Proton structure measurements at LHC

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The 11th Circum-Pan-Pacific Symposium on High Energy Spin Physics
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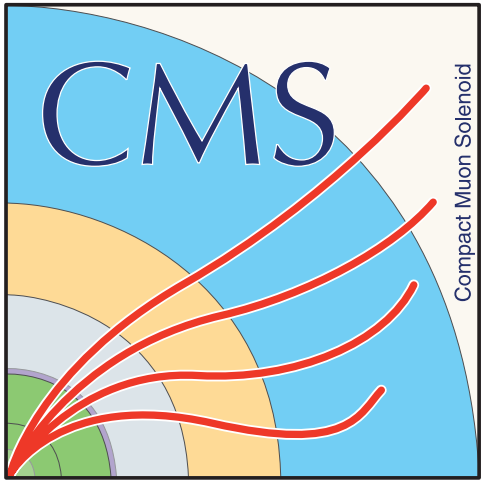


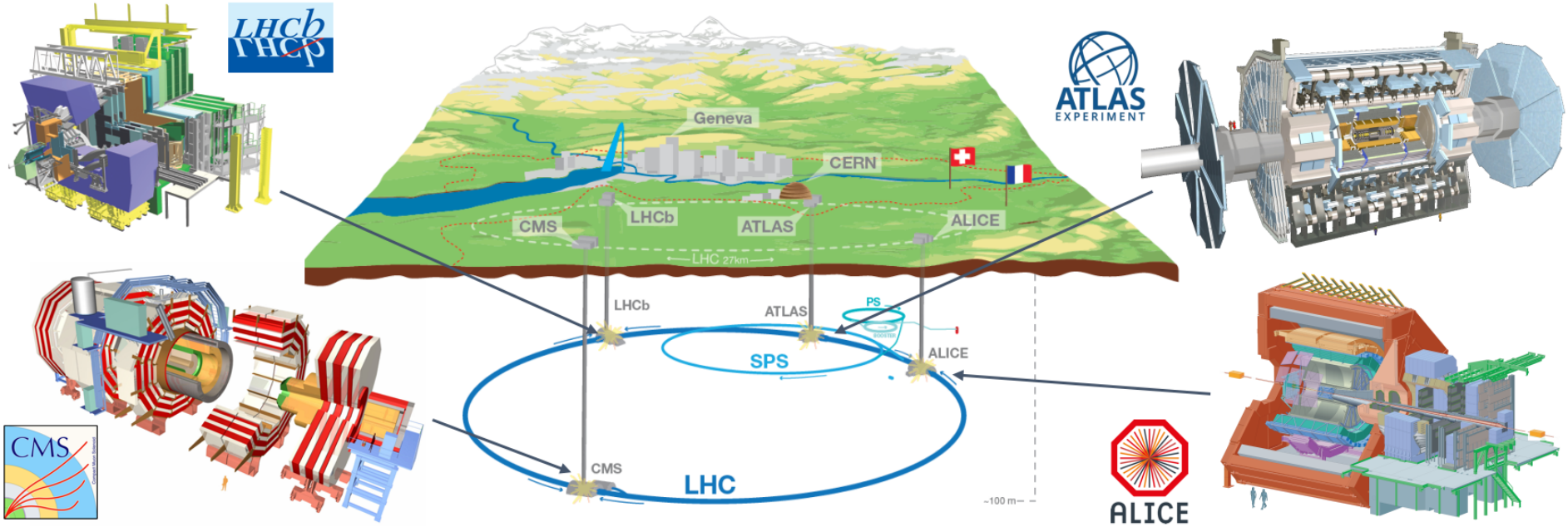
Large Hadron Collider (LHC)

- Proton-proton collider with c.m.s energy → 14 TeV (design)
  -- c.m.s. energy of elementary parton-parton collision: O(1) TeV

  → The real explorer for "TeV scale" physics
  -- Origin of EW symmetry breaking; SM Higgs
  -- New physics search: SUSY, Extra Dimension…

$$\sqrt{s}_{eff}(q-q) \approx \mathrm{O}(1)\,\mathrm{TeV}$$

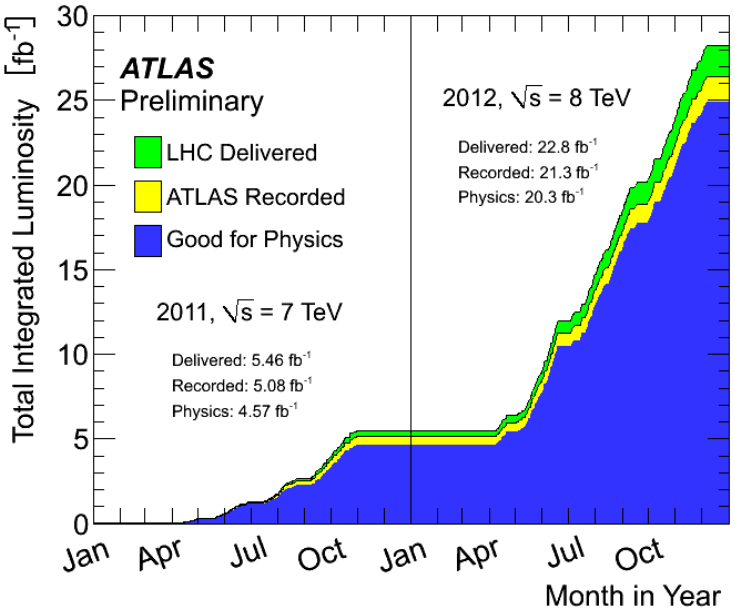
- 2 experiments with general purpose detector, covering ~4π solid angle: ATLAS and CMS
- B-physics dedicated experiment: LHCb
- Heavy-ion dedicated experiment: ALICE



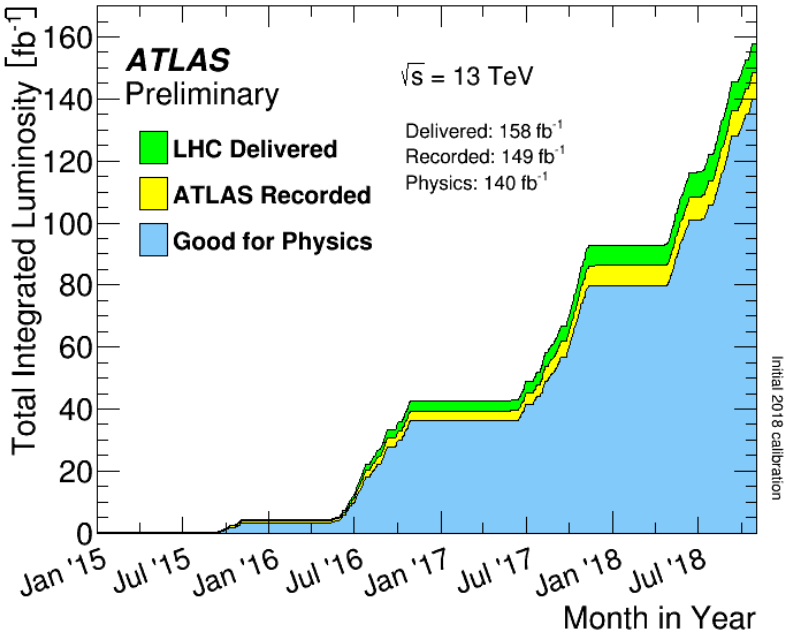
In this talk, measurements sensitive to proton structure, from ATLAS/CMS/LHCb will be presented

LHC Runs – in a nutshell

- Run-1 (2010-2012)
  - -- 2010-11: √s=7 TeV, intL* ~5 /fb
  - -- 2012: √s=8 TeV, intL ~20 /fb



- Run-2 (2015-18)
  - -- √s=13 TeV, intL ~ 140 /fb



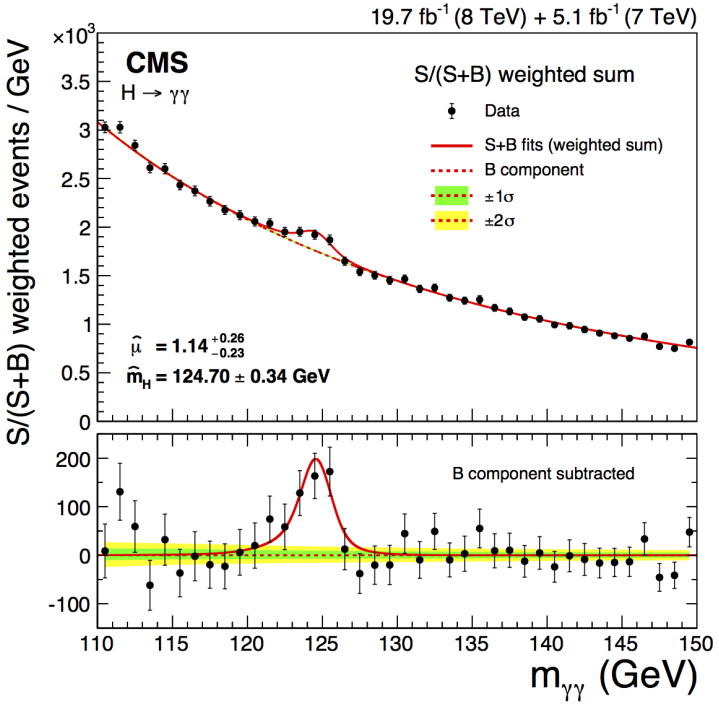
Excellent data taking efficiency and excellent data quality

* Integrated luminosity for ATLAS/CMS

LHC Runs – in a nutshell

- Run-1 (2010-2012)
  - -- 2010-11: √s=7 TeV, intL ~5 /fb
  - -- 2012: √s=8 TeV, intL ~20 /fb

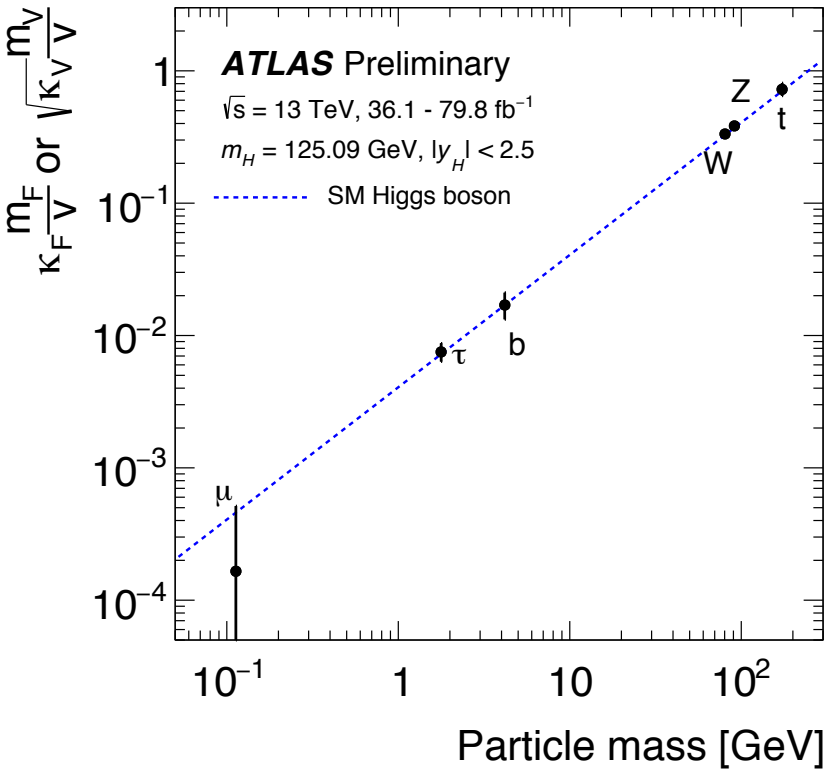
Discovery of Higgs boson



Looks so far so good – what matters for proton structure?

- Run-2 (2015-18)
  - -- √s=13 TeV, intL ~ 140 /fb

Higgs coupling
-- includes direct & first (in Run-2) observation of ttH production, H→bb, H→ττ



PDFs for LHC

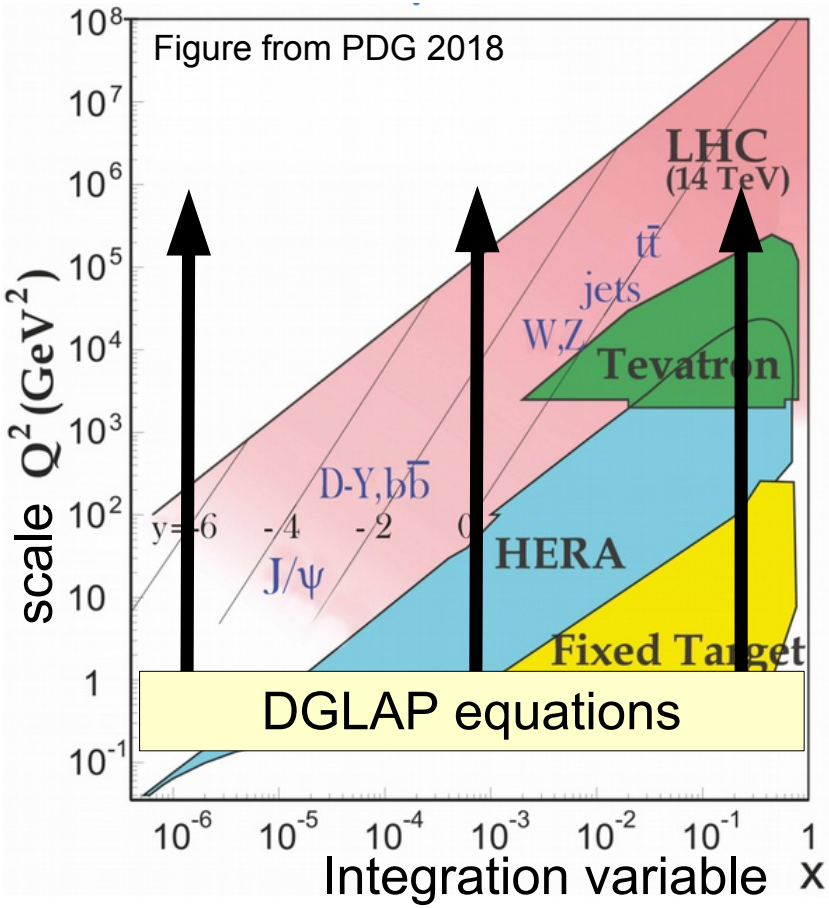
Any prediction of physics observable at hadron colliders requires knowledge of the PDFs

PDFs

Partonic cross sections

Factorisation theorem*:

$$\sigma_{p\,p\to X} = \Sigma_{i,j} \int dx_1\, dx_2 \, f_i^{\,p}(x_1,\mu)\, f_j^{\,p}(x_2,\mu) \times \sigma_{i,j}$$



DIS:

$Q^2 = -(e-e')^2$

$x \sim x_{Bj} = 2\,pq/Q^2$

Drell-Yan:

$Q^2 = m_Z^2$

$x_1 x_2 \sim M_Z^2/s$

$\frac{x_1}{x_2} \sim \exp[2y_Z]$

PDFs which are determined at lower scale (HERA, Fixed target) are extrapolated to LHC scale by using DGLAP evolution

PDFs impacts to LHC physics

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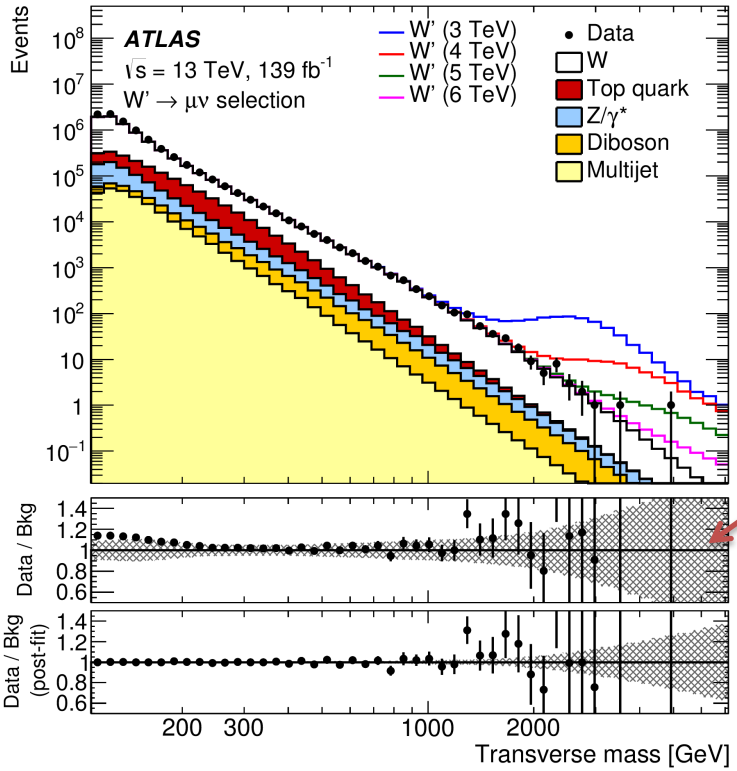
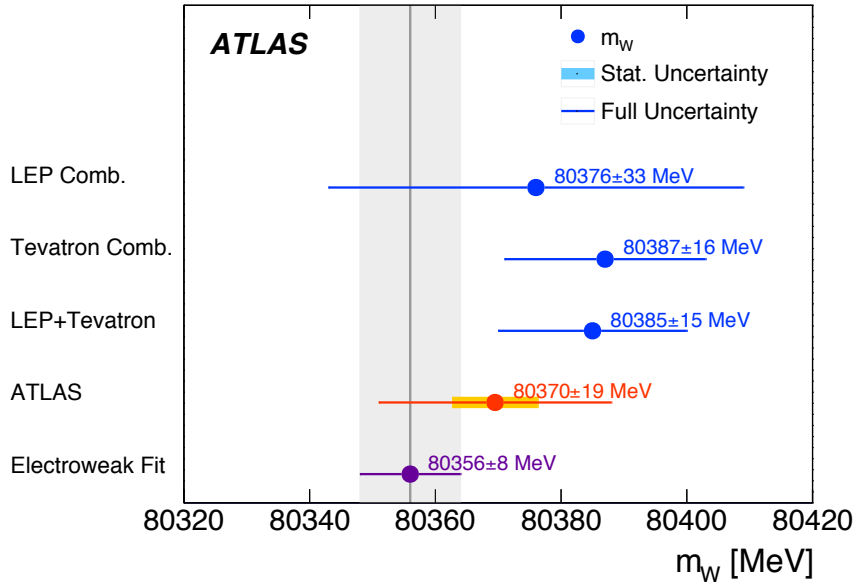
- BSM searches
  -- e.g. W' → lν: the dominant contribution to the uncertainty is PDF

arXiv:1906.05609 **(accepted by PRD)**



- Also, precision measurements
  -- Wmass measurement: the dominant systematic uncertainty is due to PDF

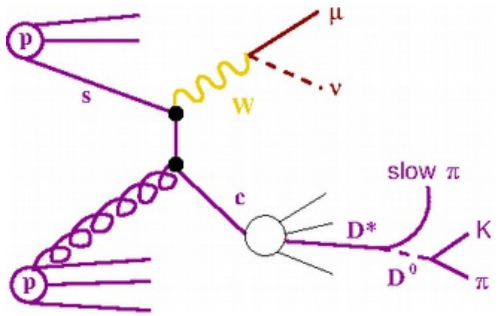


Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Crucial both fronts: search at high energy and precision measurement

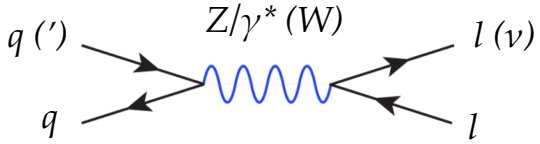
LHC data sensitivity to PDF

W + c



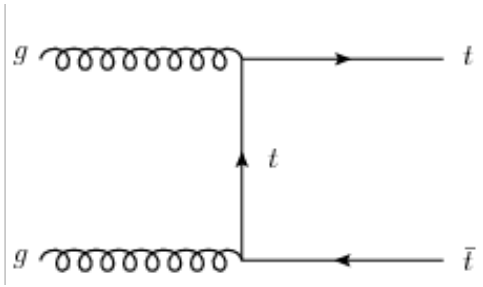
Can we constraint PDFs with our data themselves?

