Measurements of the differential and double-differential Drell-Yan cross sections in the dimuon channel with the CMS detector at the LHC

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On behalf of the CMS Collaboration

Outline

- Introduction
- The CMS detector
- Analysis procedure
  - Samples and Event Selection
  - Background Estimation
  - Acceptance and Efficiencies
  - Unfolding
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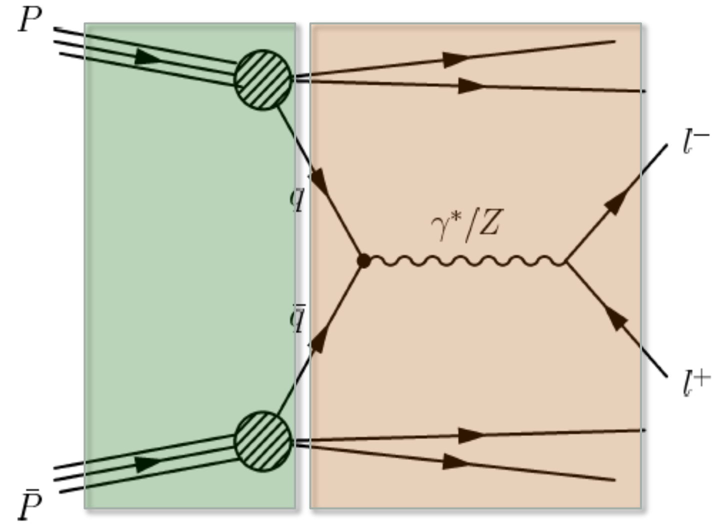
- Results

