Parton Distributions in the high-precision LHC era

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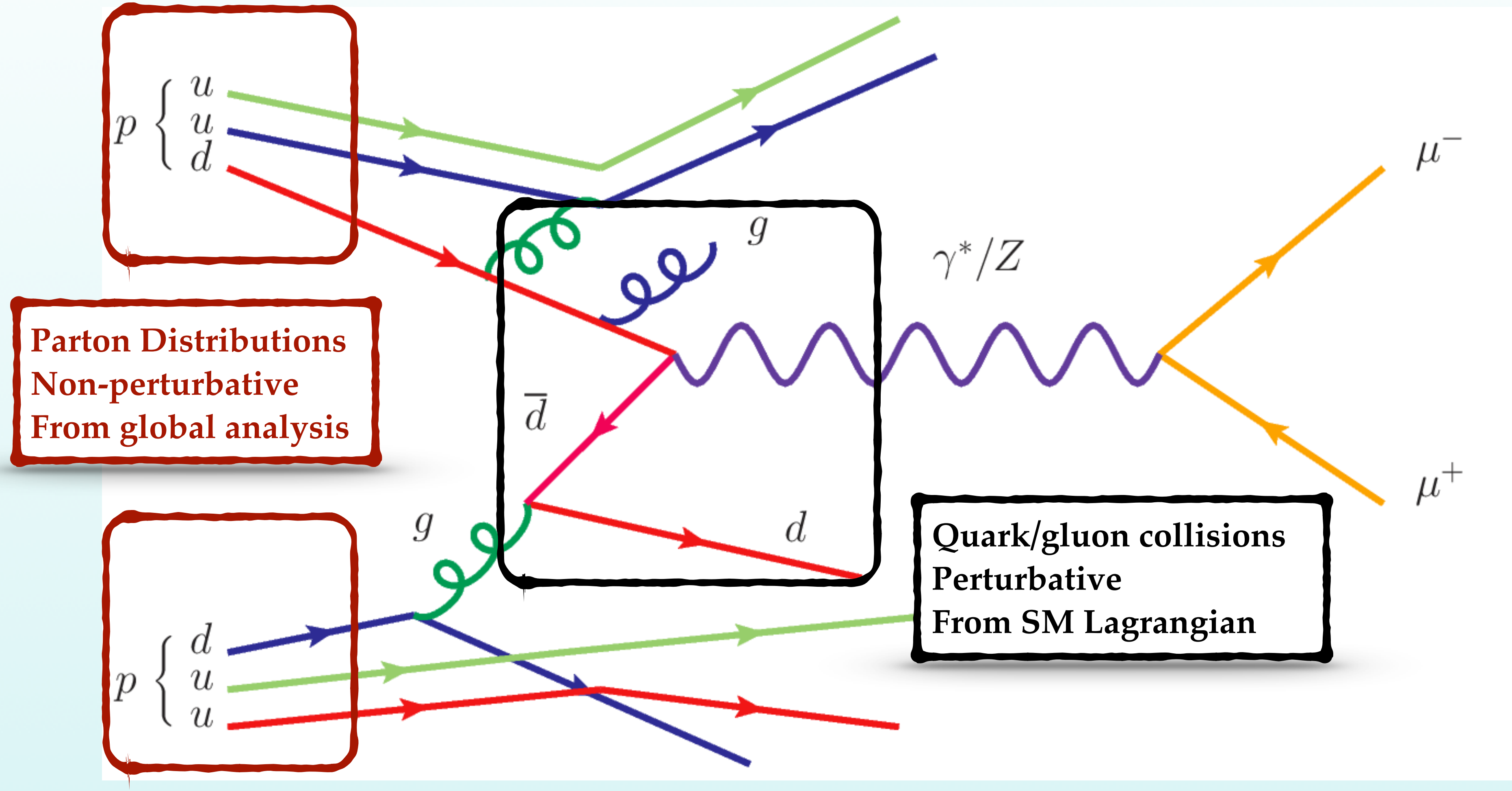
The Zurich Phenomenology Workshop 2018 (ZPW2018)
Flavours: Light, Heavy, and Dark
University of Zurich
17/01/2017

Anatomy of hadronic collisions

In high-energy **hadron colliders** the collisions involve **composite particles** (protons) with internal substructure (quarks and gluons): the LHC is actually a quark/gluon collider!



Calculations of **cross-sections** in hadron collisions require the combination of **perturbative cross-sections** with **non-perturbative parton distribution functions (PDFs)**

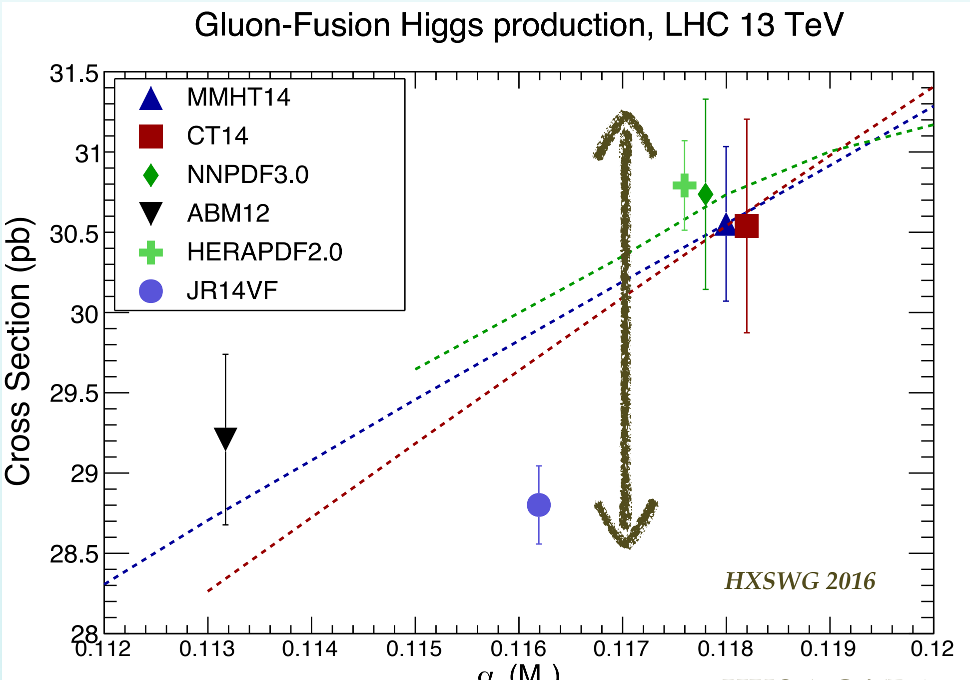
Why we need better PDFs?

Dominant TH unc for M_W measurements at LHC

ATLAS 2017

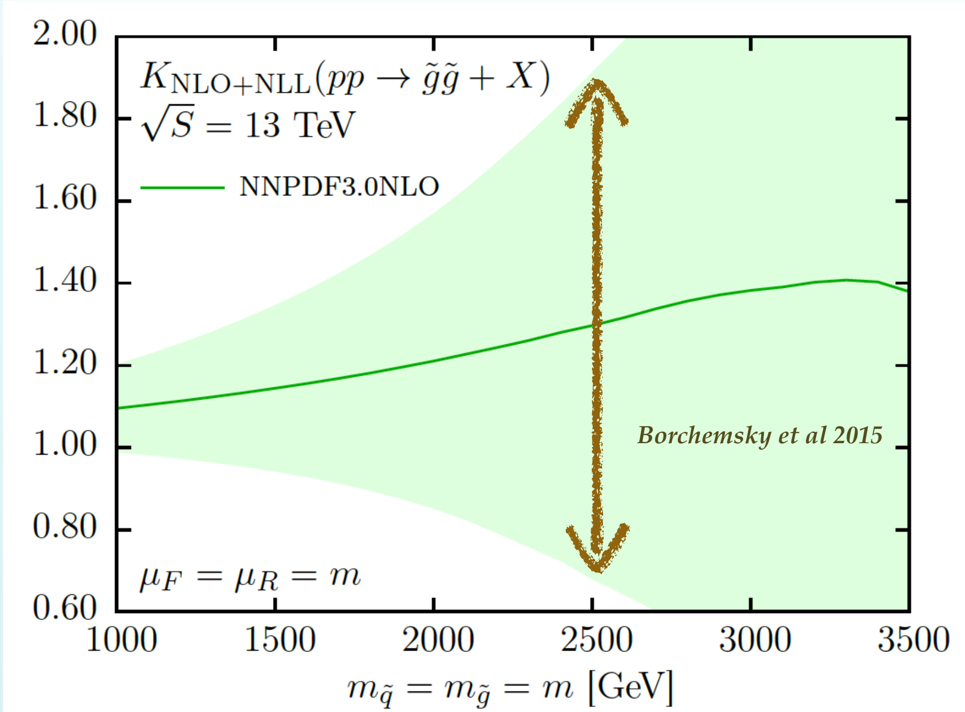
Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Higgs coupling measurements



HXSWG YR4

High-mass BSM cross-sections



The PDF fitting landscape

April 2017	**NNPDF3.0**	**MMHT2014**	**CT14**	**HERAPDF2.0**	**CJ15**	**ABMP16**
Fixed Target DIS	✔	✔	✔	✘	✔	✔
JLAB	✘	✘	✘	✘	✔	✘
HERA I+II	✔	✔	✔	✔	✔	✔
HERA jets	✘	✔	✘	✘	✘	✘
Fixed Target DY	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔	✔	✘	✔	✔
Tevatron jets	✔	✔	✔	✘	✔	✘
LHC jets	✔	✔	✔	✘	✘	✘
LHC vector boson	✔	✔	✔	✘	✘	✔
LHC top	✔	✘	✘	✘	✘	✔
Stat. treatment	Monte Carlo	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$=1	Hessian $\Delta\chi^2$=1.645	Hessian $\Delta\chi^2$=1
Parametrization	Neural Networks (259 pars)	Chebyshev (37 pars)	Bernstein (30-35 pars)	Polynomial (14 pars)	Polynomial (24 pars)	Polynomial (15 pars)
HQ scheme	FONLL	TR'	ACOT-χ	TR'	ACOT-χ	FFN (+BMST)
Order	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO	NLO/NNLO

Ubiali, DIS2017

The Structure of the Proton in the LHC Precision Era

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arXiv:1709.04922v1 [hep-ph] 14 Sep 2017

Abstract

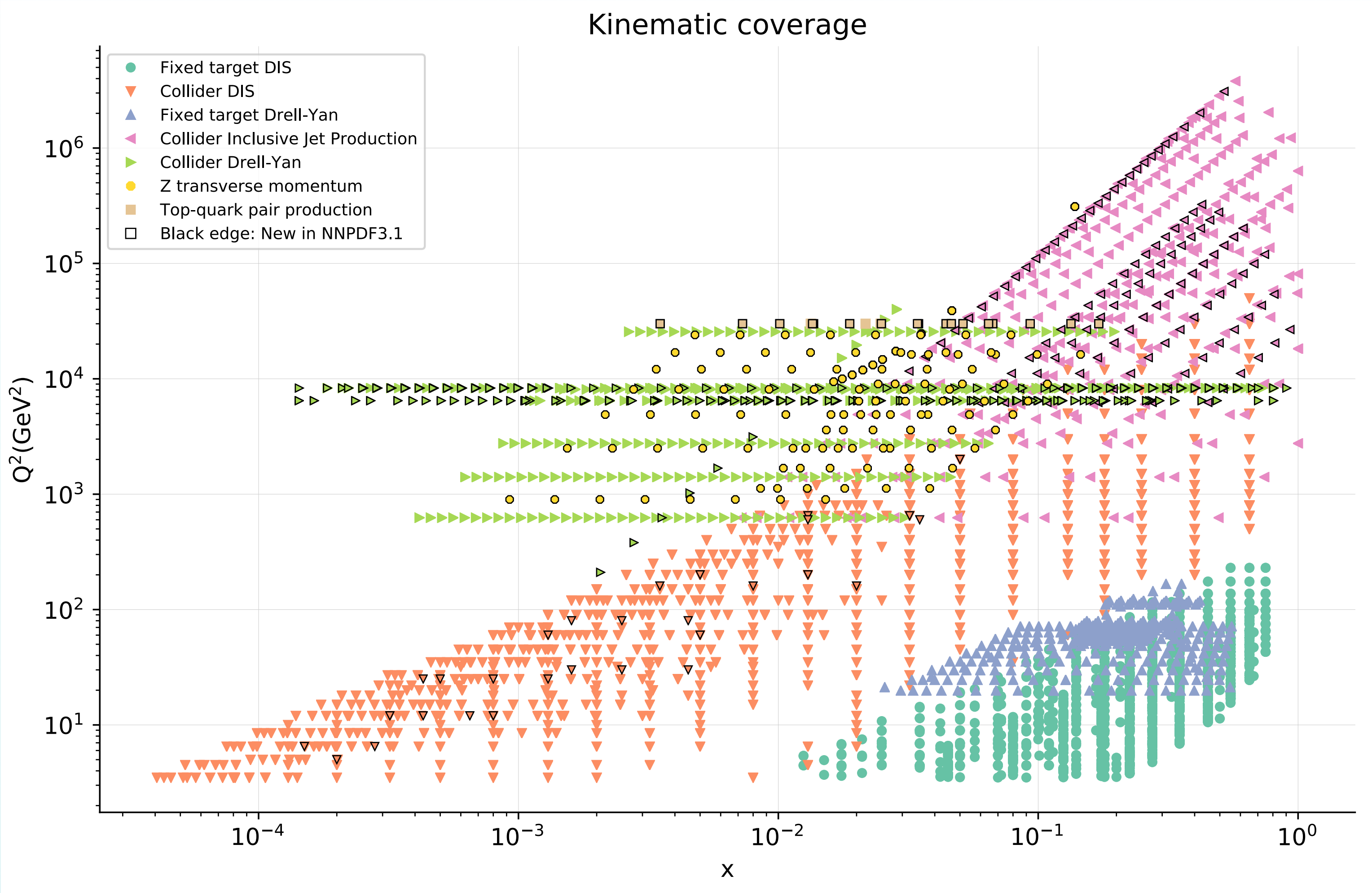
We review recent progress in the determination of the parton distribution functions (PDFs) of the proton, with emphasis on the applications for precision phenomenology at the Large Hadron Collider (LHC). First of all, we introduce the general theoretical framework underlying the global QCD analysis of the quark and gluon internal structure of protons. We then present a detailed overview of the hard-scattering measurements, and the corresponding theory predictions, that are used in state-of-the-art PDF fits. We emphasize here the role that higher-order QCD and electroweak corrections play in the description of recent high-precision collider data. We present the methodology used to extract PDFs in global analyses, including the PDF parametrization strategy and the definition and propagation of PDF uncertainties. Then we review and compare the most recent releases from the various PDF fitting collaborations, highlighting their differences and similarities. We discuss the role that QED corrections and photon-initiated contributions play in modern PDF analysis. We provide representative examples of the implications of PDF fits for high-precision LHC phenomenological applications, such as Higgs coupling measurements and searches for high-mass New Physics resonances. We conclude this report by discussing some selected topics relevant for the future of PDF determinations, including the treatment of theoretical uncertainties, the connection with lattice QCD calculations, and the role of PDFs at future high-energy colliders beyond the LHC.

