Muon reconstruction performance in ATLAS at Run-II

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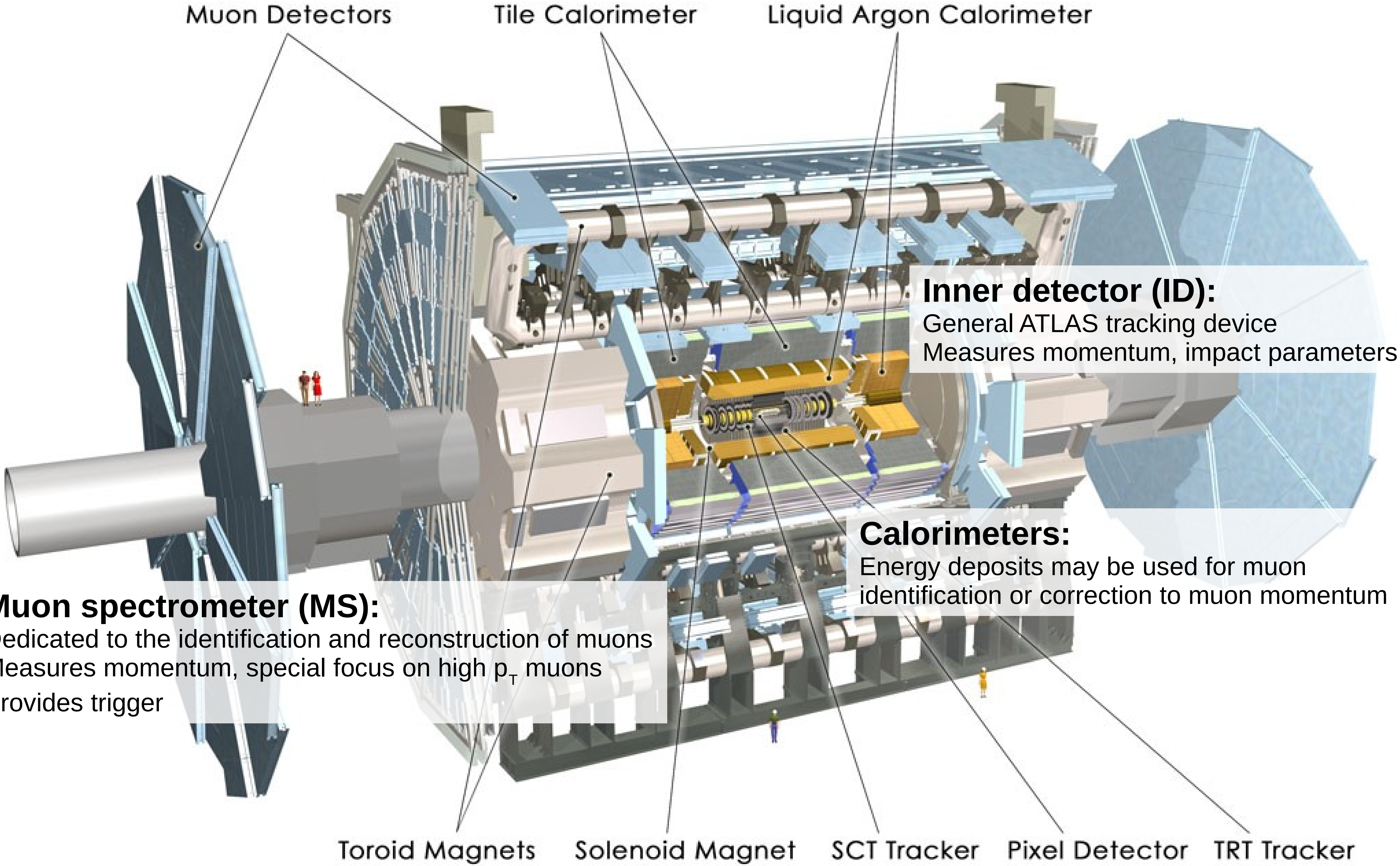
ATLAS

ATLAS detectors for muon reconstruction

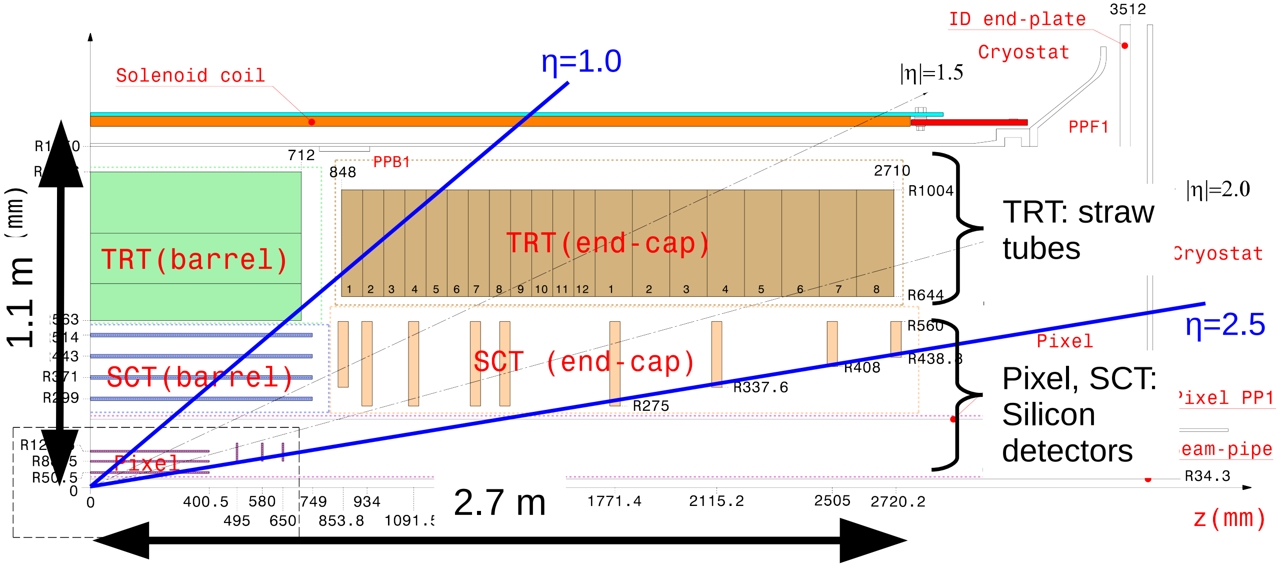


Inner detector (ID):
General ATLAS tracking device
Measures momentum, impact parameters

Calorimeters:
Energy deposits may be used for muon identification or correction to muon momentum

