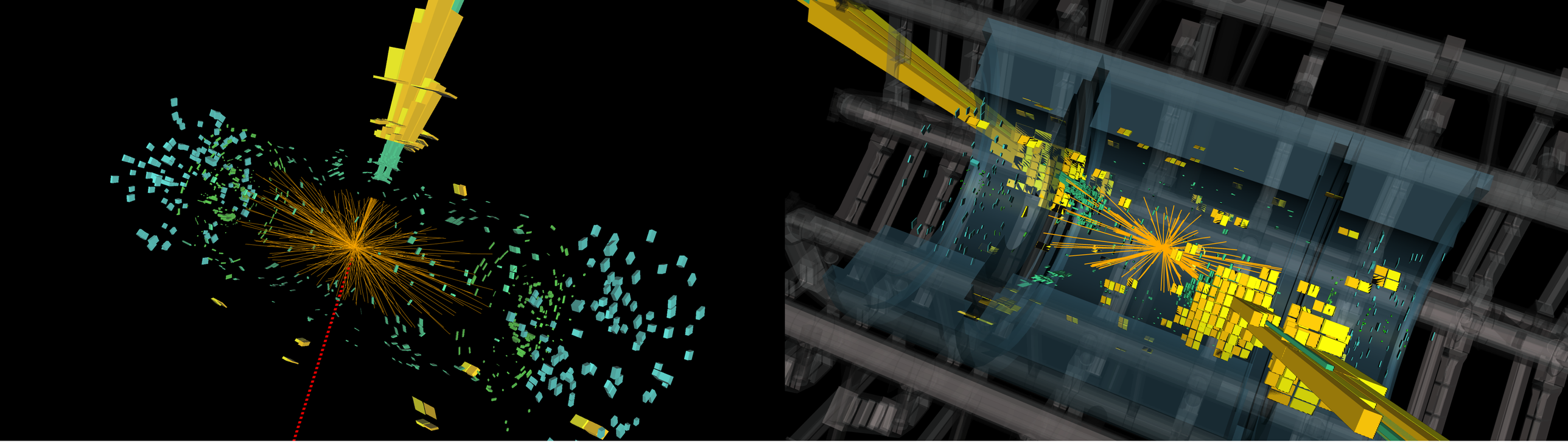


Dark matter searches with the ATLAS detector

Guglielmo Frattari on behalf of the ATLAS collaboration

XXVIII International Workshop on
Deep-Inelastic Scattering and Related Subjects

14 April 2021

Chasing dark matter at the LHC

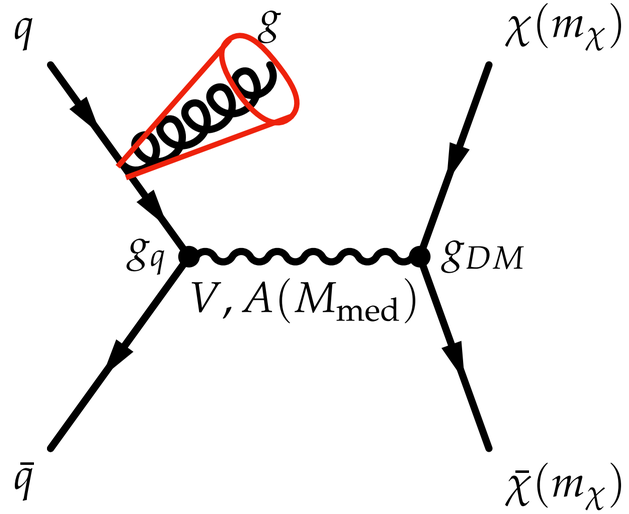
- this talk will focus on selected results on simplified dark matter models & benchmark extensions
  - ATLAS results on more complex models covered in talks by A. Sharma (SUSY) & A. Leopold (2HDM+a, H→inv.)

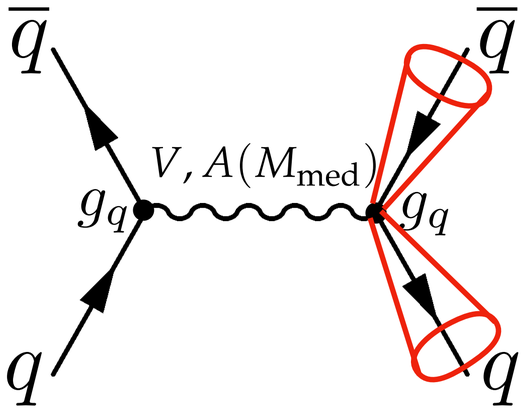
Why simplified?

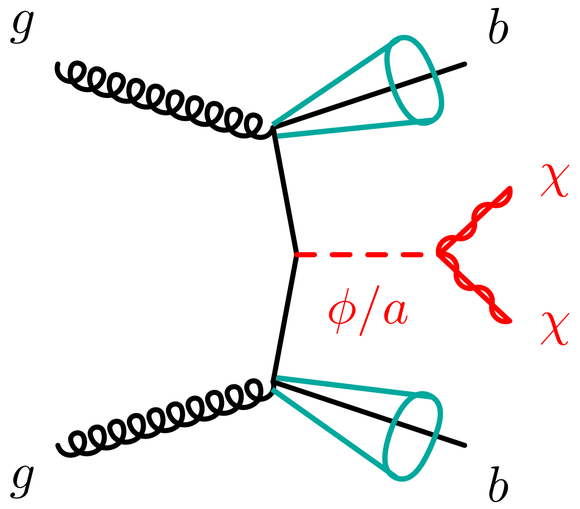
- go beyond EFT approach (Run 1 approach)
- introduce a new mediator and fermionic WIMPs
- described in general by few parameters {m_X, $m_{Z'}$, g_q, g_{DM}}

What we expect to see?

- mono-X final states: excess in the E_T^{miss} distribution
- di-jet resonant production: bump in m_{jj} spectrum
- over-production of HF + E_T^{miss} final states





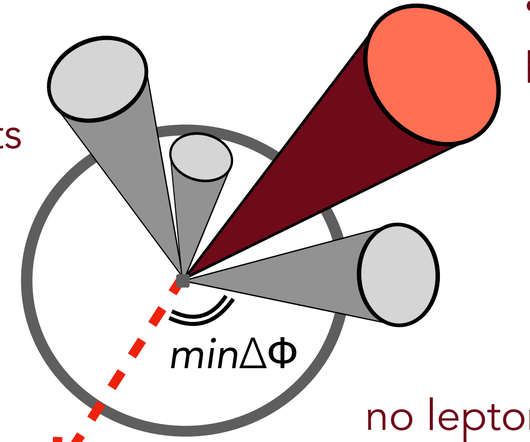


Phys.Dark Univ. 27 (2020) 100371

arXiv:2102.10874

Mono-jet in a nutshell

- **goal**: look for an excess of events in the E_T^{miss} distribution → discriminant variable
  - most general signature for BSM particles, sensitive to a wide range of DM models - more results in backup
- candidate events selection:

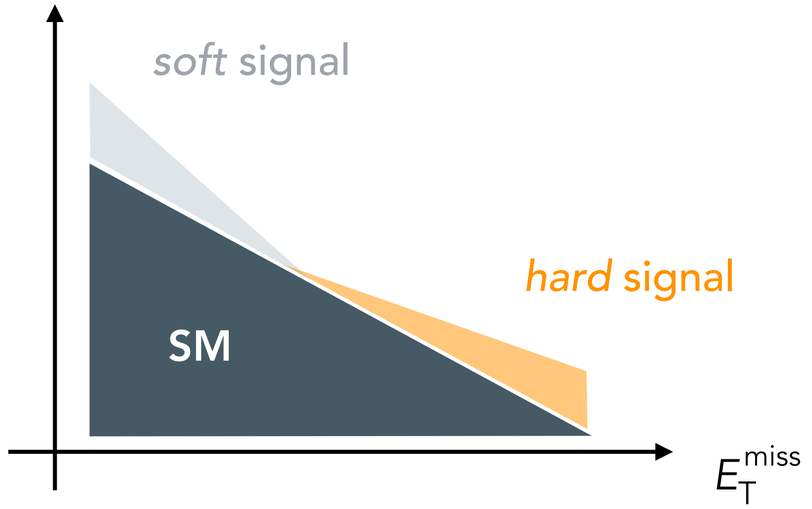


up to 3 additional jets

at least one energetic jet
p_T > 150 GeV

E_T^{miss} trigger
E_T^{miss} > 200 GeV

no leptons (incl. τ) nor photons



Dominant irreducible background: Z(→νν)+jets

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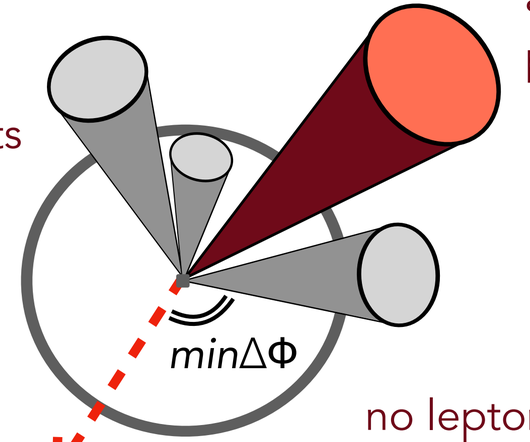

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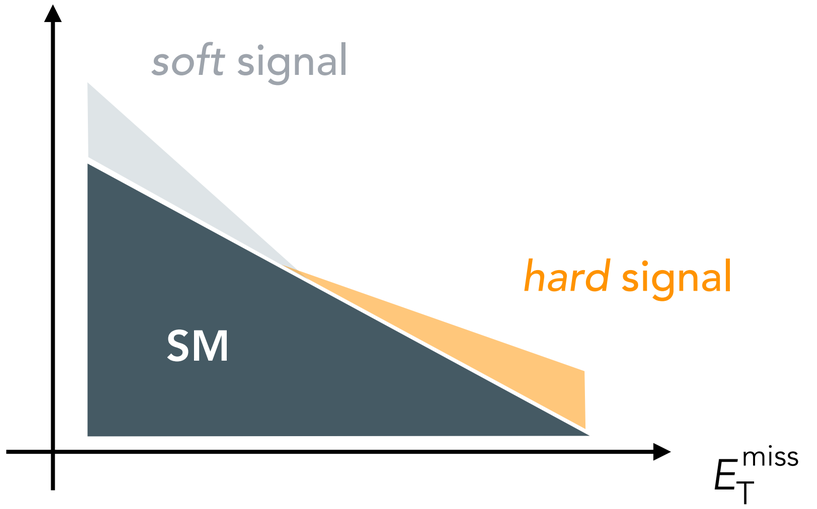
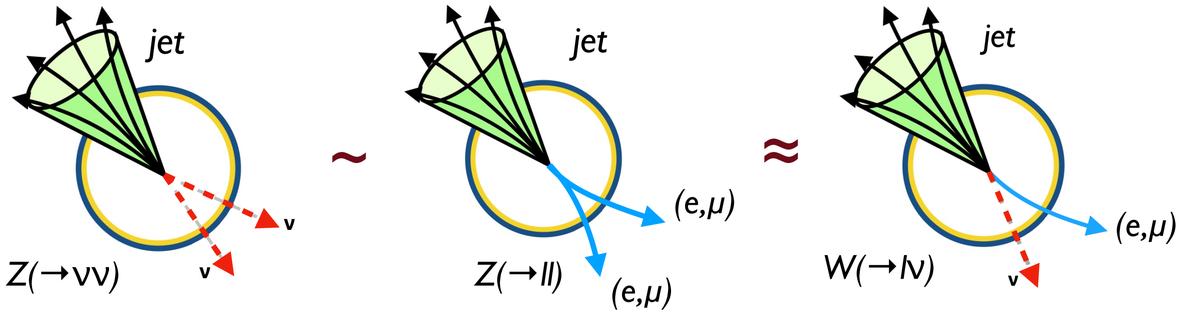


Dominant irreducible background: Z(→νν)+jets

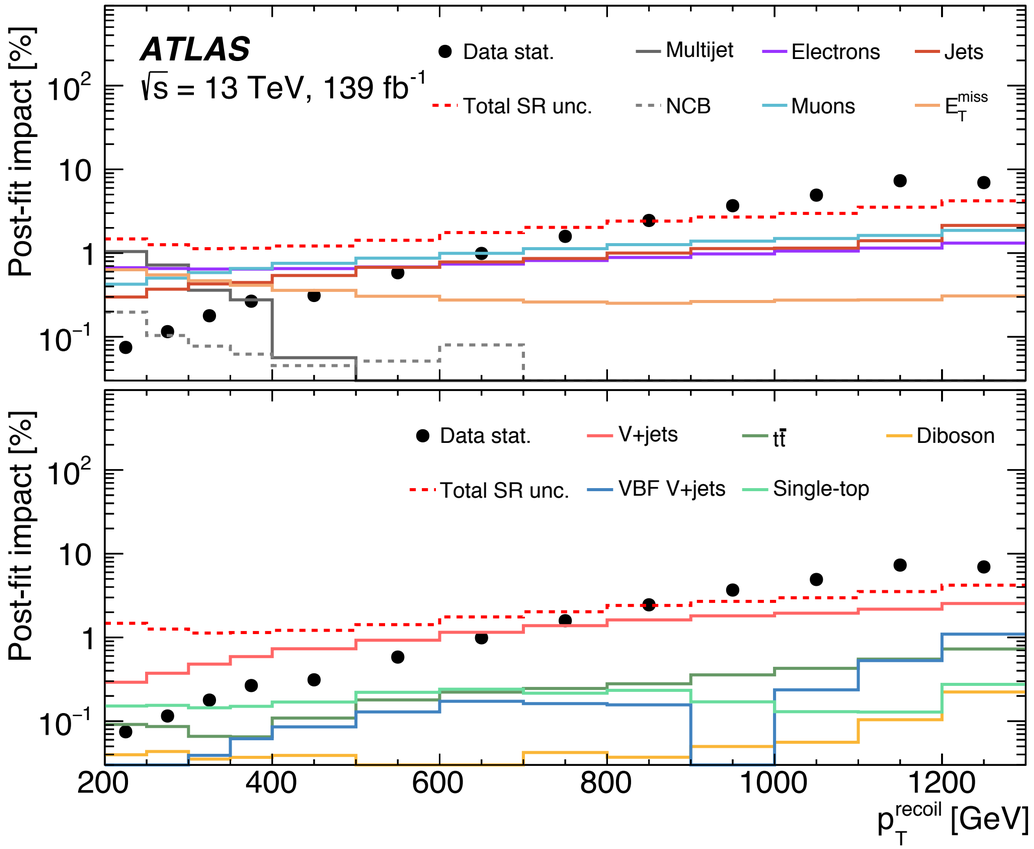
- NNLO QCD & nNLO EW corrections to V+jets processes
  - following Eur. Phys. J. C 77, 829 (2017)
- SM predictions adjusted using data in orthogonal control regions:
  - leptons treated as invisible particles: $E_T^{miss} \rightarrow p_T^{recoil}$



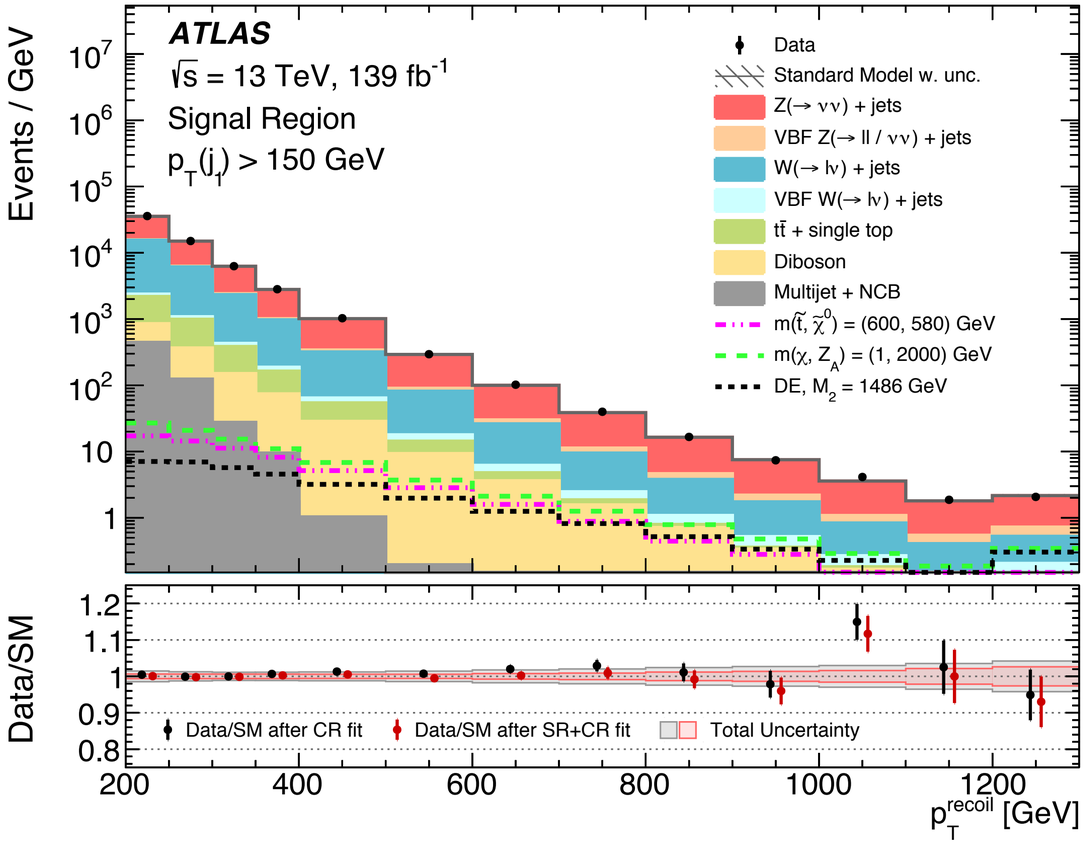
arXiv:2102.10874

Background estimation: results

- simultaneous likelihood fit to p_T^{recoil} distributions in CR to estimate SR total background
  - 1 normalisation factor for V+jets processes, 2 for top-q. processes - modelling corrected by dedicated CR



