Parton Distributions from High-Precision Collider Data

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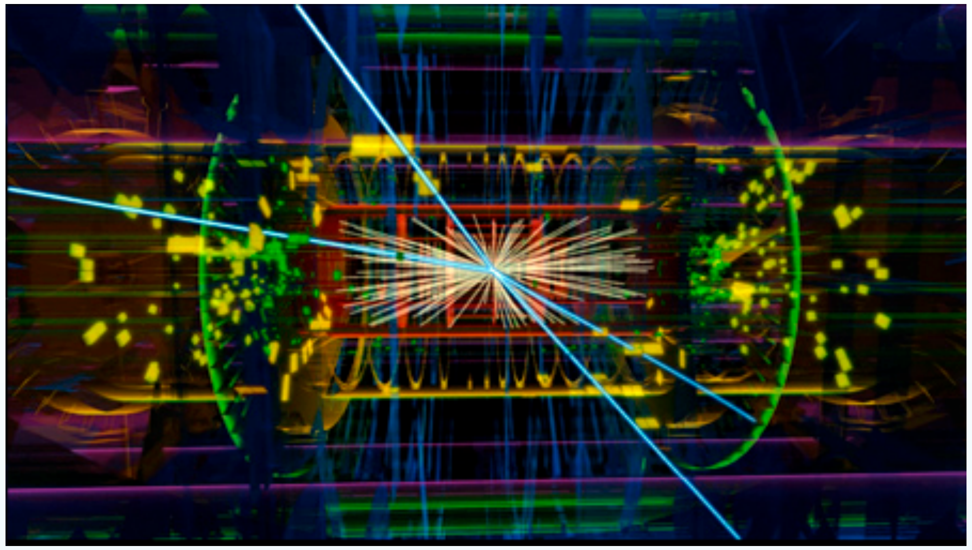
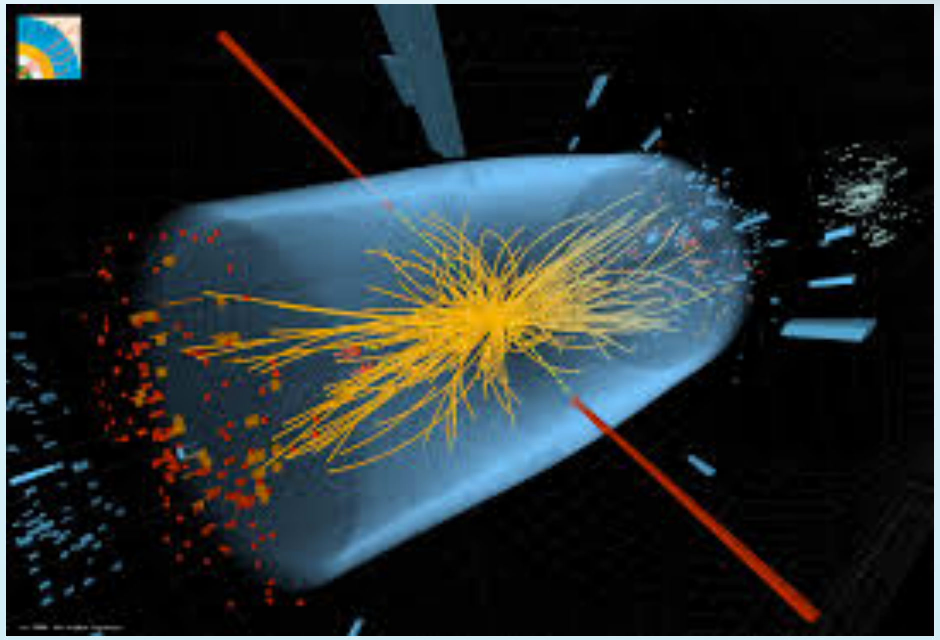
Max Plank Institute for Physics
Munich, 26/07/2017



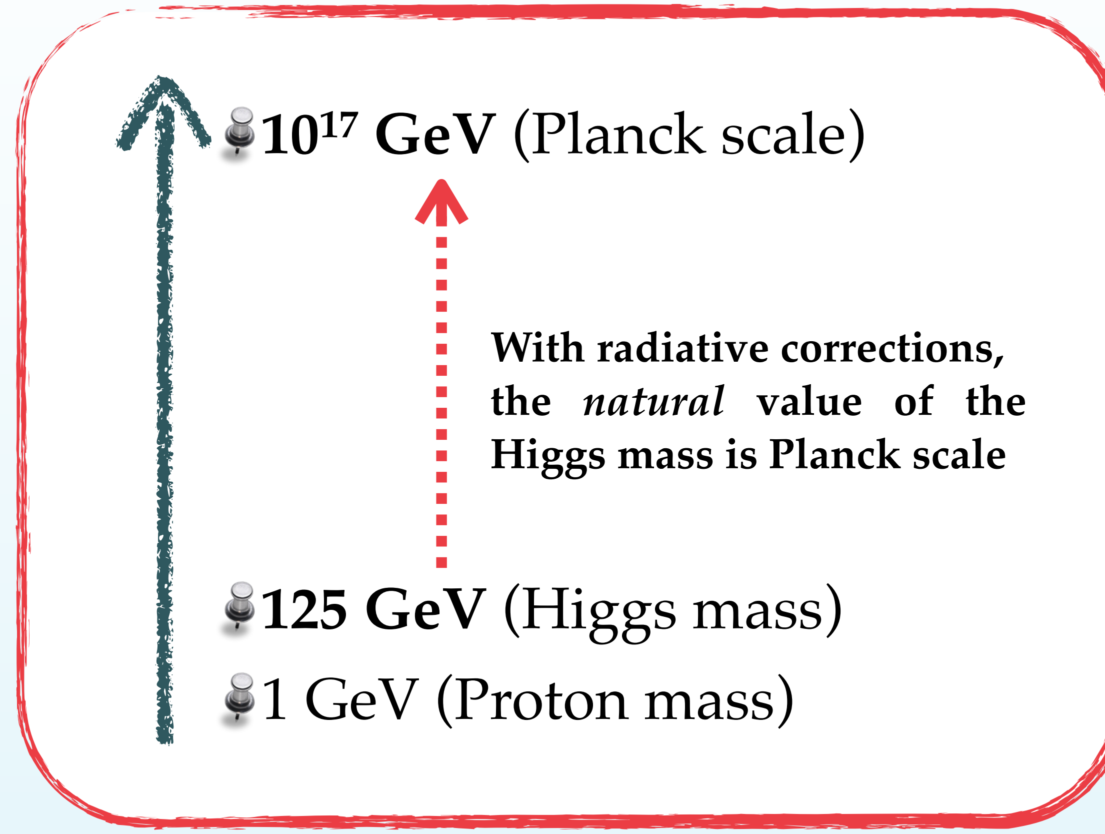
Exploring the high-energy frontier at the Large Hadron Collider

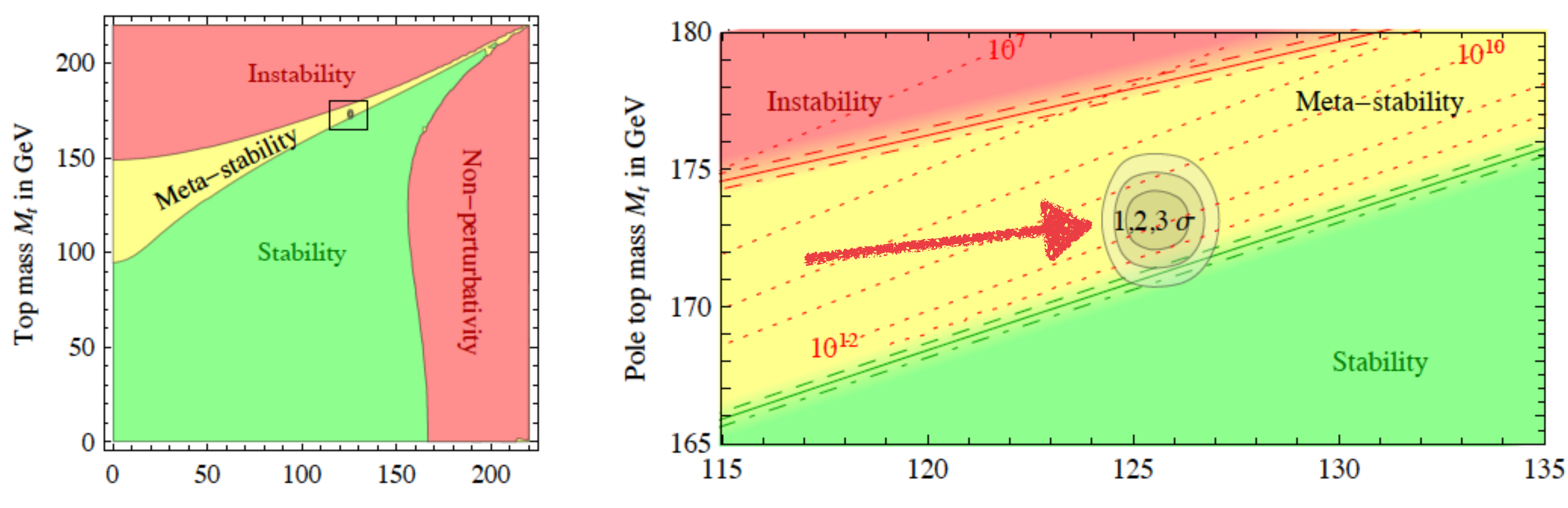


Outstanding questions in Particle Physics

The Higgs boson

- Huge gap, 10^{17}, between **Higgs and Plank scales**
- **Elementary or composite**? Additional Higgs bosons?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?





Degrassi et al 12

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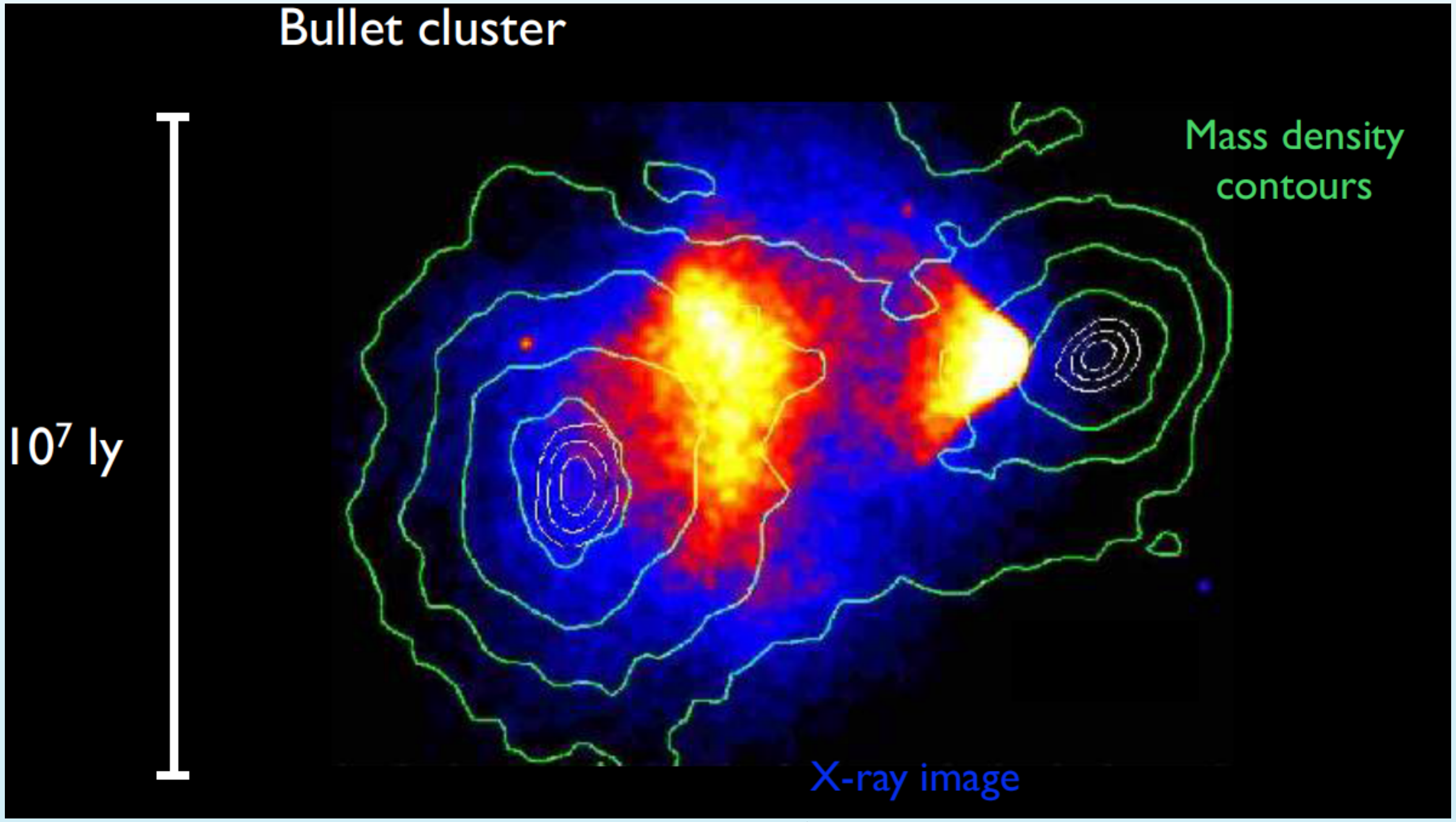
Dark Matter

- **Weakly interacting massive particles**? Sterile neutrinos? **Extremely light particles** (axions)?
- **Interactions** with Standard Model particles?
- What is the **structure of the Dark Sector**? Is Dark Matter self-interacting?



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Quarks and leptons

- **Why three families?** Can we explain **masses and mixings**?
- Origin of **Matter-Antimatter asymmetry** in the Universe?
- Are **neutrinos Majorana or Dirac**? CP violation in the lepton sector?

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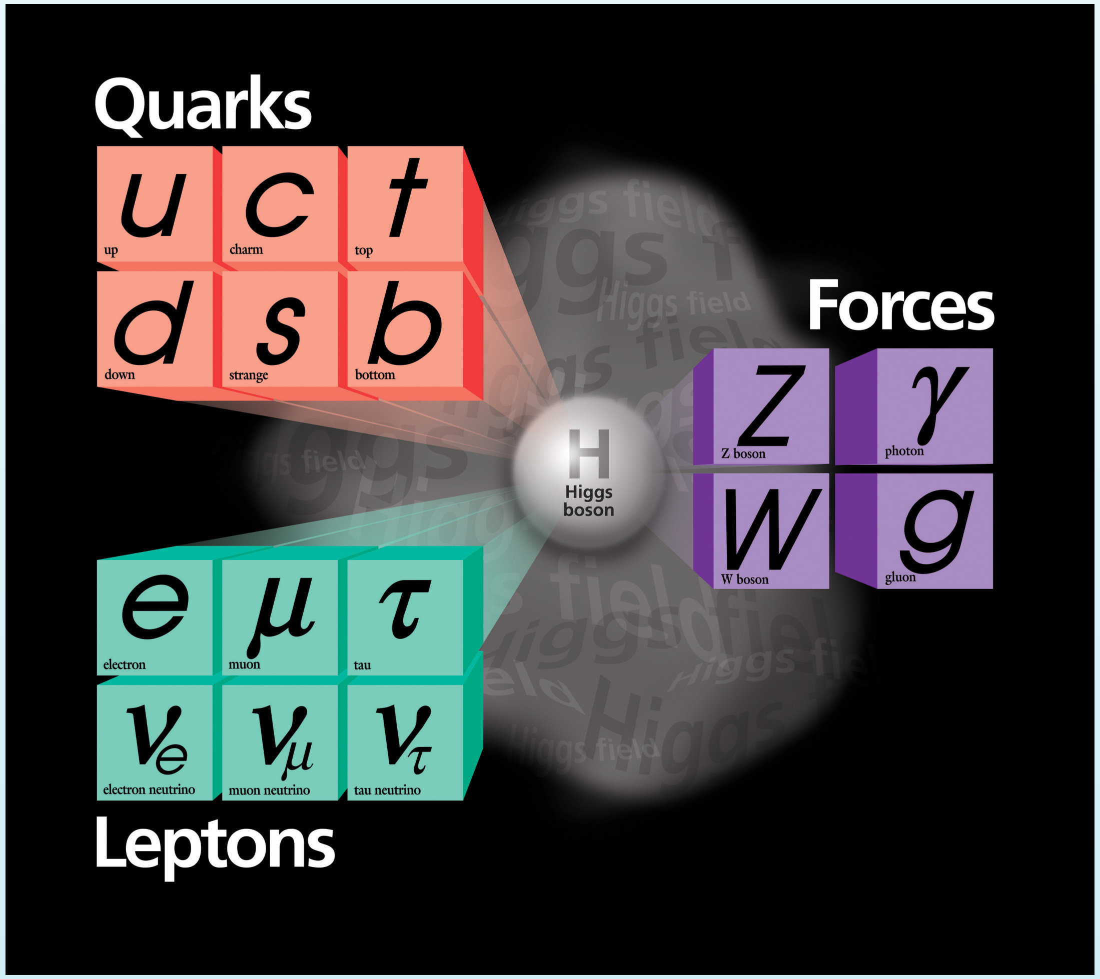

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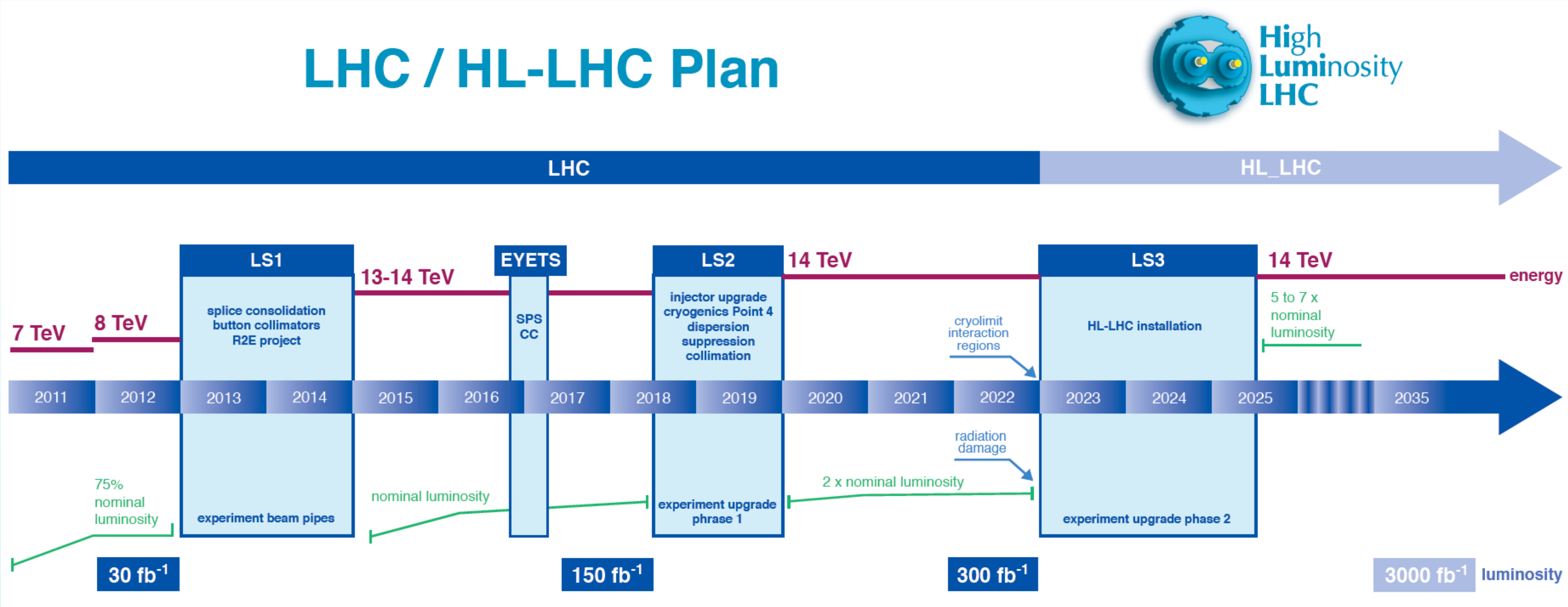
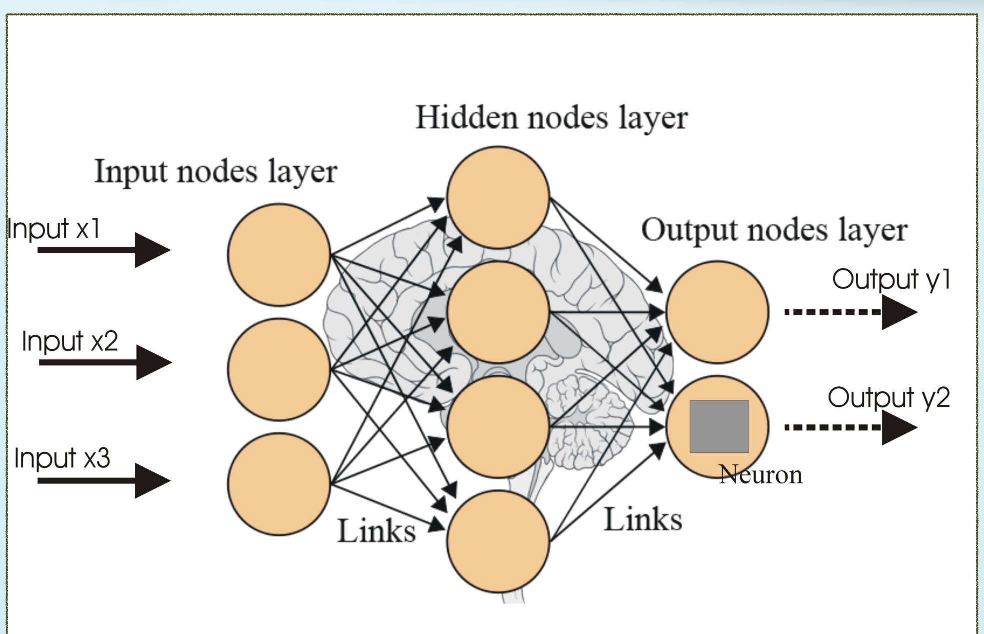


Many of these crucial questions can be addressed at the Large Hadron Collider

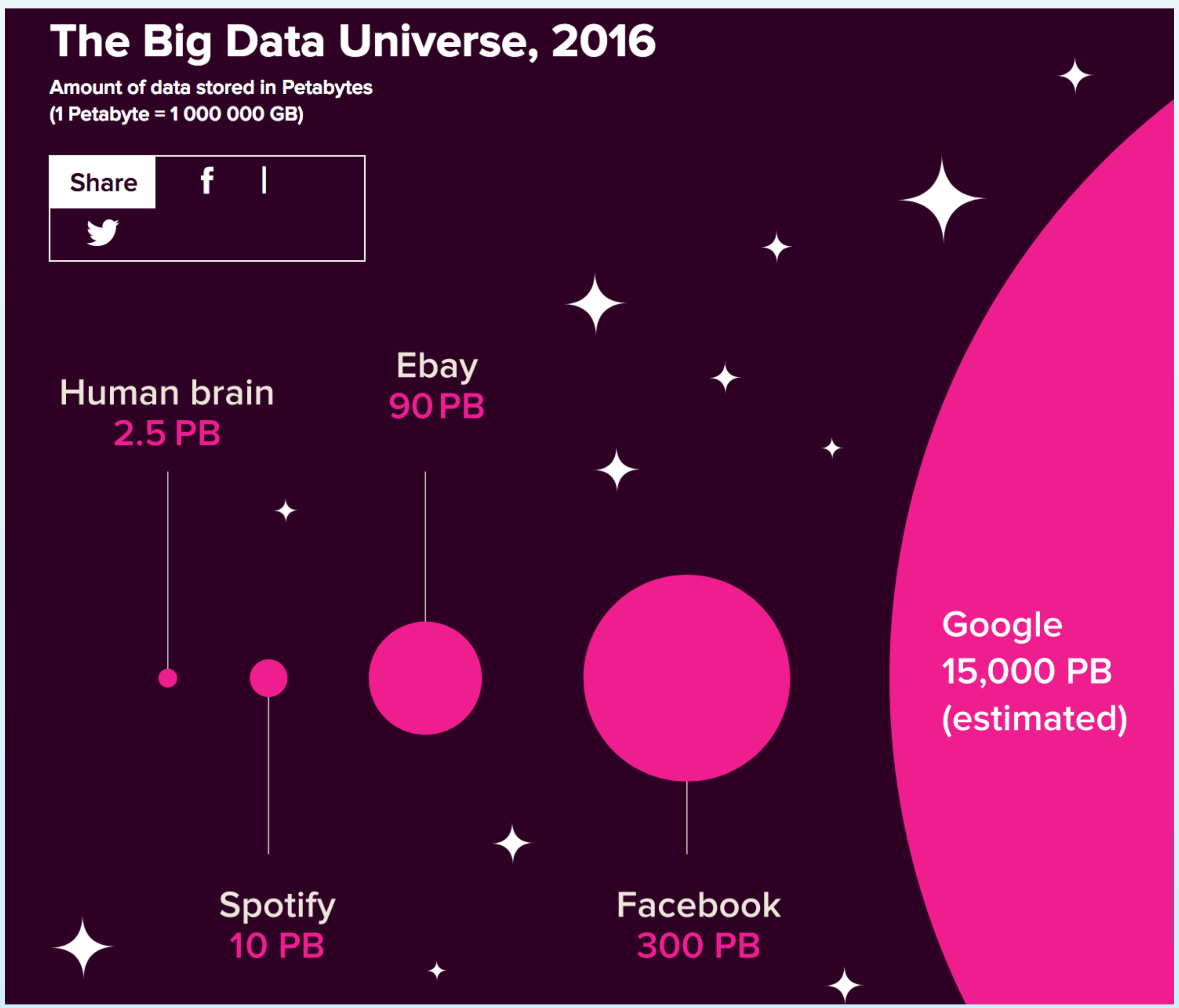
For the next 20 years, LHC will be the forefront of the exploration of the high-energy frontier

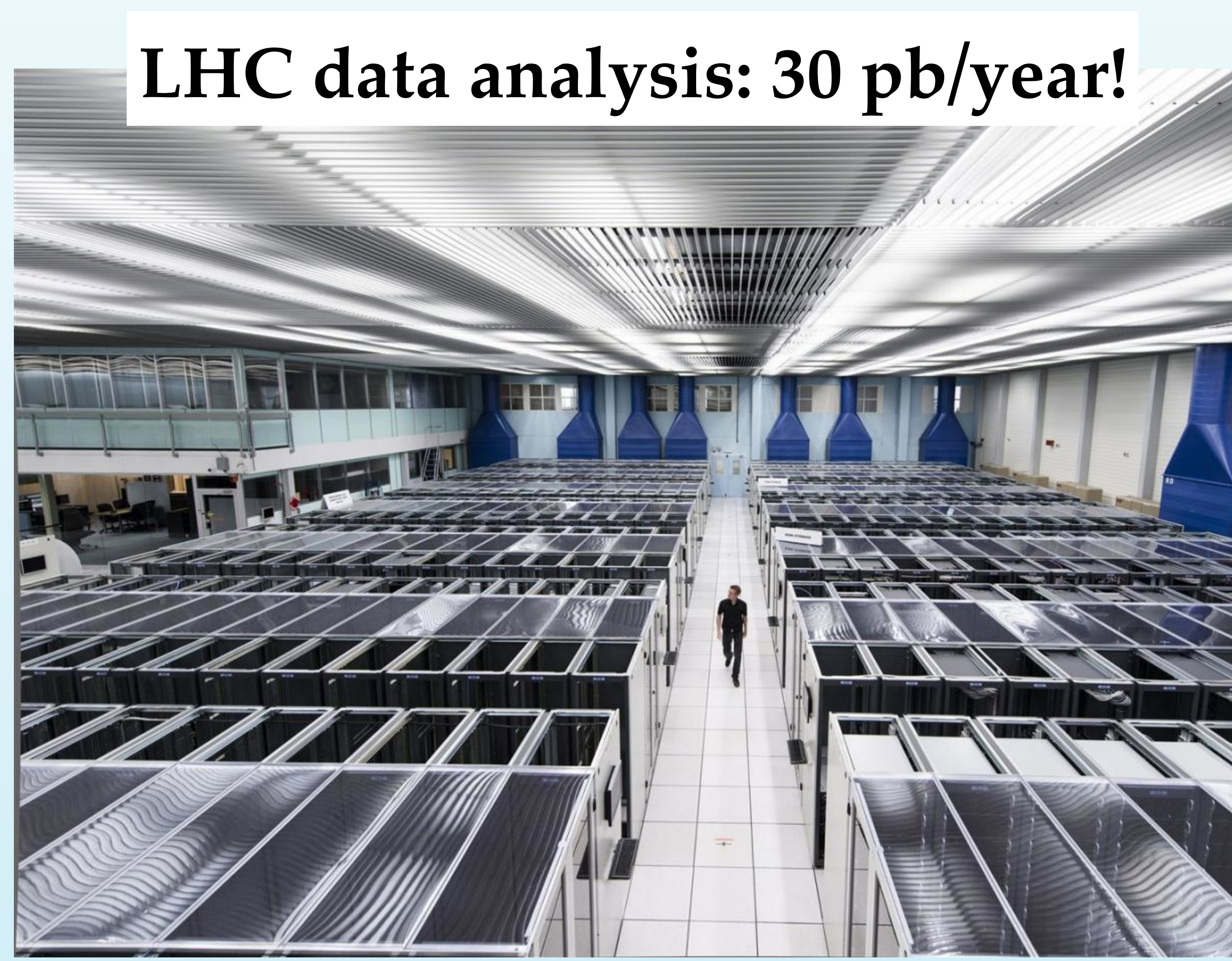
Machine Learning and Artificial Neural Networks at the LHC



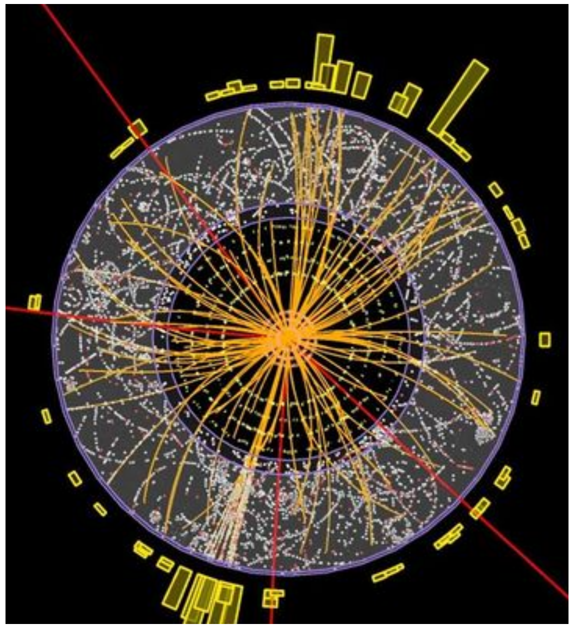
Machine Learning at the LHC

- By **Machine Learning** we usually denote those families of computer algorithms that **learn how to excel on a task** based on a **large sample of examples**, rather than on some a priori fixed rules
- ML algorithms are nowadays ubiquitous, from **driverless cars** to **Amazon's purchase suggestions**, to **automated medical imaging recognition** to beating the words best players at Go and chess
- ML tools rely on the **efficient exploitation of immense datasets**. And the **LHC** has a lot of data!

