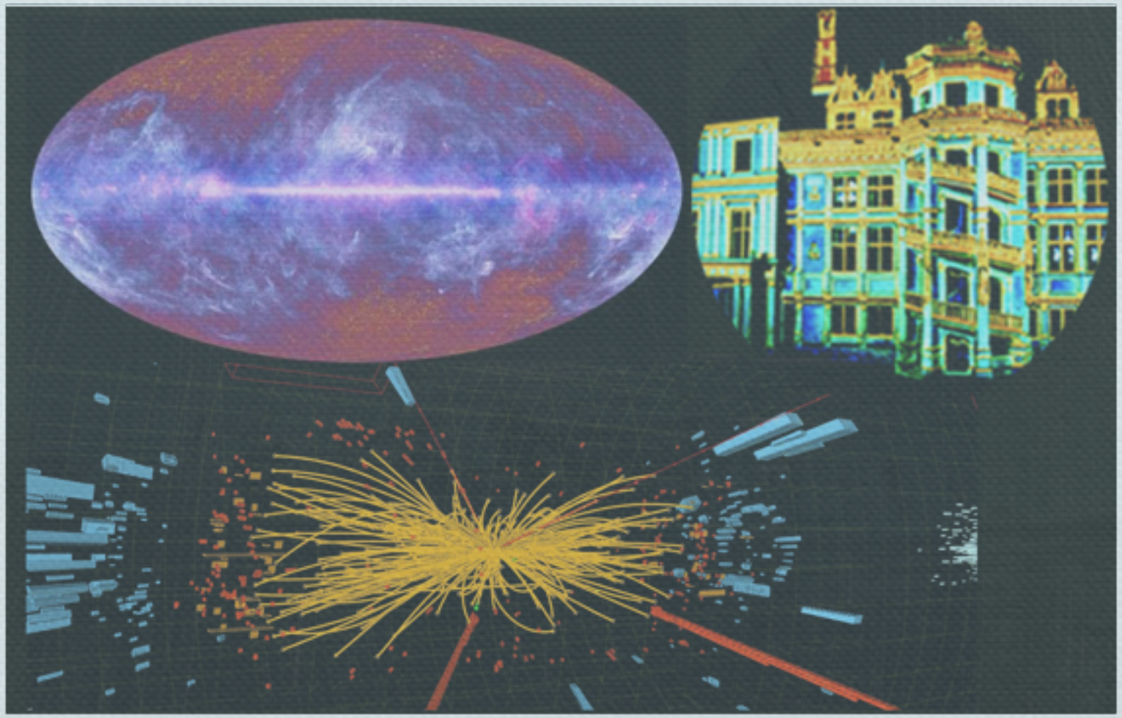
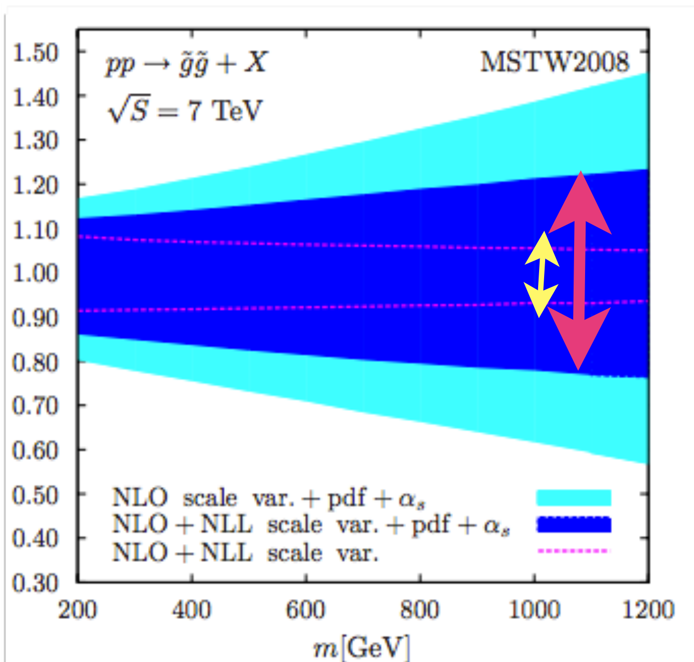
26th Rencontres de Blois, Particle Physics and Cosmology, Blois, France
20th May 2014



The structure of the proton and the LHC

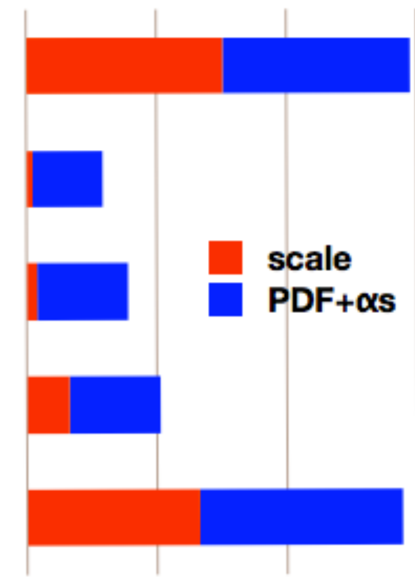
Maria Ubiali
University of Cambridge

PDFs: why bother?



Beenakker et al (2011)

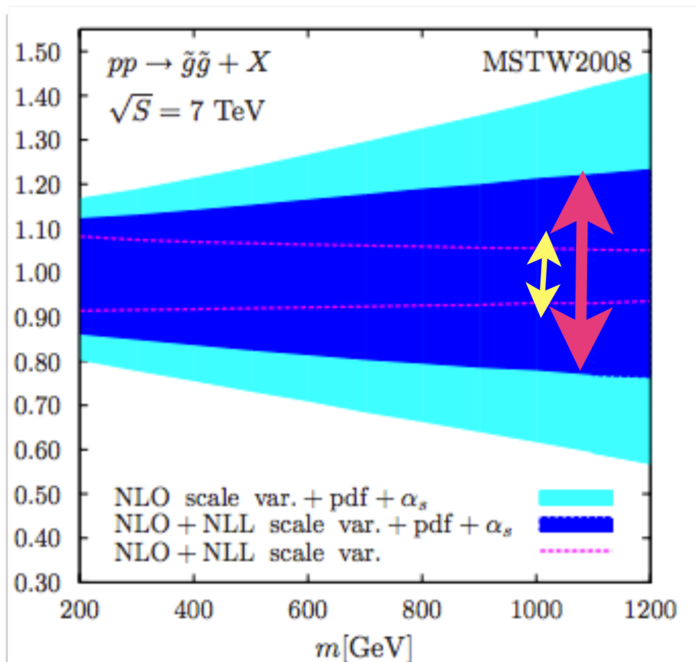
	σ (8 TeV)	uncertainty
gg→H	19.5 pb	14.7%
VBF	1.56 pb	2.9%
WH	0.70 pb	3.9%
ZH	0.39 pb	5.1%
ttH	0.13 pb	14.4%



J. Campbell, ICHEP 2012

- PDF uncertainty dominant for many SM predictions
- Precision in predicting BSM heavy particles is limited by large quark-antiquark uncertainties at large x. Reduction of theoretical uncertainty achieved by using resummed predictions still has 15% uncertainty due to PDFs

PDFs: why bother?



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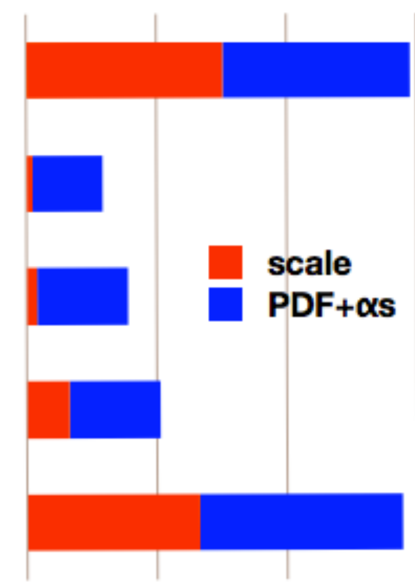


J. Campbell, ICHEP 2012

PDFs

PDFs 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
  - Parton Distribution Functions
- PDFs at the LHC
  - The state of the art
- LHC for PDFs
  - Constraints from data
- Conclusions and outlook

Parton Distribution Functions

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

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

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

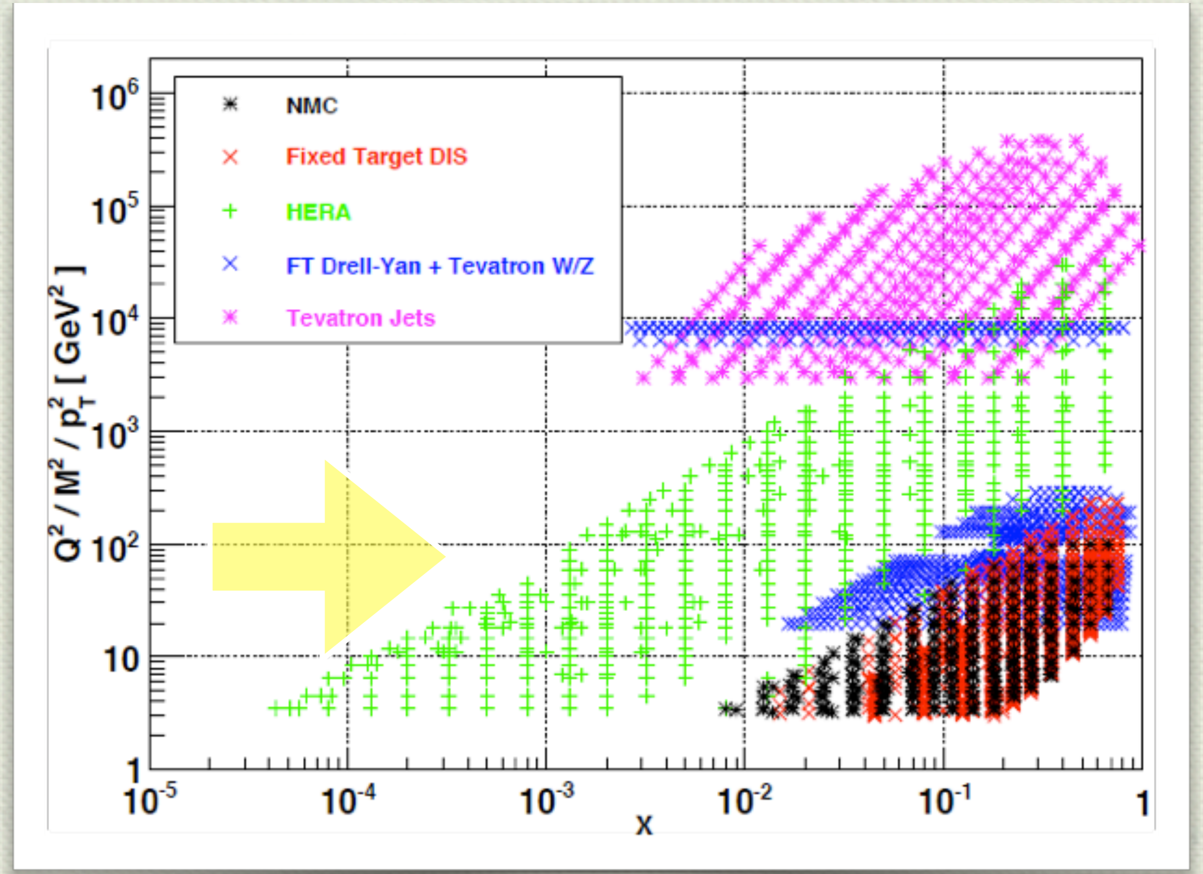
Dokshitzer, Gribov, Lipatov, Altarelli, Parisi renormalization group equations

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

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

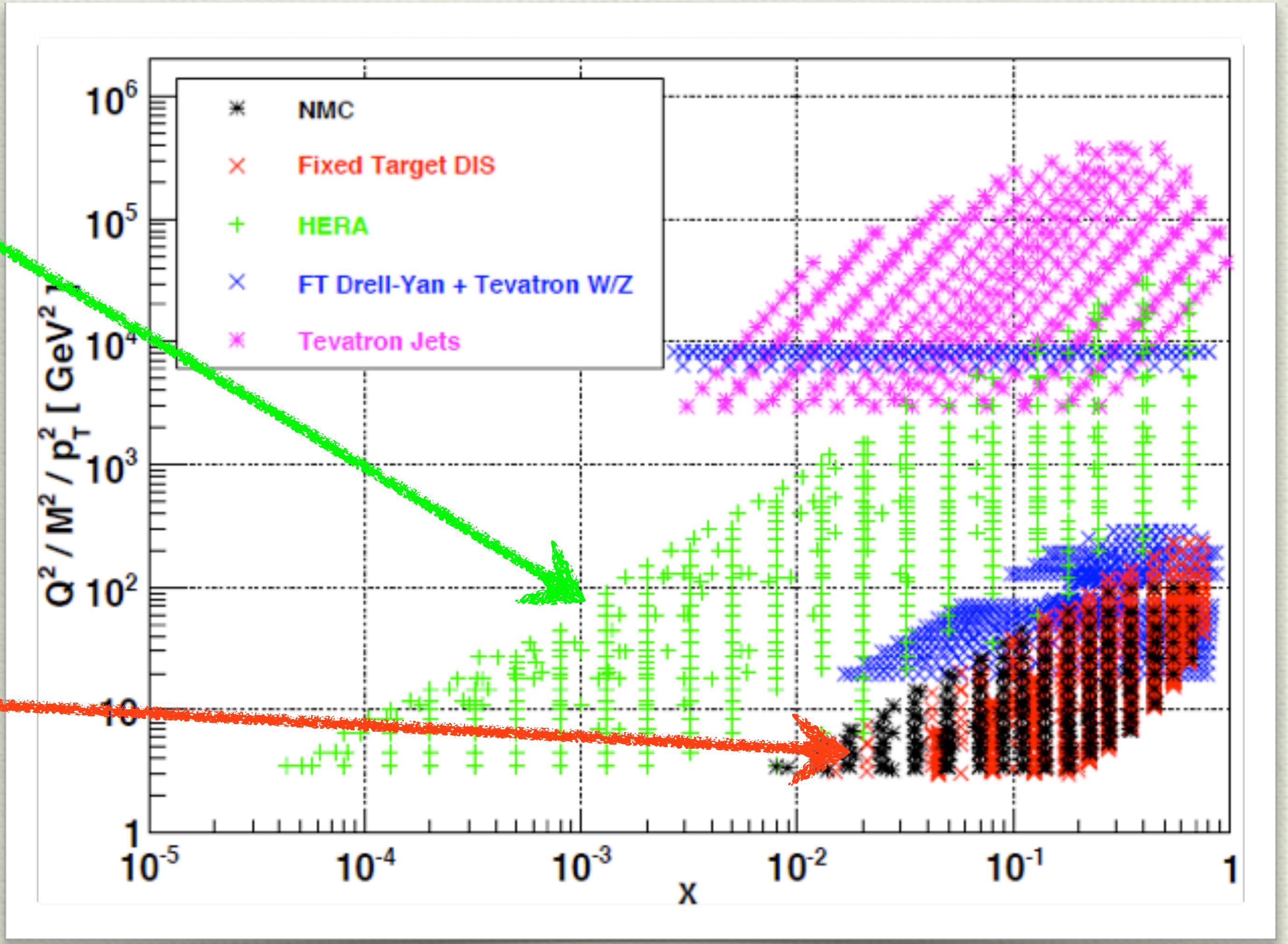
- They can be extracted from available experimental data and used as phenomenological input for theory predictions
- Different data constrain different parton combinations at different x



