Overview of LHC observables for PDF fits

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PDF whishlist at the LHC

Traditional

- Inclusive jets and dijets, central and forward: **large-x quarks and gluons**
- Inclusive W and Z production and asymmetries: **quark flavor separation, strangeness**

New @ LHC

- Isolated photons, photons+jets: **medium-x gluons**
- W production with charm quarks: **direct handle on strangeness**
- W and Z production at high p_T: **medium and small-x gluon**
- Off resonance Drell-Yan and W production at high mass: **quarks at large-x**
- Low mass Drell-Yan production: **small-x gluon**
- Top quark cross-sections and differential distributions: **large-x gluon**

Speculative

- Z+charm: **intrinsic charm PDF**
- Single top production: **gluon and bottom PDFs**
- Charmonium production: **small-x gluon**
- Open heavy quark production: **gluon and intrinsic heavy flavor**

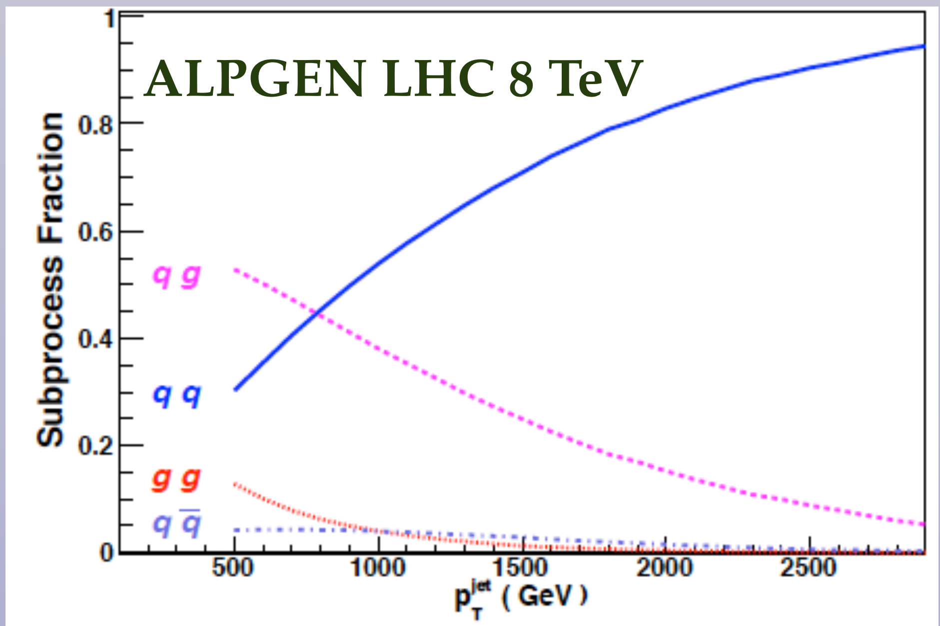
Jet production

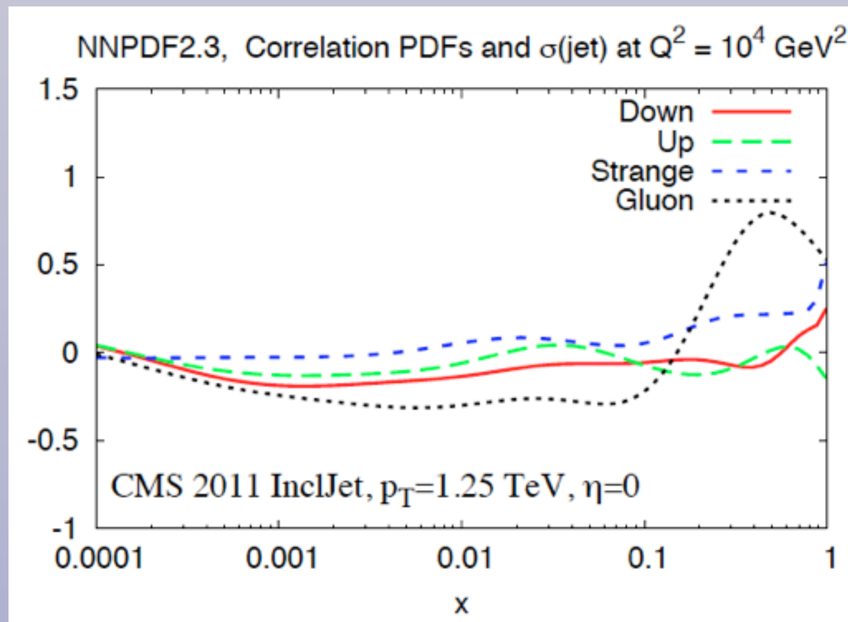
- Traditional source of information on the **gluon** in global PDF fits (as well as for α_S)
- For **p_T < 800 GeV, quark-gluon** scattering dominates, for higher p_T one is probing **quark-quark**
- The **higher the p_T,** the **higher the Bjorken-**x value one is probing

  Important since large-x PDFs have very large uncertainties

- Theoretical calculations: **NLO**, partial NNLO also available for gg

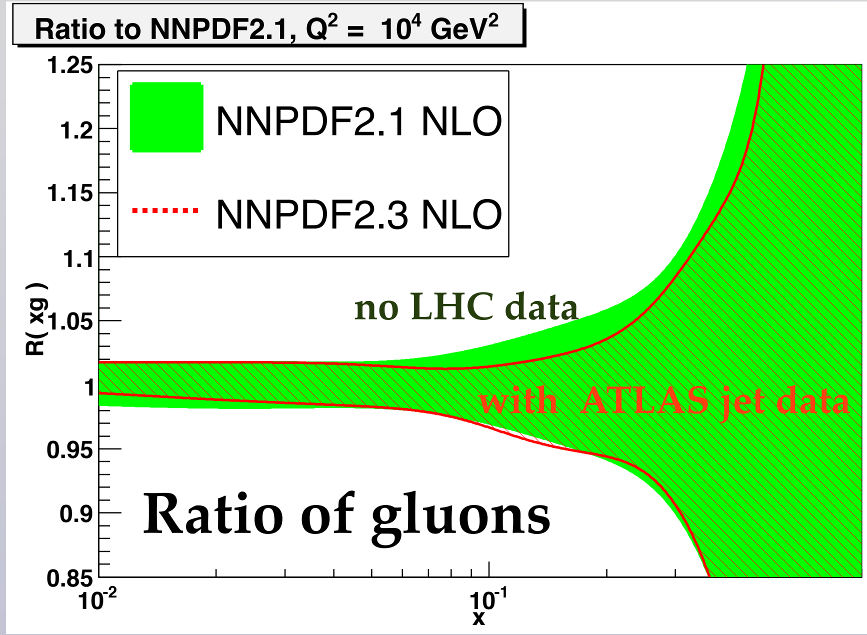
  Also substantial dependence on non-perturbative parameters from hadronization and UE

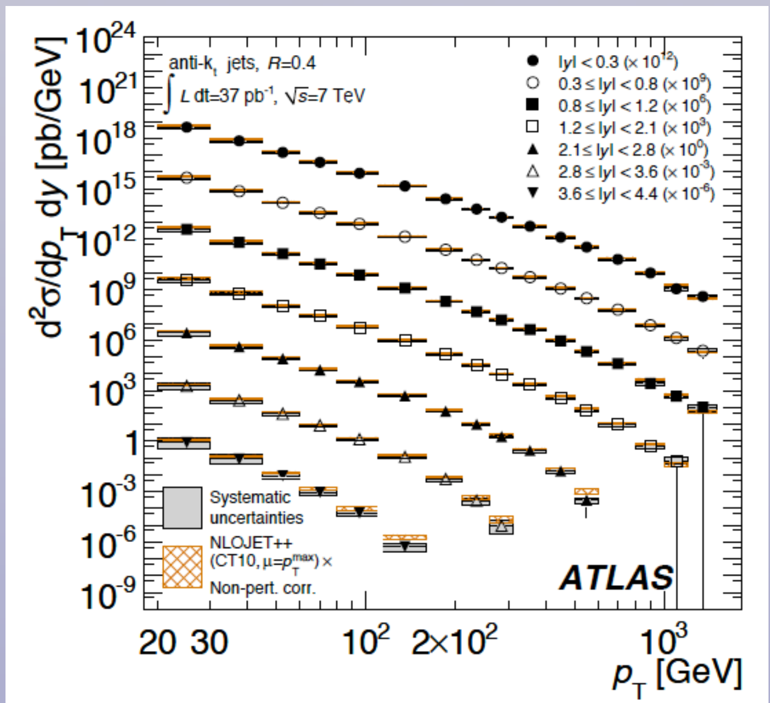


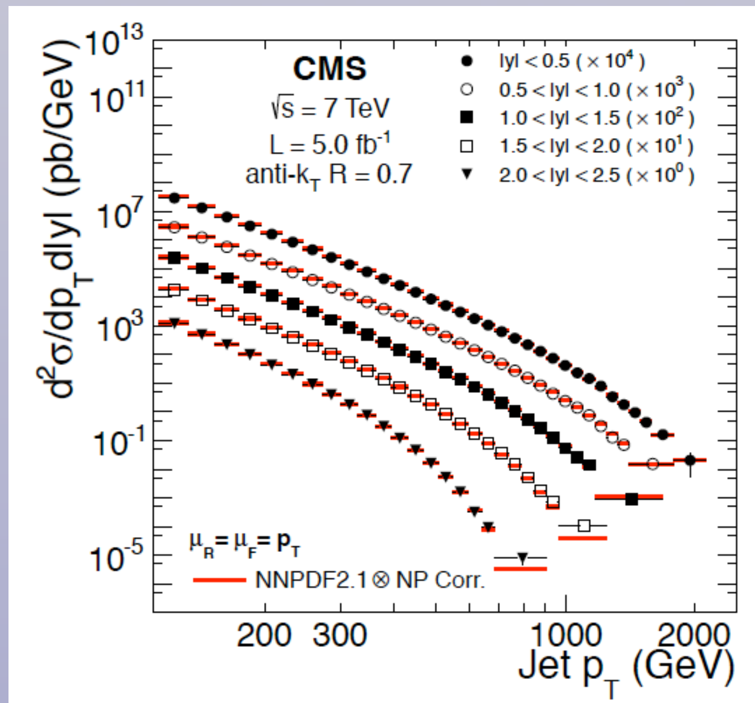


Jet production

- LHC results: **ATLAS 2010 data, CMS 2011 data** publicly available with covariance matrix
- ATLAS 2010 data: systematic uncertainties large, moderate improvement in gluon PDF
- Dijet data typically worse description than inclusive jets due to *scale choice issues*
- PDF sensitivity enhanced in **cross-section ratios between LHC energies** (see **Mark's talk,** more later)

