XLIV International Symposium on Multiparticle Dynamics

PDFs is the LHC era

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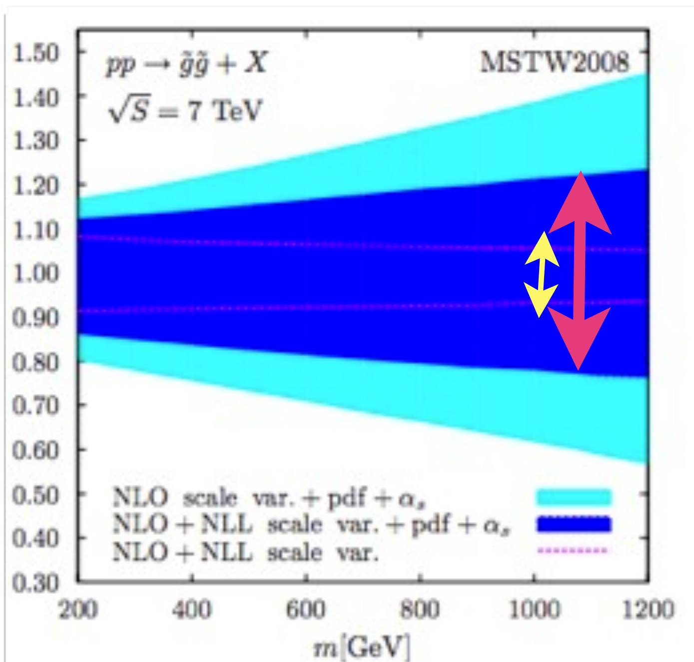
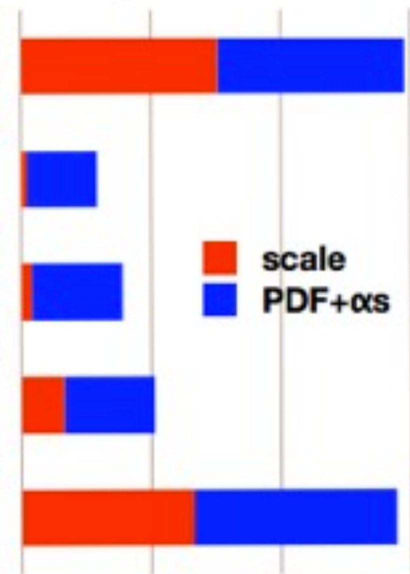
PDFs: why bother?



Beenakker et al (2011)

	σ (8 TeV)	uncertainty
gg→H	19.5 pb	14.7%
VBF	1.56 pb	2.9%
WH	0.70 pb	3.9%
ZH	0.39 pb	5.1%
ttH	0.13 pb	14.4%



J. Campbell, ICHEP 2012

PDFs

PDF uncertainties are a crucial input at the LHC, often being the limiting factor in the accuracy of theoretical predictions, both SM and BSM

LHC

Exploit the power of precise LHC data to reduce PDF uncertainties and discriminate among PDF sets

Outline

- Introduction
- Progress and frontiers in PDF determination
  - The past: progress in recent years
  - The state of the art
  - The future: frontiers in PDF determination
- Conclusions and outlook

Parton Distribution Functions

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

PDFs cannot be computed in perturbative QCD but they are universal and their evolution with the scale is predicted by pQCD

$$\mu^2 \frac{\partial\, f(x,\mu^2)}{\partial\, \mu^2} = \int_z^1 \frac{dz}{z}\, \frac{\alpha_s}{2\pi}\, P(z)\, f\left(\frac{x}{z},\mu^2\right)$$

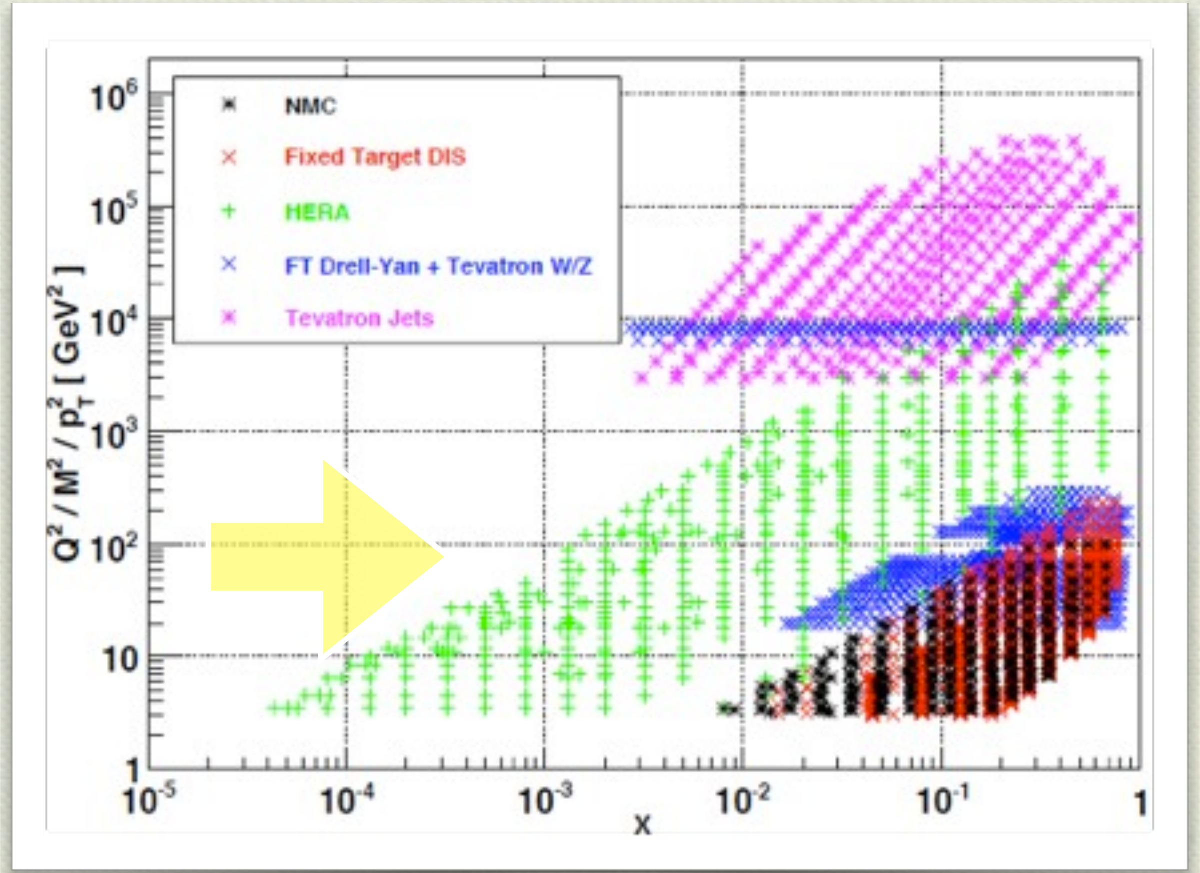
Dokshitzer, Gribov, Lipatov, Altarelli, Parisi renormalization group equations

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

Parton Distribution Functions

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

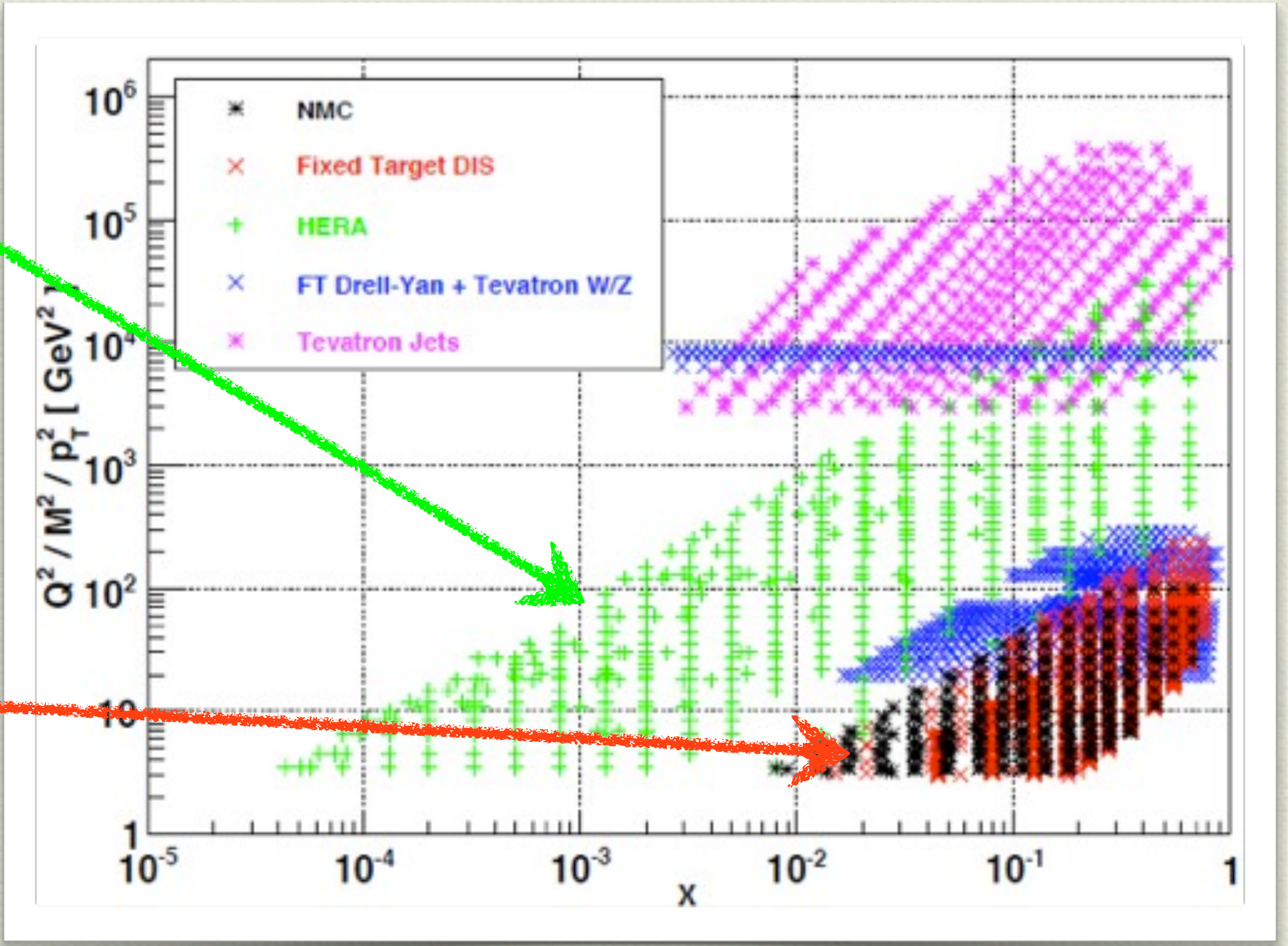
- They can be extracted from available experimental data and used as phenomenological input for theory predictions
- Different data constrain different parton combinations at different x



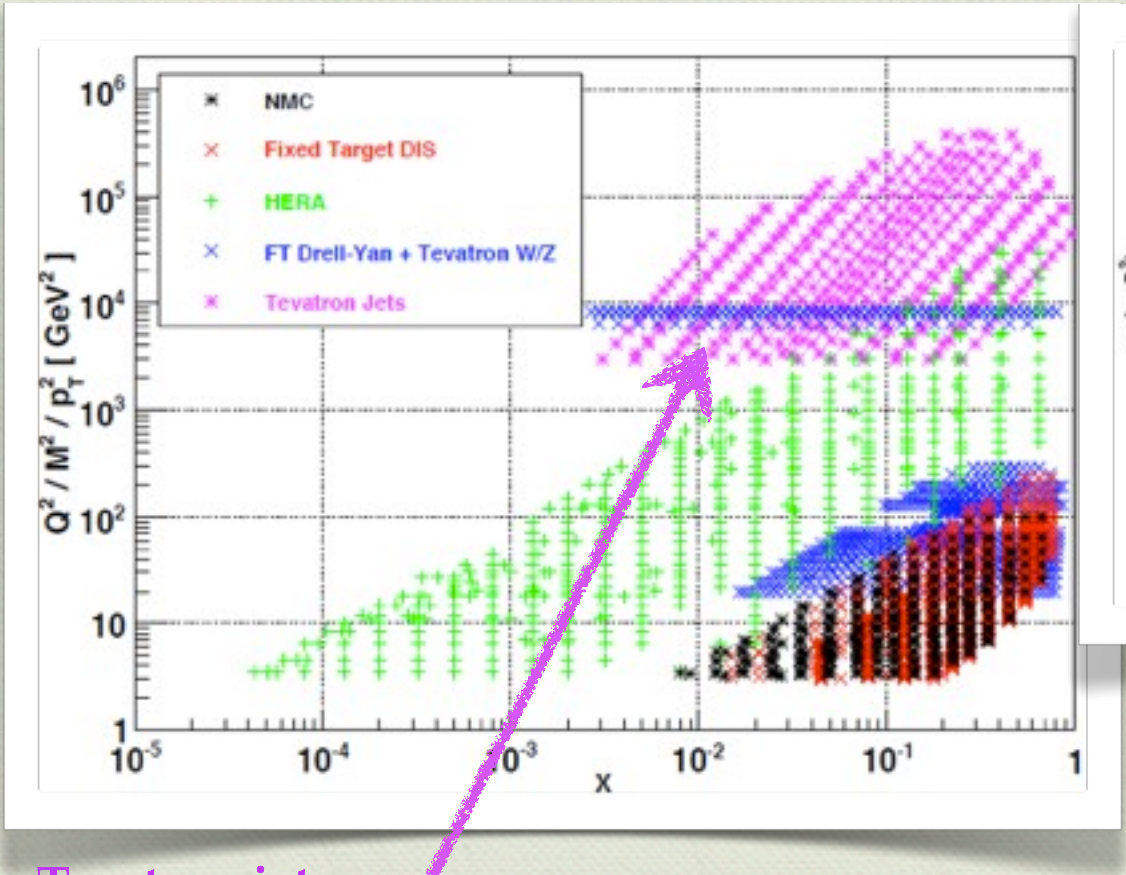
Constraints from data (pre-LHC)

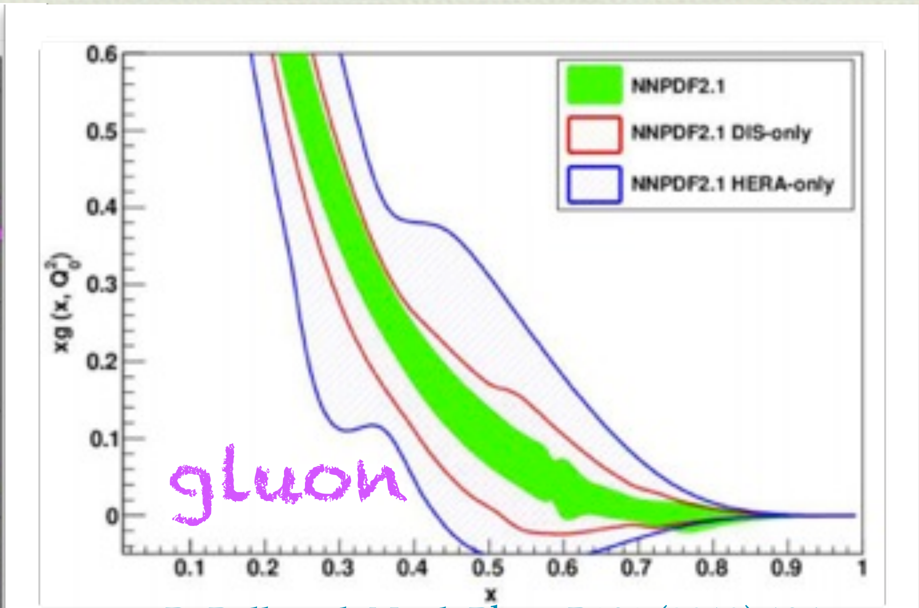
DIS data

- q,qbar at $x > 10^{-4}$
- g at small and medium x
- deuteron data: disentangle isospin triplet and singlet contributions
- neutrino DIS data: handle on strange