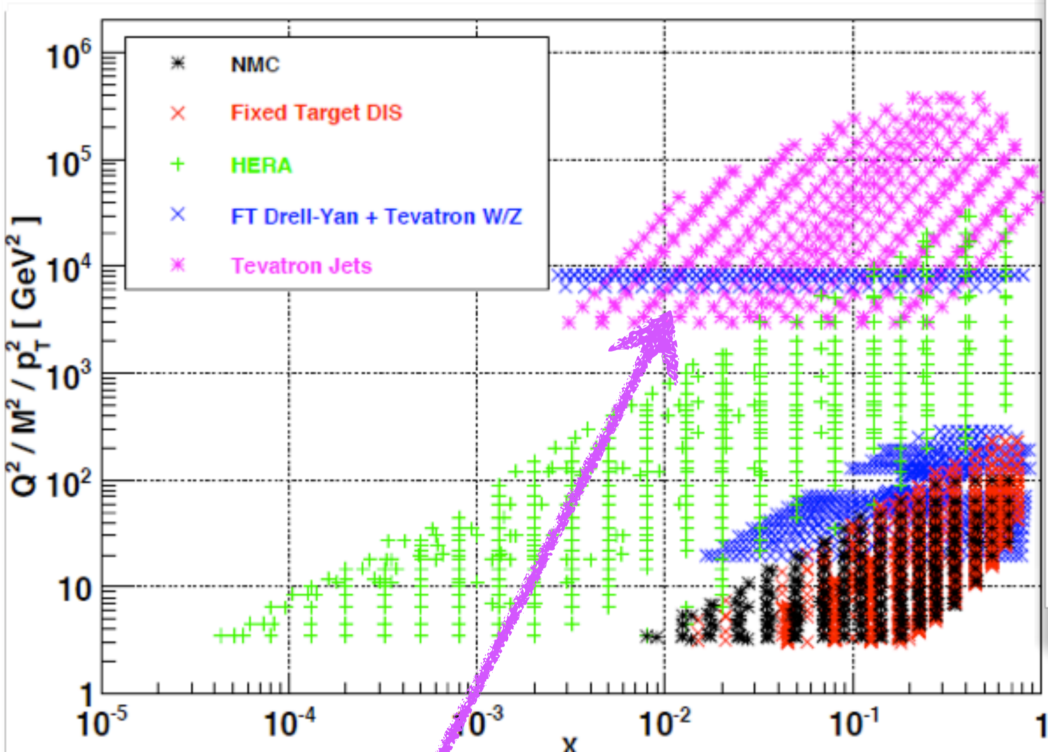
Constraints from data (pre-LHC)

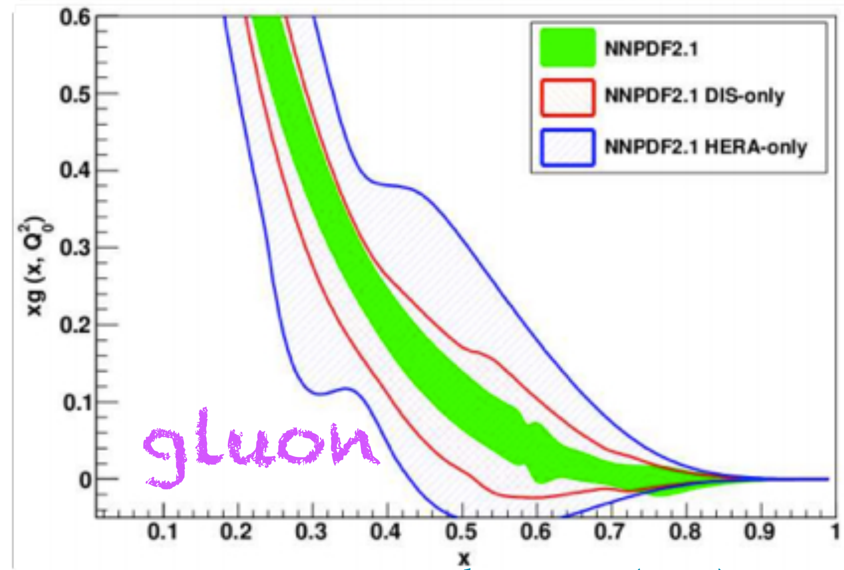
DIS data

- 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)



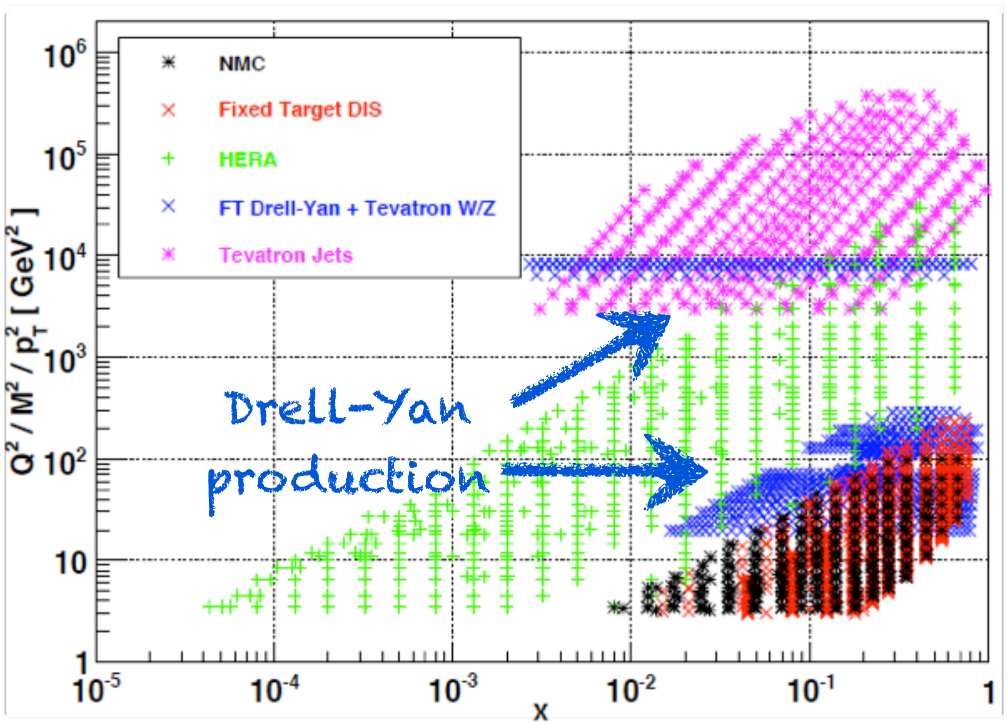


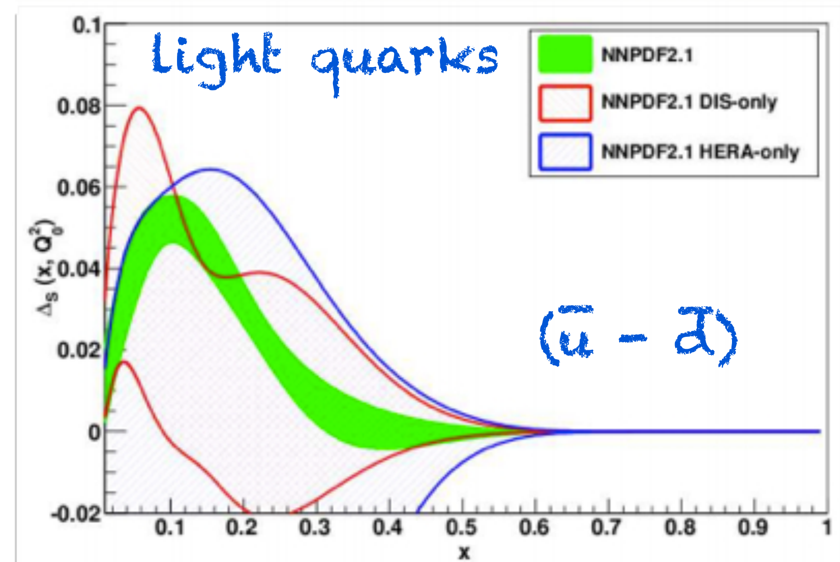
R. Ball et al. Nucl. Phys. B838 (2010) 136

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

PDFs: state of the art

Progress in PDF determination

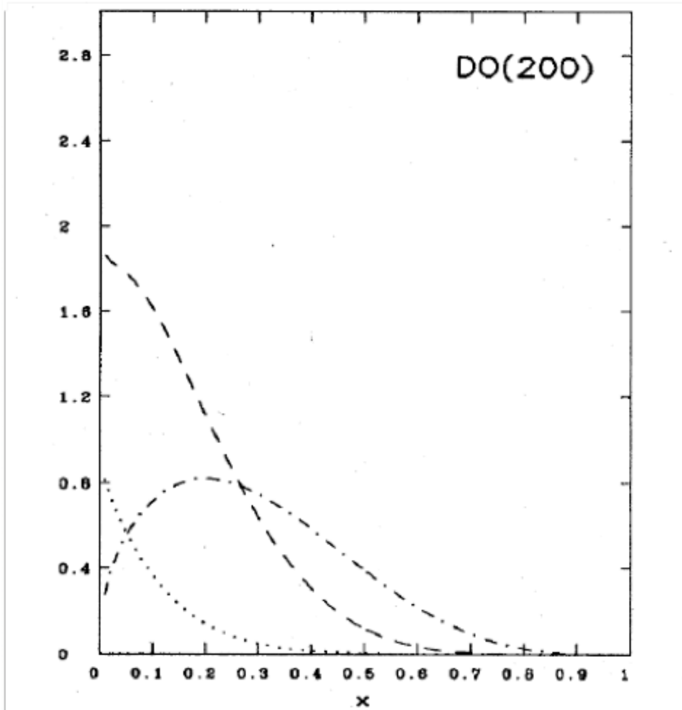
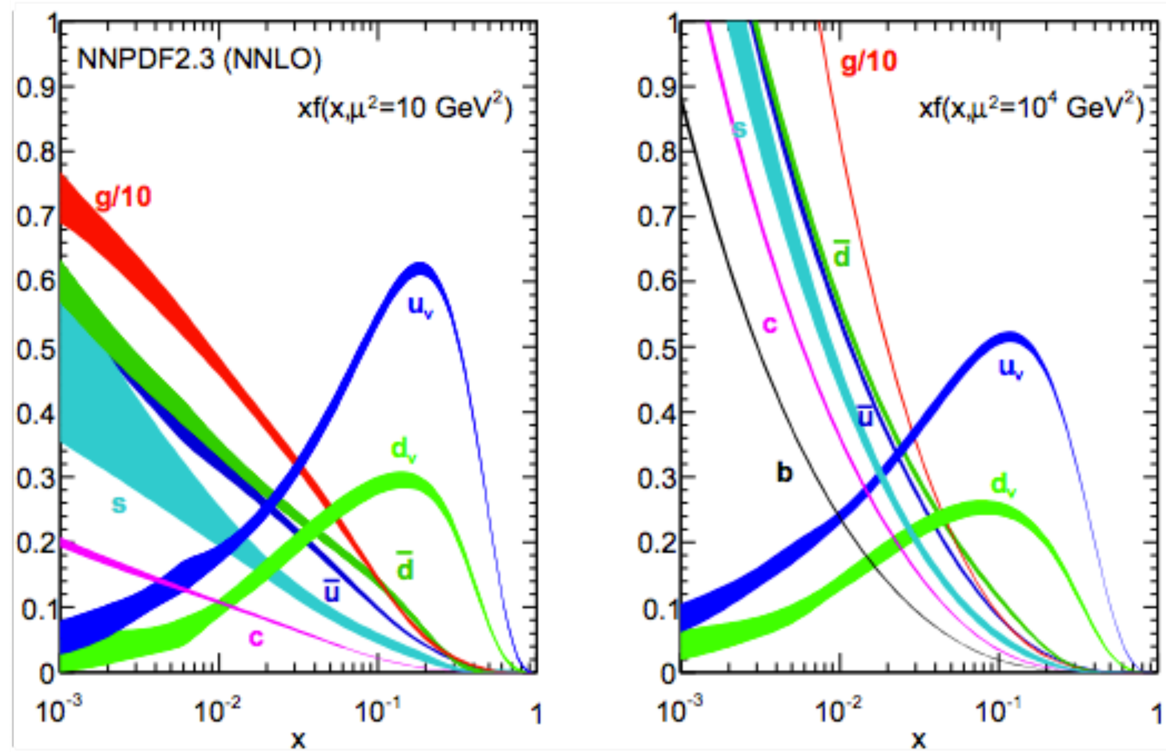


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).



