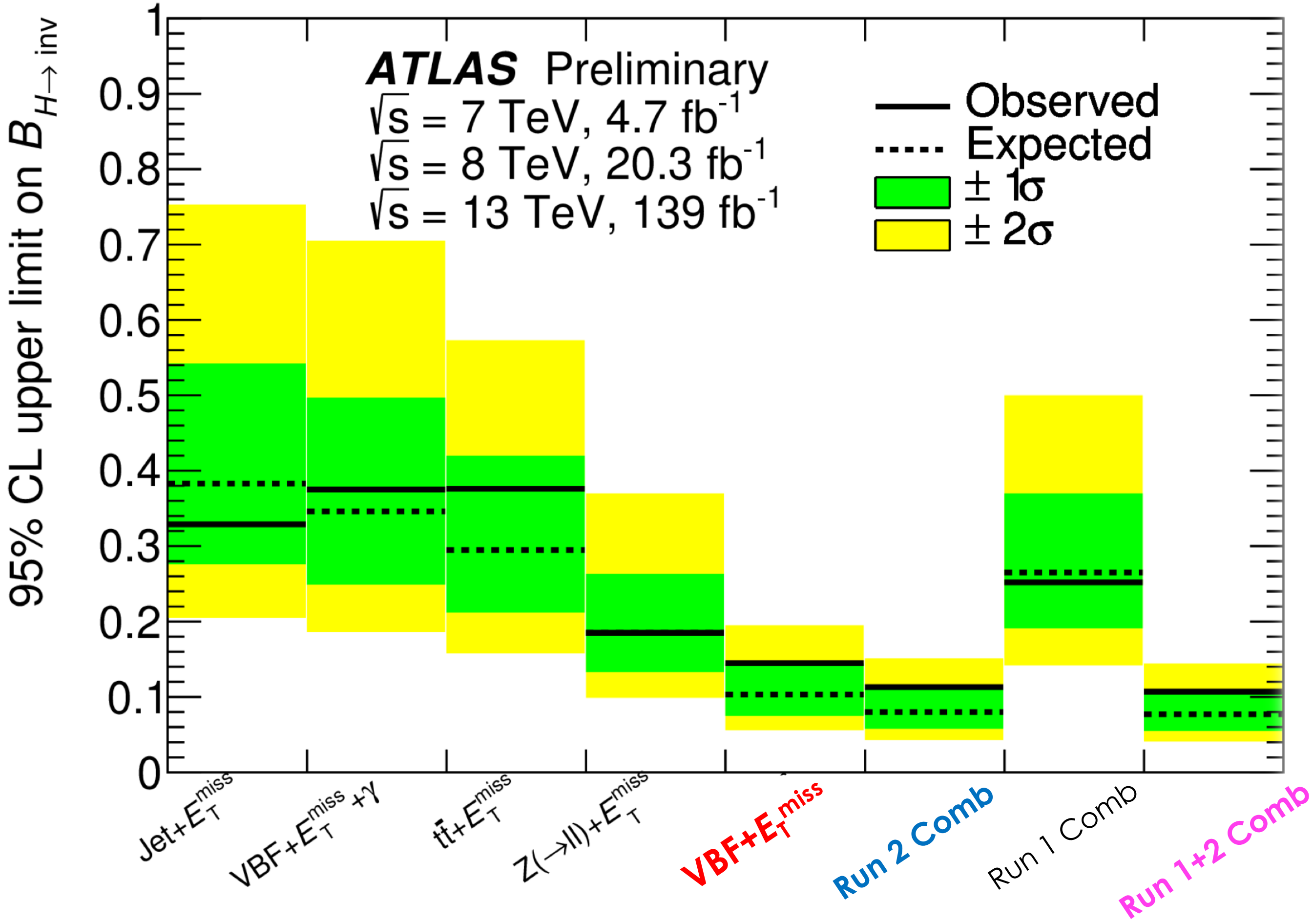
- **Observed: $B(H\to\text{inv}) < 0.145$**
- Expected: $B(H\to\text{inv}) < 0.103$

⇒ **Combine** with other Run 2 searches, plus previous Run 1 combination…

Paper in preparation

$H \rightarrow$ inv. Combination

Upper limits on B($H \rightarrow$inv.) at 95% CL



Sensitivity dominated by VBF+E_T^{miss}

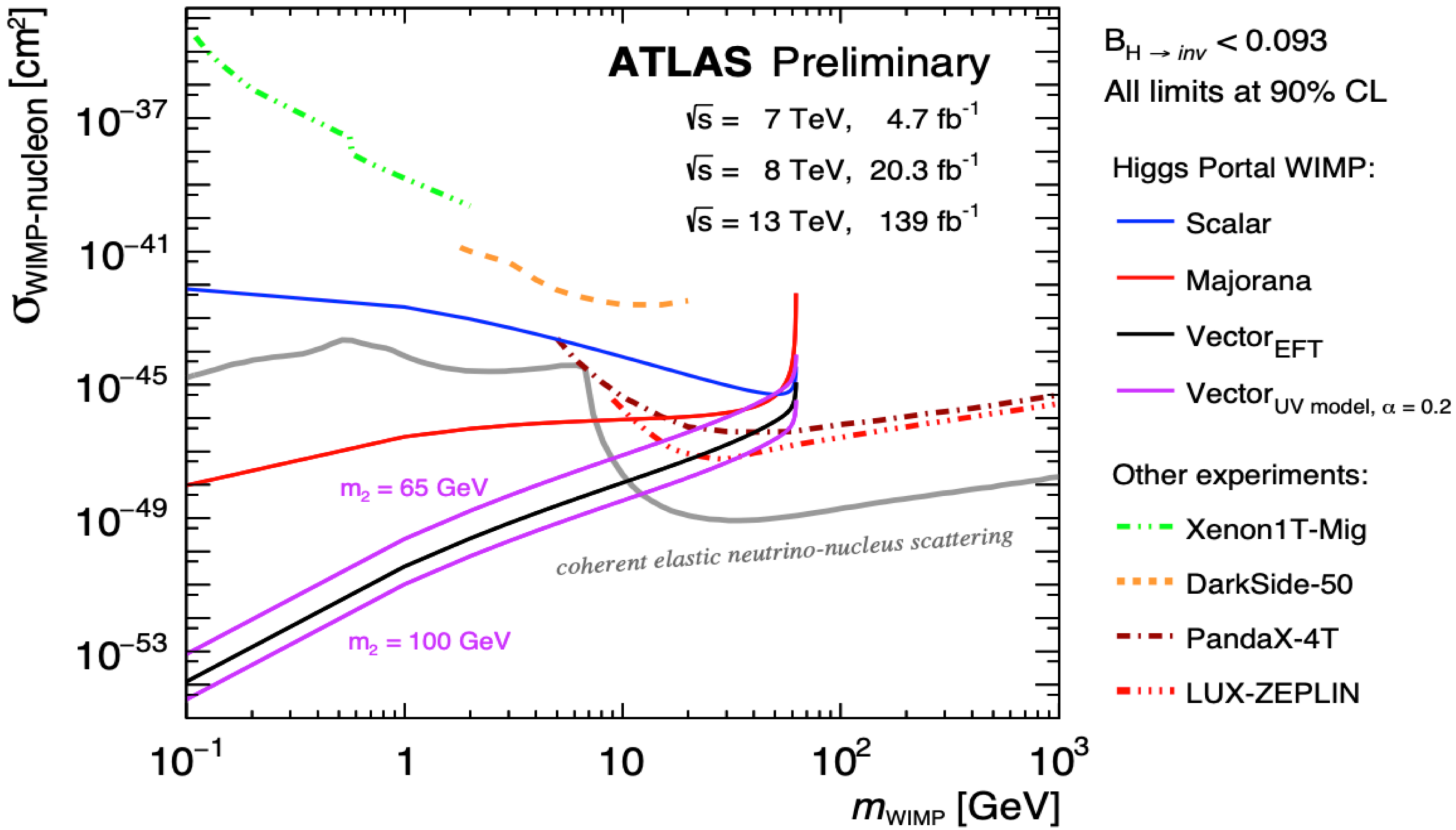
22% gain

+4% gain

$H \rightarrow$inv. Combination

Interpret in models where **Higgs is portal** to DM WIMP

- Set limits on WIMP-nucleon cross section at 90% CL
- Complementary to direct detection experiments

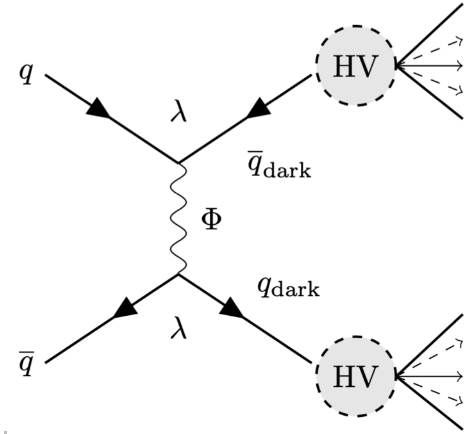


ATLAS-CONF-2022-038

Dark matter to semi-visible jets

Sensitive to strongly coupled dark sector

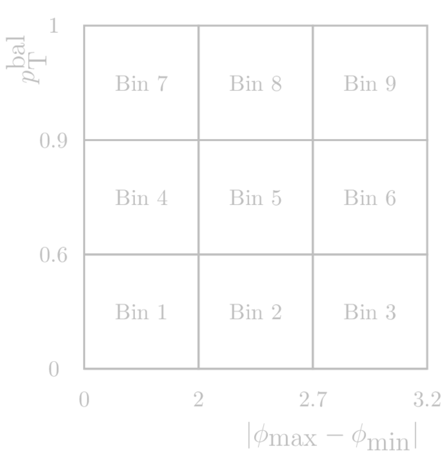
- Scalar mediator (Φ) acts as portal
- Focus on t-channel (can probe high masses)

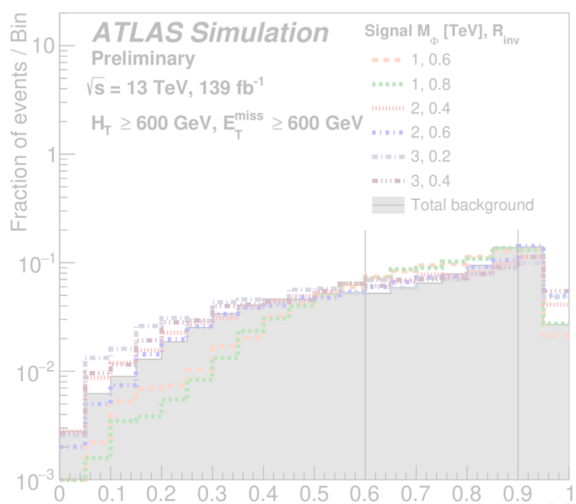


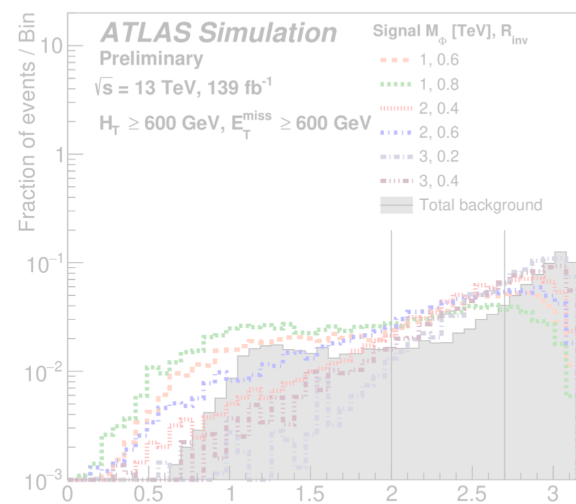
Signal: 2 semi-visible jets (SVJs)

- High $H_T = \Sigma_{\rm jets} p_T$ and high $E_T^{\rm miss}$ 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







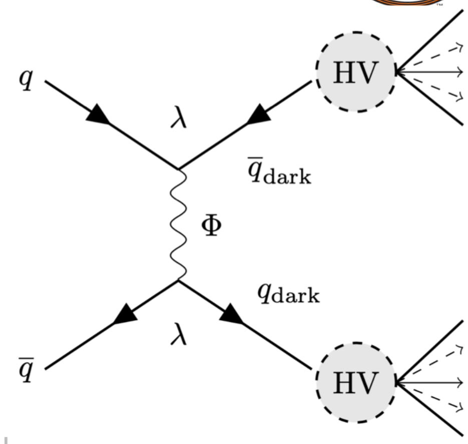
Dark matter to semi-visible jets

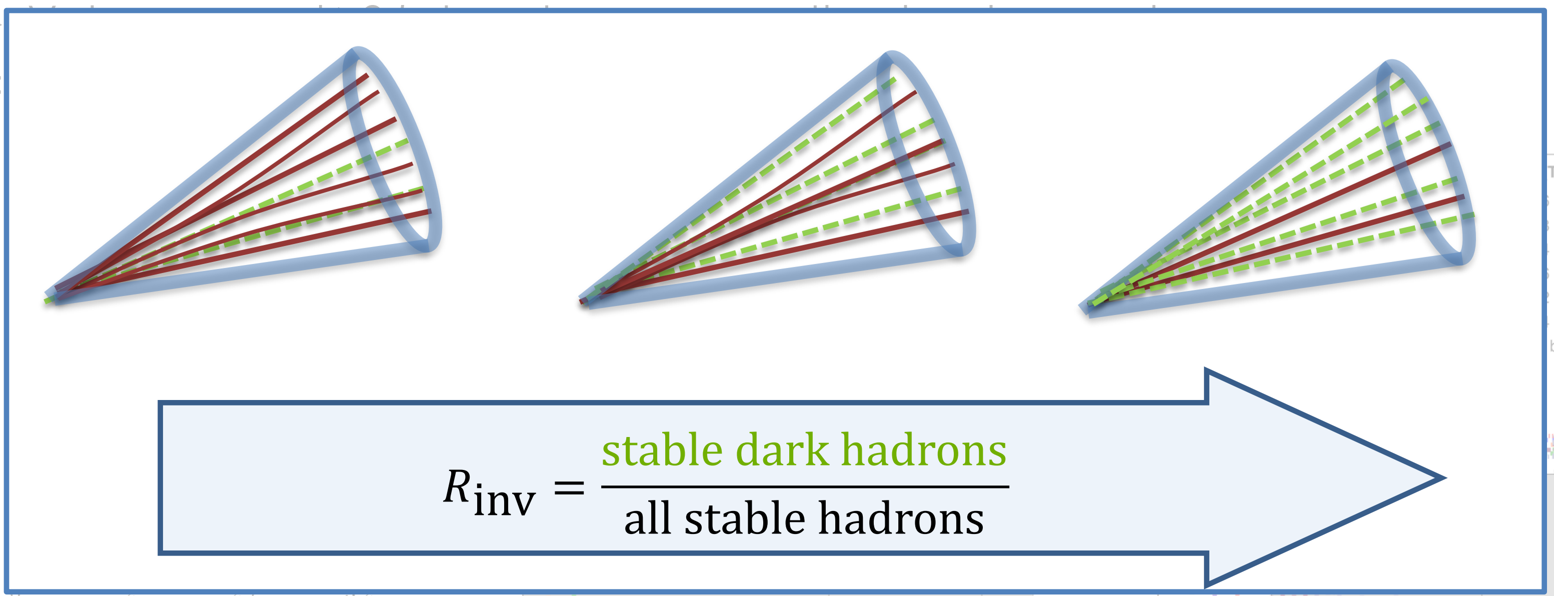
Sensitive to strongly coupled dark sector

