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Muon identification and performance in the ATLAS experiment

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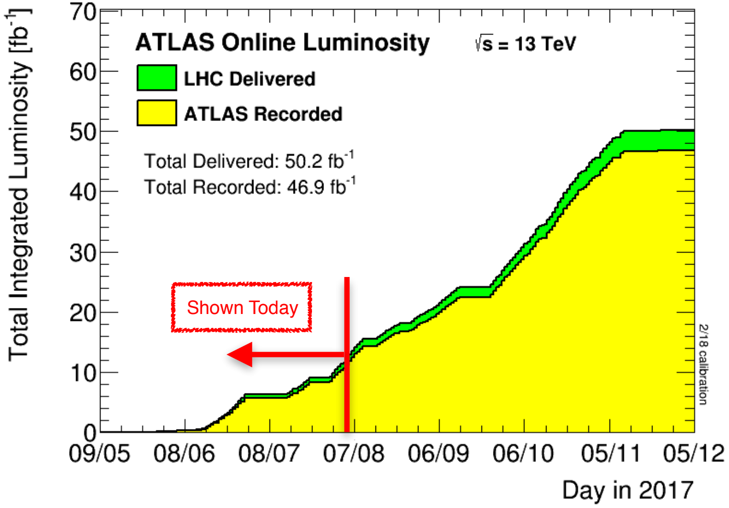
UBC

Outline

- Muon Reconstruction & Identification
- Efficiency
  - Reconstruction
  - Isolation
- Momentum Scale & Resolution
- Conclusions

Data & Monte Carlo Samples

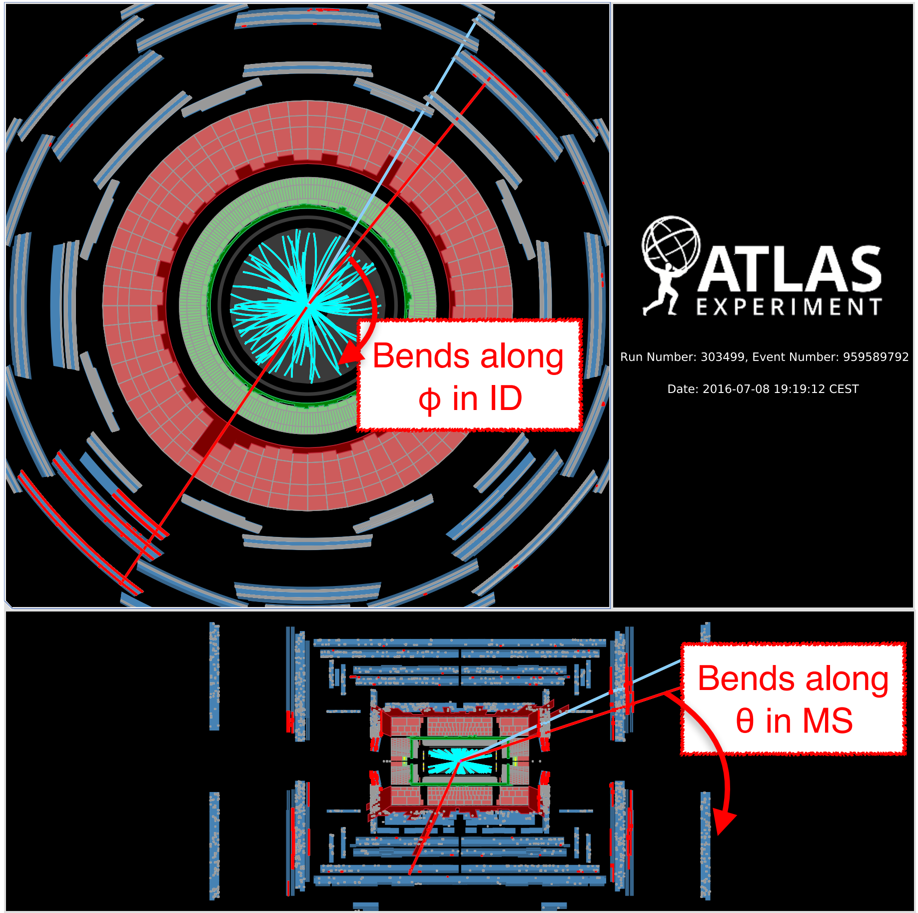
- Shown today: Run 2 pp collision data at $\sqrt{s}$ = 13 TeV
  - 2017: 15.4 fb^{-1} (partial dataset)
  - 2016: 33.3 fb^{-1} (full dataset)
  - 2015: 3.2 fb^{-1} (full dataset)
- Efficiency of detector high and taking 93.6% good physics data
- Use Z —> μμ and J/ψ —> μμ events to study detector performance
- Monte Carlo using GEANT4 for detector simulation
- More Details:
  - Muon Combined Performance (MCP): [Public Plots]
  - Early Run 2 MCP Paper: [Eur. Phys. J. C 76 (2016) 292]
  - Run 1 MCP Paper: [Eur. Phys. J. C 74 (2014) 3130]



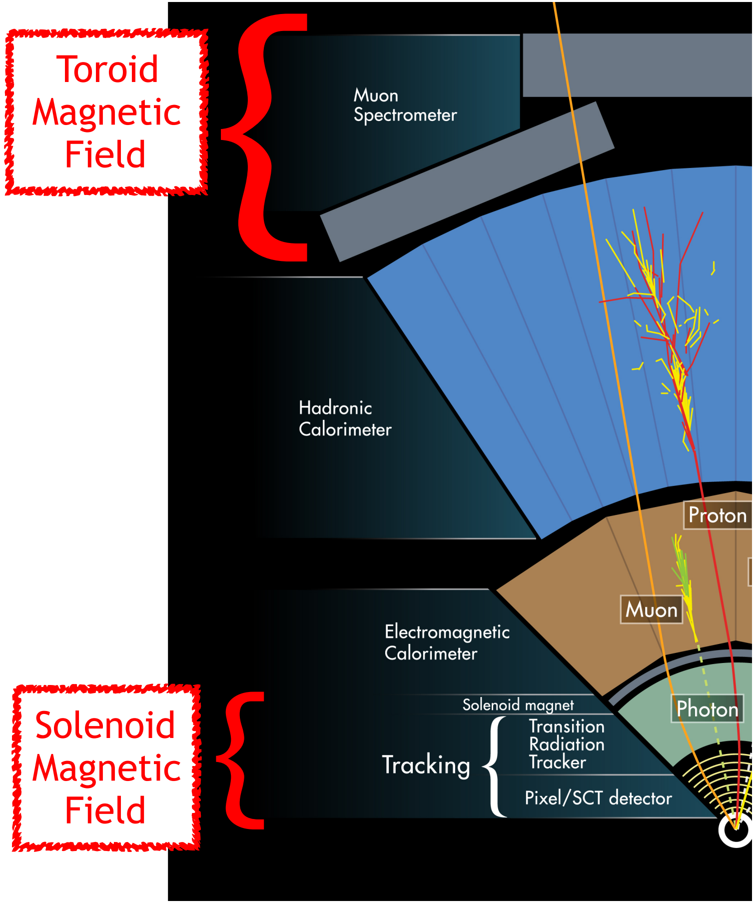
ATLAS Muon Reconstruction Basics

- From the track fit, get M = (d_0, z_0, ϕ, θ, q/p)
- Inner Detector (ID) track has very precise hits close to the Interaction Point (IP), which helps to constrain d_0/z_0 and angles
- Muon Spectrometer (MS) track has better q/p resolution at high-p_T due to longer lever arm
- Combining ID and MS hits guarantees the best p_T determination

