NEW FRONTIERS IN PDF DETERMINATION: NNPDF3.1

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Z. Dim, S. Forte (Milano), A. Guffanti (Torino)

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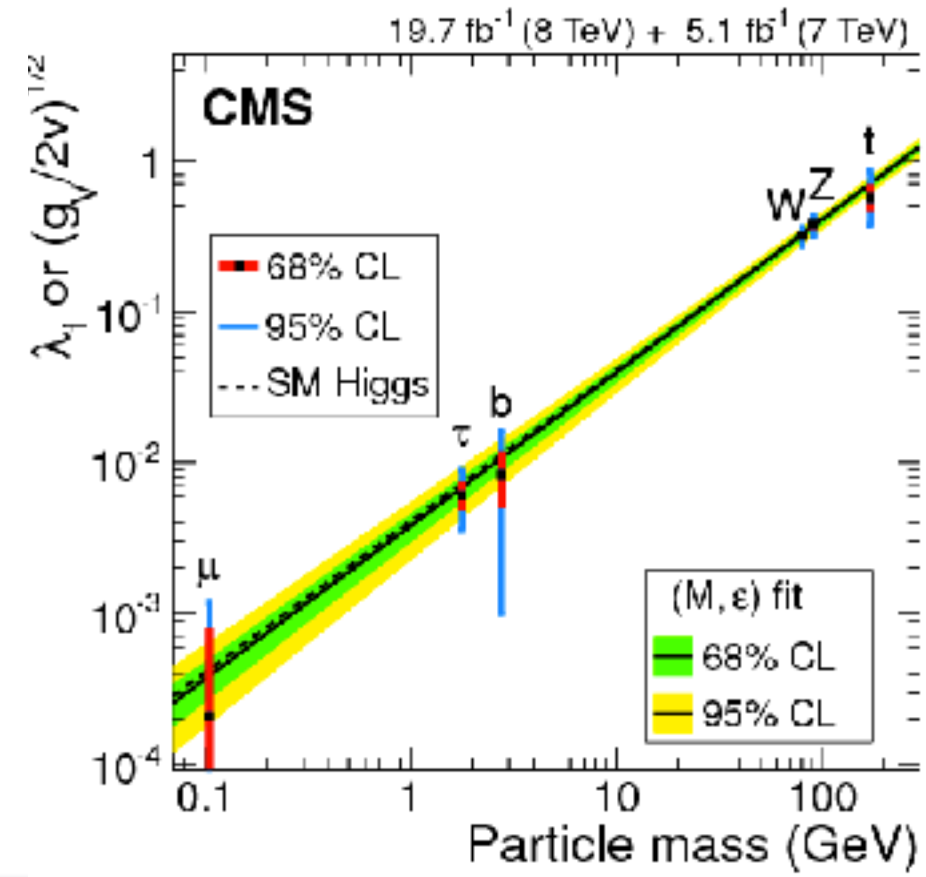
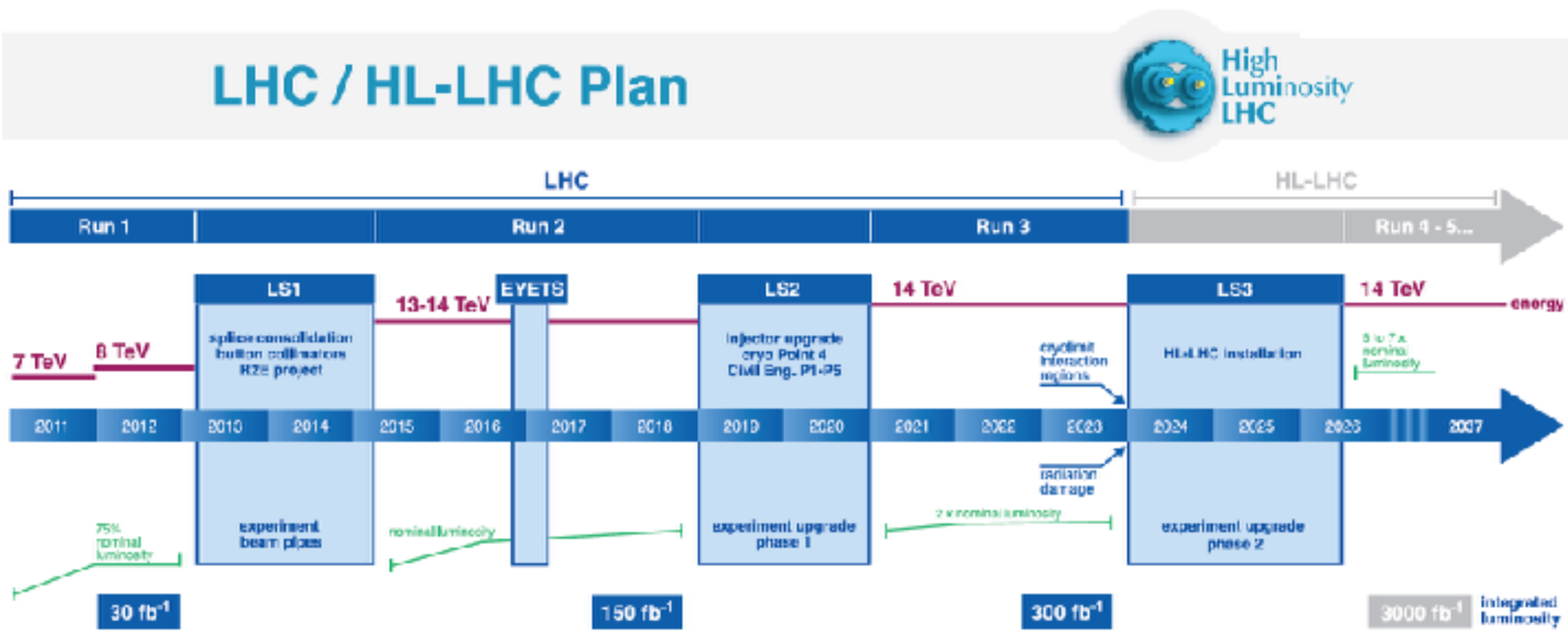
LHC Physics at Run II

- Is precision physics possible/necessary at hadron colliders?
  At the LHC a paradigm shift took place.
  Theory has to catch up with experimental precision

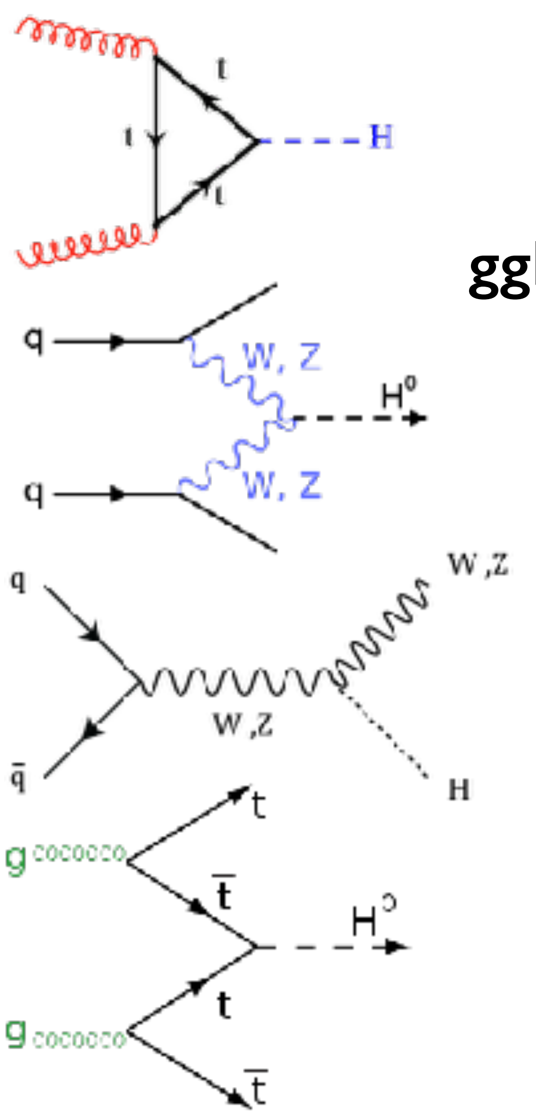
- Precise theoretical predictions are key to indirectly spot new physics signals and/or to characterise any possible "bump"

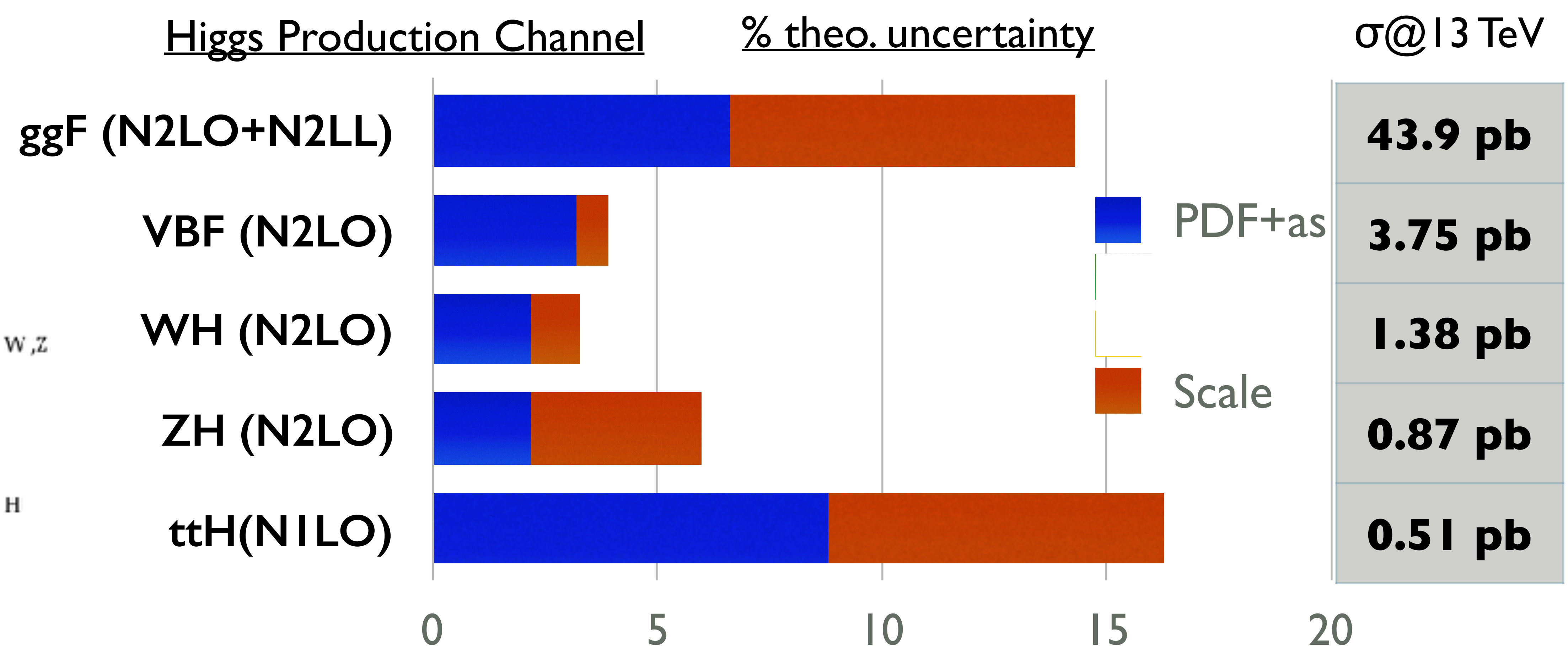




The role of PDF uncertainties

Yellow Report 3 (2013)

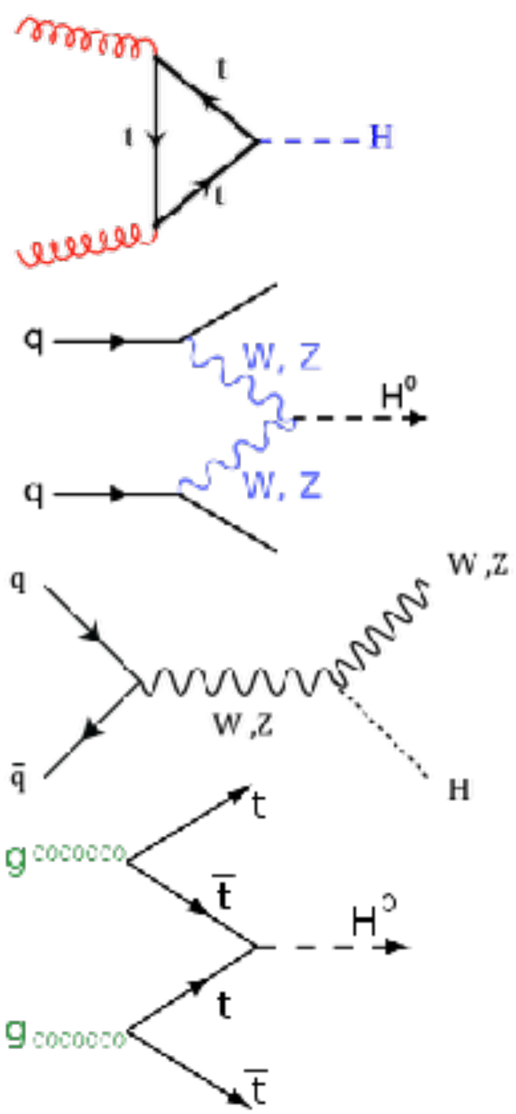


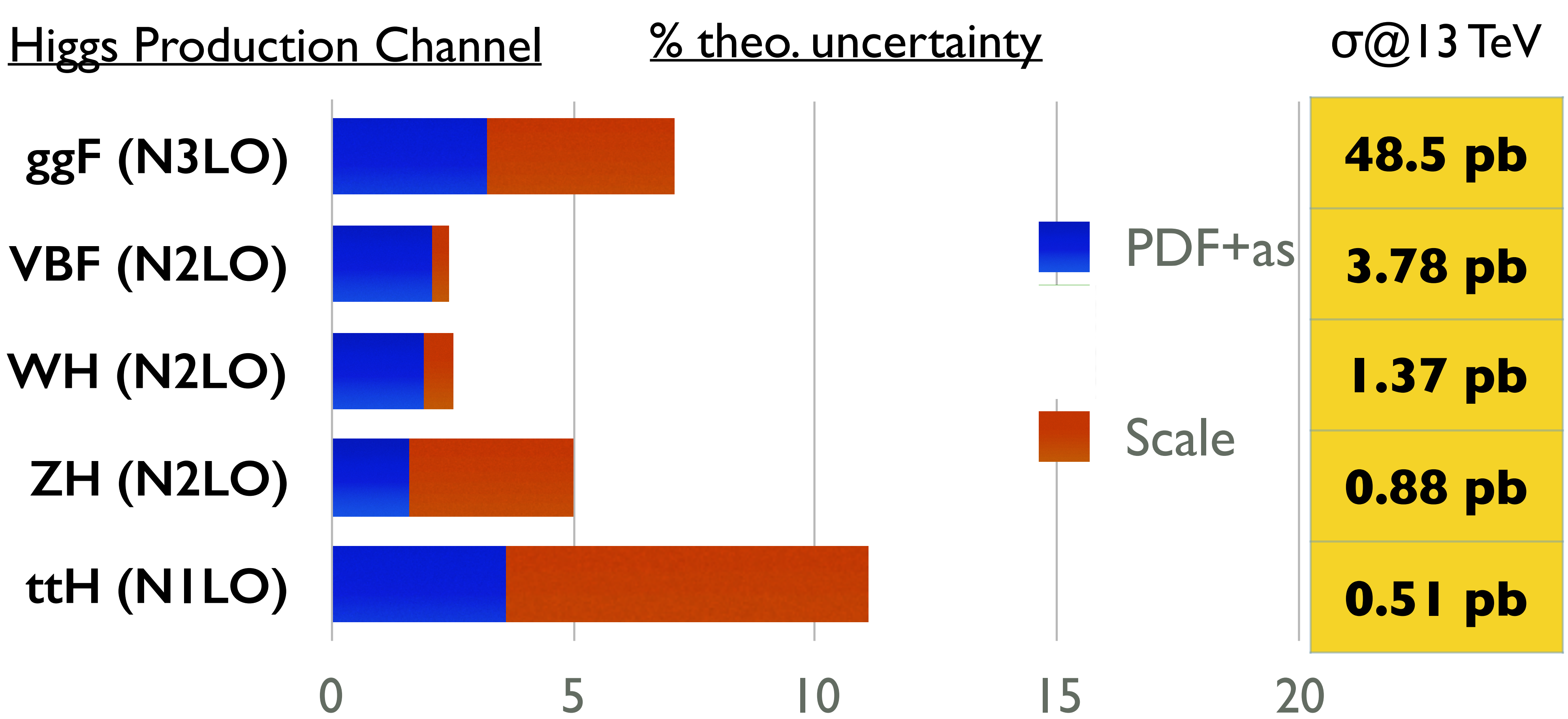


PDF uncertainties limiting factor in the accuracy of theoretical predictions

The role of PDF uncertainties

Yellow Report 4 (2016)

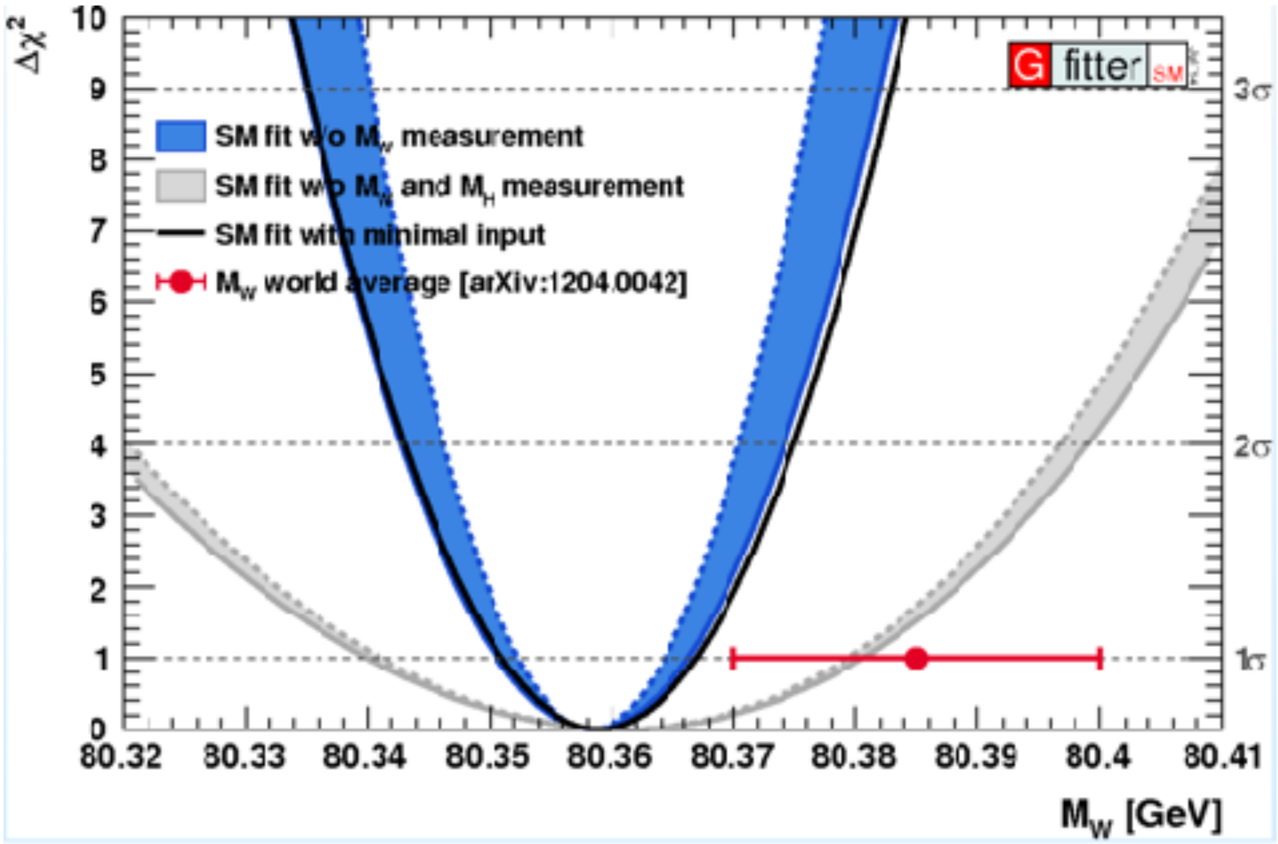




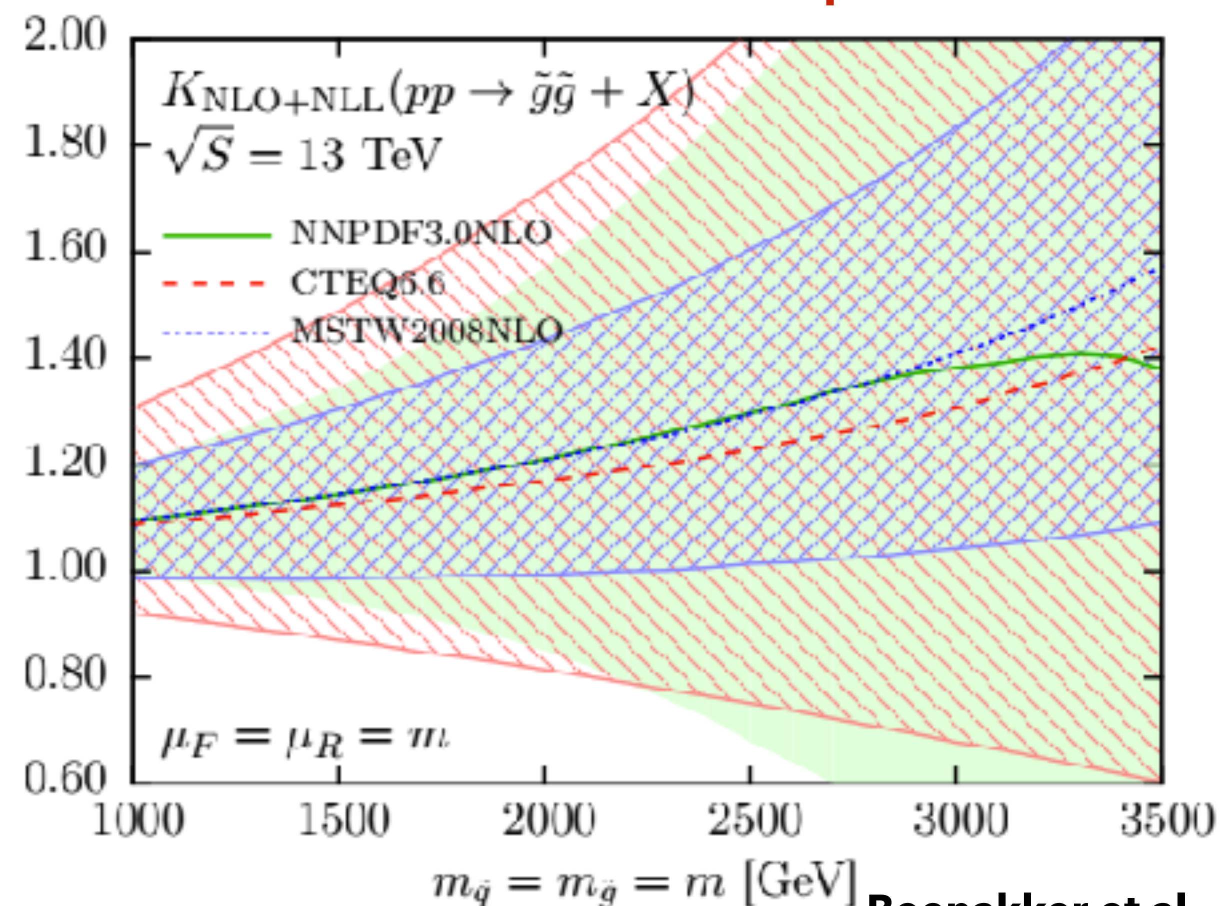
Reduced (still often dominant) PDF uncertainties

The role of PDF uncertainties

M_W determination



Gluino production



Beenakker et al. EPJC76 (2016)2, 53

ΔM_W [MeV]	present	CDF	D0	combined	LHC		
$\mathcal{L}$[fb]	7.6	10	10	20	20 (8 TeV)	300	3000
PDF	10	5	5	5	10	5	3
QED rad.	4	4	3	3	4	3	2
$p_T(W)$ model	2	2	2	2	2	1	1
other systematics	9	4	11	4	10	5	3
W statistics	9	6	8	5	1	0.2	0
Total	16	10	15	9	15	8	5

D. Wackeroth's KITP workshop 2016

Outline of the talk

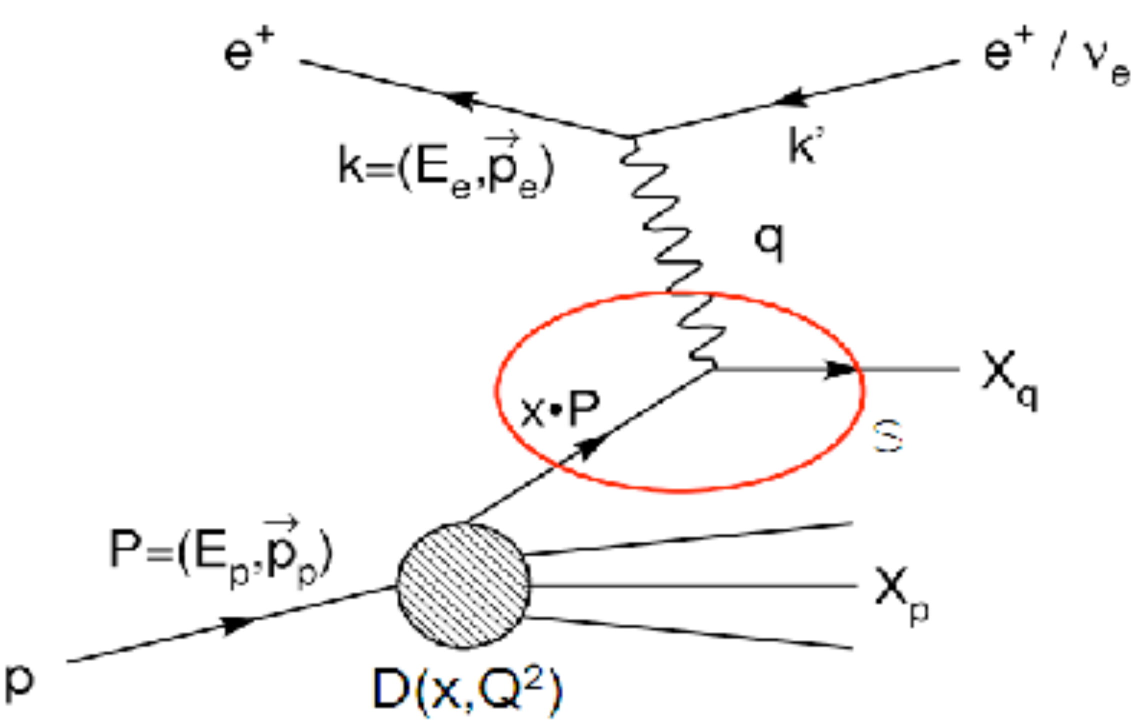
* Introduction
* Determination of PDFs
  * Methodology
  * Data & theory-driven progress
* NNPDF3.1 and frontiers in PDF determination
  * Fitted versus dynamic charm
  * New LHC data: challenges and opportunities
  * PDF hidden uncertainties
  * Photon contribution
* Conclusions

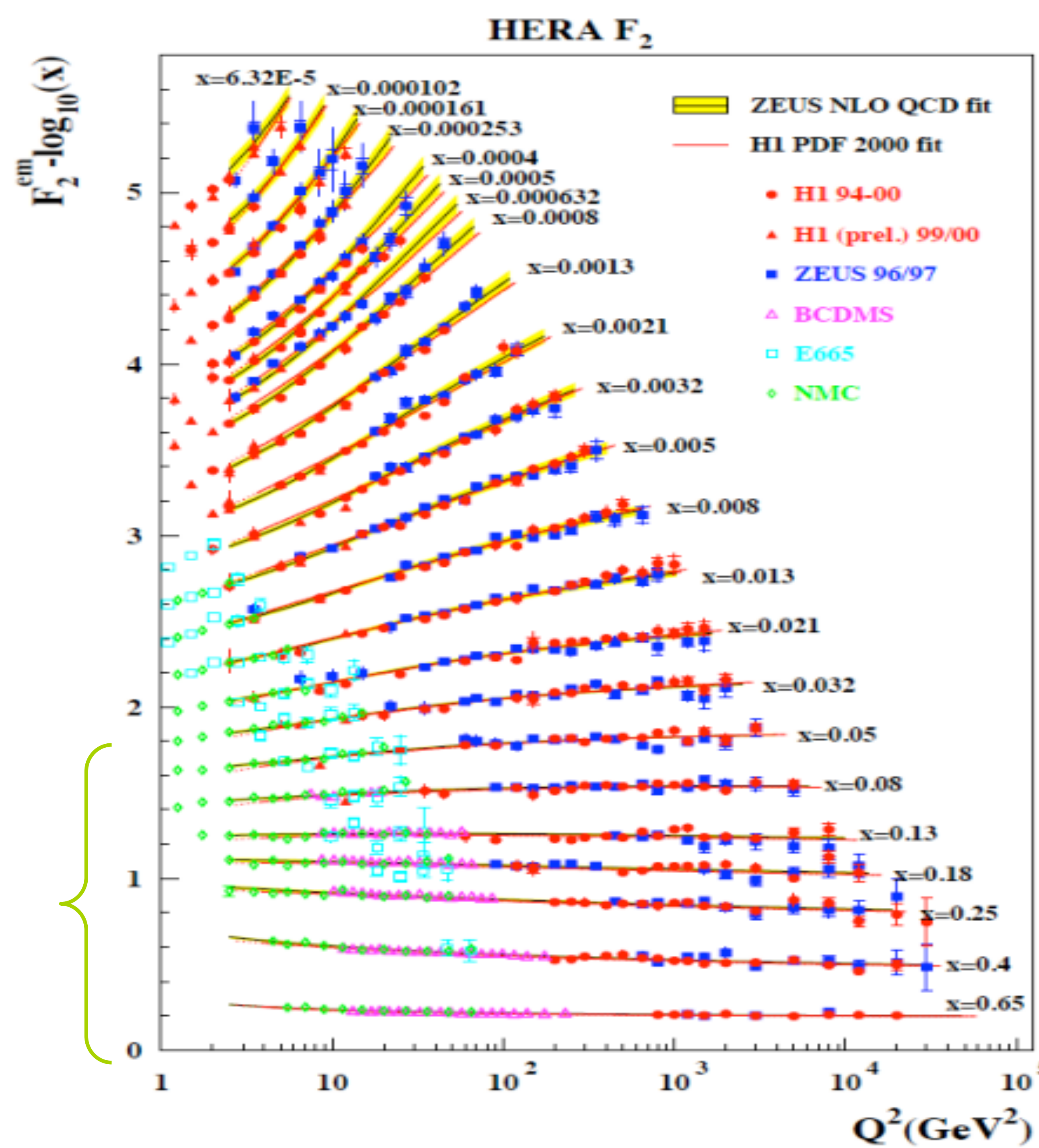
Introduction

Parton Model

The parton model **(Feynman 1969)**

- Photon scatters incoherently off massless, free, point-like, spin 1/2 partons
- The functions q(x) are the Parton Distribution Functions encode probability that a parton q carries a fraction x of parent proton's

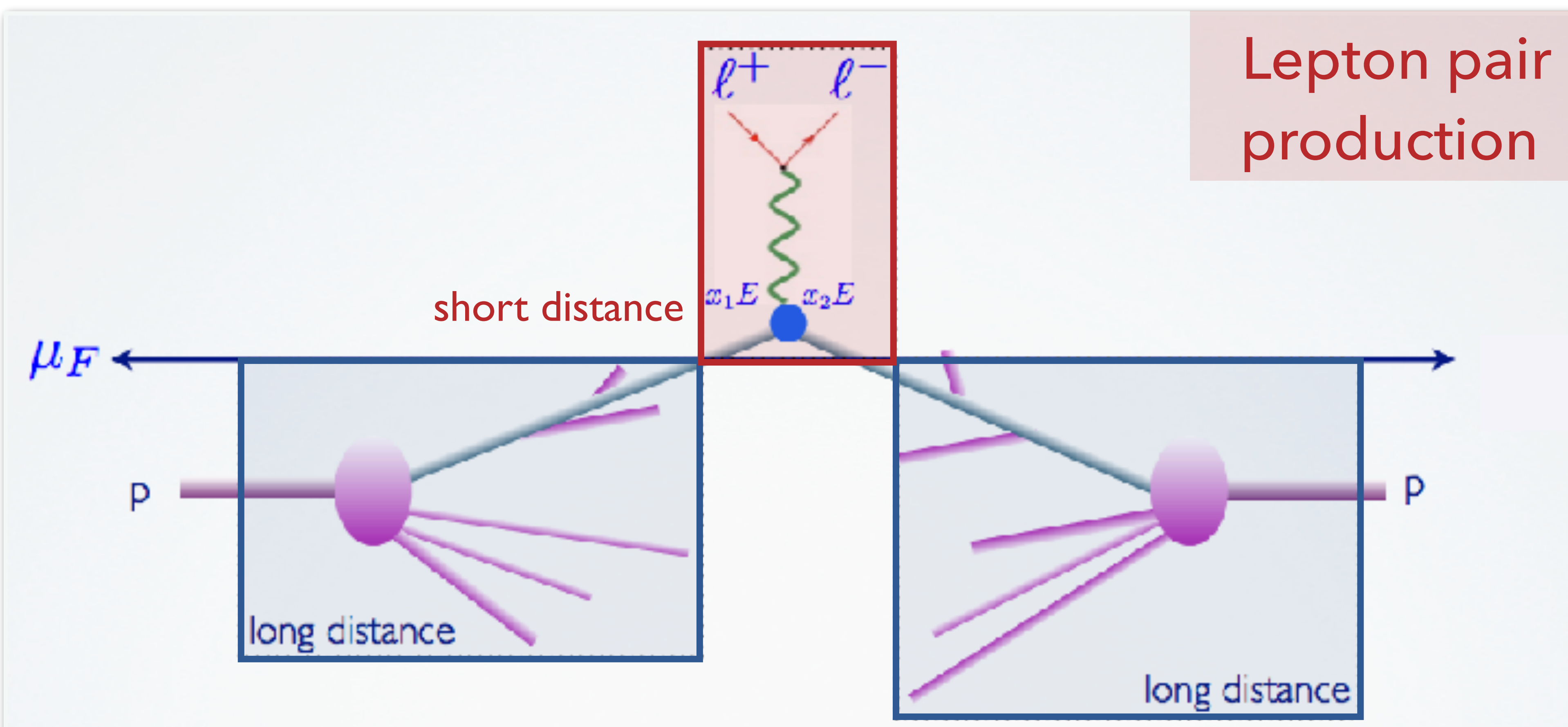




Collinear Factorisation Theorem

$$\frac{d\sigma_H^{ep\to ab}}{dX} = \sum_{i=-n_f}^{+n_f} \int_{x_B}^{1} \frac{dz}{z}\, f_i(z,\mu_F)\, \frac{d\hat{\sigma}_i^{ei}}{dX}(zS,\alpha_s(\mu_R),\mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

$$\frac{d\sigma_H^{pp\to ab}}{dX} = \sum_{i,j=-n_f}^{+n_f} \int_{\tau_0}^{1} \frac{dz_1}{z_1}\frac{dz_2}{z_2}\, f_i(z_1,\mu_F)\, f_j(z_2,\mu_F)\, \frac{d\hat{\sigma}_i^{ij}}{dX}(zS,\alpha_s(\mu_R),\mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$