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

Signal: 2 semi-visible jets (SVJs)

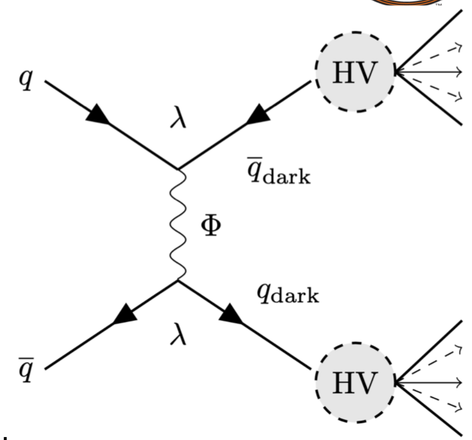
- High $H_T = \Sigma_{jets} p_T$ and high E_T^{miss} close to a jet
- ≥1 additional jet to suppress dominant multijet background





ATLAS-CONF-2022-038

Dark matter to semi-visible jets



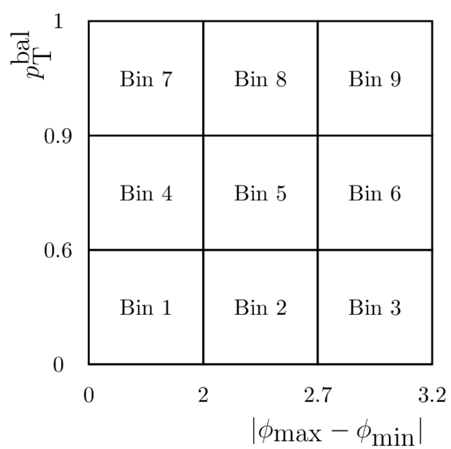
Sensitive to strongly coupled dark sector

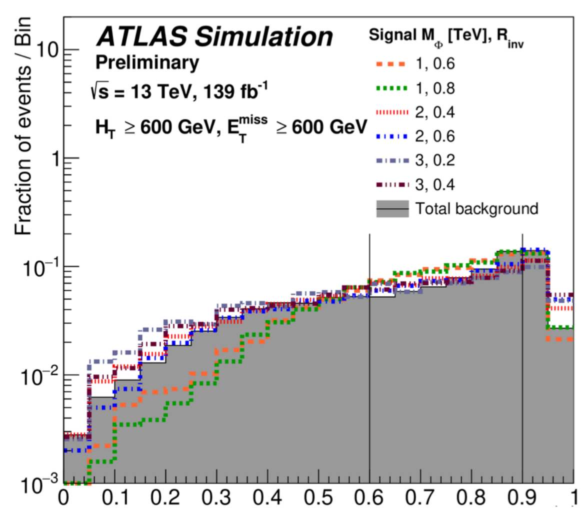
- Scalar mediator (Φ) acts as portal
- Focus on t-channel (can probe high masses)

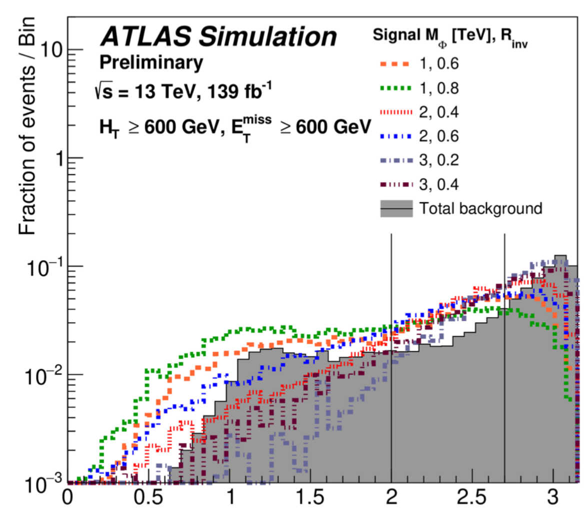
Signal: 2 semi-visible jets (SVJs)

- 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



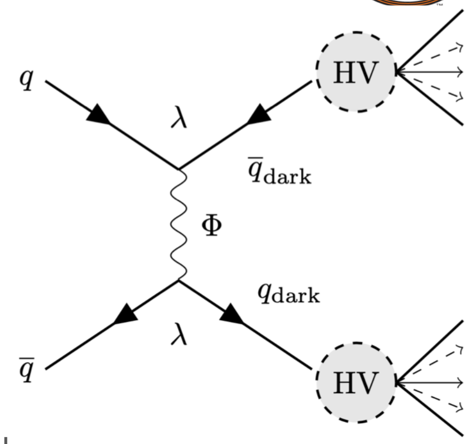




$$p_T^{bal} = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}$$

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

Dark matter to semi-visible jets



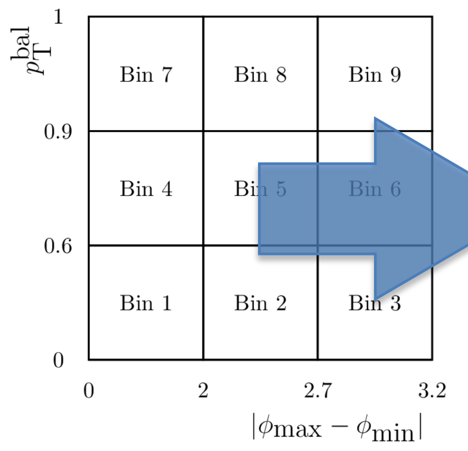
Sensitive to strongly coupled dark sector

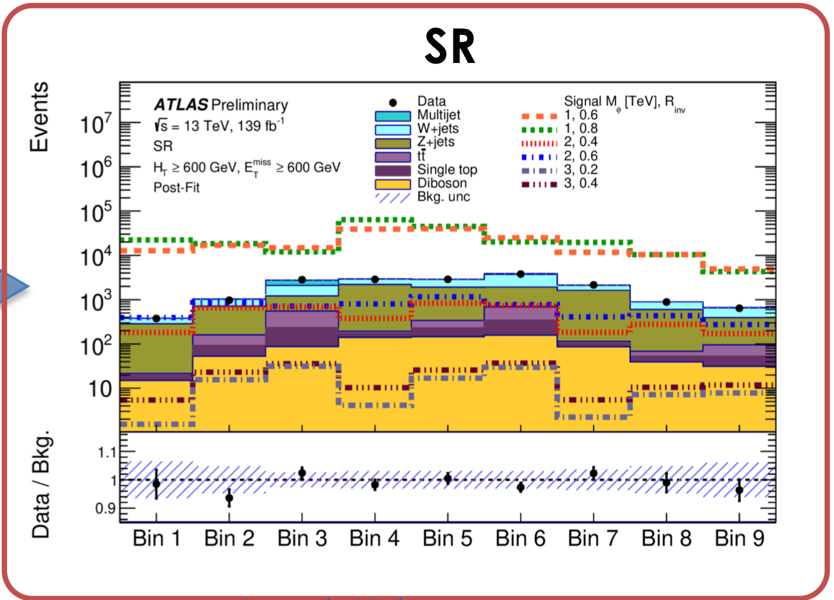
- Scalar mediator (Φ) acts as portal
- Focus on t-channel (can probe high masses)

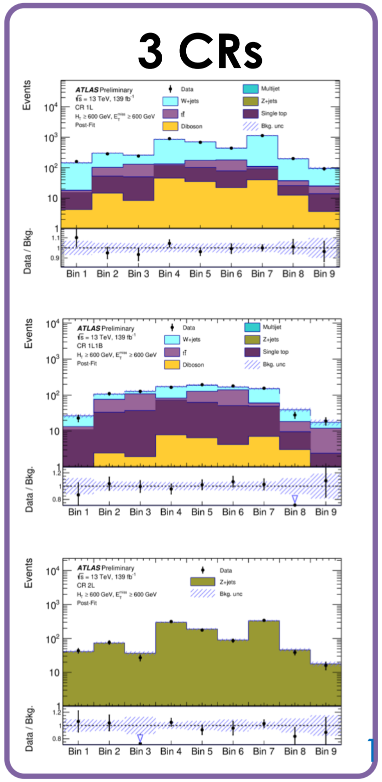
Signal: 2 semi-visible jets (SVJs)