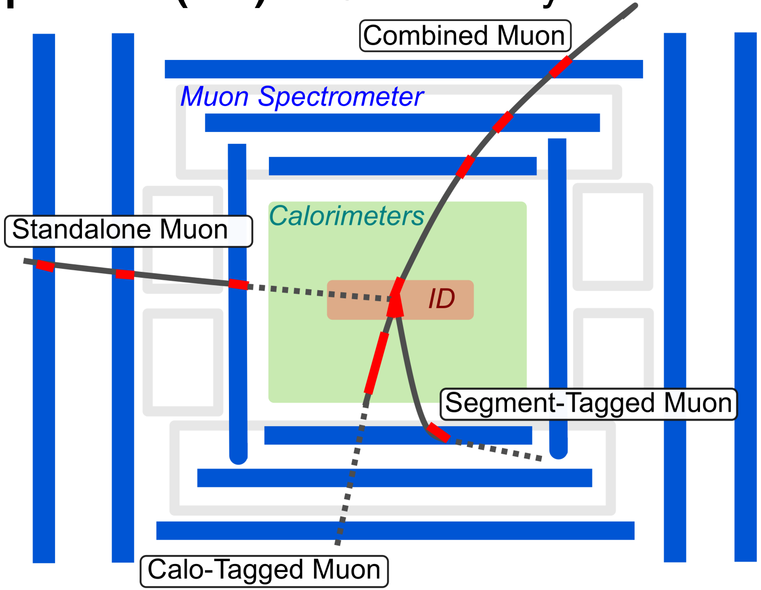
$$p_T = p \sin\theta = \frac{\sin\theta}{|q/p|}$$



Muon Reconstruction Algorithms



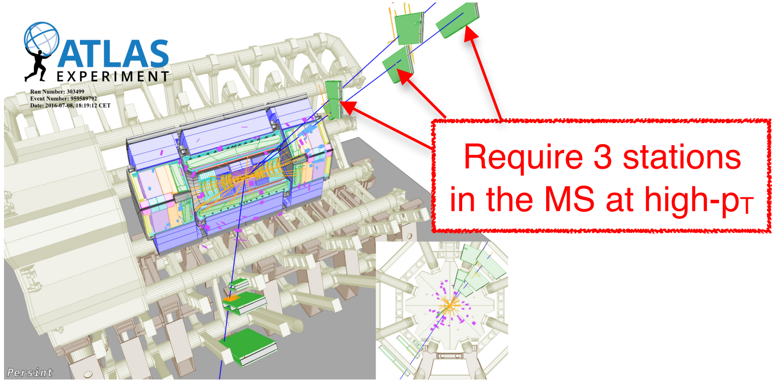
- **Combined (CB):** Global refit of ID + MS tracks
- **Segment-tagged (ST):** Track fit of ID + MS segment
- **Calorimeter-tagged (CT):** Track fit of ID + energy deposit in the calorimeter
- **Extrapolated (ME):** MS track only



Working Points

- **Loose:** Maximize reconstruction efficiency; uses all muon types
- **Medium:** Default selection for ATLAS; uses CB & ME muons
- **Tight:** Maximize purity; uses only CB & ME muons
- **Low-p_T:** Maximize efficiency and fake-rejection for $p_T < 5$ GeV
- **High-p_T:** Maximize momentum resolution for $p_T > 100$ GeV
- Optimization is on-going: Public results for high-p_T and low-p_T working points expected this summer

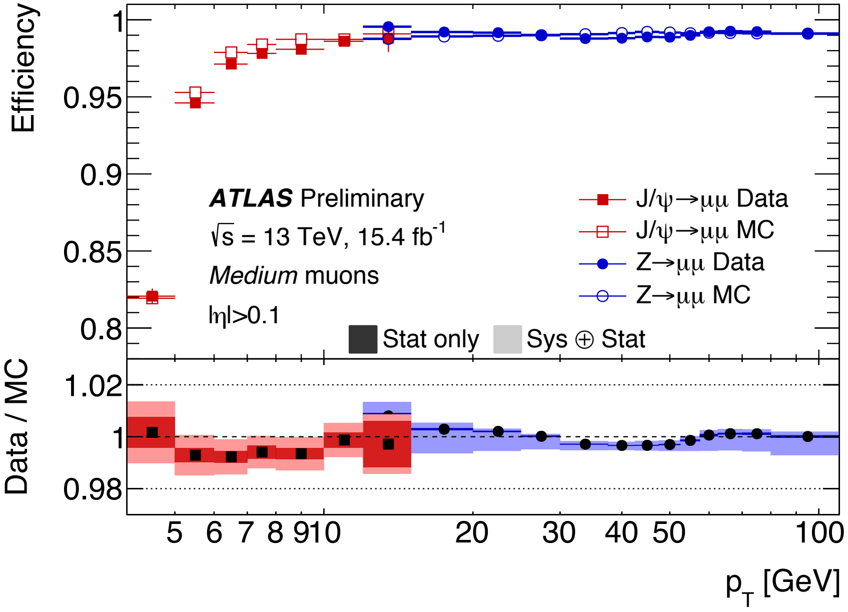
	$4 < p_T < 20$ GeV		$20 < p_T < 100$ GeV	
Selection	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11
High-p_T	78.1	0.26	80.4	0.13



Reconstruction Efficiency

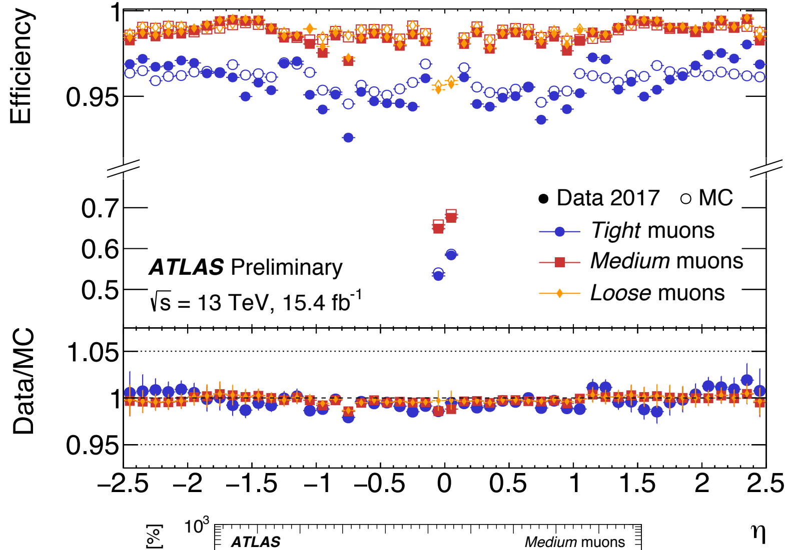
$$\epsilon(\mathrm{X}) = \epsilon(\mathrm{X}|\mathrm{ID}) \cdot \epsilon(\mathrm{ID}) = \epsilon(\mathrm{X}|\mathrm{CT}) \cdot \epsilon(\mathrm{ID}|\mathrm{MS}),\ (\mathrm{X} = \mathrm{Medium/Tight/High}\text{-}\mathrm{p_T})$$