Constraints from data (pre-LHC)



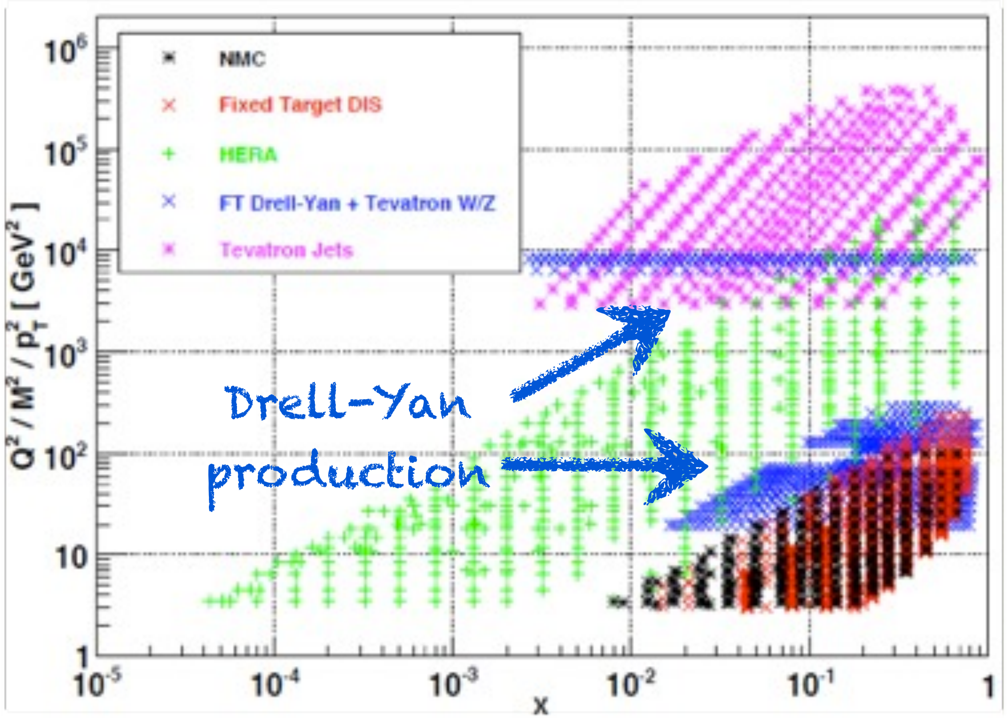


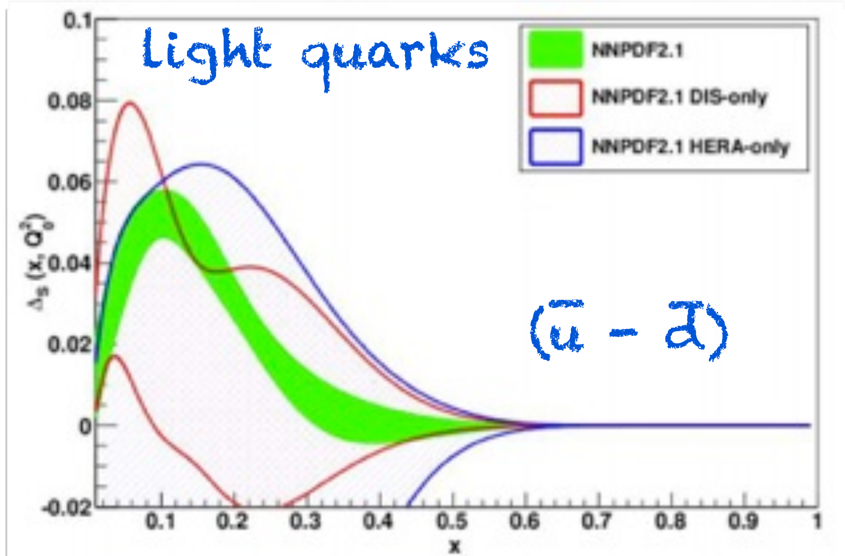
R. Ball et al. Nucl. Phys. B838 (2010) 136

Tevatron jets

- Good consistency with DIS data, i.e. scaling violation
- Largest impact on large-x gluon
- Significant improvements in accuracy, uncertainty reduced by factor of 2 for $0.1 < x < 0.7$

Constraints from data (pre-LHC)





R. Ball et al. Nucl. Phys. B838 (2010) 136

$$\sigma^{\mathrm{DY,p}} \propto u(x_1)\bar{u}(x_2) + d(x_1)\bar{d}(x_2)$$

$$\sigma^{\mathrm{DY,d}} \propto u(x_1)(\bar{u}+\bar{d})(x_2) + d(x_1)(\bar{u}+\bar{d})(x_2)$$

Old fixed-target DY **and** Tevatron vector boson production data constrain light quark separation and disentangle quark-antiquark distributions

Progress in PDF determination

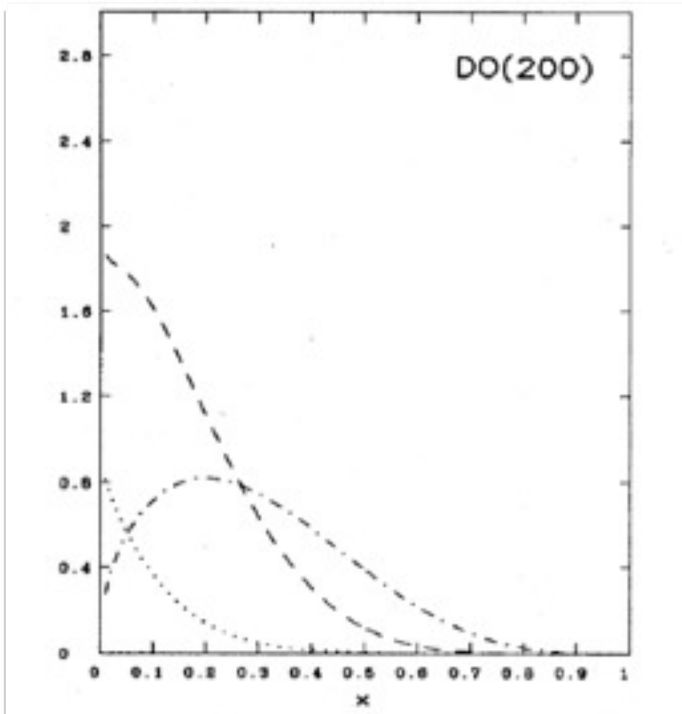
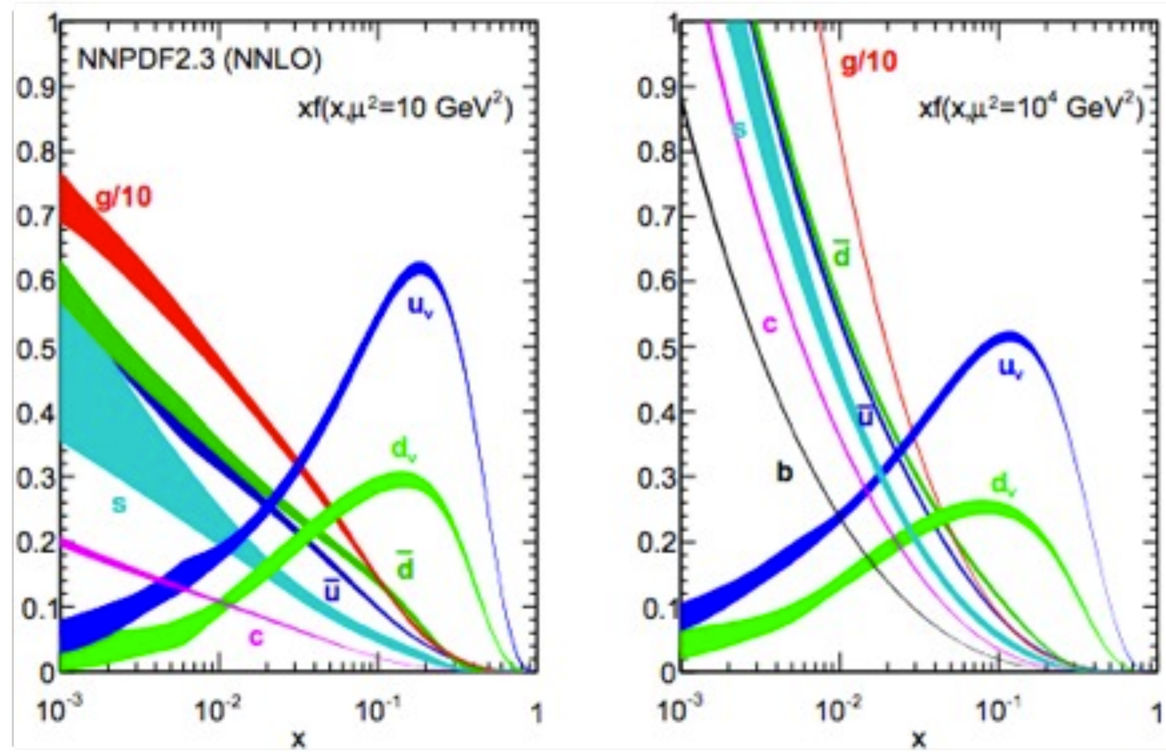


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).



PDG "Structure Functions"2013

- **< 2002:** sets without uncertainty
- **2003-2004:** first MRST, CTEQ, Alekhin sets with uncertainties
- **2004-now:** huge progress made in statistical and theoretical understanding, new players

Progress...
A personal overview

PROGRESS

THEORY

* Heavy quark schemes
* Parameters: α_S and m_Q
* (N)NLO corrections

DATA

* Treatment of correlated systematics

METH.

* Parametrization bias
* Treatment of inconsistent data

=

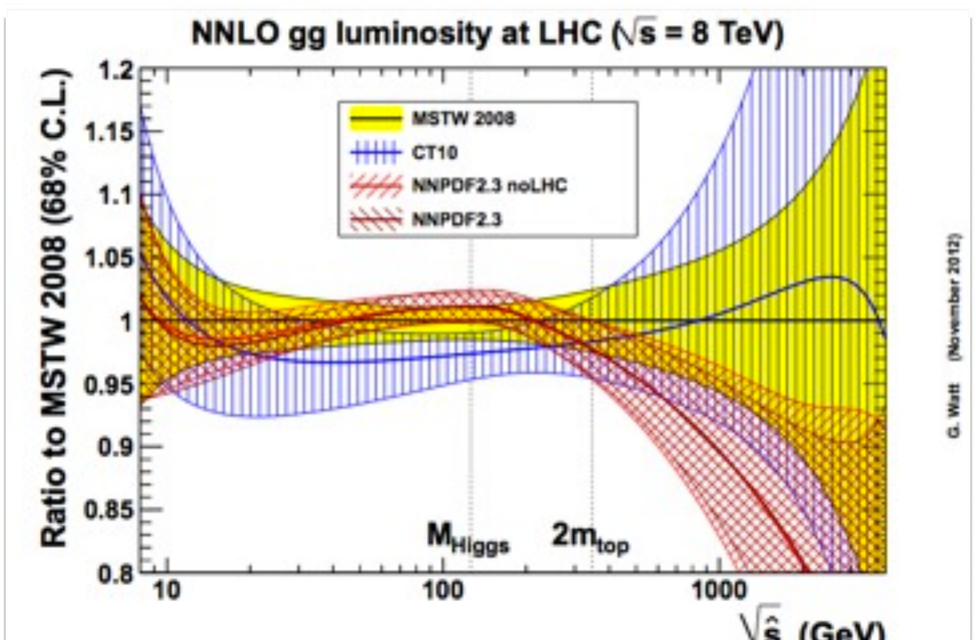
The state of the art

LHAPDF6.1.0 - https://lhapdf.hepforge.org

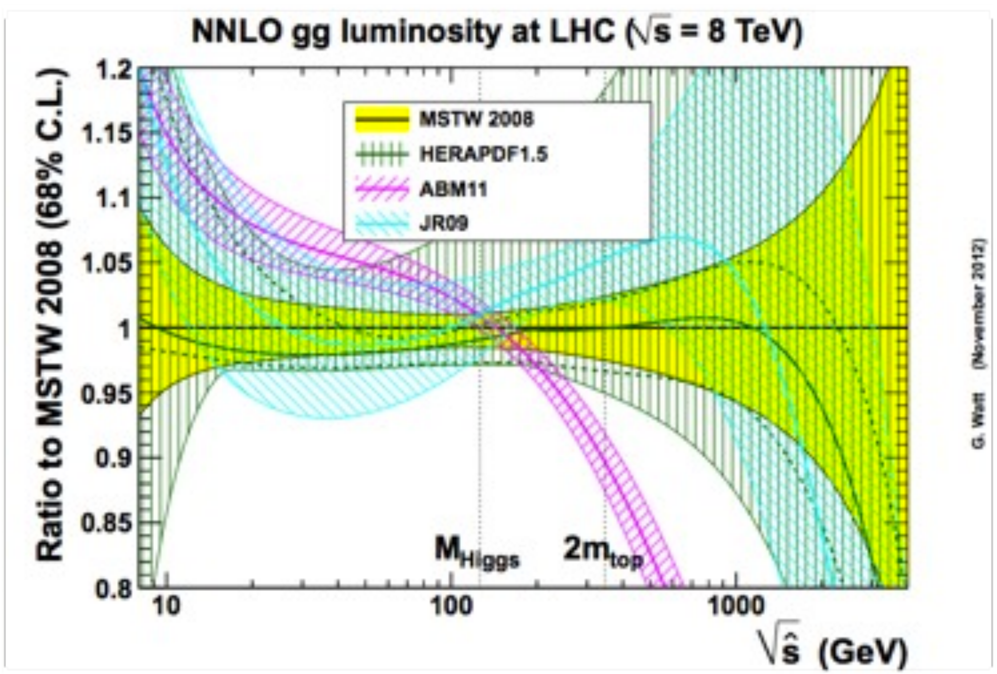
August 2014	CT10(w)	MSTW2008	NNPDF2.3	ABM12	HERAPDF15
Fixed Target DIS	✔	✔	✔	✔	✘
HERA	✔	✔	✔	✔	✔
Fixed Target DY	✔	✔	✔	✔	✘
Tevatron W,Z	✔	✔	✔	✘	✘
Tevatron jets	✔	✔	✔	✘	✘
LHC data	✘	✘	✔	✔	✘
Stat. treatment	Hessian $\Delta\chi^2 = 100$	Hessian $\Delta\chi^2$ dynamical	Monte Carlo	Hessian $\Delta\chi^2=1$	Hessian $\Delta\chi^2=1$
Parametrization	Pol. (26 pars)	Pol. (20 pars)	NN (259 pars)	Pol. (14 pars)	Pol. (14 pars)
HQ scheme	ACOT-χ	TR′	FONLL	FFN	TR′
α_S	Varied	Fitted+varied	Varied	Fitted	Varied

The state of the art

Gluon-gluon luminosity:

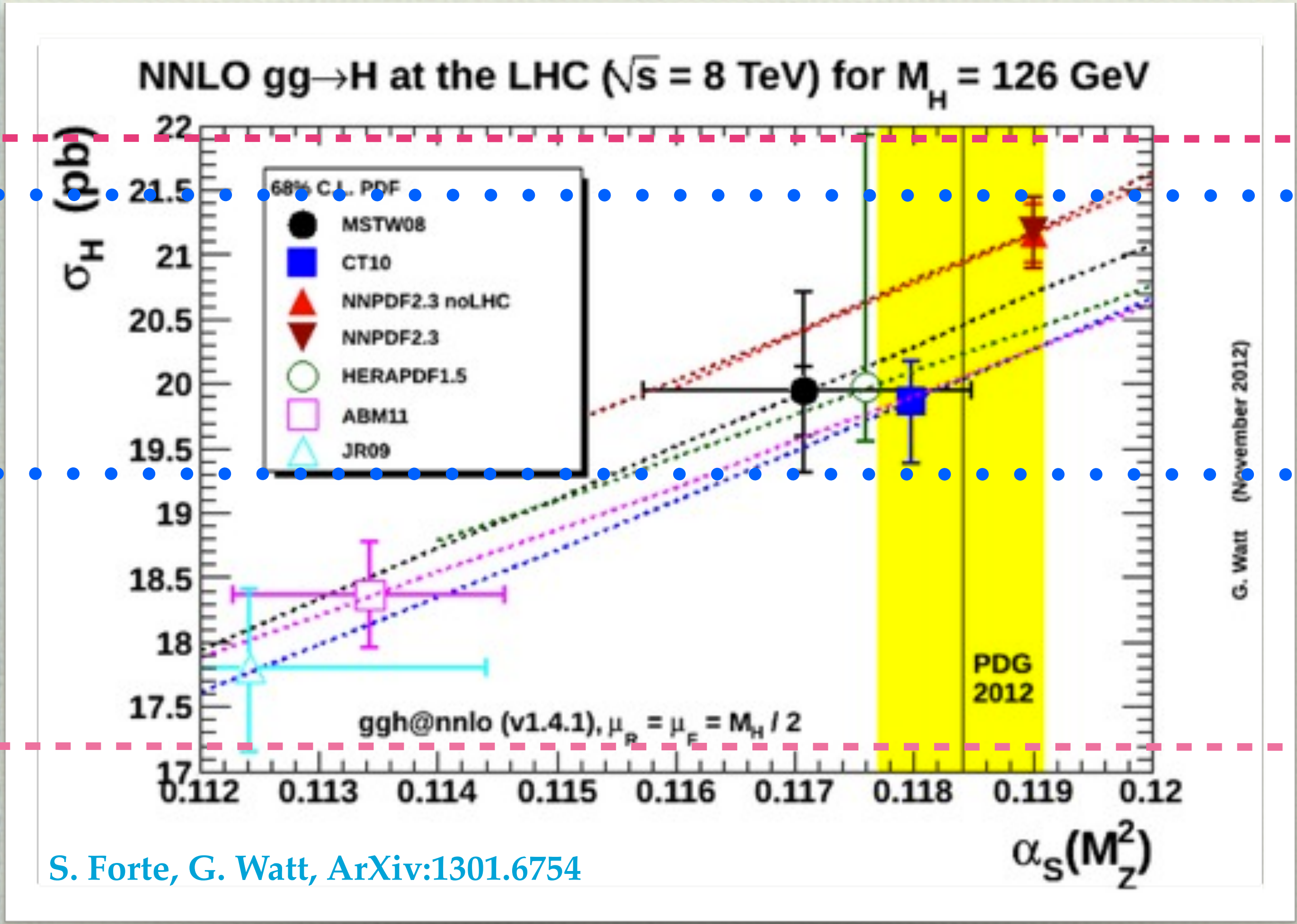


G. Watt, arXiv:1301.6754



$$\Phi_{ij}(M_X^2) = \frac{1}{s}\int_\tau^1 \frac{dx}{x} f_i(x, M_X^2)\, f_j\left(\frac{\tau}{x}, M_X^2\right)$$

The state of the art



S. Forte, G. Watt, ArXiv:1301.6754

- Gluon fusion initiated Higgs productions
- Wide spread of predictions limits accuracy in Higgs characterization
- Global sets quite close to each others and compatible to HERA analysis
- Larger discrepancies with ABM and JR
- Similar (worse) situation for ttbar cross section predictions

Progress and frontiers

A personal overview

	PROGRESS	FRONTIERS
THEORY	* Heavy quark schemes * Parameters: α_S and m_Q * (N)NLO corrections	* EW corrections * NNLO corrections * Theoretical error in PDF fits
DATA	* Treatment of correlated systematics	* LHC data, combinations from HERA, Tevatron, data from Nomad, CHORUS
METH.	* Parametrization bias * Treatment of inconsistent data	* Combine different sets of PDFs * Closure Tests

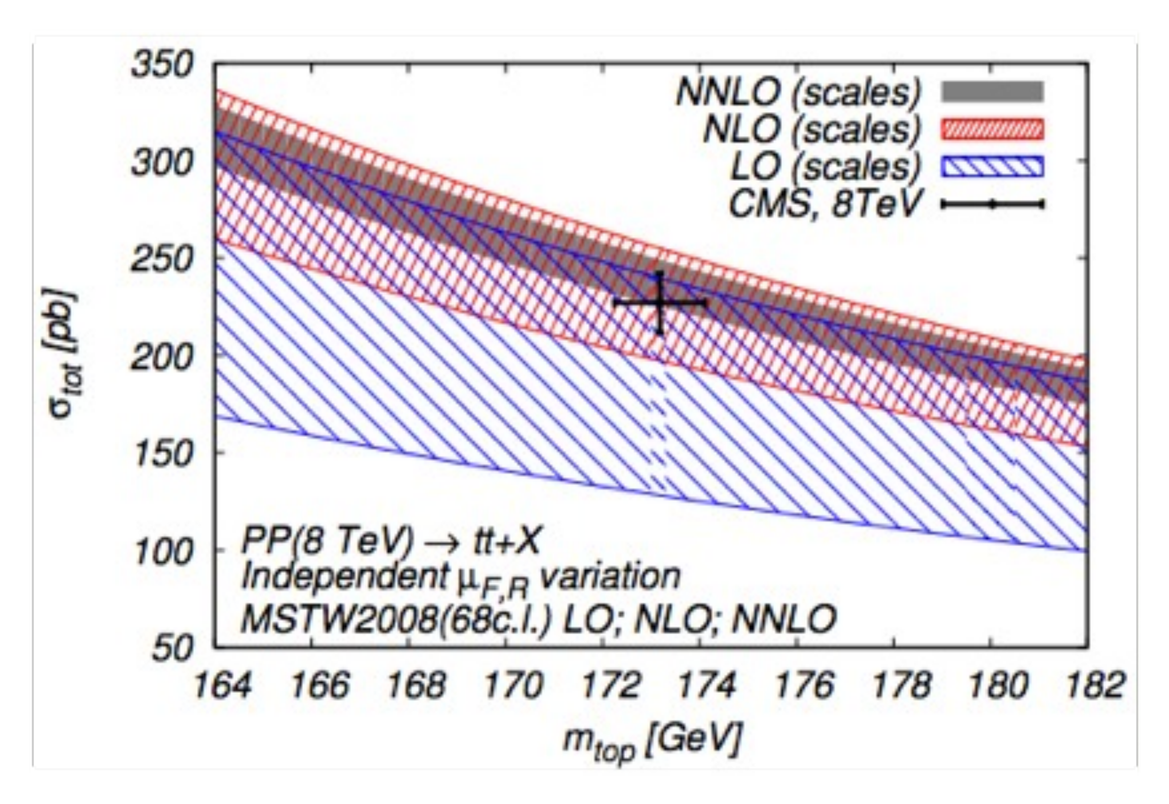
Progress and frontiers
Theory: NNLO corrections

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

✓ Full NNLO top quark production cross section is available (TOP++2.0) and differential distributions are expected soon → gluon at large x

✓ H+1j also available now at NNLO, important milestone towards Z,W+1j → gluon & quark separation

✓ NNLO inclusive jet production in the gluon gluon channel has been completed



Czakon, Fiedler, Mitov PRL 110 (2013) 25
Boughezal et al, JHEP1306 (2013) 072
Gehrmann-De Ridder et al, Phys.Rev.Lett. 110 (2013) 16

Progress and frontiers

Theory: inclusive jet cross section

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

In gg channel up to 20-25% enhancement of NNLO wrt NLO result

✓ Full NNLO top quark production cross section is available (TOP++2.0) and differential distributions are expected soon → gluon at large x

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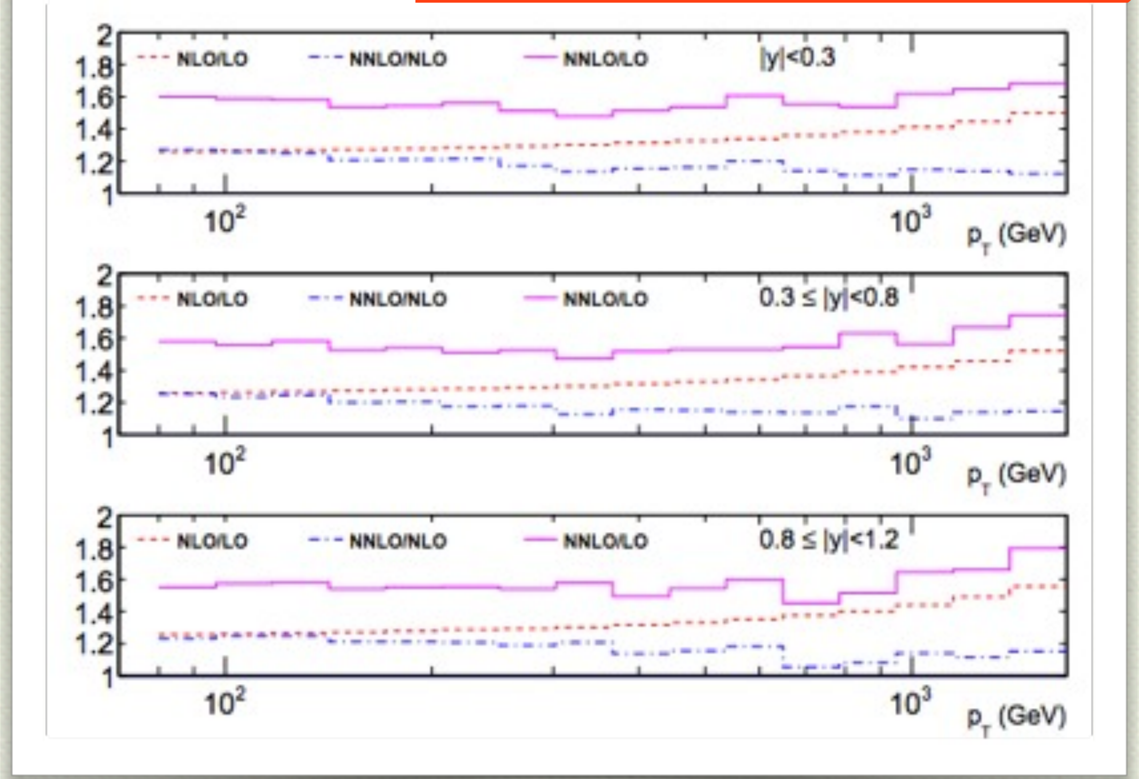


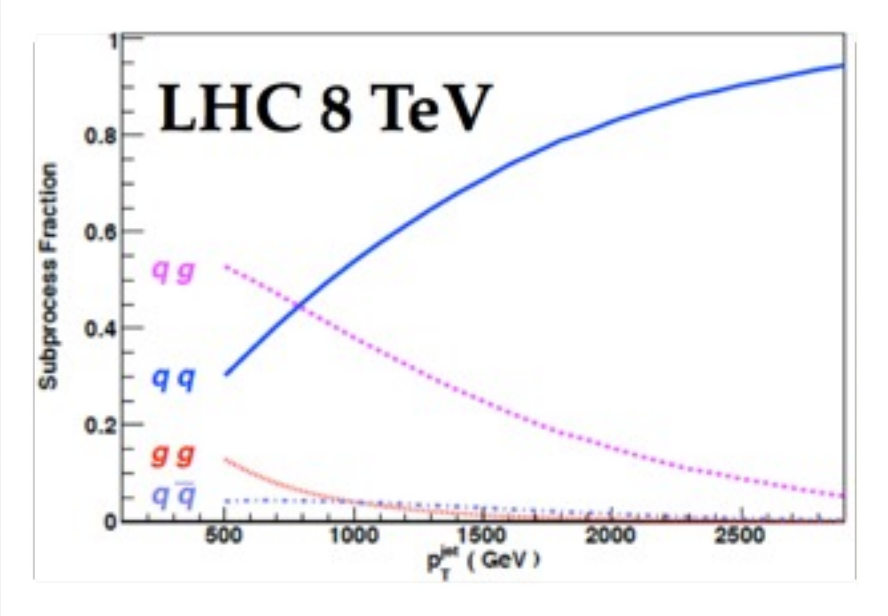
Gehrmann-De Ridder et al, Phys.Rev.Lett. 110 (2013) 16

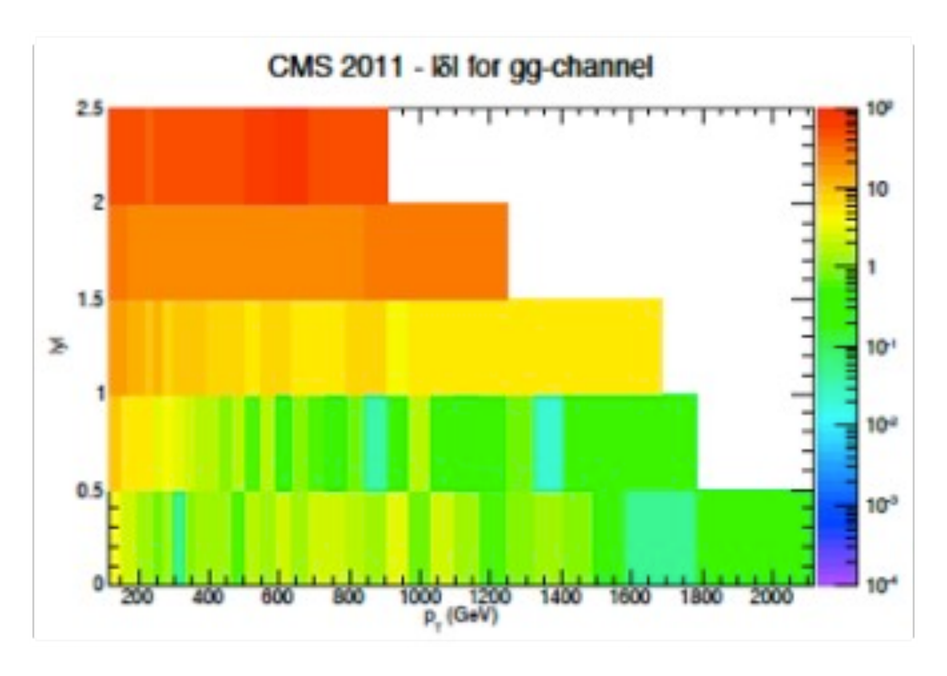
Progress and frontiers

Theory: inclusive jet cross section

- At the LHC gluon-gluon channel is small at medium-large pT
- Approximate NNLO results can be derived from the improved threshold calculation, reasonable at large pT and expected to break down at small pT

[De Florian et al, Phys.Rev.Lett. 112 (2014) 082001]





- Comparison between NNLO approximation and full NNLO in the gg channel can determine for which value of pT and η NNLO approximation can be trusted
- This assumes NNLO K-factors similar in all channels