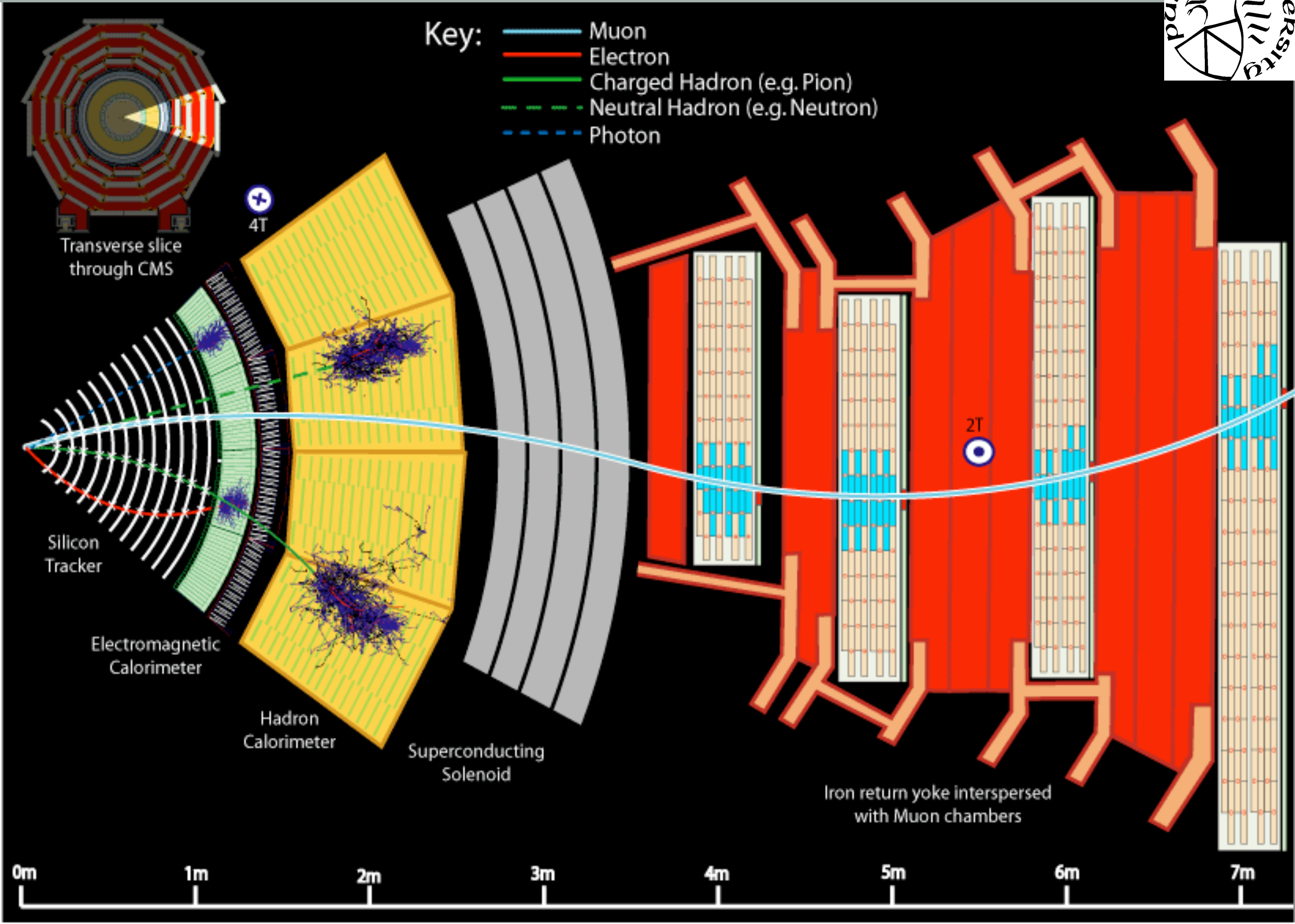
Introduction

Low p_T interactions: factored out in PDFs



High-p_T interaction: perturbative domain

- Why study the Drell-Yan process?
  - SM process, well understood theoretically
    - Possibility to test NNLO predictions
  - Important background for the searches for physics beyond the Standard Model
  - Cross section measured with hadron collider data can be used to constrain PDFs
- Why measure the double-differential cross section with the CMS detector?
  - dσ/dMdY is directly usable for the PDF constraints
  - Possibility to achieve a substantial improvement in precision compared to existing DY double-differential cross section measurements performed at low energies (fixed-target)
    - Especially for large dimuon masses
  - Identify possible deviations from fixed order Drell-Yan at low invariant masses and at large rapidities, as predicted from high energy re-summations or saturation models


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

Analysis procedure

- To measure the cross section per bin, we use the following formula:
  - $\sigma_{i,j} = N^{u}_{i,j}/(A_{i,j}\varepsilon_{i,j}\, C_{i,j}\, L_{int})$,
  - Note here, that the acceptance correction is not applied for 2D measurement, to provide a model independent measurement
- For 1D measurement, this simplifies to:
  - $\sigma_{i} = N^{u}_{i}/(A_{i}\varepsilon_{i}\, C_{i}\, L_{int})$
- **Analysis steps:**

1. Selecting Events
2. Subtraction of Backgrounds
3. Momentum scale and resolution correction
4. Acceptance and Efficiency correction using MC
5. Efficiency correction using data-driven methods
6. Correction for FSR effects based on MC
7. Systematic uncertainty estimation
8. Normalized cross section shape calculation
9. Comparison with theoretical predictions

i – mass bin
j – absolute rapidity bin
N^{U} – unfolded, background subtracted yield
A – acceptance
ε - efficiency
C – efficiency and FSR correction
L_{int} – integrated luminosity

40 mass bins for 1D measurement
6 mass bins for 2D measurement
24 absolute dimuon rapidity bins are used for all mass bins except for the highest mass bin, where 12 bins are used

Samples and Event Selection

- Full 2011 CMS dataset, containing **4.5 fb^{-1} of proton collision data** is used
- Drell-Yan samples are produced with POWHEG MC generator
- Trigger selection
  - Un-prescaled double muon trigger with no isolation requirement on the level of HLT is used (online muon p_T > 13,8 GeV)
- Candidate Selection
  - 2 muons with opposite charge
  - Select the highest vertex probability muon pair
- Kinematic selection
  - p_T > 14,9 GeV, $|\eta|$ < 2.4
- Muon identification
  - Each muon is reconstructed as a “tracker” and “global” muon
  - Muon track quality cuts
  - Track transverse impact parameter (w.r.t. beam spot) < 0.2 cm
- Isolation
  - Relative particle-flow Isolation

$$I = \sum_{particles} (p_T^{charged} + E_T^{neutral}) / p_T^{\mu}$$

- Di-muon vertex probability and 3D angle to reject cosmics and muons not coming from the same collision/process

Backgrounds (I)

- Most important backgrounds
  - Low-mass region: QCD multi-jets
  - Peak region:
    - Drell-Yan $\rightarrow \tau^+\tau^-$,
    - W $\rightarrow$ l + ν,
    - dibosons
  - High-mass region:
    - top pair production,
    - dibosons
- All the backgrounds except for QCD are estimated from MC
- The data-driven ABCD method is used to estimate the QCD background
  - Systematics is significantly lower compared to MC based estimation (1% against 20%)
- Same techniques are applied for 2D measurement

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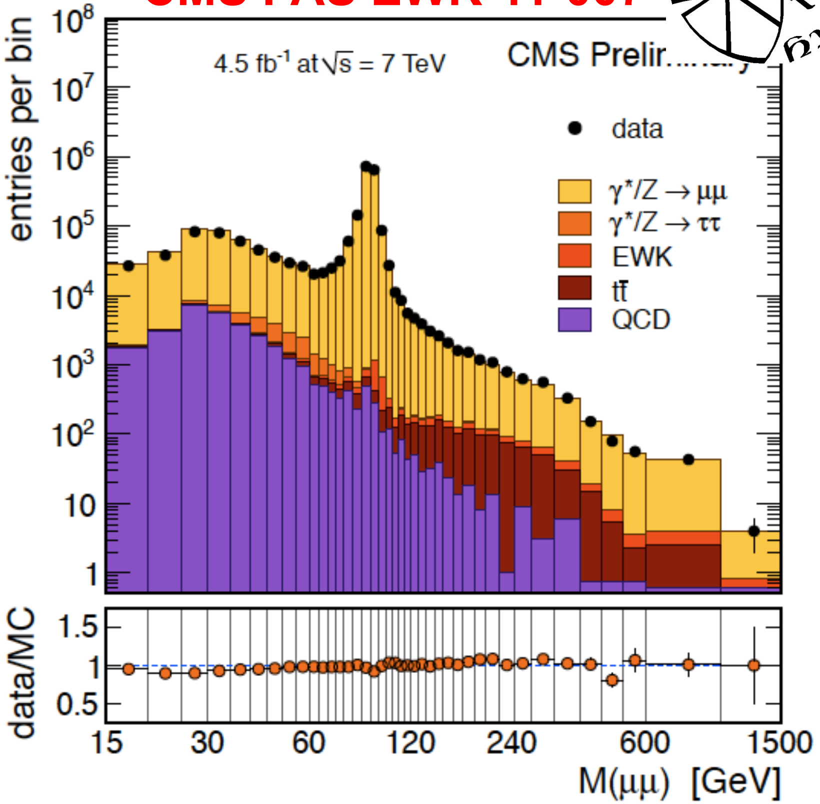

