University at Buffalo
The State University of New York

CMS
Compact Muon Solenoid

Recent CMS results and PDF constrains

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On behalf of the CMS collaboration

Precision Theory for Precise Measurements at the LHC and Future Colliders

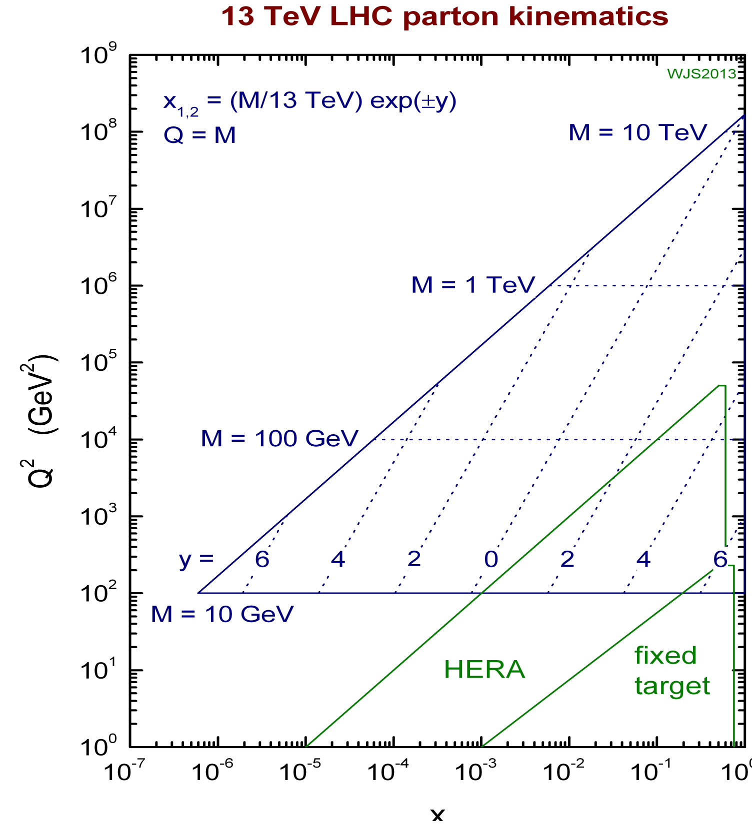
Quy Nhon, Vietnam

(Quy Nhơn, Việt Nam)

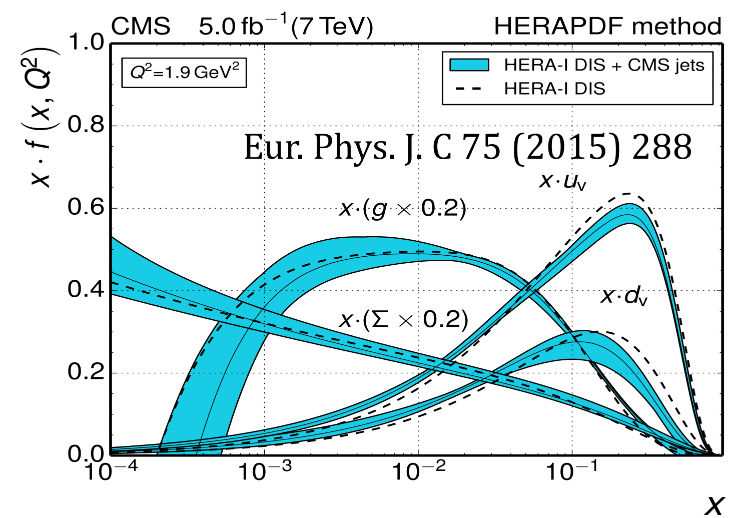
September 25-October 1, 2016

Introduction

- Precise PDFs are essential for theoretical predictions at LHC
- LHC extends parton kinematic reach → better constrains of PDFs
- Recent updated PDFs sets include LHC data at 7 TeV (NNPDF3.0, CT14, MMHT14, ABMP15)
- CMS measurements most sensitive to PDFs:
  - Covered in this talk (focus on 8 and 13 TeV)
    - W charge asymmetry
    - W, Z production
    - Drell-Yan
    - Inclusive jet and di-jet productions
    - Top pair production cross section
  - Others
    - Direct photon
    - Single top



http://www.hep.ph.ic.ac.uk/~wstirlin/plots/lhcgrid13.jpg



Eur. Phys. J. C 75 (2015) 288

Lepton charge asymmetry in pp→W+X

- Excess of W^+ compared to W^- due to two valance u quarks in the protons
- Constraint valance, sea quarks and PDF ratios
- Signal yields extracted from fits of missing transverse energy distribution to data
- Dominant systematic uncertainties: muon efficiency estimation, QCD background

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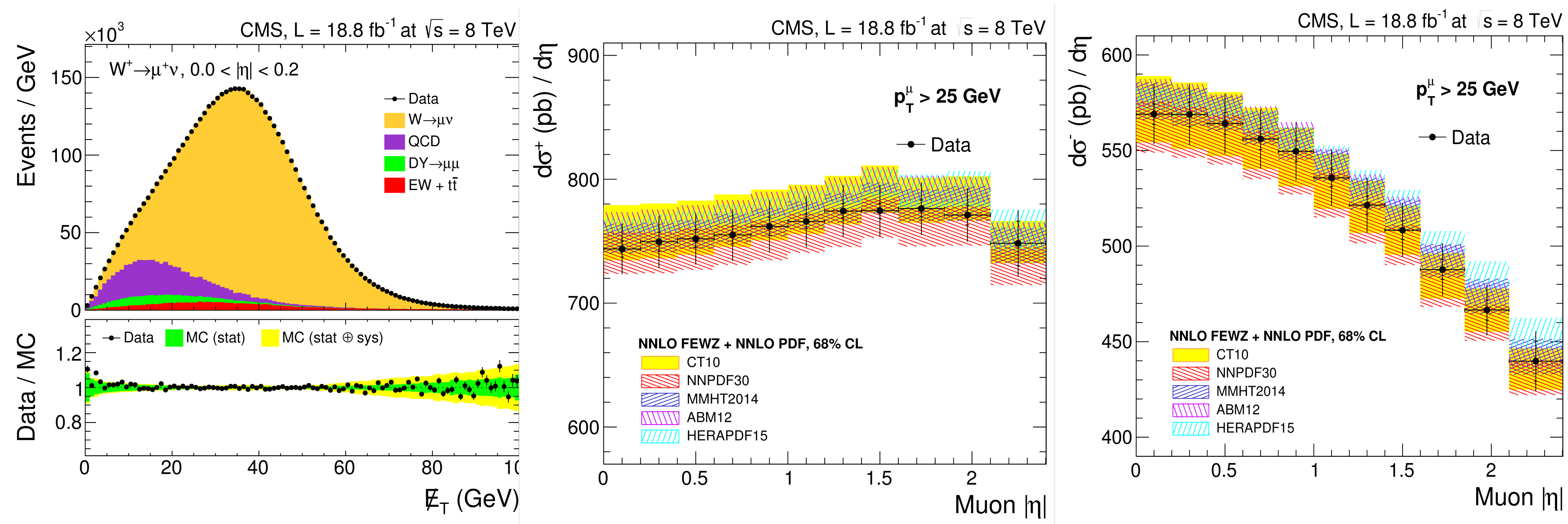
$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\overline{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\overline{\nu})}$$



Lepton charge asymmetry results at 8 TeV

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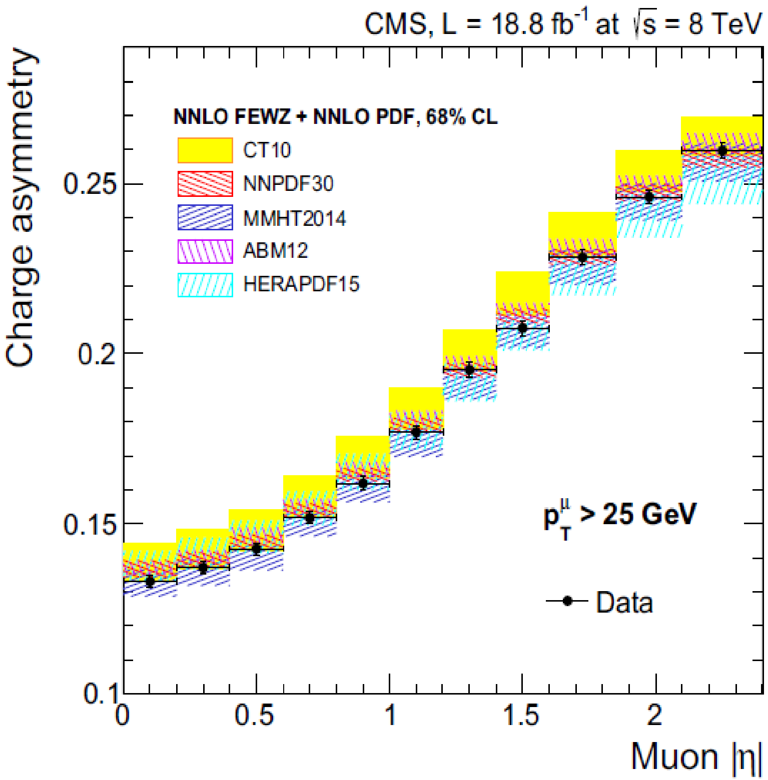

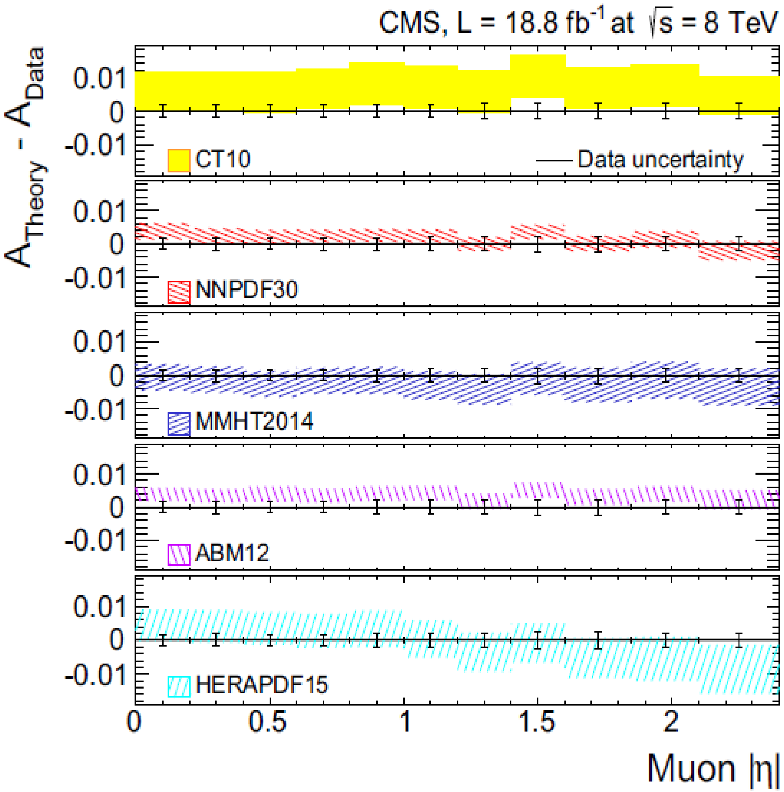

- NNLO FEWZ predictions using different choices of PDFs agree with data
- Better description of data for NNPDF3.0, MMHT2014 (CMS + ATLAS 7 TeV W lepton charge asymmetry results included)
- Central values are higher than data for CT10 and ABM12

PDF constrains with W lepton charge asymmetry data

- HERAFitter with 13 fit parameters
- Data set: HERA I+II DIS data + CMS lepton charge asymmetry at 8 TeV
- PDF shapes change but still within uncertainty
- Uncertainty is reduced

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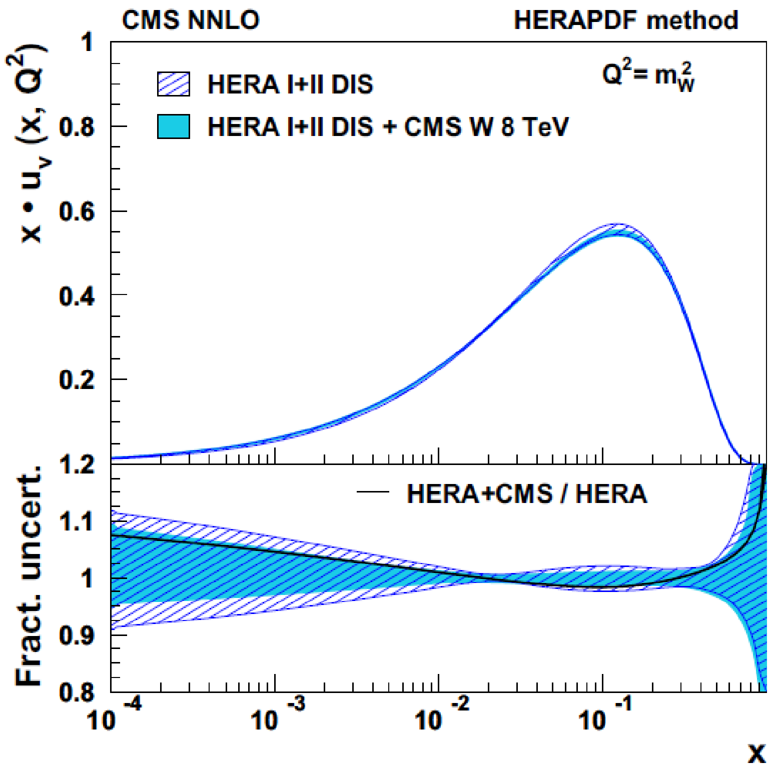
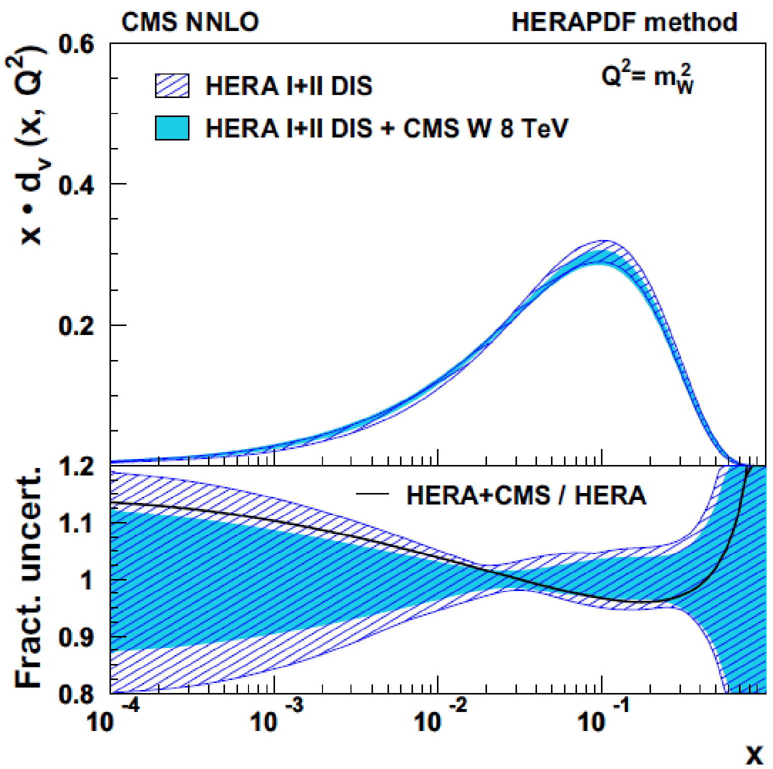
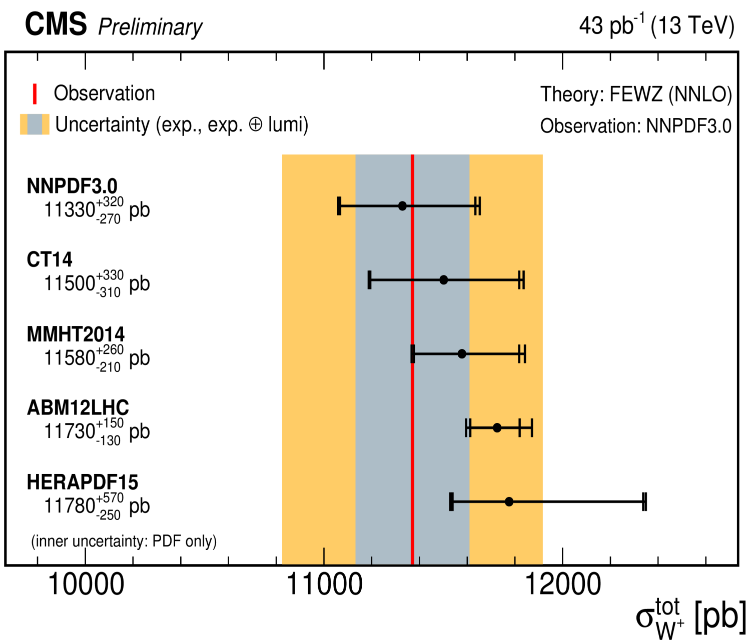




