Muon Reconstruction Performance in ATLAS at Run-II

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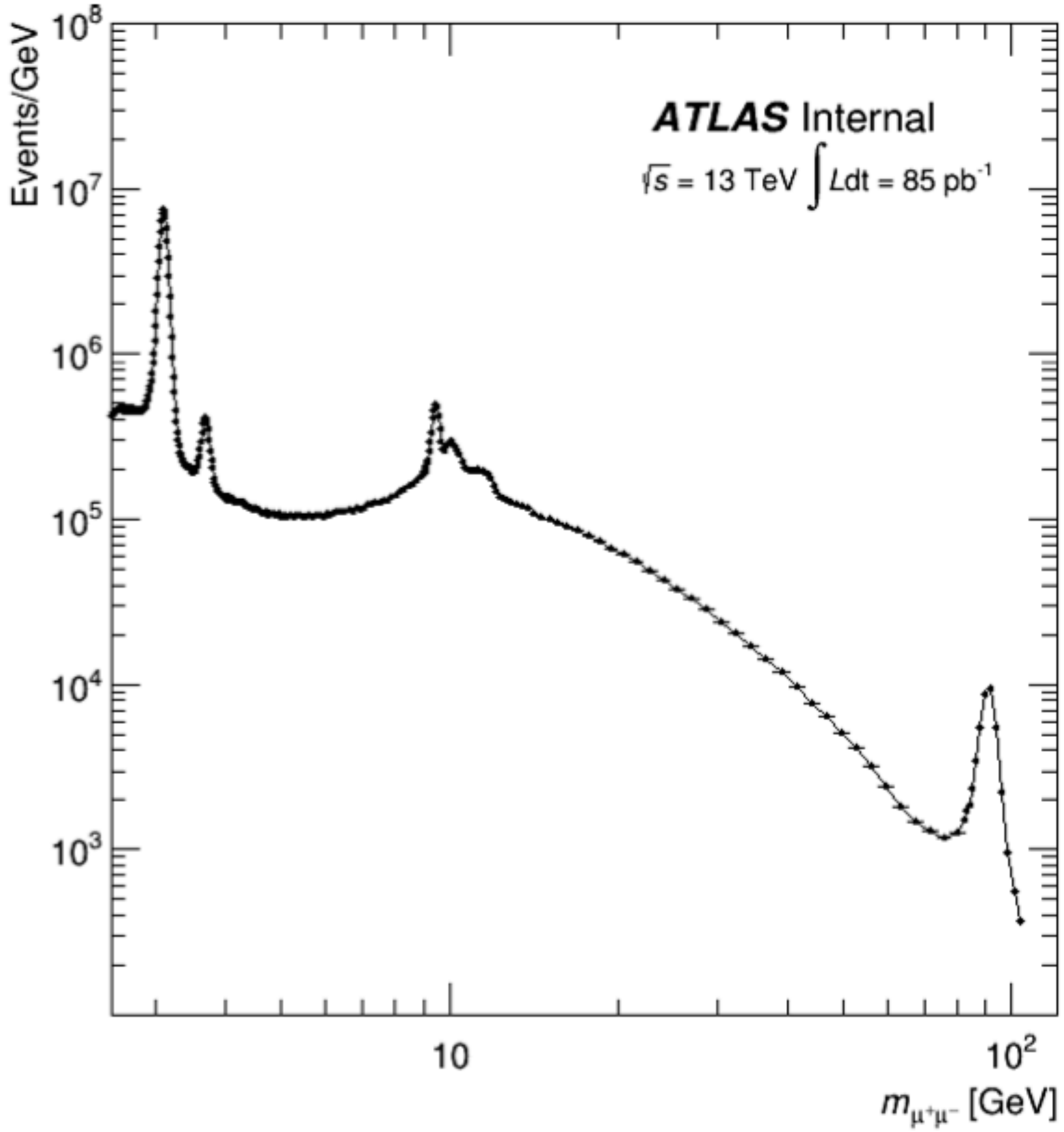
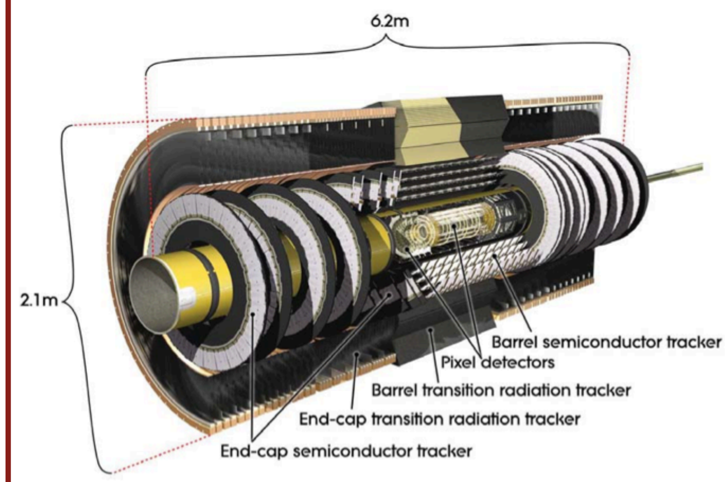
ICNFP 2015



- ATLAS Detector
- Muon Reconstruction
- Muon Reconstruction Efficiency
- Muon Isolation Efficiency
- Muon Momentum Scale and Resolution

Note: All plots in talk are from ATL-COM-MUON-2015-037 except where noted

Inner Detector



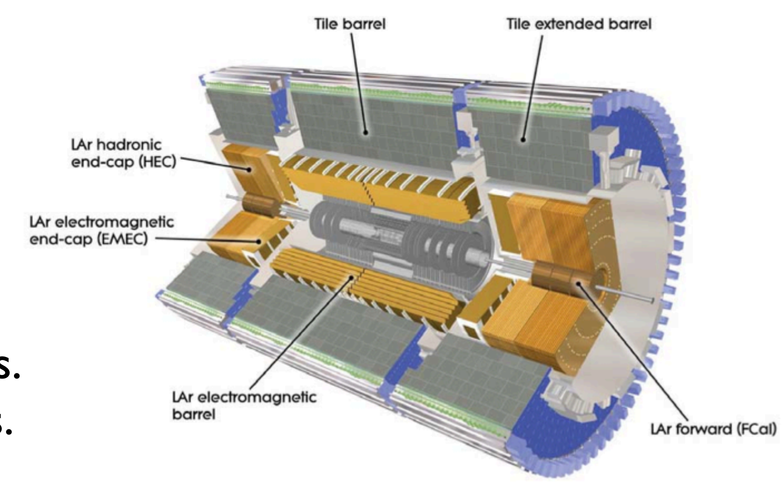
- Technologies:
  - Silicon Pixel $|\eta| < 2.5$
    - Insertable B Layer (IBL) added during LS1.
  - Semi-Conductor Tracker (SCT) $|\eta| < 2.5$
  - Transition Radiation Tracker (TRT) $|\eta| < 2.0$
- 2 T axial magnetic field for momentum measurements

Calorimetry

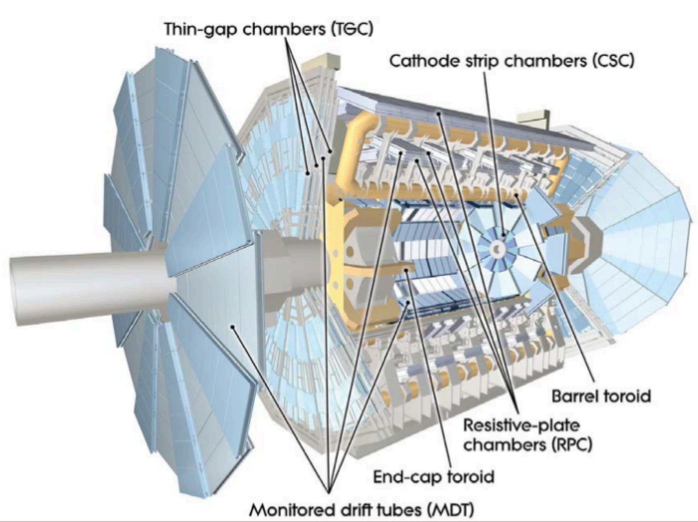
Electromagnetic:
- Sampling liquid-argon (LAr) calorimeter
- $|\eta| < 3.2$

Hadronic:
- Iron and scintillator tiles for $|\eta| < 1.5$
- LAr for larger η.

- Muon momentum measurement corrected for energy loss.
- Calo-tagged muons use energy deposits to identify muons.



