Recent progress in PDFs

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Shanghai Jiao Tong University,
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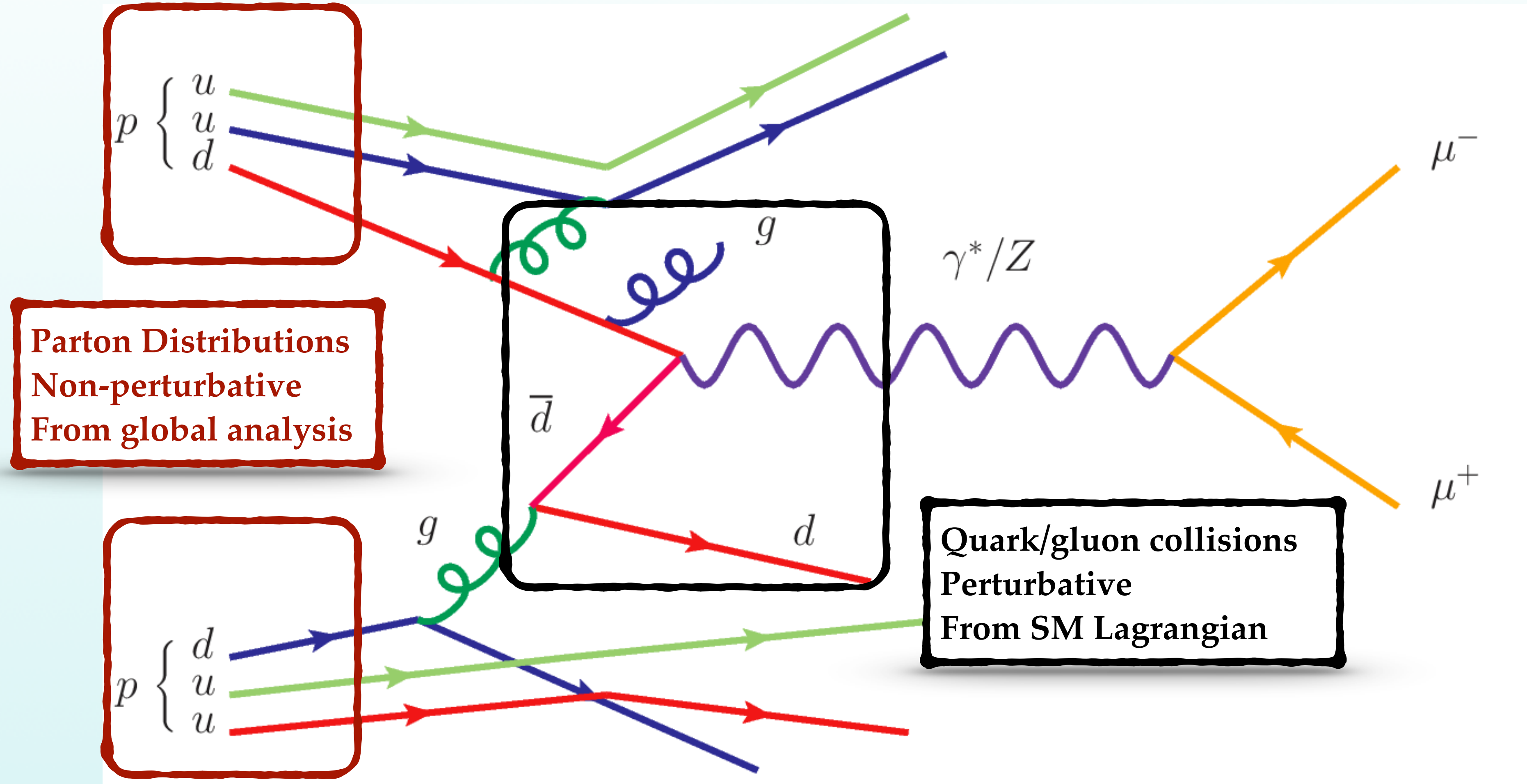
Anatomy of hadronic collisions

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)**

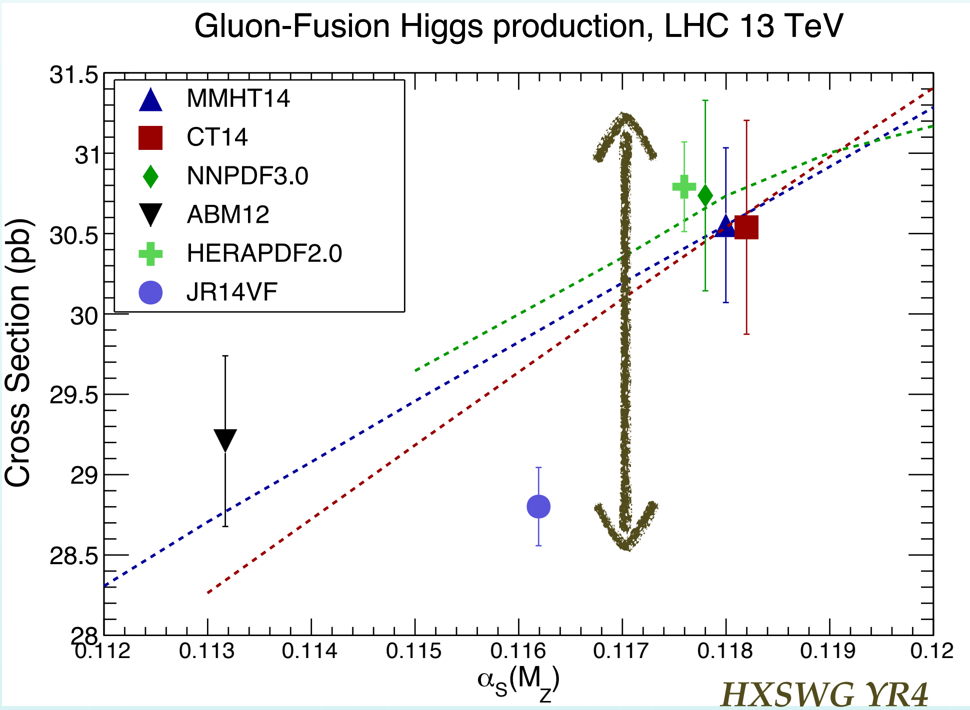
Why we need better PDFs?

Dominant TH unc for M_W measurements at LHC

ATLAS 2017

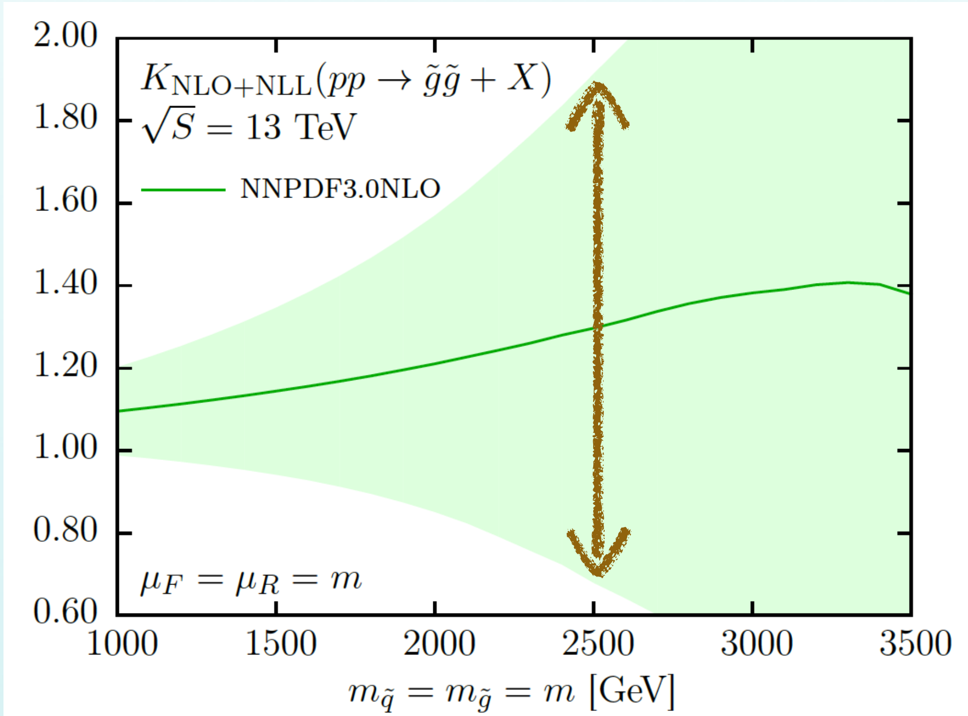
Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Higgs coupling measurements

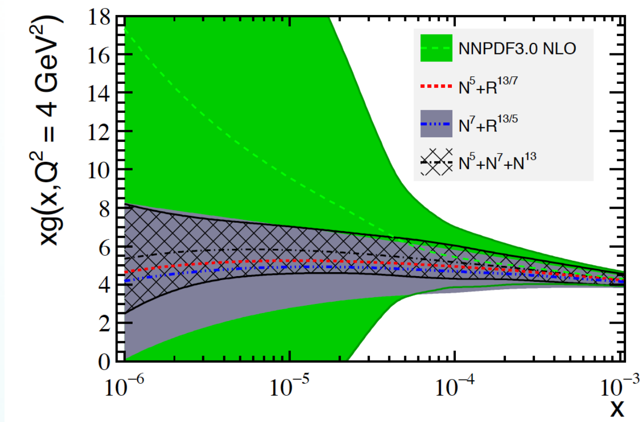


HXSWG YR4

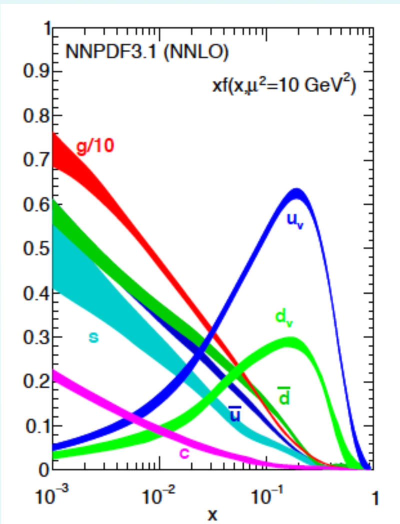
High-mass BSM cross-sections



Borchemsky et al 2015



Recent progress in proton PDF fits



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

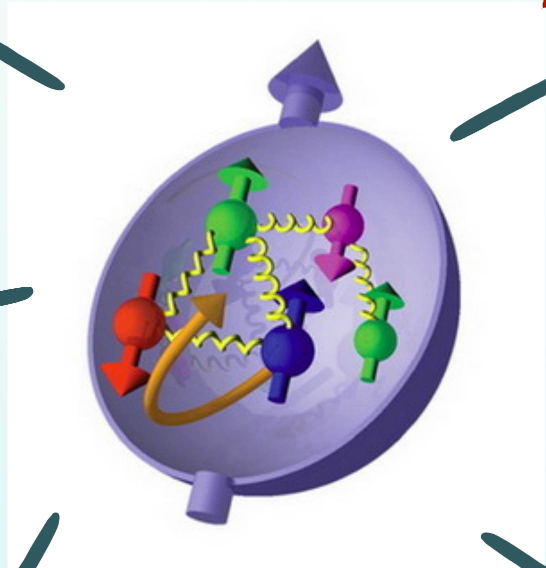
Ubiali, DIS2017

The inner life of protons

Gluon

Quark flavour separation

Photon



Strange

Charm

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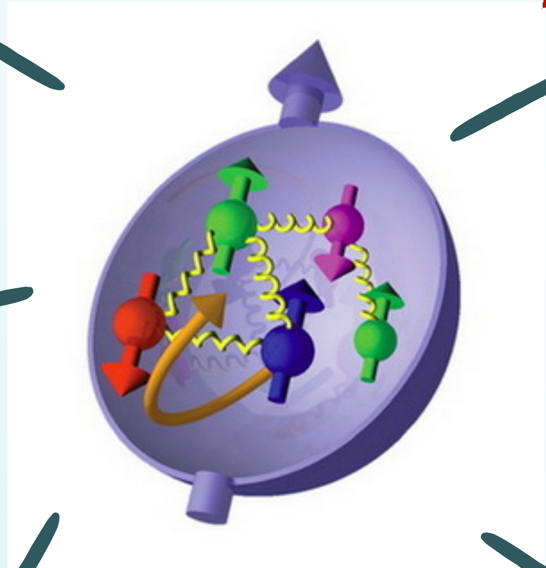

