# Run 1 legacy performance:
## Tracking, flavour tagging, muons in ATLAS

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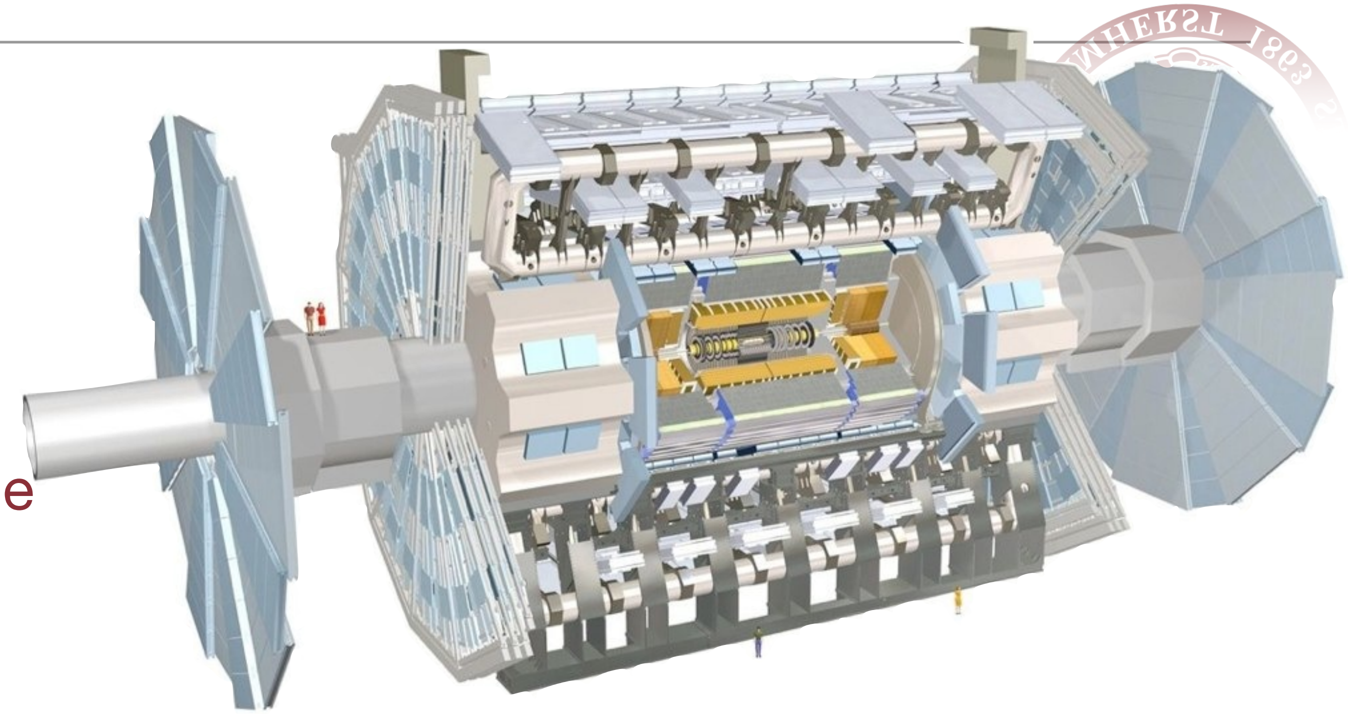
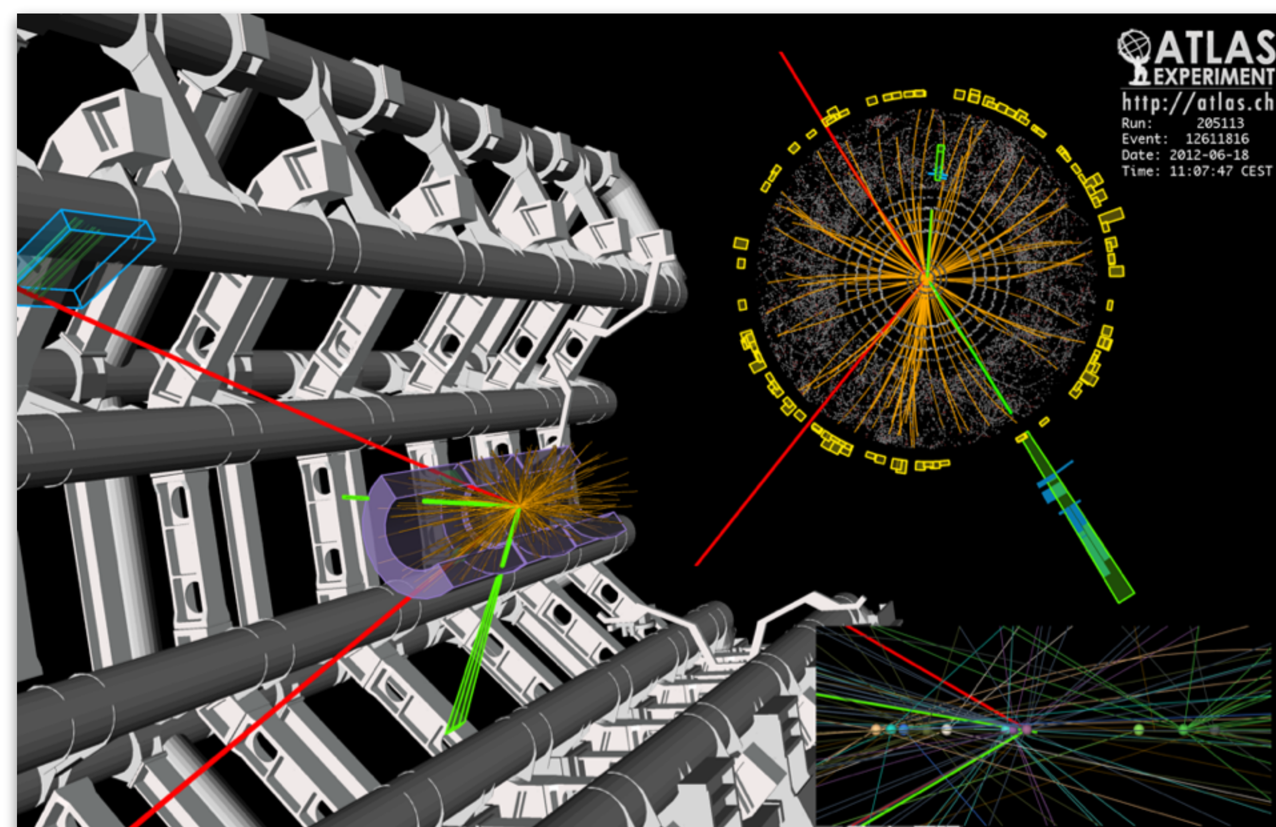
# Introduction

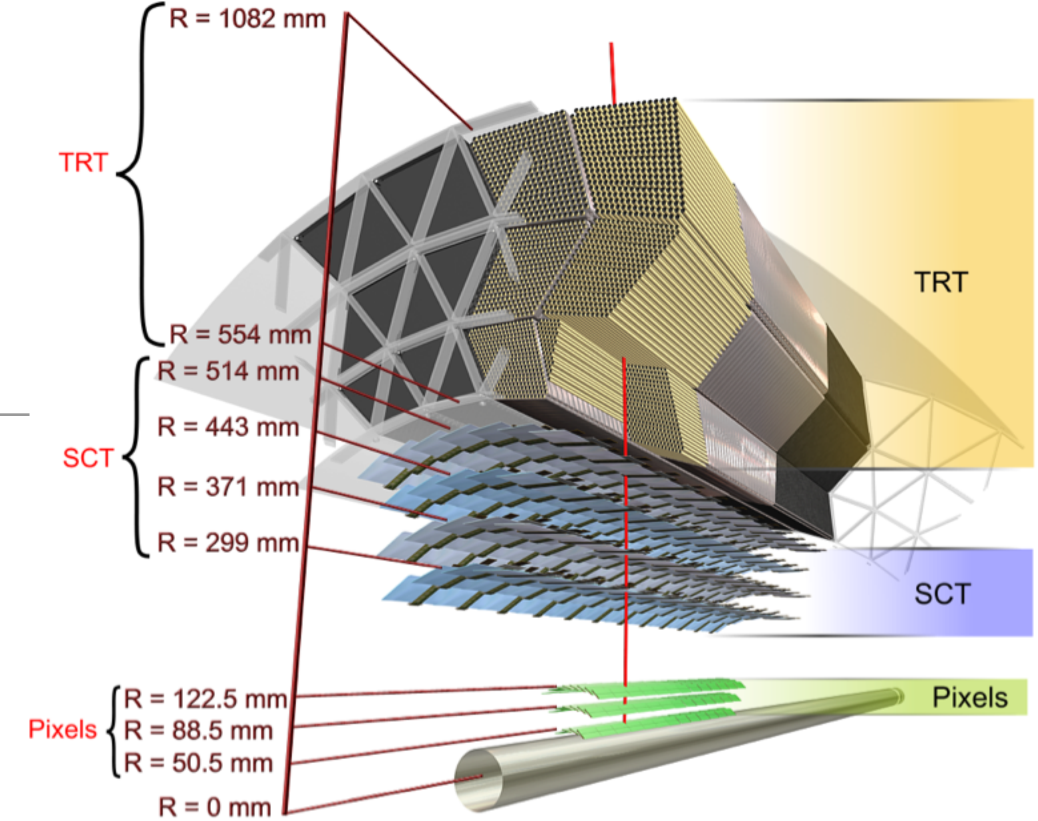
- This talk will discuss the run-1 performance of:
  - The **ATLAS** Inner Detector (Tracker)
  - The **ATLAS** Muon Spectrometer (with some comparisons to that of **CMS**)
  - See A. Rizzi's talk for the flavour tagging discussion & more details on the **CMS** Tracker performance
- Run-2 improvements will be covered briefly
  - See M. Elsing's earlier talk in Parallel Session 5 for more details…

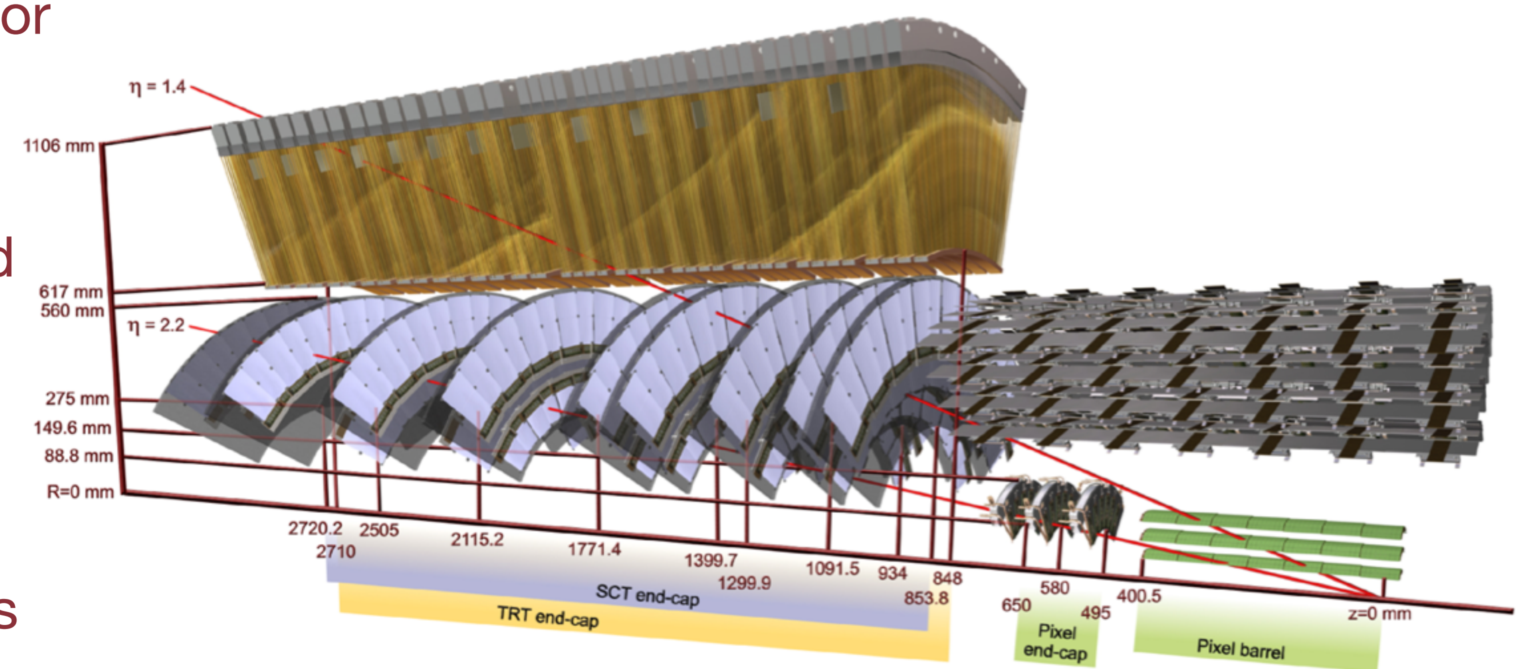




# Tracking - Introduction

- Tracking aim = reconstruction of charged particle trajectory
  - 5 track parameters: $d_0$, $z_0$, $\phi_0$, $\theta$, $q/p$
  - measured with the ATLAS Inner Detector
- We need detailed knowledge of:
  - ID material description & magnetic field
  - detector alignment
  - tracking efficiency / systematics
  - performance under complex conditions
    - high pile-up
    - tracking in dense environments

