Probing dark matter with new detector-independent measurements at colliders

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Existing DM searches at colliders

Dedicated searches targeting e.g. SUSY-inspired models:

- Rich and specific phenomenology + DM candidate at the weak scale
- Distinctive collider signatures

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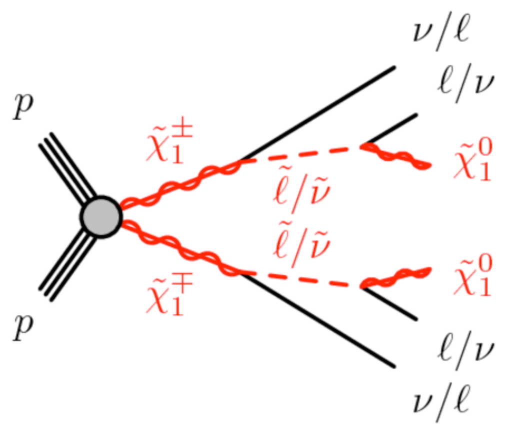
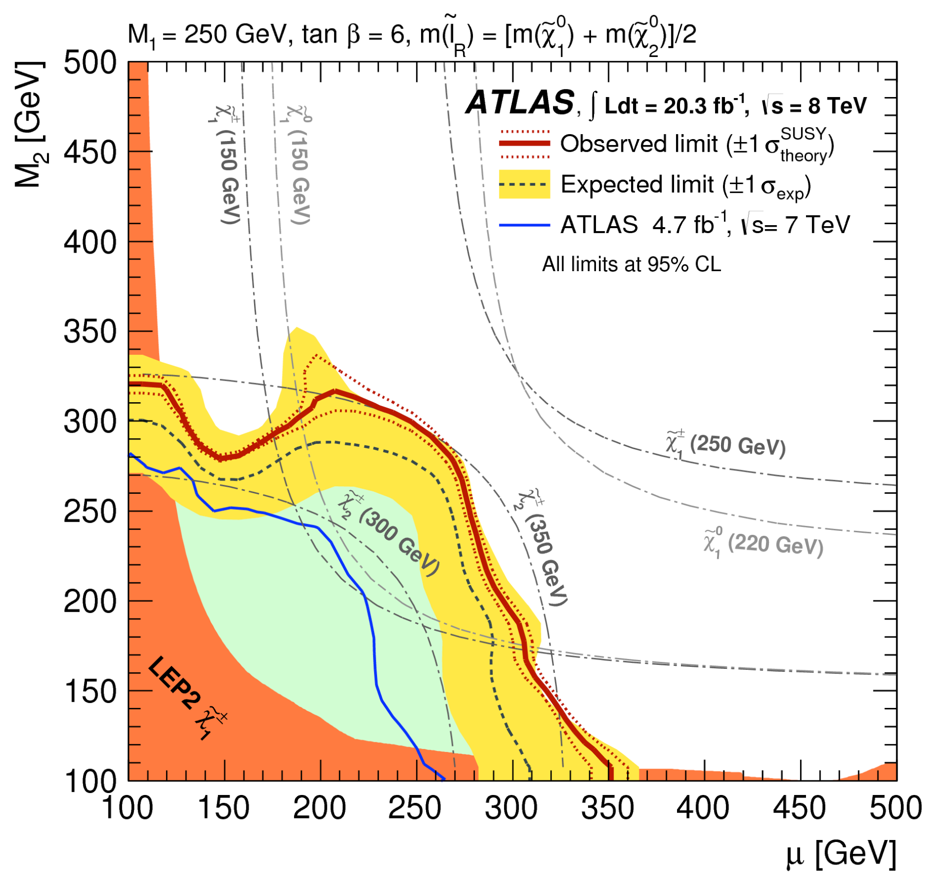
Difficulty in reinterpreting results



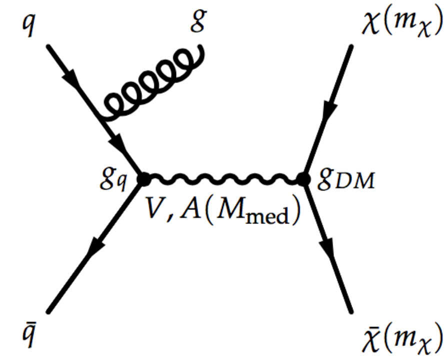
"95% CL exclusion regions in the μ–M_2 mass plane of the pMSSM with right-handed slepton mass $m^{\tilde{l}}_R = [\, m(\tilde{\chi}^0_1) + m(\tilde{\chi}^0_2)\,]/2$."

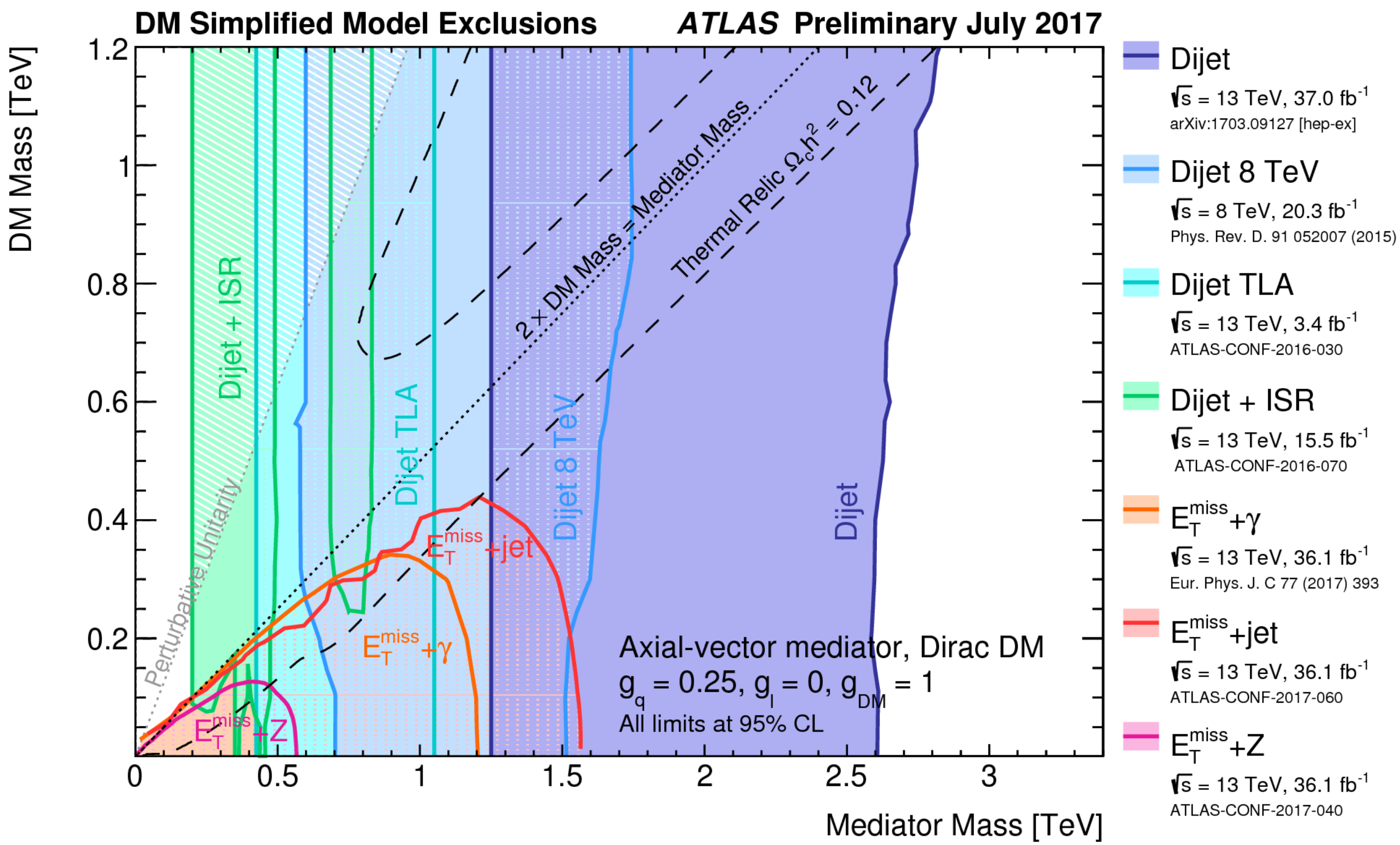


Existing DM searches at colliders

Simplified models: theory-agnostic approach

Still need to implement event selection, detector simulation, SM backgrounds to fully (re-)interpret existing searches





A need for new approaches?

Why not keep on doing (only) this?

- ☞ New dark matter theory in future? Reinterpretation.
- ☞ Looking for the wrong things? Over-optimisation.
- ☞ Improvements in SM modelling? Recalculation of limits.
- ☞ A global view on searches? Maximising sensitivity.

Moving forward

Addressing model dependence:

Make a new search for DM with as few assumptions as possible
even if this reduces our sensitivity to a previously-explored model.

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Addressing reinterpretability:

Correct the published data for detector effects: resolution/efficiency

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even if this reduces our sensitivity to a previously-explored model.

Addressing reinterpretability:

Correct the published data for detector effects: resolution/efficiency

Present data not as:

"here is what ATLAS sees in the search for DM model X"

but as

"here is how DM satisfying certain criteria looks in pp collisions at 13 TeV"

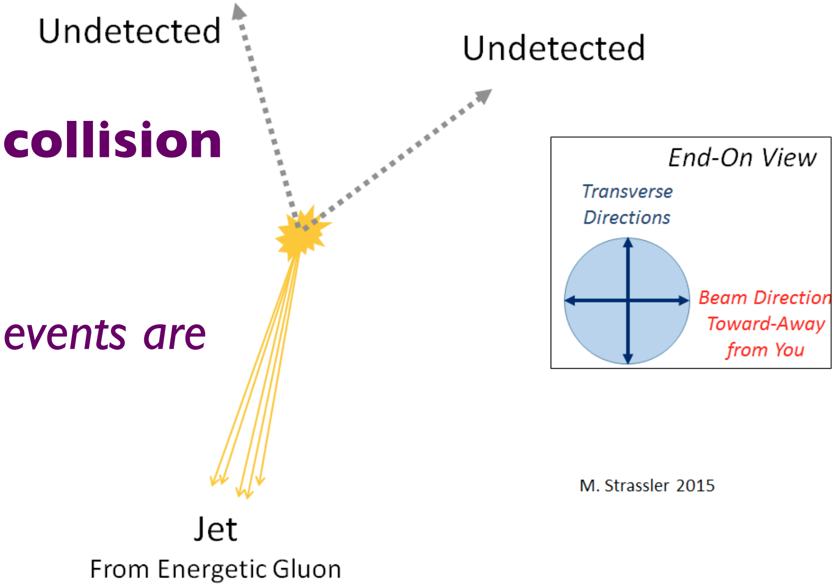
A critical distinction!

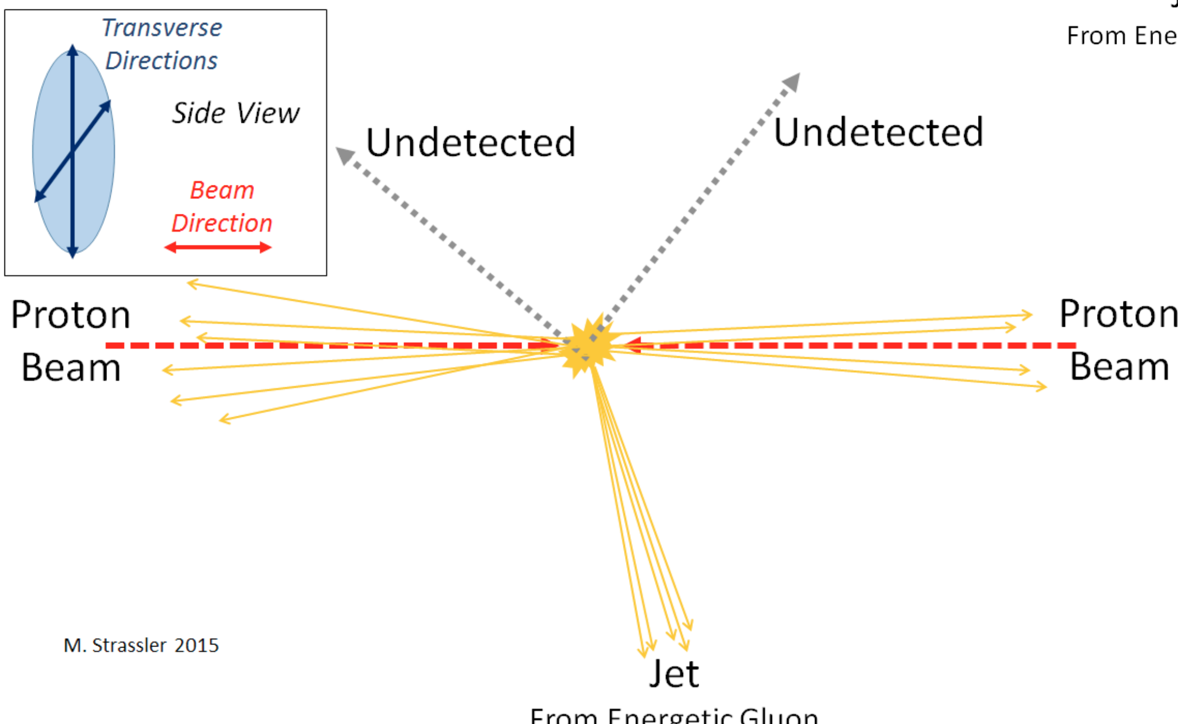
Selecting a generic experimental signature

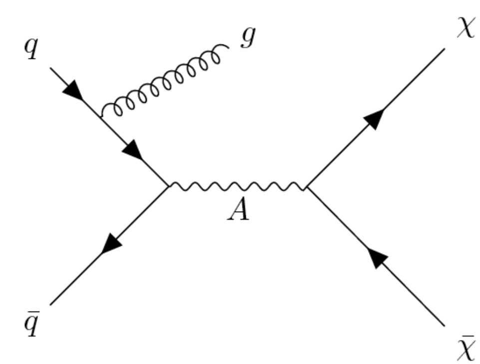
Need a visible object to identify pp collision