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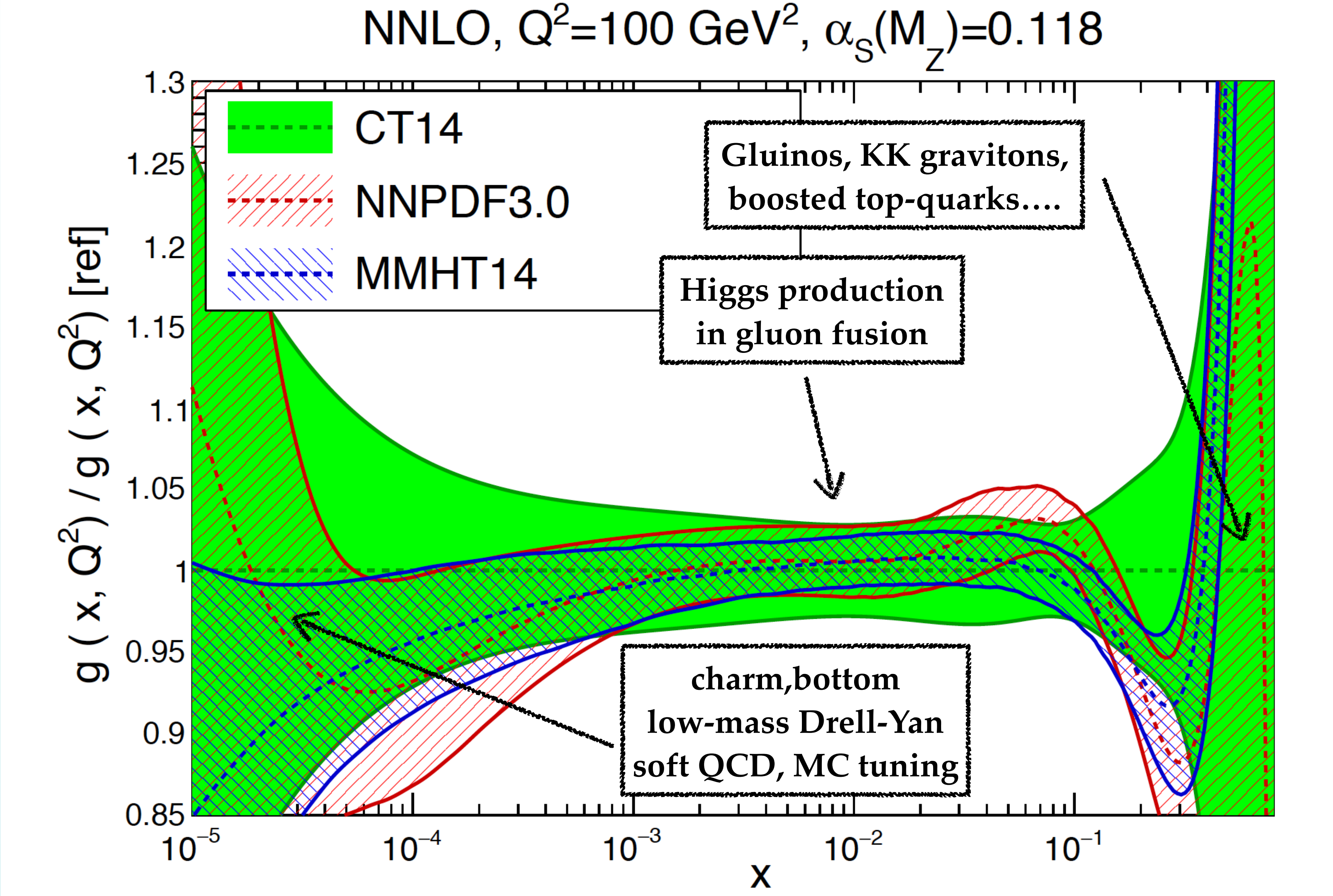
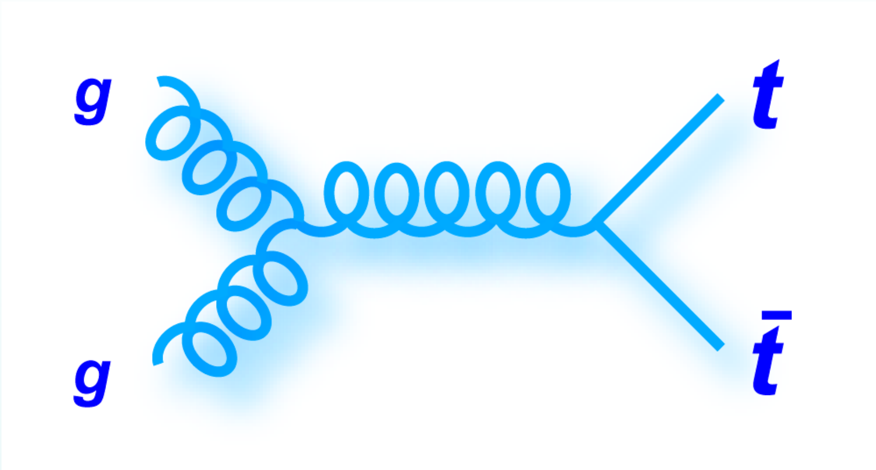
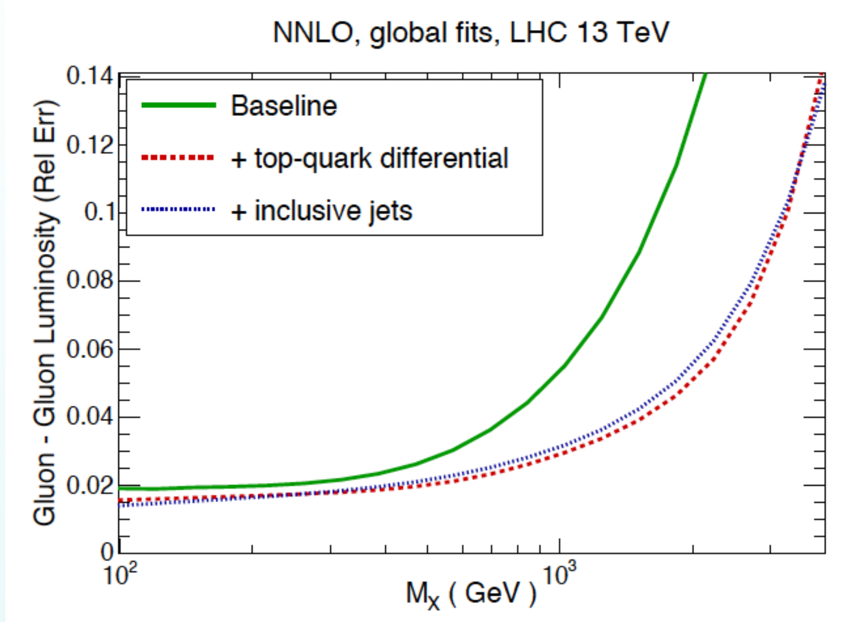
One glue to bind them all



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

The large-x gluon from differential top quarks





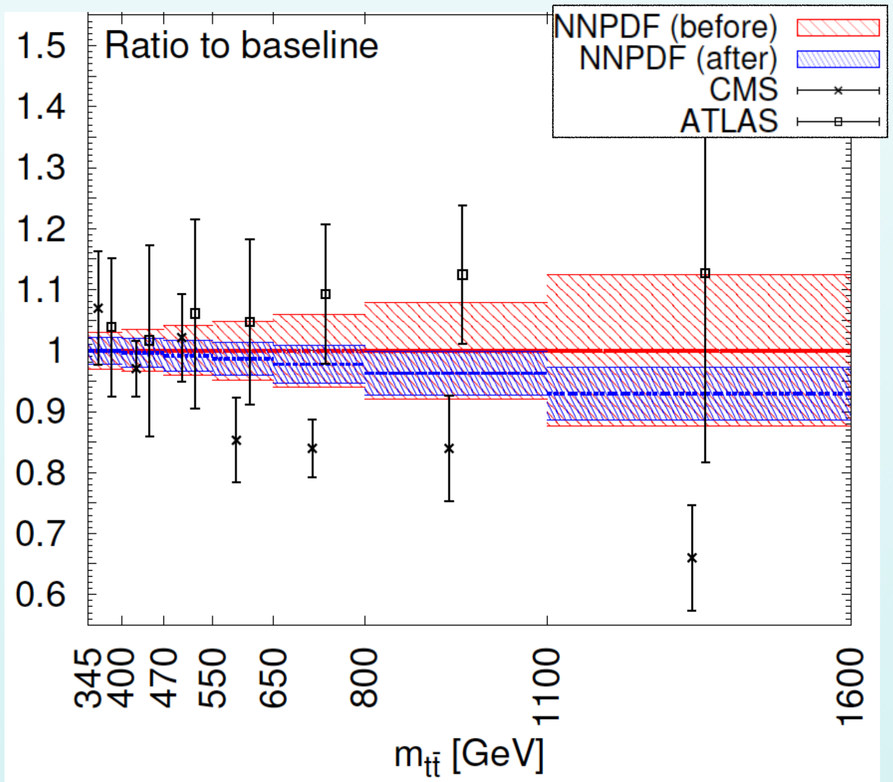
- Top-quark pair production driven by **gluon-gluon lumi**

- **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

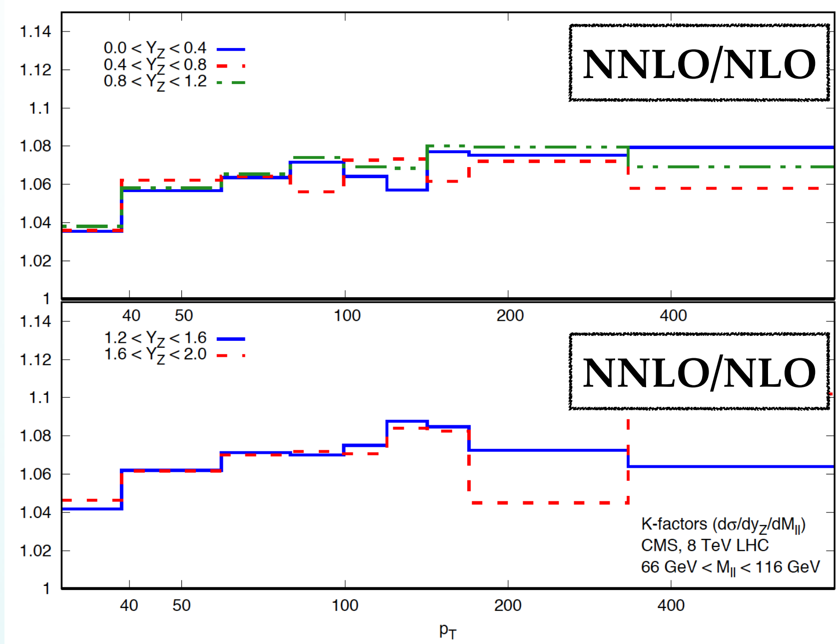
- Dominated by **quark-gluon scattering**, thus sensitive to the gluon PDF at intermediate values of x

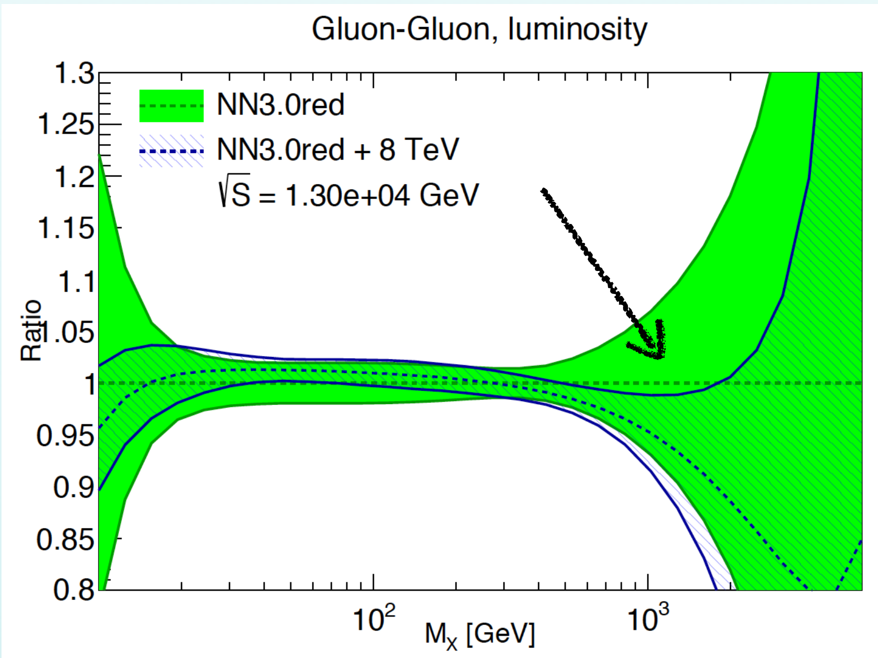
  Malik and Watt 2013, Boughezal et al 2017

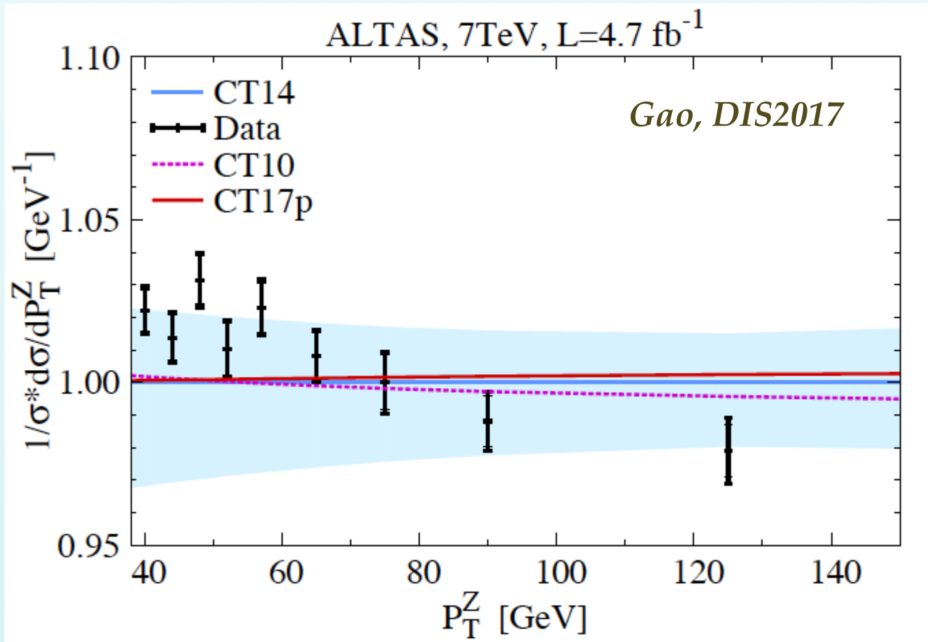
- **NNLO corrections to the Z p_T** also available: **up to 10% effects** for a measurement that has **sub-percent exp errors**