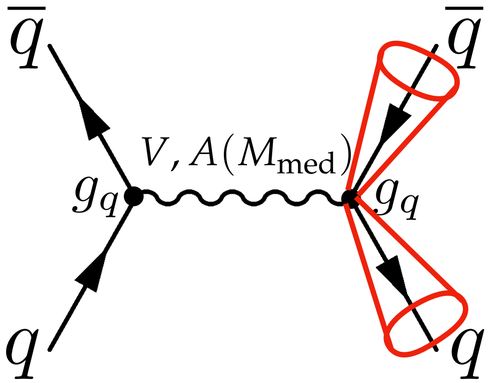
total uncertainty between 1.2% and 4%



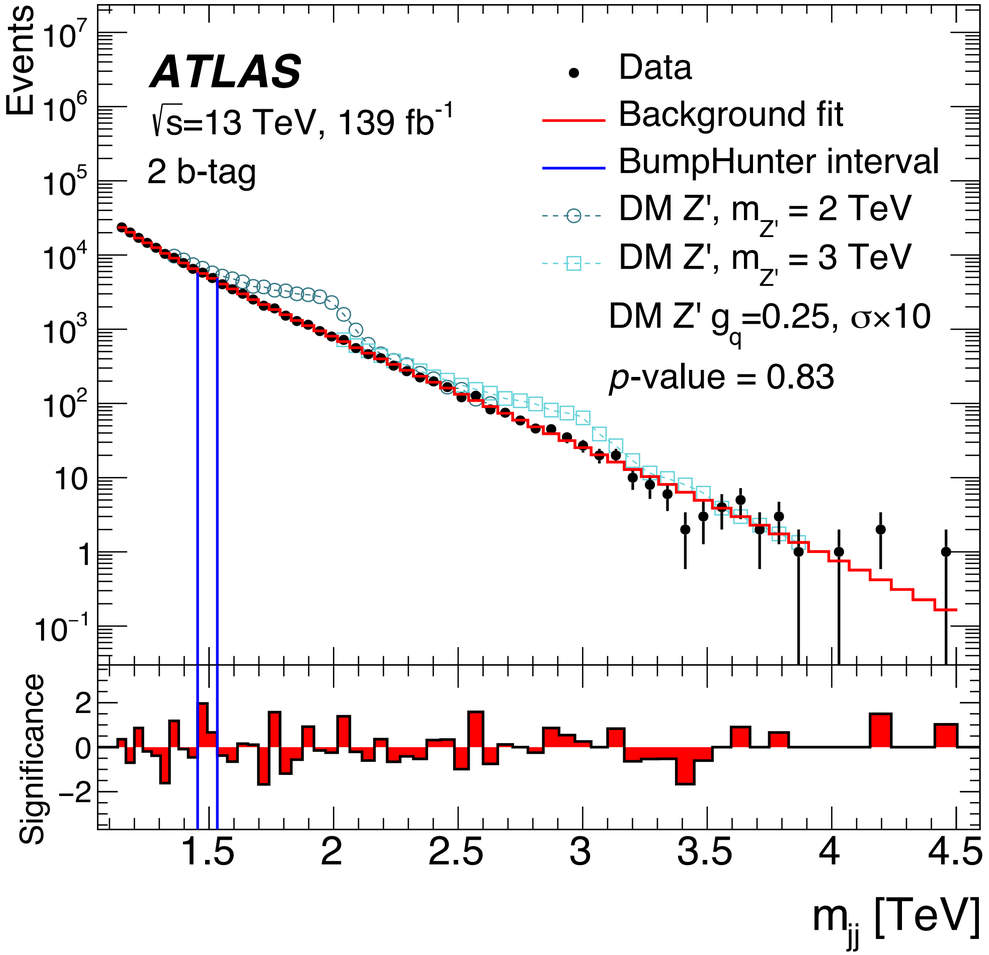
good agreement with Standard Model

Di-jet resonance searches

- goal: look for any excess over the m_{jj} spectrum - main challenge: model SM QCD background



- fully efficient ~ m_{jj} > 1 TeV
  - tested both inclusive & b-tagged spectra
- cut on rapidity gap of leading jets
  - target s-channel interactions



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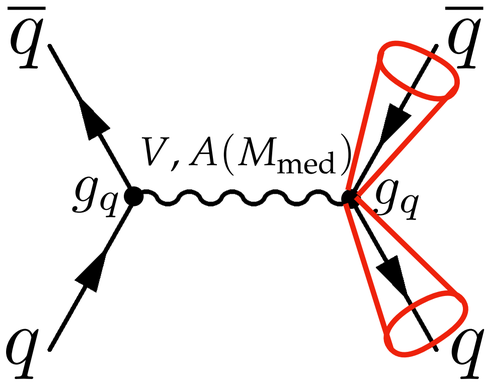

- fully efficient ~ m_{jj} > 1 TeV
  - tested both inclusive & b-tagged spectra
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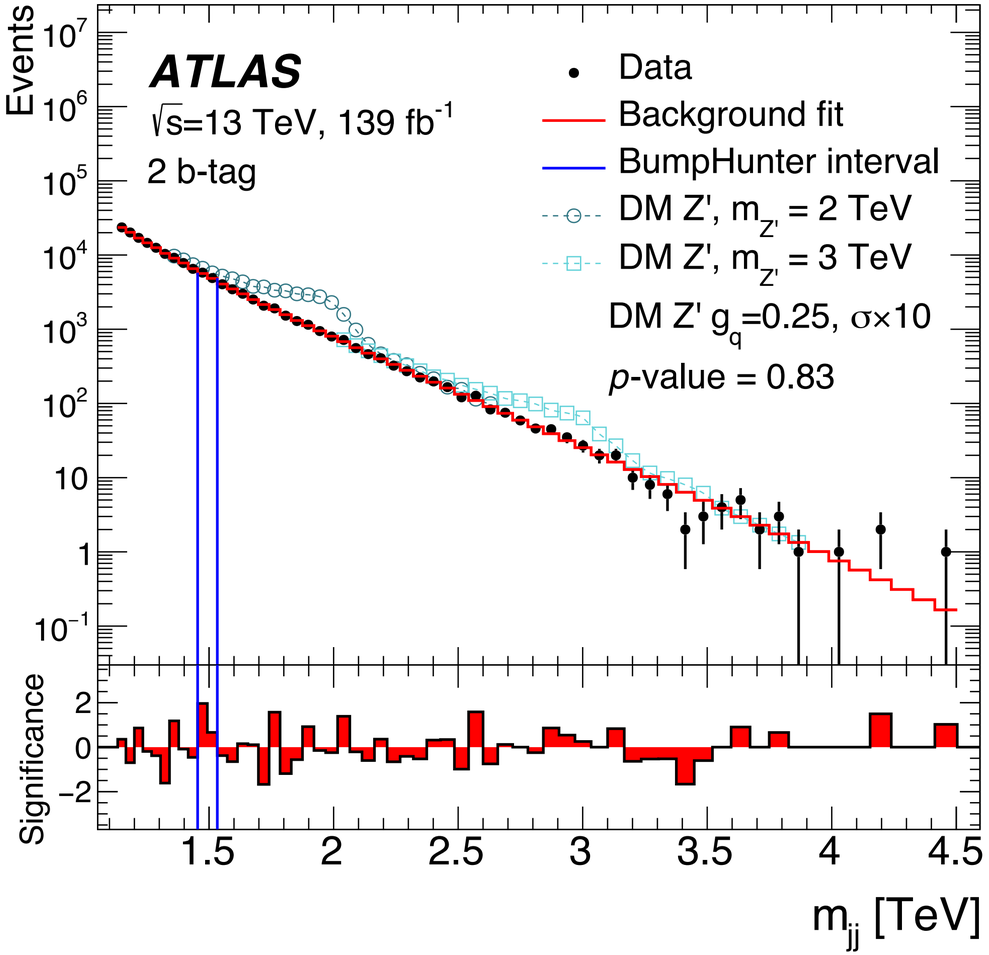
  - target s-channel interactions

Background estimation

- Sliding WIndow FiT tested on pseudo-data to find best fit function for the background
  - uncertainty from function choice: ~10% at high m_{jj}

$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x} \qquad x = m_{\mathrm{jj}}/\sqrt{s}$$

- bkg. uncertainty from:
  - stat. fluctuations of fit parameters: 0.1% - 30/40% at high m_{jj}
  - negligible contribution from spurious signal tests with Z' signal

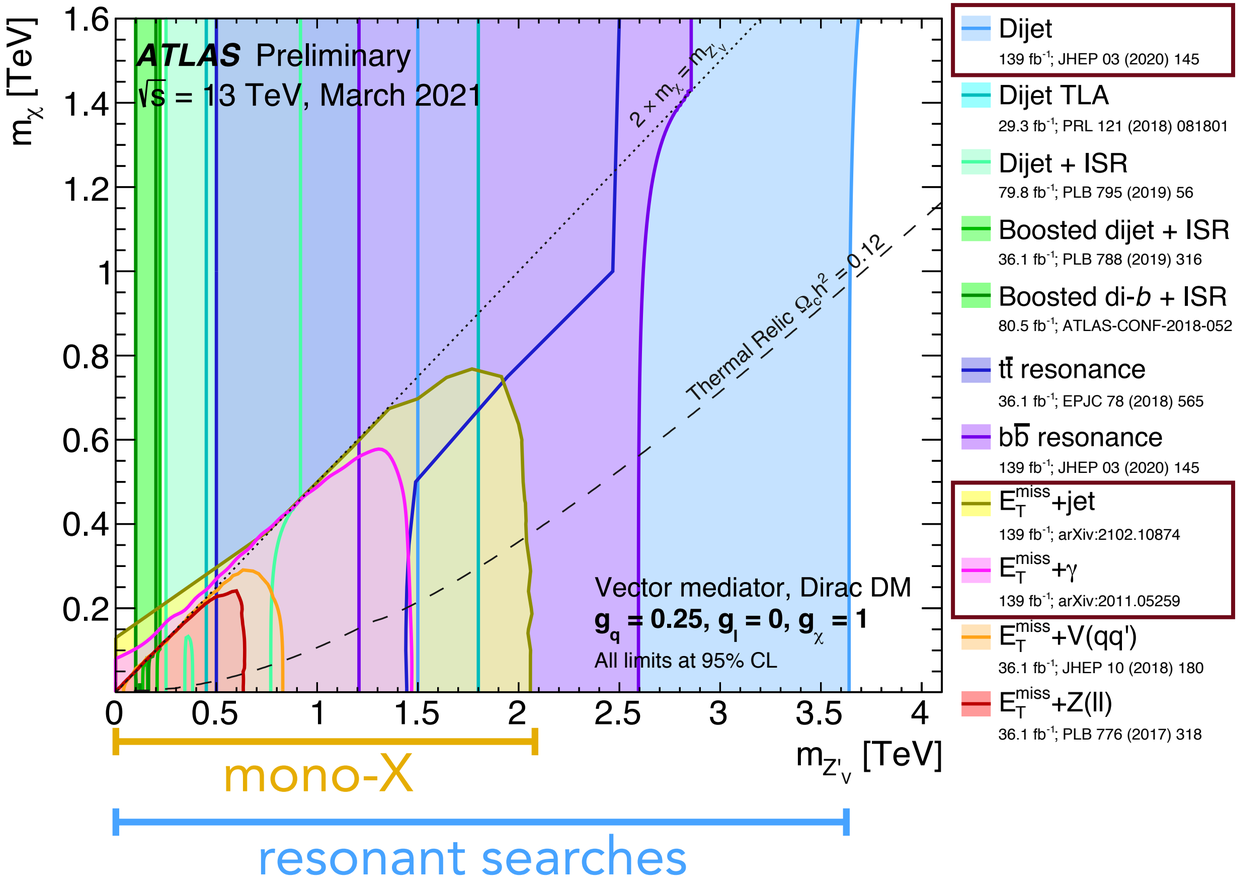


BumpHunter to evaluate significance of deviations

The ATLAS DM searches atlas

Vector mediator

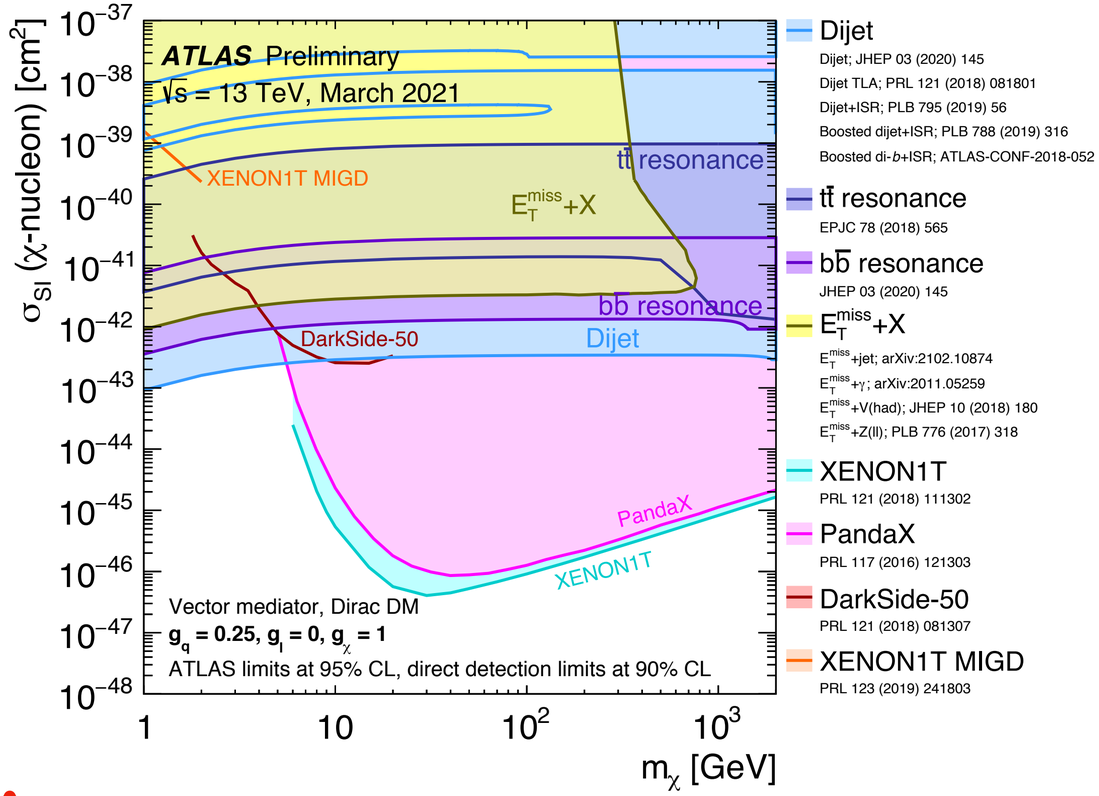
- mono-jet sets the strongest limits among mono-X searches
- inclusive dijet dominates resonant searches



- also different g_q scenarios tested — see backup

Comparison to direct detection experiments

- vector mediator → spin independent interaction

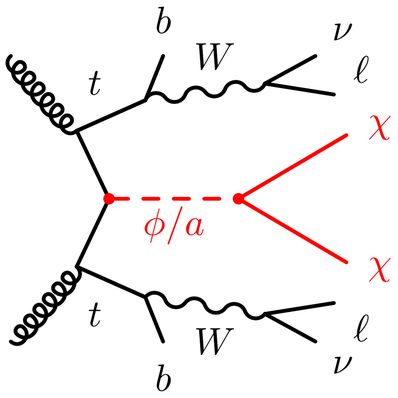


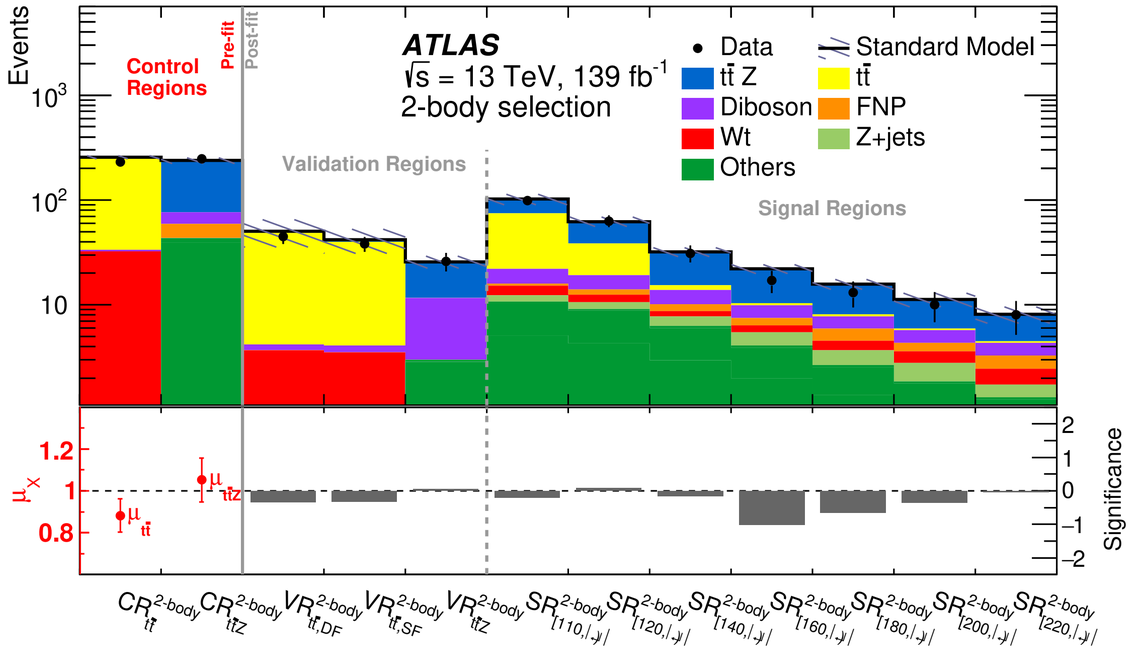
⚠ comparison depends on chosen couplings