Muon Spectrometer



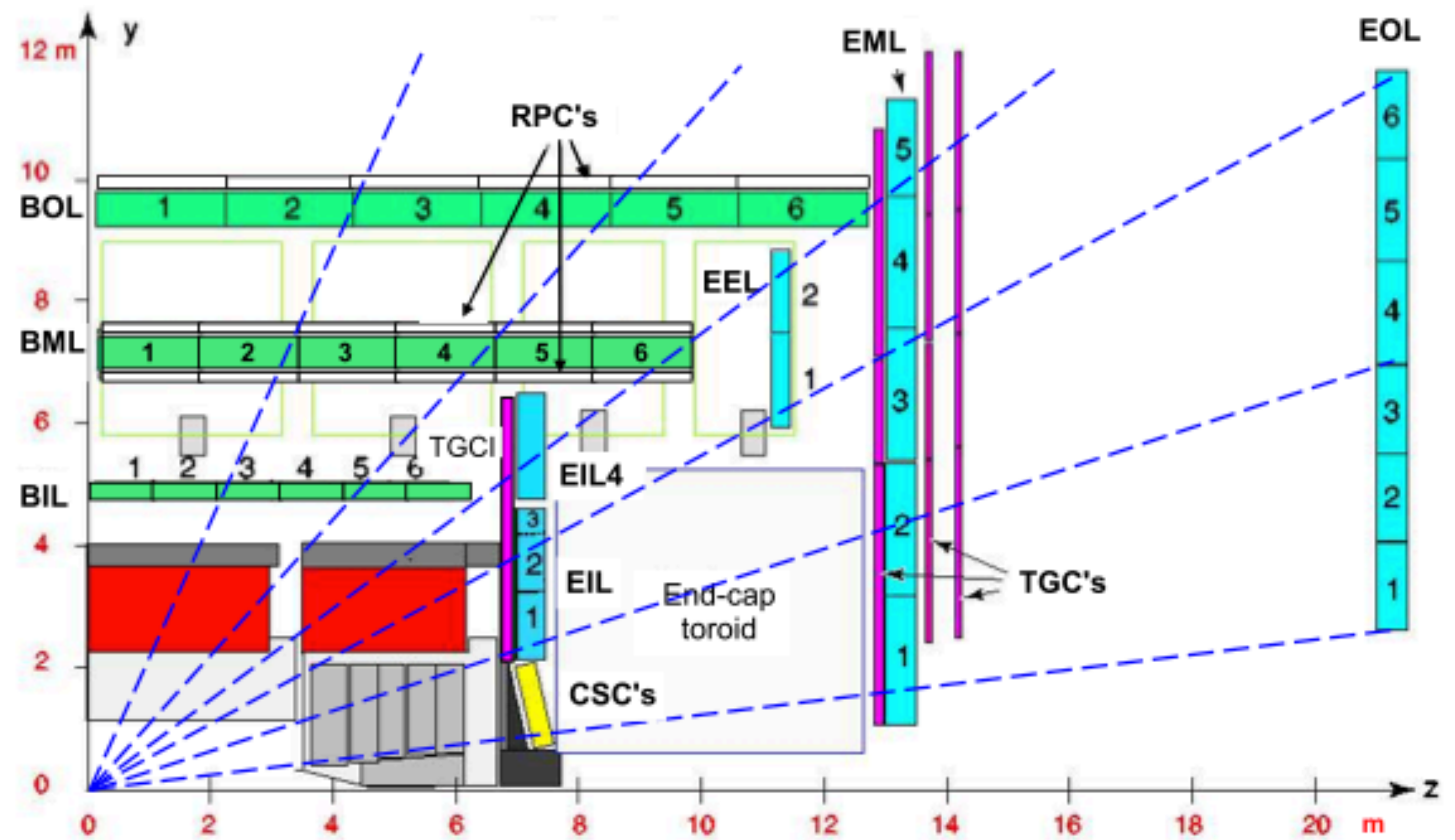
- Tracking for $|\eta| < 2.7$
- Barrel ($|\eta| < 1.05$) and two endcap sections.
- Three superconducting air-core toroids
  - Bending integral of 2.5 Tm in barrel
  - Bending integral up to 6 Tm in the end-caps.

Trigger Technologies

- Resistive Plate chambers (RPC)
  - Three doublet layers
  - $|\eta| < 1.05$
- Thin Gap Chambers (TGC)
  - Three triplet and doublet layers
  - $1.0 < |\eta| < 2.4$

Precision Technologies

- Monitored Drift Tubes (MDT)
  - Three layers each in barrel and endcap
  - Give 6-8 η measurements per chamber
  - $|\eta| < 2.7$
- Cathode Strip Chambers (CSC)
  - Inner layer with $|\eta| > 2$



LS1 Changes

- Added last missing chambers in transition region ($1.0 < |\eta| < 1.4$)
- Four RPC-equipped MDT chambers were installed in the feet region at the base of detector. (elevator chambers)
- Some of the new MDT chambers built with smaller radius allowing to cope with higher rates.

Combined (CB)

- ID track + MS track
- 96% of muons

Standalone (SA)

- MS track only
- $2.5 < |\eta| < 2.7$

Segment-tagged (ST)

- ID track + MS track segment
- Low Pt and special regions

Calo-tagged (CT)

- ID track + calorimeter energy deposit
- $|\eta| < 0.1$ and $25 < P_T < 100$ GeV

LS1 Changes

- CLHEP → Eigen for Linear Algebra Libraries has sped up reconstruction.
- Hough transform has been added to identify hit patterns to seed segment finding alg and reduce combinatorics.
- Energy loss calc has been improved with more detailed description of geometry to derive an analytic parameterization of energy loss.

Loose

- Maximize the reconstruction efficiency
- Uses all four types
- Optimized for reconstructing Higgs boson candidates in four lepton final state.
- CT and ST are restricted to $|\eta| < 0.1$ (MS is only partially instructed for cabling and services)
- SA muons are deployed between $2.5 < |\eta| < 2.7$ to extend acceptance outside the ID geometrical coverage.

Medium

- Default
- Minimize systematic uncertainties with reconstruction and calibration.
- SA: ≥ 3 prec hits in each of three layers of MDT and are employed only in $2.5 < |\eta| < 2.7$ region.
- CB: ≥ 3 hits on at least two layers of MDT except for $|\eta| < 0.1$ region where ≥ 3 in single MDT layer allowed.
- 1/p measurements in ID and MS must be compatible.

Tight

- Minimize rate of fake muons
- CB with tighter cuts on 1/p compatibility.
- Extra cut on normalized chi-squared combined track fit.

High P_T

- Maximize resolution for $P_T > 100$ GeV
- CB Medium, ≥ 3 MDT hits
- Specific regions of MS where alignment is preliminary are vetoed as precaution (i.e. new chambers)

