Systematic uncertainties at the LHC

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A typical result from a measurement

- “The fit yields a measured cross section

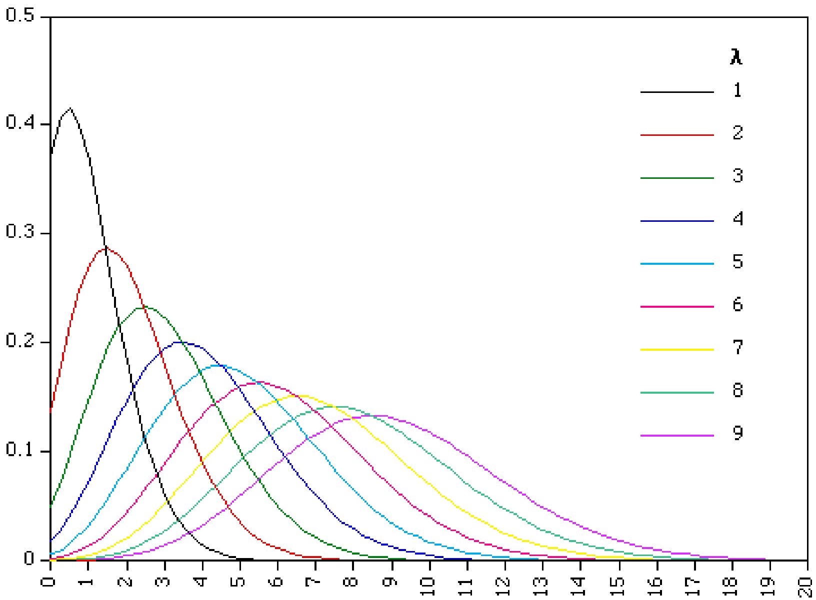
  σtt=803±2 (stat) ±25 (syst) ±20 (lumi) pb

  in agreement with the expectation from the standard model calculation at next-to-next-to-leading order...”
- Uncertainties are an integral part of each measurement, as much as the central value
- Without uncertainty, a measurement is meaningless
- But what do (stat) (syst) (lumi) (theory) uncertainties mean and how are they calculated?

Statistical uncertainties

- Come for limited size of sample used to make the measurement
- Quantum processes follow Poisson statistics, that approximate to a Gaussian for

  $\lambda > 10$, and $\sigma^2 = \lambda$
- This is why for a counting experiment with large statistics the stat. unc. is $\sqrt{N}$ and relative uncertainty is $1/\sqrt{N}$ (we run experiments for years)
  - With BG, uncertainty is higher
  - With small statistics need to use asymmetric errors
  - For more complicated cases, use toy experiments to estimate statistical uncertainties



Measuring luminosity at the LHC

- Need to divide by Lumi to obtain a Xsec

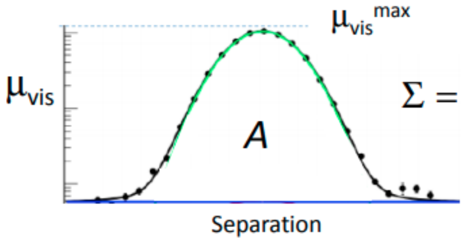
$$\mathscr{L} = \frac{f_{rev} N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

$N_1 N_2$: Measured by the accelerator instrumentation

$\Sigma_x \Sigma_y$:

- Can be derived from **nominal machine parameters with uncertainty > 10%**
- Can only be **measured directly in dedicated sessions**

VdM scan



$$\Sigma = \frac{A}{\sqrt{2\pi}\,\mu_{vis}^{max}}$$

In standard physics data-taking, the **luminosity is measured indirectly**:

$$\mathscr{L} = \frac{R_{ref}}{\sigma_{ref}}$$

σ_{ref} is the cross section for a suitable reference process

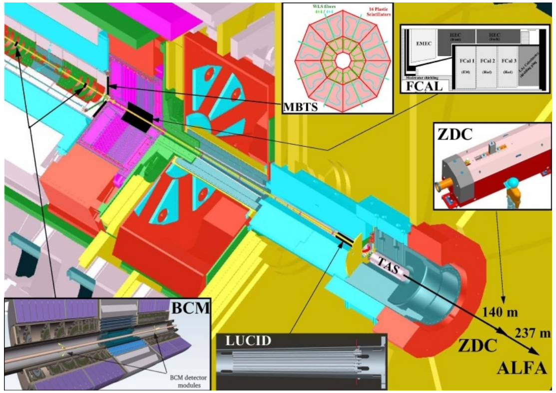
Known physical cross section (es. *Z* boson, inelastic..)

