



Measurements with PDF information from CMS

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On behalf of the CMS collaboration

PDF4LHC meeting (CERN)
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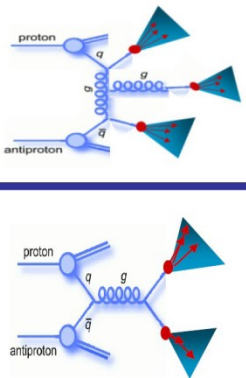
Outline

- “Measurement of the 3-jet to 2-jet rate and extraction of α_s ”
- “Drell-Yan differential cross sections at 7 TeV”
- “Associated production of a W boson and a charm jet at 7 TeV”
- Data: $\sim 5 \text{ fb}^{-1}$ pp collisions at 7 TeV (2011)
- Other CMS results sensitive to PDF:
 - Measurement of the inclusive W and Z cross sections at 8 TeV
 - W charge asymmetry
- **CMS public results:**
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP>

Measurement of the 3-jet to 2-jet rate and extraction of α_s

QCD-11-003

(<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsQCD11003>)



$\longleftrightarrow \alpha_s$

$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \rightarrow n \text{ jets} + X; n \geq 3)}{\sigma(pp \rightarrow n \text{ jets} + X; n \geq 2)} \quad \text{vs} \quad \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

- **jet $p_T > 150$ GeV**
 - **jet rapidity: $|y| < 2.5$**
 - **Average dijet p_T as scale: $(p_{T1} + p_{T2})/2$**
 - **Scale explored: $250 \text{ GeV} < (p_{T1} + p_{T2})/2 < 1400 \text{ GeV}$**
- Major **systematic uncertainties cancel in the ratio**: Experimentally \rightarrow luminosity, jet energy scale ...; theoretically \rightarrow choice of μ_r , μ_f or non-perturbative effects.
 - The measurement R_{32} is compared with **NLO pQCD theoretical predictions** using NNPDF2.1, ABM11, MSTW2008 and CT10 PDF sets.

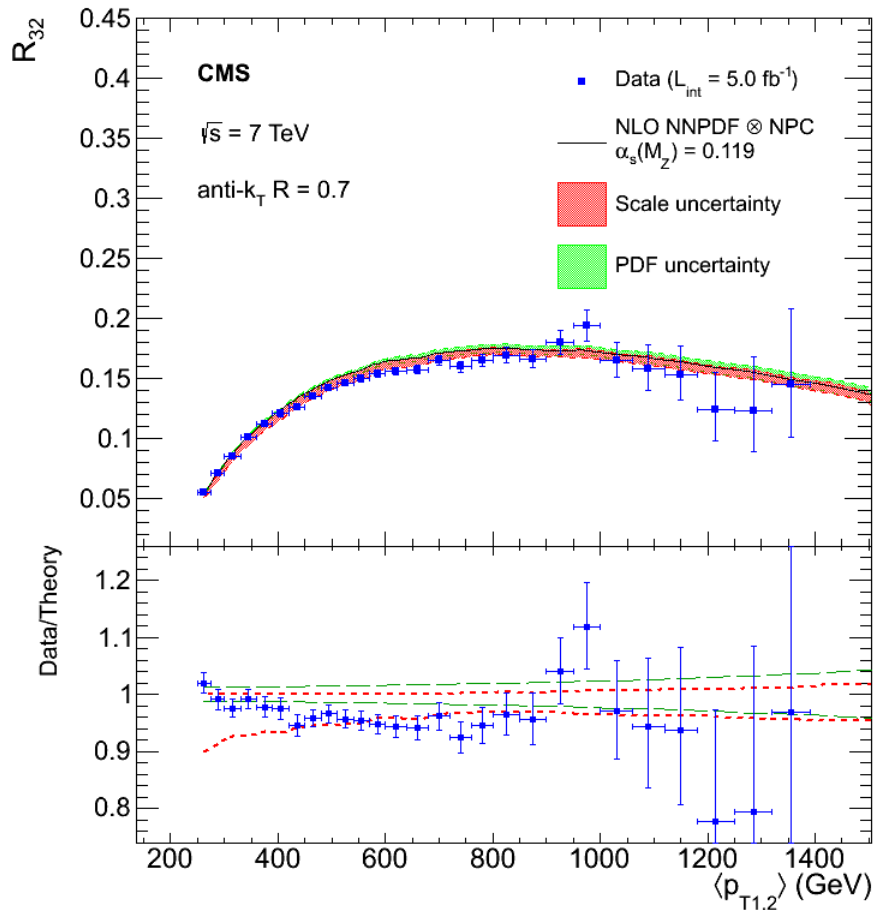
- Three different High Level single jet Triggers with eff.~100%
- **Anti- k_T** jet algorithm with **$R = 0.7$**
 - Inputs to clustering algorithm: the four-momentum vectors of reconstructed particles
 - Each particle is reconstructed with the particle-flow technique
- Jet Energy Scale Corrections
 - Syst. uncertainty $\Delta R_{32}/R_{32} \sim 1.2\%$
- R_{32} is corrected for detector smearing effects and unfolded to particle level. Unfolding corrections \sim few %
 - Syst. uncertainty $\Delta R_{32}/R_{32} < 1\%$

Analysis Summary

Selection:

- Events should have two or more jets with $p_T > 150 \text{ GeV}$ and $|y| < 2.5$
- Two jets leading in p_T

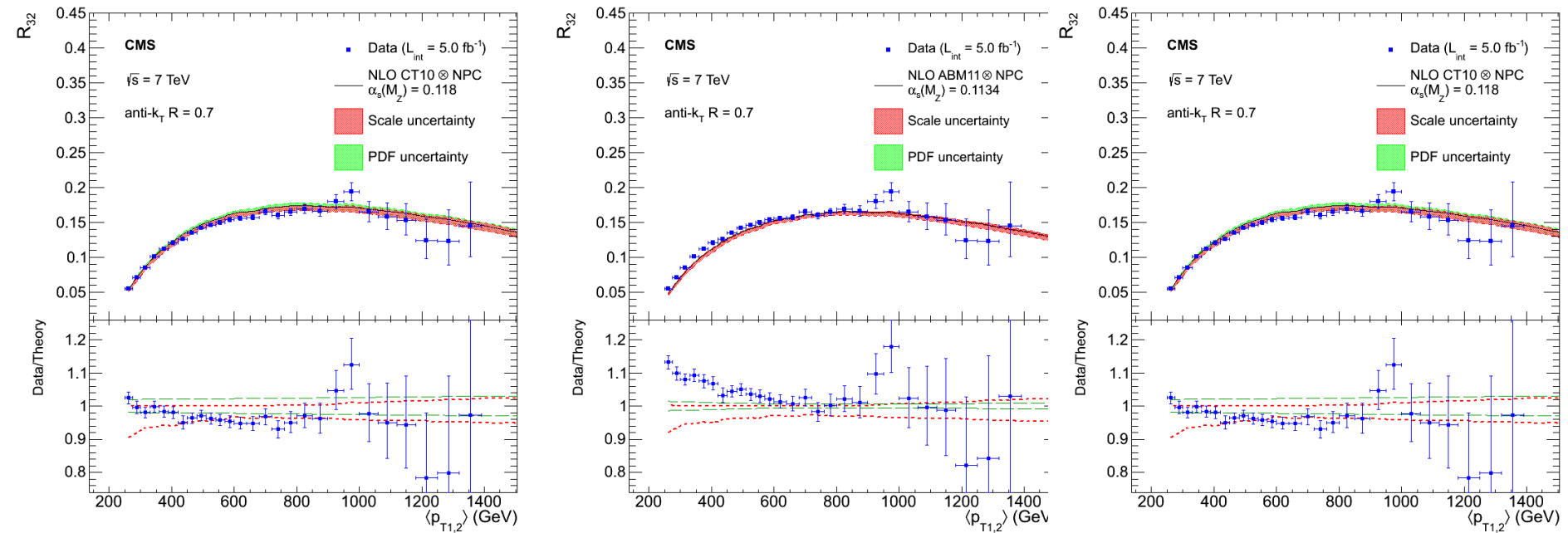
Results and comparison with theoretical predictions



- R_{32} ratio rises with increasing $\langle p_{T1,2} \rangle$ as the phase space opens up for the production of the third jet, reaching a plateau value for 600-1000 GeV. At higher $\langle p_{T1,2} \rangle$ it decreases again because of the running of α_s , smaller parton luminosities, and because 3-jet configurations reach kinematic limits earlier than dijet events.
- NLO calculations using the NNPDF2.1 PDF sets are in agreement with the measured ratio R_{32} throughout the range of this measurement.
- Scale uncertainties dominate the region up to $\langle p_{T1,2} \rangle = 400$ GeV. (Very similar behavior for every PDF set examined).

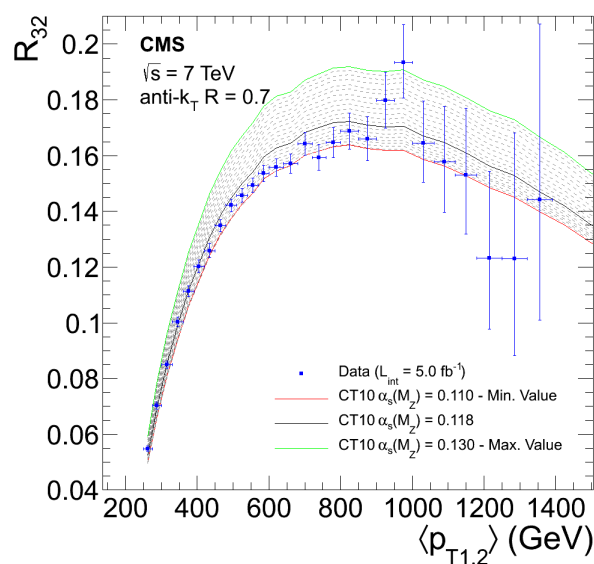
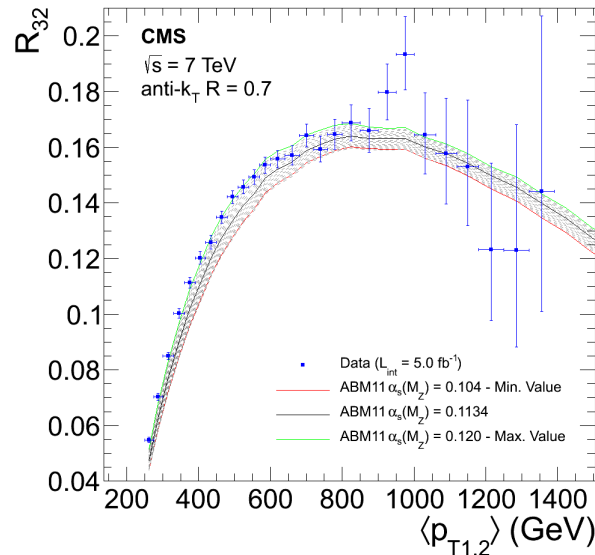
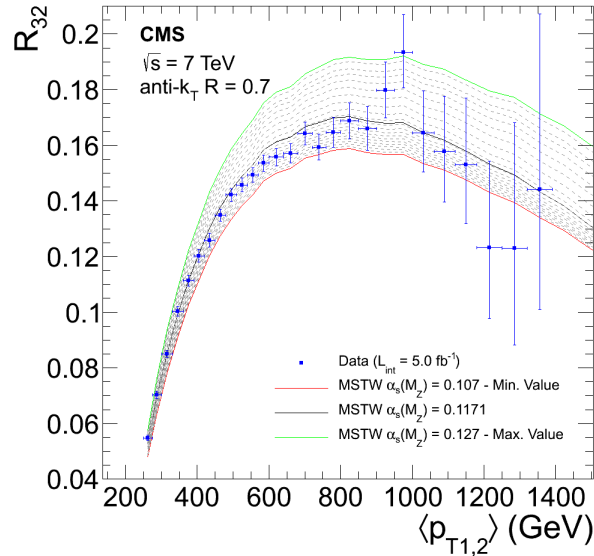
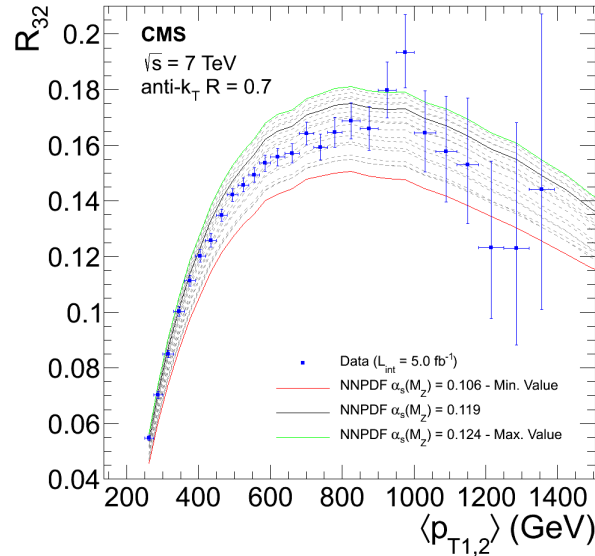
- PDF uncertainties for **NNPDF2.1** are of the order of 1.5% at 400 GeV increasing to 2.3% at 1 TeV.

