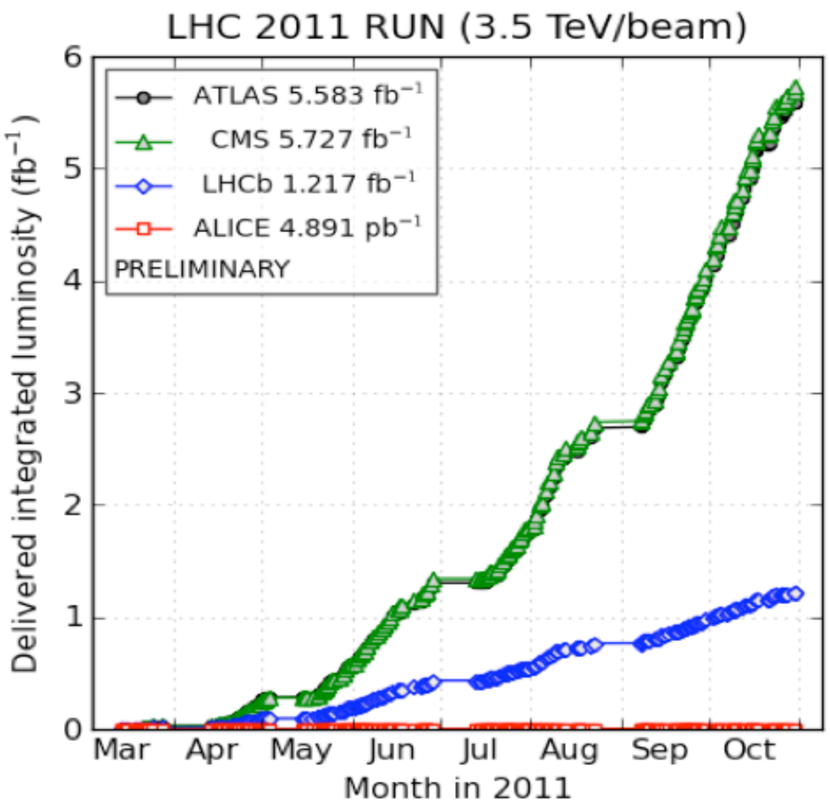
News on Parton Distribution Functions

Maria Ubiali
RWTH Aachen

RWTH AACHEN UNIVERSITY

30th November 2011
APPS, Amsterdam

The LHC era



- 2010-11: Impressive experimental performances at the LHC!
- To fully exploit the LHC physics potential a solid and quantitative understanding of strong interaction (QCD) is essential
- Need both precise computation of hard process and precise PDFs determination

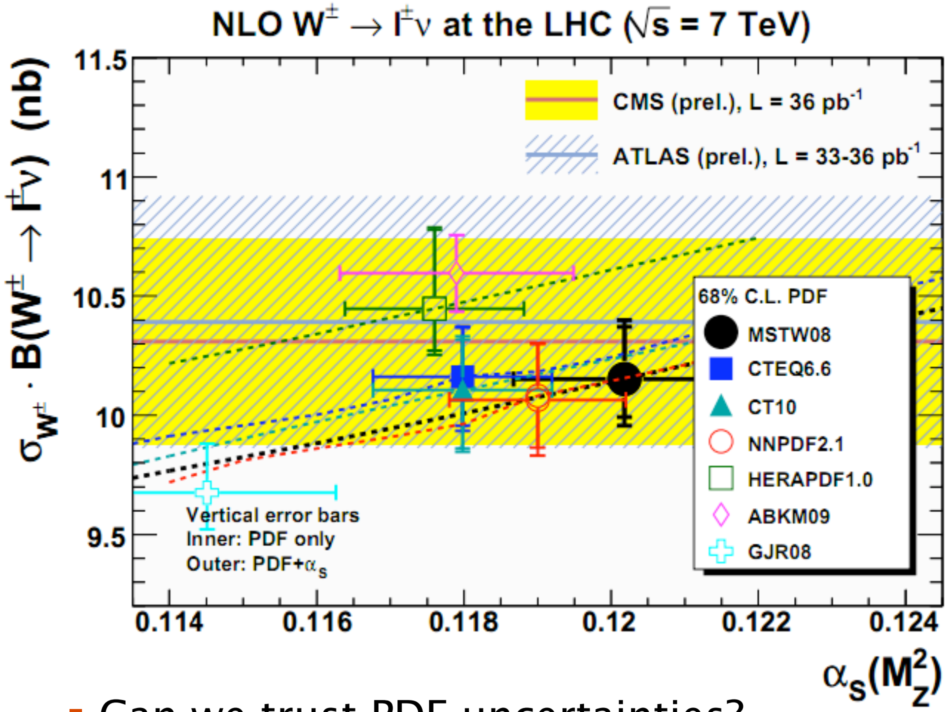
Partonic cross section

$$\frac{d\sigma_H^{pp\to AB}}{dX} = \sum_{i,j=1}^{N_f} f_i(x_1,\mu_F)\, f_j(x_2,\mu_F)\, \frac{d\hat{\sigma}^{ij\to ab}}{dX}(x_1 x_2 S_{\text{had}}, \alpha_S(\mu_R), \mu_R, \mu_F, m) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^{2n}}{S_{\text{had}}^{n}}\right)$$

Parton Distribution Functions

PDFs and LHC interplay

G. Watt, JHEP 1109 (2011) 069



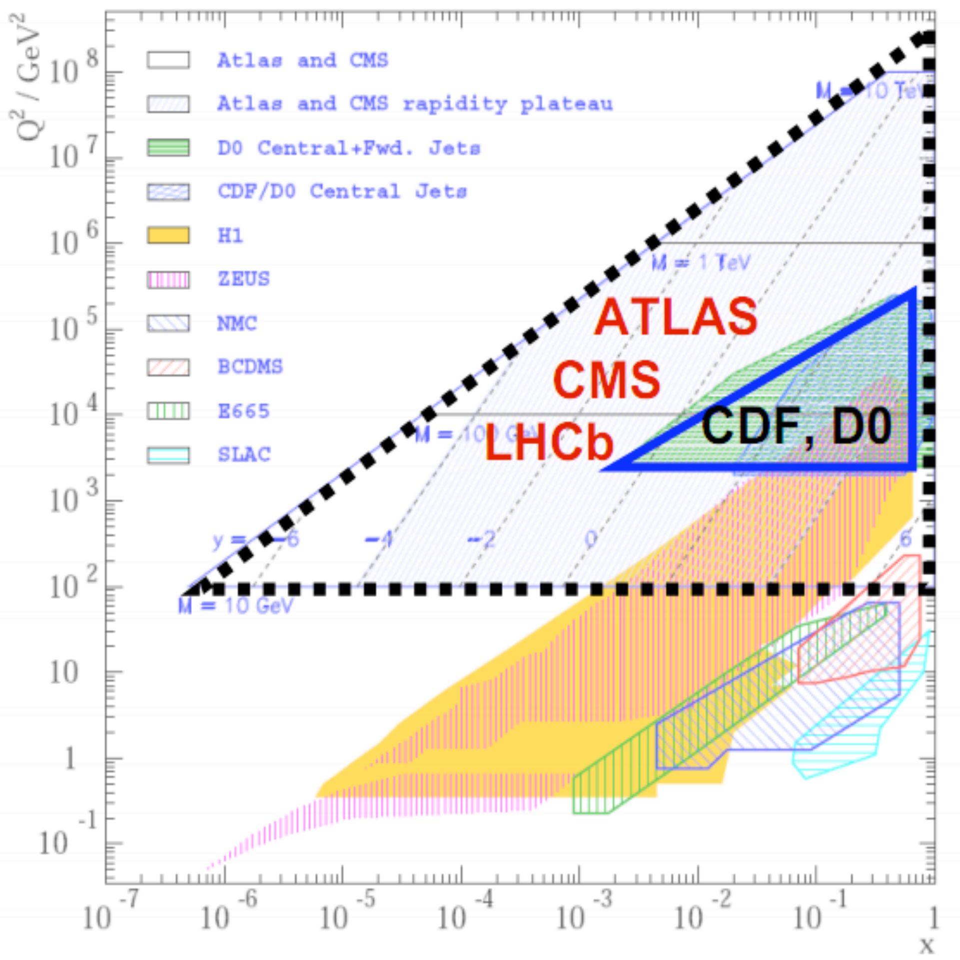
- Can we trust PDF uncertainties?
- How do we interpret the differences?
- Shall we just pick a set out of the PDFs "supermarket" shelf or take the envelope of ALL predictions?

PDF4LHC: huge effort in understanding differences & improving theoretical and statistical treatment in PDF analyses

PDFs → LHC
PDF uncertainties are crucial for LHC standard candle processes and for discovery & exclusion

LHAPDF

PDFs and LHC interplay



V. Radescu, DIS 2011

PDFs → LHC
PDF uncertainties are crucial for LHC standard candle processes and for discovery & exclusion

LHC → PDFs
Exploit the discriminating and constraining potential of the increasingly precise LHC data

Outline

❶ PDFs for LHC

- The ideal parton densities
- Current parton densities
- Towards an agreement?
- The α_S puzzle

❷ LHC for PDFs

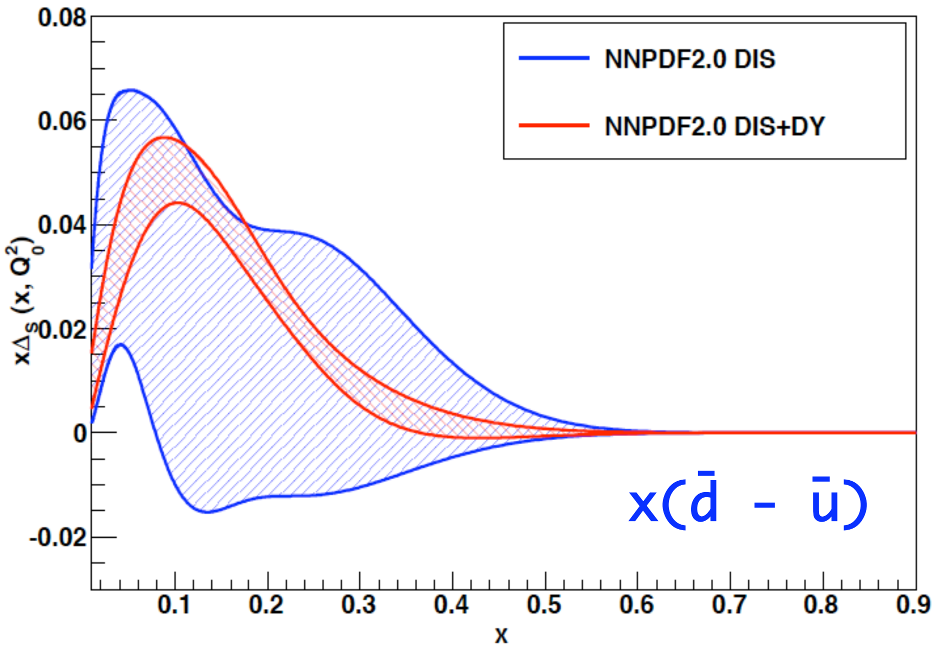
- Constraints from LHC data
- Inclusion of LHC data