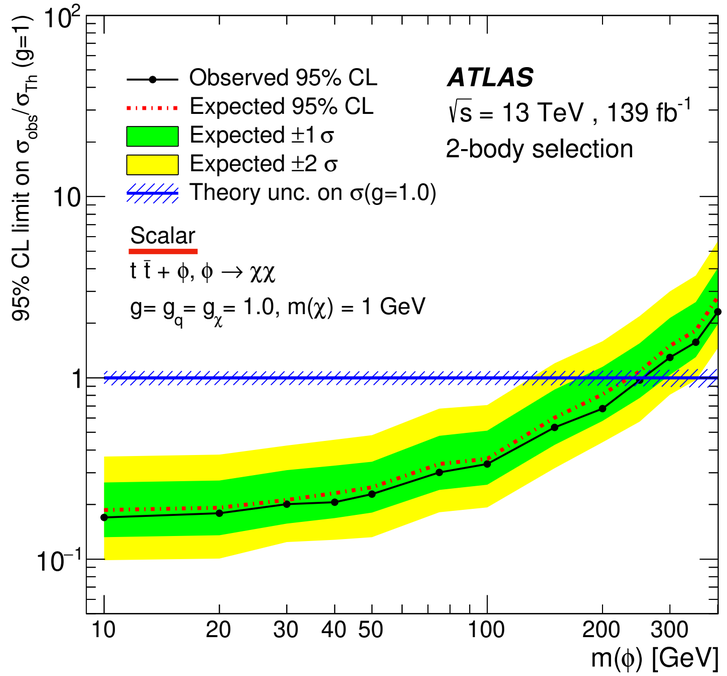
arXiv:2102.01444

Search for dark matter in $t\bar{t}+E_{\mathrm{T}}^{\mathrm{miss}}$ final states

- target simplified models with scalar (S) /pseudo-scalar (P) mediators & large coupling to HF - Yukawa like interaction
- selecting final states with ≥ 1 *b*-jets & 2 leptons - dilepton trigger
  - fake $E_{\mathrm{T}}^{\mathrm{miss}}$ limited by $E_{\mathrm{T}}^{\mathrm{miss}}$ significance cut, stransverse mass (m_{T2}) cut to reduce $t\bar{t}$ background
- binned m_{T2} signal region split for lepton flavour: different (DF) & same flavour (SF) selections
  - dedicated $t\bar{t}$ and $t\bar{t}Z$ enriched control regions to correct backgrounds normalisation
  - dominant uncertainties: jet energy scale & resolution measurements, $t\bar{t}$ modelling, MC stat



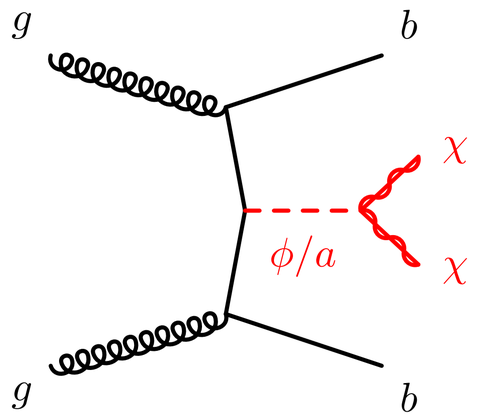


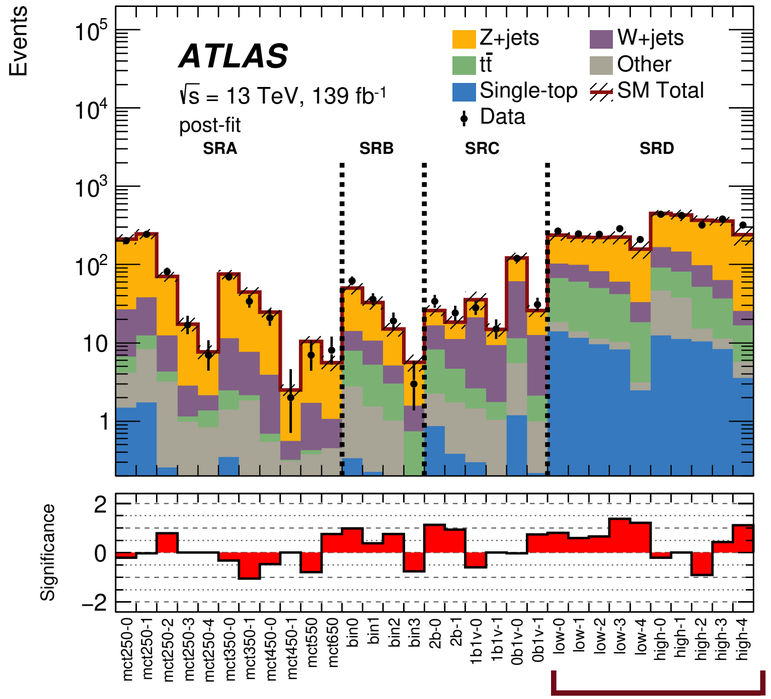


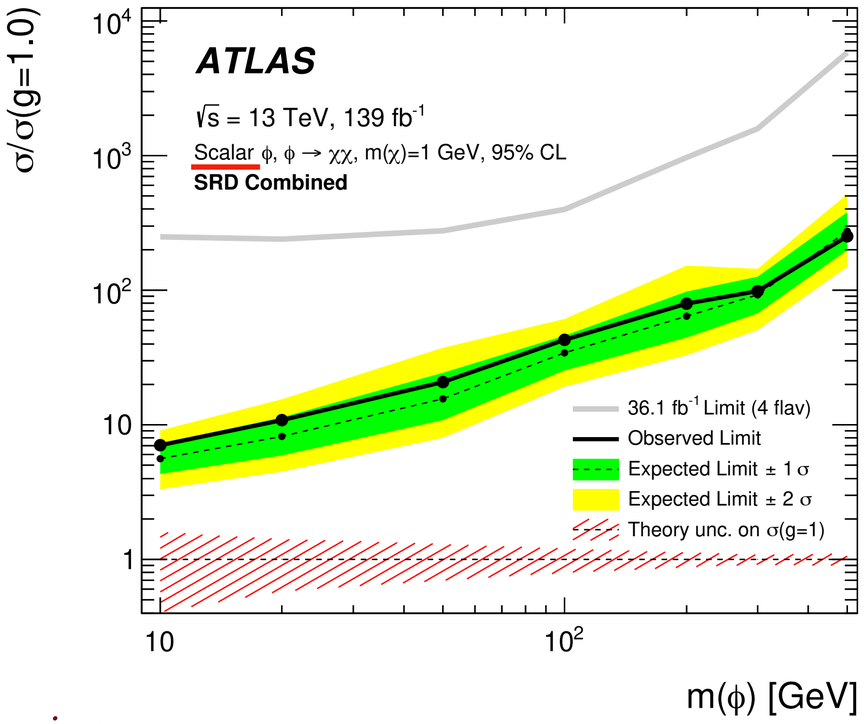
arXiv:2101.12527

Search for dark matter in $b\bar{b}+E_T^{miss}$ final states

- select events with E_T^{miss} trigger + two *b*-jets - $\varepsilon_b \approx 77\%$
  - keep selections low via a two dimensional cut on $p_T(j1)$ & E_T^{miss}
- BDT discriminants *SM $t\bar{t}$, V+jets* vs *simplified DM models* with Yukawa like interaction & S/P- mediator
- final discriminant: $\cos\theta^*_{bb} = |\tanh \Delta\eta(b_1, b_2)/2|$ — Z+≥ 2 *b*-jets control regions to correct SM predictions
  - dominant uncertainty from modelling of Z+HF process







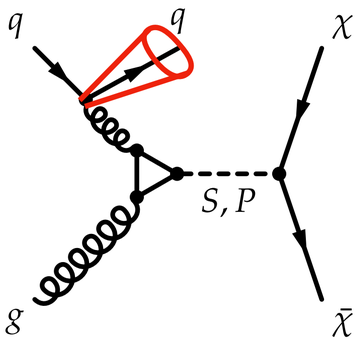
DM search dedicated signal regions

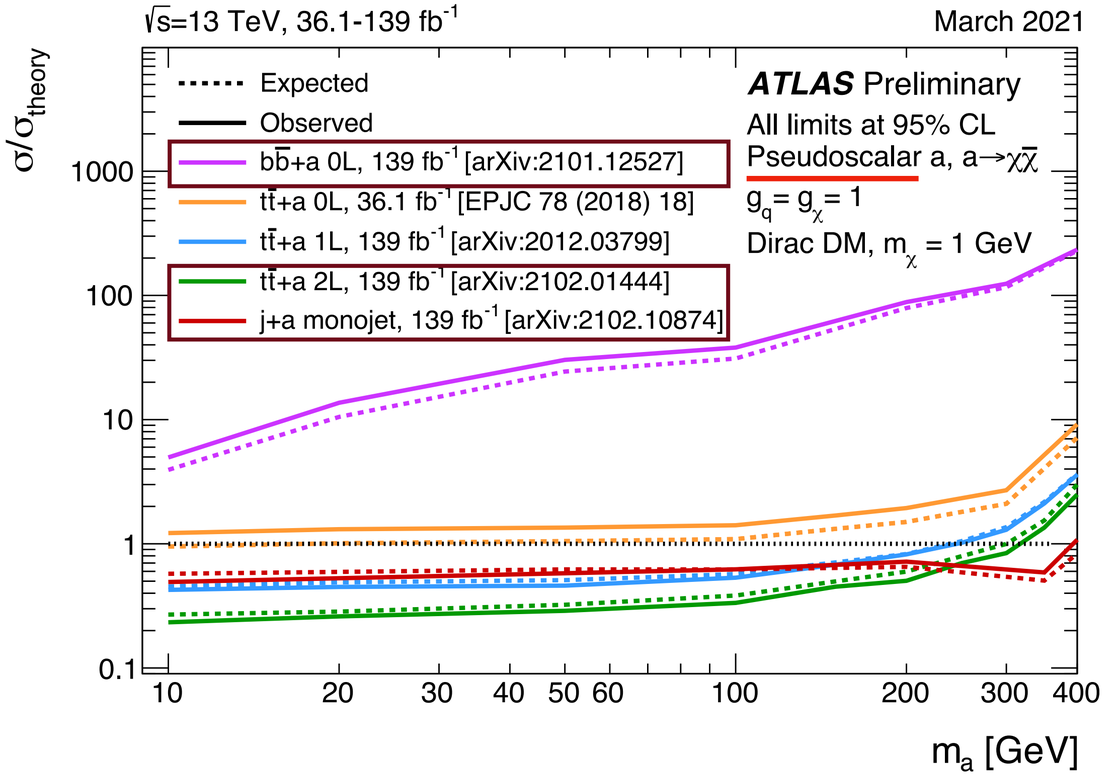
ATL-PHYS-PUB-2021-006

arXiv:2102.10874

Scalar & pseudo-scalar mediators

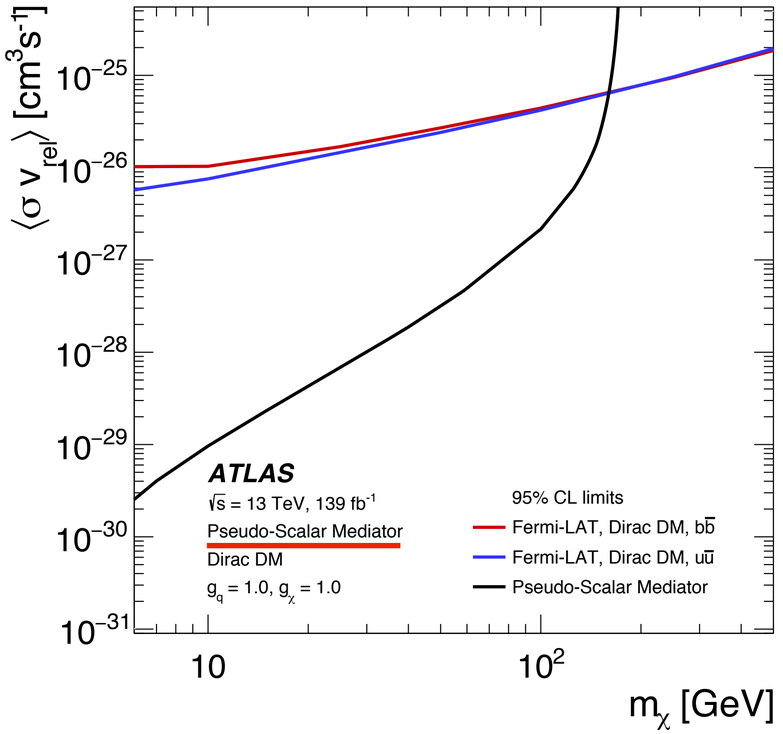
- best sensitivity looking at HF+ E_T^{miss} final states
- targeted also by mono-jet search
  - softer E_T^{miss} spectrum w.r.t. SM
  - reduced sensitivity due to large backgrounds





ATLAS vs indirect detection experiments

comparison depends on couplings

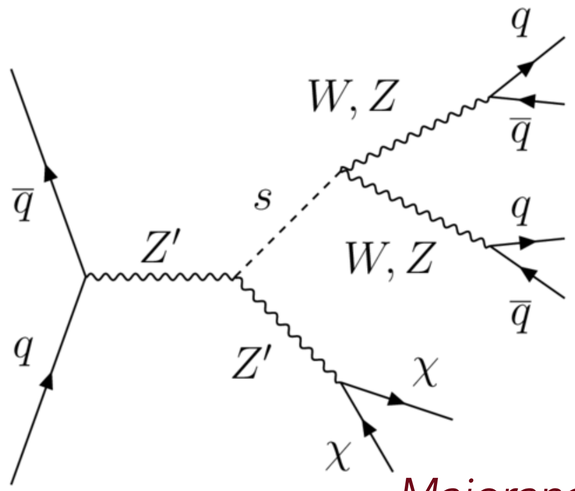


Phys. Rev. Lett. 126 (2021) 121802

Extending the dark sector

Q: If WIMPs have mass, does a dark Higgs mechanism exist?

- introduce an additional scalar particle s: the dark Higgs
  - additional parameter {m_X, $m_{Z'}$, m_s, g_q, g_X}
  - main decay mode s → WW (ZZ) for m_S > 160 (180) GeV
  - to maximise BR fully hadronic final states targeted



Majorana WIMPs

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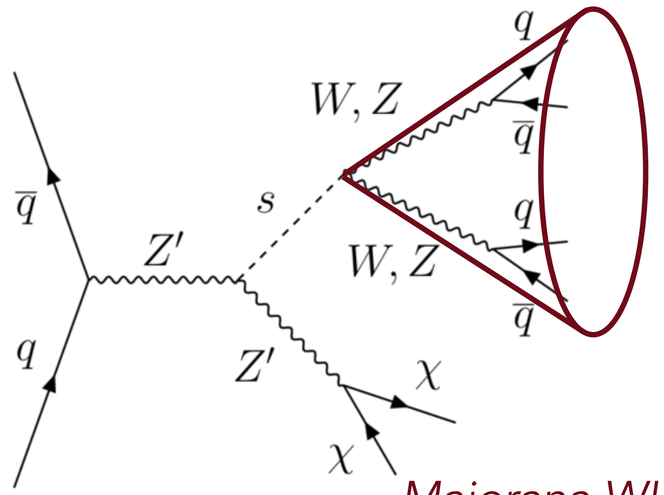
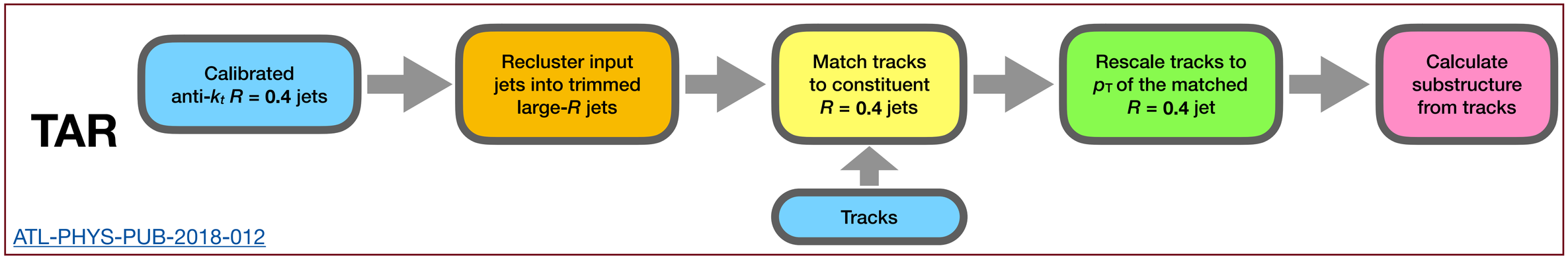
- boosted s → VV decay: better reconstruction with large-R jets, R = 0.8
  - innovative methods used to improve resolution of jet-substructure variables