Results and comparison with theoretical predictions



- For **MSTW2008** and **ABM11** PDF uncertainties are of the order of 1%.
- For **CT10** PDF uncertainties are 2% at 400 GeV increasing to 2.5% at 1 TeV.
- **ABM11** undershoots the experimental data (especially for $\langle p_{T1,2} \rangle < 600$ GeV).

Determination of α_s



$\alpha_s(M_Z)$ has been varied in steps of 0.001 and in the range:

NNPDF2.1 : (0.106-0.124)

MSTW2008 : (0.107-0.127)

ABM11 : (0.104-0.120)

CT10 : (0.110-0.130)

Variations in the R_{32} ratio are different in each of the four PDF sets

→ Difference in the experimental uncertainty in the value of $\alpha_s(M_Z)$ obtained for each PDF set

Determination of α_s

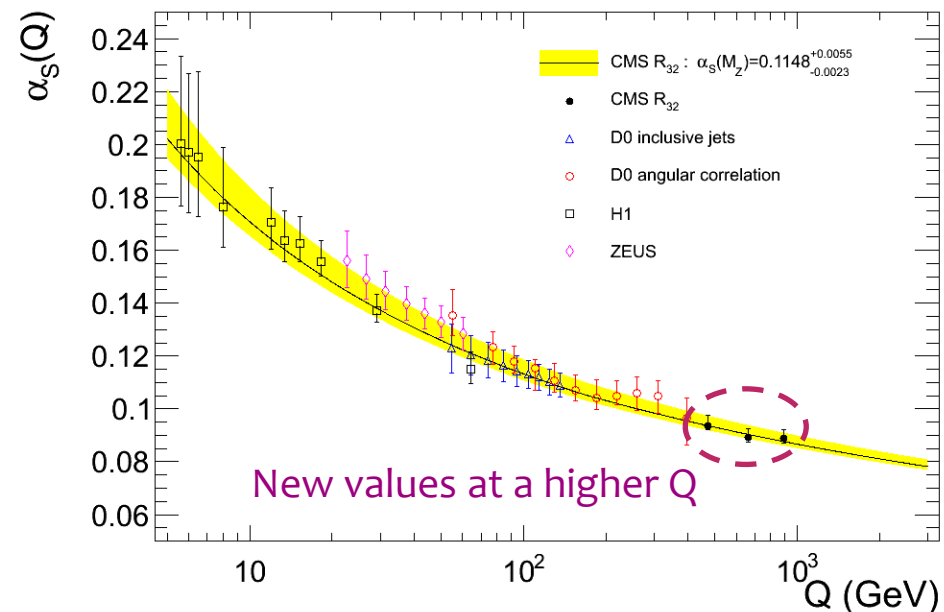
- χ^2 fit to the R_{32} distribution wrt α_s in the region $\langle p_{T1,2} \rangle > 400$ GeV taking into account experimental uncertainties (use NNPDF predictions).

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014 (\text{exp.}) \pm 0.0018 (\text{PDF})^{+0.0050}_{-0.0000} (\text{scale})$$

- **PDF uncertainty:** Repeat fit for each NNPDF replica and take RMS of the distribution of fitted α_s .
- **Scale uncertainty:** Repeat fit for six variations of (μ_r, μ_f) . Take differences between central and highest/lowest values.

PDF set	$\alpha_s(M_Z)$
MSTW2008	$0.1141 \pm 0.0022 (\text{exp.})$
CT10	$0.1135 \pm 0.0019 (\text{exp.})$
ABM11	$0.1214 \pm 0.0020 (\text{exp.})$

- Extraction of α_s also in three independent $\langle p_{T1,2} \rangle$ subranges



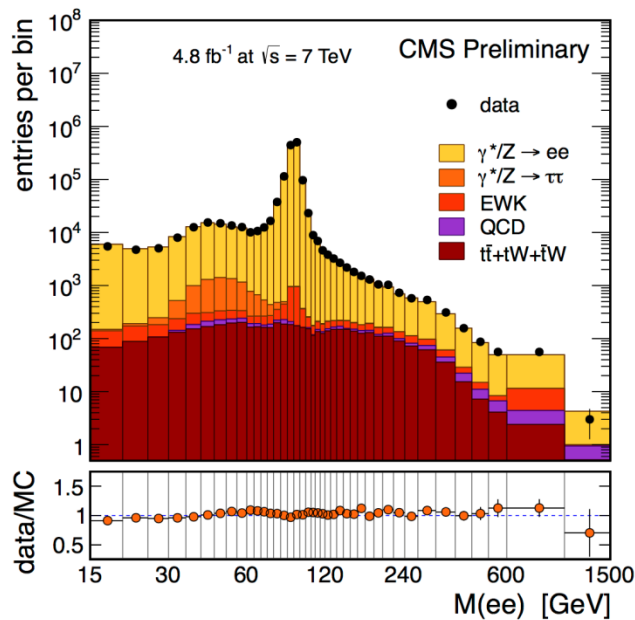
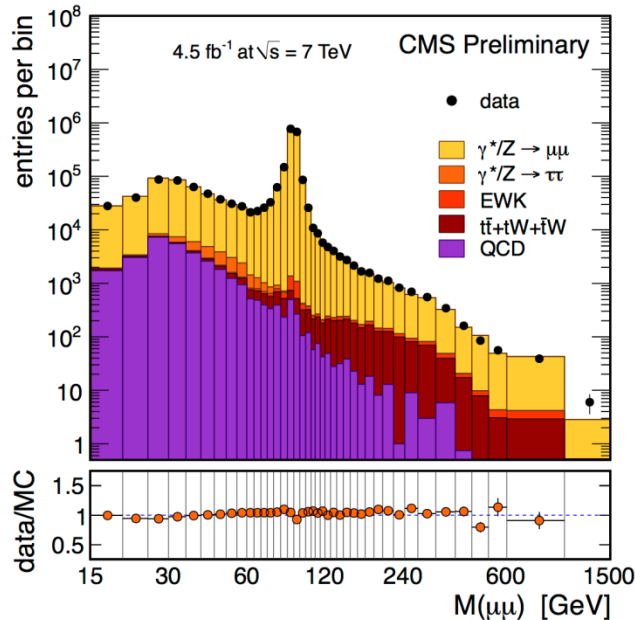
Drell-Yan differential cross sections

SMP-13-003

(<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13003>)

Drell-Yan cross section

- Standard Model benchmark channel
- Theoretical cross section calculated up to NNLO
 - allowing tests of perturbative QCD
- Differential cross section $(1/\sigma_Z)d\sigma/dM$ in dimuon and dielectron channel
 - $15 \text{ GeV} < M(\ell\ell) < 1500 \text{ GeV}$; $Y(\ell\ell) < 2.4 (\mu\mu), 2.5 (ee)$
- Double differential cross section $(1/\sigma_Z)d^2\sigma/dMdY$ sensitive to PDF. Measured in dimuon channel.
 - $20 \text{ GeV} < M(\mu\mu) < 1500 \text{ GeV}$; $Y(\mu\mu) < 2.4$
- Differential cross sections normalized to the Z-peak region ($60 \text{ GeV} < M(\ell\ell) < 120 \text{ GeV}$)
 - Syst. uncert. reduced



Analysis Summary

- Dilepton triggers
- Two high momentum and isolated muons
 - $p_T(\mu_1) > 14 \text{ GeV}, p_T(\mu_2) > 9 \text{ GeV}$
- $|\eta(\mu)| < 2.4$
- Two high momentum and isolated electrons
 - $p_T(e_1) > 20 \text{ GeV}, p_T(e_2) > 10 \text{ GeV}$
- $|\eta(e)| < 2.5$
- Corrected for:
 - Lepton momentum & energy scale ,
 - Lepton efficiencies,
 - Unfolded for detector resolution effects,
 - Final State QED effects
- Reference MC: POWHEG (NLO)+CT10, reweighted to NNLO

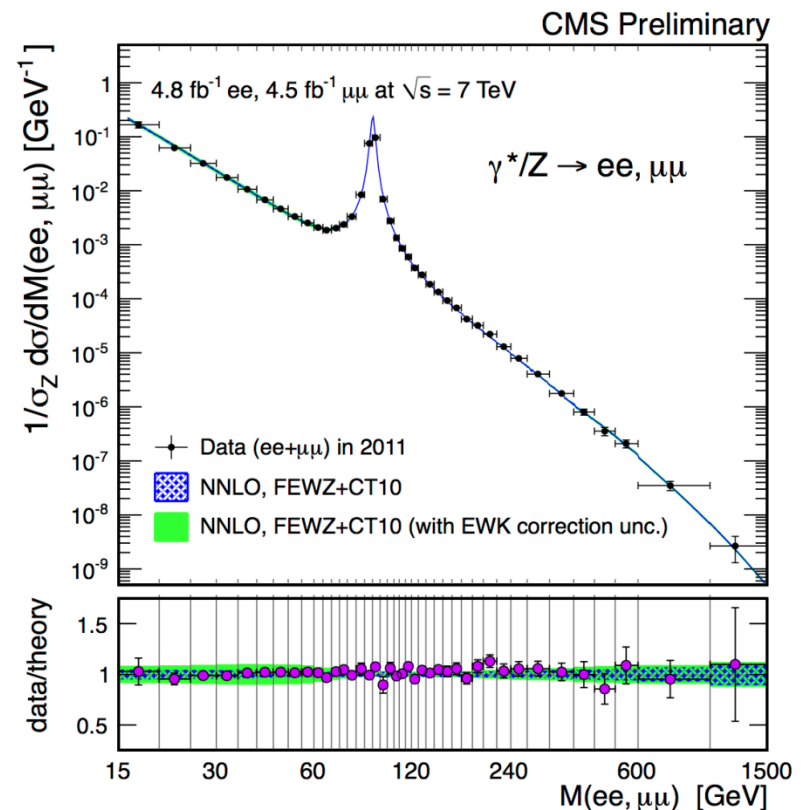
$$\omega(P_T, Y) = \frac{(d^2\sigma/dP_T dY)_{\text{FEWZ}}}{(d^2\sigma/dP_T dY)_{\text{POWHEG}}}$$

Differential cross section $d\sigma/dM$

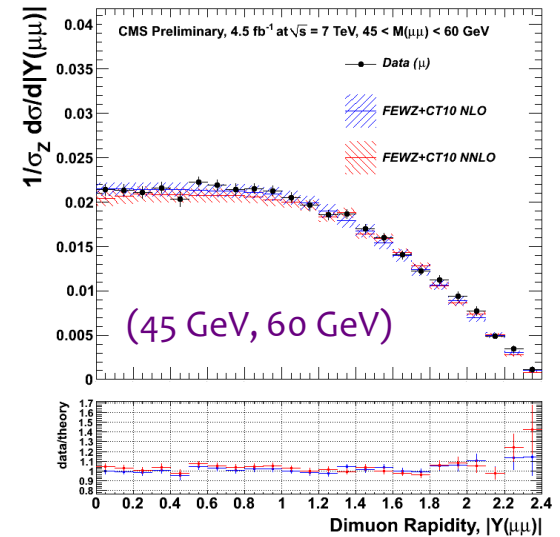
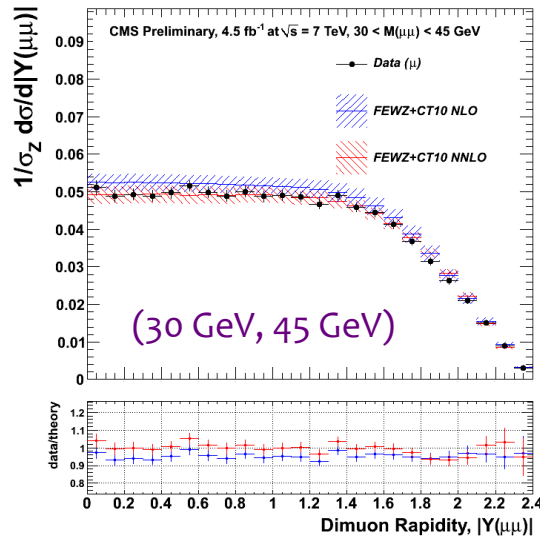
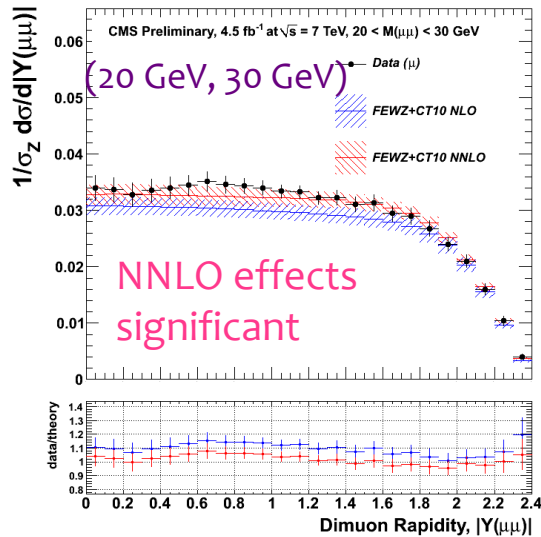
$$\sigma = \frac{N_u}{A \cdot \epsilon \cdot \rho \cdot L_{\text{int}}}$$

$$R_{\text{pre FSR}}^i = \frac{N_u^i}{A^i \epsilon^i \rho^i} / \frac{N_u^{\text{norm}}}{A^{\text{norm}} \epsilon^{\text{norm}} \rho^{\text{norm}}}$$

