PDF constraints using CMS measurements

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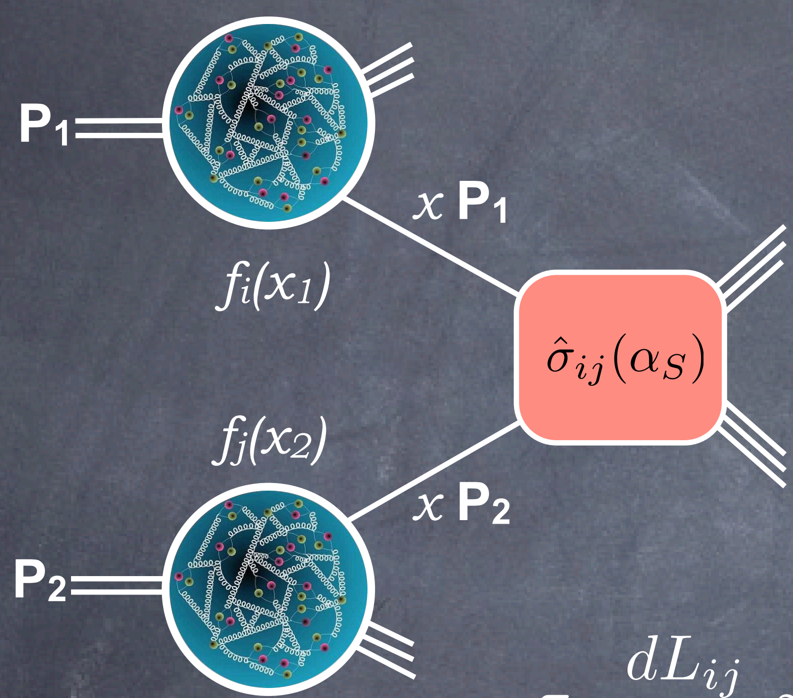
on behalf of the CMS experiment

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

ICHEP 2014 Valencia

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)

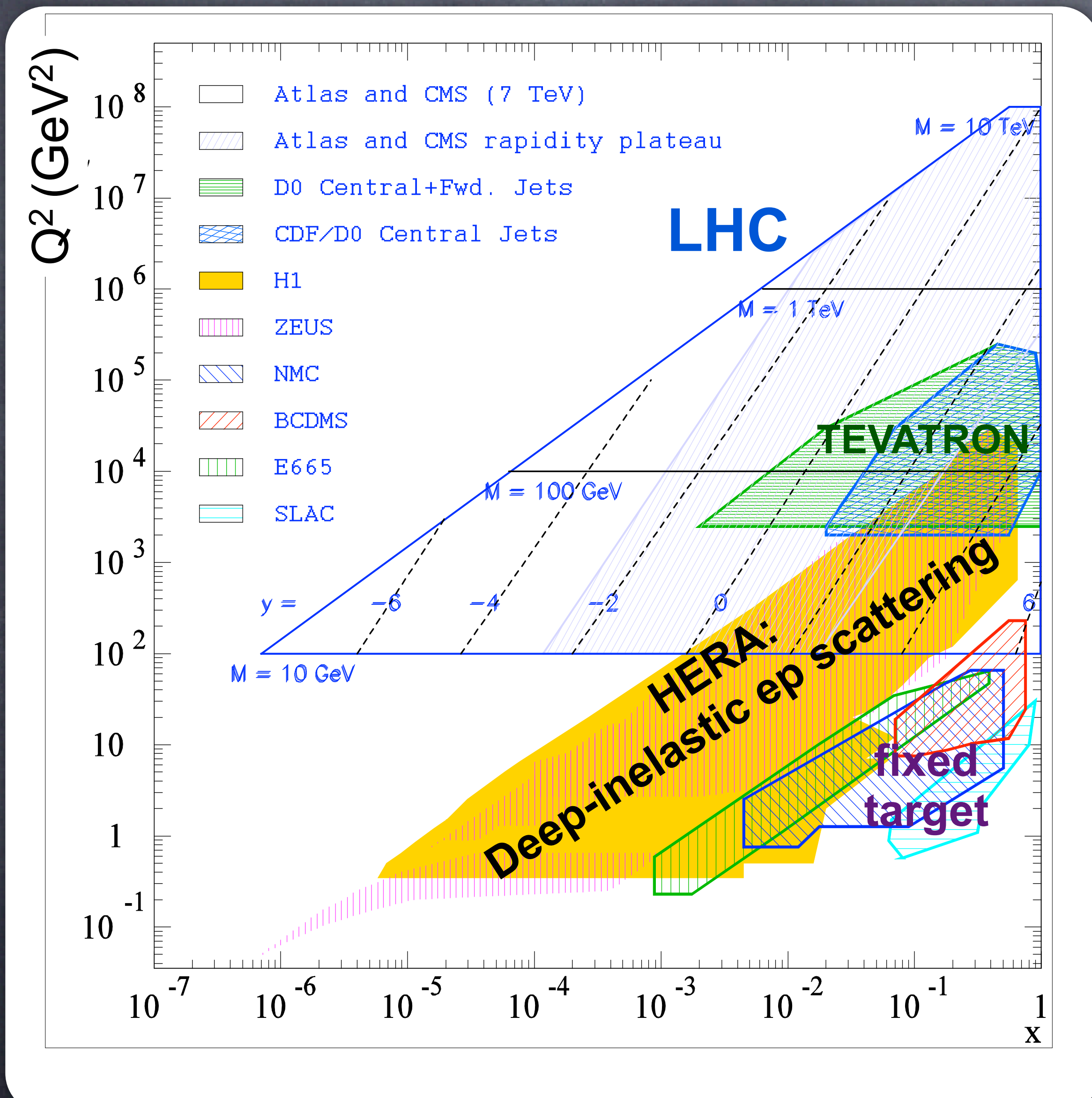
universal functions of partonic fraction *x* of proton momentum and energy scale *Q* of the process

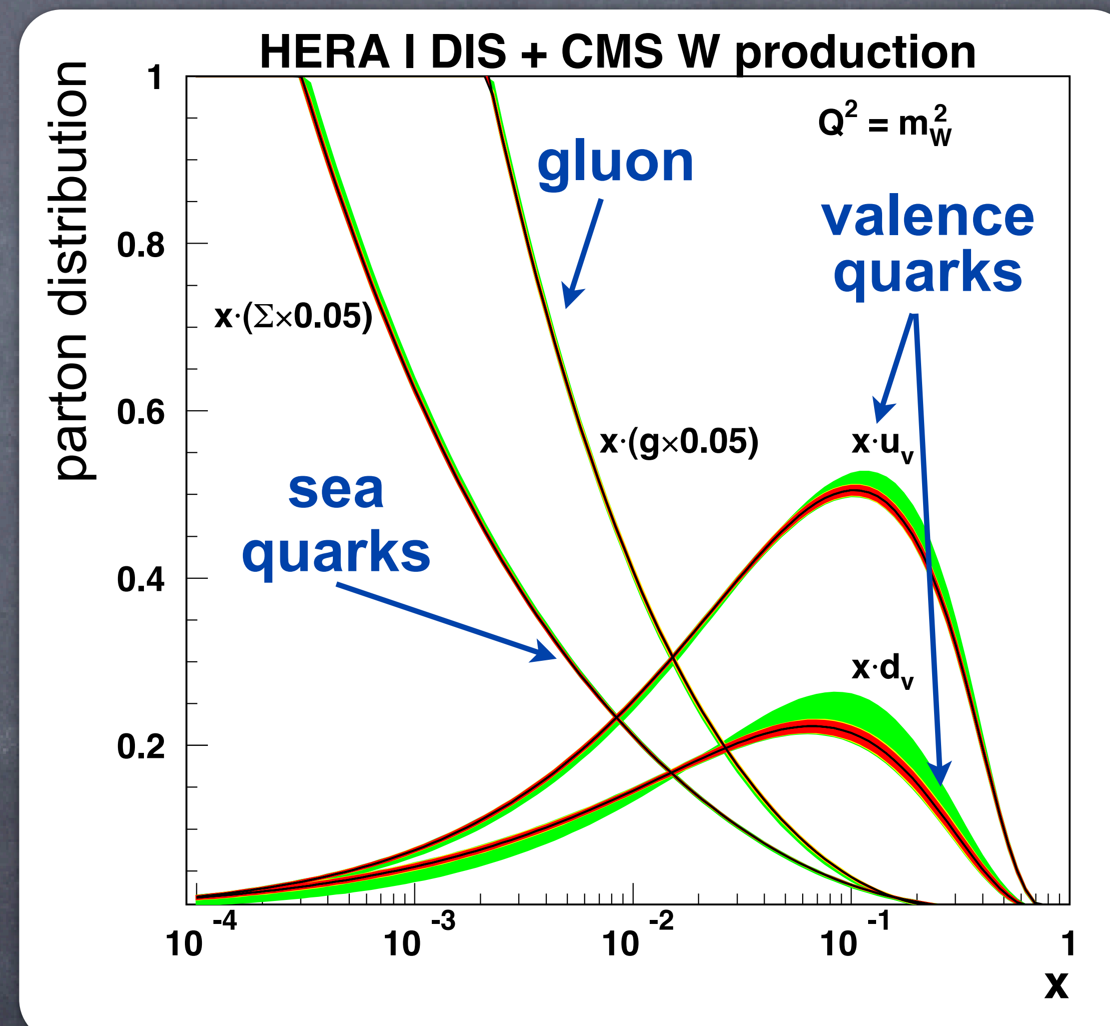
Precision of PDFs essential for interpretation of the LHC measurements
Precise LHC data are used to improve PDF constraints

How PDFs are determined

PDF for flavor i: $f_i = f_i(x, Q^2)$
Q^2 dependence predicted by QCD
x-dependence determined from data

- parameterize PDFs at a scale Q^2_0:
  $f(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$
- evolve these PDFs to $Q^2 > Q^2_0$
- construct expected cross sections
- χ^2- fit to the experimental data

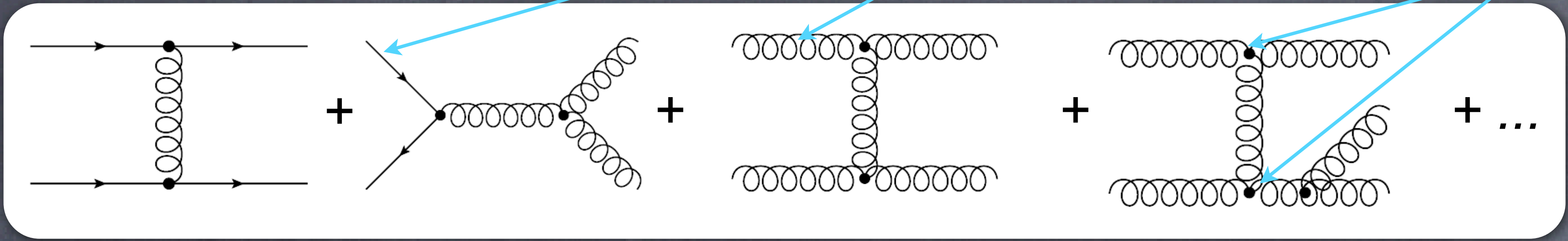




LHC provides important constraints in particular at large x

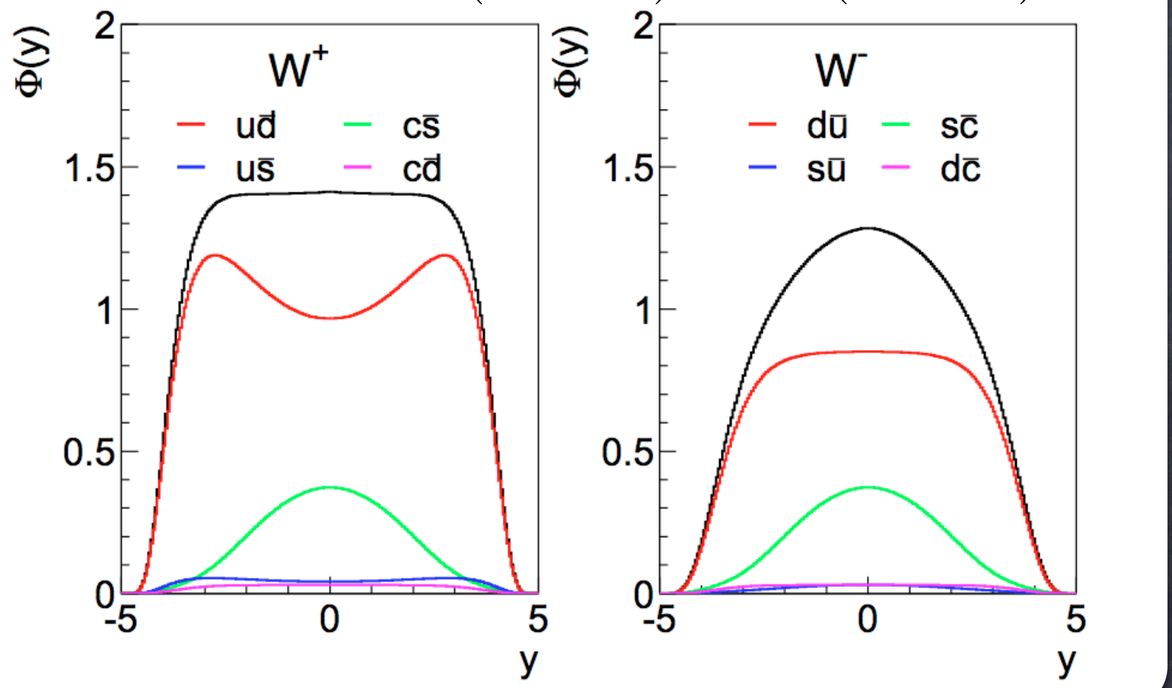
In this talk: LHC processes sensitive to PDFs

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



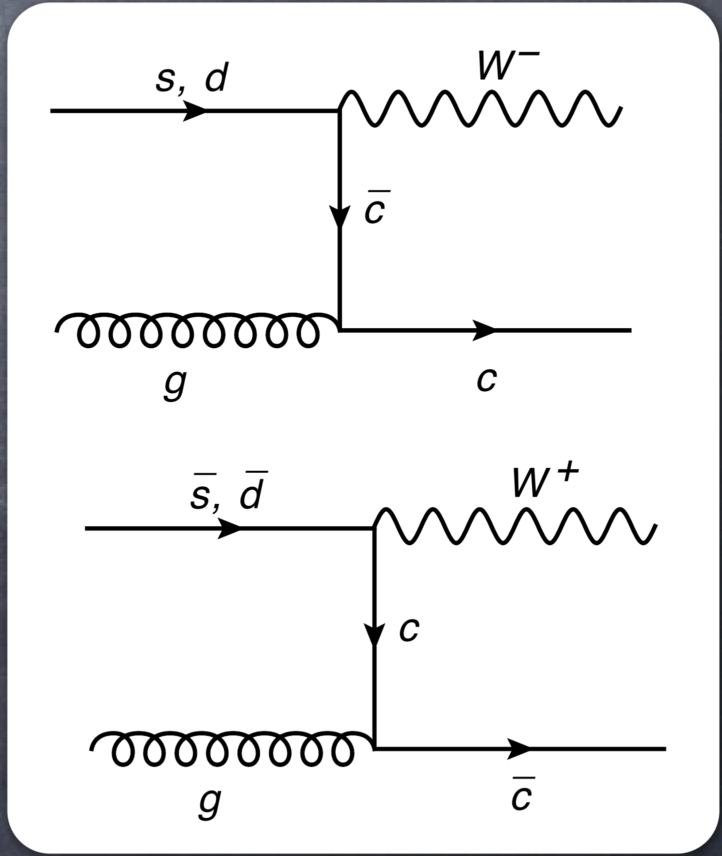
Drell-Yan production probes bi-linear quark combinations