S. Carrazza, J. Pires, arXiv:1407.7031

Progress and frontiers

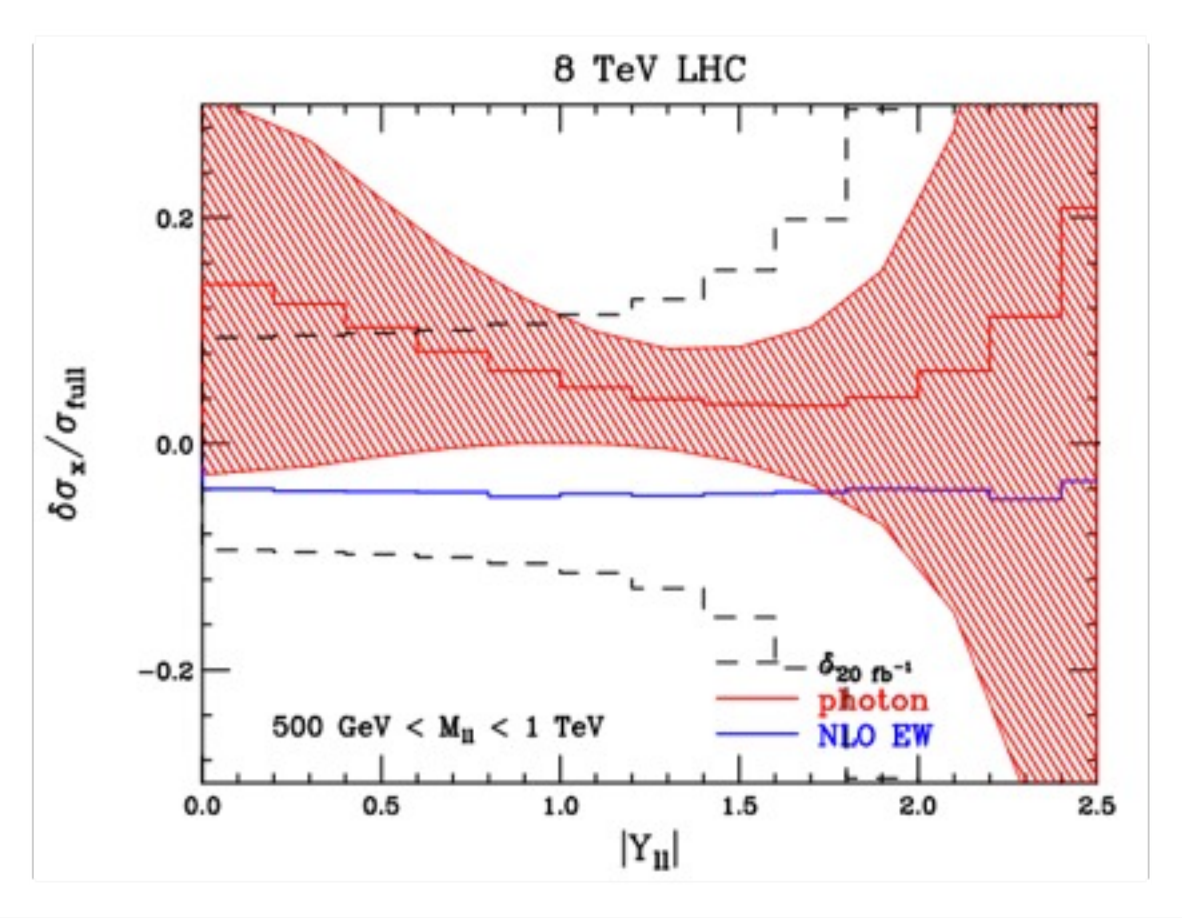
Theory: electroweak corrections

- EW corrections become relevant at the current precision level

- Several tools to compute them along with QCD corrections
[Li, Petriello, Phys.Rev. D86 (2012) 094034]

- They can be sizable especially at large invariant mass

- QED corrections affected by large uncertainty induced from uncertainty on photon PDF



Boughezal, Liu, Petriello, ArXiv:1312.4535

Progress and frontiers

Data: the LHC era

GLUON

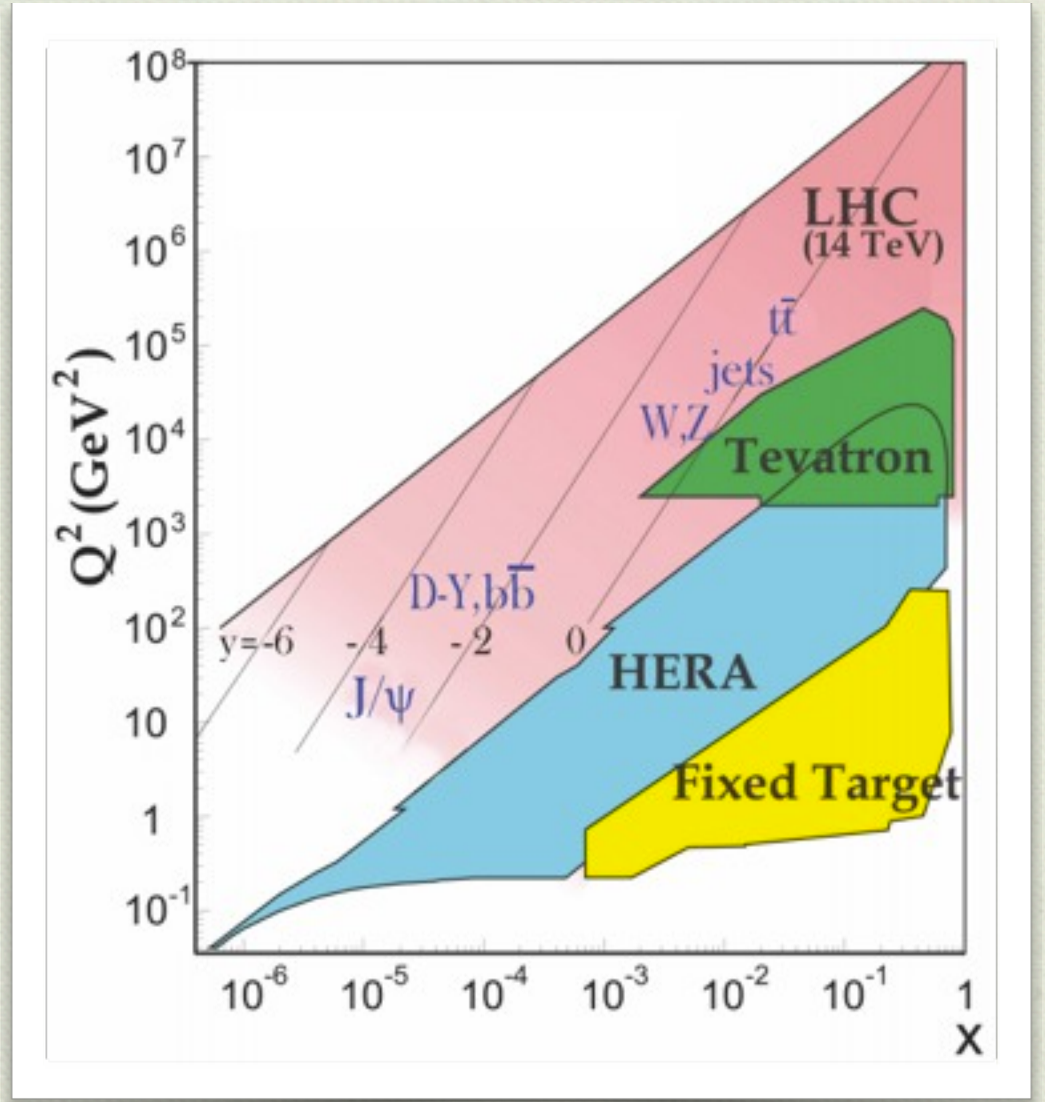
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T Z(+jets) distribution **(small/medium x)**

QUARKS

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

PHOTON

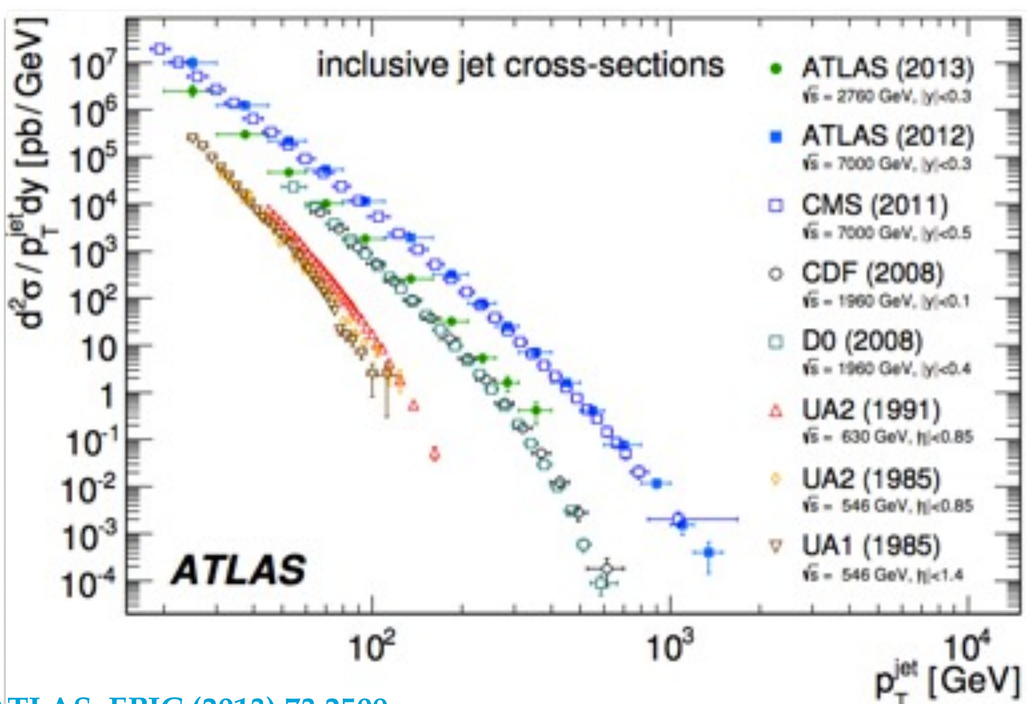
- Low and high mass Drell-Yan
- WW production



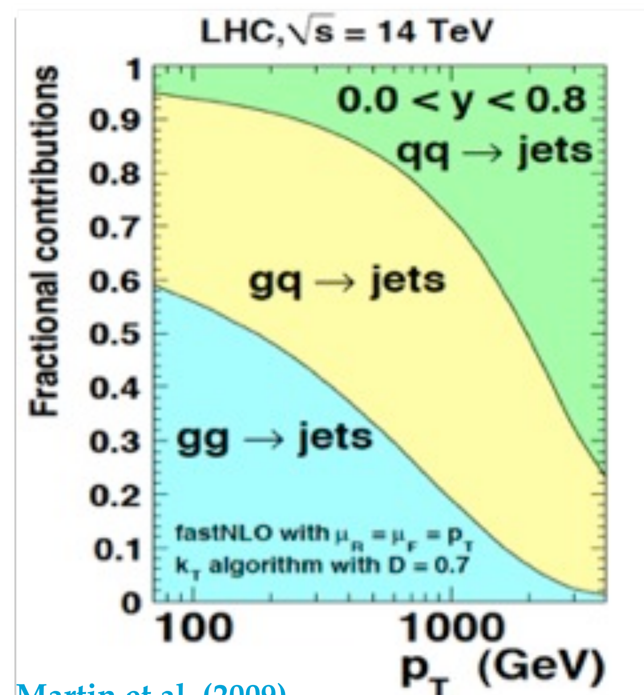
New constraints on the gluon
LHC jet data

- Jets are traditional source of information on gluon and α_S
- Large-x is the region where gluons and quarks are mostly unconstrained
- Wealth of precise experimental measurements
- Theoretical calculation: NLO and partially NNLO gg initiated contribution has been calculated

[Gehrmann et al]



ATLAS, EPJC (2013) 73 2509

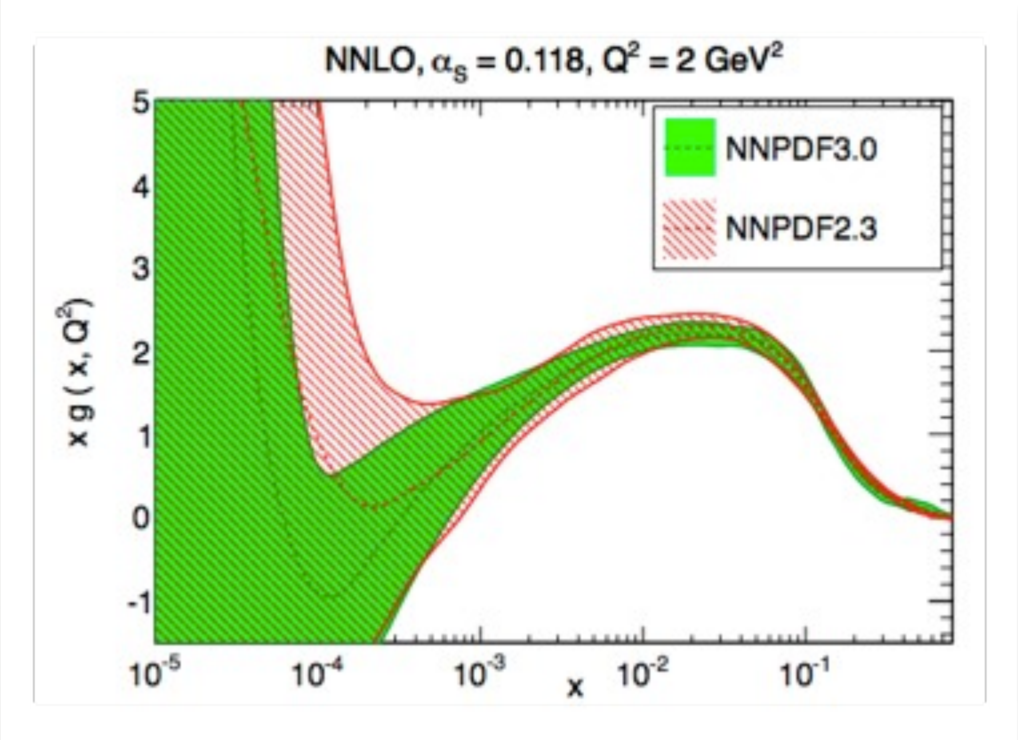


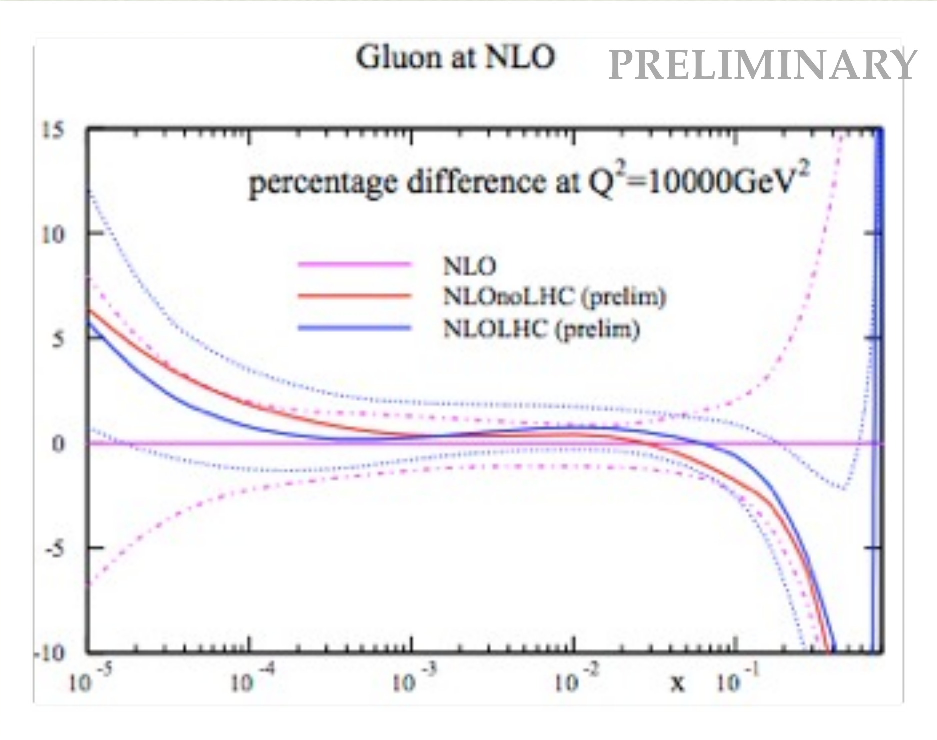
Martin et al, (2009)

