Parton distributions from HERA to the LHC

Pavel Nadolsky
Southern Methodist University
April 11, 2016

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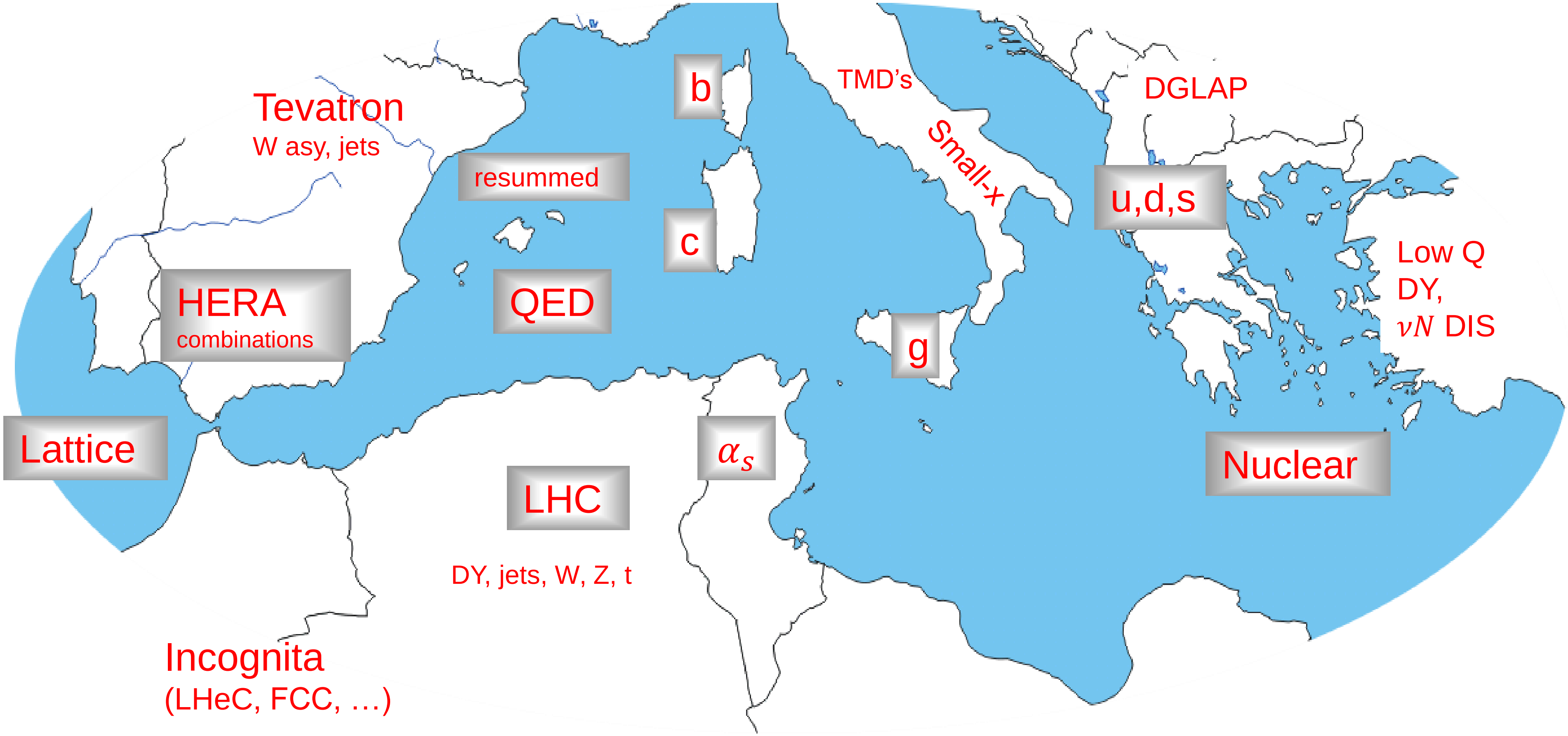
HERA
Goddess of women, marriage, and parton distributions (since 1992)

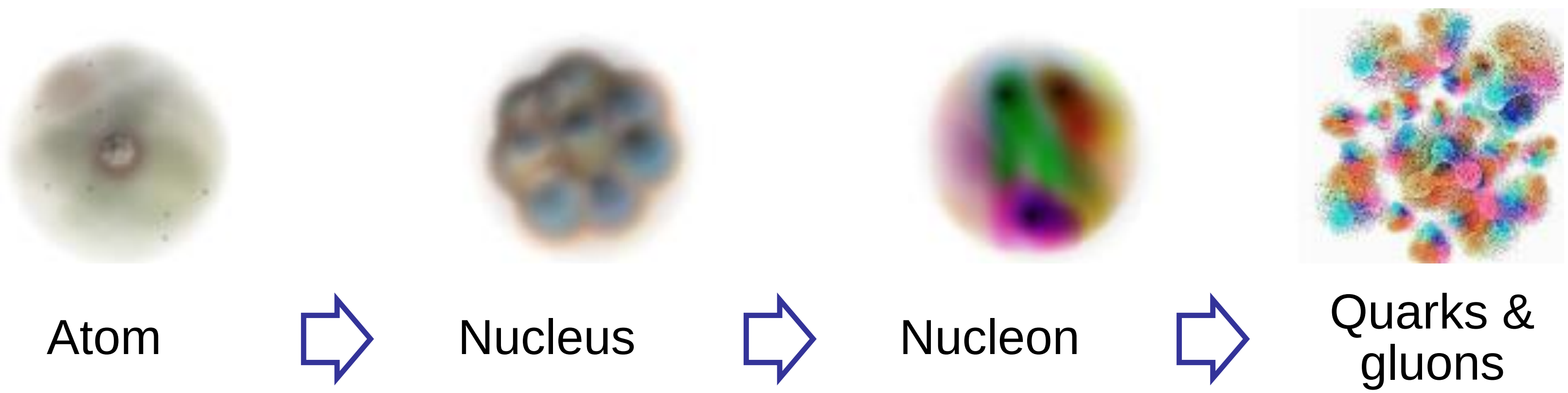
- The ep collider HERA is my scientific age-mate. One of my first papers around 20 years ago was about the rise of HERA total cross sections that has been just observed
- I was drawn into the enchanting world of QCD and parton distributions and could not leave it since then
- HERA charted a new territory in understanding of hadron structure and deepened appreciation of our field
- Let’s celebrate HERA legacy and profound insights about the PDFs that it still bestows

Oekumene of the PDF universe

as presented by topics at DIS'2016



The inner world of a hadron

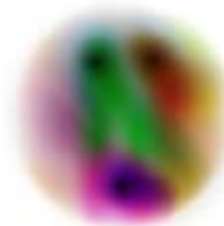


The structure of the hadron drastically changes as the resolution of the “microscope” (scattering process) increases

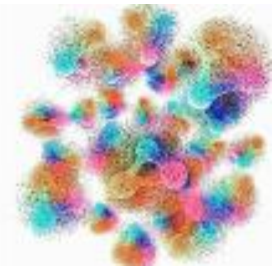
The inner world of a hadron

Atom

Nucleus

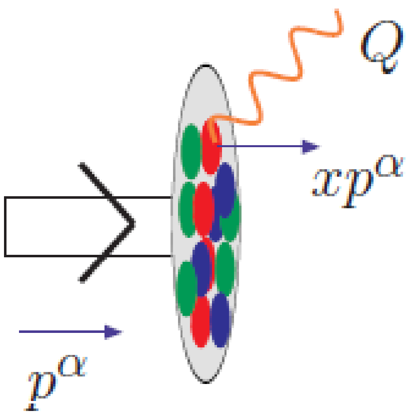


Nucleon



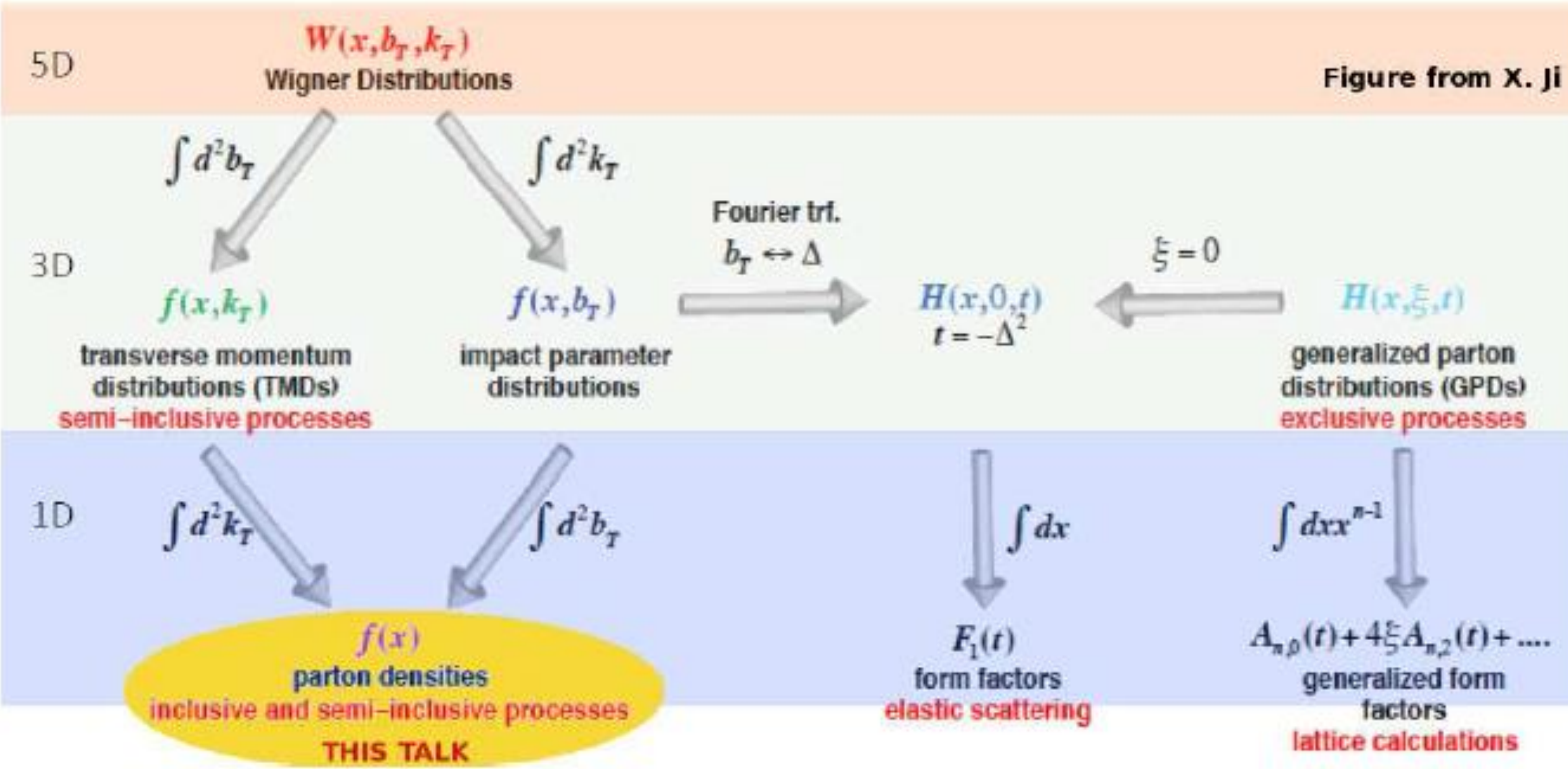
Quarks & gluons

Unpolarized collinear parton distributions $f_a(x,Q)$ are associated with probabilities for finding a parton with the "+" momentum xp^+ in a hadron with the "+" momentum p^+, at a resolution scale Q, for $p^+ \to \infty$

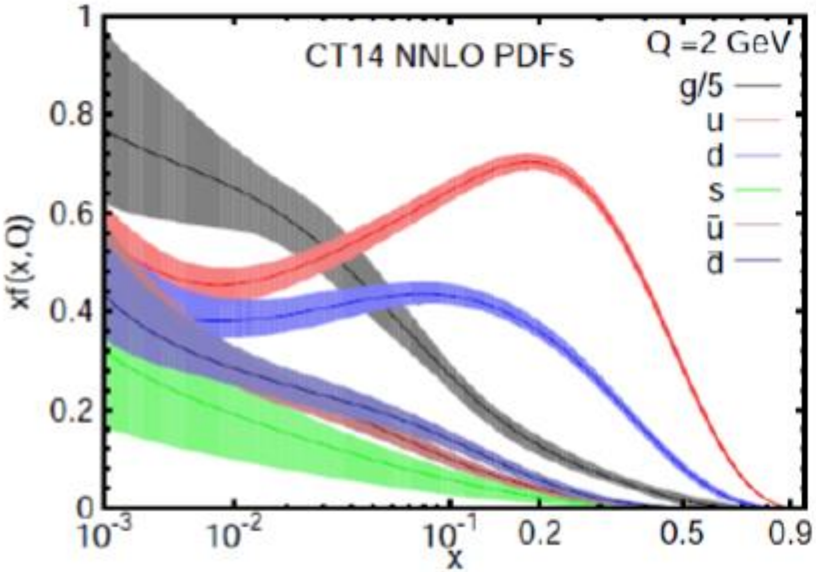


Parton distribution functions $f_{a/p}(x, Q)$...

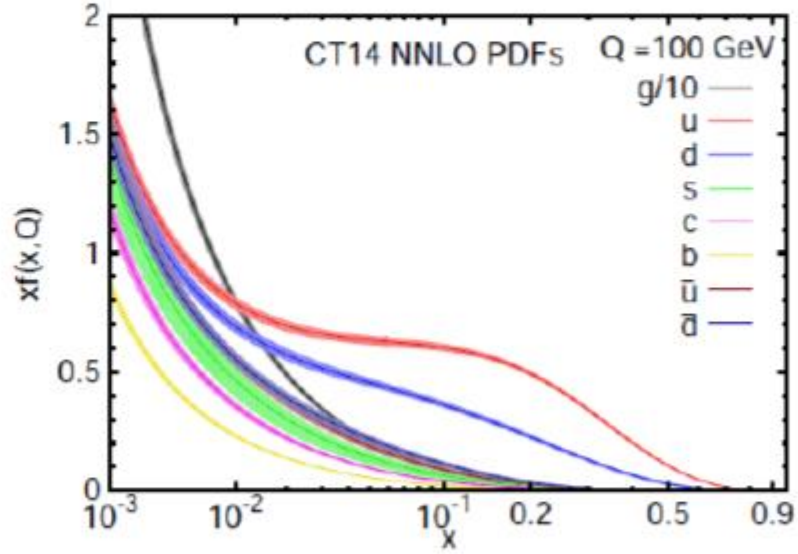
... the best-known nonperturbative functions introduced in QCD



... can be obtained from most general Wigner distribution functions $W_a(x^\alpha, p^\beta, s^\gamma)$



Q= 2 GeV



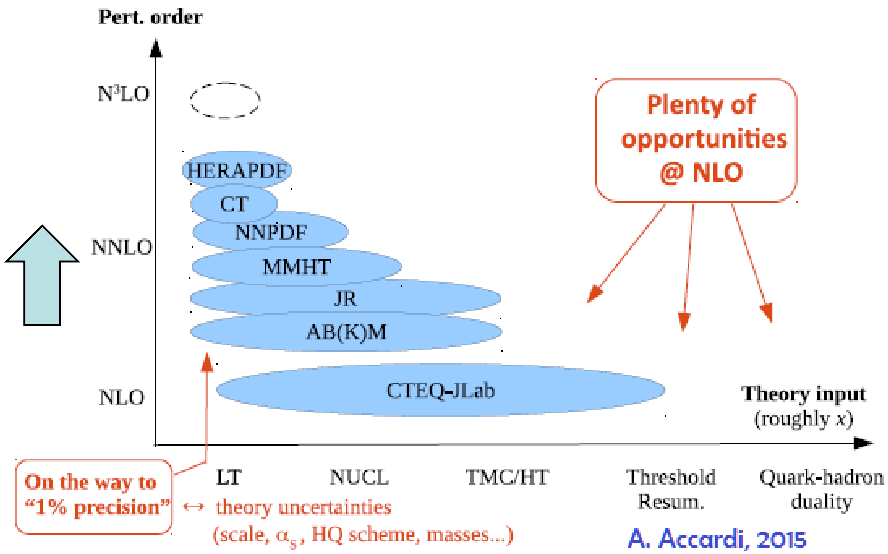
Q= 100 GeV

Phenomenological parametrizations of PDFs are provided with estimated uncertainties of multiple origins (uncertainties of measurement, theoretical model, parametrization form, statistical analysis, …)

The shape of PDFs is optimized w.r.t. hundreds of **nuisance parameters**

Two trends in the modern PDF analysis

Proton PDFs

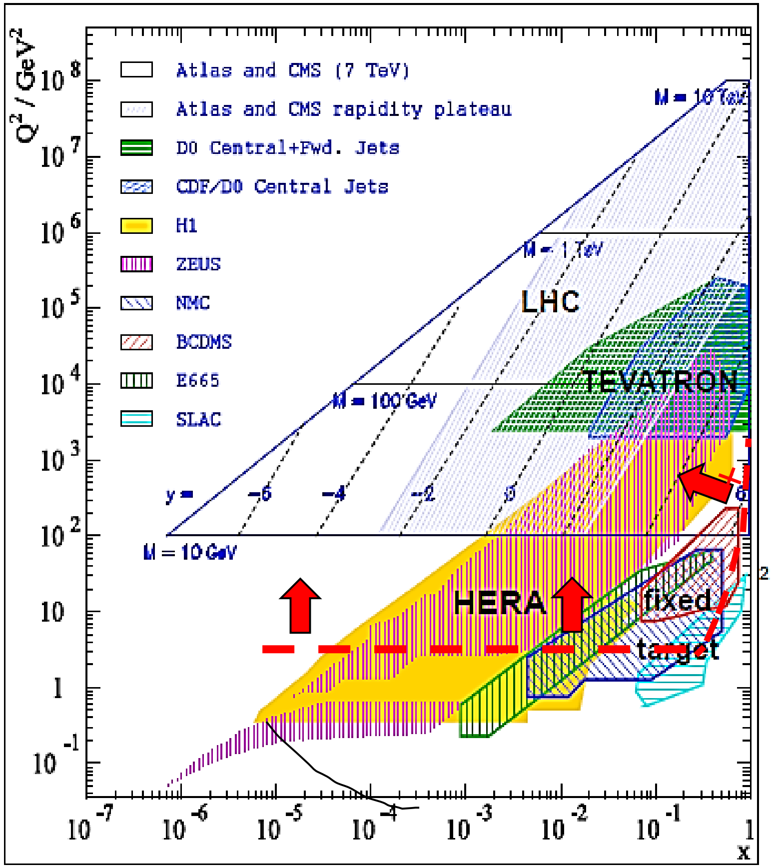


For general-purpose **nucleon** PDFs, the goal is to determine very precise parametrizations for PQCD calculations up to (N)(N)NLO in α_s. The focus is on the high-Q data that is not sensitive to higher twists, nuclear and target mass corrections

