NEW FRONTIERS IN PDF DETERMINATION

Maria Ubiali

Royal Society Dorothy Hodgkin Research Fellow
University of Cambridge

30th November 2016

CERN theory division

NNPDF

The NNPDF collaboration:

V. Bertone, N. Hartland, J. Rojo (Amsterdam)

J. I. Latorre (Barcelona) **MU** (Cambridge) S. Carrazza (CERN)

R. D. Ball, L. Del Debbio, P. G. Merrild (Edinburgh)

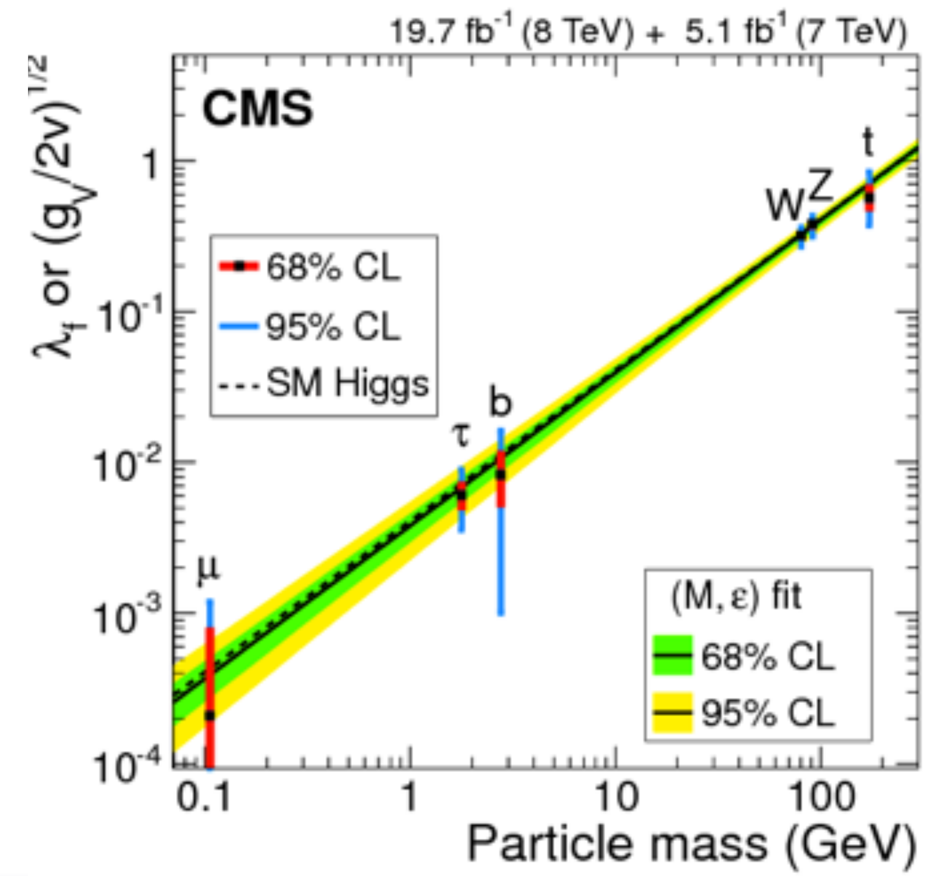
Z. Dim, S. Forte (Milano), A. Guffanti (Torino)

E. Nocera, L. Rottoli (Oxford)

LHC Physics at Run II

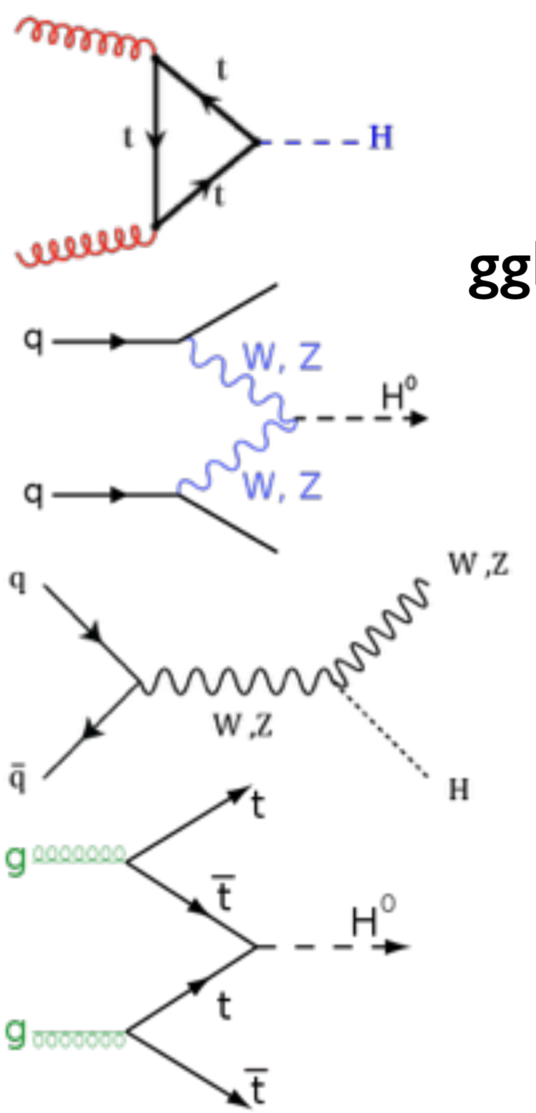
- Is precision physics possible/necessary at hadron colliders?
  At the LHC a paradigm shift took place.
  Theory has to catch up with experimental precision

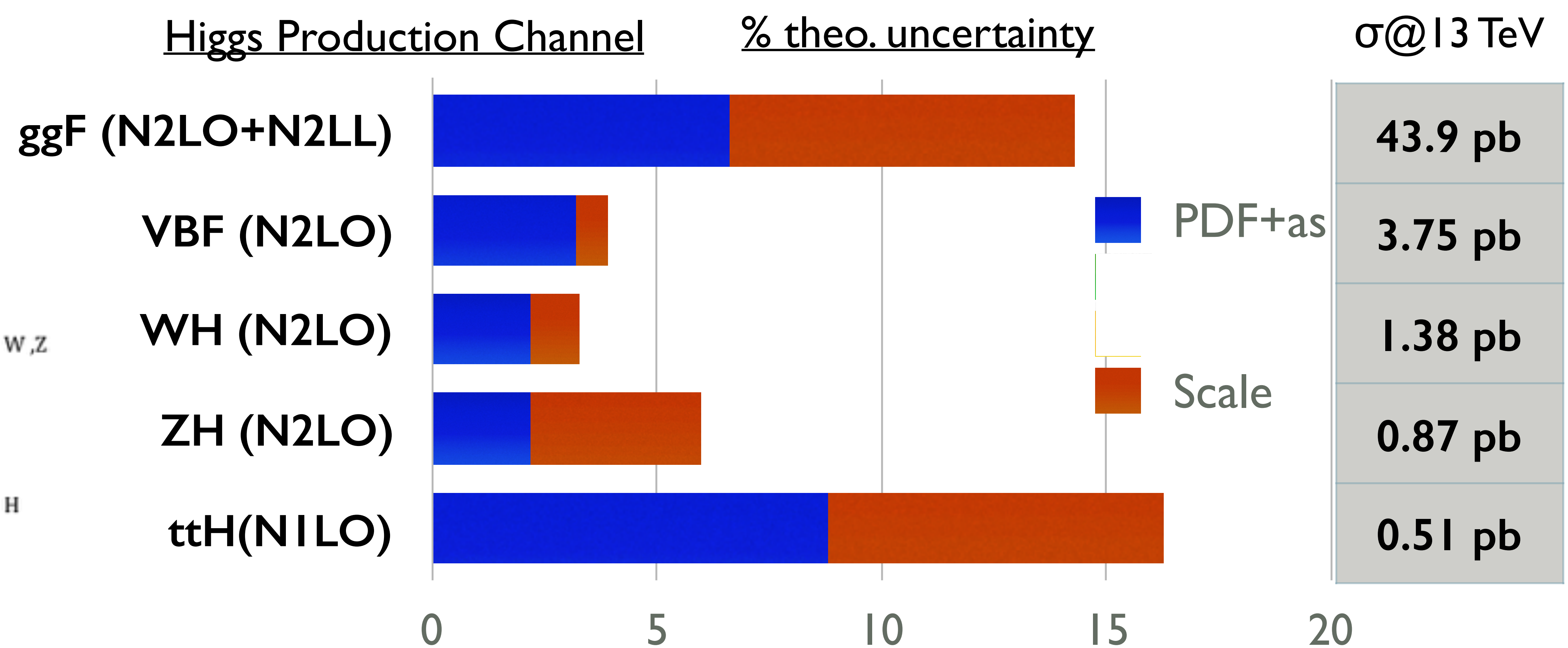
- Precise theoretical predictions are key to indirectly spot new physics signals and/or to characterise any possible "bump"



The role of PDF uncertainties

Yellow Report 3 (2013)

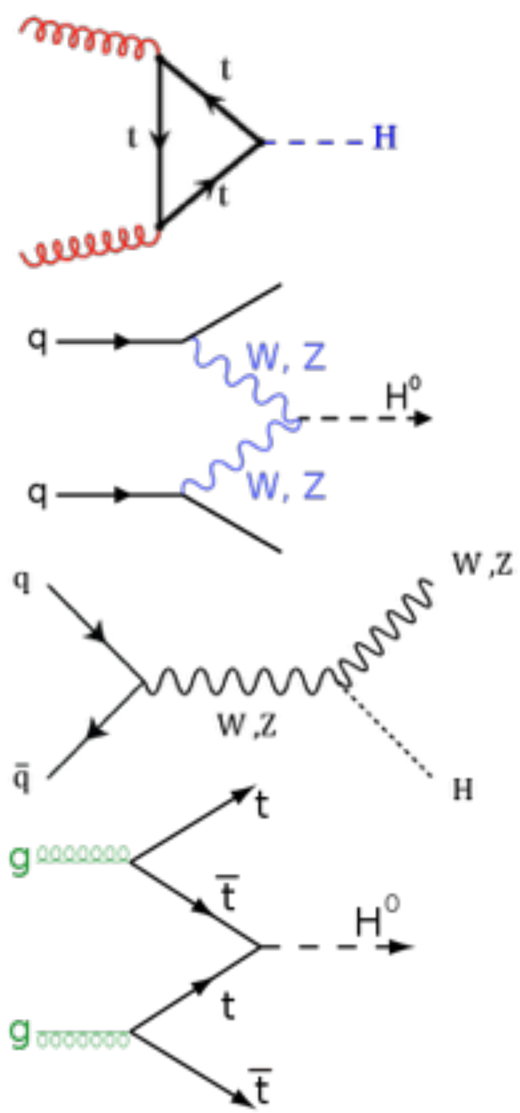


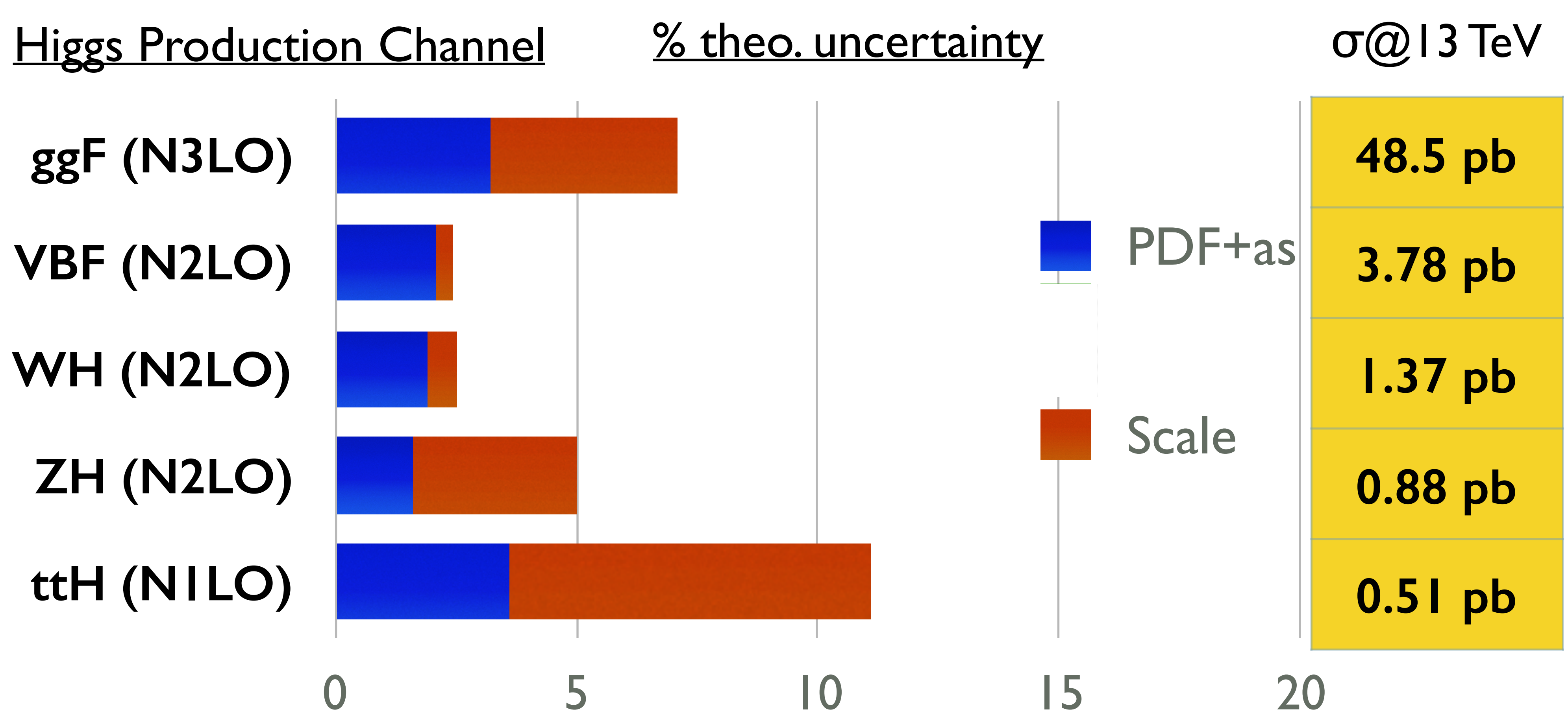


PDF uncertainties limiting factor in the accuracy of theoretical predictions

The role of PDF uncertainties

Yellow Report 4 (2016)

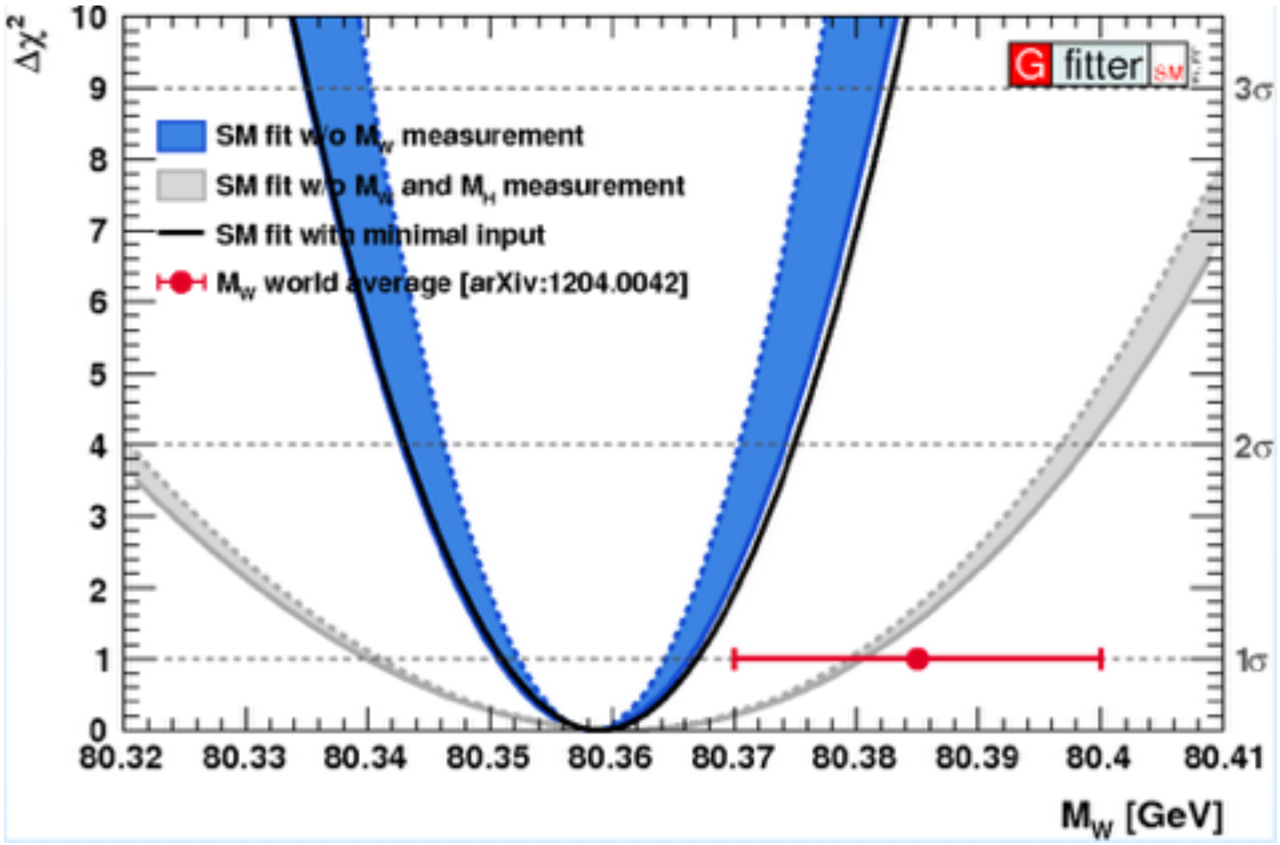




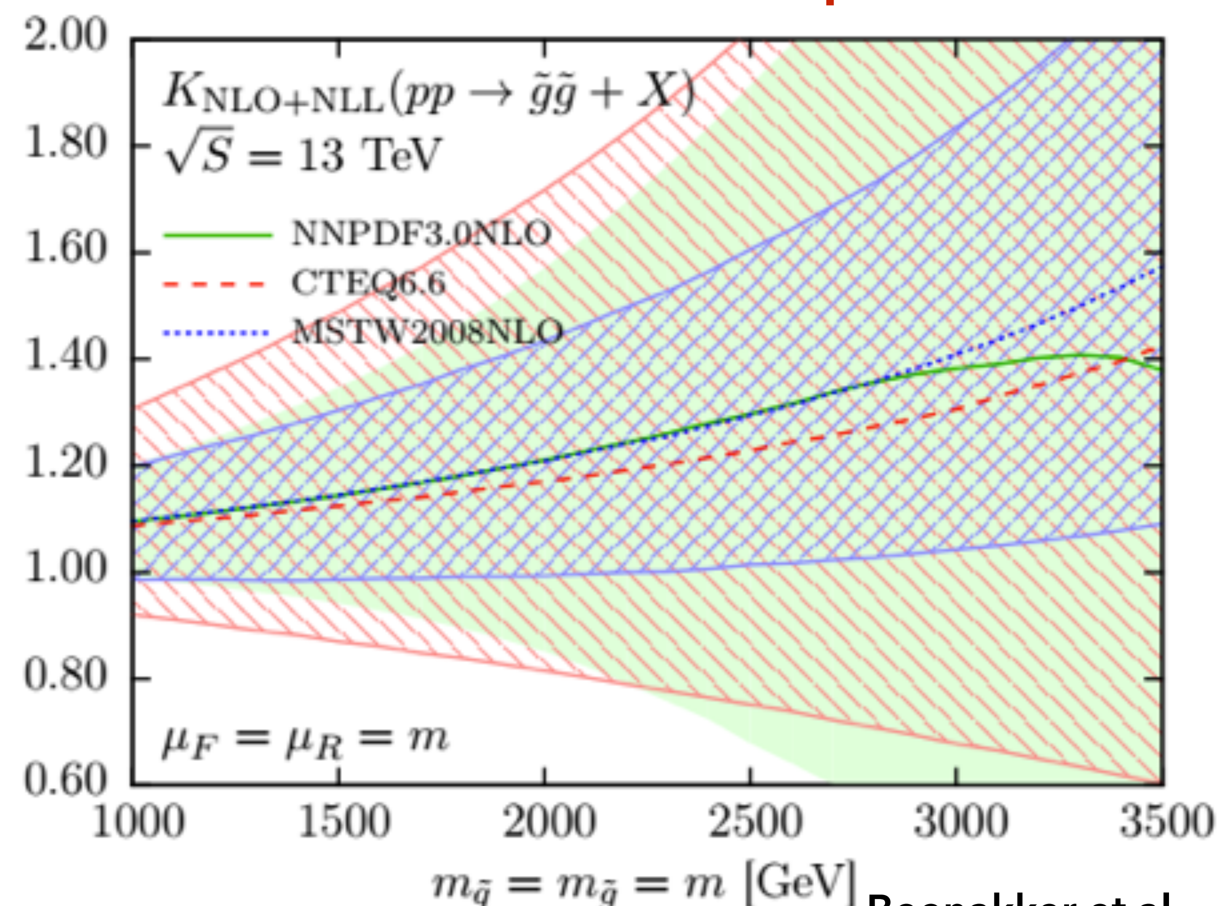
Reduced (still often dominant) PDF uncertainties

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

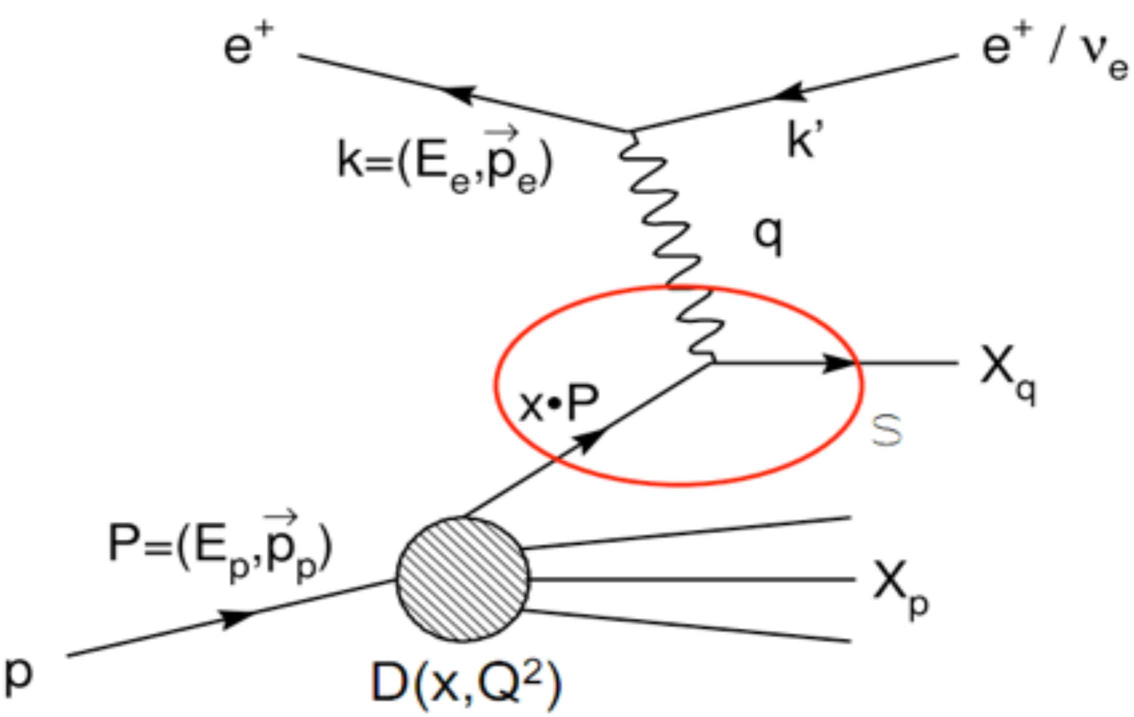
- Introduction
- Determination of PDFs
    - Methodology
    - Data & theory-driven progress
- State of the art and frontiers
    - New LHC data: challenges and opportunities
    - PDF hidden uncertainties
    - Photon contribution
    - Fitted versus dynamic charm
- Conclusions

