PDFs in the High-Precision LHC Era: Recent Progress

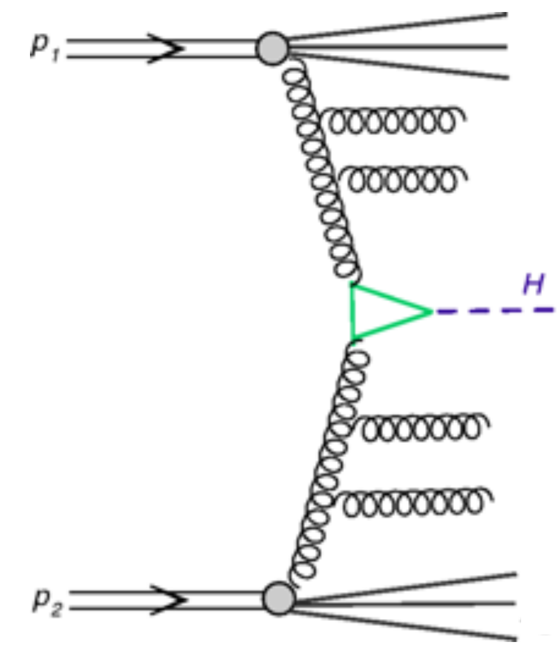
Lucian Harland-Lang, University of Oxford

Standard Model at the LHC

Berlin, 10 April 2018

UNIVERSITY OF OXFORD

PDFs at the LHC



• How do we model an LHC collision? Cross section is convolution of **parton-level cross section** and **Parton Distribution Functions** (PDFs)

$$\sigma(pp \to h + X) \sim \sigma(ab \to h) \otimes f_a(x_1, Q^2) \otimes f_b(x_2, Q^2)$$

$\sigma(ab \to h)$: parton-level cross section. $\alpha_S(m_h) \ll 1 \Rightarrow$ perturbative expansion in α_S .

$f_a(x, Q^2)$: PDF associated with probability of finding parton a, carrying momentum fraction x , at scale Q .

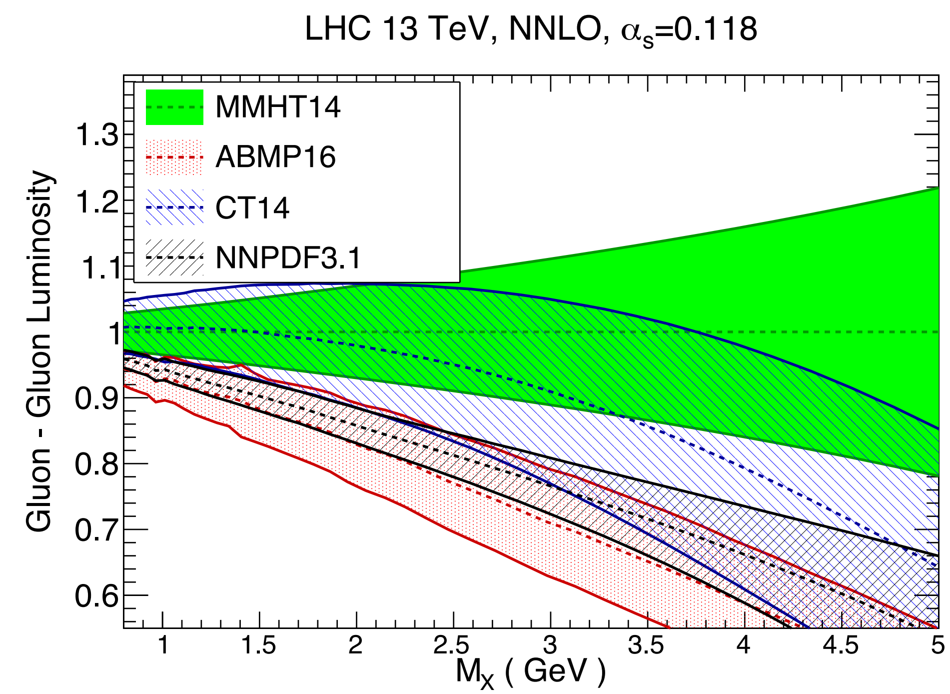
• QCD binding of quarks/gluons in the proton occurs at scale $\sim \Lambda_{\rm QCD} \Rightarrow$ cannot calculate PDFs using pQCD.

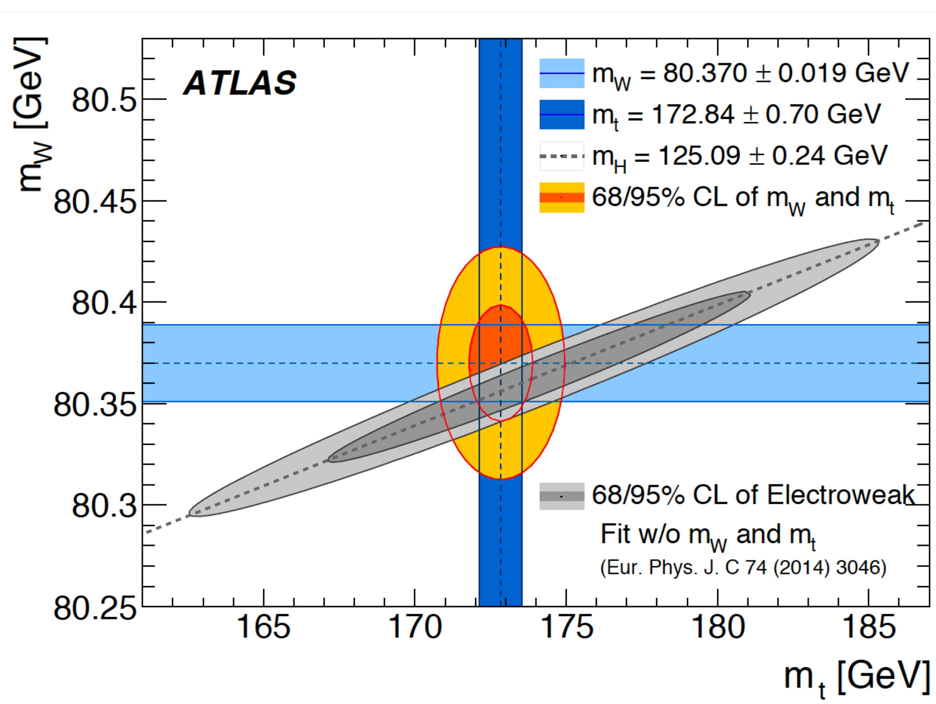
• Instead, perform **global fits** to wide range of data (DIS, fixed target, collider), to constrain PDFs to high precision.

PDFs: Why do we Care?

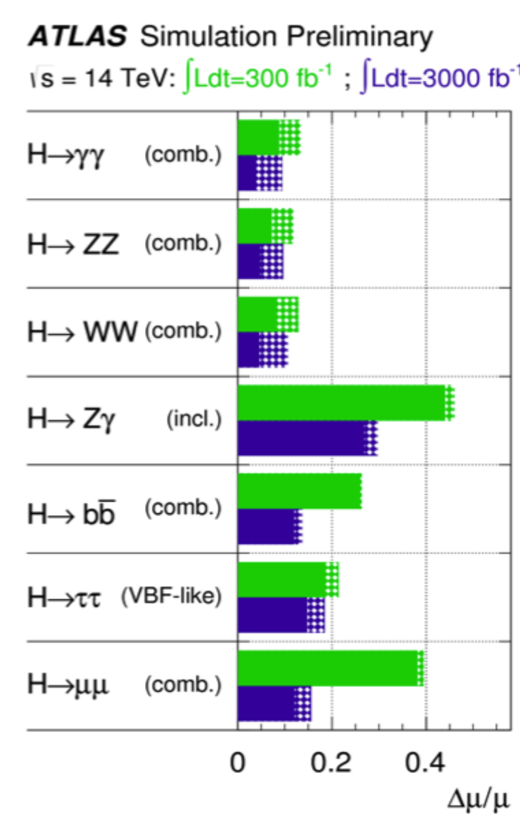
- Ultimate reach of LHC limited by knowledge of PDFs.

- **High mass searches** - PDFs in high region (currently constraints poor)





- **Higgs couplings** → need to model SM production precisely.

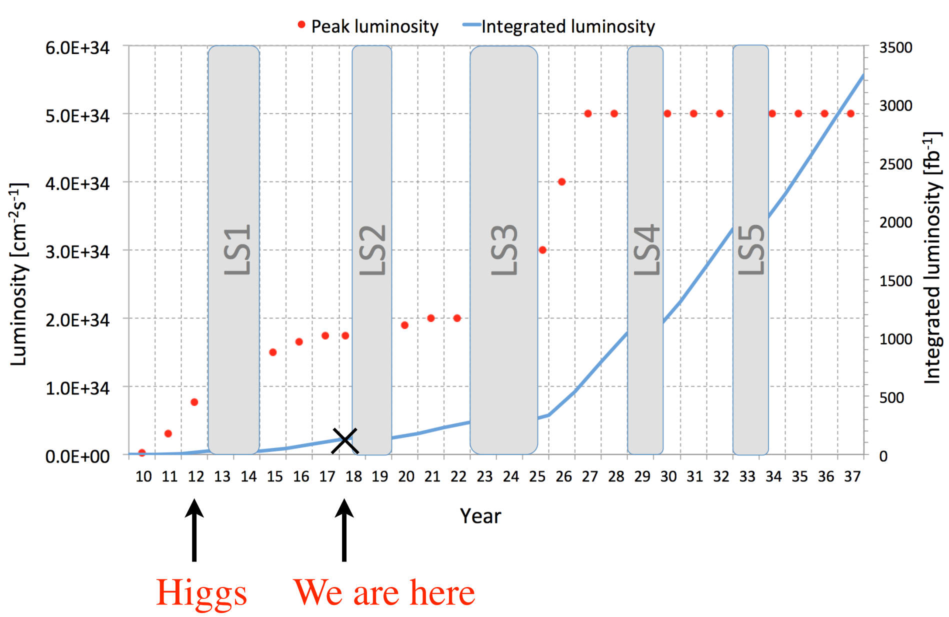


Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

- **Precision SM** measurements - PDFs dominant uncertainty for e.g. W mass.

PDFs: Precision Frontier

- Past years has seen an explosion in **NNLO** calculations ($\Rightarrow$ % level precision) for LHC processes, while precision of LHC data is rapidly increasing and will continue to do so (so far only few % of final dataset).



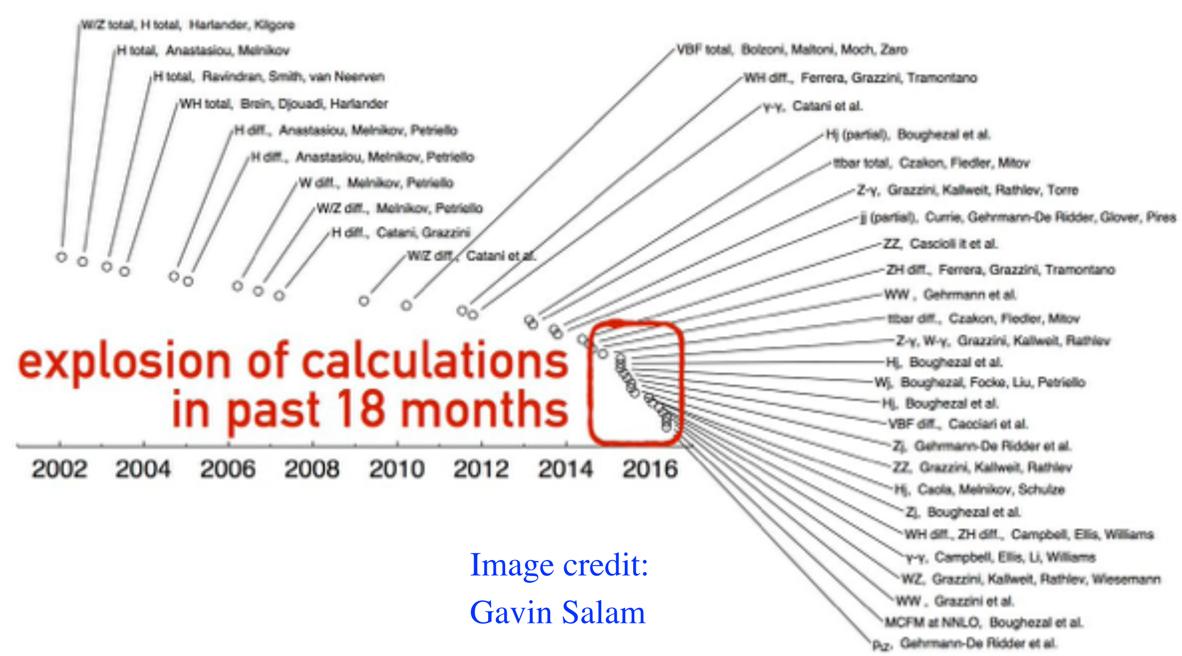


Image credit:
Gavin Salam

$\longrightarrow$ High precision LHC era: new **opportunities** and **challenges** for PDF fitting.

The Structure of the Proton in the LHC Precision Era

Jun Gao[a], Lucian Harland-Lang[b], Juan Rojo[c,d]

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[b]*Department of Physics and Astronomy, University College London, WC1E 6BT, United Kingdom*
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Abstract

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

J. Gao, LHL, J. Rojo, arXiv:1709.04922

PDFs: Recent Progress

- There has been a great deal of progress over the past year:

New Theory/ Methodology ⟷ **New Data in Fits**

New Theory/ Methodology:

★ NNLO 'standard'.

★ Photon PDF

★ Low x resummation.

★ Fast tools at NNLO.

★ Intrinsic charm.

★ Flavour threshold variation.

★ Lattice.

★...

New Data in Fits:

★ Jets.

★ W, Z and proton strangeness.

★ W, Z $p_\perp$.

★ Isolated Photon

★ Differential $t\bar{t}$

★ ...

- Even within this non-exhaustive list I will not have time to cover everything $\Rightarrow$ will cover a few representative topics.