⇒ **New results on ABM'16, CT14H2, MMHT, NNPDF3.1 analyses**

Map of experiments as a function of x and Q

For nucleon PDFs, experimental measurements are selected so as to reduce dependence on theoretical input beyond the leading power in perturbative QCD



CT14:

only DIS data with $Q^2 > 4\ GeV^2$, $W^2 > 12.25\ \ GeV^2$ (above the red line) are accepted to ensure stable perturbative predictions

Still using data from DIS and DY on **nuclear targets. CT14H2** does not use NMC DIS **on deuteron,** will be replaced by comparable future LHC/Tevatron measurements on **the proton**

LHC and Tevatron vector boson production experiments in the ABM'15 analysis

The ABM'12 parametrization form for

$$I(x) = x\left(\bar{d}(x) - \bar{u}(x)\right)$$

is now relaxed and constrained by the VBP data

Significant changes in $I(x)$ at $x < 10^{-2}$ and d/u at $x \to 1$

Alekhin et al., arXiv:1508.07923

Experiment	ATLAS	CMS	D0		LHCb	
$\sqrt{s}$ (TeV)	7	7	1.96		7	8
Final states	$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to e^+\nu$ $W^- \to e^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$
Reference	[22]	[1]	[3]	[4]	[18]	[19]
Cut on the lepton P_T	$P_T^l > 20$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 20$ GeV
Luminosity (1/fb)	0.035	4.7	7.3	9.7	1.	2.
NDP	30	11	10	13	31	17

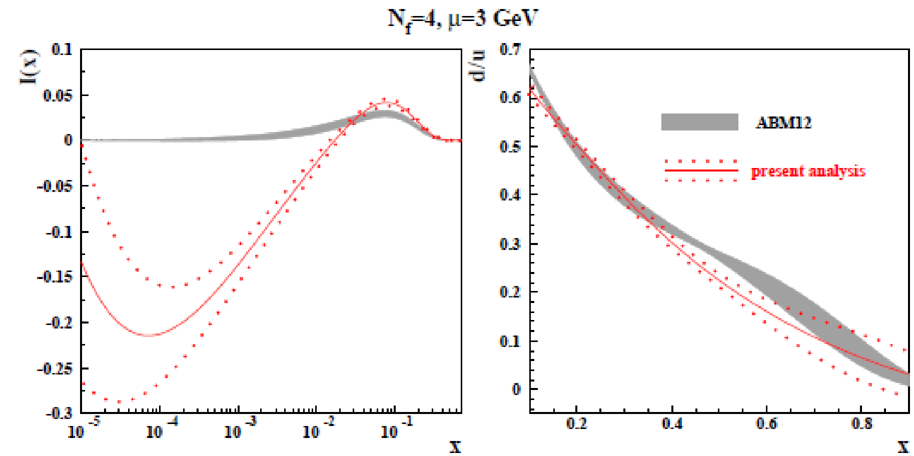


FIG. 7: Left: The iso-spin asymmetry of the sea $I(x)$ in the 4-flavor scheme at the factorization scale $\mu = 3$ GeV obtained in the present variant of the ABM12 analysis (solid lines: central value, dots: 1σ error band) in comparison to the 1σ band of $I(x)$ obtained in the ABM12 fit [8] (shaded area). Right: Same for the ratio d/u at large x.

News from NNPDF (I)

- Progress towards global fit update: **NNPDF3.1**
- Included the **HERA legacy data** and many **new Run I measurements** from ATLAS, CMS, LHCb
- Impact of **top quark pair rapidity distributions** at NNLO
- Systematic study of variations with respect to the **heavy quark masses** (pole and running)

New experiments included in NNPDF3.1

LHCb W,Z rapidity dists 7,8 TeV	2011+2012	small-x and large-x quarks
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive jets 7 TeV	2011	large-x gluon
ATLAS low-mass Drell-Yan 7 TeV	2010+2011	small-x quarks
ATLAS Z pT 7,8 TeV	2011+2012	medium-x gluon and quarks
ATLAS+CMS tt differential 8 TeV	2012	large-x gluon
CMS Z pT,y 2D xsecs 8 TeV	2012	medium-x gluon and quarks
CMS Drell-Yan low+high mass 8 TeV	2012	small-x and large-x quarks
CMS W asymmetry 8 TeV	2012	quark flavor separation
CMS 8 TeV and 2.76 TeV jets	2012	medium and large-x gluon

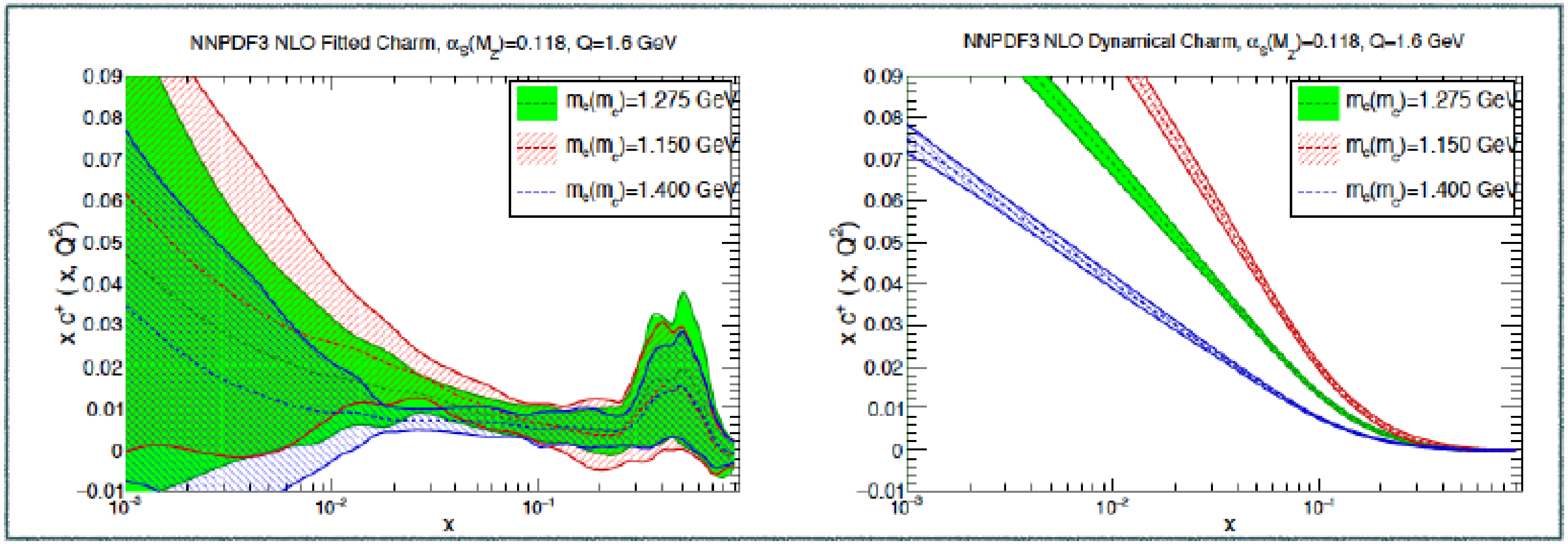
More in the talk from Juan Rojo (Tue)

- Parton Distributions with **threshold resummation** and impact on **high-mass SUSY cross-sections**

More in the talk from Marco Bonvini (Wed)

News from NNPDF (II)

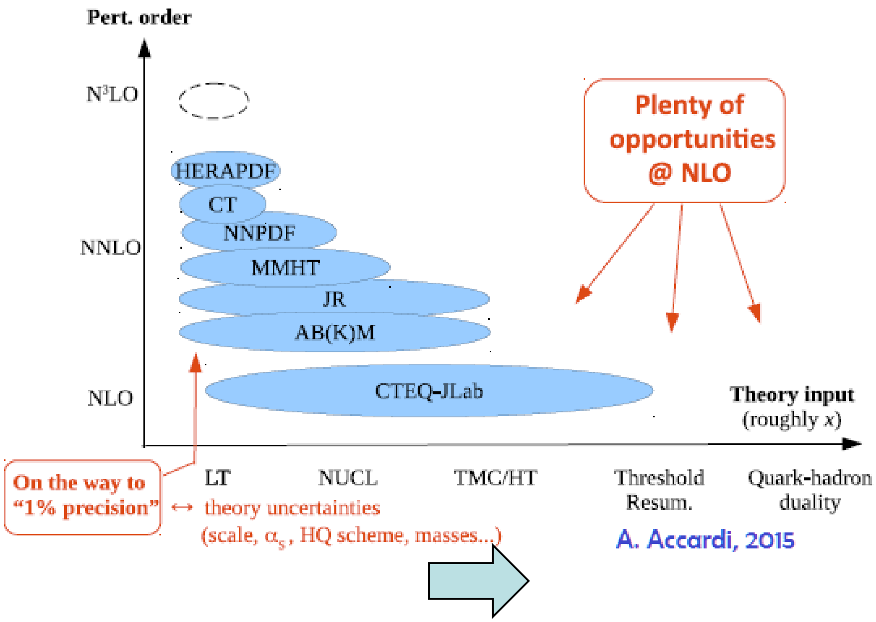
- First determination of the **fitted charm PDF** in the NNPDF framework
- **Non-perturbative charm** can account for **up to 0.8% of the proton momentum** (68% CL)
- The EMC **charm structure function data** can be satisfactorily described
- Fitting the charm PDF stabilises the **m_c dependence of high-scale cross-sections**



More in the talks from Juan Rojo (Tue) and Luca Rottoli (Wed)

Two trends in the modern PDF analysis

Proton PDFs



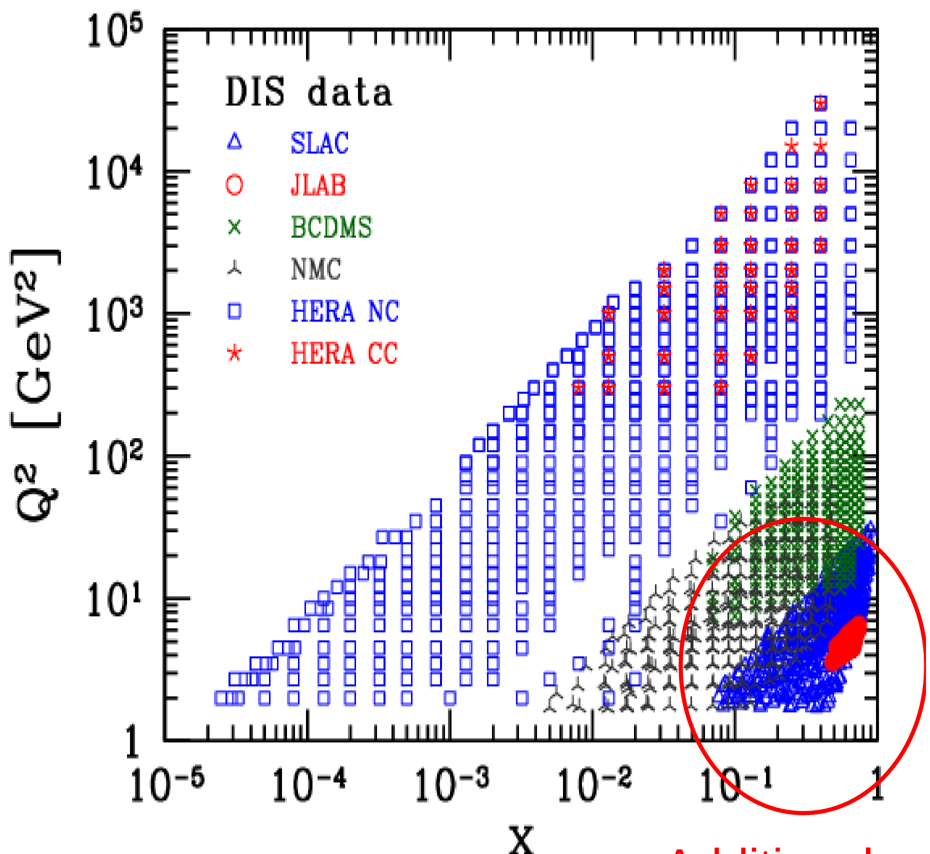
Alternatively, CJ15 nucleon PDFs focus on the interplay of leading-twist, nuclear, and target-mass corrections in high-x/low Q DIS at NLO.

Updates on CJ12: + **free neutron** SIDIS, Tevatron W asymmetry data, new $\bar{u}$ and $\bar{d}$ parametrizations, S-ACOT-χ scheme

⇒ Significant reduction in the PDF uncertainty of $d(x,Q)/u(x,Q)$ at $x \to 1$

Talk by A. Accardi

CJ15: DIS data for $Q^2 > 1.3\ GeV^2$, $W^2 > 3\ GeV^2$



Additional constraints on d/u

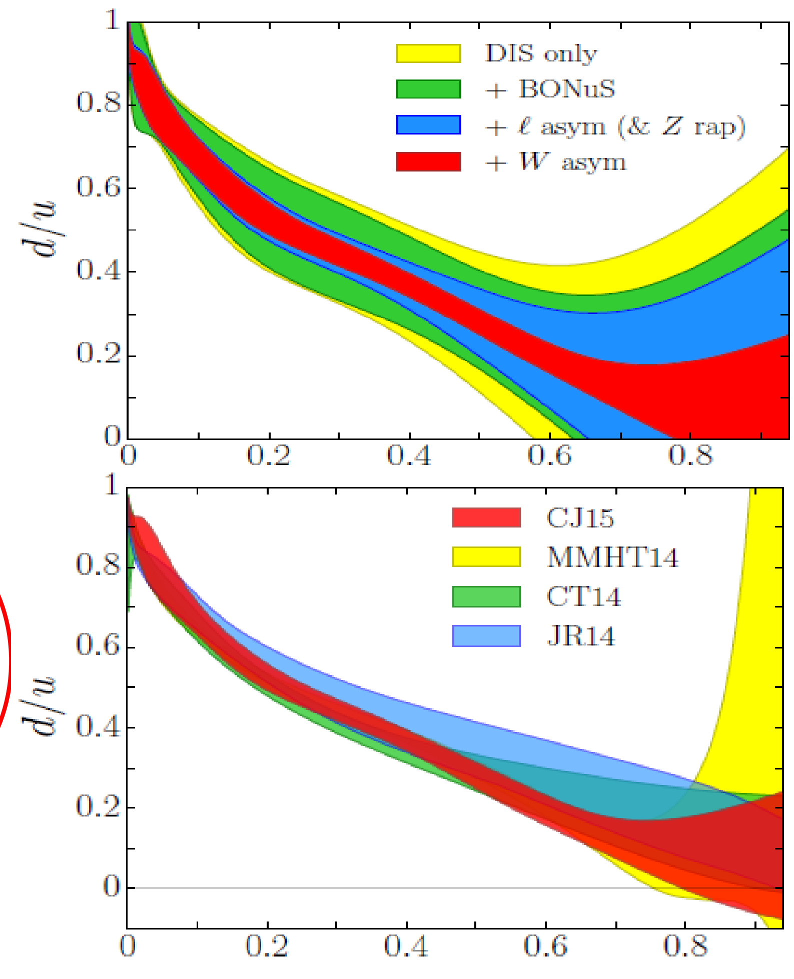
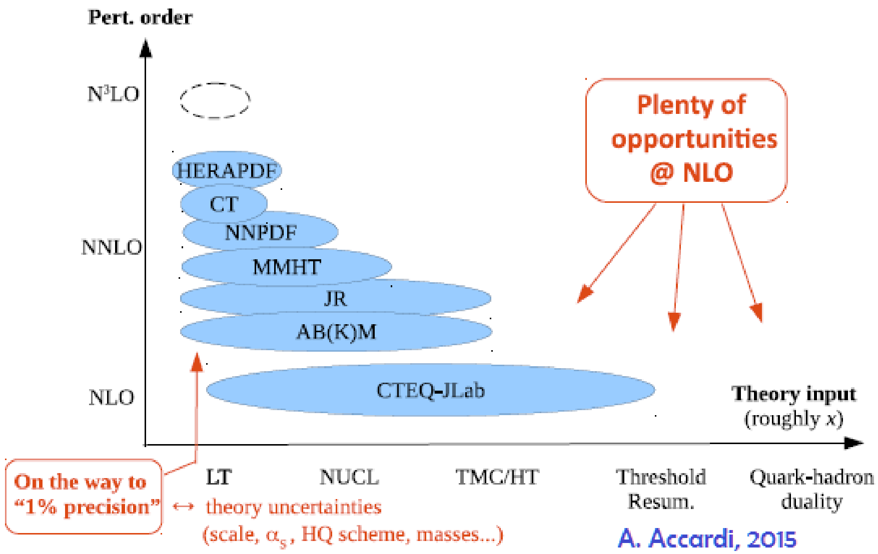


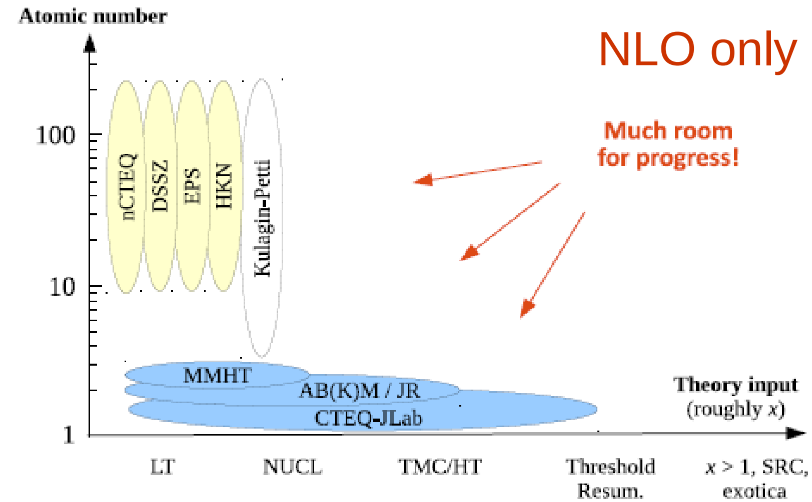
FIG. 16: Comparison of the d/u ratio at $Q^2 = 10$ GeV^2 for different PDF parametrizations: CJ15 (red band), MMHT14 [6] (yellow band), CT14 [7] (green band), and JR14 [10] (blue band).