Keywords: Parton Distributions, Quantum Chromodynamics, Large Hadron Collider, Higgs boson, Standard Model, Electroweak theory

166 pages, 82 figures, > 500 references, to appear in Physics Reports

Only time for a brief snapshot here!

A story of success



Global PDF fits: highly non-trivial validation of the **QCD factorisation framework**:

i) *including* ***O(5000) data*** *points,*

ii) *from* ***O(50) experiments****,*

iii) *several of them with* ≈***1%*** ***errors****,*

yet still manage to achieve $\chi^2/N_{dat} \approx 1$!

Higher orders matter

NNPDF3.1	NNLO	NLO
HERA	1.16	1.14
ATLAS	1.09	1.37
CMS	1.06	1.20
LHCb	1.47	1.61
TOTAL	1.148	1.168

NNPDF3.1 is the first NNPDF analysis where we find that **NNLO** gives a **markedly superior fit quality** as compared to **NLO**

Direct consequence of the **new high-precision measurements** included

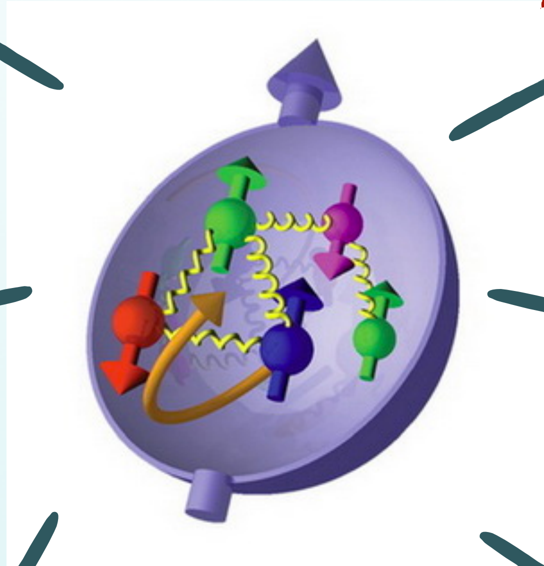
Strongly suggests that **NNLO PDFs should be the baseline** in all analyses!

The inner life of protons

Gluon

Quark flavour separation

Photon



BFKL dynamics

Strange

Charm

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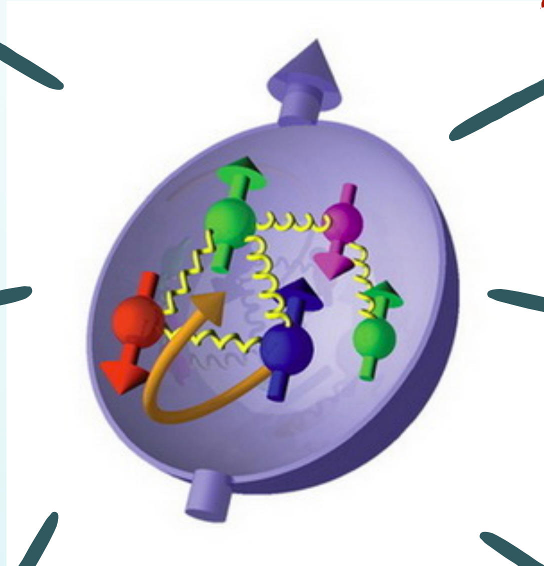

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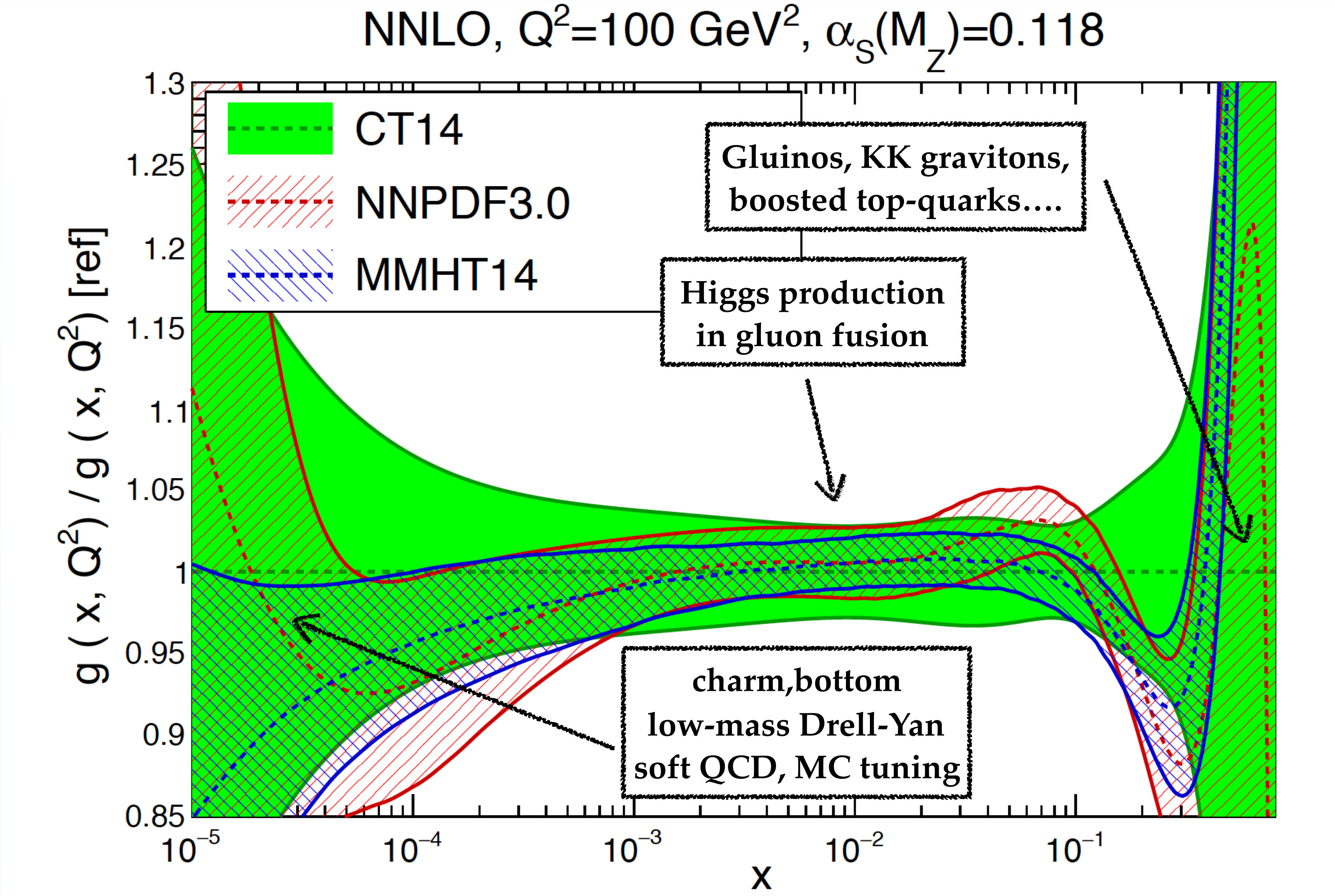
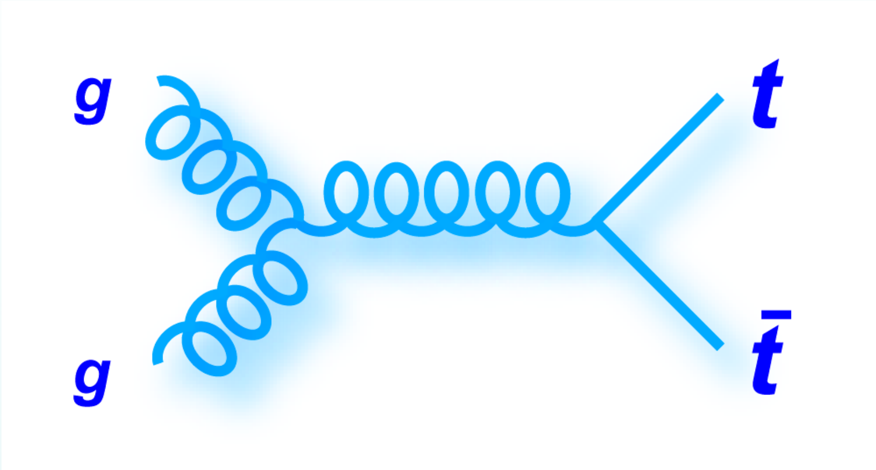
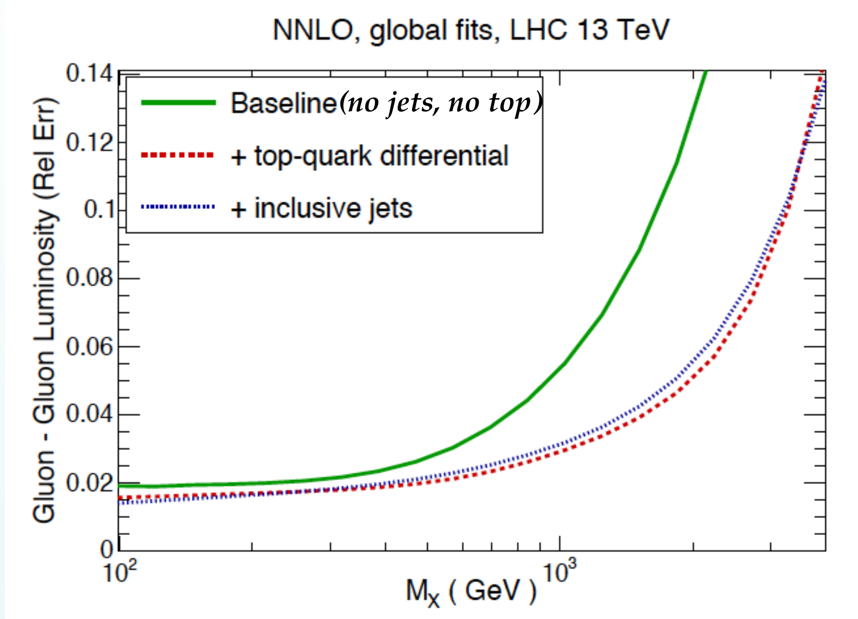
One glue to bind them all

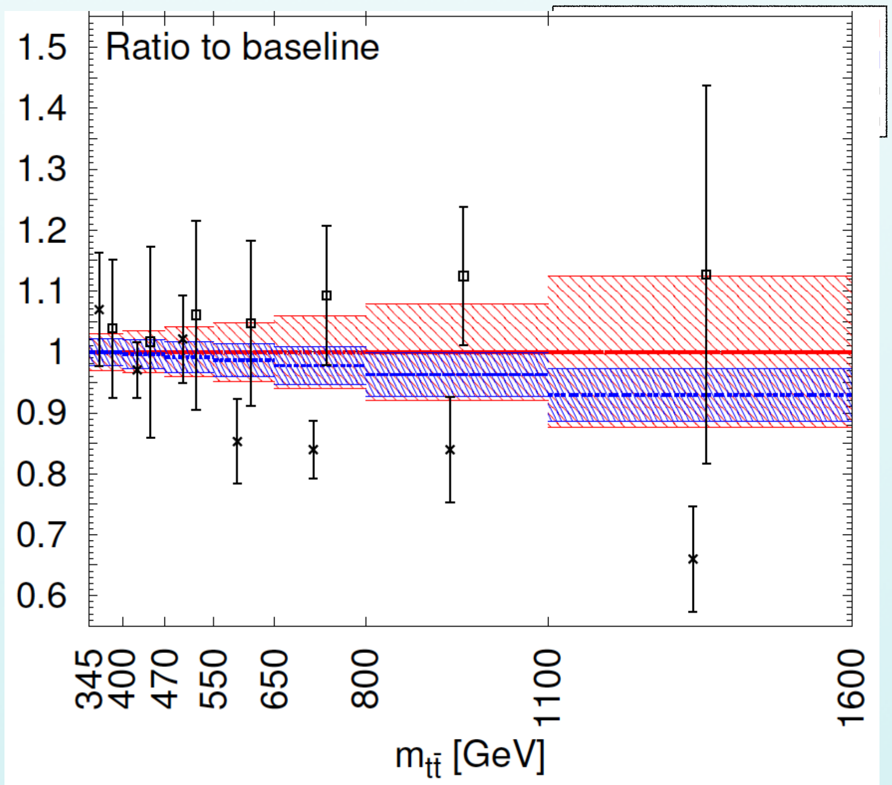


At the LHC, precise knowledge of the gluon is required **from small-x to large-x**

The large-x gluon from differential top quarks







- Top-quark production driven by **gluon-gluon scattering**
- **NNLO calculations for stable top quarks** available
  Czakon, Mitov et al 2015-2017
- **Data from ATLAS and CMS at 8 TeV** available with breakdown of systematic uncertainties
- Included **differential top data into NNPDF3.0**: constraints on the **large-*x* gluon** comparable to those of inclusive jet production *Czakon et al 2017*
- Improved theory uncertainties in **regions crucial for BSM searches**, *i.e.*, **m_{tt} > 1 TeV** (while fitting only y_t and y_{tt})

The medium-x gluon from NNLO Z p_T

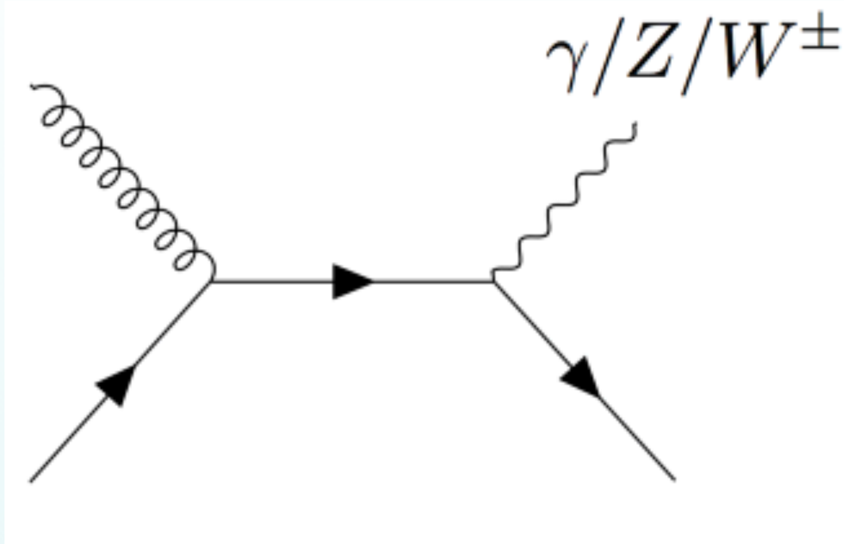
- Dominated by **quark-gluon scattering**, thus sensitive to the gluon PDF at intermediate values of x