Simplest case is one hadronic jet recoiling

Might consider to determine rate at which such events are produced in ATLAS

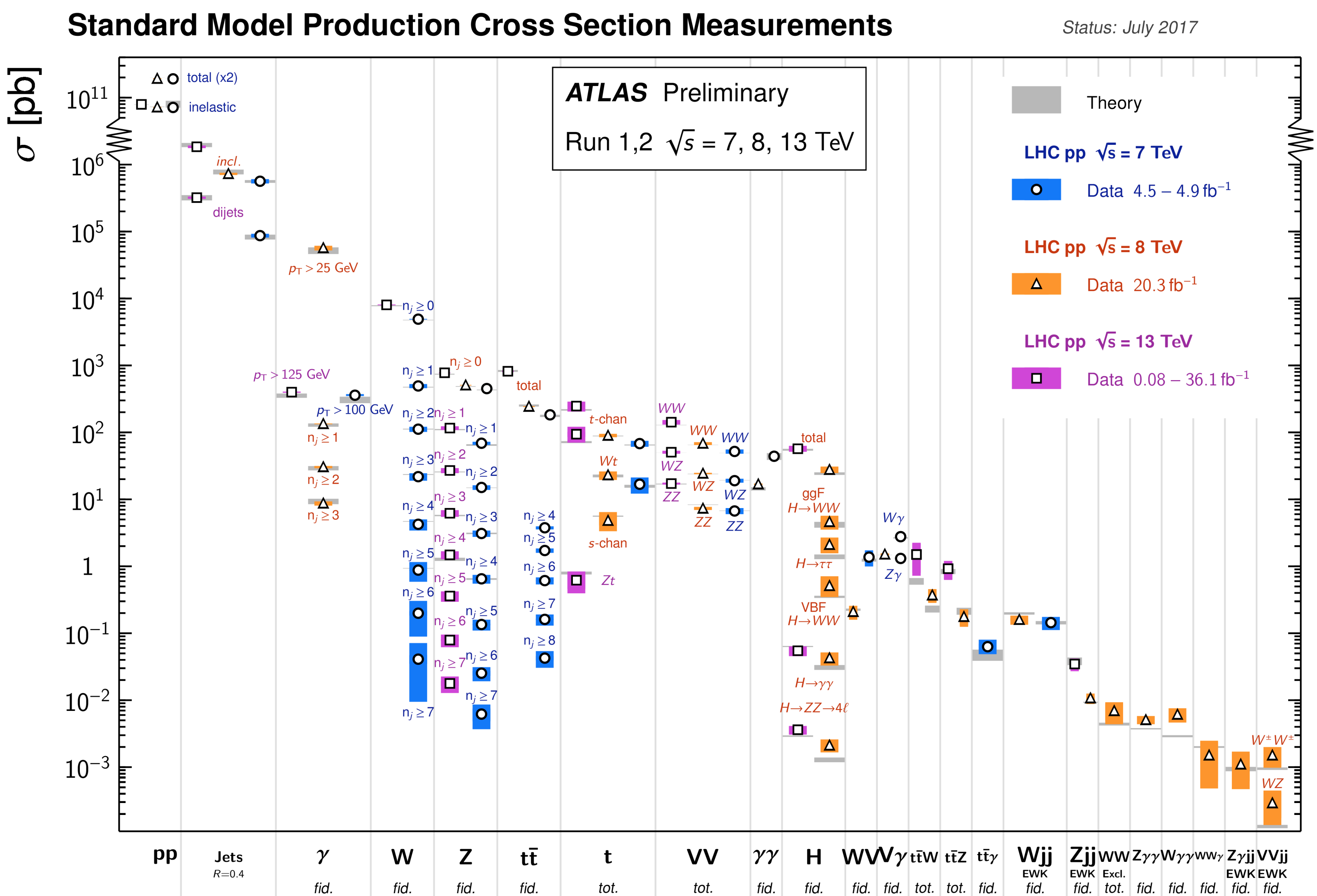






Correcting for detector effects

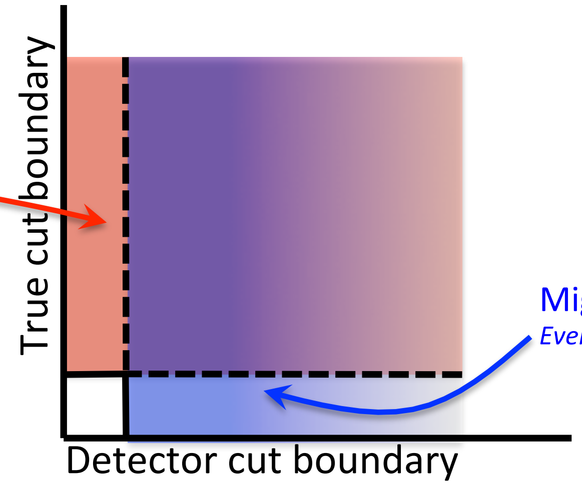
Take our lead from “Standard Model” measurements:



Correcting for detector effects

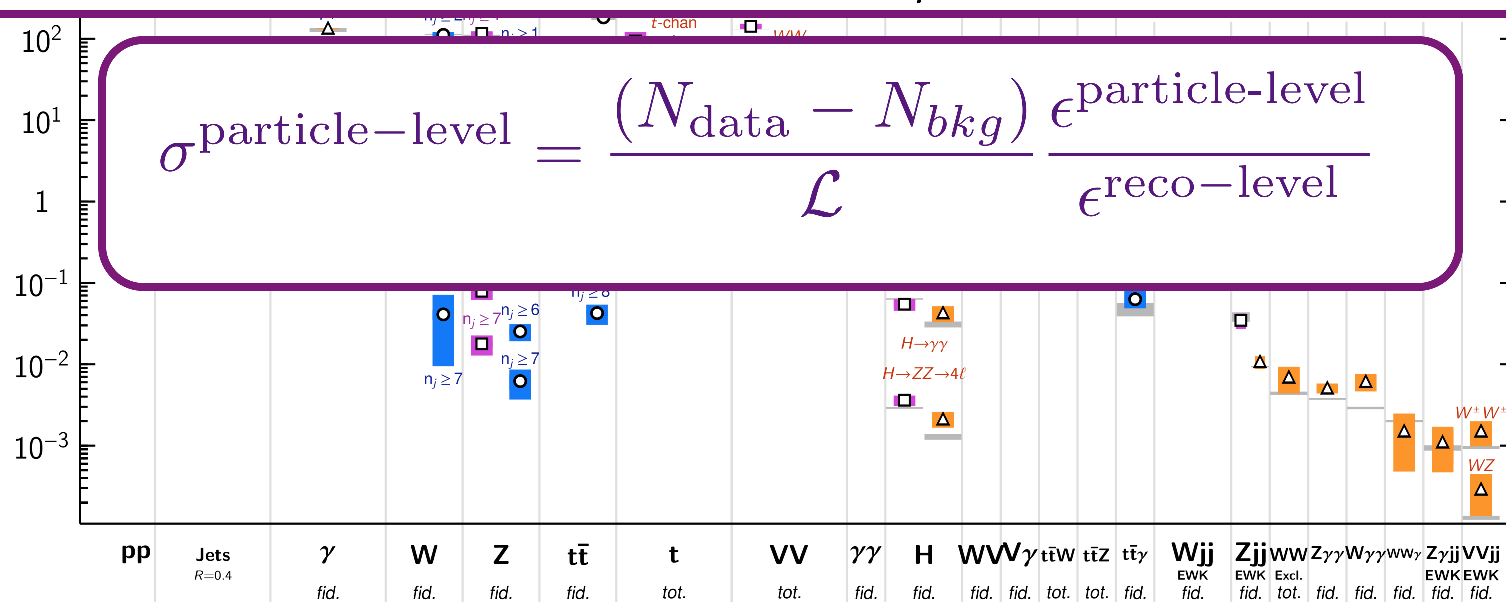
Take our lead from “Standard Model” measurements:

Migrations OUT of fiducial region
Events in fiducial region, not reconstructed



Migrations IN to fiducial region
Events reconstructed but not in fiducial region

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



Construct measurable quantity sensitive to dark matter that:

- Can be corrected for detector effects
- Has minimal model dependence

The new challenge

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Benefit: if anomaly discovered, already measuring properties!

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New observable:

Measure differential detector-corrected production cross-section ratio sensitive to new phenomena producing anomalous MET+jets rate:

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

Observable definition

Detector-corrected observable R_{miss}:

(measure differentially versus event kinematics)

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

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

Correction factor accounting for detector resolution and efficiency

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

Observable definition

Detector-corrected observable R_{miss}:

(measure differentially versus event kinematics)

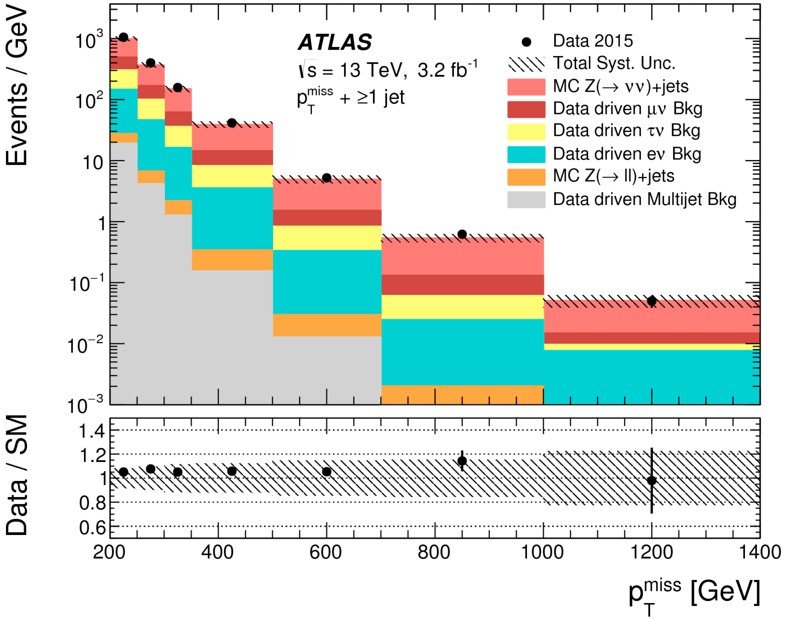
$$R_{\mathrm{miss}} = \frac{\sigma(\not{p}_T + \mathrm{jets})}{\sigma(Z(\rightarrow \ell^+\ell^-) + \mathrm{jets})} = \frac{\sigma(Z(\rightarrow \nu\bar{\nu}) + \mathrm{jets}) + \sigma(\mathrm{BSM})}{\sigma(Z(\rightarrow \ell^+\ell^-) + \mathrm{jets})}$$

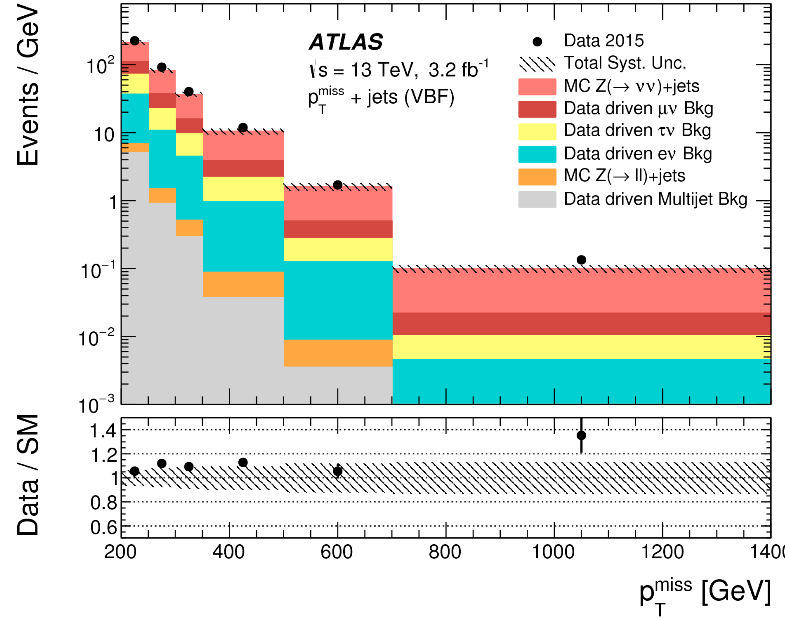
In Standard Model, only contributions to numerator come from $Z \rightarrow \nu\nu$ decays

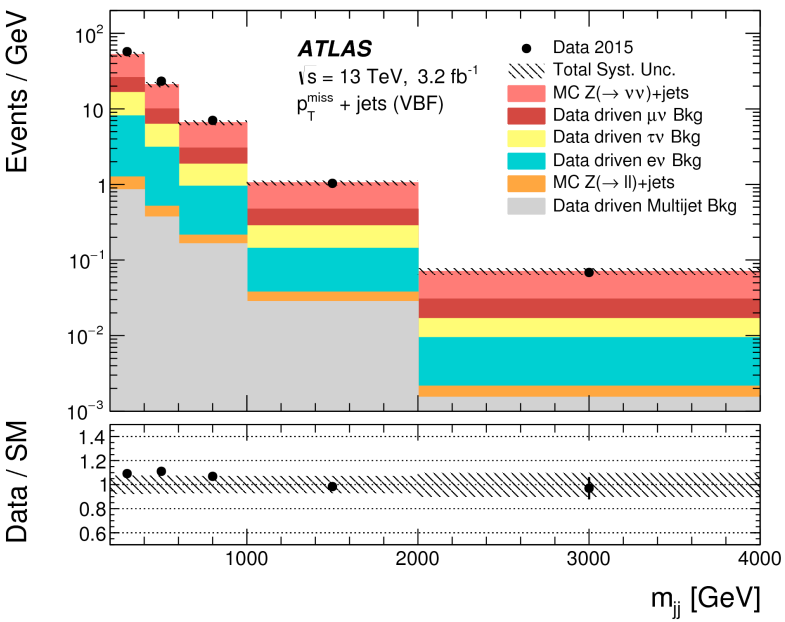
Determination of R_{miss}

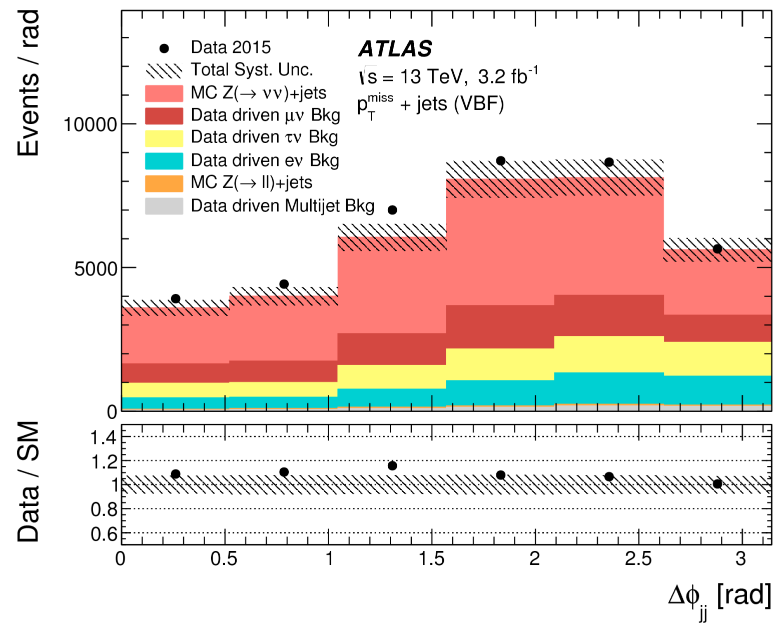
$$R_{\mathrm{miss}} = \frac{\sigma(\not{p}_T + \mathrm{jets})}{\sigma(Z \to \ell^+\ell^- + \mathrm{jets})} = \frac{1}{C_Z}\frac{N(\not{p}_T + \mathrm{jets})}{N(Z \to \ell^+\ell^- + \mathrm{jets})}$$