Visible cross section (σ_{vis}) measured in a dedicated calibration experiment

Main solution at the LHC

Luminometers: stability and uncertainties

- Small forward detectors calibrated during VdM scan, and provide instantaneous luminosity through the year



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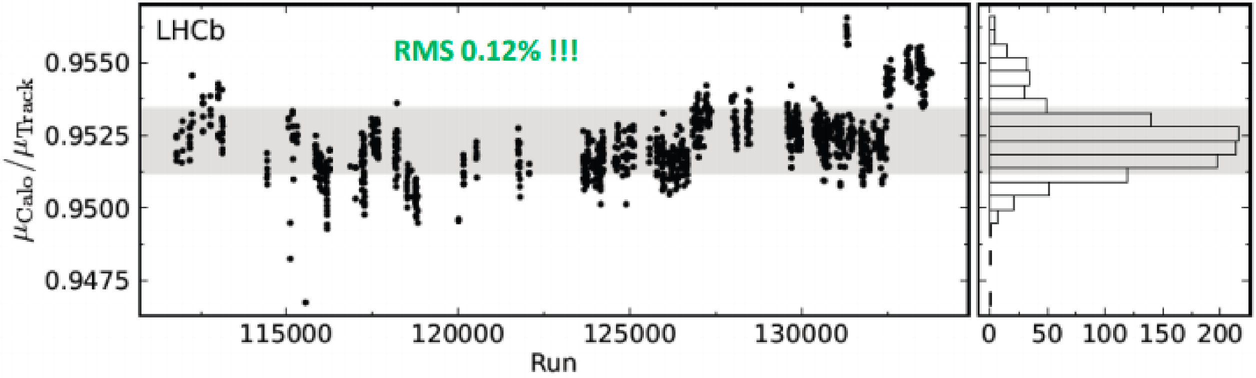
Ratio of counting rates for two of the LHCb luminometers (pp 8 TeV)



	ALICE	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS	LHCb	ATLAS	CMS
Running period	2012 pp	2012 pp	2012 pp	2012 pp	2015 pp	2015 pp	2015 pp	2015 pp	2016 pp	2016 pp
√s [TeV]	8	8	8	8	13	13	13	13	13	13
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%]	2.4	1.9	2.6	1.2	3.4	2.1	2.3	3.9 Prelim.	3.4 Prelim.	2.5

Systematic uncertainties from theory

If experimental result compared to theory (with its uncertainties), why theory uncertainties in an experimental result?

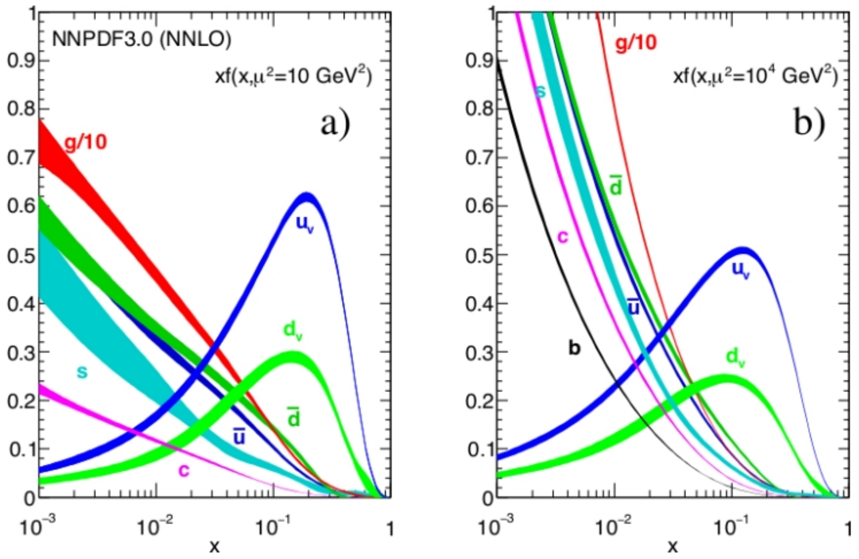
Theory enters our measurement in many ways:

- Background subtraction
- Signal efficiency
- Models for fits
- UE corrections

Determination of PDFs

Cross-sections at the LHC are convolutions of a hard matrix element and the Parton Distribution Functions of the colliding partons

$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij}$$



PDFs (and their uncertainties) determined by several groups by performing global fits of several measurements, including those from ep collider (HERA), Tevatron, LHC, neutrino scattering etc.

LHC measurements useful for PDFs determination:

- Jet production
- Top Xsection
- Vector boson production and asymmetries

Uncertainties on PDFs: eigenvalues

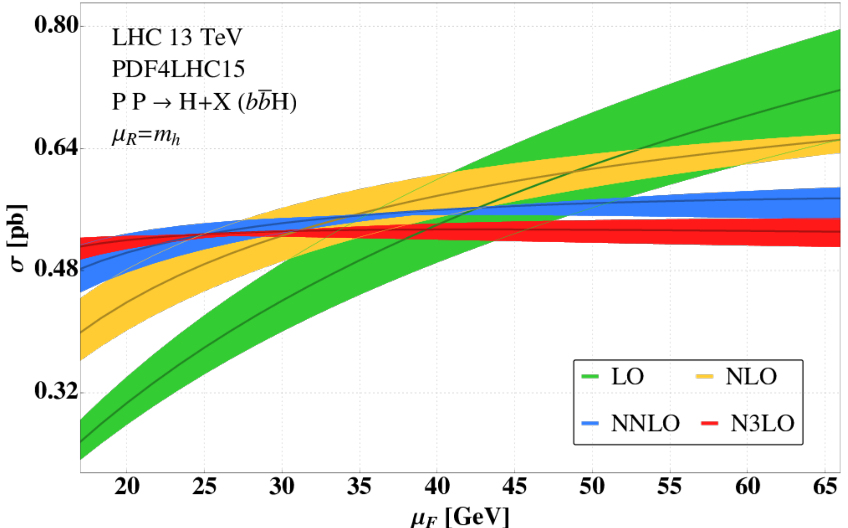
- Most PDFs are sets of parameters of an analytical formula like
- Parameters for various partons strongly correlated since coming from same measurements

$$f(x) = a_o x^{a_1} (1-x)^{a_2} e^{a_3 x + a_4 x^2}$$

- Uncertainty matrix diagonalised in a series of eigenvectors and eigenvalues
- PDF bands obtained by simultaneously varying the eigenvalues and obtaining 1sigma variations

Uncertainties on scale variation

- Theory calculations for hard scattering performed with a given renormalisation and factorisation scale, set at a relevant scale for the process like jet pT
- Choice of scale and cut value can strongly influence Xsec
- Usually uncertainty evaluated by multiplying and dividing scale by 2
- Scale dependence smaller at higher orders