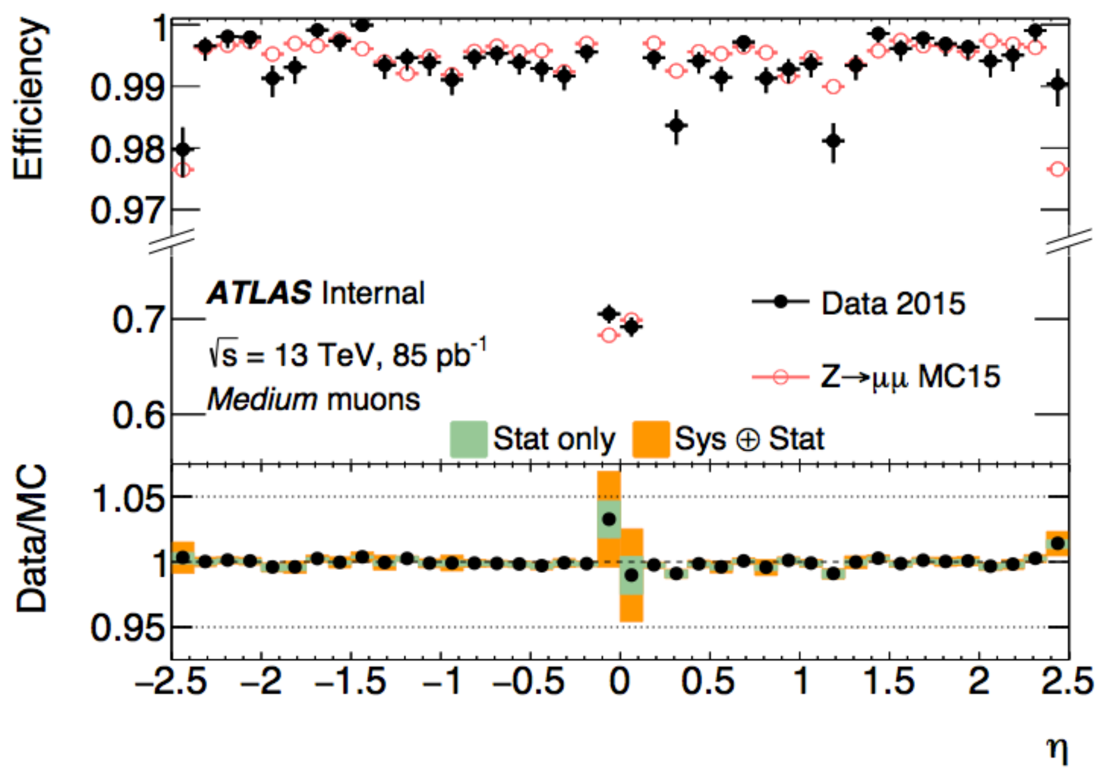
$Z \rightarrow \mu\mu$

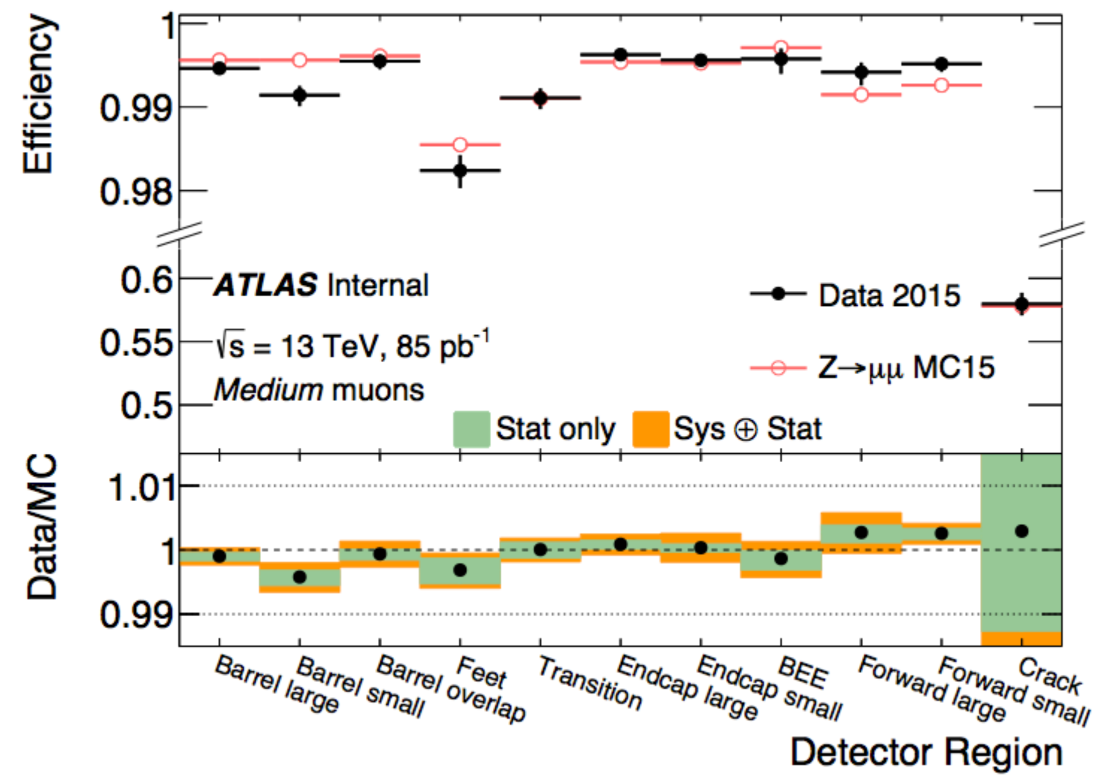
- Opposite charge
- $m_{\mu\mu}$ within 10 GeV of Z boson mass.
- Back to back ($\Delta\phi > 2$)
- Tag is isolated
- Tag with $P_T > 28$ GeV triggered event
- Probe is Calo-tagged muon with $P_T > 10$ GeV

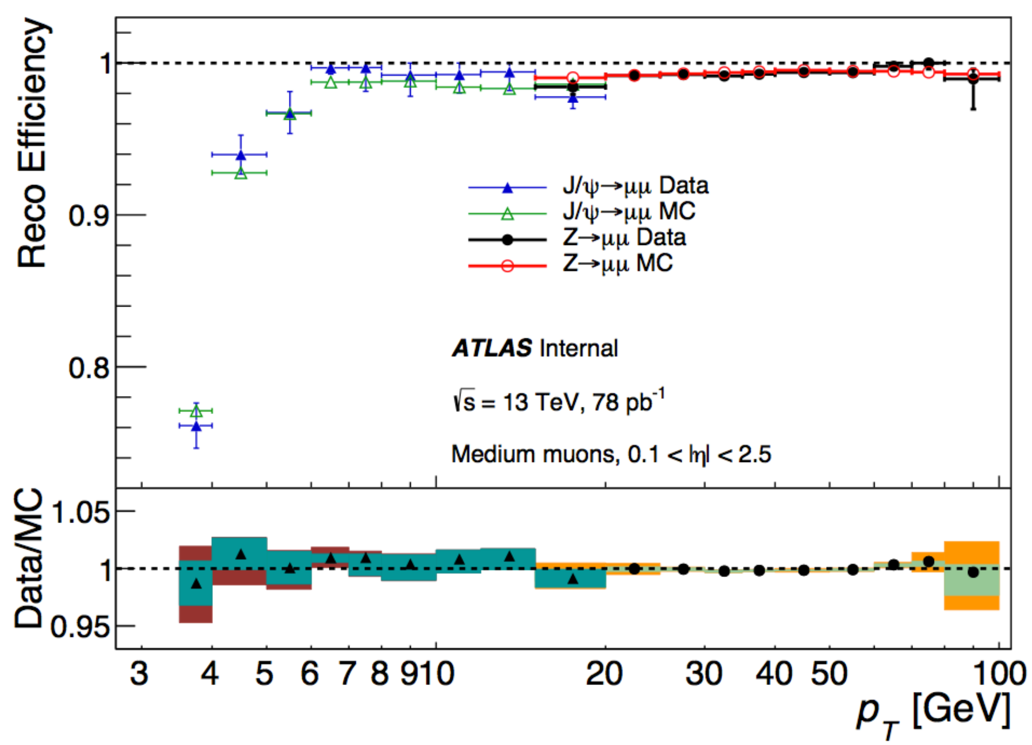
$J/\psi \rightarrow \mu\mu$

- Abundance of muons with $P_T < 20$ GeV
- Opposite charge
- 2.7 GeV $< m_{\mu\mu} <$ 3.5 GeV
- Tag with $P_T > 4$ GeV triggered event
- Probe is ID track with $P_T > 2.5$ GeV

- Probe is successful reconstructed if reco muon is found within ΔR of 0.05 around the probe track
- Measured Efficiencies are corrected for the efficiency of ID track reconstruction, using SA MS tracks as probe muons.
- Yields 50k (750k) $Z \rightarrow \mu\mu$ ($J/\psi \rightarrow \mu\mu$) events
- SF formed to correct simulation.
- Systematic uncertainty dominated by:
  - the normalization of background extracted from data
  - possible dependence of SF on muon charge.

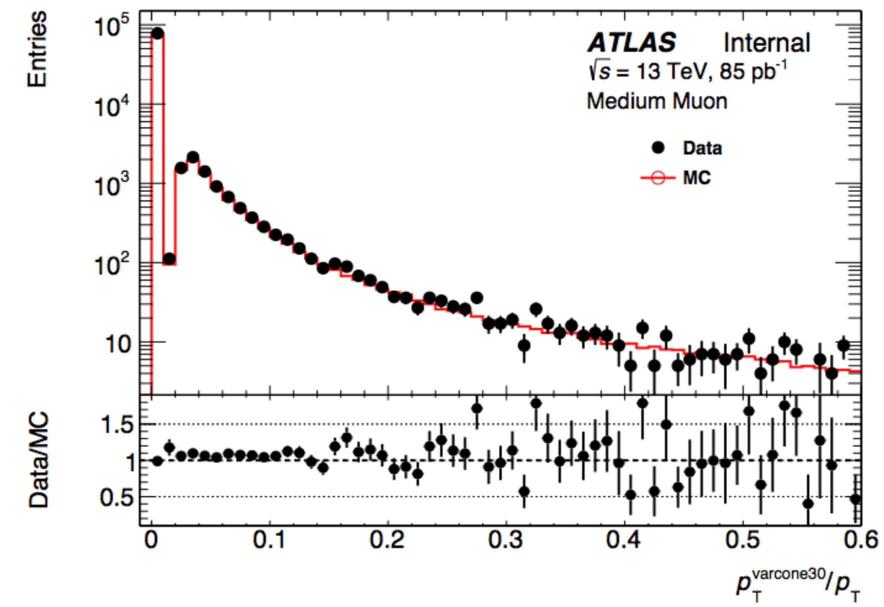

Efficiency
ATLAS Internal
√s = 13 TeV, 85 pb-1
Medium muons
Data 2015
Z→μμ MC15
Stat only
Sys ⊕ Stat
Data/MC
η