New Data

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

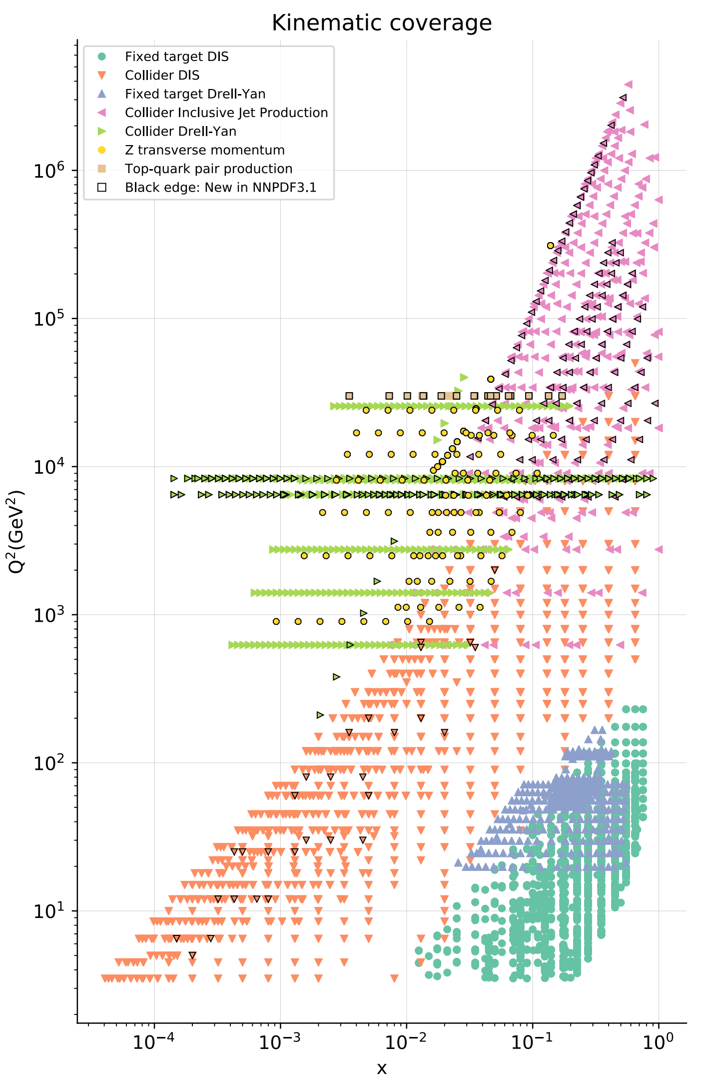
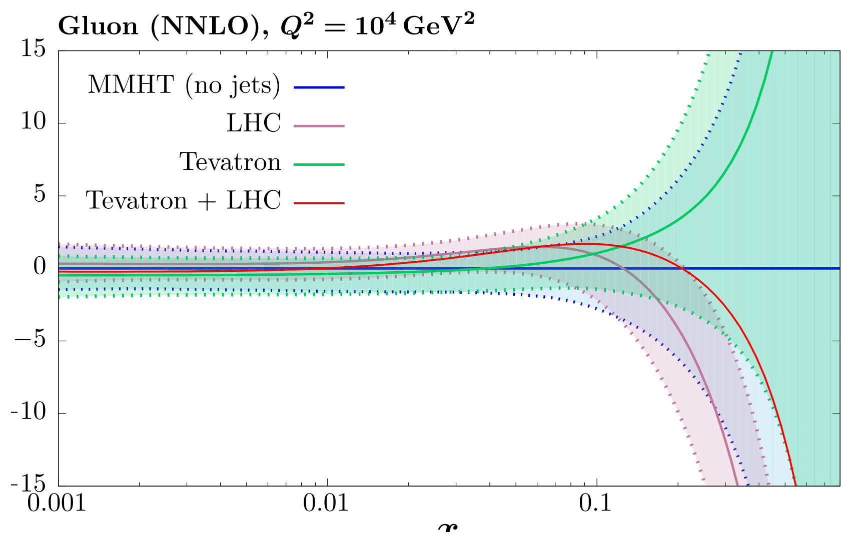
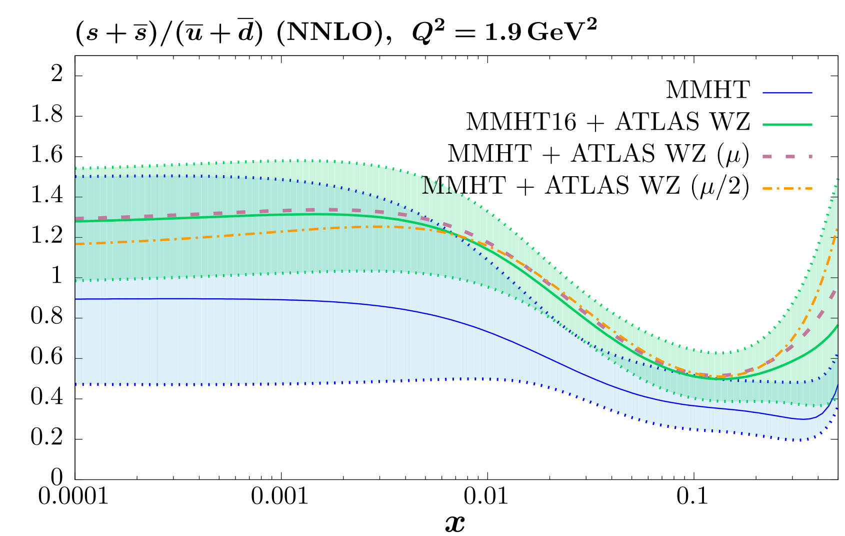


Figure 2.1: The kinematic coverage of the NNPDF3.1 dataset in the (x, Q^2) plane.



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

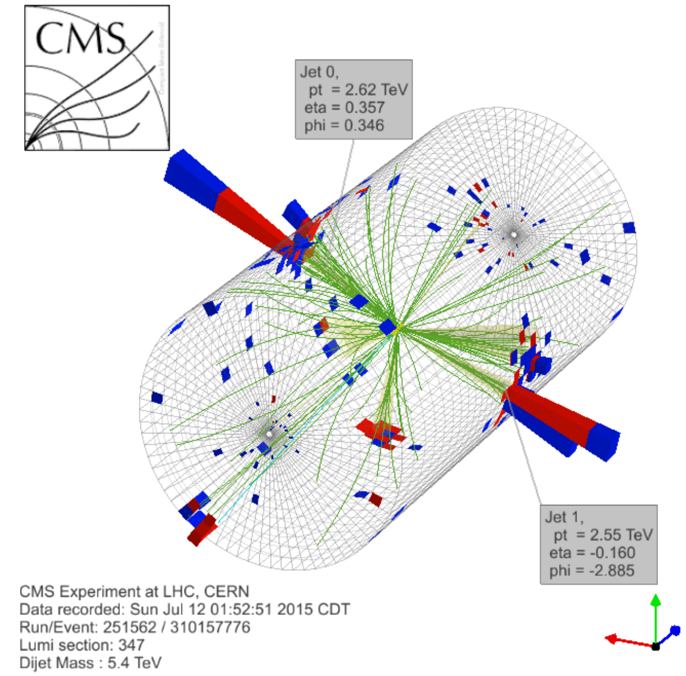


New data: LHC Jets

Jet production and PDFs

- At the LHC, **jet** production is dominated by the **gluon-initiated** parton-level processes:

$$gg \to gg,\ gg \to q\bar{q},\ gq \to gq,\ q\bar{q} \to gg\ ,$$



$\longrightarrow$ Data on jets at high transverse momenta, $p_\perp$, sensitive to **gluon PDF** at high x. Relevant for BSM and poorly constrained by DIS. Crucial role for LHC data.

- Full NNLO calculation now available $\Rightarrow$ consider impact of ATLAS/CMS jet data at this order.

NNLO QCD predictions for single jet inclusive production at the LHC

J. Currie[a], E.W.N. Glover[a], J. Pires[b]
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We report the first calculation of fully differential jet production in all partonic channels at next-to-next-to leading order (NNLO) in perturbative QCD and compare to the available ATLAS 7 TeV data. We discuss the size and shape of the perturbative corrections along with their associated scale variation across a wide range in jet transverse momentum, p_T, and rapidity, y. We find significant effects, especially at low p_T, and discuss the possible implications for Parton Distribution Function fits.

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

Recent Study

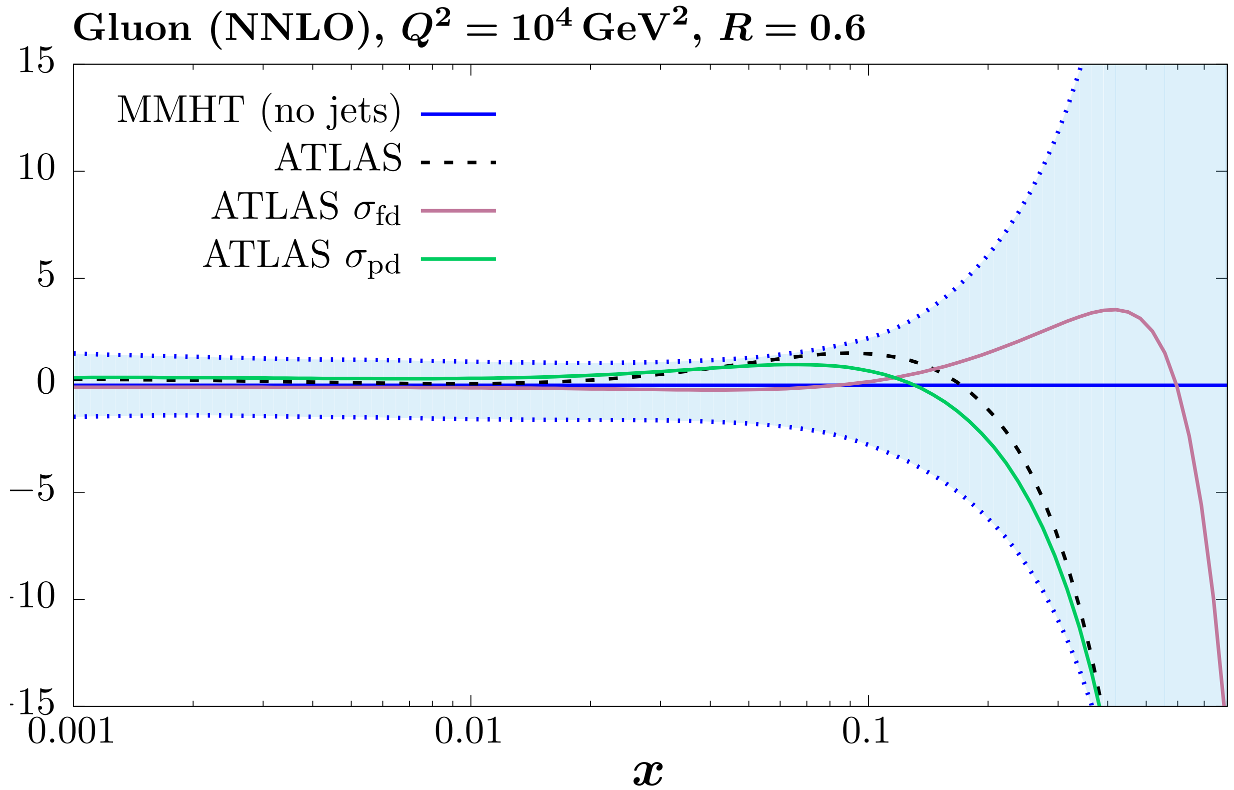
- MMHT study of final ATLAS/CMS 7 TeV inclusive jet data on NNLO fit. Fit stable with respect to:

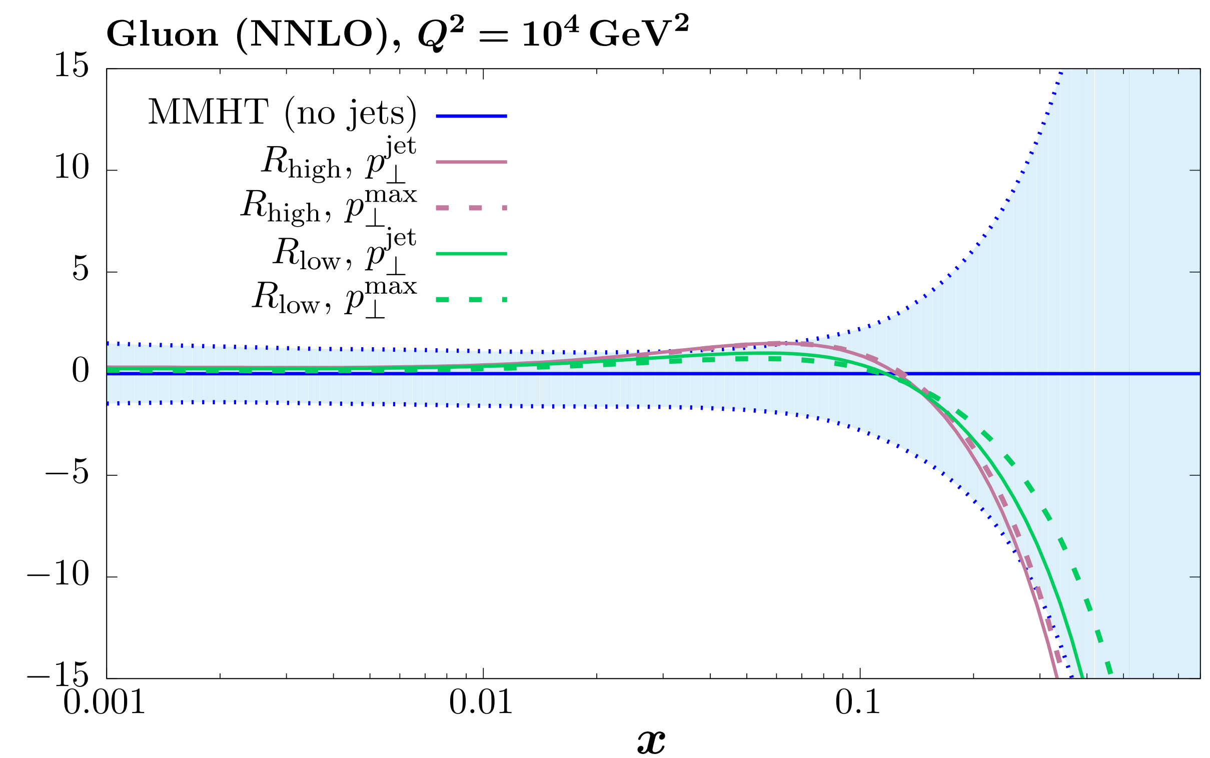
LHL, A.D. Martin, R.S. Thorne, EPJC 78 (2018) no.3, 248

★ Choice of jet scale ($p_\perp^{\rm jet}$ vs. $p_\perp^{\rm max}$).
★ Jet Radius.
} Resilience of global fit due to other data constraints

★ Treatment of ATLAS systematics, if full rapidity range included (default χ^2 high).
} PDFs stable under more realistic experiment-driven approach

ATLAS, JHEP 09, 020 (2017).

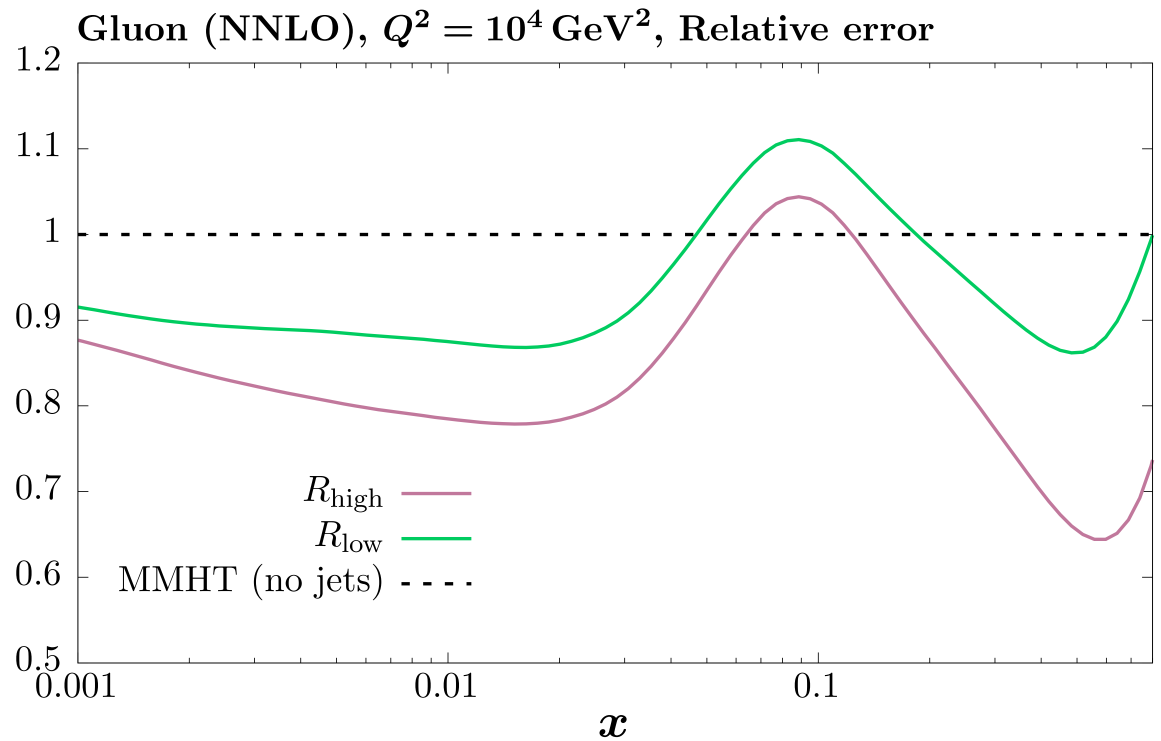




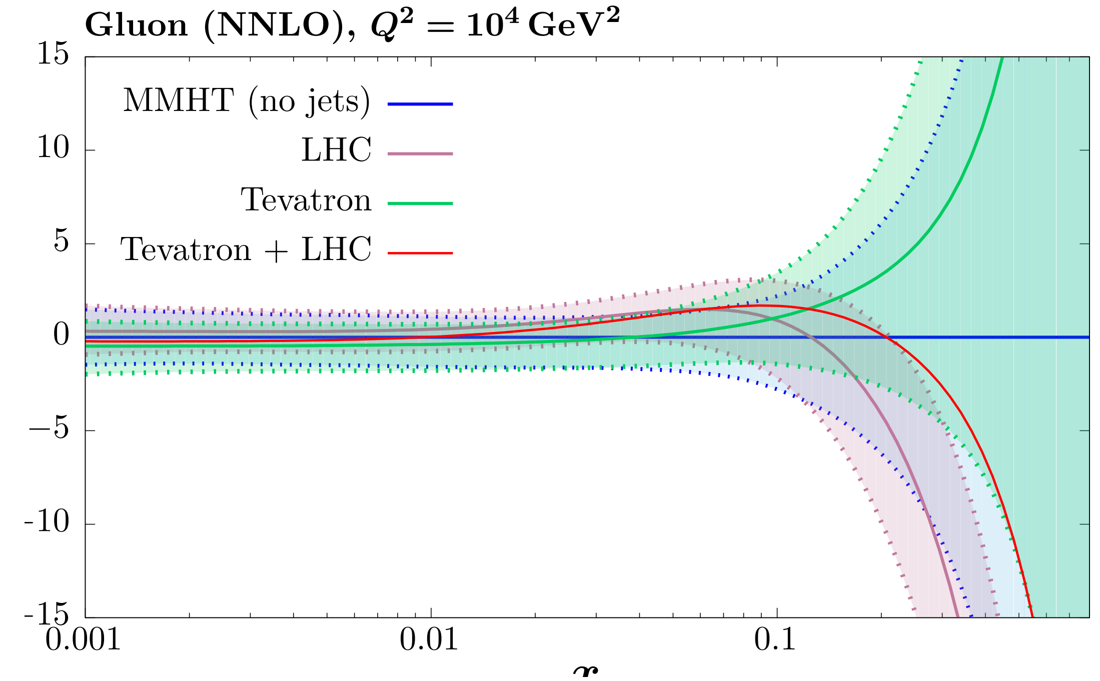
Impact

	NLO theory	NNLO
ATLAS, $R_{\rm low}$	215.3	172.3
ATLAS, $R_{\rm high}$	159.2	149.8
CMS, $R_{\rm low}$	194.2	177.8
CMS, $R_{\rm high}$	198.5	182.3