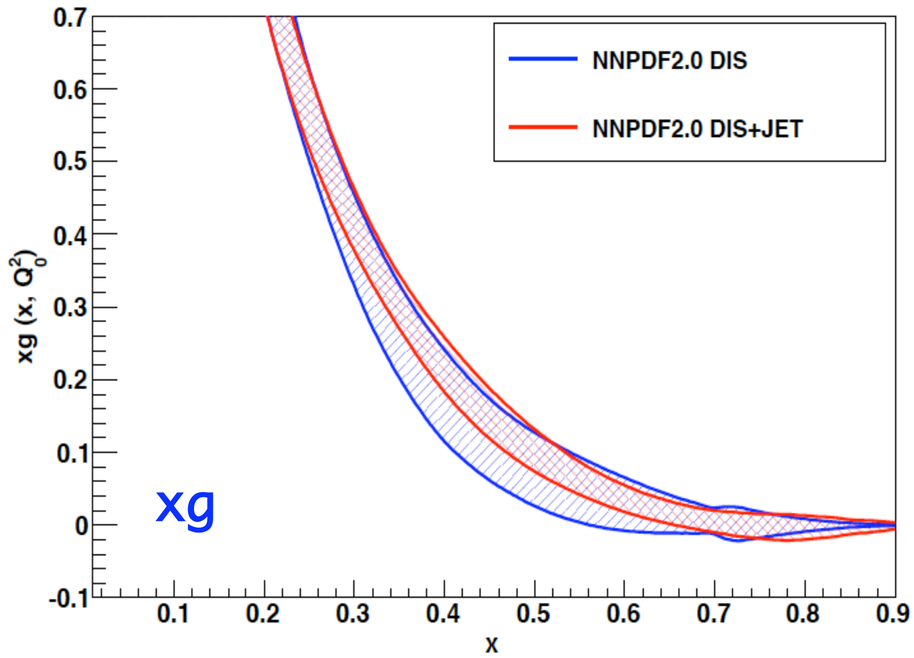
❸ Summary and open questions

The ideal PDF set

- DATA: Different data constrain different parton combinations at different x.

Use wide dataset and include correlations to retain all relevant experimental info ☑





[NNPDF, Nucl.Phys. B838 (2010)]

The ideal PDF set

- DATA: Different data constrain different parton combinations at different x.

  Use wide dataset and include correlations to retain all relevant experimental info ☑

- PARAMETRIZATION: A restrictive parametrization may be inadequate to describe data or present unrealistically small uncertainties

  Use sufficiently flexible parametrization to avoid bias ☑

- STATISTICS: Inconsistent statistical treatment may lead to inconsistent CL for individual experiments

  Provide PDF uncertainty bands checked to provide consistently-sized CL ☑

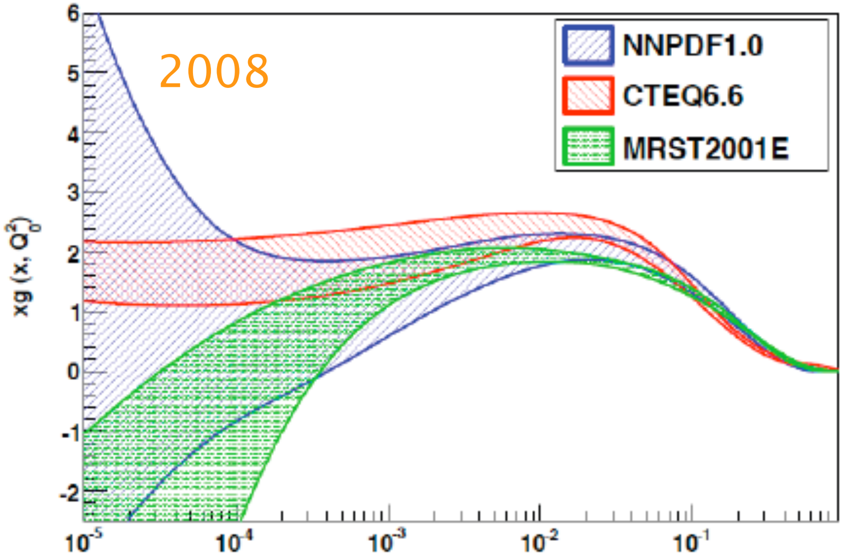
- THEORY: The theory used in the analysis must be adequate and precise

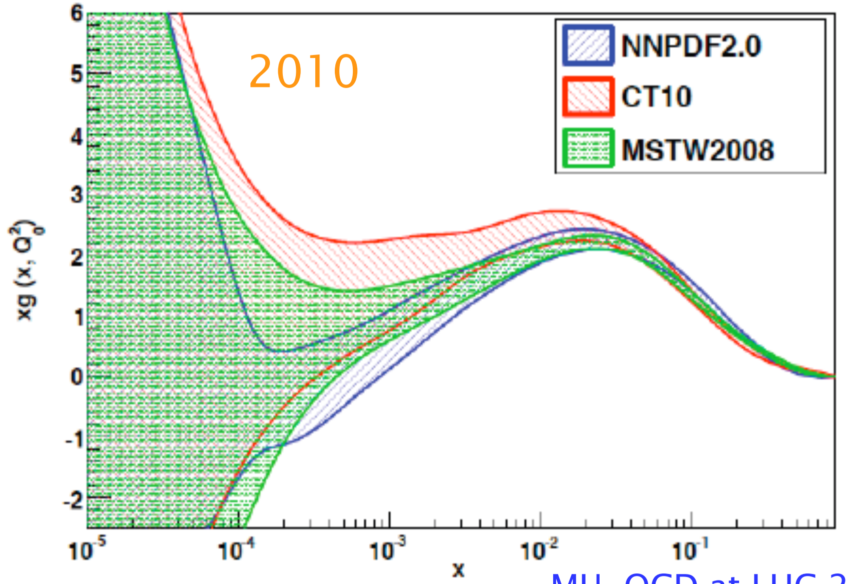
  Consistent inclusion of heavy quark mass effects ☑
  Use computation of highest available perturbative order ☑
  Estimate theoretical uncertainty due to higher order ☑

- USER-FRIENDLY: The user must be able to choose physical parameters

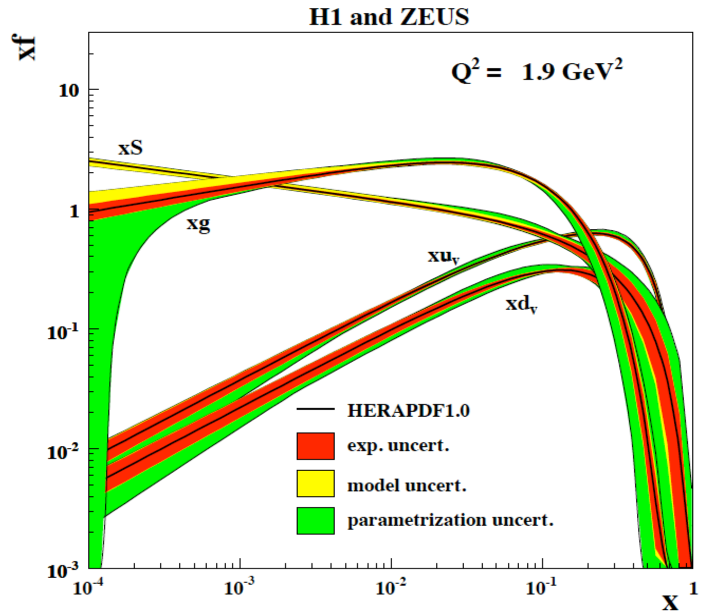
  Provide PDFs for a variety of values of α_s and heavy quark masses ☑

Steps towards the ideal
Increased parametrization flexibility





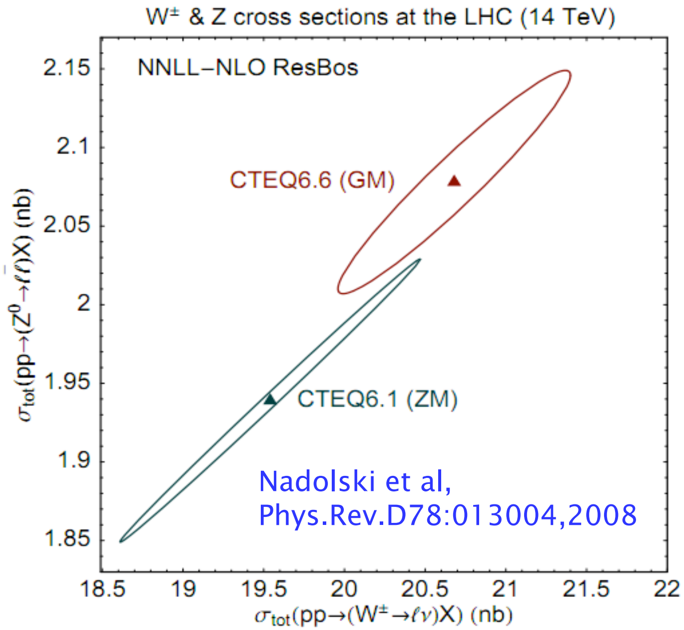
MU, QCD at LHC 2010



A. Cooper-Saarkar, DIS 2011

- **NNPDF** use always same redundant Neural Network parametrization
- **CTEQ and MSTW** added parameter (e.g. added one parameter in the small-x region)
- **HERAPDF** included parametrization error by varying around best-fit parameters

Steps towards the ideal
Heavy quark treatment and physical parameter variation



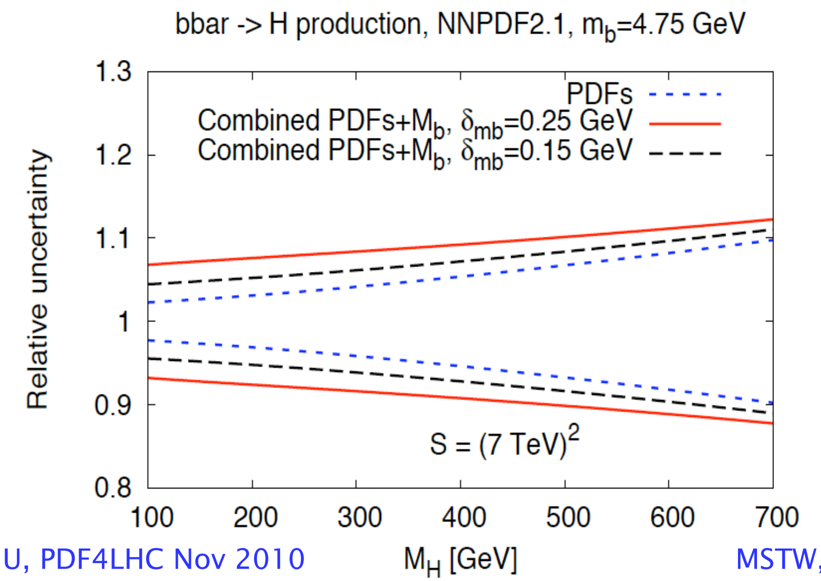
- **CTEQ61 to CTEQ66:** importance of HQ mass effects
- Global analyses adopted a GM VFN scheme
- Extensive recent work:

Tung et al., hep-ph/0611254; Thorne, hep-ph/0601245; Tung,Thorne, arXiv:0809.0714; P.N., Tung, arXiv:0903.2667; Forte,Laenen, Nason, arXiv:1001.2312; J. Rojo et al., arXiv:1003.1241;Alekhin, Moch,arXiv:1011.5790;...