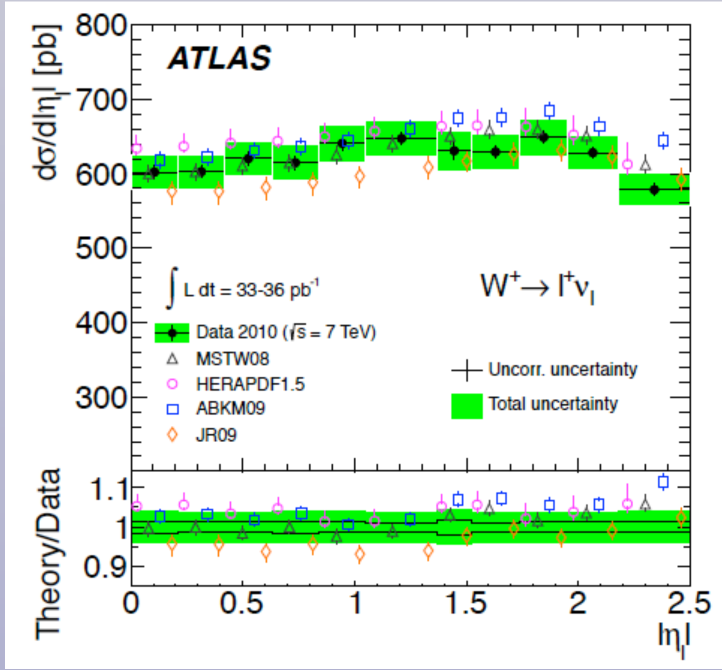


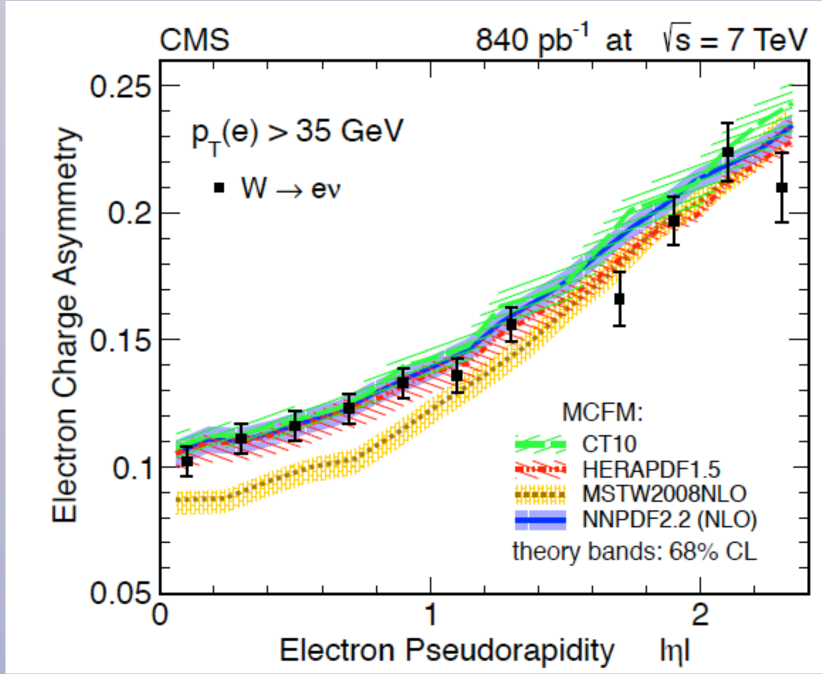




Inclusive vector boson production

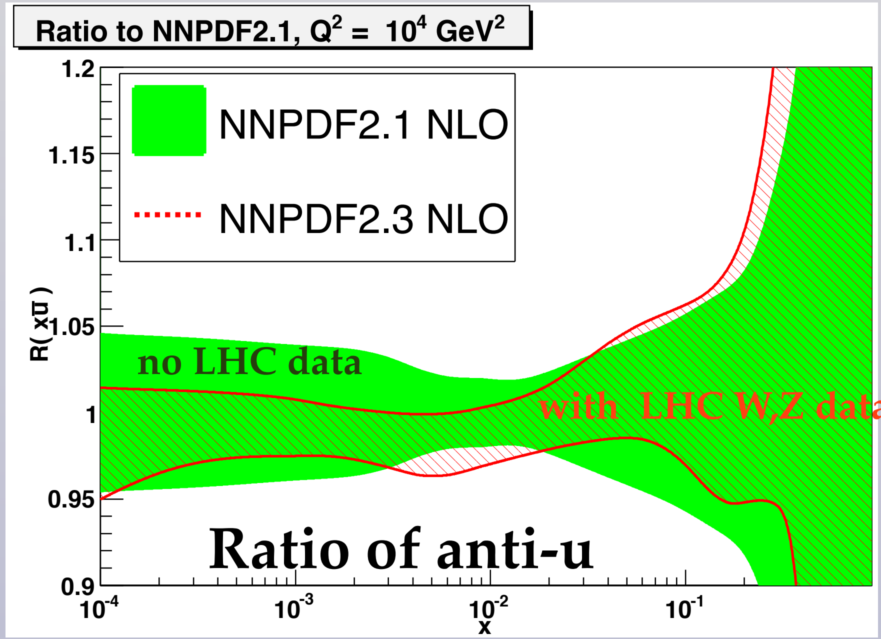
- Inclusive W and Z production probes **quark flavor separation** in a broad range of x
- Most useful: **separate differential distributions of W+, W- and Z** together with the corresponding **covariance matrix**
- Data available: ATLAS and CMS 2010 data, CMS electron W asymmetry 2011 data

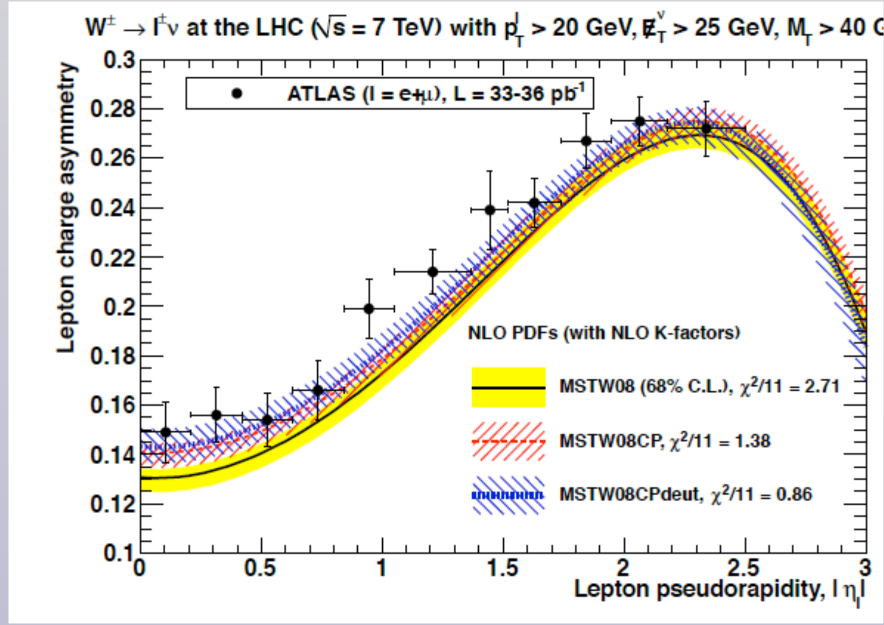




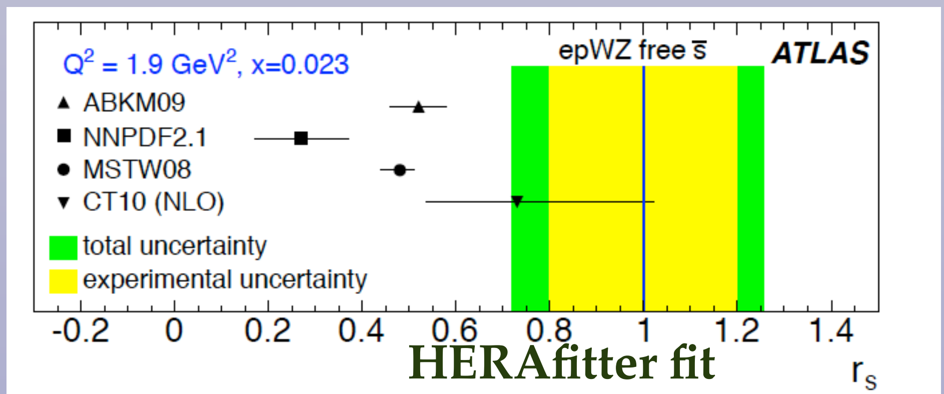
Inclusive vector boson production

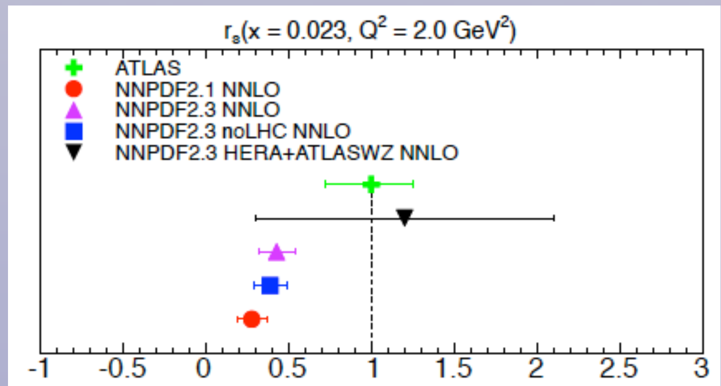
- Inclusive electroweak production **improves the PDF uncertainties in antiquarks** (NNPDF2.3), and **validates an extended MSTW parametrization** based on Chebyshev polynomials





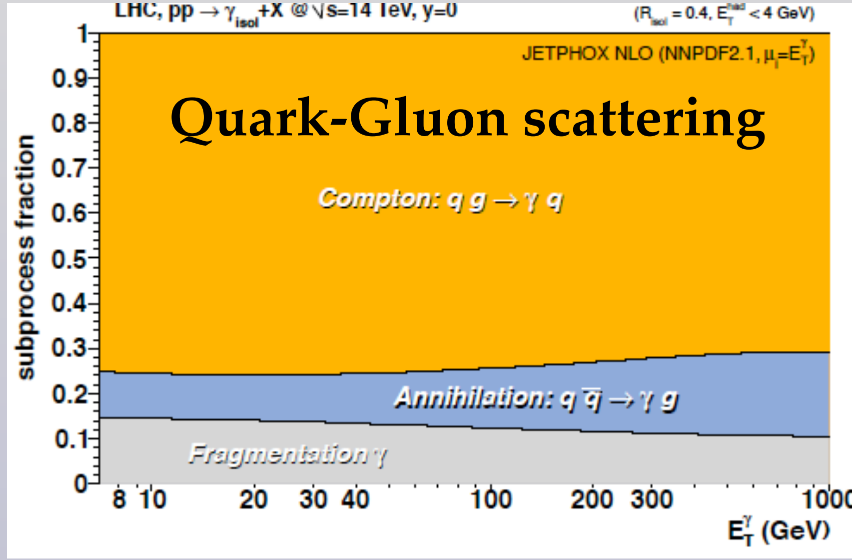
- A **QCD analysis of the ATLAS W, Z data** allows to determine **the strange PDF**. ATLAS analysis based on **HERAfitter** indicates **strange ≈ down**. **NNPDF2.3** analysis confirms central value, **but larger uncertainties**

