NNLO PDF fits with jet data

Juan Rojo
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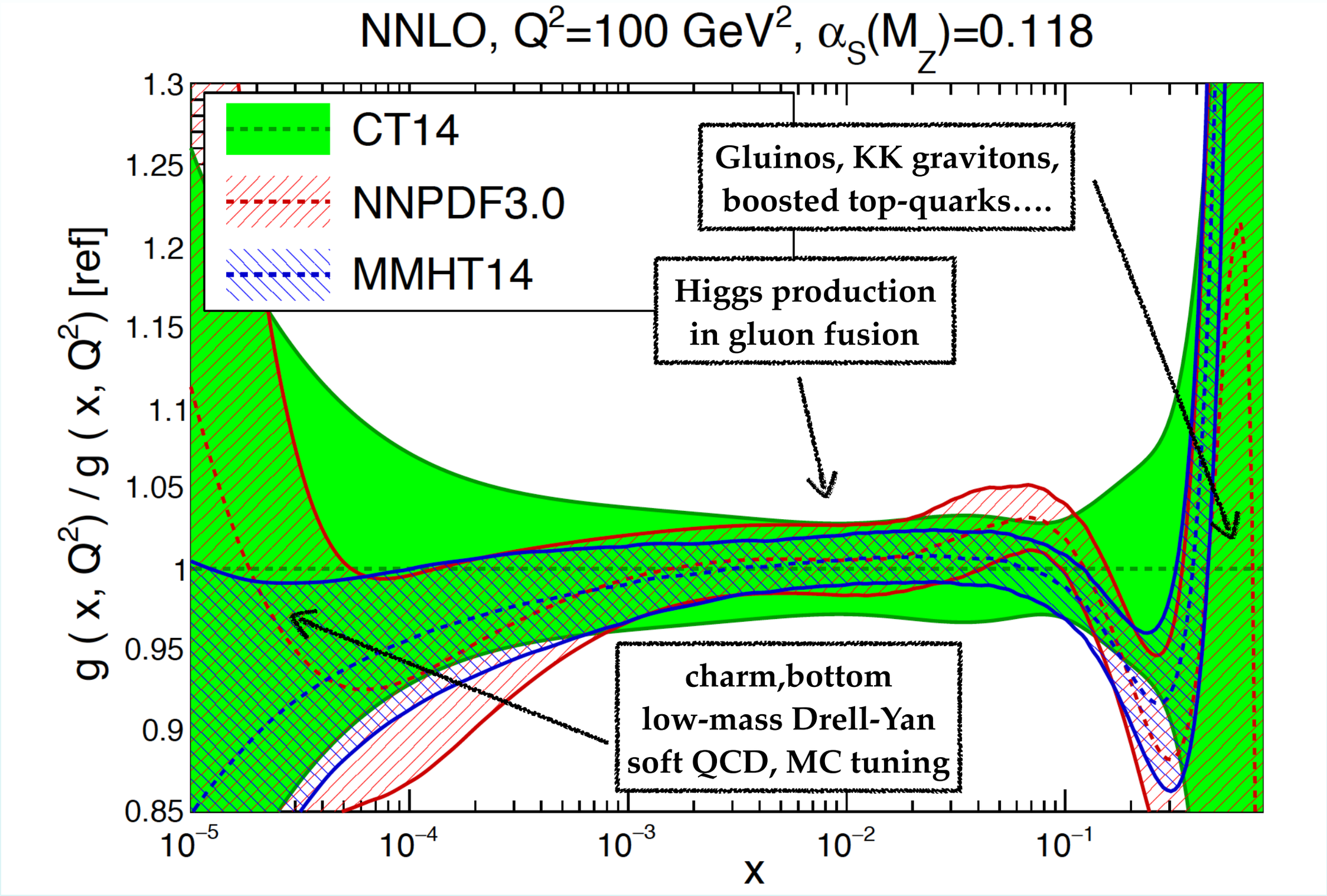
CMS SMP-Jets annual workshop
CERN, 23/01/2018

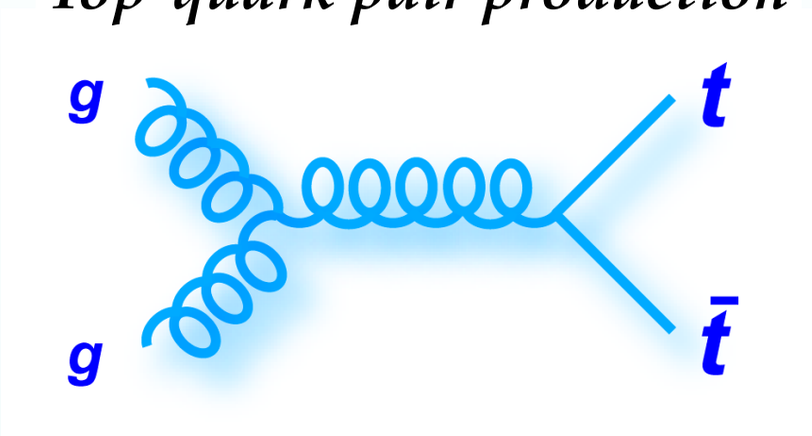
One glue to bind them all



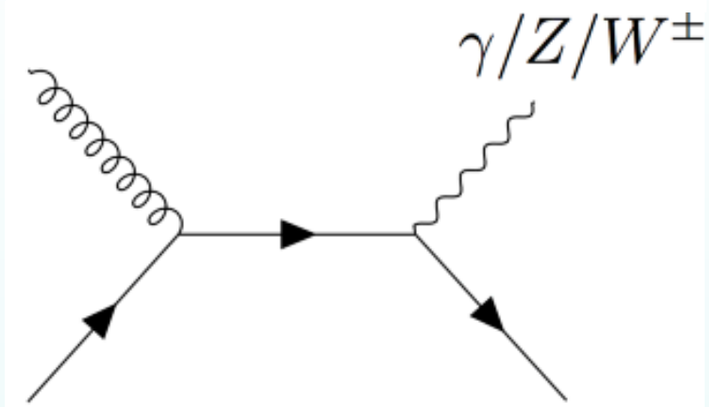
At the LHC, precise knowledge of the gluon is required **from small-x to large-x**

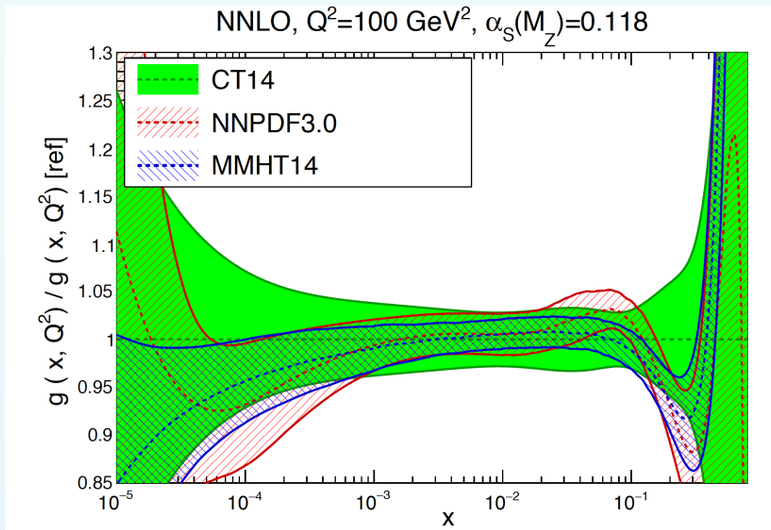
One glue to bind them all

Top-quark pair production

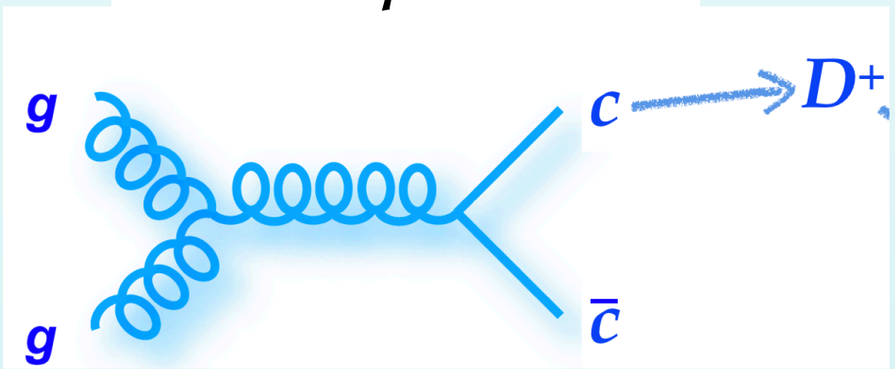


Z transverse momentum

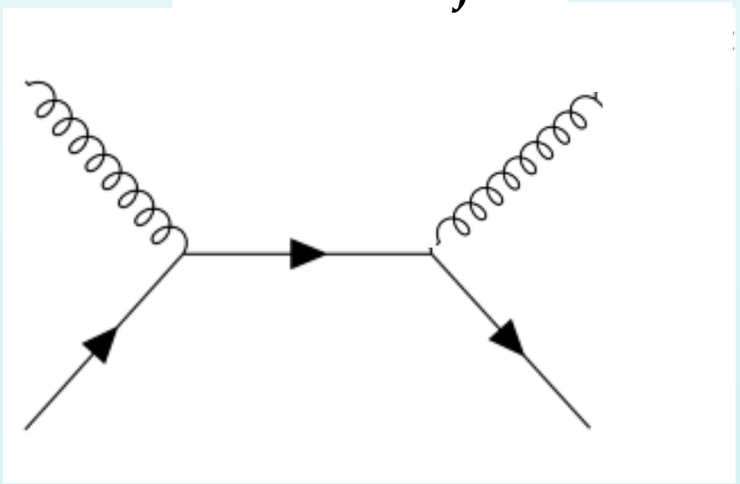




D meson production



Inclusive jets



One glue to bind them all

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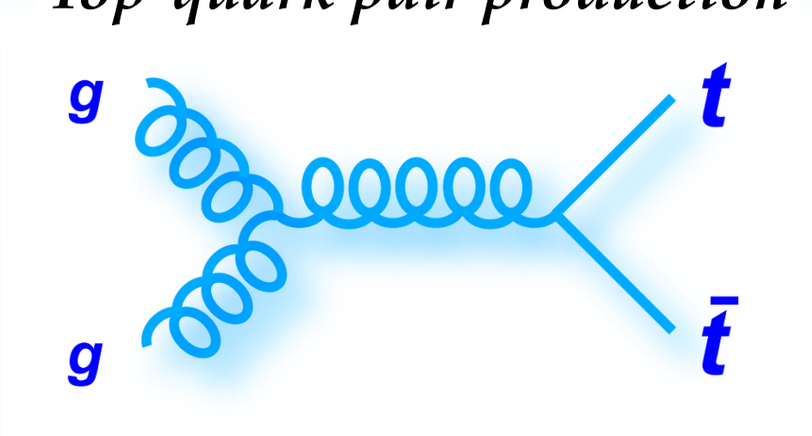

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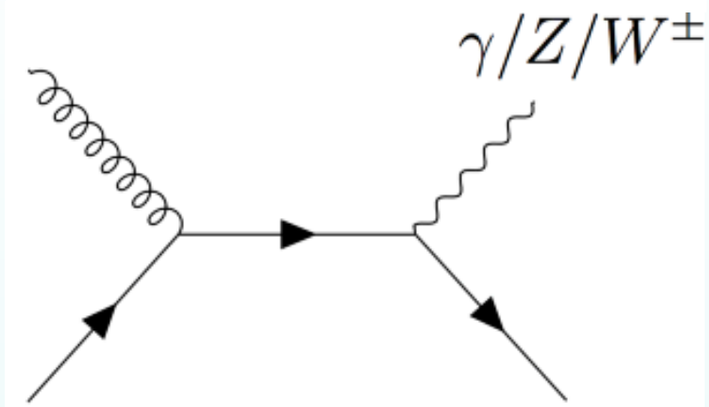