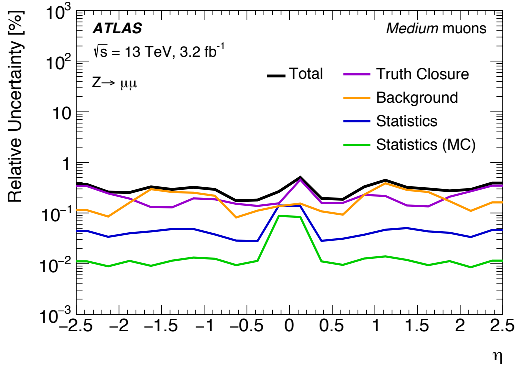
- Tag & Probe Method:
  - Use high-statistics samples of Z and J/ψ resonances
  - Tag: Medium muon that fires the trigger
  - Probe: Reconstructed by a system independent of the one being studied (e.g. calorimeter)
- Reconstruction efficiency ~99% for $p_T > 10$ GeV
- Error bars on efficiencies indicate statistical uncertainty
- Good data/MC agreement overall



Reconstruction Efficiency (continued)

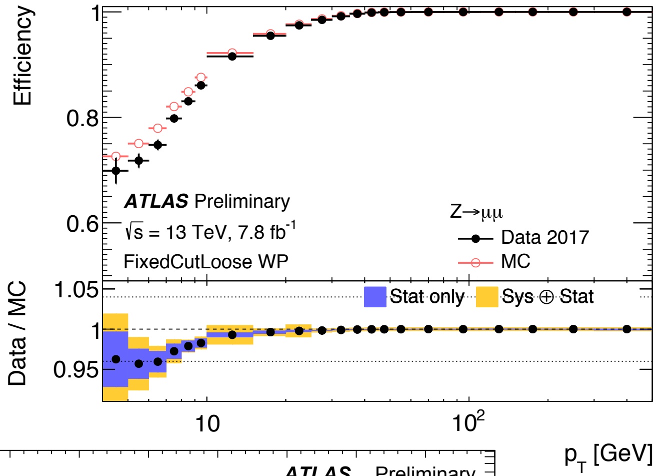
- Reconstruction efficiency > 98% for medium muons in |η| > 0.1
- Loose muons recover efficiency for |η| < 0.1
- Efficiency scale factor (ratio between expected and observed efficiencies) within 2% across entire η range
- Total systematic uncertainty < 0.5%

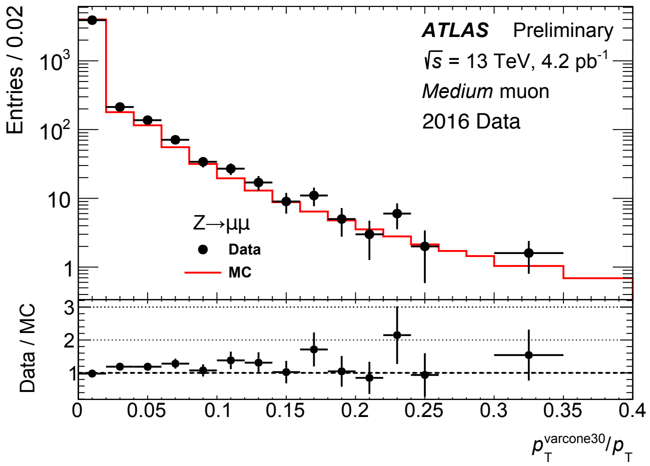




Muon Isolation

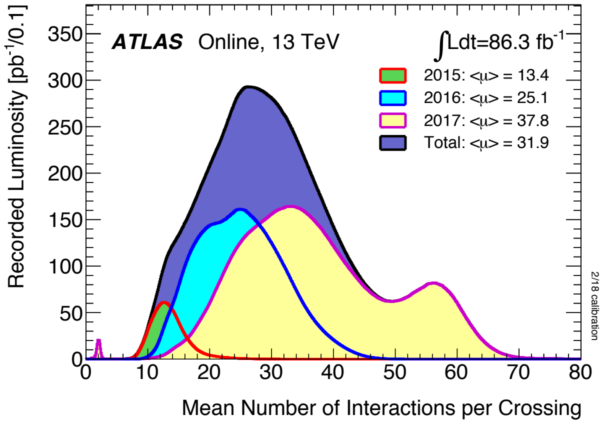
- Measure detector activity around a muon candidate for background rejection
- Use track-based & calorimeter-based variables
- Overall good agreement between data and simulation
- Uncertainties at the percent level
- **Total of seven isolation selection criteria optimized for different physics analyses**

