Searching for invisible phenomena through measurement of events with jets and large missing transverse momentum in pp collisions at ATLAS

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IOP APP / HEPP Conference
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26th March 2018

arXiv:1707.03263, Eur.Phys.J. C77 (2017) 11, 765

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Introduction

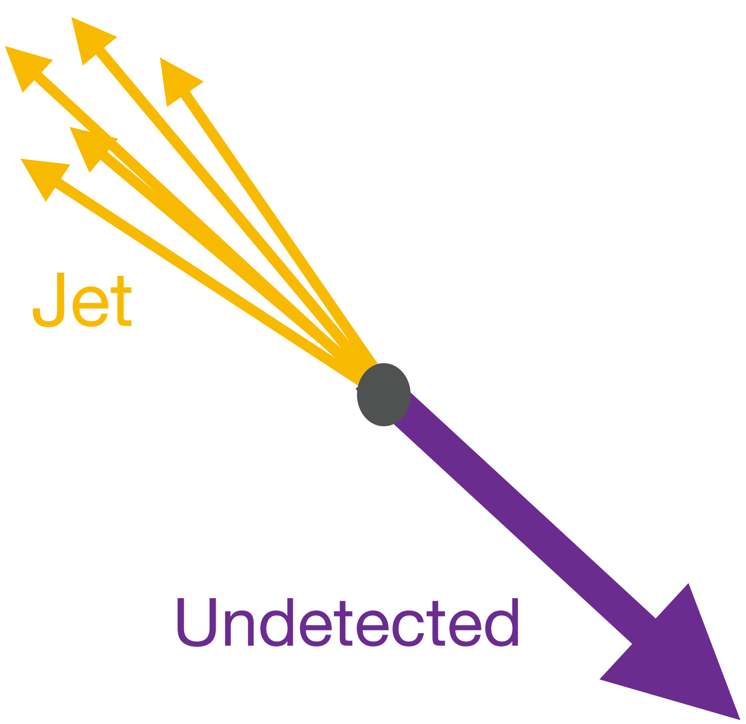
Detector-corrected measurement of missing transverse energy plus jet(s) differential production rates, sensitive to a variety of BSM invisible phenomena

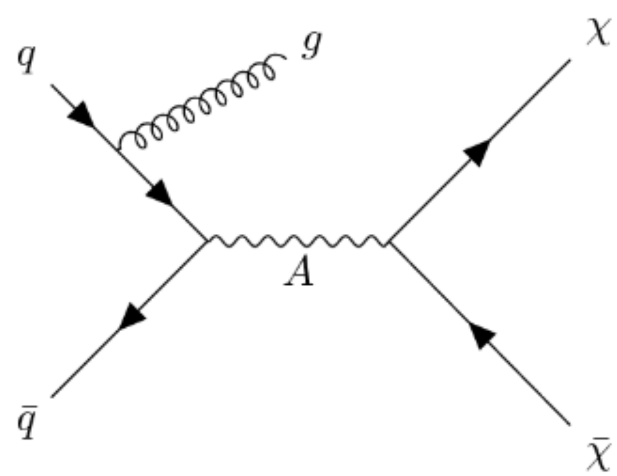
- Uses the 3.2fb^{-1} of data collected by the ATLAS detector at the LHC in 2015.
    - A small set of well understood data for proof-of-principle analysis.
- Keeps search as general as possible with as few assumptions as possible, as to not miss anything.
- Produced and published detector-corrected data for reinterpretation of new / future models.

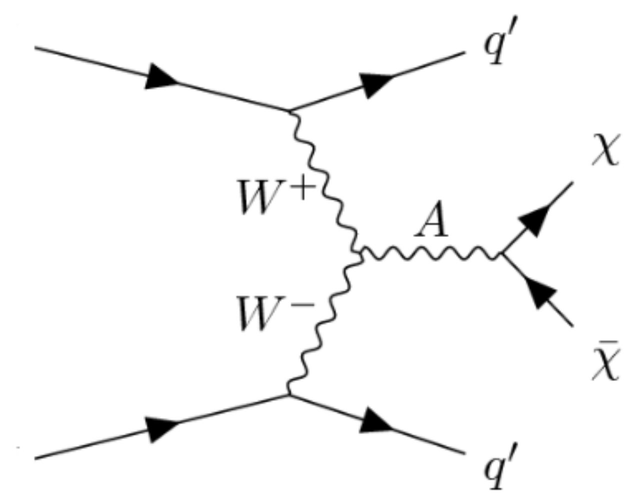

The Analysis

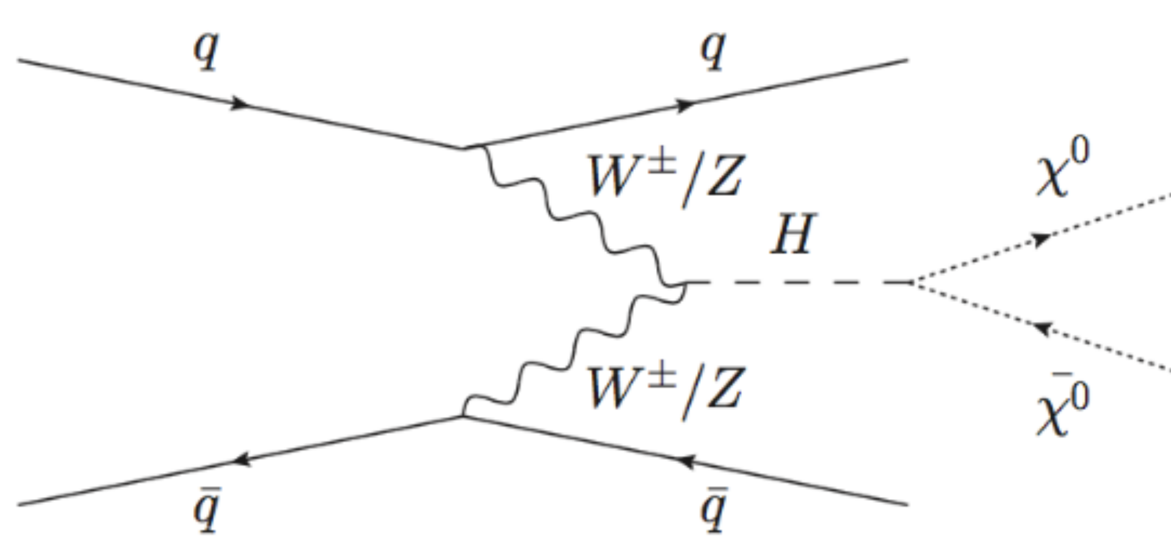
Selecting a Generic Experimental Signature

- Need a visible measurable object to identify a collision event that could produce dark matter
  - Hadronic jet(s) recoiling are well understood signatures









Using a Ratio

Measure differential detector-corrected production cross-section ratio sensitive to new phenomena producing anomalous P_T^{miss} +jets rate.

Number of background-subtracted events in MET+jets signal region

$$R_{\text{miss}} = \frac{\sigma(\not{p}_T + \text{jets})}{\sigma(Z(\rightarrow \ell^+\ell^-) + \text{jets})} = \frac{1}{C_Z}\frac{N(\not{p}_T + \text{jets})}{N(Z(\rightarrow \ell^+\ell^-) + \text{jets})}$$

Correction factor accounting for detector resolution and efficiency

Number of background-subtracted events in l^+l^-+jets signal region

In Standard Model, only contributions come from $Z \rightarrow \nu\tilde{\nu}$ decays.

Any excess above SM could indicate new physics.

Ratio reduces theoretical and experimental uncertainties.

Event Selection

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Numerator and denominator	≥ 1 jet	VBF
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV	
(Additional) lepton veto	No e, μ with $p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$	
Jet $\lvert y\rvert$	< 4.4	
Jet p_{T}	> 25 GeV	
$\Delta\phi_{\mathrm{jet_i}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}}$	> 0.4, for the four leading jets with $p_{\mathrm{T}} > 30$ GeV	
Leading jet p_{T}	> 120 GeV	> 80 GeV
Subleading jet p_{T}	–	> 50 GeV
Leading jet $\lvert\eta\rvert$	< 2.4	–
m_{jj}	–	> 200 GeV
Central-jet veto	–	No jets with $p_{\mathrm{T}} > 25$ GeV
Denominator only	≥ 1 jet and VBF	
Leading lepton p_{T}	> 80 GeV	
Subleading lepton p_{T}	> 7 GeV	
Lepton $\lvert\eta\rvert$	< 2.5	
$m_{\ell\ell}$	66–116 GeV	
ΔR (jet, lepton)	> 0.5, otherwise jet is removed	

Ratio Numerator: P_T^{miss} +jet Signal Region Data

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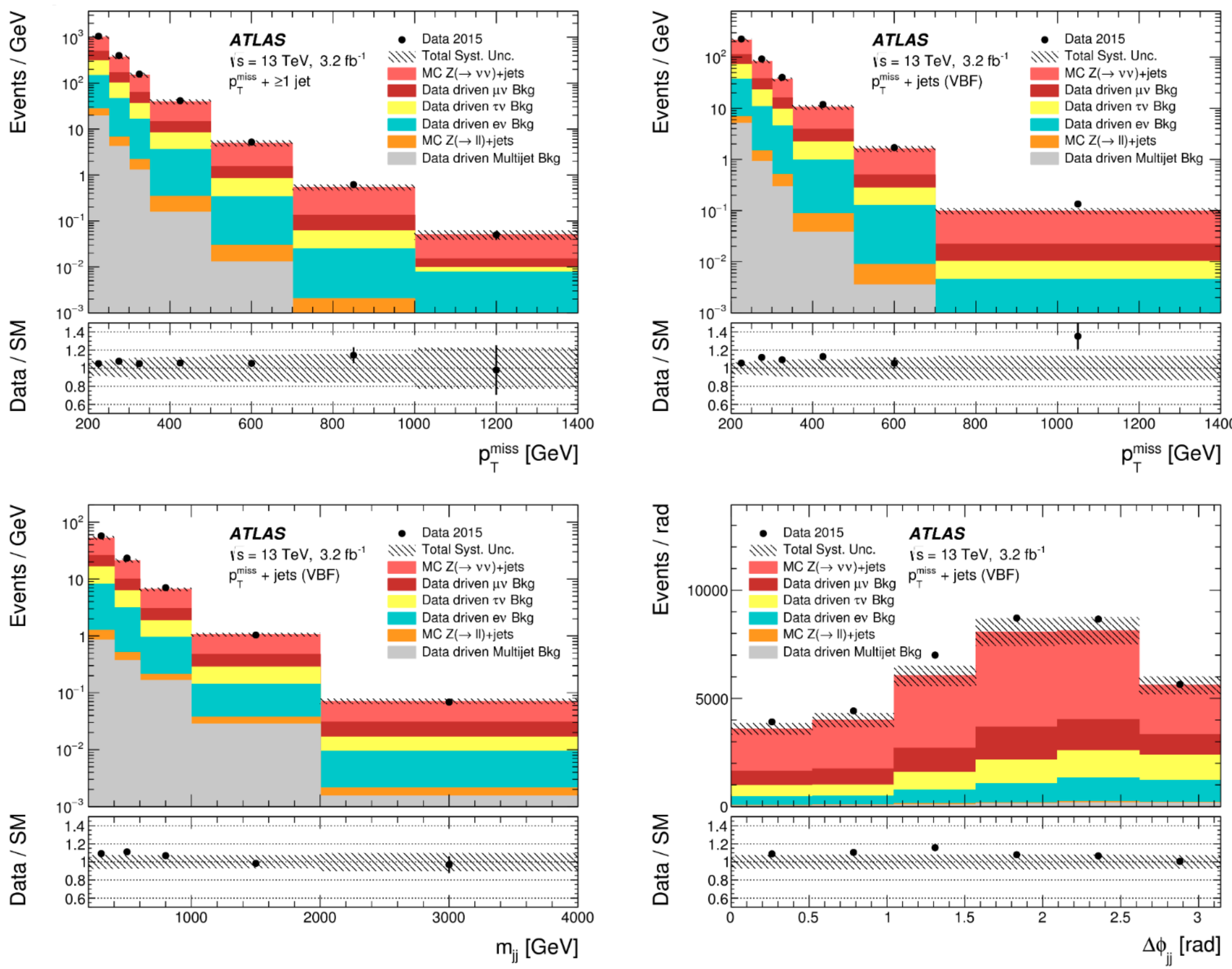