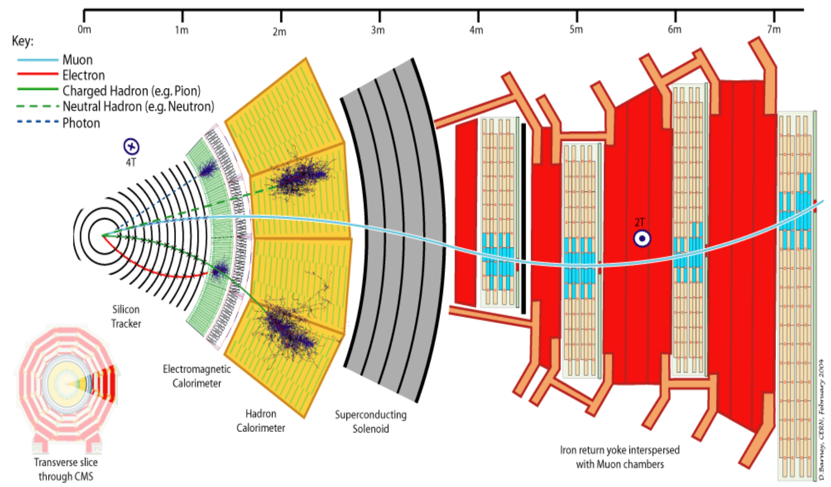




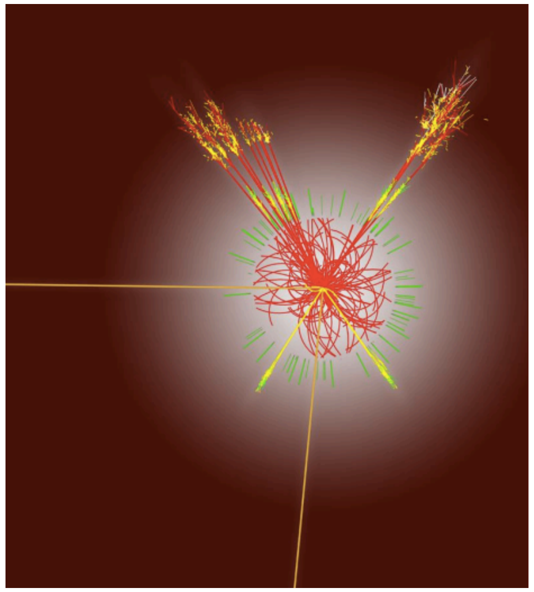
Machine Learning tools are everywhere!



Deep Kalman RNNs

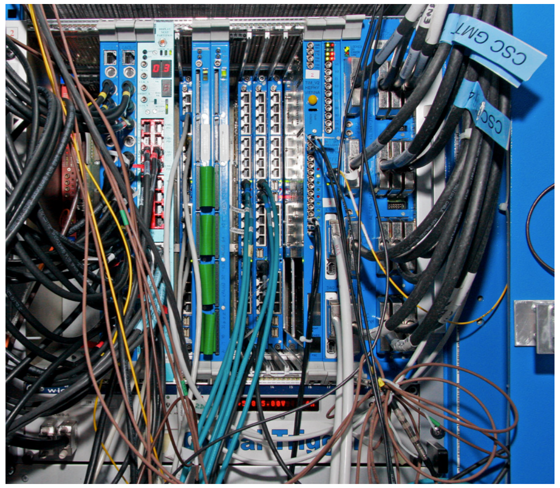


Generative Models, Adversarial Networks

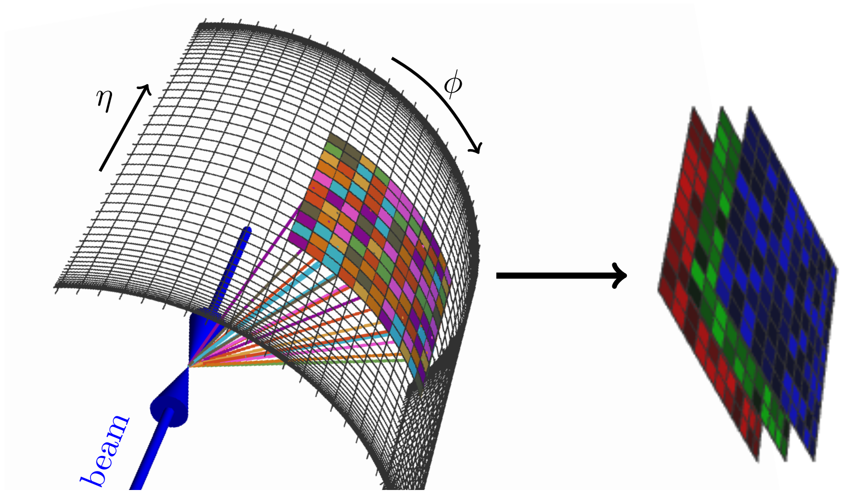


FCN, Recurrent, LSTM NN

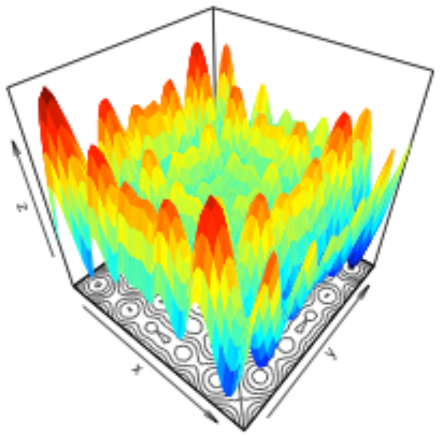
S. Glayzer



Deep ML +FPGA



Convolutional DNN

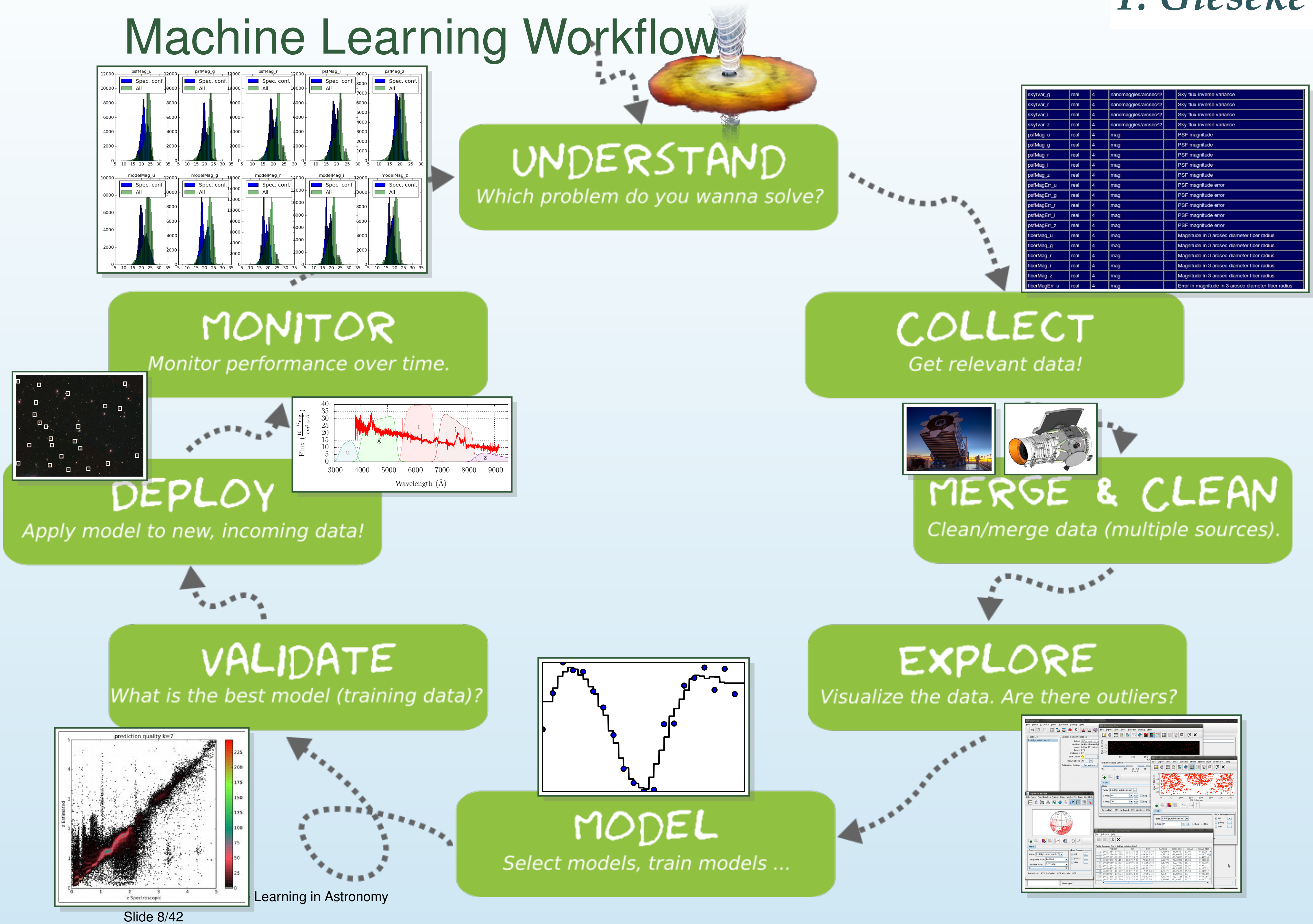


Multiobjective Regression

For many crucial applications, ML tools not just one option, but **the only option**

ML cheat sheet

F. Gieseke

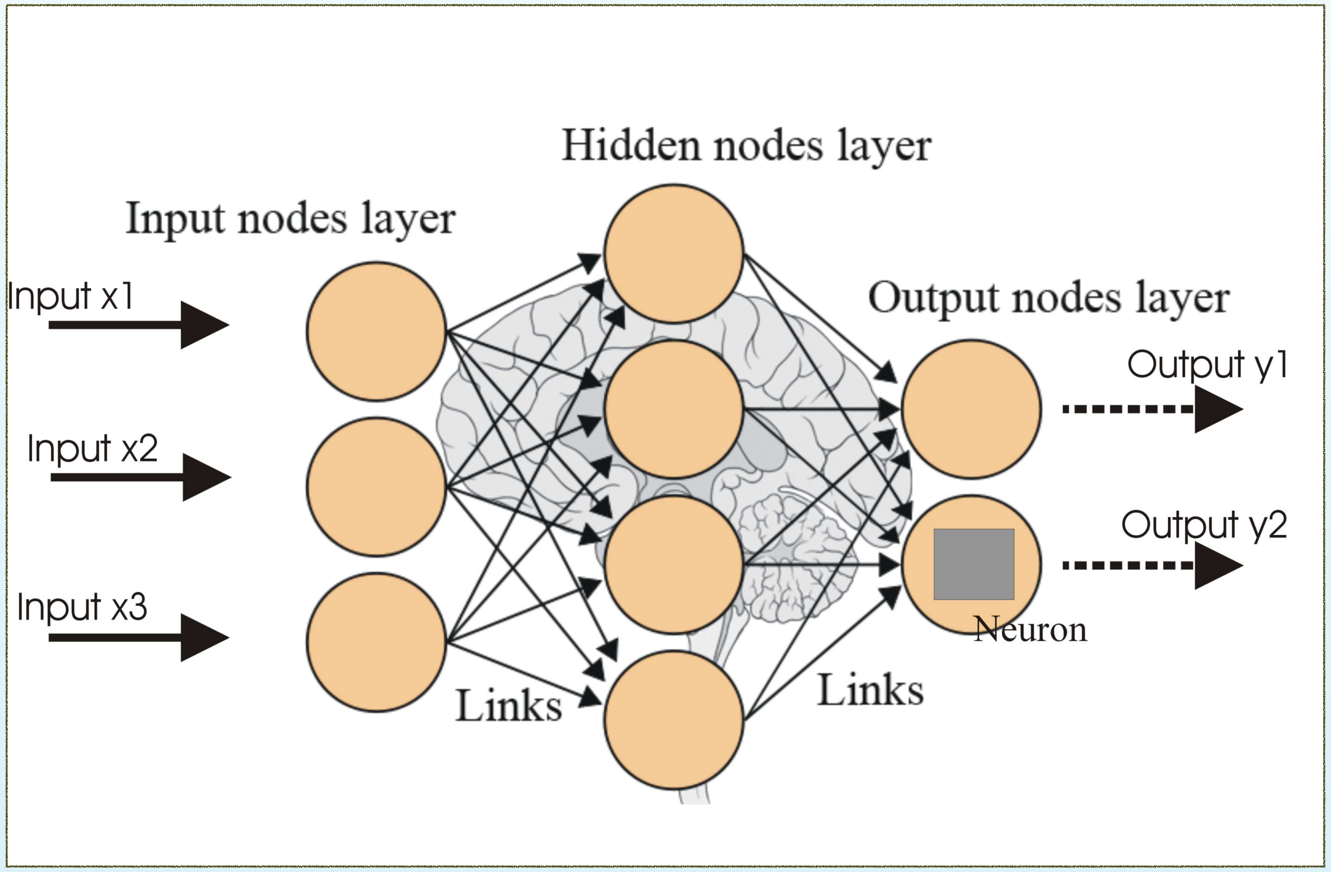


Endless possibilities - but also many non-trivial hurdles to overcome

Artificial Neural Networks

Inspired by **biological brain models**, **Artificial Neural Networks** are **mathematical algorithms** widely used in a wide range of applications, from **HEP** to **targeted marketing** and **finance forecasting**

From Biological to Artificial Neural Networks



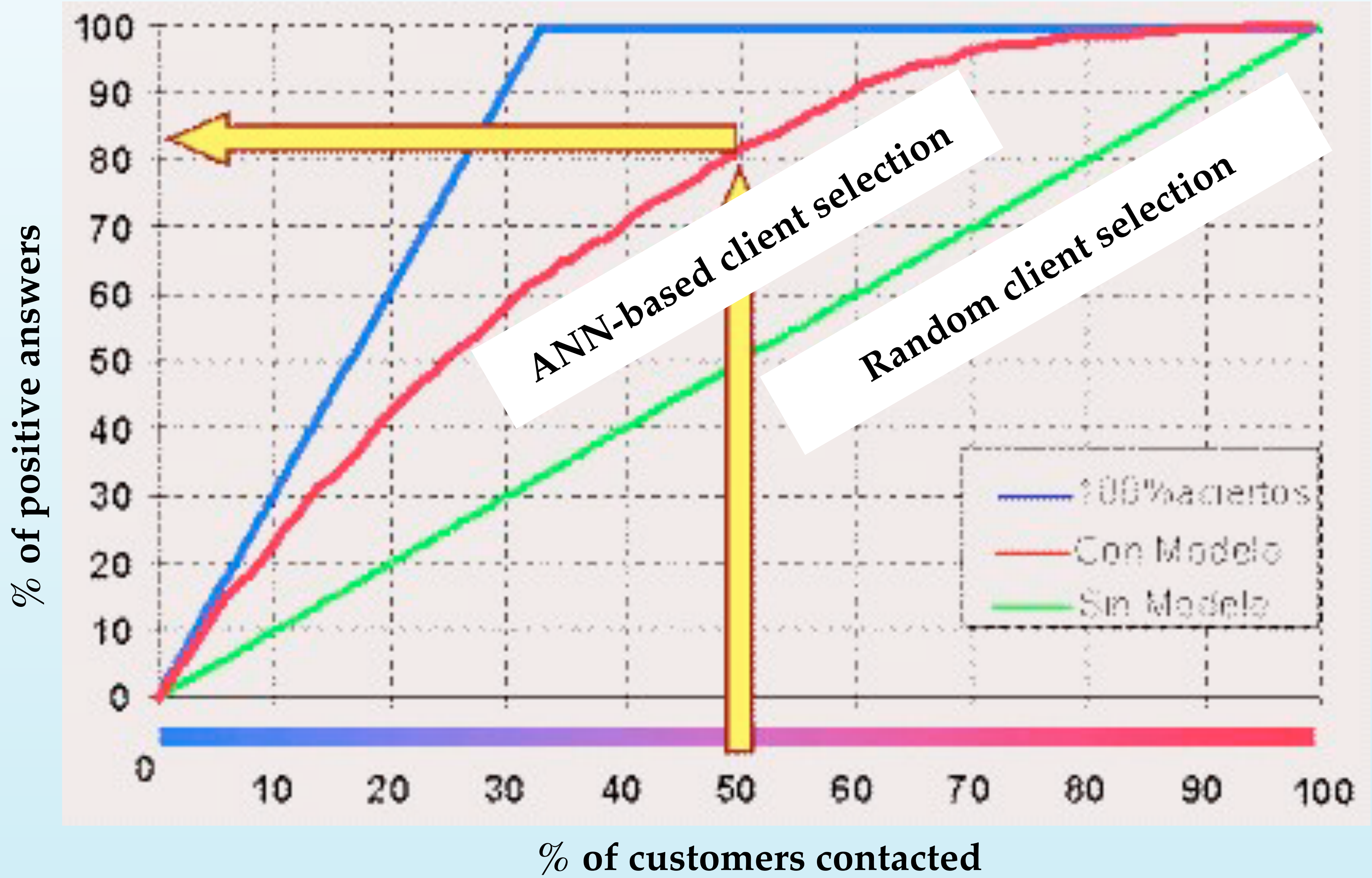
Artificial neural networks aim to excel where domains as their **evolution-driven counterparts outperforms traditional algorithms in tasks such as pattern recognition, forecasting, classification**, ...

ANNs - a marketing example

A bank wants to offer a new credit card to their clients. Two possible strategies:

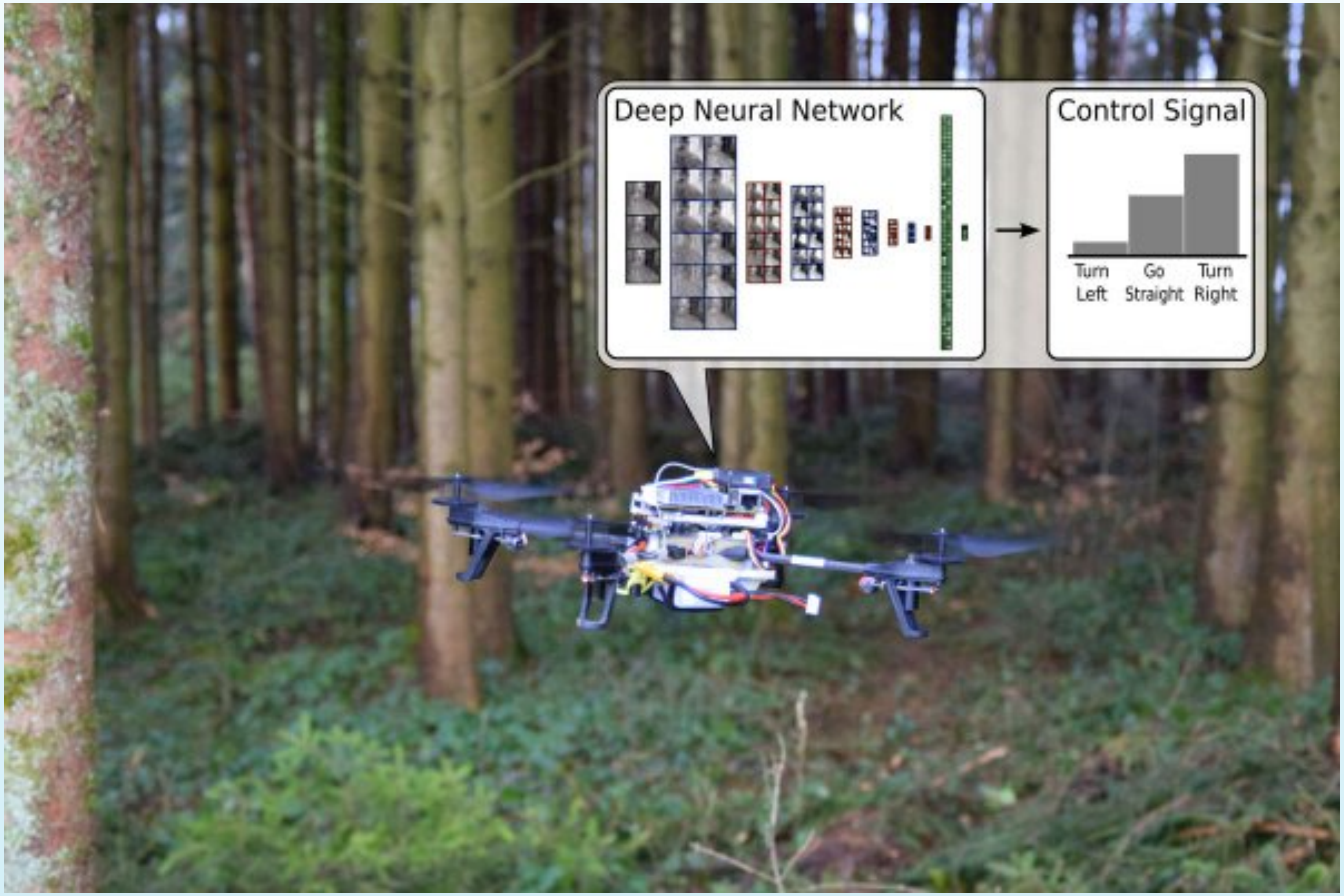
- **Contact all customers**: slow and costly
- Contact **5%** of the customers, **train a ANN with their input** (gender, income, loans) and **their output** (yes/no) and use the information to c**ontact only clients likely to accept the product**

Cost-effective method to improve marketing performance!



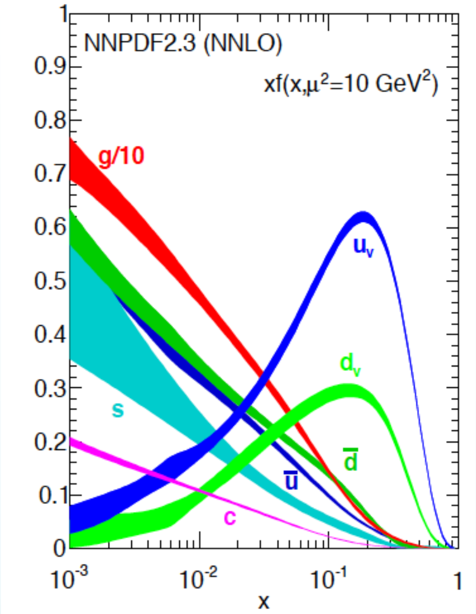
ANNs and pattern recognition

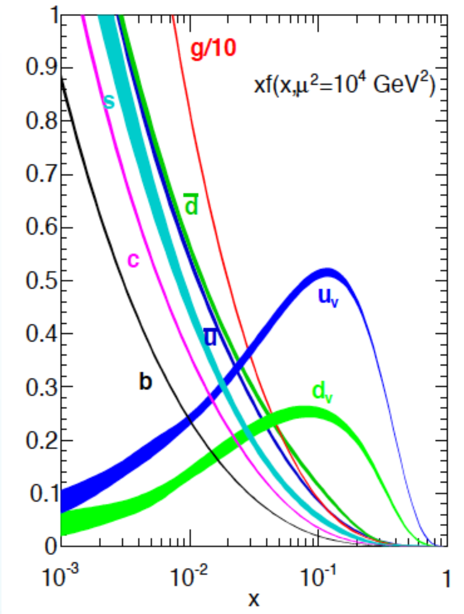
- ANNs can enable an **autonomous vision-control drone** to recognize and follow forest trails
- Image classifier operates directly on **pixel-level image intensities**
- If a trail is visible, the **software steers the drone** in the corresponding direction



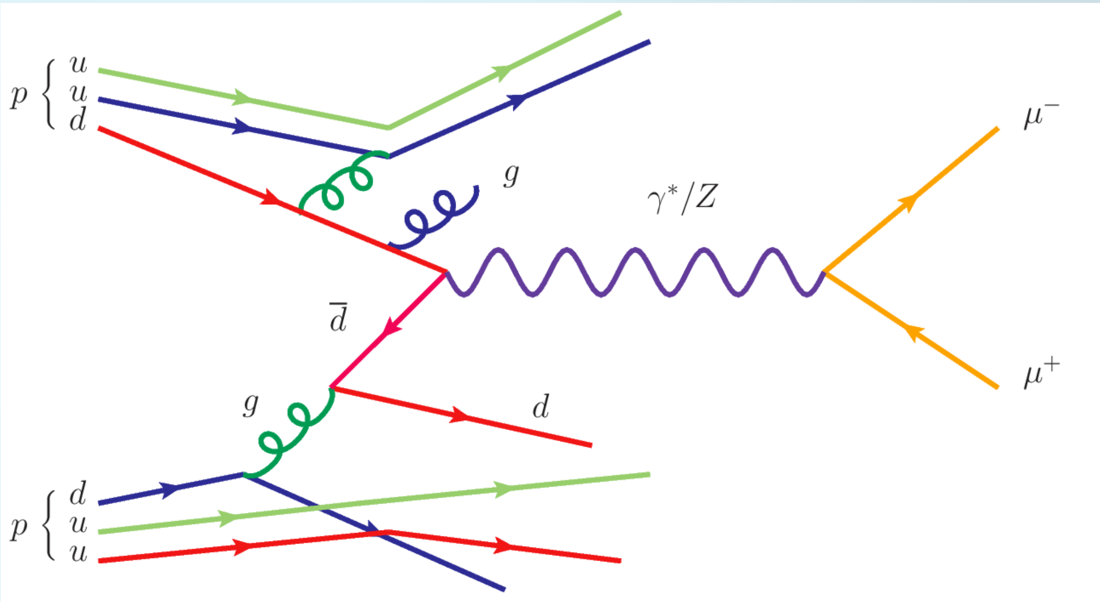
Giusti et al, IEEE Robotics and Automation Letters, 2016

Similar algorithms at work in self-driving cars!



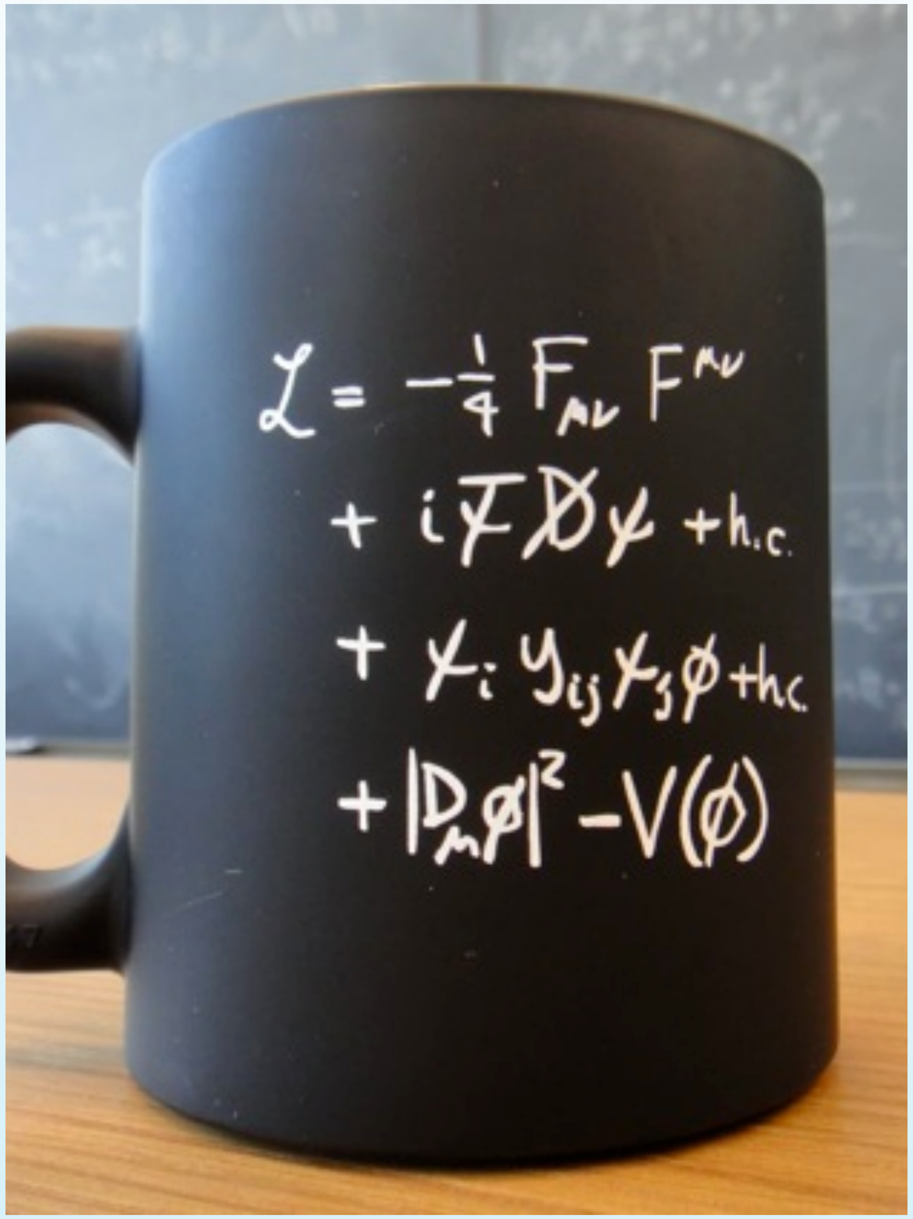


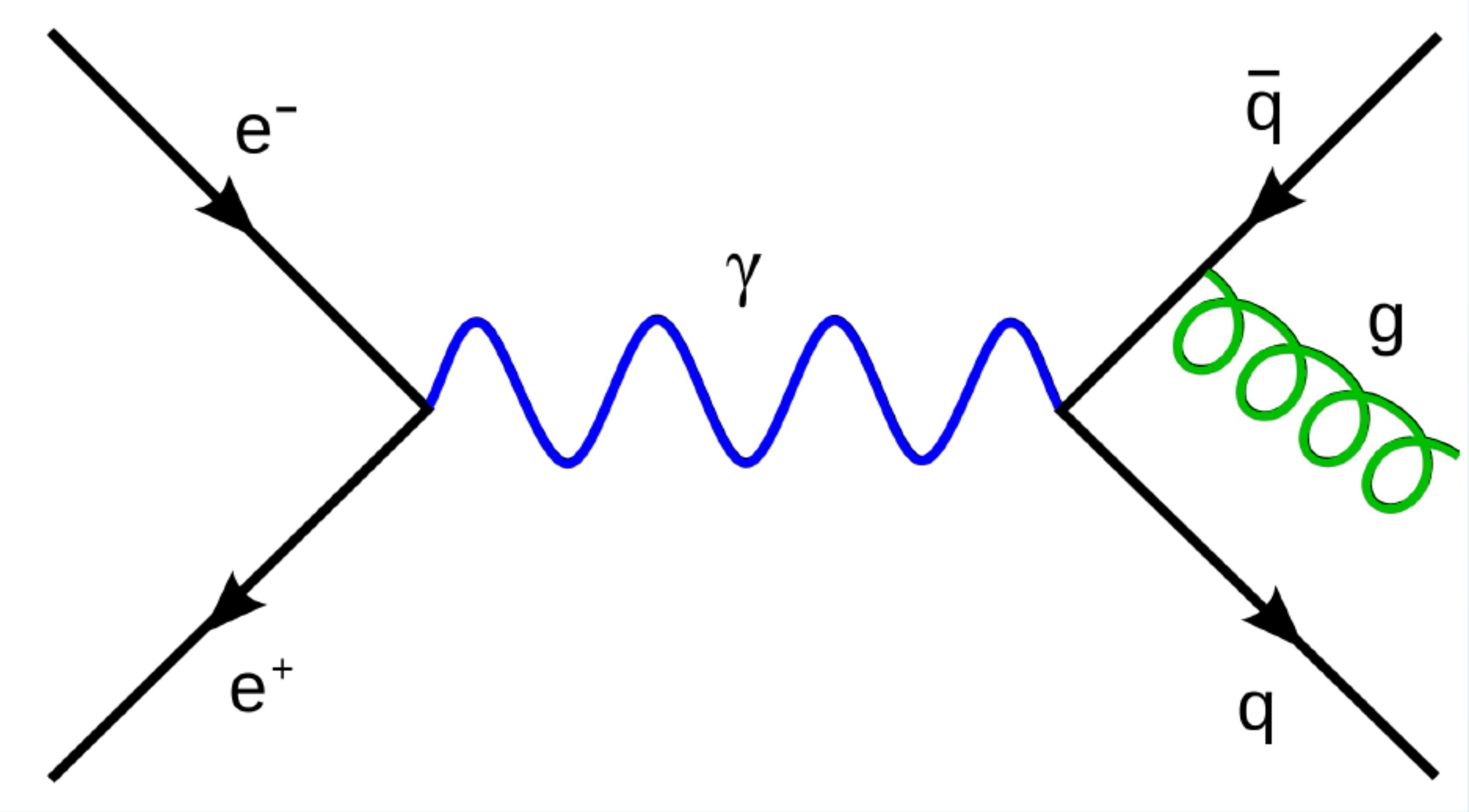
A crash course on parton distributions



Lepton vs Hadron Colliders

In high-energy **lepton colliders**, such as the **Large Electron-Positron Collider** (LEP) at CERN, the collisions involve **elementary particles** without substructure