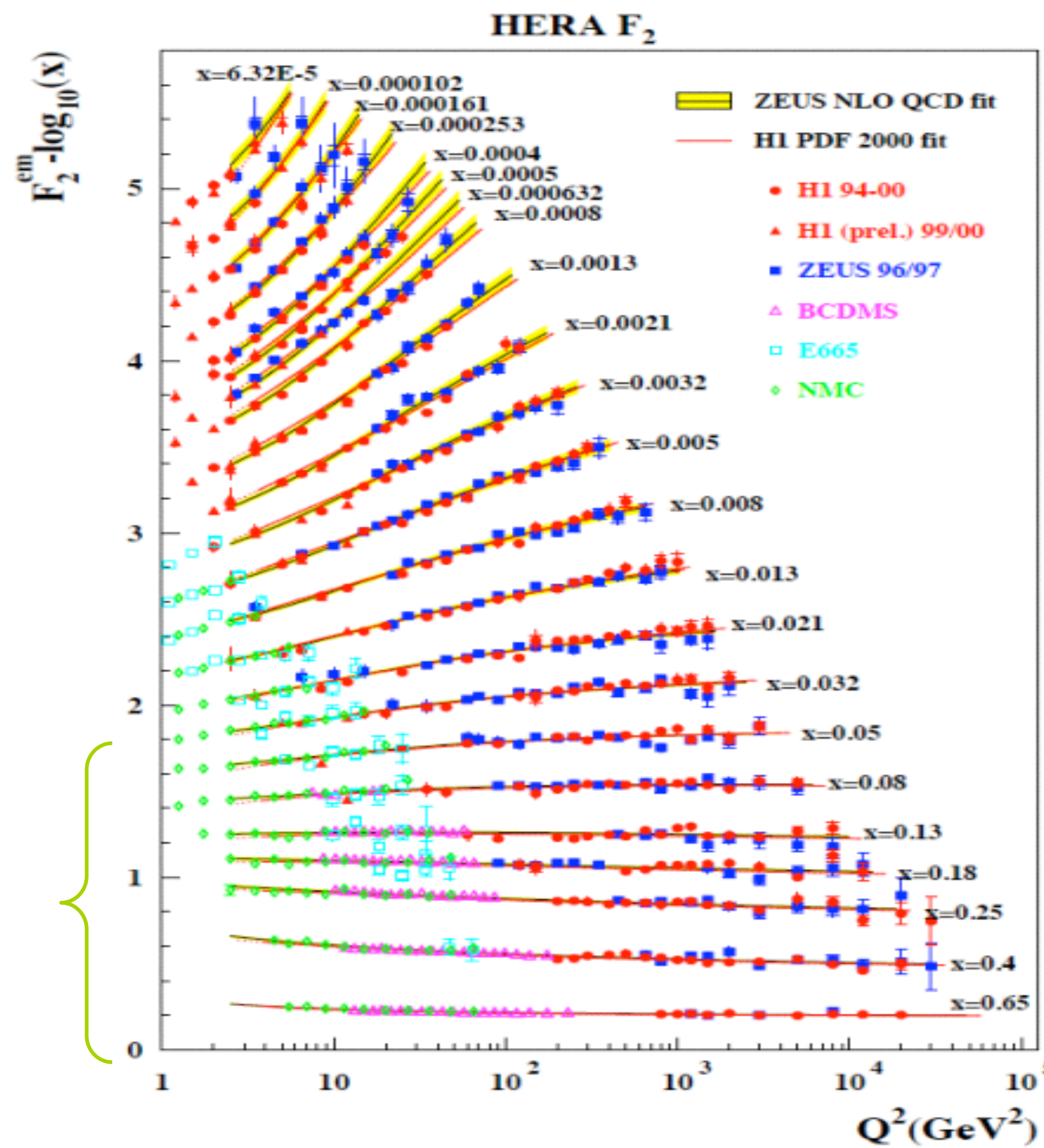
Introduction

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

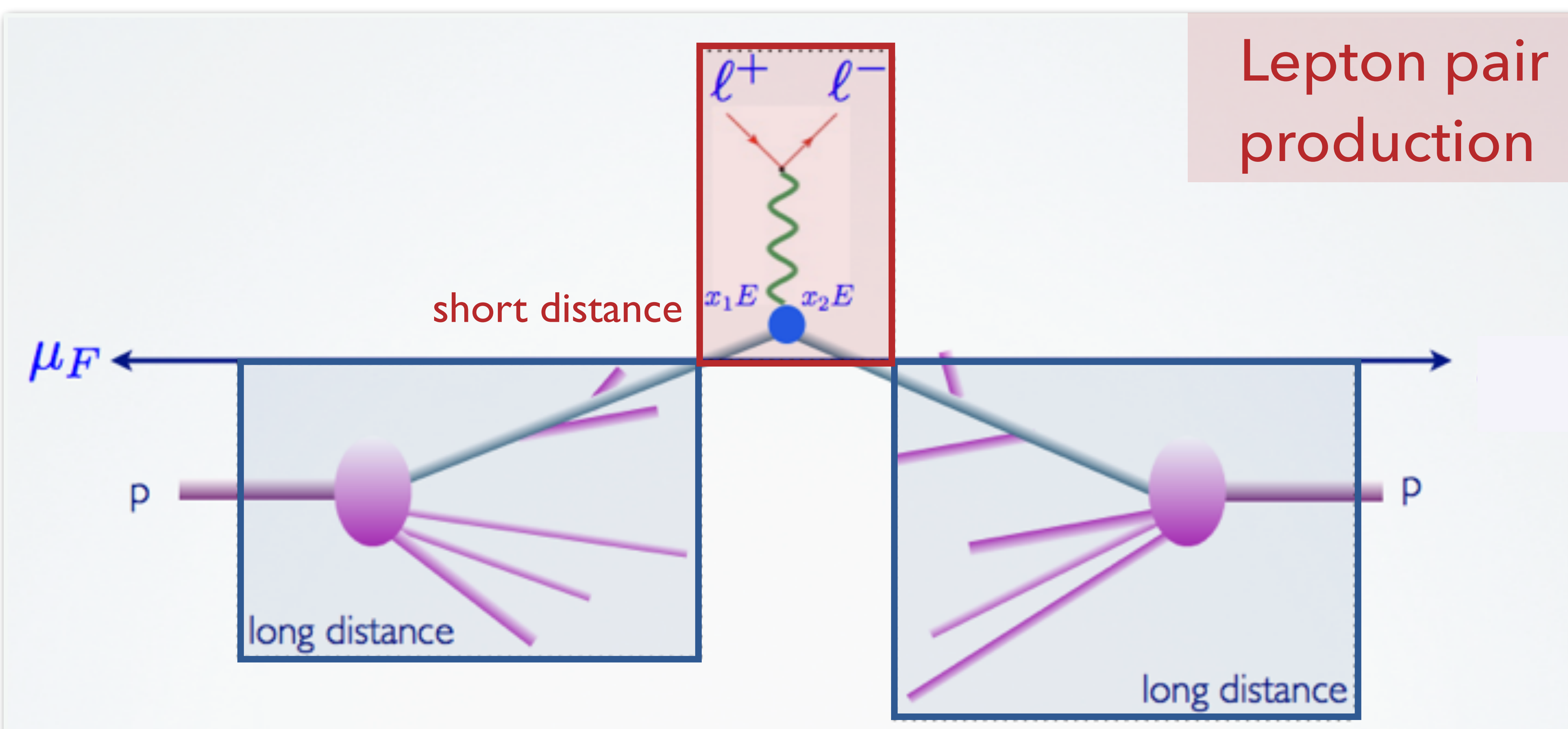




Collinear Factorisation Theorem

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

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



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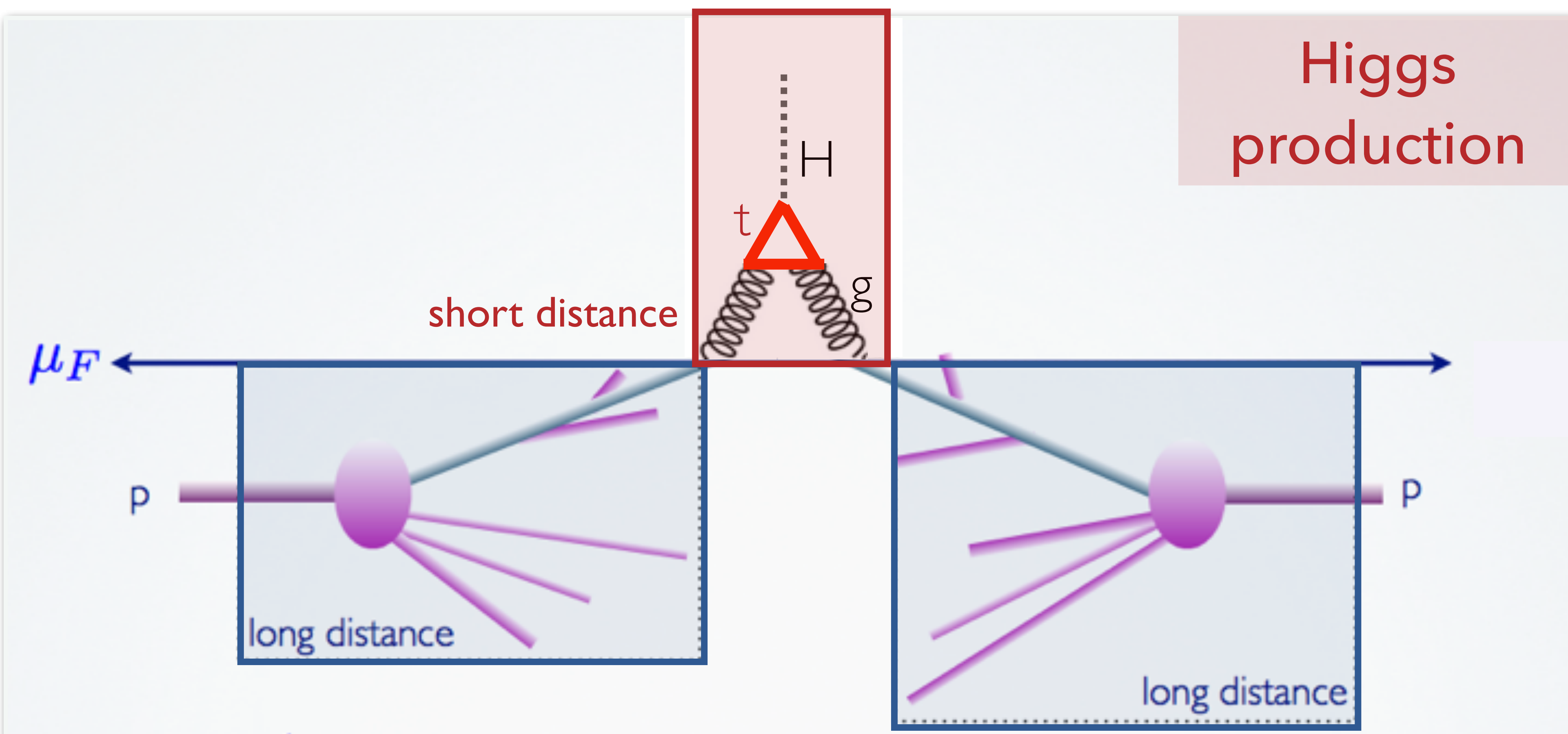

DGLAP evolution equations

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

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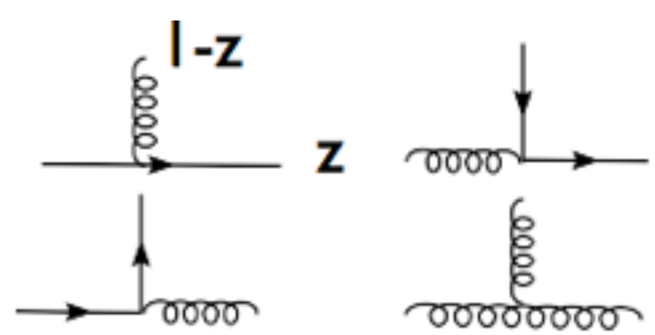
$$\frac{d}{dt}\begin{pmatrix} q_i(x,t) \\ g(x,t)\end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \sum_{j=q,\bar{q}} \frac{d\xi}{\xi}\begin{pmatrix} P_{ij}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{ig}\left(\frac{x}{\xi},\alpha_s(t)\right) \\ P_{gj}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{gg}\left(\frac{x}{\xi},\alpha_s(t)\right)\end{pmatrix}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

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



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

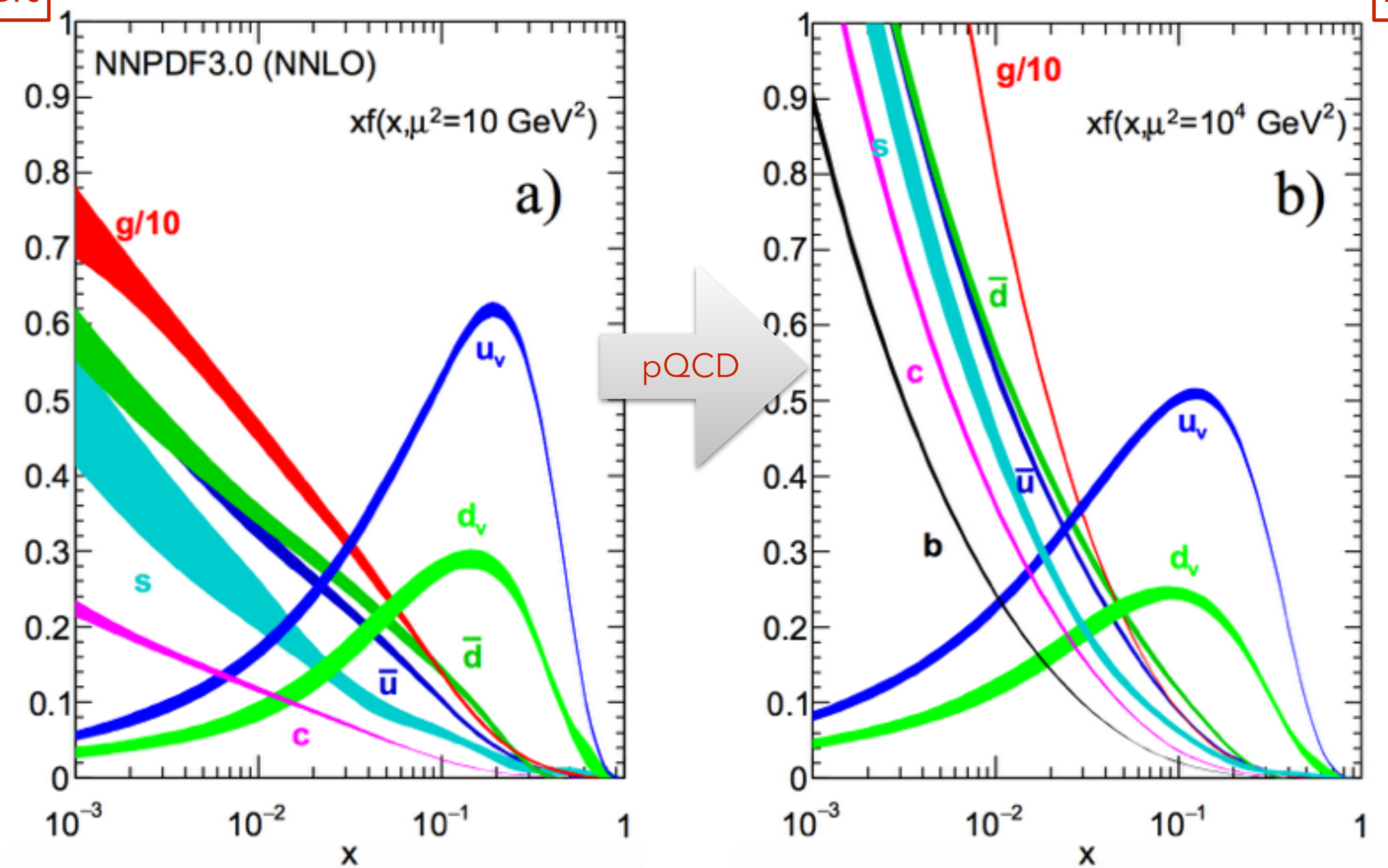
NNLO - Moch, Vermaseren, Vogt, 2004

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

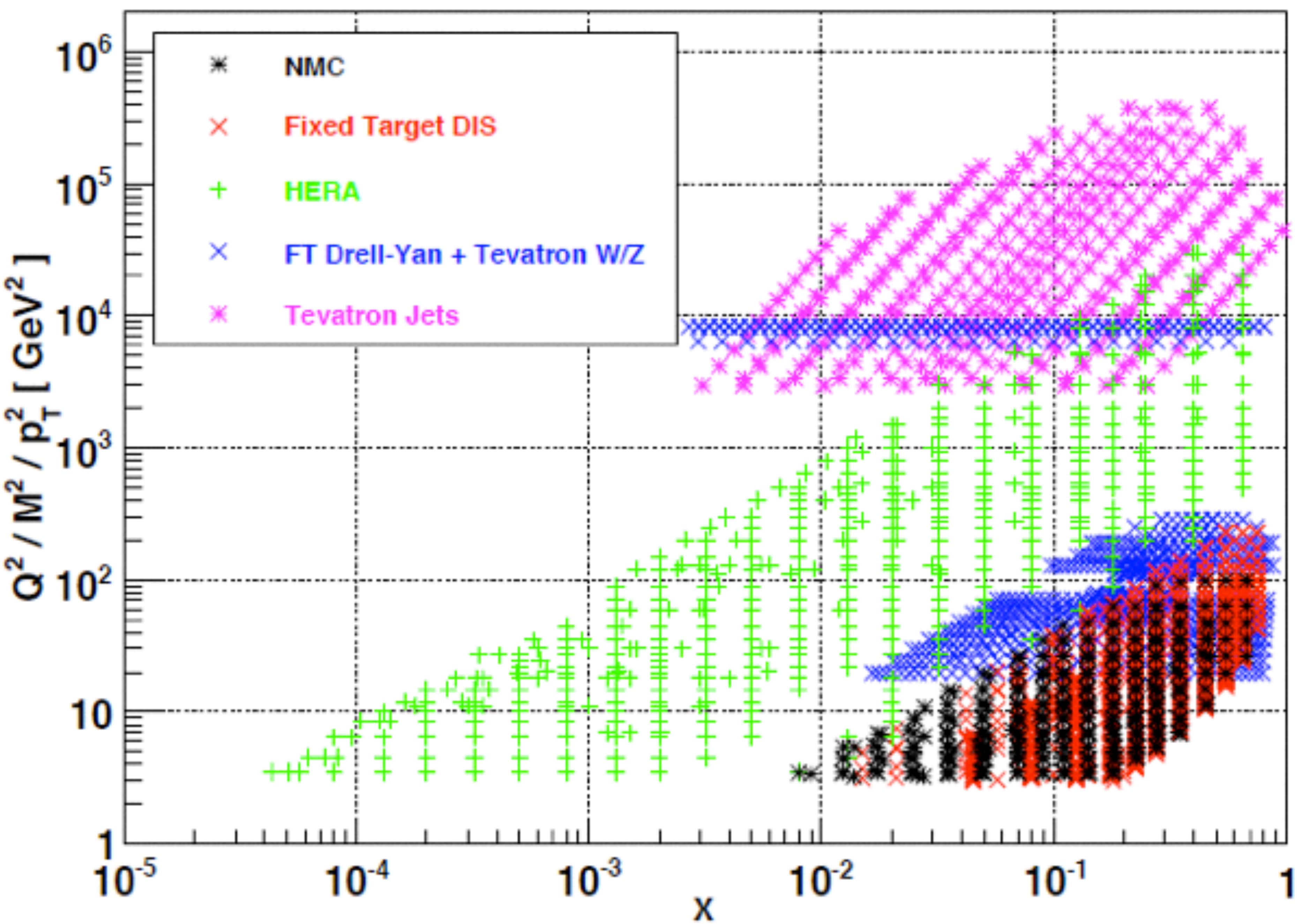
High scale: input to the LHC



PDG 2016

PDF determination

PDF determination



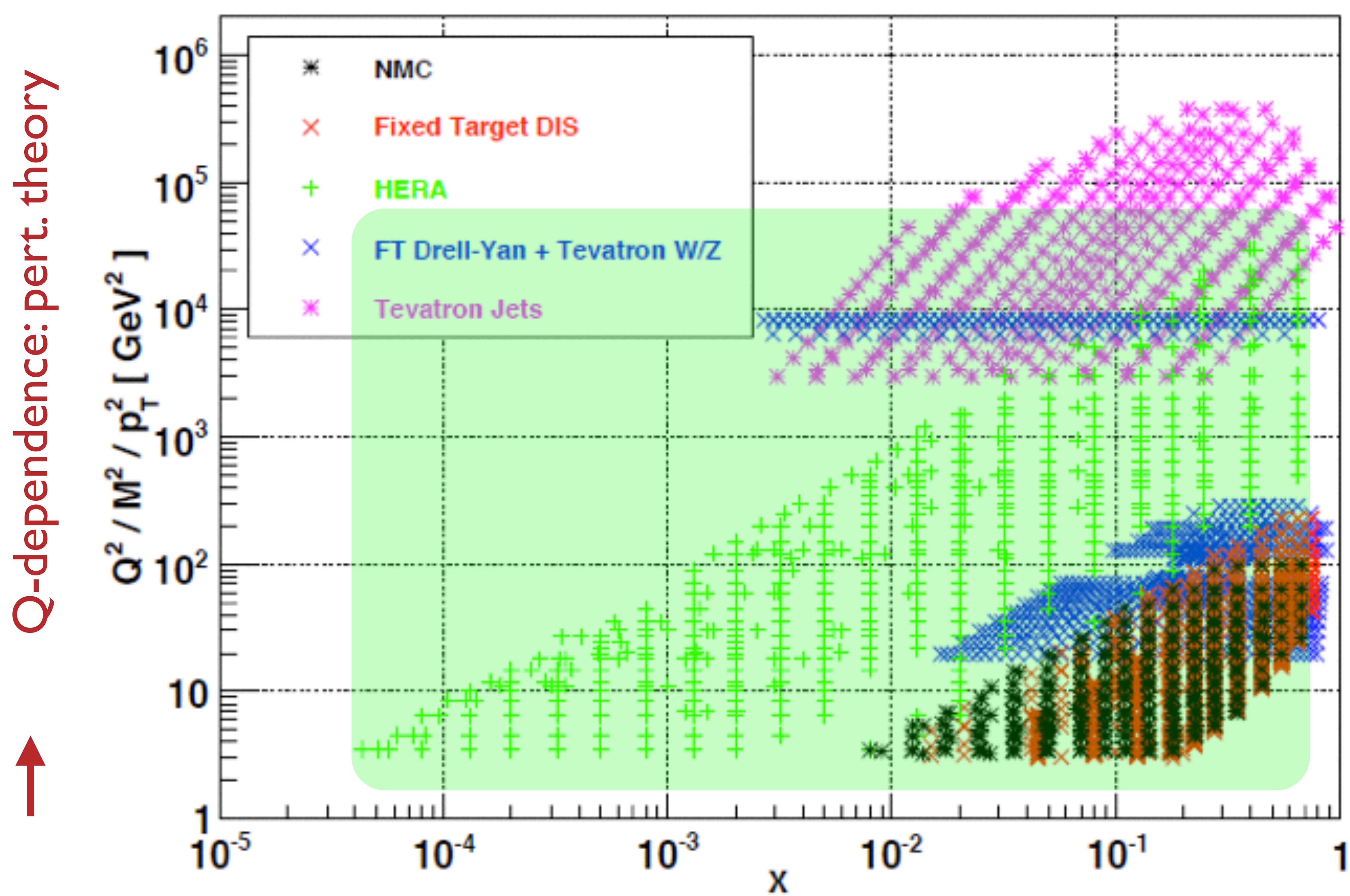
Q-dependence: pert. theory

x-dependence: from data

Different data constrain different PDF combinations in different kinematic regions.