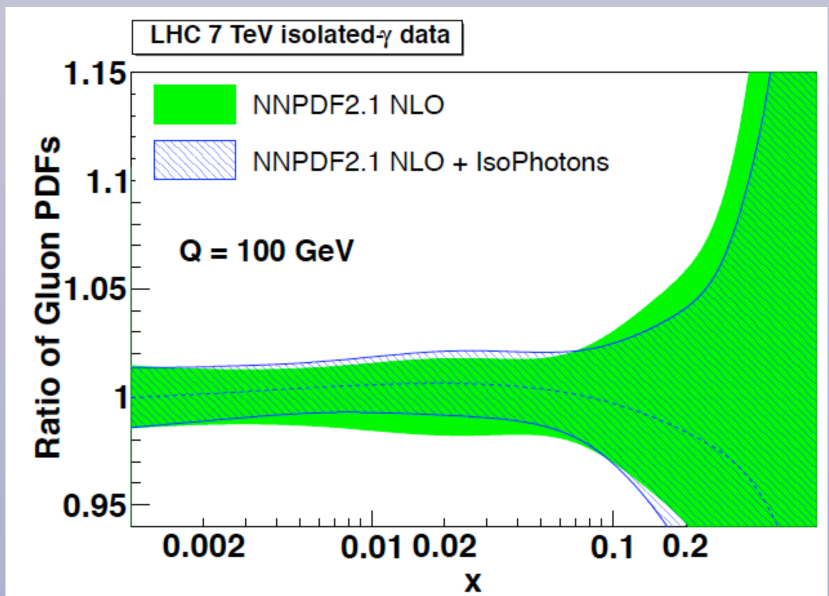


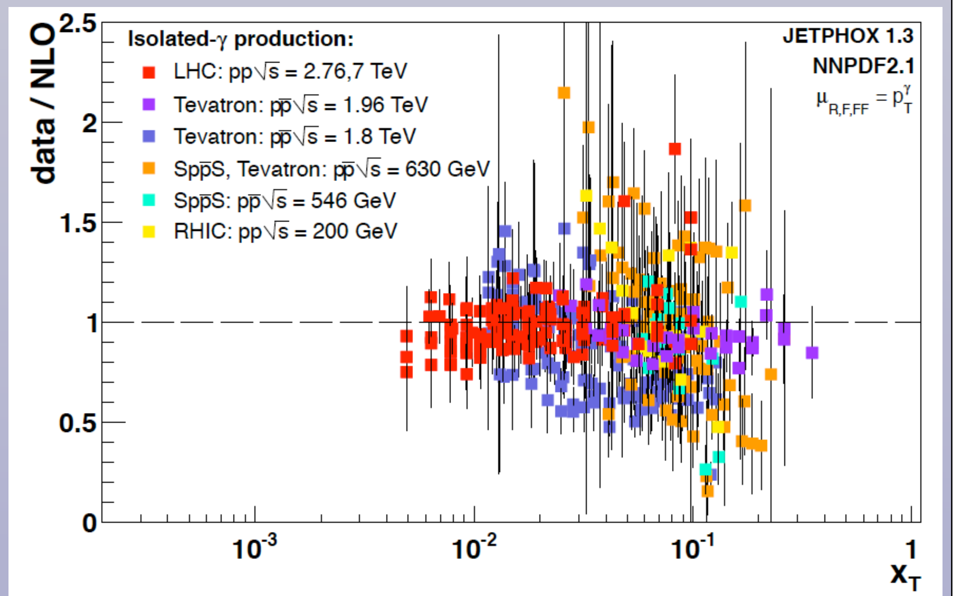


Isolated photons

- **Photon** production **directly sensitive to the gluon** via QCD Compton scattering (also Mark's talk)
- Photon production was used in **early PDF fits** for gluon constraints, then replaced by jets due to poor data/theory agreement of **some fixed-target data**
- Recently reanalysis of all **isolated collider** photon data with the most updated theory, **JetPhox+NNPDF2.1,** and found **overall agreement**
- **Moderate reduction of gluon PDF errors** from LHC photon data, in the region relevant for Higgs production in gluon fusion
- Need a **fast interface** to include photon data in PDF fits
- Need more precise data for **photon+jet production**



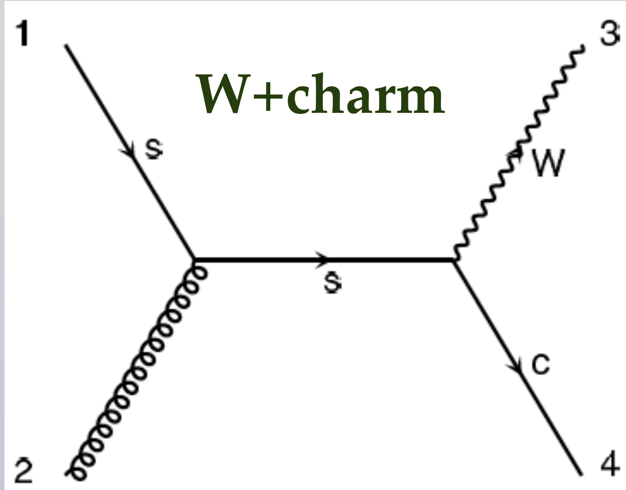


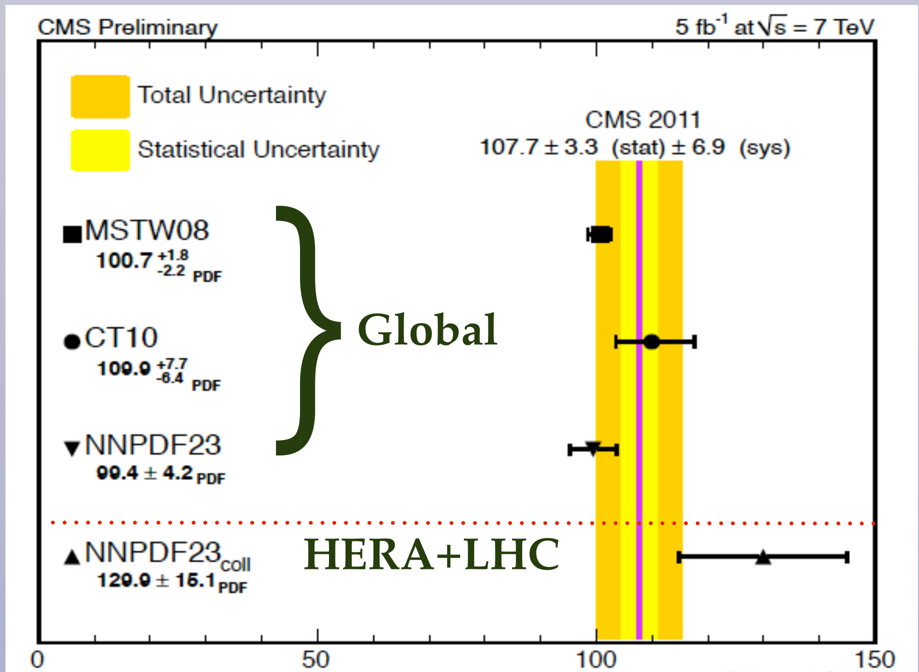


D'Enterria and J. R, arXiv:1202.1762

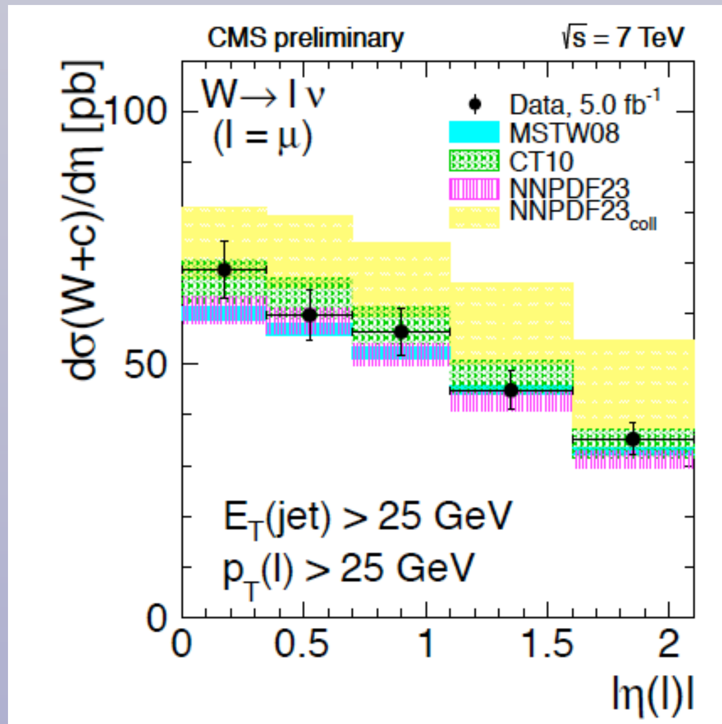
W production with charm quarks

- **Strangeness** is the worst known of all light quark PDFs
- In global PDF fits determined by **neutrino charm production** data (dimuon data, NuTeV+CHORUS)
- **W+c data from ATLAS and CMS**, total cross-sections and differential distributions, instrumental to conclusively determine **strangeness from collider-only data**
- **Recent results from CMS** are consistent with the strange PDF determined in global fits from neutrino data