The observed dimuon invariant mass spectrum in the detector acceptance for data and MC events. The signal is normalized to NNLO

Backgrounds (II)

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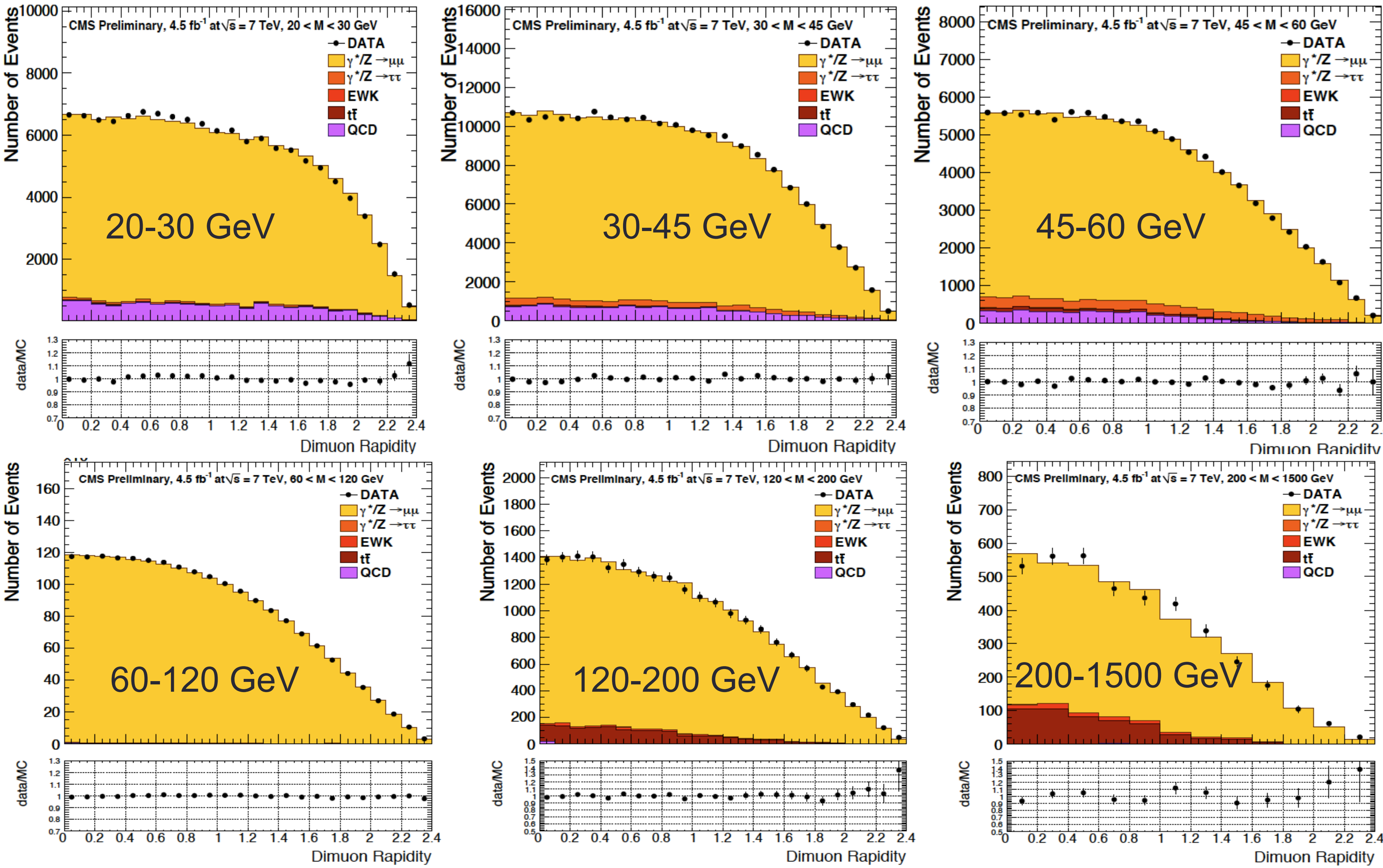

Detector resolution effects (I)