- Medium and lower-x quarks
  - -- W, Z production
  - -- W (Z) + c production
    - → strange (charm) PDF

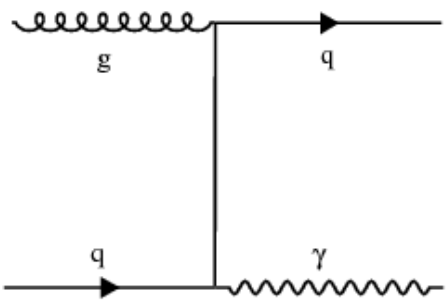


W(Z) prod.

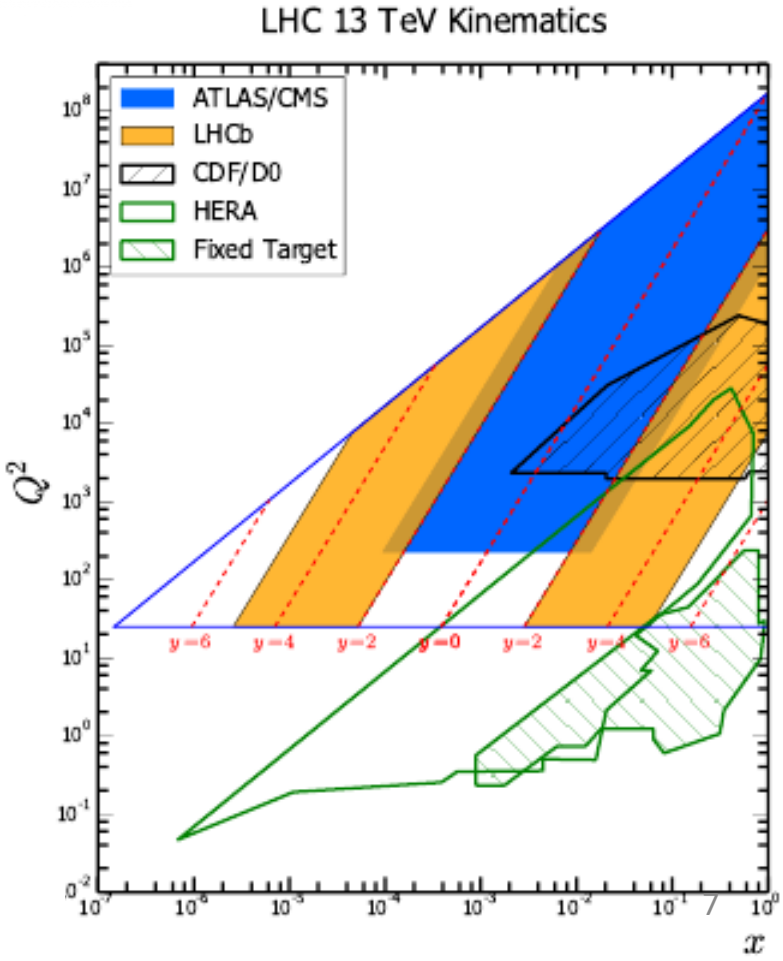
- Medium and high-x gluon
  - -- Top-pair production
  - -- Jets production
  - -- Direct photon production



Top pair



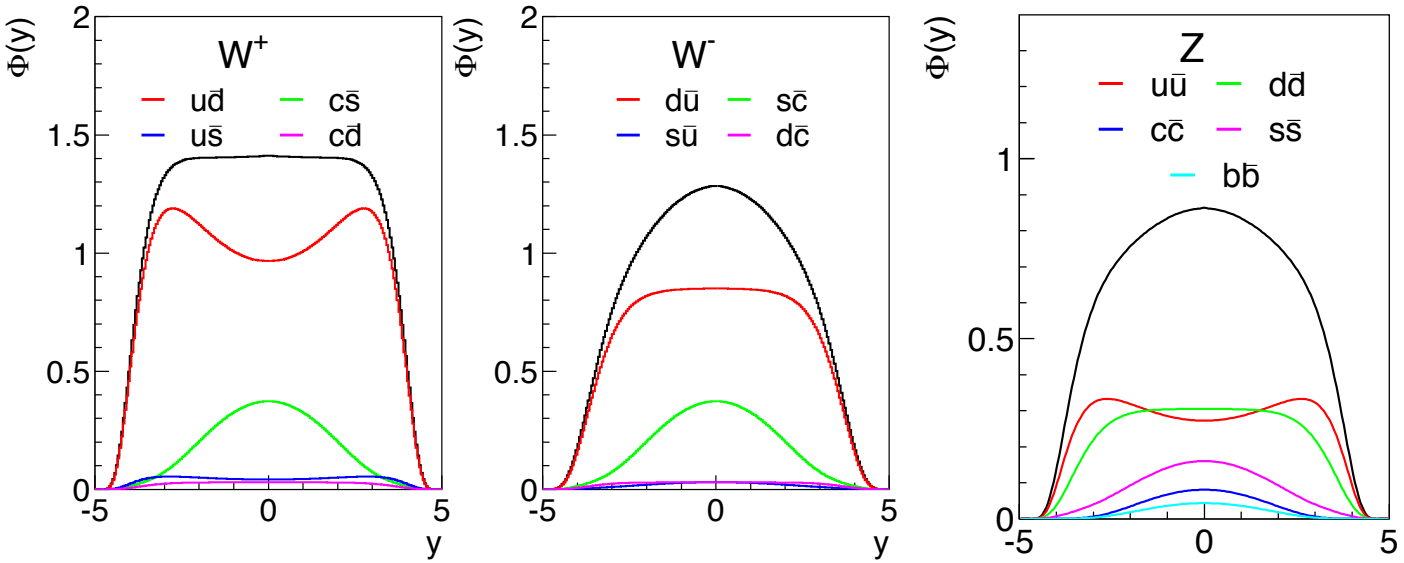
Direct γ



Inclusive W, Z production [middle-low x quarks]

- Sensitivity to light quarks

- Different quark combinations contribute to each process
  -- e.g. W charge asymmetry provides constraint on u_V and d_V PDF



plots by S. Glazov, V. Radescu

- Experimentally very precise, and the state-of-the-art theory prediction available (NNLO for QCD, NLO for EW)
  → Feasibility to be incorporated into QCD fit to determine PDF

7 TeV, 4.6 /fb

ATLAS W, Z incl. cross section [middle-low x quarks]

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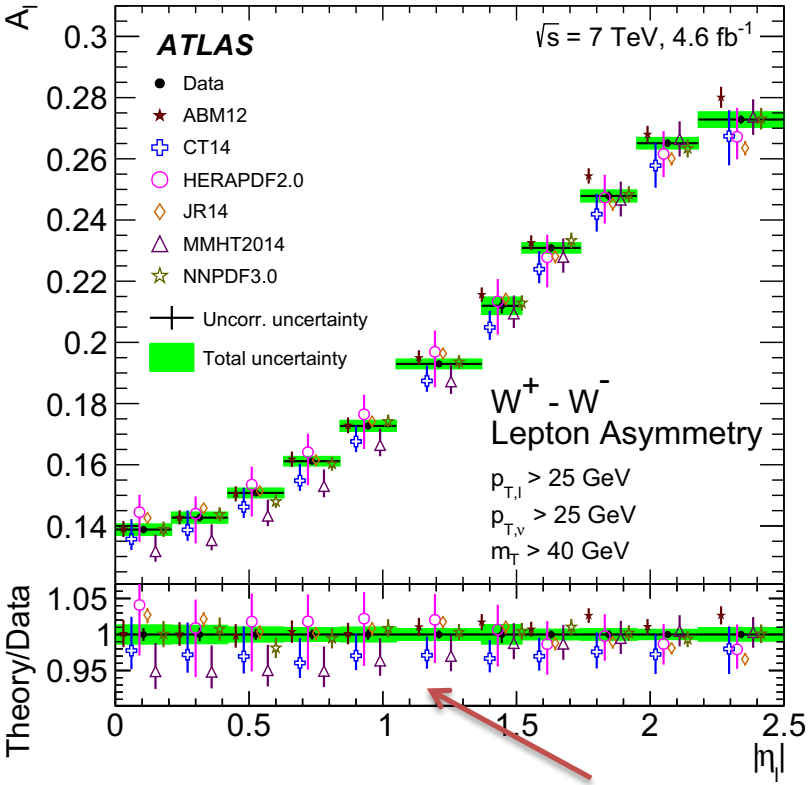
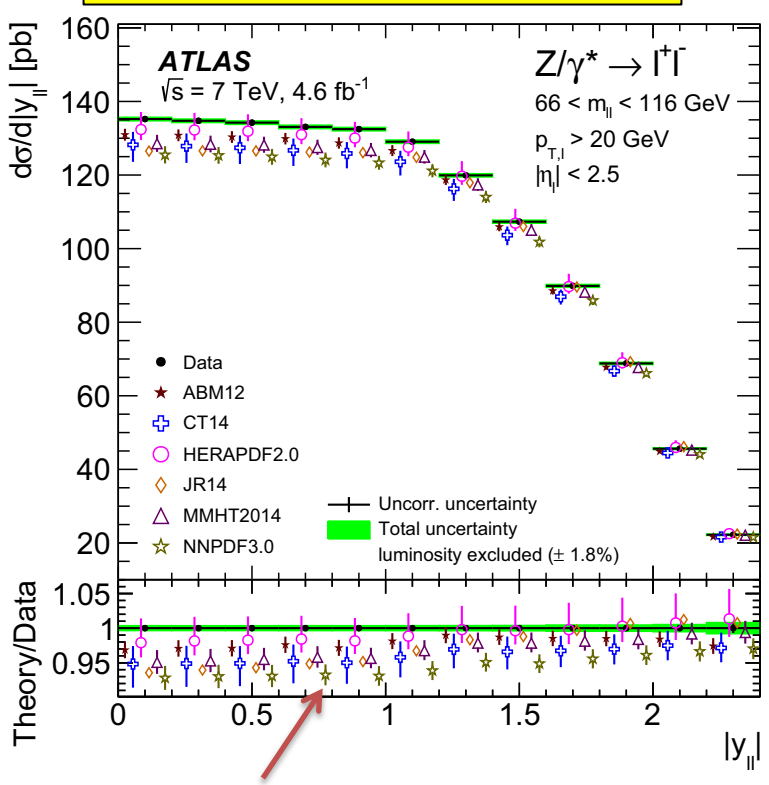
W lepton asymmetry vs. |η|



Z cross section vs. rapidity



Data showing discriminating power among different PDFs

- 7 TeV, 4.6 /fb → already extraordinary total experimental precision
  -- 0.3-1%, excluding luminosity uncertainty of 1.8%

7 TeV, 4.6 /fb

ATLAS NNLO QCD analysis of W, Z incl. σ [middle-low x quarks]

- "ATLAS-epWZ16" PDF
  - -- HERA I+II plus ATLAS (4.6 /fb) W |η| and Z |η|
  - -- NNLO QCD fits: Q^2 cut off 10 GeV^2 (←7 GeV^2), 16 parameters
  - -- Provides significant constraints on the u and d valence PDFs
  - -- Strong indication of non-suppressed strangeness

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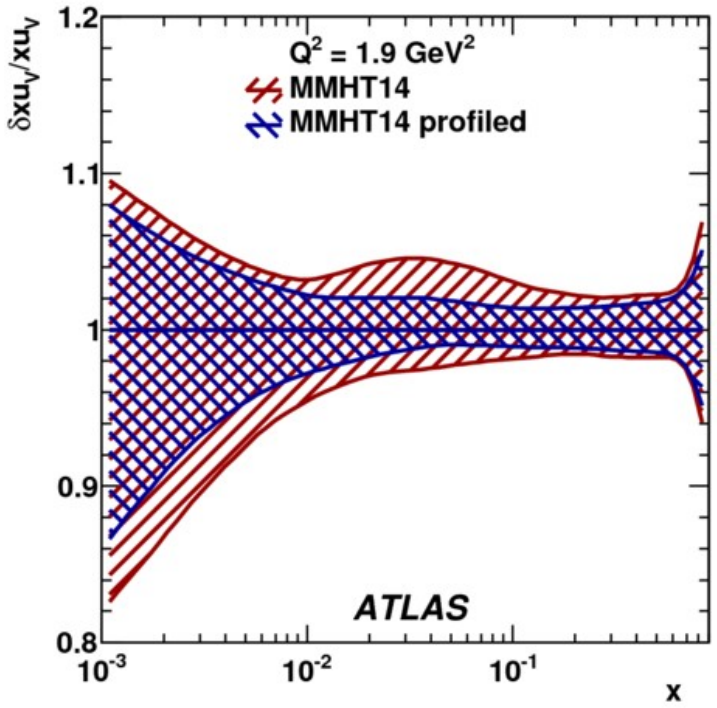
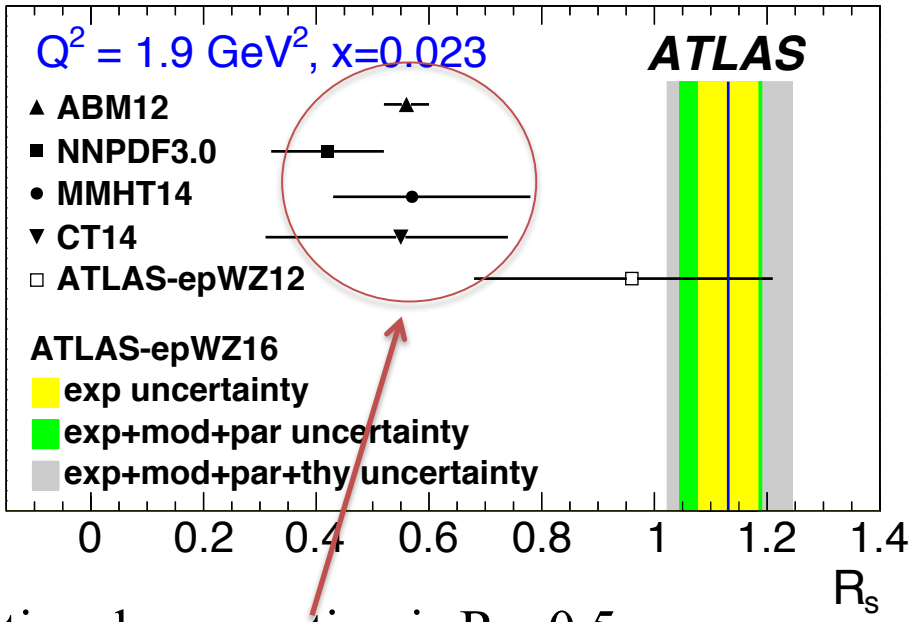
u valence uncertainty



Strangeness suppression factor

$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$



Traditional assumption is Rs~0.5
(based on fixed target νN)

8 TeV, 18.8 /fb

CMS W asymmetry [middle-low x quarks]