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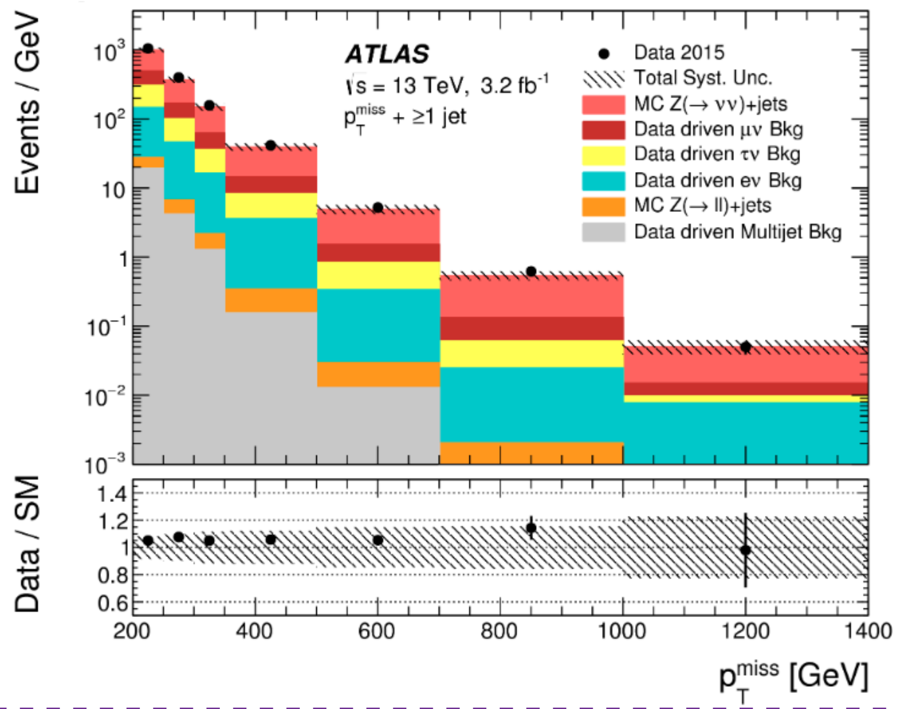
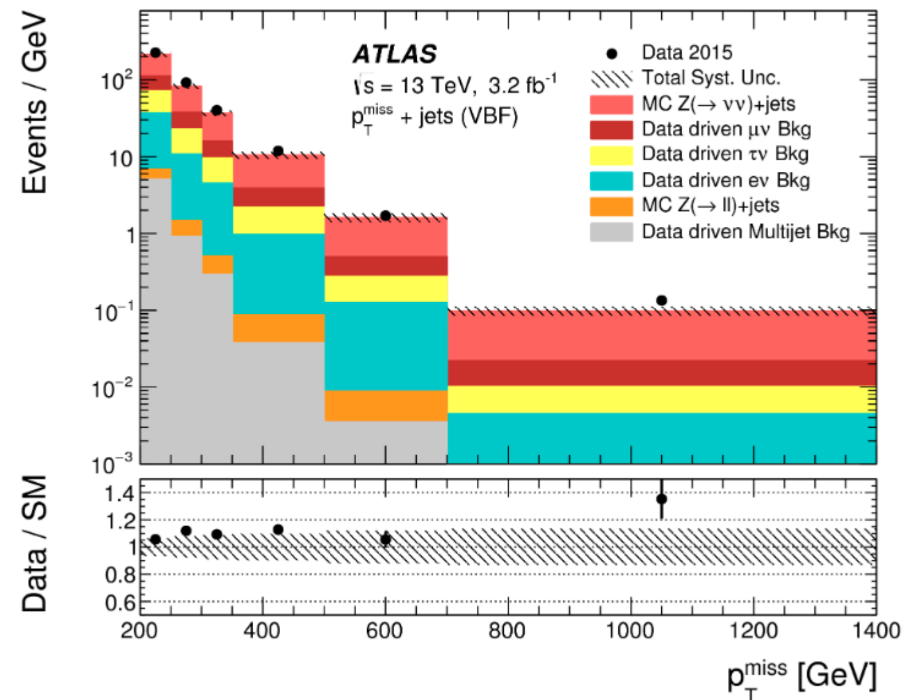
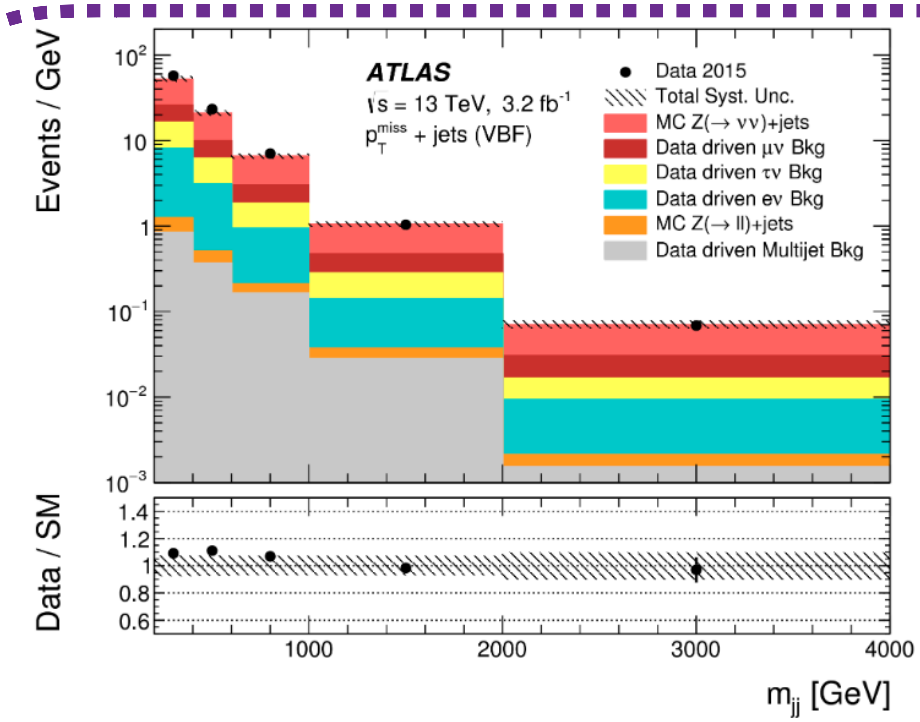
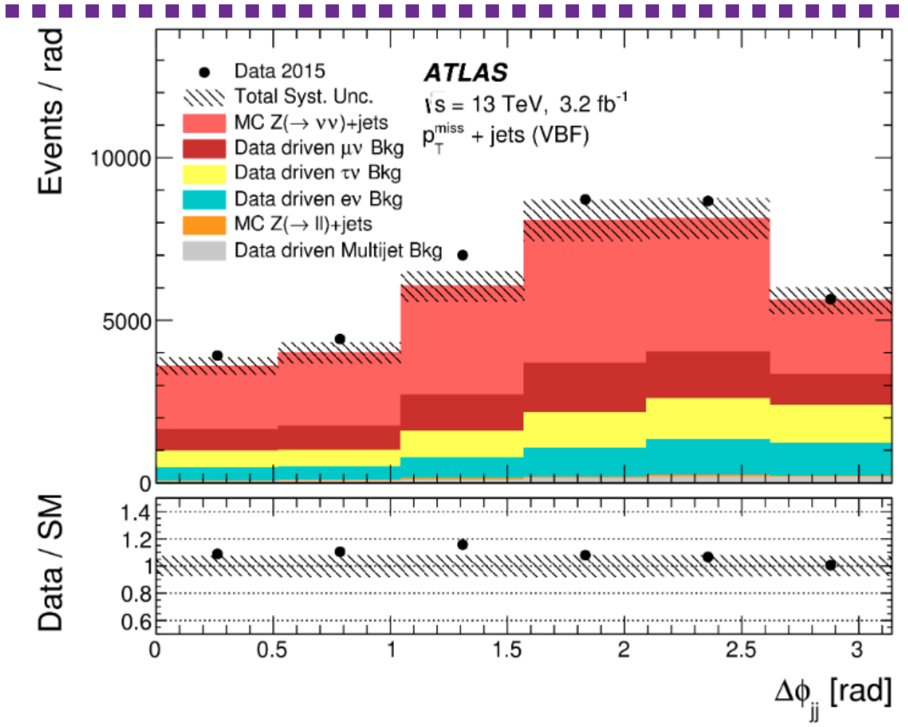
P_T^{miss}









