Muon reconstruction in ATLAS and CMS

Nenad Vranješ
Irfu - CEA Saclay

Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

ATLAS

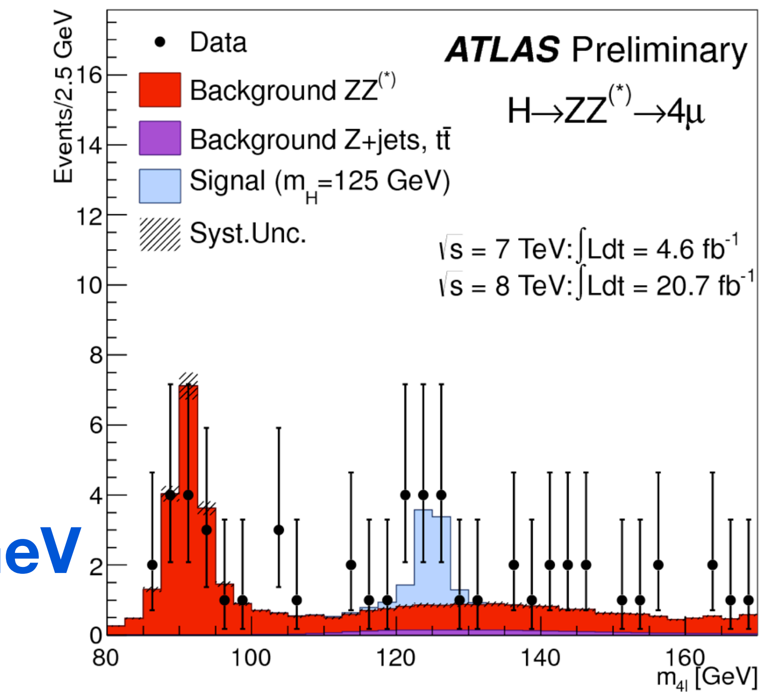
CMS

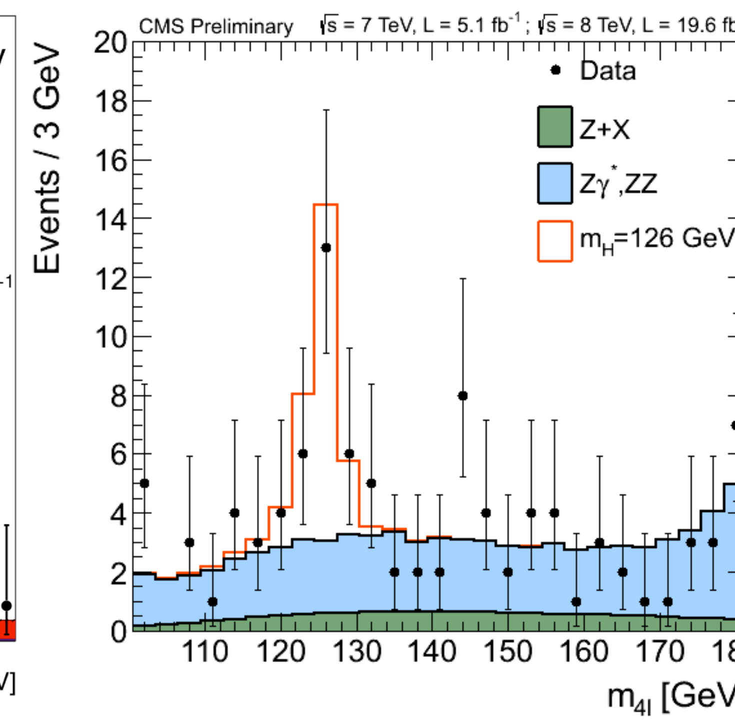
OUTLINE

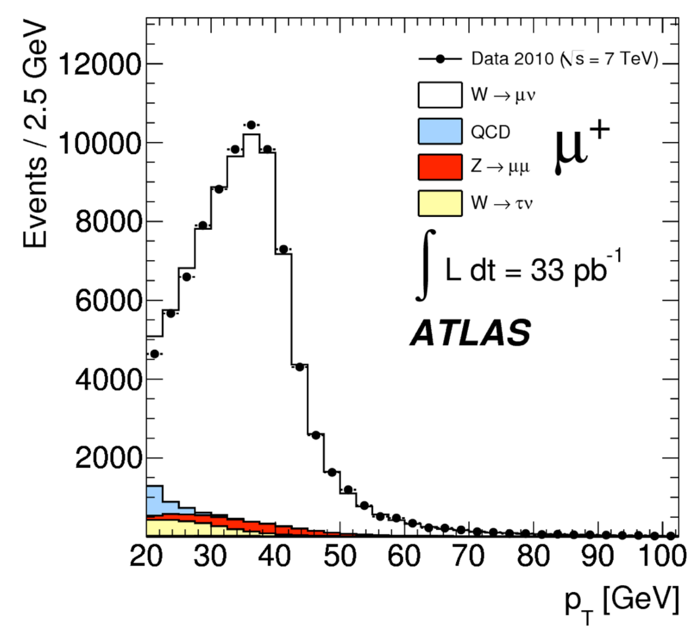
- Muon reconstruction at ATLAS and CMS
    - Muon reconstruction at ATLAS
    - CMS tracking
    - Muon identification and quality
- Muon reconstruction and identification efficiency
    - Data driven techniques using “standard candles” Z and J/ψ
    - Isolation efficiency, muon reconstruction in the presence of high pileup conditions
- Muon scale and resolution
    - Scale studies of the Muon and combined measurement
    - Resolution studies using $Z \longrightarrow \mu\mu$, corrections for the simulation
- FSR corrections for muon reconstruction
- Hight Pt muon performance (p_T>100 GeV)
    - Searches for high mass objects (W’,Z’), precision measurement (high mass DY)

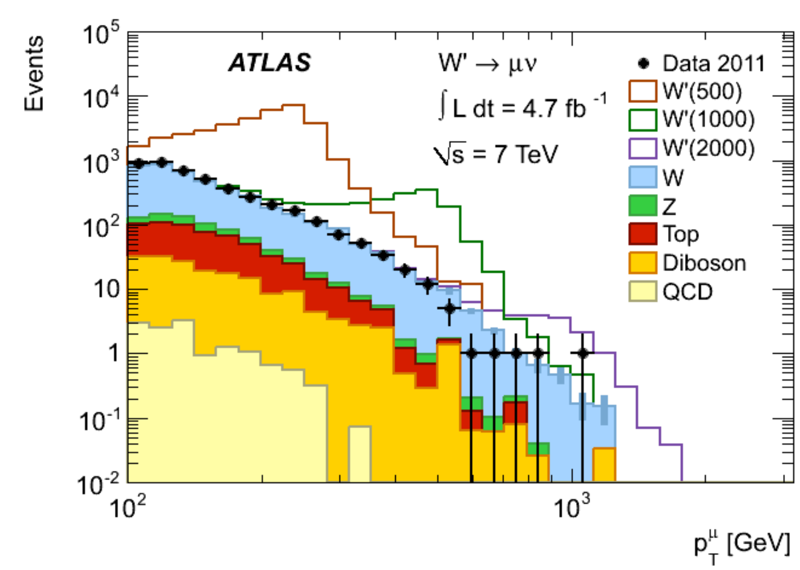
PHYSICS WITH MUONS

- B physics program $p_T \sim$ 5-20 GeV
  - $B^0_s \longrightarrow \mu\mu$, $J/\psi \longrightarrow \mu\mu$
- Precision measurement of EWK parameters
  - Leptonic signatures of W, Z and top
- Higgs physics $p_T \sim$ 50 GeV
  - H ⟶ ZZ,WW, HZ, HW, ttH
- BSM searches $p_T \lesssim$ 1-2 TeV
  - MSSM A/H/h ⟶ μμ
  - Z`, W`, leptoquarks
  - SUSY searches
- Robust muon reconstruction for different p_T regions
  - High efficiency and purity, excellent resolution and momentum scale



