Recent constraints on the parton distributions in the proton and the measurement of α_S from ATLAS and CMS

Mark Sutton

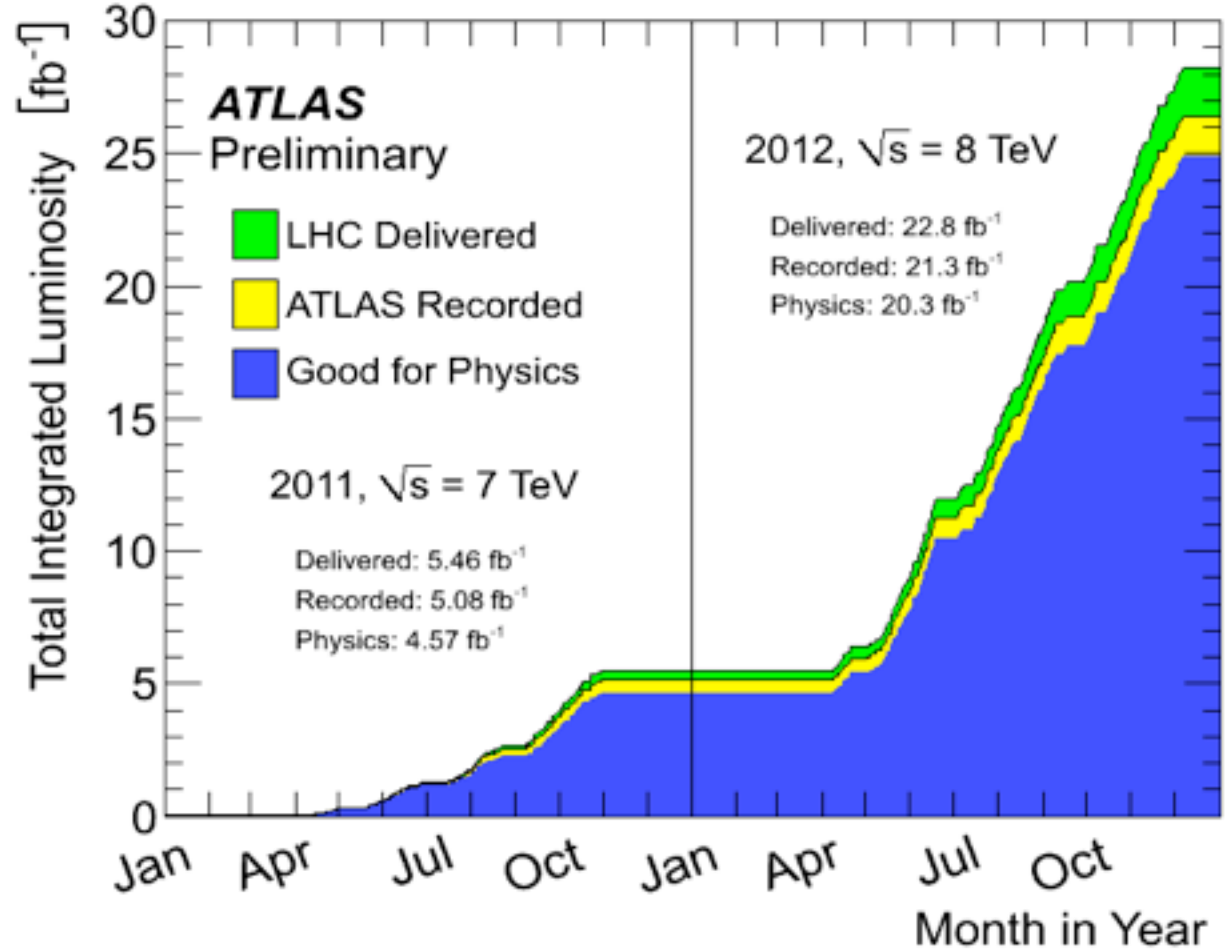
The University of Sussex

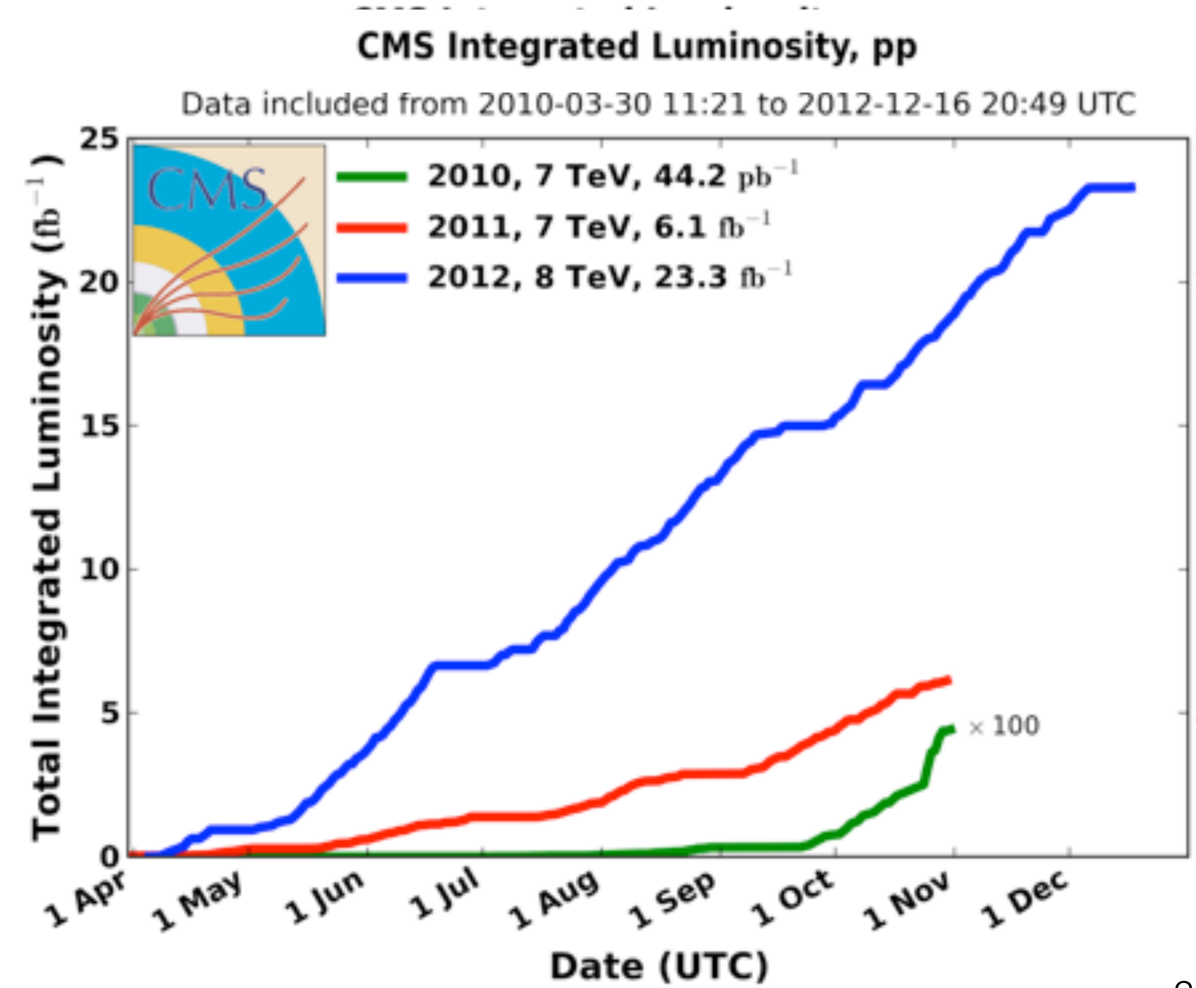
On behalf of

the ATLAS and CMS Collaborations

Preface

- The LHC performed extremely well during Run 1
- Both ATLAS and CMS were able to collect proton-proton data samples in excess of 25 fb^{-1} per experiment
    - Most analyses still with the smaller 2011 data set
    - Some analyses of 2012 data starting to become available
- Both collaborations have a large, and developing portfolio of precision measurements
    - Discuss, but a subset of those which may be useful in a QCD fit
        - inclusive jet, Dijet production
        - Inclusive prompt photon production
        - ttbar production
        - Drell-Yan production
        - Inclusive W production and W production in association with charm



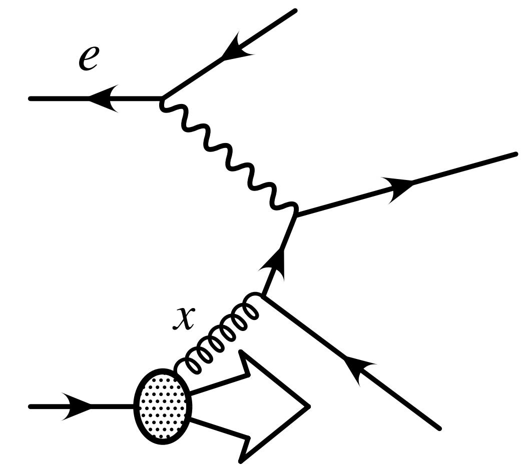


Contributions from different physics processes

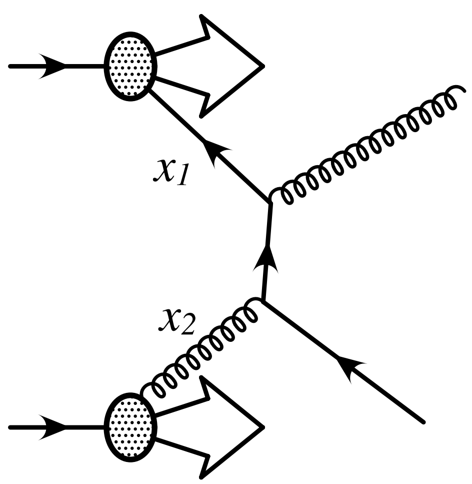
- Different final states provide information on different subprocesses
  - Use HERA DIS to constrain partons at low-x
  - At Born level, scattering off of quarks, one momentum parton fraction x

$$d\sigma_{\rm DIS} \sim (1-(1-y_{\rm Bj})^2)F_2(x,Q^2) - y_{\rm Bj}^2 F_L(x,Q^2)$$

$$F_2 = x\sum_q e_q^2(q(x)+\bar{q}(x))$$



  - Sensitive to the gluon distribution through $\mathcal{O}(\alpha_s)$ corrections

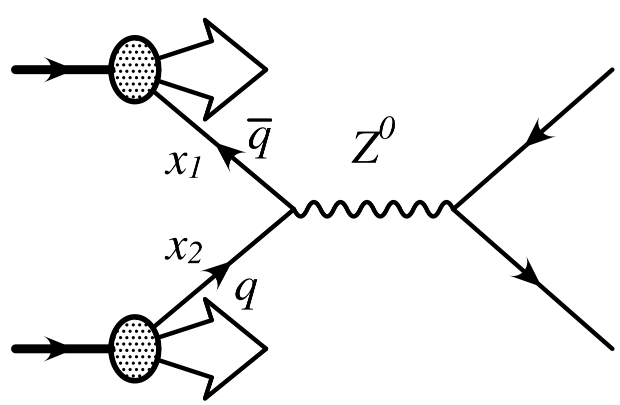


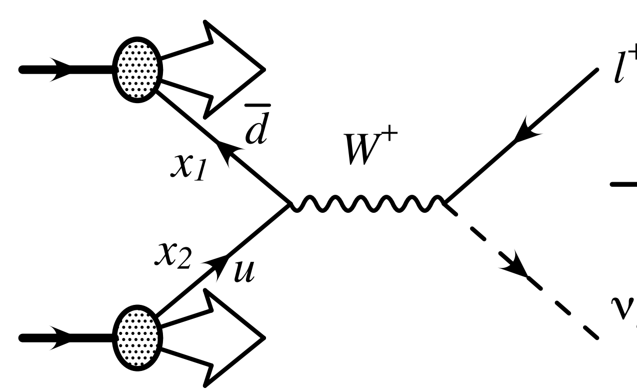
- For LHC collisions with two momentum fractions, x_1 and x_2

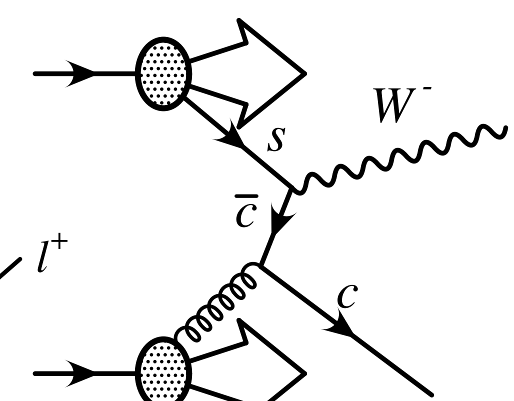
$$d\sigma = \sum_{i,j}\int dx_1 \int dx_2\; f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2)\; \hat{\sigma}_{ij}(x_1,x_2,\mu_R^2)$$

- Dijet production, ttbar, inclusive photon … all directly sensitive to the gluon distribution and the strong coupling - and the valence quarks at high E_T

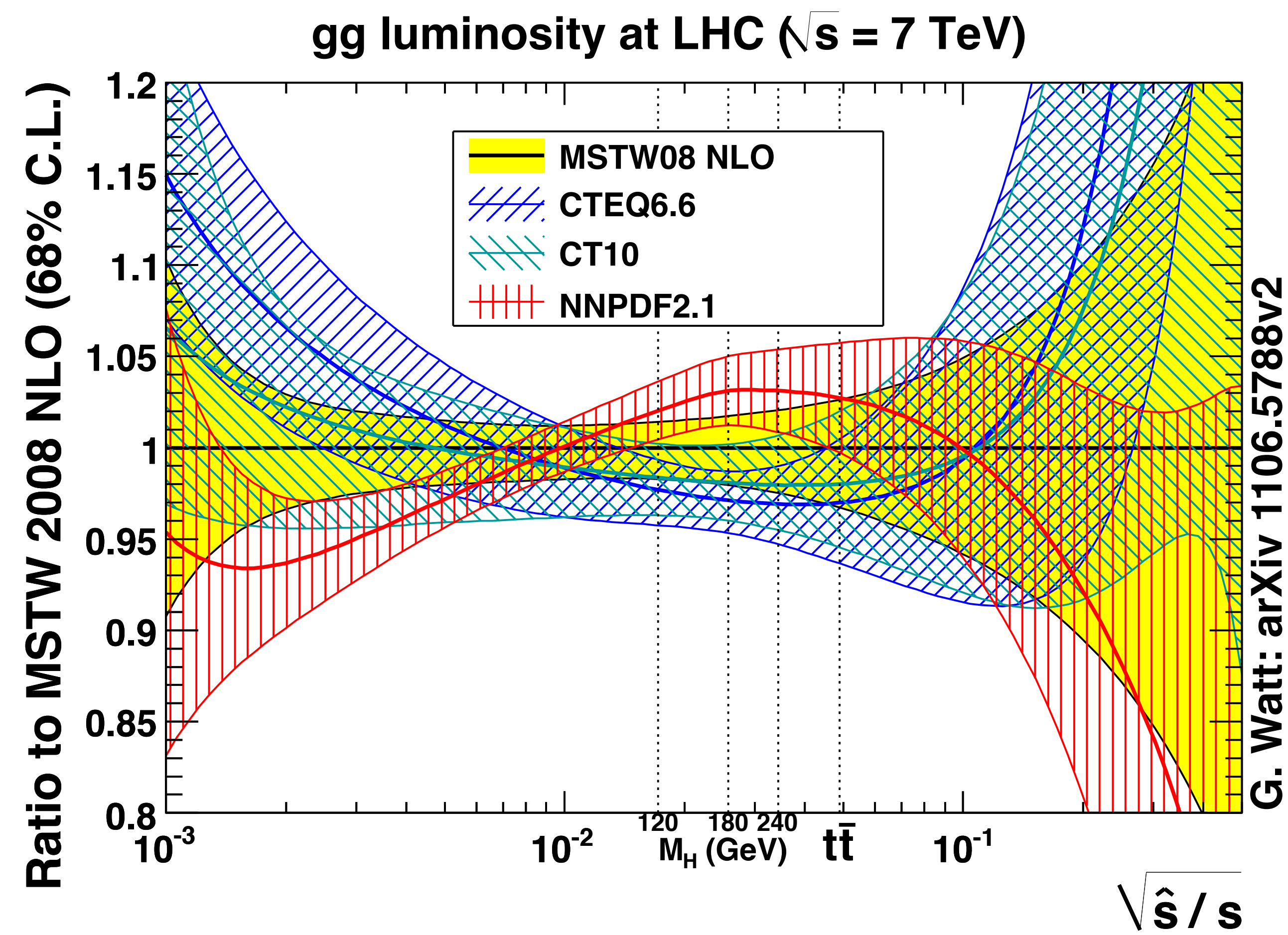
- Electroweak boson production sensitive to the valence and sea quarks distributions