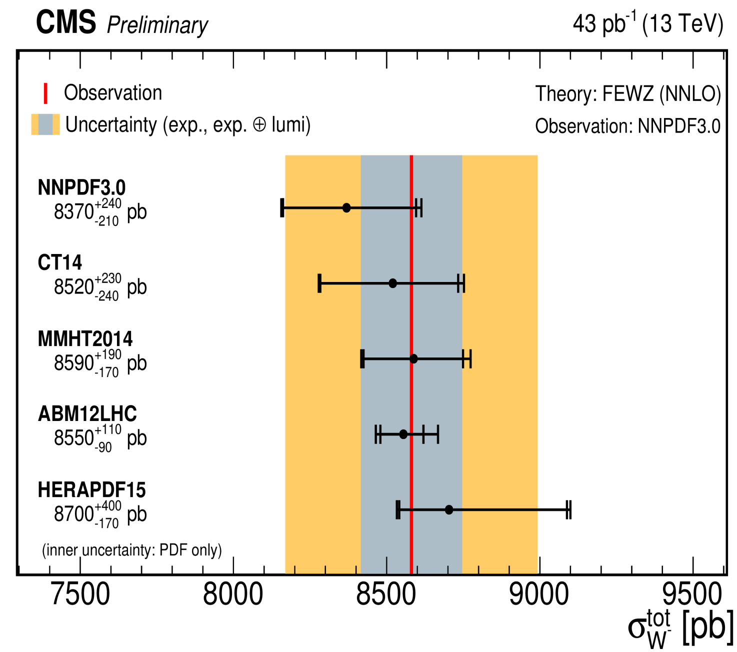
W production cross sections at 13 TeV

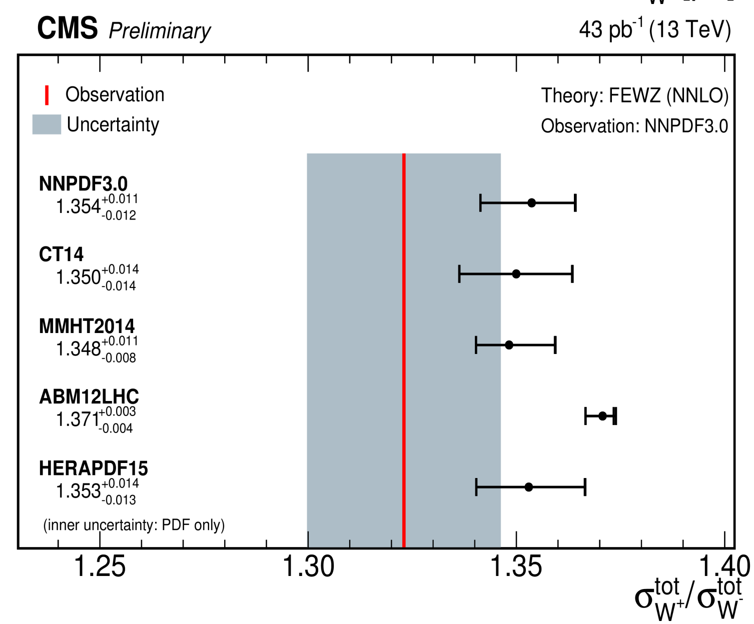
NEW

CMS-PAS-SMP-15-004



- Experimental precision approximates theoretical uncertainty.
- Luminosity uncertainty is high (4.8%)
- Measured cross sections are consistent with NNLO calculations using different PDFs





Z production at 13 TeV

CMS-PAS-SMP-15-011

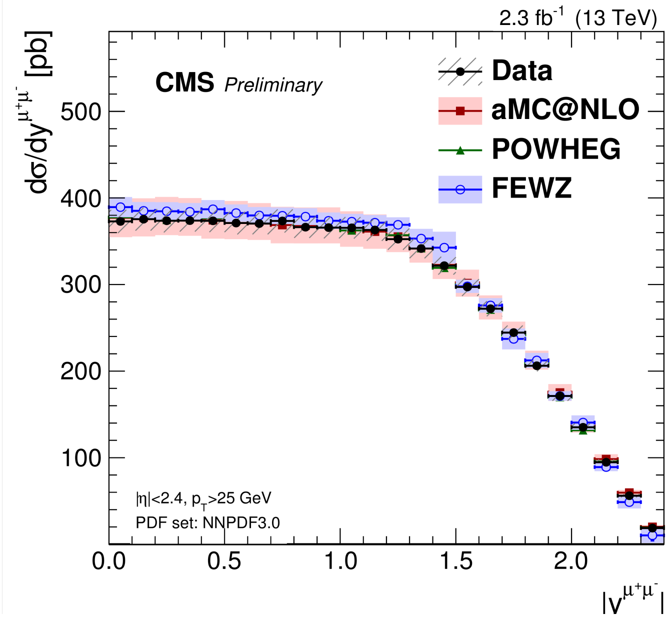
NEW

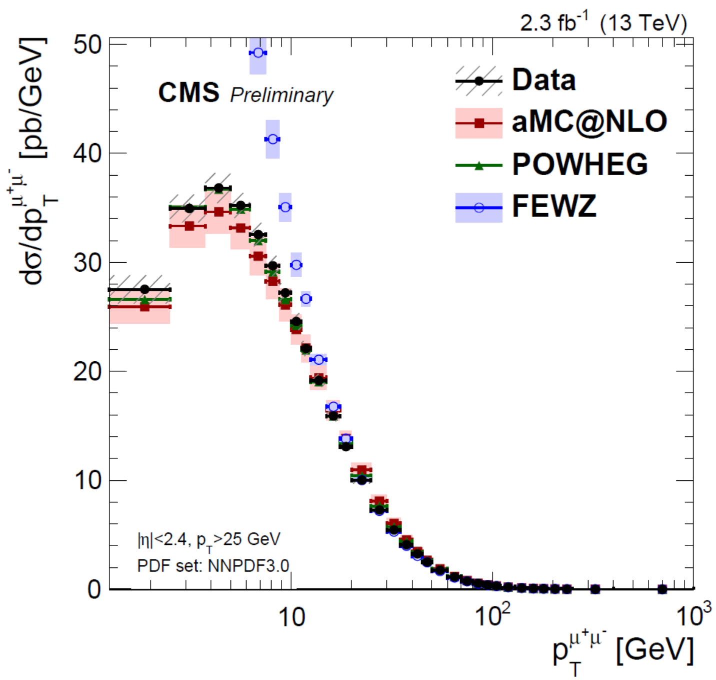
- Sensitive to light quarks and gluon PDFs
- Low Z-p_T governed by initial-state parton radiation and intrinsic p_T of initial-state parton
- High Z-p_T dominated by quark-gluon scattering
- Dimuon mass range 60 < m < 120 GeV

$$\sigma(pp \to ZX) \times \mathcal{B}(Z \to \mu^+\mu^-) = 1870 \pm 2\ (\text{stat}) \pm 35\ (\text{syst}) \pm 51\ (\text{lumi})\ \text{pb}$$

	σ_Z^{tot} [pb]
NNPDF3.0	1870^{+50}_{-40}
CT14	1900^{+50}_{-50}
MMHT2014	1920^{+40}_{-40}
ABM12LHC	1920^{+20}_{-20}
HERAPDF15	1930^{+90}_{-40}

FEWZ cross section predictions at NNLO including PDF and scale uncertainties



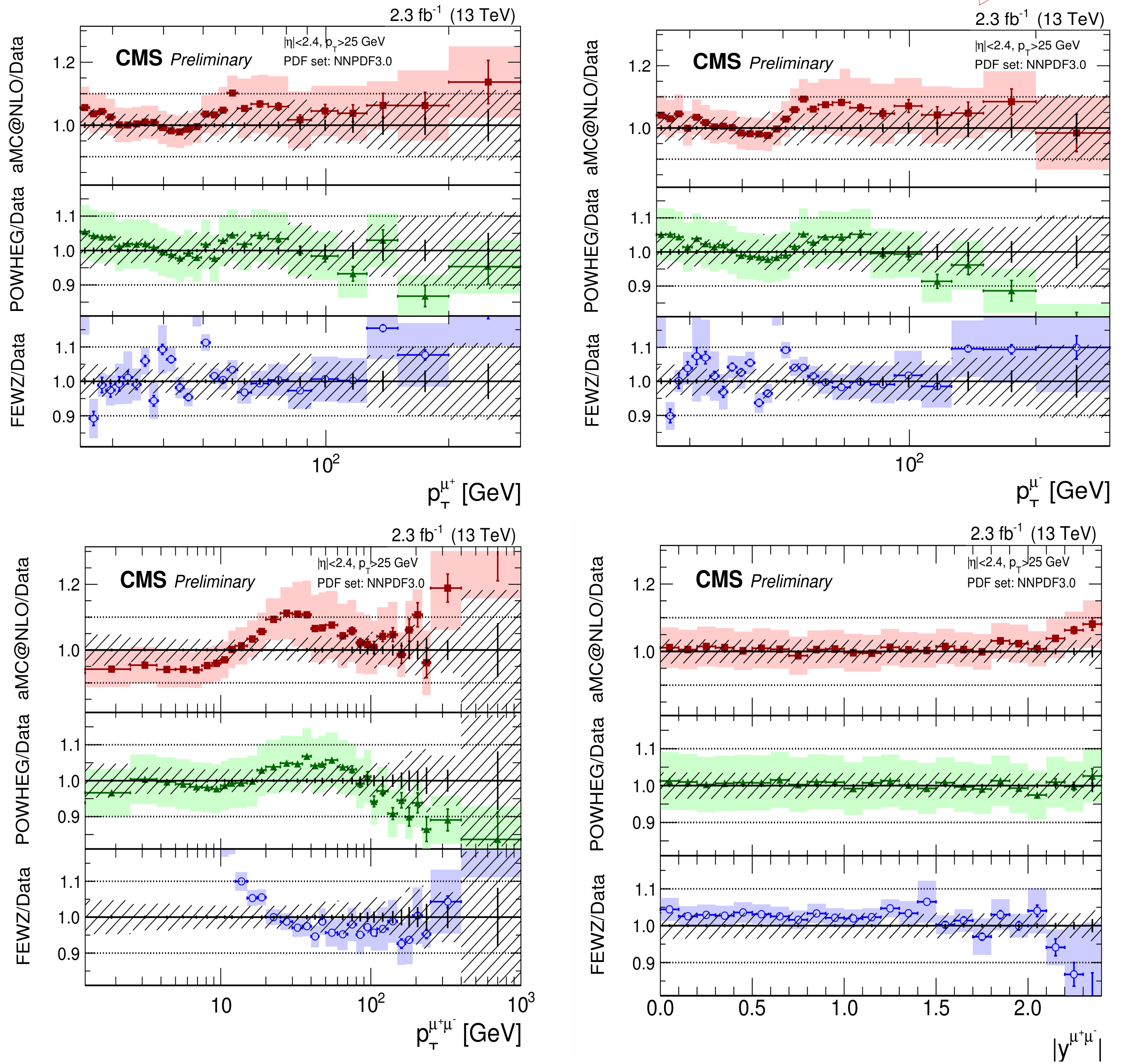


Z production at 13 TeV (cont.)

CMS-PAS-SMP-15-011

NEW

- Generator: aMC@NLO, POWHEG, FEWZ using NNPDF3.0
- Discrepencies are observed in some regions (within errors)



Drell-Yan production

- Measure differential and double-differential cross section in mass range 15 < m < 3000 GeV and di-lepton rapidity up to 2.4
- Better experimental precisions than PDFs uncertainty → possible constrains on light and strange quarks PDFs