- 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



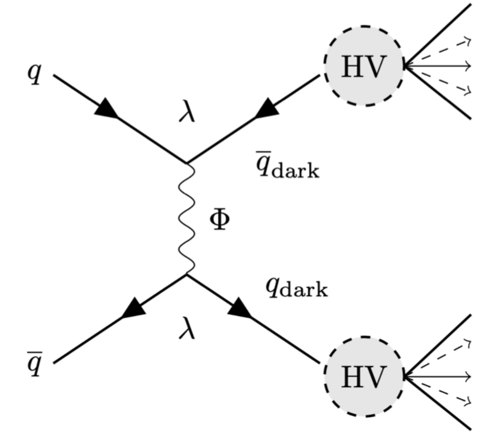


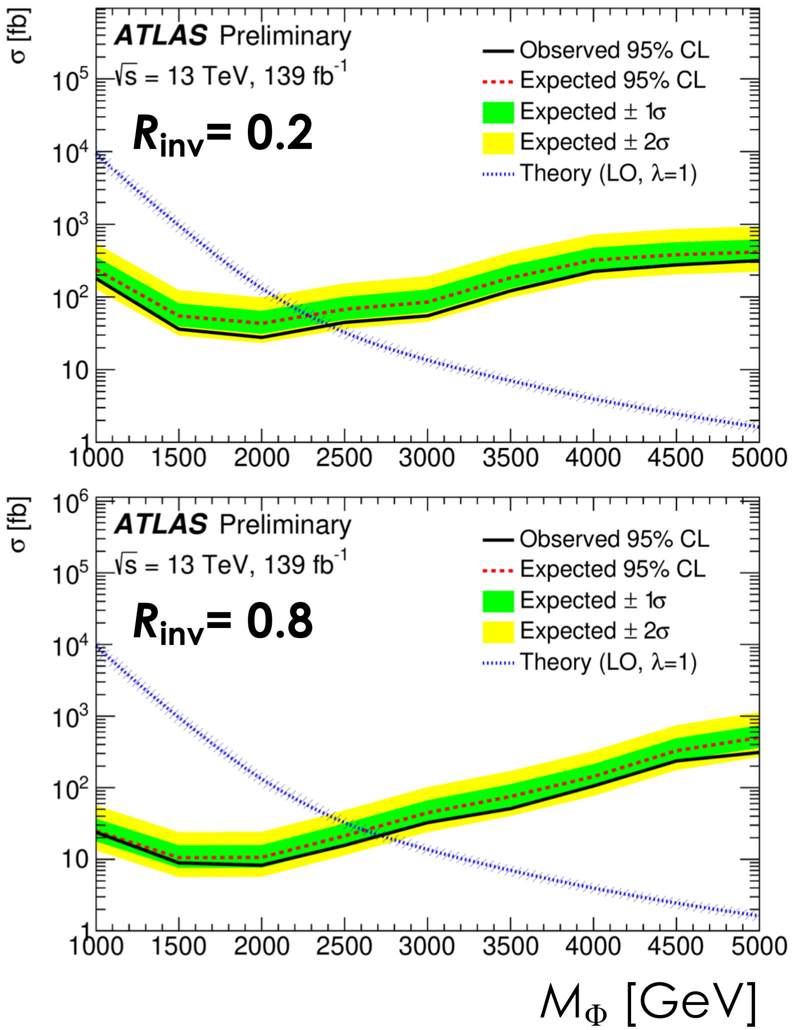


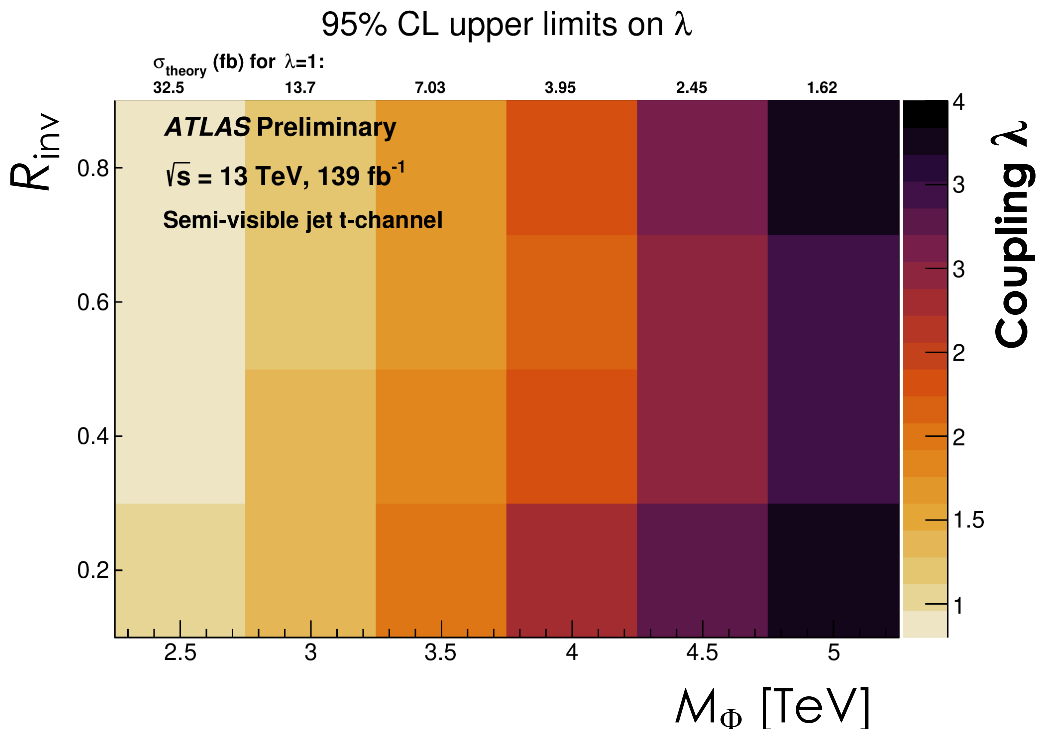
ATLAS-CONF-2022-038

Dark matter to semi-visible jets

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





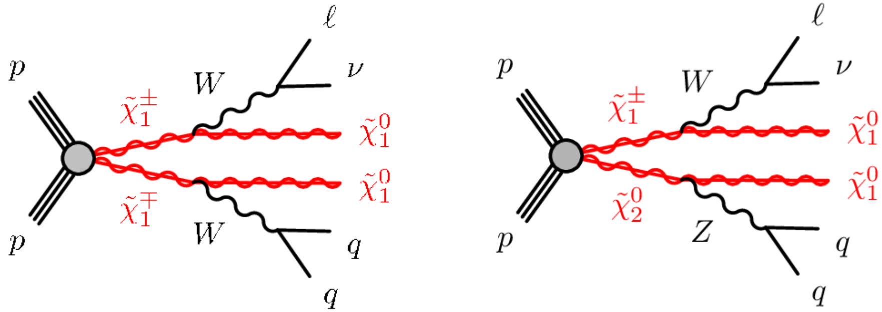


Searches for Electroweakinos

Three searches for direct neutralino/chargino production

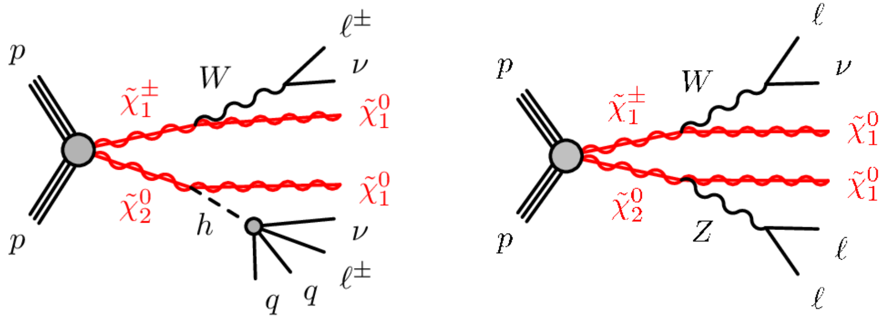
- **Lepton+jet**

  ATLAS-CONF-2022-059



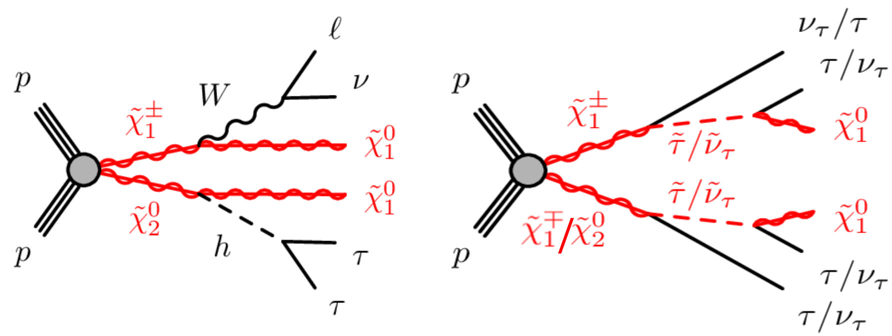
- **Same-sign/trilepton**

  ATLAS-CONF-2022-057



- **Di-tau**

  ATLAS-CONF-2022-042

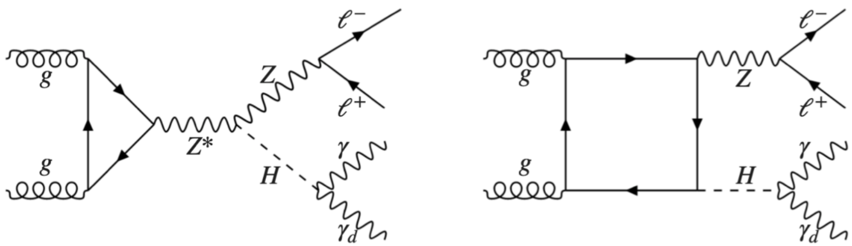


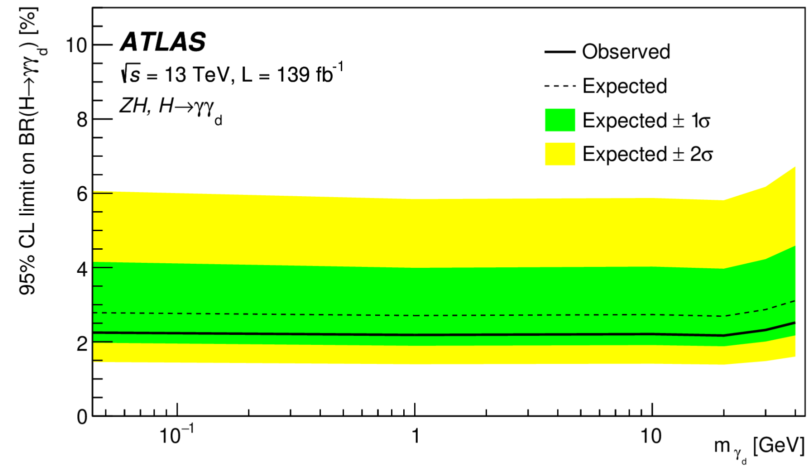
See talk by Tomohiro Yamazaki on SUSY searches
(BSM session after the coffee break)

Many more new results…

Higgs decaying to dark photons ($ZH \rightarrow \ell\ell\gamma\gamma_d$)

[2212.09649](2212.09649) (Submitted to JHEP)

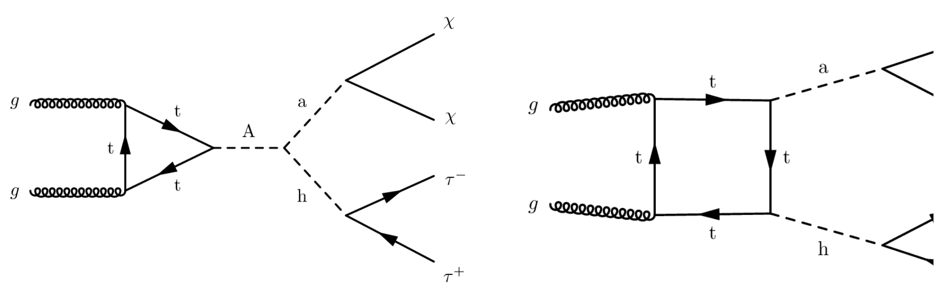


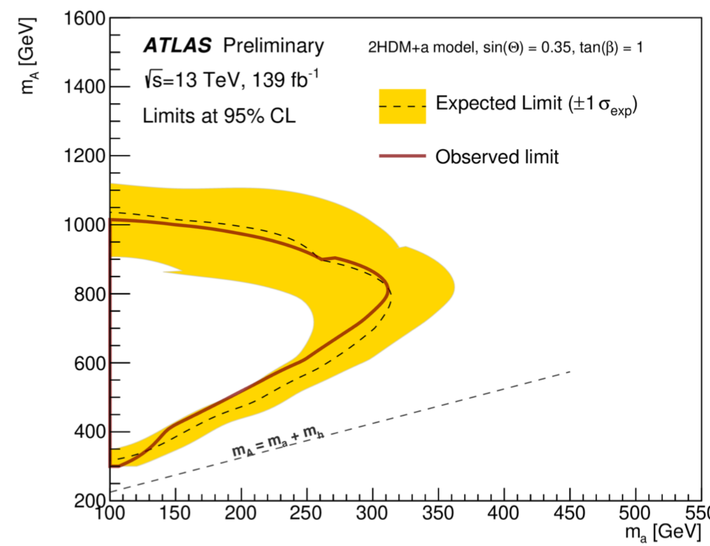


Higgs+DM with $H \rightarrow \tau\tau$

ATLAS-CONF-2022-069

- Interpret in 2HDM+a
- Set limits on heavy Higgs masses

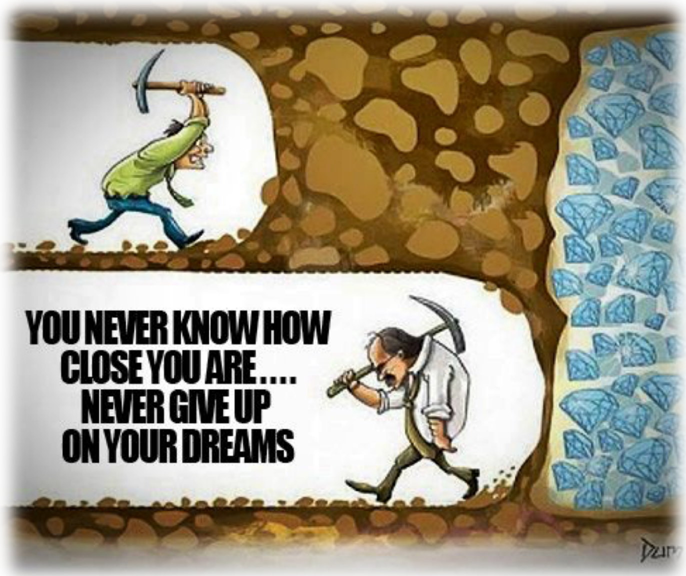




Conclusion

***Many* new 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/
  - Also see related talks by Tomohiro Yamazaki, Neza Ribaric, and Anna Ivina
- 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 to analyze in Run 3!!!

Thank you!

And special thanks to:

DOE for supporting this research

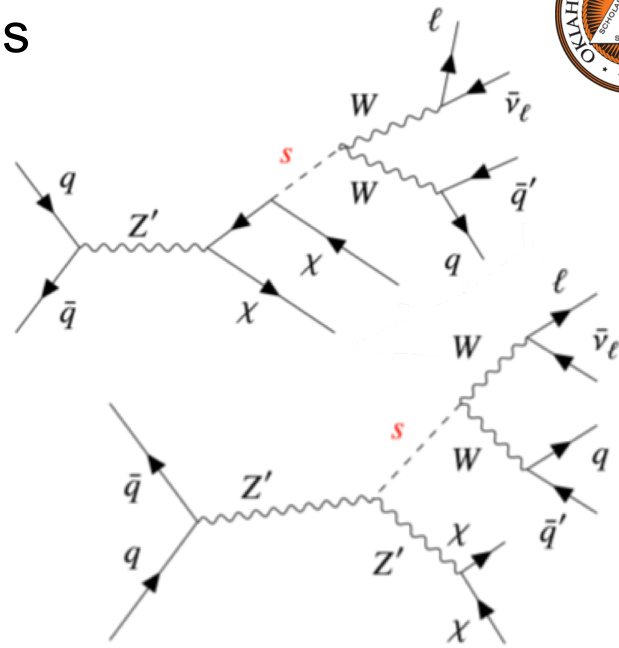
The ATLAS Collaboration

- Complete list of ATLAS dark matter results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

The HEP2023 Organizers!

Bonus Material

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

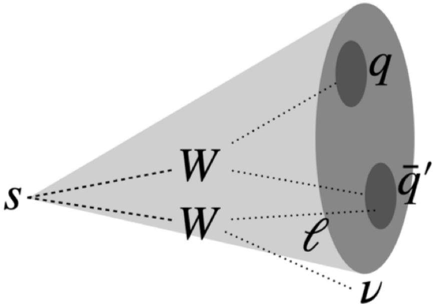


Search for **dark Higgs** ($\rightarrow WW \rightarrow \ell\nu qq$)

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

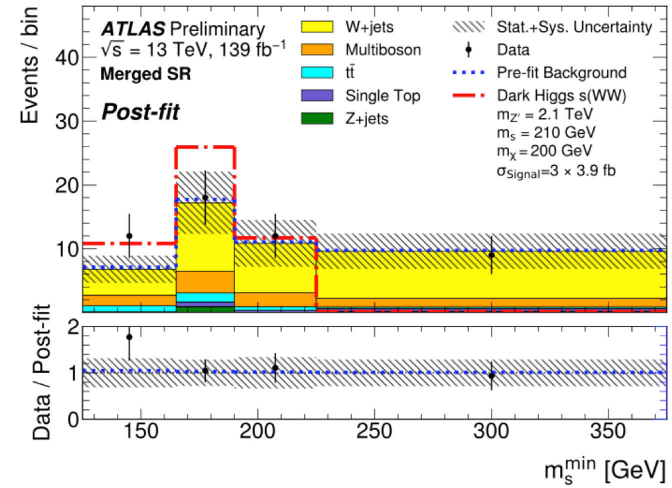
Select events with

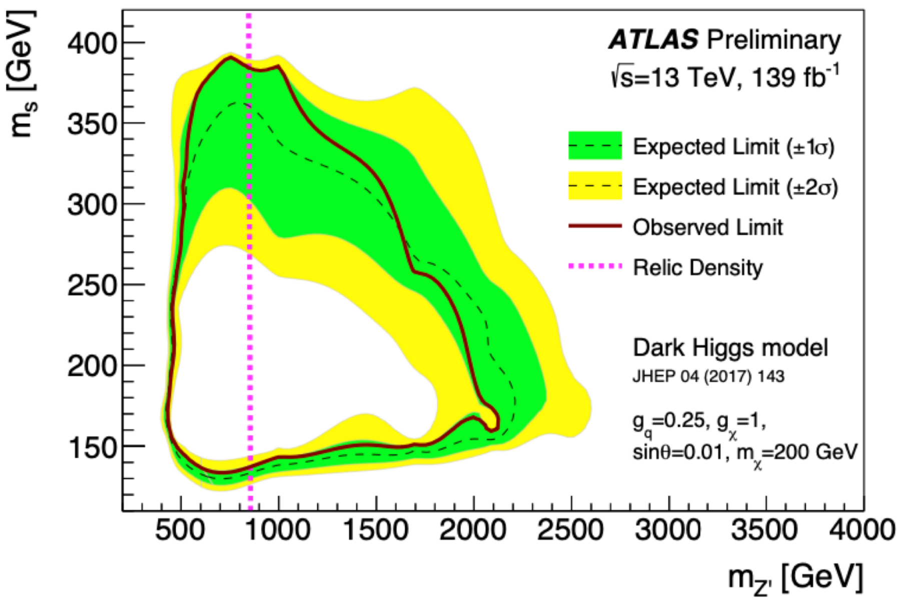
- E_T^{miss} > 200 GeV
- 1 high-p_T lepton (e/μ)
- Two categories for $W \rightarrow qq$
  - Merged: large-*R* jet with 2-prong substructure
    - Use "track-assisted reclustering" (TAR) to remove overlapping leptons
  - Resolved: two small-*R* jets
- CRs to constrain dominate *W*+jets and tt backgrounds