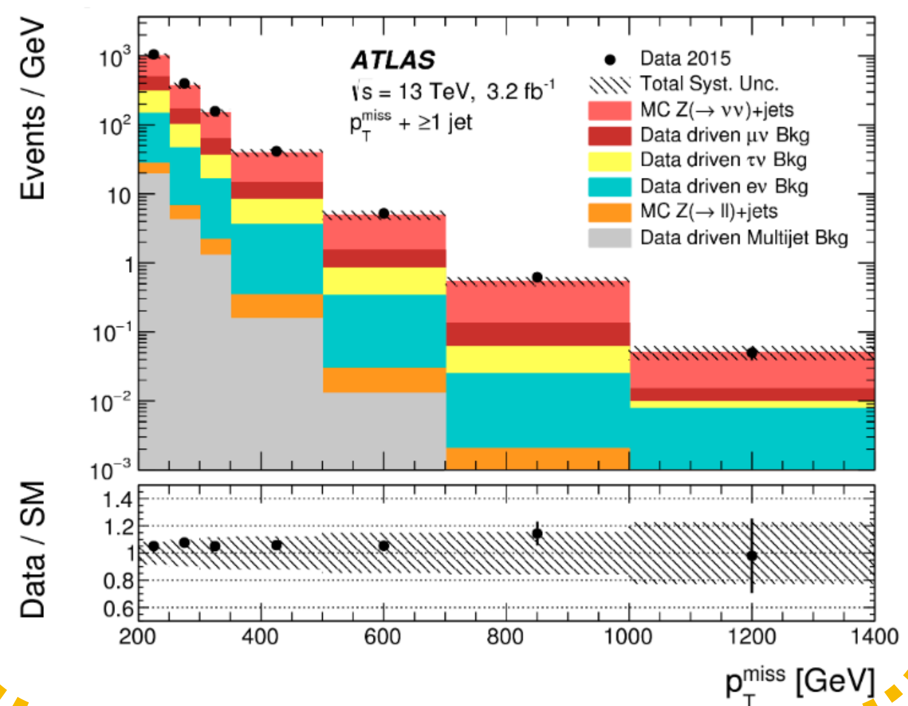
M_{jj} & $\Delta\phi_{jj}$

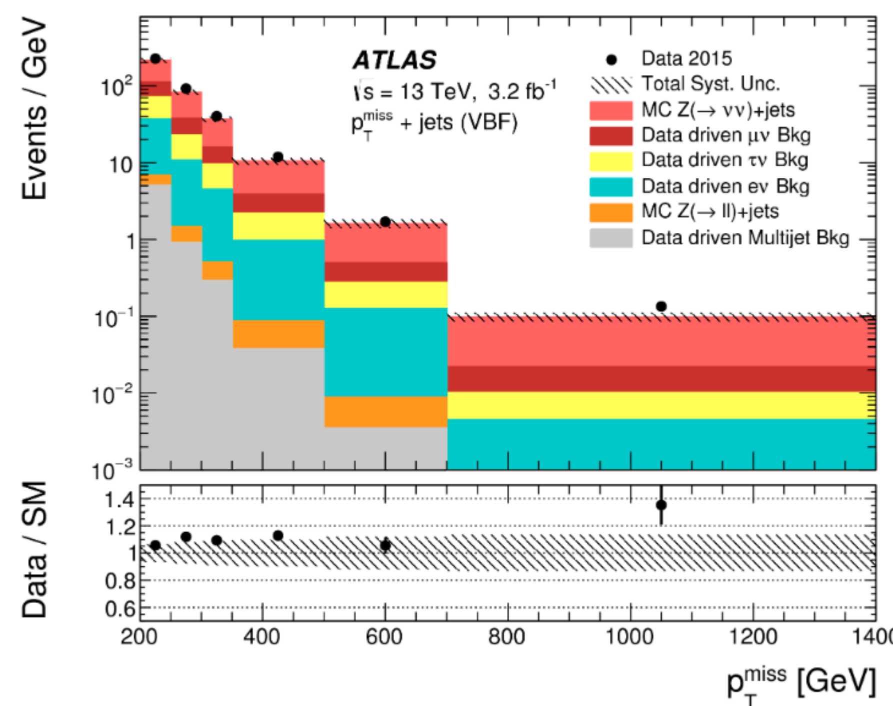
Ratio Numerator: P_T^{miss} +jet Signal Region Data

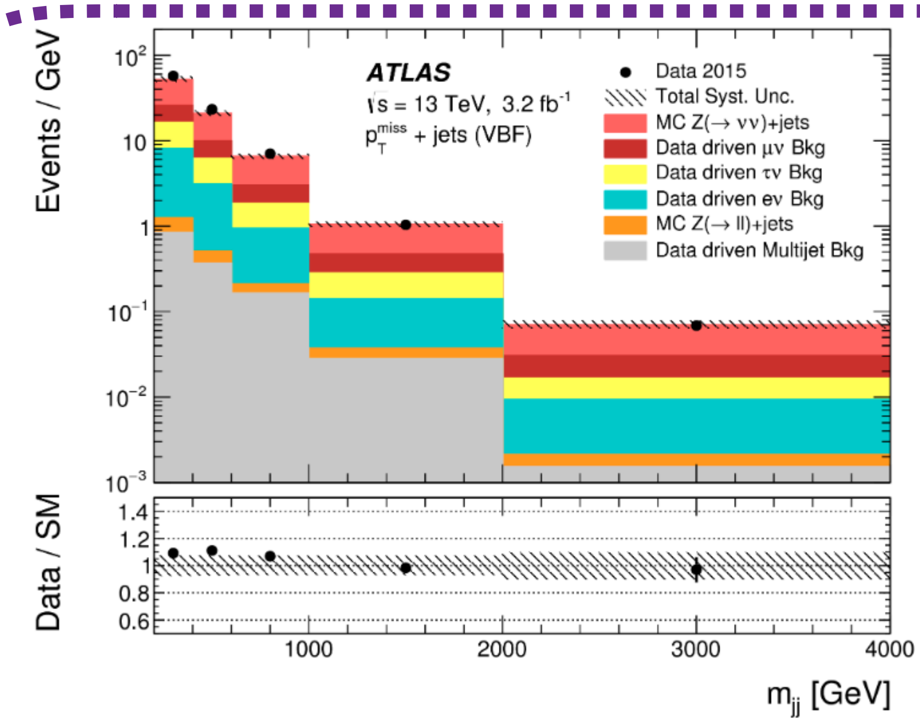
≥1 jet

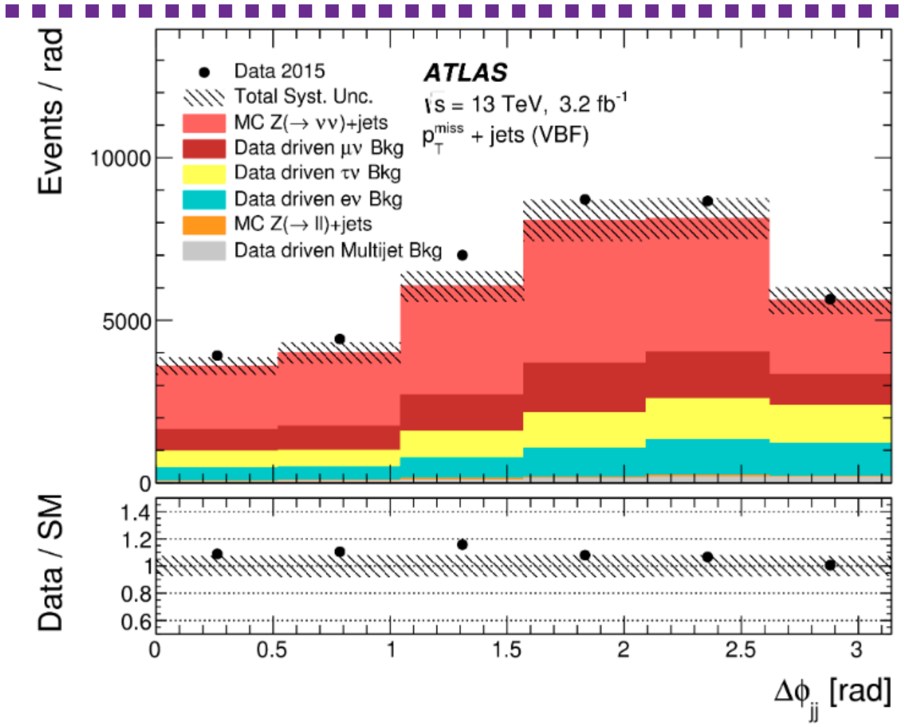
≥ 2 jets

P_T^{miss}









M_{jj} & $\Delta\phi_{jj}$

Ratio Denominator: l^+l^- + jet Signal Region Data

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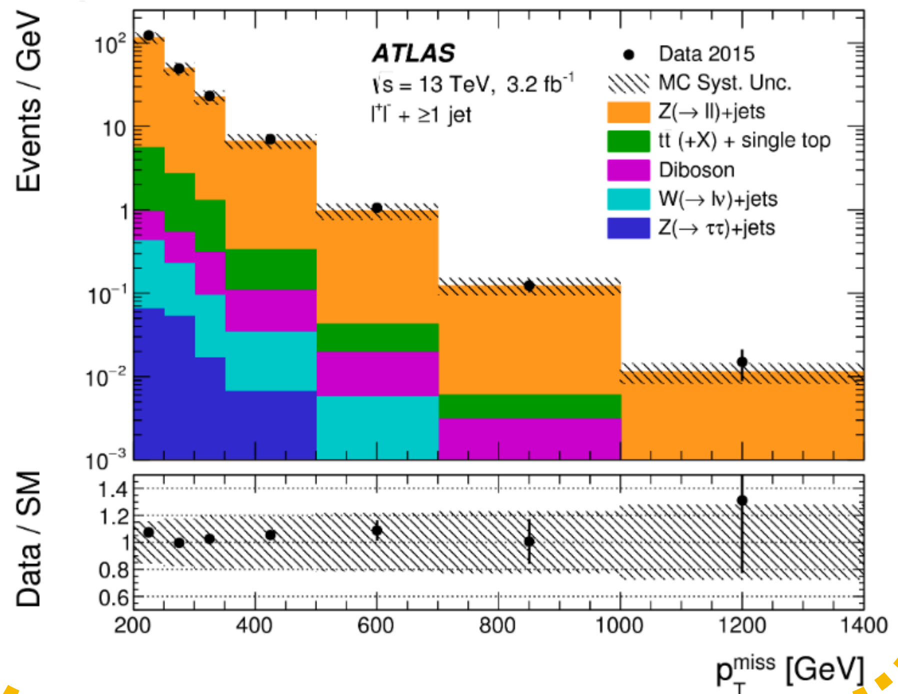
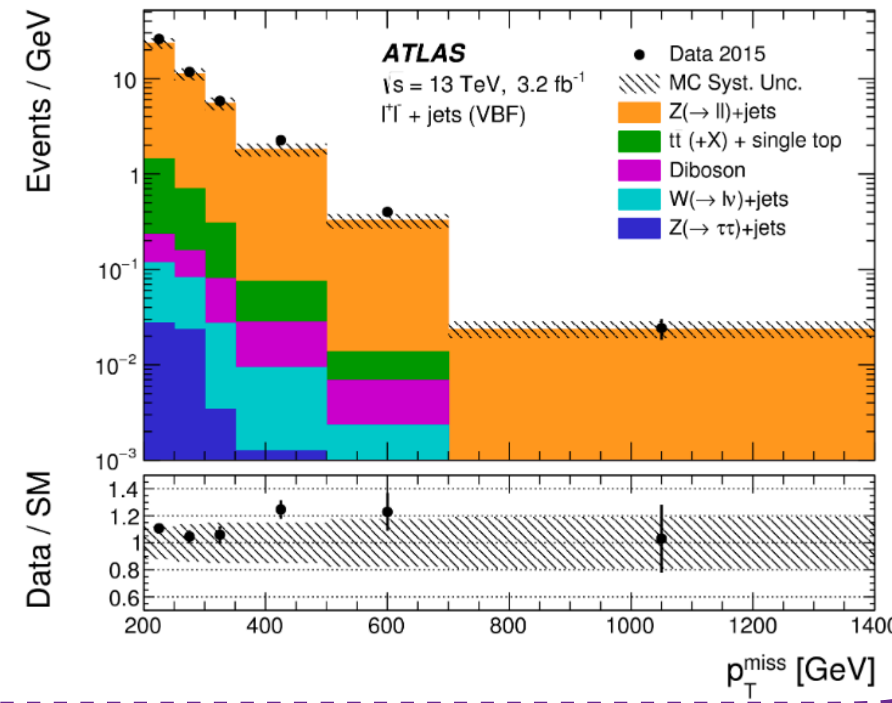
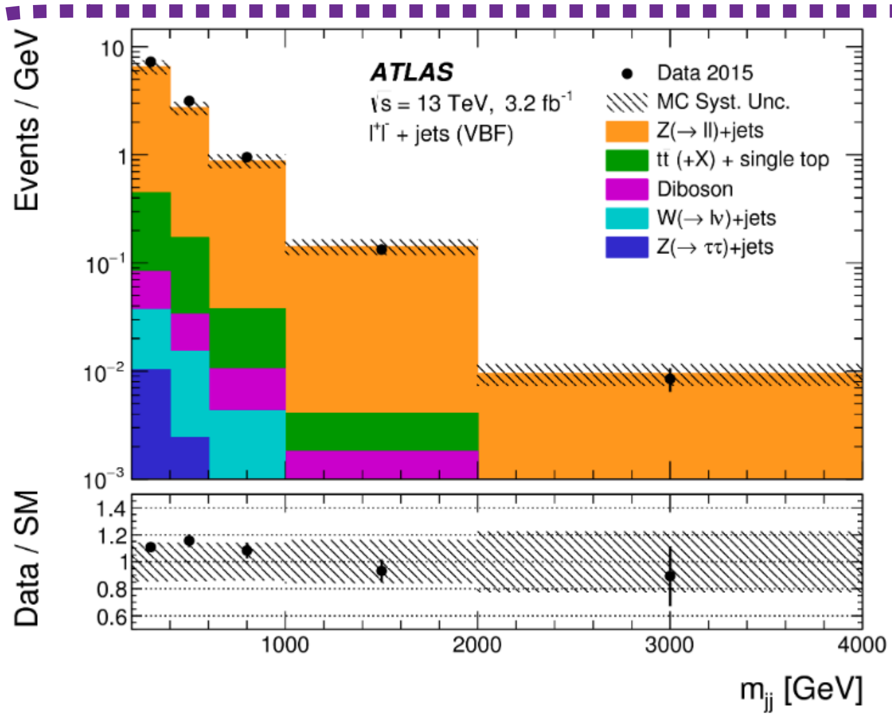
≥1 jet