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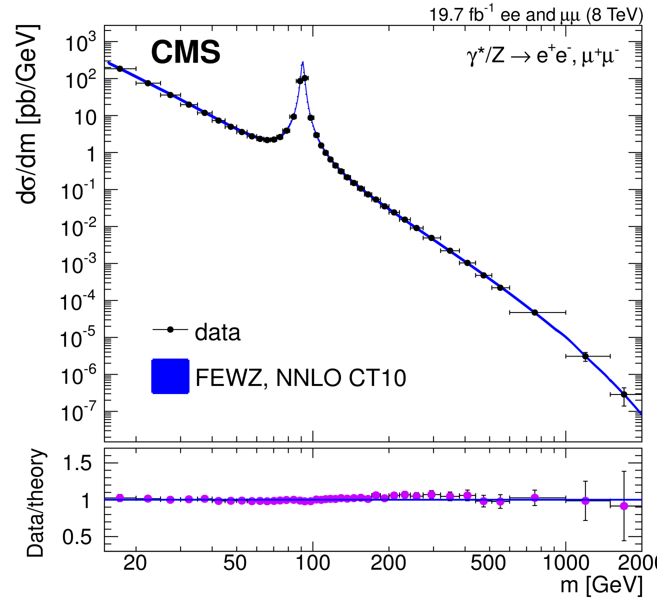
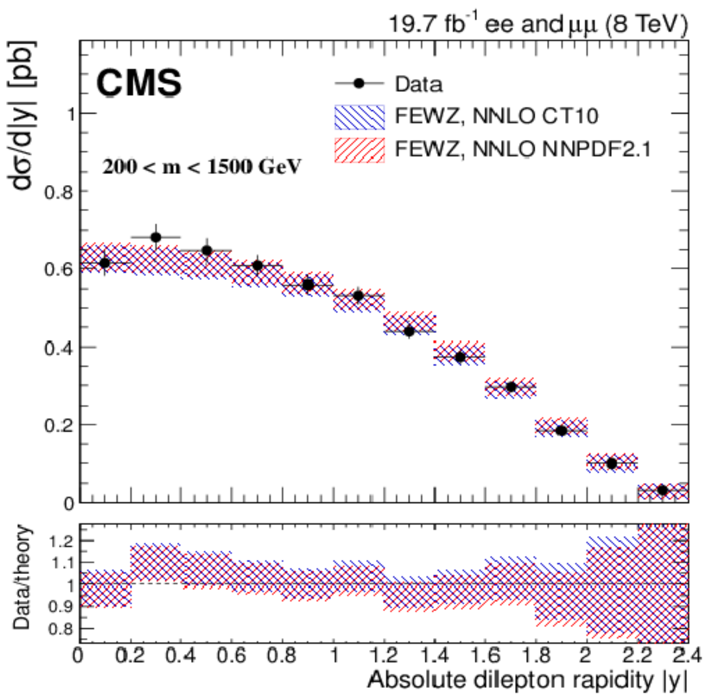
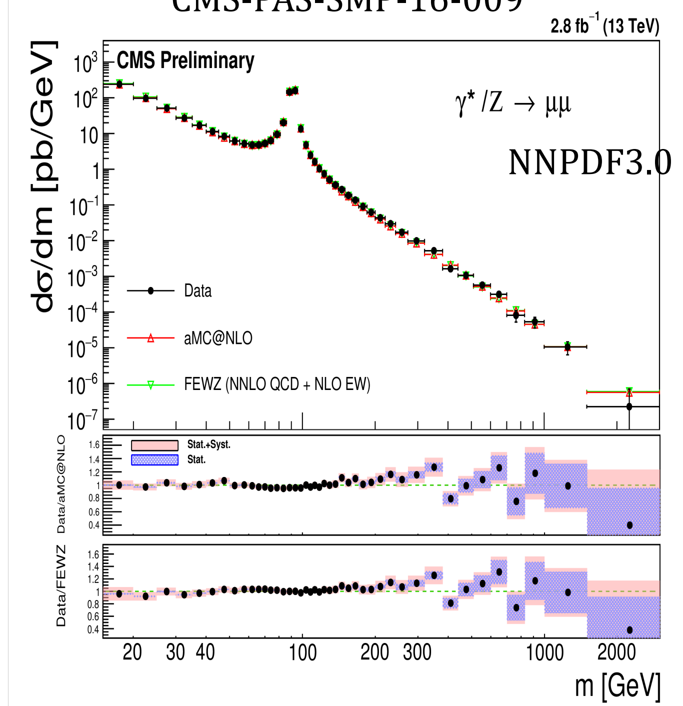




CMS-PAS-SMP-16-009



Drell-Yan cross section ratios

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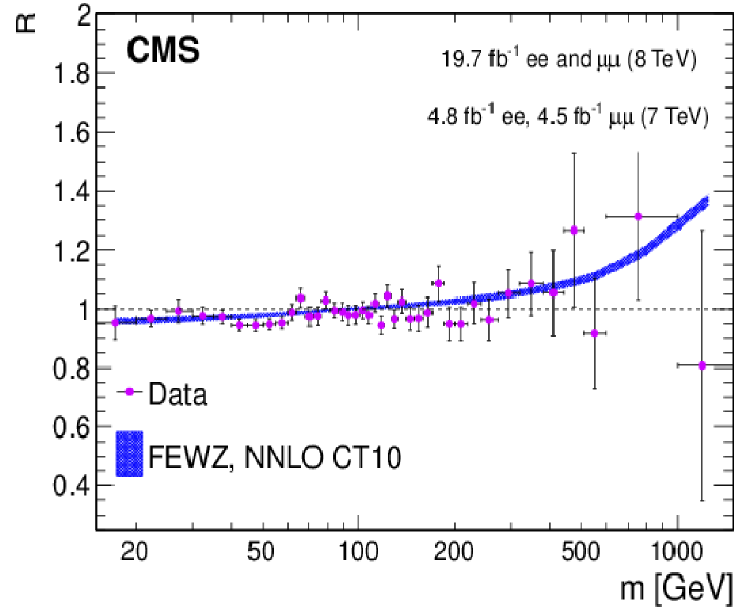
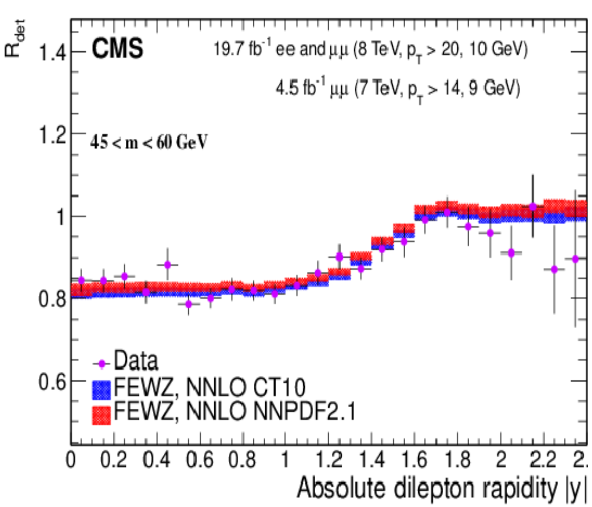
- Cross section ratios between 8 and 7 TeV

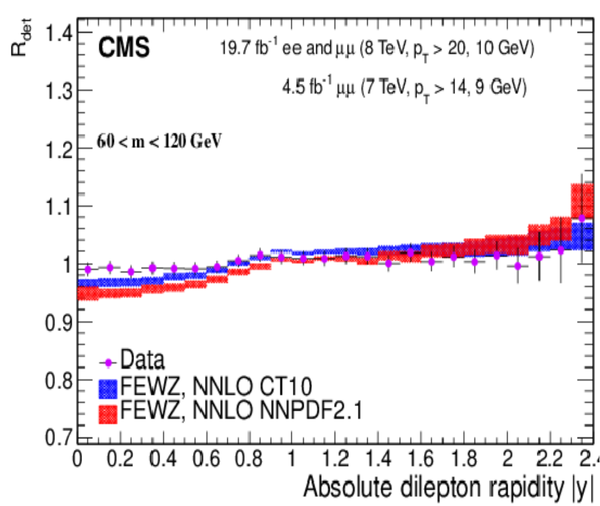
$$R(\mathrm{pp} \to \gamma^*/\mathrm{Z} \to \ell^+\ell^-) = \frac{\left(\frac{1}{\sigma_\mathrm{Z}}\frac{\mathrm{d}\sigma}{\mathrm{d}m}\right)(8\,\mathrm{TeV})}{\left(\frac{1}{\sigma_\mathrm{Z}}\frac{\mathrm{d}\sigma}{\mathrm{d}m}\right)(7\,\mathrm{TeV})}$$

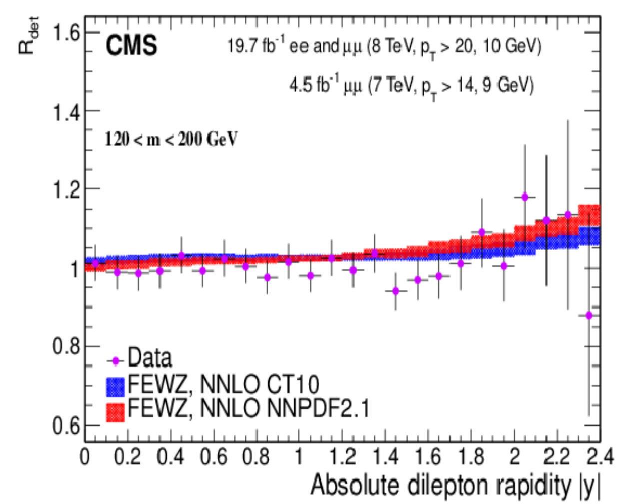
$$R_{\mathrm{det}}(\mathrm{pp} \to \gamma^*/\mathrm{Z} \to \ell^+\ell^-) = \frac{\left(\frac{1}{\sigma_\mathrm{Z}}\frac{\mathrm{d}^2\sigma}{\mathrm{d}m\,\mathrm{d}|y|}\right)(8\,\mathrm{TeV}, p_\mathrm{T} > 10, 20\,\mathrm{GeV})}{\left(\frac{1}{\sigma_\mathrm{Z}}\frac{\mathrm{d}^2\sigma}{\mathrm{d}m\,\mathrm{d}|y|}\right)(7\,\mathrm{TeV}, p_\mathrm{T} > 9, 14\,\mathrm{GeV})}$$

- High sensitivity to NNLO pQCD effects and potentially provide precise constrains on PDFs







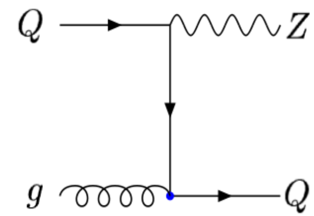


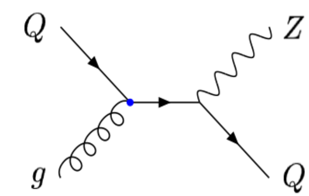
Z + c measurement at 8 TeV

NEW

CMS-PAS-SMP-15-009

- Directly probe charm PDFs
  - Intrinsic charm component existence?





Measured channel $pp \to Z + c + X$

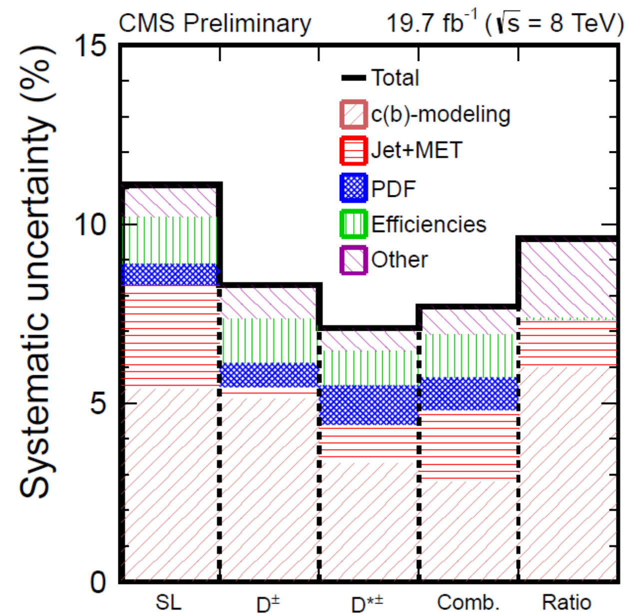
$\quad \hookrightarrow D \to K\pi\pi$

$\quad \to \ell\nu + X$

Selection cuts $p_T^\ell > 20GeV, |\eta^\ell| < 2.1, 71 < M_{\ell\ell} < 111GeV$

$p_T^{jet} > 25GeV, |\eta^{jet}| < 2.5$

$\sigma(Z+c+X) \times BR(Z \to \ell^+\ell^-)$	$8.6 \pm 0.5 \pm 0.7$
$\sigma(Z+c+X)/\sigma(Z+b+X)$	$2.0 \pm 0.2 \pm 0.2$



Theoretical prediction

	MG5_aMC@NLO (NNPDF3.0)	MCFM (MSTW08)	MCFM (CT10)
$\sigma(Z+c+X) \times BR(Z \to \ell^+\ell^-)$	$9.47 \pm 0.04(stat.) \pm 0.15(PDF) \pm 0.05(scales)$	$5.32 \pm 0.01^{+0.12}_{-0.06}(PDF)$	
$\sigma(Z+c+X)/\sigma(Z+b+X)$	$1.87 \pm 0.07(stat.) \pm 0.05(scales)$		1.58 ± 0.01

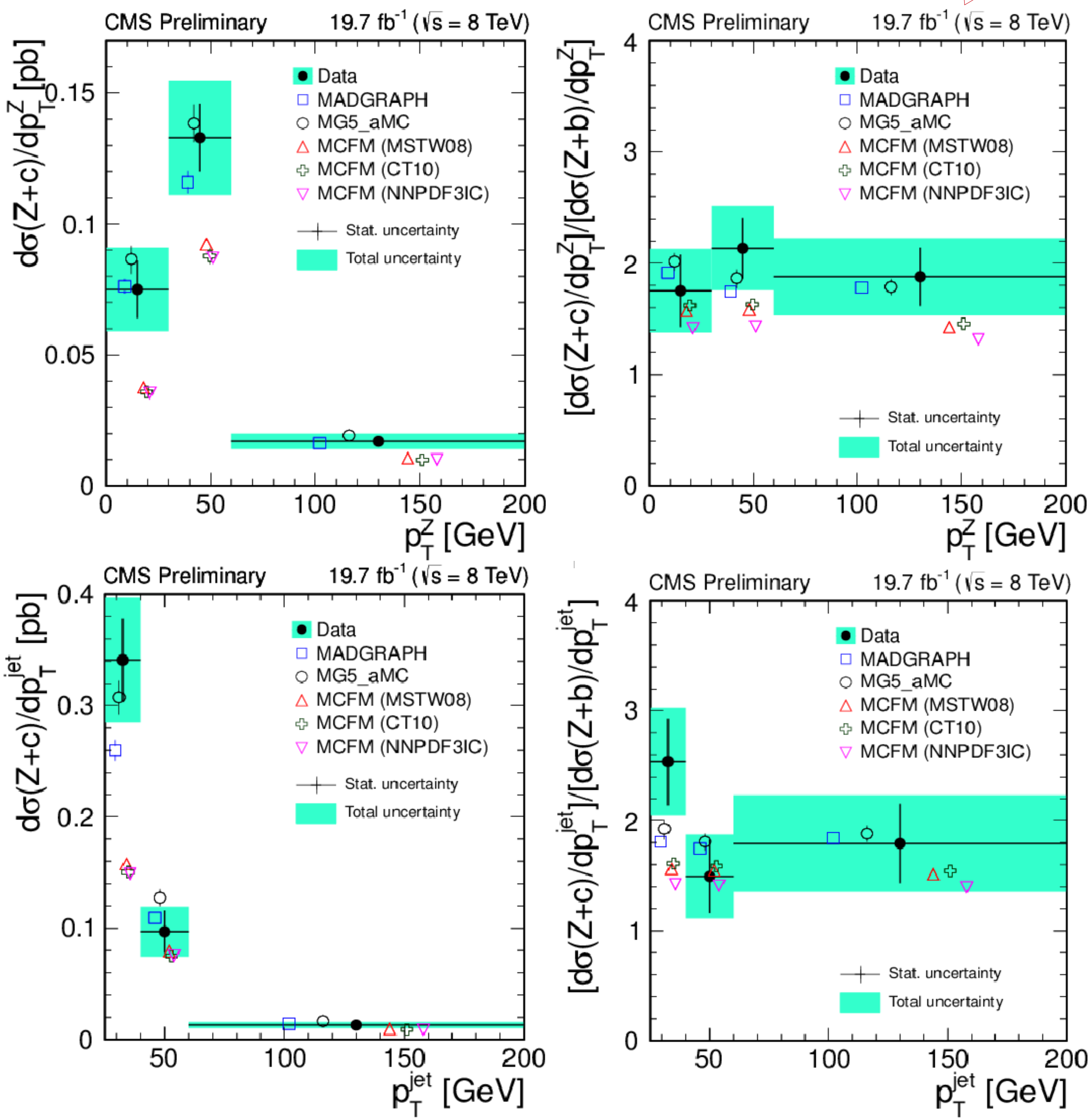
- Variations of MCFM predictions using other PDFs are within 5% lower

Z + c results (8 TeV)