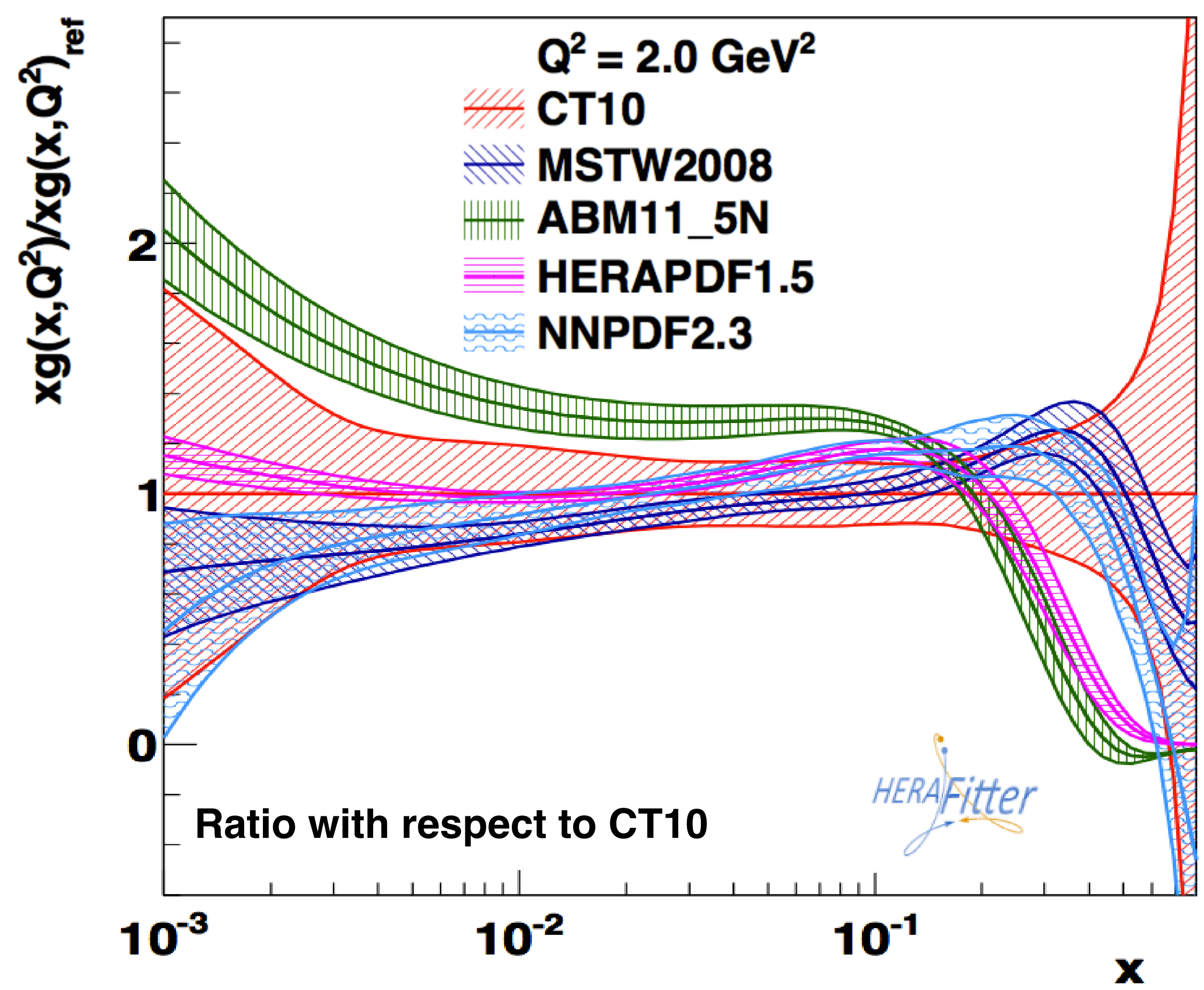






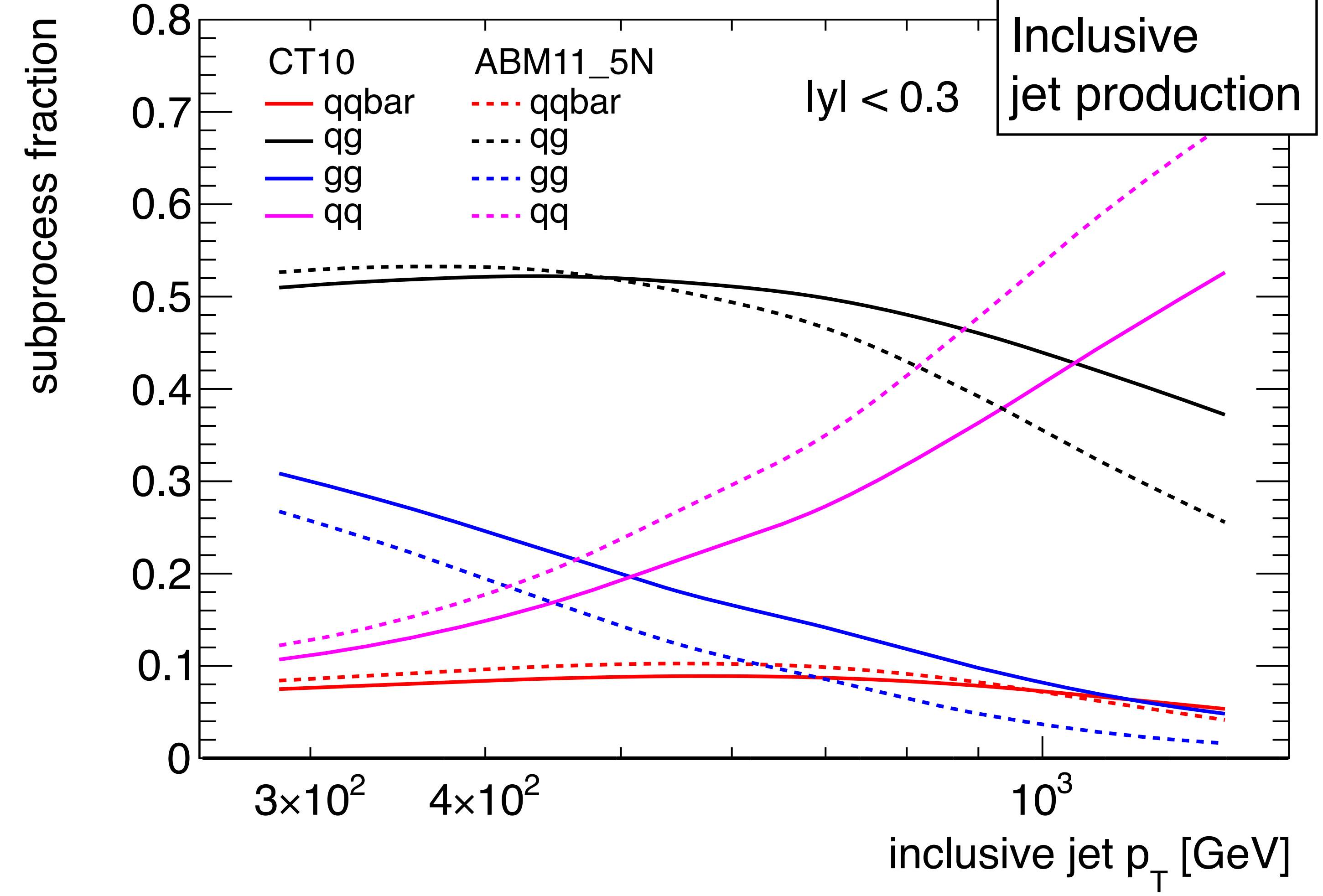
The gluon



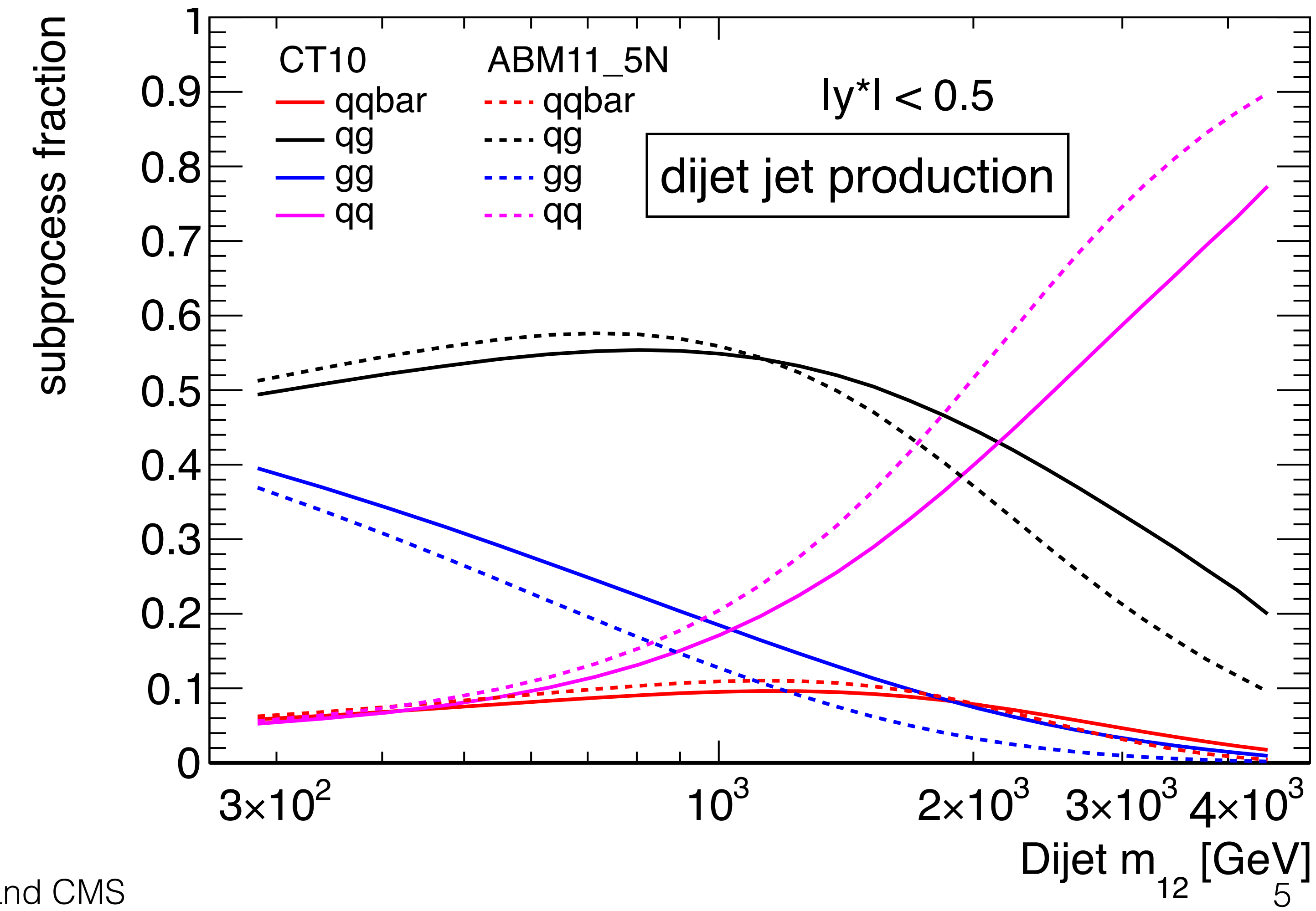


- PDF fits using only data from experiments with lower momentum transfer than available at the LHC have large uncertainties for the LHC kinematic region
  - As large as ~ 5% for the gg→Higgs (and larger) for top production
  - HERAPDF slightly softer that CT10 at high x, but normalisation the similar at lower x
  - Softer ABM gluon distribution

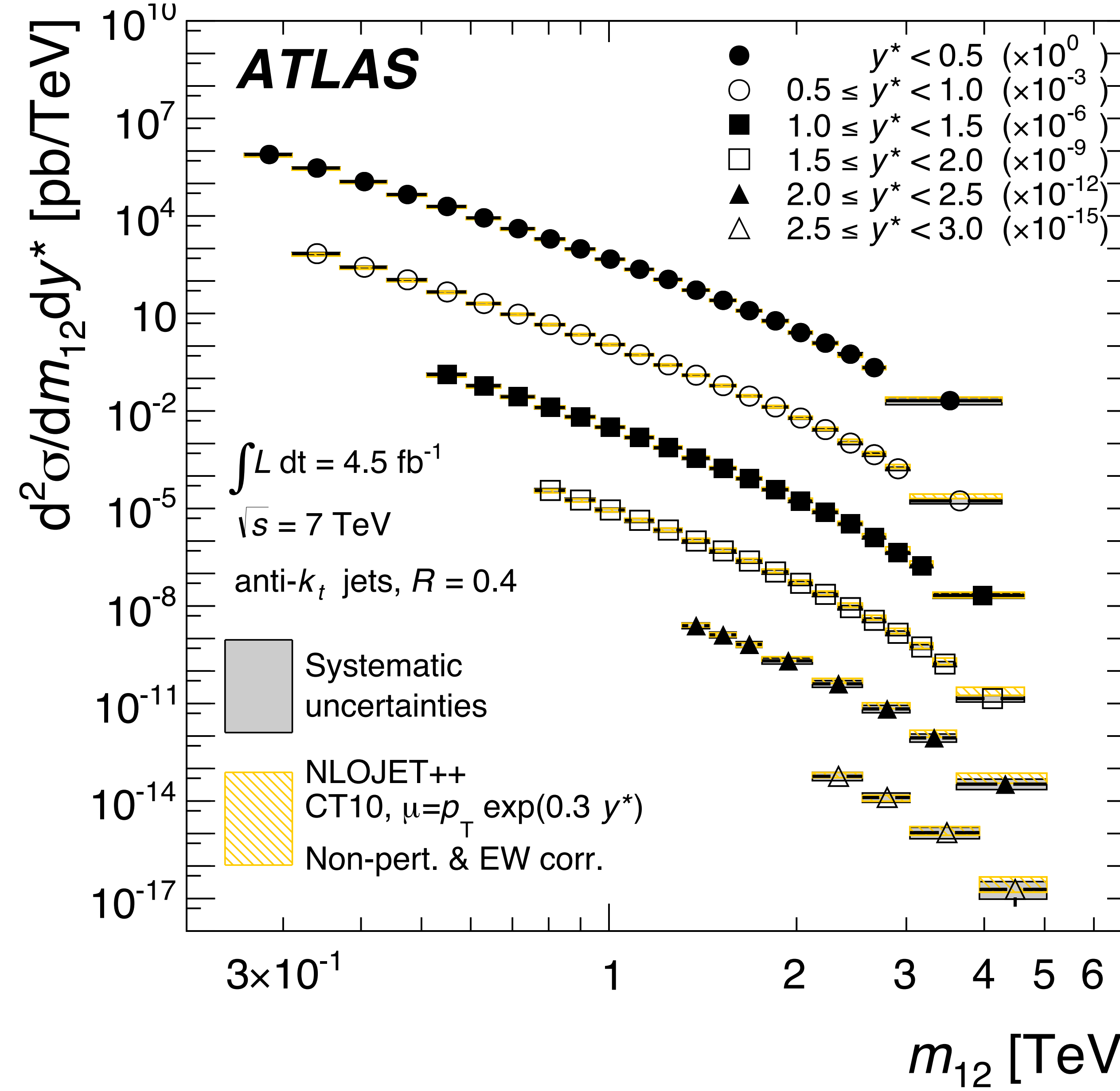
Incoming partons - inclusive jet production

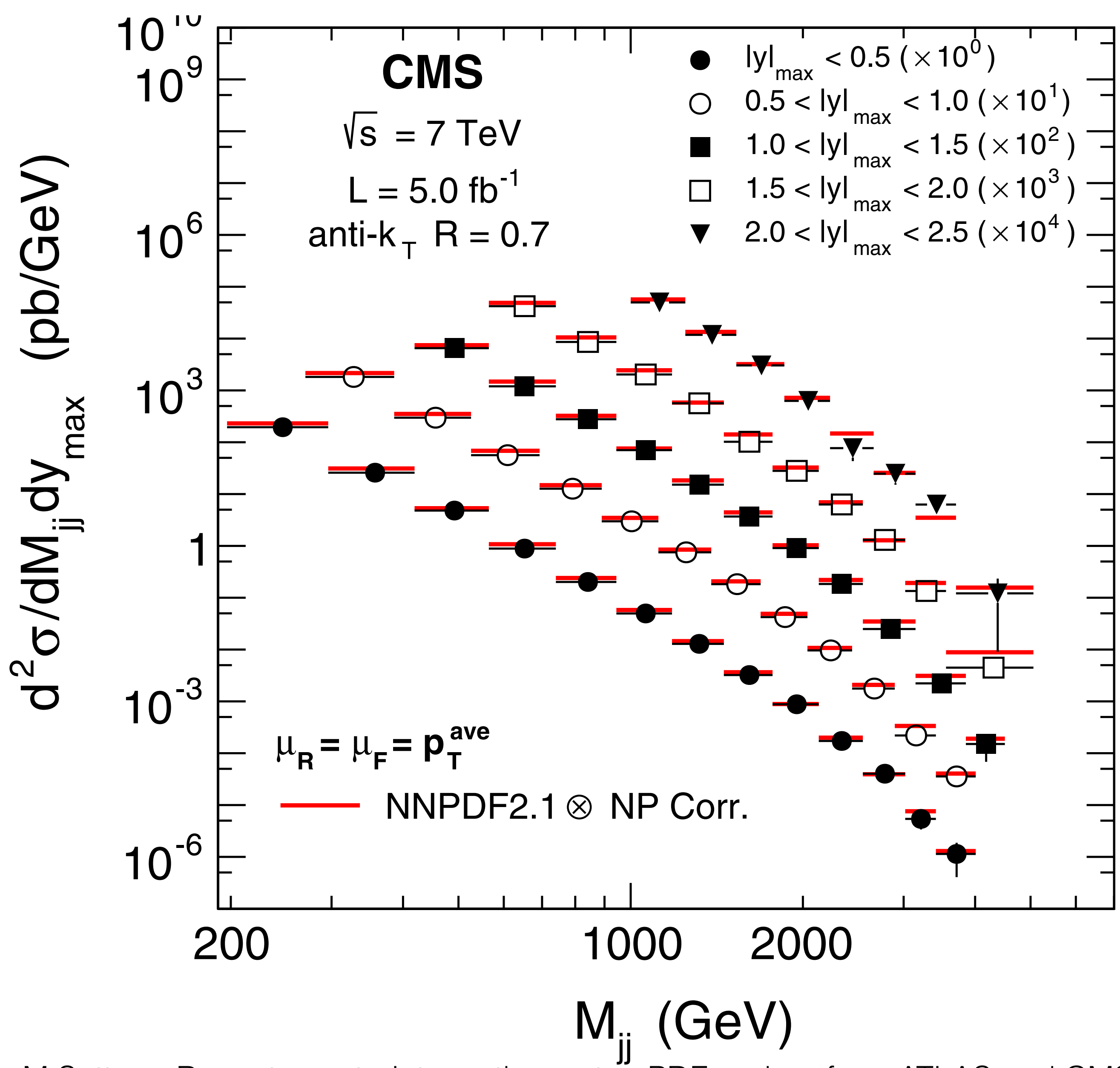


- Except at the highest E_T jets are produced predominantly by *quark-gluon* scattering
  - More significant contribution from the gluon
  - Larger phase space for initial state radiation
- At high E_T produced from partons at much higher *x - dominated by quark-quark* scattering
- Differences between PDF sets
  - Most notable at high masses and high ET where the data statistics are low and less constraining
  - Softer gluon from ABM predicts smaller fractional contribution from *qg* scattering



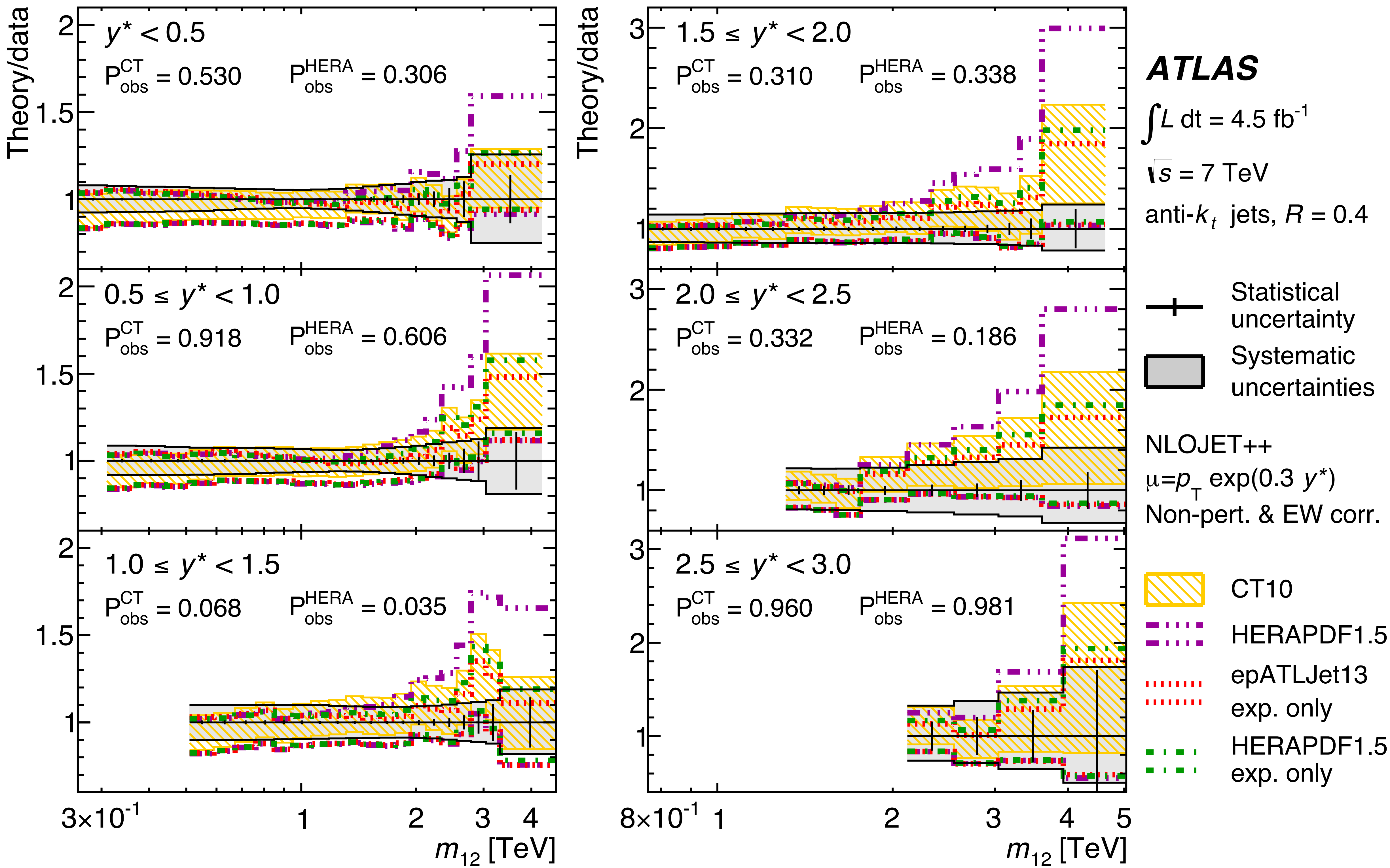
Dijet production from 2011data





- **ATLAS: Submitted to JHEP, arXiv:1312.3524**
- **CMS: Phys. Rev. D 87 (2013) 112002**
- Mass range from 200 (300) GeV to ~5 TeV
- Electroweak and hadronisation corrections included in theoretical predictions
- QCD does a reasonable job of describing the data over 8 orders of magnitude of the cross section