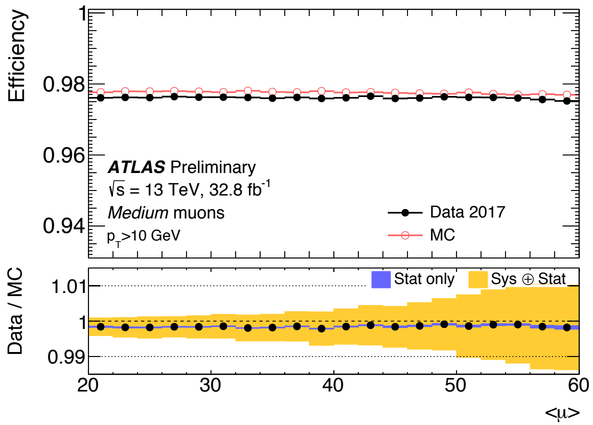


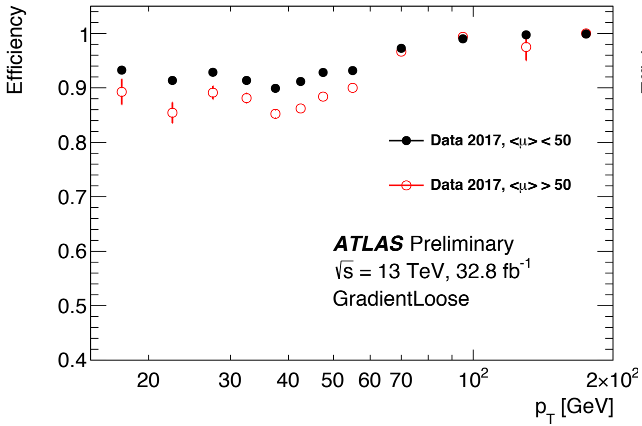


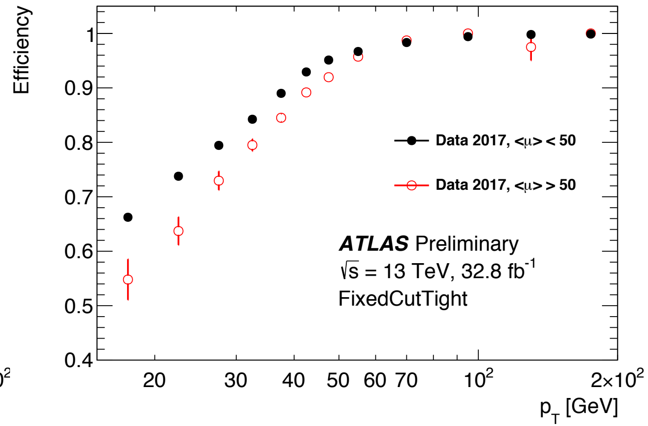
Efficiency & Pileup

- Pileup keeps increasing; need to study how efficiencies depend on <μ>
  - Slight loss of efficiency with higher <μ> with current isolation working points
  - No clear dependence of reconstruction efficiency on pileup
- Working to improve isolation definitions to be pileup robust; paving the way for the HL-LHC where we expect <μ> ~ 200



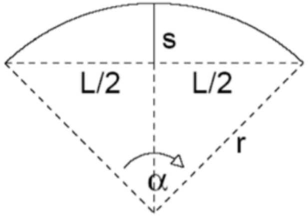


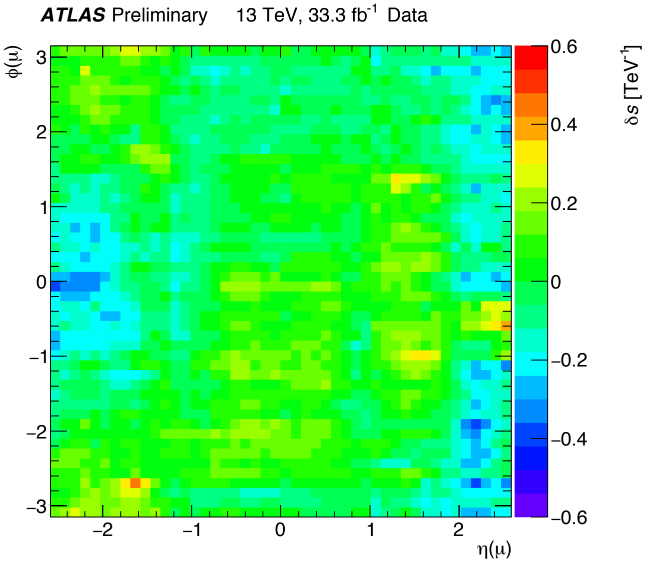




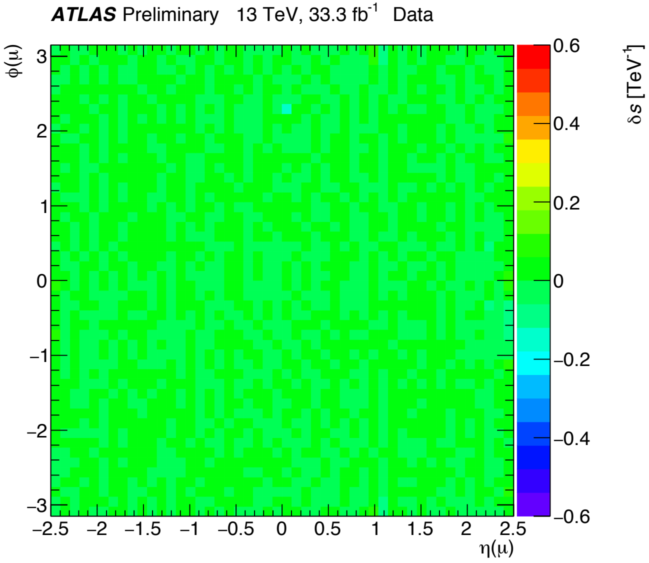
Sagitta Bias Correction

- New w.r.t. early Run 2 paper: correction applied on data on a per-tower basis in order to account for alignment biases on the sagitta
- Improves mass resolution of neutral resonances (where the sagitta bias for opposite charges produces a broadening of the peak) by a few percent





Apply Correction



Momentum Scale & Resolution

- **Goal:** Precisely describe the p_T reconstructed in the ID/MS in simulation; need to match the measurements in data
- **Method:** Extract relevant parameters from data using a binned maximum-likelihood fit with templates derived from simulation which compares $m_{\mu\mu}$ and normalized ID-MS p_T difference distributions in data and simulation
- Use Z and J/ψ samples
- ID and MS calibrated separately

Energy loss in calorimeter and other materials (MS only)

Magnetic field integral and radial distortions of the detector

p_T scale bias ~ $\Delta s_0 + (1 + \Delta s_1) \cdot p_T$

p_T resolution ~ $\sqrt{(\Delta p_0/p_T)^2 + \Delta {p_1}^2 + (\Delta p_2 \cdot p_T)^2)}$

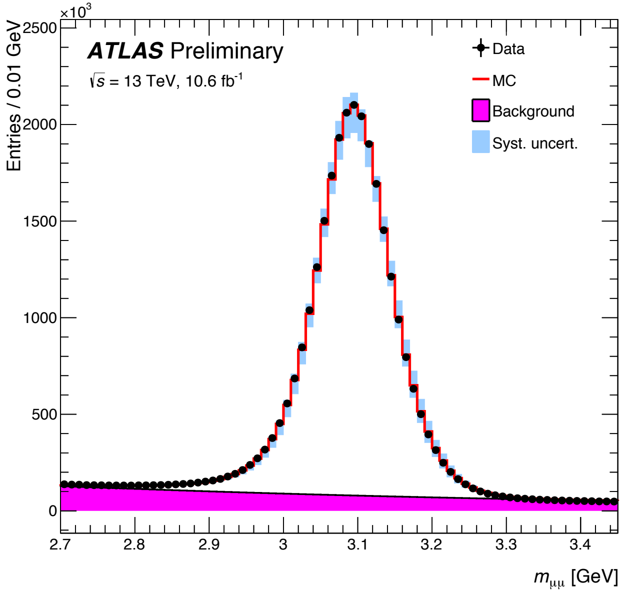
Energy loss fluctuations in the material (MS only)