Efficiency
ATLAS Internal
√s = 13 TeV, 85 pb-1
Medium muons
Data 2015
Z→μμ MC15
Stat only
Sys ⊕ Stat
Data/MC
Barrel large
Barrel small
Barrel overlap
Feet
Transition
Endcap large
Endcap small
BEE
Forward large
Forward small
Crack
Detector Region


Reco Efficiency
J/ψ→μμ Data
J/ψ→μμ MC
Z→μμ Data
Z→μμ MC
ATLAS Internal
√s = 13 TeV, 78 pb-1
Medium muons, 0.1 < |η| < 2.5
Data/MC
pT [GeV]

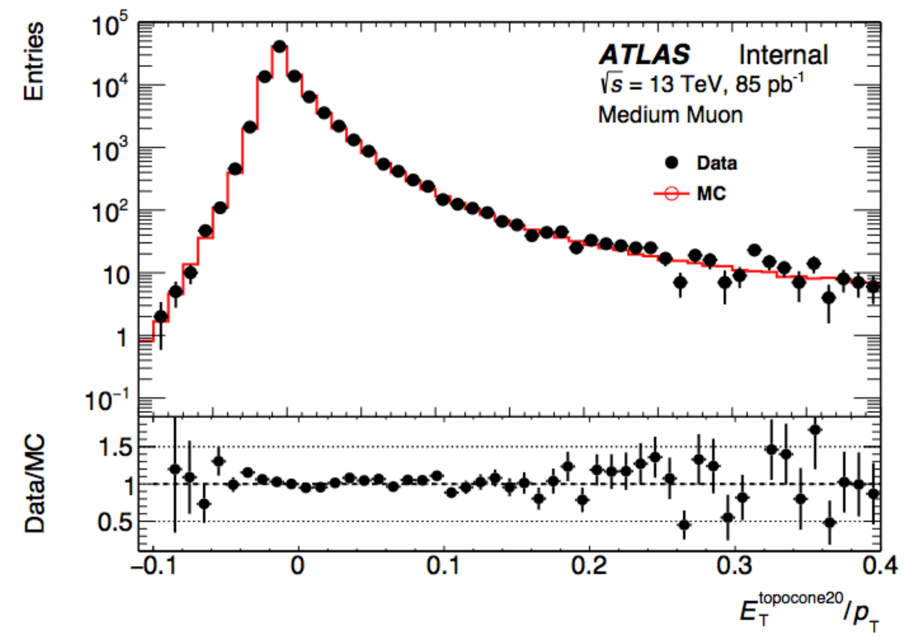
Track-based isolation ($P_T^{varcone30}$)

- Sum of the transverse momenta of the tracks in a cone of ΔR = 10 GeV/$P_{T,\mu}$ around the muon excluding the muon-track itself with maximum cone size = 0.3
- The P_T dependence improves performance for muons from boosted decays.
- Tracks considered in sum must:
  - originate from PV associated to muon track
  - P_T > 1 GeV
  - At least 9 (11) silicon hits if in |η| < (>) 1.65
  - d_0 < 3 mm.



Calorimeter-based isolation ($E_T^{topocone20}$)

- Sum of energies of the topological clusters around muon in a cone of radius ΔR = 0.2
- Clusters within a smaller ΔR = 0.1 are excluded to remove energy deposit from muon itself.
- Sum is corrected for pileup using ambient energy density computed event by event.



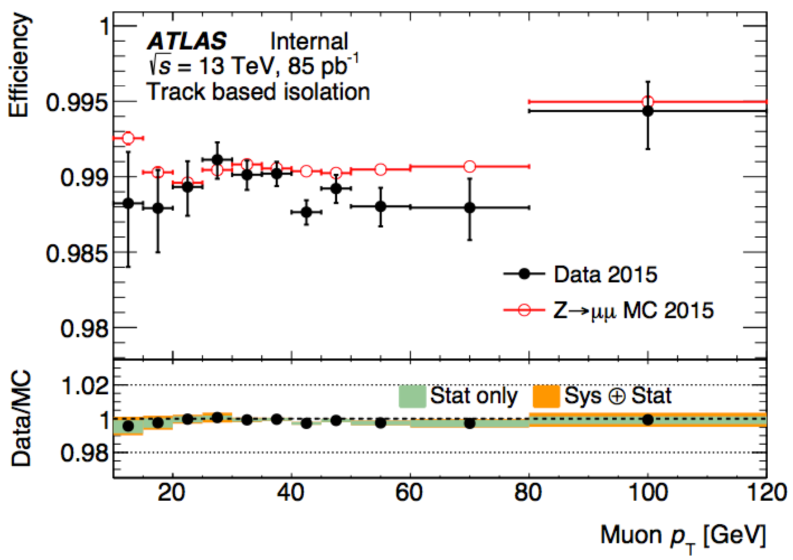
Note: Isolation studies performed on Z→μμ decays

Muon Isolation

- Isolation SFs defined as ratio between data/MC for five sets of isolation working points. (Each tuned to needs of physics analyses.)
- Track based isolation WP is defined by cuts on the relative track-based iso var.
- The other WP are defined by cuts applied separately on both relative iso variables.
- All cuts are tuned as a function of the η and P_T of the muon to obtain uniform performance.