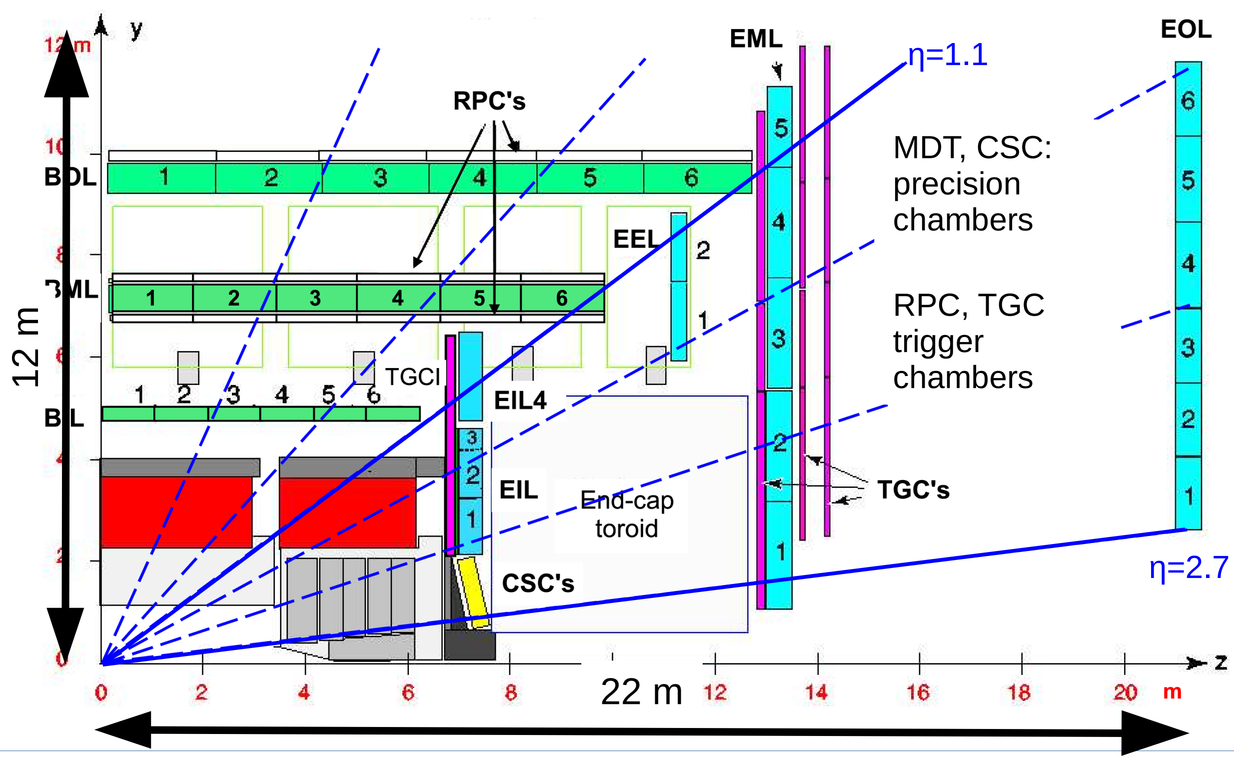
Muon spectrometer (MS):
Dedicated to the identification and reconstruction of muons
Measures momentum, special focus on high p_T muons
Provides trigger

Features of the tracking detectors



Inner detector (ID):

- Enclosed in 2T solenoid magnet
- Acceptance up to |η|=2.5
- Hermetic detector
- Resolution degrades at large |η|

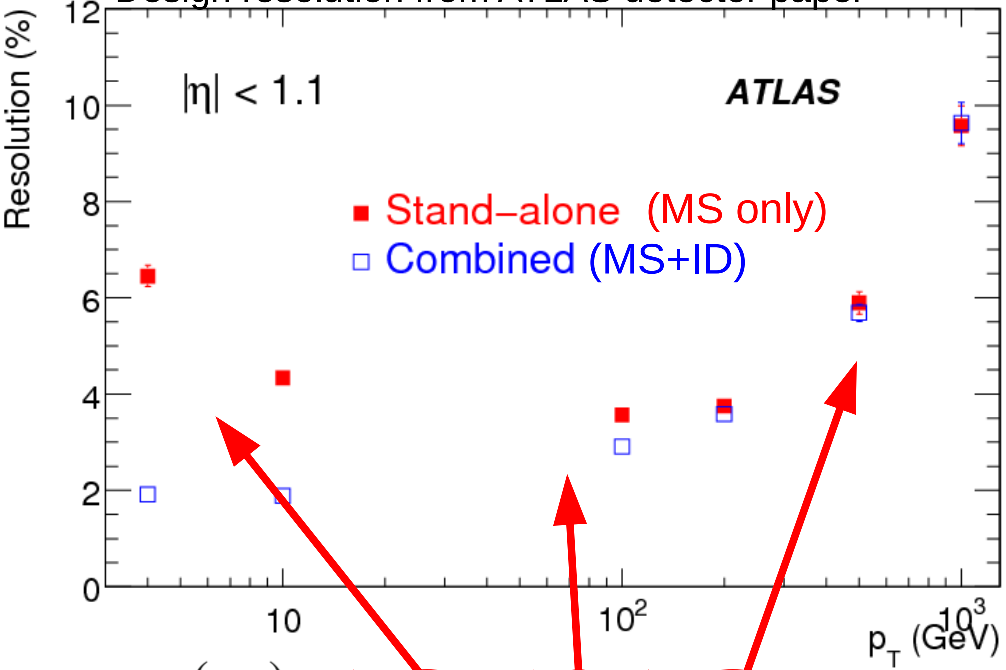


Muon spectrometer (MS):

- System of toroid magnets, inhomogeneous field ~0.5T
- Precision chambers arranged in 3 layers
- Acceptance up to |η|=2.7
- No resolution drop at large |η|
- Sophisticated layout, acceptance cracks

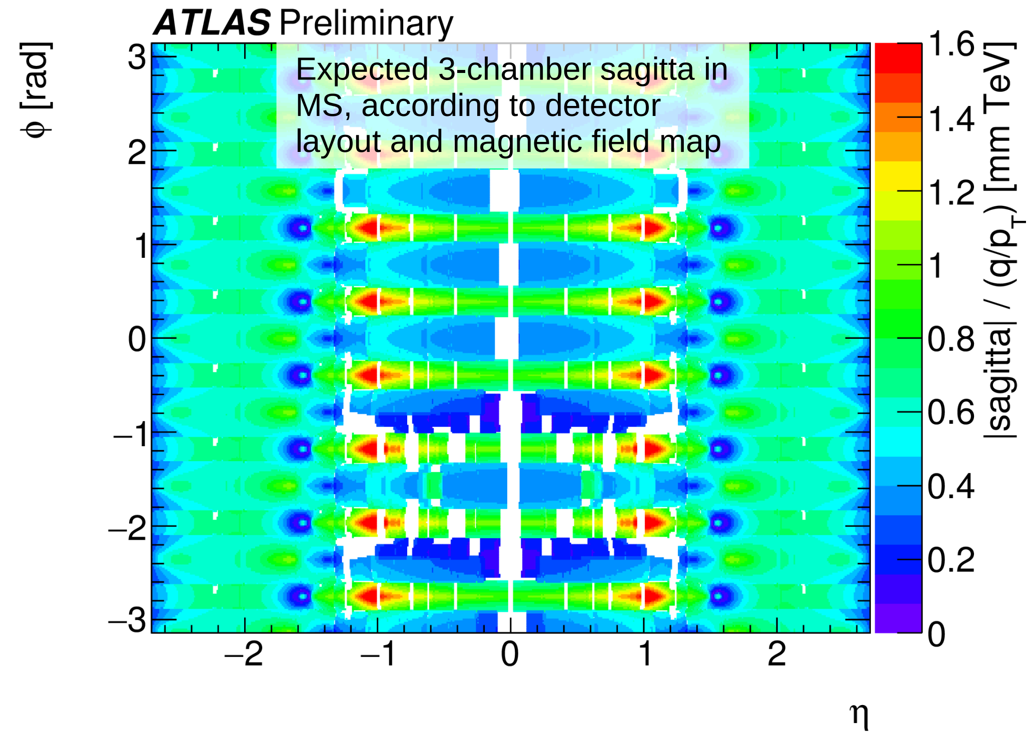
Contributors to the momentum resolution

Design resolution from ATLAS detector paper



$$\frac{\sigma(p_T)}{p_T} = r_0/p_T \oplus r_1 \oplus r_2 \cdot p_T$$

- r_0: fluctuations of the energy loss (in front tracking detector)
  - vanishes in ID
  - dominant contribution in MS at low p_T
- r_1: multiple scattering, local magnetic field inhomogeneities
  - ~2-3% in ID (|η|<1.75)
  - ~3-4% in MS
- r_2: intrinsic hit resolution, mis-alignment
  - ~0.4 TeV^{-1} in ID (|η|<1.75)
  - ~0.1 TeV^{-1} in MS