- Softer gluon at high x , opposite to pull of Tevatron jets. These apply approx. NNLO only $\longrightarrow$ will this change with full theory?



- Improvement in description from NLO to NNLO - pQCD working as it should.



- Reduction in uncertainties over broad x region.

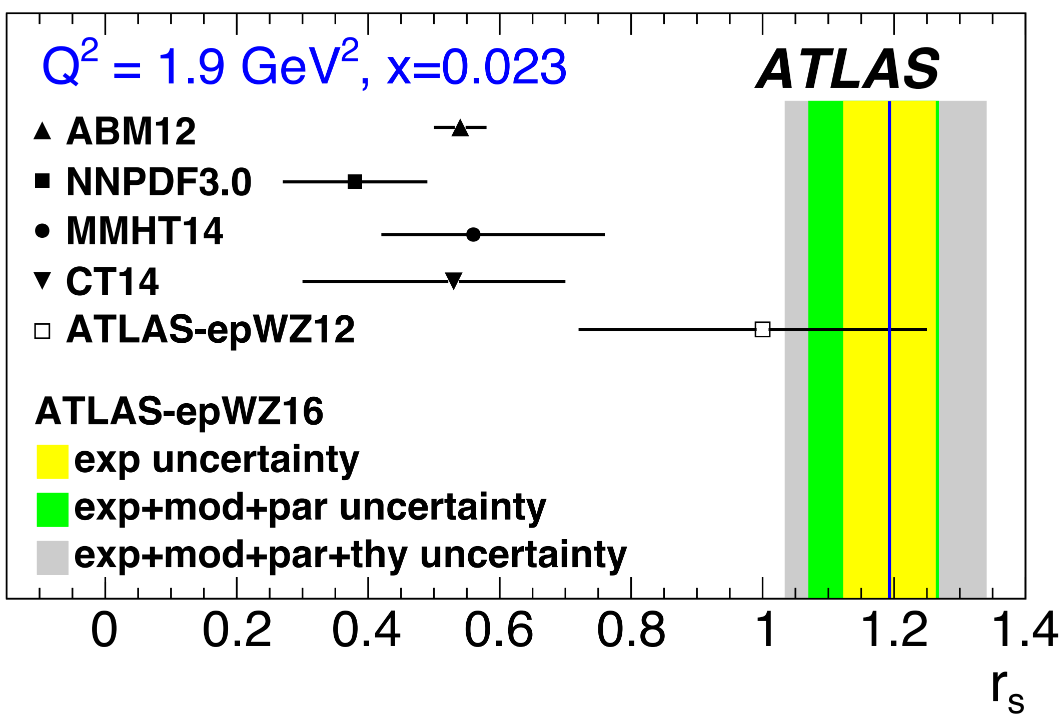
New data: LHC W, Z and Proton Strangeness

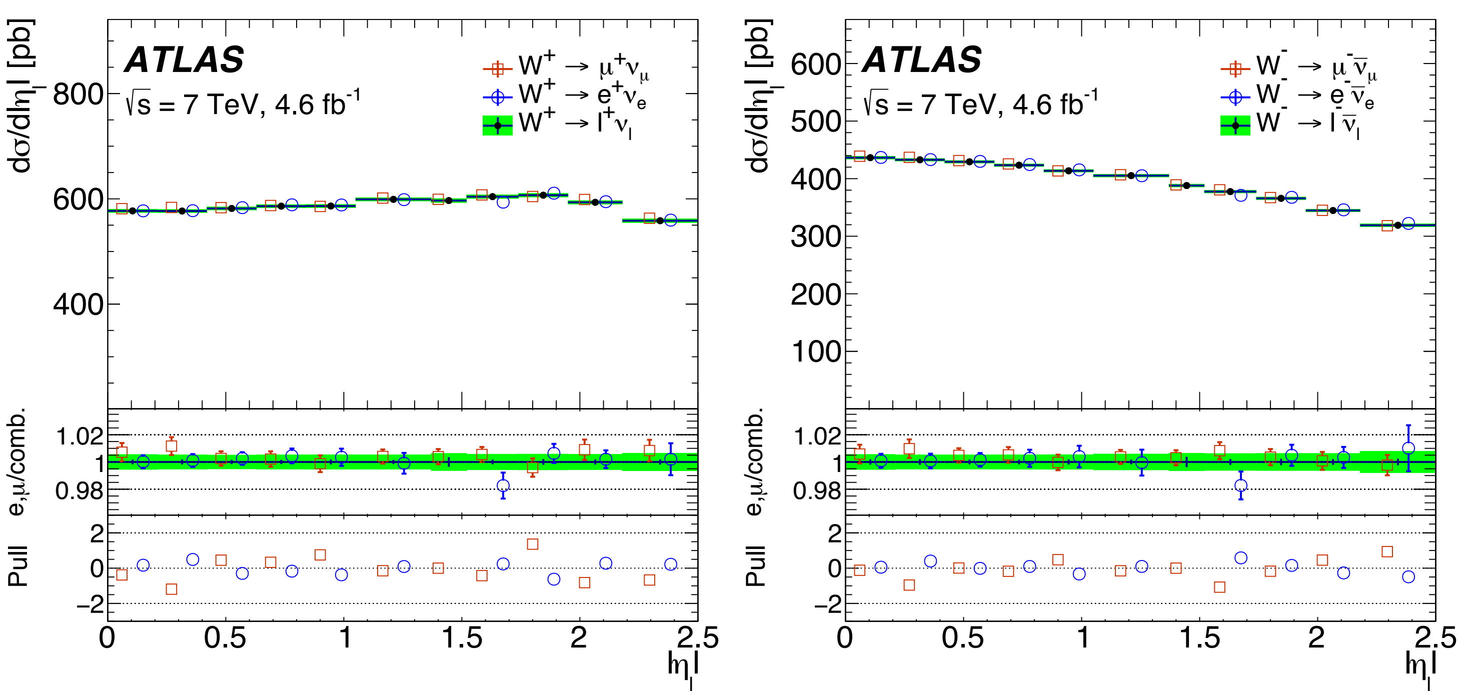
Drell-Yan and Strangeness

- W, Z production proceeds via range of channels. Least constrained involves initial-state s, $\bar{s}$ $\Rightarrow$ in principle sensitive to proton strangeness.

$$u\bar{d},\ c\bar{s} \quad (u\bar{s},\ c\bar{d}) \to W^+ \ ,$$
$$d\bar{u},\ s\bar{c} \quad (s\bar{u},\ d\bar{c}) \to W^- \ ,$$
$$q\bar{q} \to Z/\gamma^* \ ,$$

- Highest ever precision data from ATLAS: large impact on strangeness, preferring higher value than global fits (from e.g. $\bar{\nu}s \to lc$ DIS).





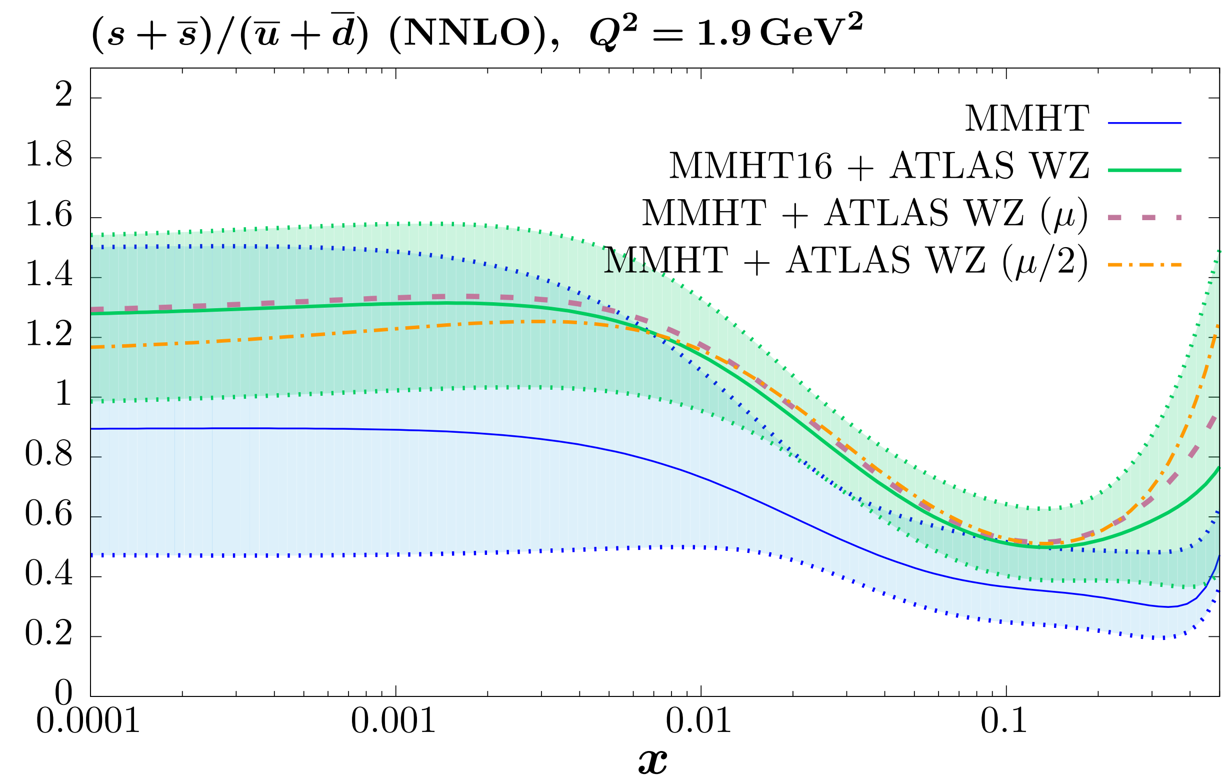
ATLAS collab., Eur. Phys. J C77 (2017) 367

- Now included in fits. Indeed prefer higher strangeness, but consistent within PDF uncertainties. But there is some small print:

★ Fit with default scale poor ($\chi^2/\text{dof} \gtrsim 2$), but improves with $\mu = \mu_0/2$, and little impact on PDFs.

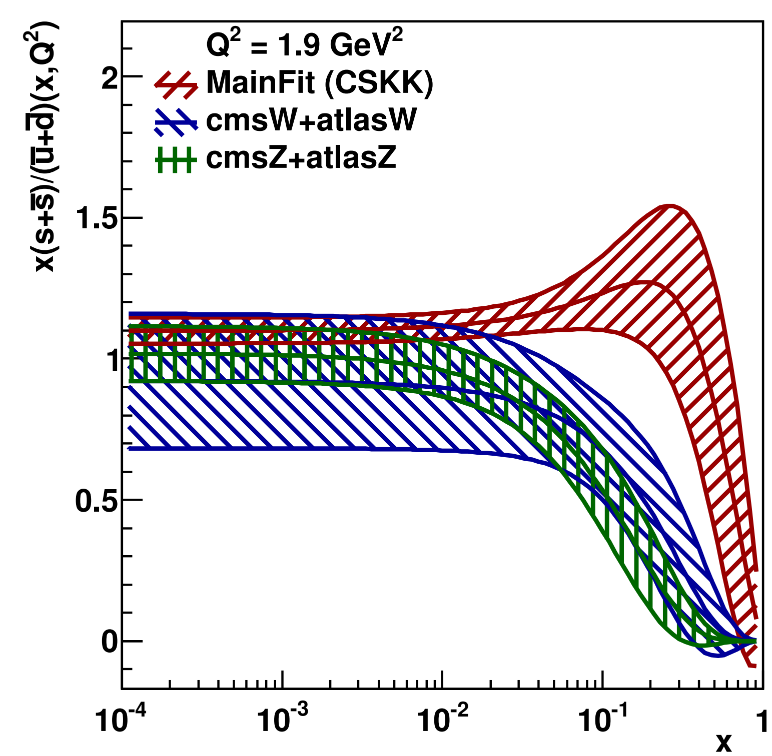
★ Globally consistent, but pulls in different direction to ν - induced charm DIS. Recent NNLO calculation should help this.

J. Gao, JHEP 1802 (2018) 026



- New combined ATLAS + CMS study of 7/8 TeV data find pull is consistent with W + Z having largest pull (correlations $\Rightarrow$ more information).
- Excluding ATLAS Z low/high M_{ll} : little effect (but χ^2 better)
- On the other hand - CMS W + c data prefer lower strangeness.

More work needed!