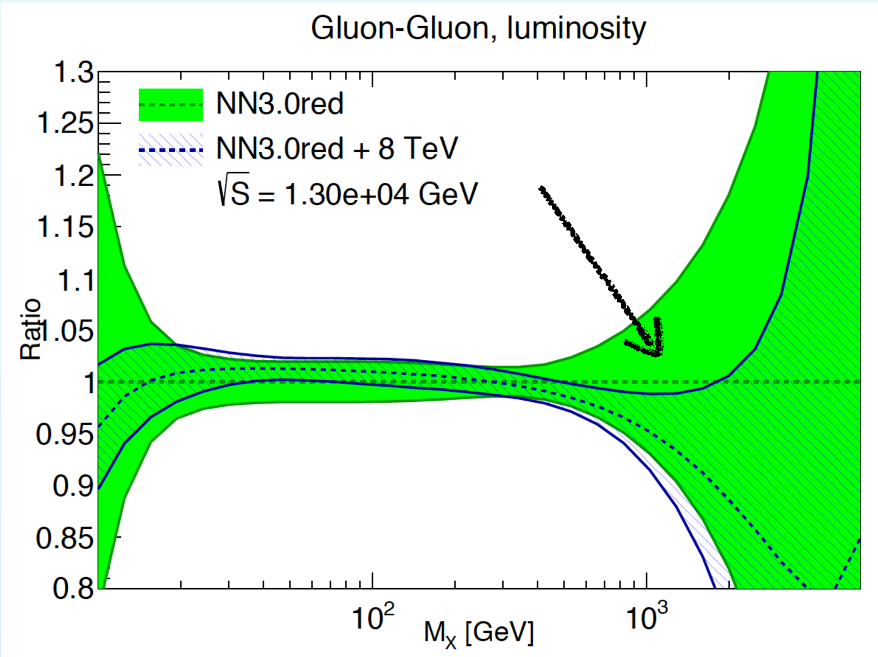
Malik and Watt 2013, Boughezal et al 2017

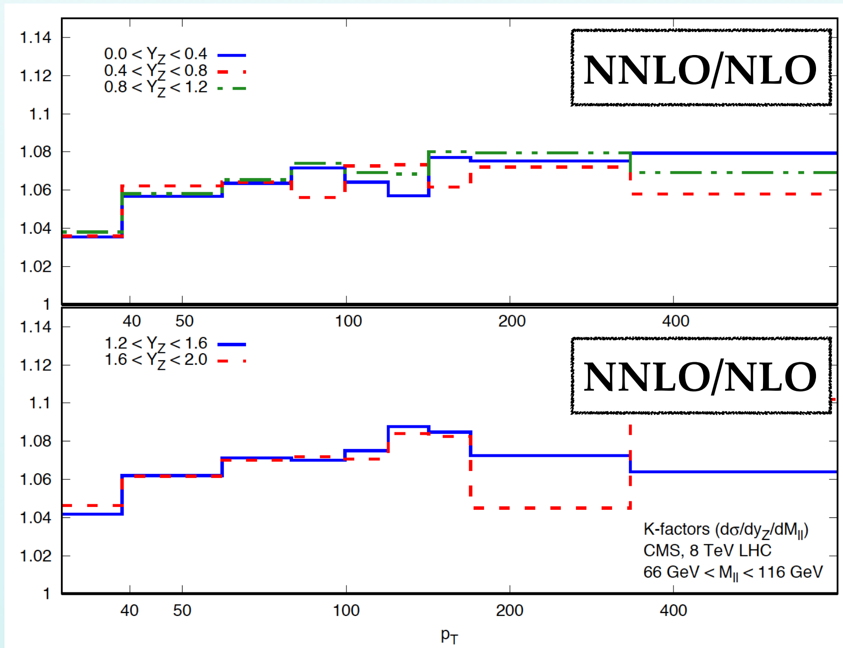
- **NNLO corrections to the Z p_T** also available: **up to 10% effects** for a measurement that has **sub-percent exp errors**

Boughezal et al 2015-2017, Gehrmann et al 2015-2017

- **Complementary information on the gluon** as compared to inclusive jets and differential top pair production

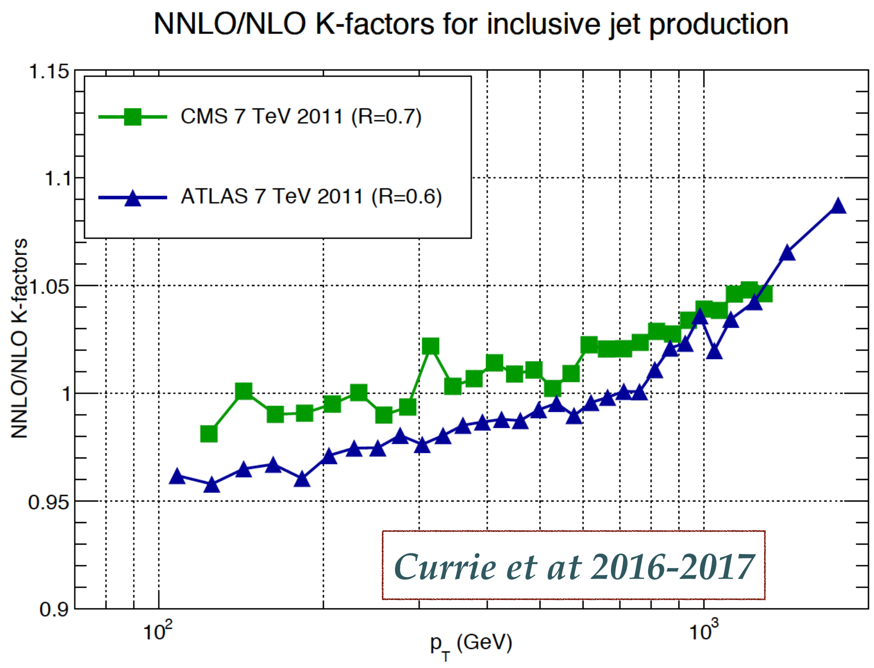


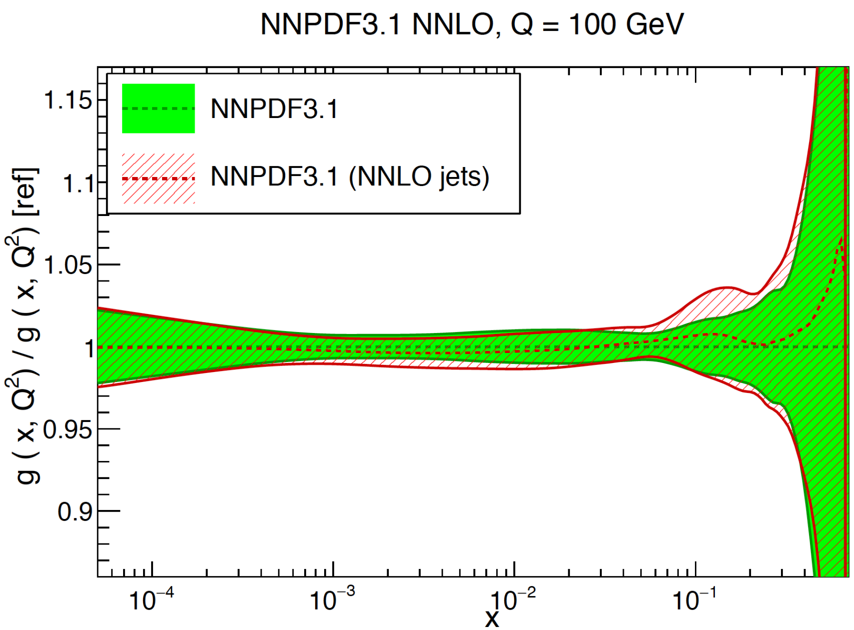




Boughezal et al 2017

The large-x gluon from NNLO jets



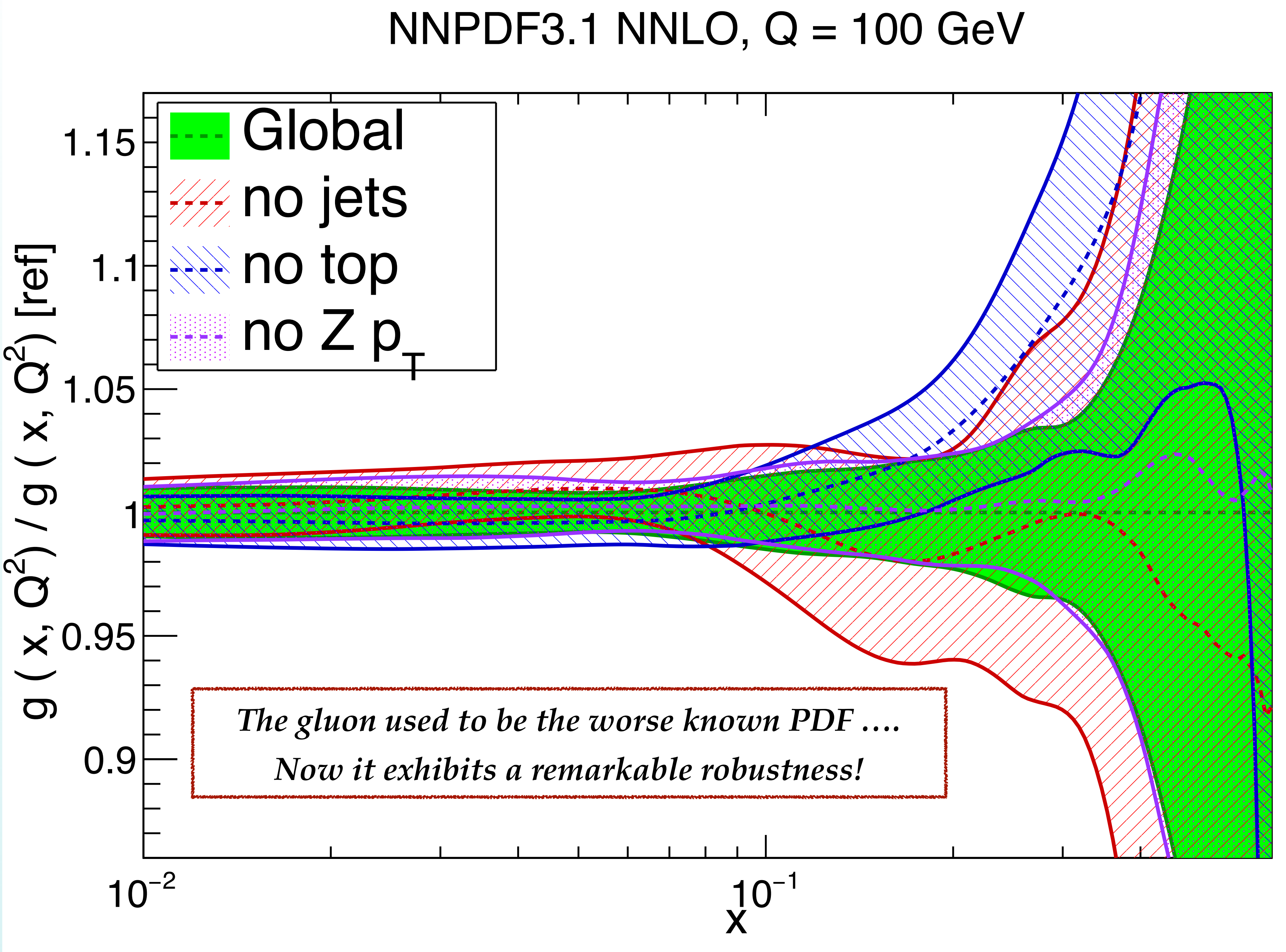


- NNPDF3.1 NNLO: includes jet data using **NNLO evolution and NLO matrix elements**, with scale variations as additional TH systematic error
- The **jet p_T** is always used as central scale choice
- Also tried variants where ATLAS and CMS 2011 7 TeV data included **using exact NNLO theory**
- Very small impact on the gluon
- Moderate improvement of the chi2
- *Only central bin of ATLAS data included - the large χ^2 once all bins are included remains there once exact NNLO theory is used*

	NNPDF3.1	exact NNLO
CDF Run II k_t jets	0.84	0.85
ATLAS jets 2.76 TeV	1.05	1.03
CMS jets 2.76 TeV	1.04	1.02
ATLAS jets 2010 7 TeV	0.96	0.95
ATLAS jets 2011 7 TeV	1.06	0.91
CMS jets 7 TeV 2011 7 TeV	0.84	0.79

See also MMHT analysis, Harland-Lang et at 16

One (upgraded) glue to bind them all



The gluon used to be the worse known PDF ….
Now it exhibits a remarkable robustness!