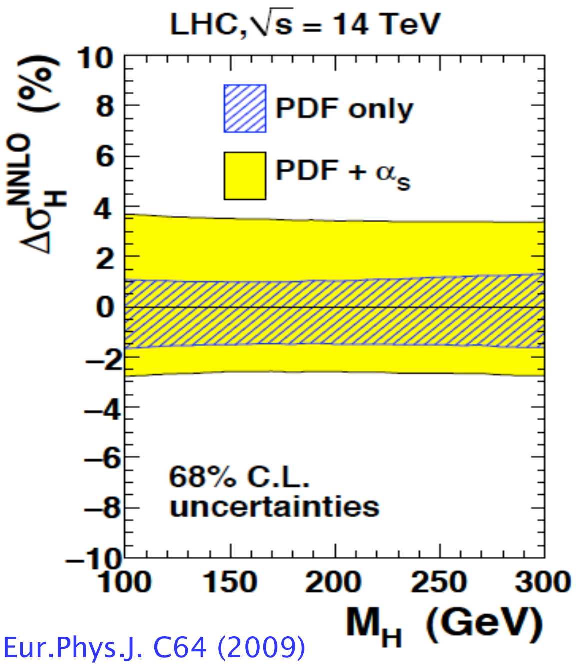
Is a consistent picture emerging?
Precise HERA F^2_c and F^2_b data will answer

Variation of **physical parameters** in PDF fit affects predictions: actual uncertainty is larger than PDF only uncertainty

Provide way to combine $(PDF+\alpha_S)$ and $(PDF+m_Q)$ variation



MU, PDF4LHC Nov 2010



MSTW, Eur.Phys.J. C64 (2009)

Current PDF sets
Where they are...

March 2010	CTEQ6.6	MSTW08	NNPDF2.0	ABKM09	HERAPDF1.0	*JR09*
Fixed-target DIS	☑	☑	☑	☑	☒	☑
HERA DIS	☑	(☑)	☑	☑	☑	☑
Fixed-target DY	☑	☑	☑	☑	☒	☑
Tevatron W,Z	☑	☑	☑	☒	☒	☒
Tevatron jets	(☑)	☑	☑	☒	☒	(☑)
GM-VFN scheme	☑	☑	☒	☒	☑	☒
NNLO	☒	☑	☒	☑	(☑)	☑
α_S variation	☑	☑	☑	☒	☒	☒
m_Q variation	☒	☑	☑	☒	☒	☒

LHAPDF v5.8.2

November 2011	CT10(w)	MSTW08	NNPDF2.1(2.2)	ABKM09	HERAPDF1.5	*JR09*
Fixed-target DIS	☑	☑	☑	☑	☒	☑
HERA DIS	☑	(☑)	☑	☑	☑	☑
Fixed-target DY	☑	☑	☑	☑	☒	☑
Tevatron W,Z	☑	☑	☑	☒	☒	☒
Tevatron jets	☑	☑	☑	☒	☒	(☑)
LHC data	☒	☒	☑	☒	☒	☒
GM-VFN scheme	☑	☑	☑	☒	☑	☒
NNLO	☒	☑	☑	☑	☑	☑
α_S variation	☑	☑	☑	☒	☑	☒
m_Q variation	☑	☑	☑	☒	☑	☒

LHAPDF v5.8.6

Implicit criterion: only what is public in LHAPDF exists

Current PDF sets
...and where they are going

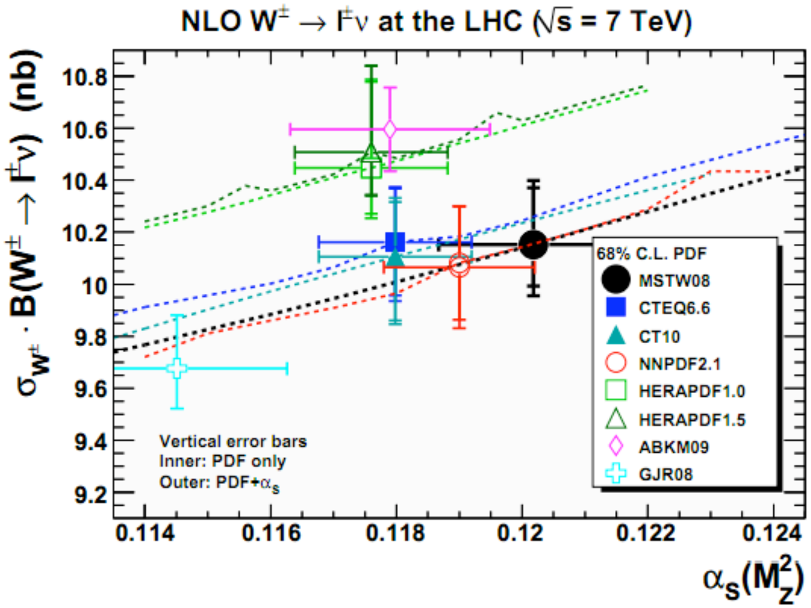
highlights from EW working group+PDF4LHC meeting, November 2011
https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=145744

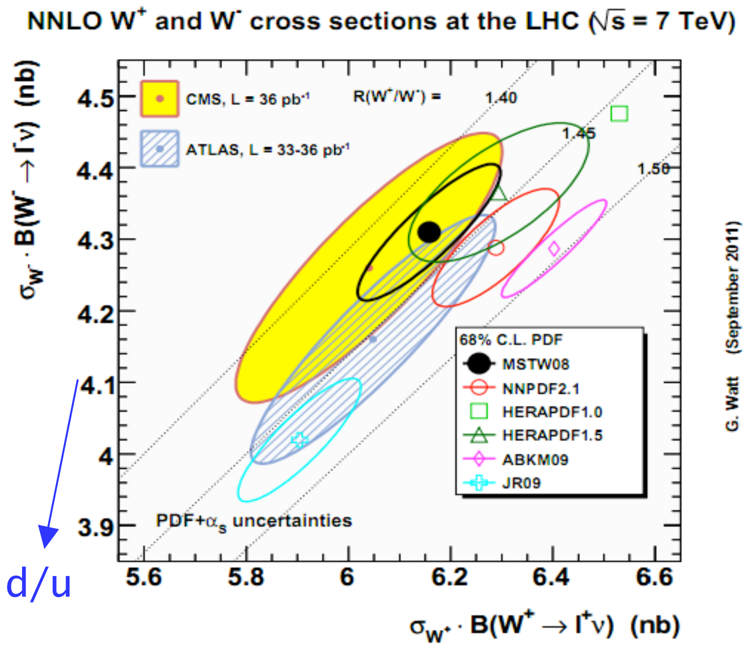
- CT10(w): release a NNLO analysis
- MSTW08: performing studies Hessian versus Monte Carlo method for uncertainty determination
- NNPDF: inclusion of more LHC data (NNPDF2.3 and NNPDF3.0)
- ABM: release ABM10 and ABM11 with more HERA data, running HQ mass
- HERAPDF: release HERAPDF1.6 and HERAPDF1.7 combining HERA-I, HERA-II and HERA jets data
- HERAFITTER: new project trying to put together HERA and LHC data

November 2011	CT10(w)	MSTW08	NNPDF2.1(2.2)	ABKM09	HERAPDF1.5	JR09
Fixed-target DIS	☑	☑	☑	☑	☒	☑
HERA DIS	☑	☑	☑	☑	☑	☑
Fixed-target DY	☑	☑	☑	☑	☒	☑
Tevatron W,Z	☑	☑	☑	☒	☒	☒
Tevatron jets	☑	☑	☑	☒	☒	☑
LHC data	☒	☒	☑	☒	☒	☒
GM-VFN scheme	☑	☑	☑	☒	☑	☒
NNLO	☒	☑	☑	☑	☑	☑
α_S variation	☑	☑	☑	☒	☑	☒
m_Q variation	☑	☑	☑	☒	☑	☒