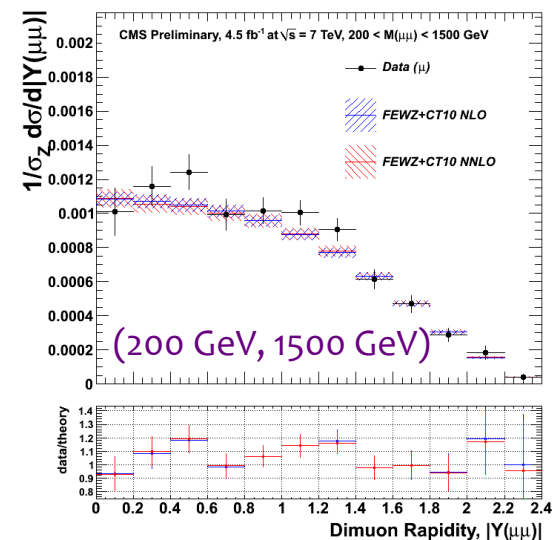
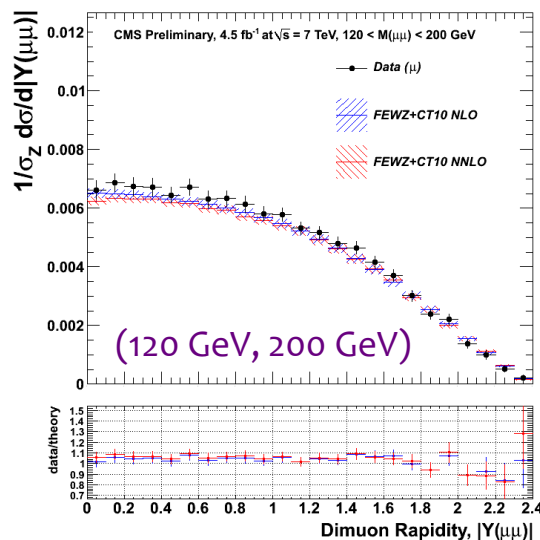
- N_u = Nb. Events after bck. Sub and unfolding,
- A = acceptance to extrapolate to full phase space (with ref. MC)
- ϵ = efficiencies (with ref. MC)
- ρ = correcting factor for eff.
- Normalized to the Z-peak (same quantities “norm”)
- Excellent agreement between muon and electron channels \rightarrow combine them



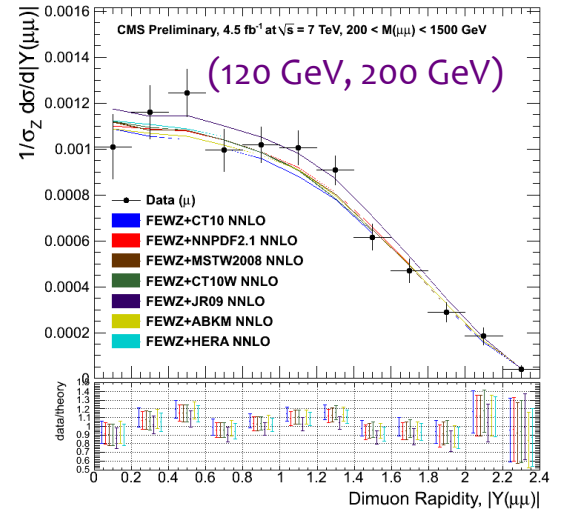
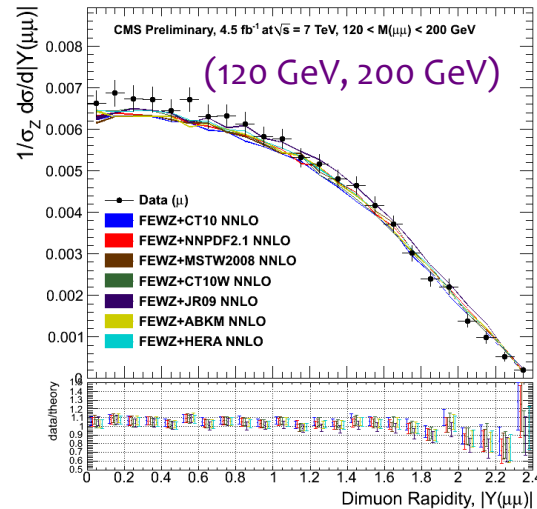
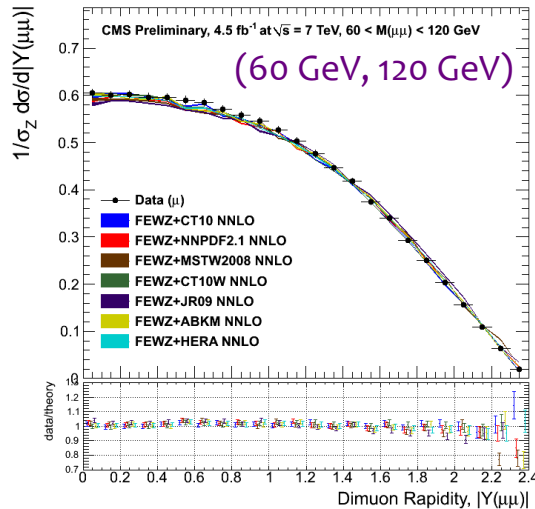
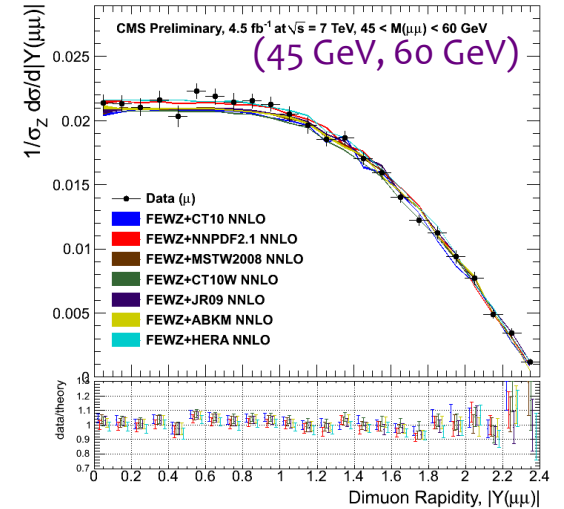
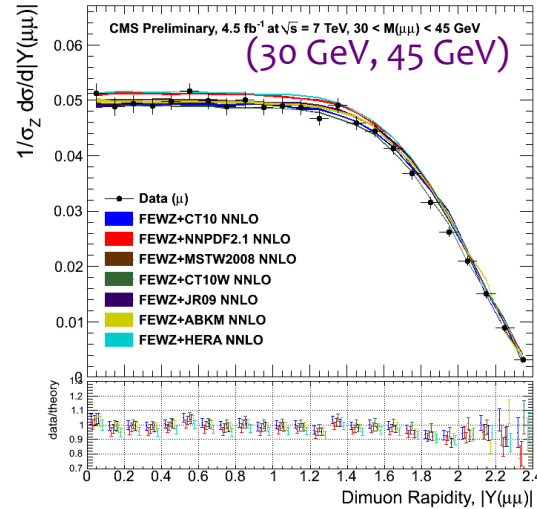
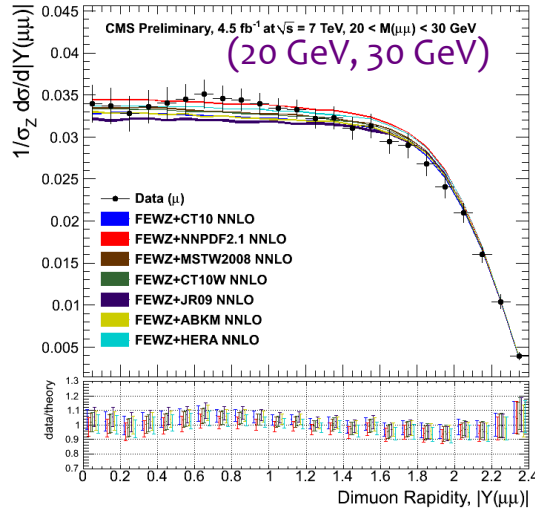
Double differential cross section $d^2\sigma/dM dY$



- Measurement within the detector acceptance, to reduce the model dependence
- Normalized to the Z peak region ($60 < M < 120 \text{ GeV}$) within $|Y| < 2.4$
- Comparing to **FEWZ + CT10 NLO** and **FEWZ + CT10 NNLO**



Double differential cross section $d^2\sigma/dM dY$



Comparison with various NNLO PDFs: **ABKM, CT10, CT10W, HERA, JR09, MSTW2008, NNPDF**

17/04/2013

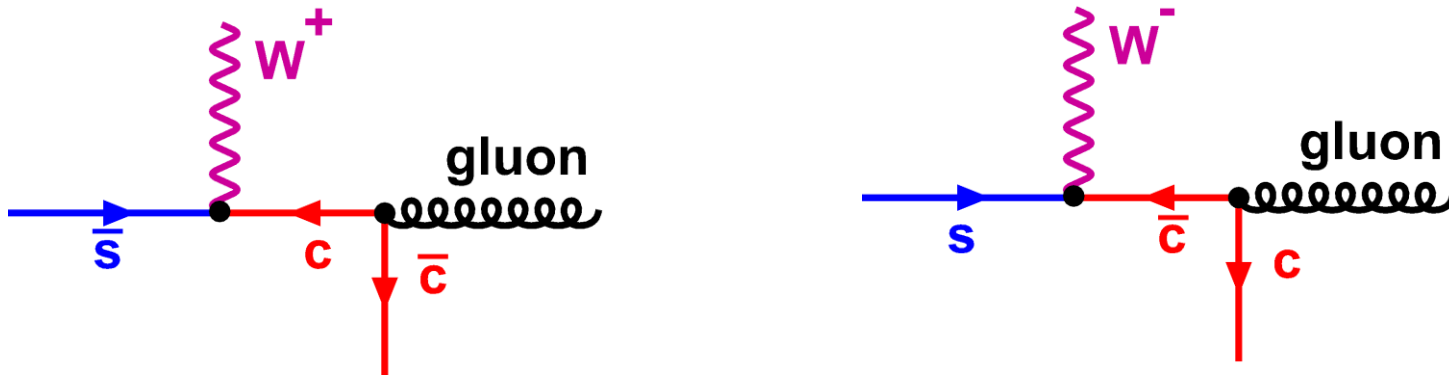
W+c associated production

SMP-12-002

(<https://cdsweb.cern.ch/record/1525727>)

Motivation

- The study of associated W plus charm quark production at hadron colliders provides direct access to the **strange quark content** of the proton at the electroweak scale \rightarrow help reducing the uncertainties on the strange parton distribution function



- Other contributions (**g+d-quark**) are small (few %)
- Total and differential $W+c$ cross sections and charge cross-section ratio $\sigma(W^++\bar{c})/\sigma(W^-+c)$**

Analysis Summary

- Standard CMS W selection:
 - Single muon/electron triggers
 - High p_T and isolated lepton:
 $p_T(\mu) > 25 \text{ GeV}$, $p_T(e) > 35 \text{ GeV}$
 - High Transverse mass:
 $M_T(\mu, \text{MET}) > 40 \text{ GeV}$, $M_T(e, \text{MET}) > 55 \text{ GeV}$
 - $|\eta(\text{lepton})| < 2.1$
- Jet reconstruction:
 - Anti- k_T , $\Delta R = 0.5$, $p_T(\text{jet}) > 25 \text{ GeV}$,
 $|\eta(\text{jet})| < 2.5$
- c-tagging:
 - Exclusive and inclusive reconstruction of D meson decays: $c^\pm \rightarrow D^\pm$,
 $c^\pm \rightarrow D^{*\pm} \rightarrow D^0 + \pi^\pm$, $c^\pm \rightarrow l^\pm$

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 - High p_T and isolated lepton:
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 - $|\eta(\text{lepton})| < 2.1$
- **Jet reconstruction:**
 - Anti- k_T , $\Delta R = 0.5$, $p_T(\text{jet}) > 25 \text{ GeV}$,
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- **c-tagging:**
 - Exclusive and inclusive reconstruction of D meson decays: $c^\pm \rightarrow D^\pm$,
 $c^\pm \rightarrow D^{*\pm} \rightarrow D^0 + \pi^\pm$, $c^\pm \rightarrow l^\pm$

Analysis Summary

In **W+c events** the charge of the **W** (and the lepton) and the charge of the **c quark** are of **opposite sign**.