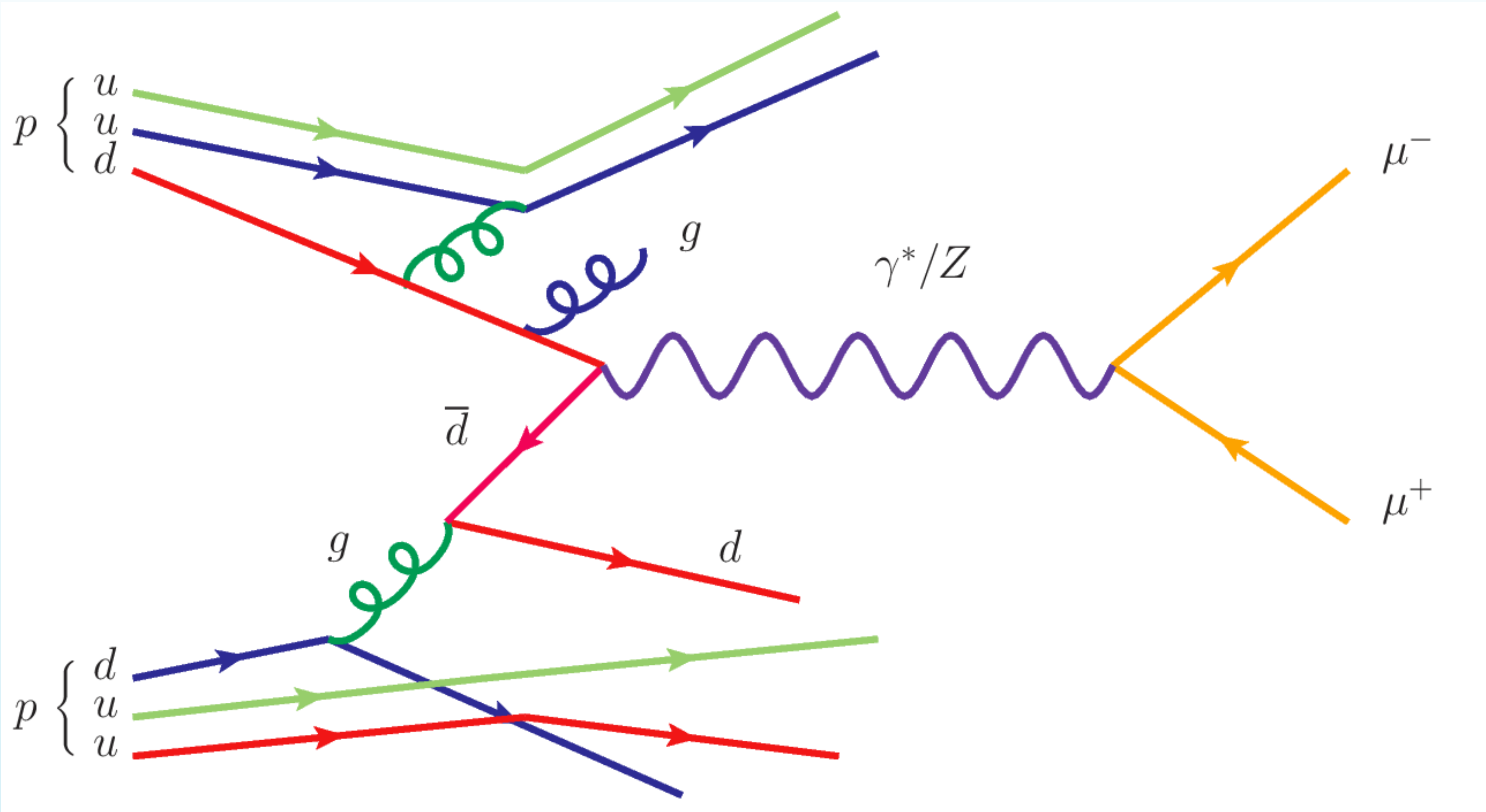




Cross-sections in lepton colliders can be computed in perturbation theory using the **Feynman rules of the Standard Model Lagrangian**

Lepton vs Hadron Colliders

In high-energy **hadron colliders**, such as the LHC, the collisions involve **composite particles** (protons) with internal structure (quarks and gluons)



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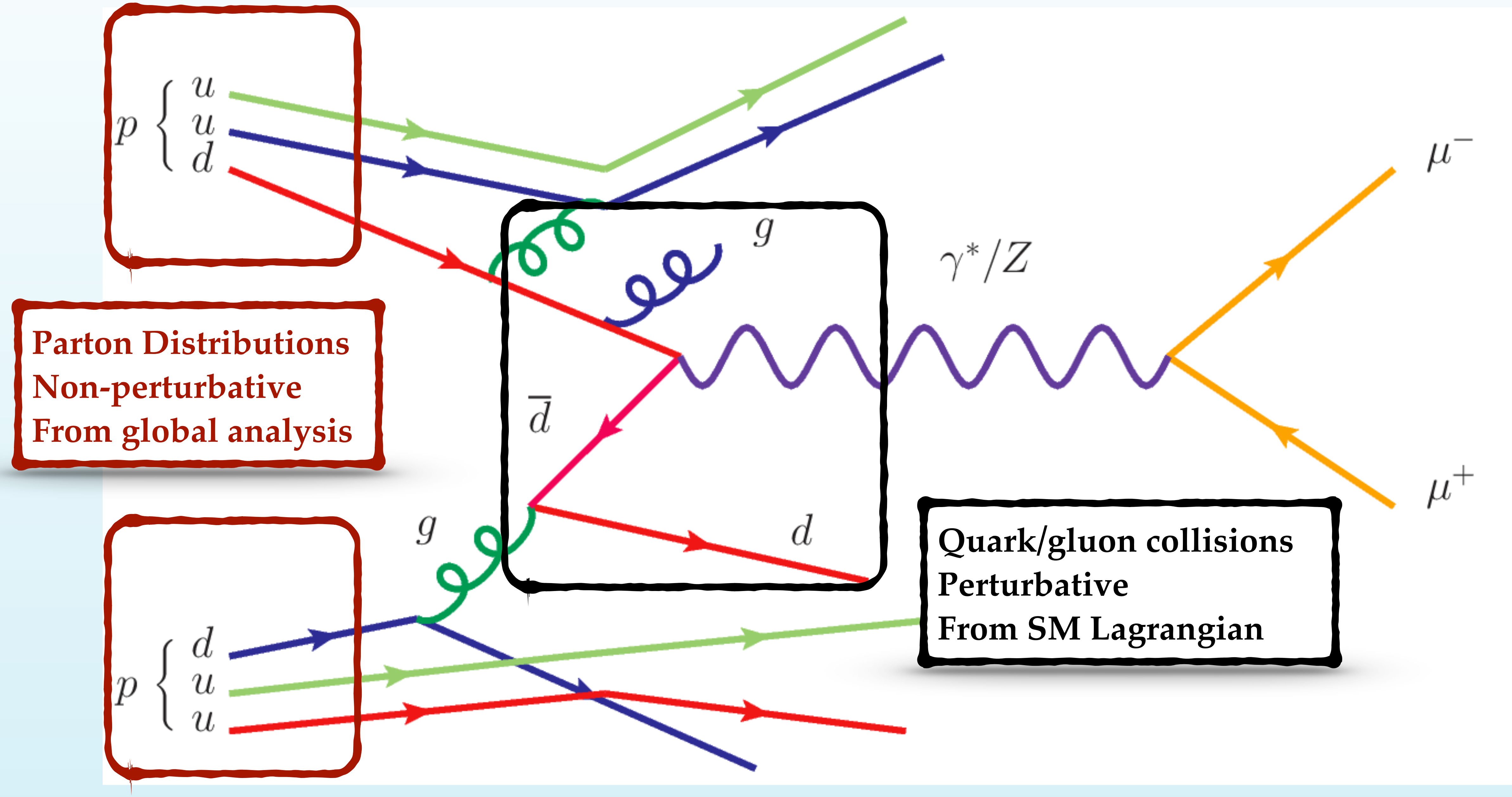

Calculations of **cross-sections** in hadron collisions require the combination of **perturbative, quark/gluon-initiated processes**, and **non-perturbative, parton distributions**, information

Parton Distributions

The distribution of energy that **quarks and gluons carry inside the proton** is quantified by the **Parton Distribution Functions (PDFs)**

$$g(x, Q)$$

Q: **Energy of the quark/gluon collision**
Inverse of the resolution length

g(x,Q): **Probability** of **finding a gluon inside a proton**, carrying a fraction *x* of the proton momentum, when probed with energy *Q*

x: **Fraction of the proton's momentum**

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- **Energy conservation** $$\int_0^1 dx\,\mathbf{x}\left(g(x,Q)+\sum_q q(x,Q)\right)=1$$

- **Dependence with quark/gluon collision energy Q** determined in perturbation theory

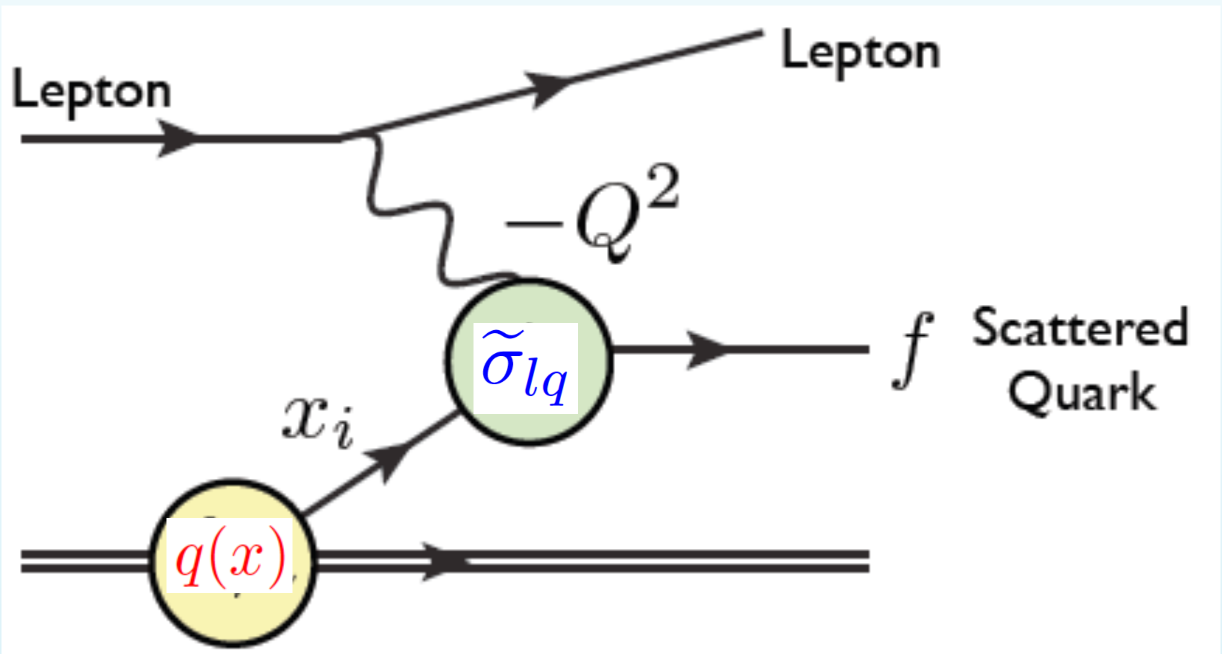
$$\frac{\partial g(x,Q)}{\partial \ln Q} = P_g\left(\alpha_s\right)\otimes g(x,Q) + P_q\left(\alpha_s\right)\otimes q(x,Q)$$

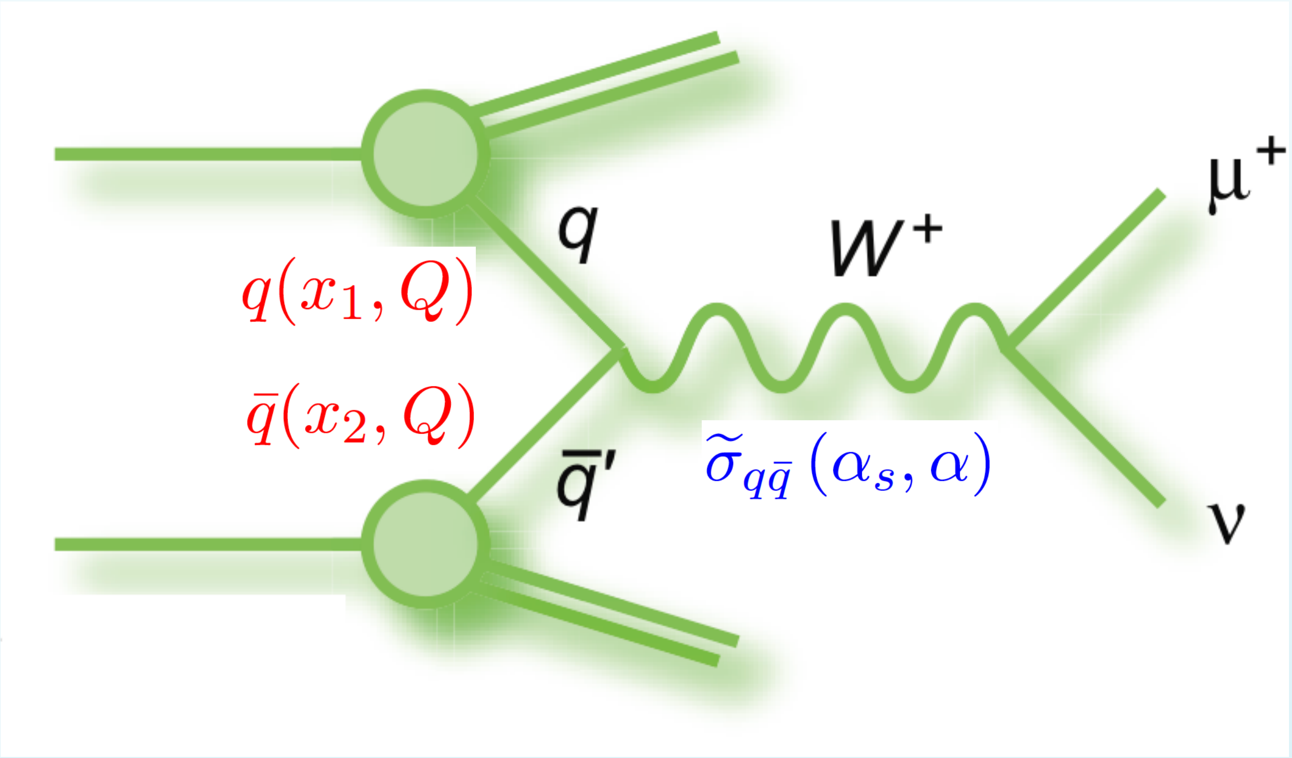
The QCD Factorization Theorem

The **QCD factorization theorem** guarantees **PDF universality: extract them from a subset of** process and use them to provide pure predictions for new processes

$$\sigma_{lp} \simeq \widetilde{\sigma}_{lq}\left(\alpha_s, \alpha\right) \otimes q(x, Q)$$

$$\sigma_{pp} \simeq \widetilde{\sigma}_{q\bar{q}}\left(\alpha_s, \alpha\right) \otimes q(x_1, Q) \otimes \bar{q}(x_2, Q)$$



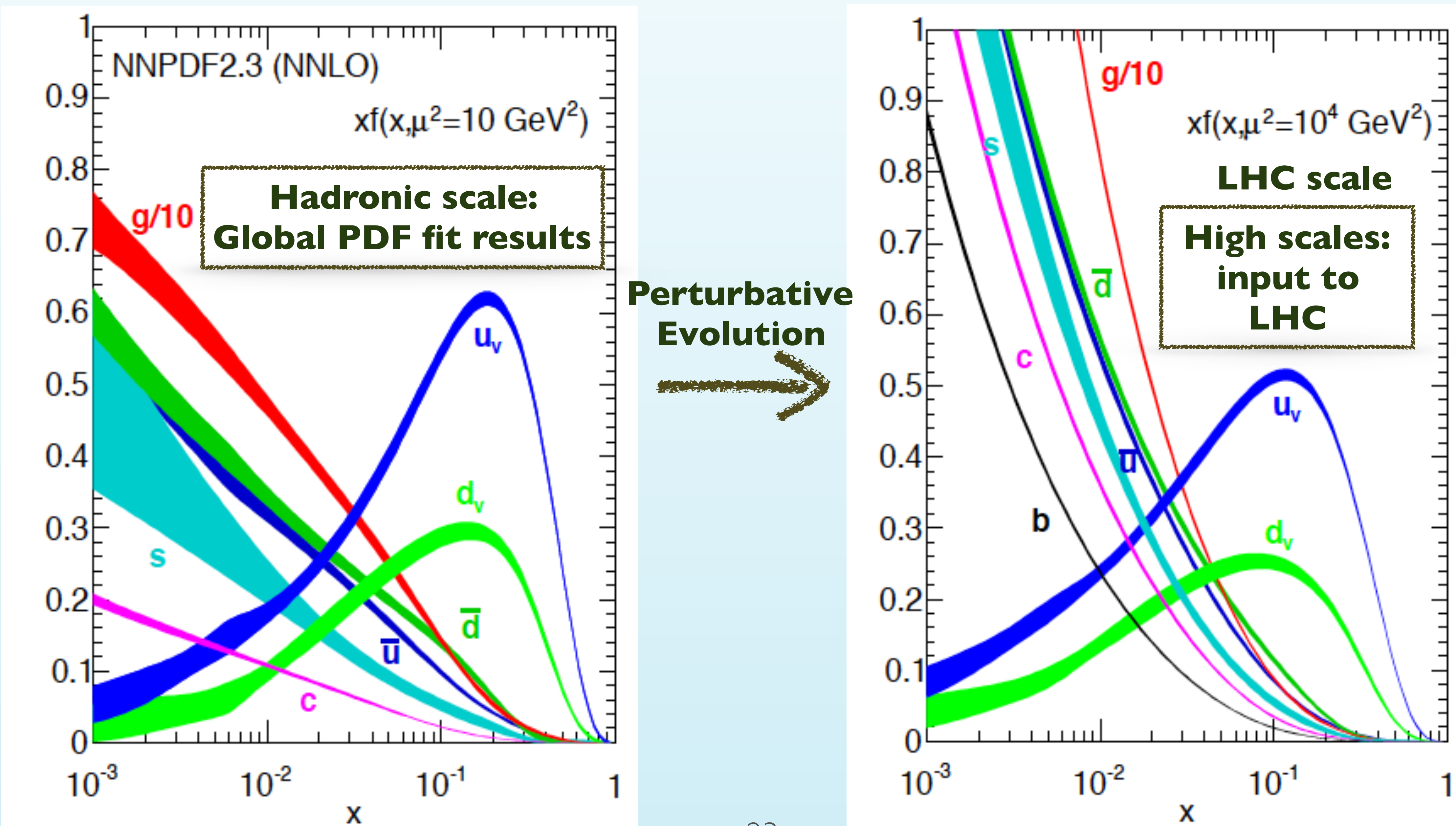


Determine PDFs in lepton-proton collisions ….

And use them to compute cross-sections in proton-proton collisions at the LHC

The global PDF analysis

- Combine **state-of-the-art theory calculations,** the **constraints from PDF-sensitive measurements** from different processes and colliders, and a **statistically robust fitting methodology**
- **Extract Parton Distributions** at hadronic scales of **a few GeV,** where non-perturbative QCD sets in
- Use **perturbative evolution** to compute PDFs at high scales as **input to LHC predictions**



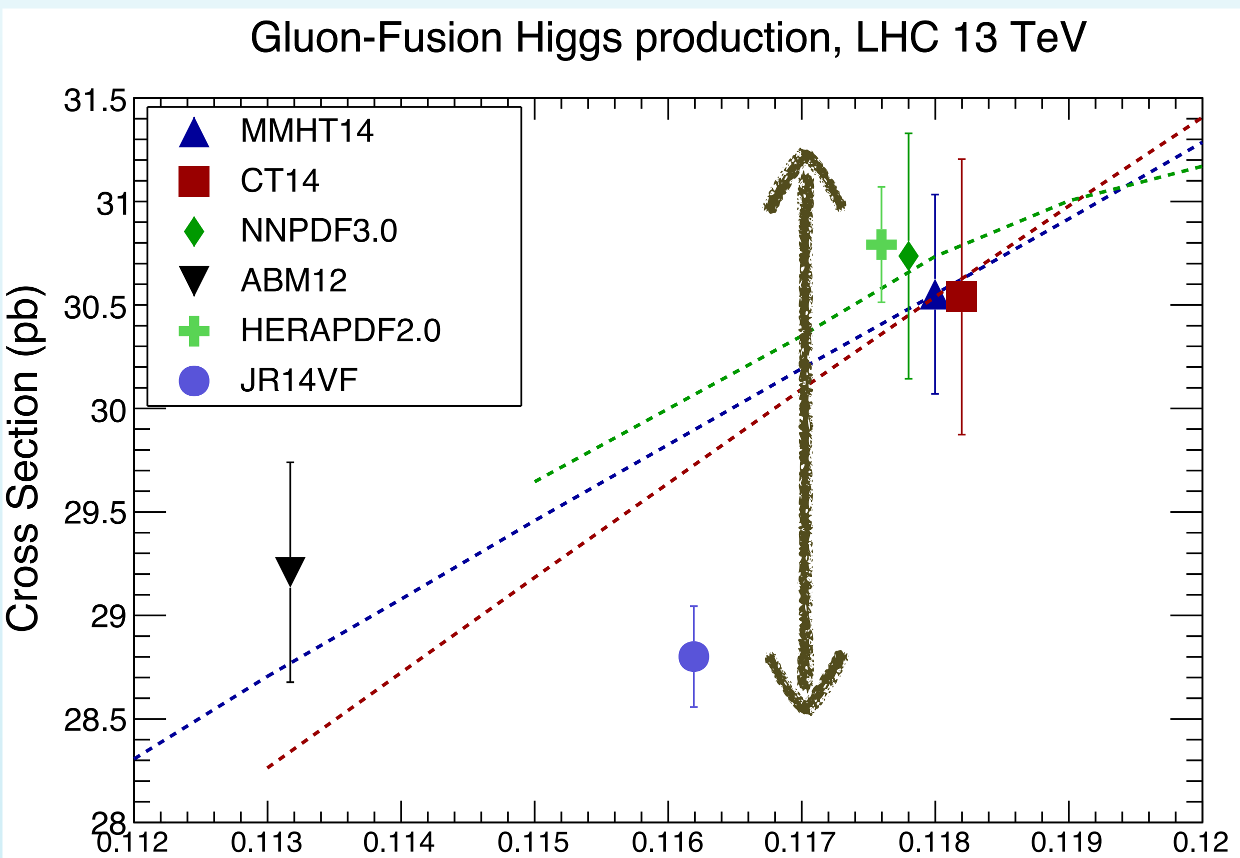
Why we need better PDFs?

Dominant TH unc for M_W measurements at LHC

ATLAS 2017

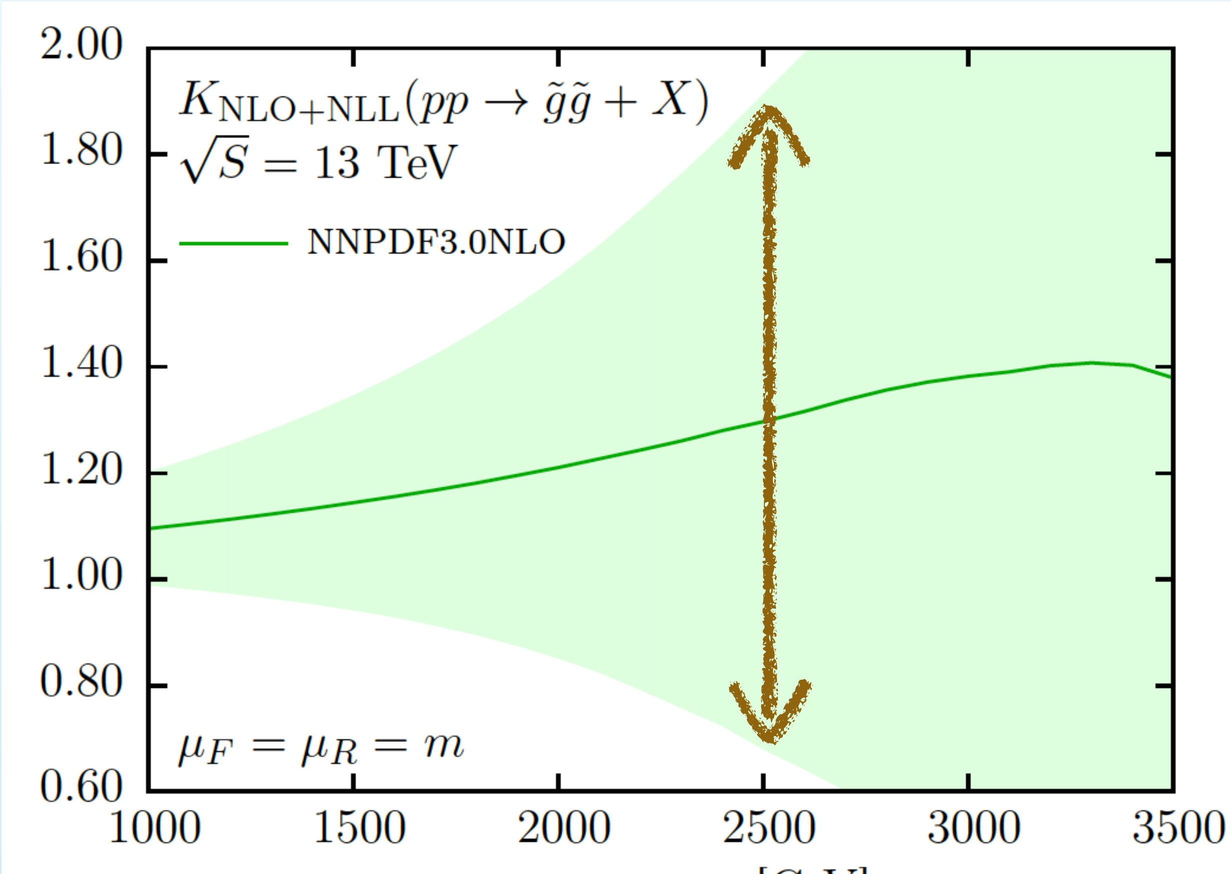
Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Higgs coupling measurements



HXSWG YR4

High-mass BSM cross-sections



Borchemsky et al 2015

The NNPDF approach

A **novel approach to PDF determination**, improving the limitations of the traditional PDF fitting methods with the use of **advanced statistical techniques** such as **machine learning** and **multivariate analysis**

Non-perturbative PDF parametrization

- **Traditional approach**: based on **restrictive functional forms** leading to strong theoretical bias
- **NNPDF solution**: use **Artificial Neural Networks** as universal unbiased interpolants

PDF uncertainties and propagation to LHC calculations

- **Traditional approach**: limited to Gaussian/linear approximation
- **NNPDF solution**: based on the **Monte Carlo replica method** to create a probability distribution in the space of PDFs. Specially critical in **extrapolation regions** (**i.e.** high-x) for New Physics searches

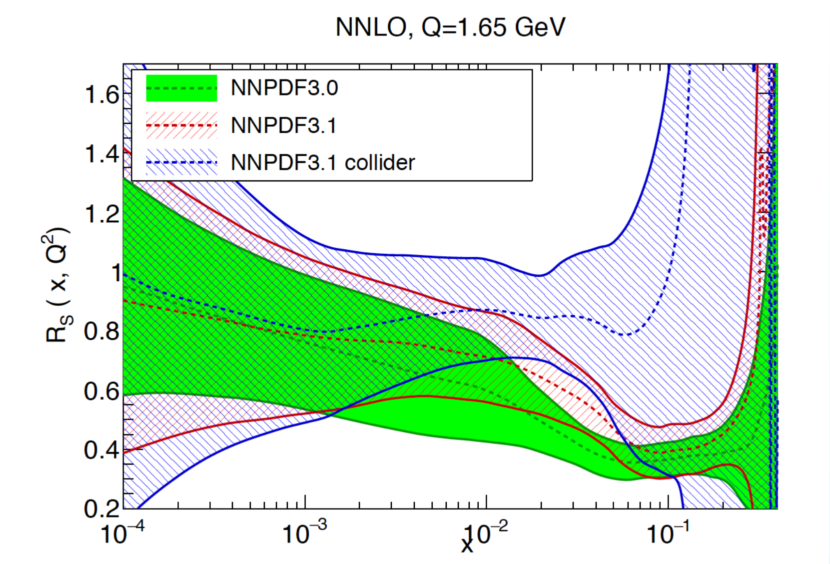
Fitting technique

- **Traditional approach**: deterministic minimization of χ^2, **flat directions** problem
- **NNPDF solution**: **Genetic Algorithms** to explore efficiently the vast parameter space, with **cross-validation** to avoid fitting stat fluctuations

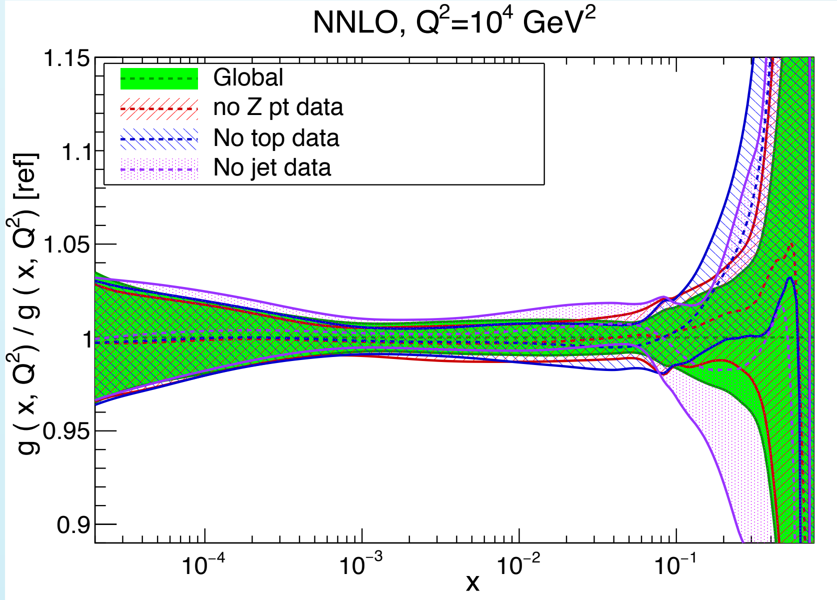
The PDF fitting landscape

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



NNPDF3.1



The NNPDF Collaboration 17

Why NNPDF3.1?