MET+jet signal region data









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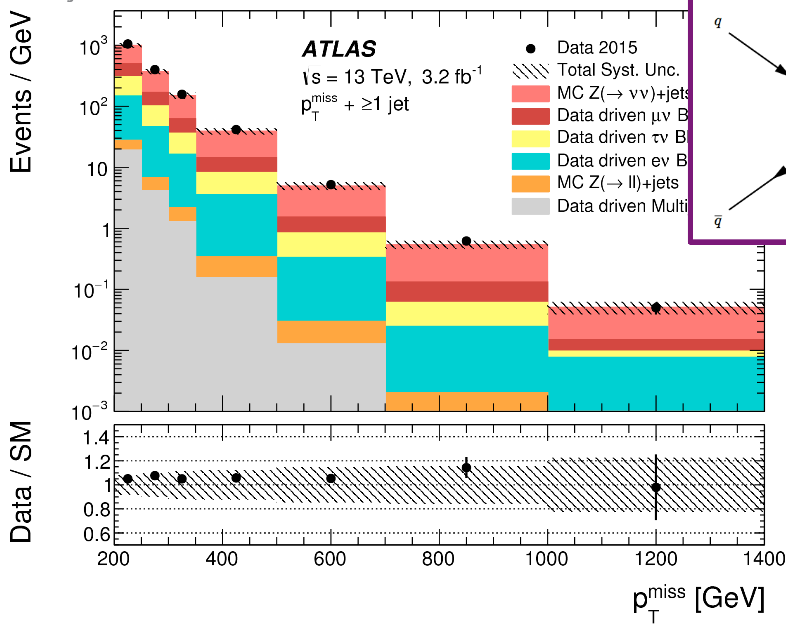
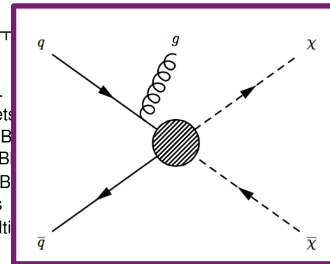
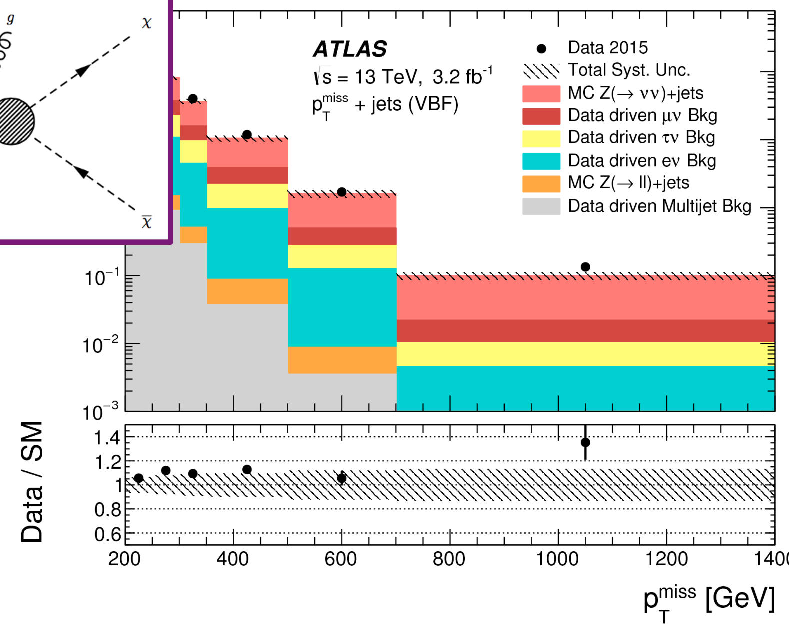
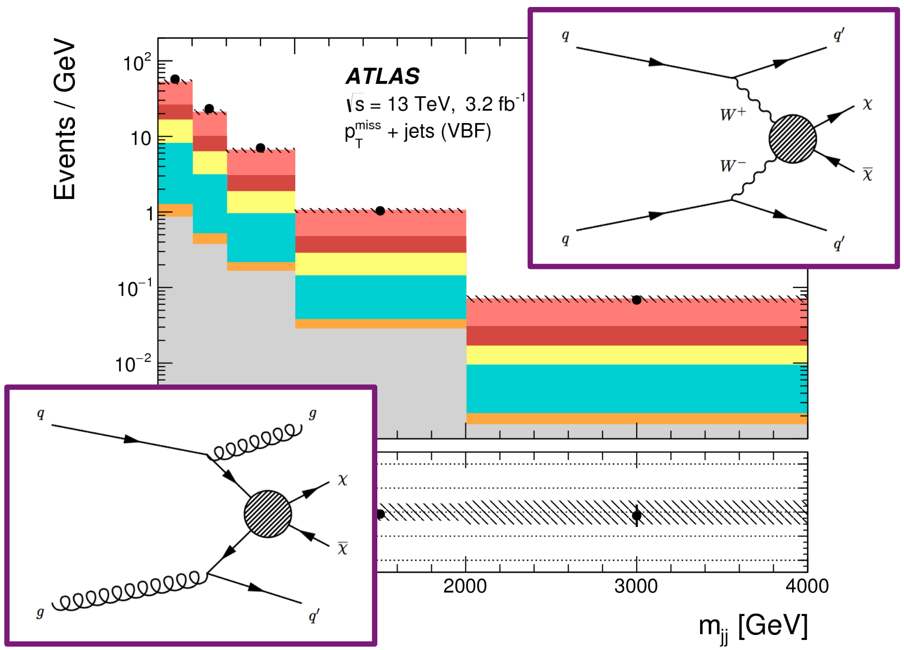
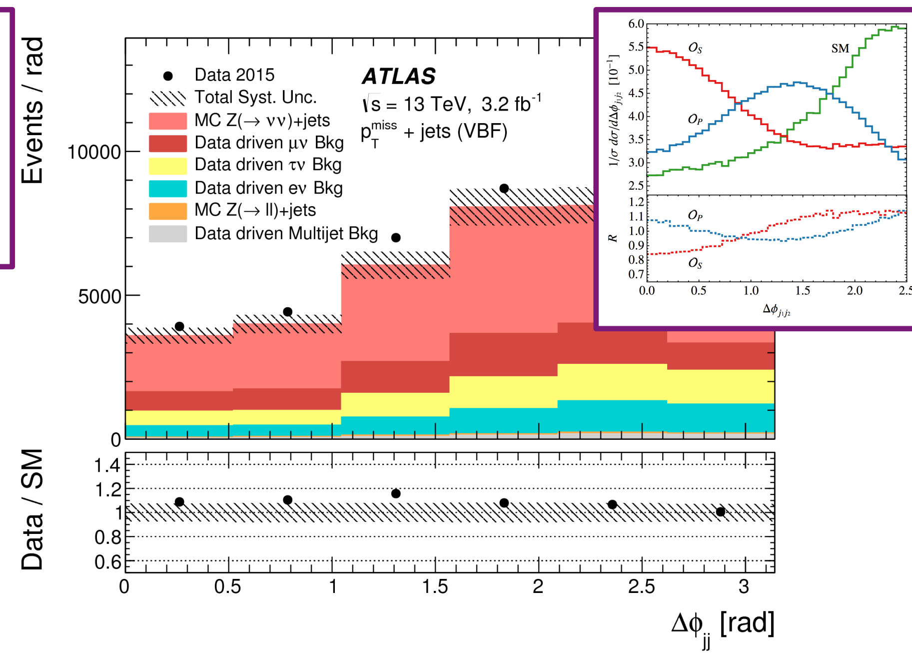