- The unfolding procedure corrects the effects of the detector resolution on the mass spectrum
  - We use the technique of response matrix inversion
- Response matrix is produced using signal MC
  - The momentum scale correction, taking into account the effects of detector misalignment, is applied
- Response matrix is nearly diagonal
  - Off-diagonal elements located adjacent: < 0.1

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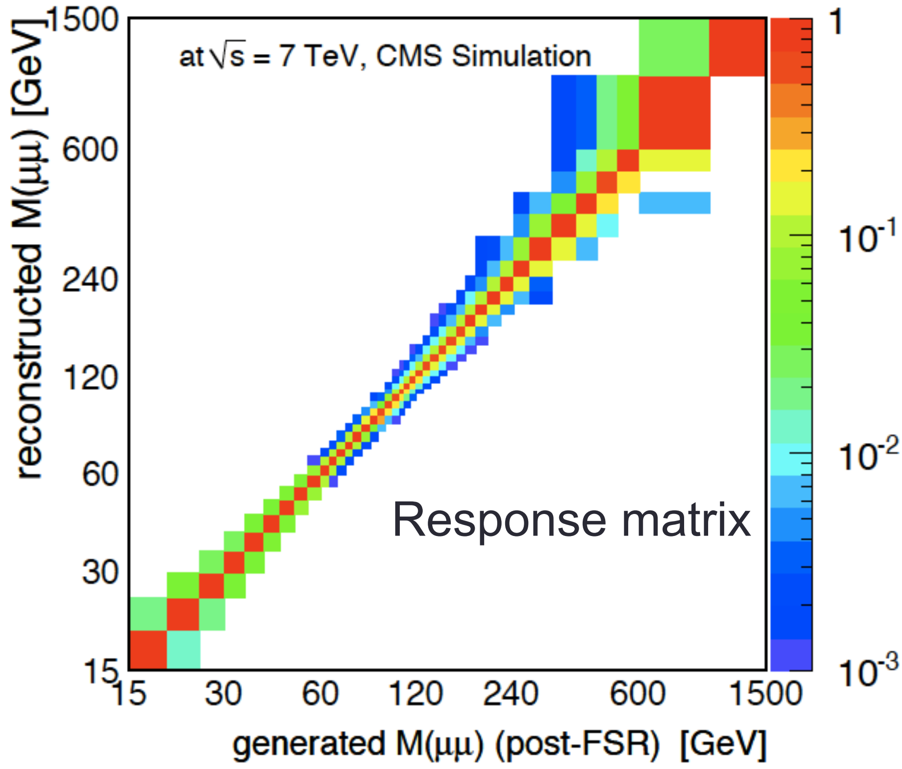
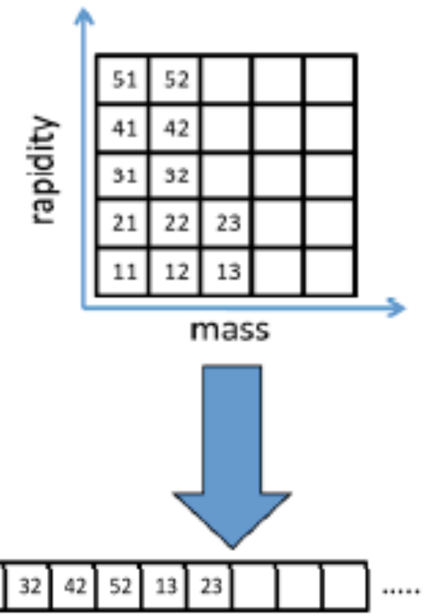
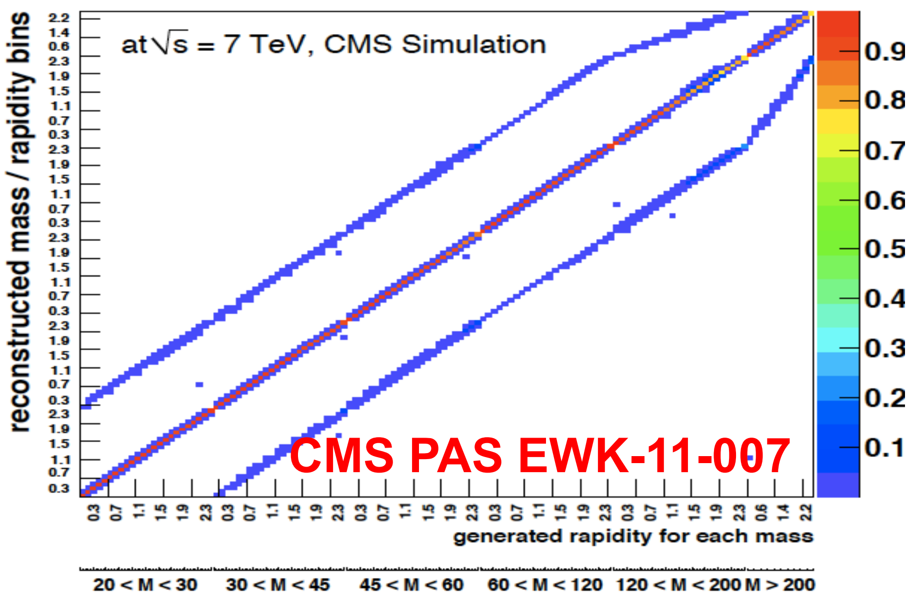