Dijet production from 2011 data



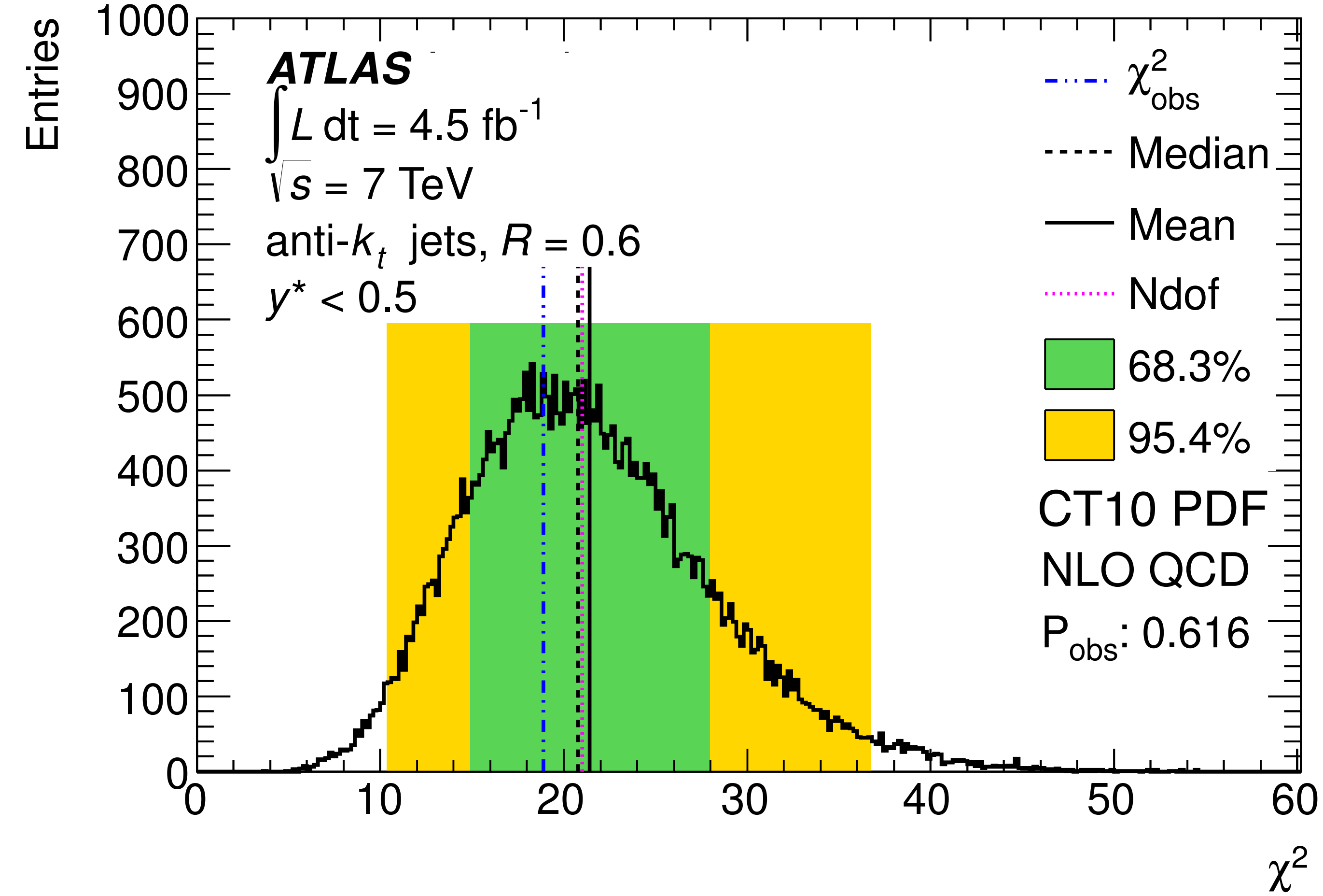
- HERAPDF, with slightly lower gluon contribution at high x than CT10, describes the data reasonably well
- ATLAS jets fit, epATLJet13 has significantly smaller uncertainties at high masses

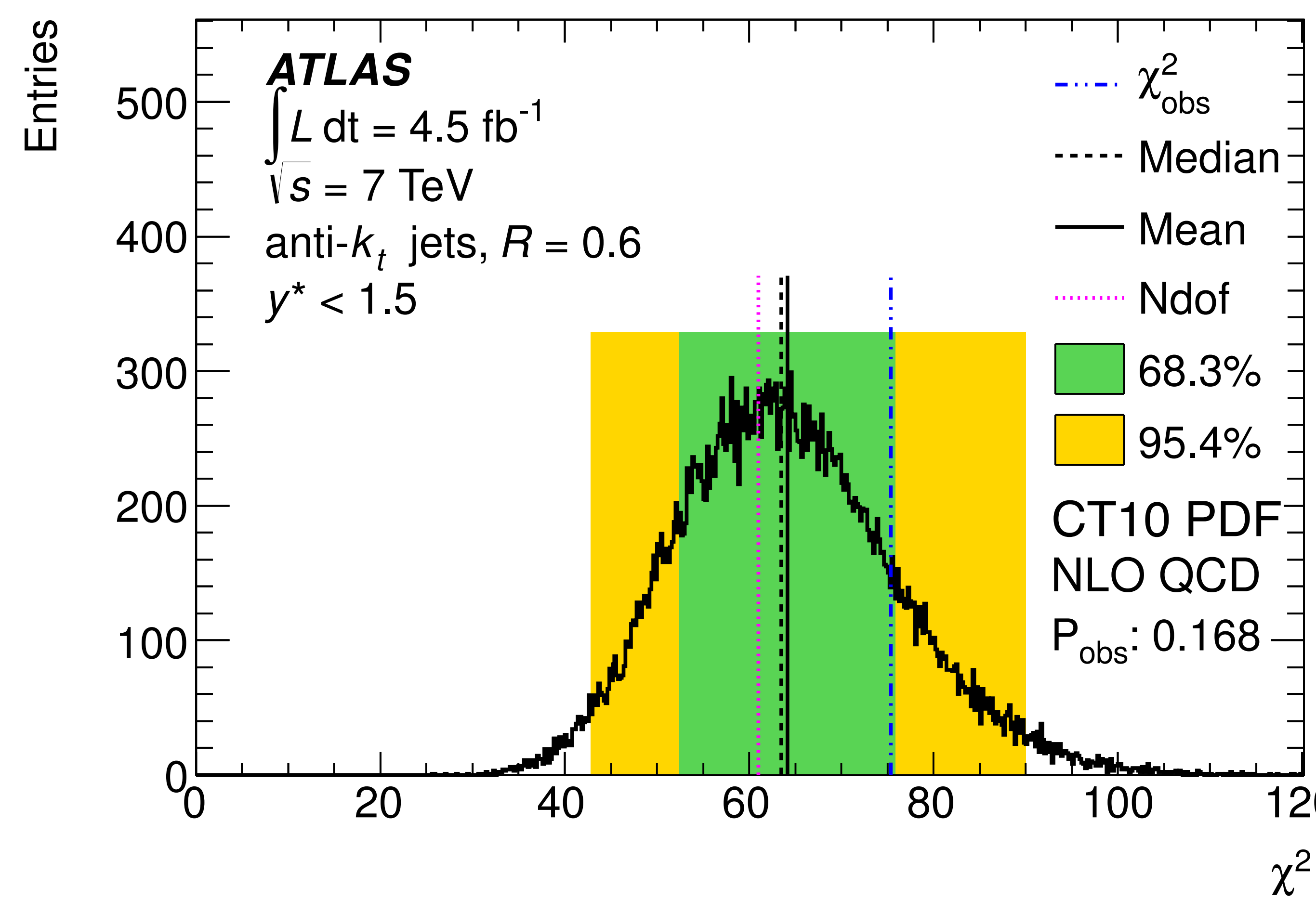
Quantitative analysis

- Generate pseudo-experiments using different PDFs
  - Include PDF and other theory uncertainties in both generation and χ^2 definition
- Calculate the χ^2 for each replica

PDF set	y^* ranges	mass range (full/high)	$\mathrm{P_{obs}}$ $R = 0.4$	$\mathrm{P_{obs}}$ $R = 0.6$
CT10	$y^* < 0.5$	high	0.742	0.785
	$y^* < 1.5$	high	0.080	0.066
	$y^* < 1.5$	full	0.324	0.168
HERAPDF1.5	$y^* < 0.5$	high	0.688	0.504
	$y^* < 1.5$	high	0.025	0.007
	$y^* < 1.5$	full	0.137	0.025
MSTW 2008	$y^* < 0.5$	high	0.328	0.533
	$y^* < 1.5$	high	0.167	0.183
	$y^* < 1.5$	full	0.470	0.352
NNPDF2.1	$y^* < 0.5$	high	0.405	0.568
	$y^* < 1.5$	high	0.151	0.125
	$y^* < 1.5$	full	0.431	0.242
ABM11	$y^* < 0.5$	high	0.024	$< 10^{-3}$
	$y^* < 1.5$	high	$< 10^{-3}$	$< 10^{-3}$
	$y^* < 1.5$	full	$< 10^{-3}$	$< 10^{-3}$

- ABM11 disfavoured





QCD fit

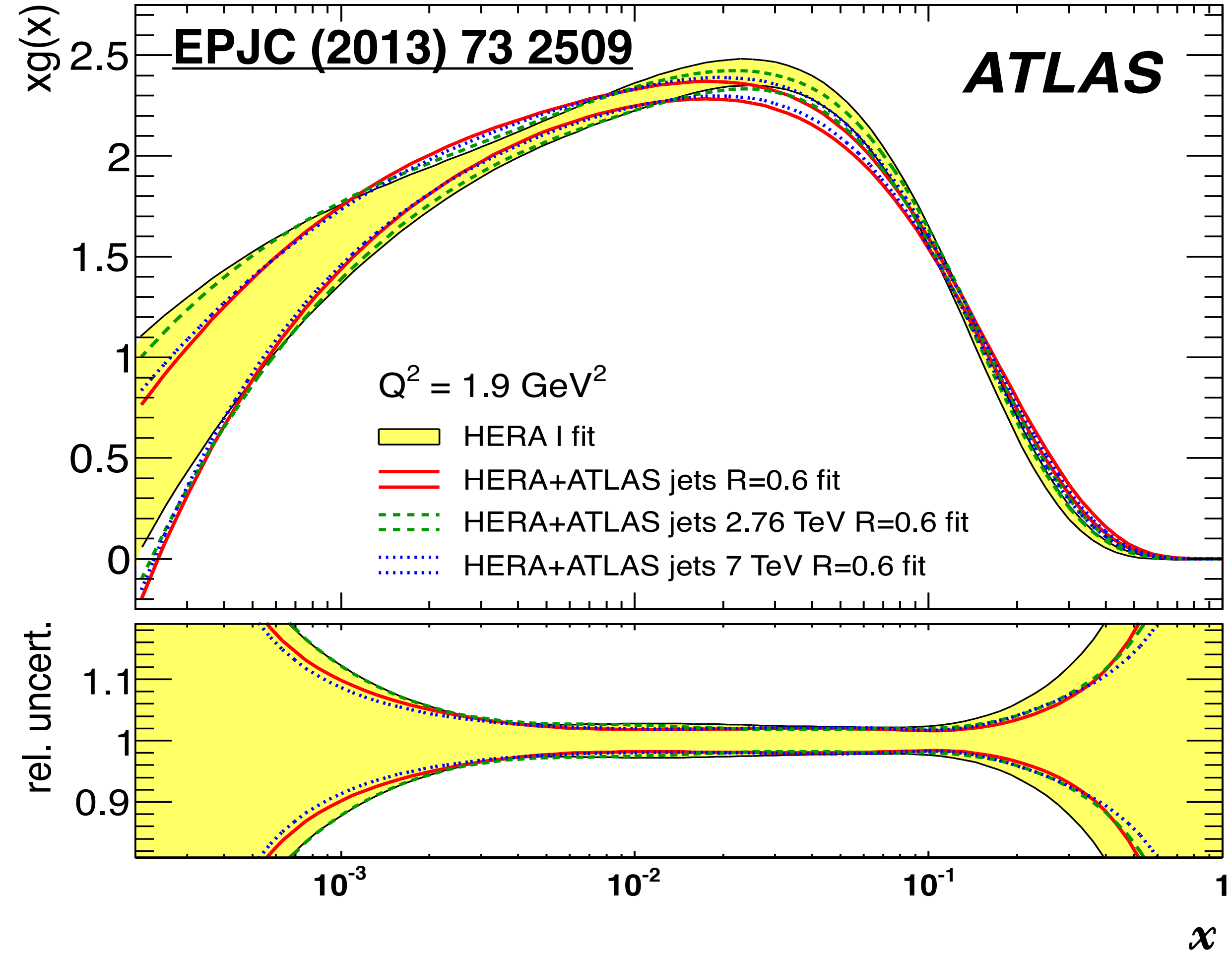
- The jet data provide constraints on the gluon distribution
- Fits are performed using DIS HERA from and either ATLAS or CMS data
  - ATLAS have, previously, used inclusive jet data from 2.76 TeV and 7 TeV data form 2010 (**EPJC (2013) 73 2509**)
  - CMS fit uses inclusive jet data from 2011 (**CMS-PAS-SMP-12-028**)
- The HERAFitter package is used, with LHC cross sections reproduced using fastNLO and APPLgrid
- Both ATLAS and CMS use the same parameterisation

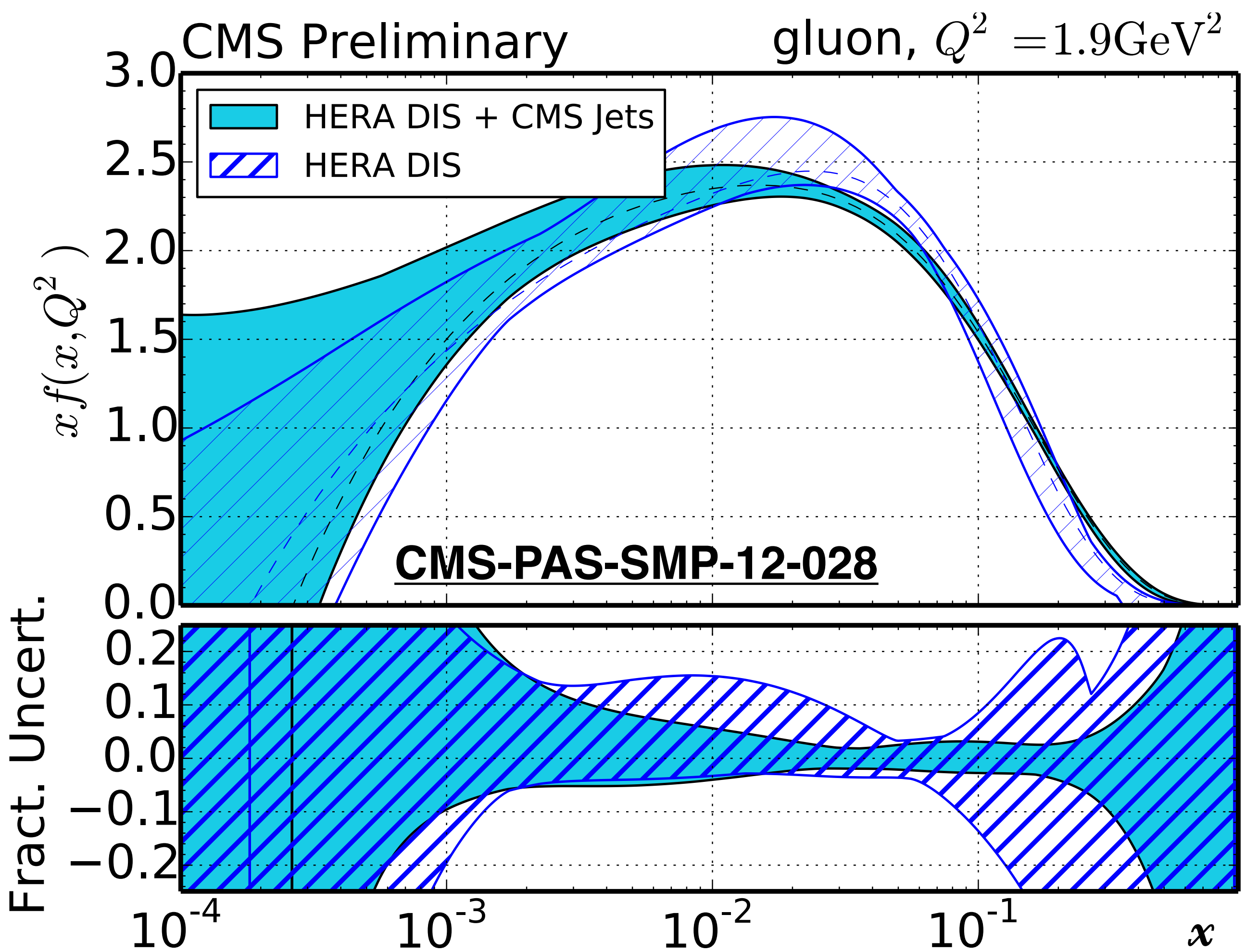
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g} \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}} \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}
\end{aligned}
$$

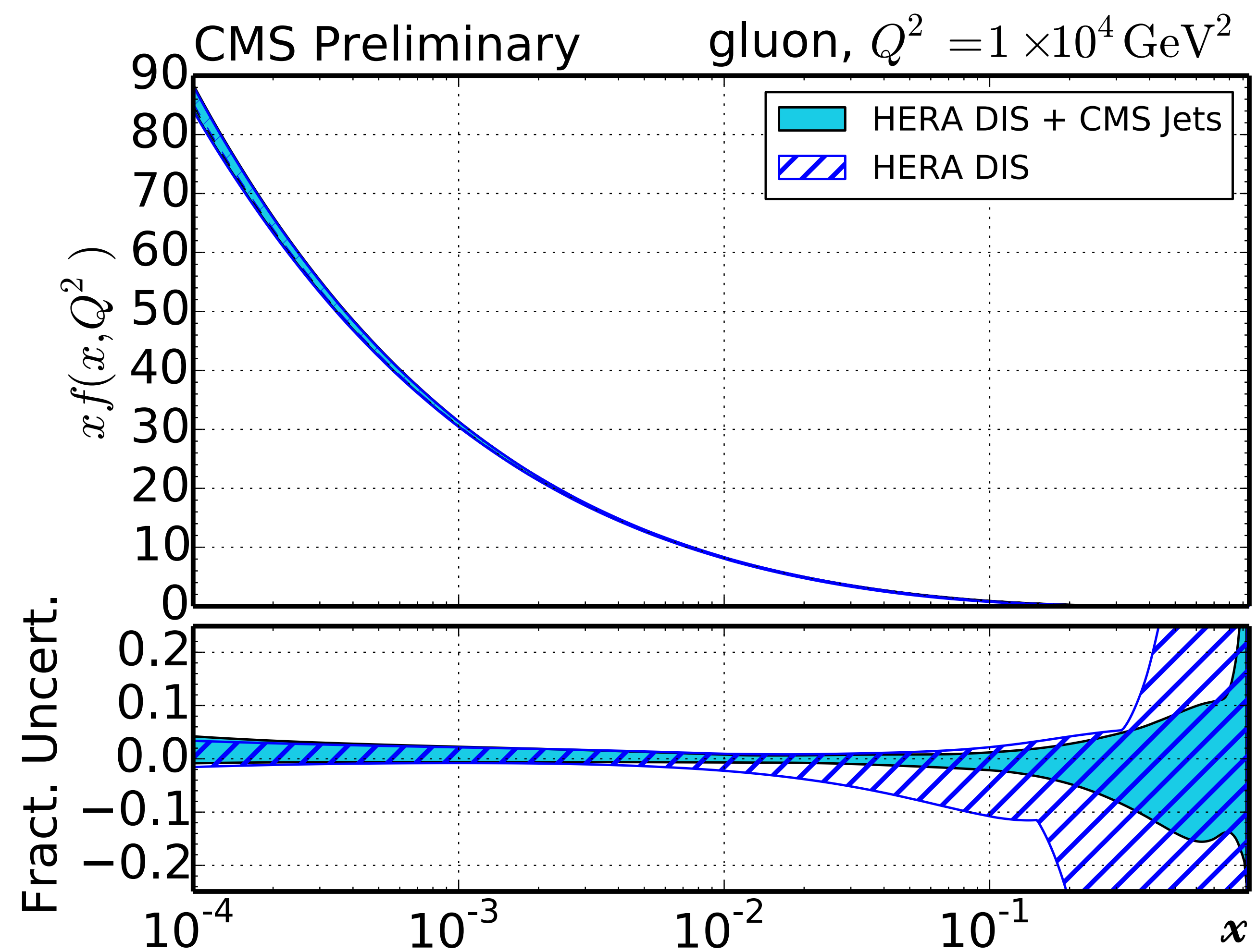
- Additional constraints, A_g, A_{u_v}, A_{d_v} from sum rules, $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}}(1-f_s)$ to ensure the same normalisation as $x \to 0$ and $C'_g = 25$
- The strange quark distribution is constrained to be proportional to the *d* type sea, $xs = xf_sD$, where $f_s = 0.31$
- This yields a 13 parameter fit, using a fixed strong coupling and a starting scale of $Q^2 = 1.9$ GeV^2