NEW

CMS-PAS-SMP-15-009

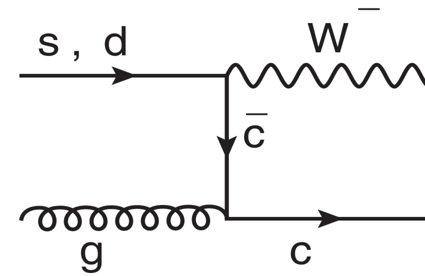
- NNPDF3IC: charm PDF is parametrized and determined together with light and gluon PDFs [arXiv:1605.06515]
- MCFM predictions are lower than data
- No significant difference using NNPDF3IC compared to other PDF set

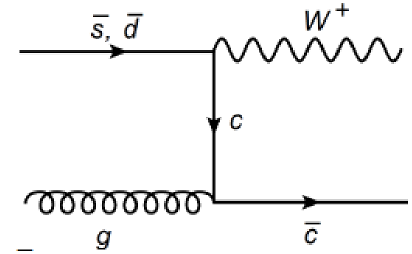


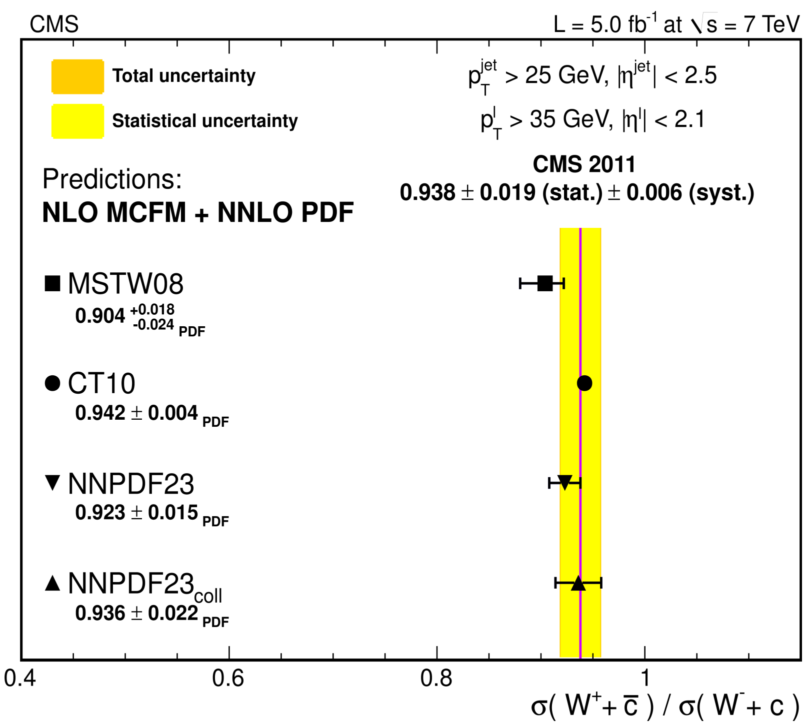
W + c measurements (7 TeV)

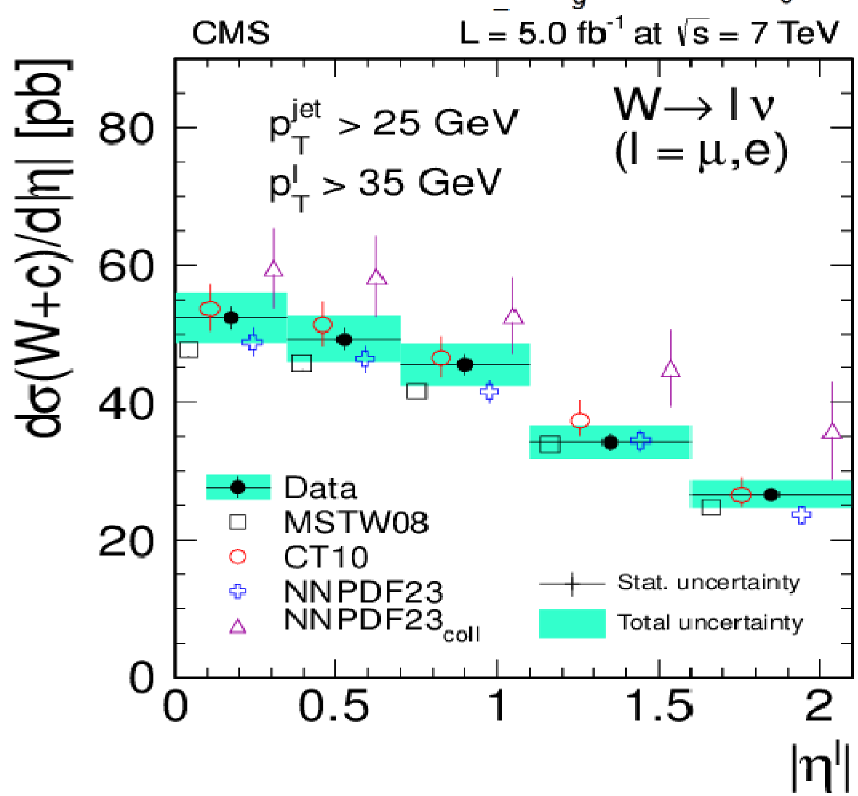
JHEP 02 (2014) 013

- Directly sensitive to s-quark content
- c-quarks are identified by hadronic or semileptonic decays of charm hadrons
- Good agreement between data and NLO calculations (MCFM) using different PDF sets (fitted from low energy data)
- NNLO2.3coll based on high energy collision data only (W, Z production data from CMS, ATLAS, LHCb)









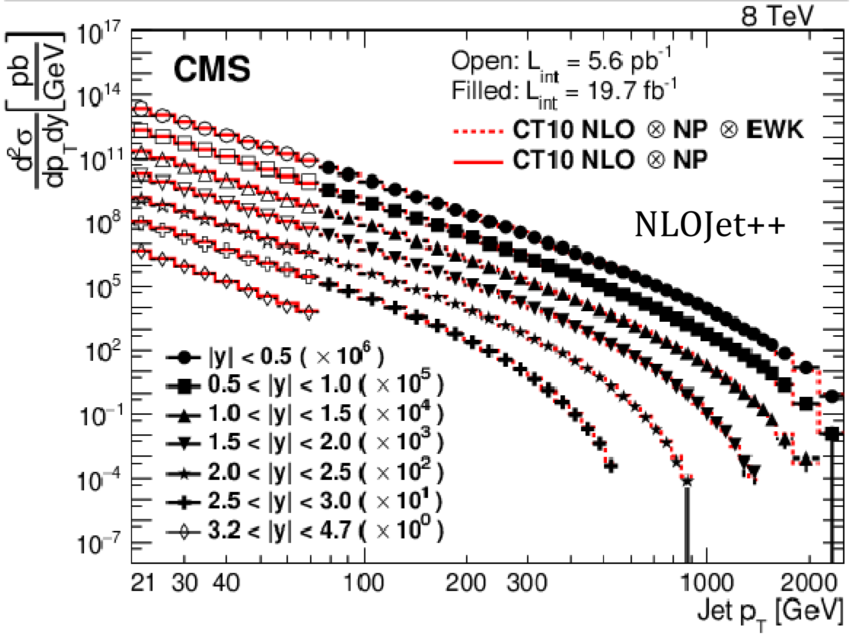
Inclusive jet cross section

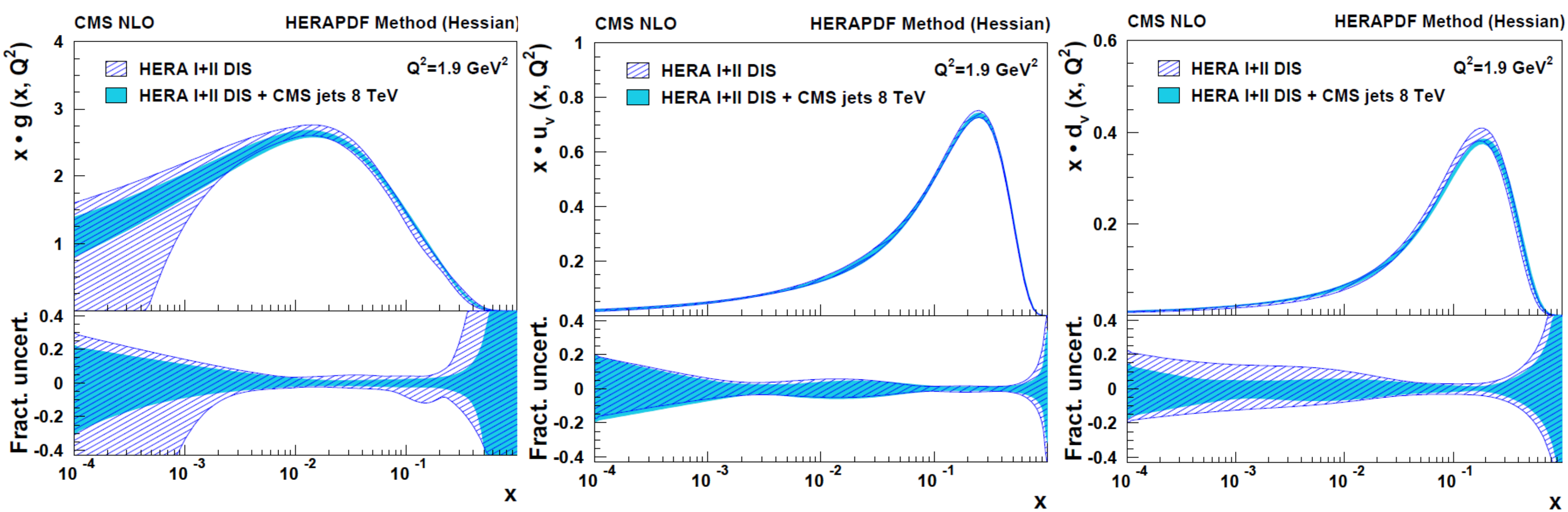
arXiv:1609.05331

- Constraint light and gluon PDFs
- Measure double-differential jet cross section up to |y| < 4.7

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{int,eff}} \frac{N_{jets}}{\Delta p_T \, (2\Delta|y|)}$$

Jet reconstructed by anti-k_t R=0.7

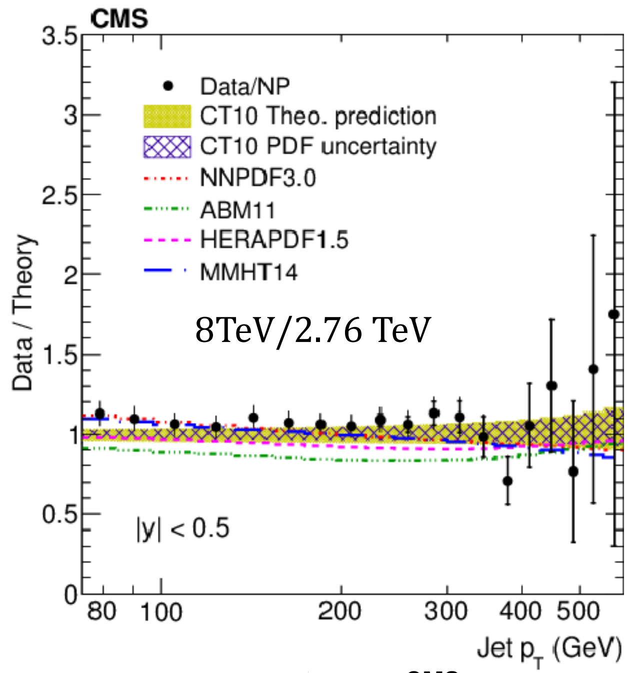


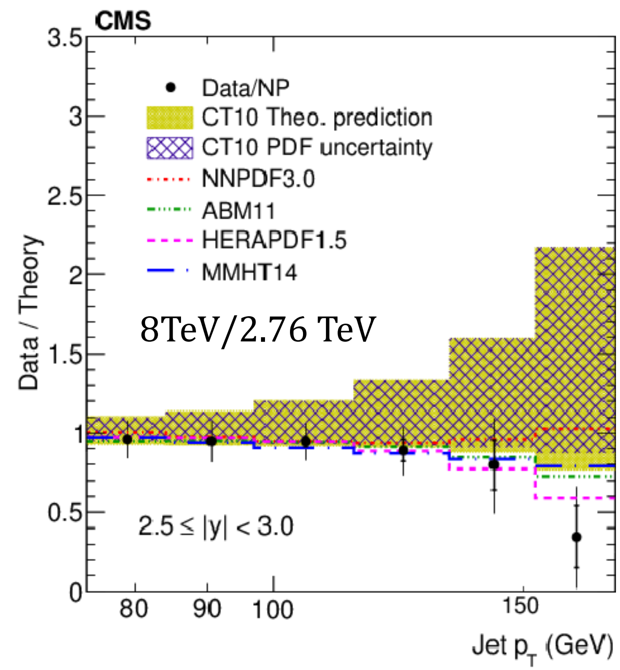


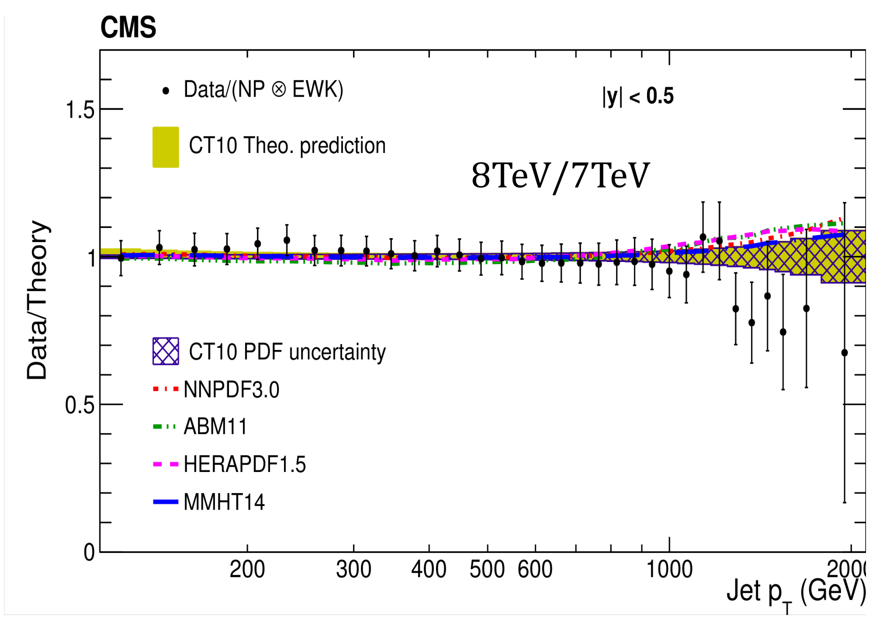
Inclusive jet cross section ratios

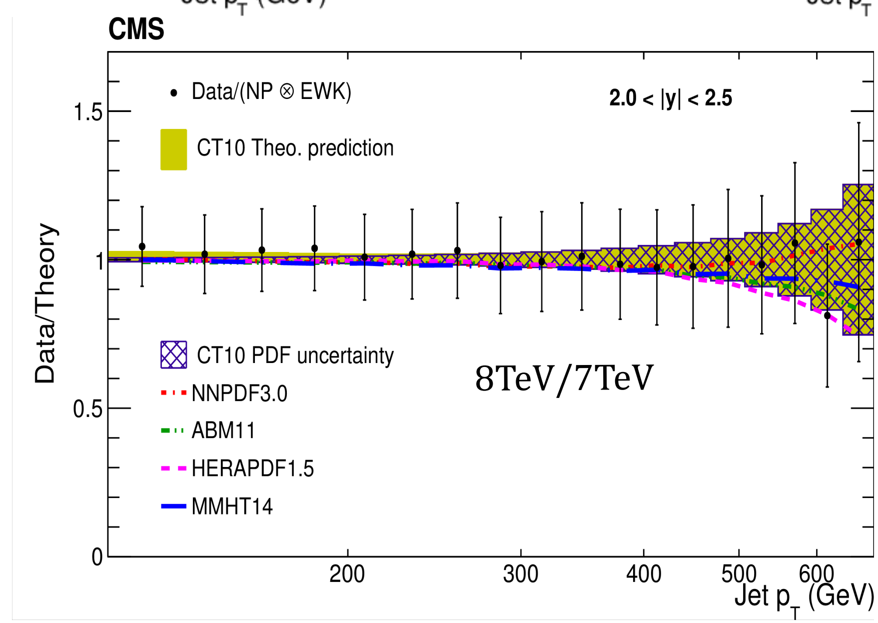
arXiv:1609.05331

- Cross section ratios measured at different energy (2.76, 7, 8 TeV) possibly provide better sensitivity to PDF (arXiv:1206.3557)
- Ratios of double-differential cross sections are shown
- Theoretical estimations are in good agreement with data