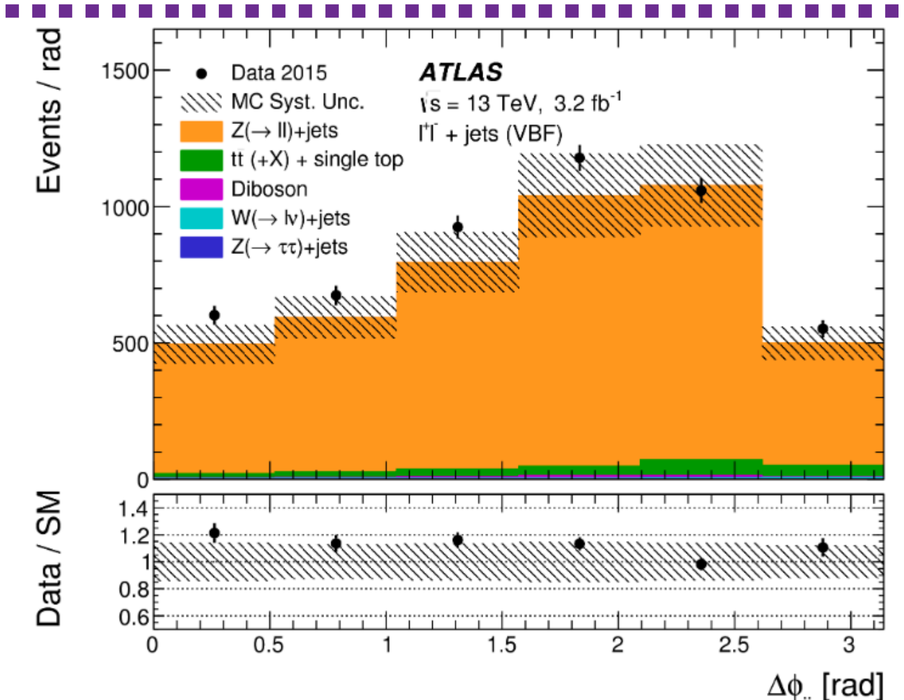
≥ 2 jets

P_T^{miss}









M_{jj} & $\Delta\phi_{jj}$

Putting the Ratio Together

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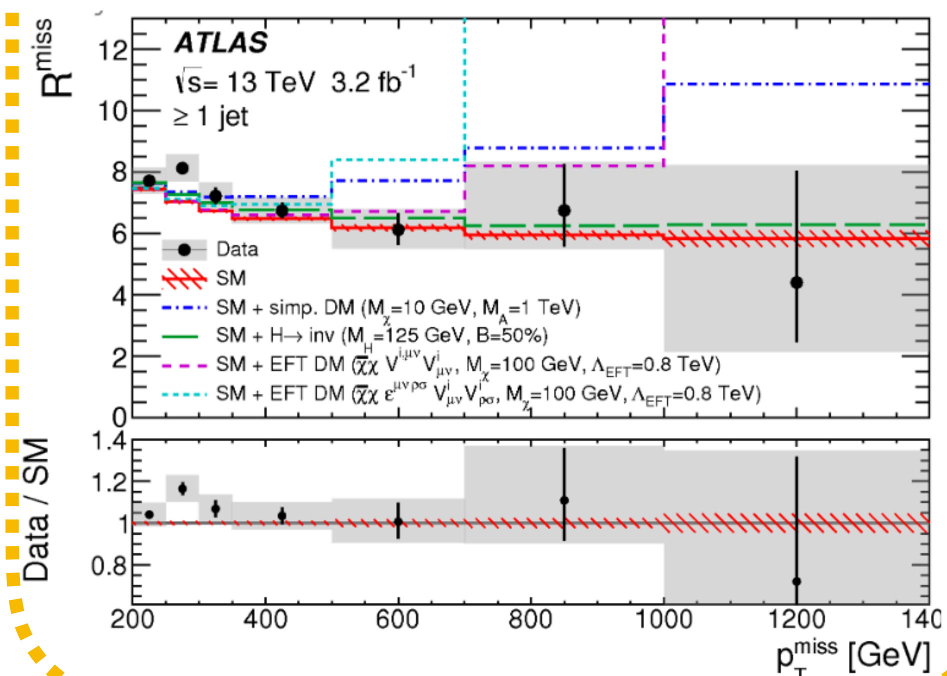
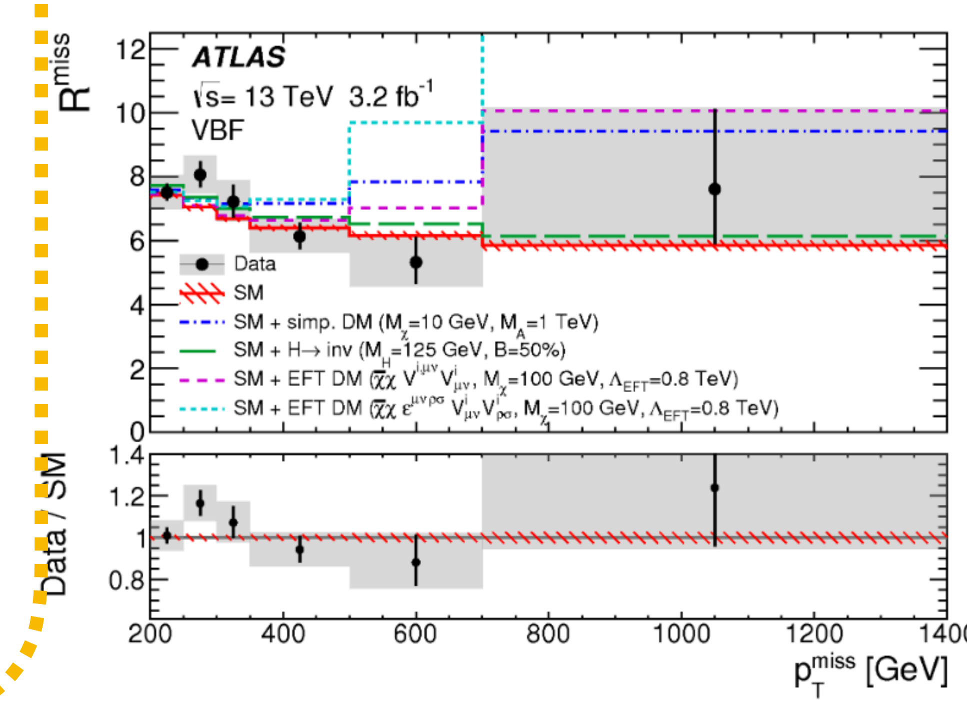
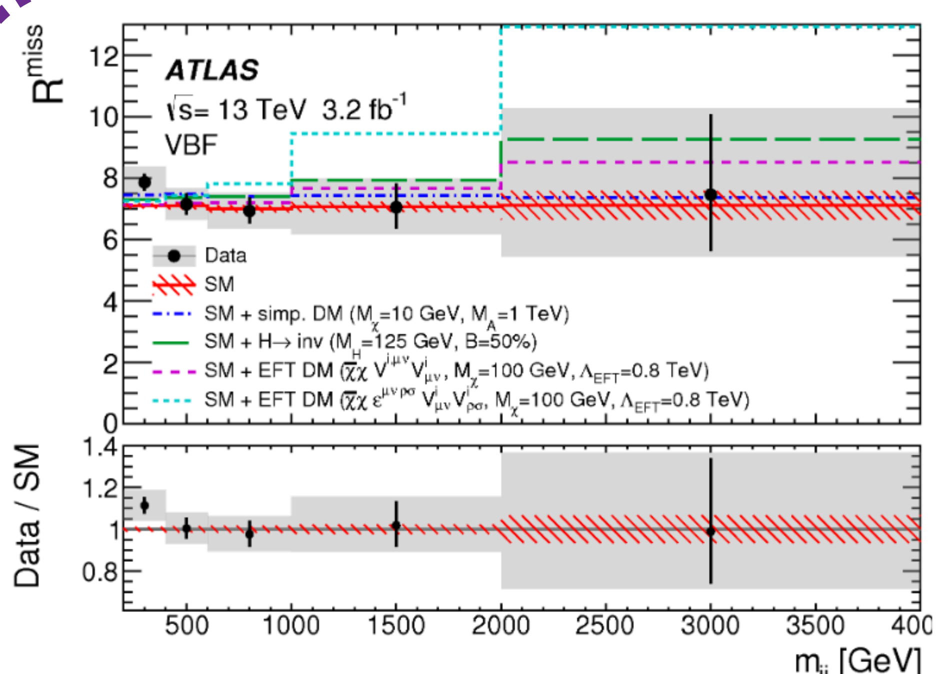
≥1 jet

