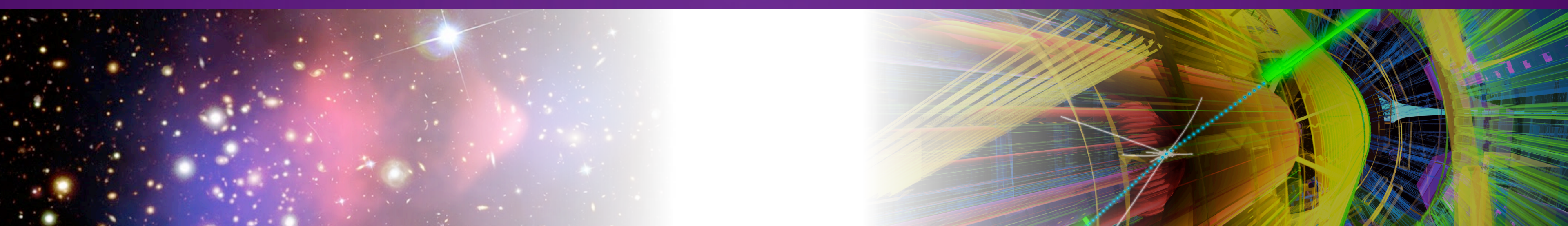
Measuring the invisible

new approaches to dark matter searches at colliders



Darren Price, University of Manchester

Particle Physics Seminar, University of Birmingham, November 22nd '17

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

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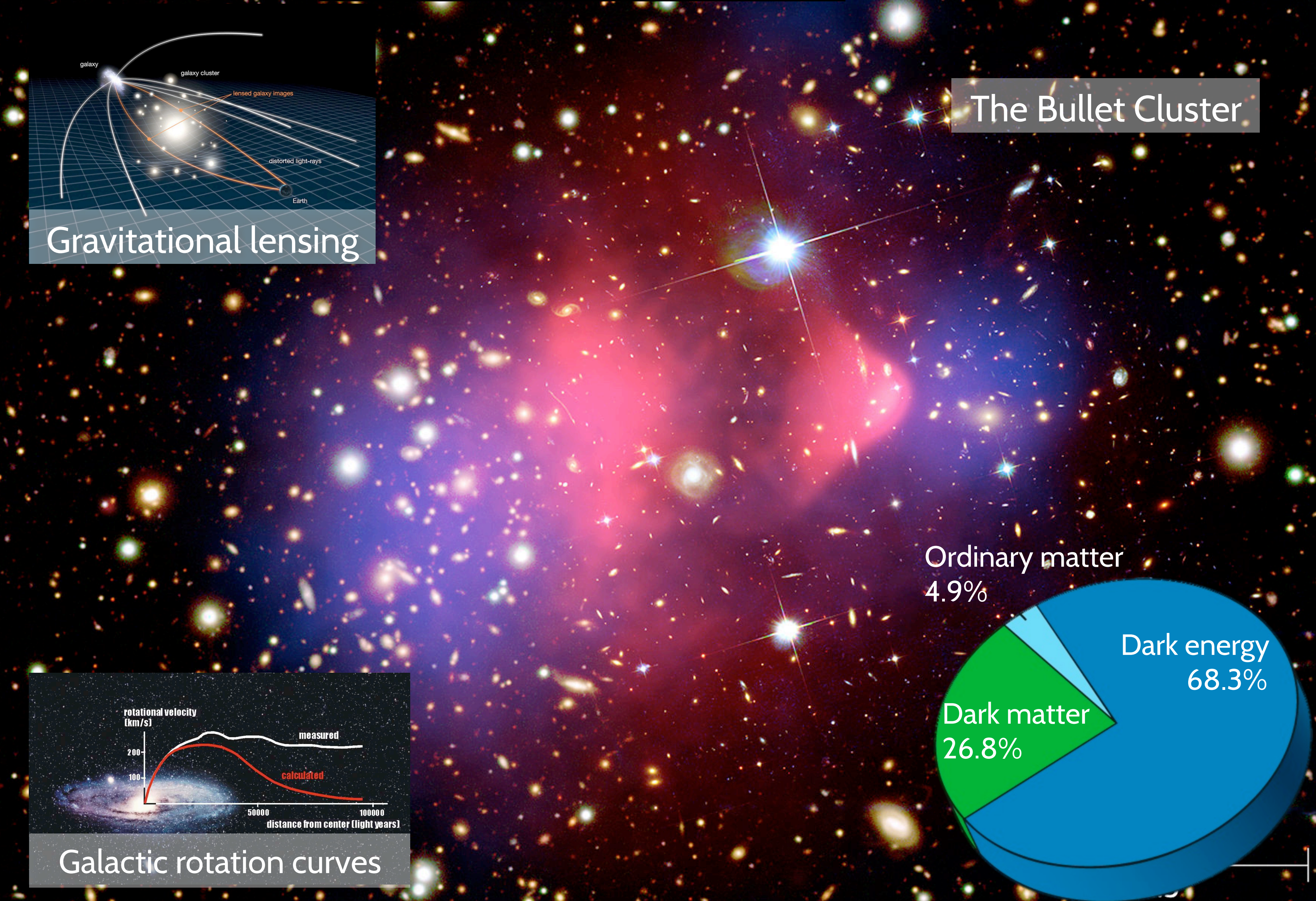
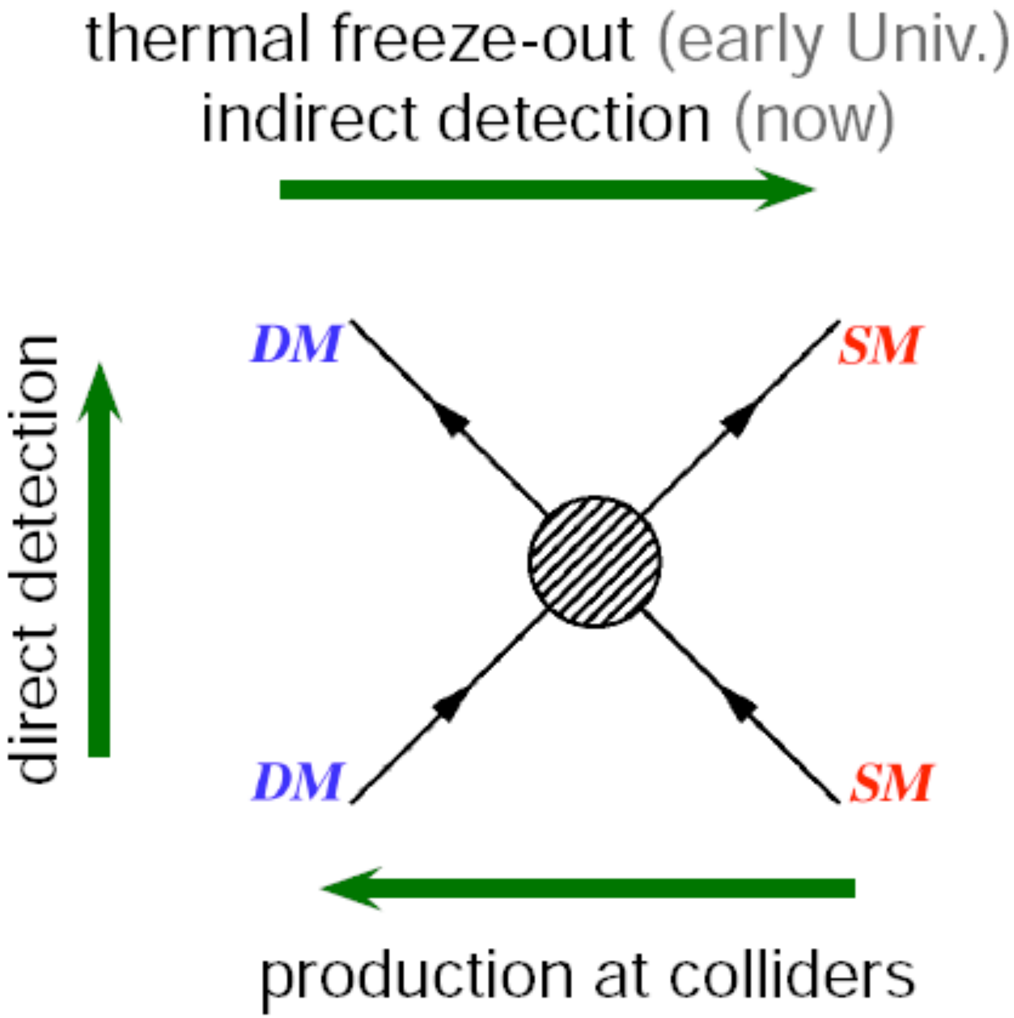
The dark matter puzzle



Detecting dark matter



Things we know about dark matter:

- Interacts gravitationally

  ...

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  …

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Things we know about dark matter:

- Interacts gravitationally

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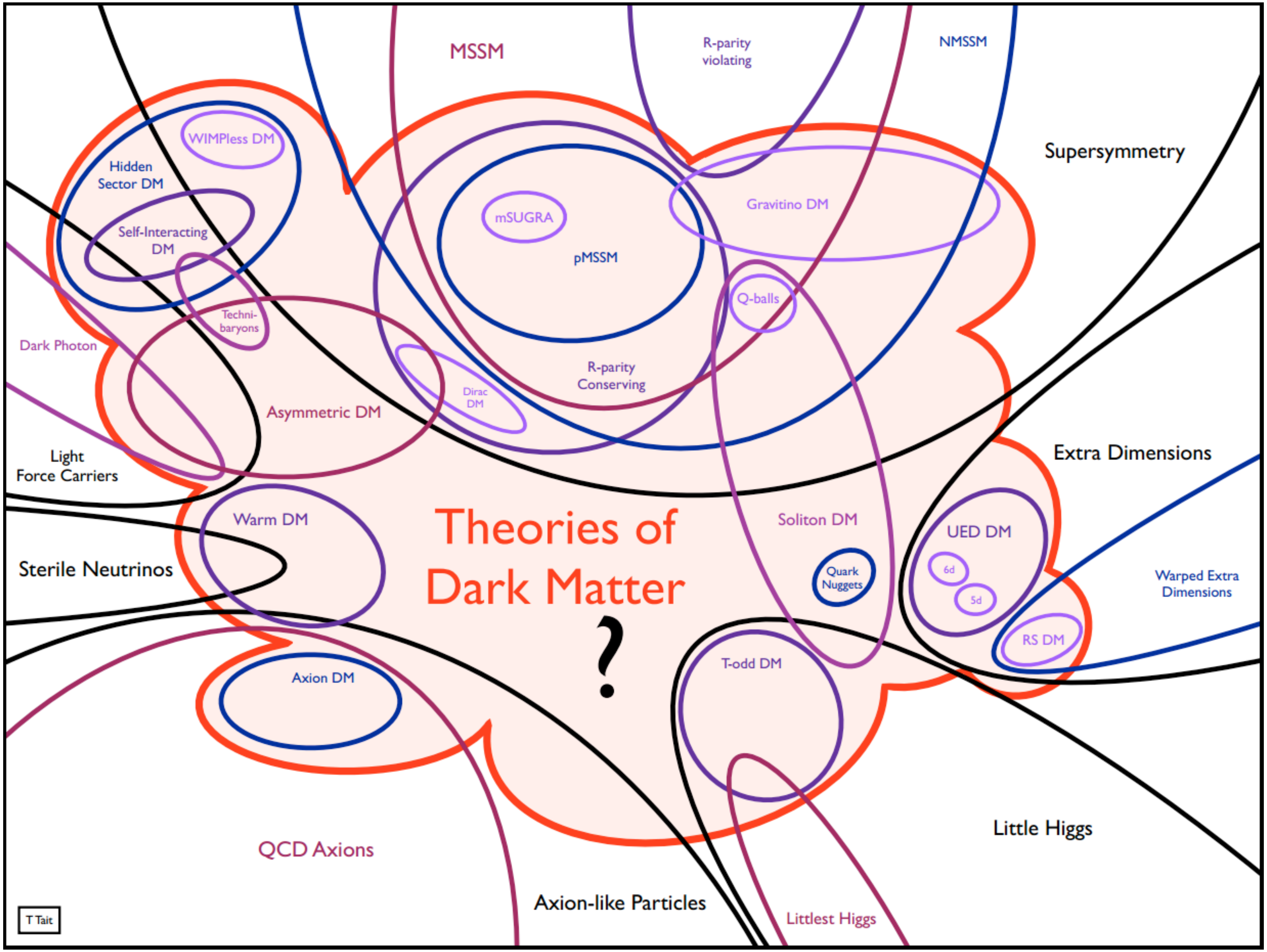
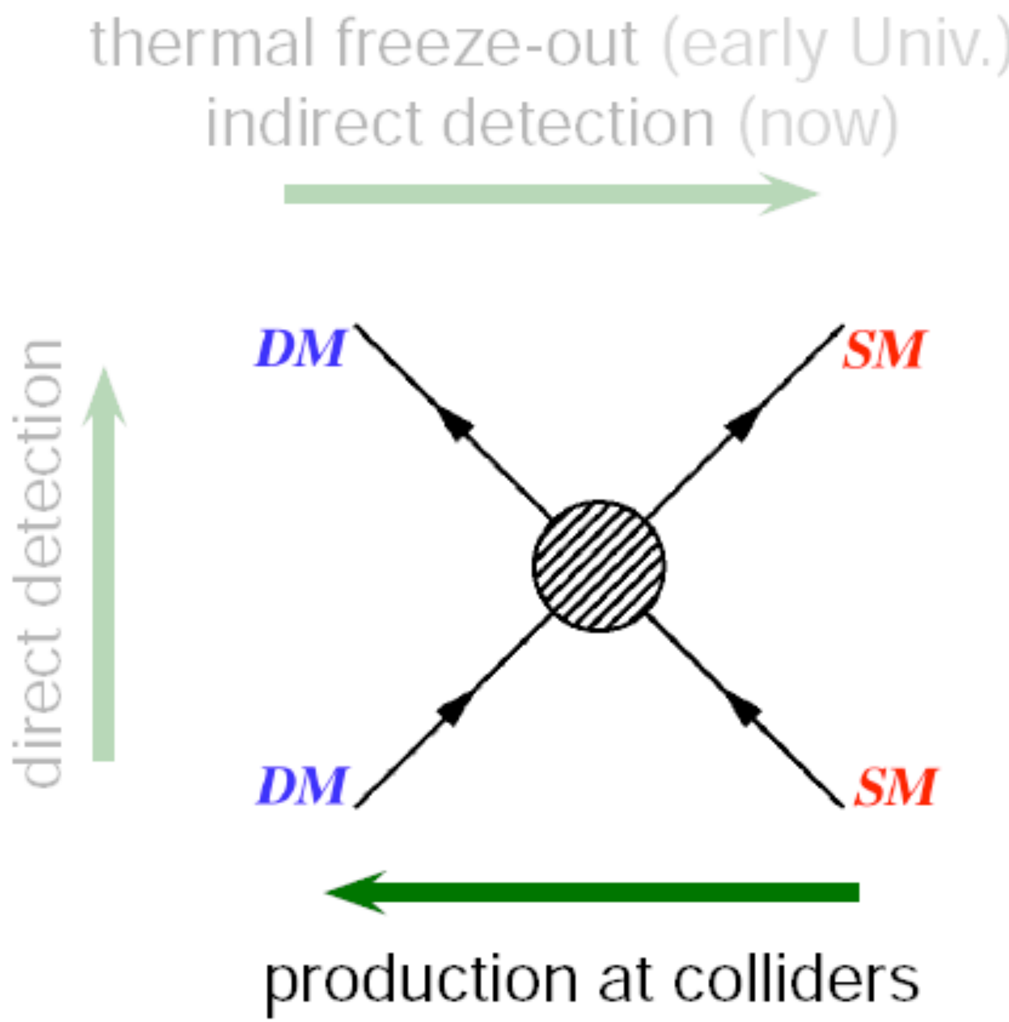
  …

- …Would be nice if it interacted via other forces…?

Explaining dark matter



Detecting dark matter: colliders

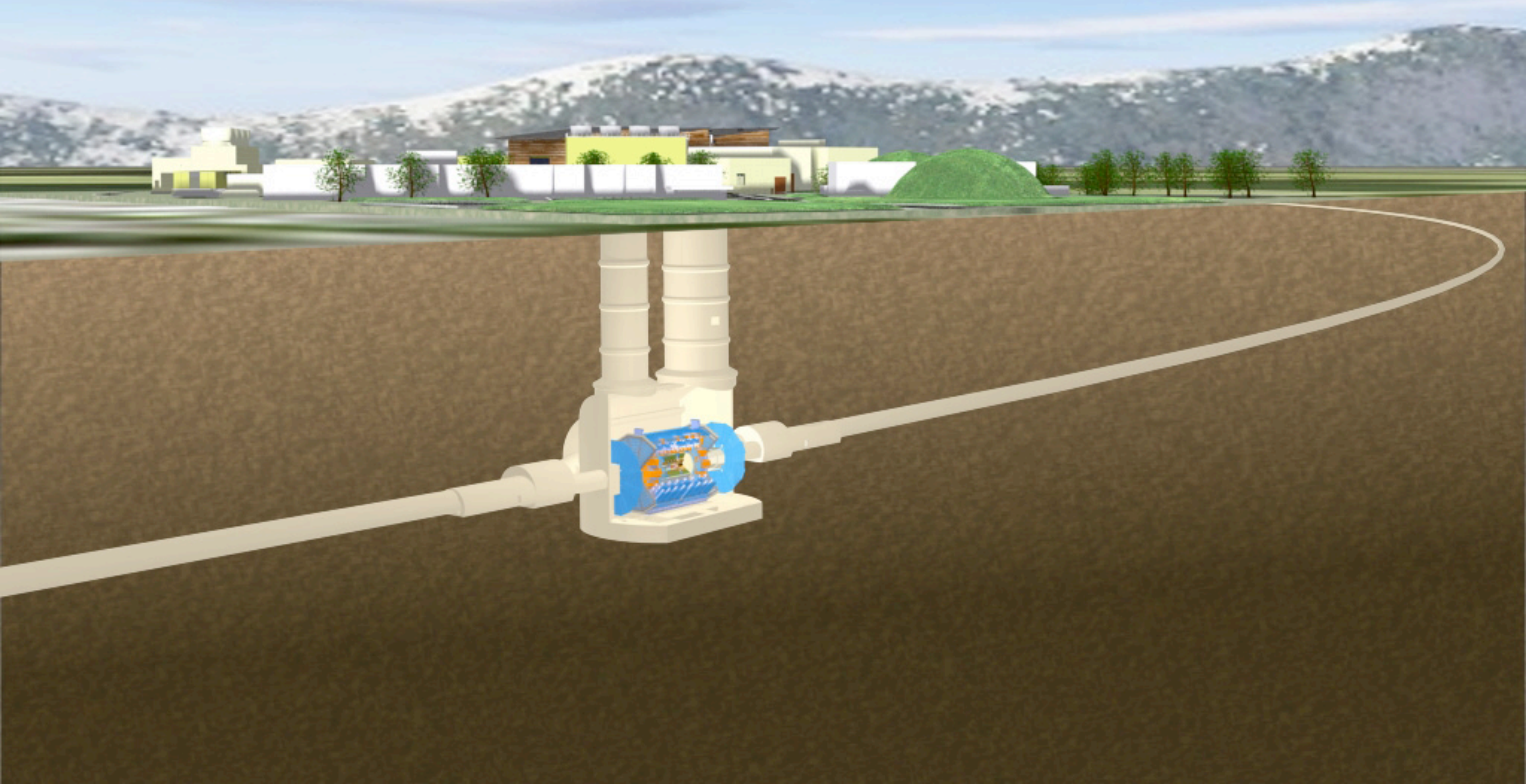


Assuming dark matter can be produced in pp collisions at √s=13 TeV, and can be distinguished from other collision processes!