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



LO with suppressed strangeness *...courtesy A.Glazov/V.Radescu*

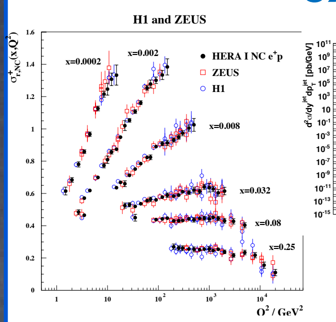
Associated W+c production probes s-quark directly at LO

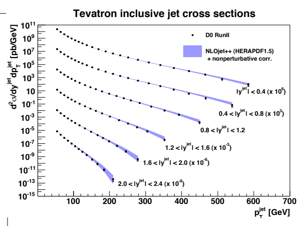


Include LHC data in PDF fit using HERAFitter

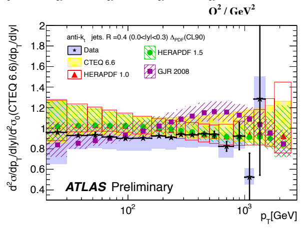
Unique tool to test impact of the measurements on e.g. PDFs **during data analysis**

experimental input





experiments:
HERA, Tevatron, LHC, fixed target



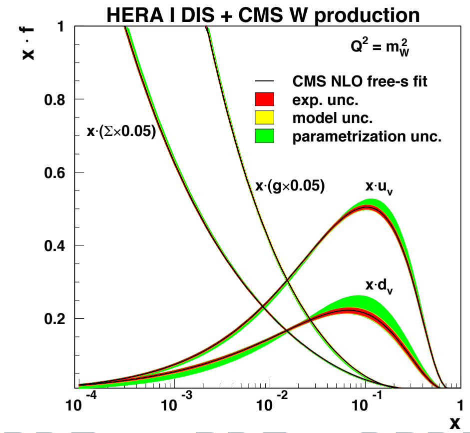
processes:
NC, CC DIS, jets, diffraction, heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or uPDF or DPDF

$\alpha_S(M_Z)$, m_c, m_b, m_t, f_s,..

Theory predictions

Benchmarking

Comparison of schemes

https://www.herafitter.org/HERAFitter

open-source QCD framework

developed by experimentalists and theorists

strong contribution from HERA, ATLAS and CMS

CMS results on PDFs shown in this talk are obtained using HERAFitter

Framework for CMS QCD analyses in this talk

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

Data in the QCD analysis:

- HERA I combined inclusive DIS data, Charged and Neutral Current *[JHEP 1001:109 (2010)]*
- Different CMS data sets (details in the next slides)

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

Model input:

- Theory calculations at NLO 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: $m_c = 1.4$ GeV, $m_b = 4.75$ GeV.

Model uncertainties: originate from variations of model input parameters:

1.35 GeV < m_c < 1.65 GeV, 4.3 GeV < m_b < 5 GeV, f_s=0.31±0.08, 3.5 GeV^2 < Q^2_{min} < 5 GeV^2

CMS QCD analyses: PDF parametrization

Basic parametrization at the starting scale Q^2_0=1.9 GeV^2 (13 free parameters):

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

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

Normalizations Au_v , Ad_v, Ag 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;

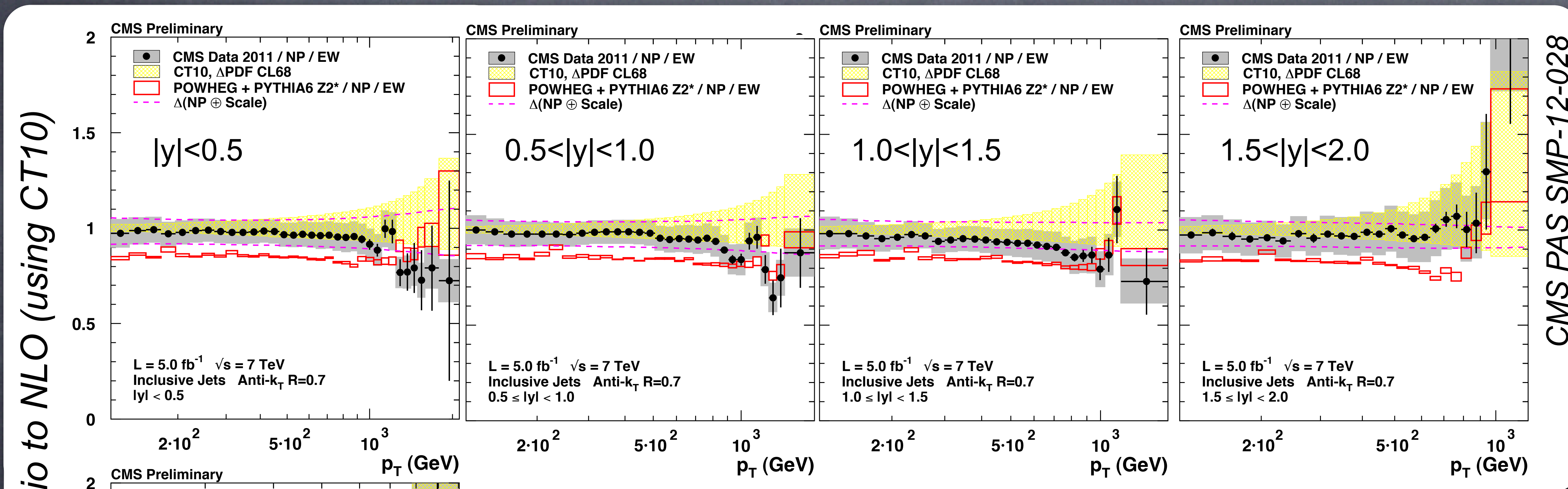
additional variation of 1. 5<Q^2_0<2.5 GeV^2

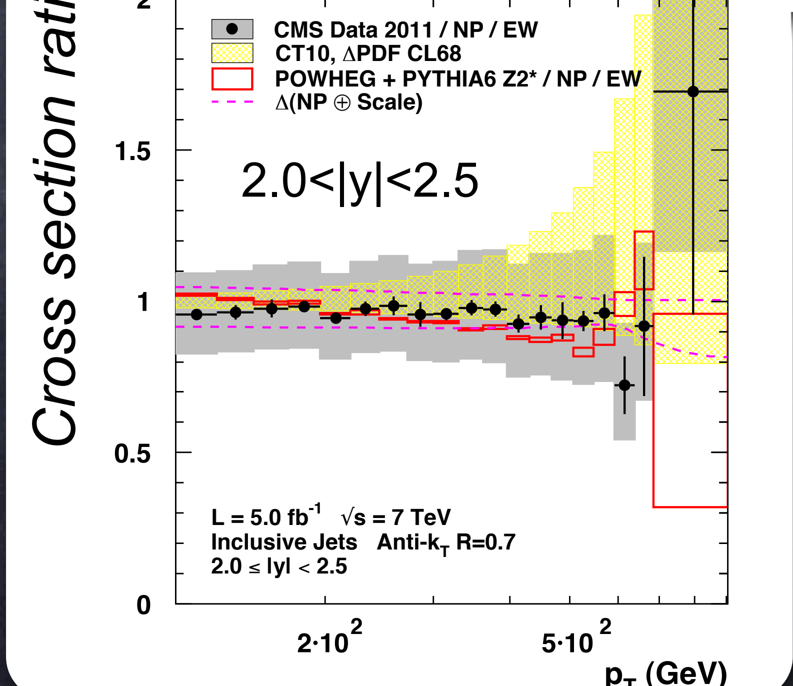
Largest difference of resulting PDFs to the central result (envelope) is assigned as uncertainty

Inclusive jet production at CMS used for PDF studies

Measurements: CMS 2011, $\sqrt{s}$=7 TeV ($\mathcal{L}$ = 5 fb^{-1}) *Phys. Rev. D 87 (2012) 12002*

Anti-k$_T$, R=0.7; double-differential cross sections as functions of p$_T$ and y.





CMS PAS SMP-12-028:

- electroweak corrections applied

[Dittmeier et at JHEP 2011, 095 (2012)]

- revised systematic correlations related to JES

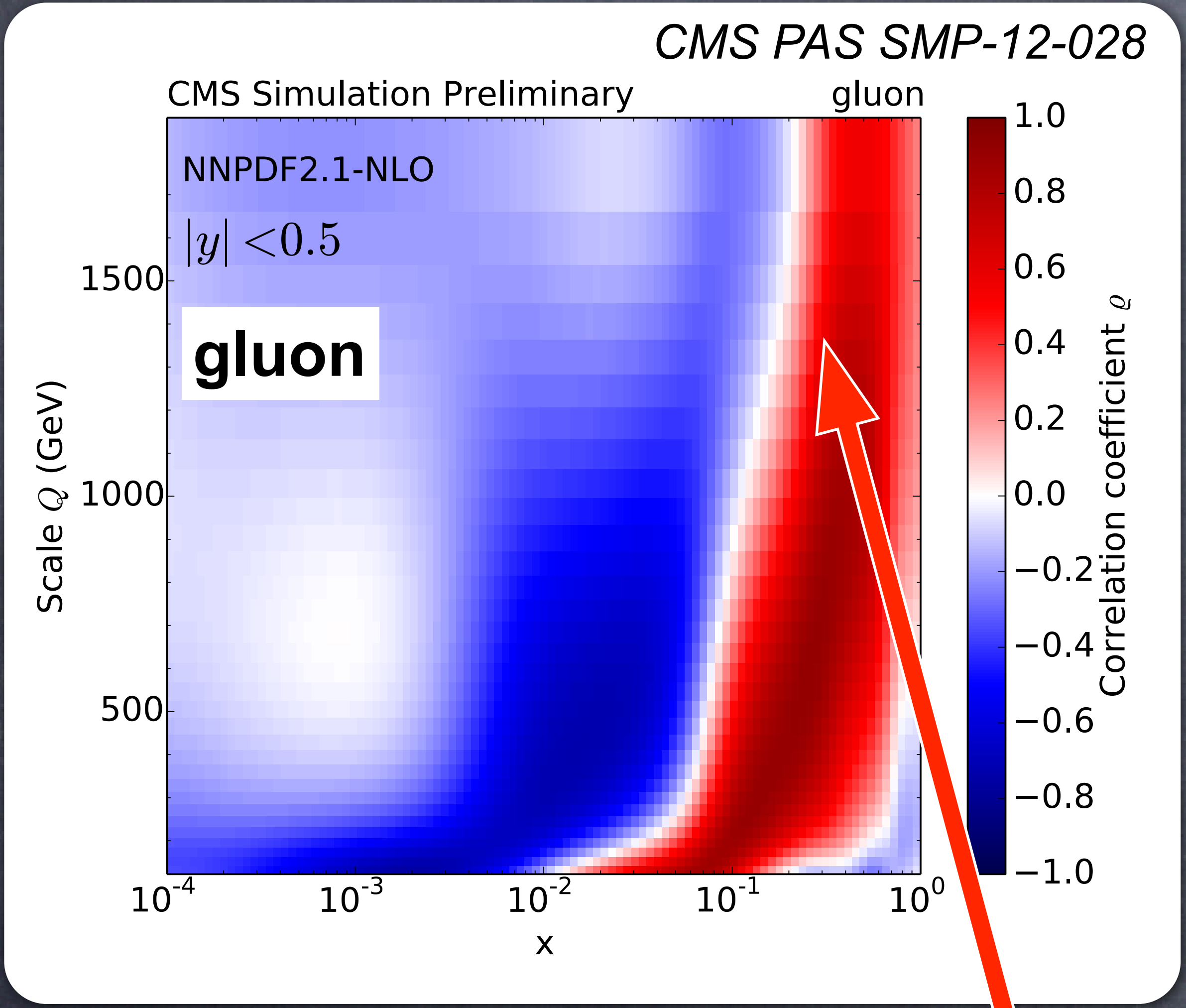
for more details on CMS jet measurements see talk G. Mavromanolakis

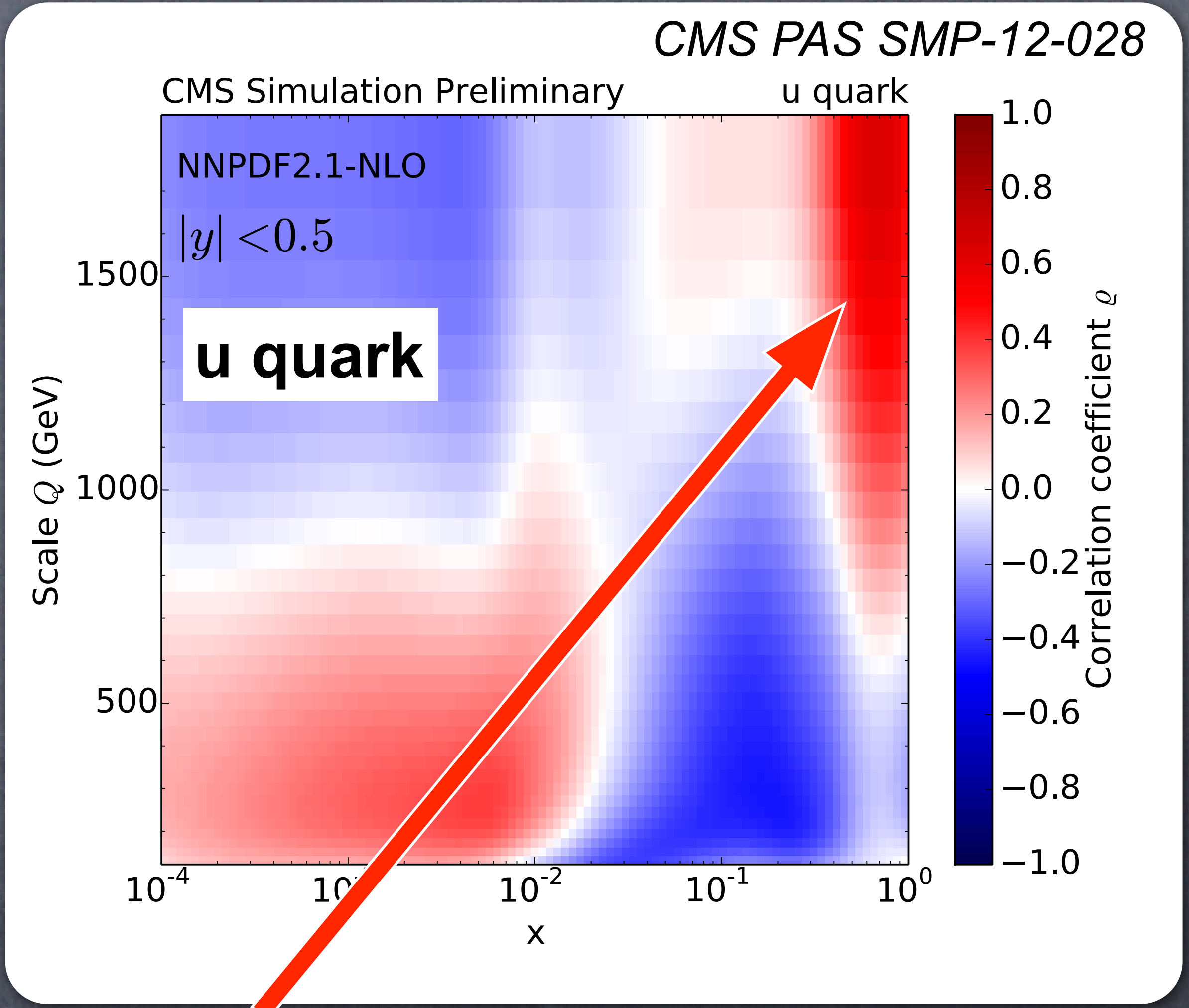
Inclusive jet production at CMS: sensitivity to PDFs