New constraints on the gluon

LHC jet data

- Many precise jet data released: CMS full 7/8 GeV dataset, ATLAS 7/8 TeV and 2.76 TeV data
- Ratio of observable at different CoM energies strongly constraint due to correlations (ATLAS)
- Data included in the new NNPDF3.0 analysis and in preliminary MSTW (MMHT) fit
- Significant impact observed in gluon



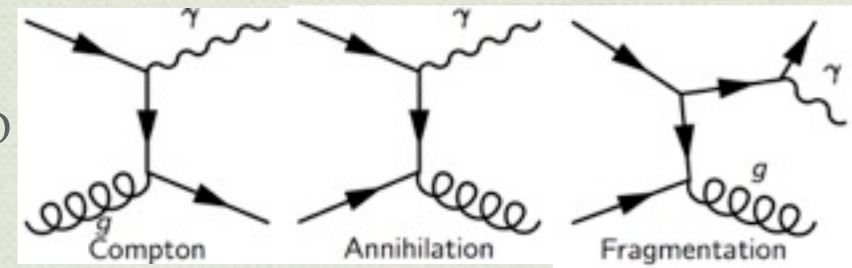


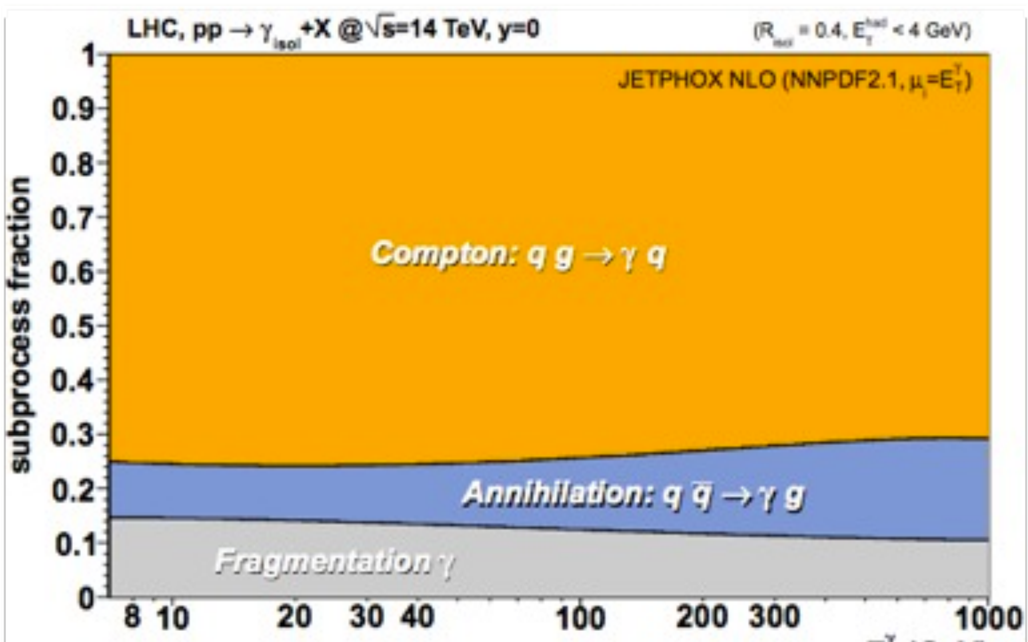
R. Ball et al, in preparation

R. Thorne, QCD@LHC

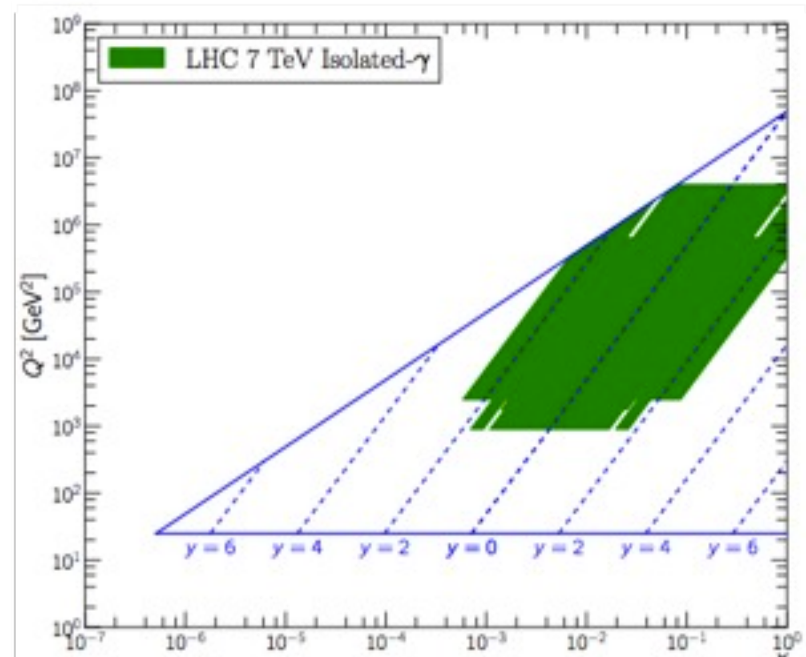
New constraints on the gluon
Prompt photon production data

- Prompt photon production directly sensitive to the gluon-quark luminosity via Compton scattering
- Isolated prompt photon data well described by NLO QCD theory
- ATLAS and CMS measurements at 7 TeV constrain medium-x region





D'Enterria, Rojo, Nucl. Phys. B860 (2012), 311



S. Farry, QCD@LHC 2013

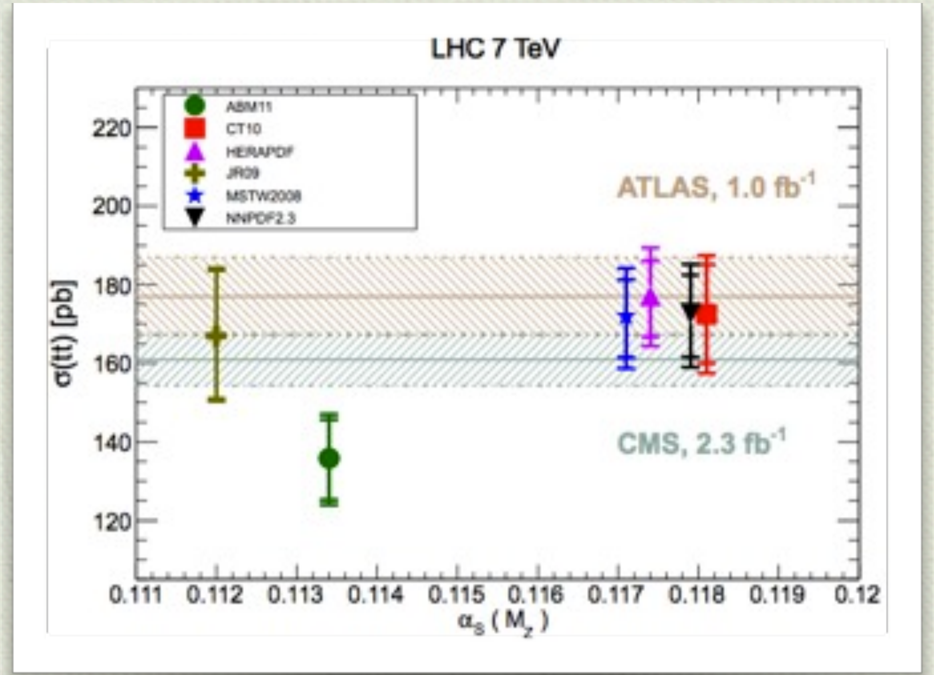
New constraints on the gluon

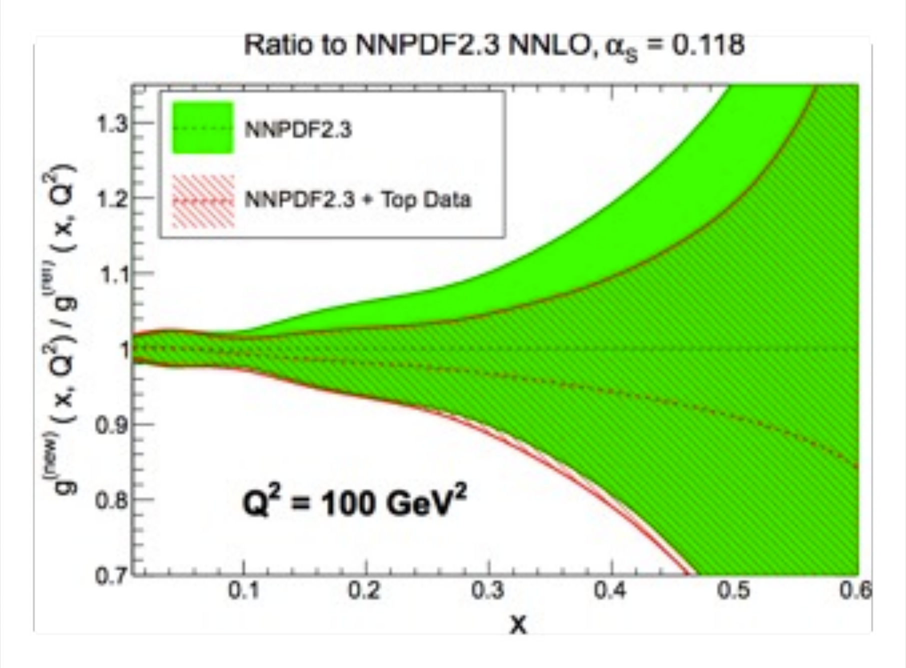
Top pair production

- At LHC, dominant channel is gg fusion
- Exp: precise measurements of total xsec by ATLAS and CMS + differential distributions
- Theory: full NNLO for total cross sections **[Czakon et al]** and NLO + NNLL code for differential distributions public soon **[Guzzi et al]**
- Significant constraints for gluon **[Czakon et al, Beneke et al]**

	TeVatron	LHC 7 TeV	LHC 8 TeV	LHC 14 TeV
gg	15.4%	84.8%	86.2%	90.2%
$qg + \bar{q}g$	-1.7%	-1.6%	-1.1%	0.5%
$q\bar{q}$	86.3%	16.8%	14.9%	9.3%

Czakon et al, JHEP 1307 (2013) 167



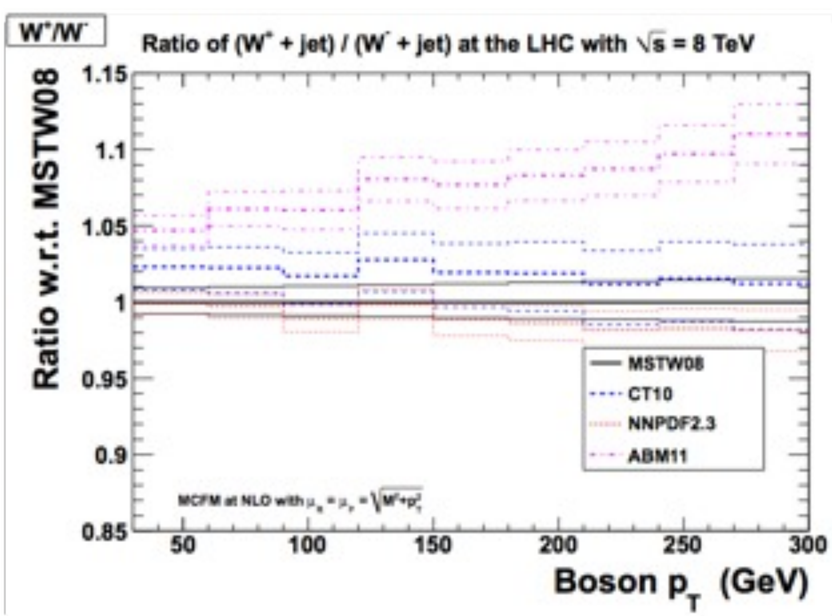


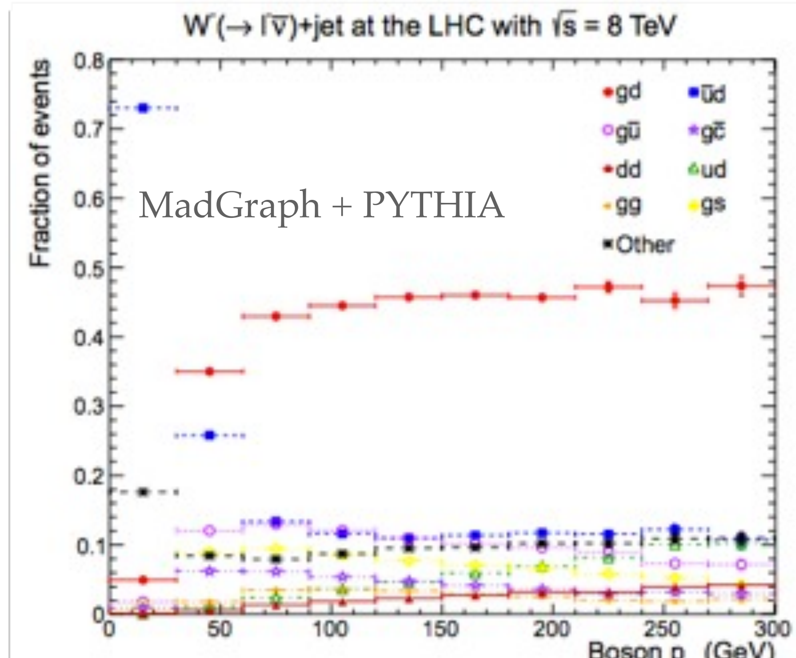
New constraints on the gluon

High pT vector boson production

- W/Z boson at large p_T (associated with jets) would provide complementary constraint to jets in x region which enters gg>H production

- At large pT, gluon up (for Z and W^+) or gluon down (for W^-) scattering dominate: can exploit these observables to constrain gluon and u/d ratio



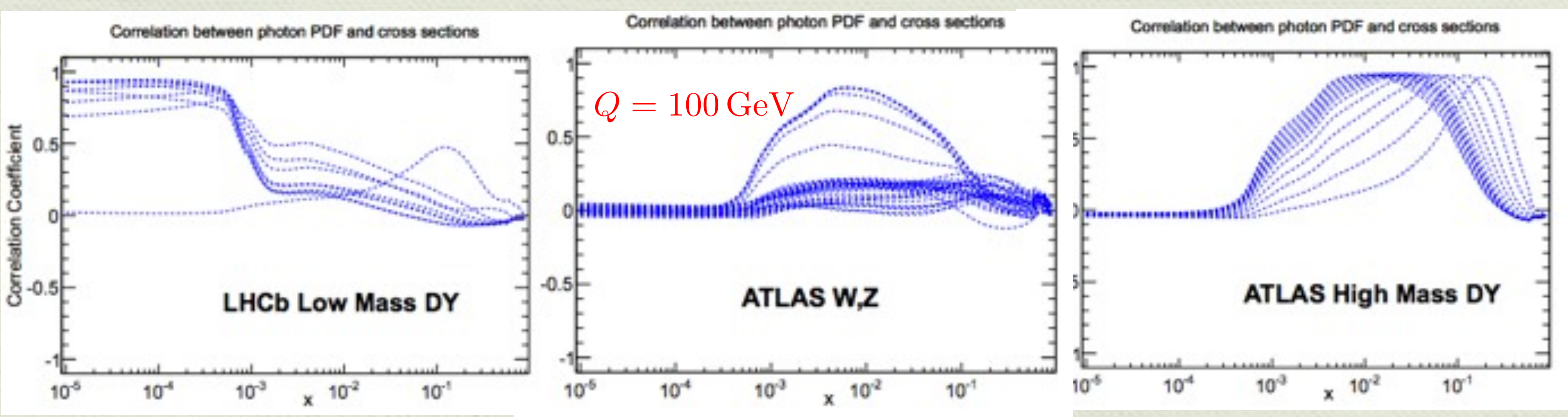


Malik,Watt ArXiv: 1304.2424

- pT spectra affected by possibly large theoretical uncertainties, soft resummation and EW corrections at small/large pT.
- Need NNLO, hopefully not too far after calculation of H+j at NNLO [Boughezal et al]
- Exploit ratios to cancel theoretical uncertainties