  Boughezal et al 2015-2017, Gerhmann et al 2015-2017

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







Boughezal et al 2017

The small-x gluon from forward charm production

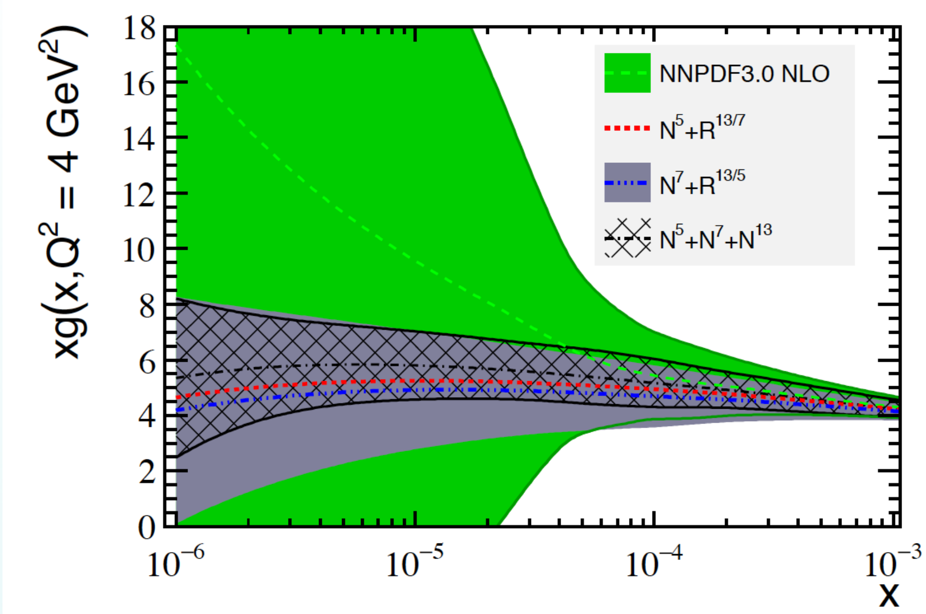
- **D and B meson production from LHCb** allow accessing the **gluon down to x=10^{-6}**, well below the HERA coverage

PROSA 2015, Gauld et al 2015

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

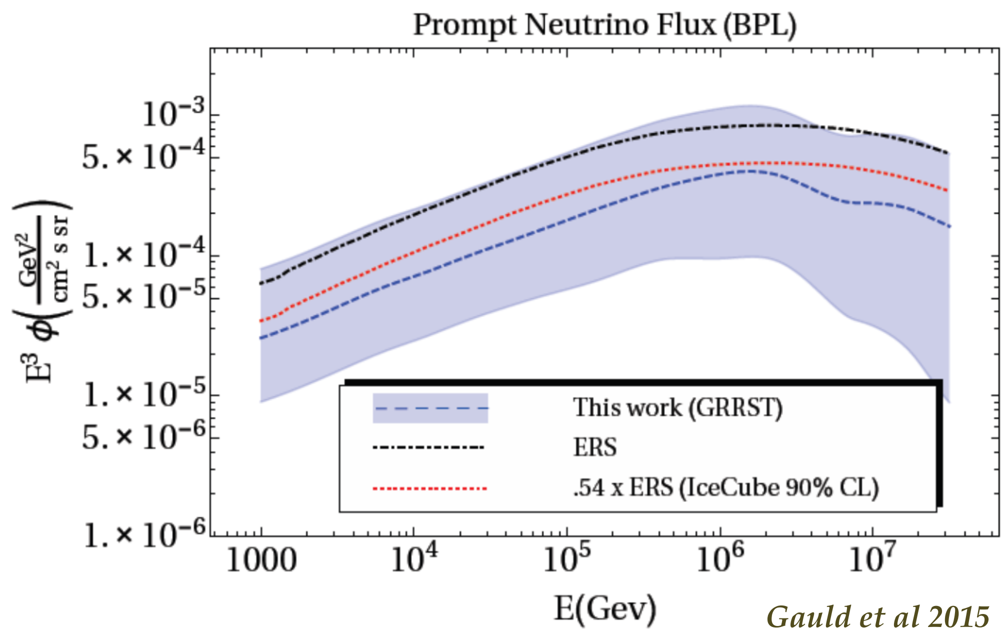
- Allows robust estimate for the ***prompt* neutrino flux**, the main background for astrophysical neutrinos at IceCube