pre-LHC data

PDF determination



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

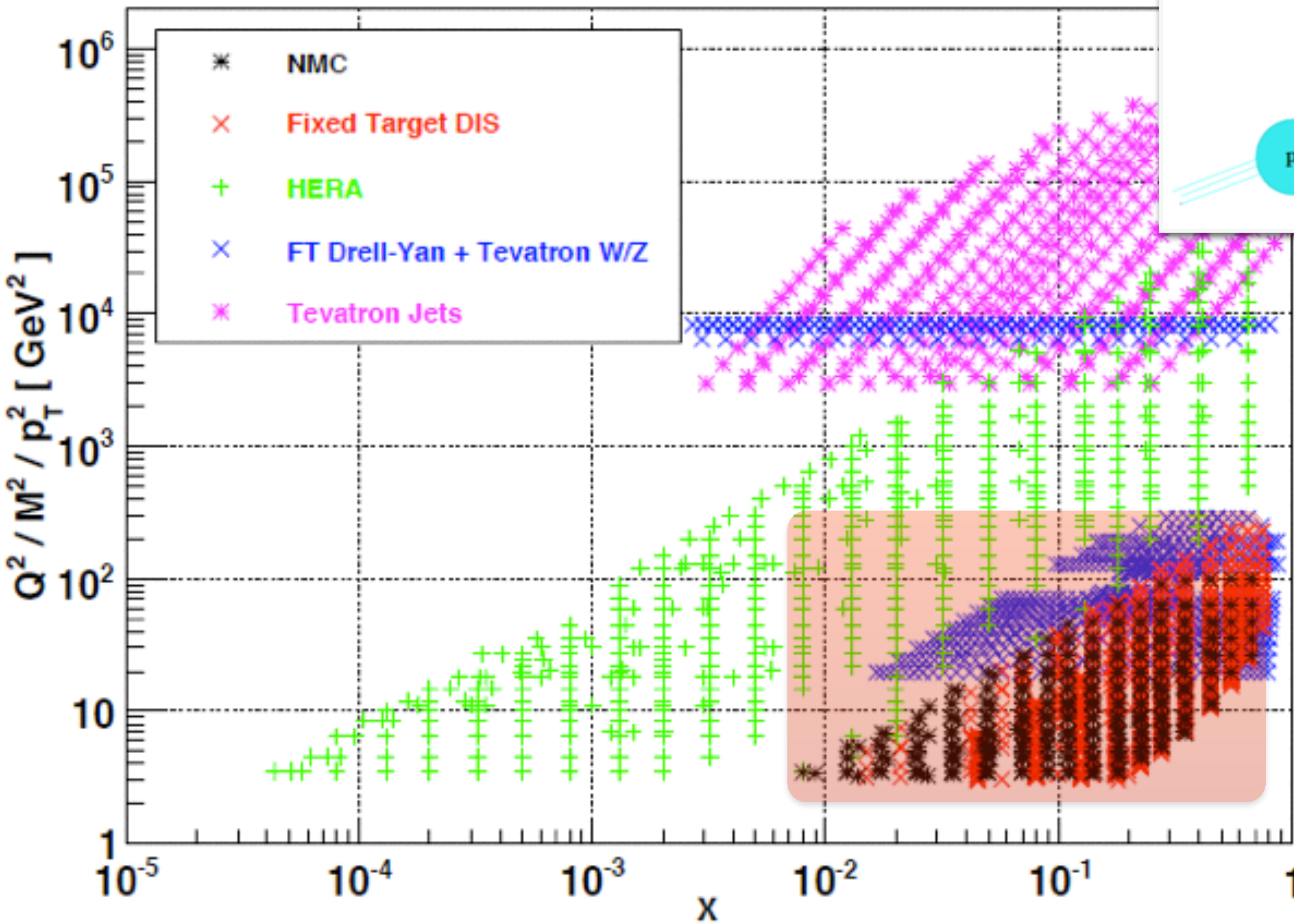
$F_2 = 2xF_1$

$x = x_B$

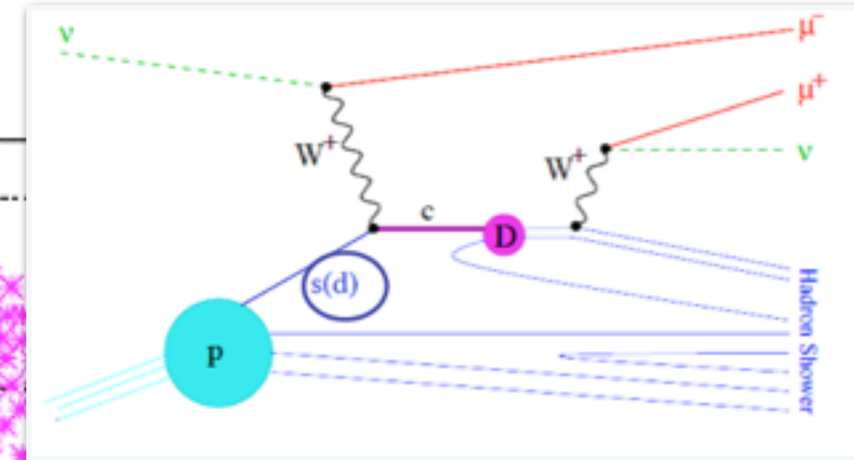
- Backbone of any PDF fit
- Structure functions known up to $O(\alpha_S{}^3$
- Constrain singlet and uv dv combinations
- Constrain g at small and moderate x

x-dependence: from data

PDF determination



x-dependence: from data

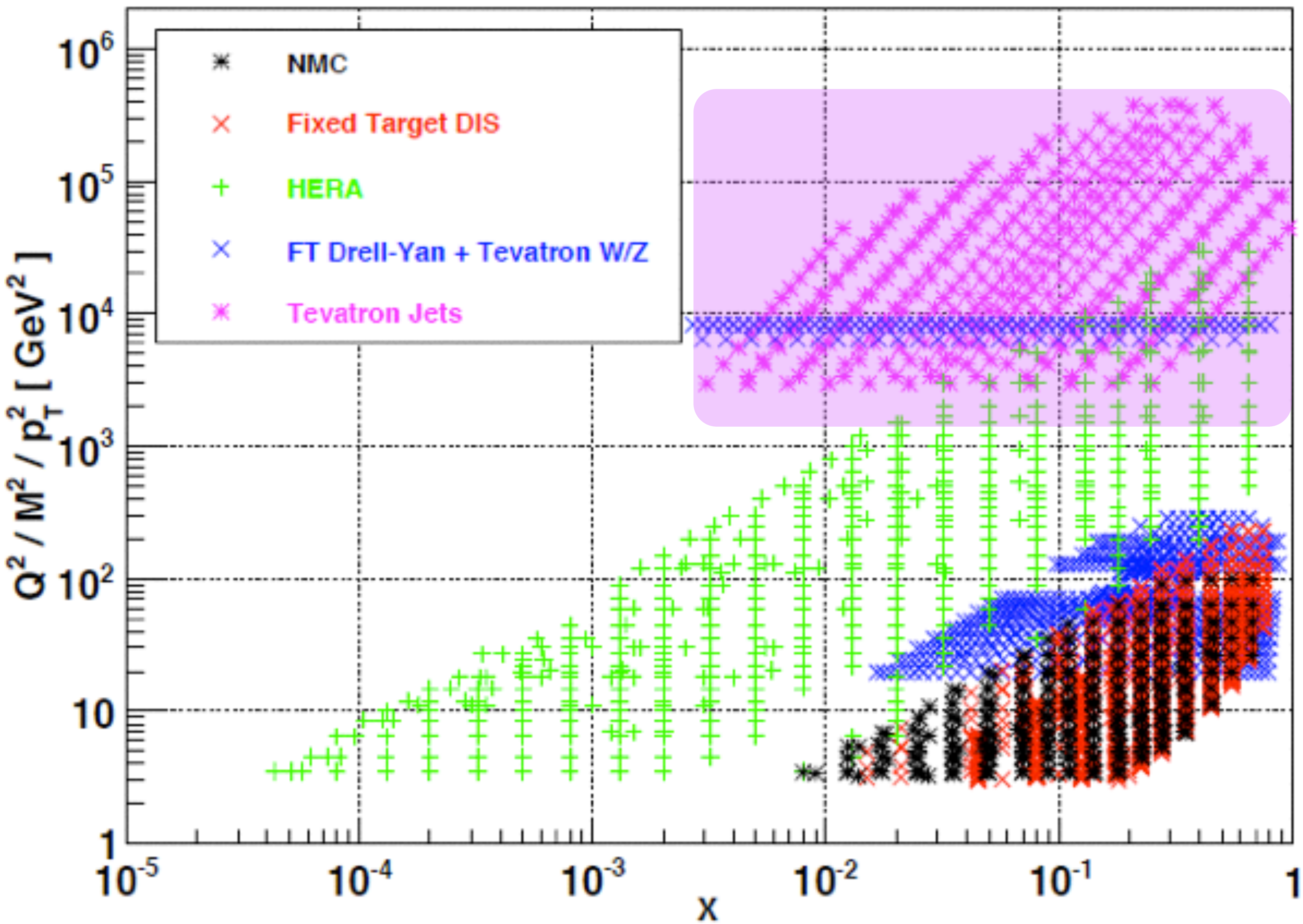


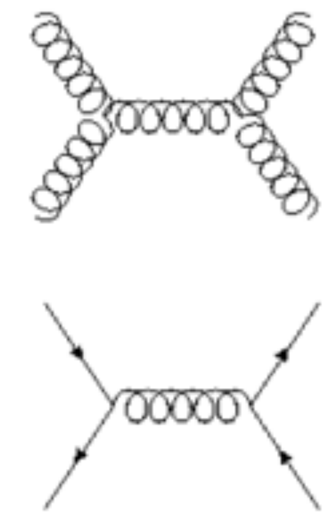
$$x = \frac{Q^2}{2M_n E_\nu y}$$

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

PDF determination

Q-dependence: pert. theory





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

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

x-dependence: from data

LHC data

GLUON

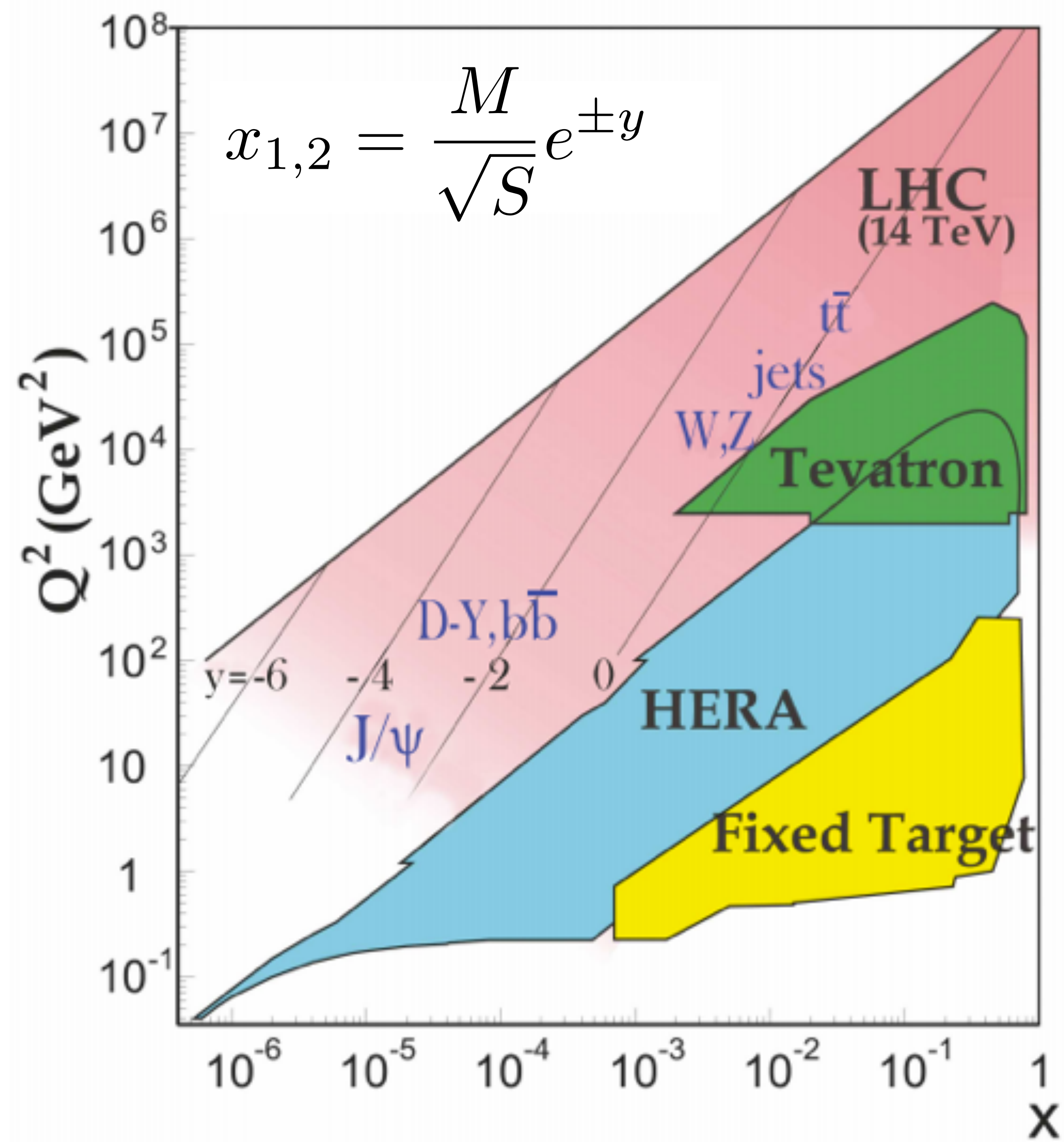
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T V(+jets) distribution **(small/medium x)**

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

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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
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- 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

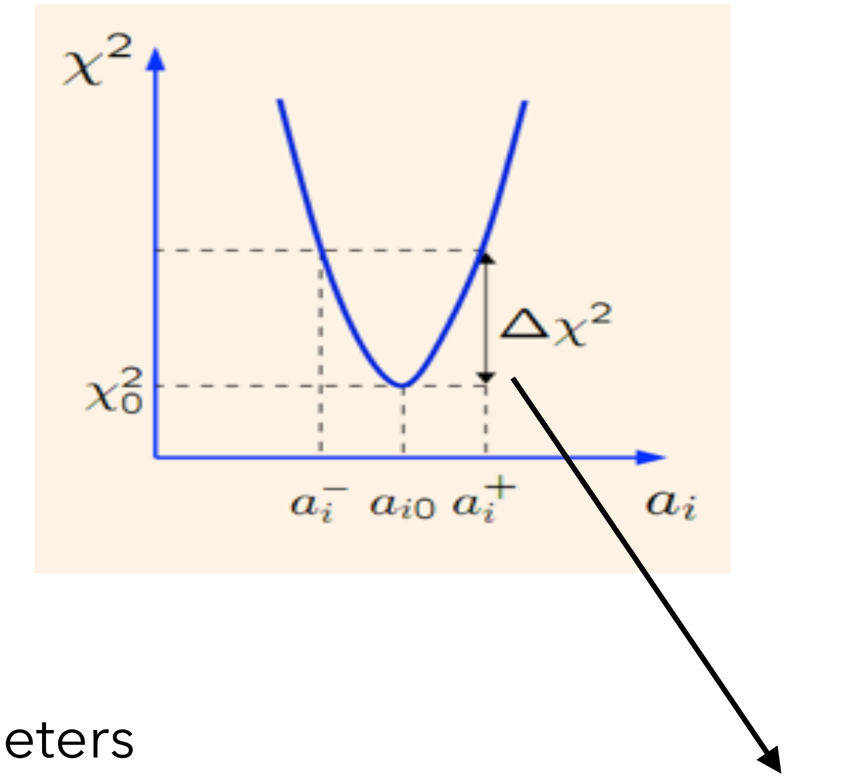
$$\langle \mathcal{O}[\{f\}] \rangle = \int [\mathcal{D}f]\, \mathcal{O}[\{f\}] \mathcal{P}[\{f\}]$$

- 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



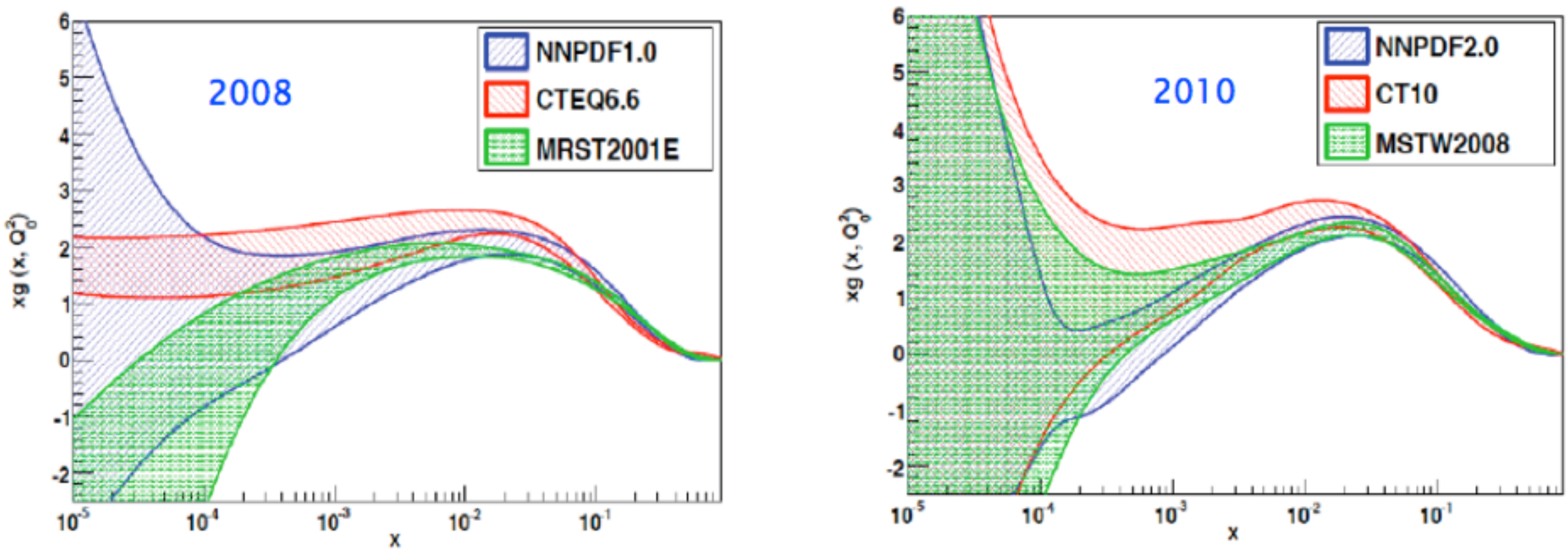
Tolerance

Parametrisation

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

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

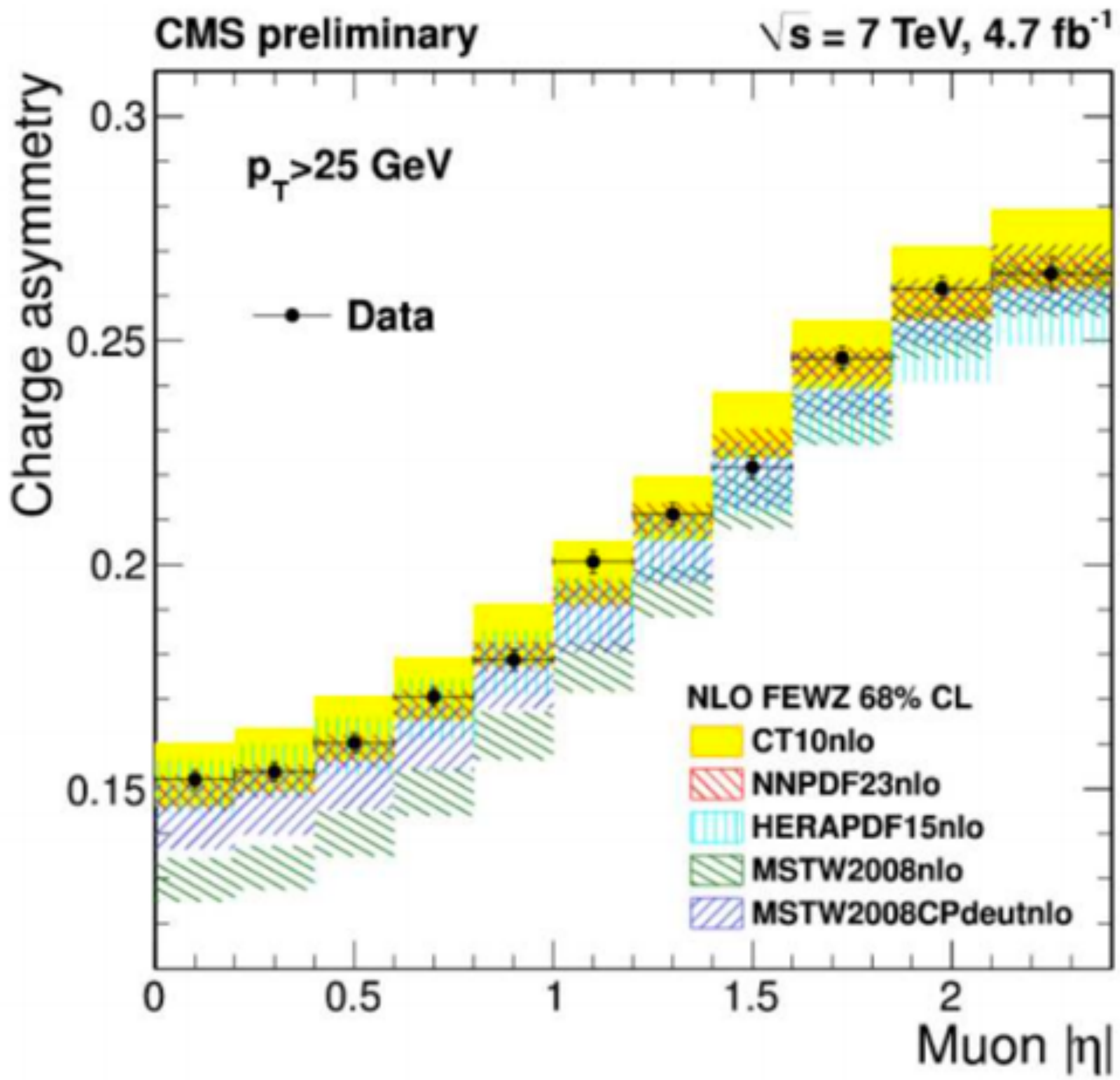
Data-driven progress

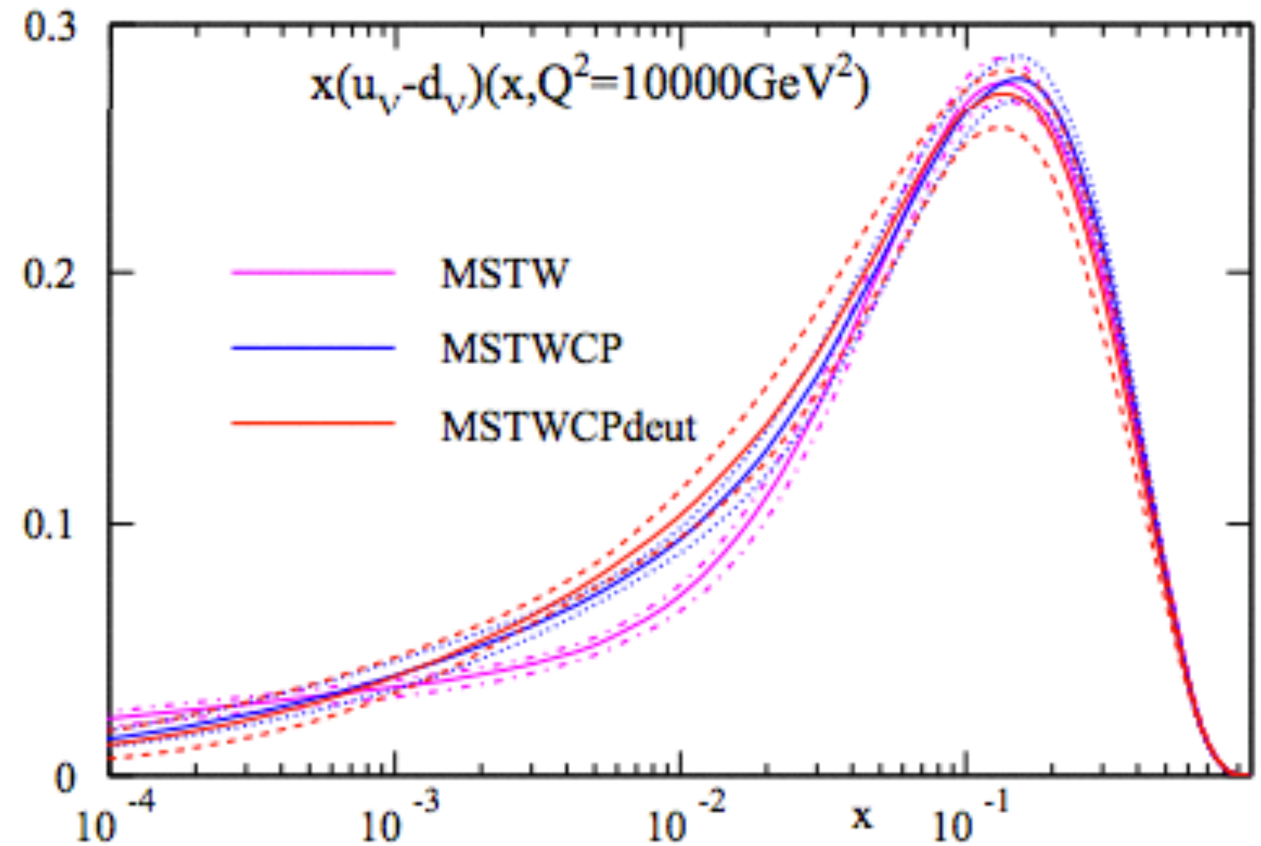


$$xg = A_g\, x^{\delta_g} (1-x)^{\eta_g} (1 + \epsilon_g \sqrt{x} + \gamma_g\, x) + A_{g'}\, x^{\delta_{g'}} (1-x)^{\eta_{g'}}$$