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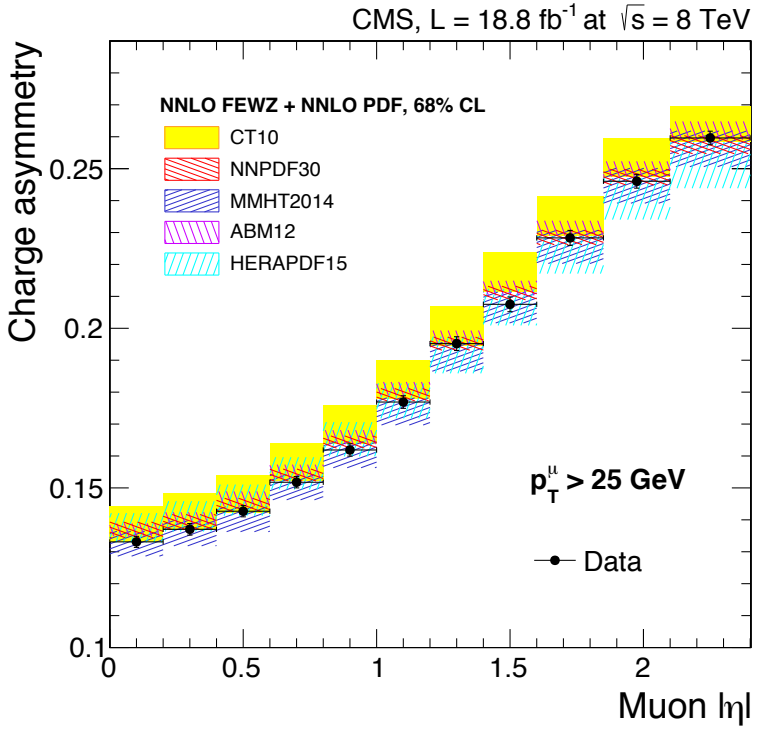
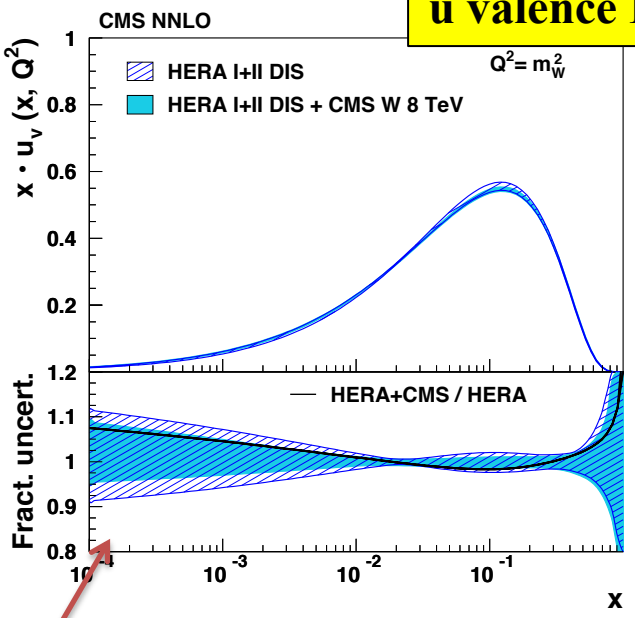
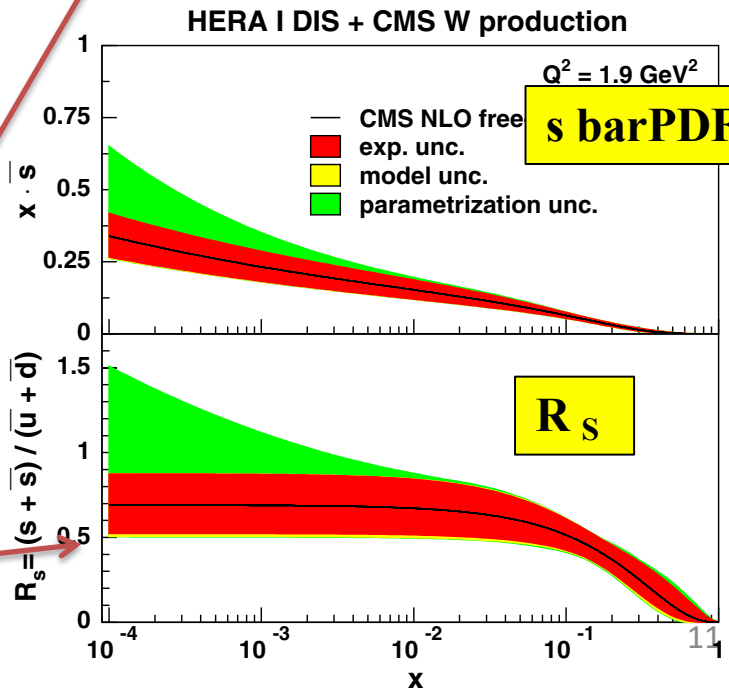
W^+/W^- vs. μ |η|



u valence PDF



s barPDF



- CMS measurement on W charge asymmetry with 8 TeV, 18.8 /fb
- CMS NNLO QCD analysis with HERA I+II + CMS W 8 TeV
  - -- Also constraints on the valence PDFs
  - -- However, suppressed strange sea (Rs~0.6) was preferred

13 TeV, 36/pb

NEW

CMS W+c [strange PDF]

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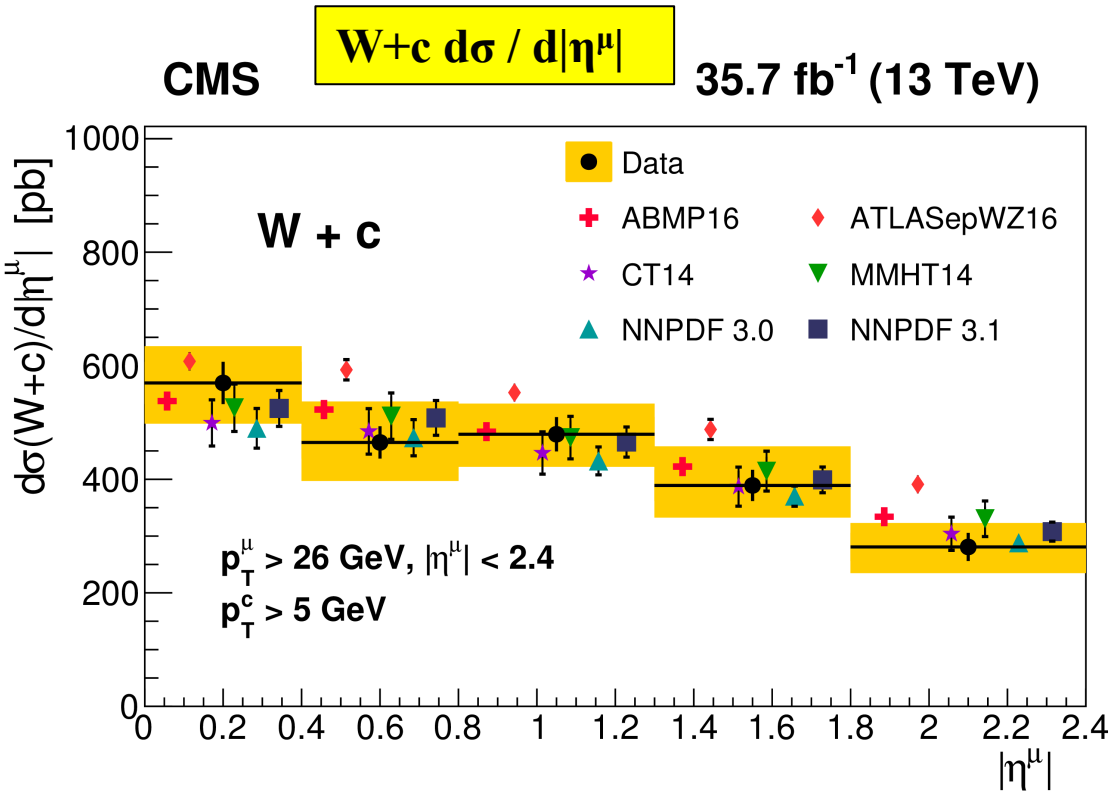
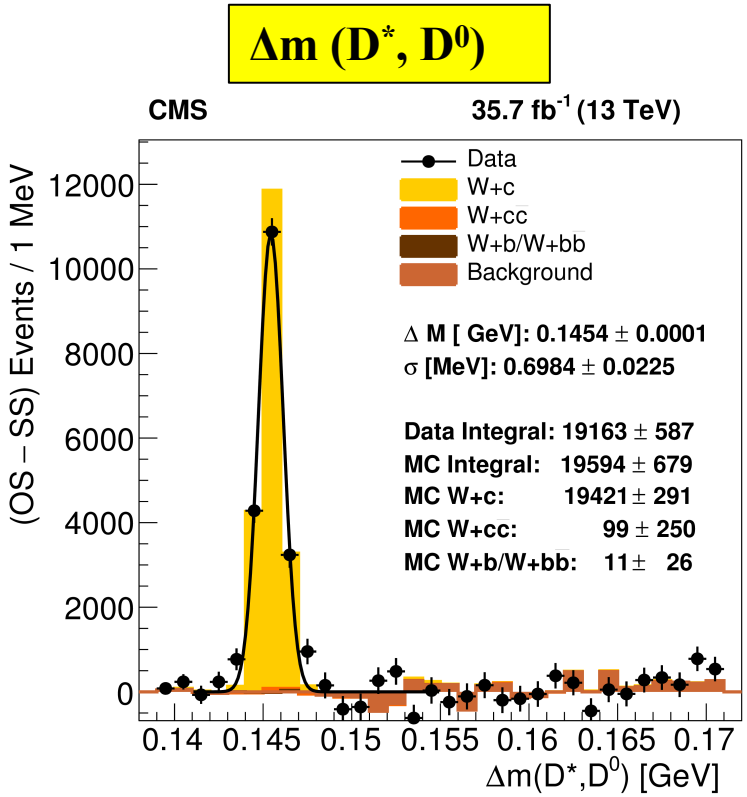
- W+c provides direct sensitivity to strange quark
  - -- Experimentally, W+ccbar and other backgrounds can be removed by using charge correlation between W and c

-- CMS 13 TeV 35.7/fb W+c

-- Cross section measured differentially in $|\eta|$ of muon from W





13 TeV, 36/pb

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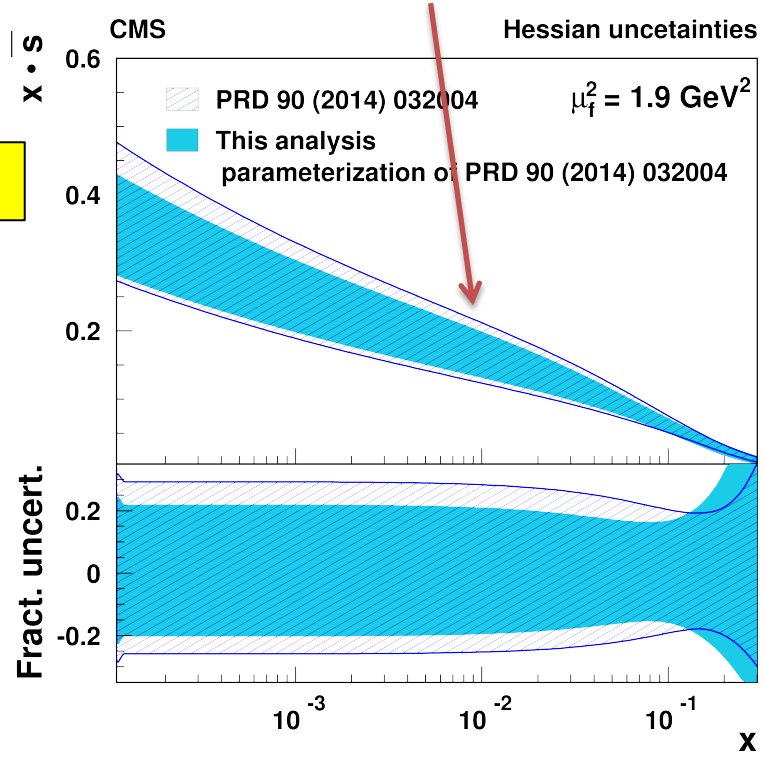
NEW

CMS QCD analysis on W+c [strange PDF]

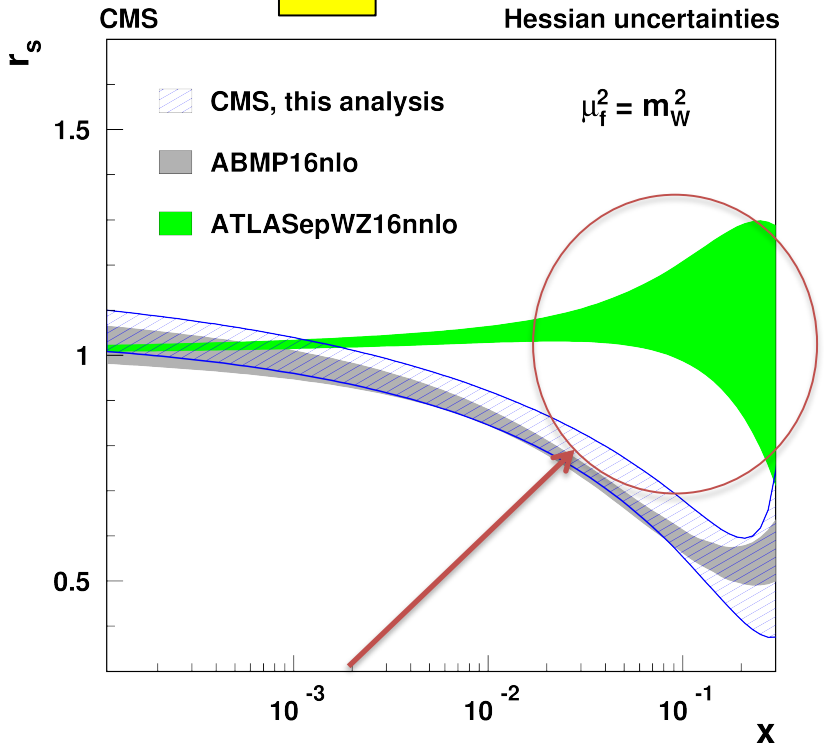
- CMS QCD analysis
  -- HERA I+II plus W asymmetry (7 TeV, 8 TeV) + W+c (7 TeV, 13 TeV)
  -- NLO for W+c with Thorn-Roberts GM FN scheme
  -- Provides constraint on strange quark PDF
    * HERA I+II + W vs. + W+c

Note: ATLAS band does not include theory (parameterization) uncertainty

s bar PDF



Rs



-- Prefers suppressed strange PDF in contrast to ATLAS W/Z

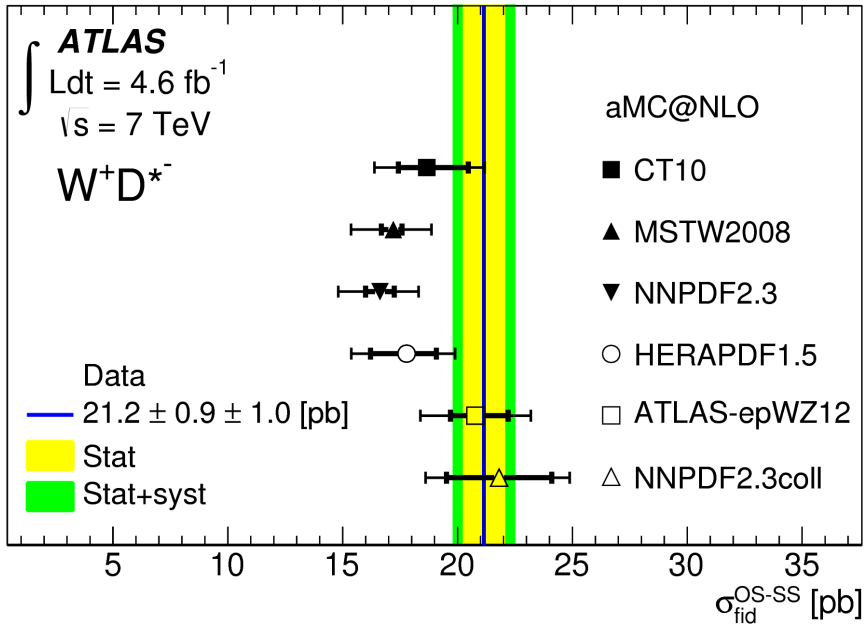
7 TeV, 4.6 /fb

JHEP 05 (2014) 068

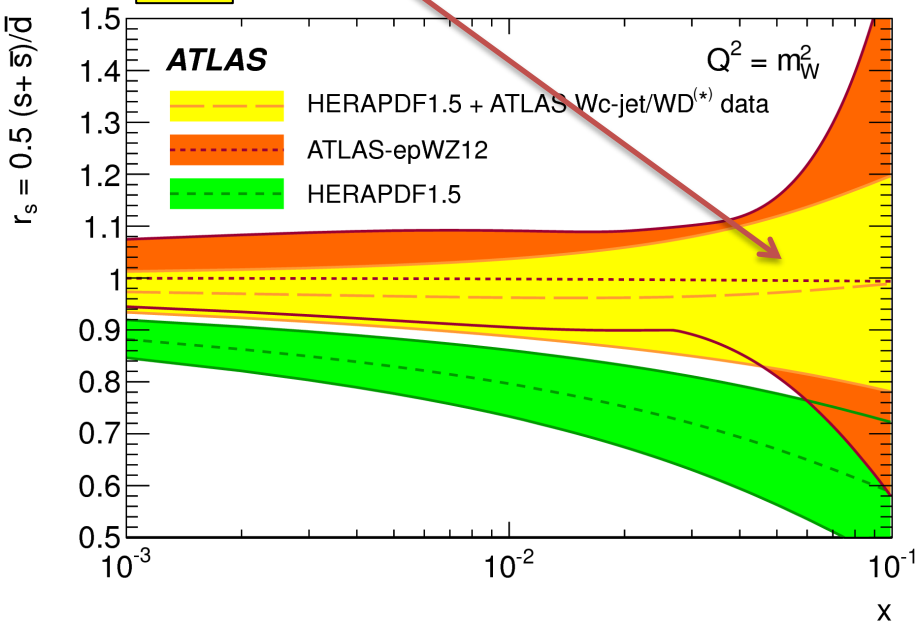
ATLAS W+c [strange PDF]

- ATLAS W+c (W+D, W+c-jet) @ 7 TeV
  - -- Cross sections of $W^{+(-)}D^{*(-+)}$, c-jet$^{(-+)}$, integrated/diff in $|\eta_l|$
  - -- NLO for W+c with aMC@NLO (MadGraph5)
  - -- An exercise to fit a free parameter strange PDF fraction in HERAPDF1.5 resulted in Rs=$0.96\,^{+0.16\ +0.21}_{-0.18\ -0.24}$

W+D*(-) cross section



Rs



-- Prefers non-suppressed strange PDF in agreement with ATLAS W/Z

(c.f. "CT18Z" sees increases of Rs at small-x wrt CT18 by using ATLAS W/Z (see backup slide))