Constraints on the photon
DIS and LHC data

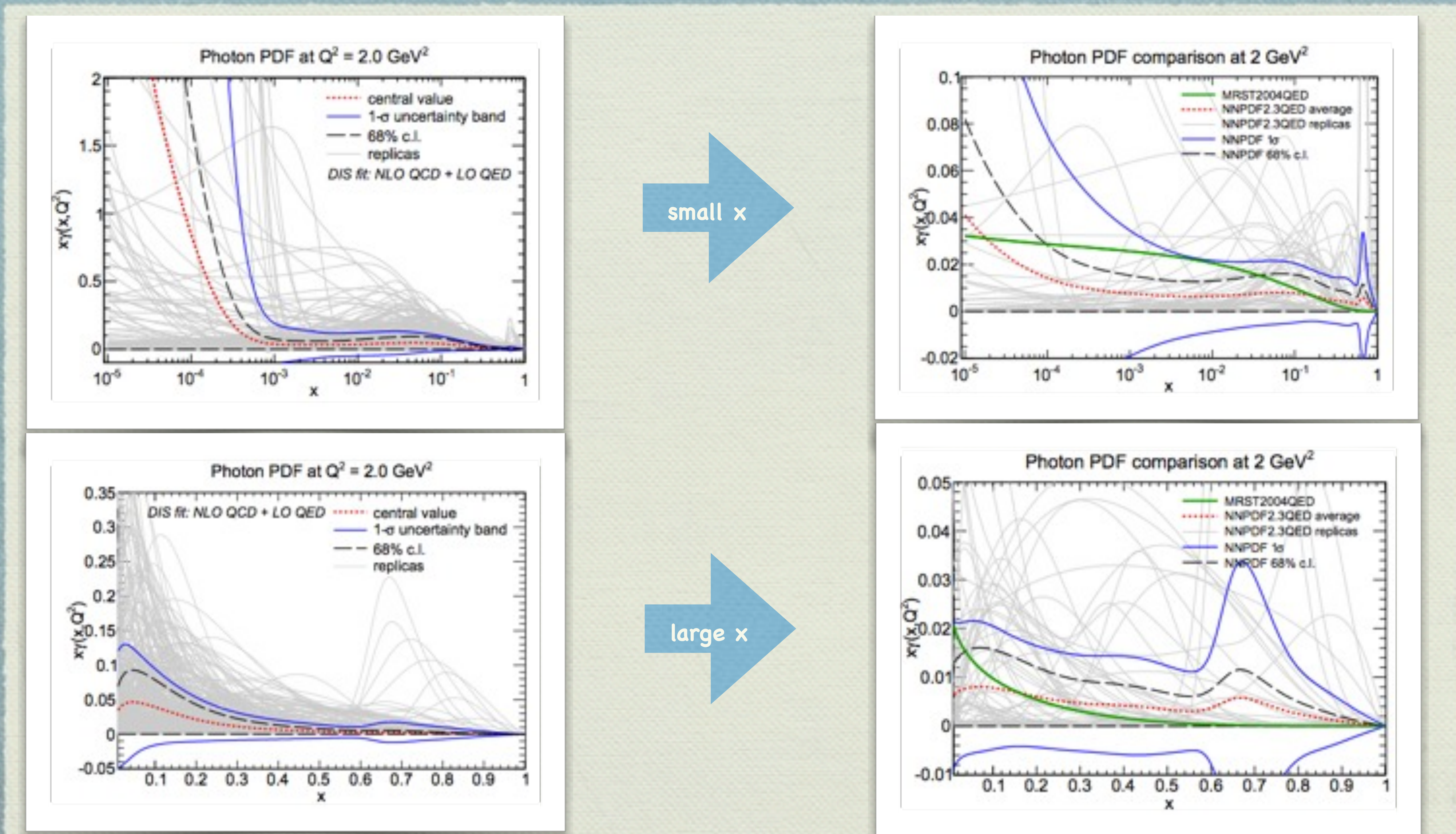
- The inclusion of EW corrections requires PDF with QED effects
- **NNPDF23QED** is a recent PDF set with uncertainties which incorporates (N)NLO QCD + LO QED effects
- Photon PDF fitted from DIS and DY data (on-shell W,Z production and low/high mass DY)
- Photon PDF is poorly determined from DIS data. Need hadron collider processes where photon contributes at LO!



Ball et al, 1308.0598

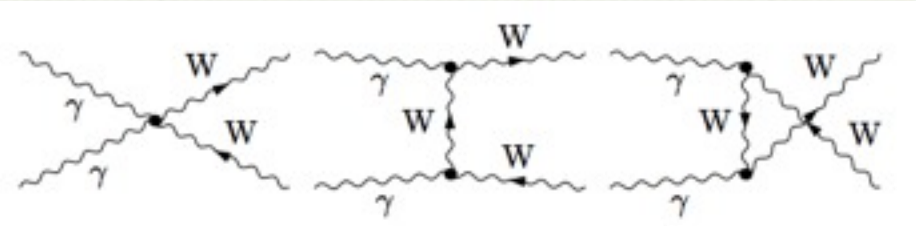
Constraints on the photon

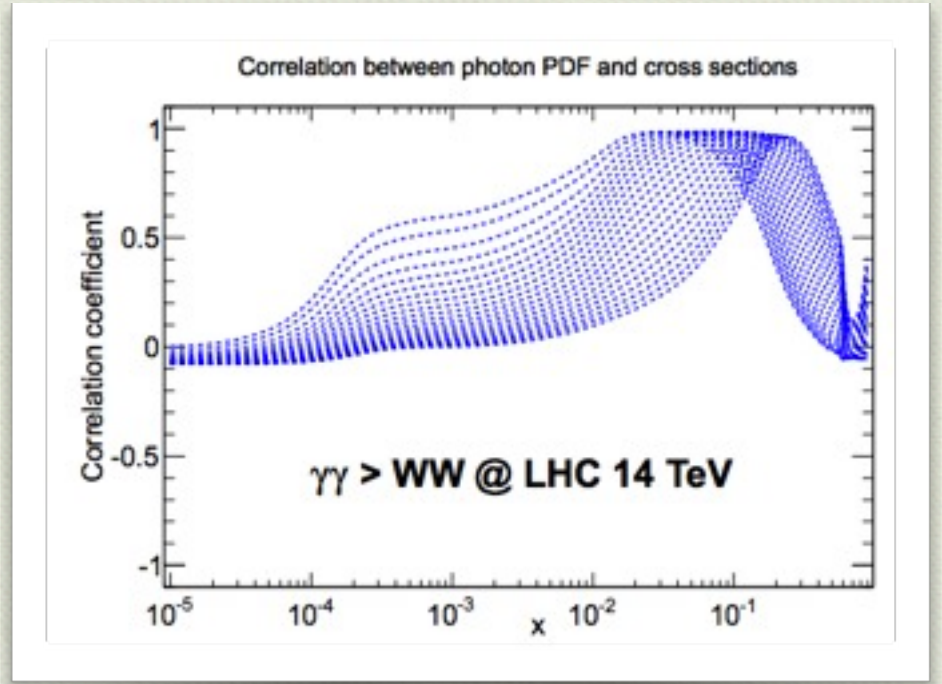
Impact of the LHC data

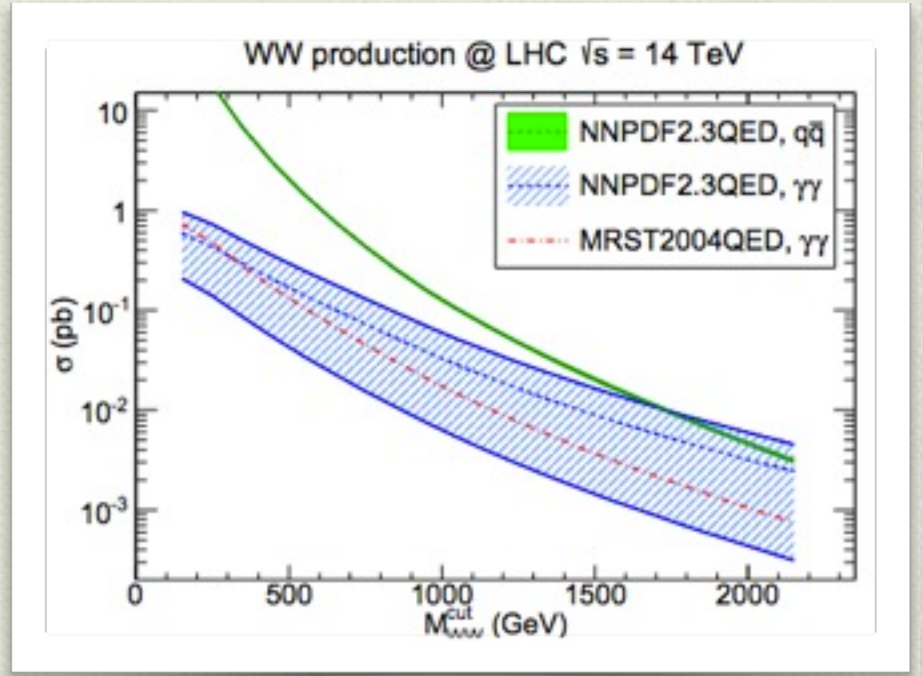


Constraints on the photon
Impact of the LHC data

- WW production is phenomenologically relevant as a background for BSM searches
- At high M_{WW}, photon-induced contribution become relevant
- The large uncertainty at large M_{WW} comes from the large uncertainty of photon PDF for $x > 0.1$
- New LHC data give unique opportunity of constraining the photon in that region

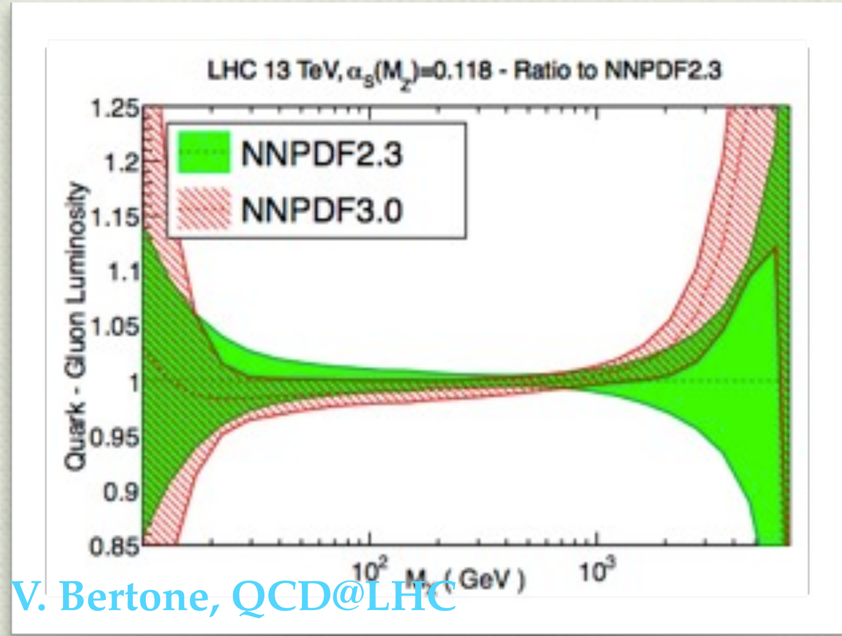




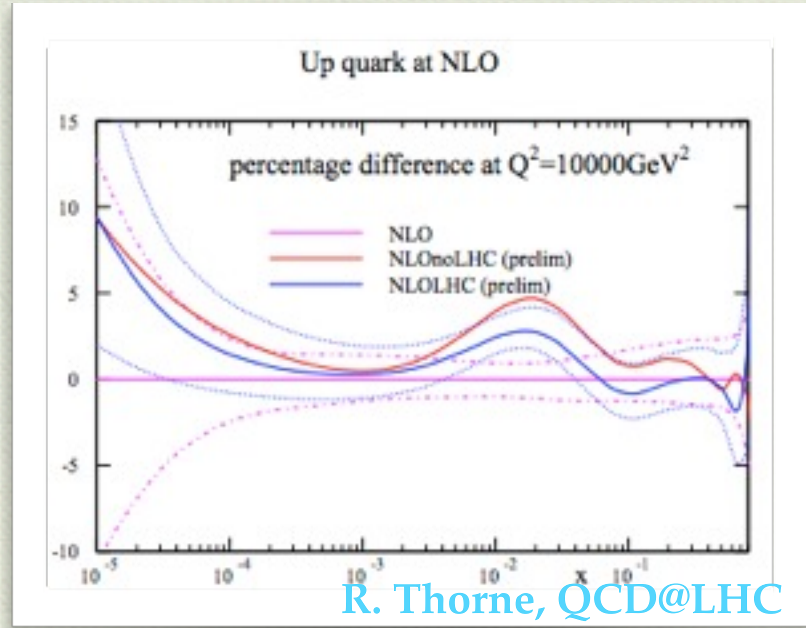


Progress and frontiers

News from PDF fitters



V. Bertone, QCD@LHC



R. Thorne, QCD@LHC

➡ Intense activity and several PDF sets with LHC data available soon

NNPDF3.0 already in LHAPDF, announced updates from MSTW, HERA, CT

➡ Theory challenges for the future: estimate of theoretical uncertainty in PDF fits, inclusion of QED+QCD, small-x and large-x resummations, EW corrections

➡ Solid statistical interpretation of PDF uncertainties is crucial!