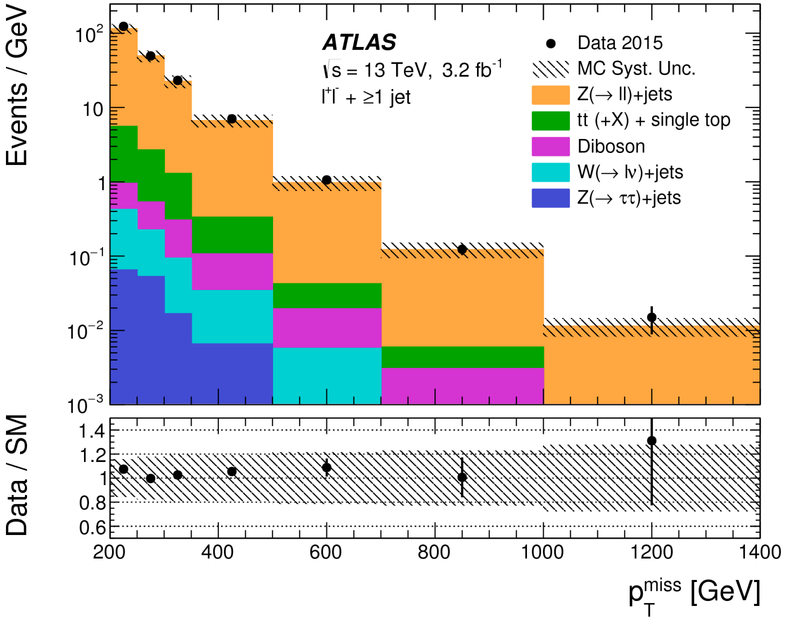


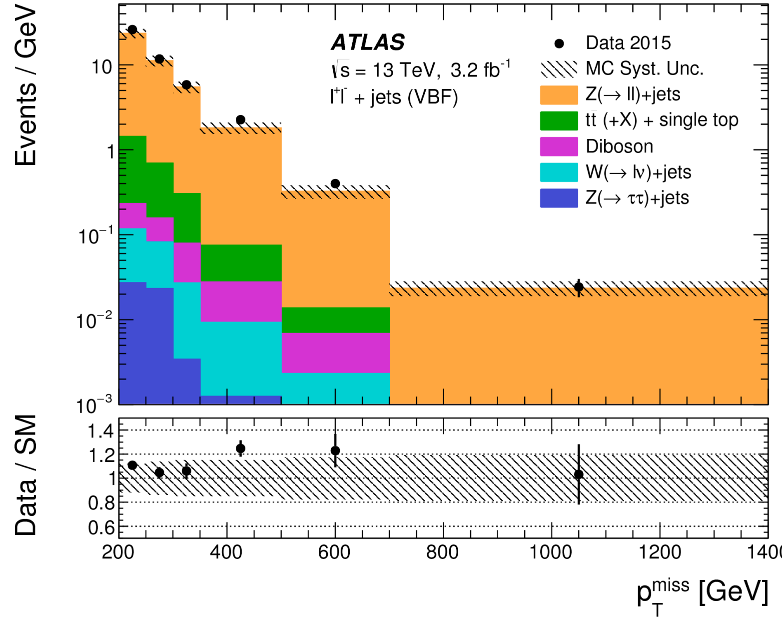


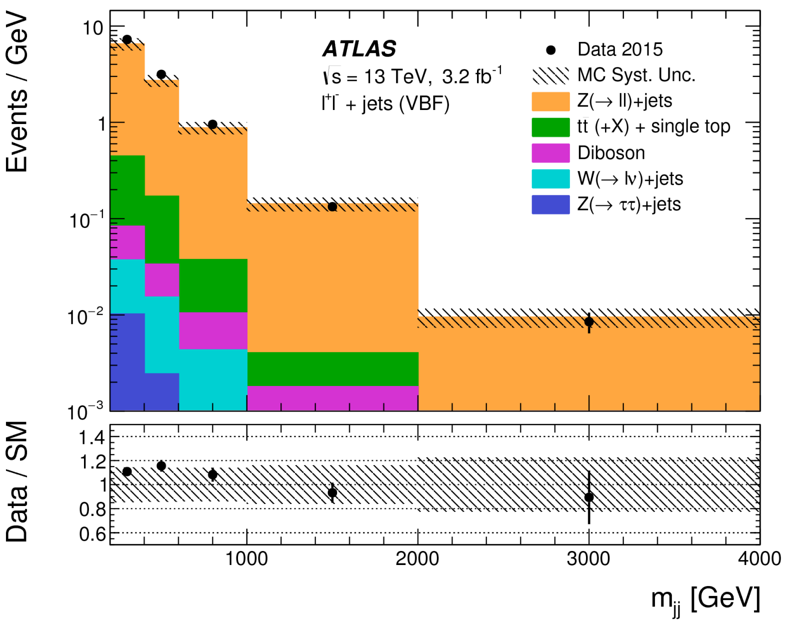


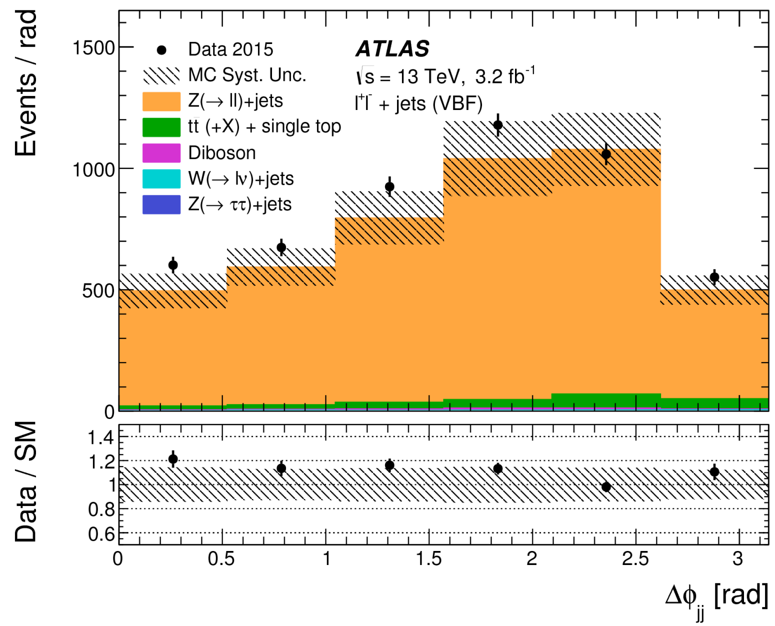


l^+l^-+jet signal region data



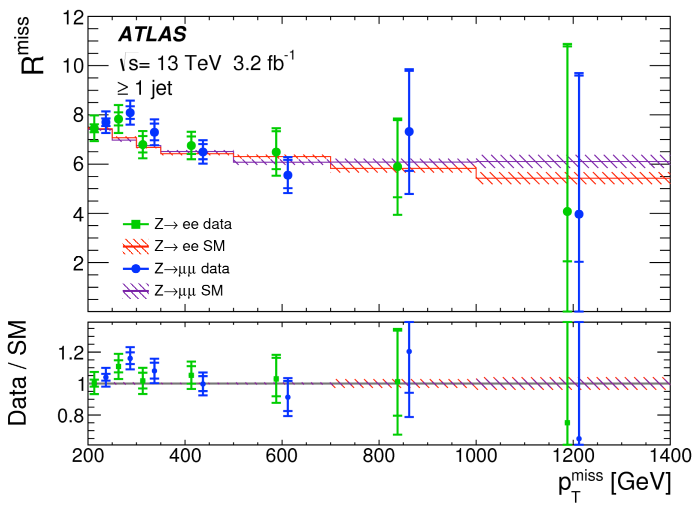






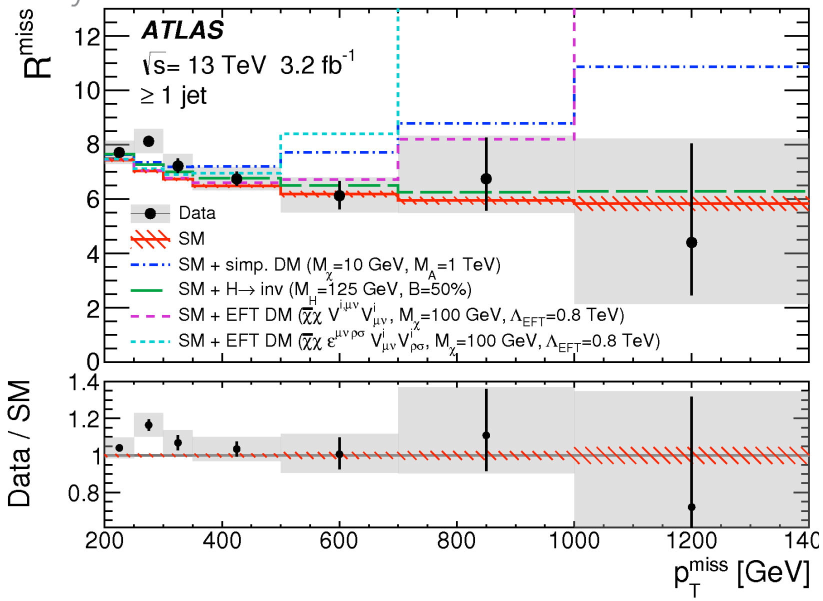
Results: putting it all together

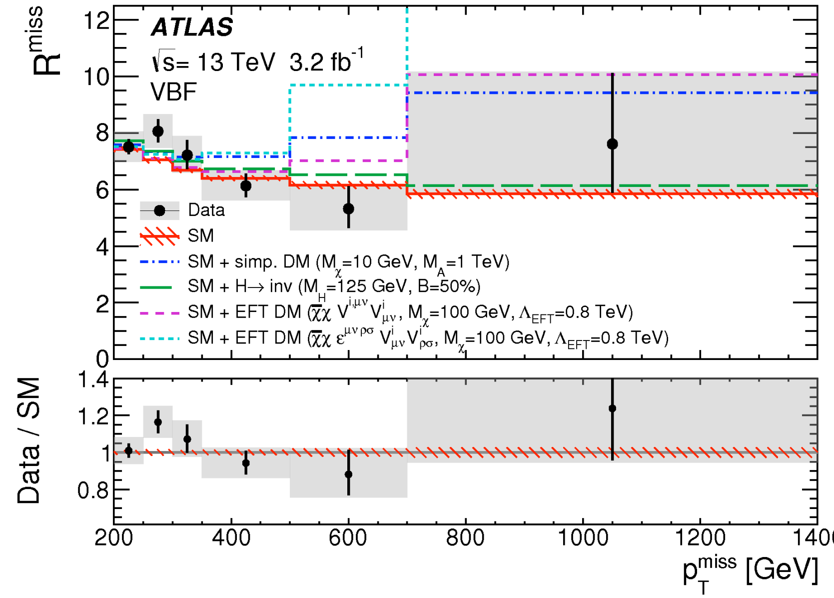
$$R_{\mathrm{miss}} = \frac{\sigma(\not{p}_T + \mathrm{jets})}{\sigma(Z \to \ell^+\ell^- + \mathrm{jets})} = \frac{1}{C_Z}\frac{N(\not{p}_T + \mathrm{jets})}{N(Z \to \ell^+\ell^- + \mathrm{jets})}$$



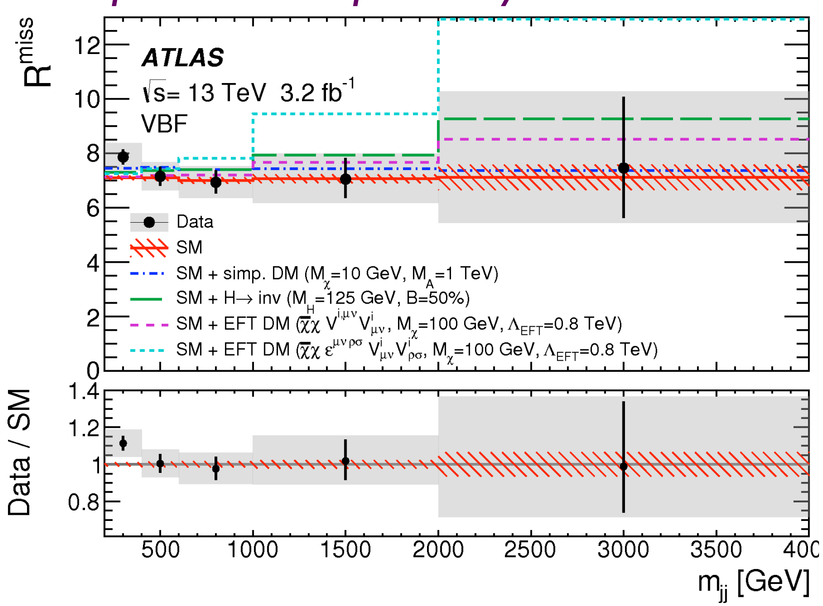
Electron and muon R_{miss} data found in good agreement, perform statistical combination

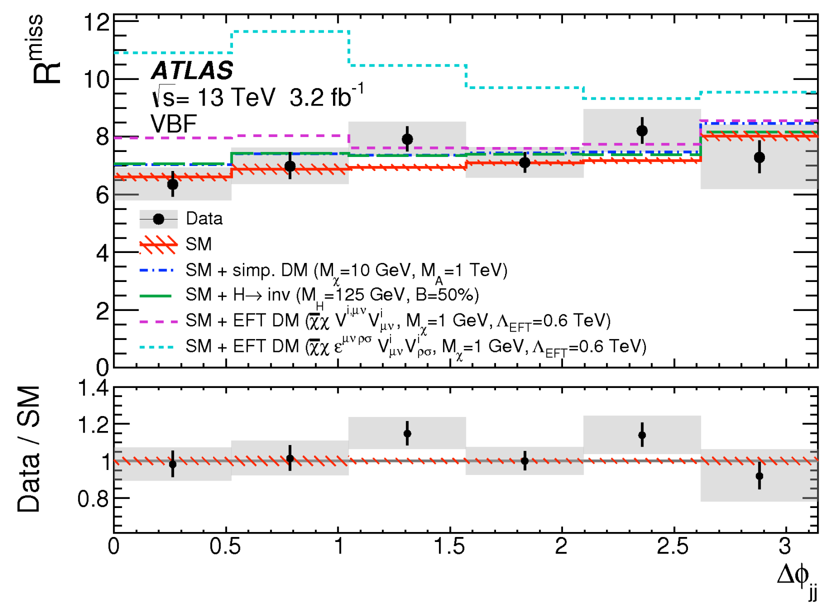
Detector-corrected results





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





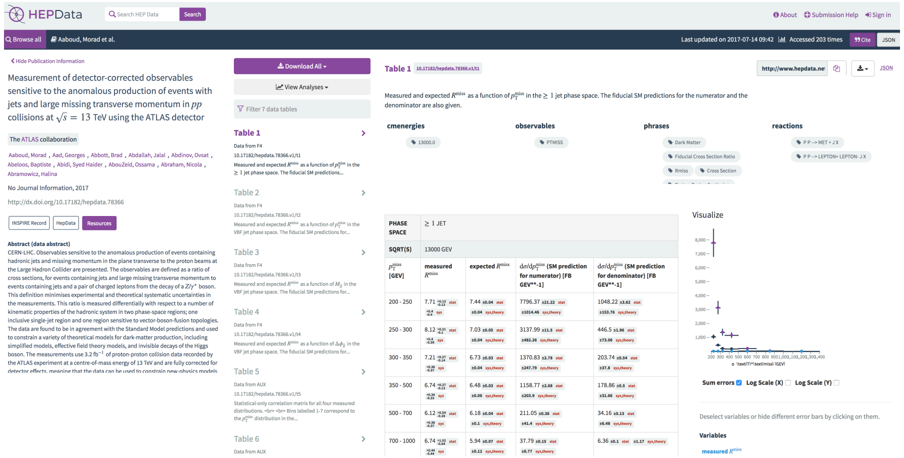
Published results

Alongside paper (arXiv:1707.03263) released supporting material:

Rivet analysis code:
https://rivet.hepforge.org/analyses/ATLAS_2017_I1609448.html

HEPDATA record: https://hepdata.net/record/ins1609448

Containing:
- Measured R_{miss},
- SM R_{miss},
- SM numerator and denominator,
- Covariance matrices



Everything necessary to perform reinterpretation of this data in terms of any BSM prediction resulting in jets plus missing transverse energy!

Workflow toward interpretation (1)

Get Monte Carlo simulation of BSM theory you want to test, and produce HepMC output file

e.g. Lagrangian → FeynRules/Mathematica → Madgraph+Pythia

Workflow toward interpretation (2)

Run Rivet analysis code over your output file from previous step (rivet.hepforge.org)

```
./rivet --analysis=ATLAS_2017_I1609448 INPUT.hepmc
```

Output is R^{miss} for your BSM model:

$$R_{\rm miss} = \frac{\sigma(\not{p}_T + {\rm jets})}{\sigma(Z(\to \ell^+\ell^-) + {\rm jets})} = \frac{\sigma(Z(\to \nu\bar{\nu}) + {\rm jets}) + \sigma({\rm BSM})}{\sigma(Z(\to \ell^+\ell^-) + {\rm jets})}$$

(you have option to change default SM predictions)

Workflow toward interpretation (3)

Perform your favourite statistical test of (your) BSM R^{miss} histograms against data histograms and R^{miss}_{SM} null hypothesis (provided)

e.g.

$$\chi^2 = \sum_{i,j}^{n} (x_i - t_i)(C^{-1})_{ij}(x_j - t_j)$$

$$\chi^2 \rightarrow p - \text{value}$$

$$CL_s = \frac{p_{SM+BSM}}{(1 - p_{SM})}$$

… and that's it!

Happy to help with a reinterpretation analysis in this framework!

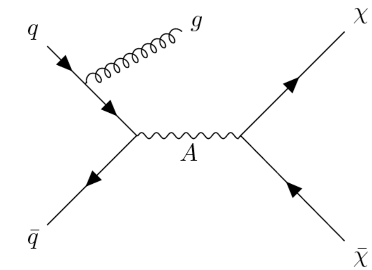
Probing dark matter models

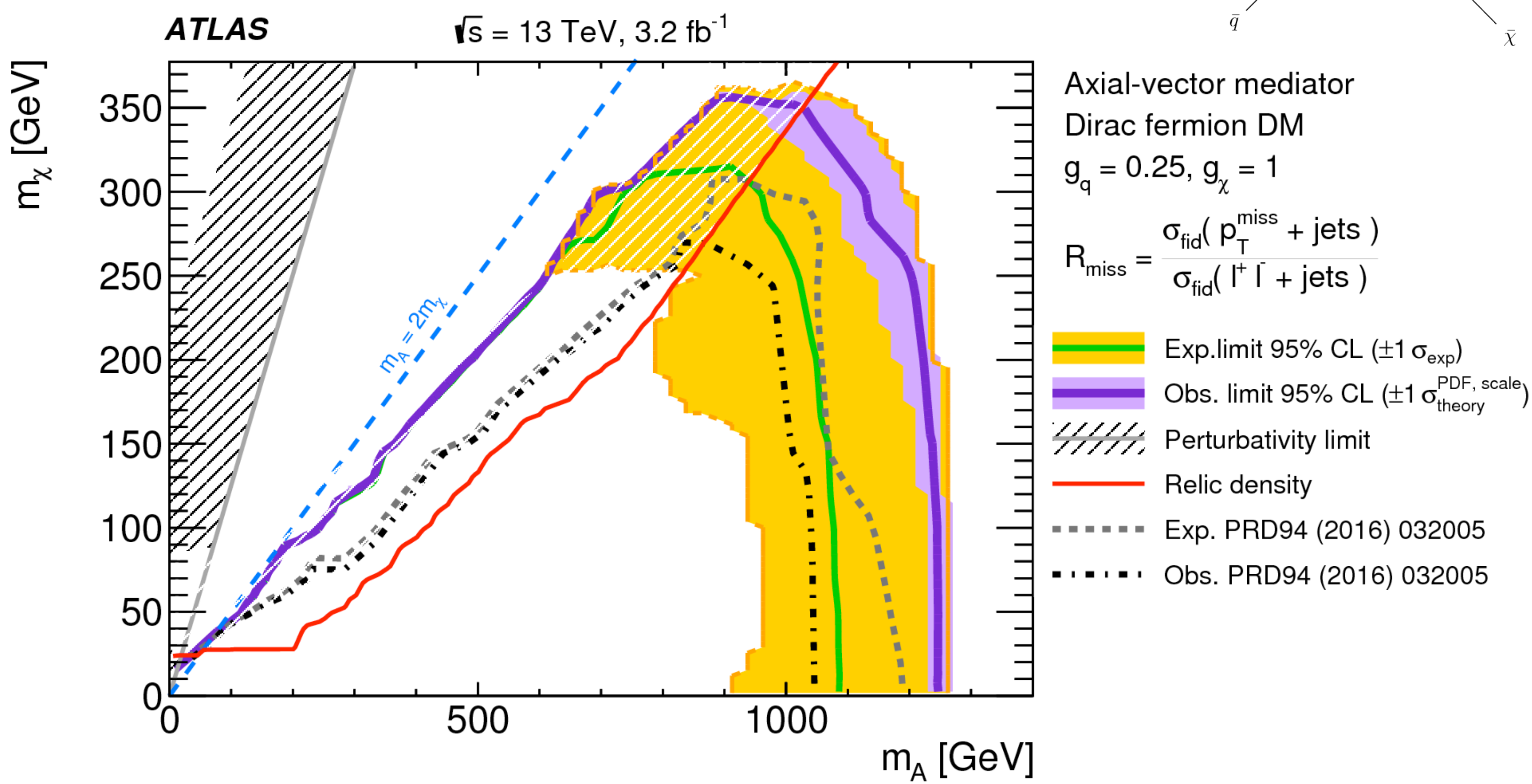
Use detector-corrected data and auxiliary material with above workflow to probe three benchmark dark matter models using publicly-released resources:

- *Dark matter coupling to quarks*
- *Dark matter coupling to EW bosons*
- *Dark matter coupling to Higgs bosons*

Dark matter coupling to quarks

Exclusion contours (at 95 % CL) in the WIMP–mediator mass plane for a simplified model with an axial-vector mediator