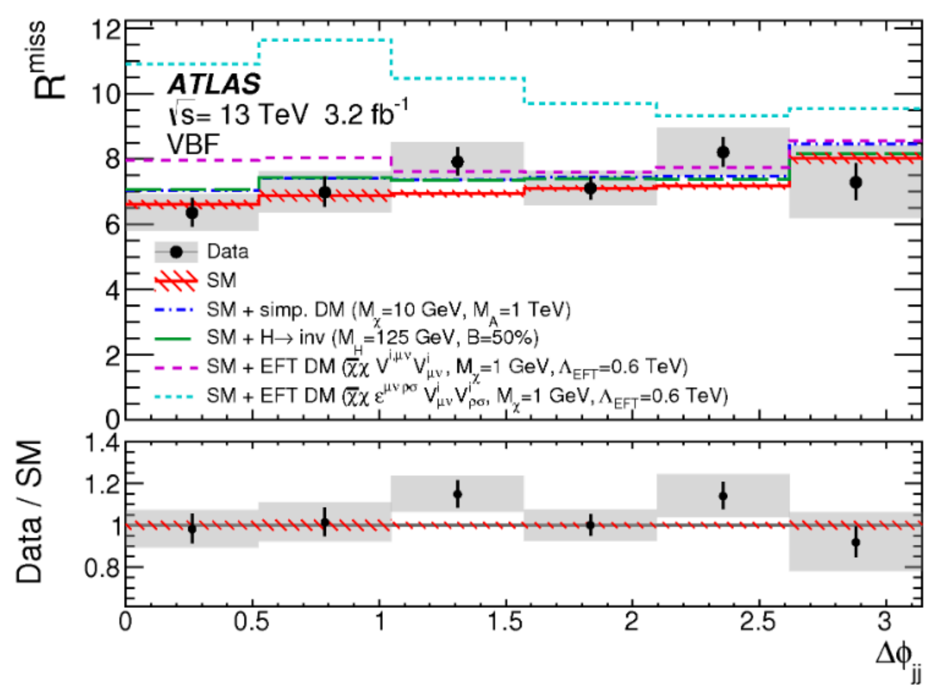
≥ 2 jets

P_T^{miss}





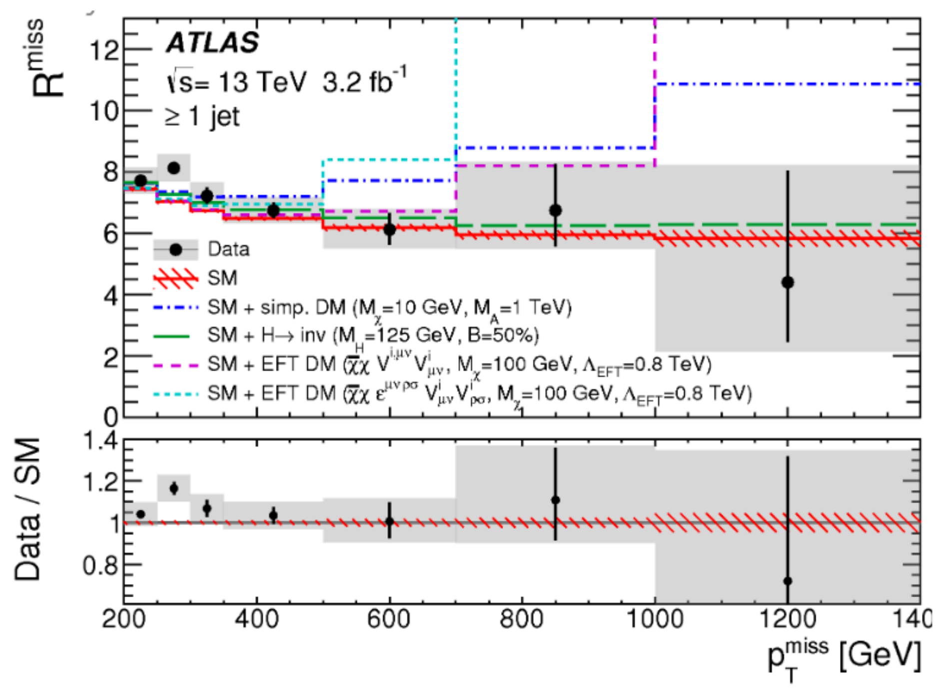


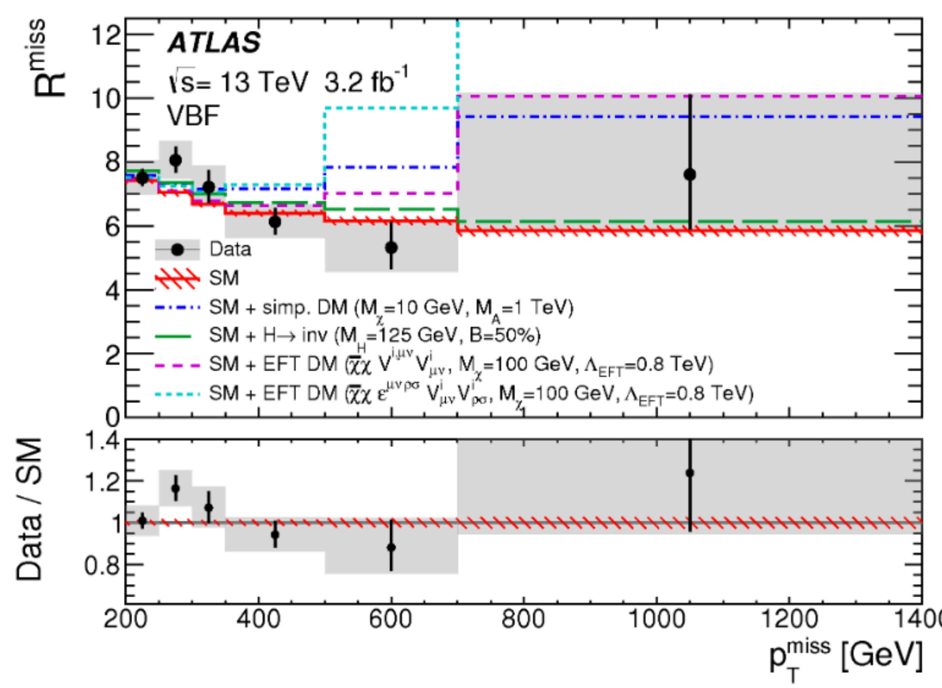


M_{jj} & $\Delta\phi_{jj}$

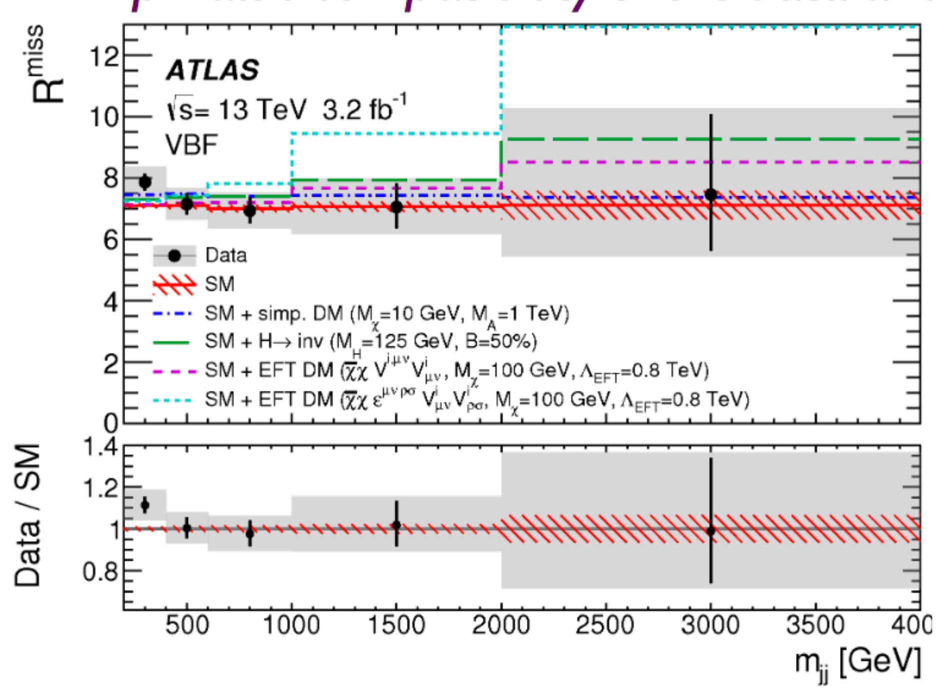
Putting the Ratio Together

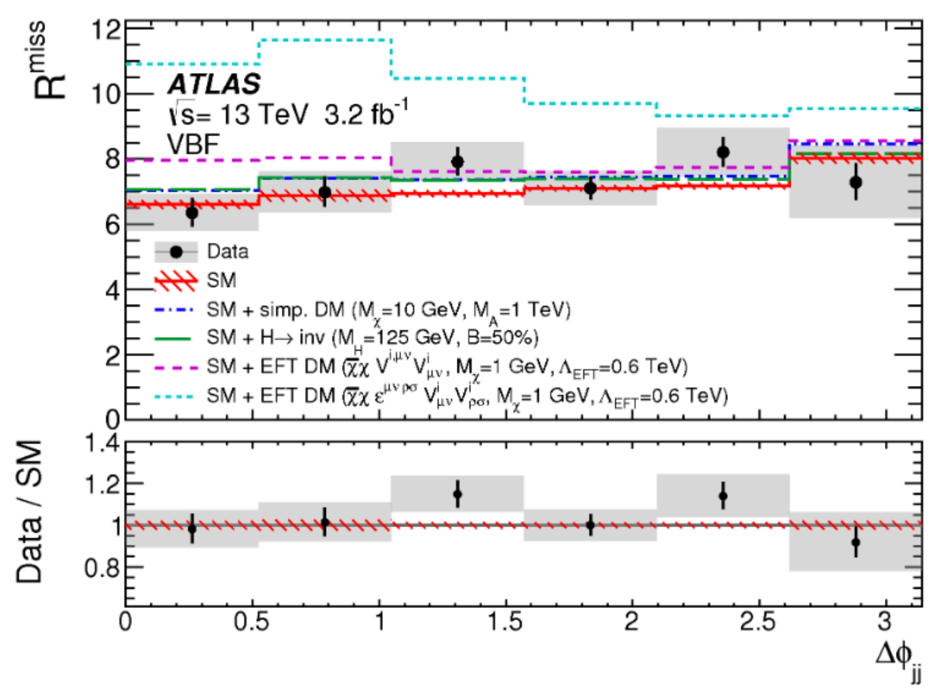
A number of different dark matter models were compared to the Standard Model.