Conclusions and outlook

	σ (8 TeV)	uncertainty
gg→H	19.5 pb	14.7%
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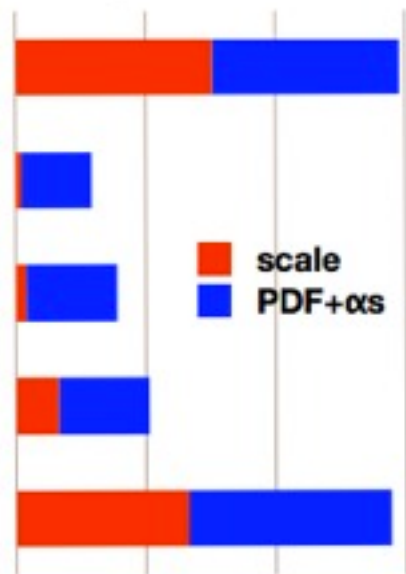
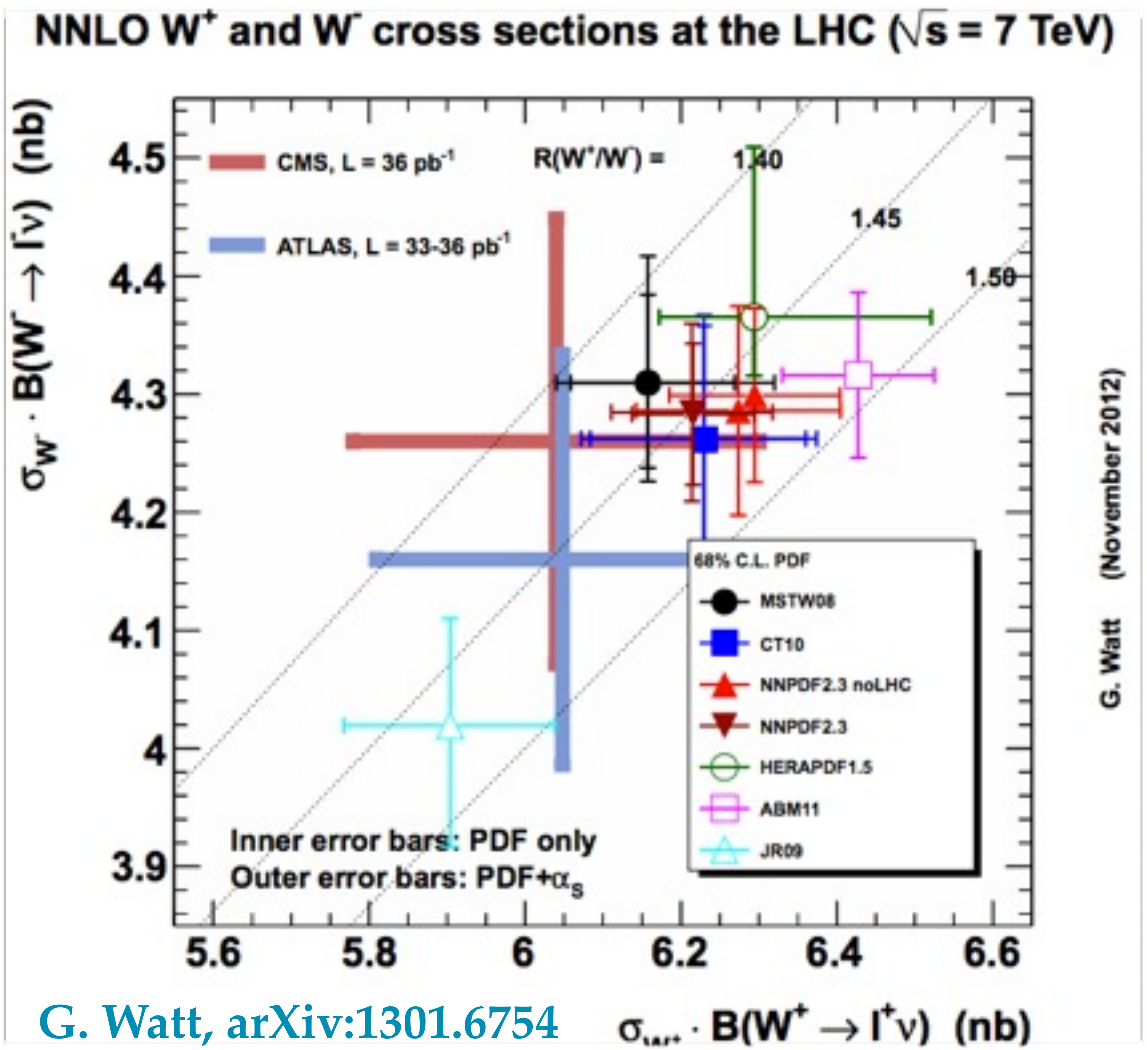


This picture is soon going to be outdated, not only thanks to the huge effort in higher order calculations but also thanks to the effort from PDF fitters.

- Reduced PDF uncertainties crucial to achieve precise predictions
- LHC data have huge potential in constraining PDFs
- Collaborations working in inclusion of LHC data and many updates coming soon
- Theoretical and methodological accuracy must catch up with experimental data

Back up

Predictions for the LHC

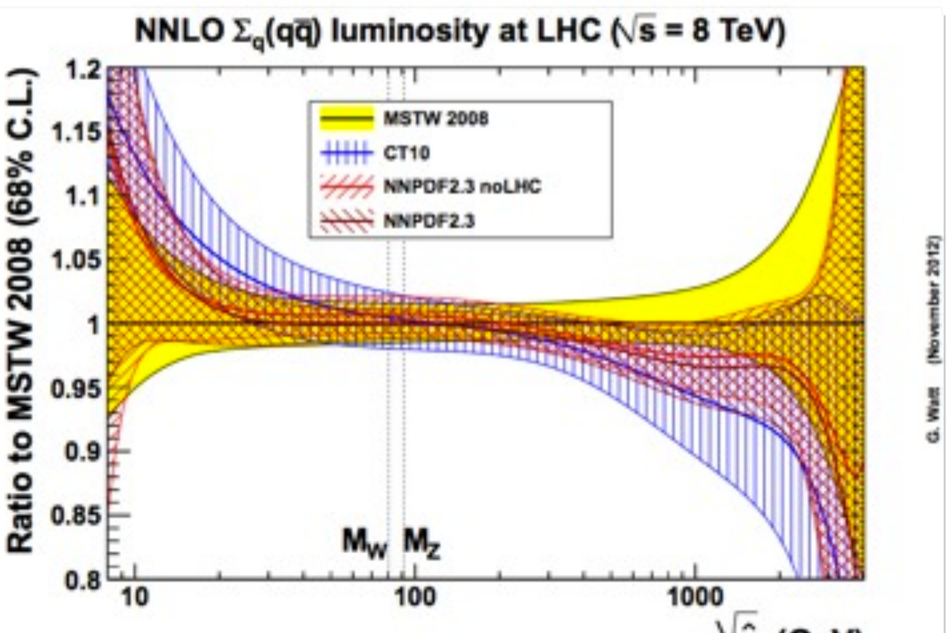


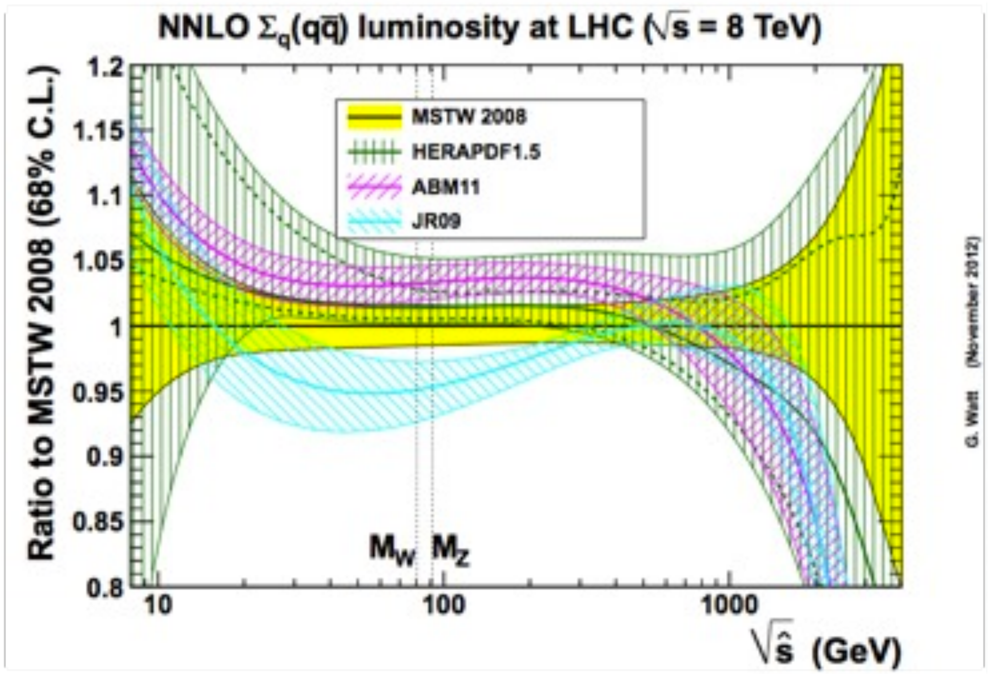
G. Watt, arXiv:1301.6754

- For W and Z productions (quark dominated) situation is less dramatic
- Predictions mostly close to each others
- More significant discrepancies with ABM and JR
- Compatible with data, although data the more precise the more discriminating

Parton Luminosities

Directly connected with quark-quark luminosity



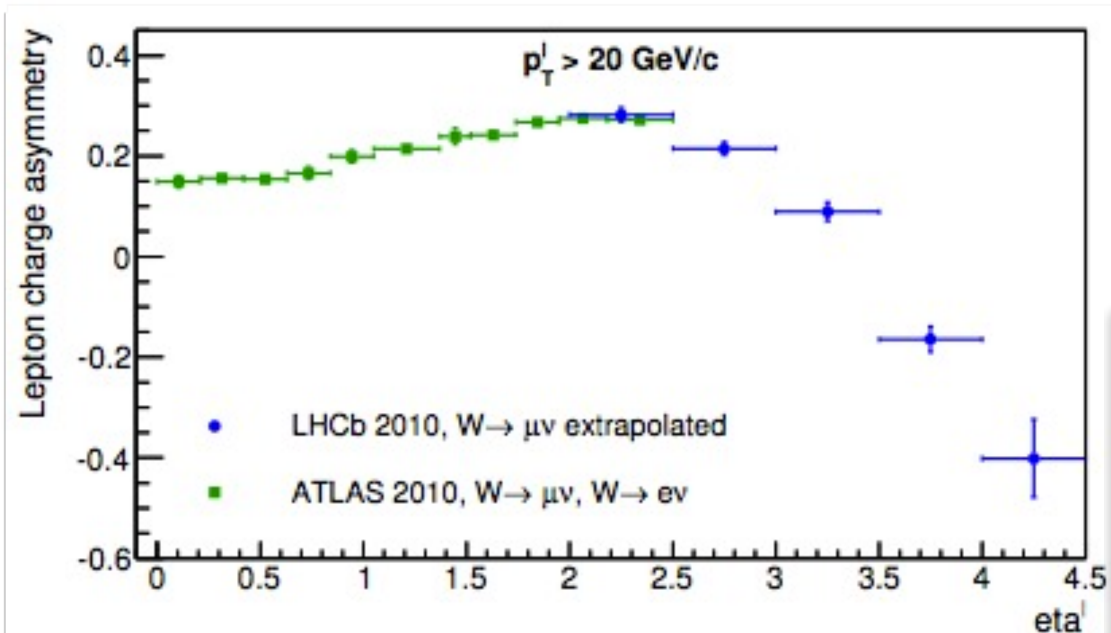


G. Watt, arXiv:1301.6754

$$\Phi_{ij}(M_X^2) = \frac{1}{s}\int_\tau^1 \frac{dx}{x}\, f_i(x, M_X^2)\, f_j\left(\frac{\tau}{x}, M_X^2\right)$$

Quark flavor separation

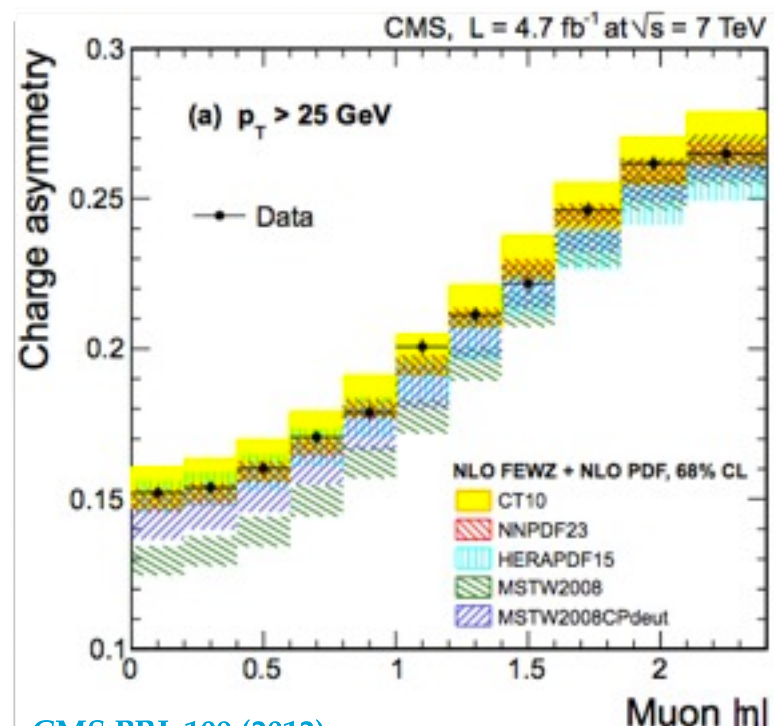
A wealth of data from LHC



LHCb-CONF-2013-005

☑ W/Z rapidity distribution, both central (CMS and ATLAS) and forward (LHCb): constrain quark flavor separation in a wide x range

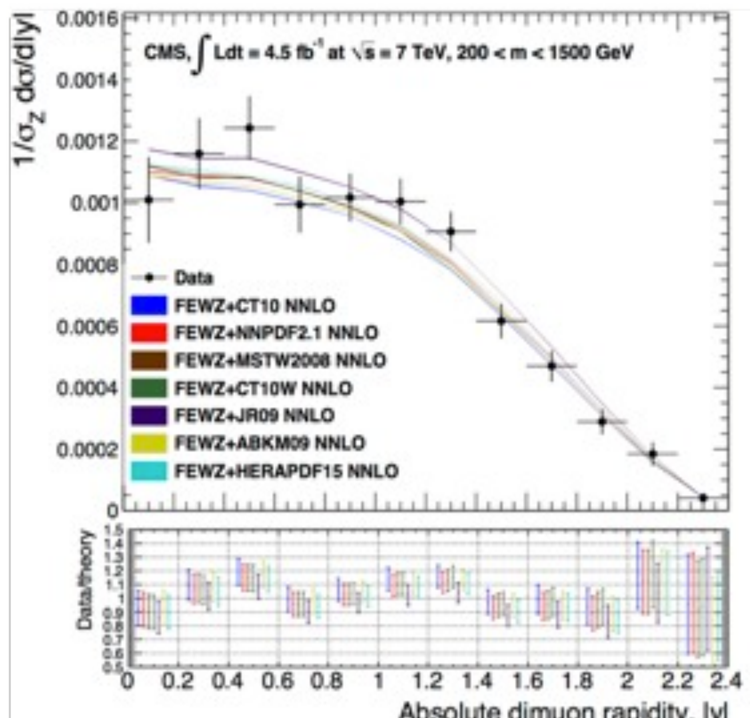
☑ W lepton charge asymmetry (ATLAS and CMS): strong constraints on up and down valence quarks and sea asymmetry



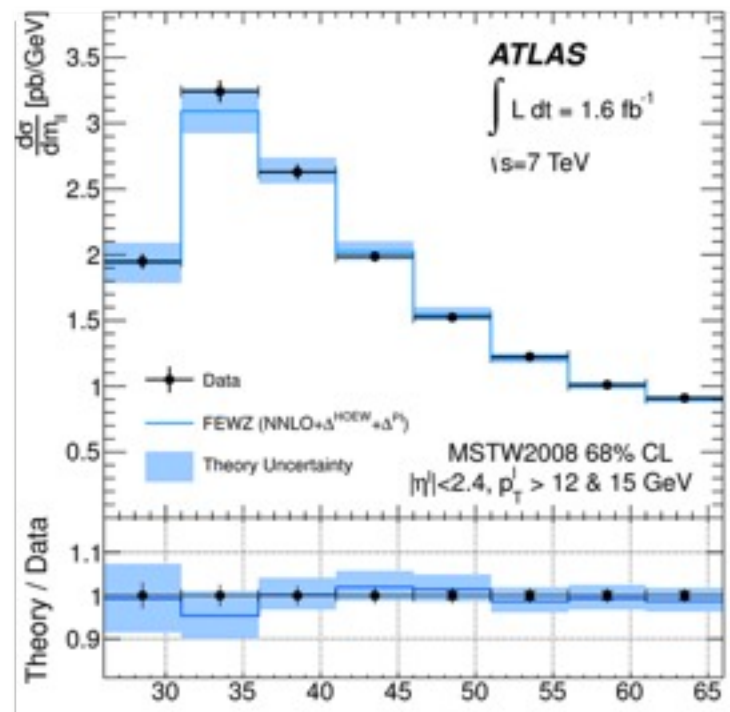
CMS PRL 109 (2012)

