Parton Distributions at the HL-LHC and HE-LHC

Lucian Harland-Lang*, University of Oxford

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Workshop on the physics of HL-LHC and perspectives at HE-LHC

CERN, 1 November 2017

*speaker

Outline

- PDFs at the HL-LHC/HE-LHC - overview.
- Recent Progress in PDF fitting.
- Theoretical uncertainties:
  - Parametric.
  - Missing higher orders.
- Role of electroweak corrections:
  - Corrections to cross sections.
  - Photon-initiated processes.
  - EW PDFs.
- PDFs with resummation:
  - High x - threshold.
  - Low x - BFKL.
- PDFs at a high energy ep/eA collider.

PDFs at the HL-LHC

LCTS/2014-47
IPPP/14/97
DCPT/14/194
May 15, 2015

New parton distribution functions from a global analysis of quantum chromodynamics

Sayipjamal Dulat,[1,2,*] Tie-Jiun Hou,[3,†] Jun Gao,[4,‡] Marco Guzzi,[5,§] Joey Huston,[2,¶] Pavel Nadolsky,[3,**] Jon Pumplin,[2,††] Carl Schmidt,[2,‡‡] Daniel Stump,[2,§§] and C.–P. Yuan[2,¶¶]

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Parton distributions in the LHC era: MMHT 2014 PDFs

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DESY 16-179
DO-TH 16/13
January 2017

NNPDF

Edinburgh 2014/15
IFUM-1034-FT
CERN-PH-TH/2013-253
OUTP-14-11p
CAVENDISH-HEP-14-11

Parton distributions for the LHC Run II

The NNPDF Collaboration:
Richard D. Ball[1,2], Valerio Bertone[2], Stefano Carrazza[4,2], Christopher S. Deans[1], Luigi Del Debbio[1], Stefano Forte[4], Alberto Guffanti[5], Nathan P. Hartland[1], José I. Latorre[3], Juan Rojo[6] and Maria Ubiali[7]

Parton Distribution Functions, α_s and Heavy-Quark Masses for LHC Run II

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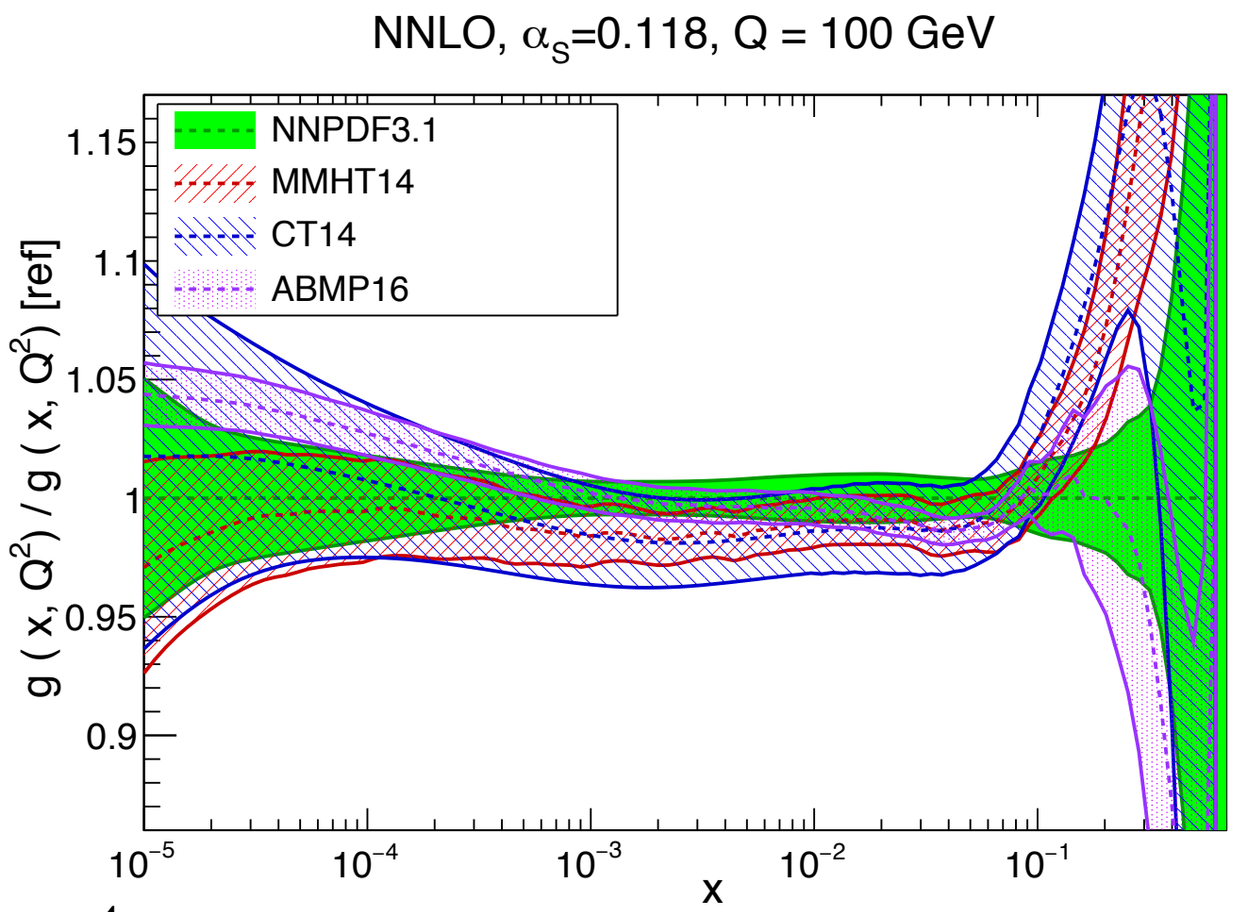
- What will we need for `**PDFs at the HL-LHC/HE-LHC**'?

PDFs at the HL-LHC

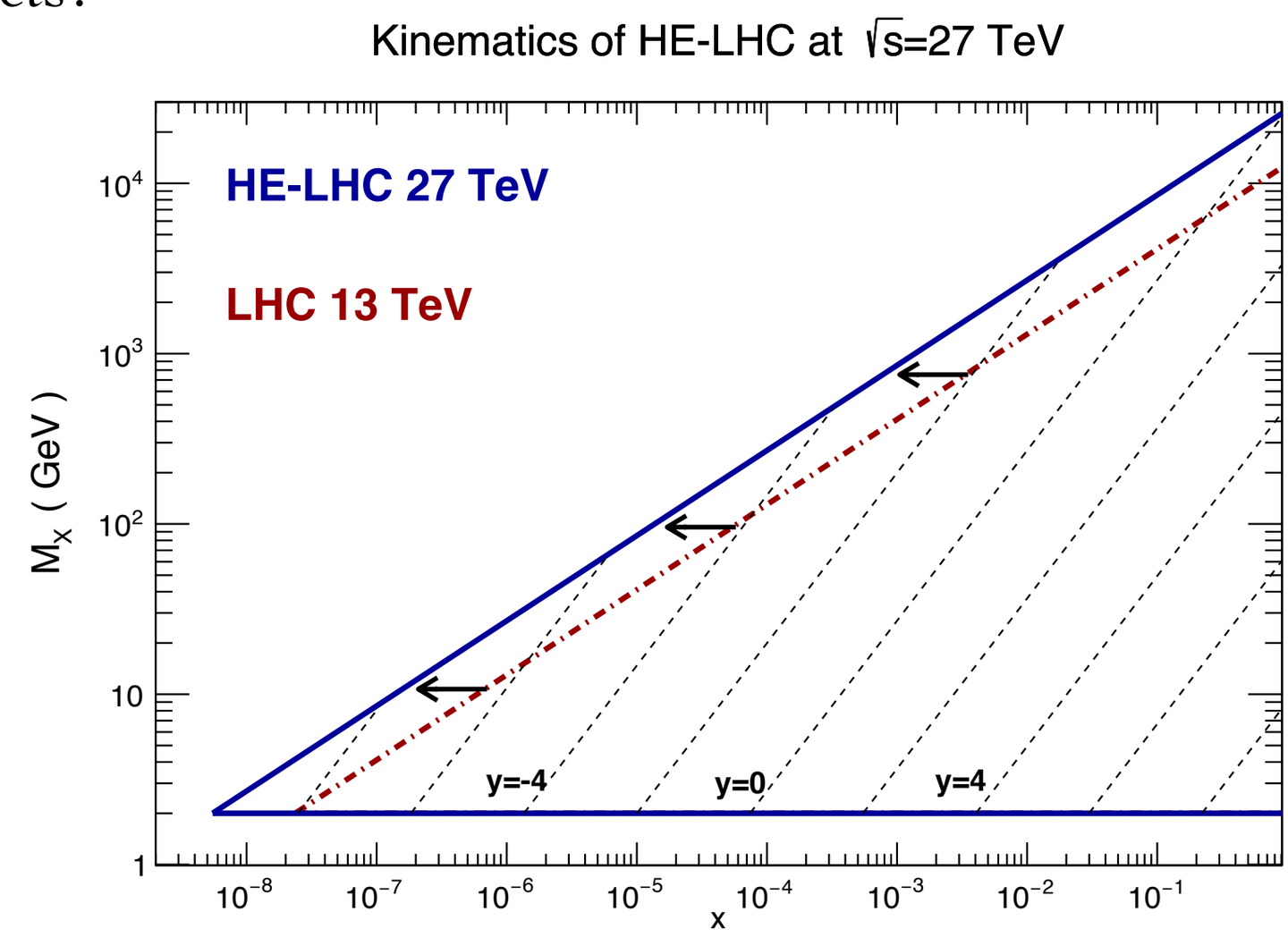
- **HL-LHC**: precision machine $\Rightarrow$ need **high precision PDFs** to control theory uncertainties for searches and precision measurements.
  - Higher statistics $\rightarrow$ increased coverage at **high x** where PDFs currently less well constrained.
  - Must systematically account for contributions/uncertainties often omitted before: **EW corrections, theoretical uncertainties**….
  - **NNLO** will be the standard. **New tools** for fitting?

- High **precision data** opportunity for PDF fitting:
  - Rarer processes increasingly abundant use in fits.
  - Increasingly differential information.



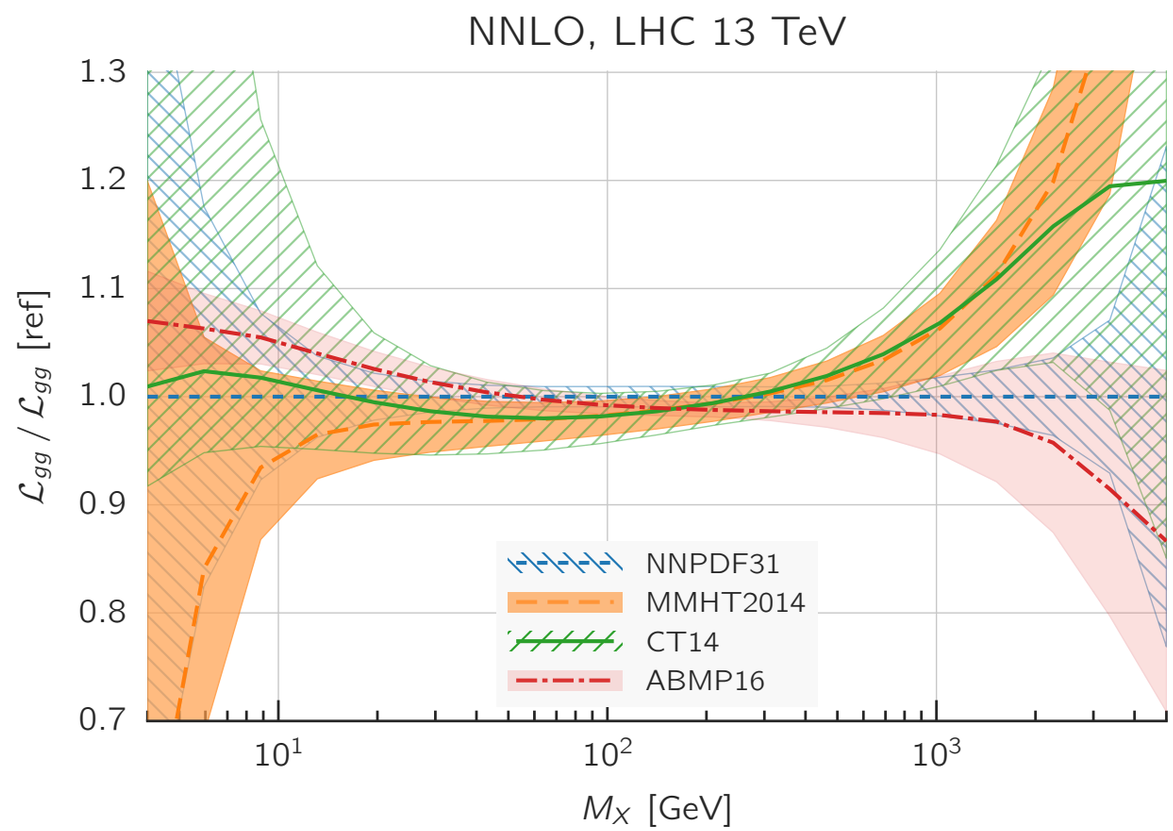
PDFs at the HE-LHC

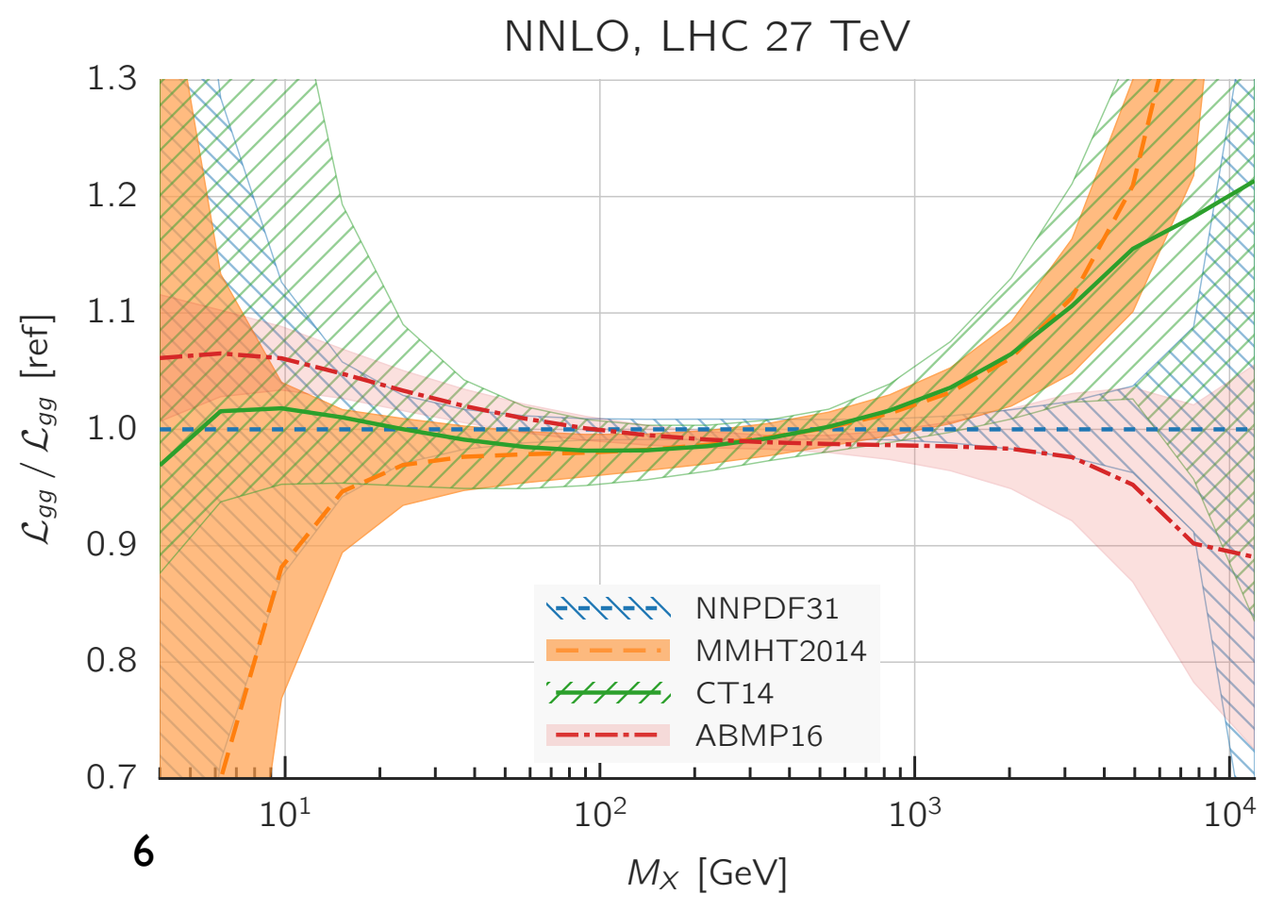
- **HE-LHC**: many/all of previous considerations apply here as well. In addition, higher energy reach:
  - Higher Q^2 coverage $\rightarrow$ role of e.g. **EW corrections** could be larger.
  - Increased coverage in lower x, higher sensitivity to e.g. **resummation** effects?



PDF luminosities

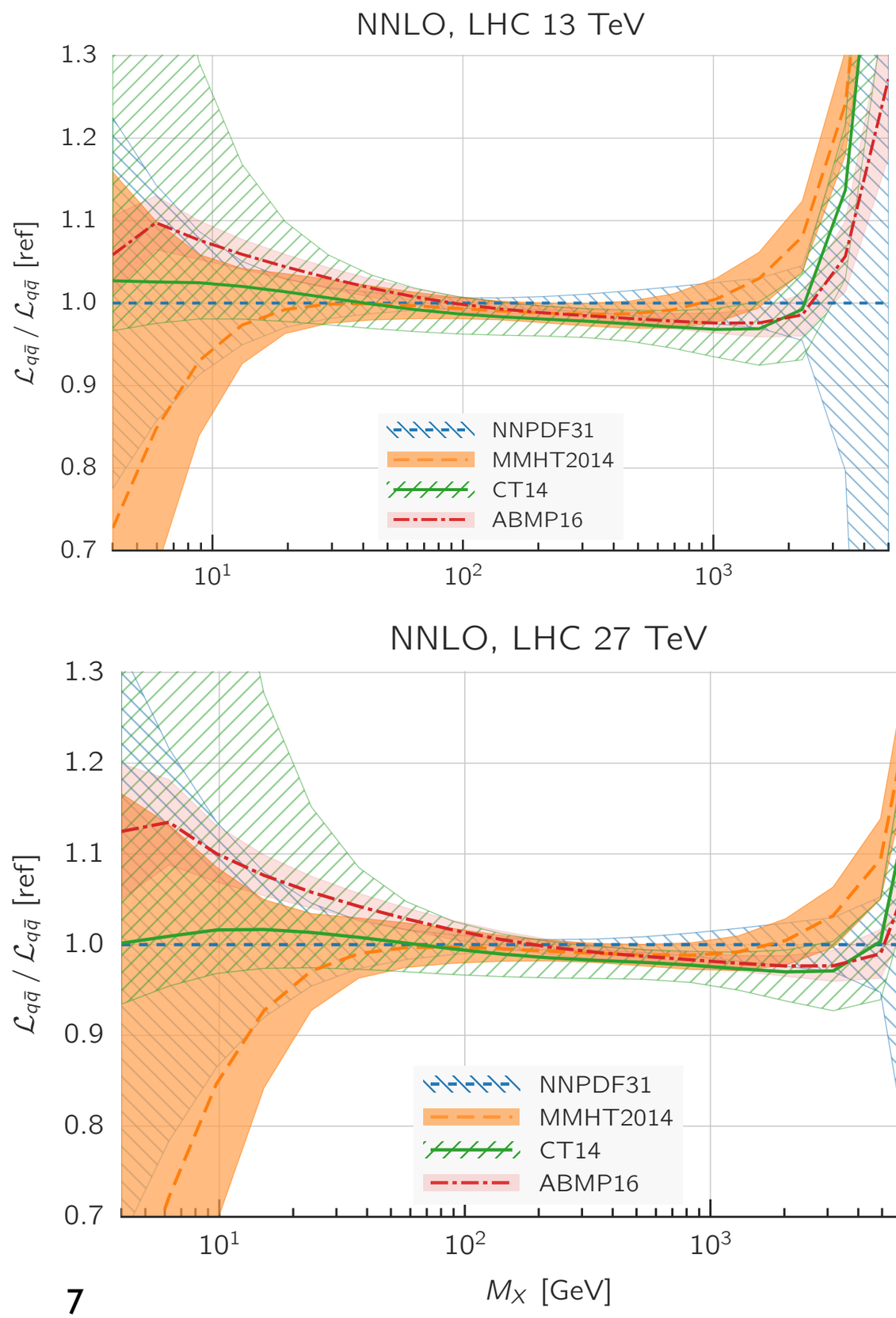
- **HE-LHC**: impact on gg luminosity not dramatic.
- **Lower masses** - uncertainties increased somewhat.
- **Higher masses** - increased reach, uncertainties somewhat lower.





PDF luminosities

- Picture similar for other luminosities, e.g. $q\bar{q}$



- Much recent progress in PDFs - this talk will only cover a small amount.
- For more details, see arXiv:1709.04922 (To appear in Physics Reports).