Inclusive jet cross section at 13 TeV

NEW

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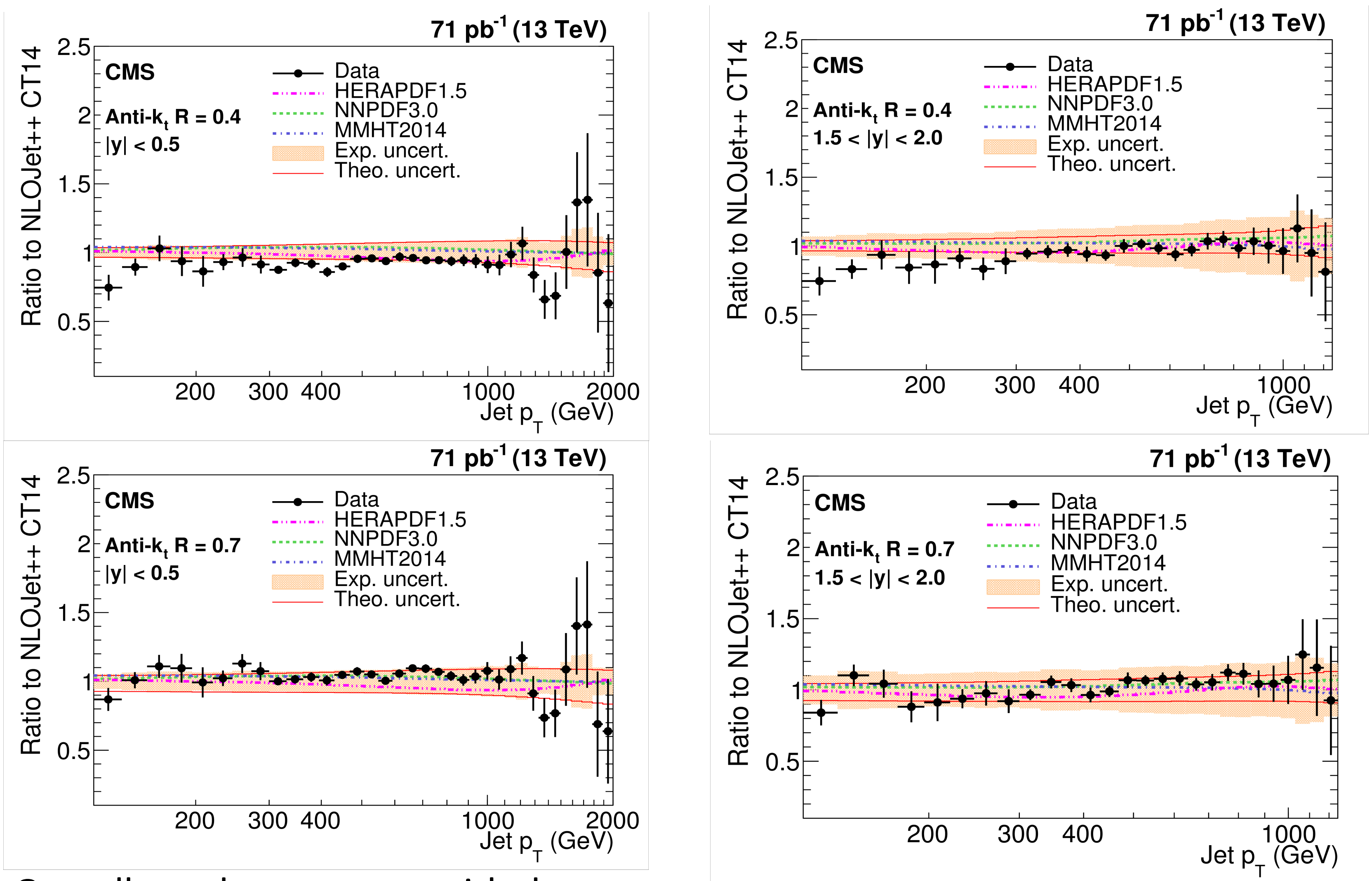
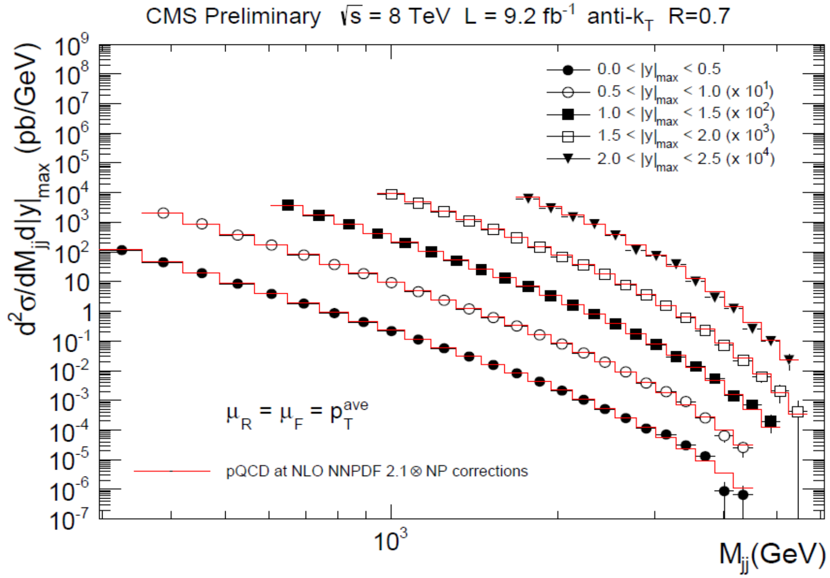


- Overall good agreement with data
- HERAPDF1.5 has lowest predicted values

Cross section vs. dijet mass

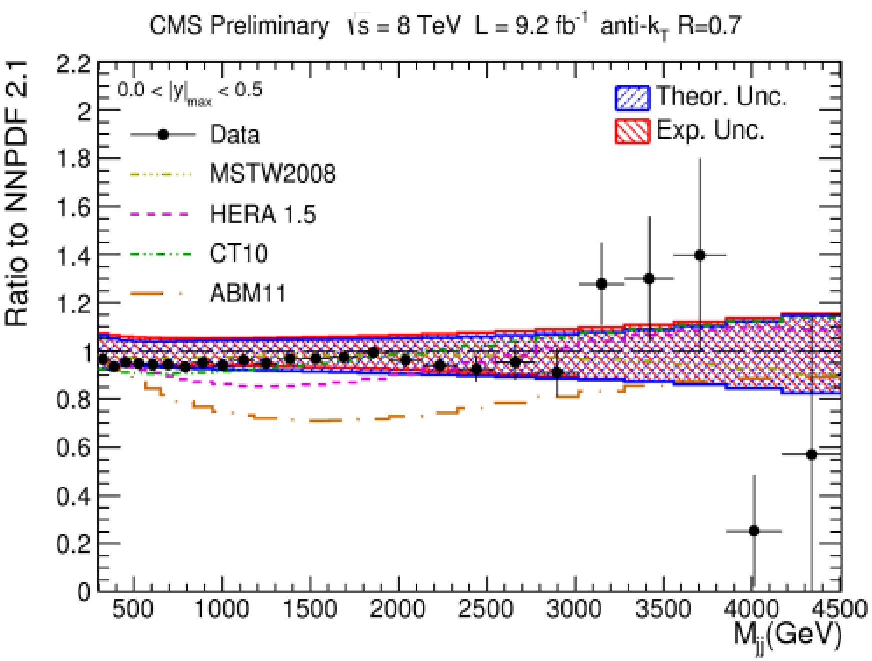
CMS-PAS-SMP-14-002

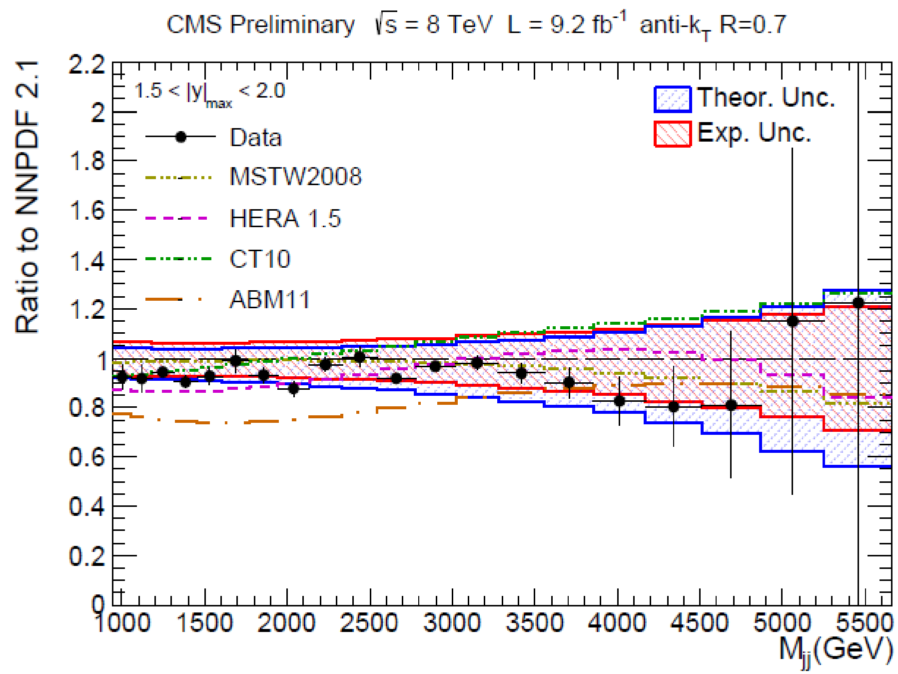


- Double-differential cross section of two leading transverse energy jets

$$\frac{d^2\sigma}{dM_{jj}\,dy_{max}} = \frac{1}{\epsilon\cdot\mathcal{L}_{eff}}\cdot\frac{N}{\Delta M_{jj}\,(2\cdot\Delta|y|_{max})}$$

PDF and scale dominants theoretical uncertainties (grow with mass and |y|)
Experimental uncertainty is dominated by JES

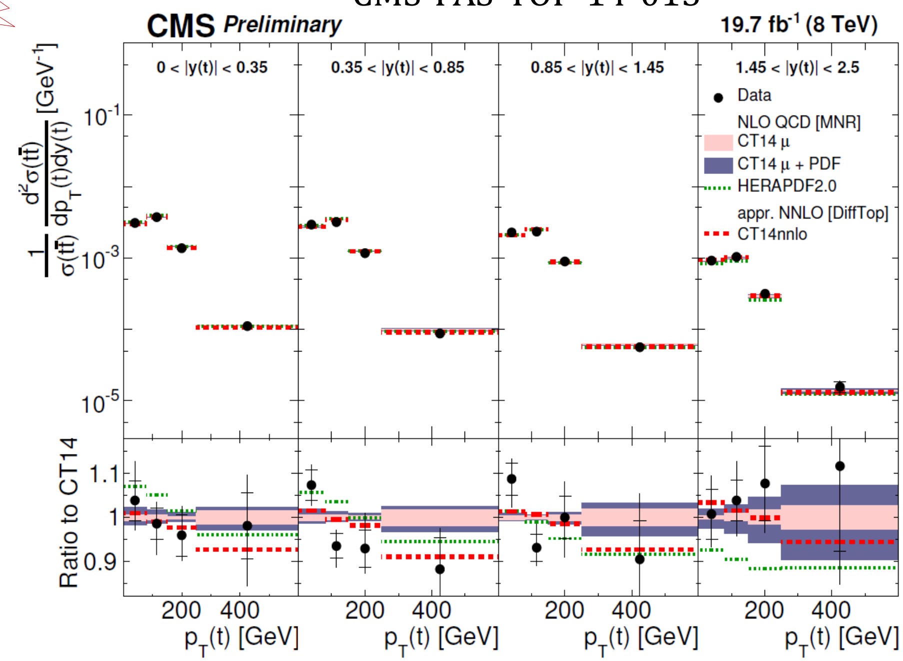




Top pair production cross section (8 TeV)

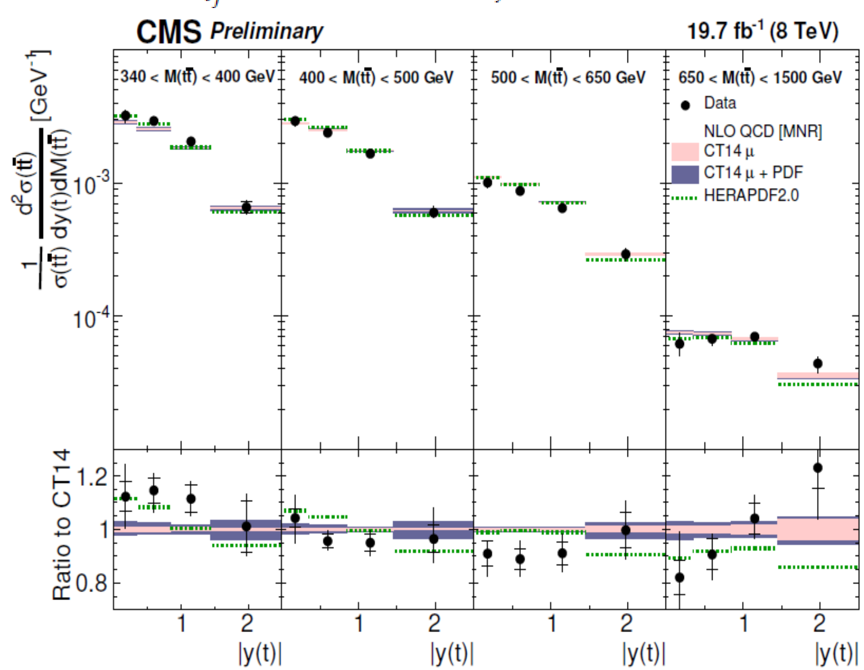
NEW

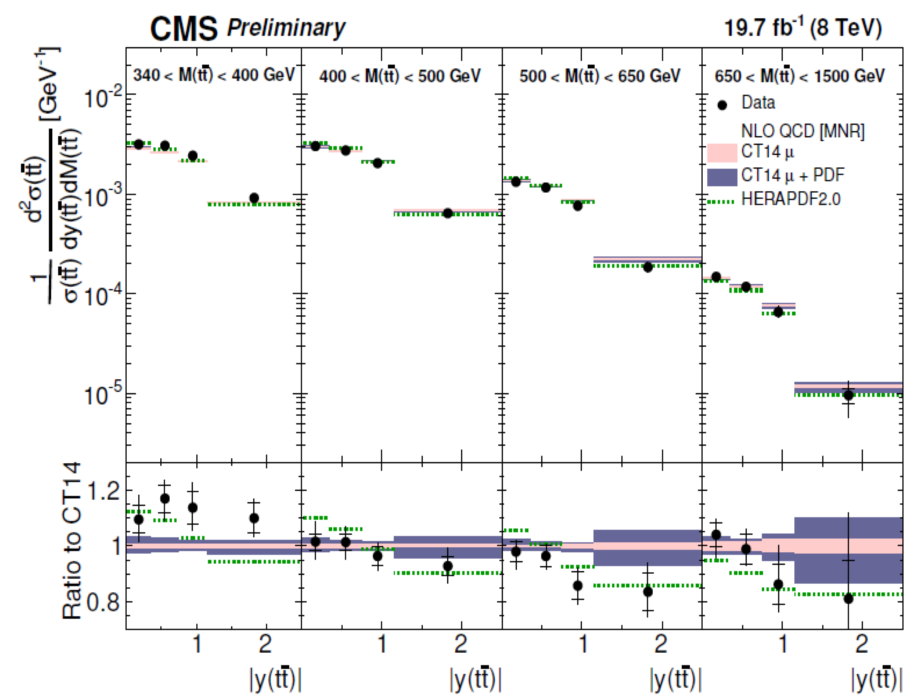
CMS-PAS-TOP-14-013



- Normalized double differential cross section
- Top pair is predominantly created by gluon-gluon fusion → sensitive to gluons PDF at large x
- Measured in emu channel of ttX (X include any number of extra jets but excluding Z/W/gamma)

$$\left(\frac{1}{\sigma}\frac{d^2\sigma}{dx\,dy}\right)_{ij} = \frac{1}{\sigma}\cdot\frac{1}{\Delta x_i}\cdot\frac{1}{\Delta y_j}\cdot\frac{N_{ij}^{\text{signal unfolded}}}{\mathcal{B}\cdot\mathcal{L}}.$$