Quark flavor separation

A wealth of data from LHC



CMS JHEP 2013



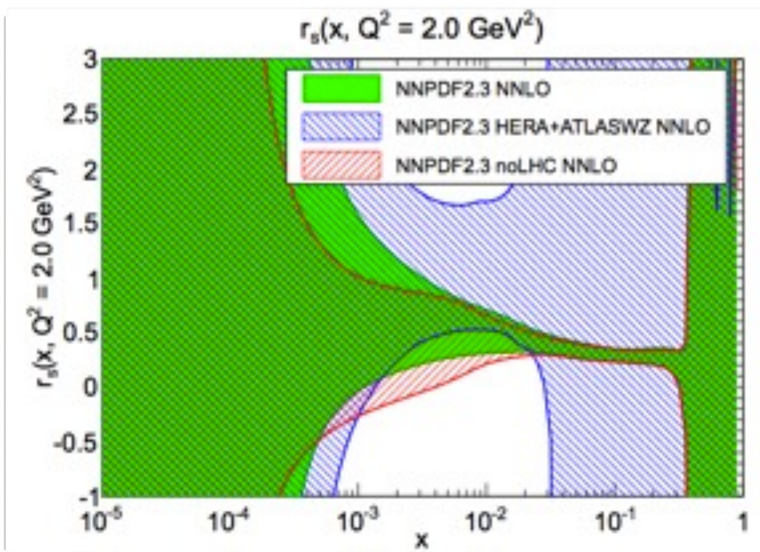
ATLAS arXiv 1404.1212

☑ High and low mass Drell-Yan distributions provide valuable constrain to quarks and antiquarks in large and small x regions

$$x^0_{1,2} = \frac{M}{\sqrt{s}} e^{\pm Y}$$

Strangeness

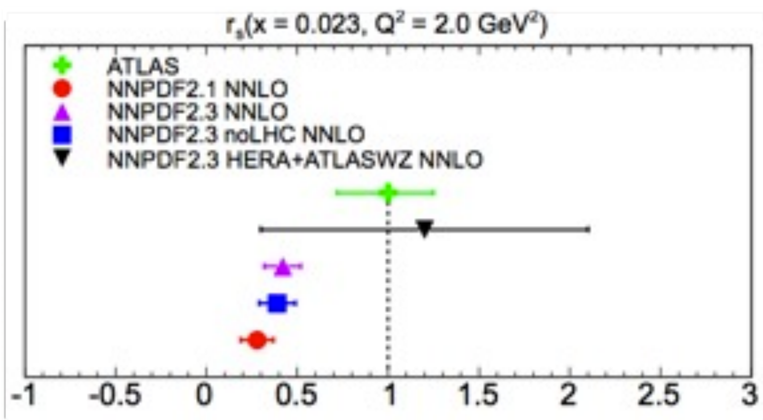
A "strange" story



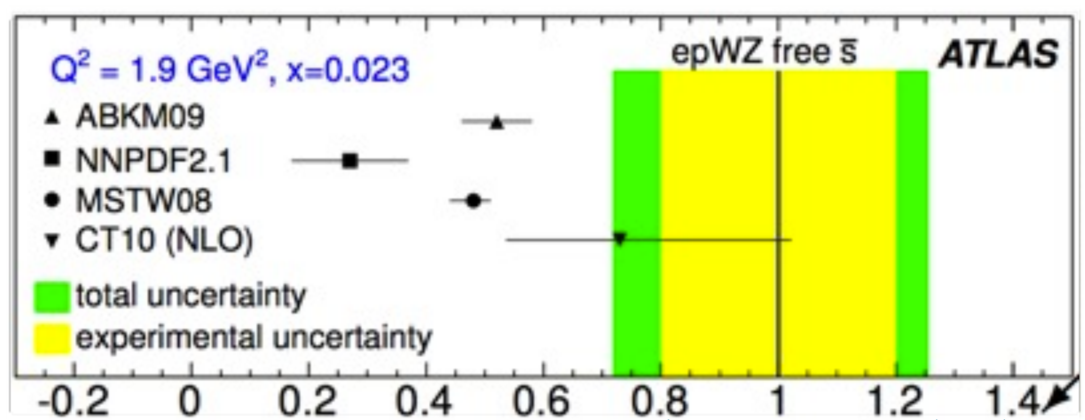
- In global analyses strangeness is mostly determined by DIS fixed target data (CHORUS, NuTeV) -> suppressed strange sea

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

- ATLAS analysis, based on the HERAFITTER approach, points to a non-suppressed strangeness
- NNPDF2.3 analysis confirms the central value of the ATLAS analysis but finds larger uncertainties.



R. Ball et al, Nucl. Phys. B867 (2013) 244

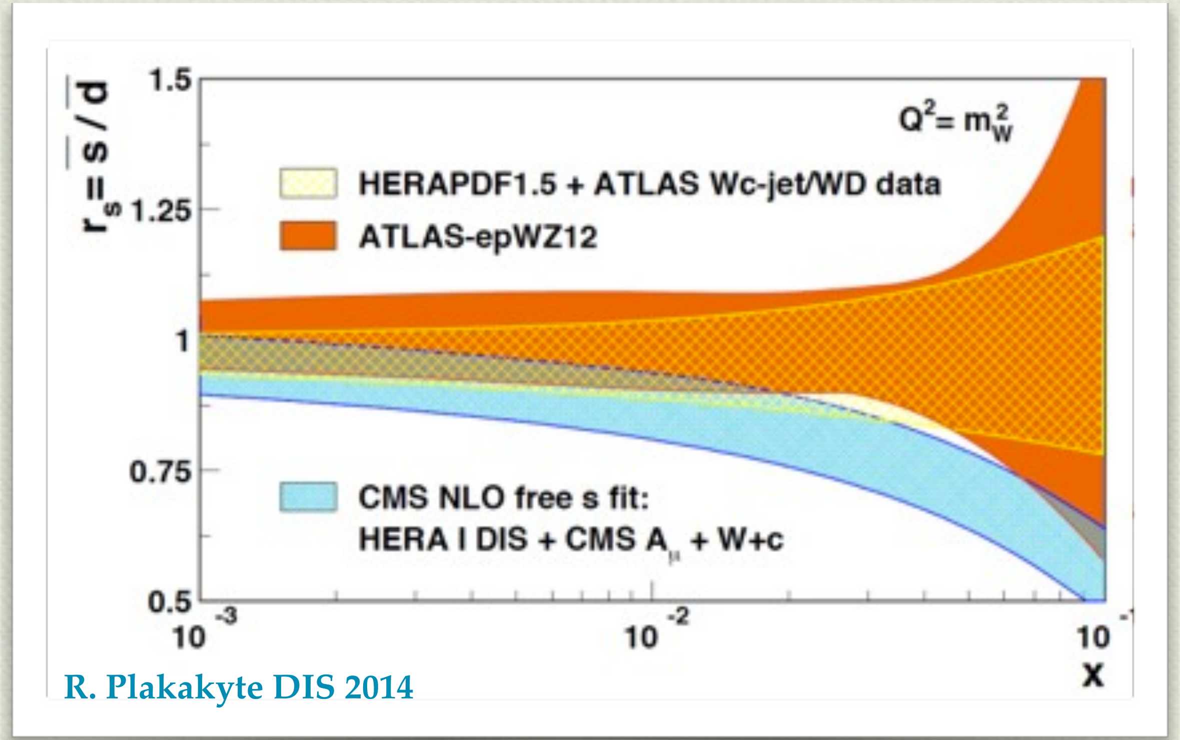


ATLAS, Phys. Rev. Lett. 109 (2012) 012001

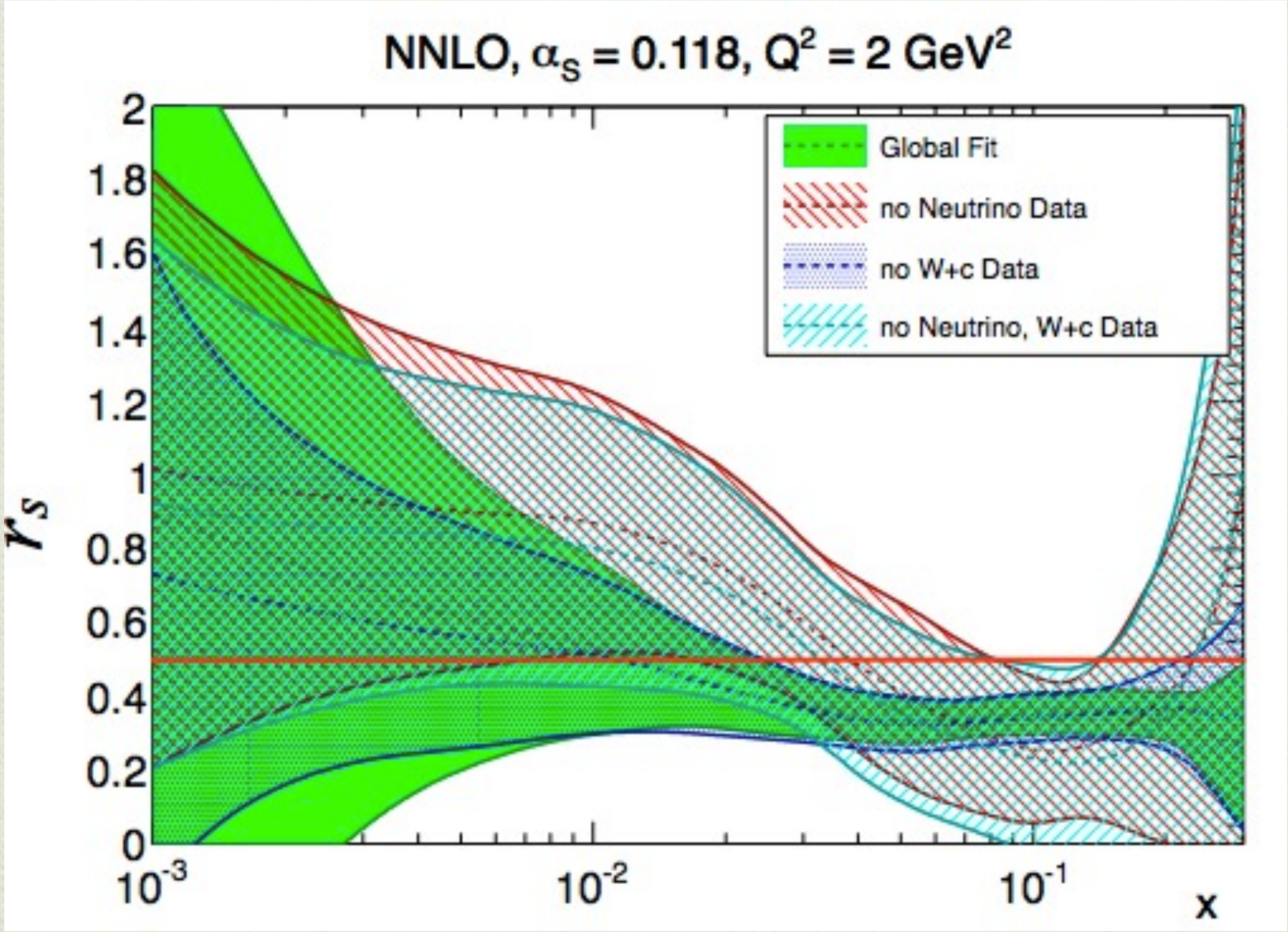
Strangeness

A "strange" story

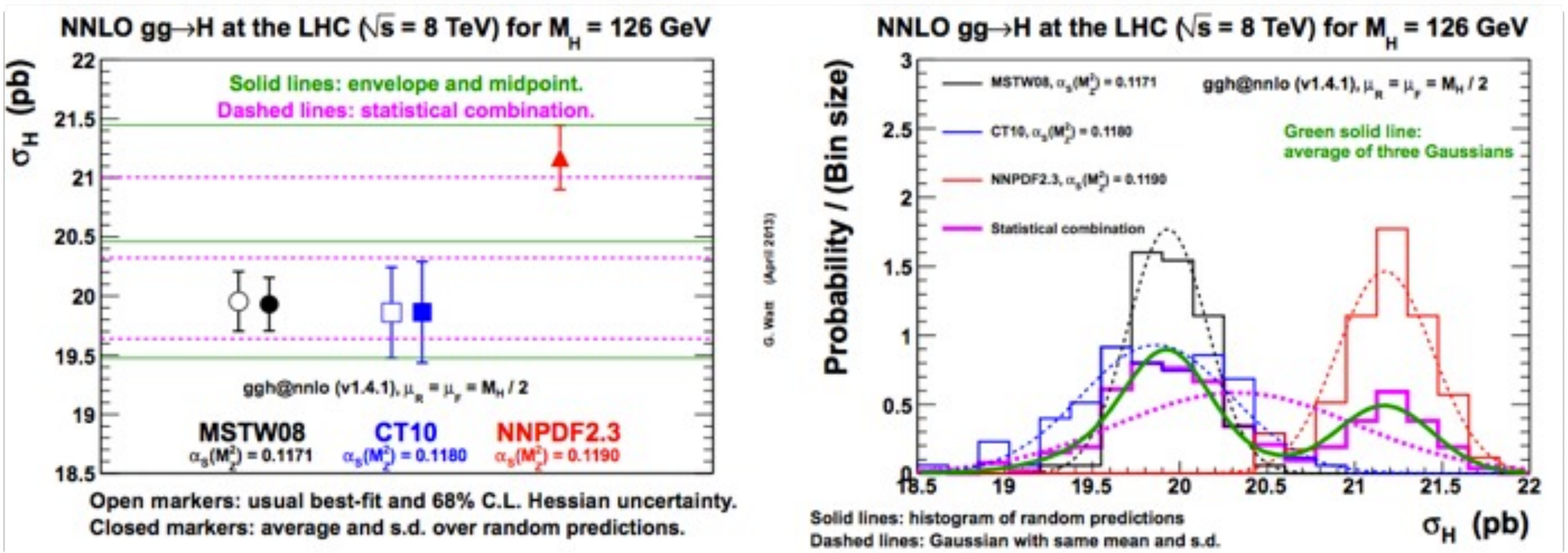
- W+charm data from ATLAS and CMS (both inclusive and distributions) provide a cleaner set of data to constrain strangeness from collider data
- ATLAS data consistent with large s, opposite to CMS data consistent with suppressed s
- Recent from NOMAD: charm dimuon production in neutrino-iron scattering consistent with NuTeV
- Ultimate answer comes from inclusion of W+c data in PDF fits



Strangeness
NNPDF3.0 preliminary



Progress and frontiers
Methodology: combining different PDF sets



G. Watt, PDF4LHC 2013

➡ Envelopes [PDF4LHC prescription arXiv 1101.0538]

➡ Statistical combination from different PDF groups generating MC sets. **[Forte, Watt, 2013]** Smaller uncertainty than envelope: 4.8% vs 3.4% for gg>H

➡ Meta-PDFs: fit with input functional form the CT, MSTW and NNPDF shapes and combine in a unique consistent set **[Gao, Nadolsky, 2014]**

➡ Crucial to decide optimal value of α_S and its uncertainty in combination