The Structure of the Proton in the LHC Precision Era

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[d] *Nikhef, Science Park 105, NL-1098 XG Amsterdam, The Netherlands*

Abstract

We review recent progress in the determination of the parton distribution functions (PDFs) of the proton,

Progress in PDF fits

Progress in PDF fits

- Global groups busily updating fits to include the plentiful and precise new LHC data. **ABMP16, NNPDF3.1** released recently, **MMHT17/18** and **CT17** on their way.

New datasets in NNPDF3.1

Measurement	Data taking	Motivation
Combined HERA inclusive data	Run I+II	quark singlet and gluon
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive W, Z rap 7 TeV	2011	strangeness
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 and 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 2.76 TeV jets	2012	medium and large-x gluon
LHCb W,Z rapidity dists 7 TeV	2011	large-x quarks
LHCb W,Z rapidity dists 8 TeV	2012	large-x quarks

CT17p — data to be included

- Previous LHC and HERA 1 data included in CT14 will be superseded by updated Run 1 and HERA 1+2 data; adding new LHC data, especially on Z boson p_T and top quark differential distributions
  - Combined HERA1+2 DIS [1506.06042] update
  - LHCb 7 TeV Z, W muon rapidity dist. [1505.07024] update
  - LHCb 8 TeV Z rapidity dist. [1503.00963] update
  - ATLAS 7 TeV inclusive jet [1410.8857] update
  - CMS 7 TeV inclusive jet (extended y range)[1406.0324] update
  - ATLAS 7 TeV Z pT dist. [1406.3660] new
  - LHCb 13 TeV Z rapidity dist. [1607.06495] update
  - CMS 8 TeV Z pT and rapidity dist. (double diff.) [1504.03511] new
  - CMS 8 TeV W, muon asymmetry dist. [1603.01803] update
  - ATLAS 7 TeV W/Z, lepton(s) rapidity dist. [1612.03016] update
  - CMS 7,8 TeV tT differential distributions new
  - ATLAS 7,8 TeV tT differential distributions new

MMHT (2016 fit)

	no. points	NLO χ^2_{pred}	NLO χ^2_{new}	NNLO χ^2_{pred}	NNLO χ^2_{new}
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	19.6	20.5	14.7	15.5
LHCb 7 TeV $W+Z$	33	50.1	45.4	46.5	42.9
LHCb 8 TeV $W+Z$	34	77.0	58.9	62.6	59.0
LHCb 8TeV e	17	37.4	33.4	30.3	28.9
CMS 8 TeV W	22	32.6	18.6	34.9	20.5
CMS 7 TeV $W+c$	10	8.5	10.0	8.7	8.0
D0 e asymmetry	13	22.2	21.5	27.3	25.8
total	3738/3405	4375.9	4336.1	3741.5	3723.7

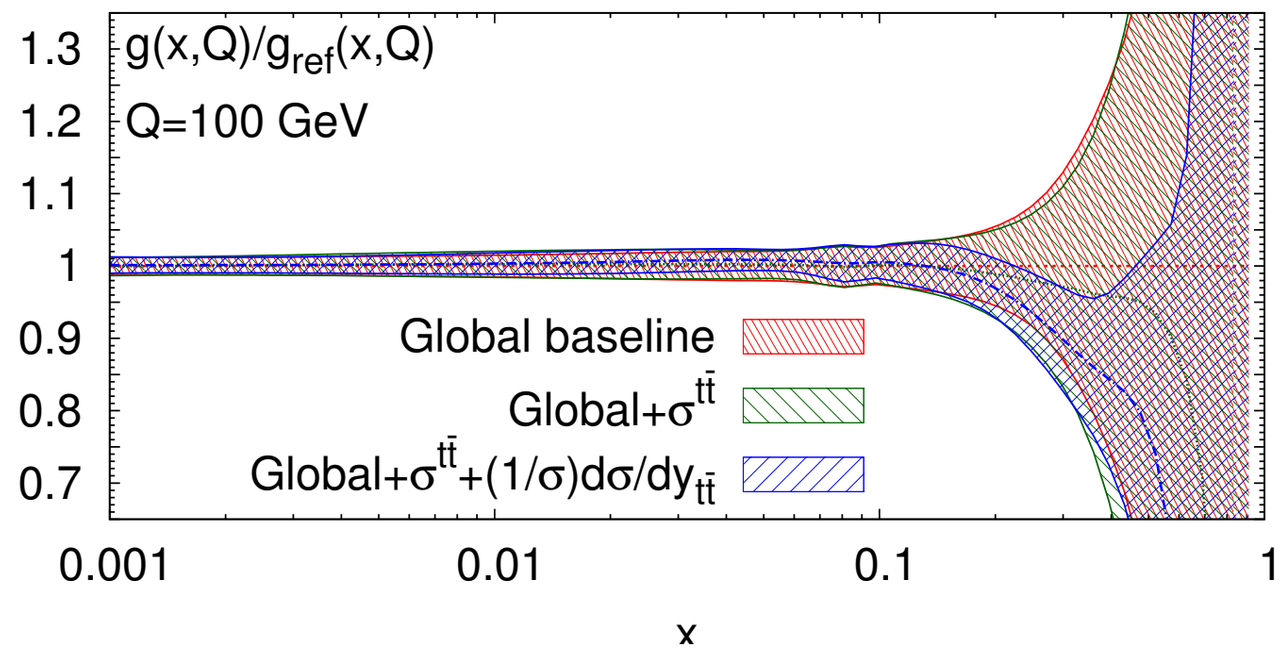
Taken from DIS'17

LHC impact

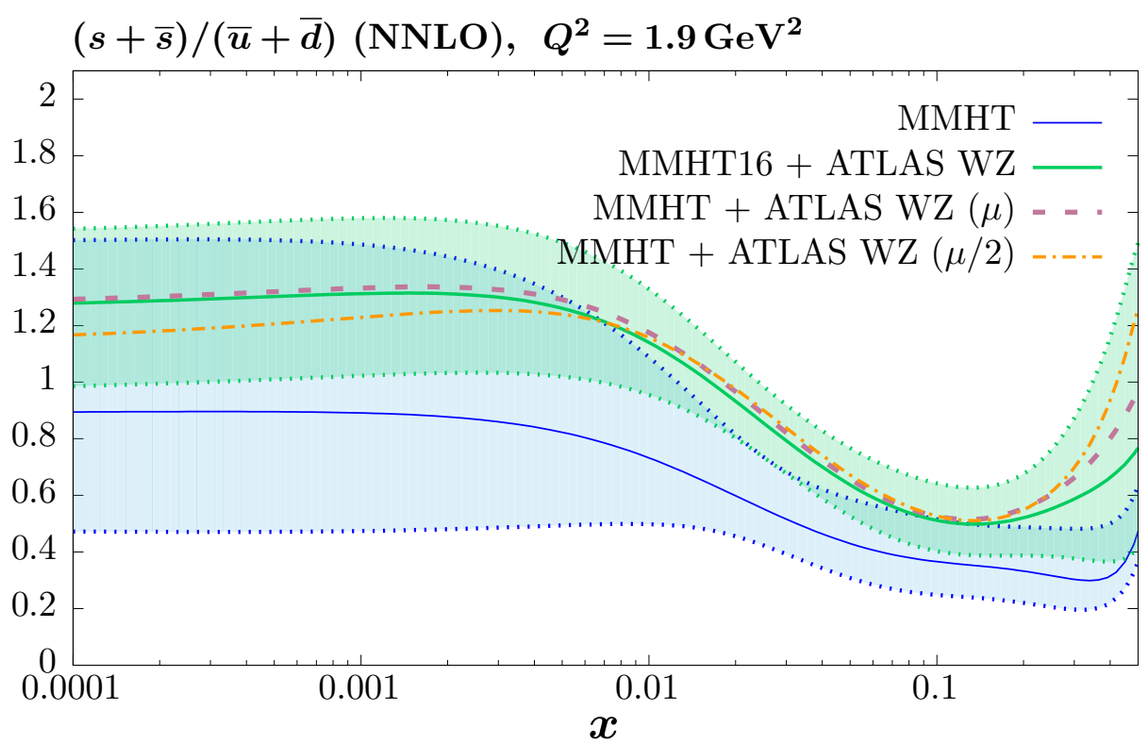
- These LHC data, combined with new NNLO theory, are now playing a significant role in constraining the PDFs.

M. Czakon et al., JHEP 1704 (2017) 044

- **Differential top**: increased sensitivity vs. total cross section.
- Fits performed with latest NNLO theory. Impact on gluon at high x .



LHL et al., arXiv:1708.00047



- High precision **ATLAS W, Z data** at 7 TeV. Sensitive to strange component.
- Impact on proton strangeness significant. Some movement towards flavour symmetric sea.

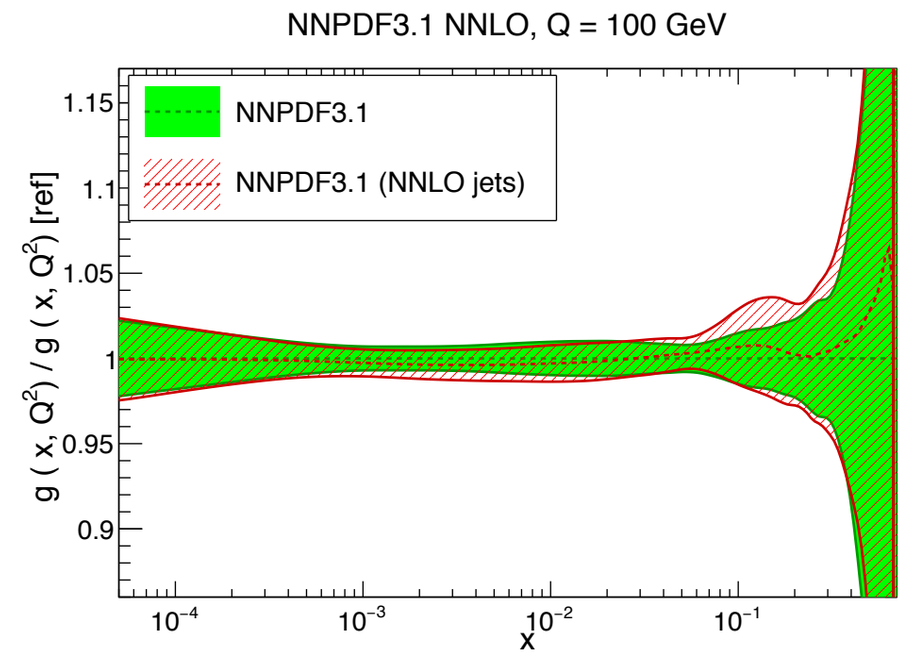
ATLAS collab., Eur. Phys. J C77 (2017) 367

LHC impact

J. Currie et al., Phys. Rev. Lett. 118 (2017) no 7 072002

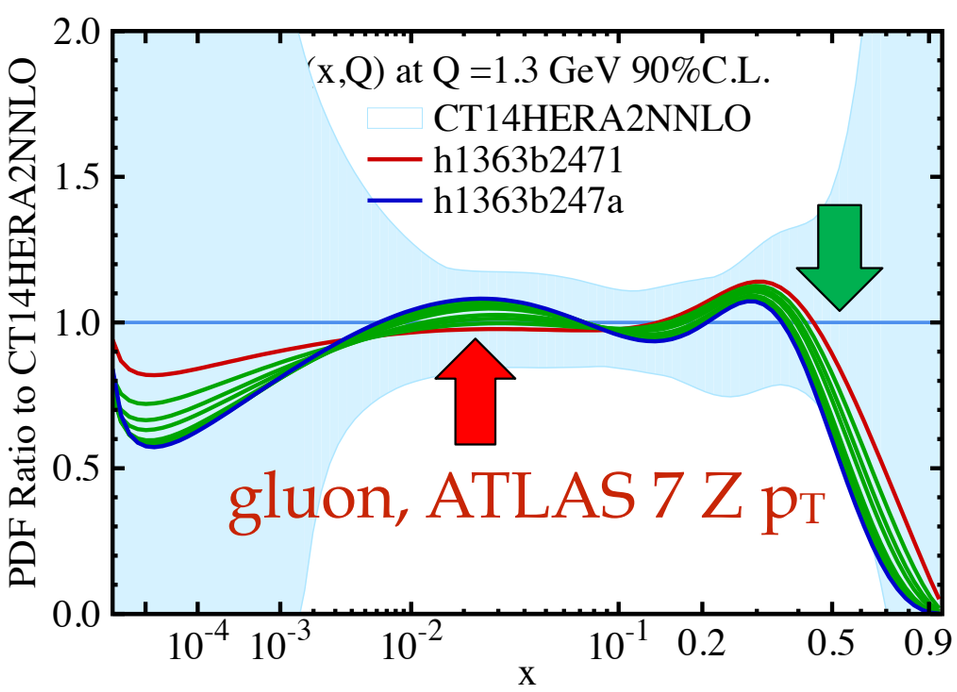
- **Inclusive jets** now calculated at NNLO → another PDF handle. LHC jet constraint on gluon consistent with e.g. $t\bar{t}$.
- Some stability when including full theory seems to be present.

R. D. Ball et al., Eur. Phys. J. C77 (2017) no. 10, 663



J. Gao, "Progress on CTEQ-TEA PDFs", DIS2017

CT17p best-fit vs. CT14 HERA2

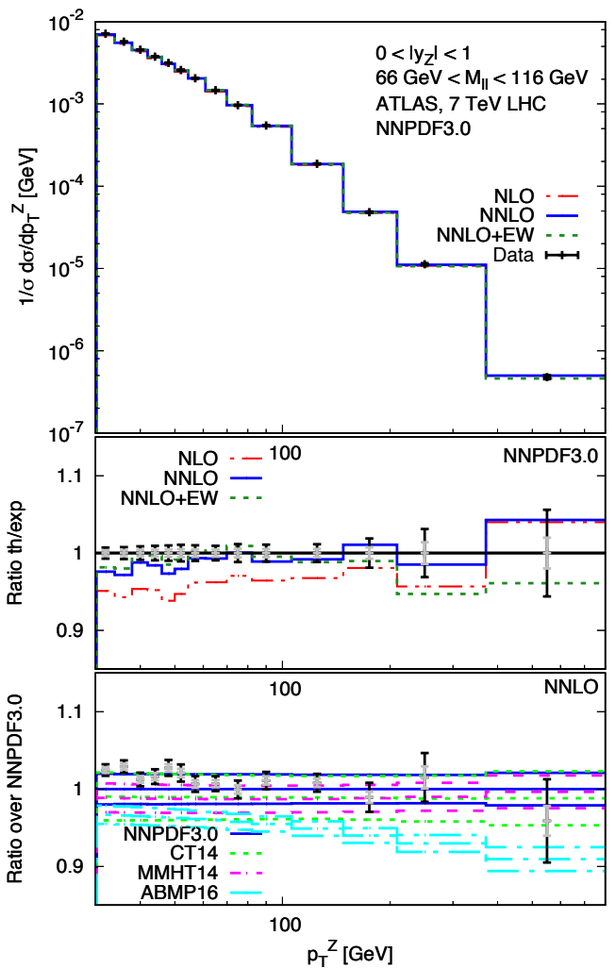


- **Z boson $p_\perp$ distribution.** Sensitive to gluon at high x. New NNLO calculation allows constraints on PDFs at this order.

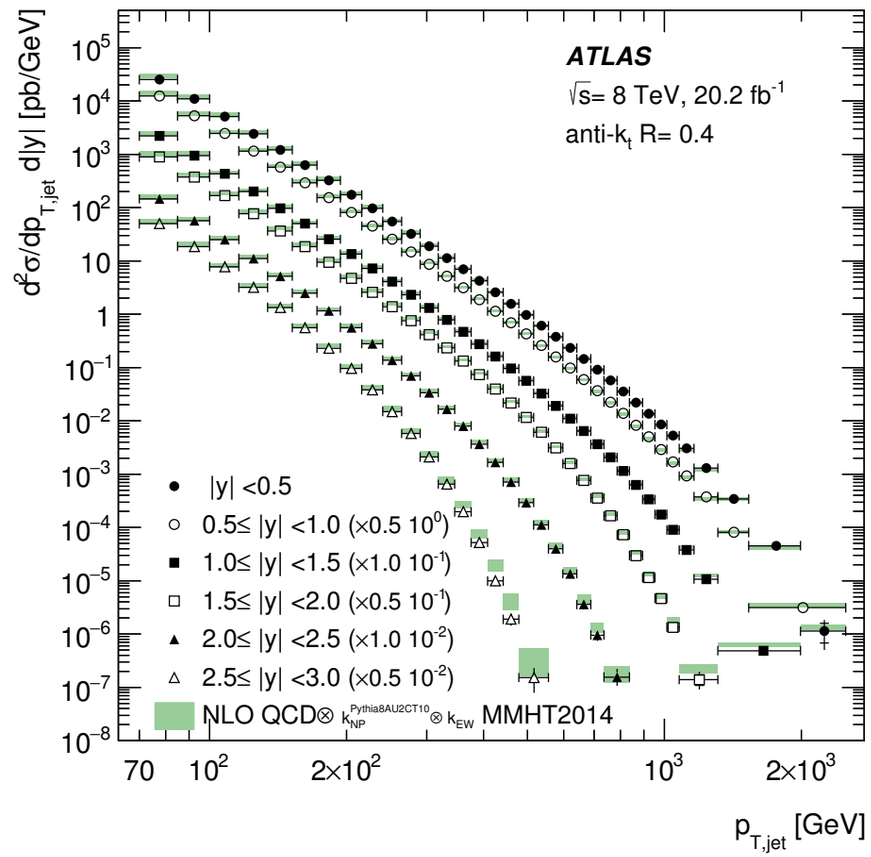
Boughezal et al., Phys. Rev. Lett. 116 (2016) no 15 152001

LHC questions

- However, **challenges** for including these increasingly precise data!



ATLAS collab., JHEP 1709(2017) 020



- **ATLAS jets**. Systematics dominated. By eye description looks good, but issues describing data across all rapidities.

χ^2/ndf	$p_T^{jet,max}$ $R = 0.4$	$R = 0.6$
$p_T > 70$ GeV		
CT14	349/171	398/171
HERAPDF2.0	415/171	424/171
NNPDF3.0	351/171	393/171
MMHT2014	356/171	400/171

- To achieve acceptable χ^2 for $Z\ p_\perp$ data, include additional $\sigma^{\text{uncorr.}}$ due to missed theory/exp. uncertainties.

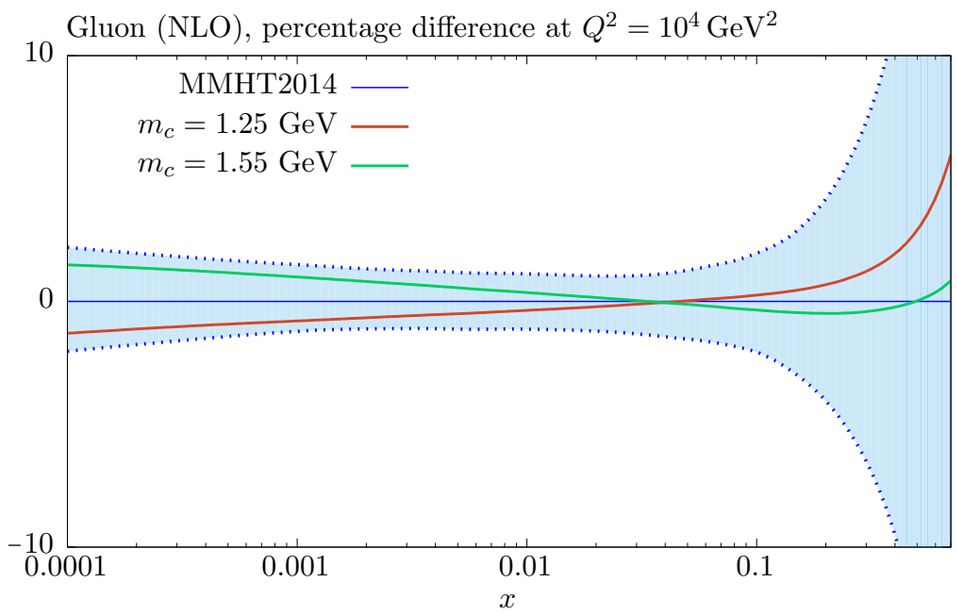
Boughezal et al., JHEP 1707 (2017) 130

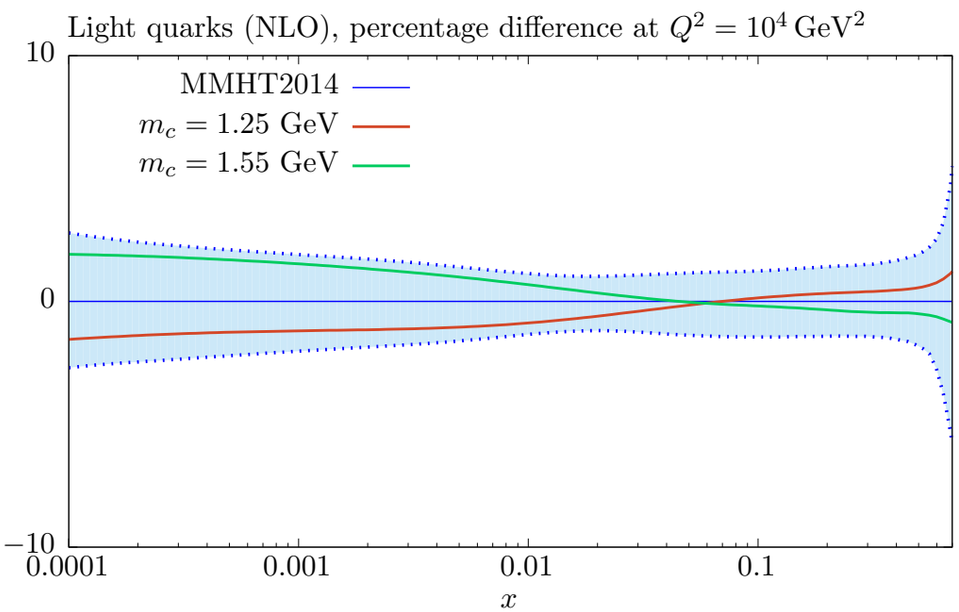
Bin	Order	N_{dat}	$\chi^2_{\text{d.o.f.}}$ (NN30)	$\chi^2_{\text{d.o.f.}}$(CT14)	$\chi^2_{\text{d.o.f.}}$ (MMHT14)	$\chi^2_{\text{d.o.f.}}$(ABMP16)
All bins	NLO	42	9.9	15	9.1	n.a.
	NNLO	42	4.9	6.7	7.4	13.
	NNLO+EW	42	3.7	5.2	5.6	12.