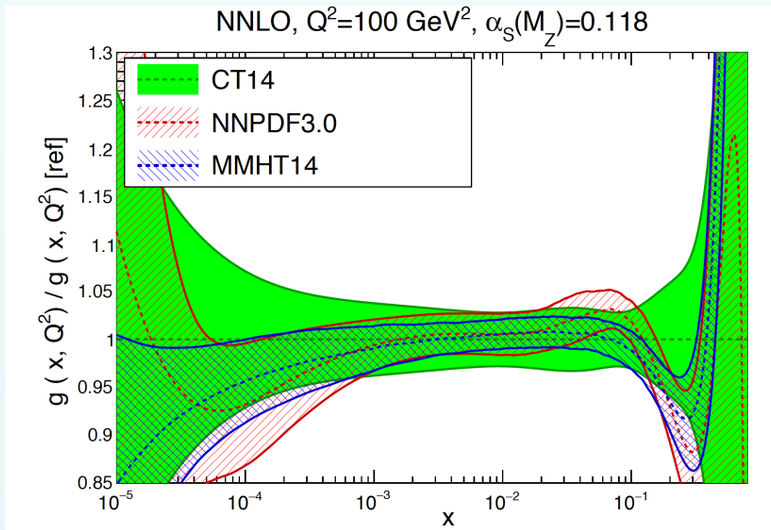

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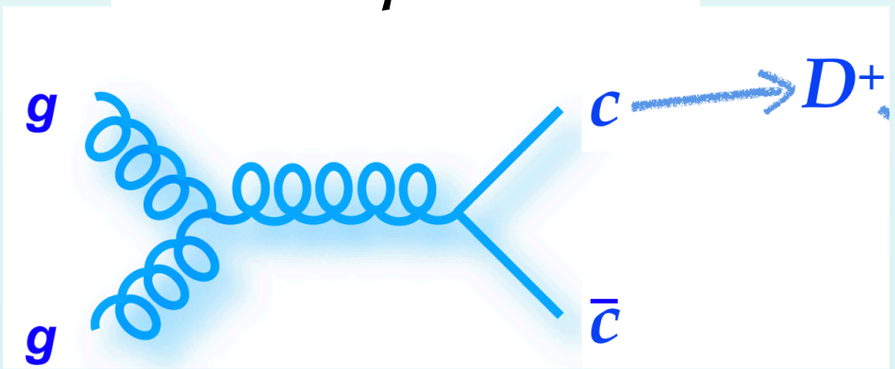

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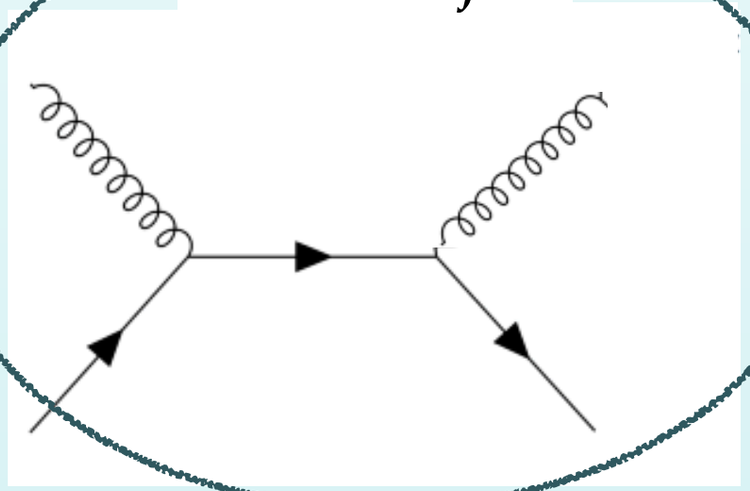
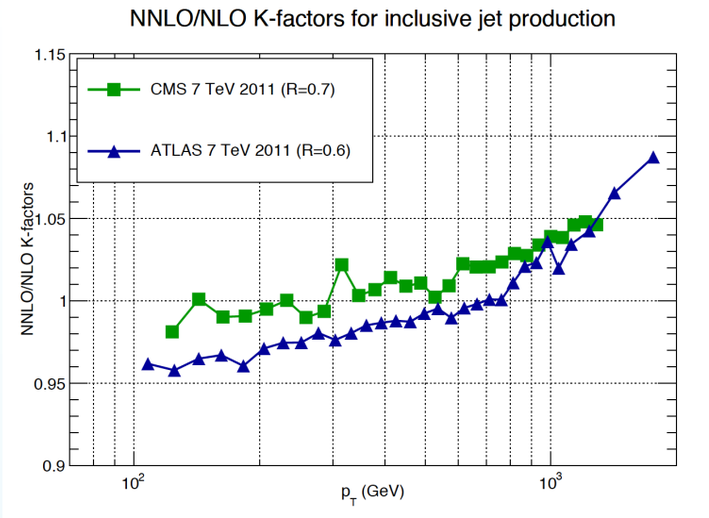
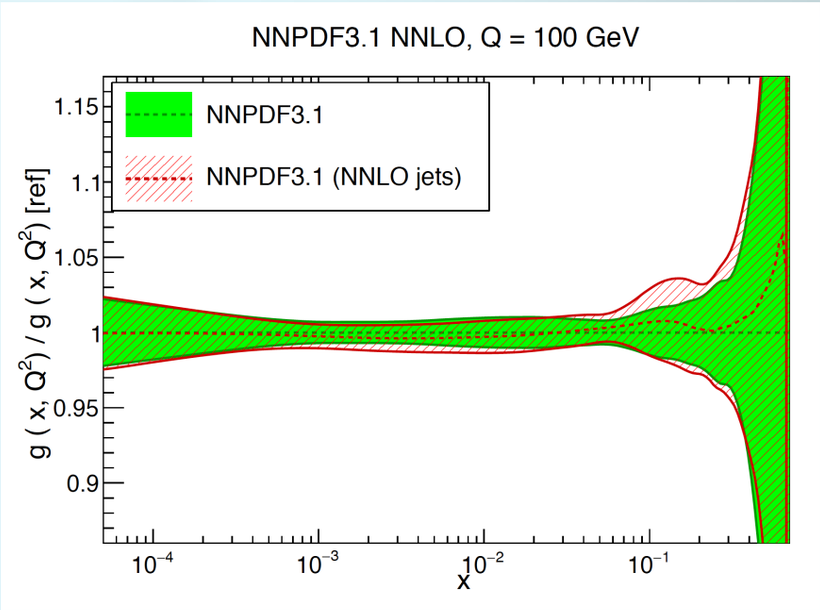


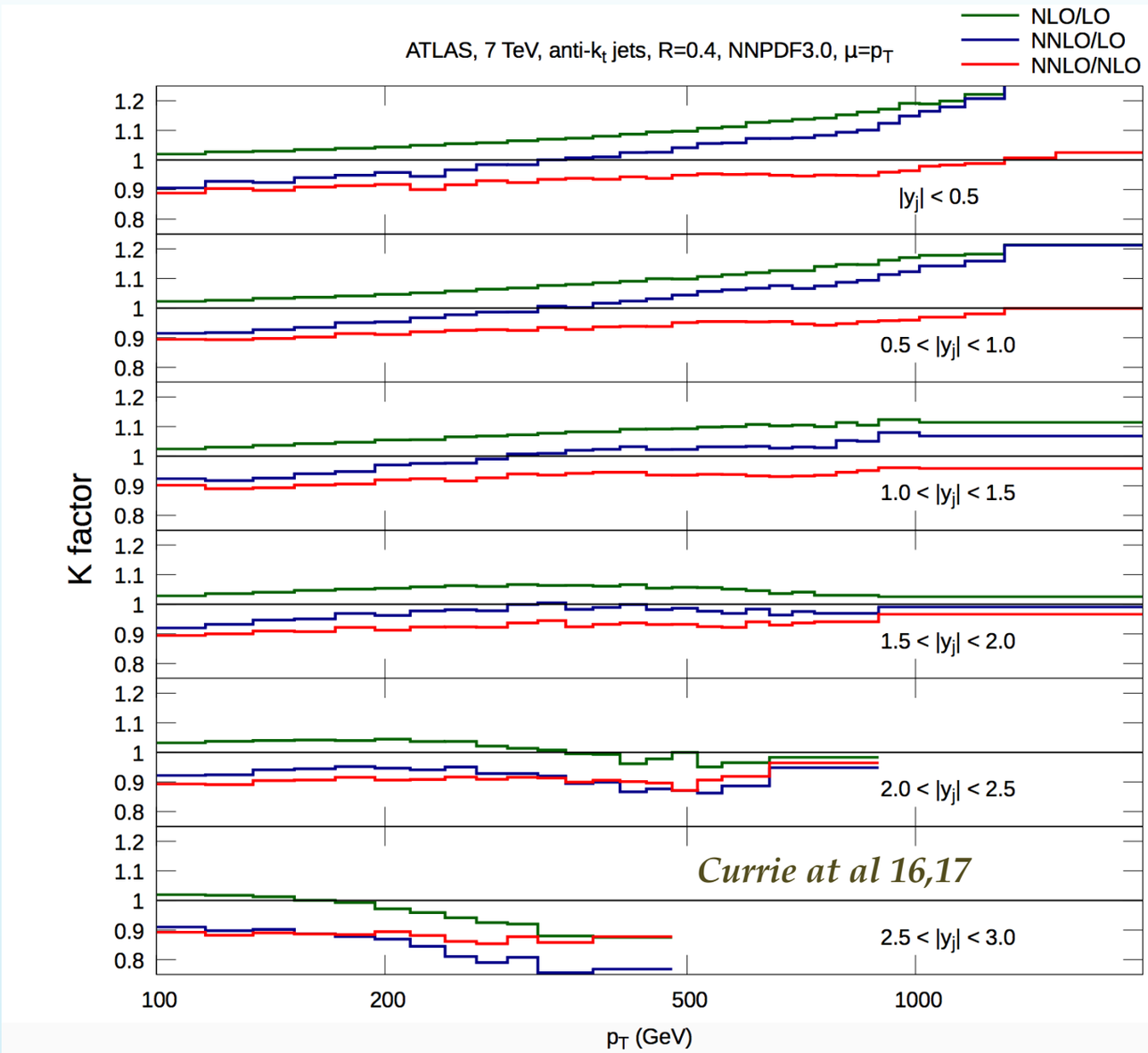


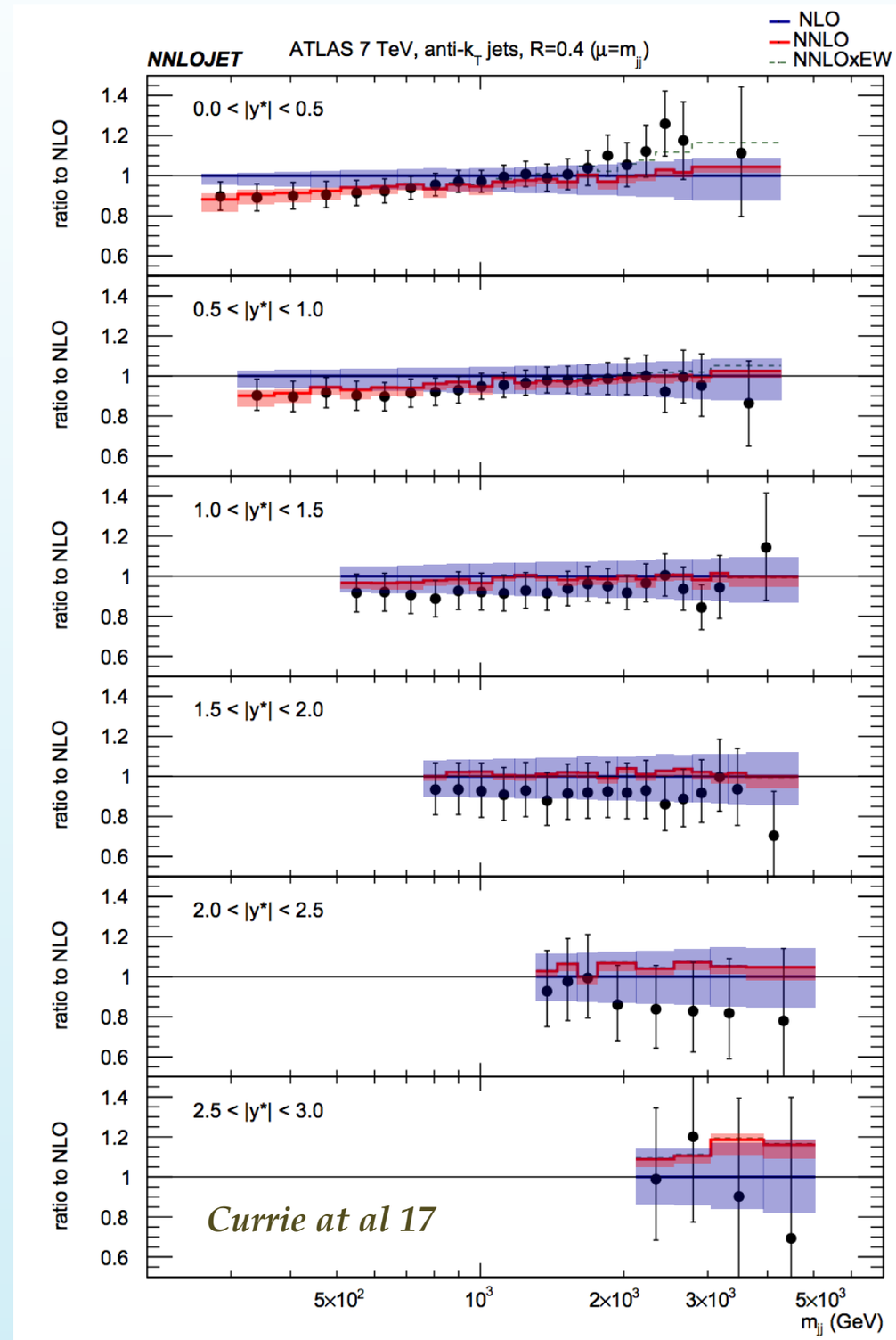
The gluon PDF from NNLO jets



Jet production at NNLO

Both **inclusive jet** and **dijet production** have now been computed at **NNLO**