CMS-SMP-12-002

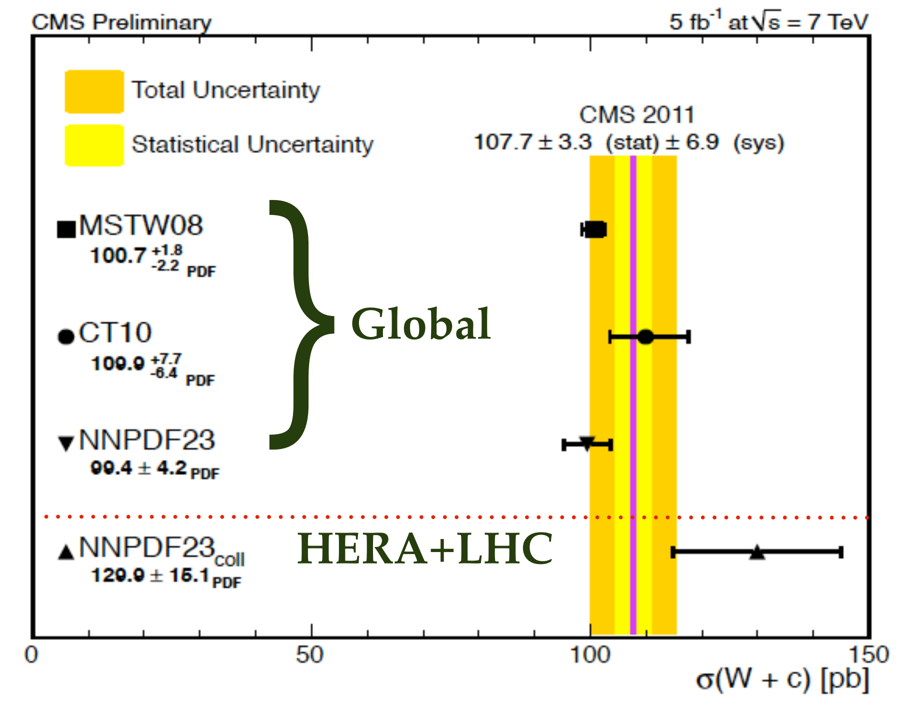


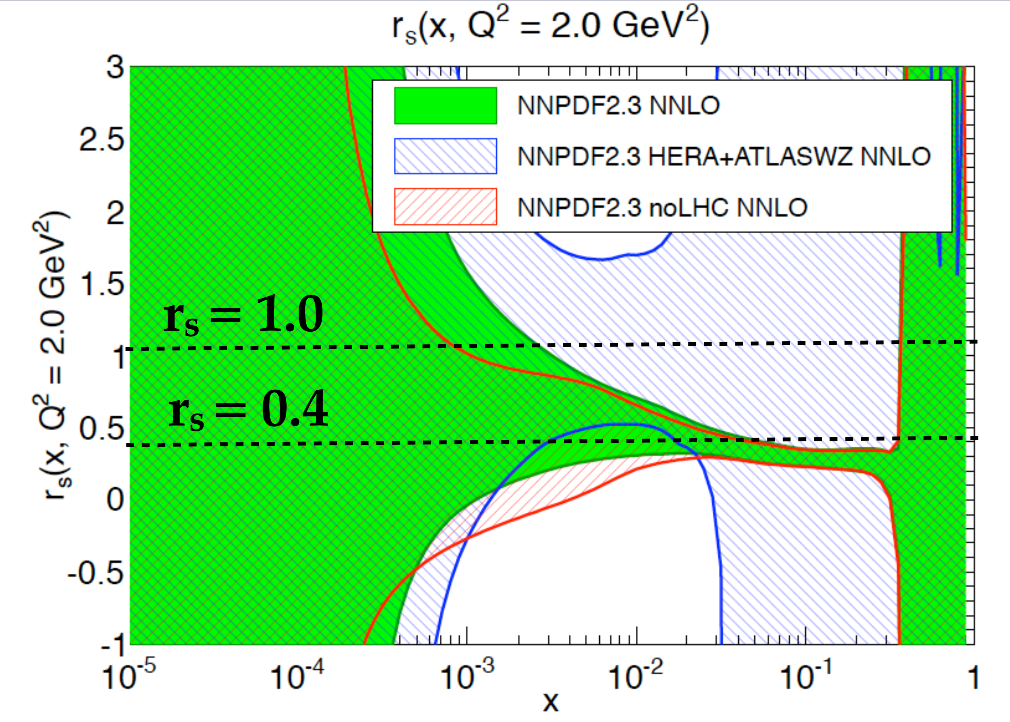
Isabel's talk

W production with charm quarks

- A PDF fit based only on **HERA, Tevatron and LHC** data (with inclusive W, Z data) favors a **symmetric strange PDF, $r_s \sim 1$**, but with large uncertainties
- **Qualitatively**, the CMS W+c direct measurement **consistent with the strangeness suppression measured in neutrino charm data**, **$r_s \sim 0.5$**, symmetric strange disfavored (consistent within uncertainties)
- Ongoing (NNPDF, HERAfitter): include the W+c differential distributions in **PDF fits** to **quantify** impact on strangeness
- No public results from ATLAS yet

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

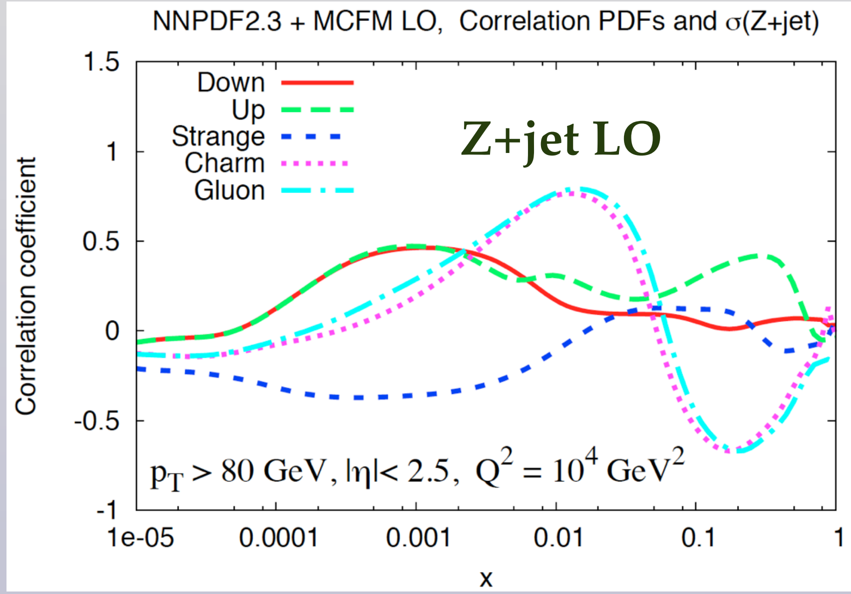


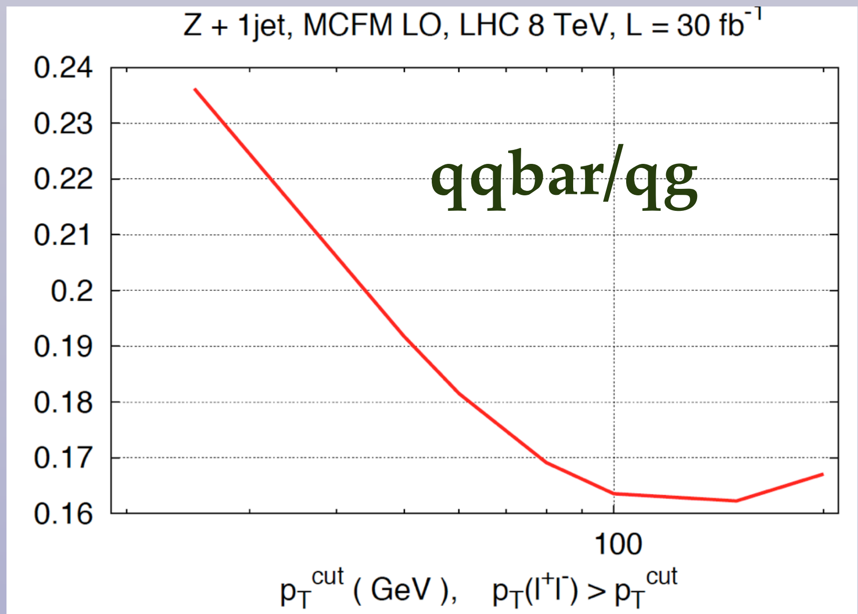


CMS-SMP-12-002

Probing the gluon with high p_T Z production

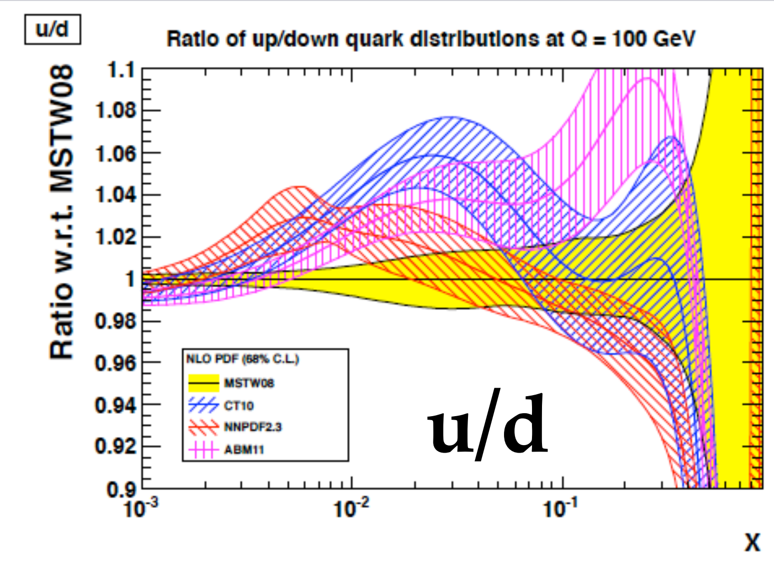
- In global PDF fits, the medium and large-x **gluon** is directly constrained by **jet data** only
- Given the crucial role of the gluon for LHC physics, **complementary LHC observables directly sensitive the gluon** would be beneficial
- One possibility is **Z/W boson production at large pT** (in association with jets). Cross section > 80% **dominated by gluon-quark scattering**
- Measurement should be only with leptons, double differential in p_T and rapidity, thus **small systematic errors** feasible
- Similar kinematic region as for **Higgs production** in gluon fusion

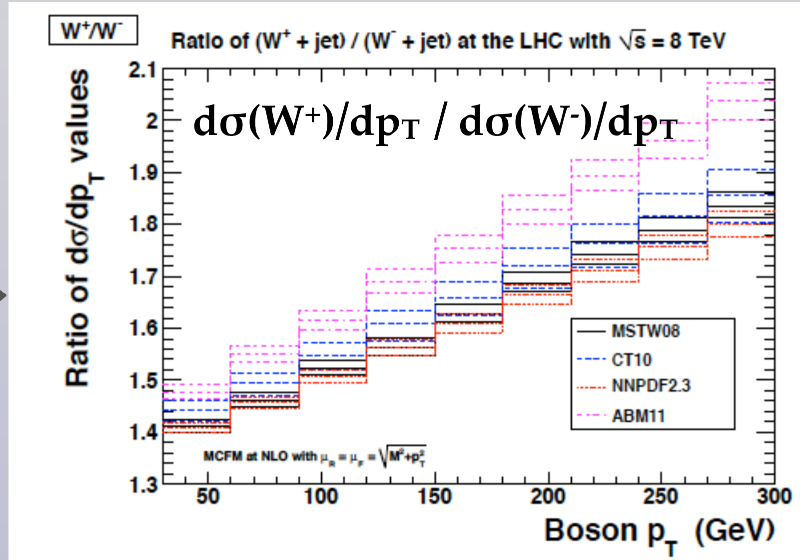


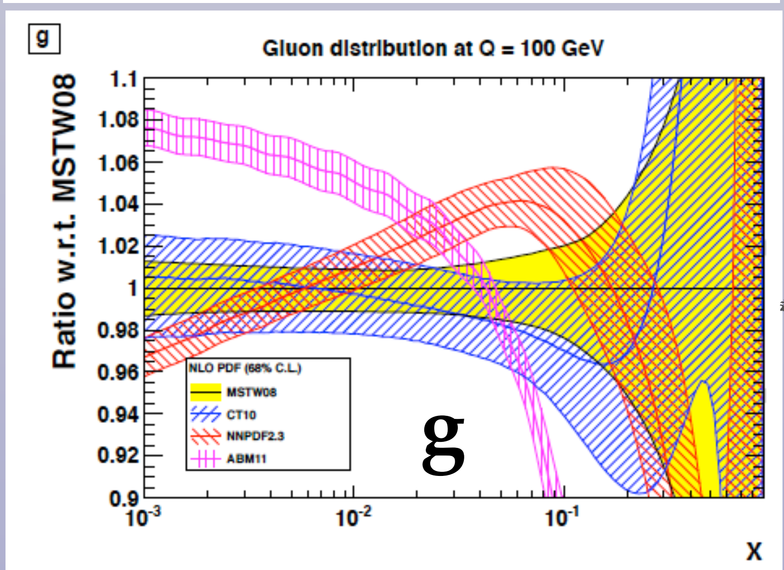


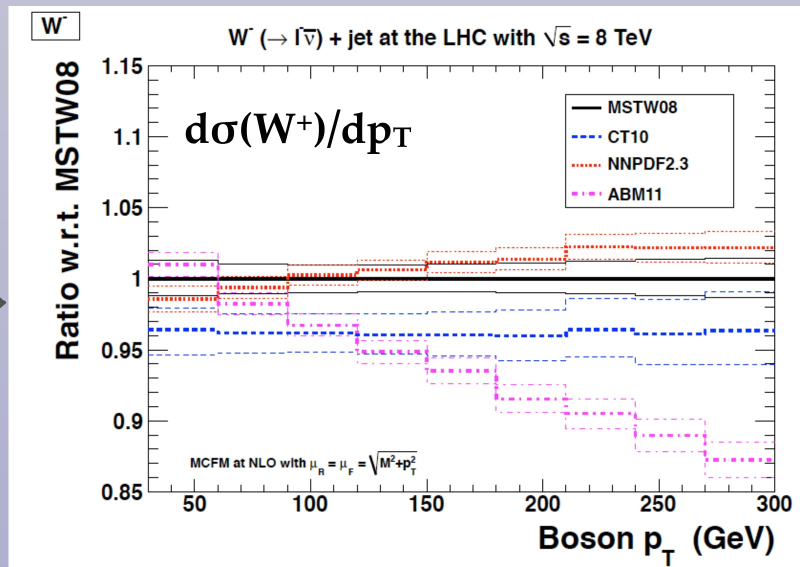
Probing the gluon with high p_T W/Z ratios

