PDF Constraints and α_s Results from CMS

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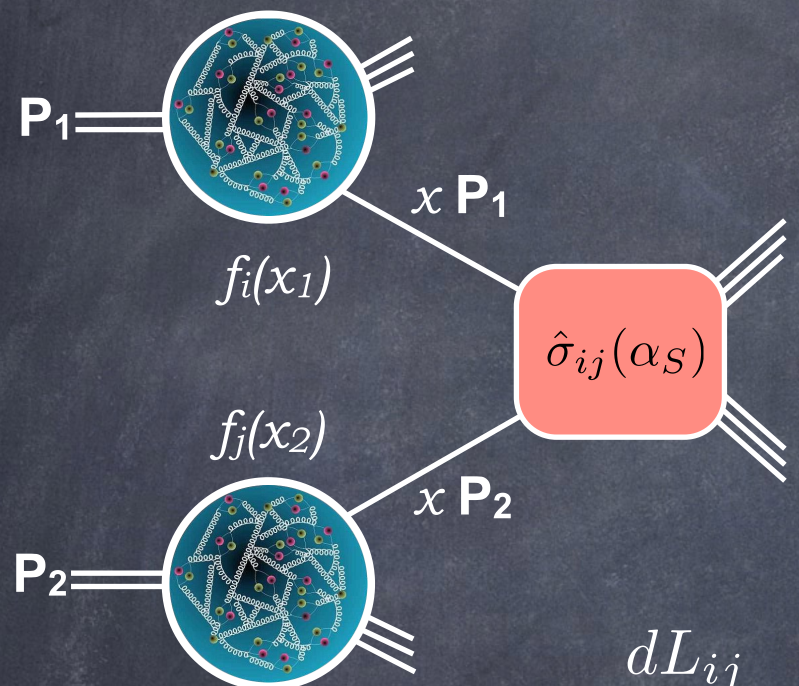
on behalf of CMS Collaboration

DIS 2016, DESY
Hamburg

HELMHOLTZ
GEMEINSCHAFT

Particle production in proton-proton collisions

proton structure hard interaction



Factorization: proton structure ⊗ sub-process ME

$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \boxed{\frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau}} \cdot \hat{s} \cdot \boxed{\hat{\sigma}_{ij}}$$

Ingredients for SM predictions for pp@LHC:

- partonic cross section calculable in pQCD
- parton luminosity:

$$\tau \cdot \frac{dL_{ij}}{d\tau} \propto \int_0^1 dx_1 dx_2 (x_1 f_i(x_1, \mu_F^2) \cdot x_2 f_j(x_2, \mu_F^2)) + (1 \leftrightarrow 2)\delta(\tau - x_1 x_2)$$

Parton Distribution Functions (PDFs)

universal functions of partonic fraction *x* of proton momentum
and energy scale *Q* of the process

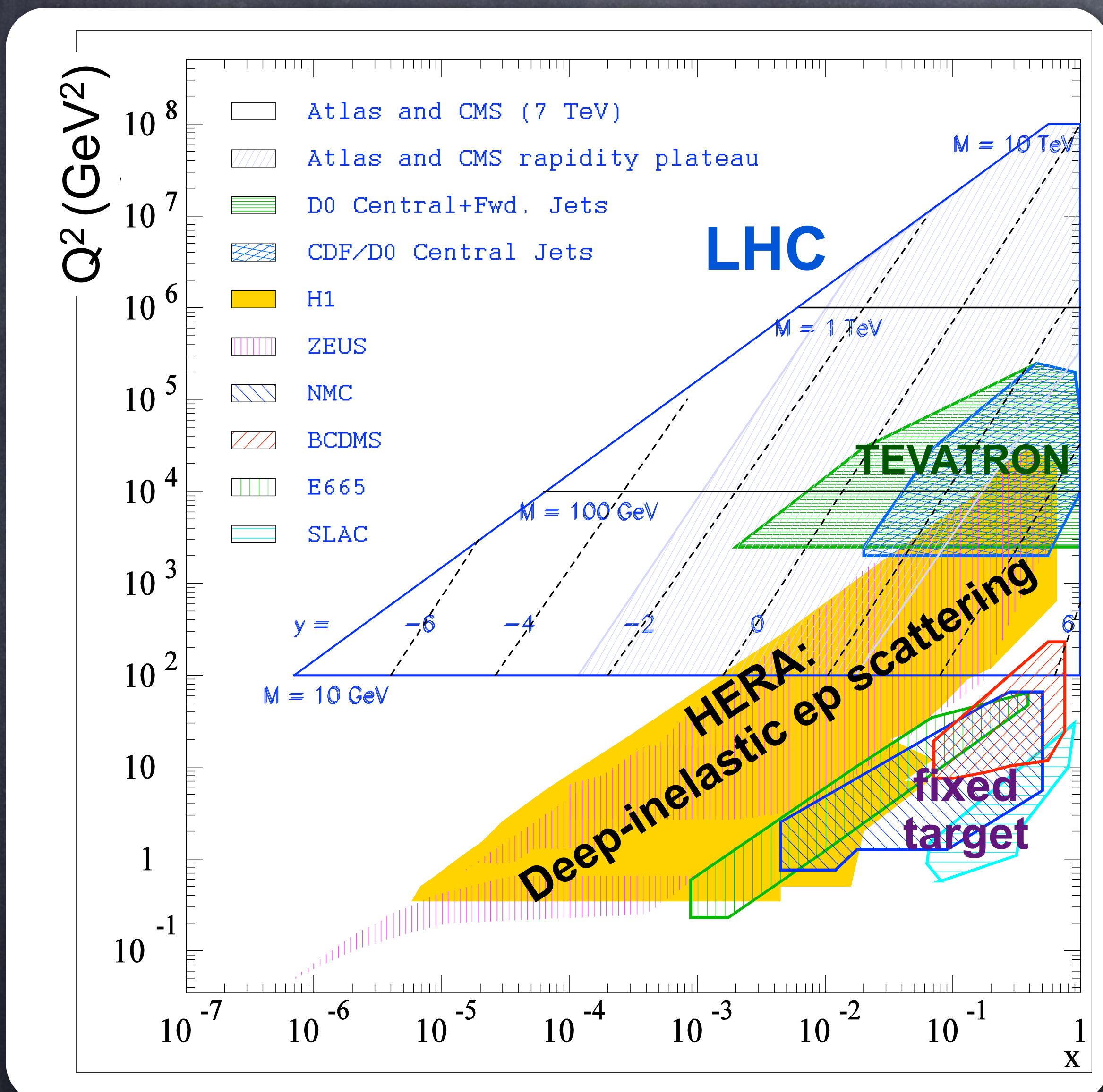
Precision of PDFs essential for interpretation of the LHC measurements
Precise LHC data are used to improve PDF constraints

How are PDFs determined ?

PDF for flavor *i*: $f_i = f_i(x, Q^2)$:

Q^2 dependence predicted by QCD

x-dependence determined from data

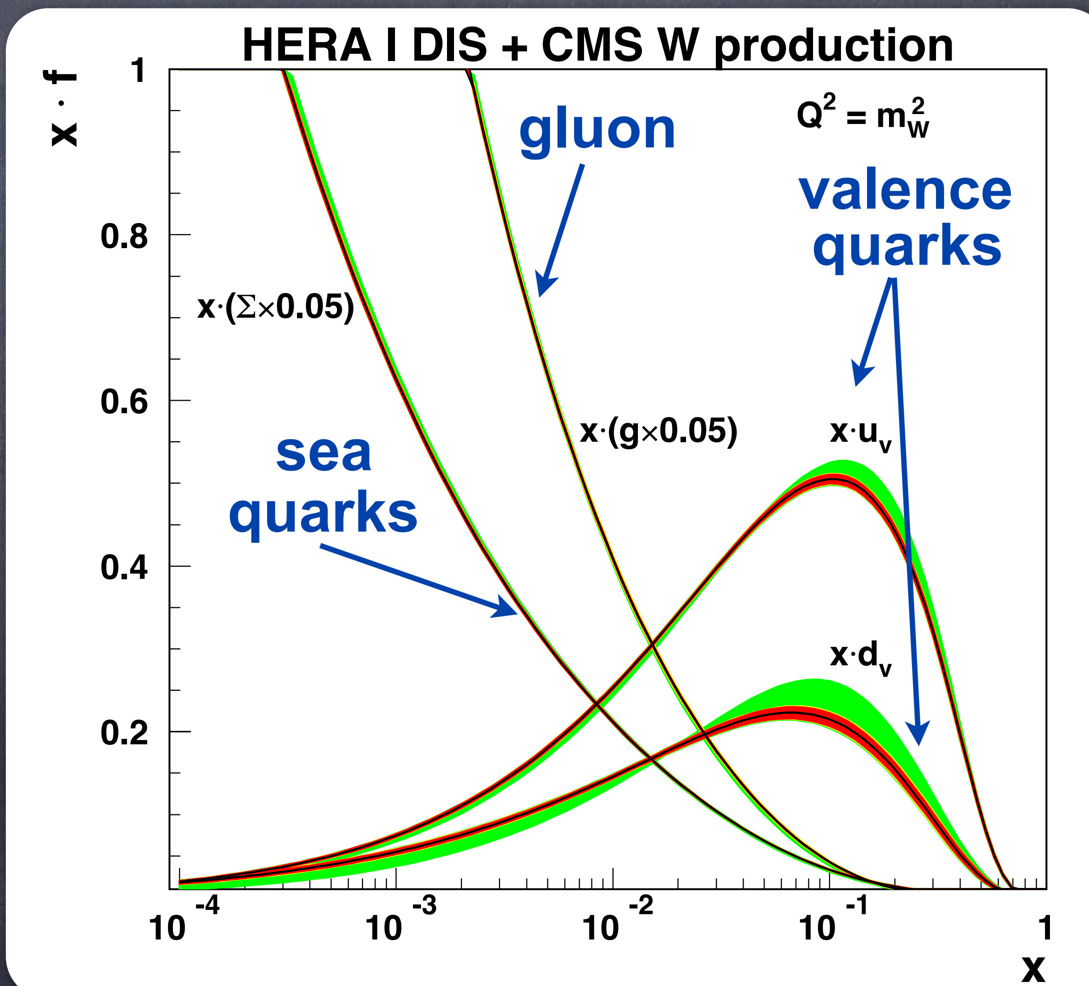


LHC provides important constraints in particular at large x

Example of PDF determination:

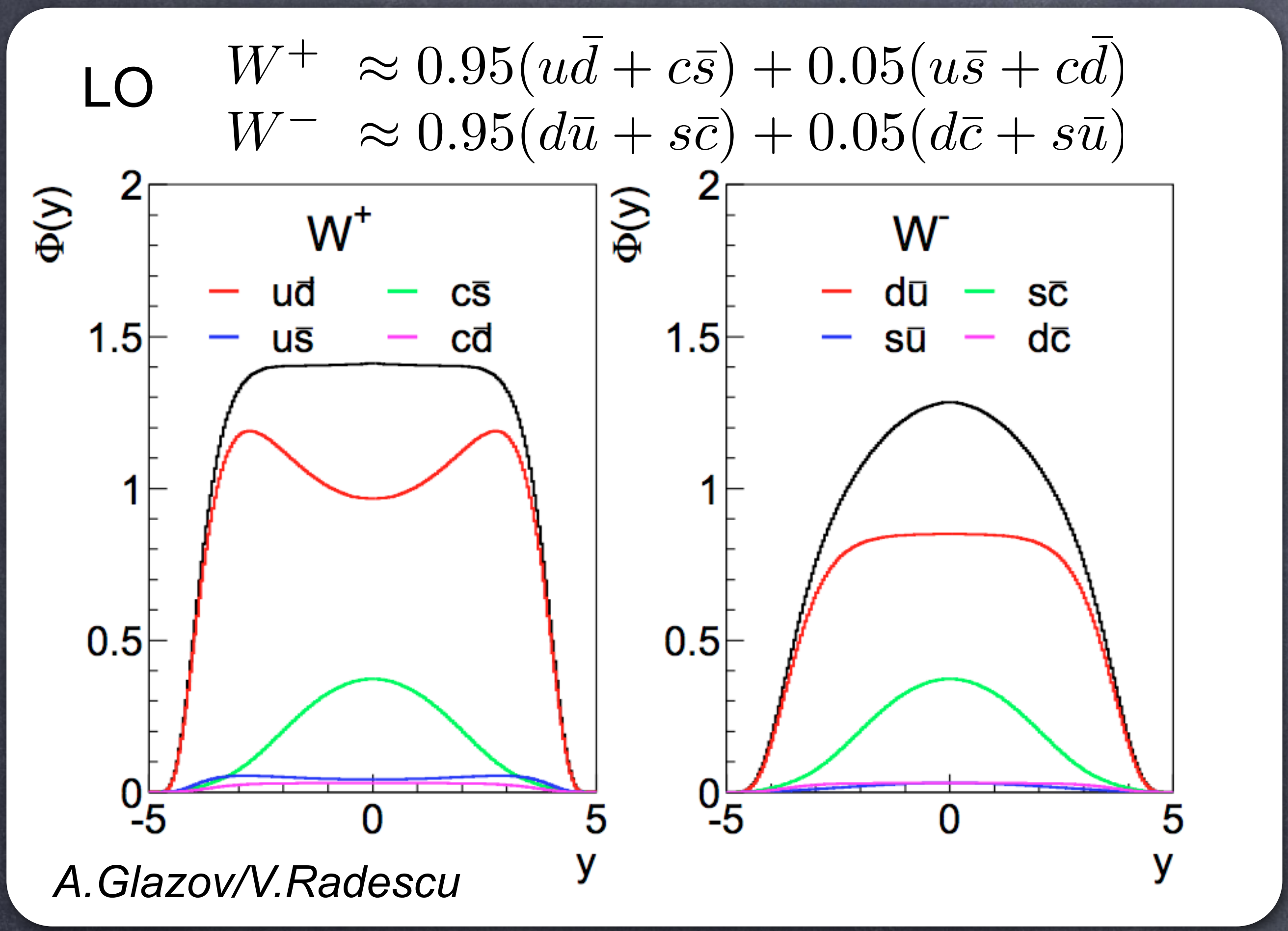
- parameterize x-shape at a scale Q^2_0:

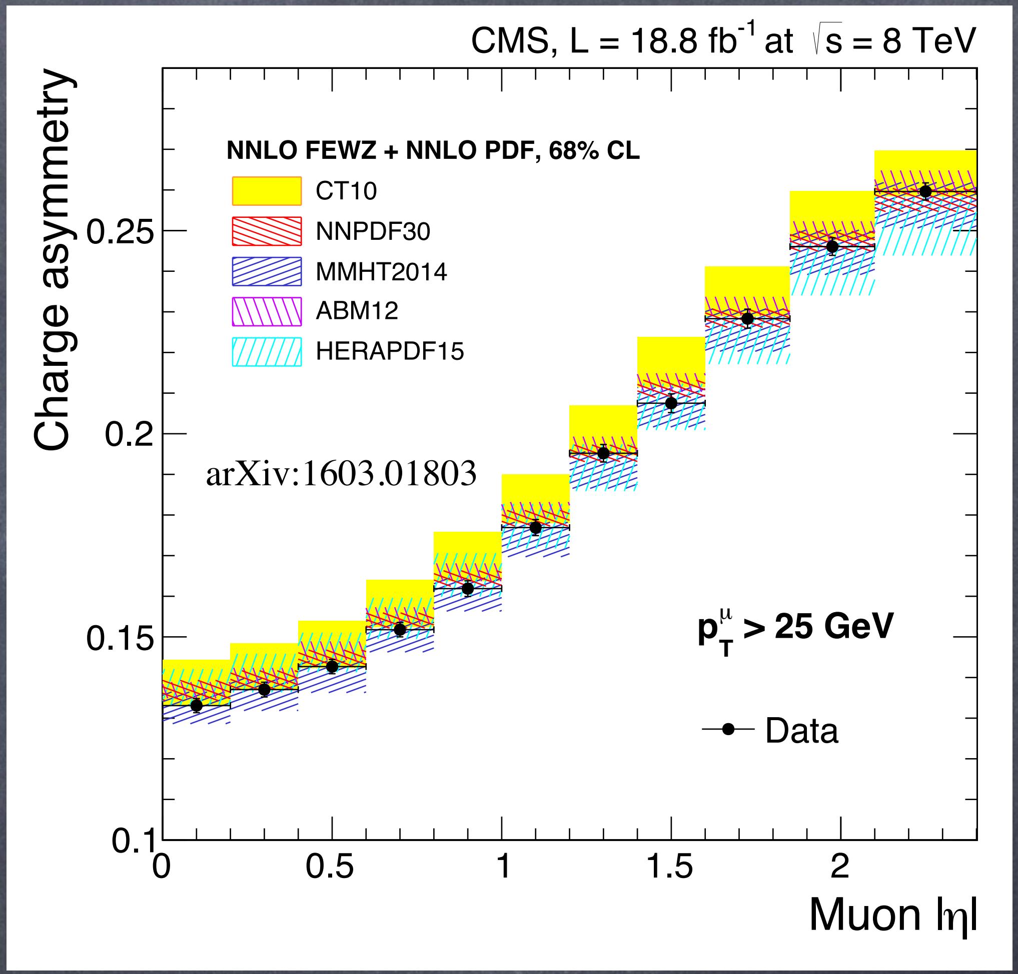
  $f(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$
- evolve these PDFs to $Q^2 > Q^2_0$ (e.g. DGLAP)
- construct expected cross sections
- χ^2- fit to the experimental data



Asymmetry in W± production at CMS

- W production probes bi-linear quark combinations





$$A(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

Muon asymmetry in W production probes quark distributions at $10^{-3} < x < 10^{-1}$

QCD analyses of W charge asymmetry data

QCD analysis at NNLO, parton evolution in Q^2 via DGLAP implemented in QCDNUM.

xFitter version 1.1.1 is used. (See O.Zenaive's talk for xFitter)

Data in the QCD analysis:

- HERA I+II combined inclusive DIS data, Charged and Neutral Current [Eur. Phys. J. C 75 (2015) 2604]
- Investigated CMS data :
  - W charge asymmetry measurement with muons @ 8 TeV [arXiv:1603.01803]

PDF Uncertainties : Quadratic sum of experimental, model and parametrisation errors.

Experimental uncertainties: originate from uncertainties of the data

- Hessian error estimate: criterion $\Delta\chi^2=1$ is applied

Model uncertainties: originate from variations of model input parameters:

- Fraction of strange quarks in the sea $f_s=0.31\pm0.08$
- Values of charm and beauty quark masses.
- Q^2 cut on inclusive DIS data.

Parametrisation uncertainties:

- Originate from variations on assumed parametrization

PDF parametrization and χ^2

Central parametrization at the starting scale Q^2_0=1.9 GeV^2 :

W Charge Asymmetry (13p)

$$xg(x) = A_g x^{B_g} \cdot (1-x)^{C_g}(1+D_g x)$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1+E_{u_v}x^2)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}}(1+E_{\overline{U}}x^2)$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}$$

Data sets	Partial χ^2/n_{dp}
HERA1+2 neutral current, e^+p, $E_p = 920$ GeV	440/377
HERA1+2 neutral current, e^+p, $E_p = 820$ GeV	69/70
HERA1+2 neutral current, e^+p, $E_p = 575$ GeV	214/254
HERA1+2 neutral current, e^+p, $E_p = 460$ GeV	210/204
HERA1+2 neutral current, e^-p, $E_p = 920$ GeV	218/159
HERA1+2 charged current, e^+p, $E_p = 920$ GeV	46/39
HERA1+2 charged current, e^-p, $E_p = 920$ GeV	50/42
CMS $W^\pm$ muon charge asymmetry $\mathcal{A}(\eta)$, $\sqrt{s} = 8$ TeV	3/11
Correlated χ^2	141
Global χ^2/n_{dof}	1391/1143

arXiv:1603.01803

Parameters A **are** determined by QCD sum rules
B: define low-x behaviour, C: high-x shape

Parametrization uncertainties :

originate from variations on assumed parametrization, in which additional parameters are added one by-one in the functional form of the parametrization;
additional variation of 1. 5<Q^2_0<2.5 GeV^2

Largest difference of resulting PDFs to the central result (envelope) is assigned as uncertainty

Asymmetry in W± production at CMS in PDF studies

QCD analysis at NNLO

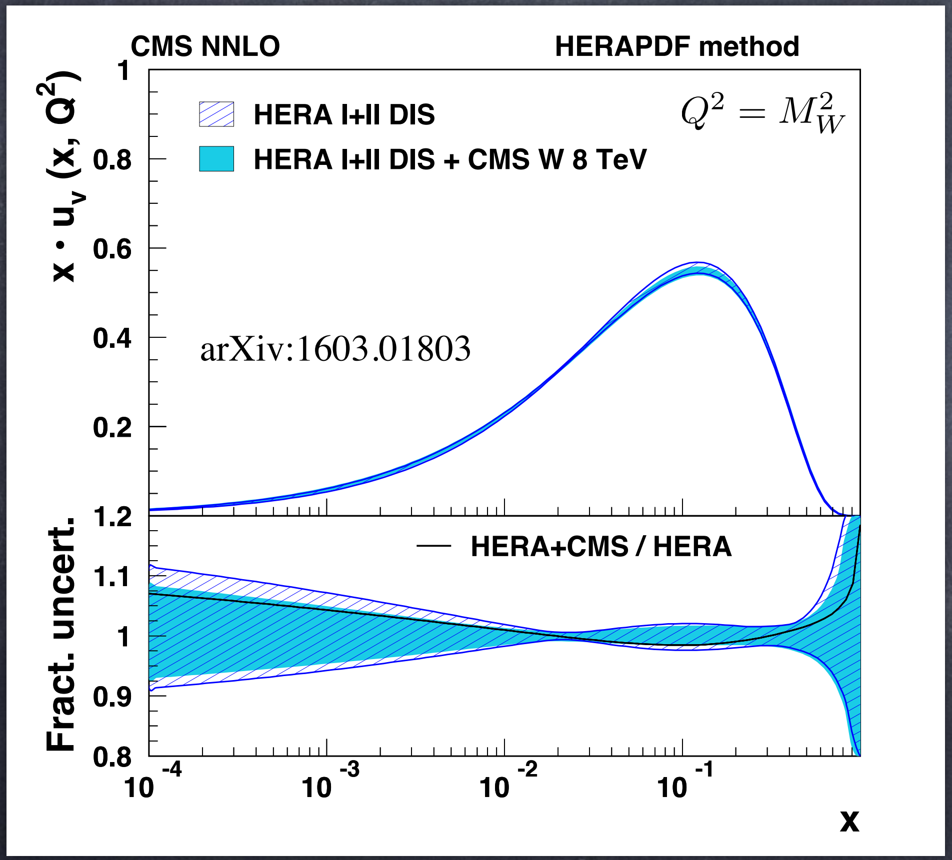
Data: Combined HERA I+II DIS data [Eur. Phys. J. C 75 (2015) 2604]