Two trends in the modern PDF analysis

Proton PDFs



Nuclear PDFs



For nuclear PDFs, the goal is to understand nuclear modifications a function of the atomic number, despite relatively weak experimental constraints. Exotic dynamics, e.g., contributions from $x > 1$. "Unbiased" PDF analysis would be interesting.

New pA and AA data from RHIC and LHC ($W, Z, J/\psi$ production) make the difference

Talks by C. Keppel, M. Koller, A. Kusina, R. Petti

nCTEQ15 nuclear PDFs w/ Uncertainties

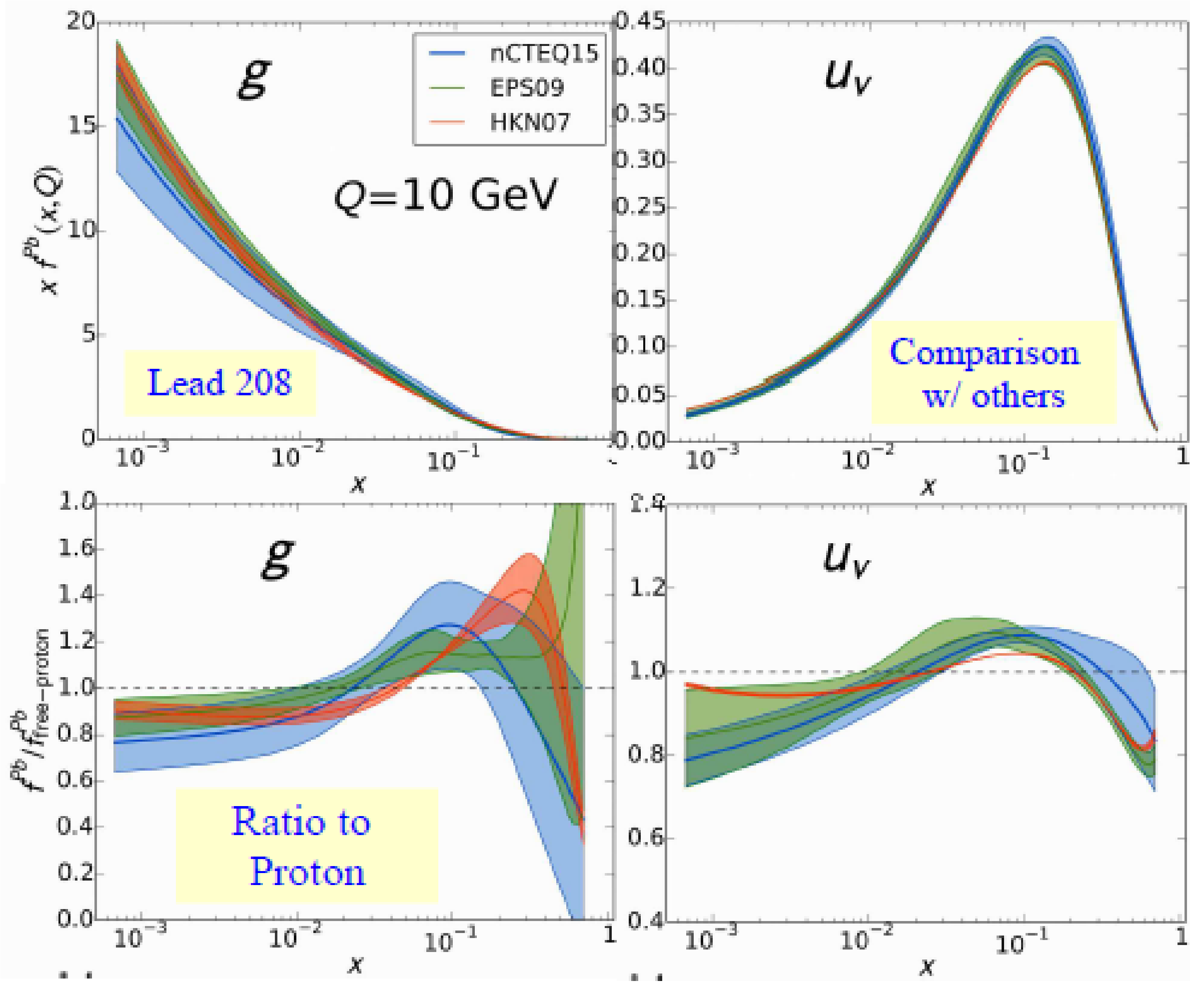
nCTEQ15 nPDFs available
grids at HepForge & LHAPDF

$$f^{Pb} = \frac{82}{208} f^{p/Pb} + \frac{208-82}{208} f^{n/Pb}$$

nPDFs:

Key For Heavy Target Data
e.g., νN DIS
Important for s(x)

LHC & RHIC heavy-ion runs
nPDF uncertainties larger
W/Z can help

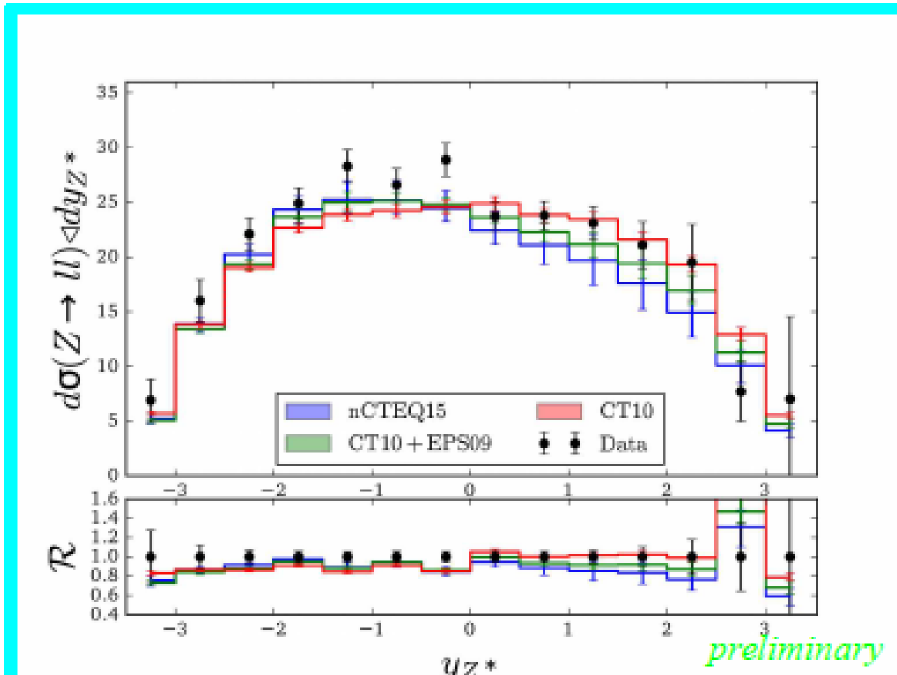


nCTEQ Group:
D.B. Clark, T. Jezo, C. Keppel, K. Kovarik, A. Kusina, F. Lyonnet, J. Morfin, F. Olness, J. Owens, I. Schienbein, J.Y. Yu

[arXiv:1509.00792]

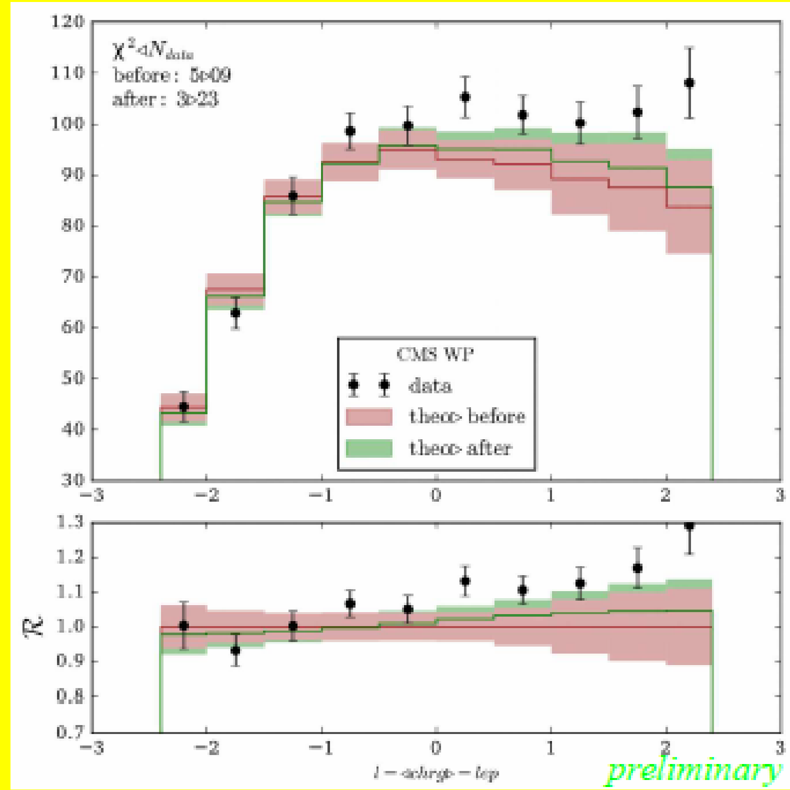
nCTEQ15 nuclear PDFs LHC Heavy Ion Run

LHC Z Production for pPb



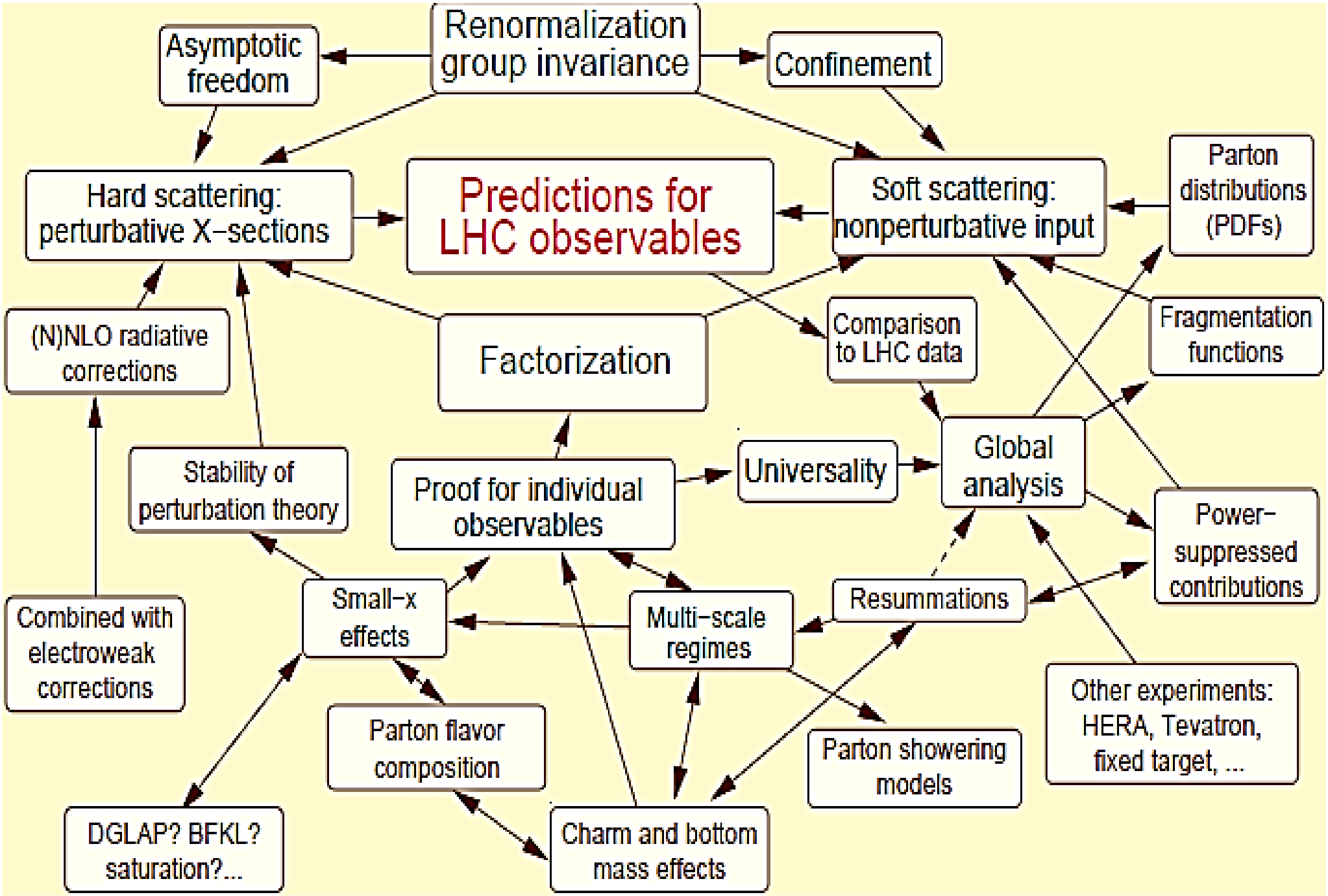
Comparison plot for ATLAS Z production in pPb collisions.

PDF Reweighting



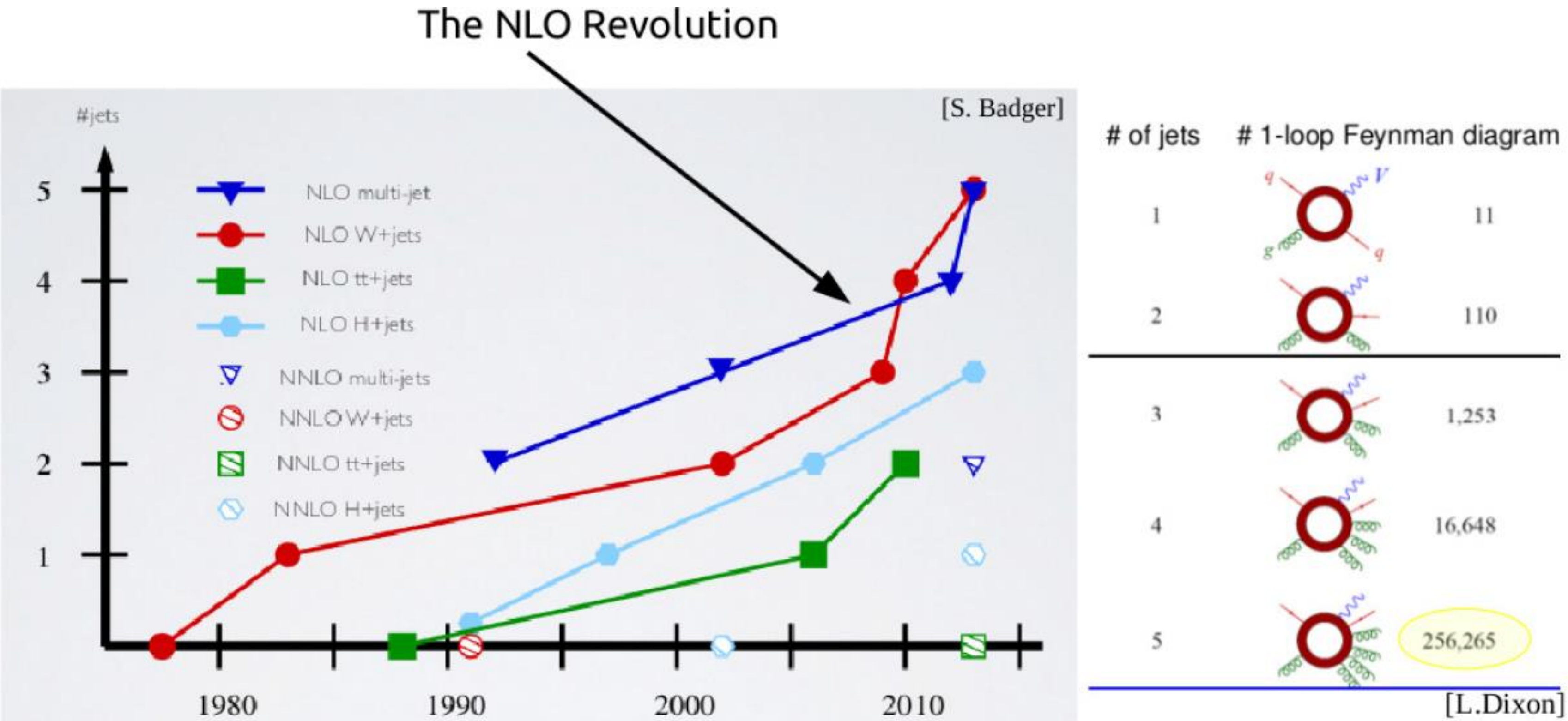
Comparison of data and theory before and after the reweighting procedure for the rapidity distributions of charged leptons in $W^{\pm}$ production measured by CMS