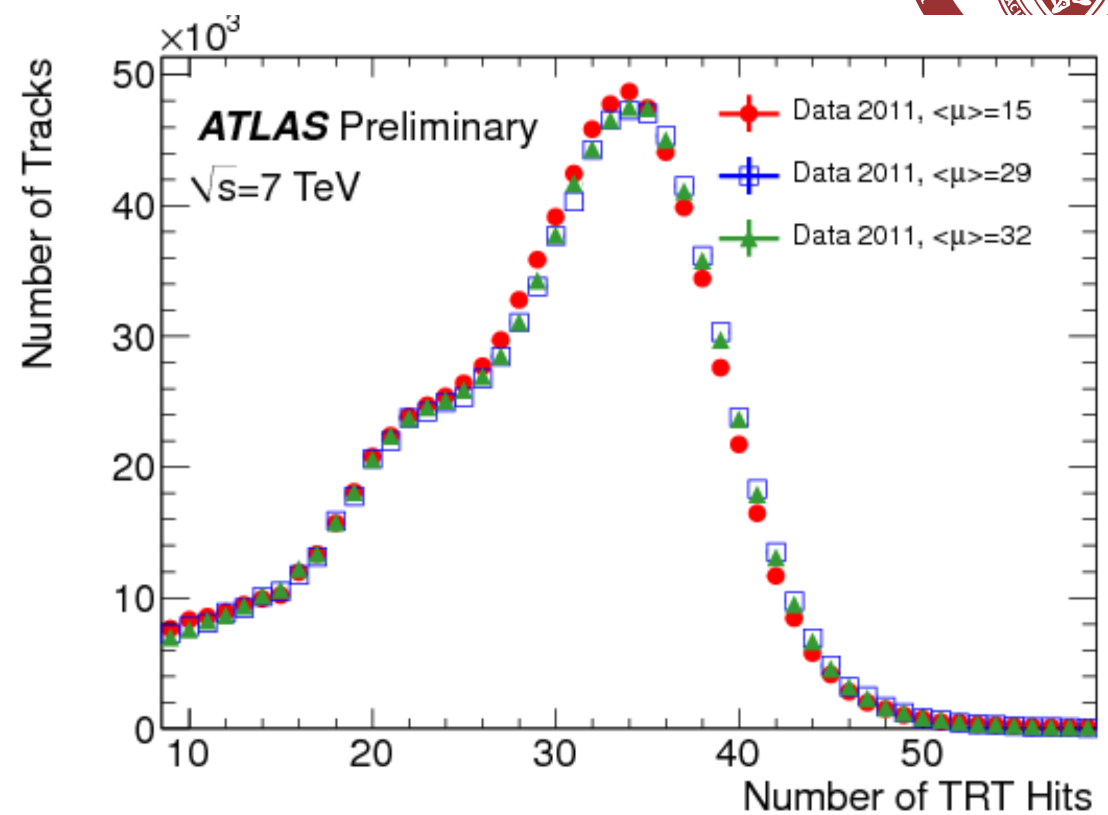


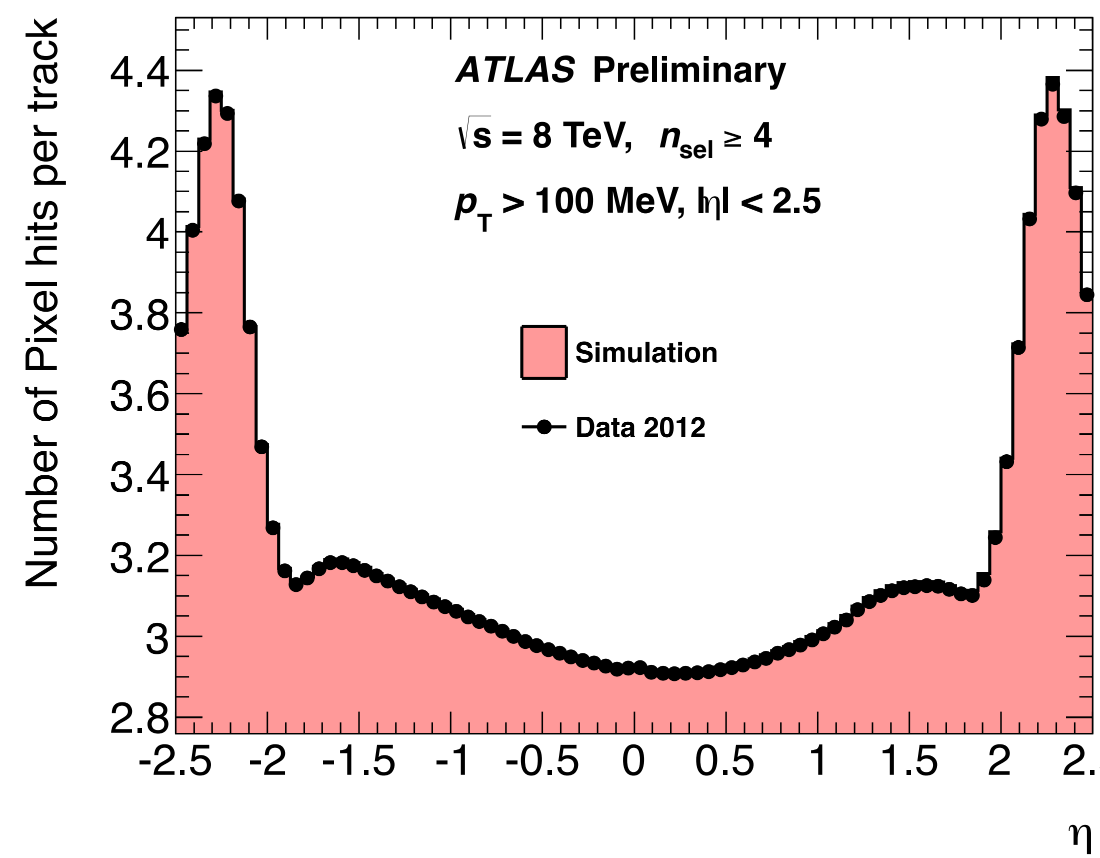




| | Pixel | SCT | TRT |
|---|---|---|---|
| barrel layers | 3 | 4 | 72 |
| end-cap layers | 2*3 | 2*9 | 2*160 |
| ∅ hits / track | 3 | 8 | ~30 |
| element size [µm] | 50x400 | 80 | 4 mm |
| resolution [µm] | 10x115 | 17x580 | 130 |
| channels | 8*10e7 | 6.3*10e6 | 3.5*10e5 |

# Tracking Performance

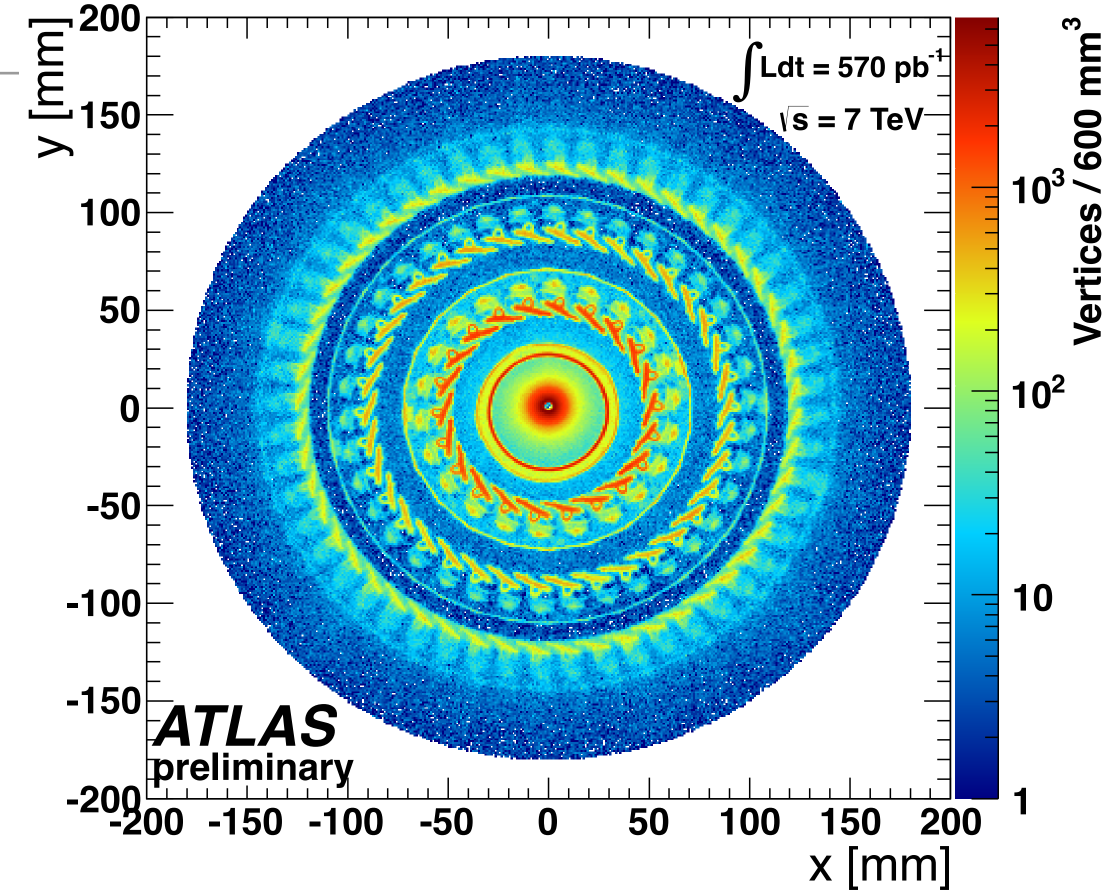
- High performance of ID components
  - hit efficiency: up to 99.9%
    - SCT >99%,  Pixel >97%,  TRT >94%
- Occupancy:
  - ~linear with pile-up, no saturation
  - All technologies are robust against pile-up
- ID hits are accurately simulated
  - nearly perfect Data/MC agreement in # of Pixel and SCT hits
  - reconstructed track parameter distributions also agree well

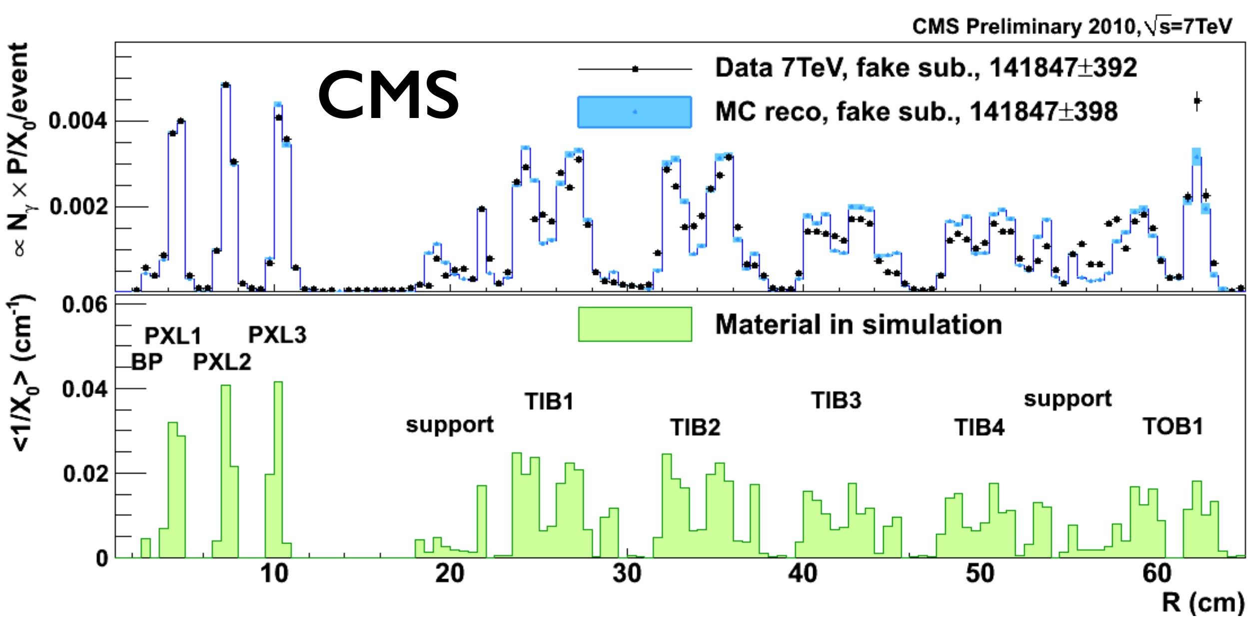


# ID material studies

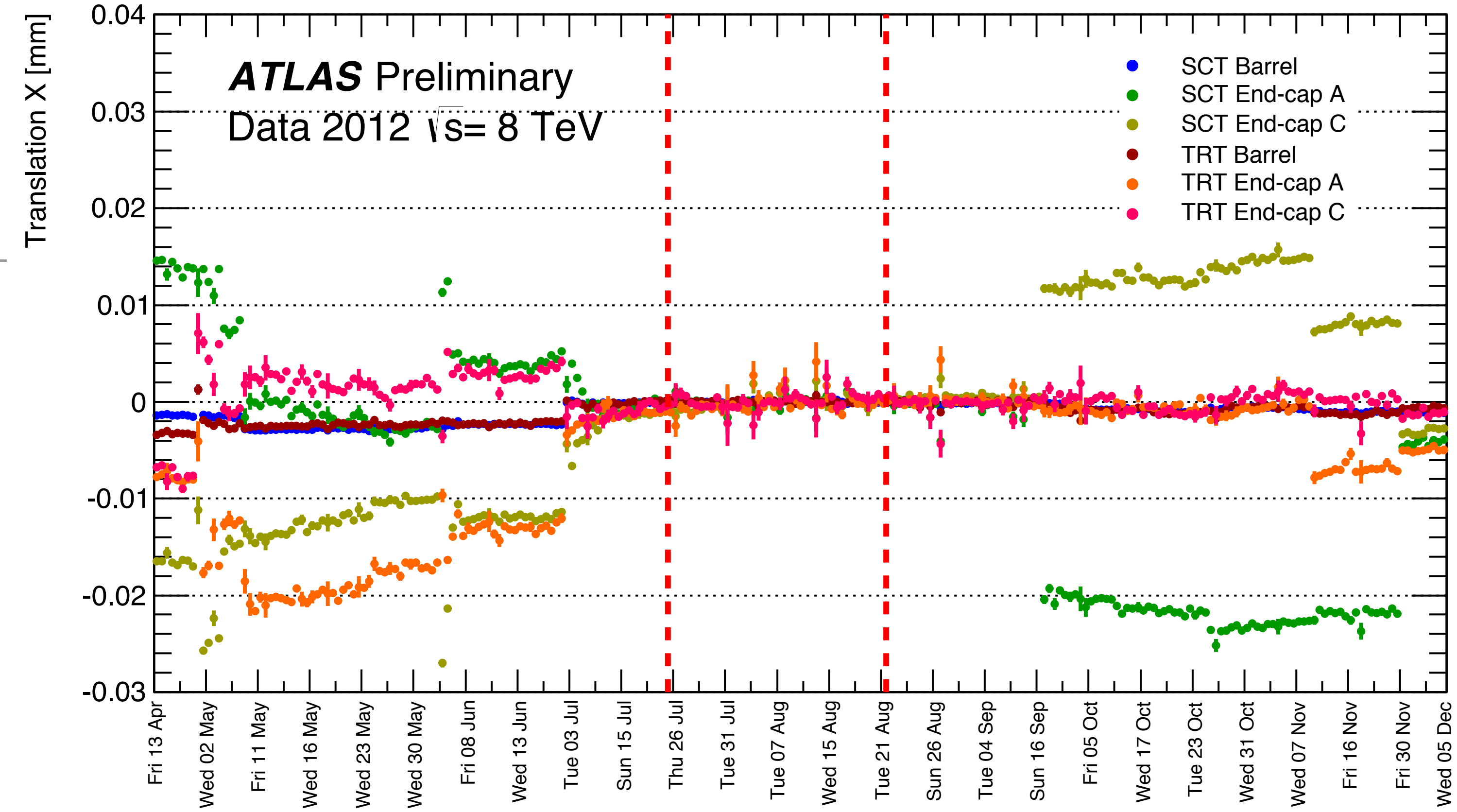
- Hadronic Interaction Vertices
  - fit tracks from hadronic interactions to vertex
    - vertex resolution @ R<100 mm = 200-300 μm (R, z)
  - result: clearly visible detector features
- Improvement of simulation
  - precise localization of data/MC disagreements
    - allows precise modelling of pixel modules, beam pipe, …
  - **[ATLAS]** validates overall material description t
    < 7% uncertainty
    - other techniques: e.g. photon conversions (see CMS plot to the right)



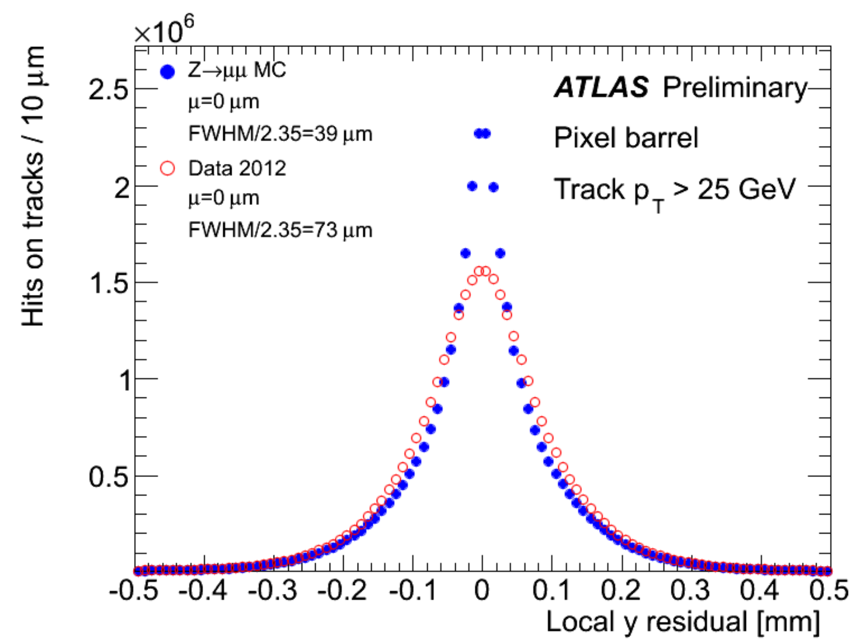



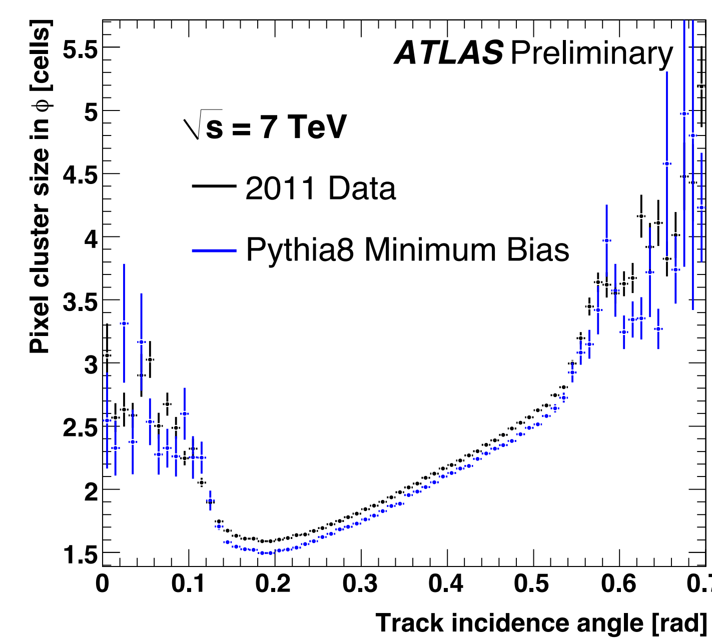
# Alignment

- ID alignment is continuously monitored by track-based alignment
    - Time-dependent alignment corrections introduced in 2012
- Track parameter biases reduced to very small values
    - sagitta bias below 0.5 $\text{TeV}^{-1}$
- Some discrepancies found, e.g. in residual distribution of pixel barrel
    - Under investigation - digitisation known to need work, as cluster size underestimated in MC
- More details in ID alignment note:
    - [ATLAS-CONF-2014-047]()




The corrections to the global X position ($T_x$) of all ID sub-detectors with respect to the Pixel detector during 2012.