Collinear Factorisation Theorem

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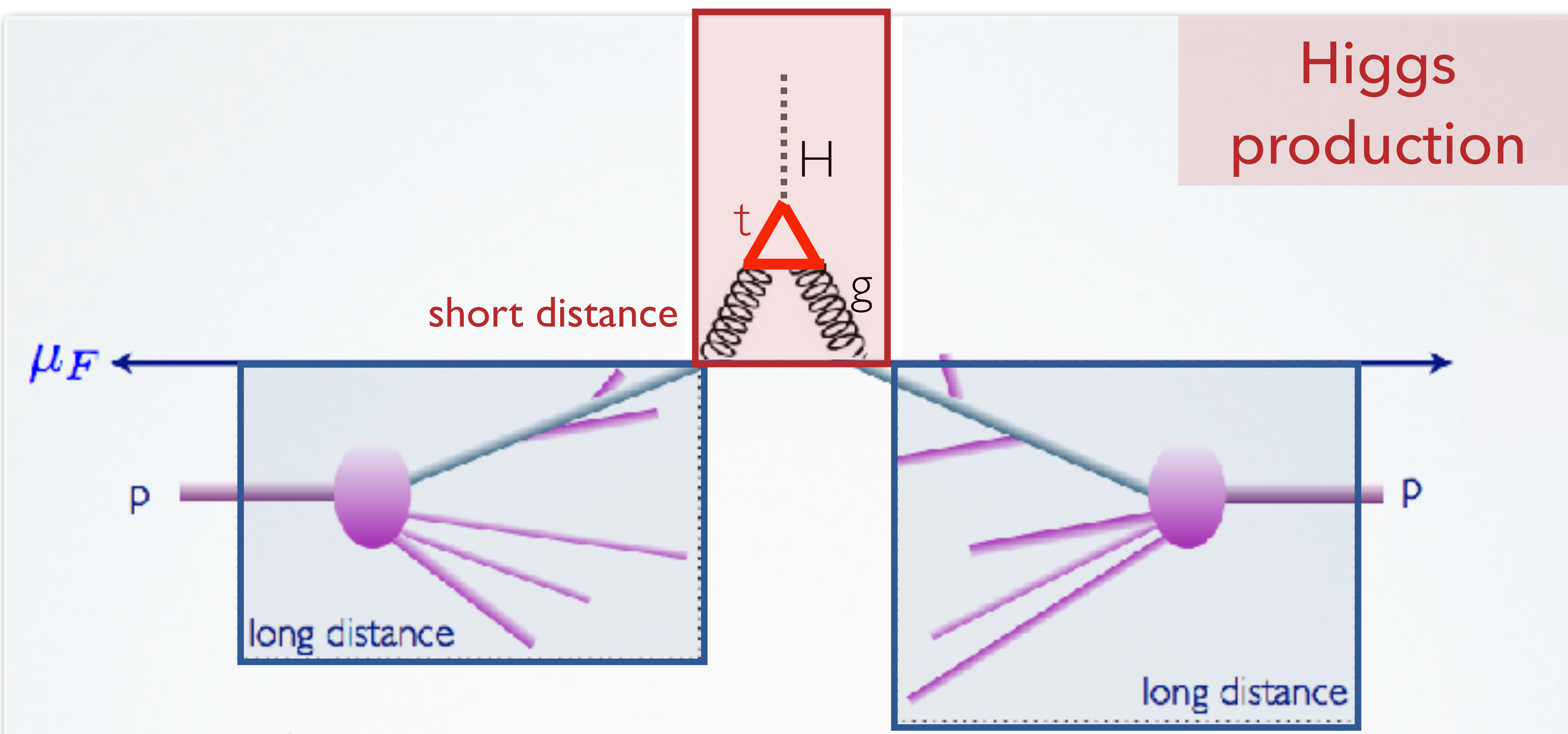

DGLAP evolution equations

$$\frac{d\sigma_H^{ep\to ab}}{dX} = \sum_{i=-n_f}^{+n_f} \int_{x_B}^{1} \frac{dz}{z}\, f_i(z,\mu_F)\, \frac{d\hat{\sigma}_i^{ei}}{dX}(zS, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

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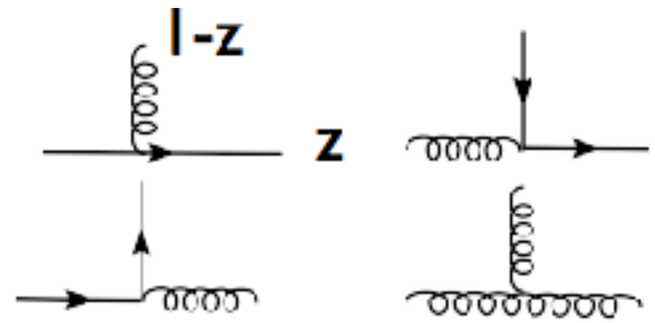
$$\frac{d}{dt}\begin{pmatrix} q_i(x,t) \\ g(x,t) \end{pmatrix} = \frac{\alpha_s(t)}{2\pi} \int_x^1 \sum_{j=q,\bar{q}} \frac{d\xi}{\xi} \begin{pmatrix} P_{ij}\left(\frac{x}{\xi}, \alpha_s(t)\right) & P_{ig}\left(\frac{x}{\xi}, \alpha_s(t)\right) \\ P_{gj}\left(\frac{x}{\xi}, \alpha_s(t)\right) & P_{gg}\left(\frac{x}{\xi}, \alpha_s(t)\right) \end{pmatrix} \otimes \begin{pmatrix} q_j(\xi,t) \\ g(\xi,t) \end{pmatrix}$$

$$t = \log \frac{Q^2}{\mu^2}$$



Dokshitzer, Gribov, Lipatov, Altarelli, Parisi renomalization group equations

LO - Dokshitzer; Gribov, Lipatov; Altarelli, Parisi, 1977

NLO - Floratos,Ross,Sachrajda; Floratos,Lacaze,Kounnas, Gonzalez-Arroyo,Lopez,Yndurain; Curci,Furmanski Petronzio, 1981

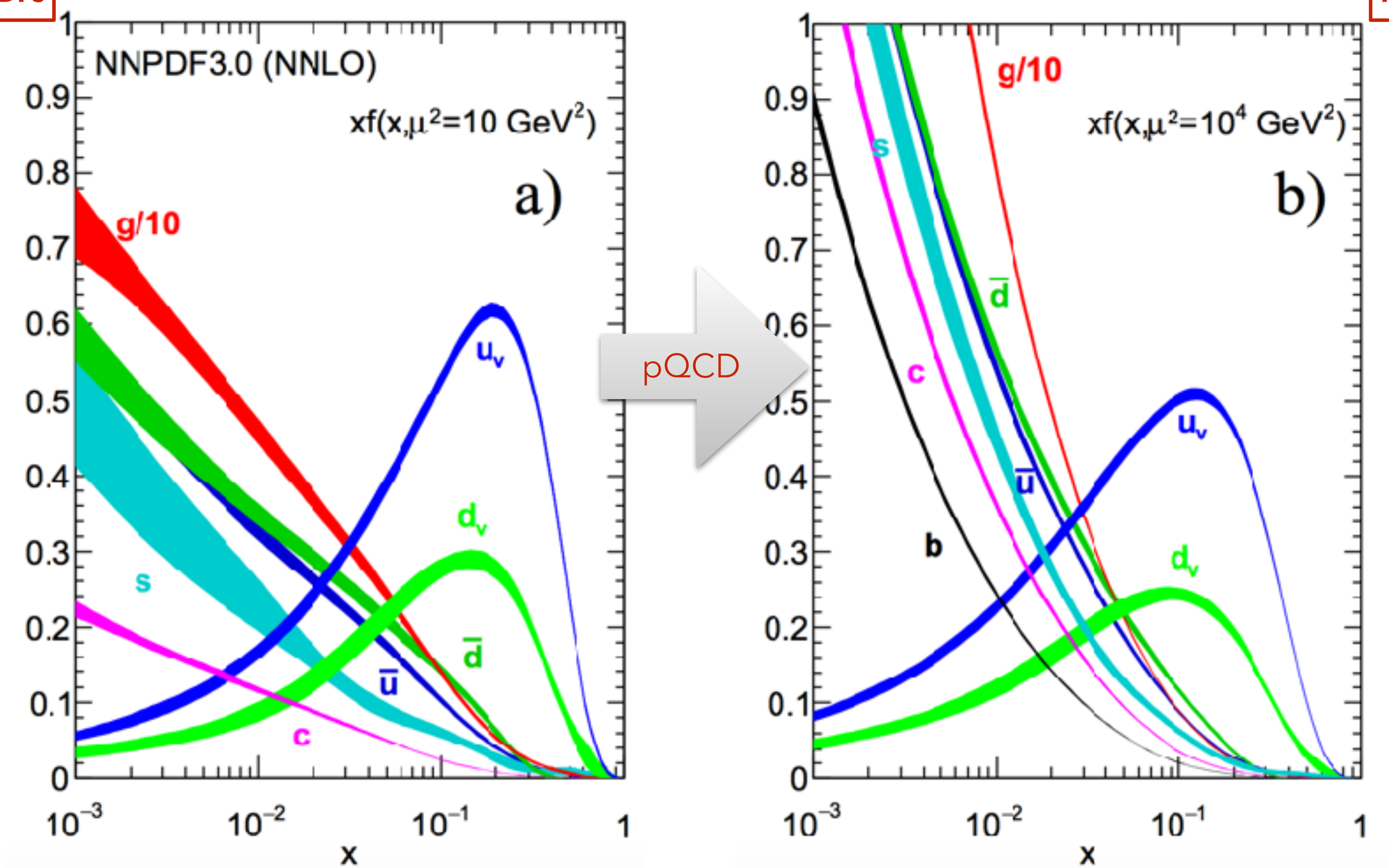
NNLO - Moch, Vermaseren, Vogt, 2004

DGLAP evolution equations

Functional dependence of PDFs on the scale is totally predicted up to NNLO accuracy by solving DGLAP evolution equations

Hadronic scale: global fit of PDFs

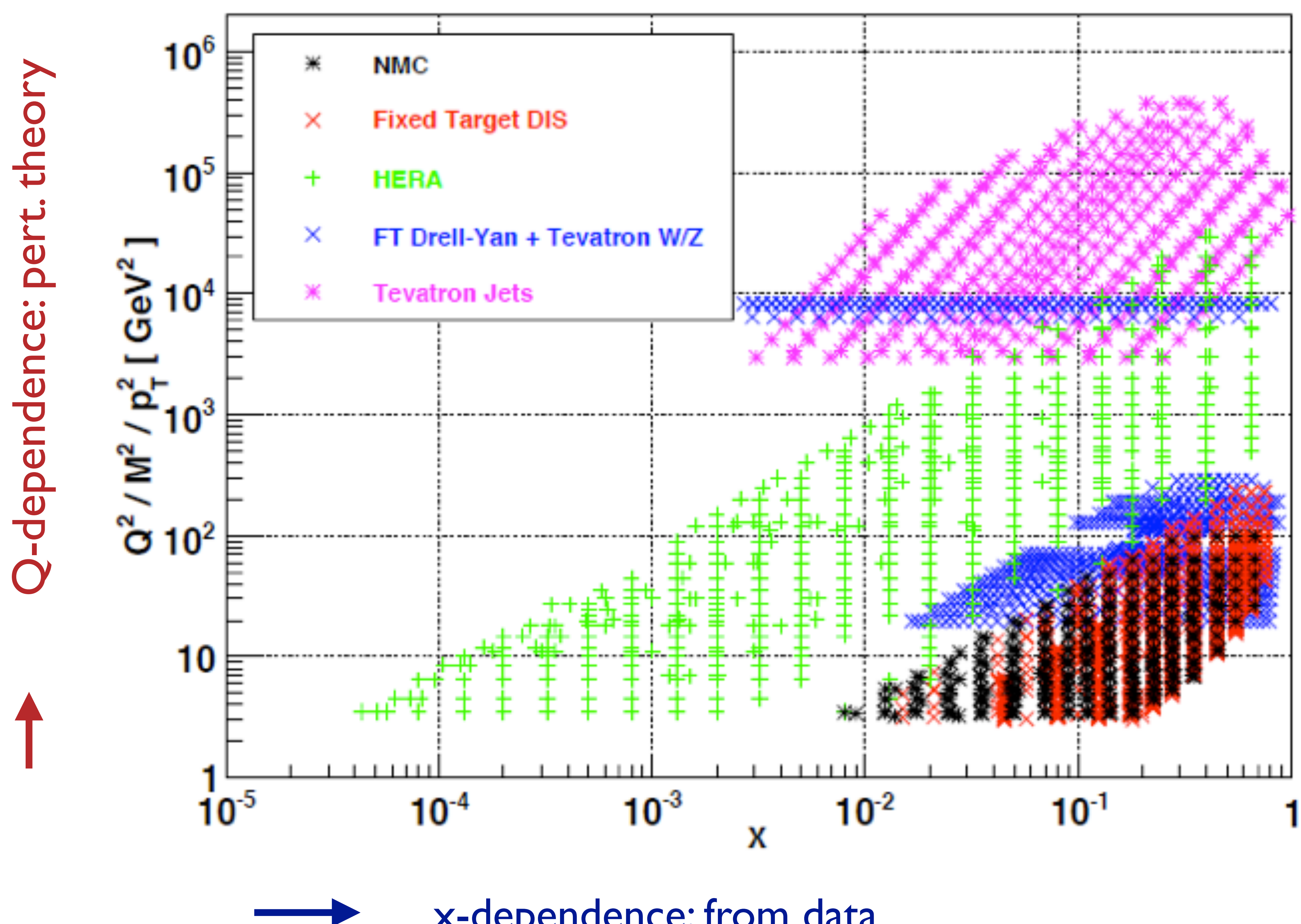
High scale: input to the LHC



PDG 2016

PDF determination

Pre-LHC data

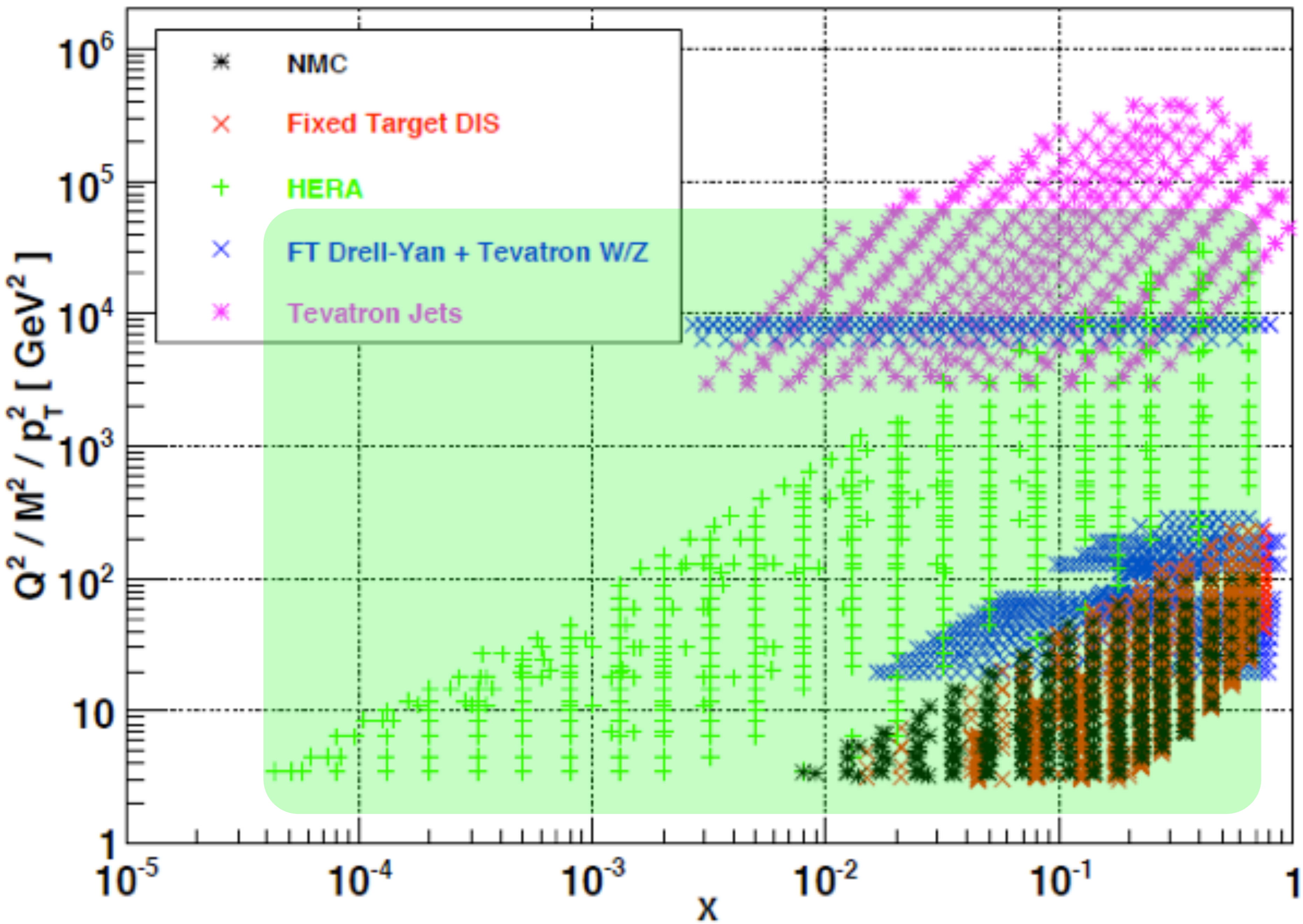


Different data constrain different PDF combinations in different kinematic regions.

pre-LHC data

Pre-LHC data

Q-dependence: pert. theory



NC $F_1^{\gamma,Z} = \sum_i e_i^2 (q_i + \bar{q}_i)$

CC $F_1^{W^+} = \bar{u} + d + s + \bar{c}$

CC $-F_3^{W^+}/2 = \bar{u} - d - s + \bar{c}$

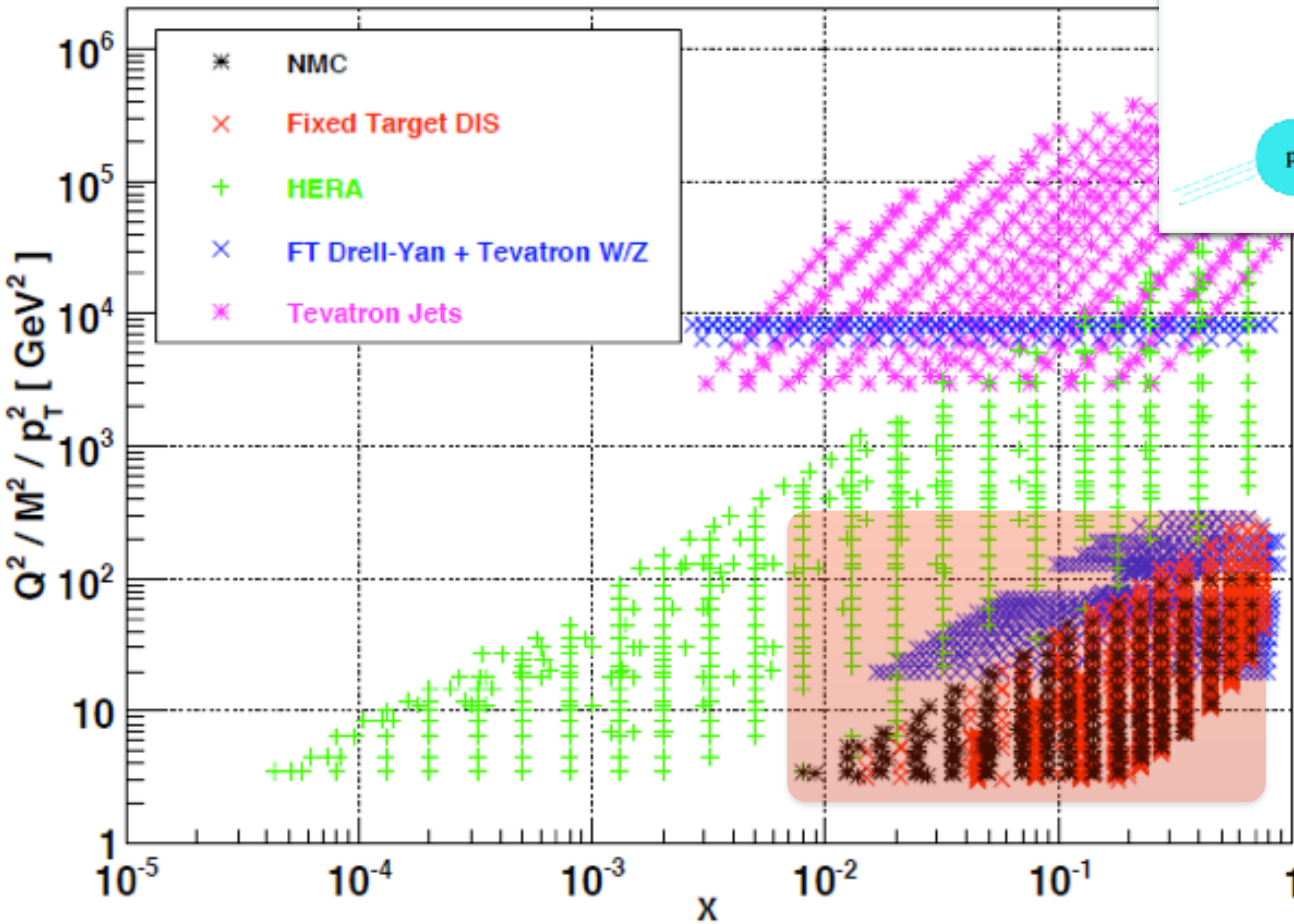
$F_2 = 2xF_1$

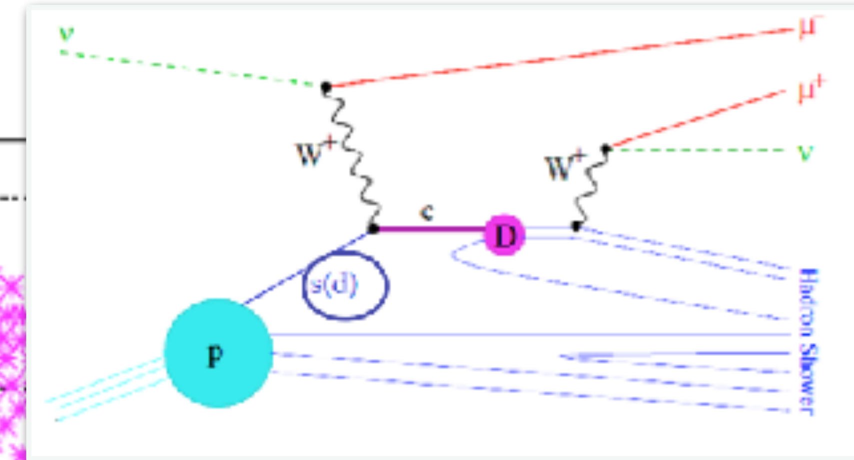
$$x = x_B$$

- Backbone of any PDF fit
- Structure functions known up to $O(\alpha_S^3$
- Constrain singlet and uv dv combinations
- Constrain g at small and moderate x

x-dependence: from data

Pre-LHC data





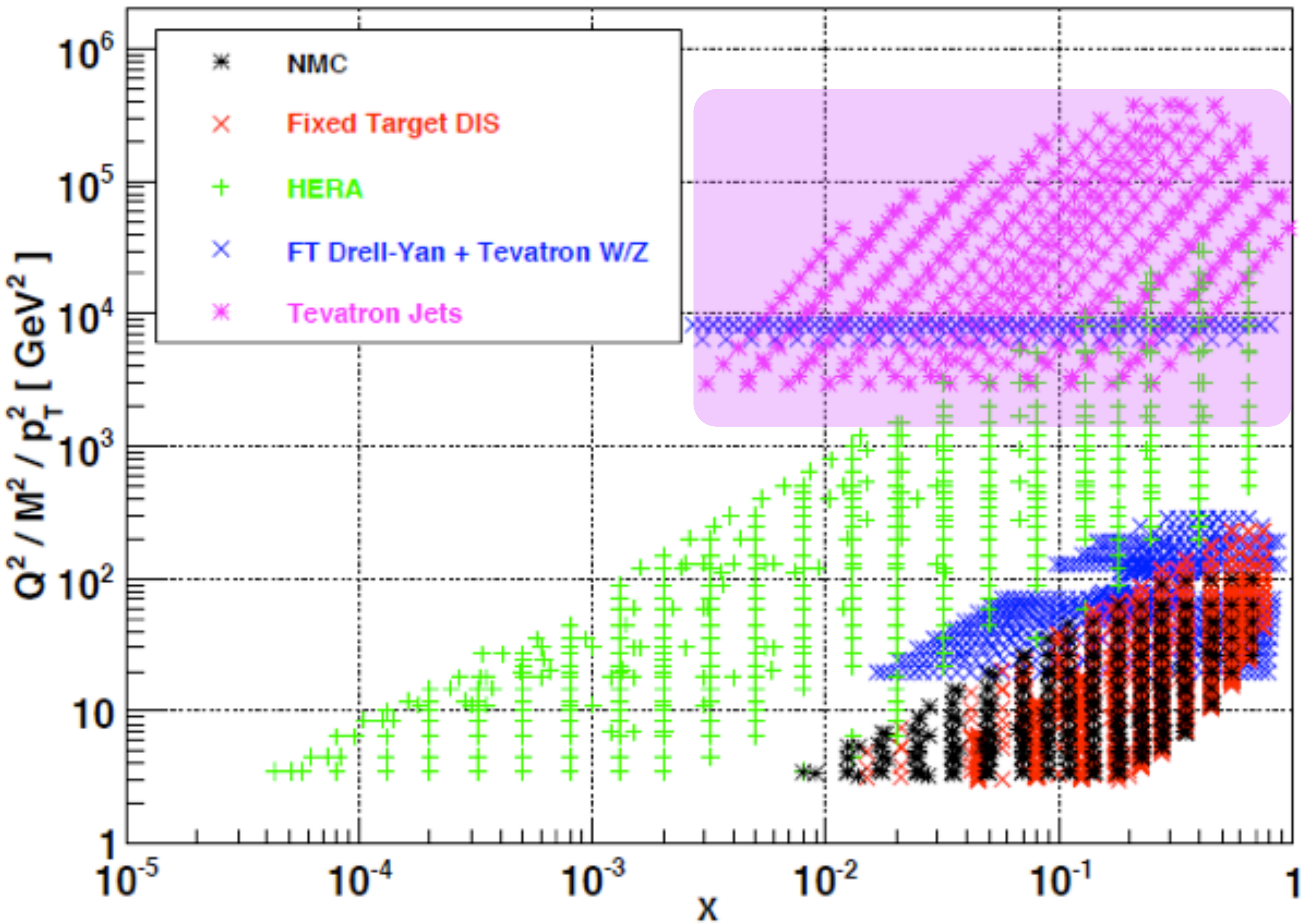
Q-dependence: pert. theory

x-dependence: from data

$$x = \frac{Q^2}{2M_n E_\nu y}$$

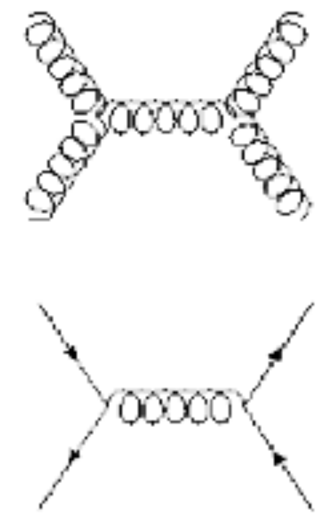
- Deep inelastic neutrino production of charm
- Constrain strange and anti-strange at moderate x > 10^{-2}

Pre-LHC data



Q-dependence: pert. theory

x-dependence: from data



$$x_{1,2} = \frac{p_T}{\sqrt{S}} e^{\pm\eta}$$

- Jet data
- Direct handle on quarks and gluons at large x

LHC data

GLUON

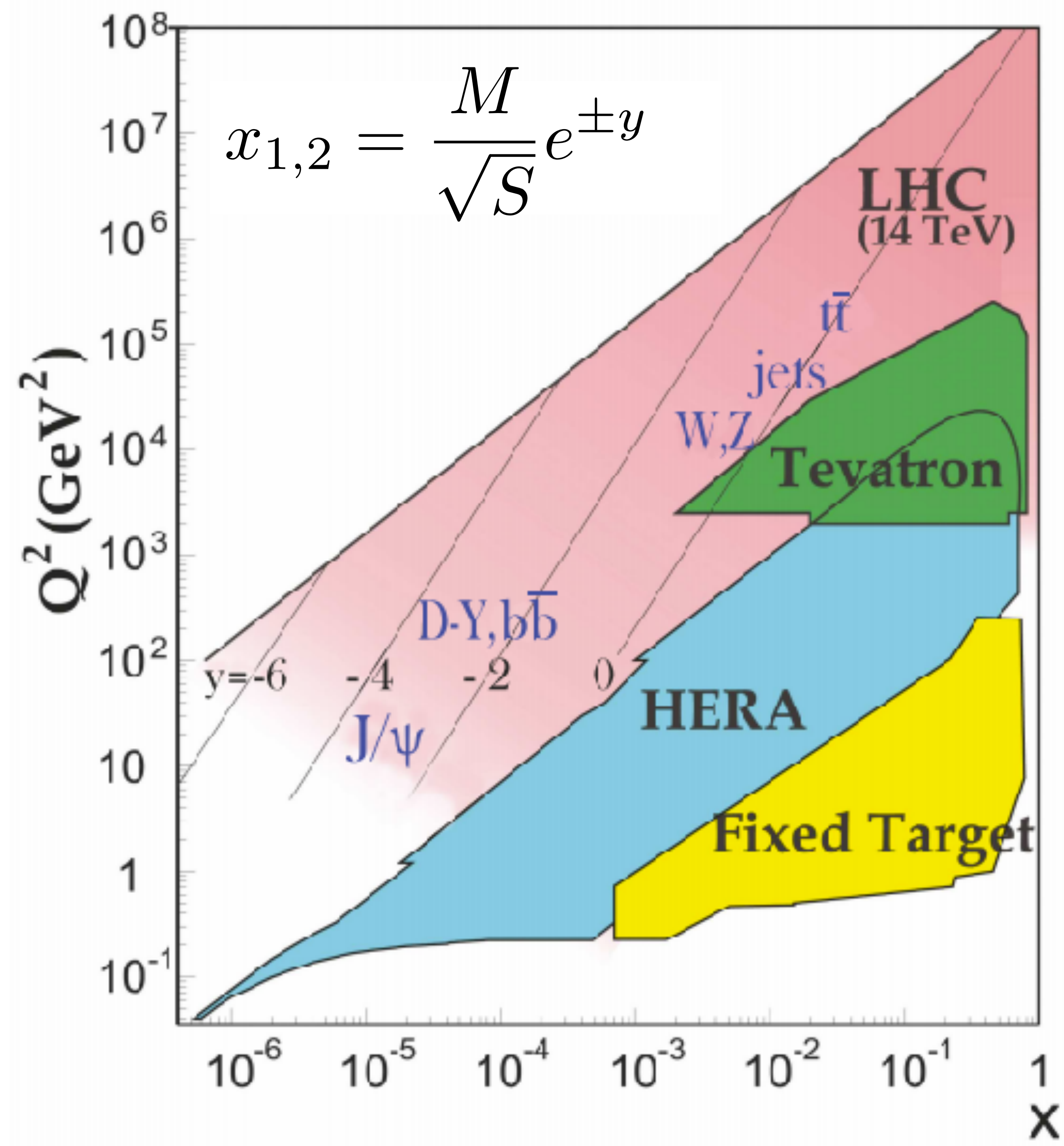
Inclusive jets and dijets
(medium/large x)
Isolated photon and γ+jets
(medium/large x)
Top pair production **(large x)**
High p_T V(+jets) distribution
(small/medium x)

QUARKS

High p_T W(+jets) ratios
(medium/large x)
W and Z production
(medium x)
Low and high mass Drell-Yan
(small and large x)
Wc **(strangeness at medium x)**

PHOTON

Low and high mass Drell-Yan
WW production



PDG 2016

The name of the game

- Choose **experimental data** to fit and include all info on correlations
- **Theory settings**: perturbative order, heavy quark mass scheme, EW corrections, intrinsic heavy quarks, α_s, quark masses value and scheme
- Choose a starting scale Q_0 where pQCD applies
- **Parametrise** independent quarks and gluon distributions at the starting scale
- Solve **DGLAP equations** from initial scale to scales of experimental data and build up observables
- **Fit** PDFs to data

The name of the game

- Choose **experimental data** to fit and include all info on correlations
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- **Fit** PDFs to data

Not as simple as it may look…

$$\langle \mathcal{O}[\{f\}] \rangle = \int [\mathcal{D}f]\, \mathcal{O}[\{f\}]\mathcal{P}[\{f\}]$$

- Given a finite number of experimental data points want a set of functions
- Want to find a infinite-dimensional object from a finite number of information

A quite complicated game

- Choose **experimental data** to fit and include all info on correlations
- **Theory settings**: perturbative order, heavy quark mass scheme, EW corrections, intrinsic heavy quarks, α_s, quark masses value and scheme
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- **Parametrise** independent quarks and gluon distributions at the starting scale
- Solve **DGLAP equations** from initial scale to scales of experimental data and build up observables
- **Fit** PDFs to data
- Provide **error sets** to compute **PDF uncertainties**

Must propagate data uncertainty into PDF uncertainty. How to deal with inconsistencies?

Hidden uncertainty: still an option?