An **update of the NNPDF global analysis** is motivated by:

☑ The availability of a wealth of **high-precision PDF-sensitive measurements** from the Tevatron, ATLAS, CMS and LHCb, including processes such as the **Z p_T** and **differential distributions in top-quark production** that have never been used before in a PDF fit

☑ The striking **recent progress in NNLO QCD calculations**, which allows to include the majority of PDF-sensitive collider measurements into a **fully consistent NNLO global analysis**

☑ The recent realisation that **fitting the charm PDF** has several advantages in the global QCD fit (beyond comparison with non-perturbative models), in particular **stabilise the dependence with m_{charm}** and improve the **data/theory agreement** for some of the most precise collider observables.

The NNPDF Collaboration 16

Fitted vs Perturbative charm

- The **change of scheme** between a theory with *3 active quarks* and another with *4 active quarks* is determined by the **matching conditions:**

$$\alpha_s^{(4)}(m_h^2) = \alpha_s^{(3)}(m_h^2) + \mathcal{O}(\alpha_s^3)\,,$$
$$f_i^{(4)}(m_h^2) = \sum_j K_{ij}(m_h^2) \otimes f_j^{(3)}(m_h^2)$$

- Most global fits (including NNPDF3.0) **assume that $c^{(3)}(x)=0$,** in other words, the scale-independent (intrinsic) charm content of the proton vanishes

- Whether or not **$c^{(3)}(x)=0$ is a good assumption** can only be **determined from data**

- Releasing this assumption leads to the **modified matching conditions**

$$f_h^{(3)} = f_h^{(4)}(Q^2) - \alpha_s^{(4)}(Q^2)\left(K_{hh}^{(1)}(m_h^2) + P_{qq}^{(0)}L\right) \otimes f_h^{(4)}(Q^2) - \alpha_s^{(4)}(Q^2) L P_{qg}^{(0)} \otimes g^{(4)}(Q^2)$$

Scale-independent (intrinsic) charm

Scale-dependent charm PDF: to be determined from data at $Q_0>m_c$

Perturbative contribution from charm-anticharm radiation off gluons

NNPDF3.1 fits obtained **both** for a **fitted** and for a **perturbative charm PDF**

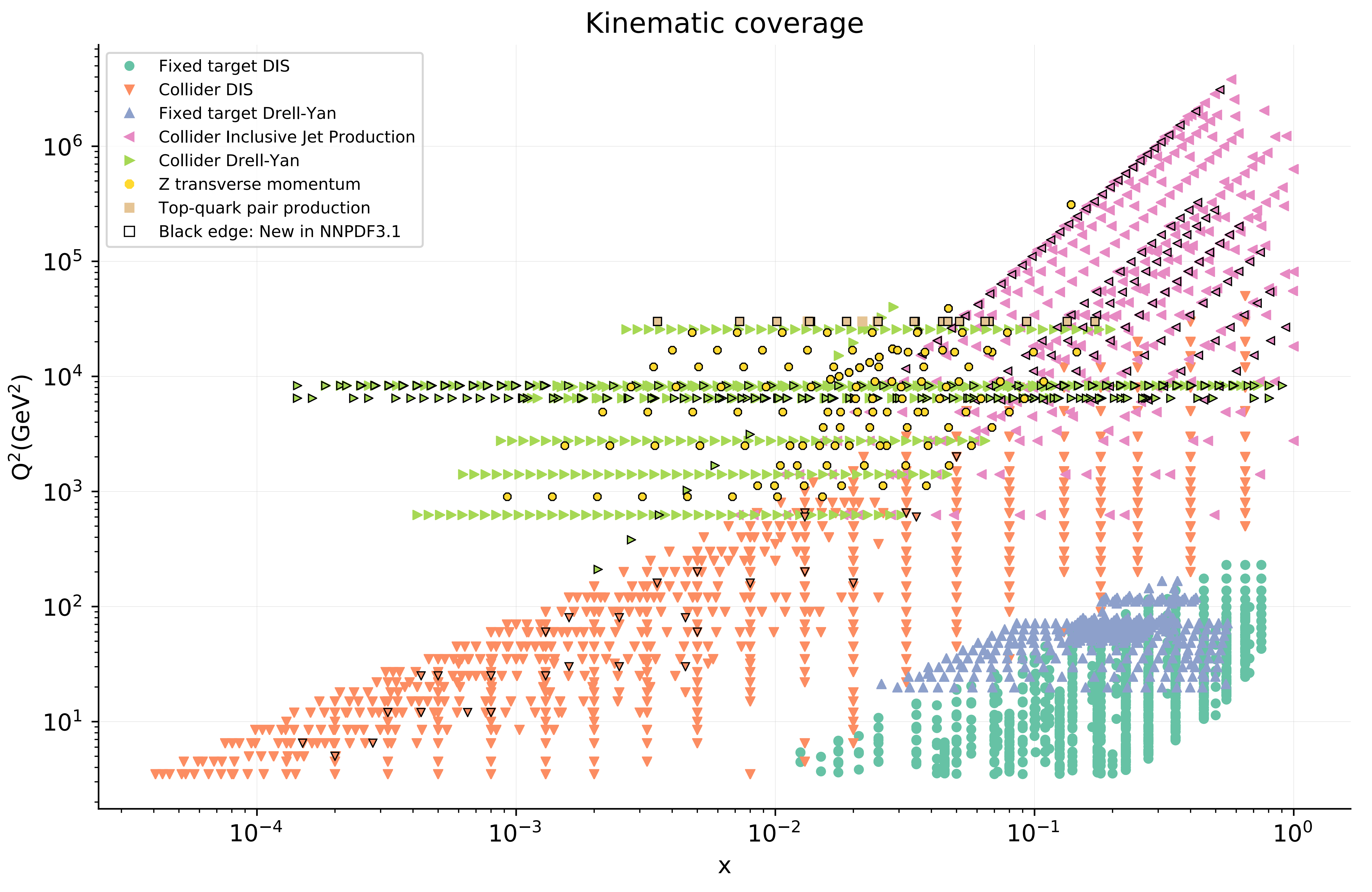
Ball, Bonvini, Rottoli, JHEP 17

Ball et al, PLB 17

New datasets in NNPDF3.1

Measurement	Data taking	Motivation
Combined HERA inclusive data	Run I+II	quark singlet and gluon
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive W, Z rap 7 TeV	2011	strangeness
ATLAS inclusive jets 7 TeV	2011	large-x gluon
ATLAS low-mass Drell-Yan 7 TeV	2010+2011	small-x quarks
ATLAS Z pT 7,8 TeV	2011+2012	medium-x gluon and quarks
ATLAS and CMS tt differential 8 TeV	2012	large-x gluon
CMS Z (pT,y) 2D xsecs 8 TeV	2012	medium-x gluon and quarks
CMS Drell-Yan low+high mass 8 TeV	2012	small-x and large-x quarks
CMS W asymmetry 8 TeV	2012	quark flavor separation
CMS 2.76 TeV jets	2012	medium and large-x gluon
LHCb W,Z rapidity dists 7 TeV	2011	large-x quarks
LHCb W,Z rapidity dists 8 TeV	2012	large-x quarks

New datasets in NNPDF3.1



Fit quality: χ^2

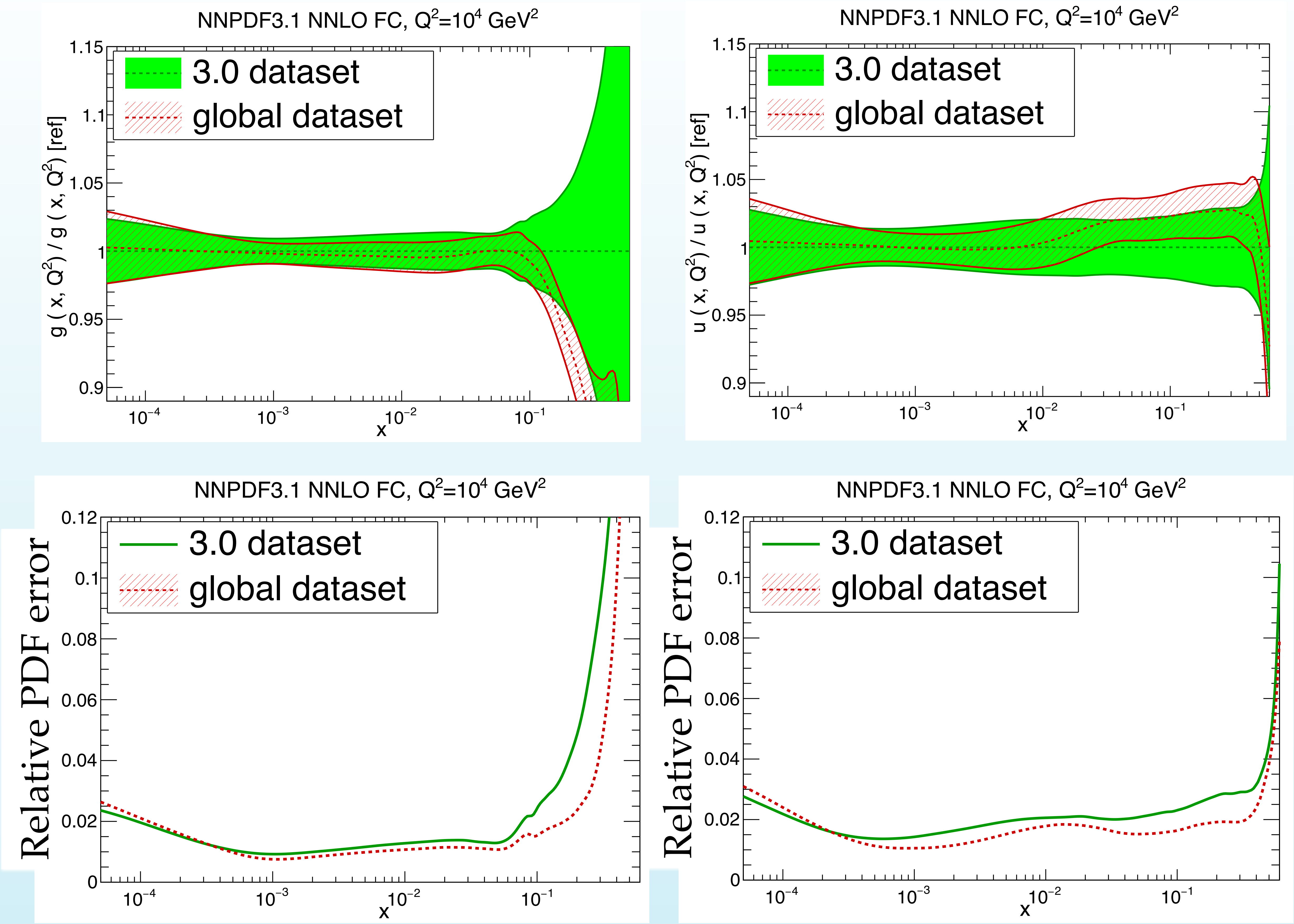
	NNLO FittedCharm	NNLO PertCharm	NLO FittedCharm	NLO PertCharm
HERA	1.16	1.21	1.14	1.15
ATLAS	1.09	1.17	1.37	1.45
CMS	1.06	1.09	1.20	1.21
LHCb	1.47	1.48	1.61	1.77
TOTAL	1.148	1.187	1.168	1.197

- For collider data, **NNLO theory** leads to a markedly better fit quality that than **NLO** (since the new data included has small experimental uncertainties, and NNLO corrections mandatory)

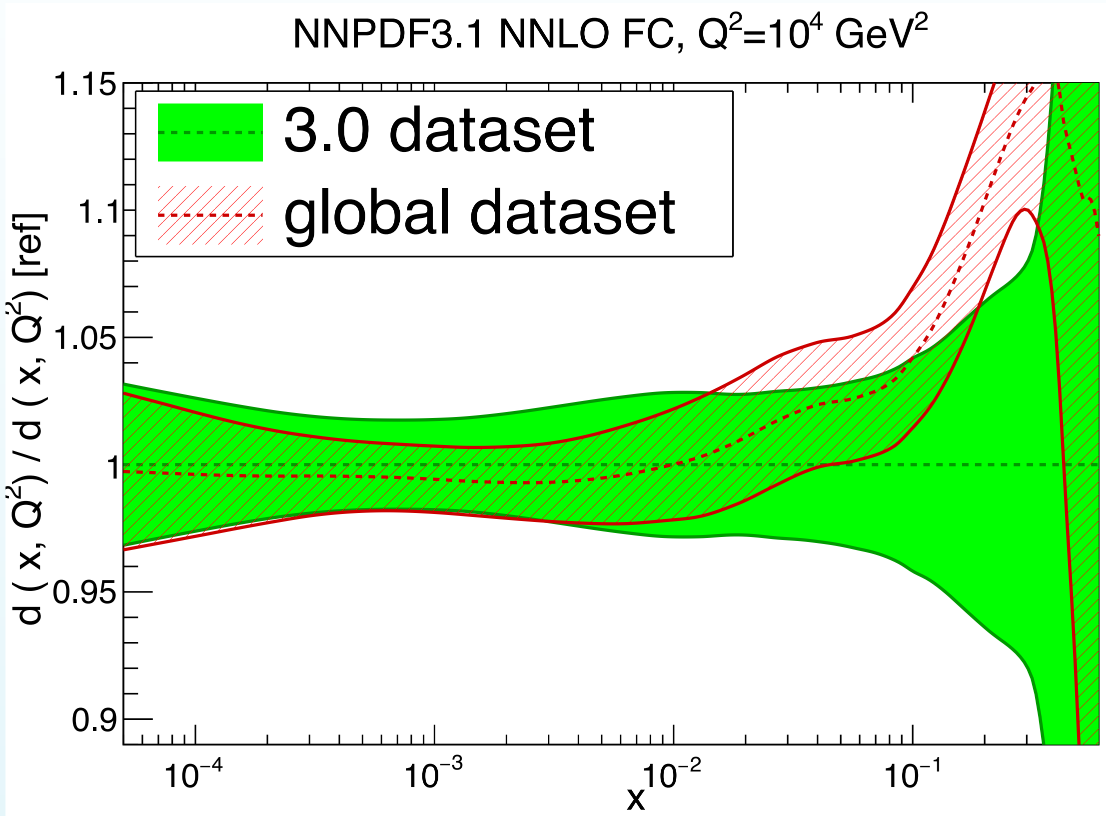
- The global PDF analysis where the charm PDF is fitted leads to a **slightly superior fit quality** than assuming a perturbatively generated charm PDF

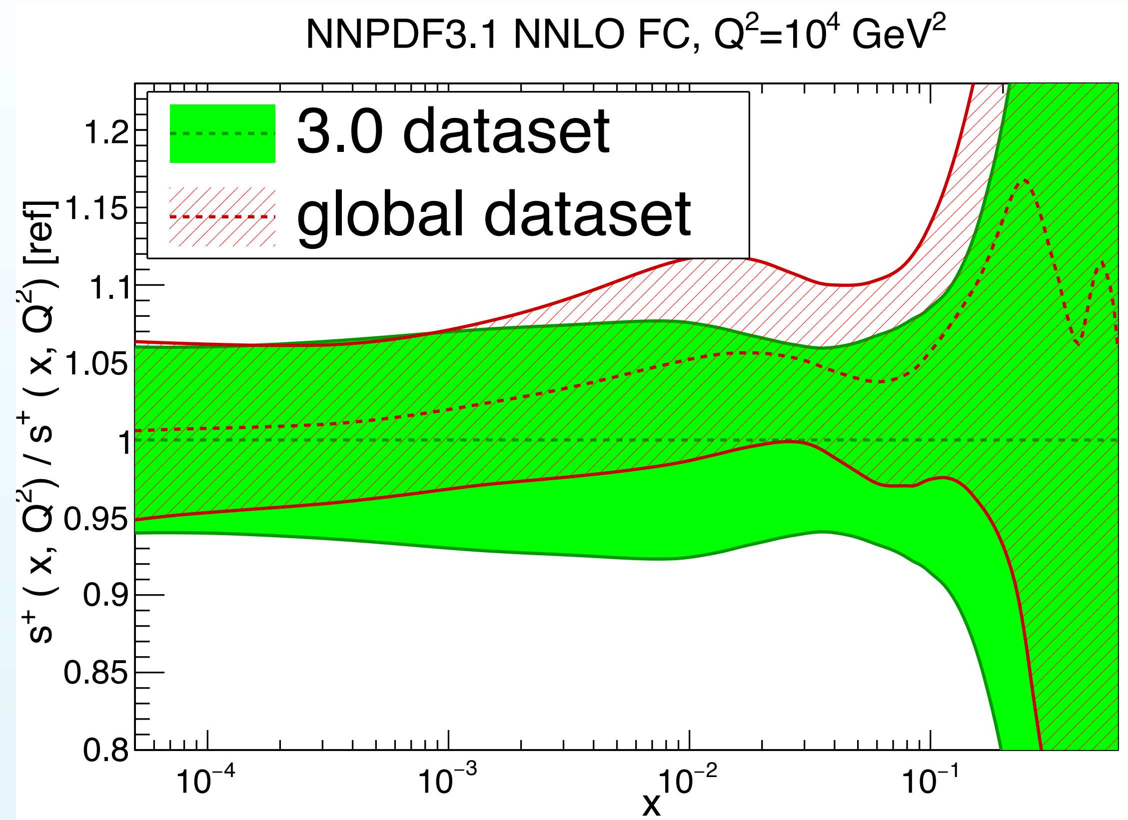
- In general **good description of all the new collider measurements** included in NNPDF3.1

Impact of new data

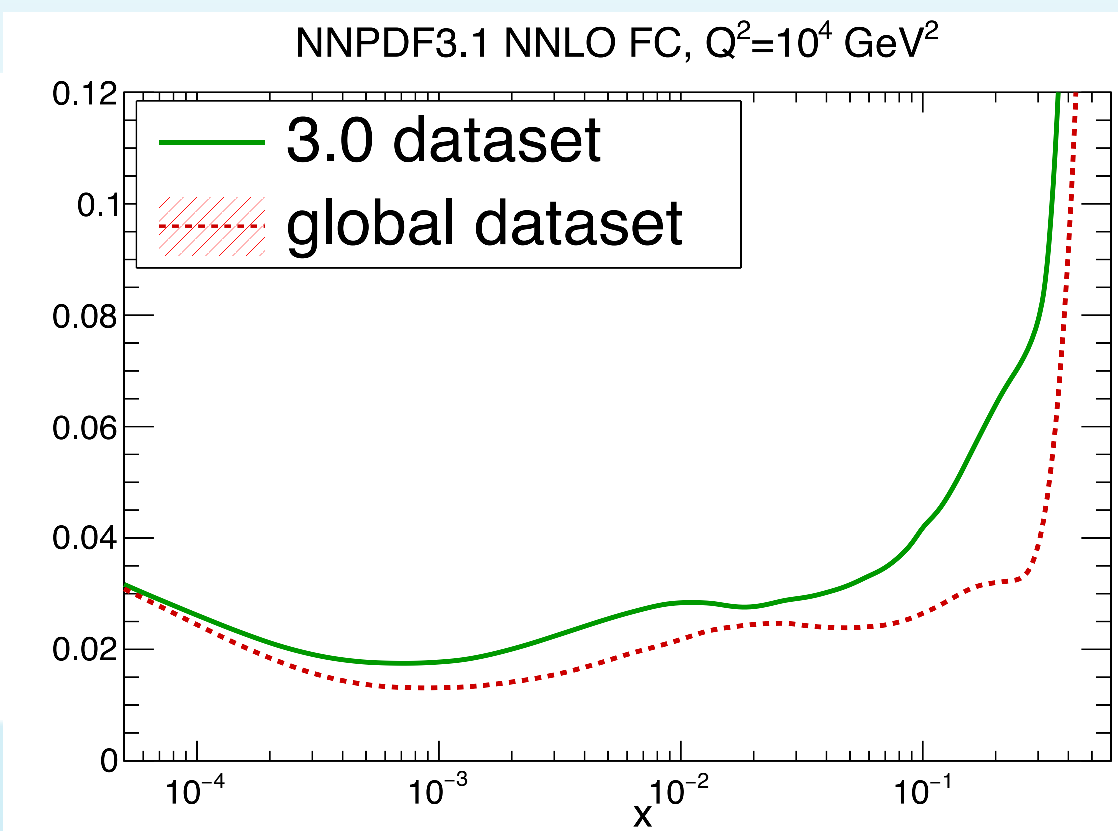


Impact of new data





Relative PDF error



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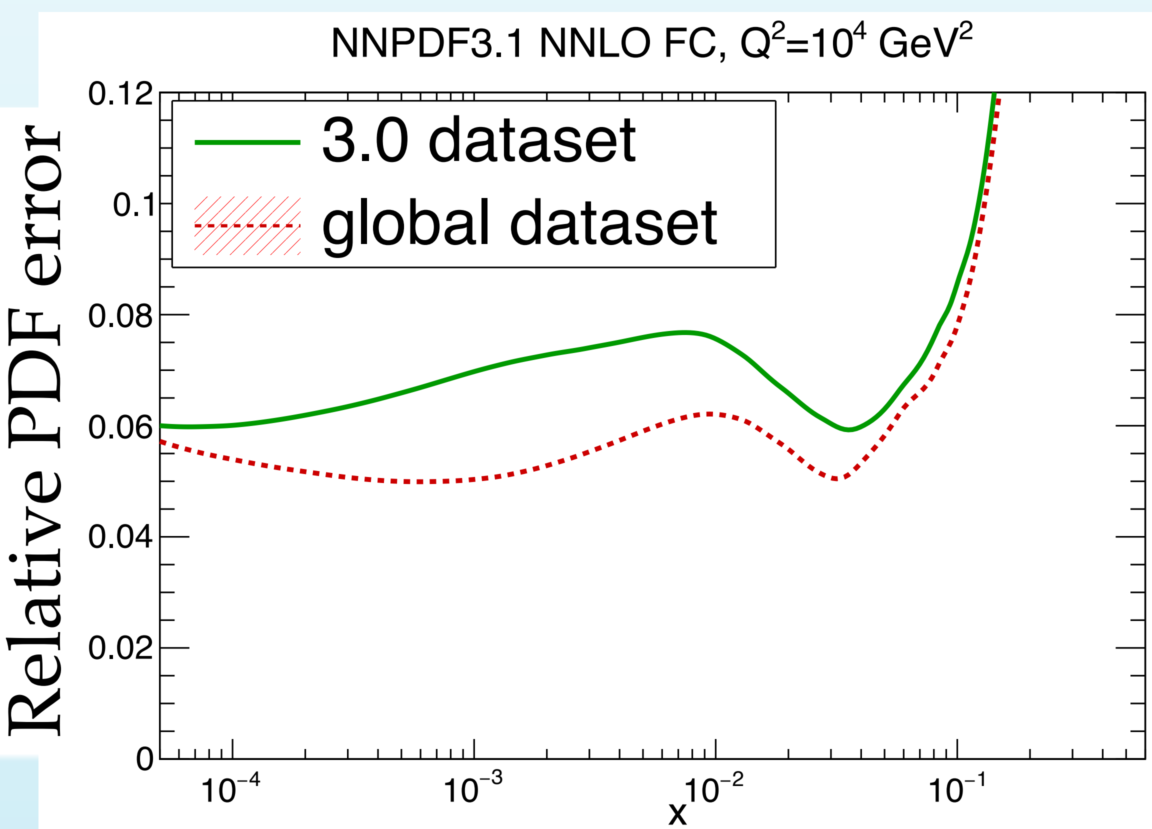

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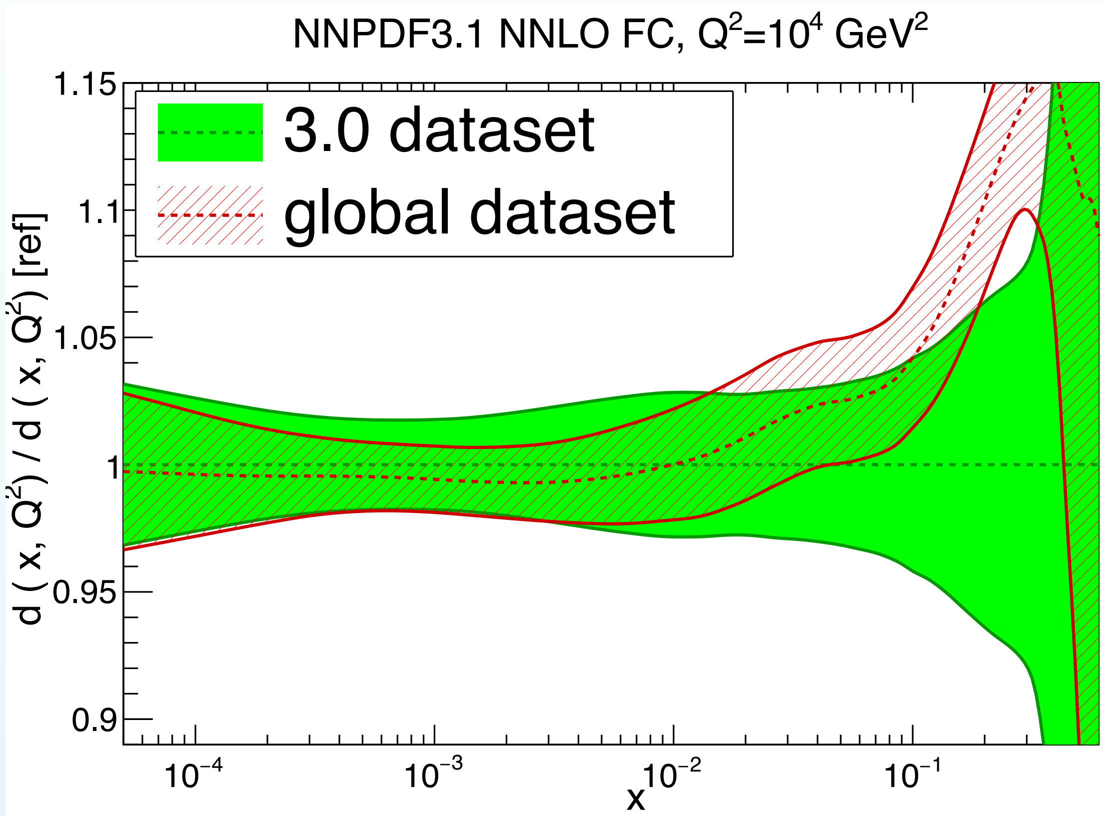
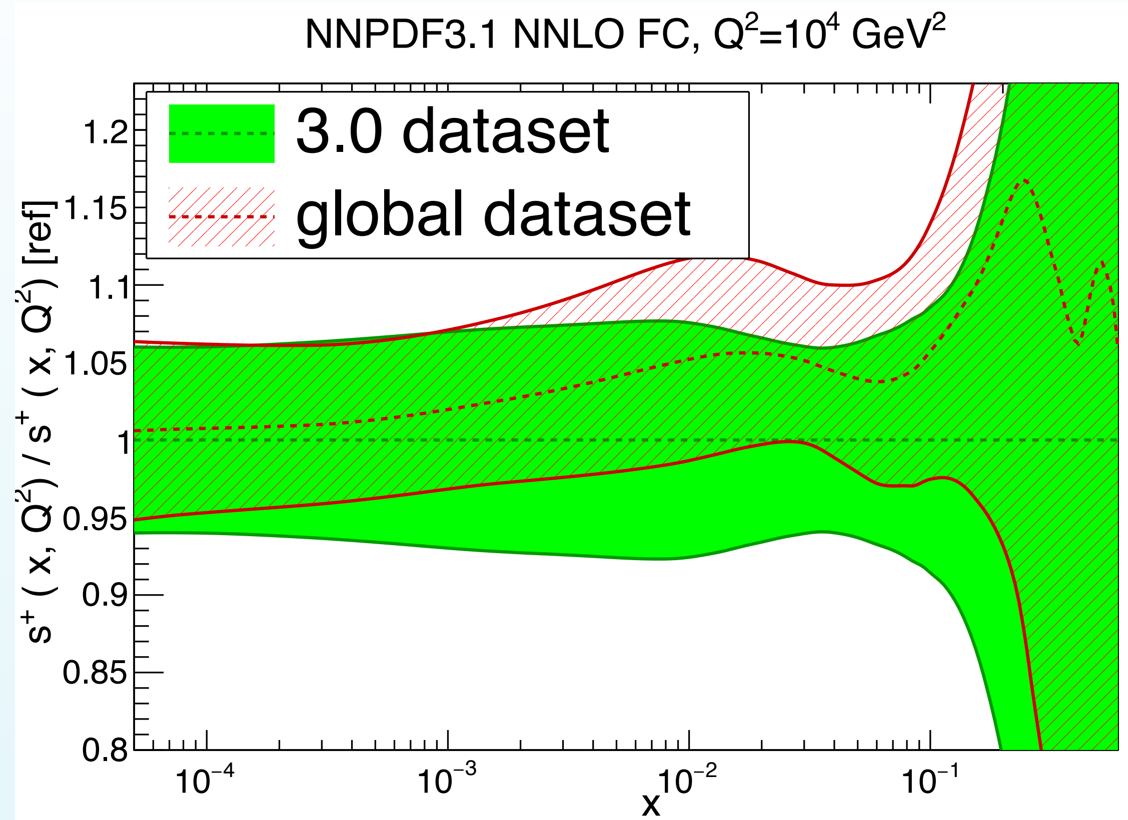
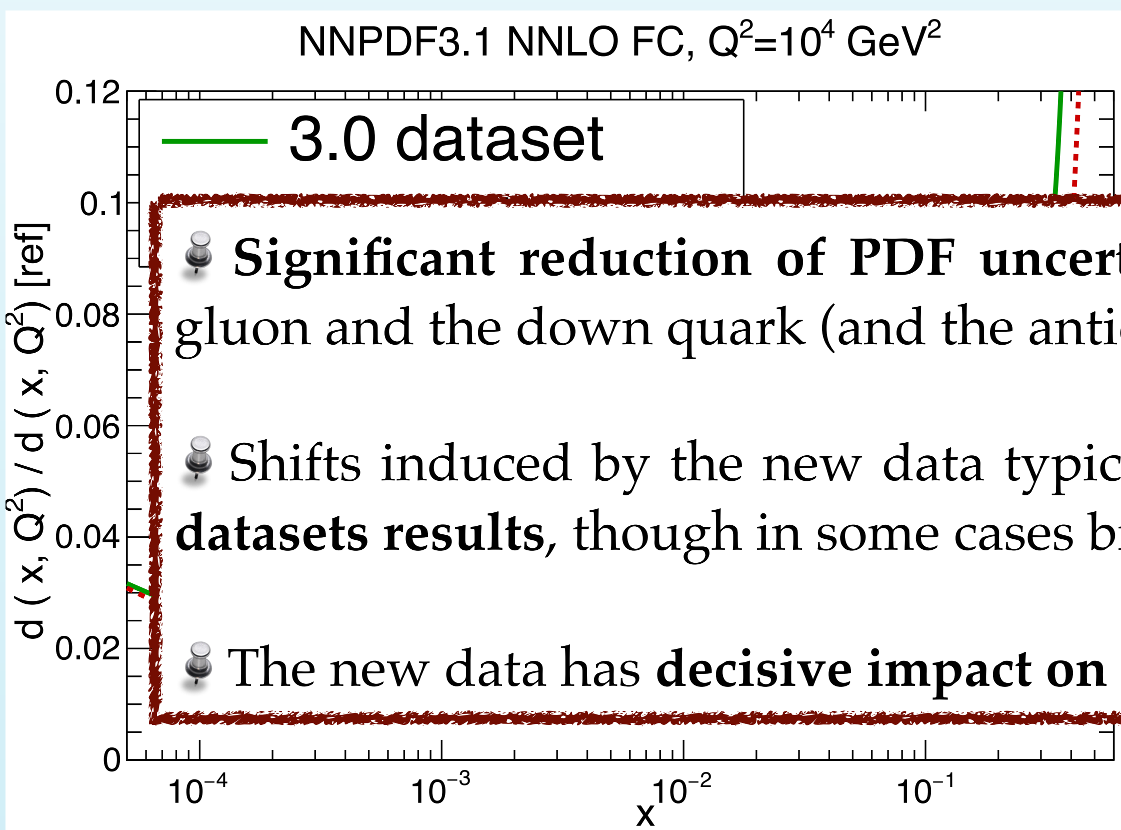
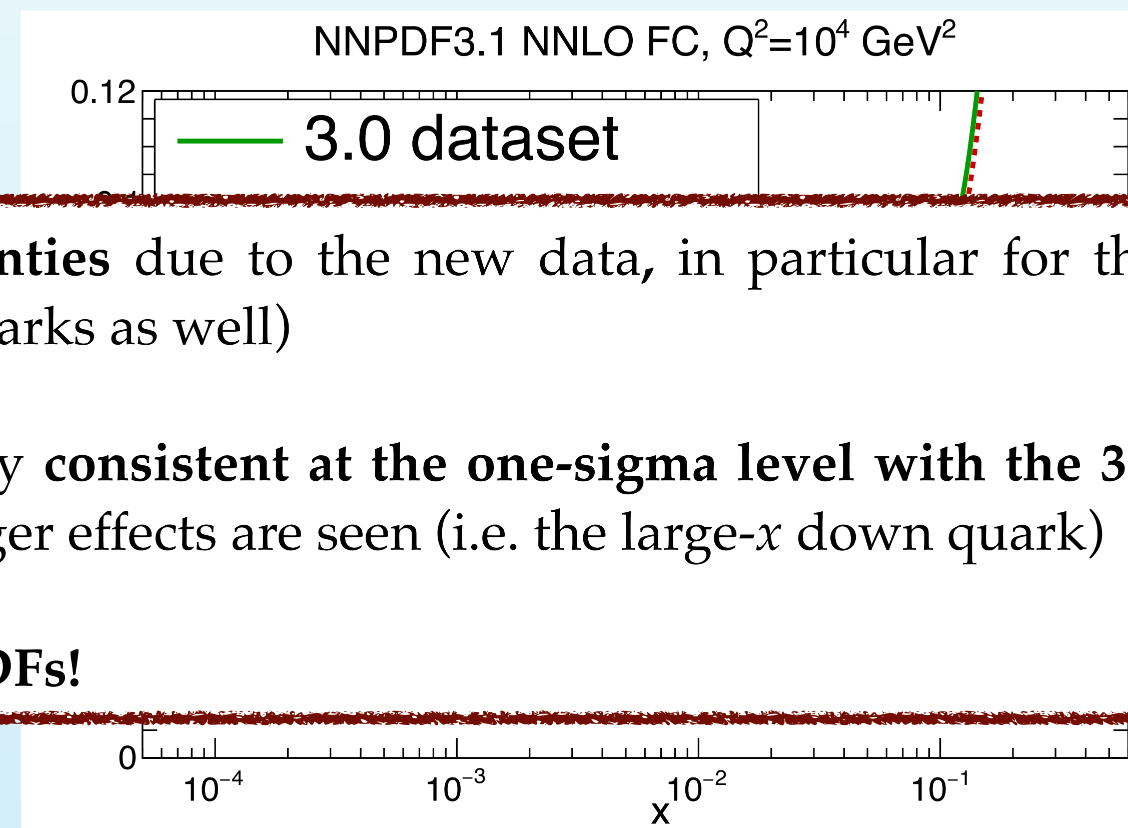