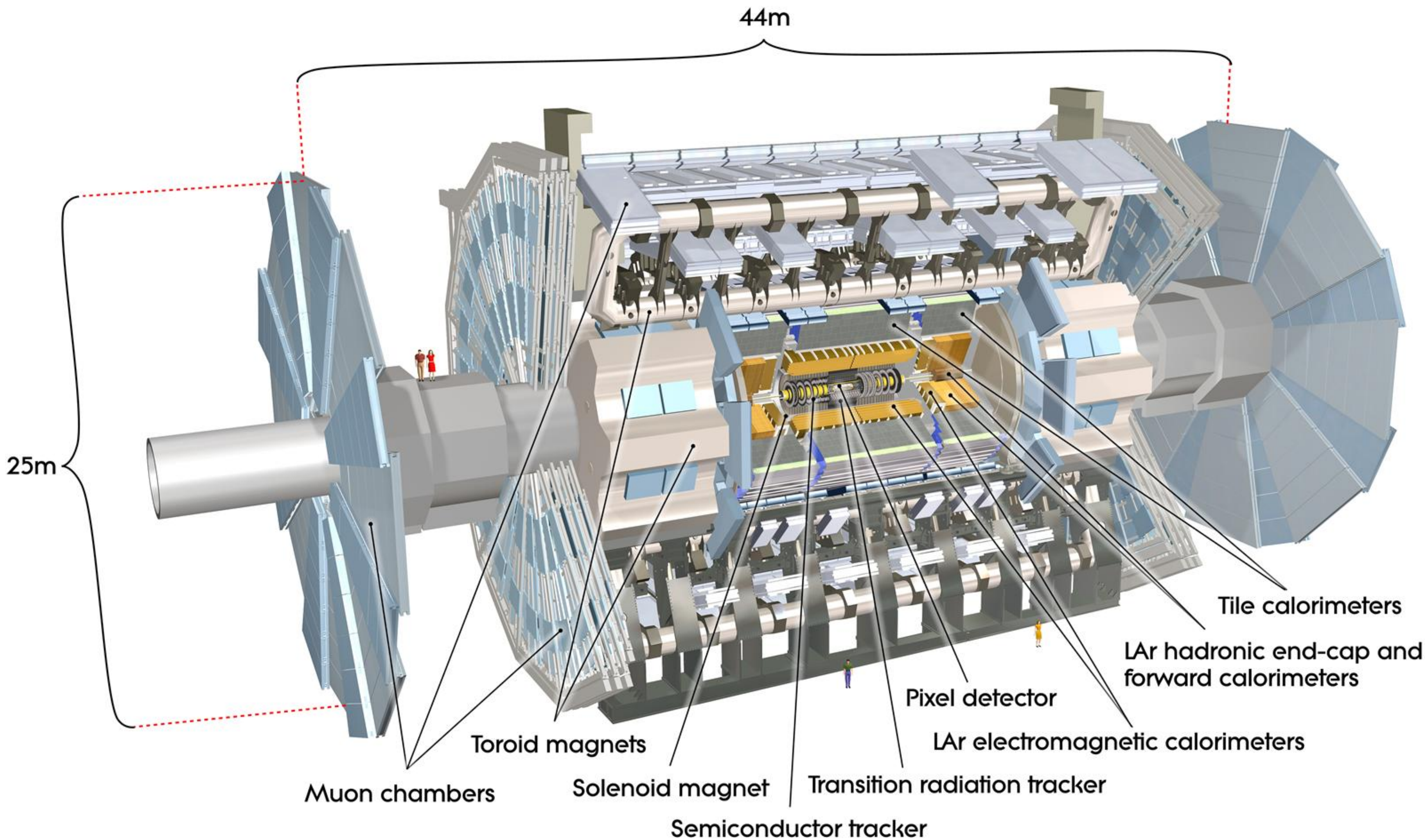
THE LARGE HADRON COLLIDER, GENEVA

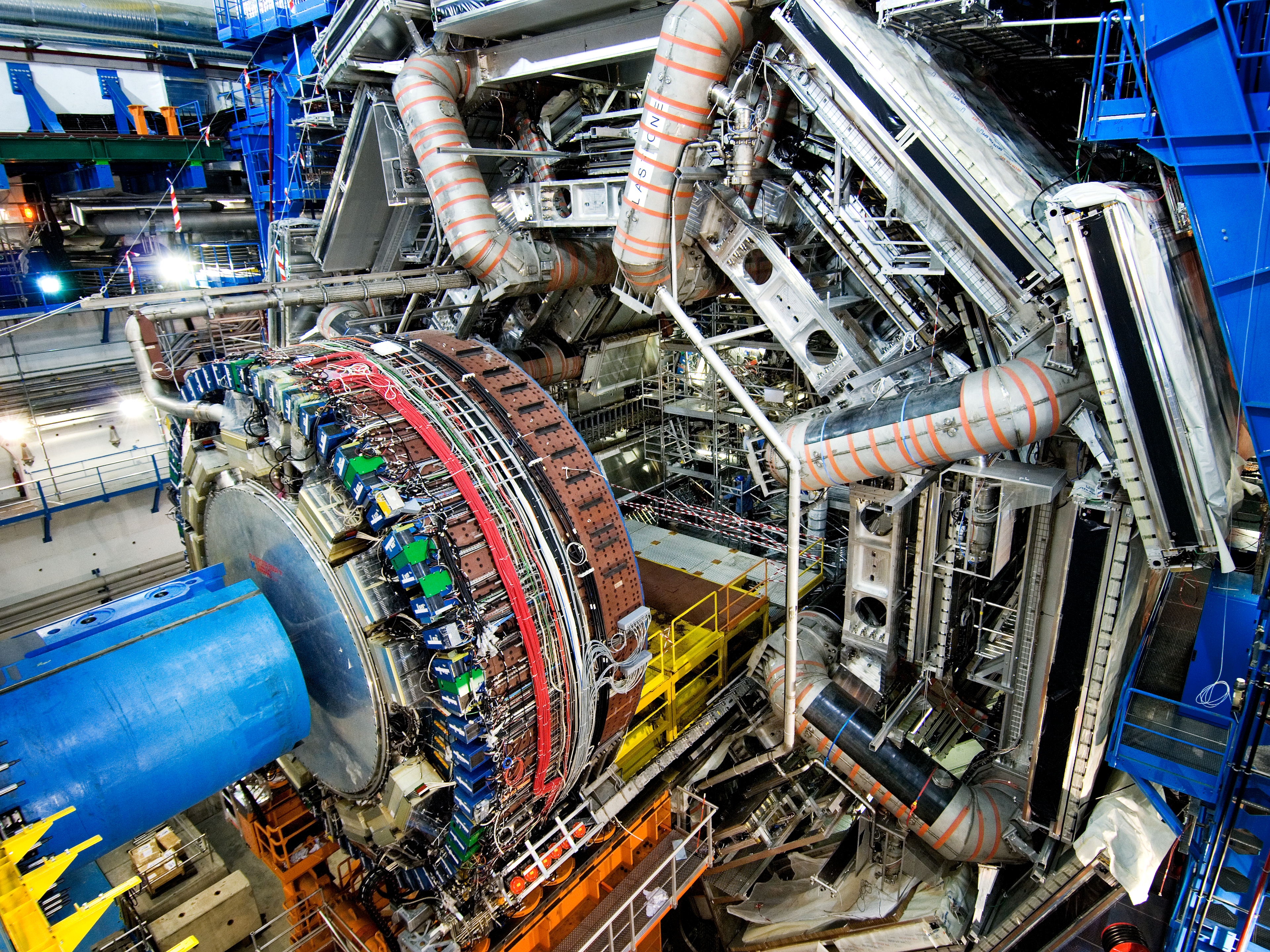
The ATLAS detector

A high-resolution camera taking photos 40 million times a second in a high radiation environment, creating conditions last seen at the Big Bang, in an accelerator colder than outer space



The ATLAS detector





Searches targeting specific theories

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

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

Used as a standard benchmark for weak scale new physics

Difficulty in reinterpreting results

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

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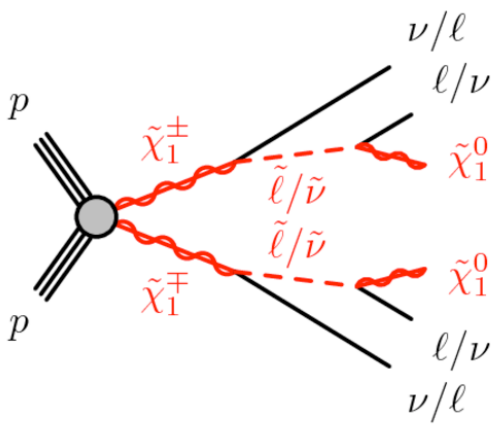
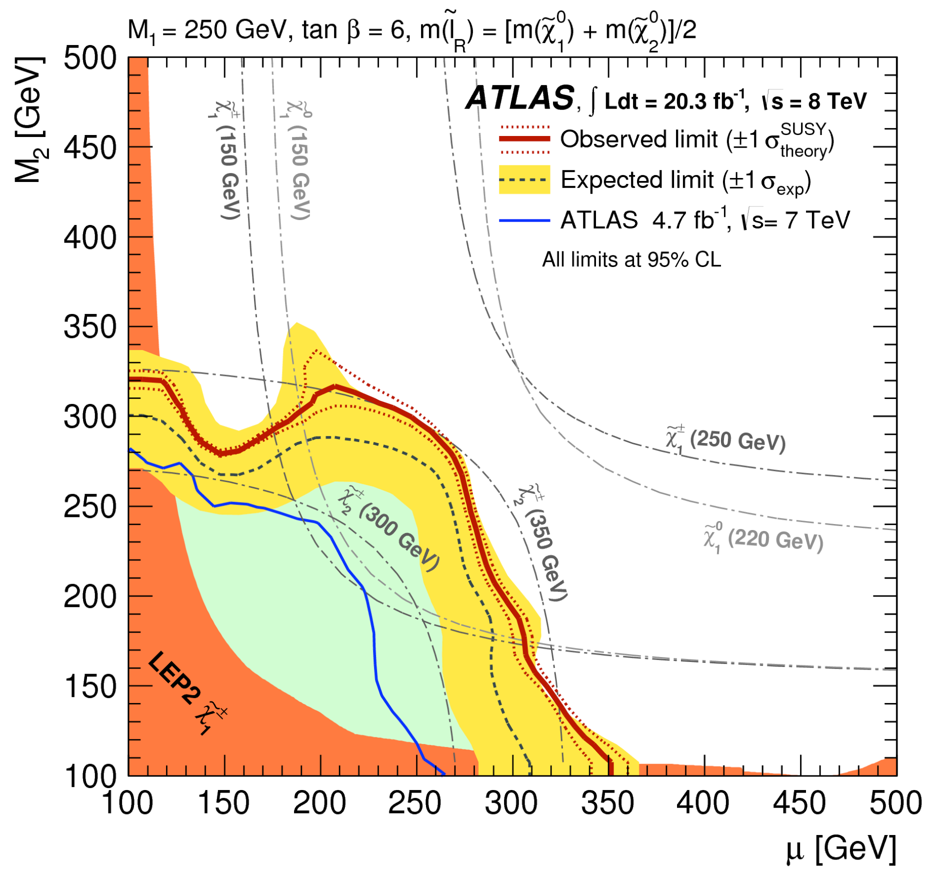


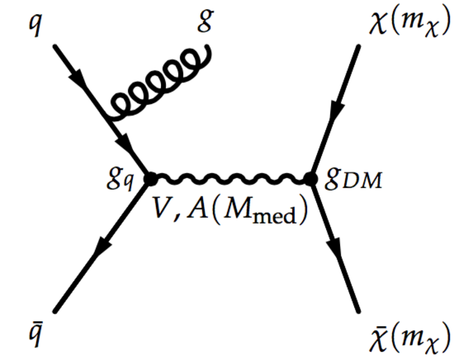
"95% CL exclusion regions in the μ–M_2 mass plane of the pMSSM with right-handed slepton mass $m^{\tilde{l}}_R$ = [$m(\chi^{\sim 0}_1)$ + $m(\chi^{\sim 0}_2)$]/2."

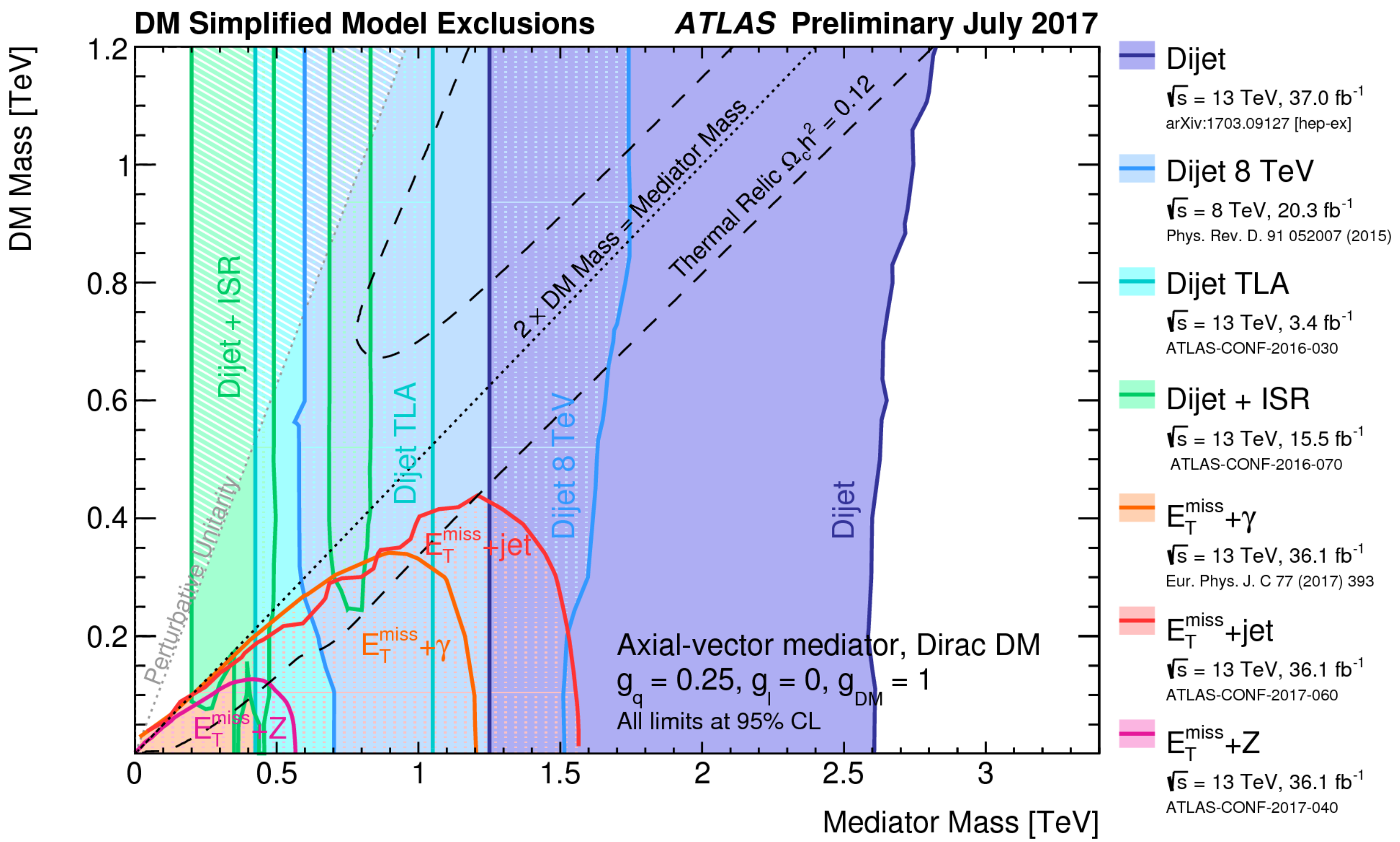


Simplified models: theory-agnostic approach

SM–DM interaction mediated by new particle

- Easier to re-interpret
- Incomplete models





A need for new approaches?

Why not keep on doing this?

- Both approaches rely on careful detector simulation and application of data selection criteria to SM backgrounds and theory under test.