JHEP 05 (2015) 109 Z(ee) 8 TeV

JHEP 10 (2016) 030 W(e) 8 TeV

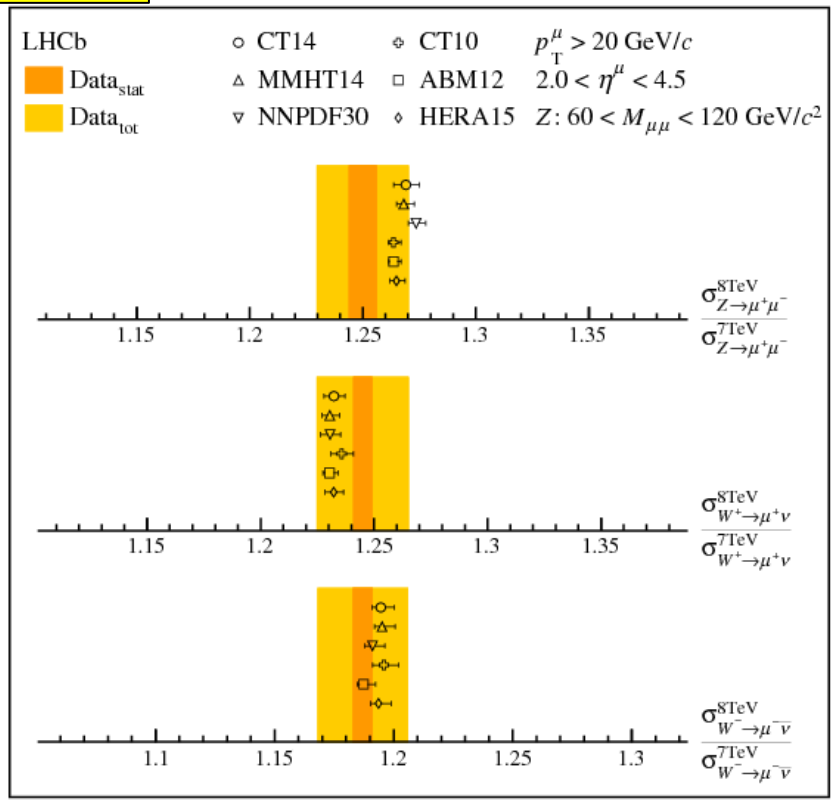
W, Z at very forward rapidity by LHCb

Z 7 TeV JHEP 08 (2015) 039

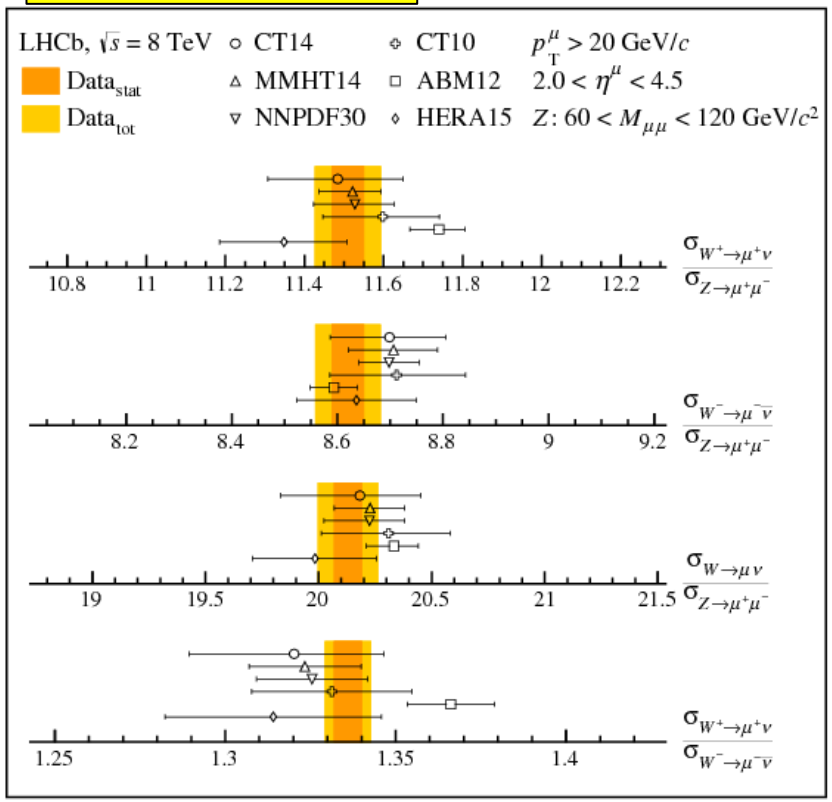
W/Z 8 TeV JHEP 01 (2016) 155

- 7 TeV: ~1.0 /fb, 8 TeV: ~2.0 /fb
  - -- Z(W) @TeV (muon)
  - -- Z(W) @ 8 TeV (muon, electron)
  - -- Measurements on:
    - * W lepton charge asymmetry
    - * W/Z ratio
    - * 7 TeV/8 TeV ratio, etc

7 TeV / 8 TeV ratio



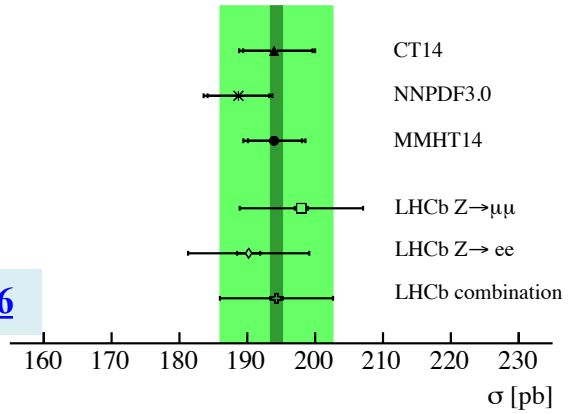
W, Z, W/Z ratio



LHCb, $\sqrt{s}$ = 13 TeV

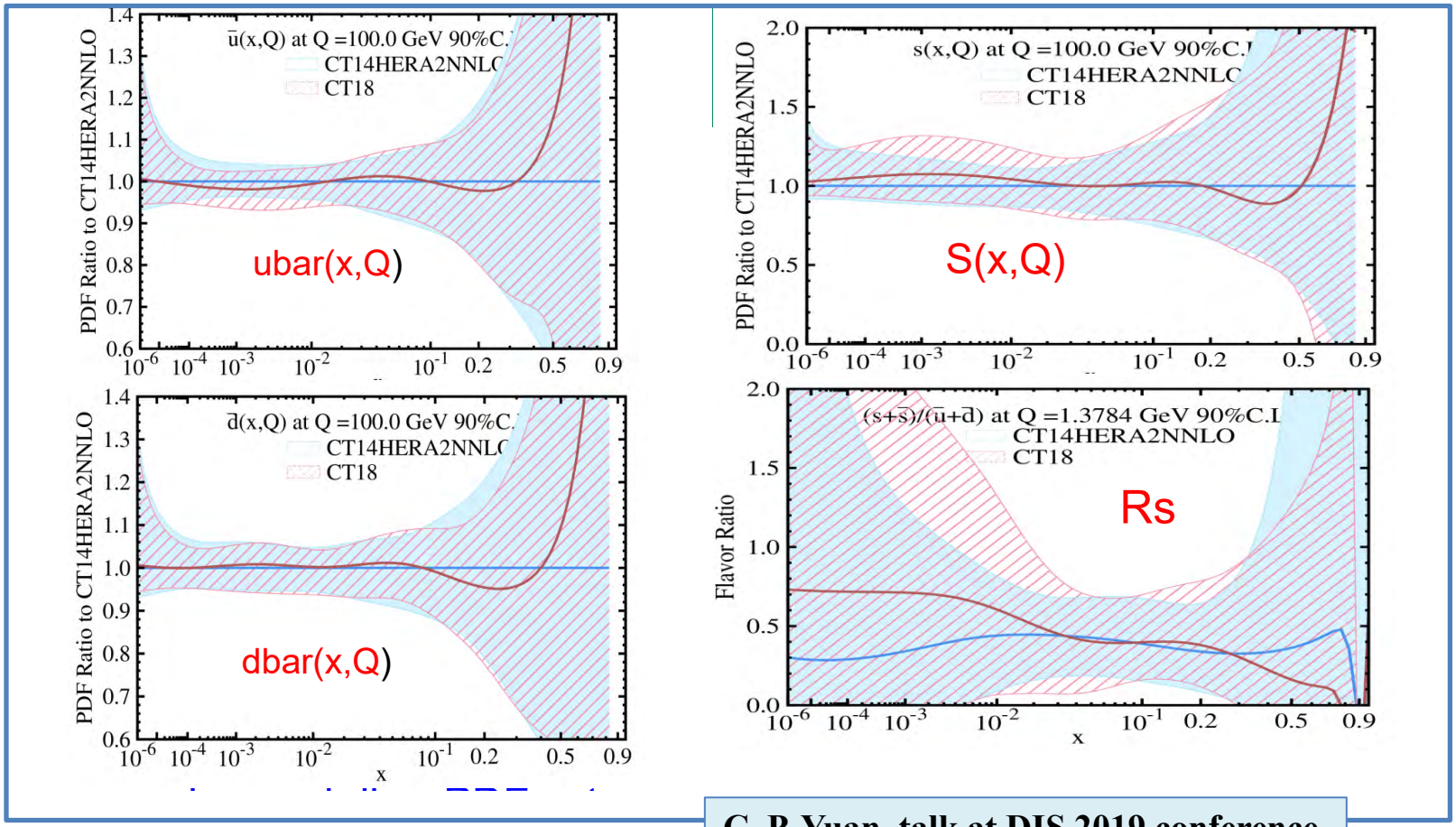
- 13 TeV: ~0.3 /fb, Z (muon, electron)

JHEP 09 (2016) 136



Example of LHCb W/Z impact [CT18]

- Latest CTEQ analysis (update from CT14)
  -- More inclusion of LHC data
  -- Minor changes on ubar and dbar at small-x due to LHCb
  -- LHCb data W/Z prefers a slightly larger strange PDF in small-x (Rs=0.5 +- 0.3)



C. P-Yuan, talk at DIS 2019 conference

8 TeV, 20.2 /fb

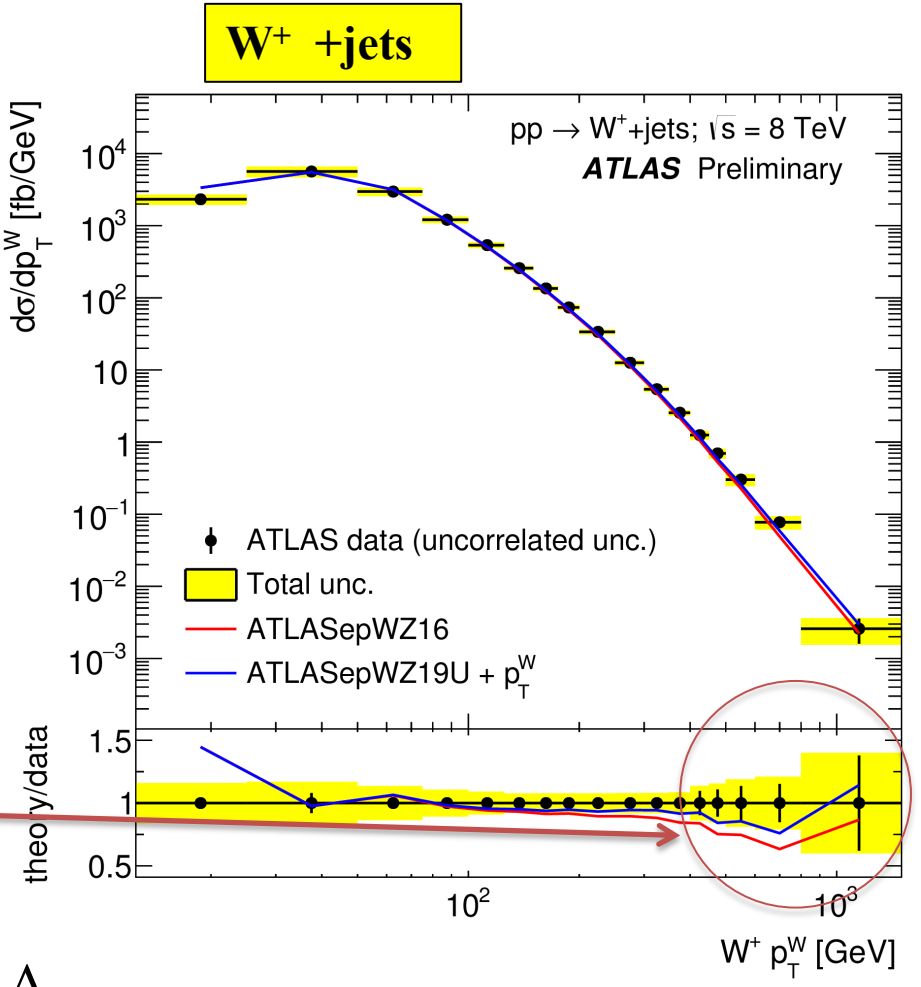
ATL-PHYS-PUB-2019-016

NEW

ATLAS W+jets

- W+jets
  -- Jet requirement increases sensitivity at high-x and Q^2 JHEP 05 (2018) 077

- "ATLAS-epWZWjet19" PDF
  -- HERA I+II plus ATLAS W, Z plus W+jet 8 TeV
  -- NNLO QCD fits
  * for W+jet NLO plus k-factor (NLO grids for fitting cross sections available at ploughshare)



Large change in W^+: u_v-dbar or u_v-sbar

$$\sigma \sim (0.97\bar{d} + 0.23\bar{s})^2$$

with dbar+sbar well constrained with HERA
→ higher σ with sbar↓ and dbar↑

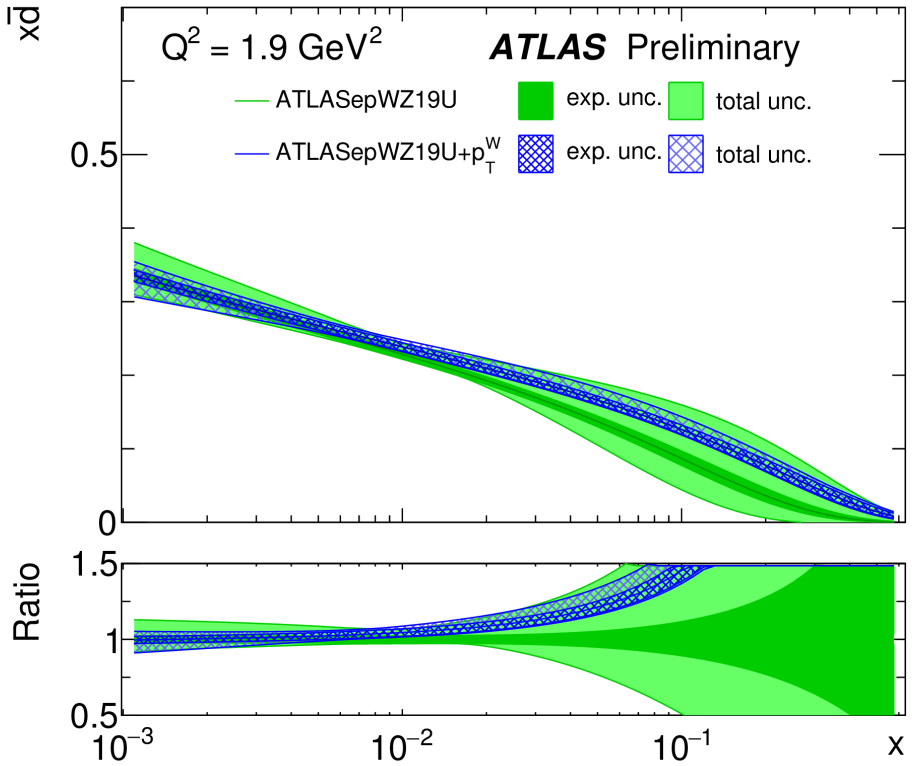
NEW

ATL-PHYS-PUB-2019-016

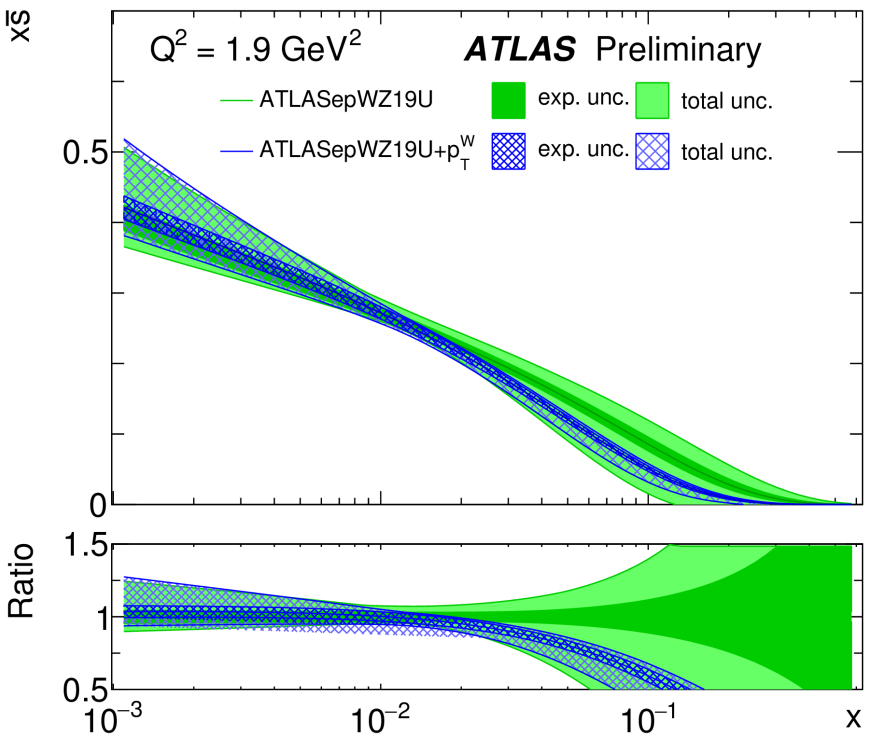
ATLAS NNLO analysis with W+jets

- "ATLAS-epWZWjet19" PDF
  -- Main impact on d and s sea PDFs

d bar PDF



s bar PDF



-- "ATLAS-epWZWjet19" PDF can be downloaded from the analysis WEB

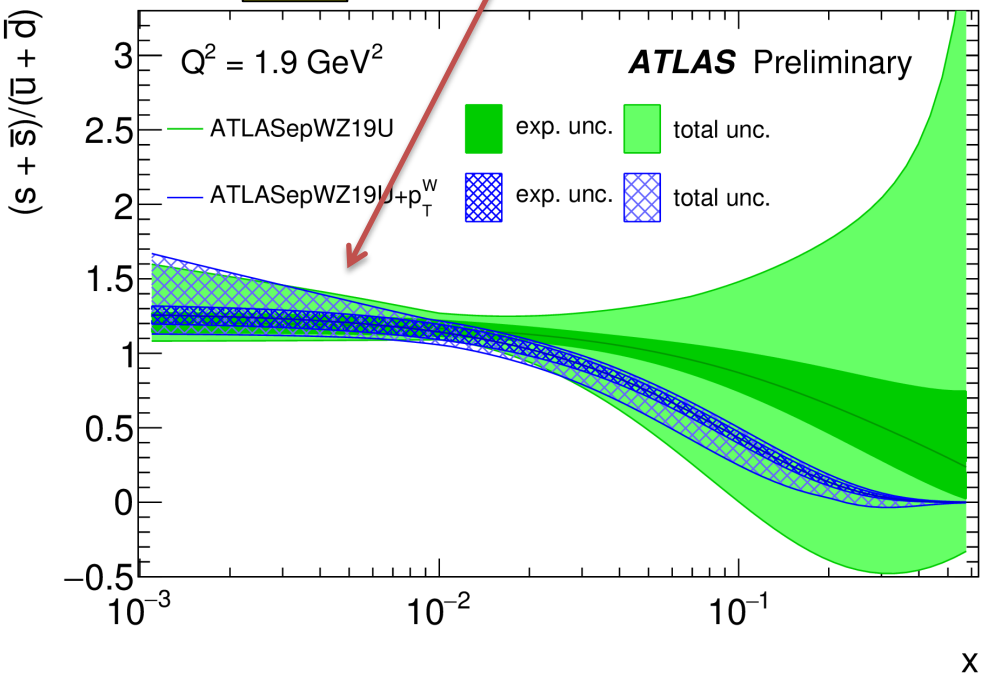
NEW

ATL-PHYS-PUB-2019-016

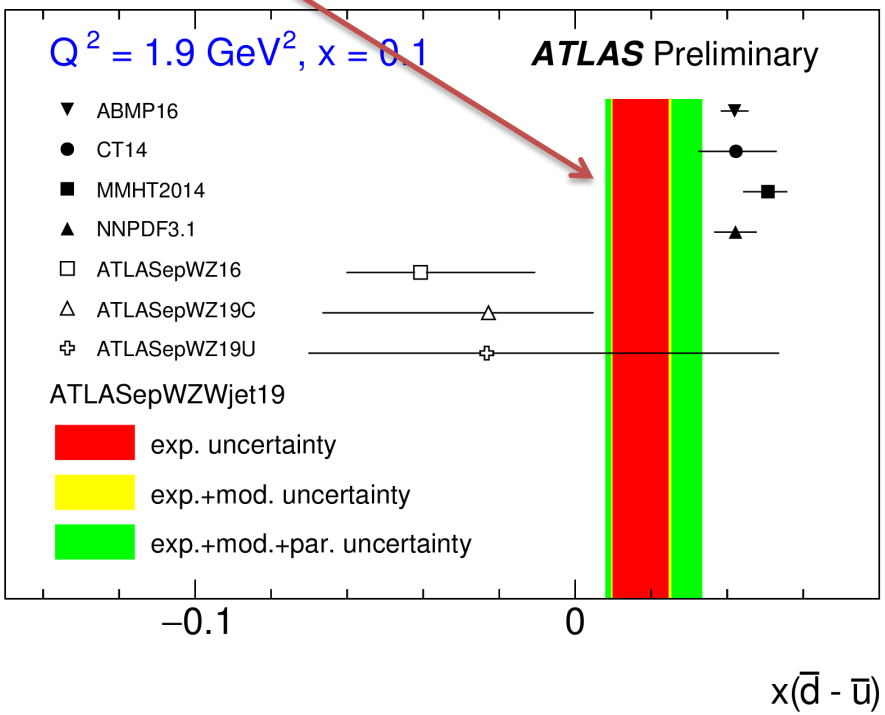
ATLAS NNLO analysis with W+jets

- "ATLAS-epWZWjet19" PDF
  -- Still consistent with enhanced strange at low x
  -- (dbar – ubar) now positive and consistent with prev. ATLAS fits