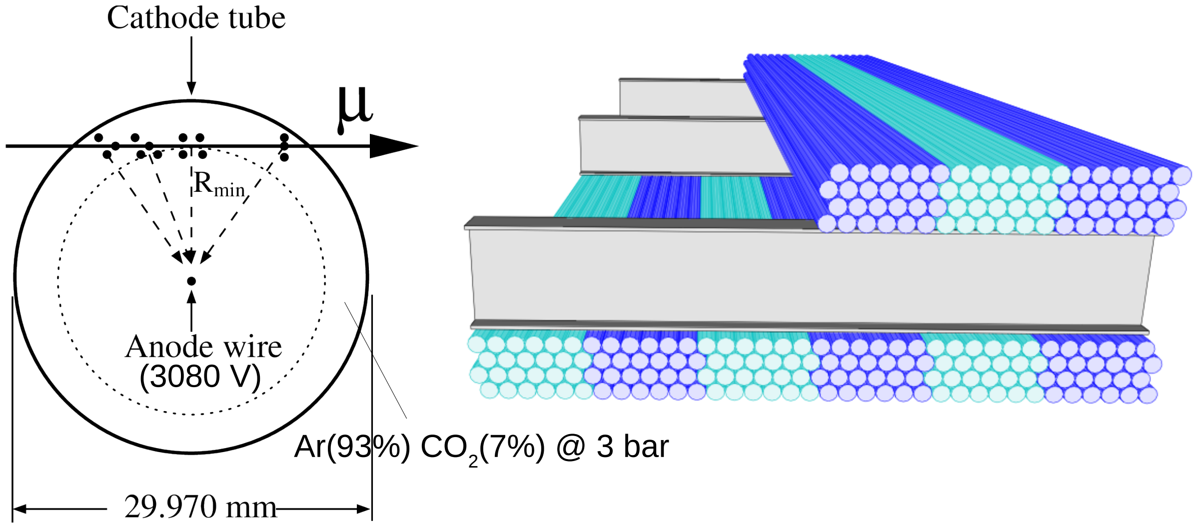


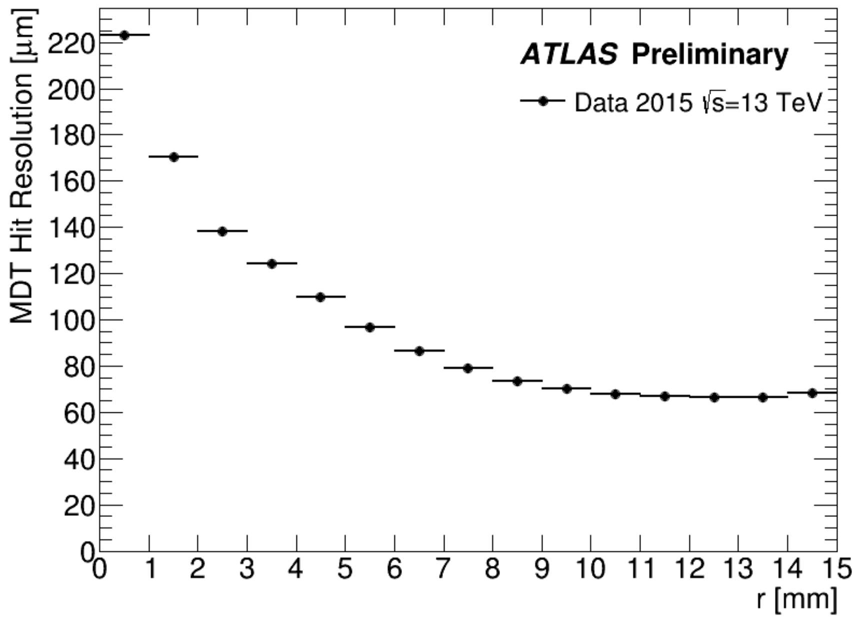
In MS: sagitta ~ 500µm @ p_T=1TeV
(with (η,φ) dependence)

⇓ (Target r_2~0.1 TeV^{-1} in MS)

Constraints on hit resolution and alignment:
$\sigma(\text{sagitta}) = \sigma_{hit}(\text{sagitta}) \oplus \sigma_{ali}(\text{sagitta})$ ~ 50 µm

MS high p_T highlight: MDT tube resolution

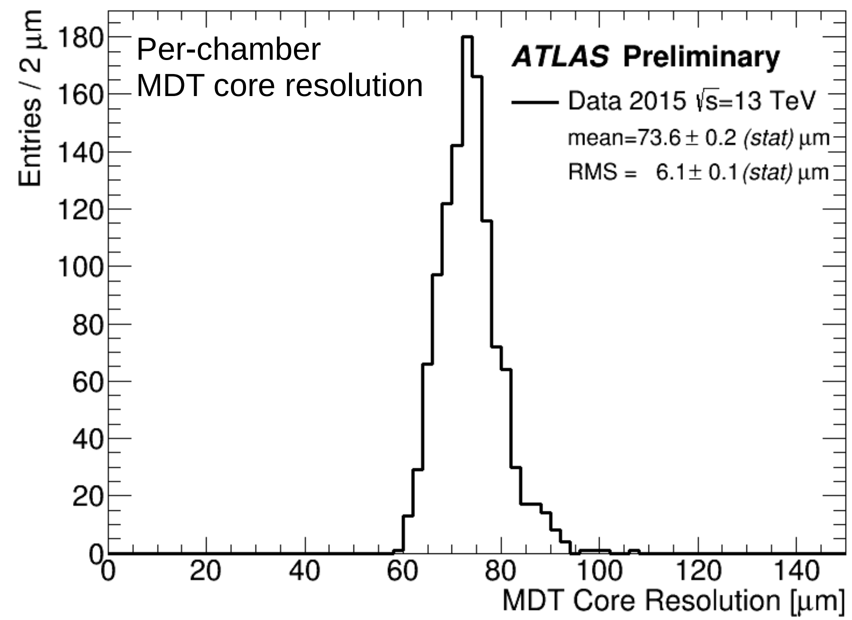




MDT drift tubes measure drift radius (R) from rising time of avalanche (T)

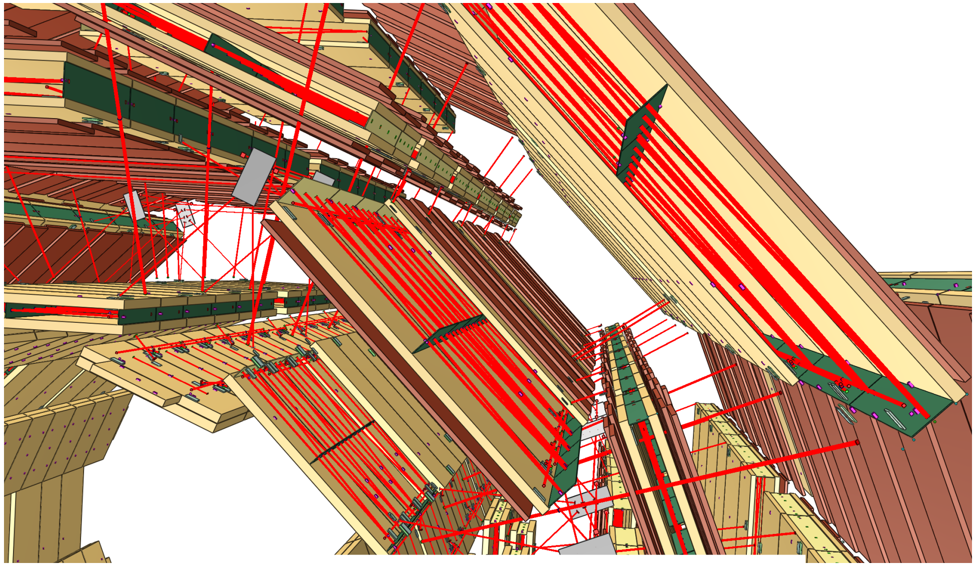
Needs calibrations:

- "Universal" R(T) relation derived from cosmics
  - Special MDT chamber located on surface
- R(T) relation then corrected for each chamber:
  - Time offset of electronics
  - Temperature, pressure, HV
  - Lorenz angle effect (at reco. level)



Shown on the right:
MDT resolution measured from unbiased hit residuals in track segments
Close to design level: σ_{hit}(R)~75μm ⇔ σ_{hit}(sagitta)~40μm

MS high p_T highlight: alignment



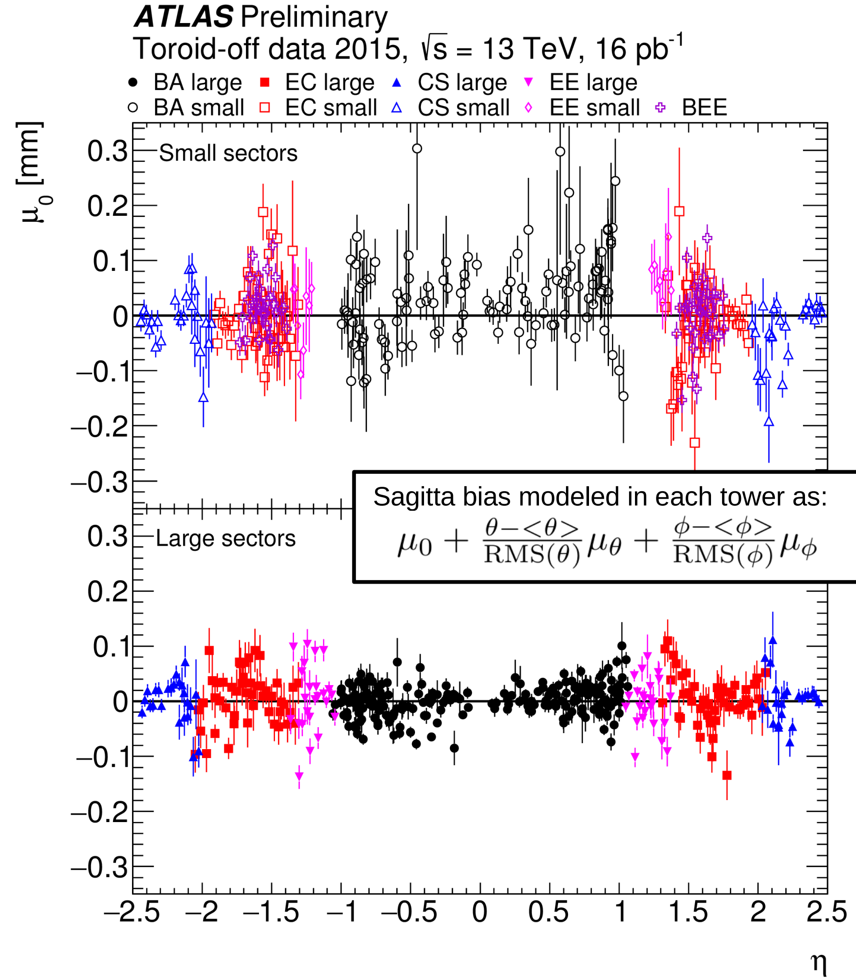
View of the barrel optical sensors (in RED)

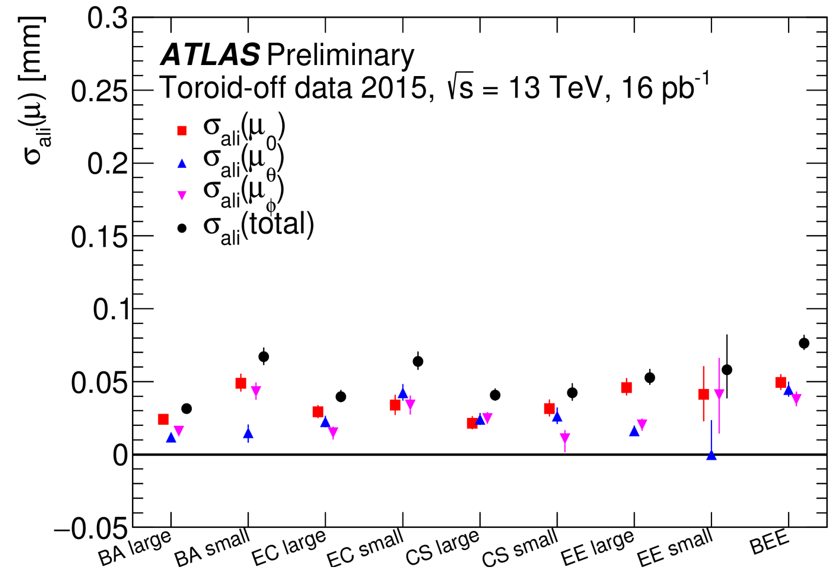
Alignment derived from array of optical sensors:

- Monitor chamber positions/deformations continuously
- Calibrated & mounted with high precision on chambers
- Special runs with **toroid field off** (cosmics + collisions) used to determine a reference geometry using tracks.
- Optical system extrapolates geometry to the physics runs with **toroid field on**

Shown on the right:

- Sagitta residuals observed in toroid-off collision runs.
- Overall alignment performance numbers σ_{ali} are derived
- Close to the design level.





Muon reconstruction: categories, qualities

Raw types from combined muon reconstruction

Combined muons (CB):
- ID track + MS track
- 96% of muons

Segment tagged muons (ST):
- ID track + MS track segment
- Low p_T muons or region of reduced acceptance in MS

Calo-tagged (CT):
- ID track + calorimeter deposit compatible with MIP
- Used in MS crack region (|η|<0.1)

MS Extrapolated (ME):
- MS track only refitted with energy loss and loose vertex constraint
- Track parameters expressed at interaction point
- Beyond ID acceptance 2.5<|η|<2.7

- For physics analyses, different **identification qualities** are defined: Loose, Medium, Tight, High-p_T
- Based on:
  - one or several raw types of the muon reconstruction
  - quality cuts on the muon candidate
- Yield different efficiencies and purities

True and fake efficiencies in $t\bar{t}$ MC sample:

	$4 < p_T < 20$ 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

Efficiency determination: tag and probe method

High purity samples of J/ψ→μμ and Z→μμ

- First muon (tag): high quality CB muon, triggers
- Second muon (probe) is reconstructed by system independent of the one being studied

Three kinds of probe muons:

- ID tracks and CT muons to determine efficiency in the MS
- MS tracks to determine efficiency in the ID

Total efficiency derived by combining several tag&probe efficiencies for the different identification qualities:

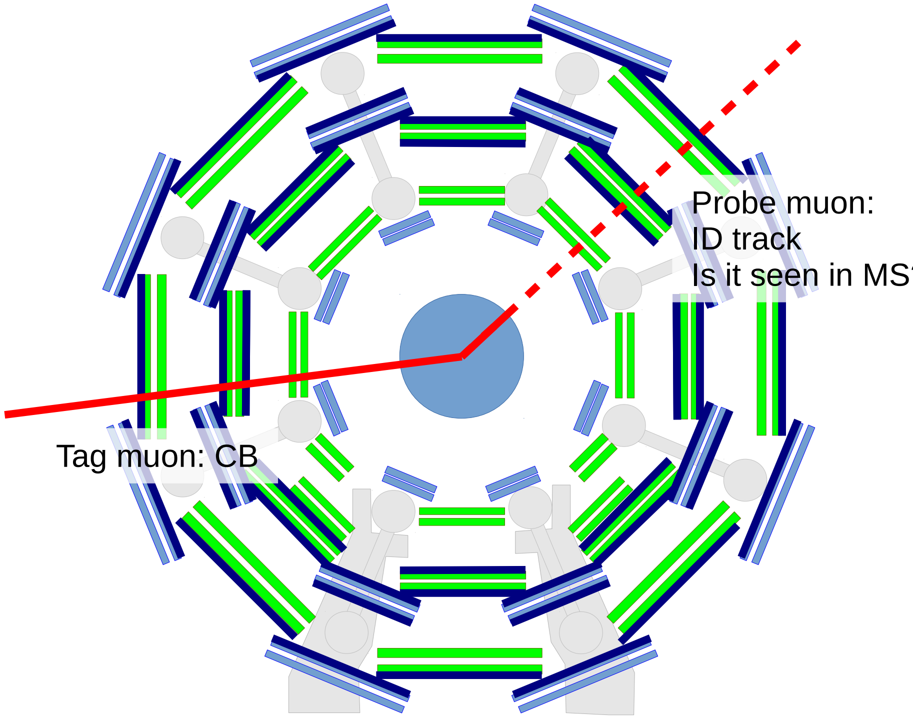
$$\epsilon\,(\mathrm{X}) = \epsilon\,(\mathrm{X|ID}) \cdot \epsilon\,(\mathrm{ID}) = \epsilon\,(\mathrm{X|CT}) \cdot \epsilon\,(\mathrm{ID|MS})$$