*NNLO corrections **improve agreement** with ATLAS/CMS measurements*

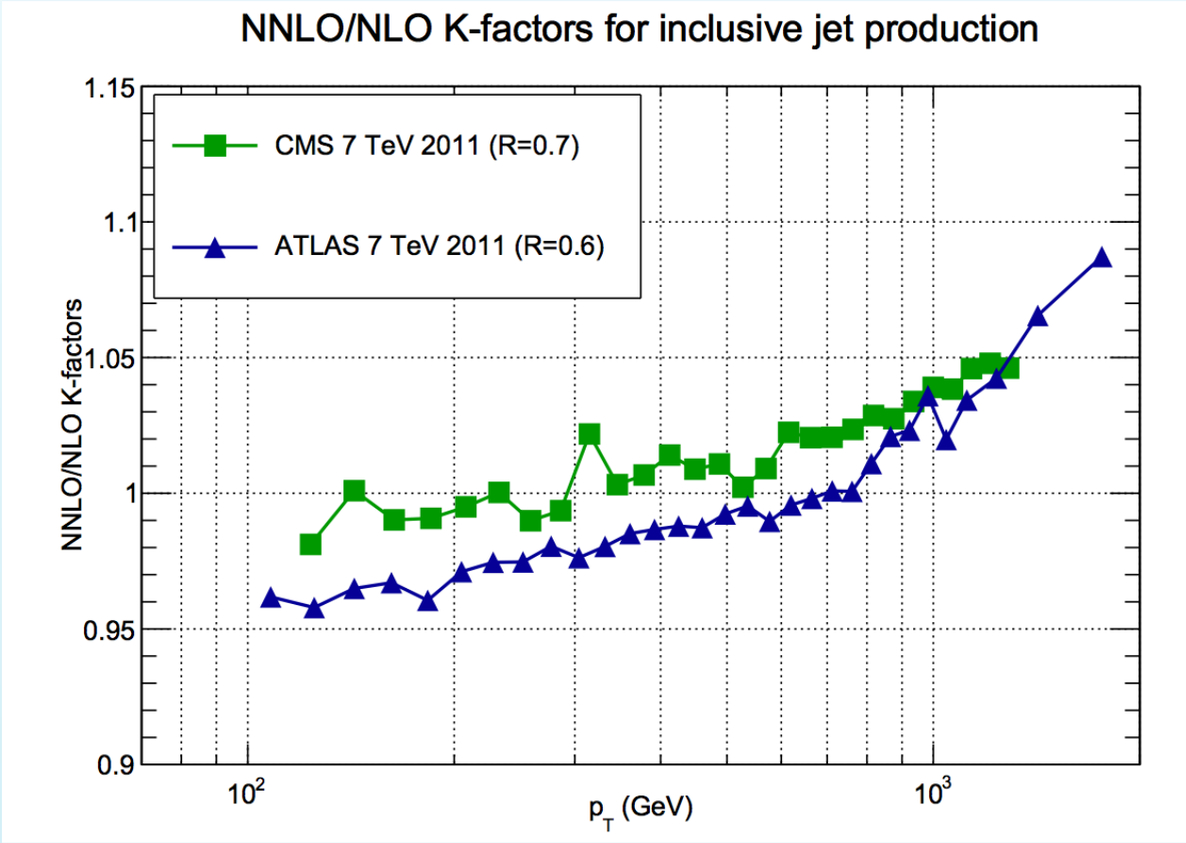
The large-x gluon from NNLO jets

- In the NNPDF3.1NNLO global analysis, inclusive jet production is treated using **NLO matrix elements** and **NNLO DGLAP evolution** (since *K*-factors not available when fit was finalised)

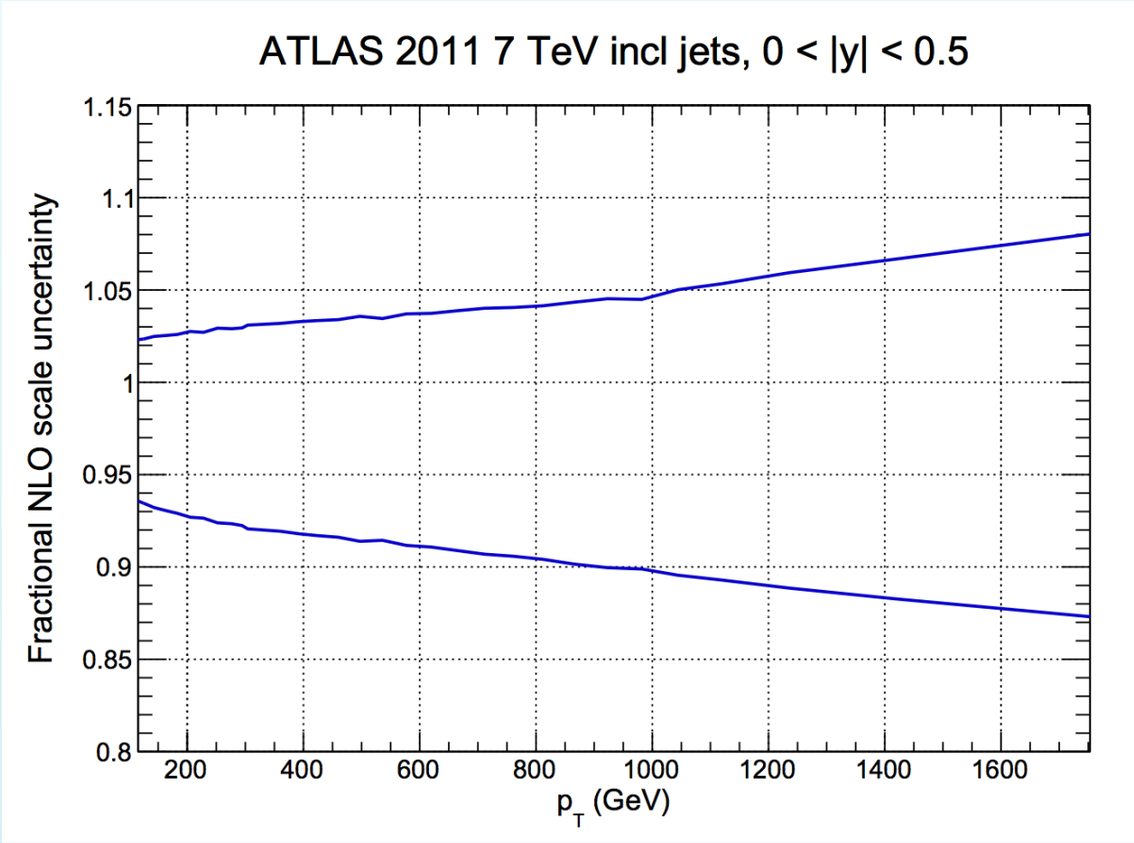
- In addition, the **NLO scale variations** were added as an additional (correlated) systematic error

- **Individual jet p_T** used for $\mu_R=\mu_F$, since it exhibits **improved perturbative convergence**

NNLO/NLO K-factors



NLO scale variations



NNPDF3.1 16

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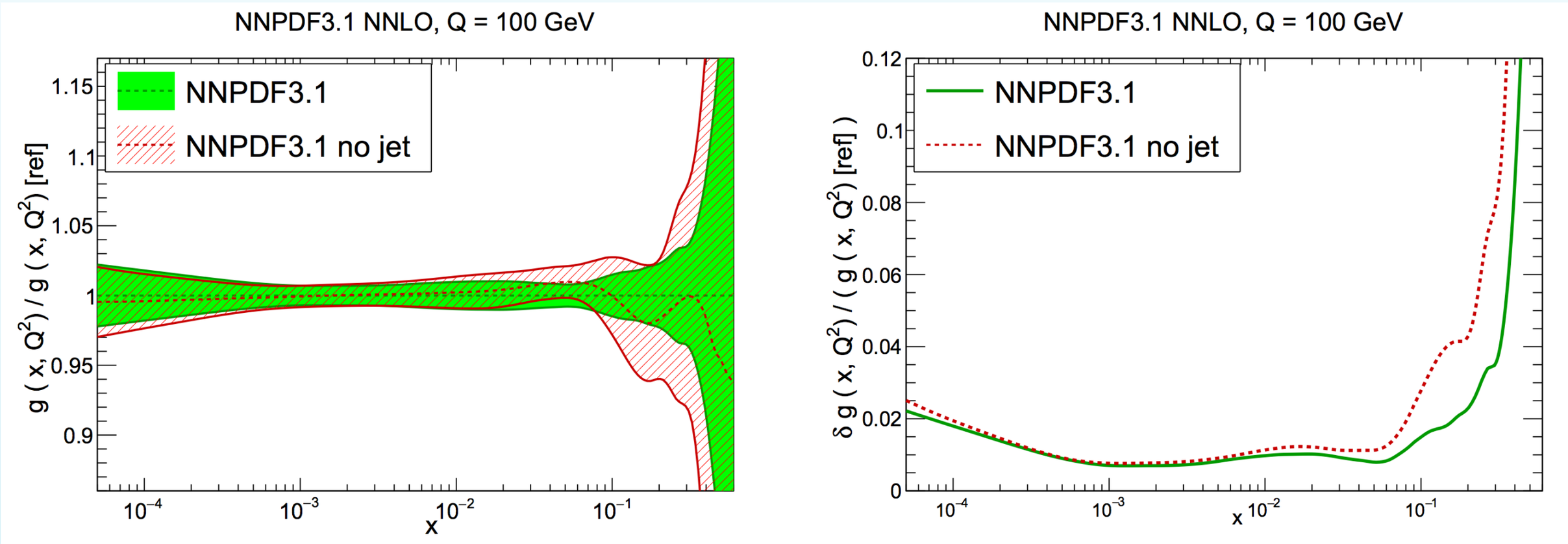


*Collider inclusive jets instrumental to **pin down the large-x gluon**….*

*though **impact less dramatic** as previously, since other processes constrain the gluon in NNPDF3.1 fit*