# Muons

# Muons - Introduction

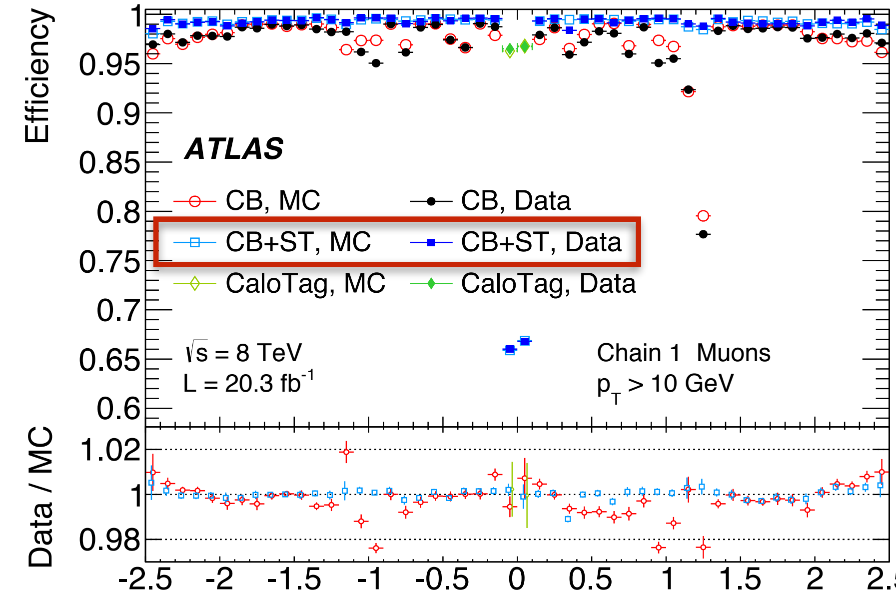
- **ATLAS** Detector status essentially unchanged over Run-1
  - Example from 2012:

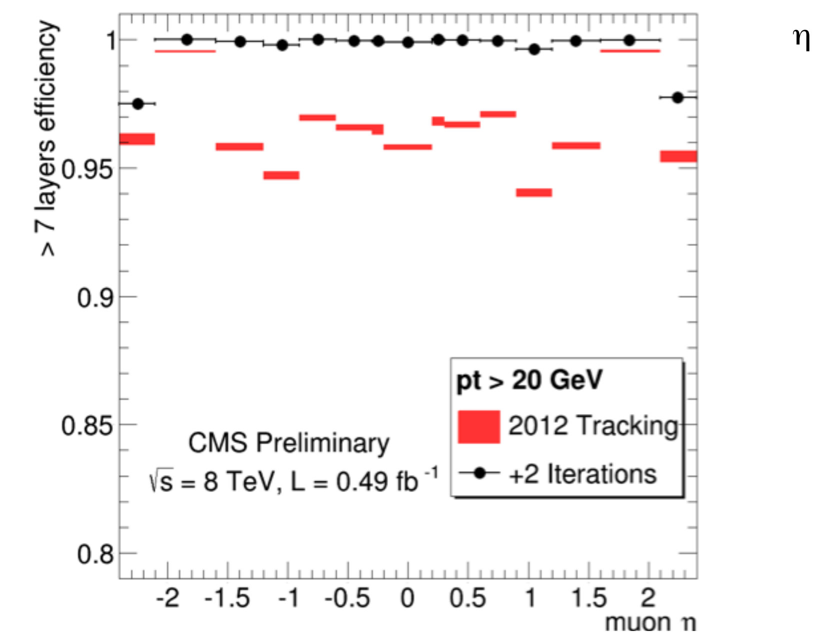
| | Number of channels | Active channel % |
|---|---|---|
| TGC | 350K | 98.3 |
| RPC | 31K | 97.5 |
| CSC | 370K | 96.1 |
| MDT | 320K | 99.7 |

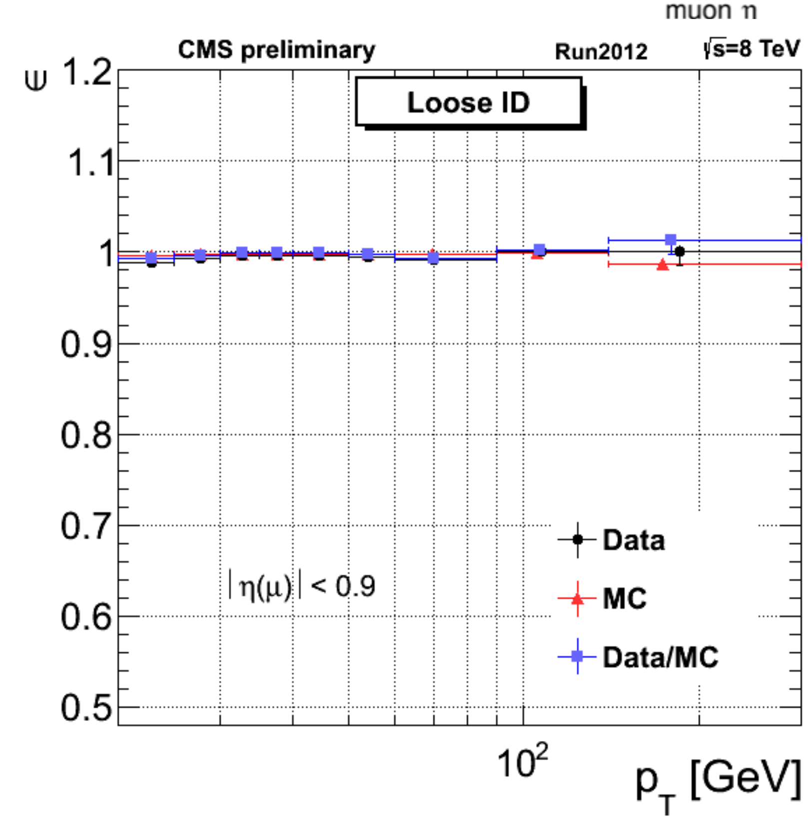
- **ATLAS** and **CMS** use multiple reconstruction techniques from several sub-detectors, in order to achieve ultimate performance
  - Basic strategy: attempt to combine tracks from Tracker & MuonSpectrometer
- Both **ATLAS** and **CMS** measure Muon efficiency w.r.t. Tracker (and for both, the Tracker has a muon efficiency of >99%)
  - Muon reconstruction efficiency is measured using 'tag-and-probe' method, using decays from J/Ψ and Z
- Resolution results depend on fit of 'standard candles'
  - e.g. J/Ψ, Upsilon and Z decays

# Muons - **CMS** & **ATLAS** Efficiency

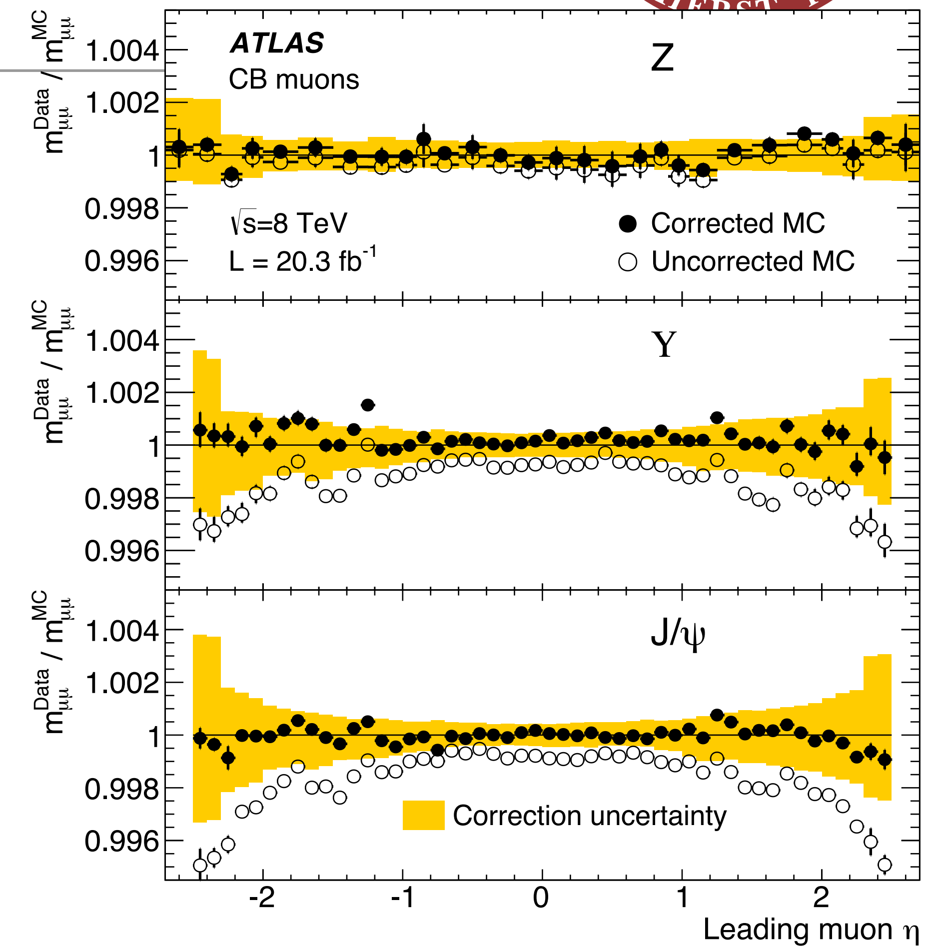
- Efficiency versus eta
  - For both **ATLAS** & **CMS**, muon reconstruction efficiency is close to 100%. No obvious pileup dependence
  - **ATLAS** & **CMS** use scale factors, to improve Data/MC agreement
    - Data/MC agreement typically at the per mille level
- Efficiency versus pT
  - **ATLAS** & **CMS** Data/MC agreement is typically at per mille level, with some divergence at low and high pT
- For more details, see:
  - [ATLAS Muon Perf Paper]() & [CMS public muon plots]()
  - (more slides in backup too)



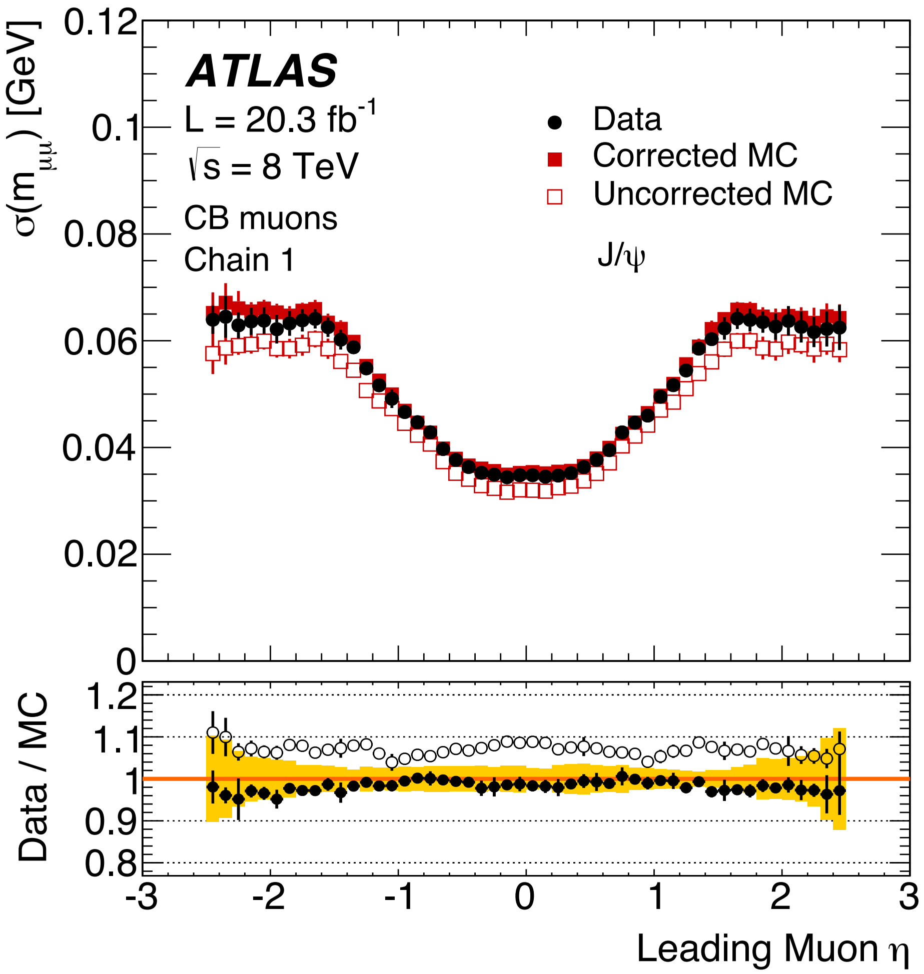



# Muons - **ATLAS** Resolution & mass scale




- Mass scale
  - Obtained from fits to J/Ψ, ϒ, and Z dimuon invariant mass distributions
  - Data/MC$_{corr}$ agreement well within systematics (e.g. 0.035% in barrel for Z decays)

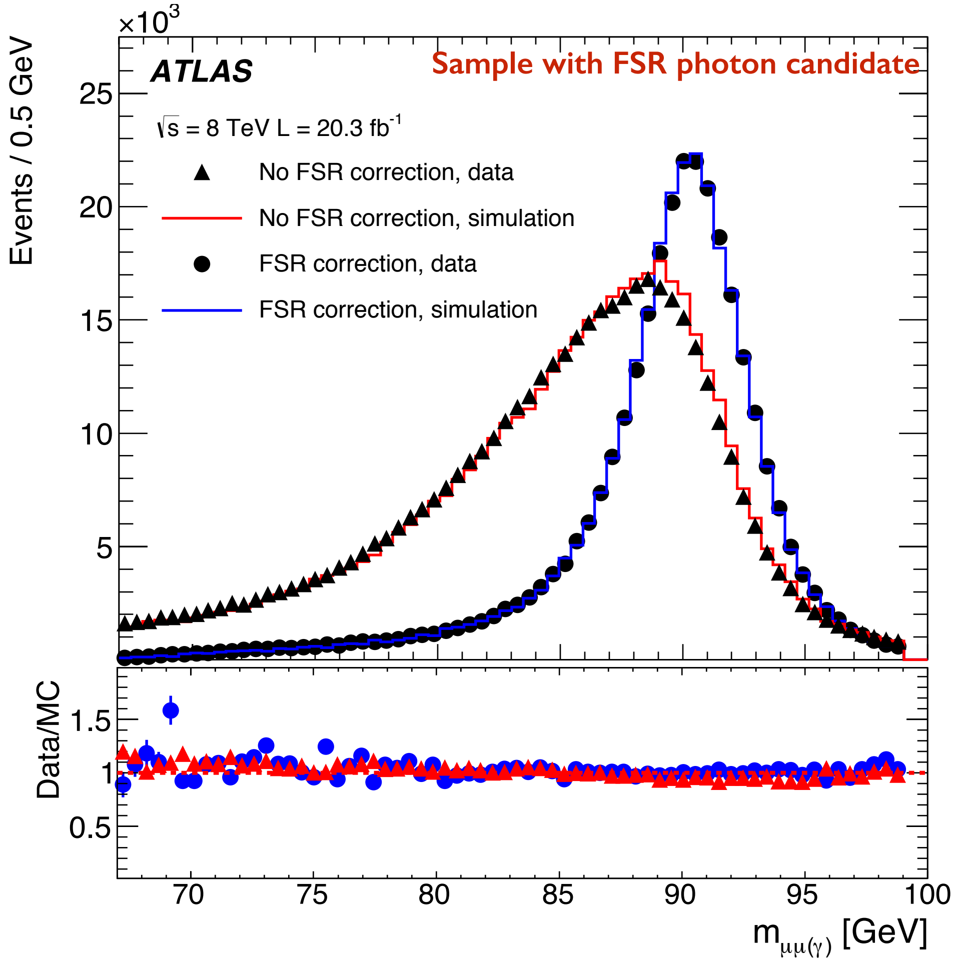



- Resolution
  - Uncorrected MC is ~5-10% smaller than data (after correction, well within uncertainties)
  - Correction procedure explained in detail in
    - [http://arxiv.org/abs/1407.3935](http://arxiv.org/abs/1407.3935)
    - (extracts in backup)