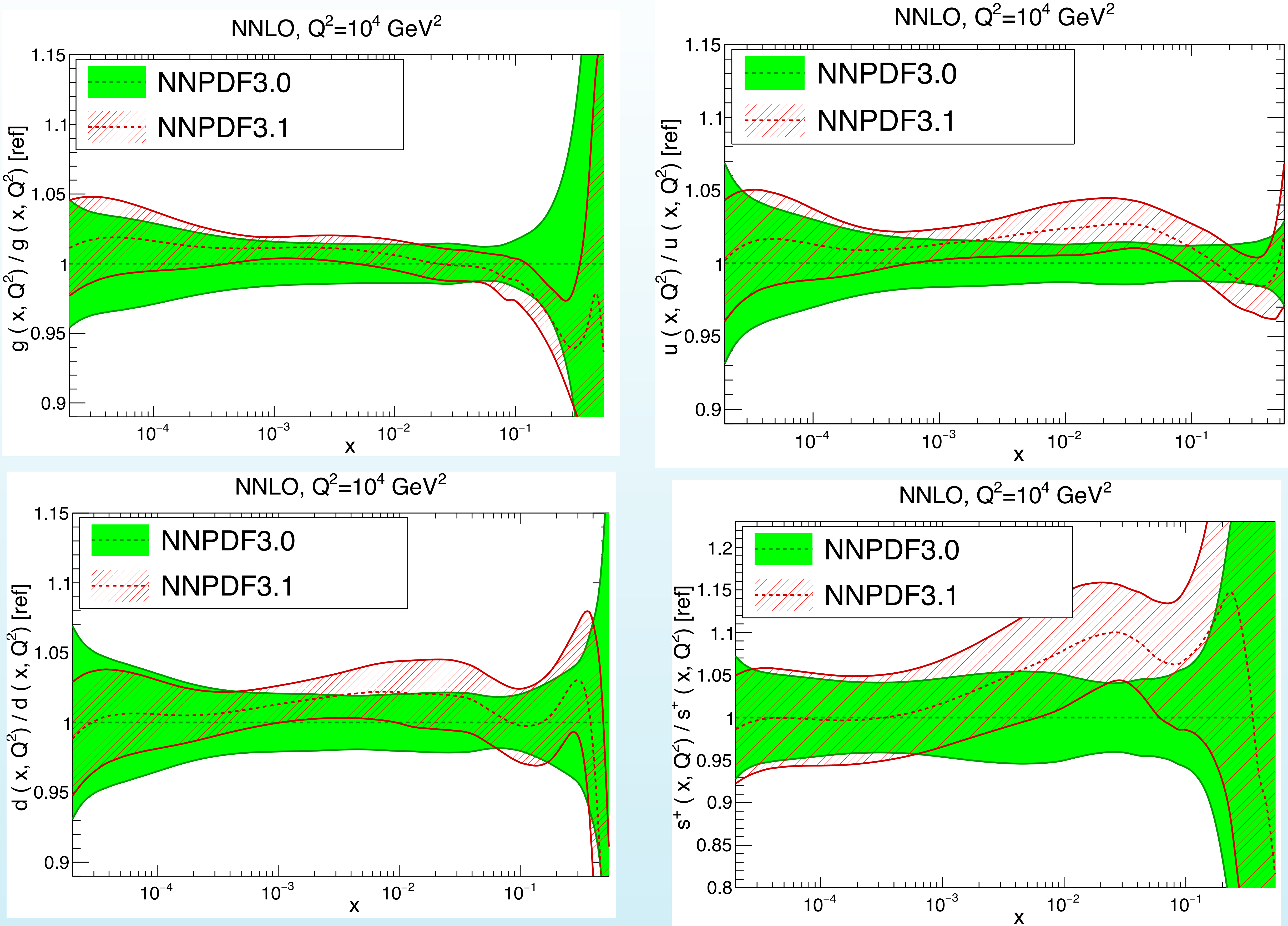






- **Significant reduction of PDF uncertainties** due to the new data, in particular for the gluon and the down quark (and the antiquarks as well)
- Shifts induced by the new data typically **consistent at the one-sigma level with the 3.0 datasets results**, though in some cases bigger effects are seen (i.e. the large-x down quark)
- The new data has **decisive impact on PDFs!**

Comparison with NNPDF3.0



The large-x gluon from top-quark production

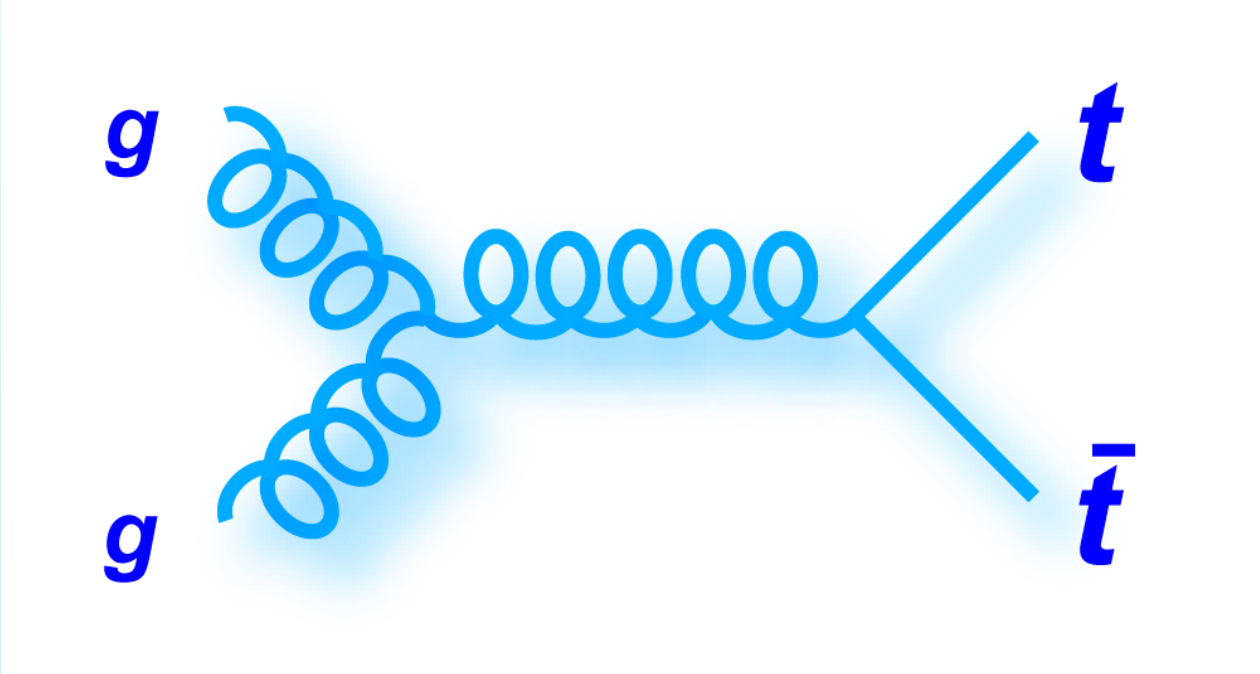
- Top-quark pair production driven by the **gluon-gluon luminosity**

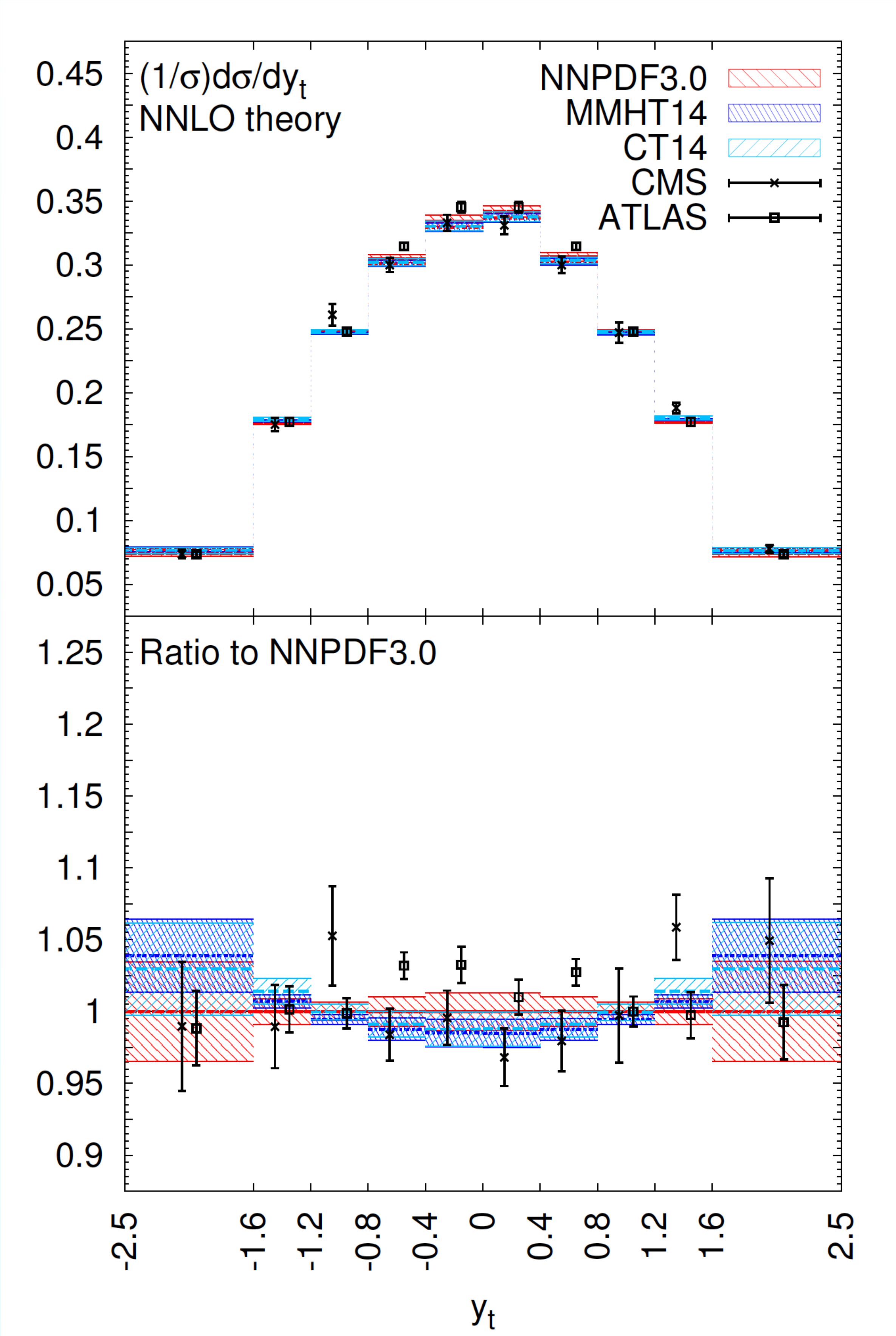
- **NNLO calculations for stable top quarks** available (with decays in the pipeline)

- Recent **precision data from ATLAS and CMS at 8 TeV** with full breakdown of statistical and systematic uncertainties

- For the first time, included ATLAS+CMS 8 TeV differential top measurements into the **global PDF fit**

Czakon, Hartland, Mitov, Nocera, Rojo 16





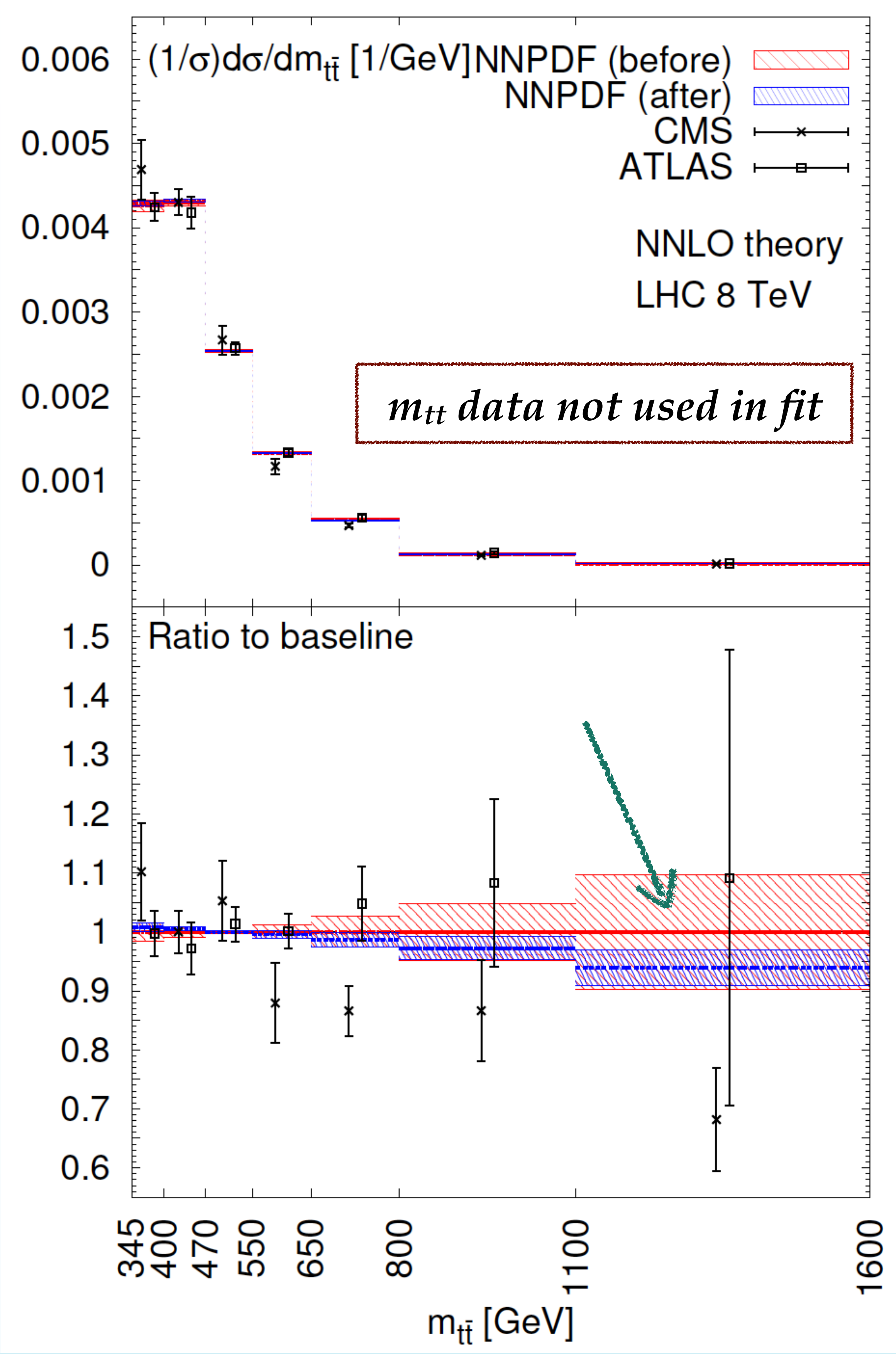
The large-x gluon from top-quark production

- PDF uncertainties reduced by more than a factor two for $\mathbf{m_{tt} \gtrsim 500}$ **GeV**

- Our choice of fitted distributions, $\mathbf{y_t}$ and $\mathbf{y_{tt}}$, reduces the **risk of** ***BSM contamination*** (kinematical suppression of resonances), which might show up instead in $\mathbf{m_{tt}}$ and $\mathbf{p^t_T}$, where PDF uncertainties are now much smaller

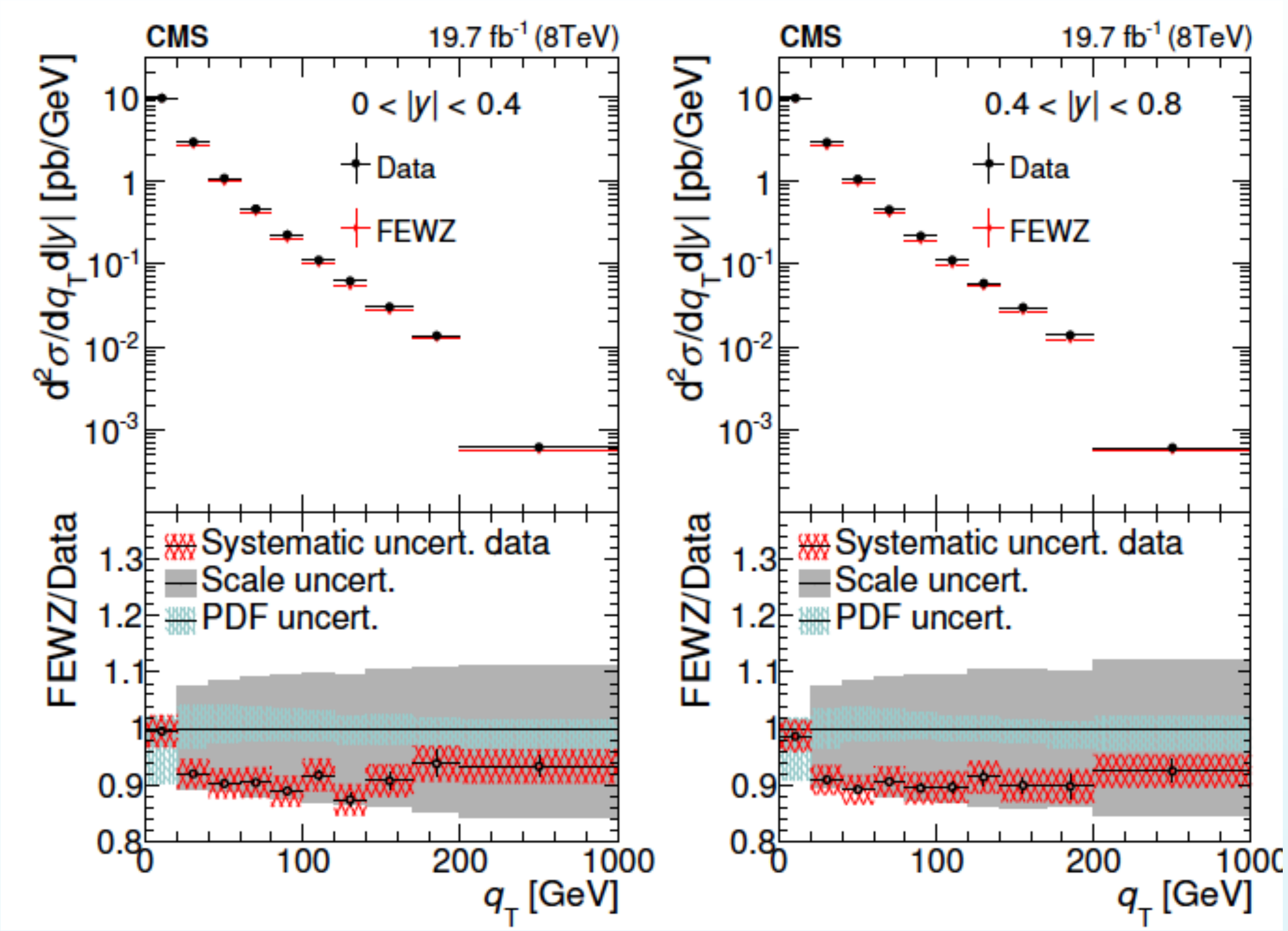
- Self-consistent program to **use top data to provide better theory predictions**

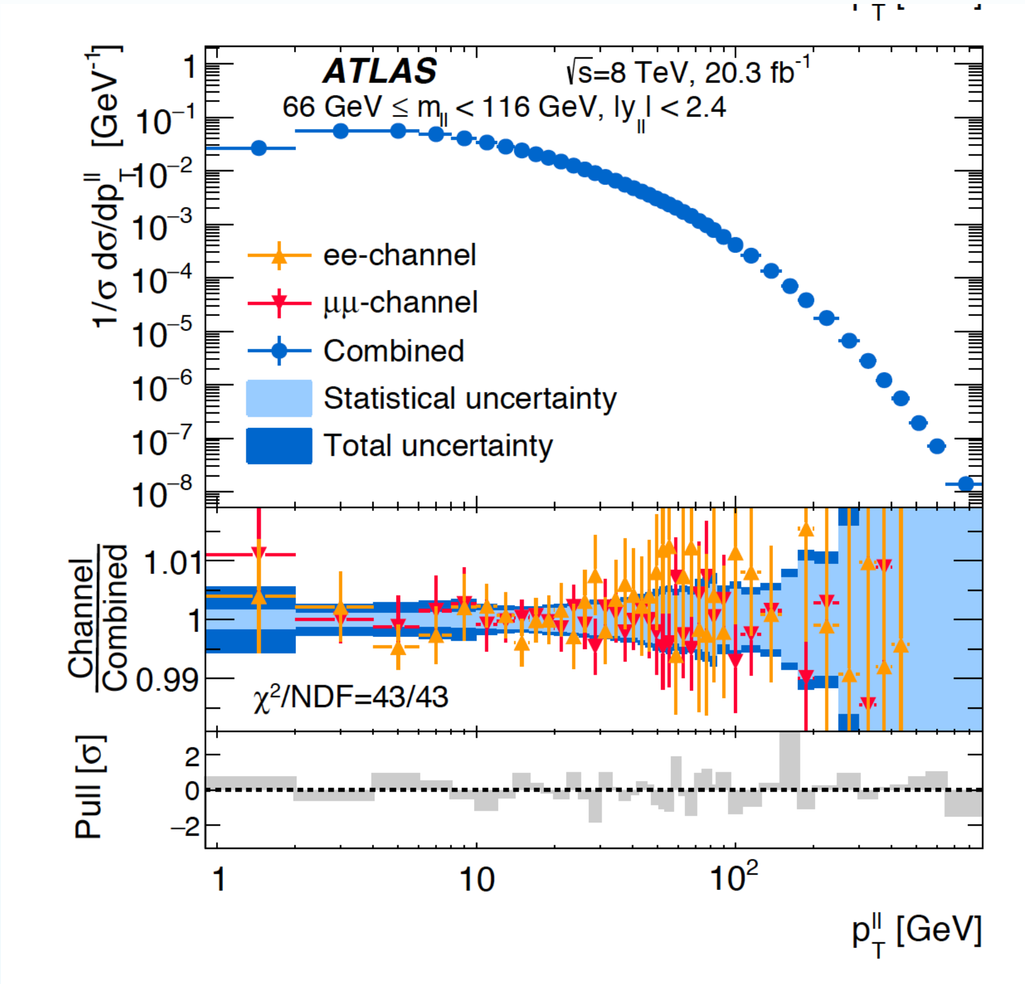
Improved sensitivity to BSM dynamics with top-quark final states



Impact of Z p_T data

See also Boughezal et al 17

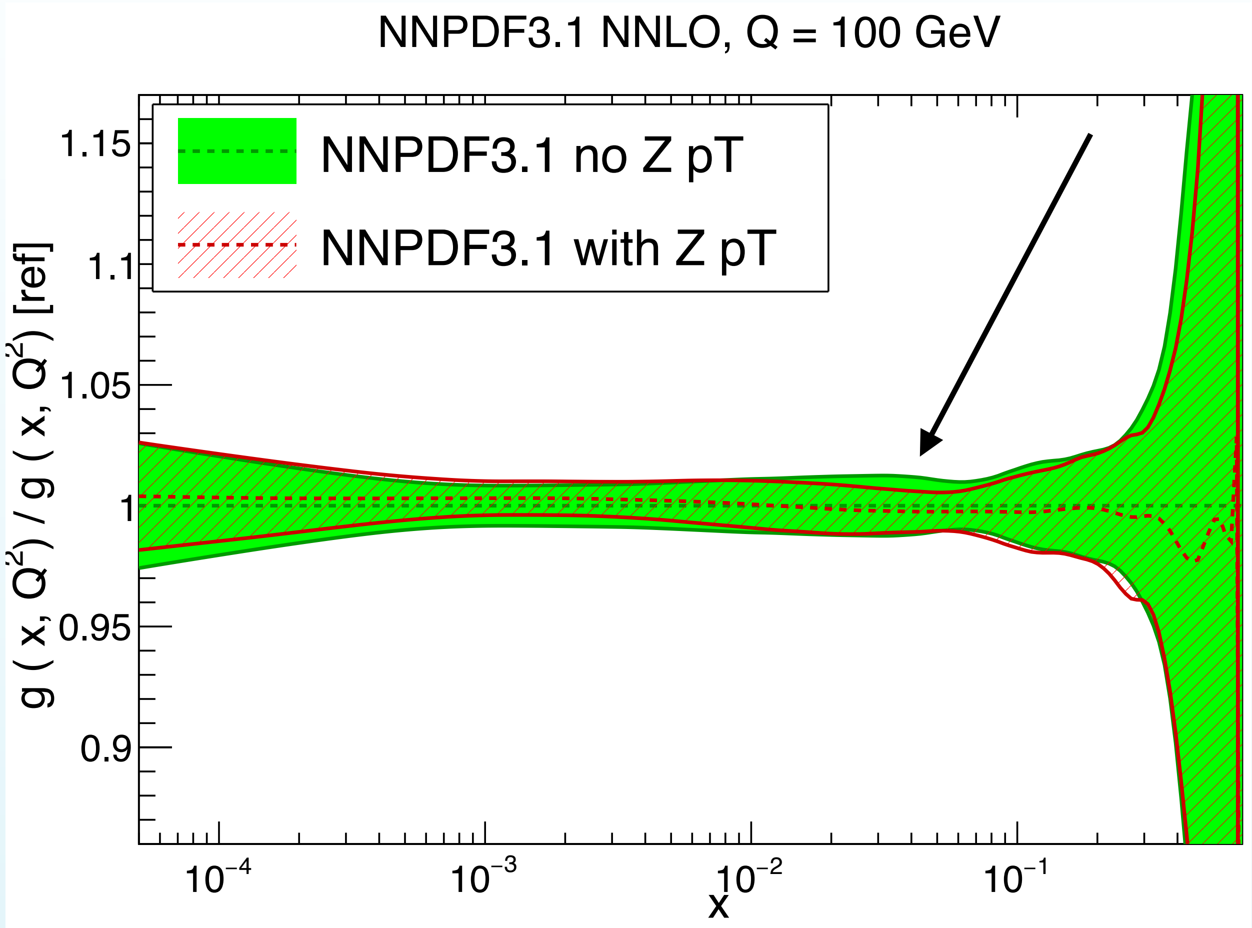


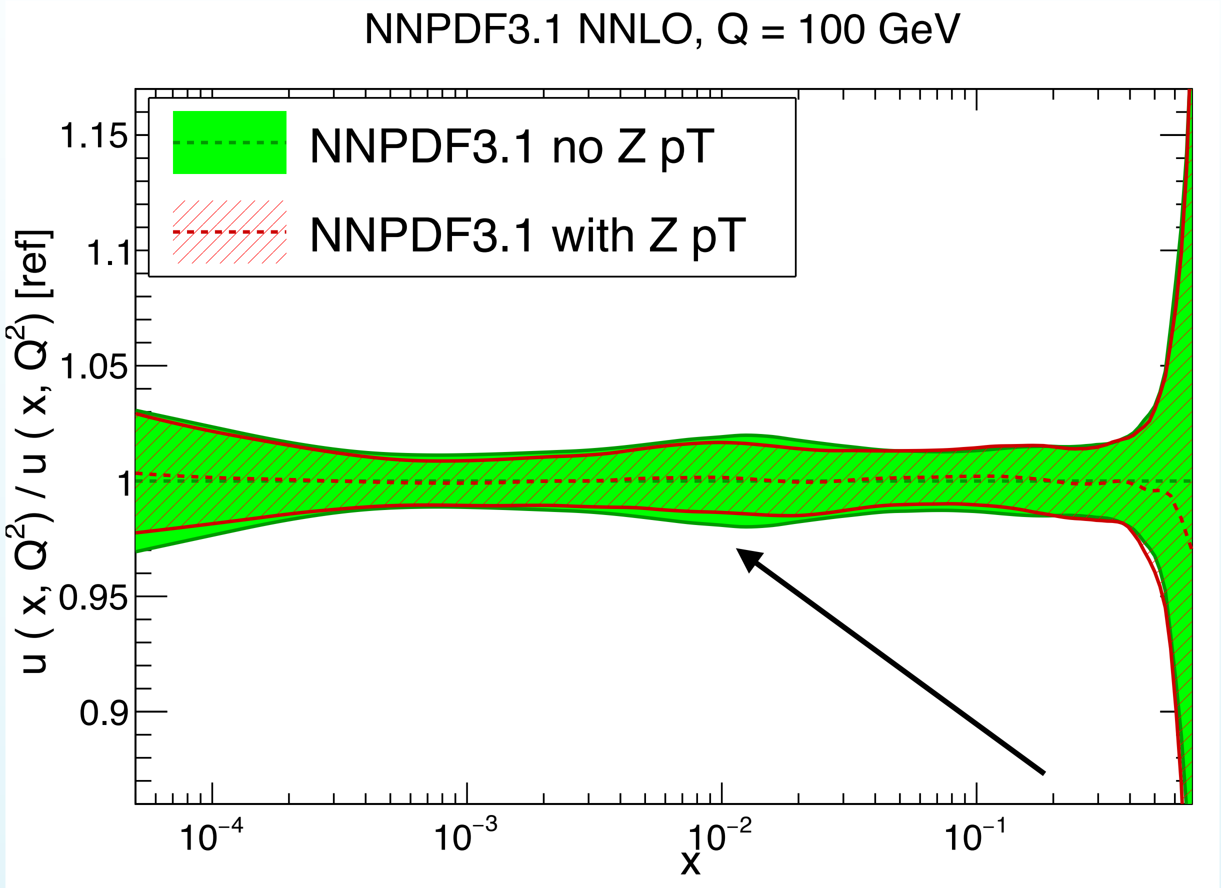


- **For the first time in a global fit, the transverse momentum of the Z boson has been included**
- **NNLO calculations for K-factors** very CPU time intensive
- All the Z p_T measurements from **ATLAS and CMS at 8 TeV** included in NNPDF3.1

	ATLAS 8 TeV (y,pT)	ATLAS 8 TeV (M,pT)	CMS 8 TeV (y,pT)
χ^2 (NNLO)	0.93	0.94	1.31
χ^2 (NLO)	1.17	1.78	3.62

Impact of Z p_T data





- **Moderate error reduction in the intermediate-x** region, excellent consistency with the other experiments in the global fit.