Large-R jet



Majorana WIMPs

Track-assisted reclustered jet algorithm

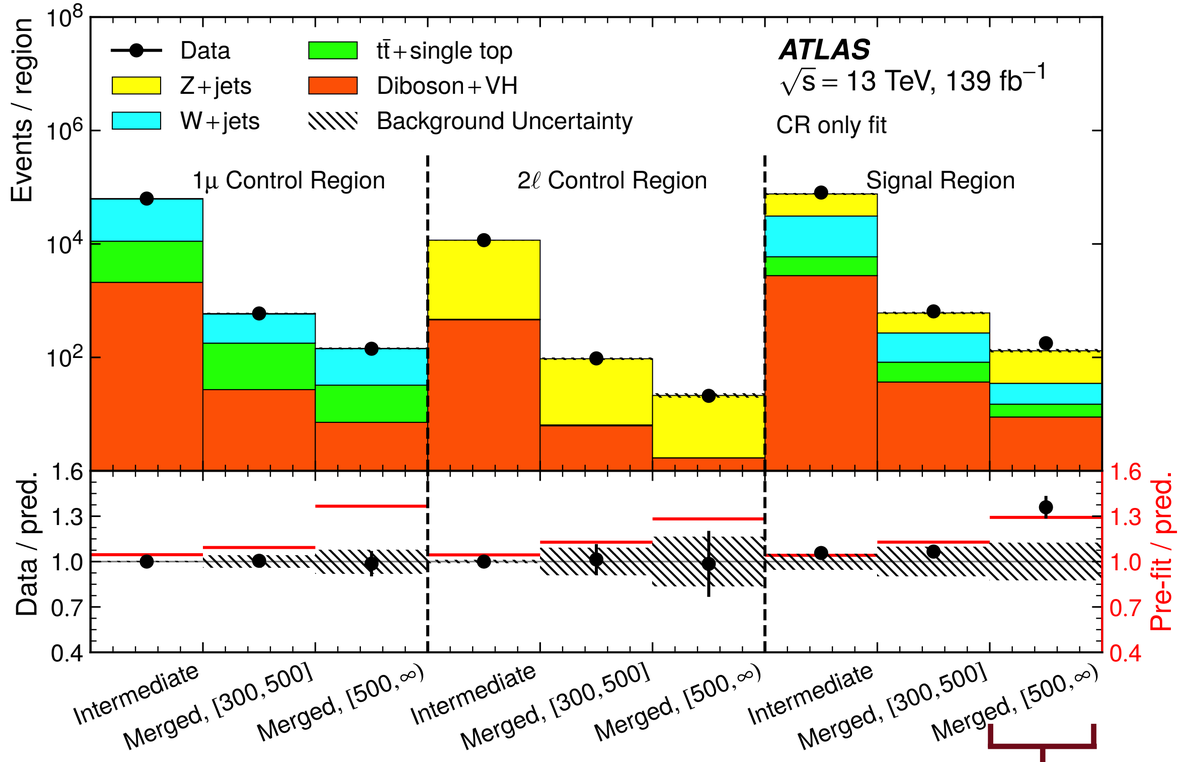


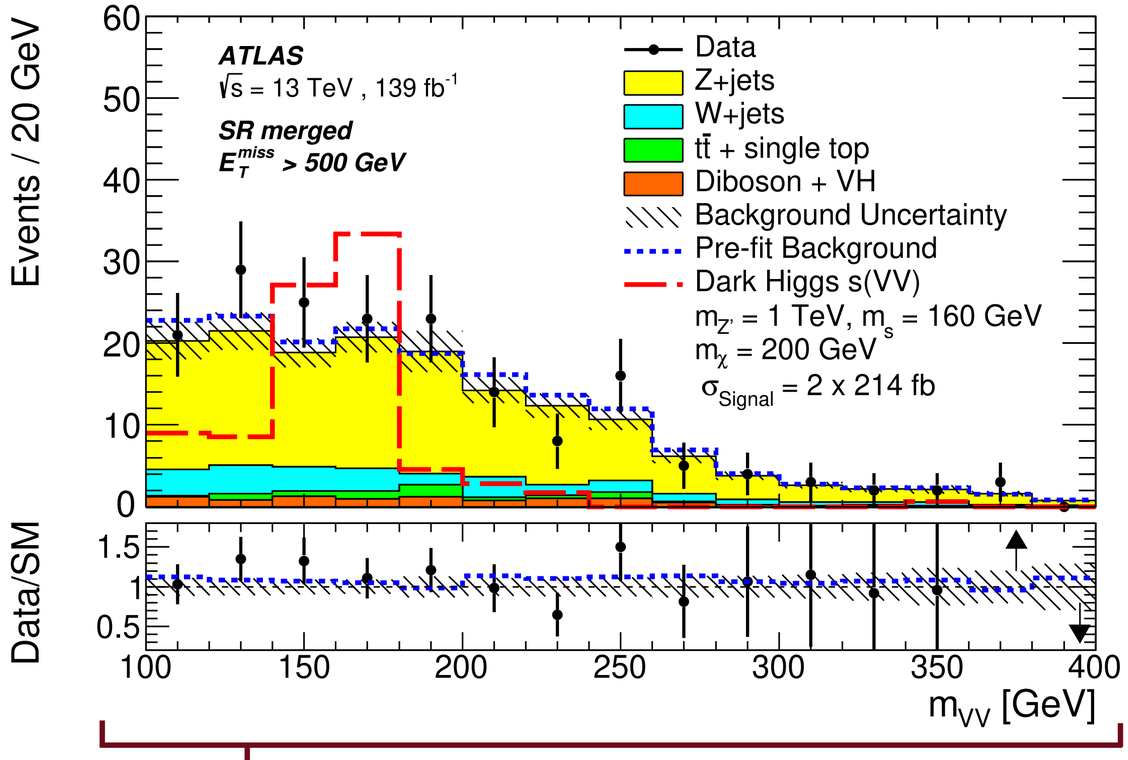
ATL-PHYS-PUB-2018-012

Phys. Rev. Lett. 126 (2021) 121802

Search for a dark Higgs boson

- *n-subjettiness* variables used to discriminate 4-prong topology within high energetic TAR jets
- events failing TAR jets selection recovered in the *Intermediate* category - include closest anti-k_t 0.4 jet
- signal regions: invariant mass of dark Higgs candidate, m_{VV} distribution
  - single-bin control regions to correct SM V+jets predictions obtained inverting lepton veto
- dominant uncertainties: V+jets modelling, jet measurements





Phys. Rev. Lett. 126 (2021) 121802

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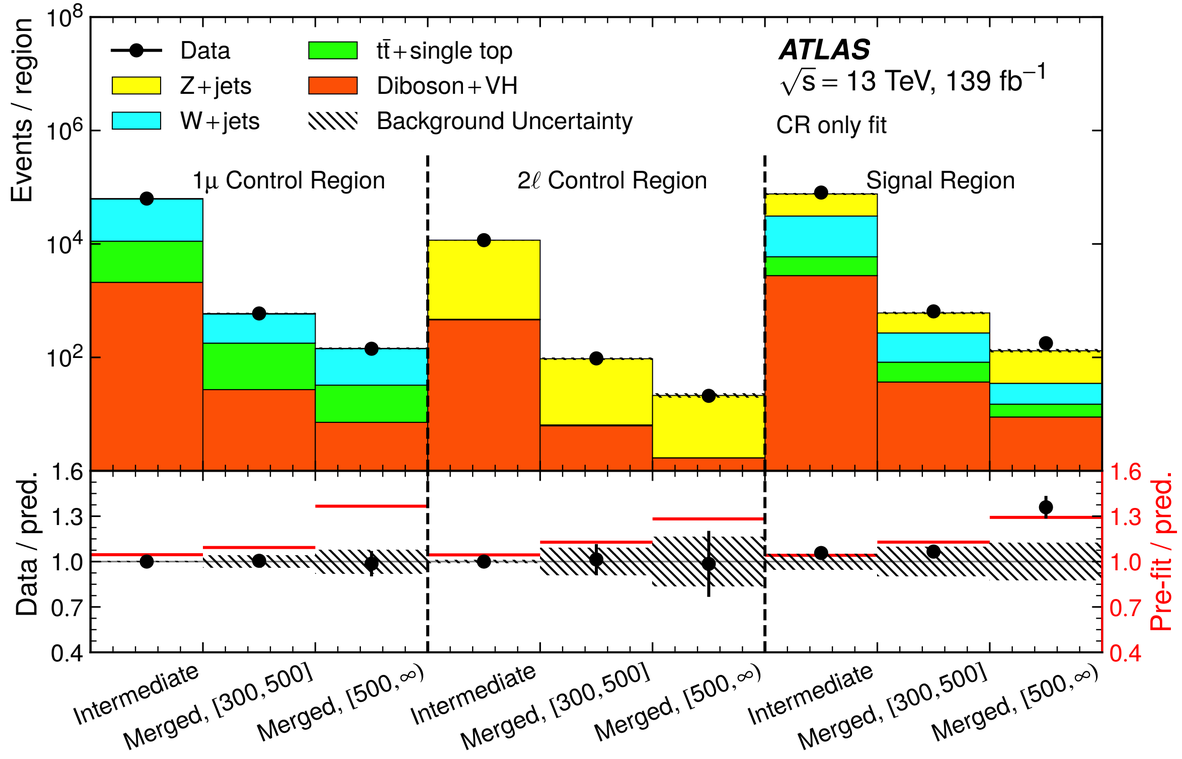
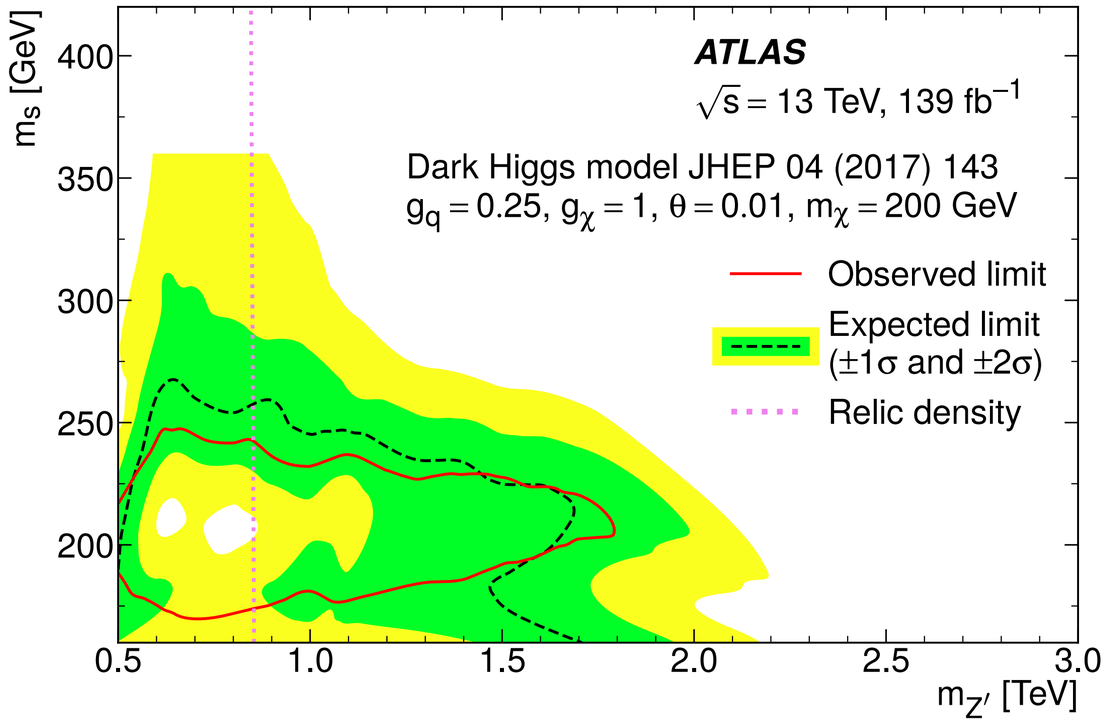
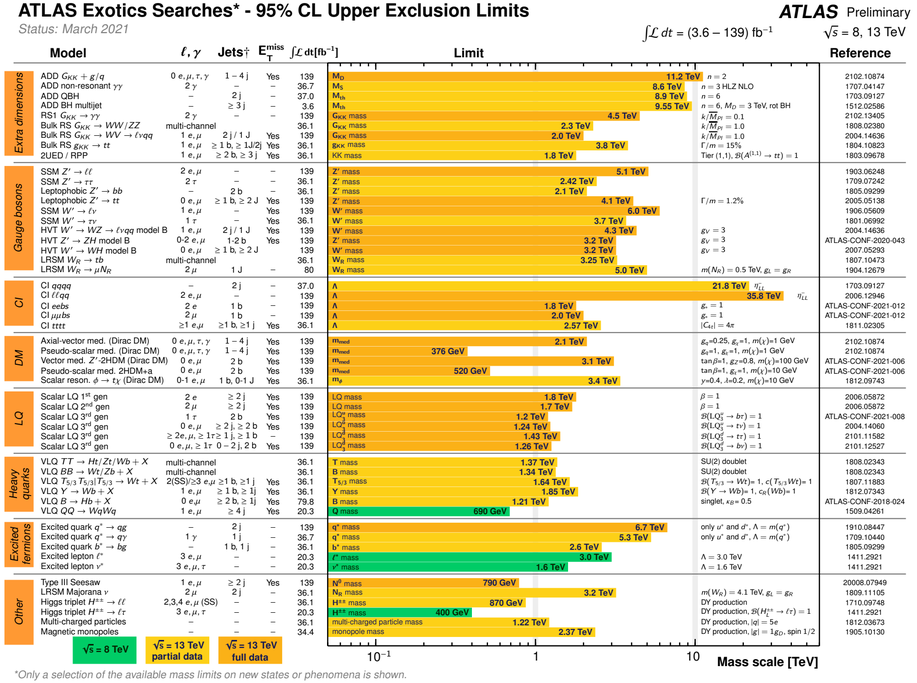
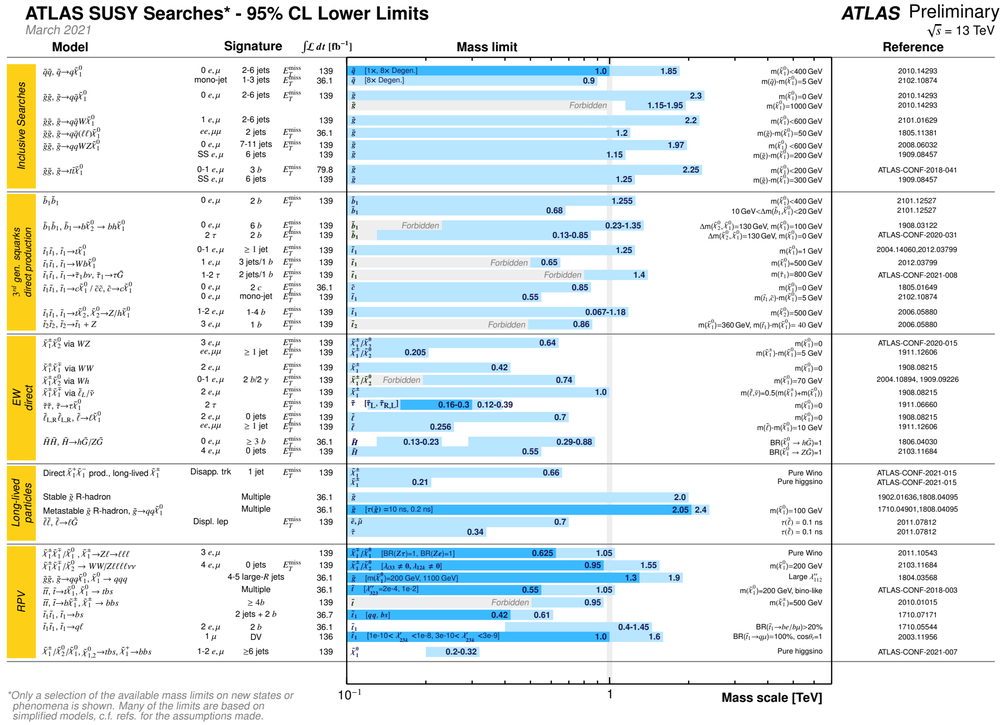




Conclusions

- presented recent results on simplified DM models
  - more extended DM models covered in Alexander's talk targeting mono-H final states & Higgs to invisible decays
  - many DM candidates might be identified in SUSY models - latest results from ATLAS in Abhishek's talk
- in general growing interest towards more exotics signatures in ATLAS
  - pushes our understanding of the detector forward!



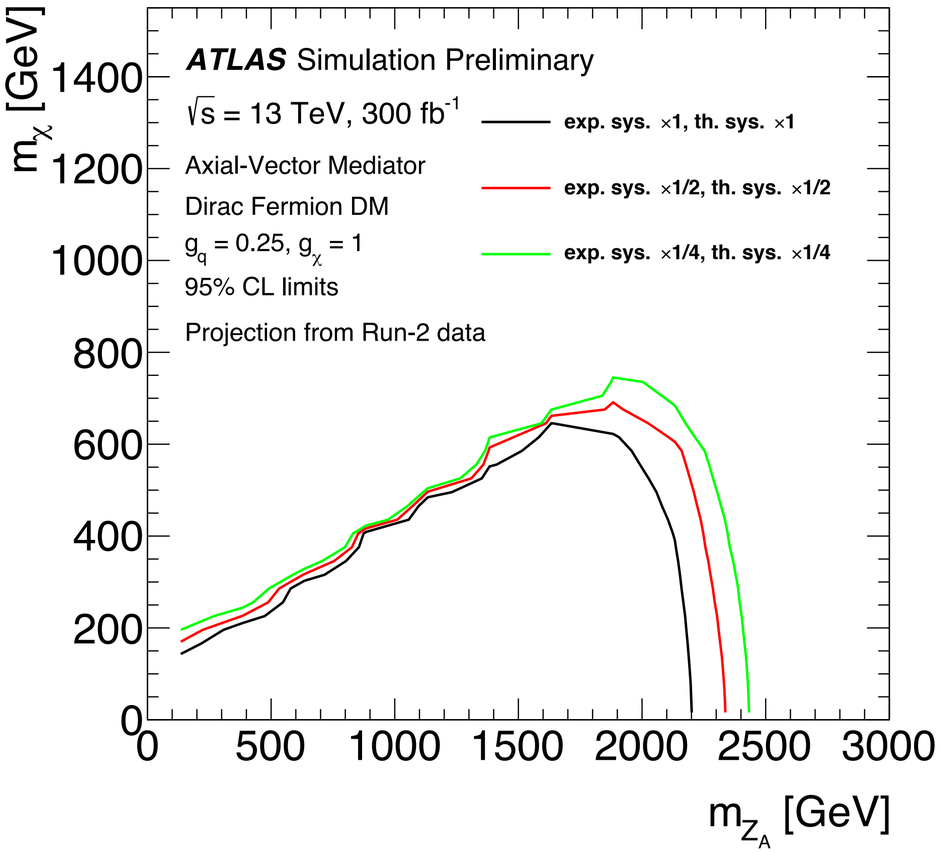


Backup slides

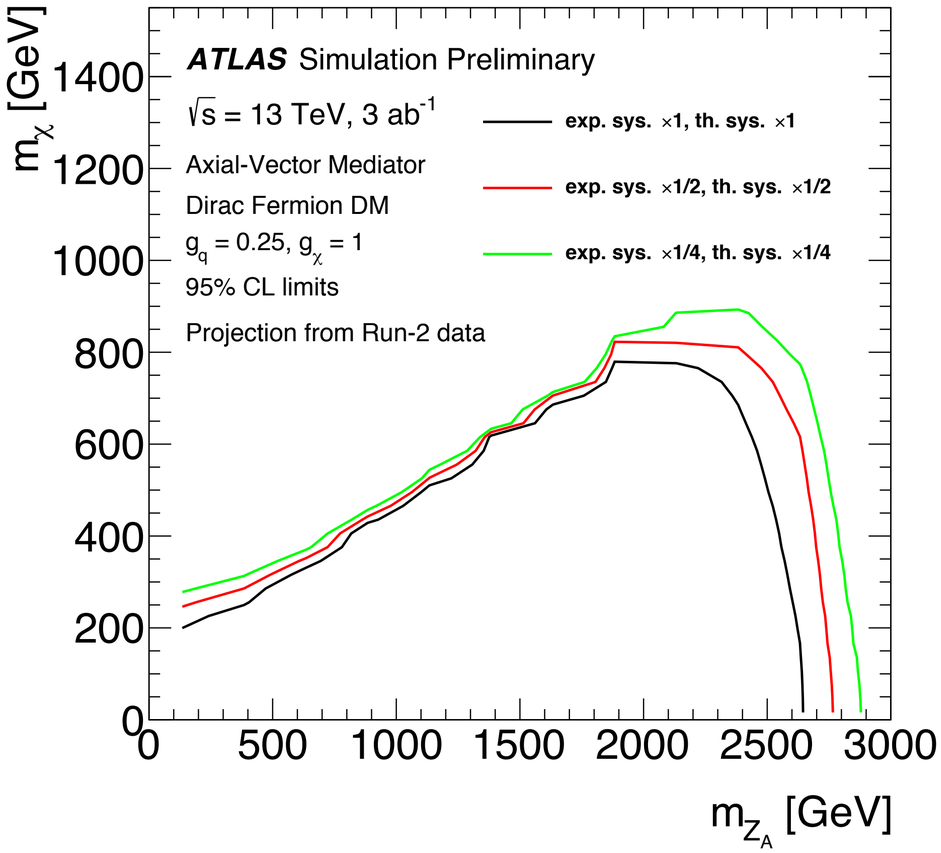
Monojet sensitivity projections for Run 3 and Phase 2