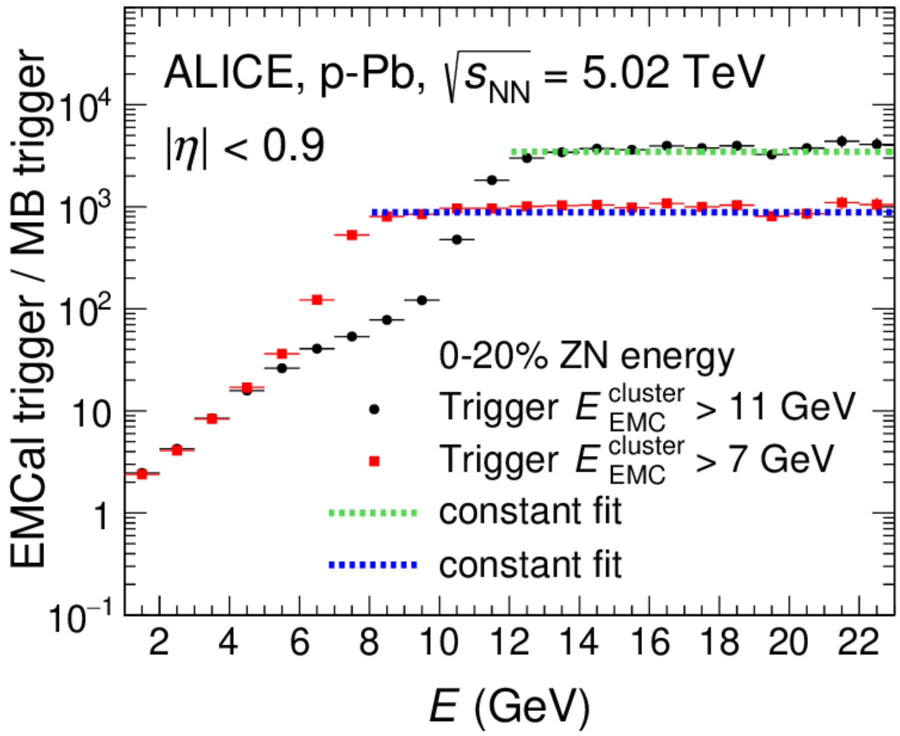


Uncertainties from MC tunes

Experimental uncertainties

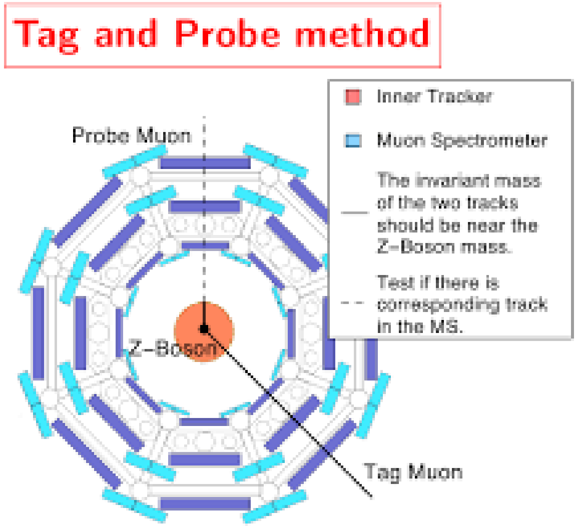
Trigger turn-on

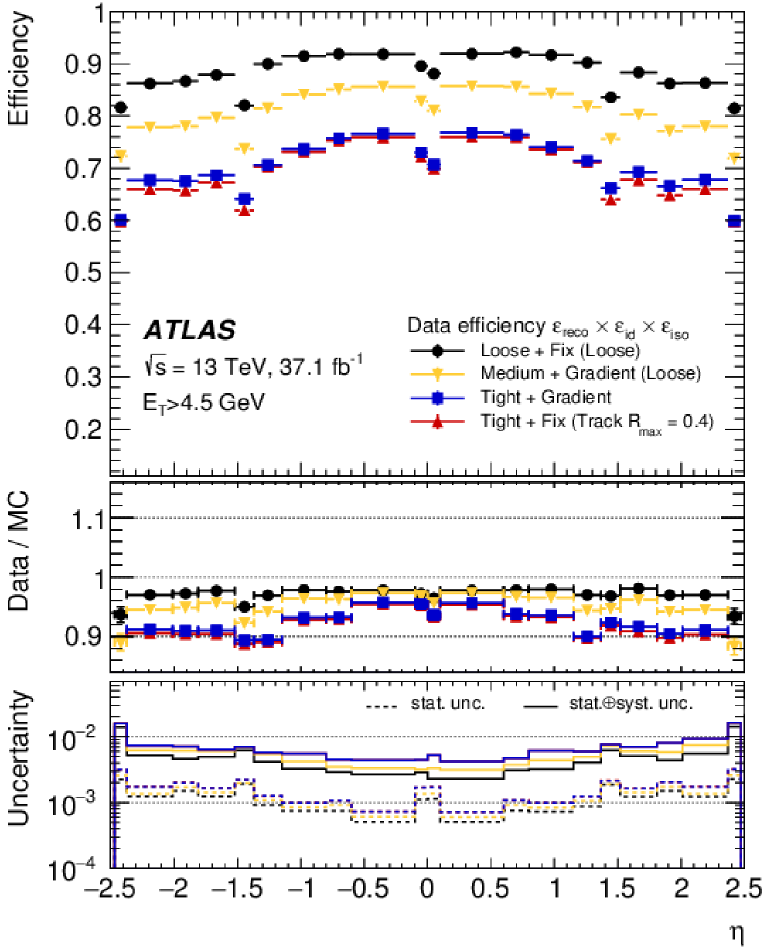
- Trigger never fully efficient
- Efficiency determined by fit to data
- Some times use trigger in rising part of efficiency curve → large uncertainties