Inclusive jet production probes gluon and quark distributions

Sensitivity of the data to parton distributions quantified by correlation coefficients

e.g. at central rapidity:





strong correlation

Expect an impact of the measurement on gluon at medium x, quarks at high x

Impact of the CMS jet measurements on PDFs

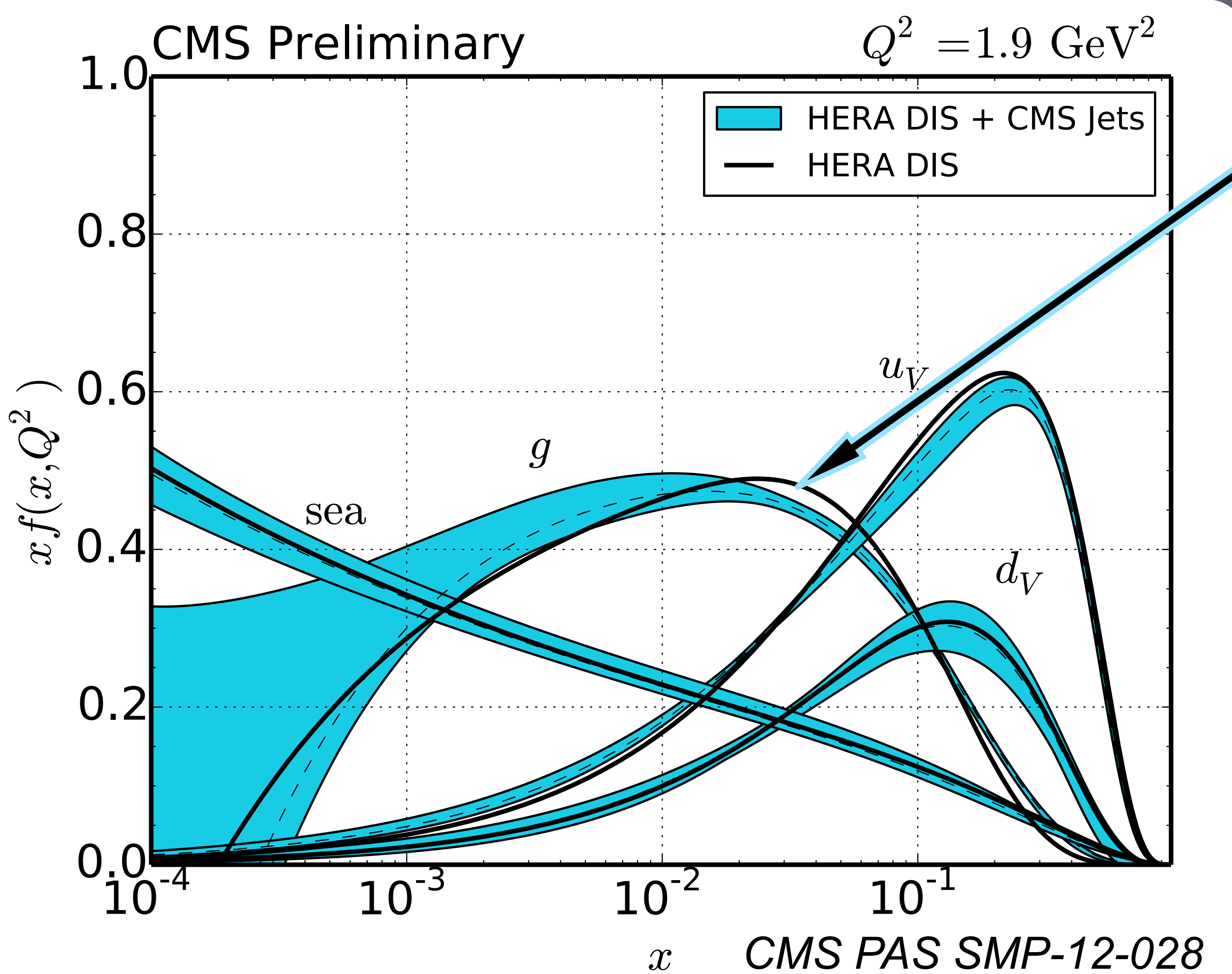
13-parameter fit using HERAFitter, DGLAP, QCD analysis at NLO

Data: combined HERA I DIS

+ CMS inclusive jet production *[Phys. Rev. D 87 (2012) 12002]*
  corrected for electroweak effects *[Dittmeier et at JHEP 2011, 095 (2012)]*

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 $\alpha_S(m_Z)$=0.1176;

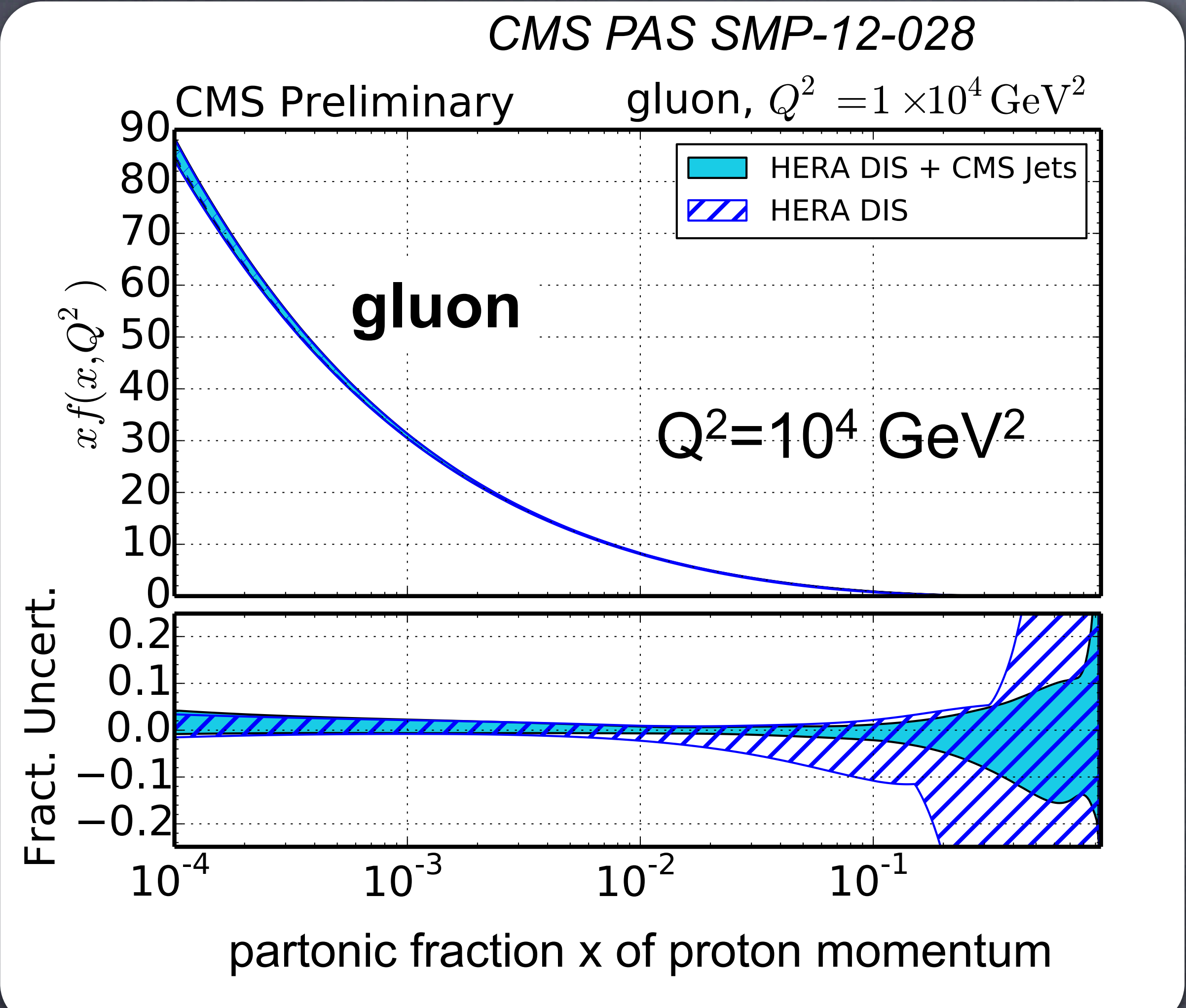


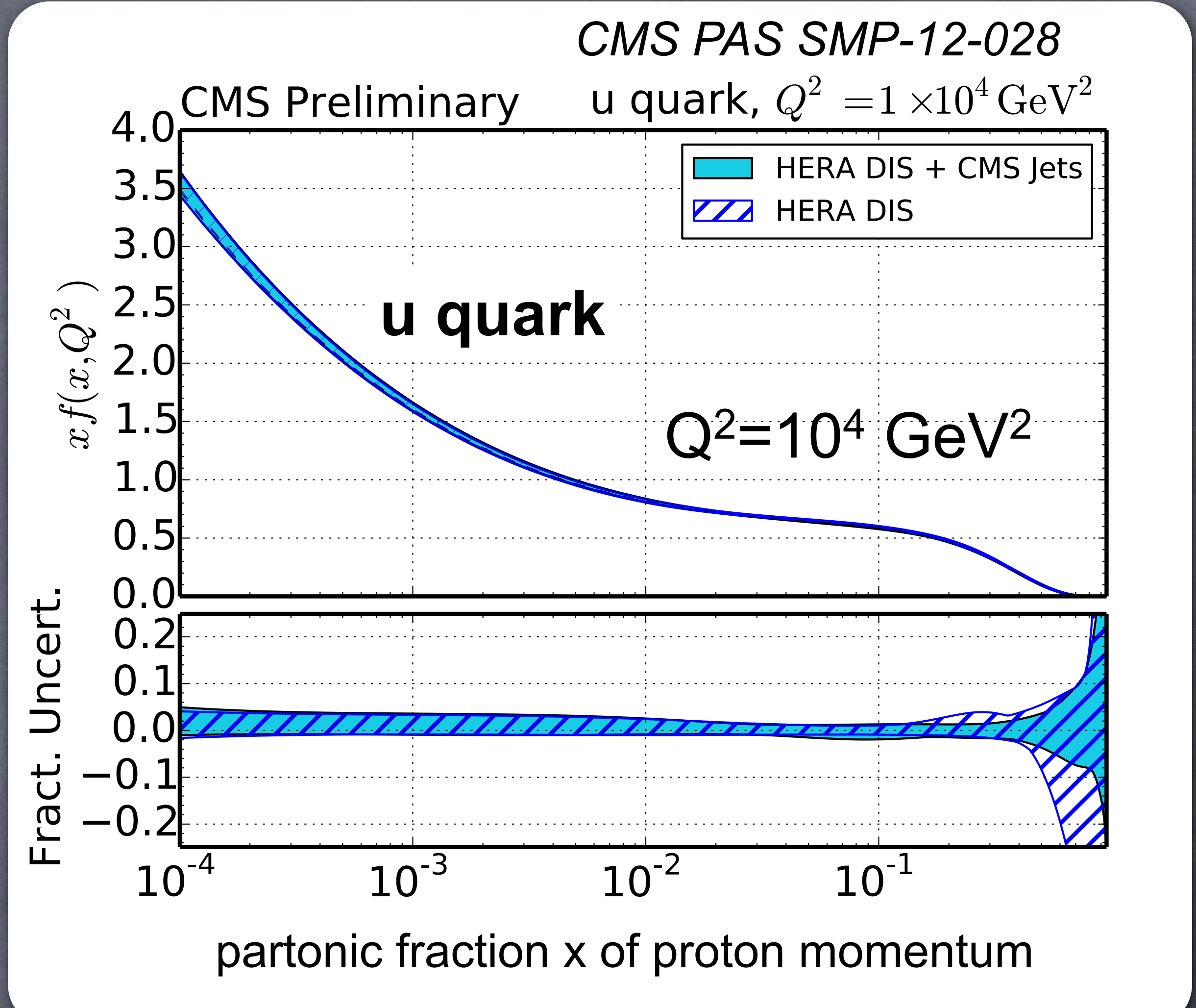
For comparison, the same fit is performed to HERA I DIS data alone

PDFs with and without CMS jets are consistent within uncertainties

CMS jet data prefer harder gluon

Impact of the CMS jet data on PDF uncertainties





- Improved constraints on the gluon and light quark distributions at high x (mostly due to significant reduction of the parametrization uncertainty)
- Simultaneous determination of PDF and $\alpha_S(m_Z) = 0.1192^{+0.0017}_{-0.0015}$ (exp)

error accounts for the experimental uncertainties of the data and the NP uncertainties

more on determination of $\alpha_S(m_Z)$ see talk by G. Mavromanolakis

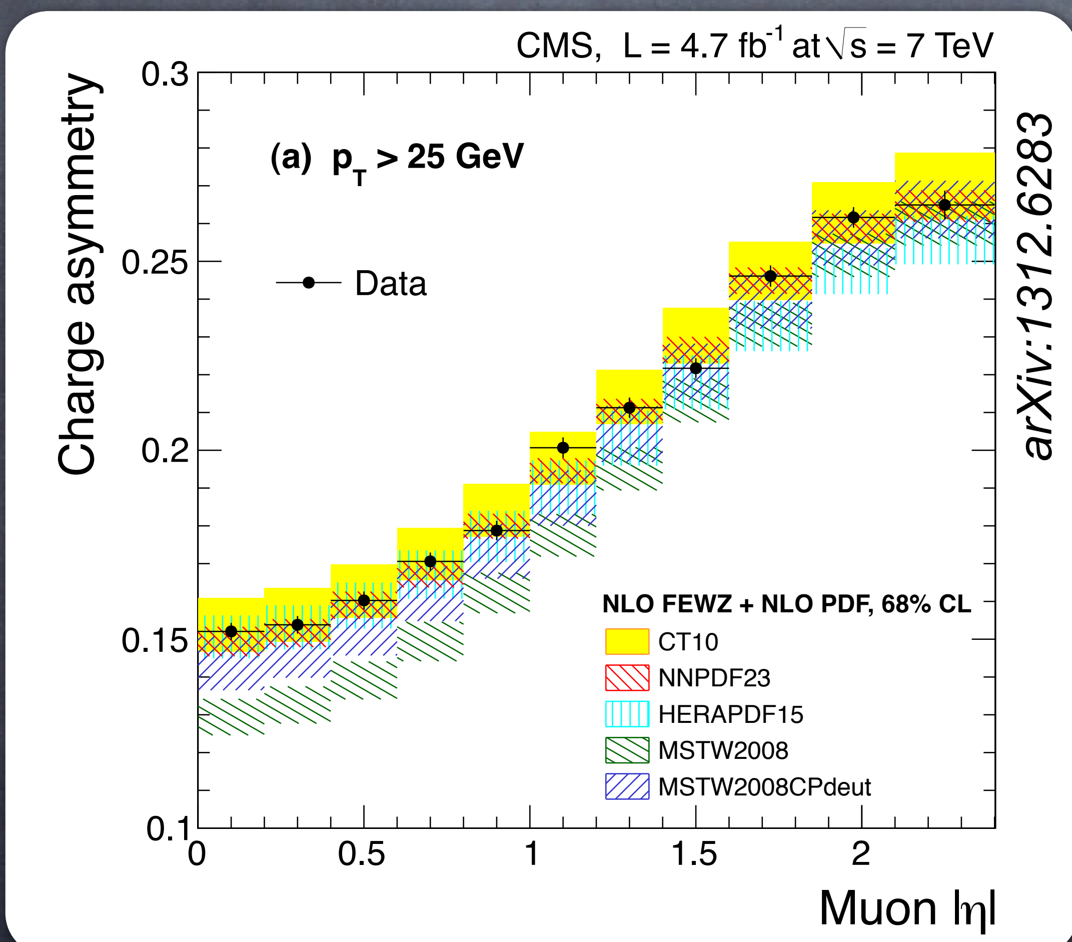
Asymmetry in W± production at CMS in PDF studies