- projections of 36fb^{-1} analysis results in different scenarios of systematic uncertainties

End of Run 3 - 300fb^{-1}



End of HL-LHC - 3000 fb^{-1}



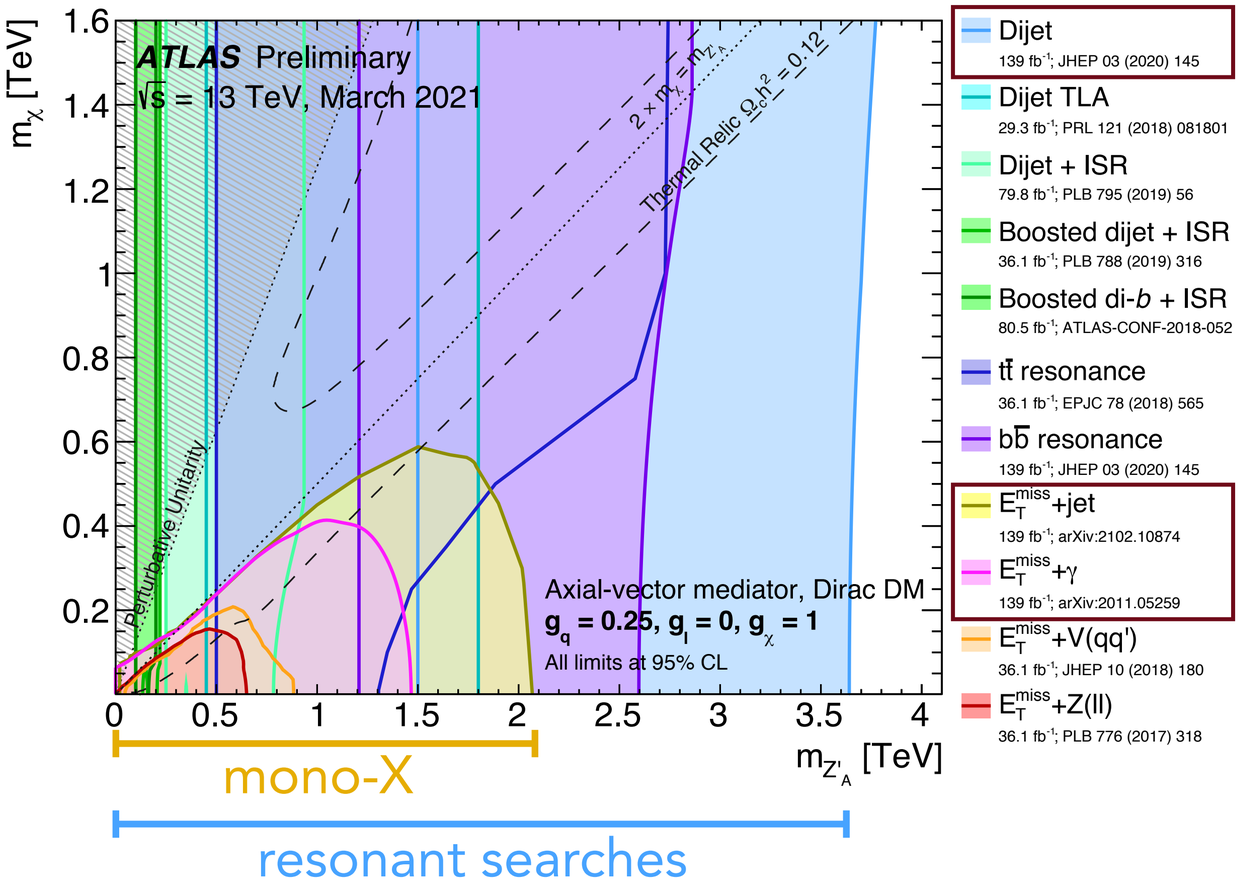
- improvements coming ~only by the reduction of theoretical V+jets uncertainties → scenario already improved!

ATL-PHYS-PUB-2021-006

Axial-vector mediator summary plots

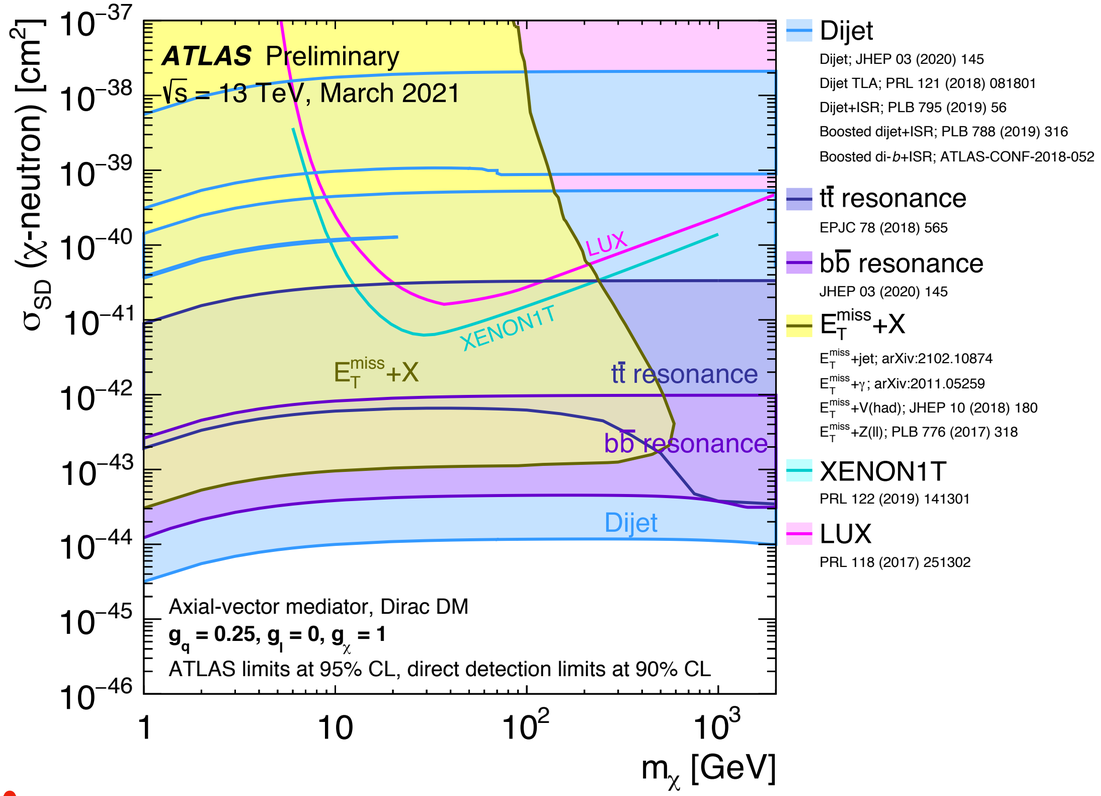
Axial-vector mediator

- mono-jet sets the strongest limits among mono-X searches
- inclusive dijet dominates resonant searches



Comparison to direct detection experiments

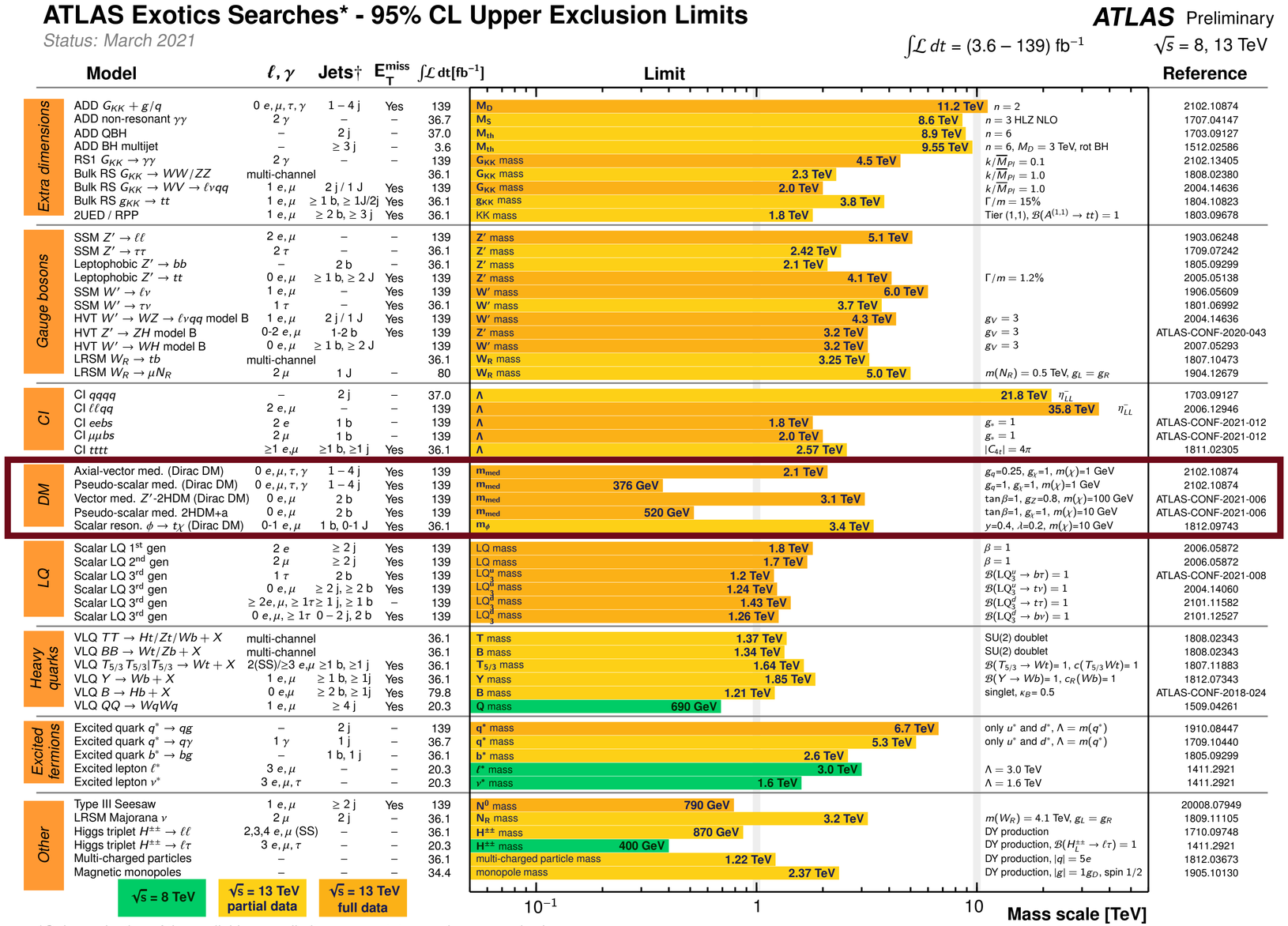
- axial-vector mediator → spin dependent interaction



⚠ comparison depends on chosen couplings

ATLAS exotics searches summary plot

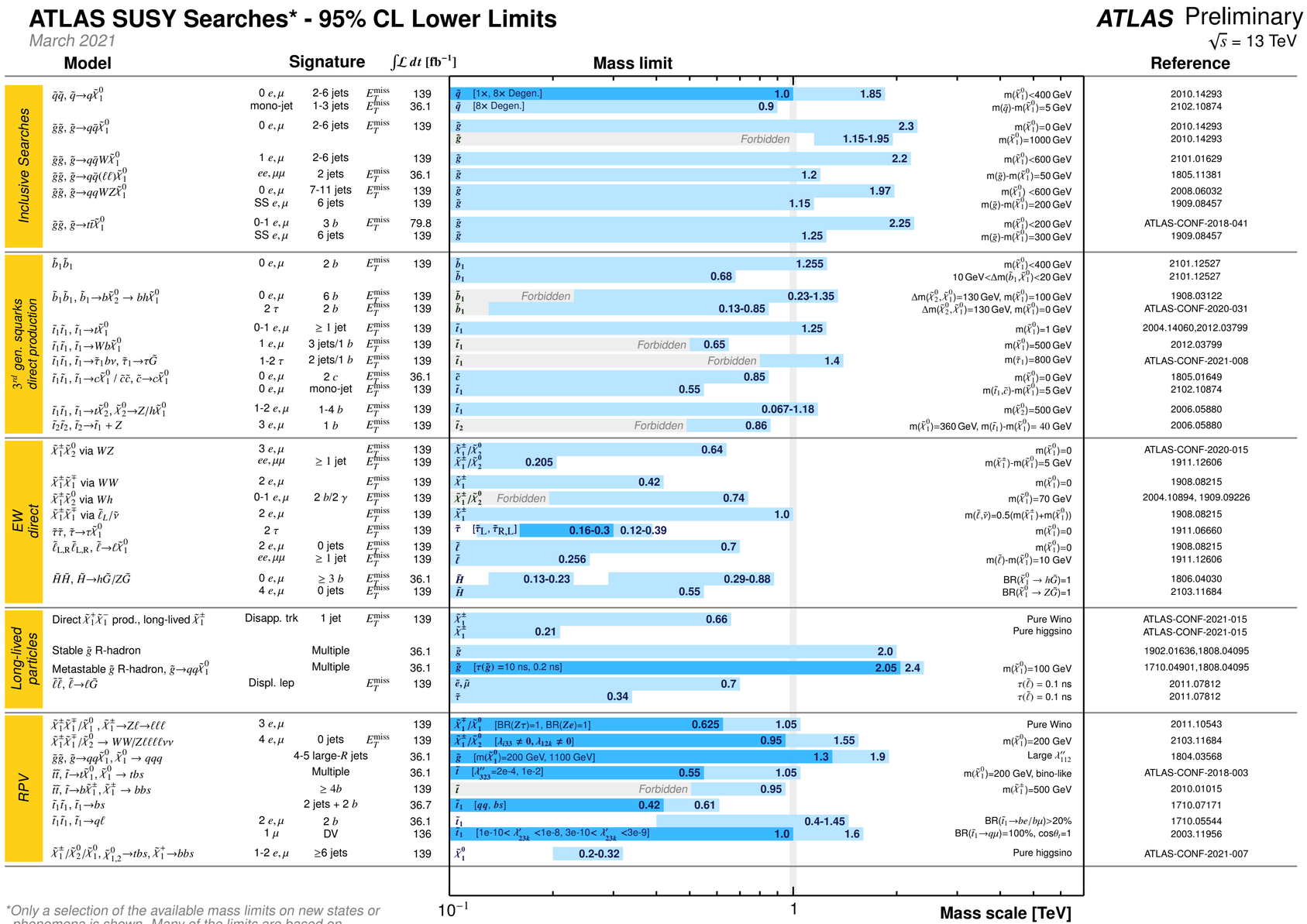
Simplified dark matter models



**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS SUSY searches summary plot

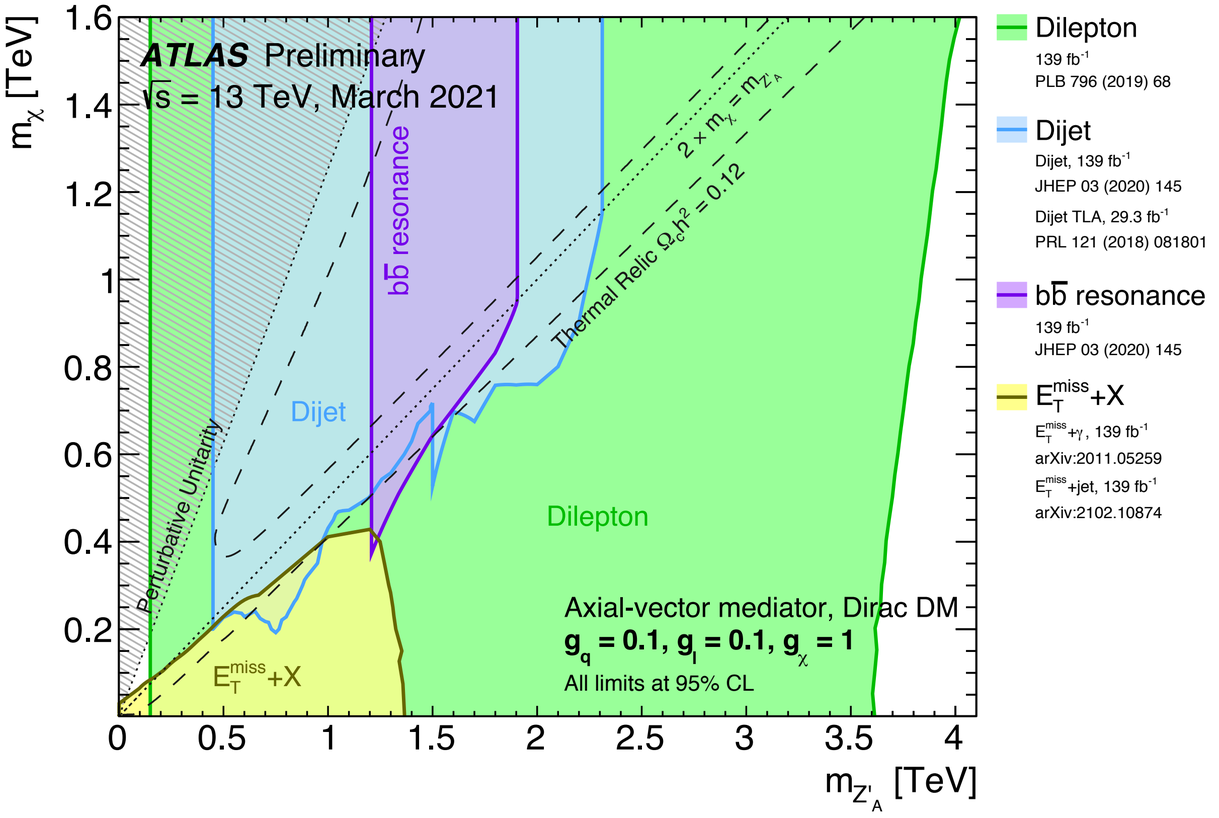


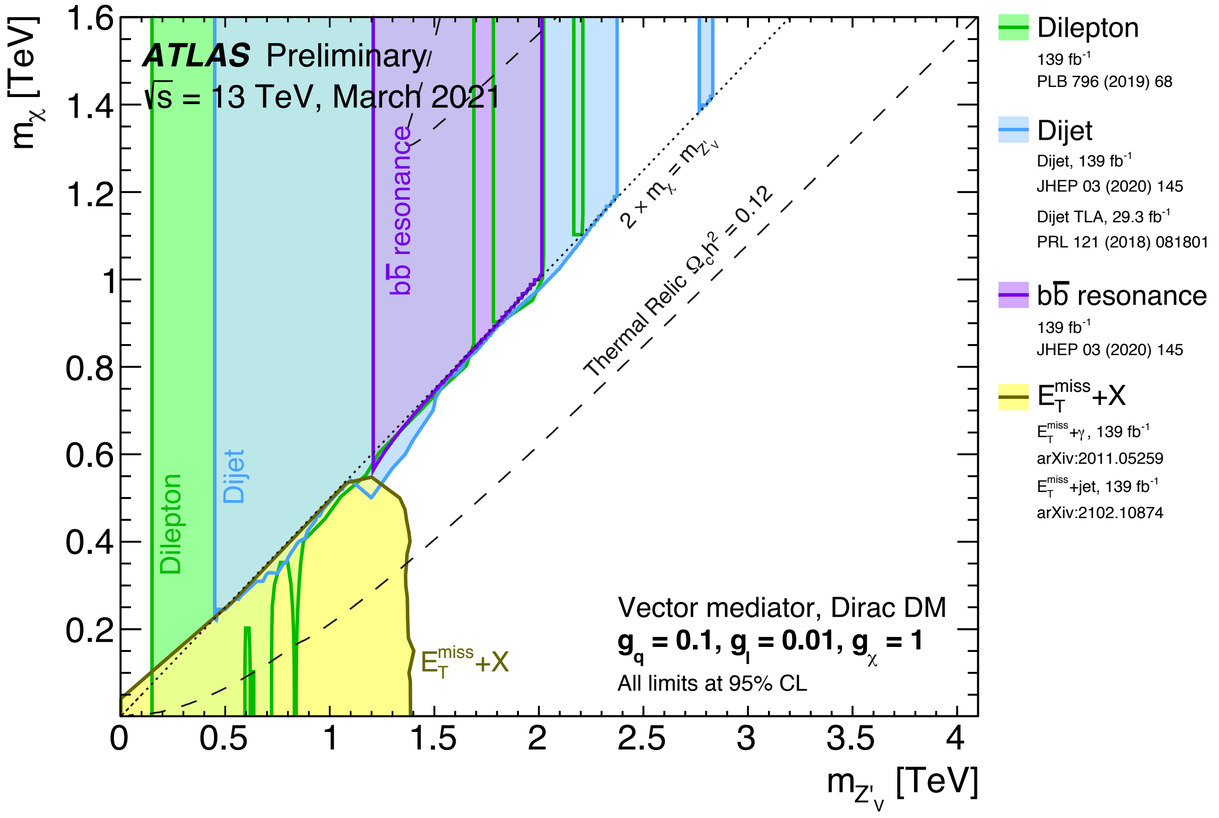
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATL-PHYS-PUB-2021-006