R_s



(dbar-ubar)



-- "ATLAS-epWZWjet19" PDF can be downloaded from the analysis WEB

8 TeV, 18.8 /fb

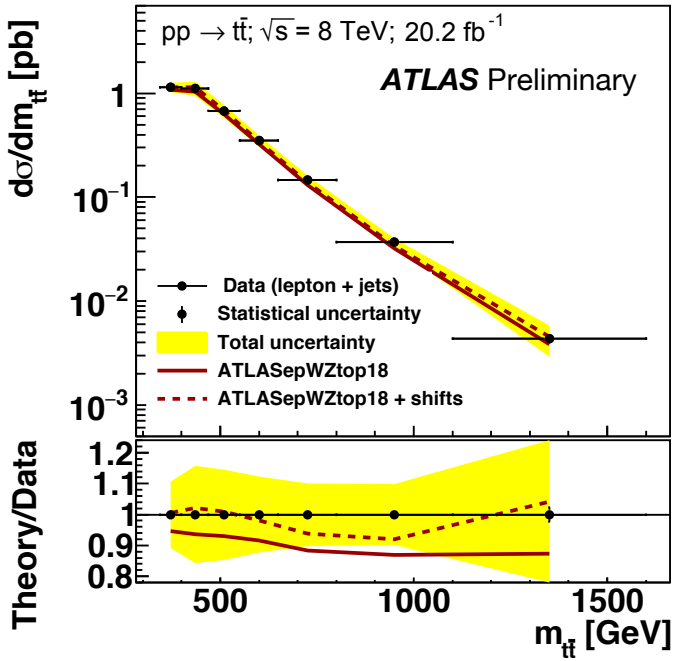
ATLAS-PHYS-PUB-2018-017

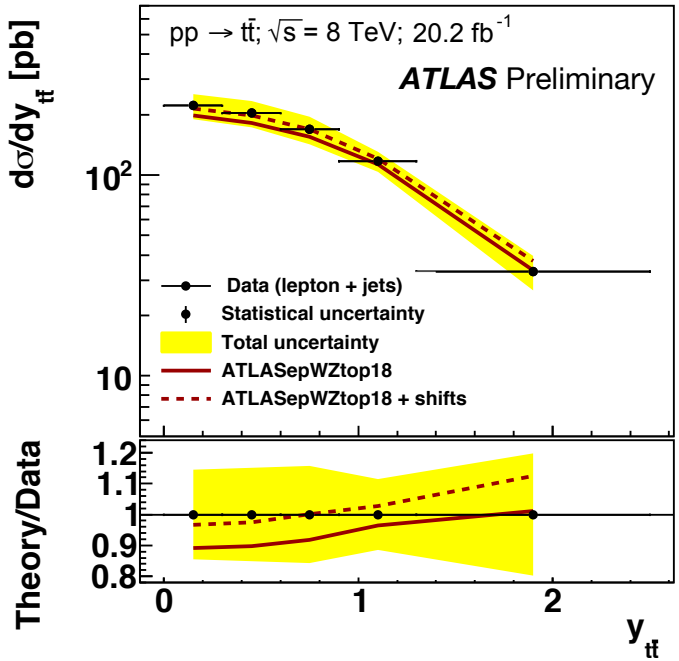
ATLAS top pair production [middle-high x gluon]

NEW

- Differential cross sections
  - -- Single differential in terms of e.g. p_T of top ($p_T(t)$), rapidity/mass of top pair ($m(tt)$,y_{tt})
  - -- Measurements with 7 TeV, 8 GeV, in l-jets and l-l modes
  - -- NNLO predictions on differential cross sections are now available.
    - → possible to include into PDF fits

- "ATLAS-epWZtop18" PDF
  - -- New ATLAS QCD analysis including top-pair production
  - -- HERA I+II + ATLAS W,Z + ATLAS ttbar (l-jets + l-l)
    - * $m(tt)$ and $p_T(t)$ from l-jets, y_{tt} from l-l





8 TeV, 18.8 /fb

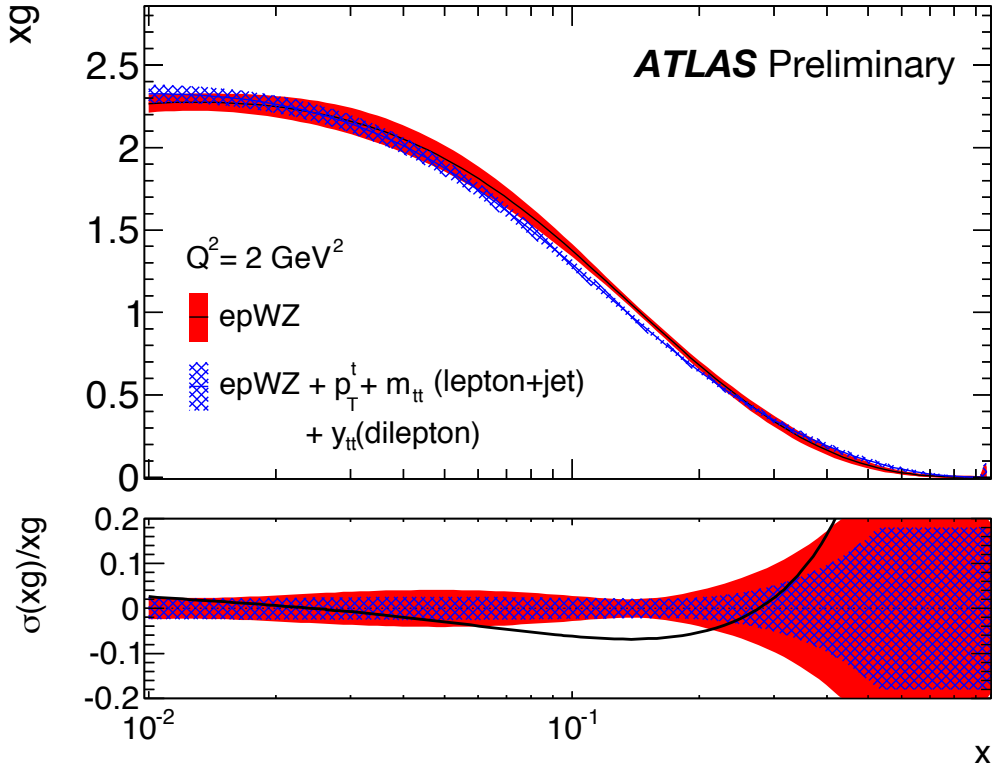
ATLAS-PHYS-PUB-2018-017

ATLAS QCD analysis with top pair production [middle-high x gluon]

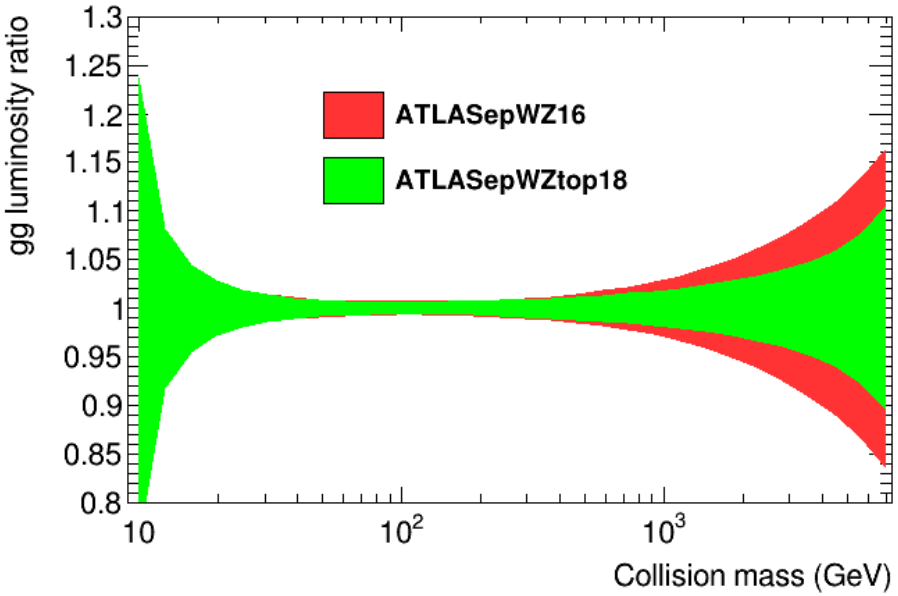
NEW

- "ATLAS-epWZtop18" PDF
  -- A harder gluon with significant additional constraint at high-x

Gluon uncertainty



g-g luminosity uncertainty

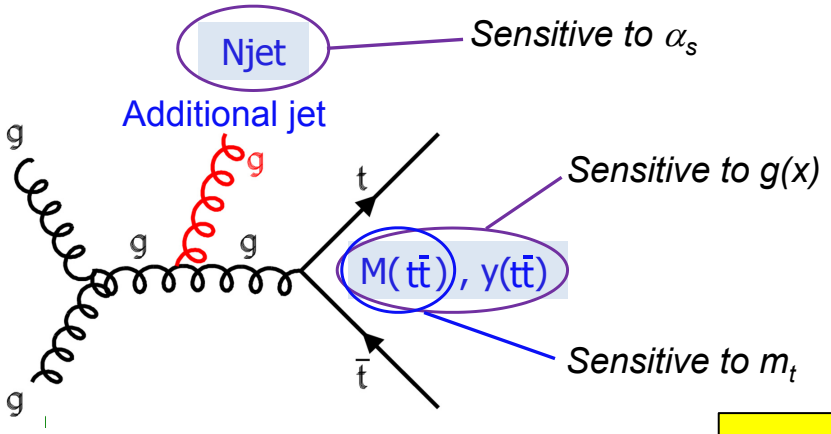


-- "ATLAS-epWZtop18" PDF available at LHAPDF

13 TeV, 36/pb

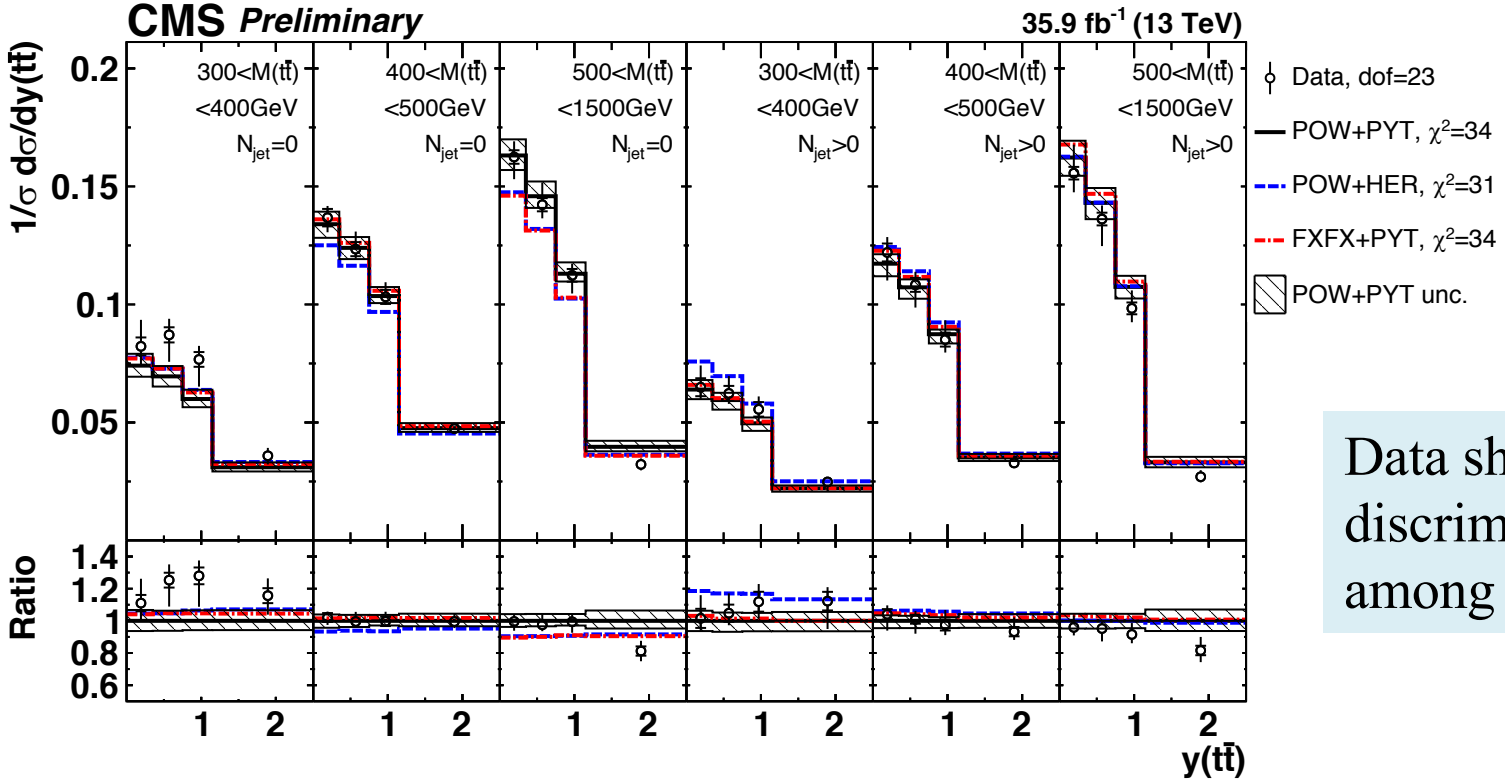
arXiv:1904.05237
(submitted to EPJC)

NEW CMS triple differential cross section $d^3\sigma_{tt}$



- First measurement of σ_{tt} vs [Njet, M(tt), y(tt)]

dσ/dy for M(tt) and Njet bins



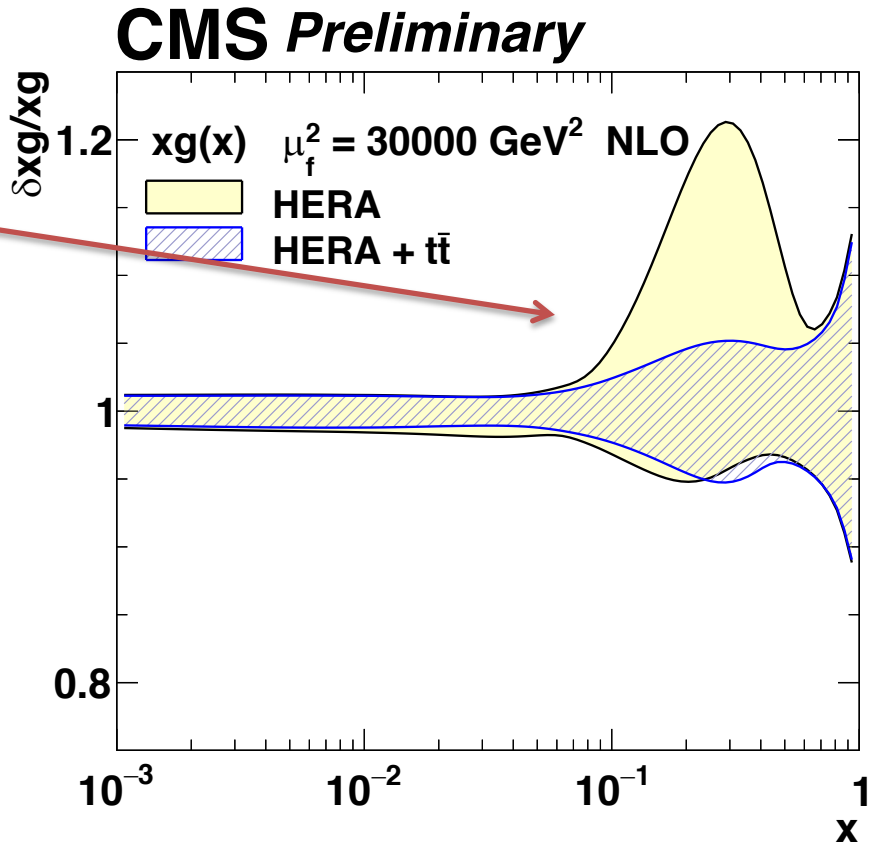
Data showing discriminating power among different PDFs

13 TeV, 36/pb

arXiv:1904.05237
(submitted to EPJC)

NEW CMS QCD analysis with $d^3\sigma_{tt}$

- A simultaneous PDF, α_s, m_t^{pole} determination
  - -- HERA-I + II plus CMS $d^3\sigma_{tt}$
  - -- Reduced gluon uncertainty at high-x



Gluon PDF uncertainty

- -- Two SM parameters (αs and top mass) determined precisely with weak correlation

$$\alpha_s(M_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{mod})^{+0.0008}_{-0.0001}(\text{par})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total}),$$

$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit})^{+0.1}_{-0.1}(\text{mod})^{+0.0}_{-0.1}(\text{par})^{+0.3}_{-0.3}(\text{scale})\ \text{GeV} = 170.5 \pm 0.8(\text{total})\ \text{GeV}.$$