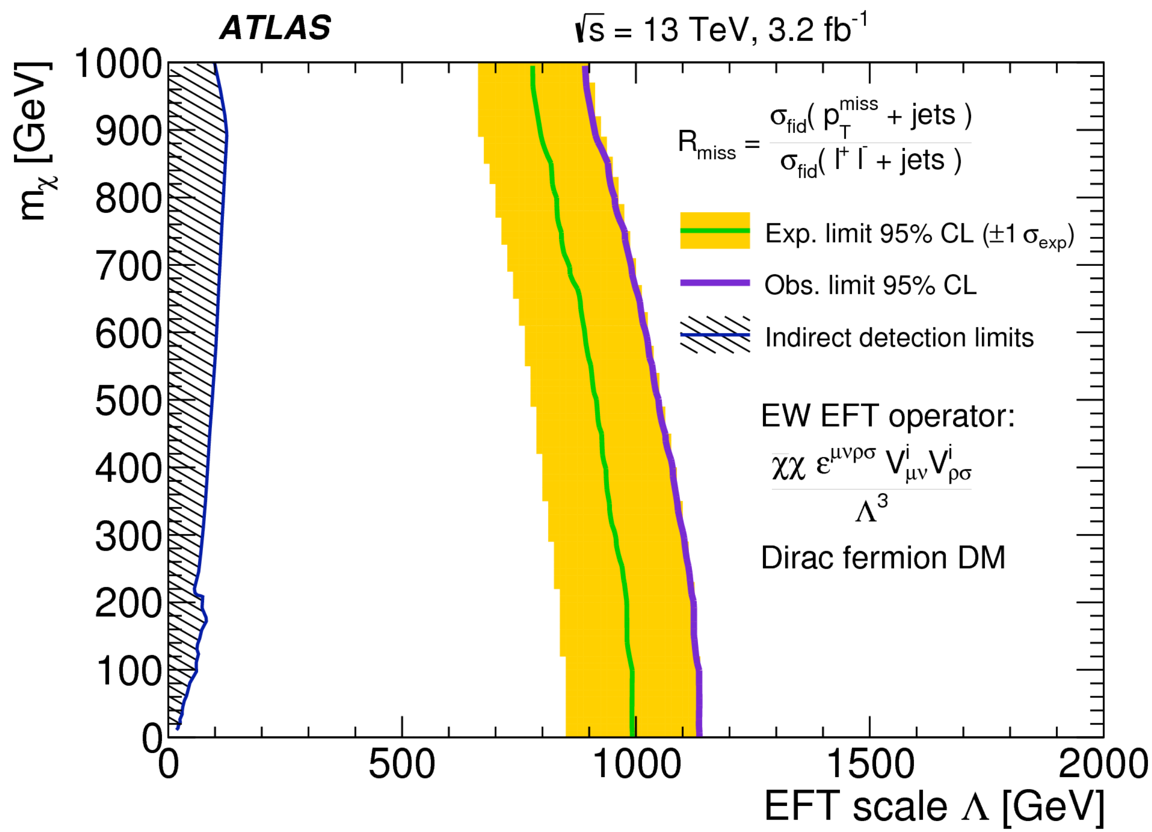


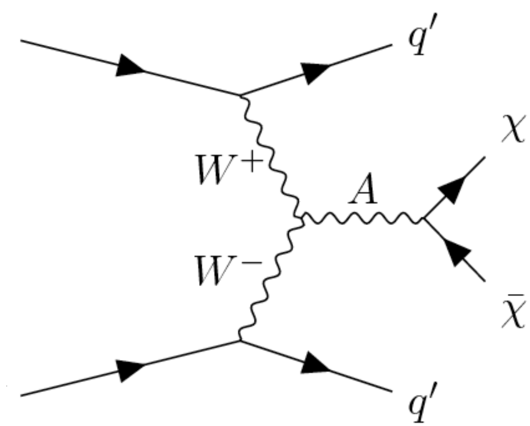


New approach competitive with **dedicated** collider searches!

Dark matter coupling to EW bosons

Exclusion contours (at 95 % CL) for Dirac-fermion dark matter produced via a contact interaction with two electroweak bosons as described in an effective field theory with a dimension-seven operator.





Most stringent constraints to-date on such interactions!

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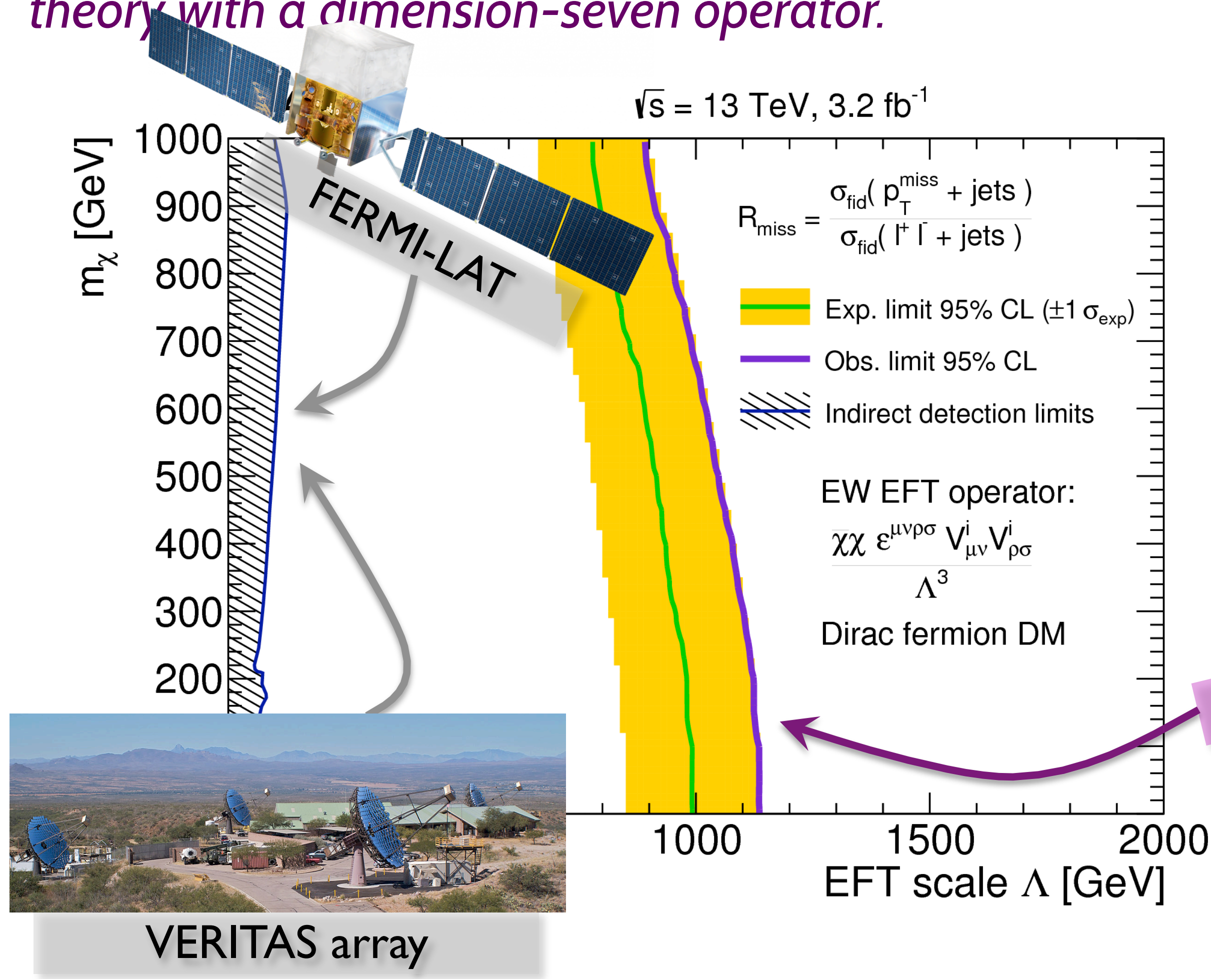
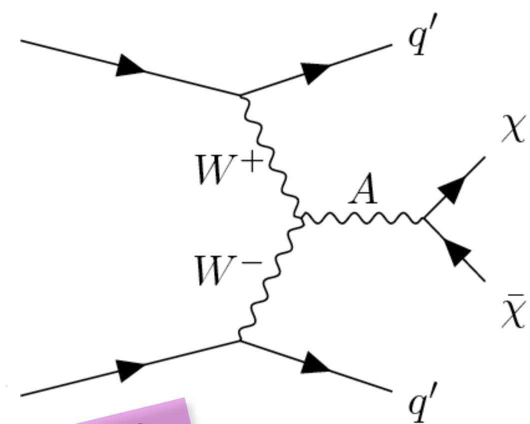
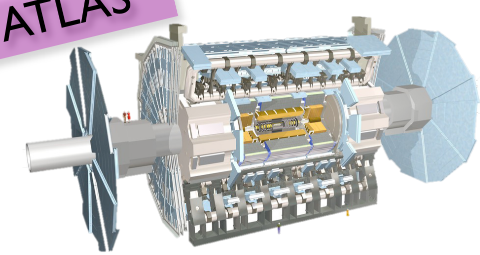




ATLAS



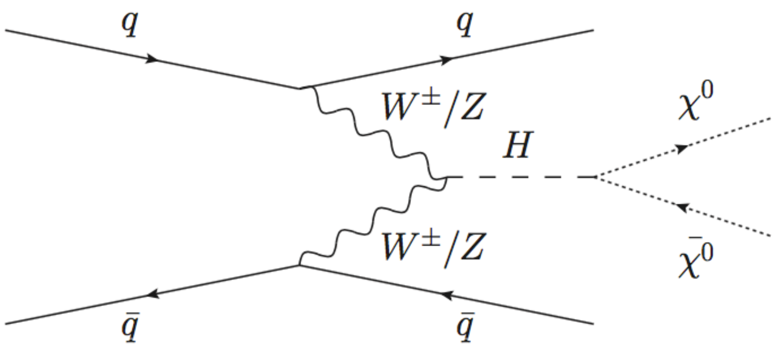
Most stringent constraints to-date on such interactions!

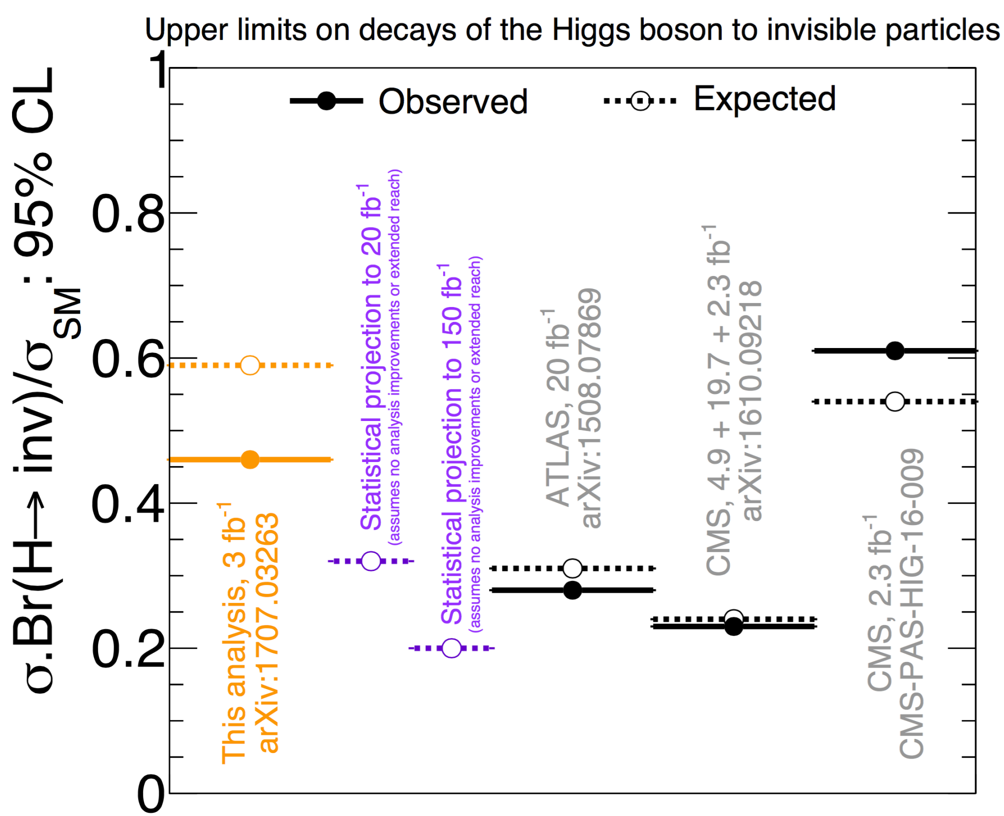
Dark matter coupling to Higgs bosons

Exclusion limits (at 95 % CL) for dark matter produced via decay of a Higgs boson (produced through gg fusion, associated production, or vector boson fusion).

$$Br^{\text{exp}}(H \to \text{inv}) < 59\%; \qquad \pm 1\sigma : [47\%, 113\%]$$

$$Br^{\text{obs}}(H \to \text{inv}) < 46\%$$





Most stringent limits on Higgs→invisible decays at the time from LHC 13 TeV!

Next steps and future plans

Existing data release can be used by anyone to place limits on models resulting in jets and missing transverse momentum

Hope is that this data will be actively used by the community

If you have a model to test, please try it out!

Plan to include x30 more data still in Run-2, plus additional event topologies / final states in future (feedback on interesting observables useful)

Summary

Presented a proof-of-concept search for general new phenomena in MET+jets final states using detector-corrected observables

Measurement approach:

- allows for **easy reinterpretation** with new SM / BSM model
- is **robust** against presence of unknown BSM signals
- allows **determination of *properties* of new phenomena**
- provides **enhanced sensitivity** to new phenomena simultaneously rivalling all dedicated benchmark search analyses tested
- **I encourage you to please try this data out yourself!**

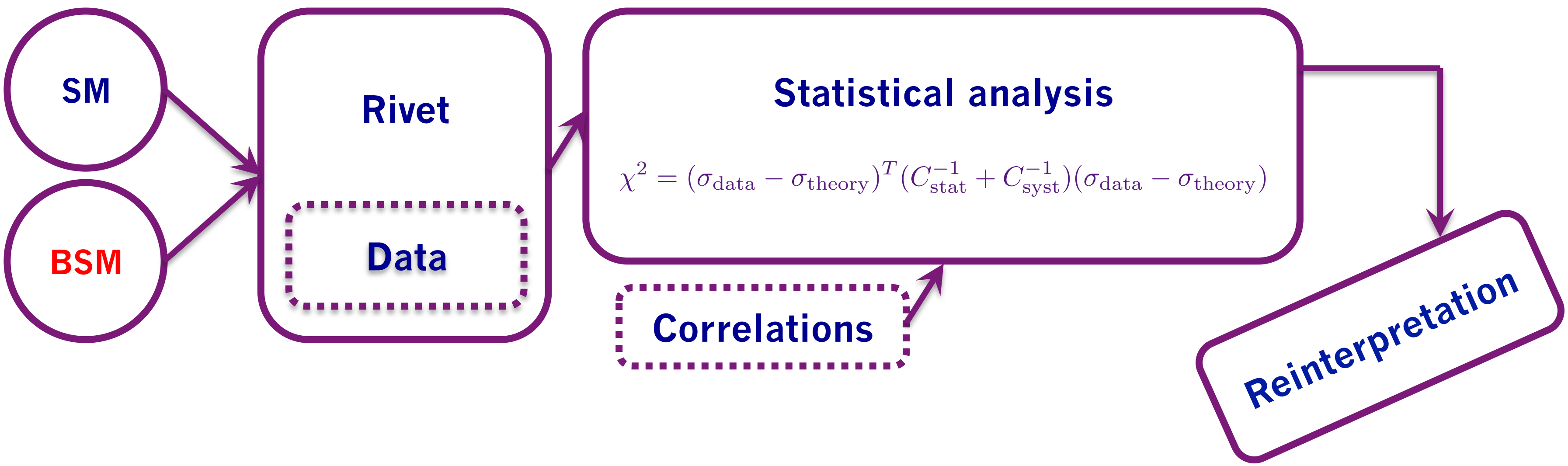
Paper: *Eur. Phys. J. C77 (2017) 11, 765; arXiv:1707.03263*
Analysis code: *https://rivet.hepforge.org/analyses/ATLAS_2017_I1609448.html*
Data: *https://hepdata.net/record/ins1609448*