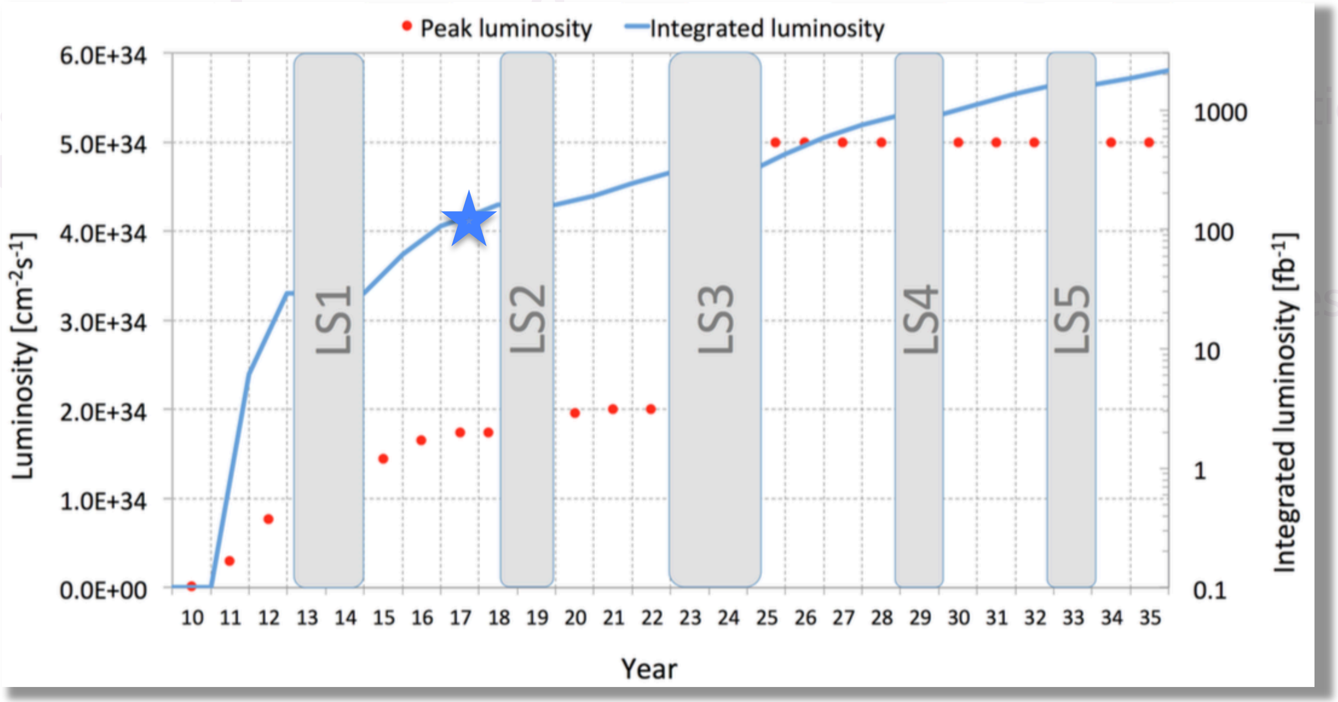
- Difficulty of application/generalisation of results to other theories.

Key considerations

☞ 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.

A need for new approaches?

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



Key considerations

- ☞ New dark matter theory in future?
- ☞ Looking for the wrong things?
- ☞ Improvements in SM modelling?
- ☞ A global view on searches?

Reinterpretation.
Over-optimisation.
Recalculation of limits.
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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Correct the published data for detector effects: resolution/efficiency

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

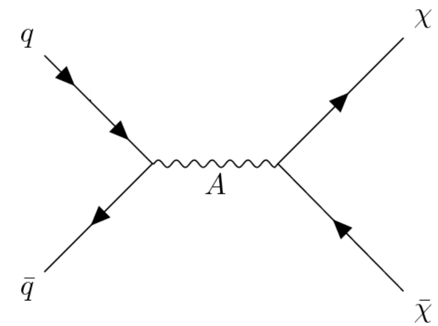
Addressing reinterpretability:

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"

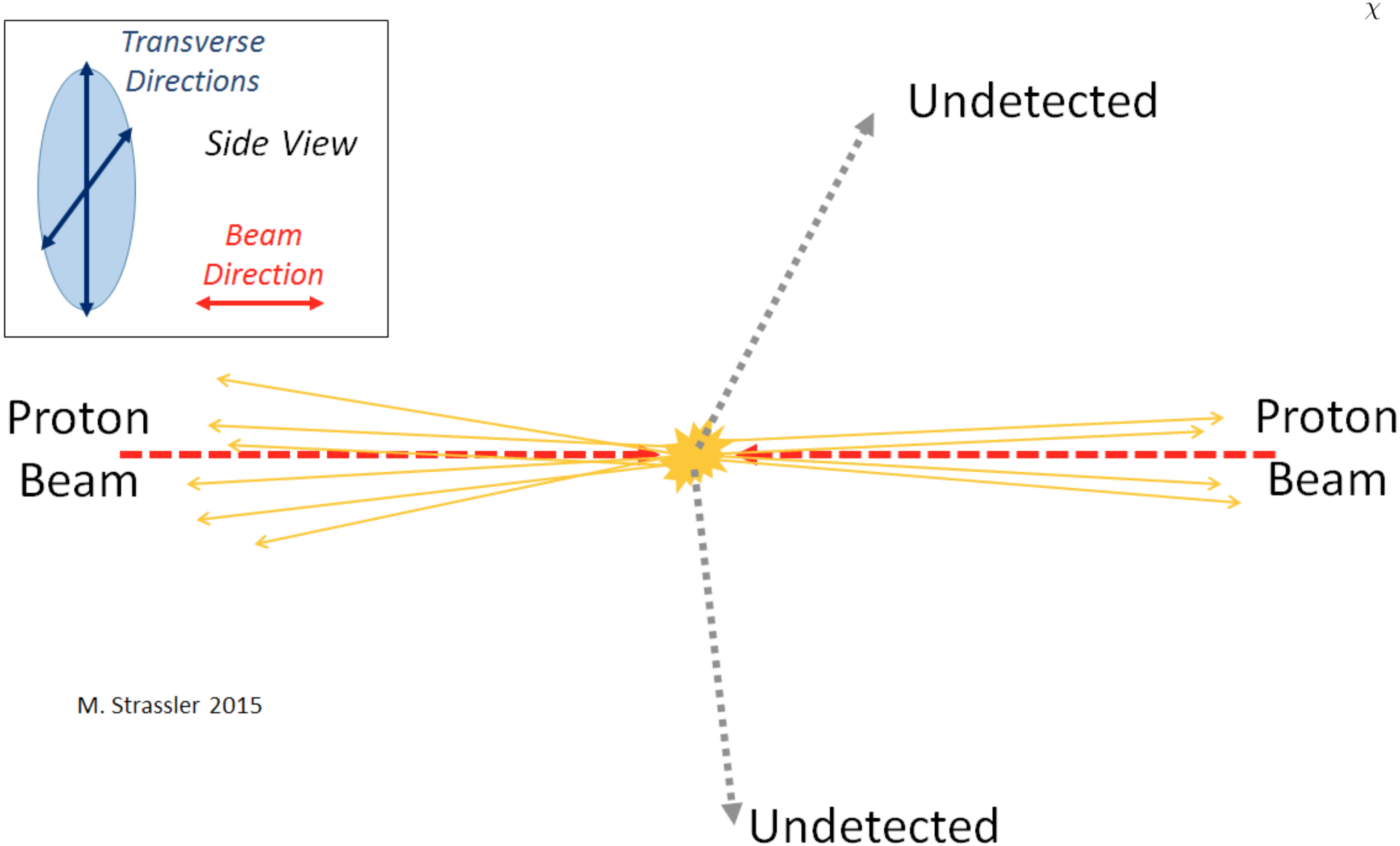
A critical distinction!

What to measure?



Model-independence: back to basics

What is the signature of dark matter produced in our detectors?



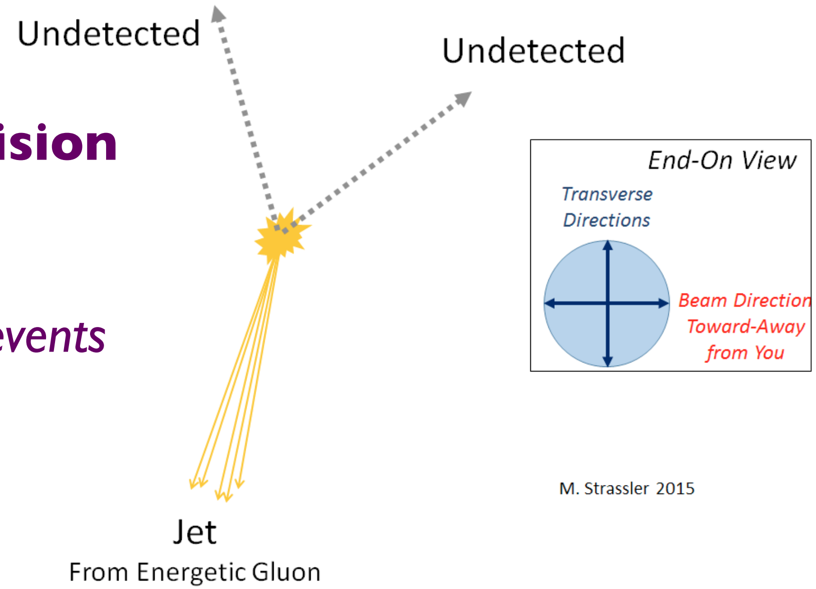
M. Strassler 2015

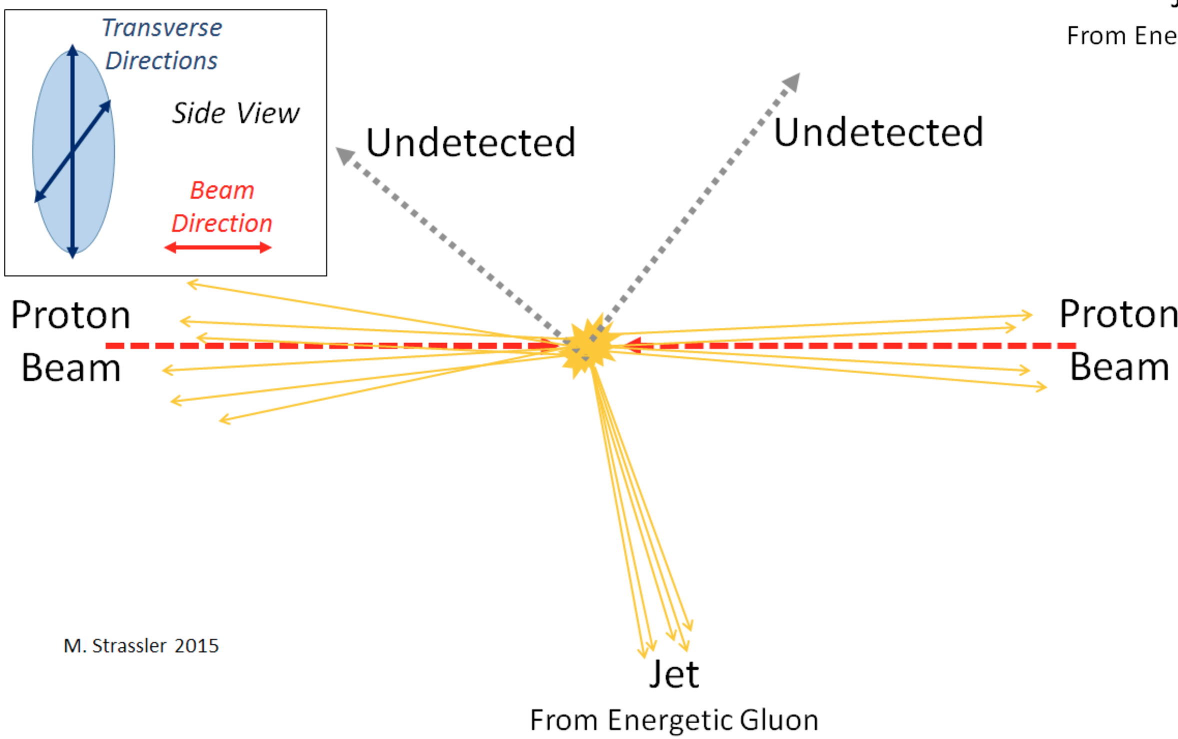
General dark matter signatures

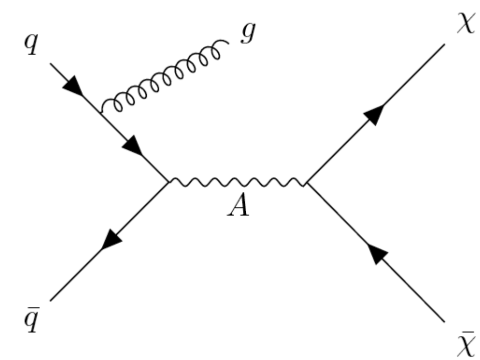
Need a visible object to identify collision

Simplest case is one hadronic jet recoiling

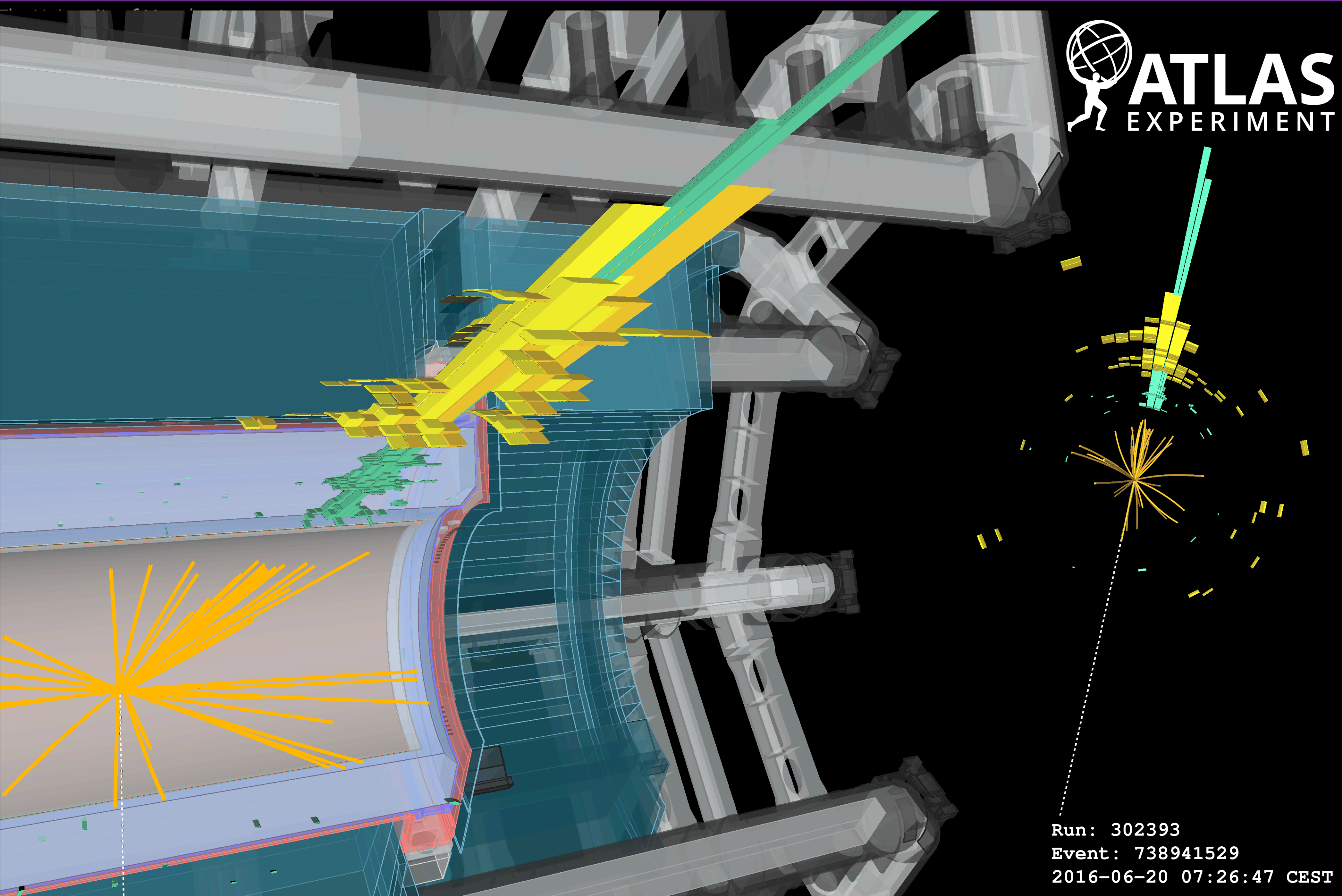
Might consider to determine rate at which such events are produced in ATLAS





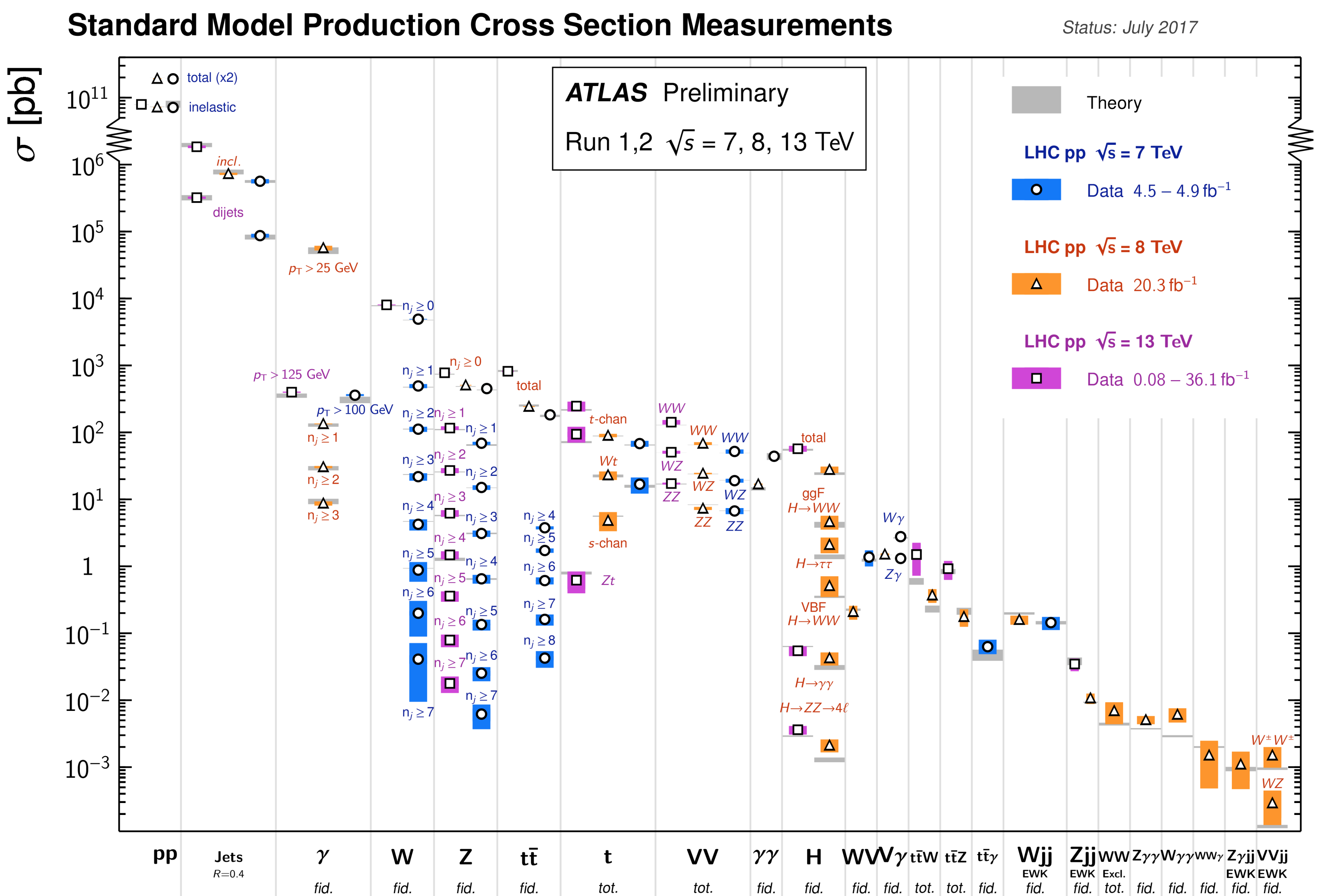


Monojet event in ATLAS



Correcting for detector effects

Take our lead from “Standard Model” measurements:



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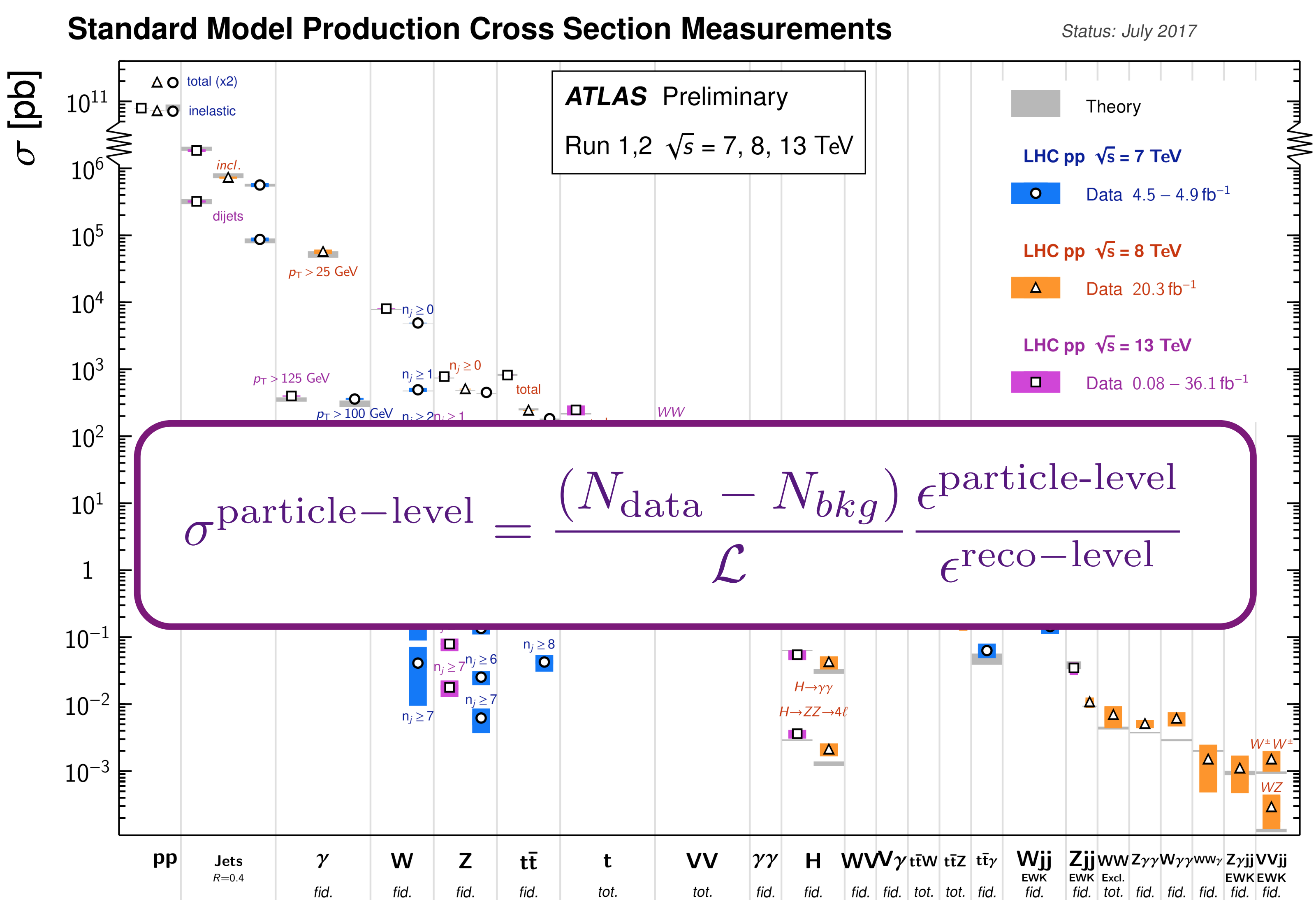

$$\sigma^{\mathrm{particle-level}} = \frac{(N_{\mathrm{data}} - N_{bkg})}{\mathcal{L}} \frac{\epsilon^{\mathrm{particle-level}}}{\epsilon^{\mathrm{reco-level}}}$$

The challenge!

Aim to make cross-section measurements of new particles that:

- we have no evidence are being produced in our detectors
- would be completely invisible even if they were
- we have little to no idea what they are
- might not exist anyway

The challenge!

Construct measurable quantity sensitive to dark matter that:

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

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New observable:

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

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

Observable definition

Detector-corrected observable R_{miss}:

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

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

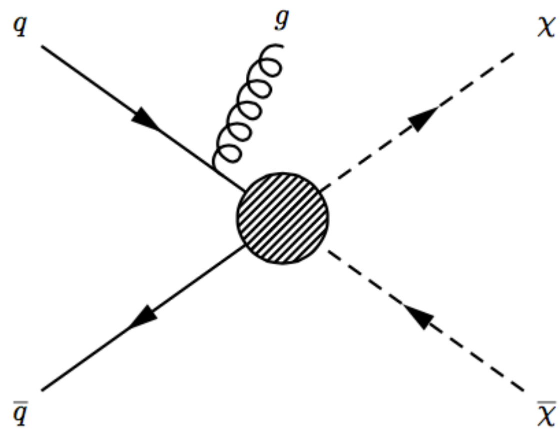
Correction factor accounting for detector resolution and efficiency

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

In Standard Model, only contributions to denominator come from Z→νν decays

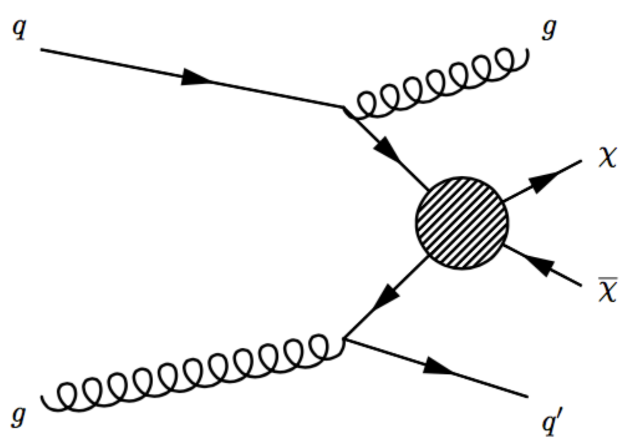
Measure detector-corrected observable as function of kinematics of event for two generic search topologies as proof-of-principle: monojet, and dijet "VBF"

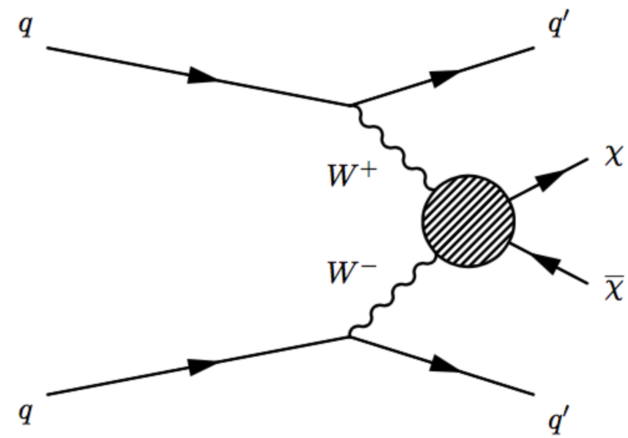
No assumption baked into measurement procedure, just a likely scenario for model sensitivity



$$\frac{dR_{\mathrm{miss}}}{d\not{p}_T}$$

$$\frac{dR_{\mathrm{miss}}}{dm_{jj}} \qquad \frac{dR_{\mathrm{miss}}}{d\Delta\phi_{jj}}$$

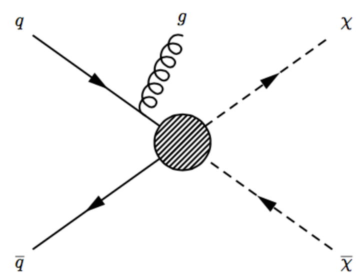


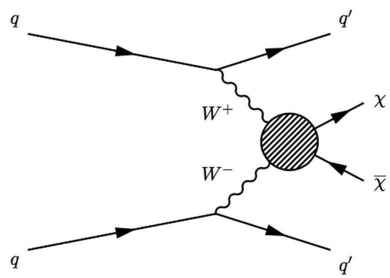


Event selection

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.

- **VBF fiducial region**
  At least two tagging 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 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

Determination of numerator (MET+jets)

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

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*
    - *Exp uncertainties largely cancel (lepton efficiency uncertainty ~1% on final SR)*

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

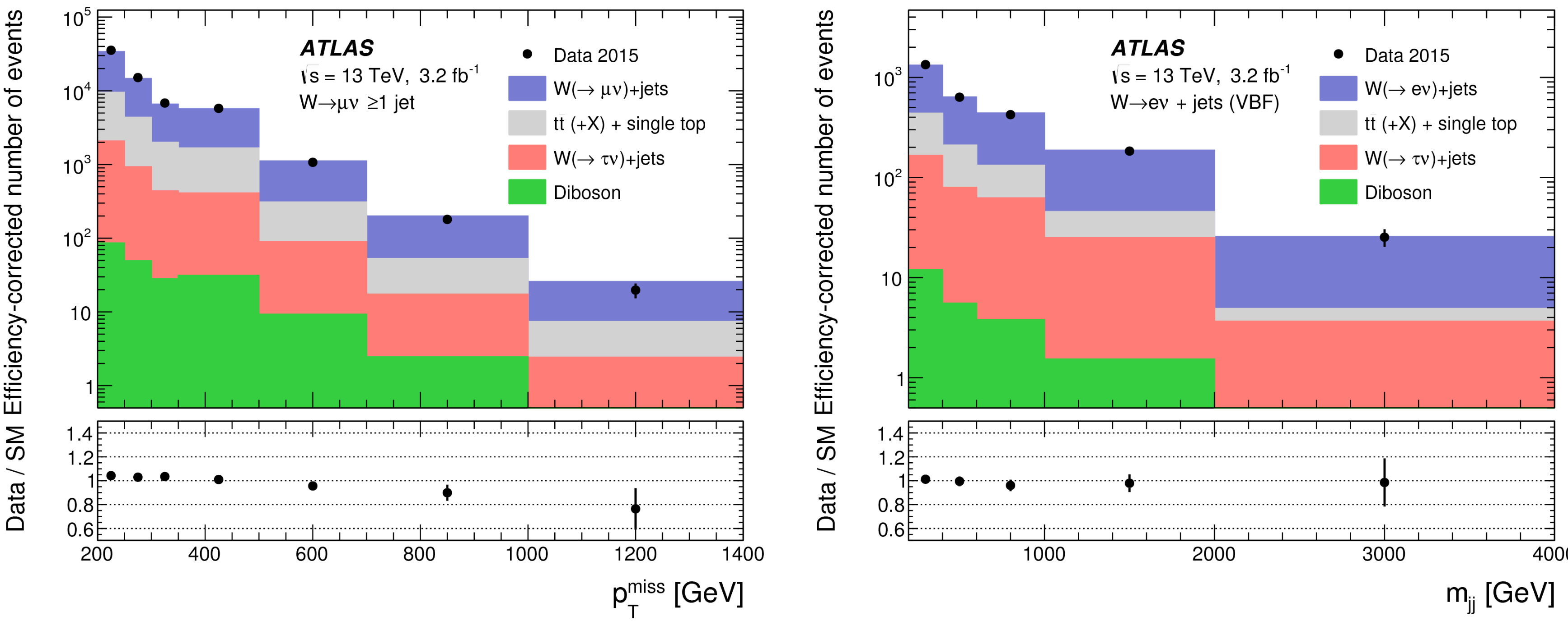
Conversion factor to account for misidentified events with one lepton in signal region

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

Efficiency-corrected event yield in control region

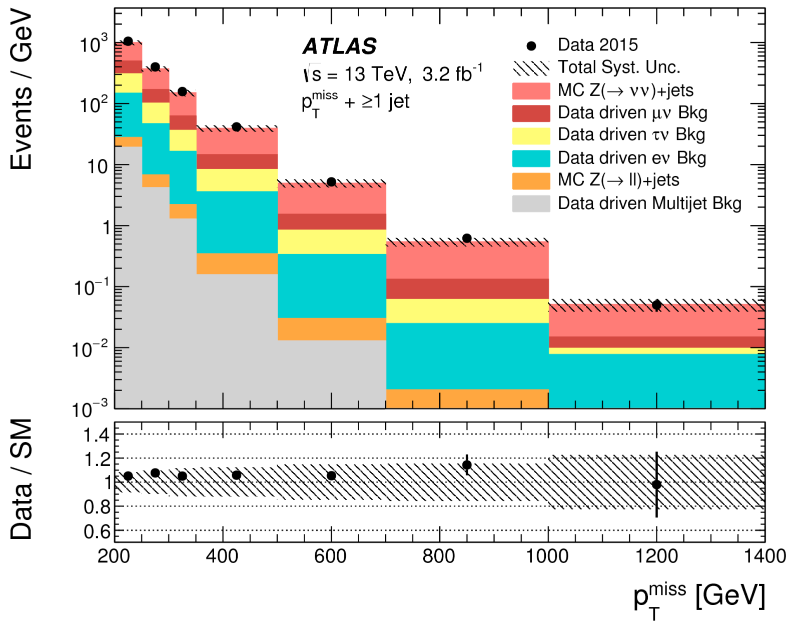
Data-driven W background determination

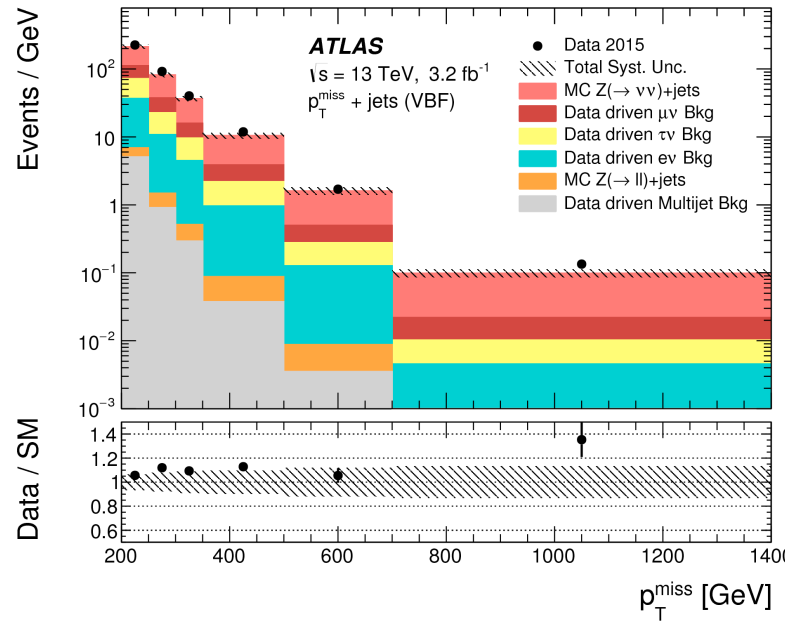
W background control region:

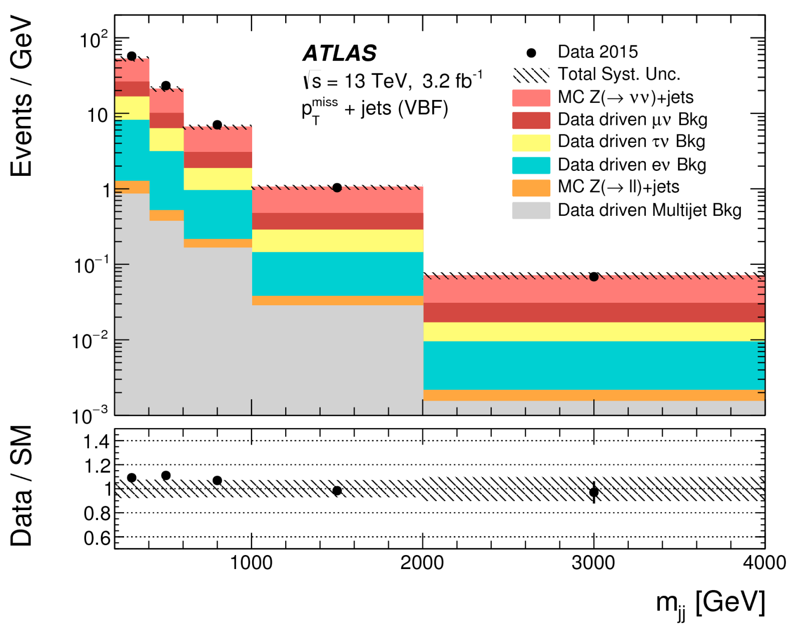


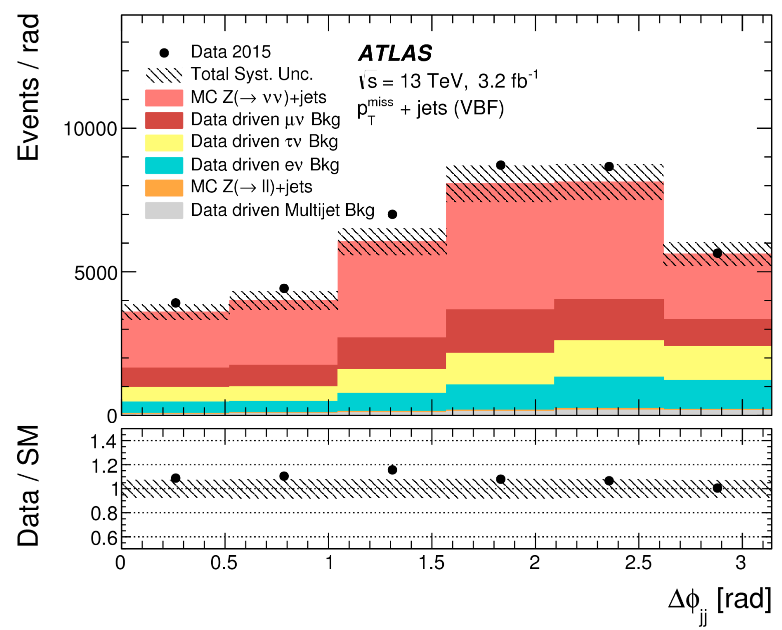
- Data driven measurement results in slightly different shapes than theory
- Good agreement with data-driven method and MC-reweighting approach