- 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)
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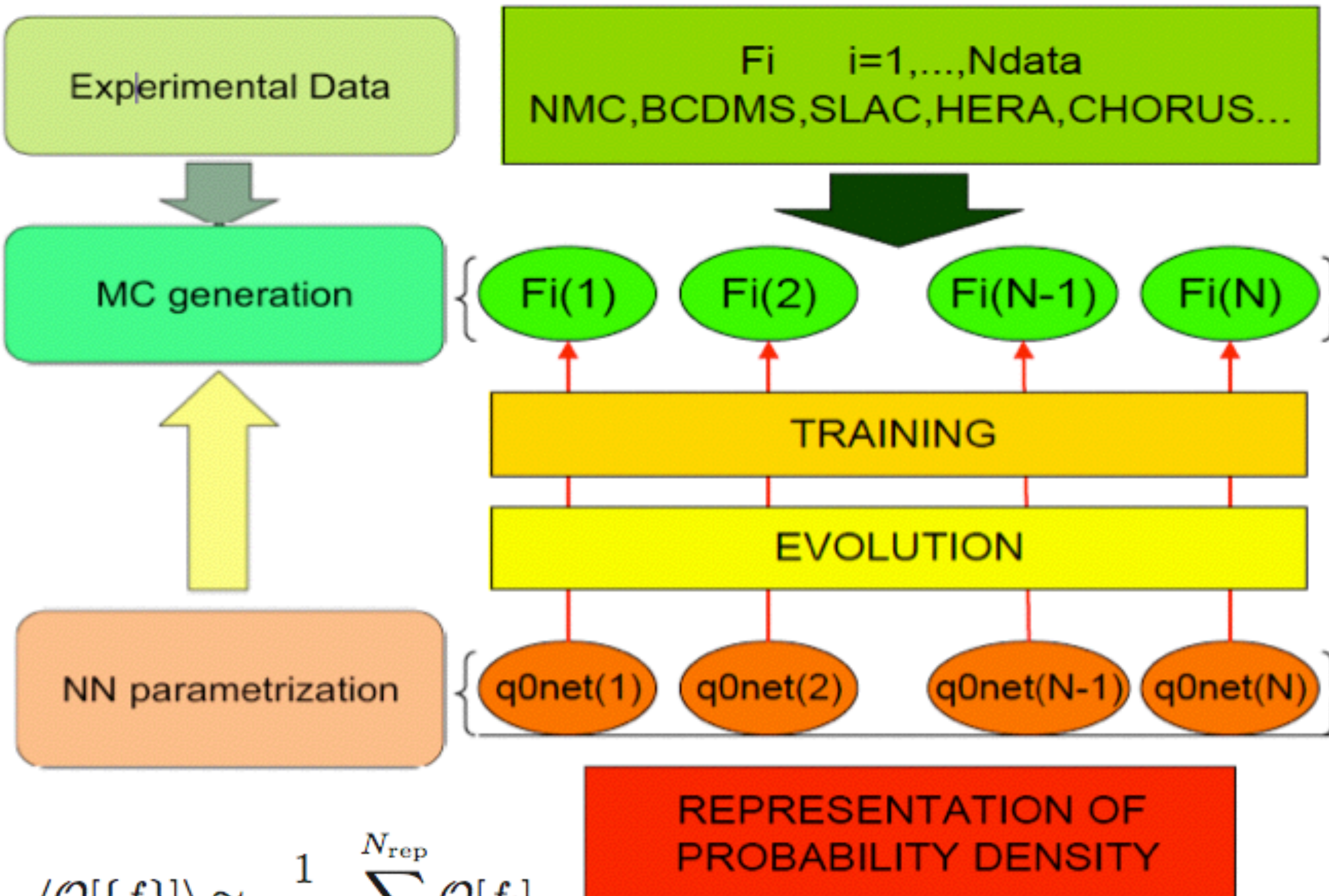
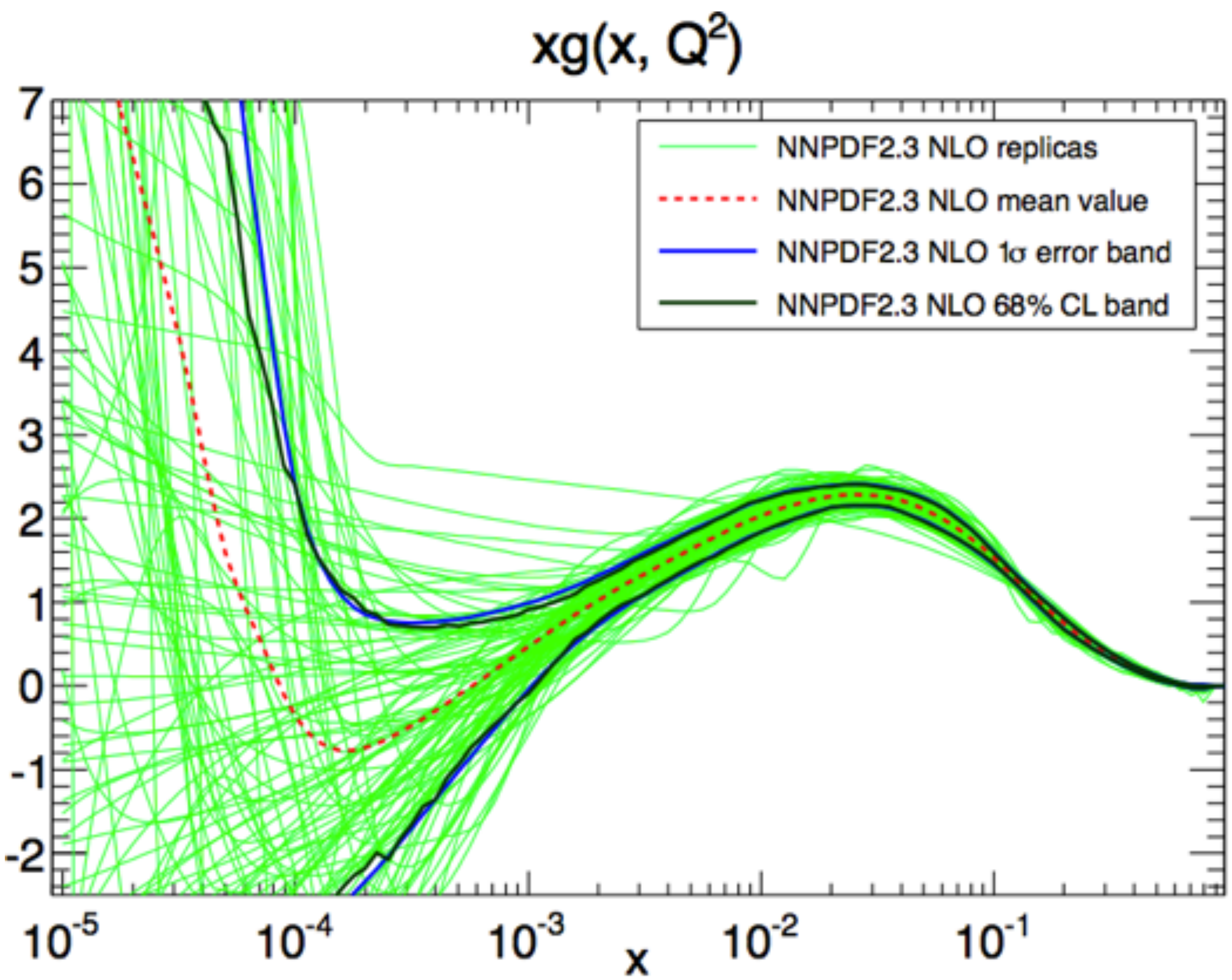
The NNPDF solution



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

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

The NNPDF solution

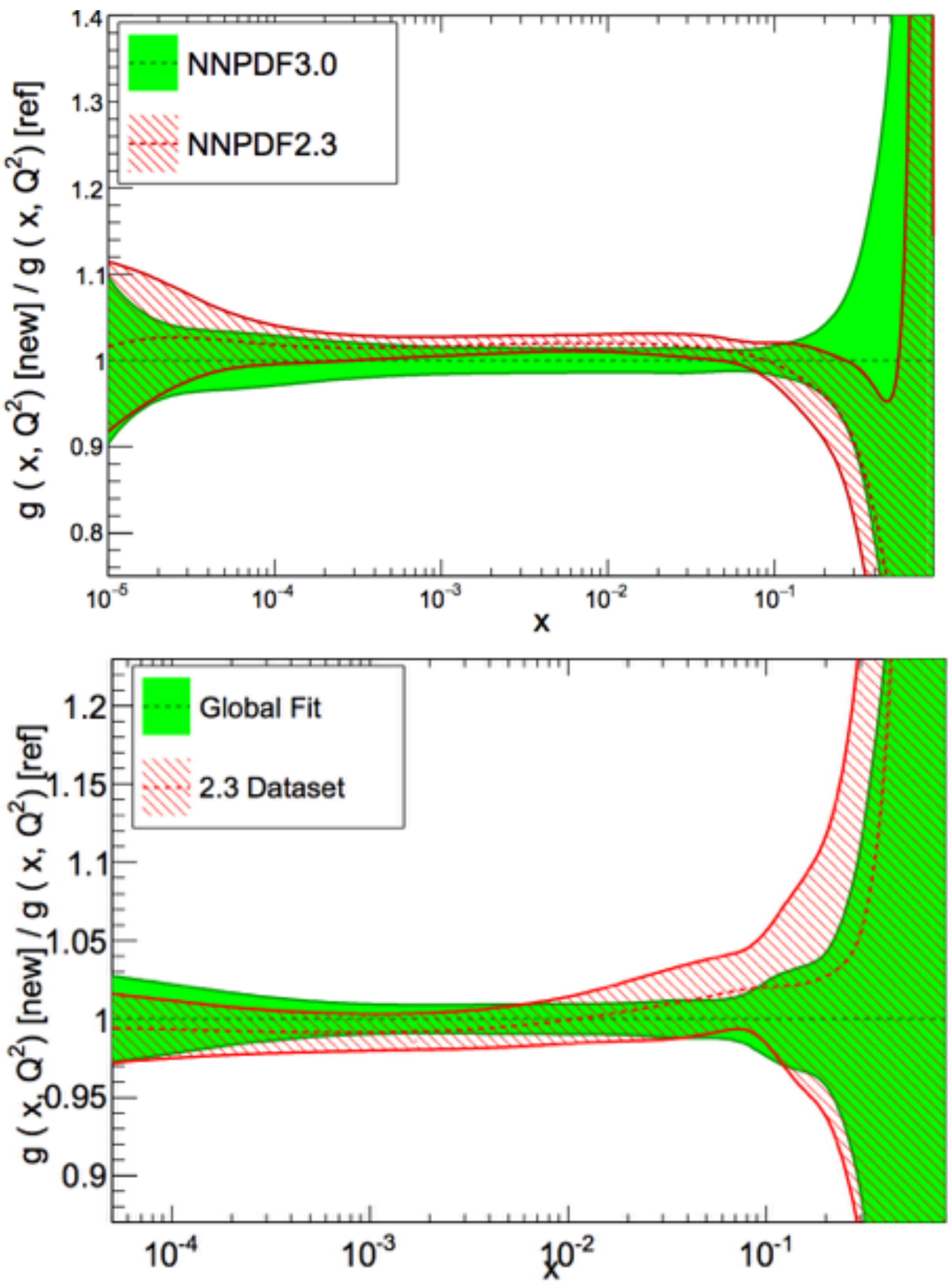


The N(eural)N(etwork)PDFs:

- 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

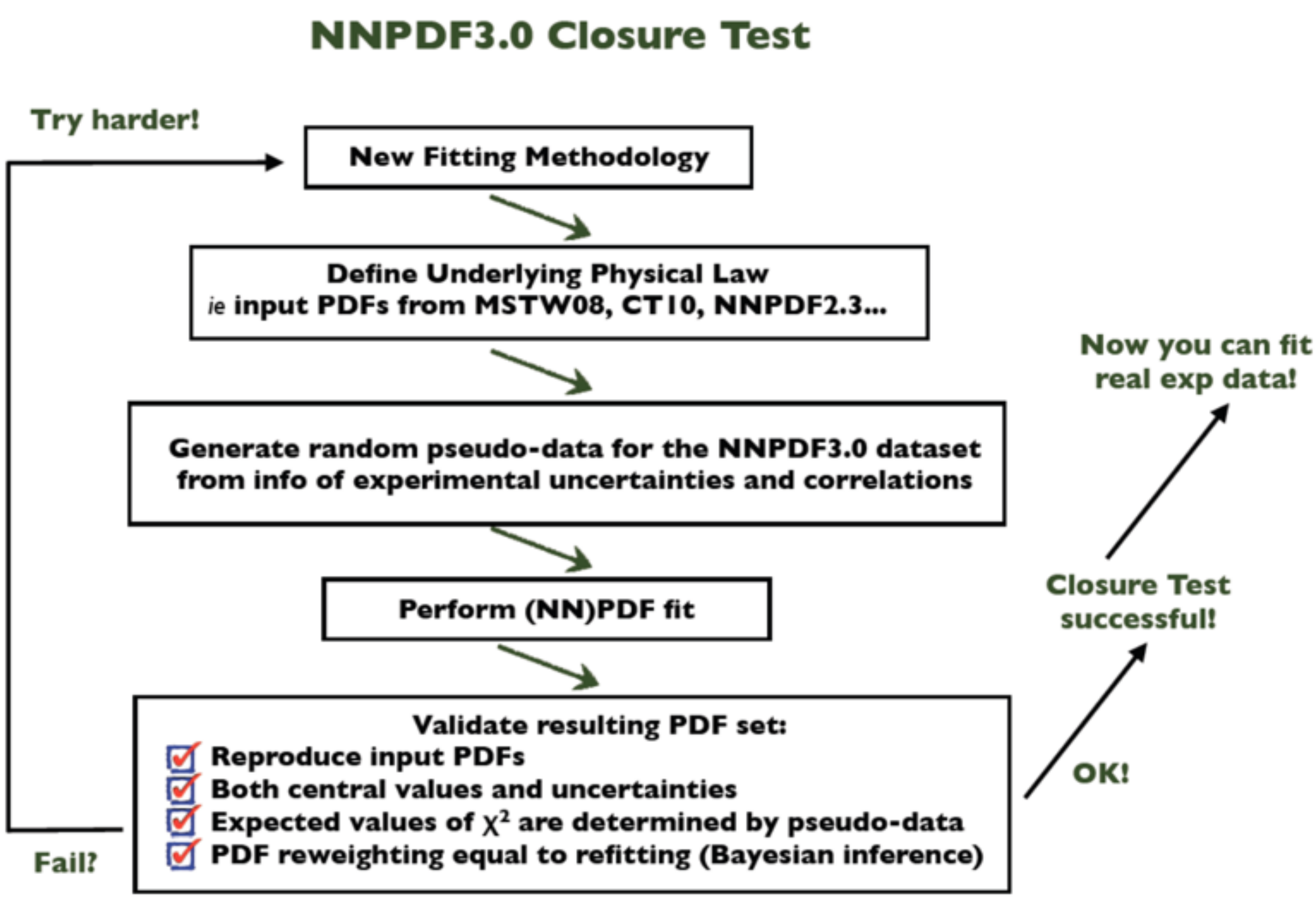
Key issue: methodology



- 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?

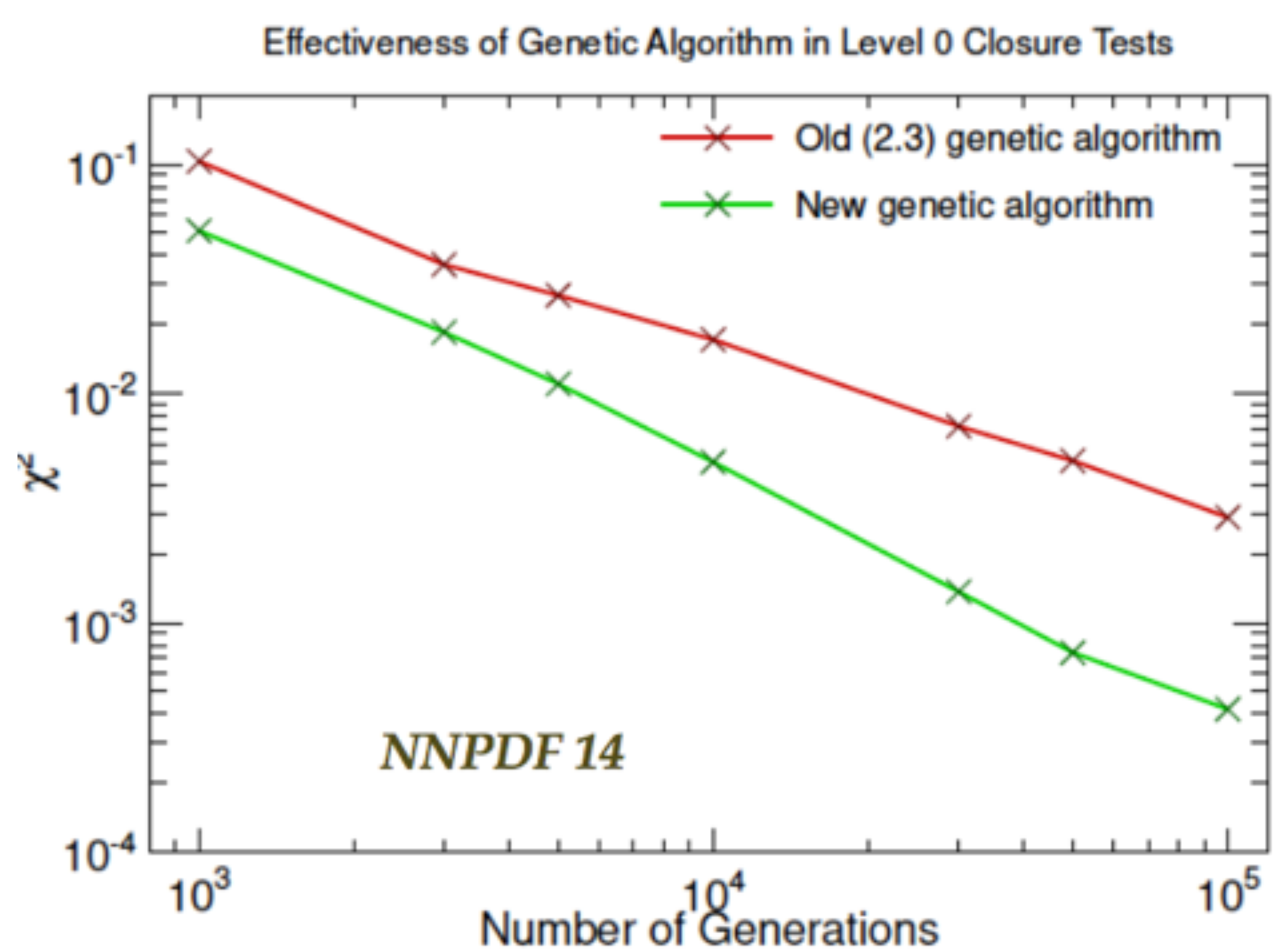
Closure test

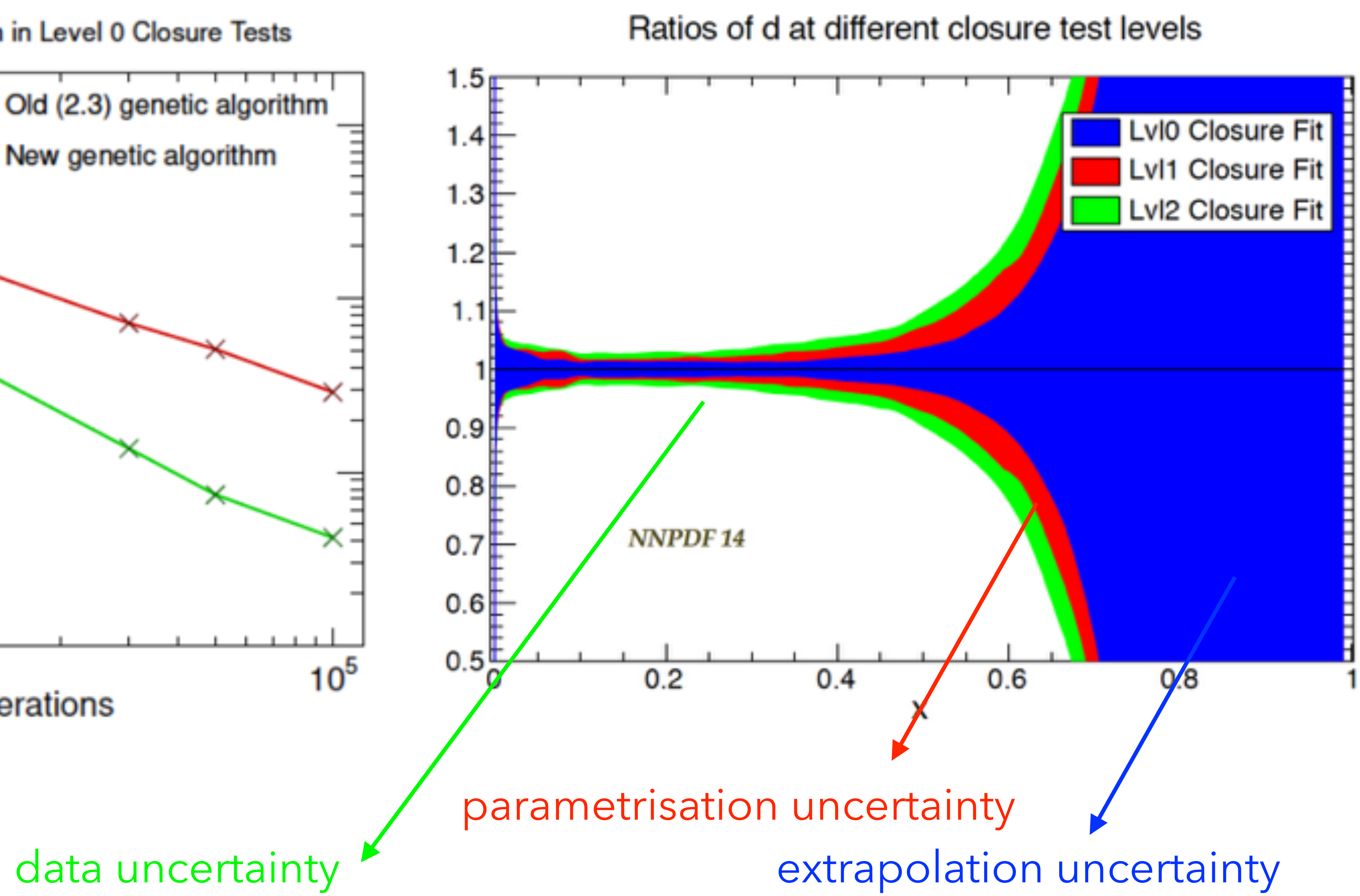
NNPDF collaboration, JHEP 1504 (2015) 040



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 $\chi^2 \to 2$





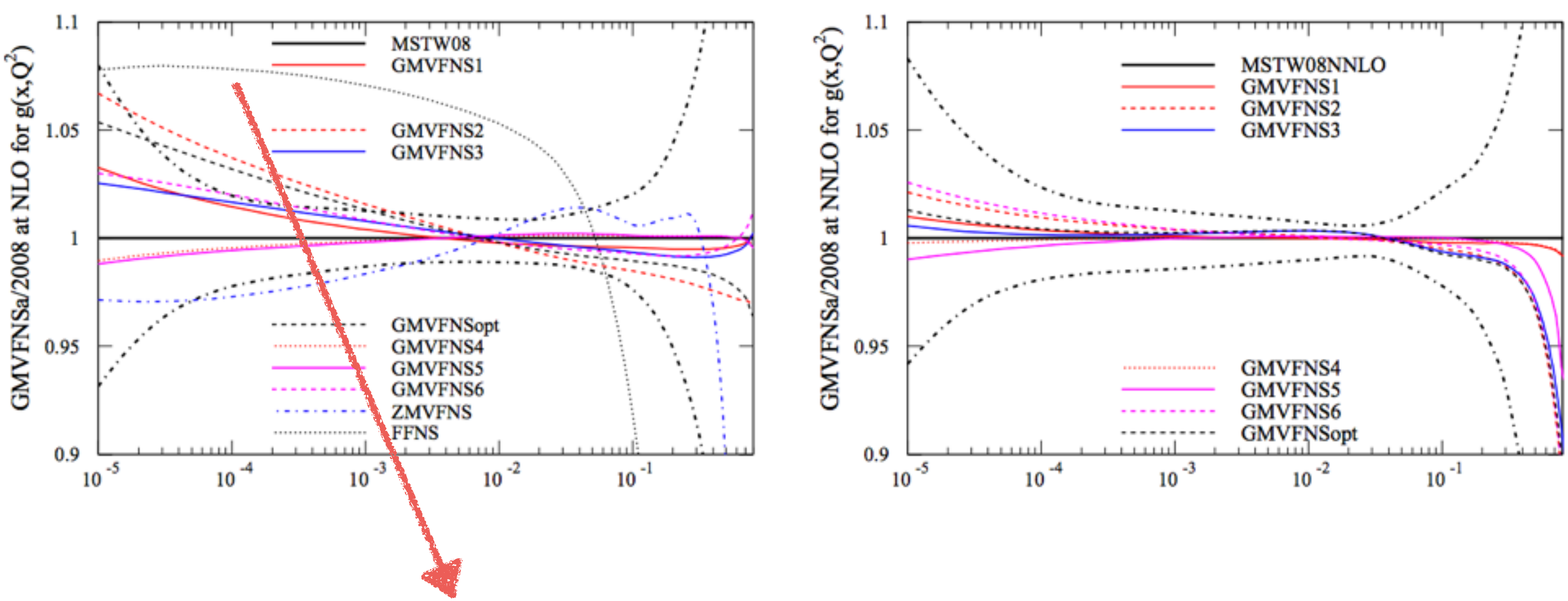
State of the art

The players

September 2016	CT14	MMHT2014	NNPDF3.0	ABM12lhc	HERAPDF15
Fixed Target DIS	✔	✔	✔	✔	✘
HERA	✔	✔	✔	✔	✔
Fixed Target DY	✔	✔	✔	✔	✘
Tevatron W,Z	✔	✔	✔	✔	✘
Tevatron jets	✔	✔	✔	✘	✘
LHC jets	✔	✔	✔	✘	✘
LHC vector boson	✔	✔	✔	✔	✘
LHC top	✘	✘	✔	✔	✘
Stat. treatment	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Monte Carlo	Hessian $\Delta\chi^2=1$	Hessian $\Delta\chi^2=1$
Parametrization	Bernstein (30-35 pars)	Chebyshev (37 pars)	Neural Networks (259 pars)	Polynomial (14 pars)	Polynomial (14 pars)
HQ scheme	ACOT-χ	TR'	FONLL	FFN	TR'
α_S	External	Fitted+external	External	Fitted+External	External