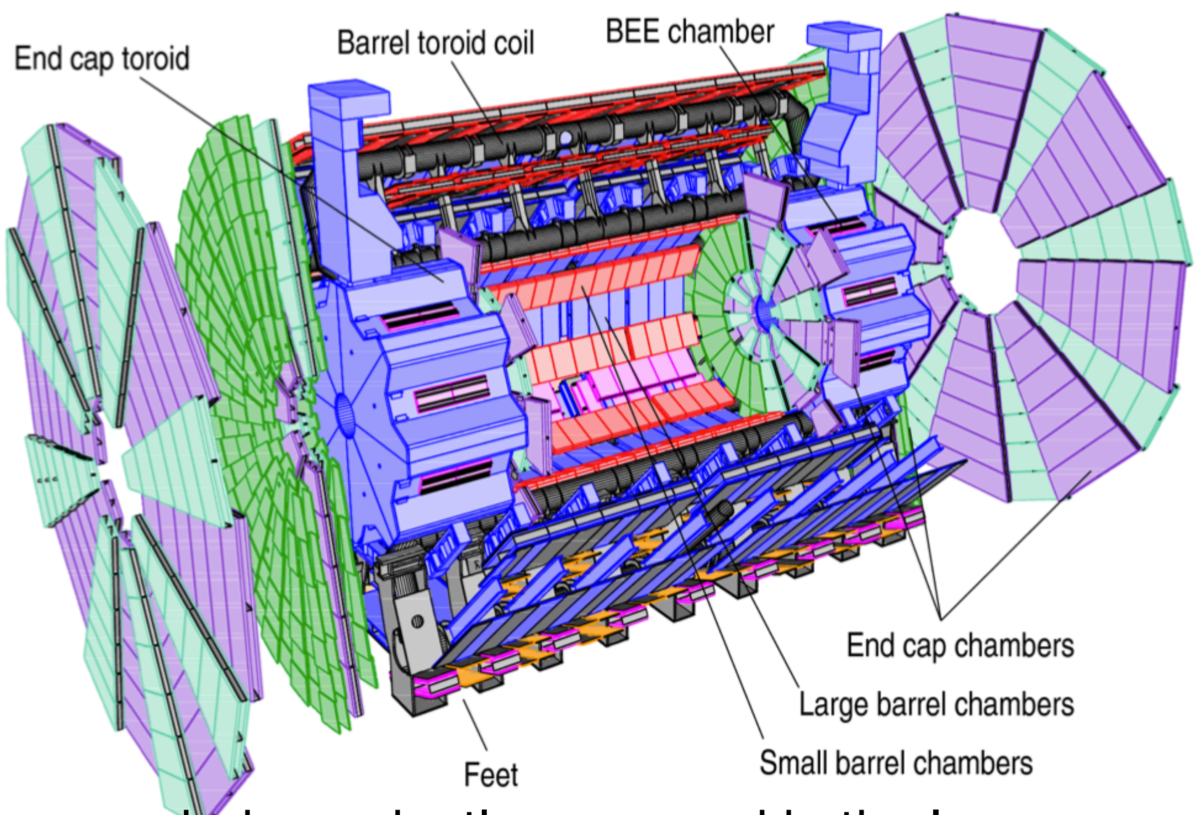


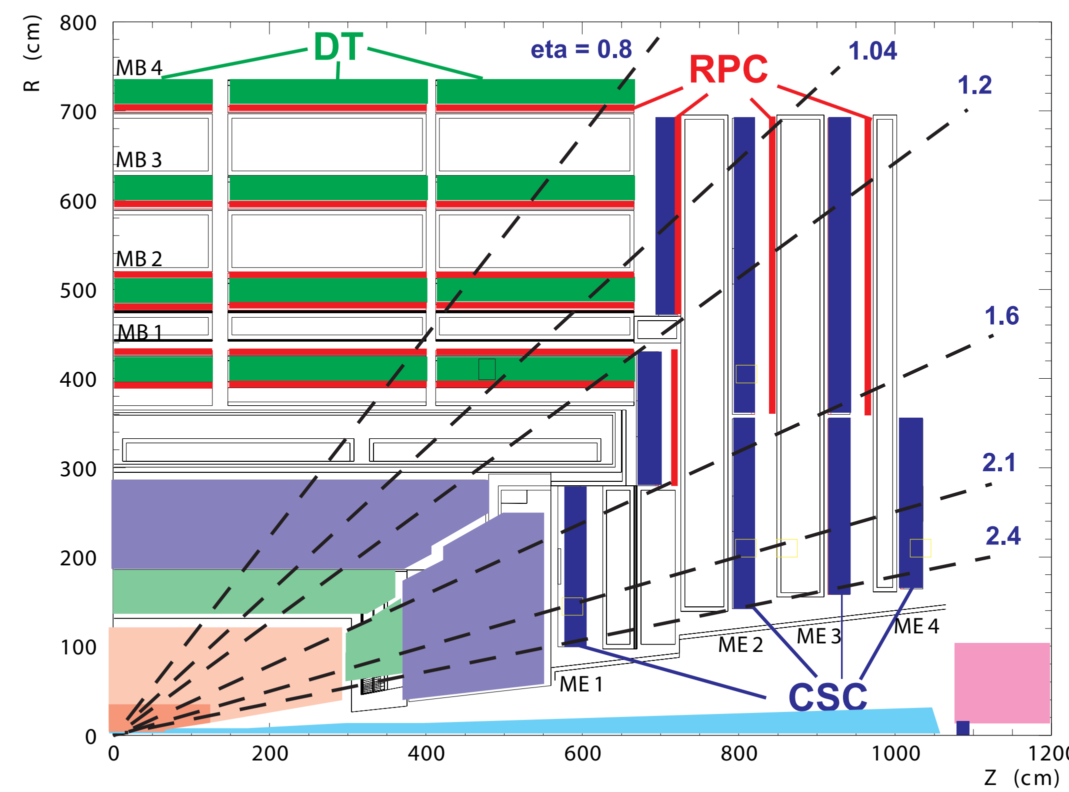




https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MuonPerformancePublicPlots
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO?skin=drupal#CMS_Muon_Results

MUON DETECTION AT ATLAS AND CMS





- Muons are independently measured in the Inner Detector (2T field, |η|<2.5), and Muon Spectrometer (approximately 0.5 T, |η|<2.7)
- MDT, CSC technology for the precision measurement RPC, TGC for triggering (|η|<2.4)
  - barrel (|η|<1.05), transition (1.05<|η|<1.7), endcap (1.7<|η|<2.0), and forward region (|η|>2.0)

- Muon reconstruction performed using all silicon inner tracker in 3.8T field, |η|<2.5
- Muon system for triggering, identification and improvement of the momentum measurement and charge determination,|η|<2.4
- DT, CSC, RPC technologies
  - barrel (|η|<0.9), transition (0.9<|η|<1.2), endcap (1.2<|η|<2.4)

✦ CMS: solenoid with higher radius and higher field ⇒ very good resolution in barrel, degrades quite fast with η

✦ ATLAS: combination of solenoid + toroid ⇒ resolution nearly constant with η

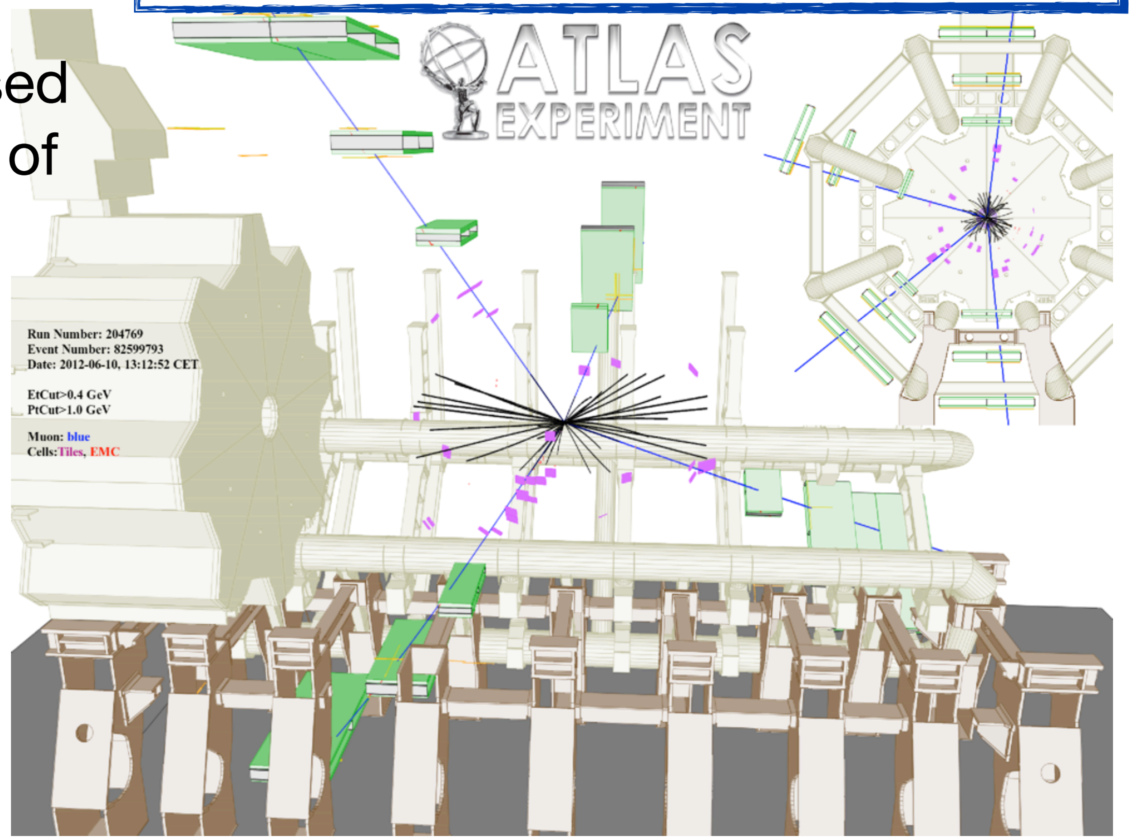
RECONSTRUCTION ALGORITHMS AT ATLAS

- Four classes of reconstructed muons
  - Stand-alone muons (SA), muon trajectory reconstructed only in MS with extrapolation of the track parameters to the interaction point taking into account energy loss in the calorimeter
  - Combined Muon (CB): track is formed from the successful combination of the SA and Inner Detector track
  - Segment Tagged (ST) muon is the ID track identified as muon if matched to at least one segment in the precision chambers
  - Calorimeter Tagged (CT), calorimeter deposition used for tagging, main application for $\eta \sim 0$, lowest purity of all muon types.
- CB muons are highest purity candidates
  - Efficiency is driven by the MS geometry
- ST higher efficiency especially for low-p_T muons
  - Overall muon efficiency reaches ~98% at the plateau
- Collections merged to avoid overlap

RECONSTRUCTION STRATEGIES

✦ Statistical combination of the ID and MS track parameters.
✦ Simultaneous track fit of the ID and MS hits. Less stringent hit requirements.

General quality criteria for the muon selection across the ATLAS, final selection analysis dependent.