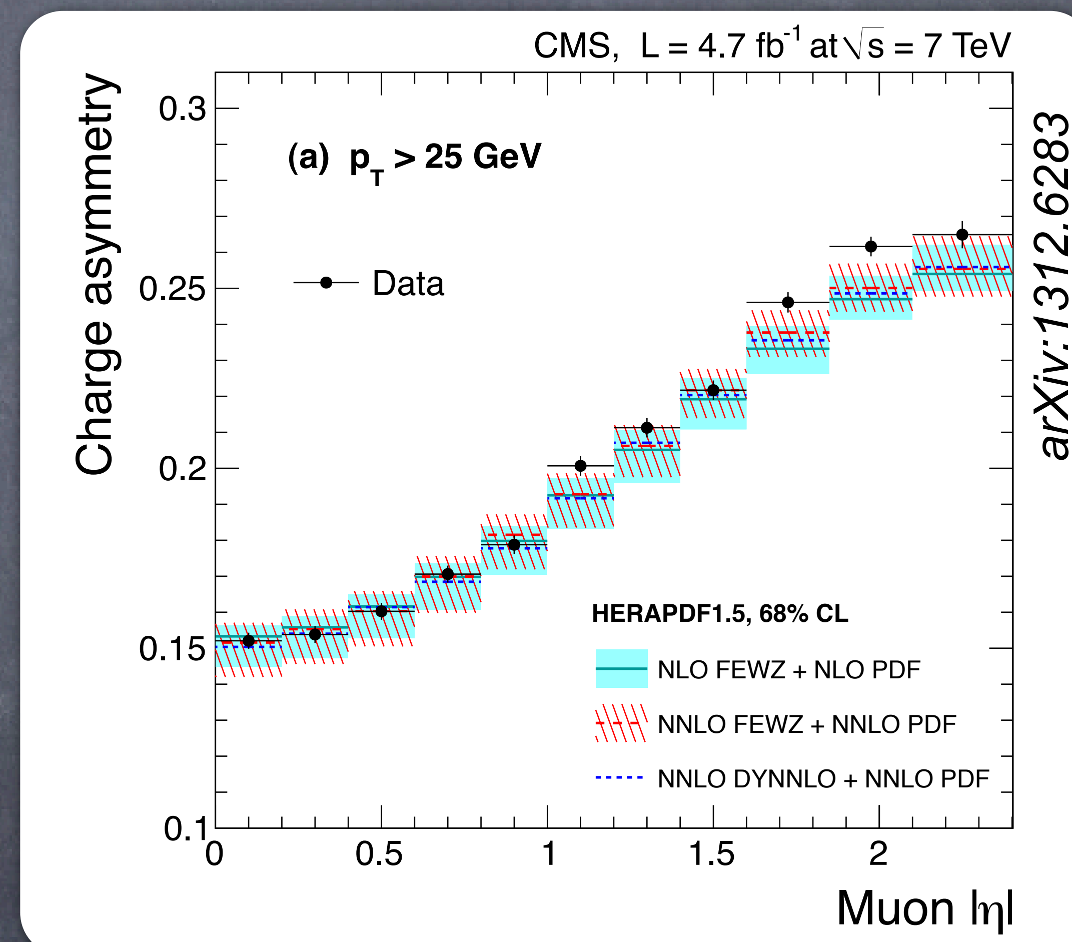
Lepton asymmetry in W production in *pp* collisions:
probes quark distributions at $10^{-3} < x < 10^{-1}$

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

Recent CMS measurement of $W \to \mu\nu$ at $\sqrt{s}$=7 TeV ($\mathcal{L}$ = 4.7 fb^{-1}) *[arXiv 1312.6283]*

… for more details on the measurement see talk by S. Ghosh





High-precision data (uncertainty 2-4%), sensitivity to PDF observed

Asymmetry in $W^{\pm}$ production at CMS in PDF studies

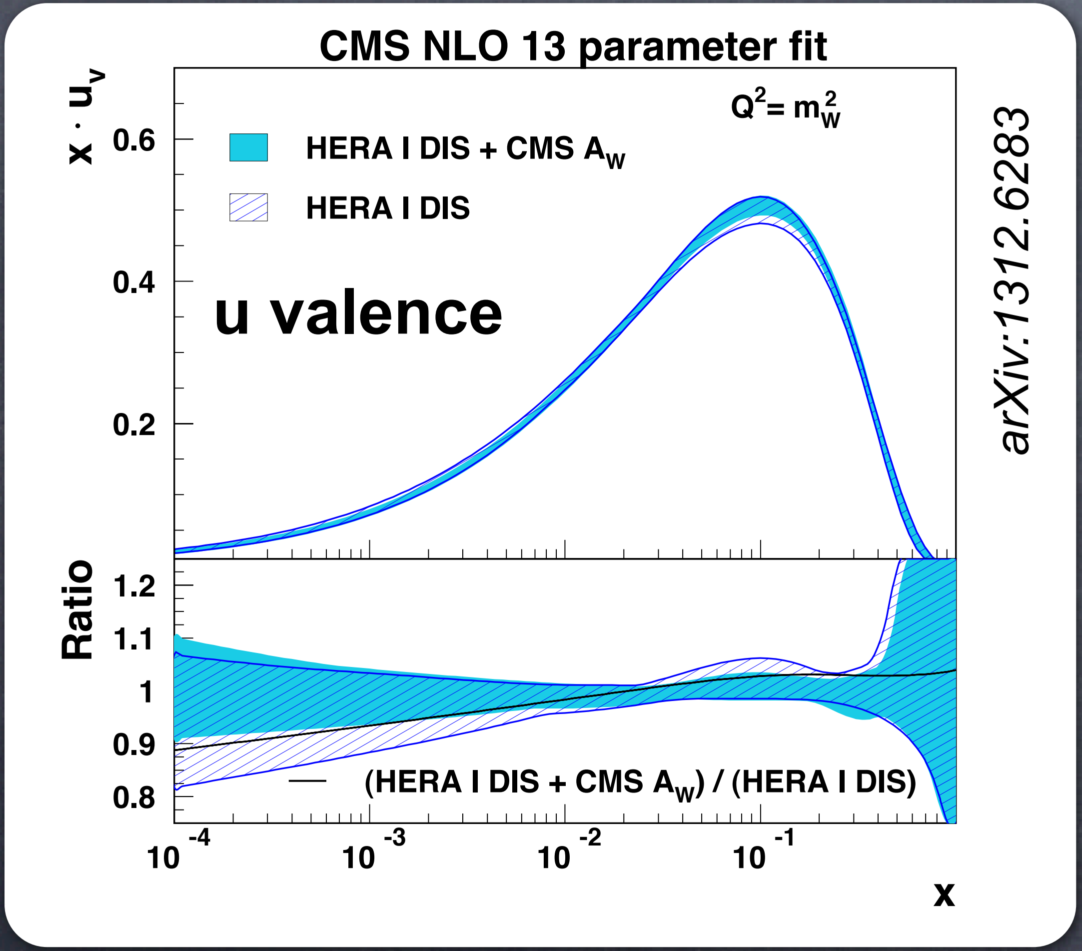
13-parameter fit using HERAFitter, DGLAP, QCD analysis at NLO

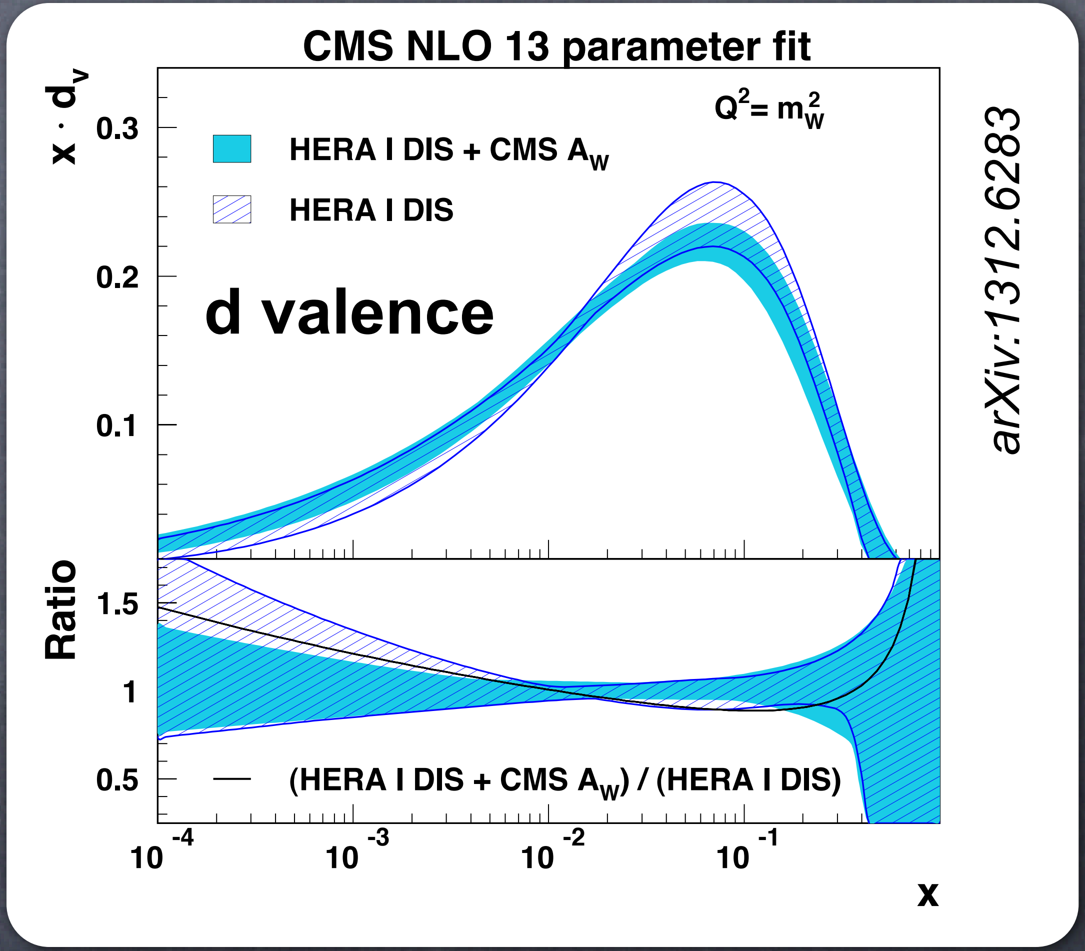
Data: combined HERA I DIS

+ CMS muon charge asymmetry measurement *[arXiv:1312.6283]*

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

QCD scales $\mu_r = \mu_f = m_W$, strong coupling $\alpha_S(m_Z)$=0.1176;

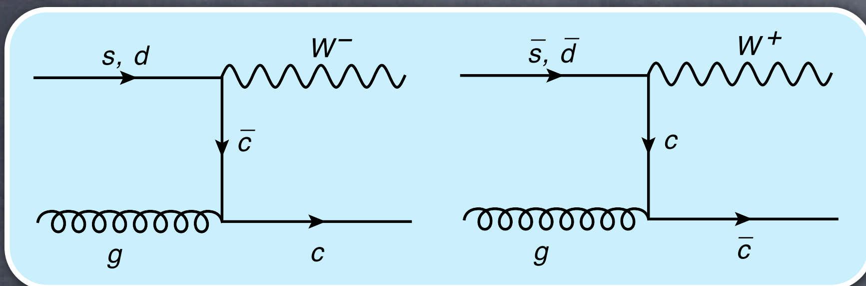




Improvement in the uncertainty of the valence-quark distributions

CMS measurements of W+c in PDF studies

probe s-quark at x~0.012, Q=m_W



CMS measurement of W+c **at parton level**

2011 data, √s=7 TeV ($\mathcal{L}$ = 5 fb^{-1}) *[JHEP 1402 (2014) 013]*

used in PDF analysis: p^{ℓ}_T > 35 GeV ($W \to \mu\nu$, $W \to e\nu$)

...for more on W(Z)+ c(b) production at CMS see talk F. Cossutti

The W+c production probes s-quark distribution directly, parametrization at Q^2_0=1.9 GeV^2 modified to 15 free parameters ("free s fit"):

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

~~$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.$~~

$$
\begin{cases}
x\ \bar{d}(x) = A_{\bar{d}}\ x^{B_{\bar{d}}}\ (1-x)^{C_{\bar{d}}} \\
x\ \bar{s}(x) = A_{\bar{s}}\ x^{B_{\bar{s}}}\ (1-x)^{C_{\bar{s}}}
\end{cases}
$$

$A_{\bar{u}} = A_{\bar{d}}\ ;\ B_{\bar{u}} = B_{\bar{d}}$ ensures same normalization for u and d- antiquarks at $x \to 0$

$B_{\bar{s}} = B_{\bar{d}}$ for the central fit, ***A_s* and *C_s* are free parameter of the fit**, assumed $s = \bar{s}$

$B_{\bar{s}} \neq B_{\bar{d}}$ fit performed, difference to results of the central fit included in parametrization uncertainty