• http://arxiv.org/abs/1407.3935

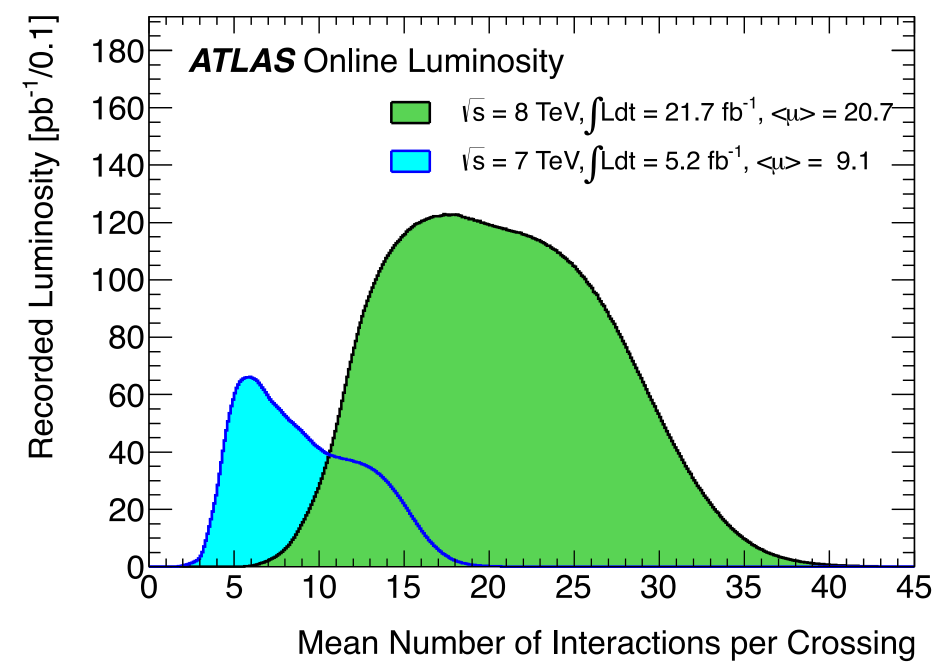
# Muons - **ATLAS** FSR

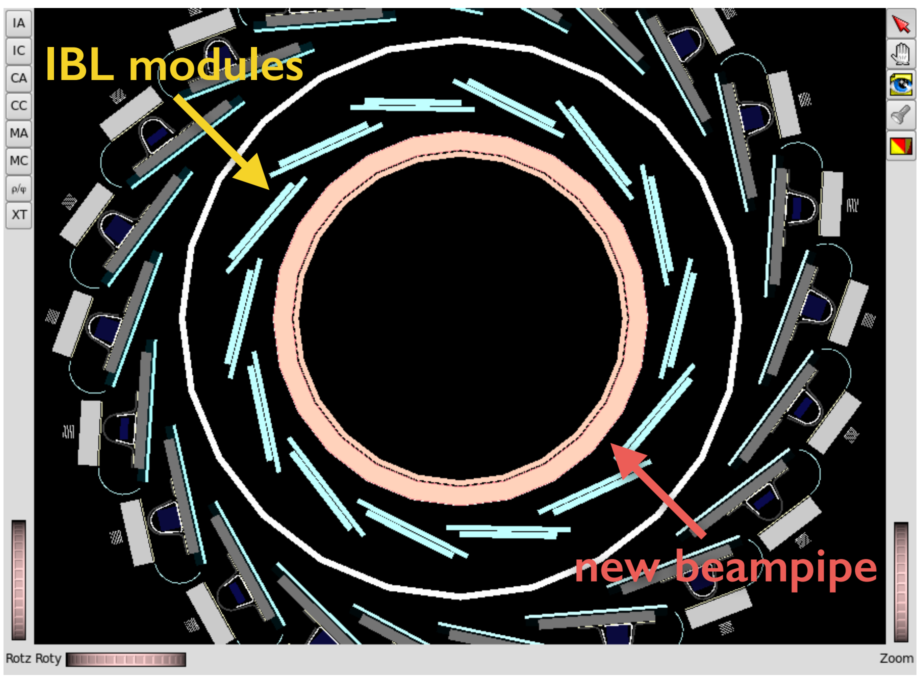
- **ATLAS** FSR recovery
  - Look for e/m clusters within narrow cone around muon (using longitudinal segmentation of LAr calorimeter to reject fakes)
    - Require that cluster has >10% of energy in first layer
  - Improves resolution of $Z \rightarrow \mu\mu$ by ~3% and shifts mass by ~40 MeV
  - Used in Higgs searches e.g. ATLAS-CONF-2013-013



# Run-2 developments

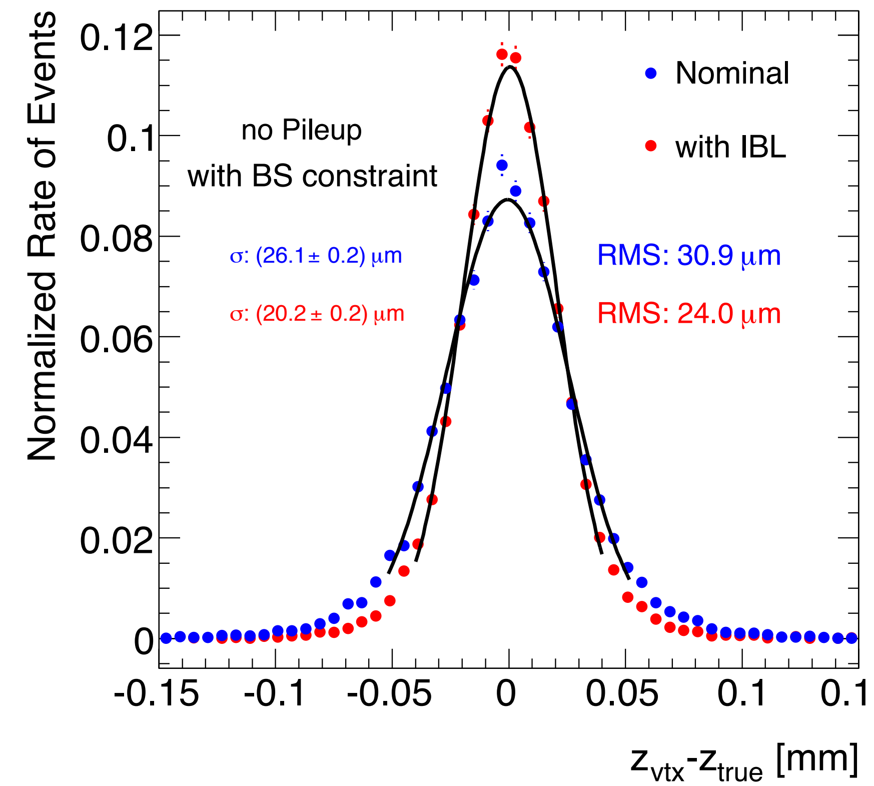
- Significant challenges, e.g. denser environment with more pileup
  - CPU / Disk space per event must be reduced.
  - Better resolution of track parameters / better vertexing
- **ATLAS** Tracker
  - installed additional (4th) Pixel layer: IBL
    - small radius: 32-38 mm
  - NN based Pixel clustering arXiv:1406.7690
    - goal: reduce #shared clusters in high-pT jets
    - Used in run-1 but re-optimised version will be core component of ATLAS tracking in Run-2



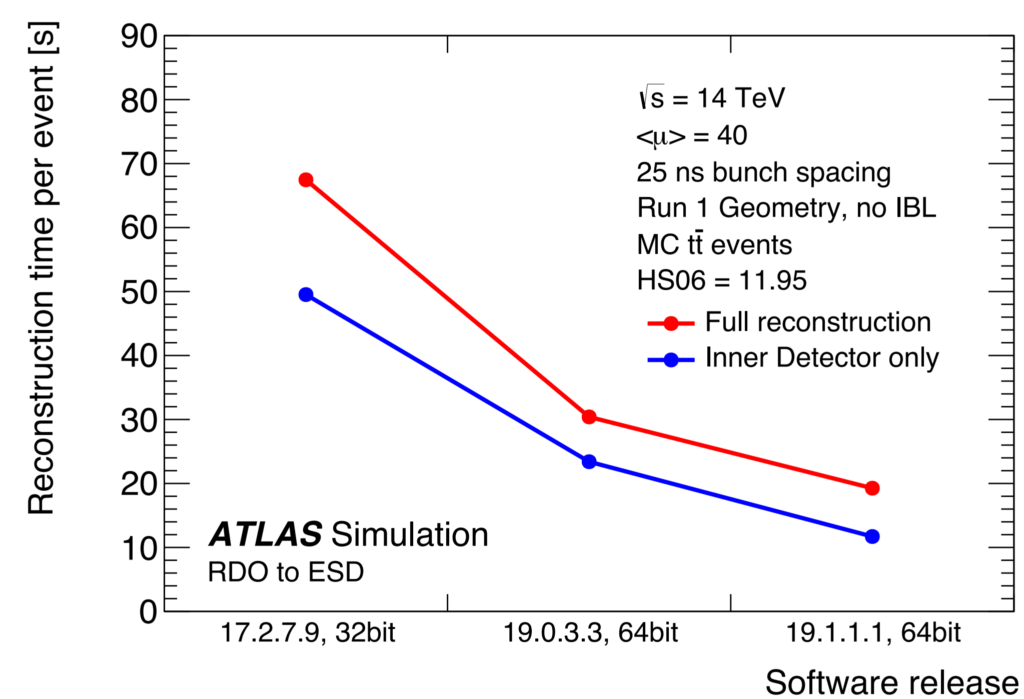



# Run-2 developments (2)

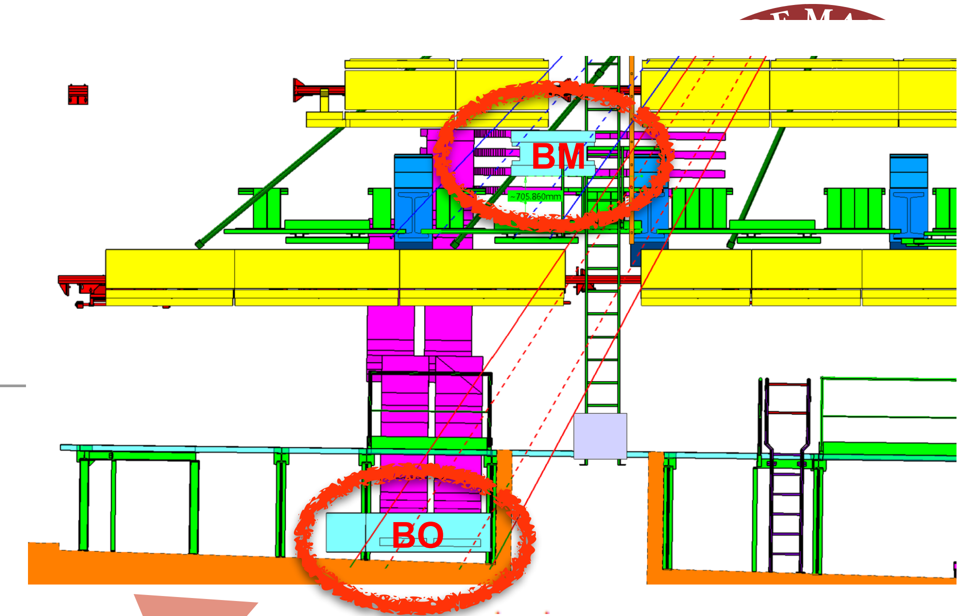
- **ATLAS** Vertexing in Run-2
  - working on a new seeding algorithm to cope with high pile-up
    - inspired by medical imaging
    - better reconstruction of close-by vertices
  - Insertable B-Layer (IBL) improves vertex efficiency and resolution
  - primary goal: keep fake and split vertices low



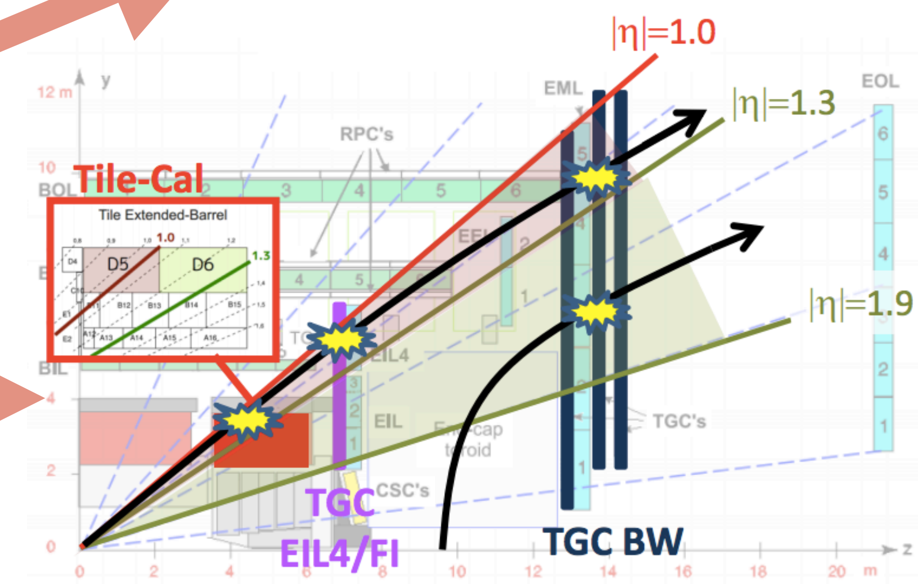

- **ATLAS** General Software
  - Software shifted from 32bit→64 bit
  - New compiler, new maths library (CLHEP → Eigen)
  - Simplified analysis Event Data Model (xAOD) reducing steps necessary to analyse data (CPU and disk savings)

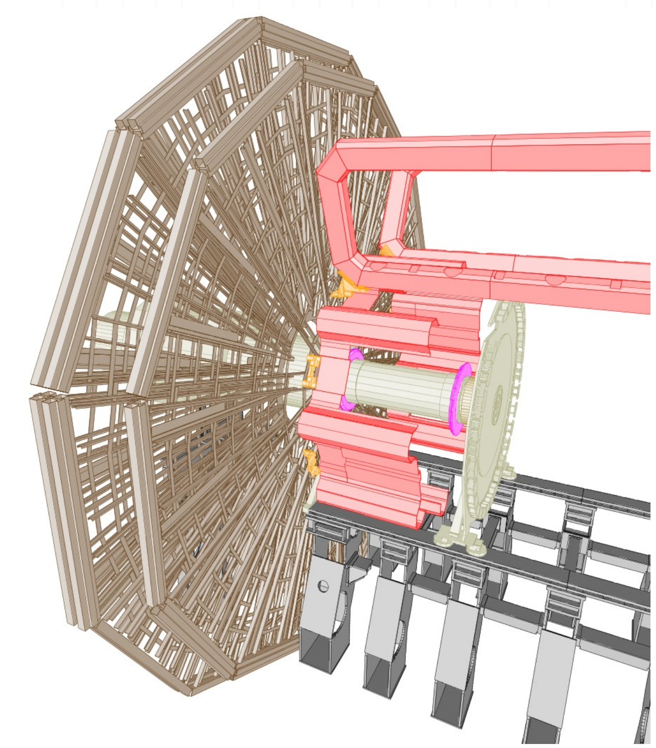


# Run-2 Developments (3)




- **ATLAS** Muons
  - New unified software reconstruction chain
  - **New chambers added** & upgrades of existing chambers performed
  - Improvements to optical alignment monitoring systems
  - **New TileCal/TGC trigger**, to reduce L1 Muon fakes
  - No longer using simulation with ‘smeared’ alignment
    - In run-1, we ‘smeared’ the positions of the simulated chambers by random amounts, corresponding to the estimated alignment uncertainty
    - This was useful, because it allowed us to tune our reconstruction techniques on a ‘realistic’ geometry, but caused some problems as actual alignment improved
    - No longer necessary for run-2 - will rely on corrections to muon momentum scale, resolution and efficiency
  - Improvements to material description