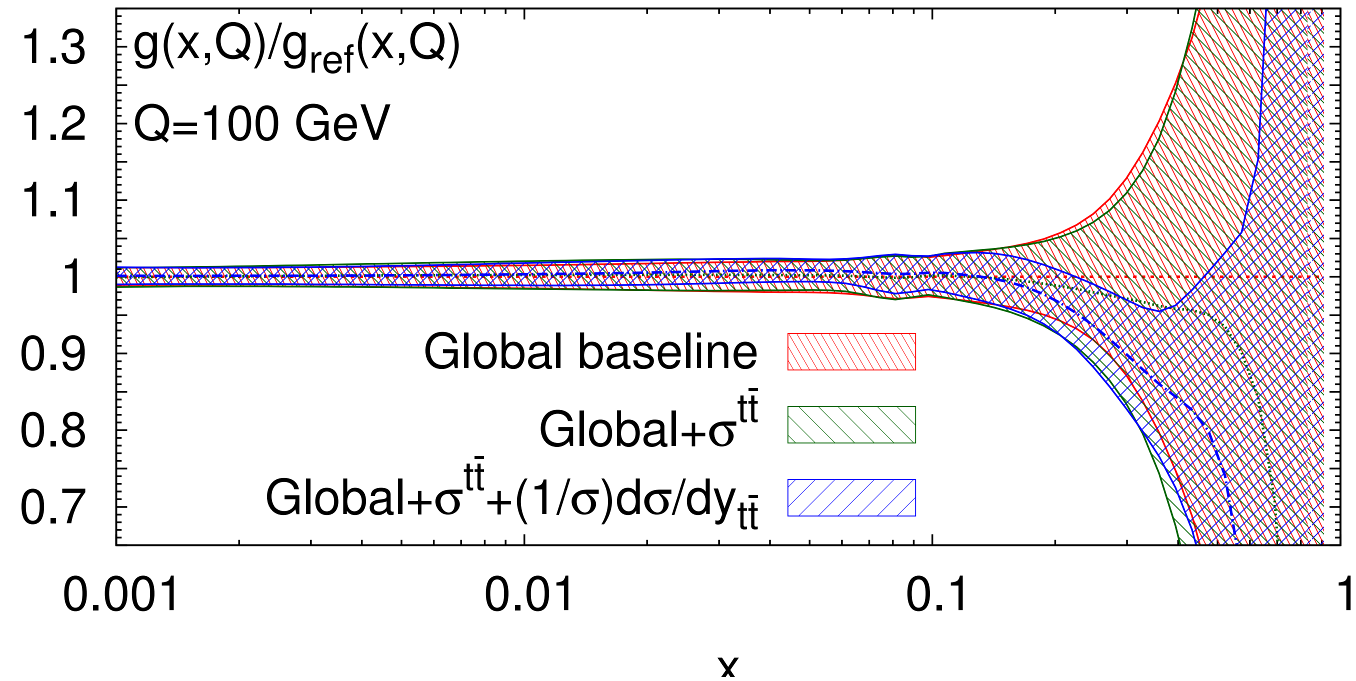
A.M. Cooper-Sarkar, K. Wichmann, arXiv:1803.00968

(More) LHC Impact

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

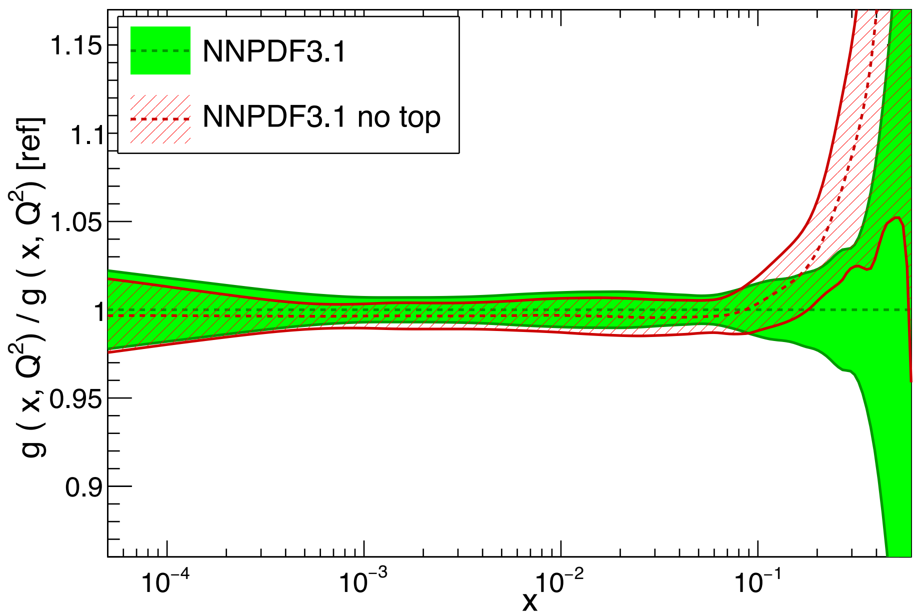
- **Differential top**: increased sensitivity vs. total cross section.
- Fits performed with latest NNLO theory. Impact on gluon at high x .
- Future: double differential?

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



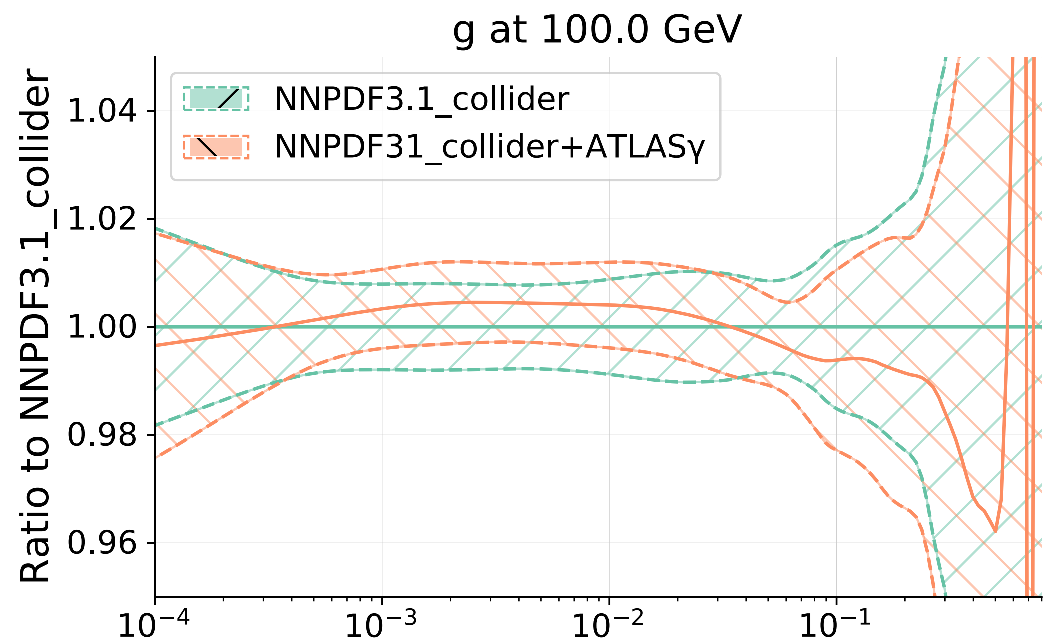
See also http://www.precision.hep.phy.cam.ac.uk/results/ttbar-fastnlo/

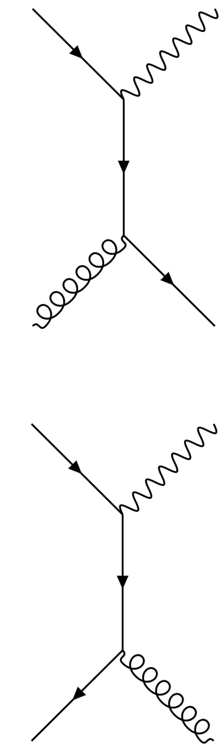
NNPDF3.1 NNLO, Q = 100 GeV



R.D. Ball et al., EPJC 77 (2017) no. 10, 663

- **Direct photon**: sensitivity to gluon at intermediate/high x.
- New NNLO calculations allows possibility for inclusion in precision fits.

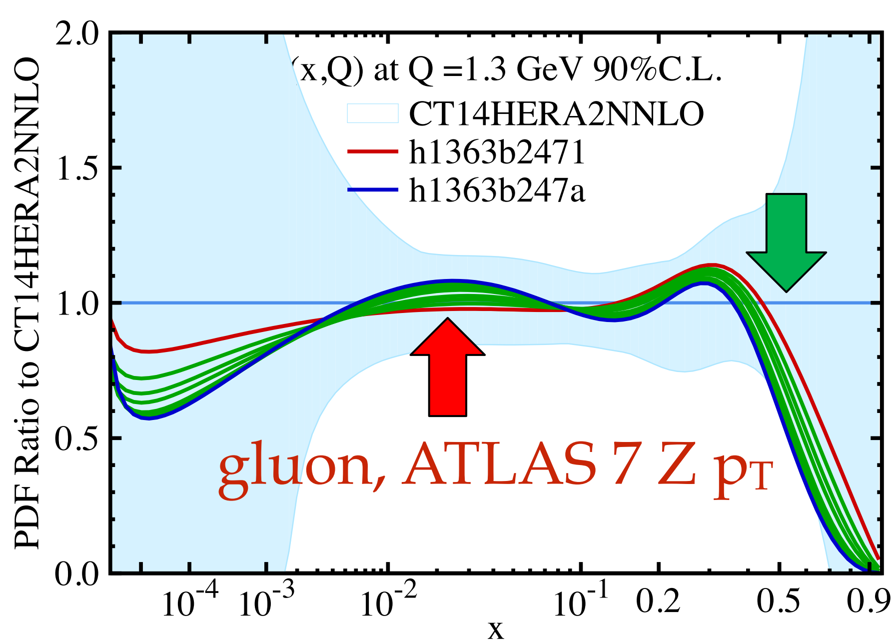




J.M. Campbell et al., arXiv:1802.03021

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

CT17p best-fit vs. CT14 HERA2



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

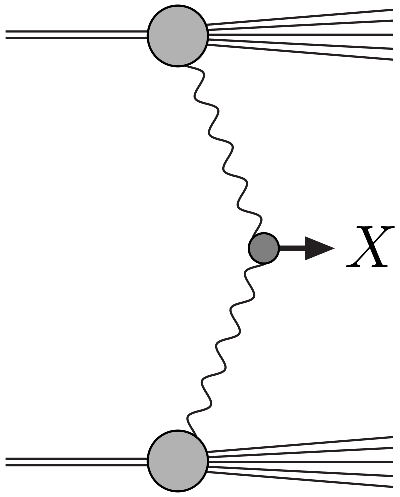
Boughezal et al., Phys. Rev. Lett. 116 (2016) no 15 152001

New Theory: The Photon PDF

The photon PDF

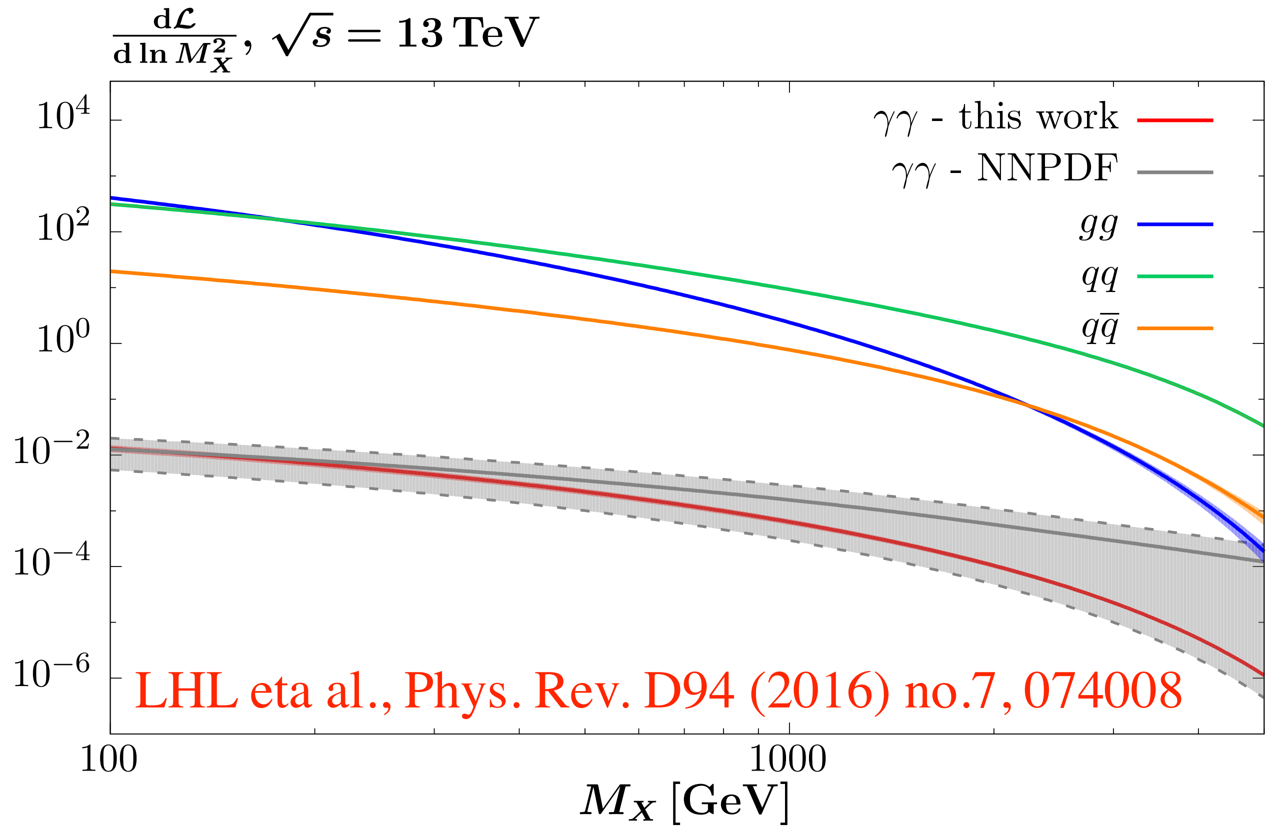
- High precision era - NNLO QCD the 'standard', but:

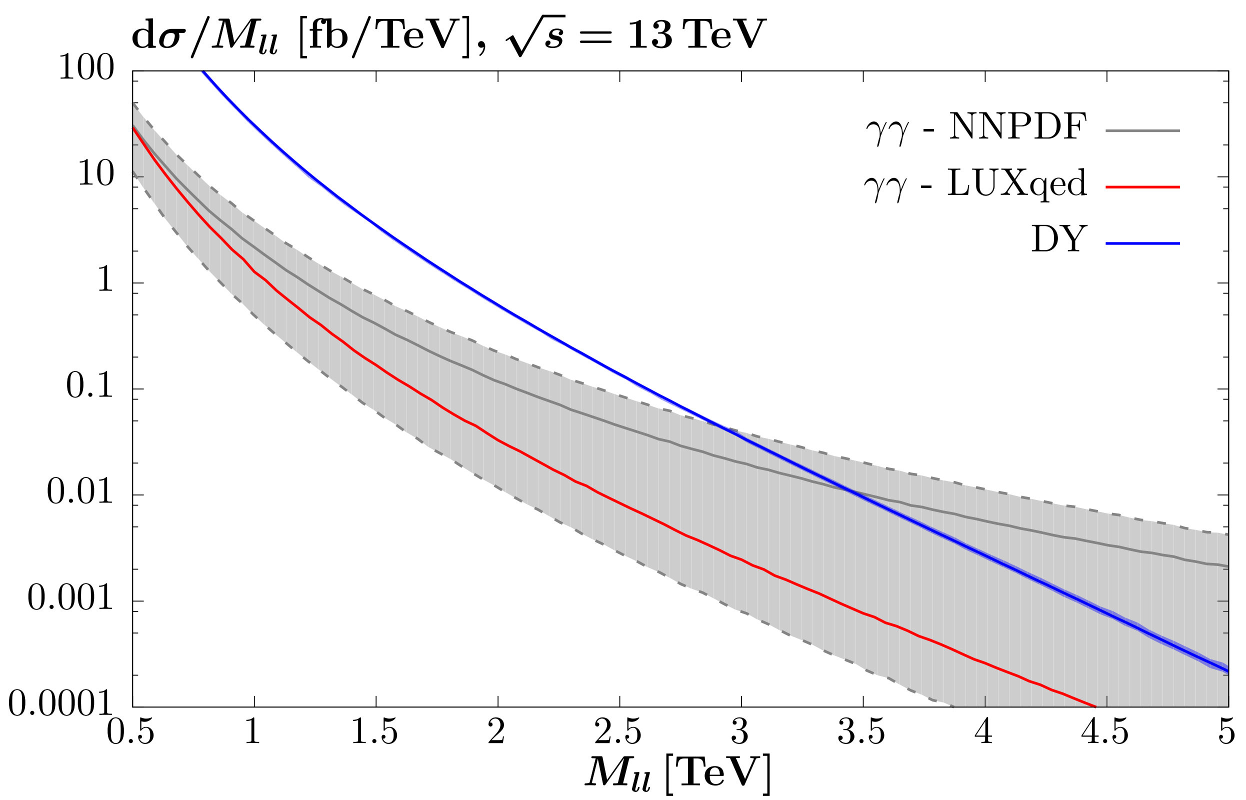
$$\alpha_S^2(M_Z) \sim 0.118^2 \sim \frac{1}{70} \qquad \alpha_{\rm QED}(M_Z) \sim \frac{1}{130}$$



$\longrightarrow$ Must include EW corrections, and thus initial-state photon contributions. Requires inclusion via **photon PDF**.