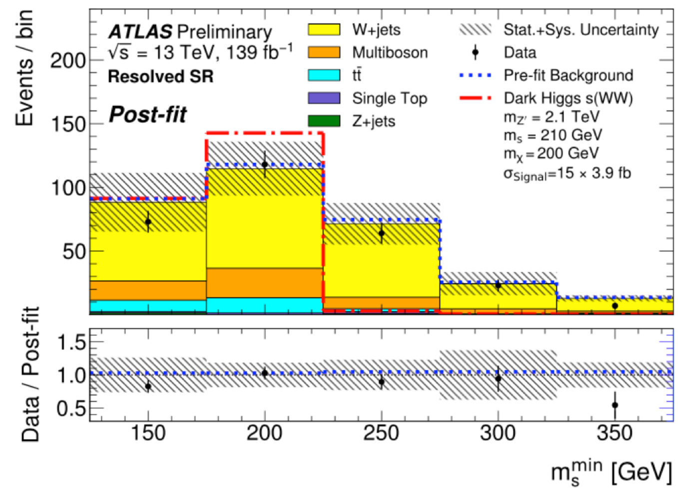


$S(WW) + E_T^{miss}$

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

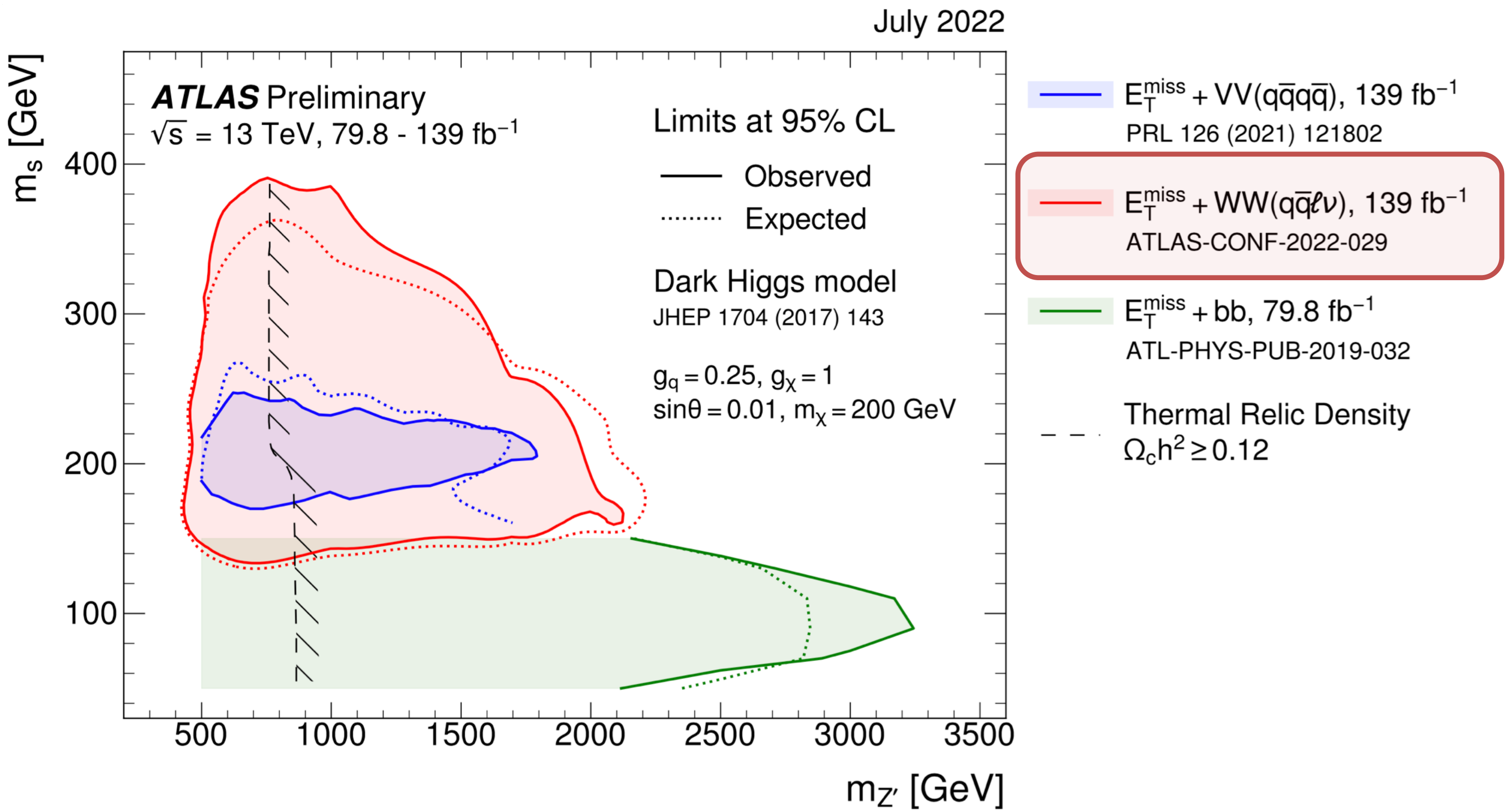






ATL-PHYS-PUB-2022-036

Dark Higgs Summary Plot

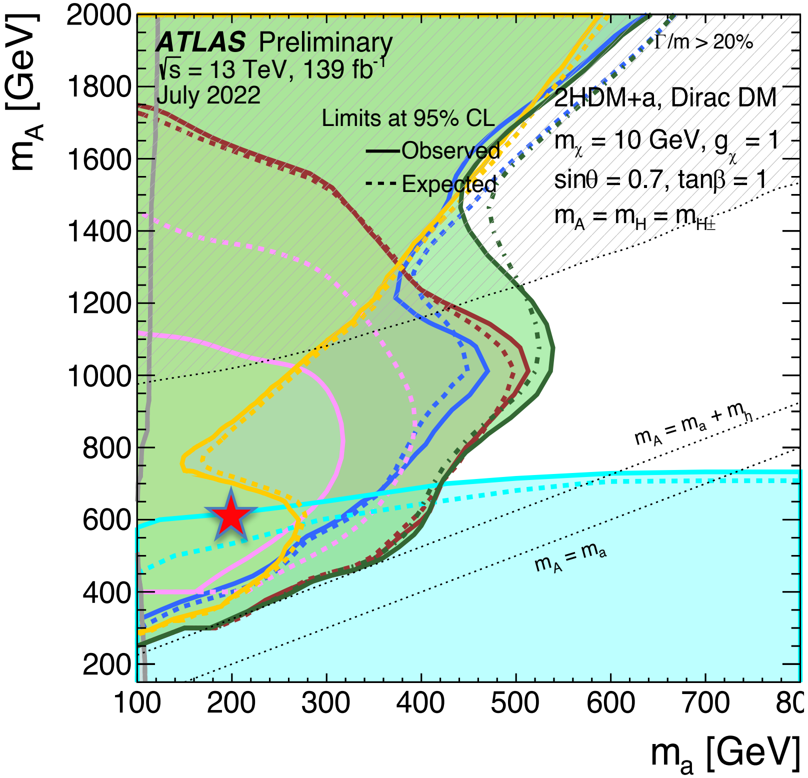


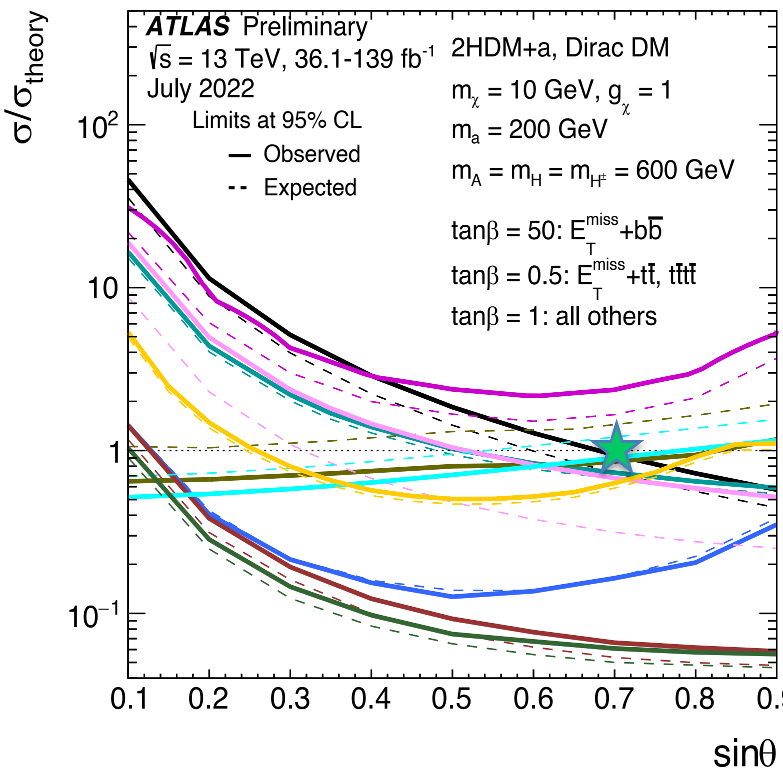
2HDM+a Summary Plots

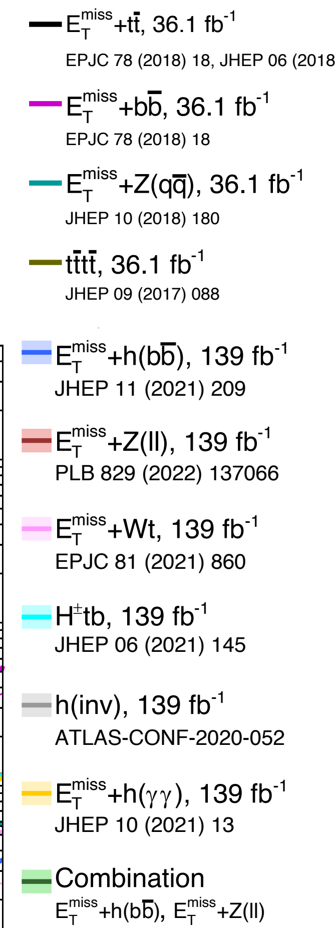
95% CL exclusion limits:

- m_A vs. m_a ($m_A = m_H = m_{H\pm}$)
  - m_χ = 10 GeV
  - g_χ = 1
  - $\sin\theta$ = 0.7
  - $\tan\beta$ = 1

- σ/σ_{th} vs. $\sin\theta$
  - m_χ = 10 GeV
  - m_a = 200 GeV
  - $m_A = m_H = m_{H\pm}$ = 600 GeV



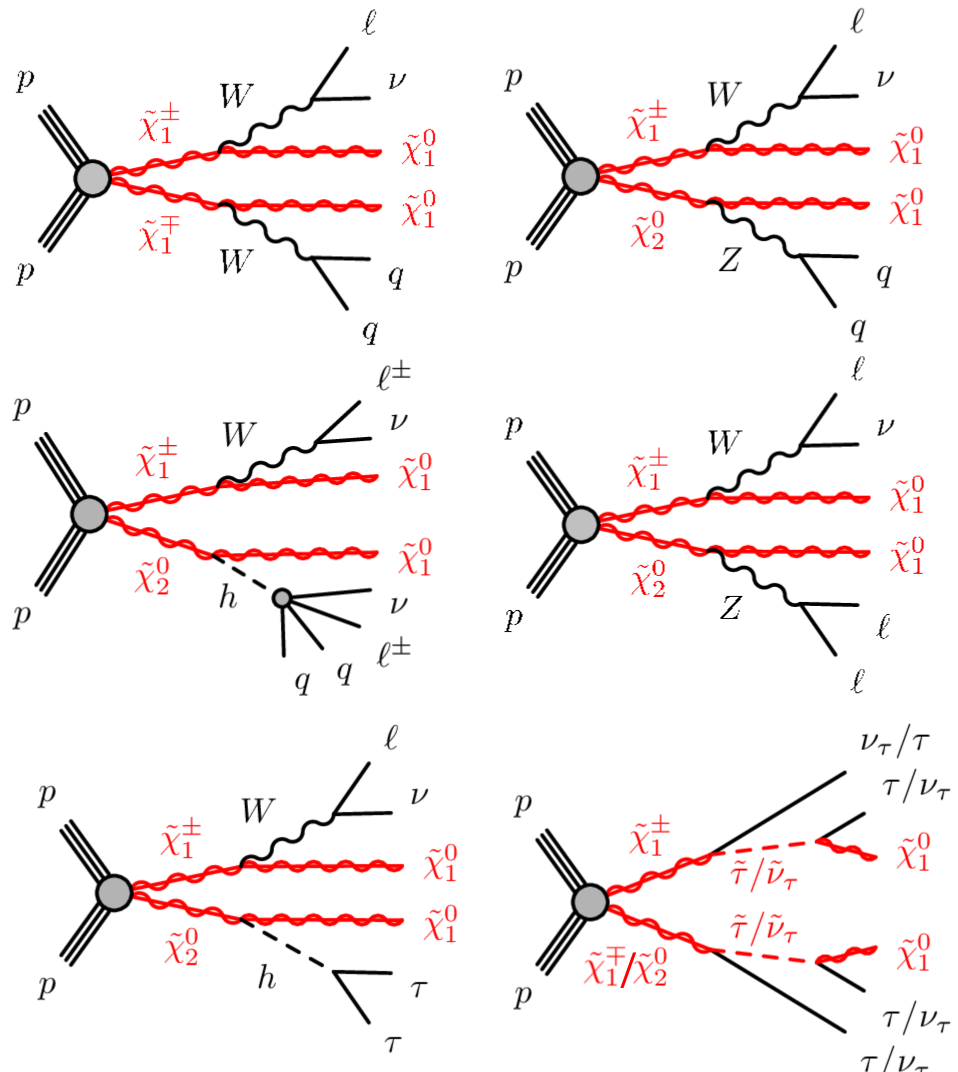




Searches for Electroweakinos

Three searches for direct neutralino/chargino production

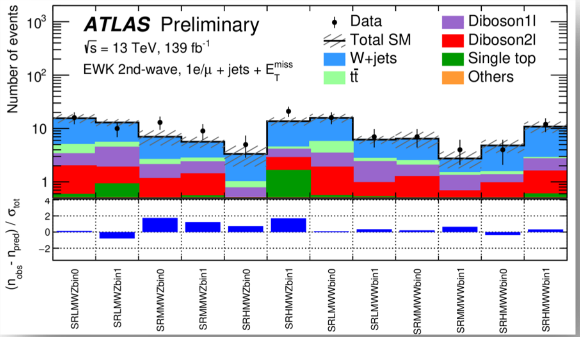
- **Lepton+jet**
  - E_T^{miss} > 200 GeV, $\sigma(E_T^{miss})$> 12
  - 1 isolated e or μ
  - 1-3 small-R jets and large-R jet w/ W or Z-tag
- **Same-sign/trilepton**
  - E_T^{miss} > 50 GeV, $\sigma(E_T^{miss})$> 6
  - 2 same-sign e/μ or 3 leptons
  - ≥1 jet, 0 b-tags
- **Di-tau**
  - ≥ 2 τ→hadronic candidates
  - 0 b-tags
  - \+ SR-specific criteria