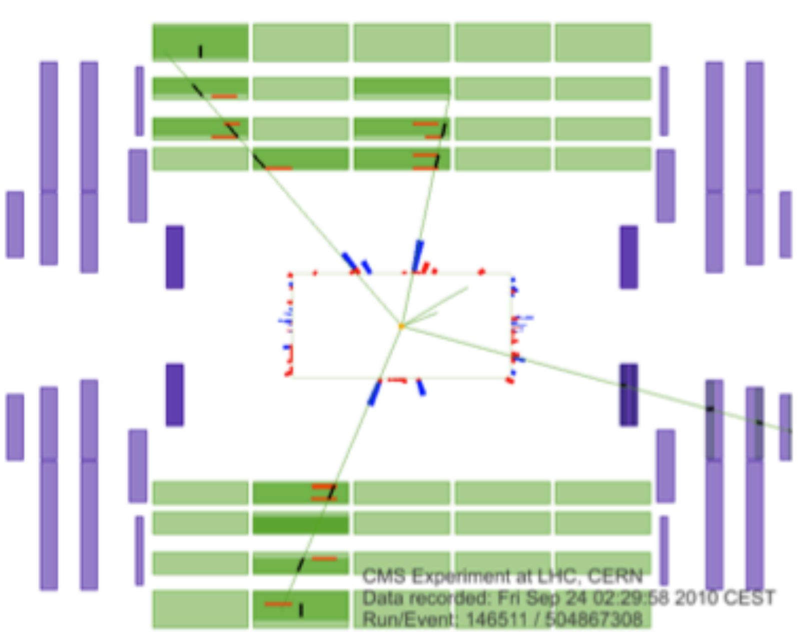


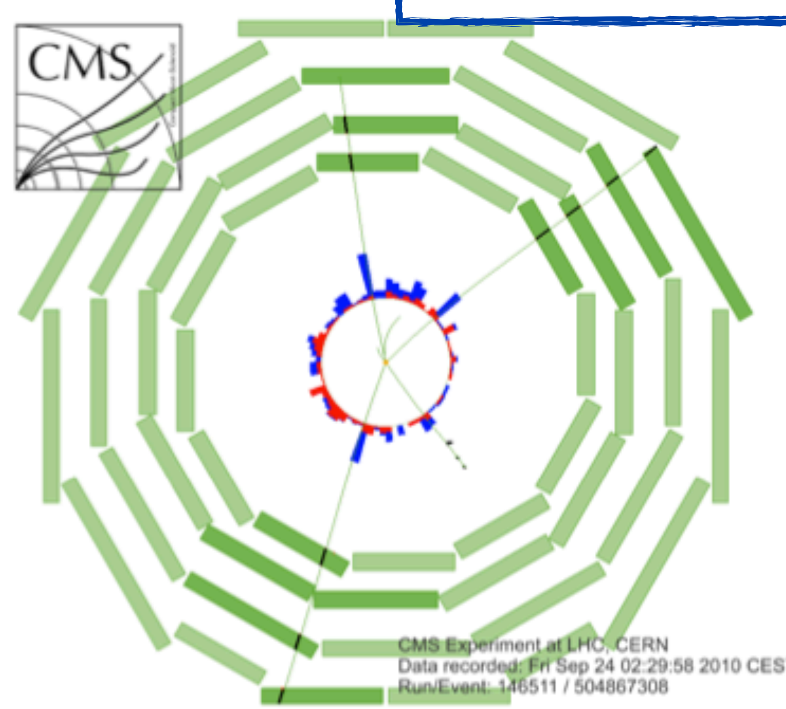
RECONSTRUCTION ALGORITHMS AT CMS

- Independent reconstruction: tracker track and standalone muon track
    - Global muon refitted using hits from two trackers using Kalman filter techniques
    - Tracker Muon: tracker track with at least one matching segment
    - Dedicated algorithms for high-p_T muons (TPFMS,Picky)
- Robust and efficient muon reconstruction
  - 99% efficiency within acceptance
  - Candidates with same inner track merged into one collection

IDENTIFICATION

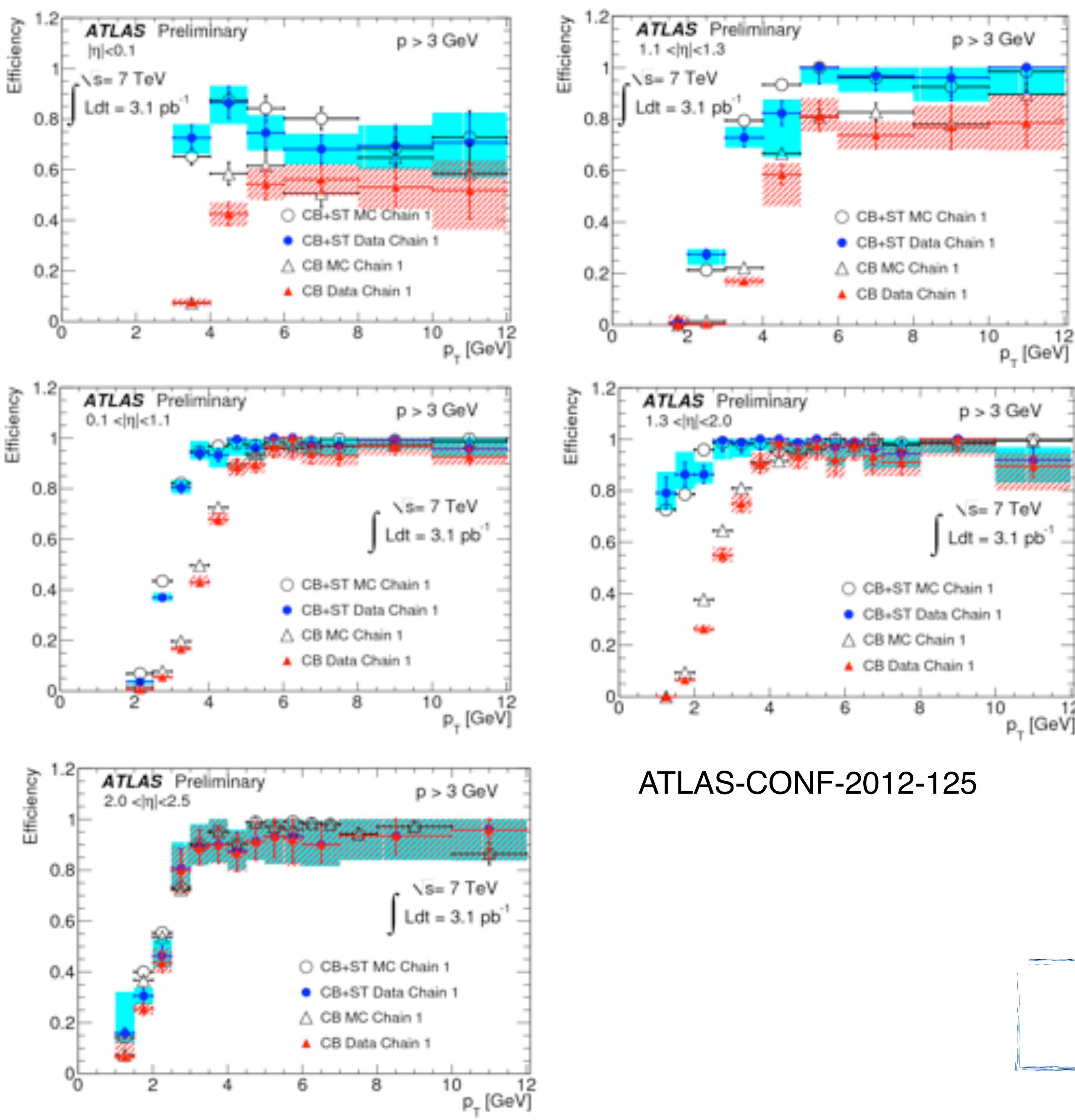
✦ Tight: global muon reconstruction + quality criteria on hits, segments and impact parameters. Used for most analysis like W/Z or Higgs.
✦ Soft: tracker muon matched with muon segment not used for other muon tracks, dedicated for muons with pT<10 GeV.
✦Loose: global or tracker muon identified by the particle flow algorithm.