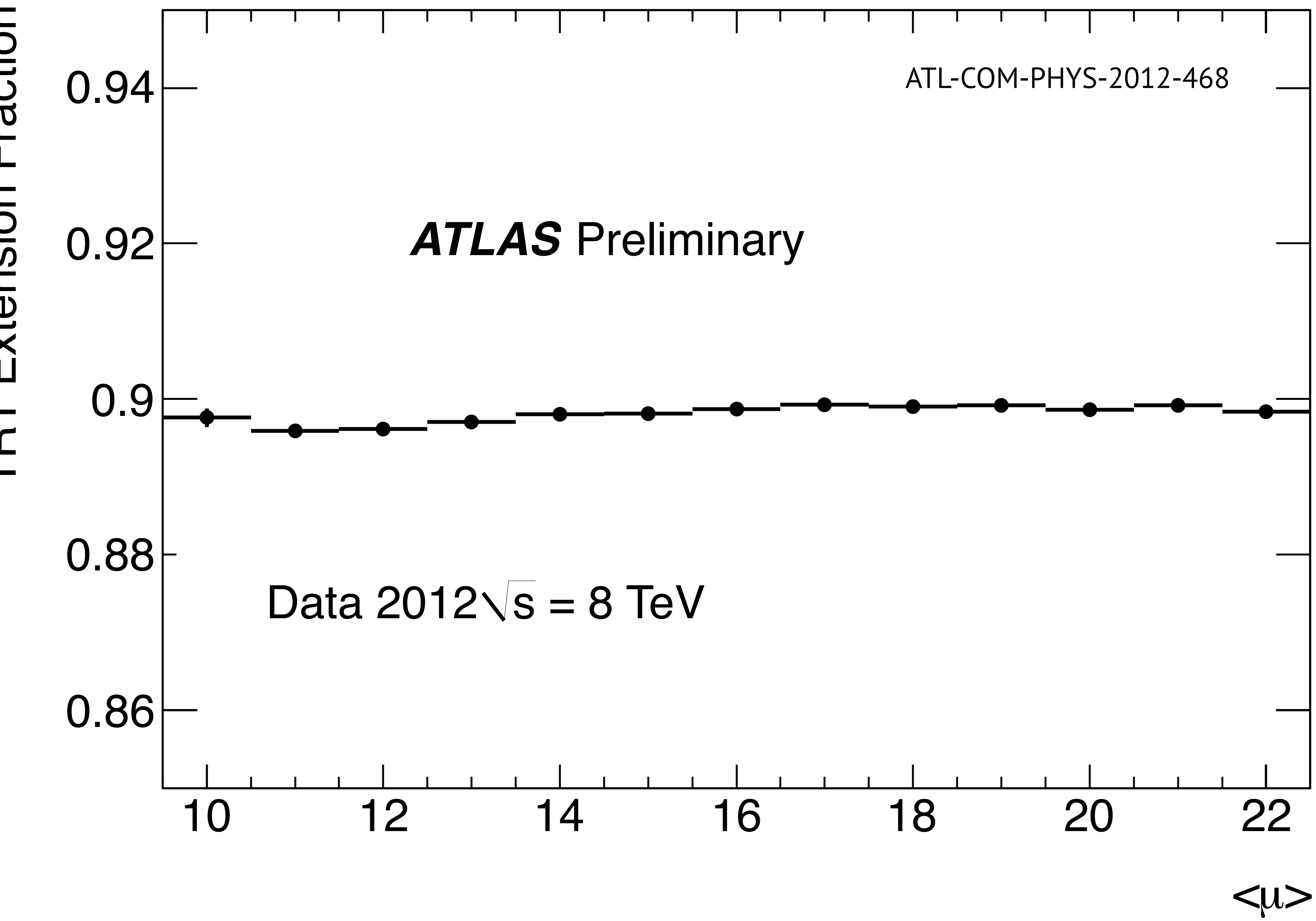
# Conclusions

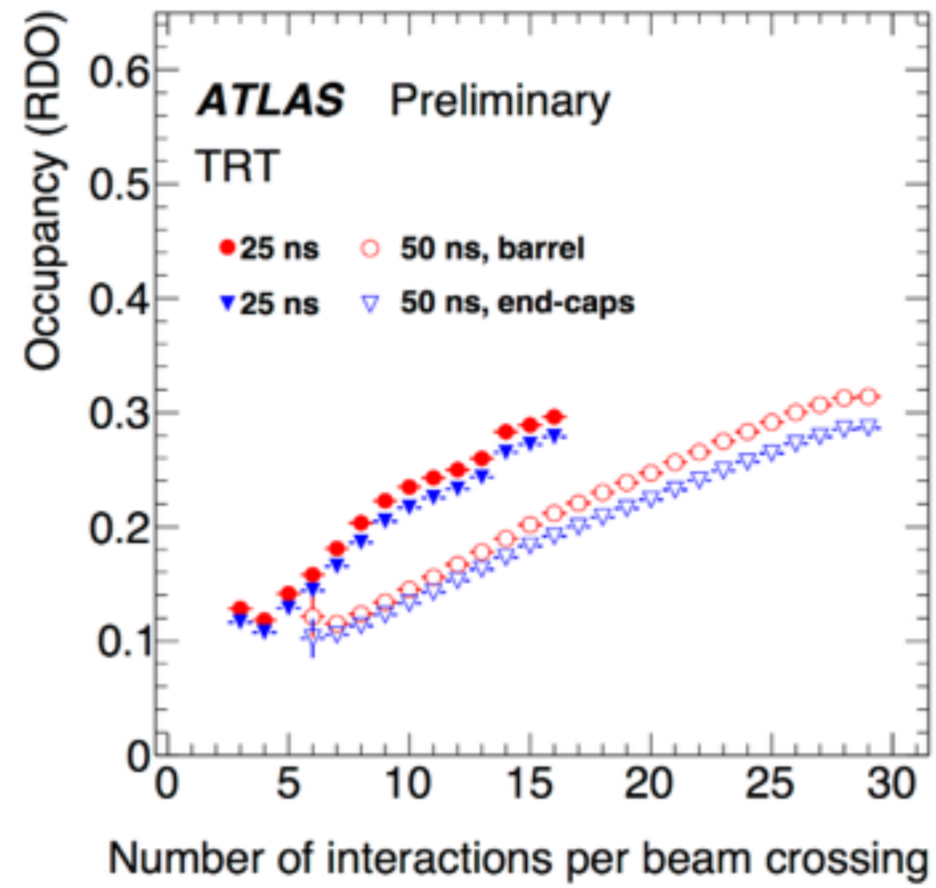
- **ATLAS** & **CMS** have both performed extremely well over over run-1, contributing in the successful discovery of a new scalar boson
  - Efficiencies to find muons ~100%, very careful studies of systematics etc
  - A lot of effort in improving material description & simulation
- Many improvements over LS1 in preparation for the challenging conditions of run-2
  - [**ATLAS**] New IBL, new Muon chambers added etc
  - New reconstruction techniques to deal with dense environment / increased pileup
  - Improvements to SW performance to cope with tight resource constraints

# Backup

# Tracker

# TRT performance vs pileup



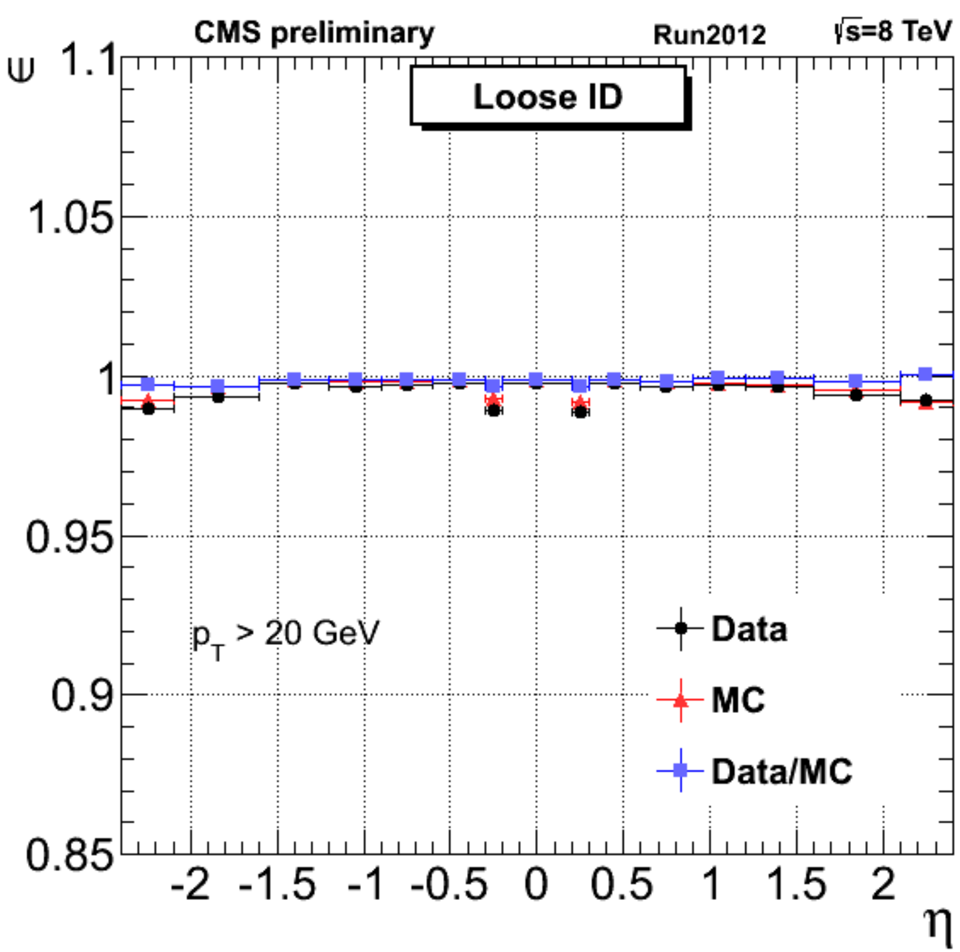

The fraction of tracks found in the silicon that have extensions found in the TRT as a function of the average number of interactions per bunch crossing. The average mu is a measure of both in-time and out-of-time pileup, which also contributes due to the 50 ns bunch spacing. TRT extensions require a minimum of 9 hits in the TRT, at least 50% of which are precision hits.

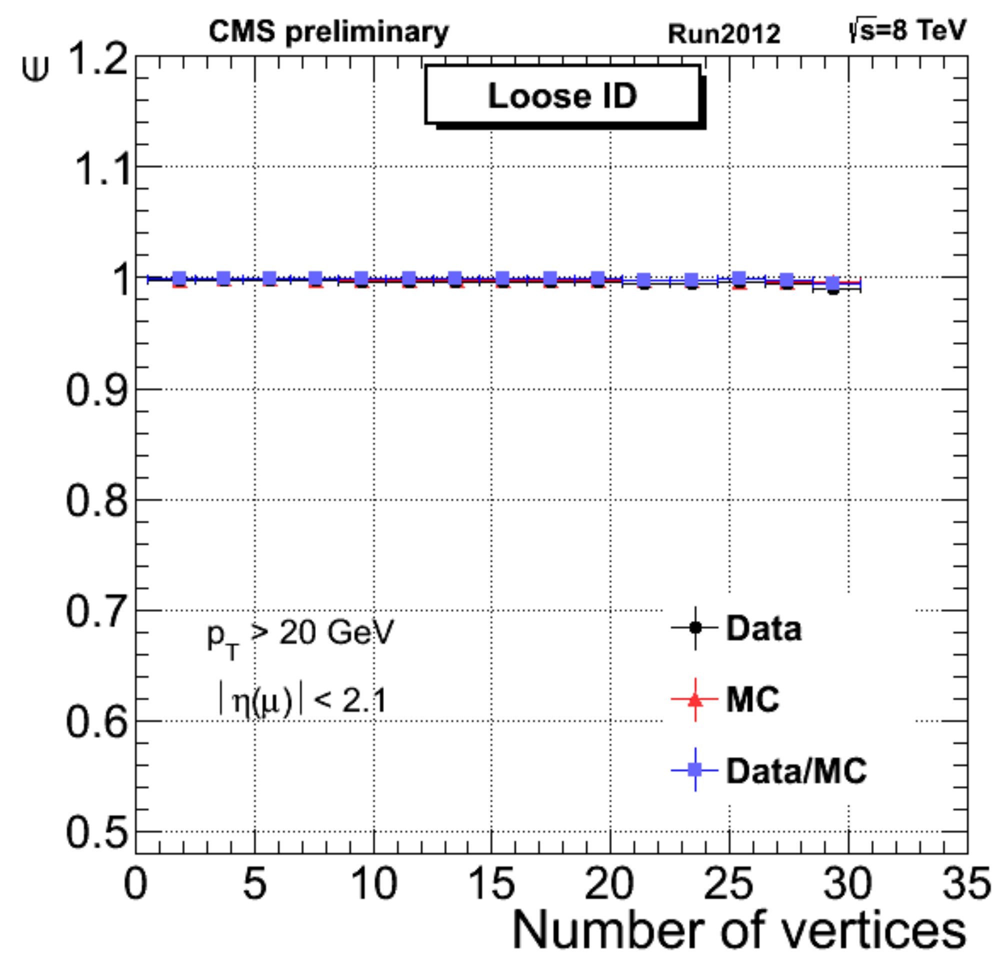
http://indico.cern.ch/event/279530/session/0/contribution/5/material/slides/0.pdf

# Muon

# **CMS** Muons

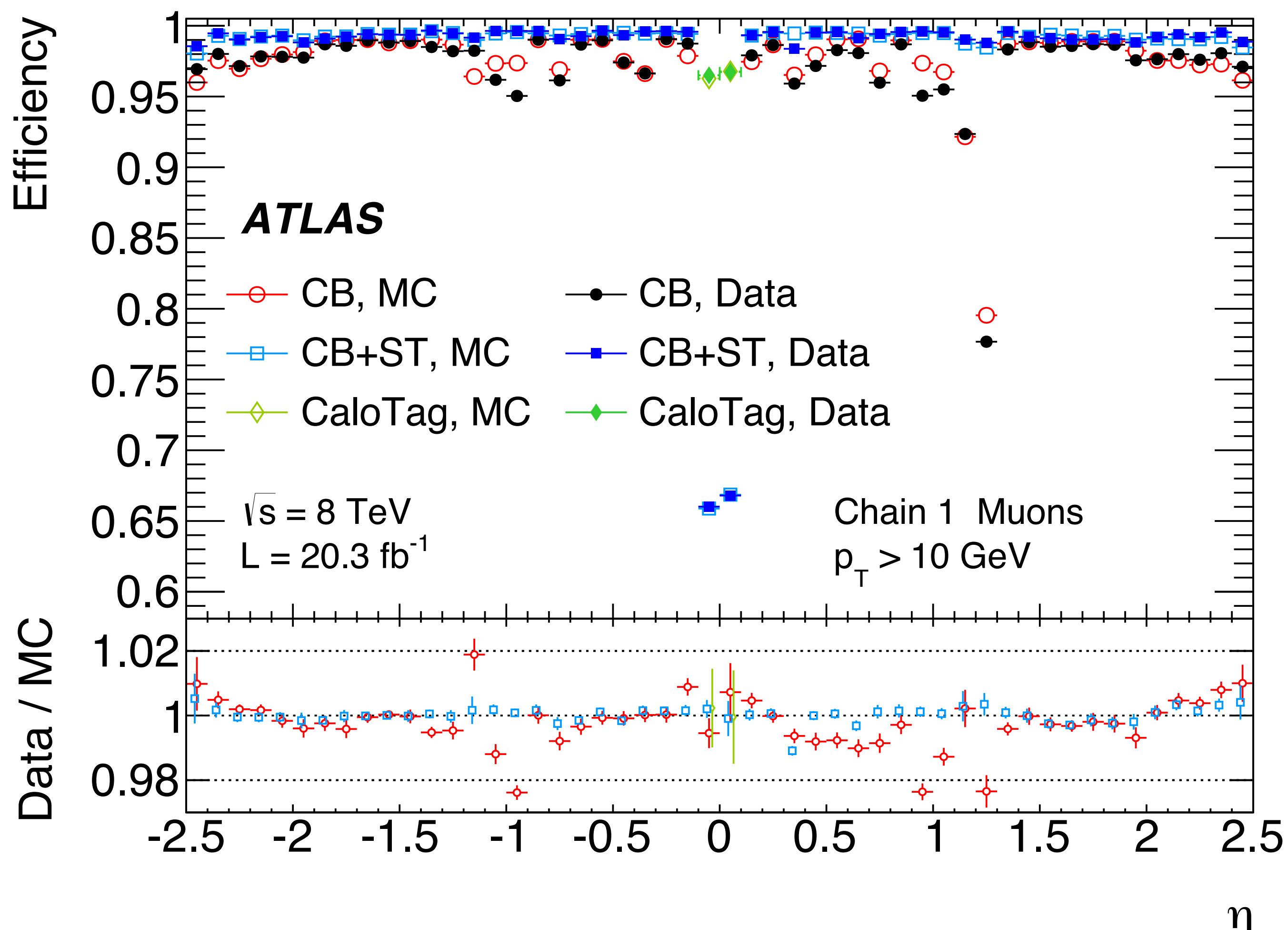
- Muon ID efficiencies:
  - **Tight**
    - global muon
    - PF muon
    - globalTrack.normalizedChi2< 10
    - globalTrack.numberOfValidMuonHits > 0
    - numberOfMatchedStations > 1
    - |dxy| < 0.2 cm, |dz| < 0.5 cm
    - numberOfValidPixelHits > 0
    - trackerLayersWithMeasurement > 5
  - **Loose**
    - PF muon
    - global or tracker muon