Detector resolution effects (II)

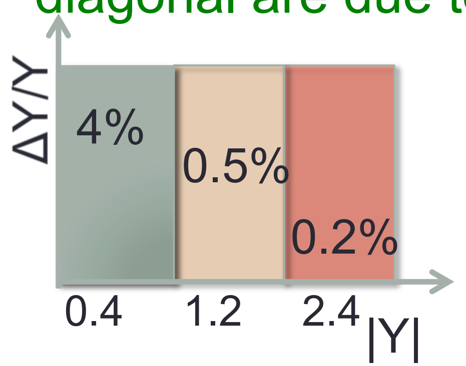
- For the 2D measurement, the conventional unfolding method is used
  - Convert the 2D rapidity-mass into a 1D mass yield distribution, apply the usual 1D unfolding procedure to the flattened spectrum (see previous slide)

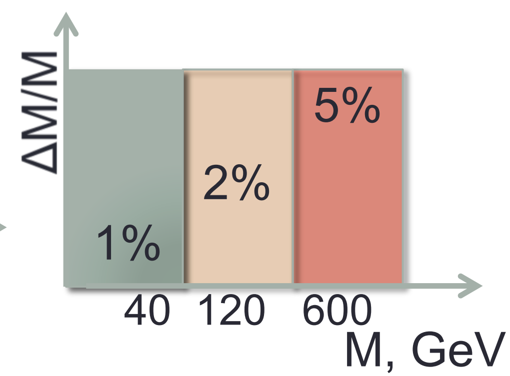




132x132 unfolding matrix

The resulting response matrix has a block-diagonal structure with each block corresponding to a given mass-rapidity bin. The entries off the main diagonal are due to migration effects





Acceptance and efficiency

- Acceptance*efficiency is derived from MC according to:

$$A*\epsilon = \frac{N_{ACC}}{N_{GEN}} \frac{N_{SEL}}{N_{ACC}} = \frac{N_{SEL}}{N_{GEN}}$$

N_X – number of generated events, with X:
GEN – initial
ACC – in the acceptance
SEL - (RECO) selected

- The acceptance accounts for the muon p_T and η cuts, the efficiency reflects the full selection
- Post-FSR muon quantities are used to calculate the di-muon invariant mass
- FEWZ NNLO reweighting procedure is applied to correct for model dependence
- Efficiency is almost independent of invariant mass (0.8-0.9), but the acceptance is increasing with mass from very low values (0.007) to about 0.9
- For the 2D measurement, only efficiency correction is applied

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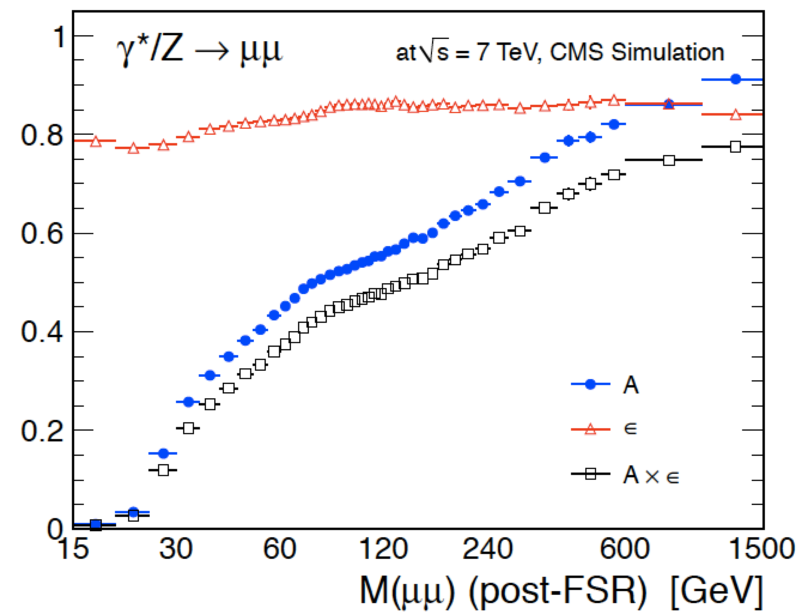
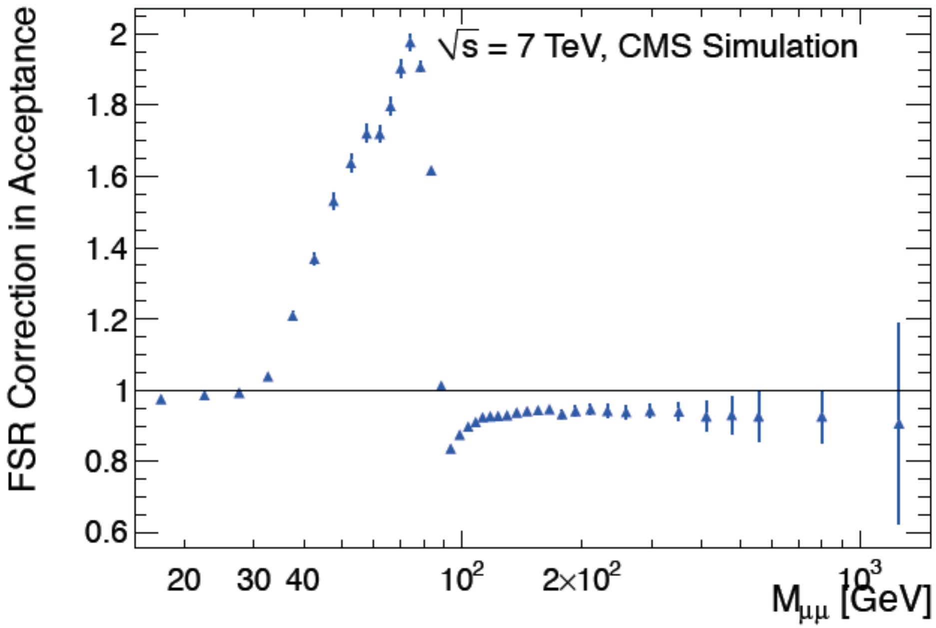