PDG "Structure Functions"2013

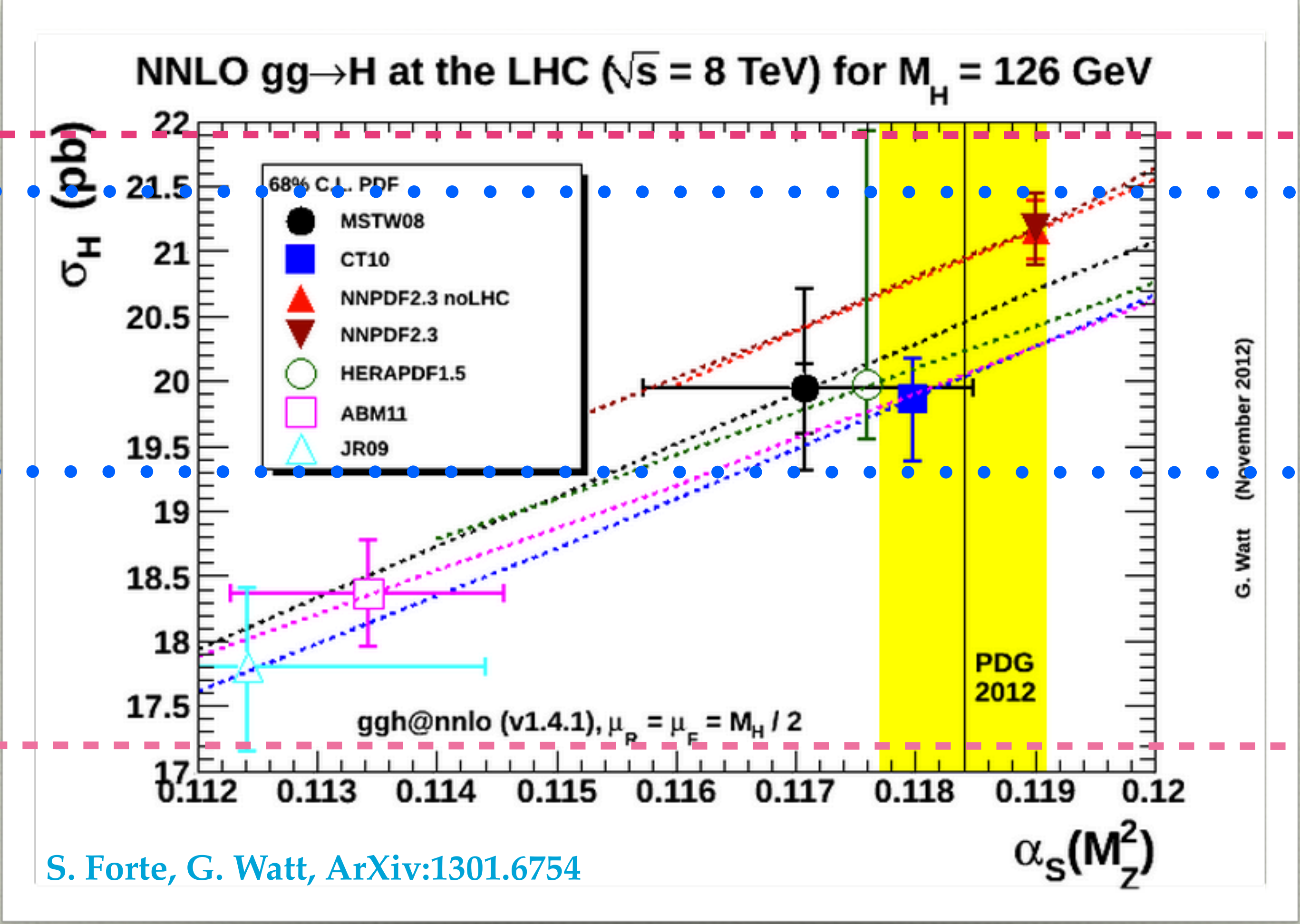
- **< 2002:** sets without uncertainty
- **2003-2004:** first MRST, CTEQ, Alekhin sets with uncertainties
- **2004-now:** huge progress made in statistical and theoretical understand, new players

Modern sets of PDFs

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

May 2014	CT10(w)	MSTW2008	NNPDF23	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 $\Delta\chi^2=100$
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

Predictions for the LHC

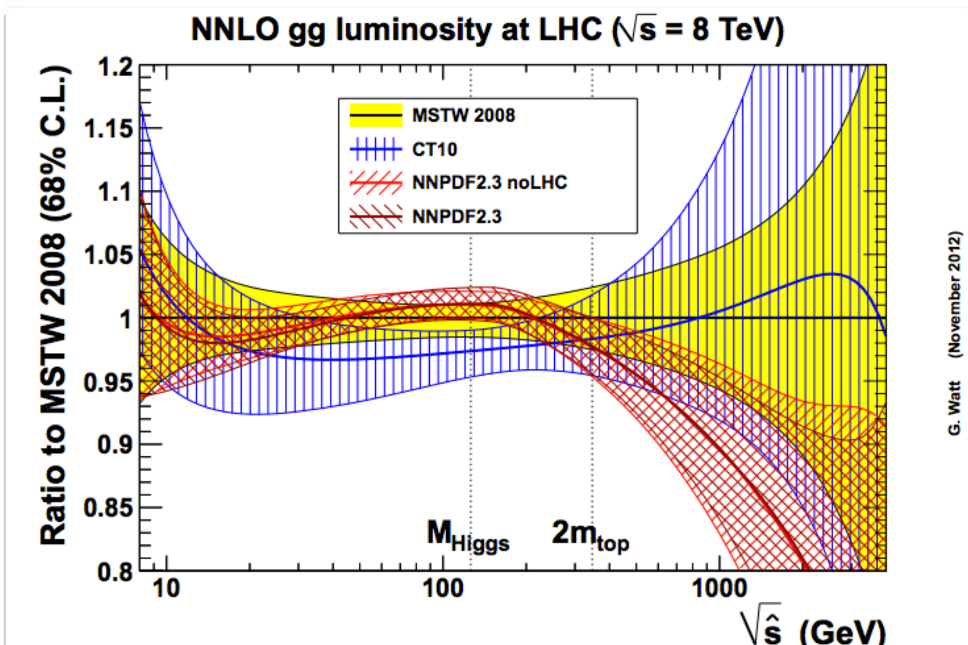


S. Forte, G. Watt, ArXiv:1301.6754

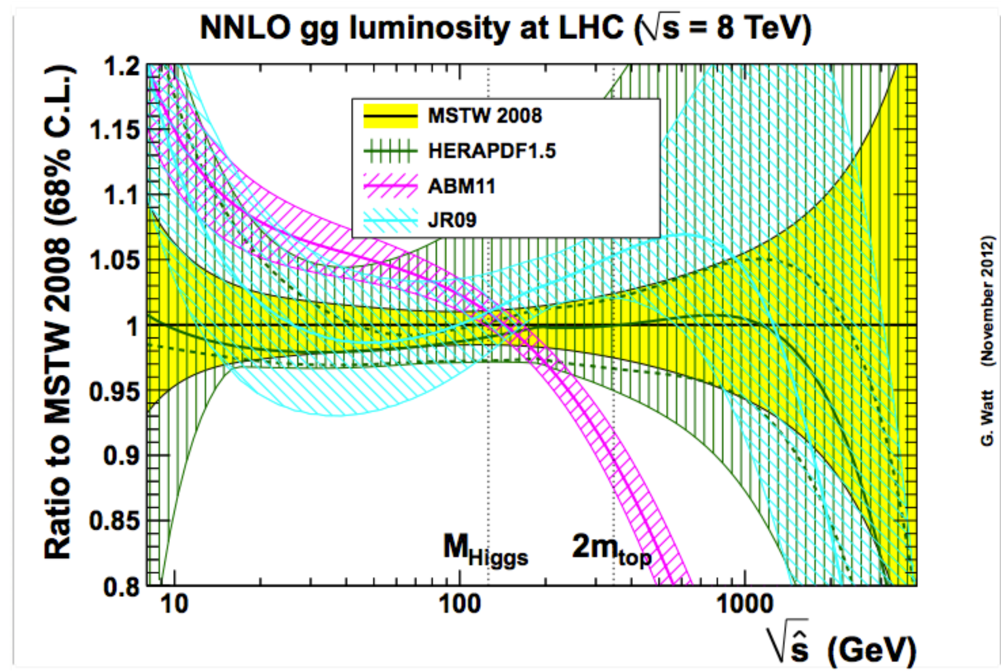
- Gluon fusion initiated Higgs productions
- Wide spread of predictions limits accuracy in Higgs characterization
- Global sets quite close to each others and compatible to HERA analysis
- Larger discrepancies with ABM and JR
- Similar (worse) situation for ttbar cross section predictions