CMS result on s-quark distribution

15-parameter free-s fit using HERAFitter, DGLAP, QCD analysis at NLO

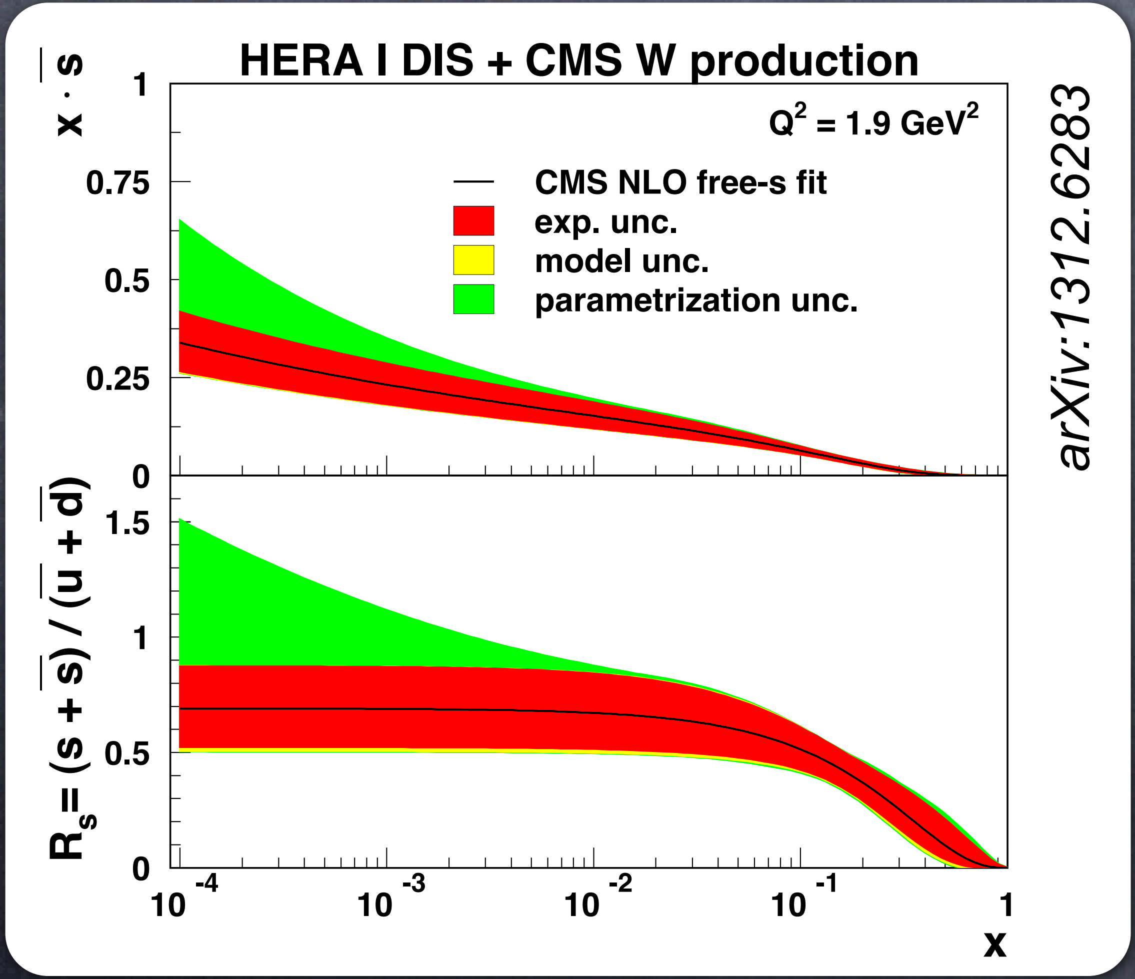
Data: combined HERA I DIS

+ CMS muon charge asymmetry measurement *[arXiv:1312.6283]*

+ *CMS associated W+c production [JHEP 1402 (2014) 013]*

Theory for A_W and W+c: NLO prediction with MCFM, interfaced via APPLGRID

QCD scales $\mu_r = \mu_f = m^T_W$, strong coupling $\alpha_S(m_Z)$ =0.1176



Strangeness suppression factor :

$$\kappa_s(Q^2) = \frac{\int_0^1 (\bar{s}(x,Q^2) + s(x,Q^2))dx}{\int_0^1 (\bar{u}(x,Q^2) + \bar{d}(x,Q^2))dx}$$

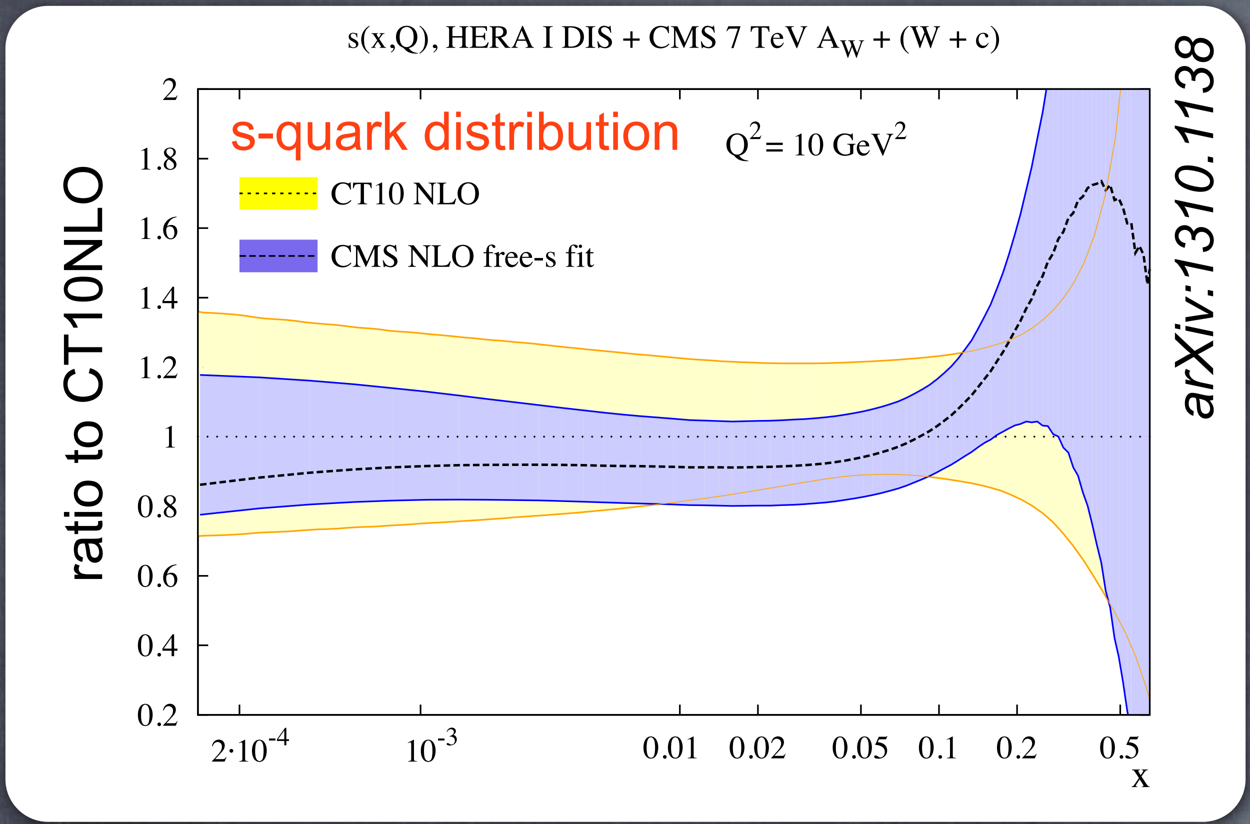
CMS result at Q^2 = 20 GeV²

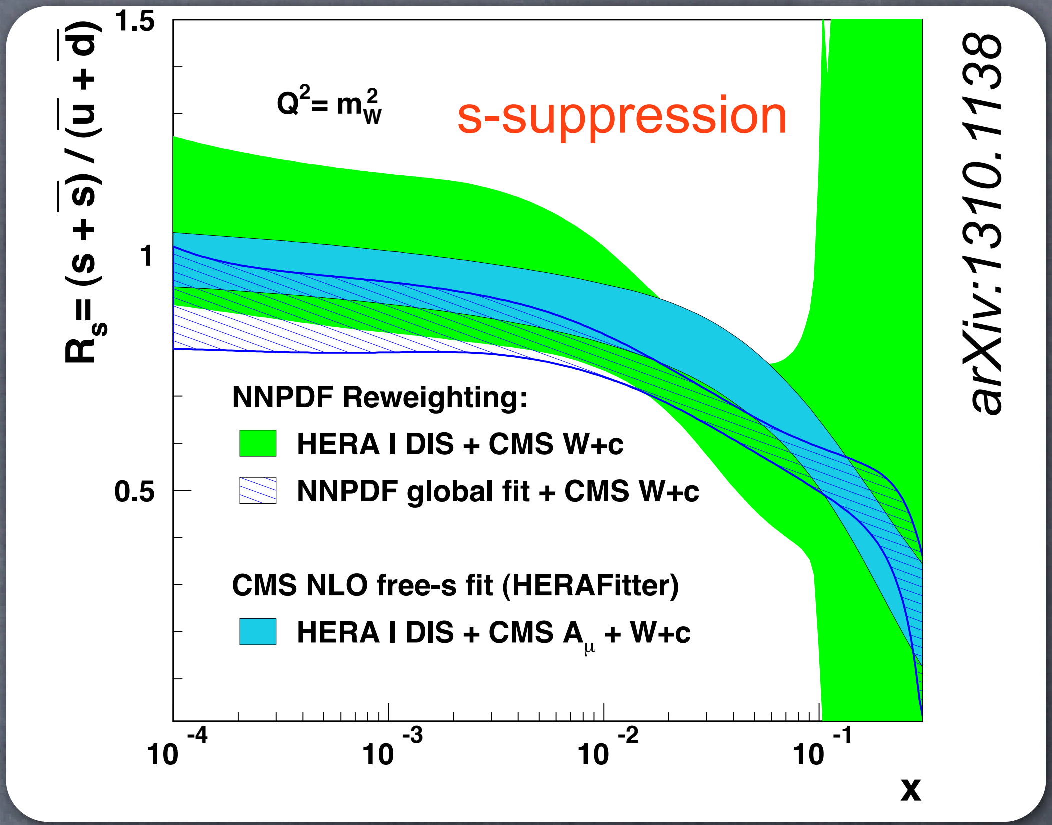
$$\kappa_s = 0.52^{+0.12}_{-0.10}(exp.)^{+0.05}_{-0.06}(mod.)^{+0.13}_{-0.10}(par.)$$

in good agreement with NOMAD

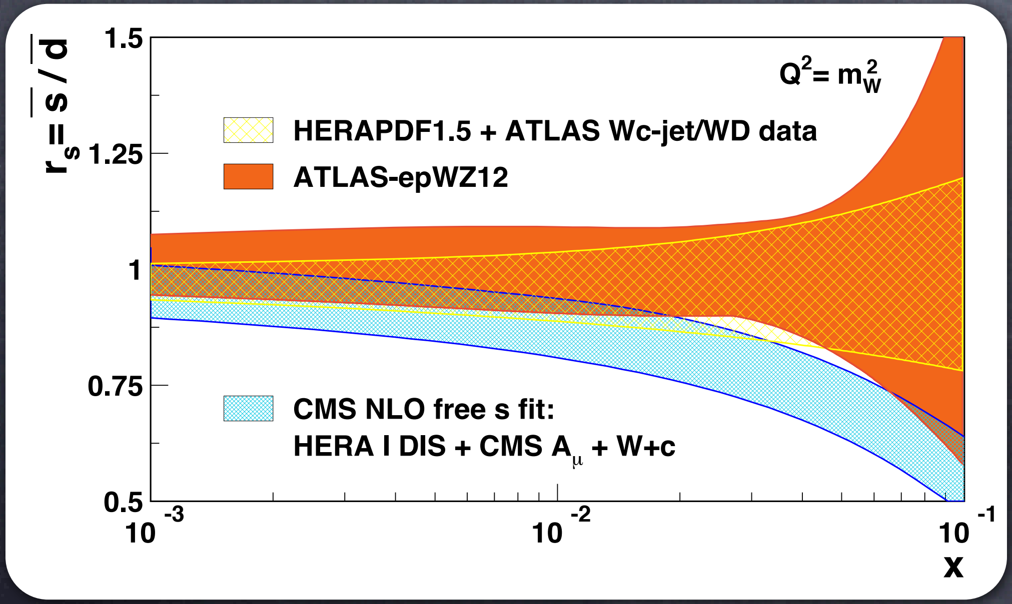
[Nucl.Phys. B876 (2013) 339, κ_s =0.59 ± 0.019]

CMS result on s-quark distribution





CMS results agree with the global PDFs *(where assumptions on s(x) are based on ν-data)*



ATLAS *arXiv:1402.6263* statistical analysis of *W+c-hadron* production **(hadron level)** consistent with the CMS full QCD analysis

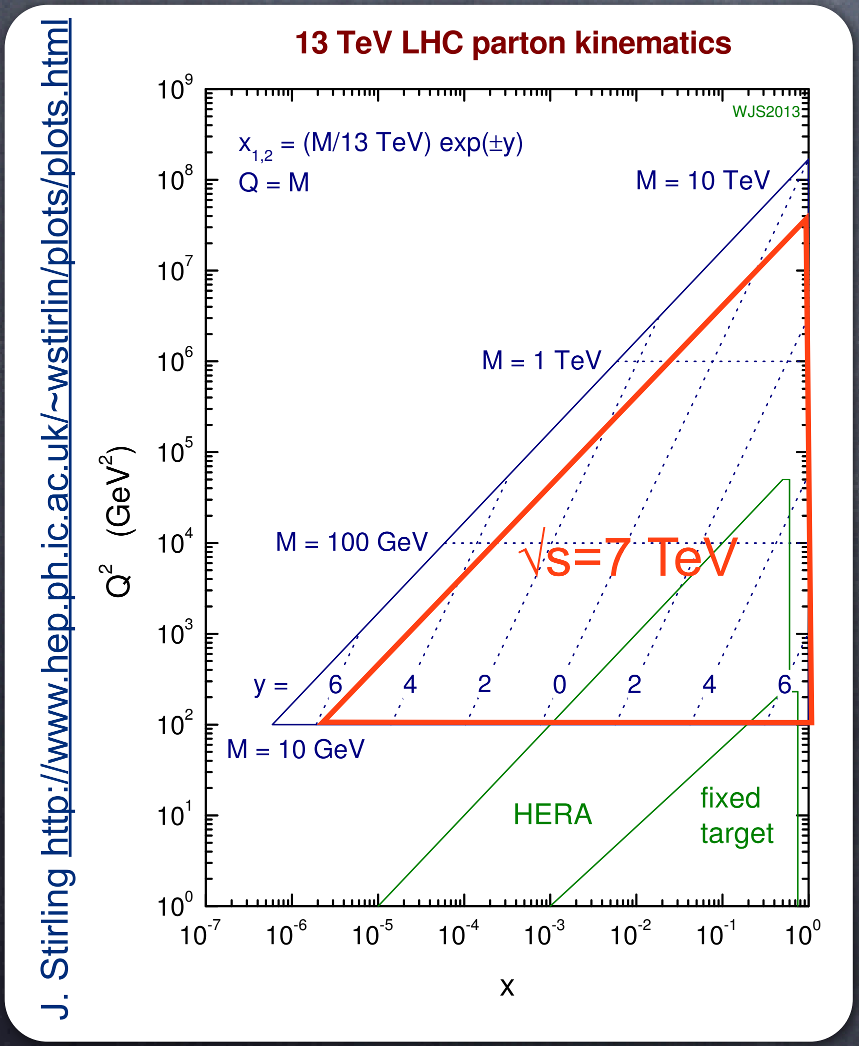
…for details on ATLAS see talk F. Ellinghaus