Theory settings

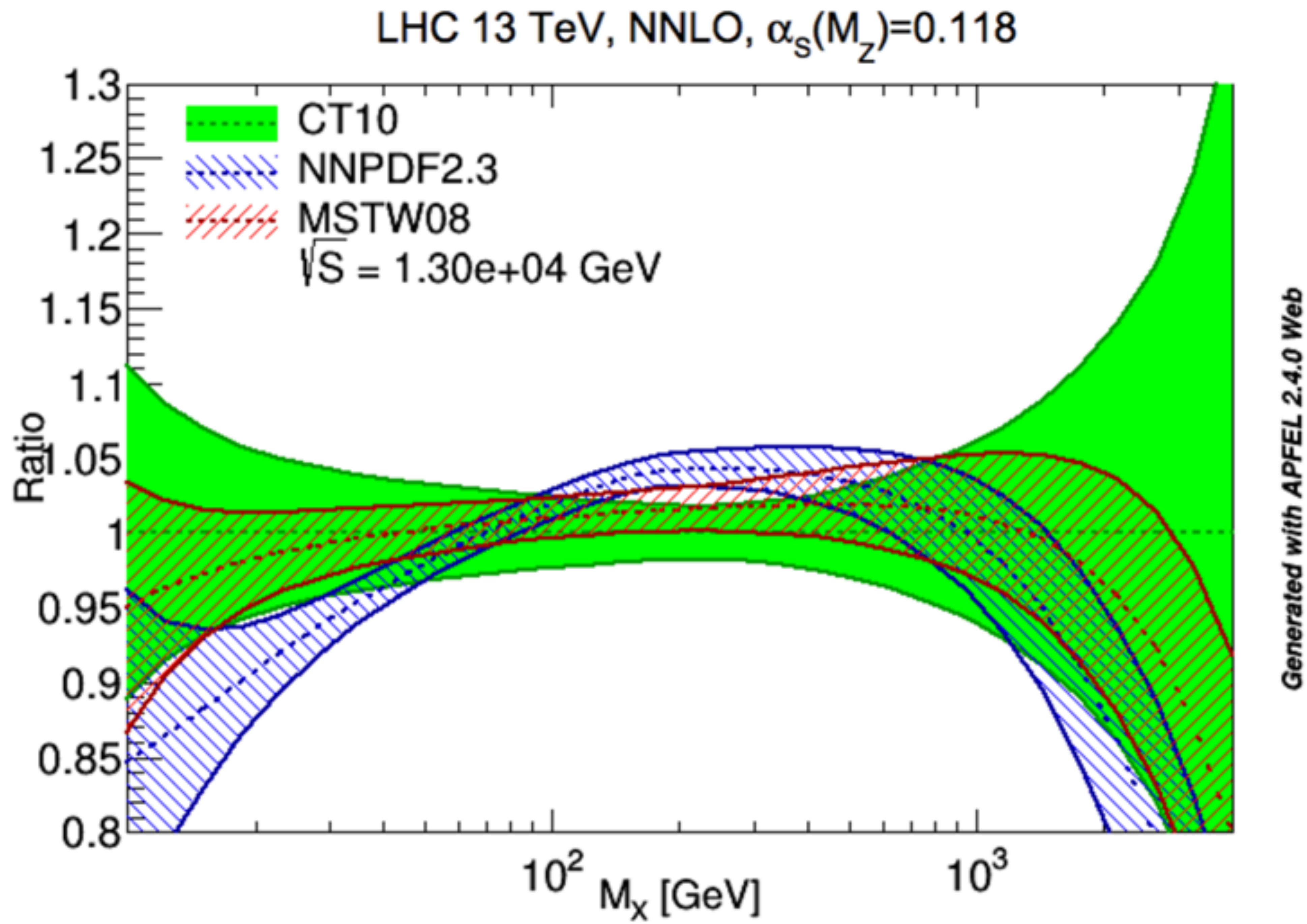
- Comparable GM-VFN schemes for inclusion of HQ masses (sub-leading differences less important at NNLO)
- Common $\alpha_S(M_Z) = 0.118$ (external parameter)
- NNLO (although with some caveat - especially concerning jets data)
- Extensive benchmarking



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

Gluon luminosity

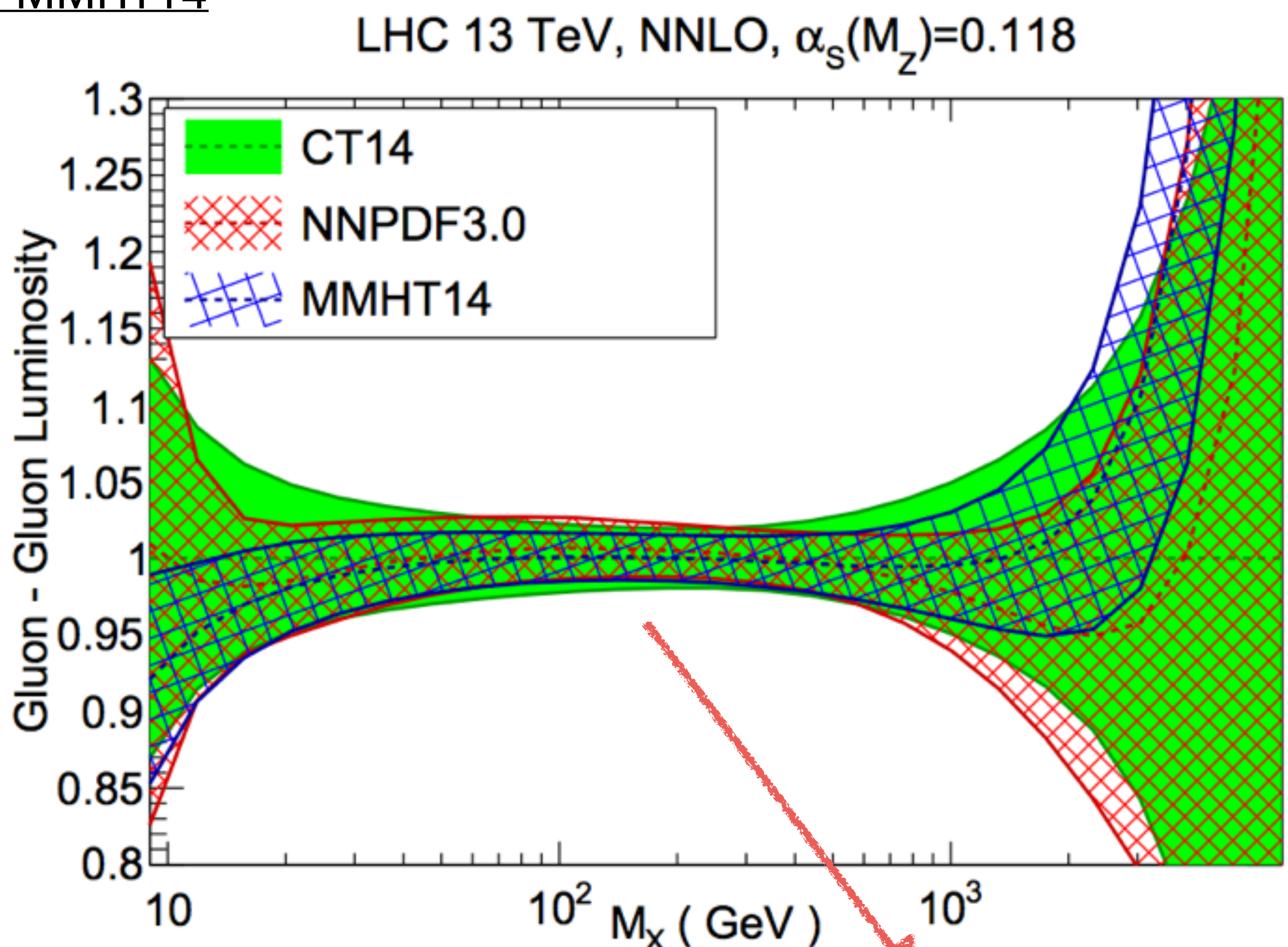
NNPDF2.3 / CT10 / MSTW2008



(2014)

Gluon luminosity

NNPDF3.0 / CT14 / MMHT14

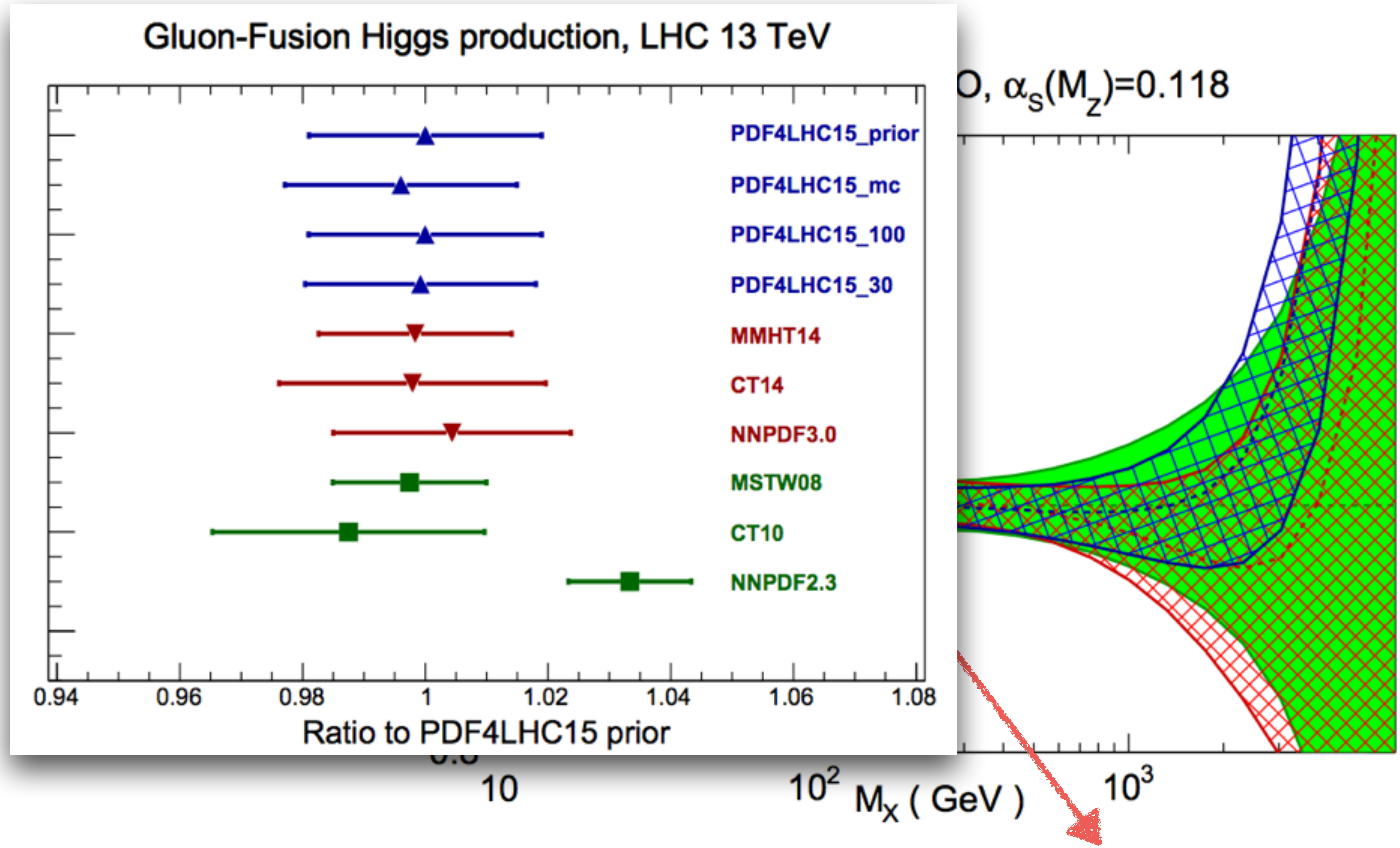


Impact on Higgs physics

(2016)

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

Consequence: Higgs physics

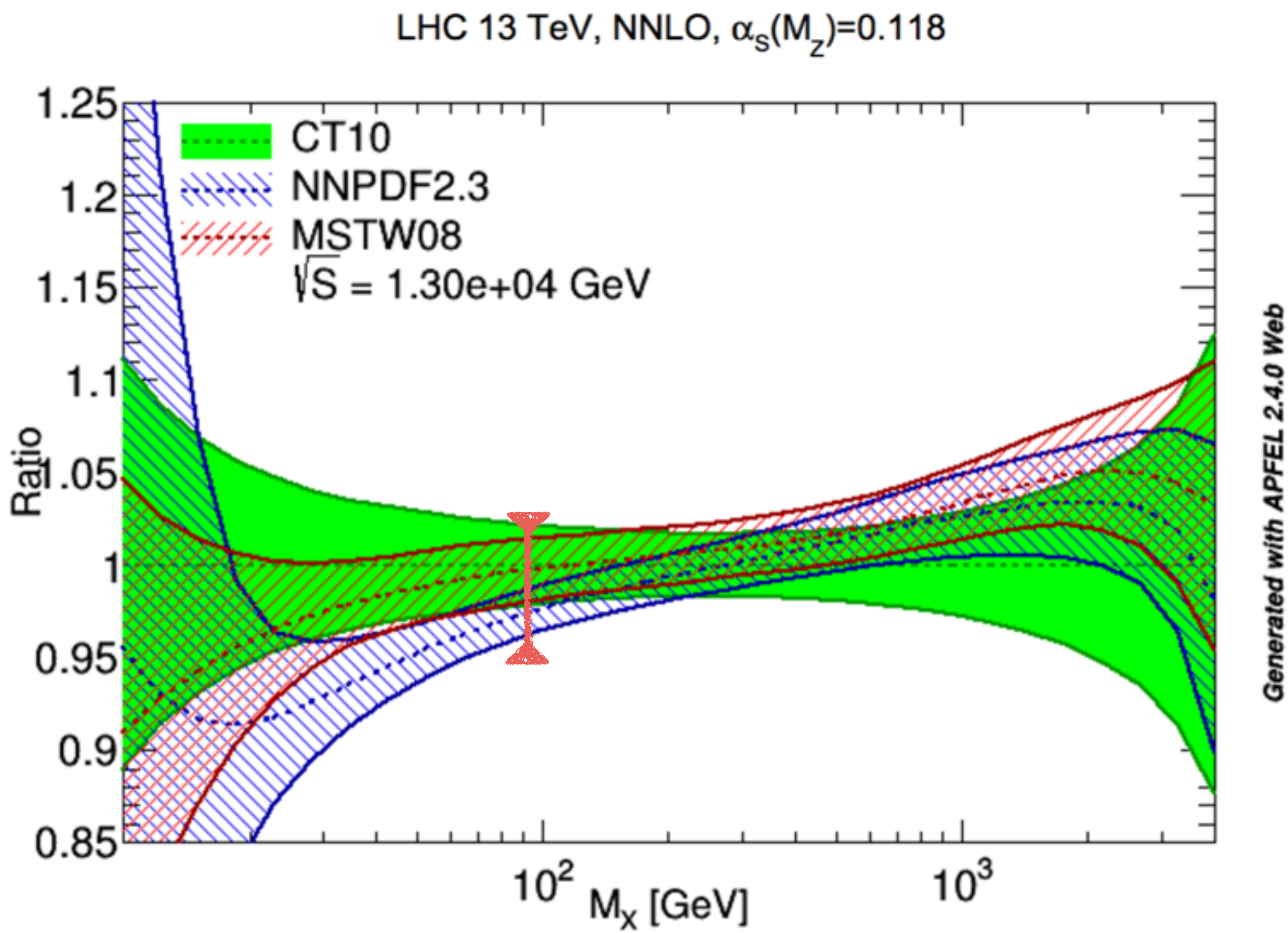


Impact on Higgs physics

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

Quark-Antiquark luminosity

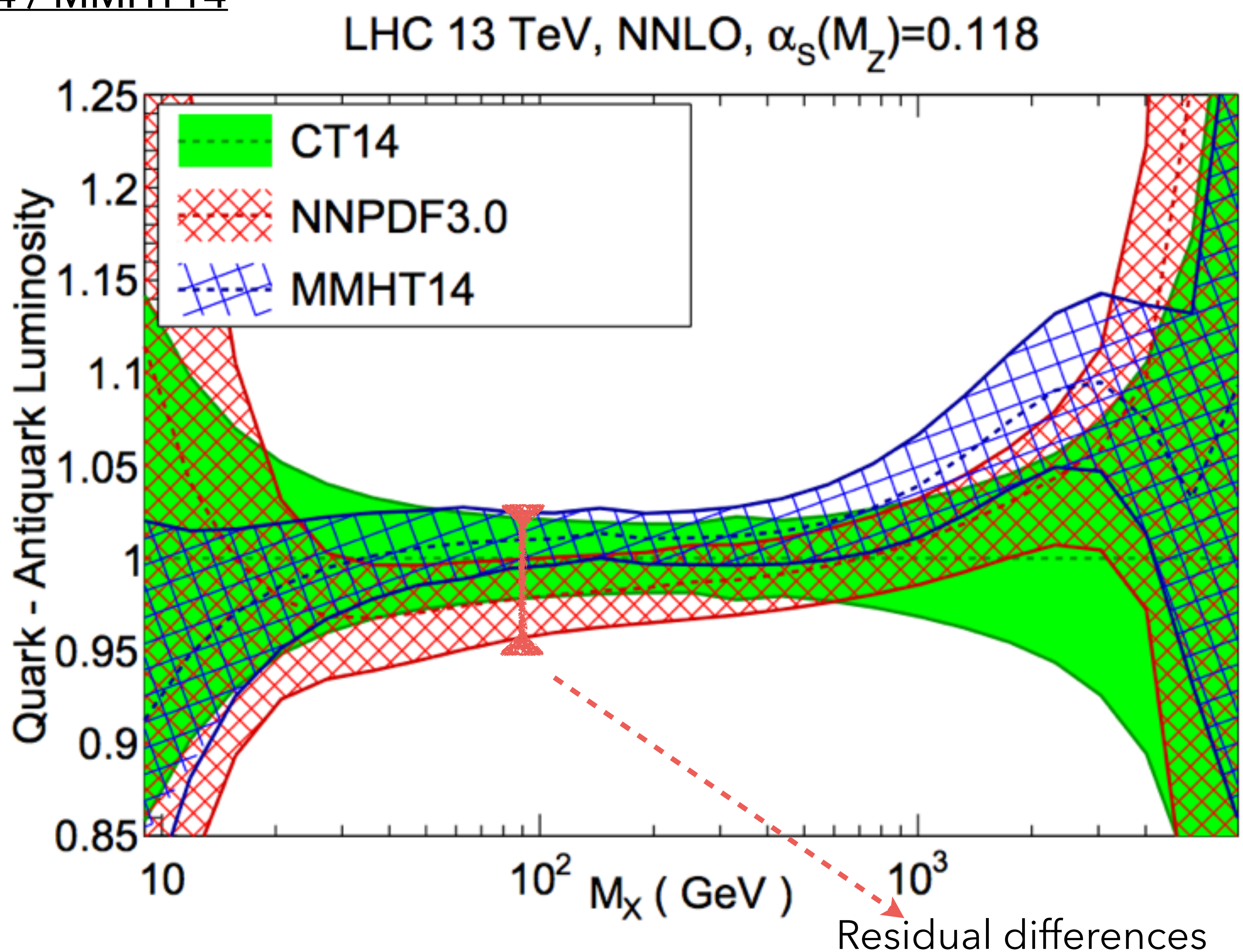
NNPDF2.3 / CT10 / MSTW2008



(2014)

Quark-Antiquark luminosity

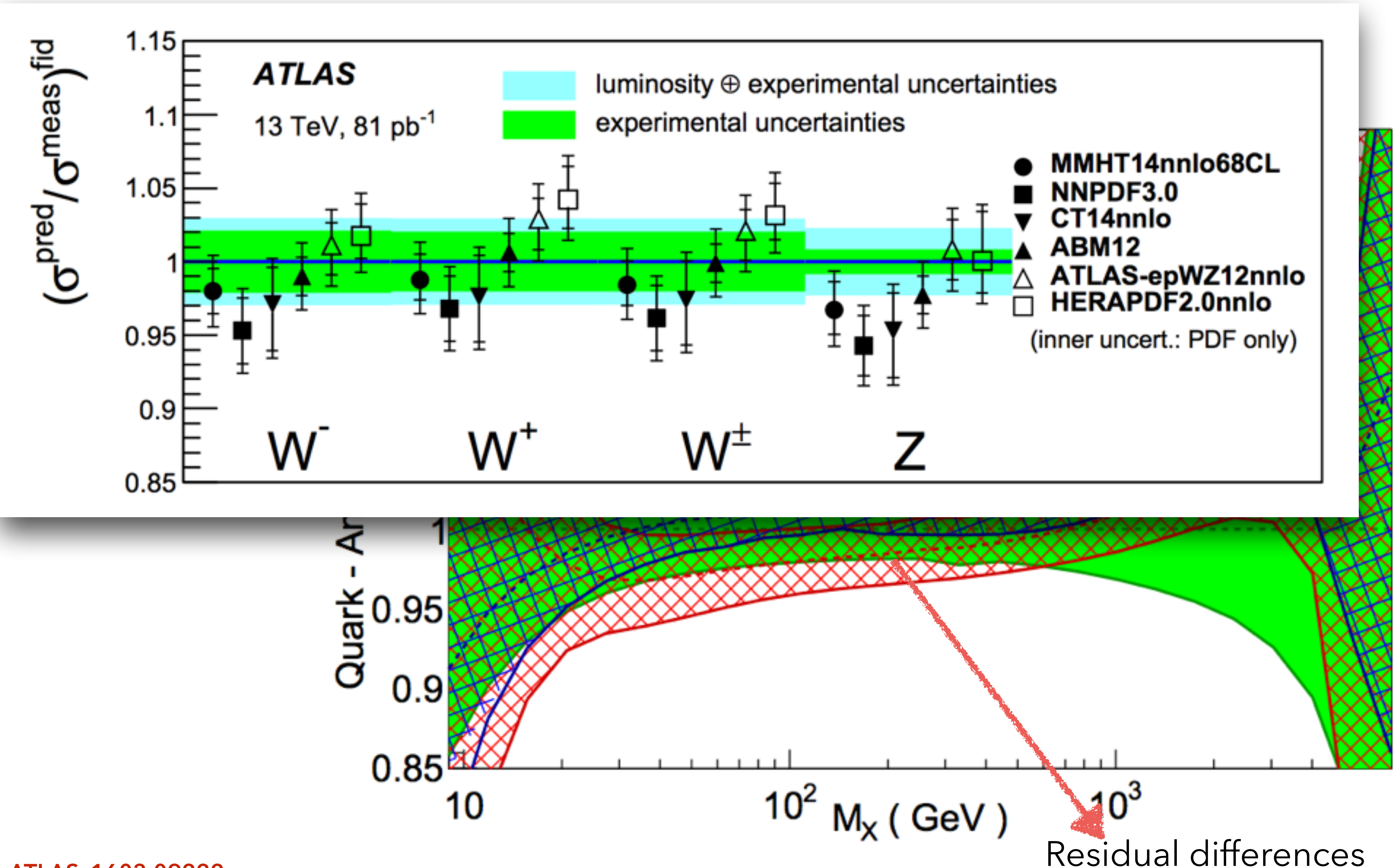
NNPDF3.0 / CT14 / MMHT14



(2016)

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

Quark-Antiquark luminosity



ATLAS, 1603.09222

Frontiers

i - New data from the LHC

NNPDF3.1

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 **+ ATLAS & CMS double diff Z pT**	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 (legacy data)**	small/large x quarks
ATLAS+CMS tt total xsec at 7/8 TeV **+ differ. distributions**	gluon large x
D0 legacy W asymmetry data	q/q~ separation

The NNLO frontier

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses
- Stunning progress has been made on some key processes for PDF determination

✓ NNLO top pair production
  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. [1611.01460]
  Gehrmann-De Ridder et al [PRL 110 (2016)
  Currie et al [JHEP 1401 (2014) 110]

The NNLO frontier

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses
- Stunning progress has been made on some key processes for PDF determination
- Great progress also in tools to interface NLO (NNLO?) codes to PDF fitting code