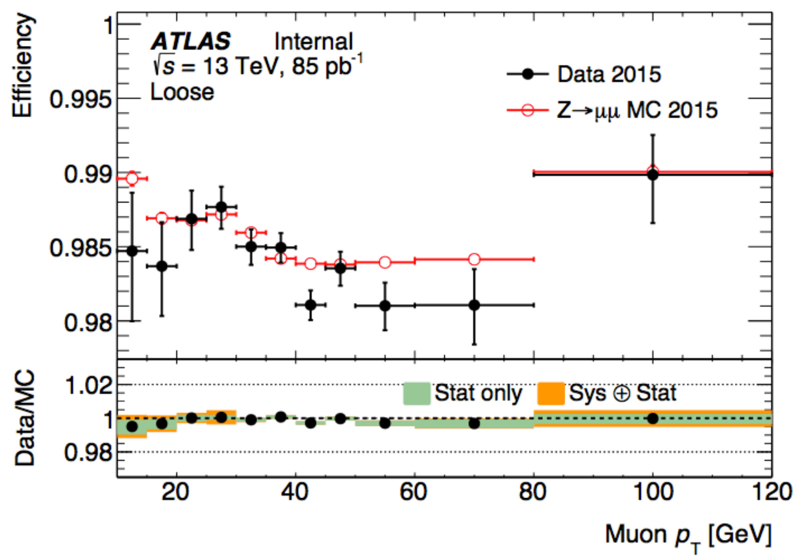
Track based isolation

- Target efficiency: ≥ 99%



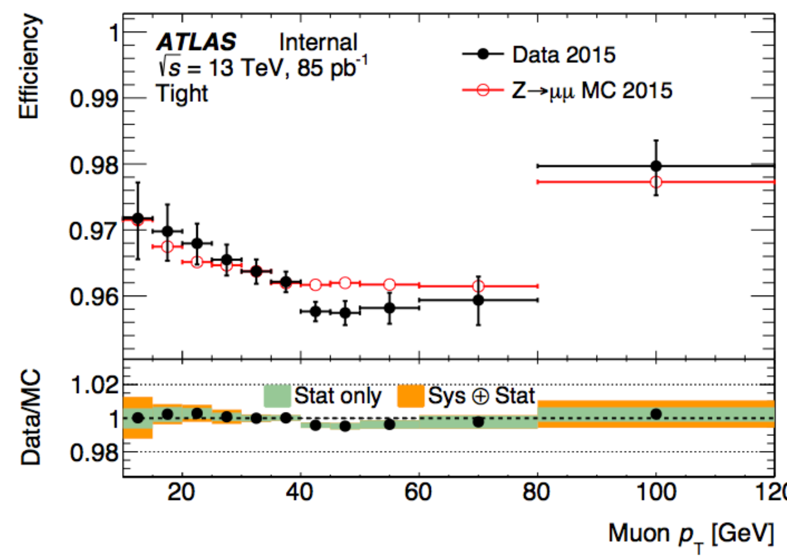
Loose

- Target efficiency: 99%



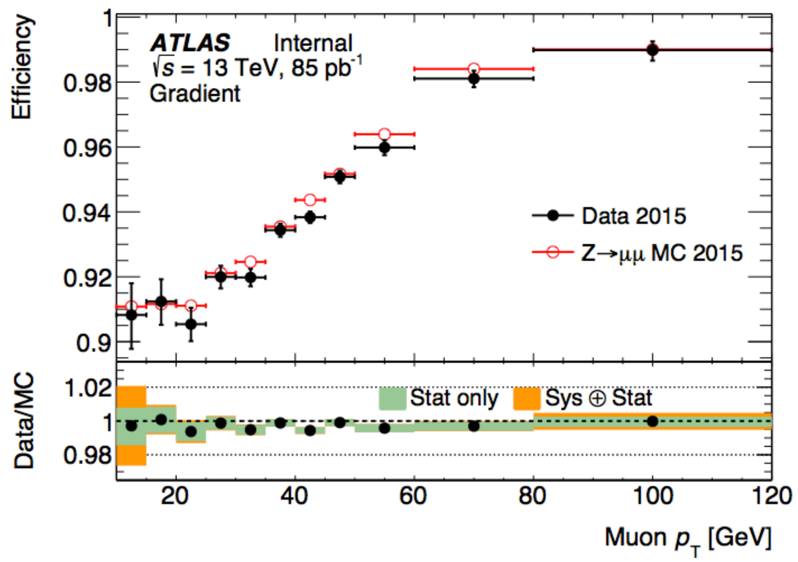
Tight

- Target efficiency: 95%



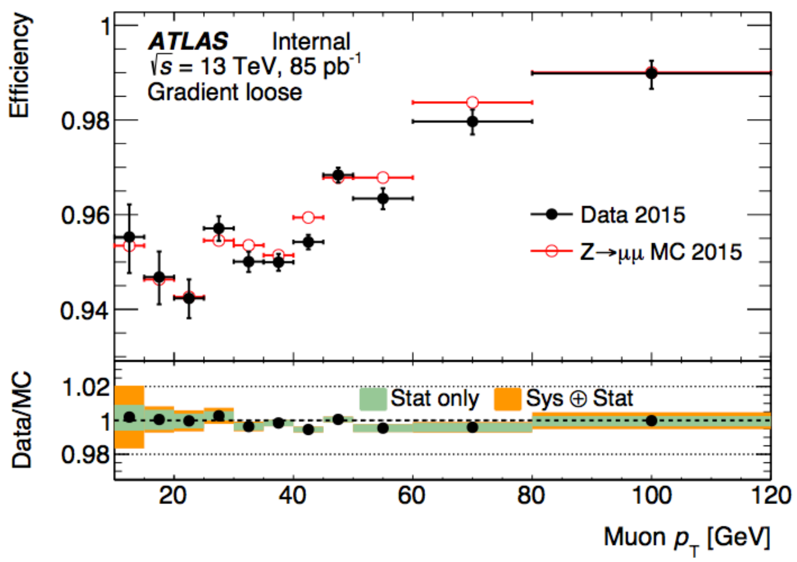
Gradient

- Target efficiency: 90% at 25 GeV
- Target efficiency: 99% at 60 GeV



Gradient Loose

- Target efficiency: 95% at 25 GeV
- Target efficiency: 99% at 60 GeV



- Systematic uncertainties on SF estimated by varying the selection criteria and background contribution within the uncertainties (cut on Z mass window, isolation of tag muon, min quality of the probe, dR between two muons and the bkgd contribution.)
- Largest arises from mass window cut in low Pt region (more bkgd) whereas high Pt is dominated by stat and systematics due to condition of dR between muons.

Muon Momentum Scale and Resolution

$$p_{\mathrm{T}} = \frac{\widetilde{p_{\mathrm{T}}} + (s_0 + s_1 \cdot \widetilde{p_{\mathrm{T}}})}{1 + \mathcal{N}(\alpha;0,1) \cdot \sqrt{(\Delta r_0/\widetilde{p_{\mathrm{T}}})^2 + \Delta r_1^2 + (\Delta r_2 \cdot \widetilde{p_{\mathrm{T}}})^2}}$$

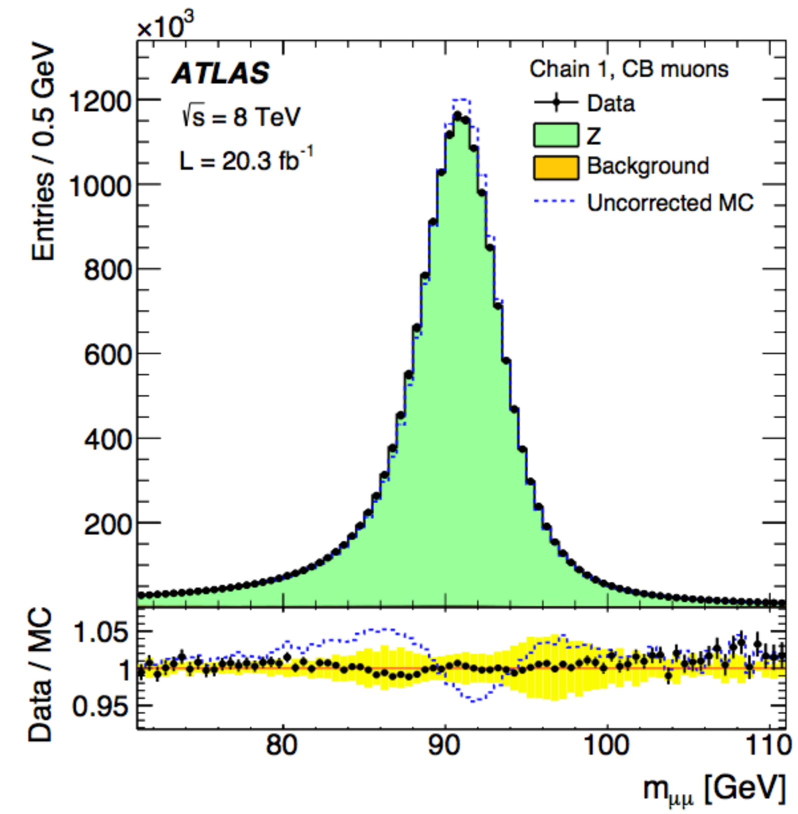
- α is a random variable distributed according to a normal distribution $\mathcal{N}(\mu=0,\sigma=1)$.
- Momentum scale:
  - s_0 corrects for energy loss in material, (MS only)
  - s_1 corrects for radial distortions or mismodeling of magnetic field integral.
- Momentum resolution residual dependence.
  - Δr_0 energy loss fluctuations in traversed material (MS only)
  - Δr_1 models multiple scattering, local magnetic field distortions, and local radial distortions.
  - Δr_2 models the instrinsic resolution effects and residual detector misalignment.
- Corrections are derived separately for the ID and MS muon momentum measurements.

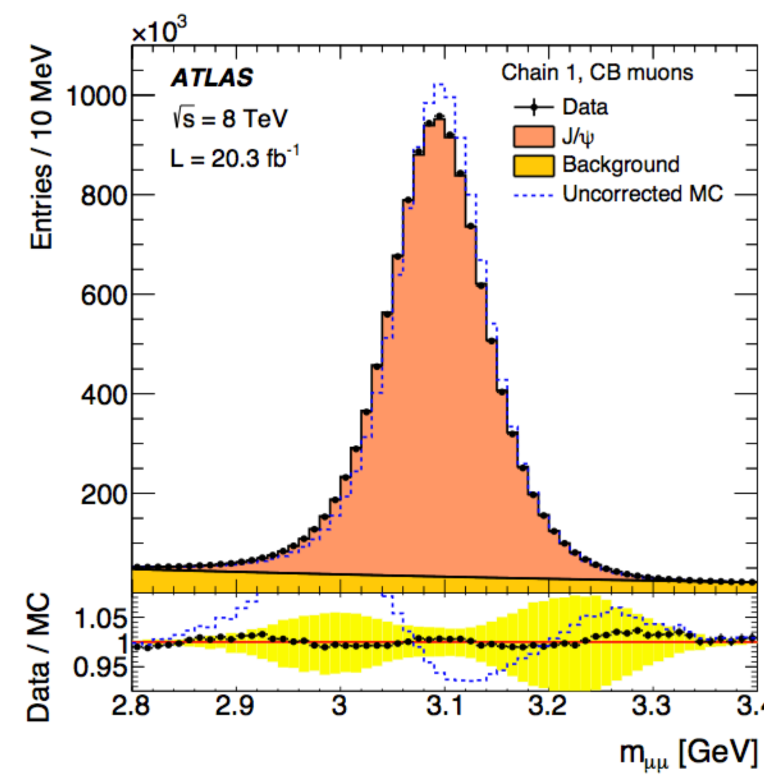
$$p_{\mathrm{T}}^{\mathrm{CB}} = f \cdot p_{\mathrm{T}}^{\mathrm{ID}} + (1 - f) \cdot p_{\mathrm{T}}^{\mathrm{MS}}$$

- f is derived from the relative weight of each momentum measurement to the CB measurement of P_T