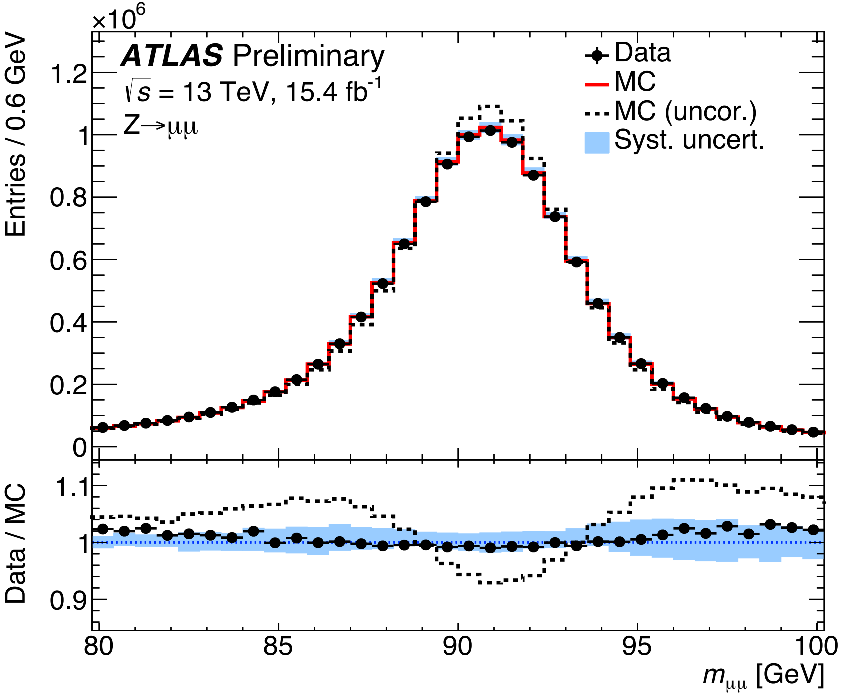
Multiple scattering, local radial distortions and local distortion of magnetic field

Intrinsic resolution and mis-alignments

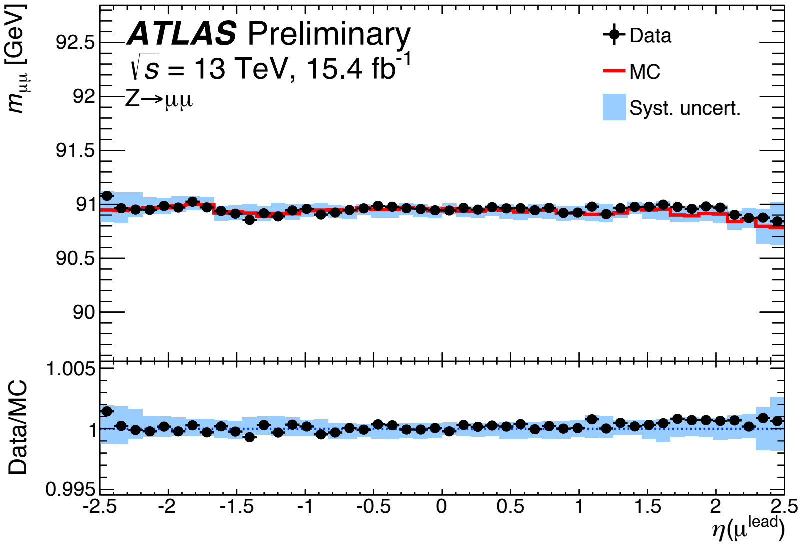
Effect Of Corrections

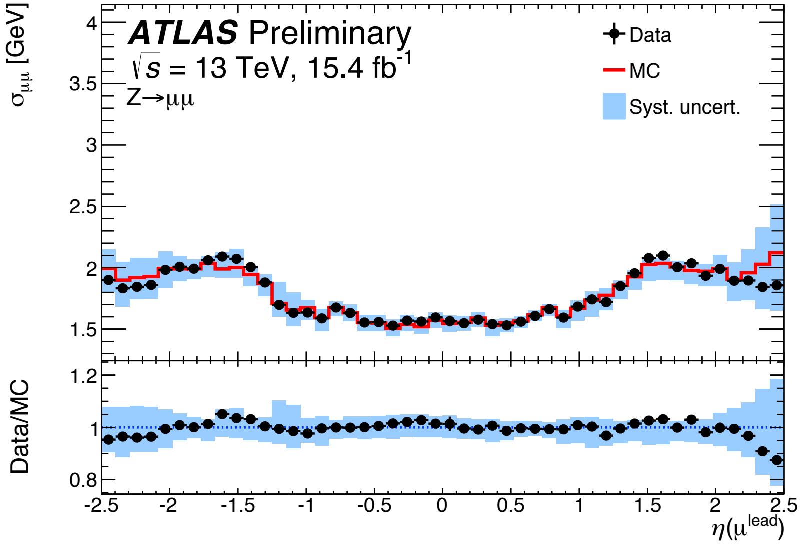
- After applying momentum corrections, the line shapes of the Z and J/ψ peak between data and simulation match very well within systematic uncertainty!





- Scale & resolution measured through Crystal Ball function
  - Tail of the Crystal Ball function models the energy loss