Parametric versus non-parametric approach

Methodology

Hessian versus MC approach MC2Hessian

Standard solution

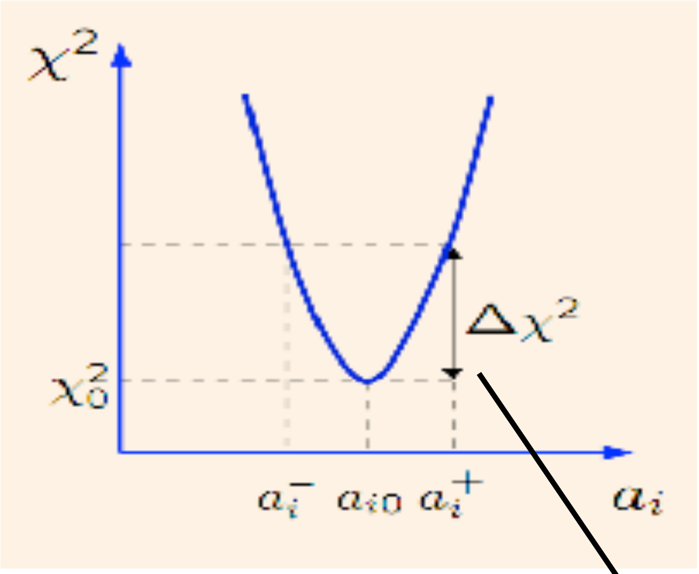
$$\langle \mathcal{O}[\{f\}] \rangle = \int [\mathcal{D}f]\, \mathcal{O}[\{f\}] \mathcal{P}[\{f\}]$$

- Given a finite number of experimental data points want a set of functions with errors
- Want to find a infinite-dimensional object from a finite number of information

Propagation of experimental uncertainty

$$\langle \mathcal{O}[\{f\}] \rangle \simeq \int da_1 da_2 \ldots da_{N_{par}}\, \mathcal{O}[\vec{a}]\, \mathcal{P}[\vec{a}]$$

- Hessian approach: Project into a n-dimensional space of parameters and use linear approximation around minimum χ^2



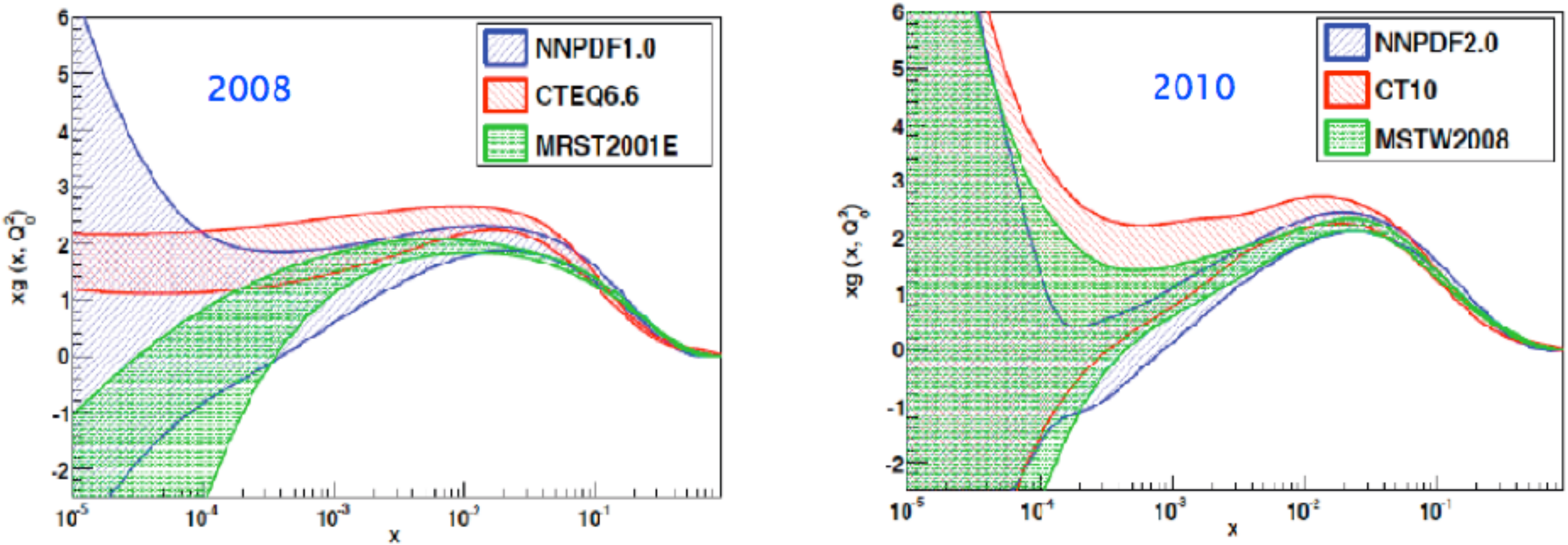
Tolerance

Parametrisation

- Introduce a simple functional form with enough free parameters
- Typically about 20-40 free parameters for 7 independent functions

$$f_i(x, Q_0^2) = a_0\, x^{a_1}\, (1-x)^{a_2} P(x, a_3, a_4, \ldots),$$

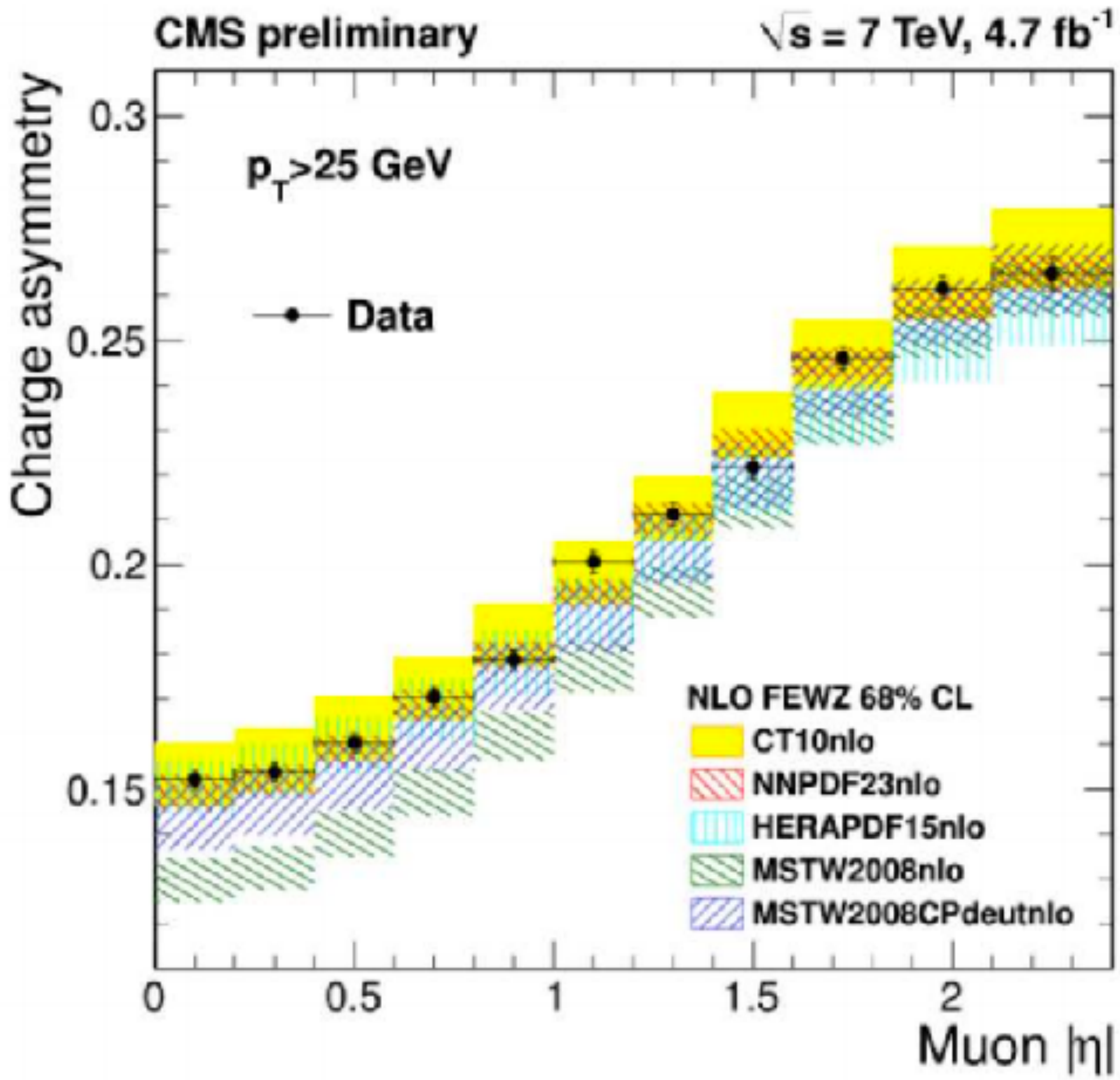
Data-driven progress

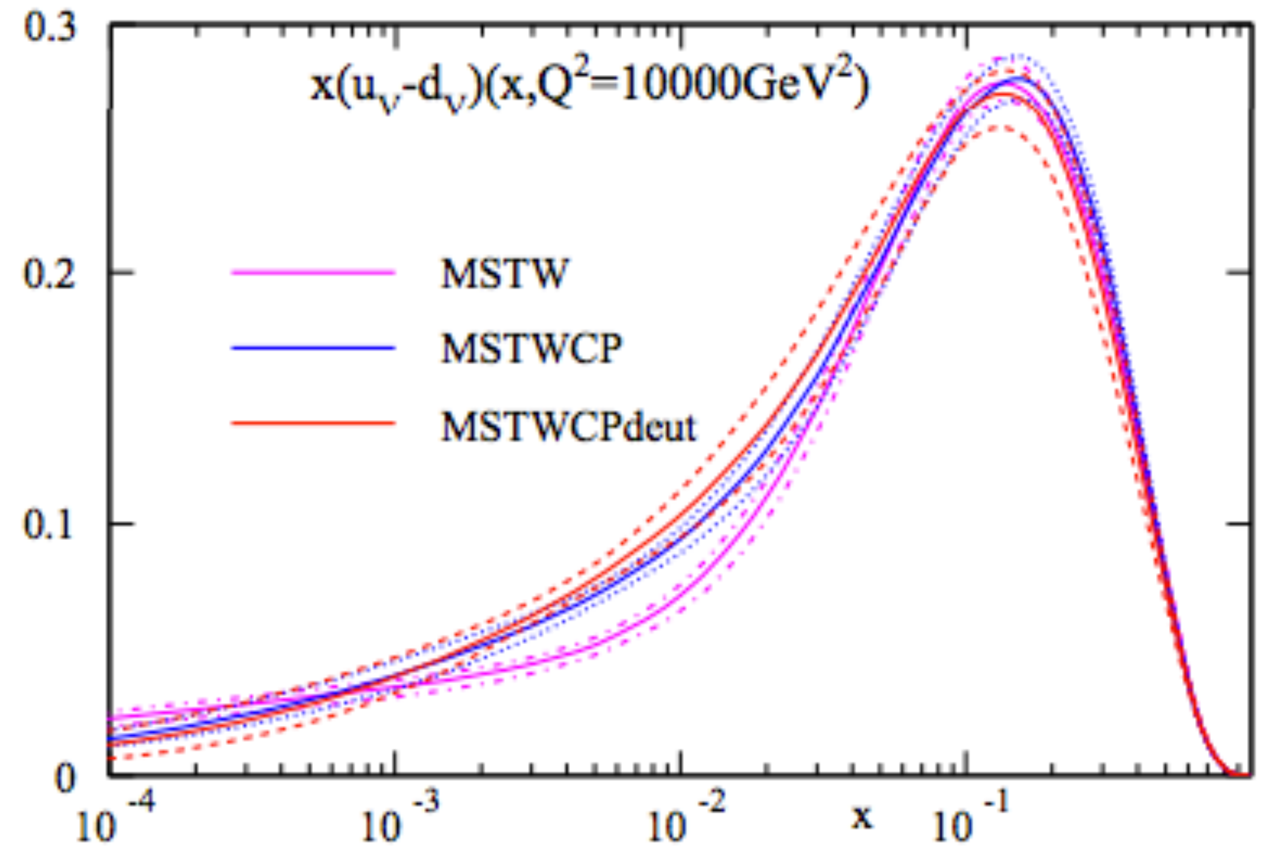


$$xg = A_g\, x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g\, x) + A_{g'}\, x^{\delta_{g'}}(1-x)^{\eta_{g'}}$$

- PDF uncertainties tuned to data (tolerance $\Delta\chi^2 > 1$ - many studies/improvements)
- Fixed parametrisation was forced to be more flexible by new data => less biased parametrisation form (a posteriori data-driven progress)

Data-driven progress

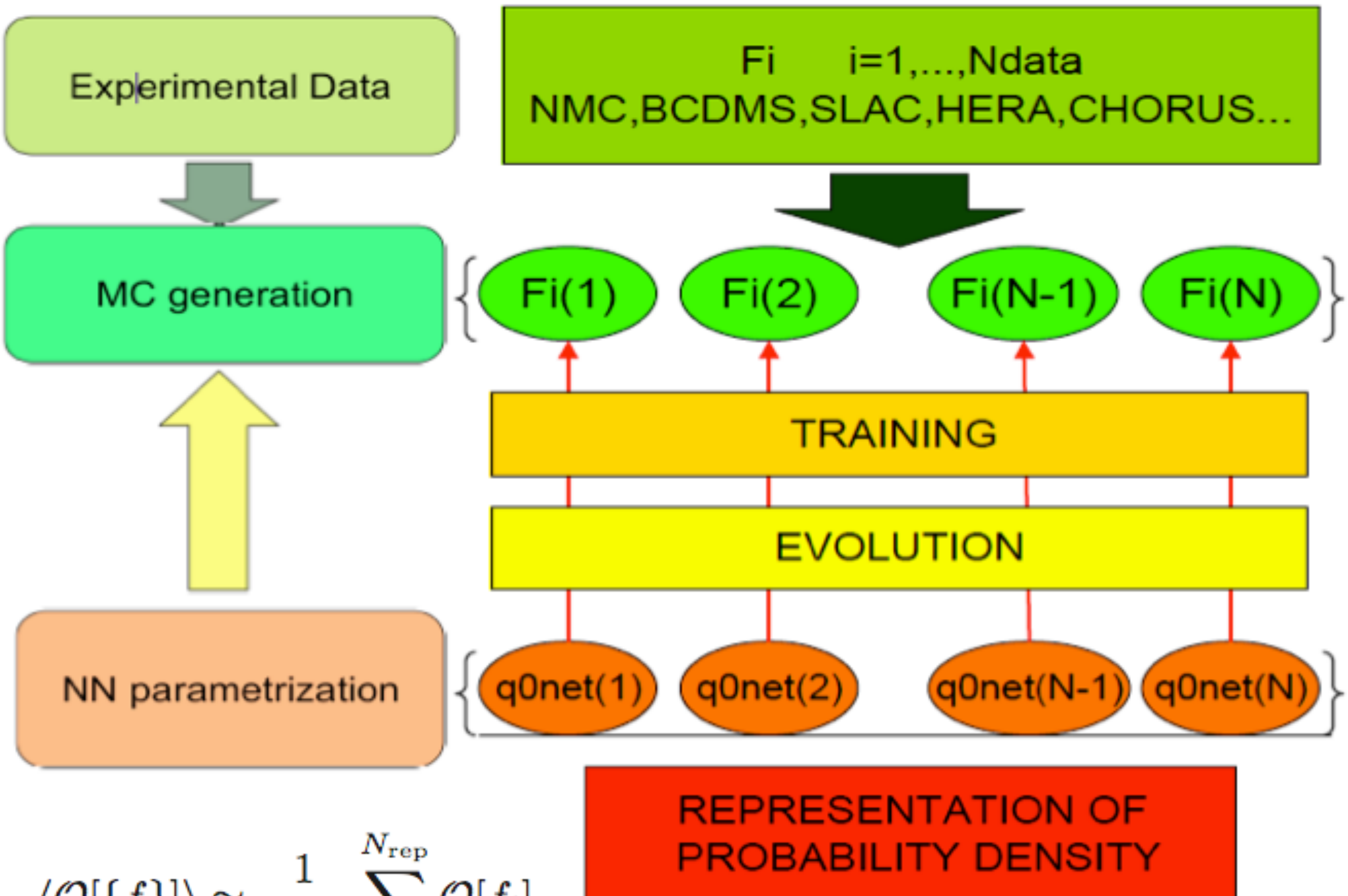




Martin et al
EPJC73 (2013) 2, 2318

- PDF uncertainties tuned to data (tolerance $\Delta\chi^2 > 1$ - many studies/improvements)
- Fixed parametrisation was forced to be more flexible by new data => less biased parametrisation form (a posteriori data-driven progress)

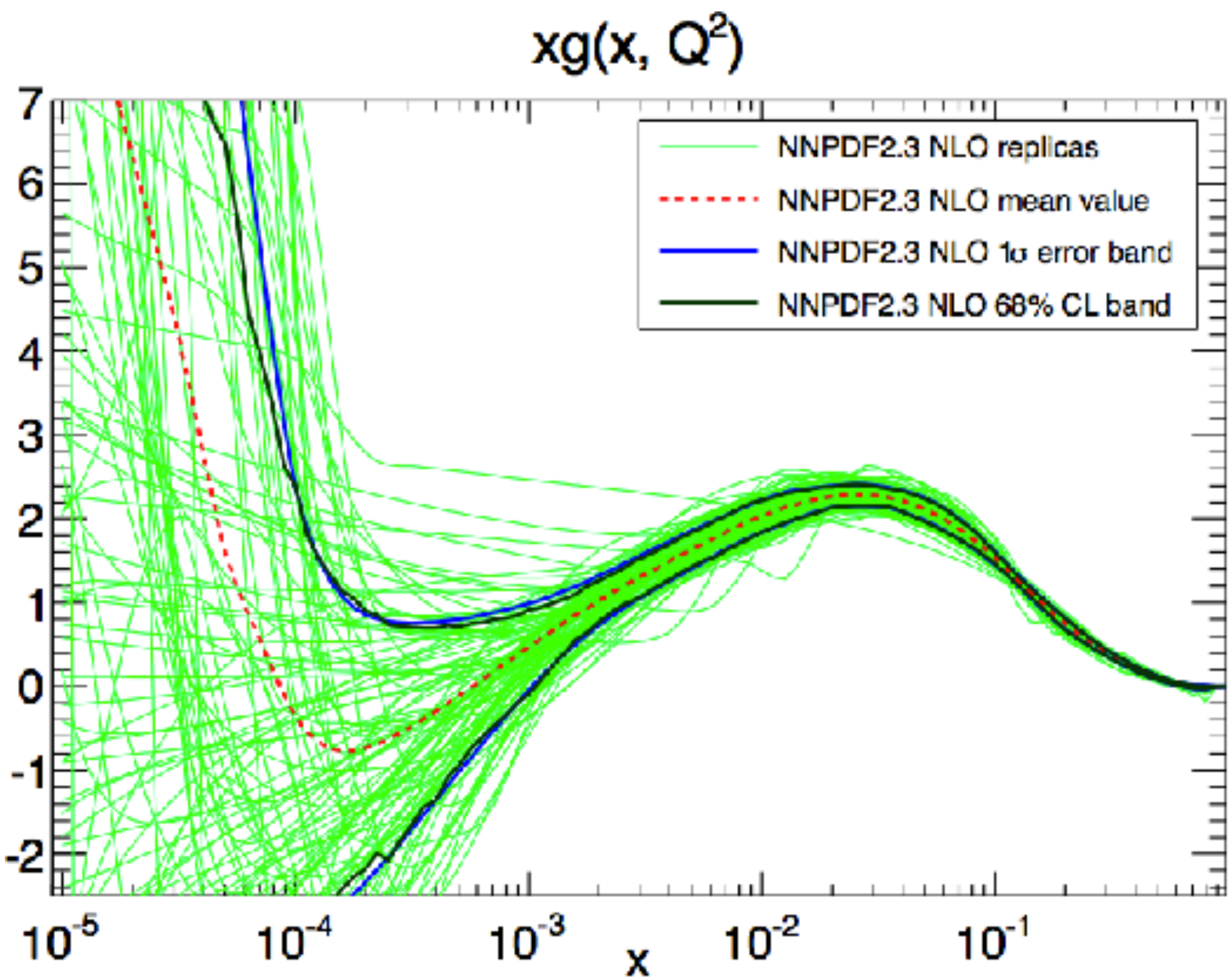
The NNPDF solution



$$\langle \mathcal{O}[\{f\}] \rangle \simeq \frac{1}{N_{\rm rep}} \sum_{i=1}^{N_{\rm rep}} \mathcal{O}[f_i],$$

Ball, Del Debbio, Forte, Guffanti, Latorre, Rojo, MU (2008)

The NNPDF solution



The N(eural)N(etwork)PDFs:

- Monte Carlo techniques: sampling the probability measure in PDF functional space
- Neural Networks: all independent PDFs are associated to an unbiased and flexible parametrization: O(300) parameters versus O(30) in polynomial parametrization
- Genetic algorithm and cross-validation methods

✓Precise error estimate not driven by theoretical prejudice
✓No need to add new parameters when new data are included
✓Statistical interpretation of uncertainty bands
✓Possibility to include data via re-weighting: no need to refit

NNPDF3.1

A fast-paced progress ...

2016 First PDF set with fitted charm

2015 First PDF set with threshold resummation

2014 NNPDF3.0: first PDF set validated with closure test

2013 NNPDF2.3QED: first PDF set with fitted photon PDF

NNPDF2.3: first PDF set with LHC data

2012 Reweighting PDFs

2011 NNPDF2.1: Heavy quark mass effects

Determination of α_S from PDF fit

2010 NNPDF2.0: First NNPDF global set

2009 NNPDF1.2: Determination of the proton strangeness: solved NuTeV anomaly

2008 NNPDF1.0: First NNPDF set - only DIS data

… to the future

April 2017 NNPDF3.1

Summer 2017 NNPDF3.1QED (à la LUXqed)

Updated determination of α_S and m_c

PDF fits with (scale)theory uncertainties

PDF set with small-x resummation

The NNPDF3.1 analysis

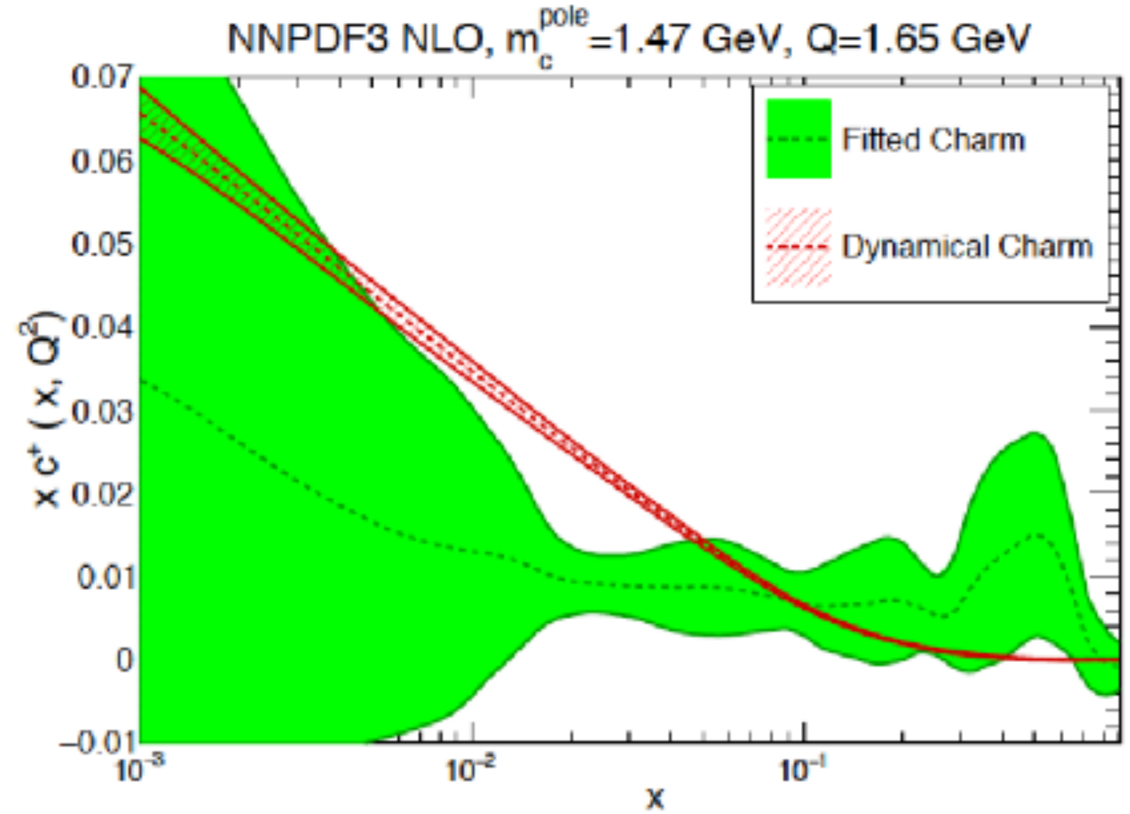
- 2014: NNPDF3.0 set with methodology tested by closure test and new data

- Plethora of new precise measurements and new available precise theoretical calculations call for an updated analysis:
  Top differential distributions, transverse momentum distribution of the Z, combined HERA I-II data, legacy data from Tevatron, full dataset 7 TeV and 8 TeV from LHCb

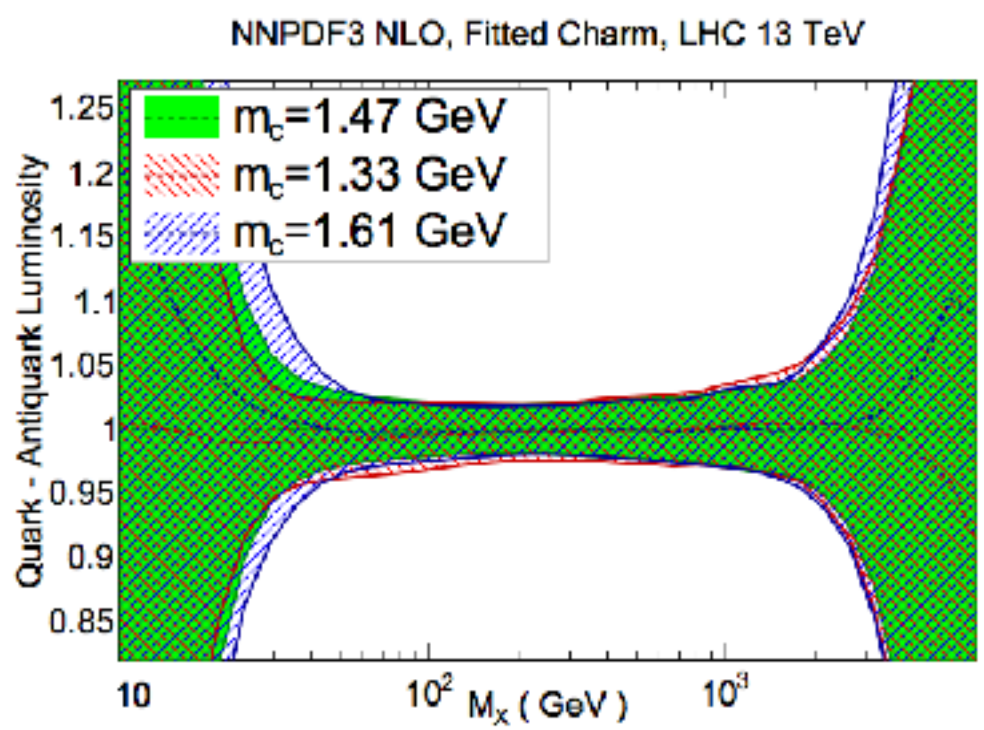
- Main methodological improvement is fitted charm PDFs, which increases stability with respect to choice of charm threshold in the fit

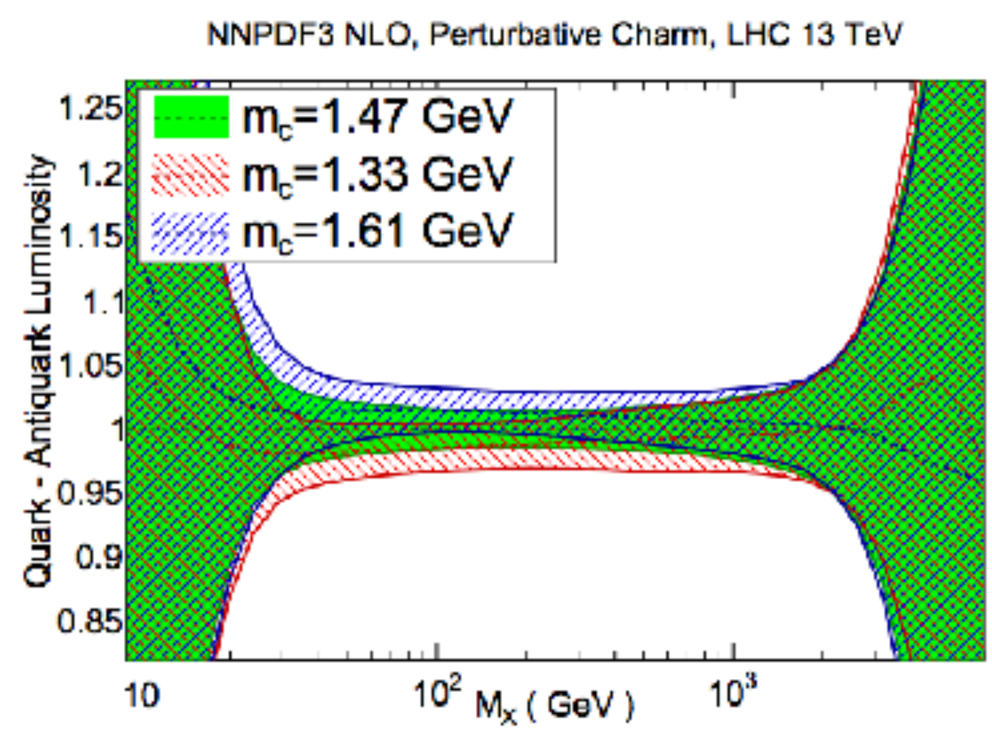
NNPDF3.1: fitted charm

- Most global fits assume scale-independent charm content of the proton vanishes
- Why fit the intrinsic component of the charm?
  - ☑ Stabilise the dependence on mc
  - ☑ Compare determination with available models
- Fitted charm improves data description



- Both fitted and perturbative charm fits will be released





Eur.Phys.J. C76 (2016) no.11, 647

NNPDF3.1: new data

NNPDF3.0 + **NNPDF3.1**

Combined HERA inclusive data	q and g at small/med x
ATLAS jets 2.76 TeV and 7 TeV **+ 2011 data 7 TeV**	gluon large x
ATLAS high-mass DY at 7 TeV **+ low mass**	**q/q~ separation**
ATLAS W pT data at 7 TeV	g and q at moderate x
ATLAS & CMS differential Z pT data at 7 & 8 TeV	**g and q at moderate x**
CMS (Y,M) double diff distributions 7 TeV **+ 8 TeV**	flavour separation
CMS jets at 7 TeV **+ 2.76 and 8 TeV jet data**	**gluon large x**
CMS muon charge asymmetry at 7 TeV **+ 8 TeV**	quark separation
CMS W+c at 7 TeV	strangeness
LHCb Z rapidity distribution at 7 TeV **+ 8 TeV (full data)**	small/large x quarks
ATLAS+CMS tt total xsec at 7/8 TeV	gluon large x
ATLAS+CMS tt differential xsec at 7/8 TeV	gluon large x
D0 legacy W asymmetry data	q/q~ separation

NNPDF3.1: data implementation

- PDF evolution and DIS structure functions up to NNLO computed with **APFEL** in **FONLL** scheme

- Hadronic data computed using **APPLgrid/fastNLO** interfaced to MCFM/ aMC@NLO/NLOjet++ & bin-by-bin NNLO/NLO C factors for each process

- **APFELgrid** used to combined PDF evolution and interpolated coefficient functions

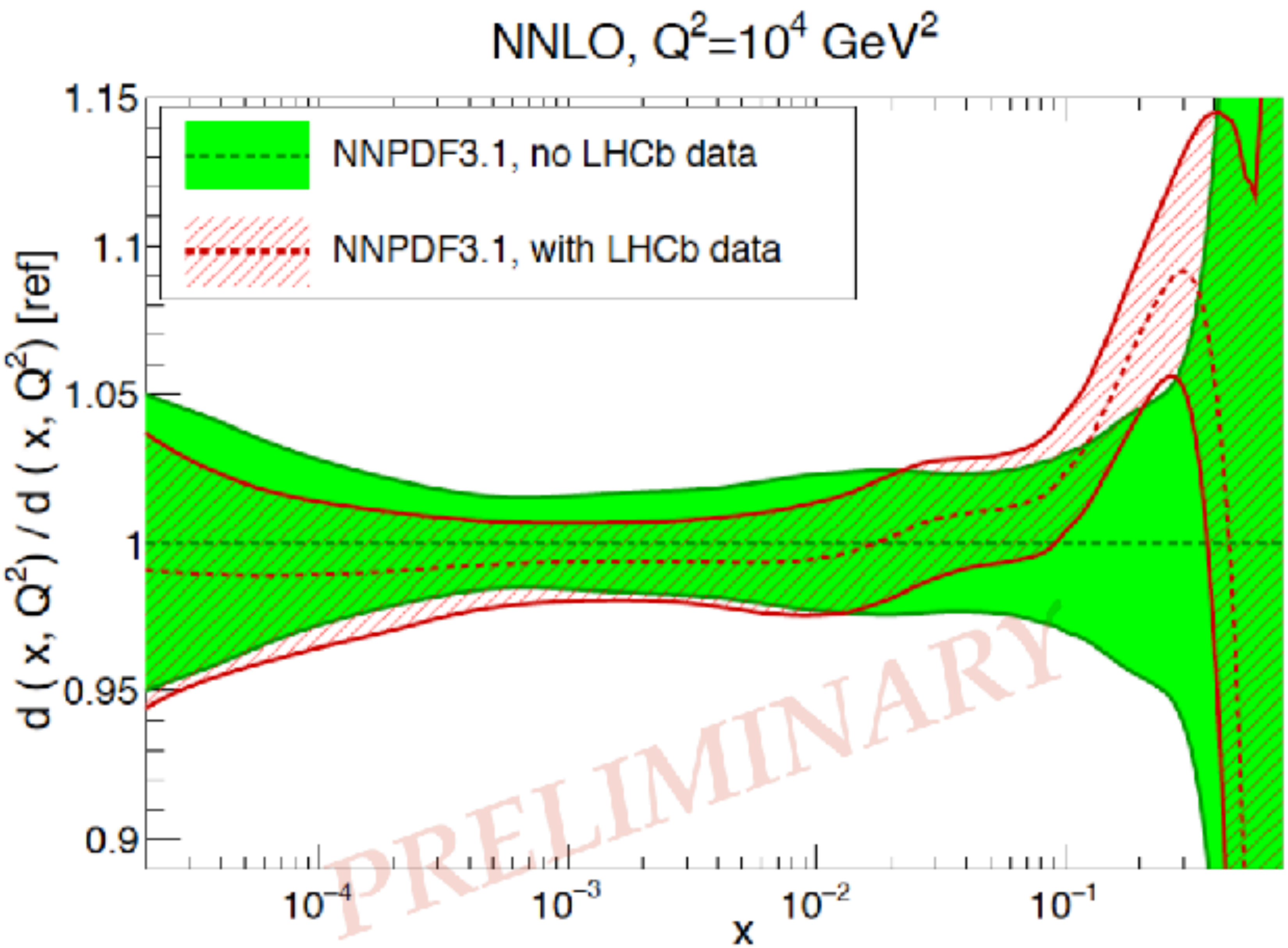
$$\sigma = \sum_{i,j}^{n_f}\sum_{\alpha,\beta}^{n_x} W_{ij\alpha\beta}\, f_i(x_\alpha, Q_0^2) f_j(x_\beta, Q_0^2)$$

Observable	APPLGRID	**APFELcomb**
W^+ production	1.03 ms	0.41 ms (2.5x)
Inclusive jet production	2.45 ms	20.1 μs (120x)

APPLgrid, Carli et al EPJC66 (2010) 503-524 & FASTNLO, Kluge et al
APFELgrid, Bertone et al 1605.02070
aMCfast, Berton et al JHEP 1408 (2014) 166
MCgrid, Del Debbio et al Comput.Phys.Commun. 185 (2014) 2115-2126

NNPDF3.1: LHCb 7 and 8 TeV data

- LHCb published complete 7 TeV and 8 TeV Z and W measurements in electron and muon channels in the forward region
- Forward W/Z production data improve flavour-separation especially at large-x
- Good theoretical description and sizeable impact



NNPDF3.1: new observables

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses
- Stunning progress has been made on some key processes for PDF determination
- Not all of them yet fully exploited (jets and direct photon production)

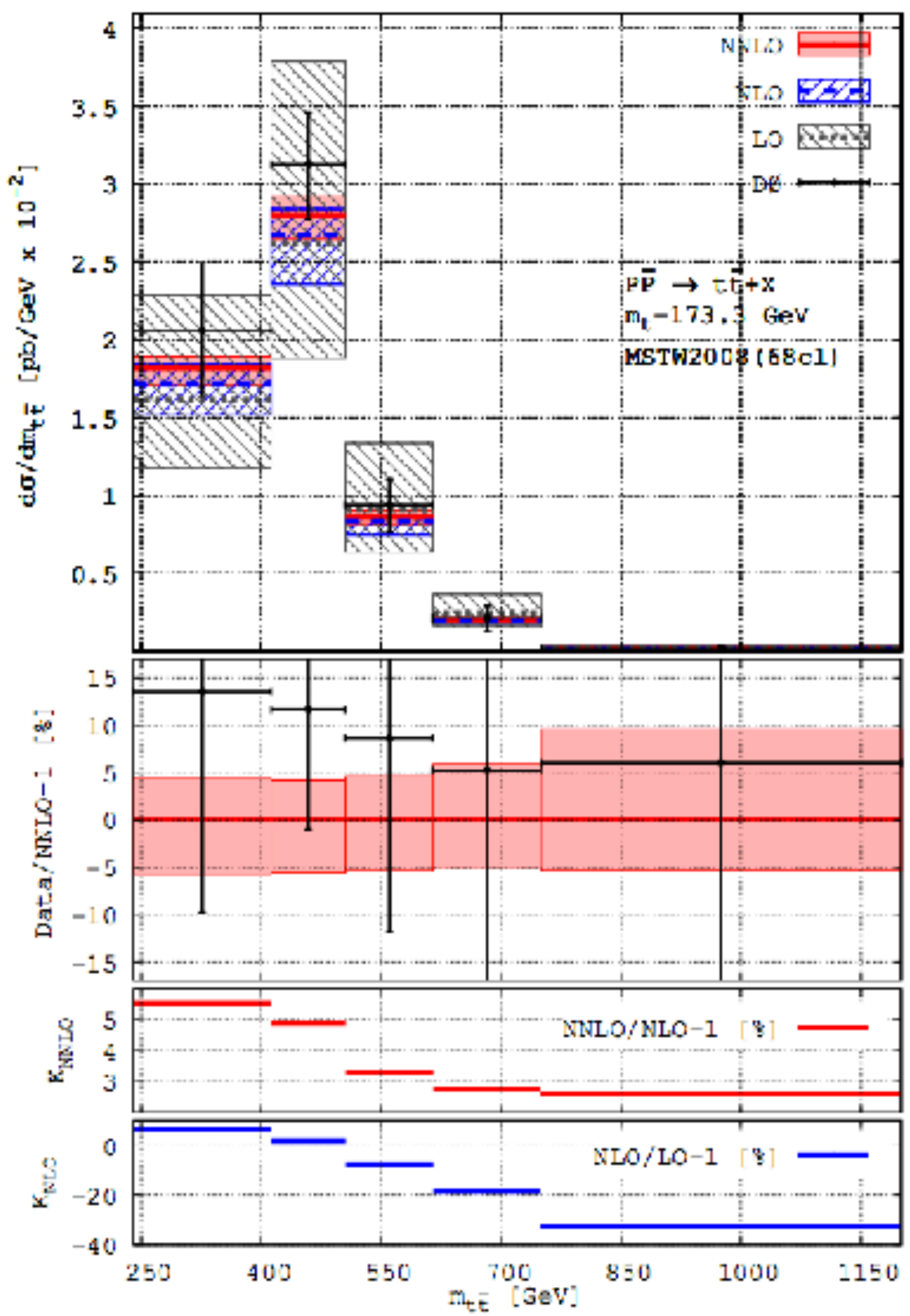
✓ NNLO top pair production (total and differential)
Czakon, Fiedler, Mitov [PRL 116(2016) 082003]
Czakon, Mitov [JHEP 1301(2015)]