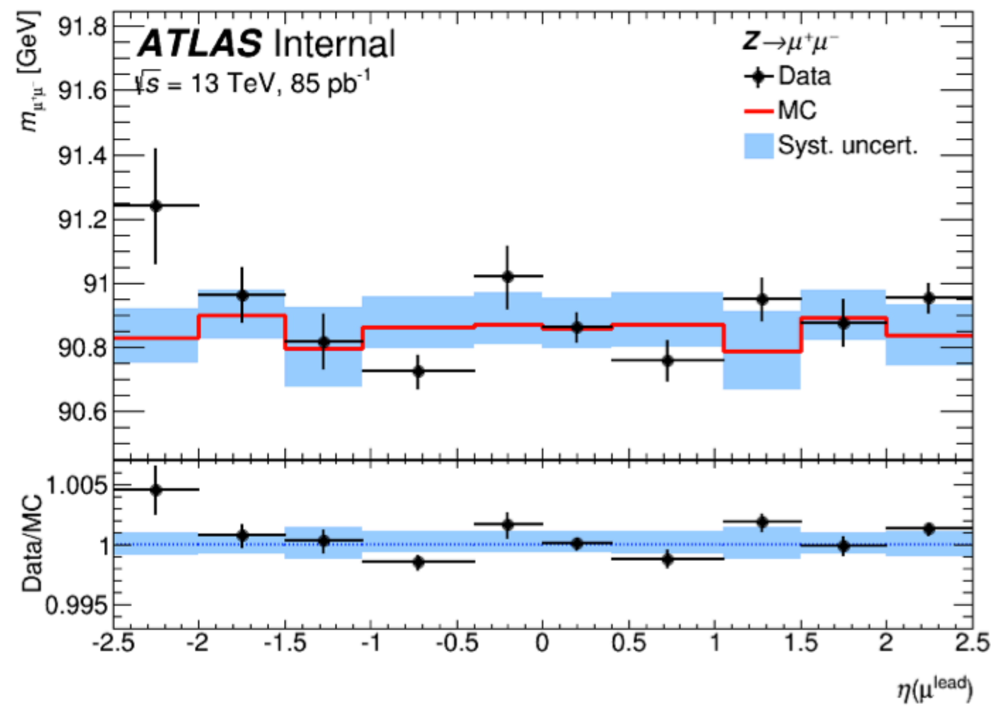
Muon Momentum Scale and Resolution

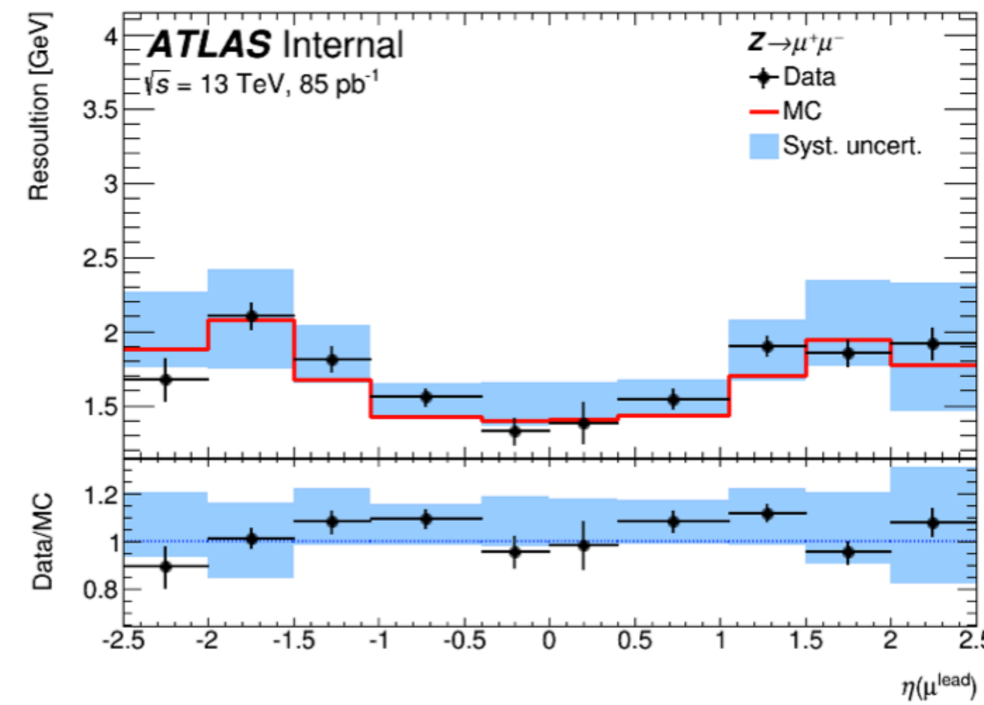
- Momentum corrections are extracted by a template-based likelihood fit from Z→μμ and J/ψ→μμ decays.
- Dimuon pair selection:
  - Two opposite charge muons
  - $|\eta| < 2.5$
  - Medium
- Muons from Z→μμ dominate the high P_T region (> 20 GeV)
  - 75 GeV < $m_{\mu\mu}$ < 105 GeV
- Muons from J/ψ→μμ provide calibration for lower momenta (5 GeV < P_T < 20 GeV)
  - 2.4 GeV < $m_{\mu\mu}$ < 3.6 GeV
- Bulk of corrections are determined from 5 fb^{-1} of 2012 data reconstructed with 2015 software.
- Residual data-to-simulation mismodelling between 2012 and 2015 is corrected using 85 pb^{-1} of 2015 pp collisions.
- Corrections validated by fitting the invariant mass spectrum of muons from J/ψ and Z decays to a parametric PDF and then comparing the fits of data and corrected MC.
- Mass spectrum modeled by a convolution of many PDFs