Efficiency corrections

- The signal efficiency is estimated using MC truth. The data-driven efficiency scale factors are applied to correct for systematic deviations between data and simulation
- Single muon efficiencies are estimated using data driven Tag-and-Probe technique
  - The Z peak resonance window is used: 2.5 M probes in the data sample
- The efficiency correction look-up tables are determined for each individual efficiency as
  - $\rho = \rho(p_T, \eta) = \varepsilon_{Data}(p_T, \eta)/\varepsilon_{MC}(p_T, \eta)$
  - The efficiency corrections are applied per muon and are used to weight the MC events (data is used only to obtain the correction factors)

FSR corrections

- FSR corrections are determined from simulation
  - FSR effects are very well modeled in MC
- FSR-correction factors are derived bin-by-bin
- Correction is applied in order to compare the measurement to the theoretical calculations which don't include FSR



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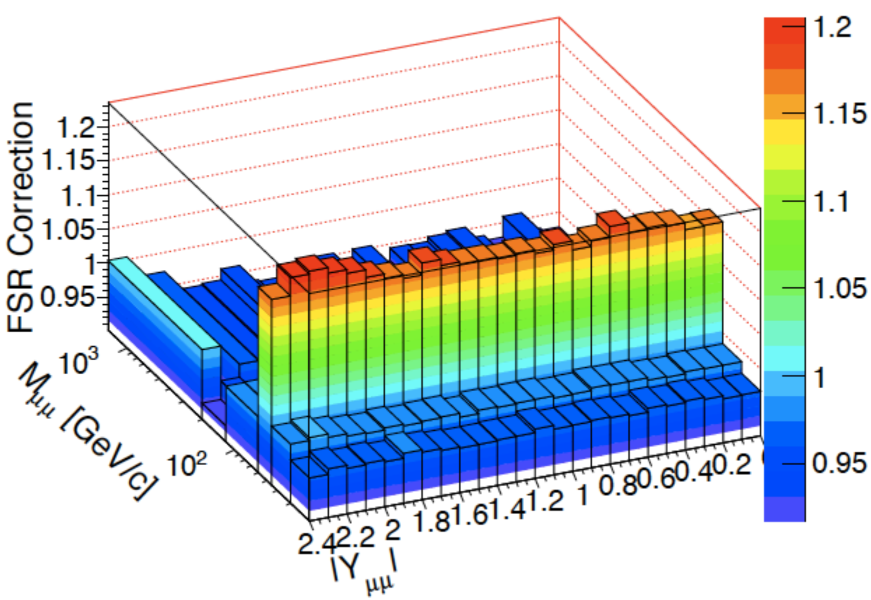


Systematic uncertainties

- Main sources of systematic uncertainties are
  - Luminosity: 4 %
  - Acceptance (dominated by the uncertainty on PDFs): up to 13 % at low masses, about 1 % at high masses (combined in quadrature)
  - Estimation of backgrounds: about 0.5 % at low masses, up to 23 % at high masses
  - Efficiency estimation: about 0.5 % at low masses, up to 3.5 % at high masses
  - Unfolding and momentum-scale corrections: about 0.5 % at low masses, 28 % in the highest mass bin
- The modeling uncertainty on acceptance is dominant at low mass (up to 10%), and the background estimation uncertainty and unfolding and momentum-scale correction uncertainty are dominant at high masses (up to about 25 %)
- The luminosity uncertainty cancels out, the PDF uncertainty on acceptance and the pile-up effect in the reconstruction efficiency; the uncertainty on the efficiency estimation are reduced in the cross section ratio