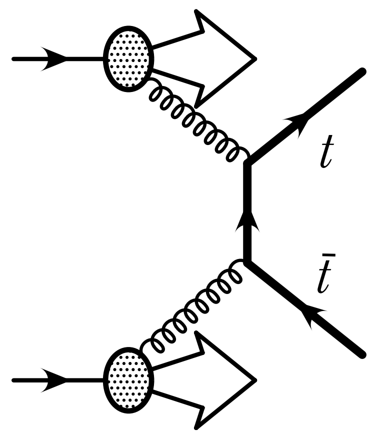
The gluon distribution

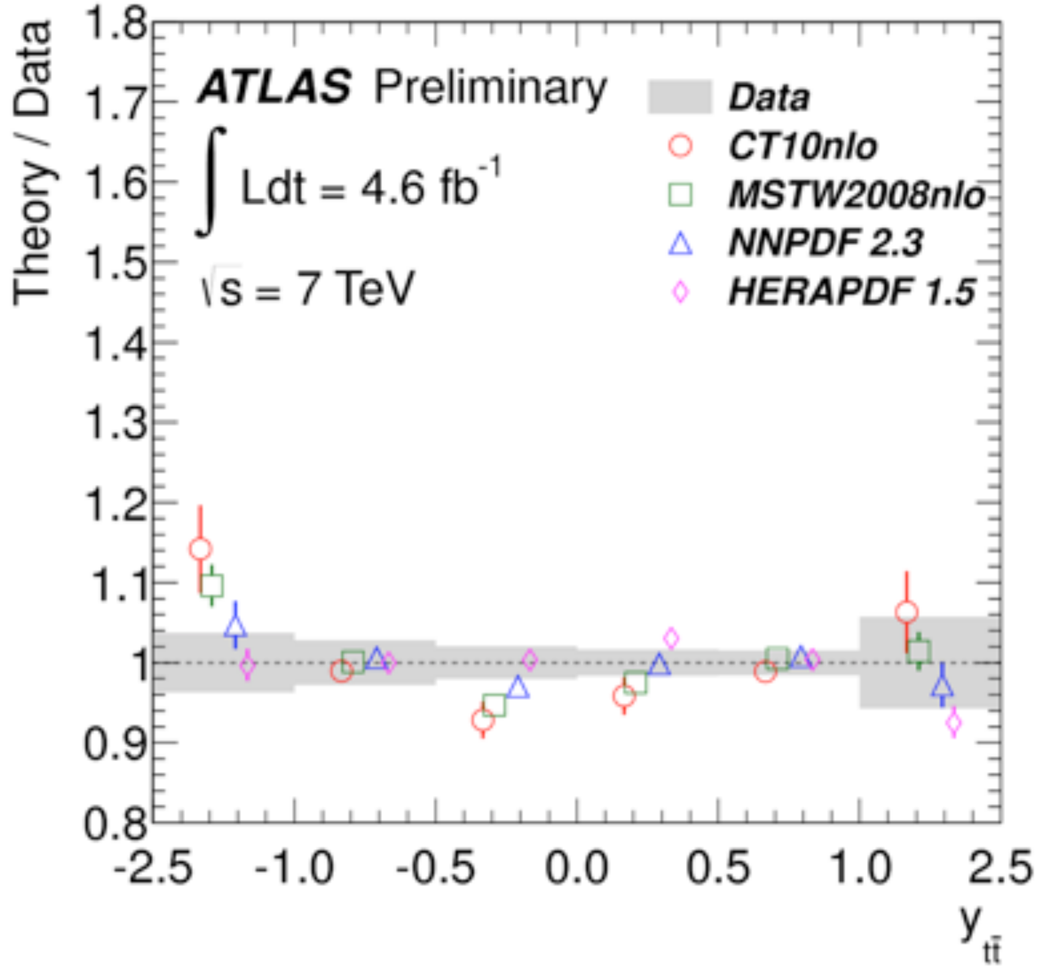
- ATLAS fit to data at 2.76 TeV and 7 TeV from 2010
  - At the same jet $E_{T,}$ different beam energies sample gluon PDF at different x, many systematics cancel
- CMS fit to higher statistics inclusive jet data from 2011
- Both ATLAS and CMS data predict a harder gluon, with a different shape with respect to the fit using HERA alone
- Fractional uncertainty is smaller at high x, partly due to increased prediction
- Measurements are systematics limited at lower jet P_T, dominated by the Jet Energy Scale uncertainty

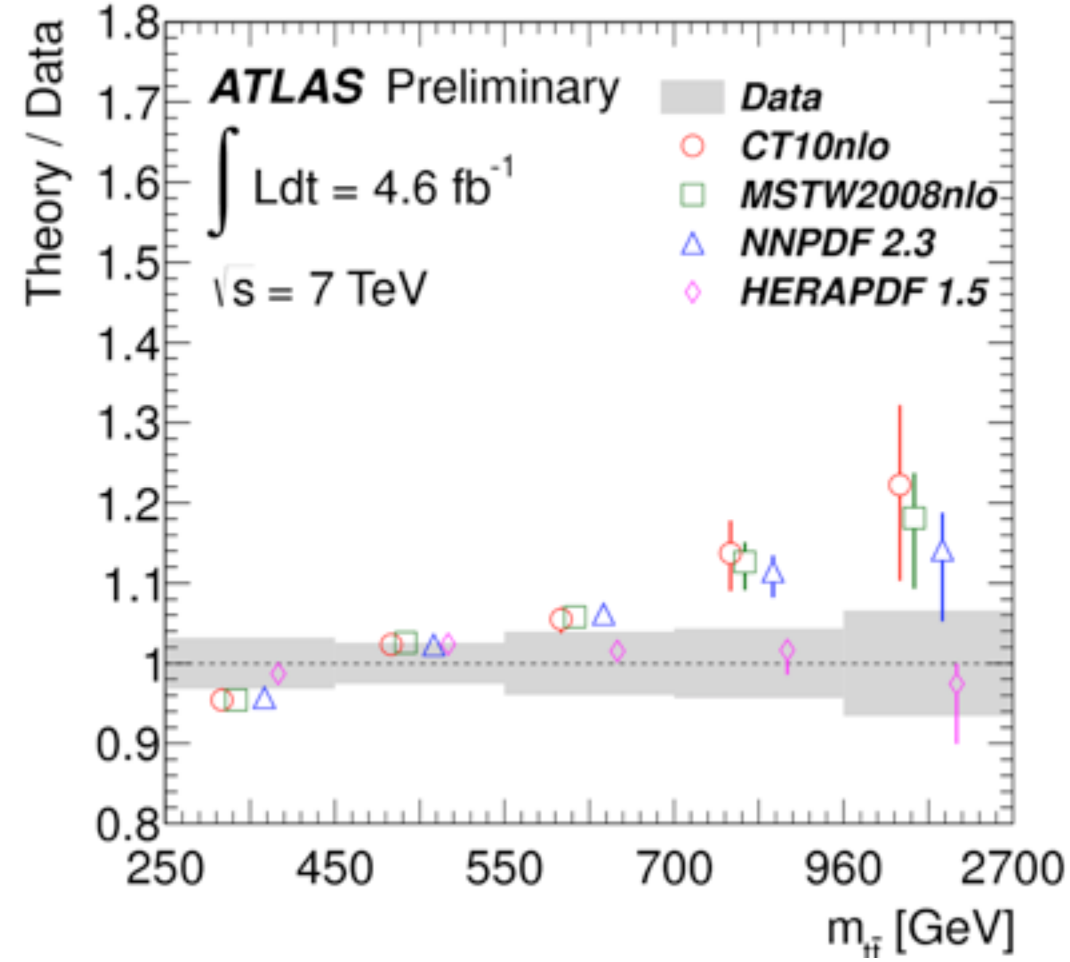






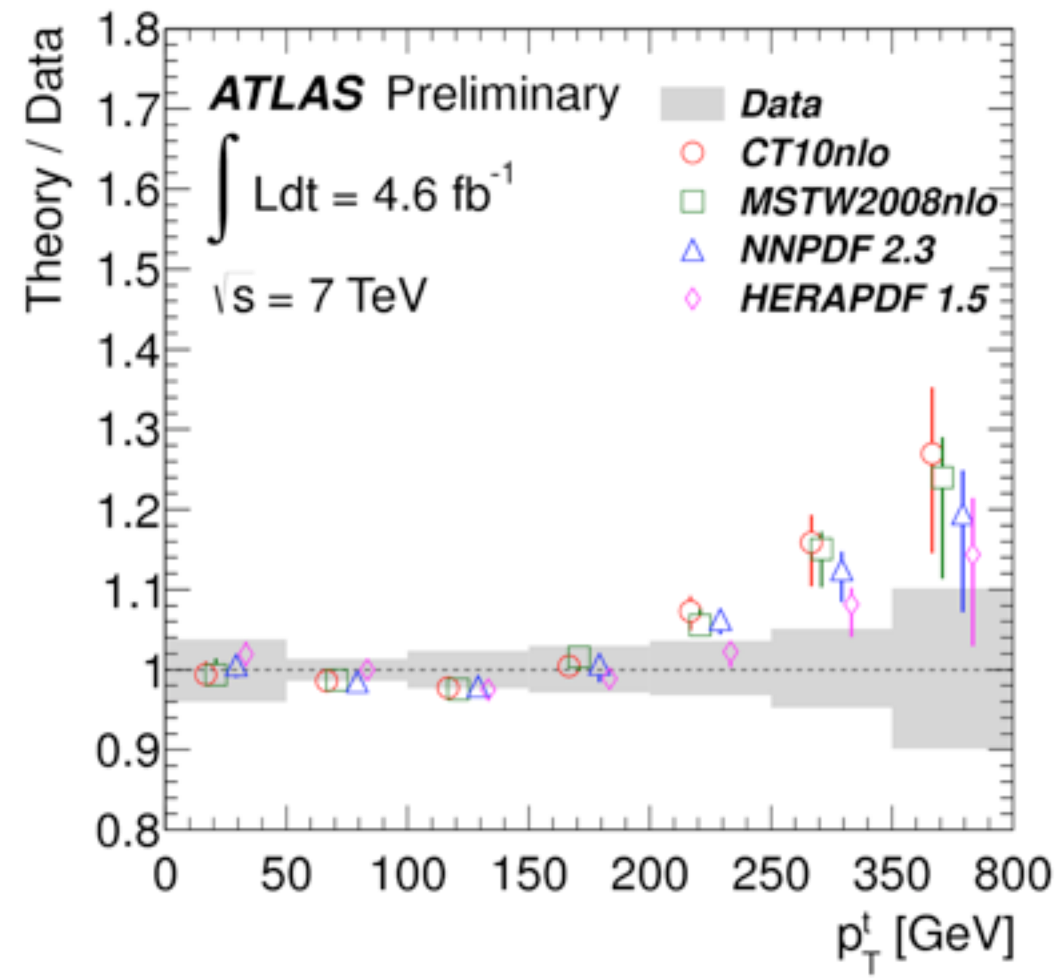


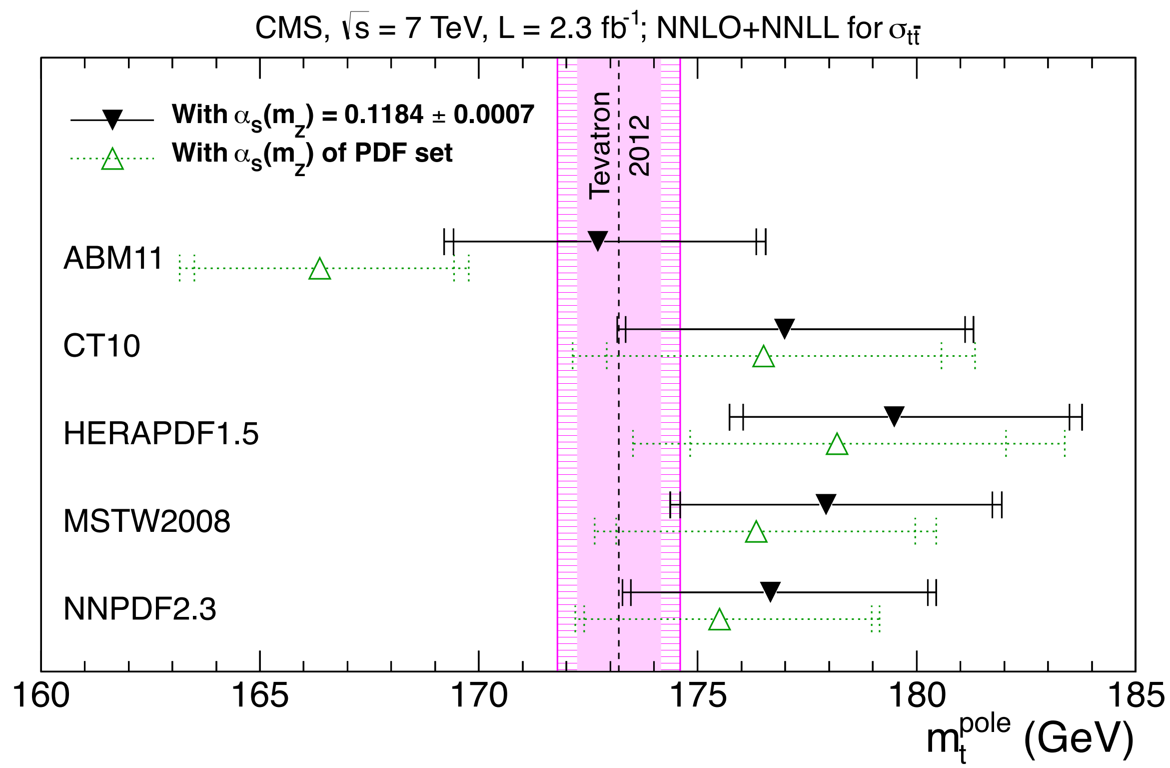


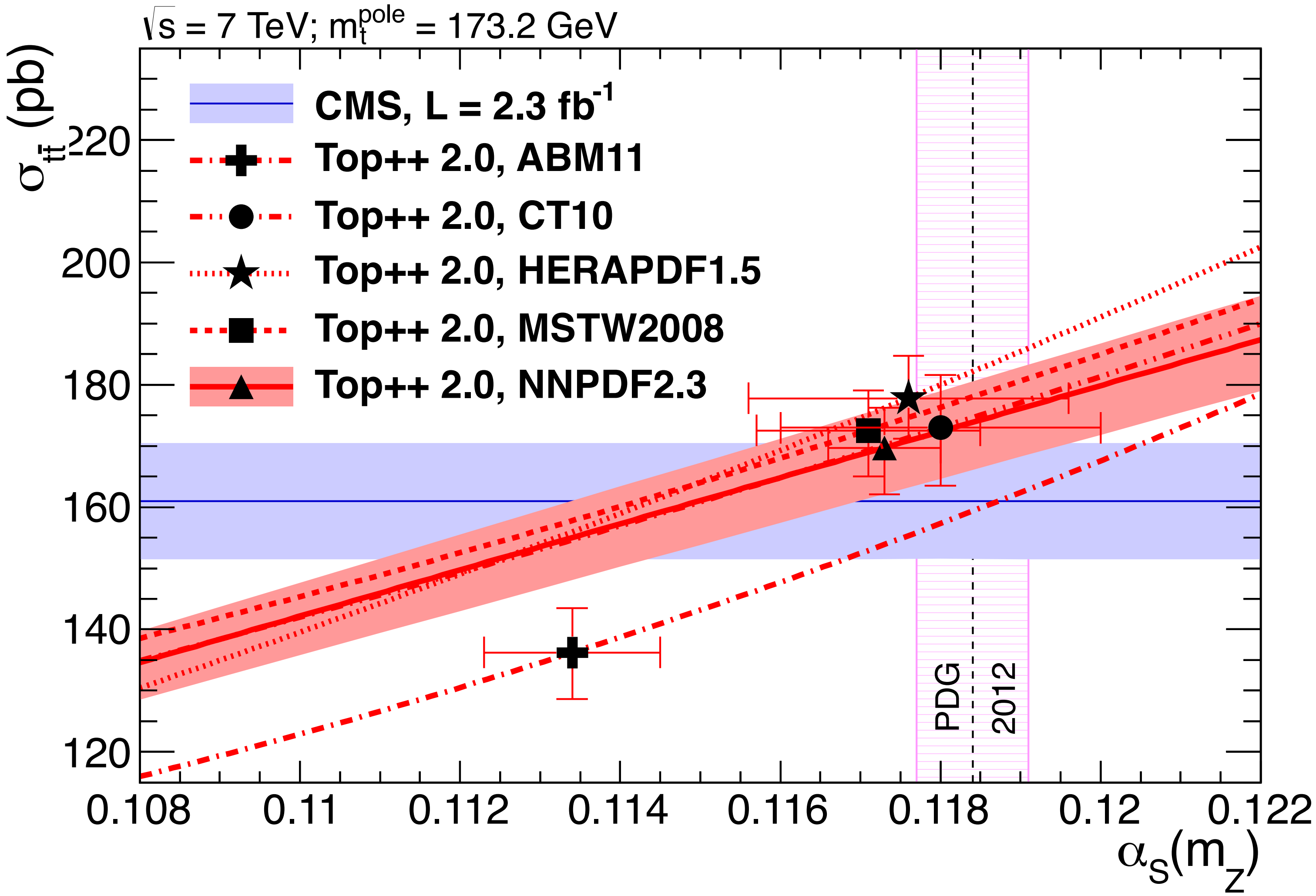


Top pair production

- **ATLAS-CONF-2013-099**
- Top pair production sensitive to the gluon distribution
- NLO calculation - potential large corrections at NNLO
- Smaller gluon contribution at high x for the HERAPDF
- Overall better agreement with the data than the harder gluons from other fits which may include the Tevatron jet data
- Can be used for extraction of α_S