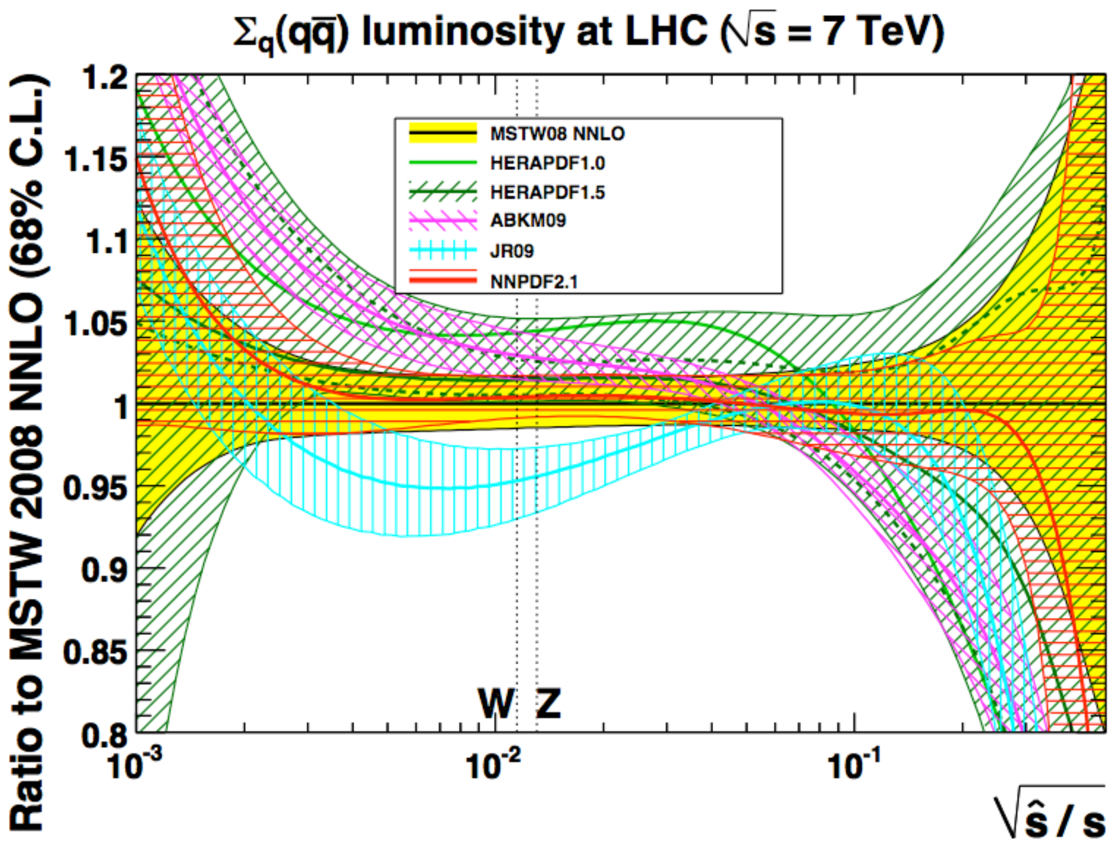
LHAPDF v5.8.6

Going towards agreement?
Quark-quark luminosities



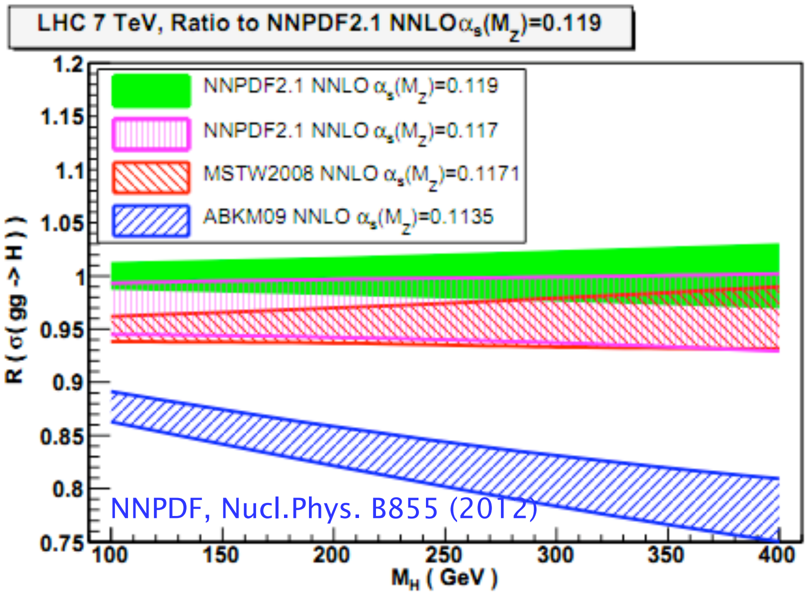


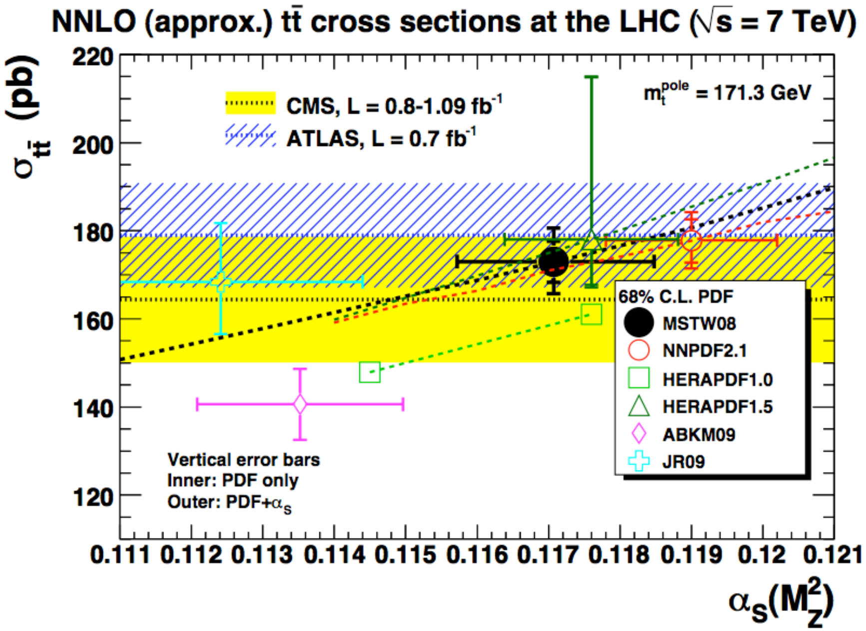
G. Watt http://projects.hepforge.org/mstwpdf/pdf4lhc/ringberg/



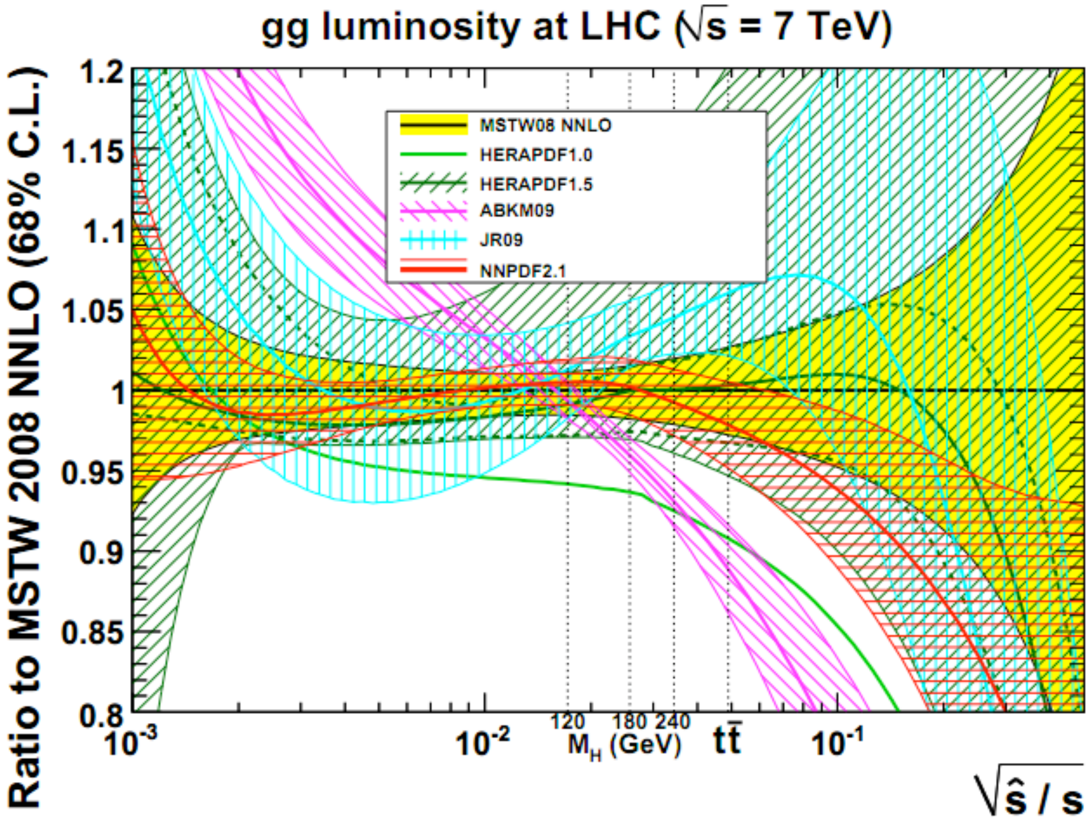
- Noticeable agreement among global sets (MSTW and NNPDF at NNLO plus CT10 at NLO)
- Less agreement with JR and ABKM
- Observables related to QQ luminosity do not depend much on $\alpha_S(m_Z)$

Going towards agreement?
Gluon-gluon luminosities





G. Watt http://projects.hepforge.org/mstwpdf/pdf4lhc/ringberg/

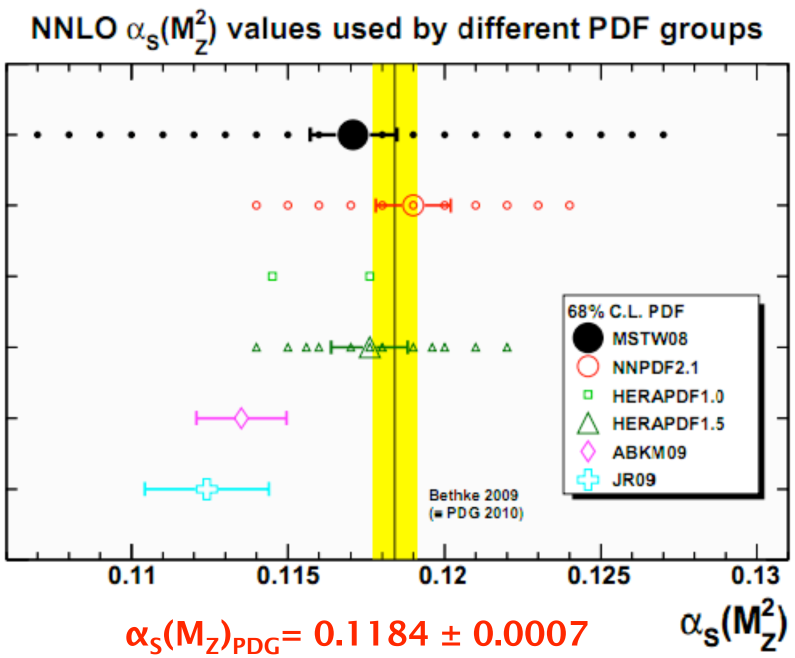


- Noticeable agreement among global sets (MSTW and NNPDF at NNLO plus CT10 at NLO)
- Less agreement with JR and ABKM
- Observables related to GG luminosity do depend a lot on $\alpha_S(m_Z)$
- The $\alpha_S(m_Z)$ puzzle