The **charge of the c quark is unequivocally determined** in the three signatures ($c^\pm \rightarrow D^\pm$, $c^\pm \rightarrow D^{*\pm} \rightarrow D^0 + \pi^\pm$, $c^\pm \rightarrow l^\pm$)

OS events = $\text{sign}(W) \times \text{sign}(c) < 0$

SS events = $\text{sign}(W) \times \text{sign}(c) > 0$

➡ **OS-SS selection**

Main bck. contribute equally to OS and SS (including gluon splitting)

➔ **Subtracted**

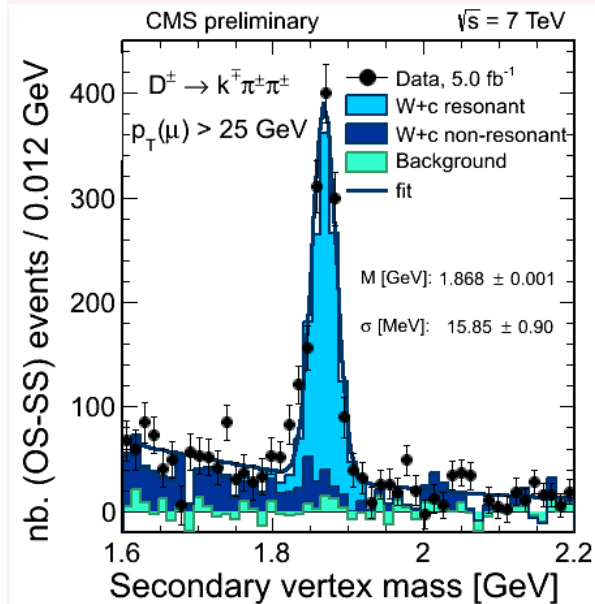
Clean samples after subtraction

1/104/2013

$$D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$$

Events with a
Secondary Vertex with
3 tracks

Signal Region: events in
the $|m^{\text{REC}} - 1.87| < 0.05$ GeV
window



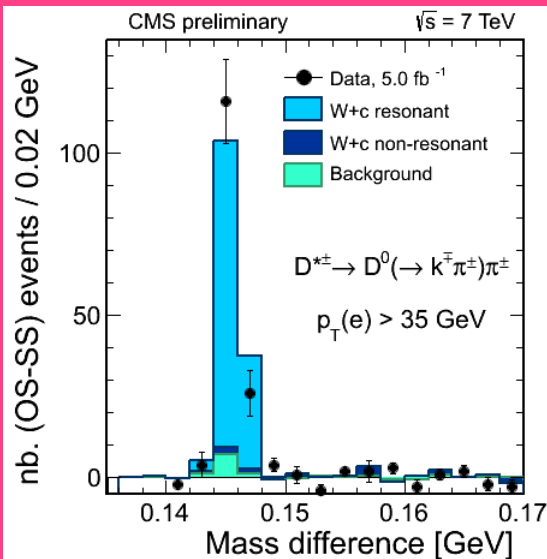
$$D^{*(2010)\pm} \rightarrow D^0 \pi^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$$

Events with a SV with 2
tracks. The SV is
combined with a PV track

M_{SV} compatible with D^0 :
 $|M_{\text{SV}} - 1.864| < 0.07$ GeV

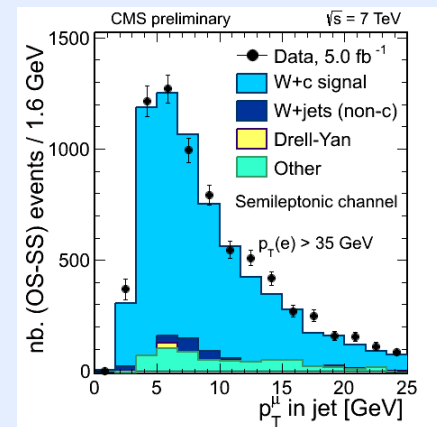
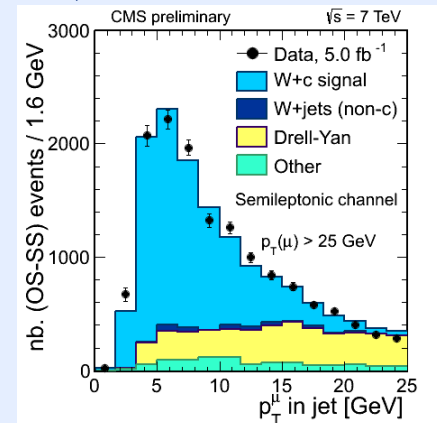
Signal Region:

$$|m_{D^*} - m_{D^0} - 145| < 5 \text{ MeV}$$



Semileptonic ($c^\pm \rightarrow \mu^\pm$)

Events with an
Identified muon within
the jet



W+c total cross section

$$\sigma(W + c) = \frac{N_{sel} - N_{bkg}}{\mathcal{L}_{int} \mathcal{B} \mathcal{A} \epsilon}$$

- Fiducial region:
 - Charm quark: $p_T(c) > 25 \text{ GeV}$, $|\eta(c)| < 2.5$
 - $W \rightarrow l \nu$: $p_T(\text{lepton}) > 25 \text{ (35) GeV}$, $|\eta(\text{lepton})| < 2.1$
- Acceptance \times efficiency:
 - Reference Monte Carlo: Madgraph+Pythia + Base PDF: MSTWo8NNLO
 - Corrected for detector effects
- Charm branching fractions from LEP
- Good agreement among different subchannels

Syst. uncert. $\sim 6\%$

$p_T(\text{lepton}) > 25 \text{ GeV}$

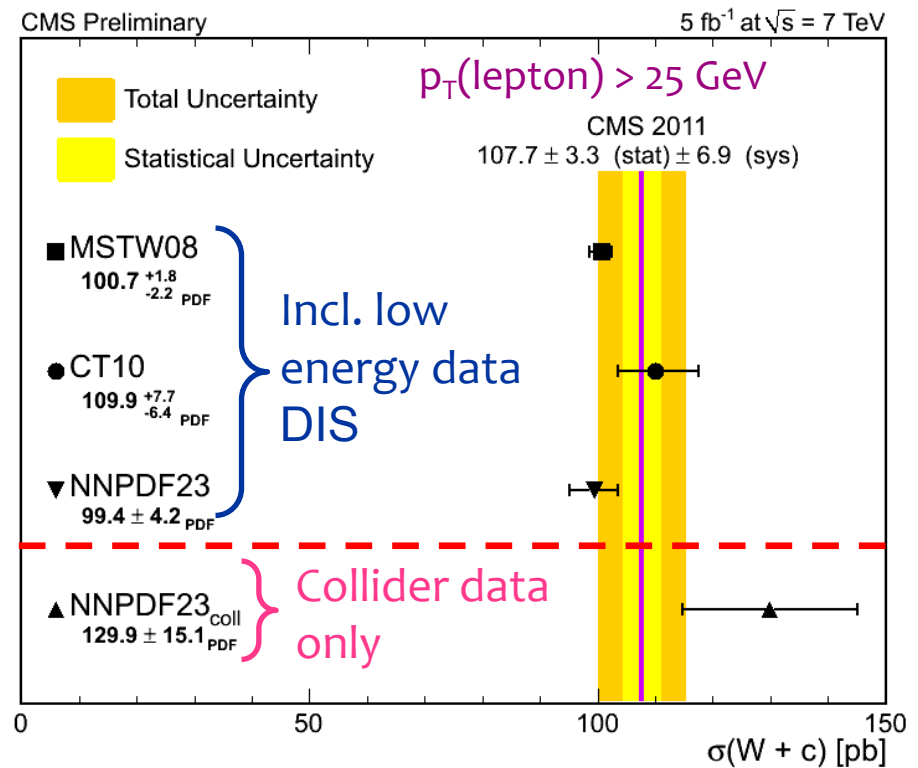
$$\sigma(pp \rightarrow W + c + X) \times \mathcal{B}(W \rightarrow \mu\nu, p_T^\mu > 25 \text{ GeV}) = 107.7 \pm 3.3 \text{ (stat.)} \pm 6.9 \text{ (syst.) pb}$$

$p_T(\text{lepton}) > 35 \text{ GeV}$

$$\sigma(pp \rightarrow W + c + X) \times \mathcal{B}(W \rightarrow \ell\nu, p_T^\ell > 35 \text{ GeV}) = 84.1 \pm 2.0 \text{ (stat.)} \pm 4.9 \text{ (syst.) pb}$$

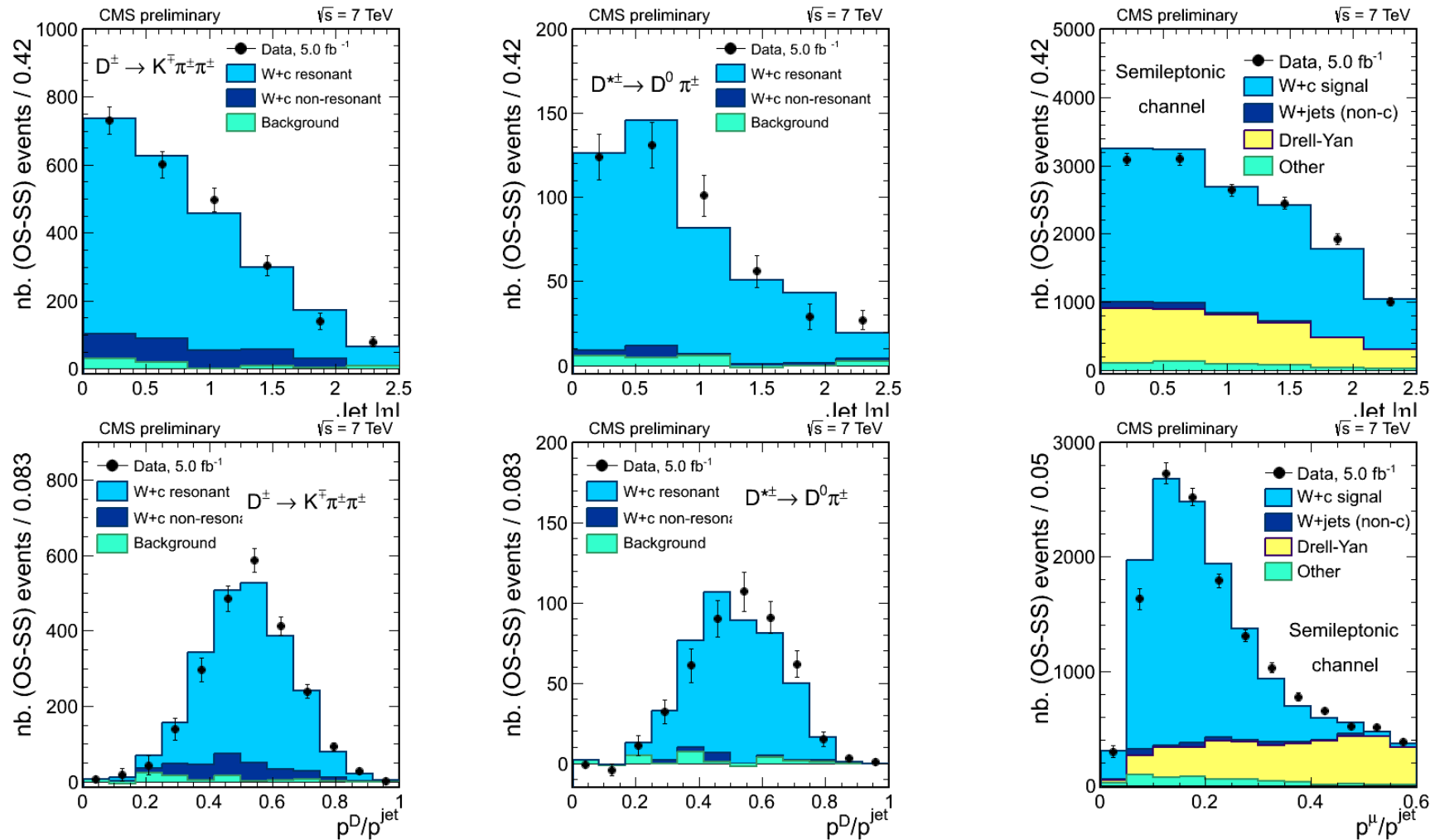
Comparison with theory

- MCFM v6.1 at **NLO** $E_T(\text{c-jet}) > 25 \text{ GeV}$, $|\eta(\text{c-jet})| < 2.5$, $\Delta R = 1$
- **MSTW08**, **CT10**, **NNPDF2.3**, **NNPDF2.3_{collider}** (all at **NNLO**)
- Size of the PDF uncertainties depends on the different methodology used by the various groups to define the 1 sigma PDF uncertainty.
- Data agree with predictions using PDF sets that include **low energy DIS data** (predict a strange suppression wrt other light quarks)
- **PDF with collider data only**: predict a symmetric light sea, but with large uncertainty. In agreement with data within 1σ