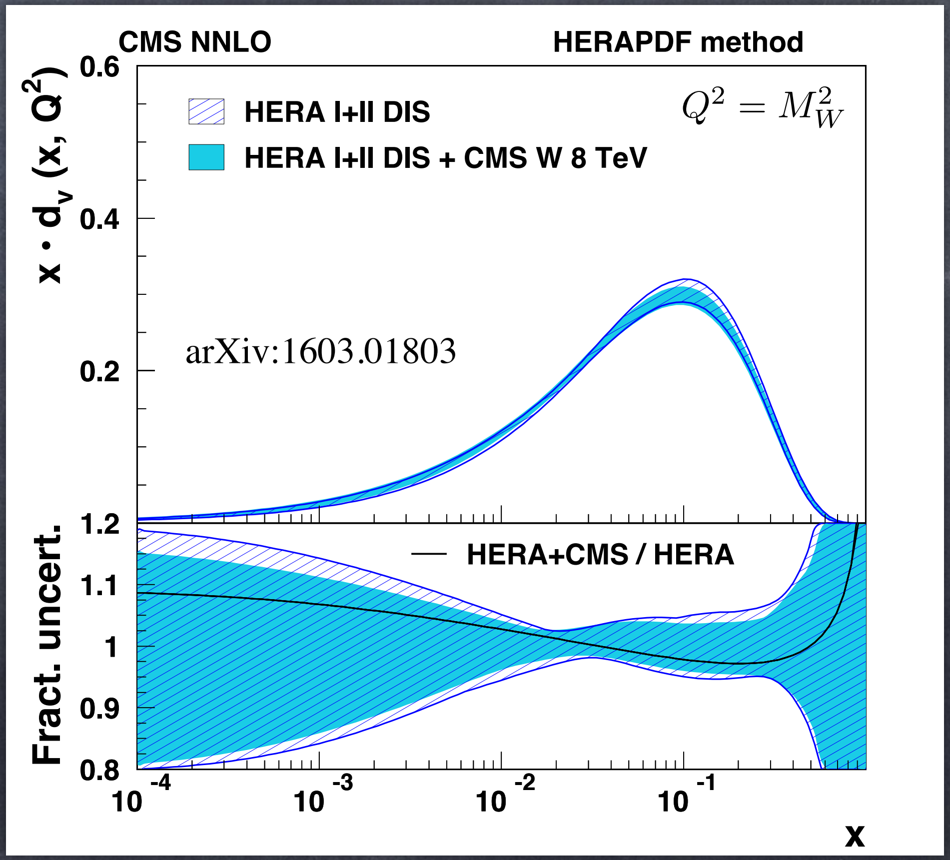
+ CMS muon charge asymmetry measurement at 8-TeV [arXiv:1603.01803]

Theory for A_W: NLO prediction with MCFM, interfaced via APPLGRID

K-factors, which are calculated by FEWZ, are applied

QCD scales $\mu_r = \mu_f = m_W$, strong coupling $\alpha_S(m_Z)$=0.118;

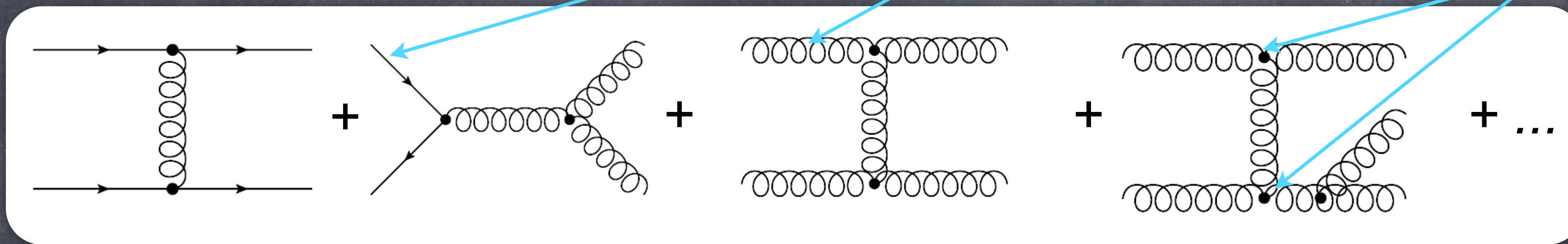




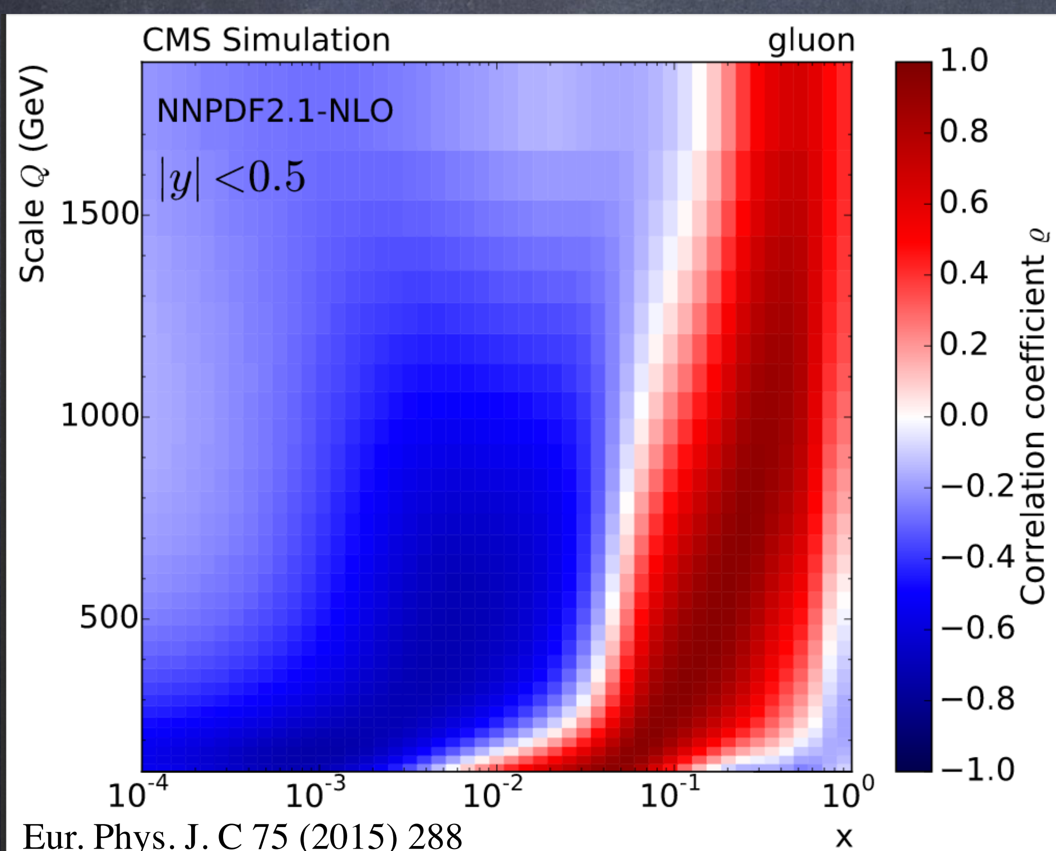
Improvement in the uncertainty of the valence-quark distributions

Probing QCD with Jet Cross Sections

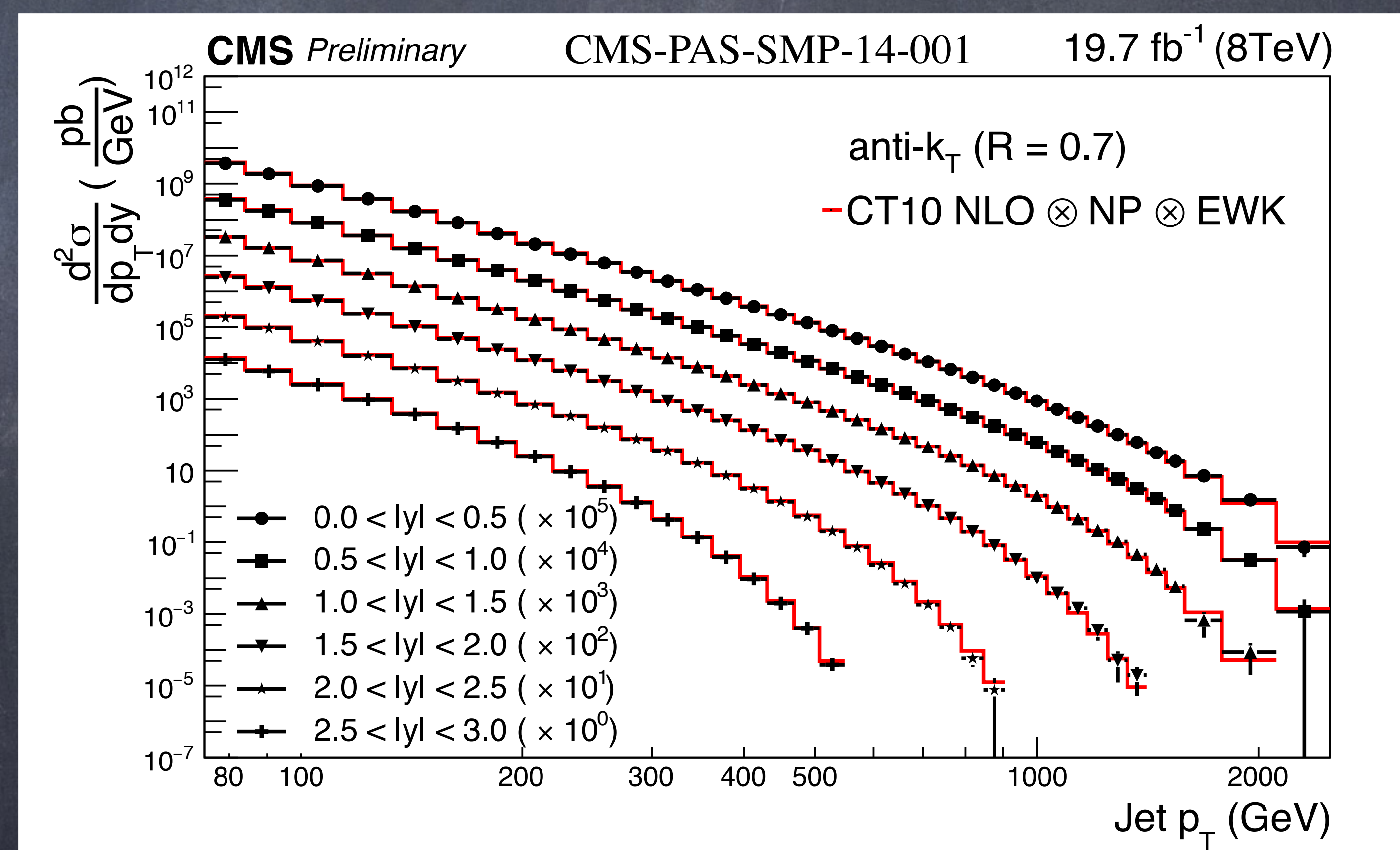
- Jet production sensitive to quark and gluon distributions, and to α_S