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

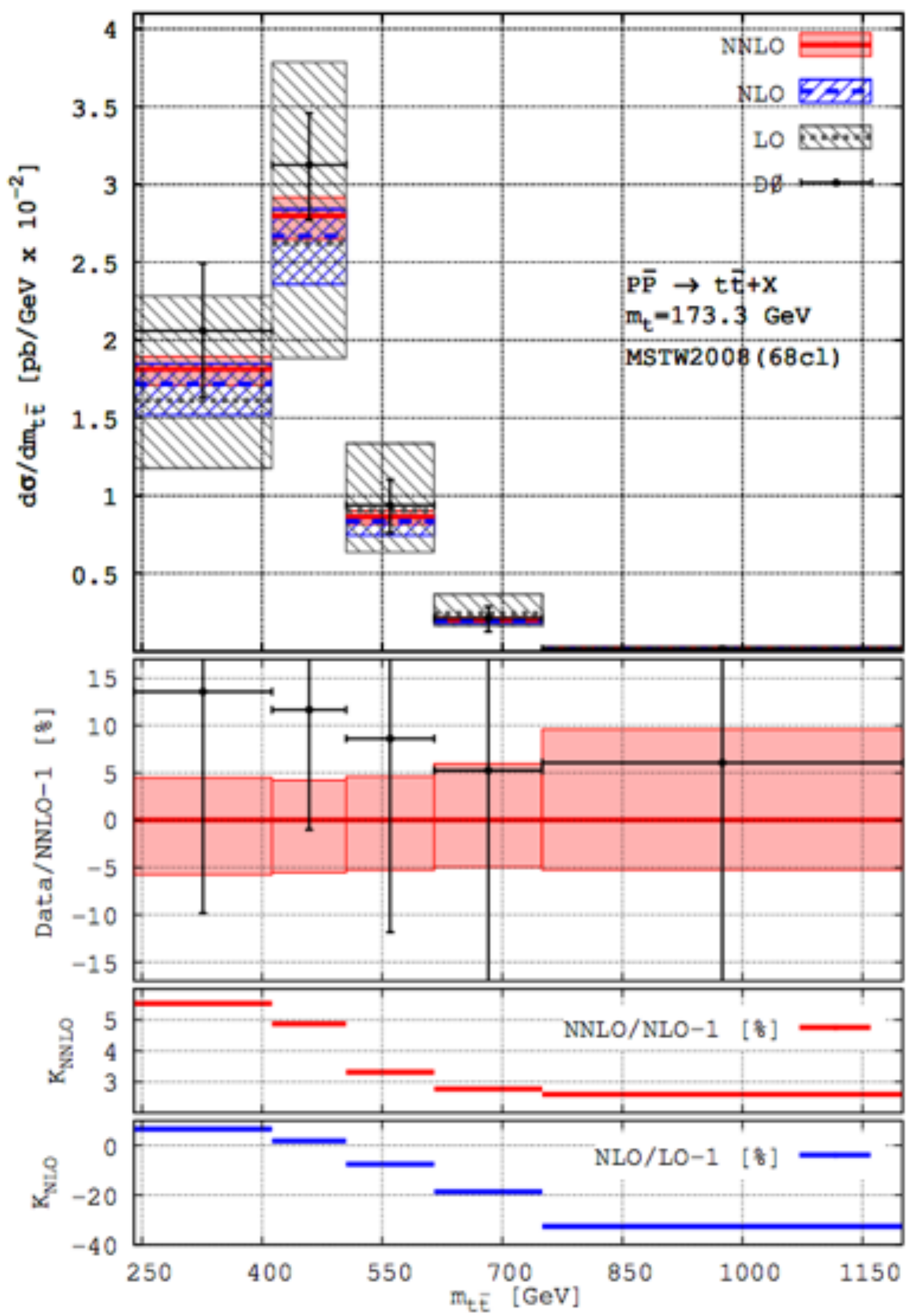
APFEL

the APPLgrid project

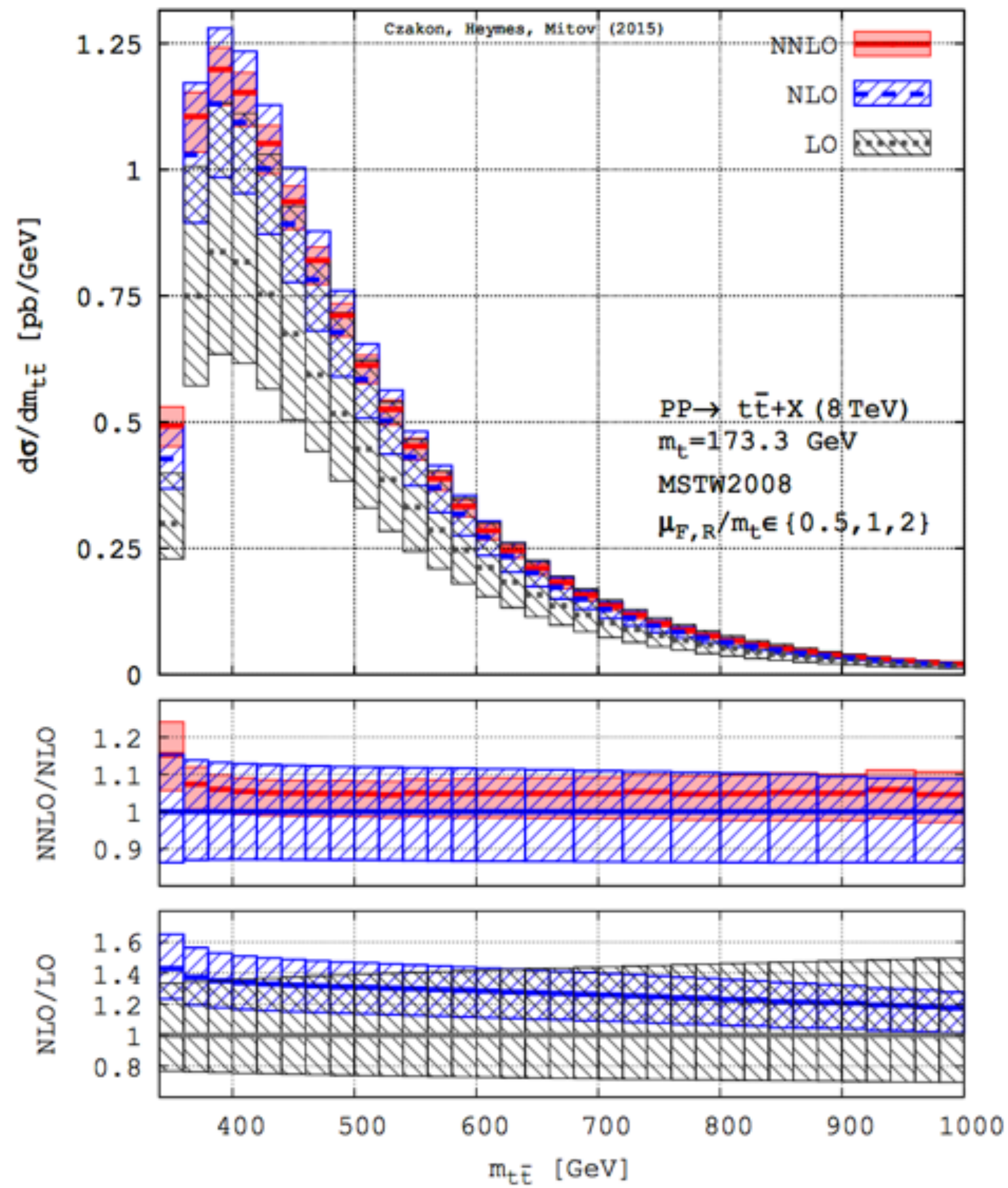
Observable	APPLGRID	**APFELcomb**
W^+ production	1.03 ms	0.41 ms (2.5x)
Inclusive jet production	2.45 ms	20.1 μs (120x)

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

The NNLO frontier - top data

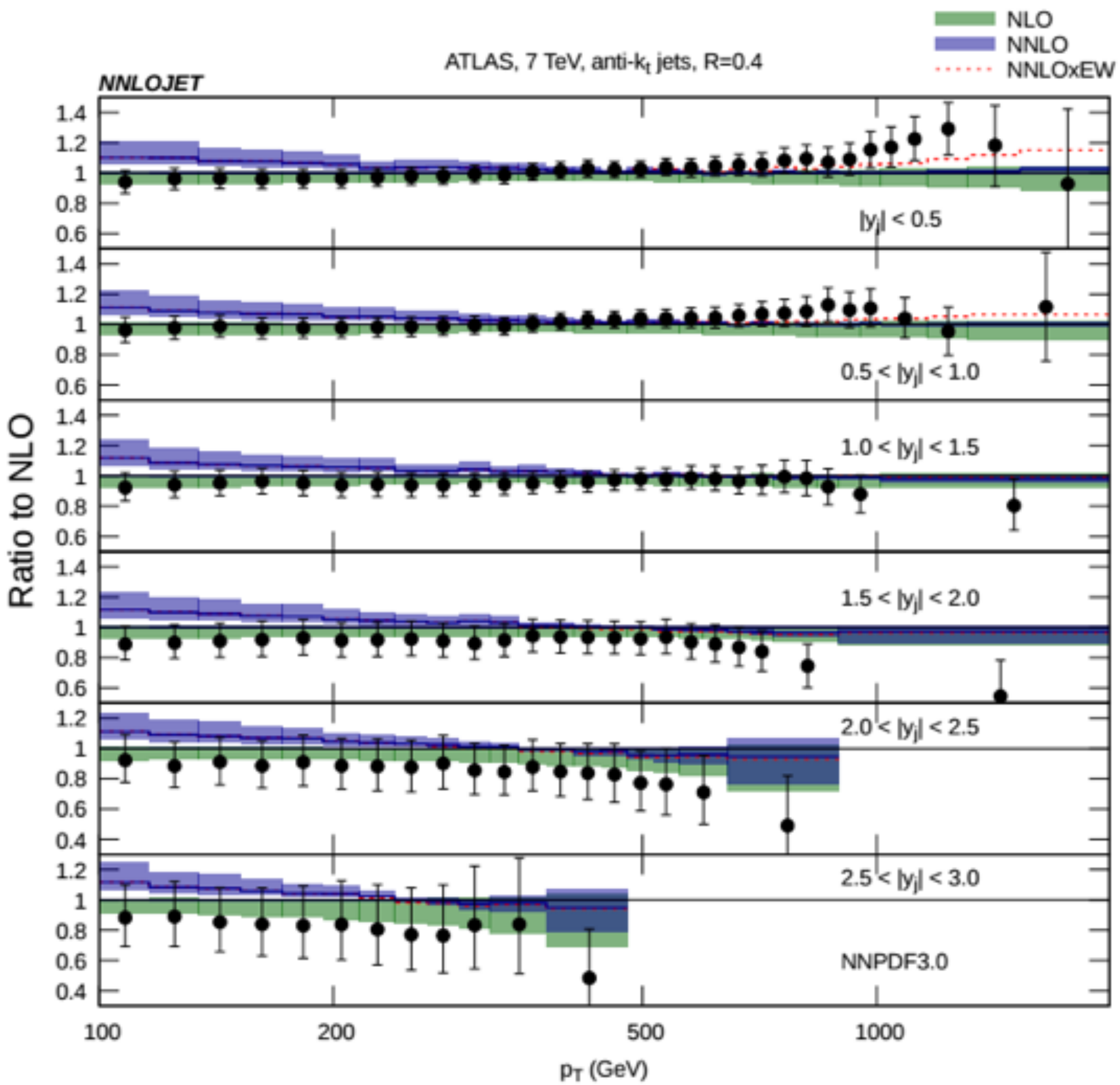


Czakon, Fiedler, Mitov [PRL 116(2016) 082003]



+ Czakon, Hartland, Mitov, Nocera and Rojo, in preparation

The NNLO frontier - jets data

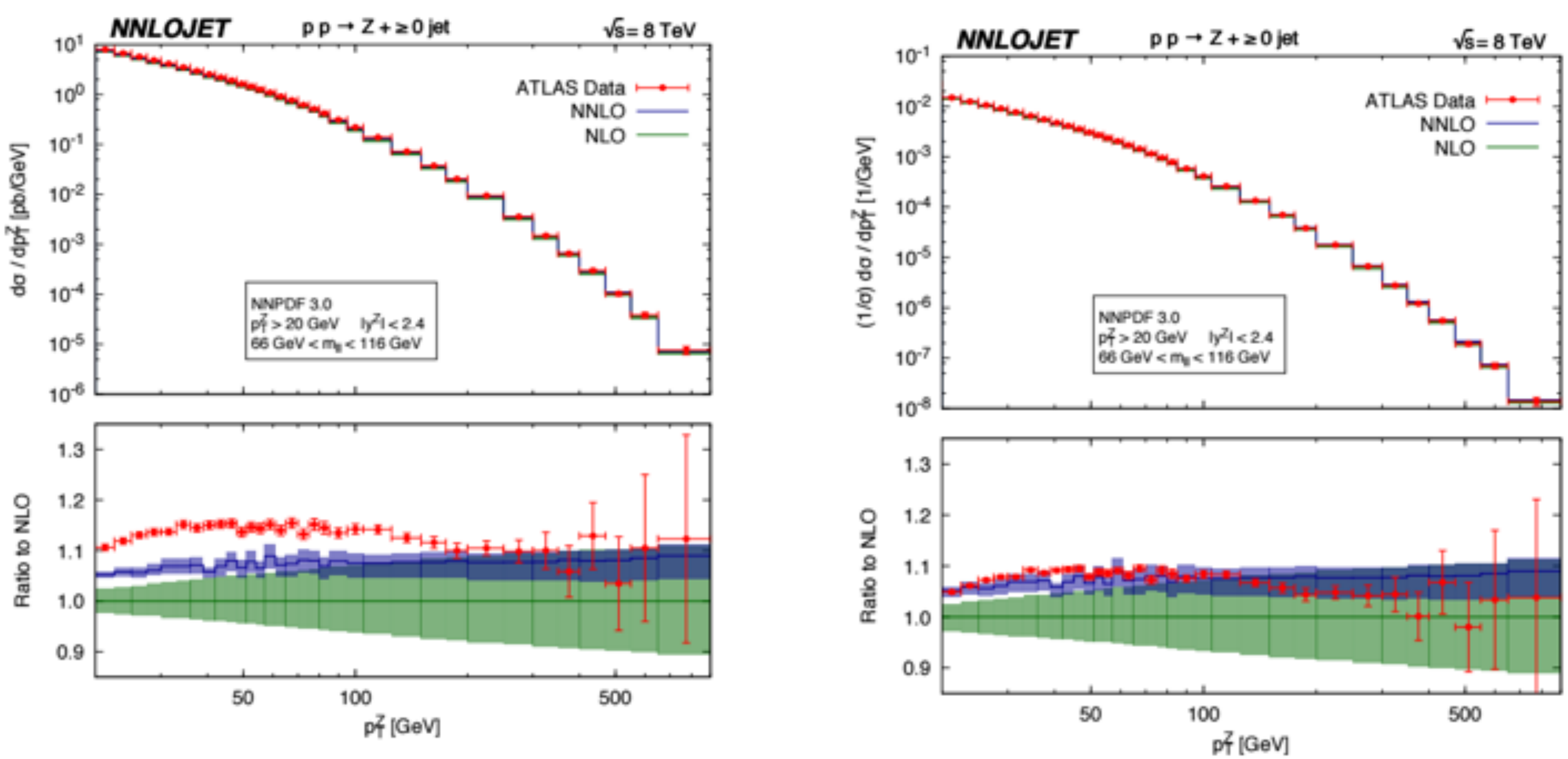


- NNLO corrections now known for all partonic channels (leading colour contribution only)
- So fare several PDF groups made different choices: CT14 includes all jet data in NNLO fit assuming overall C-factor small, MMHT14 and ABM12 do not include LHC jet data at NNLO, NNPDF3.0 include some jet data based on goodness of threshold approximation
- These choices affect precision of the gluon!

Currie et al [arXiv:1611.01460]

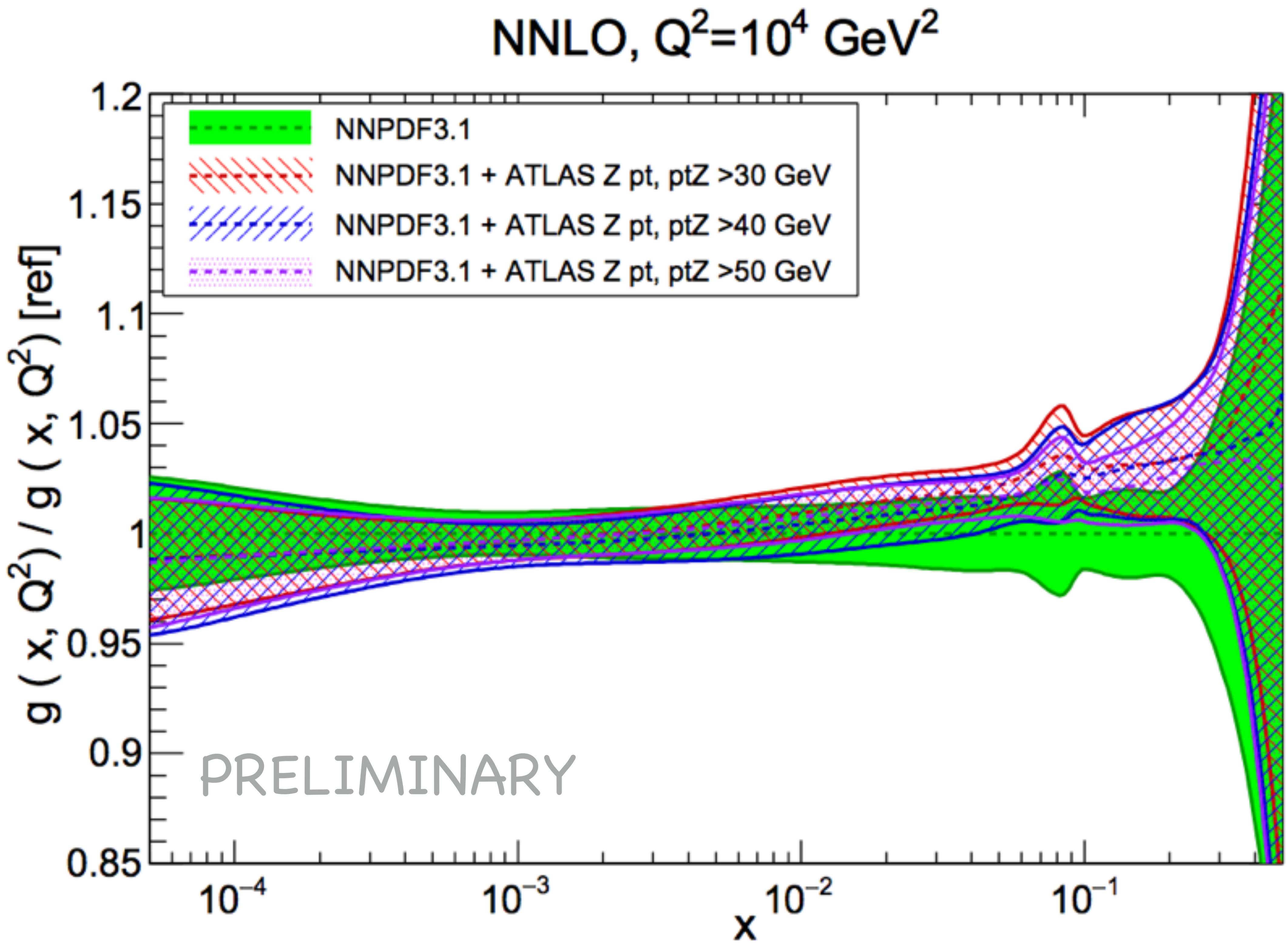
The NNLO frontier - Z pT data

- Experimental precision < 1% up to pT~200 GeV
- Data hugely dominate by correlated systematic uncertainties
- Interesting case-study to probe current theory-experiment frontier

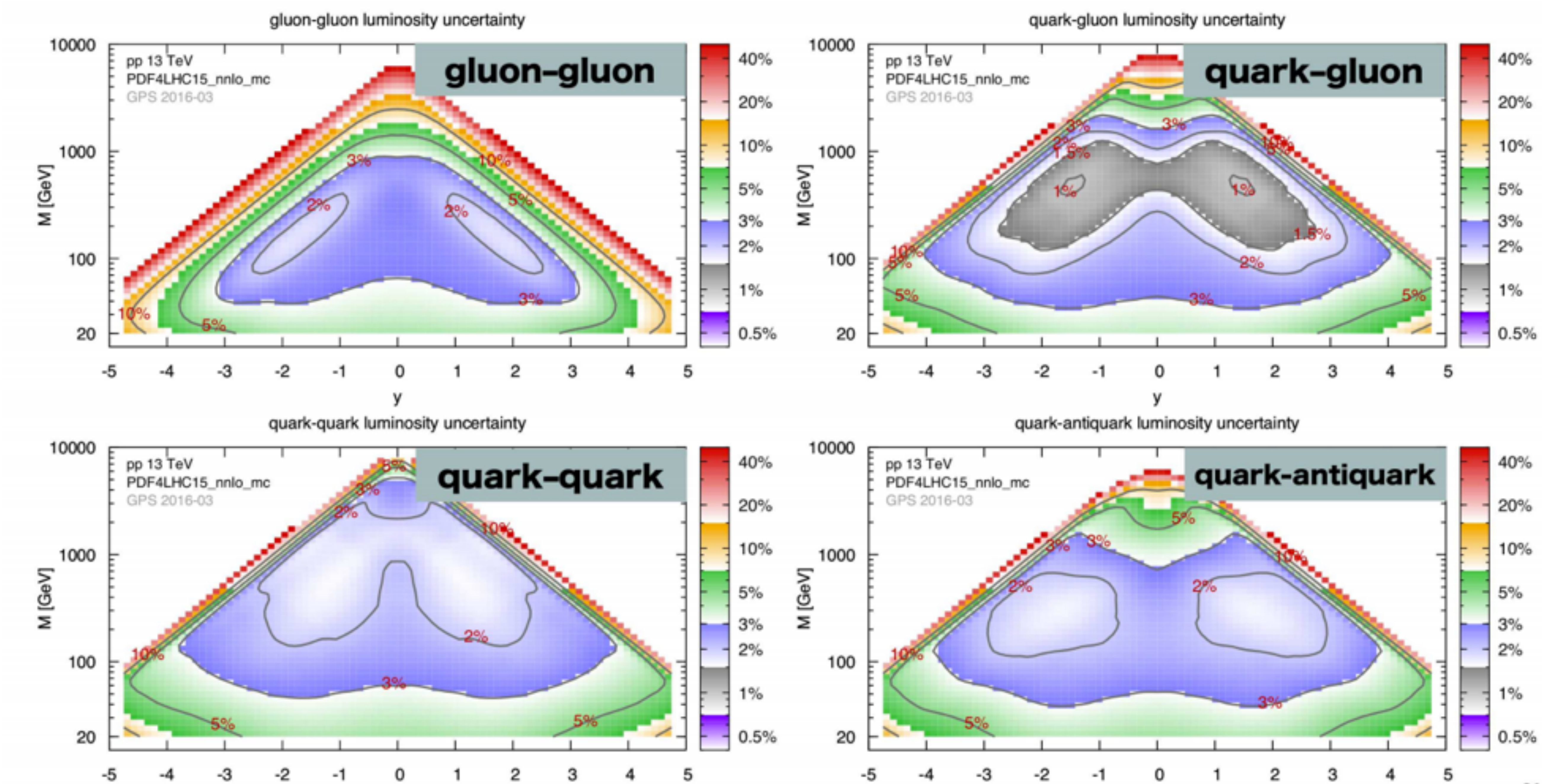


- ☑ ATLAS Z pT @LHC7, normalised distributions, 3 rapidity bins (0<Y<1, 1<Y<2, 2<Y<2.5)
  ~50 data in perturbative region pT > 30 GeV
- ☑ ATLAS Z pT @LHC8, normalised/unnormalised distributions, 6 rapidity bins in Z peak + low/high M
  ~150 data in perturbative region pT > 30 GeV
- ☑ CMS Z pT @LHC8, normalised/unnormalised distributions, 5 rapidity bins in Z peak
  ~50 data in perturbative region pT > 30 GeV

The NNLO frontier - Z pT data



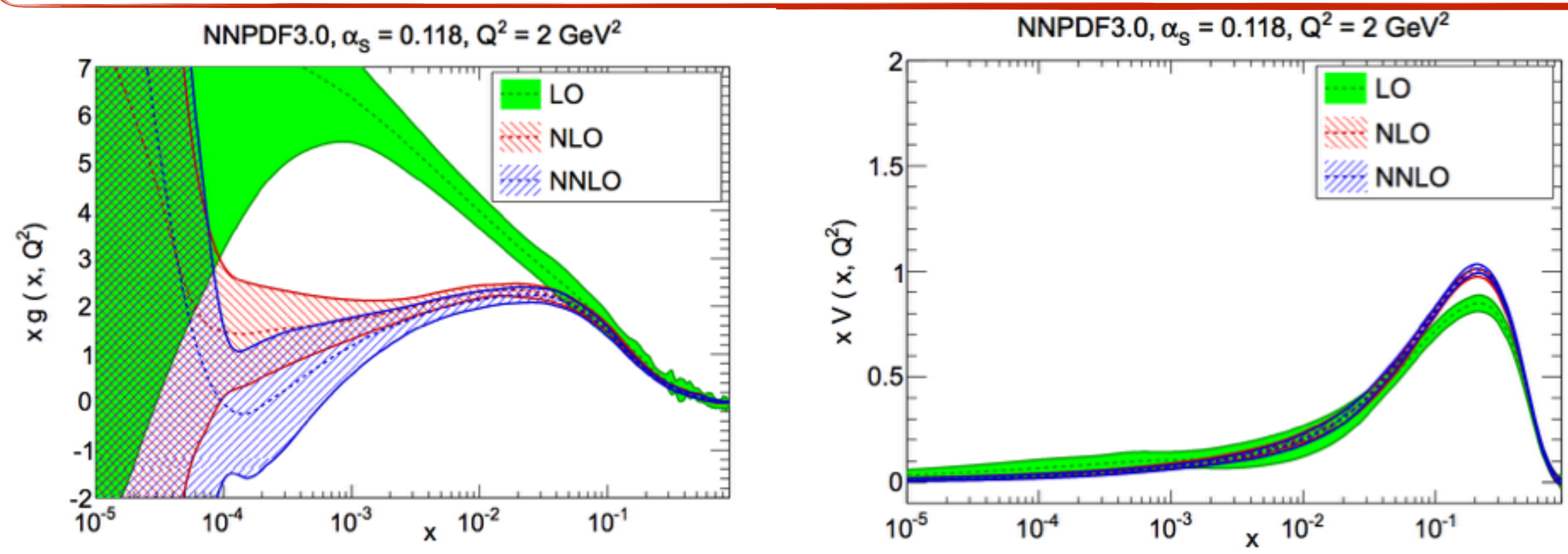
ii - PDF hidden uncertainties



G. Salam, LHCP

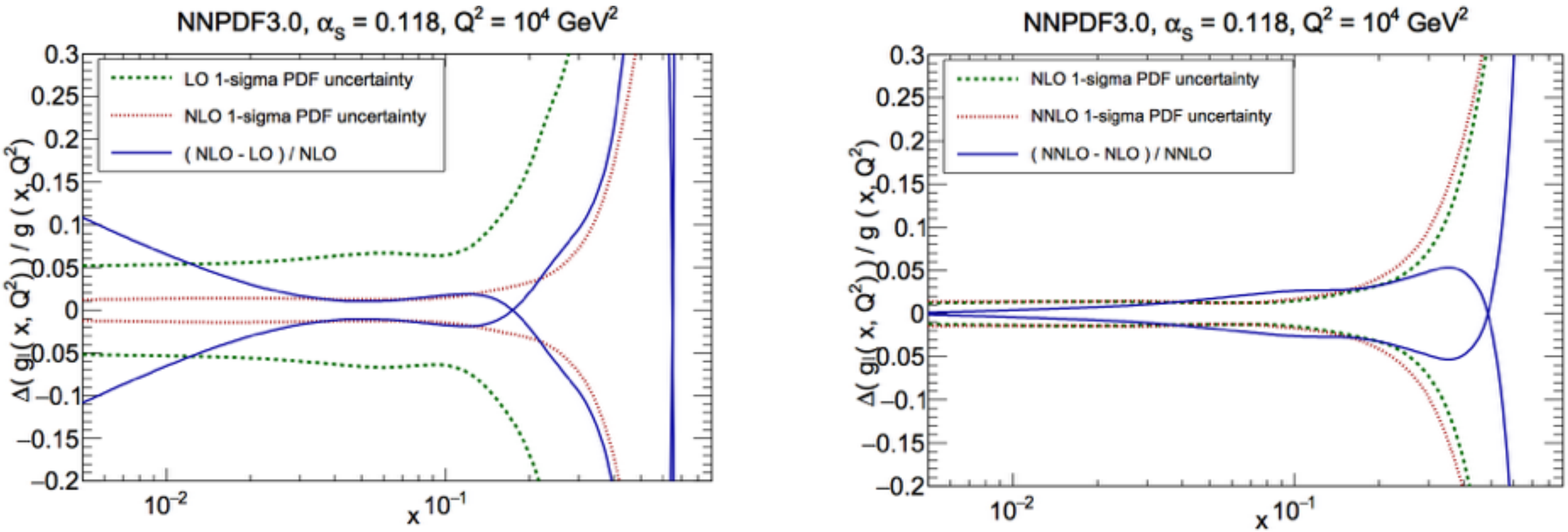
Do we trust 1% accuracy in parton luminosities?