Maps of QCD concepts



The long-term goal is to understand the cumulative effect on the PDFs at the same accuracy as for (N)NNLO hard cross sections

Perturbative QCD loop revolution

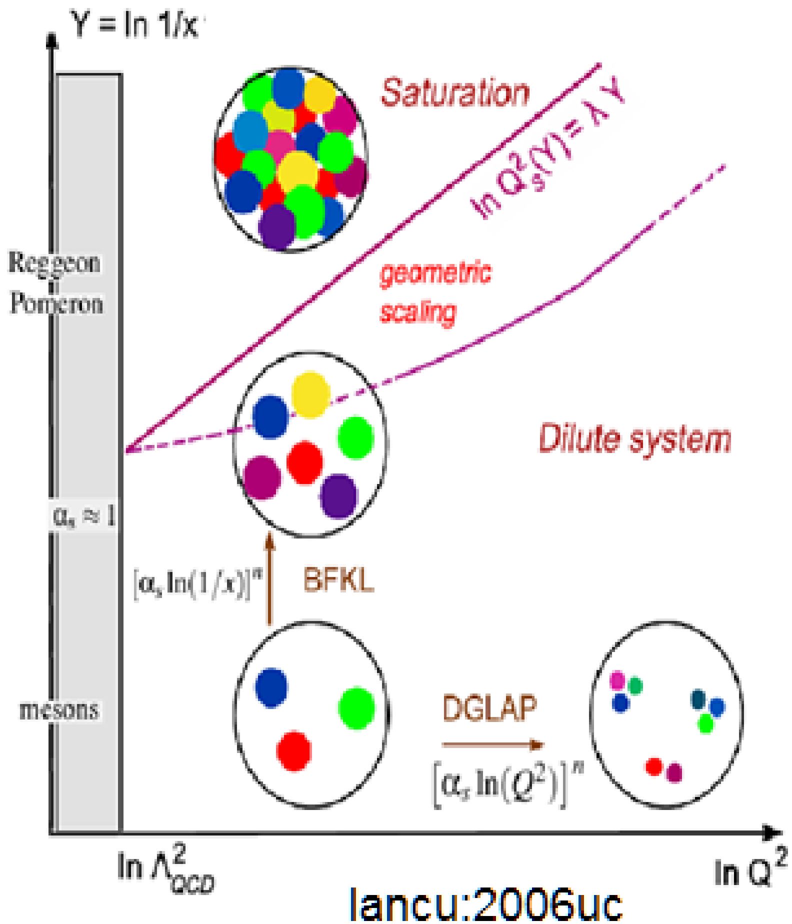


Since 2005, generalized unitarity and related methods dramatically advanced the computations of **perturbative** NLO/NNLO/N3LO hard cross sections.

To make use of it, PDF accuracy must keep up

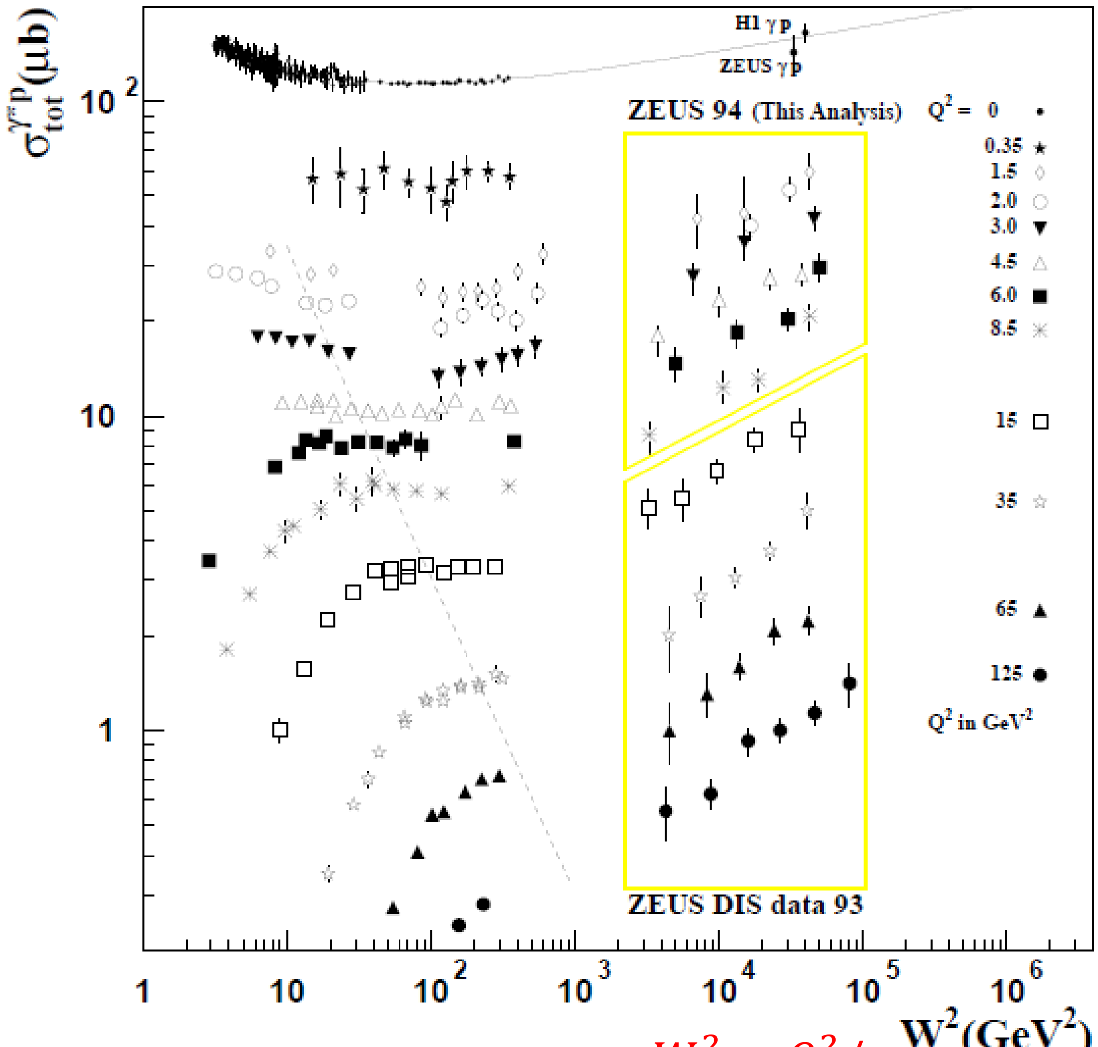
QCD dynamics vs. Q and x

Theory expectations



QCD dynamics vs. Q and x

$\gamma^* p$ total cross sections
ZEUS, hep-ex/9510009



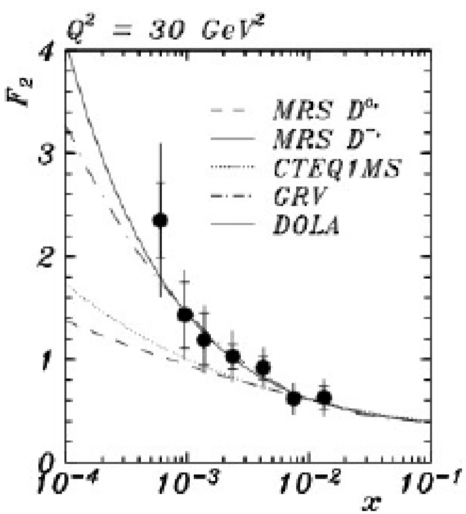
$W^2 \approx Q^2/x$

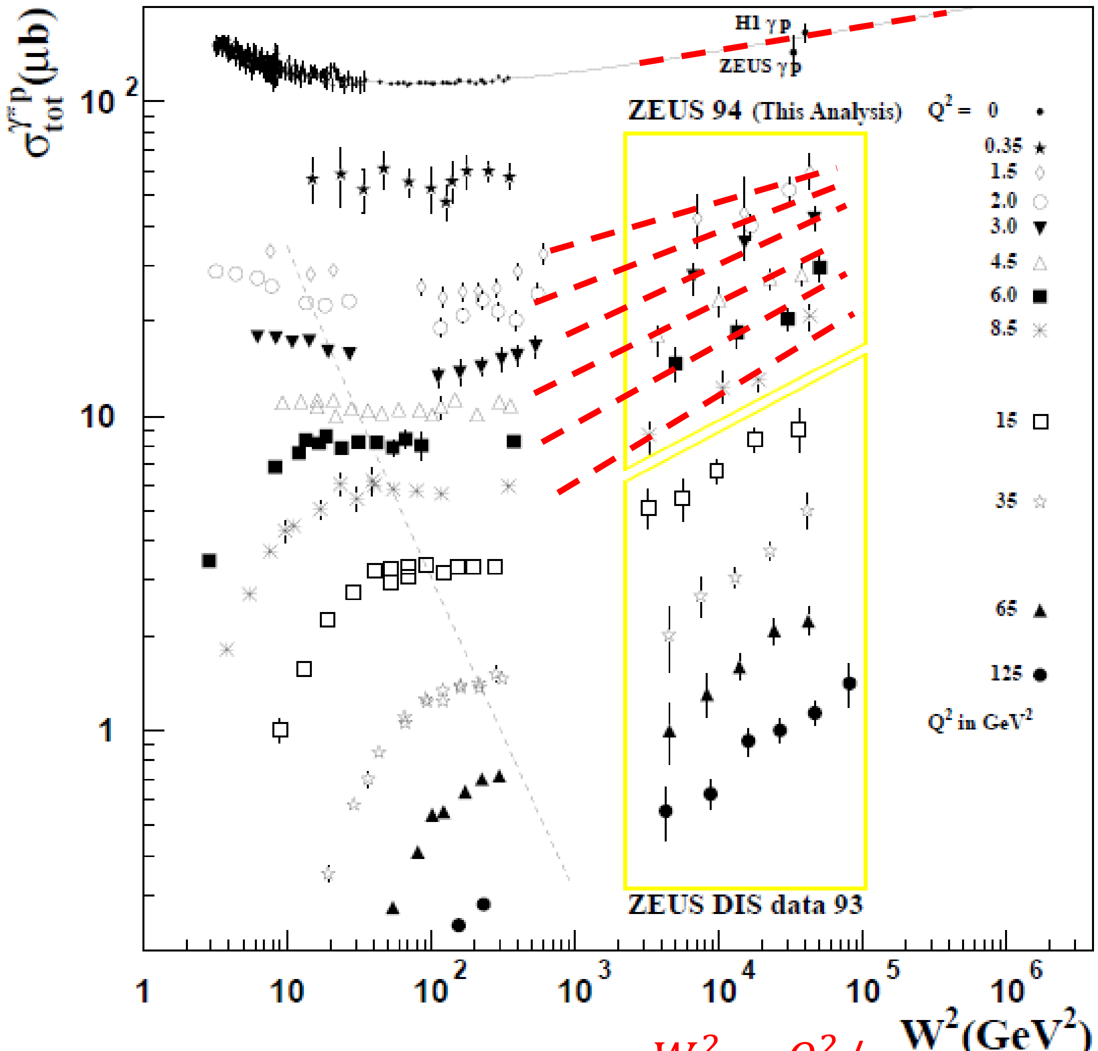
QCD dynamics vs. Q and x

$\gamma^* p$ total cross sections
ZEUS, hep-ex/9510009

Red lines "fit" $\sigma_{tot}^{\gamma^* p} \sim \sigma_{reduced}$ for a fixed Q

The slope of $\sigma_{tot}^{\gamma^* p} \sim \sigma_{red}$ vs. $1/x$ changes as a function of x and Q, predicting rapid growth of PDFs at $x \to 0$





$W^2 \approx Q^2/x$

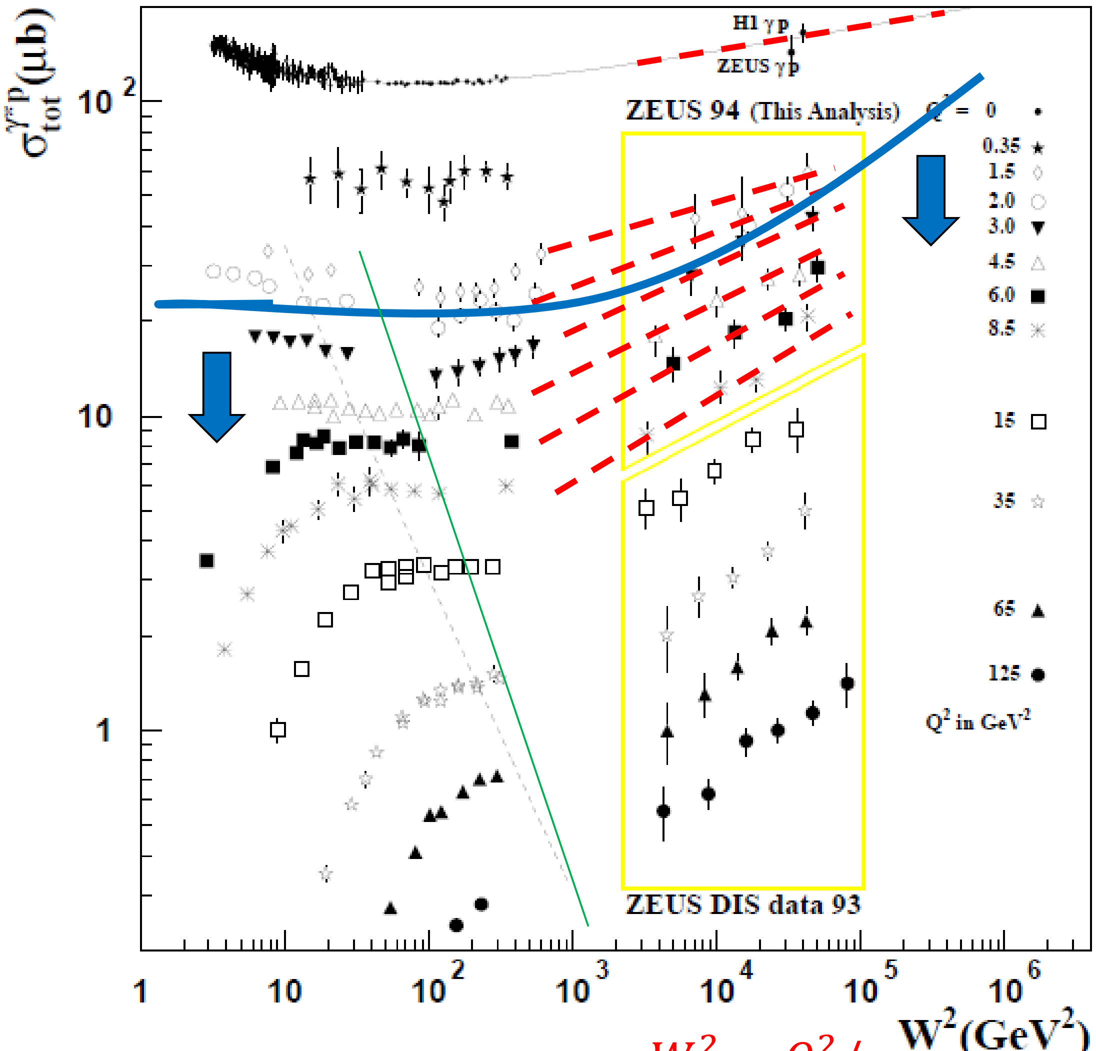
QCD dynamics vs. Q and x

$\gamma^* p$ total cross sections
ZEUS, hep-ex/9510009

For points below the blue line, expectations are consistent with DGLAP collinear factorization at NNLO

Above, we see deviations

The boundary has not been located precisely. We can try to establish it using PDF fits.