Dark matter summary plots allowing coupling to leptons

- different coupling values tested in the two scenarios

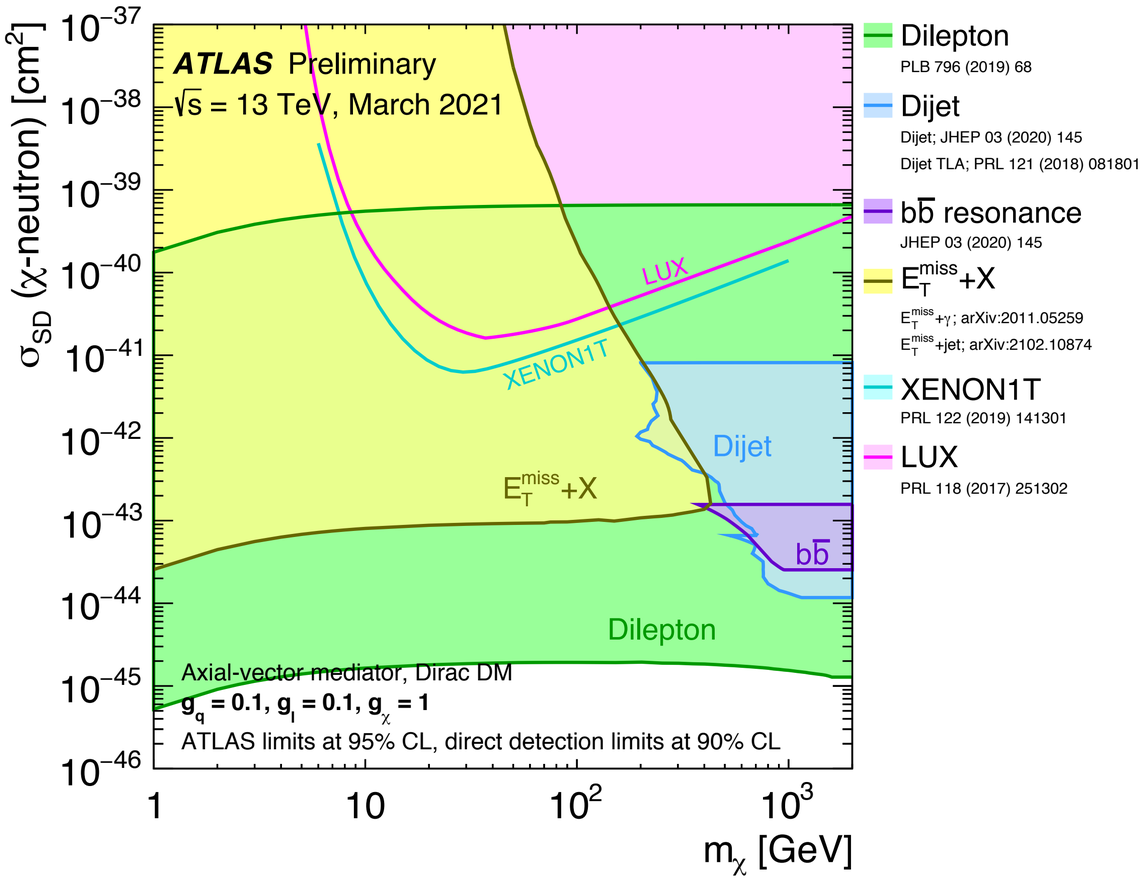


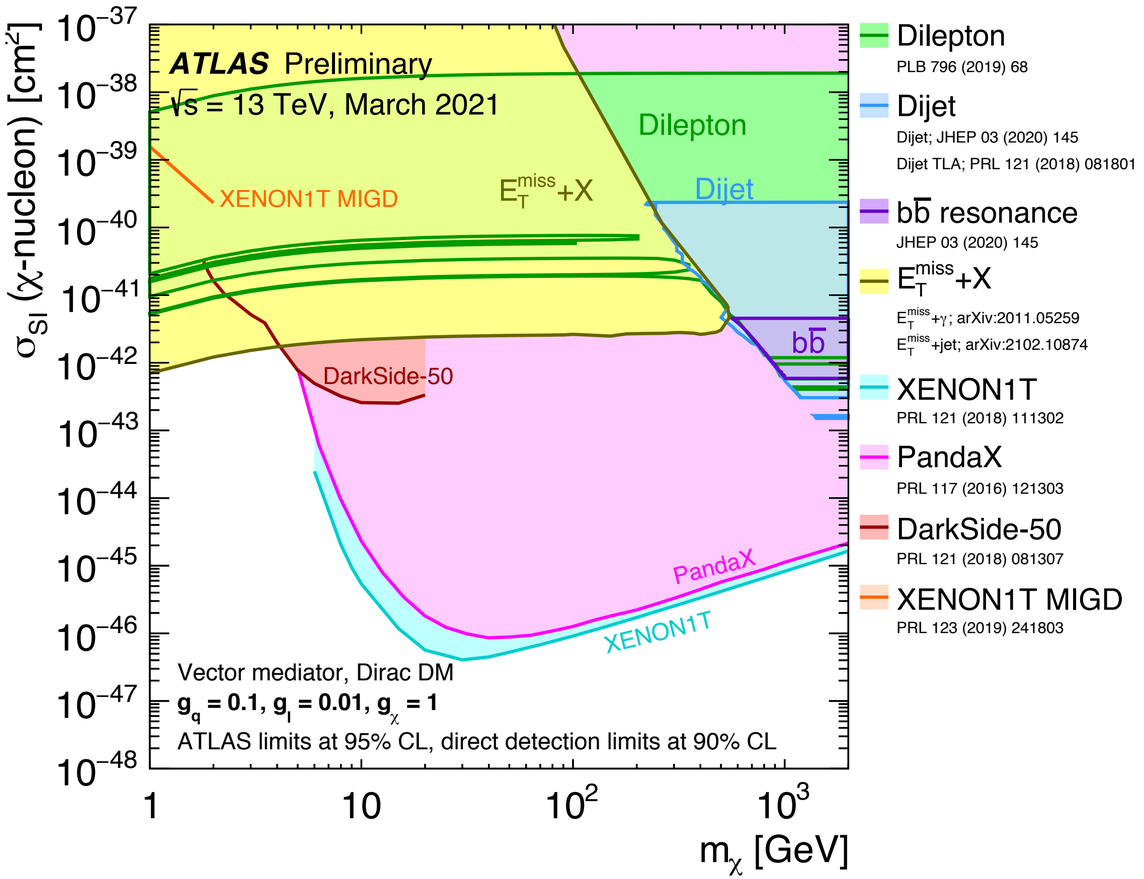


ATL-PHYS-PUB-2021-006

Dark matter summary plots allowing coupling to leptons

- different coupling values tested in the two scenarios





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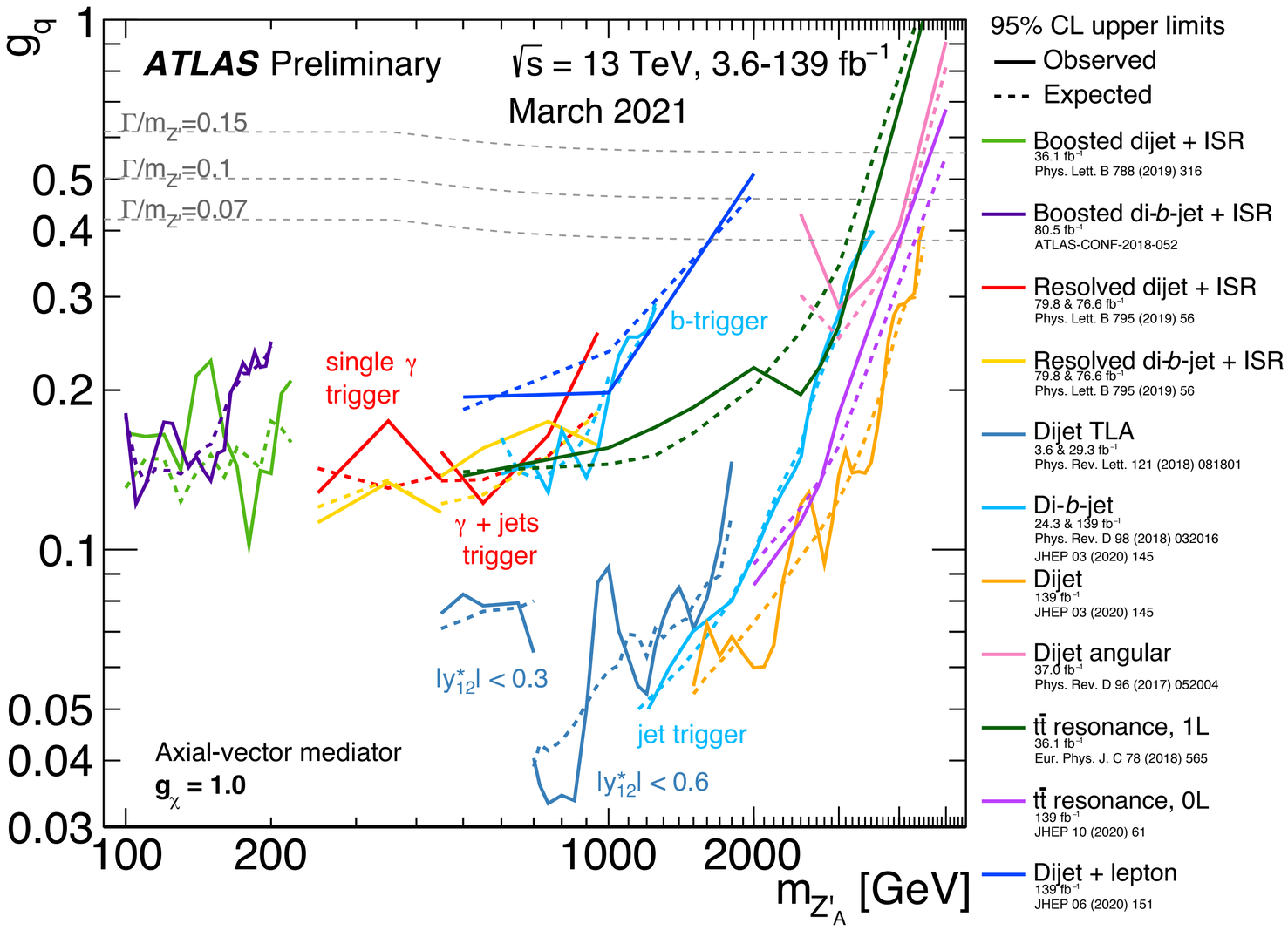
Simplified DM models couplings limits plot



arXiv:2102.10874

Monojet likelihood fit model

$$\mathcal{L}(\mu, \kappa, \theta) = \prod_r \prod_i \text{Poisson}\left(N_{ri}^{\text{obs}} \mid \mu N_{ri}^{\text{sig}}(\theta) + N_{ri}^{\text{bkg}}(\kappa, \theta)\right) f_{\text{constr}}(\theta)$$

$$N_{ri}^{\text{bkg}} = \kappa_V \left(N_{ri}^{\text{Z+jets}} + N_{ri}^{\text{W+jets}}\right) + \kappa_{t\bar{t}} N_{ri}^{t\bar{t}} + \kappa_t N_{ri}^{\text{single}-t} + N_{ri}^{\text{diboson}} + N_{ri}^{\text{VBF W/Z+jets}} + N_{ri}^{\text{multijet+NCB}}$$

- three free floating Normalisation Factors
- diboson and VBF W/Z+jets bkgs. taken directly from MC simulation
- multijet and Non-Collision Background: data driven estimate
- systematic uncertainties: *gaussian constrained* nuisance parameters

Fit strategy

- shape fit to the $p_{\text{T}}^{\text{recoil}}$ distributions in two steps:
  1. without including the Signal Region (SR) → check any excess over SM predictions
  2. SR + CR fit with signal simulation → extract upper limits on considered models

arXiv:2102.10874

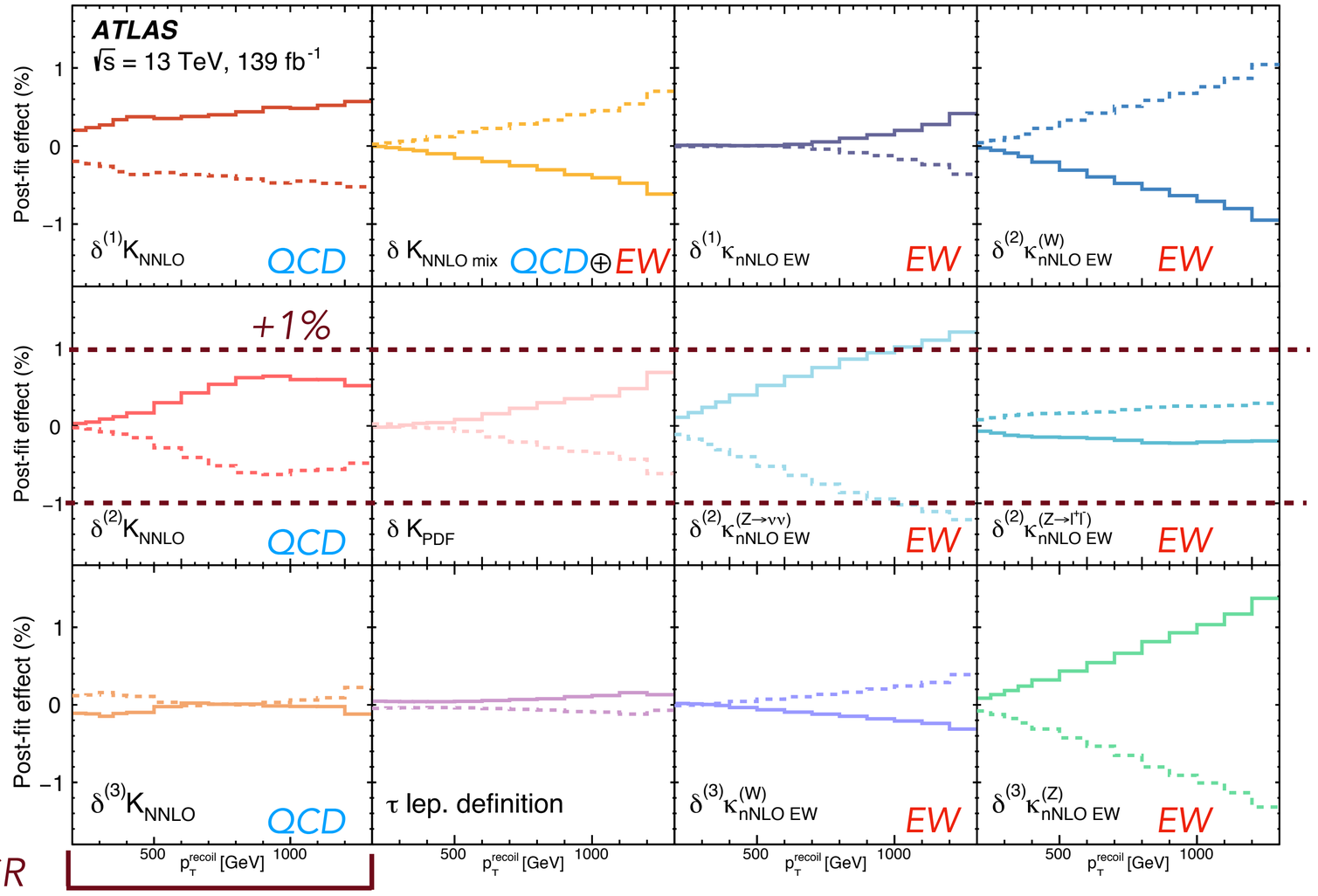
Improving V+jets predictions

- MC simulation of V+jets processes (NLO QCD, LO EW) re-weighted to higher-order (QCD & EW) via theory correction following Eur. Phys. J. C 77, 829 (2017)
  - large impact in the tail of the E_T^{miss} distribution
- allow to correlate W & Z+jets in the fit