Theoretical uncertainties

Parametric uncertainties

- Due to input of α_S and **heavy quark mass**, especially the later requires further investigation
- **MMHT** study - PDFs with different input charm pole mass ± 0.15 GeV.





LHL et al., Eur. Phys. J C76 (2016) no. 1, 10

	σ	PDF unc.	m_c var.
W^+ LHC (14 TeV)	12.5	$^{+0.22}_{-0.18}$ $\left(^{+1.8\%}_{-1.4\%}\right)$	$^{+0.091}_{-0.12}$ $\left(^{+0.73\%}_{-0.93\%}\right)$
W^- LHC (14 TeV)	9.3	$^{+0.15}_{-0.14}$ $\left(^{+1.6\%}_{-1.5\%}\right)$	$^{+0.064}_{-0.075}$ $\left(^{+0.69\%}_{-0.81\%}\right)$
Z LHC (14 TeV)	2.06	$^{+0.035}_{-0.030}$ $\left(^{+1.7\%}_{-1.5\%}\right)$	$^{+0.021}_{-0.025}$ $\left(^{+1.03\%}_{-1.2\%}\right)$

	σ	PDF unc.	m_c var.
Higgs Tevatron (1.96 TeV)	0.87	$^{+0.024}_{-0.030}$ $\left(^{+2.7\%}_{-3.4\%}\right)$	$^{-0.0060}_{+0.0070}$ $\left(^{-0.68\%}_{+0.79\%}\right)$
Higgs LHC (7 TeV)	14.6	$^{+0.21}_{-0.29}$ $\left(^{+1.4\%}_{-2.0\%}\right)$	$^{+0.025}_{-0.019}$ $\left(^{+0.17\%}_{-0.13\%}\right)$
Higgs LHC (14 TeV)	47.7	$^{+0.63}_{-0.88}$ $\left(^{+1.3\%}_{-1.8\%}\right)$	$^{+0.27}_{-0.22}$ $\left(^{+0.57\%}_{-0.48\%}\right)$

- Impact on benchmark cross sections can be as large/larger than PDF uncertainties.
- Increases at low x, i.e. **higher energies**.

Missing higher orders

- Uncertainties due to missing higher-order corrections (**MHOU**).
- Scale variations around certain nominal choice by a factors of two (widely used). Ambiguities in the nominal scale choice, underestimation issues…
- More advanced approaches:
  - **Cacciari-Houdeau**: uniform prior pdf and Bayesian approach to determined confidence interval from behaviour of known perturbative coefficients.
  - Series acceleration method: e.g., **Passarino-David**, a uniform pdf assumed between known perturbative result and the approximate full result.

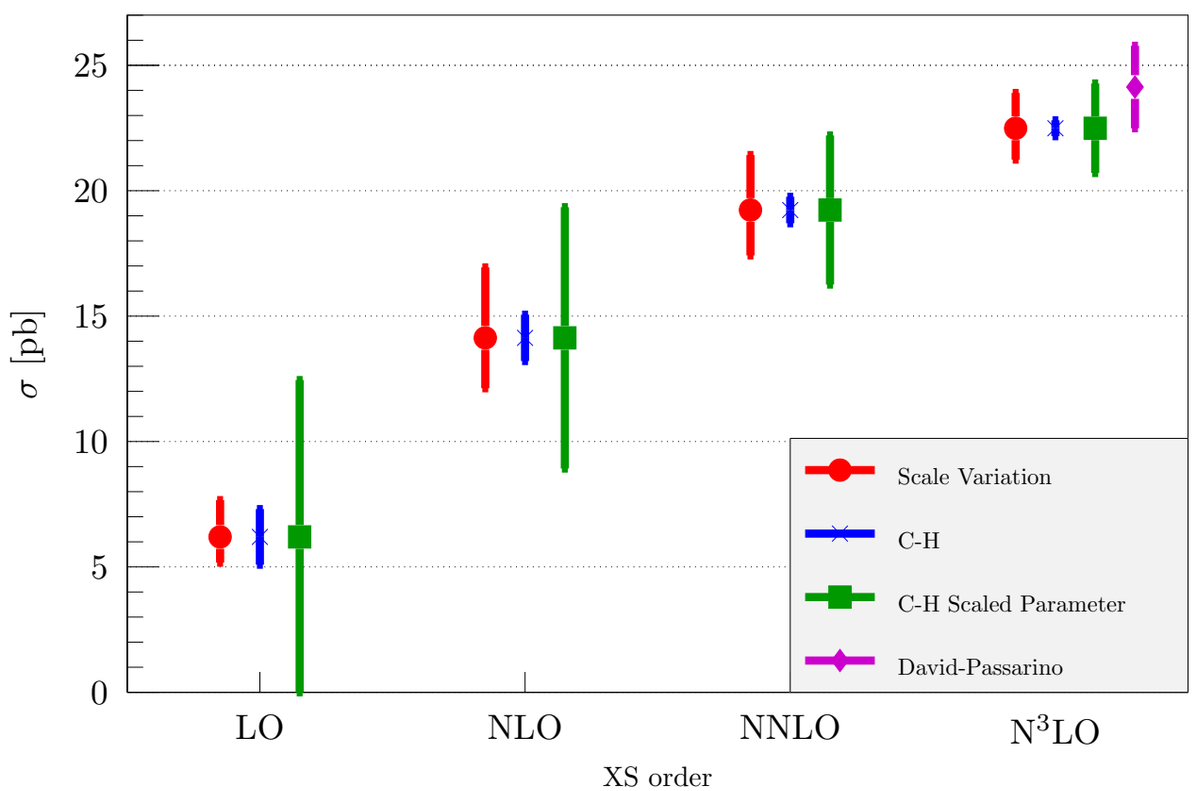


illustration for Higgs production in gluon fusion at LHC 8 TeV up to approximate N3LO

easy for a total rate; need to generate for correlations in differential observables

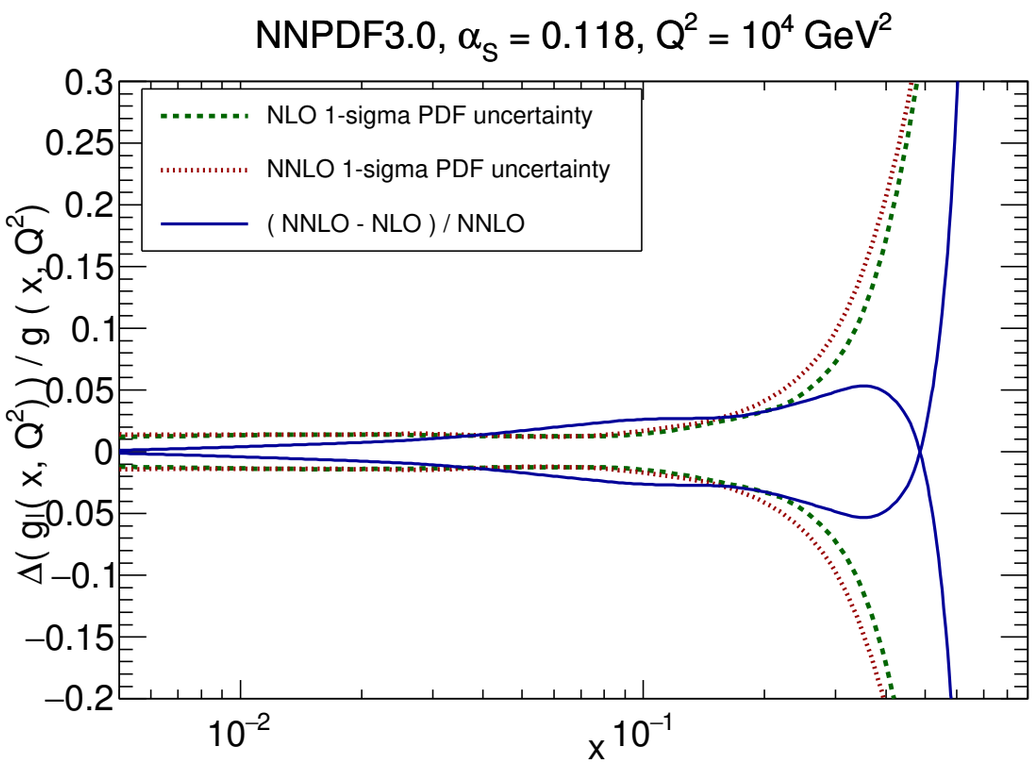
S. Forte et al., Phys. Lett. B731 (2014) 136-140

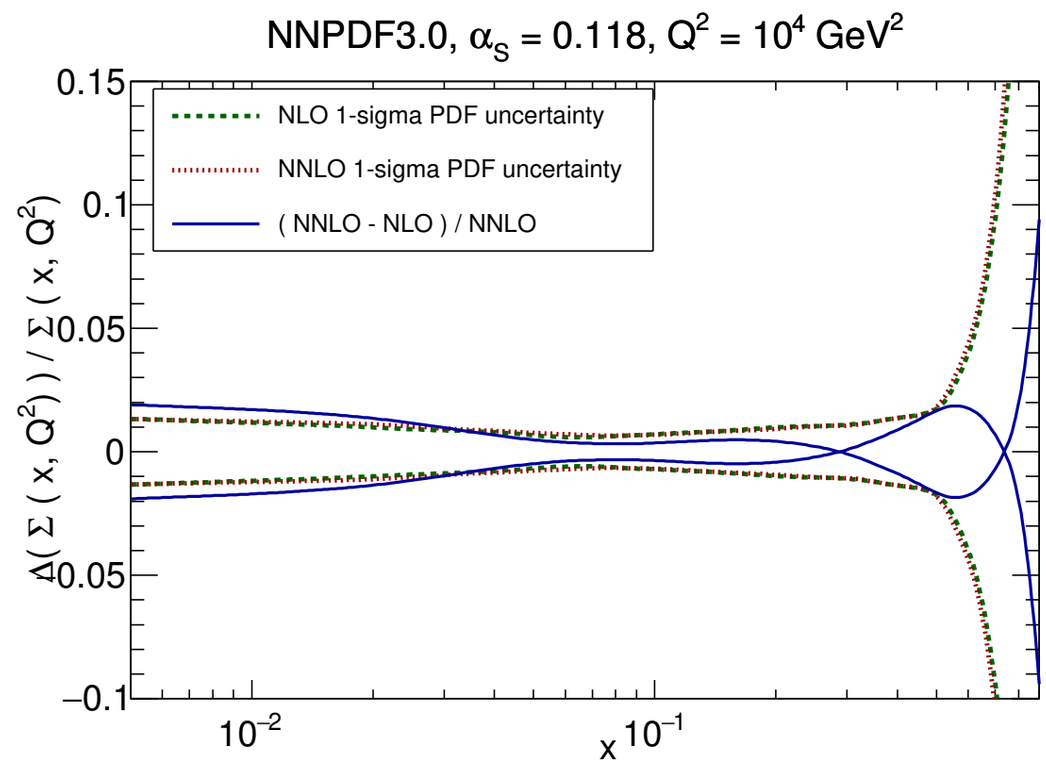
Missing higher orders - PDFs

- MHOU associated with the global analysis of PDFs, in e.g. QCD splitting kernels and matrix elements.

- **Global approaches** - comparing the outcome PDFs for fit at different orders. Gives ~ upper limit on MHOU. Can be comparable to PDF uncertainties.

R. Ball et al., JHEP 1504 (2015) 040





- **Other approaches**: compare PDFs with different scale choices or more sophisticated treatment of the MHOU as correlated systematics.

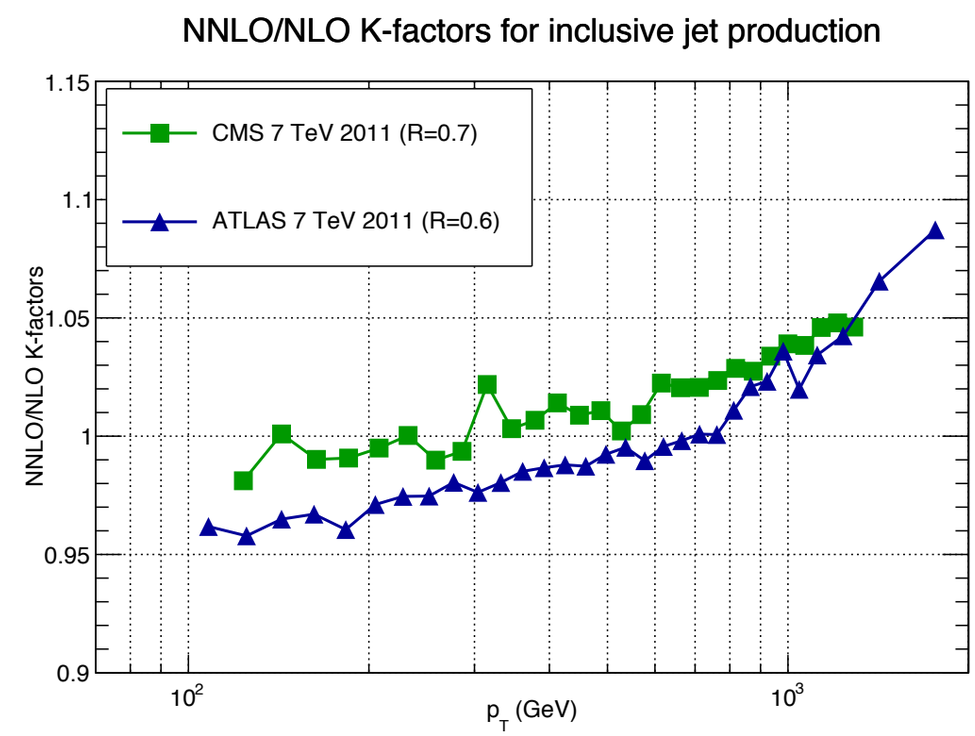
F.L. Olness, D.E. Soper, Phys. Rev. D81 (2010) 035018

The NNLO standard - tools

Tools

- **APPLgrid** and **FastNLO**: tools for storing NLO calculations to grid, for fast convolution with arbitrary PDF set.
- Essential for precise PDF fits with NLO theory.
- Huge progress in **NNLO calculations**, but very computationally expensive - not directly usable in PDF fits.
- Simple (PDF dependent) **K-factors** generally used.

$$K_{\mathrm{NNLO}} = \frac{\sigma^i_{\mathrm{NNLO}}}{\sigma^i_{\mathrm{NLO}}}$$



- Moving beyond this: the **APPLfast** project.

Tools

- **APPLfast** will make fast **NNLOJET** (IPPP, Zurich, ETH et al.) calculation feasible for inclusive W, Z, Z + jet, H + jet, inclusive jets in ep and pp…
- Compute once (~ 200K CPU hours)- after that in much less than a second!

the APPLgrid project

fastNLO

C. Gwenlain, DIS2017

job type	# jobs	events/job	runtime/job	# events	total output	total runtime
LO	10	140 M	20.6 h	1.4G	24 MB	206 h
NLO-R	200	6 M	19.0 h	1.2G	1.3 GB	3800 h
NLO-V	200	5 M	21.2 h	1.0G	1.2 GB	4240 h
NNLO-RRa	5000	60 M	22.5 h	0.3G	26 GB	112500 h
NNLO-RRb	5000	40 M	20.3 h	0.2G	27 GB	101500 h
NNLO-RV	1000	200 M	19.8 h	0.2G	6.4 GB	19800 h
NNLO-VV	300	4 M	20.5 h	1.2G	2.0 GB	6150 h
total	11710	–	–	5.5G	64 GB	248196 h

3 × 11710 grids/tables + all NNLOJET output!
Final 3 files for analysis are O(10MB) each

- This will become the standard in the future.
- **Benchmarking** exercises (are fitters using comparable NLO, NNLO input grids?) and centralising to avoid 'double counting' should be looked at.

Electroweak corrections

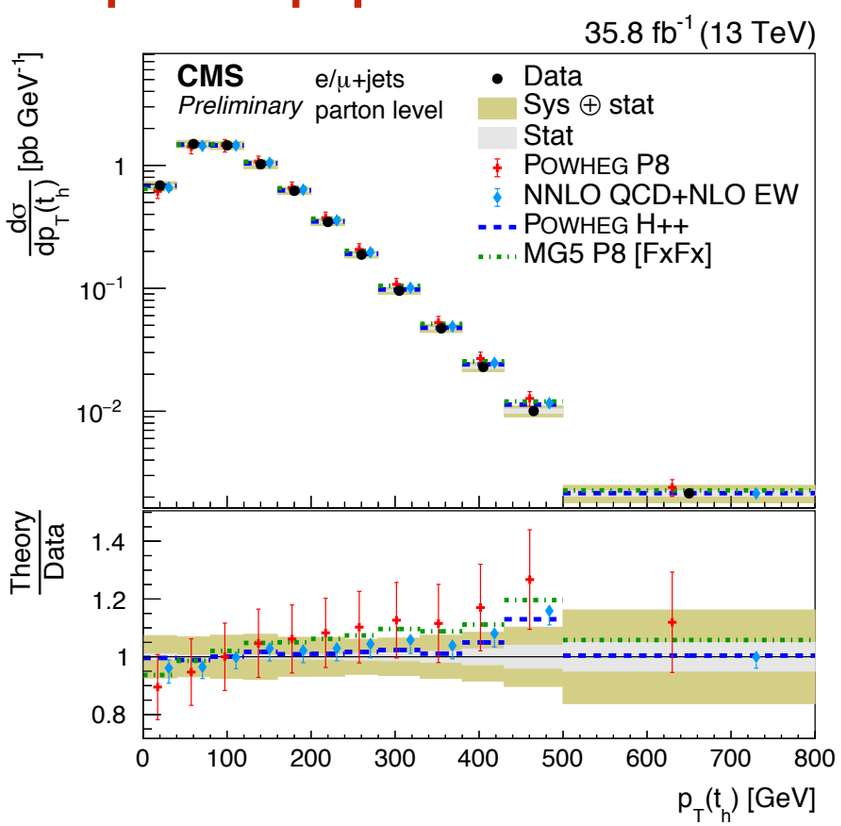
Electroweak effects - cross sections

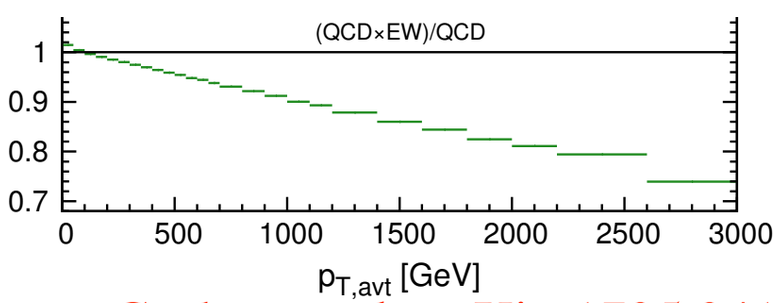
- **EW corrections** can contribute at same level as **NNLO QCD** corrections:

$$\alpha_s(M_Z)^2 \sim \alpha_{\rm EM}(M_Z)$$

- Particularly at **large $p_\perp$/invariant mass** due to the Sudakov logarithms. Can be crucial when confronting precision data at **HL-LHC**.