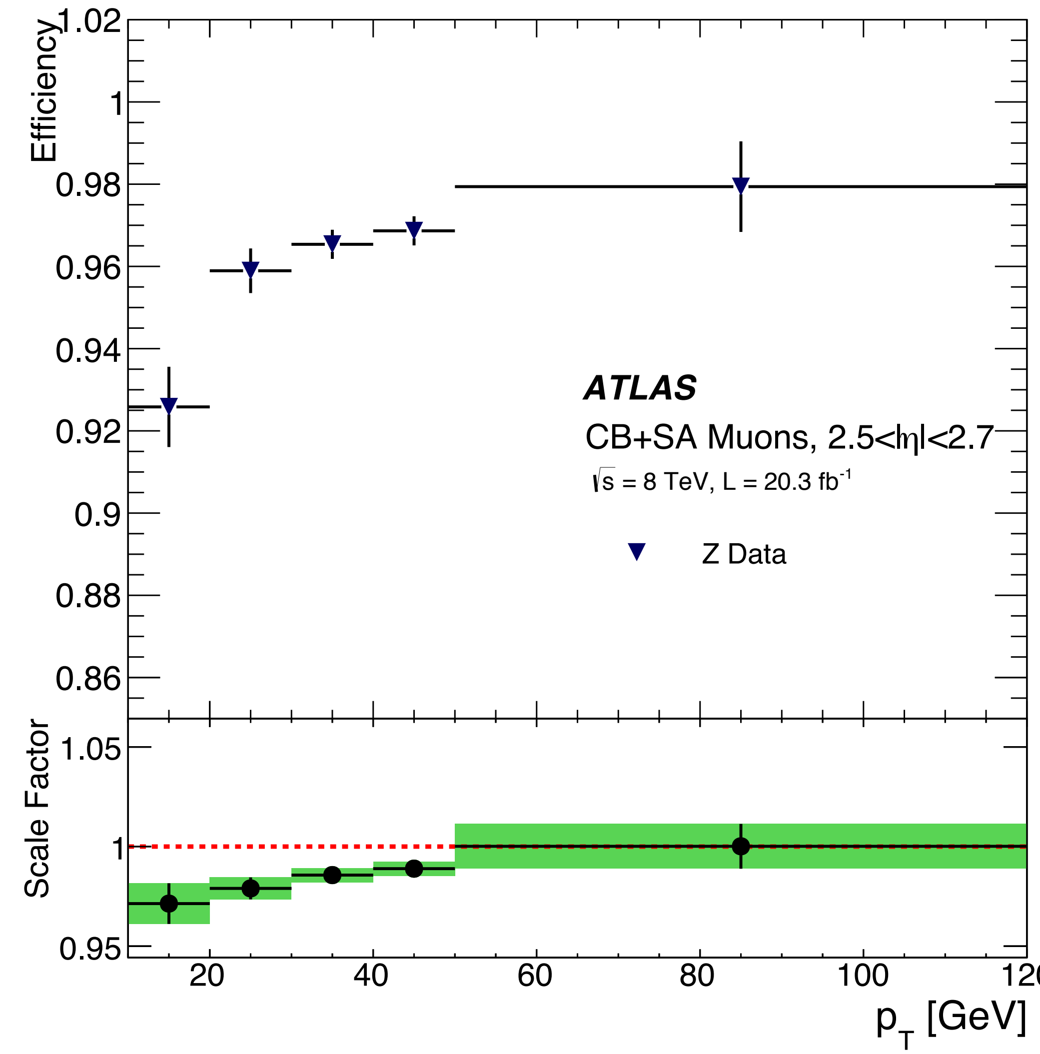




http://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20DP-2013/009

# Muons - efficiency (ATLAS)



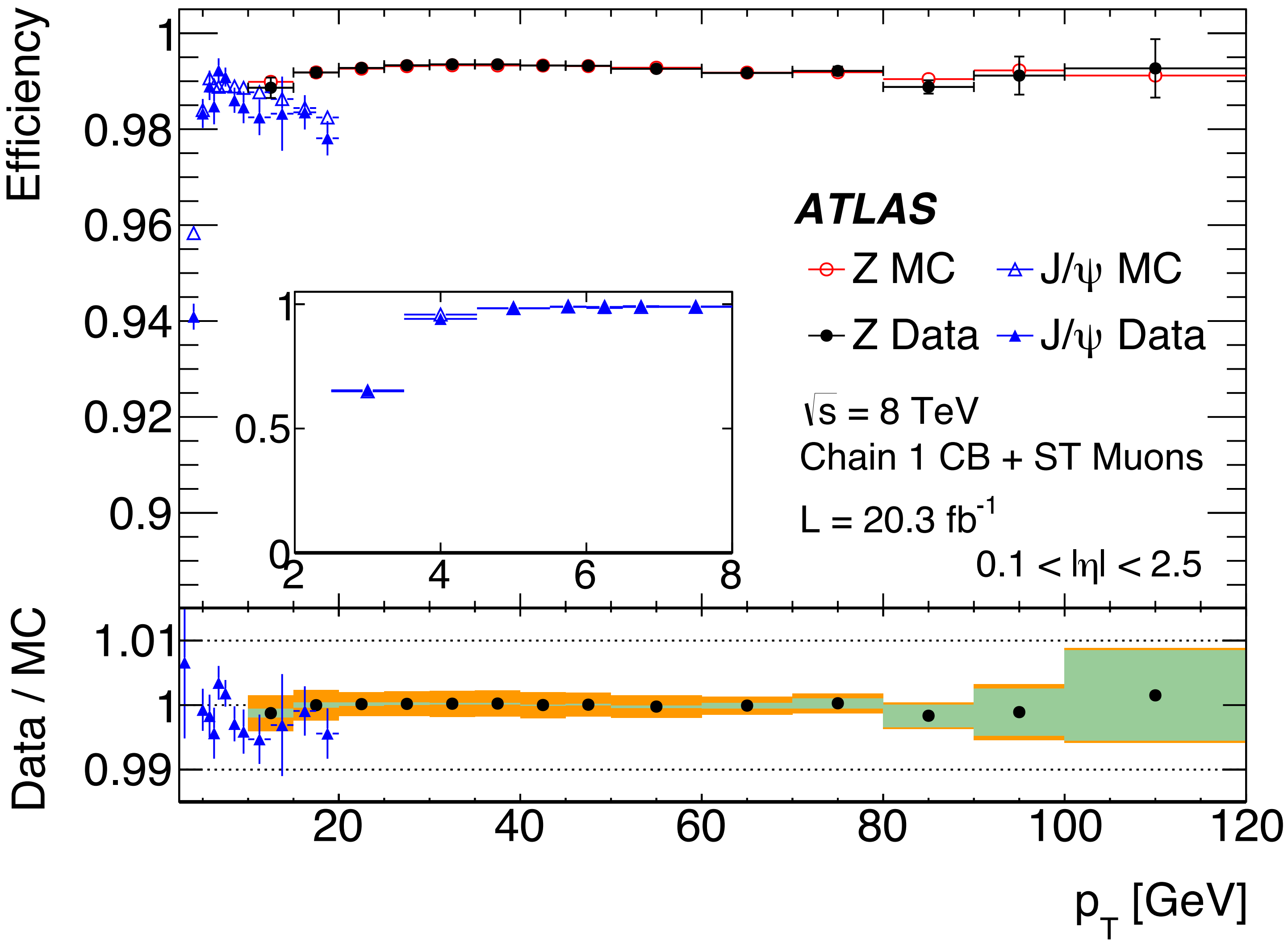

Muon reconstruction efficiency as a function of eta measured in Z->mumu events for muons with pt>10 GeV and different muon reconstruction types. CaloTag muons are only shown in the region |eta|<0.1, where they are used in physics analyses. The error bars on the efficiencies indicate the statistical uncertainty. The panel at the bottom shows the ratio between the measured and predicted efficiencies. The error bars on the ratios are the combination of statistical and systematic uncertainties.

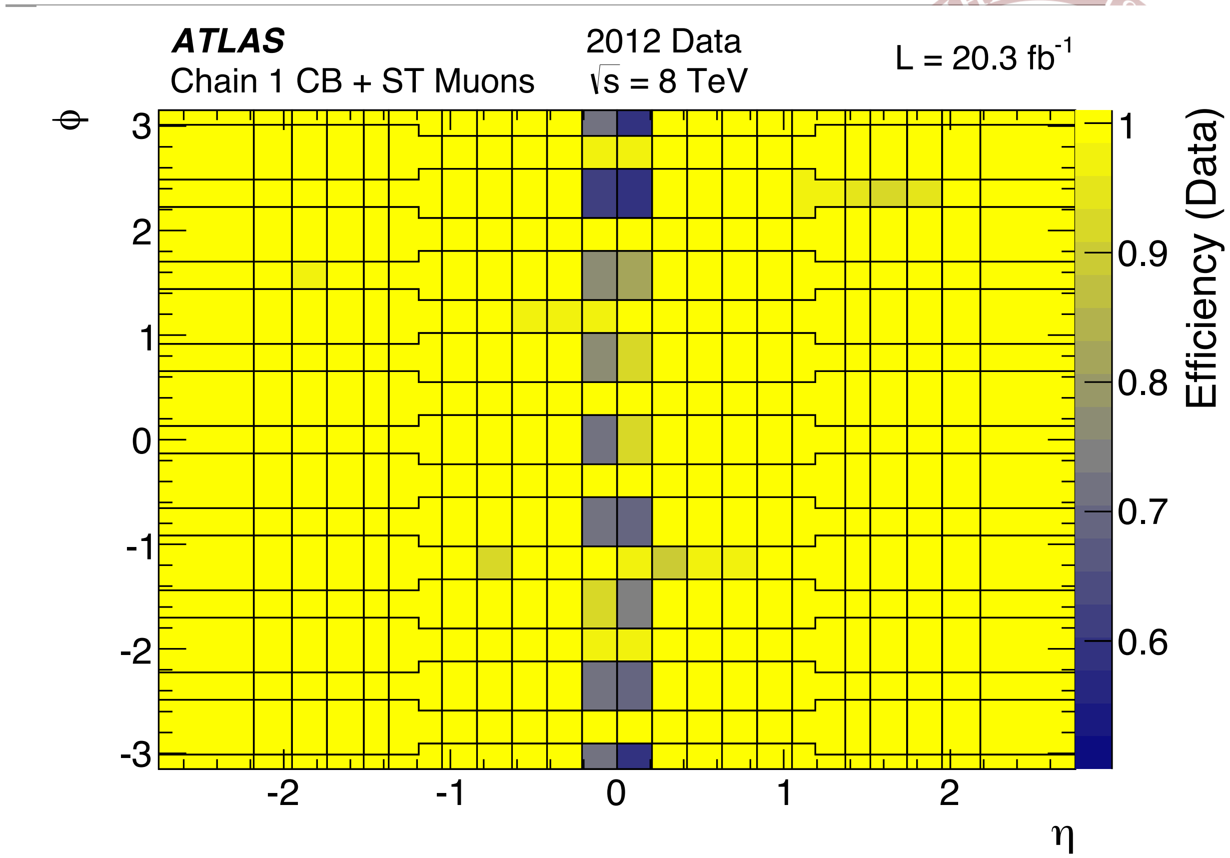



Reconstruction efficiency for muons within 2.5<|eta|<2.7 from Z->mumu events. The upper plot shows the efficiency obtained as the product of scale factor (Eq. 8) and the MC efficiency. The lower plot shows the scale factor. The error bars correspond to the statistical uncertainty while the green shaded band corresponds to the statistical and systematic uncertainty added in quadrature.