Parton Luminosities

Directly connected with gluon-gluon luminosity

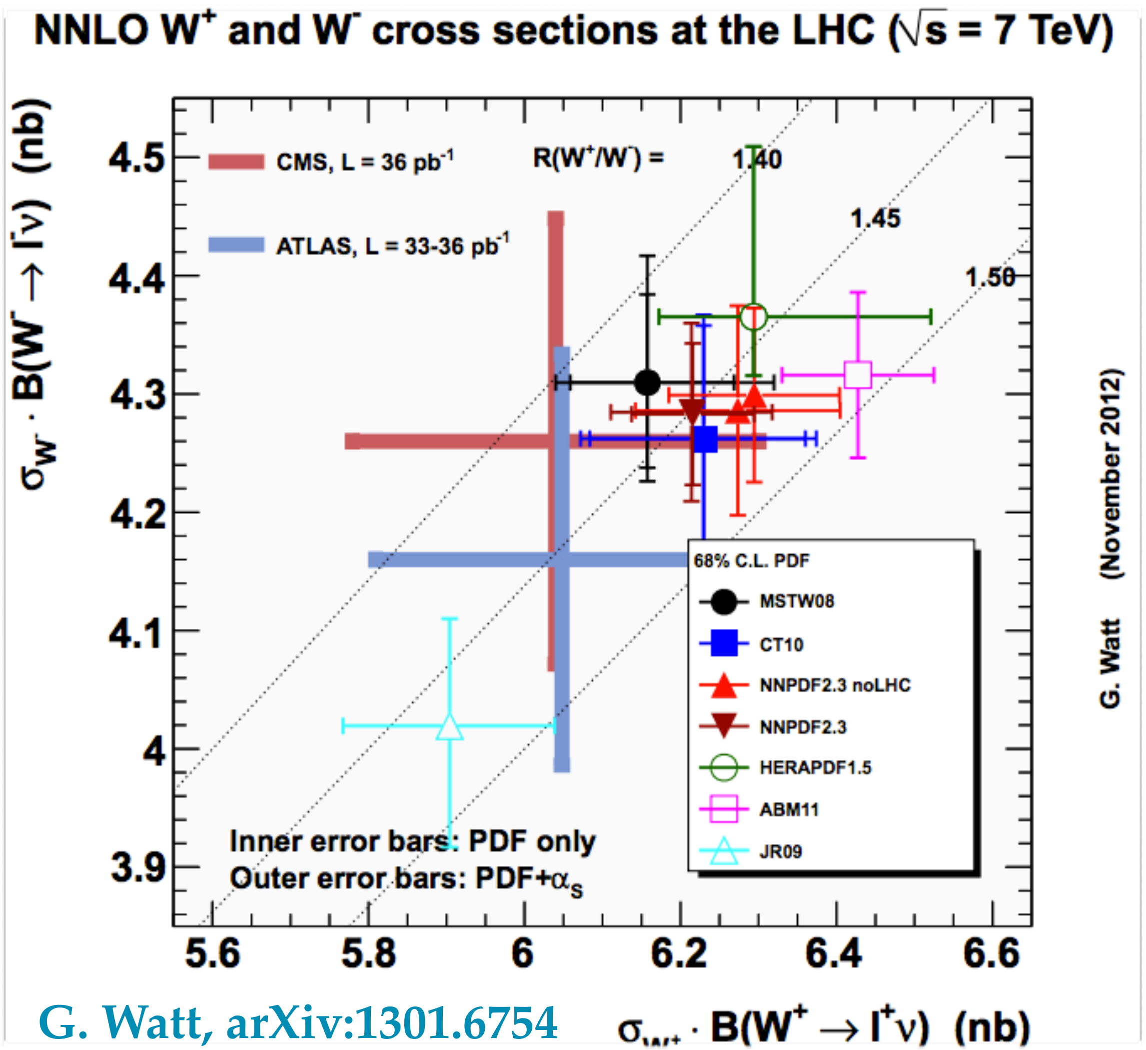


G. Watt, arXiv:1301.6754



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

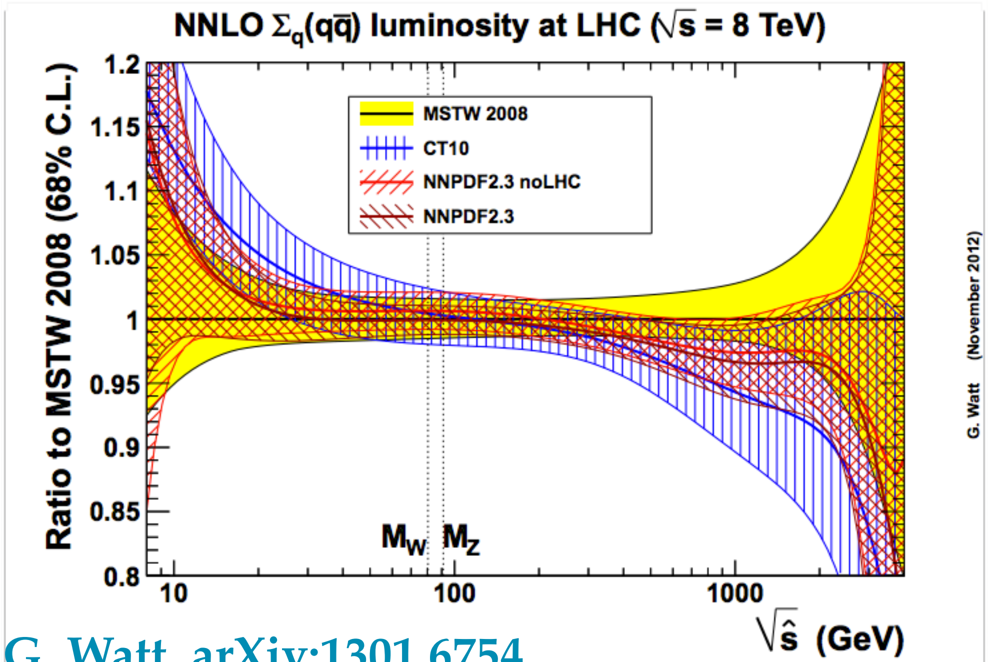
Predictions for the LHC



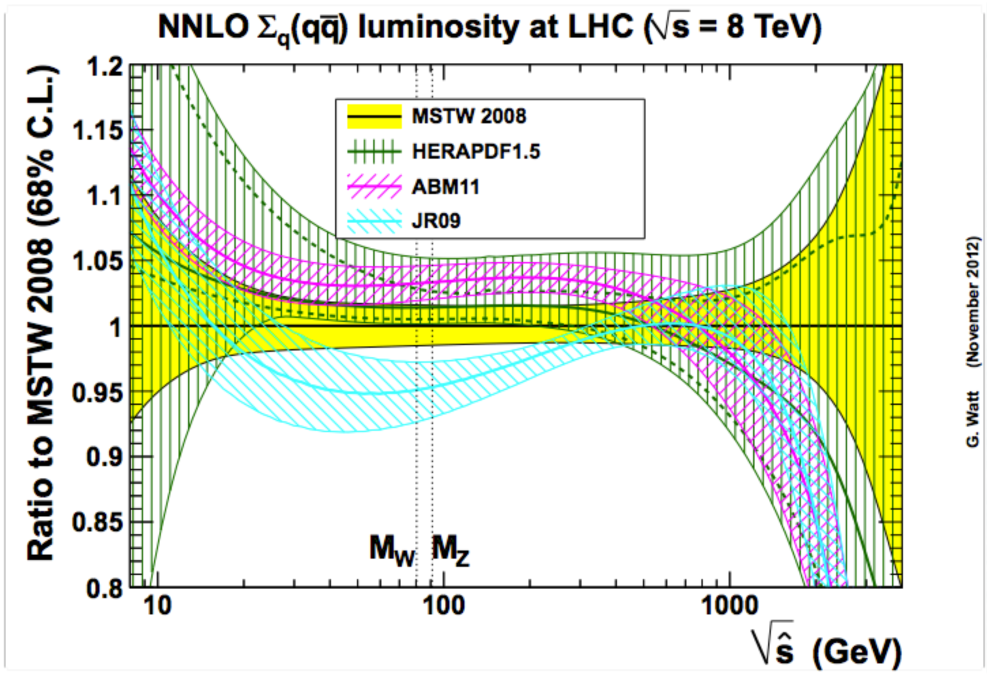
- For W and Z productions (quark dominated) situation is less dramatic
- Predictions mostly close to each others
- More significant discrepancies with ABM and JR
- Compatible with data, although data the more precise the more discriminating

Parton Luminosities

Directly connected with quark-quark luminosity

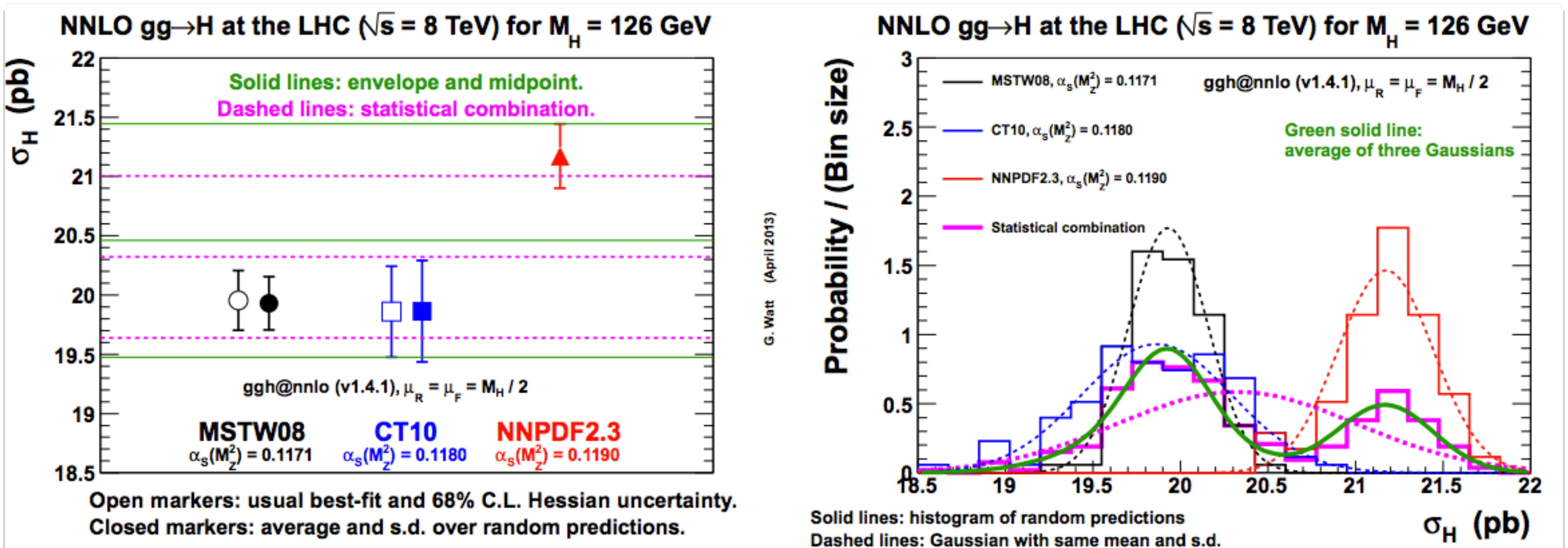


G. Watt, arXiv:1301.6754



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

How to combine them?



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

LHC data for PDFs

LHC kinematics coverage

GLUON

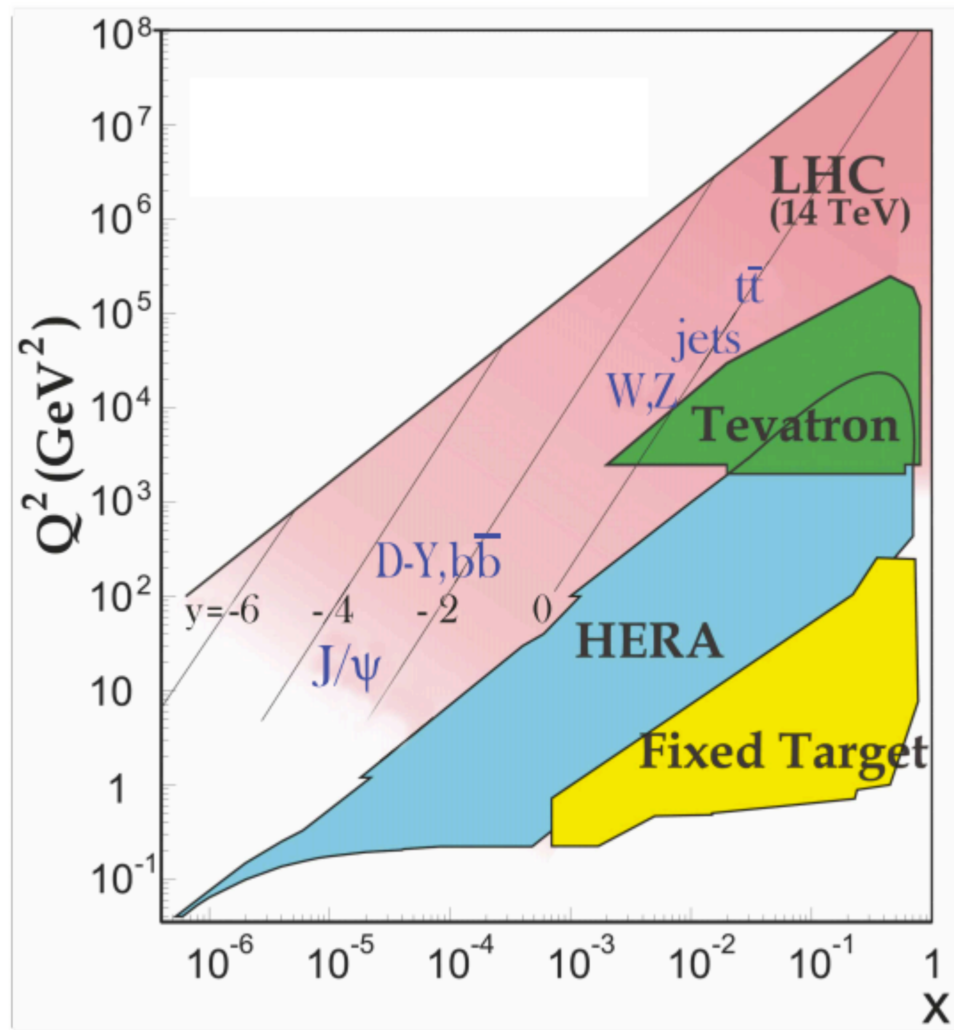
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T Z(+jets) distribution **(small/medium x)**

QUARKS

- High p_T W(+jets) ratios **(medium/large x)**
- W and Z 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