Strong correlation between inclusive jet cross section and gluon at high-middle x

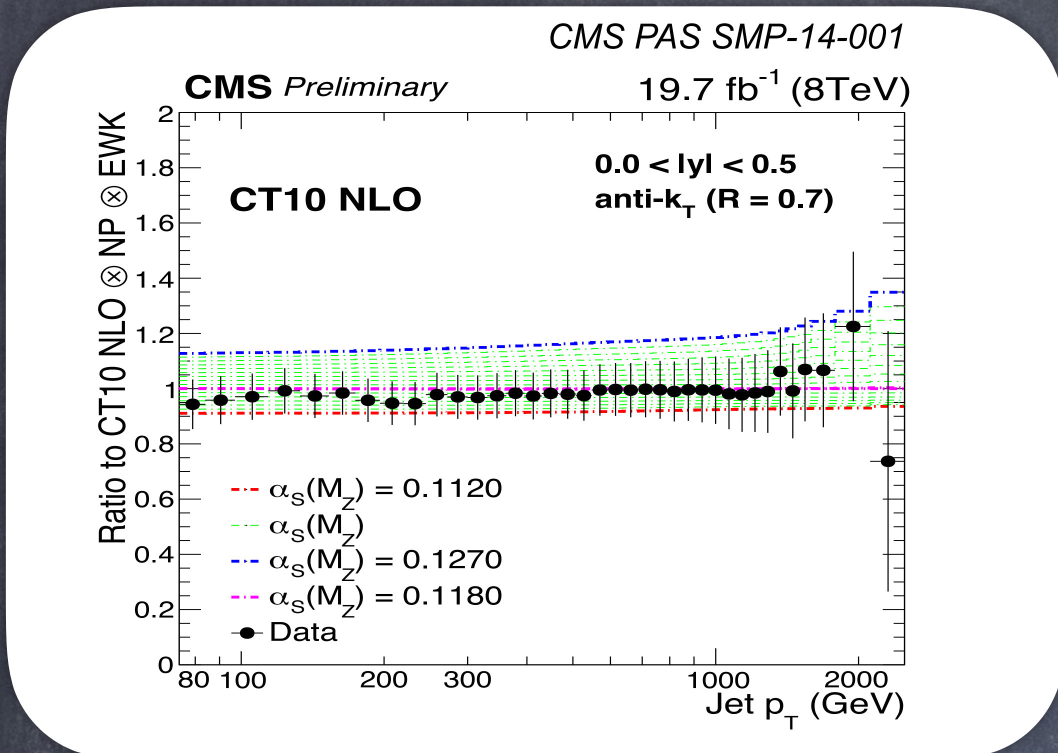


Double differential inclusive jet cross section measurement (P.Gunnellini's Talk)



cross-section ratios for different √s are also provided!

Determination of strong coupling αs : inclusive jets @ 8TeV



CMS jet cross section measurement
$\sqrt{s}$=8TeV (19.7 fb^{-1}) CMS-PAS-SMP-14-001

compared to NLO QCD ⊗ PDFs

in each bin of p_T and y
different sets of PDFs used
each set has its α_s - dependence

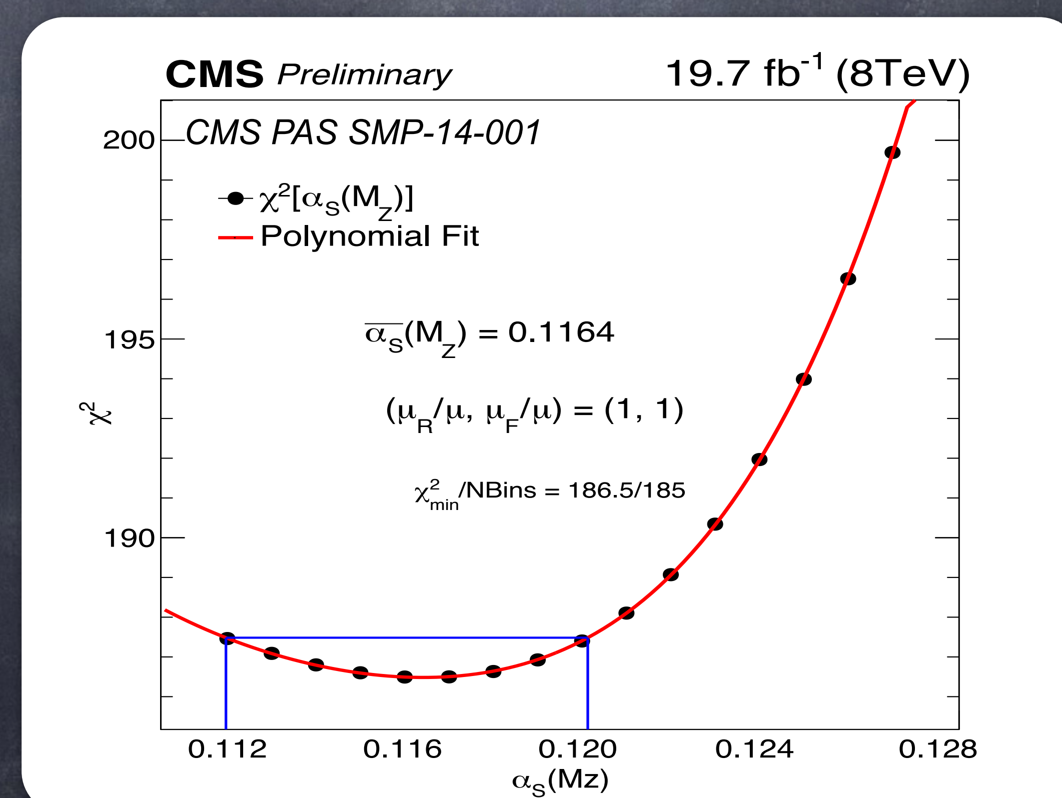
In each y bin, for each PDF, α_s is determined by minimizing χ^2 between data and NLO

Similar results obtained with different PDFs

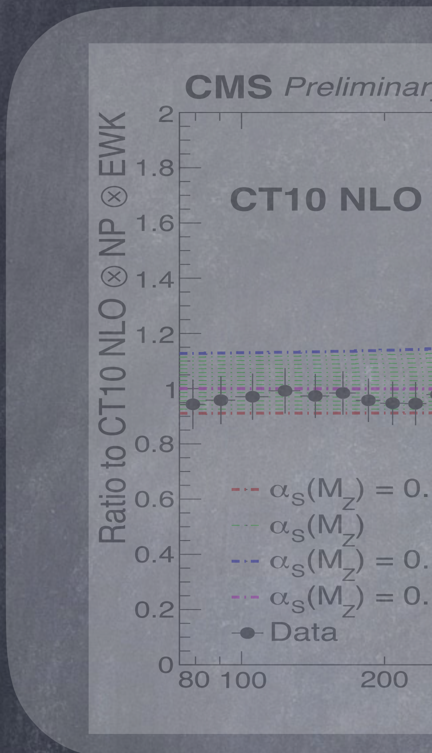
Using CT10NLO :

$$\alpha_s(M_Z) = 0.1164\,^{+0.0025}_{-0.0029}(\mathrm{PDF})\,^{+0.0053}_{-0.0028}(\mathrm{Scale}) \pm 0.0001\,(\mathrm{NP})\,^{+0.0014}_{-0.0015}(\mathrm{Exp})$$

Analysis performed in 6 p_T bins
⇛ running of $\alpha_s = \alpha_s(Q^2)$



Determination of strong coupling α_S : inclusive jets @ 8TeV



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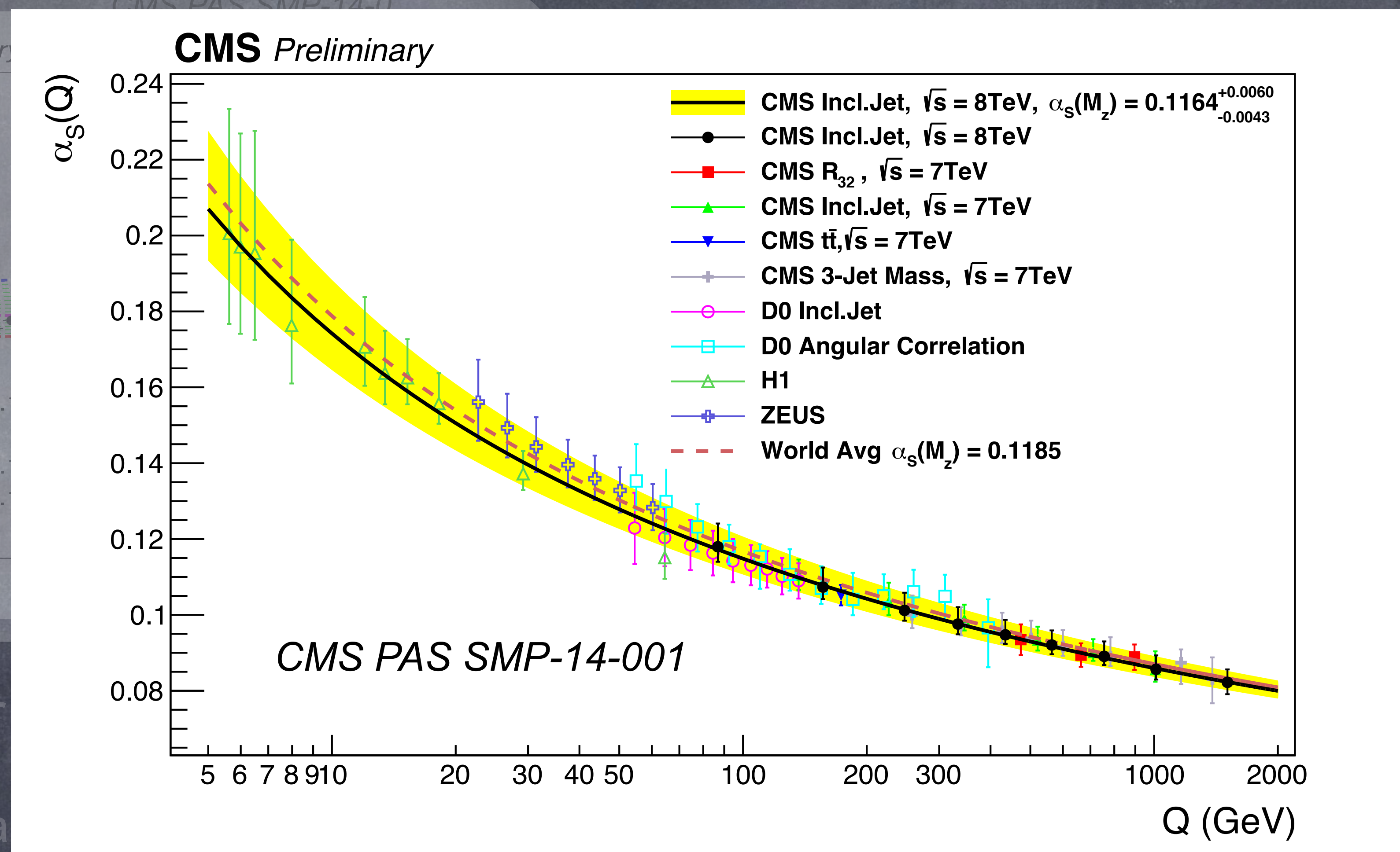
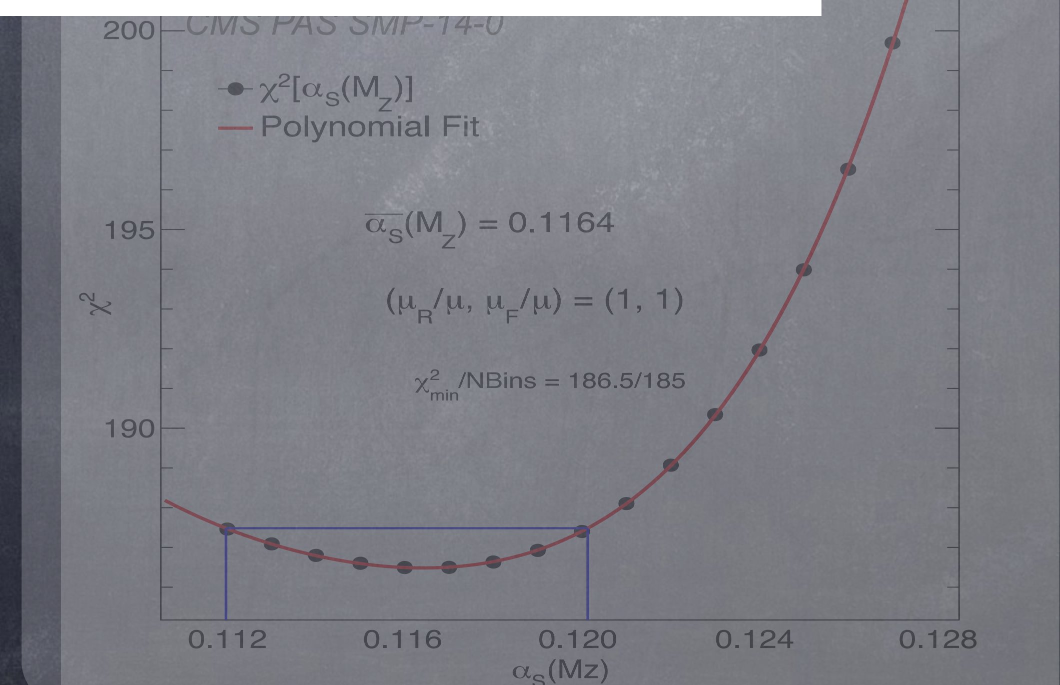
d