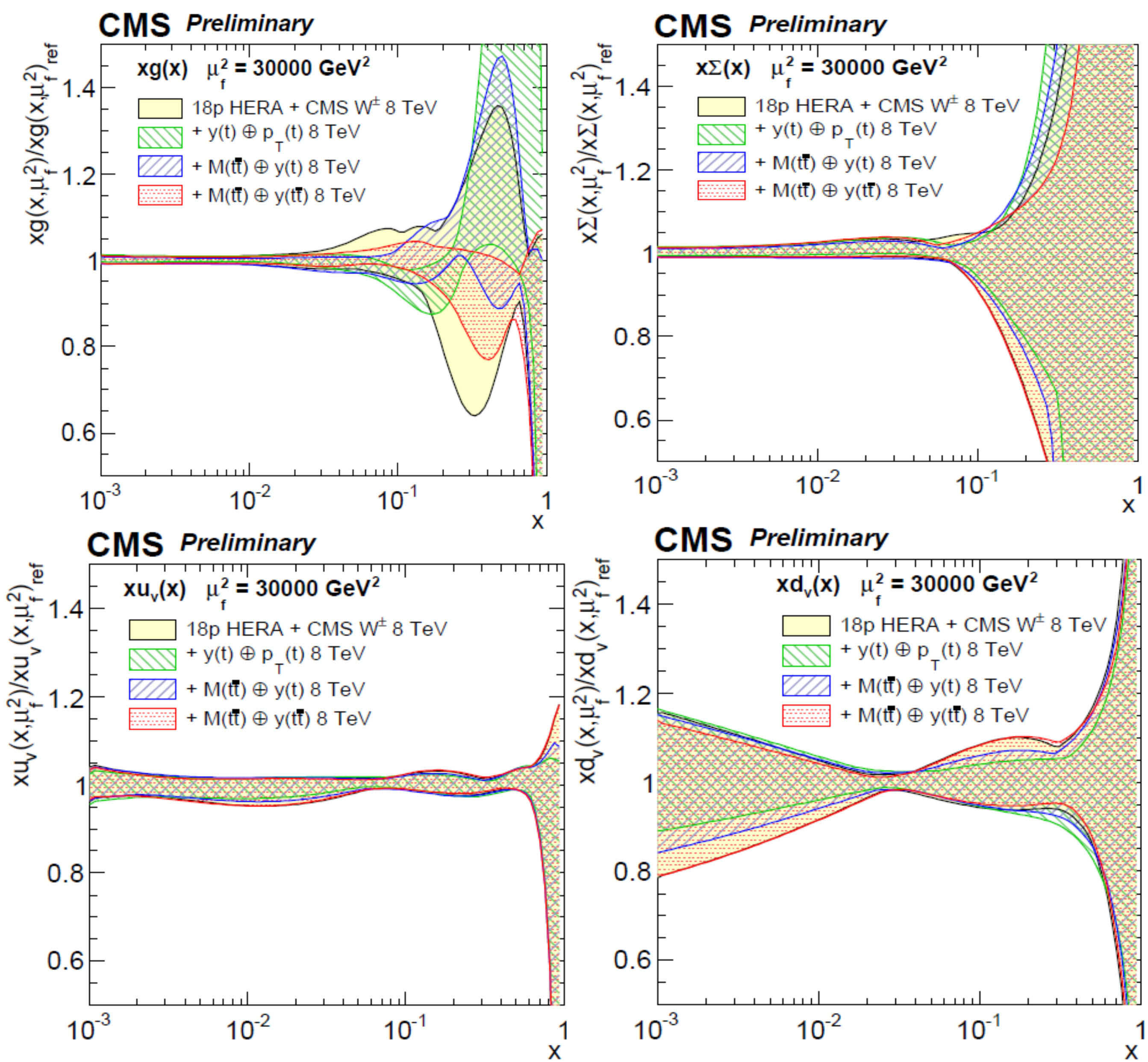


PDF constrains with top pair production cross section

CMS-PAS-TOP-14-013

NEW

- xfitter (v1.2.0) with 18-parameters fit
- Reference: fit using HERA DIS and W boson charge asymmetry
- y(t)-p_T(t), $M(t\bar{t})$-y(t), $M(t\bar{t})-y(t\bar{t})$ are added to the fit one at the time
- Significant impact on gluon PDF at high x, in particular when $y(t\bar{t})$ distributions in $M(t\bar{t})$ ranges are used ($M(t\bar{t})-y(t\bar{t})$)



Summary

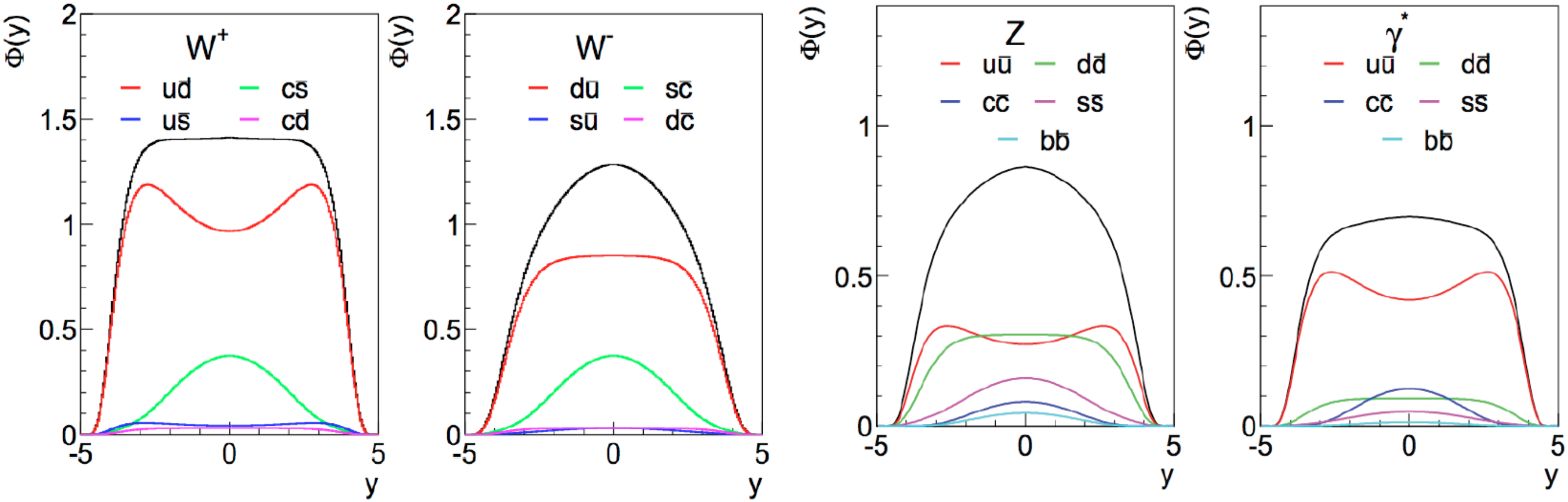
- CMS has measured variety of SM processes at 7, 8 and 13 TeV → valuable data for better understanding of the proton structure
- PDF constrains including CMS inputs modify the shapes and significantly reduce the uncertainties of PDFs
- Consistency between data and theoretical predictions is observed in CMS measurements so far
- Measurements limited by statistical errors will benefit from large data set of LHC Run II
  - W, Z, jet differential production cross sections
  - W, Z bosons in association with charm quarks
- CMS will deliver many more results at 13 TeV
  - Provide rigid tests for theoretical calculations using different PDFs sets
  - Further improve the PDF precisions

Backups

W, Z production sensitivity to flavor combination

$$W^+ \approx 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \approx 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

$$Z \approx 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$
$$\gamma^* \approx 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$

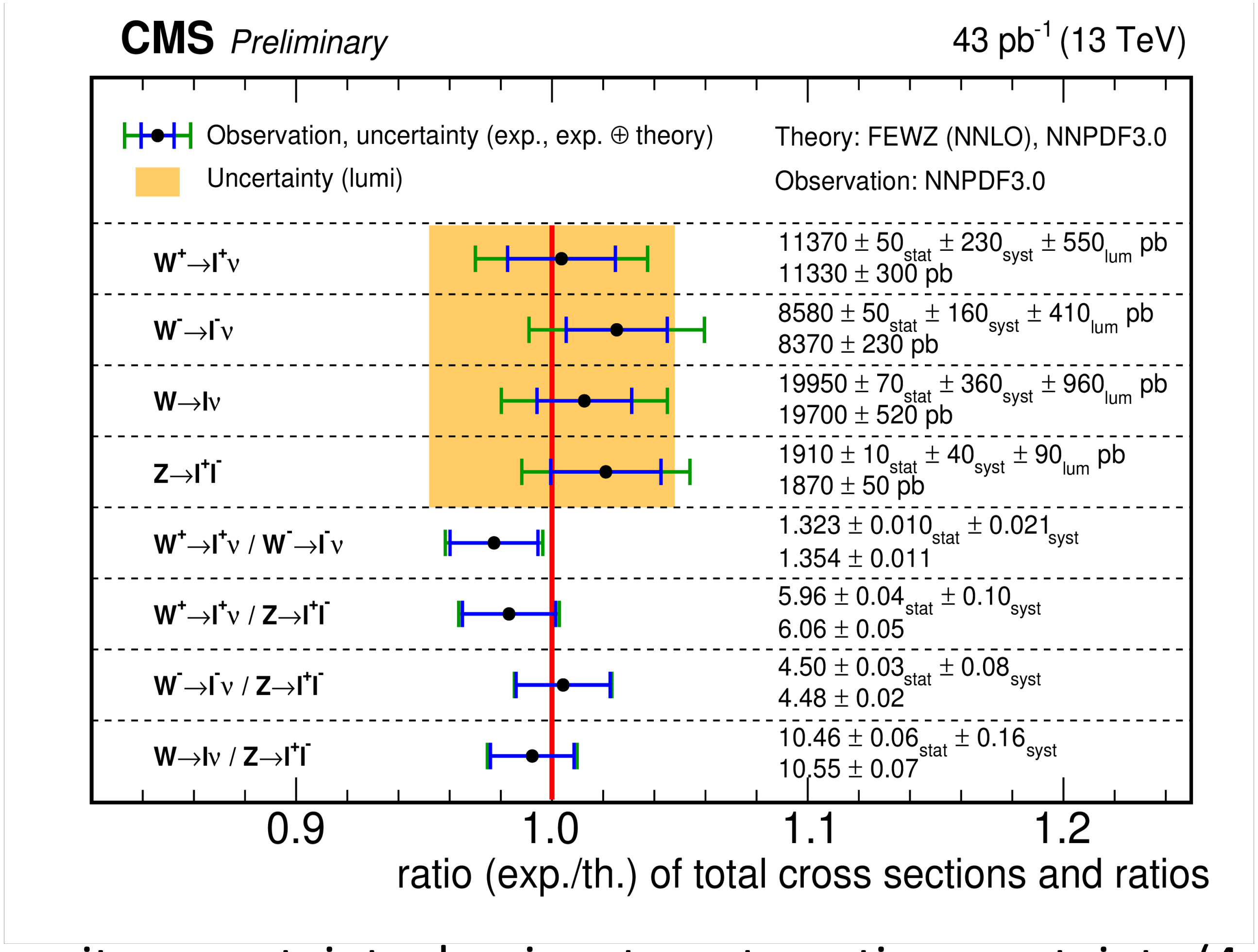


(A.Glazov/V.Radescu)