Efficiency in particle identification

- Depending on isolation cuts, efficiency to identify electrons, photons, muons etc. can be significantly lower than 1
- Efficiency vs detector position or pT evaluated using tag and probe method

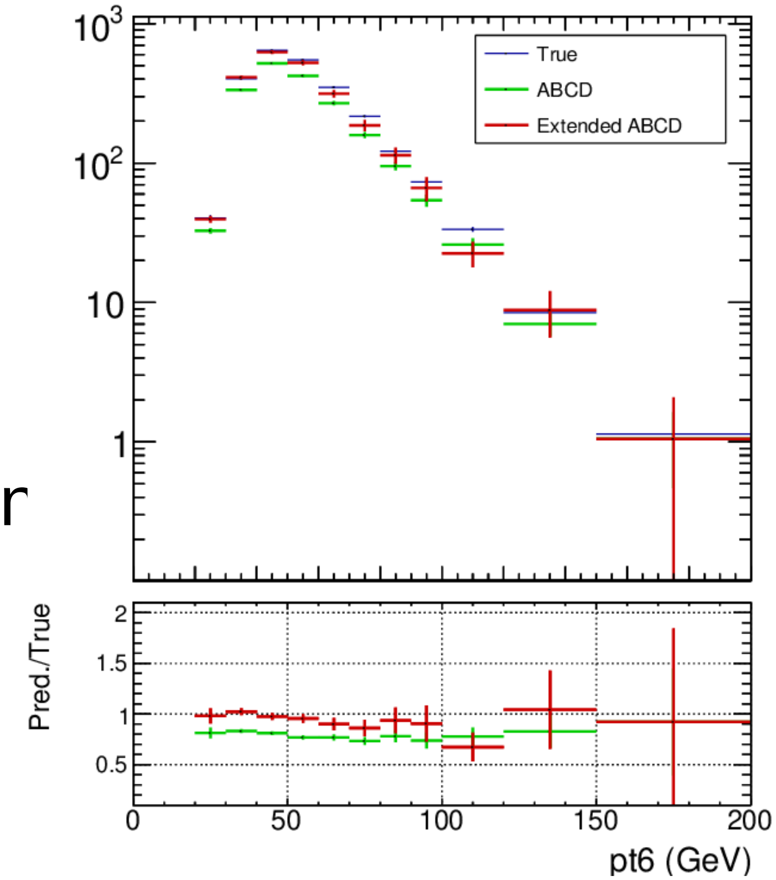




Uncertainties in background subtraction

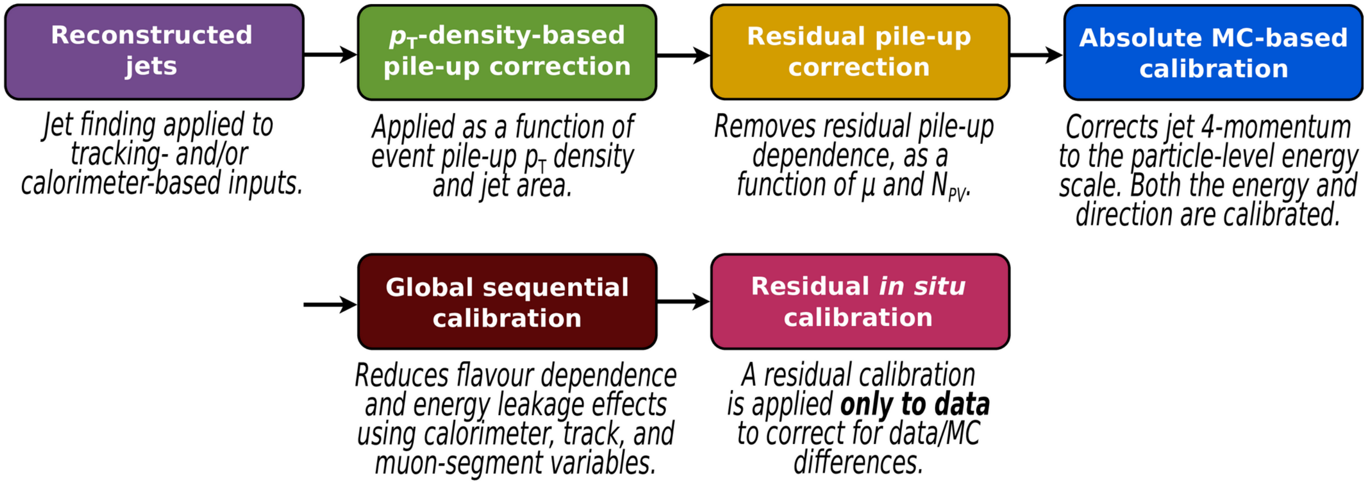