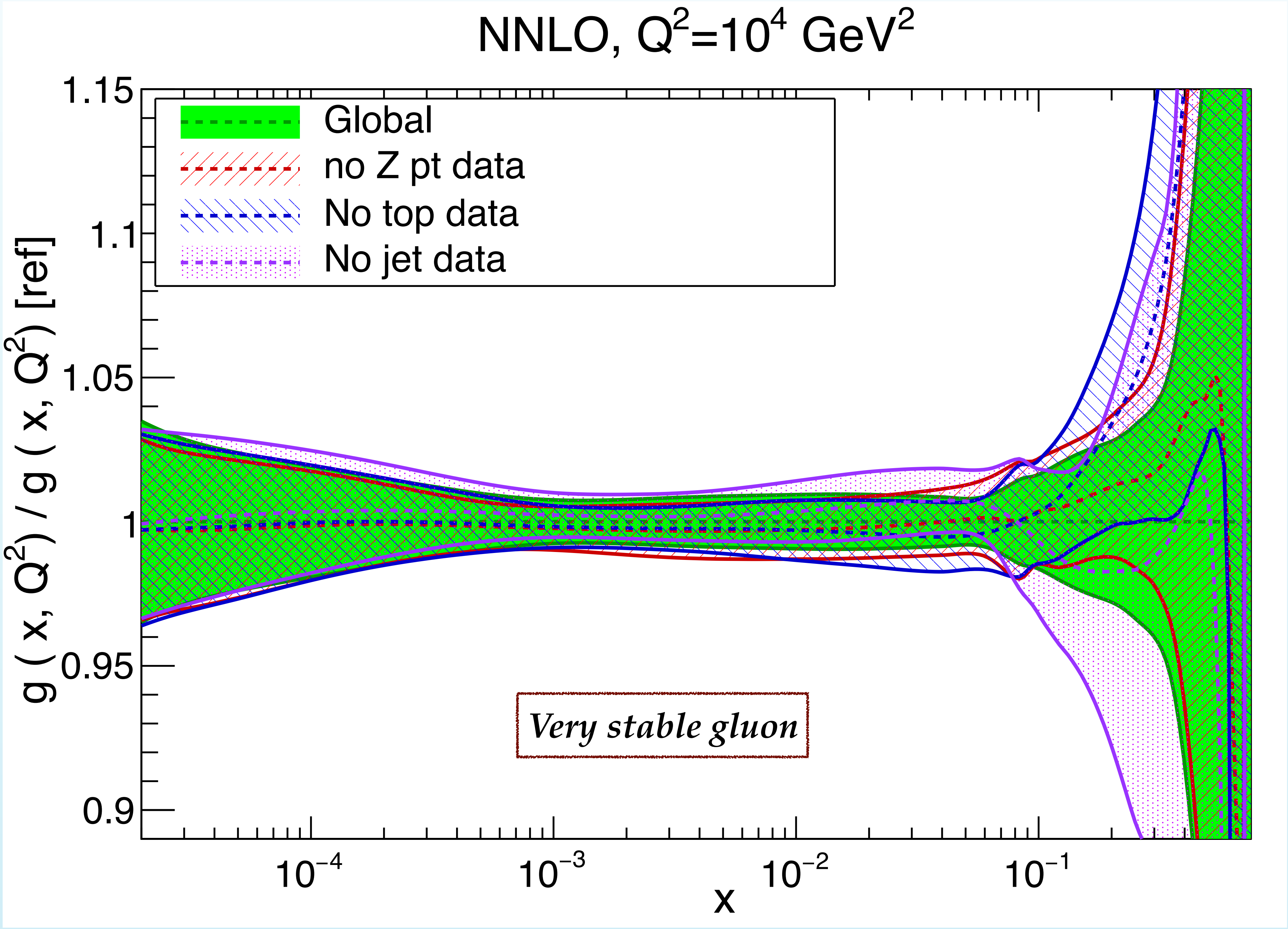
- Given very high precision (sub-percent) of these experiments, this is quite a non-trivial achievement

- The ATLAS Z p_T 7 TeV data not included in NNPDF3.1. If included, **poor data/theory agreement, χ^2 = 3.5,** and shifts in gluon and quarks. ***Tension with 8 TeV data?***

Impact on the gluon

- In NNPDF3.1 we have three groups of processes that provide **direct information on the gluon**: inclusive jets, top pair differential, and the Z transverse momentum

- Are the constraints from each of these groups **consistent among them?** Yes!



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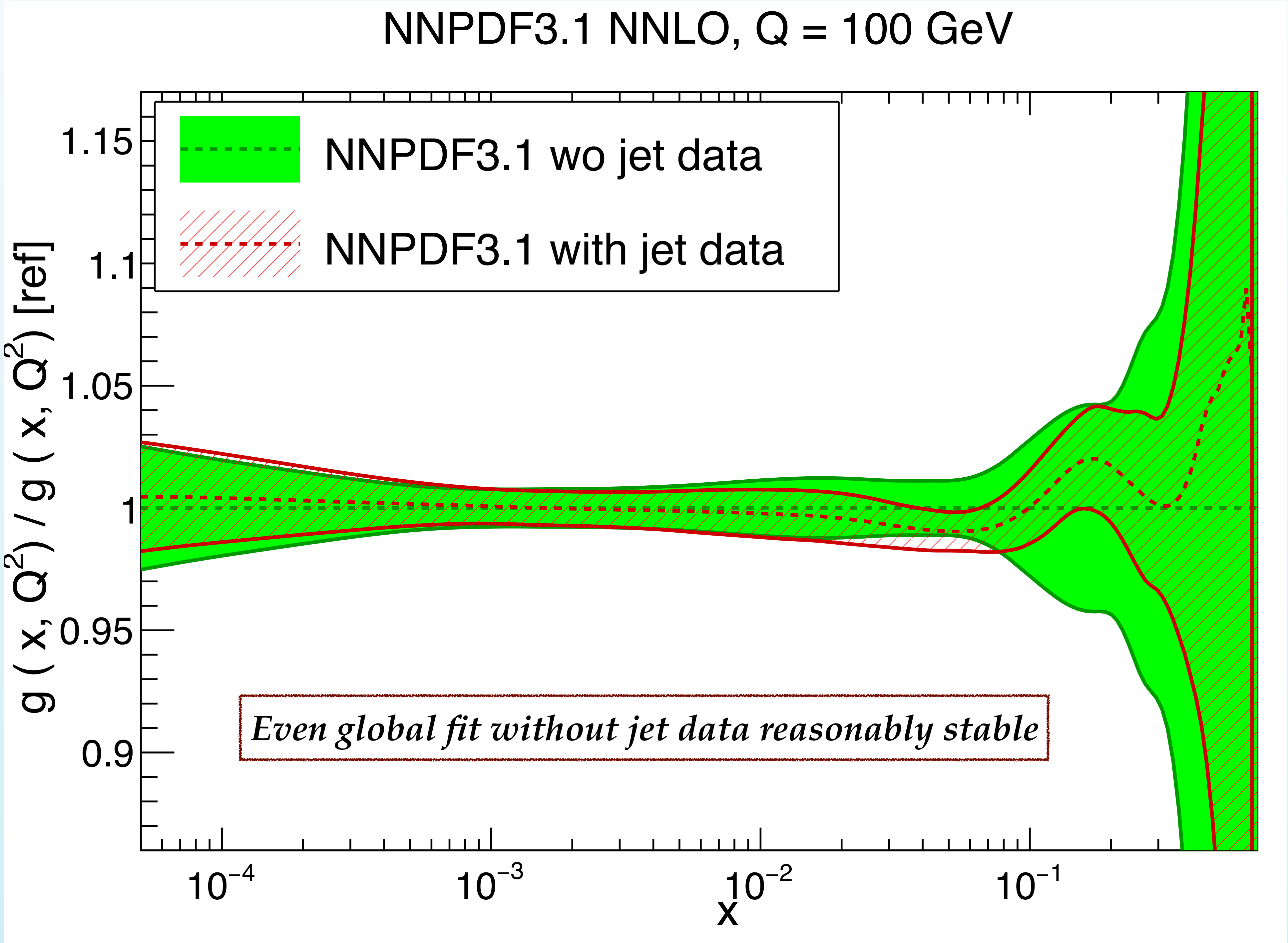
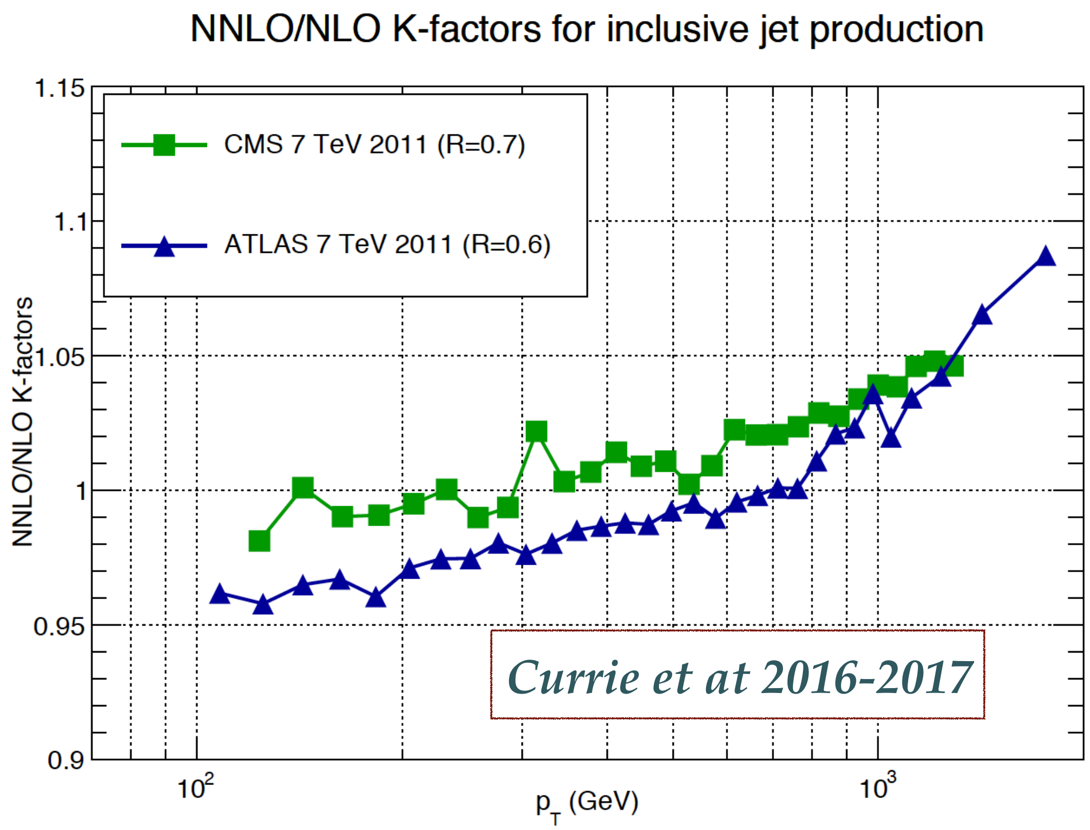
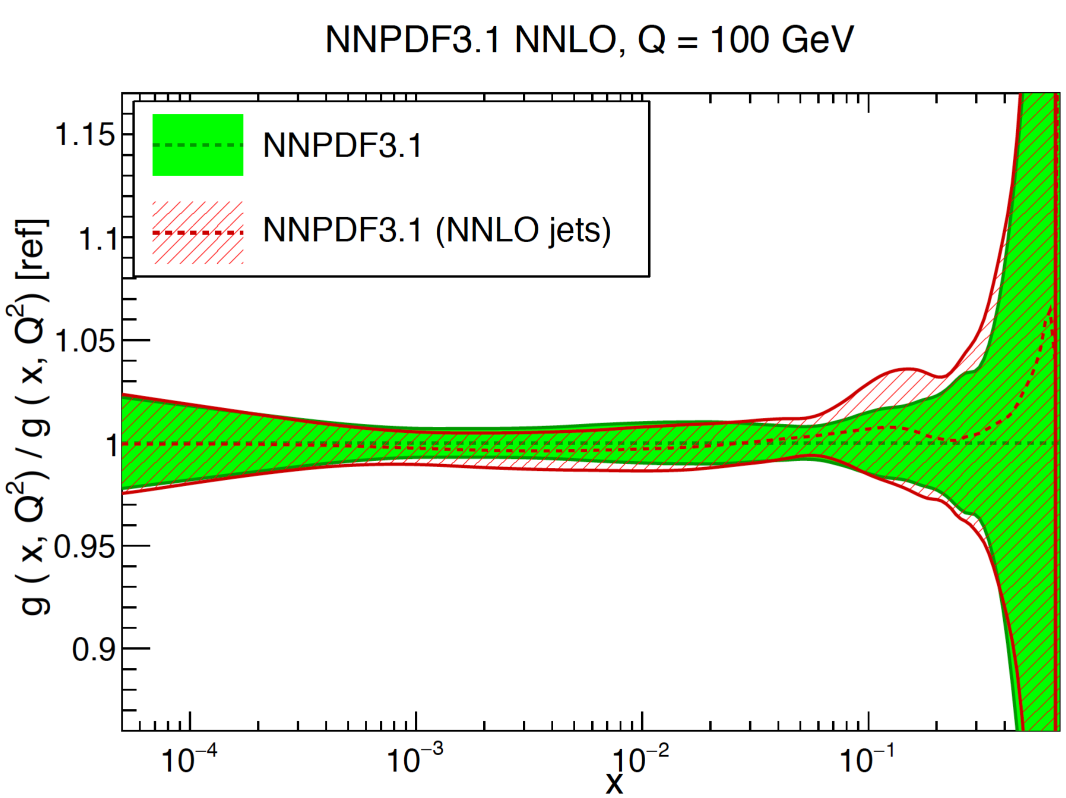


NNLO jets and PDF fits

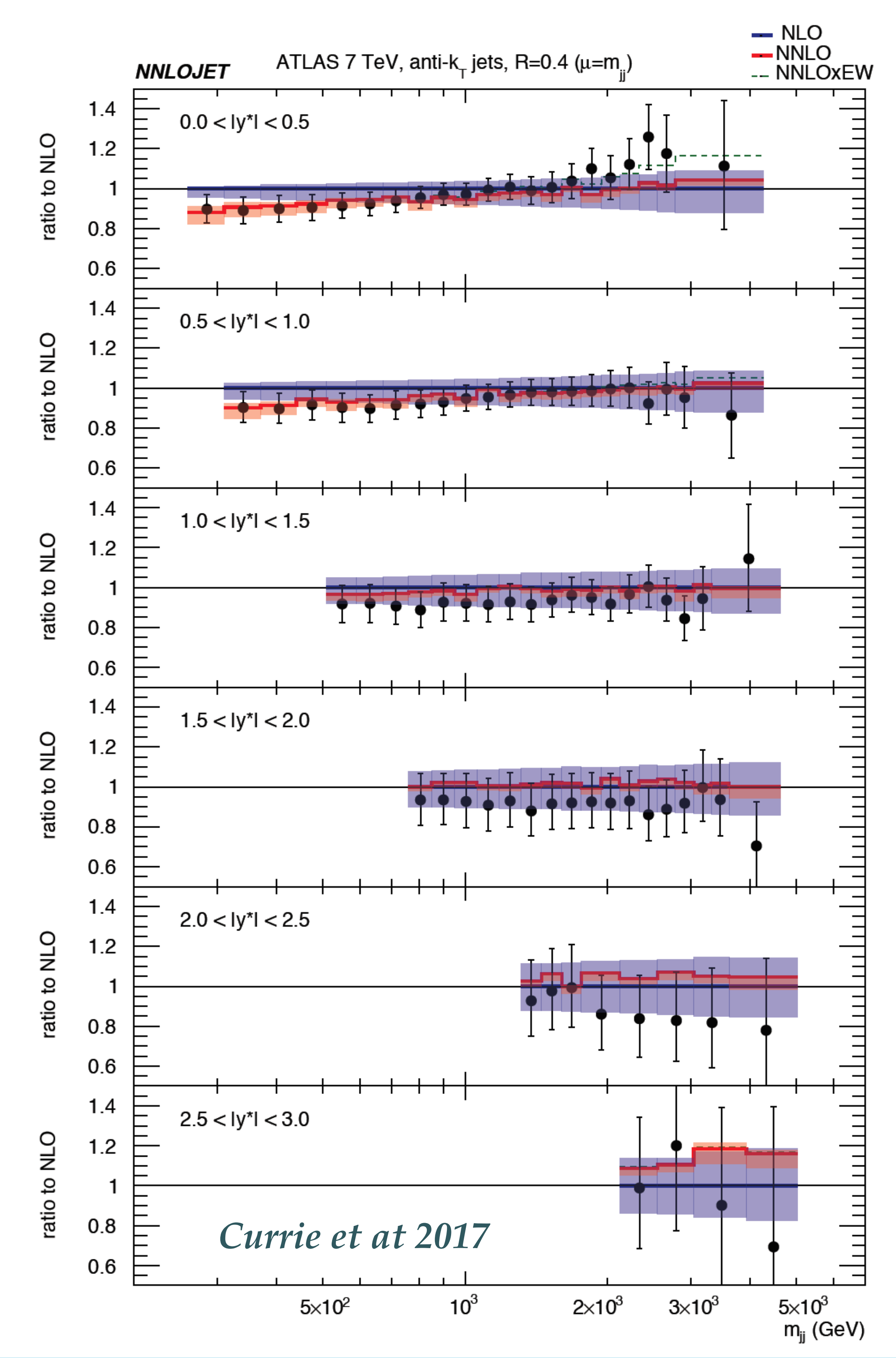




- NNPDF3.1 NNLO: includes jet data using **NNLO evolution and NLO matrix elements**, with scale variations as additional TH systematic error
- The **jet p_T** is always used as central scale choice
- Also tried variants where ATLAS and CMS 2011 7 TeV data included **using exact NNLO theory**
- Very small 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

NNLO jets and PDF fits



- The availability of **NNLO corrections** to both **inclusive jet** and **dijet production** motivates revisiting in detail their effects in the PDF fit

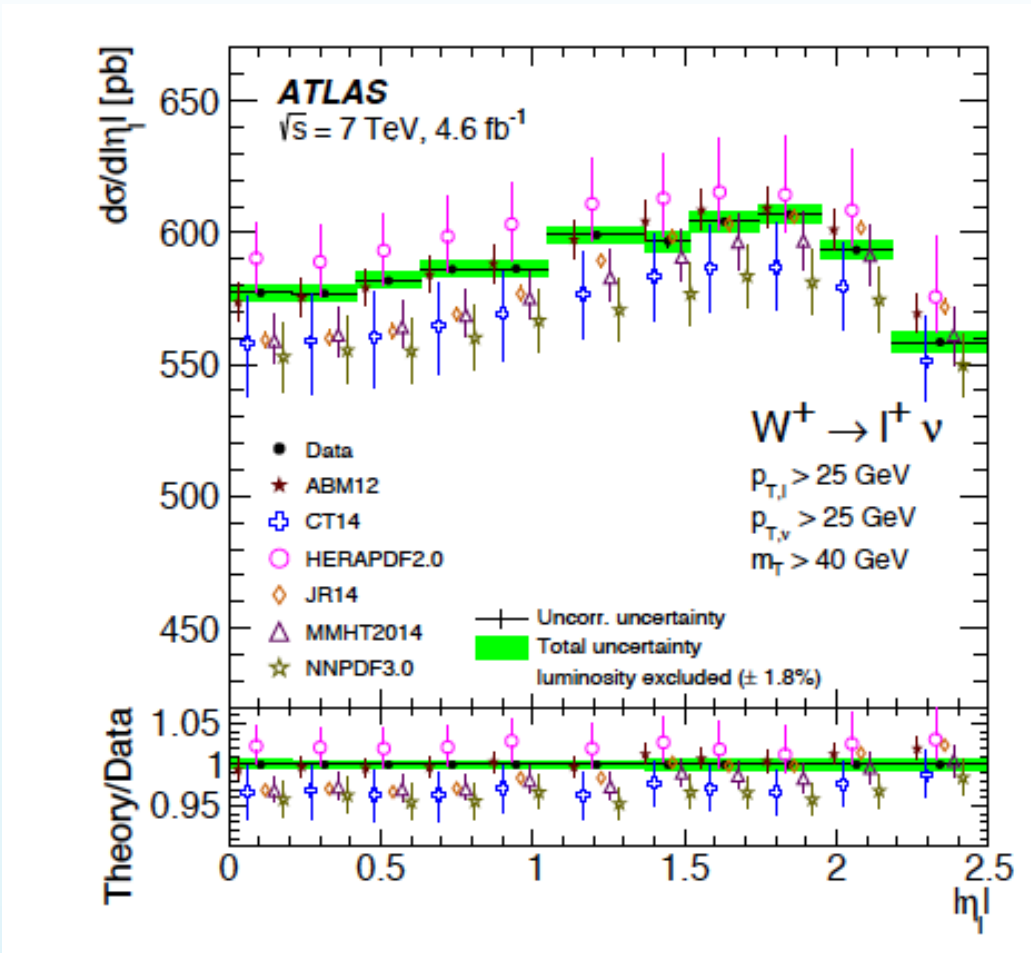
- Dijets in particular **never been included in global fits** so far since data/theory agreement at NLO poor, with a rather large scale dependence

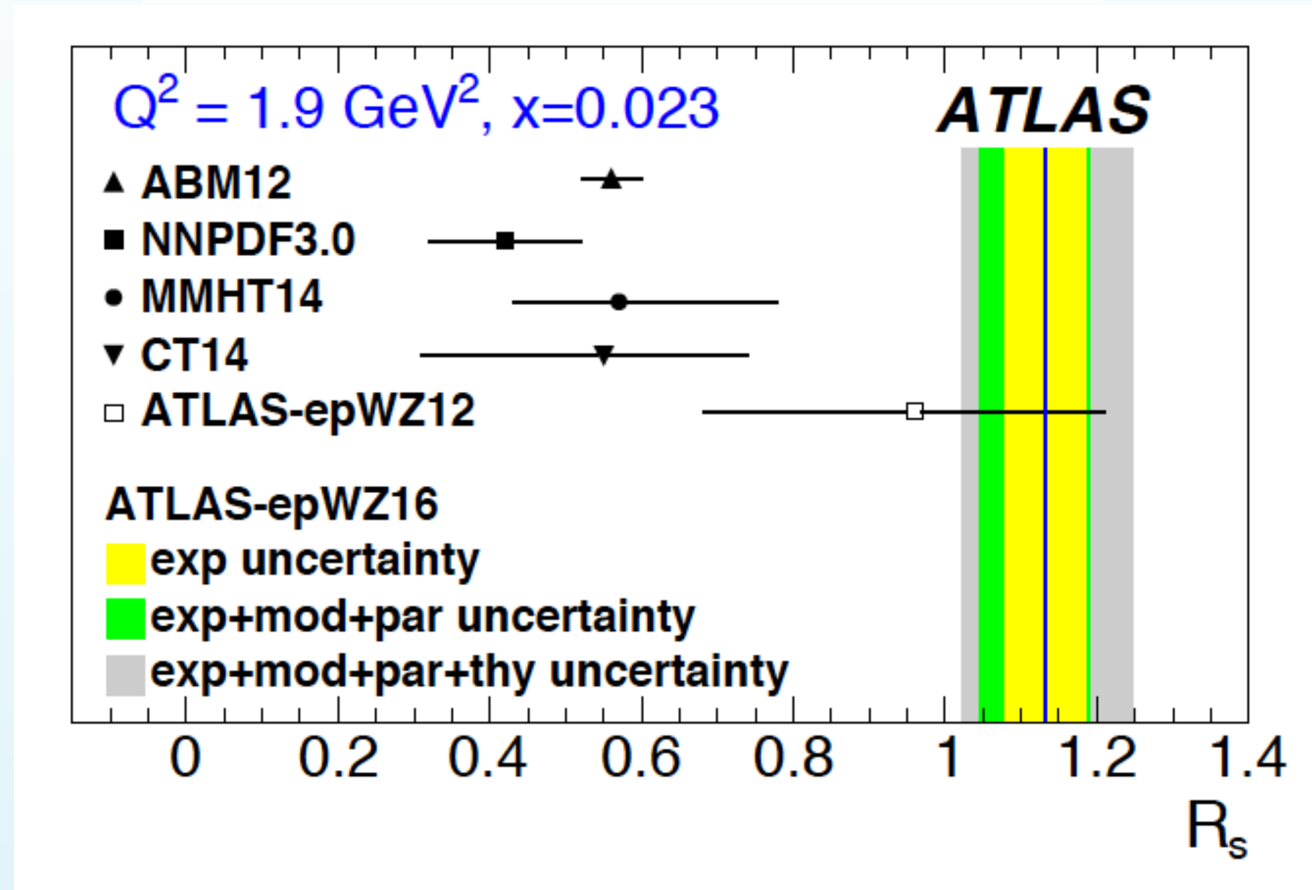
- Work in progress with **the NNLOjet authors** to include all available inclusive jet and dijet data into the NNPDF NNLO global analysis

In collaboration with
N. Glover, A. Huss, T. Gerhmann,
A. Gerhmann, J. Pires, R. Gauld

How strange is the proton?

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}$$





- **xFitter analysis** of the ATLAS W,Z 2011 inclusive data prefers a **symmetric strange sea** with small uncertainty, at odds with all other PDF fits

- Actually the ATLAS data suggest that there are **more strange than up and down sea quarks in the proton**, which is **very difficult to understand** from non-perturbative QCD arguments

- Can one accommodate the ATLAS W,Z 2011 data in the **global fit**? What happens to strangeness?

How strange is the proton?