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12021

Summary

- Inclusion of the LHC measurements into the QCD analyses started,

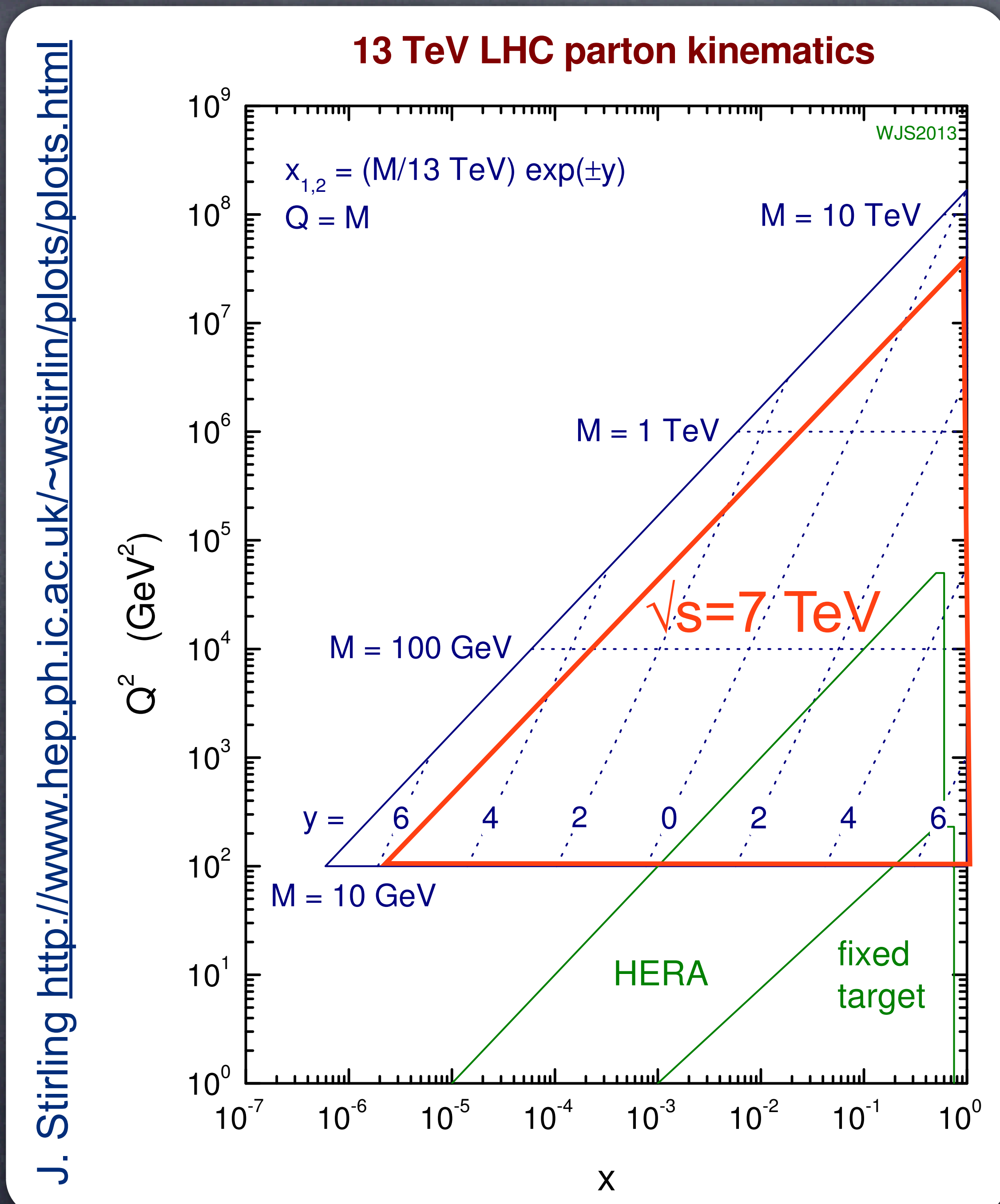
  ...followed up by relevant developments in the theory and QCD analysis tools.
- Precision of the gluon distributions improves by including CMS jet measurements
- Precision of the valence distributions improves by using CMS W asymmetry
- Strange quark is probed directly by using CMS associated W+c production



Kinematic plane of the LHC at 13(14) TeV looks very similar to that at 7(8) TeV same x-coverage at high M

QCD analyses at the LHC have to continue to be prepared for high-energy running

Outlook



Kinematic plane of the LHC at 13(14) TeV
very similar to that at 7(8) TeV
very similar x coverage at high M

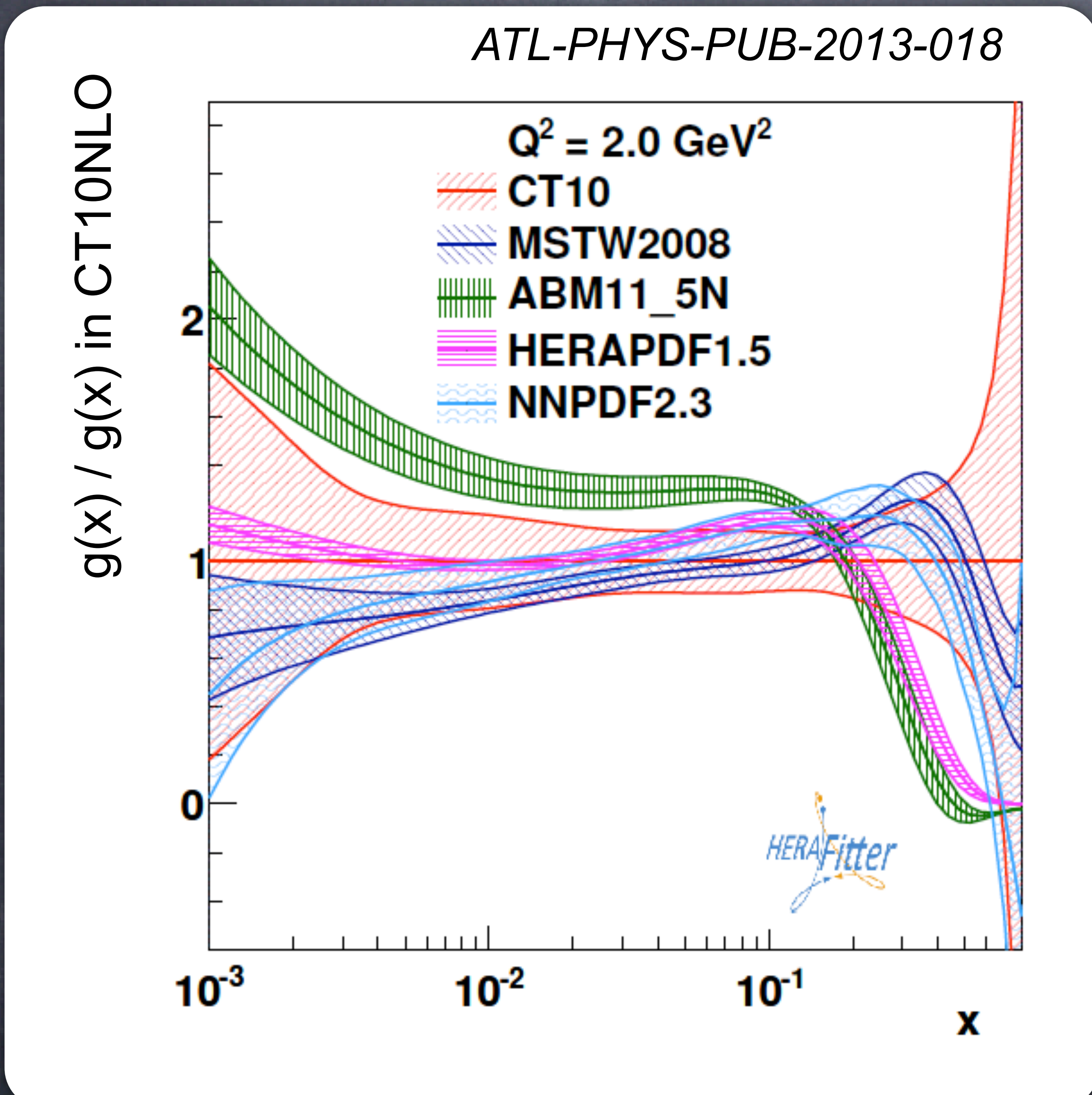
Expect similar limitations by QCD precision

Improvements in experimental precision demands better understanding of QCD

Back up slides

How well do we know PDFs

g(x) by different PDF groups:

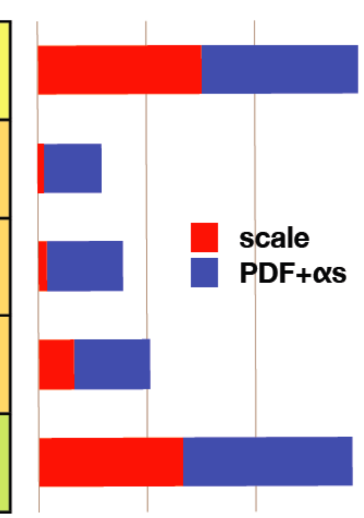


• uncertainties have to be improved
• differences have to be understood

Origins of the large spread:

- differences in phenomenological analyses (e.g. treatment of heavy quarks)
  → **requires improvements in theory**
- consistency of experimental data sets
  → **requires experimental insight**

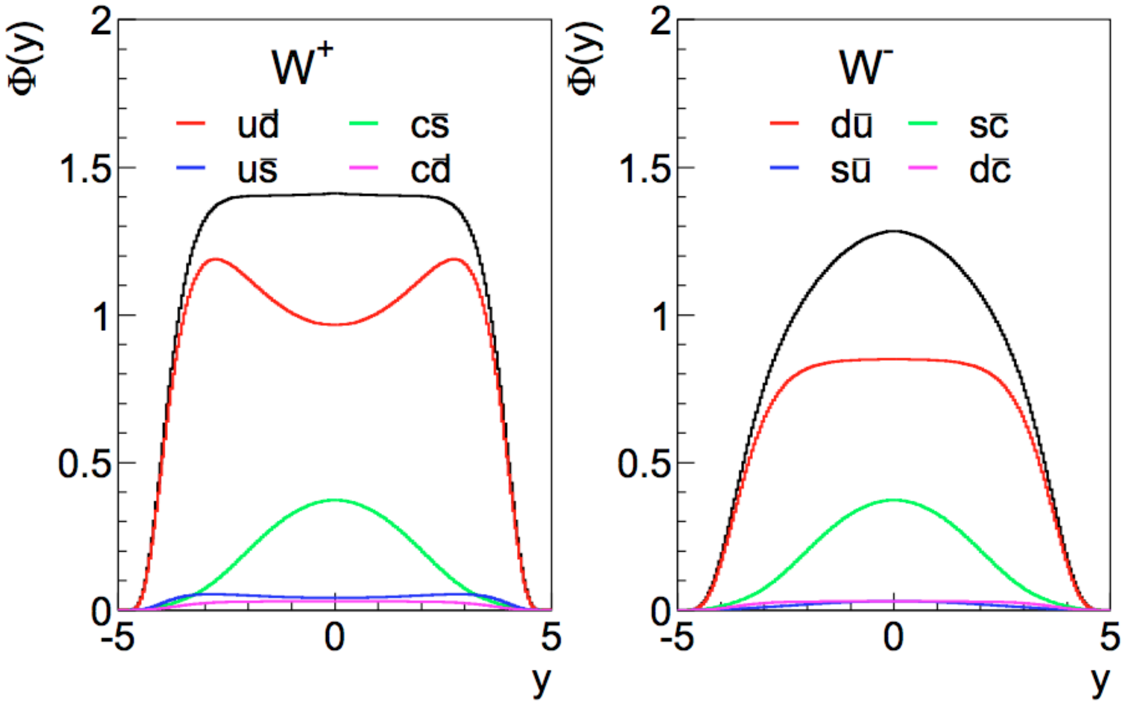
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



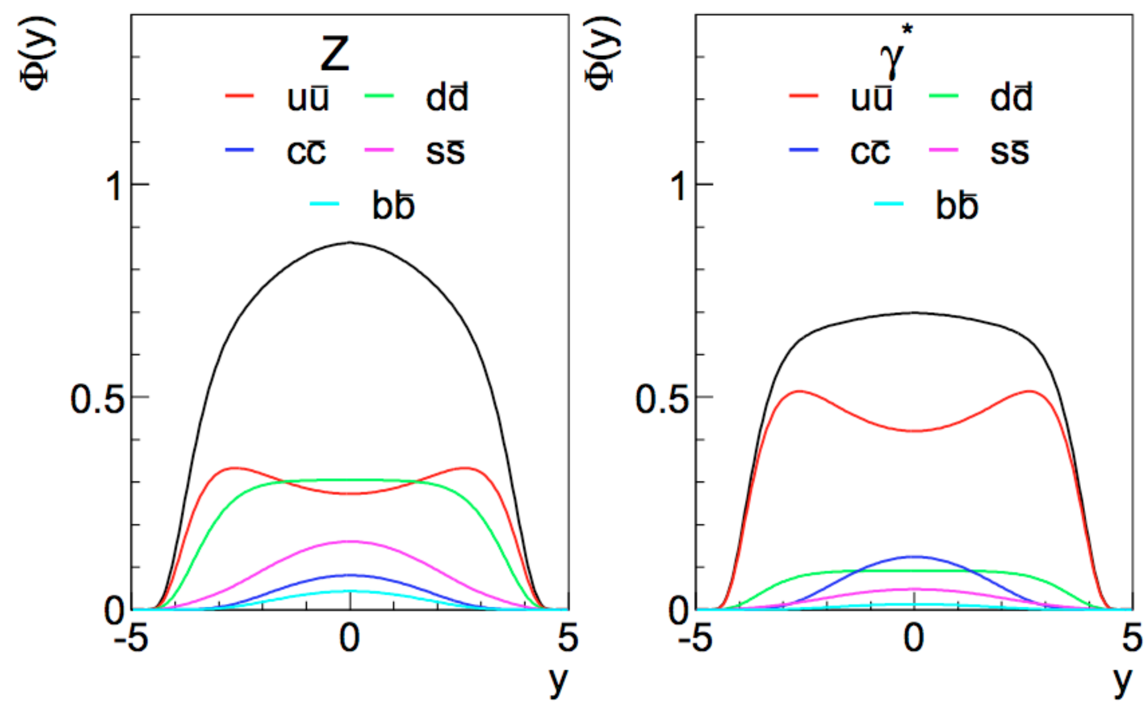
Sensitivity of electroweak boson production to PDFs

Measurements of Drell-Yan production probe bi-linear combination of PDFs

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



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



NB: LO with suppressed strangeness

...courtesy A.Glazov/V.Radescu

differential cross sections for W and Z production provide important information on light quarks and the sea decomposition

(particularly interesting is strange-quark distribution, which is poorly known)

General Strategy for a QCD analysis

QCD Factorization: e.g. DIS Structure functions for the exchange of Boson V (γ, Z, $W^{\pm}$) are expressed as convolution products

$$F_2^V(x,Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R)$$

determined by using measured cross sections

coefficient functions calculable in pQCD

universal PDF

the *x*-dependence of PDFs is not predicted by perturbative QCD. A general approach:

- parameterize PDFs at a starting scale Q^2_0 : $f(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$

  A: normalization, **B**: small-x behavior, **C:** $x \to 1$ shape
- evolve these PDFs to $Q^2 > Q^2_0$
- construct structure functions from PDFs and coefficient functions: predictions for every data point in (x, Q^2) – plane
- χ^2- fit to the experimental data

PDF parametrization at the starting scale

- 13 parameters, ***fixed strange distribution***

at Q^2_0 :

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

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

fixed s

Au_v , Ad_v, Ag are determined by QCD sum rules

- 15 parameters, "***free s fit***"

at Q^2_0 :

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

~~$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} \cdot (1-x)^{C_{\bar{D}}}.$~~

$$
\left\{
\begin{aligned}
x\,\bar{d}(x) &= A_{\bar{d}}\, x^{B_{\bar{d}}}\, (1-x)^{C_{\bar{d}}}\\
x\,\bar{s}(x) &= A_{\bar{s}}\, x^{B_{\bar{s}}}\, (1-x)^{C_{\bar{s}}}
\end{aligned}
\right.
$$

$A_{\bar{u}} = A_{\bar{d}}\,;\, B_{\bar{u}} = B_{\bar{d}}$ ensures same normalization for u and d- antiquarks at $x \to 0$

$B_{\bar{s}} = B_{\bar{d}}$ for the central fit, **A_s and C_s are free parameter of the fit**, assumed $s = \bar{s}$

$B_{\bar{s}} \neq B_{\bar{d}}$ fit performed, difference to results of the central fit included in parametrization uncertainty

Correlations between PDF and cross sections

The NNPDF Collaboration provides PDF sets in the form of an ensemble of replicas, which sample variations in the PDF parameter space allowed within uncertainties.