Same observations for $p_T(\text{lepton}) > 35 \text{ GeV}$

Characterization of the kinematics of W+c events



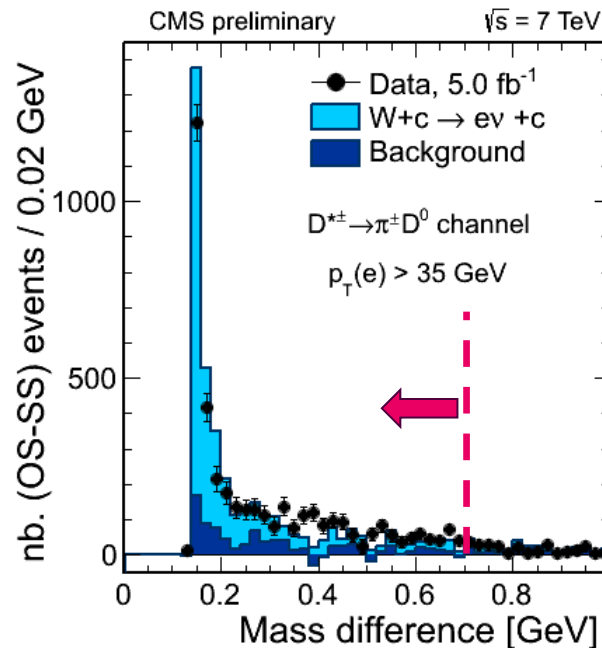
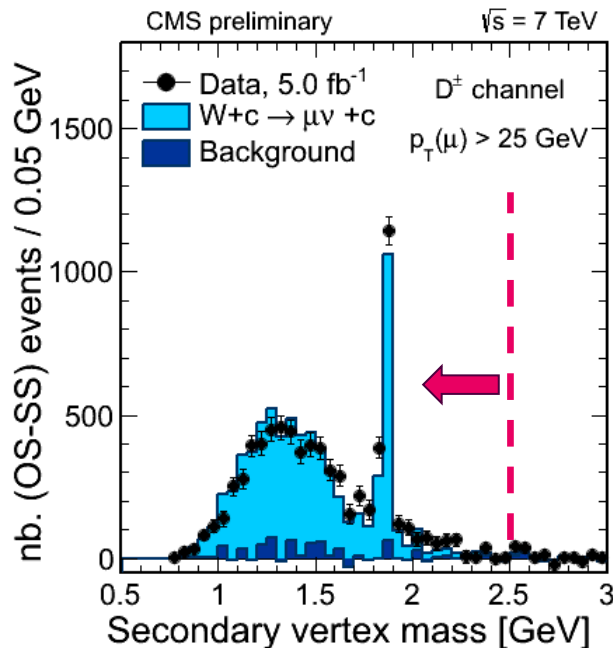
Overall good agreement

Slightly harder fragmentation spectra in data than in MC

W+c normalized differential cross-sections

$$\frac{1}{\sigma(W+c)} \frac{d\sigma(W+c)}{d\eta} = \frac{(N_{sel,i} - N_{bkg,i}) / (\mathcal{A} \epsilon)_i}{\sum_{i=1}^{i=5} (N_{sel,i} - N_{bkg,i}) / (\mathcal{A} \epsilon)_i} \times \frac{1}{\Delta\eta_i}$$

- **Differential wrt pseudorapidity of the lepton from the W decay**
- **Relative measurement** → Cancellation of efficiencies & other systematic uncertainties in the ratio (statistical uncertainties dominate).

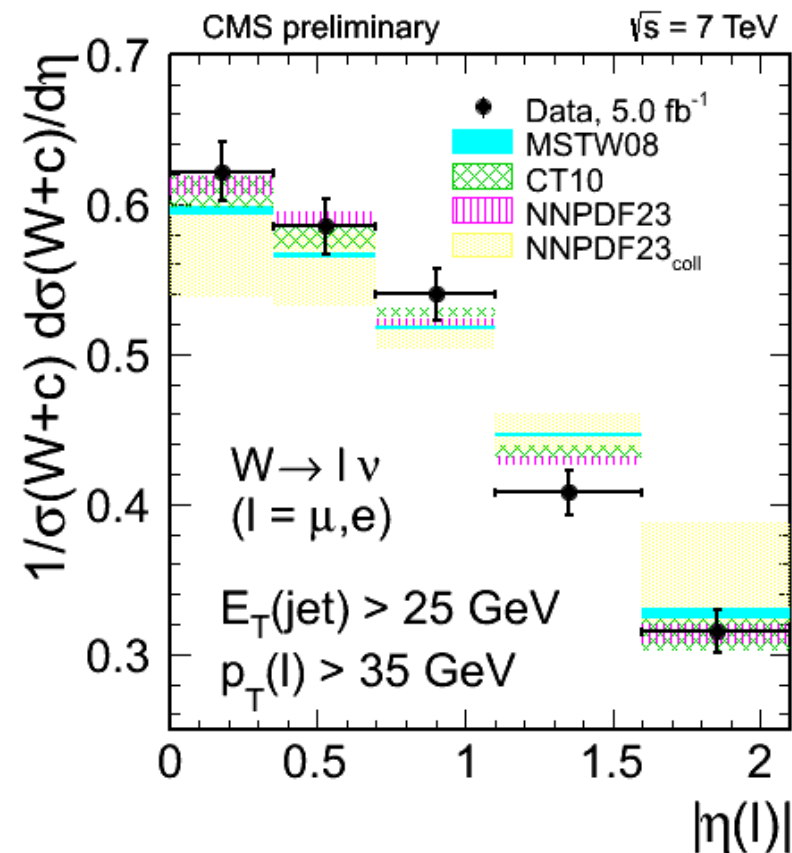
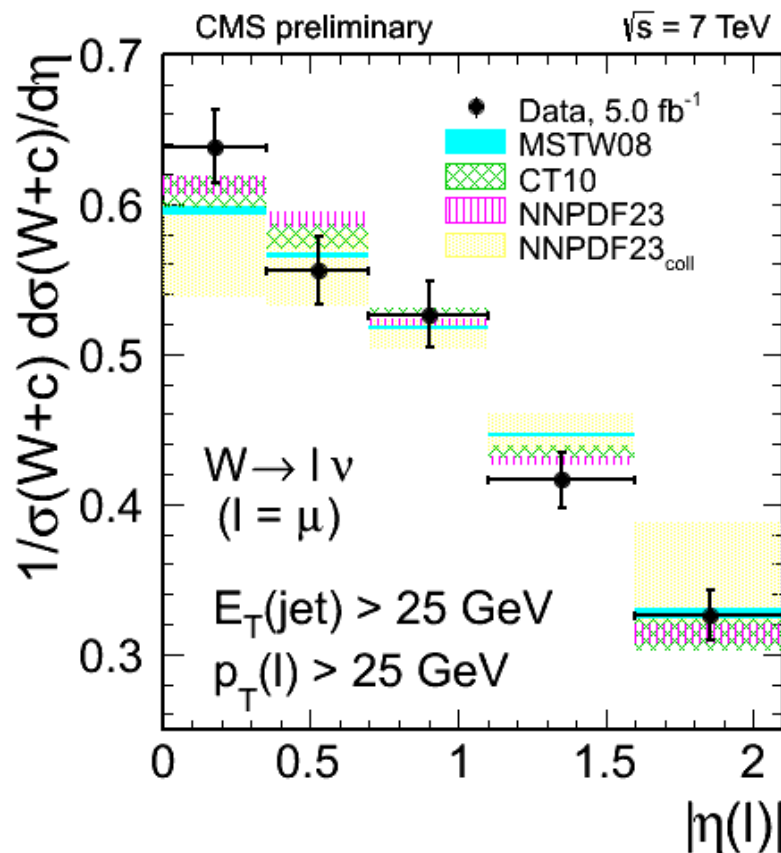


- **Inclusive selection**

- Not focused on resonances, broader phase-space
- Release selection criteria
- Enlarge statistics

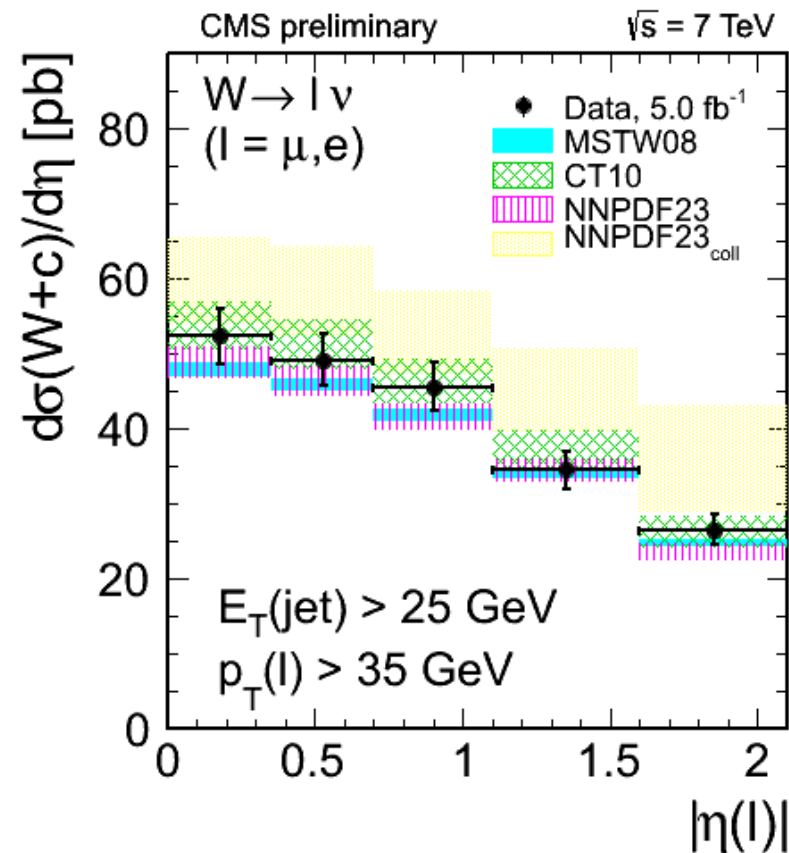
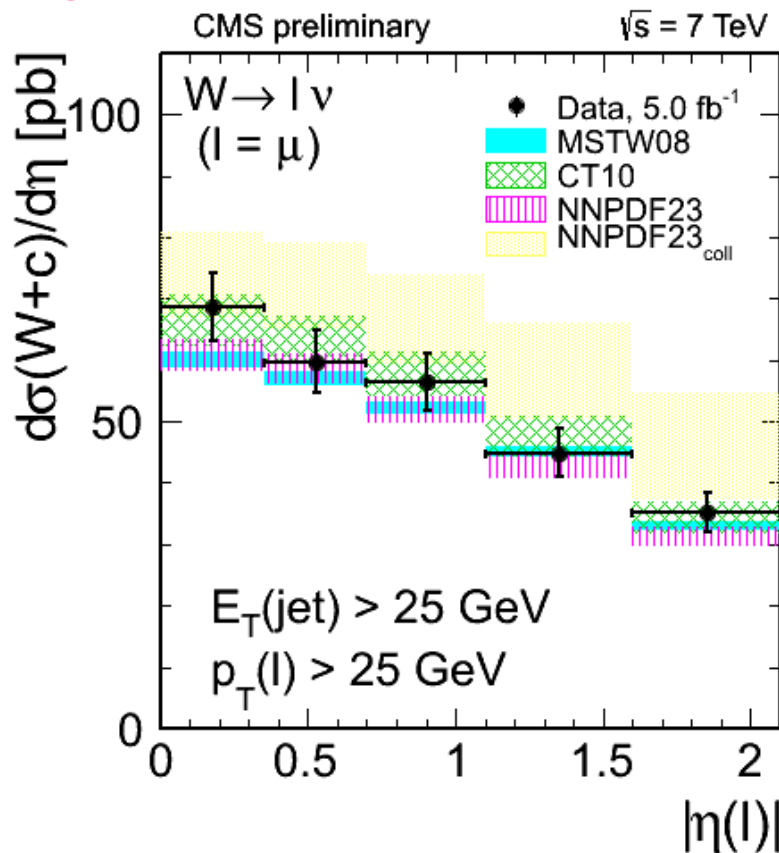
W+c normalized differential cross section