The α_s puzzle

only statistical uncertainty quoted

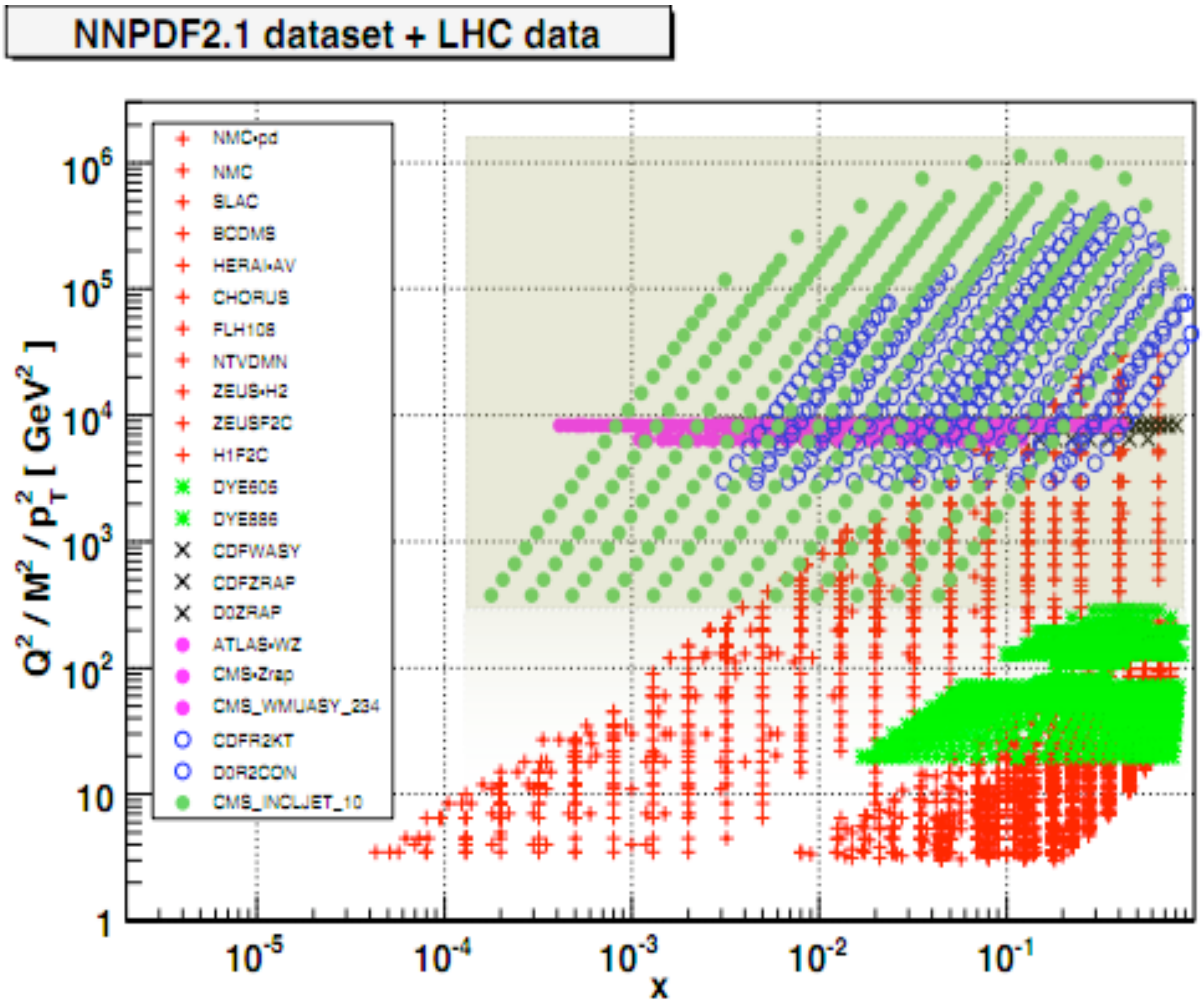
Analysis	$\alpha_s(M_Z)$ NLO	$\alpha_s(M_Z)$ NNLO	Ref.
MSTW08	$0.1202^{+0.0012}_{-0.0015}$	0.1171 ± 0.00114	MSTW, Eur.Phys.J. C63 (2009)
NNPDF2.1	0.1191 ± 0.0006	0.1173 ± 0.0007	NNPDF, Phys.Lett. B701 (2011) & 1110.2483
CT10	0.11964 ± 0.0064	*0.118 ± 0.005*	*prel. (P. Nadolsky talk)*
NNPDF2.1 (DIS only)	0.1178 ± 0.0009	0.1166 ± 0.0008	NNPDF, Phys.Lett. B701 (2011) & 1110.2483
HERAPDF		*0.1202 ± 0.0019*	*prel. (M.Cooper talk)*
ABKM09	0.1179 ± 0.0016	0.1135 ± 0.0014	Alekhin et al, Phys.Rev. D81(2010)
JR09	0.1145 ± 0.0018	0.1124 ± 0.0020	JR, Phys.Rev. D79 (2009)



$\alpha_S(M_Z)_{PDG}$= 0.1184 ± 0.0007

- Several parton sets provide range of PDF sets at several α_S values
- BUT for some PDF sets α_S is a parameter of the fit: impossible to disentangle PDF and α_S
- $\alpha_S(m_Z)$ determined in NNLO PDF analyses disagree more than quoted uncertainties
- Global sets (and prel. HERA+jets) tend to agree to a higher value compatible with PDG average
- For some non global α_S determination, $\alpha_S(M_Z)$ is much below PDG average
- Jets data stabilize analysis? Something more to be understood?

Constraints from LHC data



J. Rojo, PDF4LHC November 2011

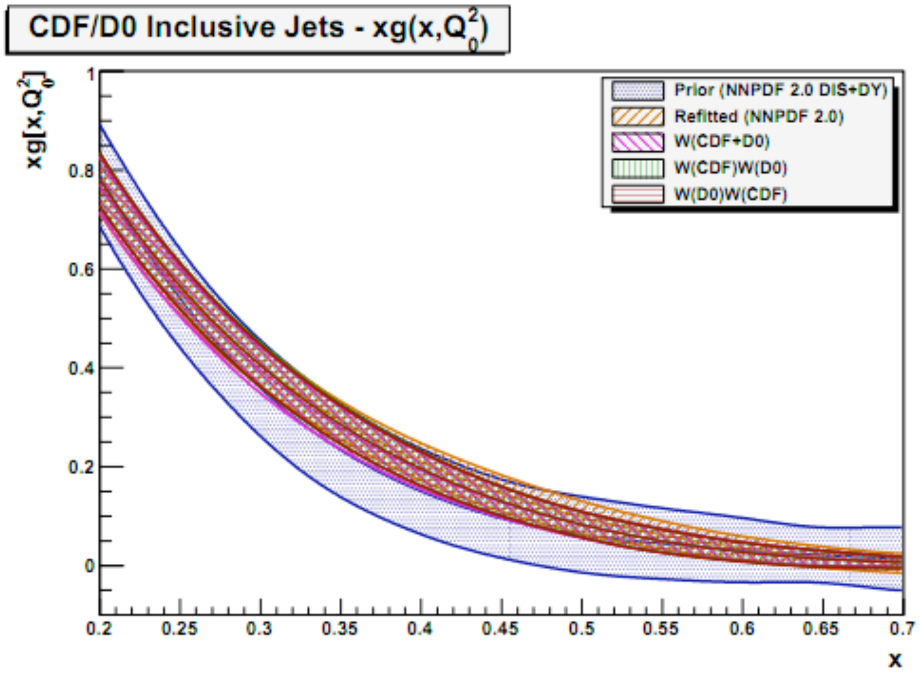
- Medium and large x gluon
  - Prompt photon
  - Precision jets data
  - Top pairs
- Light flavors at medium and small x
  - Low-mass Drell-Yan
  - Z rapidity distributions
  - W asymmetries
  - Polarized W
- Strangeness and heavy flavors
  - Wc for strangeness
  - Zc and γc for charm
  - Zb for bottom

Assess the impact of the LHC data

- To include LHC data in parton fits, TOOLS to interface slow NLO/NNLO codes to the fit are essential

APPLGRID [T. Carli et al, Eur.Phys.J. C66 (2010)]
FASTNLO [T. Kluge et al, hep-ph/0609285]
FASTDY [NNPDF, Nucl.Phys. B838 (2010)]

- It is nice to have a tool to estimate quickly the impact of new data without refitting
- Reweighting: an ensemble of MC PDF replicas gives a representation of probability density
  ➔ Update the "old" probability density upon the addition of new data



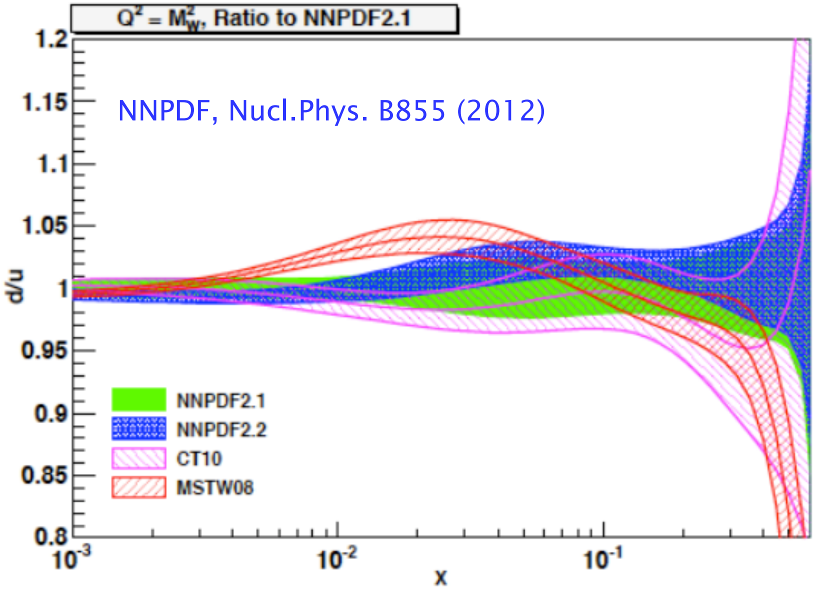
NNPDF, Nucl.Phys. B855 (2012)

✓ Reweighting equivalent to refitting
✓ Any external user can do it!