The small-x gluon from forward charm production

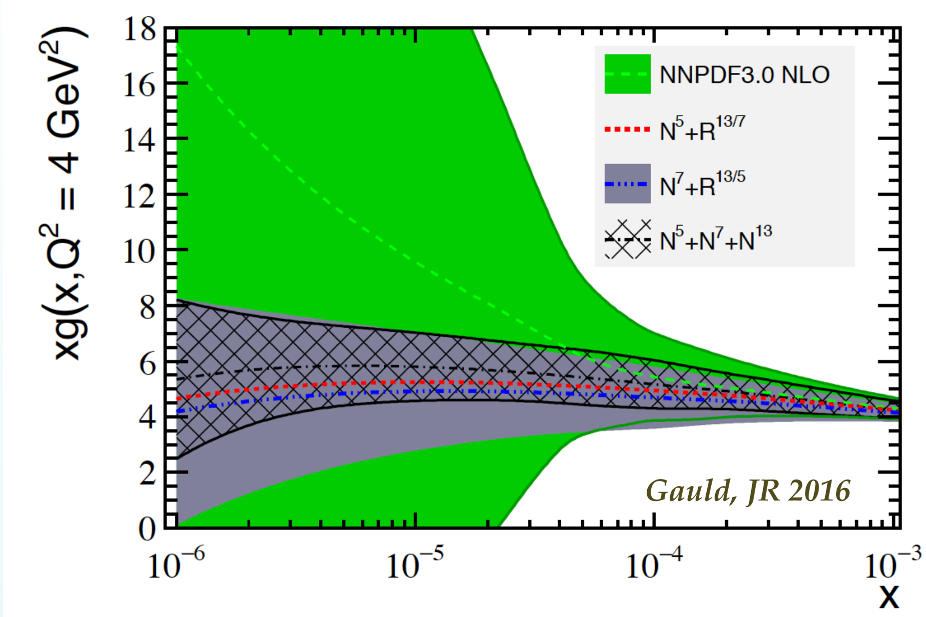
- **D and B meson production from LHCb** allow accessing the **gluon down to x=10^{-6}**, well below the HERA coverage

PROSA 2015, Gauld et al 2015

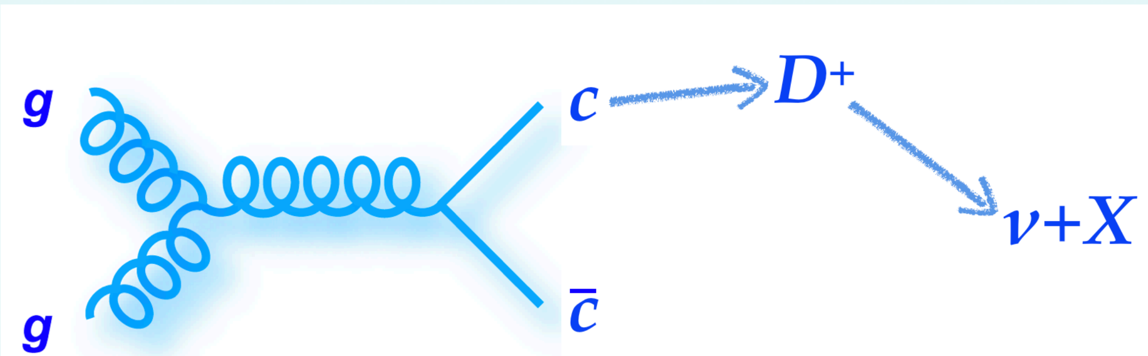
- Gluon PDF errors **reduced by up to a factor 10!**

- Allows robust estimate for the ***prompt neutrino flux***, the main background for astrophysical neutrinos at IceCube

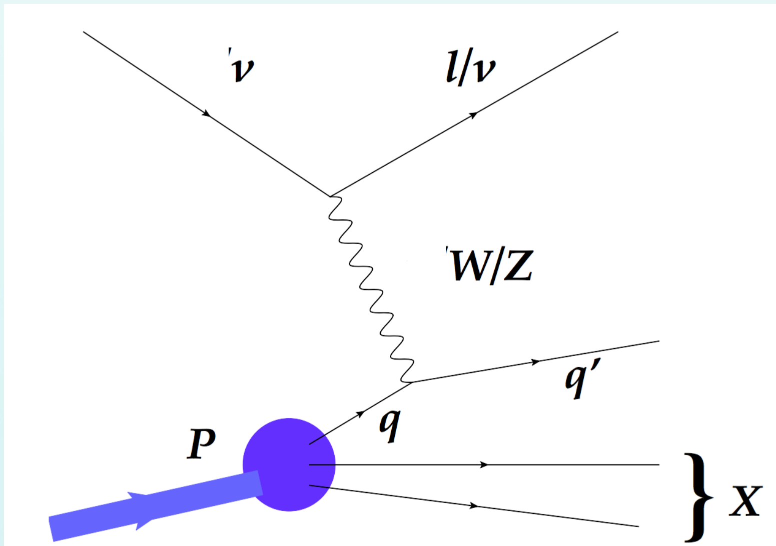
- Precision calculation of the **UHE neutrino-nucleus cross-section**, with few-percent TH errors up to $E_\nu=10^{12}$ GeV



Prompt neutrino flux at IceCube



UHE neutrino-nucleus xsecs



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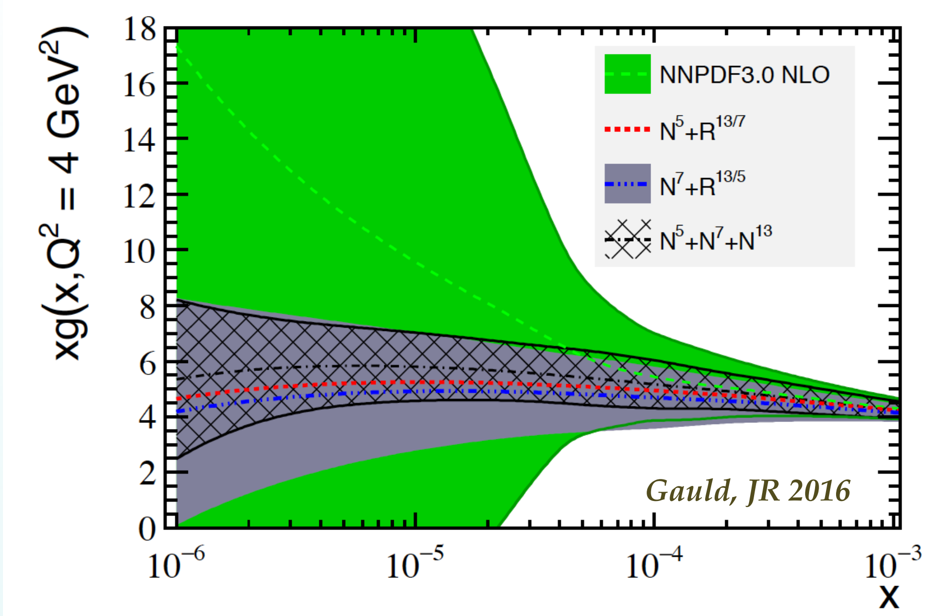
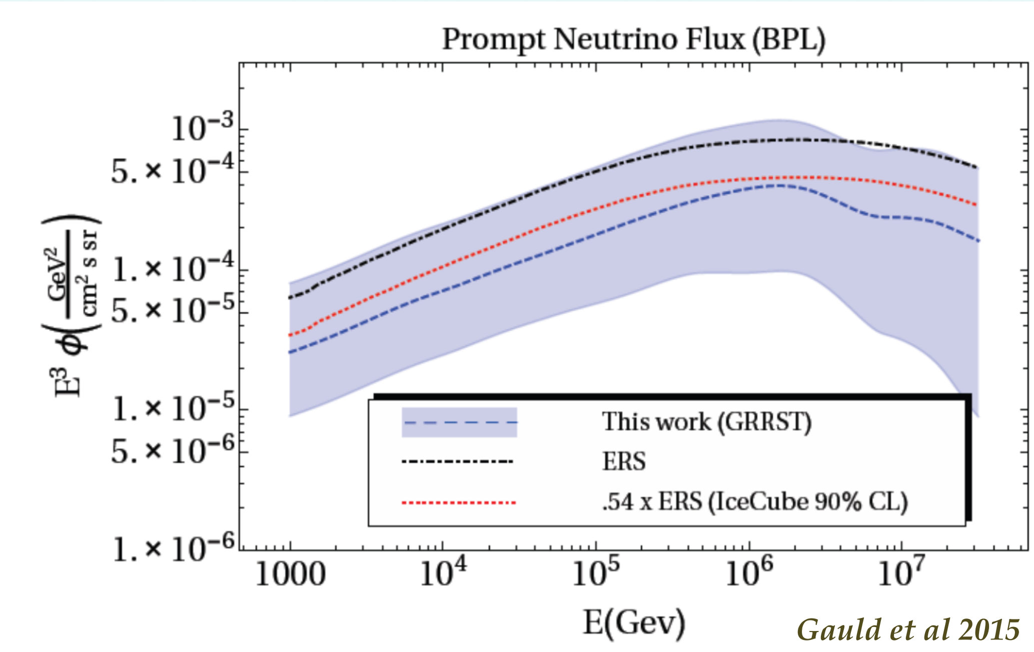


Prompt neutrino flux at IceCube



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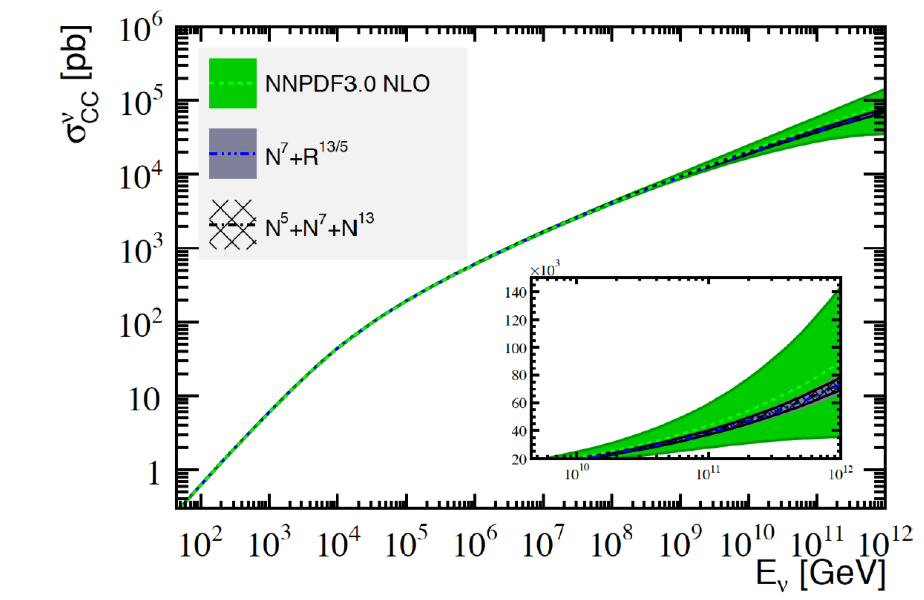
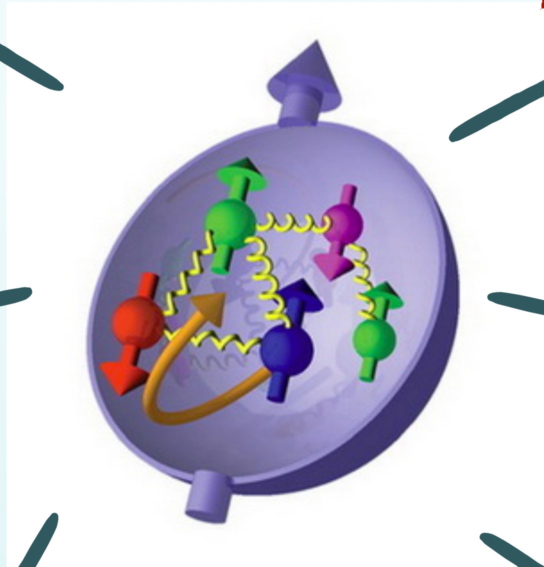


The inner life of protons

Gluon

Quark flavour separation



Photon

BFKL dynamics

Strange

Charm

Parton distributions with BFKL resummation

- **Perturbative fixed-order QCD calculations** have been extremely successful in describing a wealth of data from proton-proton and electron-proton collisions

- There are theoretical reasons that eventually we need to go beyond DGLAP: at small-x, **logarithmically enhanced terms in** ***1/x*** **become dominant** and need to be resummed to all orders

- ***BFKL/high-energy/small-x resummation*** can be matched to the **DGLAP collinear framework**, and thus be included into a standard PDF analysis

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

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

Within small-x resummation, the **N^kLO fixed-order DGLAP splitting functions** are complemented with the **N^hLLx contributions from BKFL**

ABF, CCSS, TW + others, 94-08

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

A new world at small-x

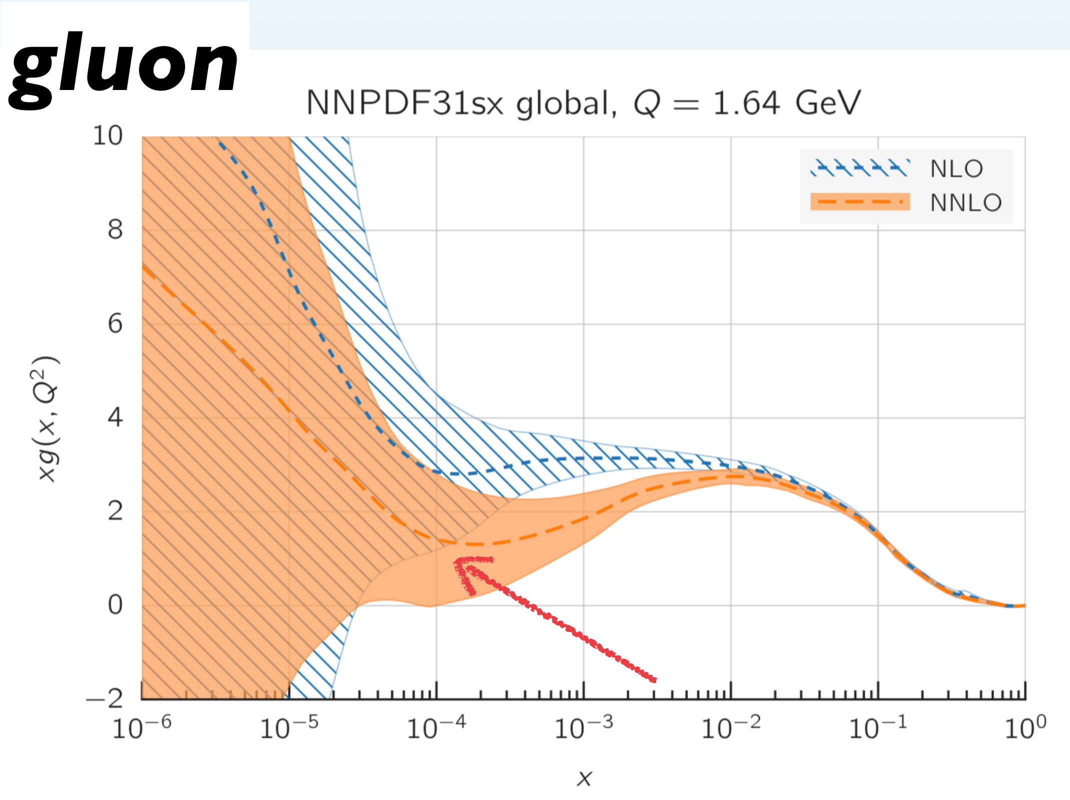
- Ultimately, the need for (or lack of) BKFL resummation in **ep and pp collider data** can only be assessed by performing a **global PDF analysis based on (N)NLO+NLLx theory**