- Recap: 2016 studies indicated that contribution to DY, $t\bar{t}$, WW ...could be large at high mass, with large uncertainty. Should we worry? No.



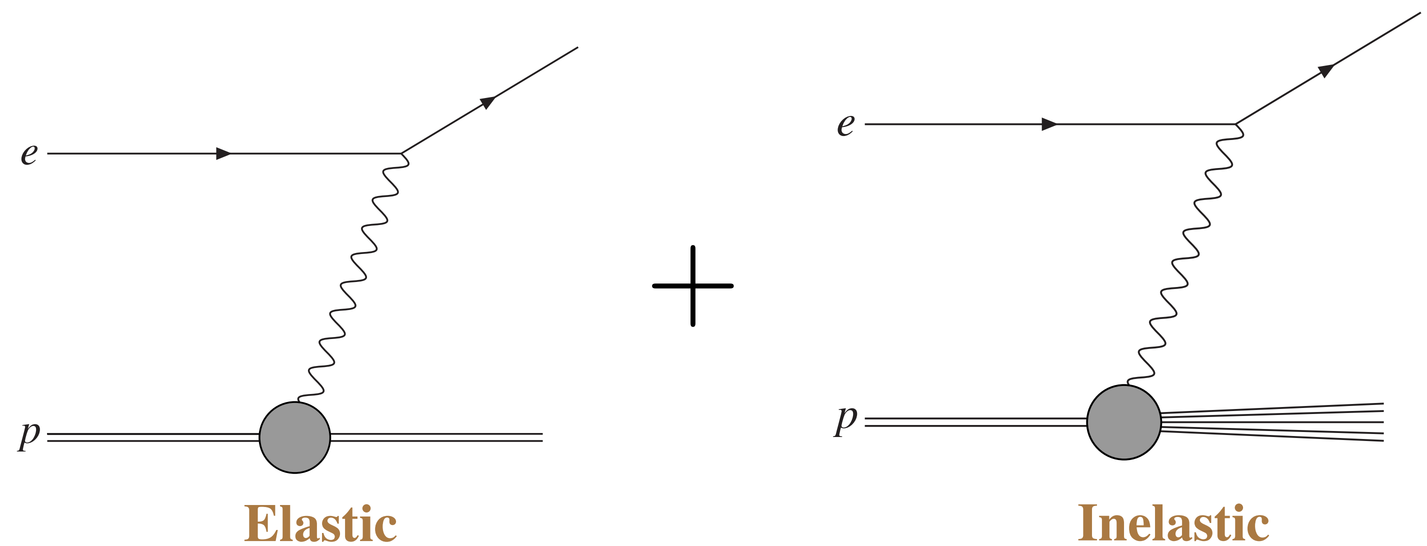


- 'Agnostic' approach of **NNPDF3.0QED** far **too conservative**. Photon PDF known to high precision in terms of measured ep scattering.

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

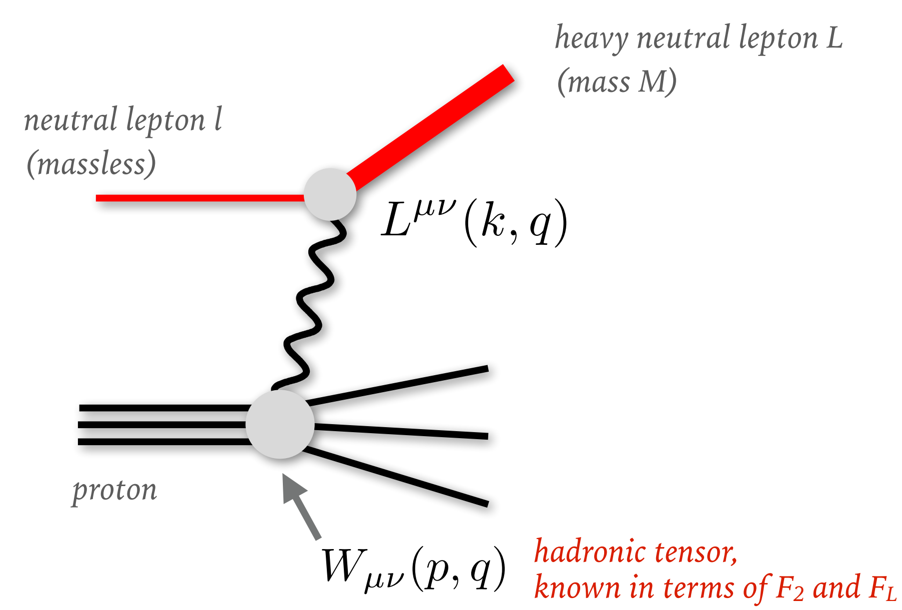
A. D. Martin, M. G. Ryskin, Eur. Phys. J. C74 (2014) 3040

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



- 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., JHEP 1712 (2017) 046

Implementing LUX

- Conclusion from above: photon has gone from being the poorest to the **best constrained** parton! However LUX formula not directly amenable to use in PDF fit:

★ Cross talk between q, g and γ?

★ Effect of refitting?

★ Neutron PDF?

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

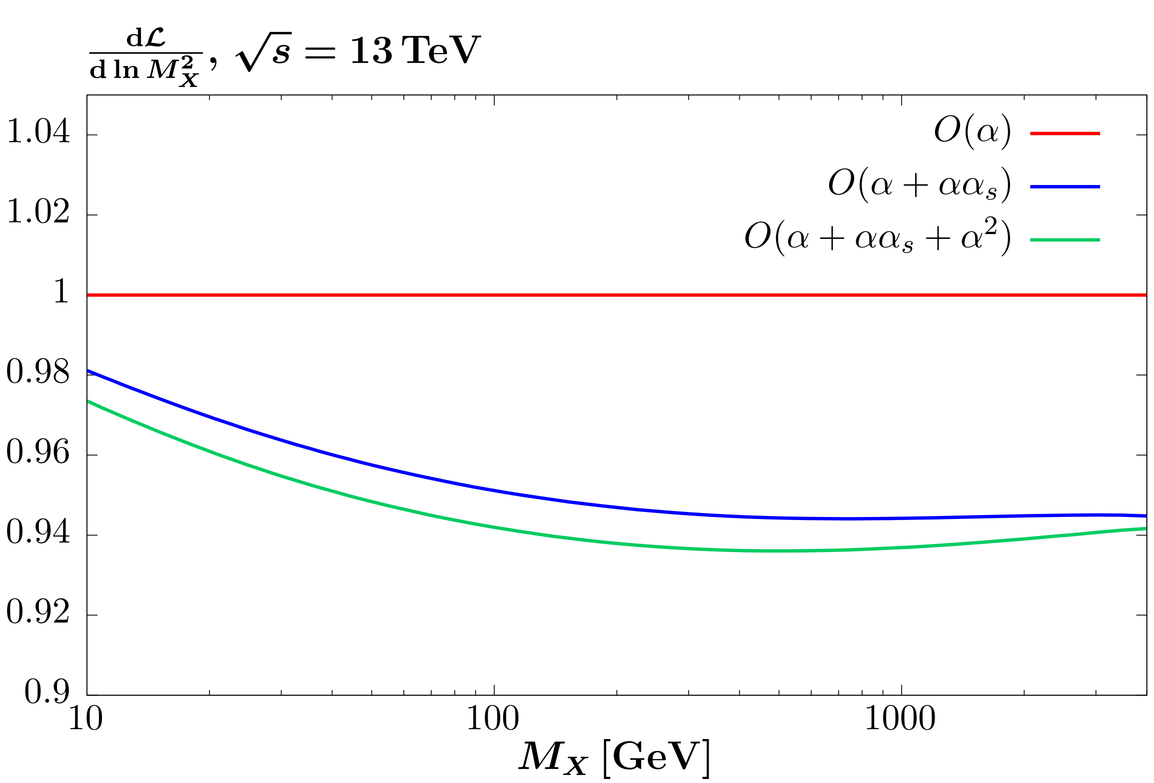
- Currently pursued by:

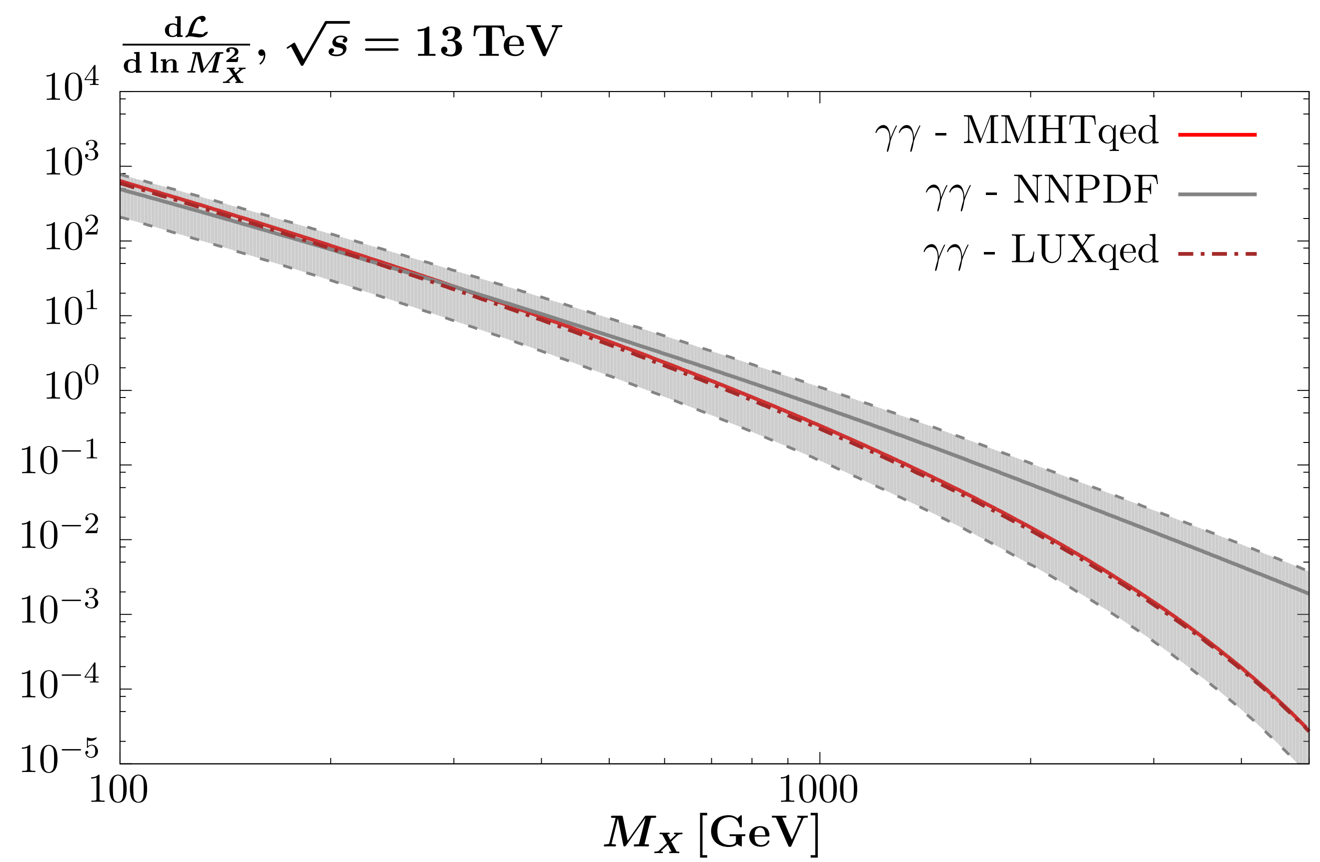
MMHTQED NNPDF3.1luxQED

- Also work in early stages for CT.
- In general, all future set should (will?) have photon included by default via high precision LUX determination. In more detail…

MMHTQED

- Ongoing work towards **MMHTQED** - connect LUXqed to standard DGLAP approach at input scale Q_0.
- $Q < Q_0$: input photon based on LUXqed formula ($\gamma(x, Q_0) \leftrightarrow F_2, F_L$), including uncertainties as in LUX.
- $Q > Q_0$: apply standard ($\alpha\alpha_s + \alpha^2$) DGLAP*.
- Results (as expected) close to LUXqed. Release coming soon.

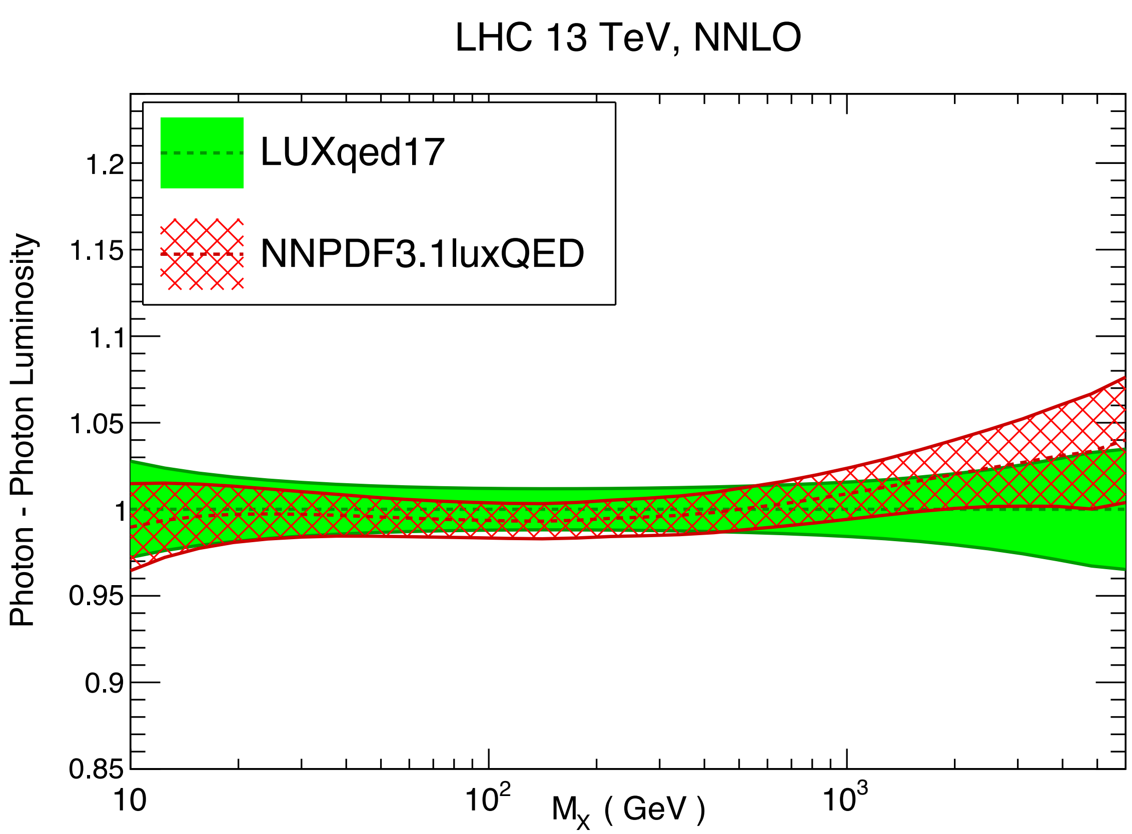




*In fact apply corrections for $\gamma_{el}(x, Q > Q_0)$, target mass corrections…

NNPDF3.1luxQED

- Recent release of **NNPDF** set including photon via LUX approach.
- LUX formula (including uncertainties) taken at $Q = 100\,\mathrm{GeV}$, evolved back to $Q_0 = 1.65\,\mathrm{GeV}$ and refit. Iterated until convergence reached.
- Results (again as expected) lie close to LUXqed, with **% level uncertainties**.