In each y bin, for

Similar results obta



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Analysis performed in 6 p_T bins
⇛ running of $\alpha_S = \alpha_S(Q^2)$

QCD analyses of Inclusive Jets at 8 TeV.

QCD analysis at NLO, parton evolution in Q^2 via DGLAP implemented in QCDNUM.

xFitter version 1.1.1 is used. (See O.Zenaive's talk for xFitter)

Data in the QCD analysis:

- HERA I+II combined inclusive DIS data, Charged and Neutral Current [Eur. Phys. J. C 75 (2015) 2604]
- Investigated CMS data :
    - Inclusive Jets @ 8 TeV [CMS-PAS-SMP-14-001]

PDF Uncertainties : Quadratic sum of experimental, model and parametrisation errors.

Experimental uncertainties: originate from uncertainties of the data

- Hessian error estimate: criterion Δx^2=1 is applied
- MC Method (as a cross check)

Model uncertainties: originate from variations of model input parameters:

- Fraction of strange quarks in the sea f_s=0.31±0.08
- Values of charm and beauty quark masses.
- Q^2 cut on inclusive DIS data.

Parametrisation uncertainties:

- Originate from variations on assumed parametrization

QCD Analysis of Inclusive Jet Measurements at 8 TeV

Central parametrization at the starting scale Q^2_0=1.9 GeV^2 :

Inclusive Jets @8TeV (18p)

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

Data sets		Partial χ^2/n_{dp}
HERA1+2 Neutral Current	e^+p, $E_p = 920$ GeV	376/332
HERA1+2 Neutral Current	e^+p, $E_p = 820$ GeV	61/63
HERA1+2 Neutral Current	e^+p, $E_p = 575$ GeV	197/234
HERA1+2 Neutral Current	e^+p, $E_p = 460$ GeV	204/187
HERA1+2 Neutral Current	e^-p	219/159
HERA1+2 Charged Current	e^+p	41/39
HERA1+2 Charged Current	e^-p	50/42
CMS inclusive jets 8TeV	$0 < y < 0.5$	53/36
	$0.5 < y < 1.0$	34/36
	$1.0 < y < 1.5$	35/35
	$1.5 < y < 2.0$	52/29
	$2.0 < y < 2.5$	49/24
	$2.5 < y < 3.0$	4.9/18
Correlated χ^2		94
Global χ^2/n_{dof}		1471/1216

Parameters A **are** determined by QCD sum rules
B: define low-x behaviour, *C:* high-x shape

Impact of the CMS jet measurements on PDFs

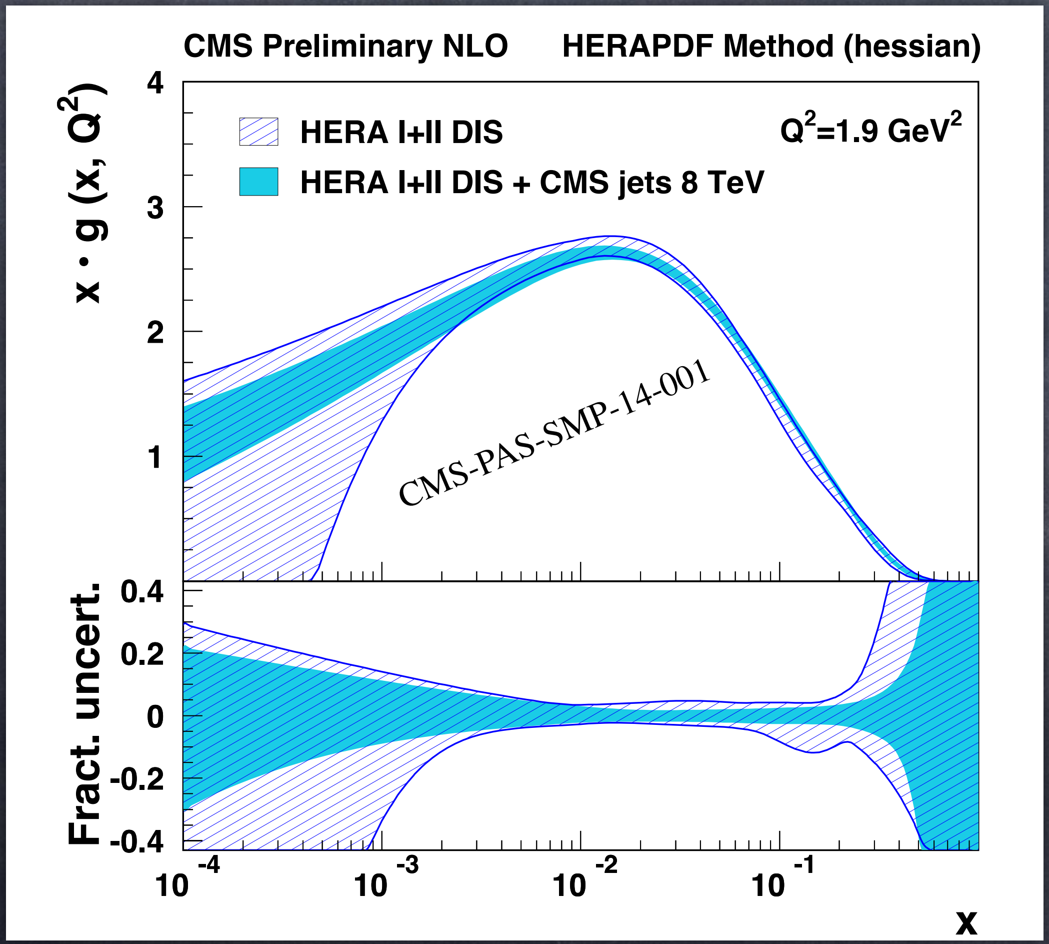
QCD analysis at NLO

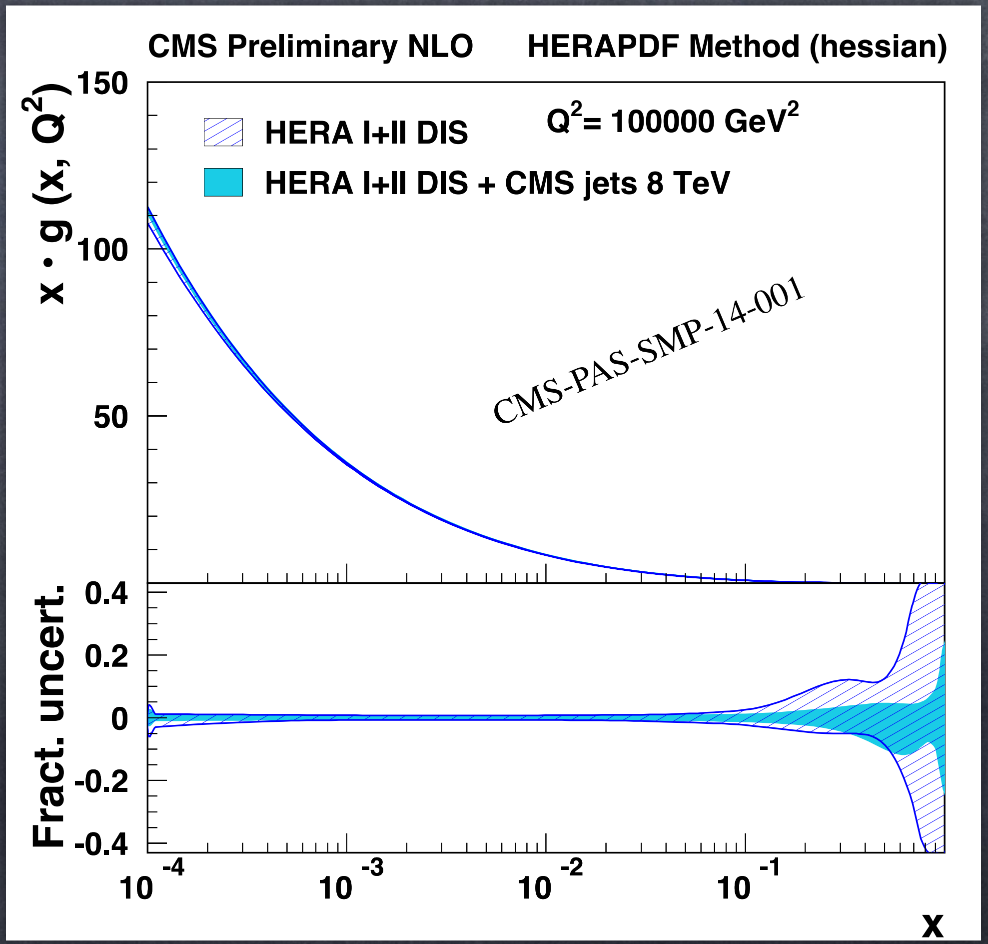
Data: combined HERA I+II DIS [Eur. Phys. J. C 75 (2015) 2604]

+ CMS inclusive jet production at 8 TeV, L = 19.71 fb^{-1}

Theory for jet production in *pp*: NLOJET++ version 4.1.3, interfaced via fastNLO

QCD scales $\mu_r = \mu_f = p_{T\,jet}$, strong coupling $\alpha_S(m_Z)$=0.1180;