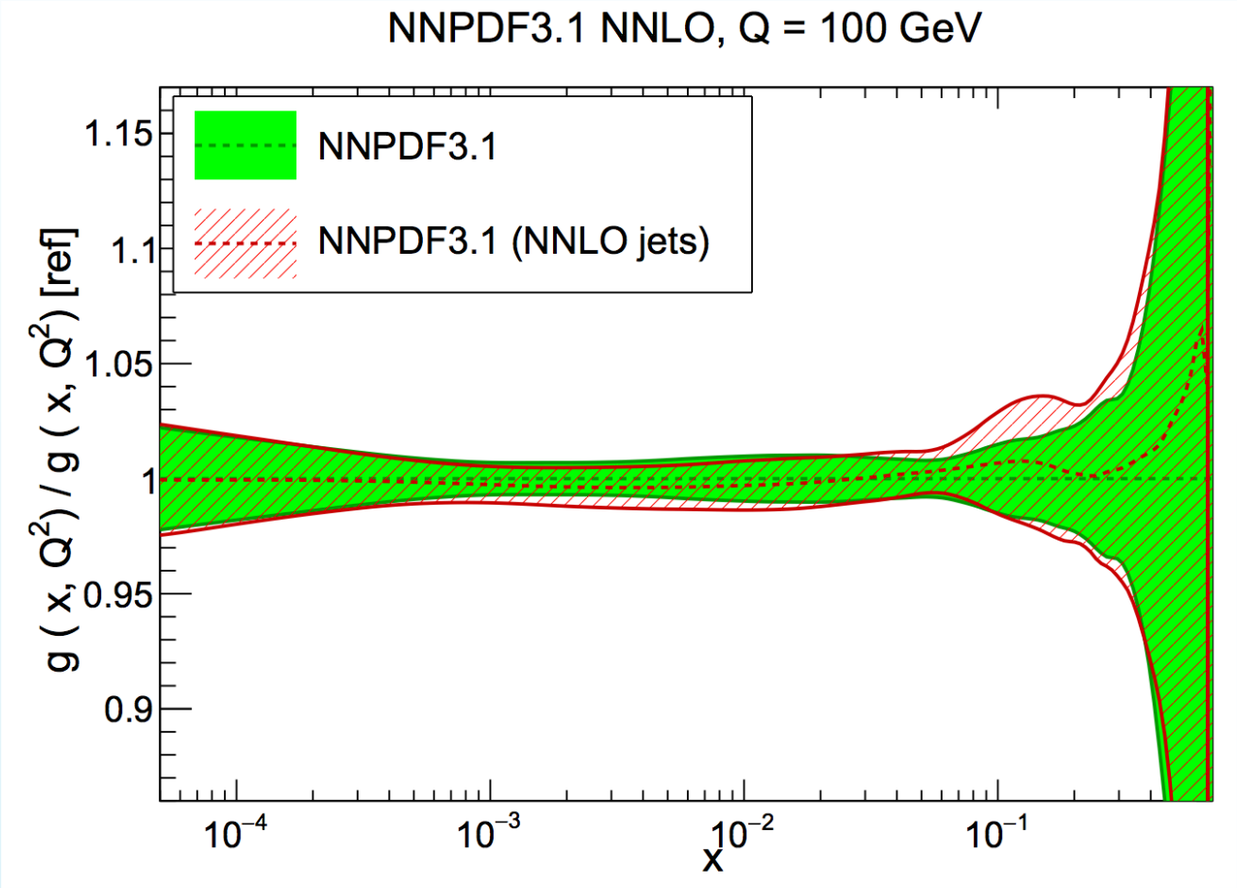
The large-x gluon from NNLO jets

- Performed variant of NNPDF3.1 where the **ATLAS and CMS jet data at 7 TeV** (2011 dataset) were included using **exact NNLO theory** (thus no extra scale errors for these experiments)

- Clear **improvement in fit quality** once exact NNLO theory used

- Central value of the gluon **reasonably stable**

- In all future NNPDF fits, all jet (and dijet) data will be treated using **exact NNLO theory**



Approximate NNLO theory →

Exact NNLO theory →

	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

NNLO jets in MMHT

- The impact of NNLO corrections to jet data within a global analysis has also been studied recently by **MMHT**
- As in NNPDF, they include the **ATLAS and CMS 7 TeV from 2011** using exact NNLO theory
- Studied impact of choices of **central scale** as well as of the **jet radius *R***

	$R_{\rm low},\ p_\perp^{\rm jet}$	$R_{\rm low},\ p_\perp^{\rm max}$	$R_{\rm high},\ p_\perp^{\rm jet}$	$R_{\rm high},\ p_\perp^{\rm max}$
ATLAS (NLO)	213.8	190.5	171.5	161.2
ATLAS (NNLO)	172.3	199.3	149.8	152.5
CMS (NLO)	190.3	185.3	195.6	193.3
CMS (NNLO)	177.8	187.0	182.3	185.4

Table 3: The χ^2 for the combined fit to the ATLAS ($N_{\rm pts} = 140$) and CMS ($N_{\rm pts} = 158$) 7 TeV jet data. The values for the ATLAS and CMS contributions are given, for different choices of jet radius and scale, at NLO and NNLO.

*Clear **improvement due to NNLO** corrections in most cases,*

*except for $\mathbf{R_{low}}$ **and** $\mathbf{p^T_{max}}$, where the fit quality is slightly degraded*

MMHT 16

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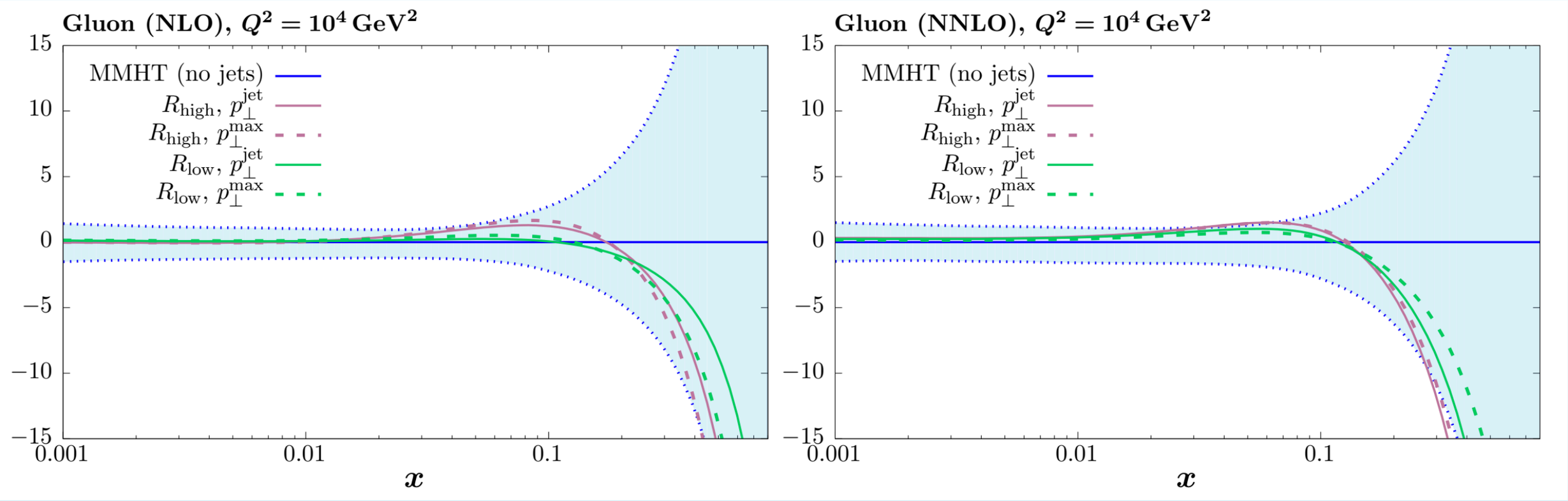

*Stable impact on the large-x gluon for the **different choices of R and central scale***

*Also, the impact of the jet data on the gluon is qualitatively similar at **NNLO and at NLO***

Impact of experimental correlation model

- Using NNLO theory, excellent results for the χ^2/N_{dat} obtained in **separate rapidity bins** for the ATLAS 2011 7 TeV jets, but much worse values obtained once **cross-correlations** are accounted for
- Same trend observed in the ATLAS 8 and 13 TeV measurements
- MMHT try different **alternative correlation models**, including a **partial and a full decorrelation** of the experimental systematic uncertainties between rapidity bins
- A variant of the partial decorrelation model partially **endorsed by ATLAS (??)**
- Why this is **not an issue for CMS**?

Partial decorrelation

Full decorrelation

	ATLAS	ATLAS, σ_{pd}	ATLAS, σ_{fd}		CMS
$R = 0.4$	350.8 (333.7)	183.1 (170.7)	128.4 (122.2)	$R = 0.5$	191.7 (163.4)
$R = 0.6$	304.0 (264.0)	178.8 (148.9)	128.9 (115.7)	$R = 0.7$	200.1 (175.2)

Table 2: The χ^2 for the ATLAS ($N_{\rm pts} = 140$) and CMS 7 TeV jet data ($N_{\rm pts} = 158$) at NNLO. The quality of the description using the baseline set is shown, while the result of re–fitting to the single jet data set is given in brackets. Results with the different treatments of the ATLAS systematic uncertainties, described in the text, are also shown.

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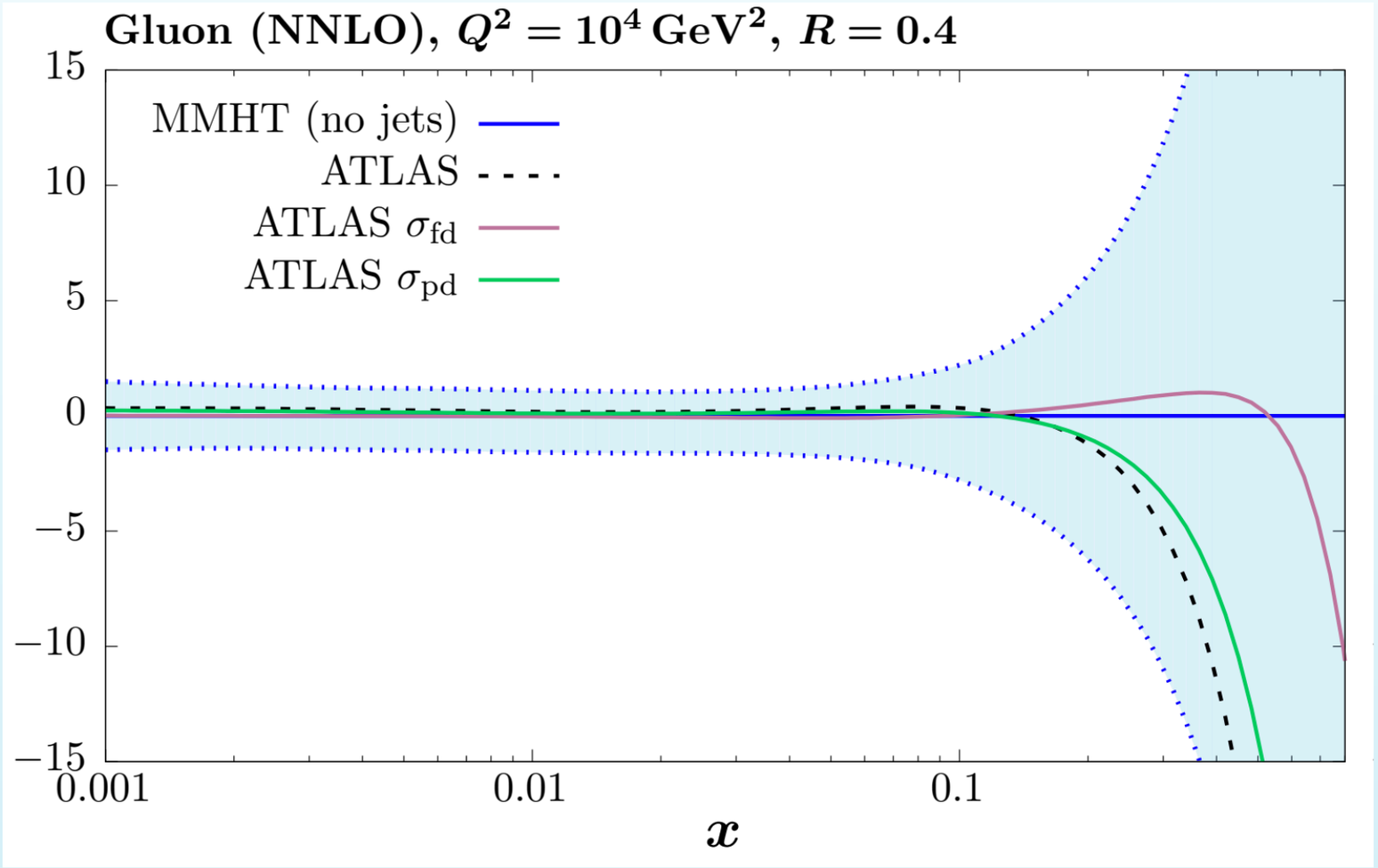


Partial decorrelation *leads to* ***very similar results*** *as using the exact ATLAS correlation model*