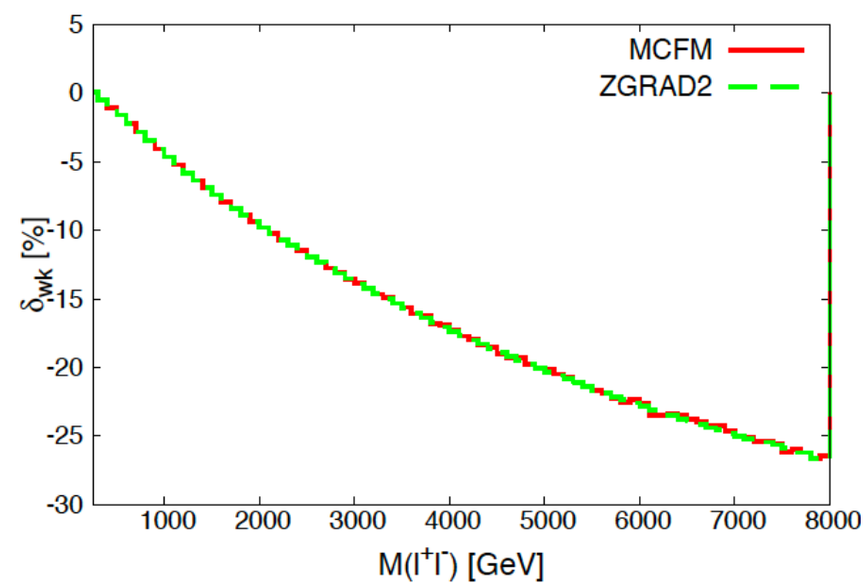
pT of top quark at LHC 13 TeV



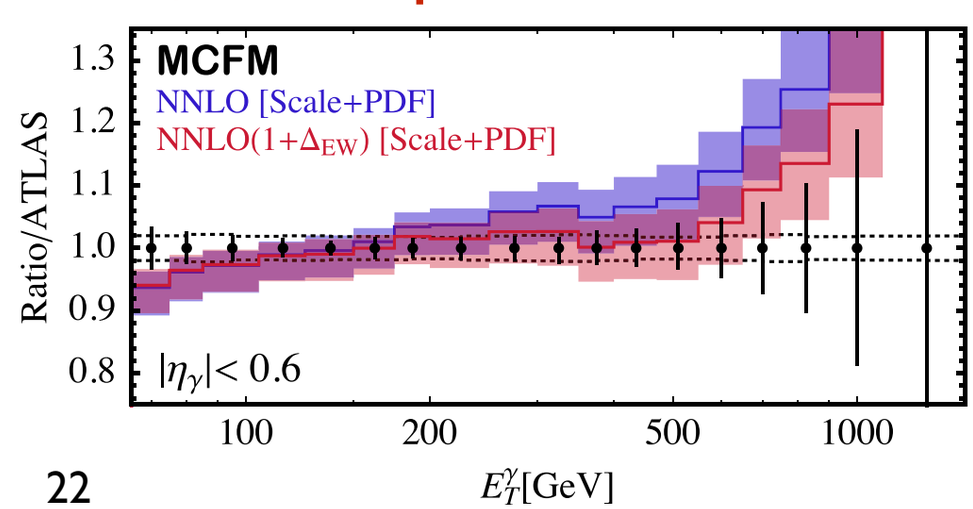


Czakon et al., arXiv:1705.04105

high mass Drell-Yan at LHC 13 TeV



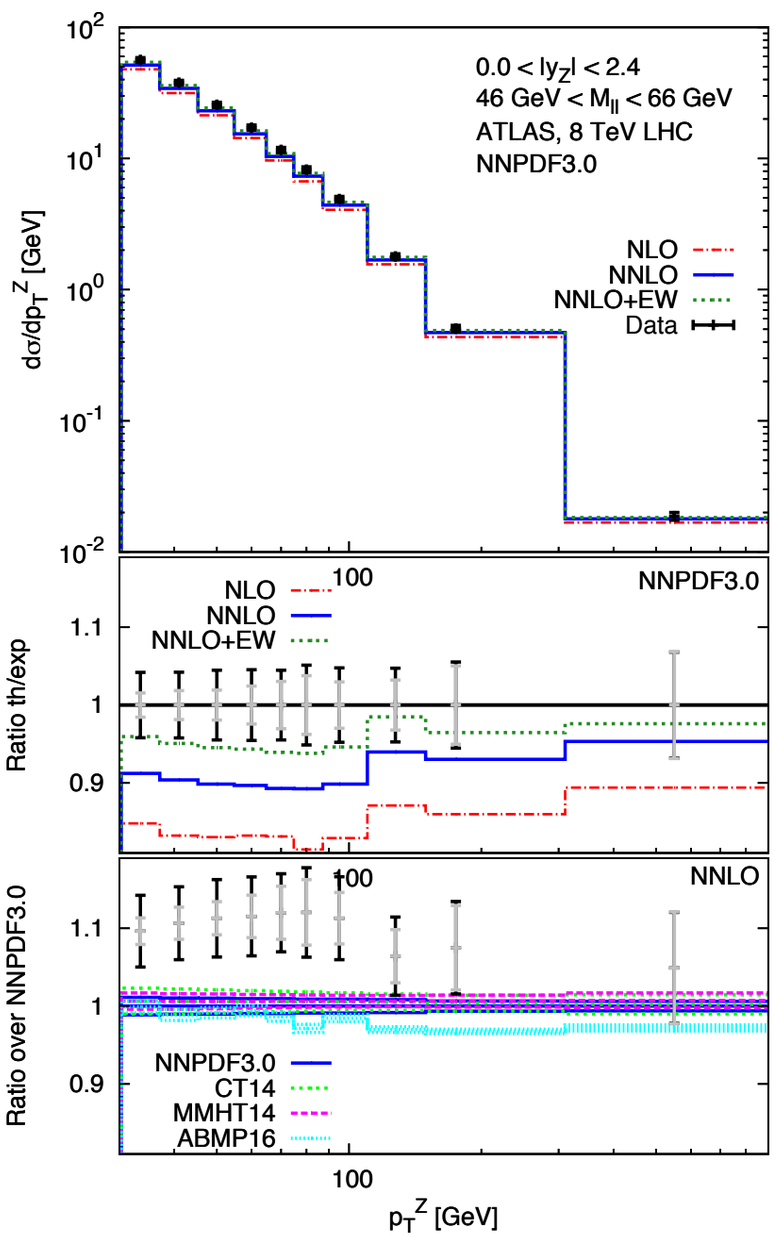
E_T of direct photon at LHC 8 TeV



Campbell et al., Phys. Rev. Lett. 118 (2017) no.22, 222001

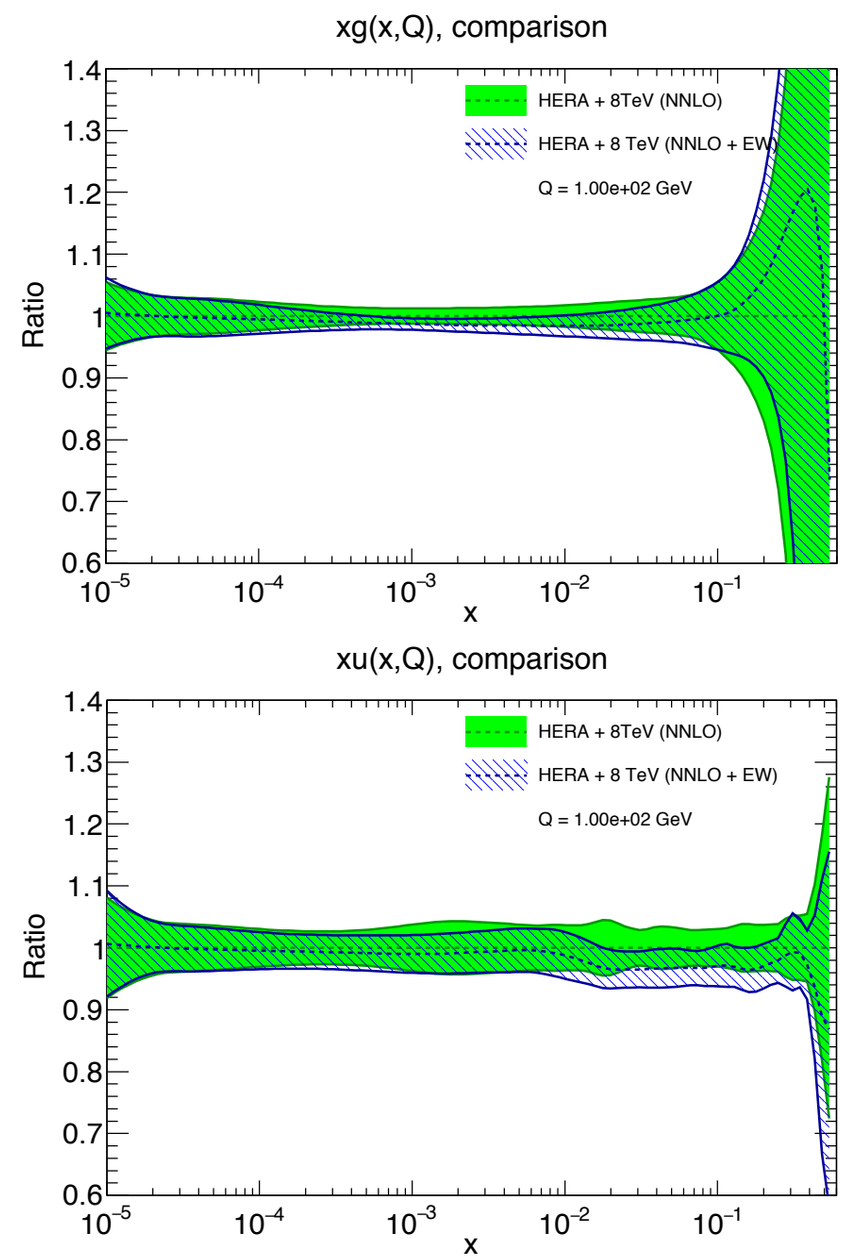
- In certain regions EW corrections must to be included in PDF fits for a good description of the data; impact on PDFs can be significant.

inclusive dilepton p_T at 8 TeV



positive EW corrections for mass below Z peak

impact on gluon and u-quark

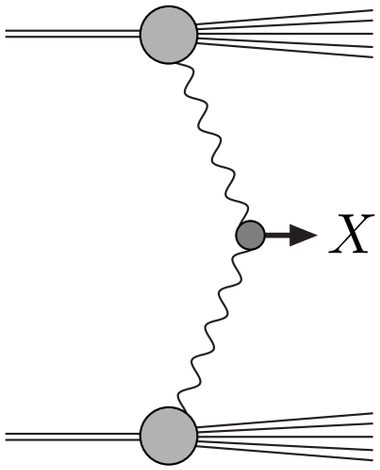


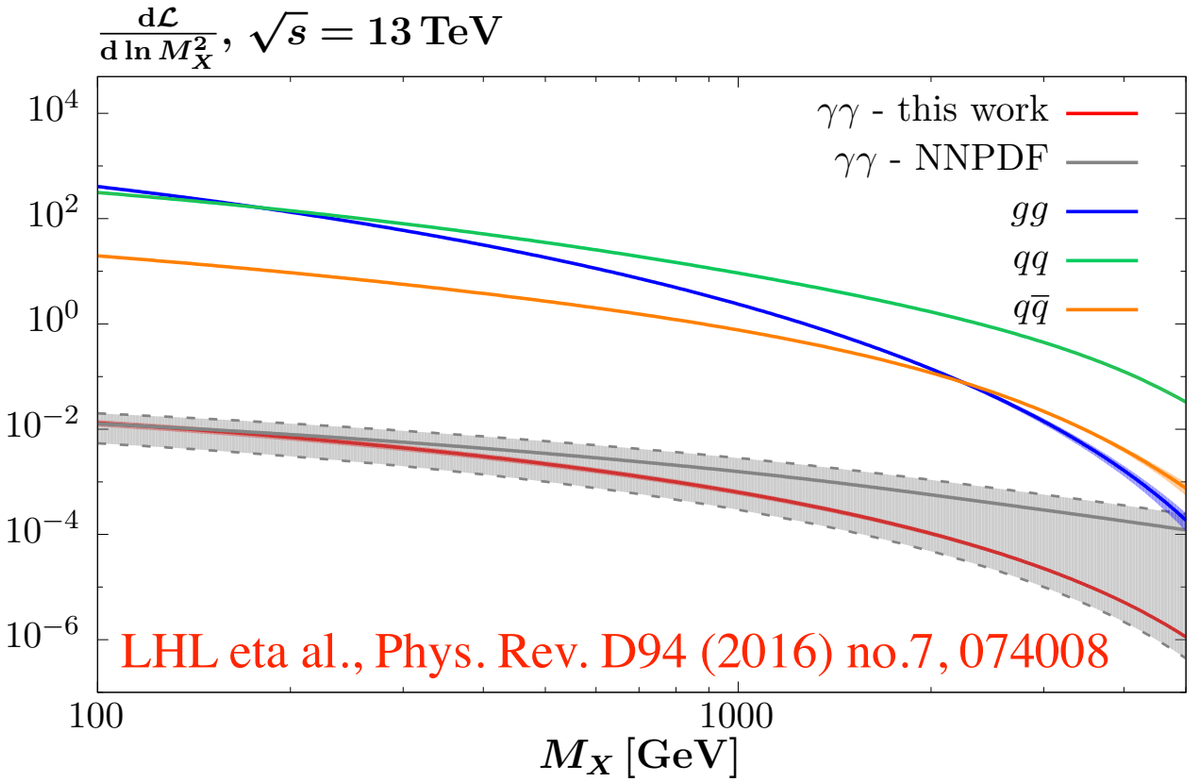
PDF fits with only HERA data and 8 TeV Z p_T data

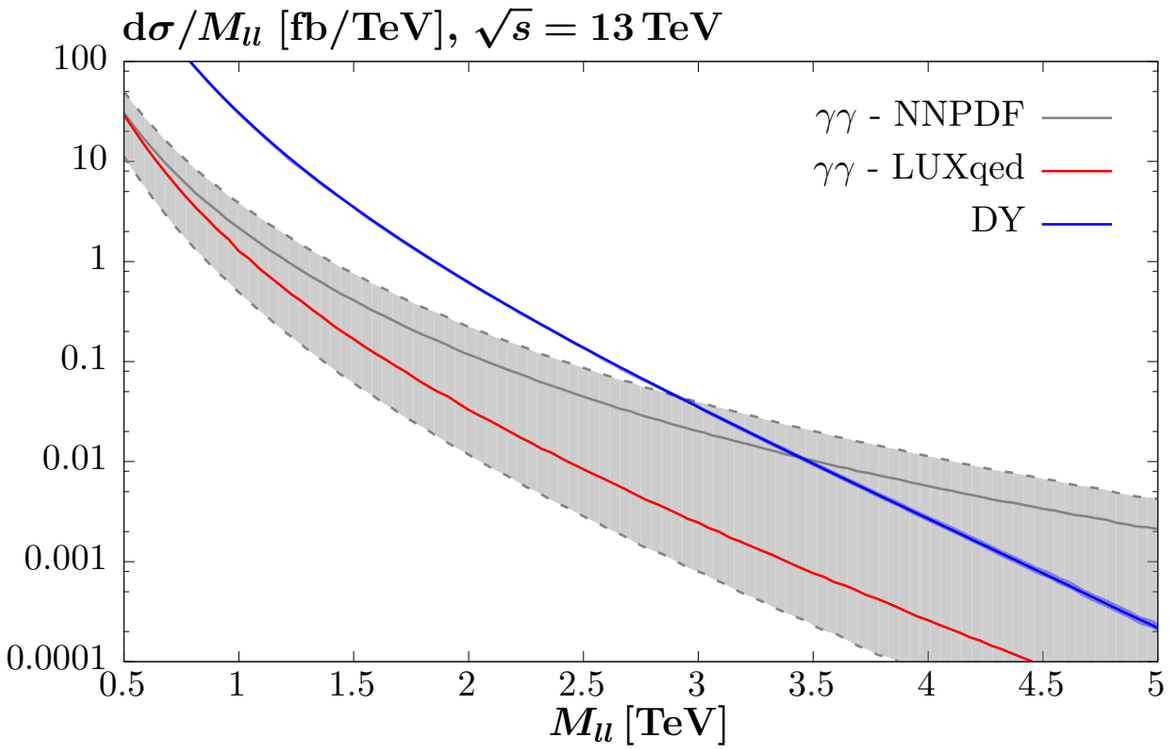
Boughezal et al., JHEP 1707 (2017) 130

The photon PDF

- Potentially important part of EW corrections is due to initial-state photon contributions. Requires inclusion via **photon PDF**.
- Recap: 2016 studies indicated that contribution to DY, WW, $t\bar{t}$ …could be large at high mass, with large uncertainty.
- Issue for high precision **HL-LHC**, or higher **HE-LHC** energies? **No!**





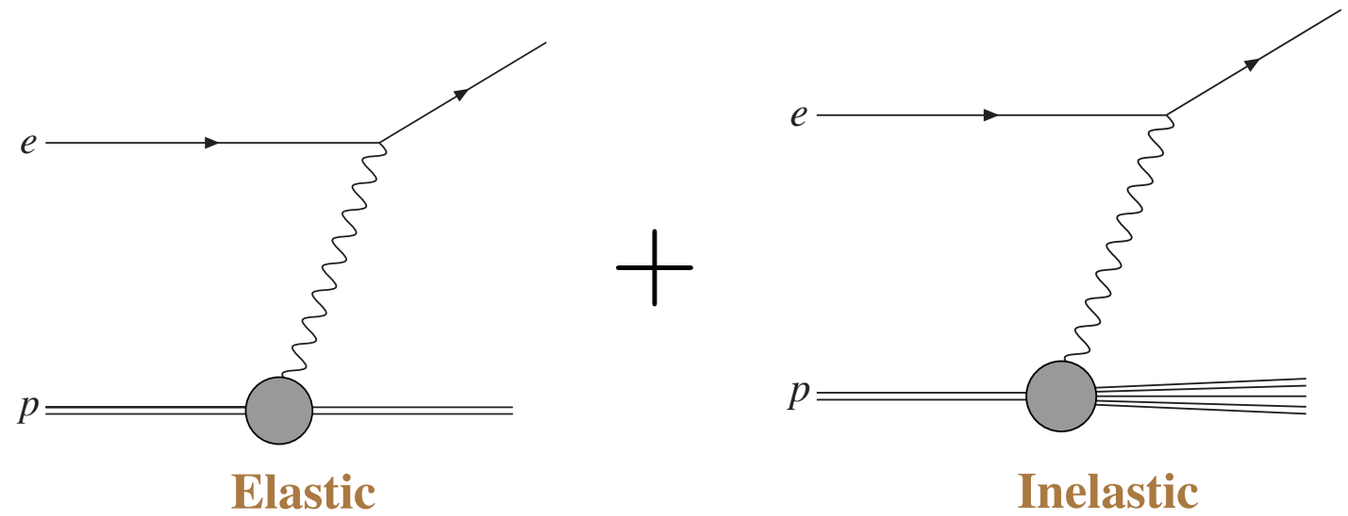


- 'Agnostic' approach of **NNPDF3.0QED** far **too conservative**. Photon PDF known to high precision in terms of measured ep scattering.

LHL eta al., Phys. Rev. D94 (2016) no.7, 074008

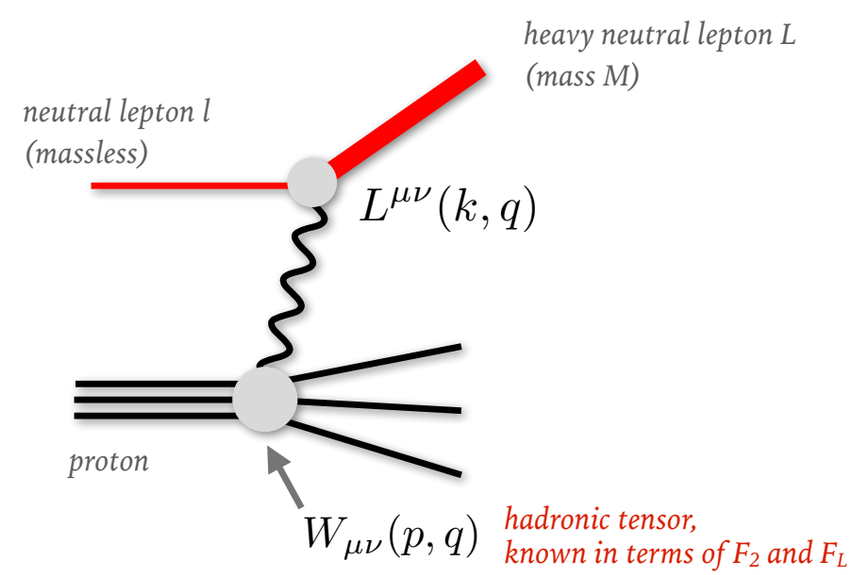
A. D. Martin, M. G. Ryskin, Eur. Phys. J. C74 (2014) 3040

$\gamma(x, Q^2) \sim$



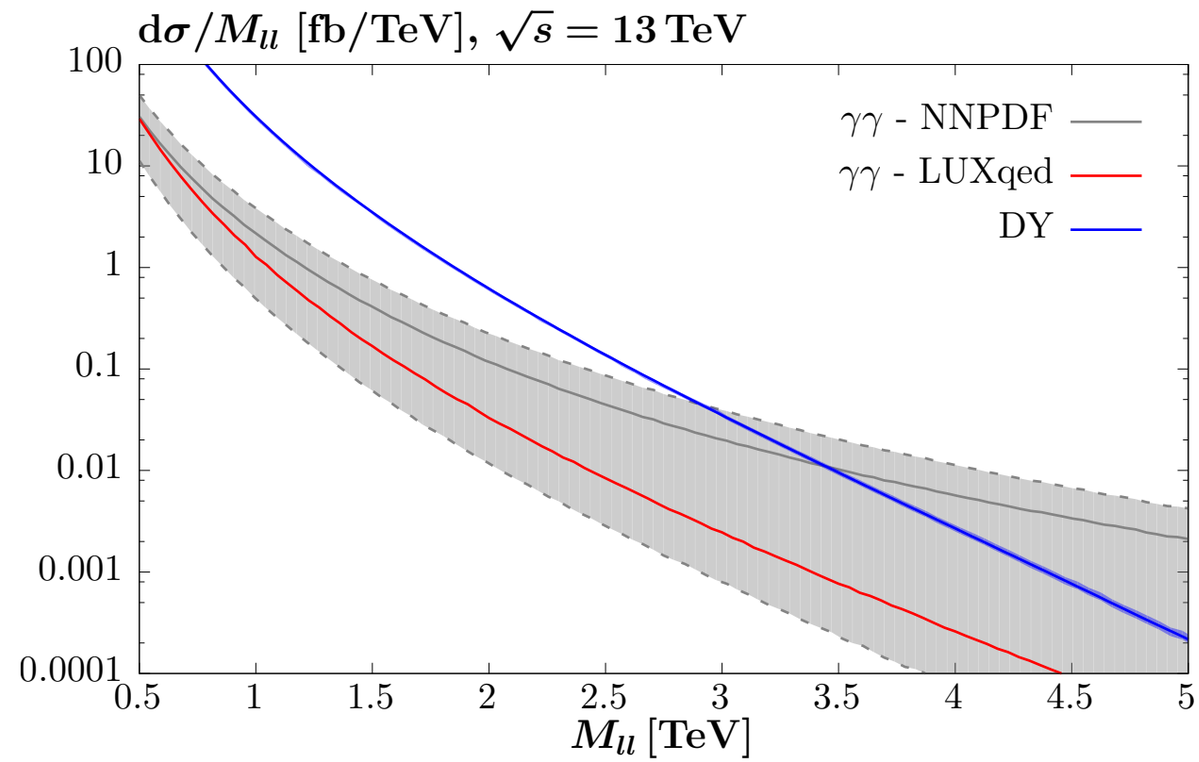
- Put on truly quantitative footing by **LUXqed** set. Photon PDF **completely determined** in terms of (well known) F_2 and F_L structure functions.