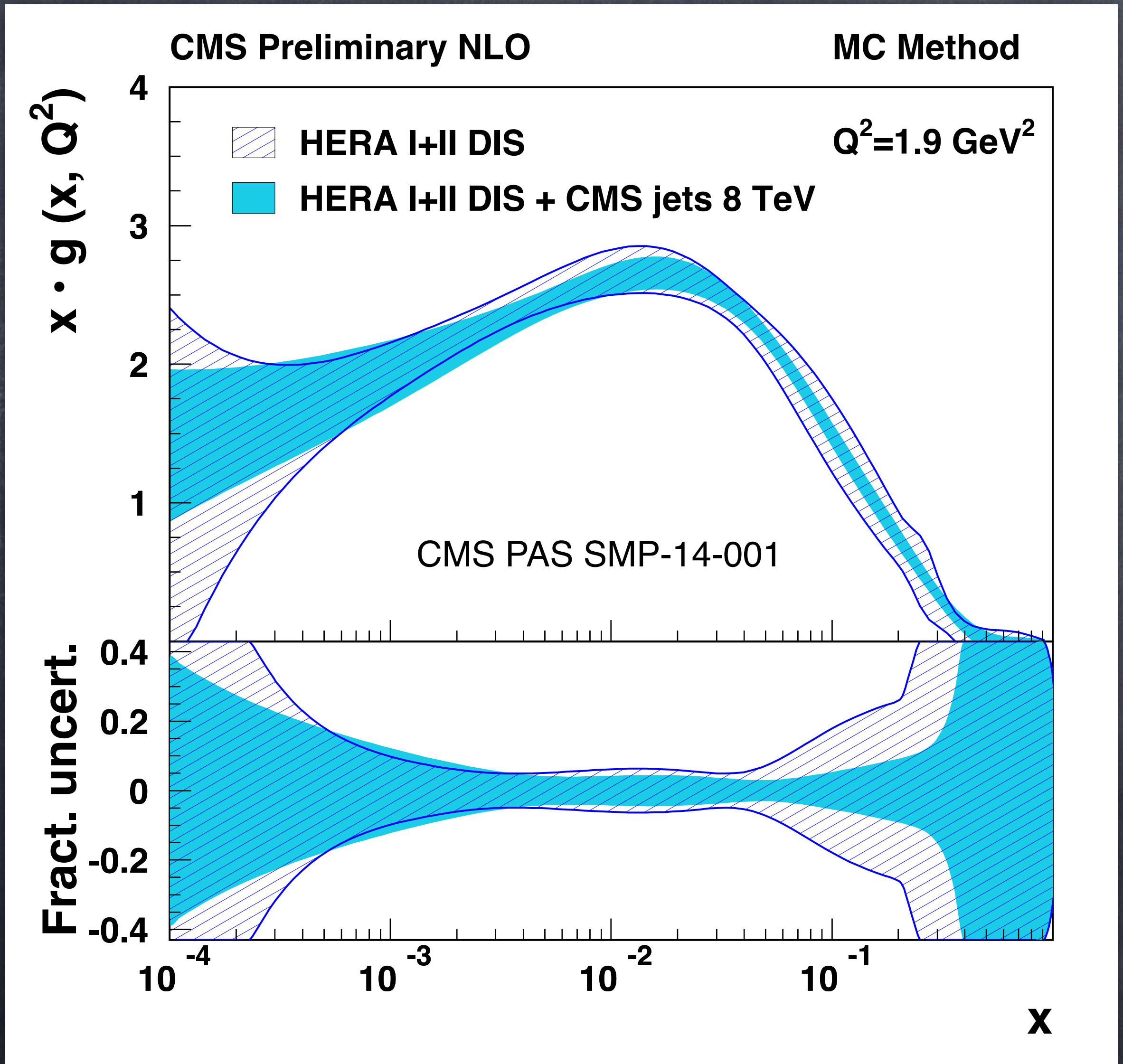




Improvement in the uncertainty of the gluon distributions at high-x

Estimation of PDF Uncertainty with MC Method

- 200 of replicas allowing the central values of cross-sections to fluctuate within their systematic and statistical uncertainties.
- For each replica, **NLO QCD** fit is performed. Errors on the PDFs are estimated from the RMS of the spread of the curves.



Similar reduction of uncertainties observed as in hessian estimate

Summary

- W Charge Asymmetry (Muon) Data :
  - ★ Precision of the valence quark distributions improves.
- CMS Inclusive Jet Data :
  - ★ Precision of the gluon distributions improves.
- Prospects :
  - ★ Both data can be used in global QCD analysis by PDF collaborations.

Backup Slides

Framework for CMS QCD analyses in this talk

QCD analysis at NLO and NNLO, parton evolution in Q^2 via DGLAP implemented in QCDNUM

Data in the QCD analysis:

- HERA I+II combined inclusive DIS data, Charged and Neutral Current [arXiv:1506.06042]
- Different CMS data sets (W charge asymmetry and Inclusive Jets @ 8TeV)

Experimental uncertainties: originate from uncertainties of the data, criterion $\Delta\chi^2=1$ is applied

Model input:

- Theory calculations at NLO and NNLO appropriate for each data set
- Starting scale of PDF evolution $Q^2_0 = 1.9$ GeV^2
- Heavy quark treatment: general mass variable flavor number scheme by Thorne-Roberts (TR)
- Heavy quark masses:
  - NLO : $m_c = 1.47$ GeV, $m_b = 4.50$ GeV.
  - NNLO : $m_c = 1.43$ GeV, $m_b = 4.50$ GeV.

Model uncertainties: originate from variations of model input parameters:

- NLO (Incl. Jets) : 1.41 GeV < m_c < 1.53 GeV and 5 GeV^2 < Q^2_{min} < 10 GeV^2
- NNLO (W asymmetry) : 1.37 GeV < m_c < 1.49 GeV and 2.5 GeV^2 < Q^2_{min} < 5 GeV^2
- 4.25 GeV < m_b < 4.75 GeV same for both.

fraction of strange quarks in the sea f_s=0.31±0.08

K-Factors and χ^2 definitions

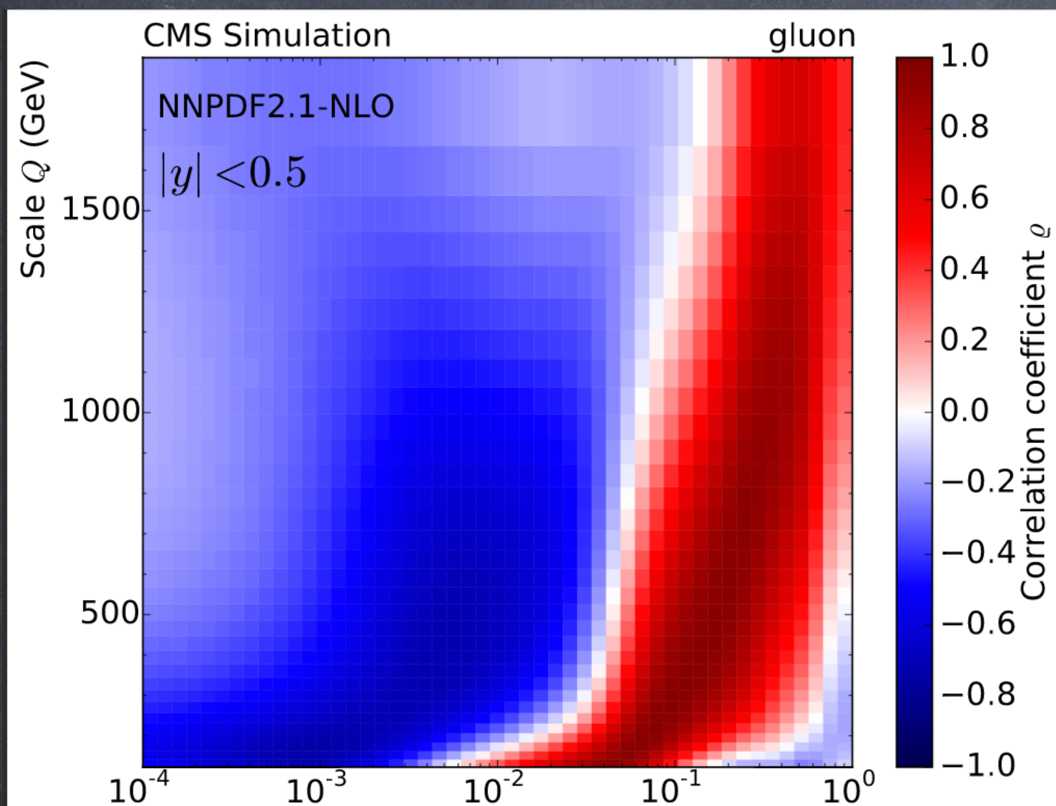
$$K = \frac{\hat{\sigma}_{NNLO} \otimes PDF(NNLO)}{\hat{\sigma}_{NLO} \otimes PDF(NNLO)}$$

$$\chi^2(m,b) = \sum_i \frac{[\mu_i - m_i(1 - \sum_j \gamma_j^i b_j)]^2}{\delta_{i,unc}^2 m_i^2 + \delta_{i,stat}\mu_i m_i(1 - \sum_j \gamma_j^i b_j)} + \sum_j b_j^2$$

$$\chi^2(m) = \sum_{i,k} (m_i - \mu_i) C_{ik}^{-1} (m_k - \mu_k)$$

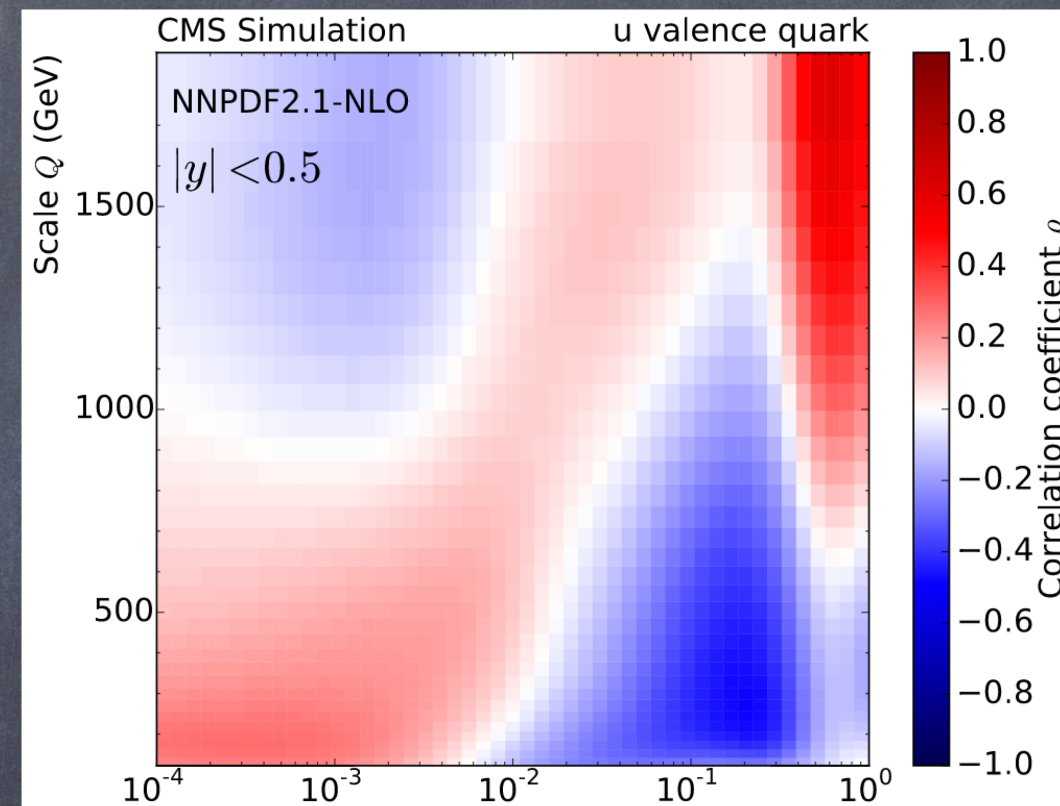
Probing QCD with Jet Cross Sections

Strong correlation between inclusive jet cross section and gluon at high-middle x