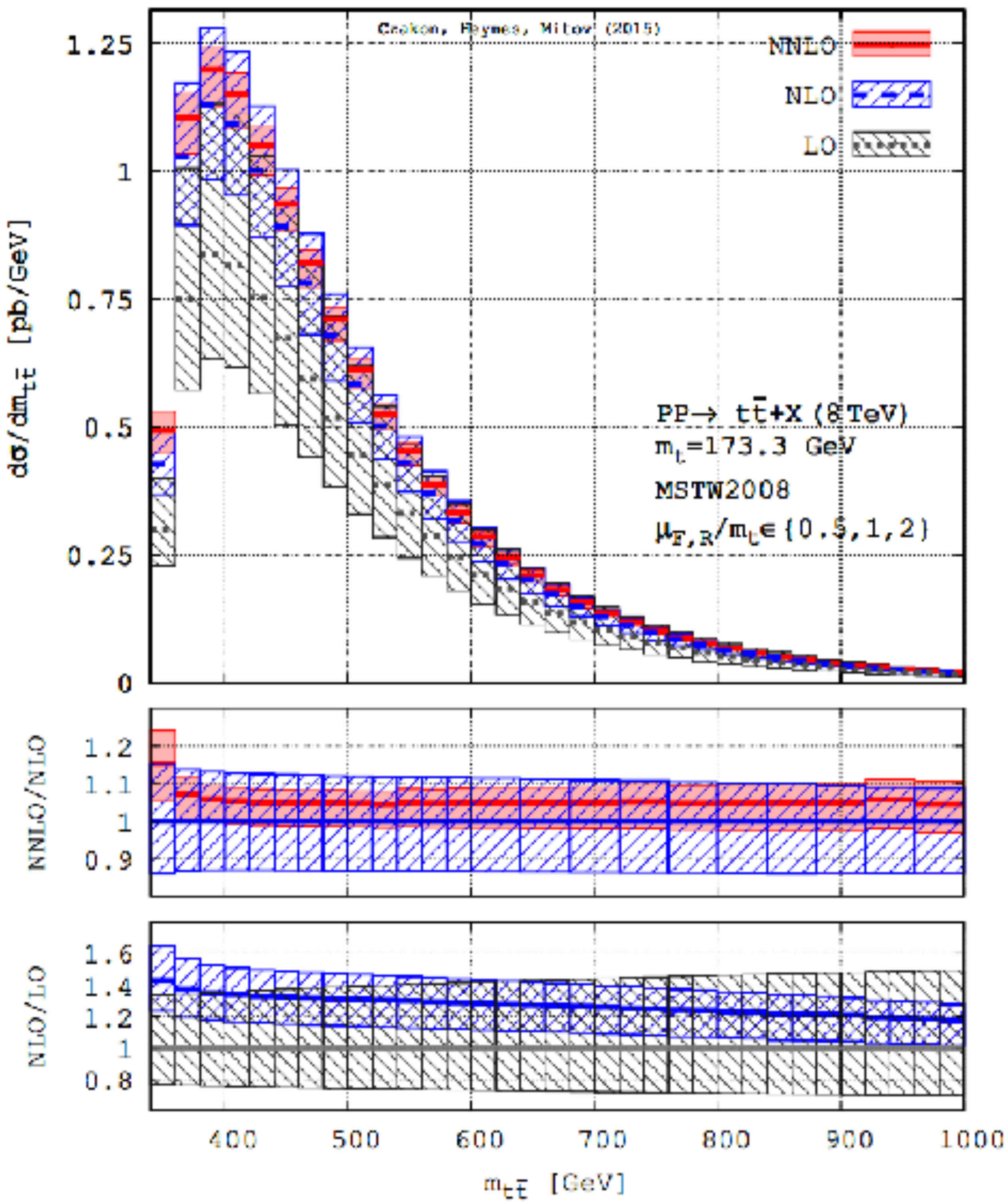
✓ W/Z+j and W/Z transverse momentum distributions
Gehrmann-De Ridder et al [1605.04295]
Boughezal, Liu, Petriello [1602.08140]
Boughezal, Liu, Petriello [1602.06965]
Boughezal et al [PRL 116(2016) 152001 & 062002]
Gehrmann-De Ridder et al [1507.02850]

✓ Inclusive jet cross section
Currie et al [JHEP 1401 (2014) 110]
Gehrmann-De Ridder et al [PRL 110 (2016) 162003]

✓ Direct photon production
Campbell, Ellis, Williams [1612.04333]

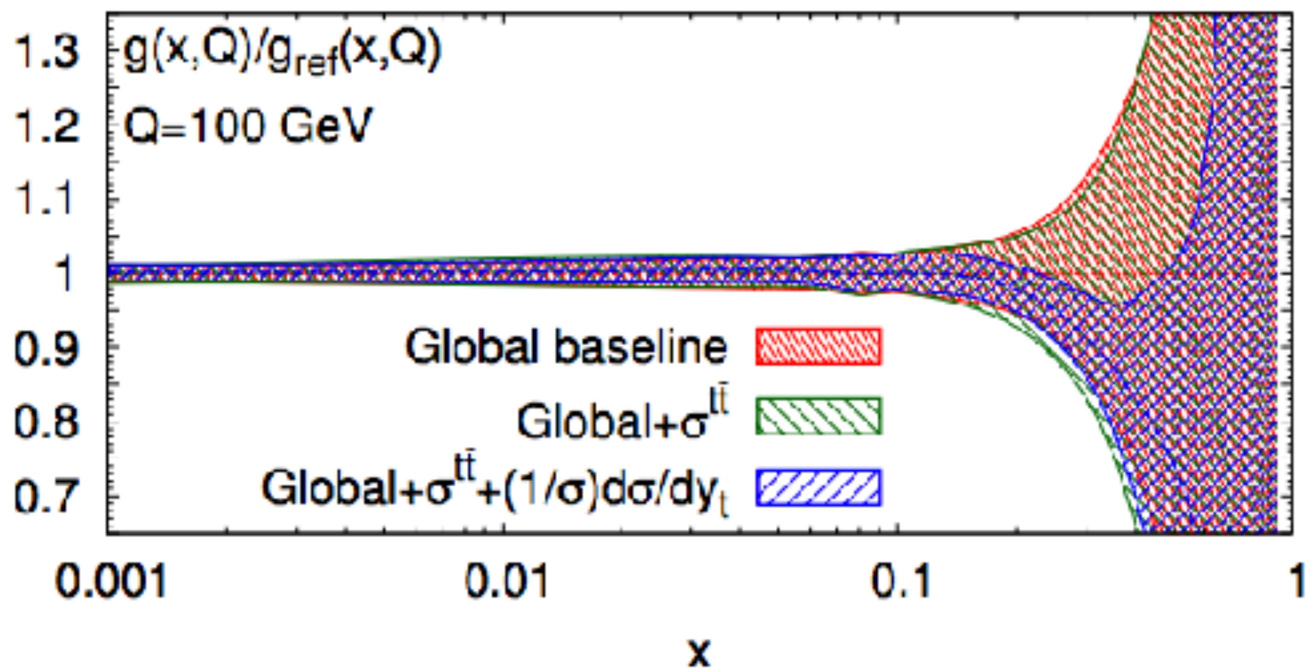
NNPDF3.1: top differential distributions

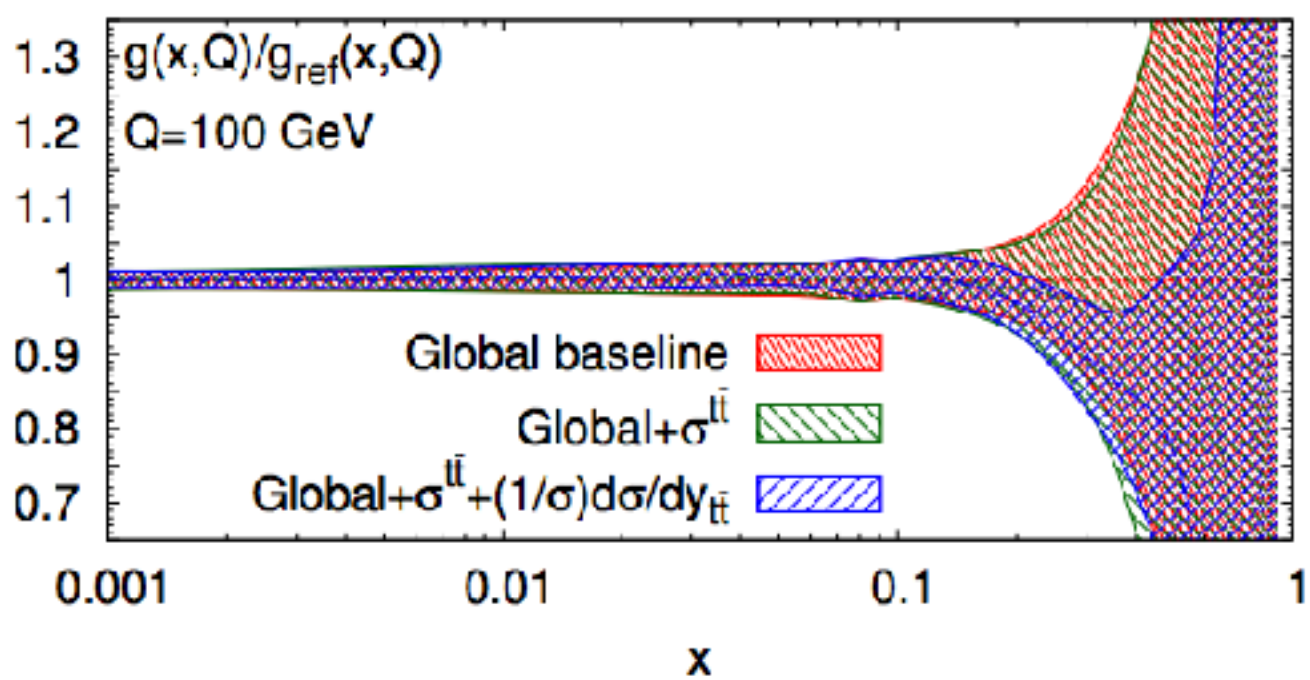


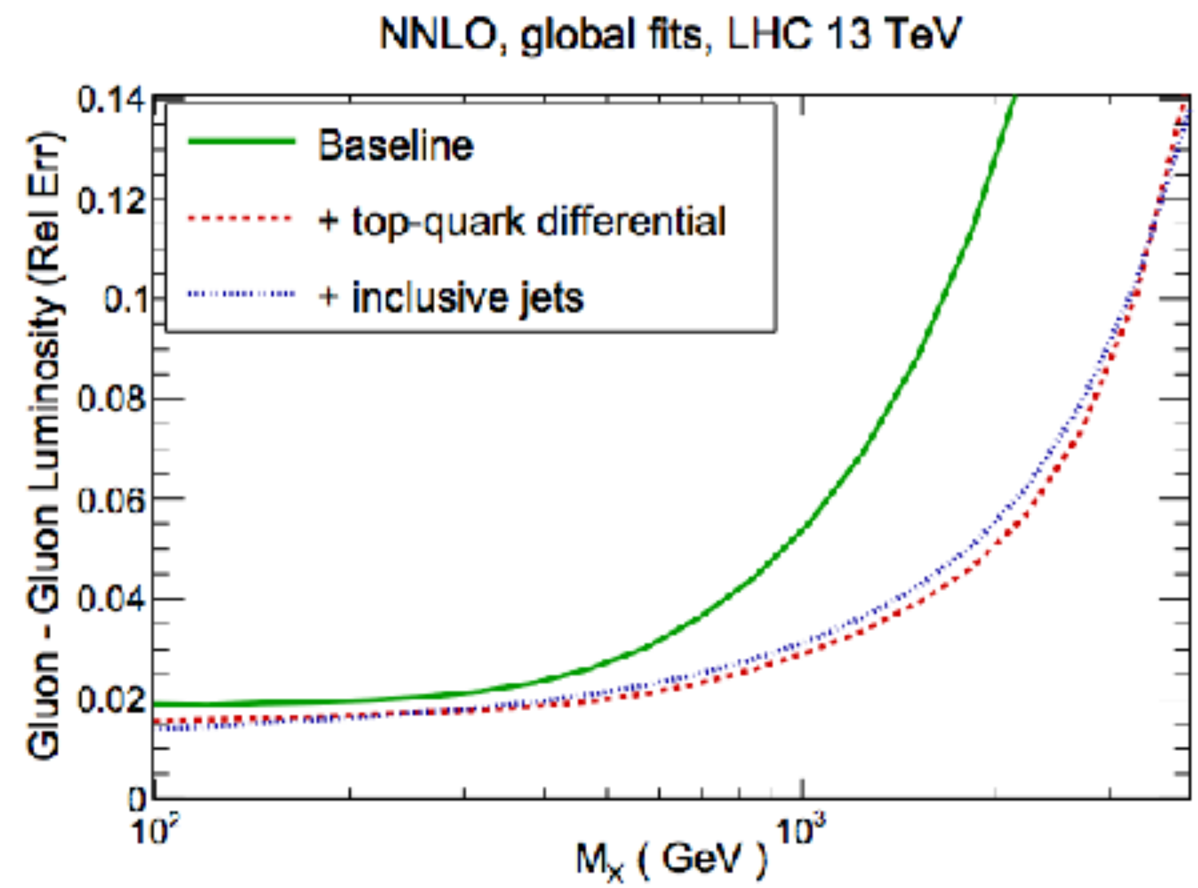


Czakon, Fiedler, Mitov [PRL 116(2016) 082003]

NNPDF3.1: top differential distributions



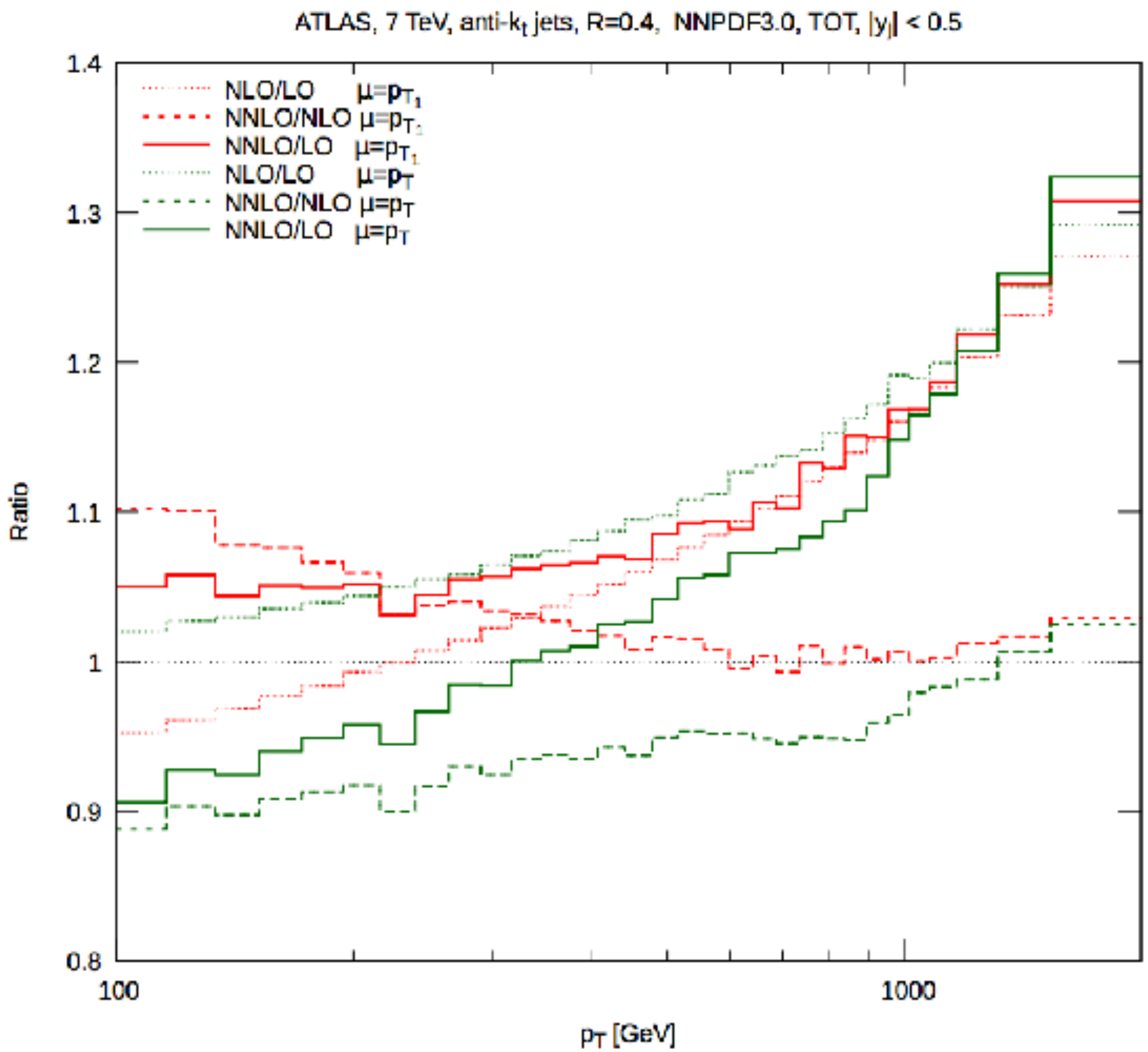




- Most constraining is inclusion of y_t list from ATLAS and y_{tt} from CMS jointly with total xsec
- Competitive reduction of gluon uncertainty with jets measurement
- Slight tension between ATLAS and CMS in NNPDF3.1 ($\chi^2_{ATLAS} \sim 1.6$, $\chi^2_{CMS} \sim 0.9$)

Czakon, Hartland, Mitov, Nocera and Rojo, arXiv: 1611.08609

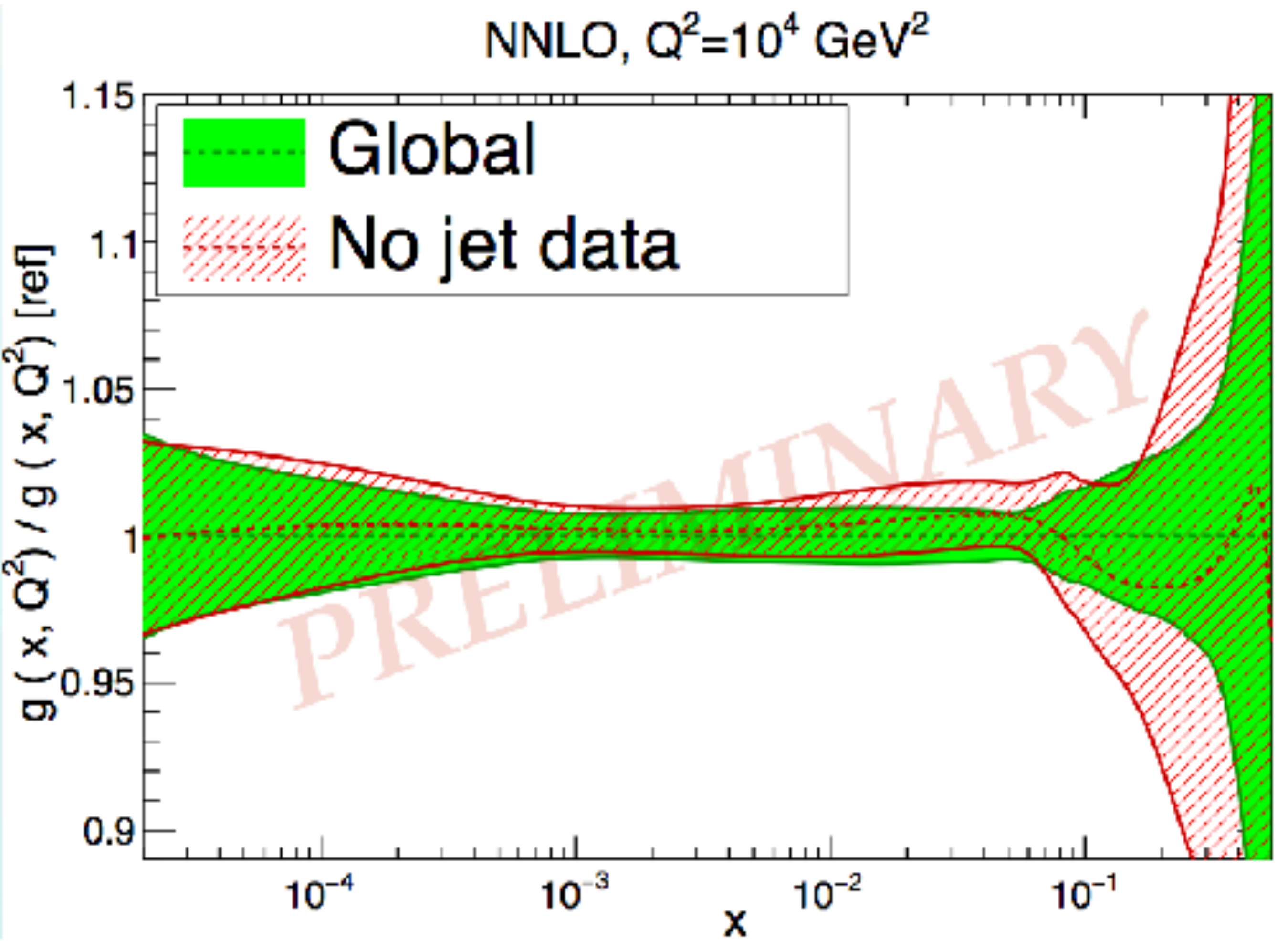
NNPDF3.1: inclusive-jet data

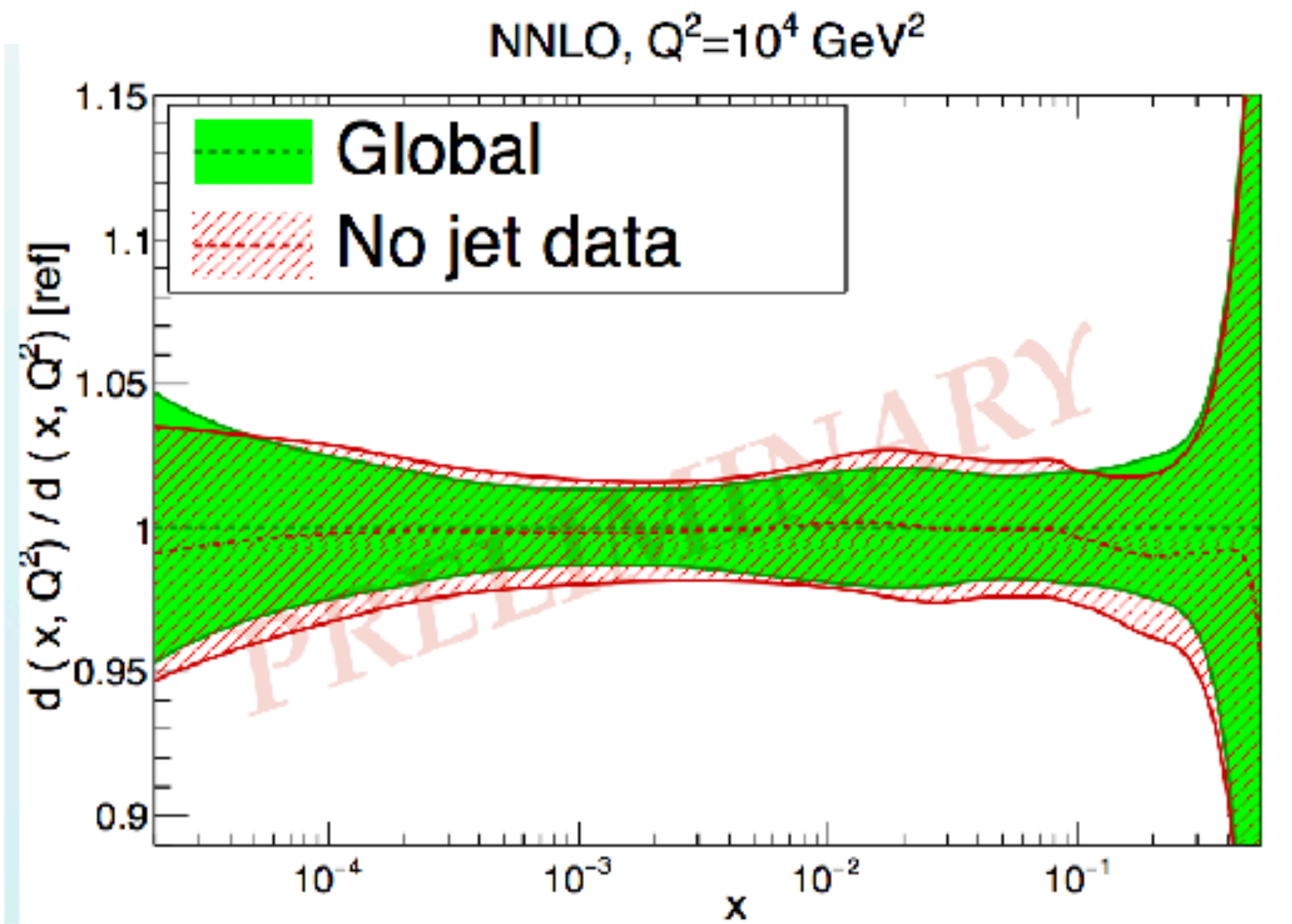


- NNLO corrections known for all partonic channels (leading colour contribution only)
- Different scales predict opposite behaviour of the K-factor
- NNLO/NLO K-factors available only for ATLAS 7 TeV data
- In NNPDF3.1 use NLO matrix elements for jets computed with individual jet pT as central scale and NLO scale uncertainty added as additional uncorrelated uncertainty

Currie et al [JHEP 1401 (2014) 110]
J. Currie, Cracow Jan 2017

NNPDF3.1: inclusive-jet data

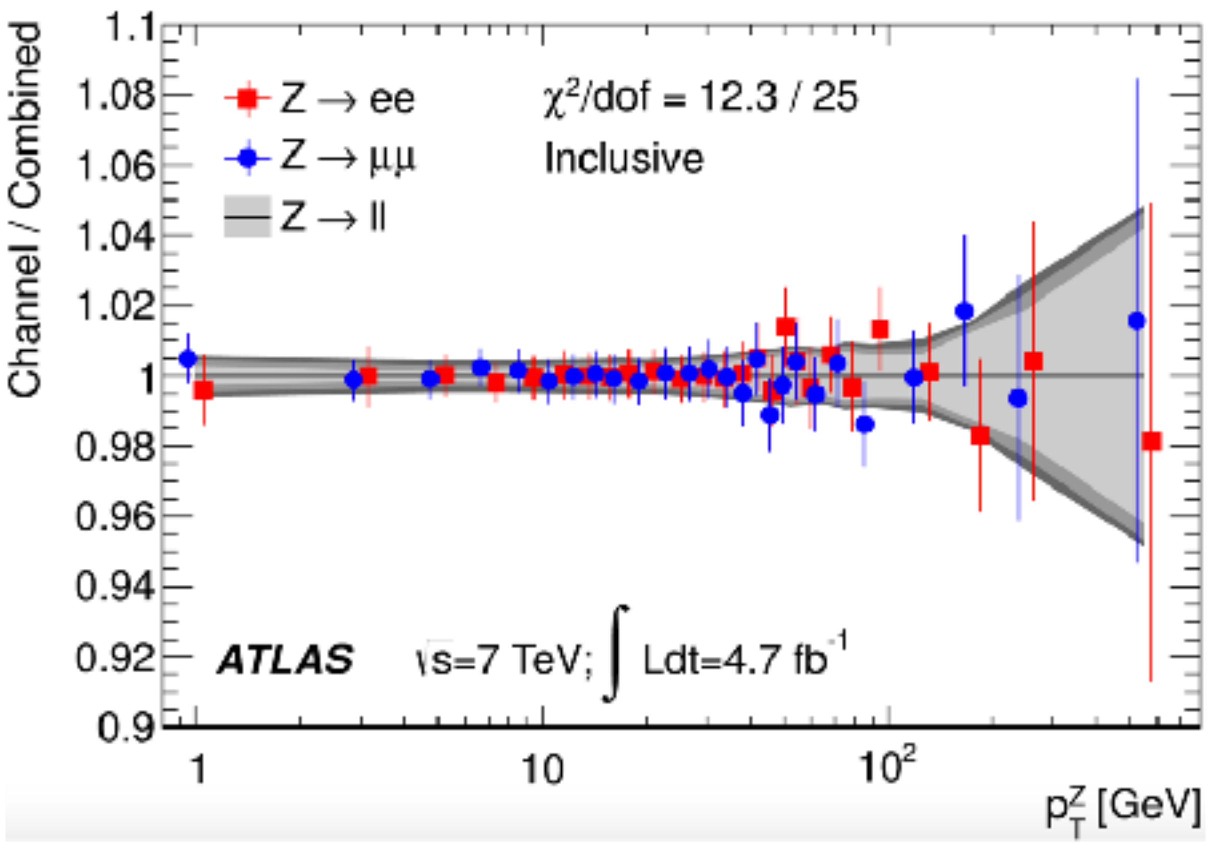


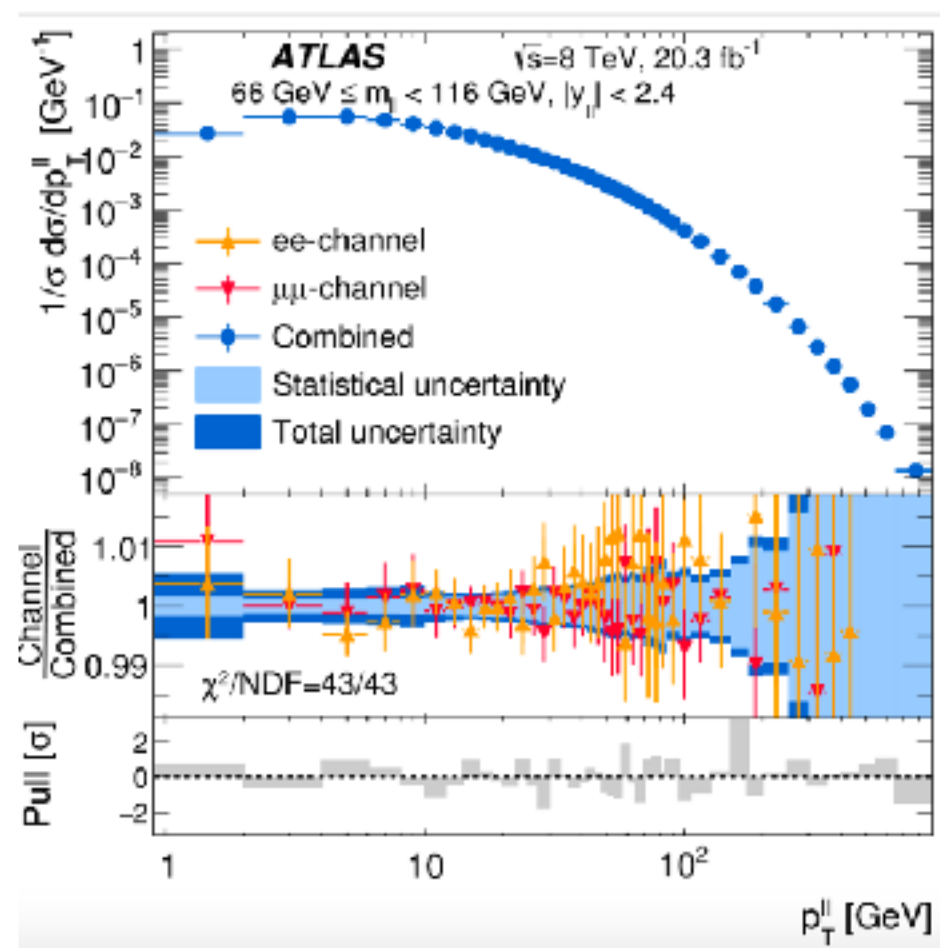


- In NNPDF3.1 included only central rapidity bin with good fit quality $\chi^2_{\mathrm{NLO}} = 1.06$, $\chi^2_{\mathrm{NNLO}} = 1.12$
- When all rapidity bins are included and full bin-by-bin correlation kept into account then description of the data becomes very bad
- Given that NLO scale uncertainty contains the NNLO - NLO shift, the issue is most likely related to experimental correlations

NNPDF3.1: Z p_T distributions

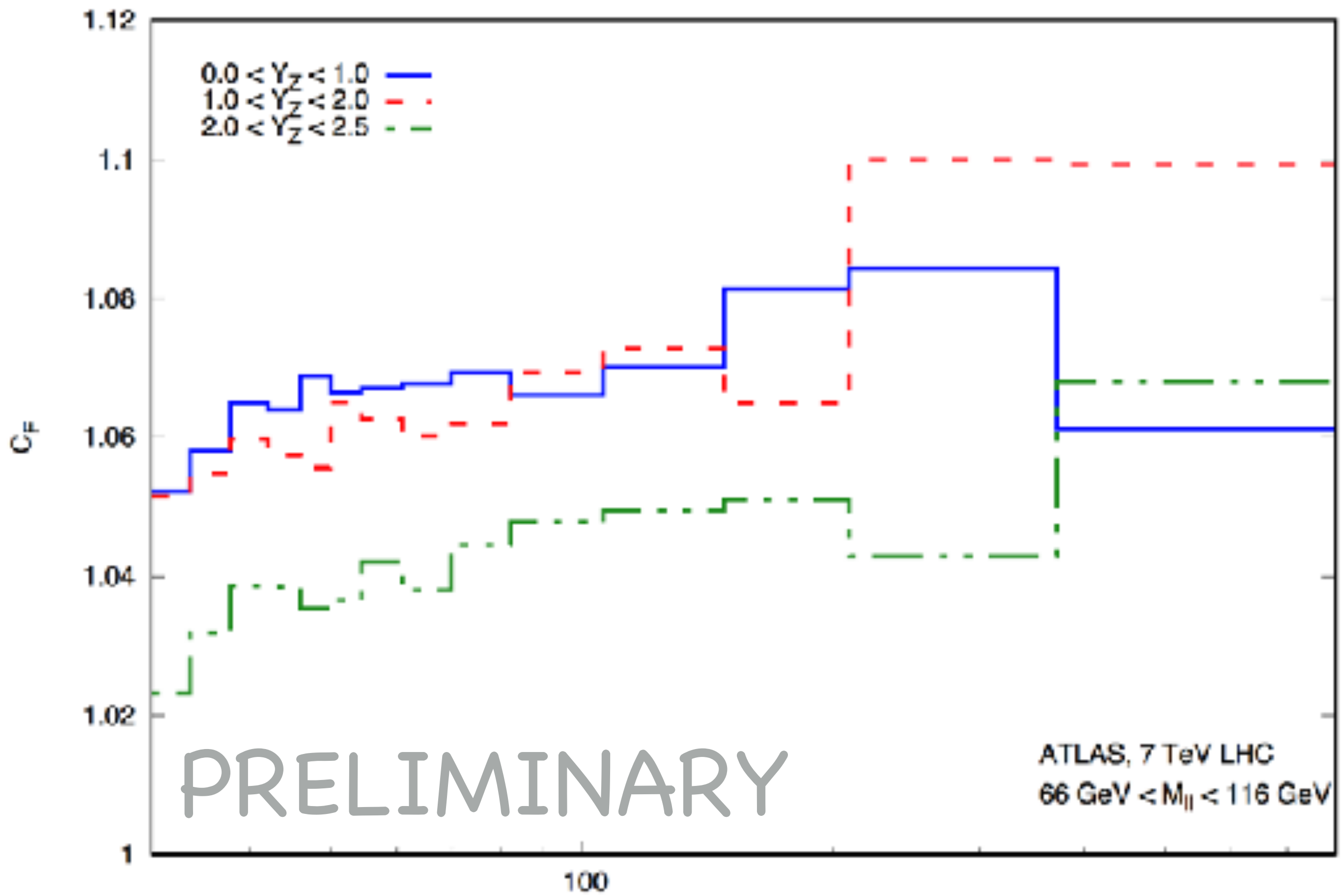
- Experimental precision < 1% up to pT~200 GeV
- Interesting case-study to probe current theory-experiment frontier





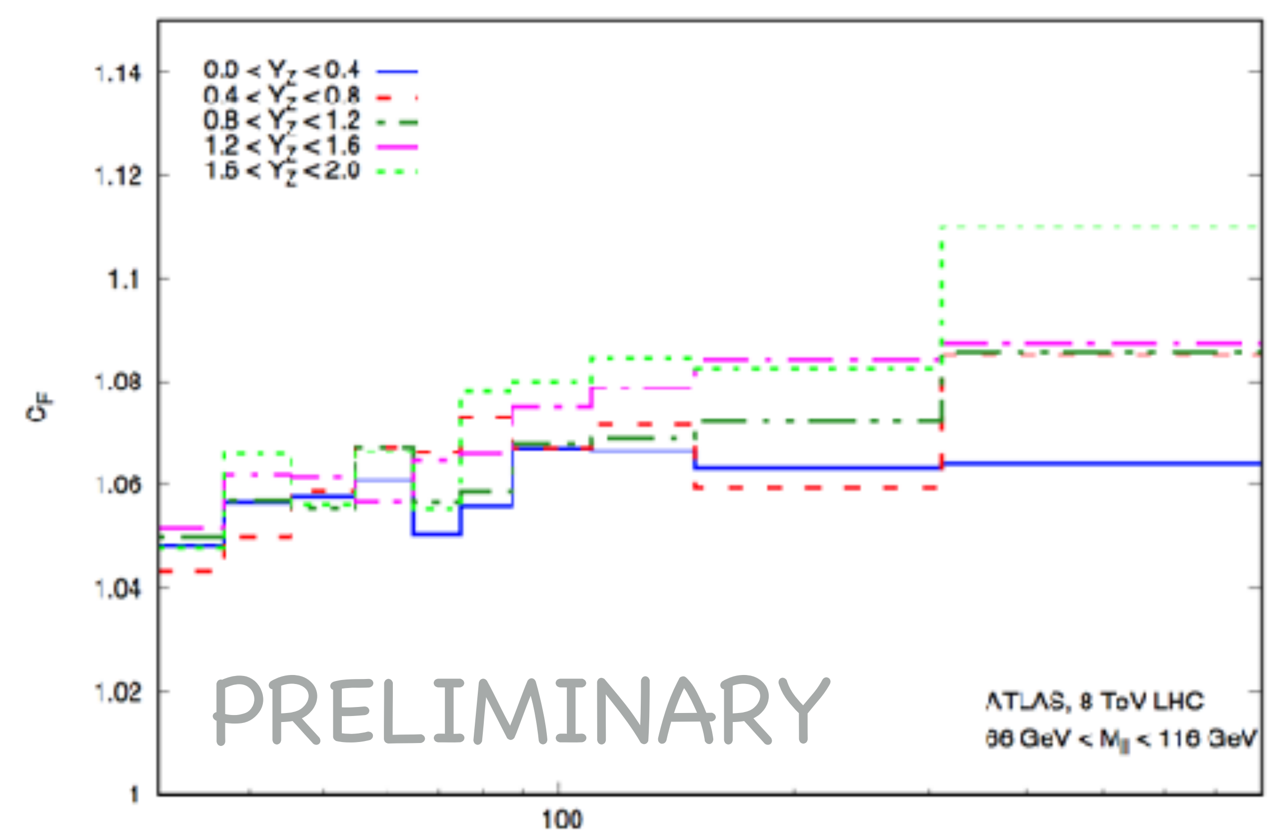
- ☑ ATLAS Z pT @LHC7, normalised distributions, 3 rapidity bins (0.0 < Y < 1.0, 1.0 < Y <2.0 , 2.0<Y<2.5)
  ~50 data in perturbative region pT > 30 GeV
- ☑ ATLAS Z pT @LHC8, normalised/unnormalised distributions, 6 rapidity bins in Z peak + low/high M
  ~150 data in perturbative region pT > 30 GeV
- ☑ CMS Z pT @LHC8, normalised/unnormalised distributions, 5 rapidity bins in Z peak
  ~50 data in perturbative region pT > 30 GeV