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \right\}, \quad (6)$$

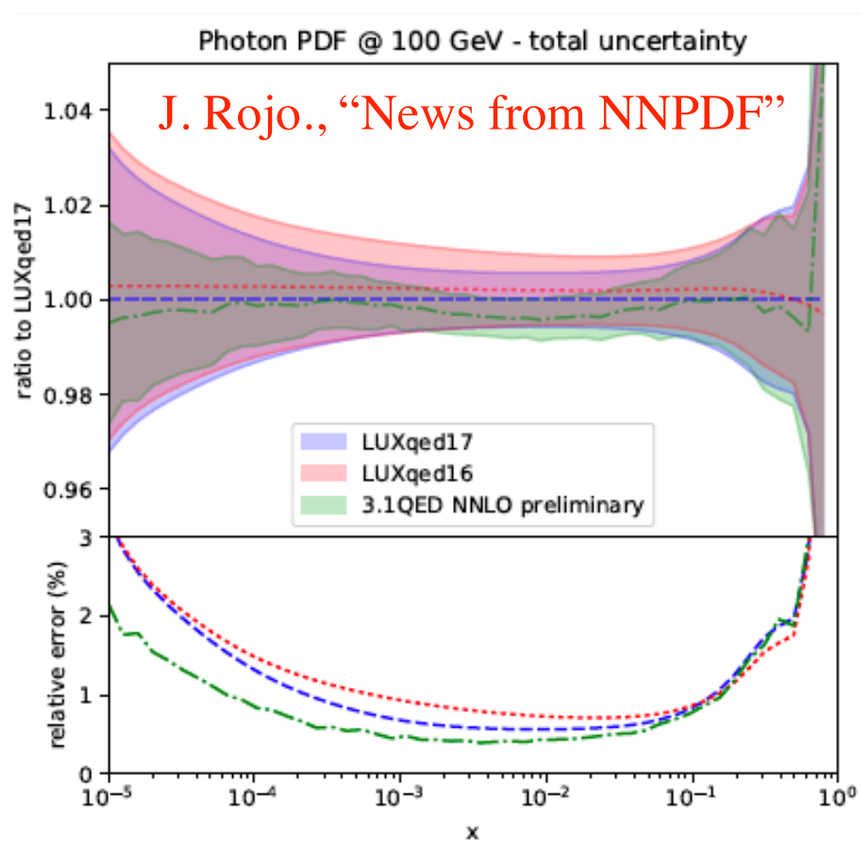


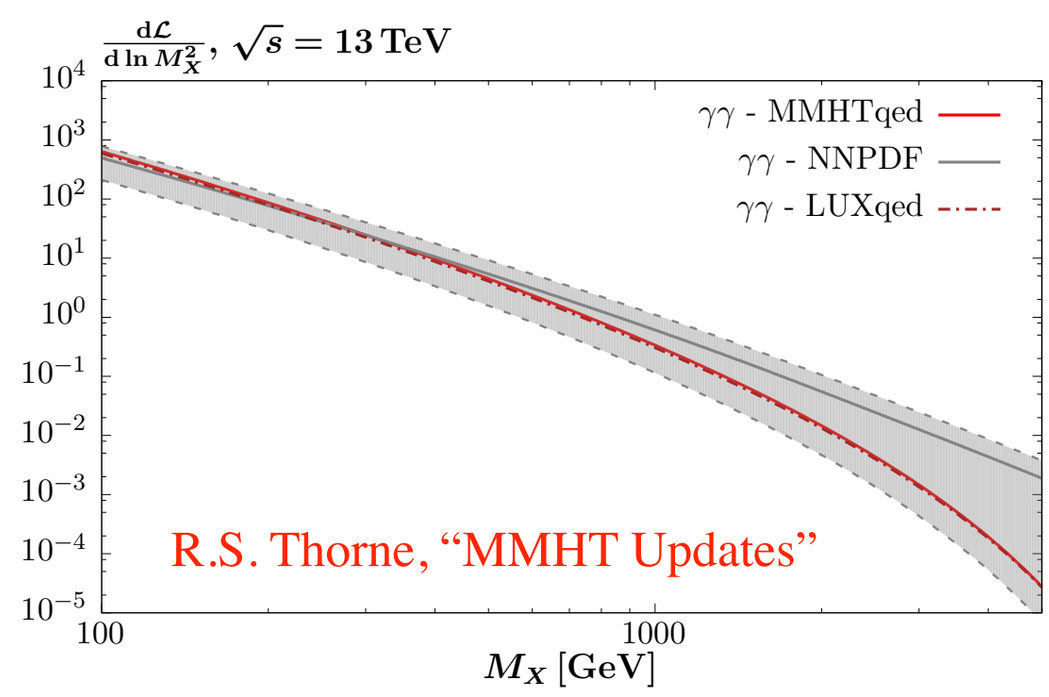
A. Manohar et al., Phys. Rev. Lett. 117 (2016) no.24, 100001
A. Manohar et al., arXiv:1708.01256

- Conclusion: photon PDF known to % level precision across relevant x .
- Moved beyond era of large photon PDF uncertainties. Photon has gone from being the poorest to the **best constrained** parton!



- **Ongoing work**: implementation into global PDF framework.





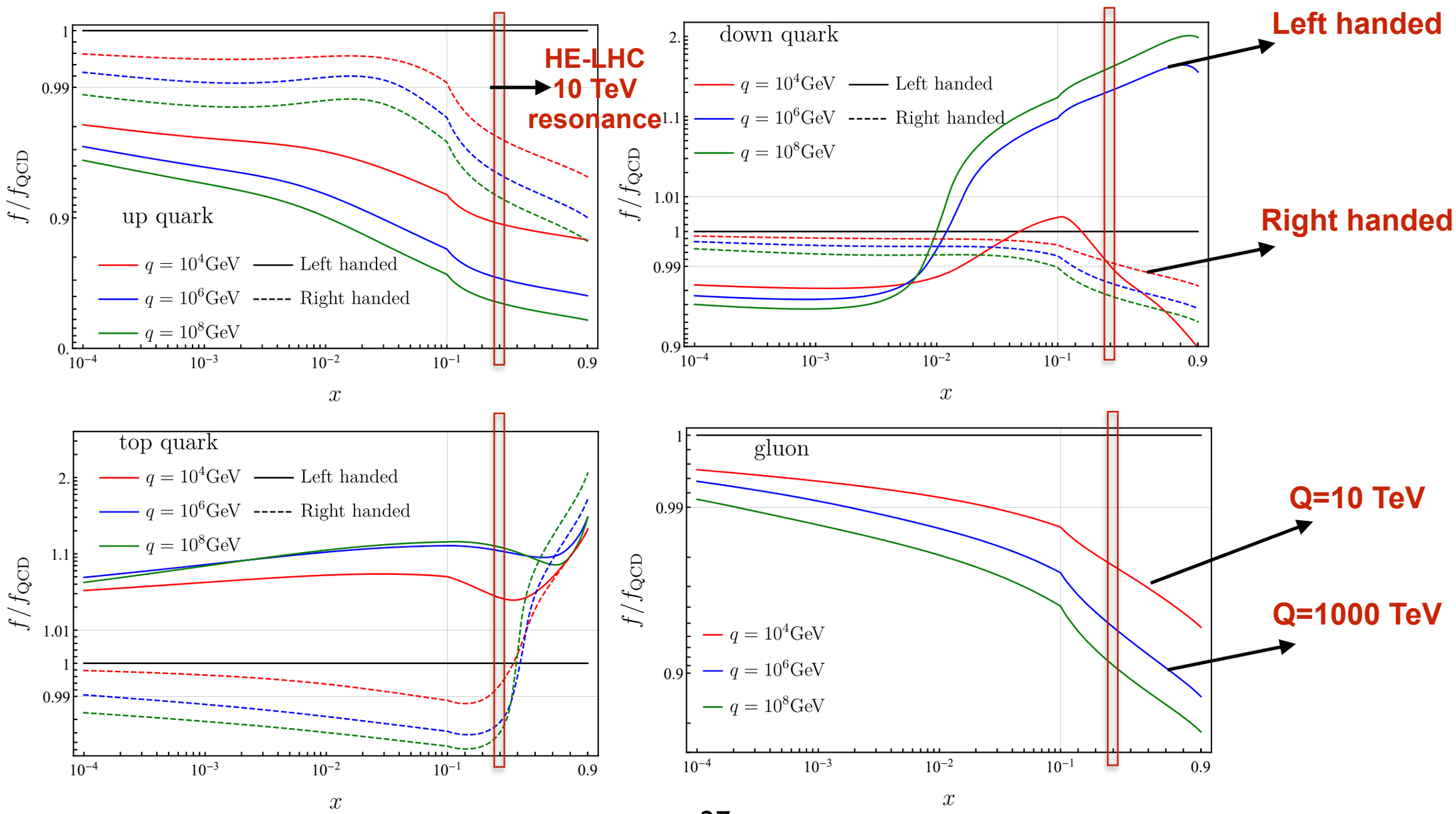
PDF4LHC Meeting Sep '17

Electroweak effects - PDFs

C. W. Bauer et al., JHEP 1708 (2017) 036

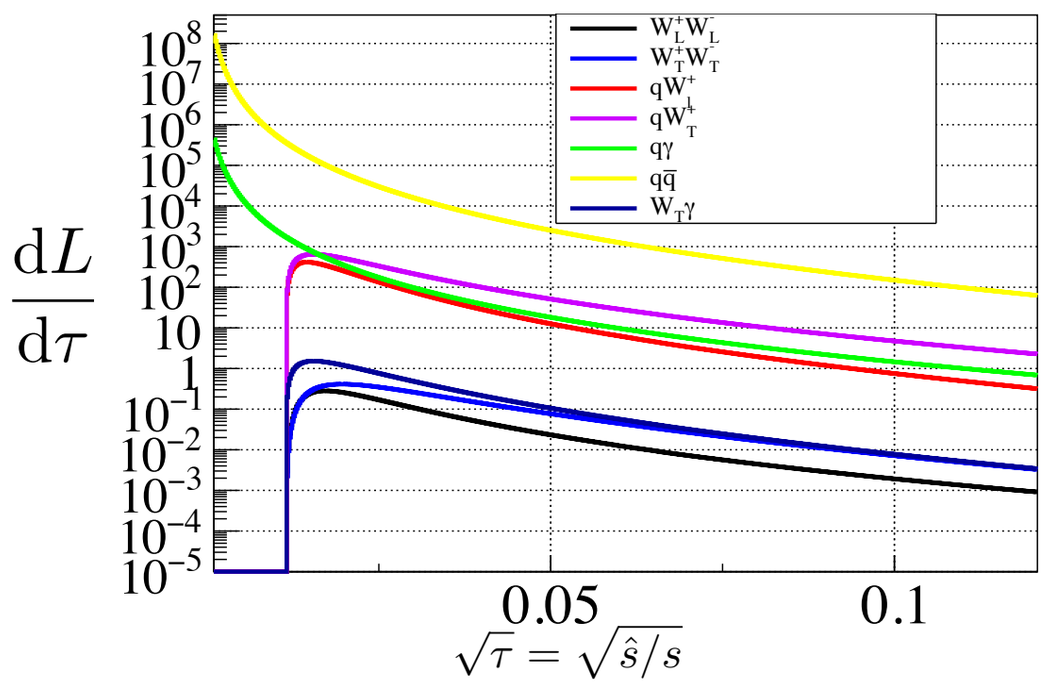
- **EW corrections** to **PDFs** also important at high energies.
- Recent numerical study for unpolarized proton with generalized DGLAP evolution (LO) in the approximation of exact SU(3)×SU(2)×U(1) symmetry.

full SM evolution vs. QCD only for quarks and gluon

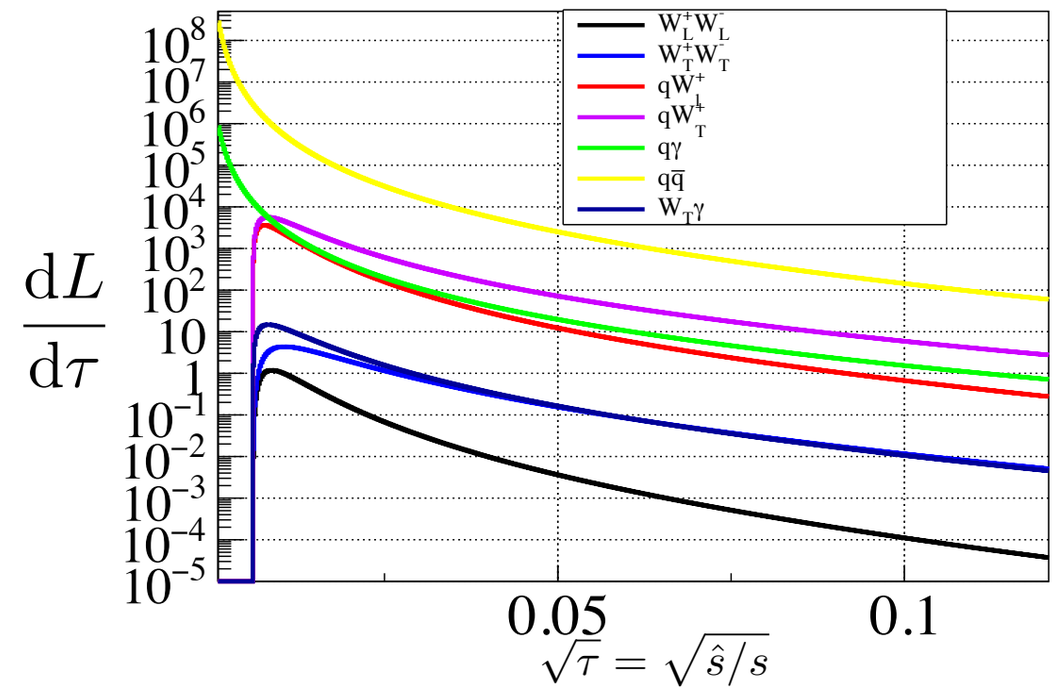


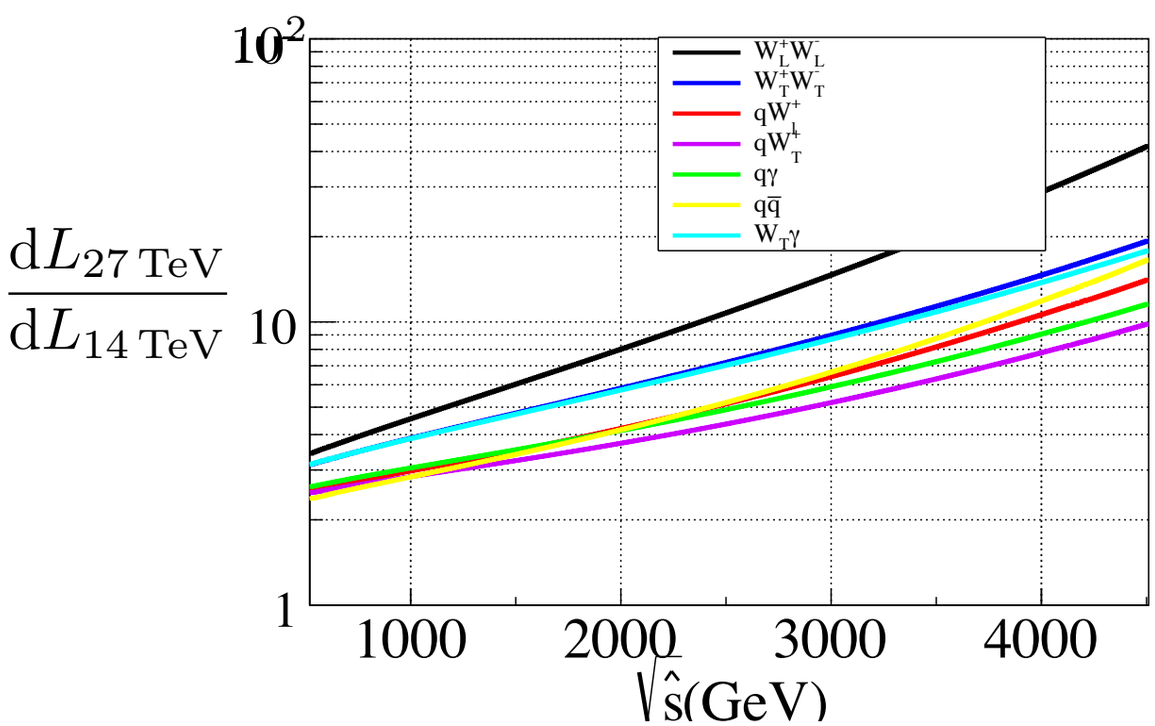
- Interesting comparisons on **EW boson PDF** luminosities at 14 and 27 TeV proton proton colliders are also available. Chen et al., arXiv:1611.00788

14 TeV



27 TeV





$$\frac{d\mathcal{L}_{V_1V_2}}{d\tau} \simeq \frac{2}{(\delta_{V_1V_2}+1)} \int_\tau^1 \frac{d\xi}{\xi} \int_{\tau/\xi}^1 \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^1 \frac{dz_2}{z_2} \times \sum_{q_1,q_2} f_{V_1\in q_1}(z_1) f_{V_2\in q_2}(z_2)\; f_{q_1\in P}(\xi) f_{q_2\in P}\left(\frac{\tau}{\xi z_1 z_2}\right)$$

$$f_{W_T^\pm\in u/d}(z) \simeq \frac{\alpha_W}{8\pi}\frac{1+\bar{z}^2}{z}\log\left(\frac{s}{4m_W^2}\right), \quad f_{W_L^\pm\in u/d}(z) \simeq \frac{\alpha_W}{4\pi}\frac{\bar{z}}{z}$$

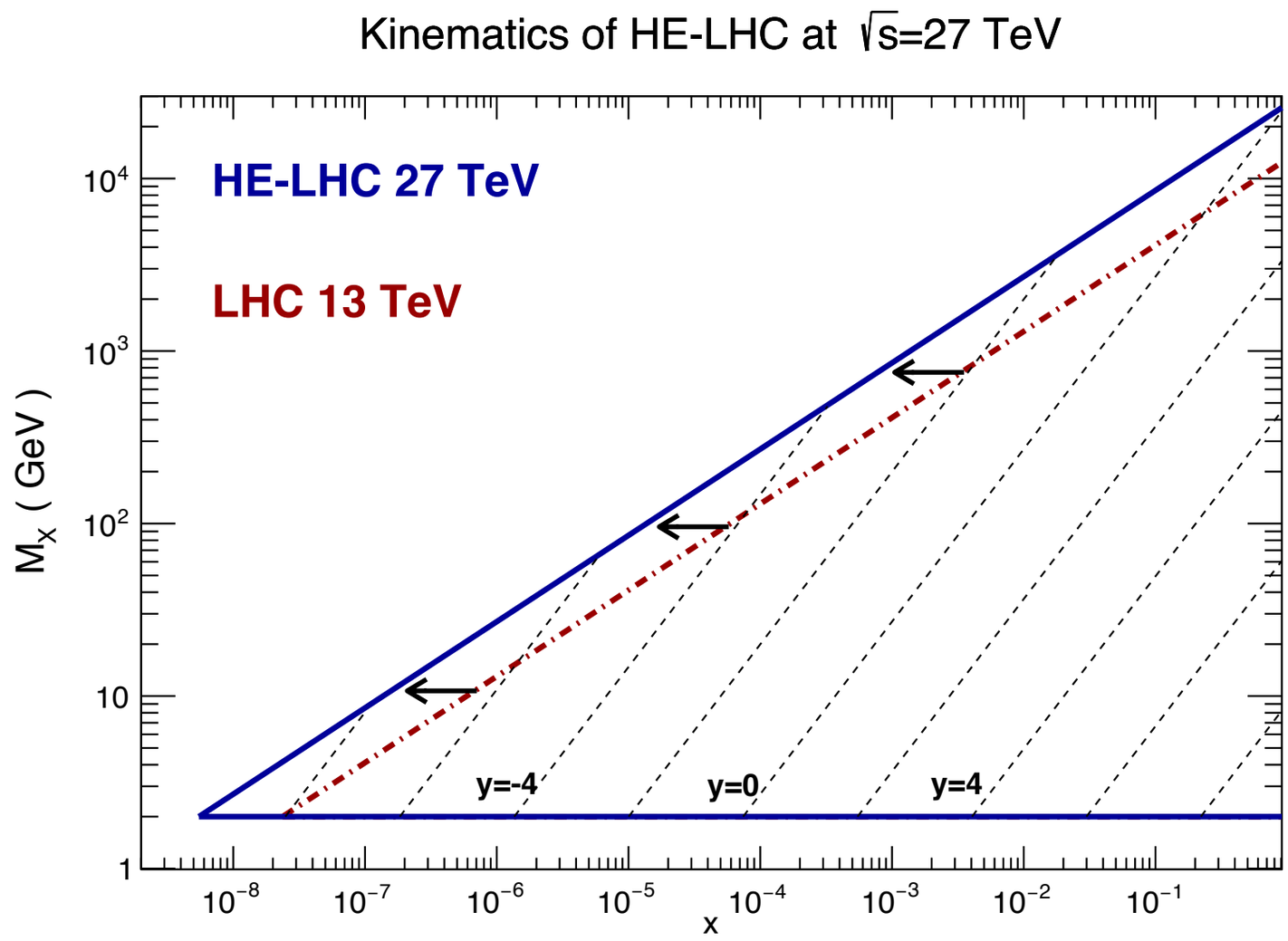
calculated at LO (fixed-order) only

PDFs with resummation

PDFs with resummation

- Higher **HL-LHC** integrated lumi will improve coverage at large x.
- **Threshold resummation** can be used there to improve perturbative expansion, construct approx. higher results…

- At **HE-LHC**, improved coverage of the small x region enhances the need for high-energy resummation.
- Small x (**high-energy/BFKL**) resummation might also be relevant for precision LHC phenomenology at Run II+III and in HL phase.
- PDFs and matrix elements should be treated consistently.