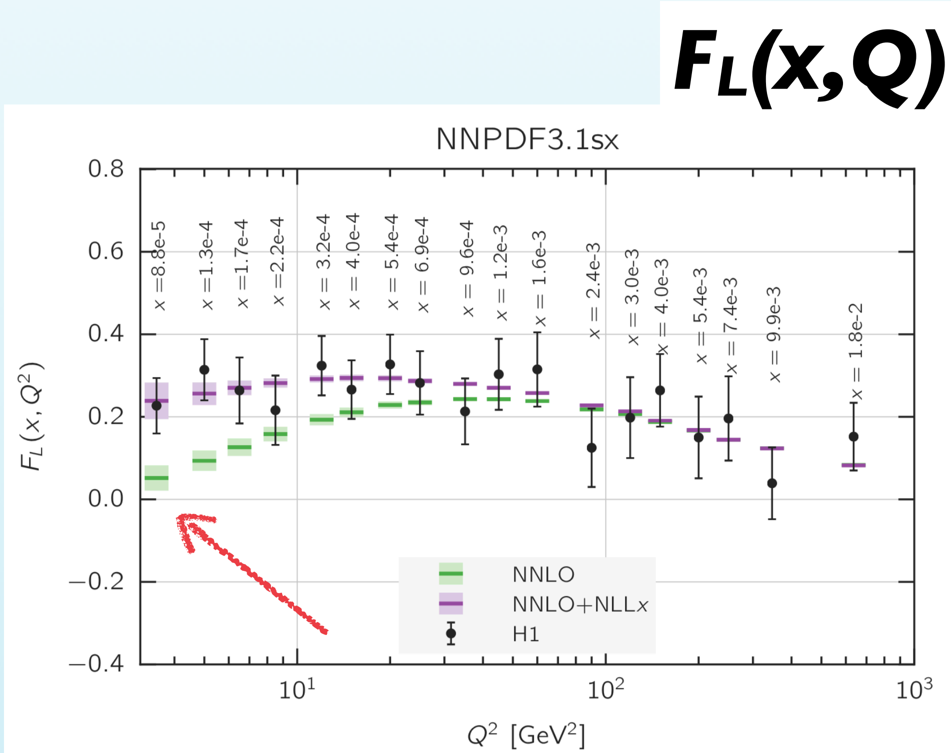
- Theoretical tools are now available: **HELL for NLLx resummation**, interfaced to **APFEL**

APFEL: Bertone, Carrazza, Rojo 13
https://apfel.hepforge.org/

HELL: Bonvini, Marzani, Peraro, Muselli 16-17
https://www.ge.infn.it/~bonvini/hell/

- NNPDF3.1 (N)NLO+NLL fits **stabilize the perturbative PDF expansion at small-*x***, in particular for the gluon, and markedly improve the **fit quality to the small-*x* HERA data**



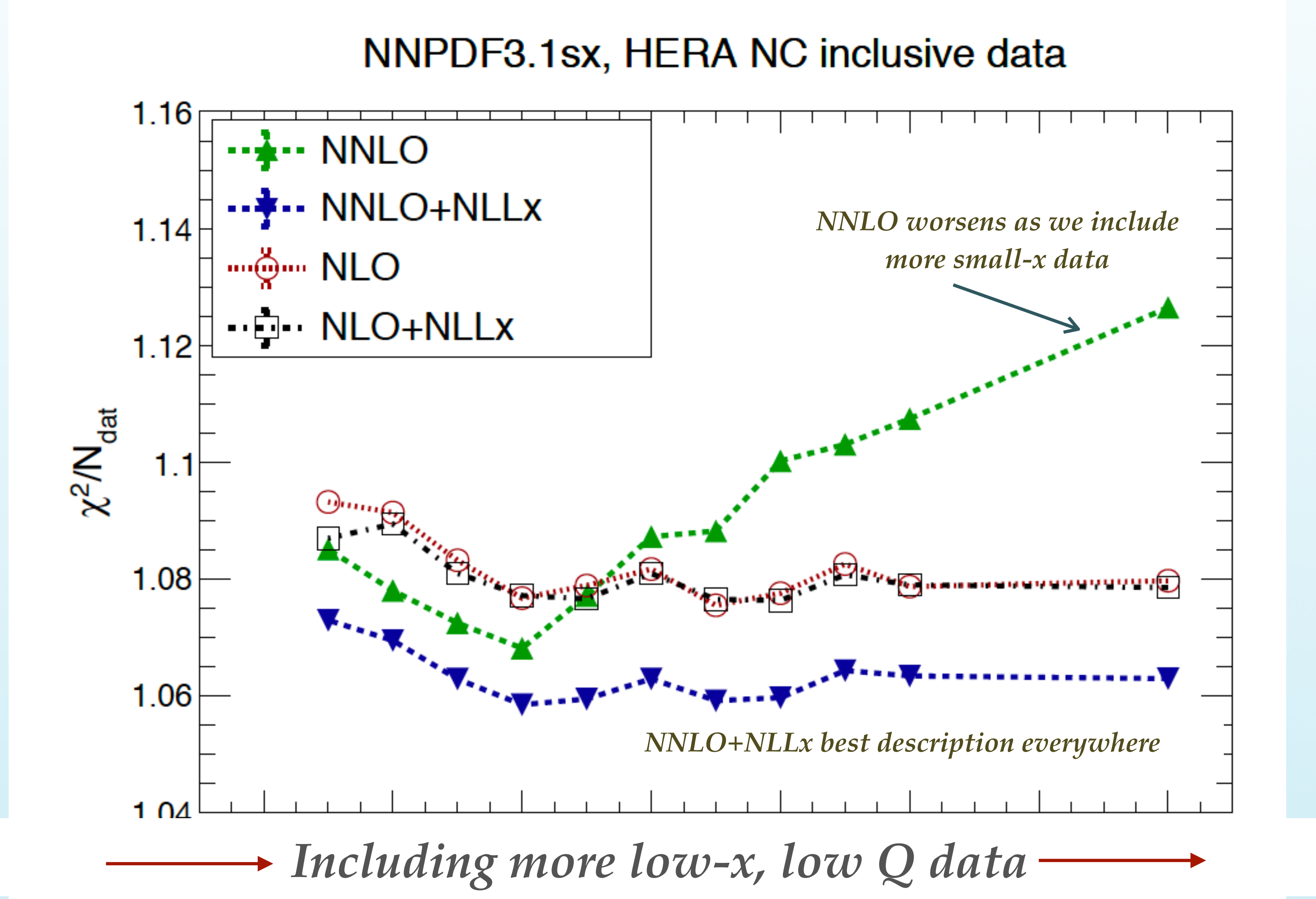


Ball, Bertone, Bonvini, Marzani, JR, Rottoli 16

Evidence for BFKL dynamics in HERA data

Using **NNLO+NLL*x* theory, the NNLO instability at small-*x* of the χ^2 disappears**

Excellent fit quality to **inclusive and charm HERA** data achieved in the **entire (x,Q²) region**



Nunca es tarde si la dicha es buena

Science
Life and Physics

After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

Jon Butterworth
@jonmbutterworth
Thu 28 Dec 2017 17.30 GMT

529 | 59

Jon Butterworth, the Guardian, 28/12/2018

In the mid 1970s, four Soviet physicists, Batlisky, Fadin, Kuraev and Lipatov, made some predictions involving the strong nuclear force which would lead to their initials entering the lore. "BFKL" became a shorthand for a difficult-to-

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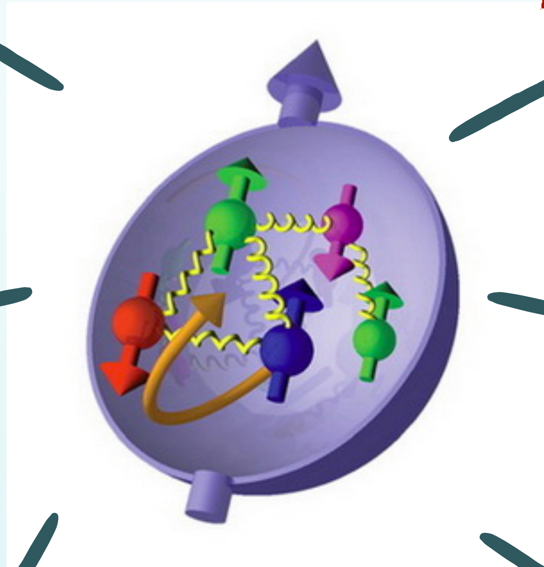


BFKL dynamics

Strange

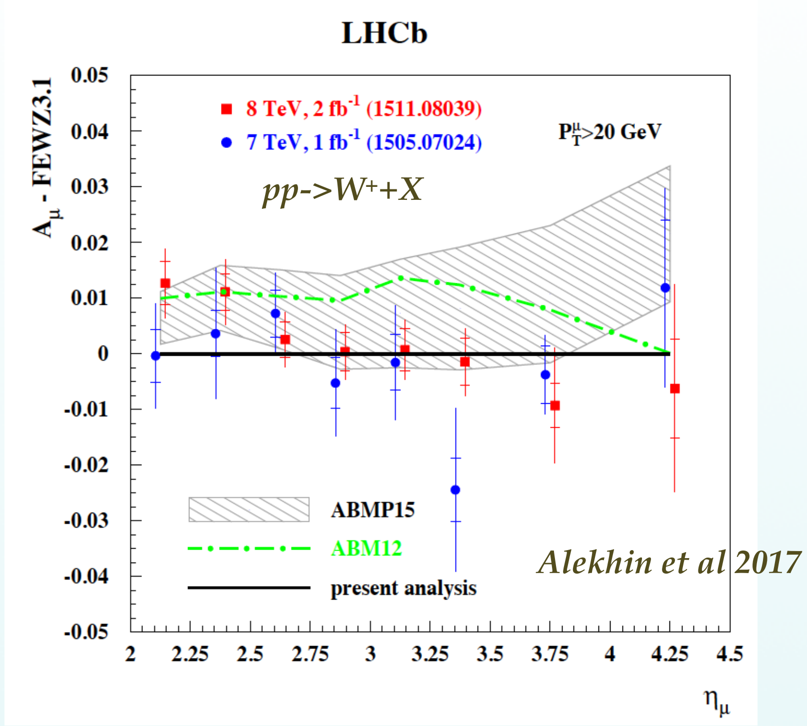
Charm

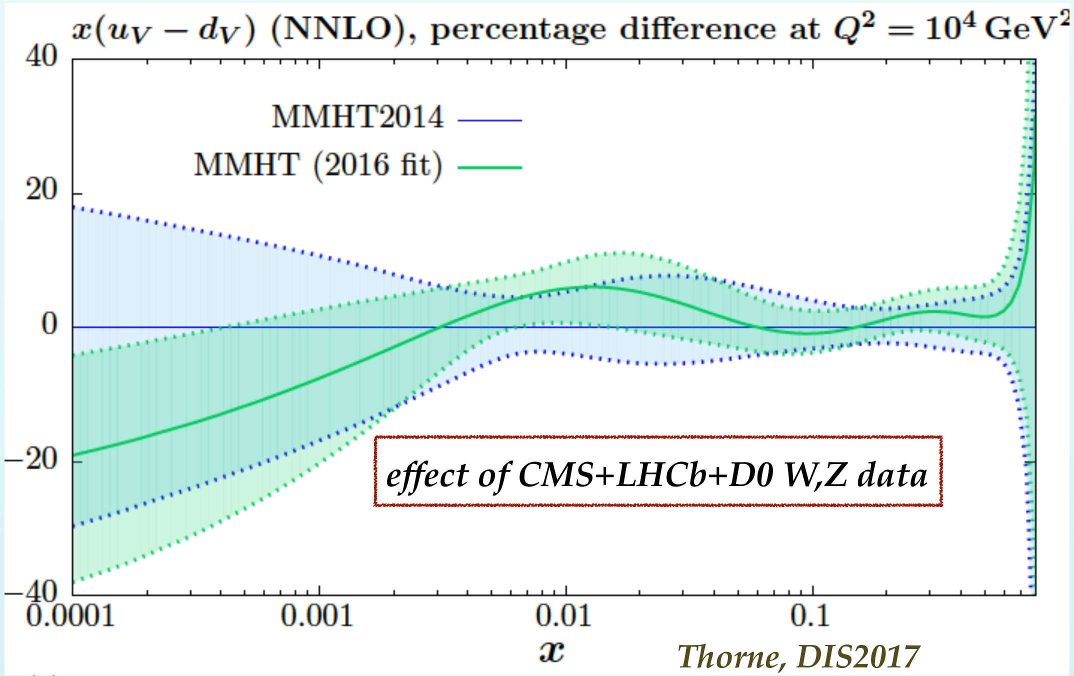
Quark flavour separation from LHC data

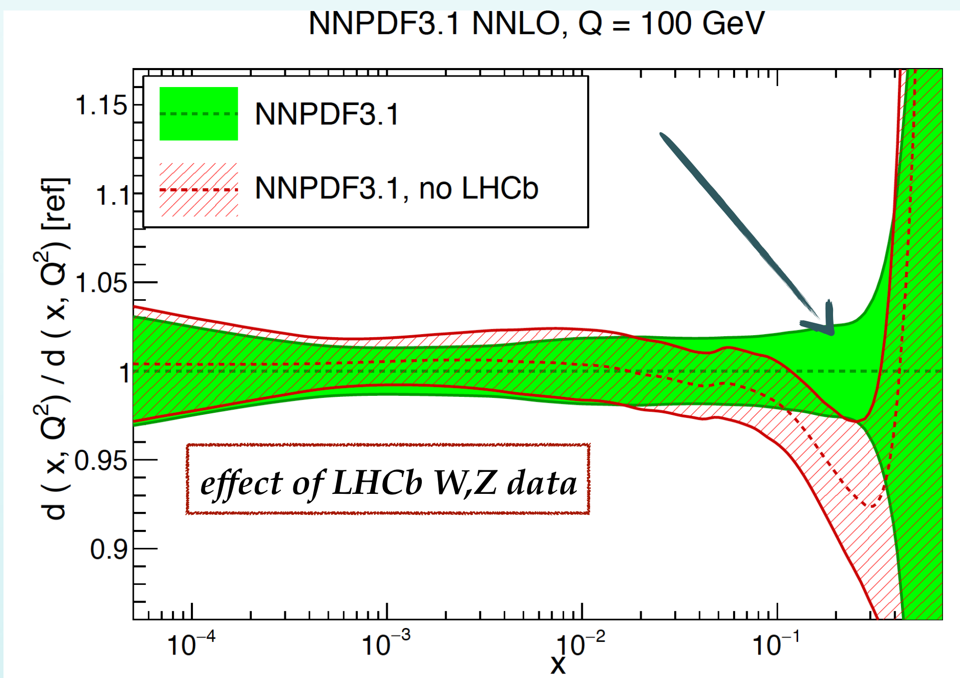
- Recent high-precision *W* **and** *Z* **production** data from **ATLAS, CMS, LHCb and D0** allow a better separation of quark and antiquark flavours

- **LHCb** data in particular provides constrains on the **light quarks at large-*x*** (*i.e.* PDF uncertainty reduction by a factor 2 in NNPDF3.1 for $x \simeq 0.1$)

- In the **MMHT (2016) fit,** the new collider *W,Z* data leads to improved determination of $\boldsymbol{x(u_V - d_V)}$







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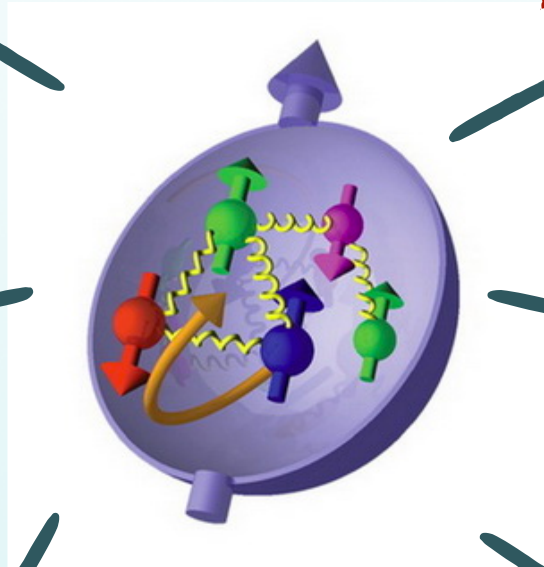

Photon

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How bright is the proton?