MET+jet signal region data





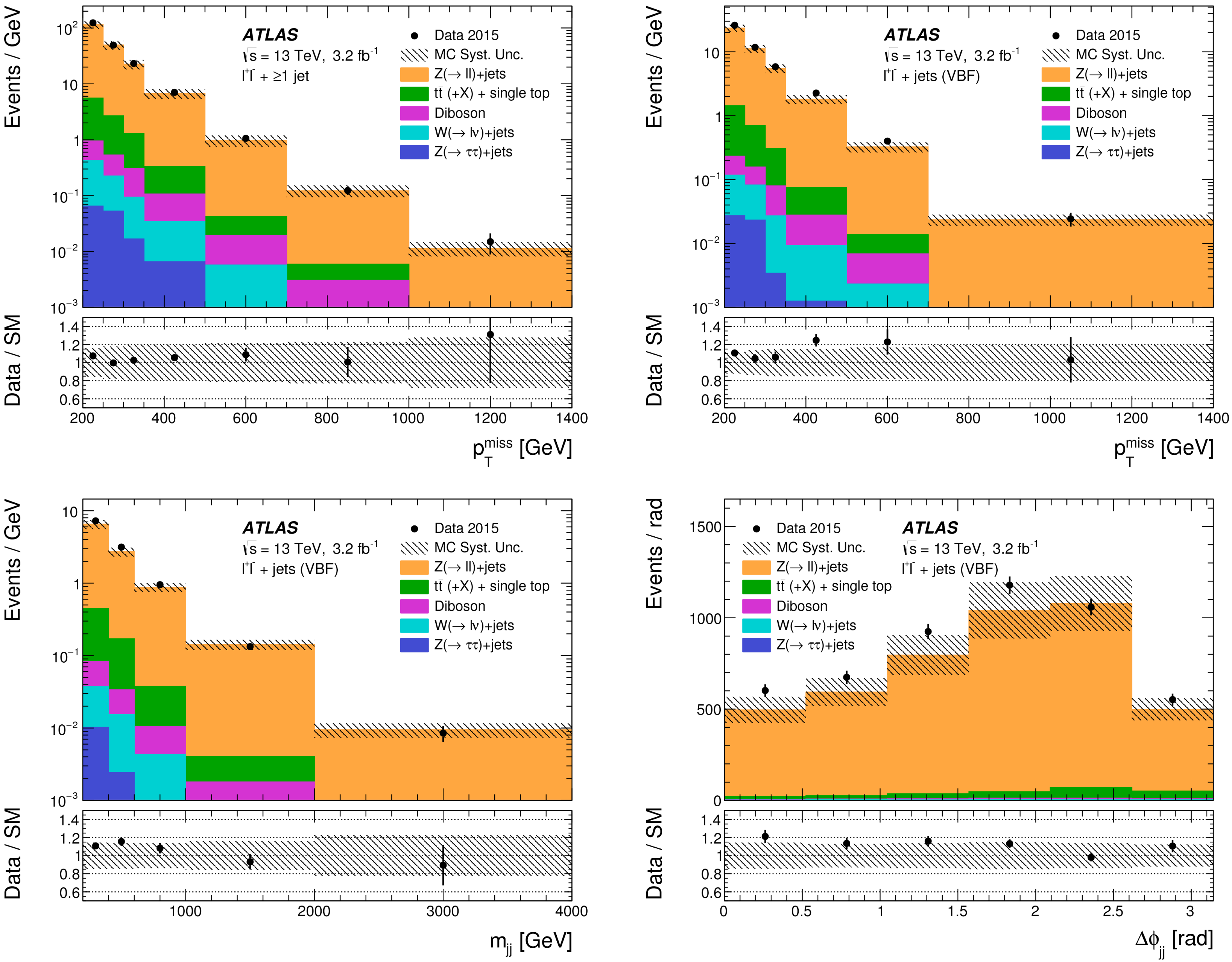




Determination of denominator (l^+l^-+jets)

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

l^+l^-+jet signal region data



Determination of correction factor

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

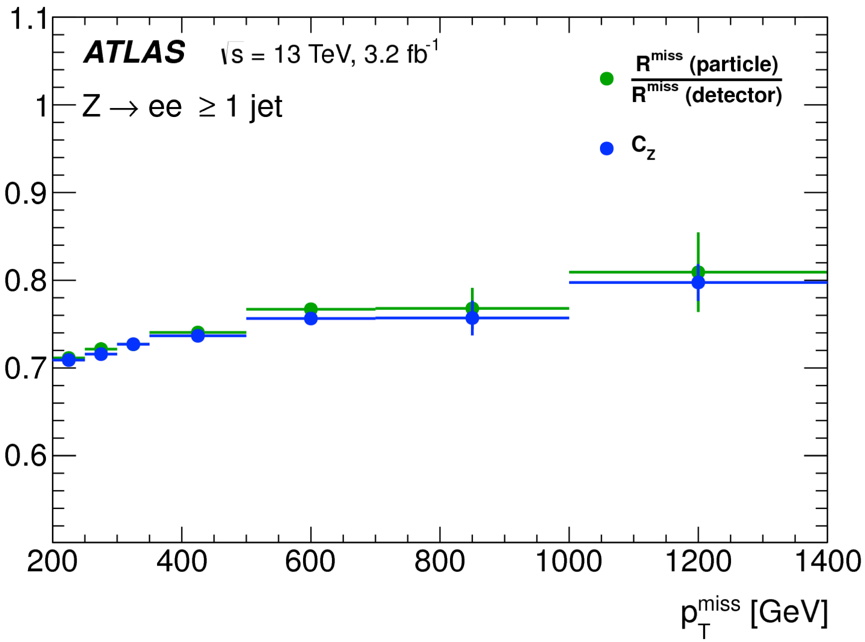
Determination of correction factor

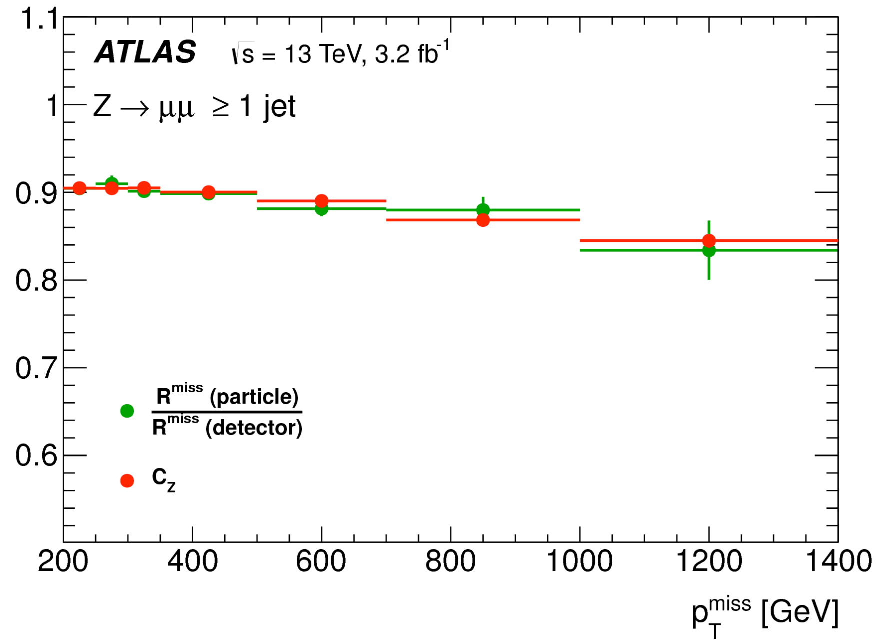
Correction factor from simulated events

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

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



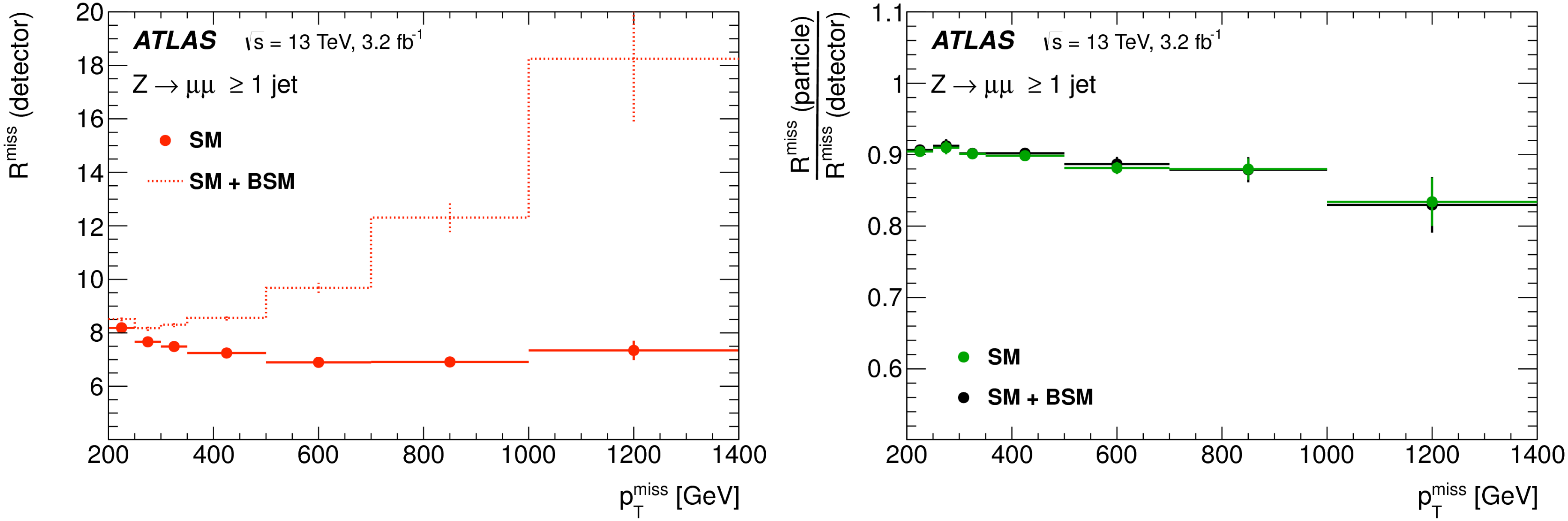


Correction factor BSM injection tests

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



Results: putting it all together

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

✔ ✔ ✔

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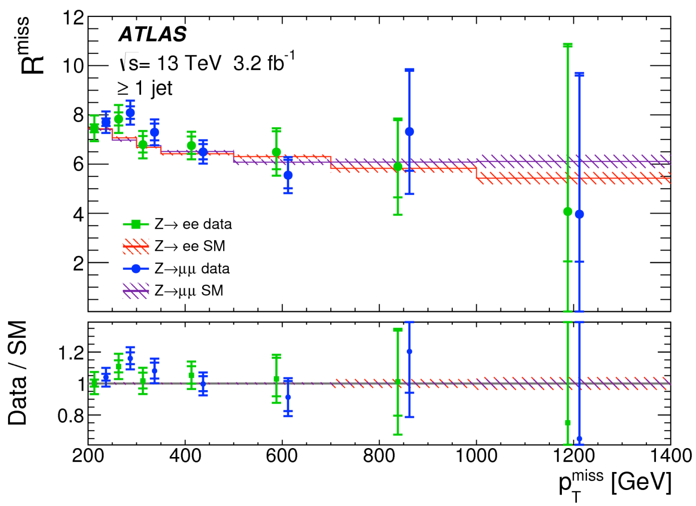
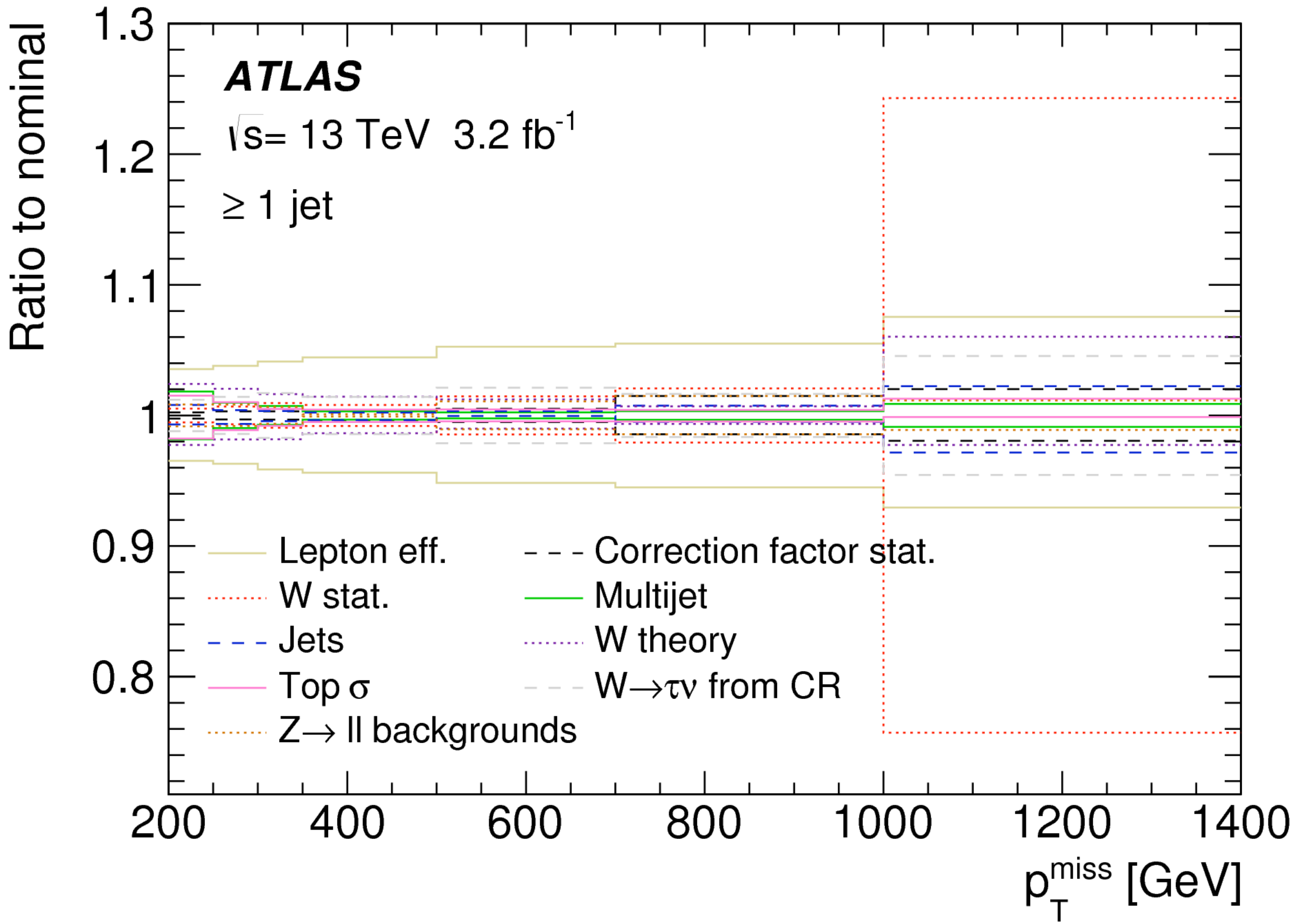


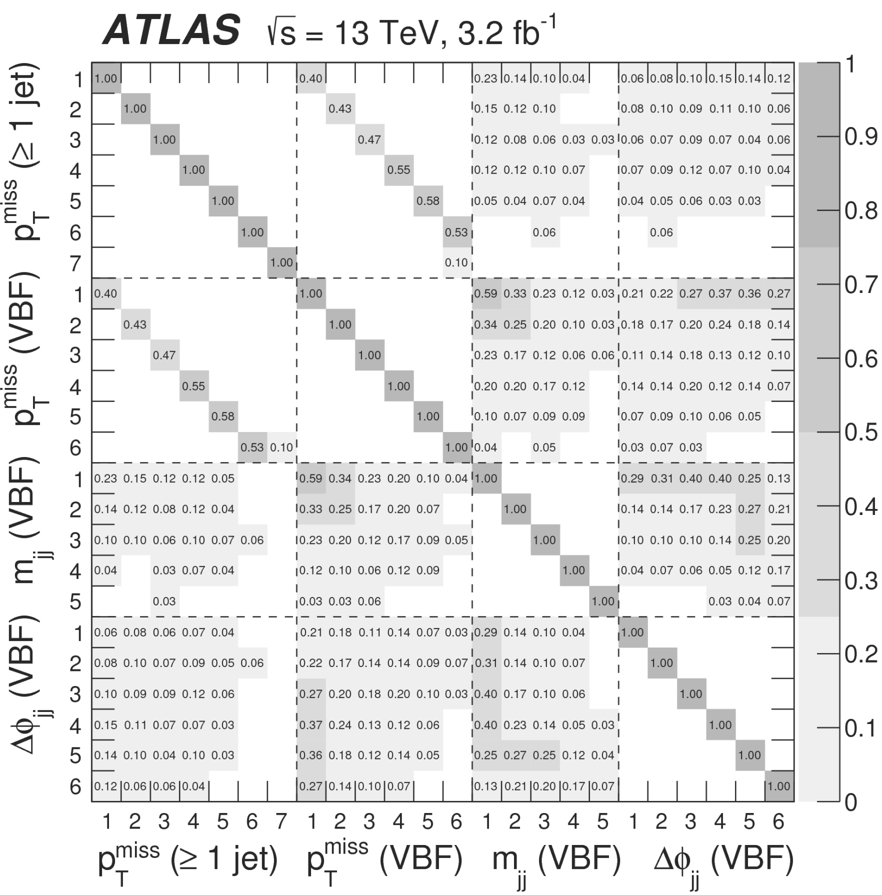
Electron and muon R_{miss} data found in good agreement, perform statistical combination