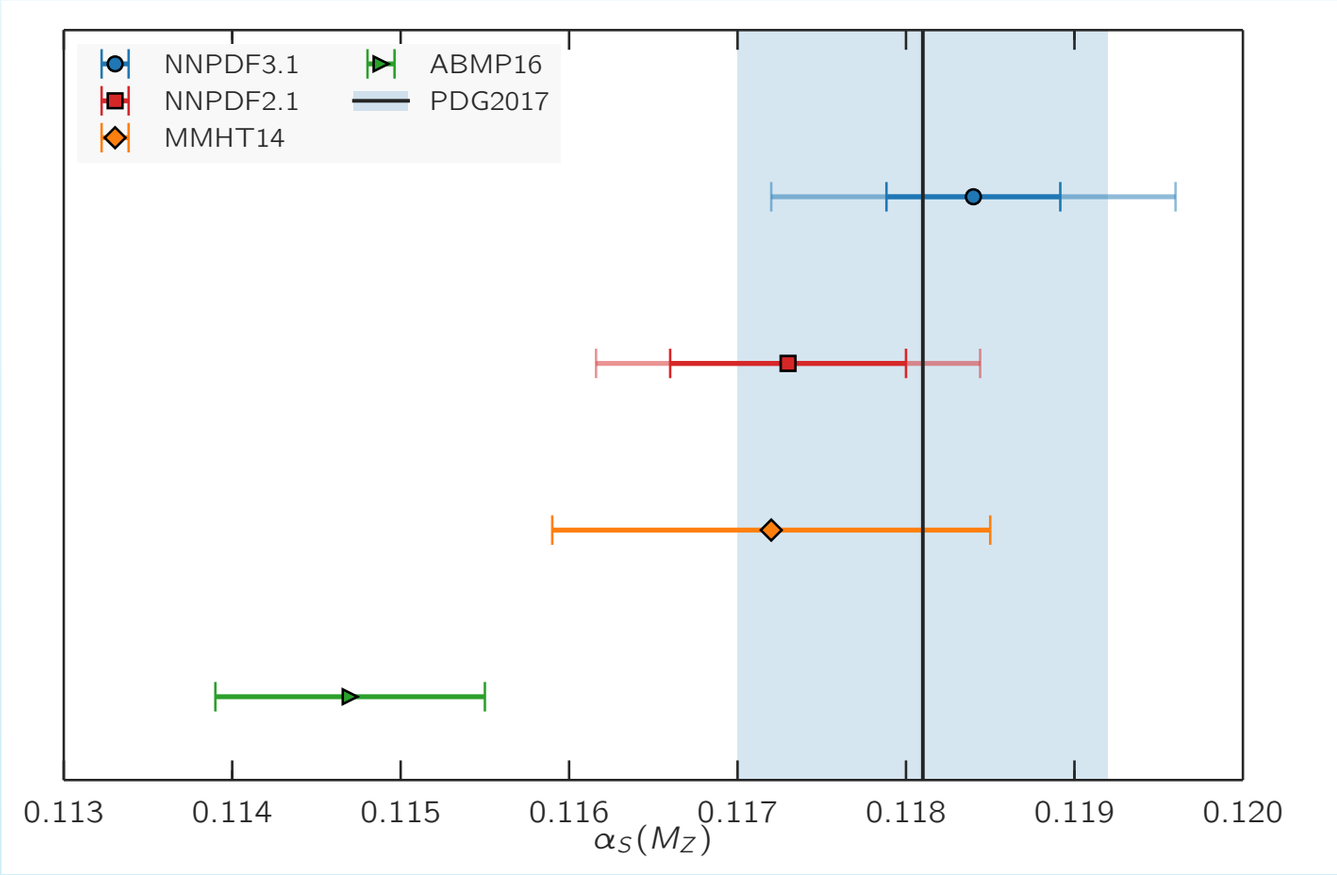
NNLO jets and the strong coupling

- Jet, dijet, multijet production **sensitive to strong coupling** $\alpha_S(m_Z)$ and its running with the scale $\alpha_S(Q)$
- Several recent determinations of from LHC data: **competitive experimental errors**, but limited by large theory uncertainties from **NLO scale variations**
- Extractions using **NNLO theory** will lead to greatly **reduced total uncertainties** on $\alpha_S(m_Z)$
- Upcoming updated determination of $\alpha_S(m_Z)$ from NNPDF3.1NNLO, where **all collider processes are treated using exact NNLO theory**, including jet production.

$$\alpha_s^{\rm NNLO}(m_Z) = 0.1185 \pm 0.0005^{\rm exp}\ (0.4\%)$$

$$\Delta\alpha_s^{\rm pert} \equiv |\alpha_s^{\rm NNLO} - \alpha_s^{\rm NLO}| = 0.0022$$

$$\delta\alpha_s^{\rm mhou} \simeq 0.0011$$



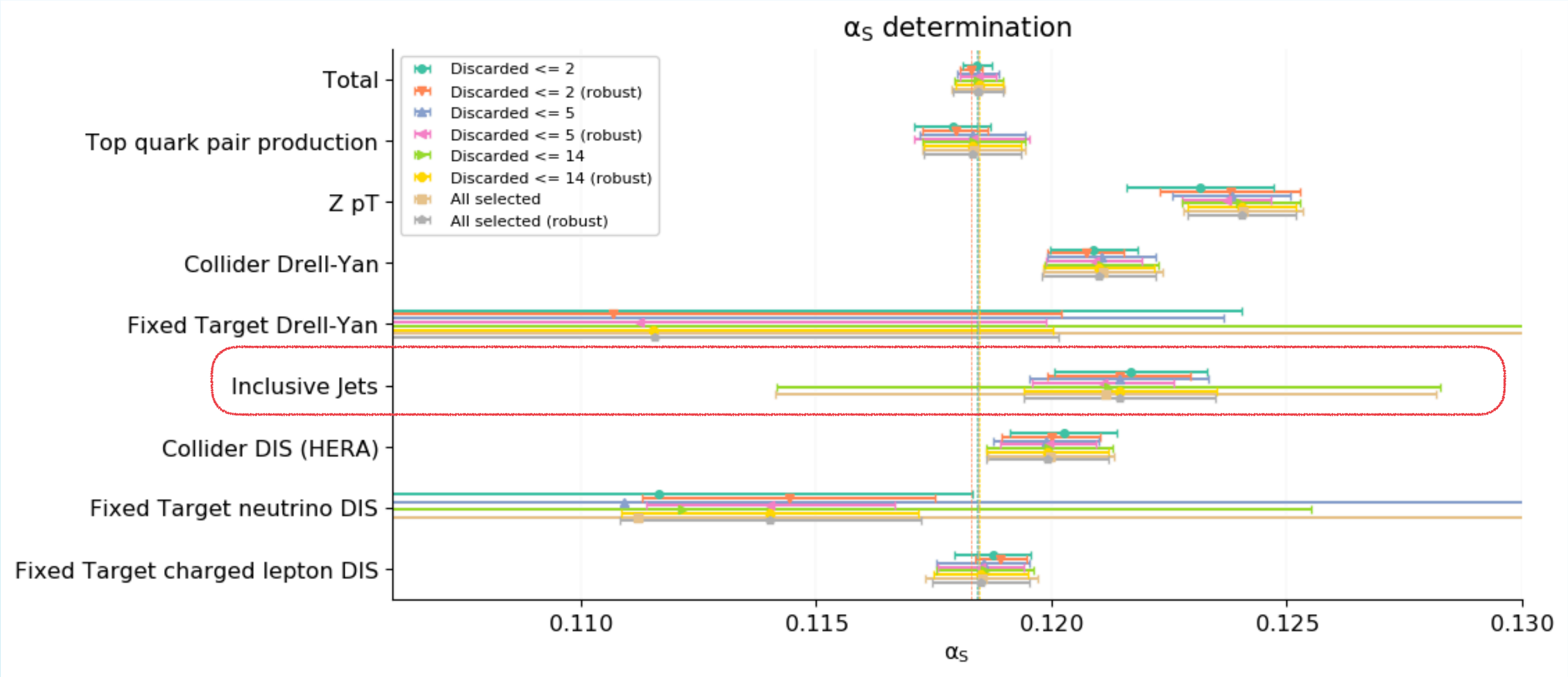
NNPDF, in preparation

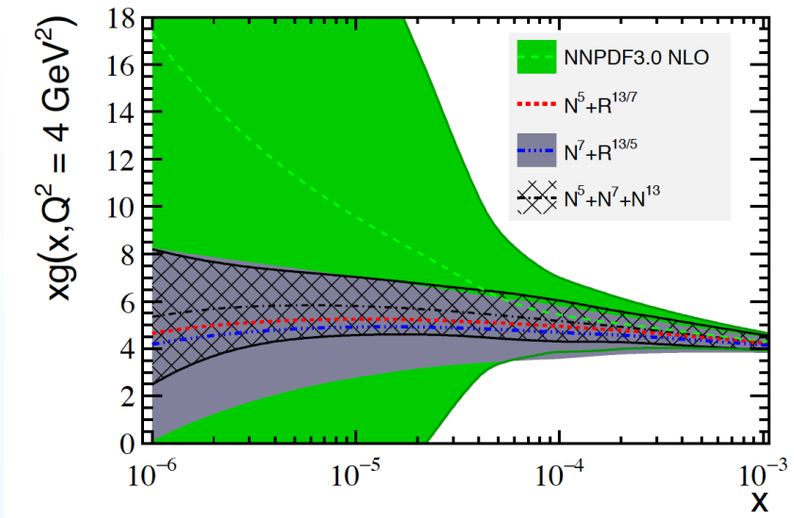
NNLO jets and the strong coupling

- The strong coupling $\alpha_S(m_Z)$ can also be determined from the **partial χ^2 within the global fit**

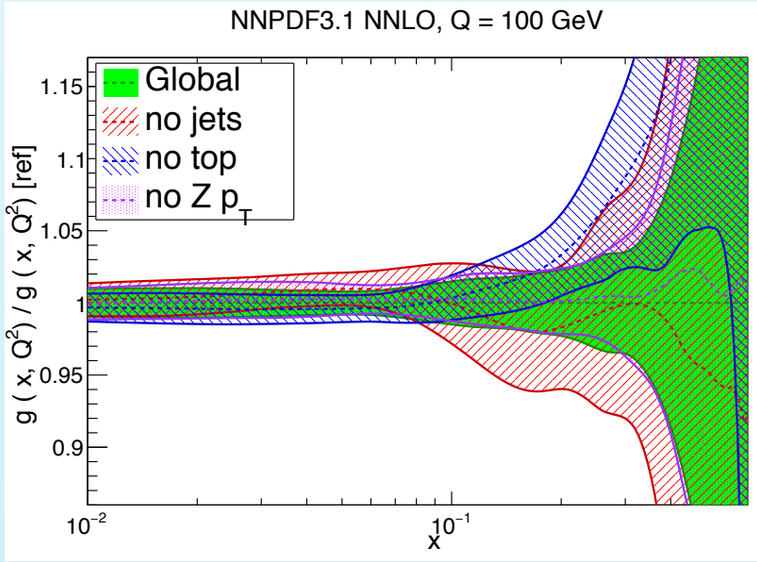
- This comparison assesses the pulls that **individual groups of experiments** have on $\alpha_S(m_Z)$, subject to the **constraints** from all other datasets in the global fit

- **Inclusive jets** have marked sensitivity to the value of $\alpha_S(m_Z)$, similarly to **Z p_T**, **top-pair**, **charged lepton DIS**