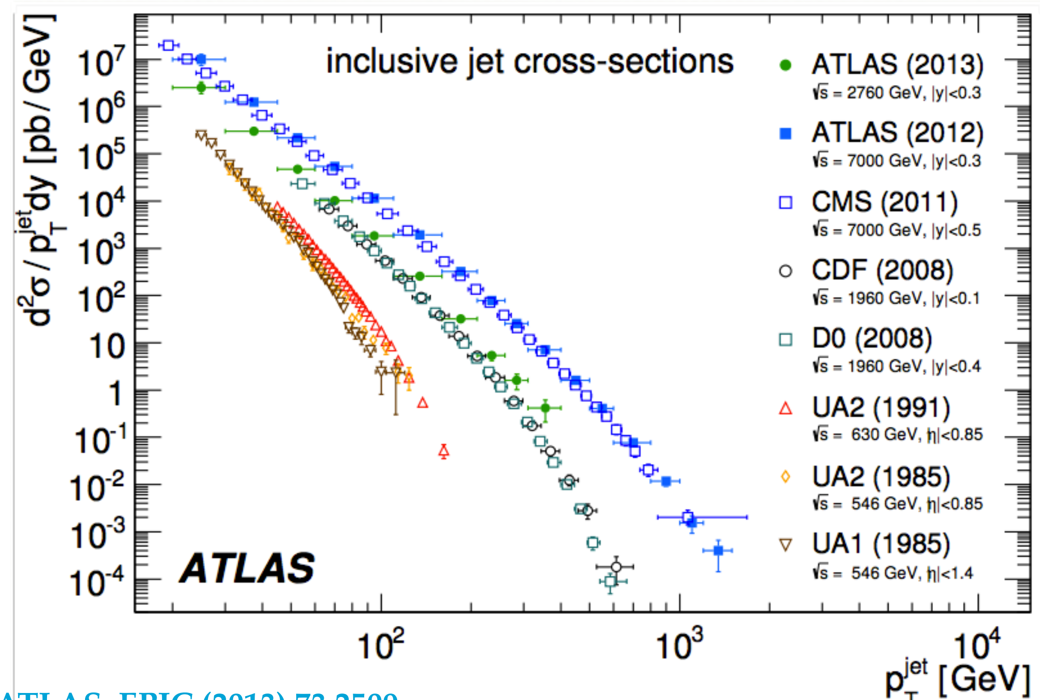


Gluons

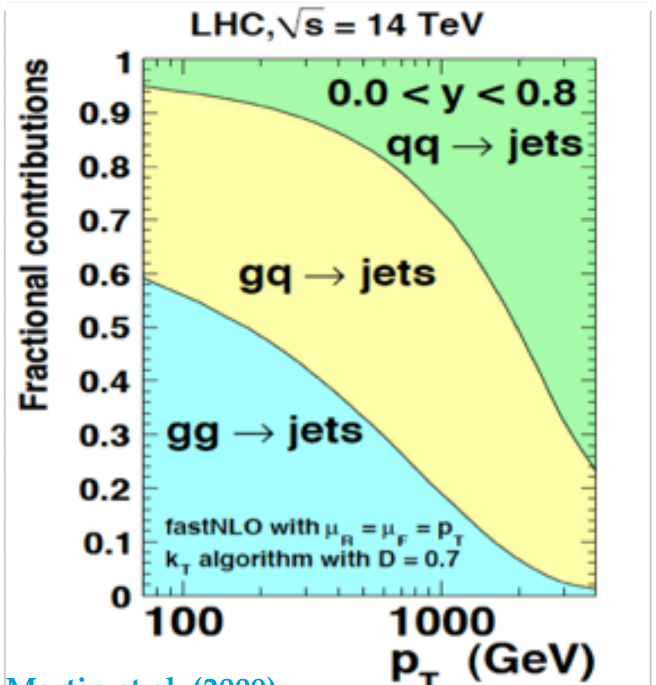
Inclusive Jets: data

- 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

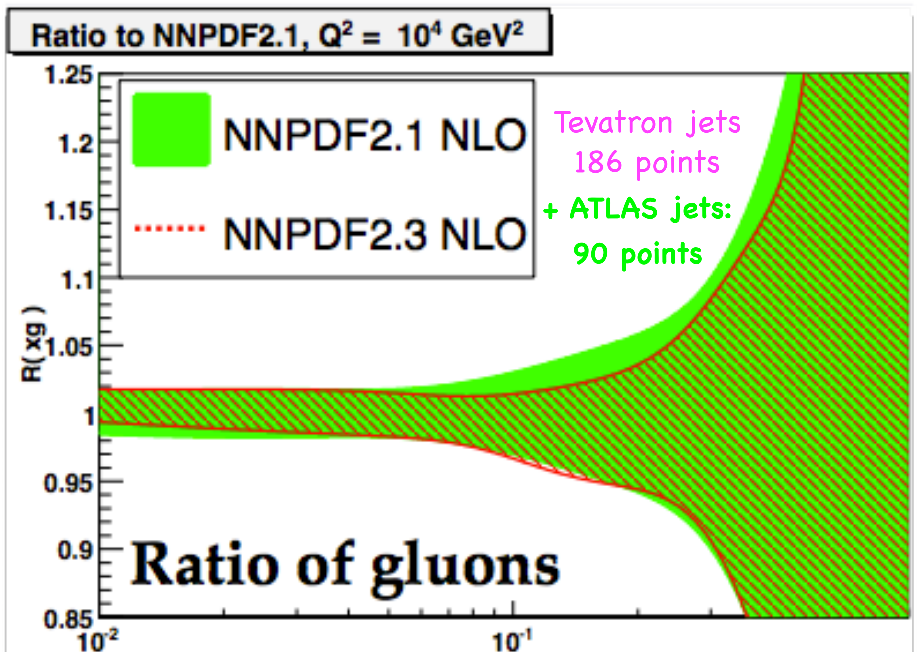


Martin et al, (2009)

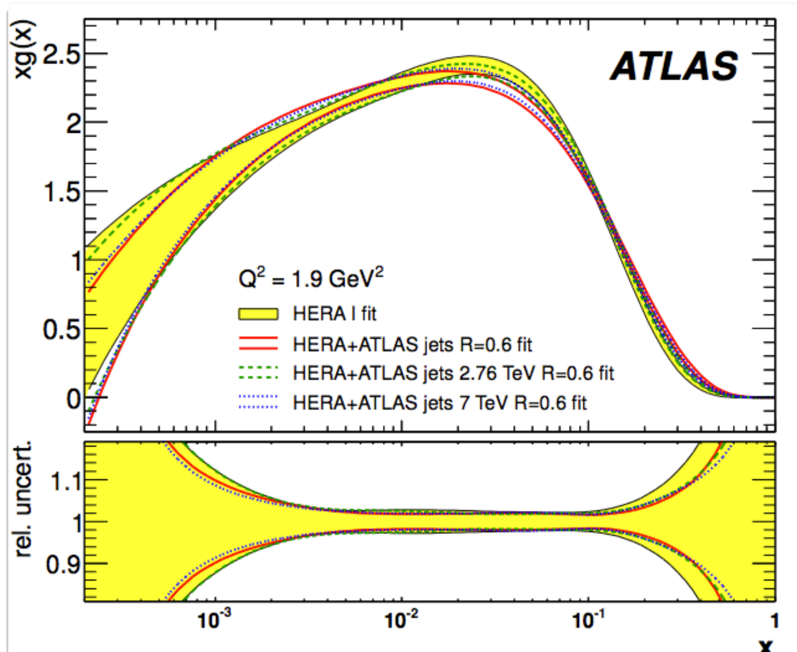
Gluons

Inclusive Jets: impact of data

- NNPDF2.3 analysis includes ATLAS 35 pb^{-1} inclusive jet data
- Moderate but significant constraint and reduction in gluon uncertainty
- Many more 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)
- CMS sizeable impact assessed by MSTW via reweighting



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



ATLAS, EPJC (2013) 73 2509

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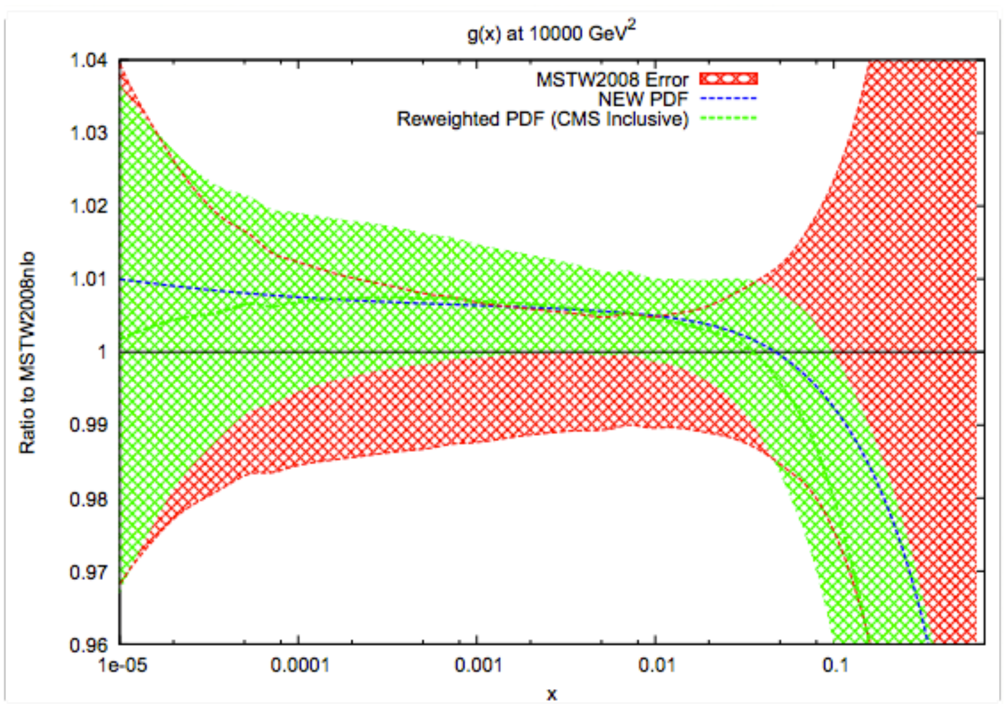
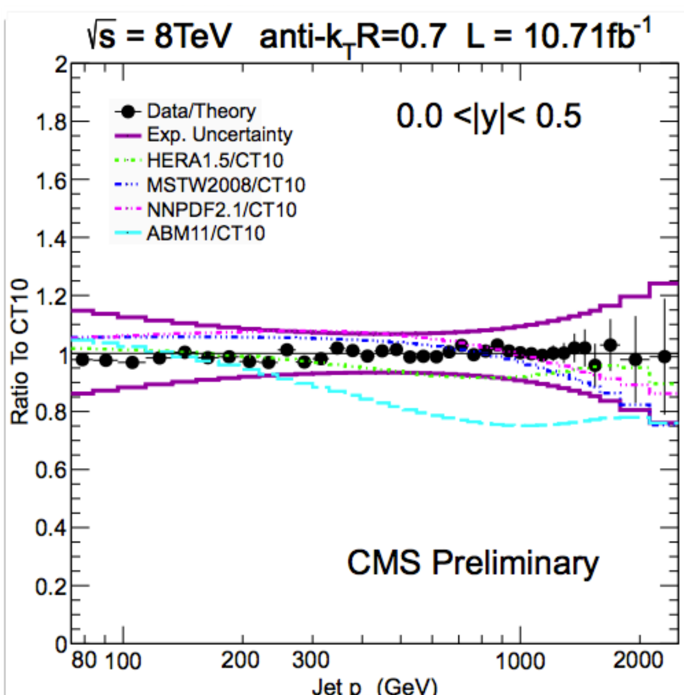