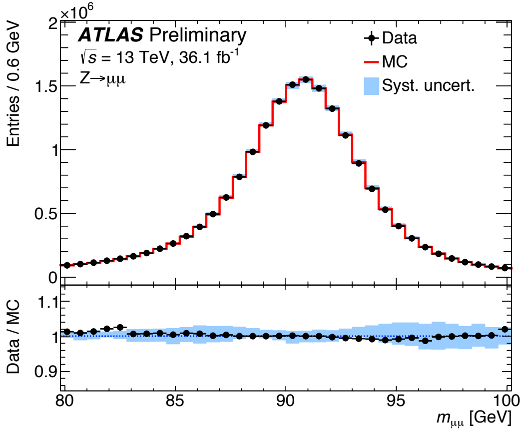


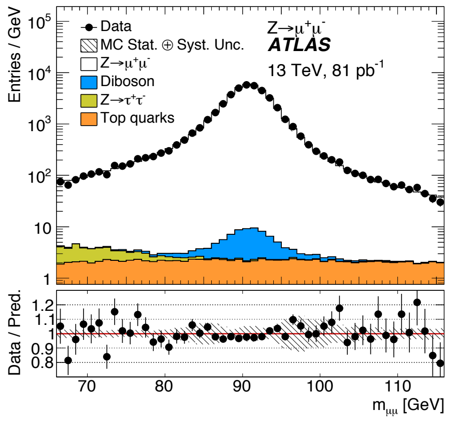


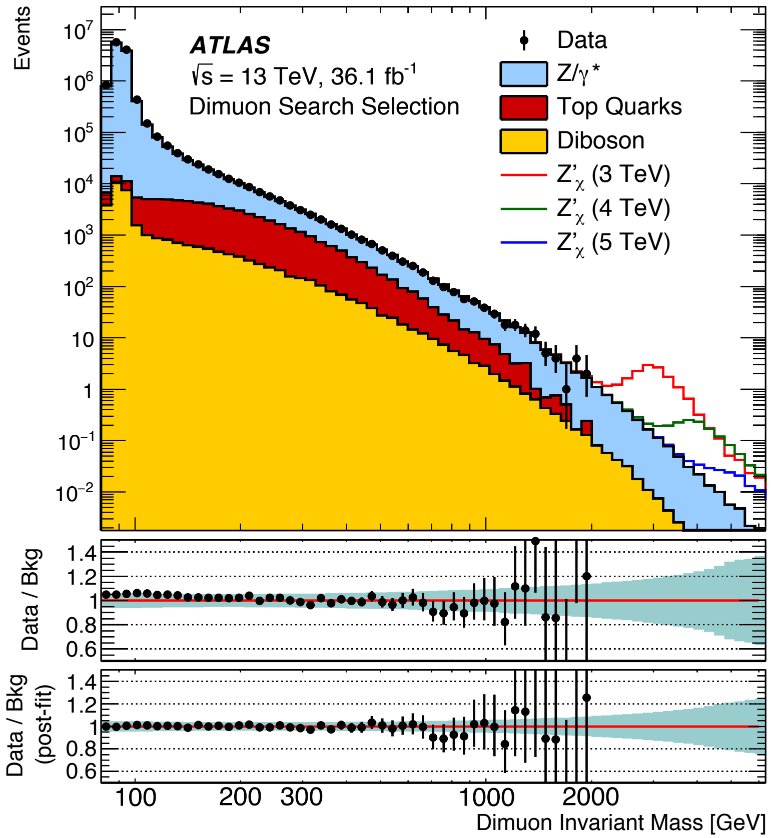
- Scale agreement at the per mille level
- Resolution agreement at the percent level

Physics Results

- MCP results extremely important for precision analyses and searches!
  - Mass of Higgs→ZZ* → 4 leptons (ATLAS-CONF-2017-046)
  - W & Z cross section measurement (Phys. Lett. B 759 (2016) 601)
  - Z' →μμ search (JHEP 10 (2017) 182)

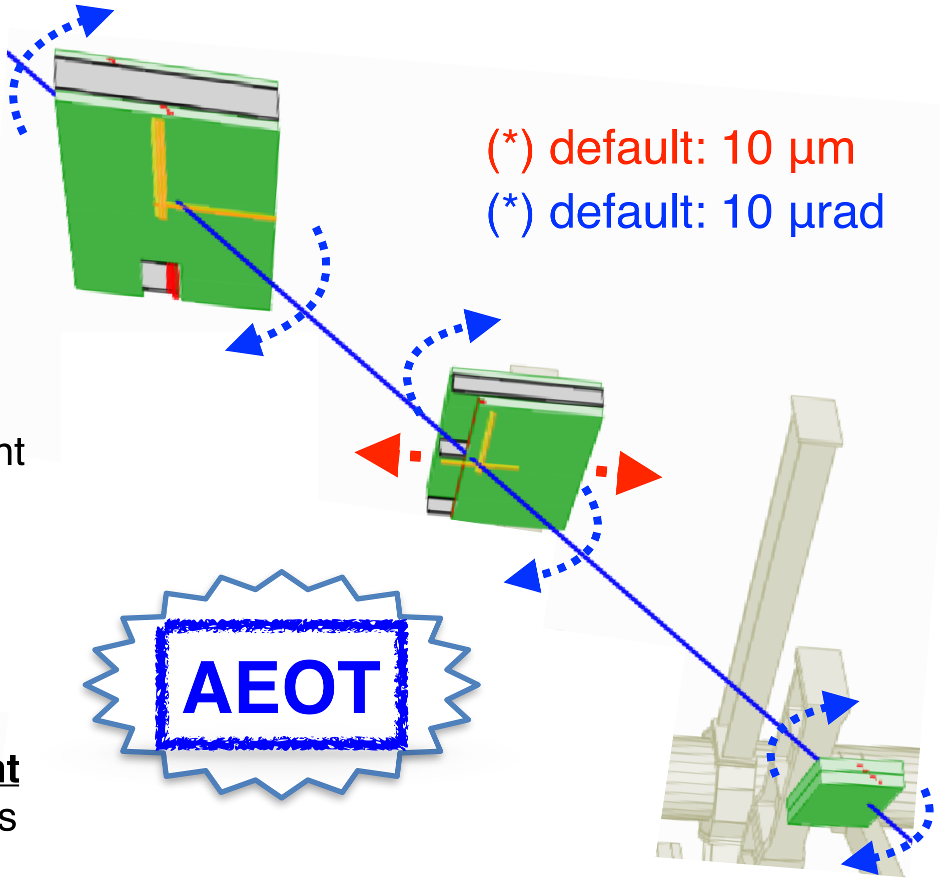






Continuously Improving ATLAS Software

- **<u>Old Reconstruction</u>**
  - Final track errors inflated to account for alignment uncertainties; chamber deweighted
  - Only in specific "critical" situations: Barrel/Endcap and Small/Large sector overlap regions, misaligned chambers, etc.
- **<u>New Reconstruction</u>**
  - Fit the alignment discontinuities
    - ⟹ More realistic errors on q/p measurement
    - ⟹ Might allow recovery of vetoed MS regions for high-p_T muons
  - Possible using `AlignmentEffectOnTrack` (AEOT): specifies position and angle uncertainties on chamber hits
  - Track fit performed using **<u>gaussian constraint</u>** on chamber hits where alignment uncertainties are used as gaussian widths



Summary

- Muon reconstruction performance measured for 15.4 fb^{-1} of 2017 data; extremely important for precision analyses and searches!
- Detector in great shape!
  - Reconstruction efficiency ~99% for $p_T > 10$ GeV
  - Isolation efficiency working as expected
  - Momentum scale and resolution between data and simulation agree over a wide p_T range:
    - Scale at the per mille level
    - Resolution at the percent level
- Continuously improving muon reconstruction (e.g. AEOTs, low-p_T algorithm optimization, MDT calibrations)!

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Thank you!
Merci!

Questions?

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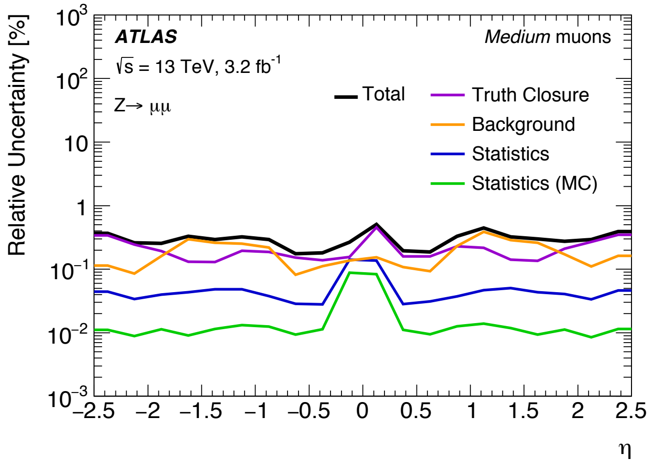
Backup