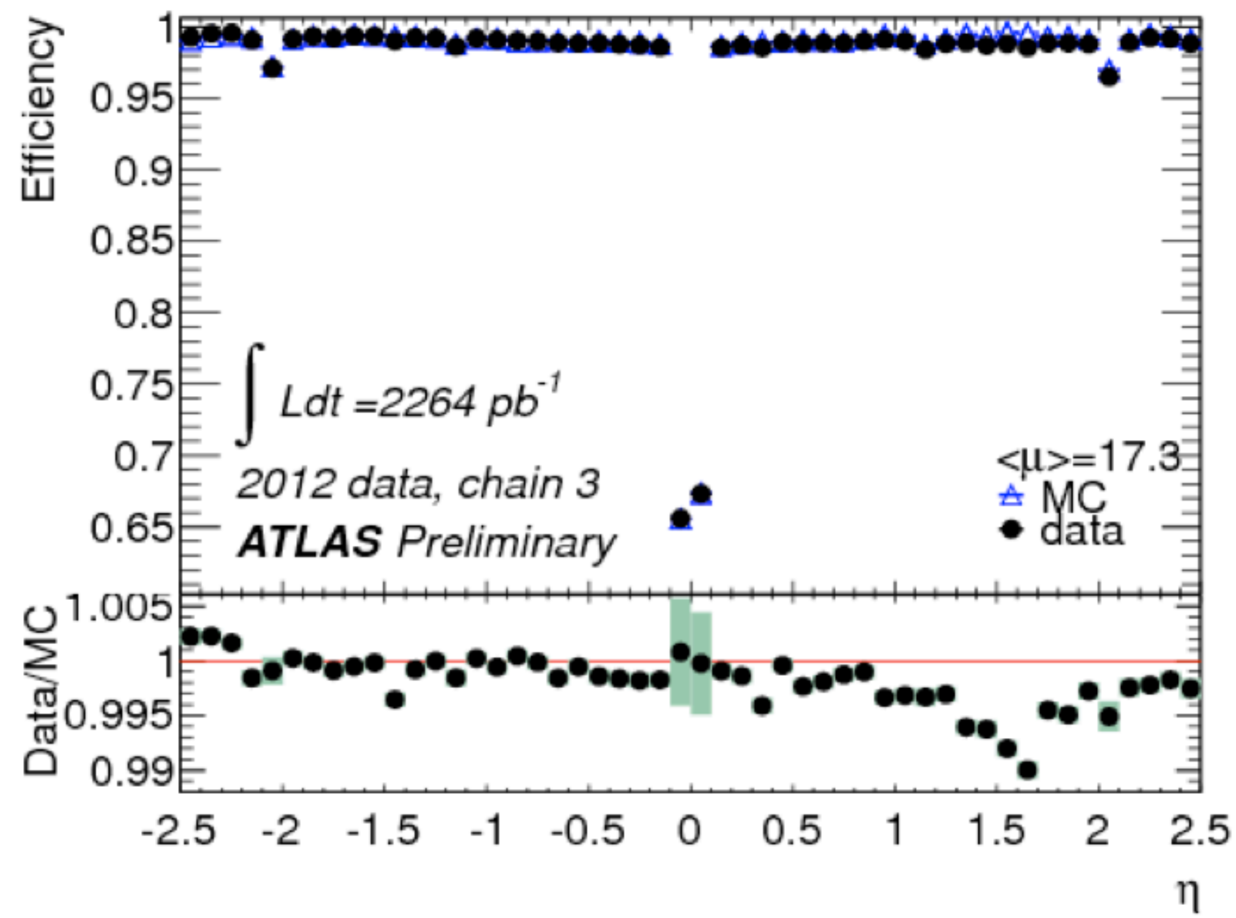


RECONSTRUCTION AND IDENTIFICATION EFFICIENCY

- J/ψ, Z ⟶ μμ tag and probe
  - unbiased measurement of the trigger and muon reconstruction efficiency
  - probes are ID or MS tracks depending of the measured quantity
  - invariant mass of the tracks around resonance (J/ψ for low p_T, Z for intermediate p_T)



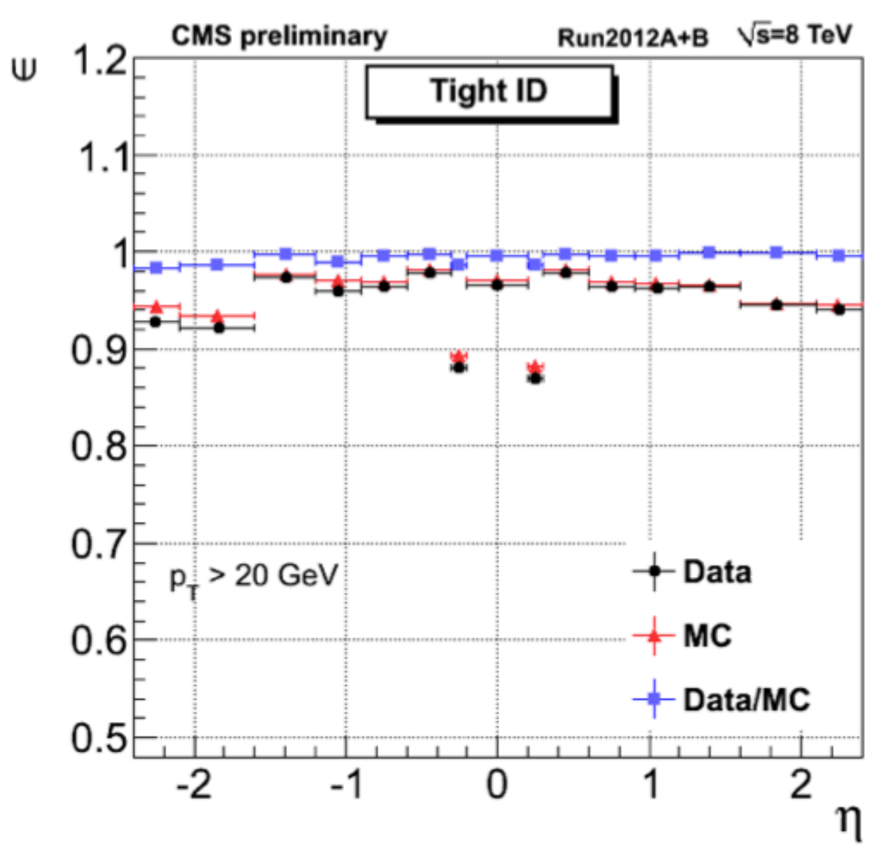
ATLAS-CONF-2012-125

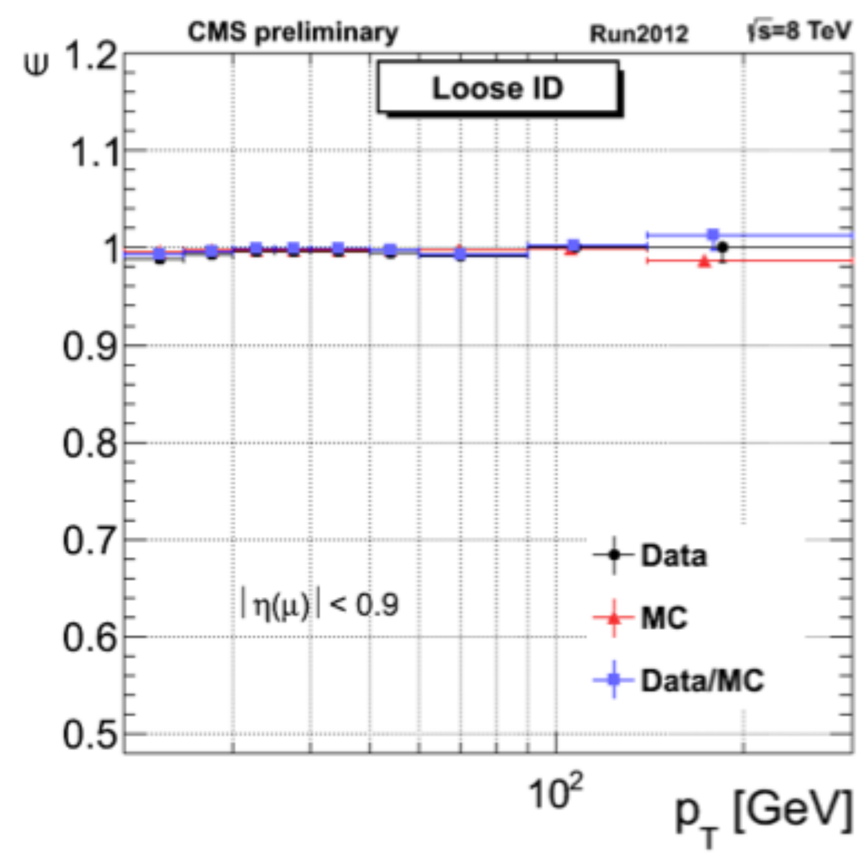


Good agreement data/mc within 1%

RECONSTRUCTION AND IDENTIFICATION EFFICIENCY (2)

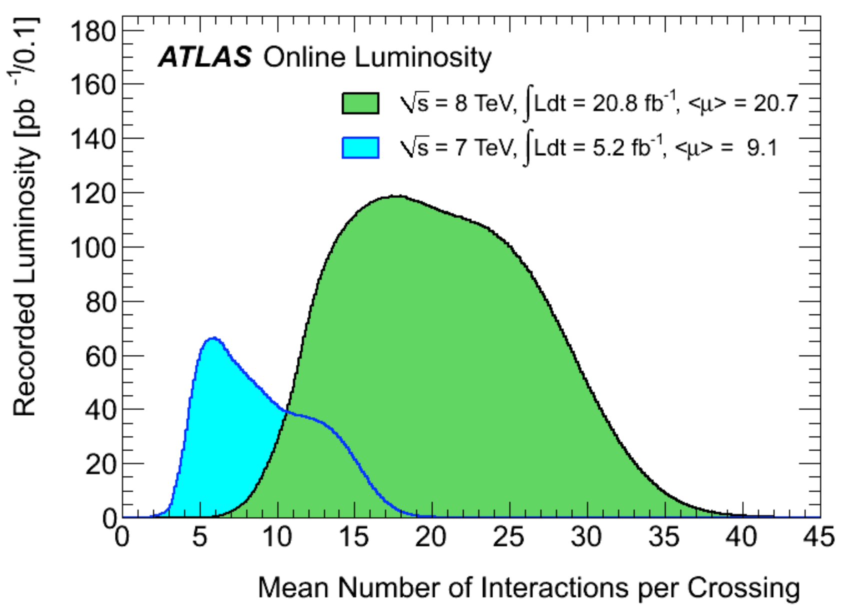
- Similar approach at CMS: $\epsilon_{\mu} = \epsilon_{track} \cdot \epsilon_{rec+id} \cdot \epsilon_{iso} \cdot \epsilon_{trig}$
- Tracker efficiency > 99% within the whole tracker acceptance
- data/MC agreement better than 1% for Tight, 1-2% for Soft (due to track-segment matching pulls)
- Tight/Soft/Loose/ muons plateau reached at p_T~10/4/6/ GeV
- Systematics: background modeling and opening angle separation (J/ψ), isolation (background) for Z