R. Thorne, QCD@LHC 2013

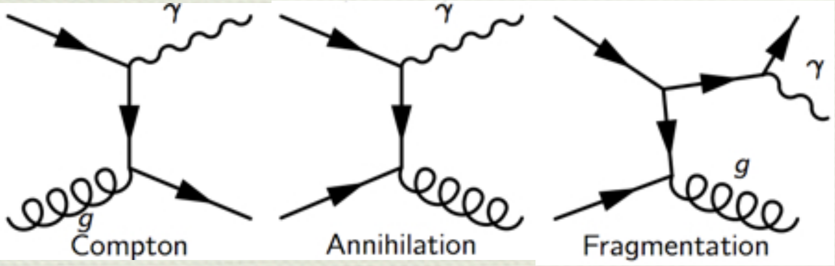


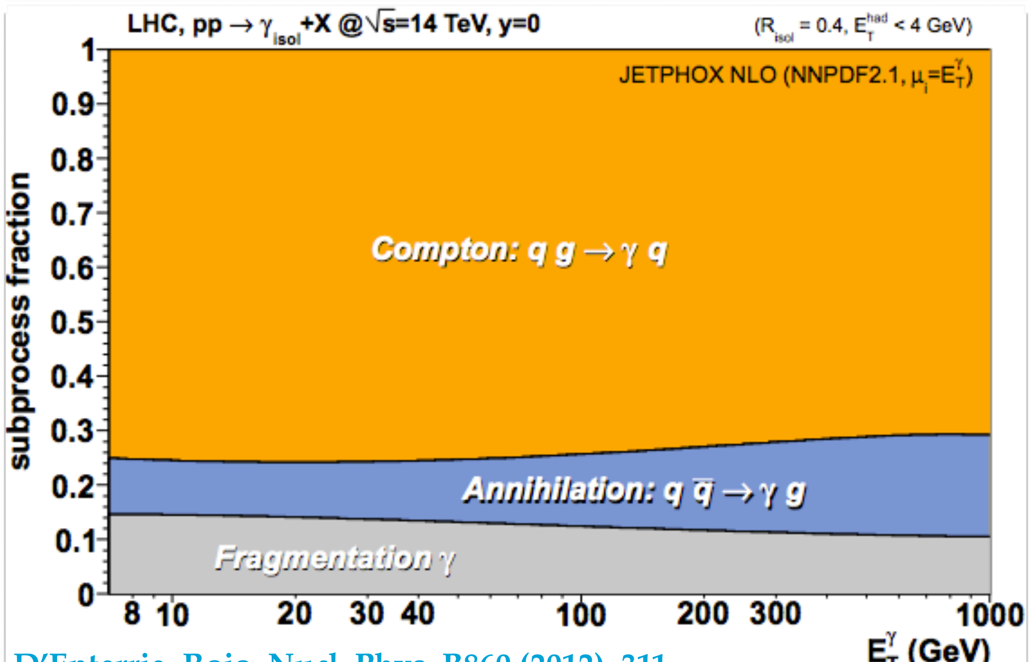
CMS-PAS-SMP-12-012

Gluons

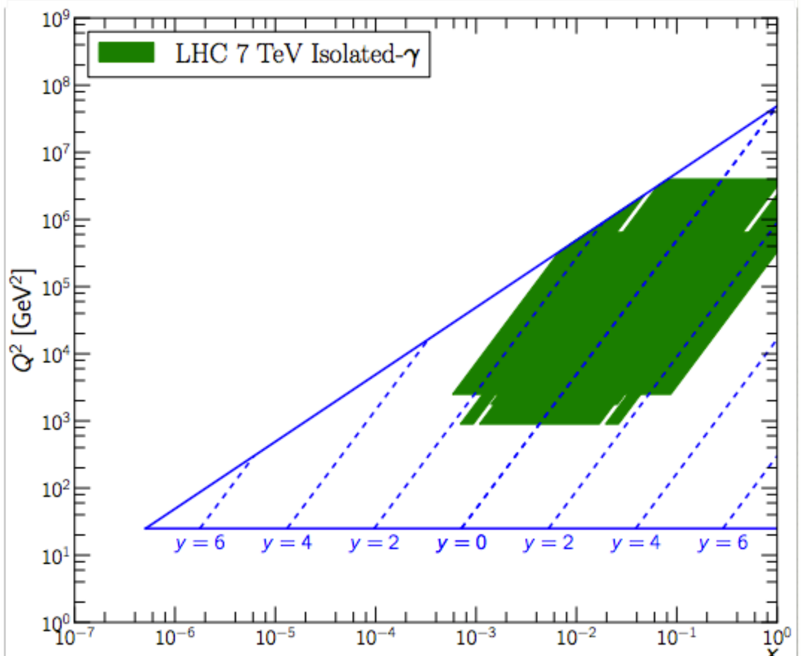
Prompt photon production: data

- 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

Gluons

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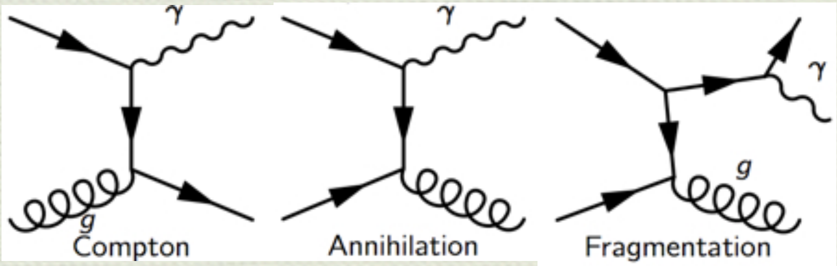
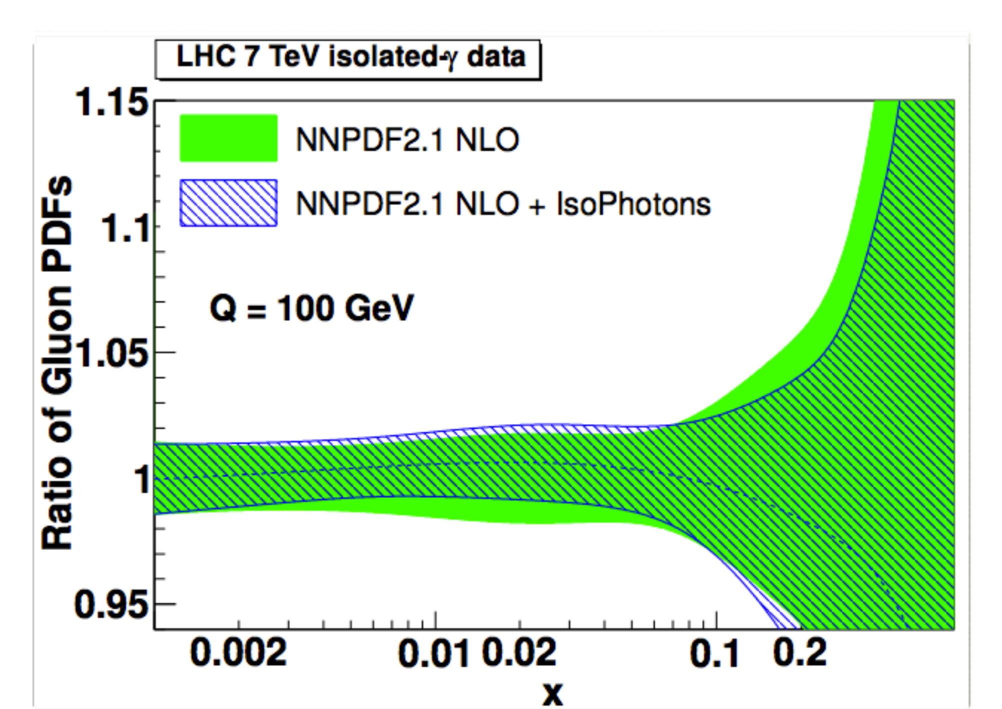




D'Enterria, Rojo, Nucl. Phys. B860 (2012), 311

- Included ATLAS 880 nb^{-1}, and 35 pb^{-1}, CMS 1.9^{-1} and 36 pb^{-1}
- Moderate uncertainty reduction in the region which affects and reduce uncertainties for Higgs gluon fusion predictions by 20%
- Issue: there is not yet a public fast interface available for JETPHOX [P. Aurenche et al] in PDF fits but it is likely to be available shortly

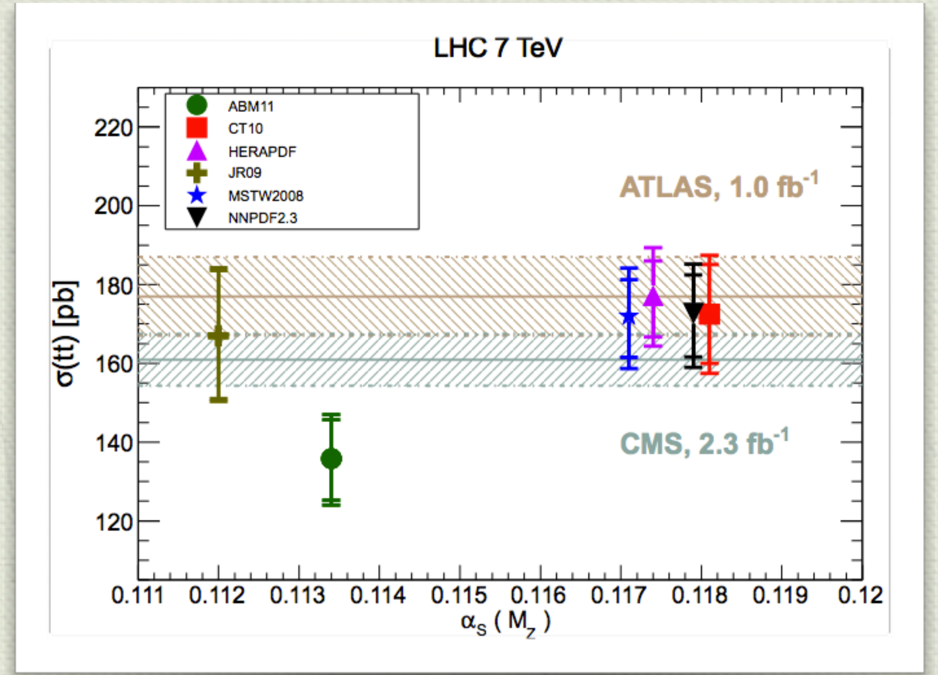
Gluons

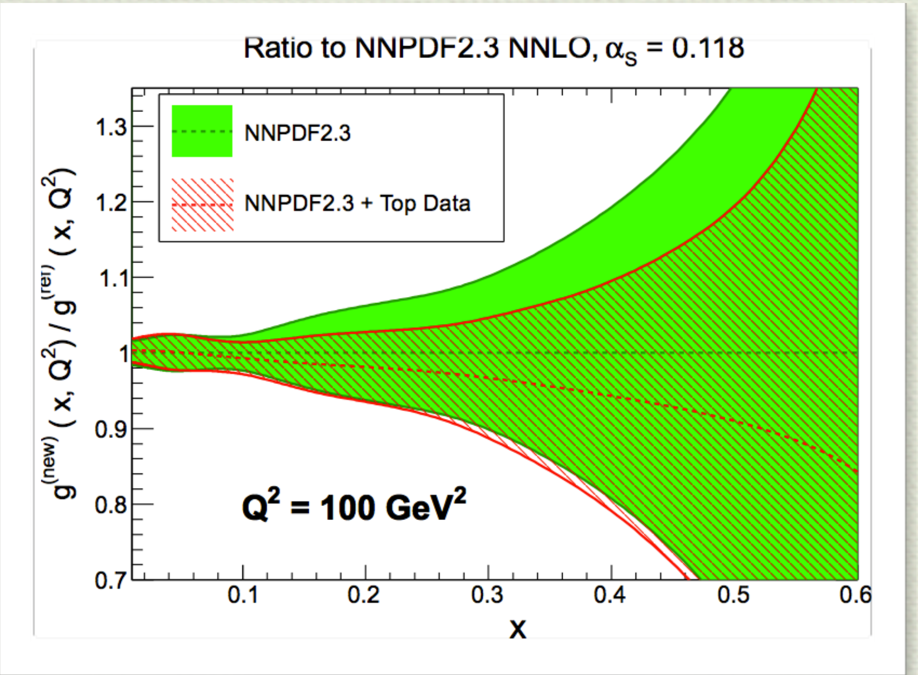
Top pair production: data and impact

- 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

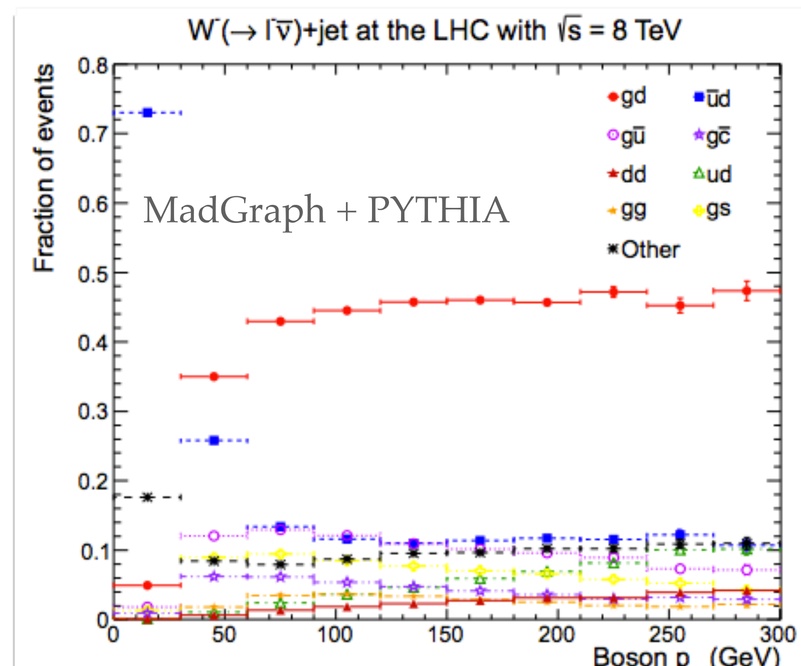




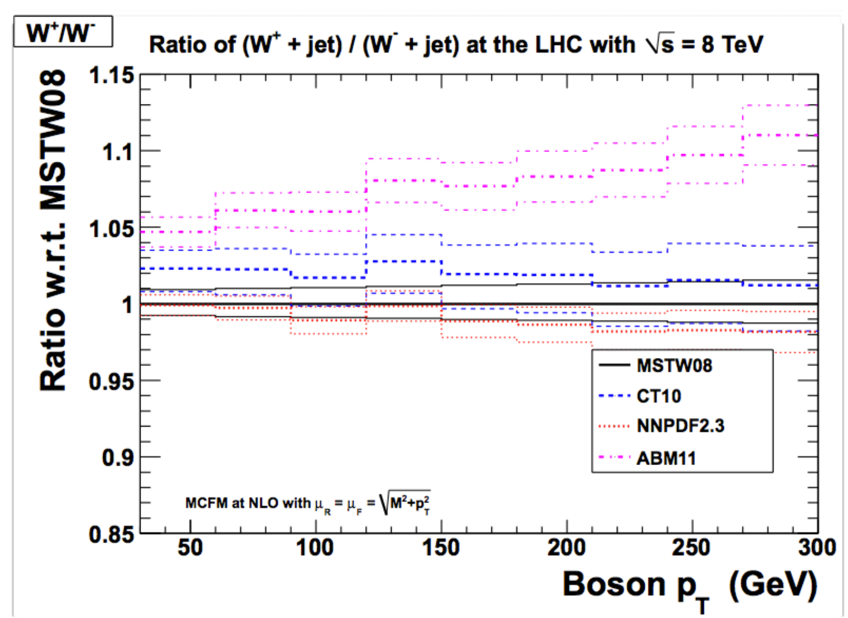
Gluons

High pT vector boson production

- In global fits, medium/large x gluon is mainly constrained by jet data.
- W/Z boson at large p_T (associated with jets) would provide a complementary constraint 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