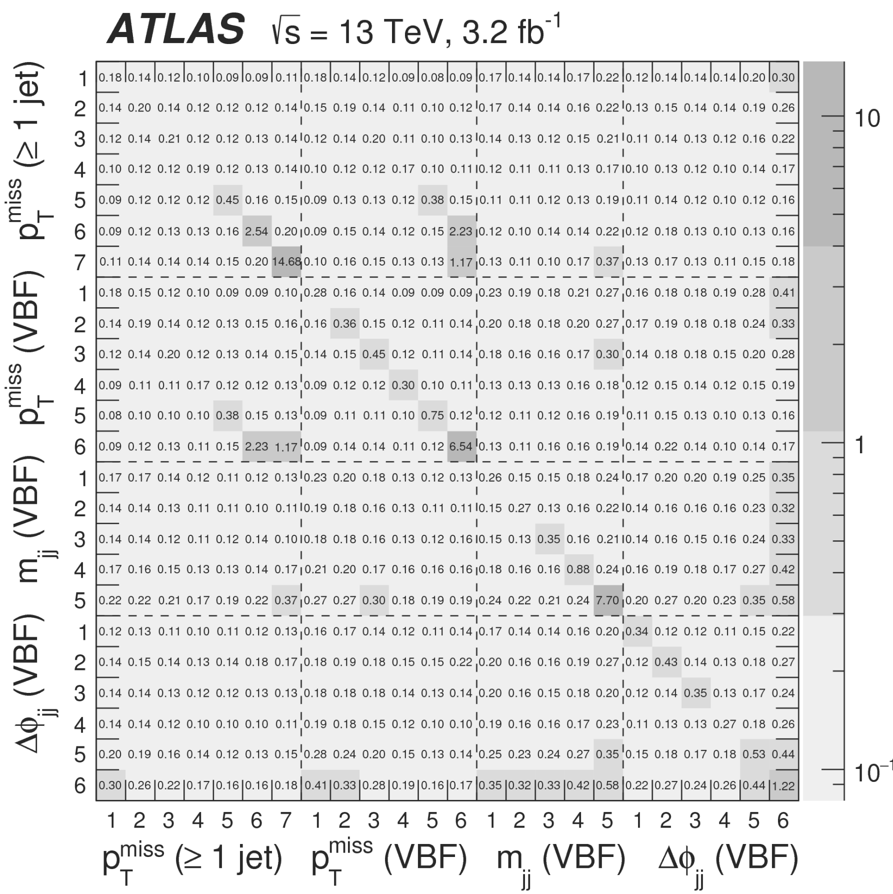
Summary of experimental uncertainties



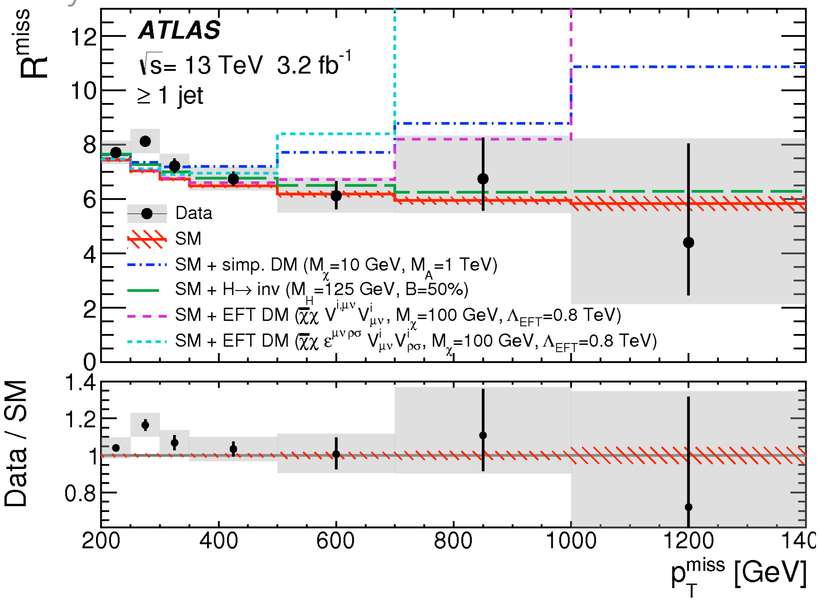
Calculating covariance in measurement

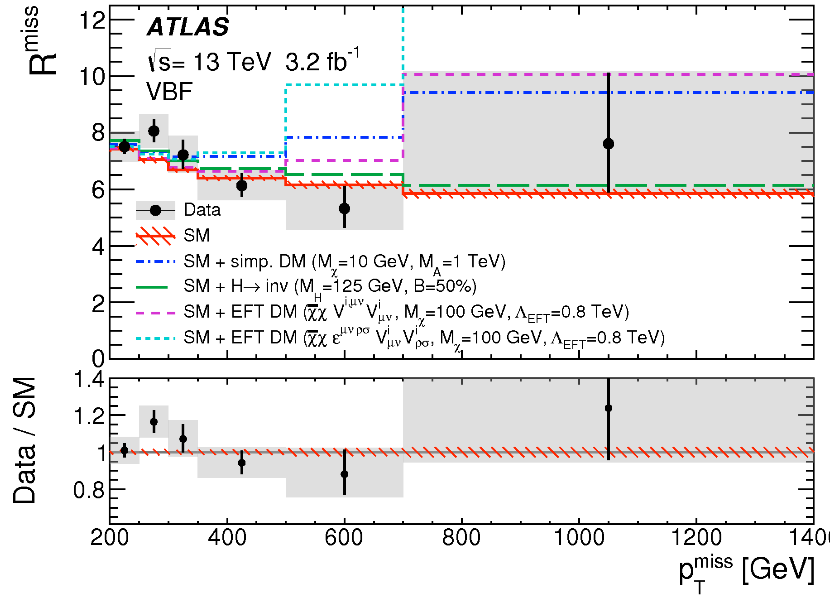
Determine statistical and systematic covariance between bins and between distributions by bootstrapping data



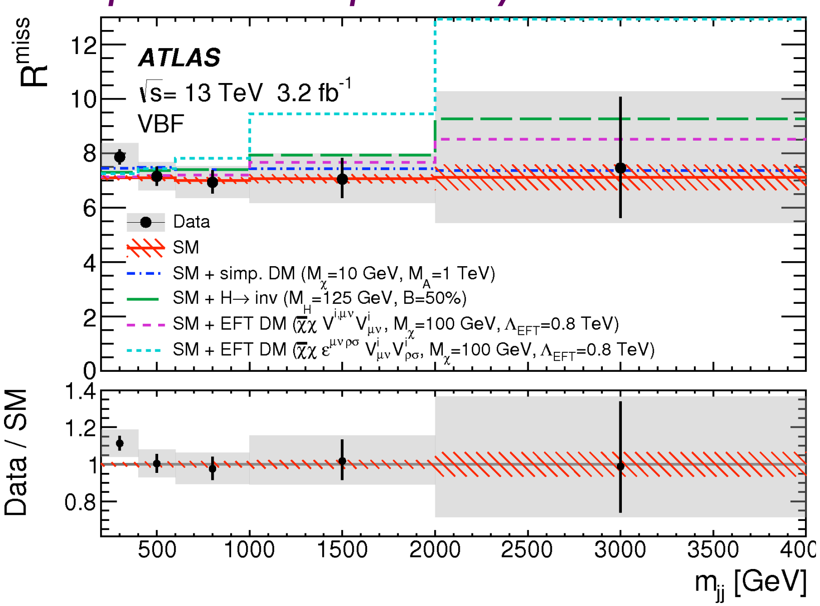


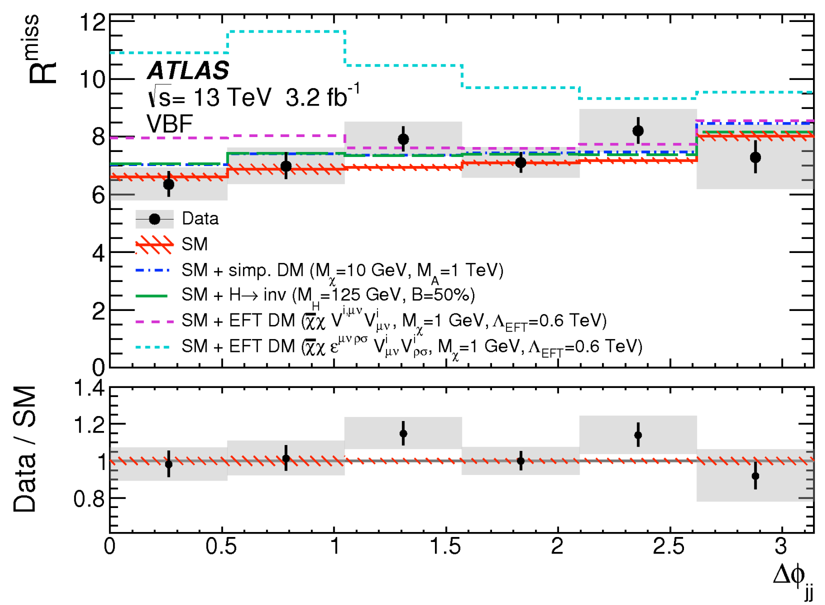
Detector-corrected results





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





Published results

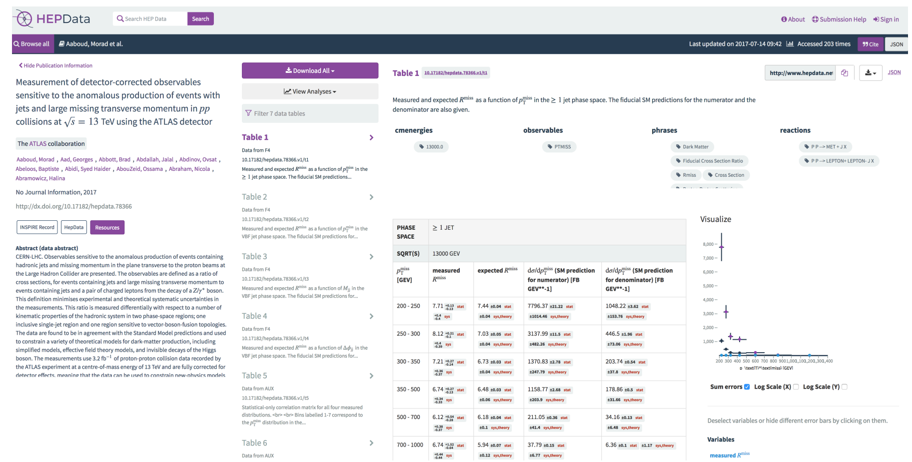
Alongside paper ([arXiv:1707.03263]()) released supporting material:

Rivet analysis code:
https://www.hepforge.org/archive/rivet/contrib/NEW/ATLAS_2017_I1609448.tar.gz

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!

Probing dark matter models

Use detector-corrected data 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*

Approach:

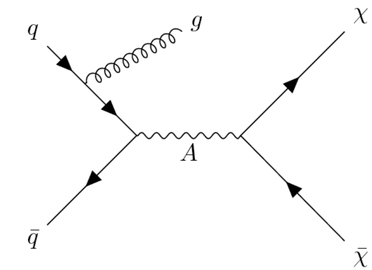
Construct χ^2 compatibility between model under test and data across all bins of all corrected distributions simultaneously:

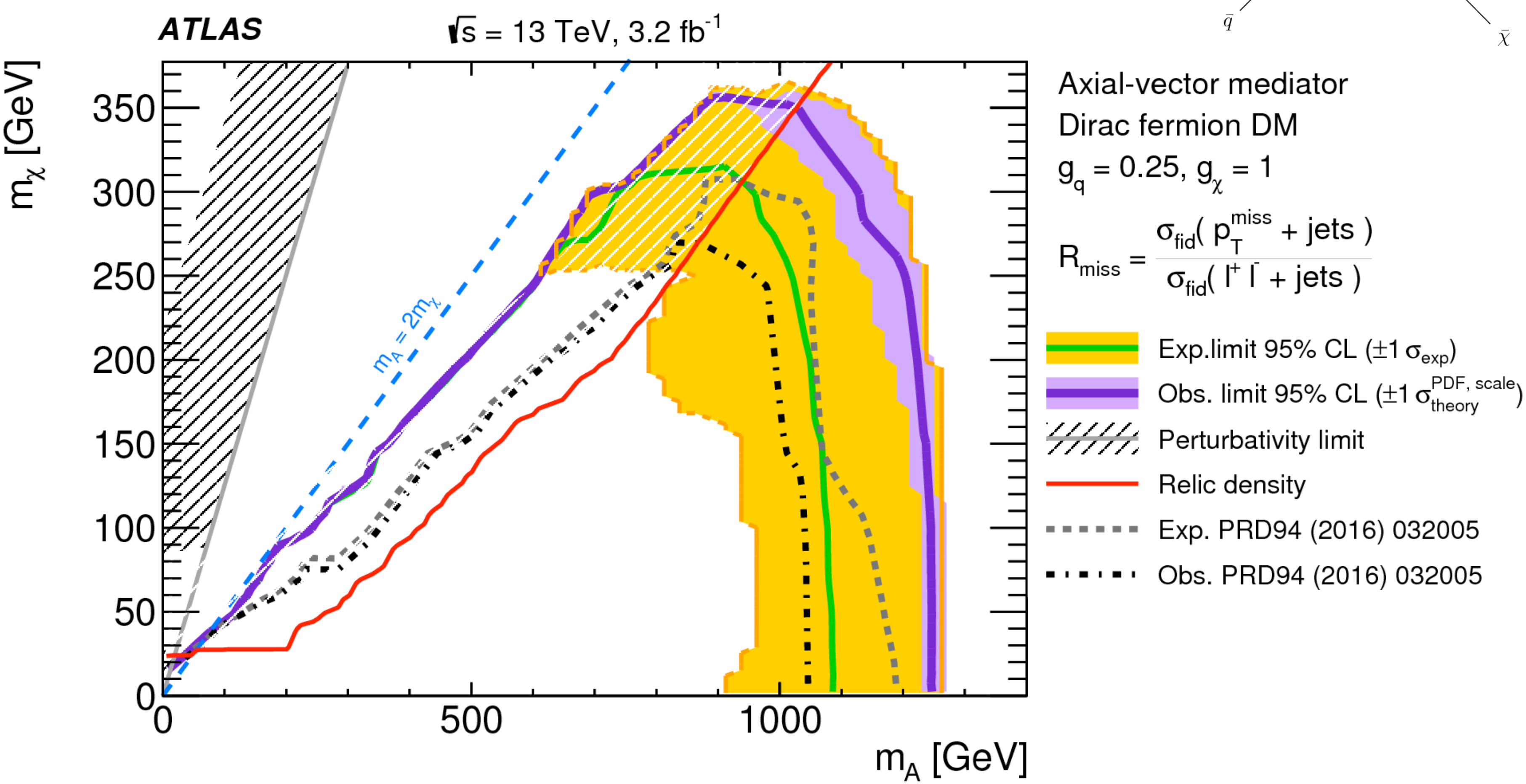
$$\chi^2 = \sum_{i,j}^{n} (x_i - t_i)(C^{-1})_{ij}(x_j - t_j)$$

The CLs technique evaluated using the asymptotic approximation is used to derive 95% CL limits.

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

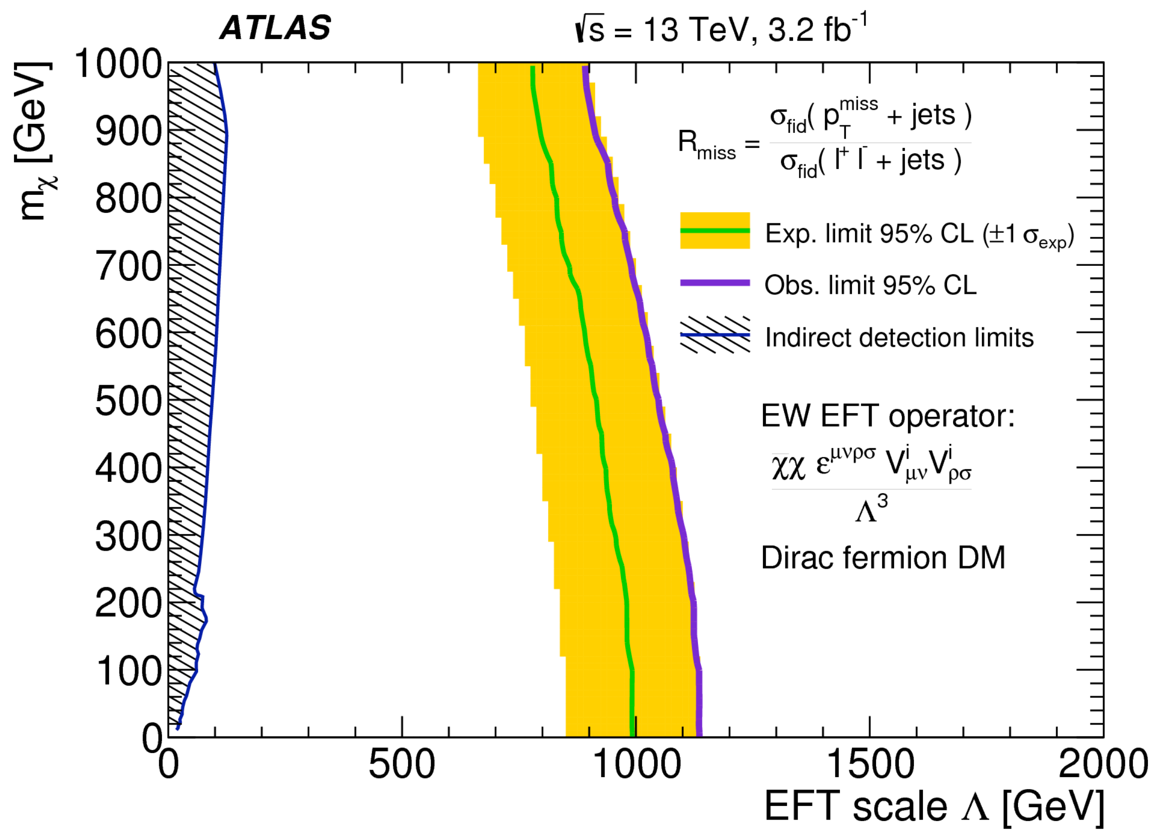


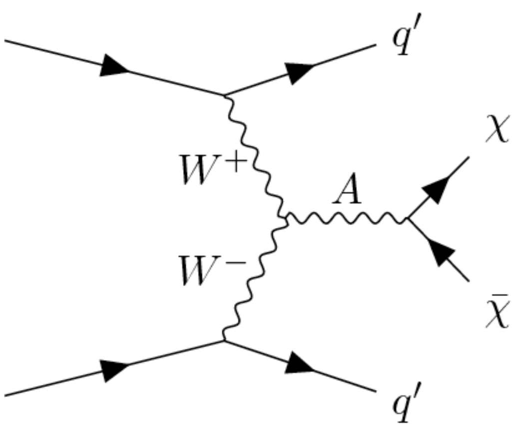


New approach competitive with **dedicated** collider searches!