Backup

Workflow for reinterpretation

Provided information for detector-corrected data:

- Fully-corrected data measurements (+uncertainties) [http://hepdata.net]
- Bin-to-bin correlations + any useful auxiliary information
  (Improved constraints)
- Rivet analysis routine [http://rivet.hepforge.org]
  (Handle object definitions to avoid ambiguity in isolation, jet algorithms, MET definition etc., observable definitions, and binning)



Fiducial measurements

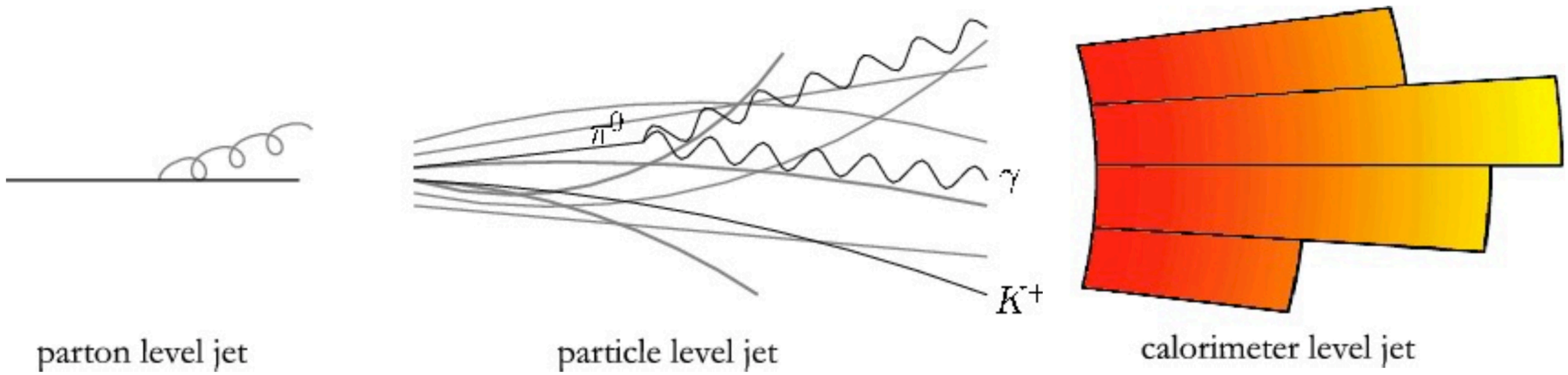
Fundamental challenge to re-interpretation:

Theory predictions developed at parton-level, measurements originate at reconstruction-level

Theory →

- Need interface to MC, or non-perturbative corrections applied

- Require good understanding of background and signal modelling
- Efficiencies and resolutions
- Cut flows / implementation of exact details of reconstruction-level selection



- Non-perturbative effects
- Large extrapolation uncertainties outside measurable regime

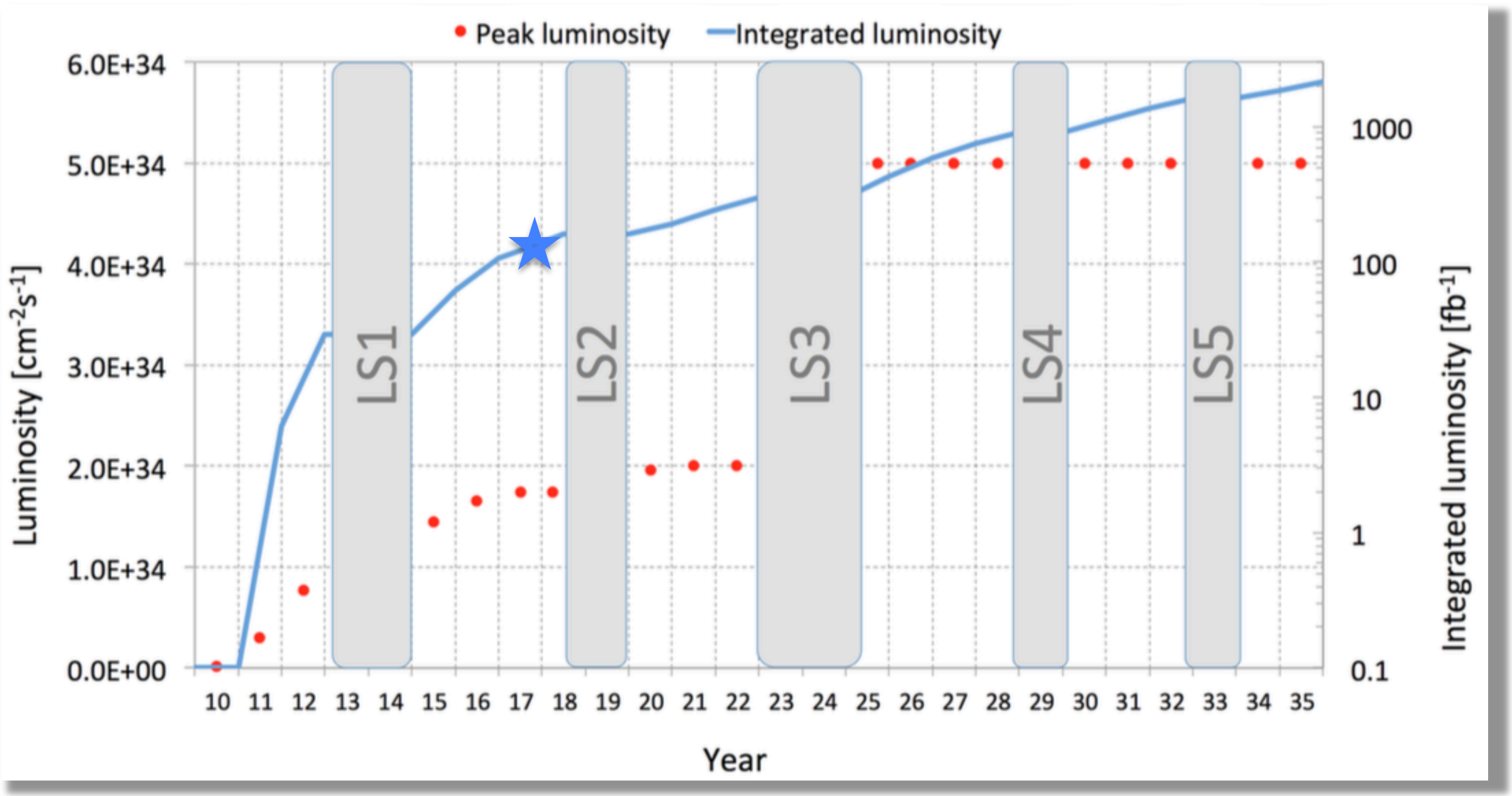
- Need to carefully unfold detector resolution and efficiency effects

← Experiment

"Meet in the middle": Report measurements at particle-level in well-defined fiducial region.

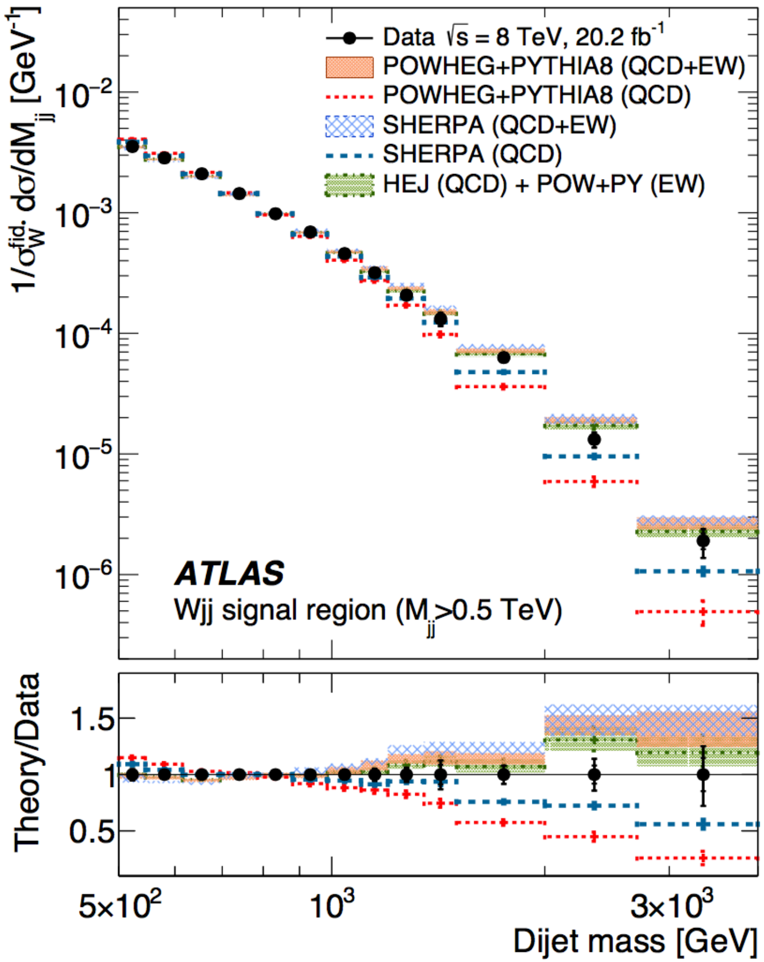
A need for new approaches?

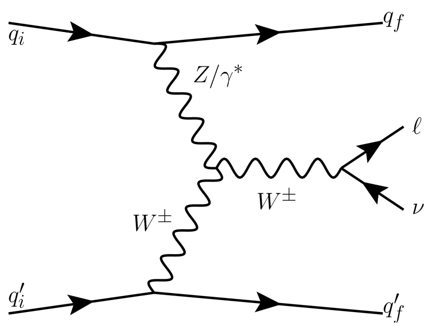
LHC luminosity evolution places increasing importance of making most of data we have!

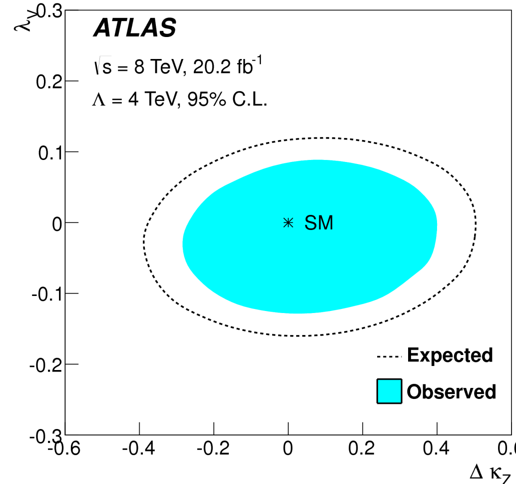


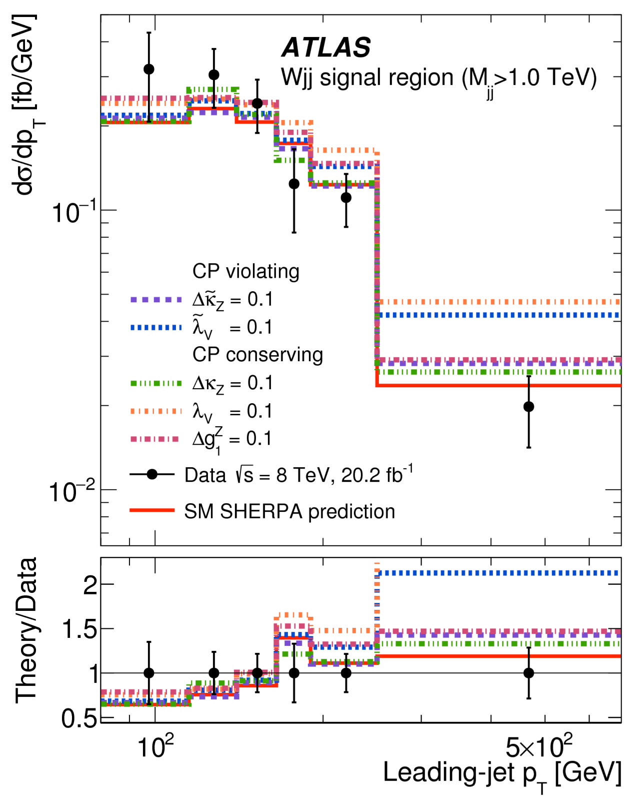
☞ A global view on searches? Maximising sensitivity.

Example from Eur.Phys.J. C77 (2017) 7, 474
arXiv:1703.04362





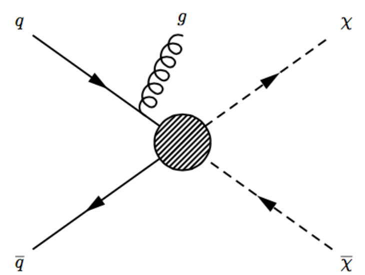


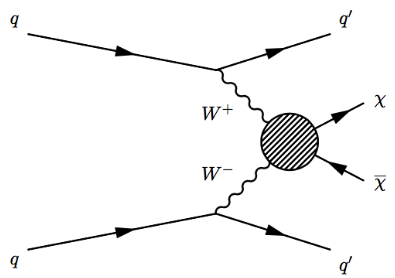


Event selection

Analyse 3.2 fb^{-1} of 13 TeV ATLAS data:

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





- **≥1 jet fiducial region**
  One+ jet with p_T>120 GeV, |y|<2.4.
  Veto on charged leptons.

- **Dijet fiducial region**
  At least two jets, p_T^{j1}>80 GeV, p_T^{j2}>50 GeV, |y|<4.4, m_{jj}>200 GeV.
  Veto on jets (p_T>25 GeV) in dijet rapidity interval, and veto on charged leptons.

Common selections:

- MET>200 GeV (trigger at 70 GeV), $\Delta\phi(\text{MET}, j_{1\ldots4})$>0.4 for jets with p_T>30 GeV
- **Denominator:**
  Two same-flavour opposite-sign leptons |y|<2.5, p_{T1}>80 GeV, p_{T2}>7 GeV,
  Lepton pair treated as invisible, require 'MET'>200 GeV, $m_{ll} \in [66,116]$ GeV

Fiducial region definition

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	
$\Delta\phi_{\mathrm{jet_i},\mathrm{p_T^{miss}}}$	> 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	

Backgrounds from W→lν

Dominant backgrounds from when a charged lepton is missed
Primarily W→lν contributions.