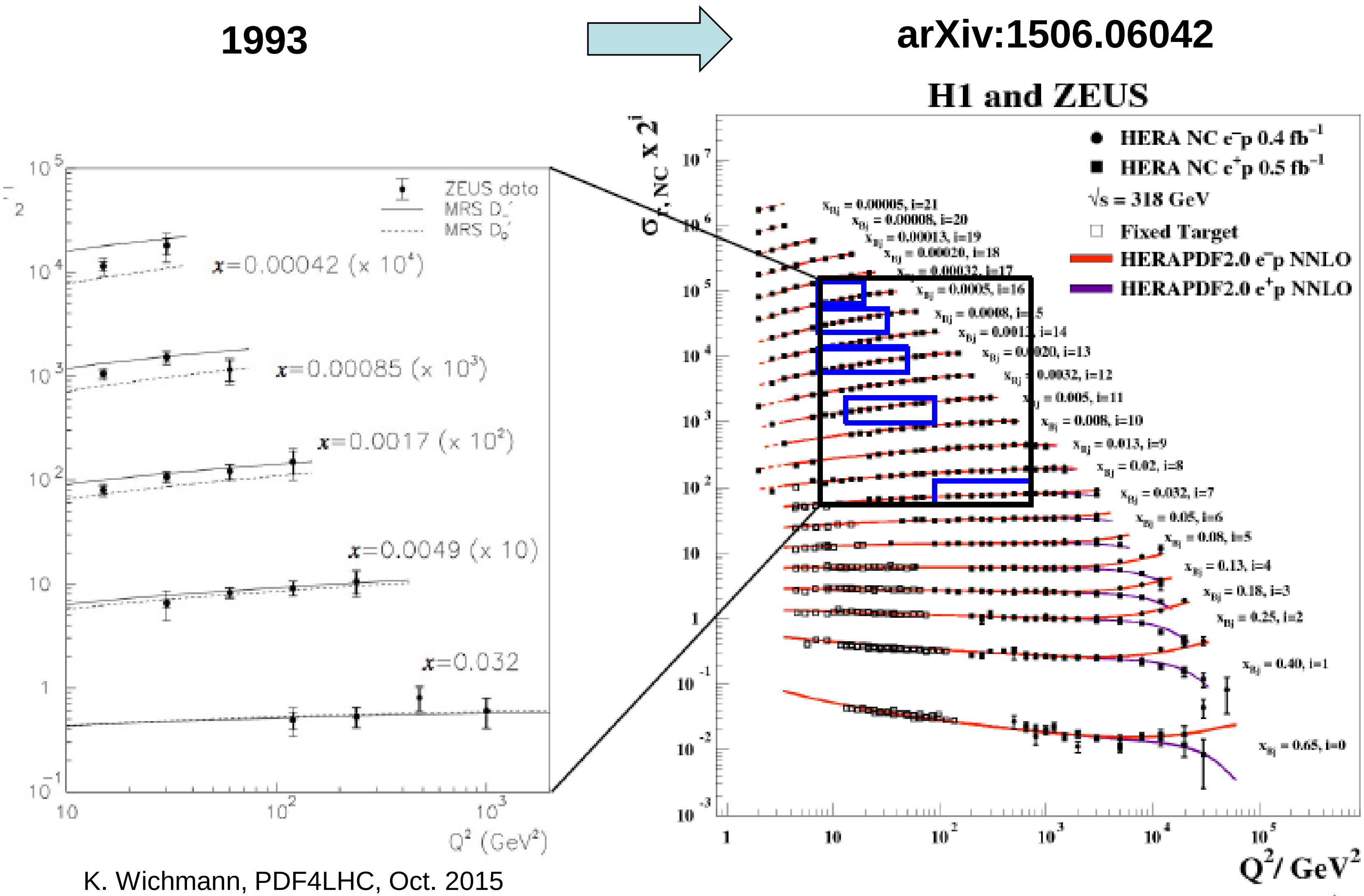


$W^2 \approx Q^2/x$

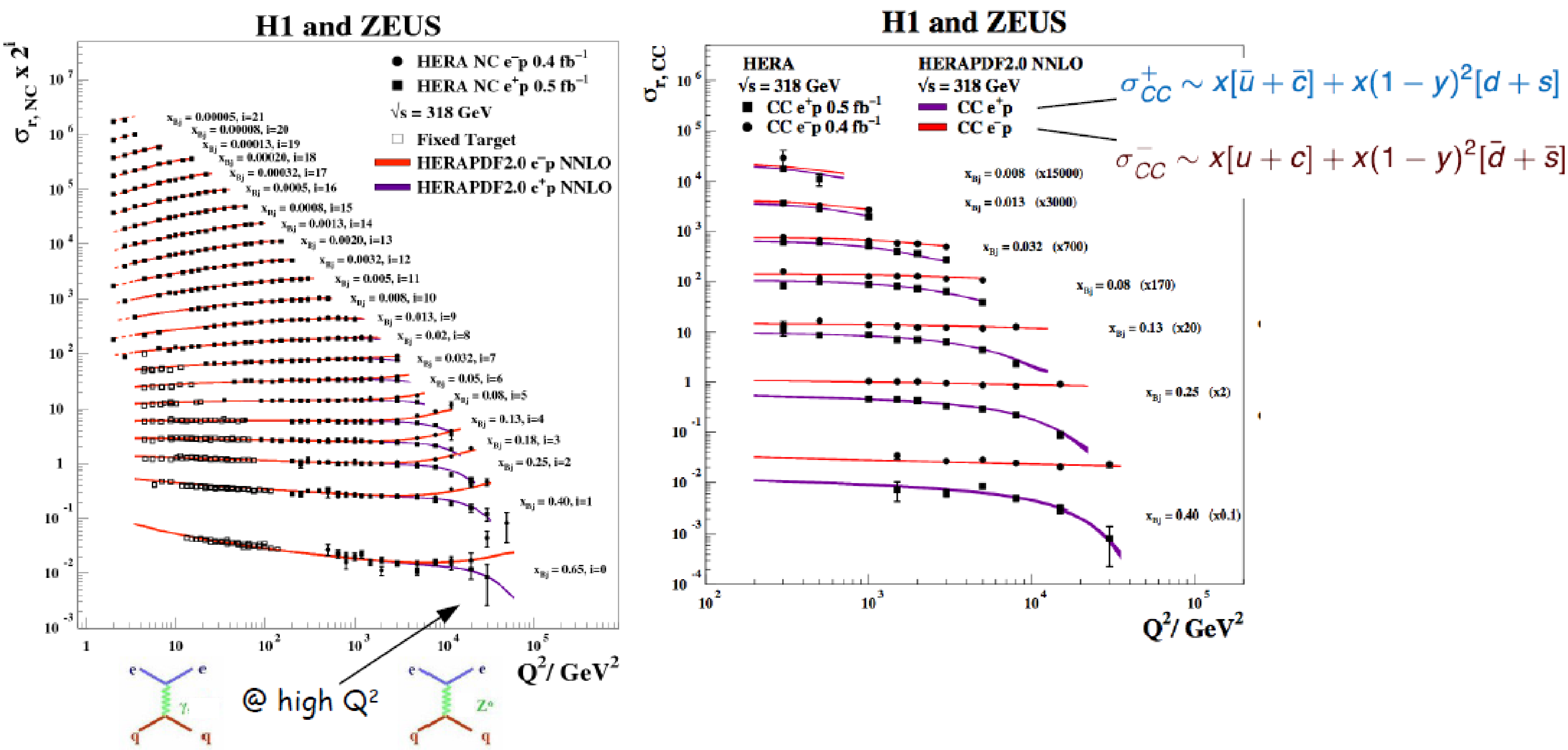
2016: we can test DGLAP factorization with combined HERAI+II data!

1993

arXiv:1506.06042

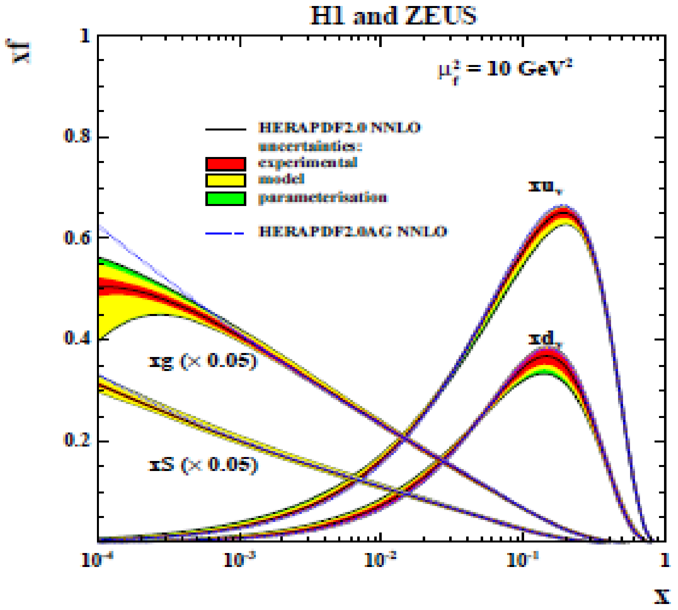


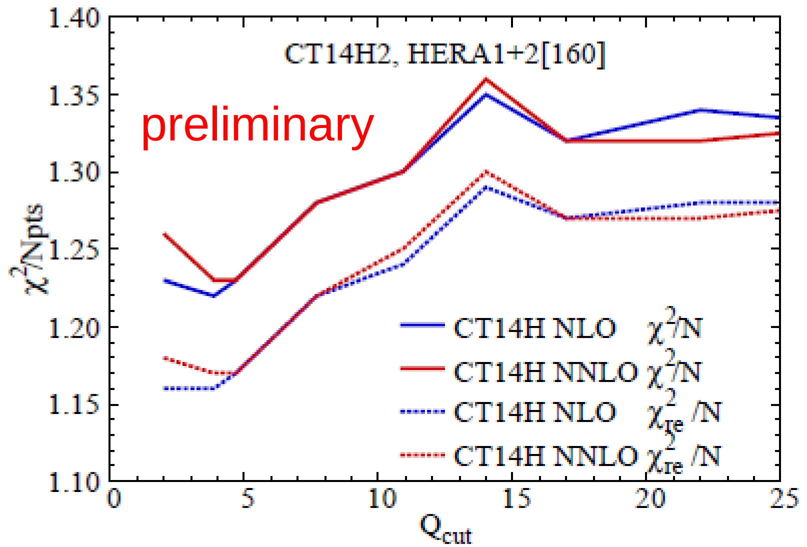
K. Wichmann, PDF4LHC, Oct. 2015



Combined H1 and ZEUS inc. cross sections in NC $e^{\pm}p$ and CC $e^{\pm}p$ DIS at 5 E_p with detailed correlation estimates (162 sources)

Strongly sensitive to $u, c,\ g$, less to d, and somewhat sensitive to $\bar{u}, \bar{d}, \bar{s}$ via CC cross sections





χ^2/N_{pts} with (top) and without (bottom) penalty for syst. shifts

The combined HERA1+2 data are included in HERA2.0, CT14H2, MMHT, and NNPDF3.1 analyses

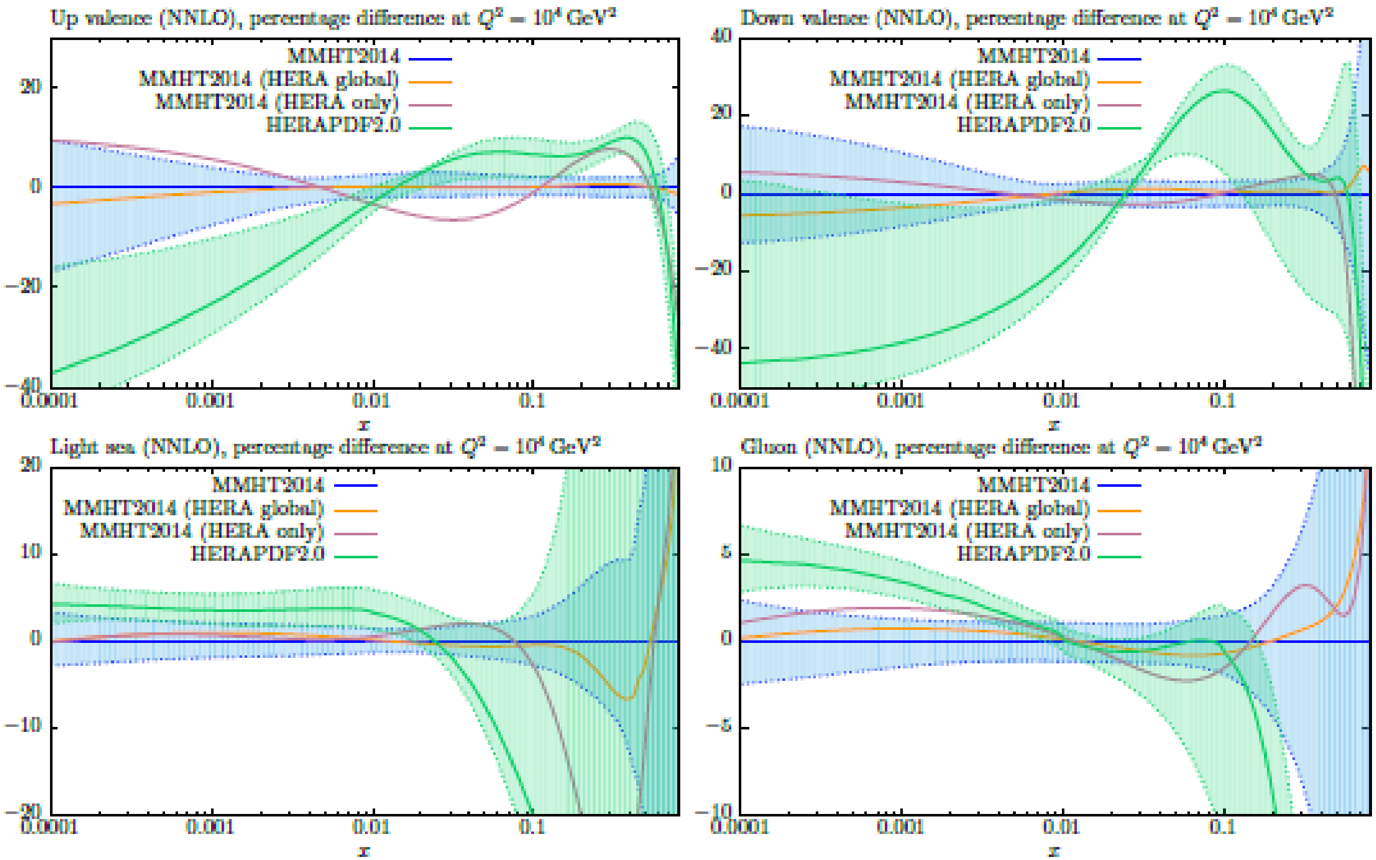
$\chi^2/d.o.f.\sim 1.2$ for HERA1+2 tends to be elevated across all analyses, compared to $\chi^2/d.o.f. < 1.1$ for combined HERA1 data

$\Rightarrow$ This tension may arise from several sources

- Higher-twist corrections to $F_L(x,Q)$ **A. Cooper-Sarkar, R. Thorne**
- Small-x/saturation **A. Luszszak**
- Experimental systematics (?) **T.-J. Hou**

The impact on global PDFs is mild, changes in PDFs do not exceed uncertainties

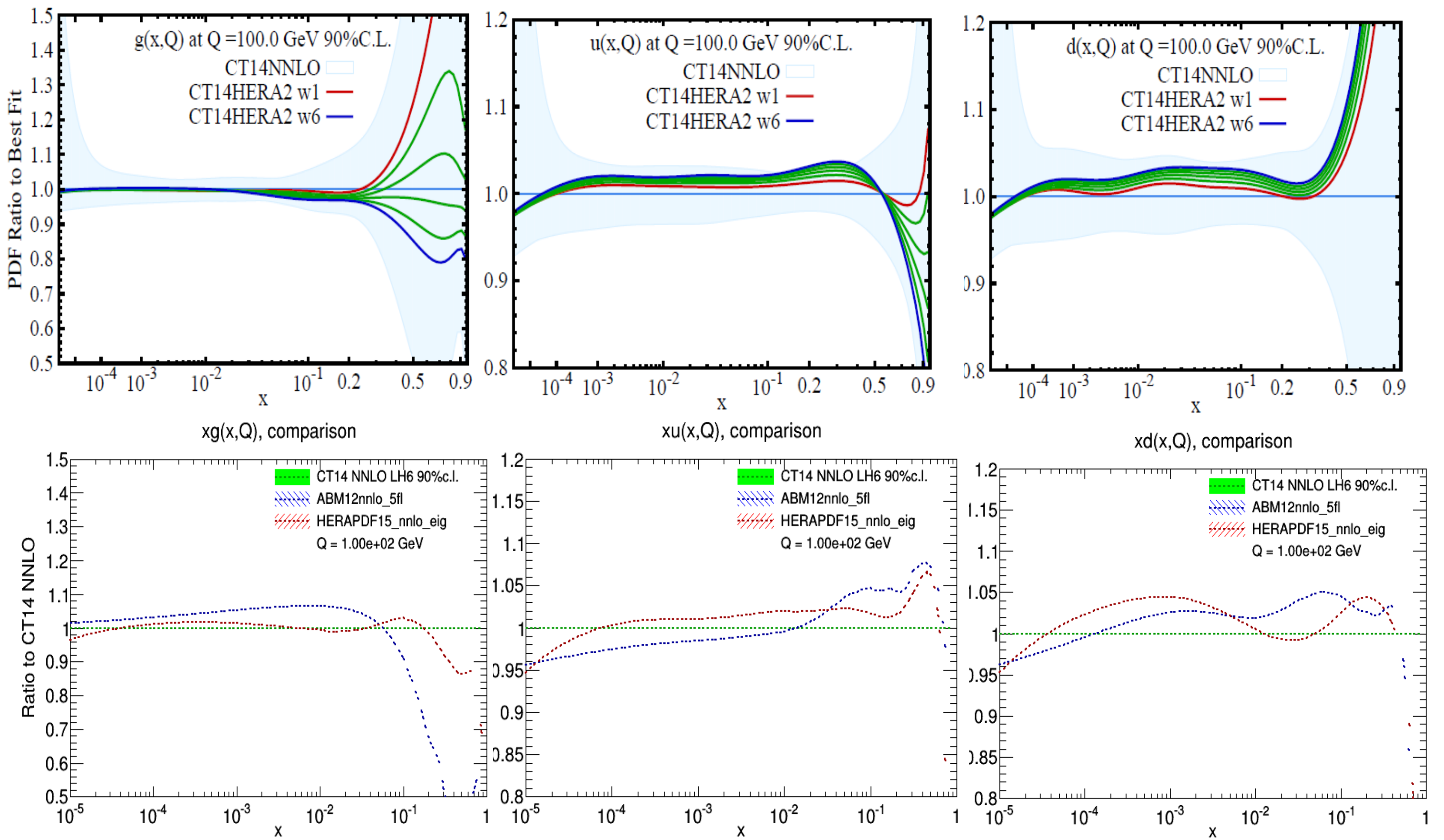
MMHT refit including combined HERA I+II data. Under refitting in global fit NLO – $\chi^2 = 1533/1185 = 1.29$ per point. NNLO – $\chi^2 = 1457/1185 = 1.23$ per point.