PDFs with large-x resummation

- Close to a production threshold ($x = 1$) terms of the form $\alpha_s^k \ln^r(1-x)$ are enhanced and need to be **resummed to all orders**.
- Working in Mellin space, a resummed partonic cross section can be constructed that includes terms of the type $\alpha_s^k \ln^p N$ to all orders.

$$\sigma(N, Q^2) = \int_0^1 dx\, x^{N-2} \sigma(x, Q^2) = \sum_{a,b} \mathcal{L}_{ab}(N, Q^2) \hat{\sigma}_{ab}\left(N, Q^2, \alpha_s\right)$$

$$\hat{\sigma}_{ab}^{(\mathrm{res})}(N, Q^2, \alpha_s) = \sigma_{ab}^{(\mathrm{born})}(N, Q^2, \alpha_s)\, C_{ab}^{(\mathrm{res})}(N, \alpha_s)$$

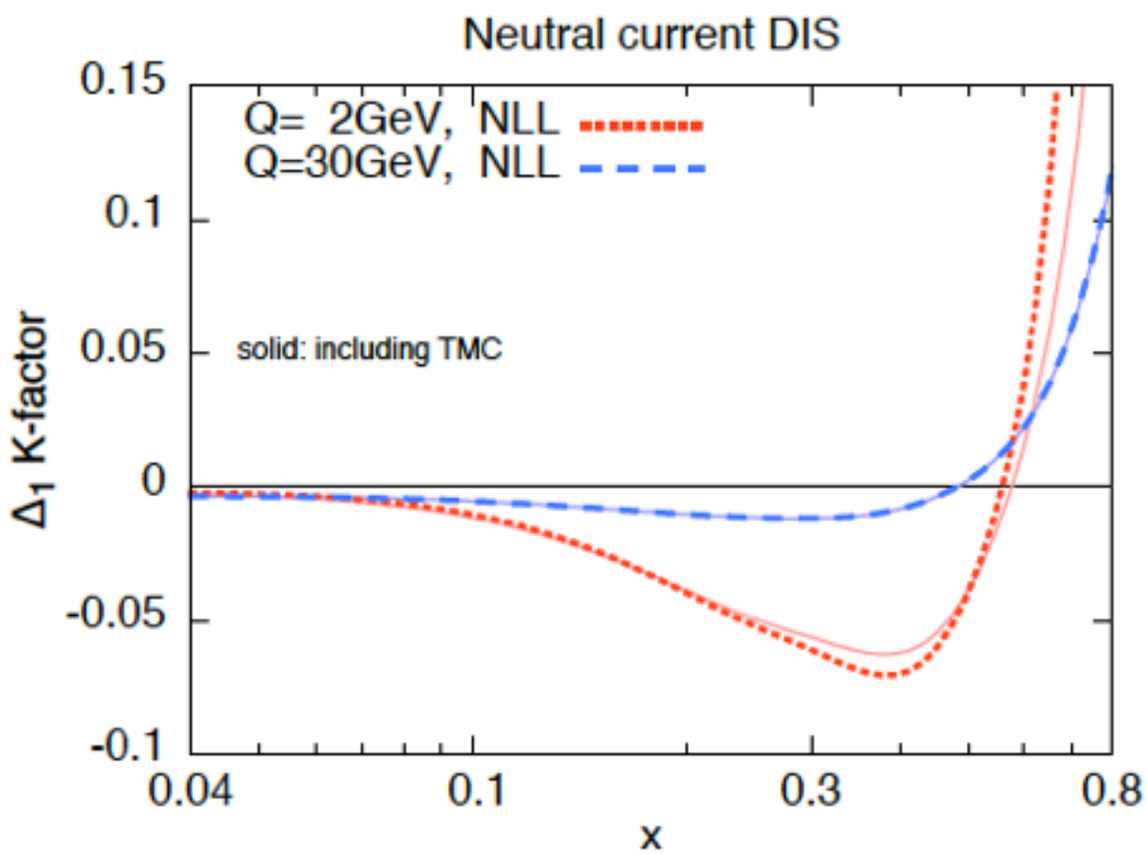
$$C^{(N\text{-soft})}(N, \alpha_s) = g_0(\alpha_s) \exp \mathcal{S}(\ln N, \alpha_s),$$

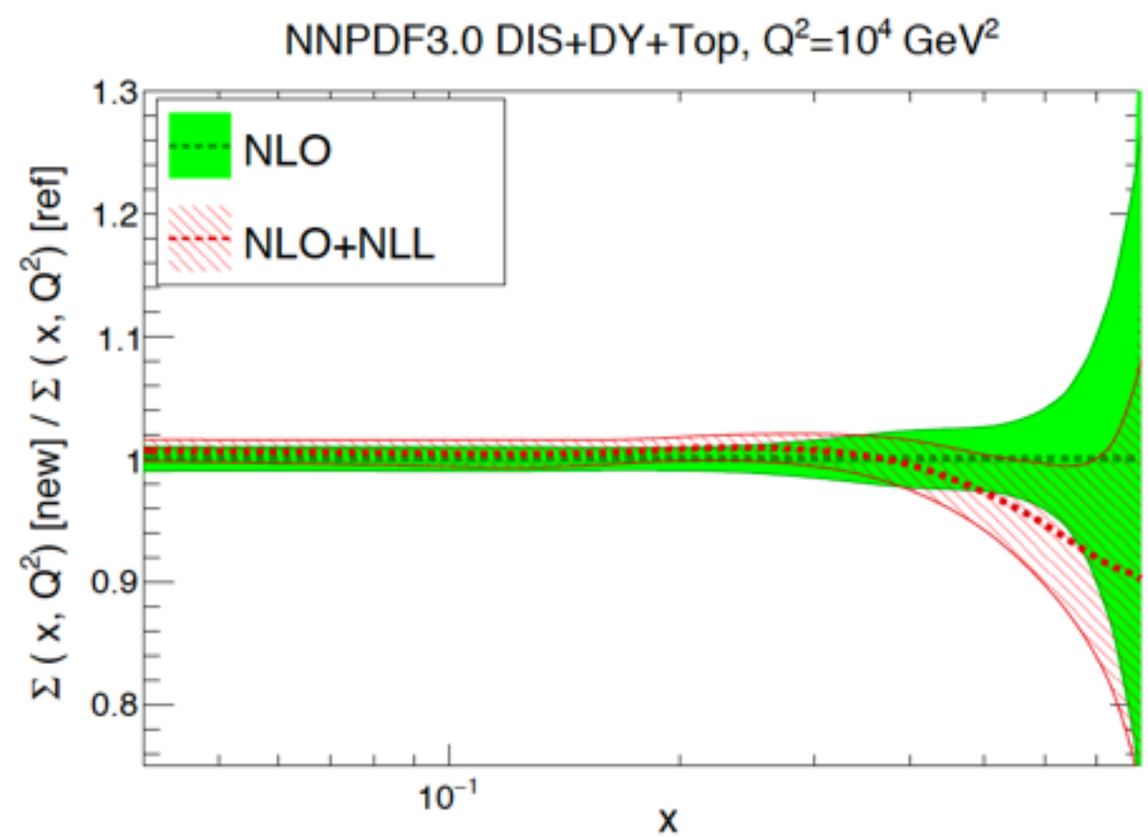
$$\mathcal{S}(\ln N, \alpha_s) = \left[\frac{1}{\alpha_s} g_1(\alpha_s \ln N) + g_2(\alpha_s \ln N) + \alpha_s g_3(\alpha_s \ln N) + \ldots\right]$$

- Threshold-resumed partonic cross-sections available for many processes: **DIS, DY, jets, top quark pair**…

- A variant of the **NNPDF3.0** fit with (N)NLL threshold resummation was produced using the resummed DIS+DY partonic cross sections from the TROLL code

$$\sigma_{\mathrm{N}^j\mathrm{LO}+\mathrm{N}^k\mathrm{LL}} = \sigma_{\mathrm{N}^j\mathrm{LO}} + \sigma_{\mathrm{LO}} \times \Delta_j K_{\mathrm{N}^k\mathrm{LL}}$$



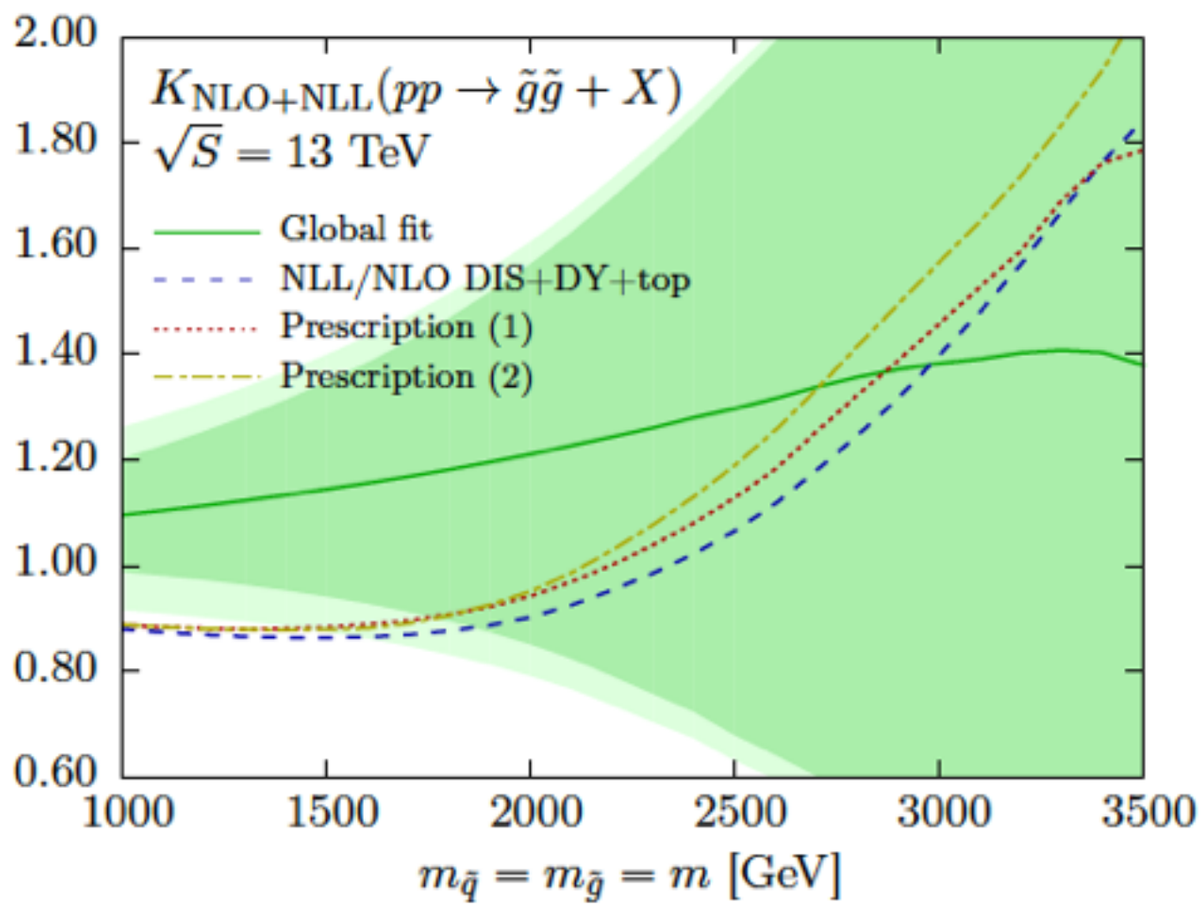


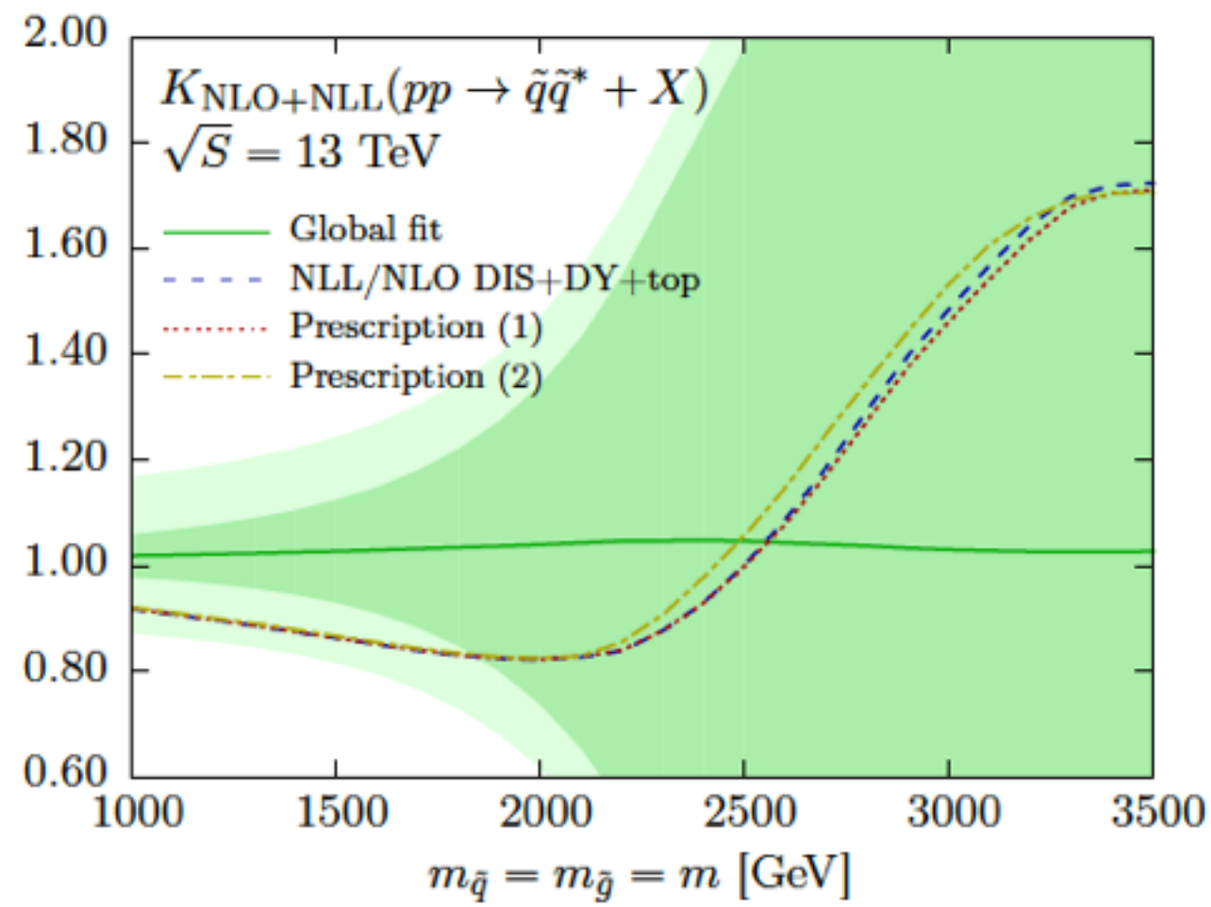
M. Bonvini et al., JHEP 1509 (2015) 191

- Main effect is **suppression** of the **large-** x PDFs to compensate increase of resummed partonic cross-sections

Impact

- Large x **resummed PDFs** can be combined with **threshold-resummed cross sections** for e.g. high-mass SUSY production.
- Shift in central values **comparable with PDF errors**: important for limit settings (and even more in the case of discovery!)