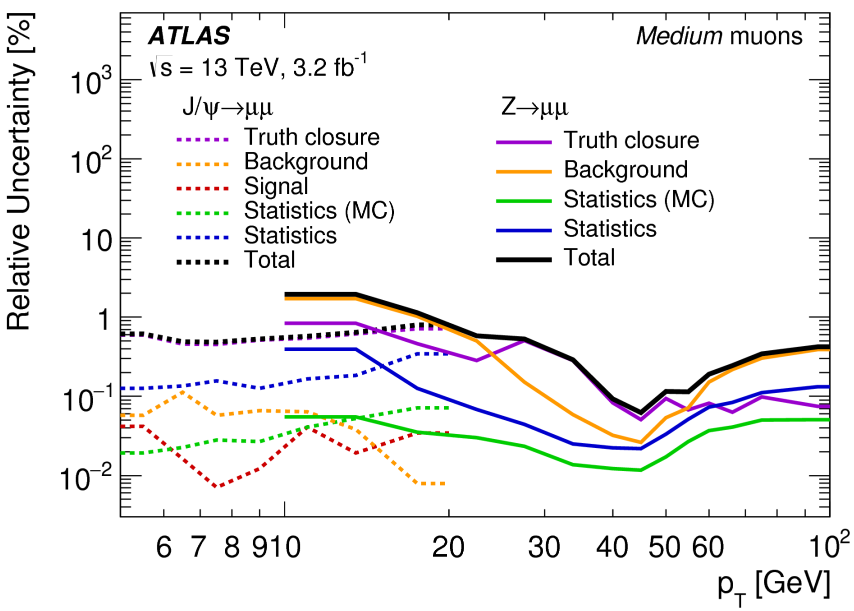
$$(\mathrm{X} = \mathit{Medium}/\mathit{Tight}/\mathit{High}\text{-}p_{\mathrm{T}}).$$

Formula relies on assumptions which are tested in MC and incorporated in systematics

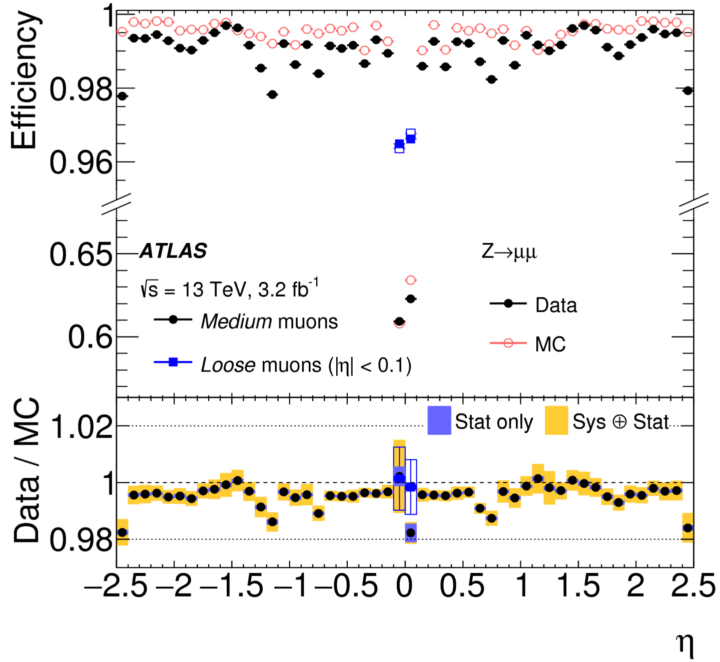
Backgrounds: combination of MC estimation and data driven techniques

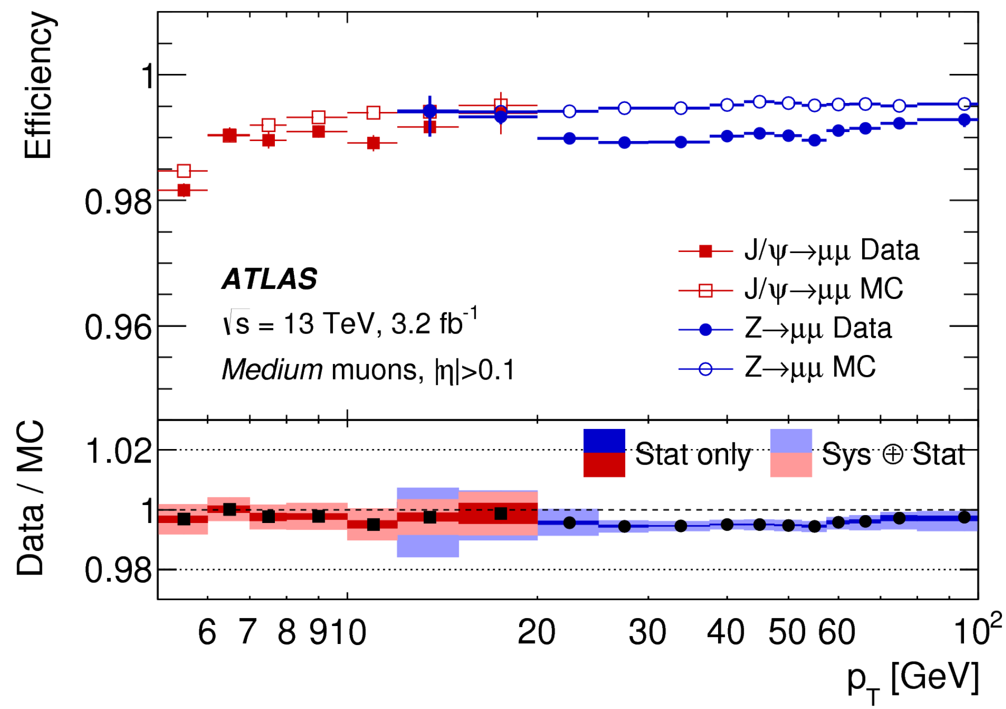
Total systematics: several ‰ on most of p_T and η range

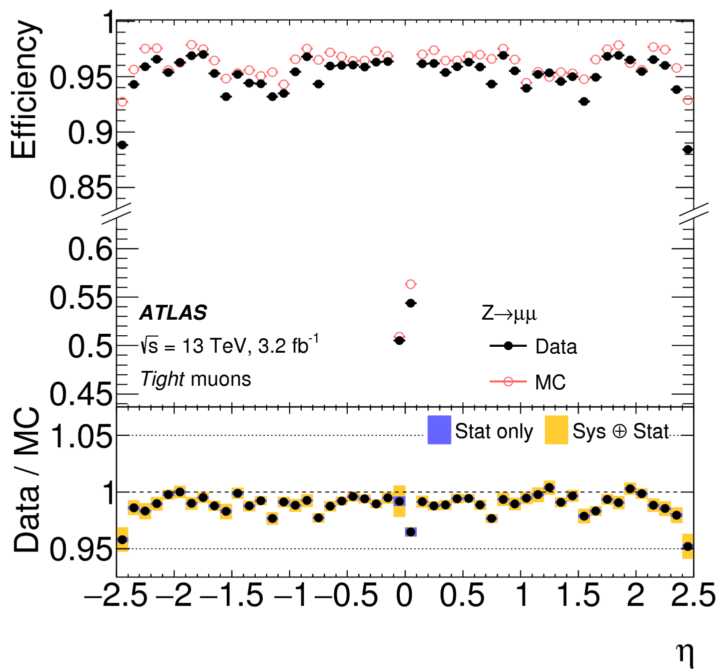




Tag and probe method: results







Efficiencies observed:

- >98% for Medium and Loose muons
- Between 90% and 98% for Tight selection

Good compatibility of efficiencies measured with $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ samples

Isolation

Many physics processes produce **isolated** muons (EW processes, decay of heavy particles,...)