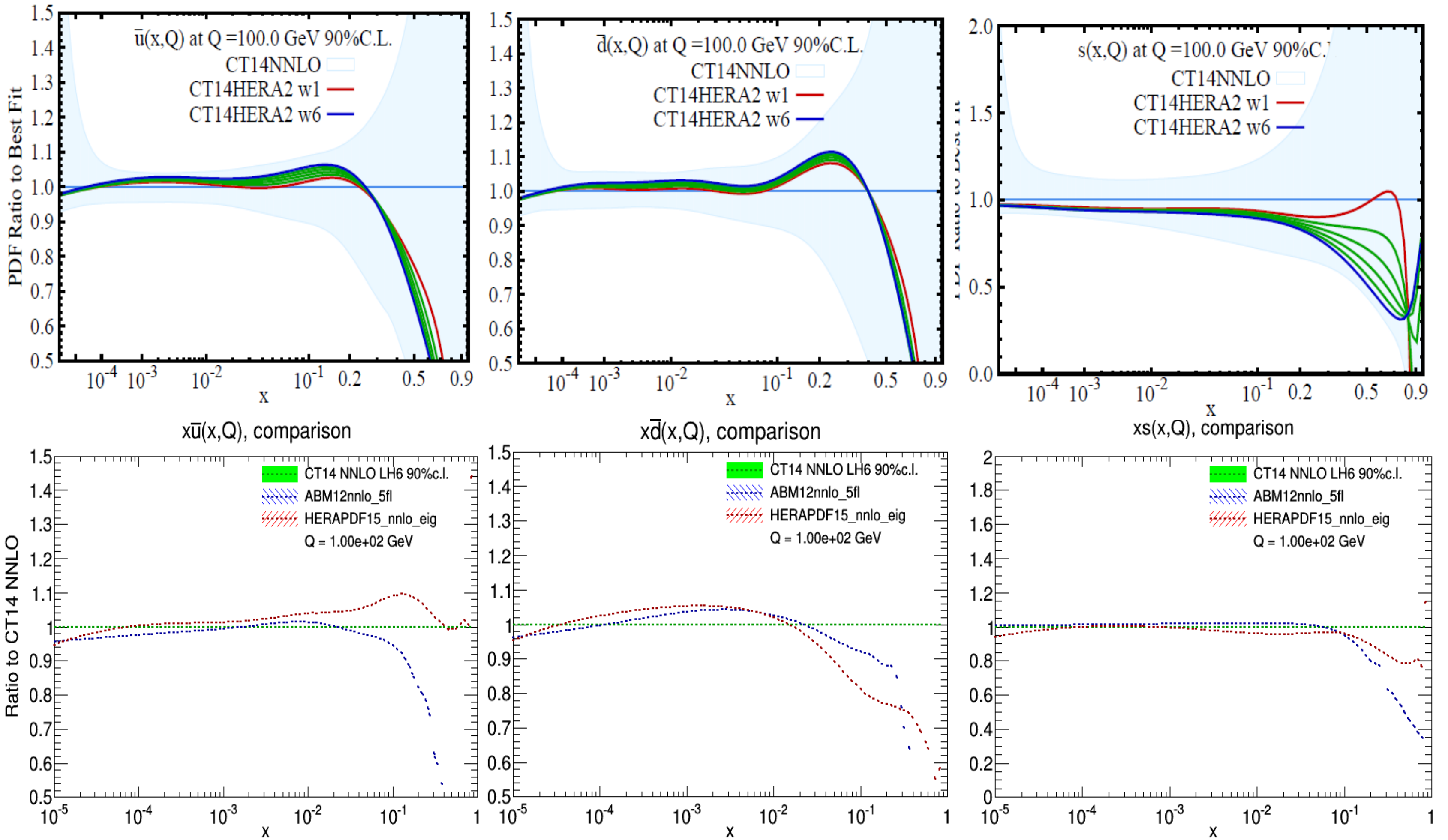
HERA II modified PDFs very well within MMHT2014 uncertainties. PDFs from HERA II data only fit in some ways similar to HERAPDF2.0.

R. Thorne

CT14HERA2: effect of increasing the statistical weight of HERAI+II data from w=1 to w=6



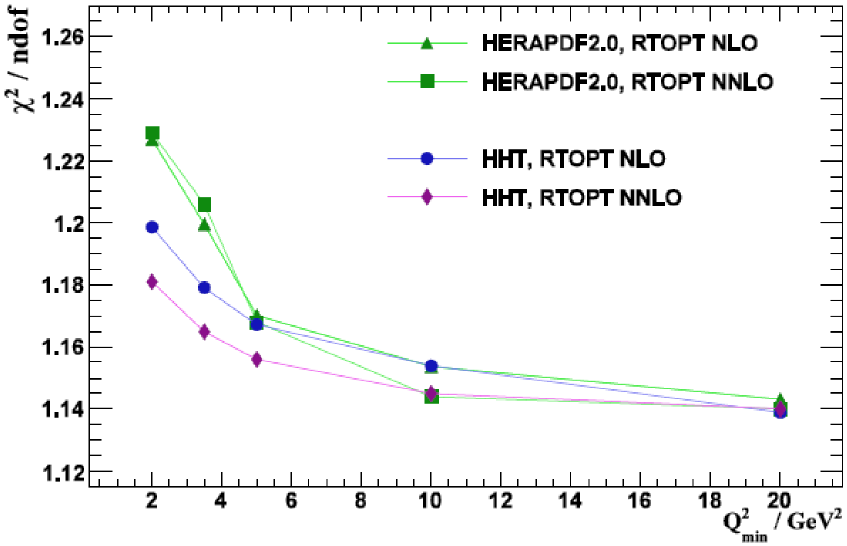
With $w = 6$, CT14HERA2 PDFs for g, u, and d are more similar to HERA2.0, not to ABM12 in a different theory framework with $\alpha_s = 0.113$



For sea PDFs, similarity is less pronounced (not as sensitive to HERA DIS)

Modifications to the HERAPDF2.0 fit called HHT

By I.Abt, **A.M.Cooper-Sarkar**, B.Foster, V.Myronenko, K.Wichmann, M.Wing

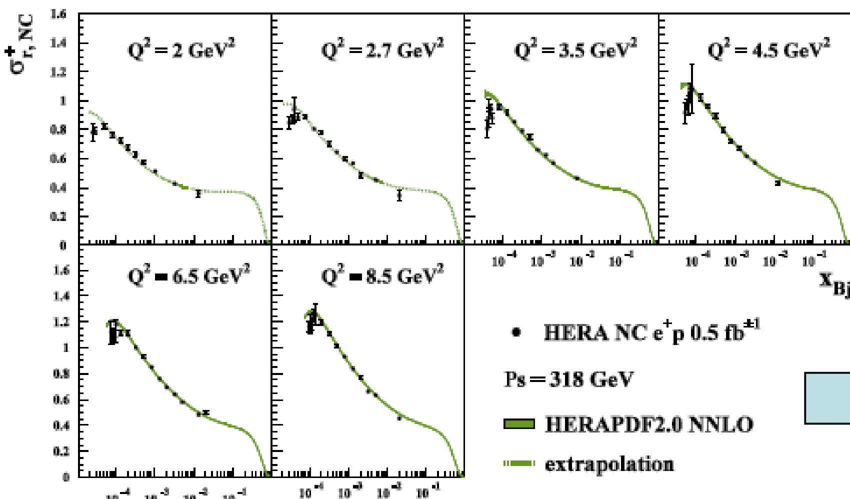


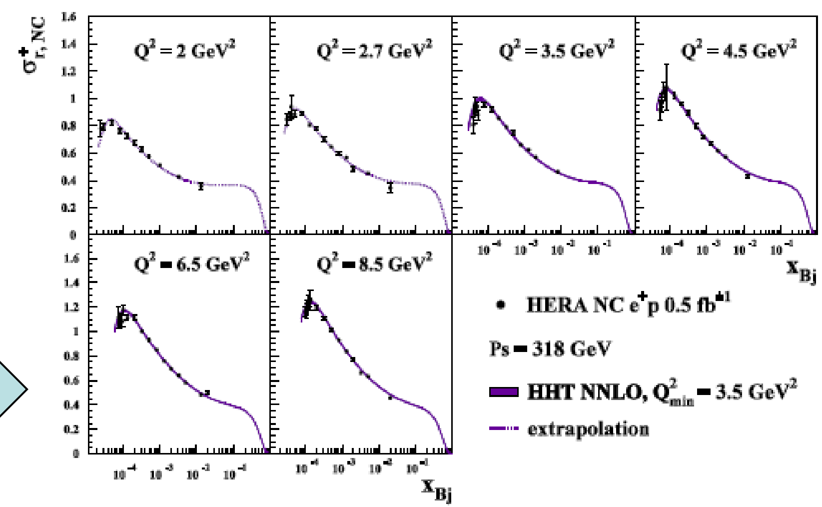
$$F_{2,L} = F_{2,L}\,(1 + A_{2,L}{}^{HT}/Q^2)$$

Addition of Higher Twist terms

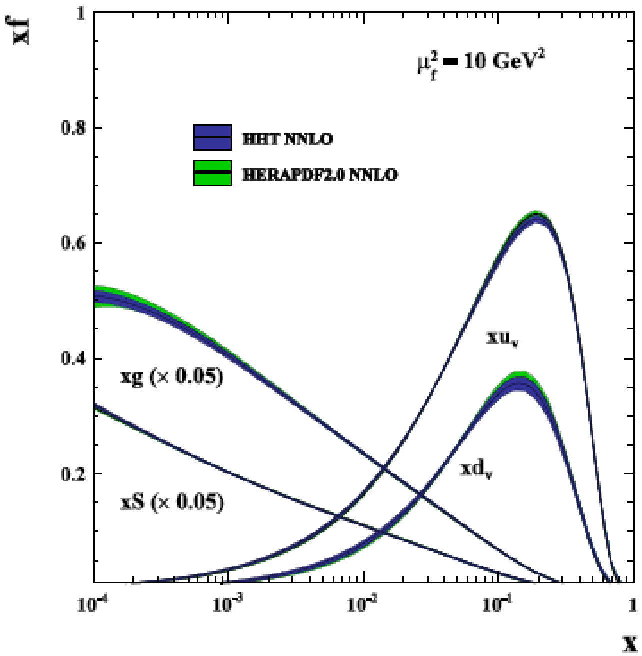
- requires only modification of F_L
- and is only important for low-x

Greatly improves the description of low-Q^2, low-x and high-y data particularly at NNLO





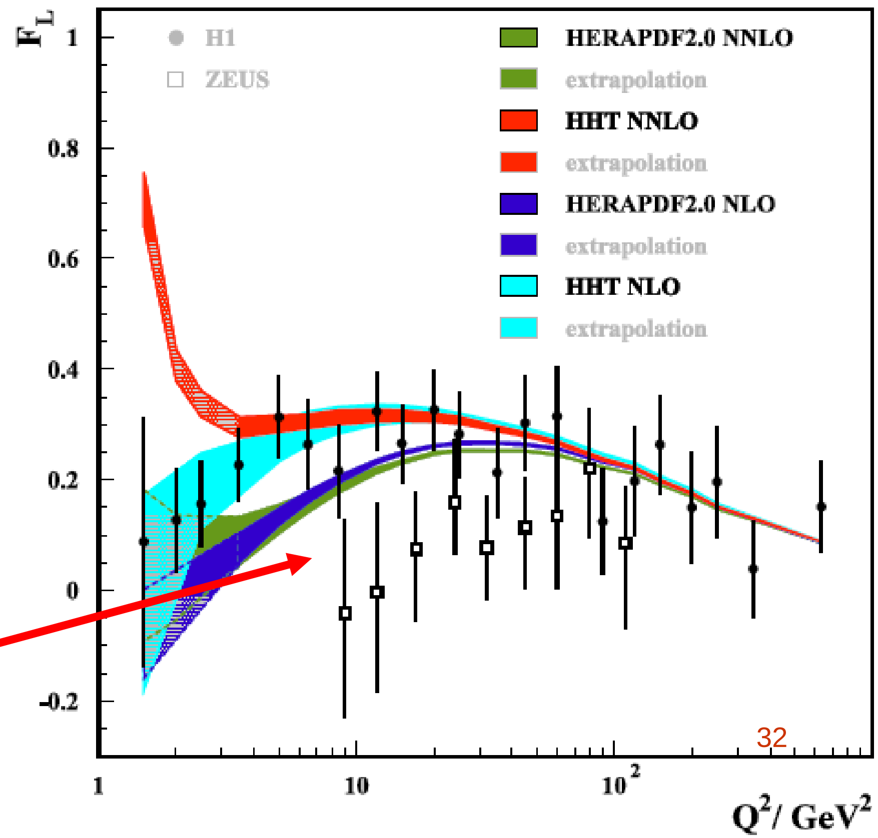
PDFs – and hence high Q^2 physics - not changed



Predicted FL - compared to the measured FL from H1 and ZEUS – is enhanced for $Q^2 < 50$ GeV^2.

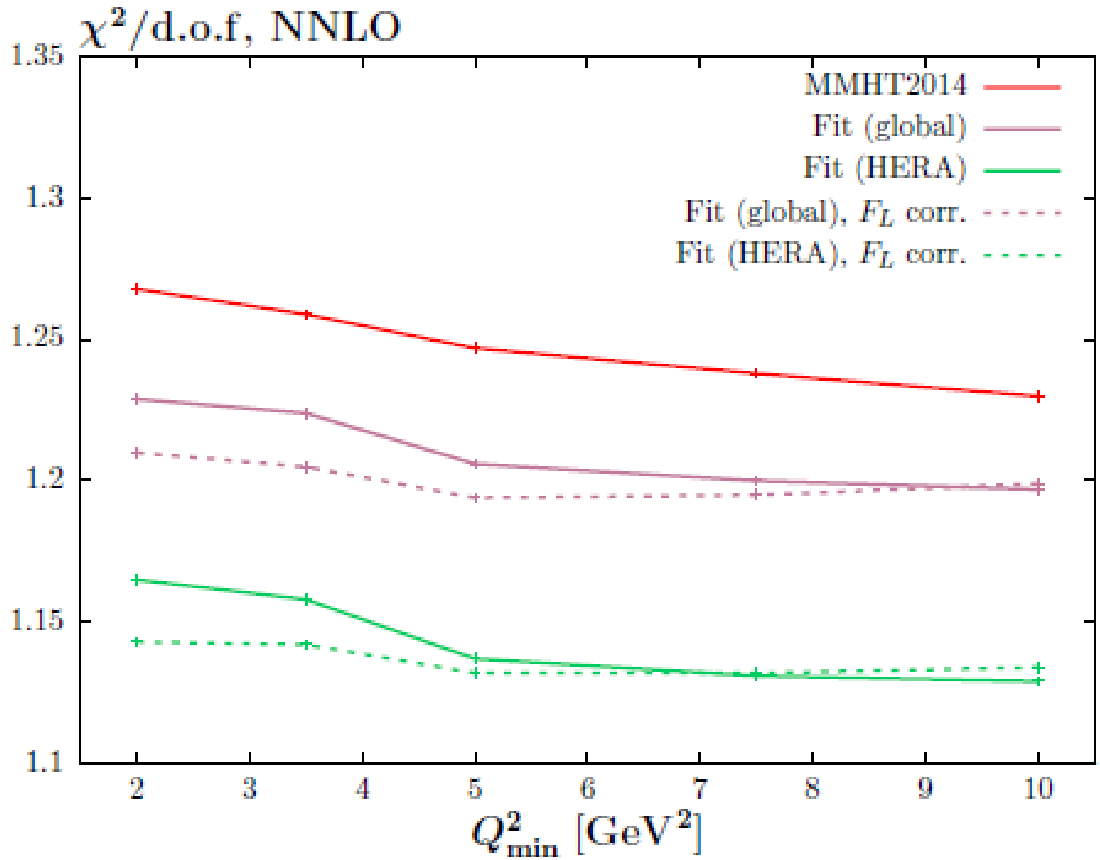
However it is clear that this approach cannot be pushed to very low $Q^2 < \sim 2$ GeV^2

P.N.: Notice differences between H1 and ZEUS



Tendency to overshoot some of the highest y points at low x and Q^2.

Try modification $F_L \rightarrow (1 + A/Q^2)F_L$ for $x < 0.01$. Refit and leaving A as a free parameter $\rightarrow \Delta\chi^2 = -24$ for $Q^2_{\rm min} = 2\ {\rm GeV}^2$. $A \approx 4$. Further modifications help little. Alternatives not as good.



Just about all evidence of a fall of χ^2 per point with $Q^2_{\rm min}$ eliminated.