- LO, suppressed strangeness

W, Z inclusive cross section at 13 TeV

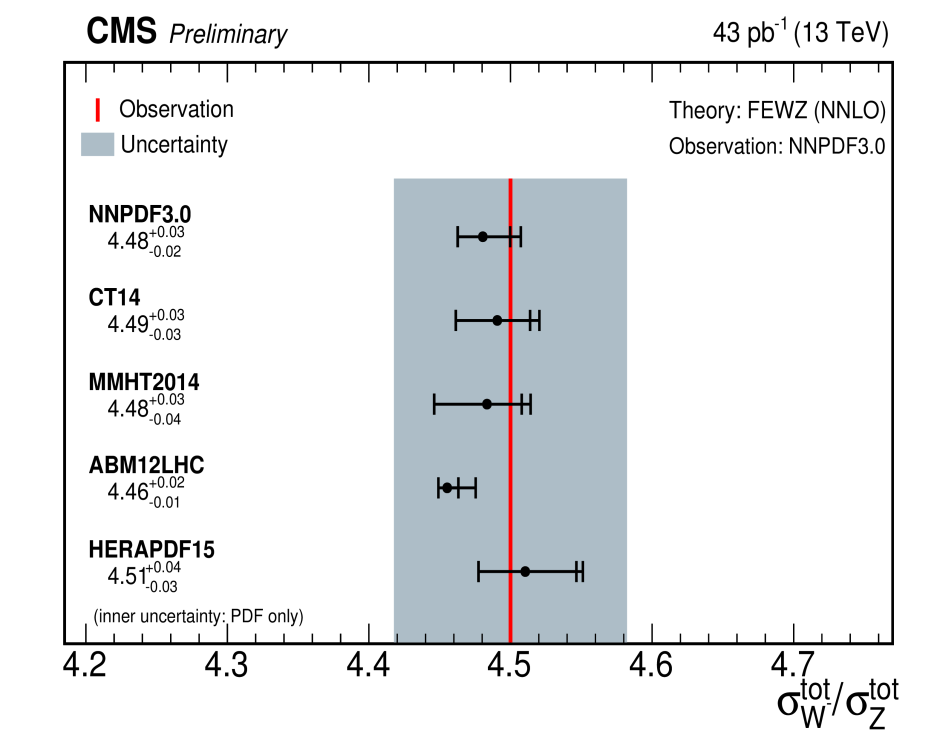
CMS-PAS-SMP-15-004

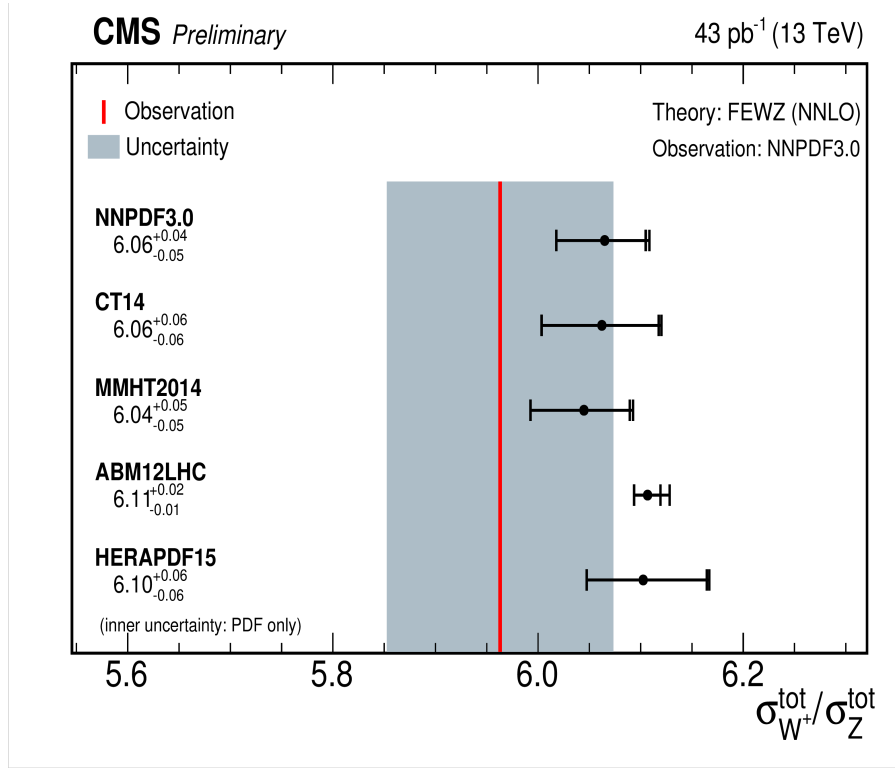


- Luminosity uncertainty dominants systematic uncertainty (4.8%)
- Experimental precision approximate theoretical uncertainty.
- Measured cross sections are consistent with NNLO calculations

W and Z cross section ratios at 13 TeV

CMS-PAS-SMP-15-004



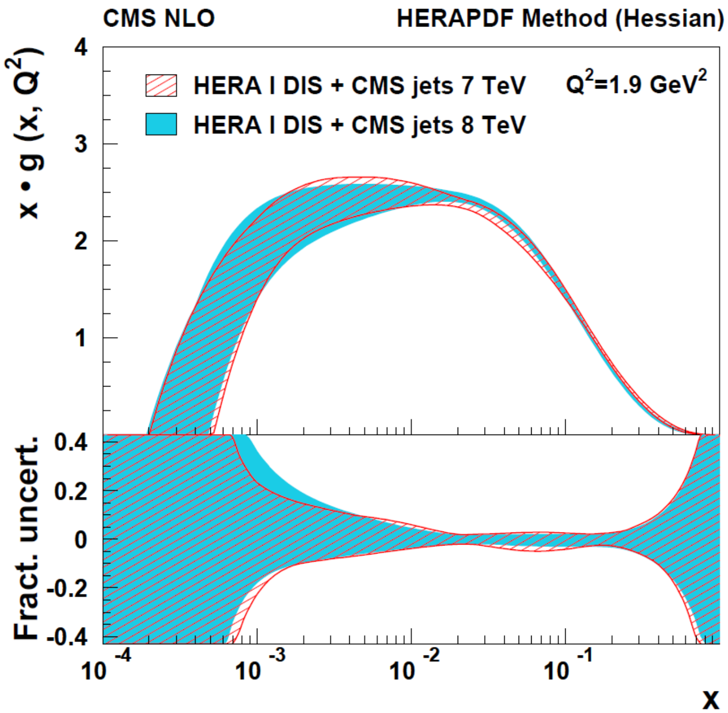


- FEWZ cross section ratio results for different PDF choices agree with measured values within errors

QCD analysis

arXiv:1609.05331

- Settings
  - HERA I+II DIS data + CMS data charge asymmetry, inclusive jets
  - 13 fit free parameters



Parametrization at $Q^2 = 1.9$ GeV^2

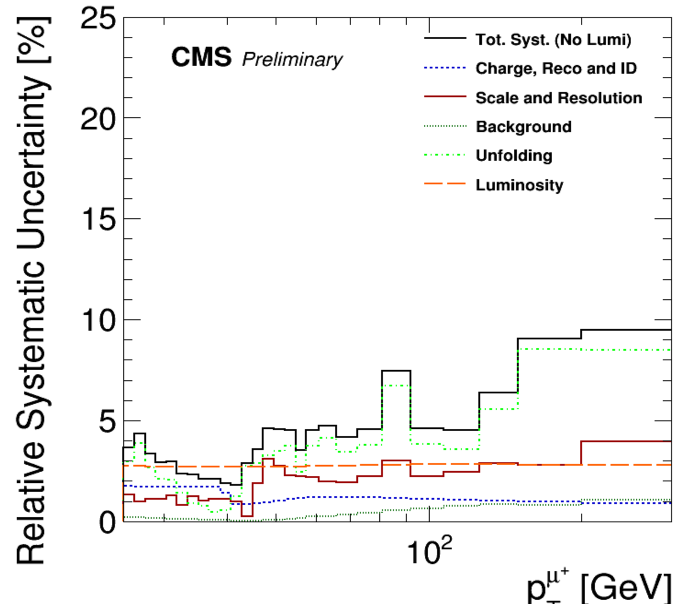
$$\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}}, \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.
\end{aligned}$$

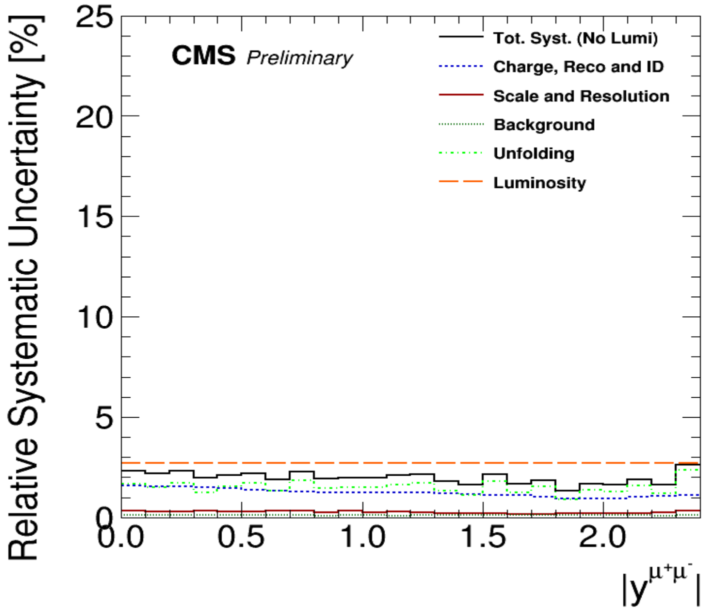
$$\begin{aligned}
x\,\overline{U} &= x\,\bar{u} \\
x\,\overline{D} &= x\,\bar{d} + x\,\bar{s} \\
B_{\overline{U}} &= B_{\overline{D}} \\
A_{\overline{U}} &= A_{\overline{D}}(1 - f_s) \\
f_s &= \bar{s}/(\bar{d} + \bar{s}) \equiv 0.31 \pm 0.08
\end{aligned}$$

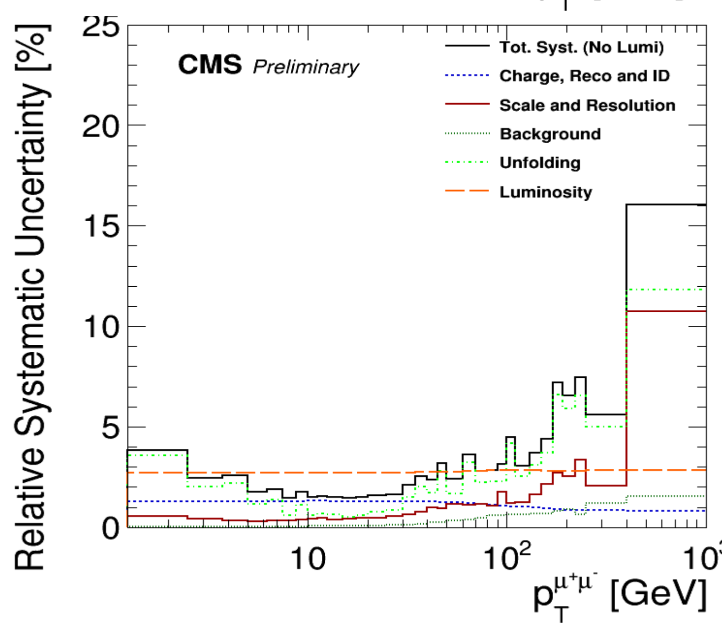
Starting scale $Q_0^2 = 1.9$ GeV^2
General mass variable flavor number scheme by Thorne-Roberts (TR)
Heavy quark mass: $m_c = 1.43$ GeV, $m_b = 4.5$ GeV
Strong coupling: 0.118
PDF uncertainties from variation of inputs parameters and parametrization

Systematic uncertainty of Z cross section at 13 TeV

CMS-PAS-SMP-15-011



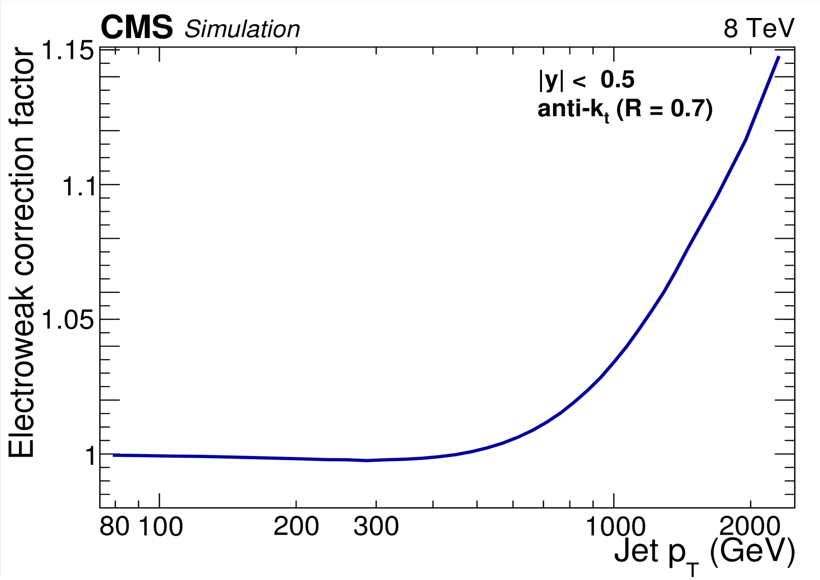


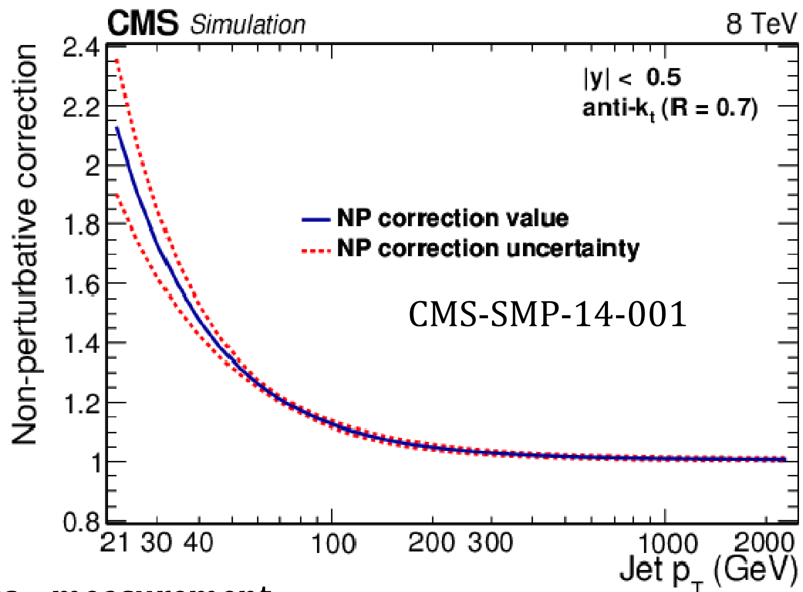


Miscellaneous plots in jet measurements

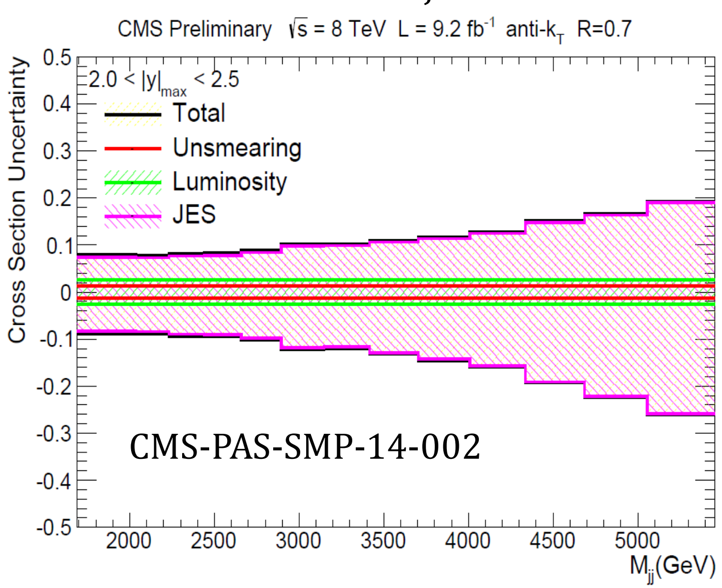
Corrections in inclusive jet measurements