- The calculation of **QED and electroweak corrections to hadron collider processes** requires by consistency to introduce the PDF of the photon in the proton, **$\gamma(x,Q)$**
- The first model-independent determination of **$\gamma(x,Q)$** from LHC *W,Z* data was **NNPDF2.3QED**, which however affected by **large uncertainties**, due to the limited experimental information
- Recently, **$\gamma(x,Q)$ computed** in terms of the well-known **inclusive structure functions F_2 and F_L**: the resulting photon PDF, exhibits now **few-percent uncertainties**

$$x\gamma(x,\mu) = \frac{1}{2\pi\alpha(\mu)}\int_x^1 \frac{dz}{z}\left\{\int_{Q^2_{\rm min}}^{\mu^2/(1-z)} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[-z^2F_L(x/z,Q^2)\right.\right.$$

$$\left.\left.+\left(zP_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2)\right]-\alpha^2(\mu)z^2F_2(x/z,\mu^2)\right\}+\mathcal{O}\left(\alpha\alpha_s,\alpha^2\right)$$

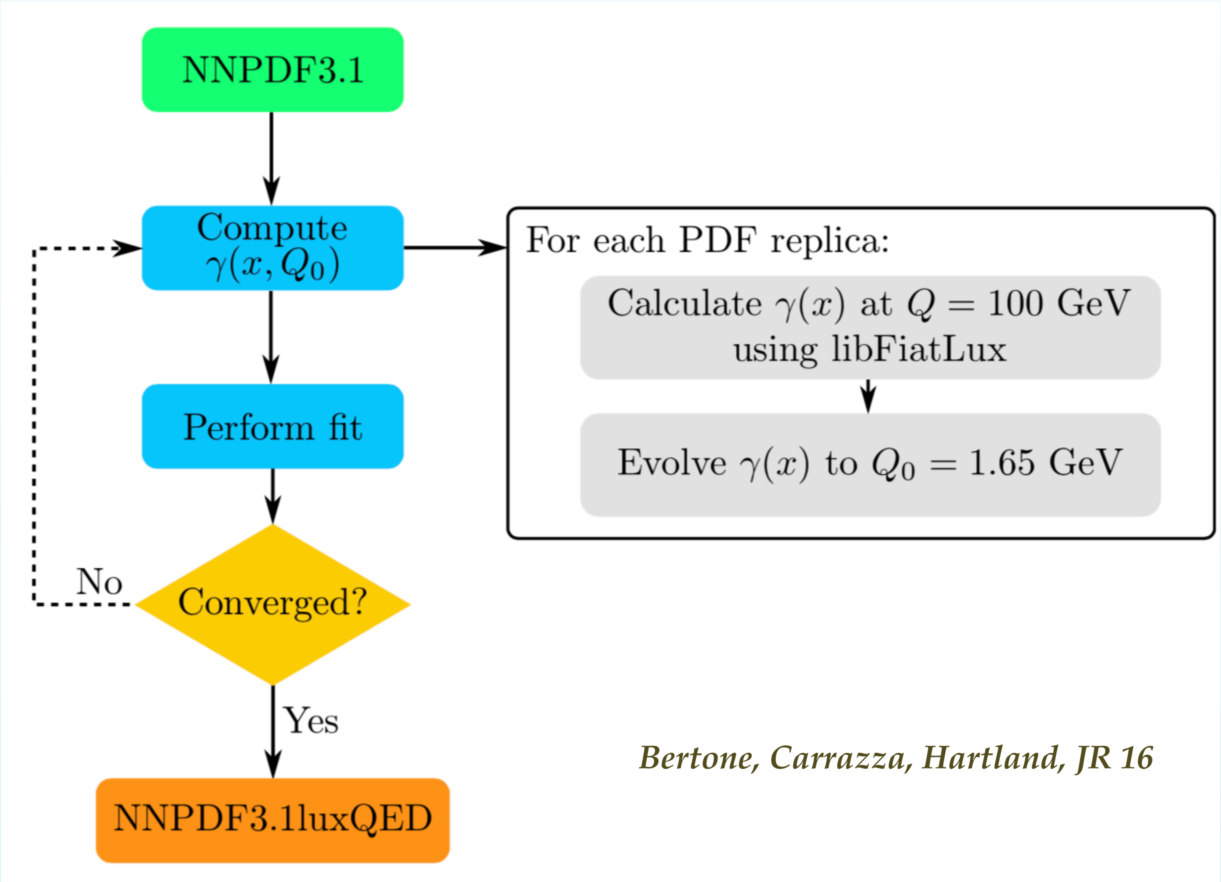
pp → H W⁺ (→ l⁺ν) + X at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0^{+4.4}_{-2.9}$ fb
photon-induced contribs (LUXqed)	4.4 ± 0.1 fb

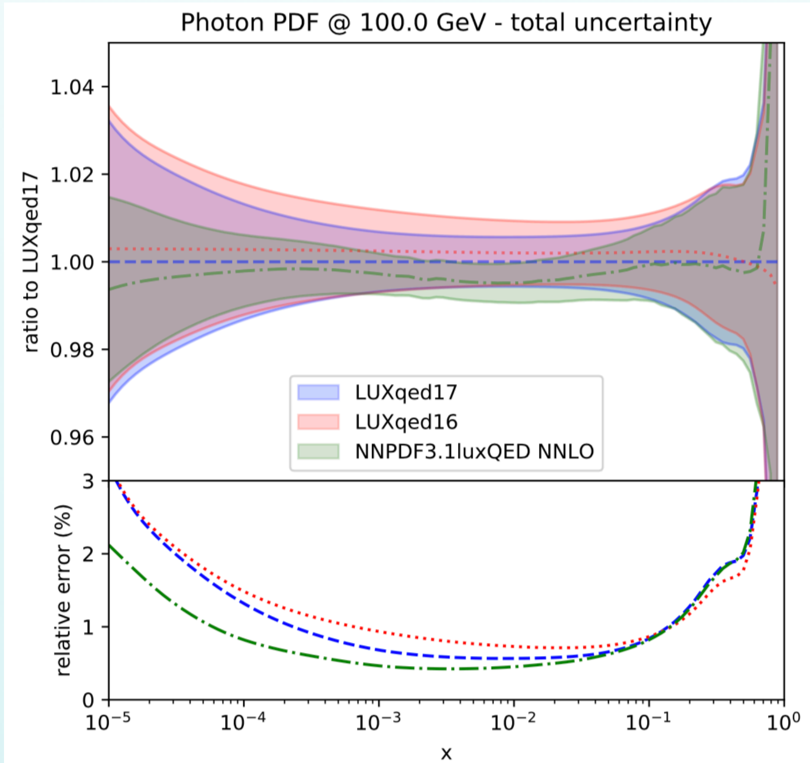
Manohar, Nason, Salam, Zanderighi, 16-17

Crucial implications for LHC pheno: high-precision determination of photon-initiated (PI) contributions

Illuminating the photon content of the proton

- **NNPDF3.1luxQED**: variant of the NNPDF3.1 global analysis supplemented by
  - *the LUXqed theoretical constraints,*
  - *NLO QED corrections to DGLAP evolution*, and
  - *NLO QED coefficients functions in DIS*
- Iterative procedure: photon PDF recomputed at each iteration until convergence is achieved

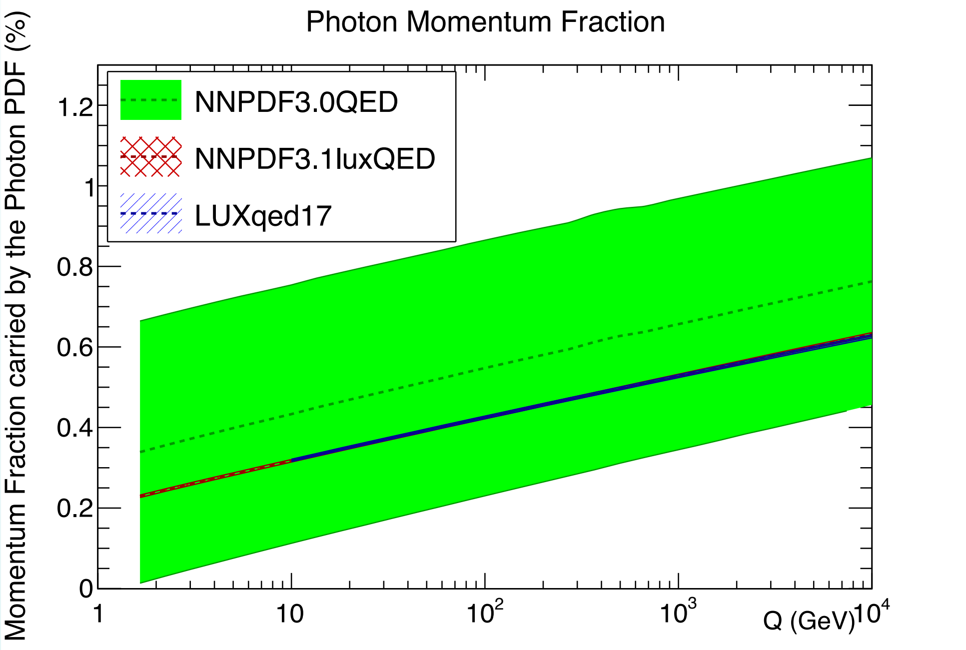


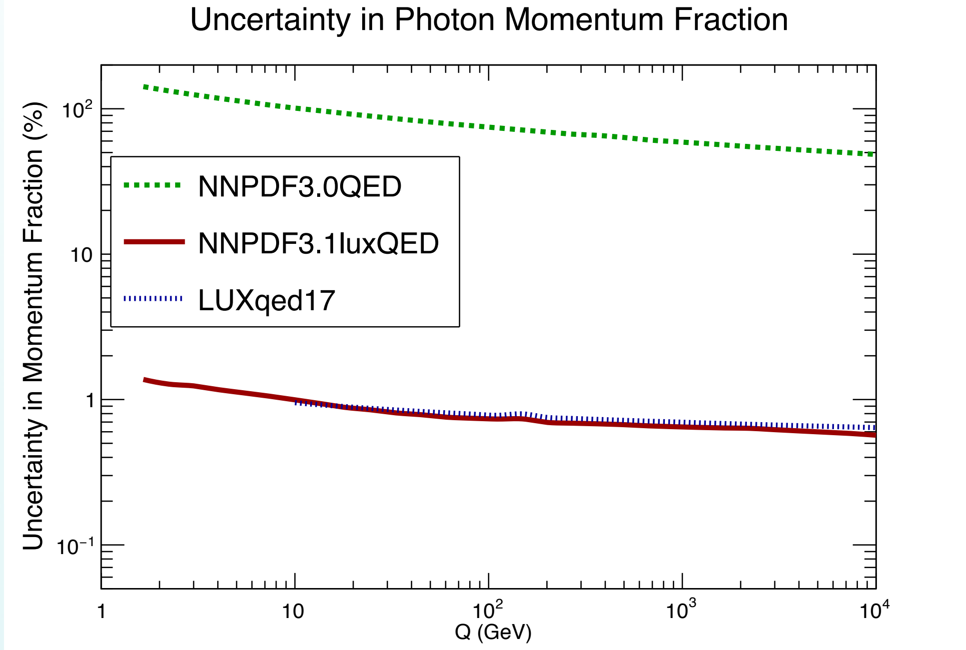


There is light in all of us

$$\langle x \rangle_\gamma (Q) \equiv \int_0^1 dx\, x\gamma(x, Q)$$

Photon momentum fraction in the proton

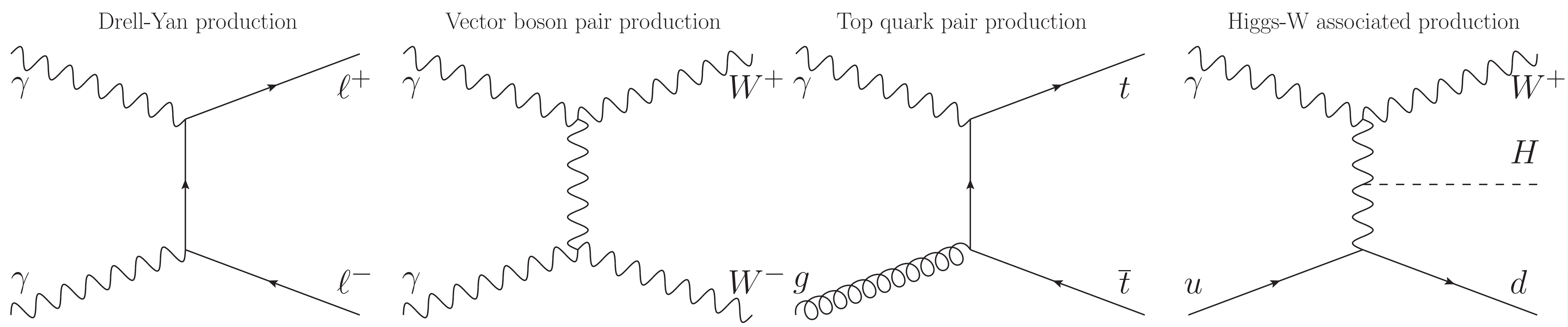




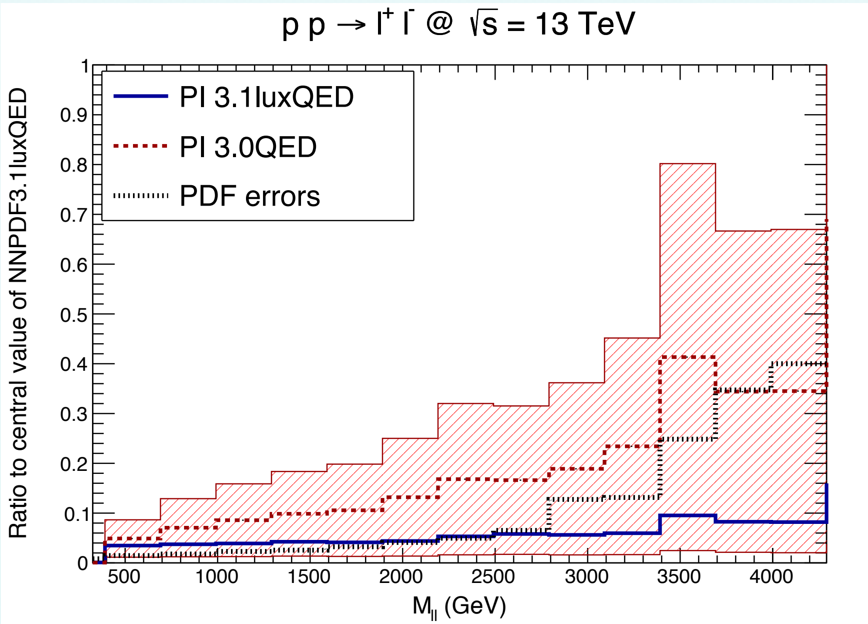
	$\langle x \rangle_\gamma (Q = 1.65\,\mathrm{GeV})$	$\langle x \rangle_\gamma (Q = m_Z)$
NNPDF3.0QED	$(0.3 \pm 0.3)\%$	$(0.5 \pm 0.3)\%$
NNPDF3.1luxQED	$(0.229 \pm 0.003)\%$	$(0.420 \pm 0.003)\%$
LUXqed17	–	$(0.421 \pm 0.003)\,\%$