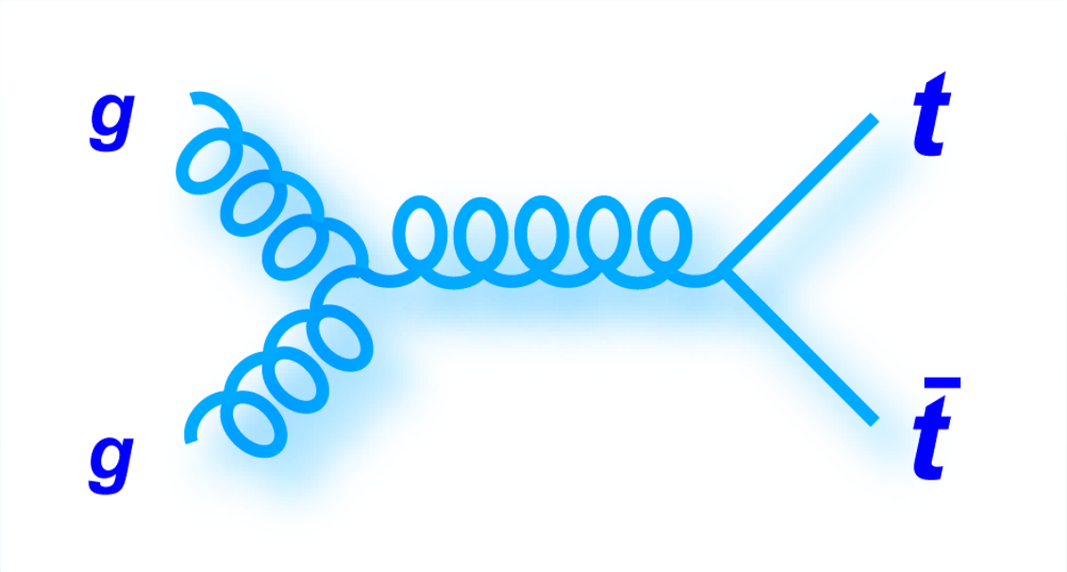


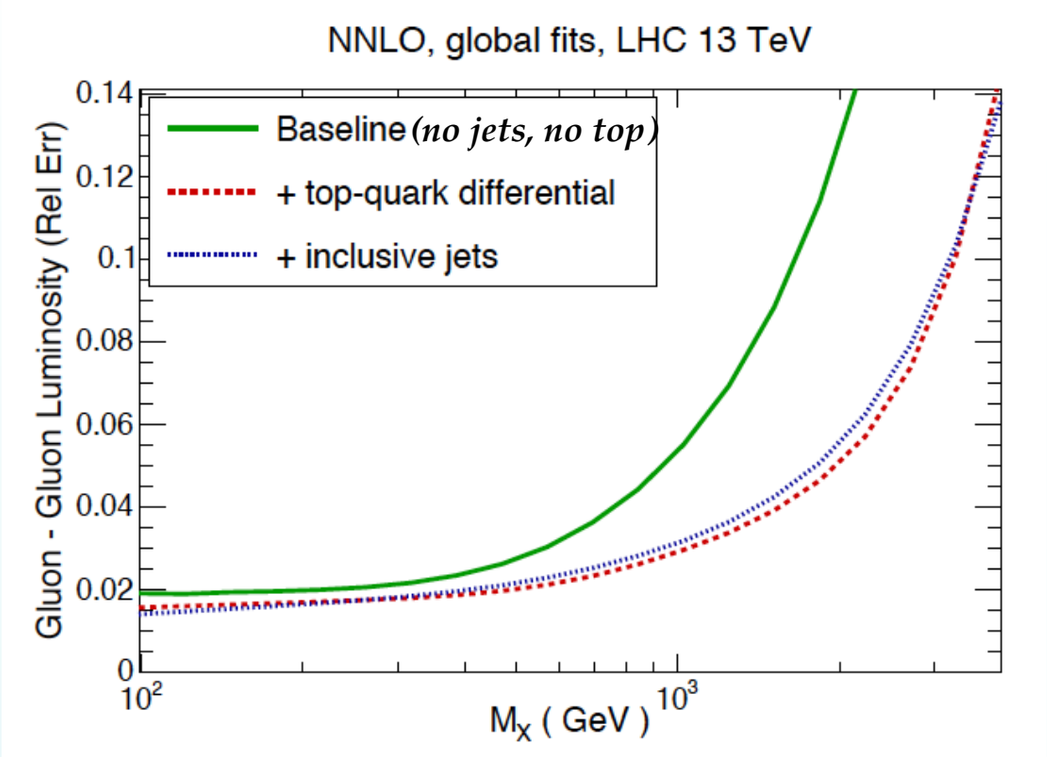


The gluon PDF from other LHC processes

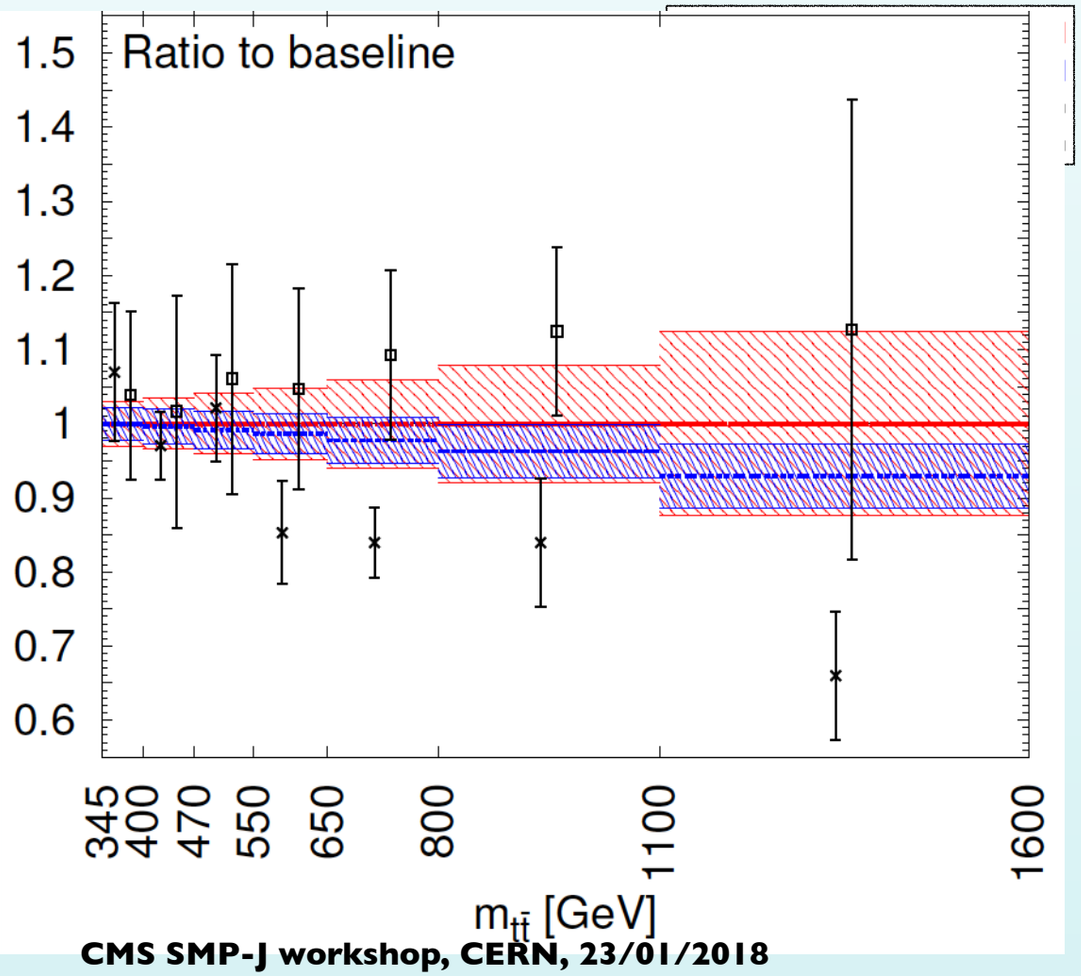


The large-x gluon from differential top quarks





- 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

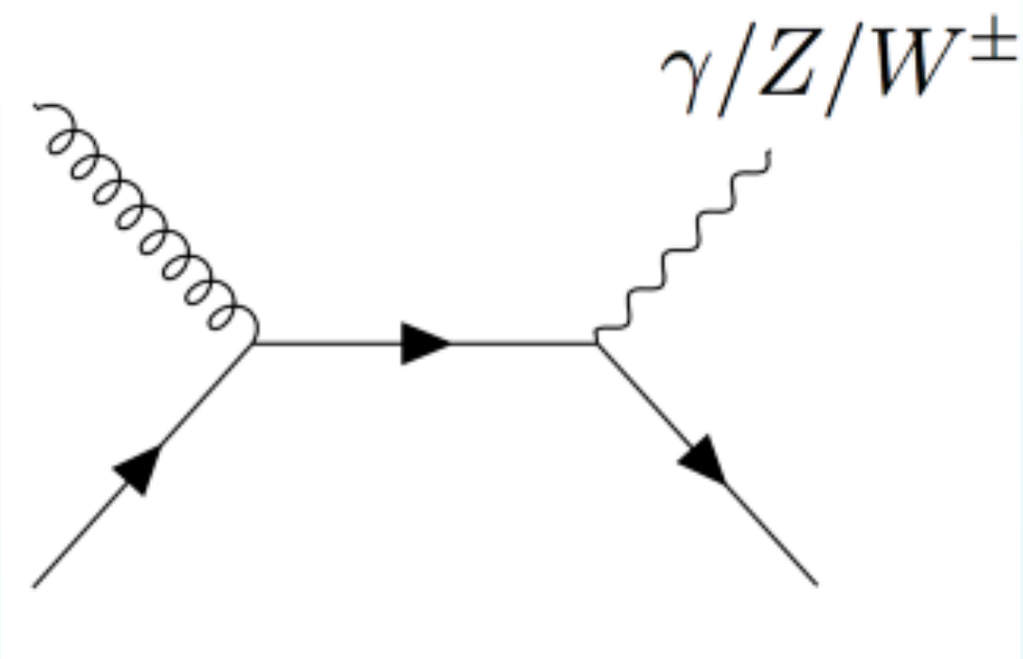
- Dominated by **quark-gluon scattering**, thus sensitive to the gluon PDF at intermediate values of x

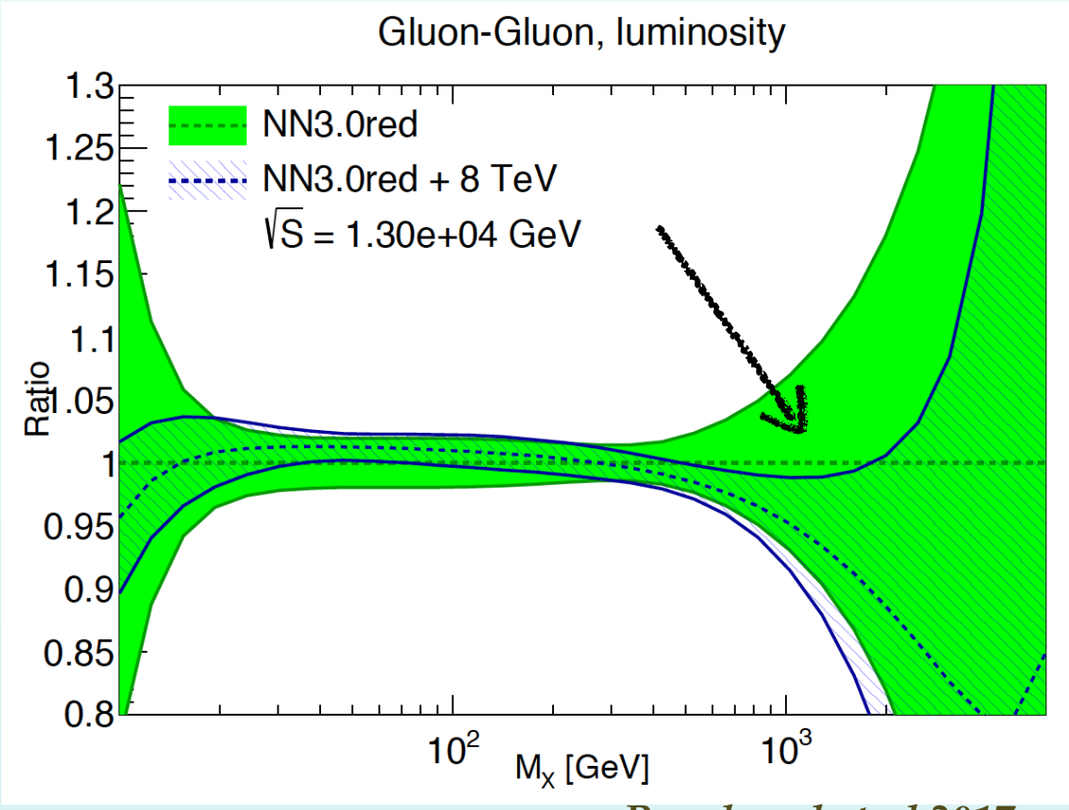
Malik and Watt 2013, Boughezal et al 2017

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

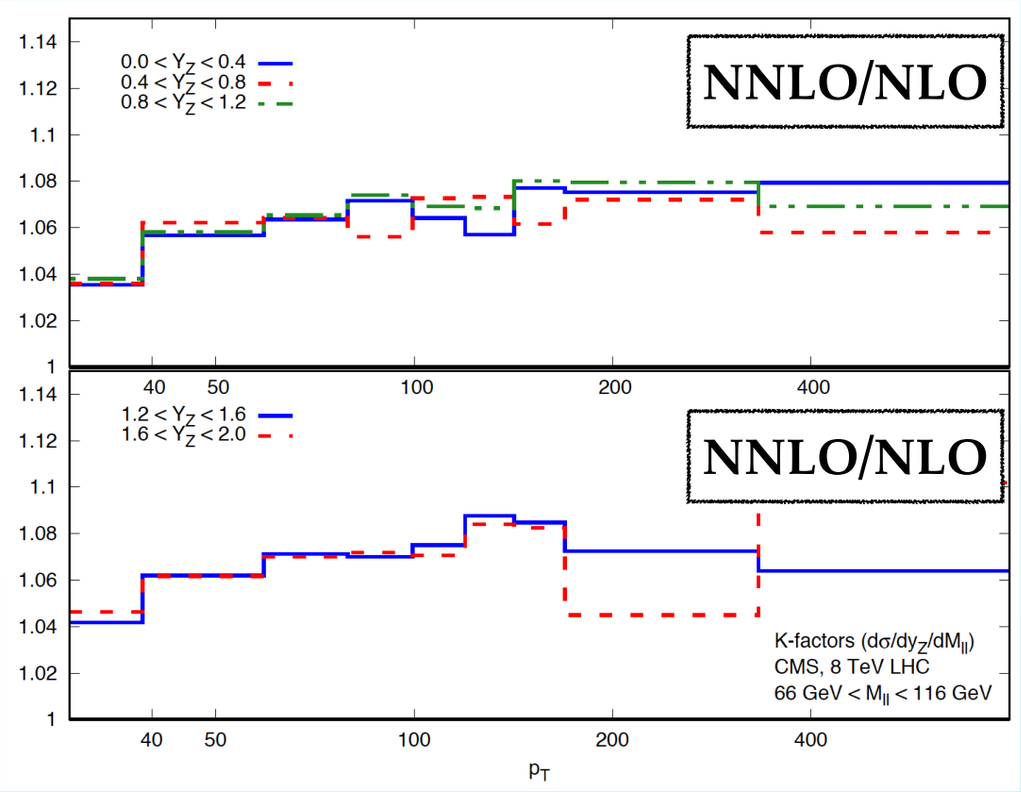
Boughezal et al 2015-2017, Gehrmann et al 2015-2017