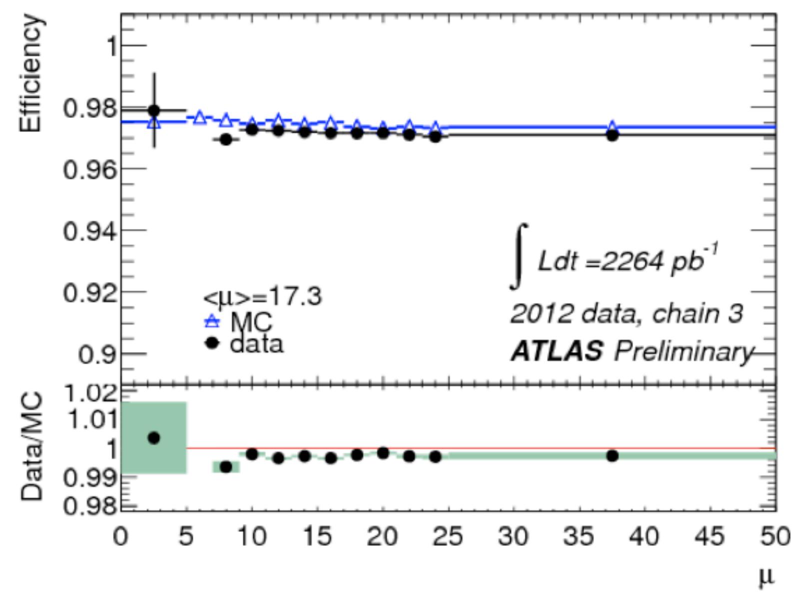




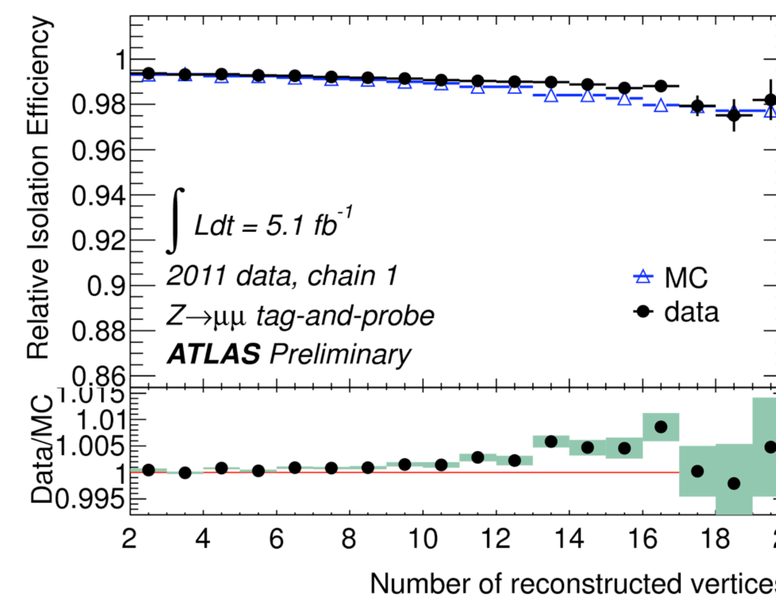
ISOLATION EFFICIENCY, PILEUP

- Important for many analysis, estimated with tag&probe $Z \longrightarrow \mu\mu$
- Effect of pileup on the muon reconstruction is small
  - flat versus N_{vtx} or <μ>, marginal impact on track isolation
  - Calorimeter isolation affected, corrected for data/mc pileup

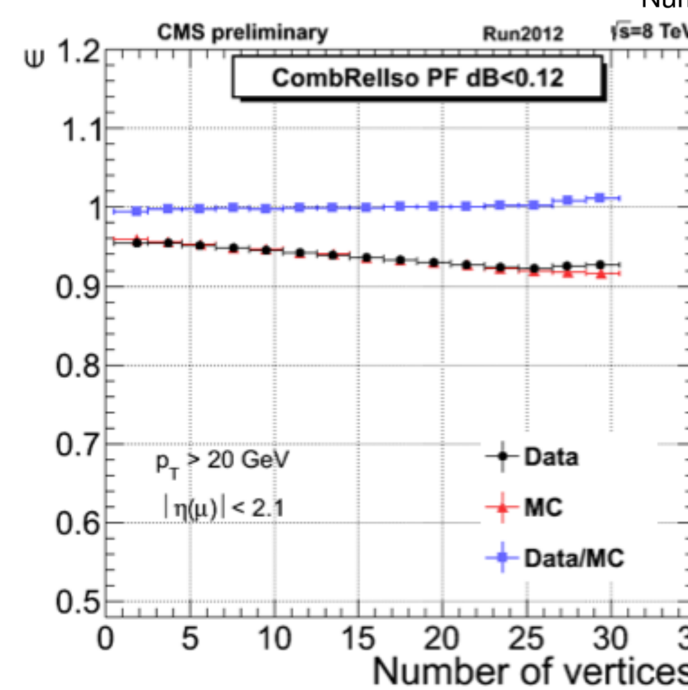




calorimeter isolation

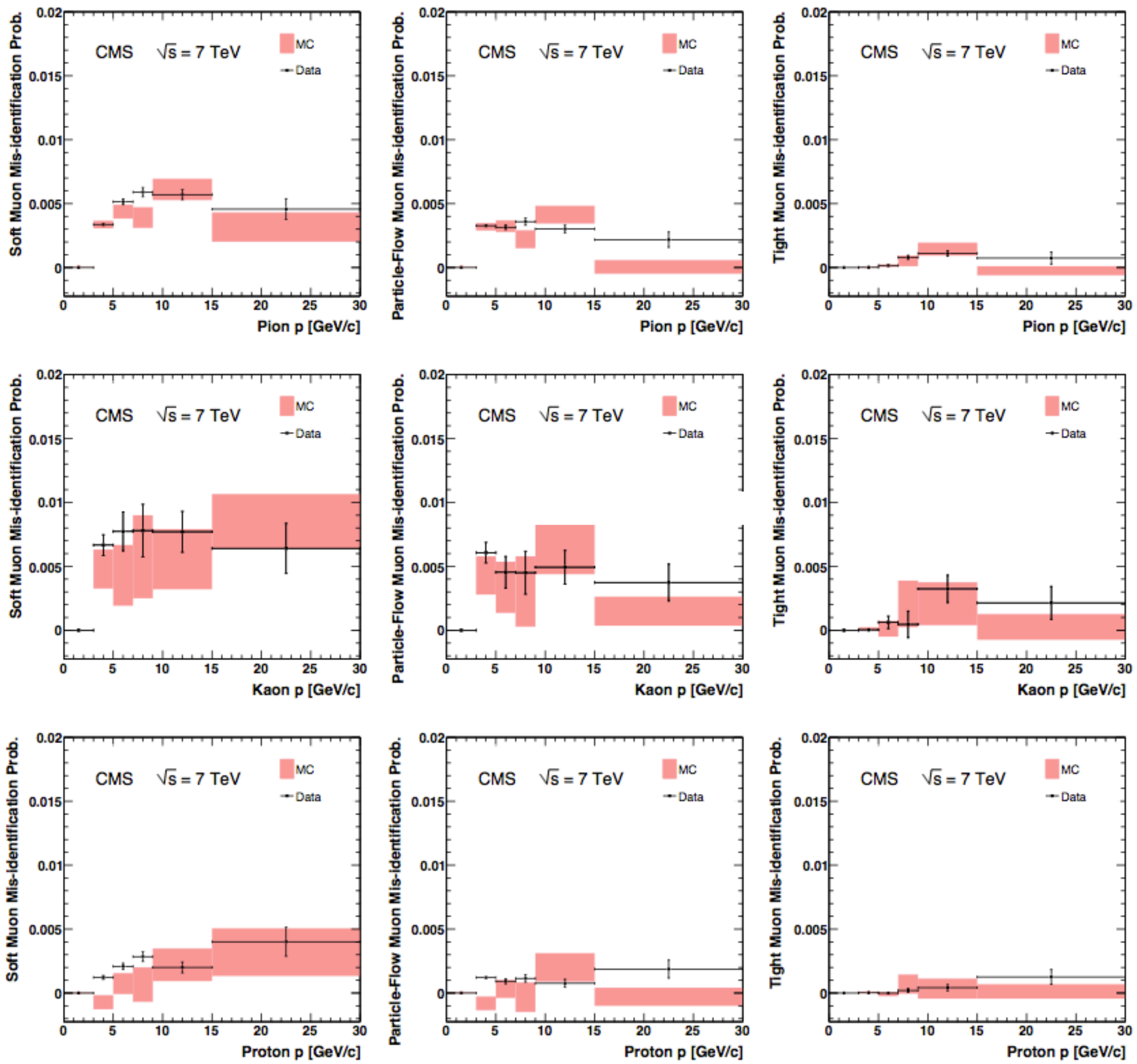


- CMS:
  - track, calorimeter, and particle flow distribution
  - Z tag and probe and LKT
    (Lepton Kinematic Template) method
  - data - MC <1.5%



MISIDENTIFICATION

- Hadron tracks could be reconstructed as muons as punch-troughs or decay in flight
- Ks, Λ, ϕ resonances
    - easy to reconstruct from tracker
    - Compute fraction of events with misidentified muons
- Fit of the mass spectrum in events with and without muon identified
    - Same method for data and MC