NNPDF3.1: Z p_T distributions



- NNLO calculation performed using N-jettiness subtraction scheme, by using recent calculation of Z+j at NNLO **[Boughezal et al, PRL 116 (2016)]** and relaxing cut on final state jet

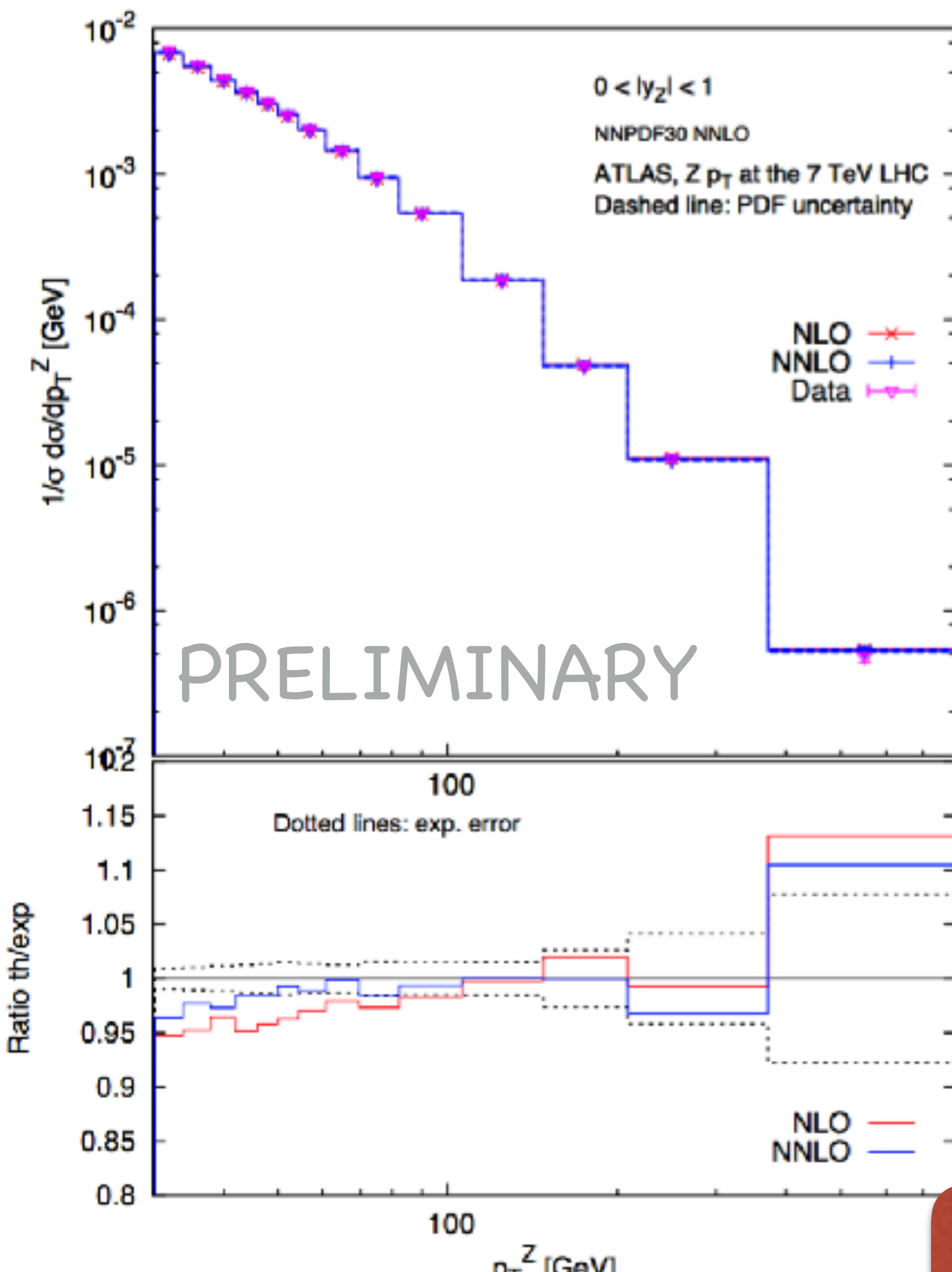
$$\mu_R = \mu_F = \sqrt{(p_T^Z)^2 + M_{ll}^2}$$



- NNLO/NLO K-factors 5% - 10% increase with p_T
- EW corrections only relevant for the highest pT bins in the Z-mass peak and for high-mass ATLAS measurement

Boughezal, Guffanti, Petriello, MU - in progress

NNPDF3.1: Z p_T distributions



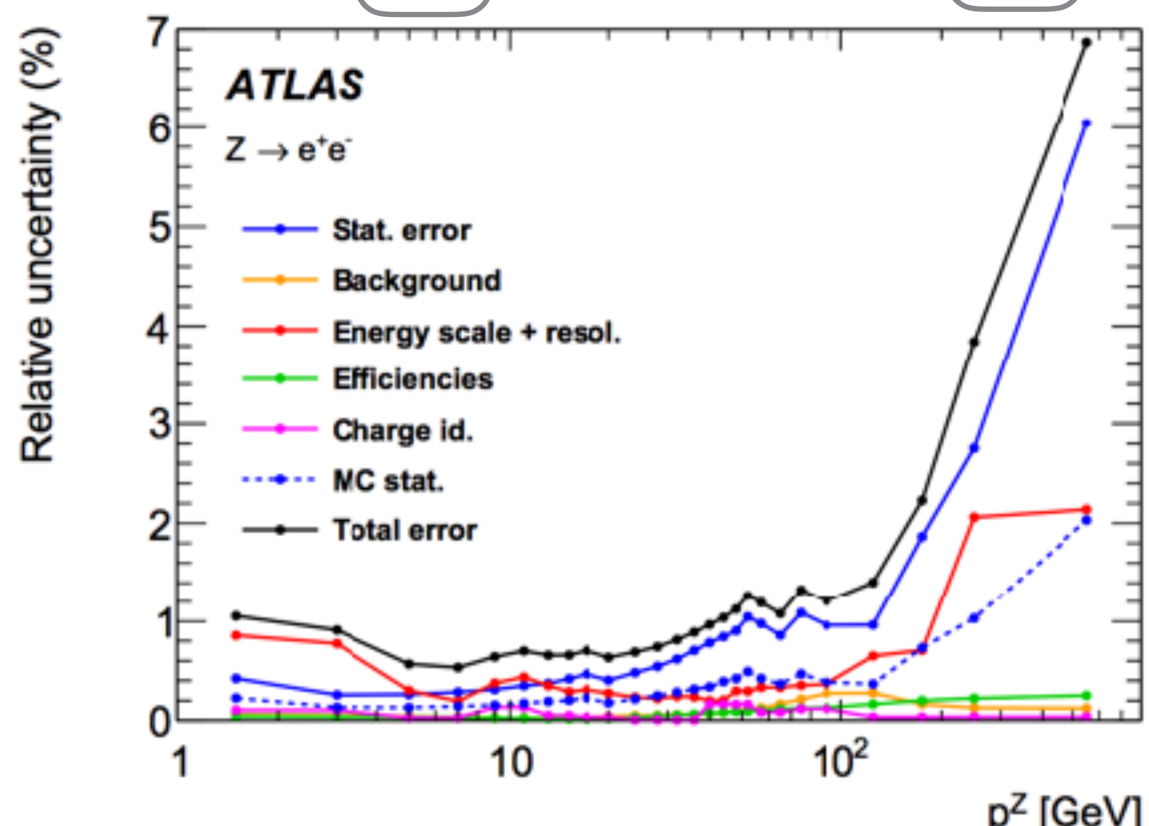
NLO

$$\chi^2_{\rm stat} = 10.$$
$$\chi^2_{\rm uncor} = 7.3$$
$$\chi^2_{\rm diag} = 6.0$$
$$\chi^2_{\rm full} = \boxed{16.}$$

NNLO

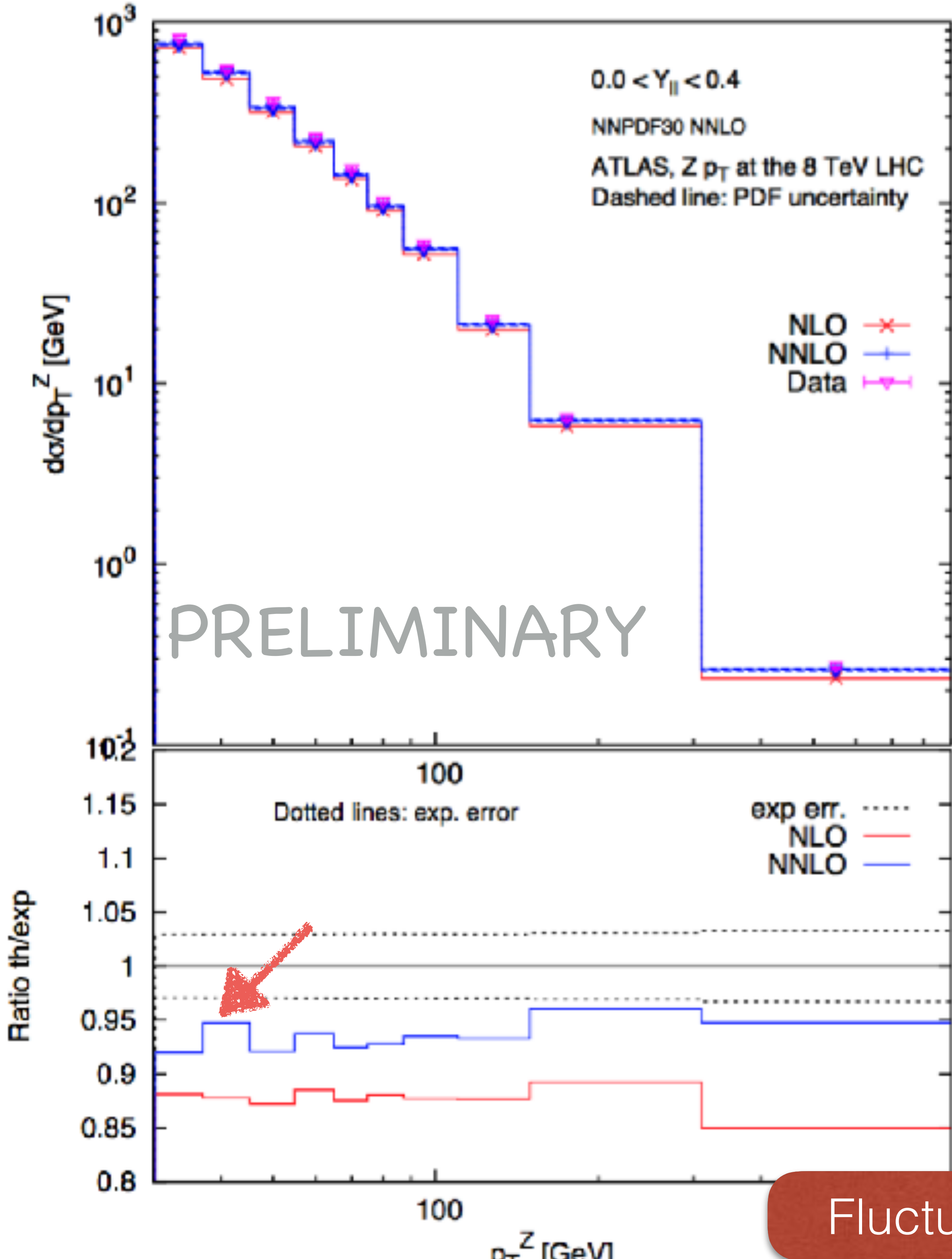
$$\chi^2_{\rm stat} = 1.3$$
$$\chi^2_{\rm uncor} = 0.9$$
$$\chi^2_{\rm diag} = 0.7$$
$$\chi^2_{\rm full} = \boxed{1.9}$$

/d.o.f.



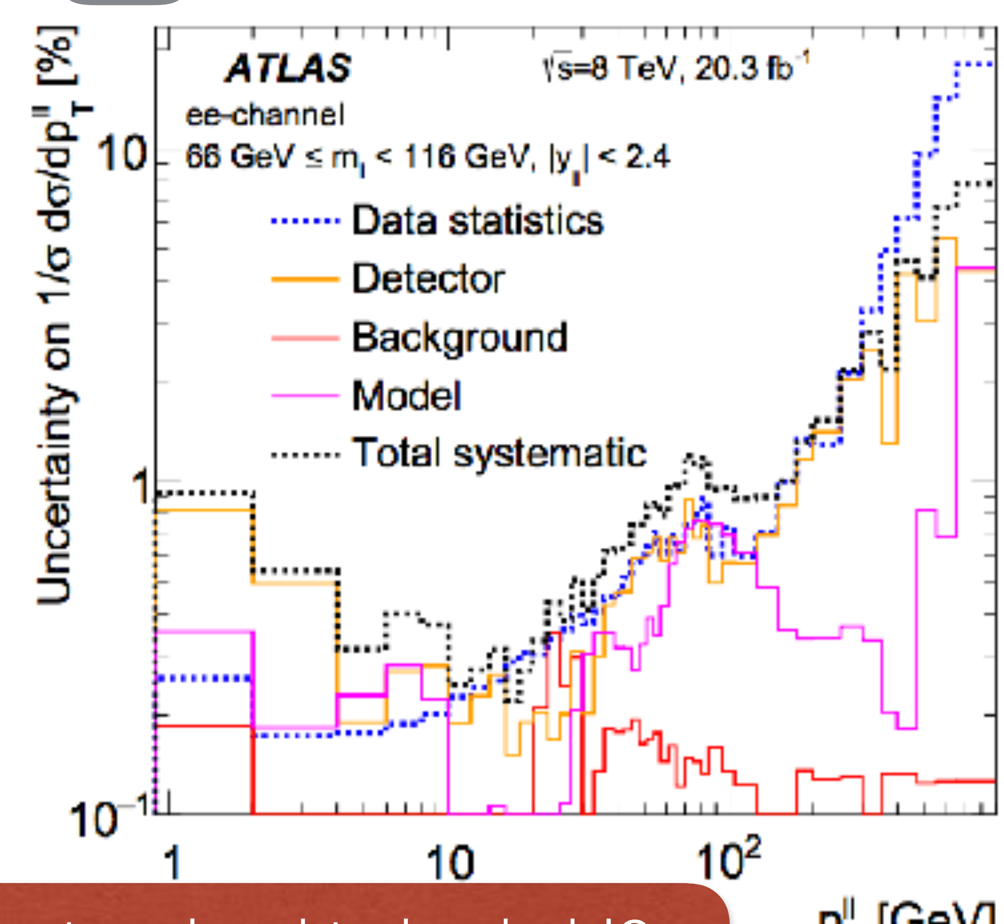
NNLO correction crucial to get the right shape!

NNPDF3.1: Z p_T distributions



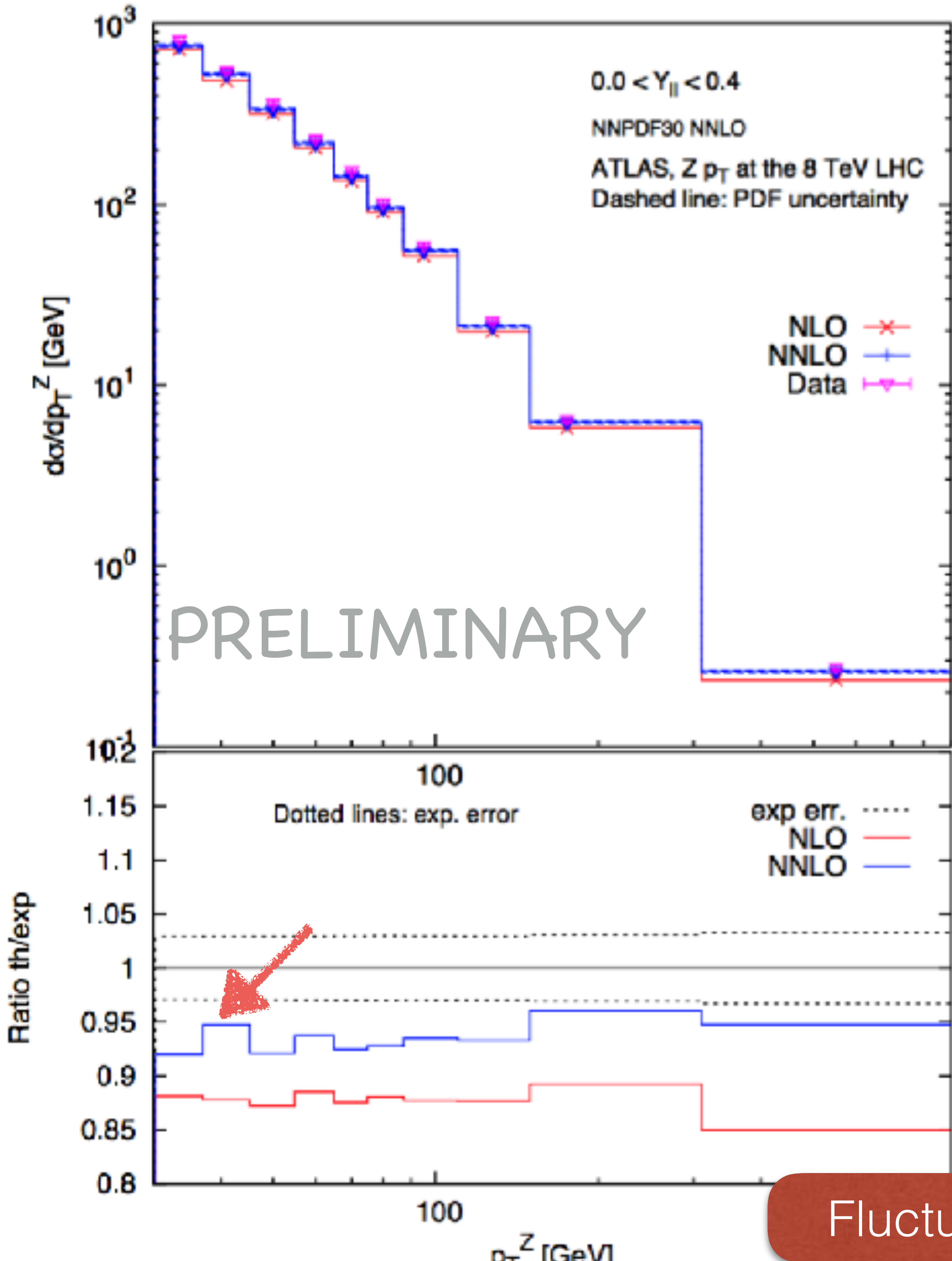
NLO	NNLO
$\chi^2_{\rm stat} = 140$	$\chi^2_{\rm stat} = 51.$
$\chi^2_{\rm uncor} = 115$	$\chi^2_{\rm uncor} = 42.$
$\chi^2_{\rm diag} = 1.70$	$\chi^2_{\rm diag} = 0.62$
$\chi^2_{\rm full} = \boxed{2.80}$	$\chi^2_{\rm full} = \boxed{5.61}$

/d.o.f.



Fluctuations in K-factors lead to bad chi2

NNPDF3.1: Z p_T distributions



NLO

$$\chi^2_{\rm stat} = 140$$
$$\chi^2_{\rm uncor} = 115$$
$$\chi^2_{\rm diag} = 1.70$$
$$\chi^2_{\rm full} = 2.80$$

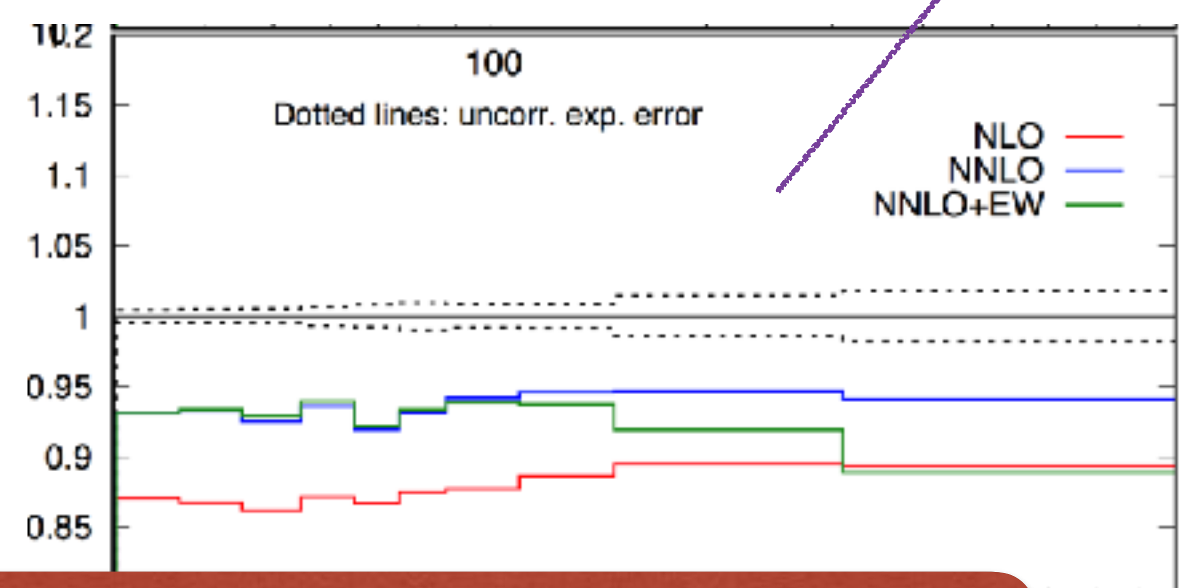
NNLO

$$\chi^2_{\rm stat} = 51.$$
$$\chi^2_{\rm uncor} = 42.$$
$$\chi^2_{\rm diag} = 0.62$$
$$\chi^2_{\rm full} = 5.61$$

/d.o.f.

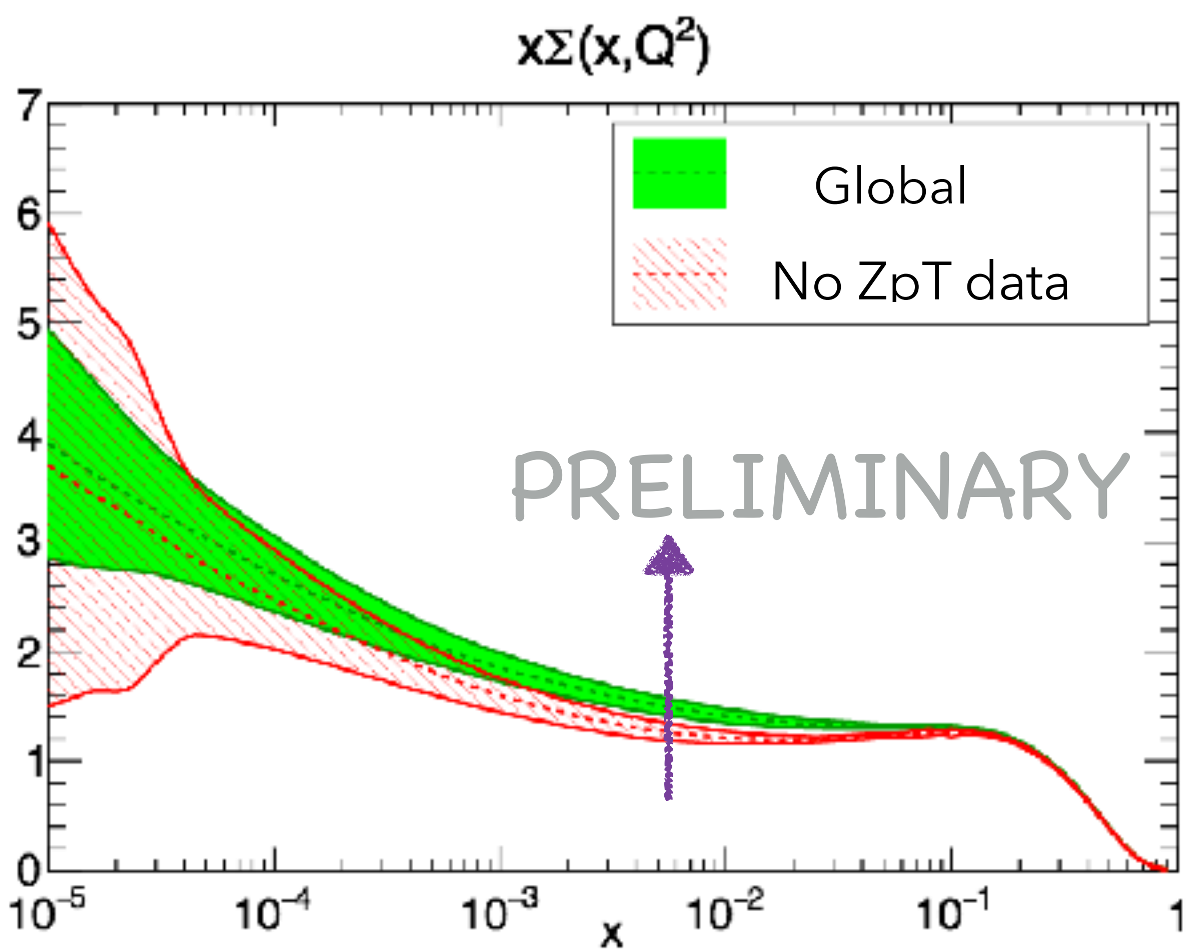
2.0

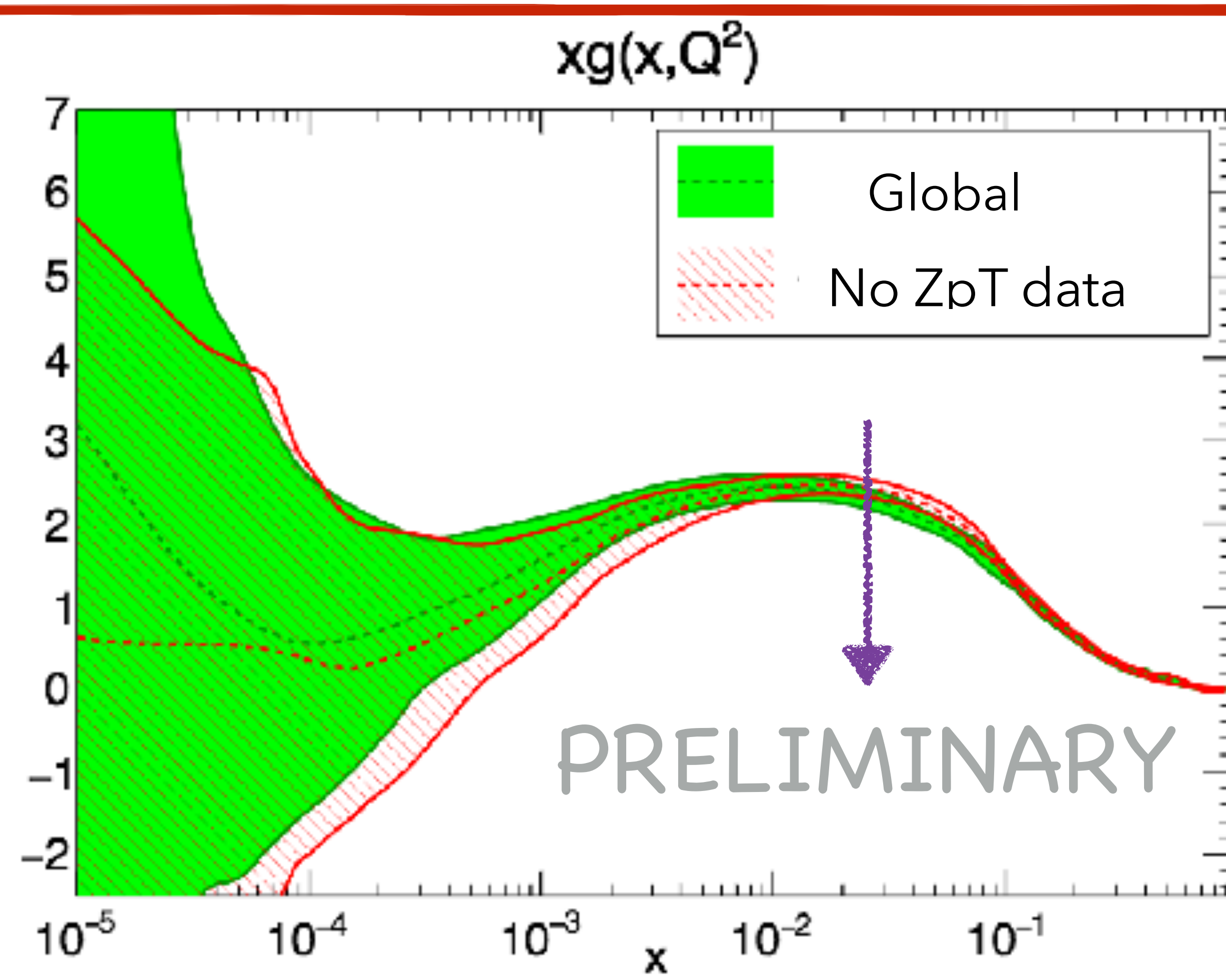
10x more statistics



Fluctuations in K-factors lead to bad chi2

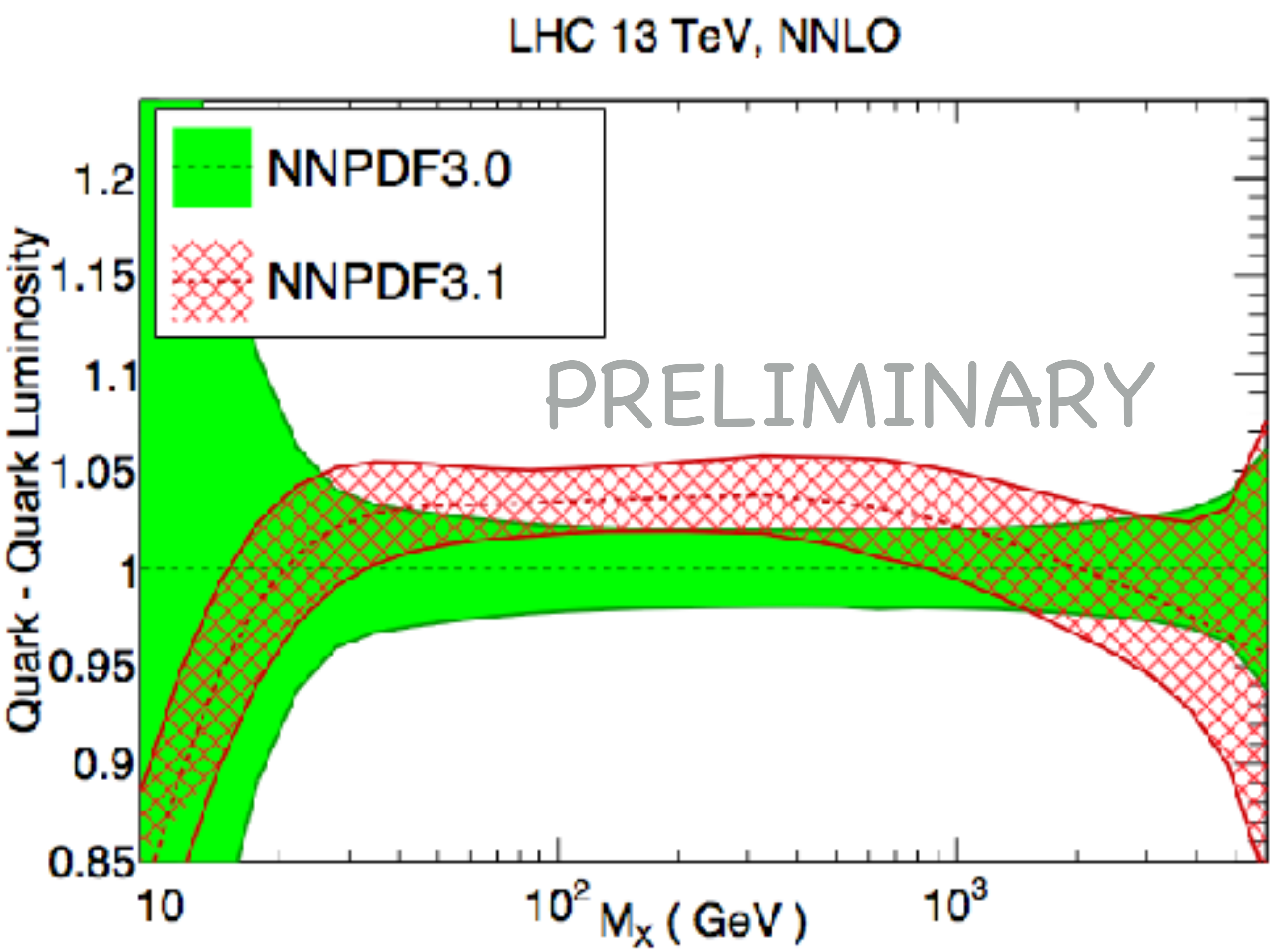
NNPDF3.1: Z p_T distributions

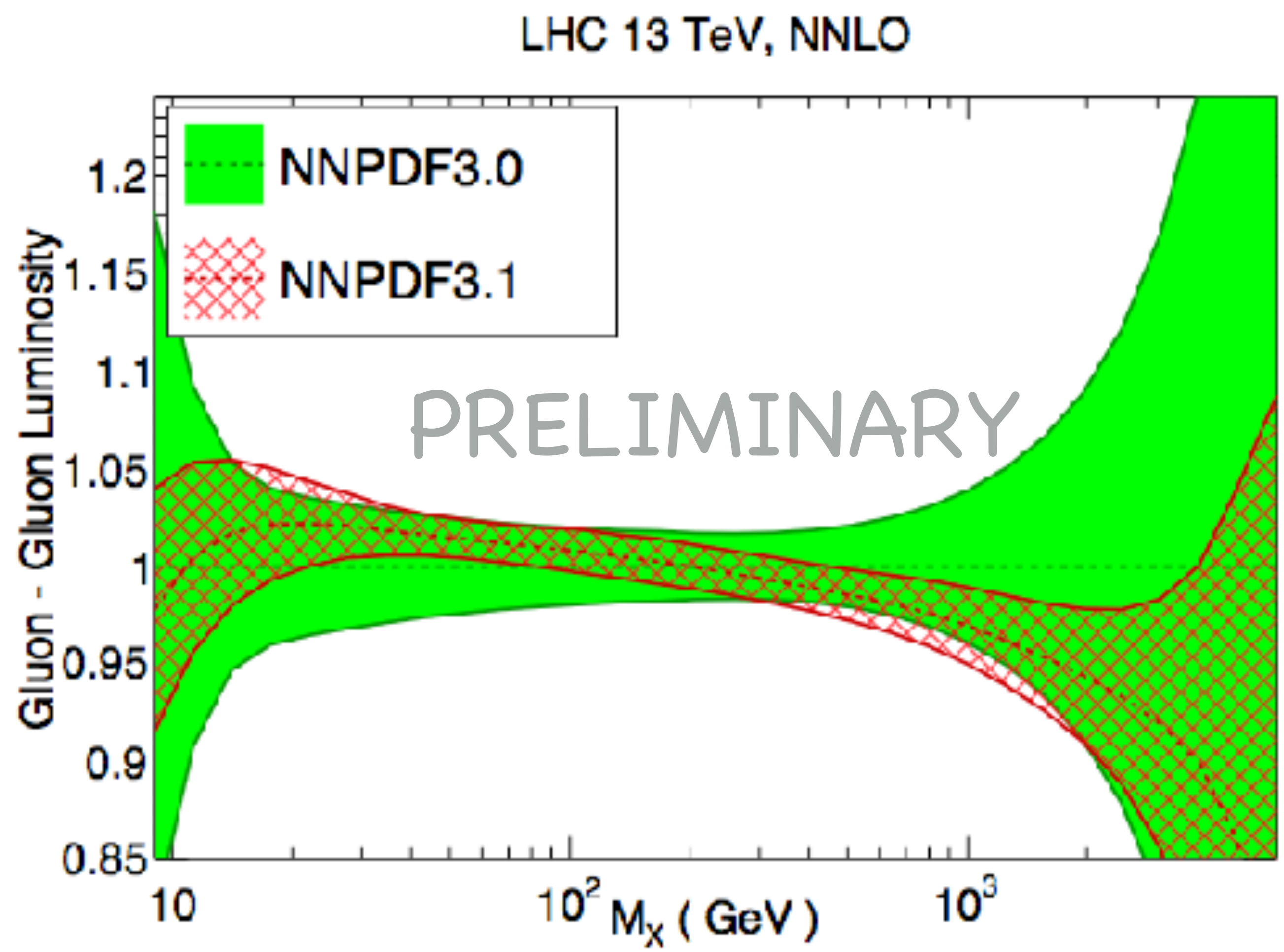




- Impact of Z pT distributions is quite strong, they increase the singlet and decrease the gluon in regions in which we expect them to be correlated with measurement
- Incompatibility between ATLAS 7 TeV data and global fit and ATLAS 7 TeV and 8 TeV data under investigation