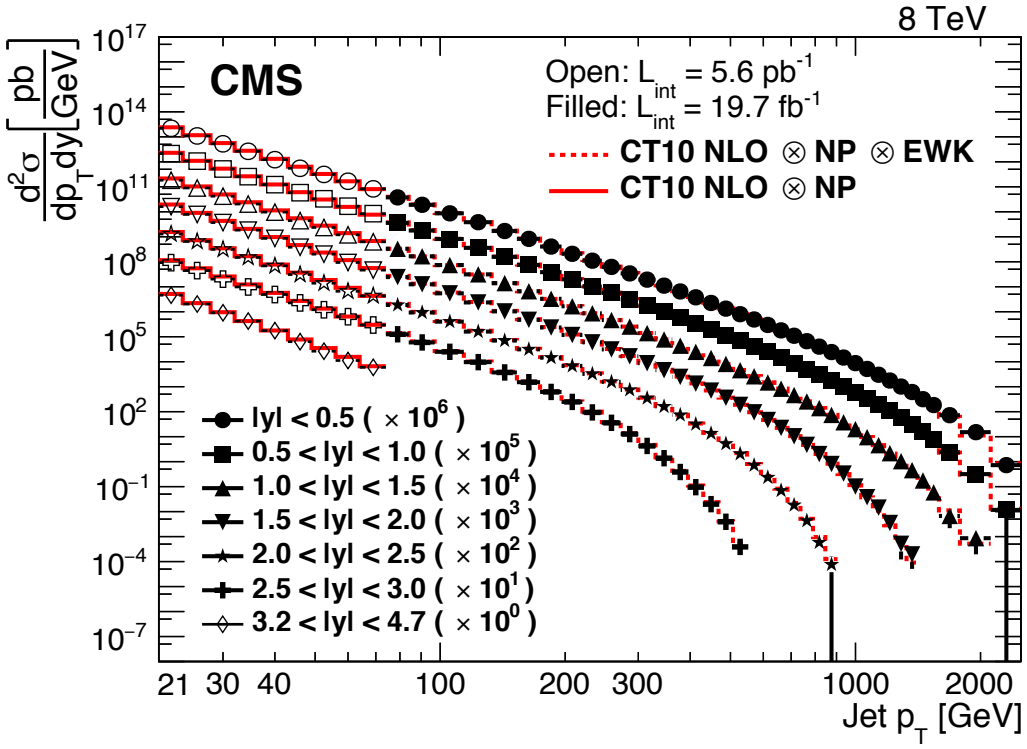
2.76, 7, 8 TeV

JHEP 03 (2017) 156

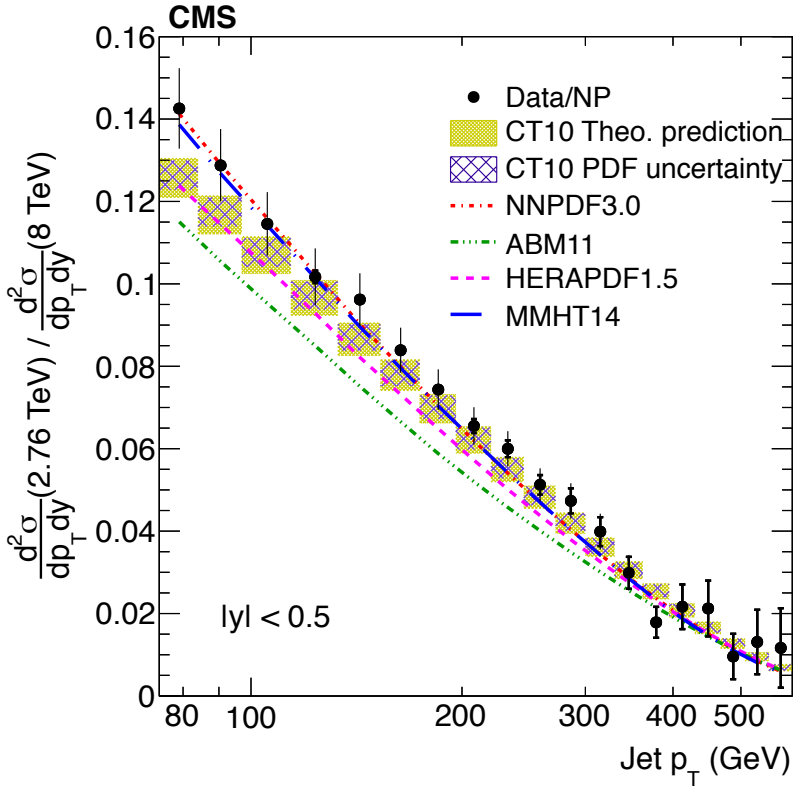
CMS Jet cross section [middle-high x gluon]

- CMS jet cross section at 8 TeV and ratios to 2.76 TeV and 7 TeV
  -- 2.76 TeV: a special data set collected in 2011

Cross section vs. jet pT



Cross section ratio (2.76 vs 8 TeV) vs. jet pT

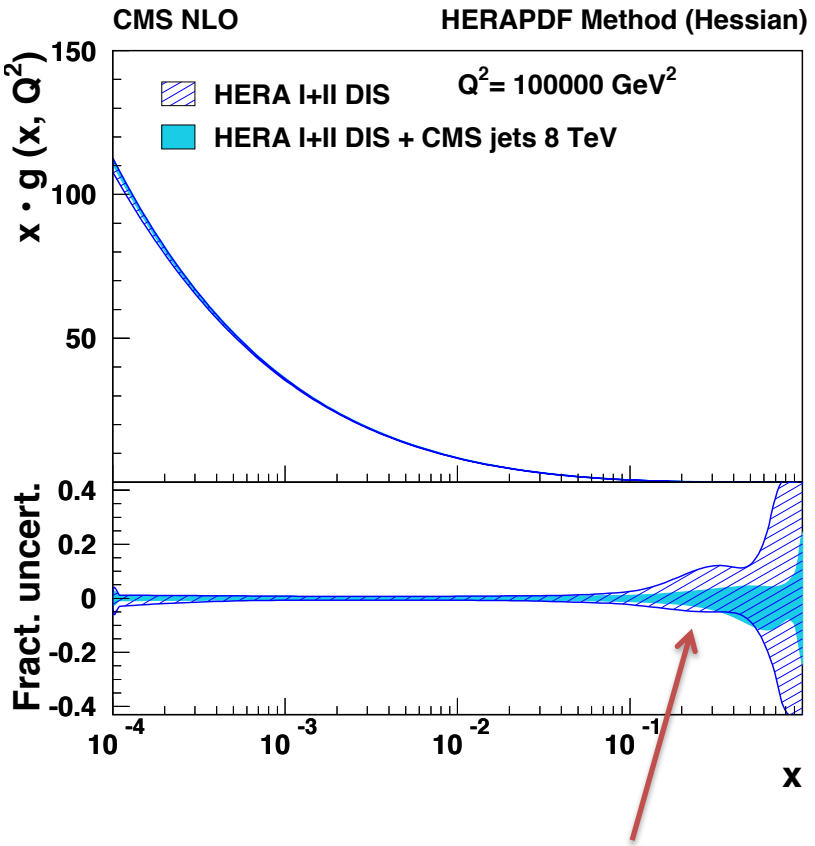


2.76, 7, 8 TeV

CMS QCD analysis with jet cross section [middle-high x gluon]

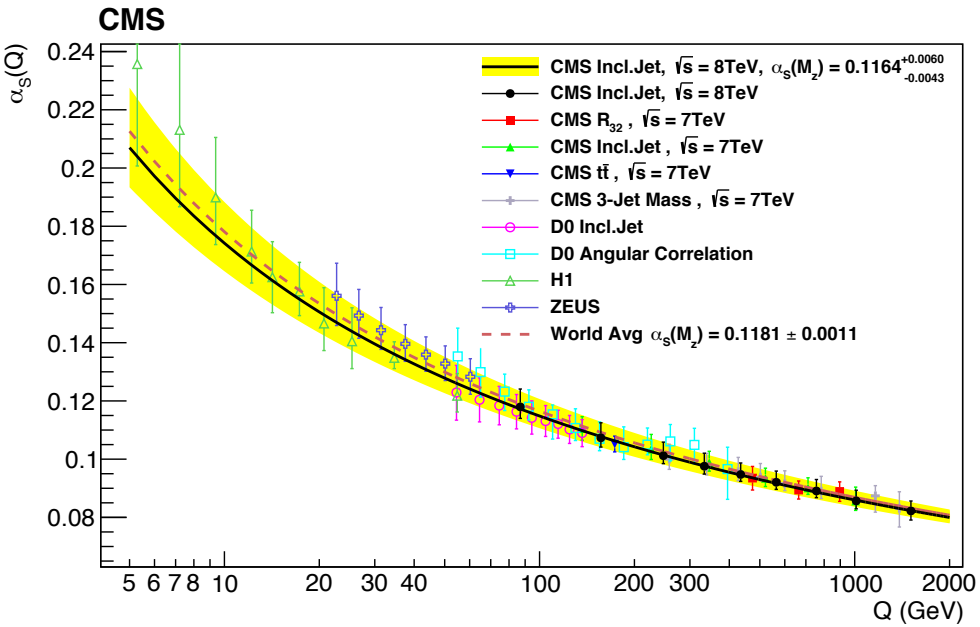
JHEP 03 (2017) 156

- NLO QCD analysis using 8 TeV jet data
  - -- NNLO was not yet available
  - -- HERA I+II + CMS jets 8 TeV (p_T(jet) > 74 GeV)



Significant constraint on high-x gluon

α_s from this analysis



- ATLAS similar analysis (2.76, 7 TeV)

Eur. Phys. J. C (2013) 73:2509

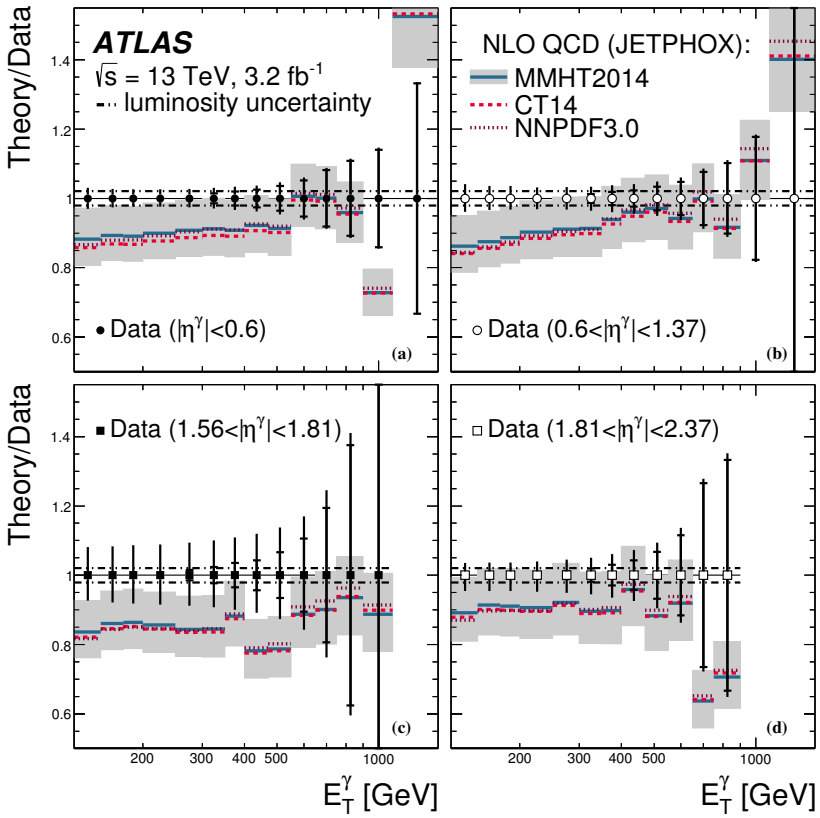
Direct photon production

- ATLAS measurements at 8 TeV and 13 TeV

JHEP 06 (2016) 005

Phys. Lett B770 (2017) 473

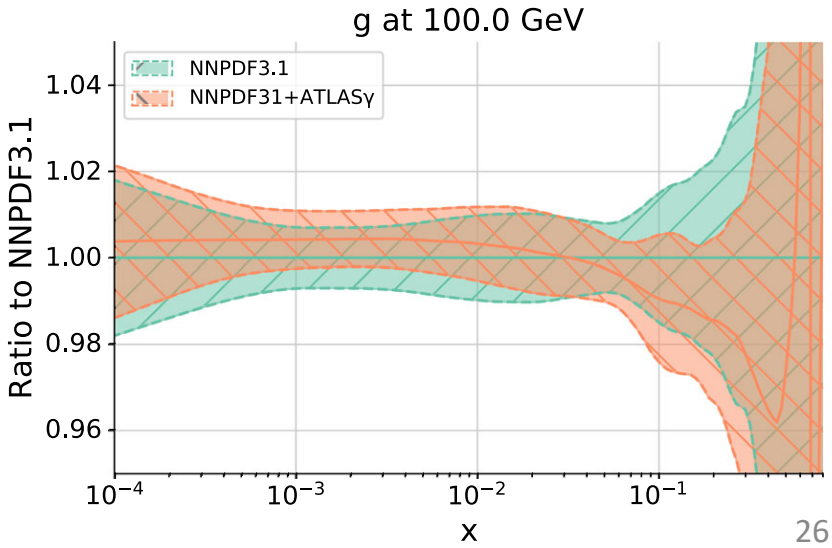
Theory/Data vs. E_T^γ



NLO (JETPHOX) reasonably describes data however with large theory uncertainty that is due to scale (NNLO / NLO)

- NNLO predictions get available recently, and a QCD analysis with NNLO direct photon:

Eur. Phys. J. C78 6 (2018) 470

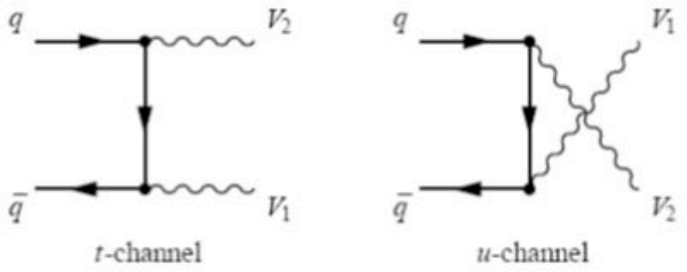


Direct photon being established as giving useful info on gluon at collider energies

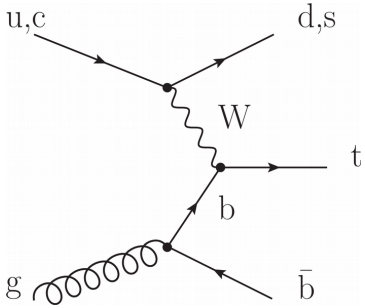
Prospects

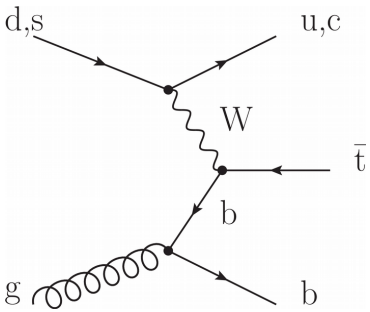
With more statistics, e.g. full Run-2 data, other measurements will likely be precise enough to be used in PDF fits, for instance:

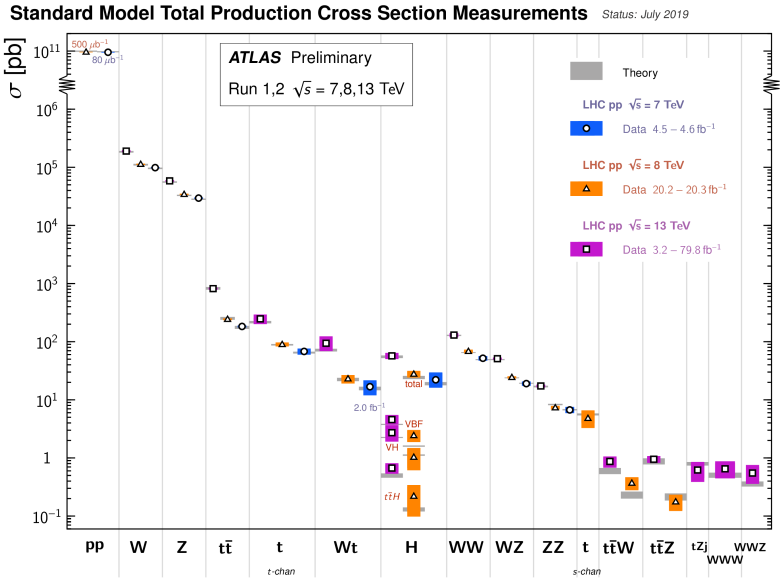
- Di-boson (WW, WZ, ZZ) productions
  -- Constraints to quarks at middle-high x

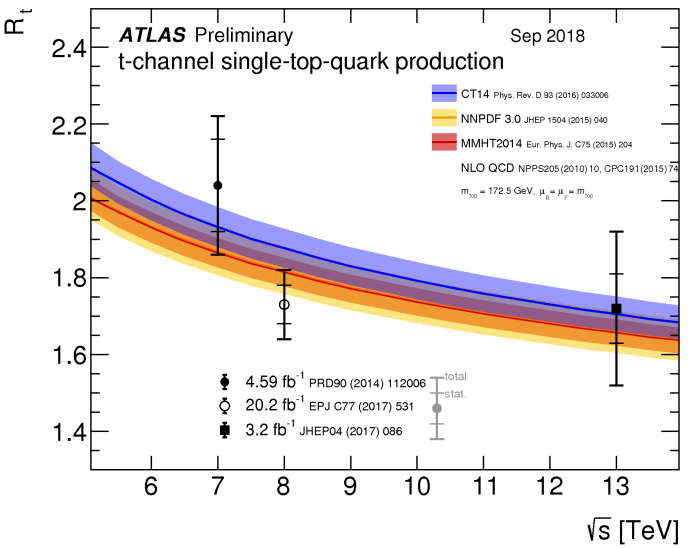


- Single top
  -- t-channel top/anti-top ratio is sensitive to u/d ratio at high-x