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

Strong correlation between inclusive jet cross section and quark at high x

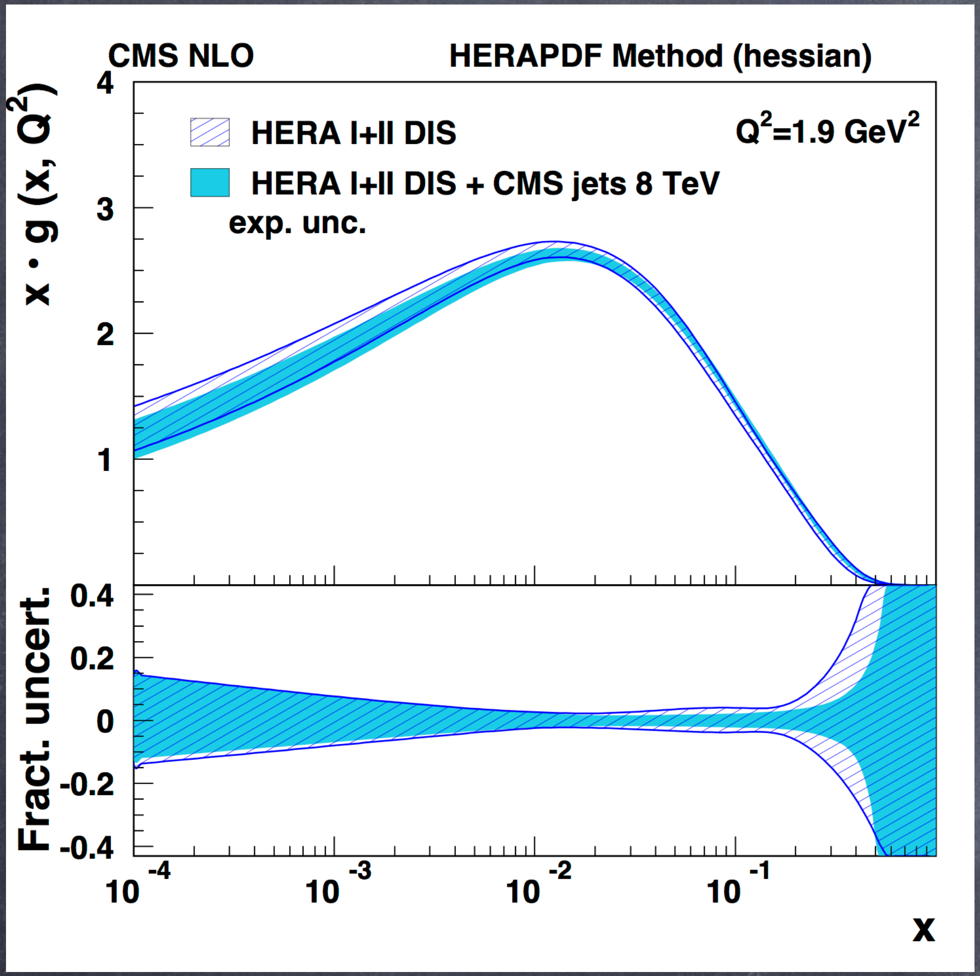


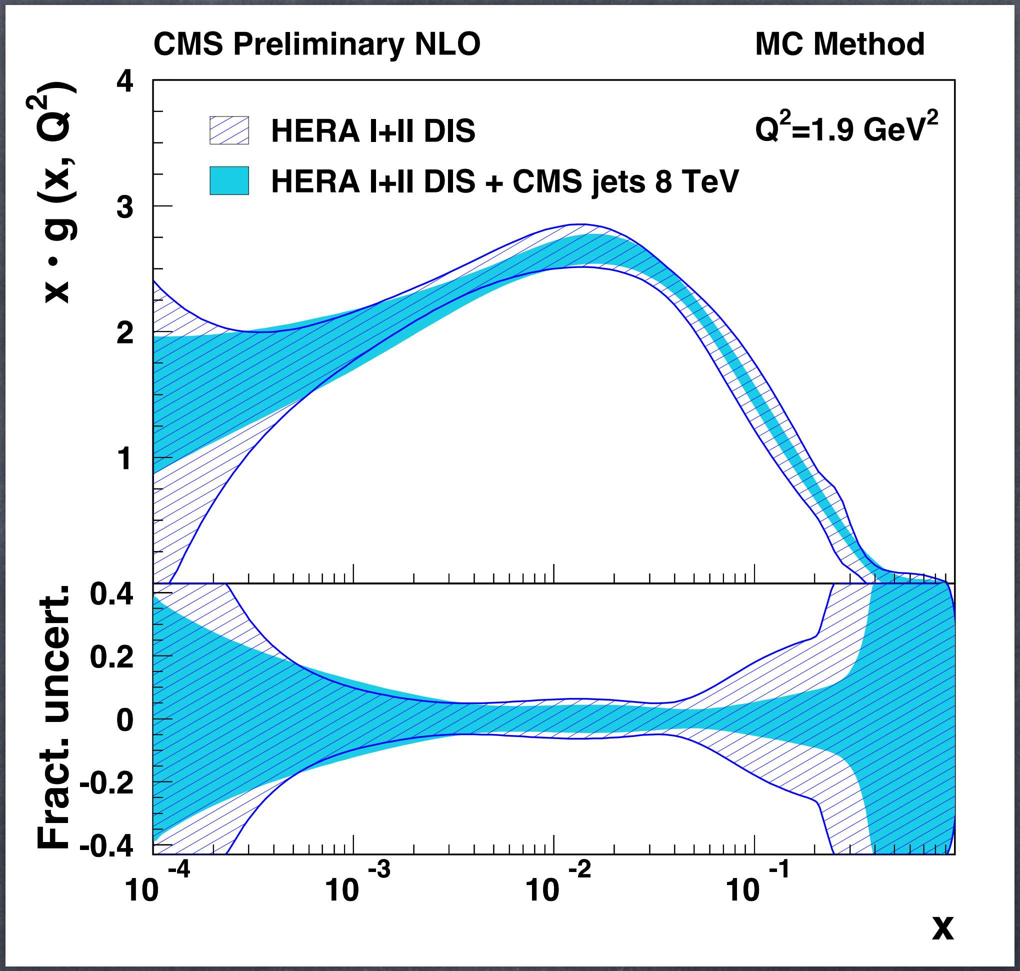
Eur. Phys. J. C 75 (2015) 288

The potential impact of the CMS inclusive jet data can be illustrated by the correlation between the inclusive jet cross section $\sigma_{\text{jet}}(Q)$ and the PDF $xf(x, Q^2)$ for any parton flavour f. The NNPDF Collaboration [63] provides PDF sets in the form of an ensemble of replicas i, which sample variations in the PDF parameter space within allowed uncertainties. The correlation coefficient $\varrho_f(x, Q)$ between a cross section and the PDF for flavour f at a point (x, Q) can be computed by evaluating means and standard deviations from an ensemble of N replicas as

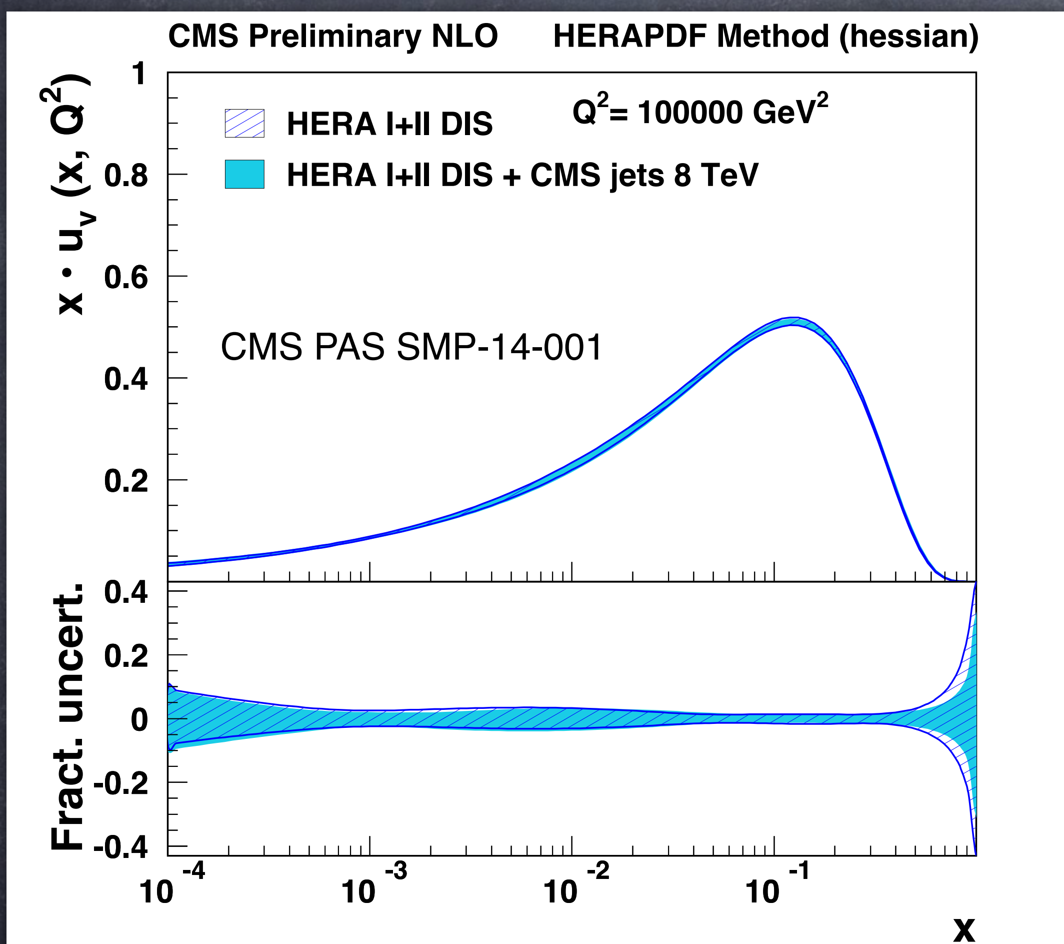
$$\varrho_f(x, Q) = \frac{N}{(N-1)} \frac{\langle \sigma_{\text{jet}}(Q)_i \cdot xf(x, Q^2)_i \rangle - \langle \sigma_{\text{jet}}(Q)_i \rangle \cdot \langle xf(x, Q^2)_i \rangle}{\Delta_{\sigma_{\text{jet}}(Q)} \Delta_{xf(x, Q^2)}}. \quad (12)$$