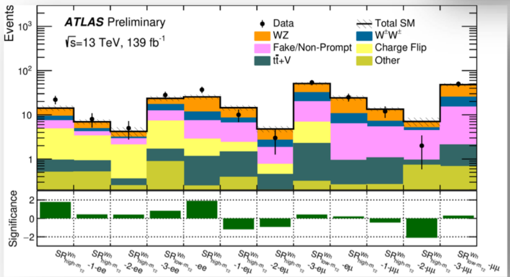


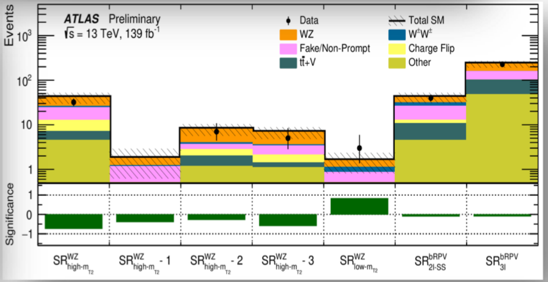
Searches for Electroweakinos

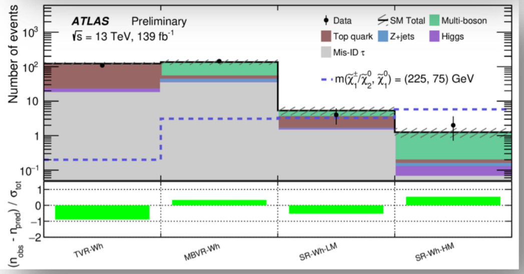
Split into multiple SRs (also CRs and VRs) to target different signals (and backgrounds)

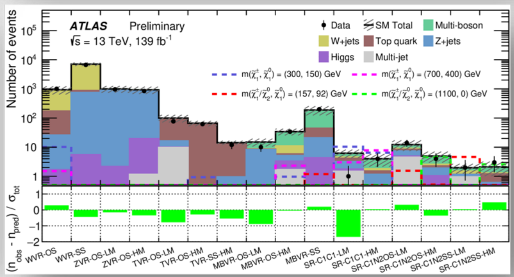
- **Lepton+jet**
  - 12 SRs used for WW and WZ channels
  - Main splitting criteria: W/Z-tag, $m_T(\ell + E_T^{miss})$, m_{eff}
- **Same-sign/trilepton**
  - 12 SRs for Wh, 5 SRs for WZ
  - Main criteria: E_T^{miss}, $\sigma(E_T^{miss})$, Lepton number/flavor, m_{T2}, m_T^{min}
- **Di-tau**
  - 4 SRs for Wh, 16 SRs for intermediate stau channels
  - Main criteria: E_T^{miss}, N_τ, $\Delta\varphi(\tau_1,\tau_2)$, $\Delta R(\tau_1,\tau_2)$, $m(\tau_1,\tau_2)$, m_{T2}, m_{Tsum}











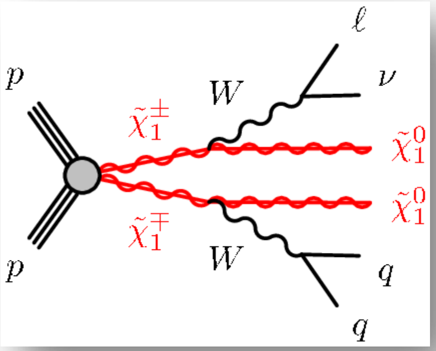
$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_{T1}(\mathbf{p}_{T1},\mathbf{q}_T), m_{T2}(\mathbf{p}_{T2},\mathbf{p}_T^{miss}-\mathbf{q}_T)\right)\right]$$

$$m_T(\mathbf{p}_T,\mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T\cdot\mathbf{q}_T)}$$

Electroweakino Limits

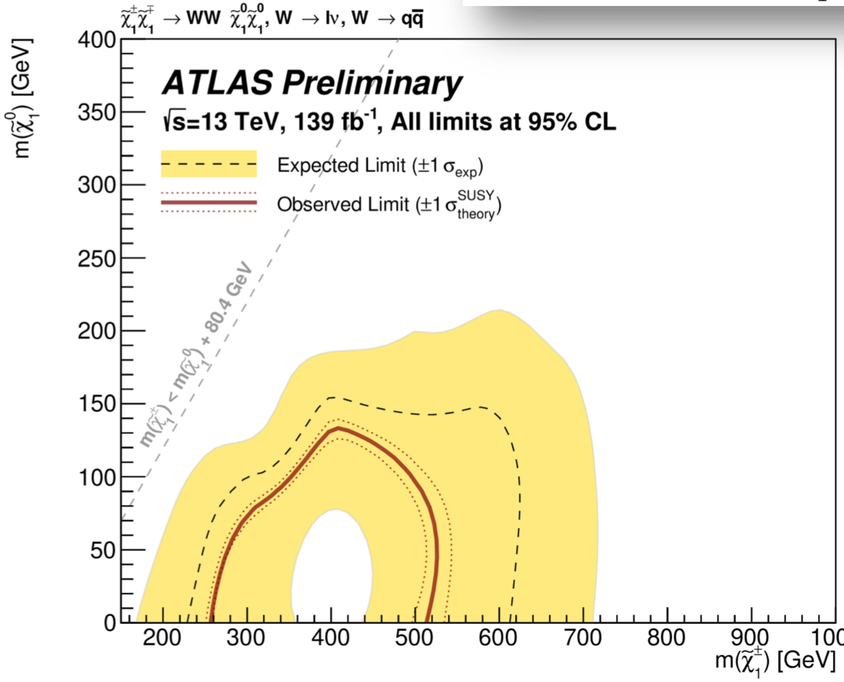
No significant deviations from SM

⇒ Set limits on DM particle masses in simplified models for various decays



$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production decaying via intermediate WW

- **Lepton+jet**
  - Exclude $m(\tilde{\chi}_1^{\pm}) \simeq [260,420]$ GeV for massless LSP
  - Exclude LSP mass below 130 GeV for $m(\tilde{\chi}_1^{\pm}) \simeq 400$ GeV



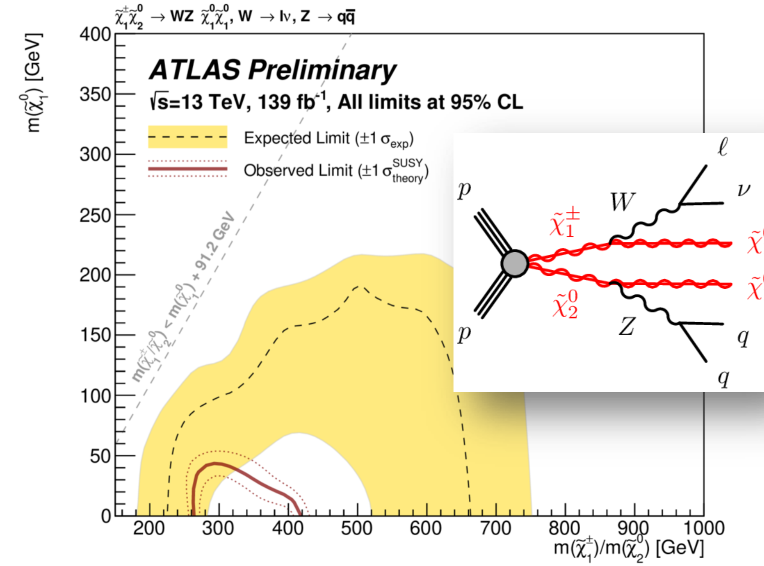
Electroweakino Limits

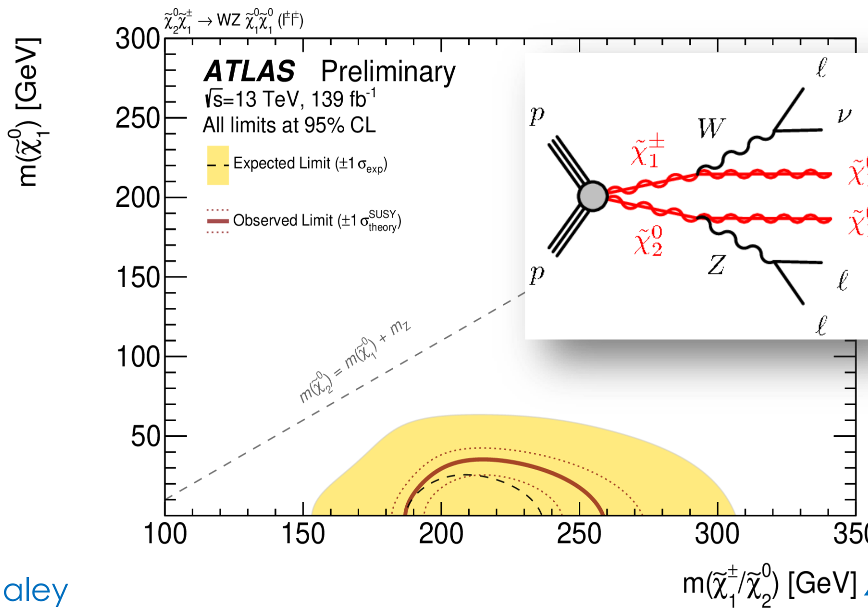
No significant deviations from SM

⇒ Set limits on DM particle masses in simplified models for various decays

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production decaying via intermediate WZ

- **Lepton+jet**
  - Exclude $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) \simeq [260,420]$ GeV for massless LSP
  - Exclude LSP mass below 40 GeV for $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) \simeq 80$ GeV
- **Same-sign/trilepton**
  - Exclude $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) \simeq [190,260]$ GeV for massless LSP
  - Exclude LSP mass below 30 GeV for $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) \simeq 210$ GeV





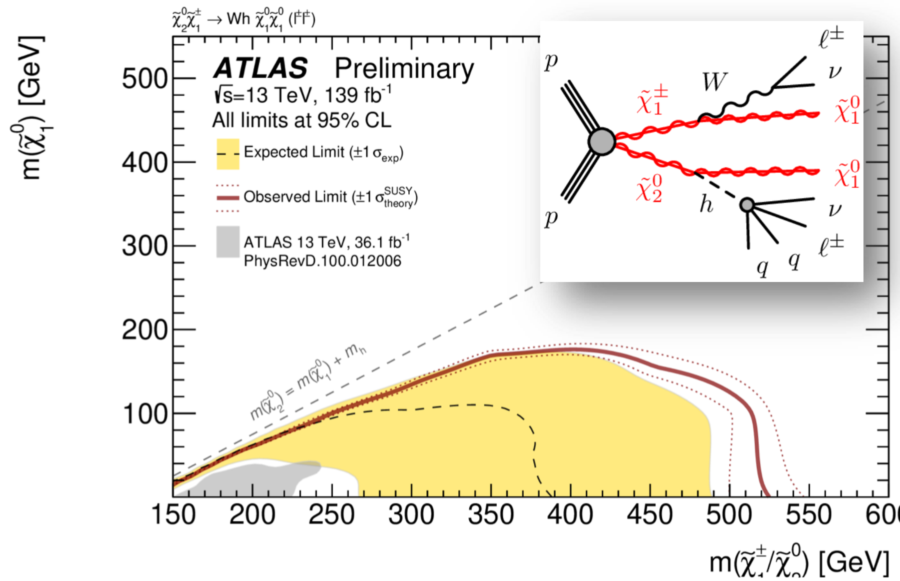
Electroweakino Limits

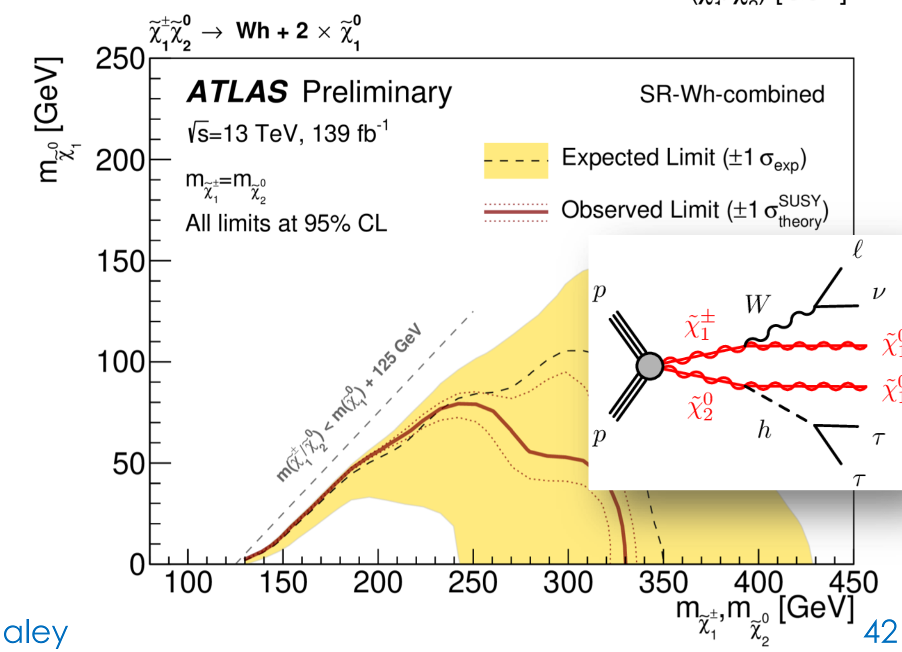
No significant deviations from SM

⇒ Set limits on DM particle masses in simplified models for various decays

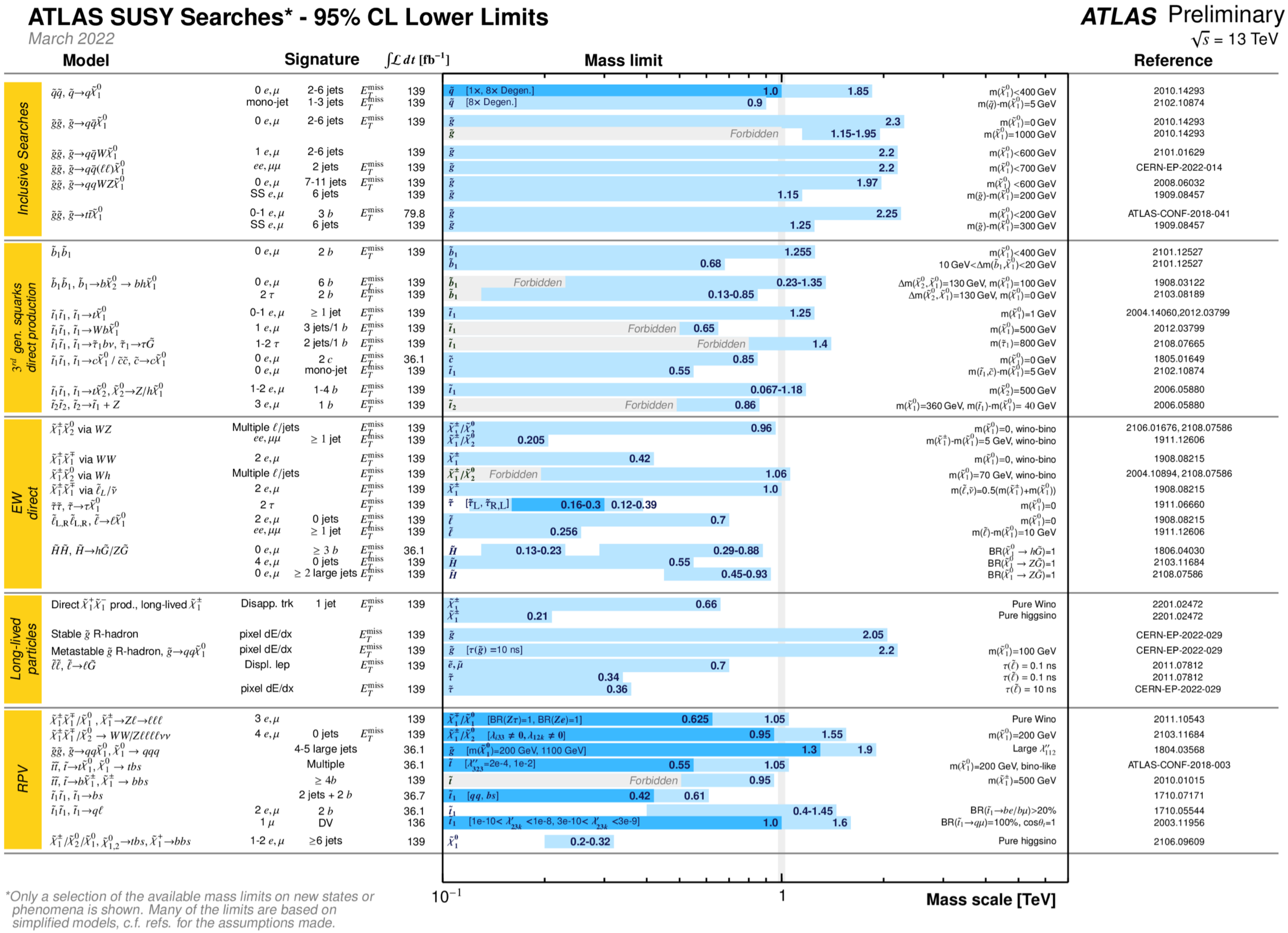
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ production decaying via intermediate Wh