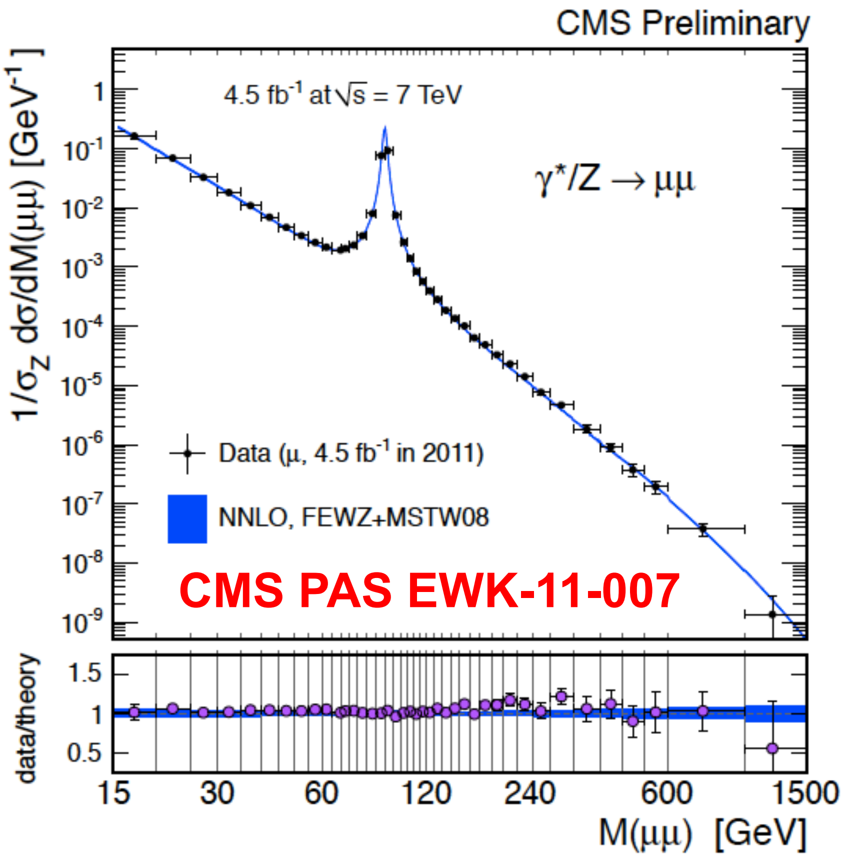
dσ/dM results

- Normalized cross-section is calculated as:

$$R^i_{pre\ FSR} = \frac{N^i_u}{A_i \epsilon_i \rho_i} / \frac{N_{u,norm}}{A_{norm} \epsilon_{norm} \rho_{norm}}$$

Here: i - mass bin index

  - Where 'norm' refers to the measurement in the normalization region (Z peak: 60 < M < 120 GeV)
  - 40 mass bins covering the range from 15 to 1500 GeV are used
- DY dimuon invariant mass spectrum, normalized to the Z resonance region, as measured and as predicted by NNLO calculations, for the full phase space is shown
  - The vertical error bar indicates the experimental (statistical and systematic) uncertainties summed in quadrature with the theory uncertainty resulting from the model-dependent kinematic distributions inside each bin



dσ/dMdY results (I)

- The first 2D measurement is performed within the detector acceptance, to reduce the model dependence
- The result of the double differential cross section measurement is presented as the following ratio per absolute rapidity bin *i* within the invariant mass slice *j*:

$$R^{i,j}_{pre\ FSR} = \frac{N^{i,j}_{u}}{\epsilon^{i,j}\rho^{i,j}} / \frac{N^{norm}_{u}}{\epsilon^{norm}\rho^{norm}}$$

  - *j* – rapidity index, *i* –mass index
  - Where ‘norm’ refers to the measurement in the normalization region (Z peak: 60 < M < 120 GeV) within |Y| < 2.4
  - 6 mass bins covering range from 20 to 1500 GeV are used
  - 24 absolute dimuon rapidity bins within |Y| < 2.4 range are used for all the mass bins except for the highest mass bin, where 12 bins is used

dσ/dMdY results (II)

The following figures show the DY rapidity-invariant mass spectrum in the dimuon channel, normalized to the Z resonance region, $r = (1/\sigma_Z d\sigma/dMdY)$, as measured and as predicted by POWHEG NLO+CT10 PDFs and FEWZ NNLO +MSTW2008NNLO PDFs calculations