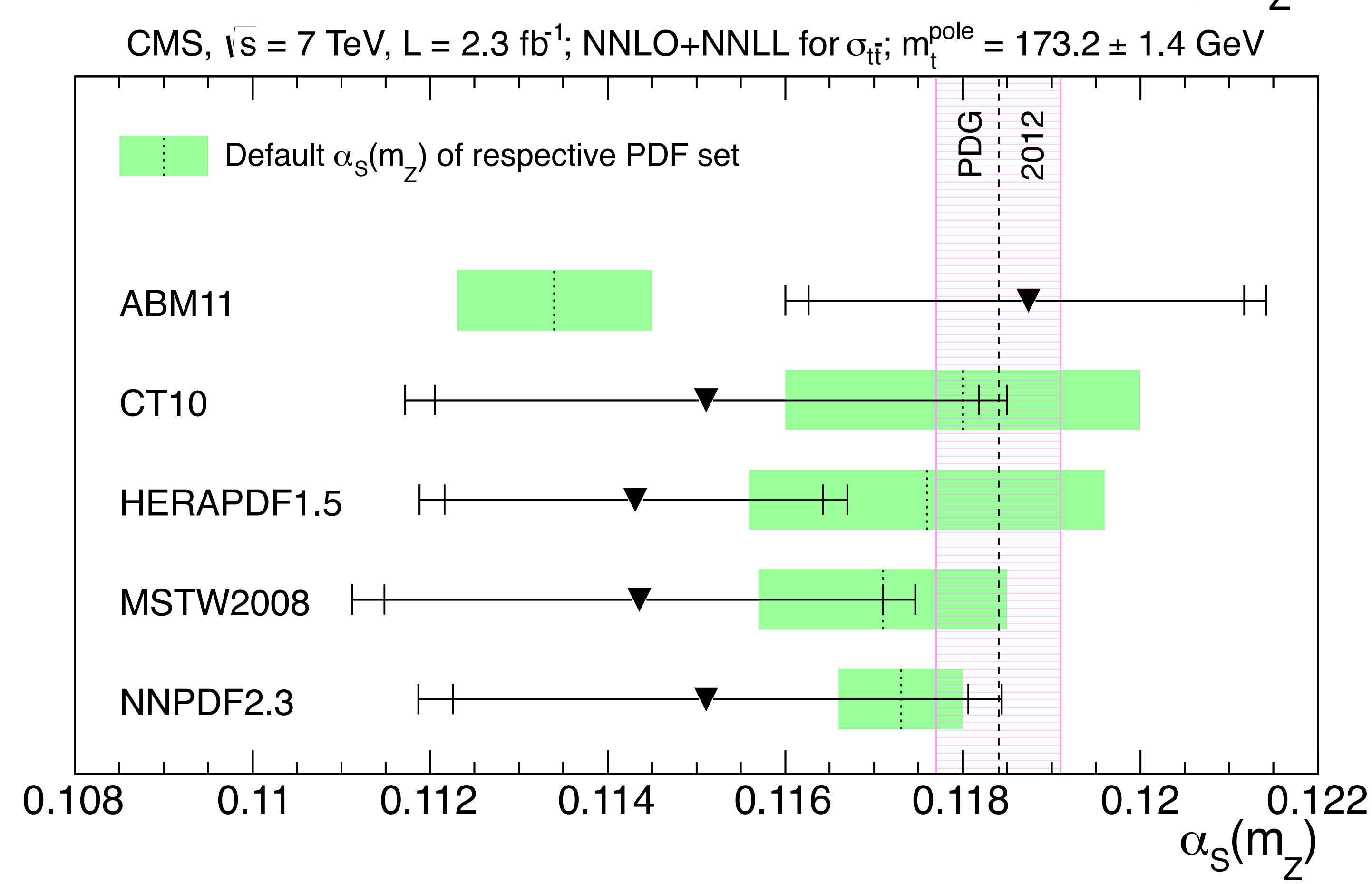


Top pair production

- **arXiv:1307.1907**
- NNLO+NLL calculation of cross section
- Can use dependence of cross section on top mass or strong coupling variation
  - Measure the strong coupling, assuming m_t^{pole} = 173.2 ± 1.4 GeV
- First measurement of the strong coupling from top quark production

$$\alpha_S(\mathrm{M_Z}) \quad = \quad 0.1151^{+0.0033}_{-0.0032}$$

- Consistent with the world average



Strong coupling

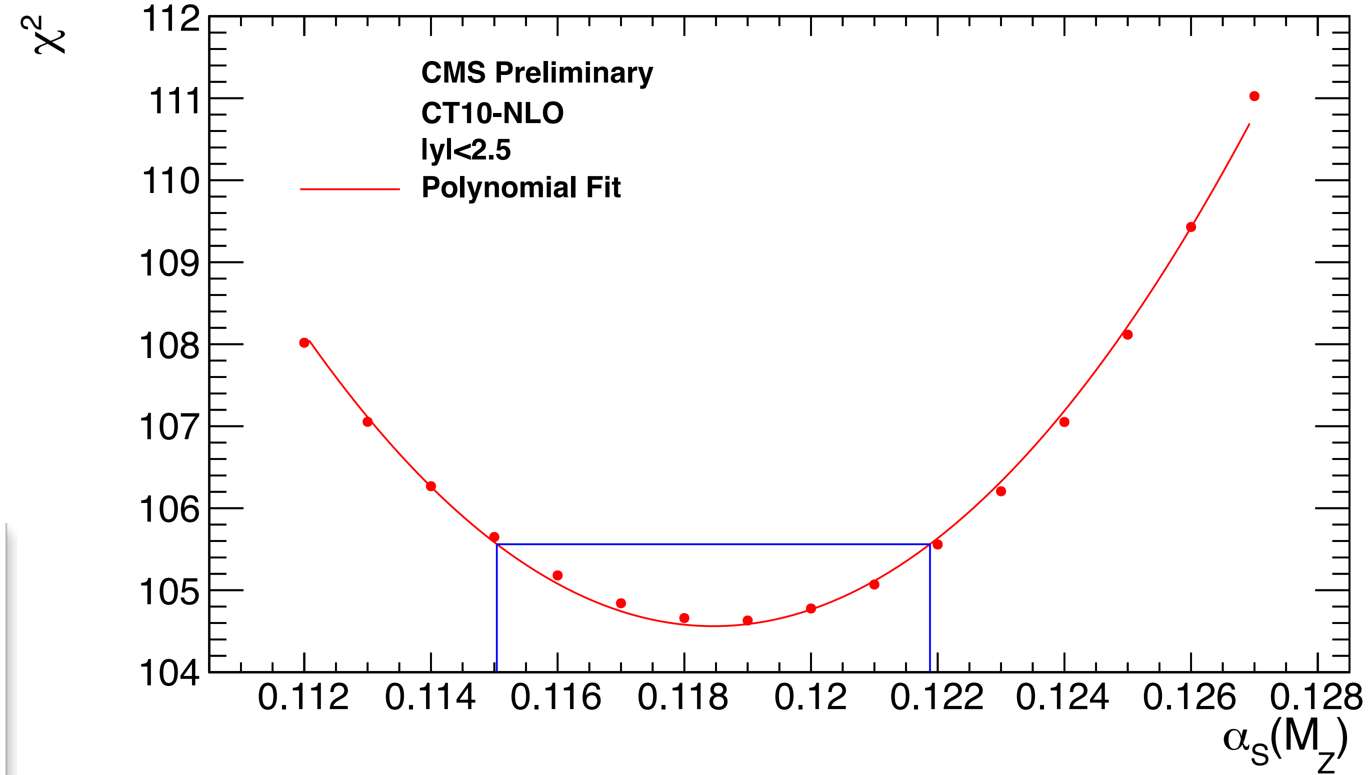
- Use a set of predictions for the cross section using different CT10 PDF sets fitted using a different strong couplings
- Fit to data from **PRD 87 (2013) 112002**

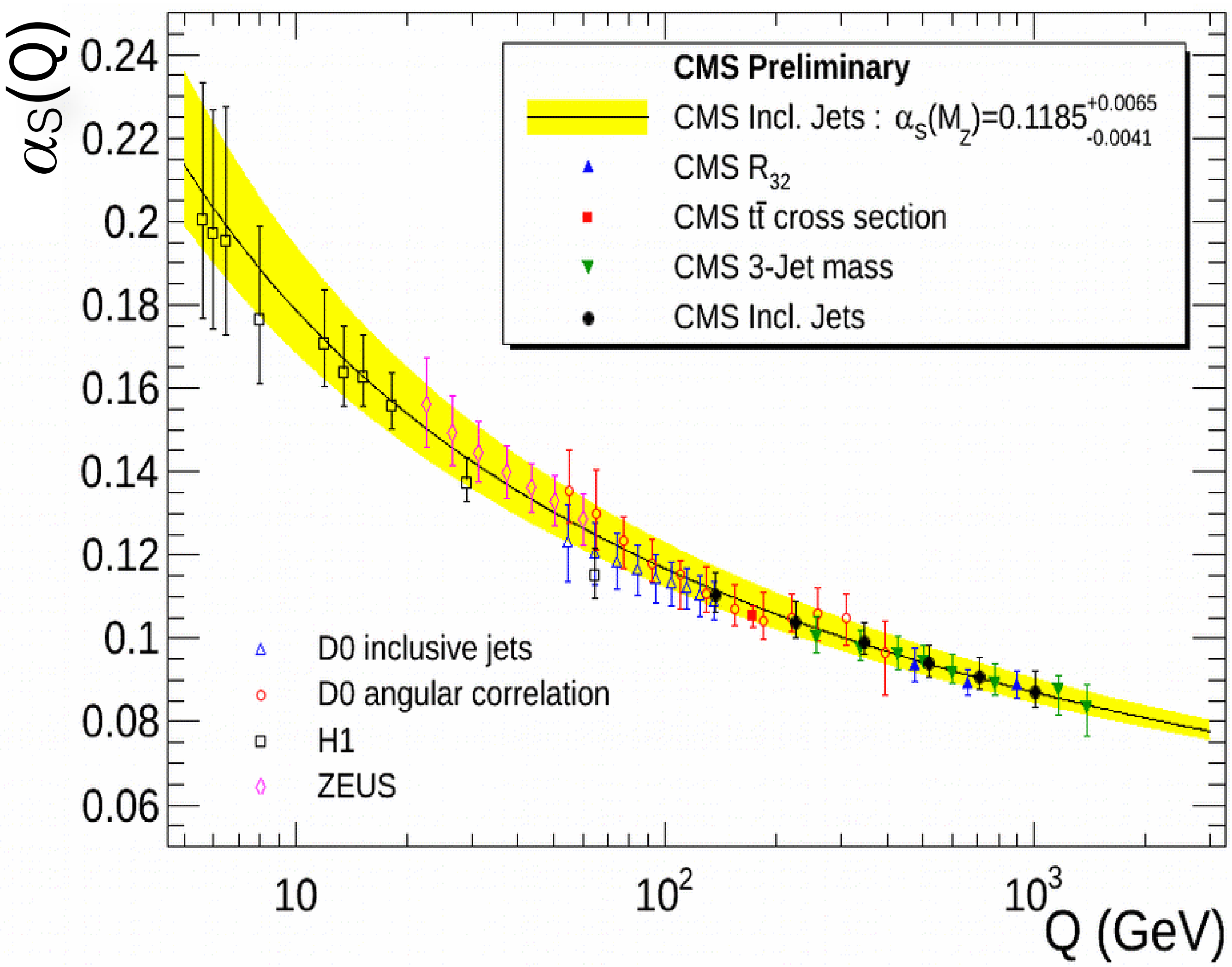
p_T range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	data points	$\chi^2/n_{\rm dof}$
114–196	136	$0.1170^{+0.0062}_{-0.0045}$	$0.1103^{+0.0054}_{-0.0039}$	20	6.2/19
196–300	226	$0.1179^{+0.0067}_{-0.0049}$	$0.1037^{+0.0052}_{-0.0037}$	20	7.6/19
300–468	345	$0.1194^{+0.0067}_{-0.0049}$	$0.0993^{+0.0045}_{-0.0033}$	25	8.2/24
468–638	521	$0.1188^{+0.0072}_{-0.0051}$	$0.0940^{+0.0044}_{-0.0032}$	20	10.6/19
638–905	711	$0.1193^{+0.0080}_{-0.0056}$	$0.0910^{+0.0044}_{-0.0033}$	22	11.4/21
905–2116	1007	$0.1180^{+0.0104}_{-0.0061}$	$0.0868^{+0.0054}_{-0.0033}$	26	39.4/25

- Combined fit yields

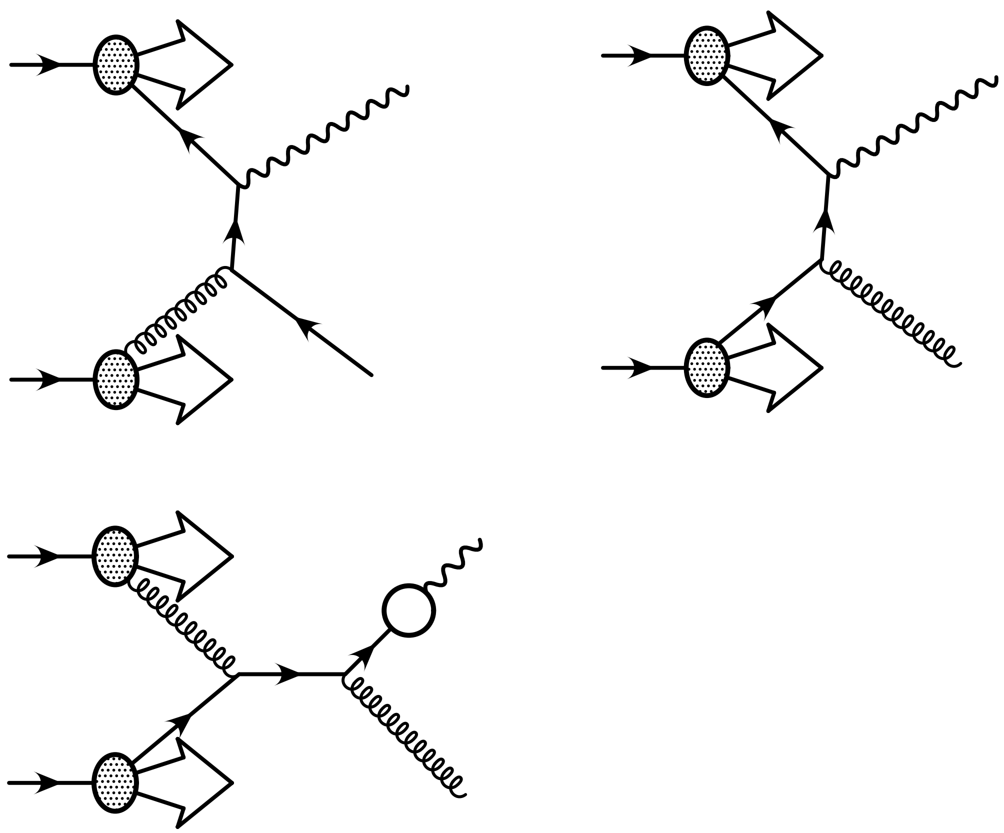
$$\alpha_S(\mathrm{M_Z}) \quad = \quad 0.1185^{+0.0065}_{-0.0041}$$

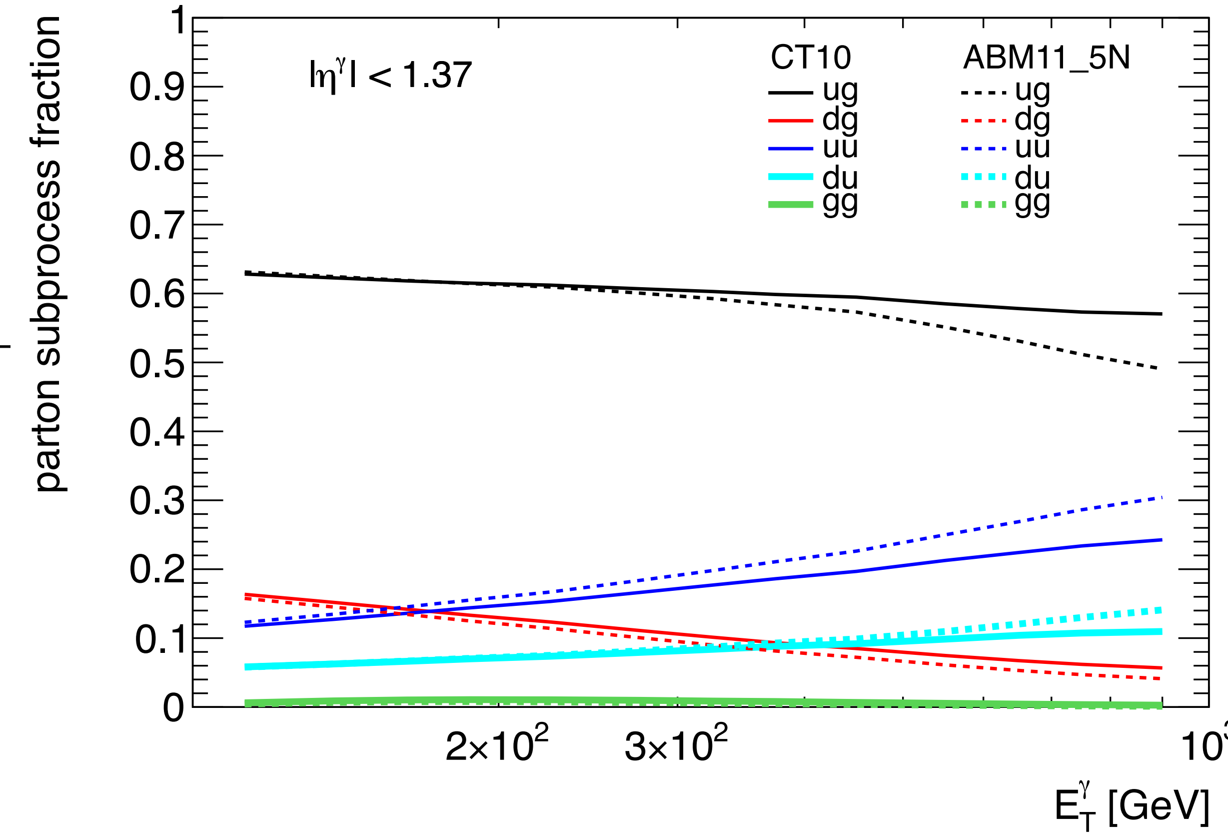
- Also shown, fits from
  - CMS tt cross section: [**arXiv:1307.1907**]
  - CMS R32: [**Eur.Phys.J. C73 (2013) 2604**]
  - CMS 3-jet mass: [**CMS-PAS-SMP-12-027**]
- Clearly see the running of the strong coupling at scales greeter than an order of magnitude larger than seen before