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

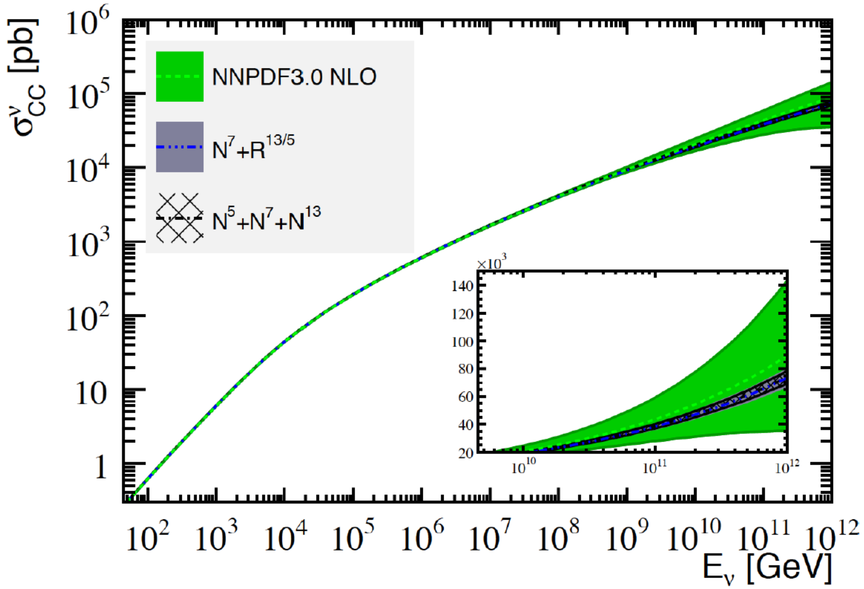


Prompt neutrino flux at IceCube

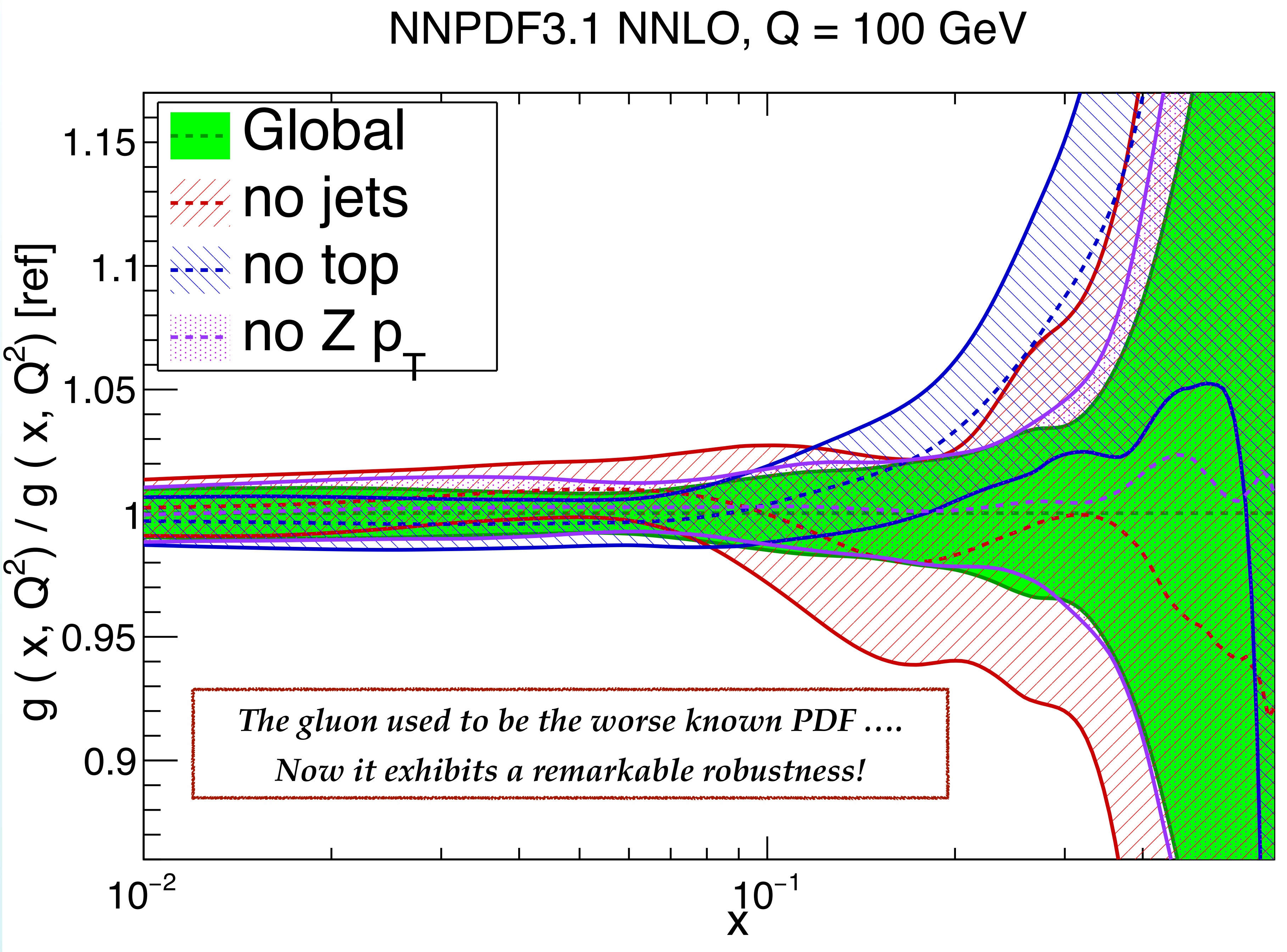
UHE neutrino-nucleus xsecs



Gauld et al 2015



One (upgraded) glue to bind them all

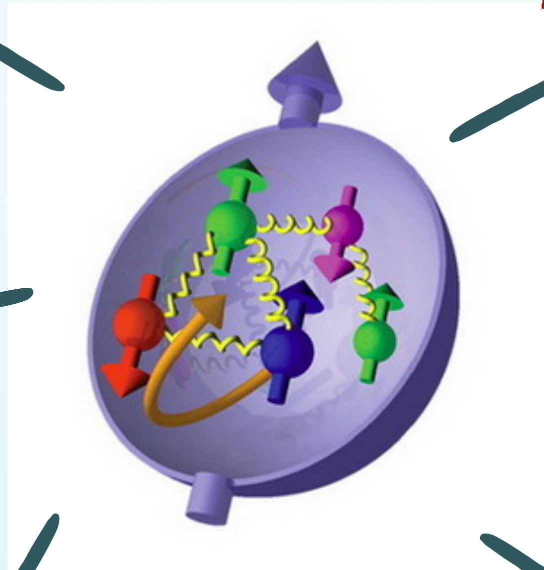


The inner life of protons

Gluon

Quark flavour separation

Photon



Strange

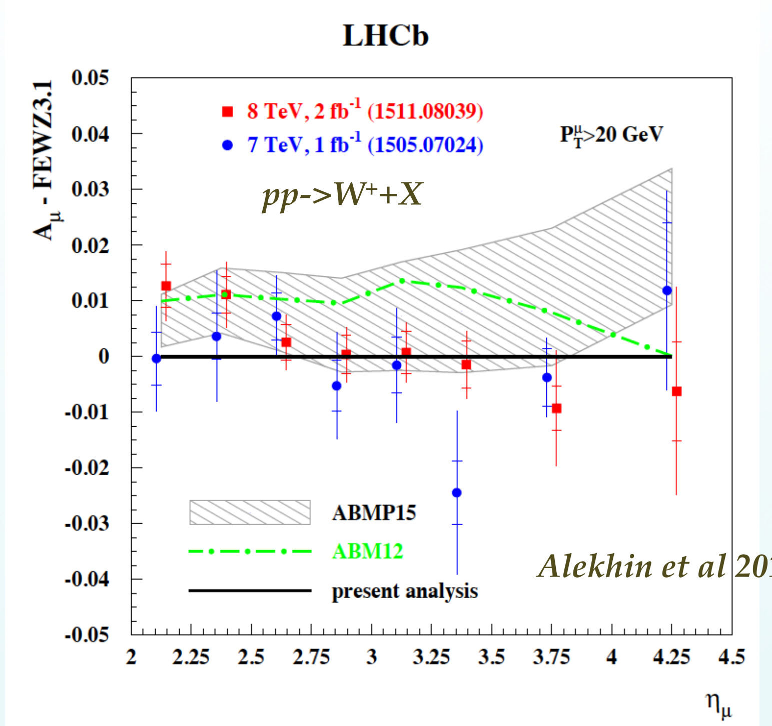
Charm

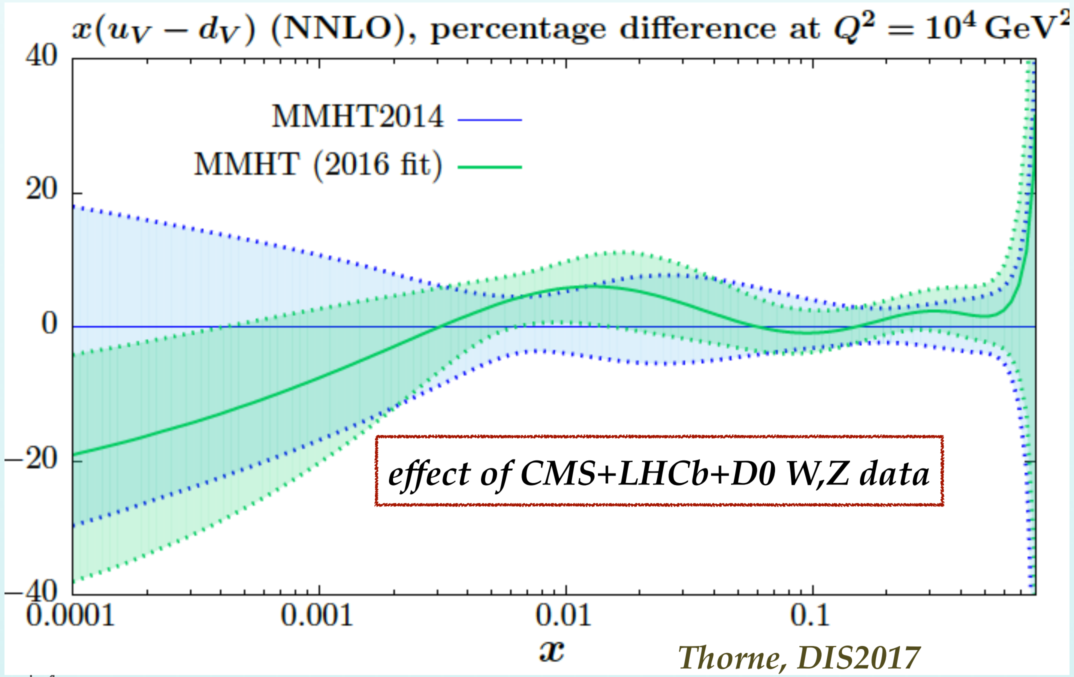
Quark flavour separation from LHC data

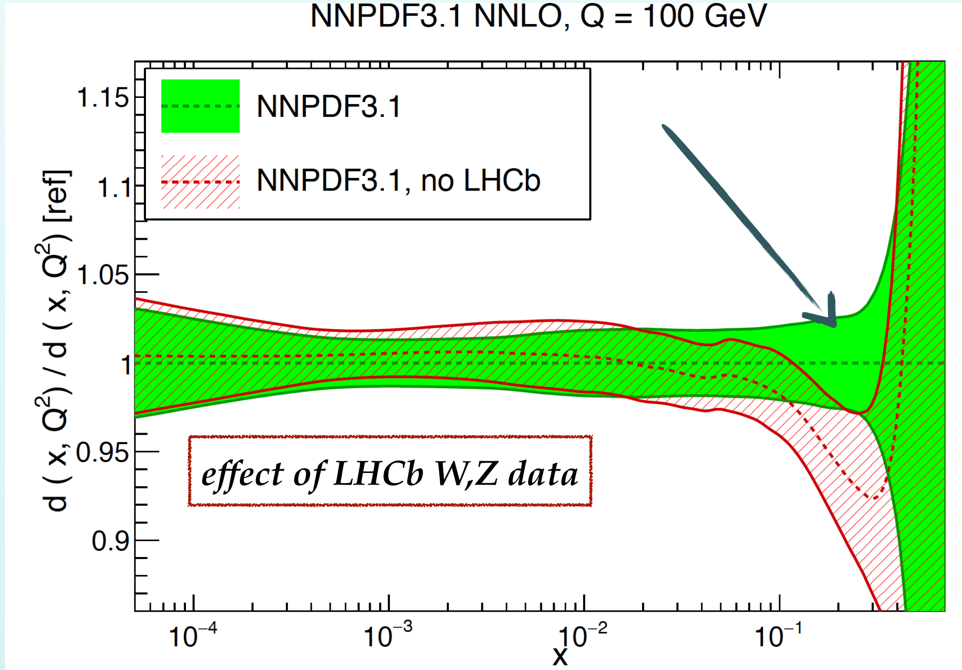
- Recent high-precision ***W* and *Z* production** data from **ATLAS, CMS, LHCb and D0** allow a better separation of quark and antiquark flavours

- **LHCb** data in particular provides constrains on the **light quarks at large-*x*** (*i.e.* error 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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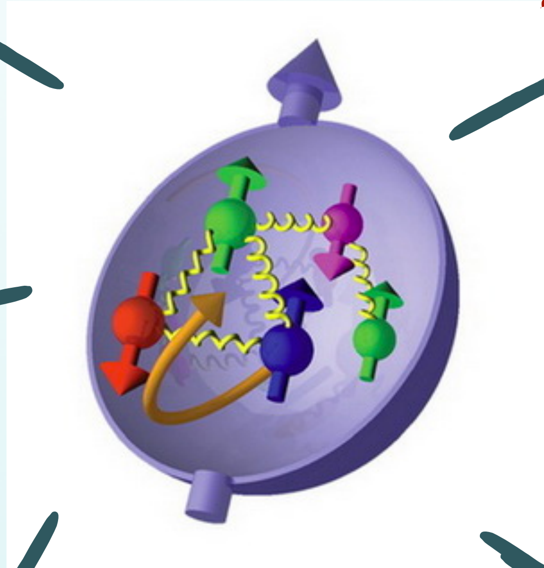

Photon

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Charm

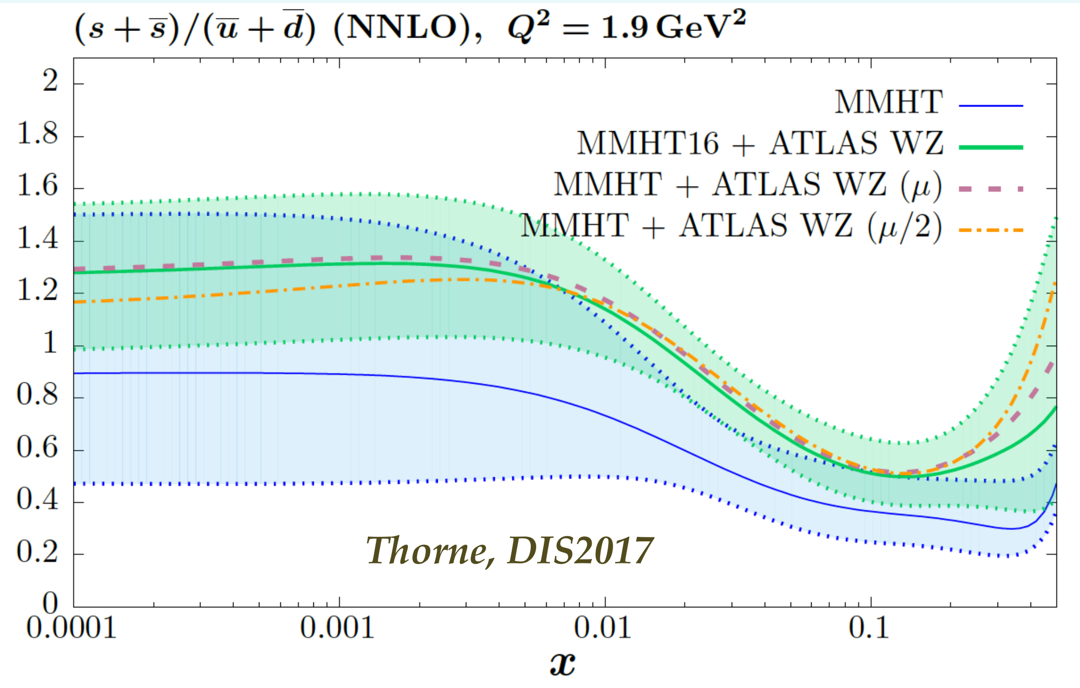
A strange conundrum

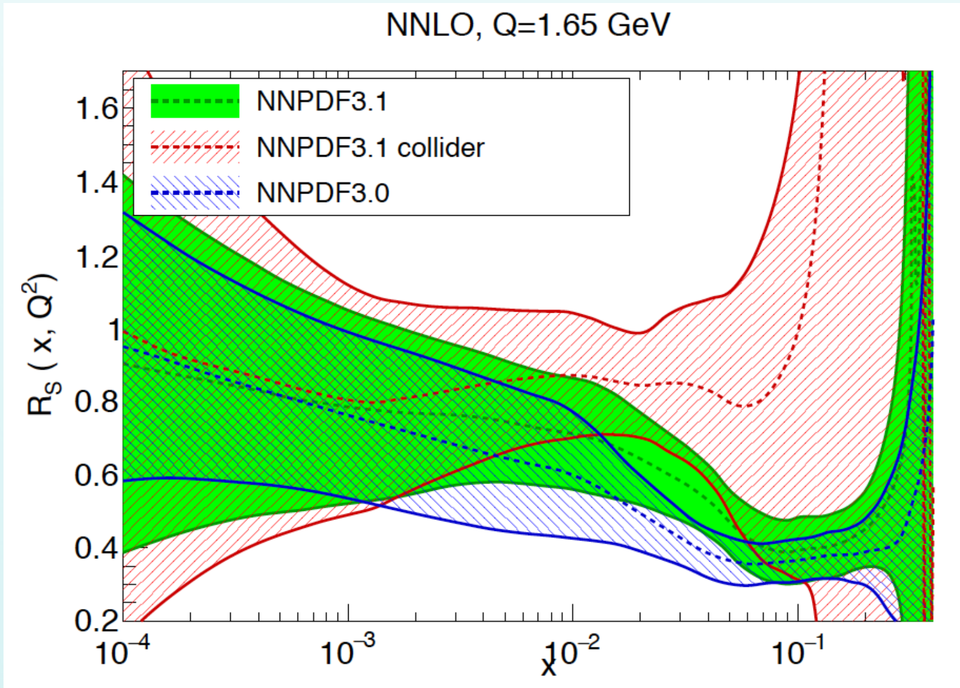
- In most PDF fits, strangeness suppressed wrt **up and down quark sea** due to **neutrino dimuon data**

- On the other hand, recent collider data, in particular the ATLAS W,Z 2011 rapidity distributions, prefer instead a **symmetric strange quark sea**

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino, CMS W+c)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$

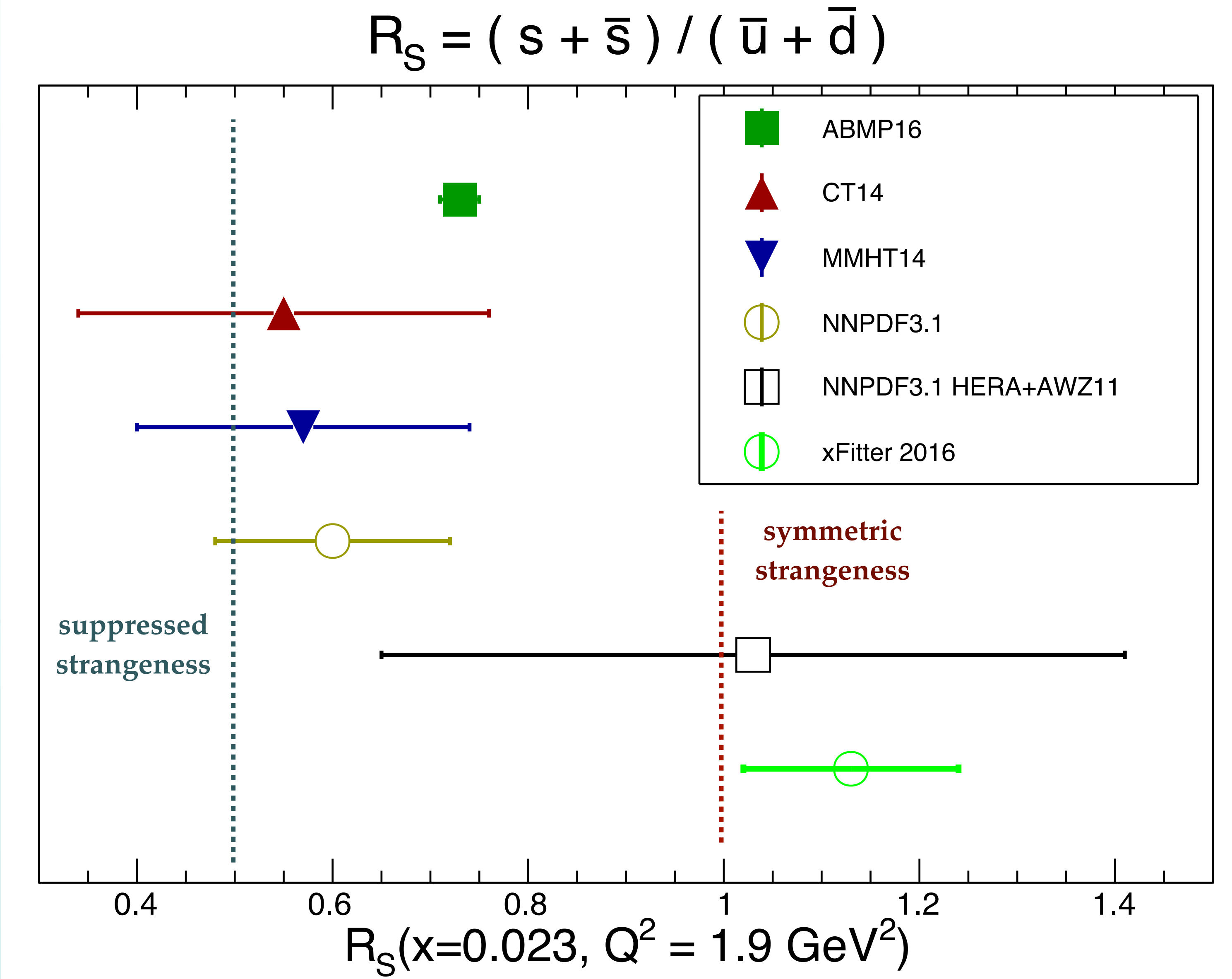
The new ATLAS data can be accommodated in the **global fits**, and *i)* indeed it **increases strangeness**, but not as much as in a collider-only fit, and *ii)* **some tension remain**s between neutrino and collider data





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!**



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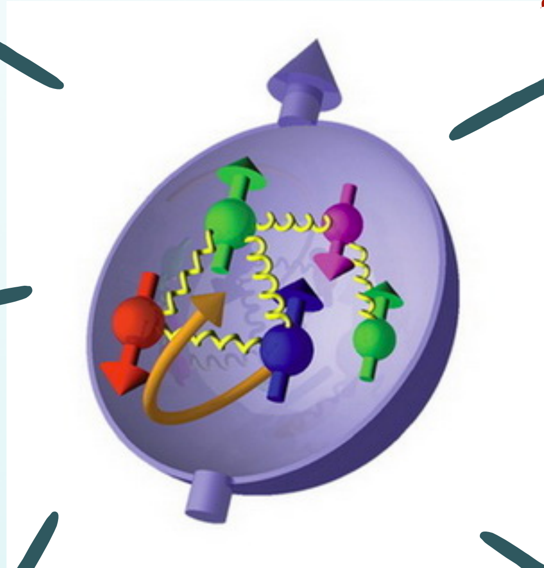

Photon

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How bright is the proton?