- Good agreement among different subchannels and muons and electrons \rightarrow combine
- Agreement with theory



W+c differential cross section

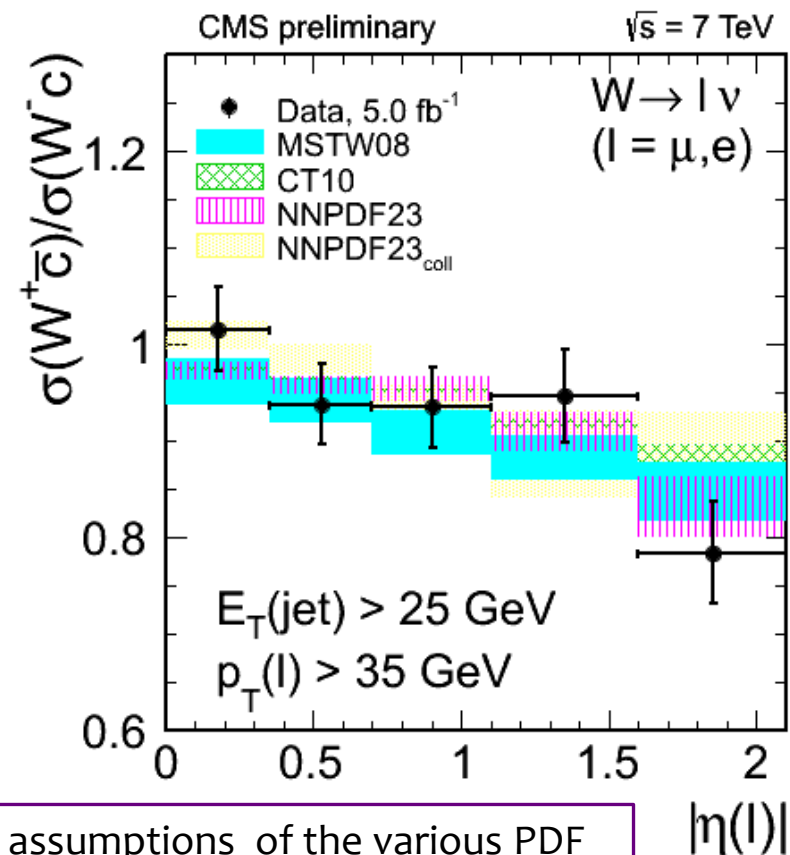
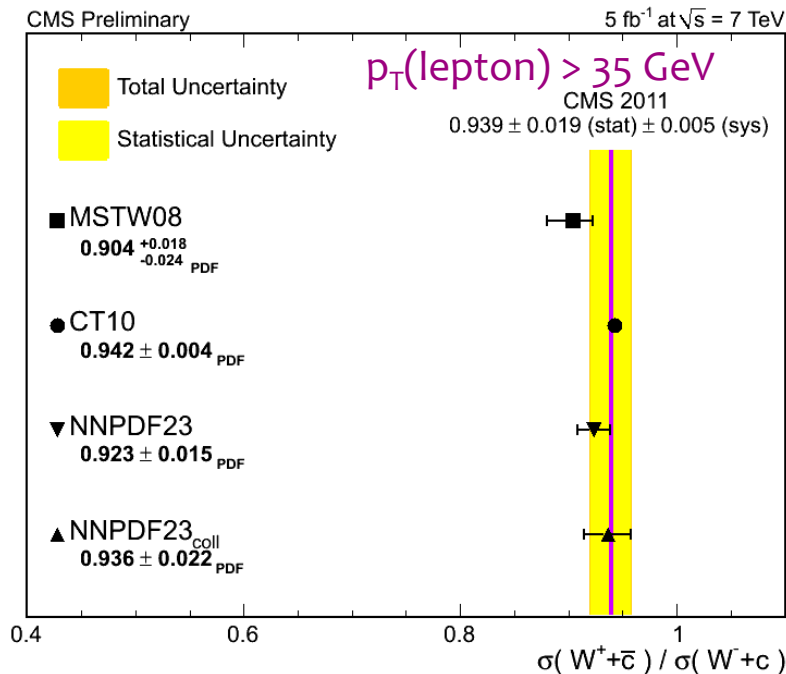
- Normalizing with the measured total $\sigma(W+c)$
- The two measurements are essentially **uncorrelated**. Systematic uncertainties come almost entirely from the total cross-section determination.
- Agreement with theory



Charged cross section ratio

- **Total** and **wrt pseudorapidity** of the **lepton** from the W decay
- **Inclusive selection**
- **Relative measurement:** Cancellation of syst. uncertainties in the ratio (lepton reco.), statistical uncertainties dominate.

$$\frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)} = \frac{(N^+_{OS} - N^+_{SS})}{(N^-_{OS} - N^-_{SS})}$$



Different assumptions of the various PDF groups (ex. $s^+ = s + \bar{s}$ and $s^- = s - \bar{s}$)

Summary

- Rich variety of CMS experimental results with PDF information at LHC energies.
- Results presented here are from pp collisions @7 TeV, still 8 TeV data to be/being analyzed, more results will come.

Documentation

- **QCD-11-003:** *Measurement of the 3-jet to 2-jet rate and extraction of α_s .*
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsQCD11003>
- **SMP-13-003:** *Drell-Yan differential cross sections at 7 TeV.*
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13003>
- **SMP-12-002:** *Associated production of a W boson and a charm jet at 7 TeV.*
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12002>
- **CMS public results:**
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP>

Thank you for your attention !!

Fitting $\alpha_s(M_Z)$

- Perform a χ^2 fit with Experimental uncertainties (taking into account correlations)
- Fitting region: 400-1400 GeV (21 data points)

$$\chi^2 = M^T C^{-1} M$$

$$M_i = R_{32}^i - T_{32}^i$$

$$C = Cov^{stat} + \sum_{n=1}^7 Cov^{JES_Sources} + \sum_{n=1}^3 Cov^{Unfold_Sources}$$

with

Cov^{stat} : is the statistical cov. matrix taking account correlations due to unfolding

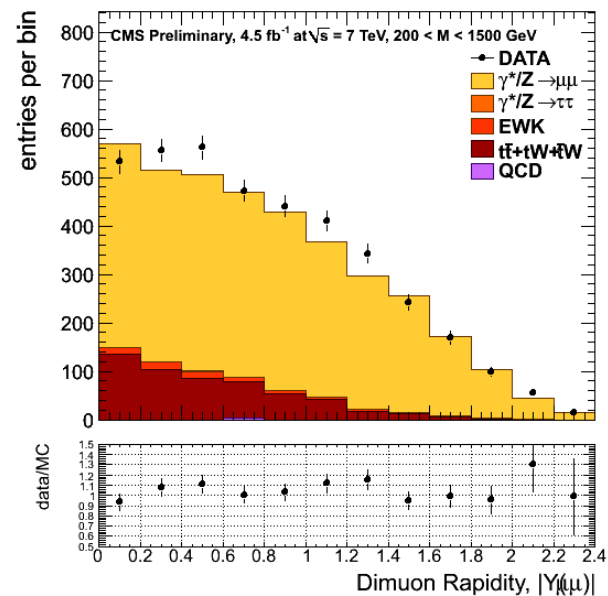
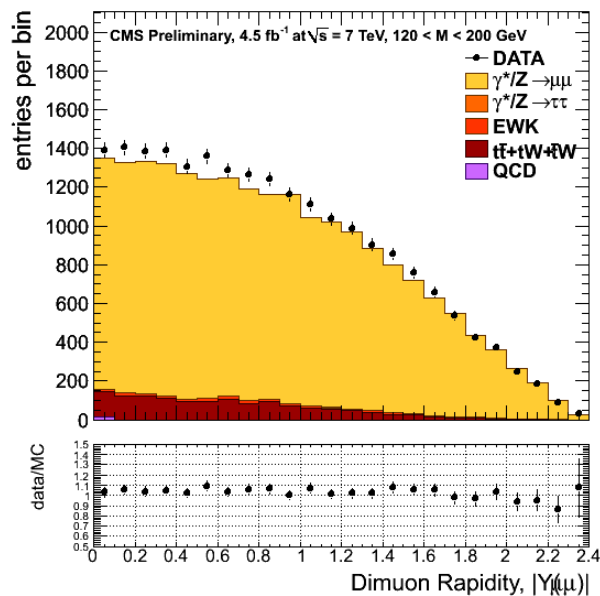
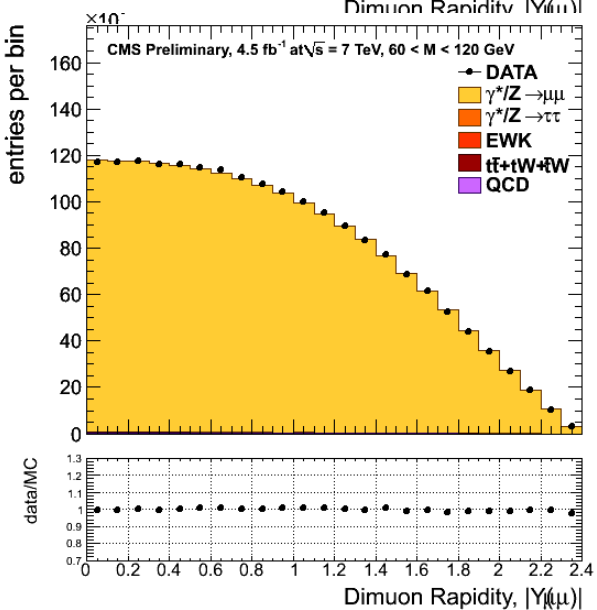
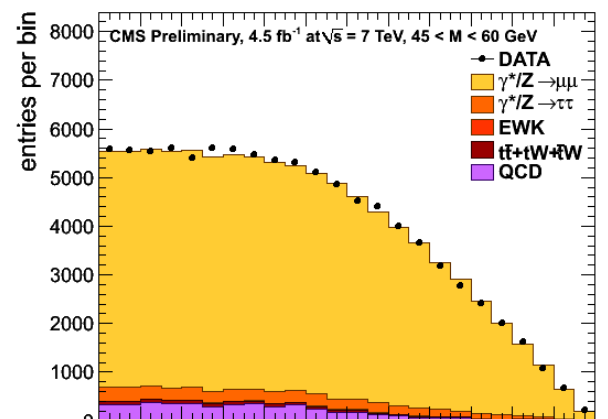
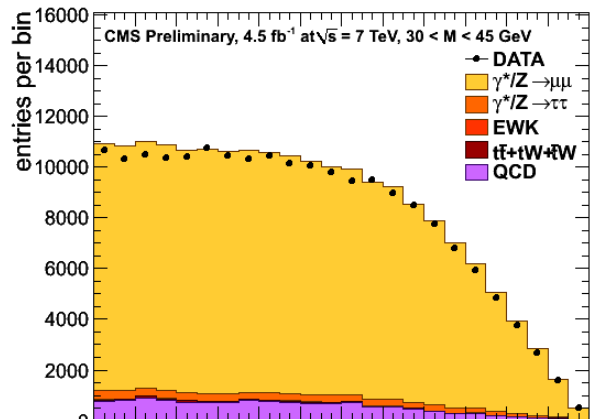
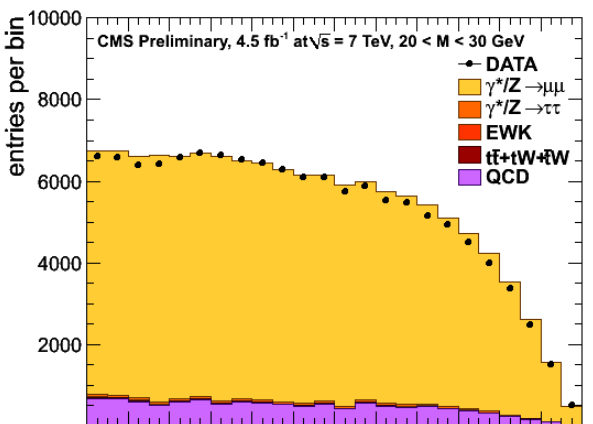
$Cov^{JES_Sources}$: the cov. matrices taking into account the JES systematic uncertainty sources

$Cov^{Unfold_Sources}$: the cov. matrices taking into account the Unfolding systematic uncertainty sources