- While the **absolute W and Z pt distributions** sensitive to the **gluon PDF**, the **ratio of W+ and W-** sensitive to the **up/down ratio** (with reduced theoretical and experimental uncertainties): see **Graeme's talk**









Malik and Watt, arxiv:1304.2424

High Mass Drell-Yan

- In global PDF fits, **fixed target Drell-Yan data** are **instrumental for quark flavor separation**, but several issues: **low energies** (thus larger scale errors), **nuclear corrections**, **no covariance matrix**: we would like to replace them with collider data

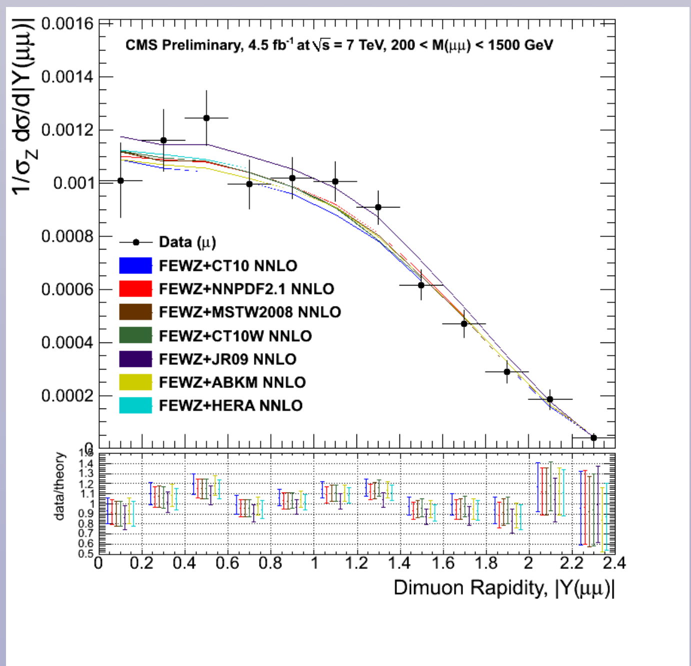
$$x_1^0 = \sqrt{\tau} e^{y} = \frac{M}{\sqrt{s}} e^{y} \,, \qquad x_2^0 = \sqrt{\tau} e^{-y} = \frac{M}{\sqrt{s}} e^{-y}$$

- At the LHC, **large mass DY** can be used to large-x quarks and antiquarks: **essential for high mass New Physics searches (see Stefano's talk)**

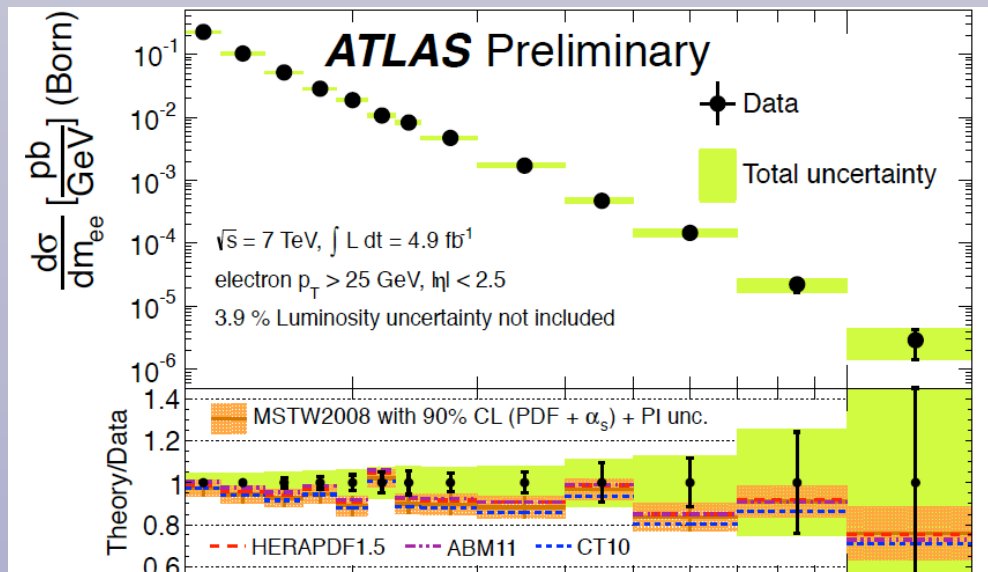
- At large masses, crucial to properly account **for electroweak corrections and photon induced processes**

- **Preliminary 7 TeV data** available both from ATLAS and CMS

CMS, 200 < M_{ee} < 1500 GeV



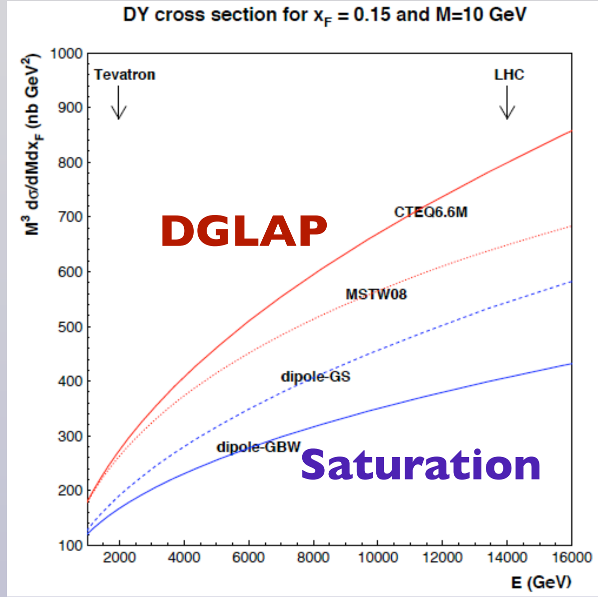
ATLAS, 116 < M_{ee} < 1500 GeV

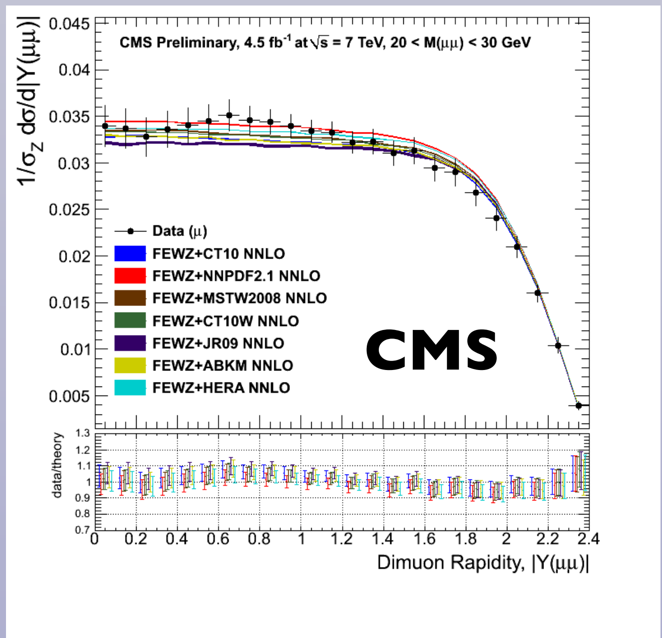


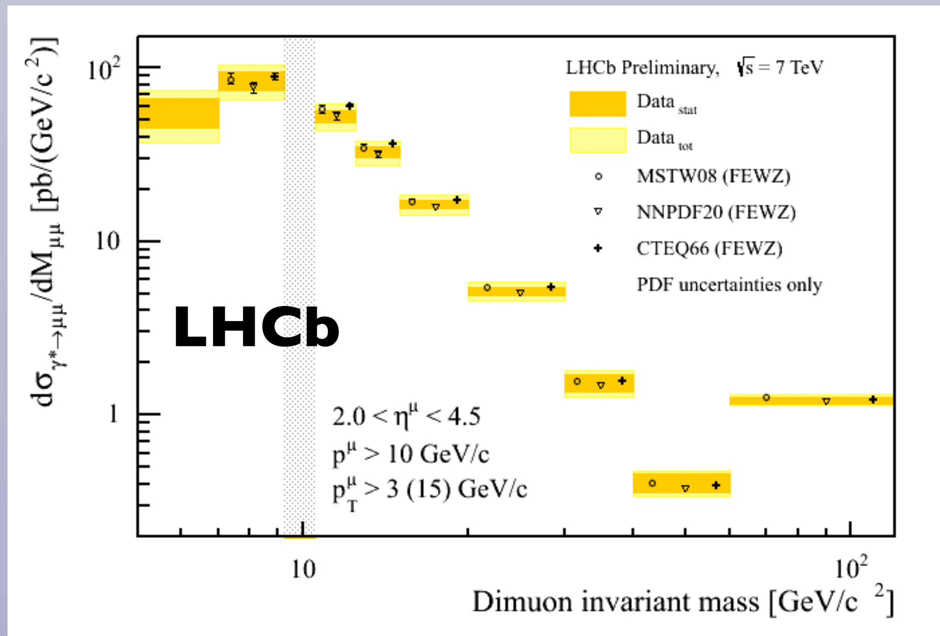
116 GeV < M < 1500 GeV

Low Mass Drell-Yan

- **Low mass DY** could constraints small-x gluon, but need resummed calculations for reliable results (**Simone's talk**)
- Potentially relevant for tests of **new regimes of QCD**, like saturation models, or high energy scenarios
- Data available from CMS and LHCb, what about ATLAS?
- PDF sensitivity enhanced by the **forward region** in LHCb kinematics







Top quarks as gluon luminometers

- Top quark pair production at the LHC is **directly sensitive to the gluon luminosity**, thus provides a potential new observable to constrain gluons in **global PDF analysis**
- The availability of the **full NNLO calculation** provides the first ever hadronic observable, **directly sensitive to the gluon**, that can be included in a **NNLO global fit**

In addition, reduced non-perturbative corrections as compared to photons and jets