W. Beenakker et al., Eur. Phys. J C76 (2016) no.2 53

PDFs with small-x resummation

- Perturbative **fixed-order QCD** calculations extremely successful in describing a wealth of data from pp and ep collisions.
- However, theoretical reasons to go **beyond DGLAP**: $\ln(1/x)$ become dominant at small x and need to be resummed to all orders.
- **Small-x resummation** can be matched to DGLAP and included into a PDF fit

DGLAP
Evolution in Q^2

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(x,\mu^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(\mu^2)\right) f_j(z,\mu^2),$$

BFKL
Evolution in x

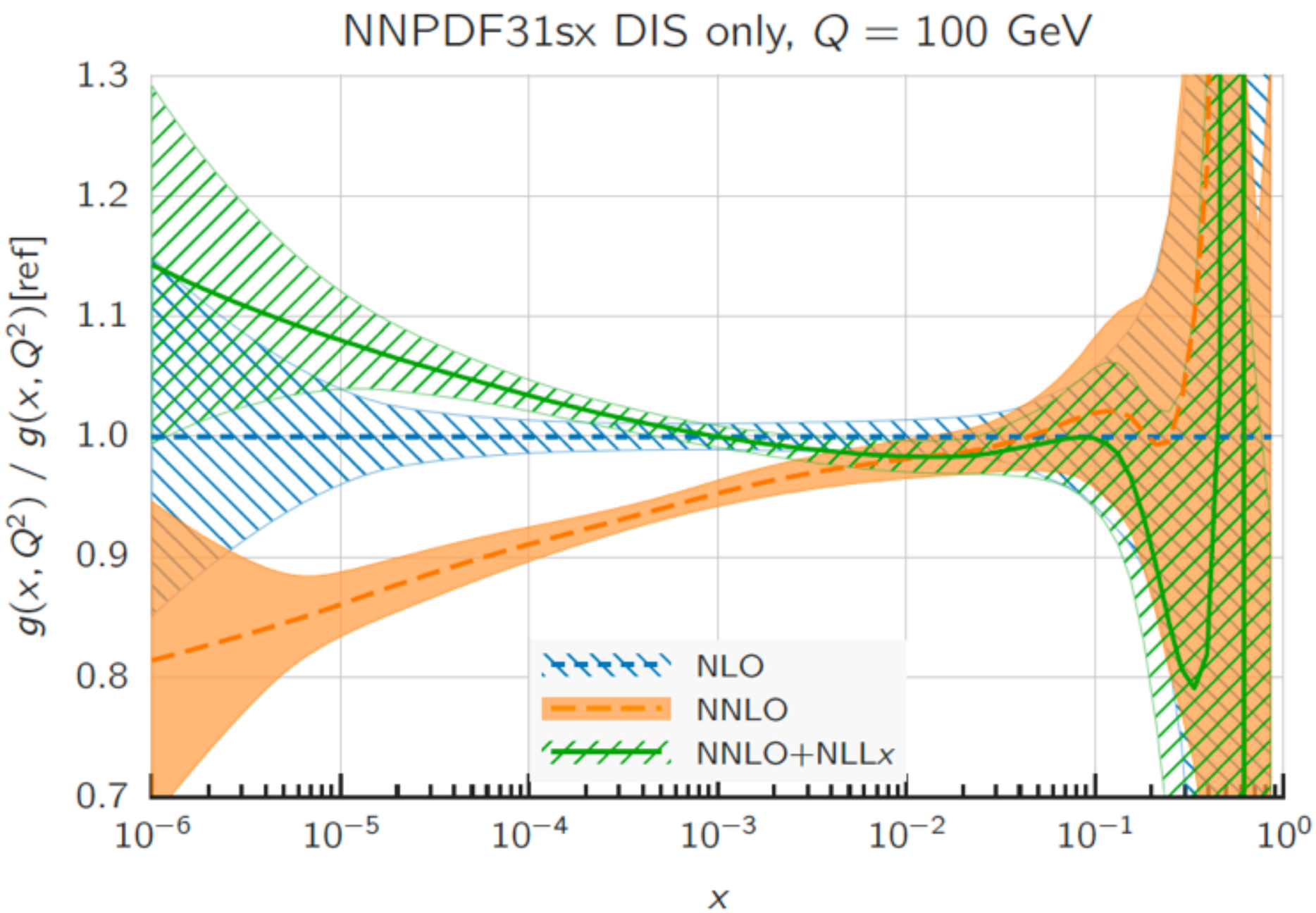
$$-x\frac{d}{dx} f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{\mu^2}{\nu^2}, \alpha_s\right) f_+(x,\nu^2)$$

- The $\mathrm{N}^k\mathrm{LO}$ fixed-order DGLAP splitting functions complemented with $\mathrm{N}^h\mathrm{LL}x$ contributions from BFKL:

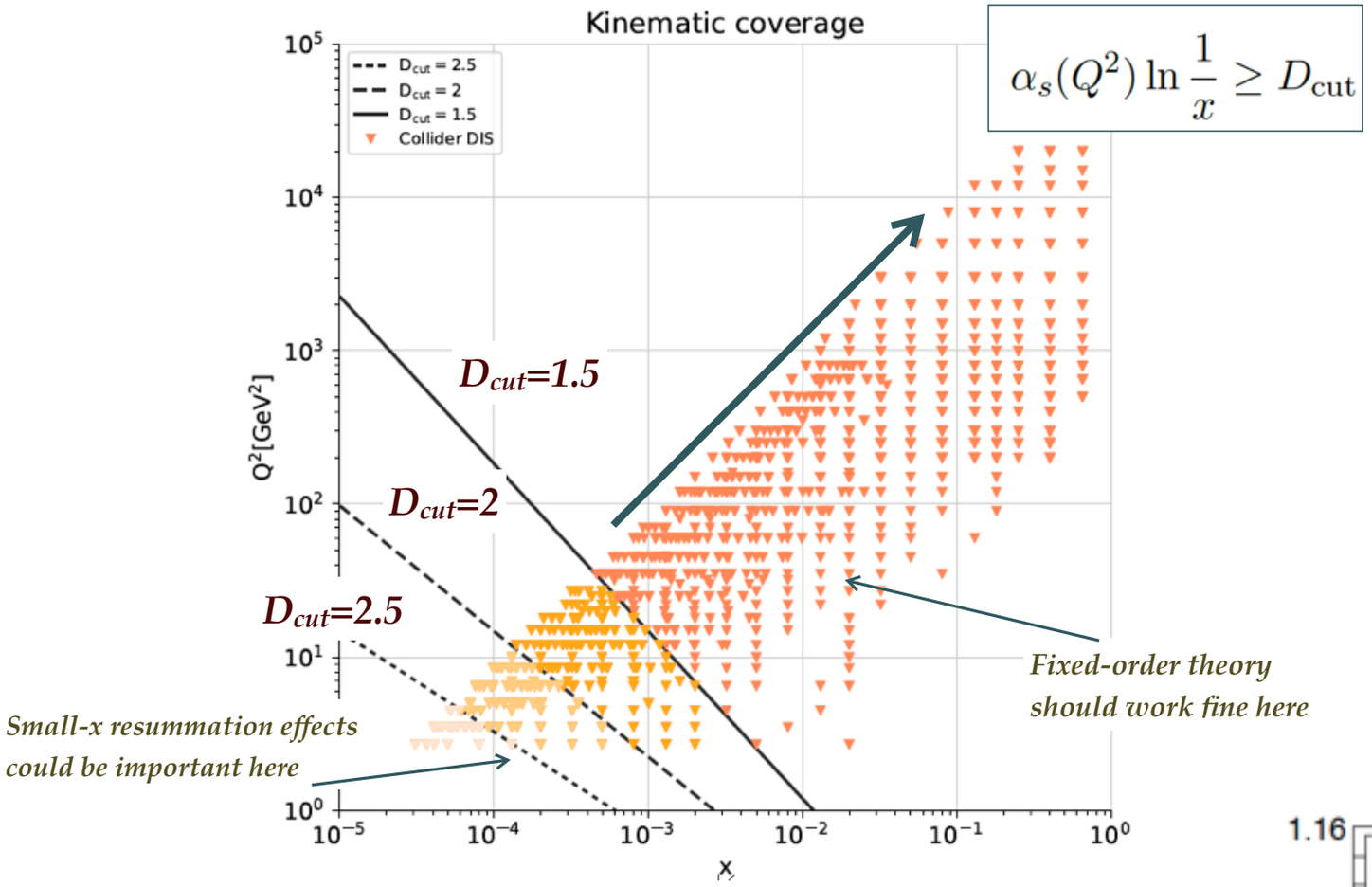
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

ABF, CCSS, TW and others, 94-08

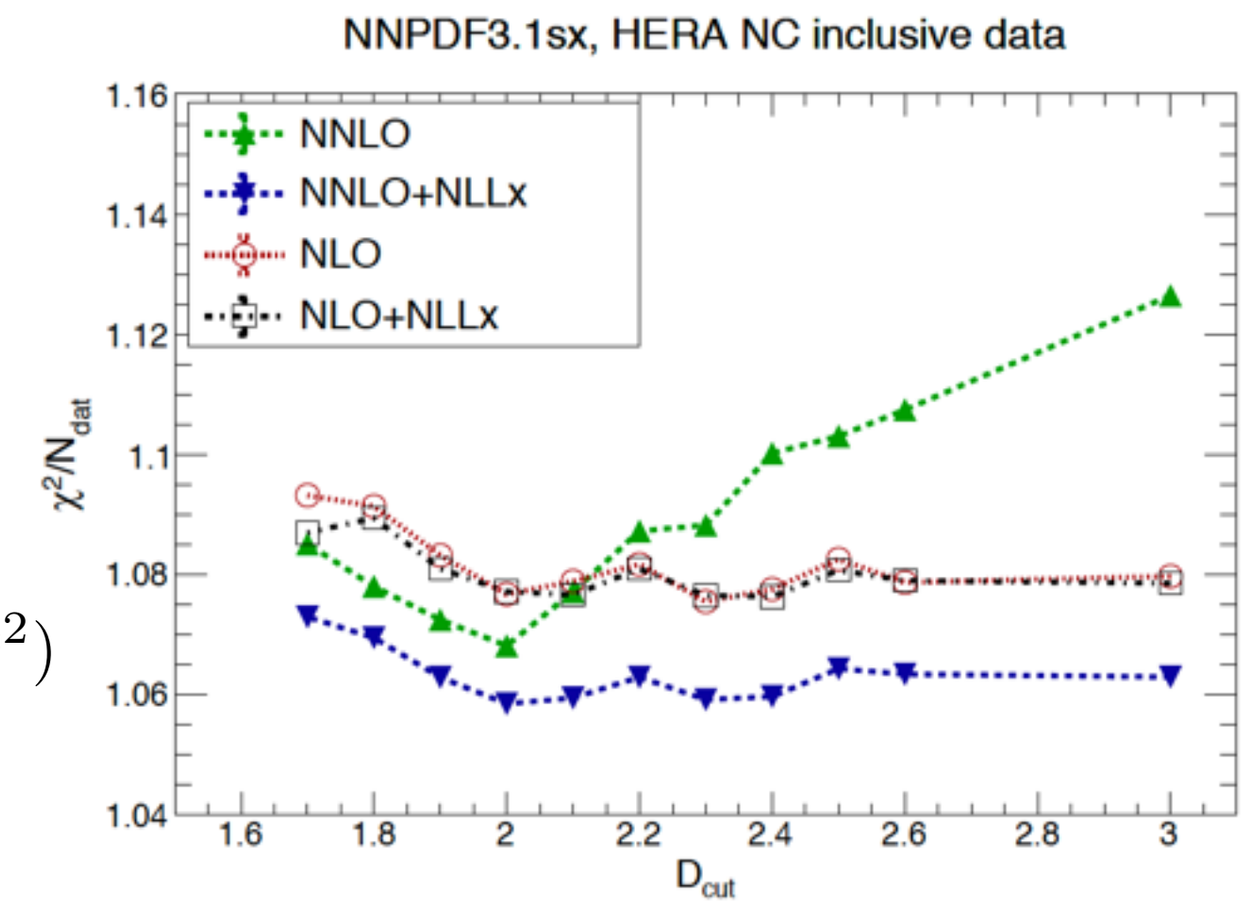
- **NNPDF3.1sx**: Variant of **NNPDF3.1** global fits using **NLO+NLLx** and **NNLO+NLLx** theory
- **NNLO+NLLx** theory stabilises small-x gluon w.r.t. perturbative order



R.D. Ball, arXiv:1710.05935

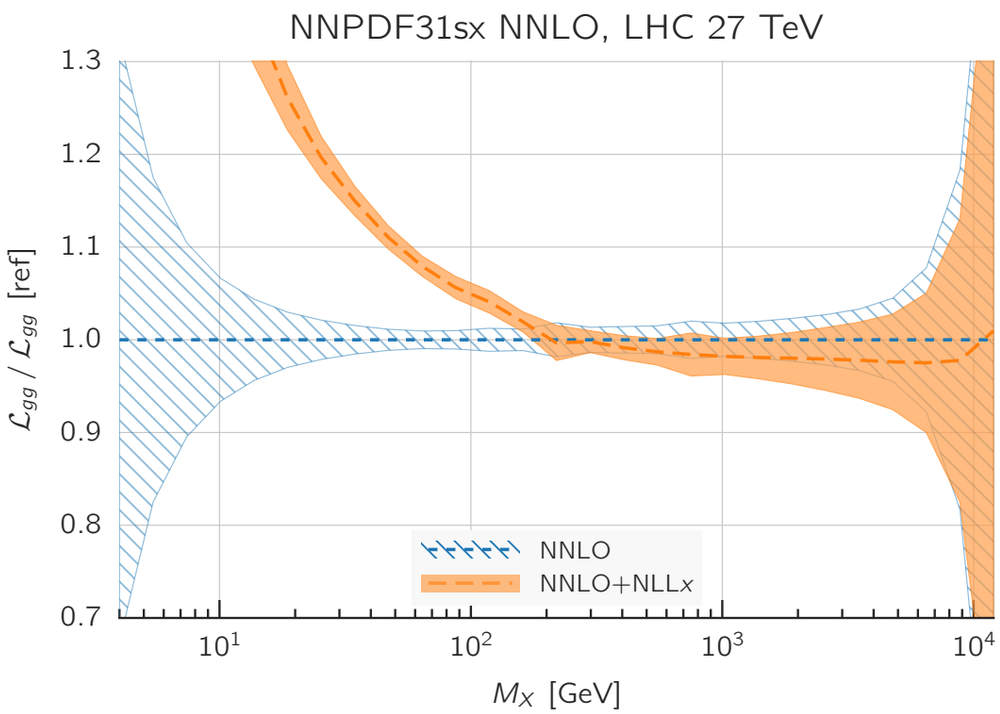


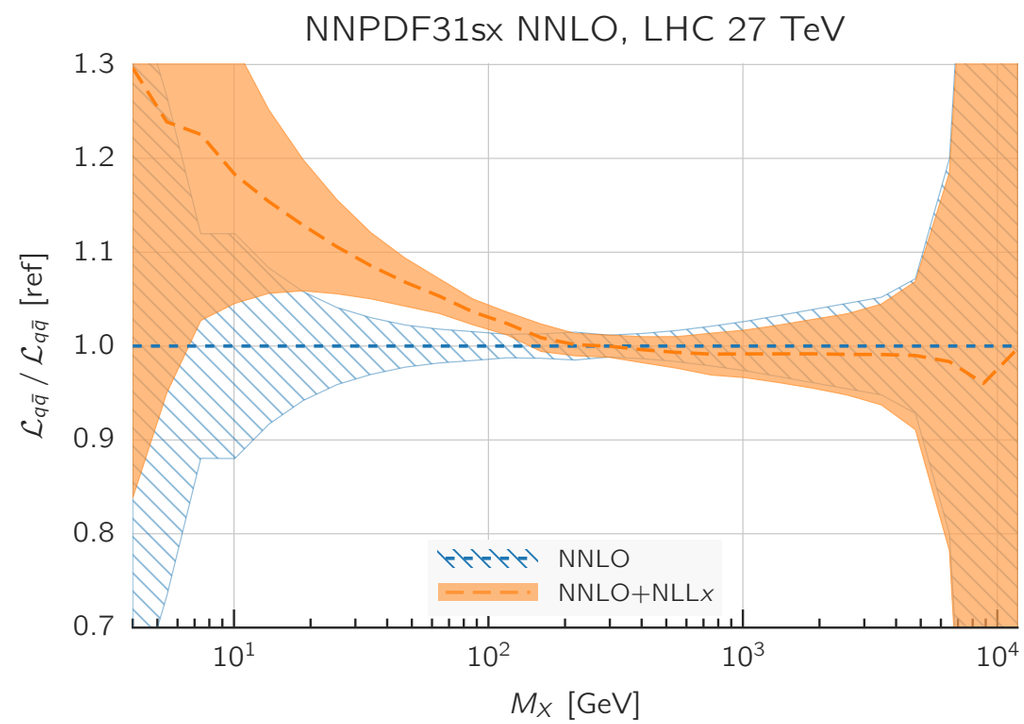
- To assess impact of small-x resummation on the **HERA data**, compute χ^2 removing data points in the region where resummation effects are expected.



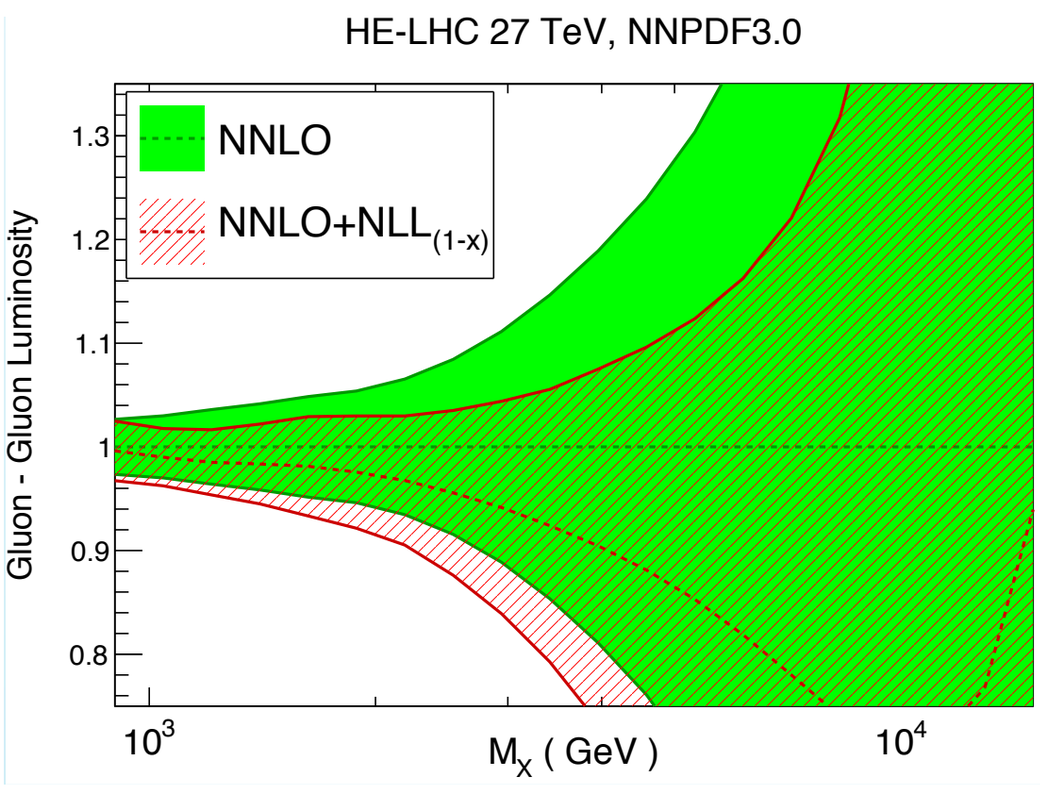
- Using **NNLO+NLLx** theory, the χ^2 trend flattens.
- Excellent fit to HERA **inclusive** and **charm** data achieved in the entire (x, Q^2) region

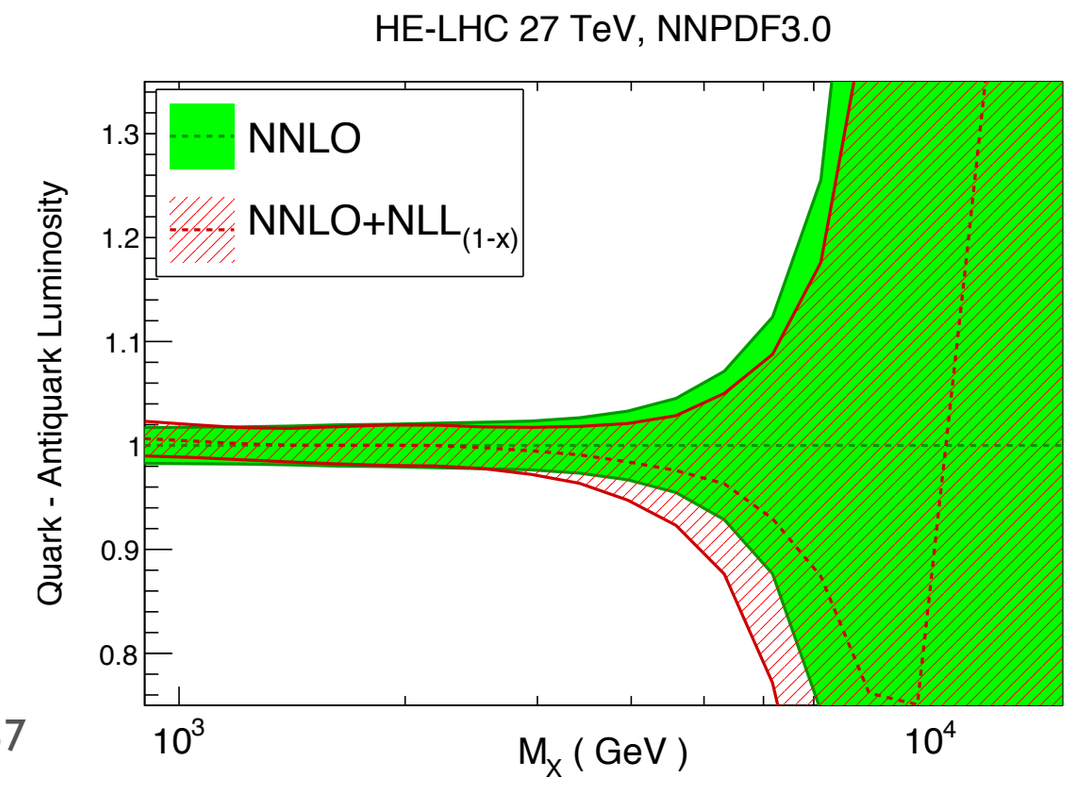
Implications for the HE-LHC





The use of PDFs with small (large) x resummation could improve predictions for low and medium (high) invariant masses at the **HE-LHC/HL-LHC**





PDFs at a high energy ep/eA collider

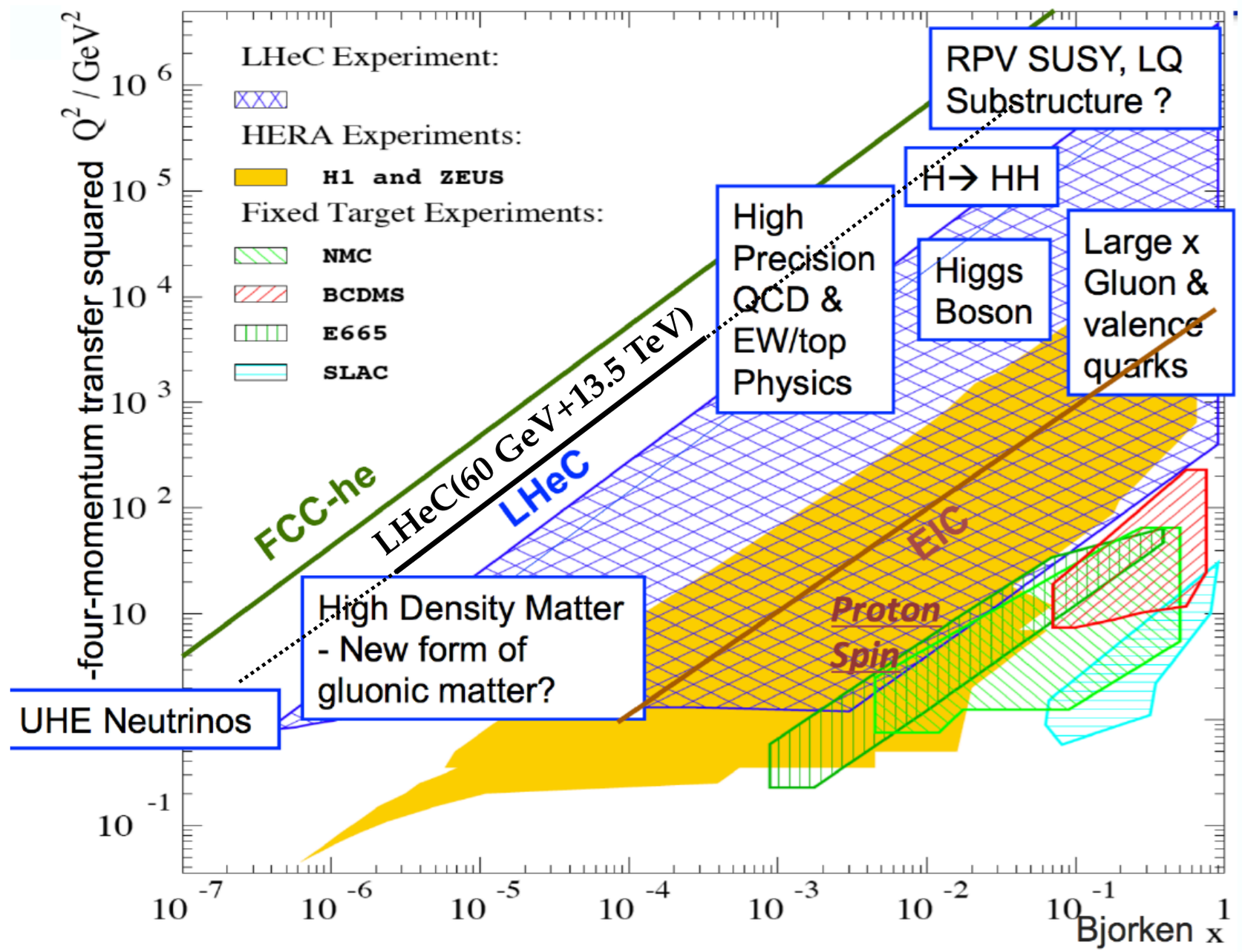
PDFs at a high energy eh collider

- **LHeC**: e beam with $E = 60$ GeV colliding with the 7 TeV LHC p in concurrent ep and pp operation mode during HL-LHC.