http://arxiv.org/abs/1407.3935

# Muons - efficiency (2) (ATLAS)



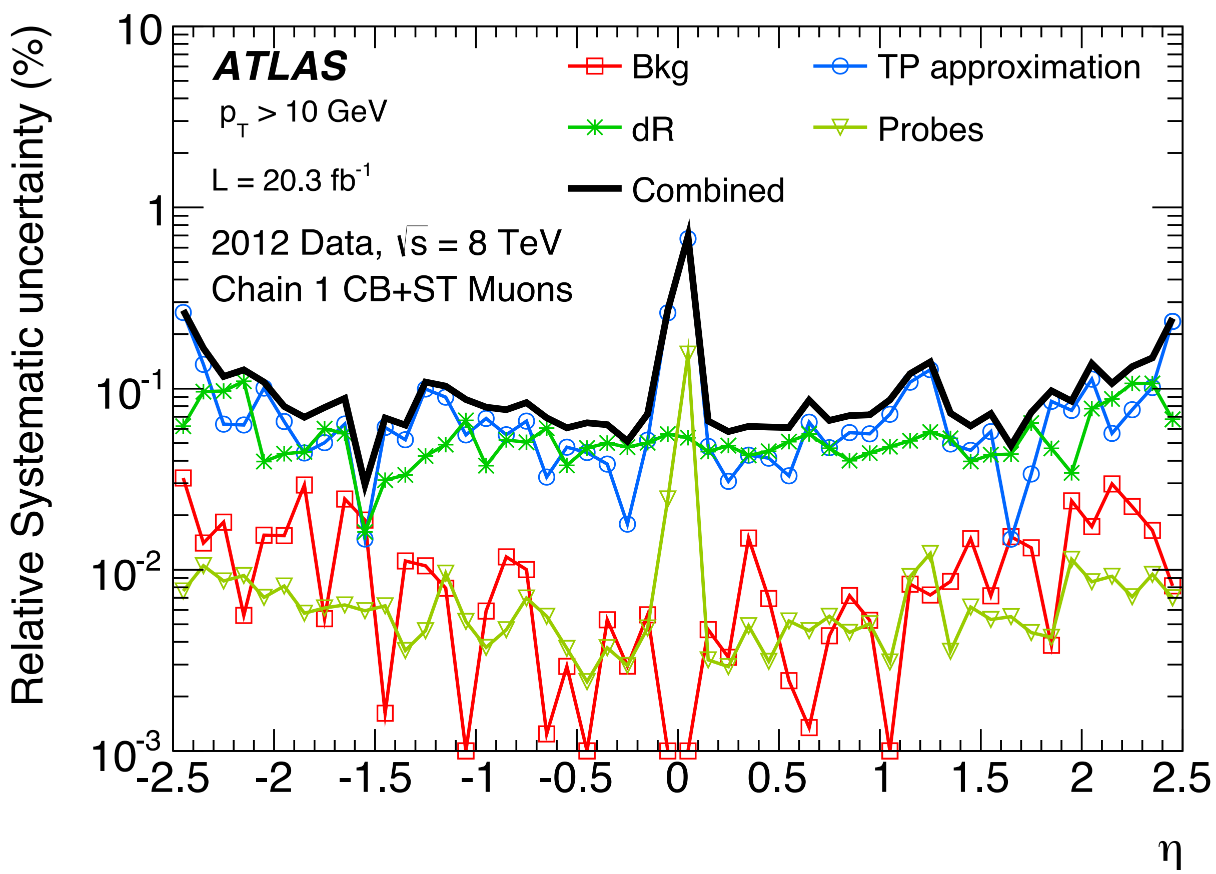



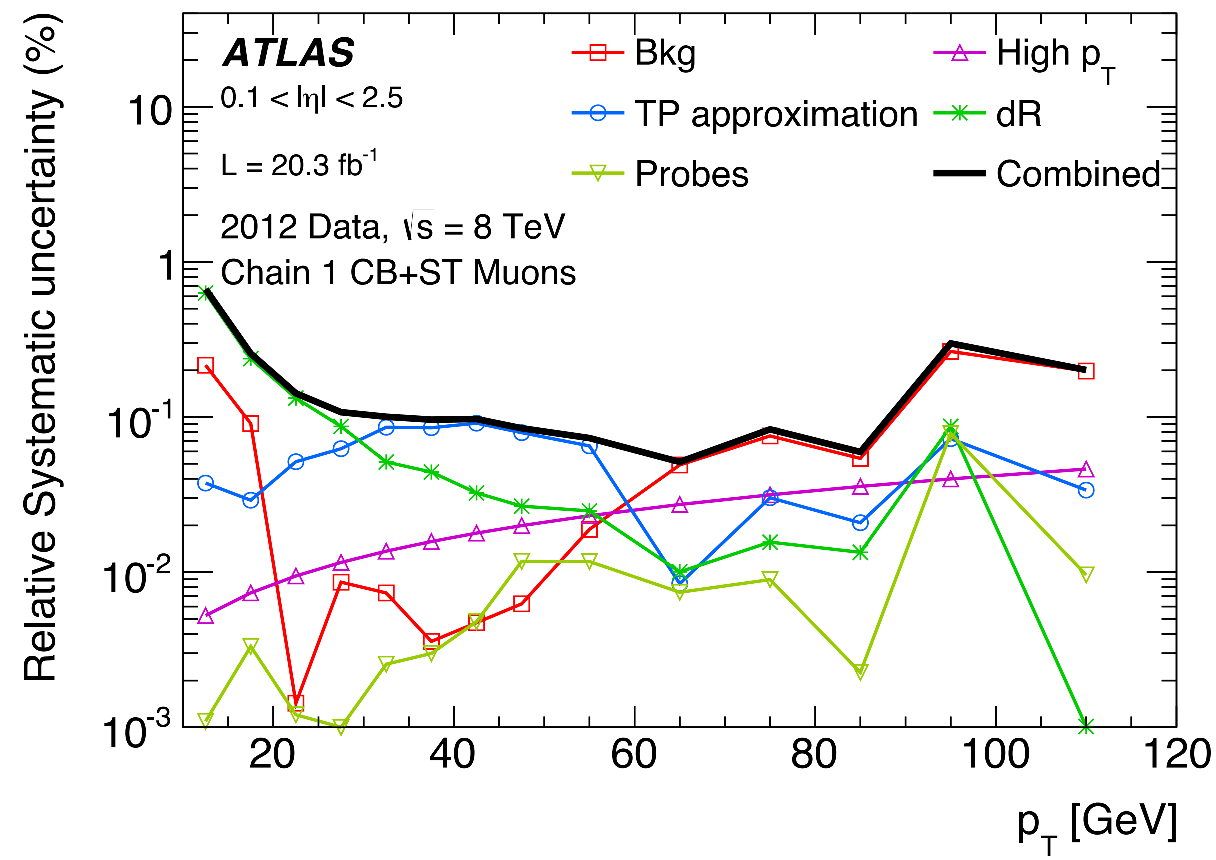

Reconstruction efficiency for CB+ST muons as a function of the pt of the muon, for muons with 0.1<|eta|<2.5. The plot also shows the result obtained with Z->mumu and J/Ψ->mumu events. The inserts on the upper plots show the detail of the efficiency as a function of pt in the low pt region. The error bars on the efficiencies indicate the statistical uncertainty for Z->mumu and include also the fit model uncertainty for J/Ψ->mumu. The panel at the bottom shows the ratio between the measured and predicted efficiencies. The green areas show the pure statistical uncertainty, while the orange areas also include systematic uncertainties.

Reconstruction efficiency measured in the experimental data CB+ST muons as a function of eta and phi for muons with pt>10 GeV.

http://arxiv.org/abs/1407.3935

# Efficiency systematics (ATLAS)

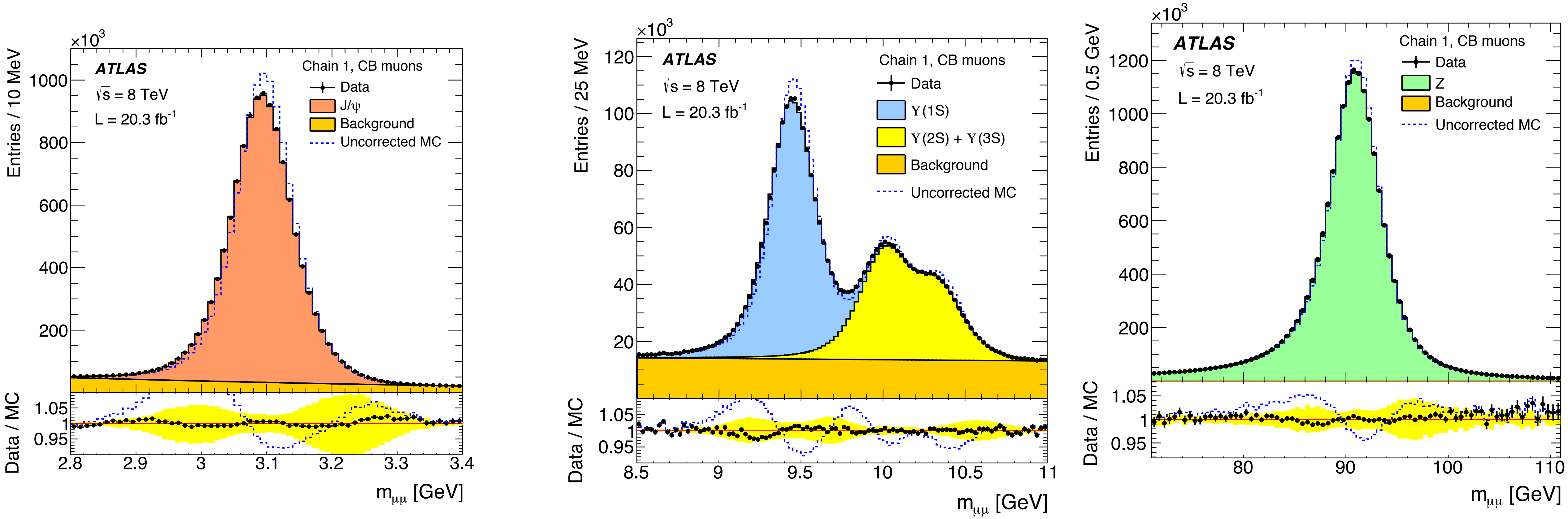



Systematic uncertainty on the efficiency scale factor for CB +ST muons, obtained from Z → μμ data, as a function of η (left) and p(right) for muons with p> 10 GeV. The background systematic uncertainty in the last two bins of the bottom plot is affected by a large statistical uncertainty. The combined systematic uncertainty is the sum in quadrature of the individual contributions

http://arxiv.org/abs/1407.3935

# Muons - resolution (ATLAS)




Dimuon invariant mass distribution of J/Ψ->mumu (left), Upsilon->mumu (center) and Z->mumu (right) candidate events reconstructed with CB muons. The upper panels show the invariant mass distribution for data and for the signal MC simulation plus the background estimate. The points show the data, the filled histograms show the simulation with the MC momentum corrections applied and the dashed histogram shows the simulation when no correction is applied. Background estimates are added to the signal simulation. The lower panels show the Data/MC ratios. The band represents the effect of the systematic uncertainties on the MC momentum corrections. In the J/Ψ case the background was fitted in a sideband region as described in the text. In the Upsilon case a simultaneous fit of the normalization of the three simulated Upsilon distributions and of a linear background was performed. In the Z case, the MC background samples are added to the signal sample according to their expected cross sections. The sum of background and signal MC is normalized to the data.

http://arxiv.org/abs/1407.3935

# Resolution correction (ATLAS)

- Uses formula

$$p_{\mathrm{T}}^{\mathrm{Cor,Det}} = \frac{p_{\mathrm{T}}^{\mathrm{MC,Det}} + \sum_{n=0}^{1} s_n^{\mathrm{Det}}(\eta,\phi) \left(p_{\mathrm{T}}^{\mathrm{MC,Det}}\right)^n}{1 + \sum_{m=0}^{2} \Delta r_m^{\mathrm{Det}}(\eta,\phi) \left(p_{\mathrm{T}}^{\mathrm{MC,Det}}\right)^{m-1} g_m} \quad (9)$$

$$(\text{with } s_0^{\mathrm{ID}} = 0 \text{ and } \Delta r_0^{\mathrm{ID}} = 0),$$

where $g_m$ are normally distributed random variables with mean 0 and width 1 and the terms $\Delta r_m^{\mathrm{Det}}(\eta,\phi)$ and $s_n^{\mathrm{Det}}(\eta,\phi$ describe, respectively, the momentum resolution smearing and the scale corrections applied in a specific $\eta$, $\phi$ detector region. The motivations for Eq. 9 are the following:

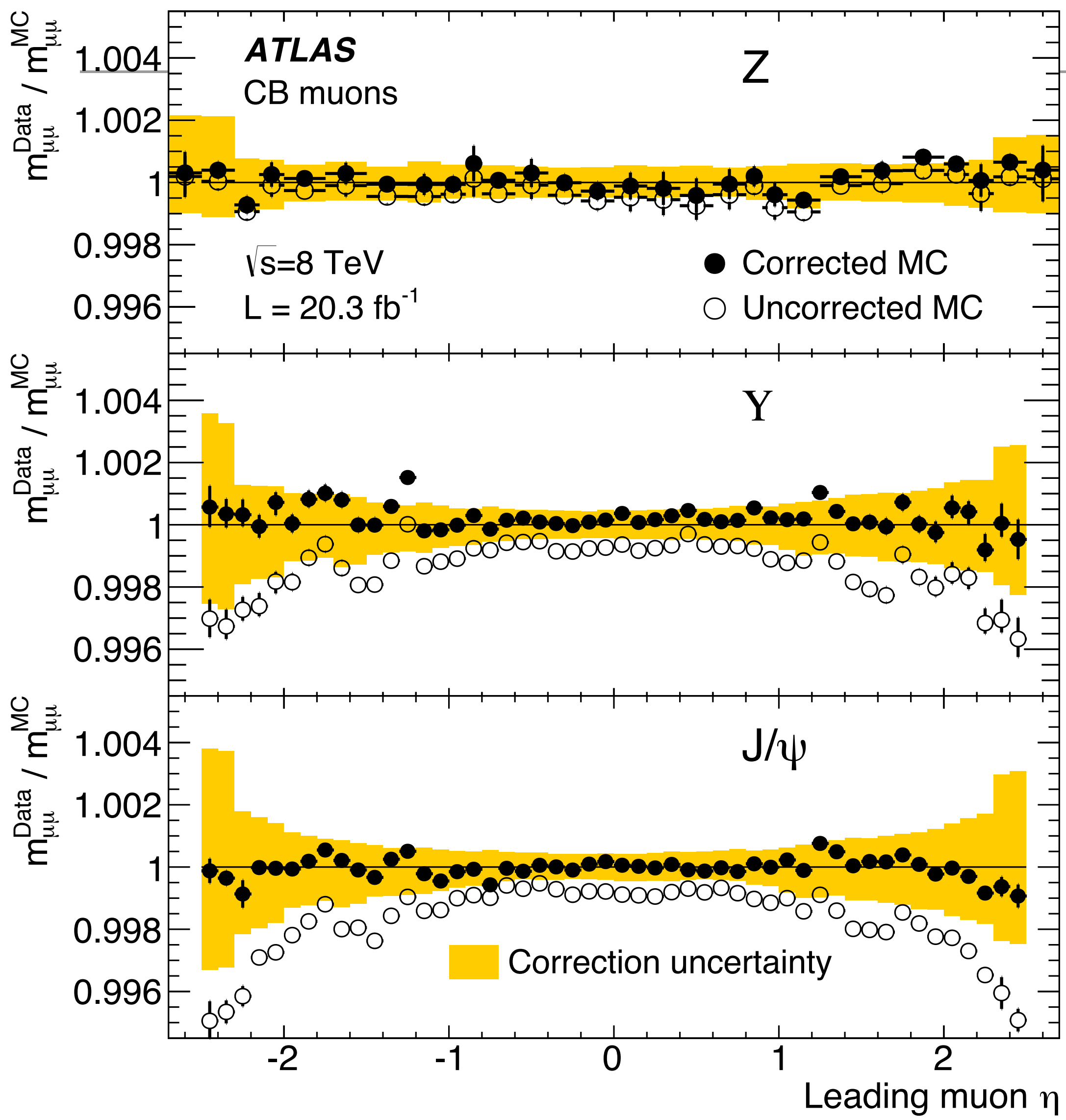
– The $\Delta r_m^{\mathrm{Det}}(\eta,\phi)$ correction terms introduce a $p_{\mathrm{T}}$ dependent momentum smearing that effectively increases the relative momentum resolution, $\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}}$, when underestimated by the simulation. The $\Delta r_m^{\mathrm{Det}}(\eta,\phi)$ terms can be related to different sources of experimental resolution by comparing the coefficient of the $p_{\mathrm{T}}$ powers in the denominator of Eq. 9 to the following empirical parametrization of the muon momentum resolution (see for example [25]):

$$\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = r_0/p_{\mathrm{T}} \oplus r_1 \oplus r_2 \cdot p_{\mathrm{T}}, \quad (10)$$

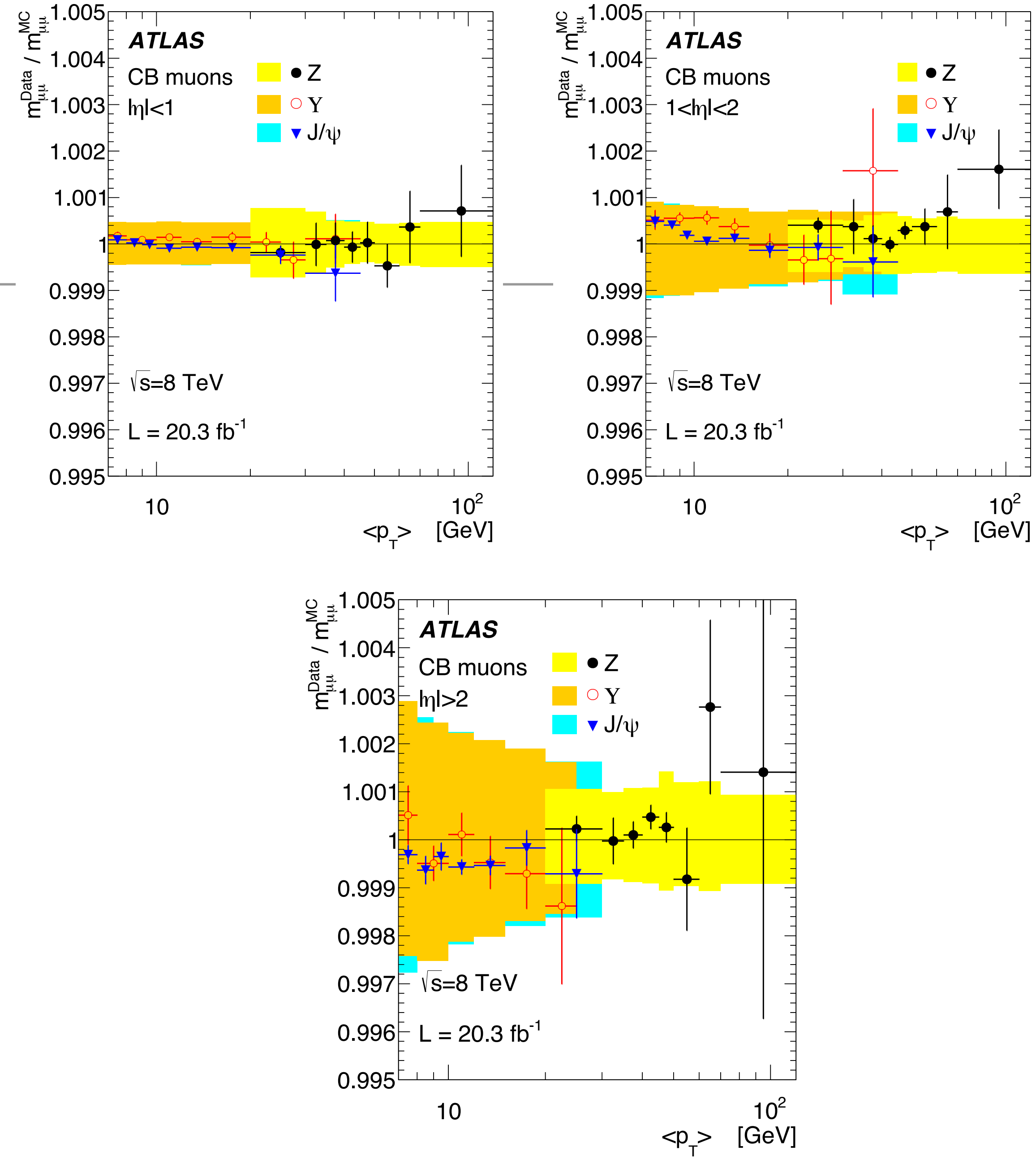
where $\oplus$ denotes a sum in quadrature. The first term (proportional to $1/p_{\mathrm{T}}$) accounts for fluctuations of the energy loss in the traversed material. Multiple scattering, local magnetic field inhomogeneities and local radial displacements are responsible for the second term (constant in $p_{\mathrm{T}}$). The third term (proportional to $p_{\mathrm{T}}$) describes intrinsic resolution effects caused by the spatial resolution of the hit measurements and by residual misalignment. Energy loss fluctuations are relevant for muons traversing the calorimeter in front of the MS but they are negligible in the ID measurement. For this reason $\Delta r_0^{\mathrm{ID}}$ is set to zero in Eq. 9.