Fixed-order accuracy



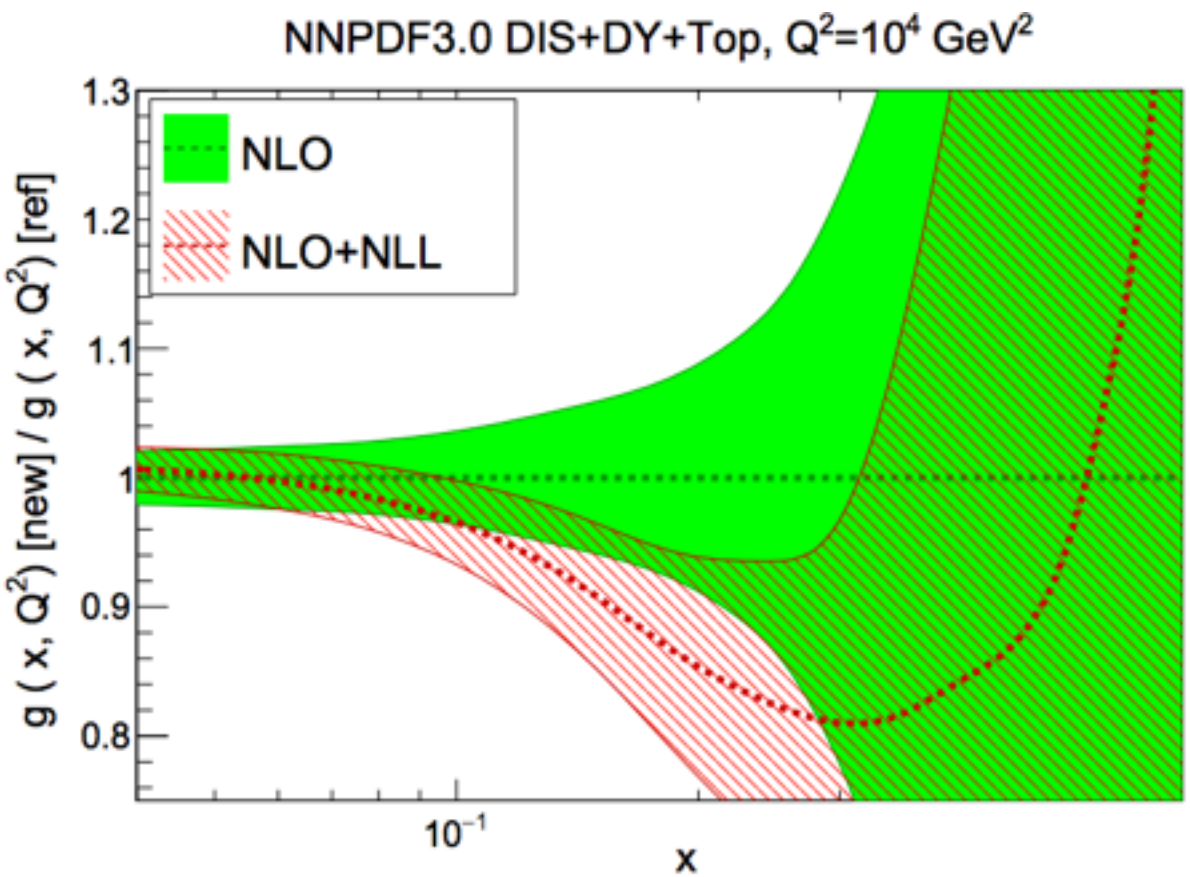
- PDF fits performed with given fixed perturbative order, value of α_S and heavy quark masses (estimated by combining PDF sets determined with different values)
- PDF uncertainties only reflect lack of information from data given the theory
- Changes in theory may cause shifts outside the error band,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

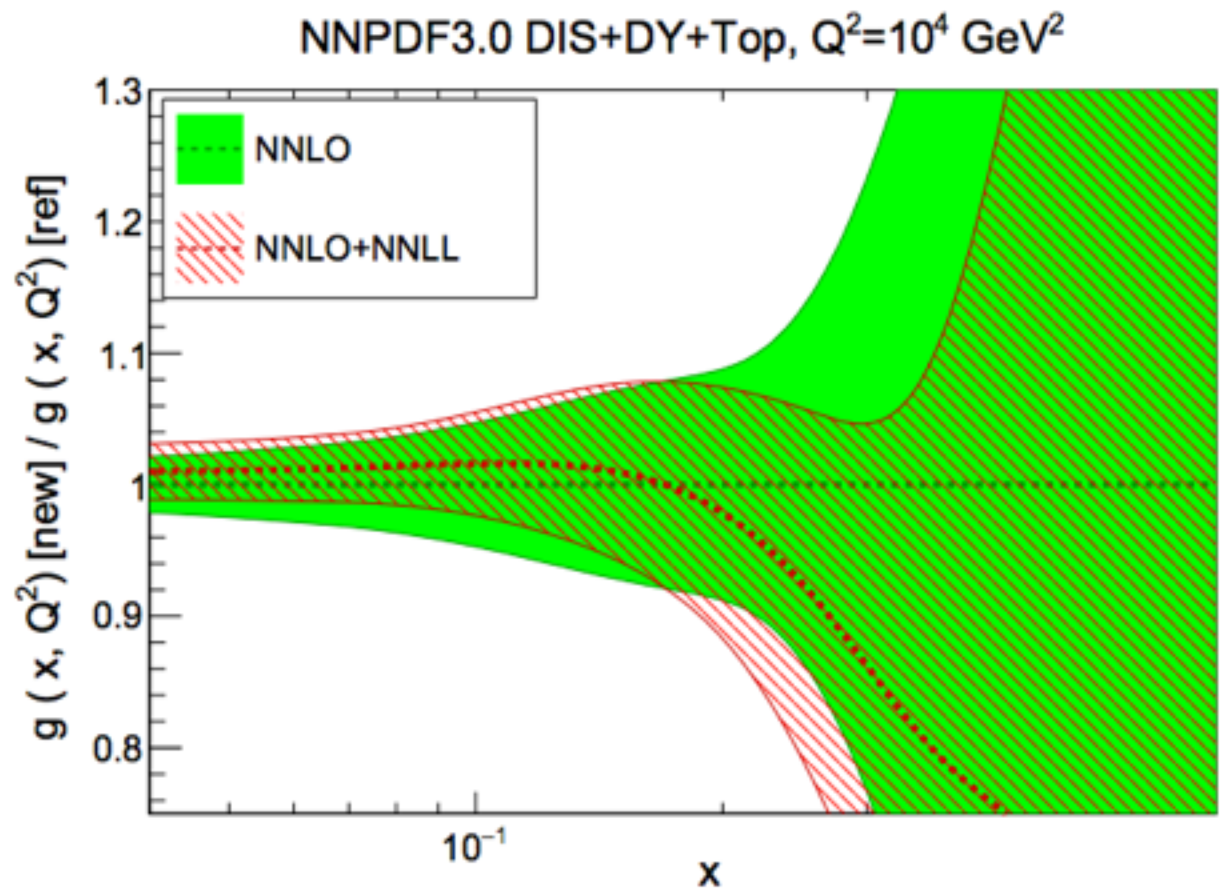
Fixed-order accuracy



- If we knew the next order we could compute the shift: at NLO theory uncertainty is comparable to the experimental one
- NNLO subdominant
- Cacciari Houdeau method **[JHEP 1109 (2011) 039]** look at the behaviour of perturbative expansion is promising -> to be explored
- What about NNNLO PDFs? Main bottleneck is missing anomalous dimensions

Beyond fixed-order accuracy





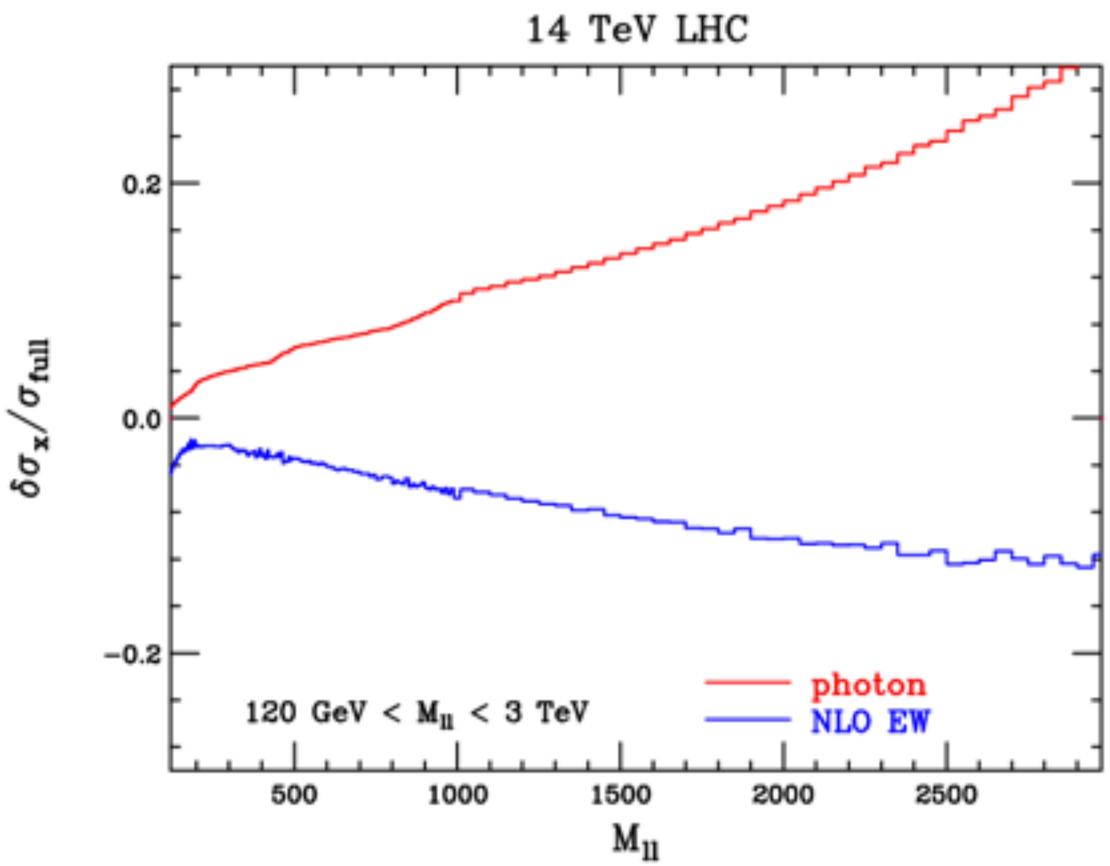
Bonvini et al, JHEP 1509 (2015) 191

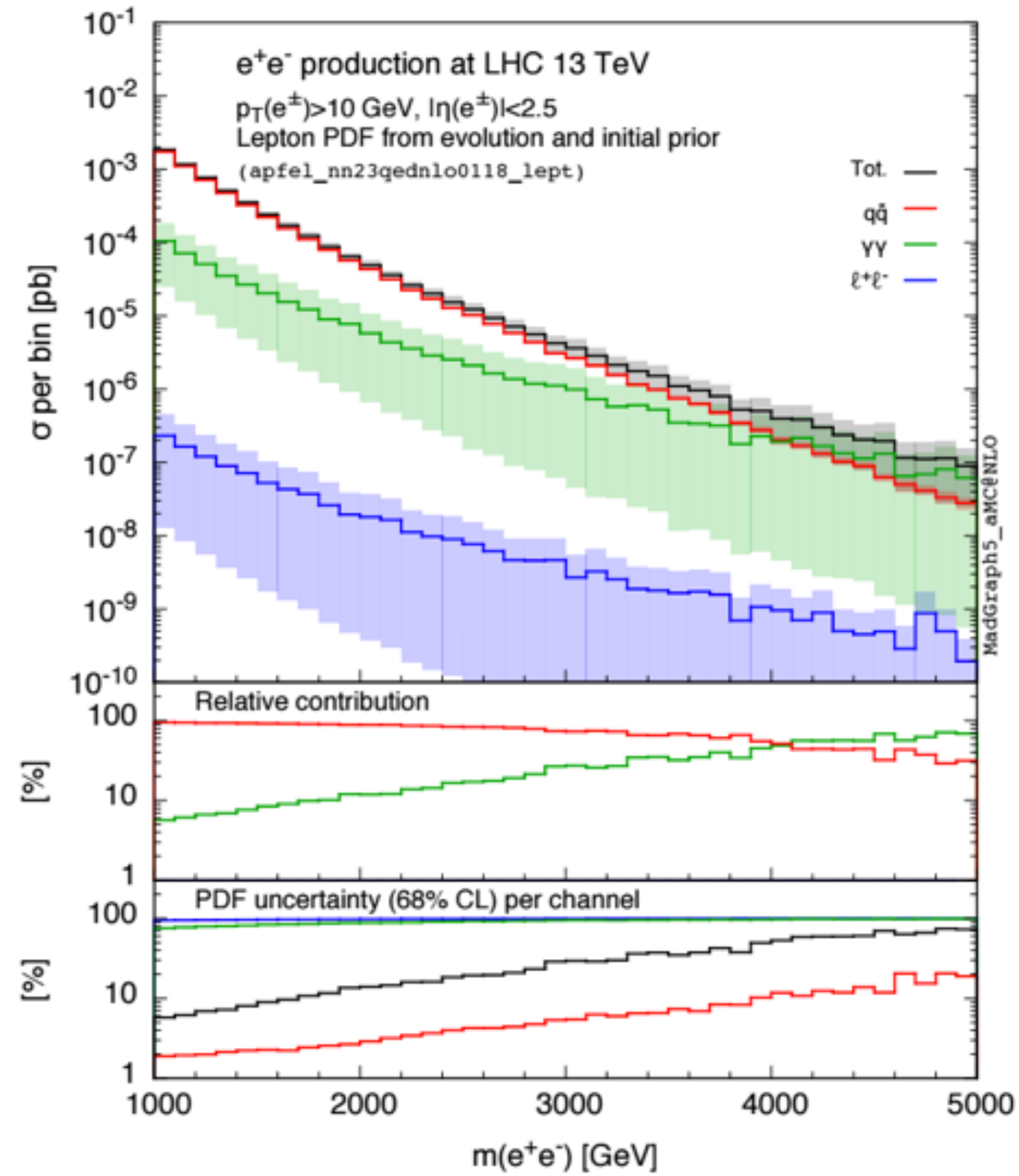
- Threshold-resummed PDFs made recently available [Bonvini et al, JHEP 1509 (2015) 191]
- Gluon suppressed as compared to fixed-order PDFs mostly due to enhancement of NLO+NLL xsecs used in the fit of DIS structure functions and DY distributions
- This suppression partially or totally compensates enhancements in partonic cross sections. Phenomenologically relevant for new physics processes [Beenakker et al. EPJC76 (2016)2, 53]
- Work in progress on small-x, pT resummation, PS resummation

iii - 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



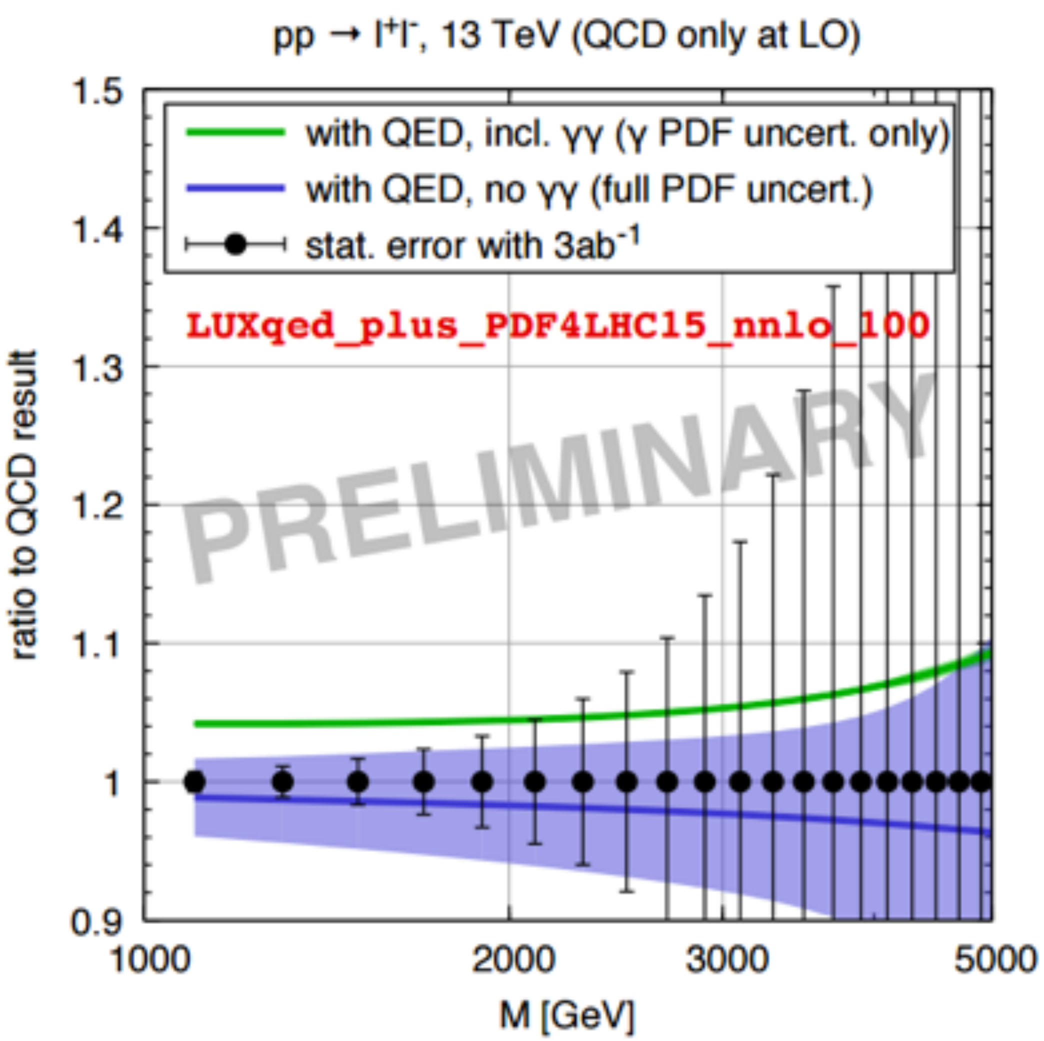


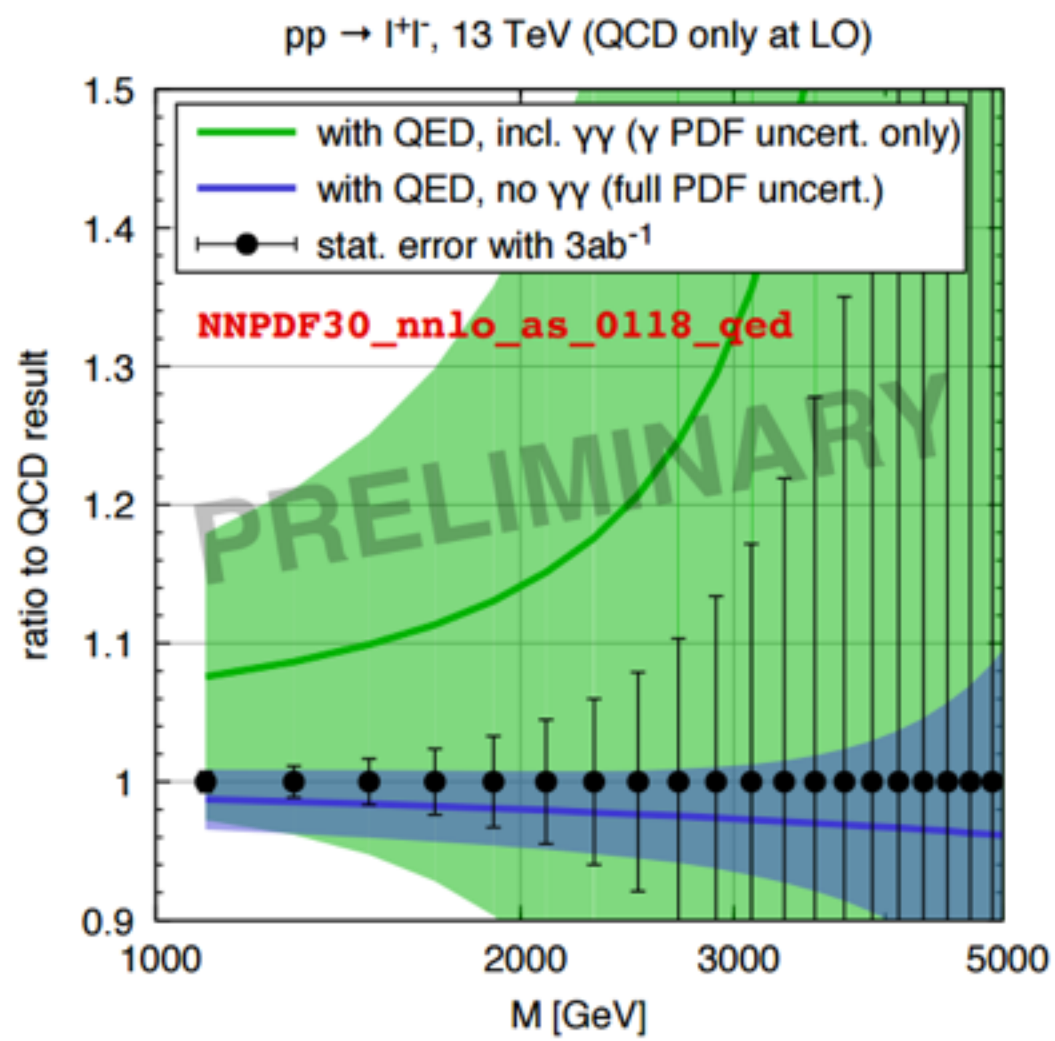
Boughezal et al [Phys.Rev. D89 (2014)3, 034030]