✓ A lot of activity in this direction

- NNPDF studies
  Tevatron W lepton asymmetry [Nucl.Phys.B849 (2011)]
  LHC W lepton asymmetry [Nucl.Phys.B855 (2012)]
  Inclusion of more LHC data [J Rojo, PDF4LHC Nov. 2011]
- LHCb studies [De Lorenzi, PDF4LHC Apr. 2010]
- Prompt photon data [D'Enterria, PDF4LHC Nov. 2011]
- MSTW prel. studies [G. Watt, PDF4LHC Nov. 2011]

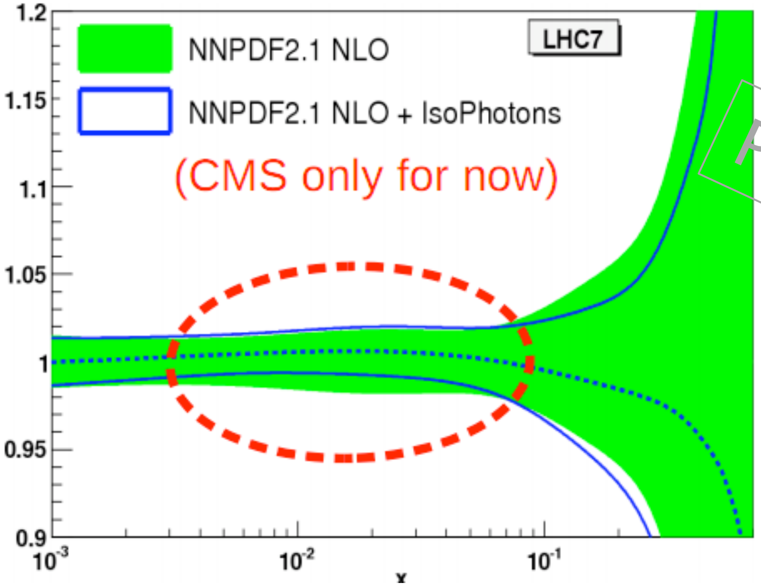
Some results



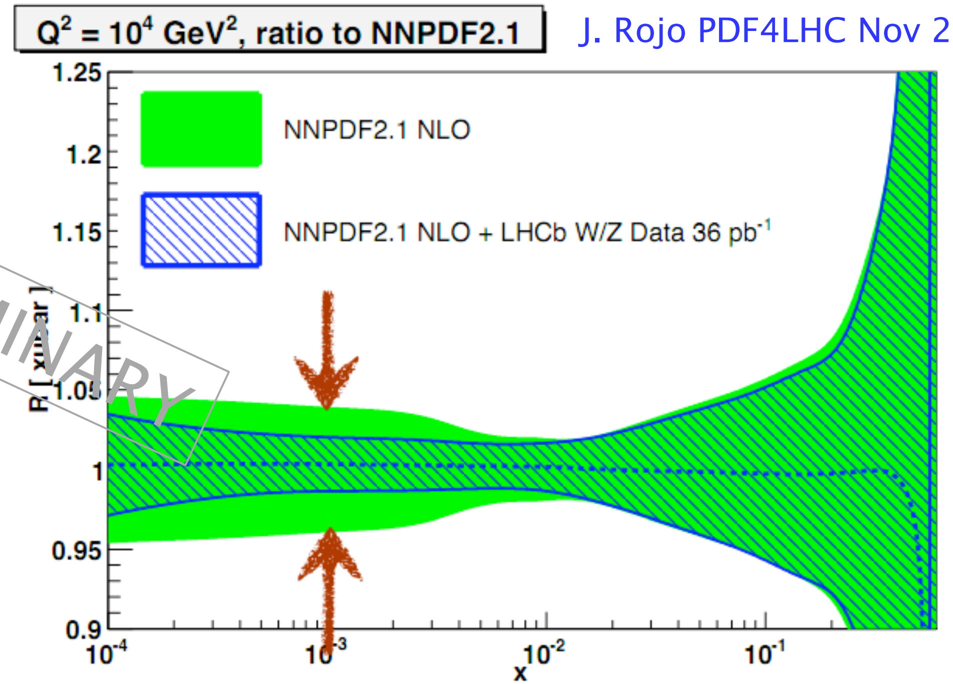
- W lepton asymmetry data from ATLAS and CMS → medium, small-x region light quarks/antiquarks
- LHCb high rapidity data → small-x region
- Direct photon → medium-x gluon

LHC data already have a non-negligible impact!!

D'Enterria, PDF4LHC Nov 2011



J. Rojo PDF4LHC Nov 2011



Summary and outlook

- PDF uncertainties play a crucial role in LHC phenomenology

- During the last few years the determination of PDFs has enormously improved both from statistical and theoretical point of views

- There are now 5 collaborations that provide up-to-date parton sets

⇨ How do we interpret the differences among these parton sets?

  - Here provided some criteria: parametrization, data, α_S ...
  - Still some discrepancies are unclear: more benchmarks needed? Probably yes...
  - Envelope of 5 predictions is a poor solution!
  - PDF4LHC recipe: choose global fits (predictions tend to agree to each others)

- PDF uncertainties are purely experimental

⇨ Theoretical uncertainty is still an unexplored field, time to start!

- LHC data already provide important constraints to PDFs and start discriminating among predictions!

⇨ Inclusion by reweighting/refitting is crucial for obtaining up-to-date parton sets

⇨ Towards collider only fit (HERA, Tevatron, LHC)?

Back-up

Alternative tables

	Data	Parametrization	Stat. treatment	Pert. Order	HQ scheme	α_S
CT10(w)	global DIS (FT + HERA) DY (FT + TeV) Inclusive Jets	* 6 independent f_i * Polynomial par (26 pars)	Hessian with fixed tolerance	NLO	S-ACOT-χ	external parameter - several α_S values
MSTW08	global DIS (FT + HERA) DY (FT + TeV) Inclusive Jets	* 7 independent f_i * Polynomial par (20 pars)	Hessian with dynamic tolerance	LO NLO NNLO	ACOT + TR'	external parameter - several α_S values + fitted
NNPDF2.1 (NNPDF2.2)	global DIS (FT + HERA) DY (FT + TeV) Inclusive Jets (+ LHC data)	* 7 independent f_i * Neural Networks (259 pars)	Monte Carlo sampling + Cross validation	LO NLO NNLO	FONLL-A	external parameter - several α_S values
HERAPDF1.5	only DIS HERA-I + prel. HERA-II	* 5 independent f_i * Polynomial par (14 pars)	Conventional Hessian (Monte Carlo)	NLO NNLO	ACOT + TR'	external parameter
ABKM09	only DIS + Fixed-Target DY	* 6 independent f_i * Polynomial par (13 pars)	Hessian wo tolerance	NLO NNLO	FFNS n_f=3,4,5	fitted,not external parameter
JR09	DIS + Jets + Fixed-Target DY	* 5 independent f_i * Valence-like assumptions	Hessian with fixed tolerance	NLO NNLO	FFN, nf=3,4,5 and VFN	fitted,not external parameter

The name of the game

- The name of the game:
Determine a set of functions and their errors starting from a bunch of experimental data

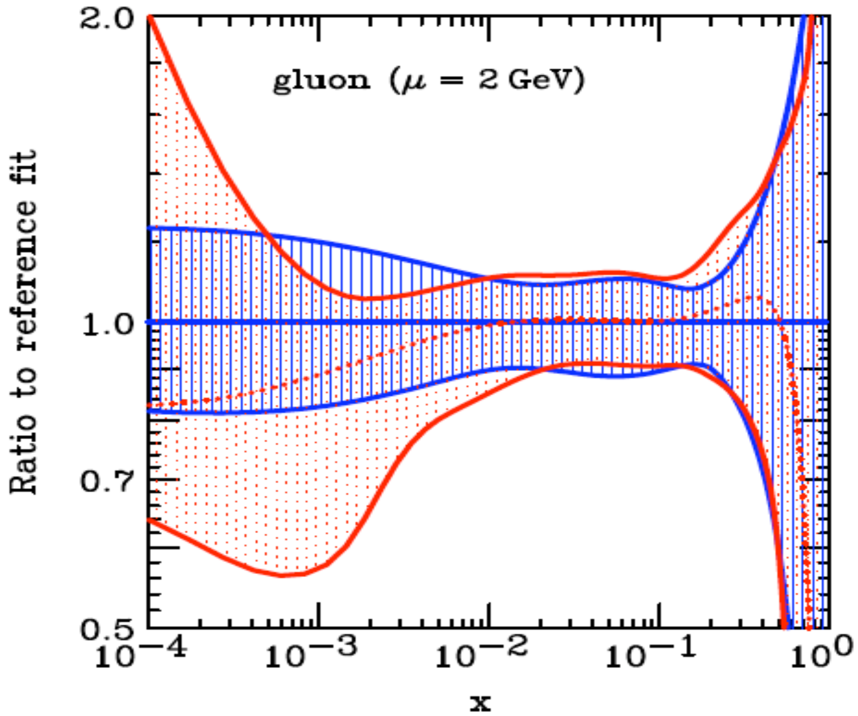
$$\langle \mathcal{F}[f(x)] \rangle = \int [\mathcal{D}f] \, \mathcal{F}[f(x)] \mathcal{P}[f(x)]$$

- Determine a infinite-dimensional object with a finite number of constraints!

- Standard approach:
Project into a space of parameters and use Hessian method

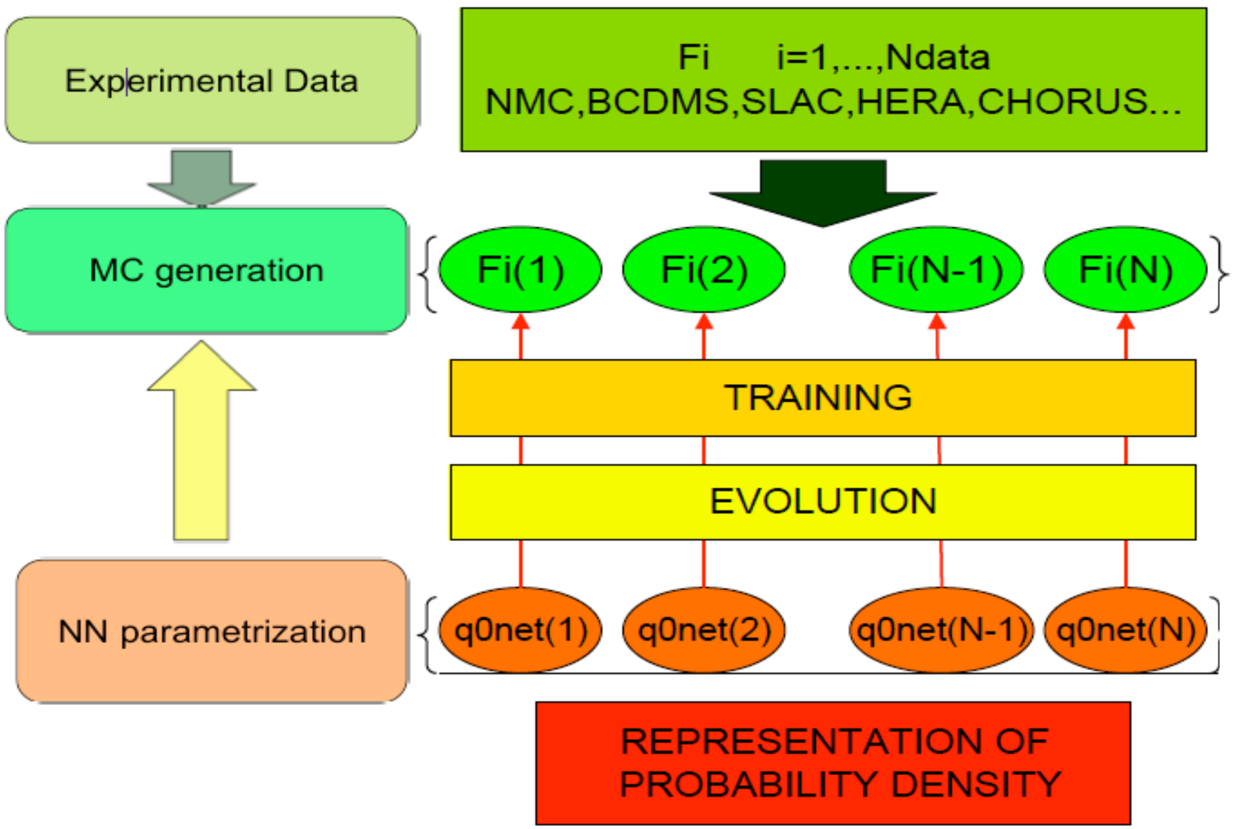
$$f_i(x, Q_0^2) = a_0 \, x^{a_1} \, (1-x)^{a_2} P(x, a_3, a_4, \ldots),$$