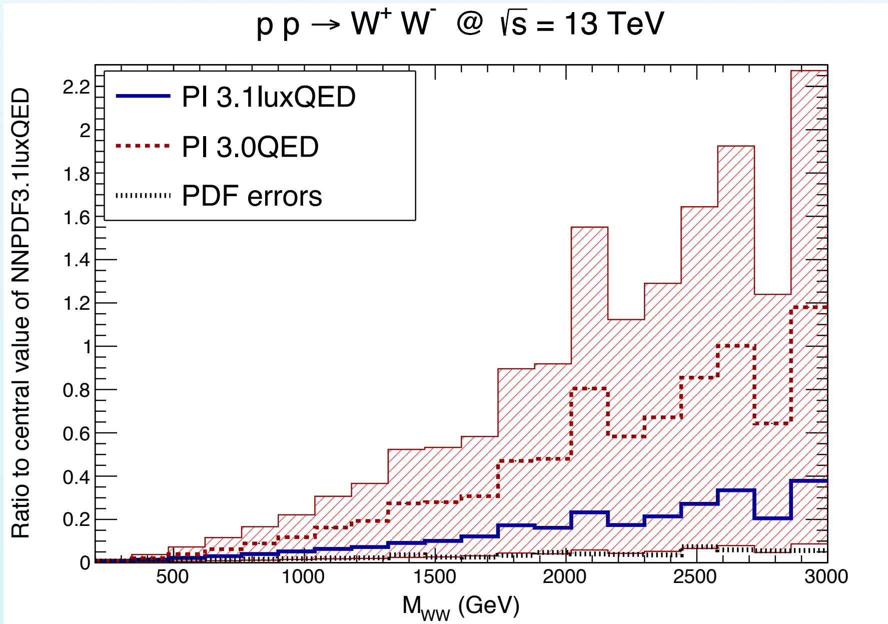
*In LHC collisions, up to **0.5%** of the momentum carried by the protons corresponds to its photon component!*

Photon-intiated processes at the LHC



- NNPDF3.1luxQED results are **consistent** with NNPDF3.0QED, with **much reduced uncertainties**
- PI effects can be up to **10% (Drell-Yan) and 30% (WW) at the LHC**, with opposite sign wrt **EW corrections**



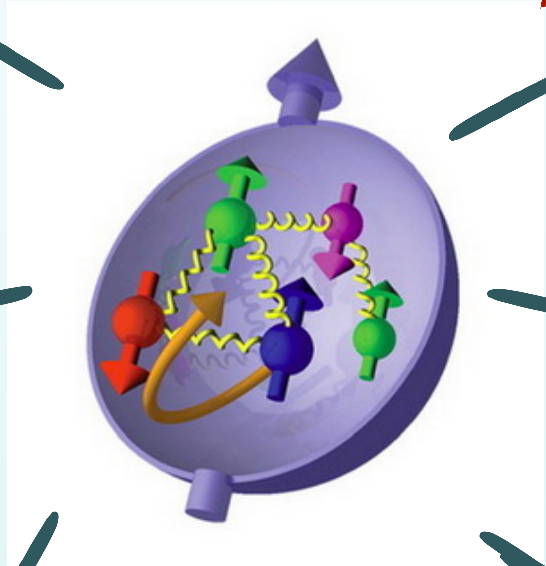


The inner life of protons

Gluon

Quark flavour separation

Photon



BFKL dynamics

Strange

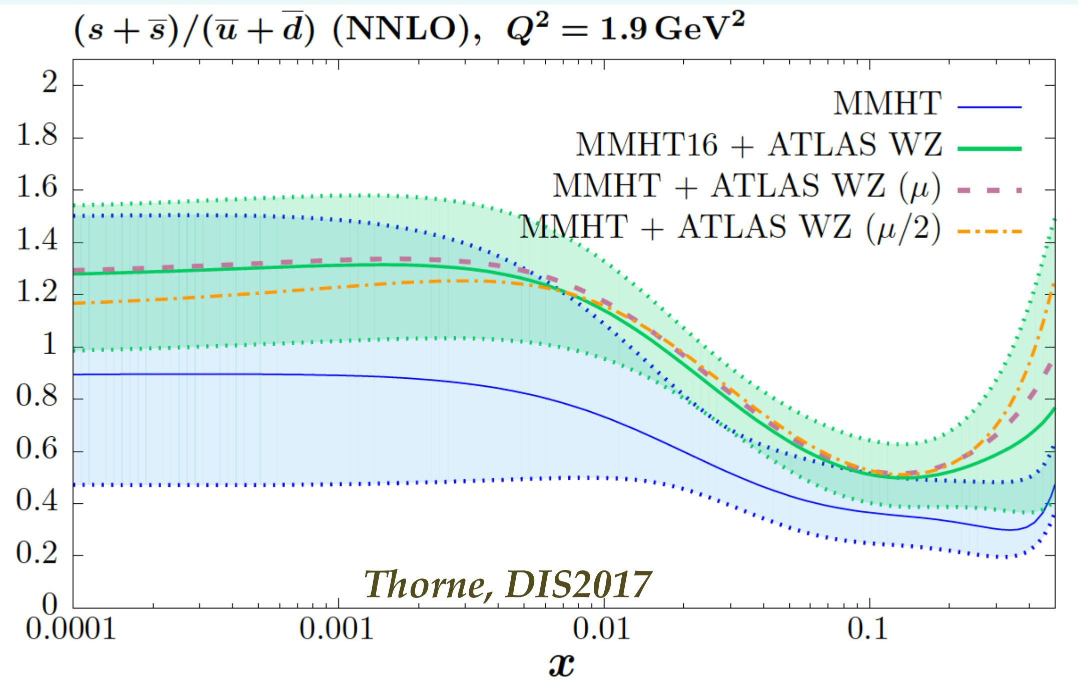
Charm

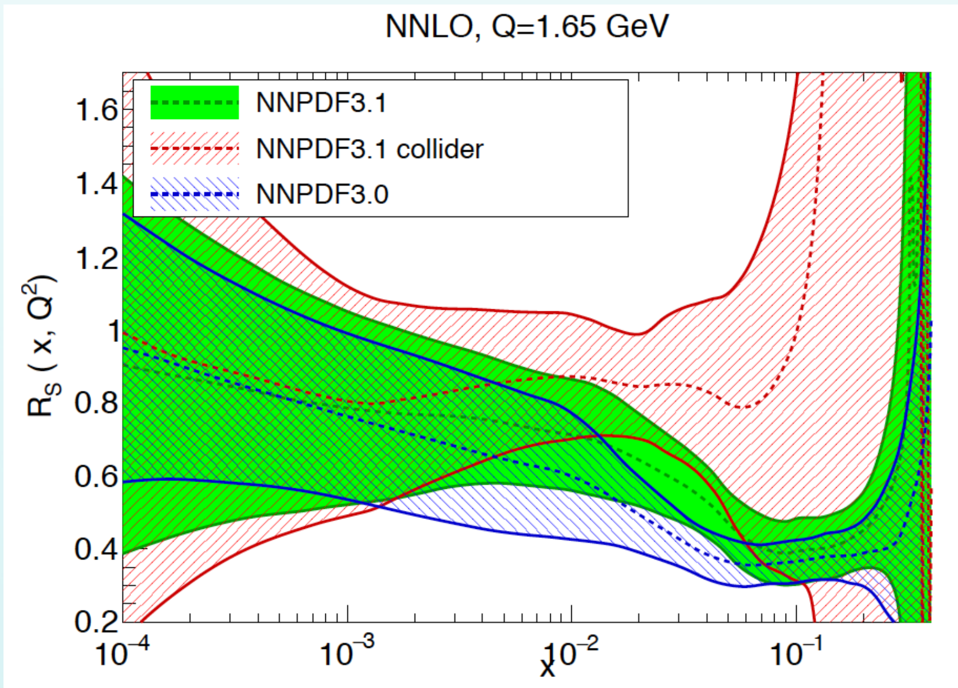
A strange conundrum

- In most PDF fits, strangeness suppressed wrt **up and down quark sea** due to **neutrino dimuon data**
- On the other hand, recent collider data, in particular the ATLAS W,Z 2011 rapidity distributions, prefer instead a **symmetric strange quark sea**

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \left\{ \begin{array}{l} \approx 0.5 \textit{ (from neutrino, CMS W+c)} \\ \approx 1.0 \textit{ (from ATLAS W,Z)} \end{array} \right.$$

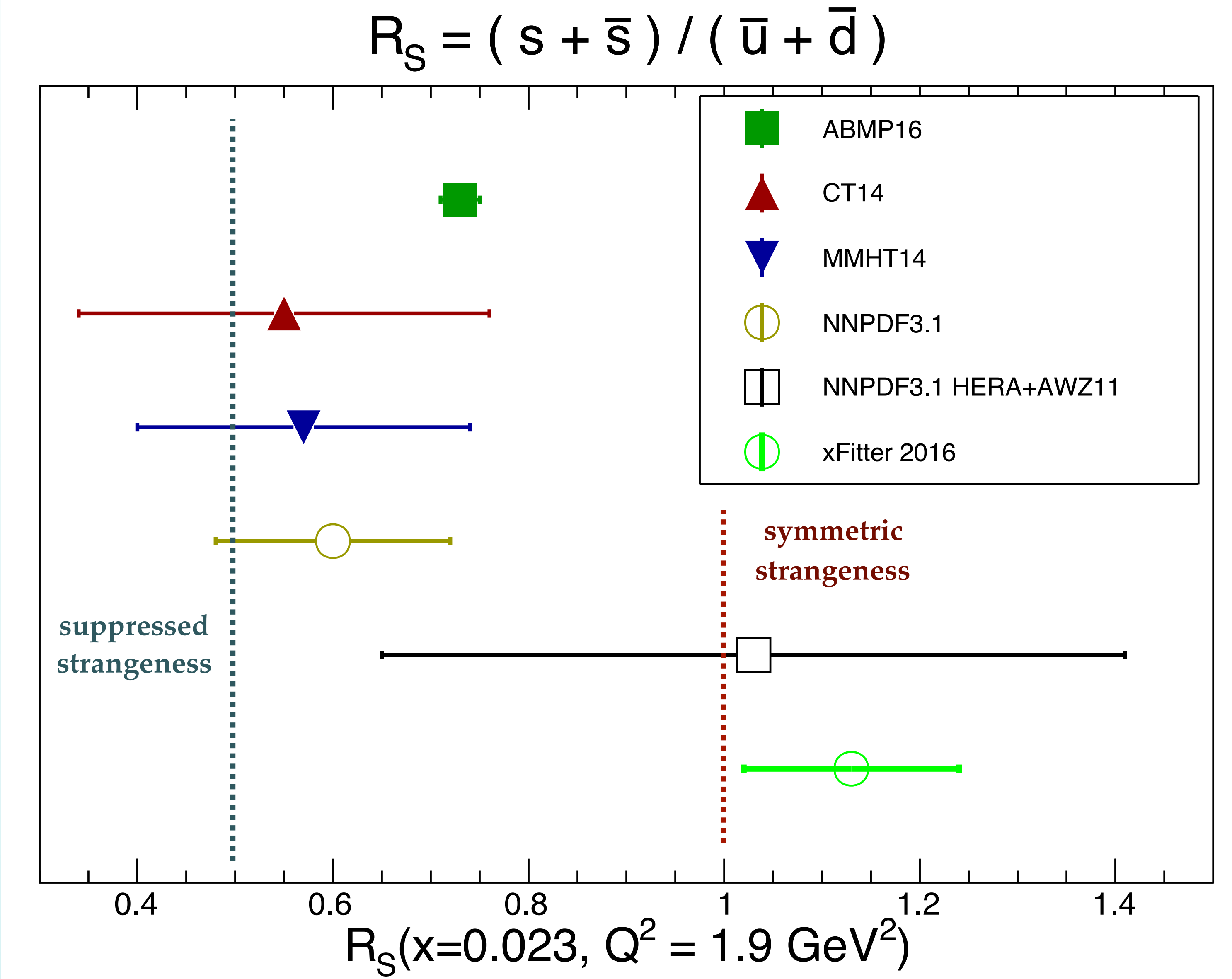
The new ATLAS data can be accommodated in the **global fits**, and *i)* indeed it **increases strangeness**, but not as much as in a collider-only fit, and *ii)* **some tension remain**s between neutrino and collider data





How strange is the proton?