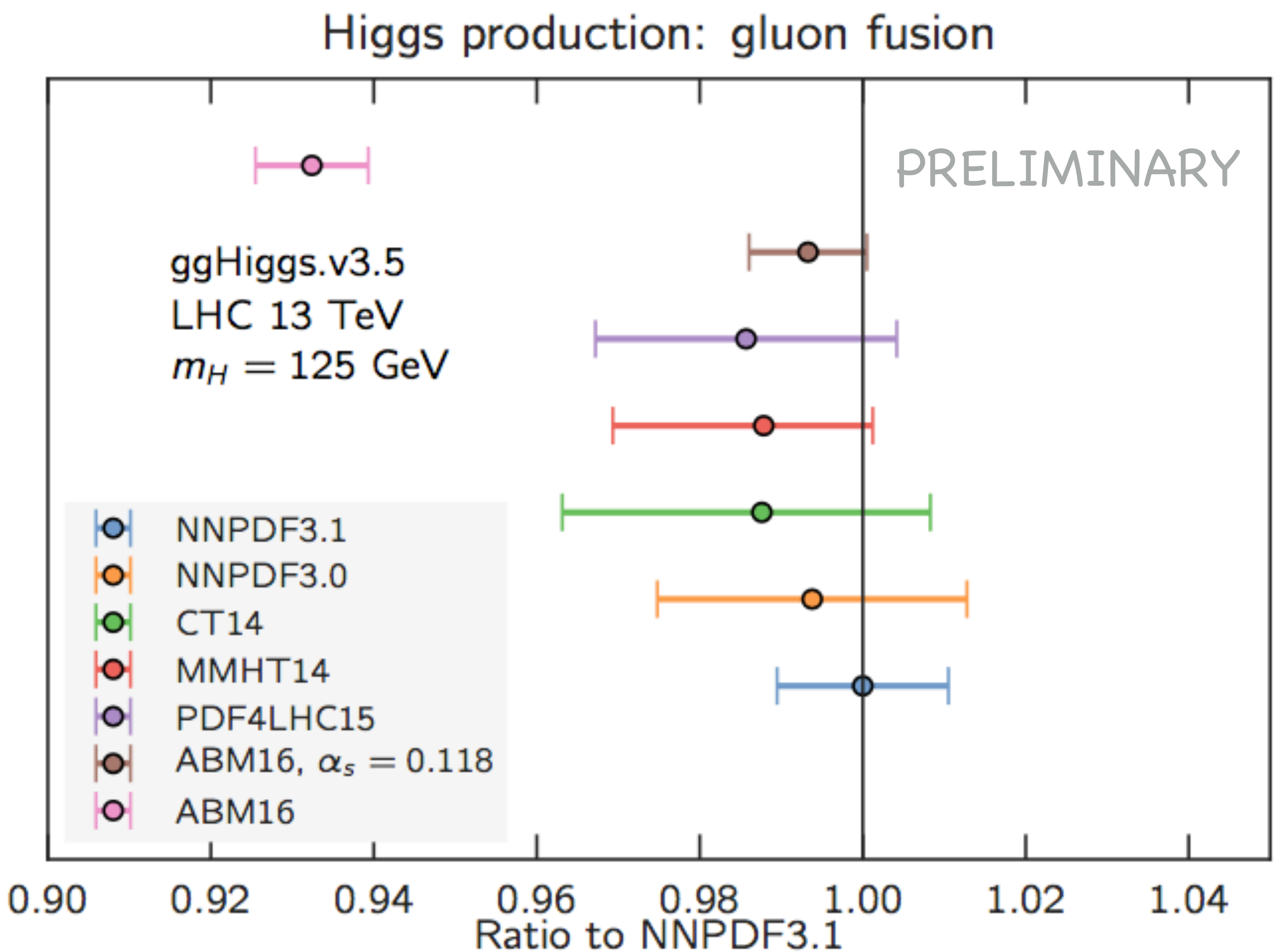
The NNPDF3.1 set



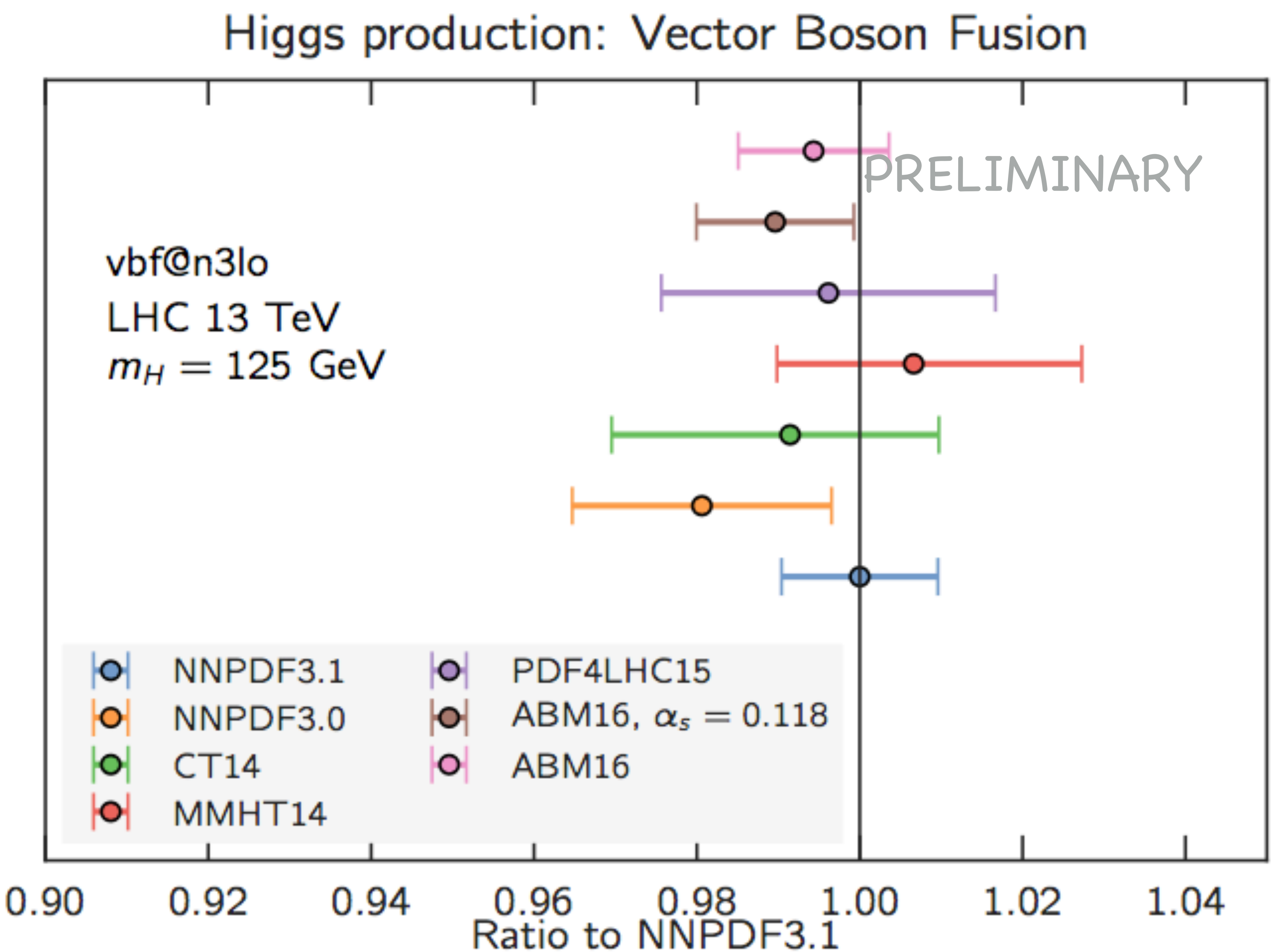


- Changes in gluon mostly due to new data, mostly reducing gluon uncertainty (top dist, jet dist, Z pT dist)
- Still under investigation, but jets, top and Z pT (8 TeV) seem to point in the same direction, no tension
- Changes in quarks due partially to new data (LHCb, Tevatron, CMS) and partially to fitted charm

Phenomenology

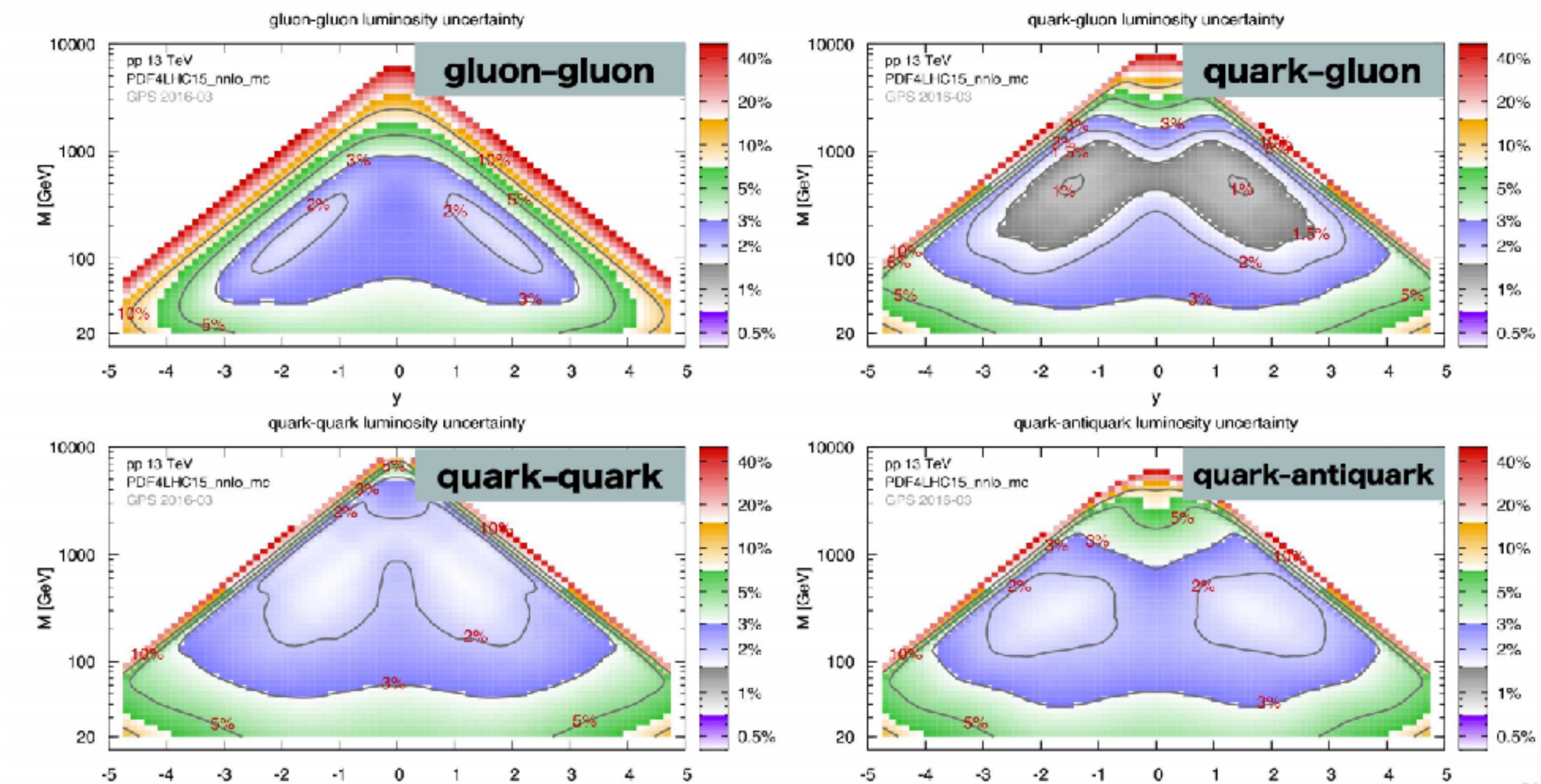


Phenomenology



New frontiers

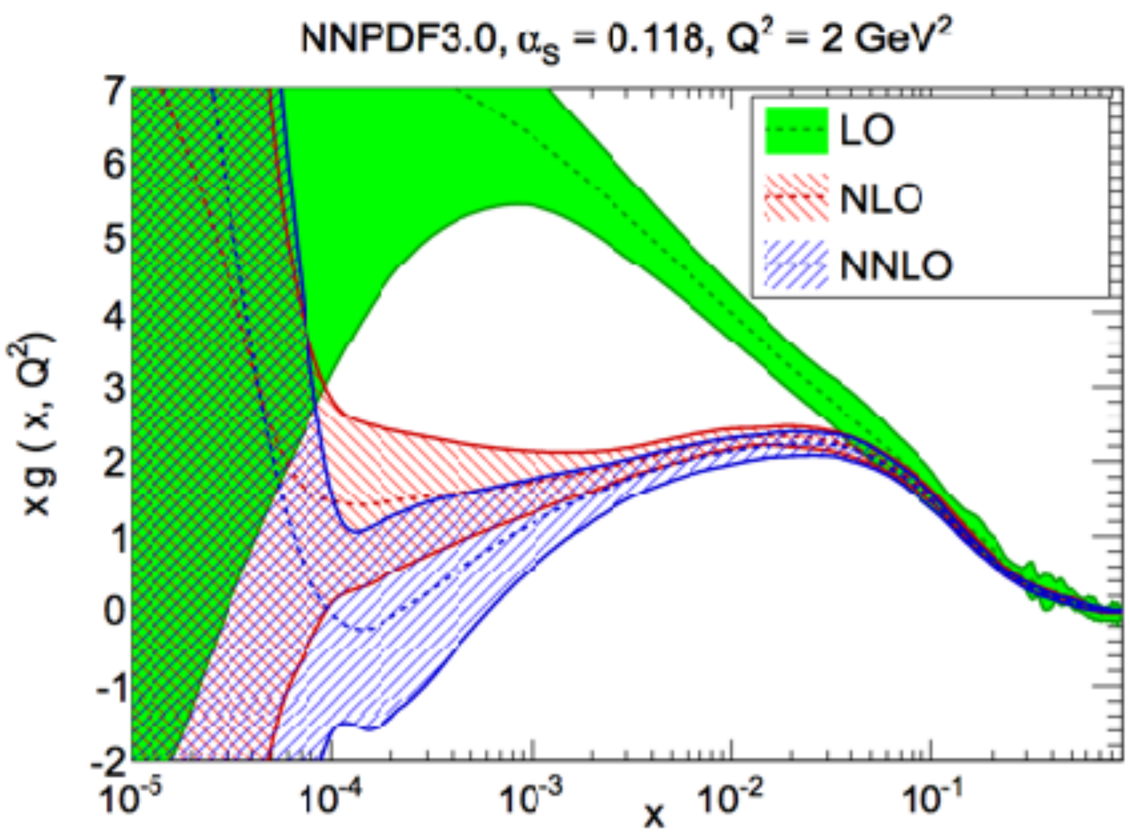
PDF uncertainties

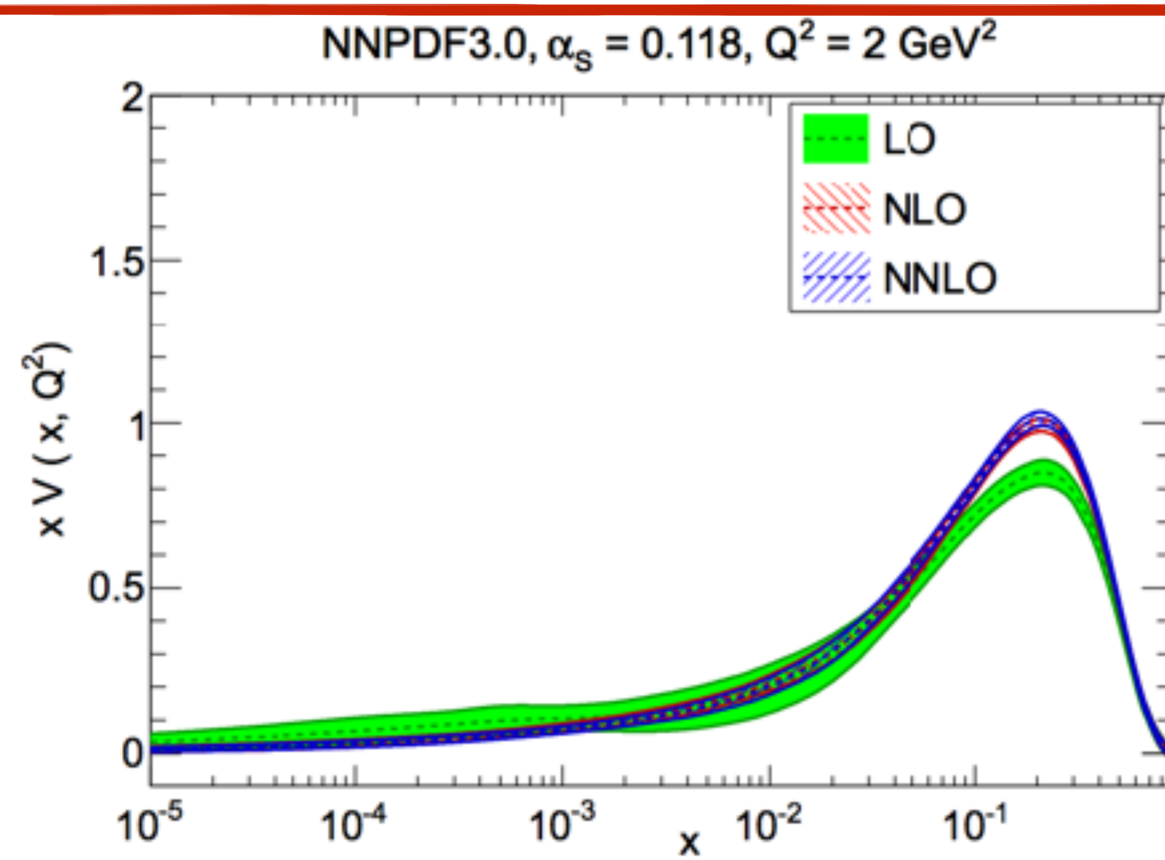


G. Salam, LHCP

Do we trust 1% accuracy in parton luminosities?

Theory uncertainties

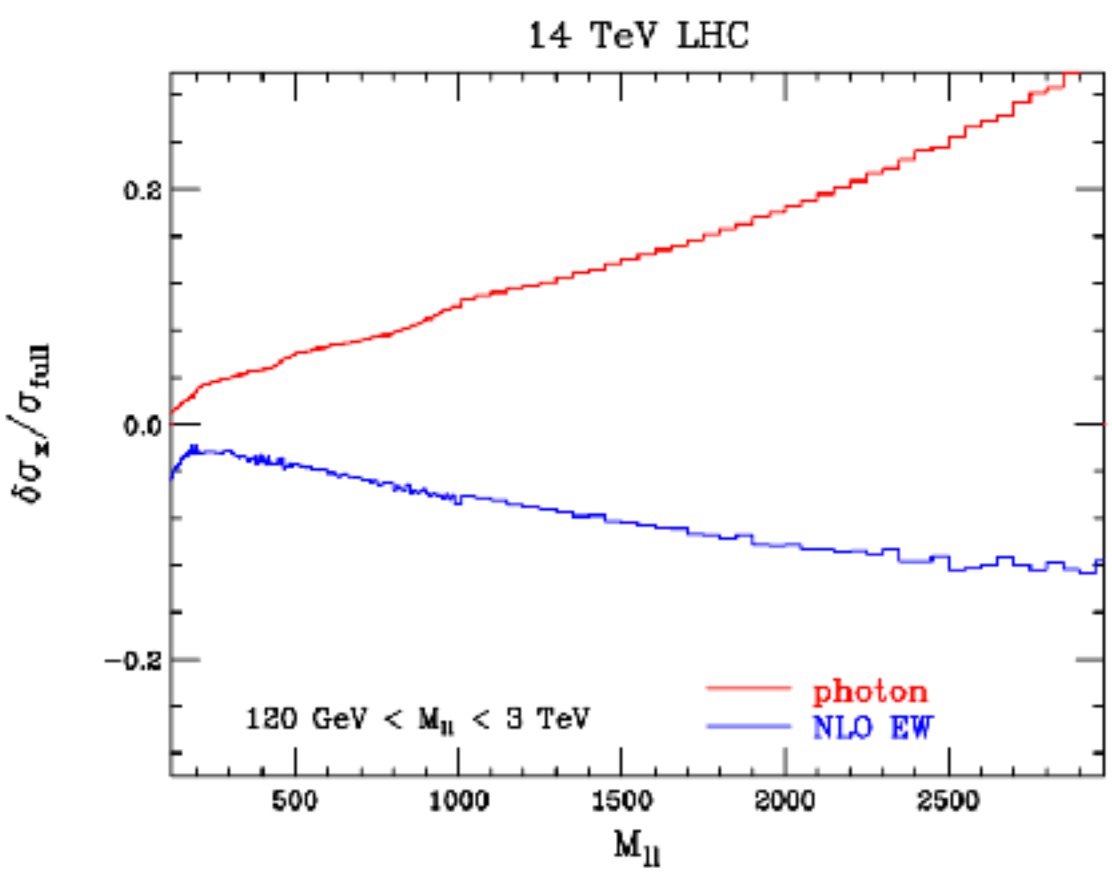




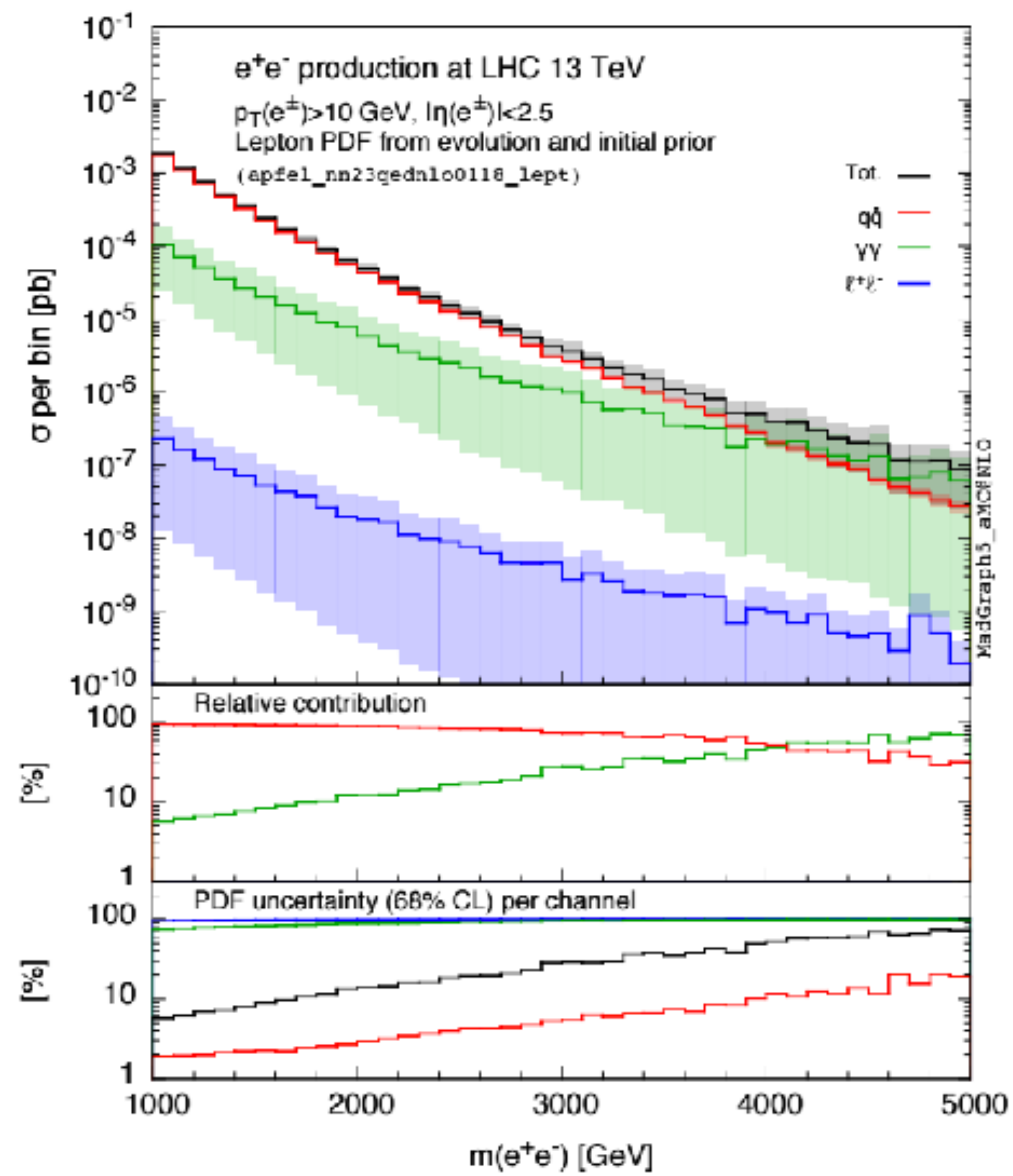
- PDF fits performed with given fixed perturbative order, value of α_S and heavy quark masses (estimated by combining PDF sets determined with different values
- PDF uncertainties only reflect lack of information from data given the theory
- Changes in theory may cause shifts outside the error band, can we estimate that?
- LO fits are merely qualitative, NLO quantitative and NNLO precise, but how much?

EW corrections

- EW corrections become relevant at the current precision level as are sizeable at large invariant mass
- Full inclusion of EW corrections requires initial γ PDF



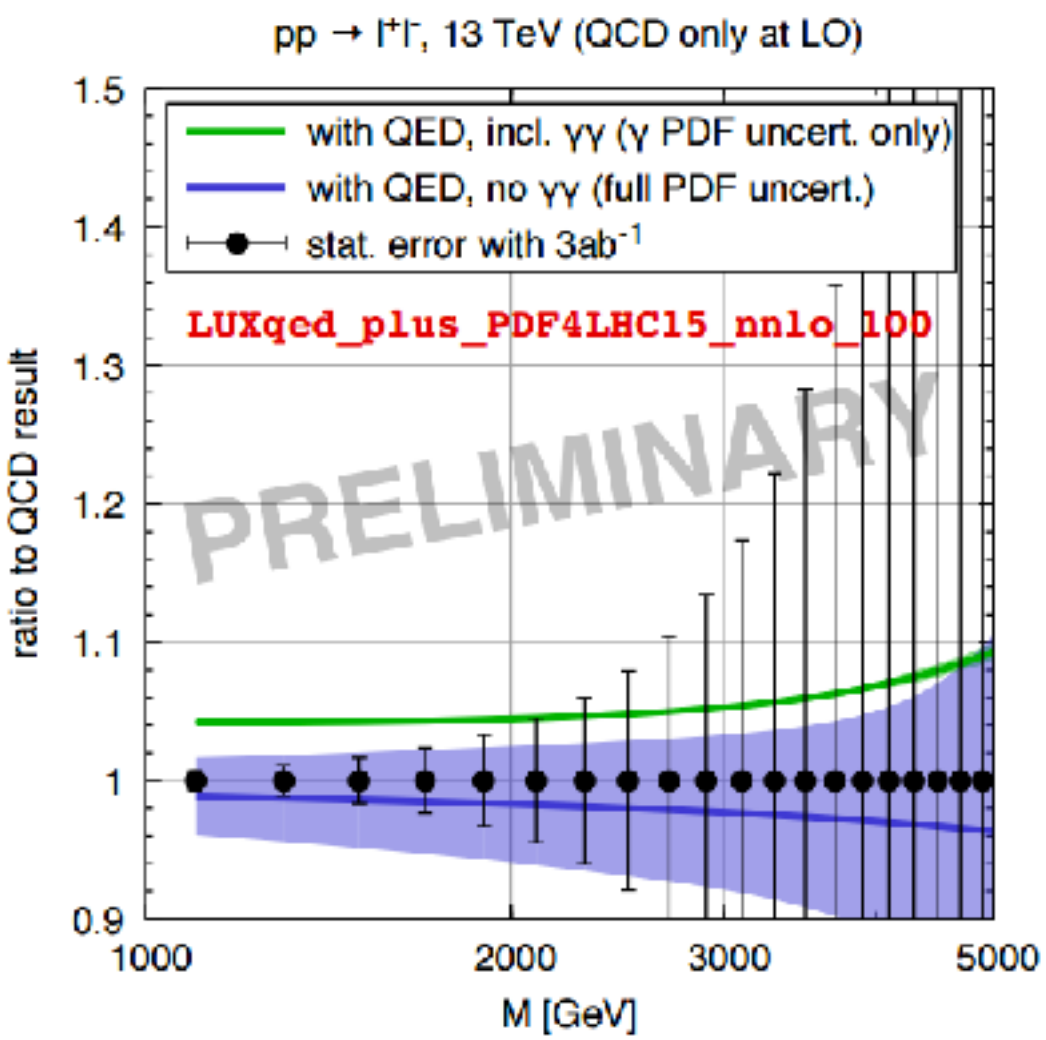
Boughezal et al [Phys.Rev. D89 (2014)3, 034030]

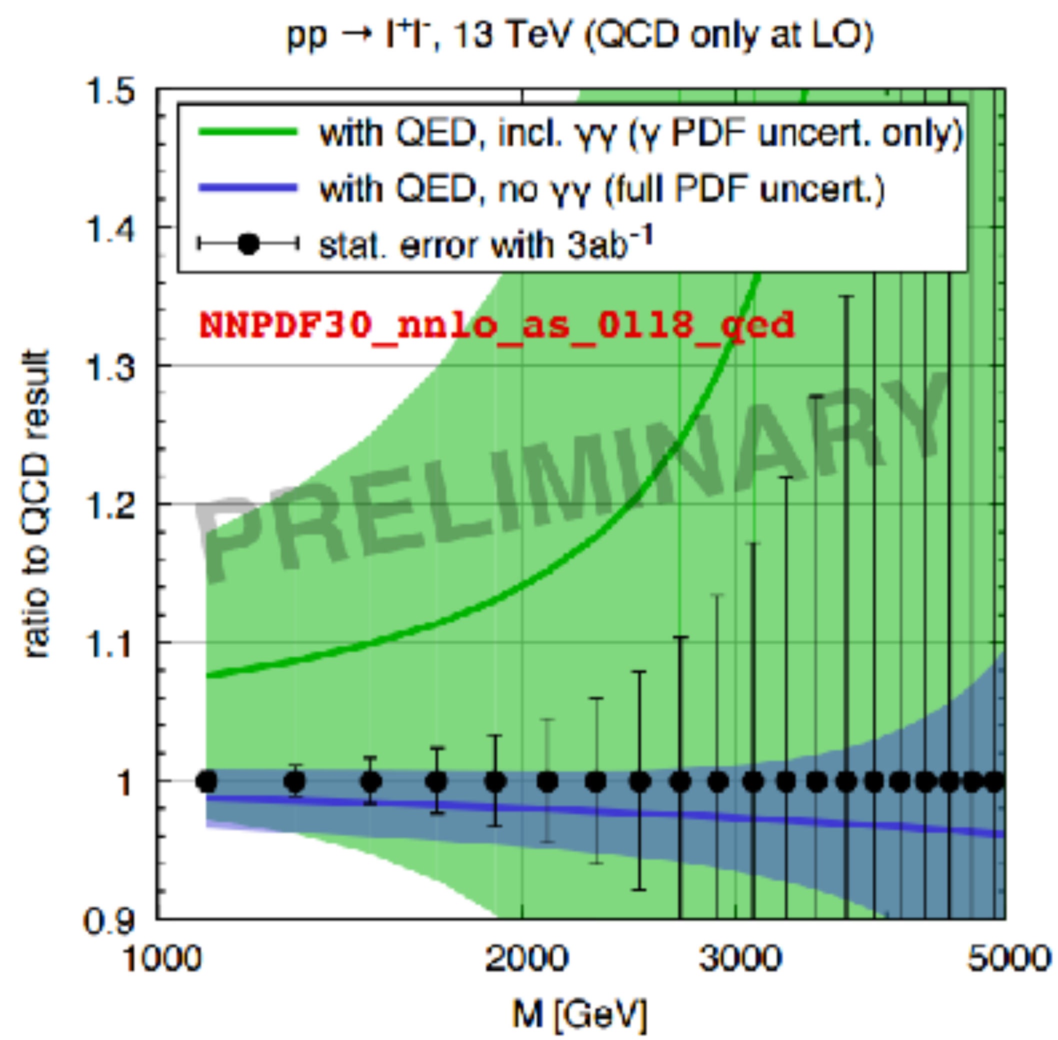


Bertone et al [JHEP 1511 (2015) 194]

Photon PDF

- Data-driven NNPDF approach inducing a large uncertainty on photon PDF
- Breakthrough: LUX PDF [Manohar, Nason, Salam, Zanderighi,1607.04266]
- Take a BSM interaction, compute the cross section with the Master Formula or with the Parton Model formula
- Extract photon PDF by identifying the two cross sections.
- Theory constraint reduces uncertainty by a huge factor

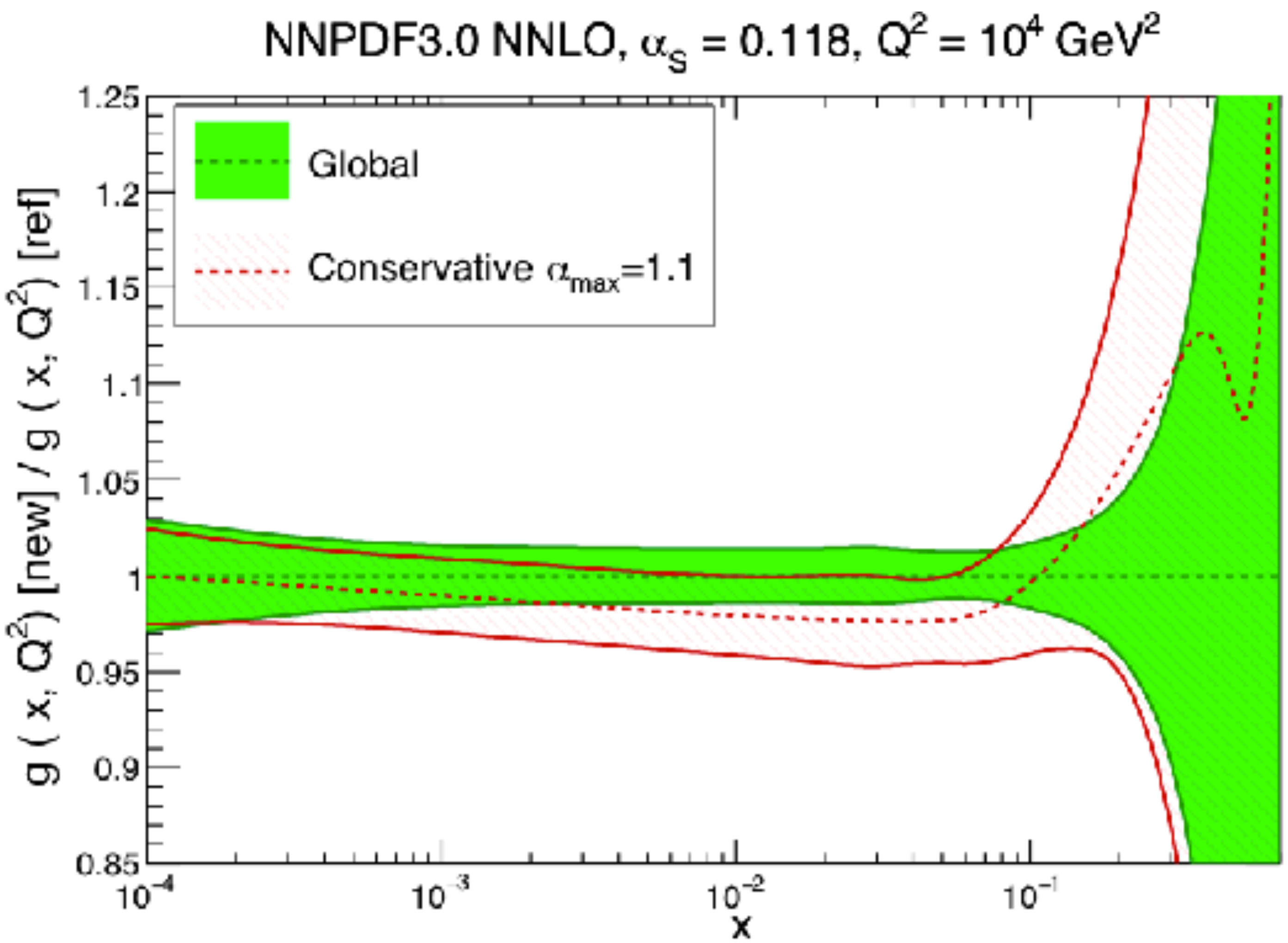




P. Nason, talk in Durham

Conservative partons

- Q: As more data at higher energy will be released, how can we make sure that we will not absorb new physics in the PDFs?
- Inconsistencies between data that enter a global PDF analysis can distort statistical interpretation of PDF uncertainties
- Inconsistency of any individual dataset with the bulk of global fit may suggest that its understanding (theory or experiment) is incomplete
- Set of **conservative partons** based on measure of consistency are crucial to systematically study inclusion of new data