- Is the parametrization flexible enough?
- What is the error associated to any particular choice?
- Has to rely on linear propagation of errors and on tolerances



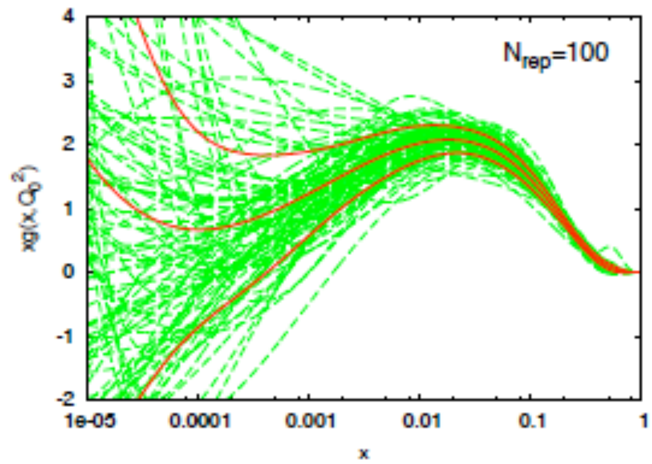
Lai et al.,Phys.Rev. D82 (2010) 074024

The NNPDF method for extracting PDFs



$$\langle \mathcal{F}[f(x)] \rangle = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \mathcal{F}[f^{(k)({\rm net})}(x)]$$

$$\sigma_{\mathcal{F}[f(x)]} = \sqrt{\langle \mathcal{F}[f(x)]^2 \rangle - \langle \mathcal{F}[f(x)] \rangle^2}$$



$$F_{i,p}^{(art)(k)} = S_{p,N}^{(k)} F_{i,p}^{\rm exp} \left(1 + r_p^{(k)} \sigma_p^{\rm stat} + \sum_{j=1}^{N_{\rm sys}} r_{p,j}^{(k)} \sigma_{p,j}^{\rm sys} \right)$$

FONLL: heavy quark scheme

- NNPDF2.1 implements the **FONLL method**:
  prescription for combining **massive quarks** in the decoupling scheme $N_F = 3$ and **massless quarks** in the $\overline{MS}$ scheme $N_F = 4$, at any given order, **avoiding double counting**.
  Reference: S.Forte, E.Laenen, P.Nason, J. Rojo [ArXiv:1001.2312]

- Definition of FONLL structure function:

$$F^{\text{FONLL}}(x, Q^2) = F^{(n_f+1)}(x, Q^2) + F^{(n_f)}(x, Q^2) - F^{(n_f,0)}(x, Q^2)$$

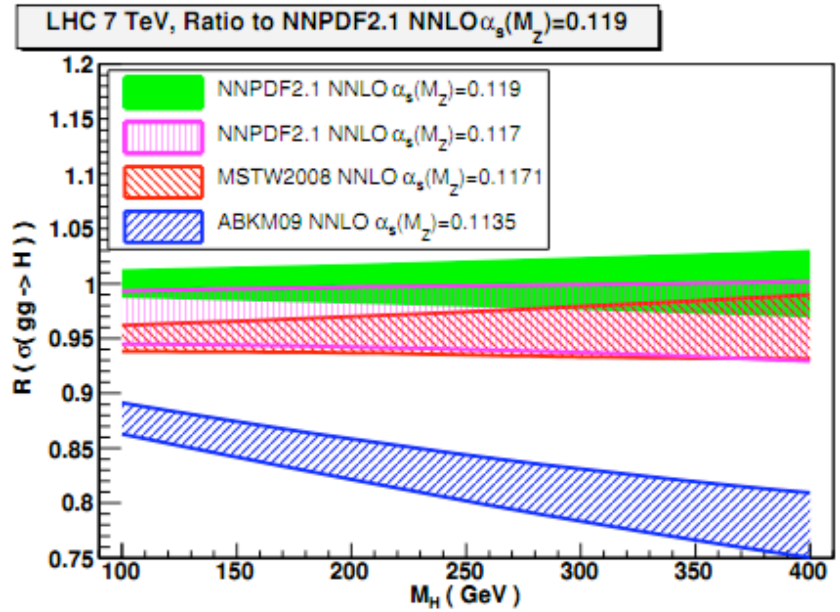
  $F^{(n_f+1)}(x, Q^2)$: massless-scheme structure function
  $F^{(n_f)}(x, Q^2)$: massive-scheme structure function $\Rightarrow$ inclusion of the mass suppressed terms
  $F^{(n_f,0)}(x, Q^2)$: massless limit of $F^{(n_f)}(x, Q^2)$ $\Rightarrow$ subtraction of the double counting terms

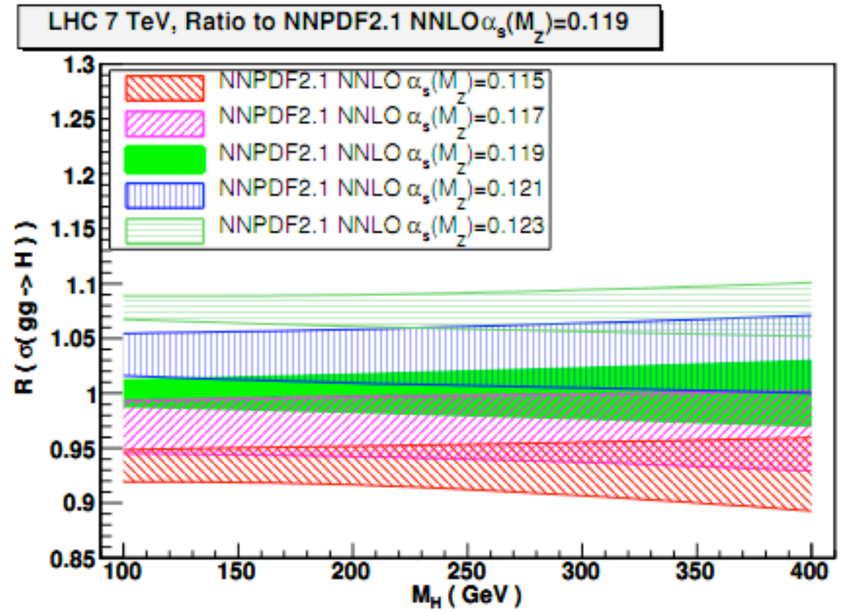
- At the moment, three possibilities:
  - FONLL-A: $\mathcal{O}(\alpha_s)$ PDFs + $\mathcal{O}(\alpha_s)$ coefficient functions (NNPDF2.1 NLO set),
  - FONLL-B: $\mathcal{O}(\alpha_s)$ PDFs + $\mathcal{O}(\alpha_s^2)$ coefficient functions,
  - FONLL-C: $\mathcal{O}(\alpha_s^2)$ PDFs + $\mathcal{O}(\alpha_s^2)$ coefficient functions (NNPDF2.1 NNLO set).

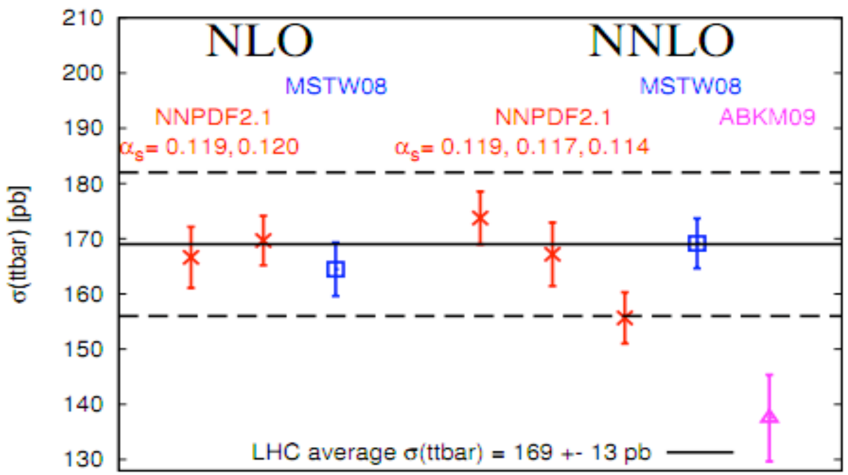
- $\mathcal{O}(\alpha_s^2)$ coefficient functions available only in the NC and not the CC sector.

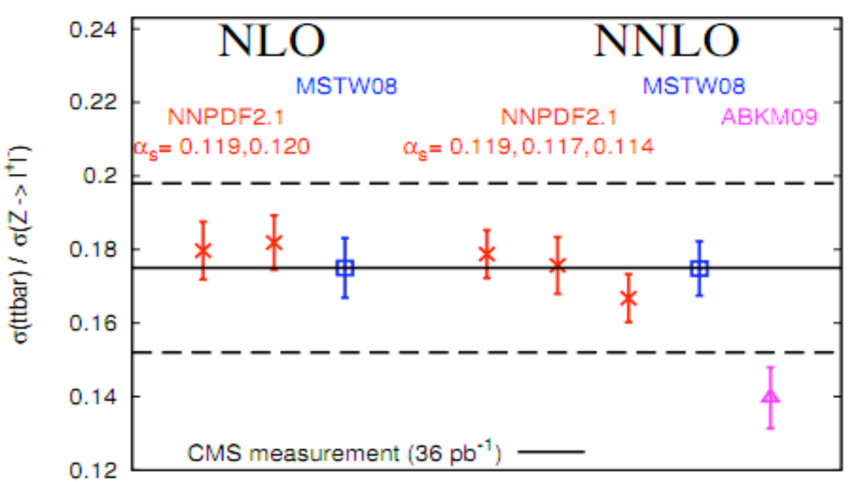
- **NNPDF2.1** is presently available in **all** the above schemes.