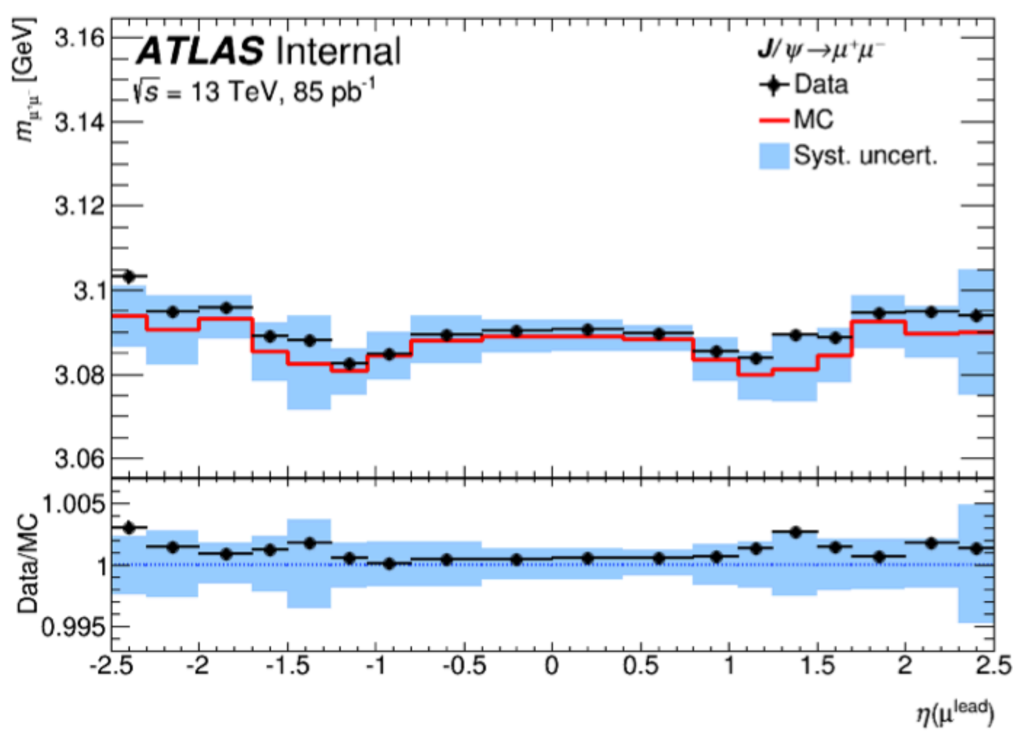


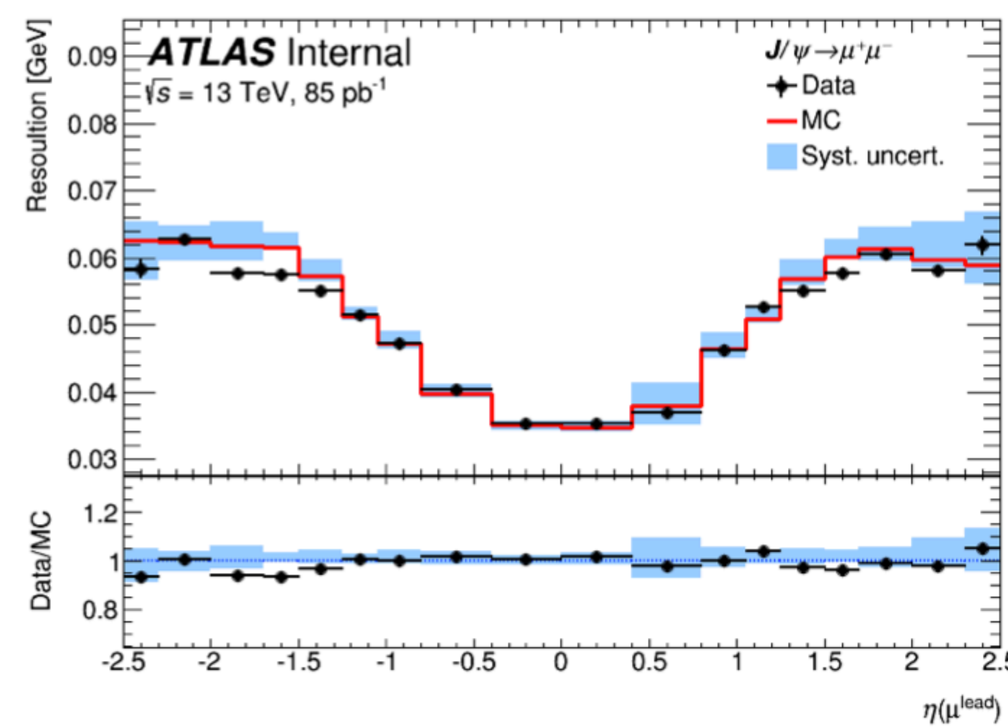


Note: Plots from Eur. Phys. J. C74.11 (2014) 3130


ATLAS Internal
√s = 13 TeV, 85 pb-1
Z→μ+μ-
Data
MC
Syst. uncert.
m_μ+μ- [GeV]
Data/MC
η(μlead)


ATLAS Internal
√s = 13 TeV, 85 pb-1
Z→μ+μ-
Data
MC
Syst. uncert.
Resoultion [GeV]
Data/MC
η(μlead)


ATLAS Internal
√s = 13 TeV, 85 pb-1
J/ψ→μ+μ-
Data
MC
Syst. uncert.
m_μ+μ- [GeV]
Data/MC
η(μlead)


ATLAS Internal
√s = 13 TeV, 85 pb-1
J/ψ→μ+μ-
Data
MC
Syst. uncert.
Resoultion [GeV]
Data/MC
η(μlead)

Backup

Muon Momentum Scale and Resolution PDFs

Crystal Ball

- Gaussian component estimates detector resolution.
- Exponential component approximates the residual energy loss of the muon from traversing material.

Breit-wigner

- Accounts for large width of Z
- Mean fixed to Crystal Ball mean
- Width fixed to Z width

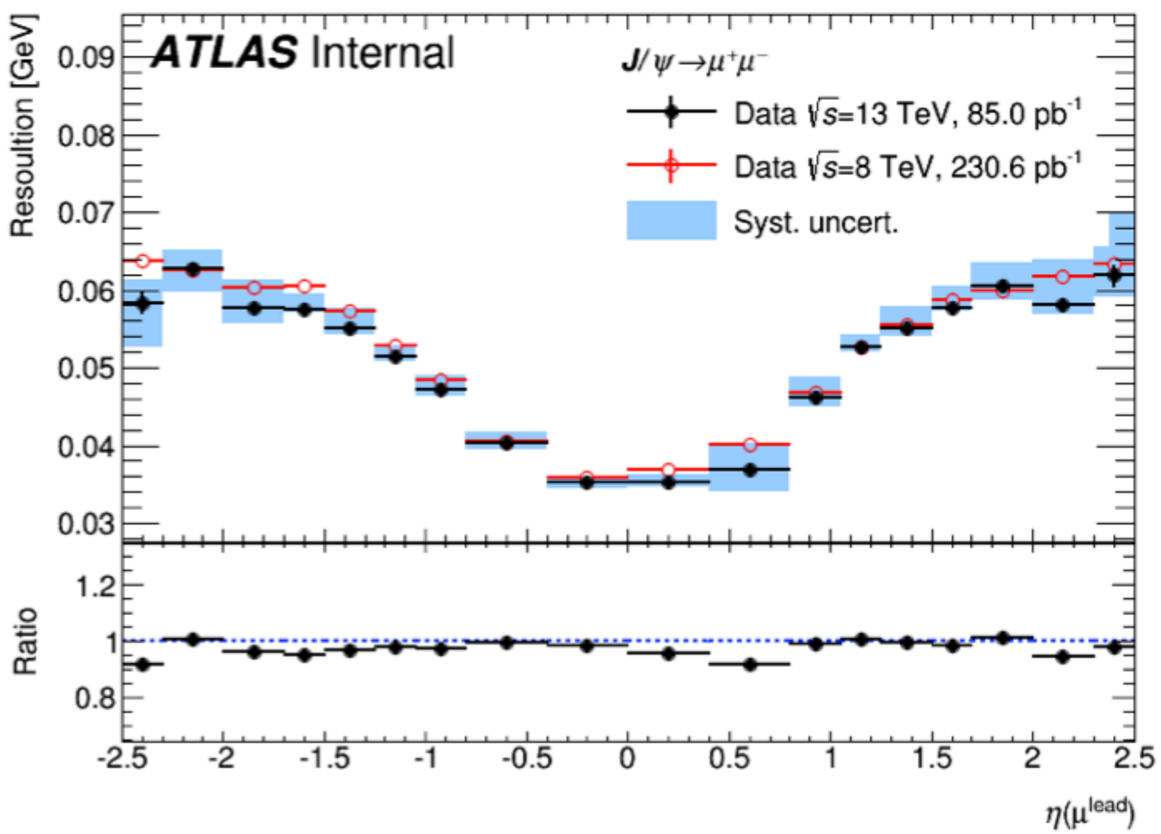
Gaussian

- Accounts for residual resolution effects
- Amplitude and resolution estimated from sim as a function of leading muon η.

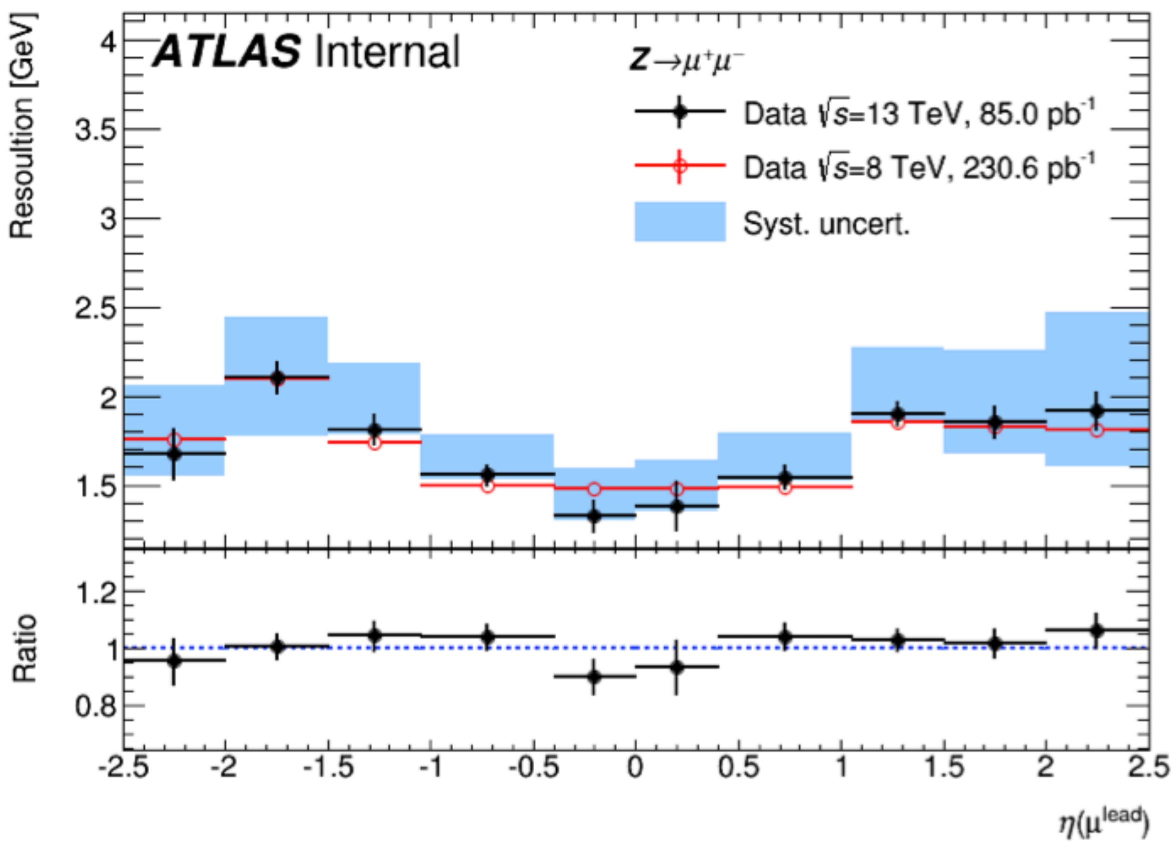
Exponential

- Used with $J/\psi \rightarrow \mu\mu$ decays to account for non-negligable fraction of combinatorial background.