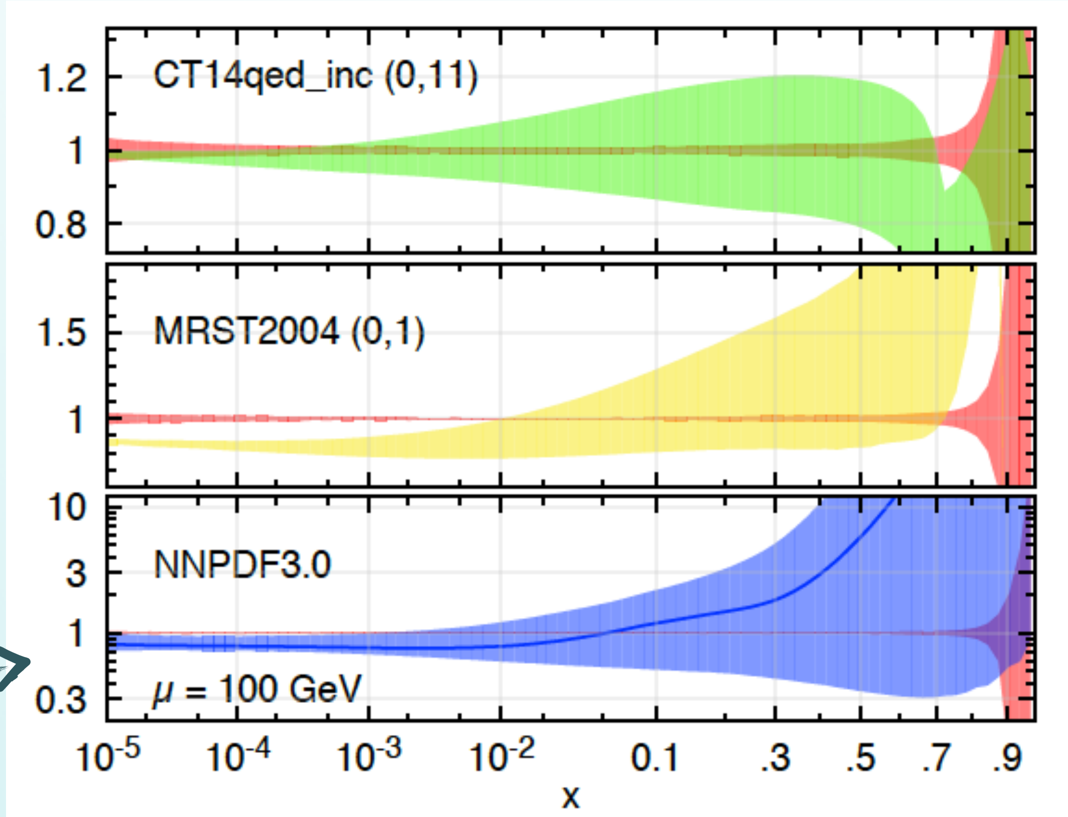
- The calculation of **QED and electroweak corrections to hadron collider processes** requires by consistency to introduce the PDF of the photon in the proton, **γ(x,Q)**
- The first model-independent determination of **γ(x,Q)** from LHC *W,Z* data was **NNPDF2.3QED**, which however affected by **large uncertainties**, O(100%), due to limited experimental information
- Last year it was shown how to compute **γ(x,Q)** in terms of the well-known **inclusive structure functions F_2 and F_L**: the resulting photon PDF, **LUXqed**, exhibits now **few-percent uncertainties**

*The photon PDF **γ(x,Q)** in **LUXqed***

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

Good agreement with NNPDF3.0QED, model-independent fit from LHC DY data

γ(x,Q)**, ratio to **LUXqed



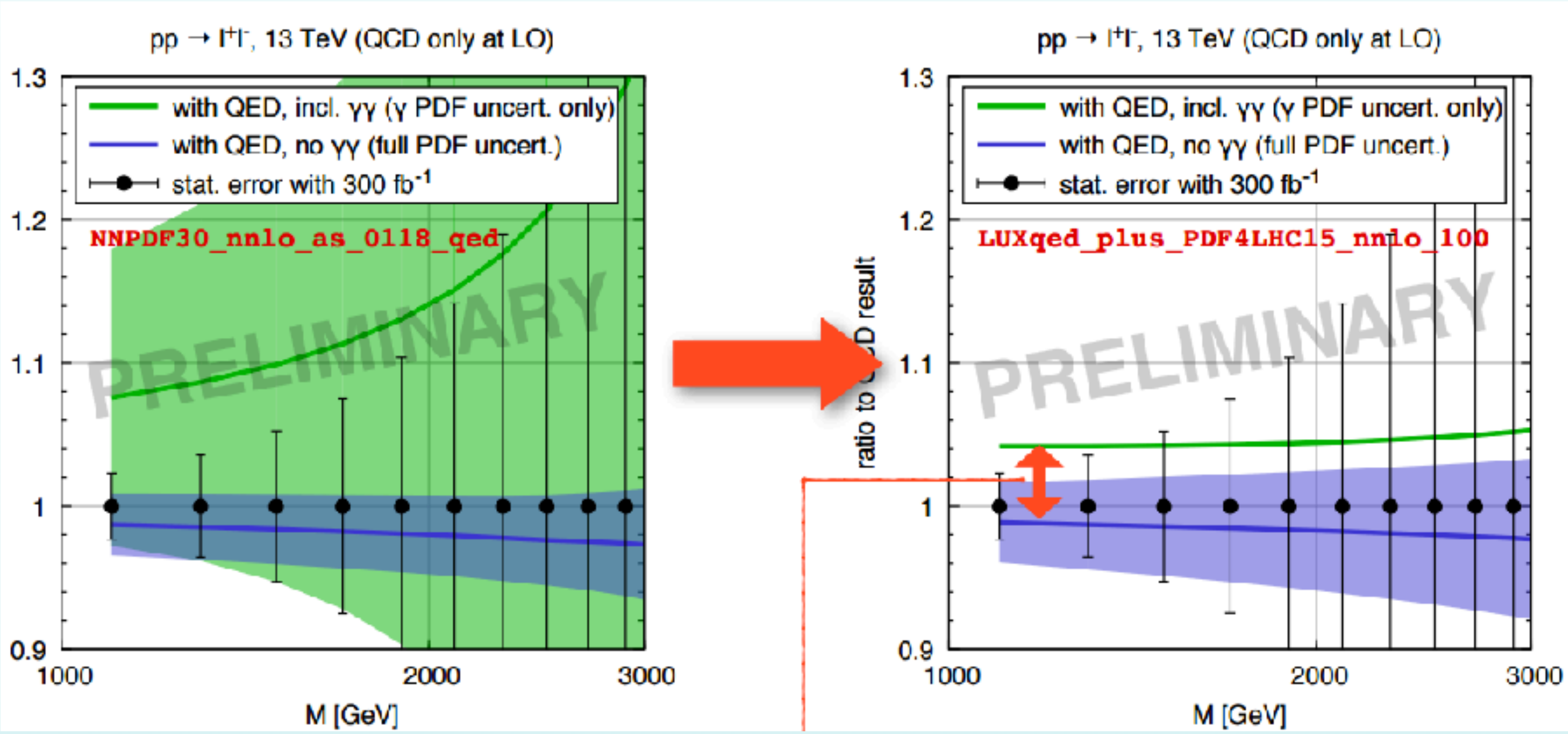
Manohar et al 16

How bright is the proton?

- The **precision determination of $\gamma(x,Q)$ in LUXqed** reduces theory uncertainties in several high-mass processes relevant for BSM searches, i.e., **Dilepton (Drell-Yan) production at the TeV**
- Also for **Higgs cross-sections** with EW corrections
- The upcoming NNPDF3.1QED set will be based on the LUXqed master formula for **$\gamma(x,Q)$**

G. Salam, Oxford colloquium 02/17

$pp \to H W^+ (\to l^+\nu) + X$ 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



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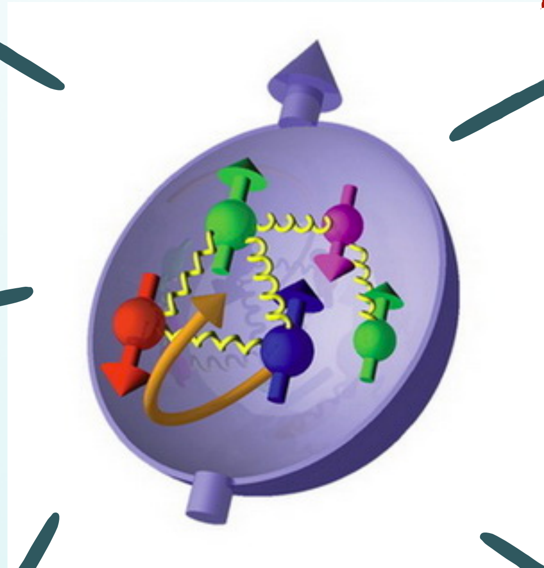

Photon

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Charm

A charming story

In global PDF fits there are **two options** 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**

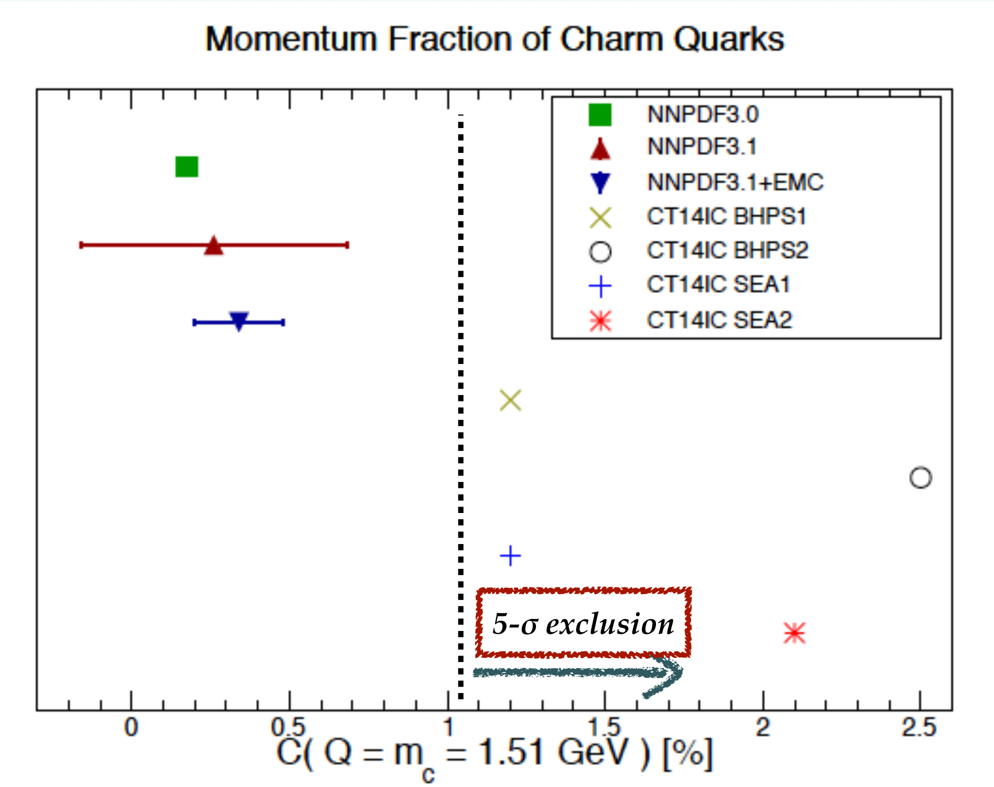
***Fitting the charm PDFs** has many important advantages even with for a vanishing non-perturbative component*

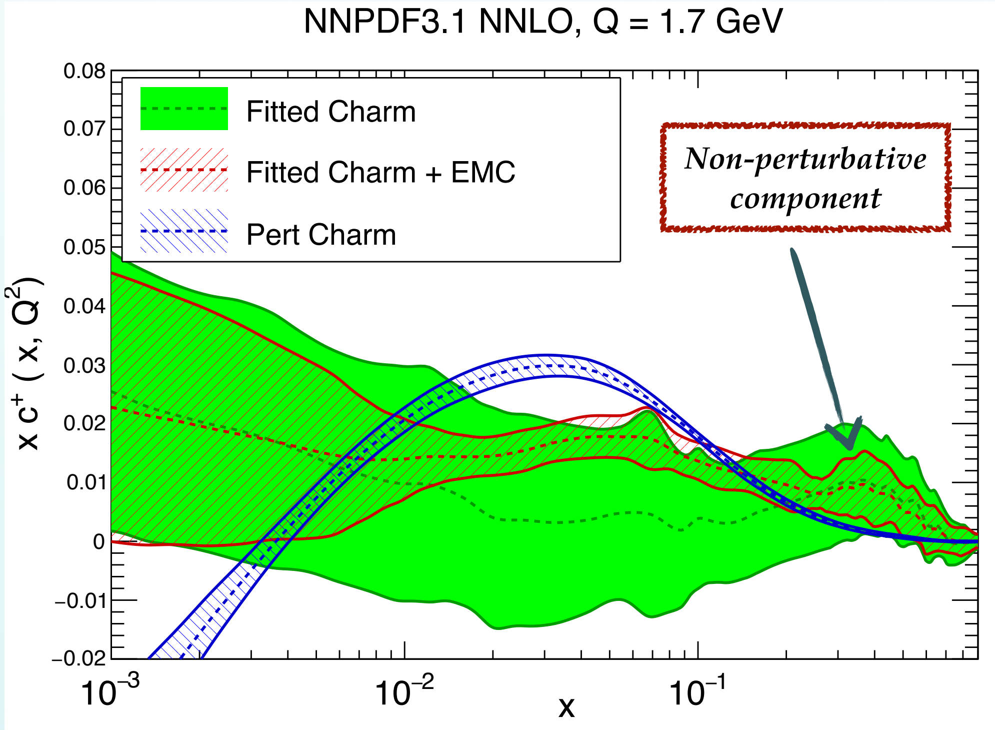
A charming story

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$_c$**

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

Charm momentum fraction in the proton





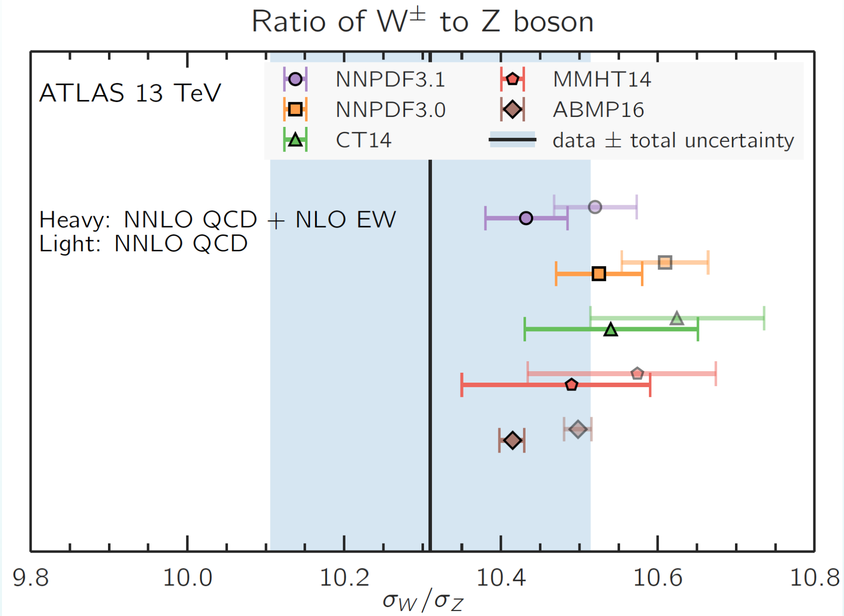
We also find some indications of a **non-perturbative component of the charm PDF localised at large-*x***, though evidence is still limited at the 1.5-sigma level