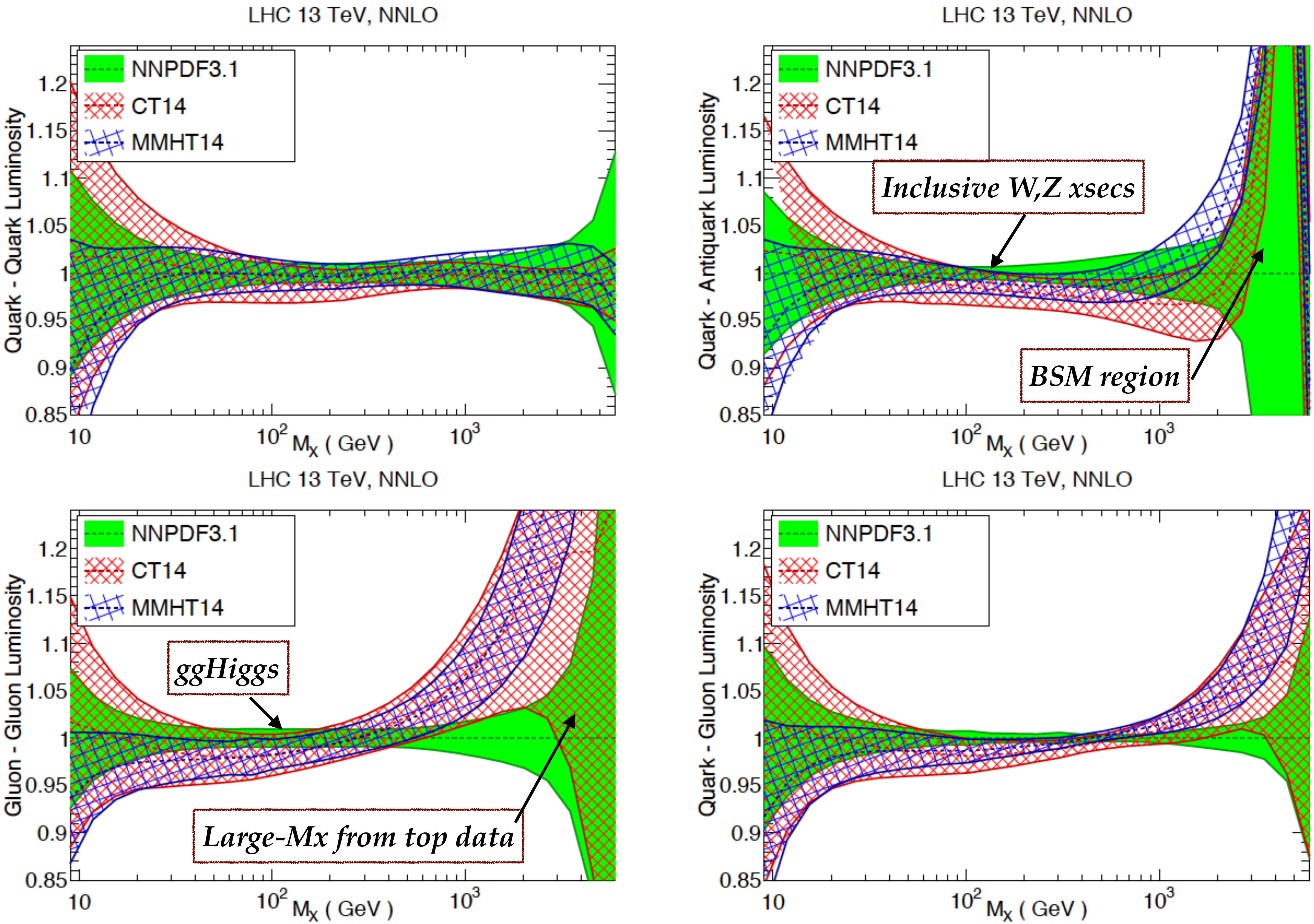
PDF set	$R_s(x = 0.023, Q = 1.65\ \mathrm{GeV})$	$R_s(x = 0.013, Q = M_Z)$
NNPDF3.0	0.47±0.09	0.79±0.04
NNPDF3.1	0.62±0.12	0.83±0.05
NNPDF3.1 collider-only	0.86±0.17	0.94±0.07
NNPDF3.1 HERA + ATLAS W, Z	0.96±0.20	0.98±0.09
ATLAS W, Z 2011 `xFitter` (Ref. [93])	$1.13^{+0.11}_{-0.11}$	-
ATLAS W, Z 2010 `HERAfitter` (Ref. [120])	$1.00^{+0.25}_{-0.28}$ (*)	$1.00^{+0.09}_{-0.10}$ (*)

- **Confirmed the strange symmetric fit** preferred by the ATLAS W,Z 2011 measurements, though we find PDF uncertainties larger by a factor 2

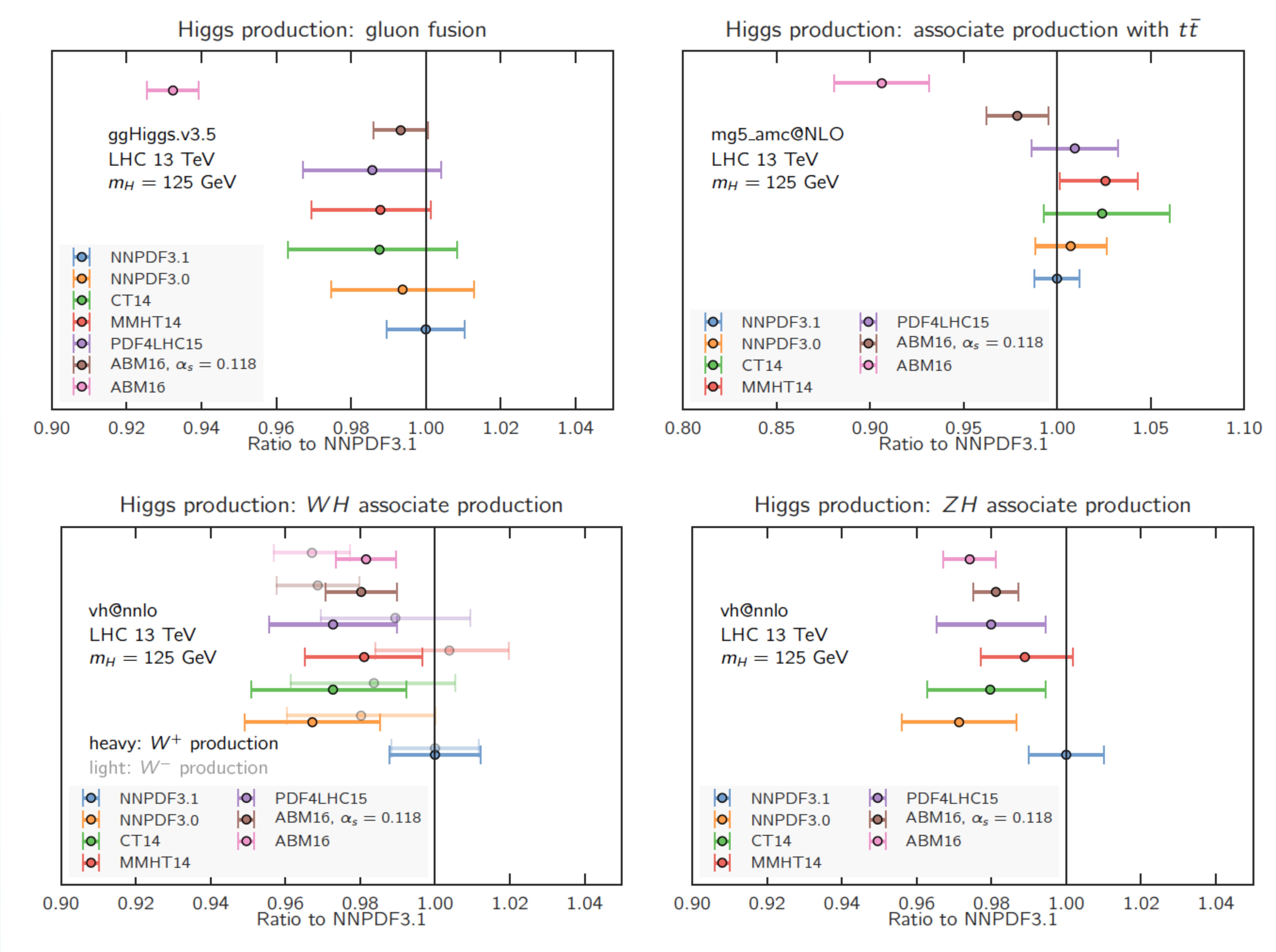
- The **global fit** accommodates both the neutrino data and the ATLAS W,Z 2011 ($\boldsymbol{\chi^2_{\mathrm{nutev}}=1.1}$, $\boldsymbol{\chi^2_{\mathrm{AWZ11}}=2.1}$) finding a compromise value for **R_S=0.62+-0.12**

- **Mild tension** in the global fit (1.5-sigma level at most) when simultaneously included neutrino data, CMS W+charm and ATLAS W,Z 2010+2011

PDF luminosities



Higgs production cross-sections



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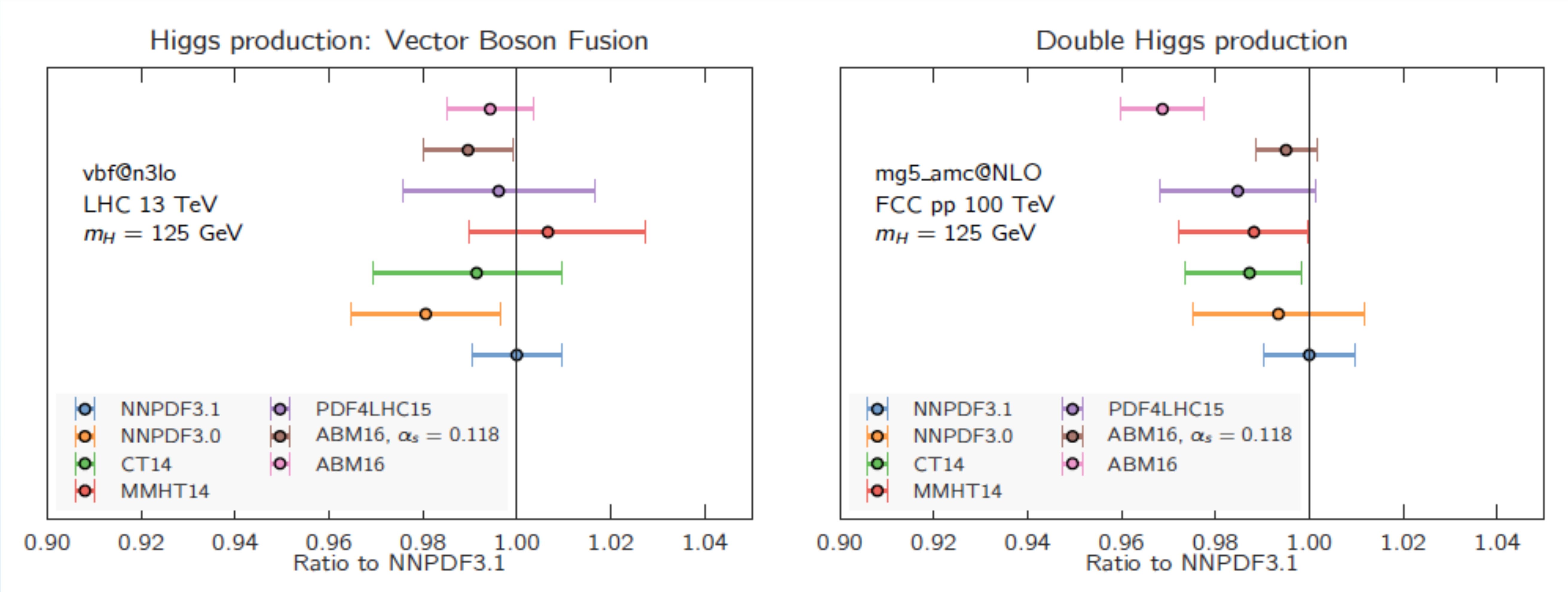
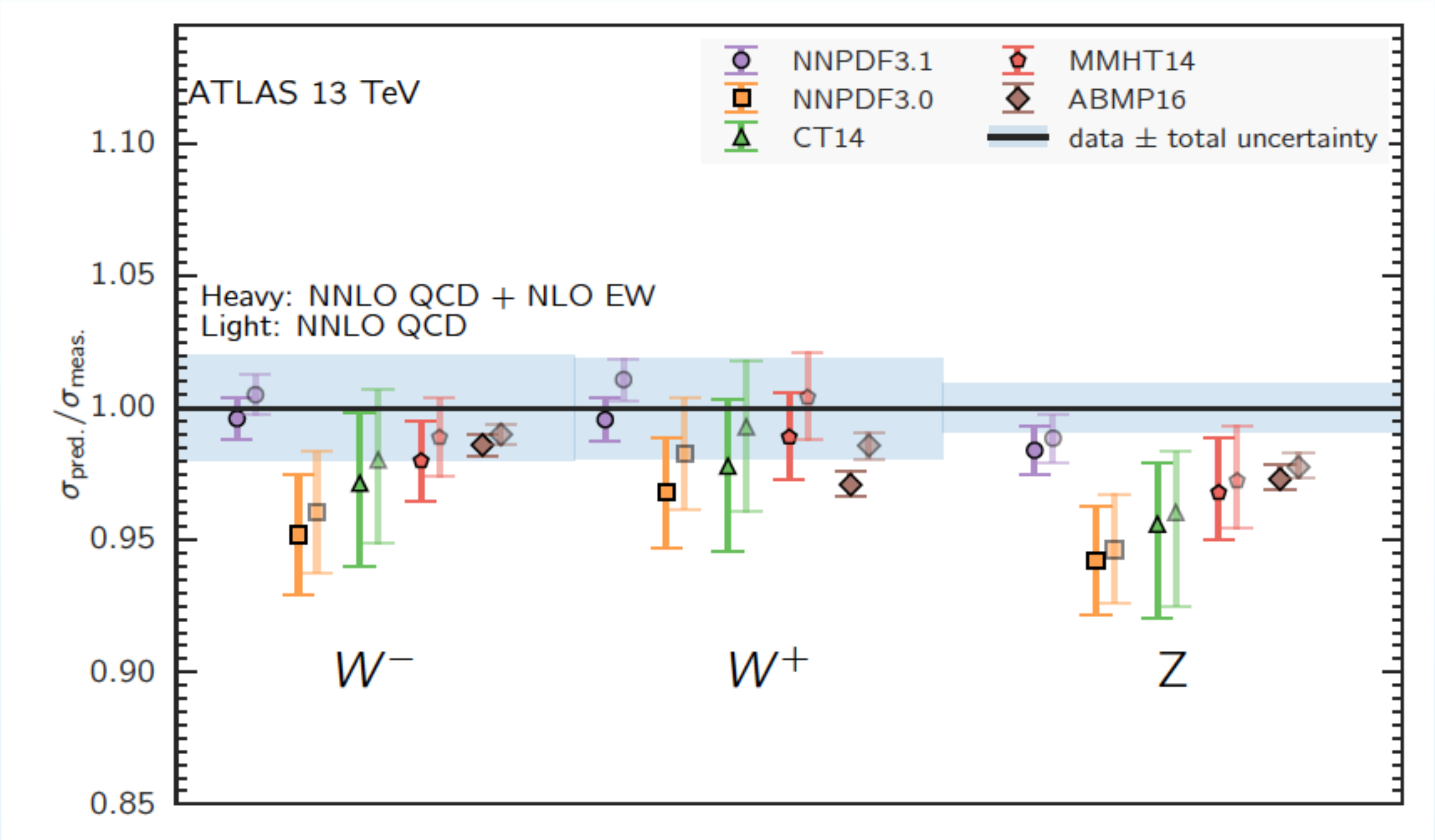


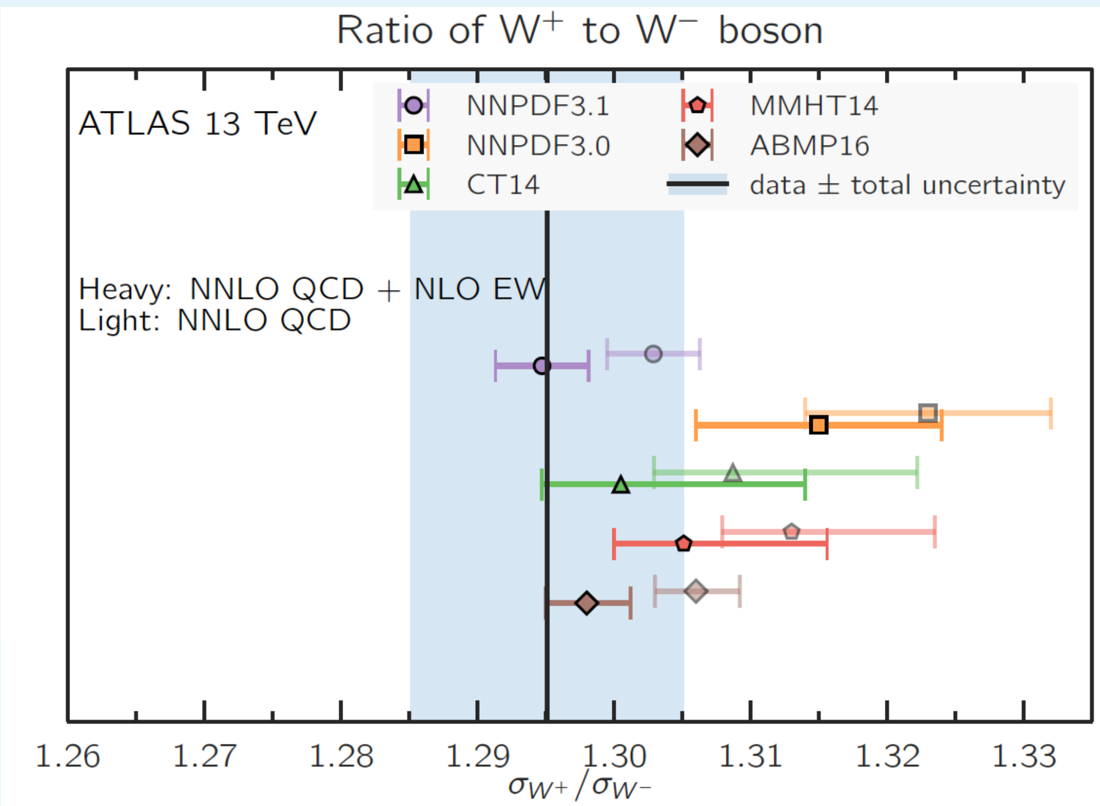
- For **gluon-initiated processes**, good agreement between 3.1 and 3.0 with reduced PDF uncertainties in the latter case

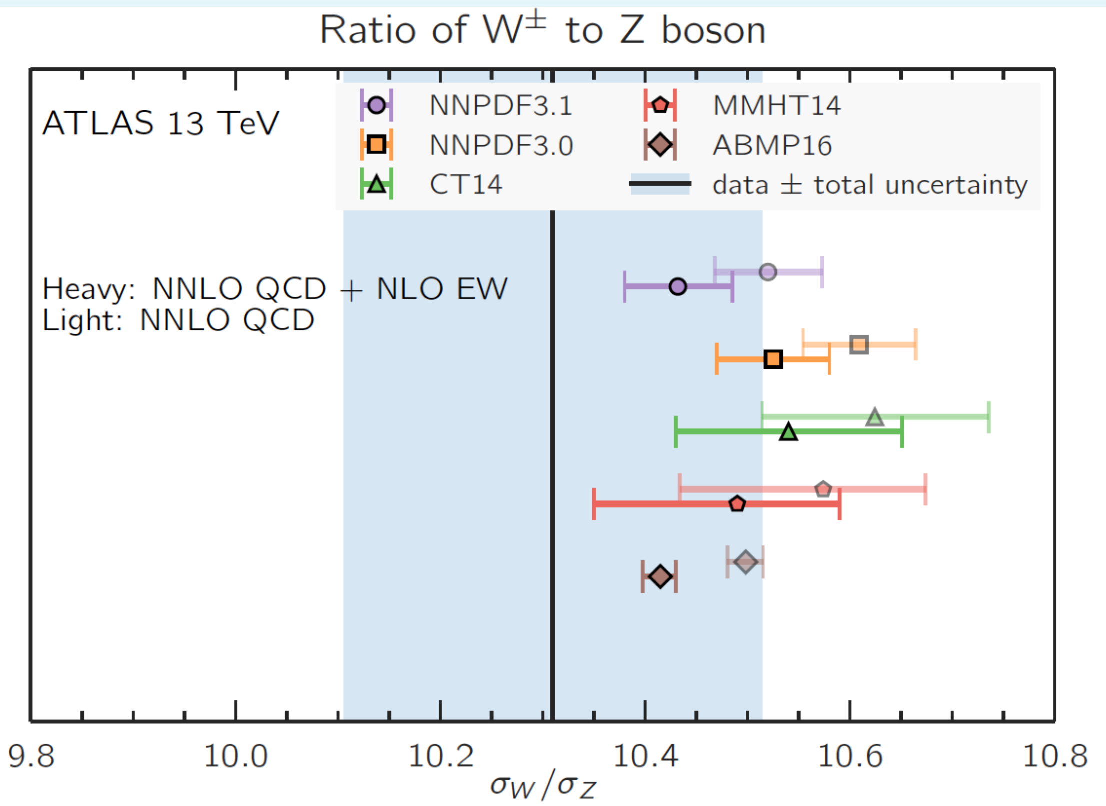
- For **quark-initiated processes**, the new collider data pulls towards higher cross-sections

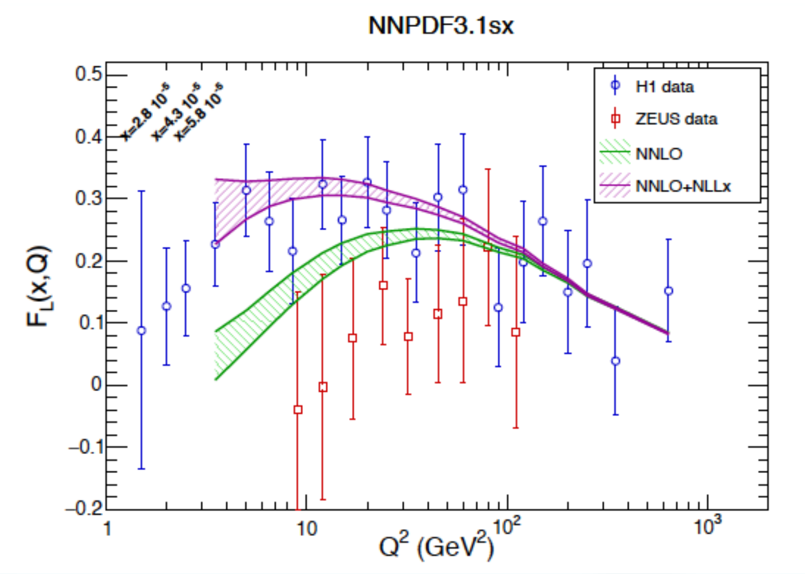
- The new **ABMP16 set** is in reasonable agreement with the other sets provided the PDG value of the strong coupling is used

W, Z production at 13 TeV

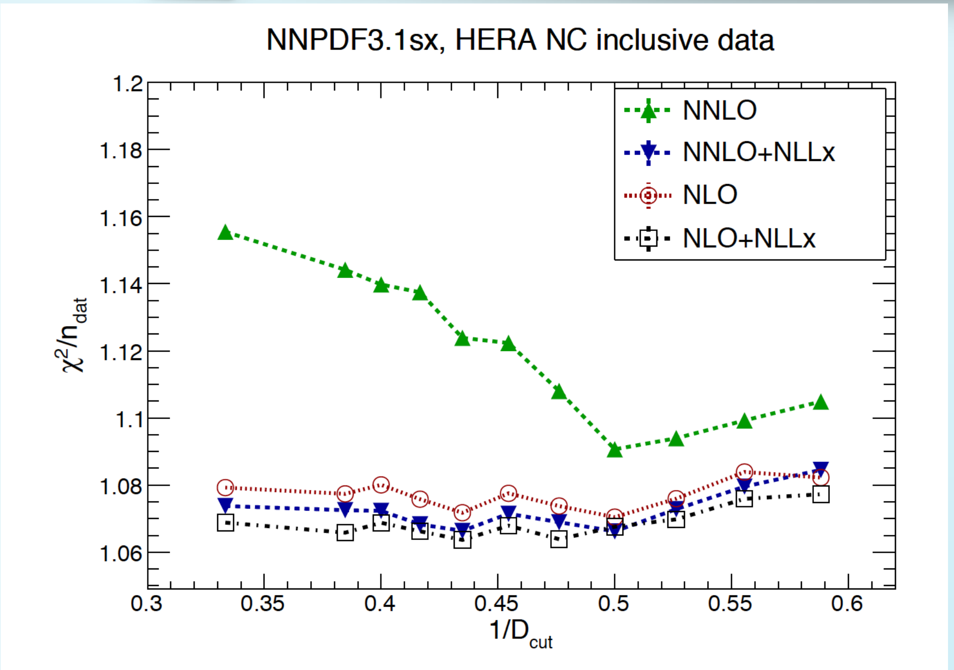








Parton Distributions with BFKL resummation



Bonvini, Marzani, Peraro 16
The NNPDF Collaboration, in preparation

Beyond fixed-order DGLAP

- **Perturbative fixed-order QCD calculations** have been extremely successful in describing a wealth of data from proton-proton and electron-proton collisions
- However, there are theoretical indications that eventually we might need to go beyond DGLAP:
  - At very small-x, **logarithmically enhanced terms in 1/x become dominant** and need to be resummed: small-x/high-energy/BFKL resummation formalism.
  - The **steep rise in the small-x gluon** will eventually trigger **non-linear** recombinations: **gluon saturation**, BK/JIMWLK equations …..
- Crucially, **BFKL resummation** can be matched to the DGLAP collinear framework

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

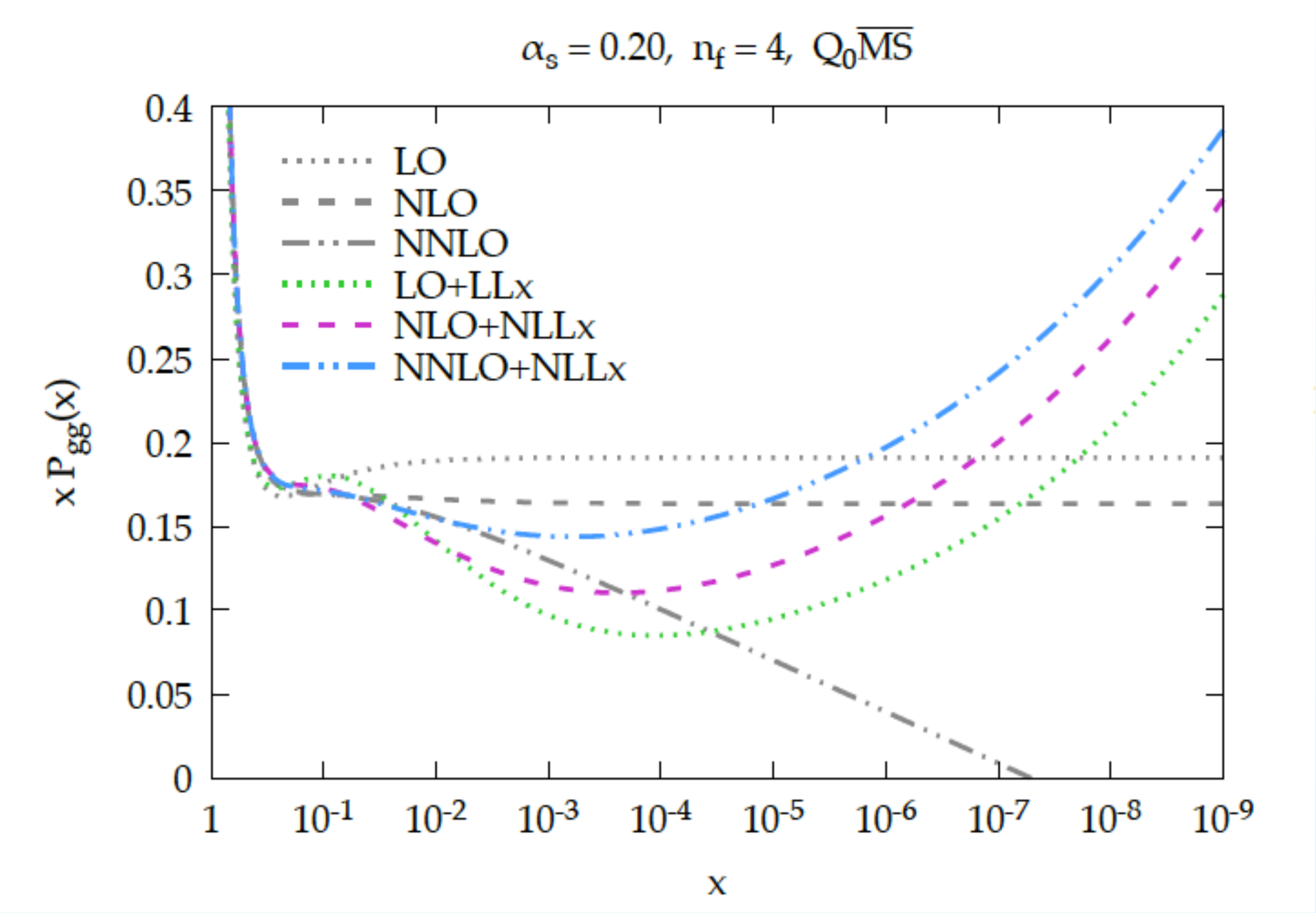
$$-x\frac{d}{dx} f_+(x,M) = \chi(M,\alpha_s)\, f_+(x,M)$$

$$f_+(x,M) = \int_{-\infty}^{\infty} \frac{dQ^2}{Q^2} \left(\frac{Q^2}{Q_0^2}\right)^{-M} f_+(x,Q^2)$$

PDFs with BFKL resummation

- Ultimately, the need for (or lack of) BKFL resummation can only be assessed by performing a **global PDF analysis with (N)NLO+NLLx matched theory**

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



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

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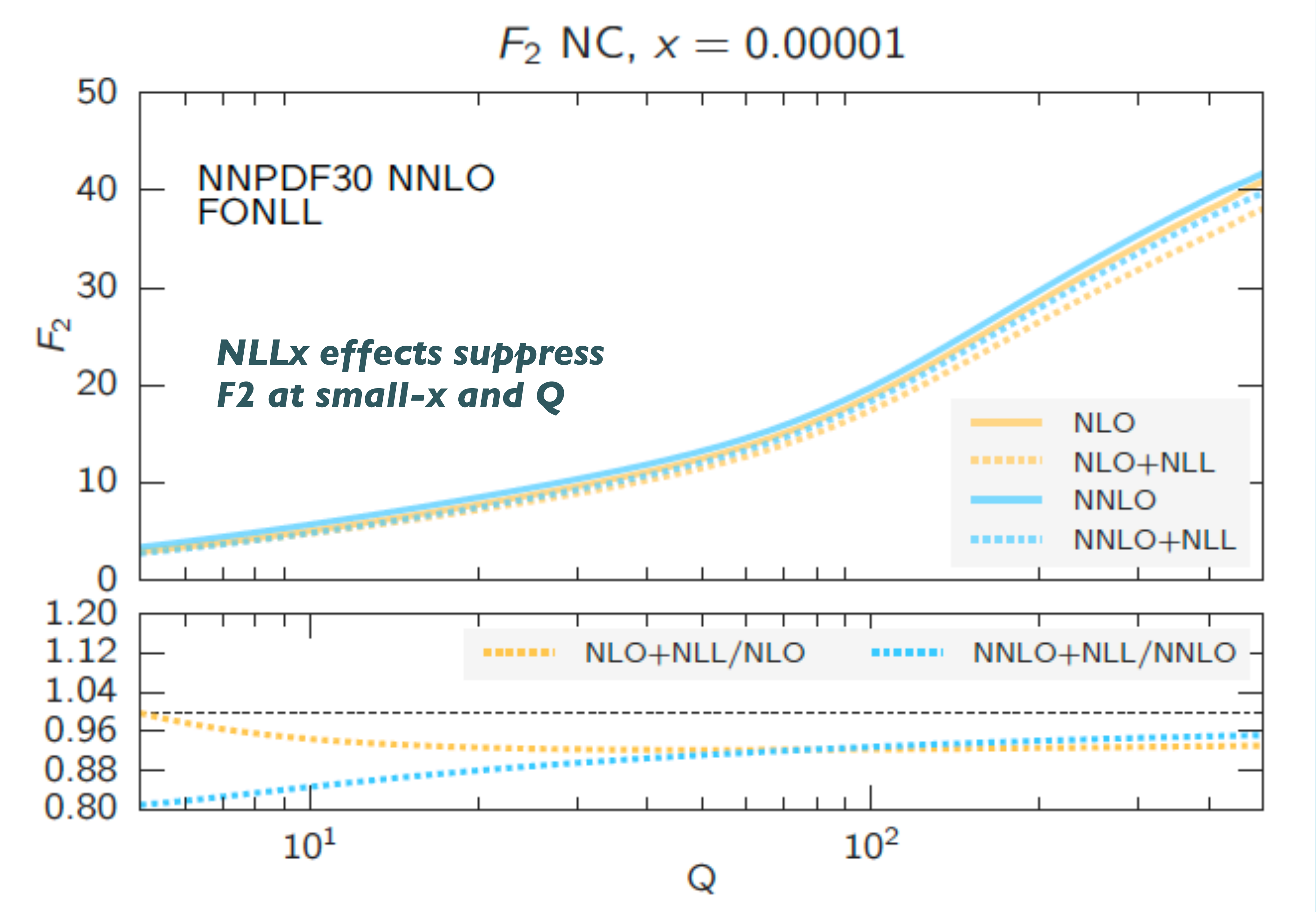
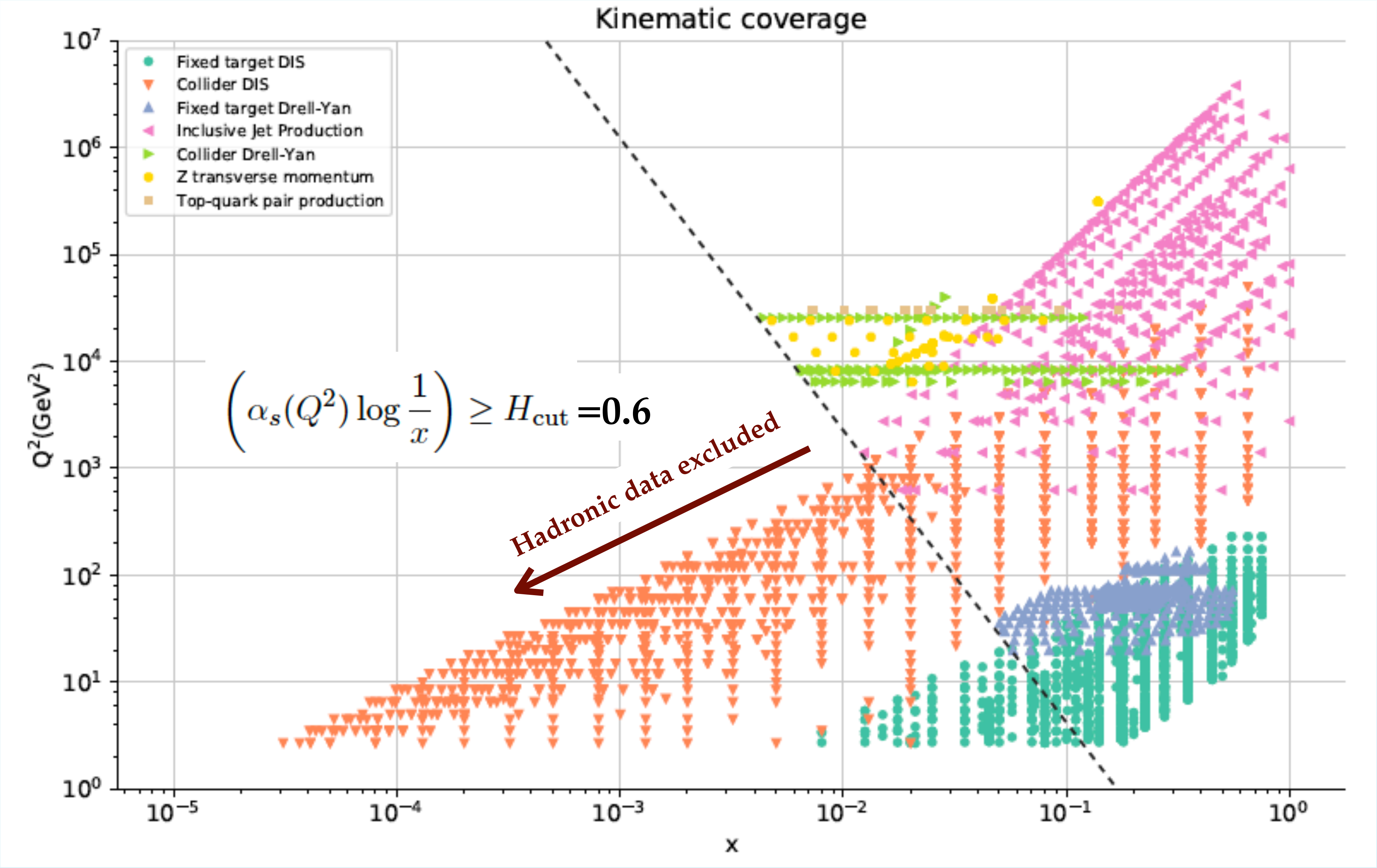