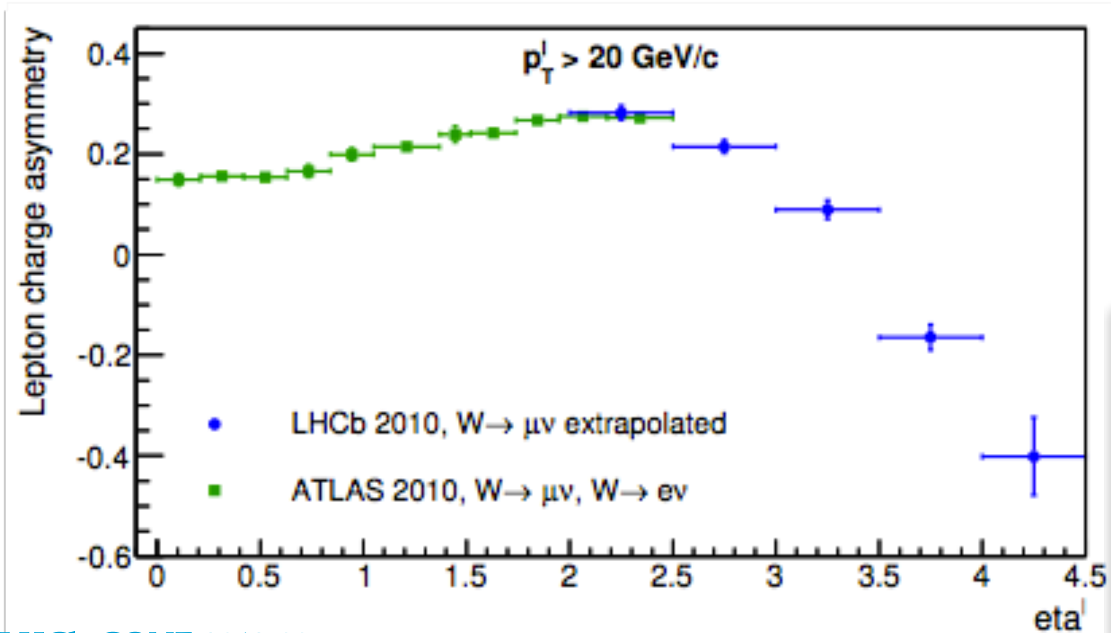
Malik,Watt ArXiv: 1304.2424



- 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

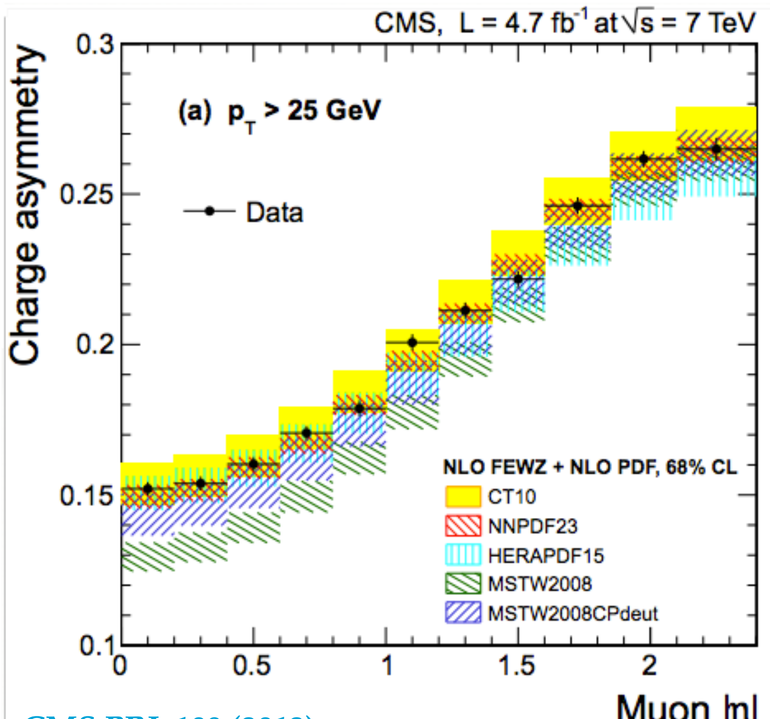
Quark flavor separation

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

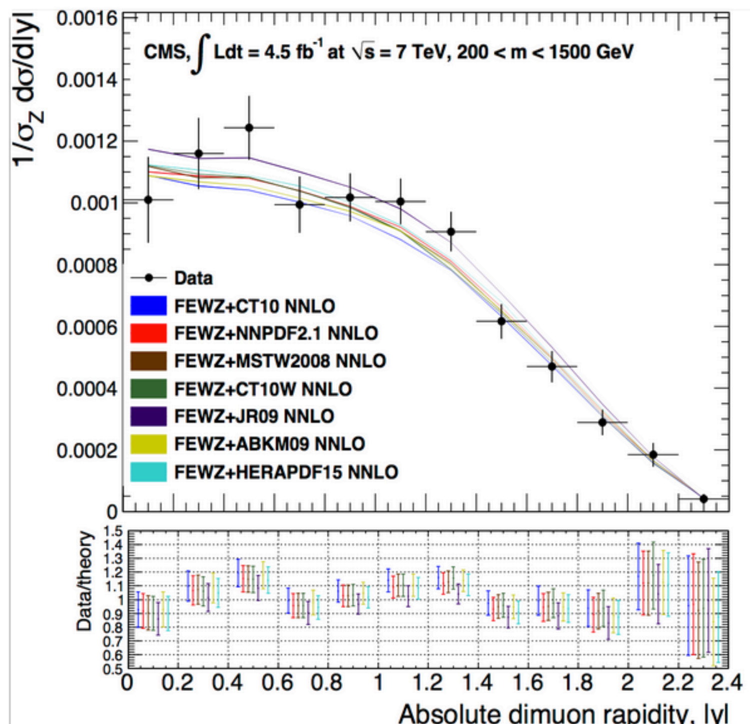


CMS PRL 109 (2012)

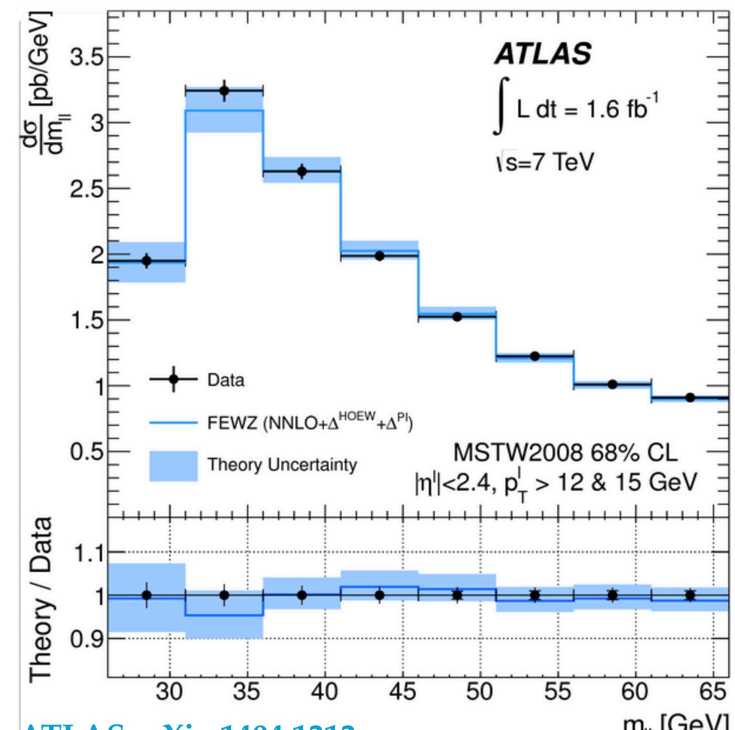
☑ W charge lepton asymmetry (ATLAS and CMS) Strong constraints on up and down valence quarks and sea asymmetry

Quark flavor separation

A wealth of data from LHC



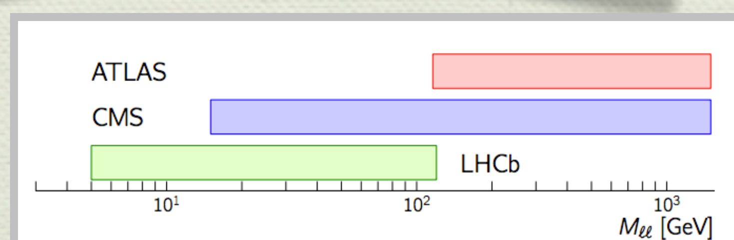
CMS JHEP 2013



ATLAS arXiv 1404.1212

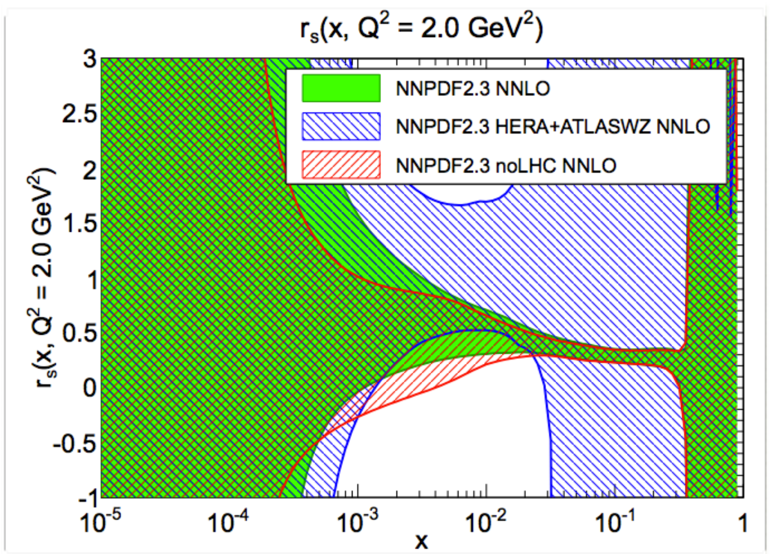
☑ High and low mass Drell-Yan distributions provide valuable constrain to quarks and antiquarks in large and small x regions

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



Strangeness

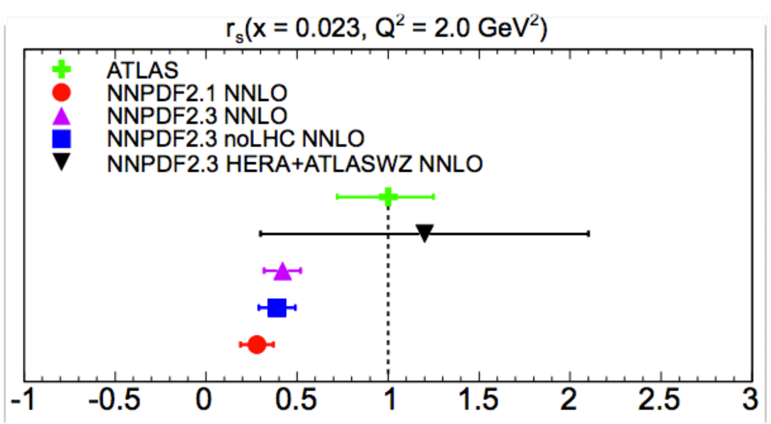
A "strange" story



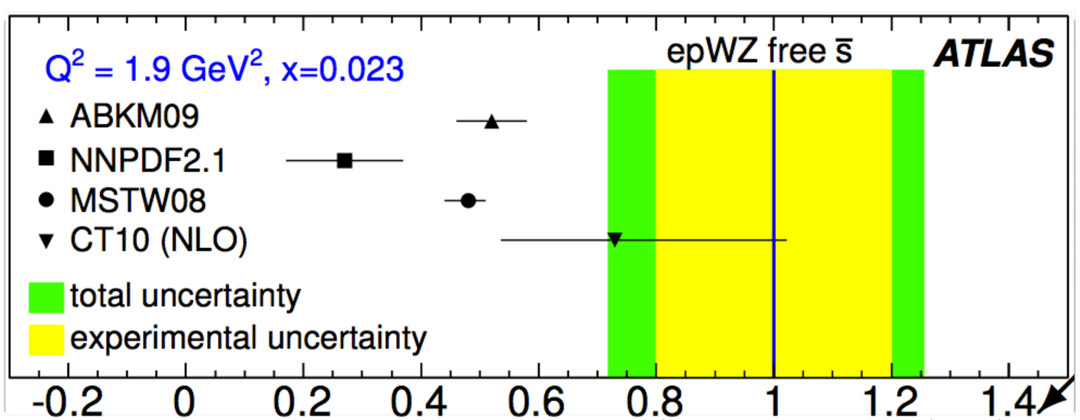
- In global analyses strangeness is mostly determined by DIS fixed target data (CHORUS, NuTeV) -> suppressed strange sea

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

- 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.



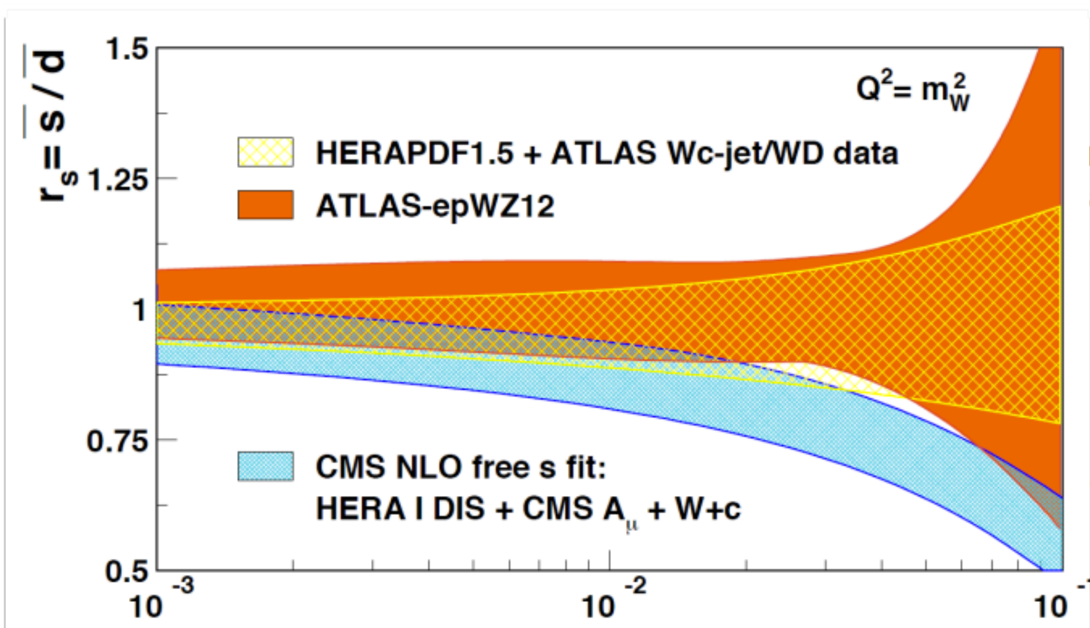
R. Ball et al, Nucl. Phys. B867 (2013) 244



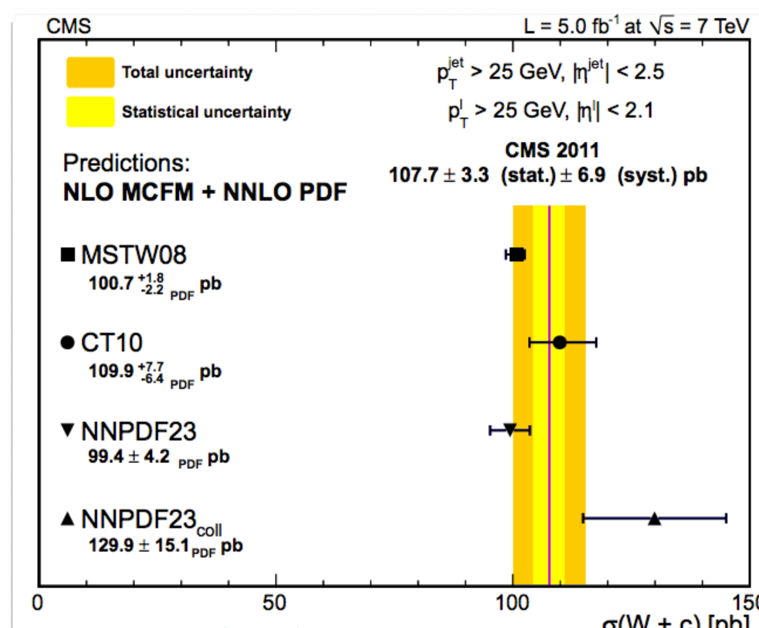
ATLAS, Phys. Rev. Lett. 109 (2012) 012001