Systematic Uncertainties

- Truth Closure: Comparison of efficiency measured with the tag-and-probe method with "true" efficiency given by the fraction of generator-level muons that are successfully reconstructed. Accounts for possible biases the tag-and-probe method, such as biases due to different kinematic distributions between reconstructed probes and generated muons or correlations between ID and MS efficiencies.
- Background: For Z, take the maximum variation of the transfer factor T as described in the Run 1 paper. For J/ψ, change function used in the fit to model the background from first-order polynomial to exponential.



p_T Smearing & Scaling

- Muon momentum is calculated using

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

where Det ∈ [ID, MS], g_m is a normally distributed random variables with zero mean and unit width, $\Delta r_m^{Det}(\eta,\phi)$ describes the momentum resolution smearing, and $s_n^{Det}(\eta,\phi)$ describes the scale corrections

Combined Muon p_T

- Obtained by combining the ID and MS corrected momenta using a weighted average:

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

with the weight *f* derived from:

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

Abstract

- Muon reconstruction and identification play a fundamental role in many analyses of central importance in the LHC run-2 Physics programme. The algorithms and the criteria used in ATLAS for the reconstruction and identification of muons with transverse momentum from a few GeV to the TeV scale will be presented. Their performance is measured in data based on the decays of Z and J/ψ to pair of muons, that provide a large statistics calibration sample. Reconstruction and identification efficiencies are evaluated, as well as momentum scales and resolutions, and the results are used to derive precise MC simulation corrections. Isolation selection criteria and their performances in presence of high pileup will also be presented.

Working Points

	Loose	Medium	Tight
Muon Type	Combined, ME, ST/ CT ($\|\eta\|<0.1$)	Combined, ME (only in $2.5<\|\eta\|<2.7$)	Combined
# Precision Layers	N/A	≥2, ≥3 for ME	≥2
q/p Significance	N/A	< 7	< 7
χ^2 Requirement	N/A	N/A	< 8
Selection Efficiency for $4 < p_T < 20$ GeV (%)	96.7	95.5	89.9
Selection Efficiency for $20 < p_T < 100$ GeV (%)	98.1	96.1	91.8

$$\rho = \frac{\mathrm{p_T^{ID}} - \mathrm{p_T^{MS}}}{\mathrm{p_T^{ID}}}$$

isBadMuon: $$\left|\frac{[\sigma_{q/p}/(q/p)]^{ID}}{[\sigma_{q/p}/(q/p)]^{CB}}\right| < 0.8 \text{ or } \left|\frac{[\sigma_{q/p}/(q/p)]^{ME}}{[\sigma_{q/p}/(q/p)]^{CB}}\right| < 0.8$$

Tight muons included in medium muons, both included in loose muons.

Current High-p_T Working Point

- **Goal of the High-p_T Working Point (WP):** Select tracks with the best momentum resolution and scale

Energy loss in calorimeter and other materials (MS only)

Magnetic field integral and radial distortions of the detector

p_T scale bias ~ $\Delta s_0 + (1 + \Delta s_1) \cdot p_T$

Δs_i: Scale Corrections

p_T resolution ~ $\sqrt{(\Delta p_0/p_T)^2 + \Delta {p_1}^2 + (\Delta p_2 \cdot p_T)^2)}$

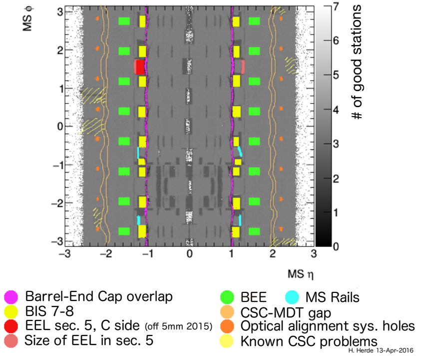
Energy loss fluctuations in the material (MS only)

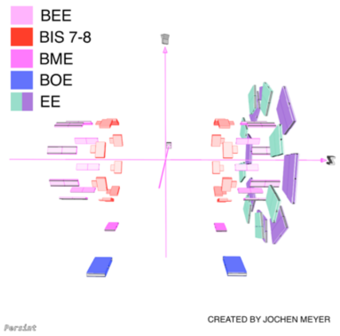
Multiple scattering, local radial distortions and local distortion of magnetic field

Intrinsic resolution and mis-alignments

Δp_i: Momentum resolution smearing corrections

- **High-p_T WP**
  - Require **combined (CB)** muon
  - Require **3 stations** in the MS (4 in the BEE region)
  - Apply **chamber vetoes** based on η-ϕ MS track coordinates in poorly aligned regions
  - Barrel-Endcap **overlap** (1.01 < |η| < 1.1) **excluded**
  - Apply **1/p significance cut at 7σ** (ID vs ME measurement)
  - Selection efficiency ~ 80%