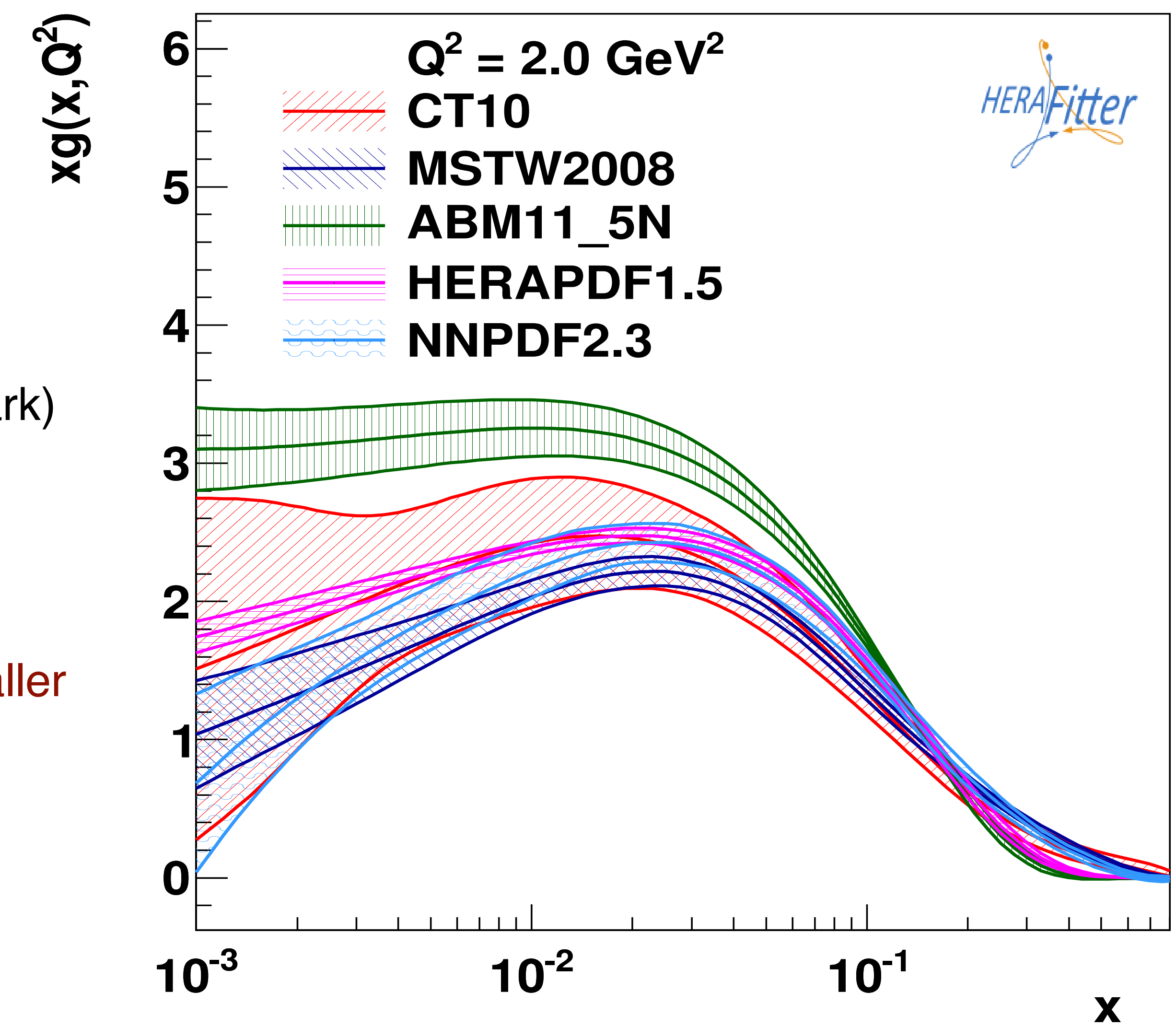




Inclusive direct (prompt) photon production

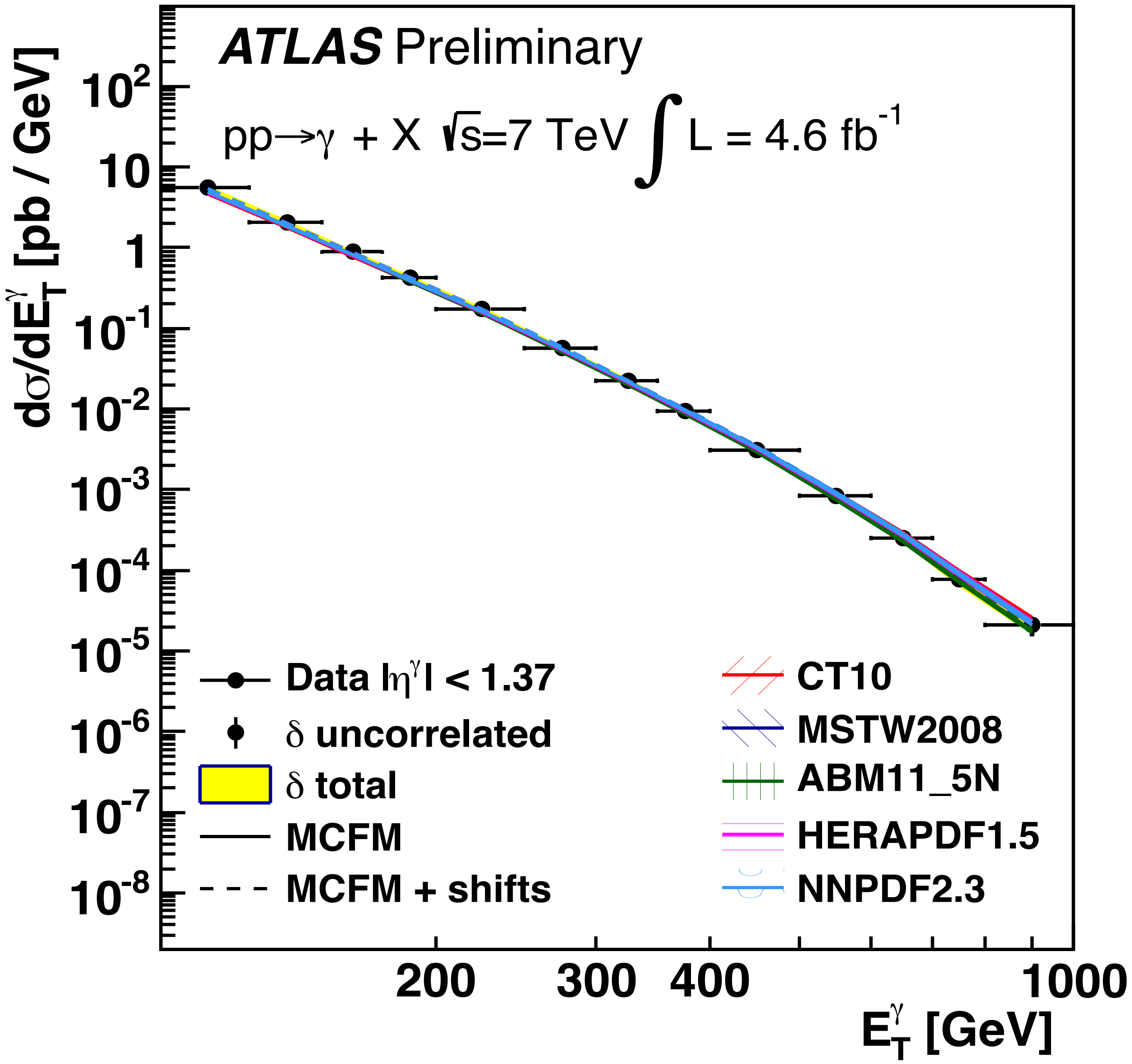


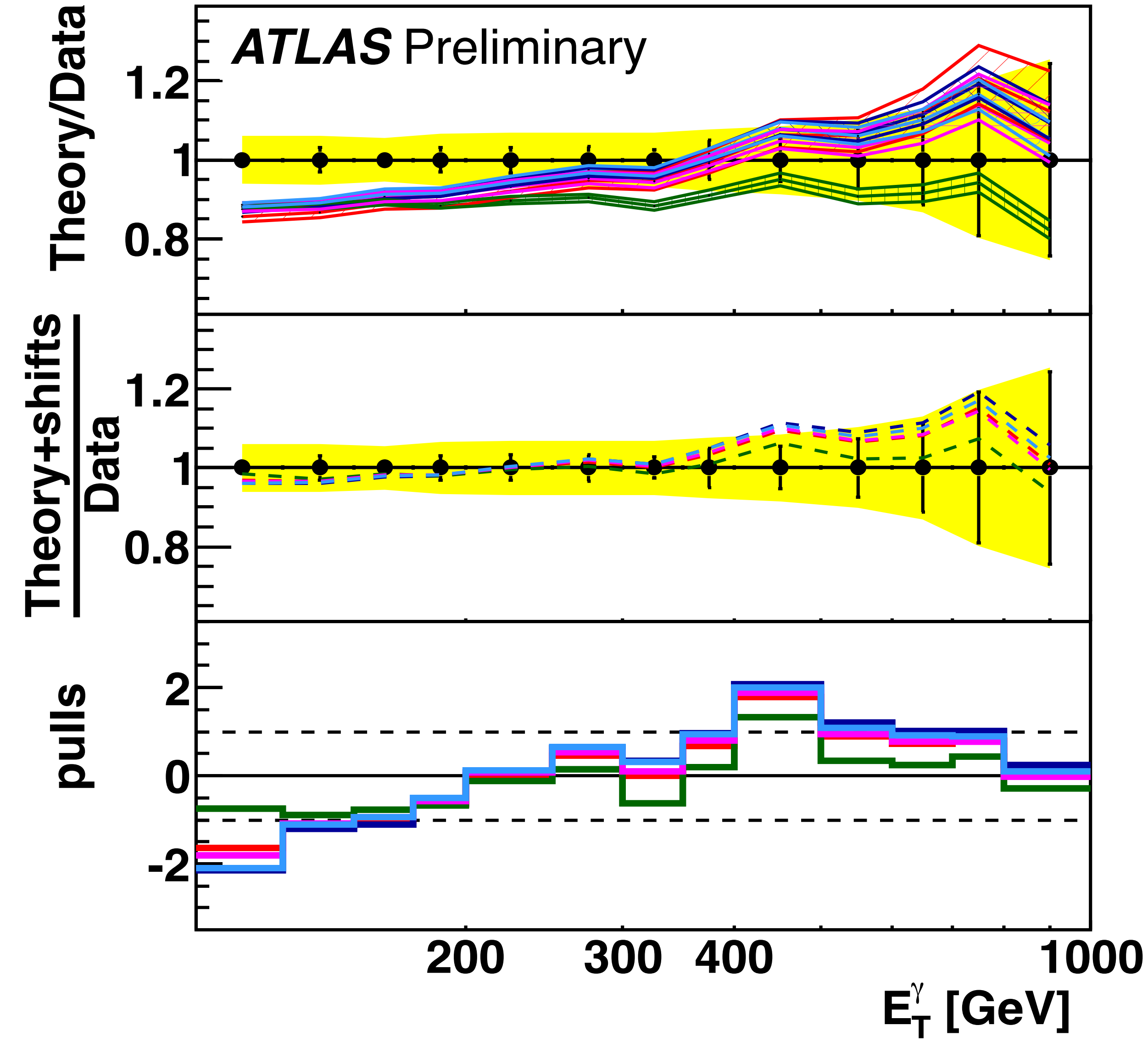




- Prompt photon cross section sensitive to the gluon (and u quark) density at leading order
  - The *ug* contribution dominates due to the large u quark charge
  - Again, softer ABM gluon contribution - *ug* contribution smaller at high E_T
- Smaller differences for forward photons
- Process only recently implemented in APPLgrid using MCFM

Central photon production

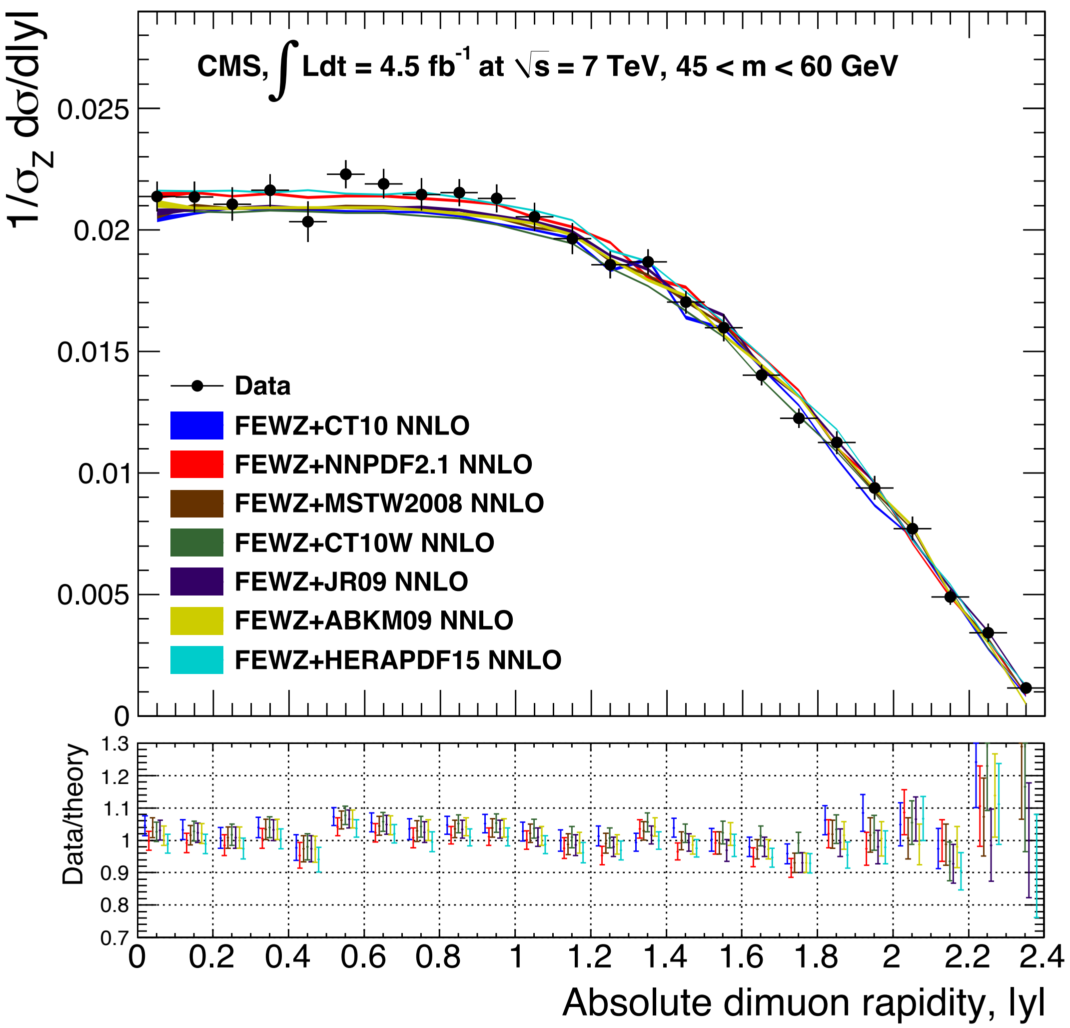


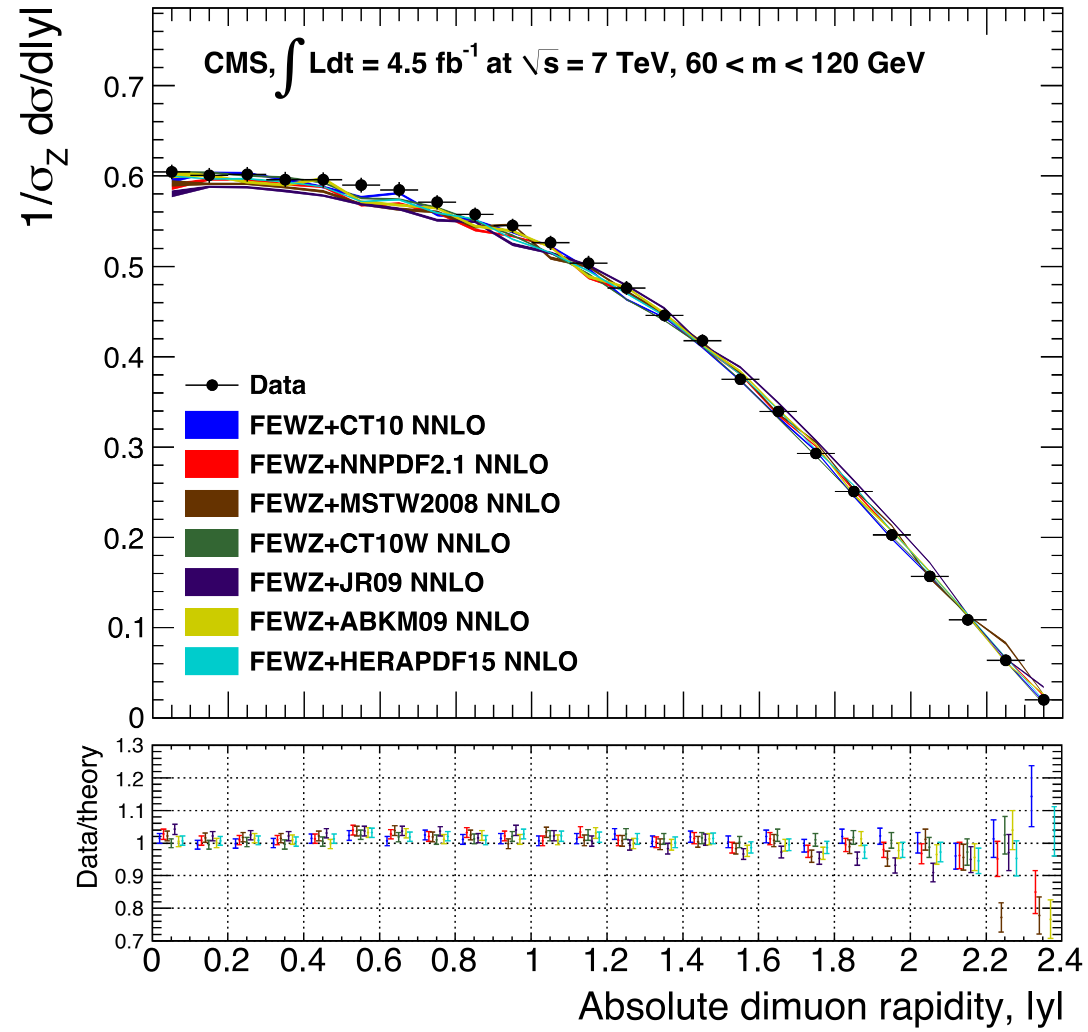


	Excluding PDF uncertainties		Including PDF uncertainties	
	$\mu_r = \mu_f = E_T^\gamma$	Envelope	$\mu_r = \mu_f = E_T^\gamma$	Envelope
CT10	49.1	34.7 - 63.1	29.8	20.0 - 38.4
MSTW2008	39.9	27.2 - 52.7	32.0	21.3 - 42.3
ABM11_5N	16.2	9.2 - 25.5	15.7	8.9 - 24.9
HERAPDF1.5	28.7	19.0 - 38.9	23.6	15.7 - 32.0
NNPDF2.3	33.5	22.6 - 44.7	27.6	18.7 - 36.9

χ^2 for 23 degrees of freedom

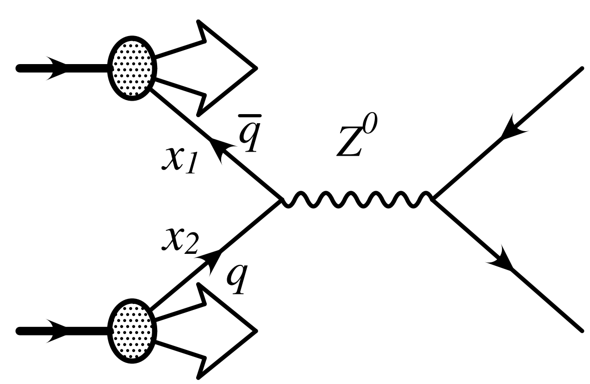
- **ATL-PHYS-PUB-2013-018**
- Data from **arXiv:1311.1440**
- Large variation of the predictions from MCFM with each PDF
  - Again, ABM11 softer at high E_T

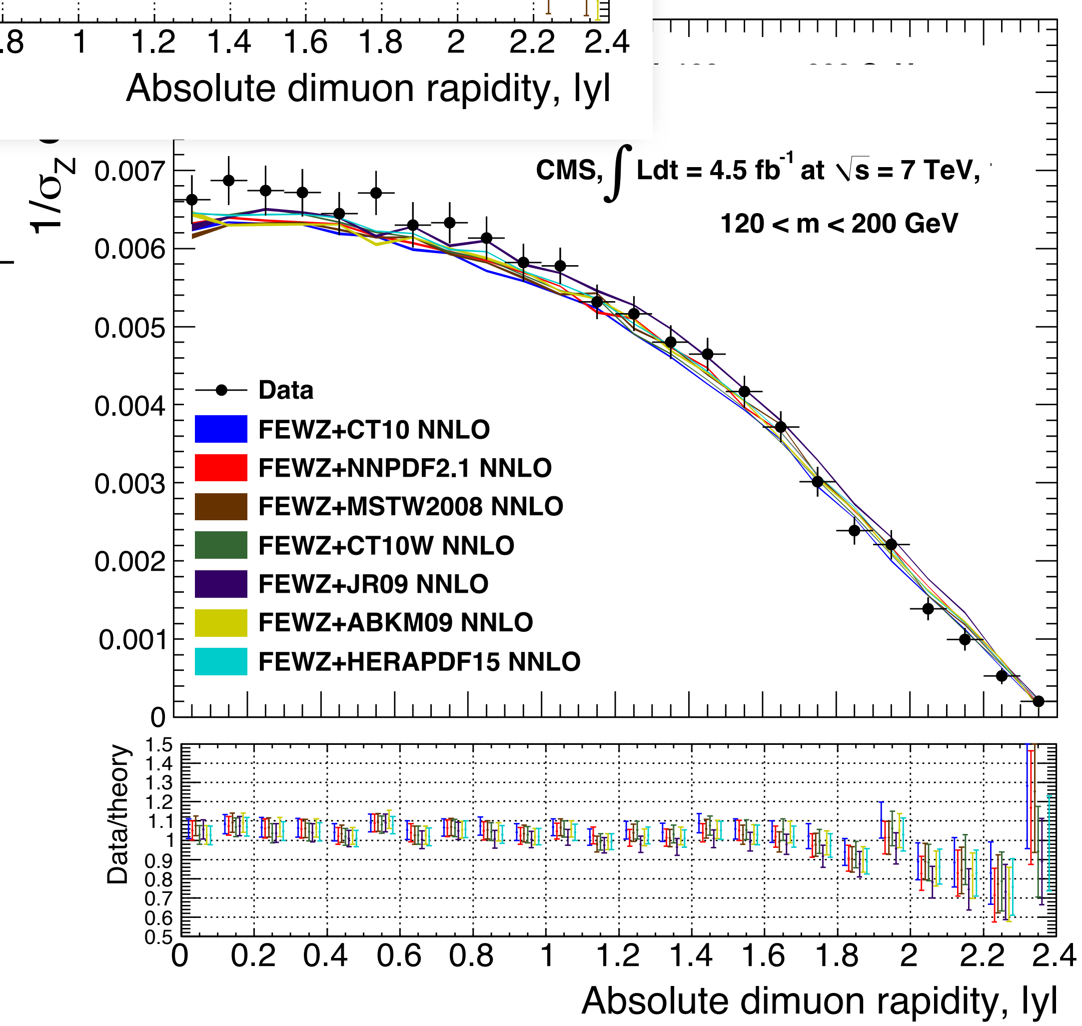




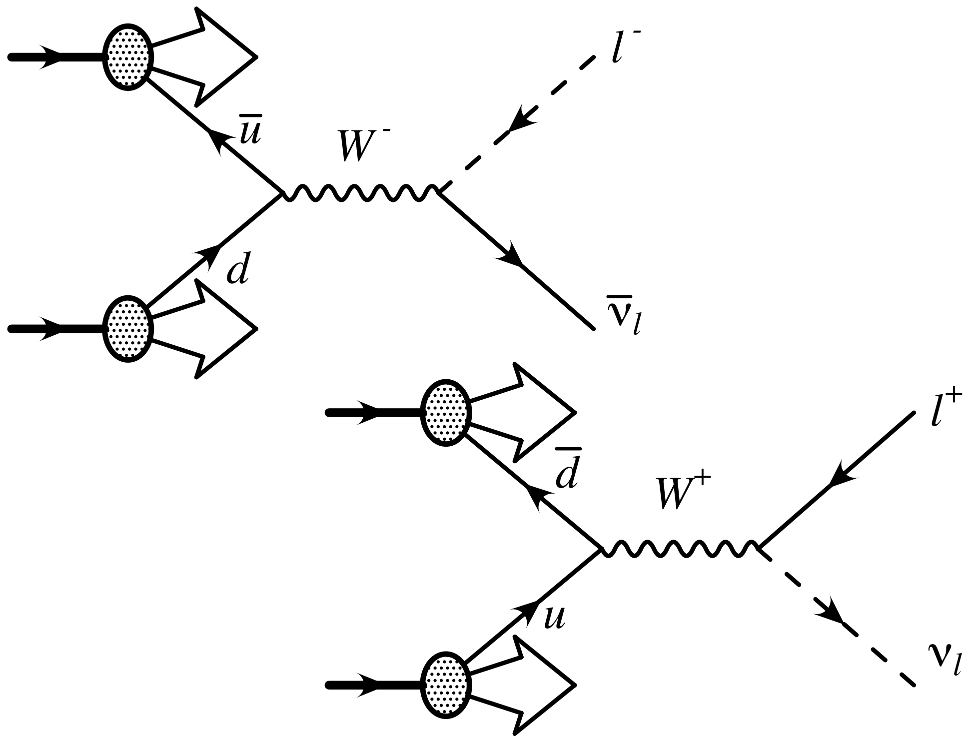
Drell-Yan production at CMS

- **JHEP 12 (2013) 030**
- Inclusive Z production data now becoming very precise
- Data underestimated by NNLO QCD for many fits