- **Same-sign/trilepton**
  - Exclude $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0}) < 520$ GeV for massless LSP
  - Exclude LSP mass below 170 GeV for $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0}) \simeq 400$ GeV
- **Di-tau**
  - Exclude $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0}) \simeq [80,330]$ GeV for massless LSP
  - Exclude LSP mass below 70 GeV for $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0}) \simeq 240$ GeV





Much more SUSY



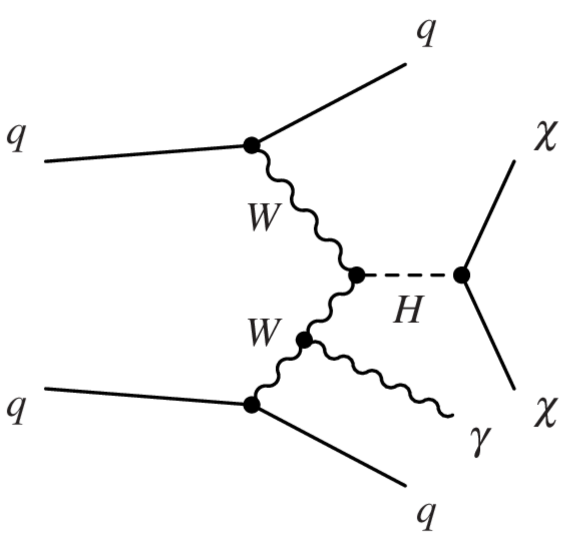
Talk by Tomohiro Yamazaki on SUSY searches with prompt decays.

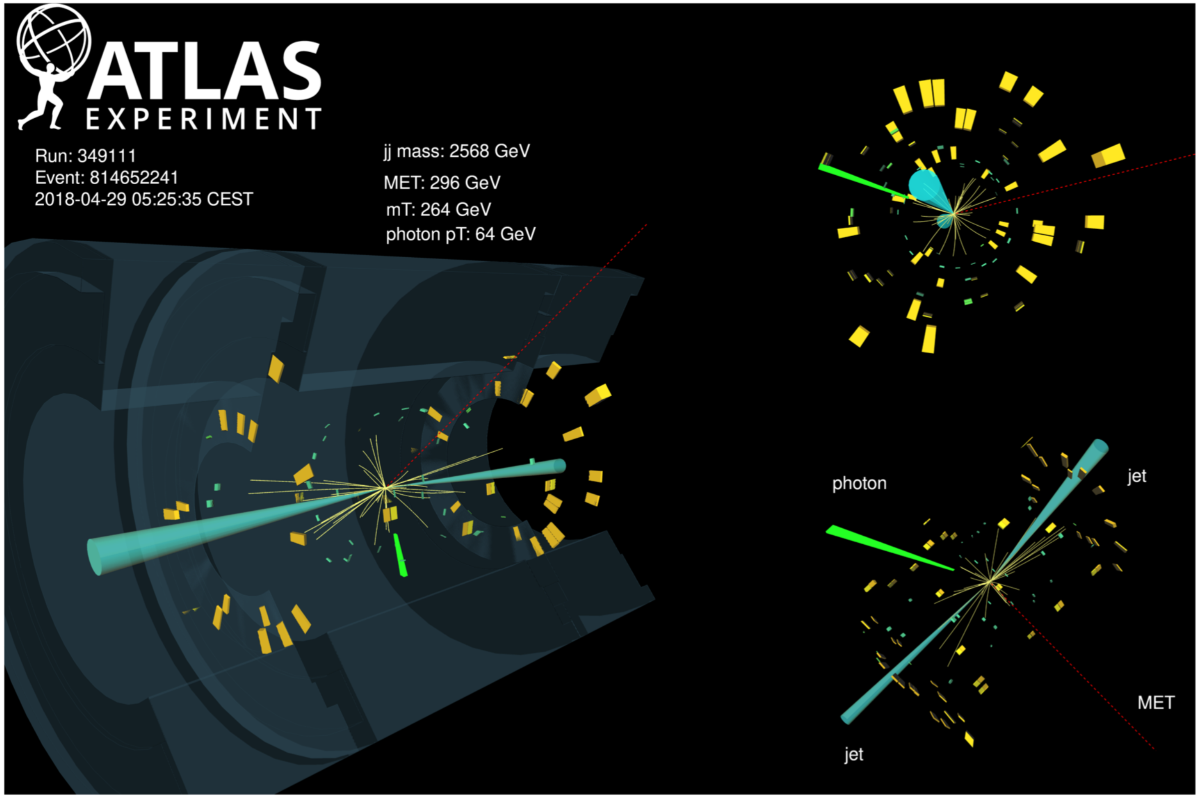
Eur. Phys. J. C82 (2022) 105

VBF + γ + E_T^{miss}

Similar to VBF, but require a high-p_T photon

- Smaller cross section, but much higher signal purity
- Higher signal efficiency and background rejection





Eur. Phys. J. C82 (2022) 105

VBF + γ + E_T^{miss}

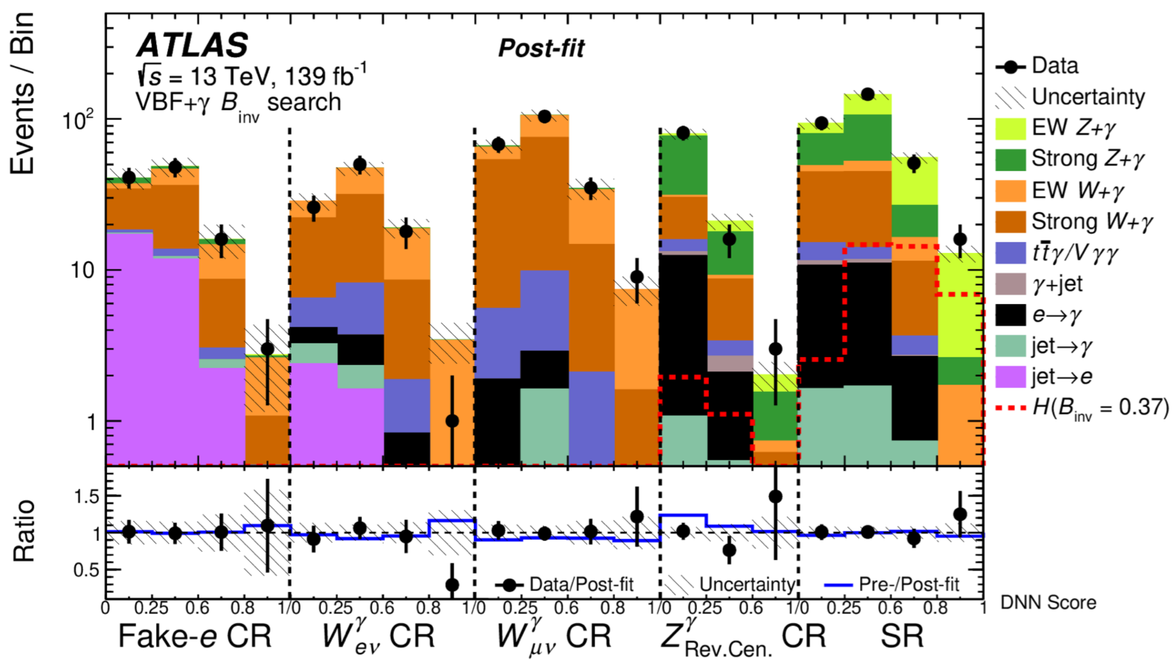
Similar to VBF, but require a high-p_T photon

- Smaller cross section, but much higher signal purity
- Looser selection, then use Deep Neural Net (DNN) to improve sensitivity

- Limit on B(H➞inv) @ 95% CL:

  Observed: > 0.37

  Expected: > 0.34



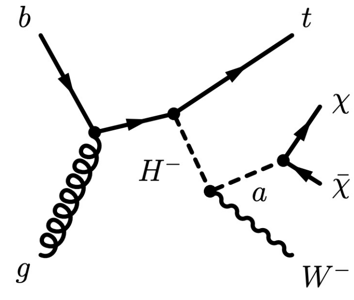
ATLAS-CONF-2022-012

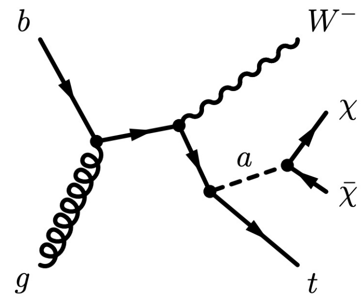
E_T^{miss} + *tW*

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

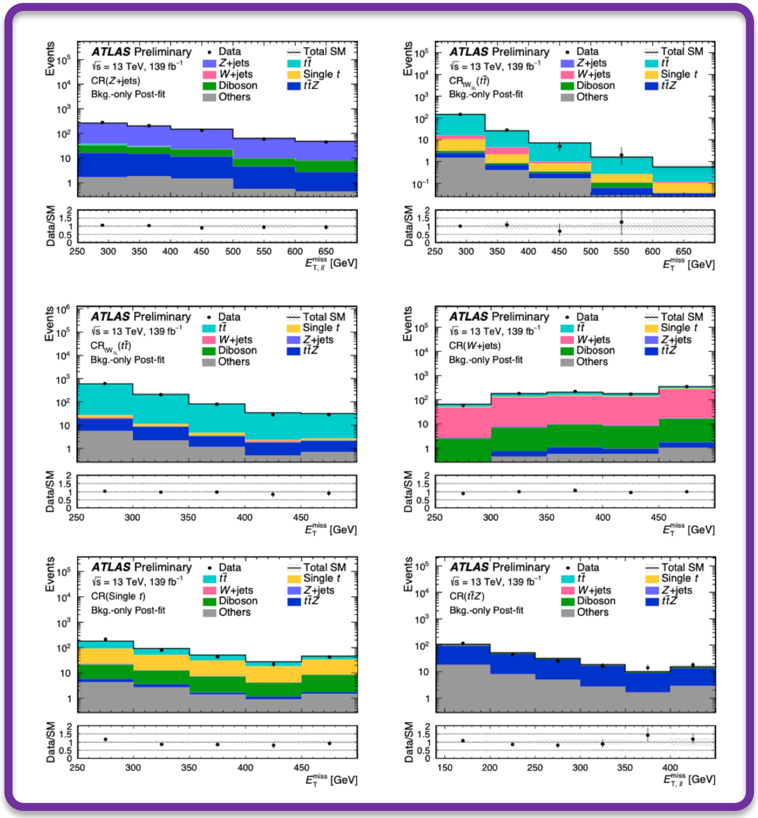




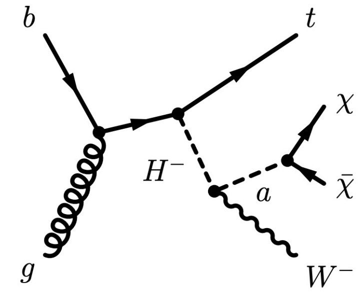
- Six CRs to constrain main backgrounds (*t*, *tt*, *W*/*Z*+jets, *ttZ*)
- Three SRs (binned in E_T^{miss})
  - ➢ *t W* ➞ had had / had lep / lep had

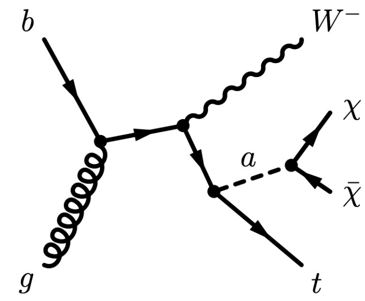
Interpret in 2HDM+*a* model

- 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*

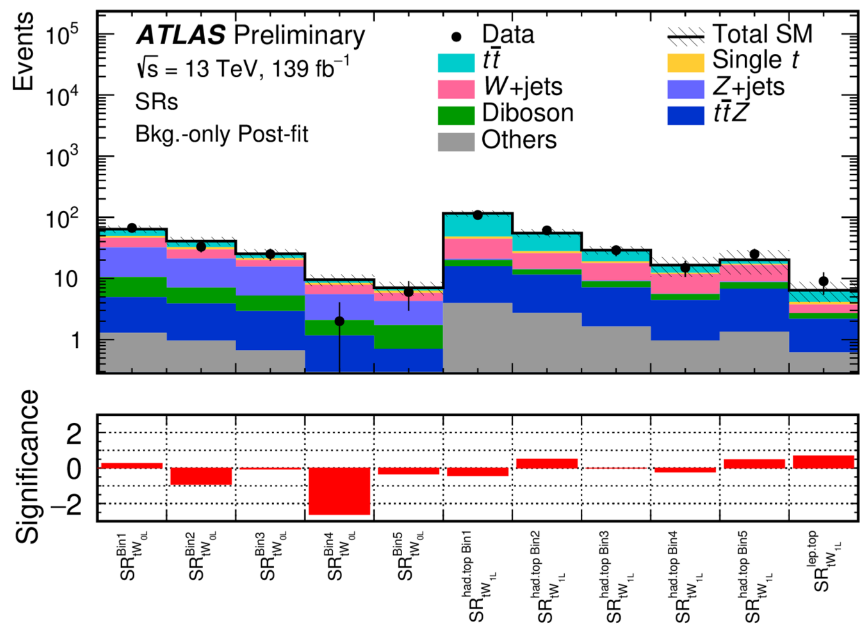
Target events with 0 or 1 lepton from top decay and hadronic *W* decay