Evaluating means and variance using the replicas, obtain predictions and uncertainties for PDF-dependent observables.

correlation coefficient

number of replicas in NNPDF ensemble

inclusive jet cross section

parton distribution for flavour i

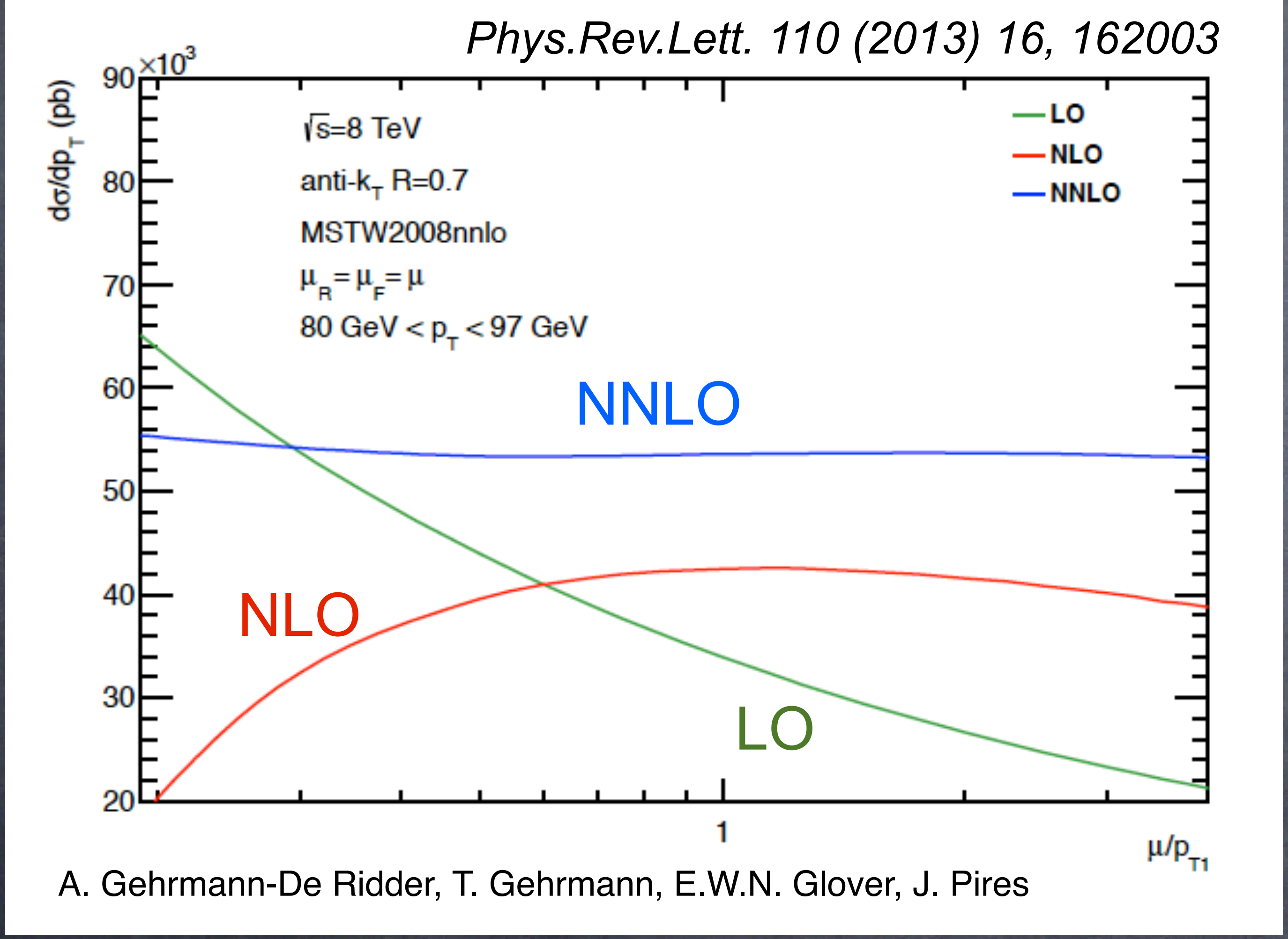
$$\varrho_i \left[\sigma_{\text{jet}}(x,Q^2), xf_i(x,Q^2)\right] = \frac{N_{\text{rep}}}{(N_{\text{rep}}-1)} \frac{\langle \sigma_{\text{jet}}(x,Q^2)\, xf_i(x,Q^2)\rangle - \langle \sigma_{\text{jet}}\rangle \langle xf_i(x,Q^2)\rangle}{\Delta_{\sigma_{\text{jet}}(x,Q^2)}\, \Delta_{xf_i(x,Q^2)}}$$

uncertainties of measured cross sections

uncertainties of PDFs

Theory uncertainties: progress at NNLO

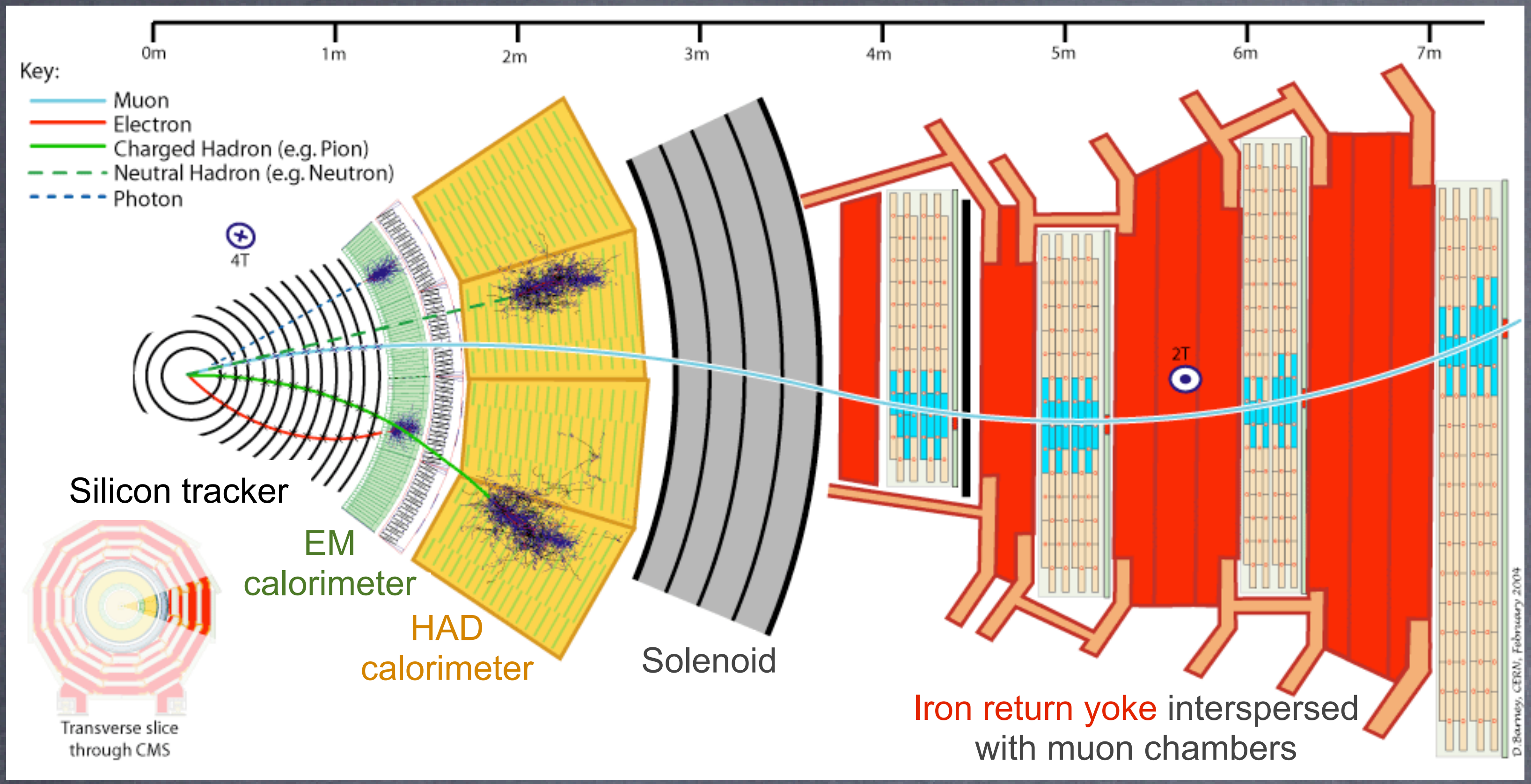
Scale dependence of the inclusive jet cross section for
pp @ √s = 8 TeV, anti-kT, R = 0.7
|y| < 4.4 and 80 GeV < pT < 97 GeV



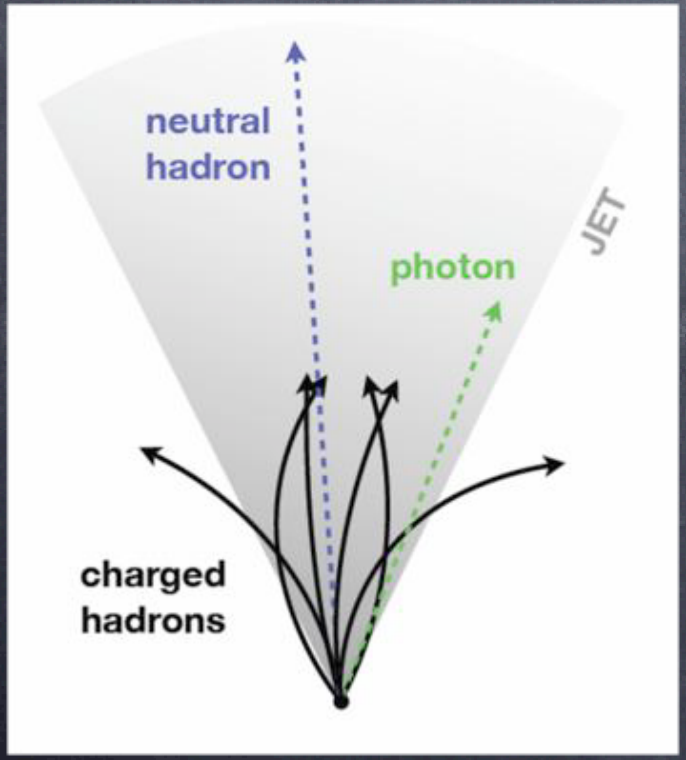
significant progress in theory calculation of pp collisions

Jet reconstruction (e.g. at CMS)

CMS detector



Acceptance:
Tracking: $|\eta|<2.5$
Central calorimetry $|\eta|<3$
Forward calorimetry $3<|\eta|<5$



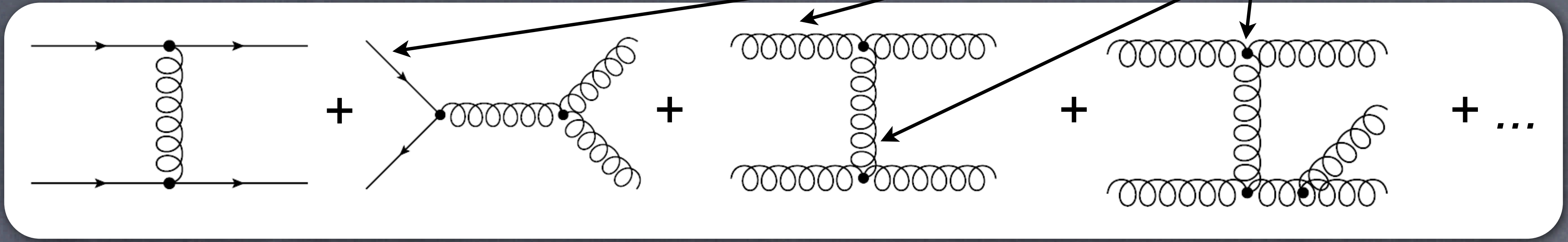
CMS global event reconstruction: reconstructs and identifies all stable particles in the event, through the optimal combination of all sub-detectors.

Particle Flow jets are the output of anti-k_T algorithm, running on the reconstructed particles. Infrared and collinear safe, different R used.