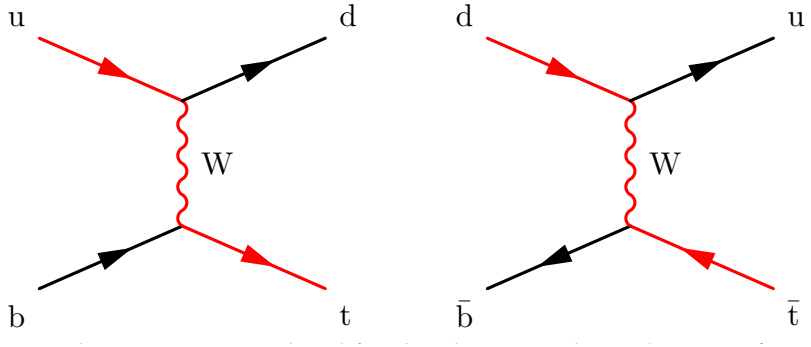




13 TeV, 36/pb

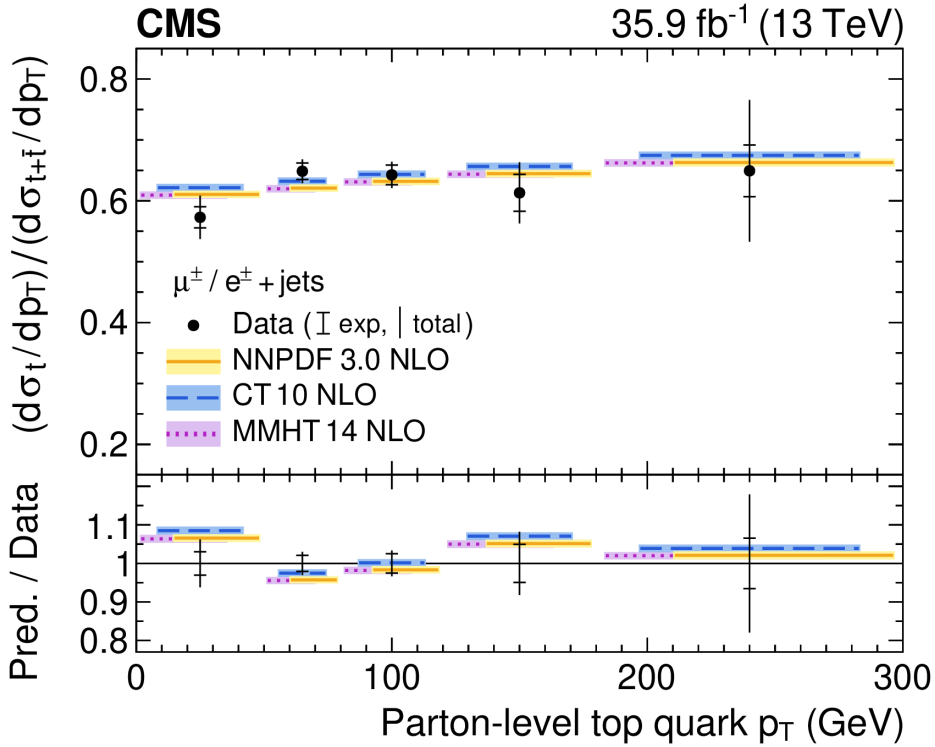
CMS t-channel single top production

NEW

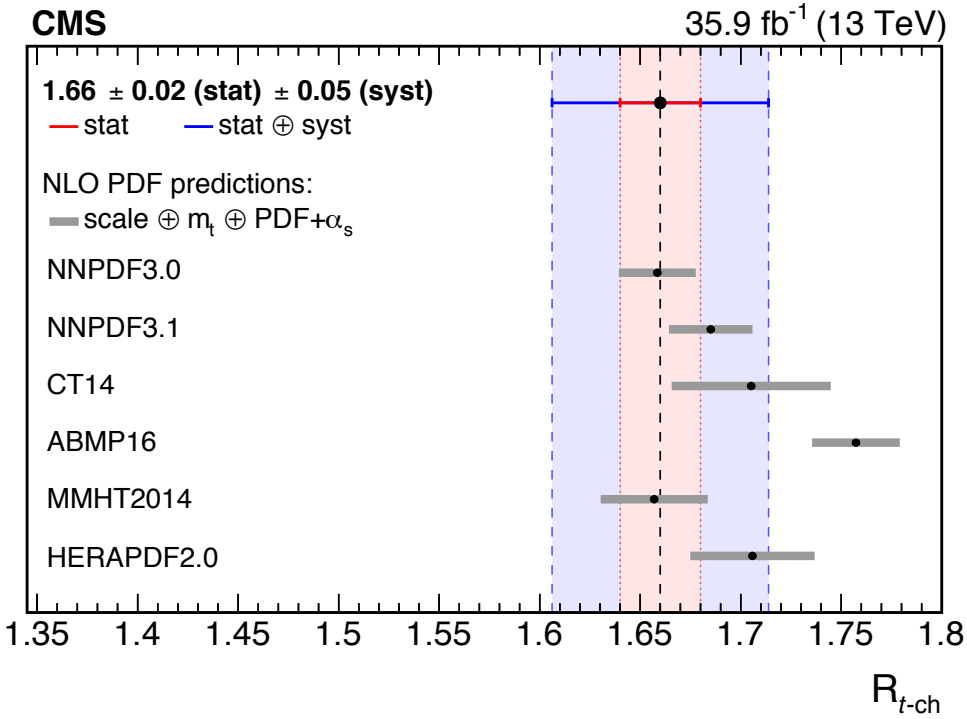


arXiv:1812.10514
(submitted to Phys.Lett.B)

- Differential single top cross section
  -- vs. POWHEG NLO with 3 PDFs which agree with data

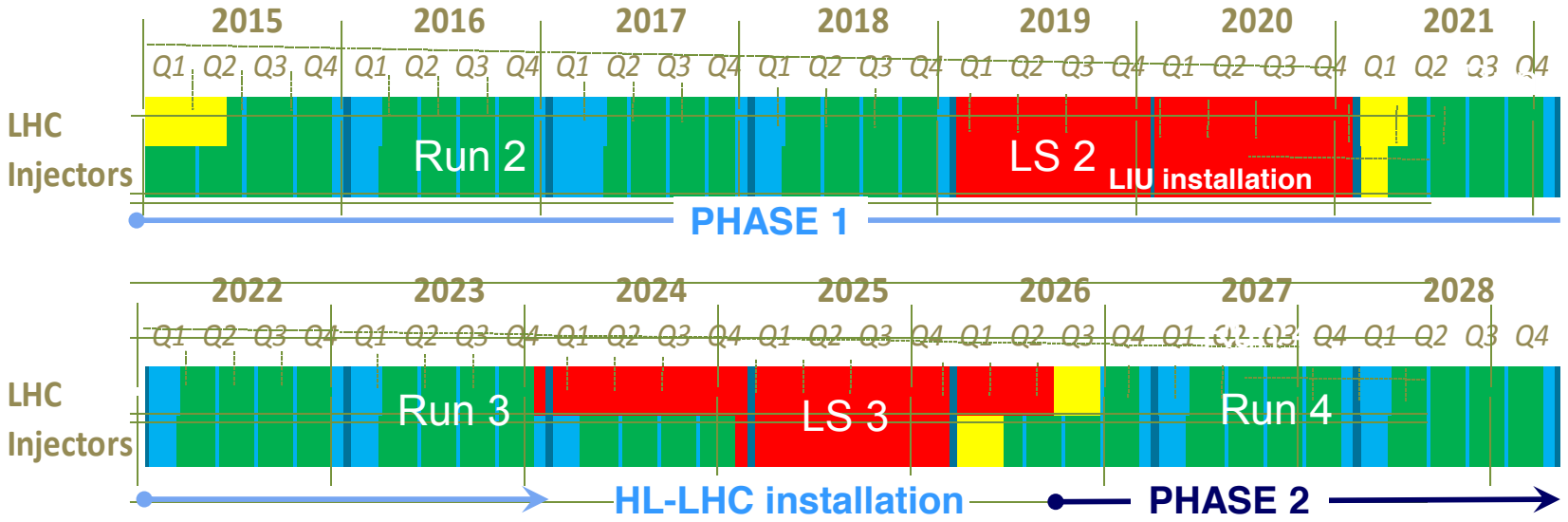


- Top / anti-top ratio in t-channel: $R_{t\text{-ch}}$
  -- Sensitive to u/d
  -- Most PDFs describe data well



arXiv:1907.08330
(submitted to Eur.Phys.J)

Prospects



- Run-3: 2021-2023
  - -- √s=14 TeV
  - -- intL ~150 /fb (~Run-2)

- Run-4: High-Luminosity LHC (HL-LHC) 2026-
  - -- √s=14 TeV
  - -- intL ~3000 /fb (~300 /fb per year)

Knowledge on PDFs should become more and more precise at future!

Summary

- PDF is a vital input for LHC physics both for BSM hunting and precision measurement

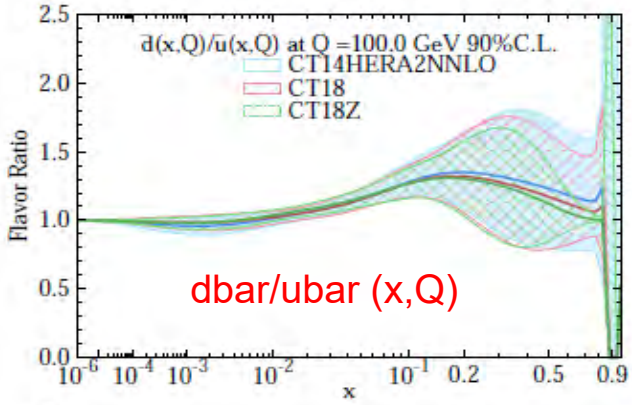
- At the same time, LHC data themselves have valuable sensitivities for corner of phase spaces that are not covered by low energy DIS experiments, for instance:
  -- Middle-high x quarks with W, Z production
  -- Middle-high x gluon with ttbar, jet, direct photon productions
  -- u/d at high-x with single t

Backup Slides

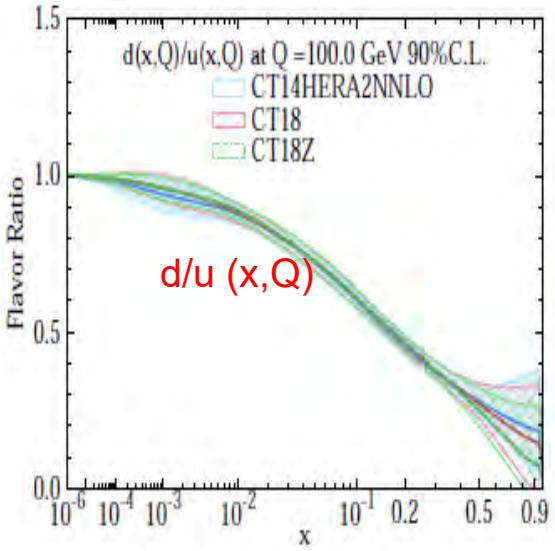
CT18Z strange-PDF

- Latest CTEQ analysis "CT18" (update from CT14)
  -- "CT18Z" = "CT18" + adding ATLAS W/Z rapidity

CT18Z vs.CT18 PDFs



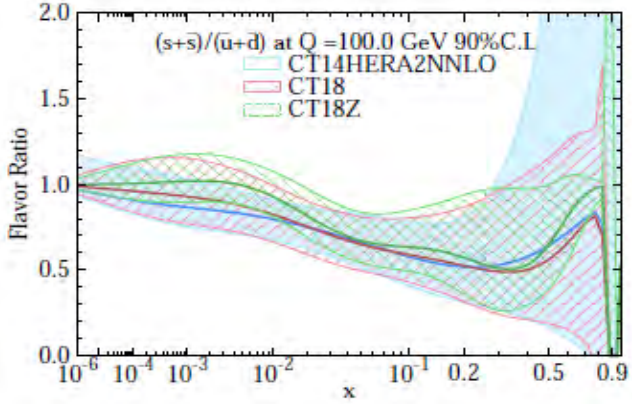
dbar/ubar (x,Q)



d/u (x,Q)

d/u decreases at large-x

Rs increases at small-x



(s+sbar)/(ubar+dbar) (x,Q)

C. P-Yuan, talk at DIS 2019 conference

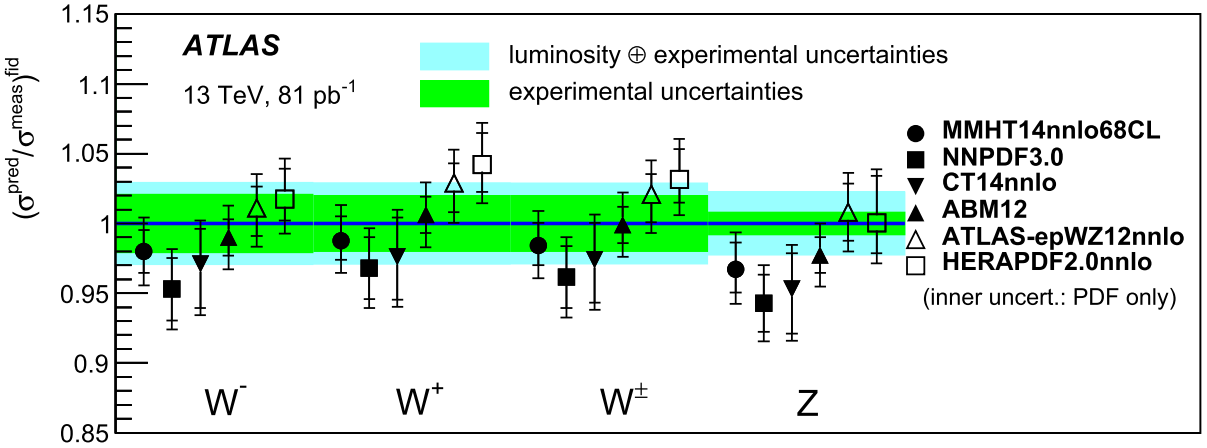
Q=100 GeV; at 90%CL

13 TeV, 81/pb

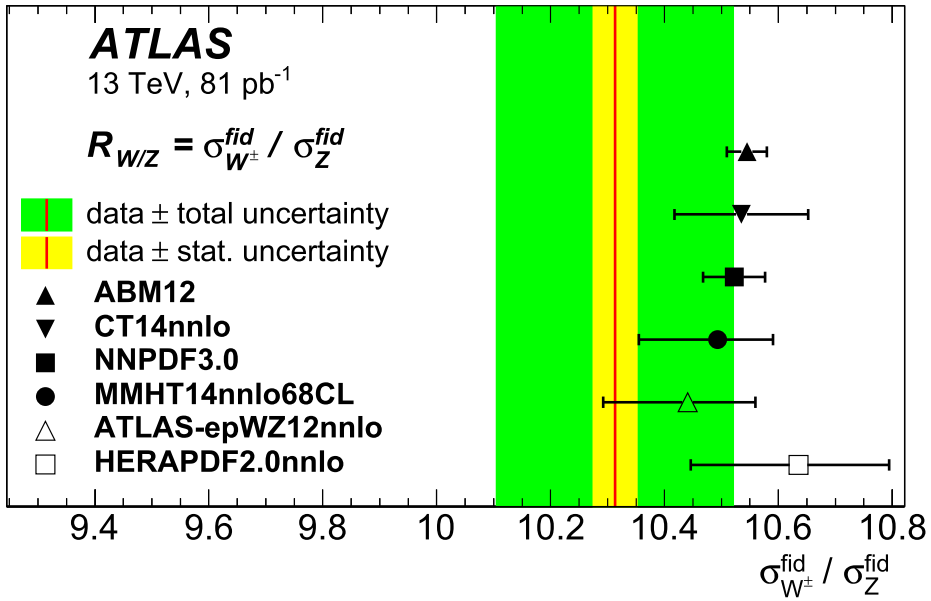
ATLAS inclusive W, Z at 13 TeV [middle-low x quarks]

- Measurements at higher energy give access to different region in x

Phys. Lett. B759 (2016) 601



W, Z cross sections vs. various PDFs predictions

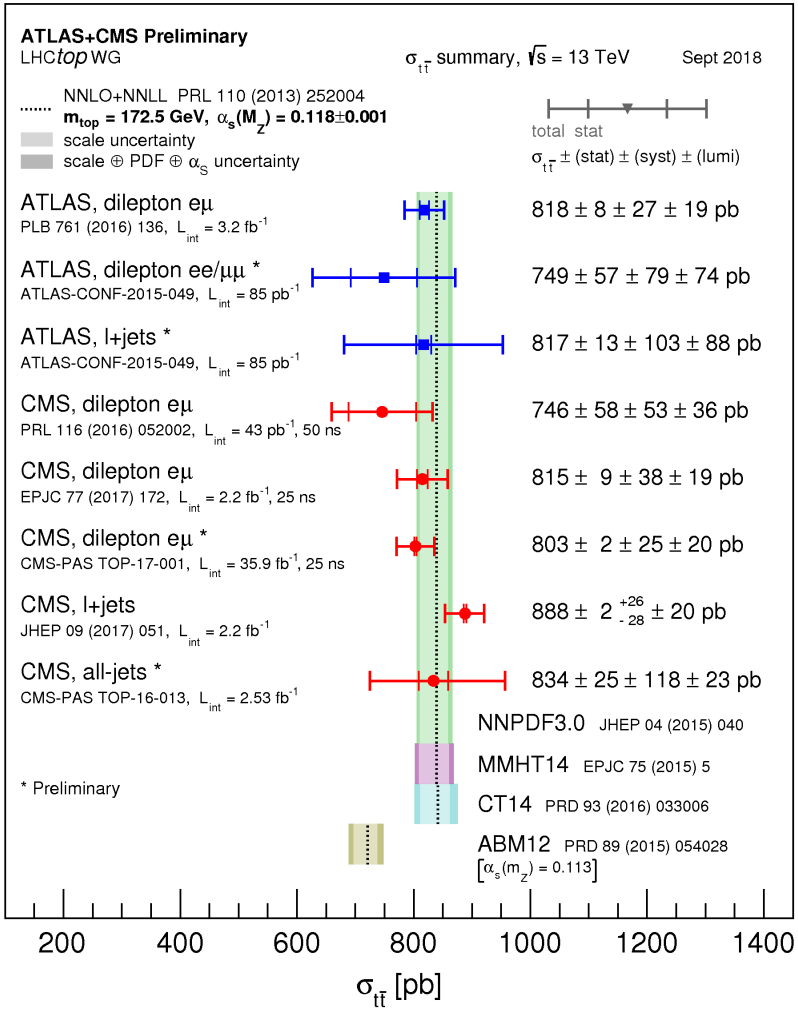


- Ratios of W/Z cross section
  - -- Luminosity uncertainty cancels
  - -- Sensitive to strange PDF
    - → Supports ATLAS-epWZ16 finding of 'unsuppressed' strange