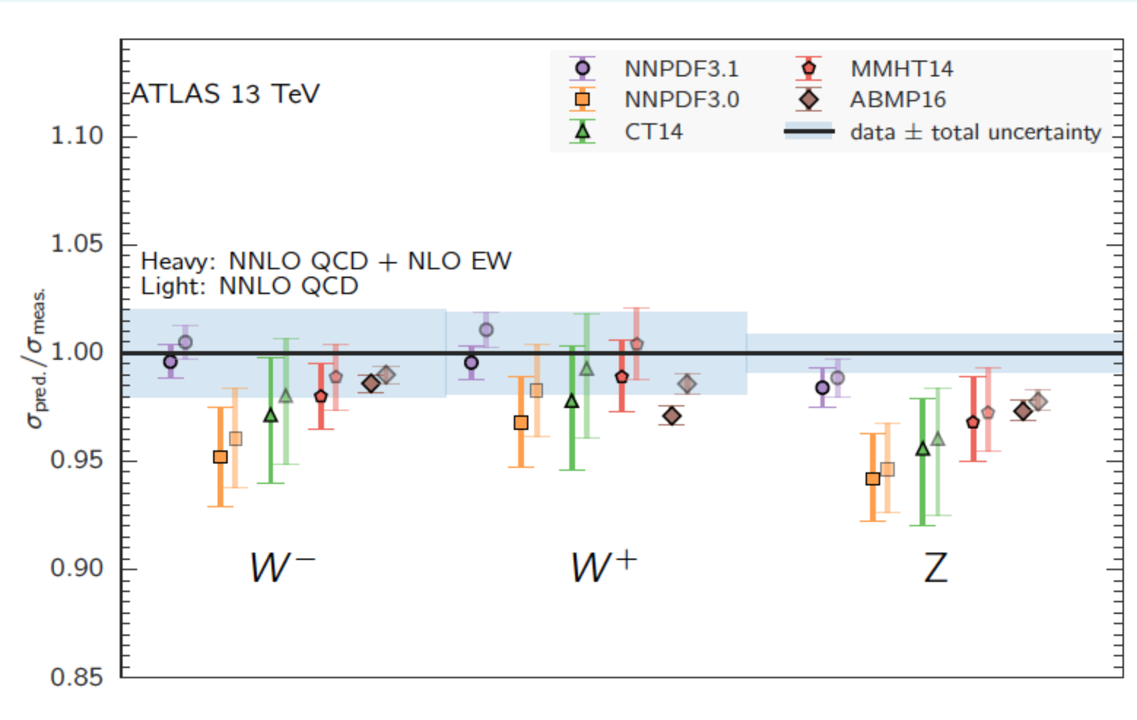
PDFs and precision physics at the LHC Run II

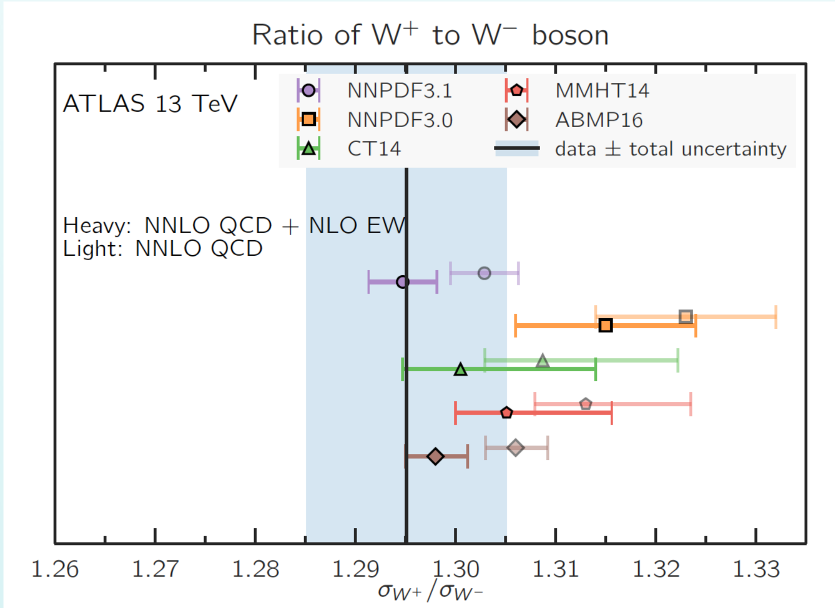
Compare recent PDF fits with **fiducial W,Z cross-sections at 13 TeV** from ATLAS

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**!







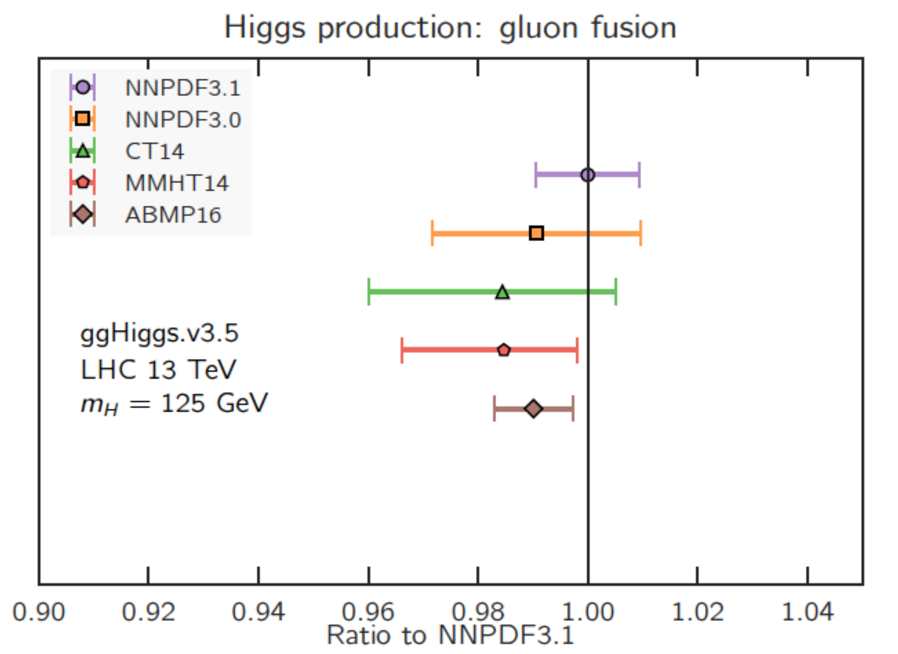
PDFs and precision physics at the LHC Run II

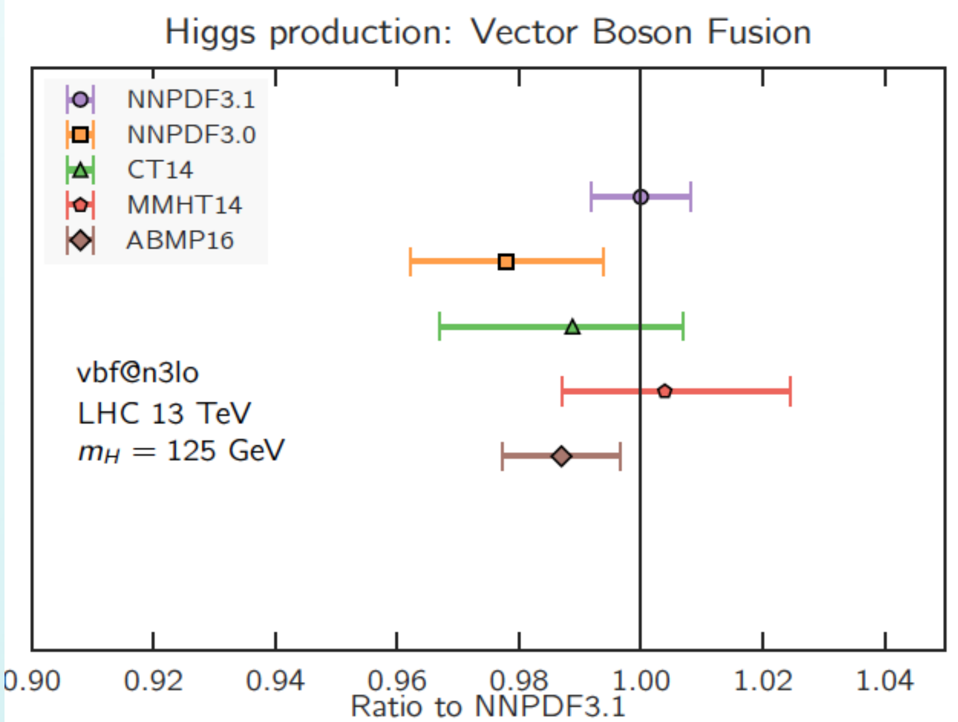
Compare recent PDF fits for the theory predictions for **Higgs production cross-sections at 13 TeV**

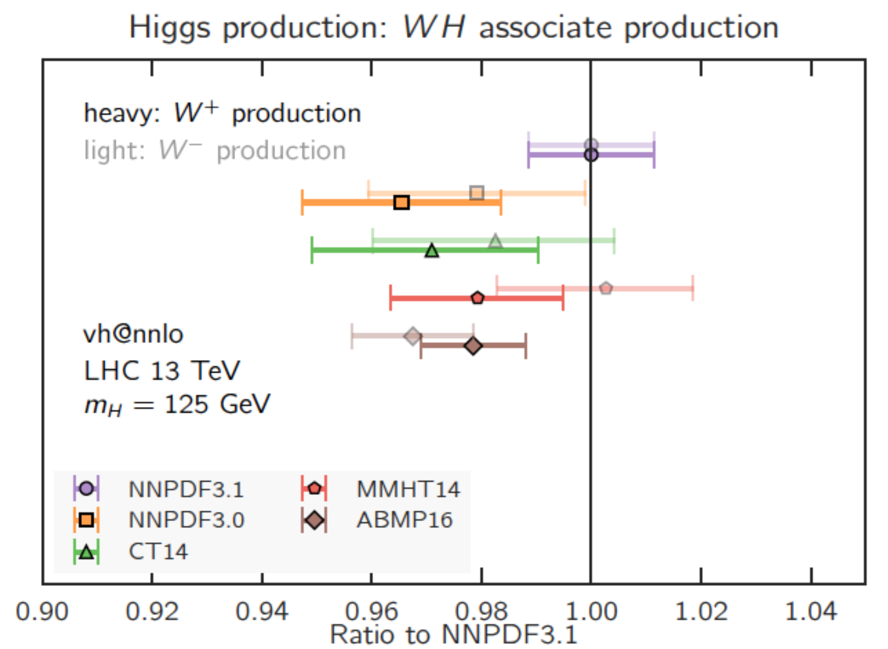
The dominant production mode, gluon-fusion, is **stable wrt the addition of the recent LHC data**

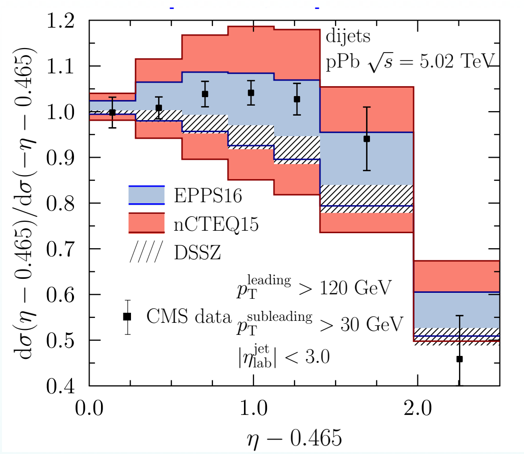
Note improved agreement between **ABMP16 and the global fits** (common value of $\alpha_S(m_Z)$=0.118)