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



R. Plakakyte DIS 2014

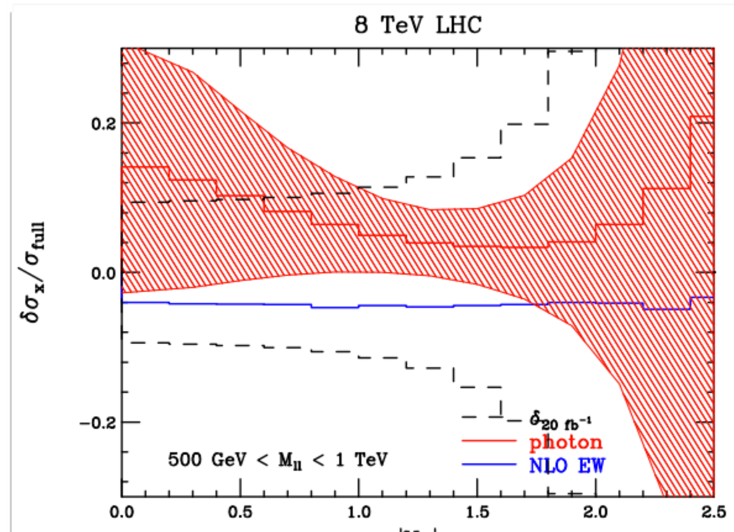


CMS JHEP (2014)

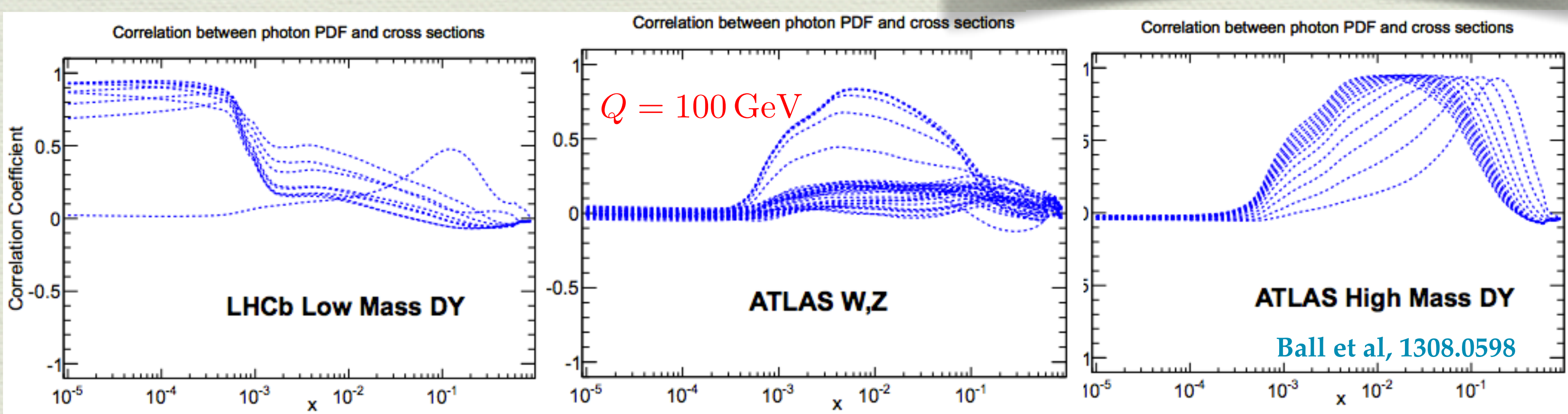
Photon

Electroweak corrections

- EW corrections become relevant at the current precision level
- Their inclusion requires PDF with QED effects
- NNPDF23QED is new 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!



Boughezal, Liu, Petriello, ArXiv:1312.4535

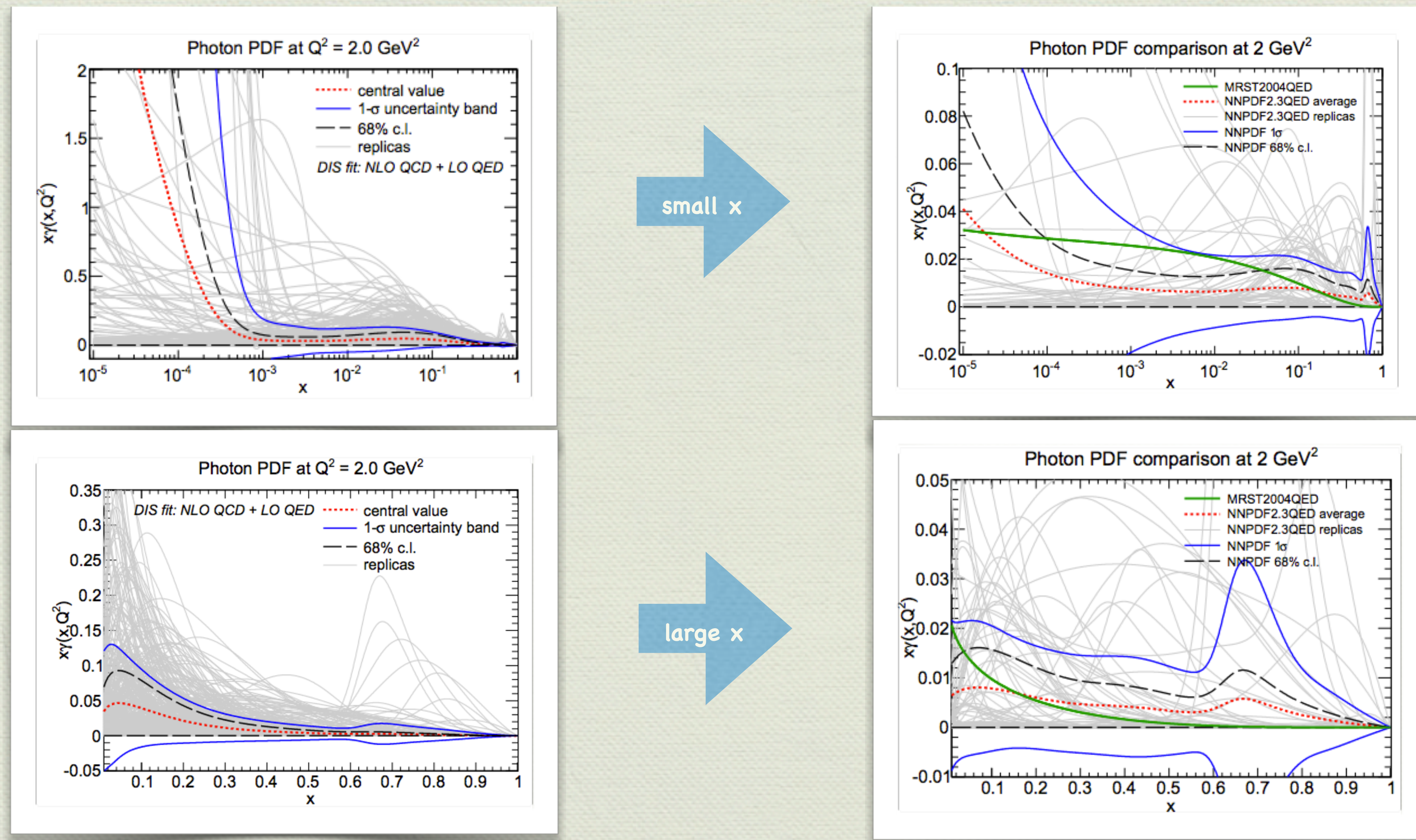


Ball et al, 1308.0598

Photon

Constraints from LHC

Ball et al, 1308.0598

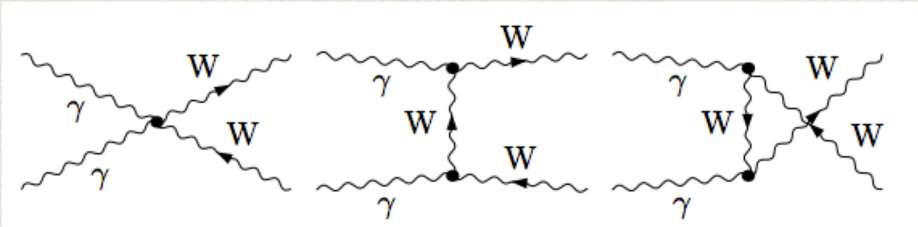


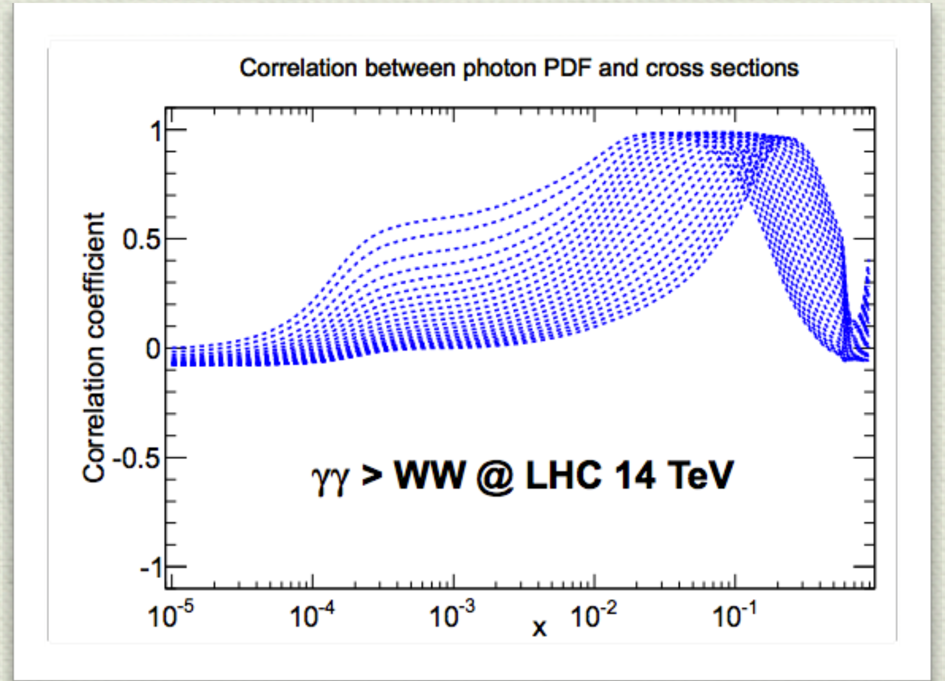
Photon

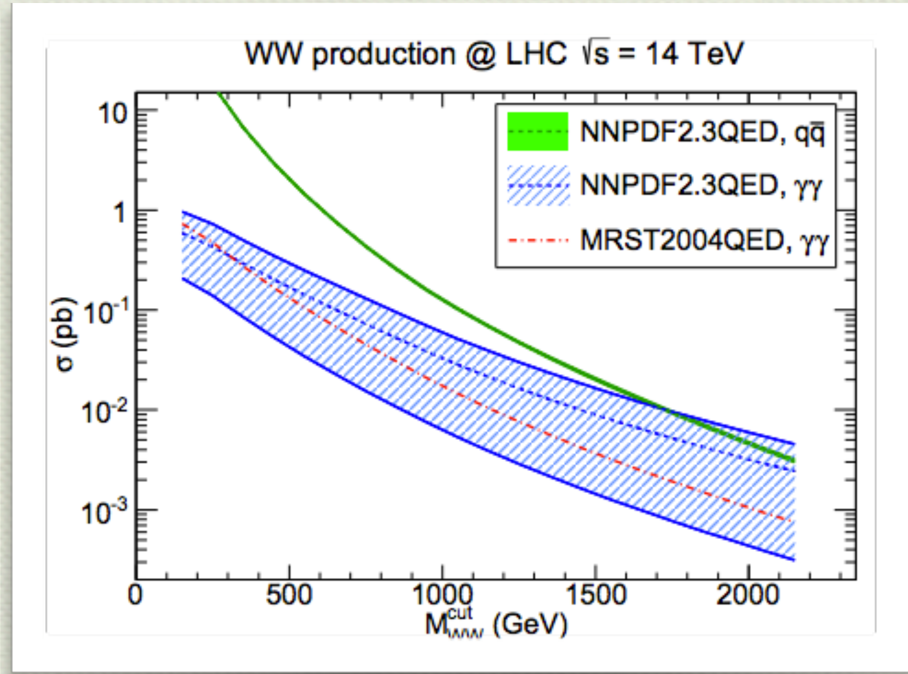
More constraints from LHC

Ball et al, 1308.0598

- 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







Conclusions and outlook

- PDF uncertainties are often limiting factor in achieving precise predictions
- LHC data have huge potential in constraining PDFs
  - ✓ Inclusive jets and dijets both central and forward: large-x quarks and gluons
  - ✓ Inclusive W and Z productions and asymmetries: quark-flavor separation, strangeness, photon
  - ✓ Isolated photon: medium-x gluon
  - ✓ High-pT Z/W transverse momentum distribution
  - ✓ W+charm: direct handle on strangeness
  - ✓ W,Z + jets: gluon at medium-x and u/d ratio
  - ✓ Off-resonance Drell-Yan at small and large mass: quarks & photon at small and large x
  - ✓ WW production: photon and light quarks
  - ✓ Top quark inclusive and differential distribution: large-x gluon
  - ✓ Ratios at different CME
  - ✓ Z+c: intrinsic charm PDF
  - ✓ Z+b: gluon and bottom PDF
  - ✓ Single top production: gluon and bottom PDFs
- Most collaborations working in inclusion of LHC data (NNPDF3.0)
- Towards collider only fits?
- Theoretical accuracy must catch up with experimental accuracy