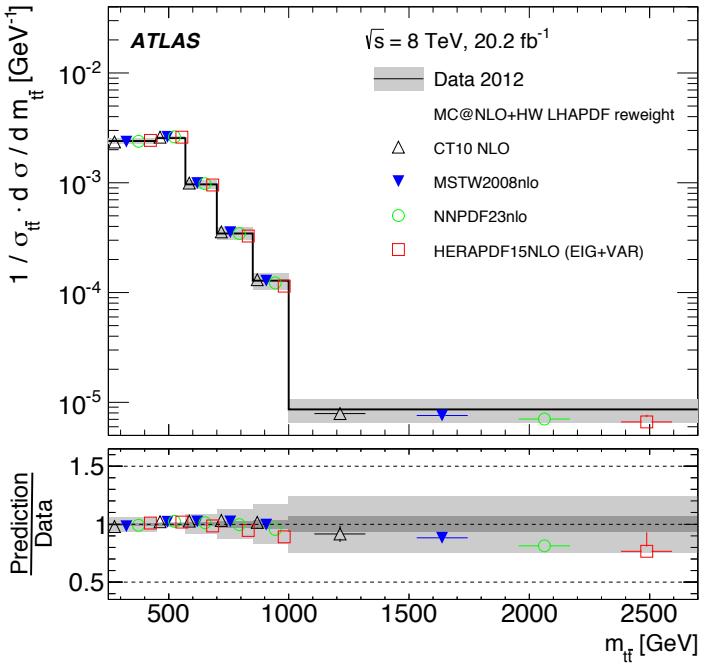
8 TeV, 18.8 /fb

Top pair production [middle-high x gluon]

- Inclusive cross section
  -- Already included in the latest global PDF fits, as MMHT, NNPDF



- Differential cross sections
  -- Single differential in terms of rapidity, pT of top, and rapidity and mass of top pair
  -- Measurements with 7 TeV, 8 GeV, in l-jets and l-l modes, both from ATLAS and CMS
  -- NNLO predictions on differential cross sections are now available.
  → possible to include into PDF fits



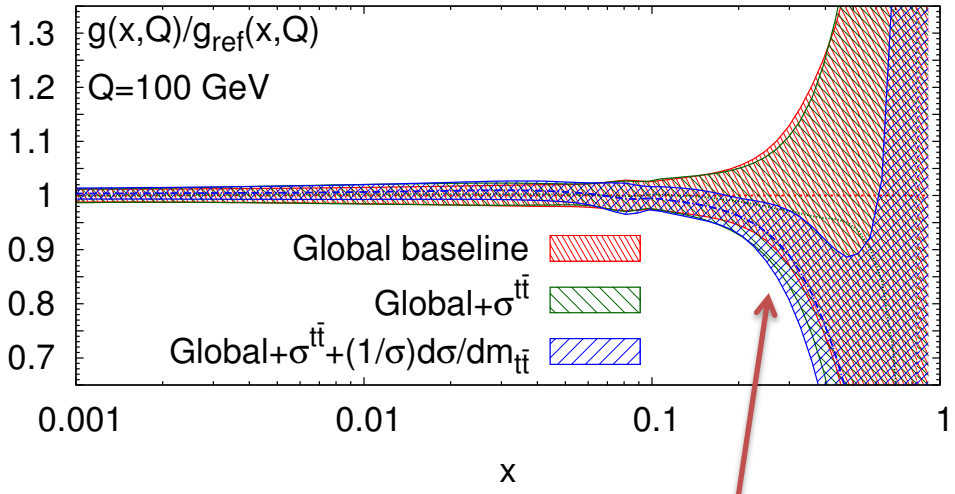
8 TeV, 18.8 /fb

Top pair production [middle-high x gluon]

JHEP 04 (2017) 044, arXiv:1611.08609

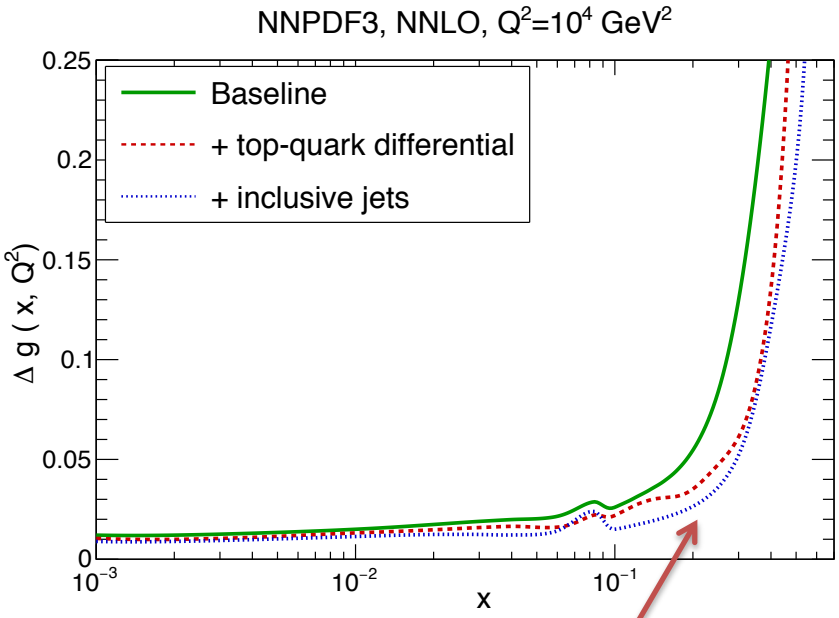
- Impact to PDF fits studied by NNPDF
  -- Including ttbar 8 TeV ATLAS and CMS, l-jets

Gluon uncertainty



ttbar (in particular differentials) significantly improves high-x gluon

Gluon uncertainty



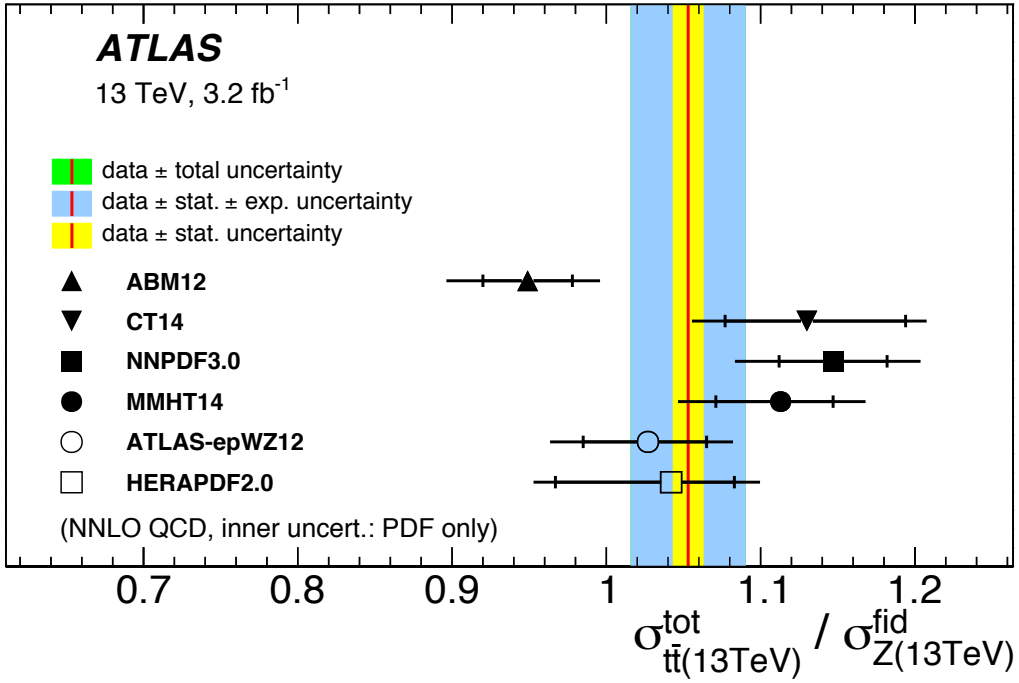
ttbar sensitivity to gluon is as similar to jets data (Tevatron, LHC)

JHEP 02 (2017) 117

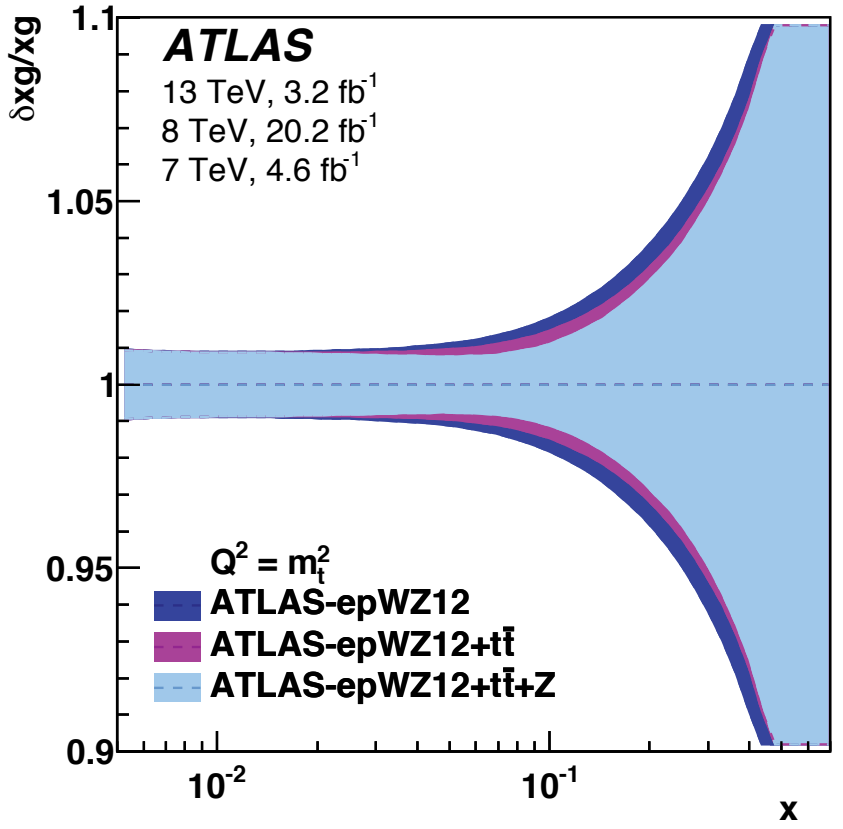
Top pair / Z ratio [middle-high x gluon]

- ttbar / Z ratio
  -- Luminosity uncertainty cancels

ttbar / Z ratio at 13 TeV



Gluon uncertainty



Provide even better constraints on gluon PDF at high-x

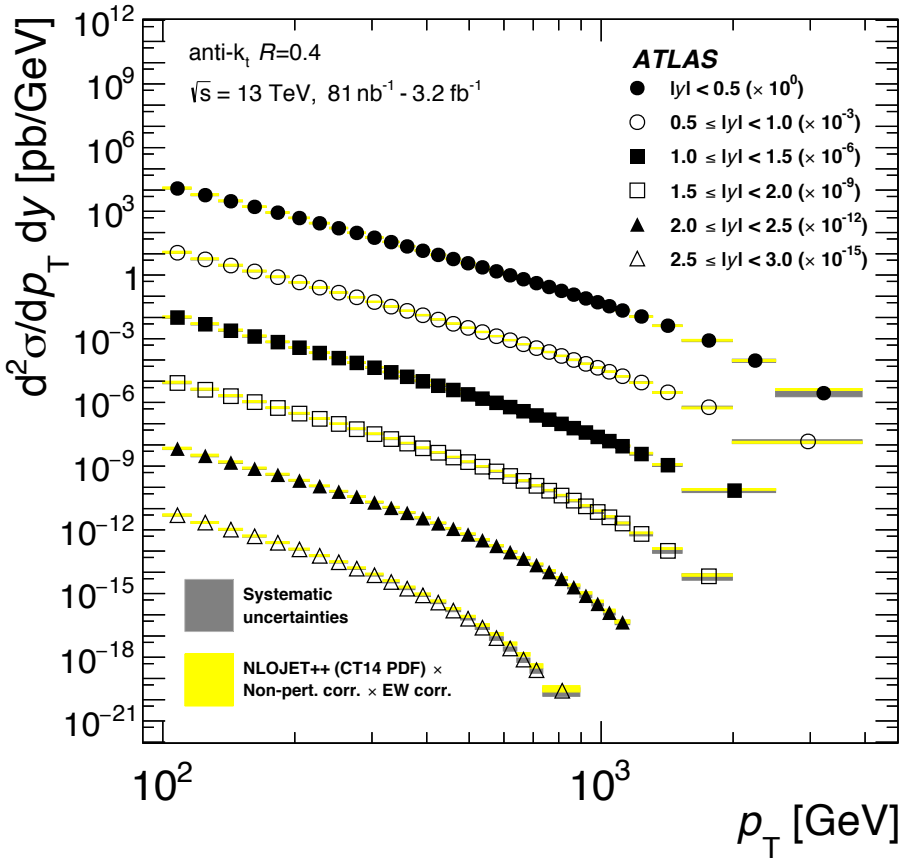
13 TeV, -3.2/fb

Jet cross section @ 13 TeV [middle-high x gluon]

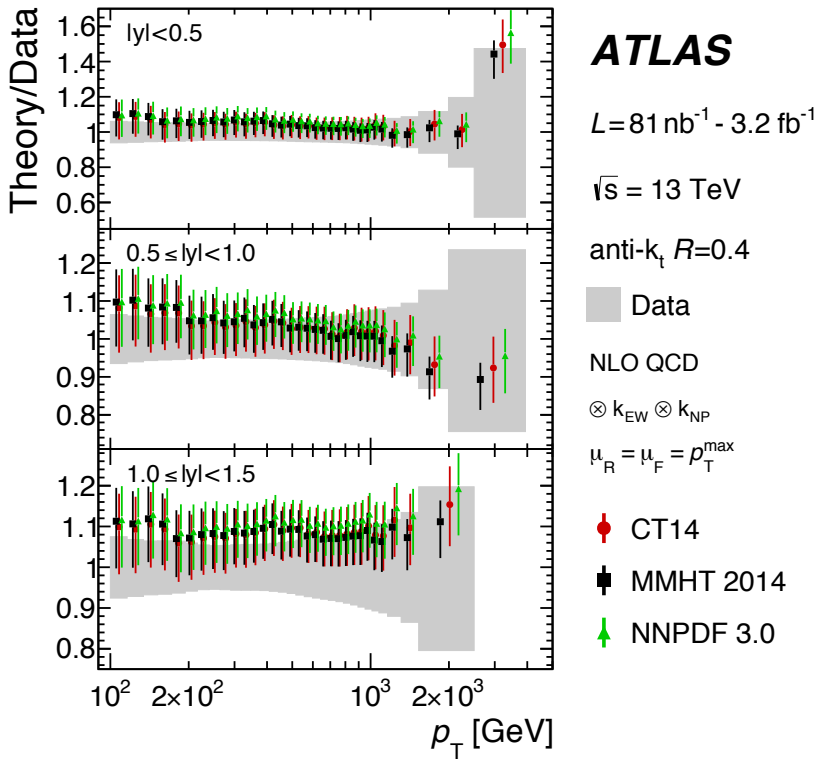
- ATLAS 13 TeV measurements of inclusive jets and di-jets cross sections
  -- Up to p_T(jet) =3.5 TeV

JHEP 05 (2018) 195

Cross section vs. jet pT



Theory/Data for some rapidity bins



13 TeV, -3.2/fb

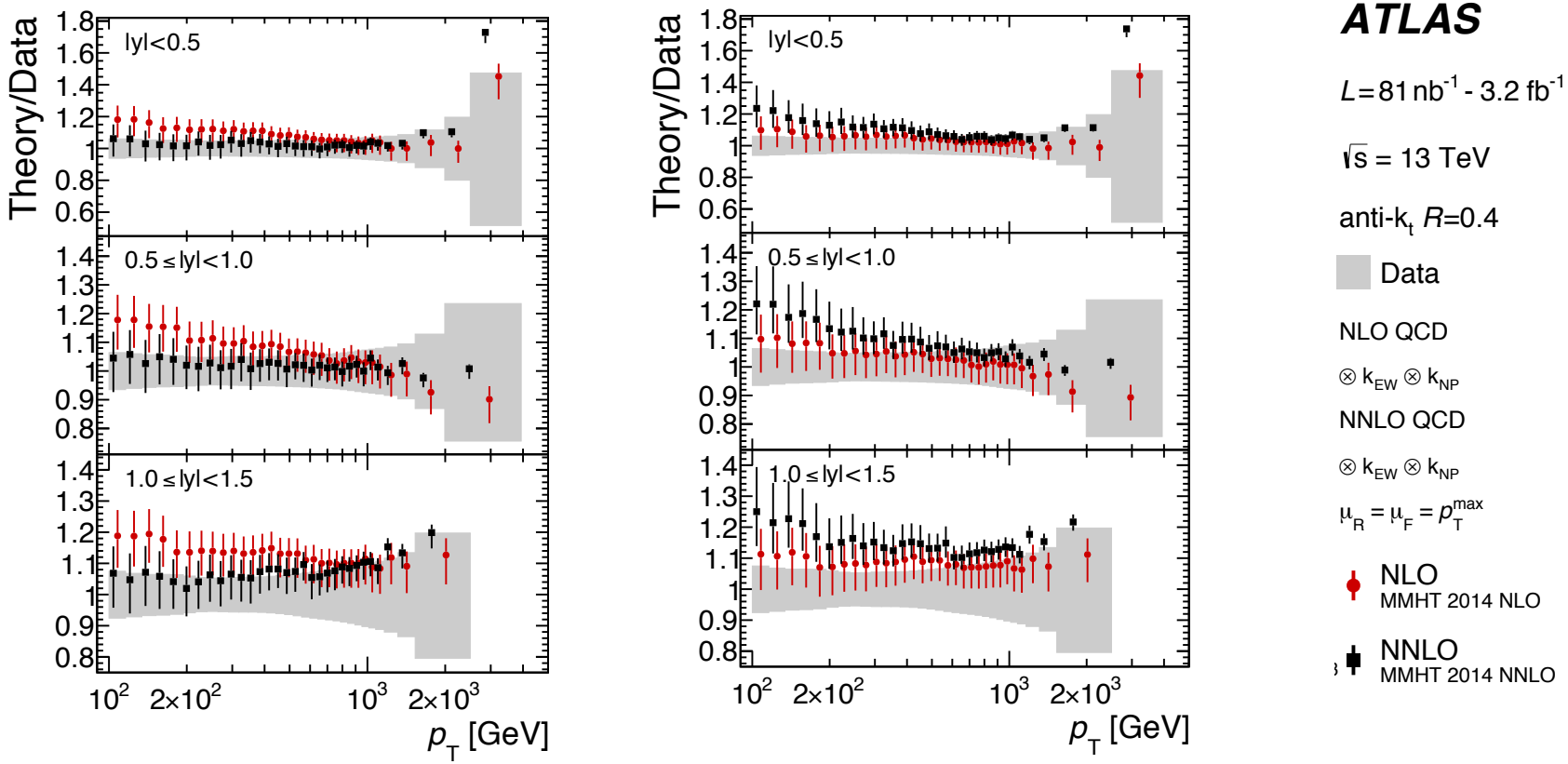
NNLO impact to Jet cross section

- NNLO can describe data better?

NNLO ($\mu=p_T^{jet}$)

NNLO ($\mu=p_T^{max}$)

JHEP 05 (2018) 195



Scale choice is sensitive: with $\mu=p_T^{jet}$ and R=0.6 anti-kT, NNLO describes data better than NLO