In the global fit, the resulting strange PDF is the best compromise between the **pulls from individual experiments.** More strange-sensitive measurements are needed to shed more light in this **strange mystery!**



The inner life of protons

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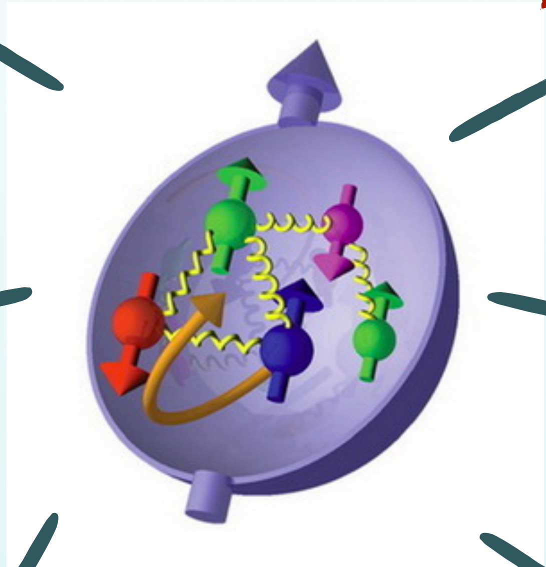
Quark flavour separation



Photon

BFKL dynamics

Strange

Charm

A charming story

In global PDF fits there are **two strategies** to treat the **charm PDF:**

- The charm PDF is **generated perturbatively** via collinear splittings **off gluons and light quarks:**

$$c(x,Q) = 0\,, \quad Q < m_c$$
$$c(x,Q) \simeq \alpha_s(Q^2) \ln \frac{Q^2}{m_c^2} \int_x^1 \frac{dy}{y} P_{gg}^{(0)}(y) g\left(\frac{y}{x}, Q^2\right)\,, \quad Q \geq m_c$$

- The charm PDF is **fitted from data**, that is, it is treated on an **equal footing to light quarks:**

$$c(x,Q_0) = f(x,\{a_i\})\,, \qquad Q_0 > m_c$$

Note that the first option is necessarily an **assumption**, which can only be validated by comparing with the results of a **direct fit of the charm PDF**

Moreover **fitting the charm PDF** offers several advantages:

- ☑ **Reduce the dependence of high-scale cross-sections** with respect of the value of the **charm mass**
- ☑ Improve the description of **high-precision collider data** that depend on **quark flavor separation**
- ☑ Compare with models of the **non-perturbative (``*intrinsic*") charm content of the proton**

***Fitting the charm PDFs** has many advantages even with for a vanishing non-perturbative component*

Some charm really improves things

	NNLO Fitted Charm	NNLO Pert Charm	NLO Fitted Charm	NLO Pert Charm
HERA	1.16	1.21	1.14	1.15
ATLAS	1.09	1.17	1.37	1.45
CMS	1.06	1.09	1.20	1.21
LHCb	1.47	1.48	1.61	1.77
TOTAL	1.148	1.187	1.168	1.197

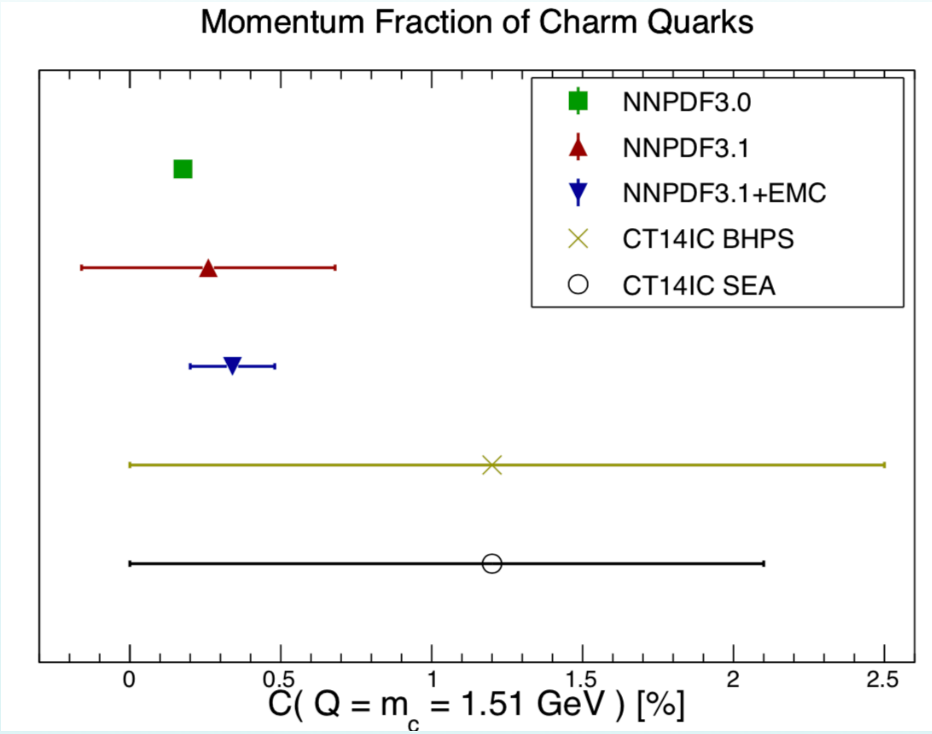
- In NNPDF3.1, for collider data, **NNLO theory** leads to a markedly better fit quality that than **NLO**
- The new precision data included has small experimental errors, with **NNLO corrections mandatory**
- The global PDF analysis where the charm PDF is fitted leads to a **slightly superior fit quality** than assuming a perturbatively generated charm PDF

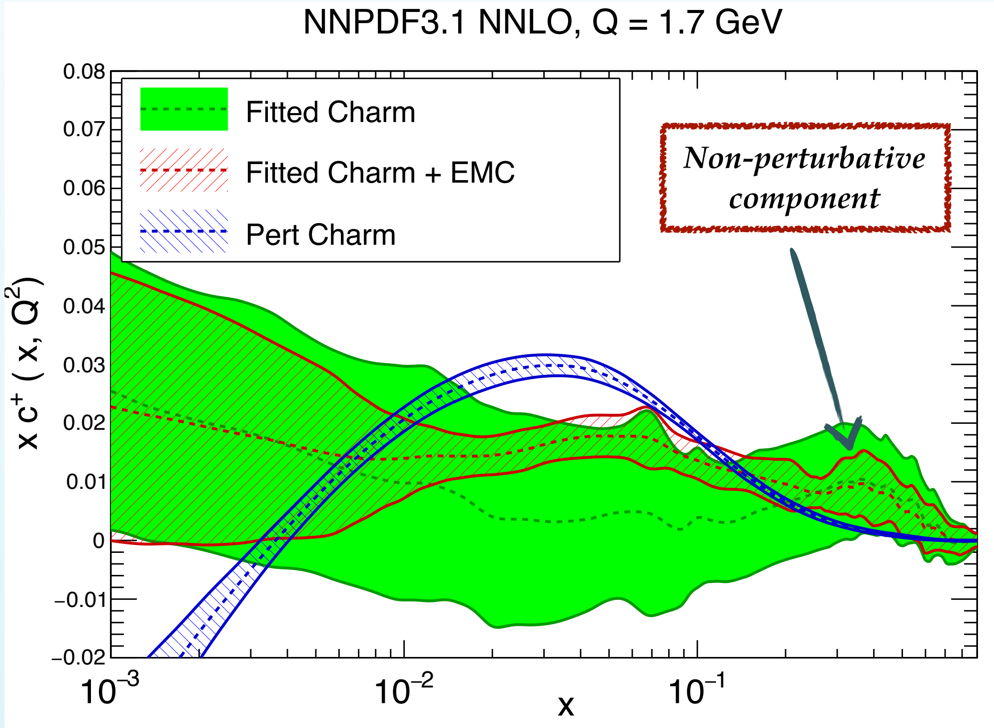
A charming story

The NNPDF3.1 global analysis is performed with a **fitted charm PDF**. The recent LHC *W,Z* data, in particular from LHCb, impose stringent constraints on the **size of the charm PDFs at Q=m$_c$**

$$C(Q^2) \equiv \int_0^1 dx\, x\, \left(c(c, Q^2) + \bar{c}(x, Q^2)\right)$$

Charm momentum fraction in the proton





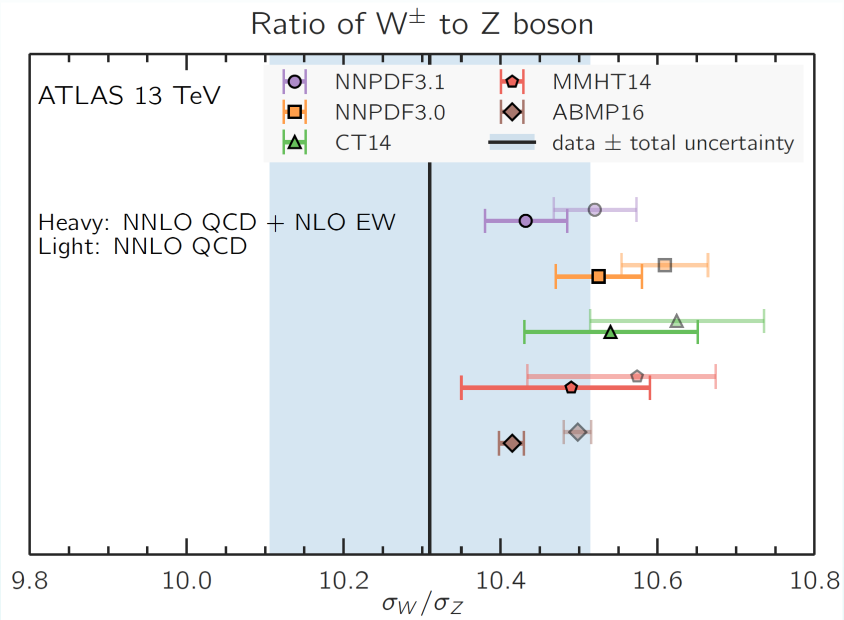
Indications of a **non-perturbative component of the charm PDF localised at large-*x***, though its statistical significance is still limited….

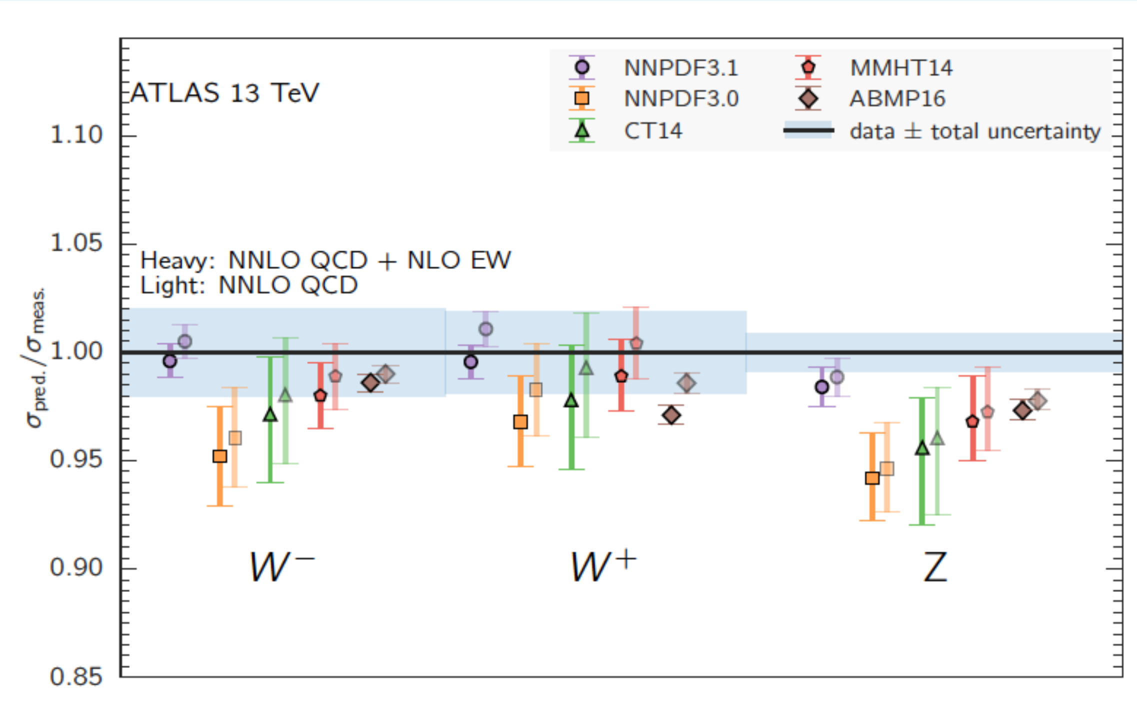
PDFs and precision physics at the LHC Run II

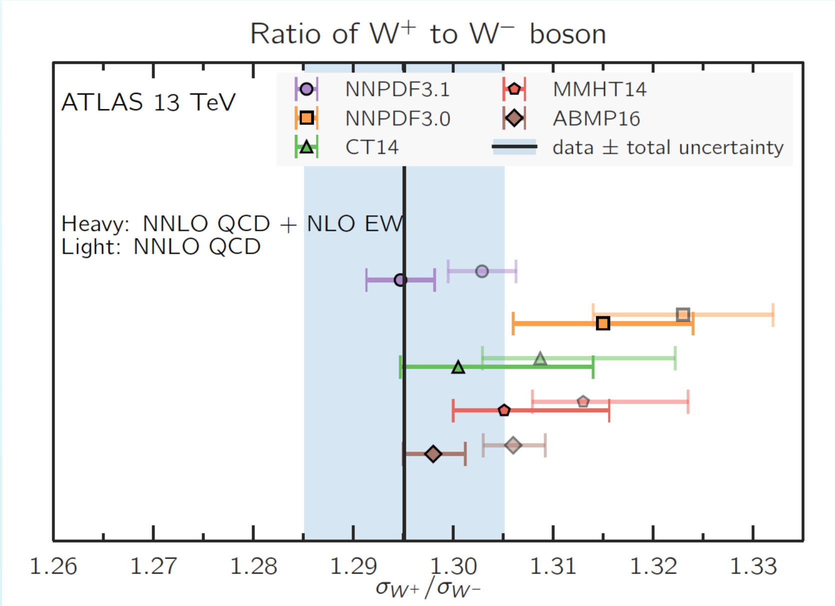
Compare recent PDF fits with **fiducial W,Z cross-sections at 13 TeV** from ATLAS

Theory calculations with FEWZ and Horace: **NNLO QCD + NLO EW**. The latter improves agreement with data

Qualitative agreement between theory and data for most cases - now looking forward to **differential measurements**!







Summary and outlook

- Recent developments in our understanding of the **quark and gluon structure of the proton** have been driven by a combination of:

  - ☑ **Theory**: Progress in NNLO QCD and NLO EW calculations for many collider processes: differential top pairs, inclusive jets, the Z transverse momentum … Also the calculation of the photon PDF in terms of DIS structure functions

  - ☑ **Data**: a wealth of high-precision measurements from HERA, Tevatron, ATLAS, CMS and LHCb, in several cases with sub-percent uncertainties.

  - ☑ **Methodology**: fitted charm PDF, combination/reduction methods for different PDFs, new software for PDF fits, fast NLO/NNLO interfaces, ….

- Improvements for **many Run II analysis**: Higgs couplings, M_W measurements, heavy BSM particle production, precision SM studies, MC validation, …

- **Theory uncertainties** now likely to be a limiting factor in PDF fits and PDF-related studies: urgent need to provide PDF analysis with robust estimates of TH errors, including MHOUs

Summary and outlook

Recent developments in our understanding of the **quark and gluon structure of the proton** have been driven by a combination of:

- **Theory**: Progress in NNLO QCD and NLO EW calculations ... der processes: differential top pairs, inclusive jets, the Z trans... he calculation of the photon PDF in terms of DIS stru...

- **Data**: a wealth of high-p... and LHCb, in sever...

- ... for different PDFs,

PDFs are in excellent shape for the exploitation of the Run II harvest!

Thanks for your attention!

I... : Higgs couplings, M_W measurements, heavy BSM part... studies, MC validation, …

The... ncertainties now likely to be a limiting factor in PDF fits and PDF-related studies: urgent need to provide PDF analysis with robust estimates of TH errors, including MHOUs