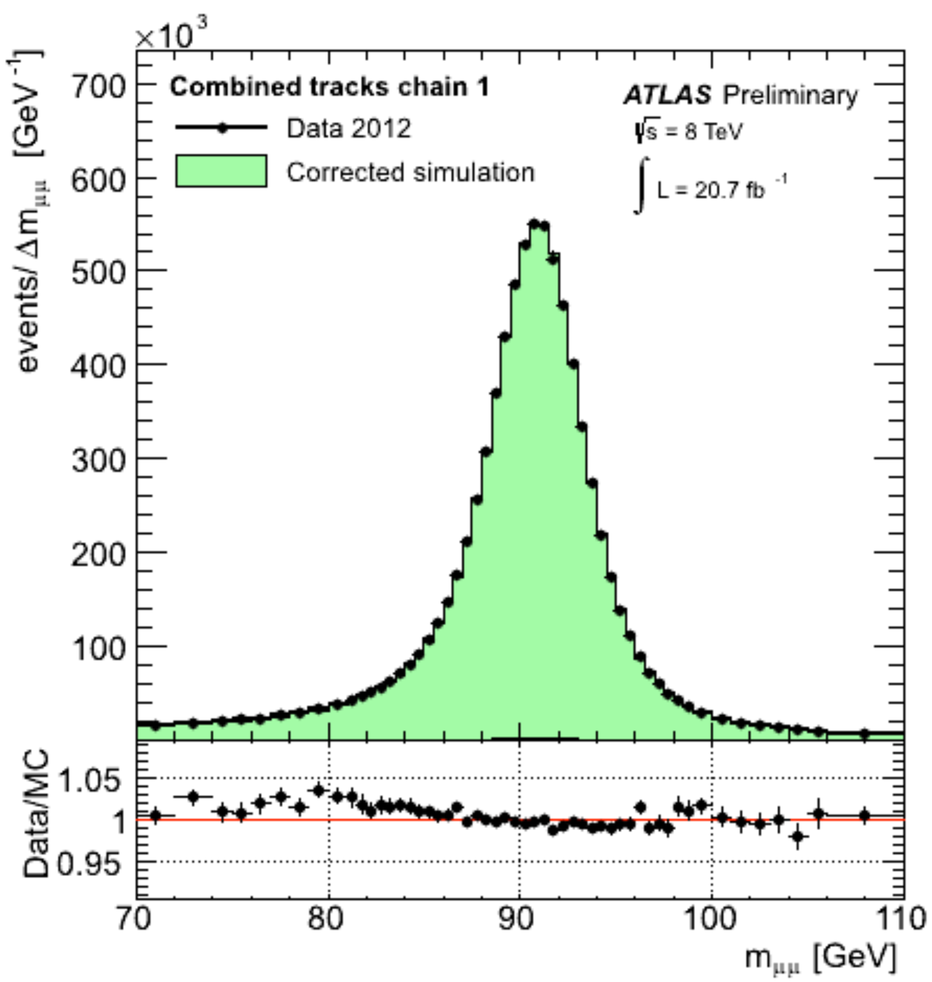


2012 JINST 7 P10002

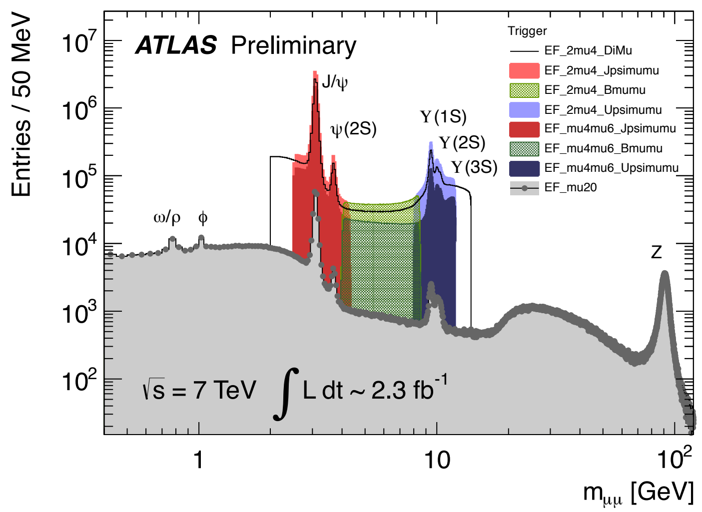
- Overall small fake rate:
    - Pions and Kaons at ‰ level, significantly decrease p_T >10-15 GeV, protons 0.1%
    - mainly for Soft and Loose muons, much less for Tight
    - independent of the azimuthal angle and decay length.

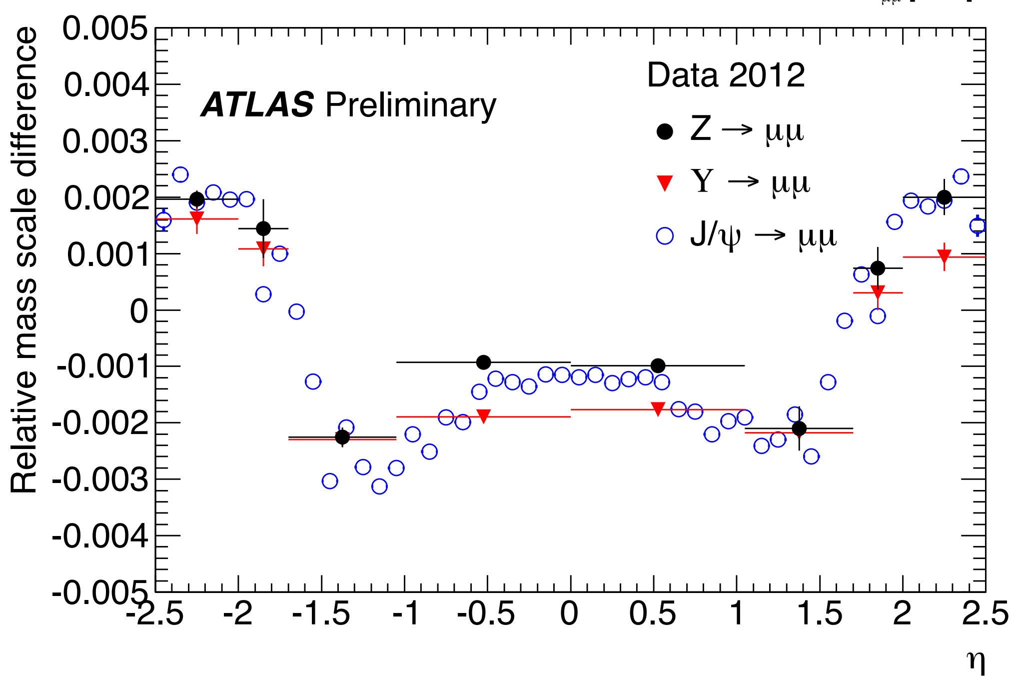
MOMENTUM SCALE

- Muon p_T is highly sensitive to the alignment of the tracker and of the muon chambers, to the composition of material and its distribution inside the tracking volume, and to the knowledge of the magnetic field inside and outside the solenoid volume.
  - CB momentum in addition suffers from relative ID-MS misalignment
- High statistics J/ψ, Υ(1s,2s,3s), and Z ⟶ μμ scales used to assess muon scale calibration and derive systematic uncertainty
- Absolute scale shift ~1.0 ‰ - 2.0 ‰ with good linearity in p_T



Effect of corrections (full 2012 dataset).





MUON MOMENTUM RESOLUTION

- Studies using Z ⟶ μμ, resolution is the width of a Gaussian which is convoluted with the dimuon mass resolution at generator level.

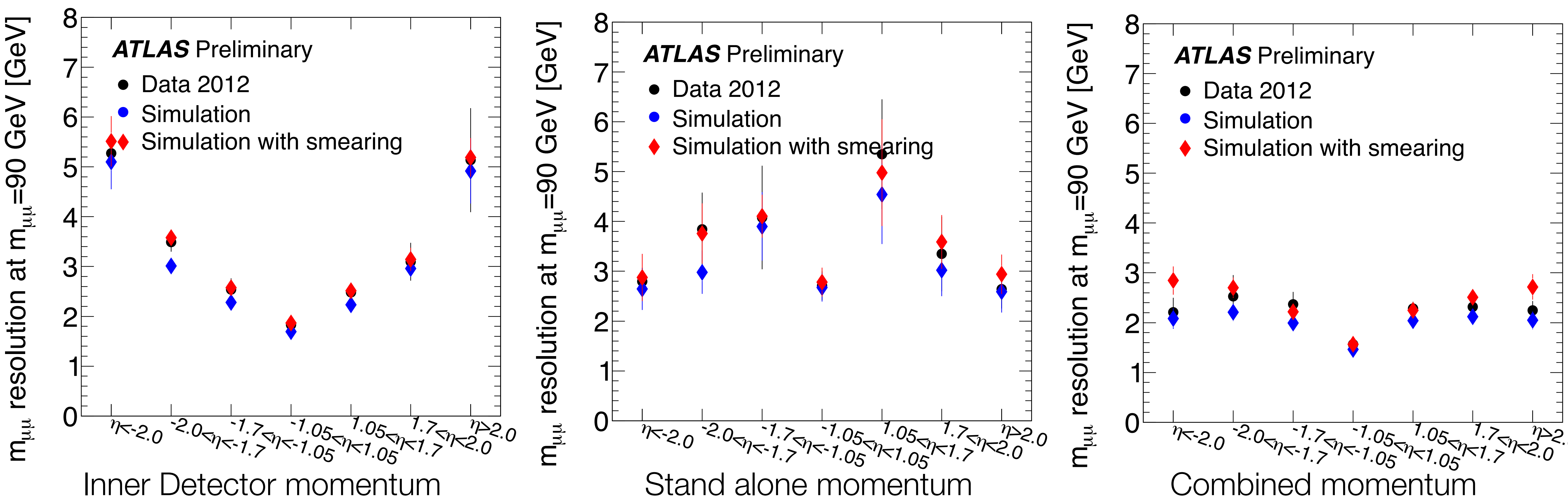
	a (%)	b (1/TeV)	c (GeV)
ID	***1.60 ± 0.32***	***049 ± 0.04***	
MS	***3.75 ± 0.10***	***0.24 ± 0.04***	***0.23 ± 0.01***

$$\frac{\sigma_{ID}(p_{\mathrm{T}})}{p_{\mathrm{T}}} = a_{ID}(\eta) \oplus b_{ID}(\eta) \cdot p_{\mathrm{T}}$$

$$\frac{\sigma_{SA}(p_{\mathrm{T}})}{p_{\mathrm{T}}} = a_{MS}(\eta,\phi) \oplus b_{MS}(\eta,\phi) \cdot p_{\mathrm{T}} \oplus \frac{c(\eta,\phi)}{p_{\mathrm{T}}}$$