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

- 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)



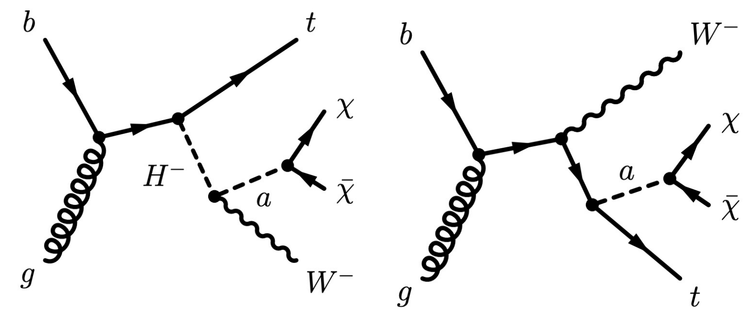
ATLAS-CONF-2022-012

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

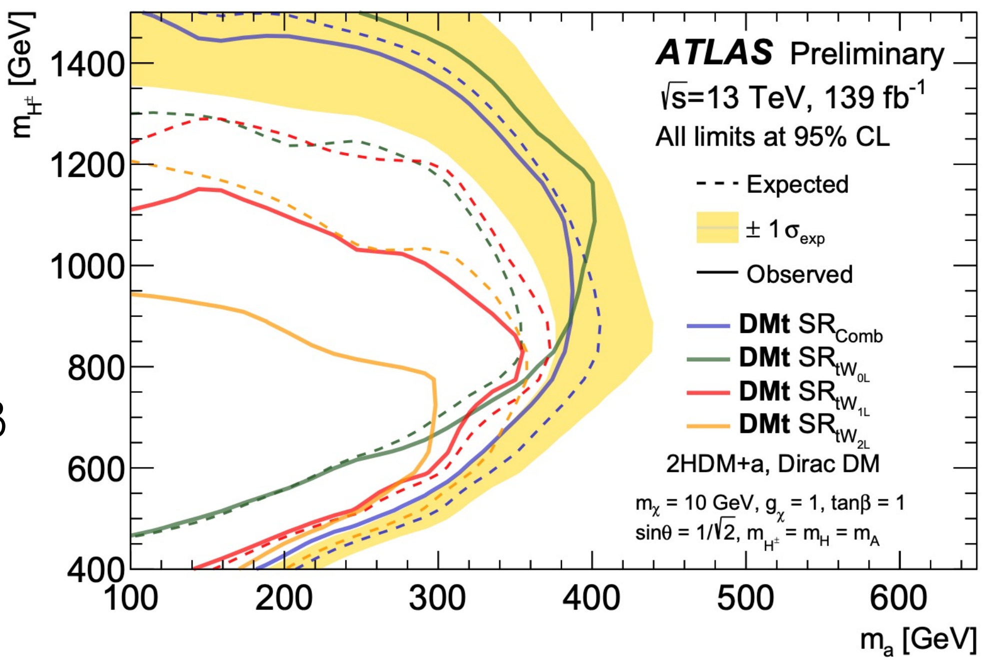
- *W*-tagged large-*R* jet or two small-*R* jets
- Combined with previous 2 lepton analysis



- 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)



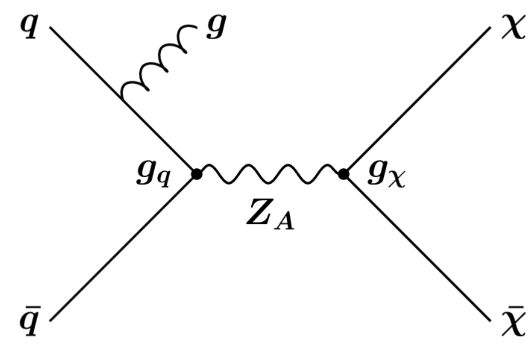
Phys. Rev. D 103, 112006 (2021)

E_T^{miss} + jet

Sensitive to Pseudo-scalar and Axial-vector mediators

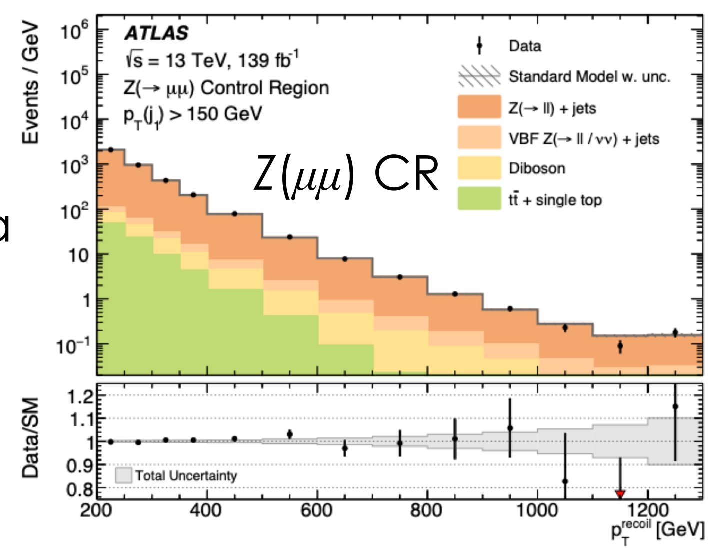
Select events with:

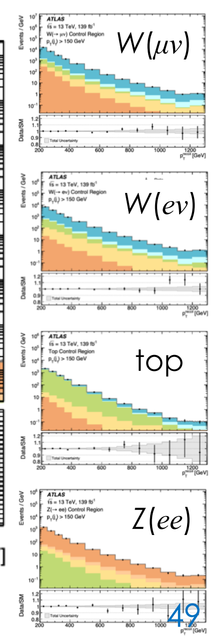
- Large missing momentum: E_T^{miss} > 200 GeV
- High-p_T jet from initial state radiation: p_T^{jet} > 150 GeV
- Veto events with e, μ, τ, γ



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 tt + single top





Phys. Rev. D 103, 112006 (2021)

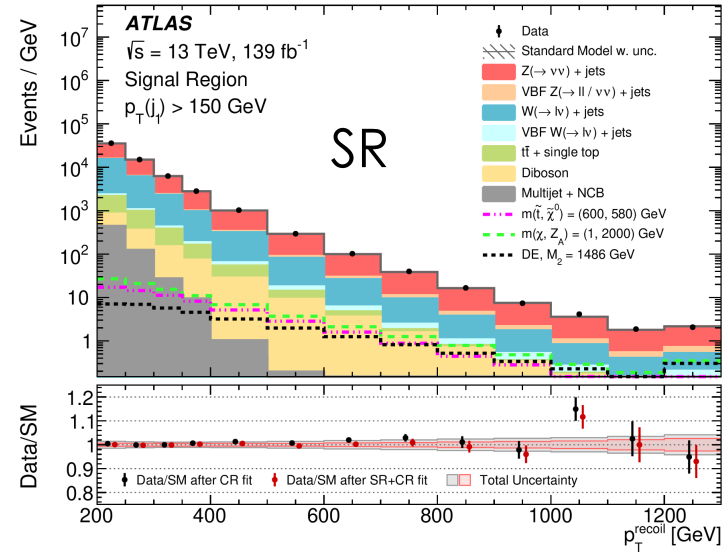
E_T^{miss} + jet

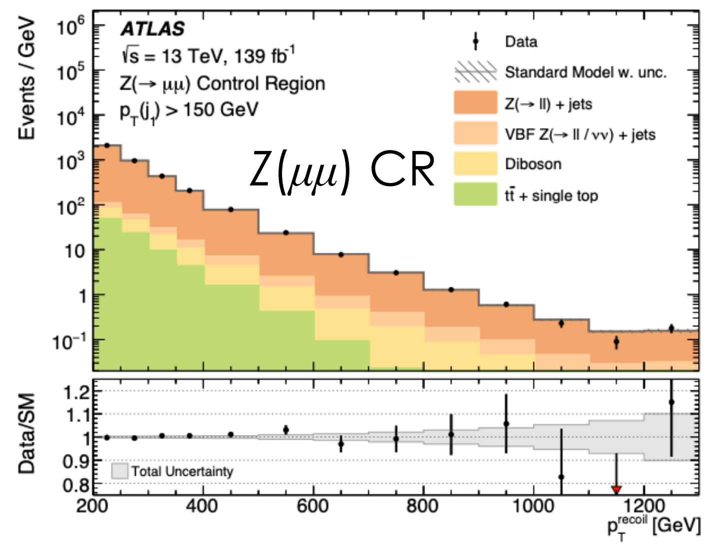
Perform profile likelihood fit

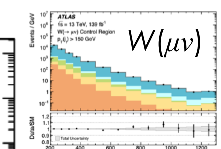
- Simultaneous fit in five CRs and one Signal Region (SR)
- Fit $p_T^{recoil} = |\mathbf{p}_T|$ of system recoiling against hadronic activity
  (In SR: $p_T^{recoil} \equiv E_T^{miss}$)
- 1.5-4.2% total uncertainty on background prediction

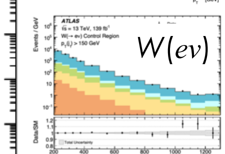
• Fit consistent with SM

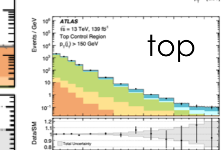
⇒ Set limits on DM production cross-section and parameters

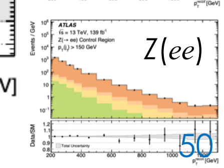








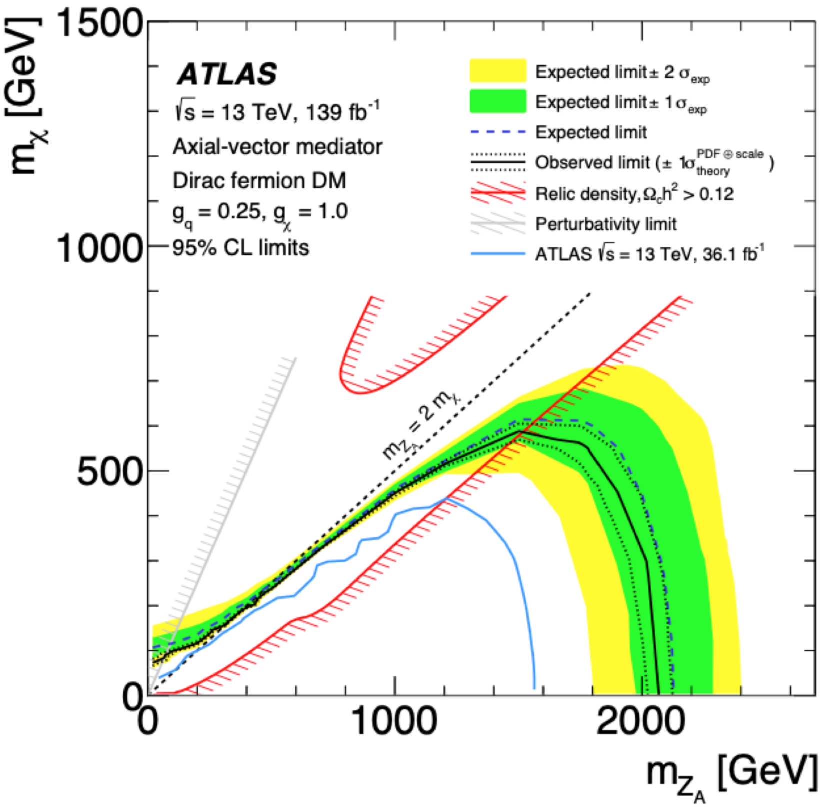


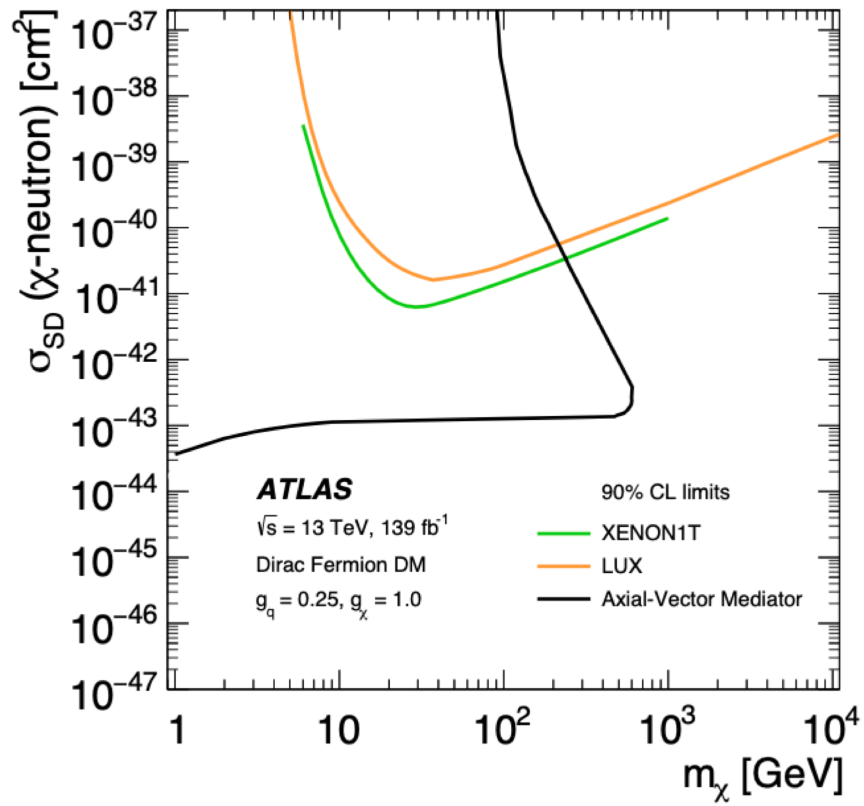


Phys. Rev. D 103, 112006 (2021)

E_T^{miss} + jet

Limits on Axial-Vector Mediator:

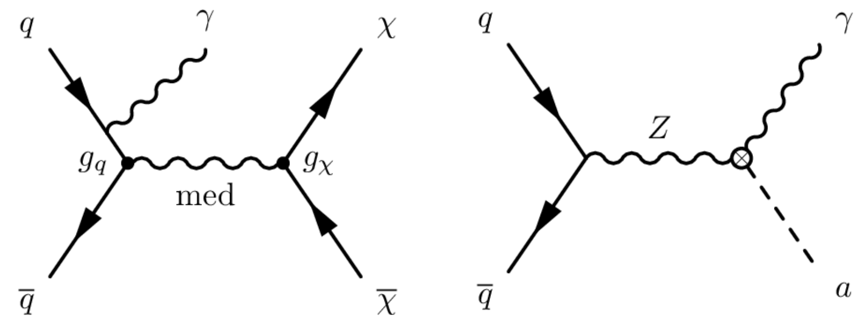




See paper for additional limits on pseudo-scalar model, squark production, large extra-dimensions, and invisible Higgs