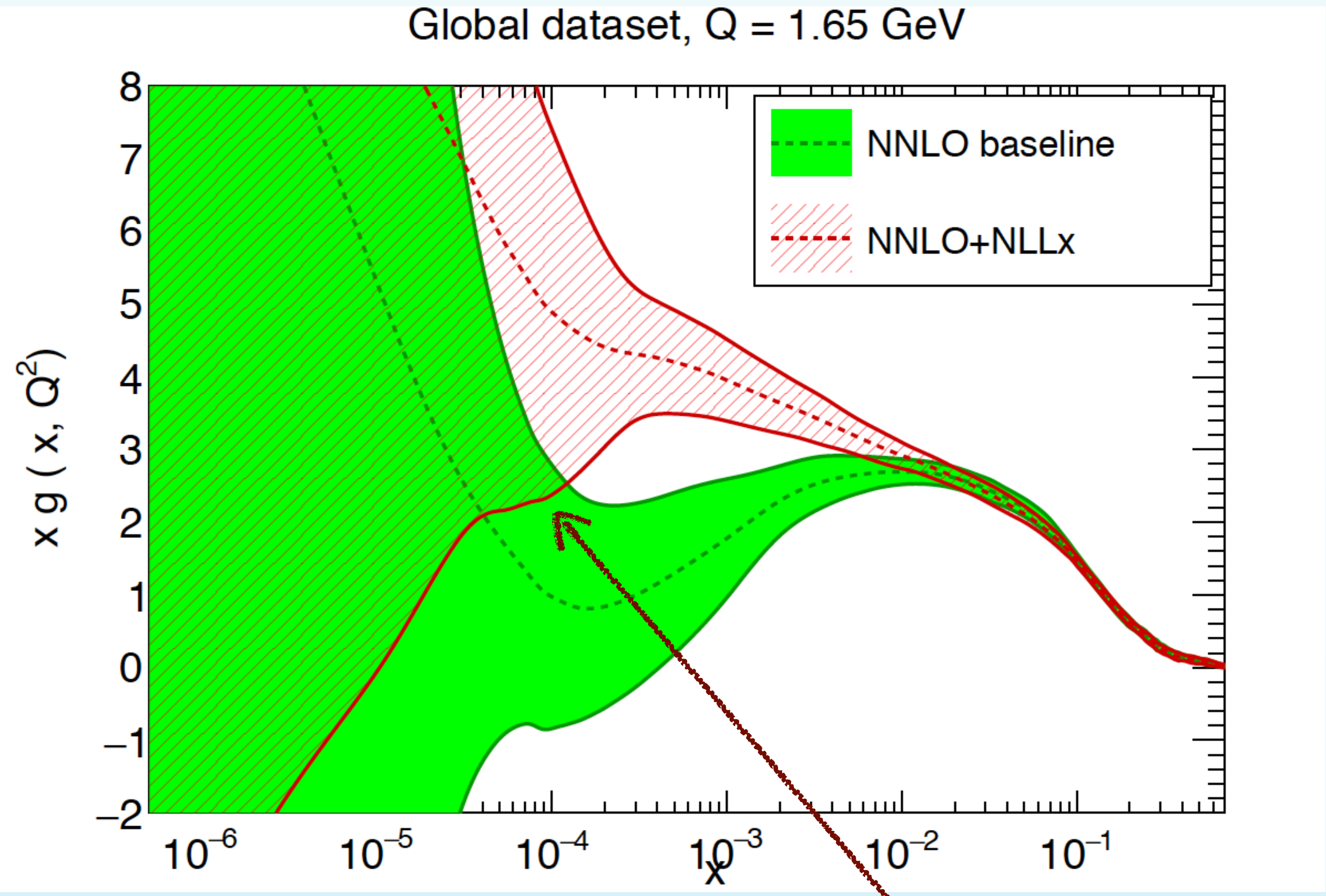
NNPDF3.1sx

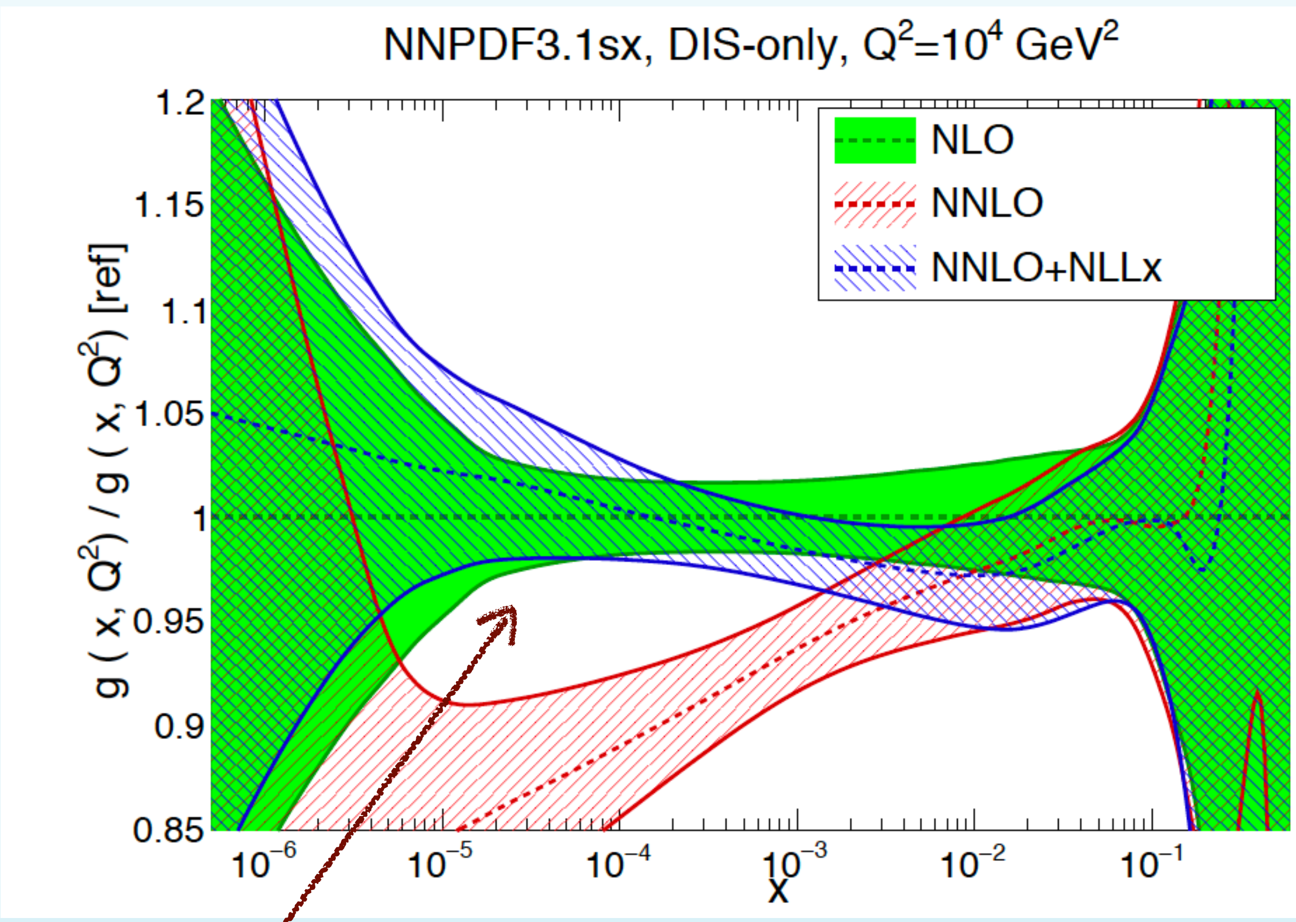
Same fit settings as in NNPDF3.1, with **additional cuts to hadronic data**: NLLx resummation not yet available for most collider processes



Global PDFs with BFKL resummation

- Small-x resummation cures the **instability at small-x of the NNLO perturbative expansion**
- **Unambiguous evidence of the onset of BFKL dynamics** in inclusive HERA data





Improved **perturbative convergence of the small-x gluons**

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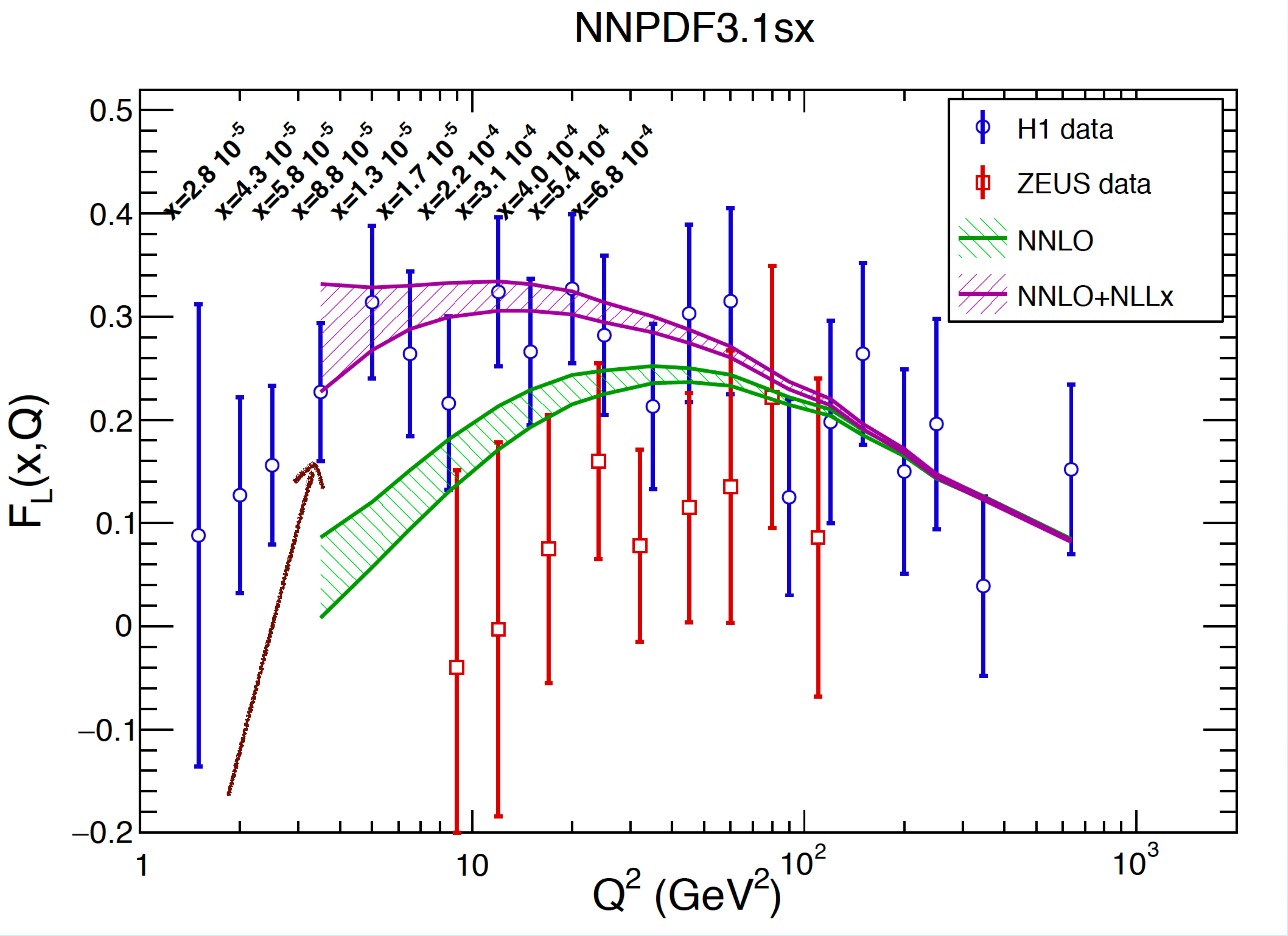

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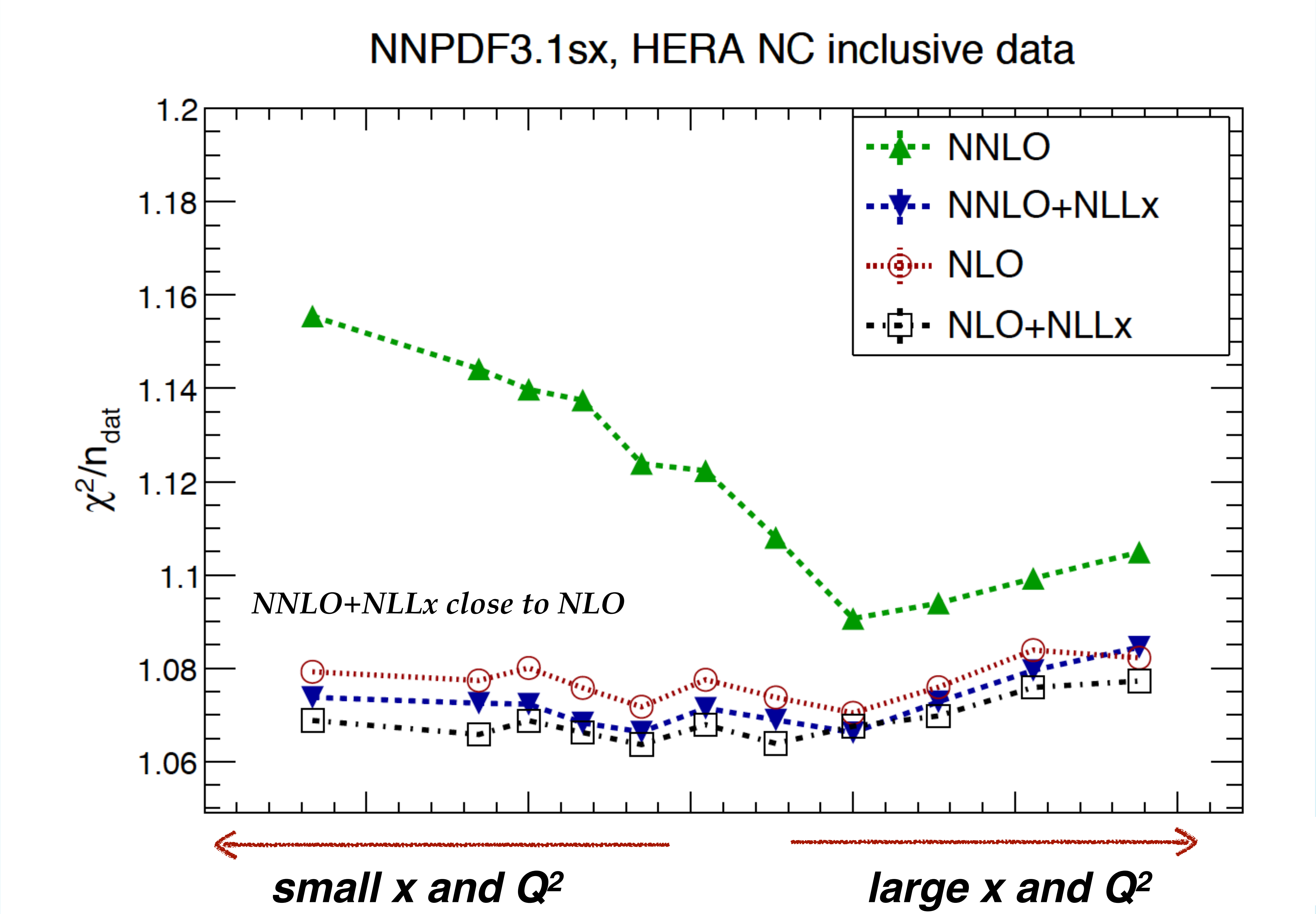

Cut in small-x and Q HERA data

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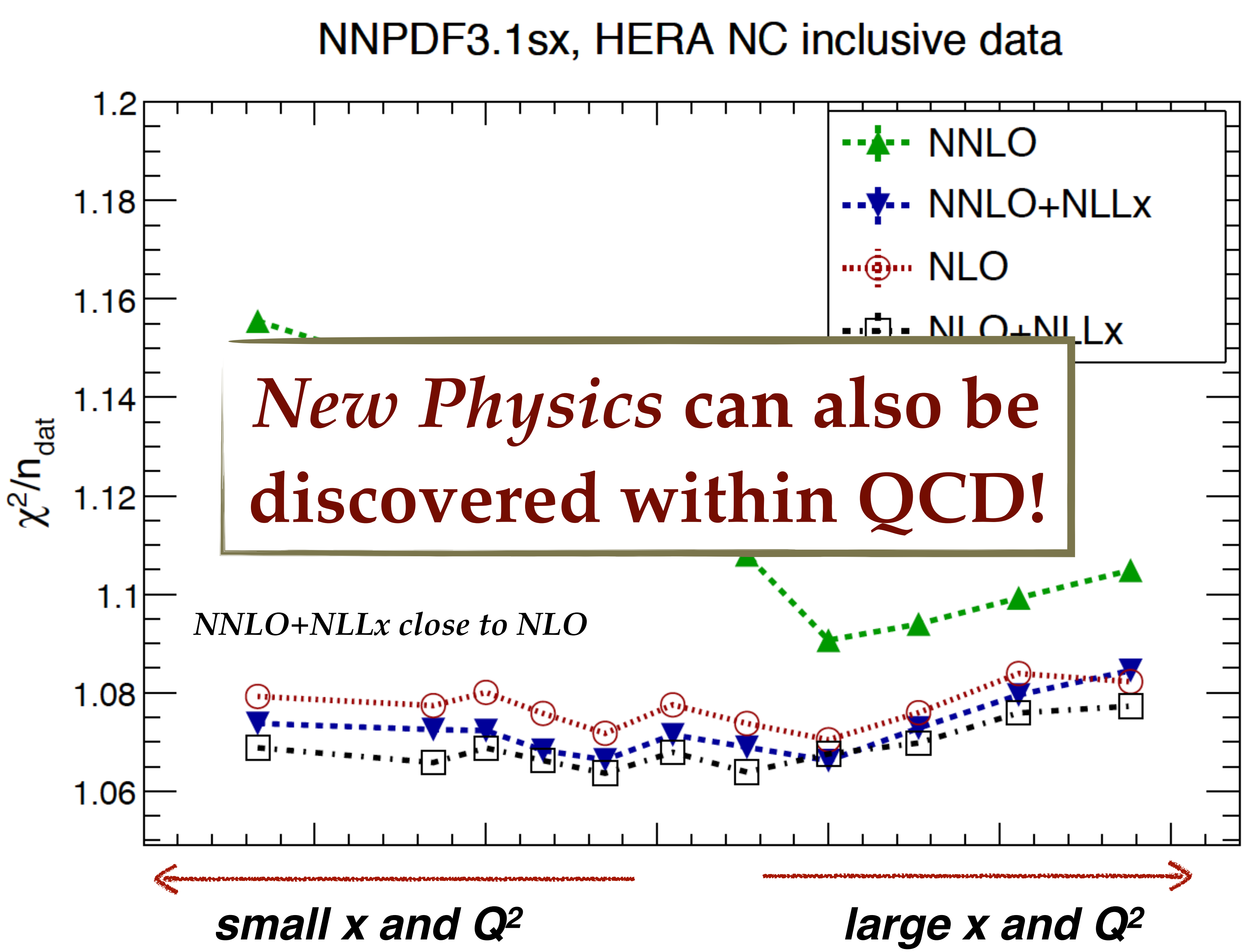


New Physics **can also be discovered within QCD!**

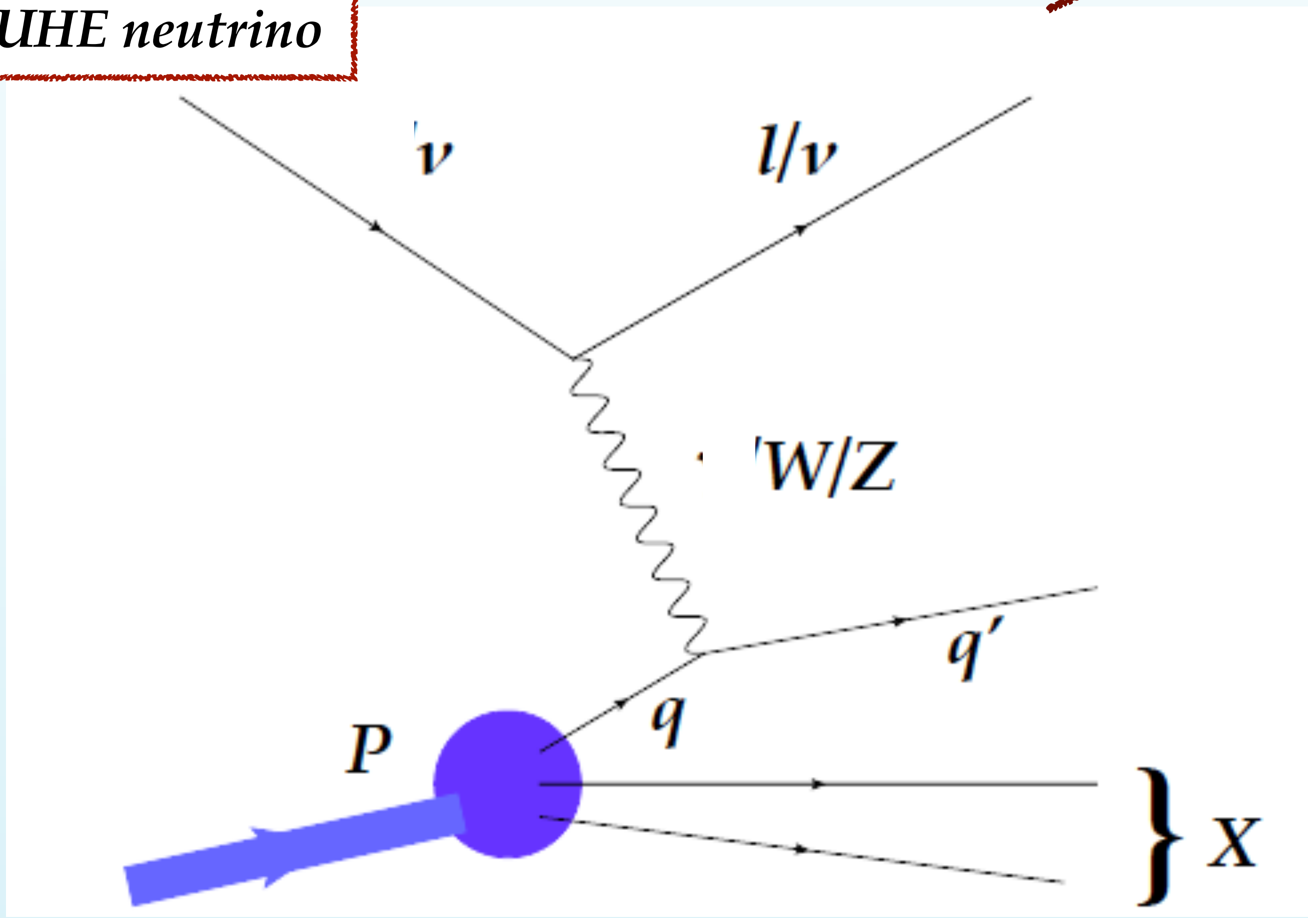
Cut in small-x and Q HERA data

From the LHC to Neutrino Telescopes

Provide state-of-the-art predictions for the UHE neutrino nucleus cross-sections for neutrino telescopes

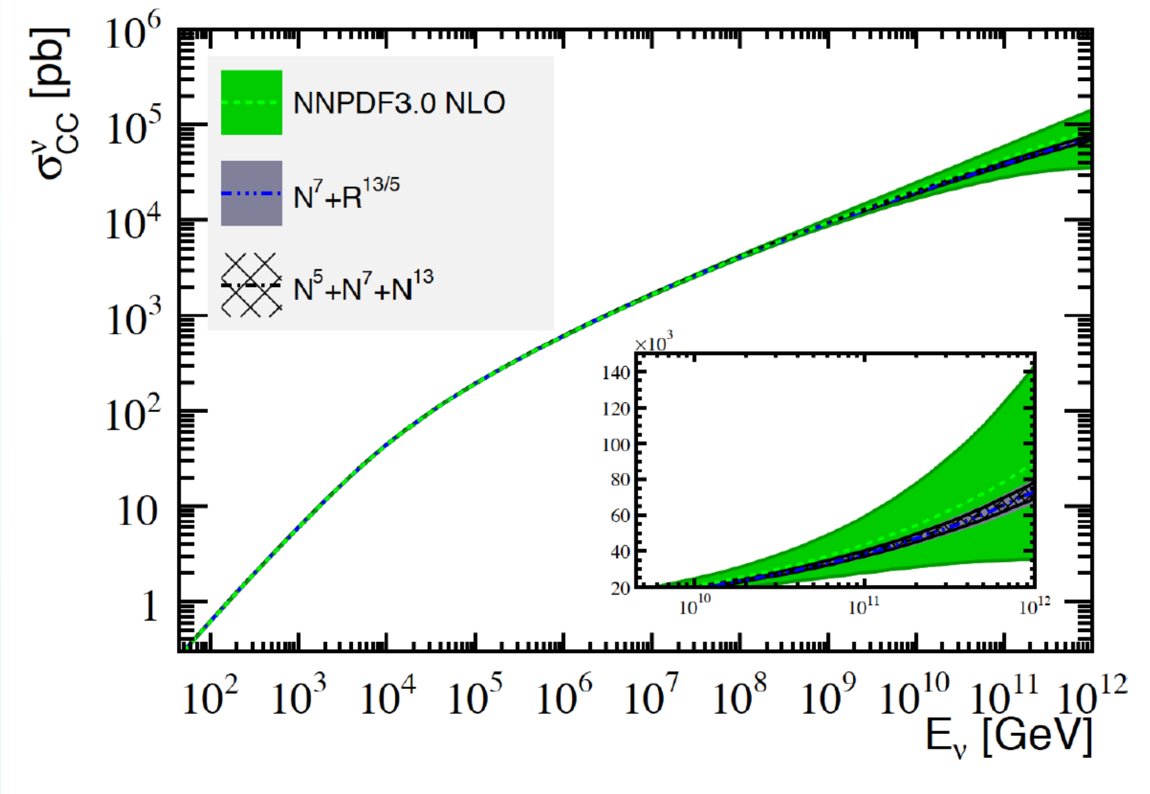
Using better data

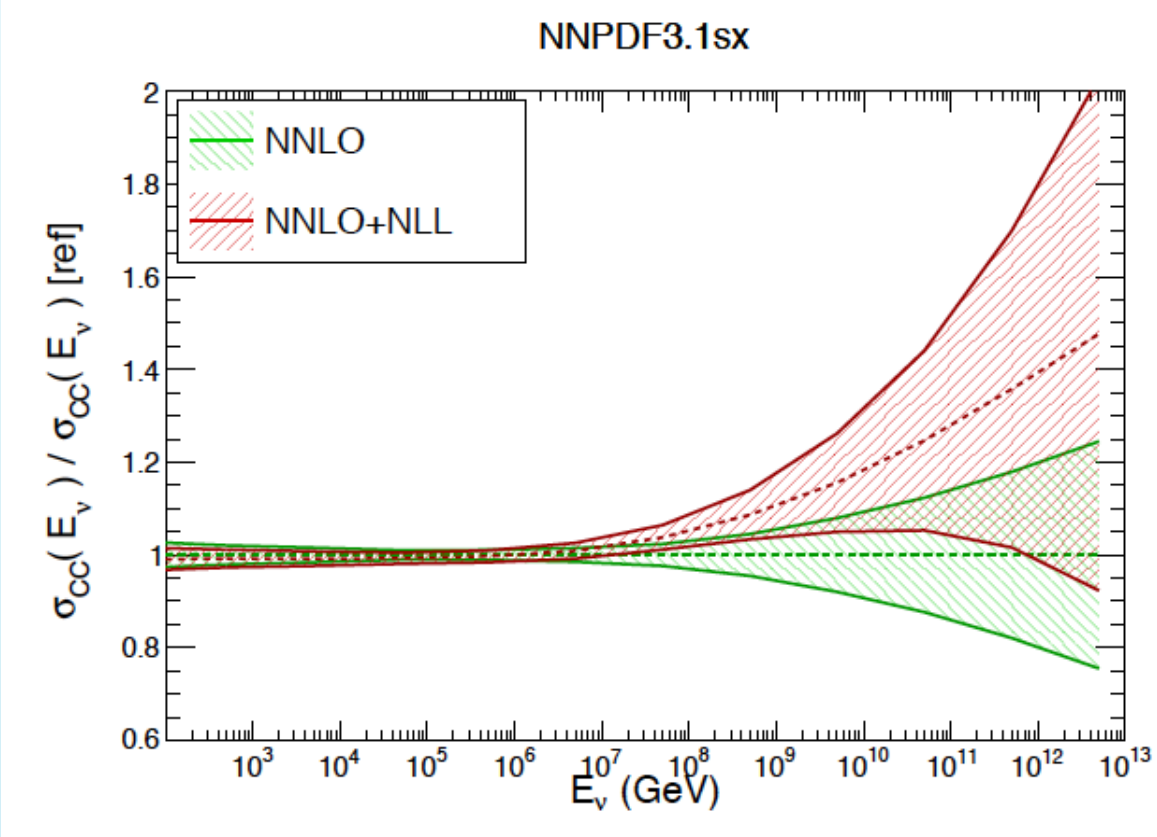
UHE neutrino



Using better theory

Constraints from LHCb D production





Constraints from BFKL resummation

Summary and outlook

- **Parton distributions** are a crucial aspect of the **LHC precision phenomenology program**, with direct implications from Higgs characterisation to BSM searches

- **NNPDF3.1** is a state-of-the-art global PDF analysis, including a **wealth of precision LHC measurements**, some of them for the first time such as the 8 Z p_T data and top quark production differential distributions

- Good **stability with respect to NNPDF3.0,** with main differences being a **reduction of the large-*x* PDF uncertainties** and an **improved quark flavour separation**

- **Improved stability of the gluon** from the combination of **top, Z p_T, and jet data**

- **Improved fit quality once the charm PDF is fitted**, rather than perturbatively generated

- The perturbative convergence of small-x QCD can be improved by matching to BFKL evolution using **small-x resummation**

- Clear evidence of the **onset of BFKL dynamics** in HERA data: *New Physics* **within QCD!**

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Thanks for your attention!