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.





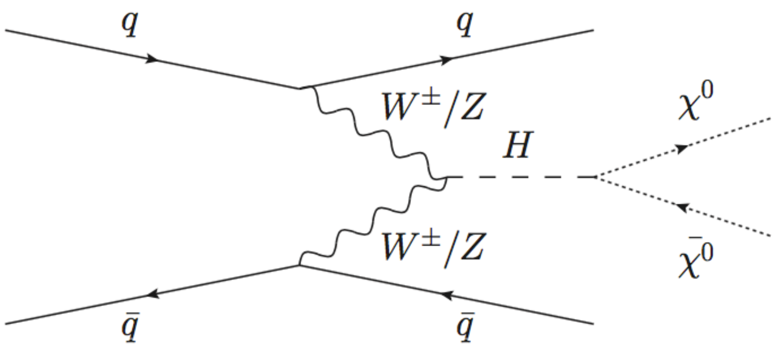
Most stringent constraints to-date on such interactions!

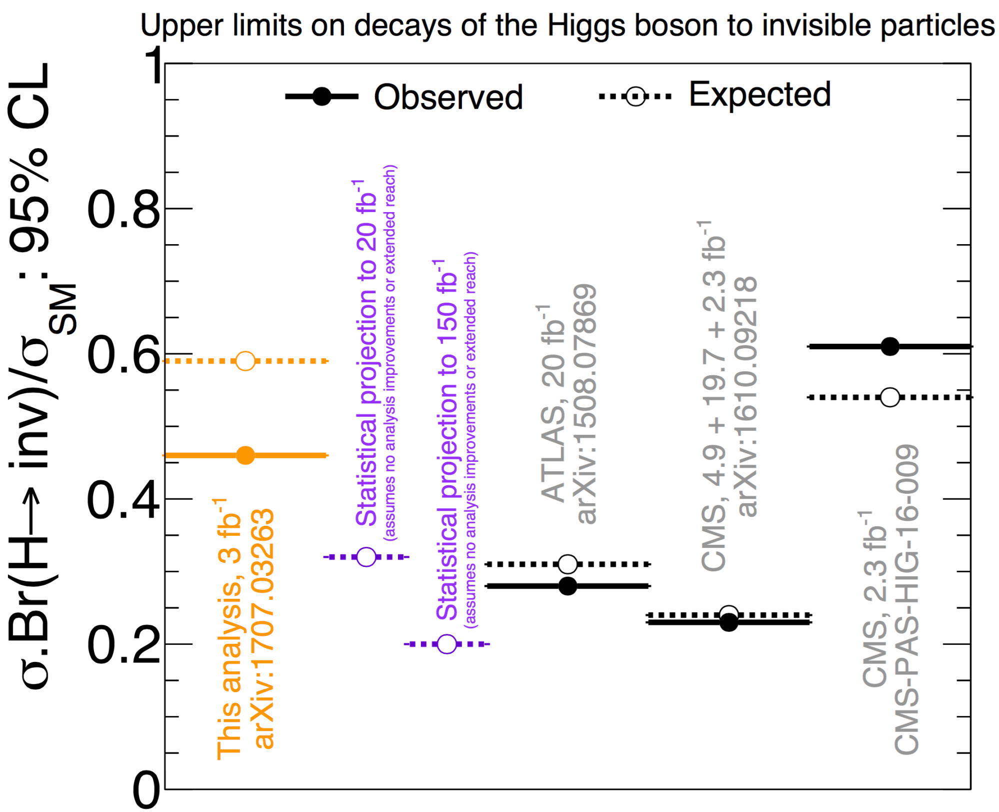
Dark matter coupling to Higgs bosons

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 from LHC 13 TeV!

Next steps and future plans

Existing data release can be used by anyone to place limits on models with jets and missing transverse momentum: use by wider community?

Plans

- Improvements to SM signal definitions
- Improvements to SM control region constraints
- ×30 times more data for Run-2
- Additional event topologies
- More final states (generalisation of technique to other new phenomena)

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

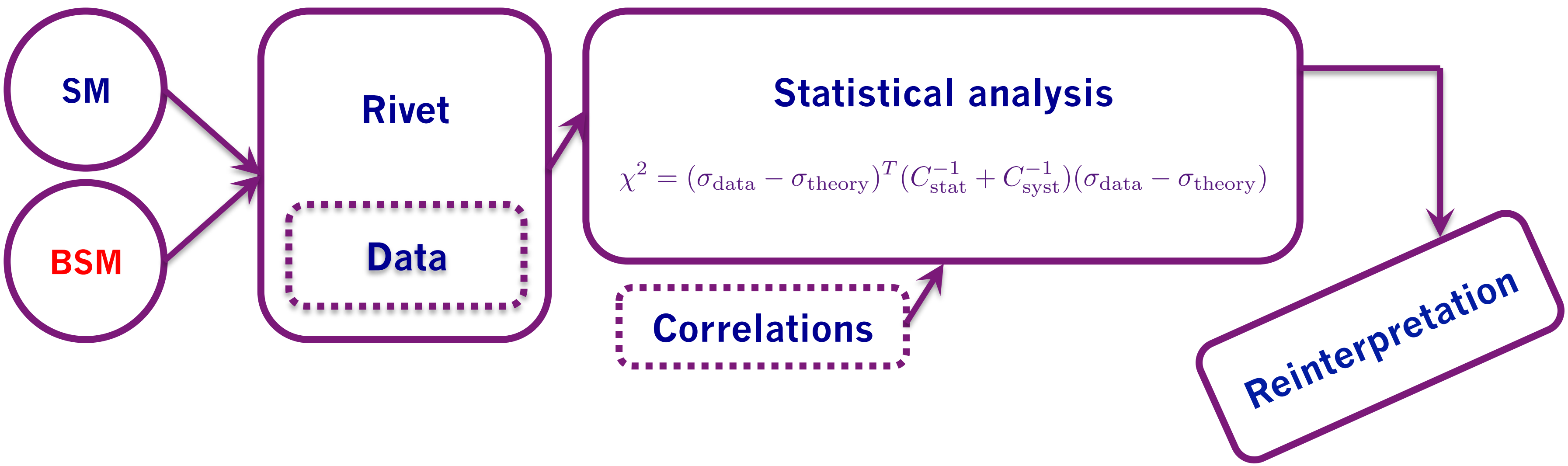
Paper: Eur. Phys. J. C77 (2017) 11, 765; arXiv:1707.03263
Analysis code: https://www.hepforge.org/archive/rivet/contrib/NEW/ATLAS_2017_I1609448.tar.gz
Data: https://hepdata.net/record/ins1609448

Backup

Workflow for reintroduction

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

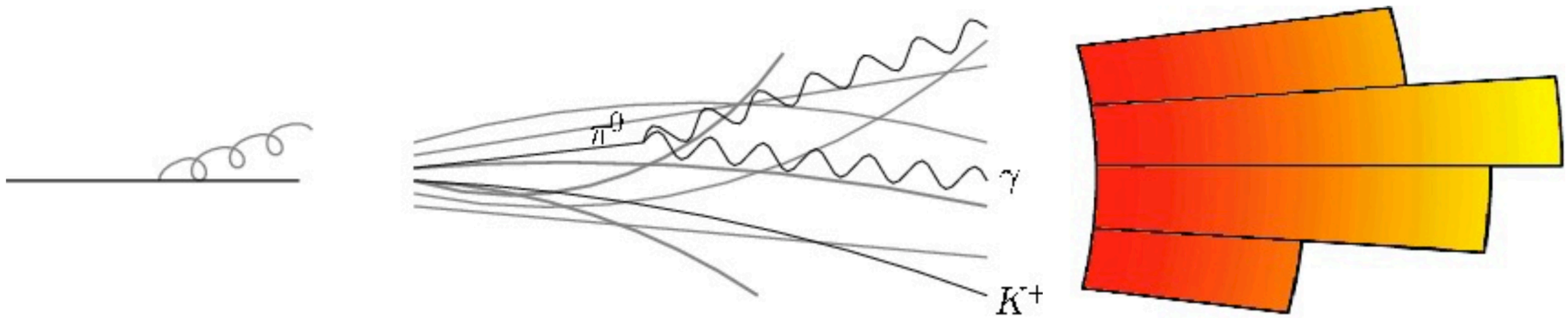
Fundamental challenge to re-interpretation:

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



parton level jet — particle level jet — calorimeter level jet

- 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.

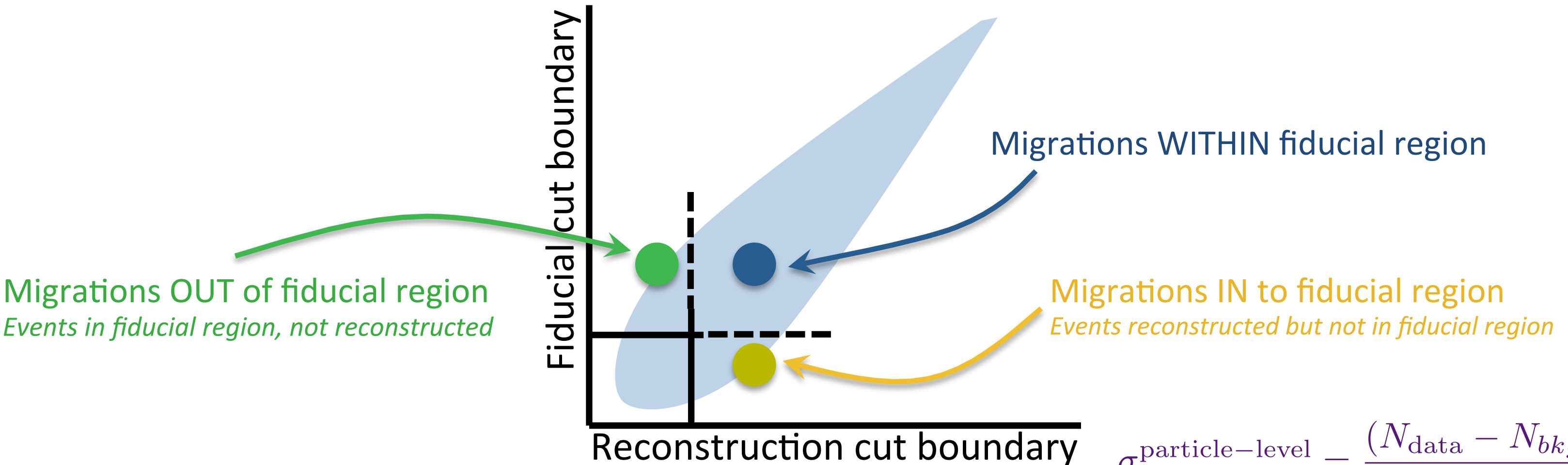
Fiducial measurements

Standard Model cross-sections generally measured in well-defined fiducial region, region of phase space well-understood, high efficiency, minimal extrapolation.

Correct measured data for:
- background contamination,
- migrations in, out, and within fiducial region due to efficiency and resolution effects.

$$\sigma_i^{\text{particle}-\text{level}} = \sum_j \frac{(N_{\text{data}} - N_{bkg})_j \cdot \epsilon_j^{\text{reco-level}} M_{ij}}{\mathcal{L}\, \epsilon_i^{\text{particle}-\text{level}}}$$

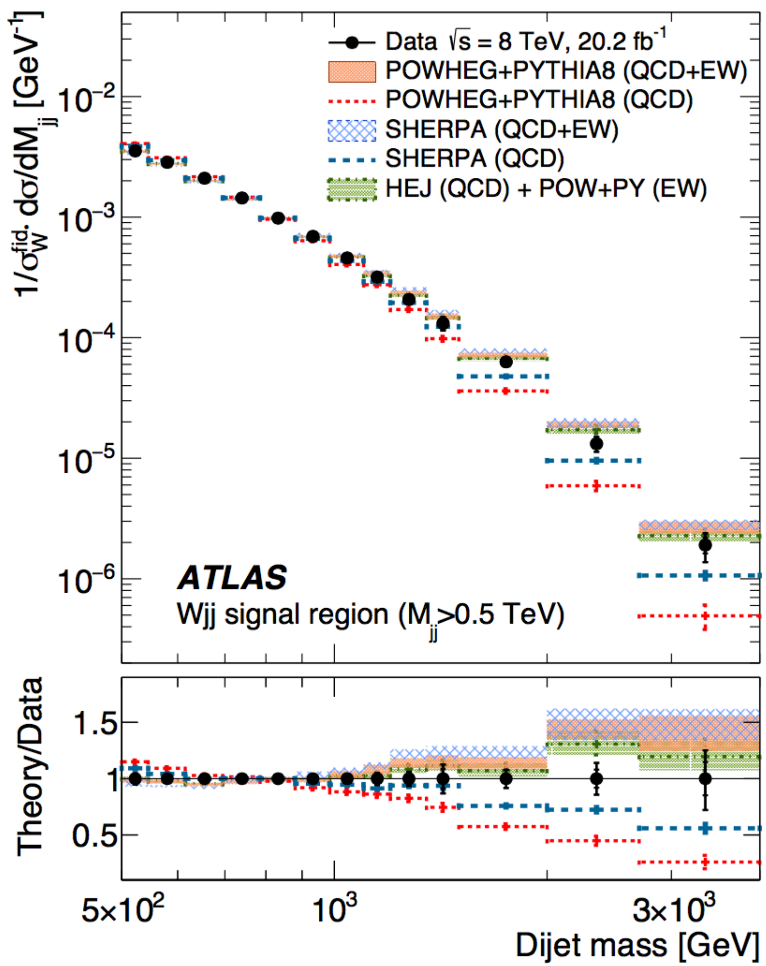
Resulting measurement independent of prior assumptions; unfolding uncertainties assessed

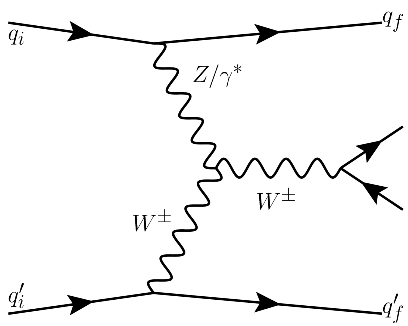


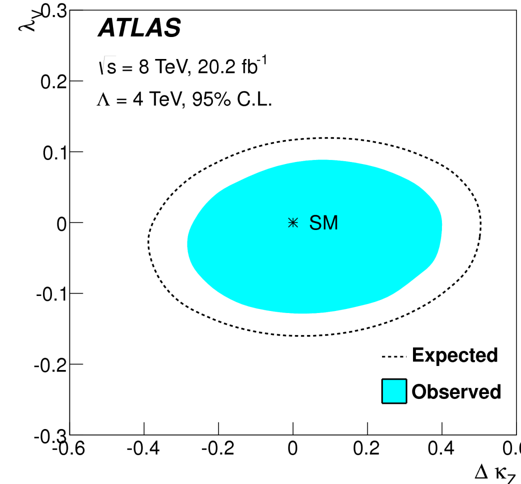
$$\sigma^{\text{particle}-\text{level}} = \frac{(N_{\text{data}} - N_{bkg})}{\mathcal{L}} \frac{\epsilon^{\text{reco-level}}}{\epsilon^{\text{particle}-\text{level}}}$$