HERA-LHC connection

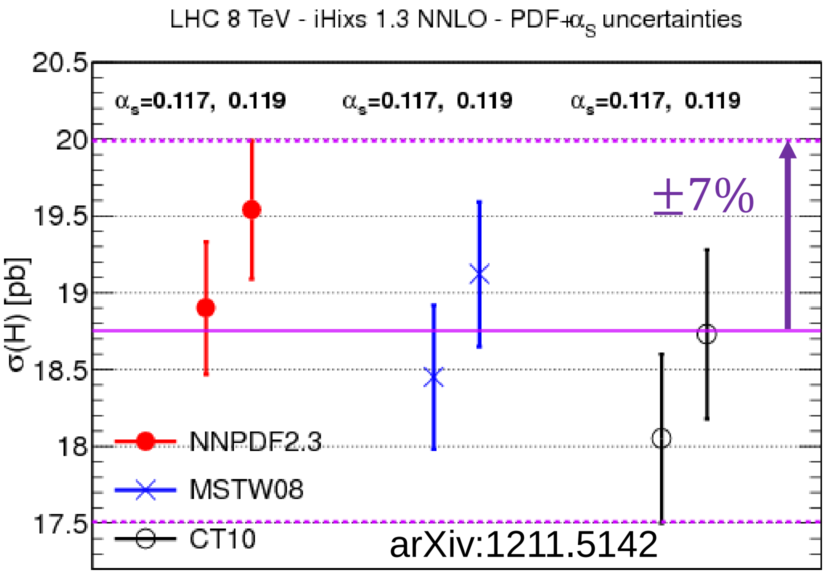
Assumptions of fits to HERA data directly affect PDFs at the LHC

Significant effort is being put into

- validating methodologies of NNLO fits to better control various sources of PDF uncertainties at the LHC
- developing recommendations for better usage of PDFs across a variety of LHC processes
- developing new methods for combining PDF ensembles before the computation of LHC cross sections (combined PDF4LHC’2015 PDFs)

These efforts are important, as usage of PDFs is increasingly sophisticated and dependent on numerous inputs

Example: $gg \rightarrow H^0_{SM}$ at the LHC



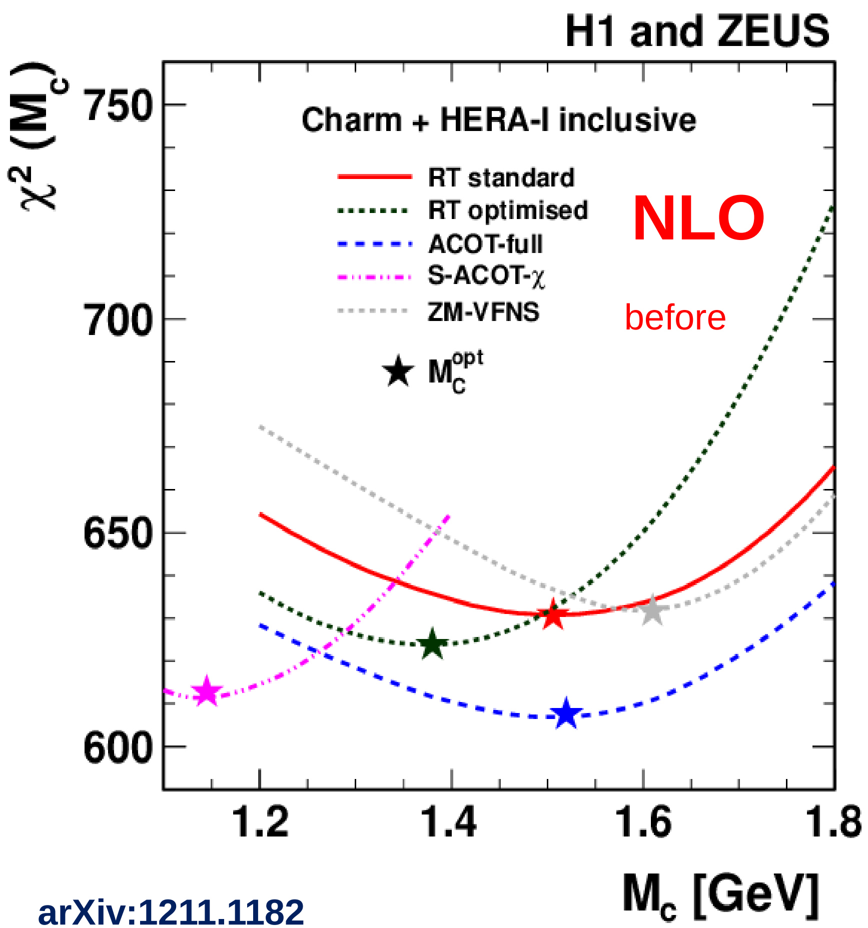
	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

J.Huston, PDF4LHC, April 2015

For example, Higgs cross sections based on 3 **latest** global fits has reduced from 7% to within 3%, i.e., the PDF uncertainty is of now order of N3LO QCD scale uncertainty

This improvement is due to benchmarking of general-mass factorization schemes; but can there be hidden sources of uncertainties on $\sigma(gg \rightarrow H)$, e.g., associated with massive charm DIS contributions, cf. arXiv:1603.08906?

NLO=$O(\alpha_s)$: GM-VFN predictions have large dependence on matching scales

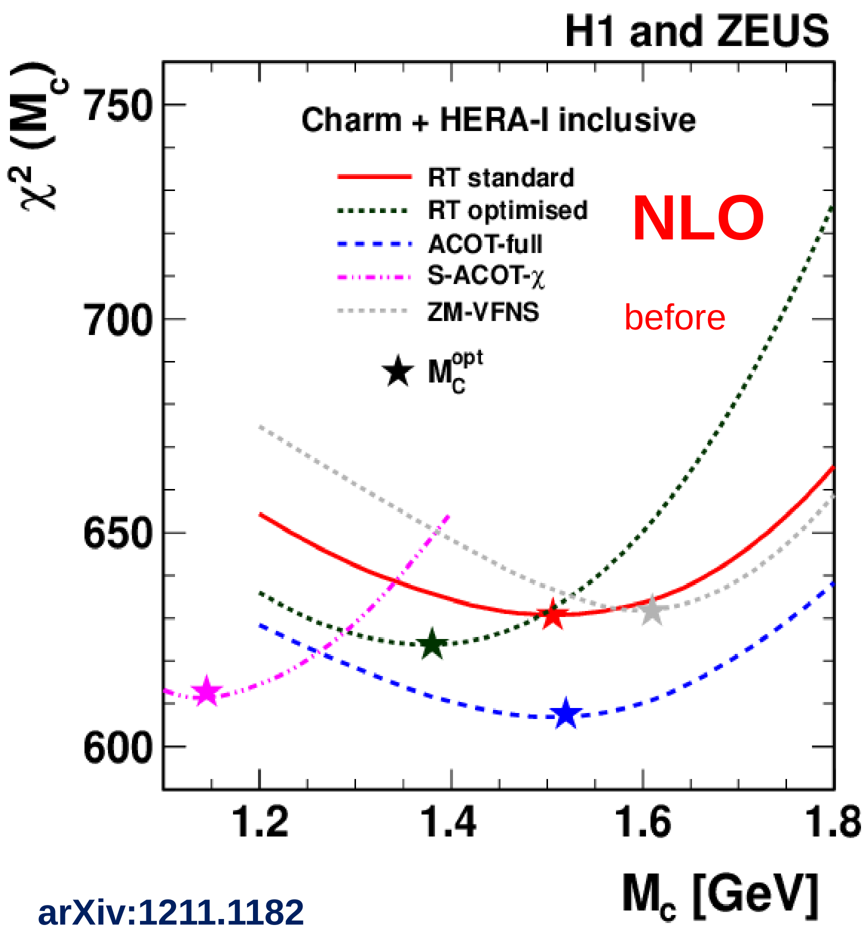


arXiv:1211.1182

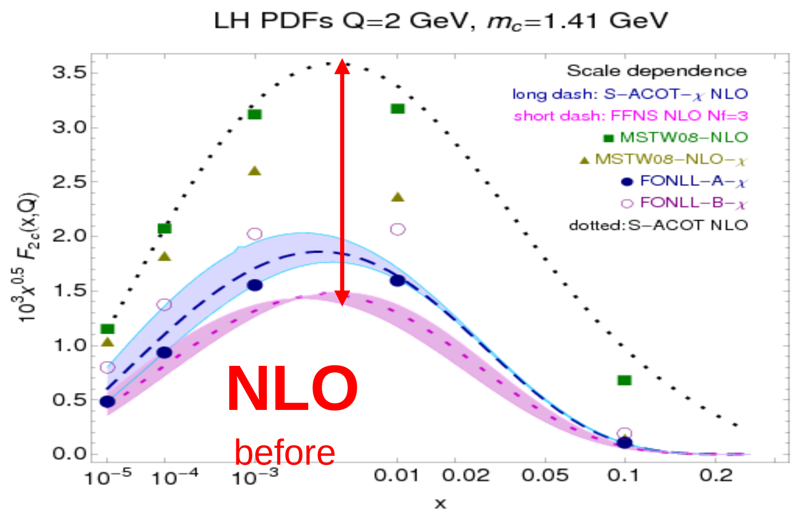
Besides the physical mass m_c, GM-VFN schemes introduce matching energy scales of order m_c

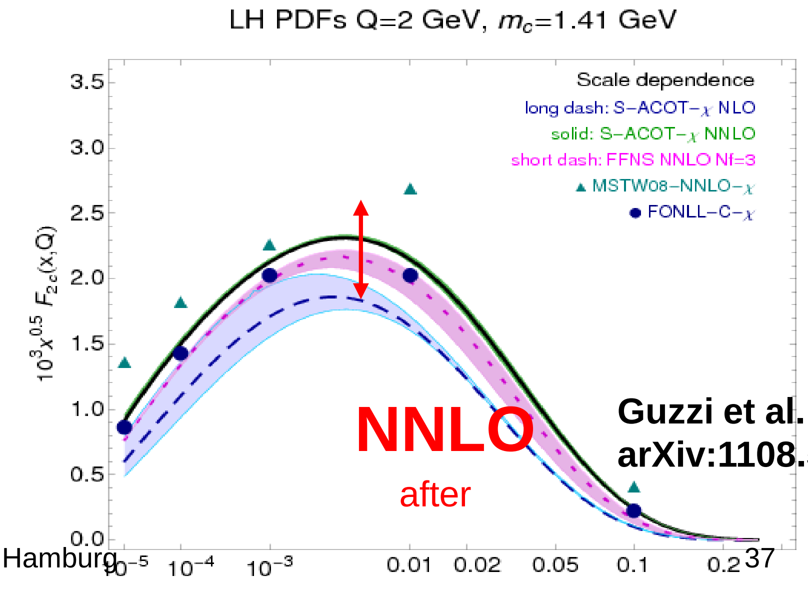
At NLO, uncertainty due to matching parameters is large; each scheme prefers an "optimal" m_c that brings χ^2 to comparable levels (cf. the figure)

NNLO=$O(\alpha_s^2)$: dependence on matching parameters is suppressed, GM-VFN schemes are more similar



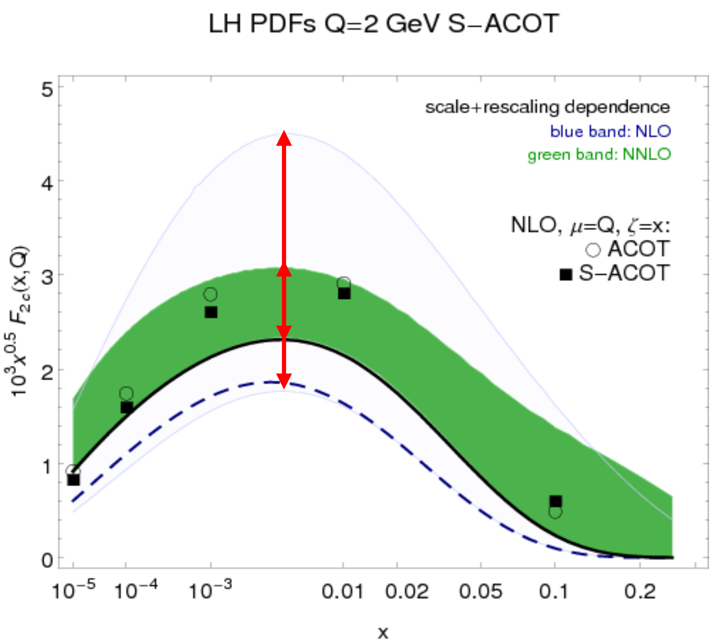
arXiv:1211.1182



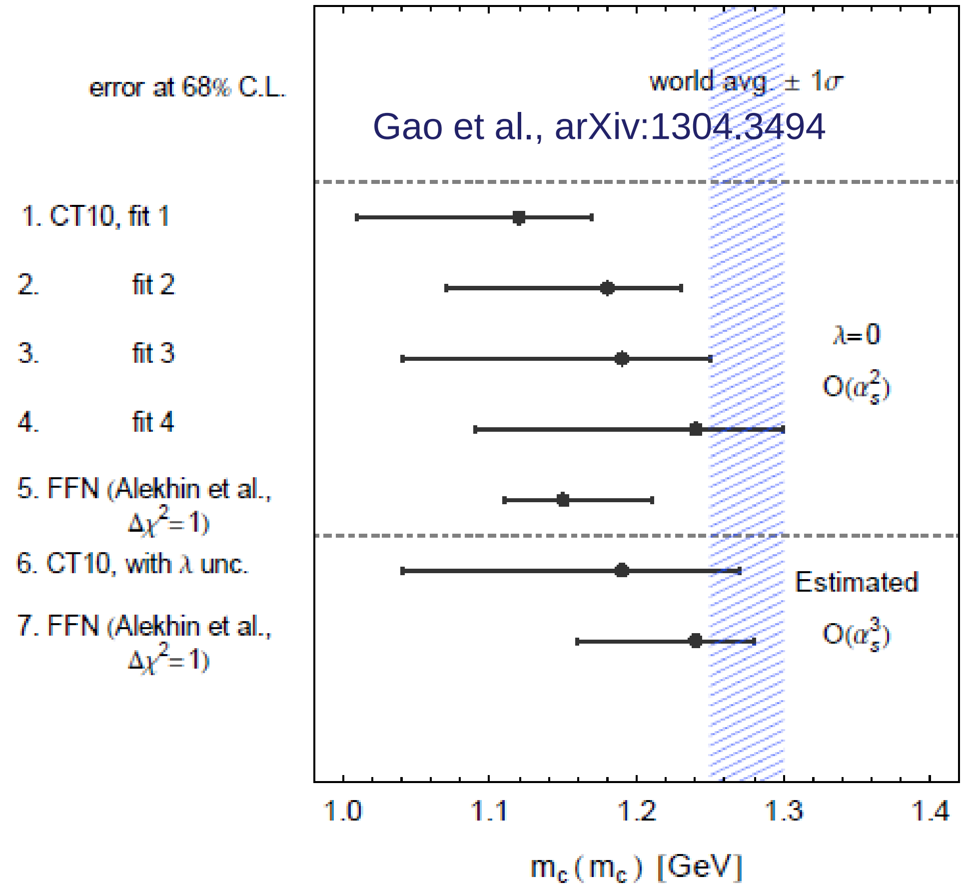


Guzzi et al.;
arXiv:1108.5112

GM-VFN schemes are more predictive at NNLO

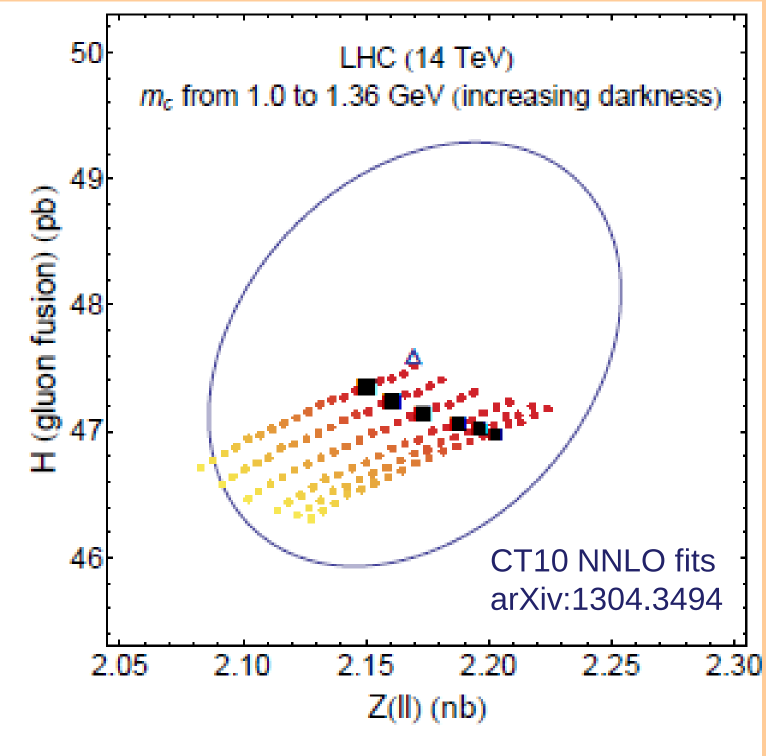


From Guzzi et al.; arXiv:1108.5112;
see also J. Rojo et al., 1003.1241, p. 110

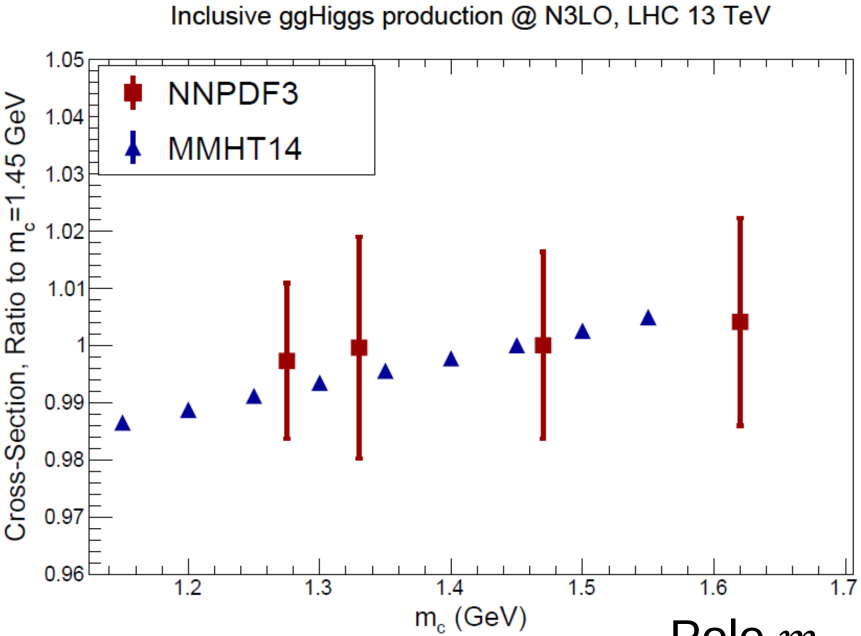


At $O(\alpha_s^2)$ and approximate $O(\alpha_s^3)$, constraints on $m_c(m_c)$ have been first obtained from combined HERA-I data in the FFN scheme (1212.2355). Constraints on both m_c^{pole} or $m_c(m_c)$ in GM-VFNS have been also obtained in CT, MMHT, and NNPDF fits under varied assumptions. They are comparable with FFNS and the PDG value for $m_c(m_c)$.