CERN-TH-2017-235
Nikhef/2017-064

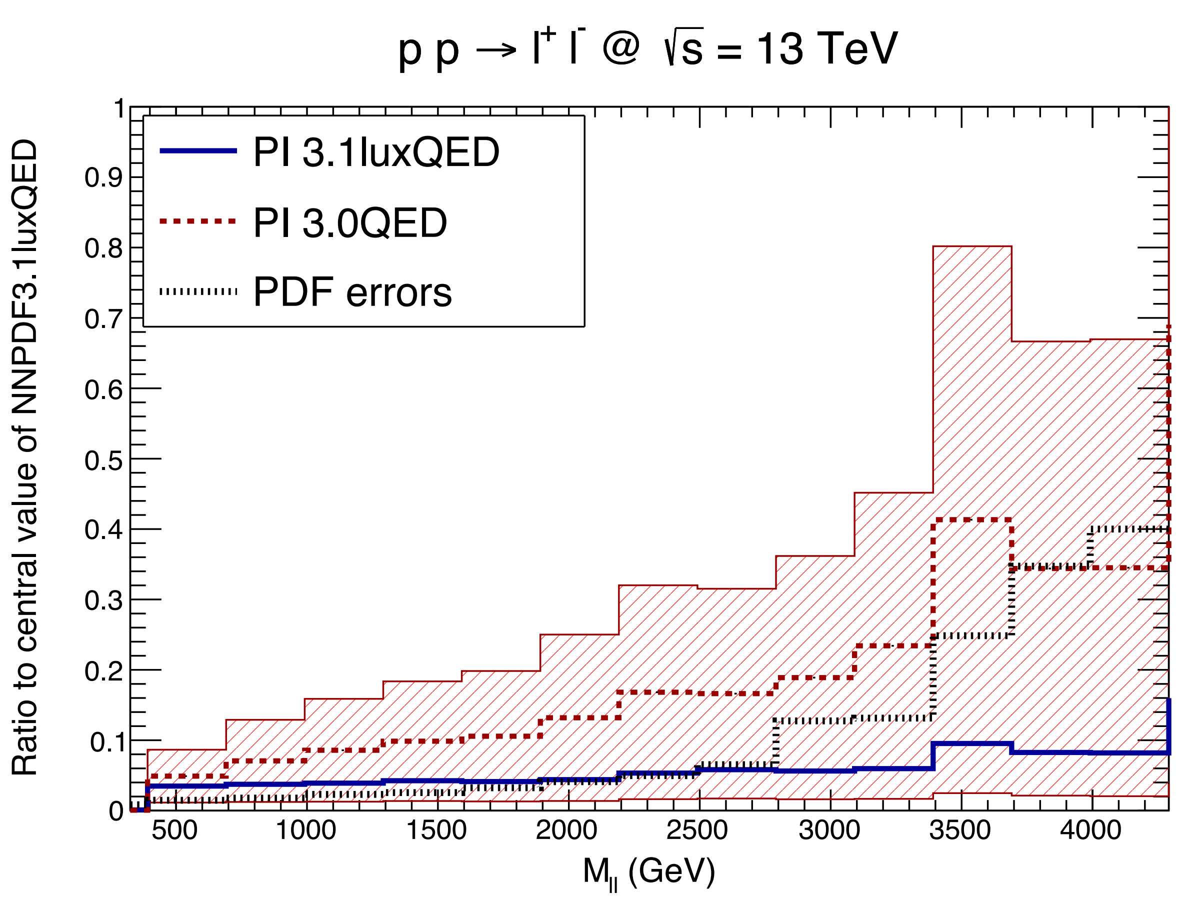
Illuminating the photon content
of the proton within a global PDF analysis

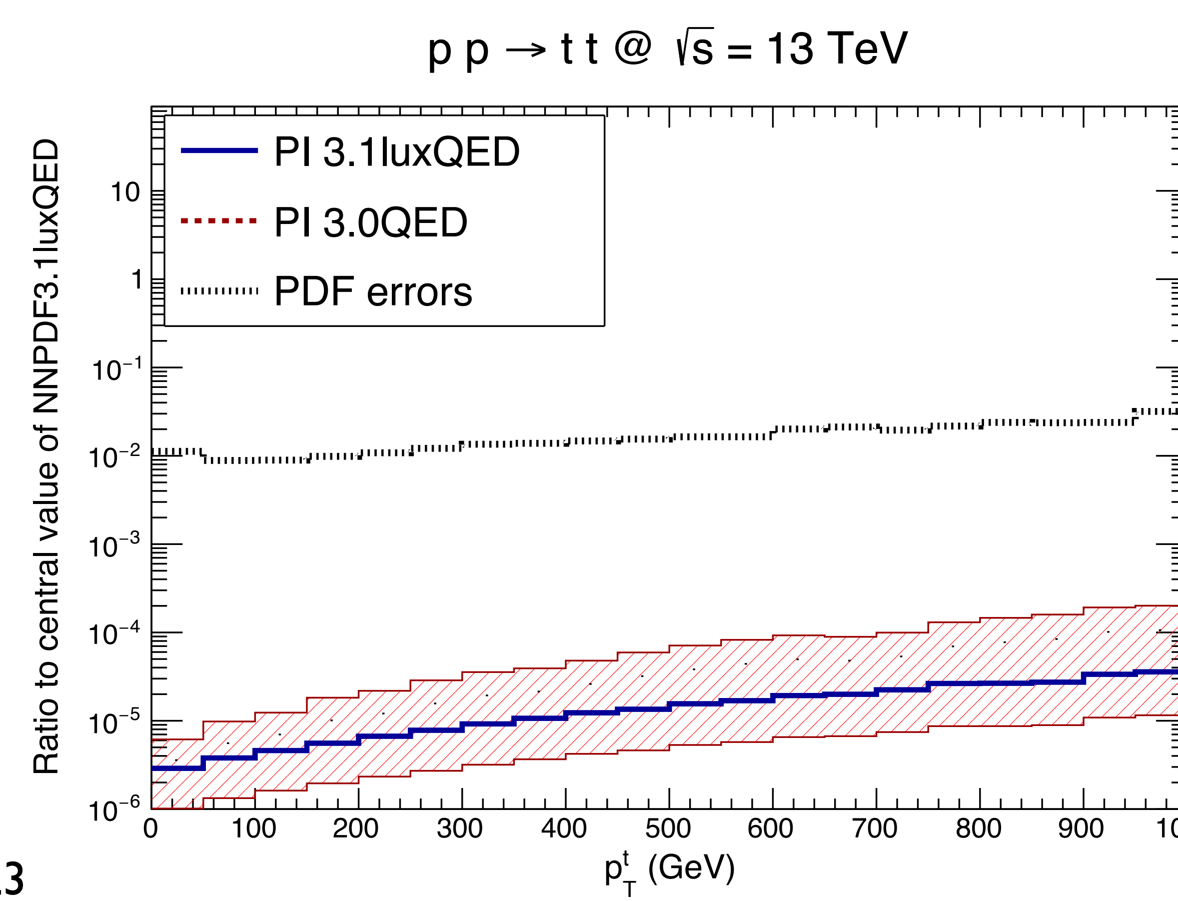
The NNPDF Collaboration:
Valerio Bertone,[1] Stefano Carrazza,[2] Nathan P. Hartland,[1] and Juan Rojo.[1]

V. Bertone et al. arXiv:1712.07053

Photon-initiated production at the LHC

- What are the pheno. implications of this? From NNPDF study:
  - **Drell-Yan**: PI ~ a few %. Comparable to (larger than) PDF uncertainties at low (high) mass.
  - W^+W^-: as high as ~ 30 % for $M_{WW} \sim 3\,\text{TeV}$, but ~ 1 % at $p_\perp^W \sim 0.3\,\text{TeV}$. In both cases comparable to/larger than PDF errors.
  - $t\bar{t}$: at most at permille level, even at highest $m_{t\bar{t}}$. Well below PDF uncertainties.
  - HW: can be ~ 5% and larger than PDF uncertainties.



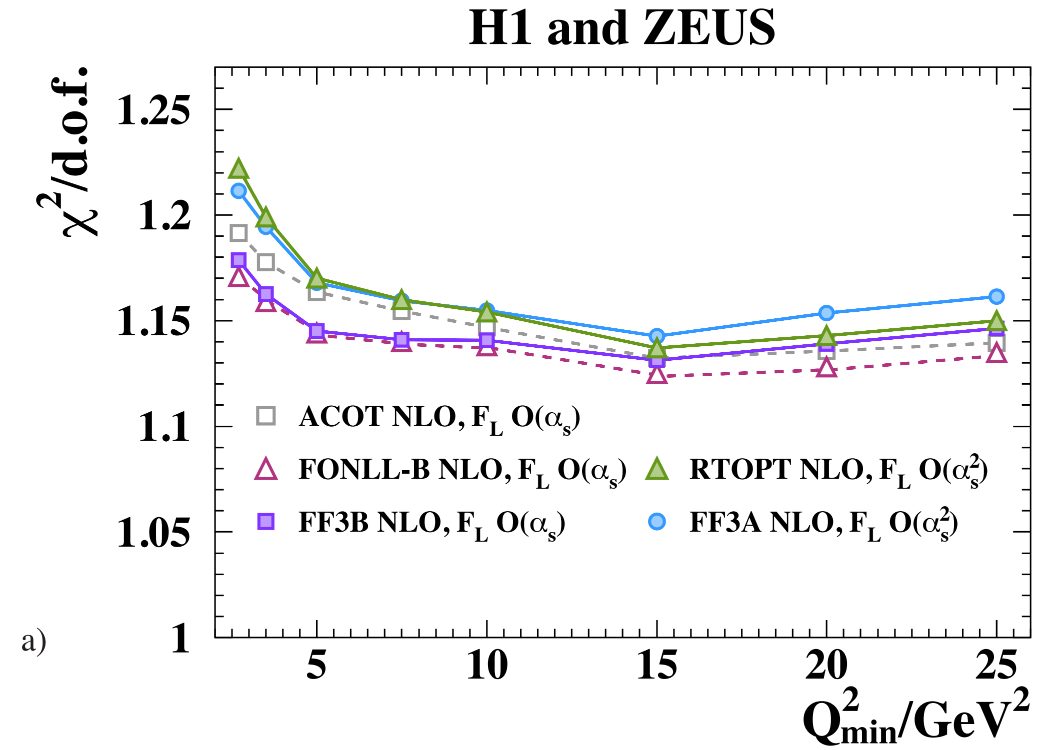


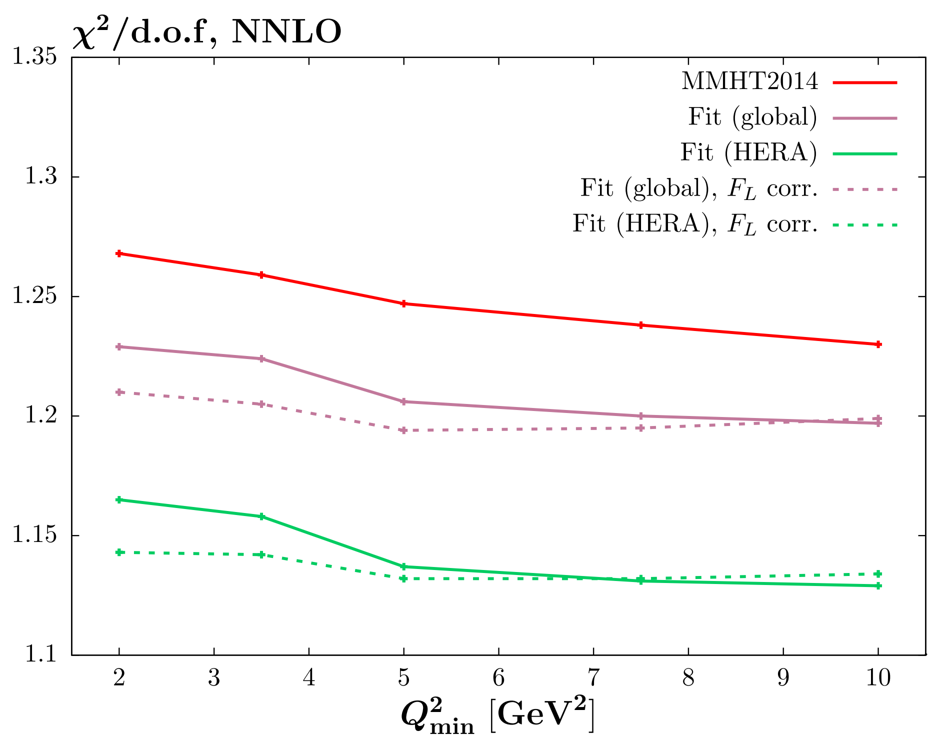
New Theory: PDFs and low x

Describing HERA data at low x, Q^2

- Known effect in description of combined HERA Run I+II data - χ^2/d.o.f. ↑ as cut on Q^2 ↓.

H1 and Zeus Collab., EPJC 75 (2015) no.12, 580





LHL el al., EPJC 76 (2016) no 4., 186

- Subsequent studies found that correction term to improved description: $\tilde{\sigma}(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y^2)} F_L(x,Q^2)$.

$$F_L^{(1)}(x,Q^2) = F_L(x,Q^2)\left(1 + \frac{a}{Q^2}\right) .$$

$$y = \frac{Q^2}{sx}$$

- Higher twist? Low x ? High $y \Rightarrow$ strong correlation $x \propto Q^2$. **Hard to disentangle**.

DGLAP + BFKL

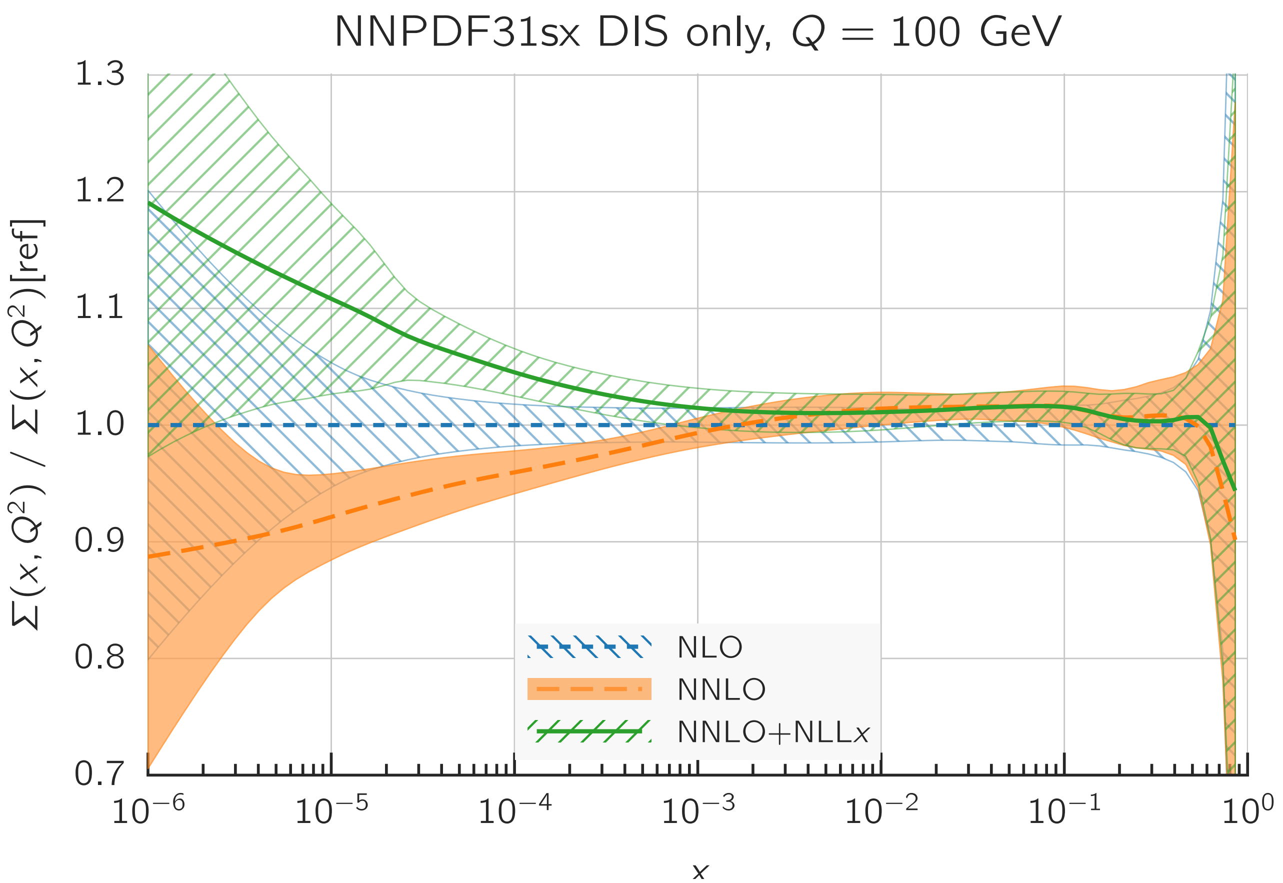
- Perturbative **fixed-order QCD** calculations extremely successful in describing a wealth of data from pp and ep collisions.
- However, theoretical reasons to go **beyond DGLAP**: $\ln(1/x)$ become dominant at small x and need to be resummed to all orders.
- Recent NNPDF study: **small-x resummation**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