Within the detector acceptance

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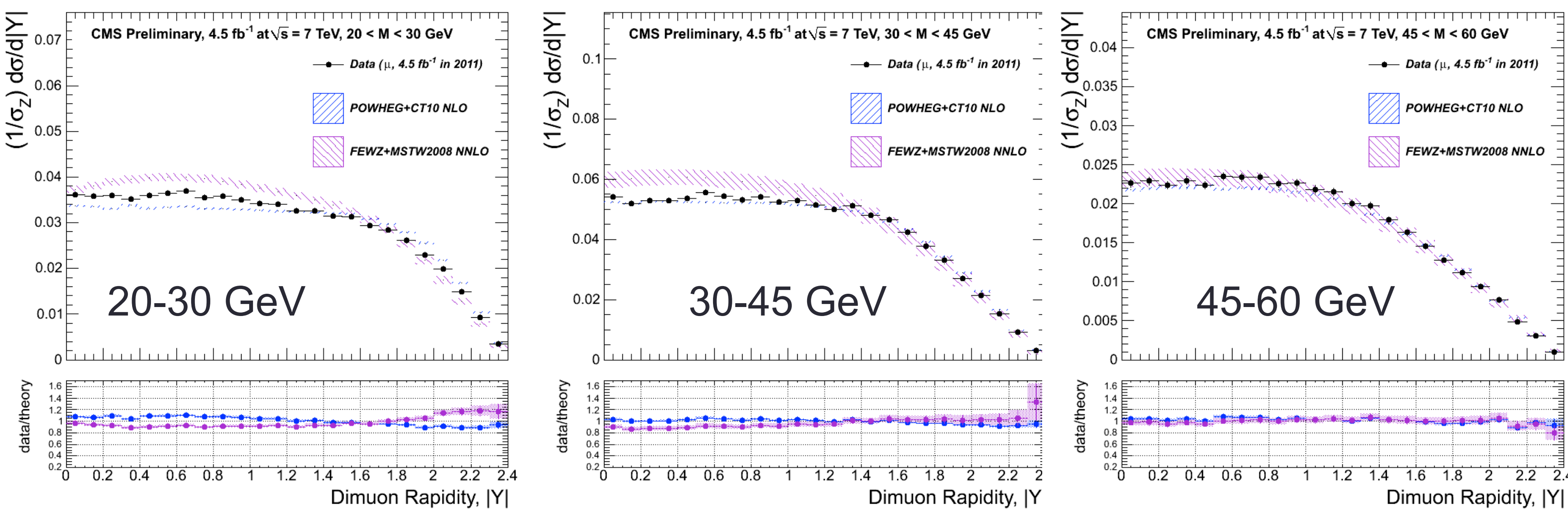

dσ/dMdY results (III)

Within the detector acceptance

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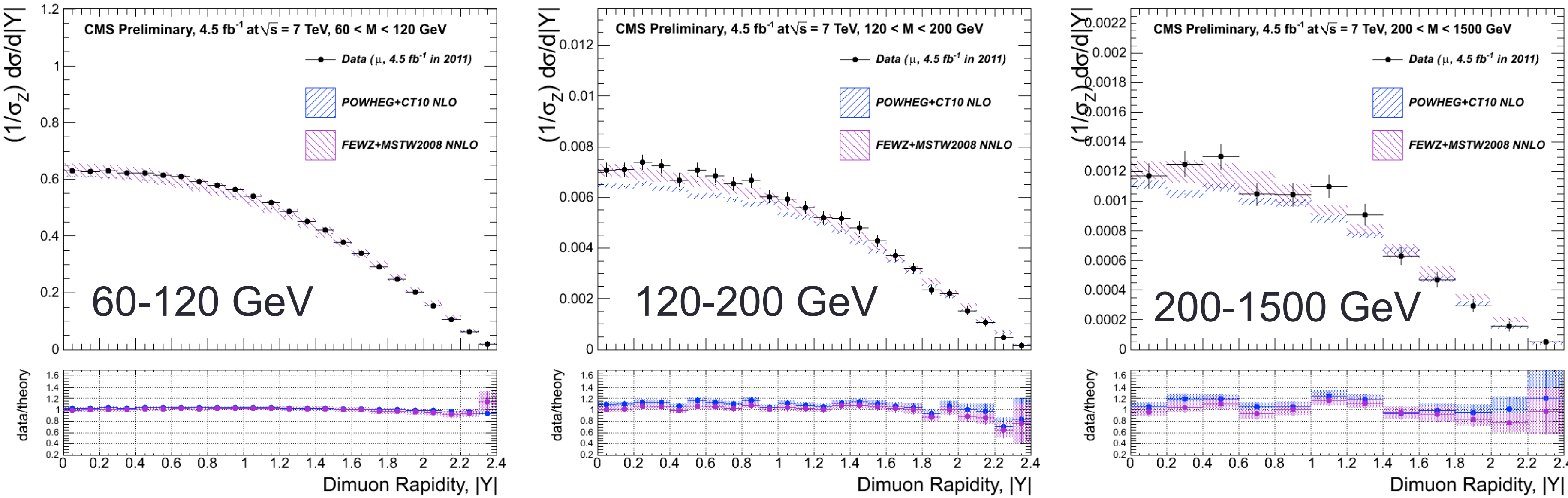

- Good agreement observed for most mass bins except the lowest mass bin
- Low mass region is very sensitive to the PDF uncertainties

- To properly take into account the PDF uncertainty, the comparisons with various NNLO PDF sets are being performed (including NNPDF2.1, JR09VFNS, ABKM and CT10W NNLO PDF sets)

Summary

- We have measured the normalized cross section of the Drell-Yan process in the muon channel with 40 mass bins, covering the mass range of 15-1500 GeV
  - The full 2011 dataset was used: 4.5 fb^{-1}
  - The results agree with NNLO theory calculations
  - The precision makes the measurement sensitive to the NNLO theoretical predictions
- We have performed the double-differential cross section measurement with hadron collider data. The measurement was performed in 6 invariant mass bin covering the mass range of 20-1500 GeV and absolute rapidity range of $|Y| < 2.4$
  - The measurement is performed within the detector acceptance to reduce the model dependence of the result
  - The $d\sigma/dMdY$ measurement results can be directly used for the PDF constraints