Even when data-drive, background subtraction is not perfect:

- Correlation assumptions
- Method used
- Statistics of sample used for predictior
- Templates or forms used for fitting

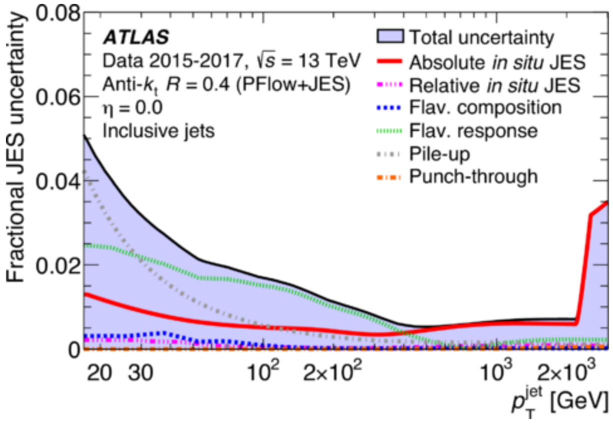


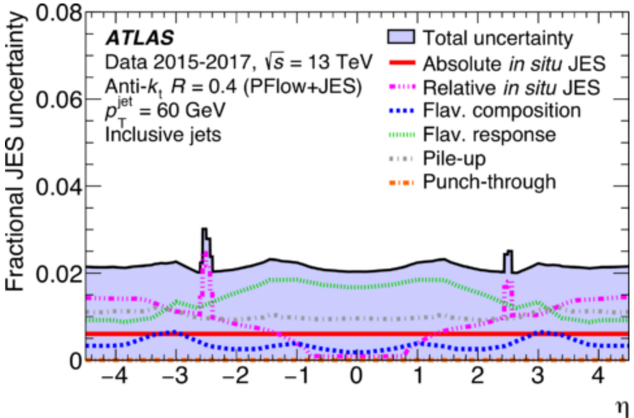
Jet Energy Scale

- Main uncertainty for jet measurement. Jet calibration steps:



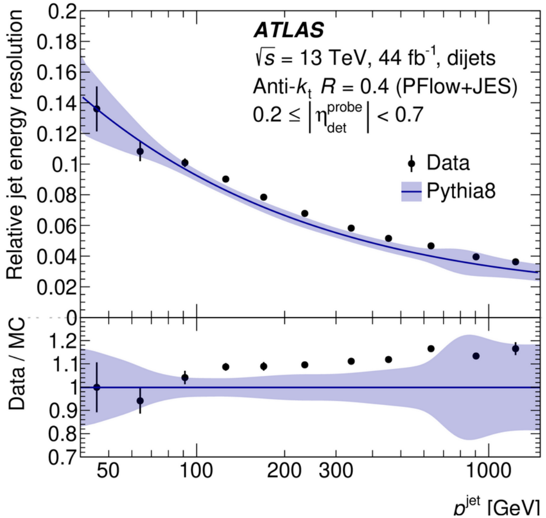
Even if JES ~ 1%, it leads to large effects if convoluted with a steeply falling distribution

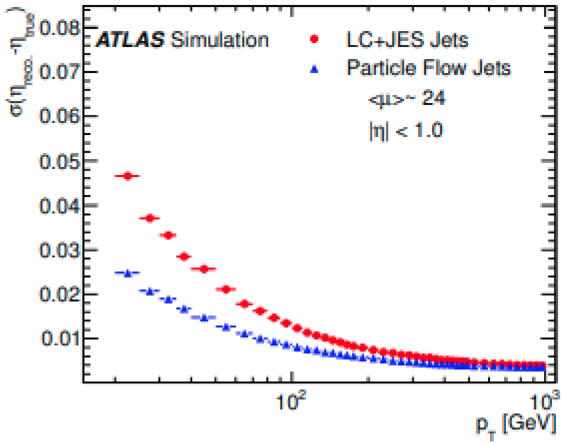


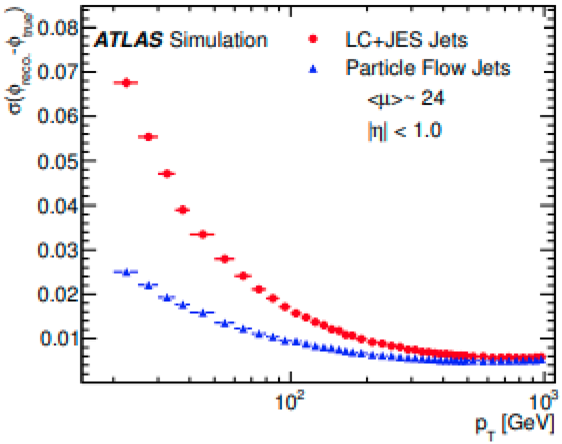


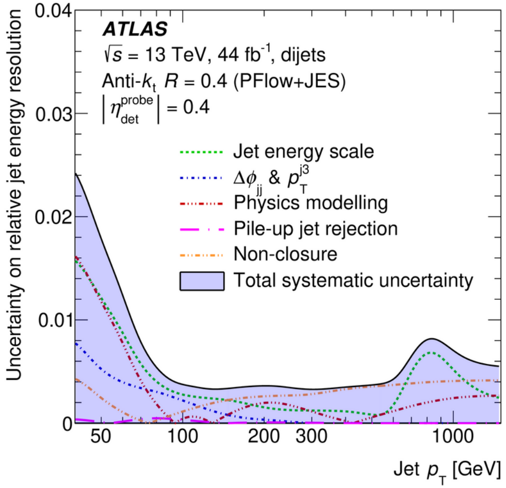
Jet Energy and Angular Resolution

- They impact effect of pT cuts and dijet mass reconstruction.
- Quite well known, but still need to account for them