- include systematics to account for higher-order effects

Background uncertainty in SR

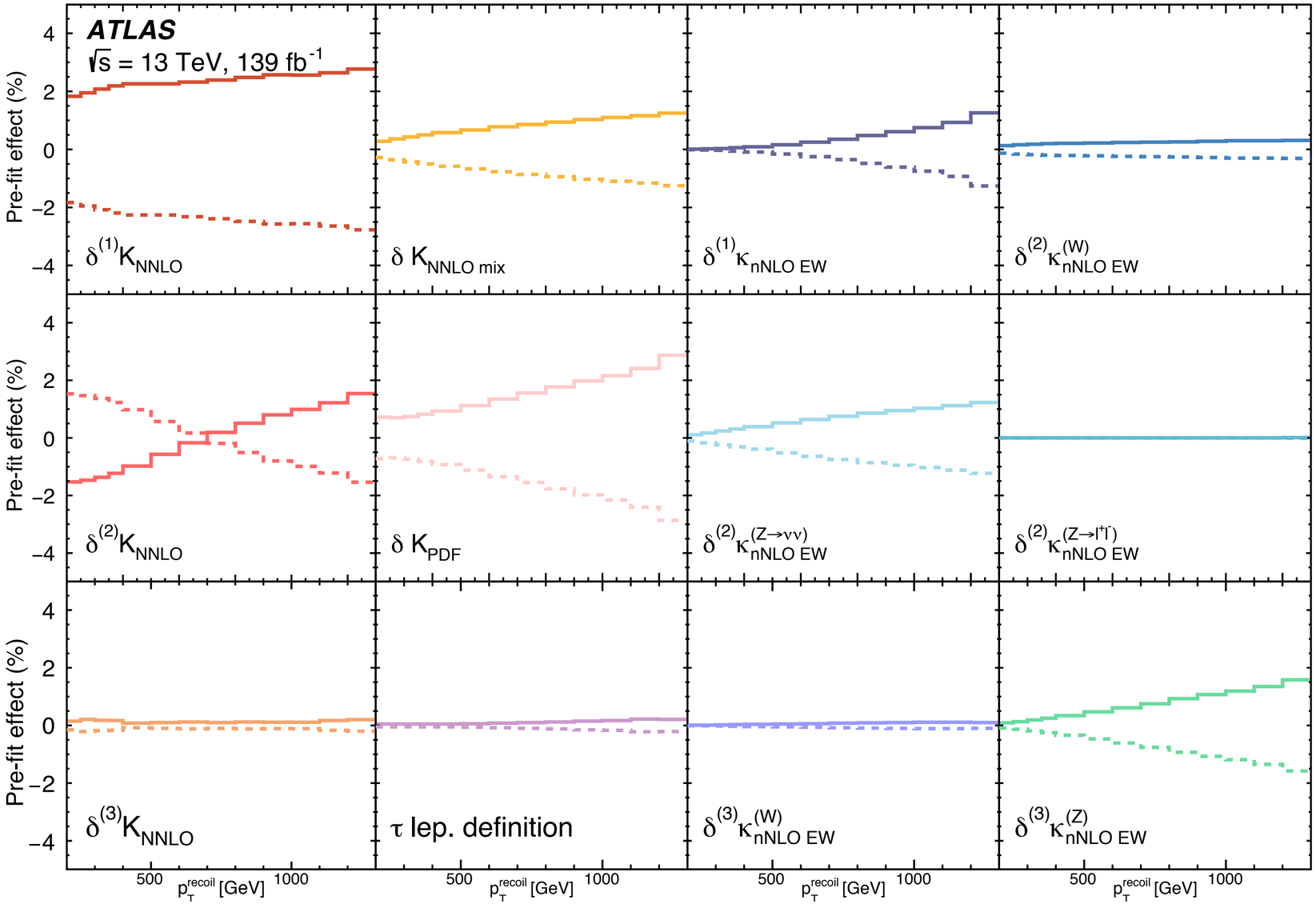
- QCD uncertainties effects < 1%
- EW: 0.2 ~ 1.6% - affecting tail of E_T^{miss} distribution



$p_T^{recoil} = E_T^{miss}$ *in SR*

arXiv:2102.10874

Pre-fit effect of V+jets theoretical systematics



V+jets theoretical systematics

Table 1: Uncertainties considered in the reweighting of V + jets samples to higher-order QCD and EW parton-level calculations. For reference, the correspondence with the nuisance parameters included in Table 3 from Ref. is also indicated.

Source of uncertainty	**Correlation**	**Nuisance parameter name(s) in Ref.**
Truncation of perturbative expansion in α_s	Correlated across p_T^{recoil} bins and V + jets processes	$\delta^{(1)} K_{NNLO}$
Shape of the vector-boson distribution and extrapolation from low p_T to high p_T	Correlated across p_T^{recoil} bins and V + jets processes	$\delta^{(2)} K_{NNLO}$
Difference in QCD corrections between W + jets and Z + jets	Correlated across p_T^{recoil} bins and V + jets processes	$\delta^{(3)} K_{NNLO}$
Unknown Sudakov logarithms beyond NNLO	Correlated across p_T^{recoil} bins and V + jets processes	$\delta^{(1)} \kappa_{nNLO\ EW}$
Additional possible NNLO effects	Correlated across p_T^{recoil} bins, uncorrelated between V + jets processes	$\delta^{(2)} \kappa^{(W)}_{nNLO\ EW}$, $\delta^{(2)} \kappa^{(Z\to\ell^+\ell^-)}_{nNLO\ EW}$, $\delta^{(2)} \kappa^{(Z\to\nu\nu)}_{nNLO\ EW}$
Limitations of the Sudakov approximation at two loops	Correlated across p_T^{recoil} bins, uncorrelated between W + jets and Z + jets processes	$\delta^{(3)} \kappa^{(W)}_{nNLO\ EW}$, $\delta^{(3)} \kappa^{(Z)}_{nNLO\ EW}$
Interference terms between QCD and EW corrections	Correlated across p_T^{recoil} bins and V + jets processes	$\delta K_{NNLO\ mix}$
PDF uncertainties	Correlated across p_T^{recoil} bins and V + jets processes	sum in quadrature of $\delta K^{(i)}_{PDF}$
Different definition of τ-leptons between parton-level calculation and simulation	Correlated across p_T^{recoil} bins and V + jets processes	–

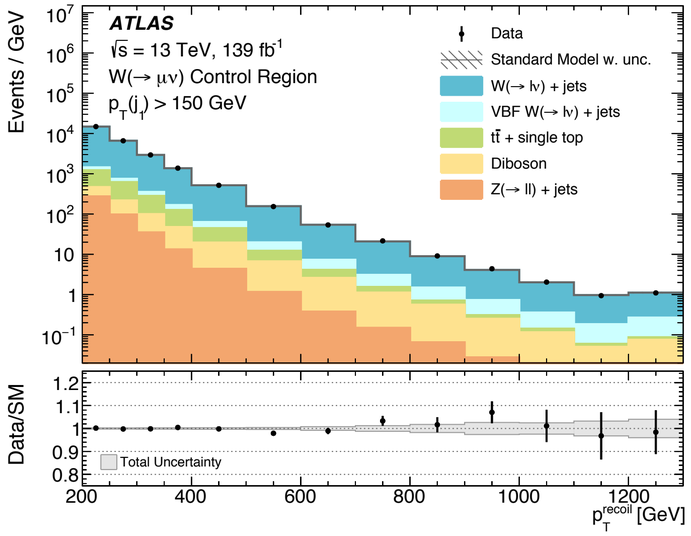
arXiv:2102.10874

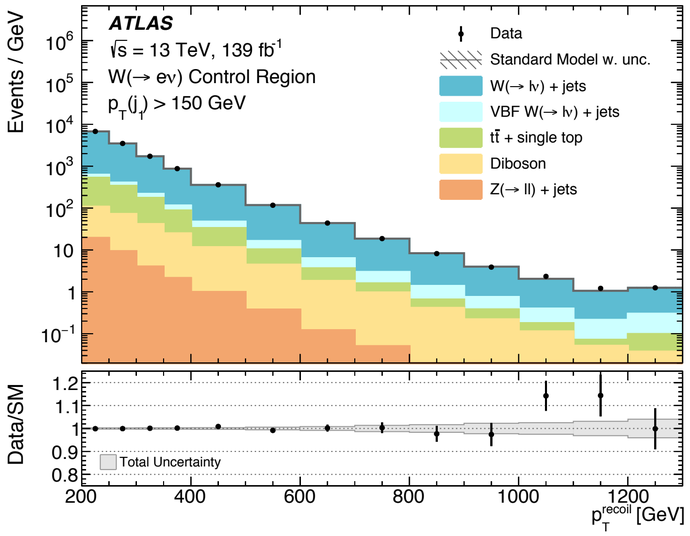
Monojet search: systematic uncertainties effect

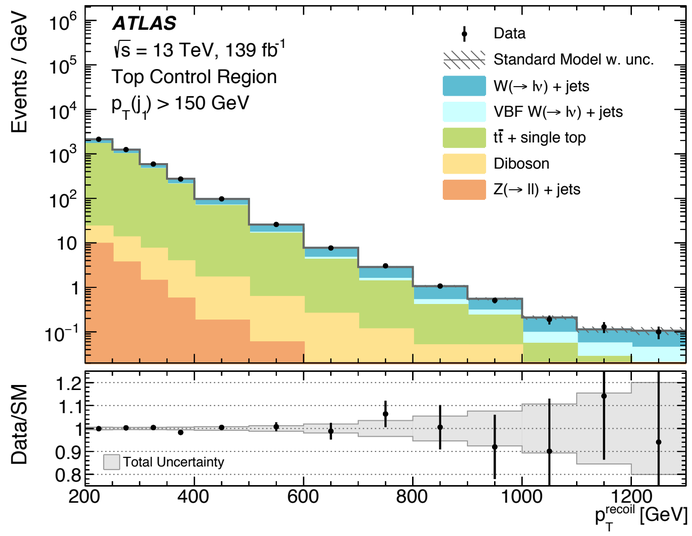
Source of uncertainty and effect on the total SR background estimate [%]			
Flavor tagging	0.1 – 0.9	τ-lepton identification efficiency	0.1 – 0.07
Jet energy scale	0.17 – 1.0	Luminosity	0.01 – 0.05
Jet energy resolution	0.15 – 1.3	Noncollision background	0.2 – 0.0
Jet JVT efficiency	0.01 – 0.03	Multijet background	1.0 – 0.0
Pileup reweighting	0.4 – 0.24	Diboson theory	0.01 – 0.22
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	0.34 – 0.04	Single-top theory	0.13 – 0.28
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	0.5 – 0.25	$t\bar{t}$ theory	0.06 – 0.7
Electron and photon energy resolution	0.01 – 0.08	V+jets τ-lepton definition	0.04 – 0.16
Electron and photon energy scale	0.3 – 0.7	V+jets pure QCD corrections	0.24 – 1.1
Electron identification efficiency	0.5 – 1.0	V+jets pure EW corrections	0.17 – 2.2
Electron reconstruction efficiency	0.15 – 0.2	V+jets mixed QCD–EW corrections	0.02 – 0.7
Electron isolation efficiency	0.04 – 0.19	V+jets PDF	0.01 – 0.7
Muon identification efficiency	0.03 – 0.9	VBF EW V+jets backgrounds	0.02 – 1.1
Muon reconstruction efficiency	0.4 – 1.5	Limited MC statistics	0.05 – 1.9
Muon momentum scale	0.1 – 0.7		
Total background uncertainty in the Signal Region: 1.5%–4.2%			

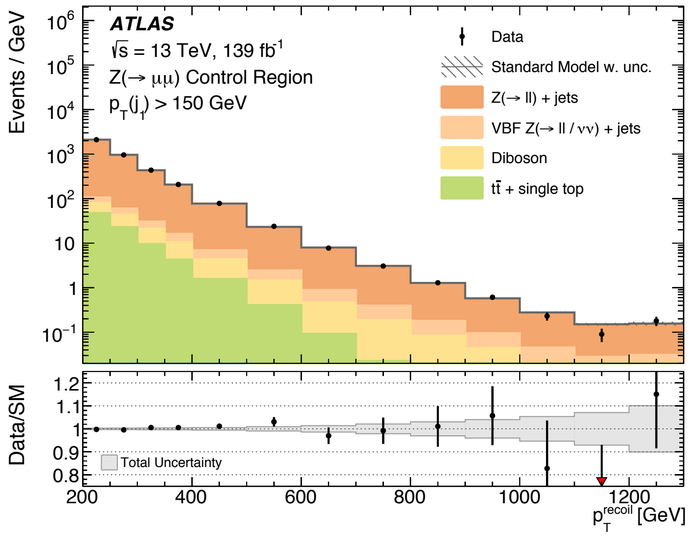
arXiv:2102.10874

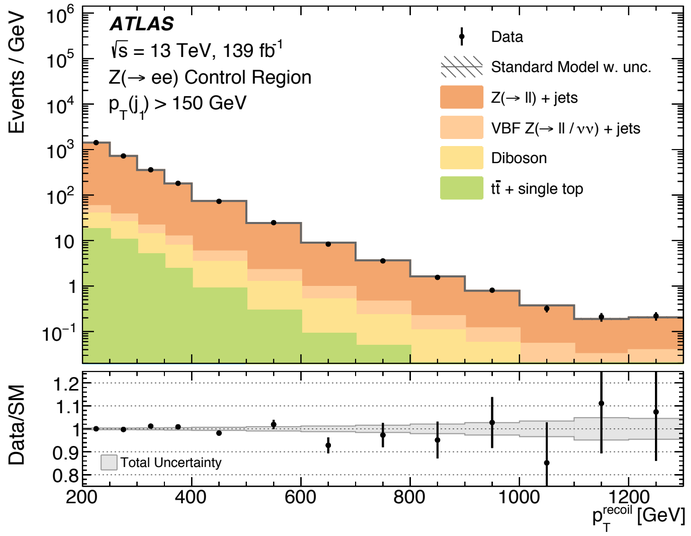
Monojet control regions distributions





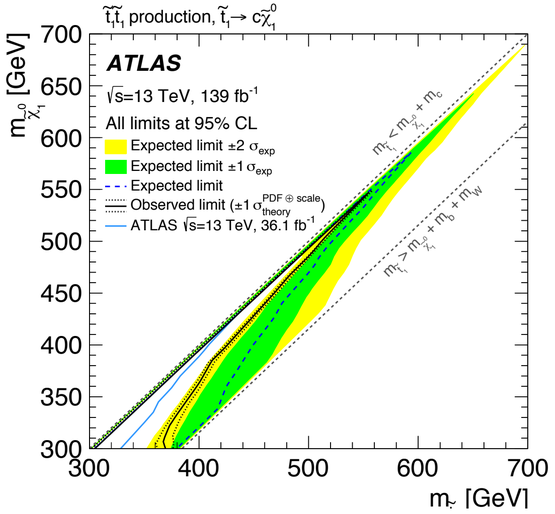


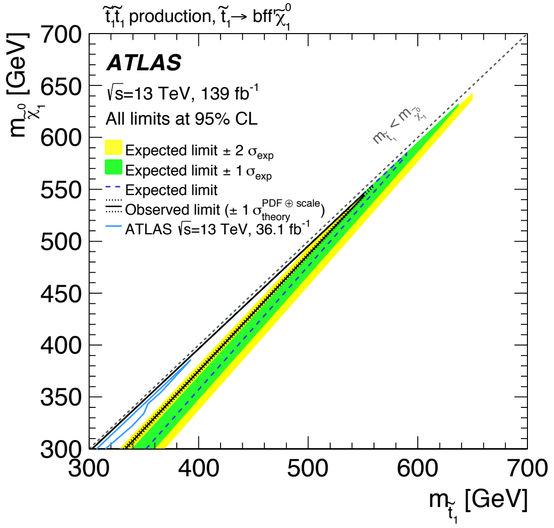


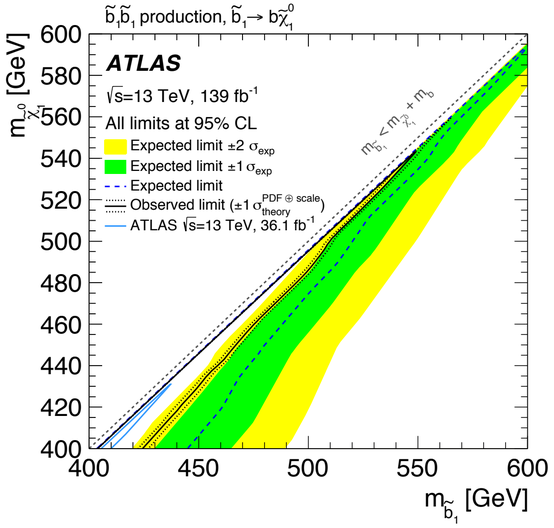


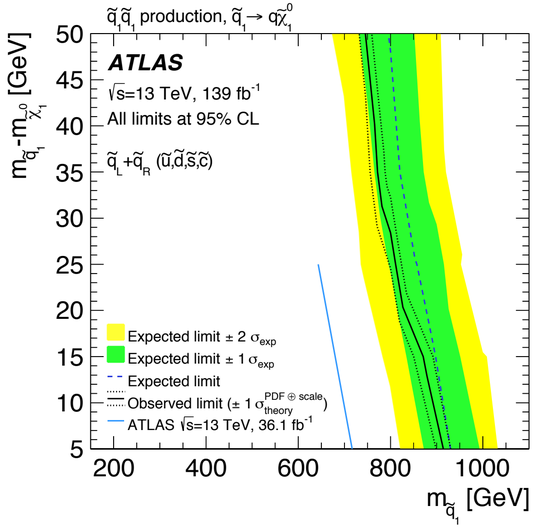
arXiv:2102.10874

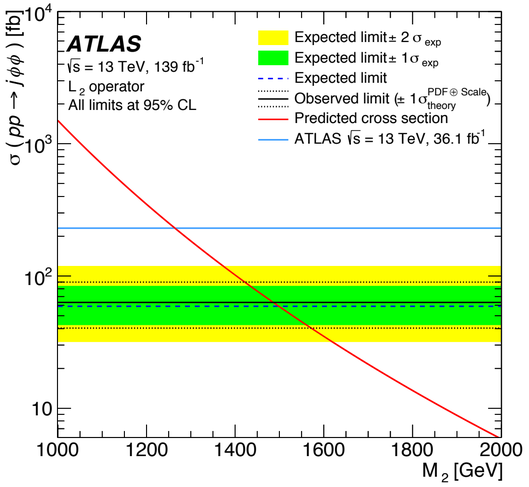
New physics interpretations in the monojet search