– Imperfect knowledge of the magnetic field integral and of the radial dimension of the detector are reflected in the multiplicative momentum scale difference $s_1^{\mathrm{Det}}$ between data and simulation. In addition, the $s_0^{\mathrm{MS}}(\eta,\phi)$ term is necessary to model the $p_{\mathrm{T}}$ scale dependence observed in the MS momentum reconstruction due to differences between data and MC in the energy loss of muons passing through the calorimeter and other materials between the interaction point and the MS. As the energy loss between the interaction point and the ID is negligible, $s_0^{\mathrm{ID}}(\eta)$ is set to zero.

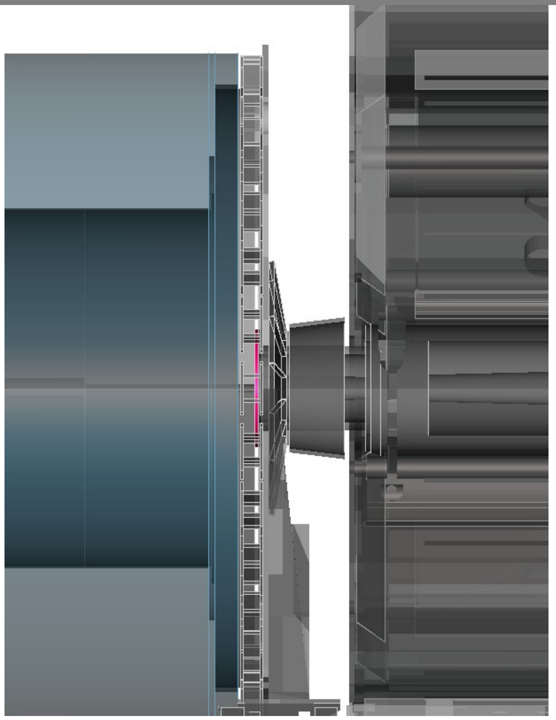
# http://arxiv.org/abs/1407.3935




Ratio of the fitted mean mass, $\langle m_{\mu\mu} \rangle$, for data and corrected MC from Z (top), Upsilon (middle), and $J/Ψ$ (bottom) events as a function of the pseudorapidity of the highest-pt muon. The ratio is shown for corrected MC (filled symbols) and uncorrected MC (empty symbols). The error bars represent the statistical and the systematic uncertainty on the mass fits added in quadrature. The bands show the uncertainty on the MC corrections calculated separately for the three samples.

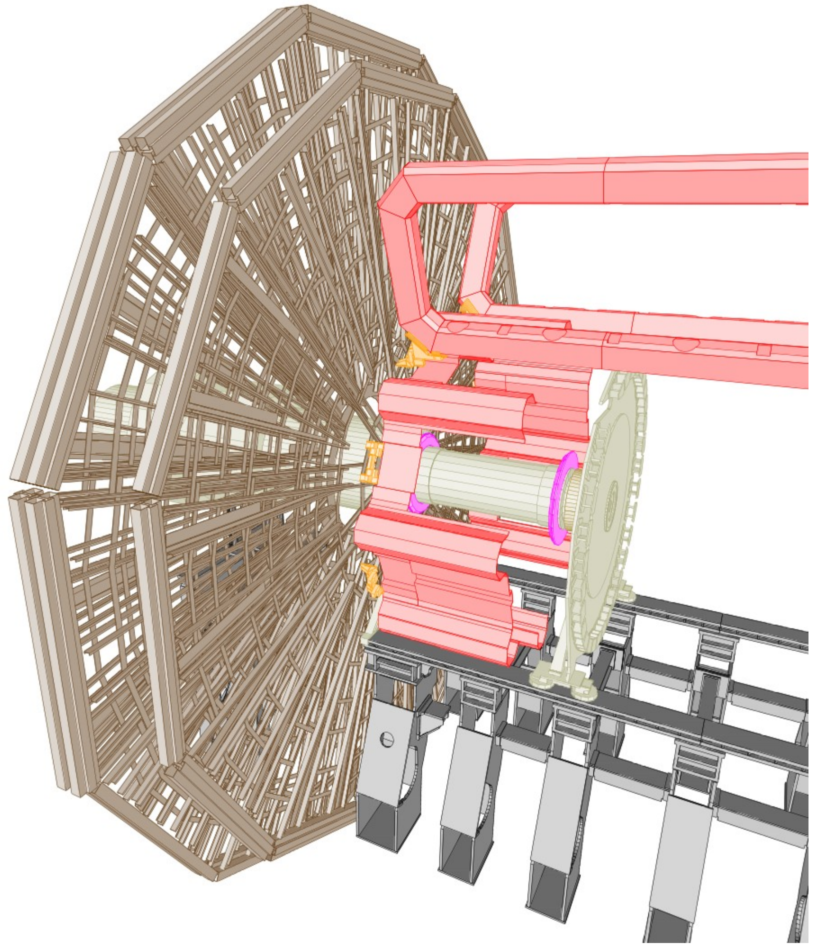


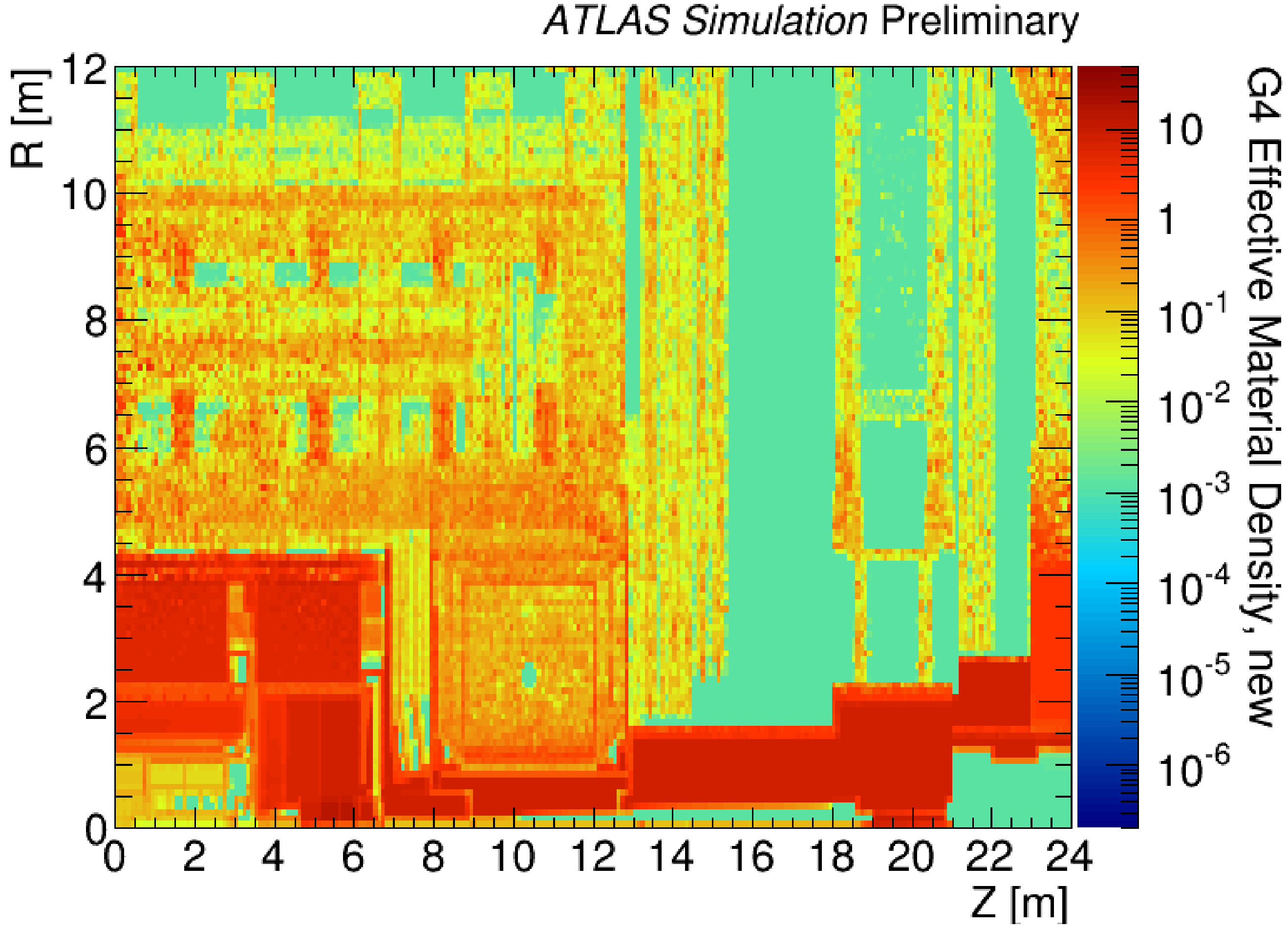

Ratio of the fitted mean mass, , for data and corrected MC from J/Ψ, Upsilon and Z events as a function of the average transverse momentum in three |eta| ranges, using combined reconstruction. Both muons are required to be in the same |eta| range. The J/Ψ and Upsilon data are shown as a function of pt(bar) = 1/2*(pt1+pt2) while for Z data are plotted as a function of pt* as defined in Eq.16. The error bars represent the statistical uncertainty and the systematic uncertainty on the fit added in quadrature. The bands show the uncertainty on the MC corrections calculated separately for the three samples.



major updates of the Geant4 geometry:

- thermal shielding for all toroid coils (red)
- additional shielding inside end cap toroid (magenta) at |z|≈9m and |z|≈13m and r≈1m
- reimplemented end cap support (brown) at |z|≈14m
- calorimeter crates at |z|≈3.5m and r≈6.5m
- shielding installed during winter shutdown 2011/2012 at |z|≈6.5m and r≈1m






LPCC https://indico.cern.ch/event/279530/other-view?view=standard

# Flavour-tagging

# ATLAS-CONF-2014-004

Calibration of $b$-tagging using dileptonic top pair events in a combinatorial likelihood approach with the ATLAS experiment

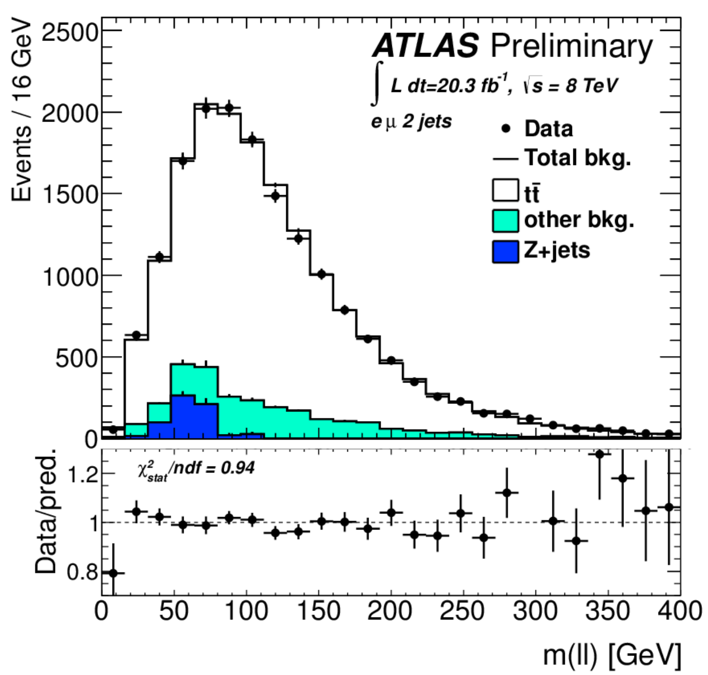
## Combinatorial likelihood calibration: *b*-tagging efficiency

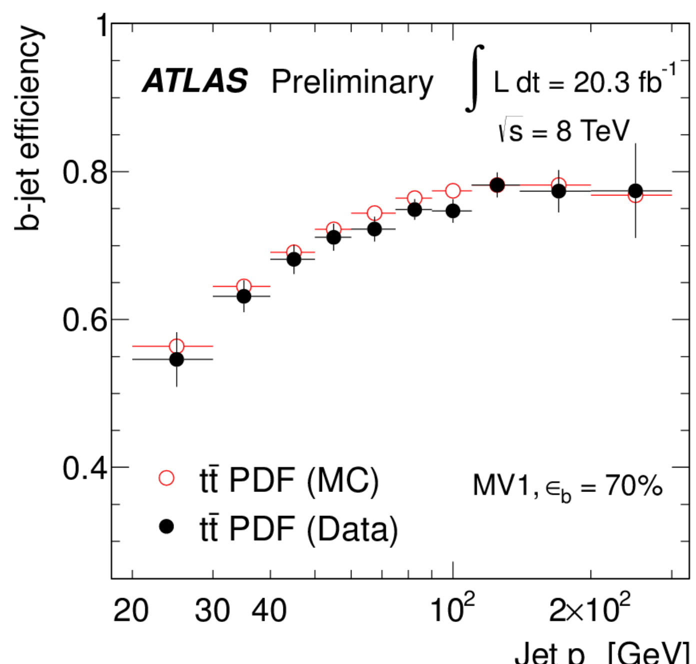
- $t\bar{t}$ dilepton events can provide very pure $b$-jet sample, using $e\mu, ee + \mu\mu$ channels in 2 and 3 jet bins.
- Event level correlation between the jet flavors can be exploited to achieve greater precision.

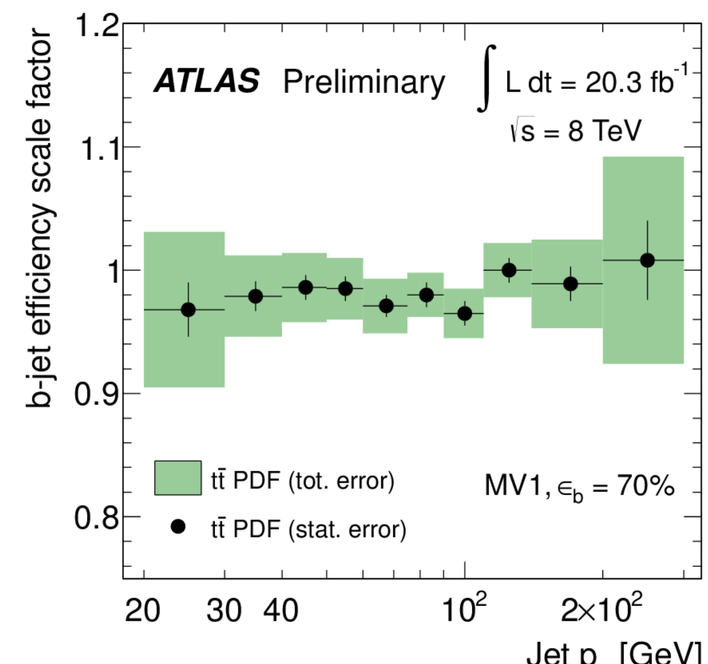
$$f_{2\ \mathrm{tags}} = f_{bb}\epsilon_b^2 + f_{bj}\epsilon_j\epsilon_b + \left(1 - f_{bb} - f_{bj}\right)\epsilon_j^2$$
$$f_{1\ \mathrm{tag}} = 2f_{bb}\epsilon_b(1-\epsilon_b) + f_{bj}\left[\epsilon_j(1-\epsilon_b) + \left(1-\epsilon_j\right)\epsilon_b\right] + \left(1 - f_{bb} - f_{bj}\right)2\epsilon_j(1-\epsilon_j)$$

- $\epsilon_b(\epsilon_j)$ is the $b$-jet (non $b$-jet) efficiency.
- $f_{bb}(f_{bj})$ is the fraction of events with a true $bb$ ($bj$) jet pair.

- $b$-tagging efficiency can be obtained by maximizing a likelihood function, taking both $f_{1\ \mathrm{tag}}$ and $f_{2\ \mathrm{tags}}$ from data, with $f_{bb}$, $f_{bj}$ and $\epsilon_j$ from simulation.




The total uncertainty on the scale factors is ~2% for jets with $p_T$ around 100 GeV for MV1 70% operating point.

https://cds.cern.ch/record/1743179

**ATLAS-CONF-2014-004**