Define W-enhanced control samples in data with identified electrons / muons with identical MET and jet requirements to those in signal region

In control region:

- **Muons**: treat as invisible and re-run p_T^{miss} calculation
- **Electrons**: energy included in p_T^{miss} calibrated as a jet

Constrain modelling of MC predictions in signal region:

$$\frac{dN^{SR}_{\text{predicted}}}{dX} = \left[\frac{dN^{SR}/dX}{dN^{CR}/dX}\right]_{\text{theory}} \times \frac{dN^{CR}_{\text{measured}}}{dX}$$

Backgrounds from W→lν

Dominant background from W→lν (charged lepton missed)

Alternative (new) approach:

1. Define W-enriched control samples in data as before
2. Correct events on event-by-event basis for data-driven reconstruction efficiencies and geometrical acceptance
   - *Can predict contribution from W→eν in W→μν signal region and vice versa*
   - *PDF uncertainties important for acceptance ratios*

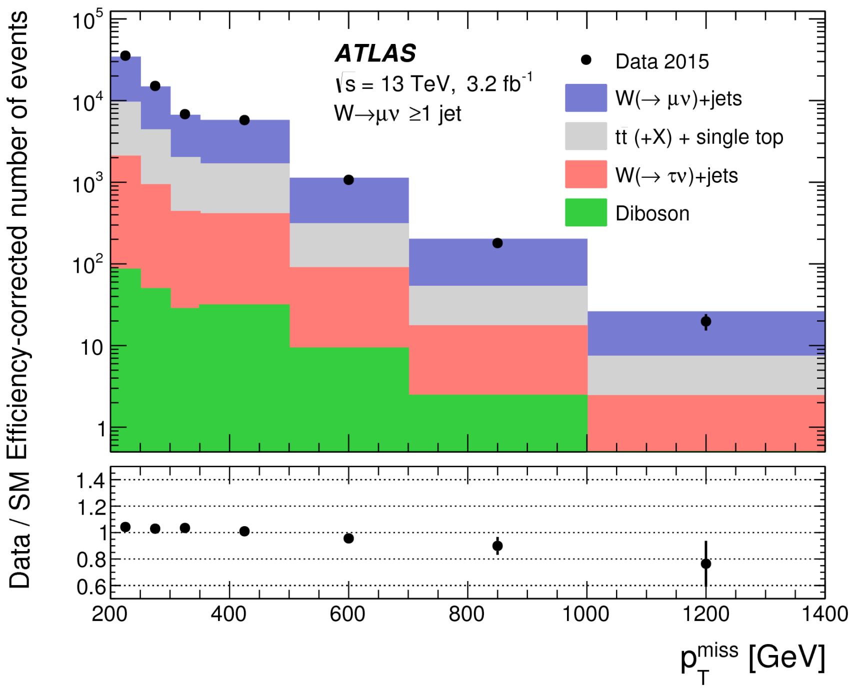
Conversion factor to account for out-of-acceptance events in signal region

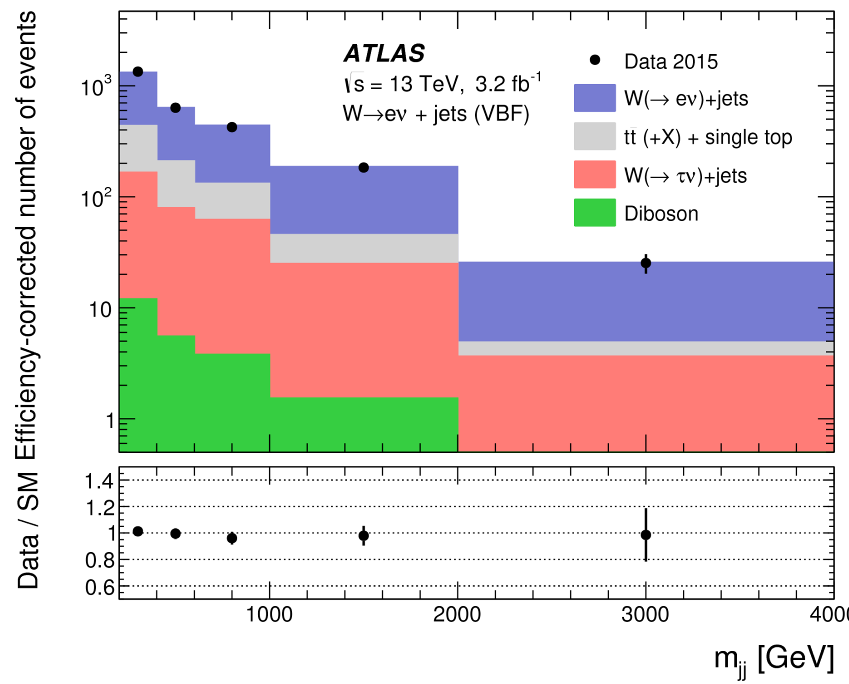
Conversion factor to account for misidentified events with one lepton in signal region

$$N_{\rm bkg} = \frac{(1-a_7)}{a_{25}}\frac{N_{\rm control}}{\epsilon_i} + \frac{(1-\epsilon_j)a_7}{a_{25}}\frac{N_{\rm control}}{\epsilon_i}$$

Efficiency-corrected event yield in control region

W background control region:





- Data driven measurement results in slightly different shapes than theory
- Good agreement with data-driven method and MC-reweighting approach

Determination of correction factor

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

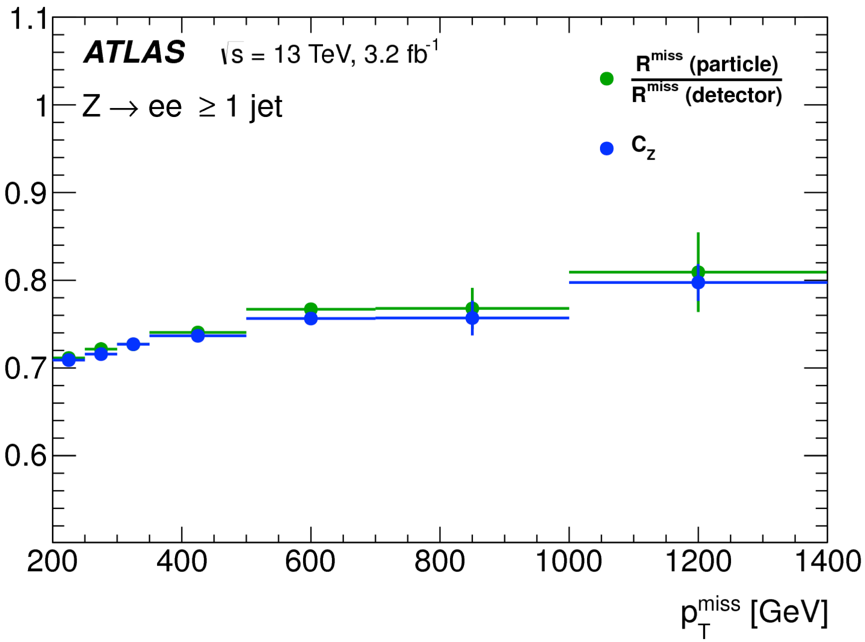
Determination of correction factor

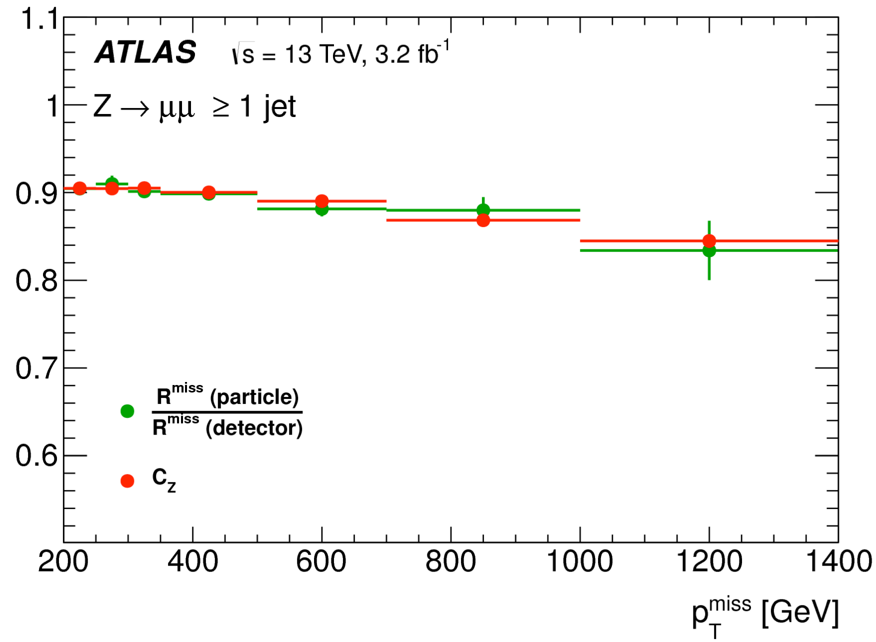
Correction factor from simulated events

$$C_Z = \frac{N^{\mathrm{reco}}_{\ell+\ell-}}{N^{\mathrm{truth}}_{\ell+\ell-}}$$

Object reconstruction in fiducial region very similar in l^+l^-+jets and MET+jets events

Main differences due to lepton reconstruction efficiency, resolution, trigger effects



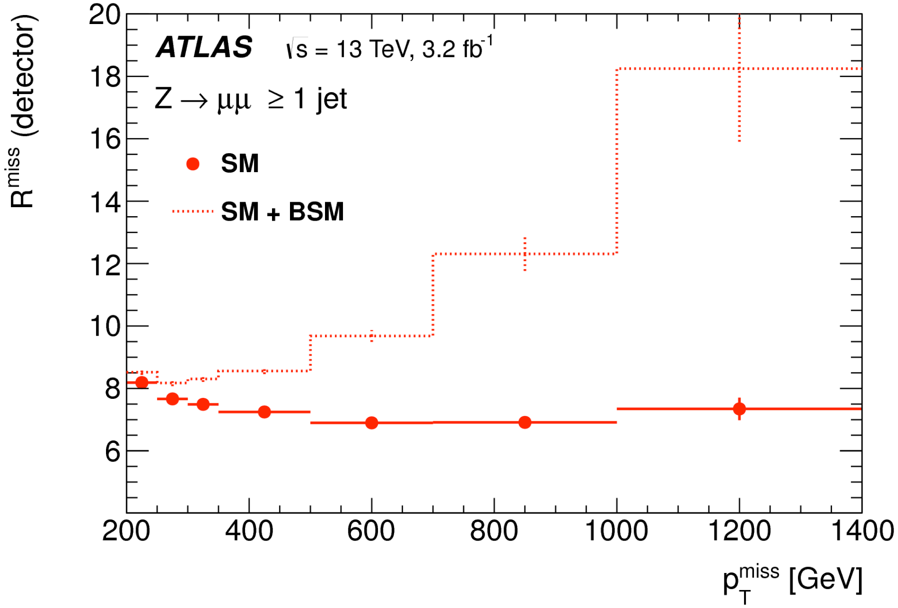


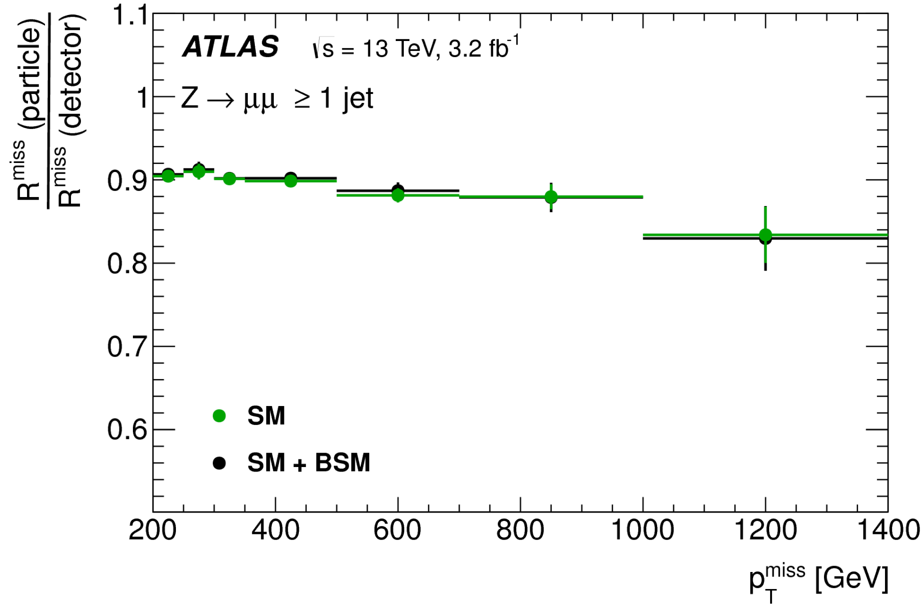
Correction factor BSM injection tests

Various tests of model independence of procedure performed.

One example: Injection of BSM dark matter model enhancing MET distribution:

- Causes large changes in numerator and shape of R_{miss}
- **Negligible effect on correction factor!**
- Such large enhancements are anyway ruled out by the measured data