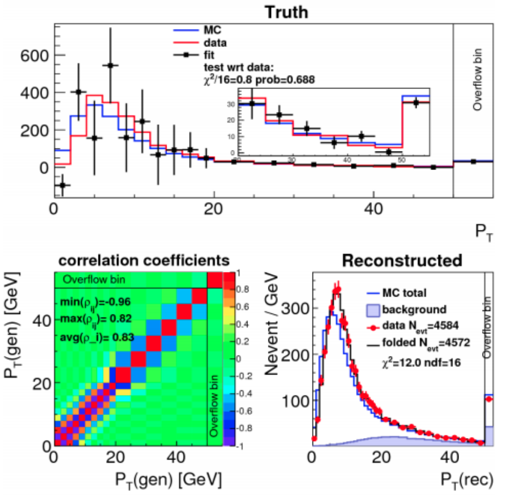


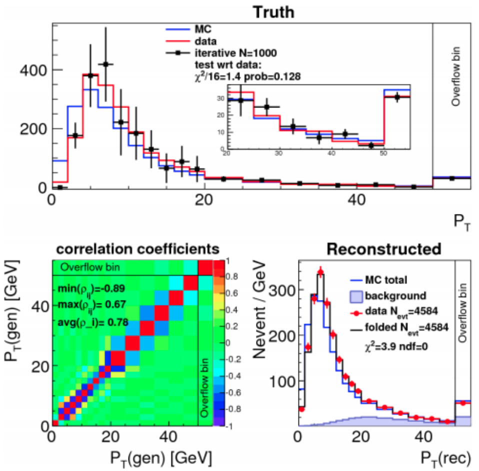


Unfolding: correcting for detector effects

- The detector will distort “truth-level” distributions, the ones we want to publish and compare to theory and the other experiments
- Truth x detector x fluctuations → measurement
- Truth ← unfolding ← measurement
- For binned distributions detector is a matrix:

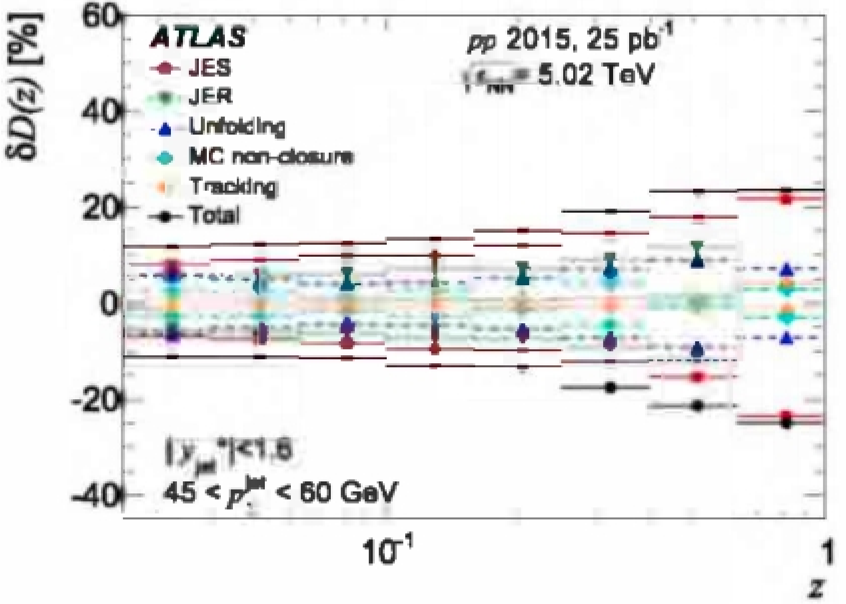
  R = M T
- Just inverting the matrix leads to large fluctuations
- Often iterative methods are used where we start from a truth distribution hypothesis, and correct it until we get to the reconstructed distribution





Uncertainties associated with Unfolding

- Choice of prior (usually from MC)
- Non-closure
  - If you unfold the same MC used to build the transfer matrix you should get the same result
- MC model:
  - Difference in results by unfolding with matrices coming from different MC mode



Conclusions

- Systematics uncertainties are the heart of your measurement
- Can be very subtle, and touch every aspect of the analysis
- While statistical uncertainties will automatically decrease with more data, reducing systematics requires hard work from experts in detector, reconstruction, analysis and even theory!