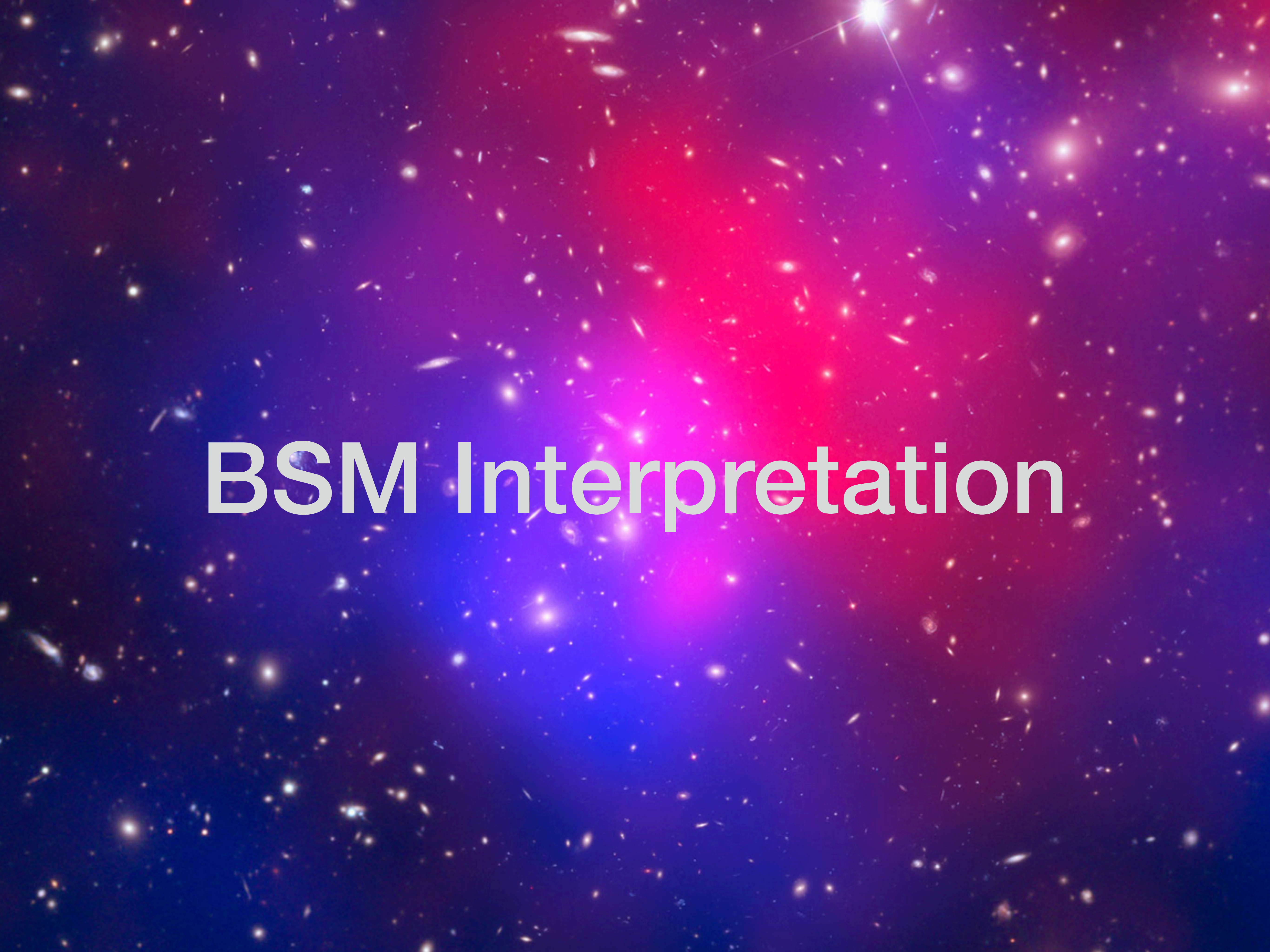




***p*-value compatibility of the data and the SM across all four distributions is 78%**

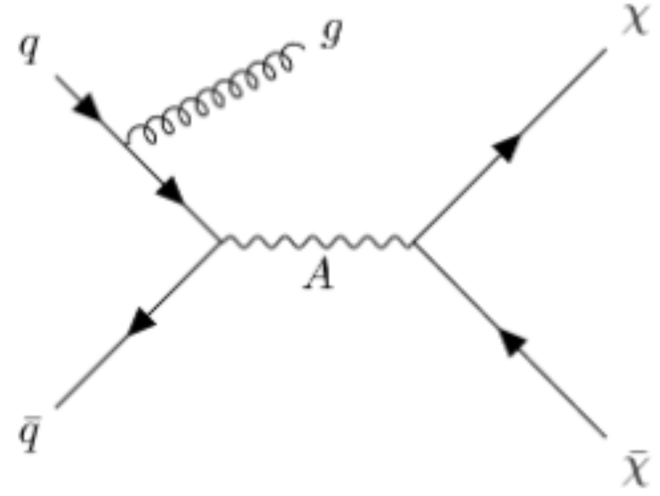


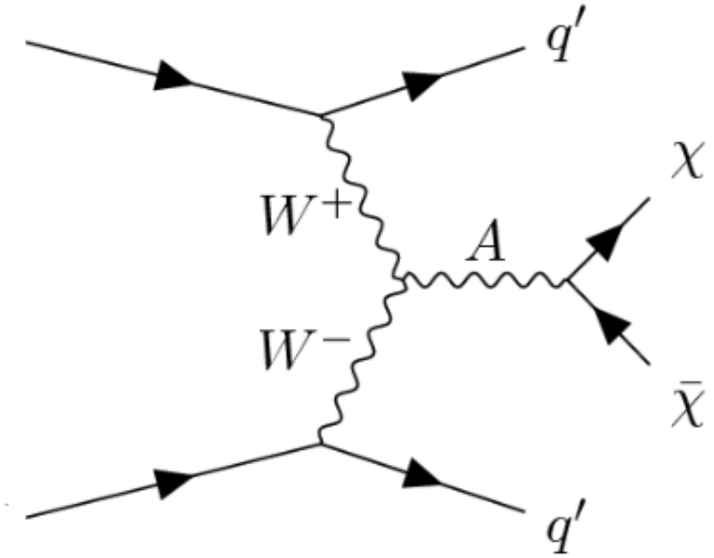


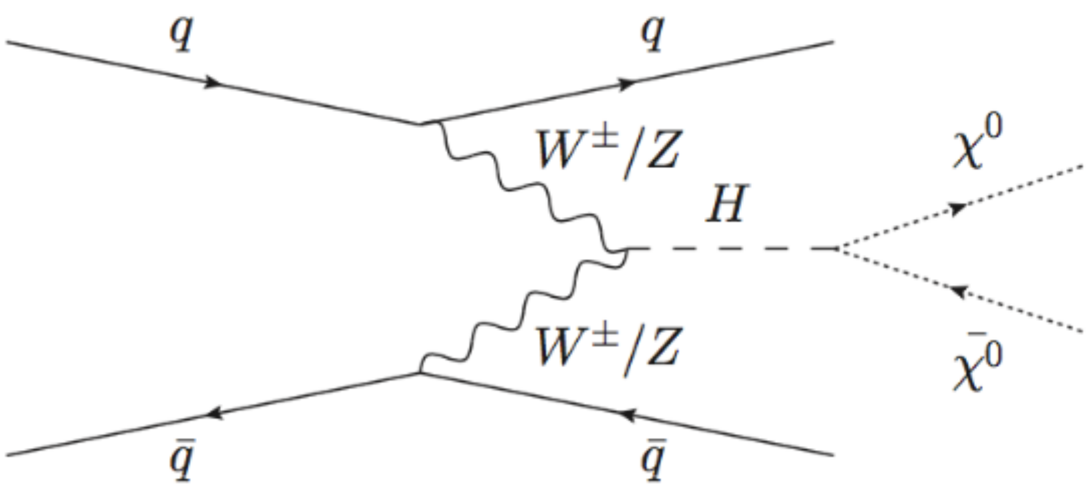

BSM Interpretation

Investigating Dark Matter Models

- Use detector-corrected data to investigate three benchmark dark matter models:
  - Dark matter coupling to quarks
  - Dark matter coupling to EW bosons
  - Dark matter coupling to Higgs bosons



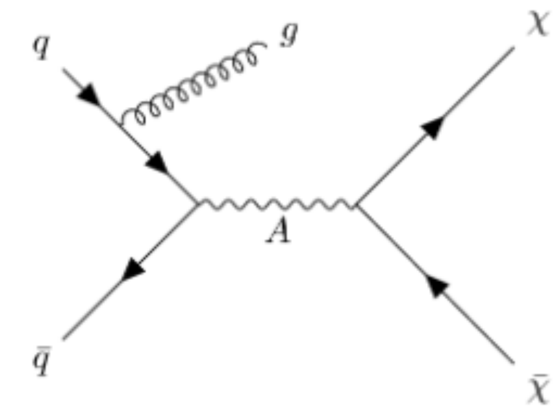


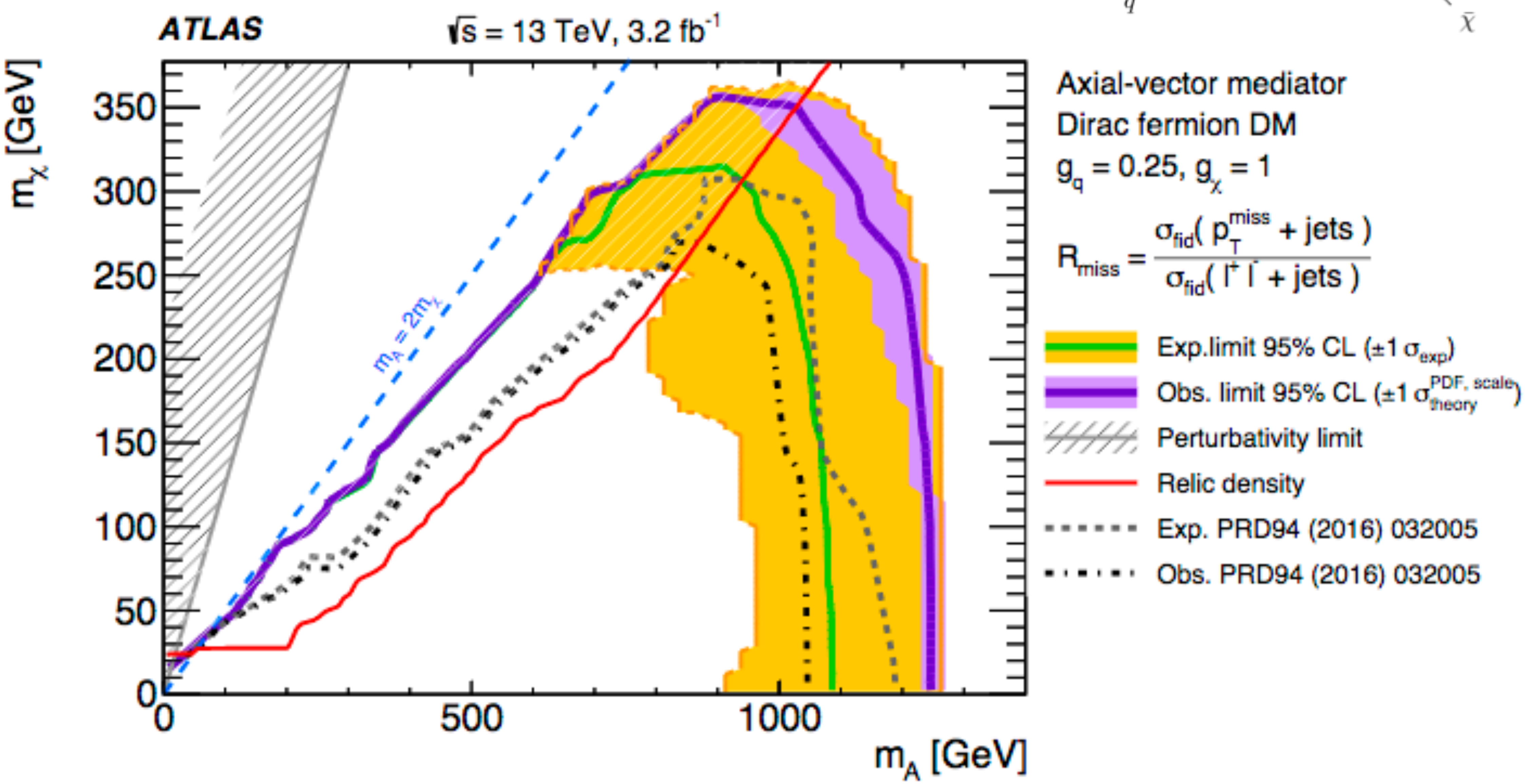


Limits set using CLs method with detector corrected ratio and all uncertainty information.