Higgs and ttbar: gluon luminosity

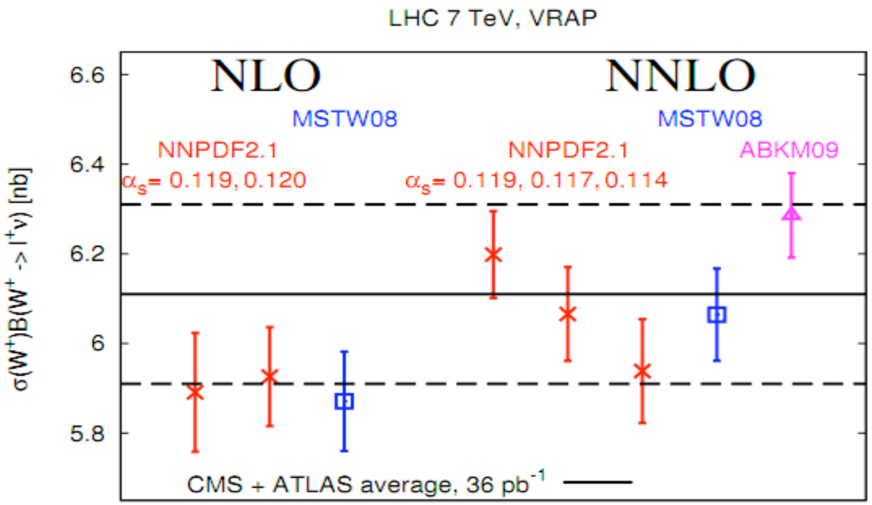


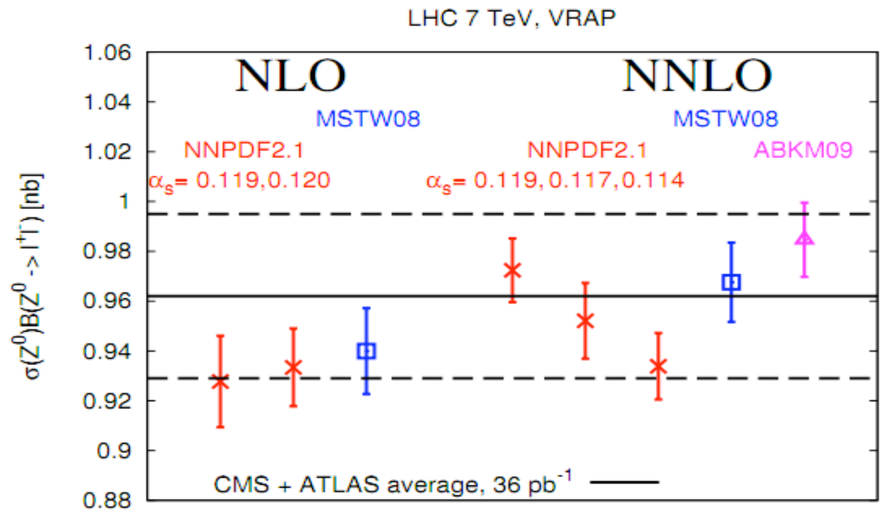




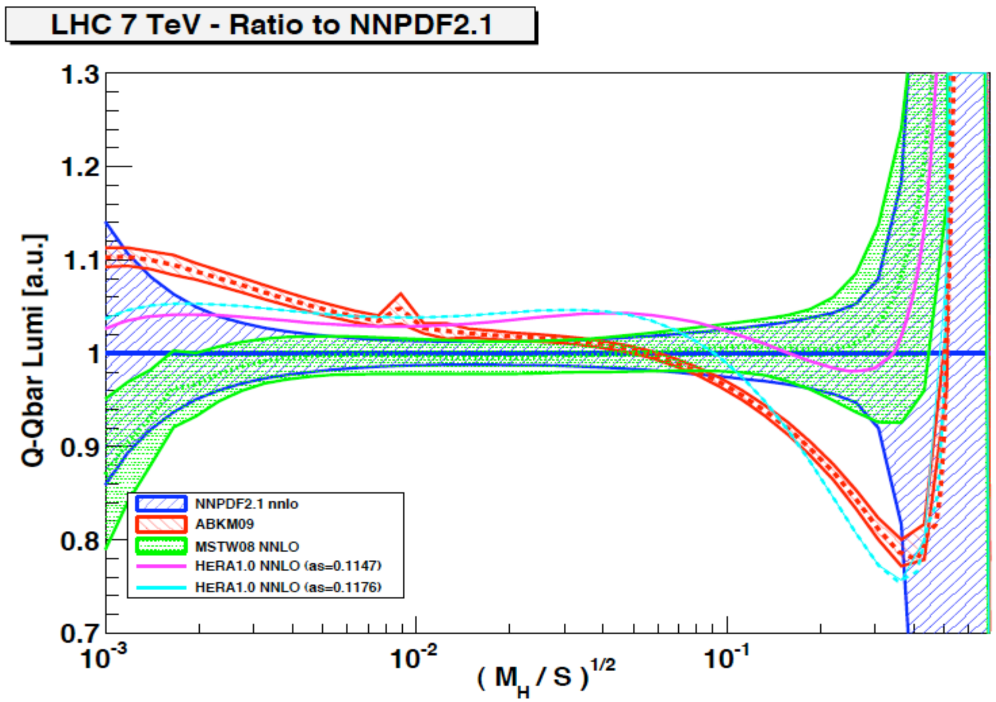


W and Z production: light flavor decomposition

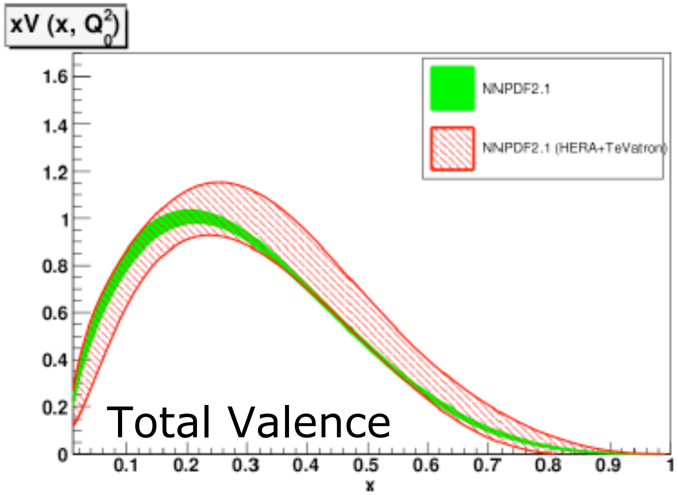


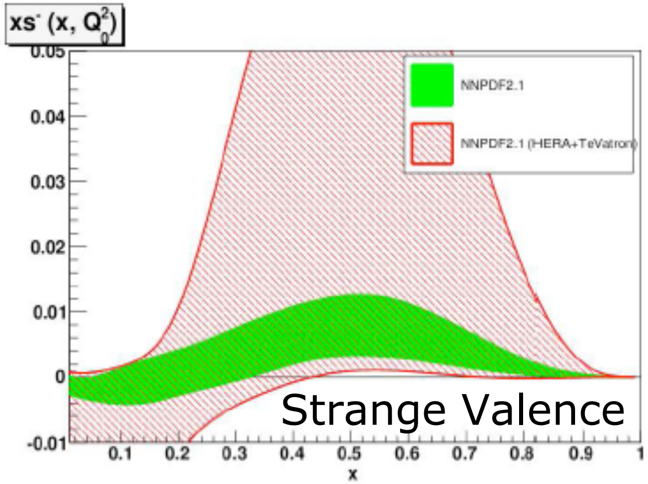


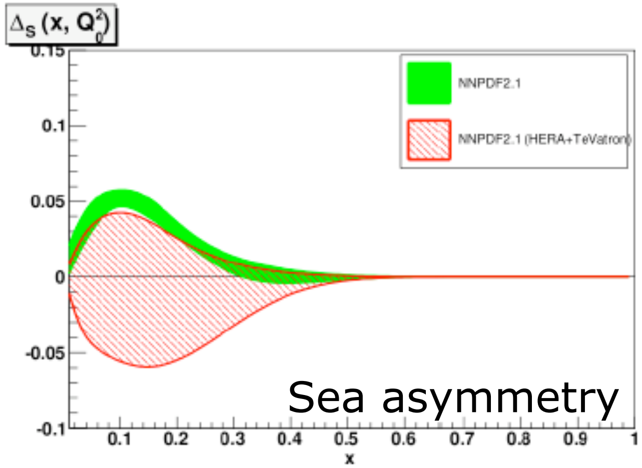
- Weaker dependence on α_S value
- Higher order corrections are important
- Less significant differences between PDF sets

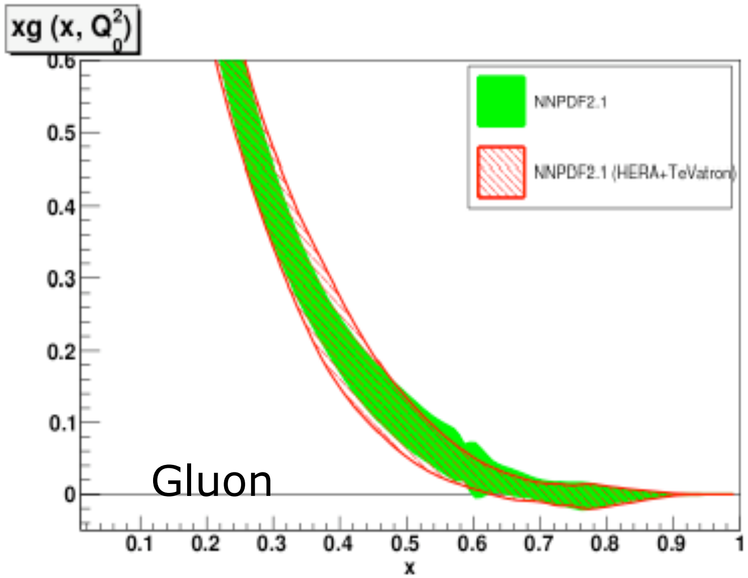


Collider-only fit









- No fixed target data
- No low energy troubles
  (nuclear corrections, higher twists...)

- HERA + Tevatron:
  - Good accuracy for gluon
  - Loss of accuracy for flavor separation and strange
  - What about HERA + Tevatron + LHC?

W lepton asymmetry data