The resulting uncertainty on $\sigma(gg \to H)$ is <2-3%



σ_{tot} for $m_c(m_c) = 1 - 1.36$ GeV and matching parameter λ varied independently, $Q_0 = 1$ GeV. Black boxes are for $m_c(m_c) = 1.28$ GeV (close to world average), for the explored λ. The error ellipse is for nominal 90% C.L. @ $Q_0 = 1.3$ GeV.



Pole m_c

Intrinsic charm only reduces correlated dependence on m_c, Q_0, and matching

J. Rojo's talk

Bottom line: GM-VFN schemes agree well at NNLO because of perturbative convergence, not because of m_c tuning

Estimation of PDF uncertainties on LHC observables

$pp \to t\bar{t}X$

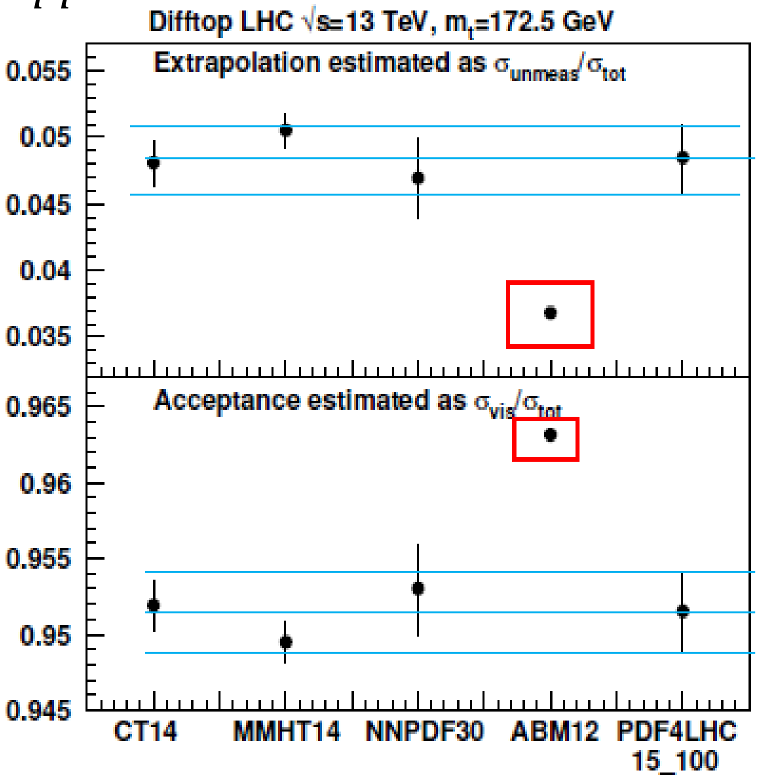


Figure: K. Lipka
1603.08906

The procedure for computing the PDF uncertainty must vary depending on the goals of the analysis. The options may include

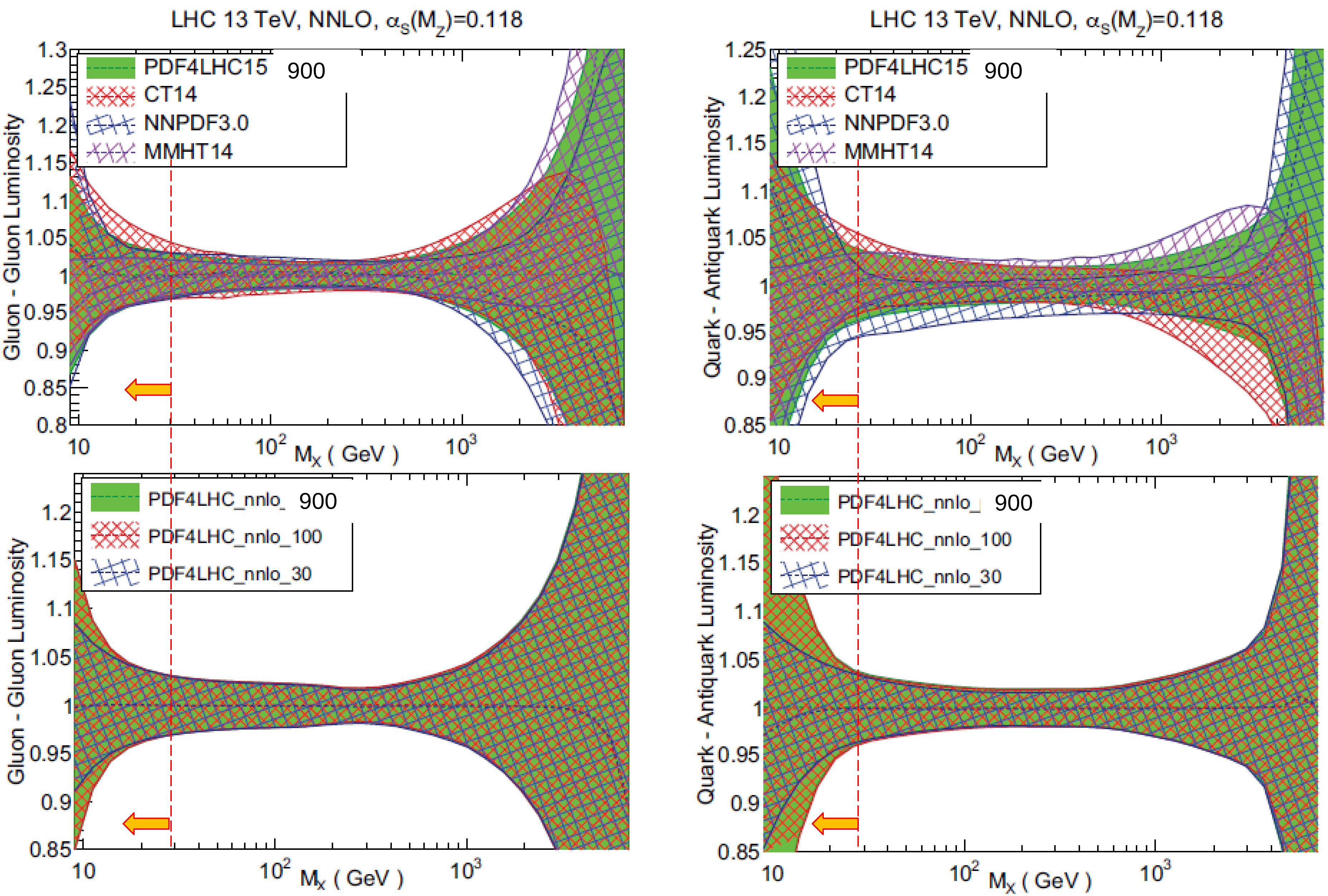
a) Using one individual set out of several similar ones (e.g., CT, MMHT, or NNPDF)

b) Using an envelope of all sets, including the outlier sets

c) New (arXiv:1510.03865)**:** using a combined PDFLHC15 set constructed from CT14, MMHT14, NNPDF3.0

- A statistical combination of 3 sets
- Reproduces the total uncertainty with only 30-100 error sets
- Eliminates redundant comparisons of 3 global sets
- can be used in many (not all) cases

PDF4LHC15 combined sets (900, 100, 30 replicas) vs. CT14, MMHT, NNPDF

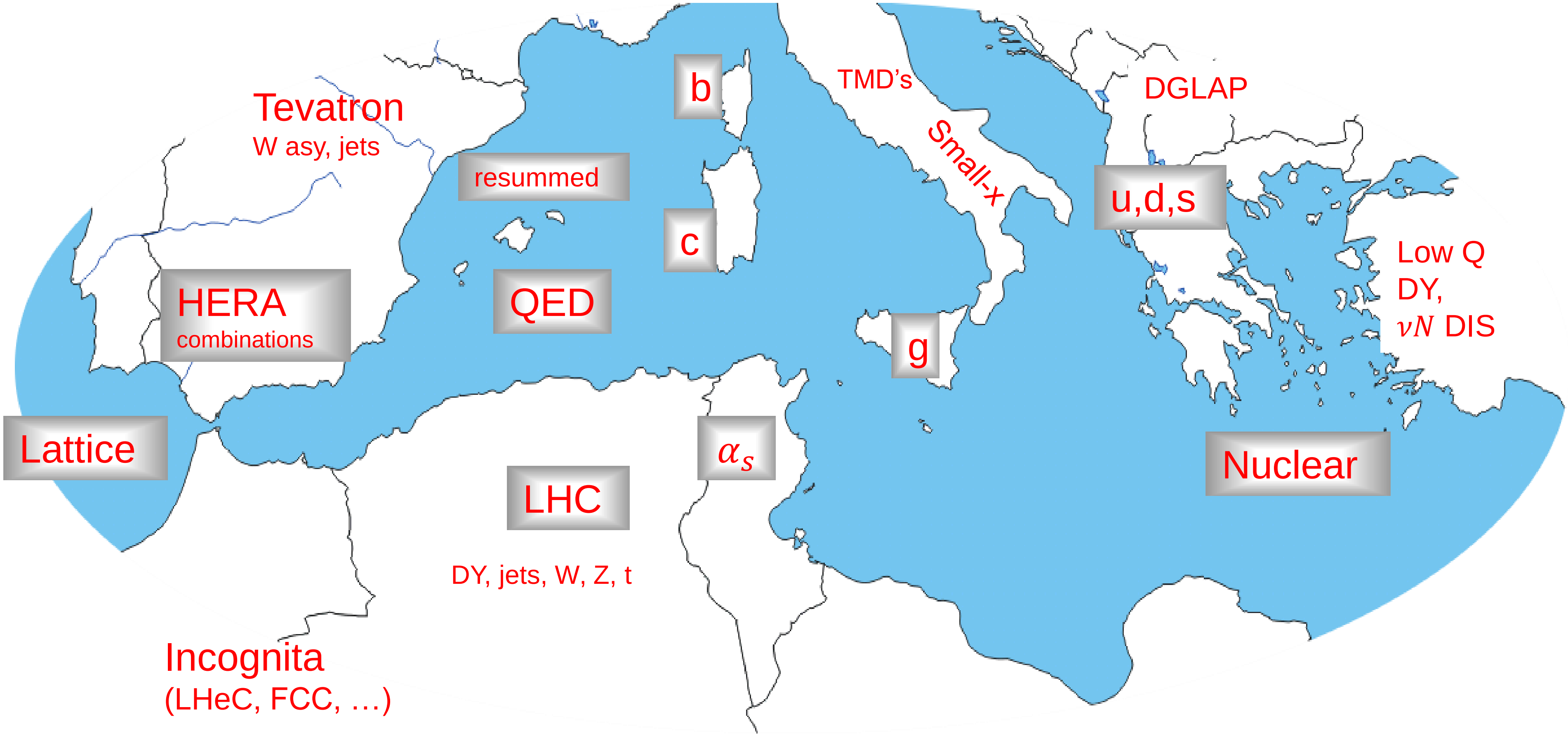


Tuesday, April 12: discussion of the PDF4LHC15 recommendation and its critical appraisal

12:00	[167] The PDF4LHC 2015 recommendations for Run II	ROJO, Juan
12:20	[134] PDF4LHC recommendations for LHC Run II: A critical appraisal	PLACAKYTE, Ringaile
12:40	[323] Discussion	

Oekumene of the PDF universe

as presented by topics at DIS'2016



A lattice calculation for parton distributions

Fernanda Steffens

- Very first results for $u(x) - d(x)$ and $\bar{d}(x) - \bar{u}(x)$ by the ETM collaboration

$$q(x,\mu_R) = \tilde{q}(x,\Lambda,P_3) - \frac{\alpha_s}{2\pi}\tilde{q}(x,\Lambda,P_3)\delta Z_F^{(1)}\left(\frac{\mu_R}{P_3},\frac{\Lambda}{P_3}\right) - \frac{\alpha_s}{2\pi}\int_{-1}^{1} Z^{(1)}\left(\frac{x}{y},\frac{\mu_R}{P_3},\frac{\Lambda}{P_3}\right)\tilde{q}(y,\Lambda,P_3)\frac{dy}{|y|} + \mathcal{O}(\alpha_s^2),$$

- Based on a method by X. Ji, "Parton Physics on a Euclidean Lattice," arXiv:1305.1539.

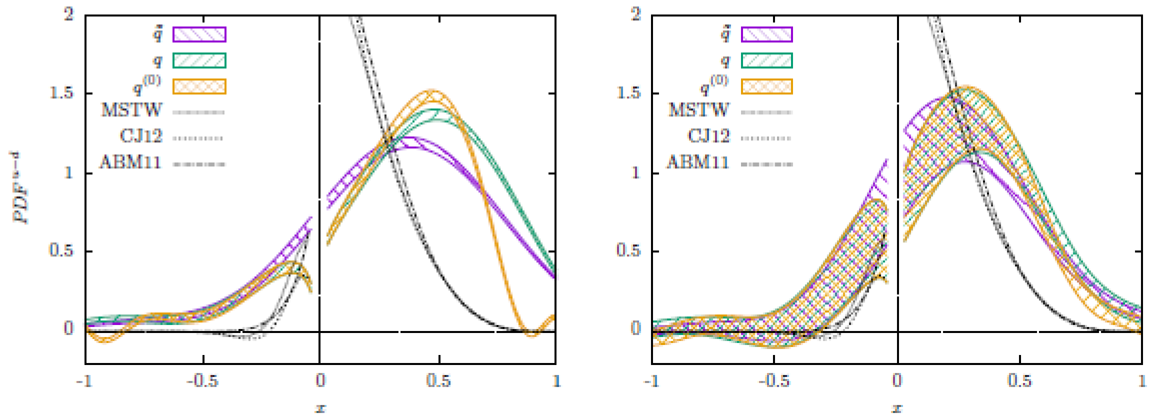


Figure 5: The resulting quasidistribution $\tilde{q}$, PDF without subtracting the mass correction q, and final PDF $q^{(0)}$, **left**: $P_3 = 4\pi/L$, **right**: $P_3 = 6\pi/L$, **from top to bottom**: 0 steps, 2 steps, 5 steps of HYP smearing, negative region: $\bar{q}(x) = -q(-x)$, comparison with phenomenological $u(x) - d(x)$ curves at $Q^2 = 6.25\,\mathrm{MeV}^2$ (MSTW [29], CJ12 [30], ABM11 [31]).

APFEL

V. Bertone

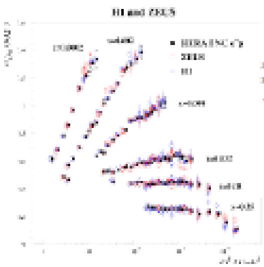
- APFEL is a **public** library for PDF evolution:
  - up to NNLO in QCD combined to LO QED corrections.
  - FFNS and VFNS.
  - Pole and $\overline{\text{MS}}$ heavy quark masses.
  - Module for the fast computation of DIS NC and CC observables up to NNLO in different mass schemes (ZM-VFNS, FFNS and FONLL).
  - interfaces to FORTRAN, C/C++ and Python.
  - Amazing web interface available on http://apfel.mi.infn.it.
  - APFEL is available from http://apfel.hepforge.org/.
- Interfaced to xFitter and Alpos.
- Used for the next generation of the NNPDF fits.

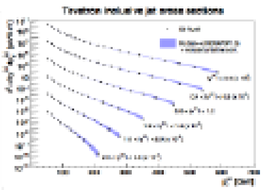
xFitter

https://www.~~herafitter~~.org

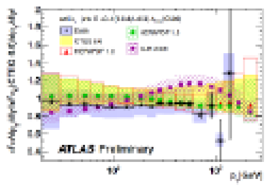
O. Zenaiev

experimental input





experiments:
HERA, Tevatron, LHC, fixed target



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

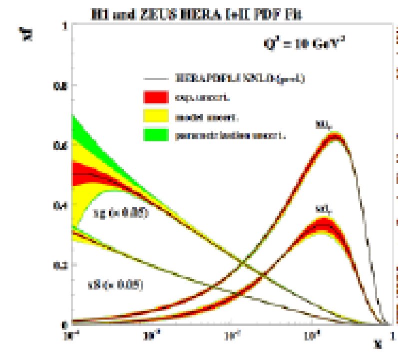
theoretical calculations/tools

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~~

xFitter



PDF or uPDF or DPDF

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

Theory predictions

Benchmarking

Comparison of schemes

Thank you for your attention!

Benchmark comparisons of PDF analyses

1. J. Gao et al., MEKS: a program for computation of inclusive jet cross sections at hadron colliders , arXiv:1207.0513

Codes for NLO jet production

2. R. Ball et al., Parton Distribution benchmarking with LHC data, arXiv:1211.5142

(N)NLO LHC cross sections

3. S. Alekhin et al., ABM11 PDFs and the cross section benchmarks in NNLO, arXiv:1302.1516; The ABM parton distributions tuned to LHC data; arXiv:1310.3059

W/Z, $t\bar{t}$,…

4. A.Cooper-Sarkar et al., PDF dependence of the Higgs production cross section in gluon fusion from HERA data, 2013 Les Houches Proceedings, arXiv:1405.1067, p. 37

NC DIS;
CC DIS

5. S. Forte and J. Rojo, Dataset sensitivity of the gg->H cross-section in the NNPDF analysis, arXiv:1405.1067, p. 56

Benchmark comparisons of DIS cross sections

2013 Les Houches Proceedings, arXiv:1405.1067, p. 37 and 56

1. Detailed studies of reduced cross sections $\sigma_{r,NC}^{\pm}$ and structure functions $F_{1,2}$ from CT, HERA, MSTW, NNPDF
   - for neutral-current DIS (published), charged-current DIS
   - at LO, NLO, and NNLO
   - separately for light quarks and heavy quarks
   - with Les Houches toy PDFs
   - in various heavy-quark schemes

2. Fits to HERA data only, using 4 fitting codes
   - with native and varied PDF parametrizations
   - with various Q cuts
   - with various treatment of systematic errors
   - with varied heavy-quark masses