	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%
qq	86.3%	16.8%	14.9%	9.3%

Contribution to the NNLO+NNLL cross section from different subprocesses

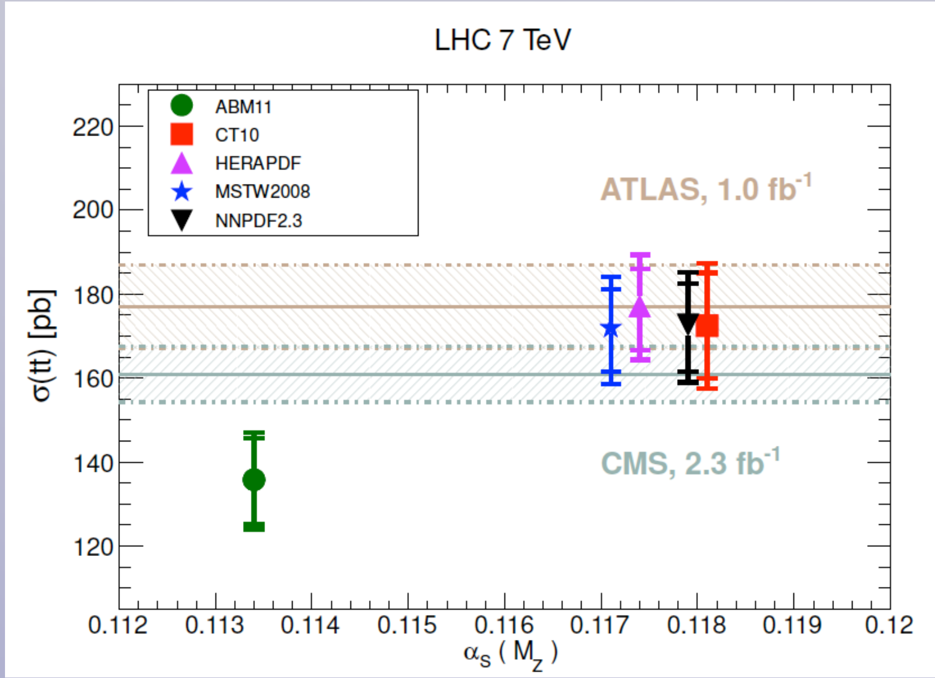
In recent paper we explored the **phenomenology of the NNLO top cross-section,** here show an overview of selected results

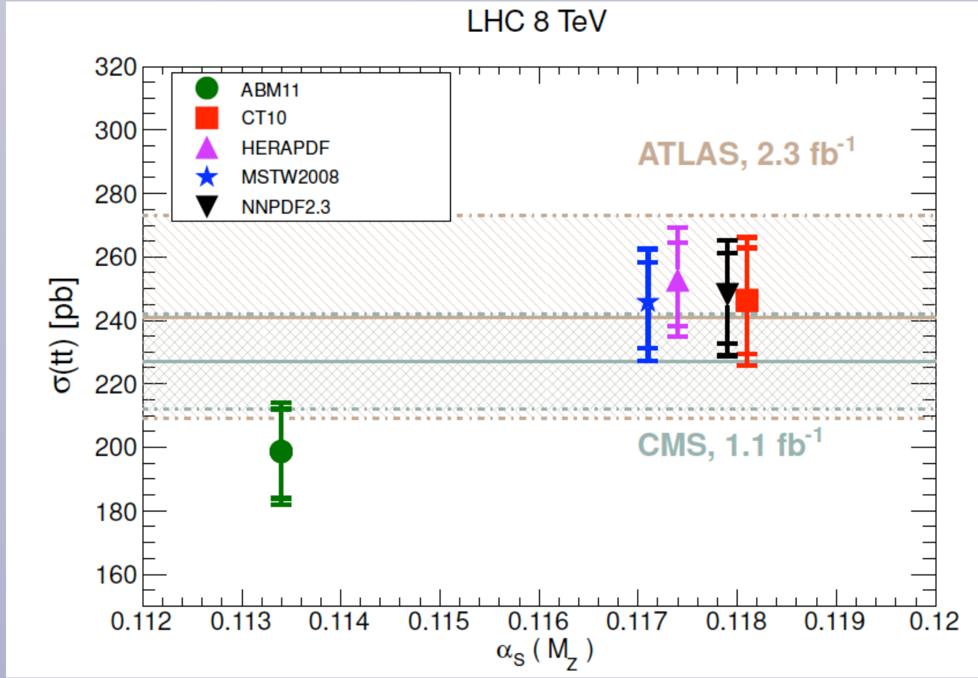
Czakon, Mangano, Mitov, Rojo, arXiv:1303.7215

Top quarks as gluon luminometers

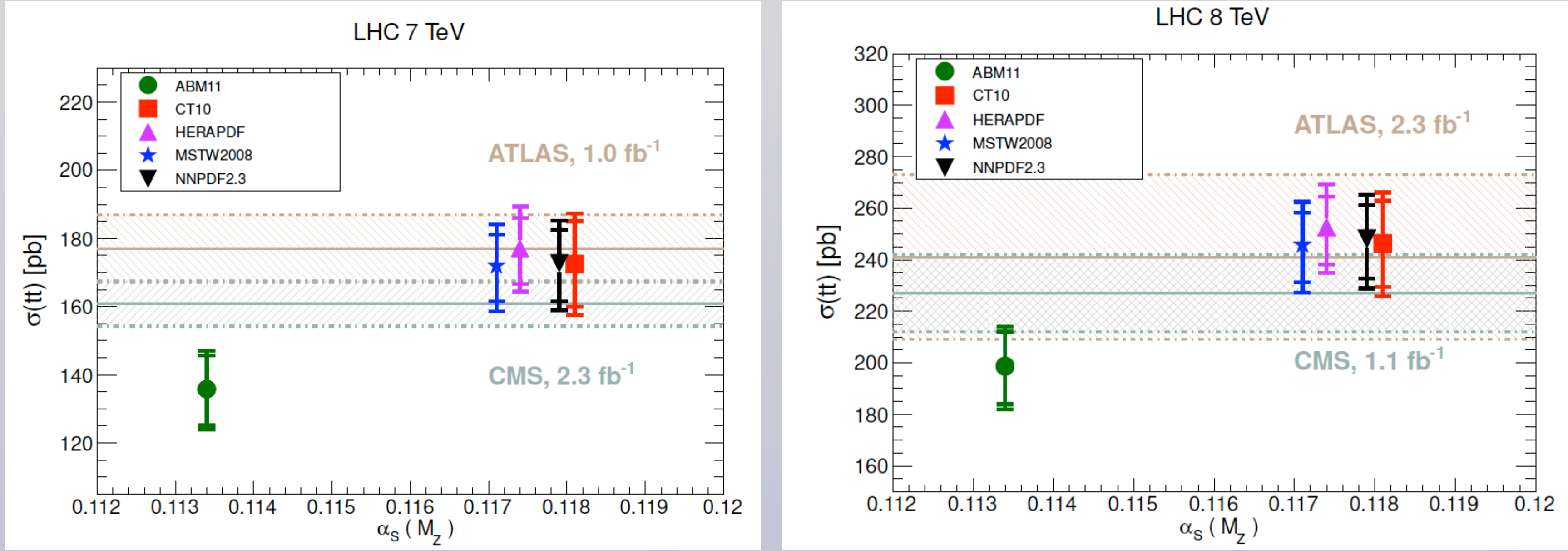
- Compute predictions at NNLO+NNLL with top++2.0 for different PDF sets with the associated theoretical uncertainties
- Top mass fixed to $\mathbf{m_t = 173.3}$ **GeV**. Assume $\mathbf{\delta m_t = 1}$ **GeV**, and $\boldsymbol{\delta\alpha_S = 0.007}$
- Parametric uncertainties (PDFs, m_t ,α_S) added in quadrature, then linearly to scale uncertainty
- Compare to the most precise **ATLAS** and **CMS** 7 and 8 TeV data

When available, correct cross section to mt = 173.3 GeV





Top quarks as gluon luminometers



Most PDF sets provide a **good quantitative description** of Tevatron and LHC top data

$$\chi^2 = \sum_{i=1}^{N_{\rm dat}} \frac{\left(\sigma_{t\bar{t}}^{(\rm exp)} - \sigma_{t\bar{t}}^{(\rm th)}\right)^2}{\delta_{\rm tot}^{(\rm exp)2}}$$

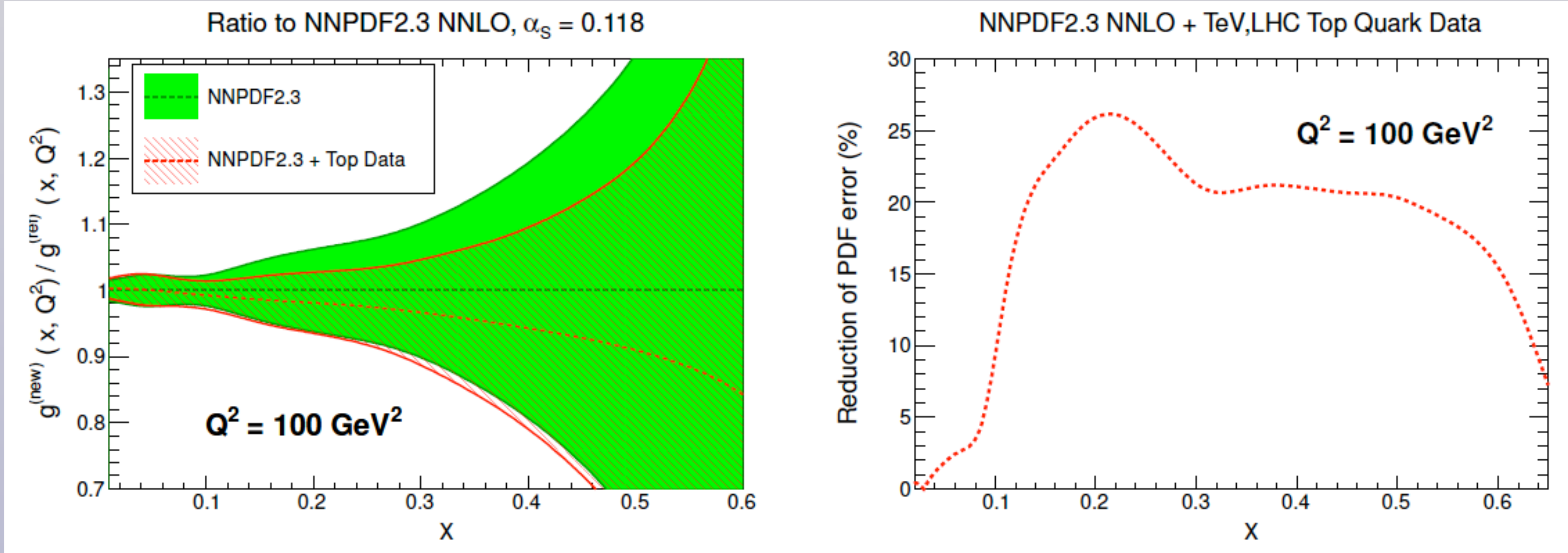
$$P = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} \frac{\left(\sigma_{t\bar{t}}^{(\rm exp)} - \sigma_{t\bar{t}}^{(\rm th)}\right)^2}{\delta_{\rm tot}^{(\rm exp)2} + \delta_{\rm tot}^{(\rm th)2}}$$

	$\chi^2_{\rm tev}$	$\chi^2_{\rm lhc7}$	$\chi^2_{\rm lhc8}$	$\chi^2_{\rm tot}$	$\chi^2_{\rm tot}/N_{\rm dat}$	P
AMB11	3.5	31.4	5.3	40.2	8.0	3.2
CT10	0.4	3.3	1.7	5.3	1.1	0.3
HERAPDF15	0.0	6.1	3.1	9.2	1.8	0.5
MSTW08	1.3	3.1	1.6	6.0	1.2	0.4
NNPDF2.3	0.9	3.4	2.0	6.3	1.3	0.4