2012 vs 2015

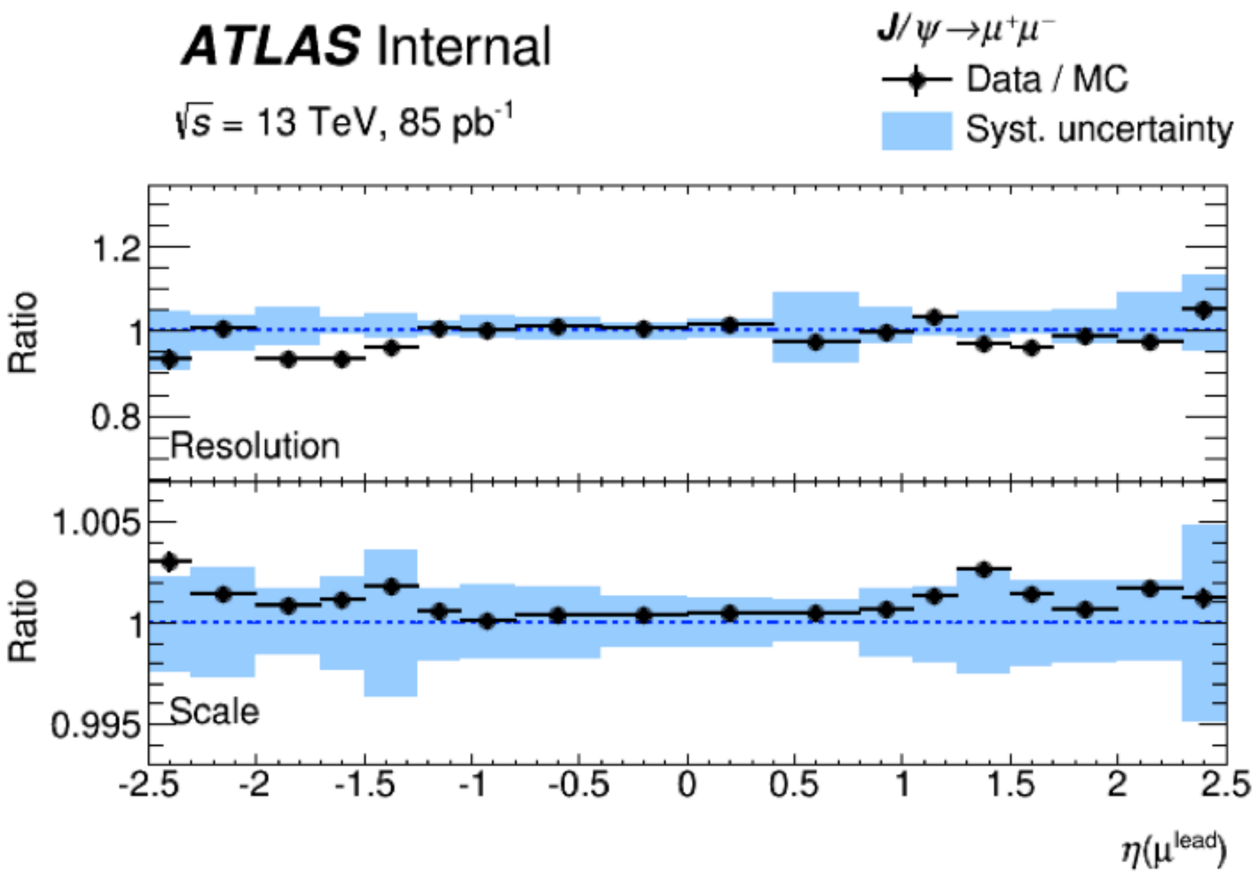


ATLAS Internal
J/ψ→μ⁺μ⁻
Data √s=13 TeV, 85.0 pb⁻¹
Data √s=8 TeV, 230.6 pb⁻¹
Syst. uncert.
Resoultion [GeV]
Ratio
η(μ^lead)

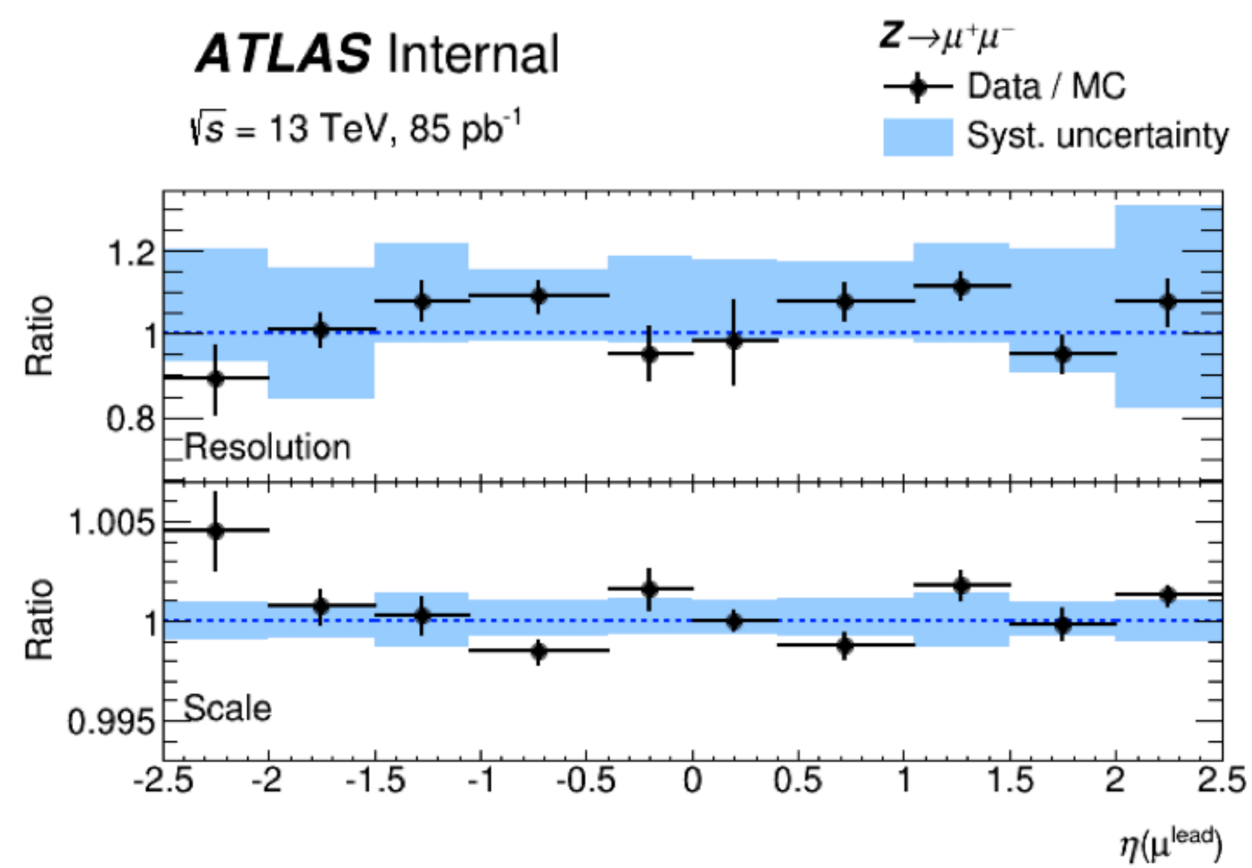


ATLAS Internal
Z→μ⁺μ⁻
Data √s=13 TeV, 85.0 pb⁻¹
Data √s=8 TeV, 230.6 pb⁻¹
Syst. uncert.
Resoultion [GeV]
Ratio
η(μ^lead)

Ratio Plots



ATLAS Internal
$\sqrt{s}$ = 13 TeV, 85 pb^{-1}
$J/\psi \to \mu^+\mu^-$
Data / MC
Syst. uncertainty
Ratio
Resolution
Scale
$\eta(\mu^{lead})$



ATLAS Internal
$\sqrt{s}$ = 13 TeV, 85 pb^{-1}
$Z \to \mu^+\mu^-$
Data / MC
Syst. uncertainty
Ratio
Resolution
Scale
$\eta(\mu^{lead})$