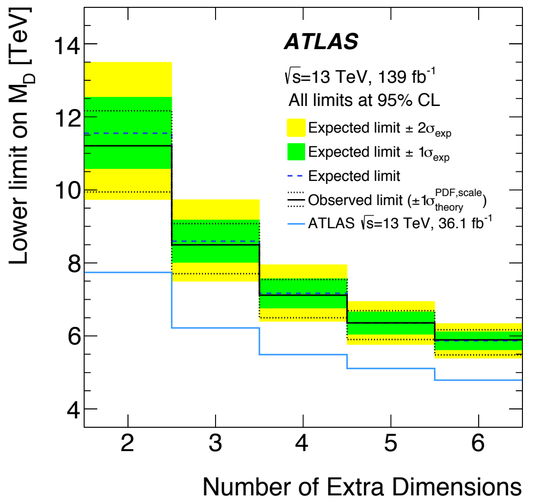


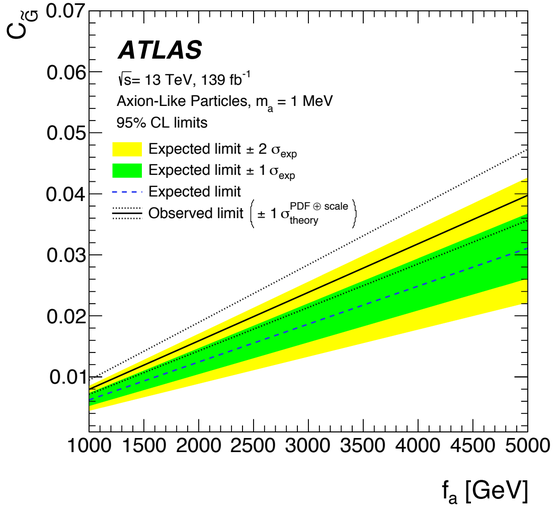


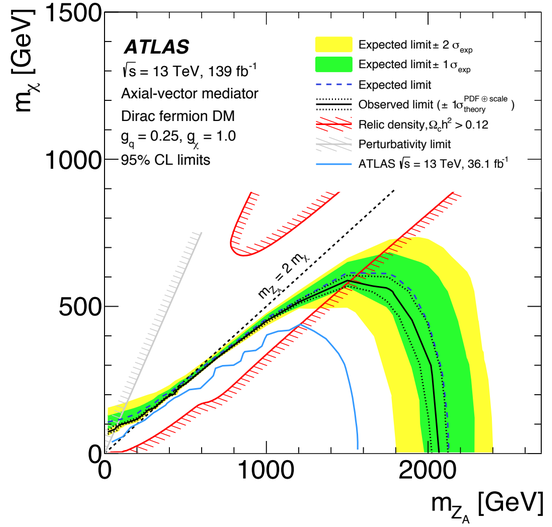












B(H→inv) obs (exp) = $0.34\ (0.39^{+0.16}_{-0.11})$

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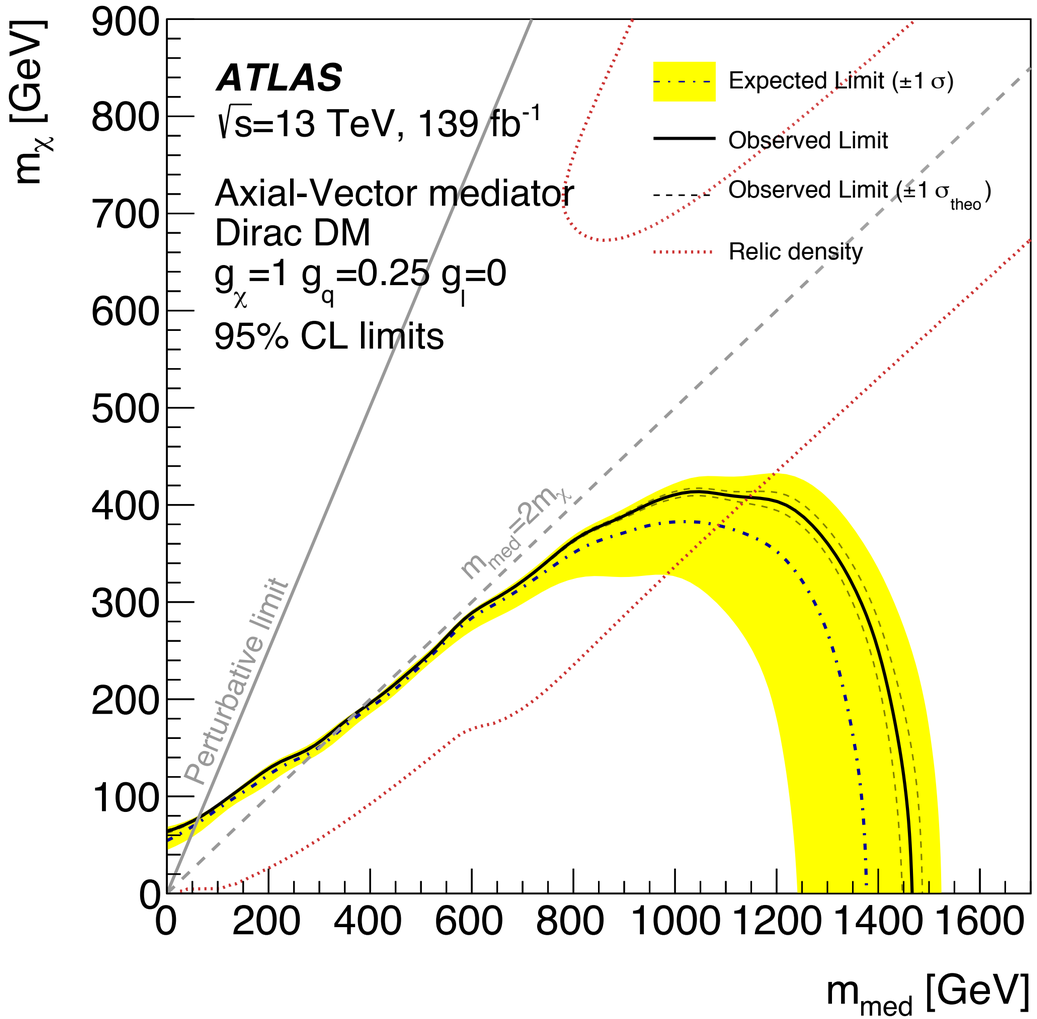
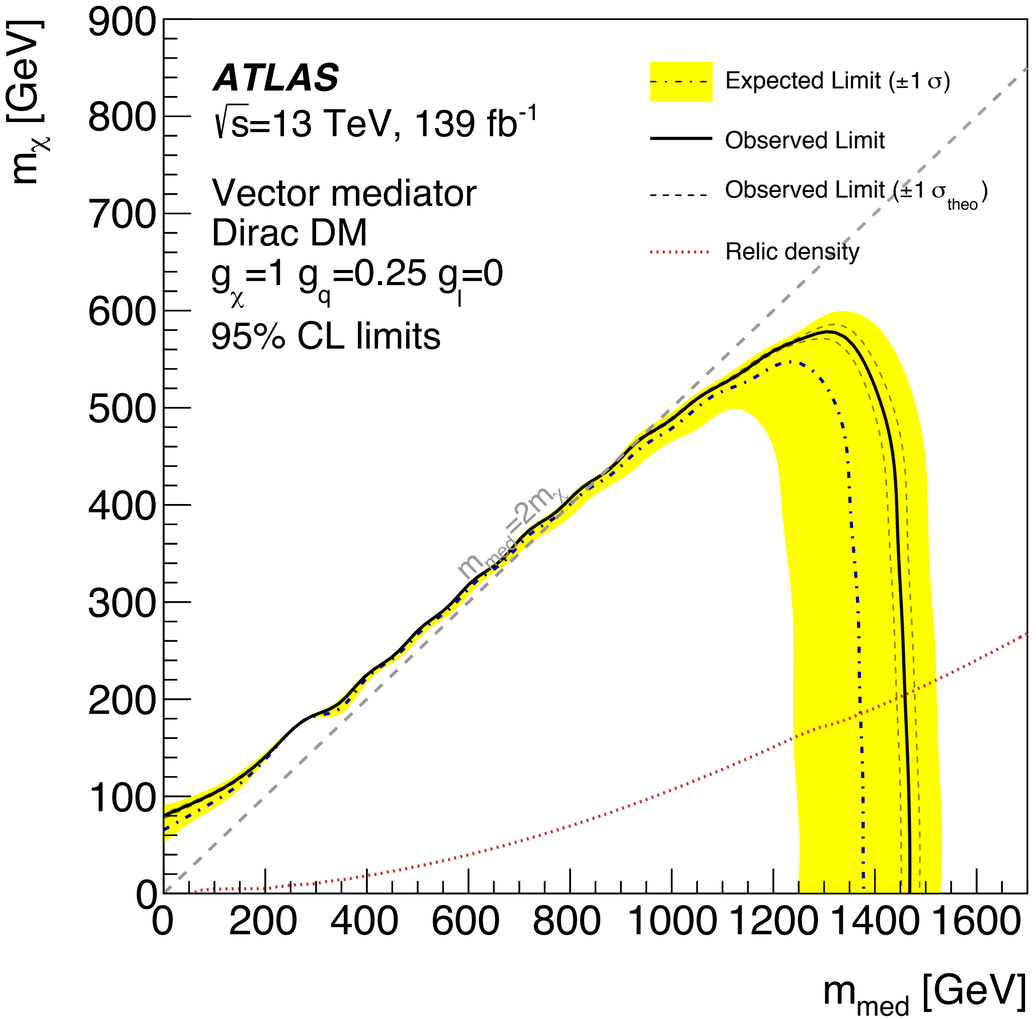
Mono-photon simplified DM models results





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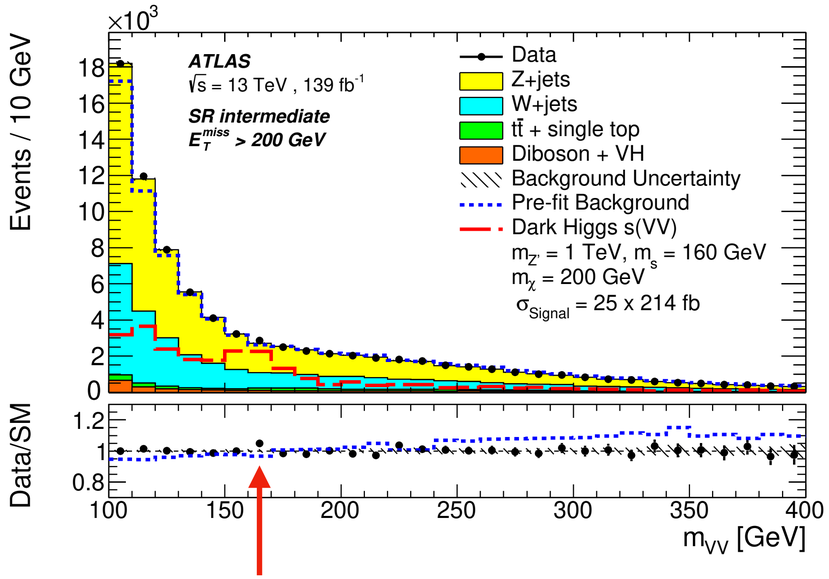
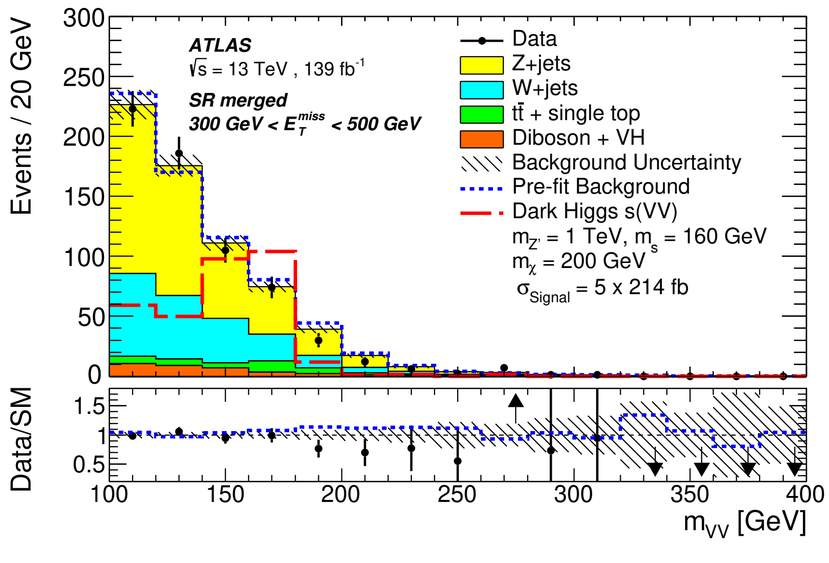
Additional distributions for dark Higgs search

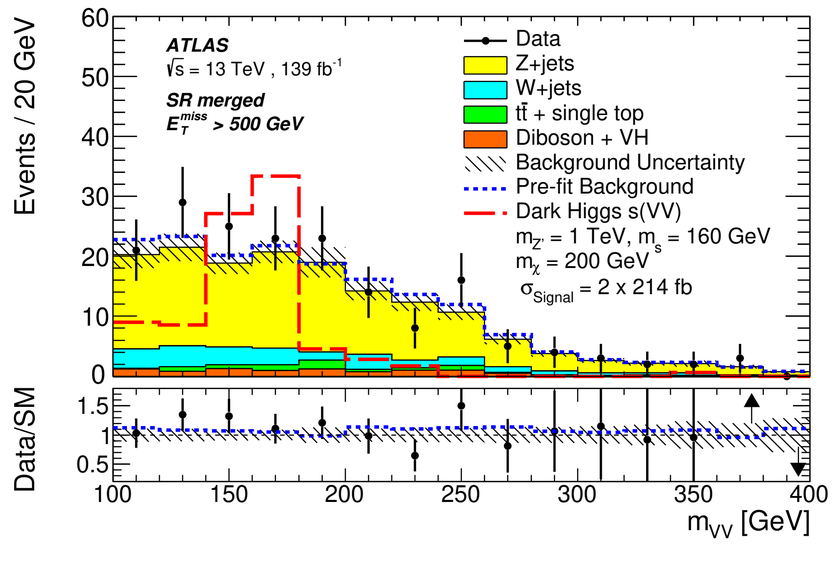
- signal region candidate m_S distributions

Intermediate topology



Merged topology





fluctuation reduces sensitivity to m_S =160 GeV signal

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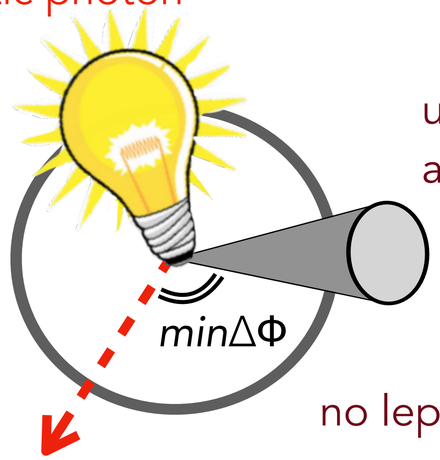
Shedding light on dark matter

- mono-photon final states can also be used to constrain simplified dark matter models

at least one energetic photon
p_T > 150 GeV

single-γ trigger

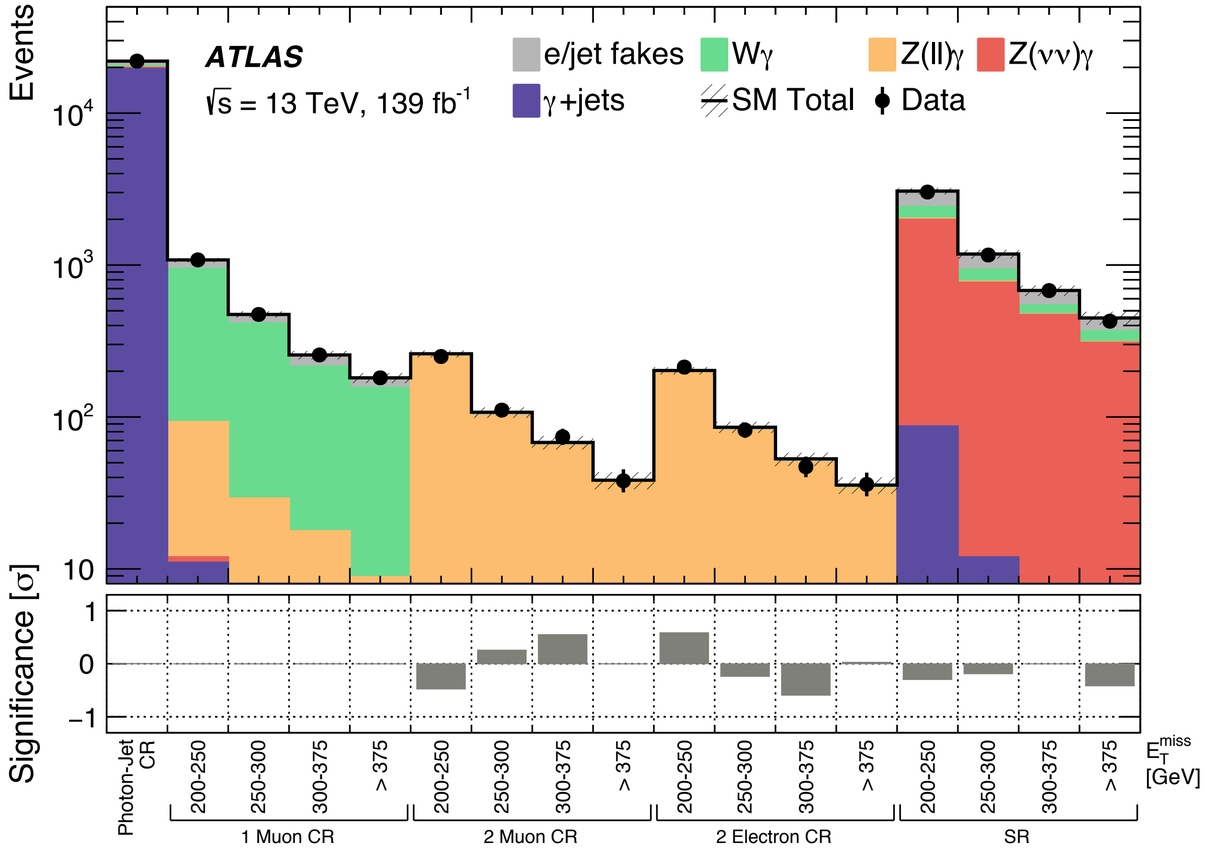


up to one additional jet

no leptons

E_T^{miss} > 200 GeV

object based E_T^{miss} significance cut



- irreducible background Z(vv)+γ and reducible Wγ controlled via CR, similar to mono-jet

- electrons & jets faking photons estimated in a data-driven way

Statistically limited analysis