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

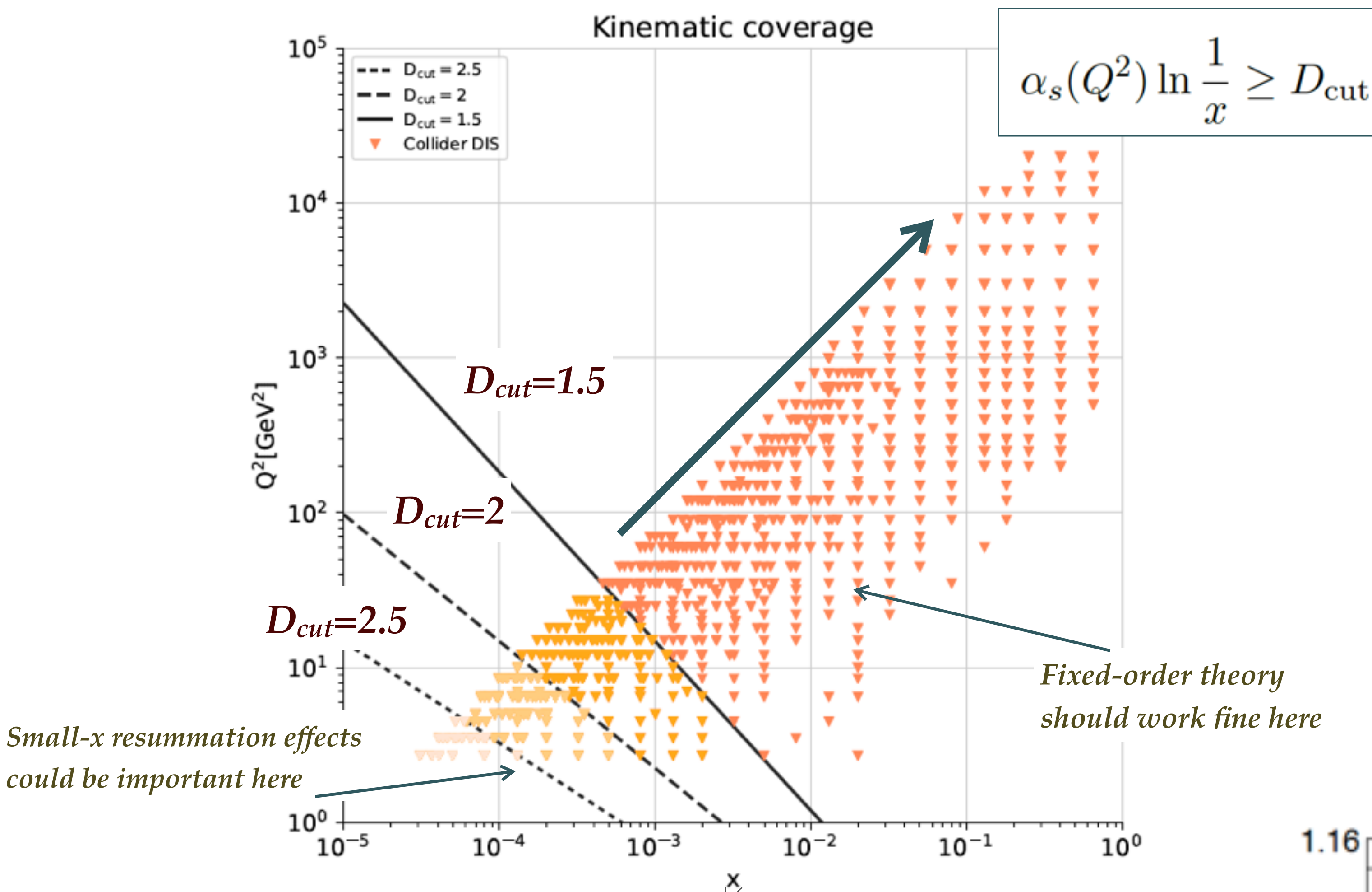
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

- Available in public `HELL` code.

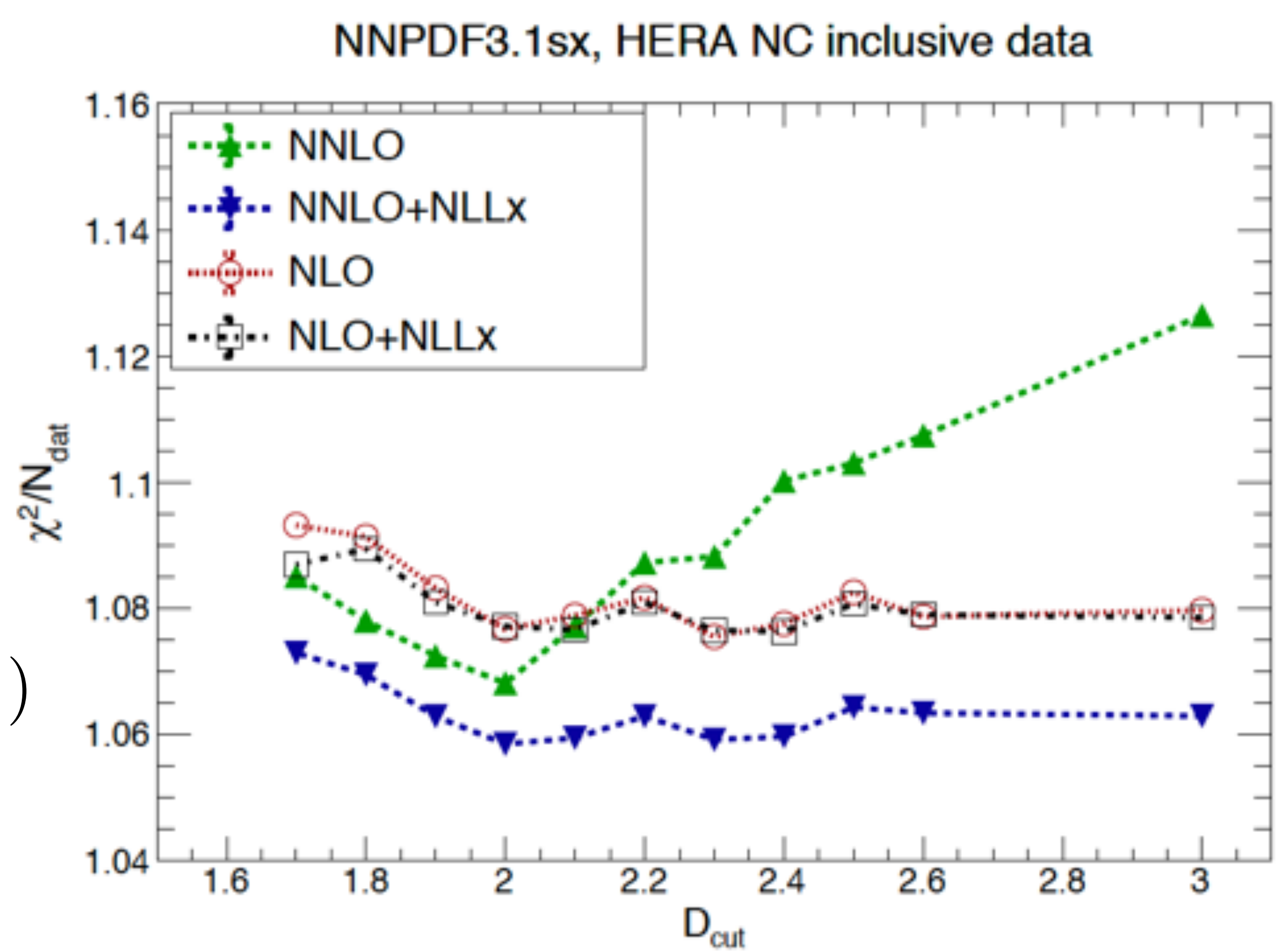
M. Bonvini, S. Marzani, C. Muselli, JHEP 1712 (2017) 117



R.D. Ball et al., arXiv:1710.05935



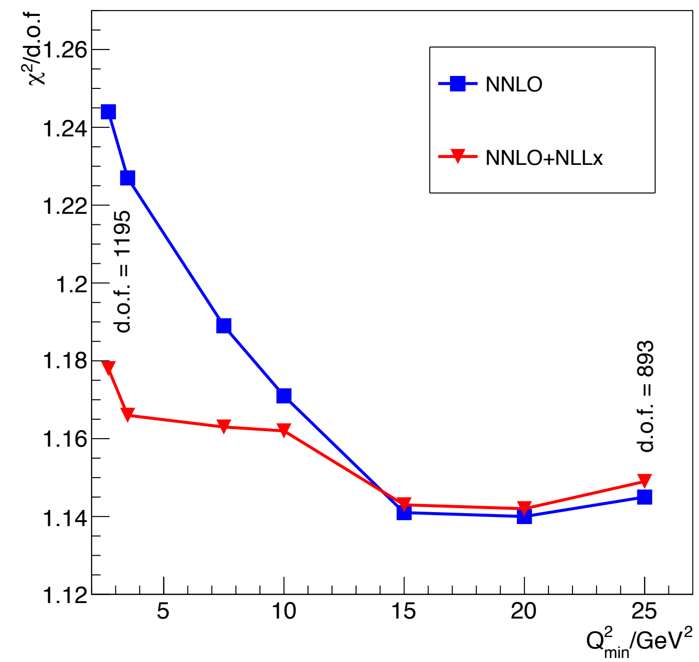
- To assess impact of small-x resummation on the **HERA data**, compute χ^2 removing data points in the region where resummation effects are expected.



- 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

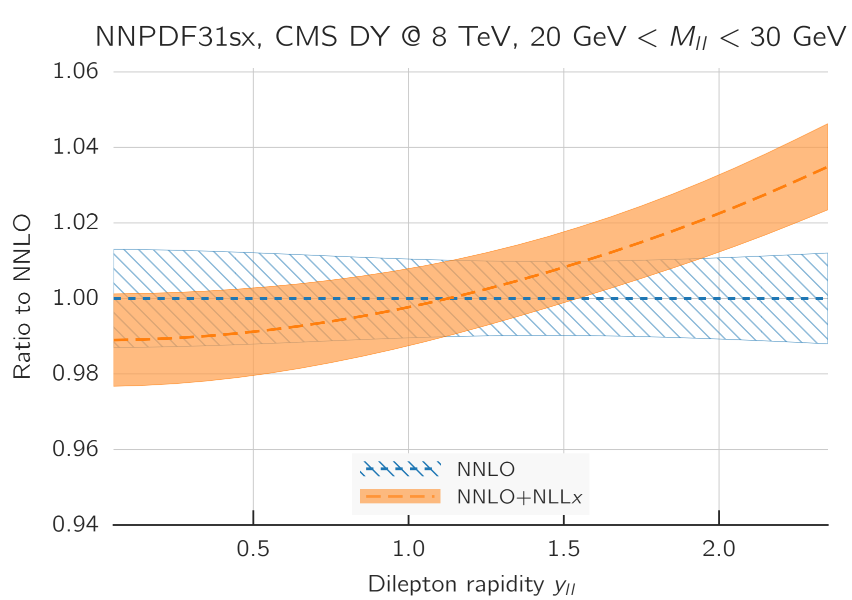
- Trend confirmed in subseqent **xFitter** study (though not in charm data).

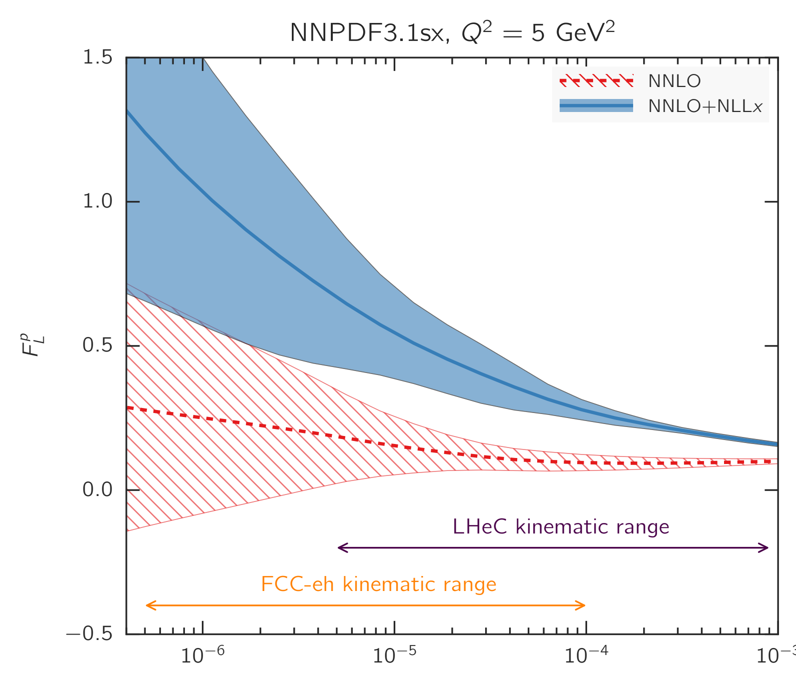
H. Abdolmaleki et al., arXiv:1802.00064



⟶ Clear indication that low x (BFKL) resummed predictions preferred by HERA data at low x, Q^2.

- Outlook - LHC data at low M/high y should be sensitive to these effects motivation to include in fits, and/or may provide further evidence.
- Outlook - impact at future colliders (HE-LHC, LHeC) larger.