2 isolation variables, to suppress QCD background:

- $p_T^{varcone30}$: sum of tracks p_T in cone of size $\Delta R = \min(10\ \text{GeV}/p_T^{\mu}, 0.3)$ around muon.
- $E_T^{topocone20}$: sum of calorimeter topological clusters in cone of size $\Delta R = 0.2$ around muon

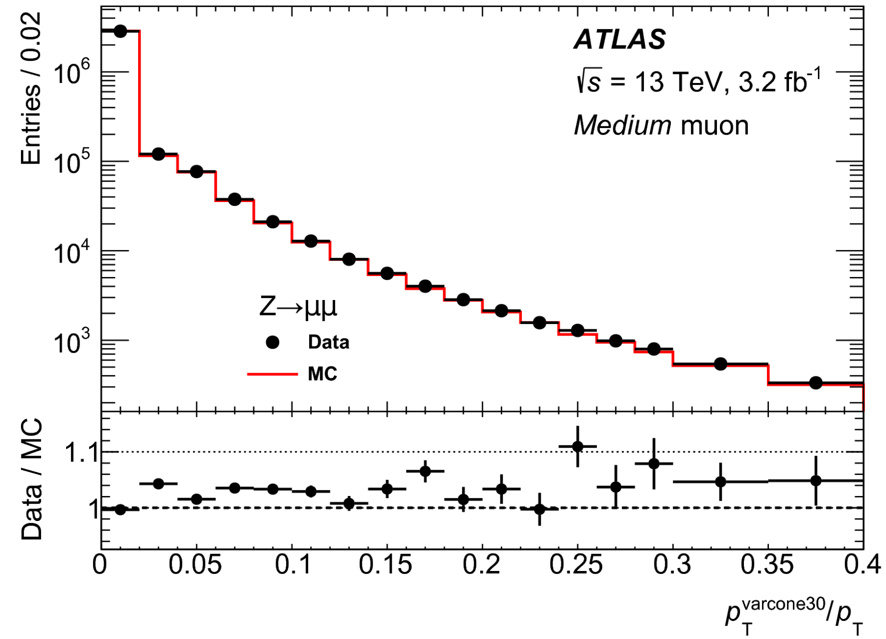
Define several *isolation working points* with standardized cuts on $p_T^{varcone30}$ and $E_T^{topocone20}$

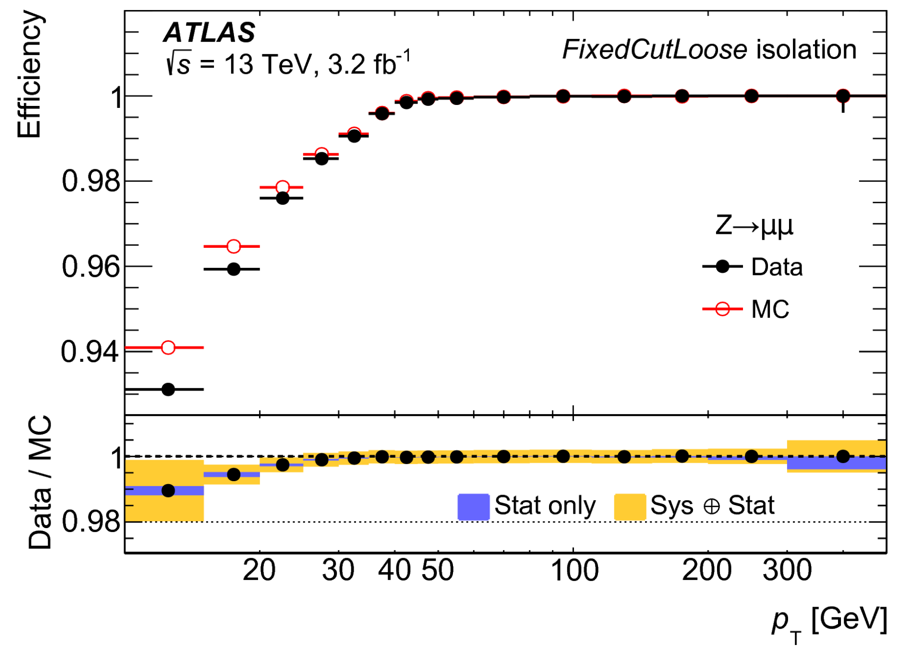
Efficiency scale factors are determined:

- With tag & probe method from previous slides
- p_T-dependent
- For each isolation working point

Systematics are few ‰ over most of p_T range

- Background, cut variation around Z peak, η dependence

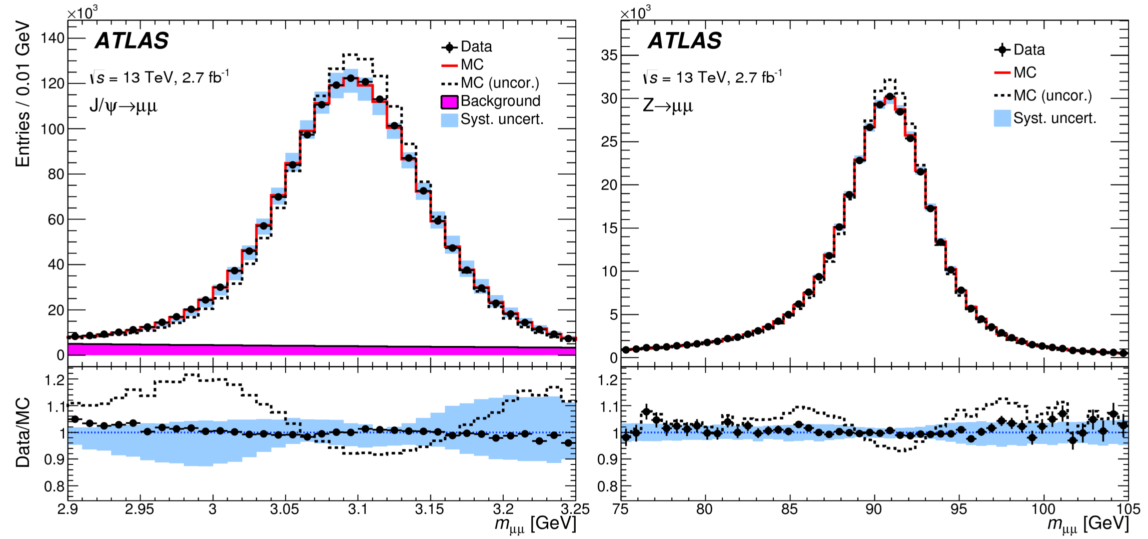




Momentum scale and resolution with J/ψ, Z

MC simulation of ATLAS detector needs small corrections to reproduce momentum scale and resolution

Scale and smearing parameters are determined using template fits to J/ψ→μμ and Z→μμ mass distributions.



s_0: energy loss correction (MS only)

s_1: momentum scale

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

Det=MS, ID

Resolution parameters

Binning in η,φ

Standard normal distribution

Momentum scale results for ID and MS:

Region	$s_1^{\mathrm{ID}}(\times 10^{-3})$
$\lvert\eta\rvert < 1.05$	$-0.6^{+0.1}_{-0.2}$
$1.05 \leq \lvert\eta\rvert < 2.0$	$-0.5^{+0.2}_{-0.5}$
$\lvert\eta\rvert \geq 2.0$	$1.0^{+3.5}_{-1.6}$

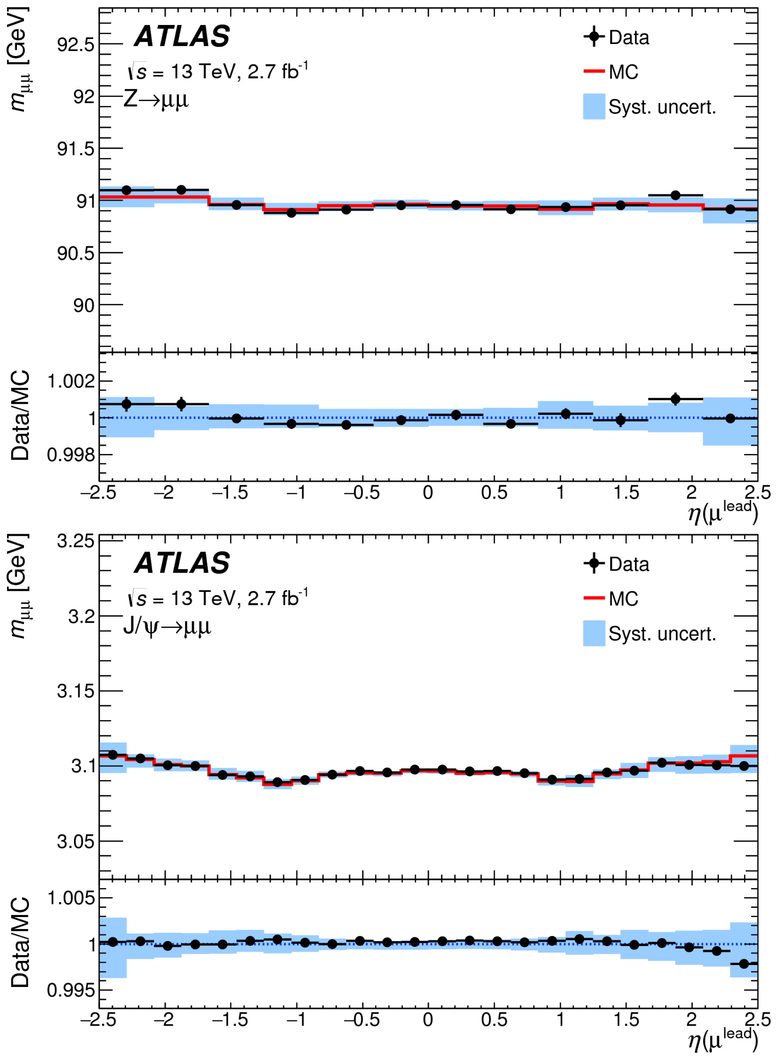
Region	s_0^{MS} [MeV]	$s_1^{\mathrm{MS}}(\times 10^{-3})$
$\lvert\eta\rvert < 1.05$ (small)	-23 ± 5	-0.9 ± 0.3
$\lvert\eta\rvert < 1.05$ (large)	-26^{+8}_{-5}	$1.8^{+0.4}_{-0.3}$
$1.05 \leq \lvert\eta\rvert < 2.0$ (small)	-13 ± 6	-1.4 ± 0.4
$1.05 \leq \lvert\eta\rvert < 2.0$ (large)	-15 ± 10	$-1.1^{+0.5}_{-0.6}$
$\lvert\eta\rvert \geq 2.0$ (small)	-6^{+6}_{-7}	$0.7^{+0.4}_{-0.3}$
$\lvert\eta\rvert \geq 2.0$ (large)	-3^{+13}_{-10}	$0.3^{+0.6}_{-0.7}$

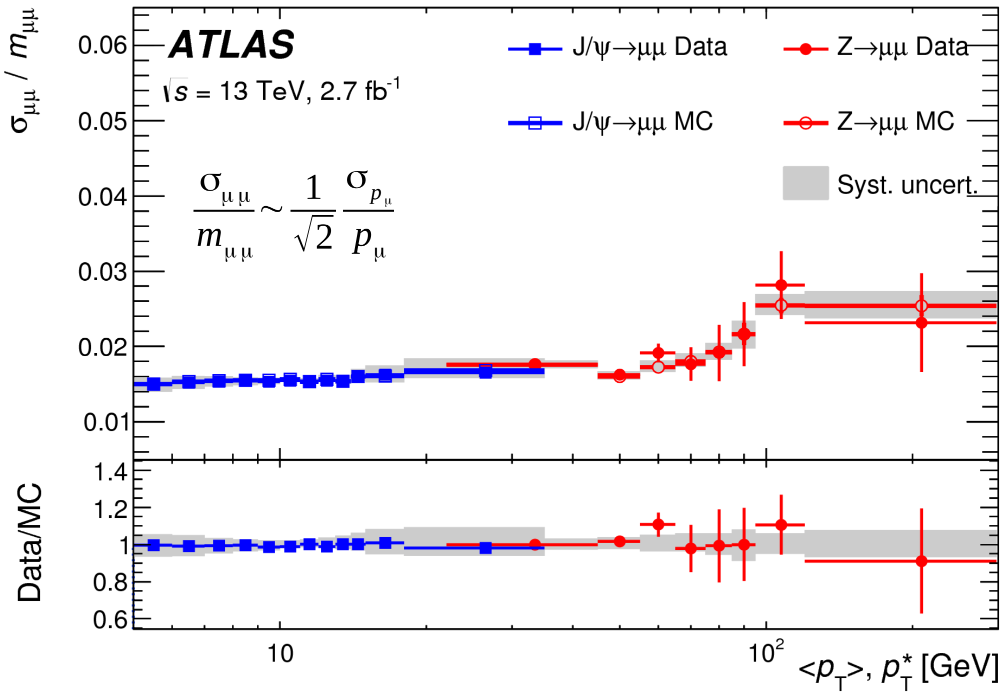
Separate corrections for ID and MS tracks.
CB momentum re-built after correction.

Systematics: cut variations, background, compatibility of J/ψ and Z.
Total error:

- ~ 0.5 to 3 ‰ for the momentum scale
- ~ 5 % for the resolution

Momentum scale and resolution with J/ψ, Z: results





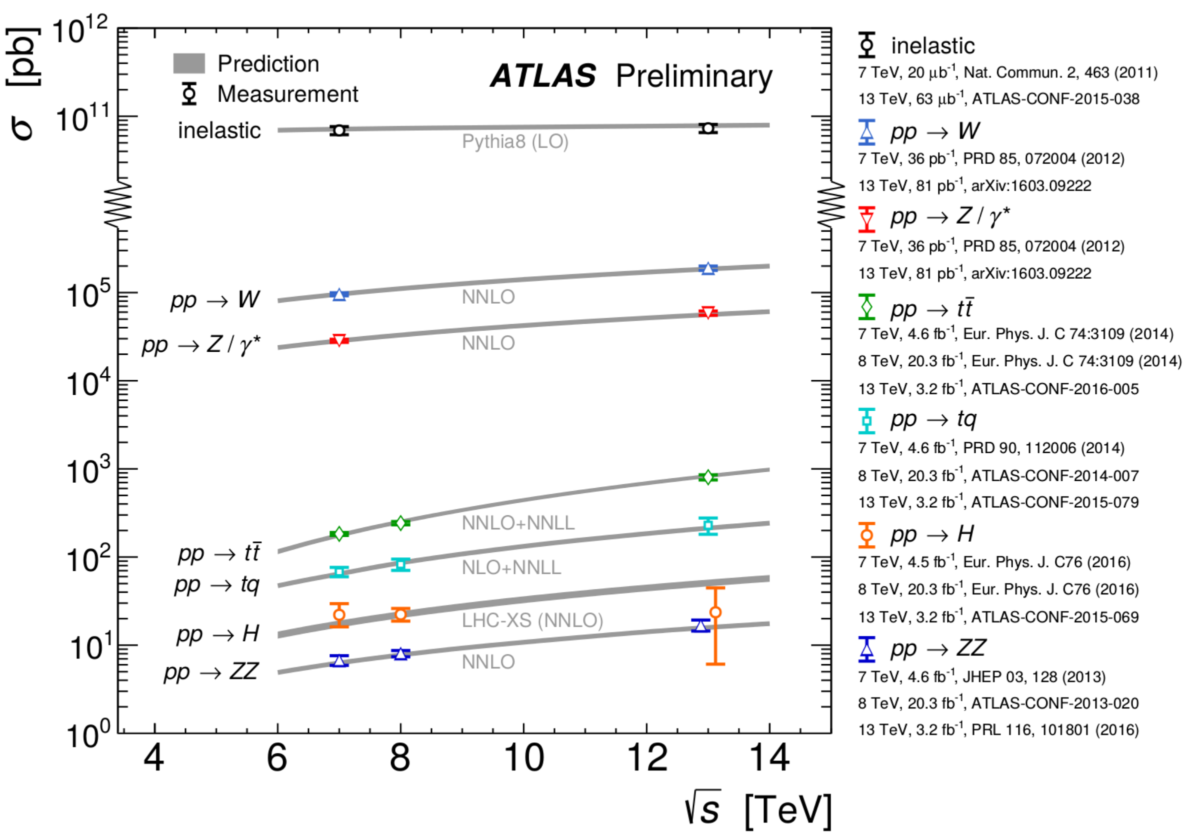
$$\frac{\sigma_{\mu\mu}}{m_{\mu\mu}} \sim \frac{1}{\sqrt{2}} \frac{\sigma_{p_\mu}}{p_\mu}$$

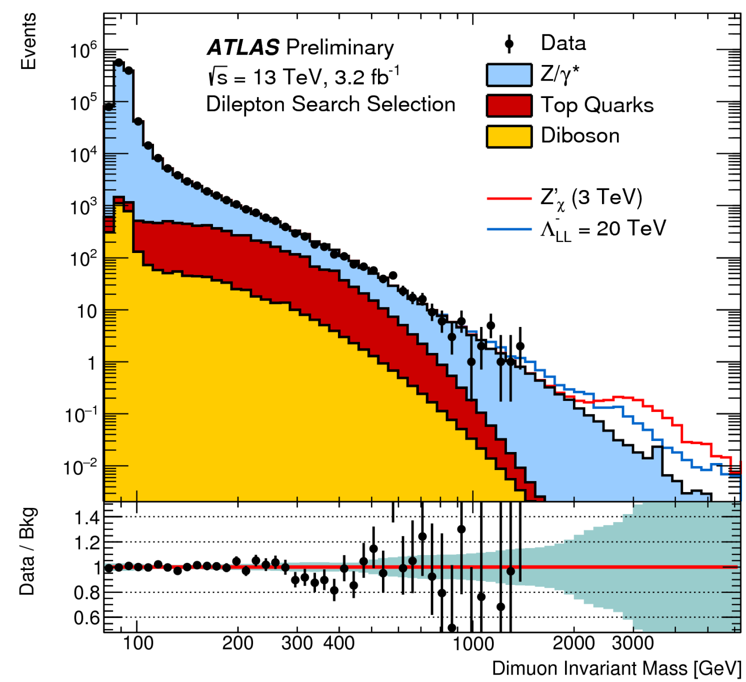
Plots illustrate the compatibility of MC after correction with data:

- Mass scale well modeled for $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$
- Good compatibility of the resolution between $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$
- Momentum dependence of the resolution well reproduced

Conclusion

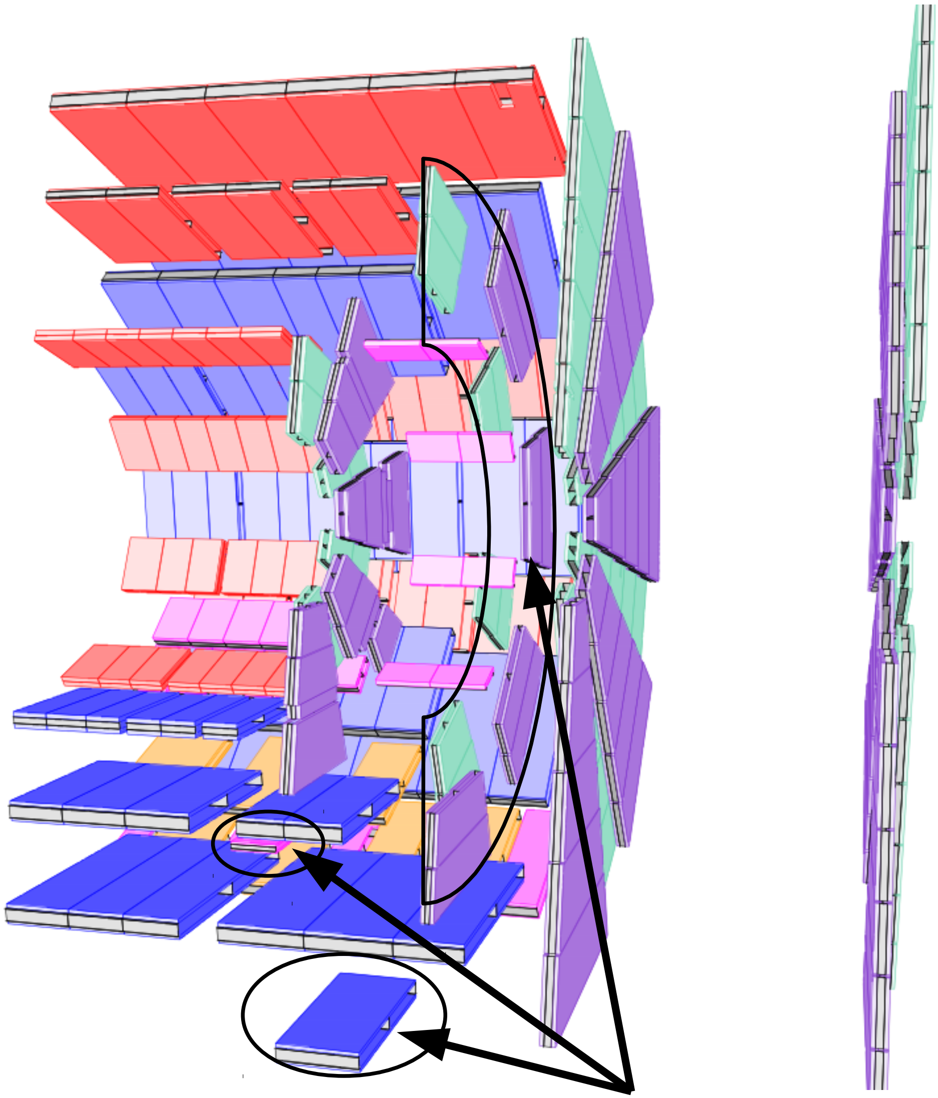
- All muon performance results are documented in:
  Eur. Phys. J. C (2016) 76:292
- Muon reconstruction is performing well, close to design level
  - MDT detector resolution: ~ 75 µm
  - MS alignment: ~ 30 to 70 µm (depending on region)
  - Reconstruction efficiency: close to 99% over large portion of (η,p_T) acceptance
  - Momentum scale uncertainty: ~ 0.5 to 3 ‰ (depending on η)
  - Momentum resolution: modeled with ~ 5 % uncertainty
- Many physics results with muons from ATLAS shown in this conference





Backup

Evolution with respect to run 1



Newly installed chambers during long shutdown 1 (2013-2014)