Dark Matter coupling to Quarks

Simplified model with an axial-vector mediator.





Reinterpretation of measured ratios results in competitive limits with dedicated collider searches

Dark Matter Coupling to EW Bosons

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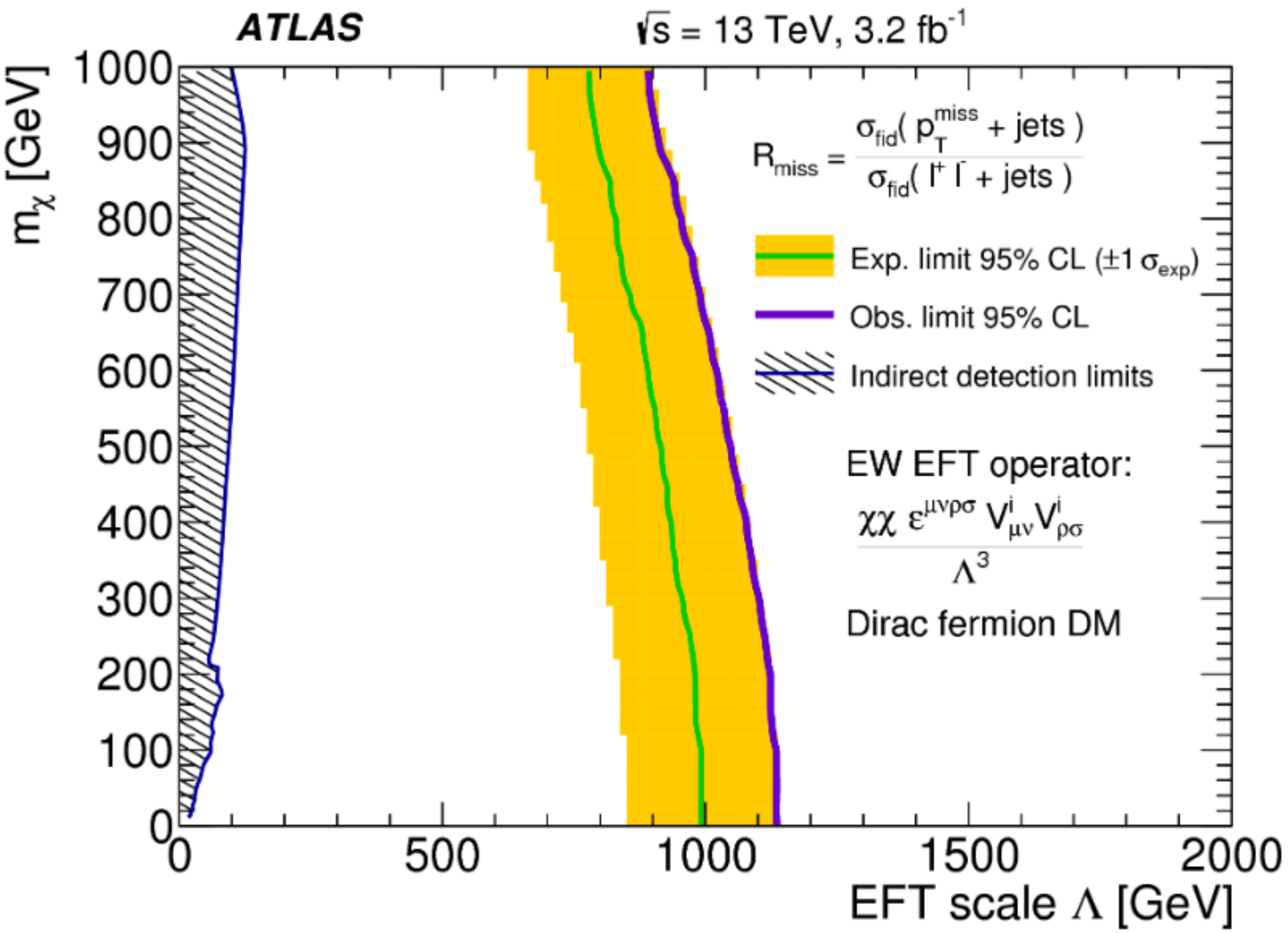
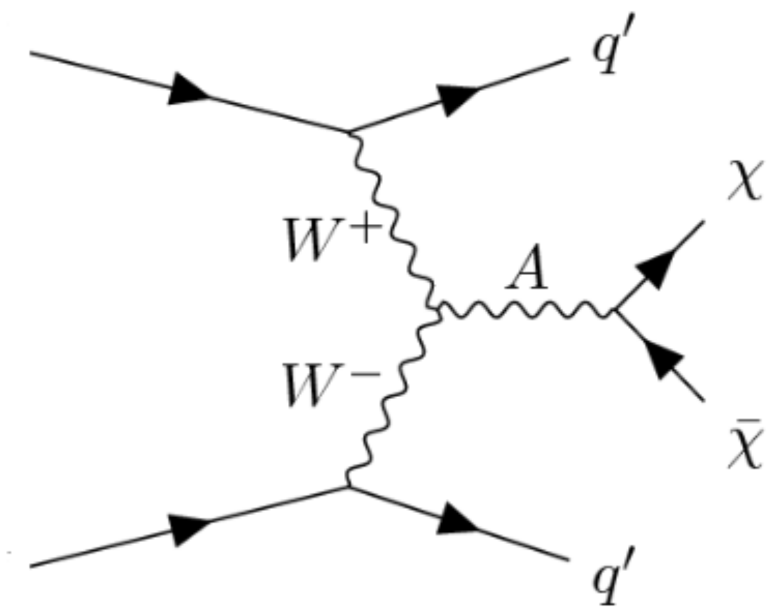
Dirac-Fermion dark matter produced via Vector Boson Fusion

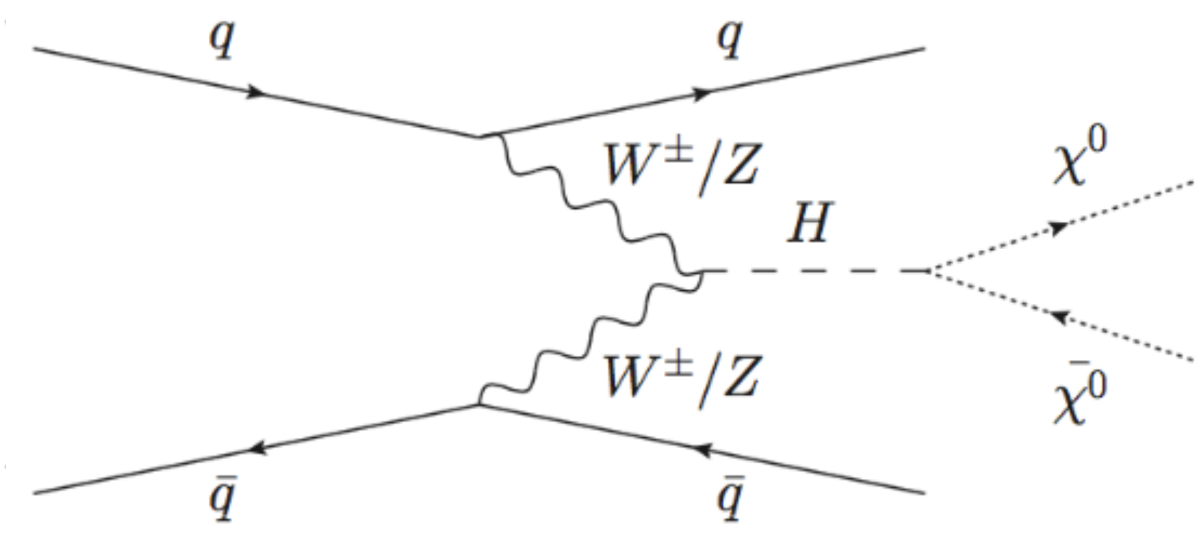


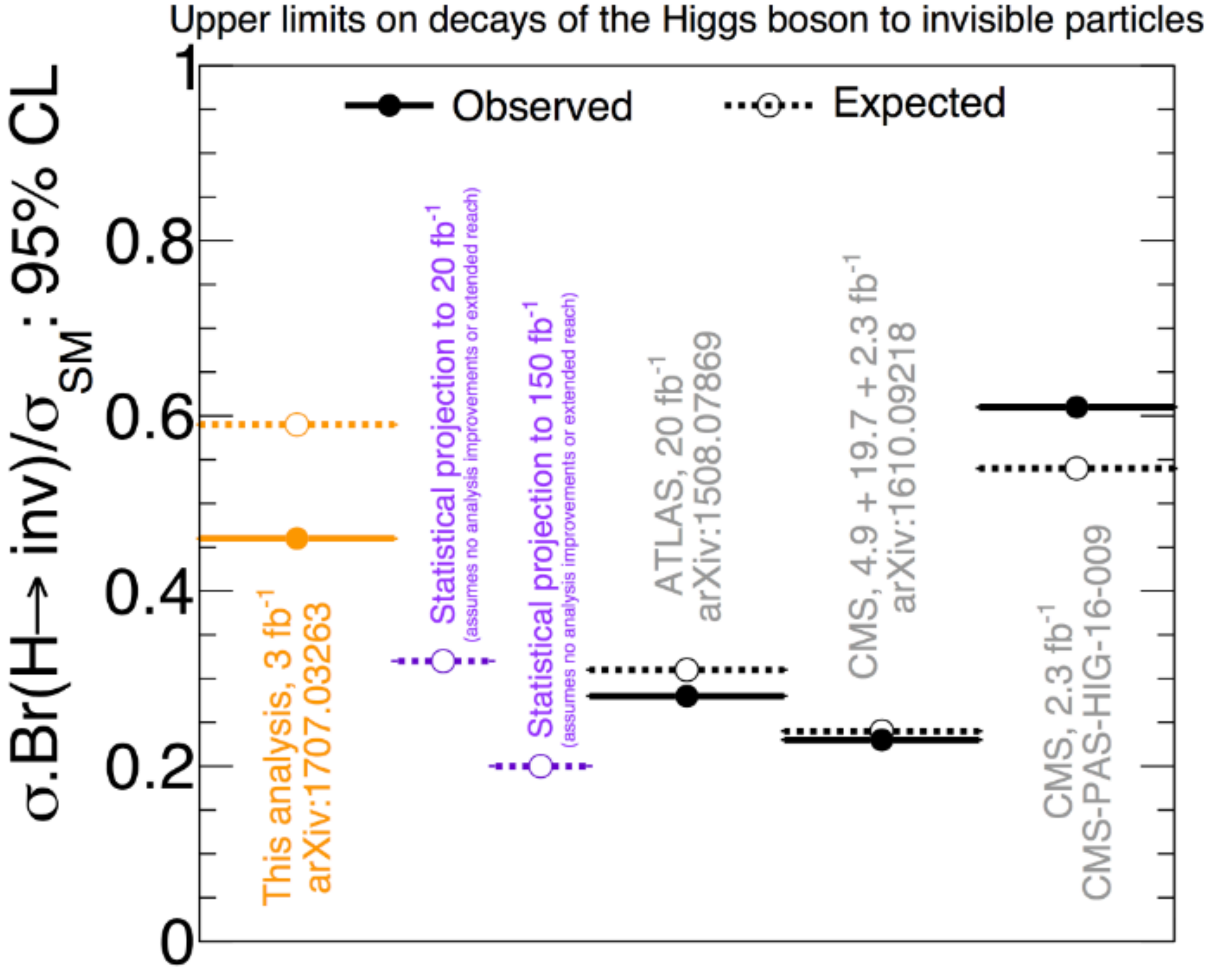


Strongest Limits so far on such interactions.