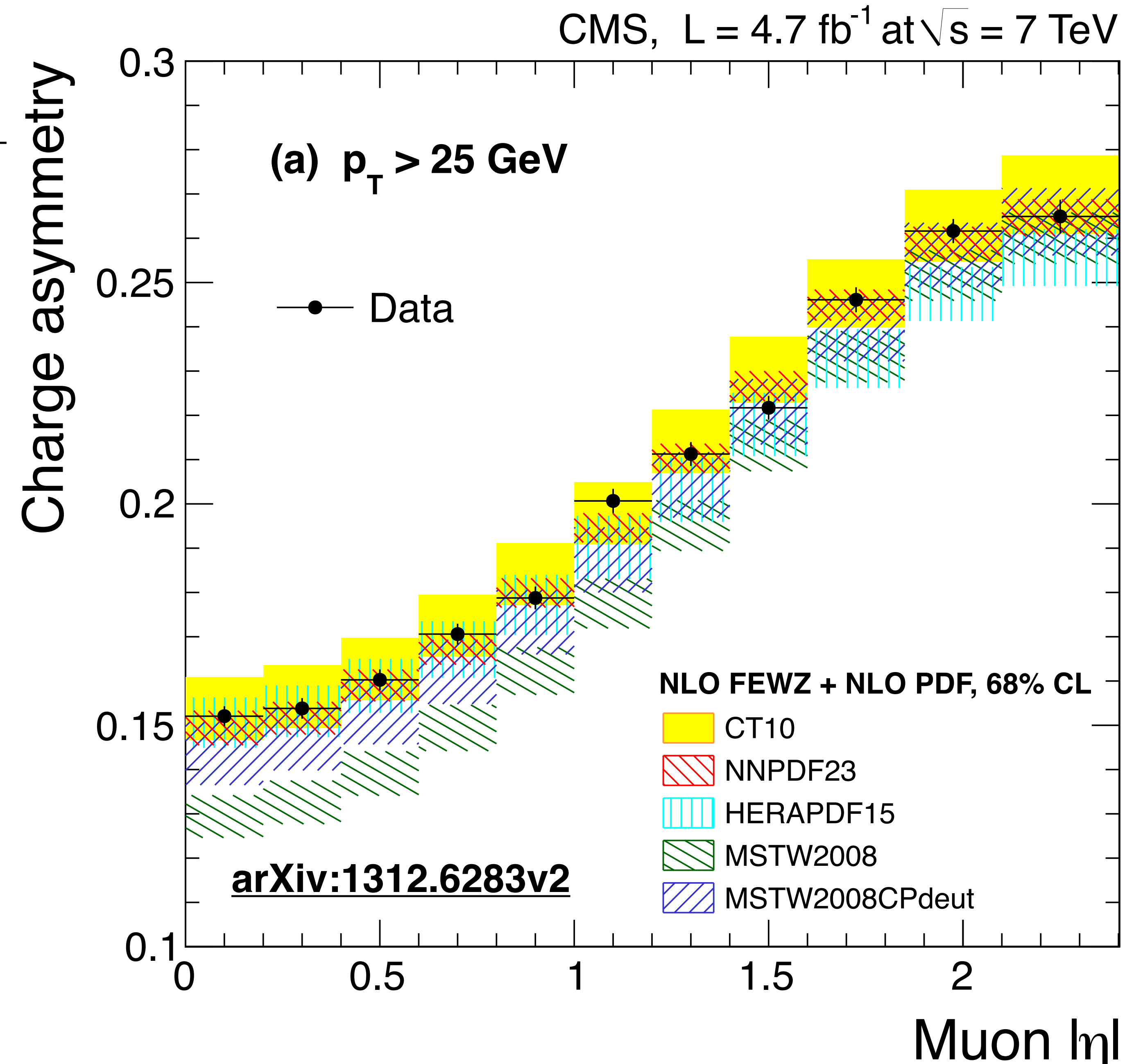


The W charge asymmetry



- Charge asymmetry for W bosons sensitive to u and d valence quark distributions - if the u and d sea quark distributions are approximately the same, then

$$\mathcal{A}_{\mathrm{W}} \approx \frac{u_v - d_v}{u + d}$$

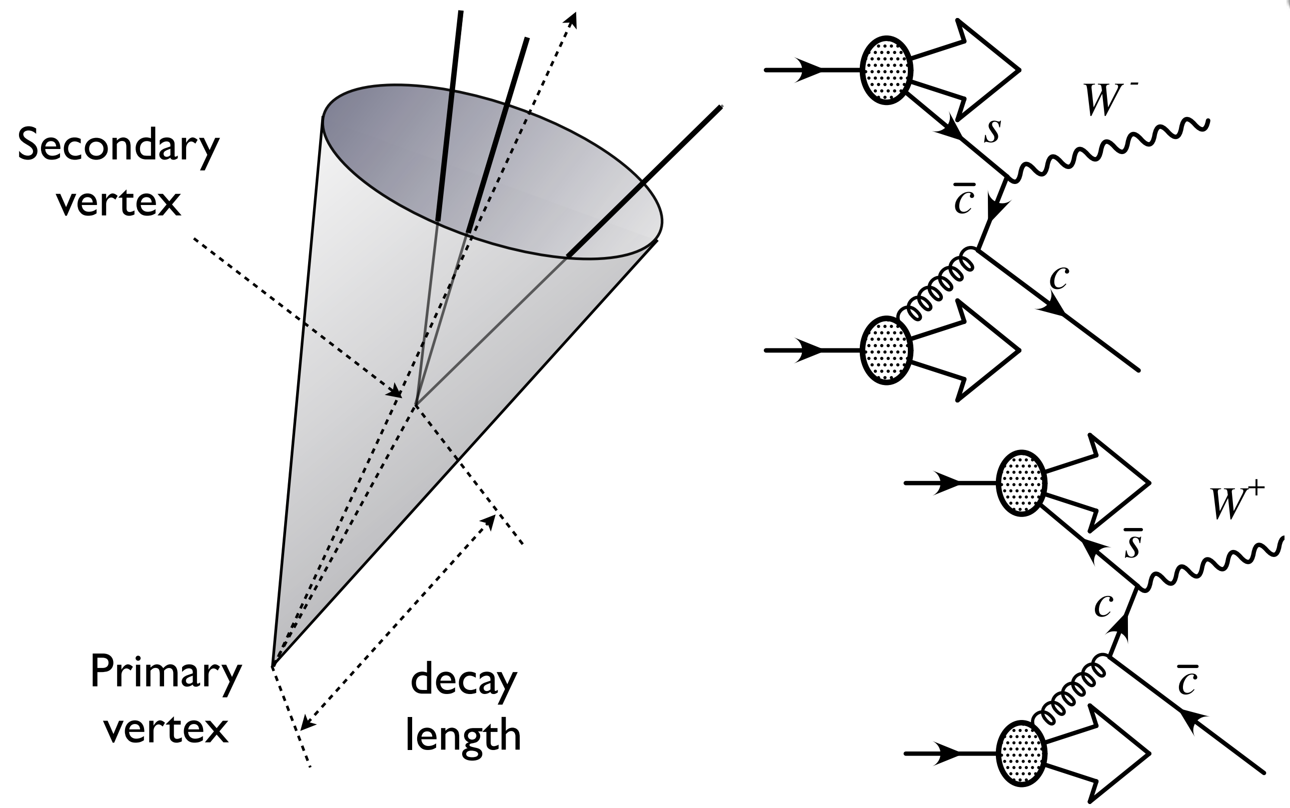


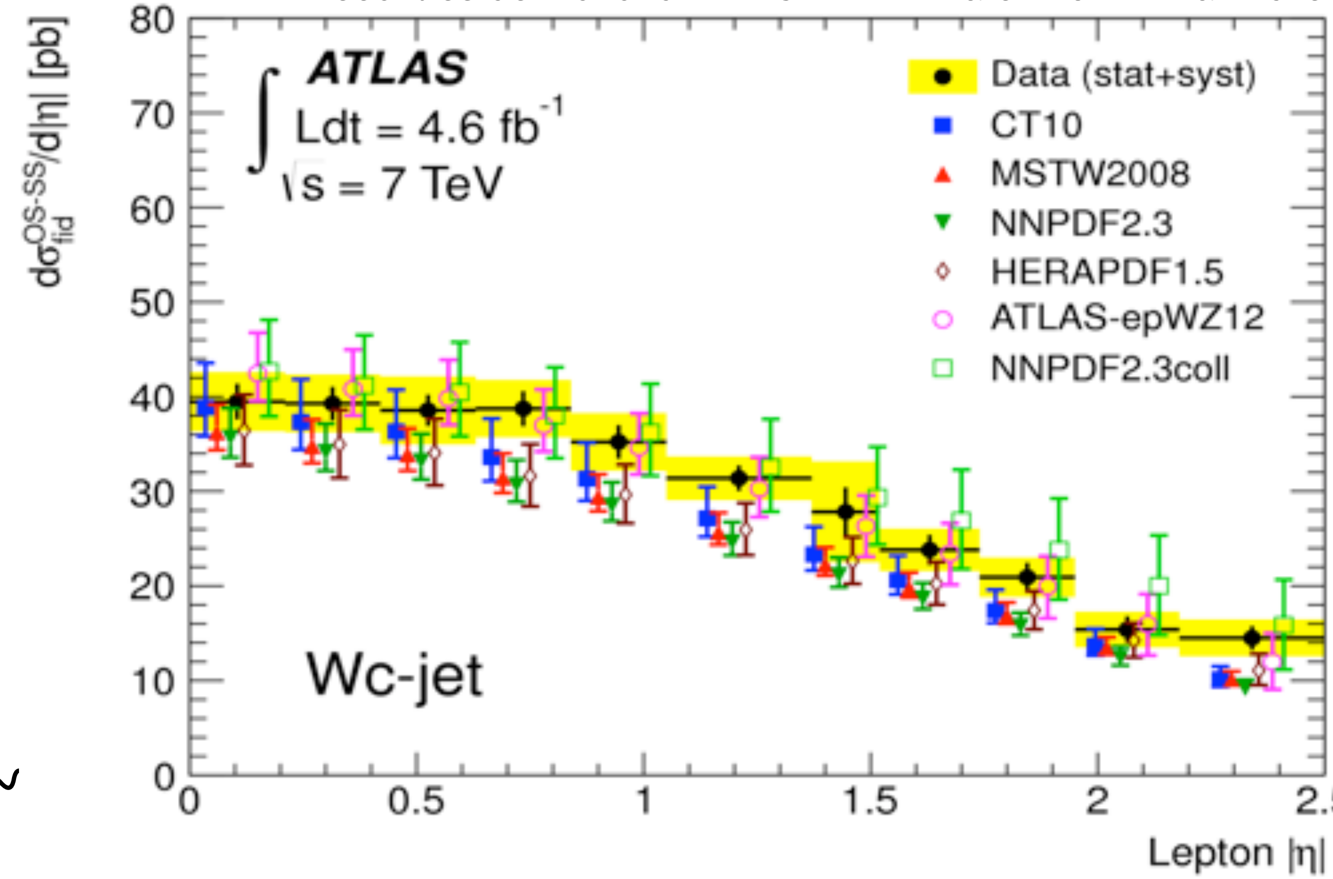
- Cross section uncertainty dominated by gluon distribution - cancels in the asymmetry, as do many systematic uncertainties.
- Due to the *v*, cannot reconstruct the W kinematics completely, but the charged lepton asymmetry

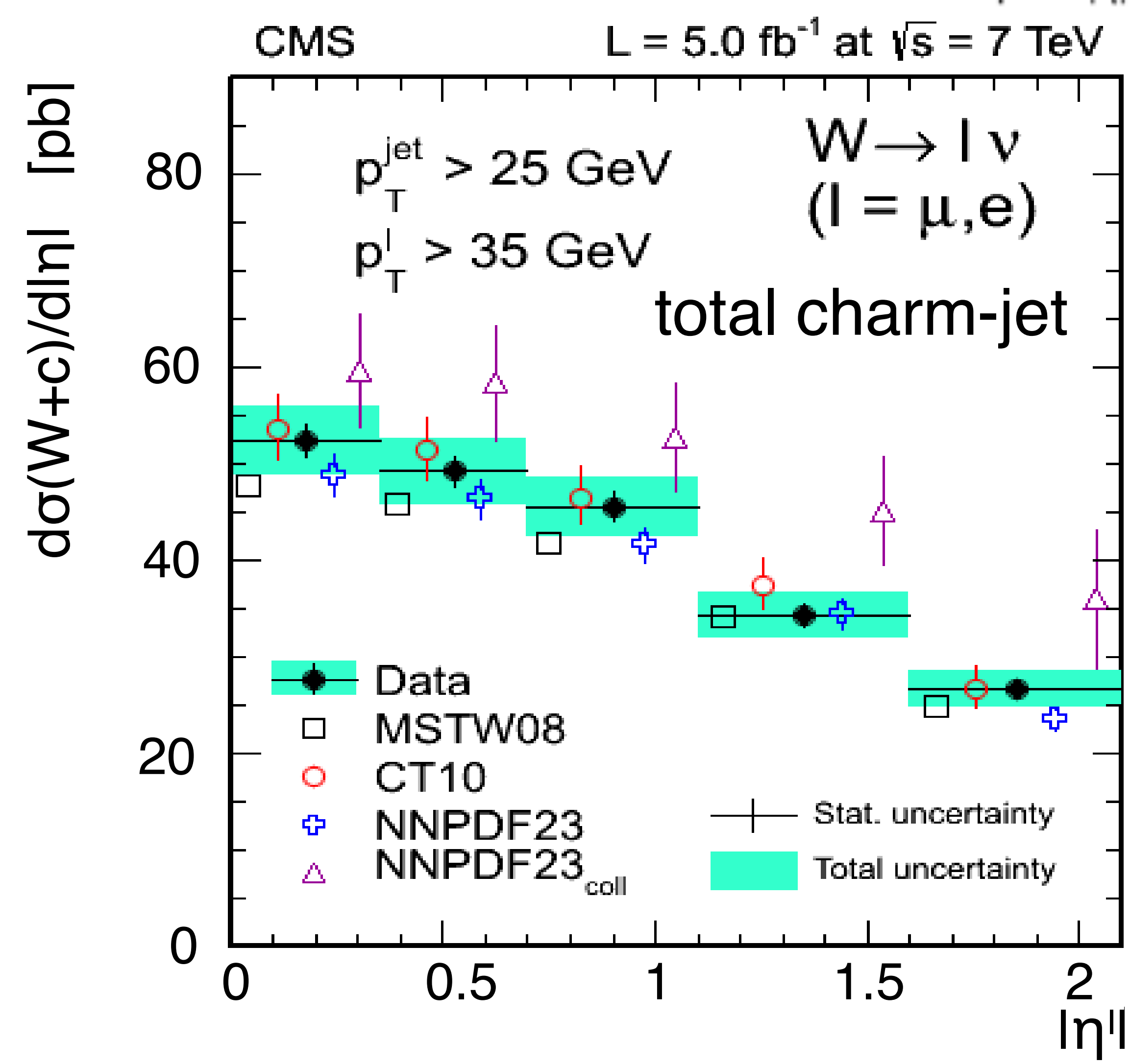
$$\mathcal{A}^l_{\mathrm{W}} = \frac{d\sigma_{W^+}/d\eta_{l^+} - d\sigma_{W^-}/d\eta_{l^-}}{d\sigma_{W^+}/d\eta_{l^+} + d\sigma_{W^-}/d\eta_{l^-}}$$

also sensitive to the valence quark distribution.

W+charm production







- W + charm data is directly sensitive to the strange quark density
- **ATLAS: arXiv:1402.6263v1**
- **CMS: arXiv:1310.1138**
- Measure fully reconstructed $D^{(*)}$ mesons or soft leptons within a jet
  - Same sign lepton pair contributions subtracted from opposite sign lepton pair distributions to eliminate background
- Cross section predicted at NLO using aMC@NLO (ATLAS) or POWHEG (CMS)
- More details on the data can be seen in presentation from **Lindsey Gray** from the session this morning

Fits to the EW Boson data

- For the fits to the boson data, both ATLAS and CMS perform fits both with constrained strange density, and where where the A and C coefficients of the strange density are allowed to vary independently

$$xs(x) \quad = \quad A_{\bar{s}} x^{B_s} (1-x)^{C_s}$$

- So a 15 parameter fit, with

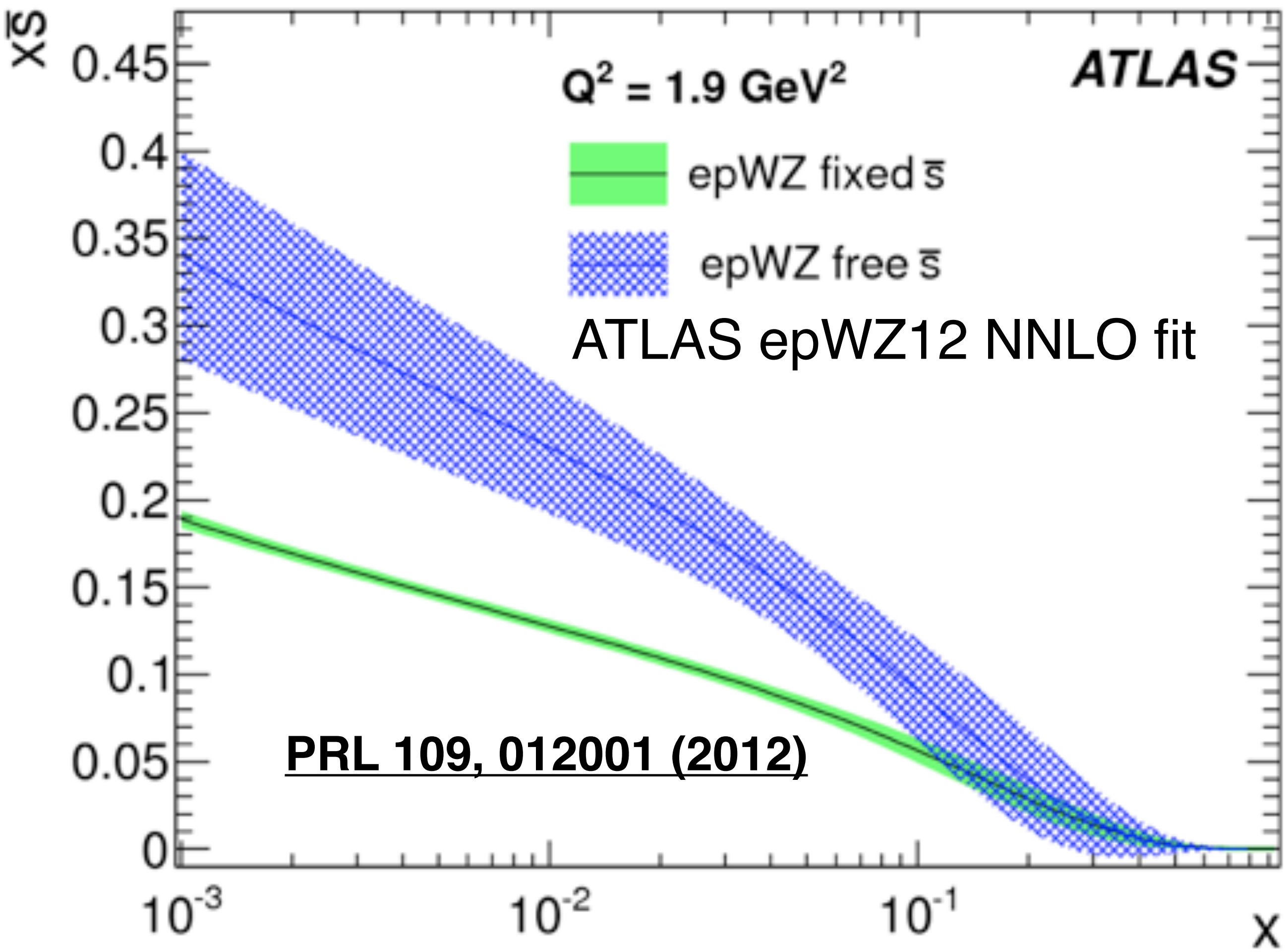
$$\begin{aligned} r_s &= (s+\bar{s})/2\bar{d} \\ R_s &= (s+\bar{s})/(\bar{d}+\bar{u}) \end{aligned}$$