Comparison to be updated with the upcoming new releases from CT and MMHT

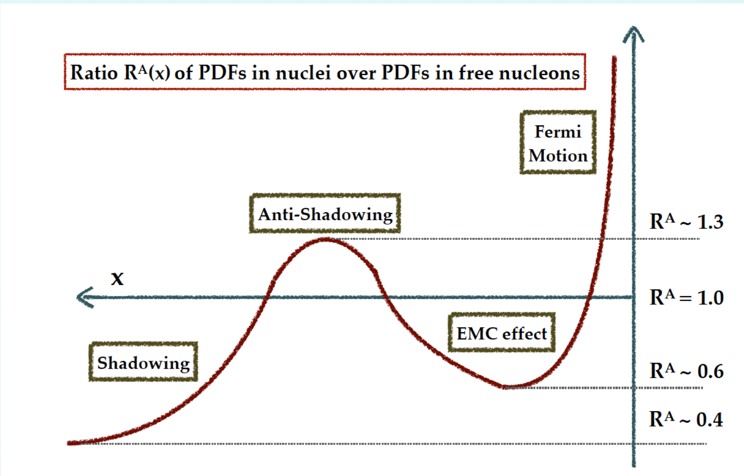






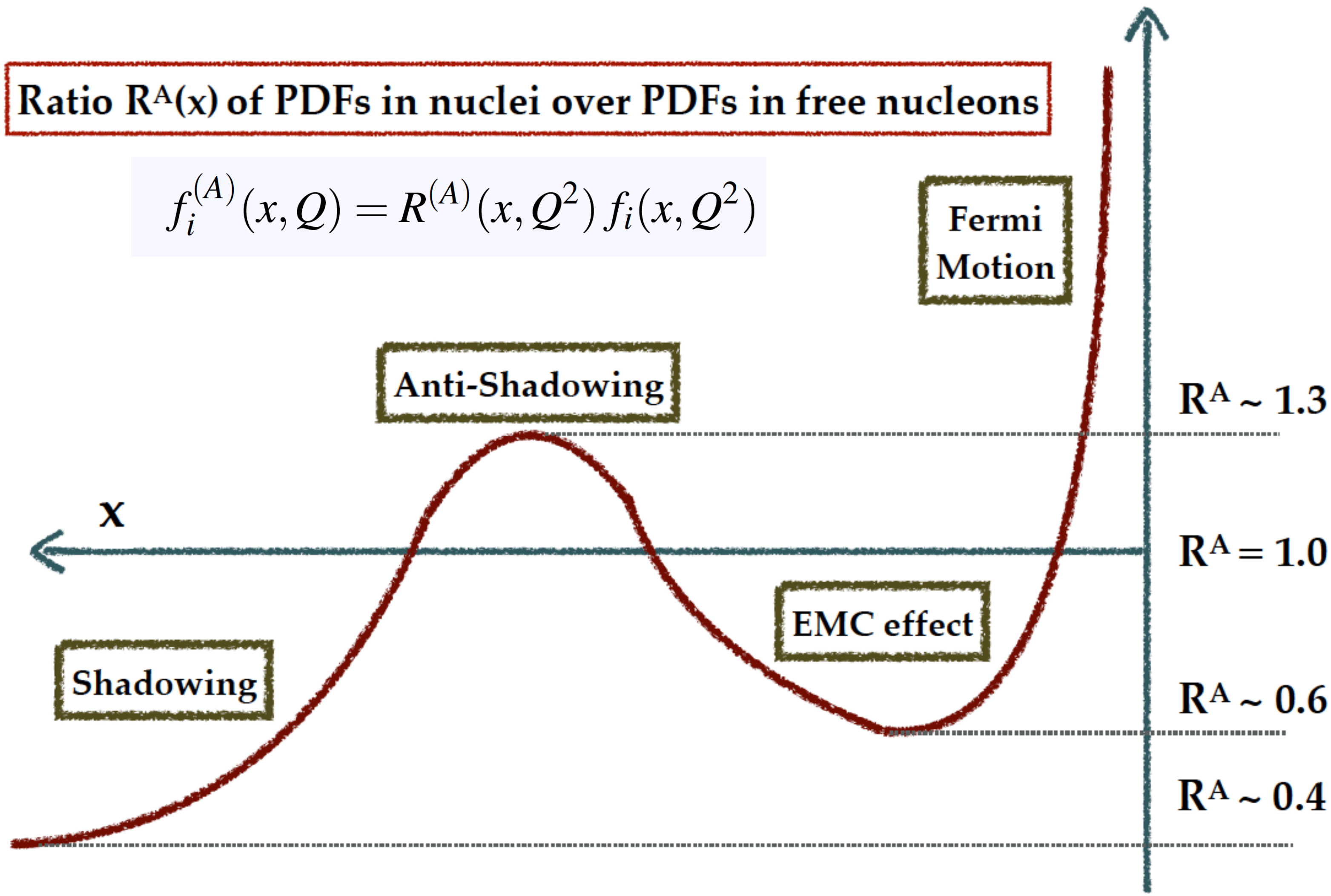


Recent progress in nuclear PDFs



Why nuclear PDFs?

Quark and gluons **inside bound nucleons** exhibit different behaviour than free-nucleon PDFs



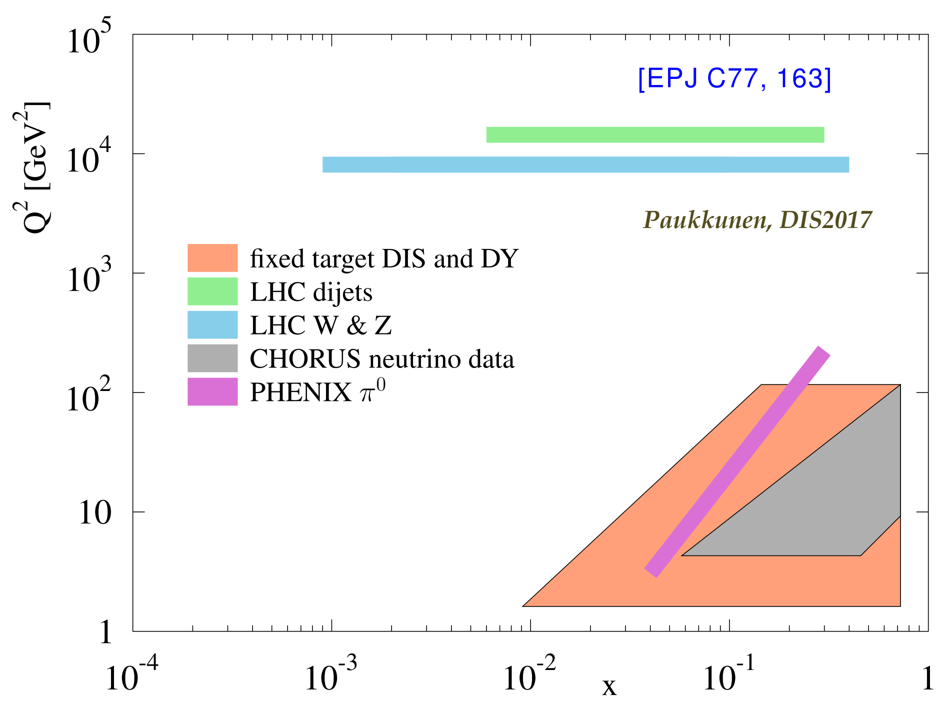
So far constraints available mostly from fixed-target DIS, but **now LHC is the game-changer!**

Why nuclear PDFs?

- A robust understanding of **cold nuclear matter effects** are of paramount importance as baseline for the **interpretation of heavy-ion collisions**
- Deviations from **linear DGLAP evolution** (*i.e.* saturation) should be enhanced in nuclei
- The **QCD factorisation theorem** in collisions involving **heavy ions** has been validated only in a restricted kinematical range

Experiment	Process	Observables	Motivation
ALICE	Heavy quark production	$p_T^D, p_T^{D\to e}$	large-x gluon
ALICE	Charged jets	$p_T^{\text{ch-jet}}$	medium and large-x gluon
ALICE	Charged hadron production	p_T^h	medium and large-x gluon
ALICE	Dijet correlations	$k_{Ty} = p_{T\,\text{jet}} \sin(\Delta\phi_{\text{dijet}})$	medium and large-x gluon
ALICE	Inclusive W production	$y_{W\to l}$	quark flavor separation large-x quarks
ATLAS	Inclusive charged particles	p_T	large-x gluon
ATLAS	Inclusive W production	$y_{W\to l}$	quark flavor separation medium-x quarks
ATLAS	Inclusive Z production	y_Z and p_T^Z	quark flavor separation medium-x quarks
CMS	Heavy quark jets	$p_T^{\text{b-jet}}$	medium-x gluon in-medium fragmentation
CMS	B meson production	p_T^B	medium-x gluon in-medium fragmentation
CMS	Dijet production	η^{dijet} and E_T^{dijet}	medium and large-x gluon
CMS	Inclusive W,Z production	$y_{W\to l}$ y_Z and p_T^Z	quark flavour separation medium-x quarks
LHCb	D meson production	p_T^{D}	small-x gluon
LHCb	Inclusive Z production	$\sigma(Z\to l^+l^-)$	quark flavor separation small-x quarks

*The availability of LHC p+Pb data makes possible realising **global nuclear PDF fits!***



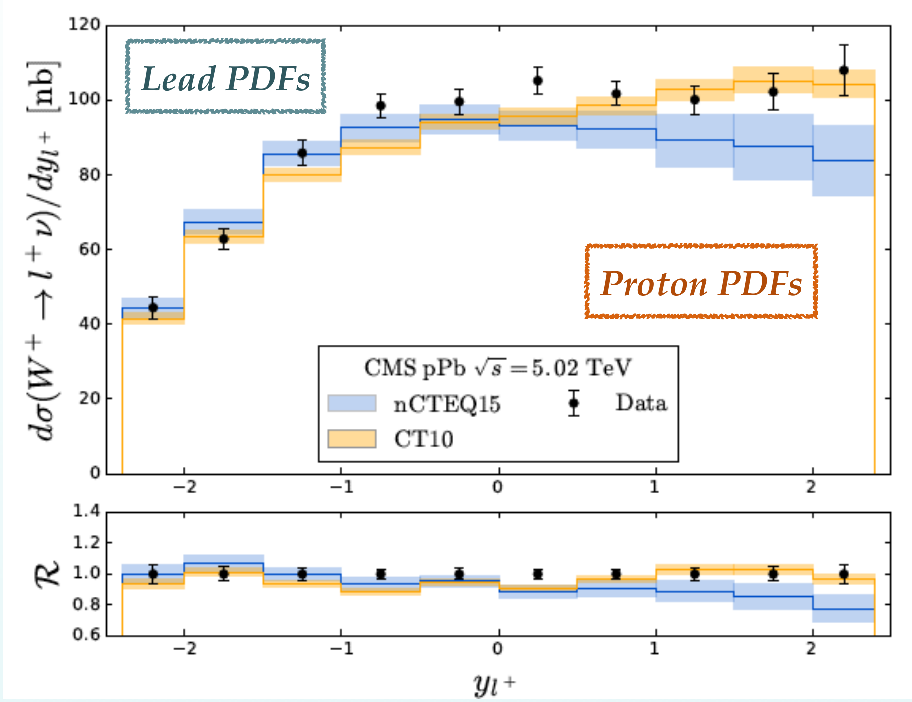
The nuclear PDF landscape

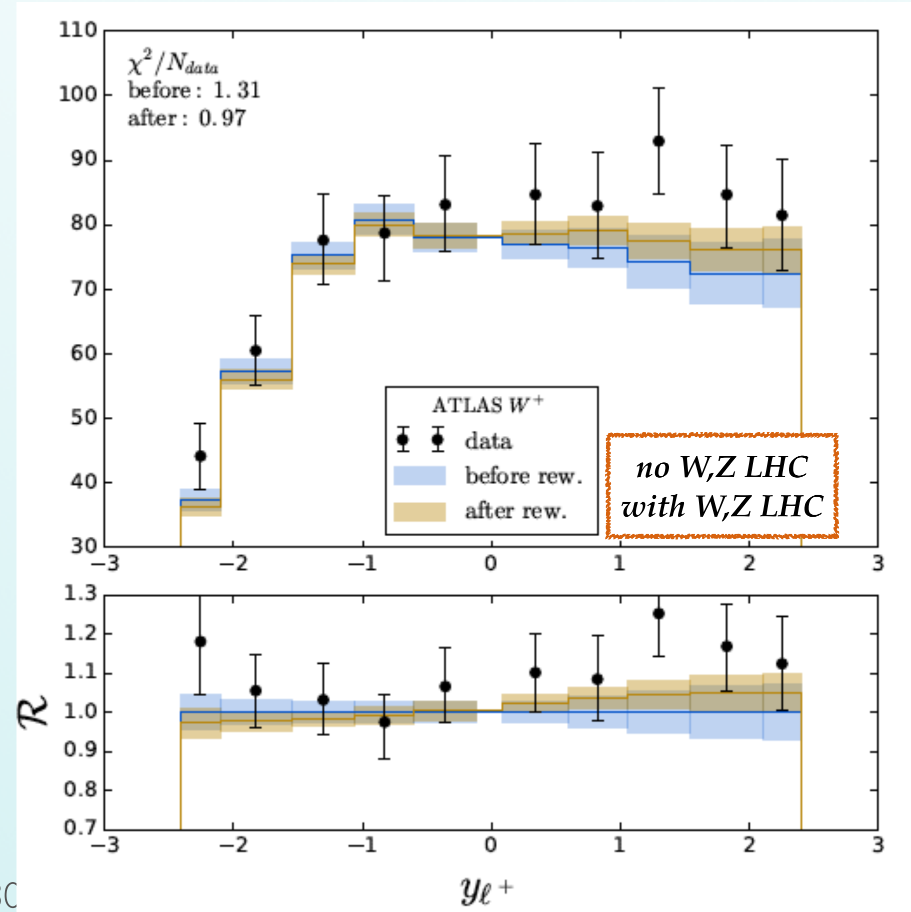
	EPS09	NCTEQ15	EPPS16
Order in α_s	NLO	NLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓	✓
Neutrino-nucleus DIS			✓
LHC p+Pb jet data			✓
LHC p+Pb W, Z data			✓
Drell-Yan dilepton $\pi+A$			✓
Q^2 cut in DIS	$1.3\,\mathrm{GeV}$	$2\,\mathrm{GeV}$	$1.3\,\mathrm{GeV}$
datapoints	929	708	1811
free parameters	15	17	20
error analysis	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	35	52
Free proton baseline PDFs	CTEQ6.1	CTEQ6M-LIKE	CT14NLO
Heavy quark treatment	ZM-VFNS	GM-VFNS	GM-VFNS
Flavour separation	none	some	✓
Weight data in χ^2	yes	no	no
Reference	[JHEP 0904 065]	[PR D93 085037]	[EPJ C77, 163]