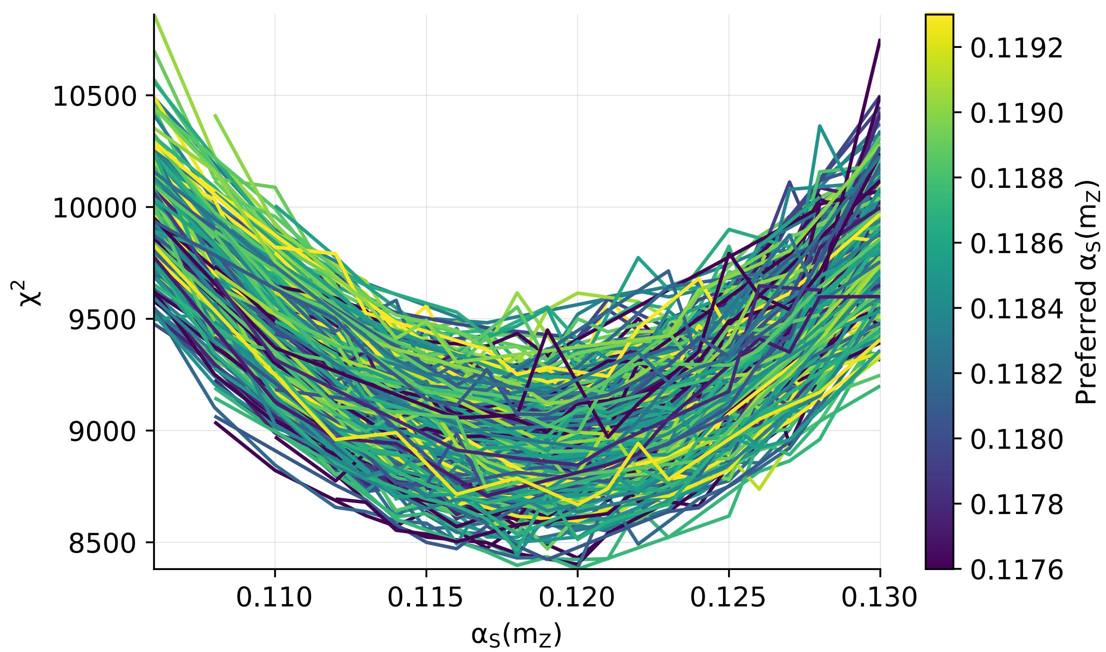


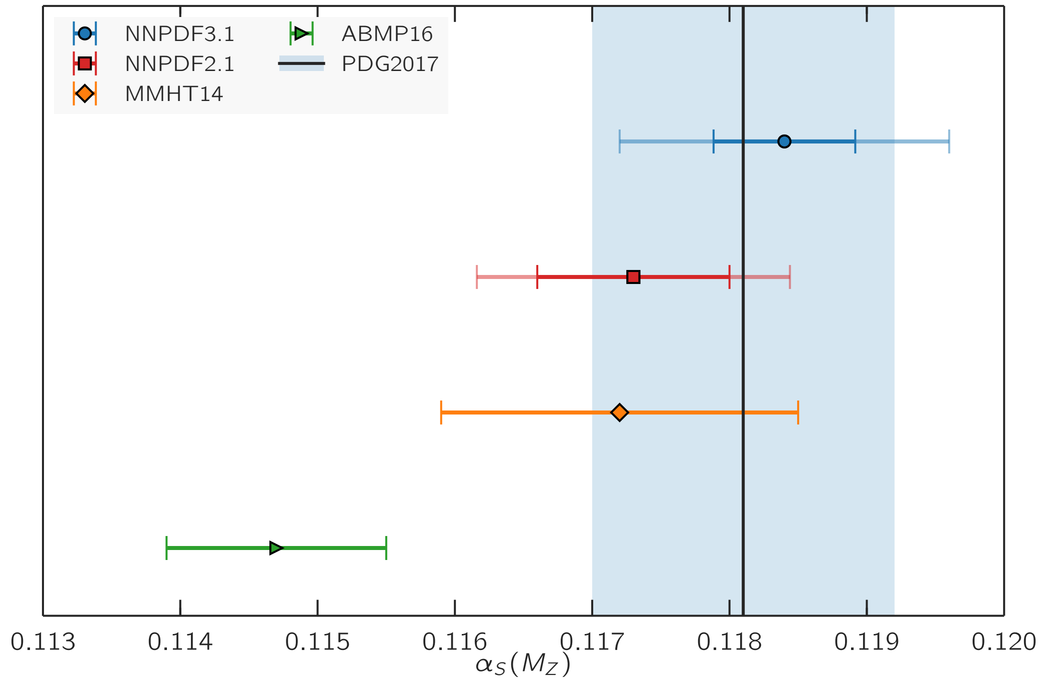
PDFs and the Strong Coupling

PDFs and Strong Coupling

- The strong coupling can be treated as an additional free variable $\Rightarrow$ global fits can provide valuable information about α_S .
- Recent NNPDF study: minimisation in (PDF, α_S) space to each data replica. Ensemble then used to provide value for α_S , using NNPDF dataset ($\Rightarrow$ much new LHC data).
- 'Methodological' and 'theoretical' (missing higher orders) also included. Find:

$$\alpha_s^{\rm NNLO}(M_Z) = 0.1185 \pm 0.0005^{\rm exp} \pm 0.0001^{\rm meth} \pm 0.0011^{\rm th} = 0.1185 \pm 0.0012\ (1\%)$$





R.D. Ball et al., arXiv:1802.03398

- Central value somewhat larger than MMHT14. What about more recent fits?

- Central value somewhat larger than MMHT14:

$$\alpha_S(M_Z^2) = 0.1172 \pm 0.0013$$

(0.1178 when world average added as data point).

- How has this changed with more recent fits?

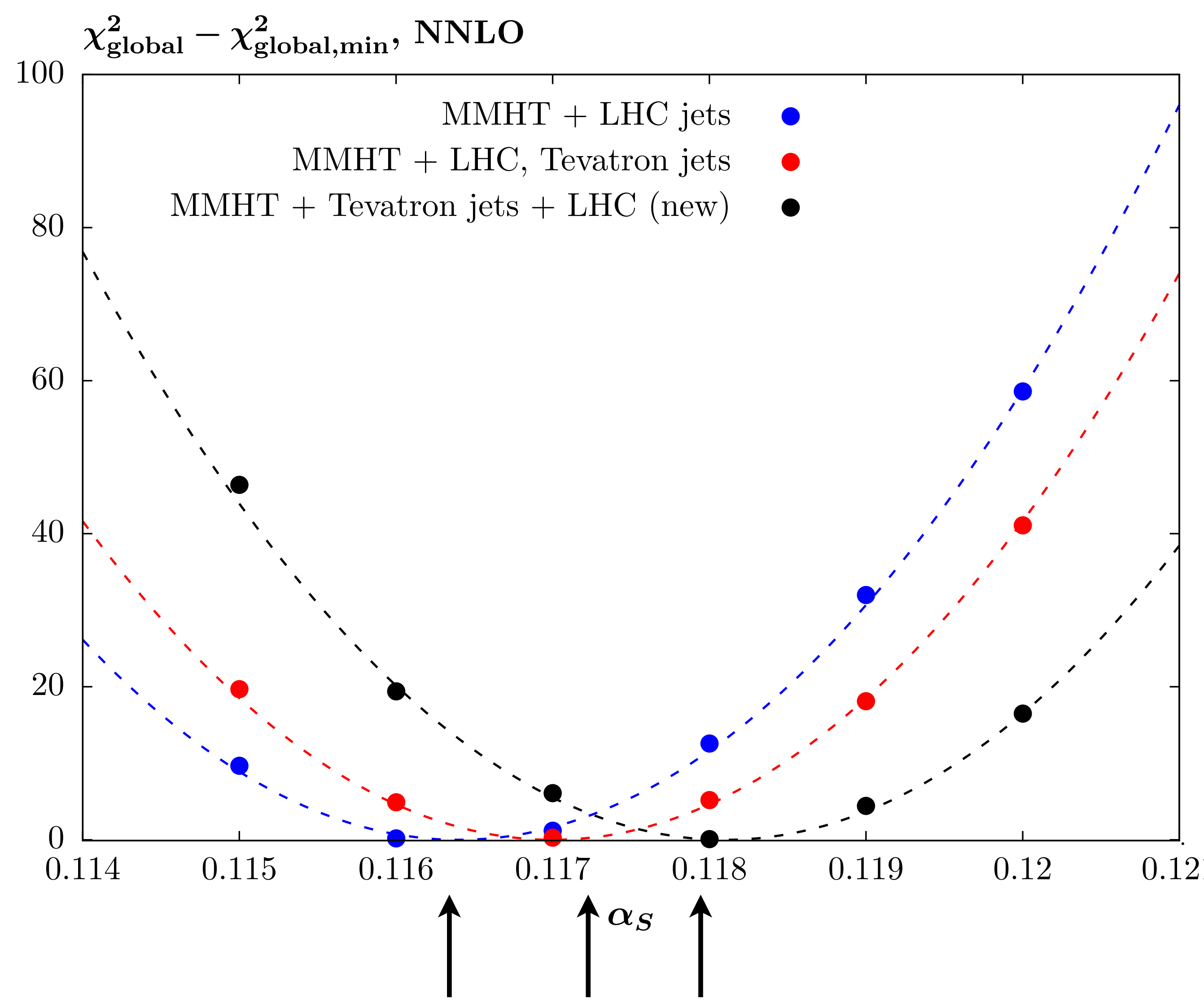
★ HERA I+II + new LHC $t\bar{t}$: 0.118.

★ Omit Tevatron jets (no NNLO) and include LHC jets: 0.1164

★ Include Tevatron jets: 0.1173

★ New LHC W, Z data (no LHC jets): 0.118

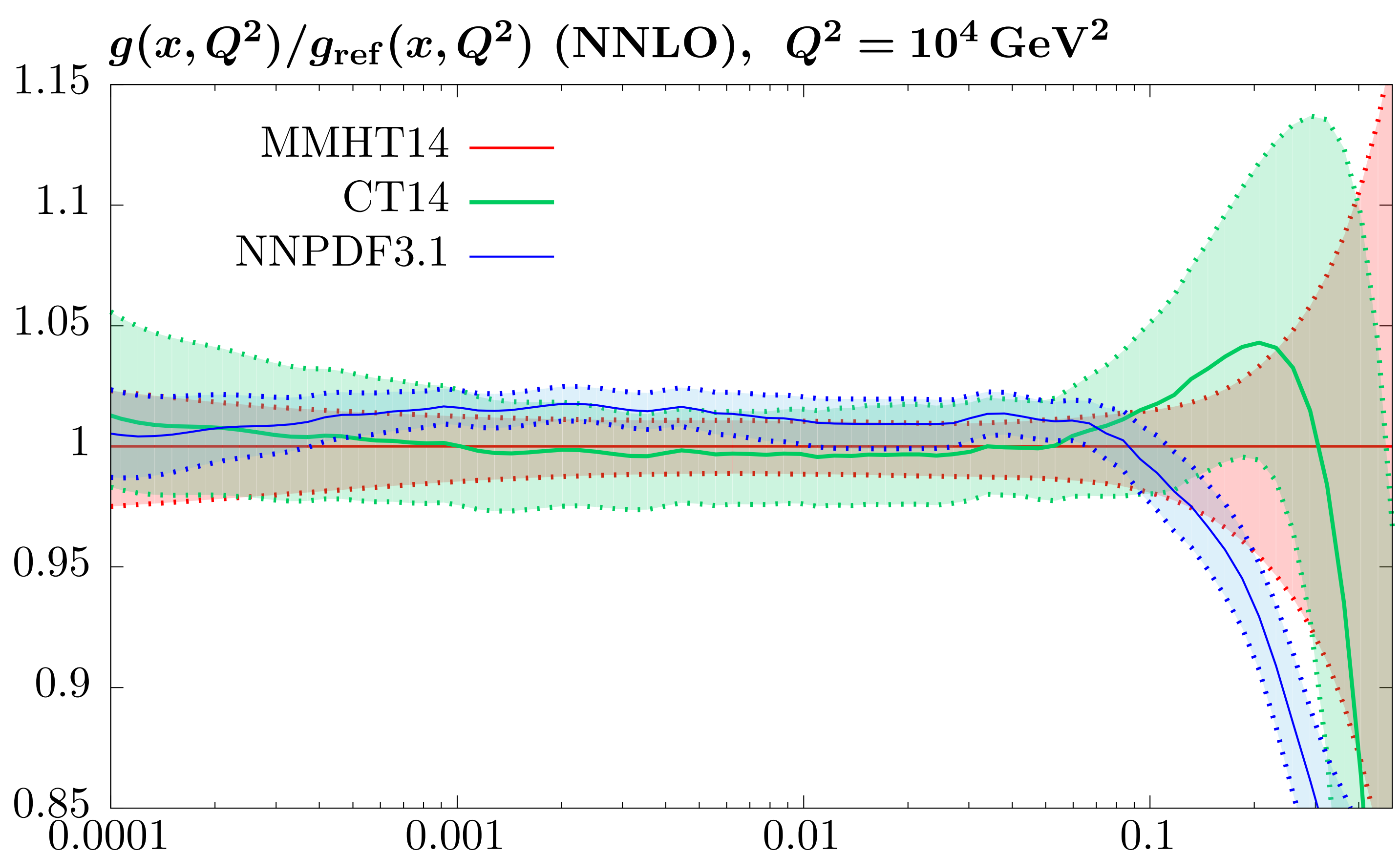
★ New LHC W,Z + jets data: 0.1176



$\longrightarrow$ LHC jet data prefers somewhat lower α_S, but stabilised by addition of ATLAS, CMS + LHC W,Z data.

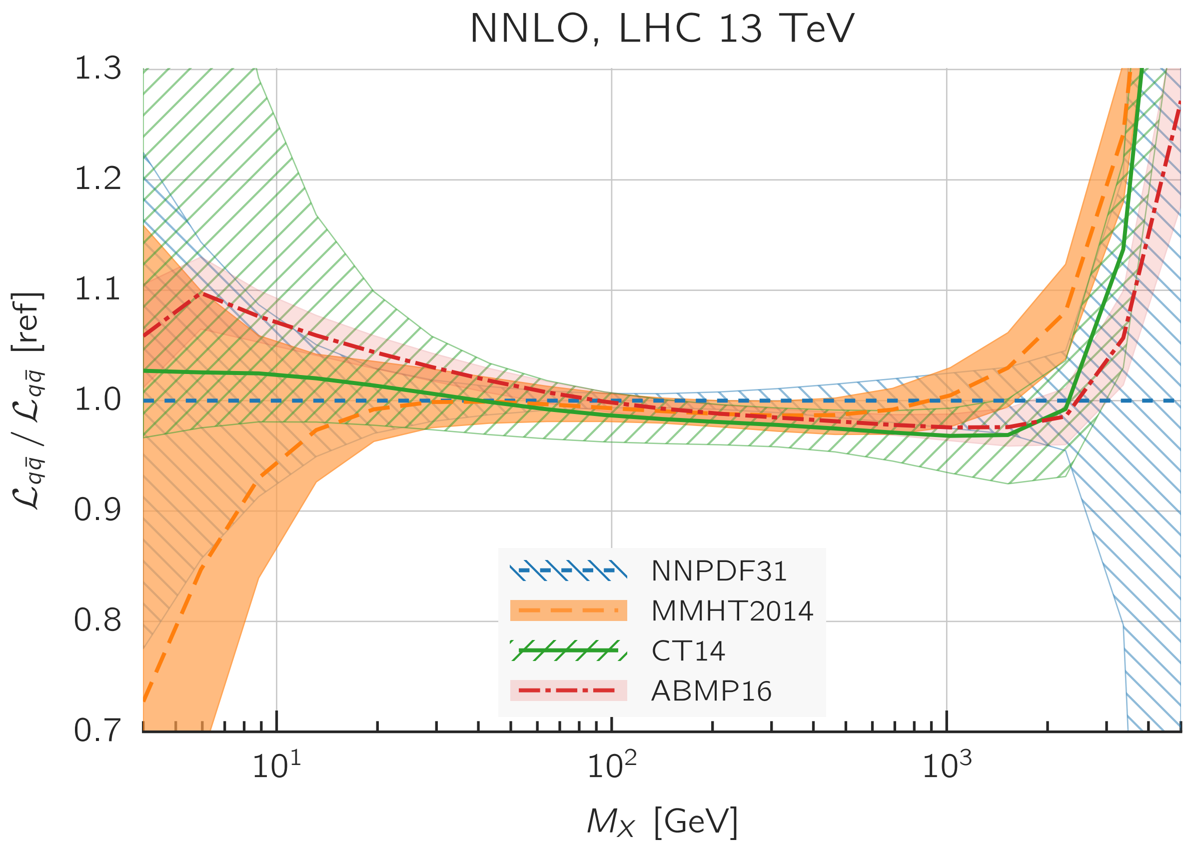
Where do we stand?

- Consider gluon as representative example. Despite varying approaches, global fits **~ consistent** (not true in past).
- Biggest difference at high x , with NNPDF3.1 lower - includes more LHC data ($t\bar{t}$, jets…).
- Expect updates from other groups soon: work ongoing towards CT17 and MMHT18. In all cases LHC data now playing significant role.
- New **PDF4LHC** combination under (early) discussion.



Looking to Future

- The HL-LHC will provide a vast range of data with a direct impact on the PDFs (in particular in poorly known high x region).
- **Question:** what exactly can we expect that impact to be?
- To address this, collaborative effort to produce '**Ultimate**' PDF set ongoing: final precision that can be expected from the HL-LHC (w/ possible extension to HE-LHC).
- Produced via pseudo-data generated according to final expected kinematic coverage and experimental precision we can expect to reach.



→ ?

Thank you for listening