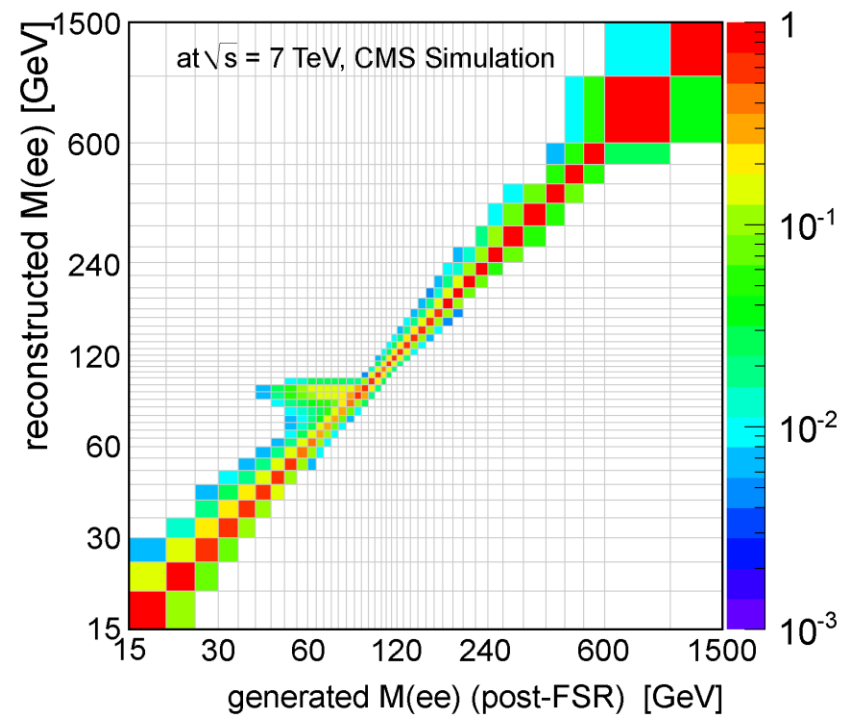
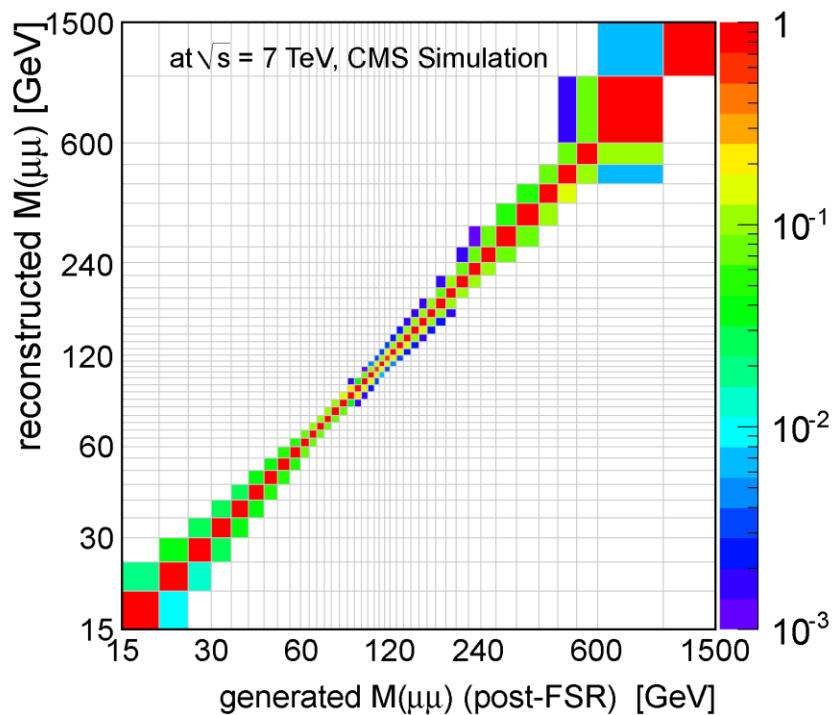
- Each JES and Unfolding systematic source is treated as 100% correlated across the $\langle p_{T1,2} \rangle$ bins.
- PDF and Scale uncertainties are treated separately.

R32 experimental uncertainties

- Jet energy correction, known to 2.0 - 2.5%: $\rightarrow \Delta R/R \sim 1.2\%$
 - Provided as 16 mutually uncorrelated sources; fully correlated within source; Gaussian behaviour assumed
 - Dominated by absolute scale, followed by high p_T extrapolation
- Unfolding uncertainty accounting for:
 - Variation of jet p_T spectral slopes following differences from Pythia6 Z2 (agrees with MadGraph) and Herwig++ 2.3
 - Variation of jet energy resolution (JER) $\rightarrow \Delta R/R < 1\%$
- Addition of non-Gaussian tails to JER
- Luminosity (normalization) uncertainty cancels
- No assumptions on bin-to-bin correlations with respect to y necessary, only 1 bin considered
- Statistical uncertainties propagated via unfolding