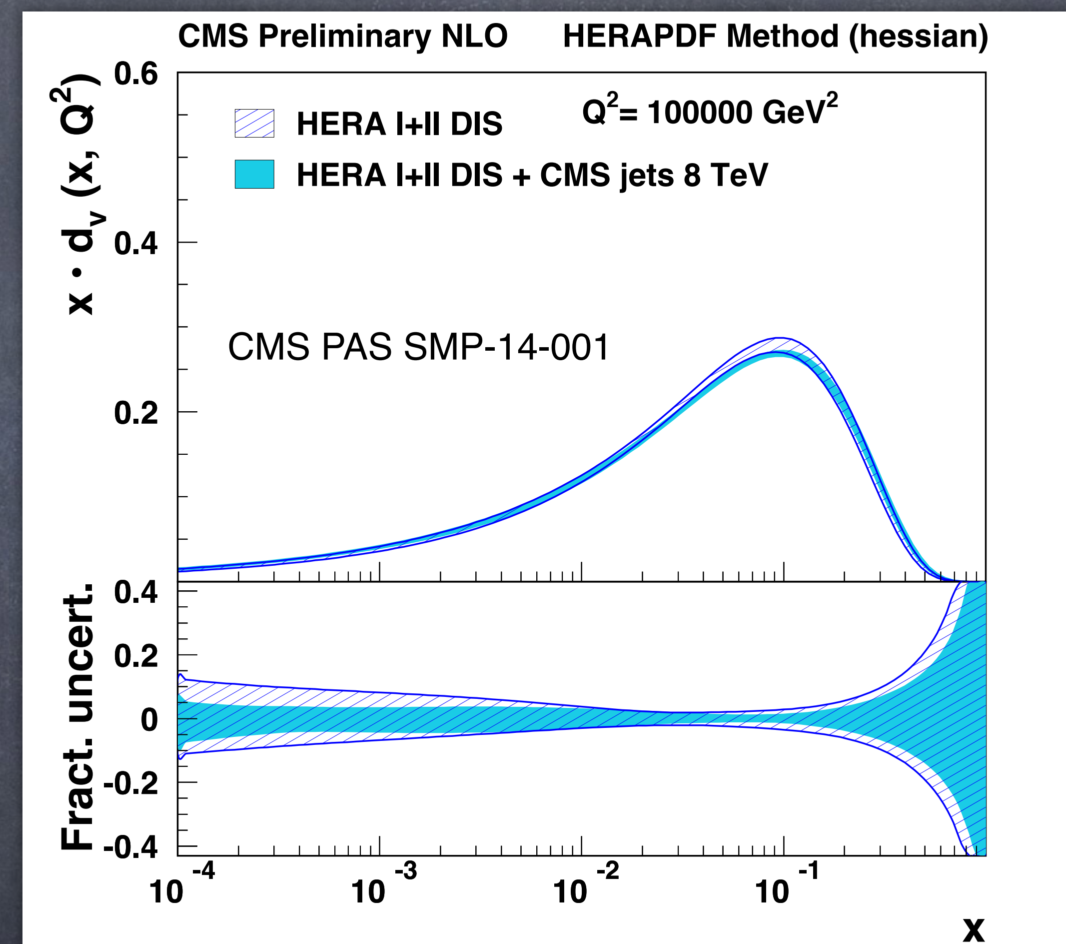
Hessian vs MC



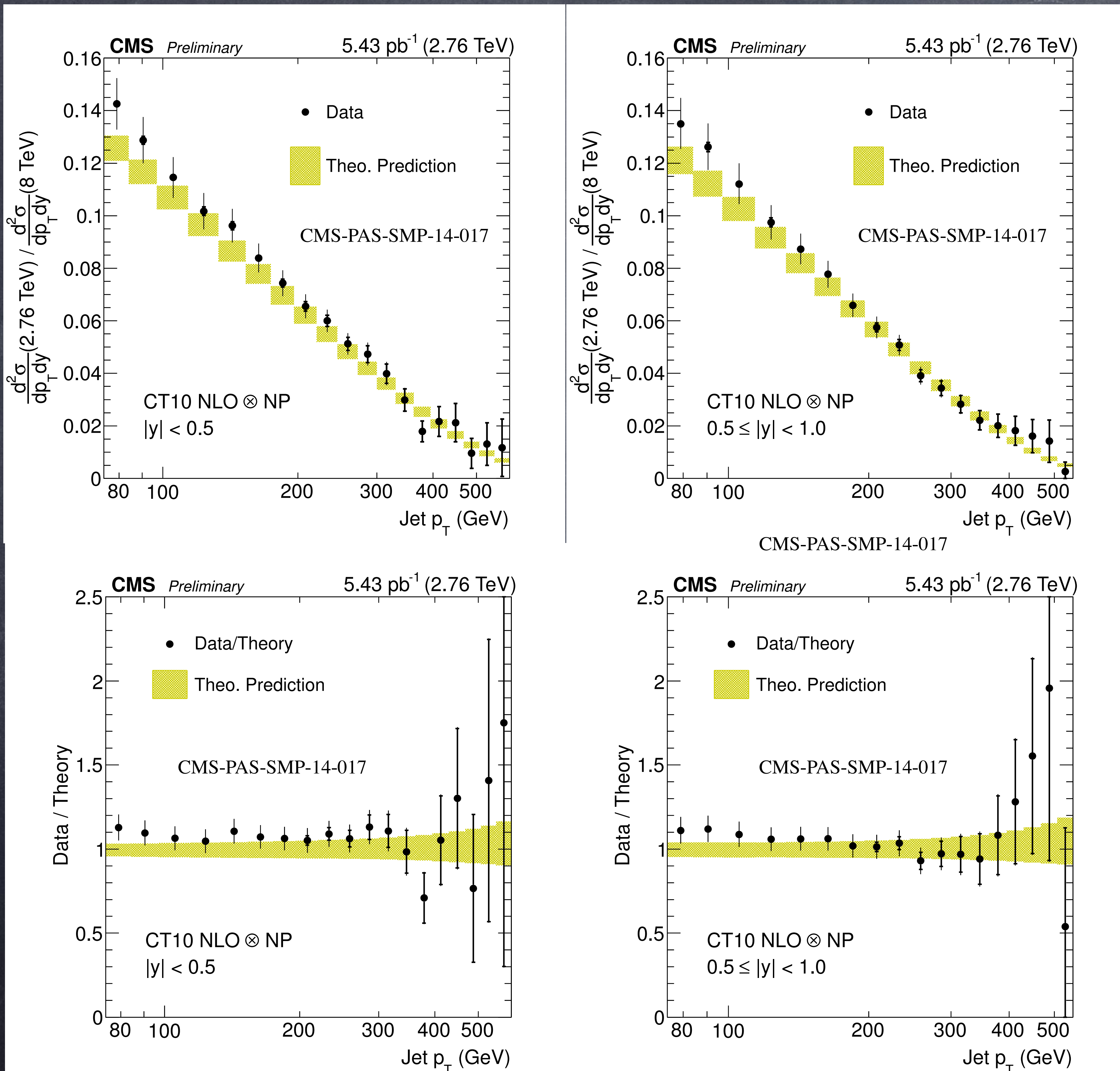


u and d valence PDFs from inclusive jet @8TeV



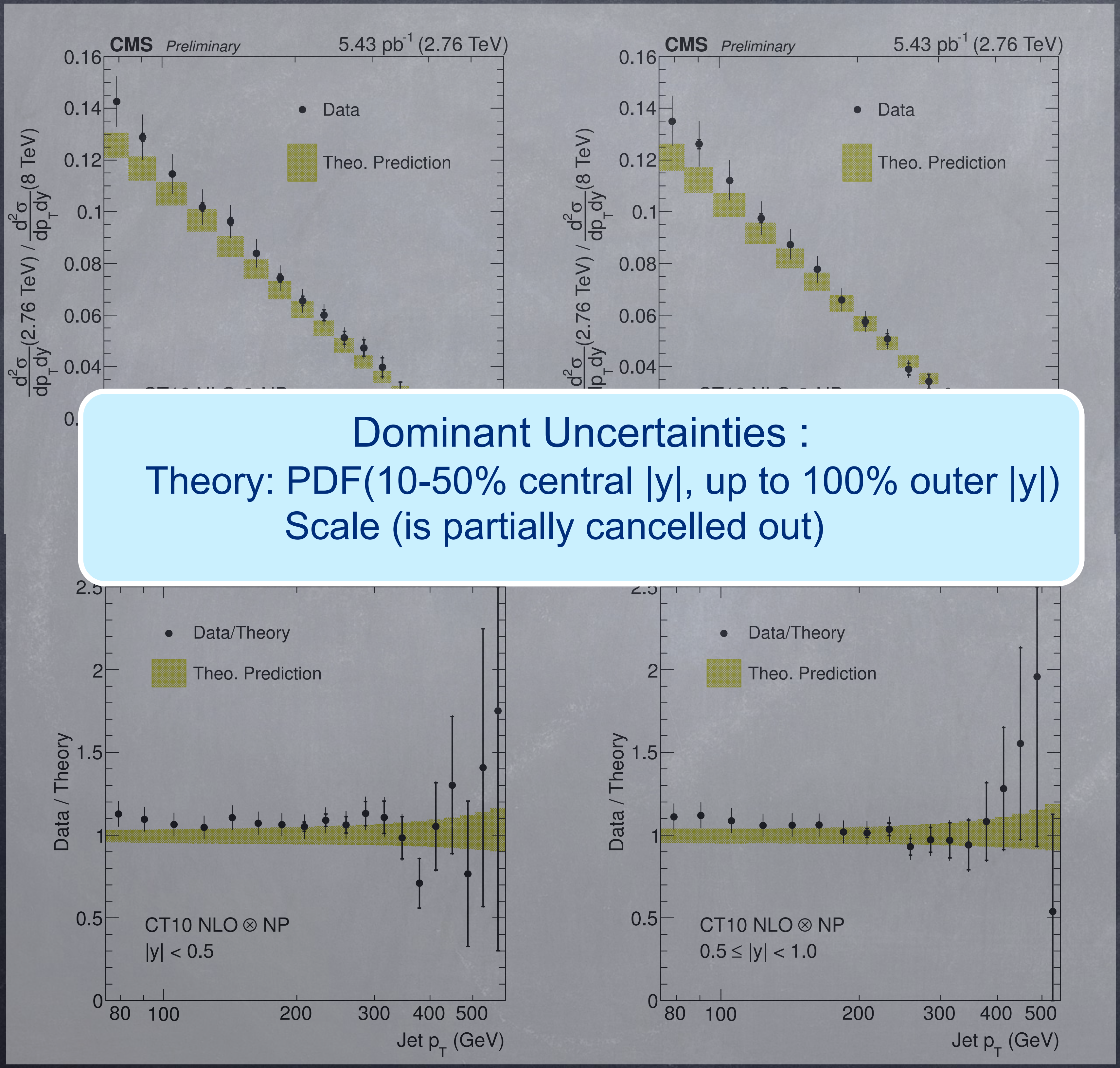


Inclusive Jet Cross Section Ratio 2.76 / 8TeV



- Careful study of the uncertainty between 8 and 2.76 TeV is performed.
- Partial cancelation of systematic uncertainties!
- This measurement can be used to constrain Pdfs.

Inclusive Jet Cross Section Ratio 2.76 / 8TeV



Dominant Uncertainties :

Theory: PDF(10-50% central |y|, up to 100% outer |y|)

Scale (is partially cancelled out)

- Careful study of the uncertainty between 8 and 2.76 TeV is performed.
- Partial cancelation of systematic uncertainties!
- This measurement can constrain Pdfs.

Parametrisation Uncertainty

Center

18p

18p + Euv

18p + DDbar

18p + Edv

……

Converged fits

- Get the largest difference
- Construct envelope