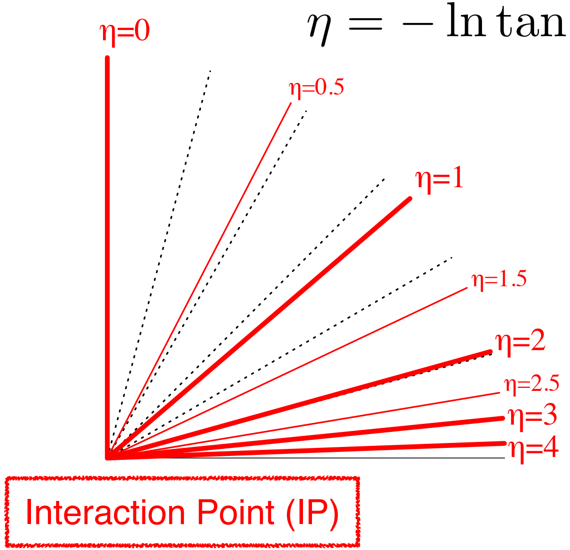


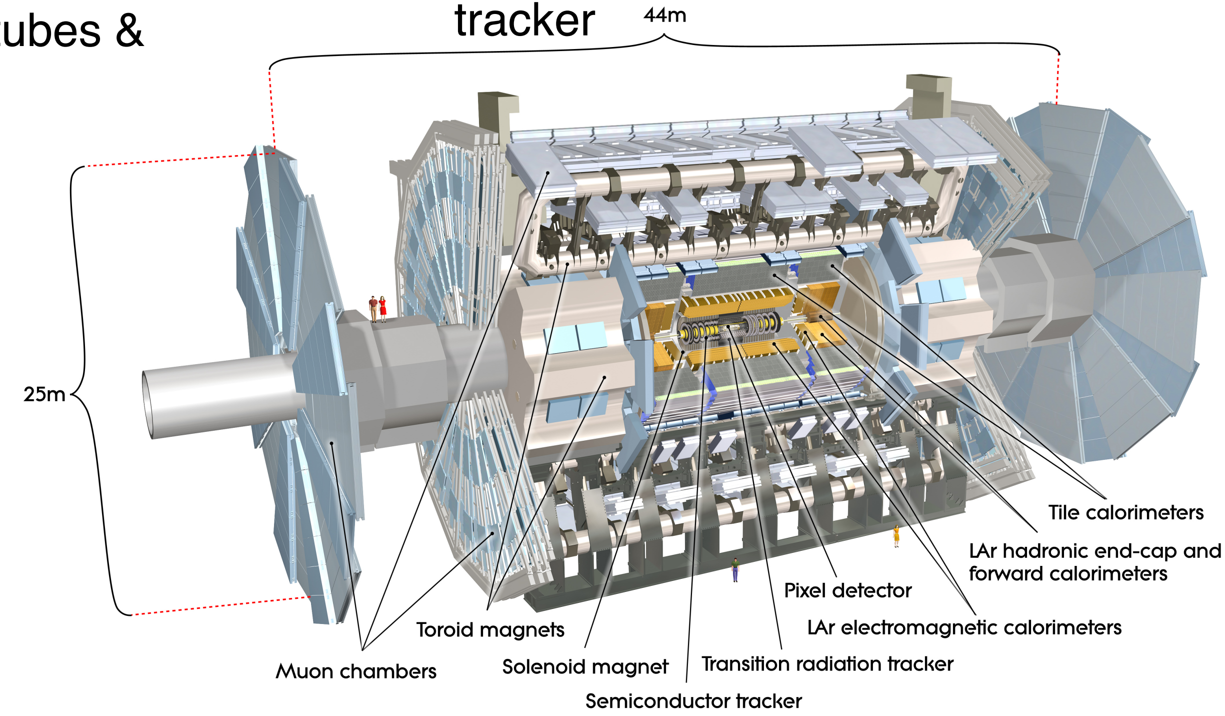


Muons In ATLAS

- Muon Spectrometer (MS): |η| < 2.7
  - Triggering: Resistive plate chambers & thin gap chambers
  - Tracking: Monitored drift tubes & cathode strip chambers
- Inner Detector (ID): |η| < 2.5
  - Silicon pixels, semiconductor tracker, and transition radiation tracker

$$\eta = -\ln \tan(\theta/2)$$





Muon System Details

Precision chambers

- 3 layers of Monitored Drift Tube chambers ($|\eta| < 2.7$)
- Innermost layer replaced by Cathode Strip Chambers ($|\eta| > 2.0$)

Trigger chambers

- 3 layers of Resistive Plate Chambers ($|\eta| < 1.05$)
- 3 layers of Thin Gap Chambers ($1.05 < |\eta| < 2.4$)

ID acceptance $|\eta| < 2.5$ operating in a 2T solenoidal field

- 3 layers of pixel sensors (50 cm < r < 12 cm)
- 4 layers of silicon strips (30 cm <r< 51 cm)
- 72 straw layers of transition radiation tracker modules (55 cm < r < 108cm)

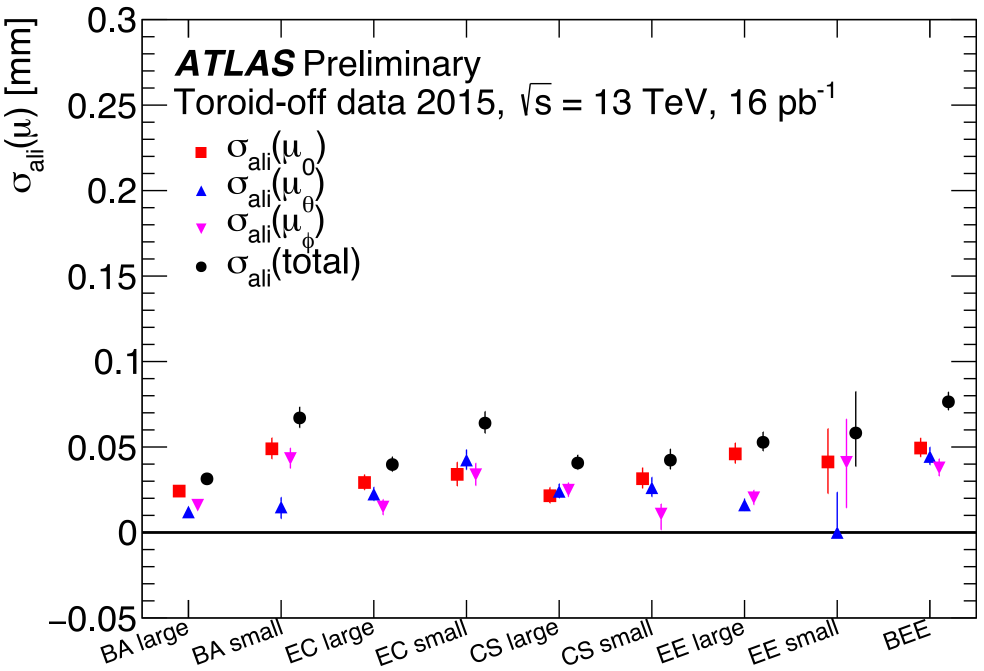
Data Quality

- RPC inefficiencies currently under investigation

ATLAS pp 25ns run: June 5-November 10 2017										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	99.3	99.5	99.4	99.9	97.8	99.9	100	100	99.2
Good for physics: 93.6% (43.8 fb^{-1})										

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between June 5 – November 10 2017, corresponding to a delivered integrated luminosity of 50.4 fb^{-1} and a recorded integrated luminosity of 46.8 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.5 fb^{-1}. Analyses that don't require the toroid magnet can use these data.

Muon Spectrometer Alignment



[μm]	$\sigma_{\text{ali}}(\mu_0)$	$\sigma_{\text{ali}}(\mu_\theta)$	$\sigma_{\text{ali}}(\mu_\phi)$	$\sigma_{\text{ali}}(\text{total})$
BA large	24 ± 2	12 ± 1	16 ± 2	31 ± 2
BA small	49 ± 6	15 ± 6	43 ± 6	67 ± 6
EC large	29 ± 4	22 ± 4	15 ± 4	40 ± 4
EC small	34 ± 7	42 ± 6	34 ± 7	64 ± 6
CS large	21 ± 5	24 ± 4	25 ± 4	41 ± 4
CS small	31 ± 6	26 ± 6	11^{+6}_{-9}	42 ± 6
EE large	46 ± 6	16 ± 3	20 ± 4	53 ± 6
EE small	41 ± 19	0^{+24}_{-0}	41 ± 26	58^{+24}_{-20}
BEE	49 ± 5	44 ± 5	38 ± 5	76 ± 5

$$\delta_S = \mu_0 + \frac{\theta - \langle\theta\rangle}{\text{RMS}(\theta)}\mu_\theta + \frac{\phi - \langle\phi\rangle}{\text{RMS}(\phi)}\mu_\phi$$

- $p_T^{varcone30}$: scalar sum of p_T of the tracks with $p_T > 1$ GeV in a cone of size $\Delta R = \min(10\ \mathrm{GeV}/p_T, 0.3)$ around the muon
- $E_T^{topocone20}$: sum of the transverse energy of topological clusters in cone of size $\Delta R = 0.2$ around the muon