JHEP 02 (2021) 226

$E_T^{miss} + \gamma$

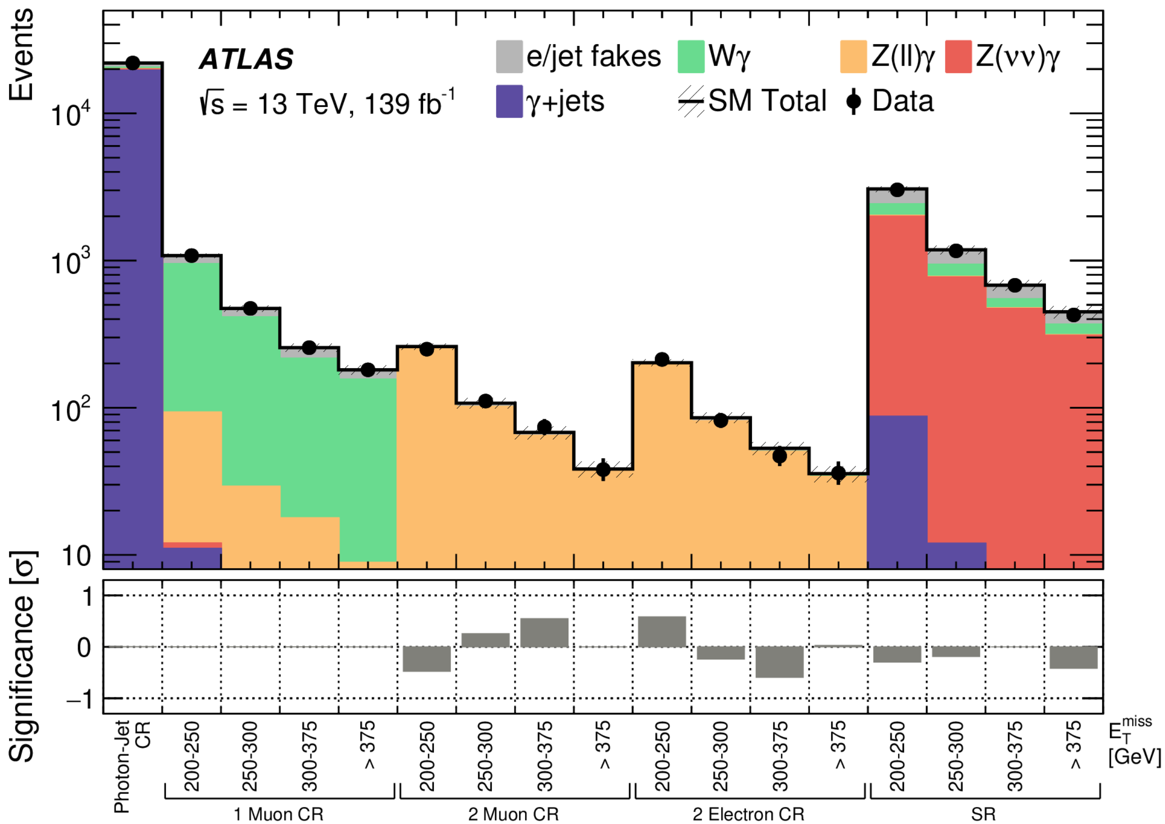


Select events with

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

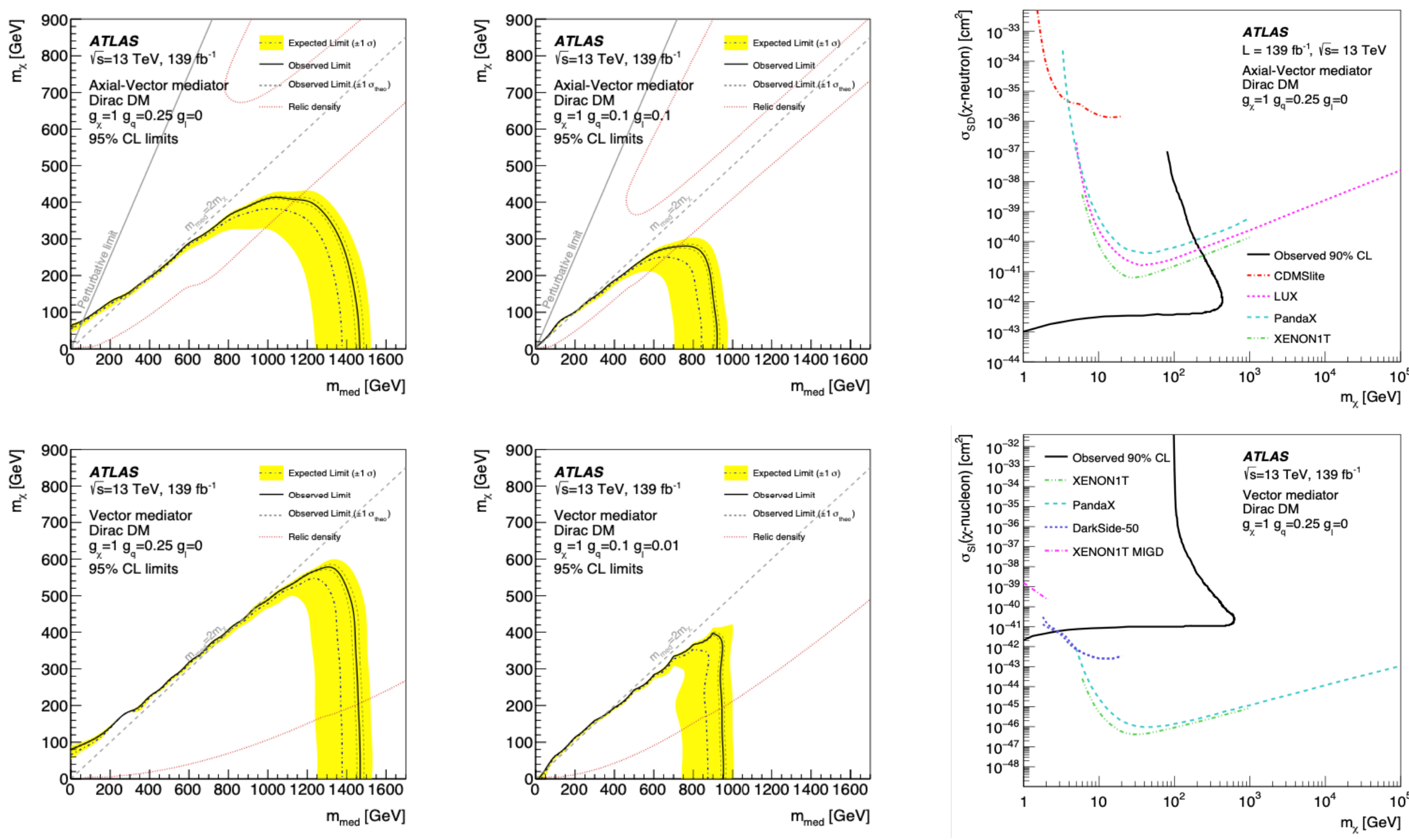
Fit SR and 4 CRs in bins of E_T^{miss}

- Normalization of main backgrounds from fit to data



JHEP 02 (2021) 226

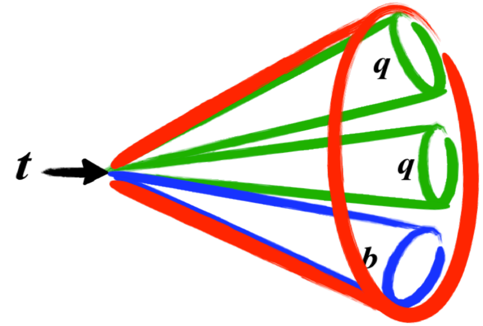
$\gamma + E_T^{miss}$



top-tagging

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

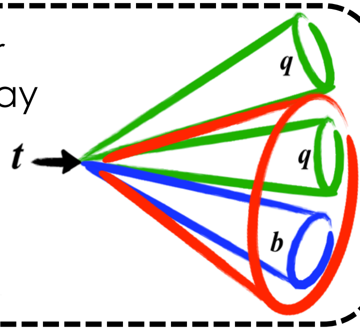
- Large-radius jet with highly collimated sub-jets, including one b-jet

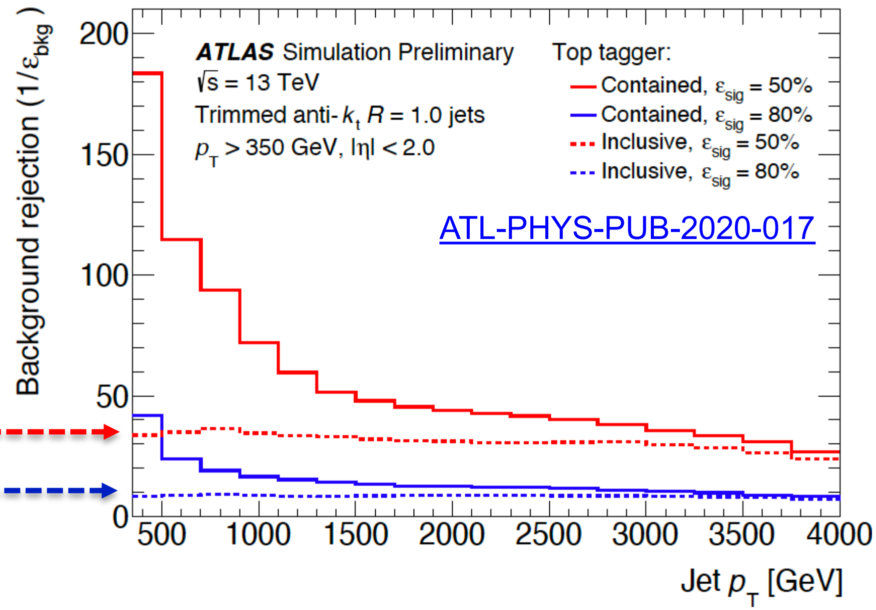


⇒ Deep Neural Network top-tagger

- 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

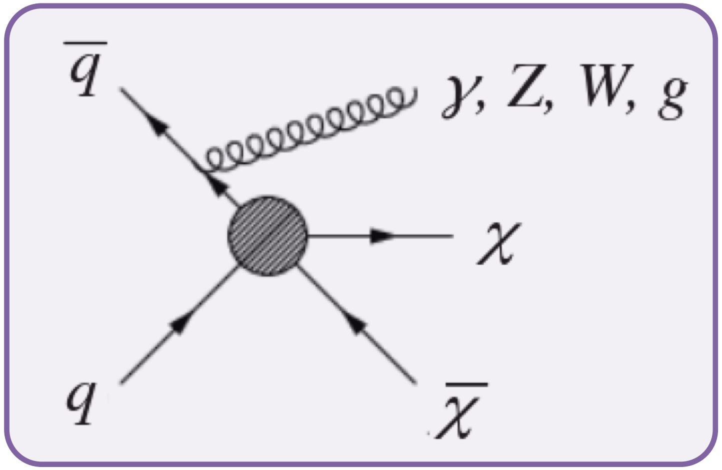


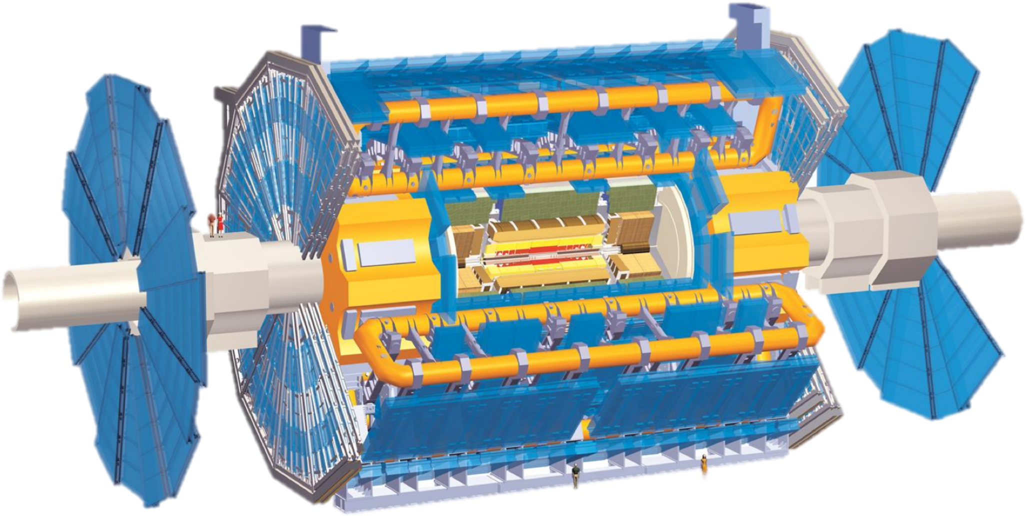


(Some analyses define their own custom taggers, but idea is the same)

Collider Strategy

- Resonance searches: $\chi \rightarrow jj/bb/tt/\ell\ell$
- **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*, …



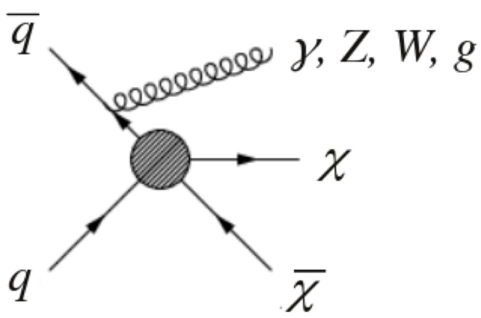


This talk:

- 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

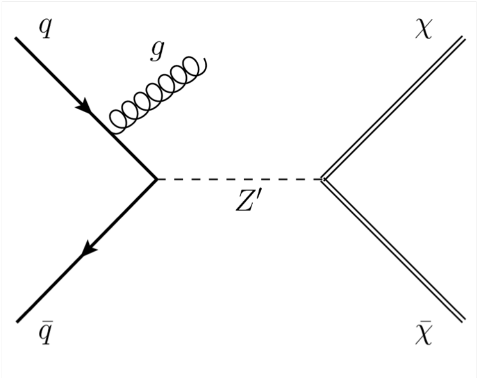
Interpreting DM Production

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

JHEP 08 (2022) 104

VBF + E_T^{miss}

Dedicated VRs and CRs to validate and constrain backgrounds

16 SRs of varying purity and composition

Interpret in models where **Higgs is portal** to DM WIMP

- Set limits on WIMP-nucleon cross section at 90% CL
- Complementary to direct detection experiments