Dark Matter Coupled to Higgs Bosons

Higgs Boson Decay





Measured ratio results in competitive sensitivity in comparison to dedicated searches, despite being unoptimised for this channel.

Summary

- Presented an overview of a proof-of-principle search for general BSM physics in final states with jets and missing transverse momentum using detector-corrected observables.
- Measurement:
  - Has sensitivity to properties of new phenomena
  - Competitive with benchmark specialised searches
  - Can be reinterpreted with new / future models

Paper: Eur. Phys. J. C77 (2017) 11, 765; arXiv:1707.03263
Rivet Analysis Code: https://rivet.hepforge.org/analyses/ATLAS_2017_I1609448.html
Data: https://hepdata.net/record/ins1609448

Backup

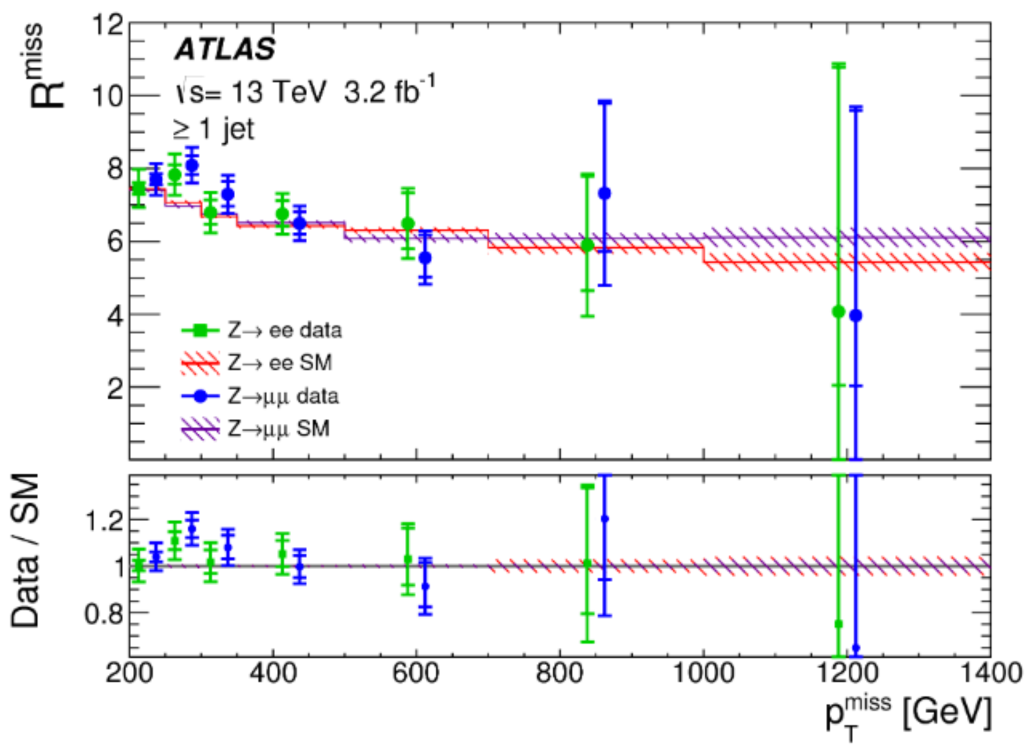
The published Detector-Corrected Results

Everything necessary to perform a reinterpretation of this data has been published.

- Paper: arXiv:1707.03263
- Rivet analysis code: https://rivet.hepforge.org/analyses/ATLAS_2017_I1609448.html
- HEPData Record: https://hepdata.net/record/ins1609448
    - Containing:
        - Measured Ratio
        - SM Ratio
        - SM numerator and denominator
        - Covariance matrices

The Ratio

- The denominator provides a constraint on the SM numerator.
- Sources of uncertainty cancel because the requirements on the hadronic system and the measured variables are similar in numerator and denominator.
- This is done by treating the identified leptons as invisible when calculating the P_T^{miss}.



Number of background-subtracted events in MET+jets signal region

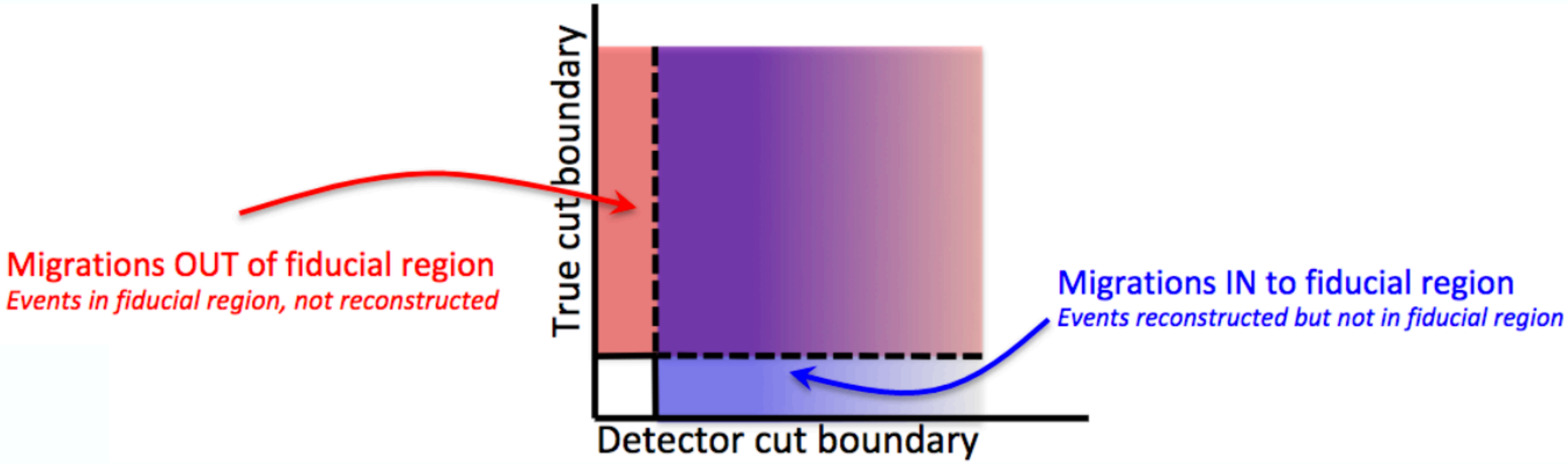
$$R_{\text{miss}} = \frac{\sigma(\not{p}_T + \text{jets})}{\sigma(Z(\to \ell^+\ell^-) + \text{jets})} = \frac{1}{C_Z}\frac{N(\not{p}_T + \text{jets})}{N(Z(\to \ell^+\ell^-) + \text{jets})}$$

Correction factor accounting for detector resolution and efficiency

Number of background-subtracted events in l^+l^-+jets signal region

Electron and Muon Ratio Data found to have good agreement.

Correcting for Detector Effects



$$\sigma^{\text{particle-level}} = \frac{(N_{\text{data}} - N_{bkg})}{\mathcal{L}} \frac{\epsilon^{\text{particle-level}}}{\epsilon^{\text{reco-level}}}$$

- Corrections for P_T^{miss}, jet-based variables, and lepton veto efficiencies almost completely cancel in the ratio.
- The dominant correction factor arises from the inefficiency of reconstructing the charged leptons in the denominator.
- The correction factor is 0.9-0.85 in the muon channel and 0.7-0.8 in the electron channel. (Reconstruction for muons has higher efficiency than for electrons in this analysis)

Monte Carlo Simulation

- Events containing Z and W bosons were generated using MC event generators
- Samples contributing to inclusive Z+jets production were used for the detector corrections.
- Samples of W -> l v were used to estimate backgrounds.
- Sherpa was used for events containing single Z and W bosons.

Backgrounds

- The dominant background for P_T^{miss} +jets numerator is from an leptonically decaying W boson produced with jets.
    - This would pass the veto on additional leptons if the lepton is not reconstructed, or is outside the acceptance of the detector.
    - Two control regions were used to estimate this background: W -> e v and W-> μ v.
- A smaller background arises from multi jet events in which jets are mismeasured, leading to P_T^{miss} .
    - Most of this background is removed by placing a requirement on Δϕ(jet, P_T^{miss}).
    - A control region where one of the four leading jets has Δϕ(jet, P_T^{miss}) < 0.1.
- The background to the denominator is dominated by top-antitop quark pairs, with smaller contributions from diboson, single-top-quark, W+jet and Z -> $\tau^+\tau^-$.

Systematic and Statistical Uncertainties

Systematic uncertainty source	Low p_T^{miss} [%]	High p_T^{miss} [%]	Low m_{jj} [%]	High m_{jj} [%]
Lepton efficiency	+3.5, −3.5	+7.6, −7.1	+3.7, −3.6	+4.6, −4.4
Jets	+0.8, −0.7	+2.2, −2.8	+1.1, −1.0	+9.0, −0.5
$W \to \tau\nu$ from control region	+1.2, −1.2	+4.6, −4.6	+1.3, −1.3	+3.9, −3.9
Multijet	+1.8, −1.8	+0.9, −0.9	+1.4, −1.4	+2.5, −2.5
Correction factor statistical	+0.2, −0.2	+2.0, −1.9	+0.4, −0.4	+3.8, −3.6
W statistical	+0.5, −0.5	+24, −24	+1.1, −1.1	+6.8, −6.8
W theory	+2.4, −2.3	+6.0, −2.3	+3.1, −3.0	+4.9, −5.1
Top cross-section	+1.5, −1.8	+1.3, −0.1	+1.1, −1.2	+0.5, −0.4
$Z \to \ell\ell$ backgrounds	+0.9, −0.8	+1.1, −1.1	+1.0, −1.0	+0.1, −0.1
Total systematic uncertainty	+5.2, −5.2	+27, −26	+5.6, −5.5	+14, −11
Statistical uncertainty	+1.7, −1.7	+83, −44	+3.5, −3.4	+35, −25
Total uncertainty	+5.5, −5.4	+87, −51	+6.6, −6.5	+38, −27