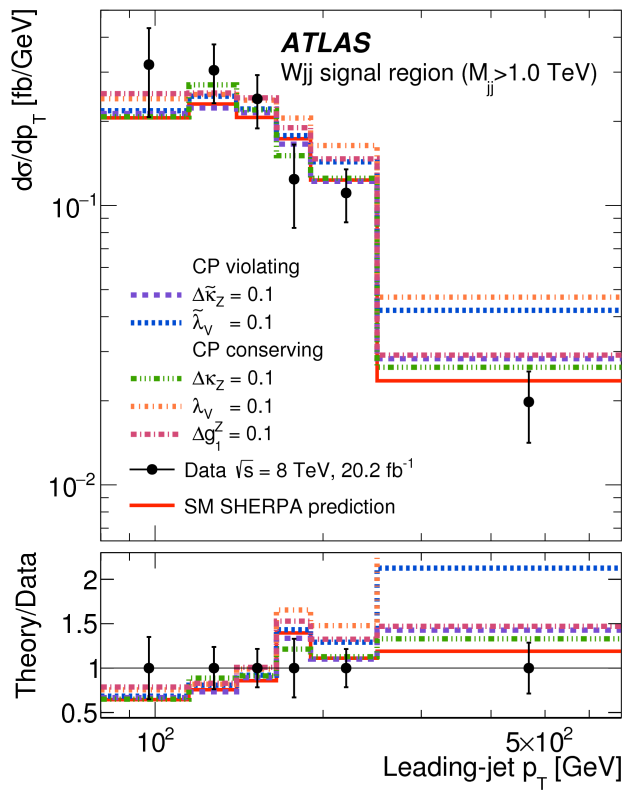
SM measurements and reinterpretation

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









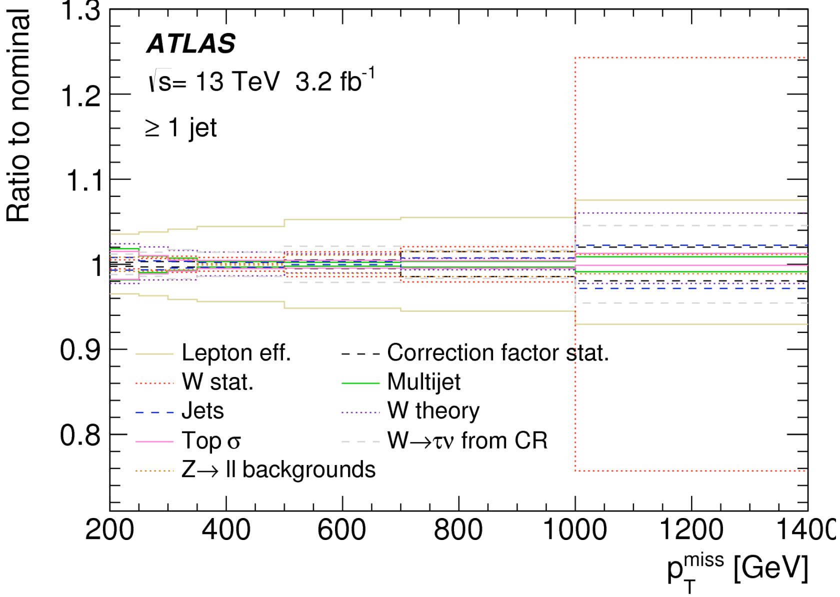
Fiducial region definition

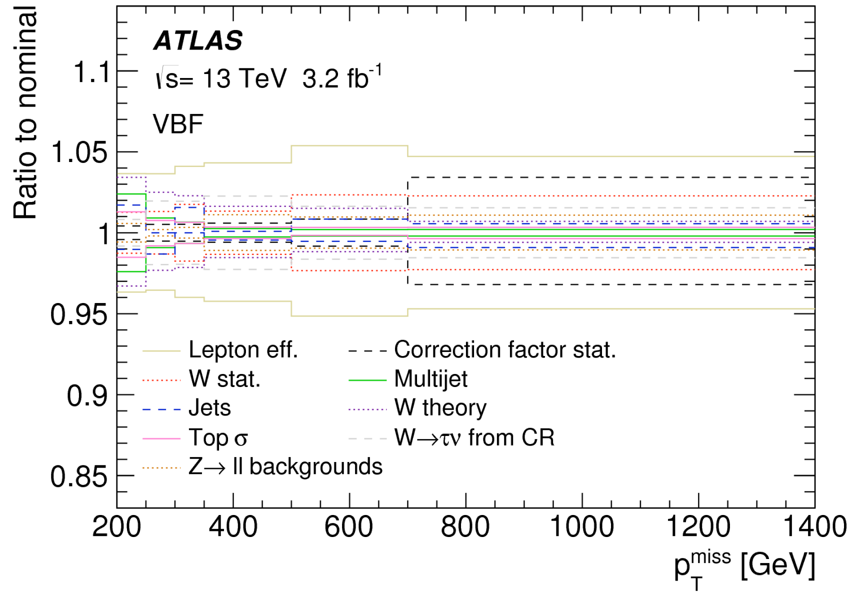
Numerator and denominator	≥ 1 jet	VBF
p_T^{miss}	> 200 GeV	
(Additional) lepton veto	No e, μ with $p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$	
Jet $\lvert y\rvert$	< 4.4	
Jet p_T	> 25 GeV	
$\Delta\phi_{\mathrm{jet}_i, p_T^{miss}}$	> 0.4, for the four leading jets with $p_T > 30$ GeV	
Leading jet p_T	> 120 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 $p_T > 25$ 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	

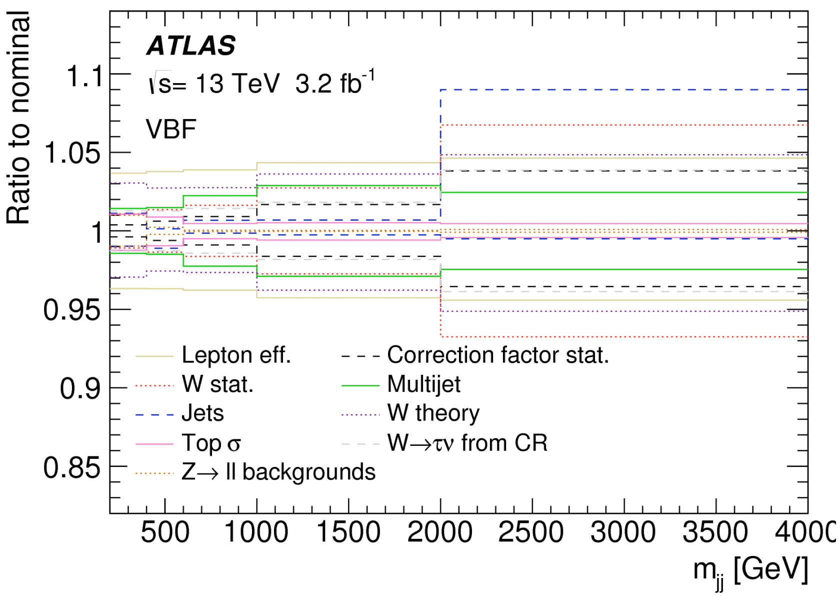
Systematic uncertainty overview

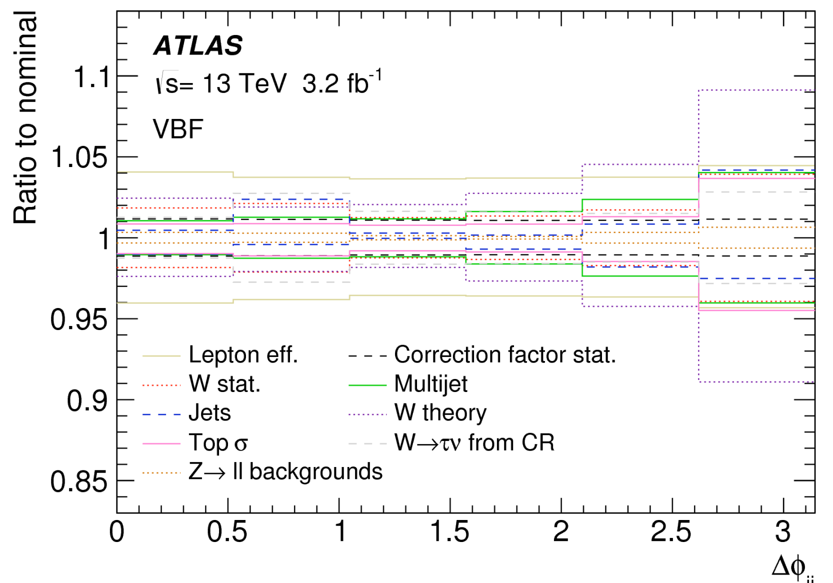
Systematic uncertainty source	Low $p_{\mathrm{T}}^{\mathrm{miss}}$ [%]	High $p_{\mathrm{T}}^{\mathrm{miss}}$ [%]	Low m_{jj} [%]	High m_{jj} [%]
Lepton efficiency	$+3.5, -3.5$	$+7.6, -7.1$	$+3.7, -3.6$	$+4.6, -4.4$
Jets	$+0.8, -0.7$	$+2.2, -2.8$	$+1.1, -1.0$	$+9.0, -0.5$
$W \to \tau\nu$ from control region	$+1.2, -1.2$	$+4.6, -4.6$	$+1.3, -1.3$	$+3.9, -3.9$
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

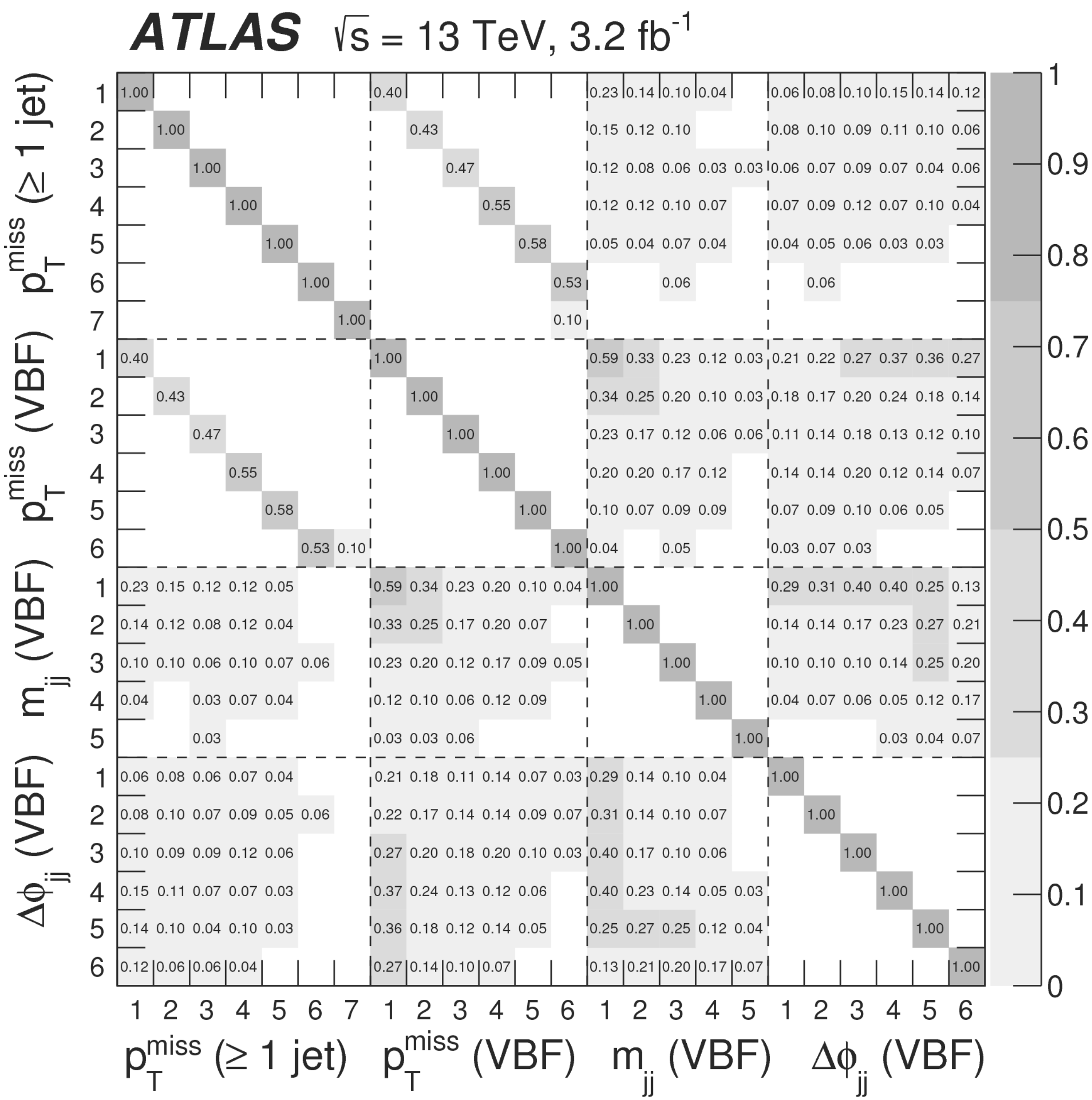




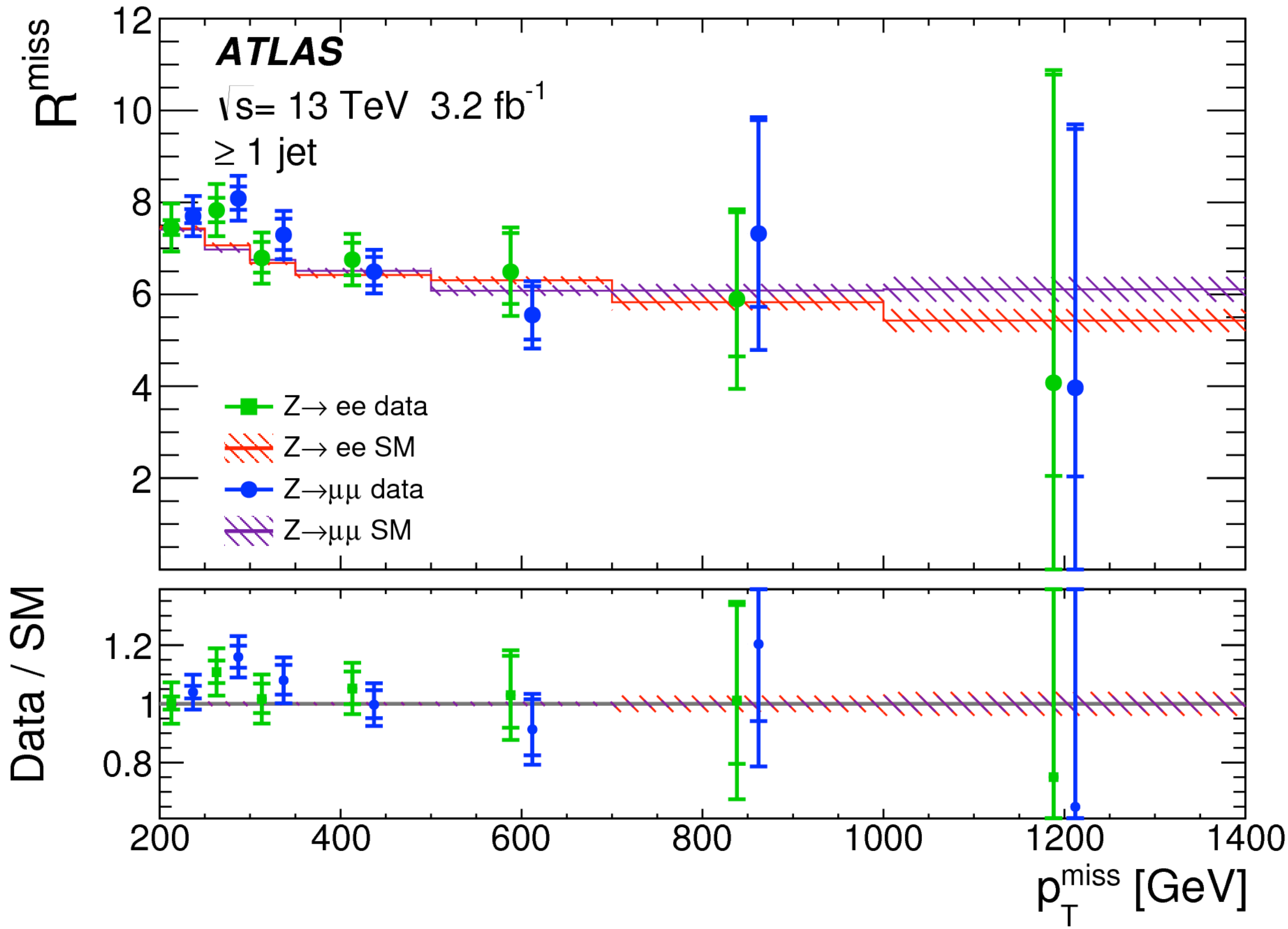




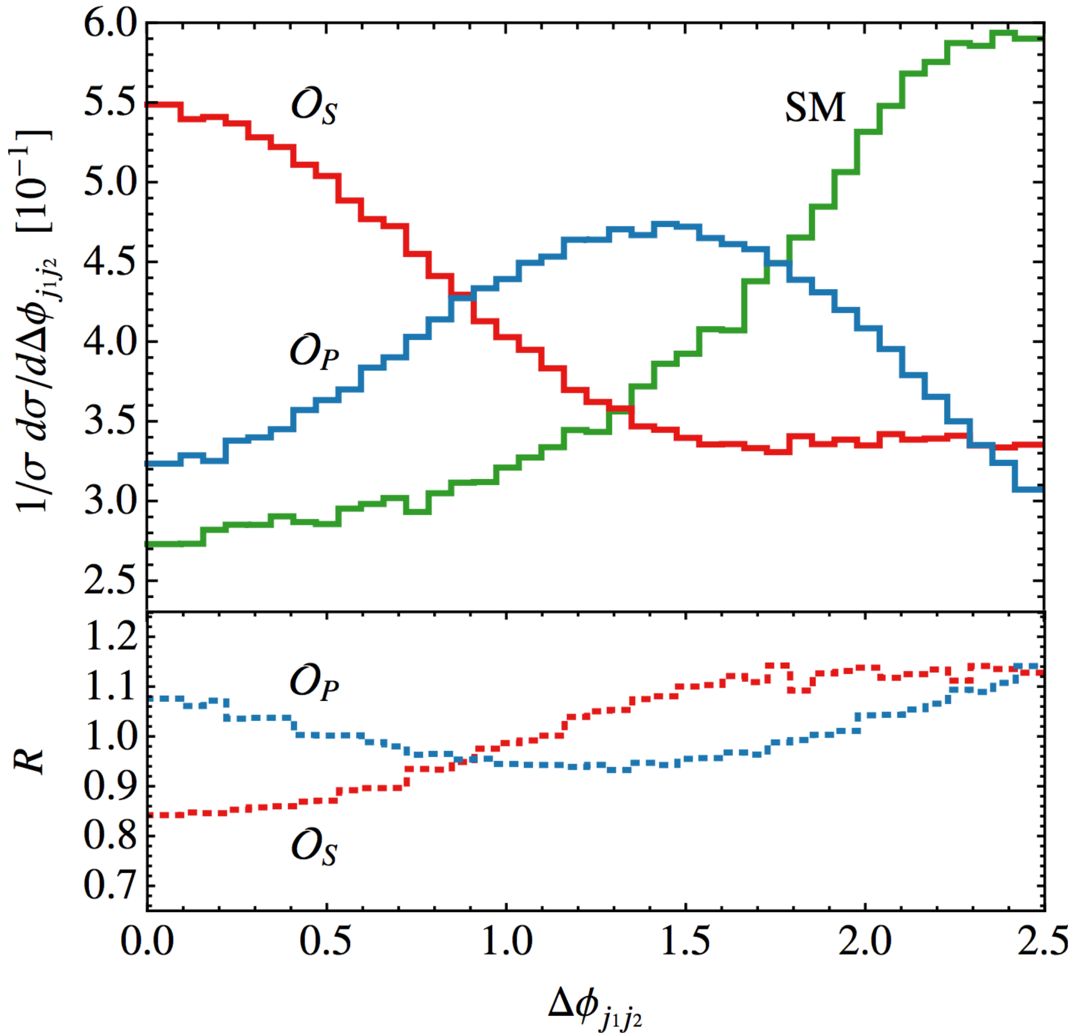
Statistical covariance matrix



Electron vs. muon measurements



MET+dijet azimuthal angle correlations



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