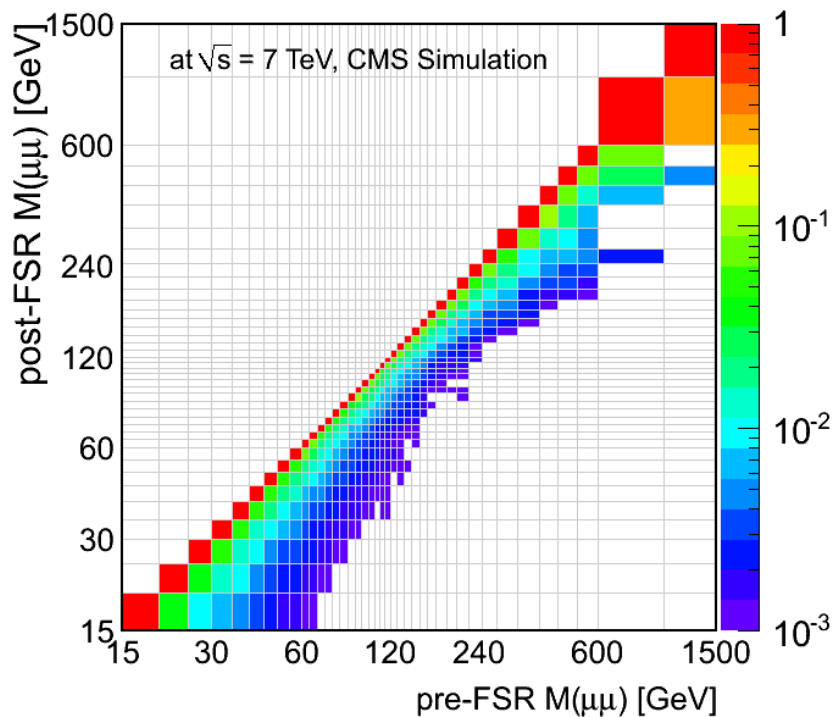


Unfolding matrices for DY cross sections

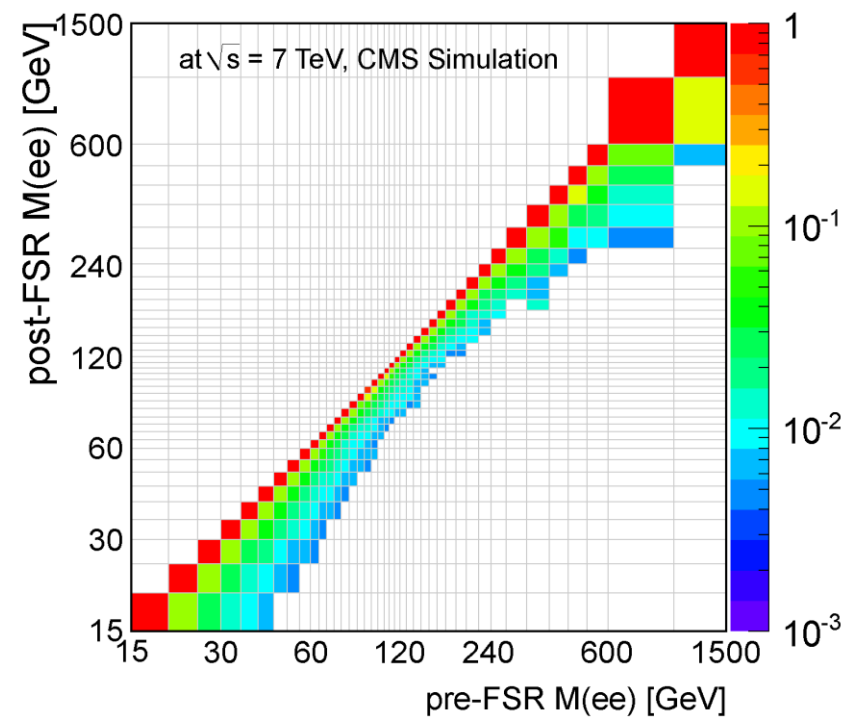


FSR-unfolding matrices for DY cross sections

Drell-Yan $\rightarrow \mu\mu$

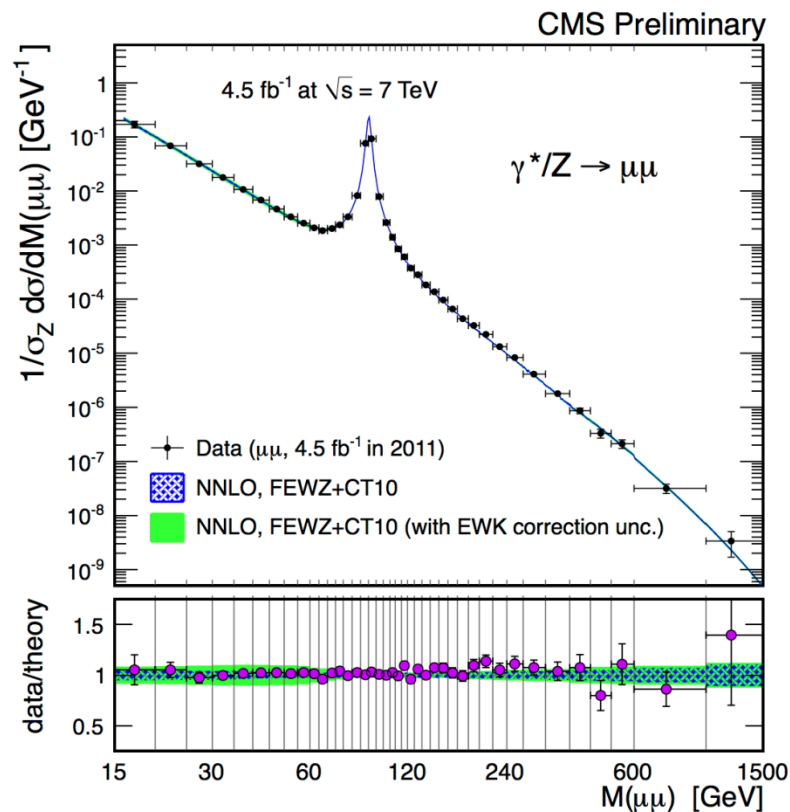


Drell-Yan $\rightarrow ee$

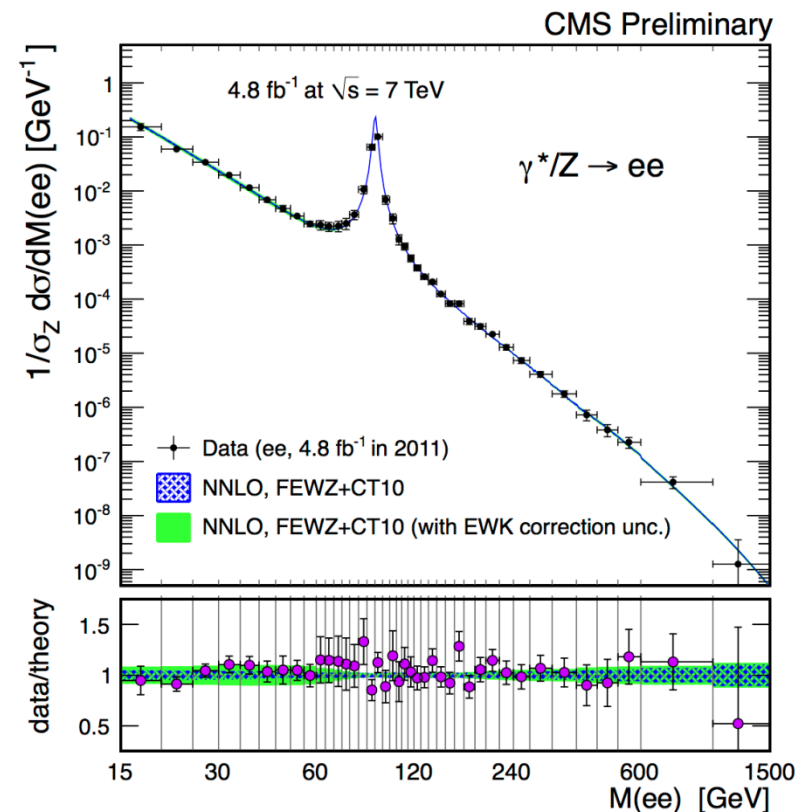


Differential cross section $d\sigma/dM$

Drell-Yan $\rightarrow \mu\mu$



Drell-Yan $\rightarrow ee$

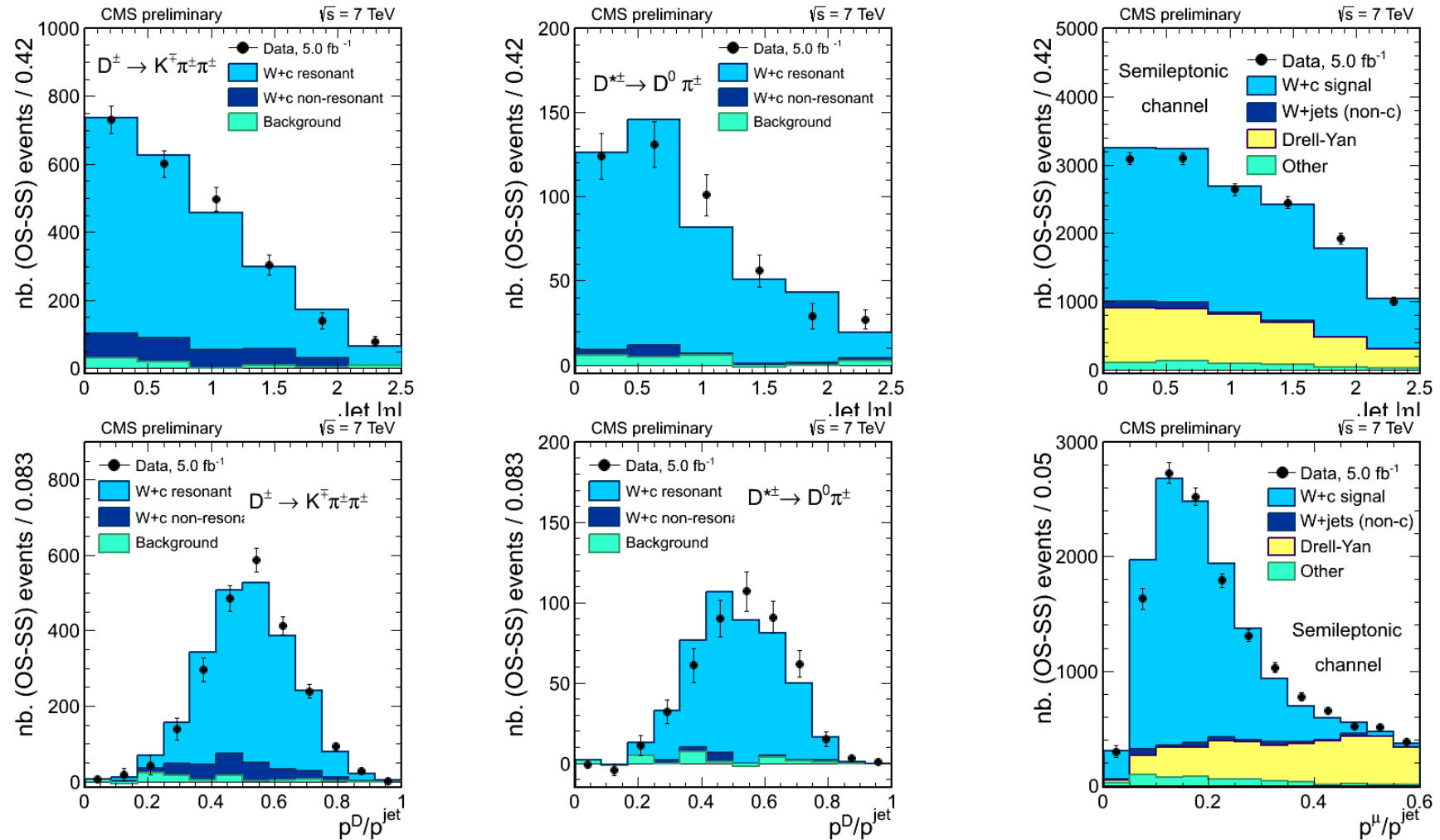


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Systematic uncertainties on $W+c$ total cross section

Source	$p_T^\mu > 25 \text{ GeV}$ $\Delta_{\text{syst}} [\%]$	$p_T^\ell > 35 \text{ GeV}$ $\Delta_{\text{syst}} [\%]$
MC statistics	1.6	1.3
Lepton efficiency, resolution	0.8	1.5
Muon efficiency in charm decay	1.4	1.5
Vertex reconstruction	1.8	1.7
Pileup	0.9	0.8
Jet energy scale	3.0	1.7
E_T	2.0	2.0
$\mathcal{B}(c \rightarrow D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm)$	1.5	1.5
$\mathcal{B}(c \rightarrow D^{*\pm}(2010) \rightarrow D^0 \rightarrow K^\mp \pi^\pm)$	0.7	0.6
$\mathcal{B}(c \rightarrow \ell)$	2.6	2.7
ISR and Q^2 -matching	0.2	0.2
Fragmentation function	0.8	0.6
Other theory uncertainties on $\mathcal{A} \epsilon$	0.8	0.7
DY background	1.4	0.9
Luminosity	2.2	2.2
Total	6.3	5.7

Characterization of the kinematics of W+c events

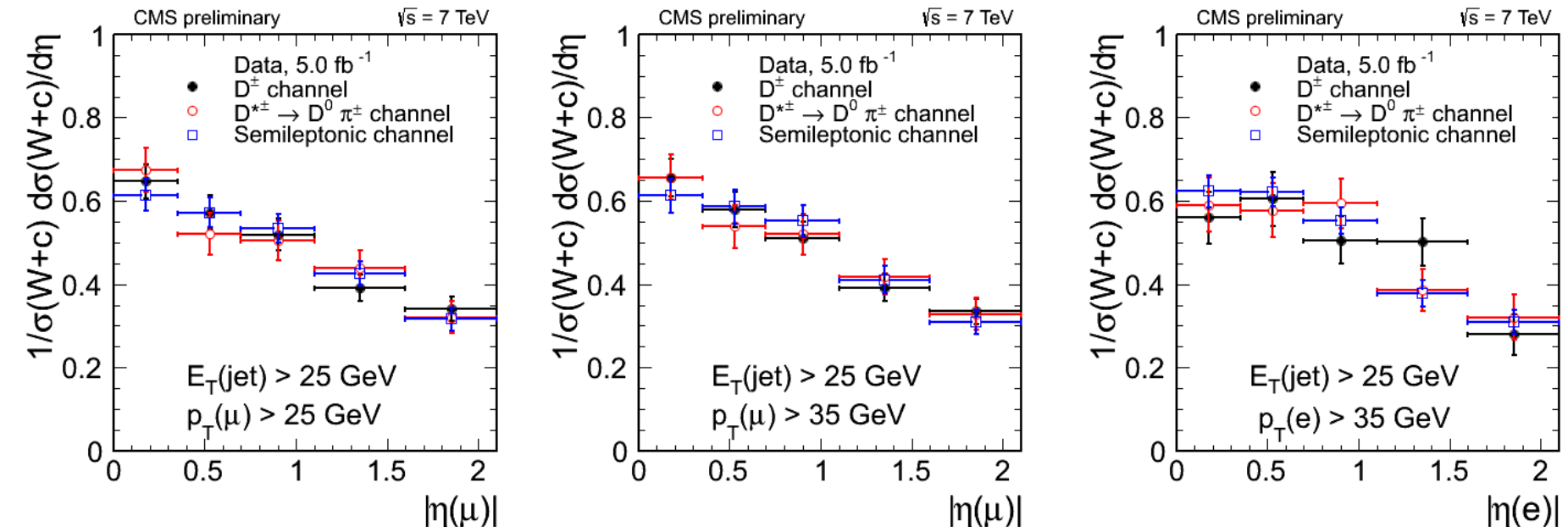


Overall good agreement

Slightly harder fragmentation spectra in data than in MC

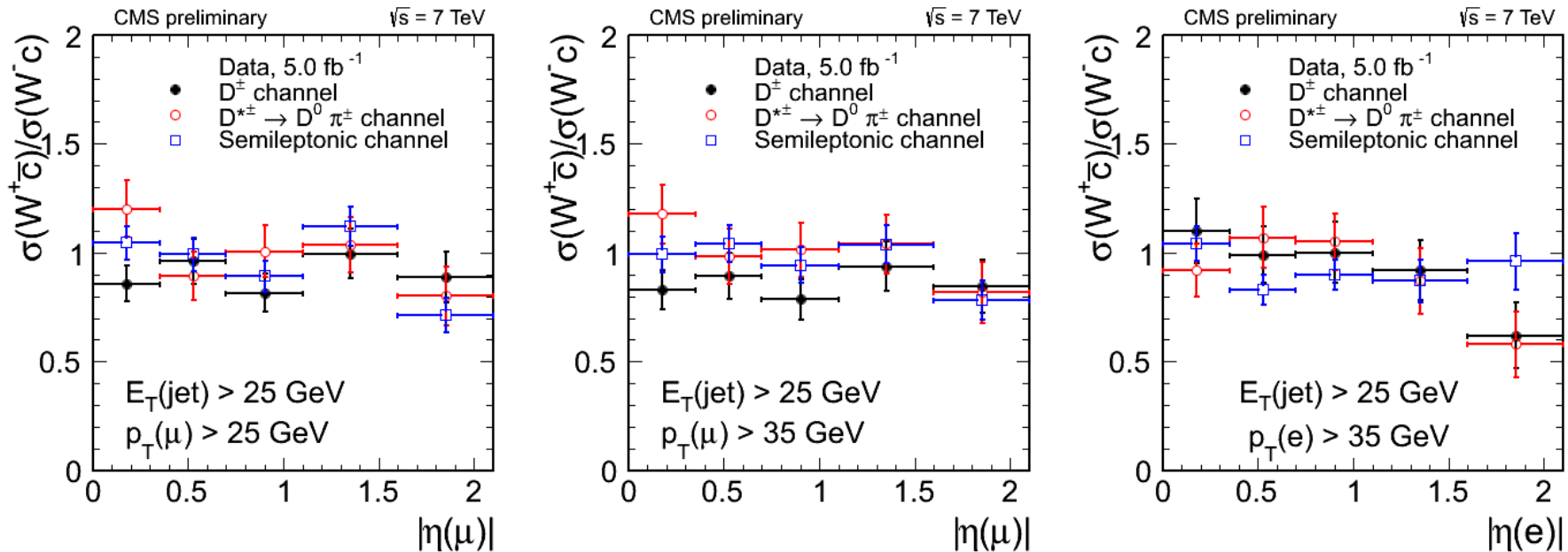
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Normalized differential cross section



- Good agreement between the three independent D-tagging channels
- Good agreement of the average values of the electron and muon channels ($p_T > 35$ GeV WP)
- Full errors drawn. Main syst. effects cancel in the ratio

Cross section ratio



- Good agreement between the three independent D-tagging channels
- Good agreement of the average values of the electron and muon channels ($p_T > 35$ GeV WP)
- Full errors drawn. Main syst. effects cancel in the ratio

Systematic Uncertainties on differential cross section

- Most of the effects cancel in the ratio.

	Normalized Diff Xsec.
MC statistics	3-5%
Muon Momentum Scale and Resolution	0.2-0.4%
Electron Momentum Scale and Resolution	1(B)%-1.5%(E)
Muon Reco&ID	0.35%
Electron Reco&ID	0.25%
Background subtraction	0.3%

- Other systematic uncertainties (MET, PileUp Reweighting, Jet Scale and resolution, PDF uncertainties, Charm fragmentation) have been found to have no effect on the ratios
- Statistical error: 5 - 7% → **Normalized diff. measurement dominated by statistical uncertainties**

Systematic uncertainties in the cross section ratio

- Overall negligible (effects cancelled out in the measured ratios)
- Remaining uncertainties come from effects on the lepton reconstruction

	Charge Ratio
Muon Momentum Scale and Resolution	0.4-0.8% (0.2-0.3% incl.)
Electron Momentum Scale and Resolution	1(B)%-1.5%(E)

- Lepton charge misidentification $< 0.3\%$ (electrons), $\sim 10^{-4}$ (muons). The associated systematic uncertainty in the positive to negative cross section ratio $\propto (1 - \text{charge ratio})$. Charge ratio ~ 1 \rightarrow effect is negligible.
- **Dominated by statistical uncertainties**