NNPDF collaboration, JHEP04(2015)040

Conclusions

- Parton Distribution Functions essential ingredient for LHC phenomenology
- Accurate PDFs are required for precision SM measurements
- NNPDF3.1 includes many new precise data from HERA combination to Tevatron legacy data to new LHC data (some never fitted before such as Z pT and top differential distributions)
- Good stability with respect to 3.0, reduced uncertainty in the gluon and better quark-flavour separation
- Precision of the data and correlation-dominated uncertainties very challenging for PDF fitters: is an additional uncorrelated uncertainty the way forward?
- Fitted charm improves the quality of the fit, both perturbative charm set and fitter charm sets will be released

Outlook

[…] Global QCD Analysis of available hard processes critically tests the validity of the PQCD framework, allows the determination of the non-perturbative parton distribution functions, thereby provides the necessary input to calculate and predict most Standard Model and New Physics processes for future, higher, energy interactions. **After two decades of steady progress in this venture, has global QCD analysis of parton distributions reached the End of the Road (as some have proclaimed); or, will the physics challenges of the next generation of colliders usher in the Dawn of a New Era, with fresh ideas and more powerful methodology (as some have promised)? That, is the question.**

Wu-Ki Tung - CERN-TH colloquium 2000

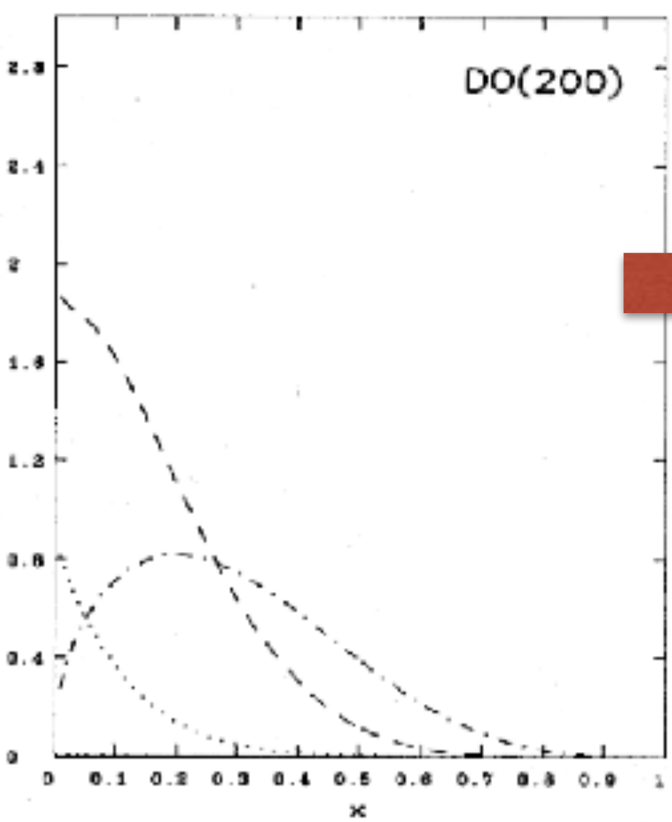
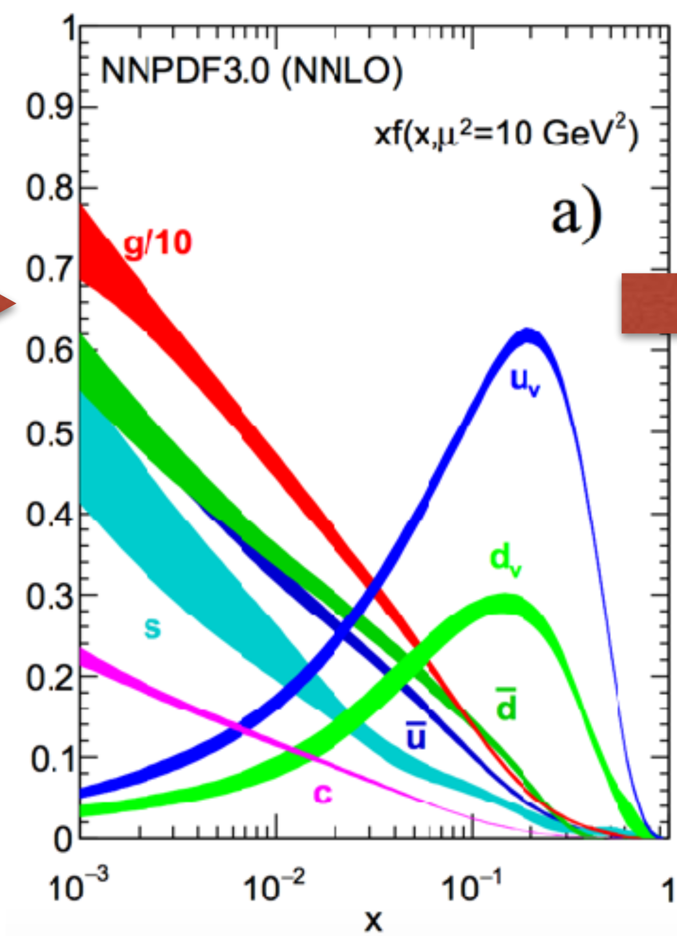
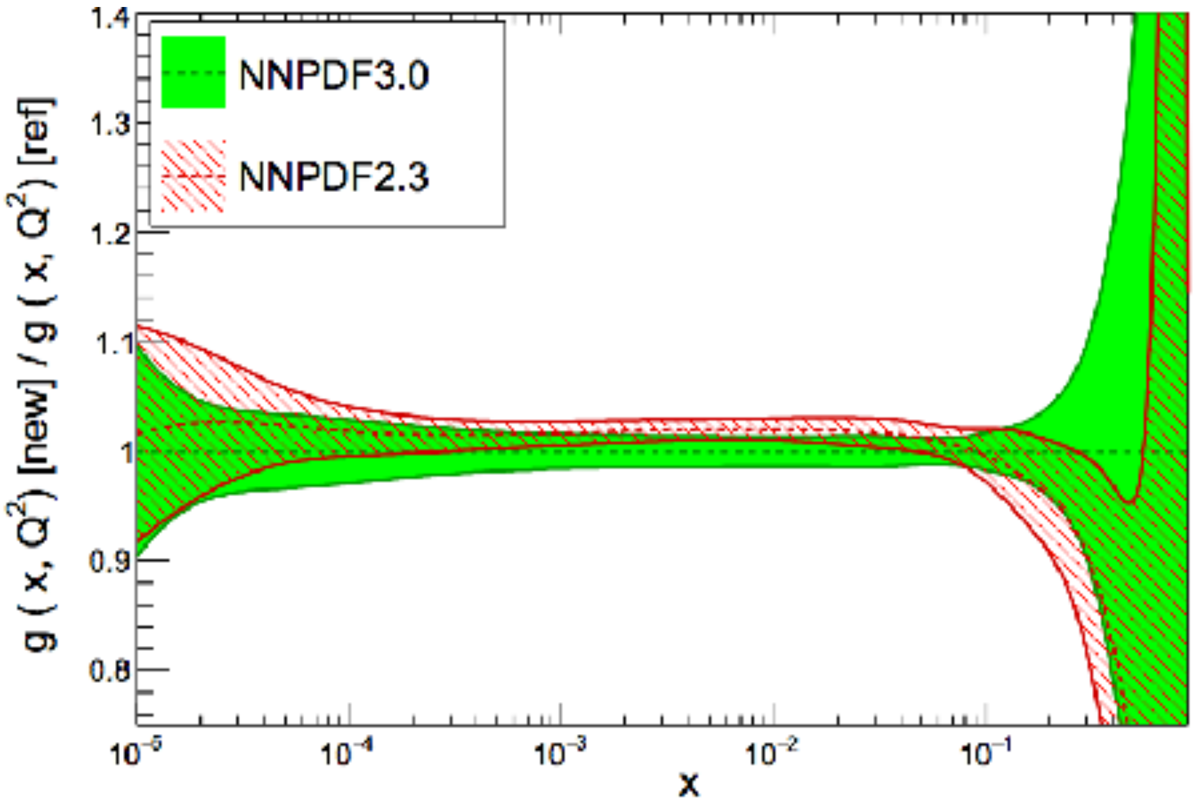


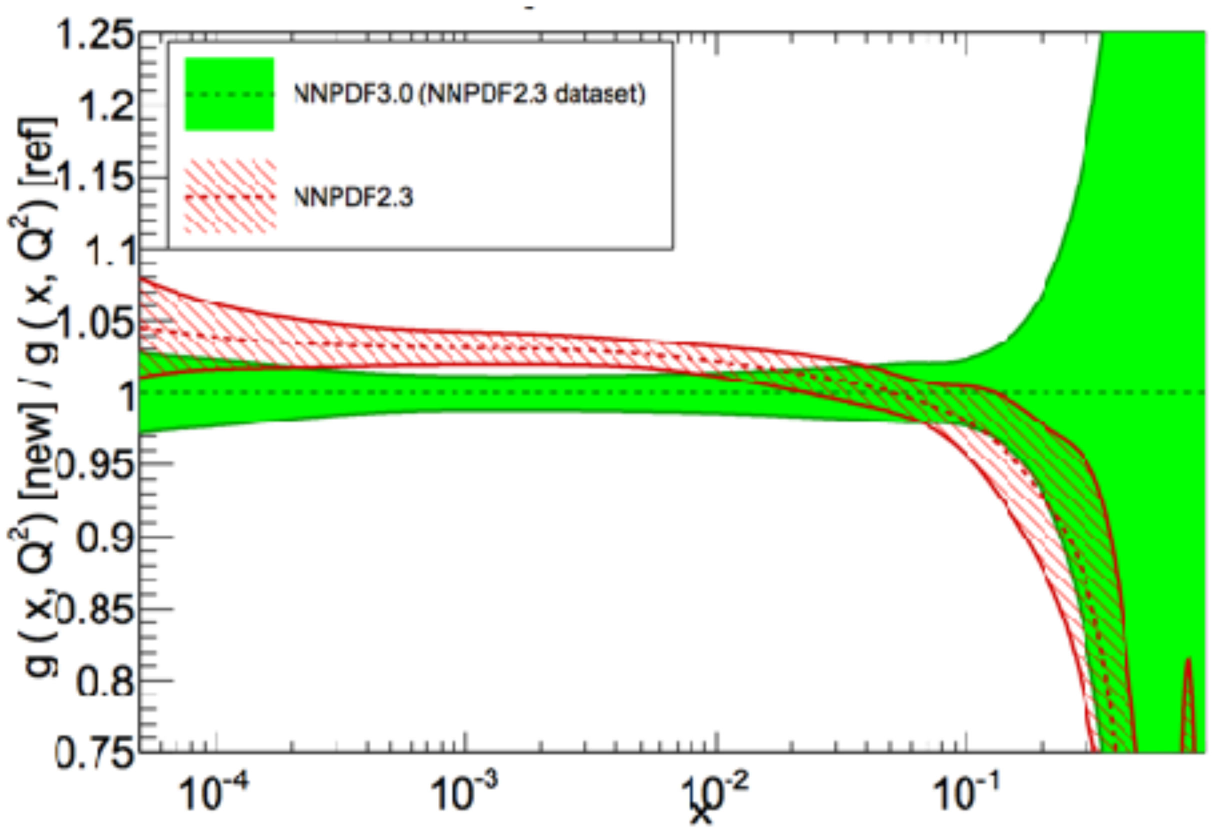
FIG. 27. "Soft-gluon" (Λ = 200 MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

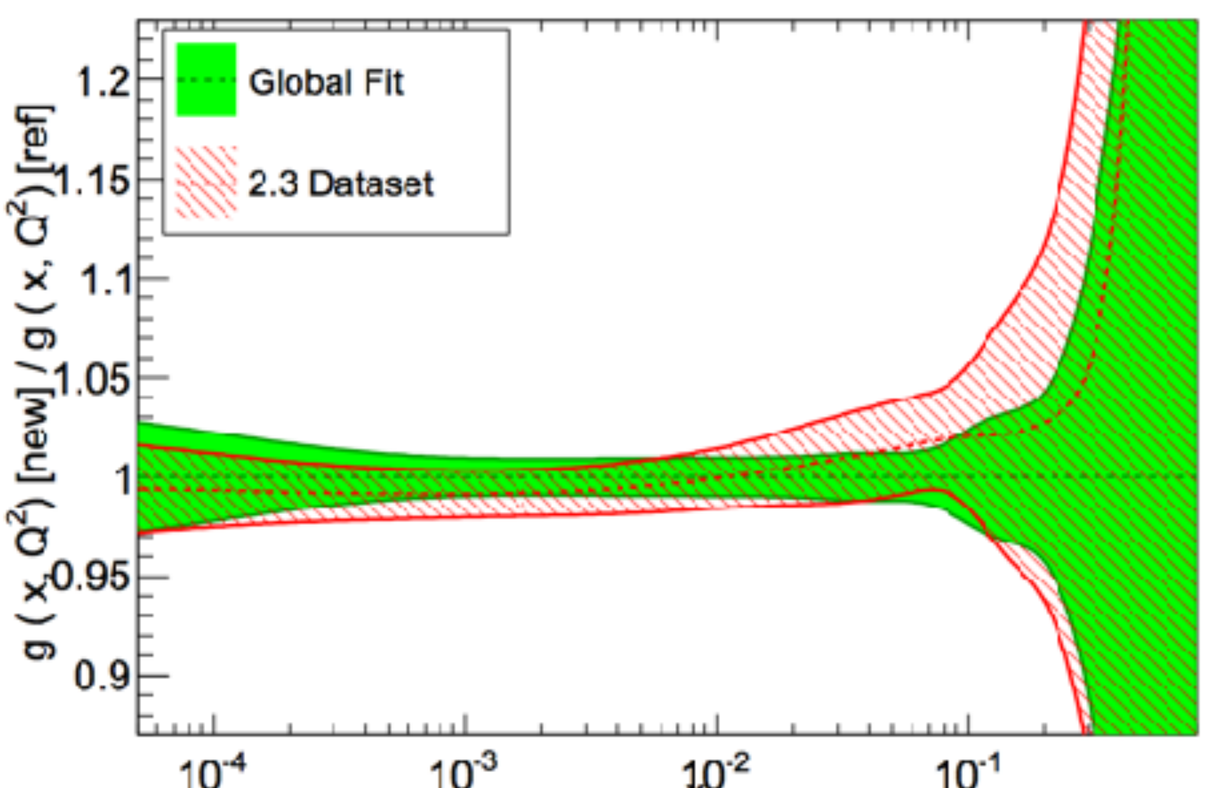


Back-up slides

Key issue: methodology



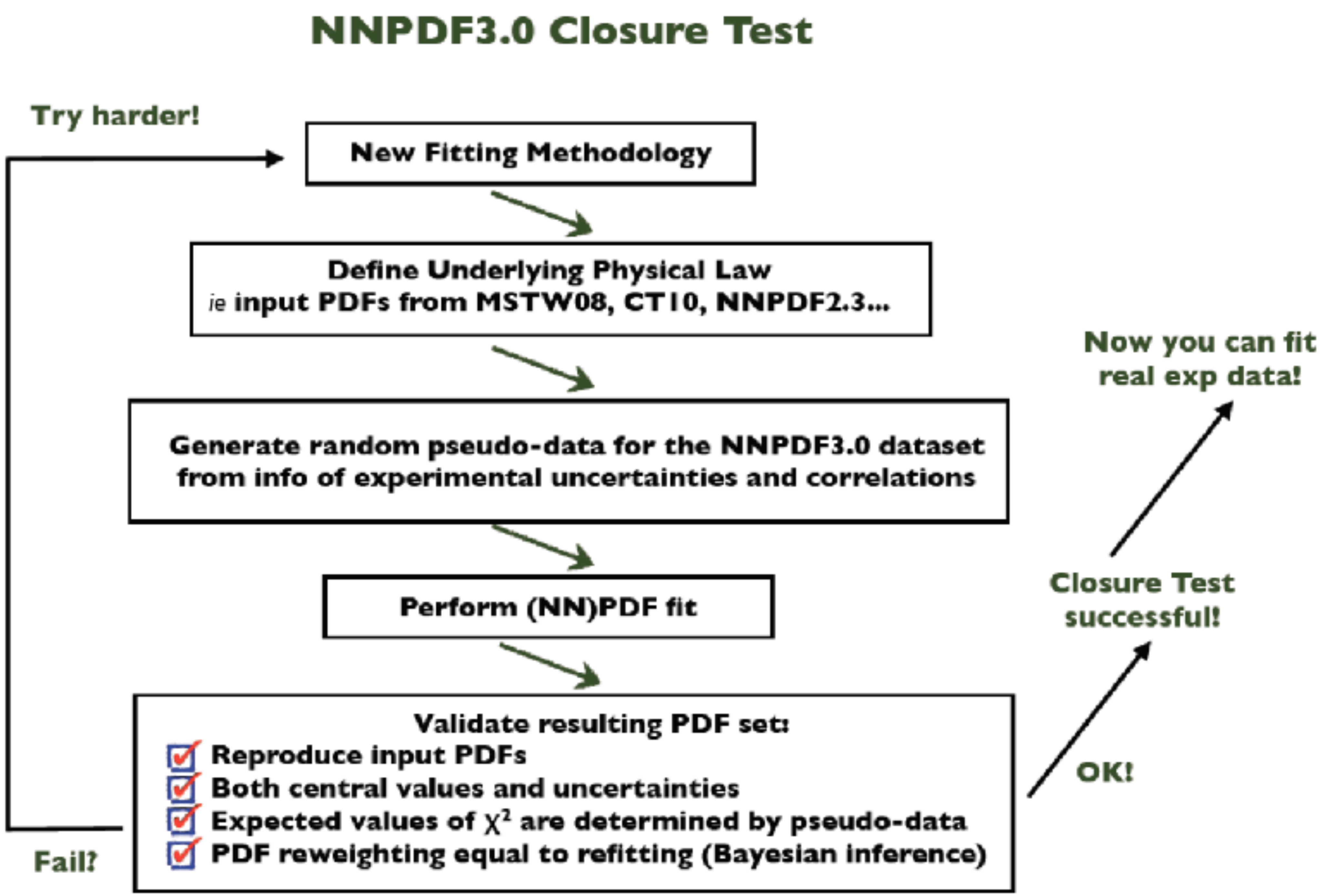




- NNPDF2.3 -> NNPDF3.0: included many new data (LHC and combined HERA) & change in fitting methodology (genetic algorithm and stopping criterion)
- Main changes in the gluon are due to the change in methodology
- How to make sure that we have a “perfect” methodology?

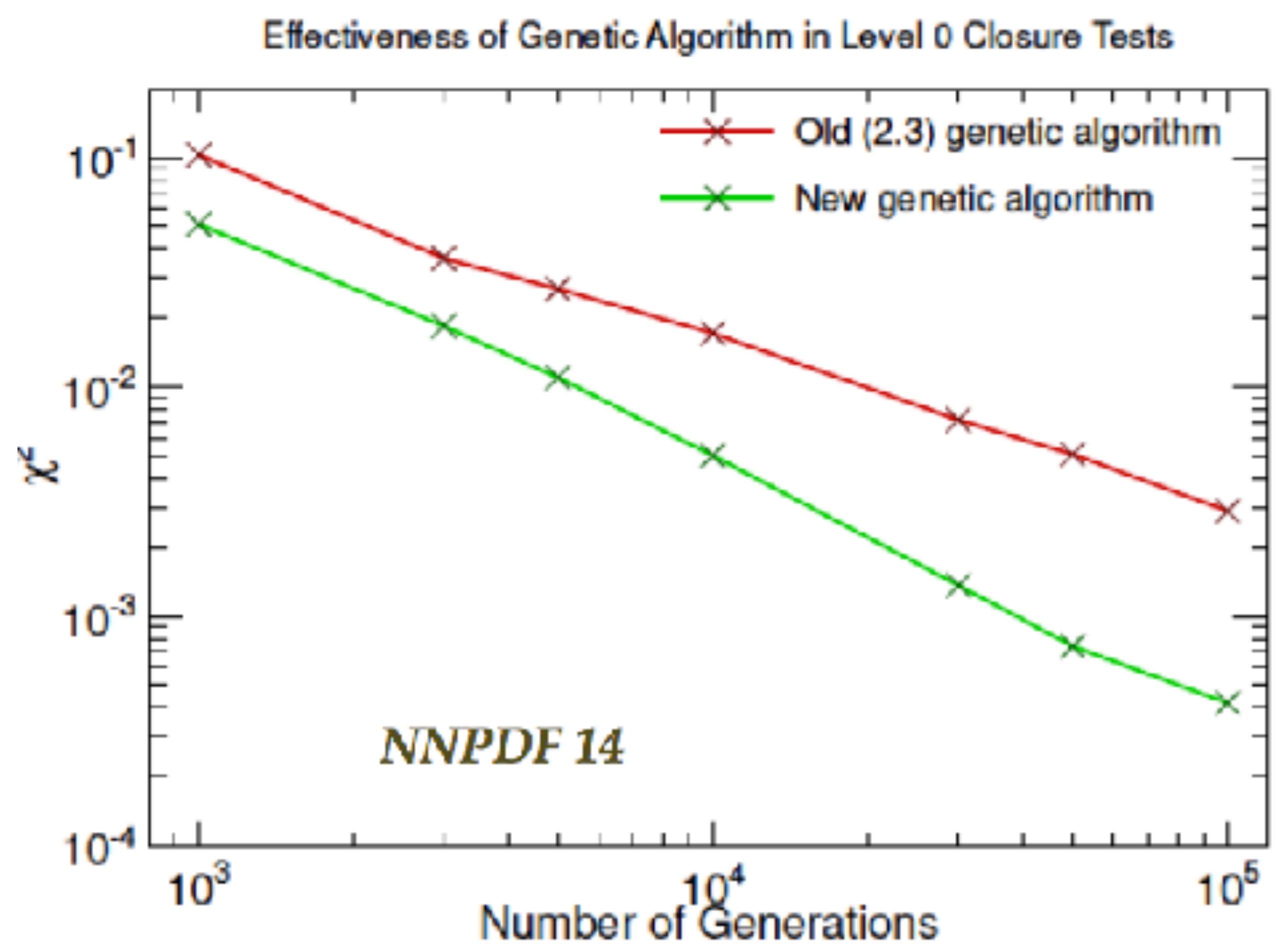
Closure test

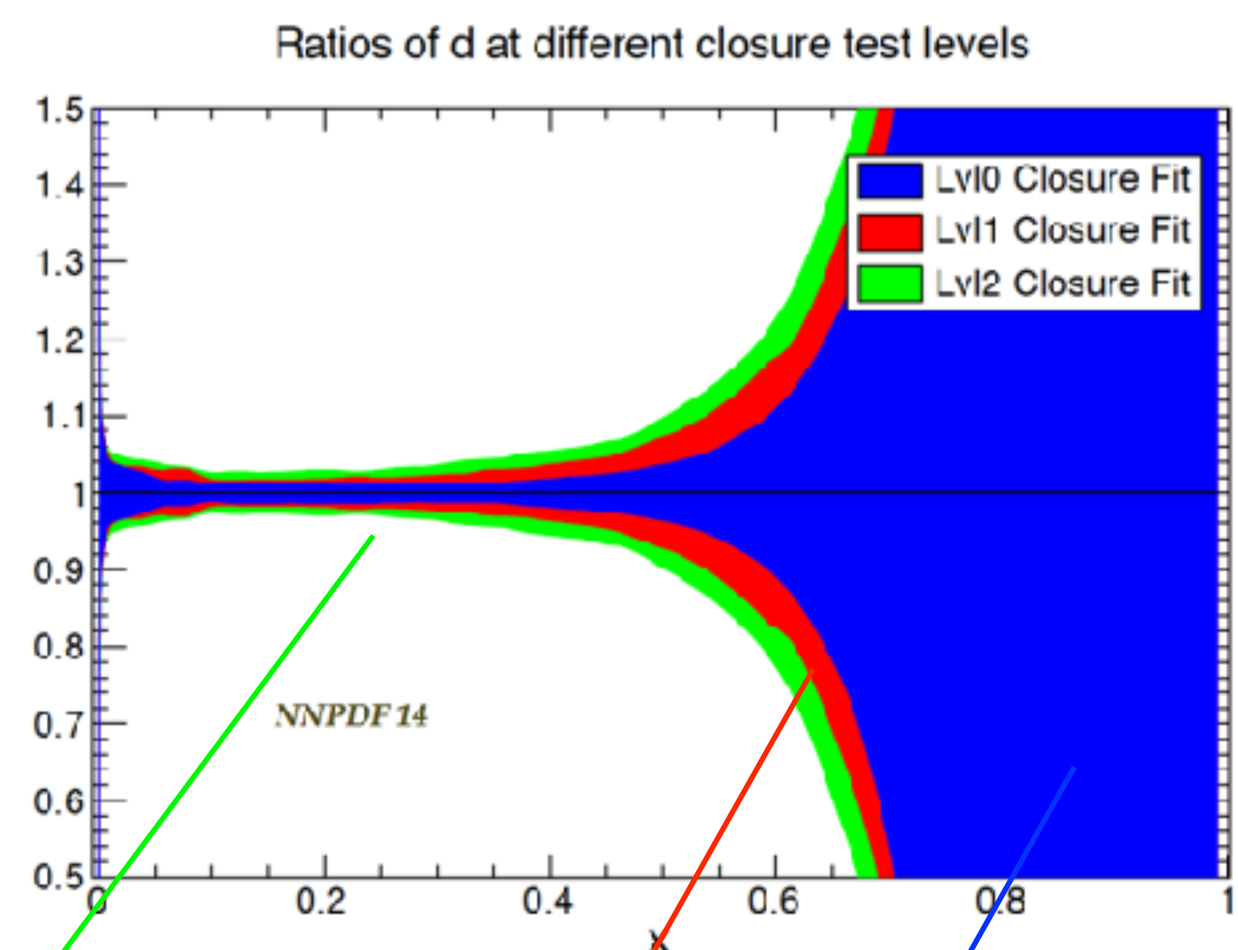
NNPDF collaboration, JHEP 1504 (2015) 040



Closure test

- Level-0: if pseudo-data are identical to the input theory, then agreement with theory should be arbitrarily good, i.e. $\chi^2 \to 0$
- Level-1: let pseudo-data fluctuate about their central values within data uncertainty, then $\chi^2 \to 1$
- Level-2: generate Monte Carlo replicas of pseudo-data with fluctuations, then $\chi^2 \to 2$





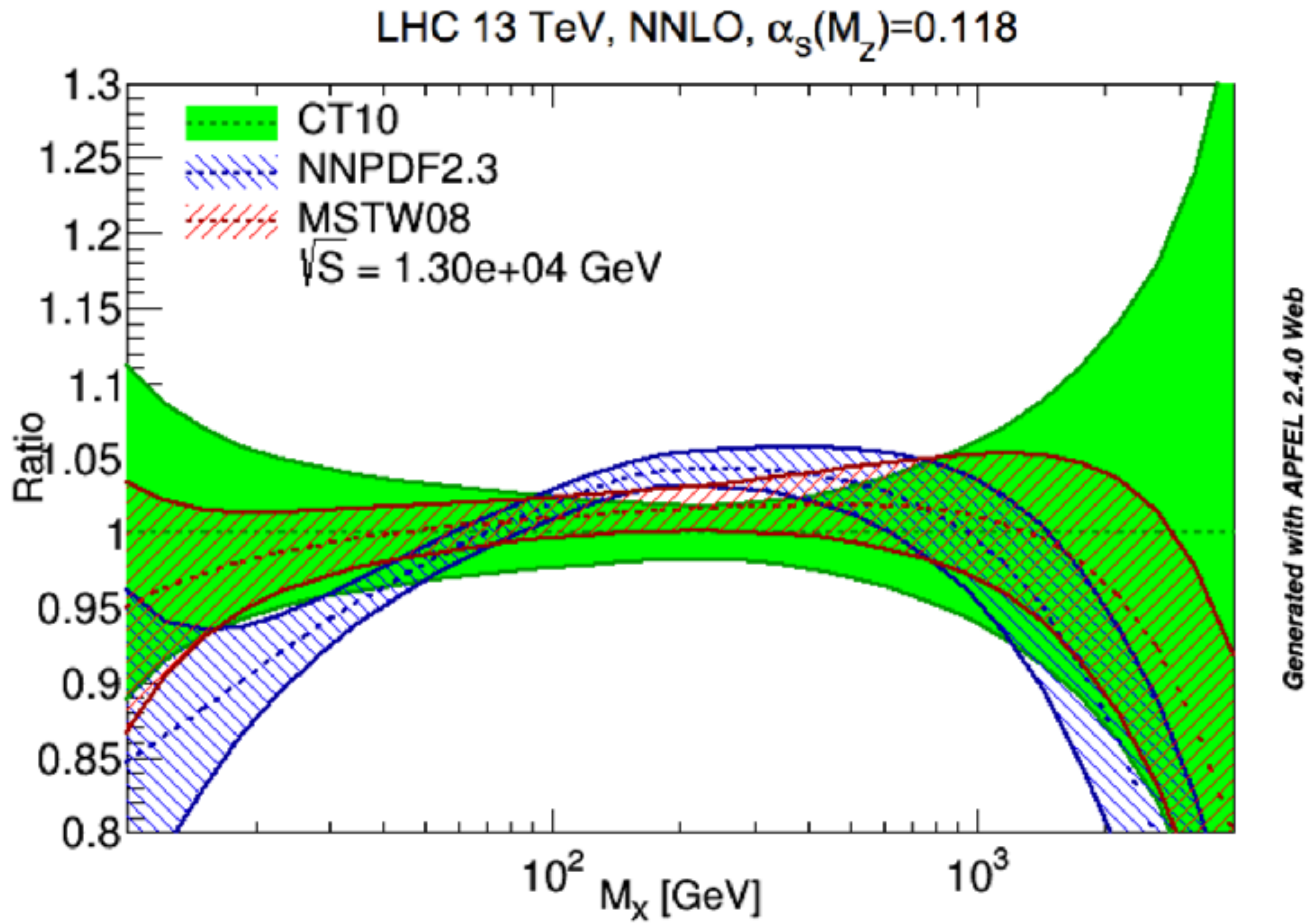
parametrisation uncertainty

data uncertainty

extrapolation uncertainty

Convergence of global analyses

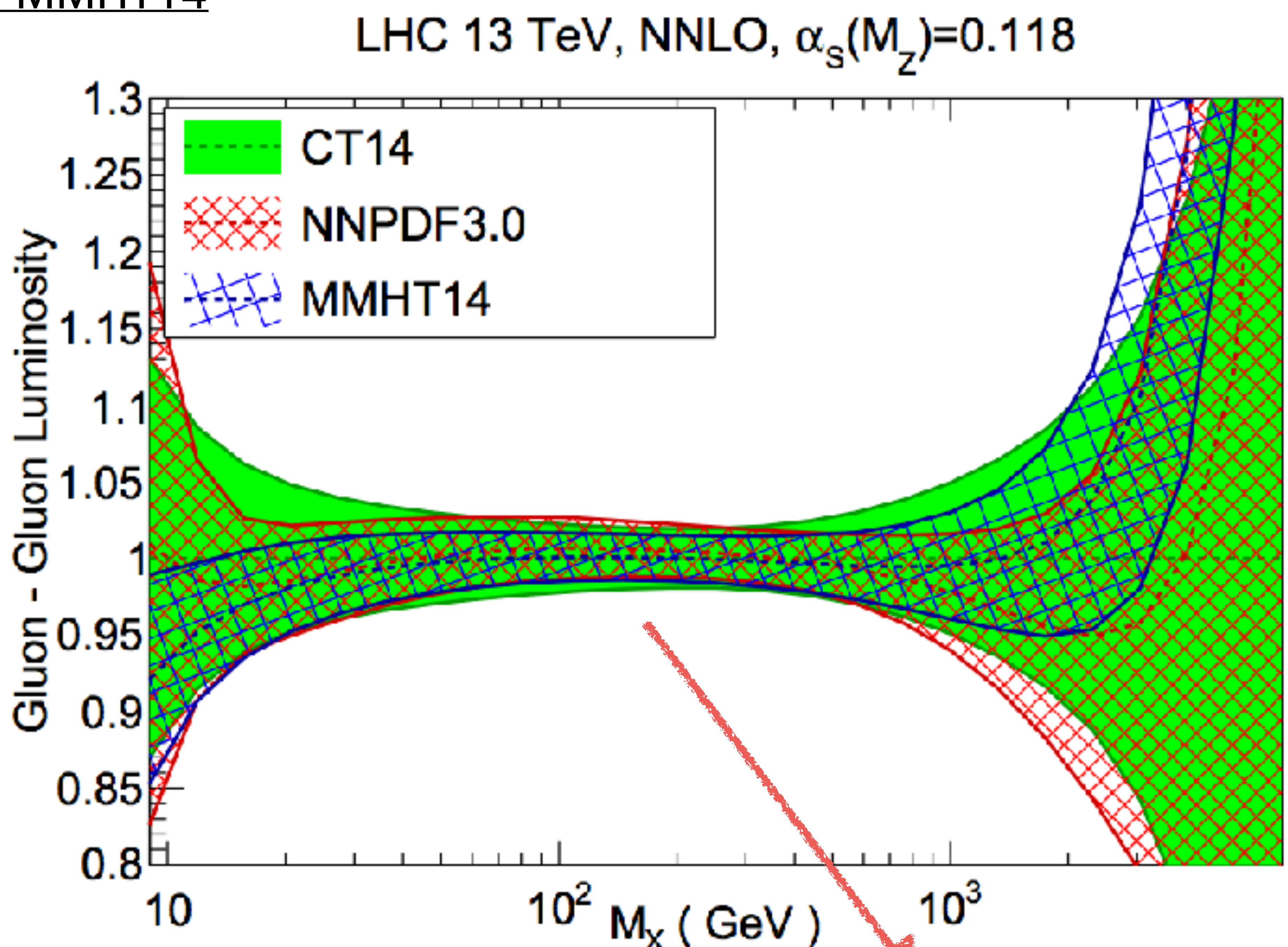
NNPDF2.3 / CT10 / MSTW2008



(2014)