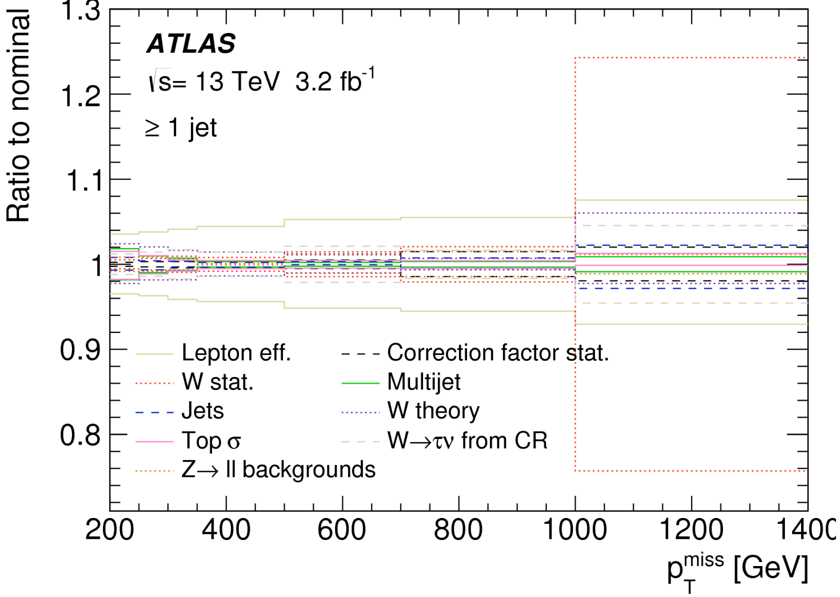


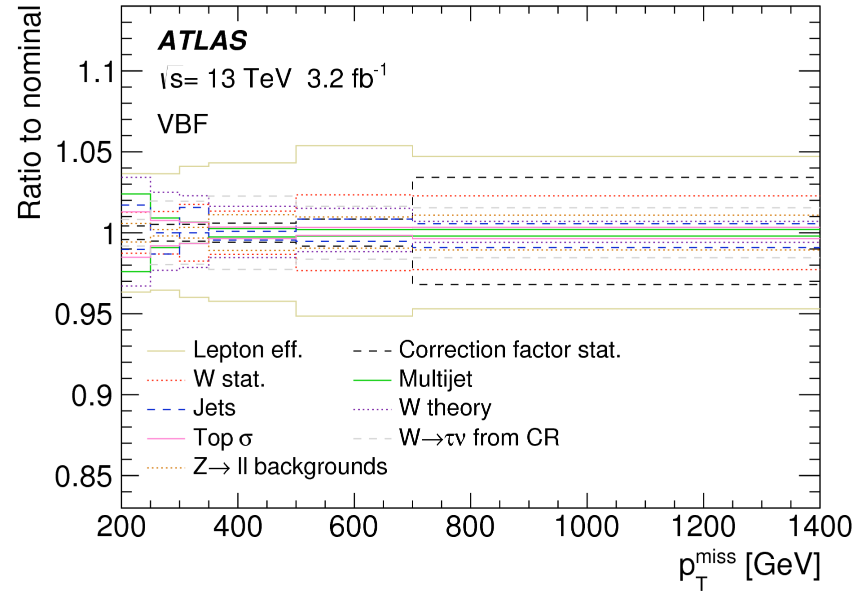


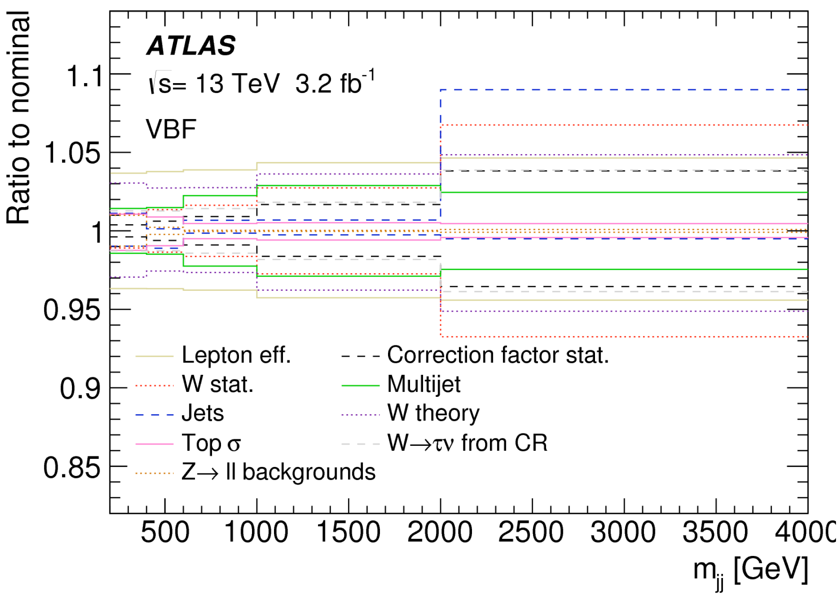
Systematic uncertainty overview

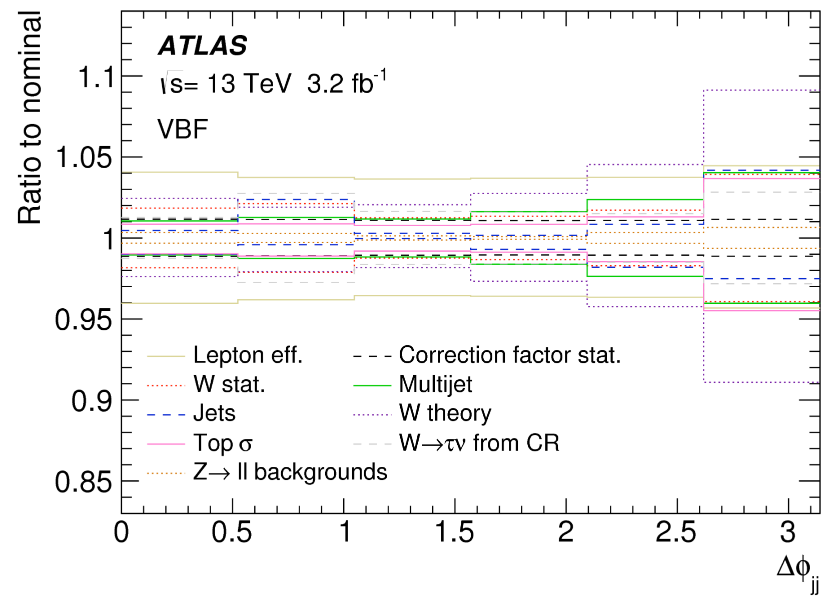
Systematic uncertainty source	Low p_T^{miss} [%]	High p_T^{miss} [%]	Low m_{jj} [%]	High m_{jj} [%]
Lepton efficiency	$+3.5, -3.5$	$+7.6, -7.1$	$+3.7, -3.6$	$+4.6, -4.4$
Jets	$+0.8, -0.7$	$+2.2, -2.8$	$+1.1, -1.0$	$+9.0, -0.5$
$W \to \tau\nu$ from control region	$+1.2, -1.2$	$+4.6, -4.6$	$+1.3, -1.3$	$+3.9, -3.9$
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	$+5.5, -5.4$	$+87, -51$	$+6.6, -6.5$	$+38, -27$

Summary of experimental uncertainties

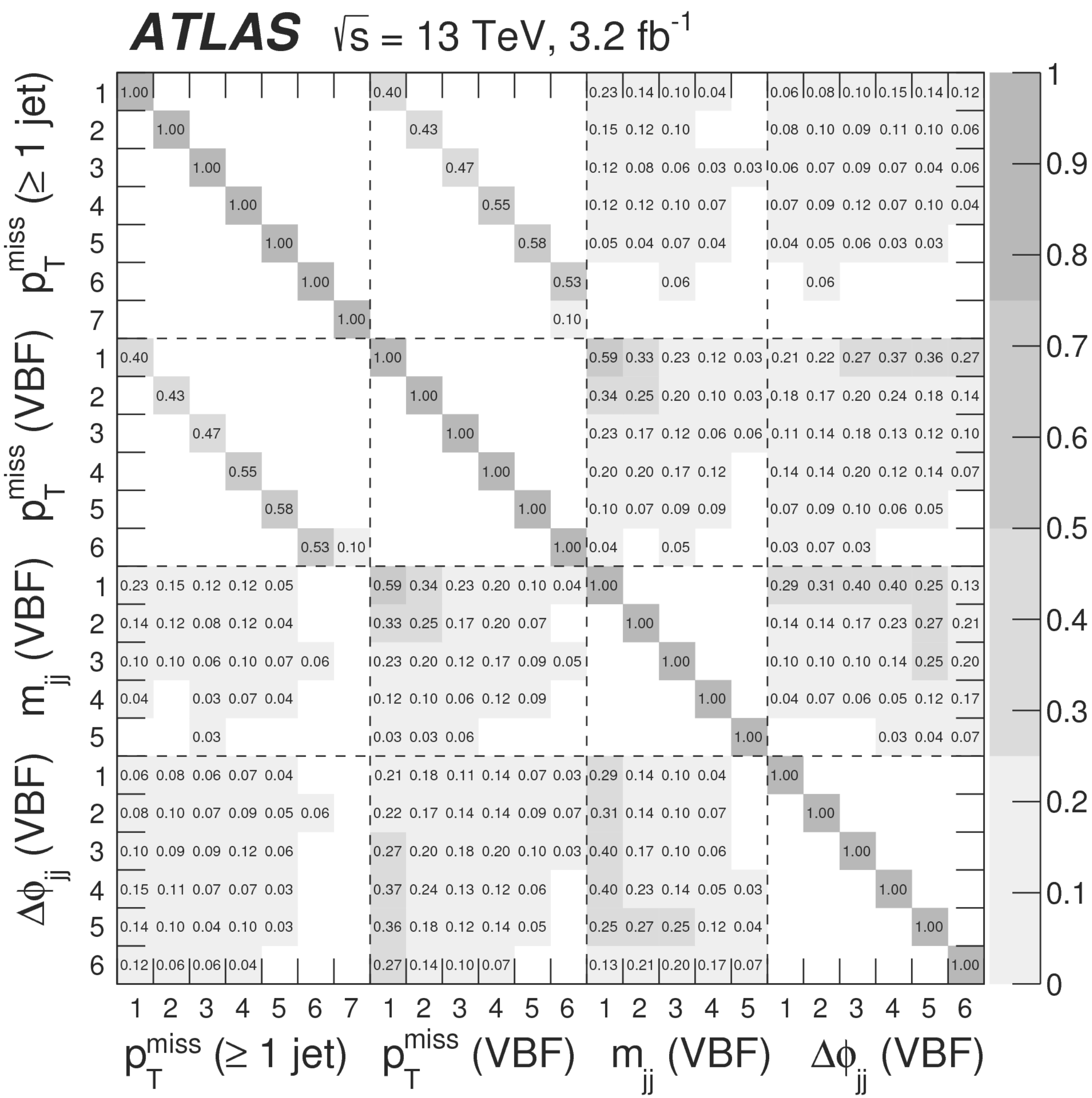




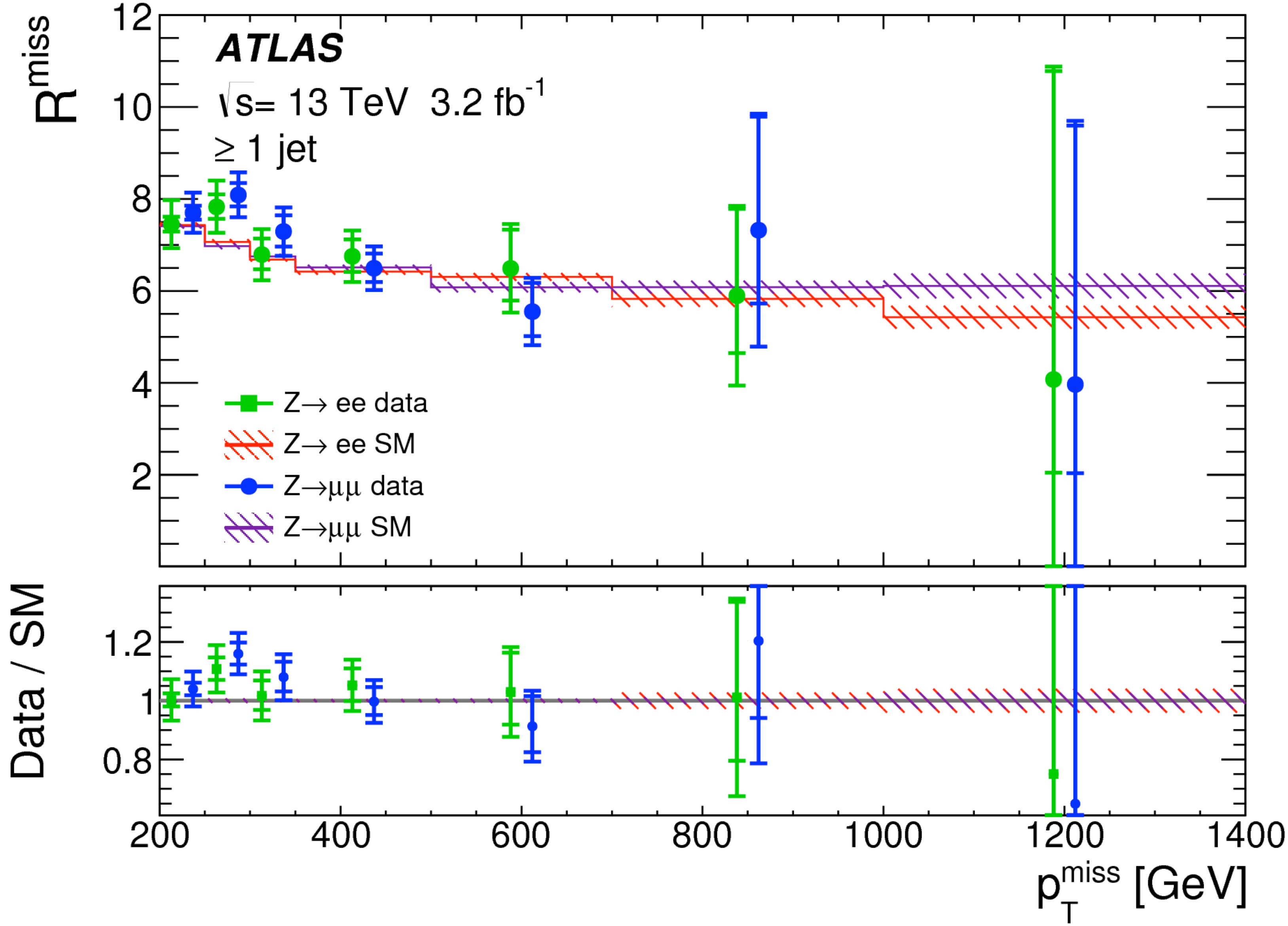




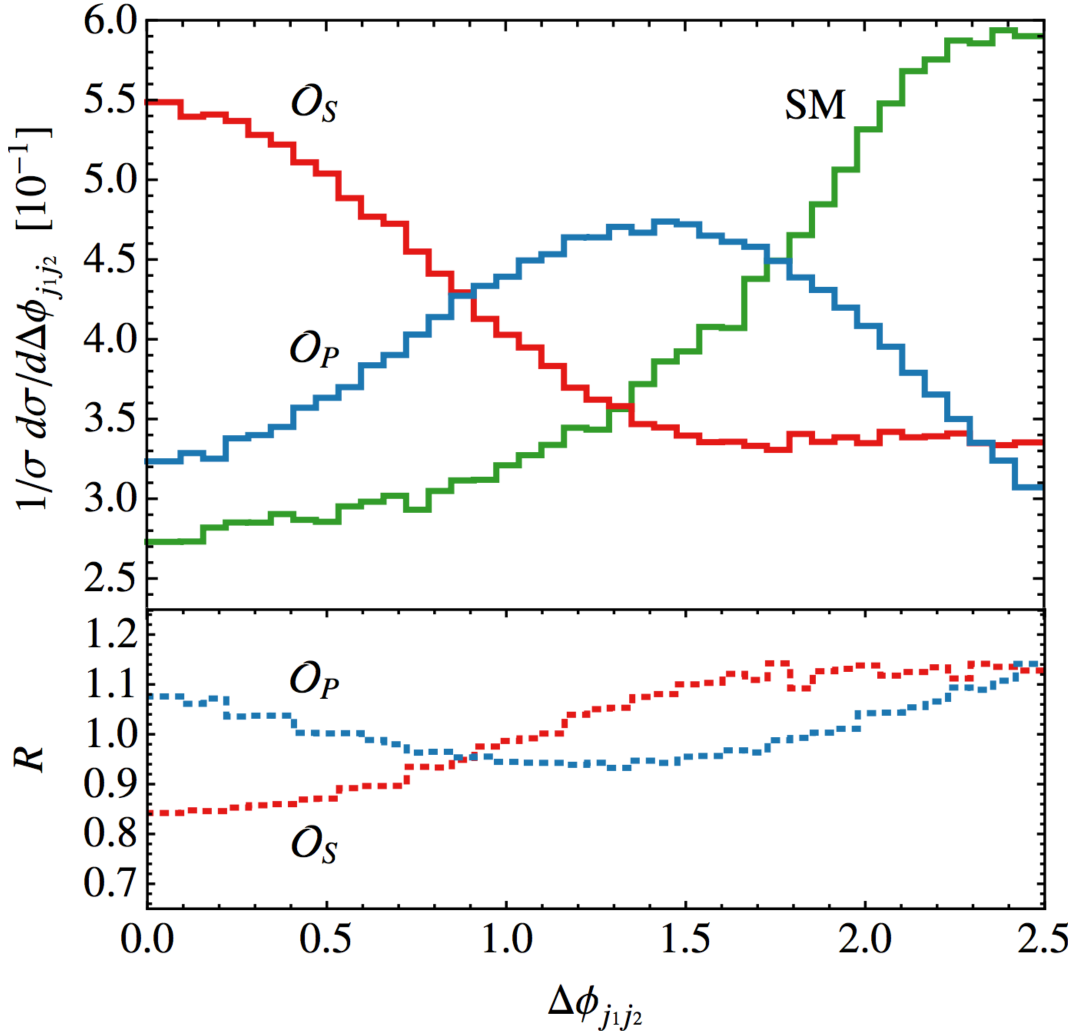
Statistical covariance matrix



Electron vs. muon measurements



MET+dijet azimuthal angle correlations



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