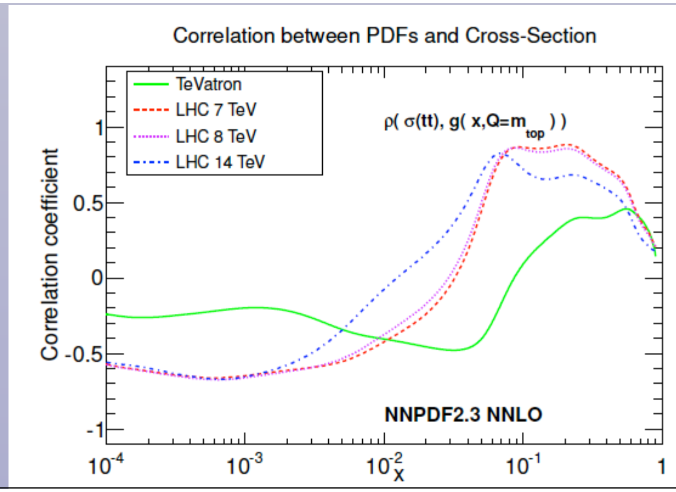
LHC top data already discriminates between PDF sets

Top quarks as gluon luminometers

- Top quark cross-section data **discriminates between PDF sets**
- In addition, it can also be used to **reduce the PDF uncertainties** within a single PDF set
- Included the most precise top quark data into the **NNPDF2.3** global PDF analysis



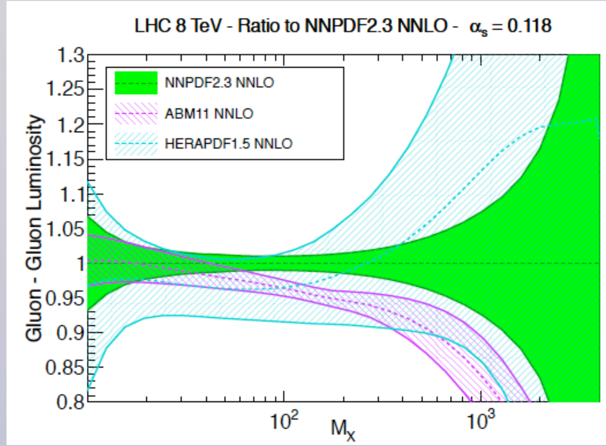
- Top quark cross-section data **reduces the PDF uncertainty** in the **large-x gluon** by up to **20%**
- The impact is restricted to the region between **0.1<x<0.5**, where the correlation between the gluon and the top cross section is most significant



Juan Rojo

Top quarks as gluon luminometers

- PDF fits based on **reduced datasets**, such as HERAPDF, display **large PDF uncertainties for the gluon** due to the lack of direct constraints

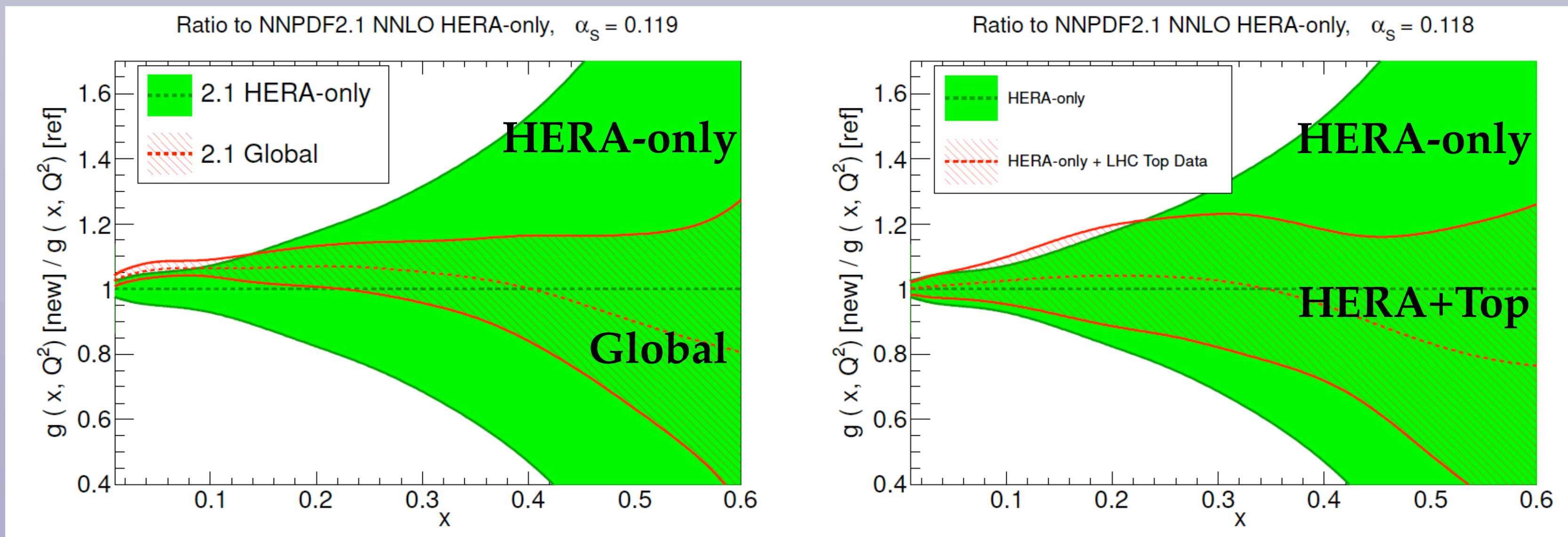


gg luminosity

- Top quark data can be included in a **NNLO fit based on HERA data**

  Substantial reduction of PDF uncertainties

  The HERA+Top gluon PDF is close to the gluon from the global PDF fit

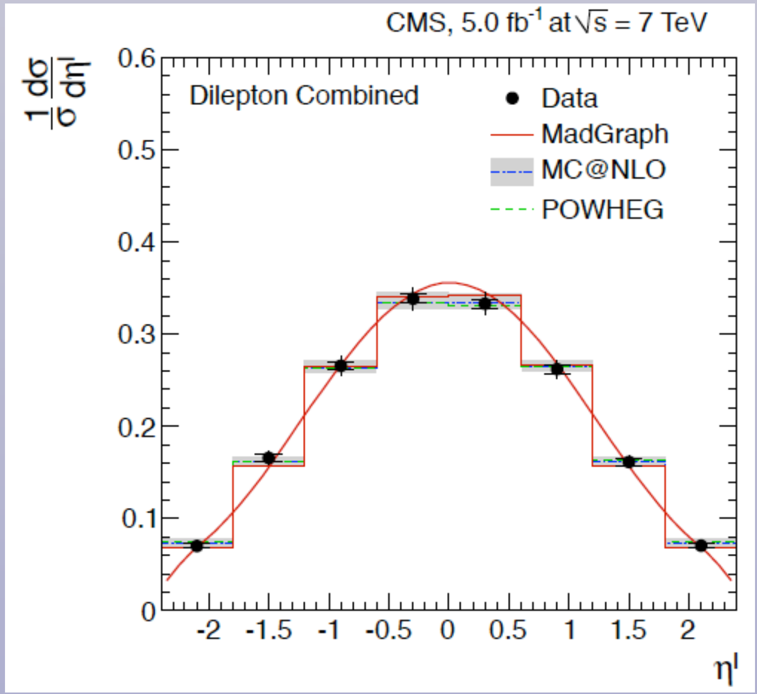


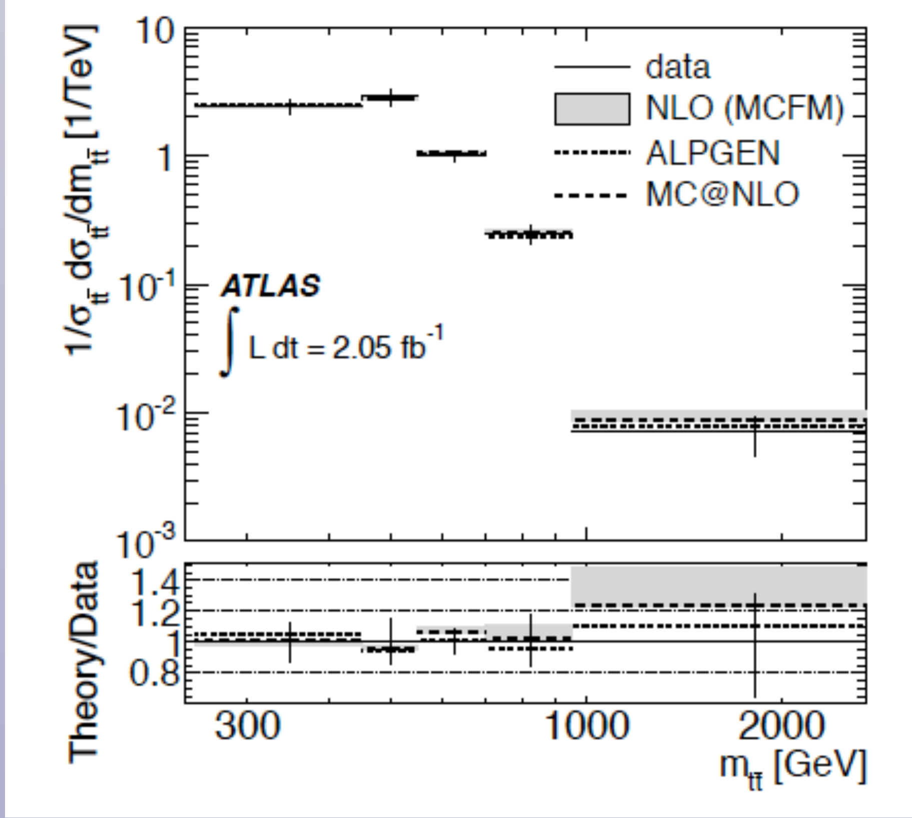
Top quarks as gluon luminometers

- On top of inclusive top cross sections, ATLAS and CMS have also measured **differential distributions** of top quarks and their decay products
- **Full experimental covariance matrix** available
- NNLO not available, only NLO + resummation for some distributions

ATLAS, arxiv:1207.5644

CMS, arxiv:1211.2220



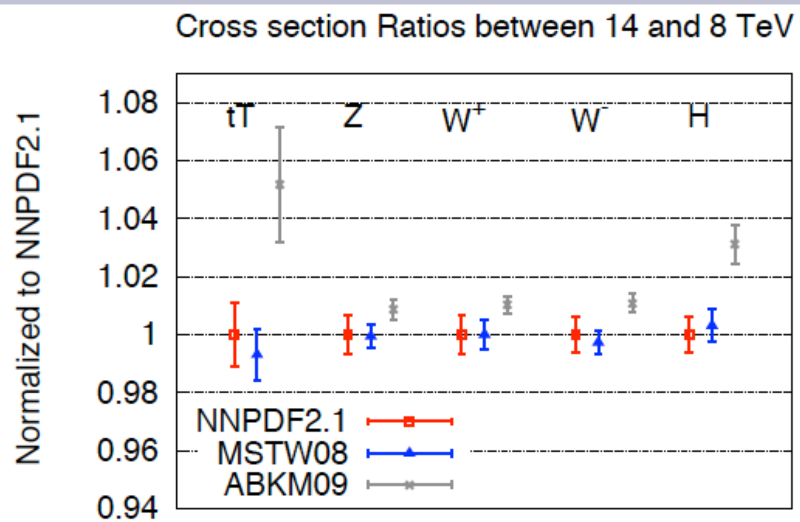


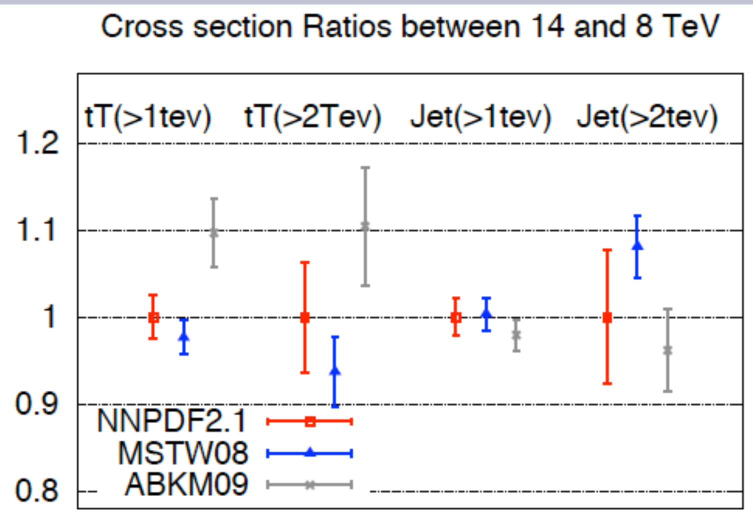
Cross section Ratios between 2.76,7 and 8 TeV