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





Boughezal et al 2017



The small-x gluon from forward charm production

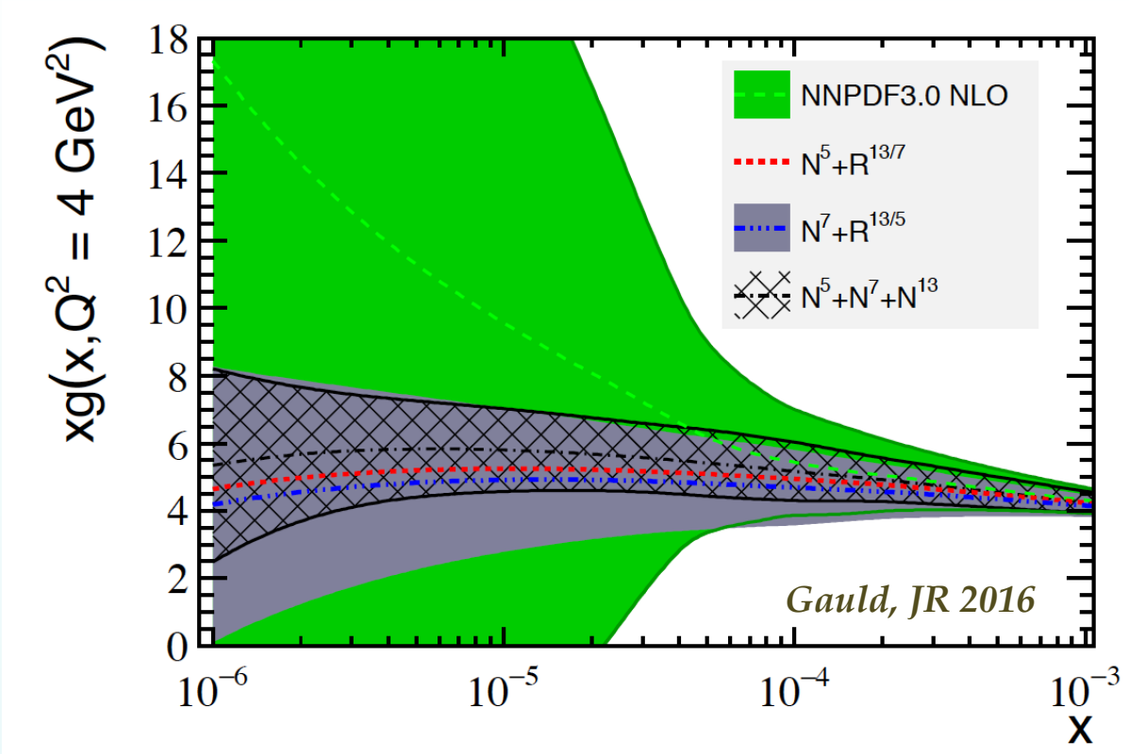
- **D and B meson production from LHCb** allow accessing the **gluon down to x≃10^{-6}**, well below the HERA coverage

PROSA 2015, Gauld et al 2015

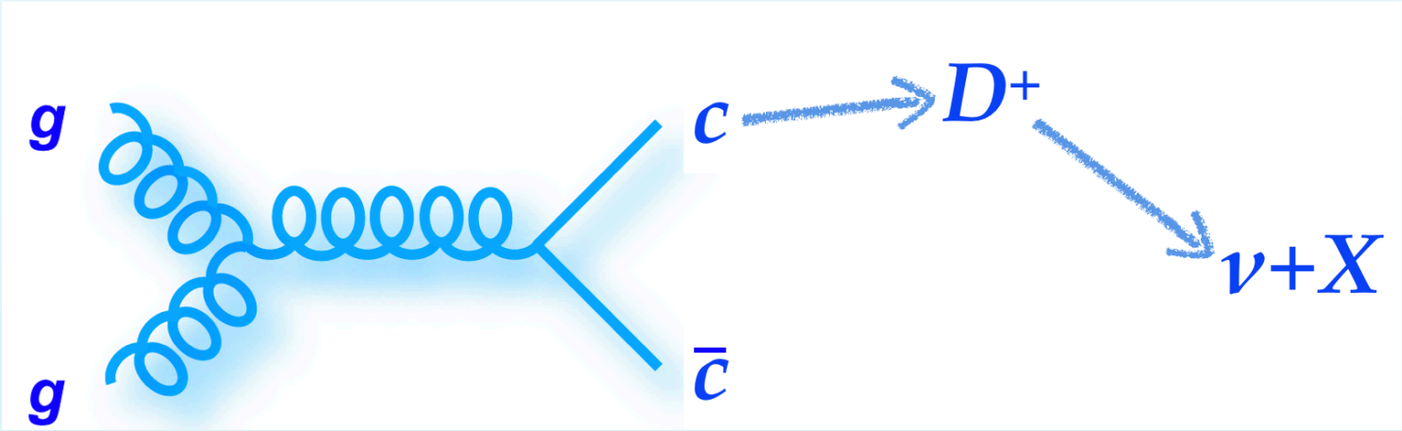
- Gluon PDF errors **reduced by up to a factor 10!**

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

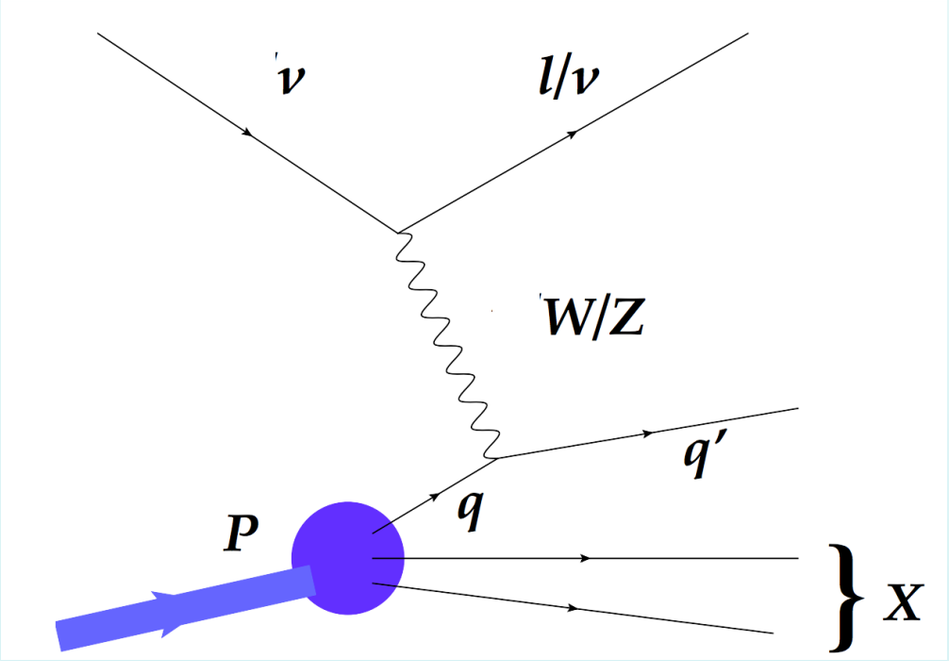
- Precision calculation of the **UHE neutrino-nucleus cross-section**, with few-percent TH errors up to **E_ν=10^{12} GeV**



Prompt neutrino flux at IceCube



UHE neutrino-nucleus xsecs



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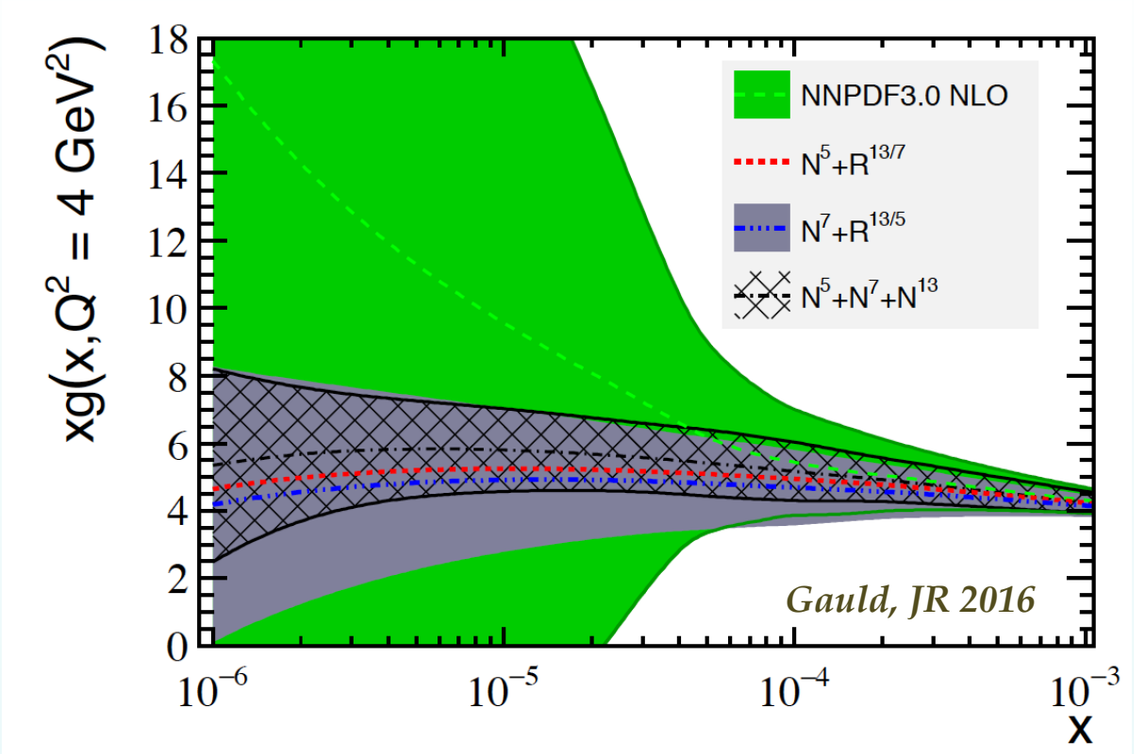

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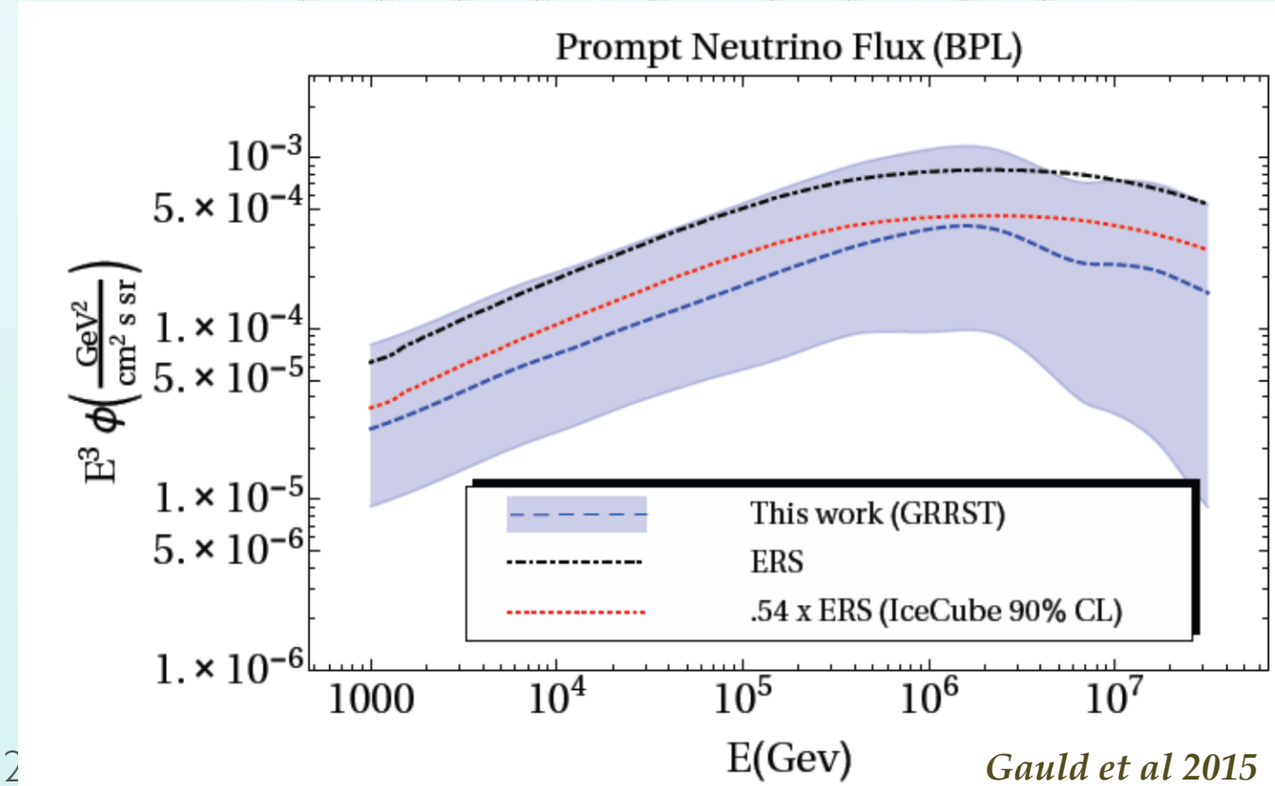