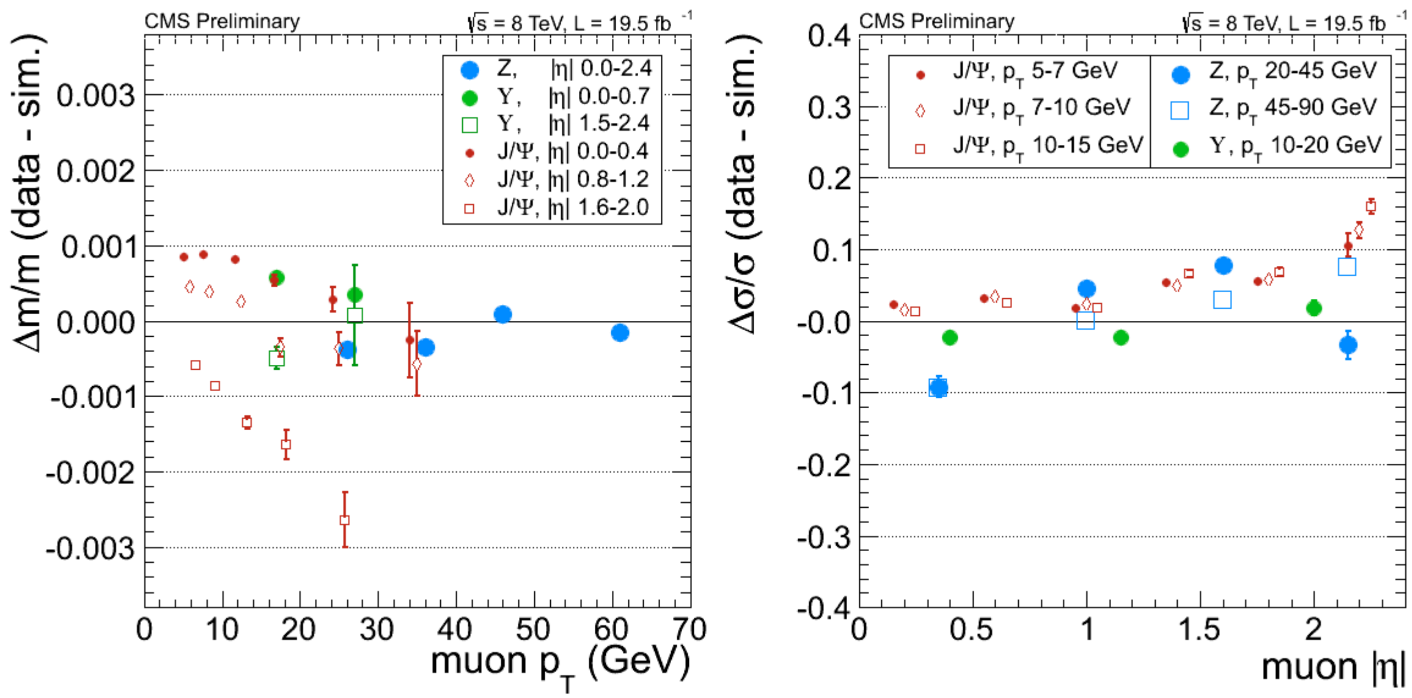
a - multiple scattering, **b-** intrinsic resolution, **c** - fluctuations of energy loss (MS only)

- Residual smearing corrections to the reconstructed muon momenta applied by the amounts necessary to reproduce the measured mass resolutions. Corrections in η- and ϕ- bins.



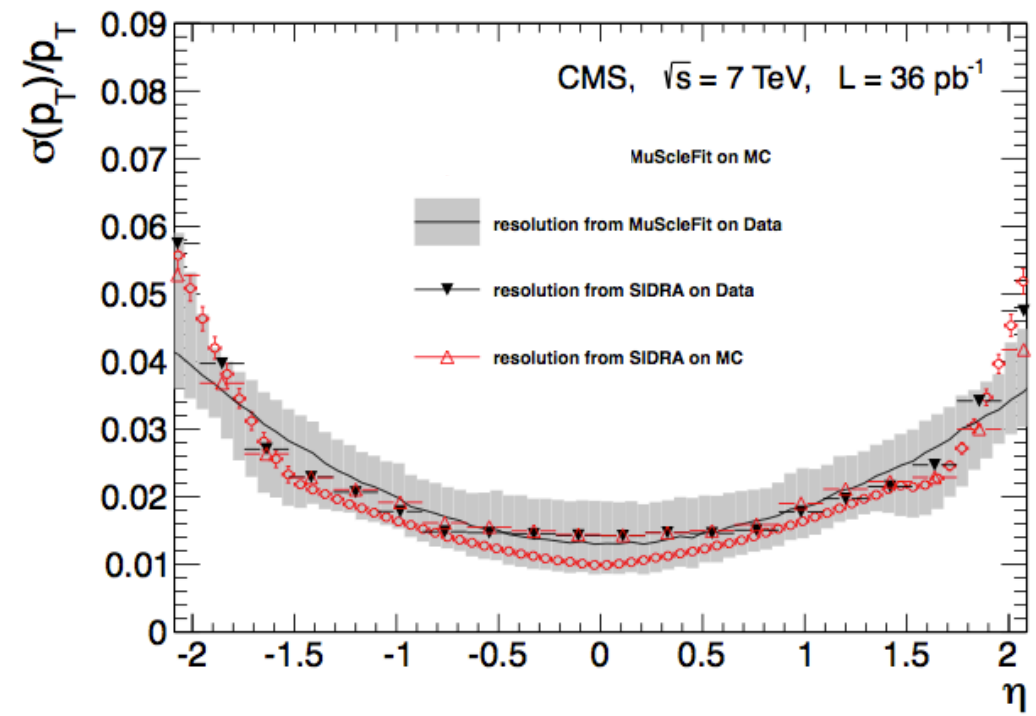
MOMENTUM SCALE & RESOLUTION AT CMS

- Momentum scale determined in-situ using J/ψ, Z ⟶ μμ, and cosmic rays
  - Muon momentum Scale Calibration Fit, absolute scale and resolution, Z lineshape convoluted with Gaussian
  - Correction by matching $1/p_T$ distribution of muons from Z to generator level in bins of (charge, p_T, η)
- Overall 0.1% uncertainty on the momentum scale



CMS-PAS-HIG-13-002

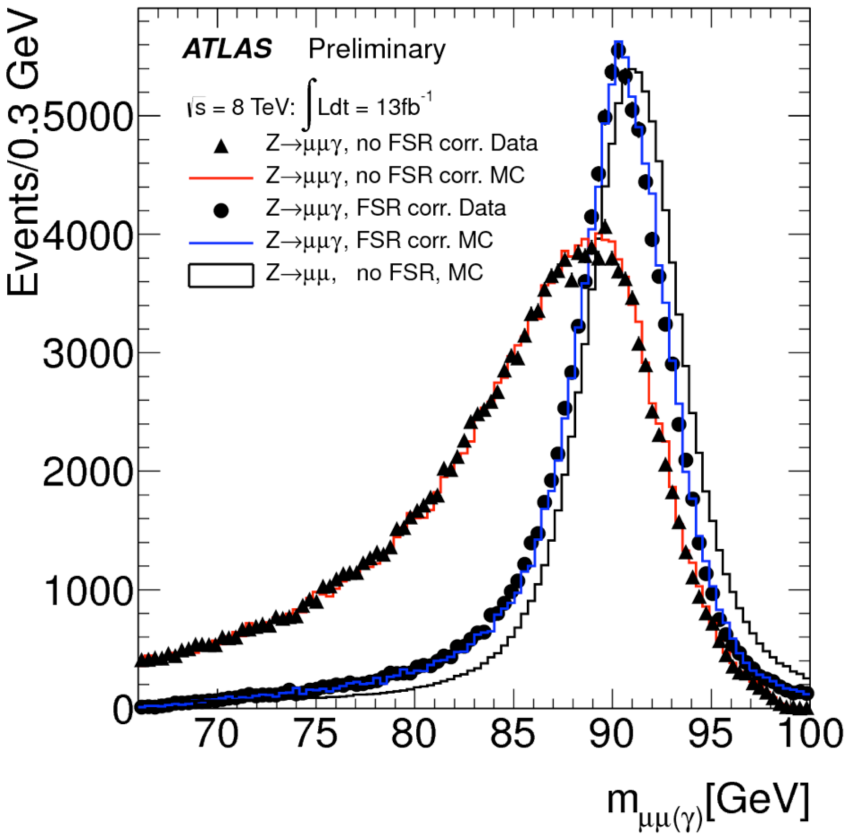
- Resolution studies: MuScleFit
- Correlation between two muons from Z, neglecting angle resolution and covariance terms
- Uncertainties dominated by the choice of the functional form of the resolution and theory
- Relative uncertainty 1.3-2% in barrel, and up to 6% in the endcap for $p_T \sim M_Z/2$
- Good agreement between data and simulation

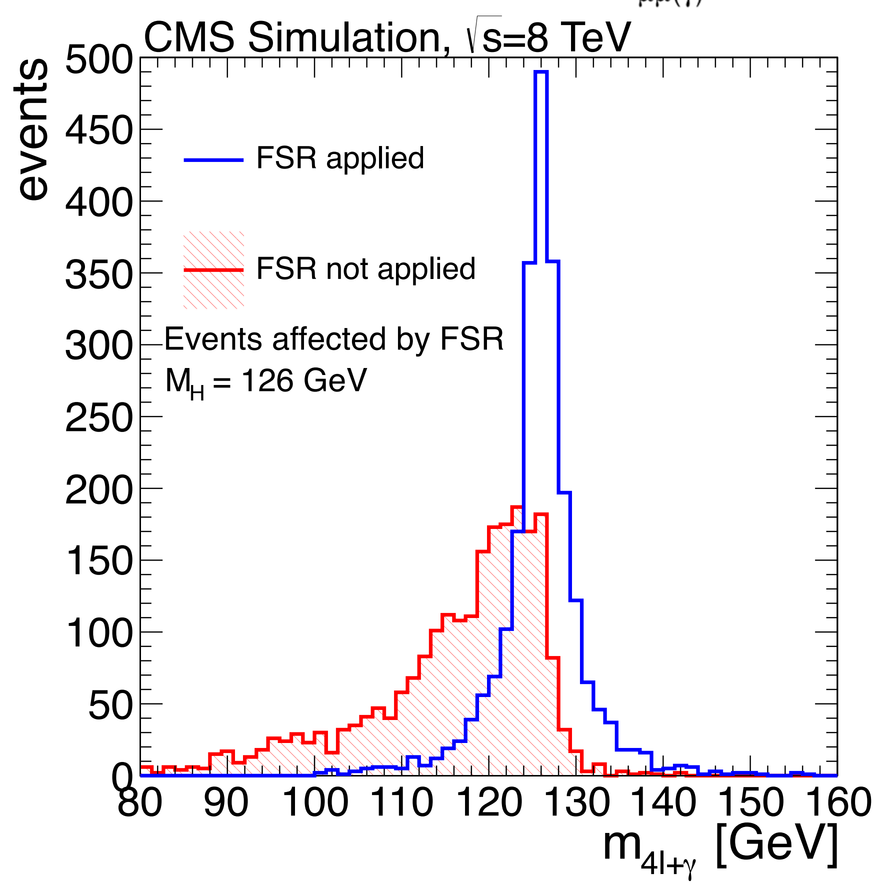


$$p'_T = p_T(1 + b \cdot p_T + c \cdot \eta^2 + q \cdot d \cdot p_T \cdot \sin(\phi + e))$$