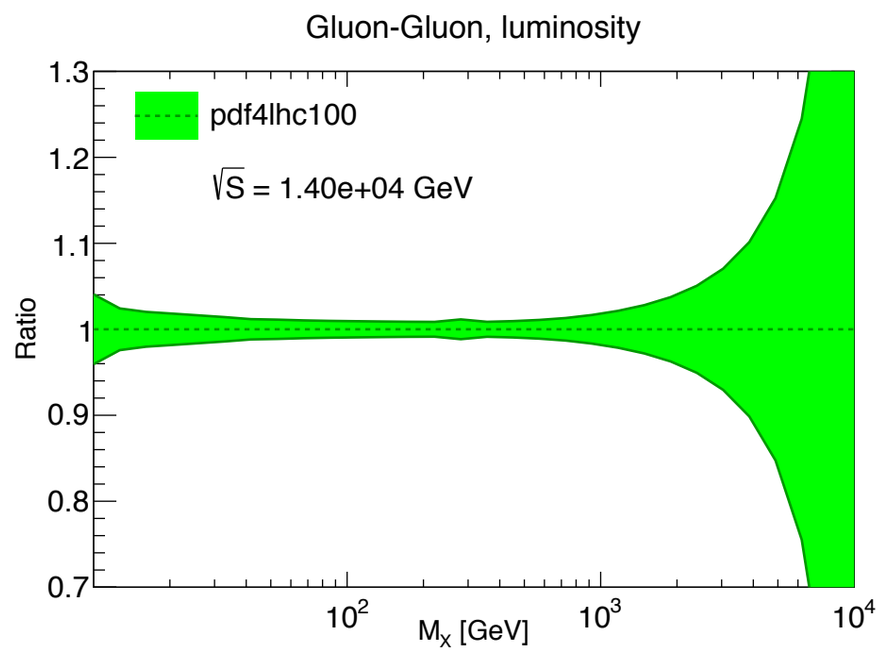
- **Expands kinematic** coverage of HERA by more than an order of magnitude at **small** x and **high** Q^2

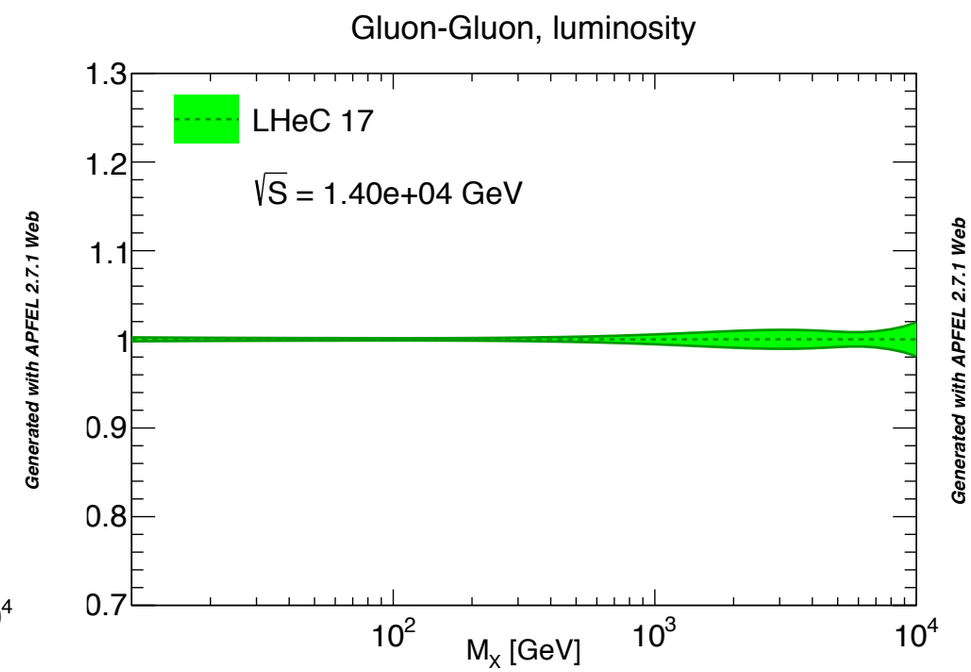
- Higher **Luminosity and** Q^2 - increased coverage at **high** x for clean PDF determination.

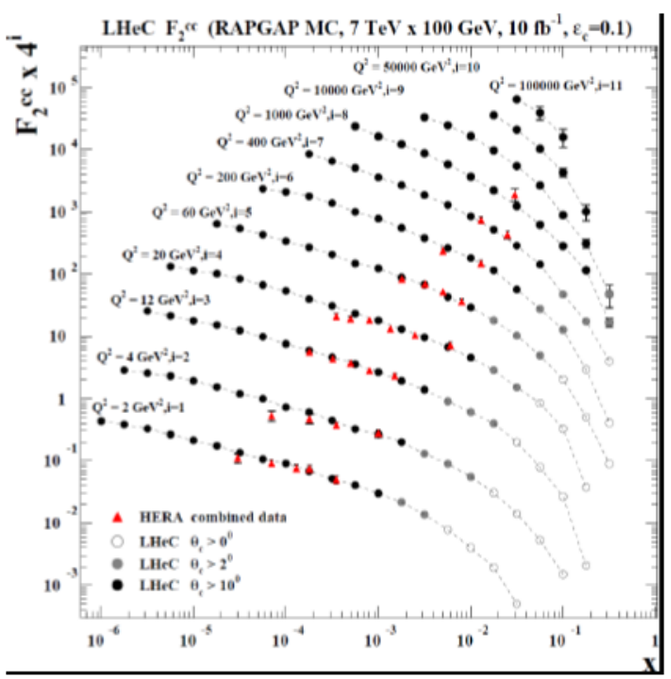
- Expanded coverage crucial for **nuclear PDFs** (no 'nuclear HERA' available).

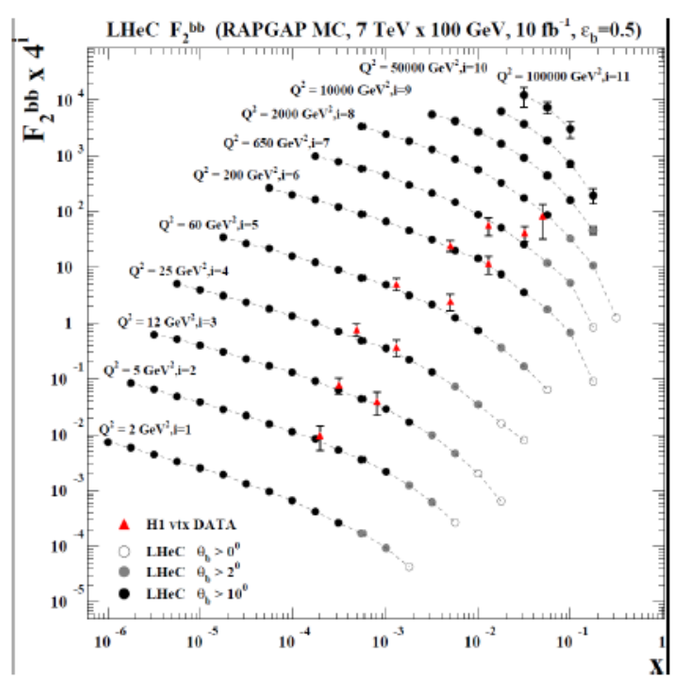


- LHeC provides **unprecedented precision** for parton structure determination of protons/nuclei compared to LHC alone.



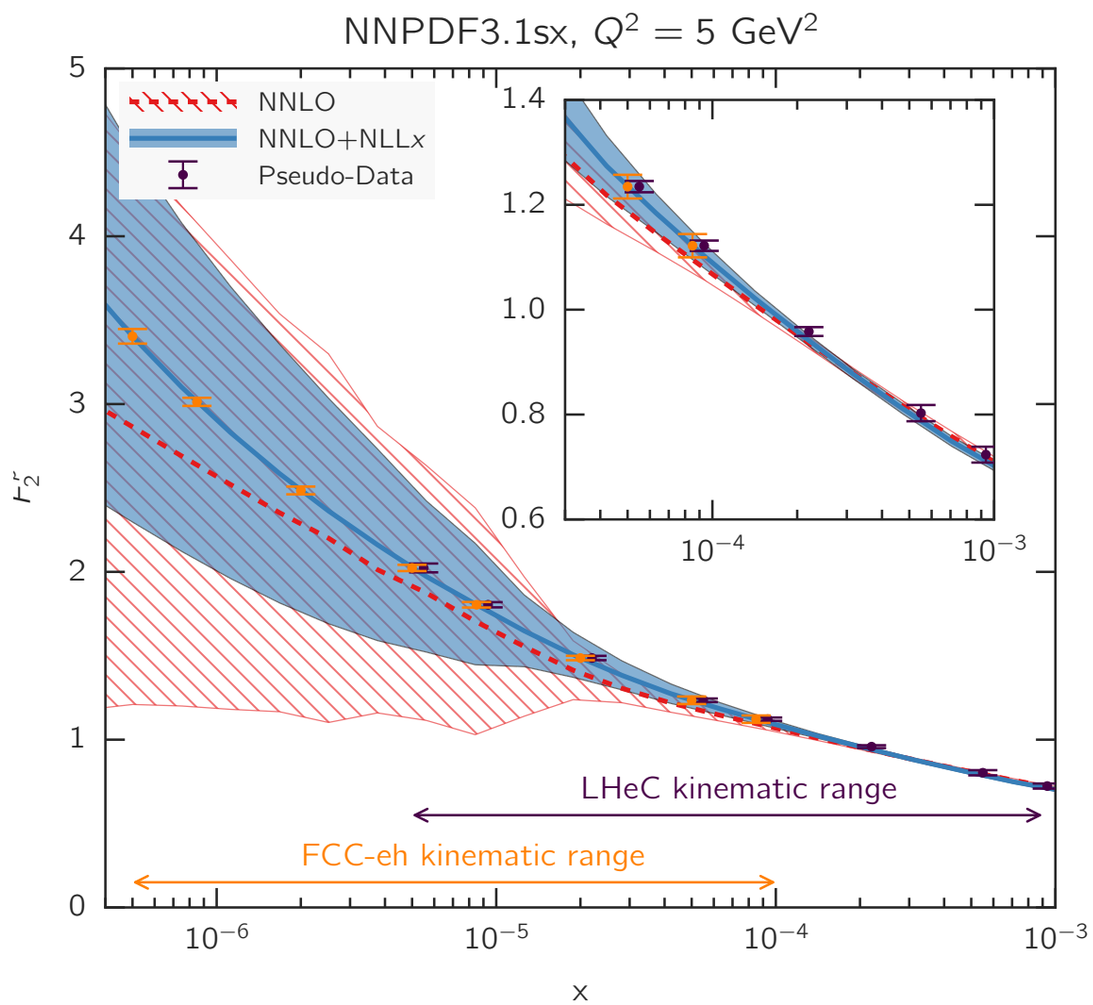


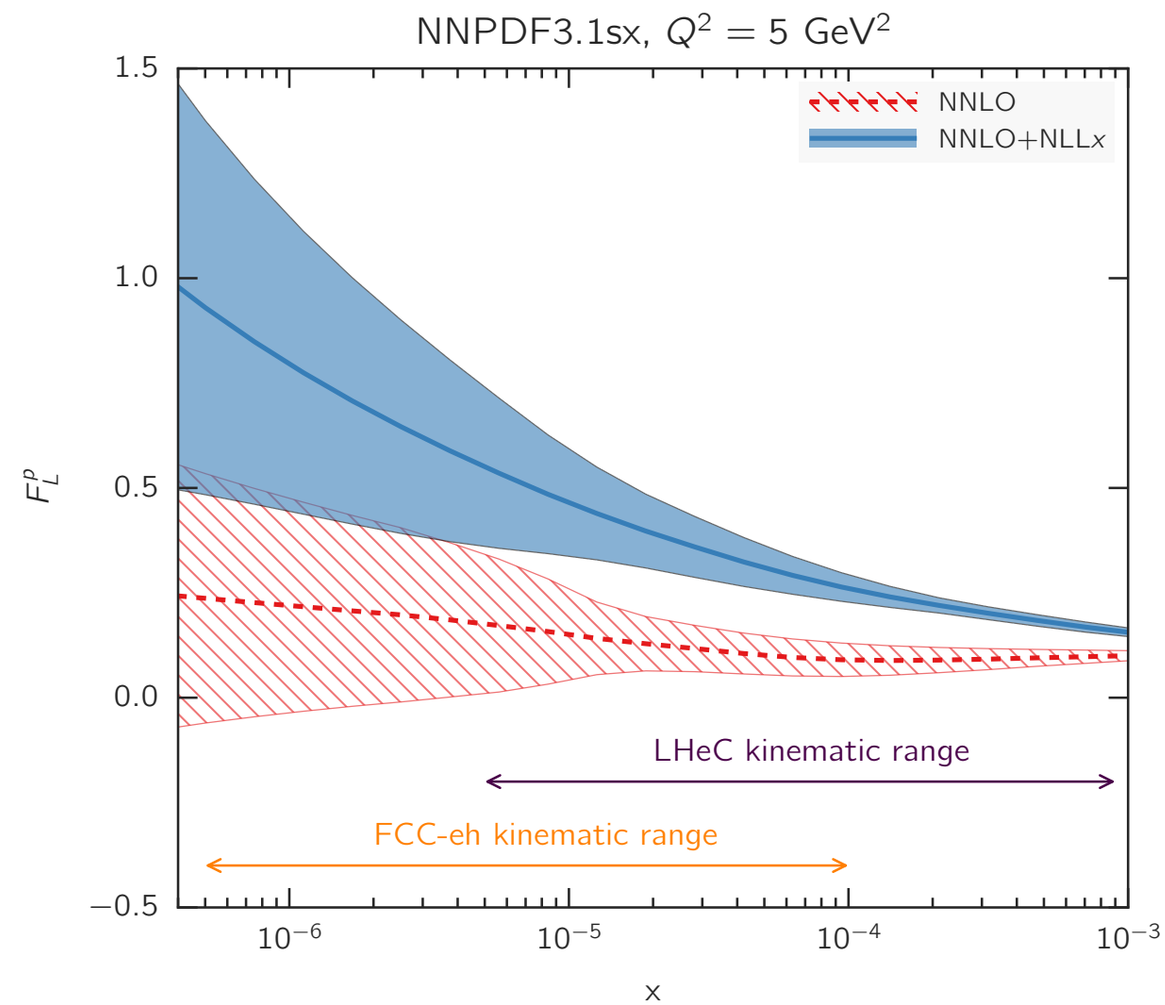




- Improvements both at **small and high** x (increased coverage/ statistics) and for quark flavour separation (direct measurements of s, c, b structure functions), with less assumptions.

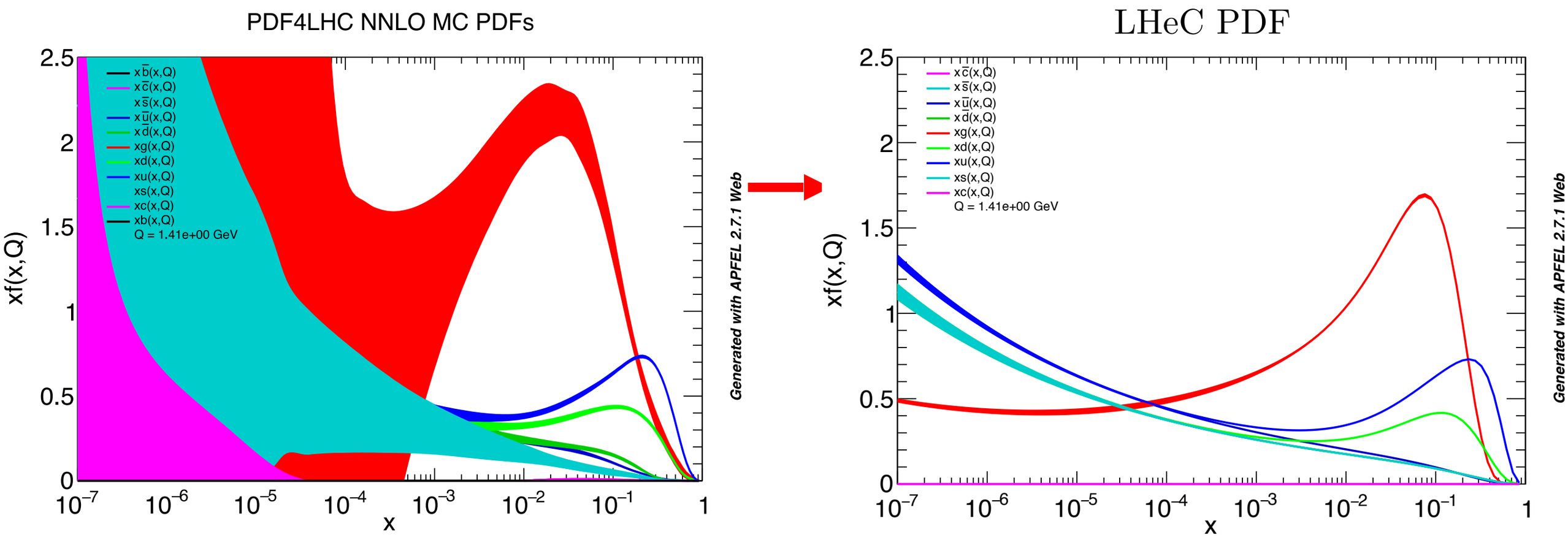
- Extended coverage probes novel dynamical regimes of QCD: **BFKL dynamics, saturation, non-linear effects**.
- Studies with pseudo-data can be used to quantify sensitivity to non-standard QCD effects.
- Measurements of the longitudinal structure function F_L represent smoking gun for such studies.





R.D. Ball, arXiv:1710.05935

- Many other important QCD/EW measurements possible: **strong coupling** to 0.1% (exp), 0.5% (theor), **electroweak couplings**….
- Possibility for N^3LO PDF extraction (given splitting functions).



- **LHeC PDFs** available in **LHAPDF** format.
- Work **actively ongoing** on studies/projections. Expect updates next year for input to European Strategy.

Conclusions and Outlook

- The HL-LHC/HE-LHC projects raises many new questions, challenges and opportunities for PDF fitters:
  - High precision PDFs, dealing with high precision data.
  - Include EW corrections systematically.
  - Complete treatment of theoretical uncertainties.
  - The NNLO standard - tools being developed for this. Benchmarking exercises worthwhile.
  - Extended high/low x reach: important of resummation?
  - Increasingly precise/differential LHC data great opportunity but also challenge for PDF groups to include in fit.
- The LHeC proposal:
  - Greatly extend HERA reach in x and Q^2. Huge potential for clean and precise extraction of PDFs.
  - Many other possibilities: probes of low x physics, nuclear PDFs, many preicision EW/QCD measurements.
  - Ongoing and active project.

Backup

PDF luminosities