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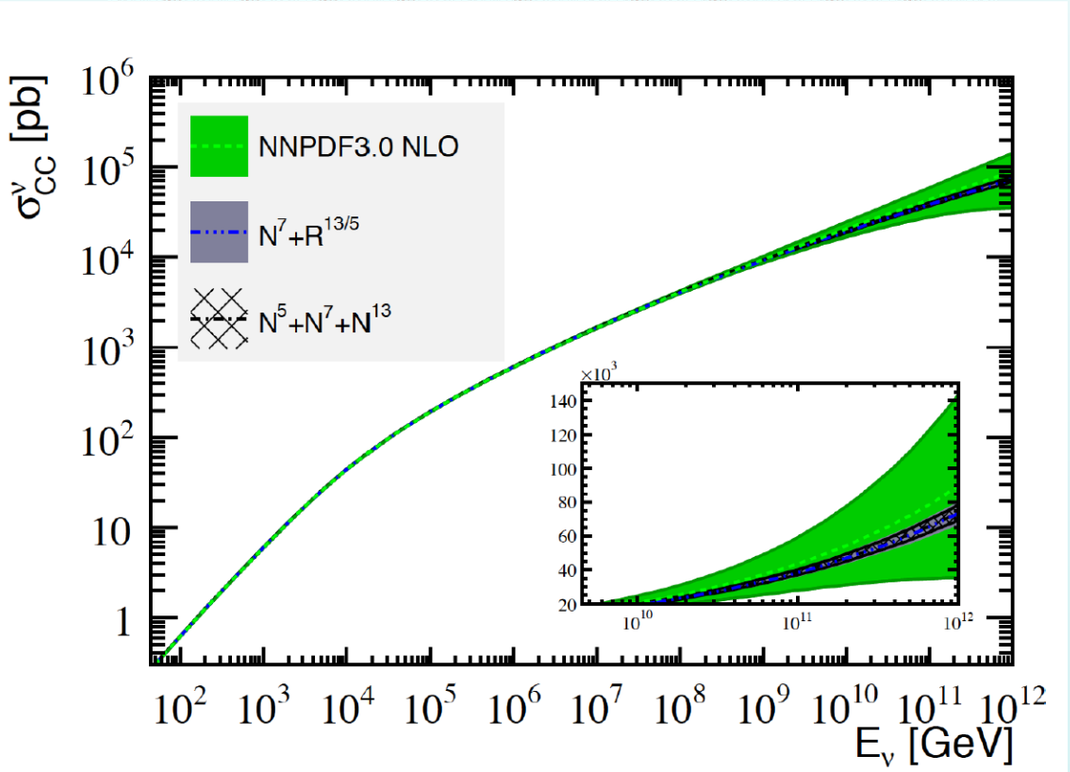
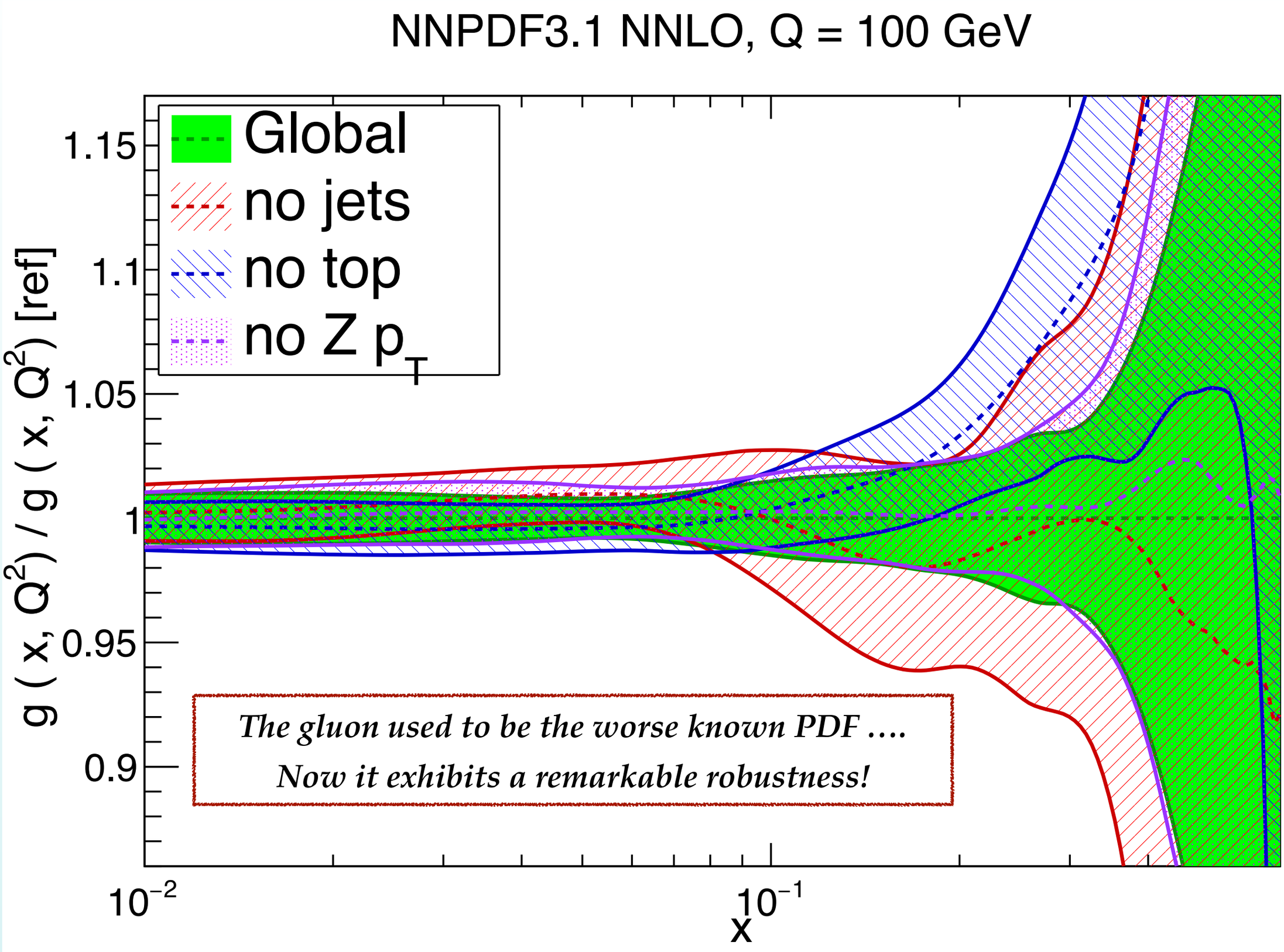
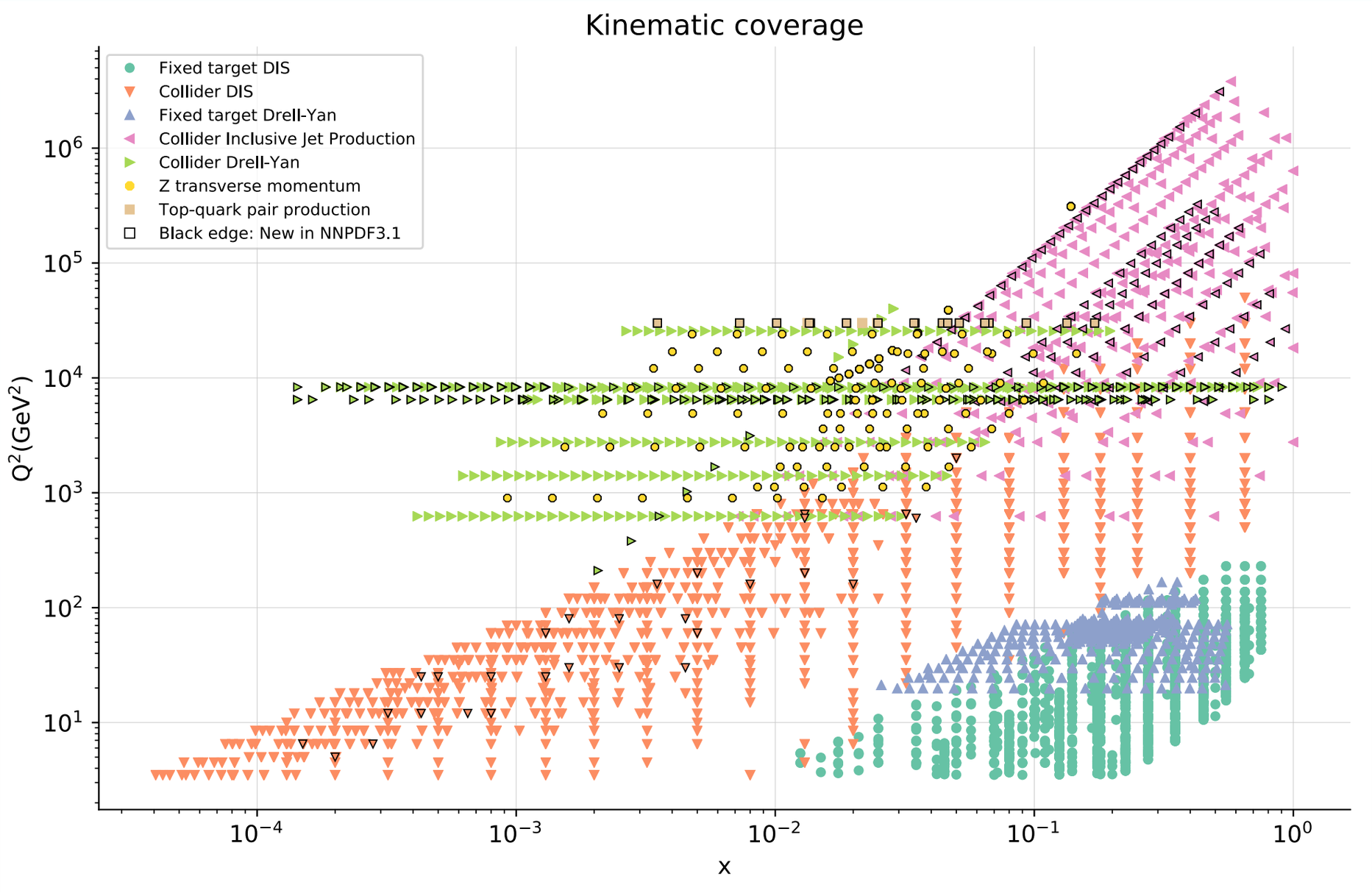


One (upgraded) glue to bind them all



global PDF fits: 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 $\chi^2/N_{dat} \approx 1$!

Summary and outlook

- Inclusive jet production is an important ingredient of the global PDF fitting framework, in particular to **constrain the large-*x* gluon**

- The recent calculation of **NNLO QCD corrections** allows to include both inclusive jet and dijet production consistently in a NNLO global analysis

- **Fit quality improved** as compared to NLO, impact on the large-x gluon similar at the two orders. Results also stable upon variations of choice for μ_R, μ_F and of the **jet radius *R***

- The NNLO calculation will also allow **improved extractions of $\alpha_S(m_Z)$** from jet production

- What next? Implementation of the ATLAS and CMS **dijet measurements into NNLO PDF fits**