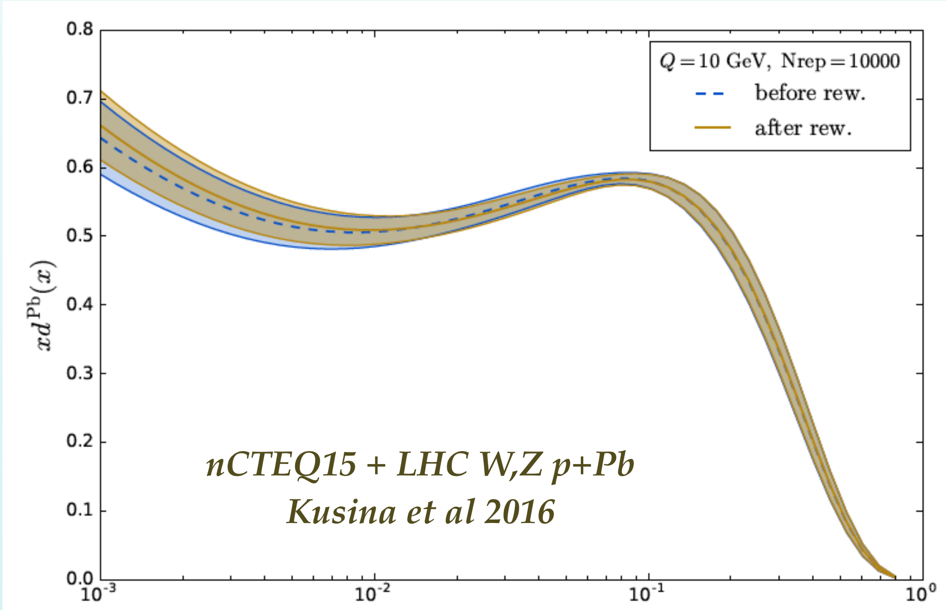
Paukkunen, DIS2017

Quark nuclear PDFs from W,Z in p+Pb

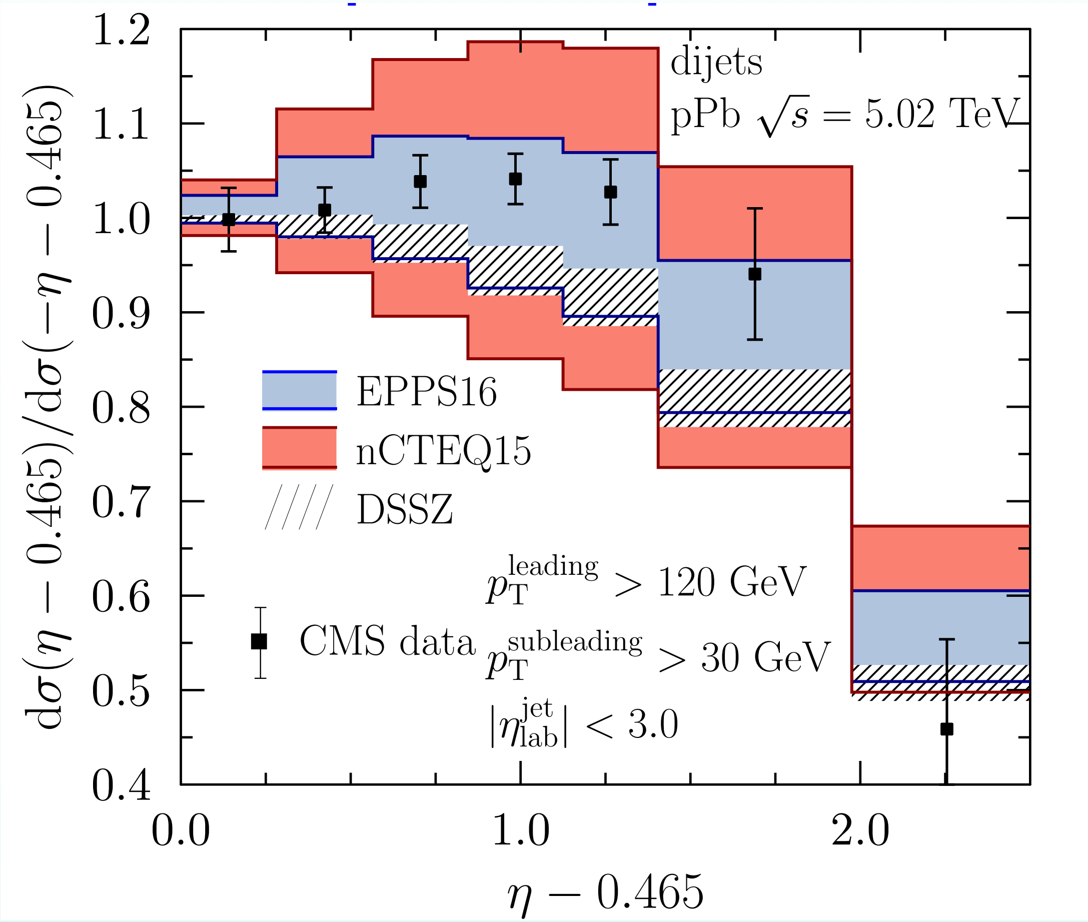
- *W* and *Z* production in p+Pb collisions at the LHC allow **disentangling quark and antiquark nuclear PDFs**
- Adding LHC data into nuclear PDF fits **improves its description**, but constraints on nPDFs still moderate
- Looking forward to the 8 TeV p+Pb data!





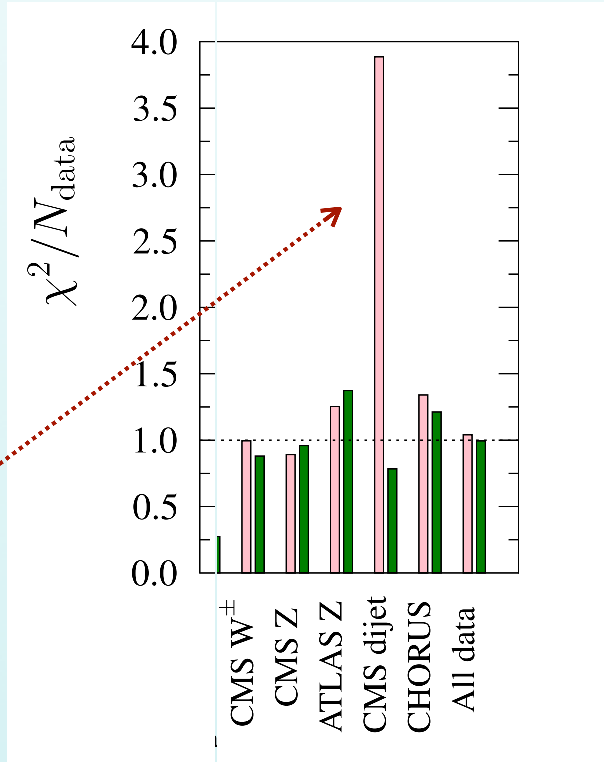


Gluon nuclear PDF from dijets in p+Pb



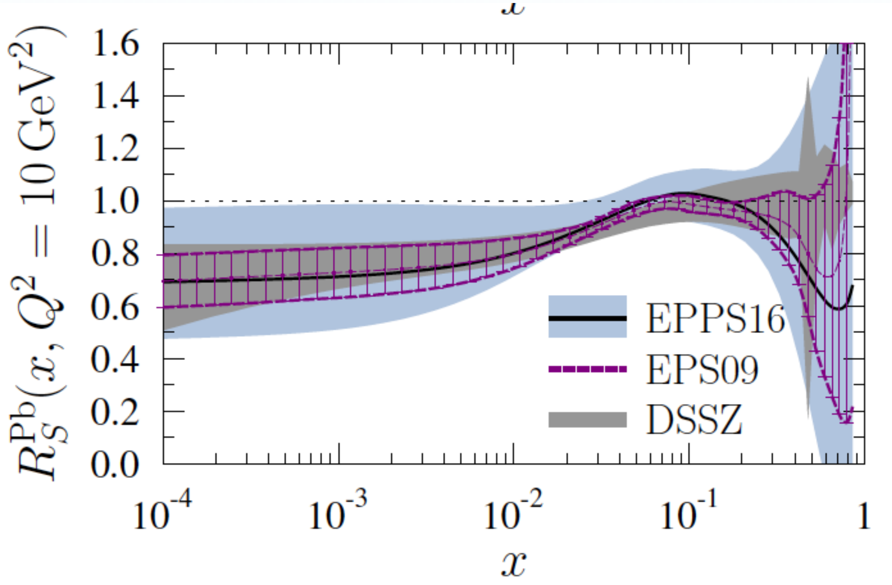
- **Dijet production** in p+Pb provides information on **poorly known gluon PDF**
- Available CMS data already allows to **discriminate between nPDF sets**
- In the EPPS16 analysis this data is central to establish the **gluon EMC effects**

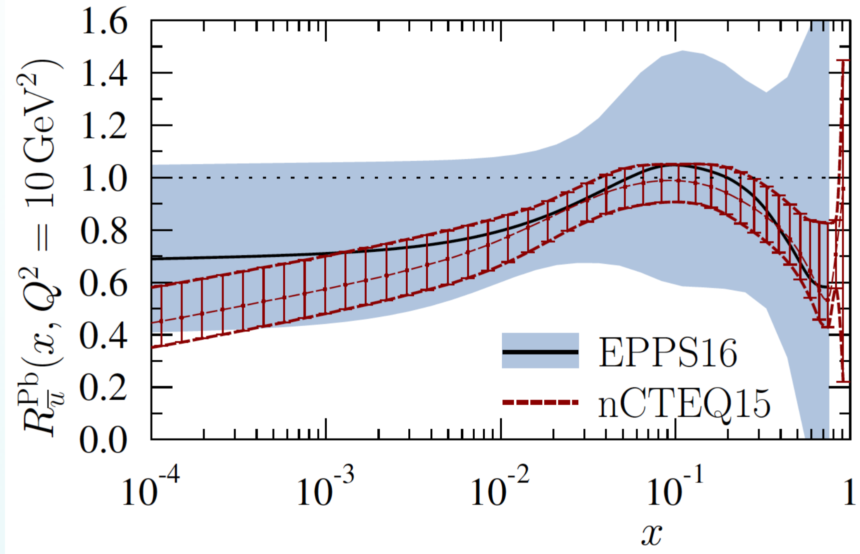
*The **description of the CMS dijet** data improves sizeably once it is included in the global nPDF fit*

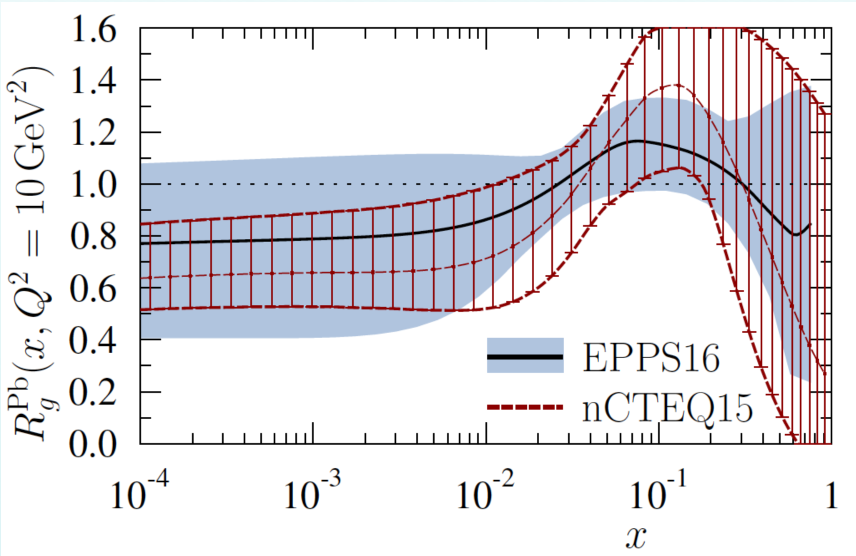


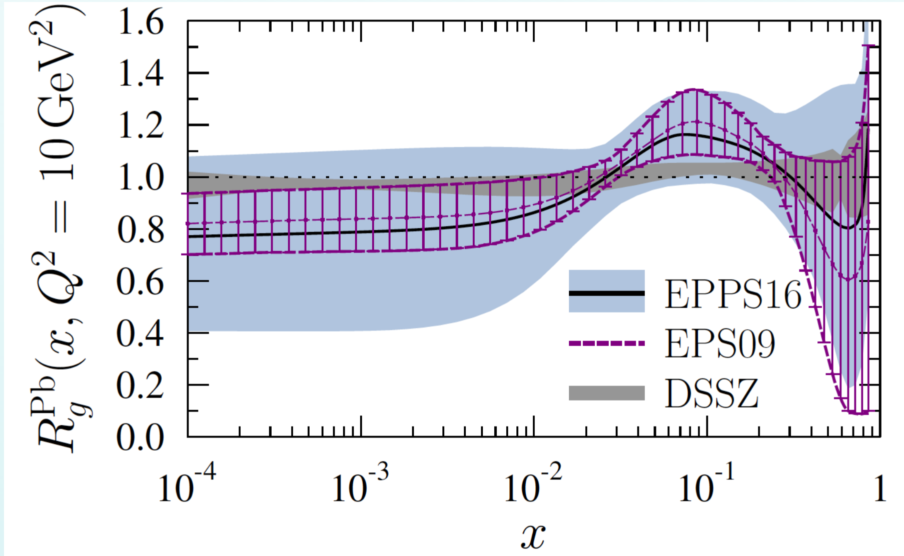
Eskola et al 2016

nPDFs: the big picture









- Despite being based on the widest dataset, EPPS16 **exhibits largest uncertainties,** showcasing that **methodological uncertainties** are still a dominant component of nPDFs fits
- **nPDF fits getting closer to proton global fits, but need more LHC p+Pb data**

Summary and outlook

- Recent developments in our understanding of the **quark/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 ….

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

  - ☑ **Methodology**: fitted charm PDF, combination/reduction methods for different PDFs,…

- Improvements for **many Run II analysis**: Higgs couplings, MW measurements, heavy BSM particle production ….

- The availability of **LHC data on hard probes in p+Pb collision** is a game-changer for nuclear PDF fits: getting closer to global proton PDF fits. Now looking forward to the p+Pb data from Run II.

Summary and outlook

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- Th… …C **data on hard probes in p+Pb collision** is a game-changer for nucle… …ts: getting closer to global proton PDF fits. Now looking forward to the p+Pb data from Run II.

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

Thanks for your attention!