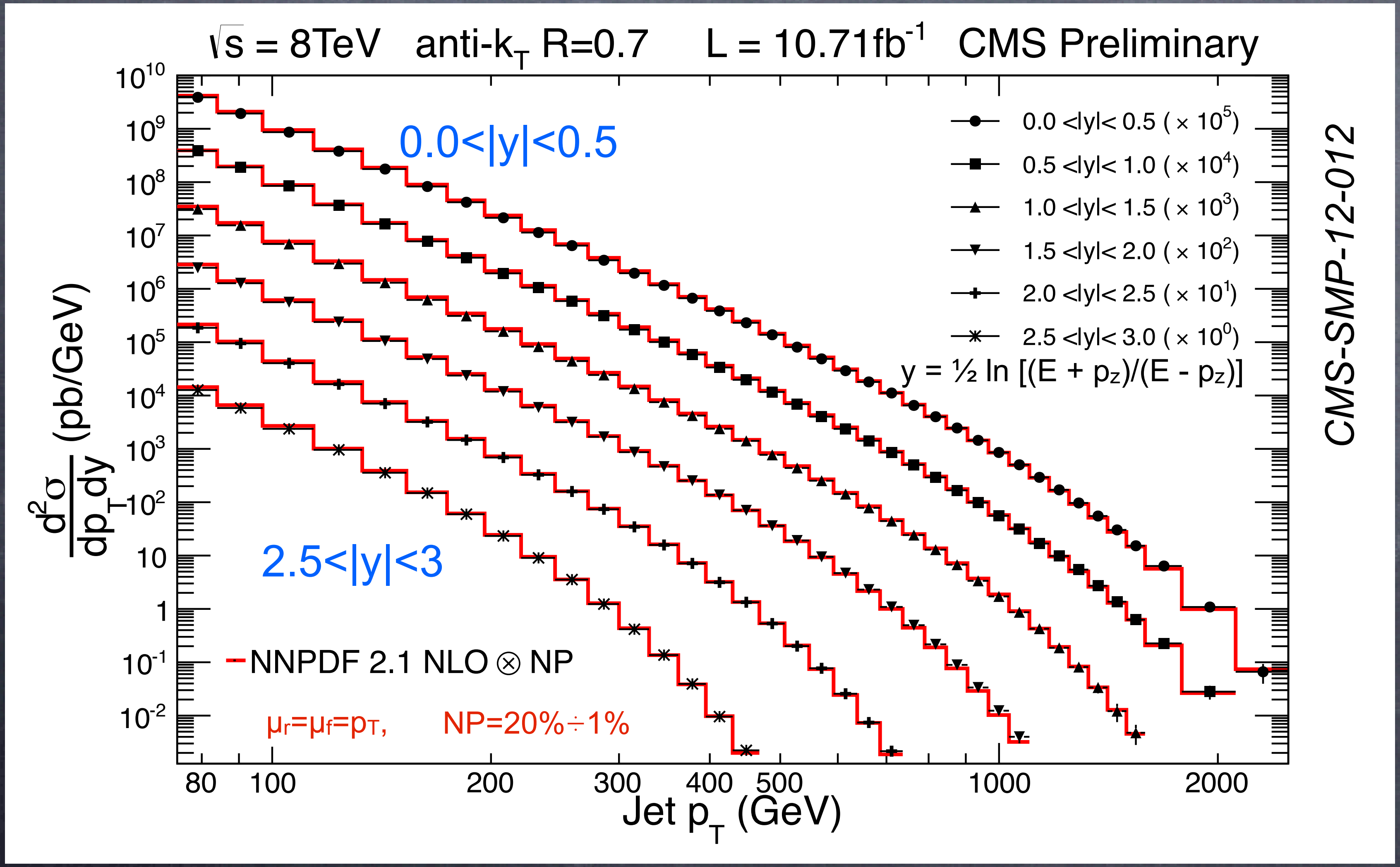
Jet p_T resolution ≈ 9% at 100 GeV

LHC data testing QCD factorization

Jet production in pp collisions directly sensitive to PDFs and α_S, ideal to test factorization



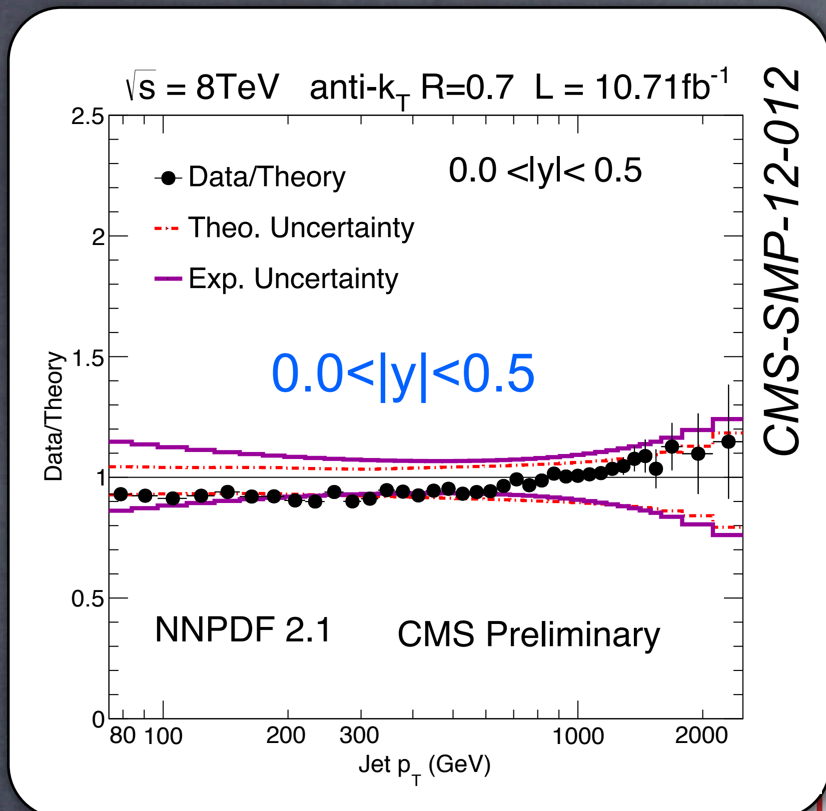
Confront theory calculations with high precision measurements

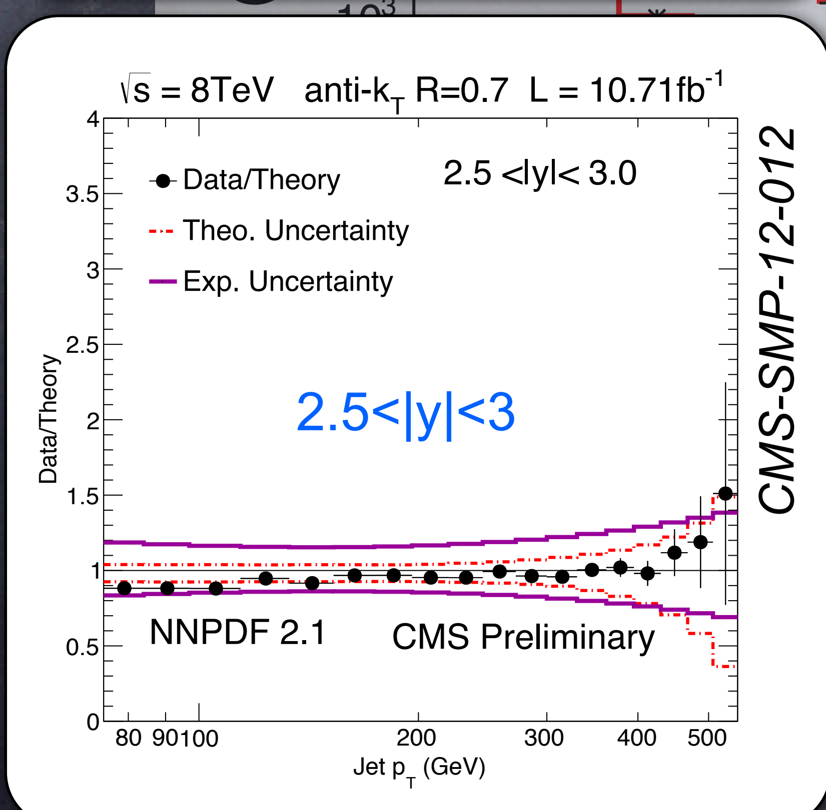


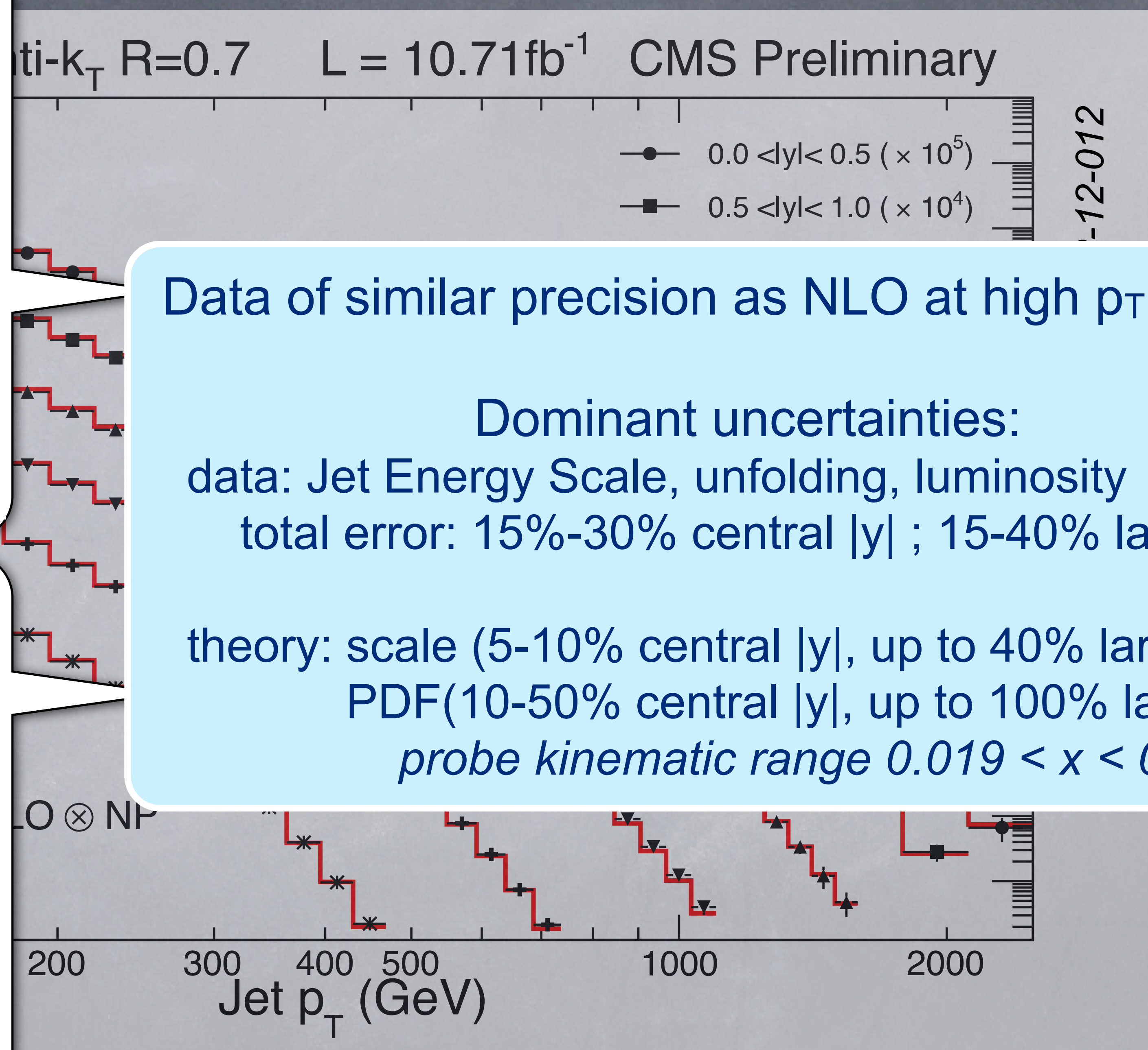
Transverse momenta range from 74 GeV to 2.5 TeV

Good description by **NLO QCD**

Inclusive jet production: precision of data vs theory







Data of similar precision as NLO at high p_T (high x)

Dominant uncertainties:

data: Jet Energy Scale, unfolding, luminosity

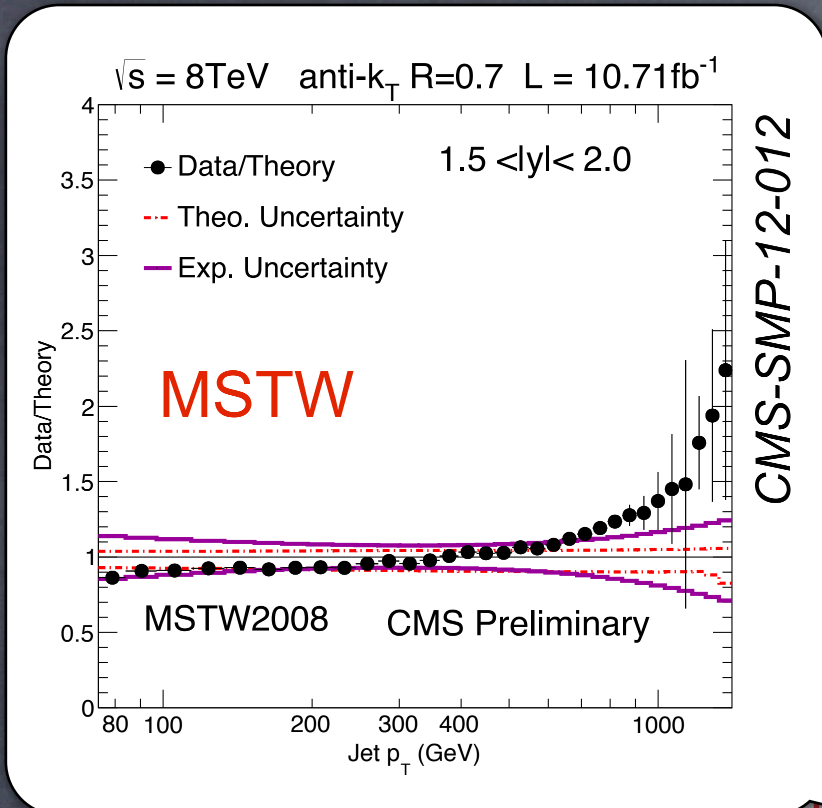
total error: 15%-30% central |y| ; 15-40% larger |y|

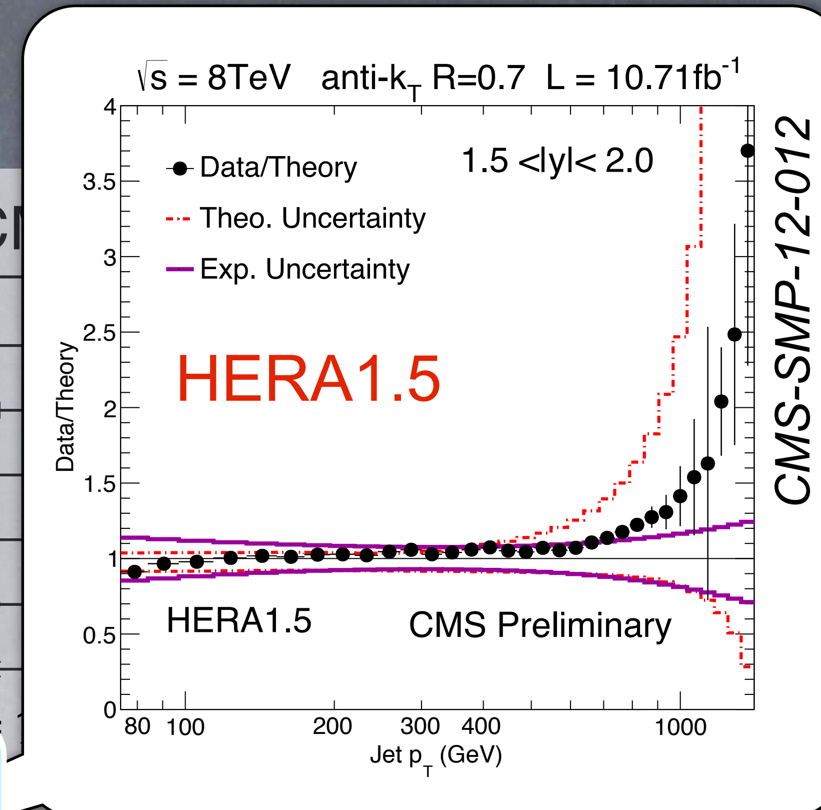
theory: scale (5-10% central |y|, up to 40% larger |y|

PDF(10-50% central |y|, up to 100% larger |y|)

probe kinematic range 0.019 < x < 0.625

Inclusive jet production: sensitivity to PDFs





Large theory uncertainty mostly due to **differences** in PDF sets