2012 JINST 7 P10002

RECONSTRUCTION OF COLLINEAR QED FINAL STATE RADIATION PHOTONS IN Z →μμ





- Standard ATLAS reconstruction of photons well-separated from Z-boson muons is extended by exploiting the longitudinal segmentation of the ATLAS liquid argon calorimeter to reconstruct photons collinear with the muons emitted in the Z decay.
  - Reconstructed clusters are classified as signal (FSR photons from Z decays), hadronic background (including the contribution of pile up interactions) and clusters originating from muon ionization in the EM LAr calorimeter.
  - Improvement to the scale and resolution of the reconstructed Z events
  - Collinear FSR improvement is applicable to 5% of $Z \to \mu\mu$ even.

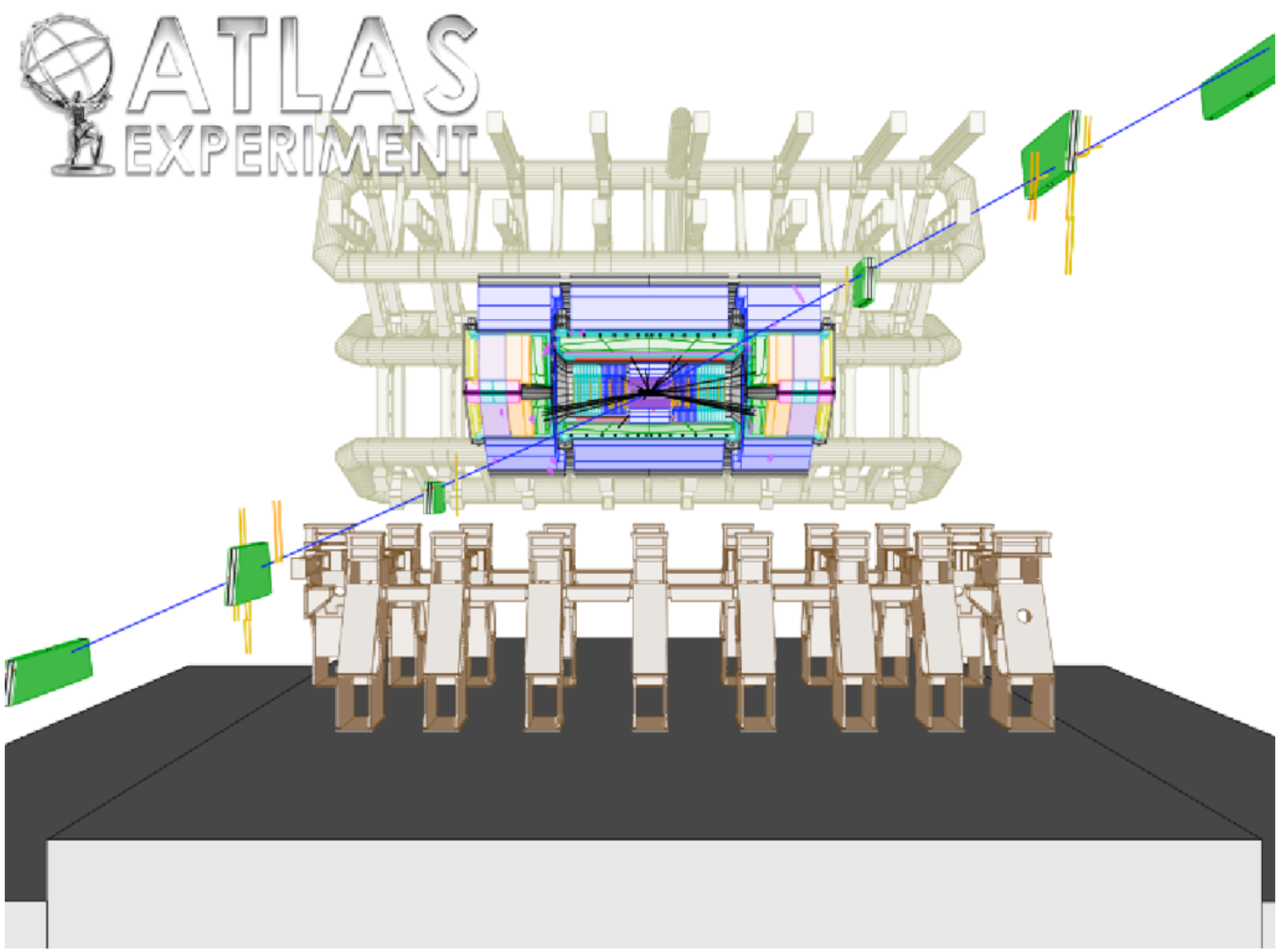
ATLAS-CONF-2012-143
ATLAS-CONF-2013-013

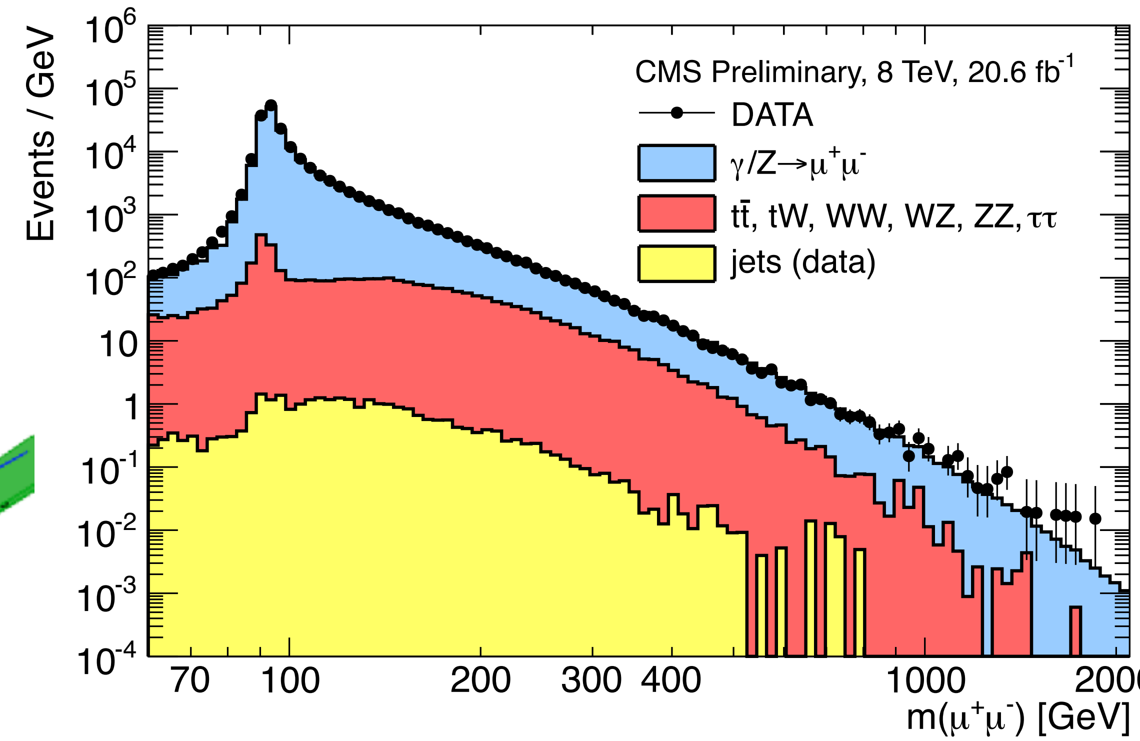
- FSR correction applied in CMS Higgs to 4μ/4e/2μ2e search
  - Selection of (isolated) photons with p_T>2(4) GeV for $\Delta R(\gamma,\mu)<0.07(0.5)$
  - Isolation is obtained by summing over the transverse momenta of charged Iso hadrons, other photons and neutral hadrons identified by the PF
  - 3/2/1% gain in efficiency for $H \to 4\mu/2e2\mu/4e$

CMS-PAS-HIG-12-016

HIGH MOMENTUM PERFORMANCE

- Exotic searches (e.g. W’,Z’), probe muons with *O*(1TeV)
- Mainly affected by misalignment and catastrophic energy loss, as well as pattern recognition problems due to showers in the Muon system
- Rely on the Z checks and extrapolation based on simulation
- Constrained with cosmic ray studies at the beginning of data taking





Event display of the selected event with the highest dimuon invariant mass. The highest momentum muon has a p_T of 289 GeV and an η of 1.54. The subleading muon has a p_T of 274 GeV and an η of -1.35. The invariant mass of the pair is 1258 GeV.

SUMMARY

- Muon objects are used in most of the analysis at ATLAS and CMS
  - Several algorithms developed to ensure robust and high efficient reconstruction and identification of muons
  - exploit different parts of the detector: tracker, muon system and calorimeter
  - efficiency close to 99% within acceptance
- In situ techniques for the measurement of the muon reconstruction efficiency, momentum scale and resolution using standard candles such as J/ψ, Υ, and $Z \longrightarrow \mu\mu$
- Correction factor estimated to remove residual discrepancies of data and simulation
- Typical systematic uncertainties 1% for efficiency to 0.1% for scale and resolution
- Further studies needed to constraint systematic uncertainties for the very high precision measurements like in Mw