- The **staged increase of the LHC beam energy** provides a new class of interesting observables: **cross section ratios** for different beam energies

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X,E_2)}{\sigma(X,E_1)} \qquad R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)}$$

- These ratios can be computed with **very high precision** due to the **correlation of theoretical uncertainties** at different energies
- **Experimentally** these ratios can also be measured accurately since many systematics, like luminosity or jet energy scale, **cancel partially in the ratios**
- These ratios allow **stringent precision tests of the SM**, in particular **PDF discrimination**





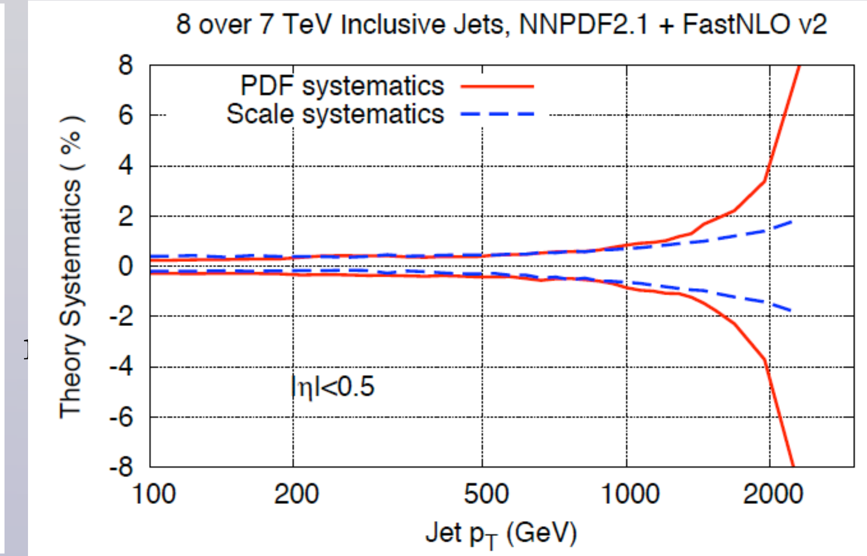
M. Mangano, J. Rojo, arXiv:1206.3557

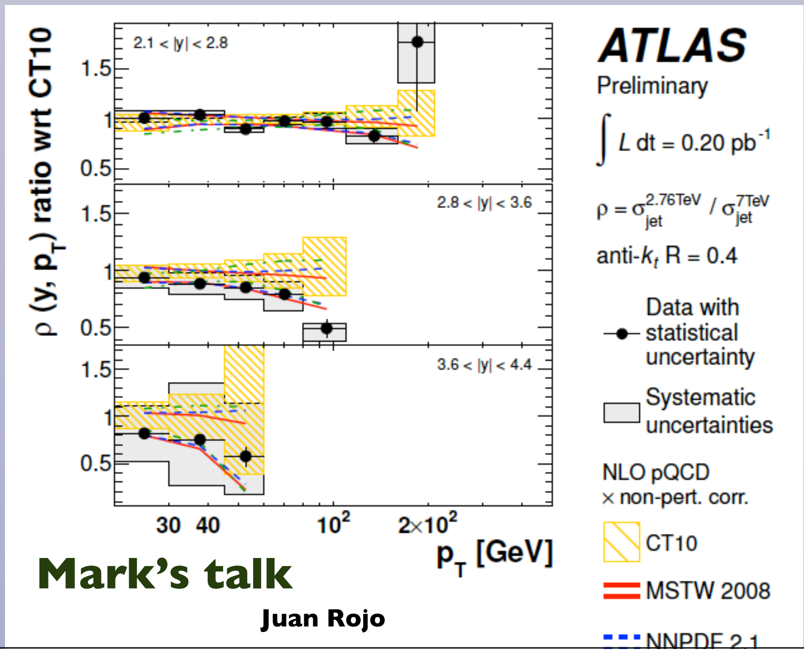
Cross section Ratios between 2.76,7 and 8 TeV

- Cross section ratios **cancel most of theory systematics**, **PDFs dominant** remainder, specially at large masses

8/7 TeV

Cross Section	$R^{\rm th,nnpdf}$	$\delta_{\rm PDF}(\%)$	δ_{α_s} (%)	$\delta_{\rm scales}$ (%)
$t\bar{t}/Z$	2.12	$\pm$ 1.3	$-0.8 - 0.8$	$-0.4 - 1.1$
$t\bar{t}$	3.90	$\pm$ 1.1	$-0.5 - 0.7$	$-0.4 - 1.1$
Z	1.84	$\pm$ 0.7	$-0.1 - 0.3$	$-0.3 - 0.2$
W^+	1.75	$\pm$ 0.7	$-0.0 - 0.3$	$-0.3 - 0.2$
W^-	1.86	$\pm$ 0.6	$-0.1 - 0.3$	$-0.3 - 0.1$
W^+/W^-	0.94	$\pm$ 0.3	$-0.0 - 0.0$	$-0.0 - 0.0$
W/Z	0.98	$\pm$ 0.1	$-0.1 - 0.0$	$-0.0 - 0.0$
ggH	2.56	$\pm$ 0.6	$-0.1 - 0.1$	$-0.9 - 1.0$
$t\bar{t}(M_{tt} \geq 1$ TeV$)$	8.18	$\pm$ 2.5	$-1.3 - 1.1$	$-1.6 - 2.1$
$t\bar{t}(M_{tt} \geq 2$ TeV$)$	24.9	$\pm$ 6.3	$-0.0 - 0.3$	$-3.0 - 1.1$
$\sigma_{\rm jet}(p_T \geq 1$ TeV$)$	15.1	$\pm$ 2.1	$-0.4 - 0.0$	$-1.9 - 2.4$
$\sigma_{\rm jet}(p_T \geq 2$ TeV$)$	182	$\pm$ 7.7	$-0.3 - 0.2$	$-5.7 - 4.0$





Mark's talk

- Cross section ratios should be pursued as a **novel approach to constrain PDF**
- First measurement of cross section ratios by **ATLAS: jet cross sections between 7 and 2.76 TeV**
- Reduced experimental and theory (scale) uncertainties, potentially can **improve the sensitivity to PDFs of 7 TeV ATLAS jet data alone**

ToDo

TH

EXP

PDF whishlist at the LHC

- Inclusive **jets:** *full NNLO calculation*, *exp. data extending to higher pt with smaller systematics*

- Inclusive **W and Z production** and asymmetries: *update to 2011, 2012 data, correlation between W,Z and between experiments*, *photon-induced effects*

- Isolated **photons and photon+jets**: *full NNLO, fast interface*, *experimental covariance matrix, extend high pt coverage, covariance matrix, reduced systematics*

- **W production with charm**: *results from ATLAS, update to 2012 data*, *quantify impact in strangeness*

- **W and Z production at high p_T**: *full NNLO*, *experimental measurements in format suitable for PDF analysis*

- Off resonance **Drell-Yan and W production at high mass**: *update to 8 TeV*, *validation of NNLO codes and electroweak corrections*

- Low mass Drell-Yan production: *Understand better theory systematics*

- **Top quark** cross-sections and differential distributions: *full NNLO for differential*, *update to full 8 TeV dataset*

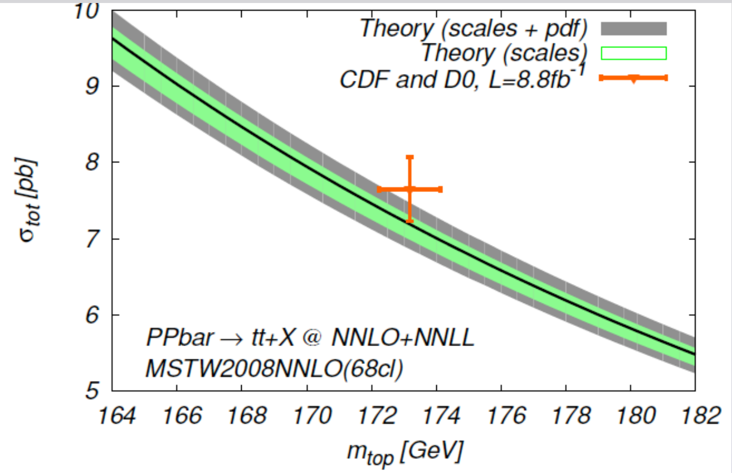
- **Cross-section ratios** between 2.76, 7 and 8 TeV: *measure in other processes on top of jets*

EXTRA MATERIAL

Dependence on the top quark mass

- Compare total theory uncertainty **with** and **without top quark mass uncertainty**

- Thanks to the improvement of the NNLO calculation, now all theory uncertainties of similar size, only **mild reduction (< 1.5%)** in the total theory errors if one assumes that $\boldsymbol{\delta_{mt} \approx 0}$



Collider	σ_{tt} (pb)	$\delta_{\mathrm{PDF+scales}+\alpha_s}$ (pb)	δ_{tot} (pb)
Tevatron	7.258	$+0.267$ $(+3.7\%)$ -0.352 (-4.9%)	$+0.390$ $(+5.4\%)$ -0.469 (-6.5%)
LHC 7 TeV	172.7	$+10.4$ $(+6.0\%)$ -11.8 (-6.8%)	$+12.5$ $(+7.2\%)$ -13.7 (-8.0%)
LHC 8 TeV	248.1	$+14.0$ $(+5.6\%)$ -16.2 (-6.5%)	$+17.1$ $(+6.9\%)$ -19.1 (-7.7%)
LHC 14 TeV	977.5	$+44.1$ $(+4.5\%)$ -55.8 (-5.7%)	$+57.4$ $(+5.9\%)$ -68.5 (-7.0%)

Pinning down the gluon with top data

- Adding data from lower energy colliders: reduced theory uncertainties at higher energies
- Adding **TeV+LHC7** data to NNPDF2.3, we obtain the **best possible theory prediction for LHC8**
- Not only PDF uncertainty reduced, also central value **shifts** to increase agreement with data

Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

PDF uncertainty only

- Using TeV+LHC7 data, optimal fit description for LHC8
- The **precise LHC7** data carry most of the information, but full 8 TeV analysis still missing

Collider	χ^2 (Total, $N_{\mathrm{dat}} = 5$)	χ^2 (LHC 8 TeV, $N_{\mathrm{dat}} = 2$)
NNPDF2.3	6.28	1.64
NNPDF2.3 + TeV,LHC data	4.88	1.24
NNPDF2.3 + TeV,LHC7 data	4.87	1.24