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

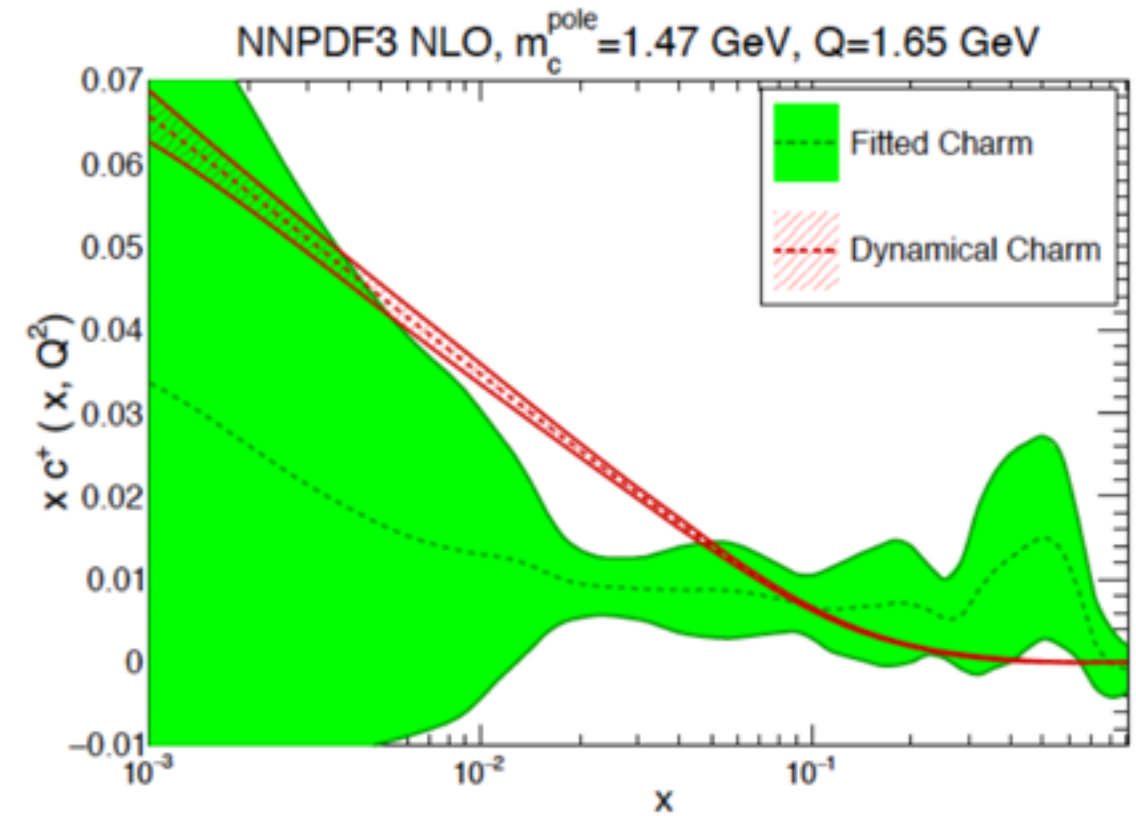




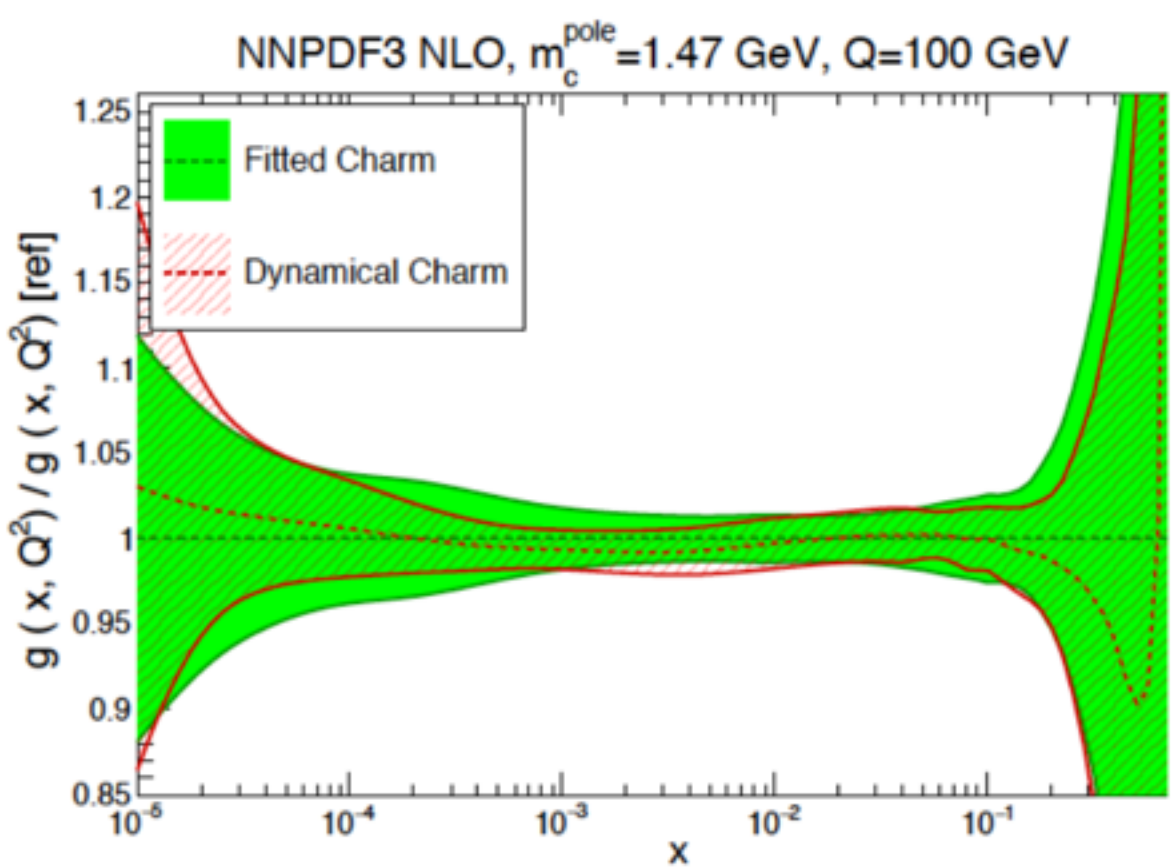
P. Nason, talk in Durham

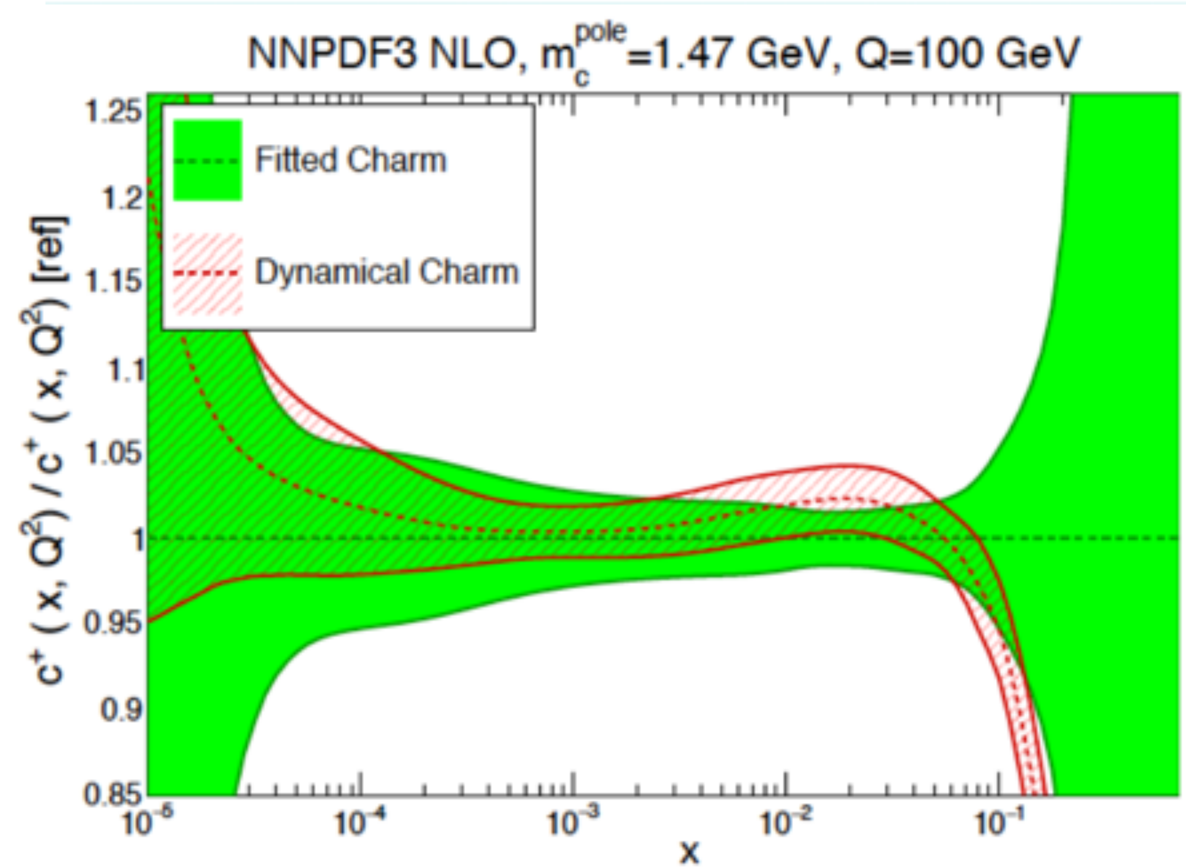
iv - Intrinsic charm and charm mass

- Recent analysis on intrinsic charm, free parametrisation for charm, same dataset as NNPDF3.0 + EMC data (charm structure function meas.)
- Stability of non-charm PDFs
- Better stability of charm with respect to charm mass variations



NNPDF collaboration, Eur.Phys.J. C76 (2016)





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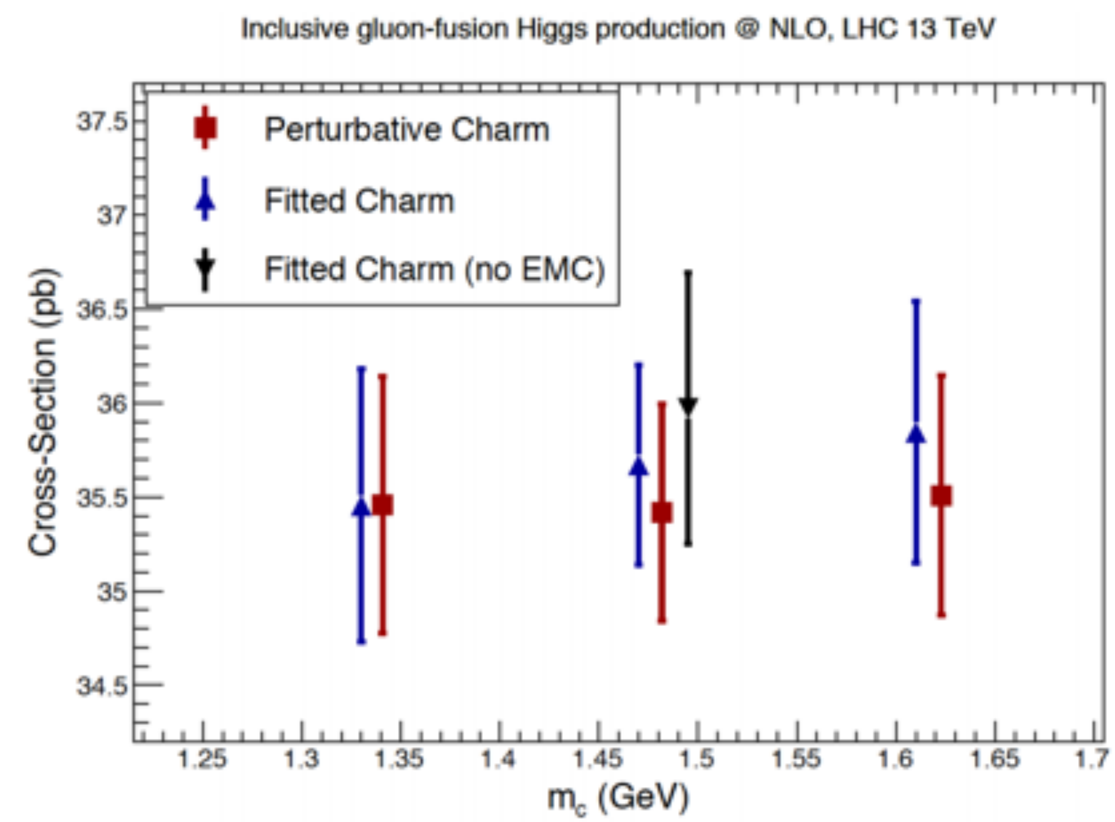
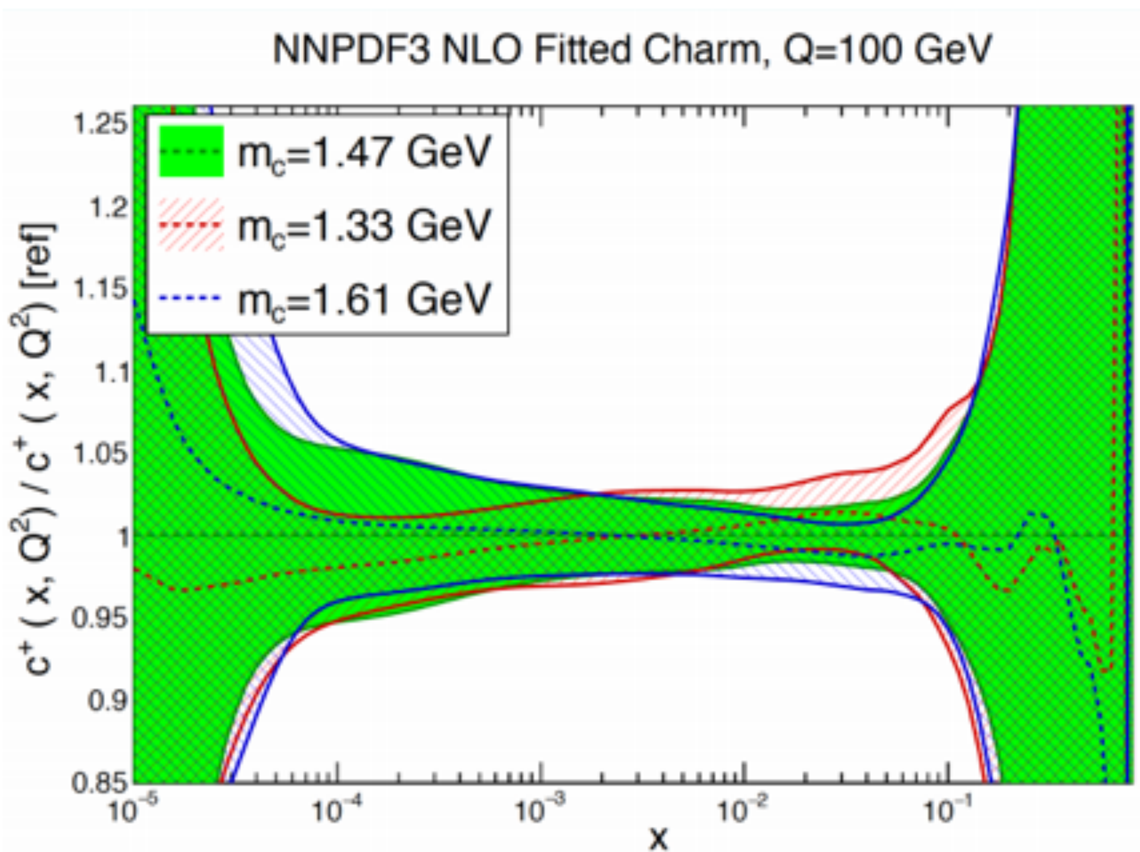
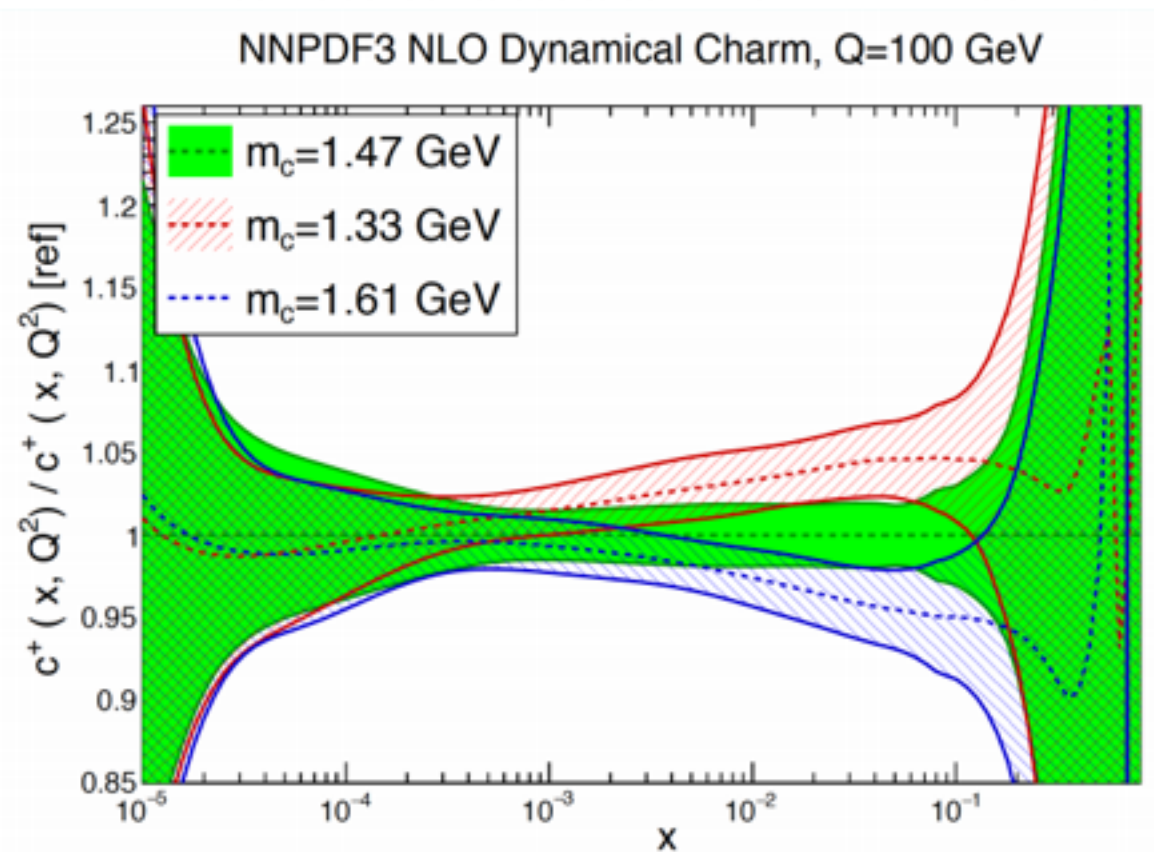
NNPDF collaboration, Eur.Phys.J. C76 (2016)

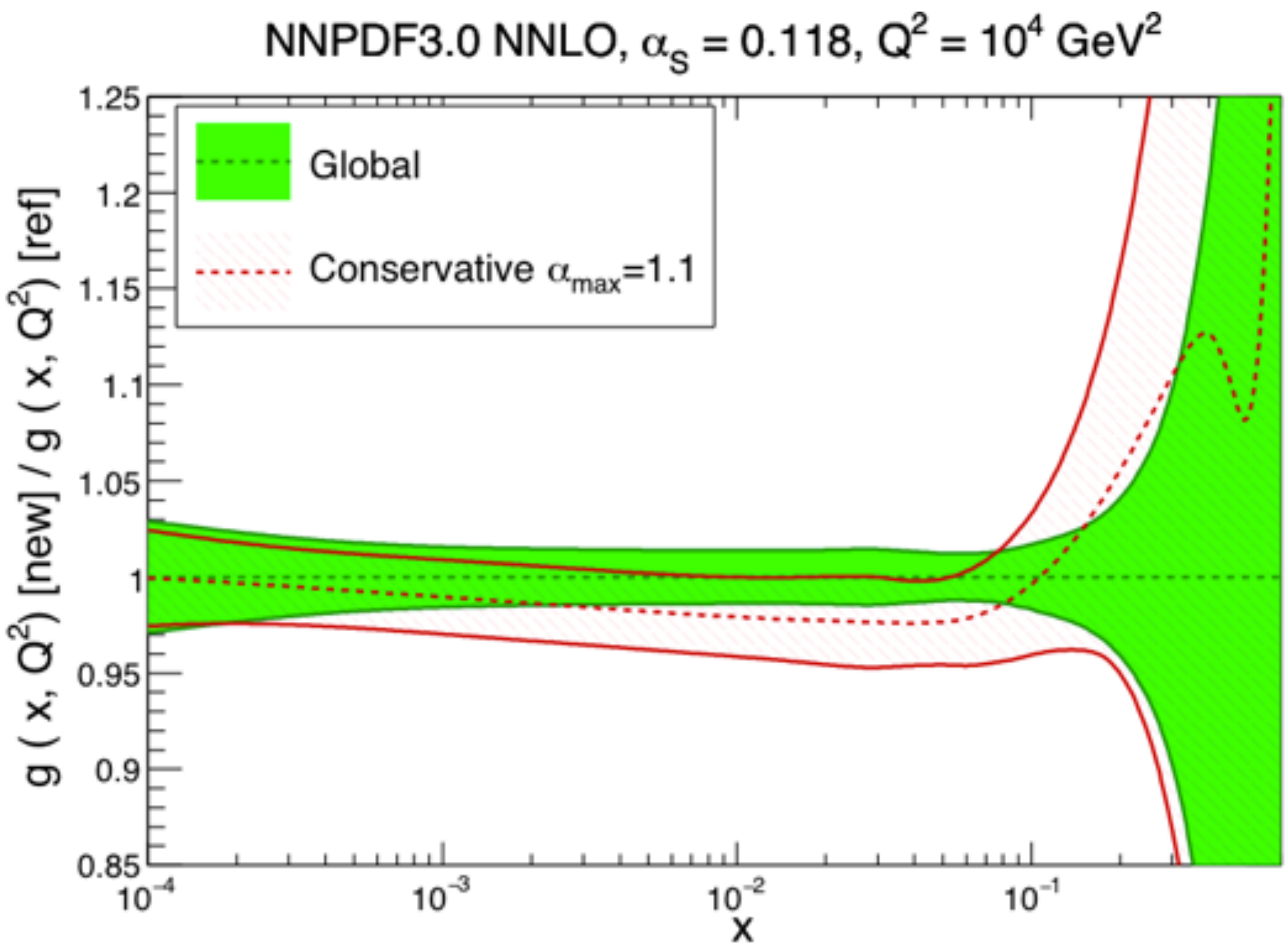






v - Conservative partons

- 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

[…] 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

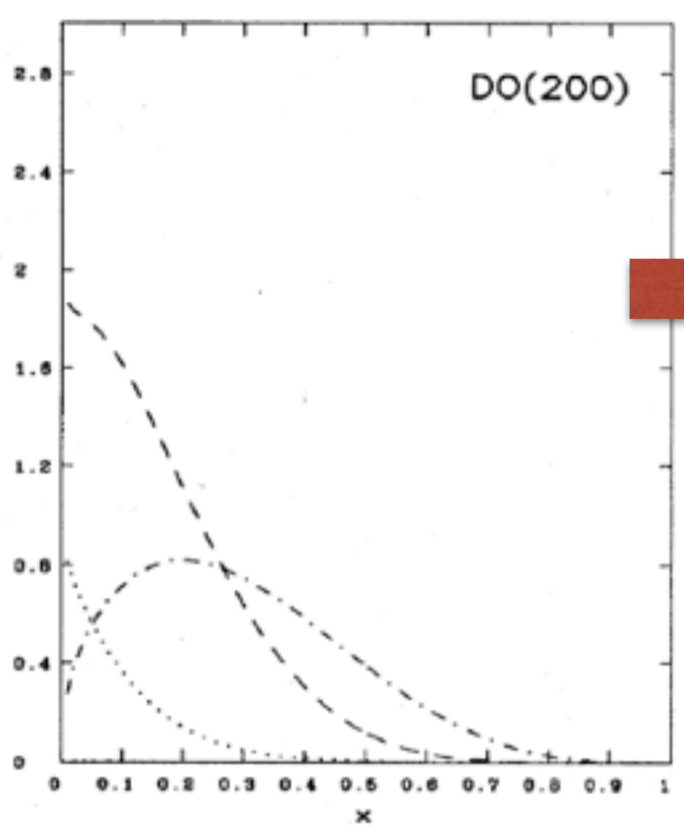
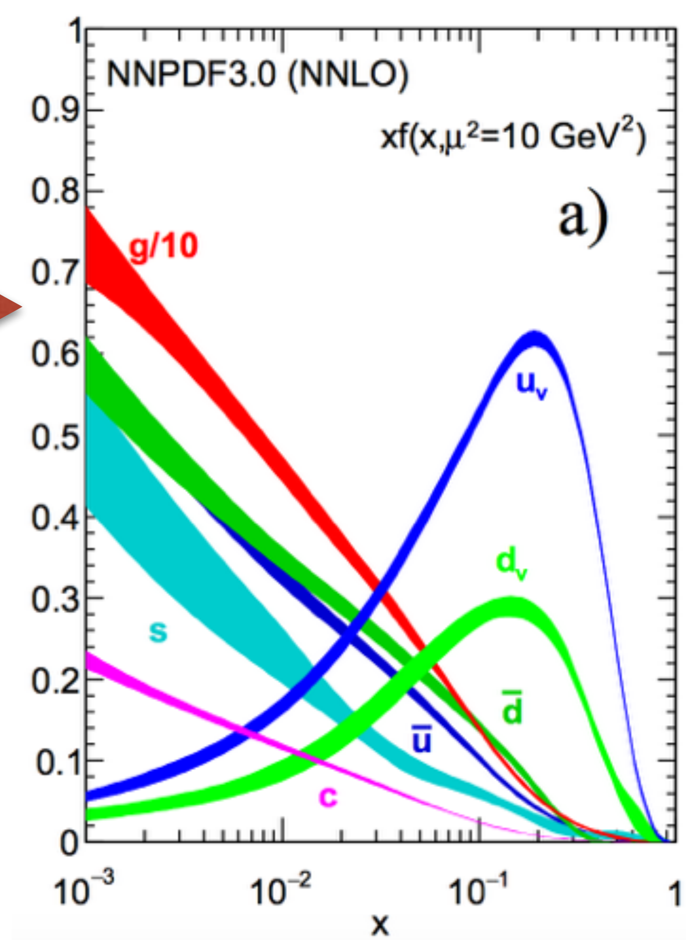


FIG. 27. "Soft-gluon" ($\Lambda=200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).



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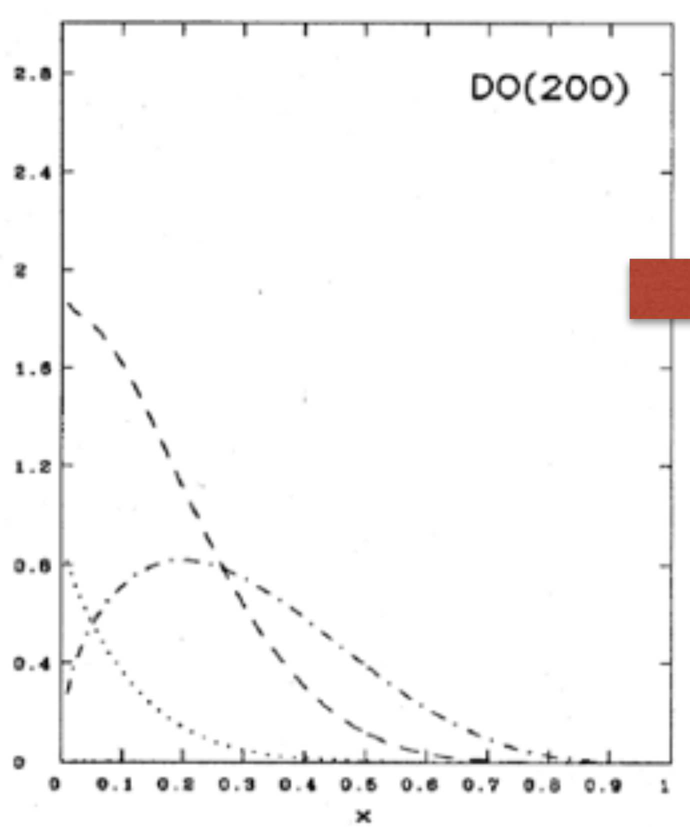

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