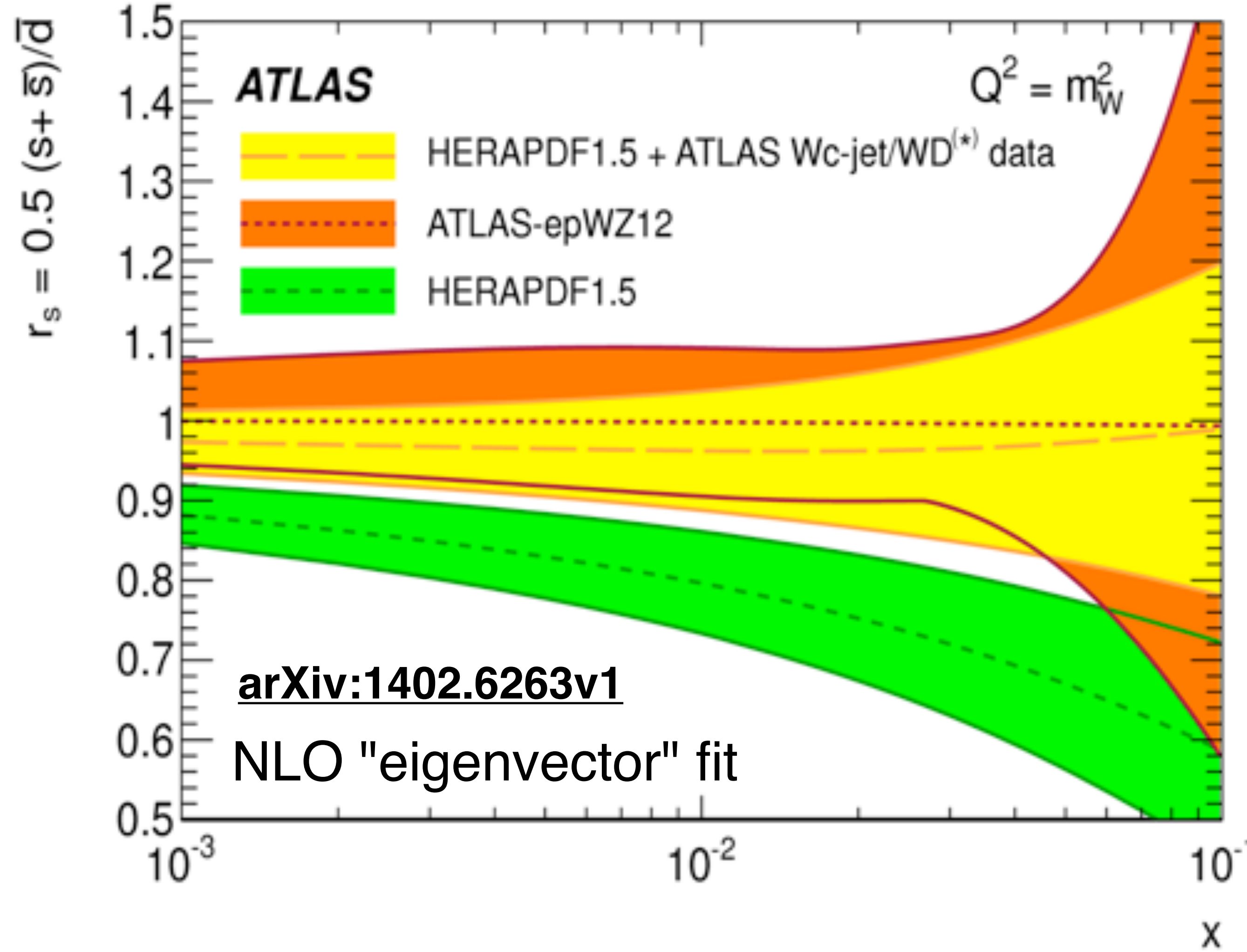
- APPLgrid interfaced to MCFM used for the reproduction of the W, Z, and W+c cross section at NLO, or at NNLO using K-factors from FEWZ

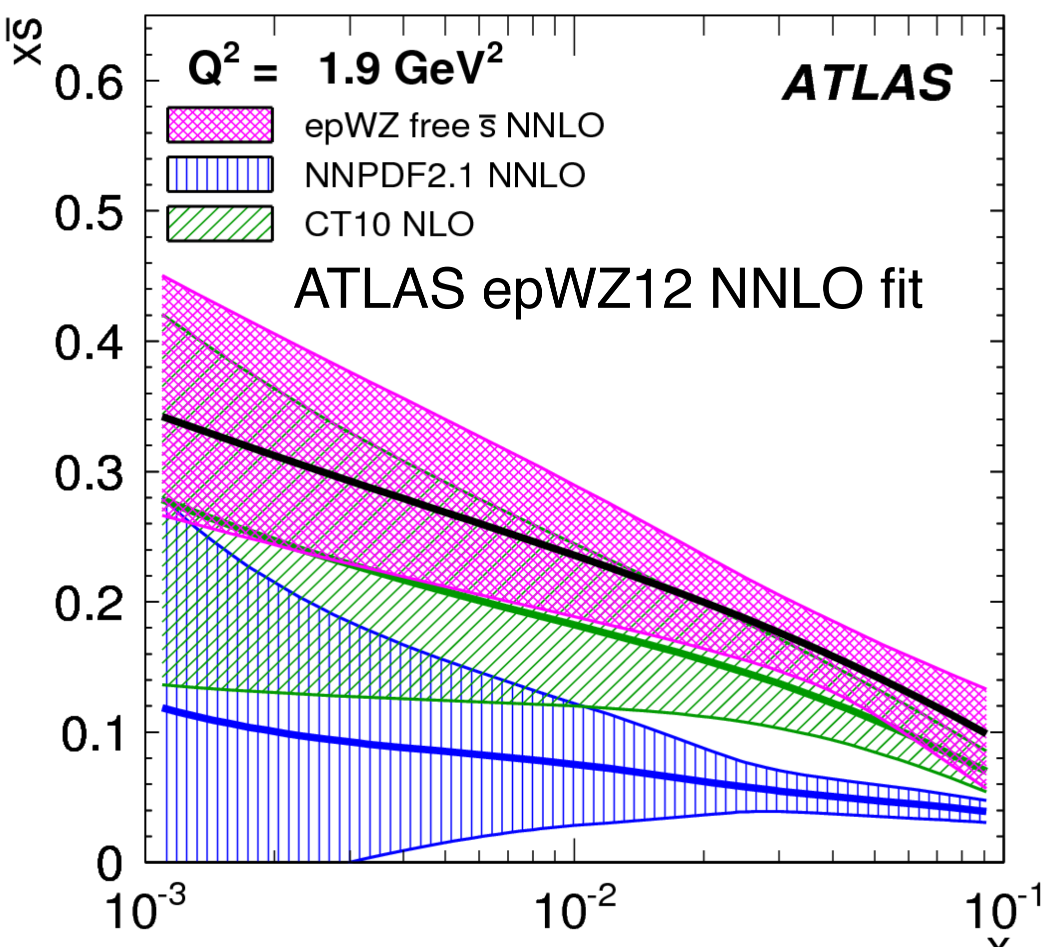
- The ATLAS-epWZ12 NNLO fit (NLO and LO also performed): **PRL 109, 012001 (2012)**
  - The W charge asymmetry data help to constrain the u and d valence distributions
  - Z data provides some constraint on the strange distribution

- The CMS fit, uses W asymmetry data and W+c to constrain the strange quark distribution: **arXiv:1312.6283v2**
  - MCFM calculation at the bare charm level - fit uses data unfolded using charm fragmentation fractions for comparison

- ATLAS "eigenvector" fit to the new ATLAS W+c data: **arXiv:1402.6263v1**
  - Using combination of cross section predictions from the eigenvector sets of the HERA PDF1.5 in aMC@NLO including full parton shower and fragmentation







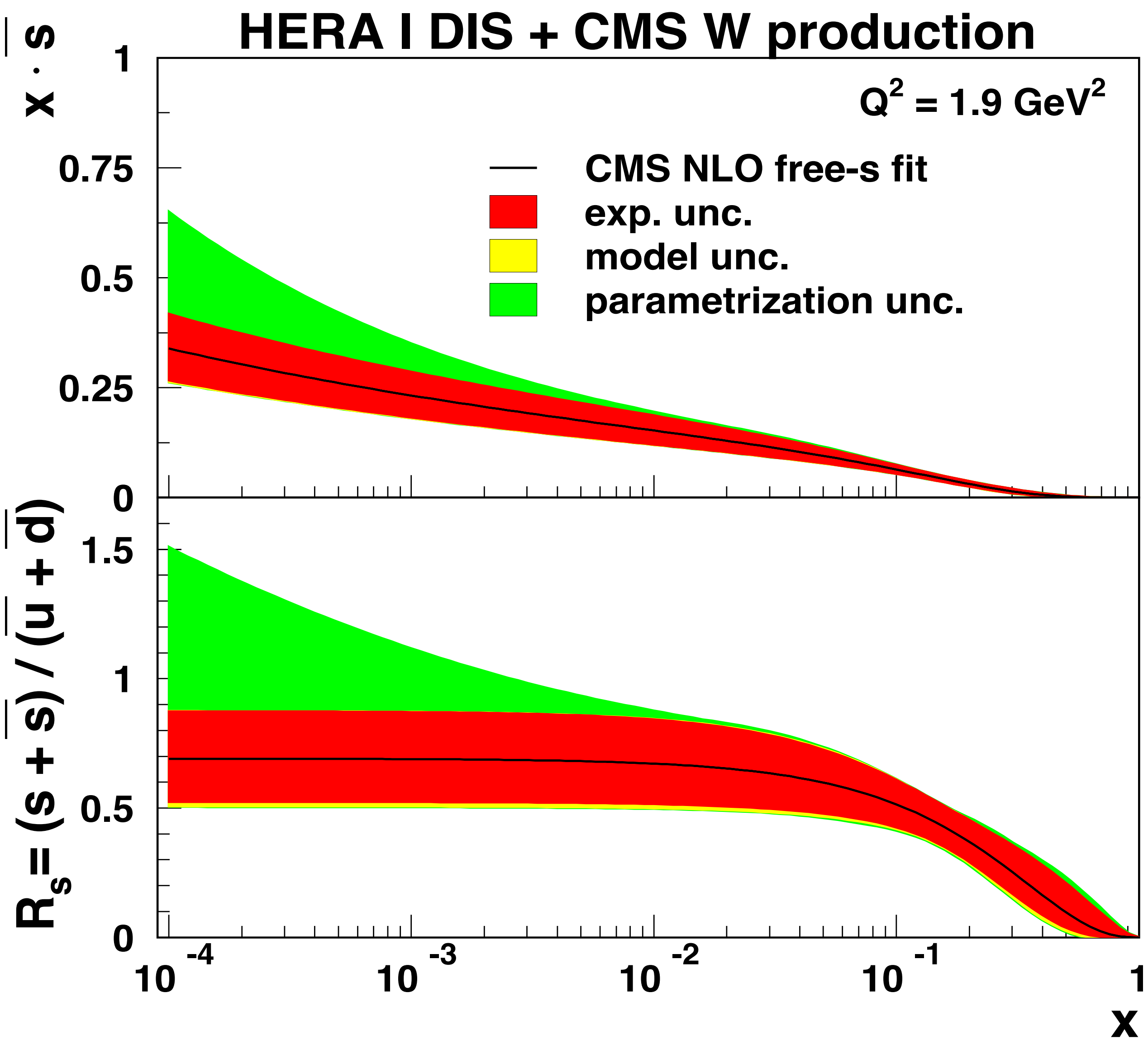
ATLAS strangeness contribution

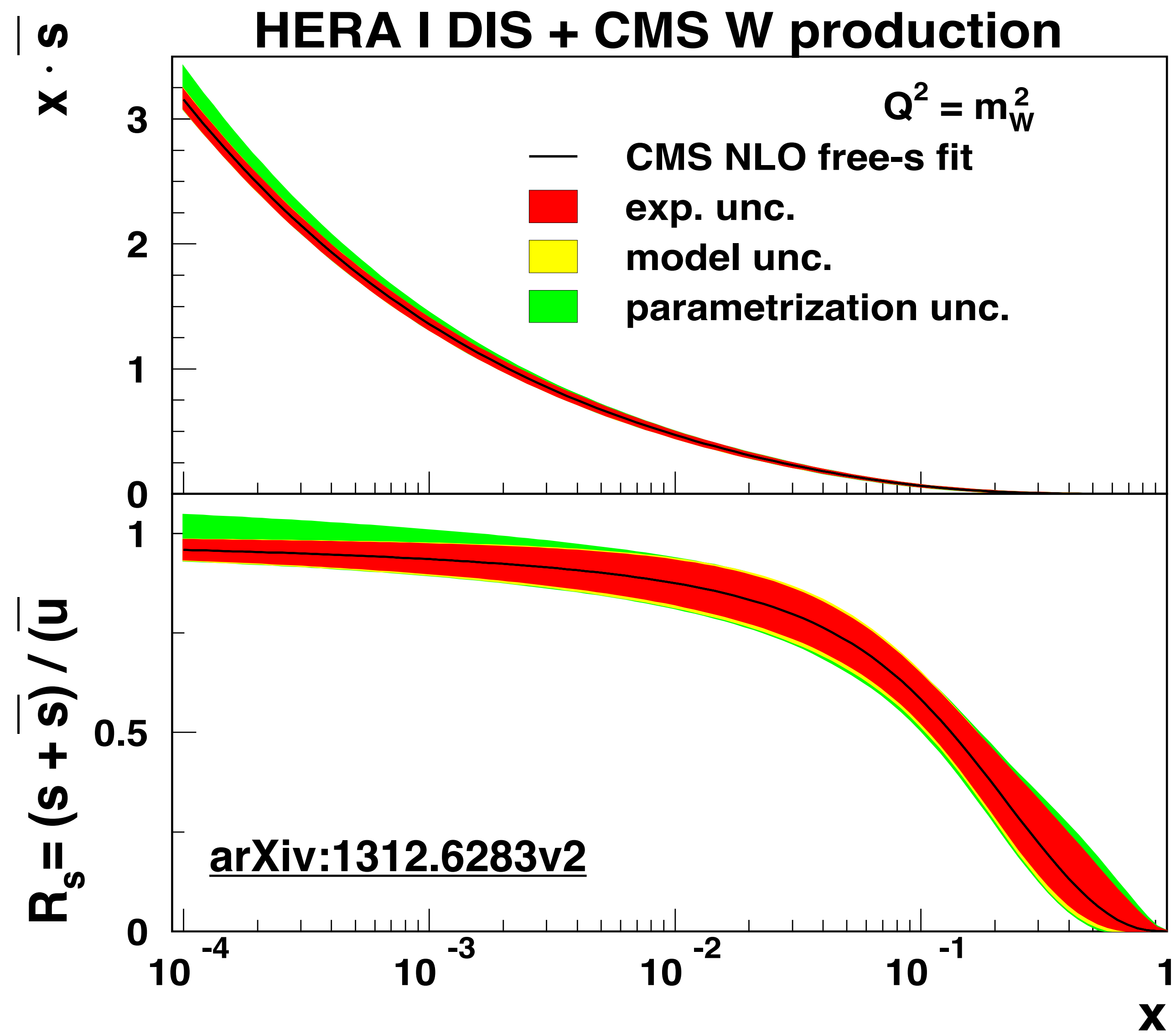
- Original ATLAS epWZ12 fit at NNLO fitting only inclusive Z and $W^\pm$ found an enhanced strangeness contribution

$$r_s = 1.00 \pm 0.07(\mathrm{exp}) \pm 0.03(\mathrm{mod})^{+0.04}_{-0.06}(\mathrm{par}) \pm 0.02(\alpha_S) \pm 0.03(\mathrm{th})$$

- New "eigenvector" fit to only W+c data supports enhanced strange contribution with respect to the HERA PDF1.5 fit

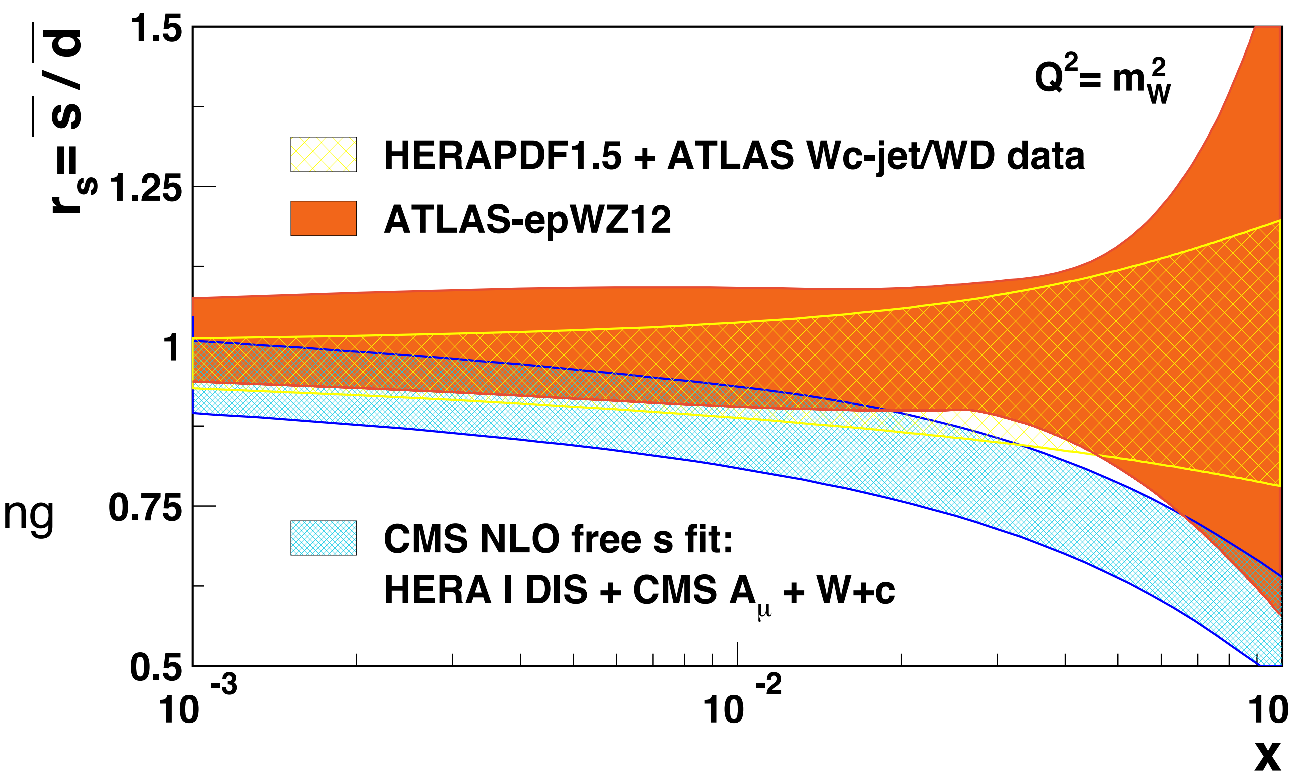
$$r_s = 0.96^{+0.16}_{-0.18}(\mathrm{th,exp})^{+0.21}_{-0.24}(\mathrm{scale})$$





Strangeness contribution from CMS NLO QCD fit

- Rs ~ 0.7 at low-x at the starting scale
- Some tension between ATLAS and CMS result at high-x
- Promising for full combined fit to the EW boson data, including W charge asymmetry, W+c and Z data



Summary

- Both ATLAS and CMS have a large, and growing portfolio of precision measurements available that all have the potential to help constrain the parton distributions in the proton
  - Inclusive jet and dijet production
  - W and Z data, including with Charm
  - Prompt photon,
  - Heavy quark and top pair production
- Only a small selection of the data has been discussed here - higher luminosity is already available and being analysed with a view to reducing both the statistical and systematic uncertainties
- For many measurements, theoretical uncertainties are often comparable to, or larger, than those from the data
- Already including the currently available data in the fit is seen to significantly reduce the uncertainties on both on the gluon and quark distributions
- Developments in the grid technology (fastNLO and APPLgrid) mean that these data can be used in a QCD fit
  - We have come a long way, and have started out on the journey towards realising the full potential of the data

- It will be a very interesting time ahead ...