Convergence of global analyses

NNPDF3.0 / CT14 / MMHT14

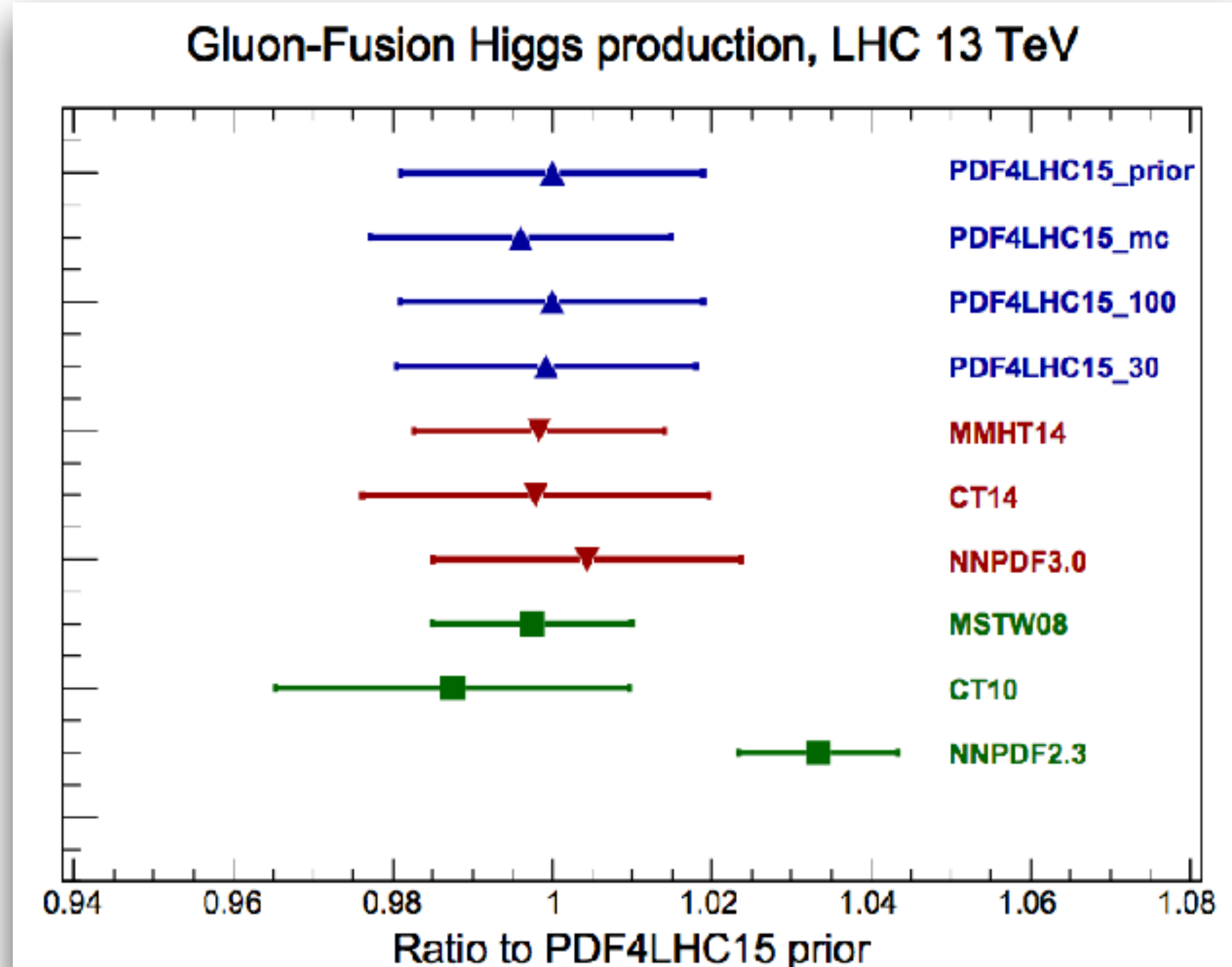


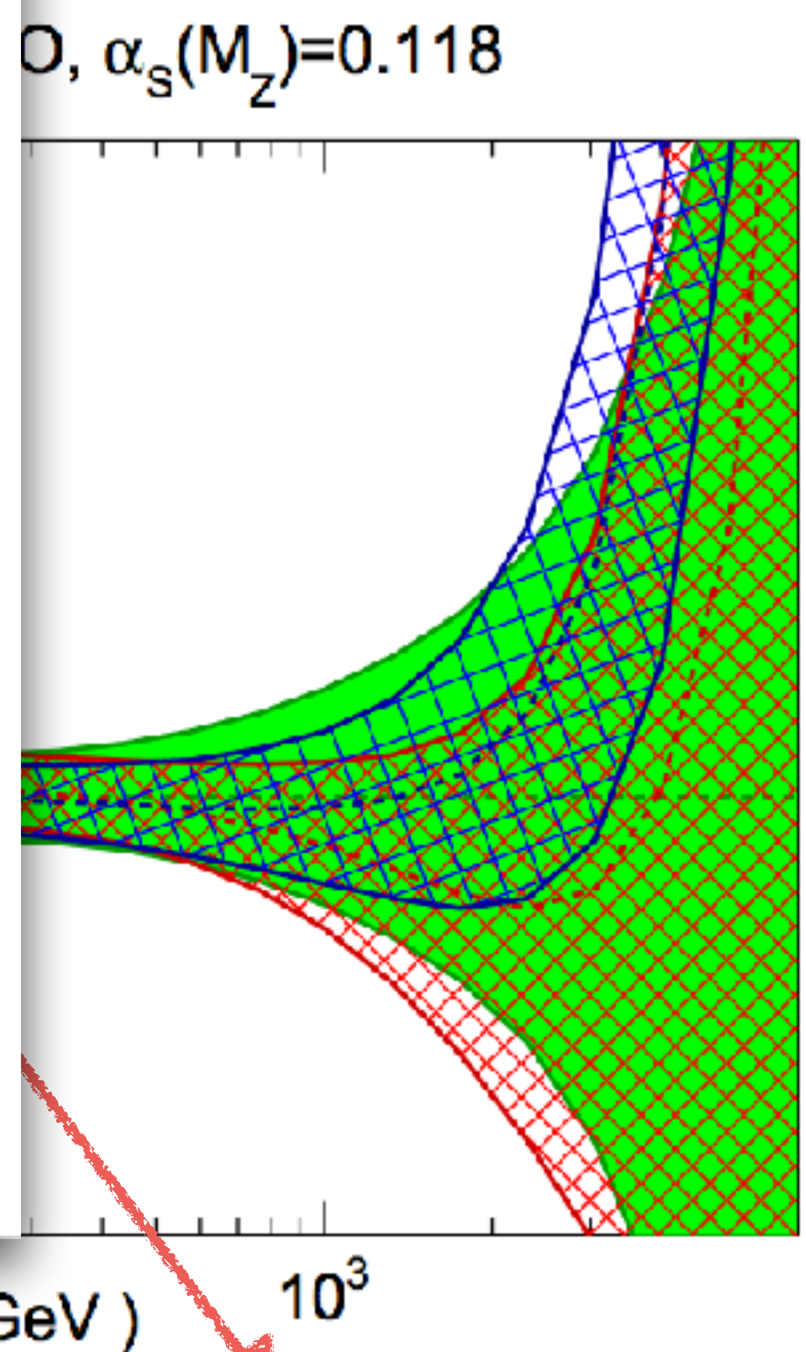
Impact on Higgs physics

(2016)

J. Butterworth et al, J.Phys. G43 (2016) 023001

Convergence of global analyses



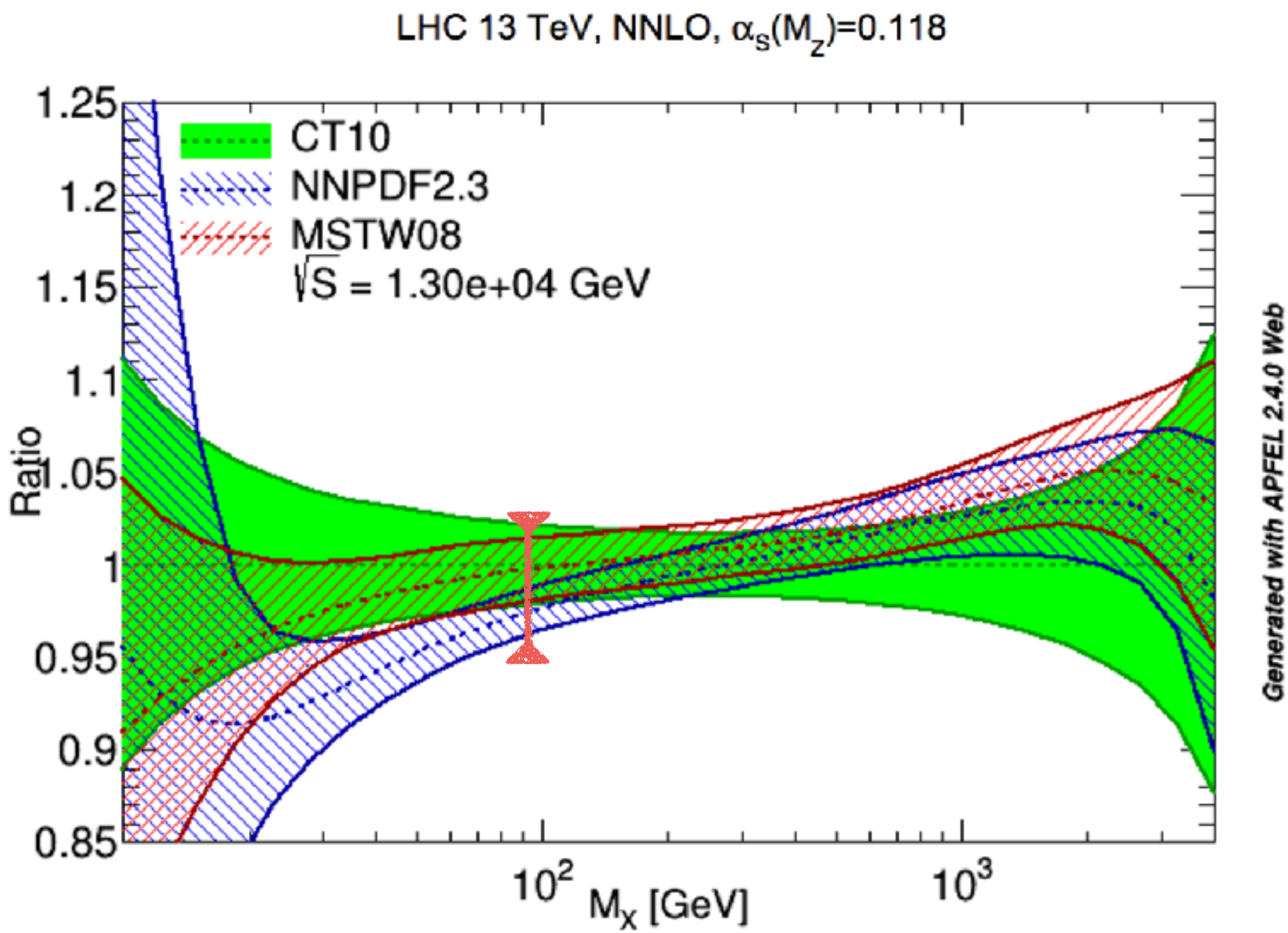


Impact on Higgs physics

J. Butterworth et al, J.Phys. G43 (2016) 023001

Convergence of global analyses

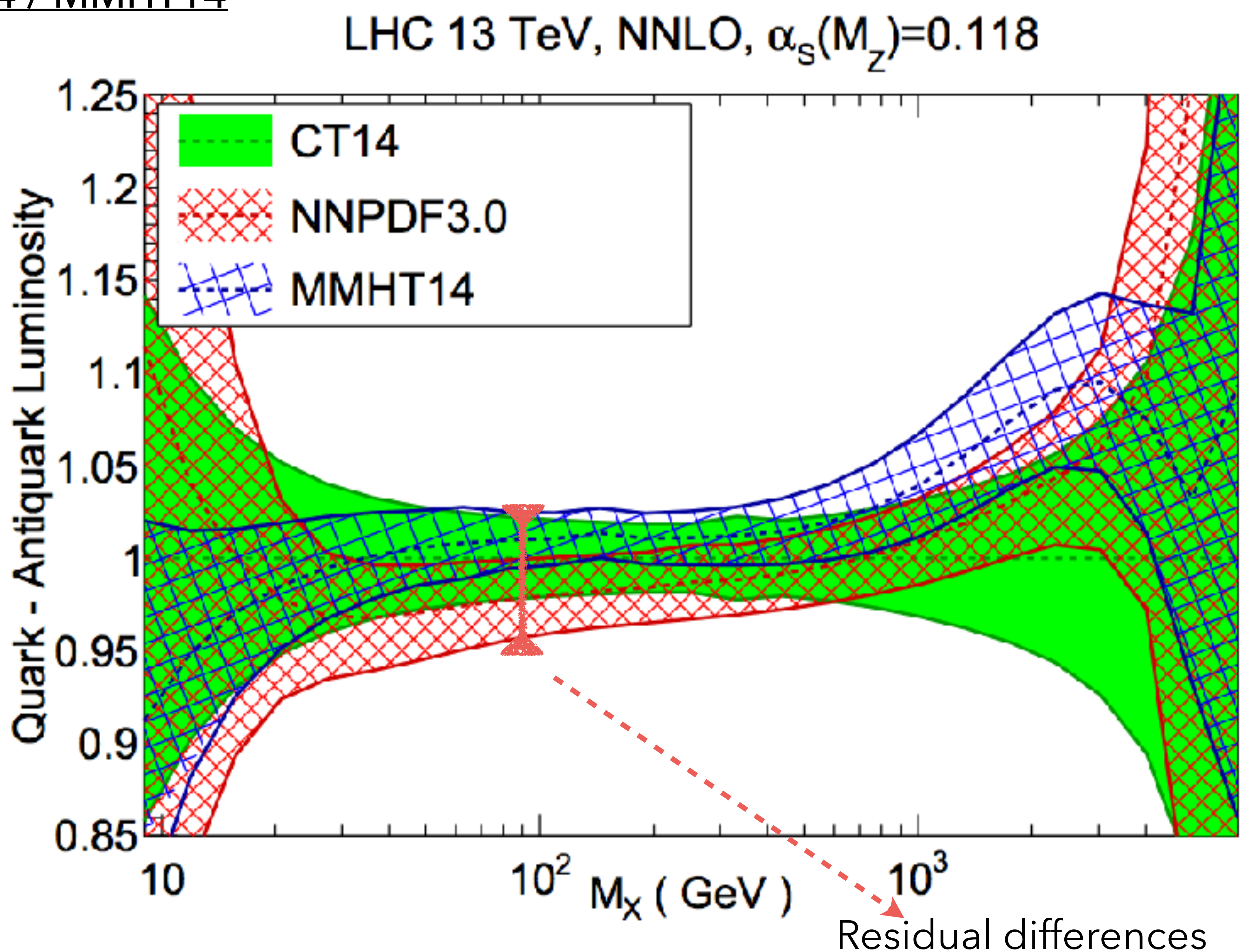
NNPDF2.3 / CT10 / MSTW2008



(2014)

Convergence of global analyses

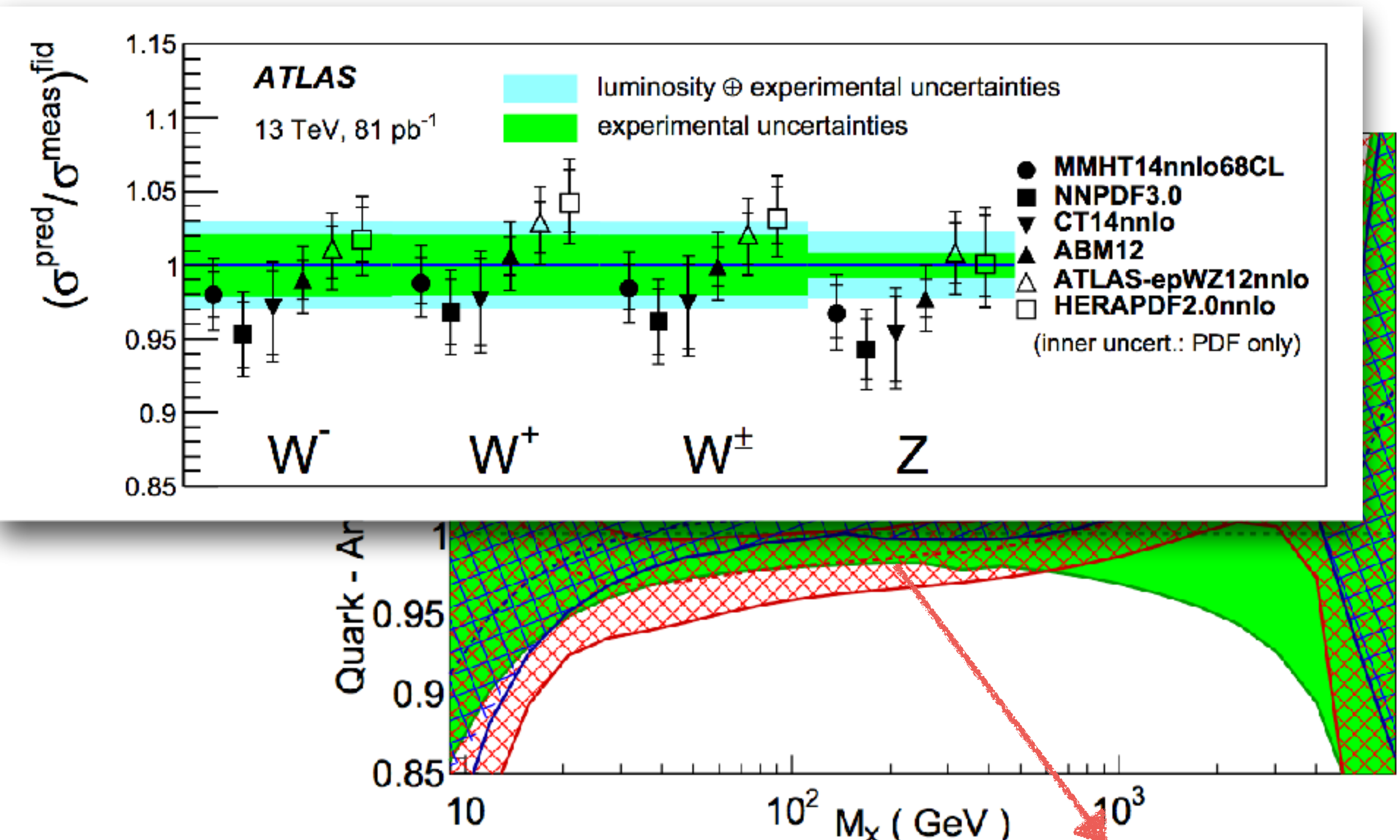
NNPDF3.0 / CT14 / MMHT14



(2016)

J. Butterworth et al, J.Phys. G43 (2016) 023001

Convergence of global analyses



Residual differences

ATLAS, 1603.09222

Data convergence

- Increasingly wide dataset used in PDF analyses: from DIS structure functions only to global analyses including jets, top, W/Z, HQ observables
- HERA PDFs based on maximally consistent set of data, others have to deal with inconsistencies

	2008		2009		2010		2011	2012		2013		2014		2015
SET / MONTH	CT6.6 (02)	NN1.0 (08)	MSTW (01)	ABKM09 (08)	NN2.0 (02)	CT10(N) (07)	NN2.1(NN) (07)	ABM11 (02)	NN2.3 (07)	CT10(NN) (02)	ABM12 (10)	NN3.0 (10)	MMHT (12)	CT14 (06)
F. T. DIS	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
ZEUS+H1-HI	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
COMB. HI	✗	✗	✗	✗	✔	✗	✔	✗	✔	✗	✔	✔	✗	✗
ZEUS+H1-HII	✗	✗	✗	✗	✗	✗	some	✗	✗	some	✗	✔	✗	✗
HERA JETS	✗	✗	✔	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗
F. T. DY	✔	✗	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
TEV. W+Z	✔	✗	✔	✗	✔	✔	✔	✗	✔	✔		✔	✔	✔
TEV. JETS	✔	✗	✔	✗	✔	✔	✗	✔	✔	✔	✗	✔	✔	✔
LHC W+Z	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	some	✔	✔	✔
LHC JETS	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✔	✔	✔
TOP	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✔	✗	✗
W+C	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗
W p_T	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗

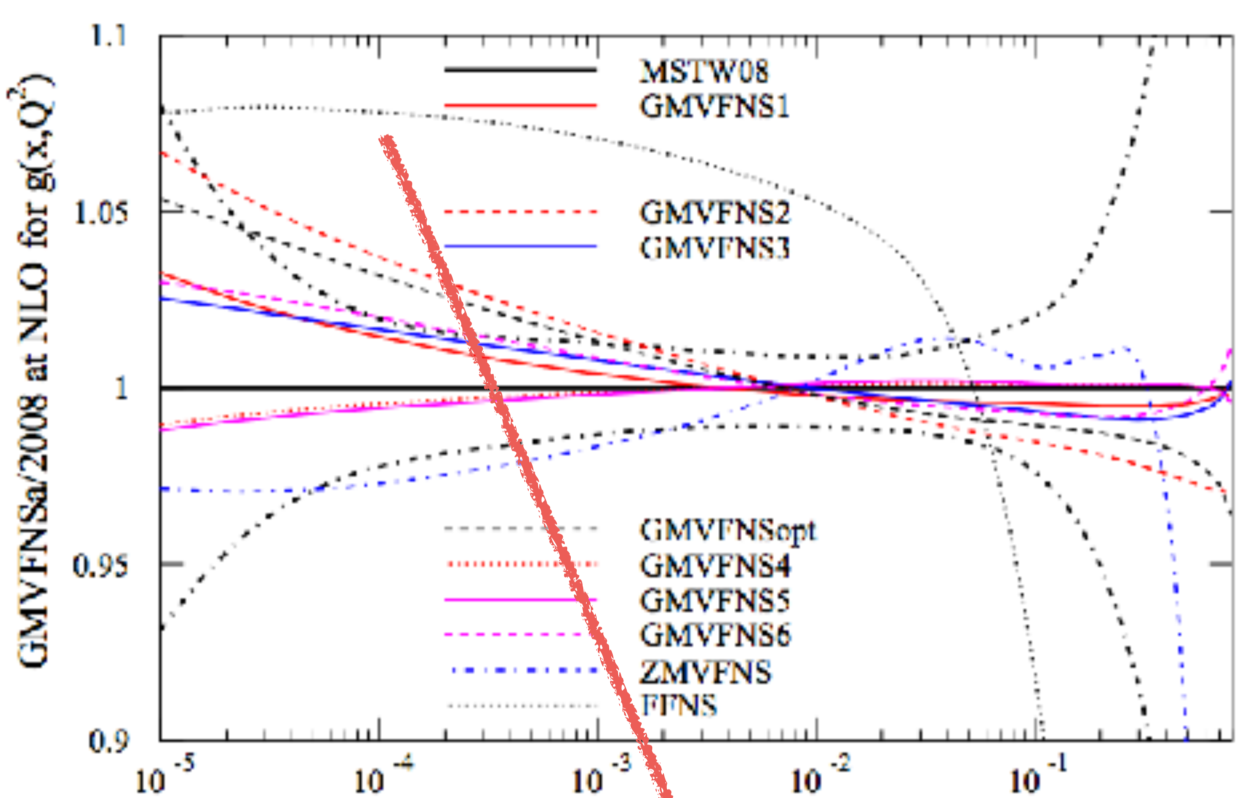
pre-LHC

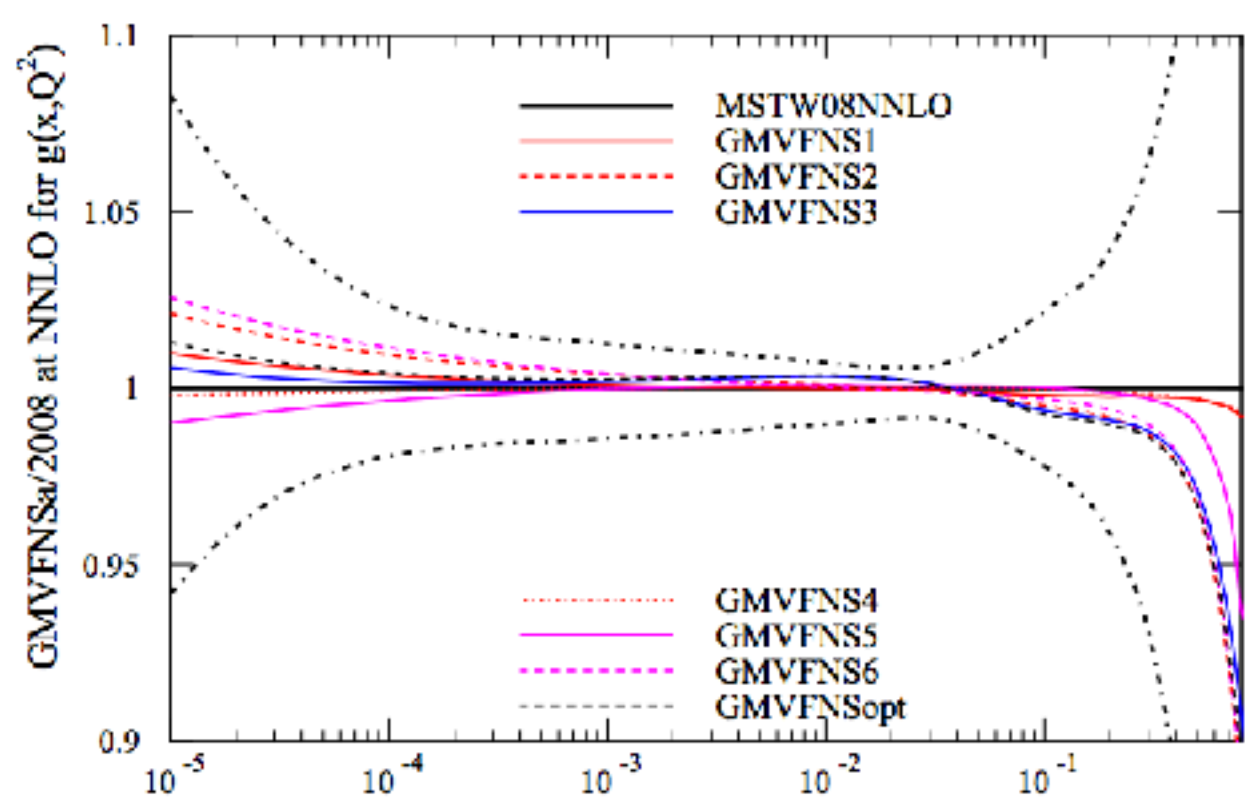
post-LHC

S. Forte, talk in Durham

Theory convergence

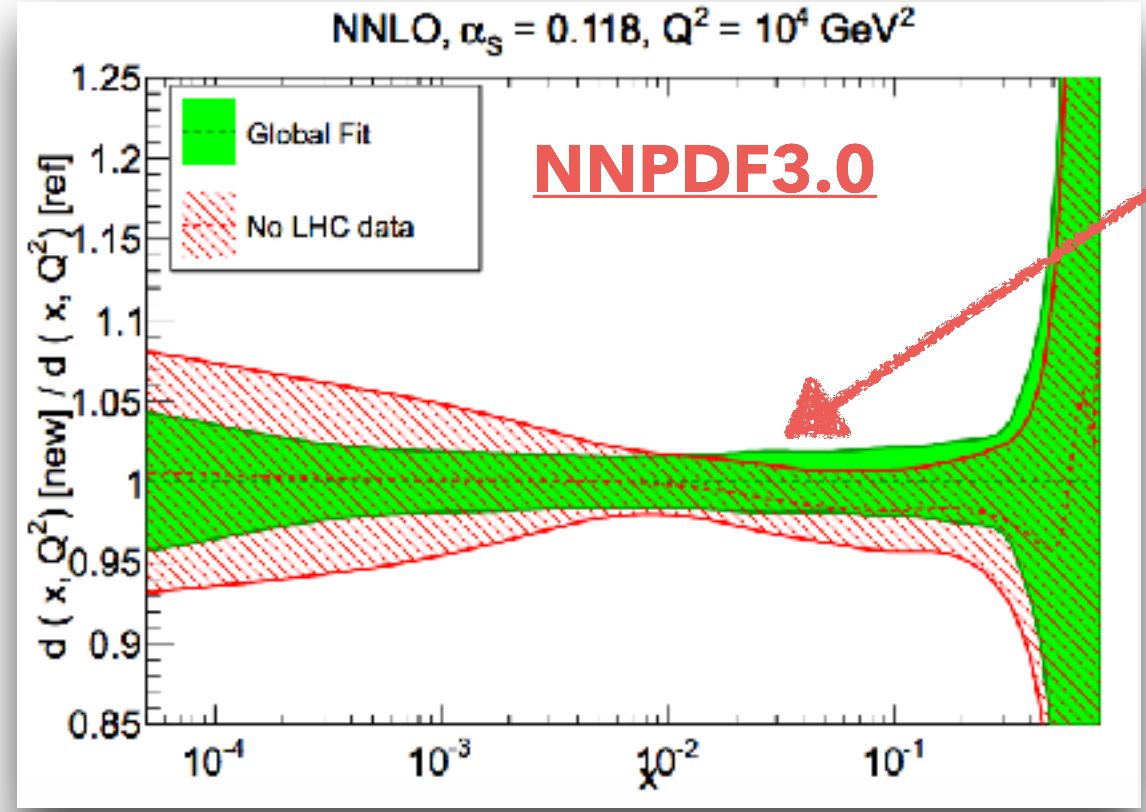
- Comparable GM-VFN schemes for inclusion of HQ masses (sub-leading differences less important at NNLO)
- Common $\alpha_S(M_Z) = 0.118$ (external parameter)
- NNLO (although with some caveat - especially concerning jets data)
- Extensive benchmarking

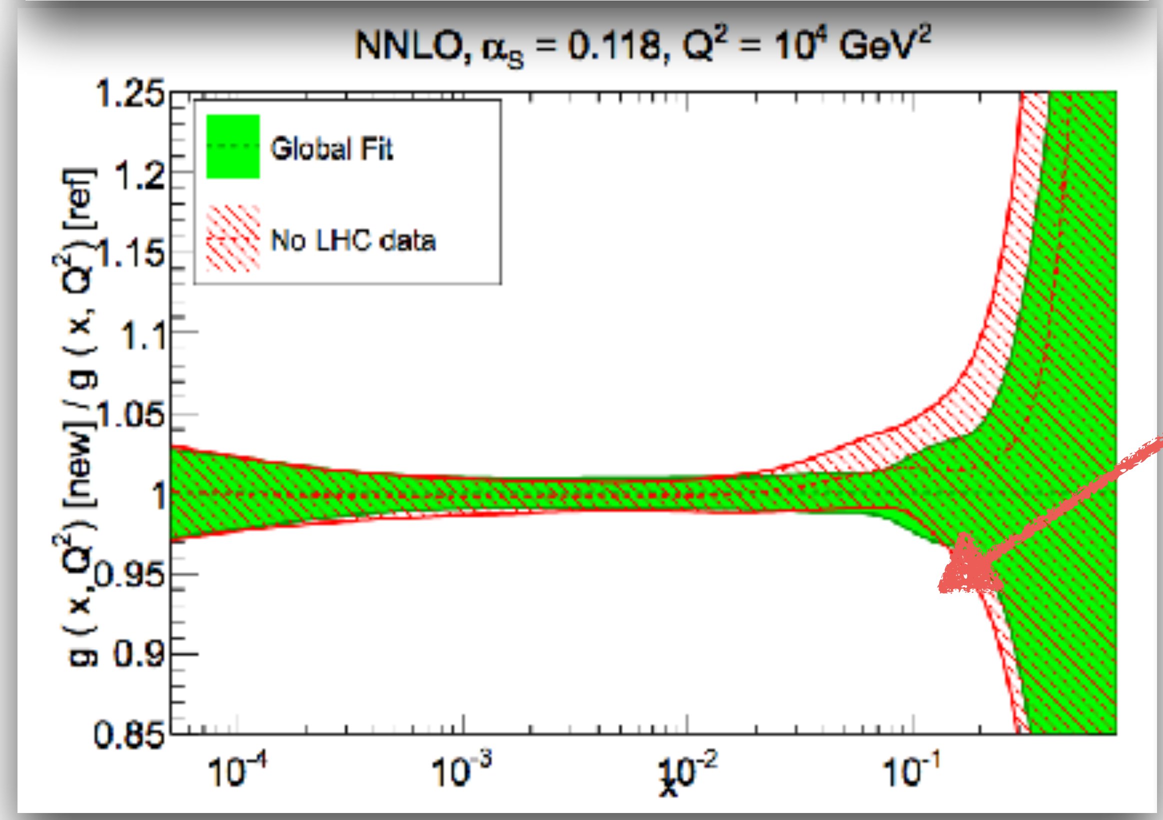




Compensate by lower $\alpha_S(M_Z)$ in structure function scaling

LHC data

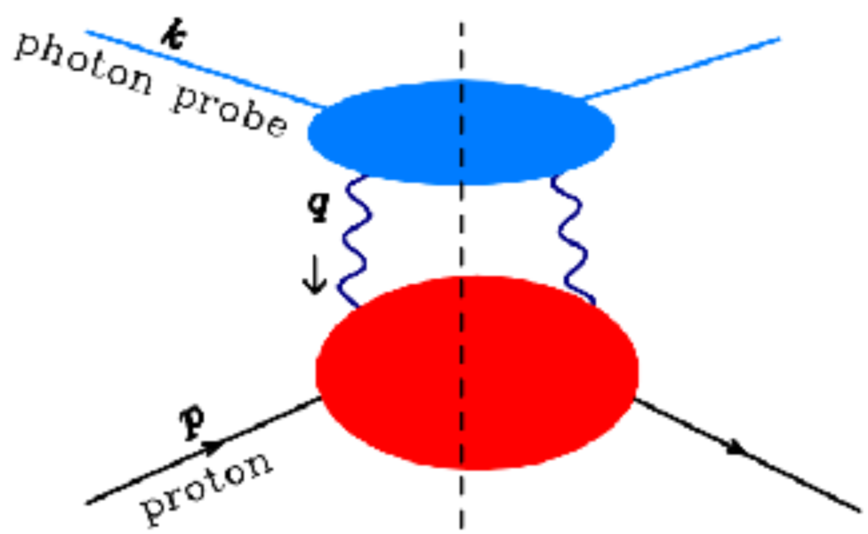




ATLAS jets 2.76 TeV and 7 TeV	g at large x
ATLAS high-mass DY at 7 TeV	q/q~ sep.
ATLAS W pT data at 7 TeV	g and q at med. x
CMS (Y,M) double diff distributions 7 TeV	q/q~ sep.
CMS jets at 7 TeV	g at large x
CMS muon charge asymmetry at 7 TeV	q/q~ sep.
CMS W+c at 7 TeV	strange
LHCb Z rapidity distribution at 7 TeV	small/large x q
ATLAS+CMS tt total xsec at 7/8 TeV	g at large x

LUX, master equation

The Master Equation



$$\sigma = \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \frac{e^4_{\mathrm{phys}}(q^2)}{q^4}$$
$$\times \langle k|\tilde{J}_p^{\ \mu}(-q) J_p^{\nu}(0)|k\rangle$$
$$\times \langle p|\tilde{J}_\mu(q) J_\nu(0)|p\rangle$$

Kinematics constraints:

$$Q^2 = -q^2 > 0,$$
$$0 < x_{\mathrm{bj}} = Q^2/(2p \cdot q) \leq 1.$$

- Same kinematic restrictions as in DIS.
- $\frac{1}{4\pi}\langle p|\tilde{J}_\mu(q) J_\nu(0)|p\rangle = -g_{\mu\nu} F_1(Q^2, x_{\mathrm{bj}}) + \frac{p^\mu p^\nu}{p \cdot q} F_2(Q^2, x_{\mathrm{bj}}) + \ldots$
(Notice: full F_1 and F_2, not only inelastic)
- Photon induced process can be given in terms of F_1, F_2
- Hence: the photon PDF must be calculable in terms of F_1, F_2.

The photon PDF

- **NNPDF23QED** provides γ PDF and its uncertainty at (N)NLO QCD + LO QED, by reweighting photon PDF
  Ball et al [Nucl.Phys. B877 (2013)]

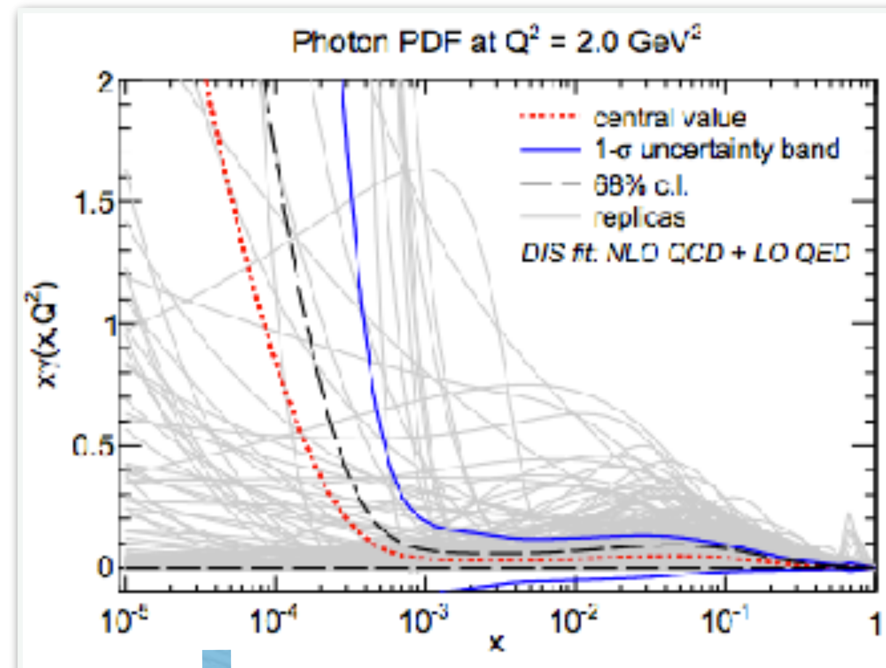
- **CT14QED** set based on two-parameter ansatz from model of photon radiate from valence quarks (extension to MRST2004QED model)
  Schmidt et al [1509.02905]

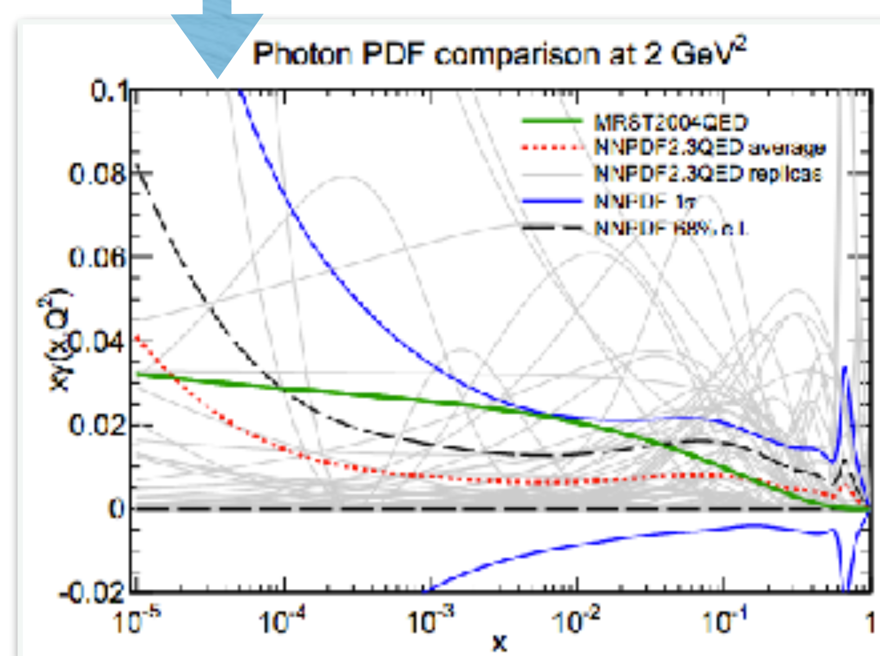
$$\begin{aligned} f_{\gamma/p}(x,Q_0) &= \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q}\circ u^0(x) + A_d e_d^2 \tilde{P}_{\gamma q}\circ d^0(x)\right) \\ f_{\gamma/n}(x,Q_0) &= \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q}\circ d^0(x) + A_d e_d^2 \tilde{P}_{\gamma q}\circ u^0(x)\right) \end{aligned}$$

- γ PDF poorly determined by DIS data. Need hadron collider processes where γ contributes at LO (on-shell W,Z production and low/high mass DY)

- NNPDF plan: fit photon along with other PDFs (thanks to upgrade of APFEL - simultaneous diagonalization of QCD and QED evolution matrices - and APFELgrid - now includes photon-induced processes)

DIS





DIS+LHC