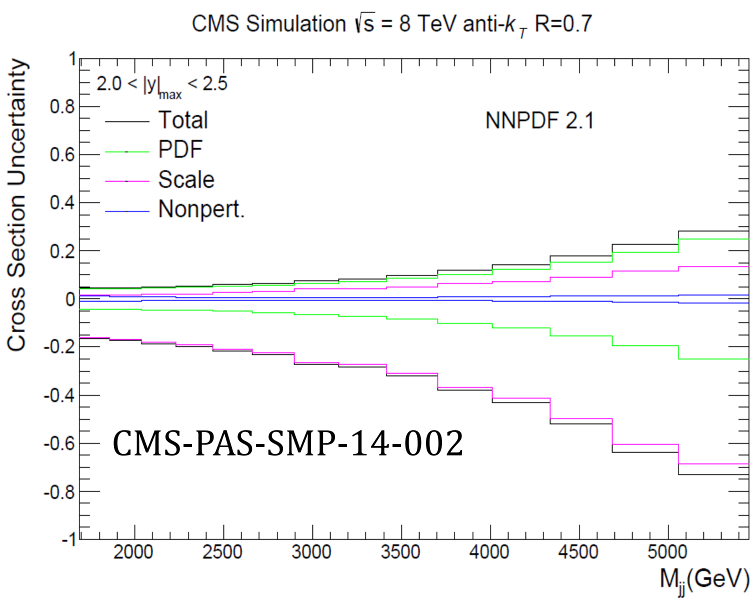
CMS-SMP-14-001





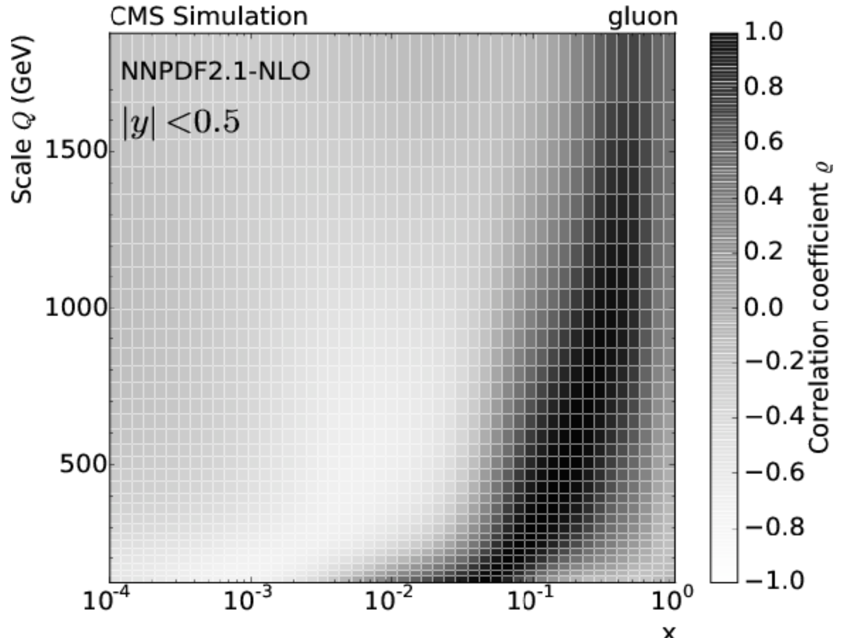
Uncertainties in differential jet cross section vs. jet mass measurement





Sensitivity of inclusive jet measurement on PDFs

- Inclusive jet results expect to impact gluon at medium x and quark at high x



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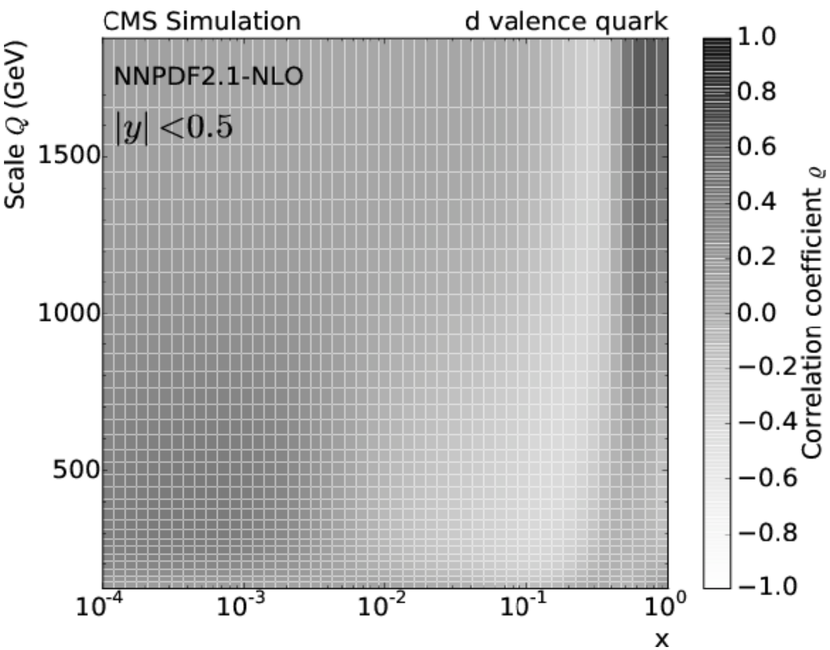

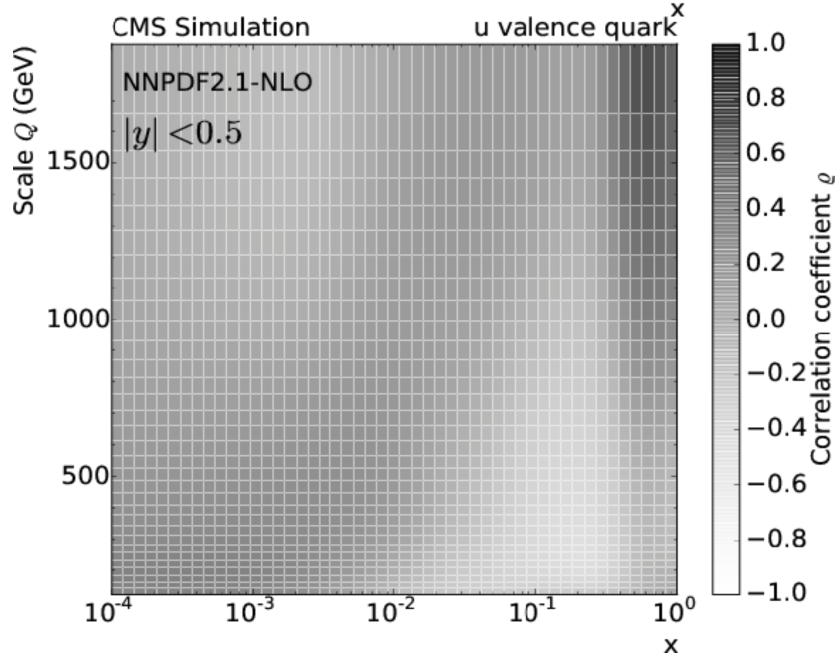

Double-differential 3-jet cross section

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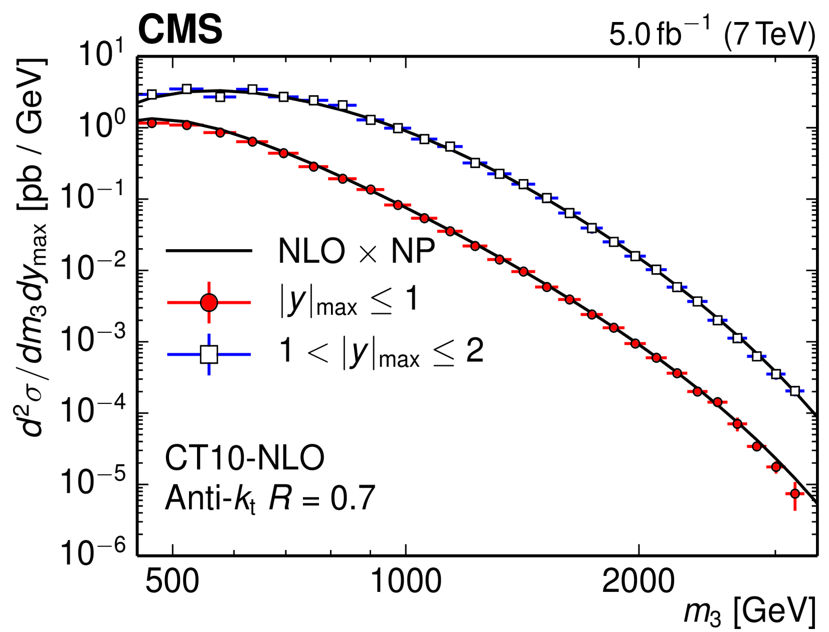
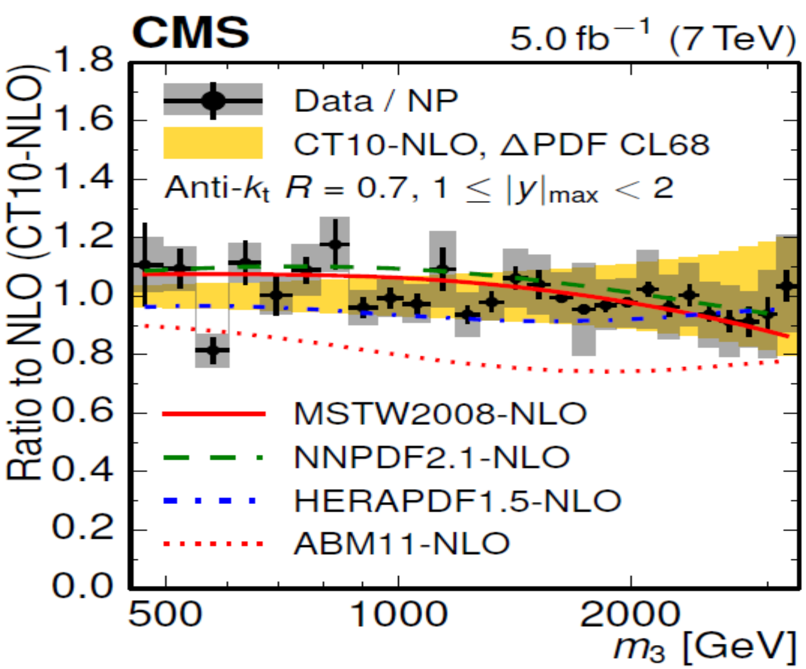
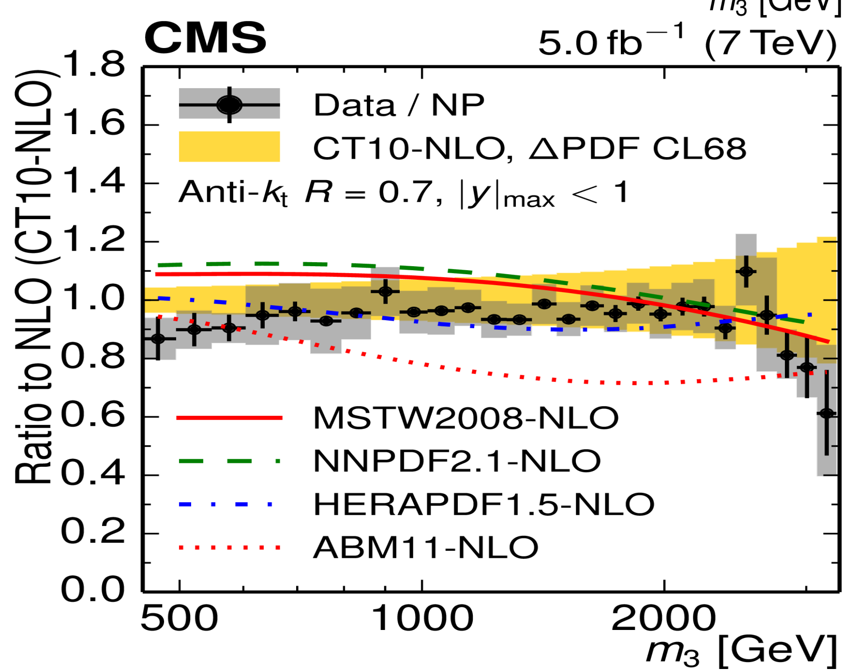
- Three leading E_T jets are used

$$\frac{d^2\sigma}{dm_3\, dy_{max}} = \frac{1}{\epsilon \mathcal{L}} \frac{N}{\Delta m_3 (2\Delta |y|_{max})}$$

- Experimental and theoretical uncertainties are comparable (as high as 20%)
  - Measurement is limited by statistical uncertainties
  - Scale uncertainty is higher than PDFs unc. (up to 15%)







PDF fits using top pair production cross section results

CMS-PAS-TOP-14-013

- PDF parametrization at $\mu_{f0}^2 = 1.9 GeV^2$

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+E_g x^2+F_g x^3) - A'_g x^{B'_g}(1-x)^{C'_g} \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v}x+E_{u_v}x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}(1+D_{\overline{U}}x+F_{\overline{U}}x^3), \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}},
\end{aligned}
$$

$$
\begin{aligned}
x\overline{U} &= x\overline{u} \\
x\overline{D} &= x\overline{d} + x\overline{s} \\
C'_g &= 25
\end{aligned}
$$

$$B_{\overline{U}} = B_{\overline{D}} \text{ and } A_{\overline{U}} = A_{\overline{D}}(1-f_s)$$

$$f_s = x\overline{s}/(x\overline{d}+x\overline{s}) \text{ is fixed to } f_s = 0.4$$

Thorne-Roberts variable-flavor-number scheme at NLO with $n_f = 5$ is used

$M_c = 1.43\,\mathrm{GeV}$ $M_b = 4.5\,\mathrm{GeV}$

HERA data $Q^2 > Q^2_{\mathrm{min}} = 3.5\,\mathrm{GeV}^2$

Strong coupling $\alpha_s(m_Z) = 0.118$

PDF uncertainties: fit, model and parametrization

Fit: $\Delta\chi^2 = 1$

Model:

$4.25 \le M_b \le 4.75\,\mathrm{GeV}$

$1.37 \le M_c \le 1.49\,\mathrm{GeV}$

$0.3 \le f_s \le 0.5$

$2.5 \le Q^2_{\mathrm{min}} \le 5.0\,\mathrm{GeV}^2$

Parametrization:

Additional parameters to functional forms

$\mu_{f0}^2 = 1.6\,\mathrm{GeV}^2$ and $\mu_{f0}^2 = 2.2\,\mathrm{GeV}^2$

Variant of the fit	Nominal	+ $y(\mathrm{t})$ $p_{\mathrm{T}}(\mathrm{t})$	+ $M(\mathrm{t\bar{t}})$ $y(\mathrm{t})$	+ $M(\mathrm{t\bar{t}})$ $y(\mathrm{t\bar{t}})$
CMS double differential $\mathrm{t\bar{t}}$		10 / 15	7.4 / 15	7.6 / 15
HERA CC e^-p $E_p = 920\,\mathrm{GeV}$	57 / 42	56 / 42	56 / 42	57 / 42
HERA CC e^+p $E_p = 920\,\mathrm{GeV}$	44 / 39	44 / 39	44 / 39	43 / 39
HERA NC e^-p $E_p = 920\,\mathrm{GeV}$	219 / 159	219 / 159	219 / 159	218 / 159
HERA NC e^+p $E_p = 920\,\mathrm{GeV}$	440 / 377	437 / 377	439 / 377	441 / 377
HERA NC e^+p $E_p = 820\,\mathrm{GeV}$	69 / 70	68 / 70	68 / 70	69 / 70
HERA NC e^+p $E_p = 575\,\mathrm{GeV}$	221 / 254	220 / 254	221 / 254	221 / 254
HERA NC e^+p $E_p = 460\,\mathrm{GeV}$	219 / 204	219 / 204	219 / 204	219 / 204
CMS $W^\pm$ asymmetry	4.7 / 11	4.6 / 11	4.8 / 11	4.9 / 11
Correlated χ^2	82	87	91	89
Log penalty χ^2	-2.5	+2.6	-2.2	-3.3
Total χ^2 / dof	1352 / 1138	1368 / 1153	1368 / 1153	1366 / 1153