PDF-sensitive measurements at the LHC

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高エネルギーQCD・核子構造勉強会
東工大, 28 April 2016

Useful references

- Workshop “Parton Distributions for the LHC”

  15-21 Feb 2015, Benasque, Spain, http://benasque.org/2015lhc/
  (many plots taken from this workshop)

- “The PDF4LHC report on PDFs and LHC data”

  J. Rojo et al., arXiv:1507.00556, J. Phys. G42 (2015) 103103

- HERAPDF2.0 - latest PDF from final H1+ZEUS data

  arXiv:1506.06042, Eur. Phys. J. C75 (2015) 580

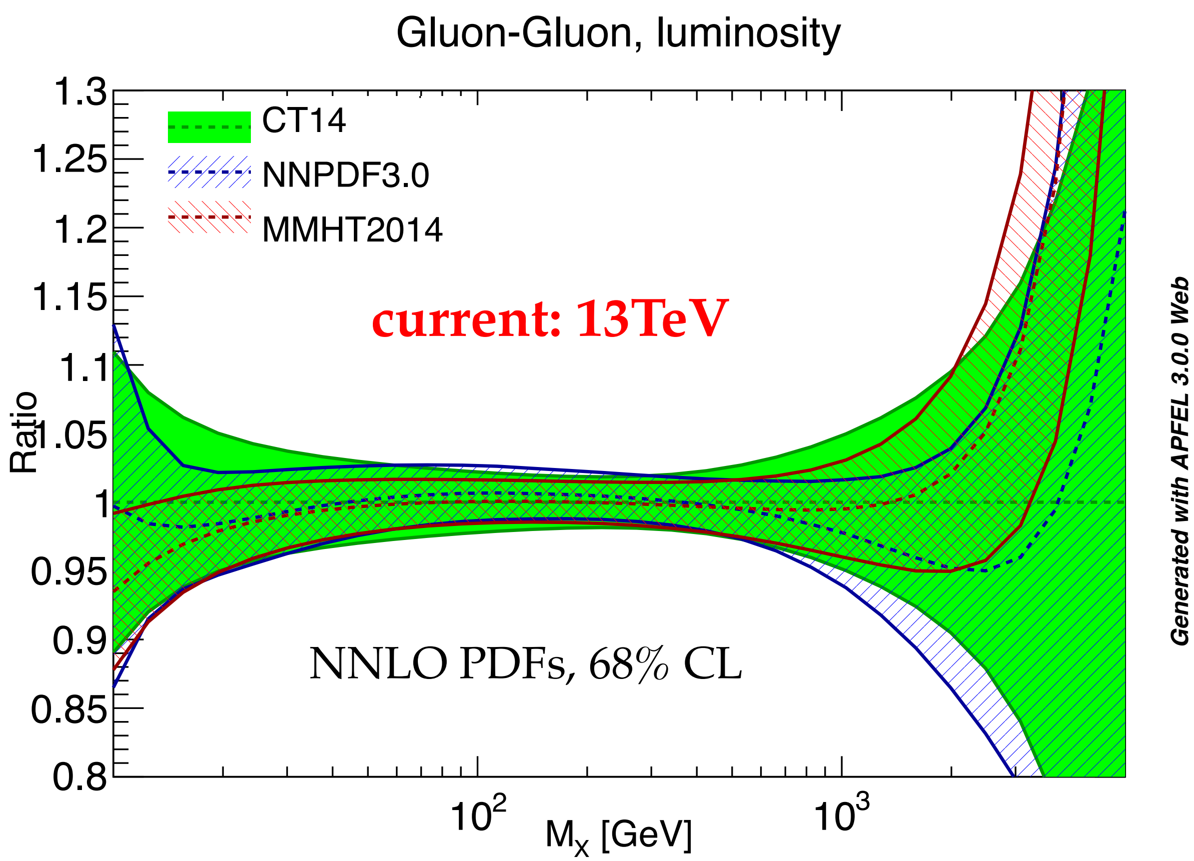
- LHeC workshop

  24-26 Jun 2015, CERN & Chavannes-de-Bogis
  http://indico.cern.ch/event/356714/

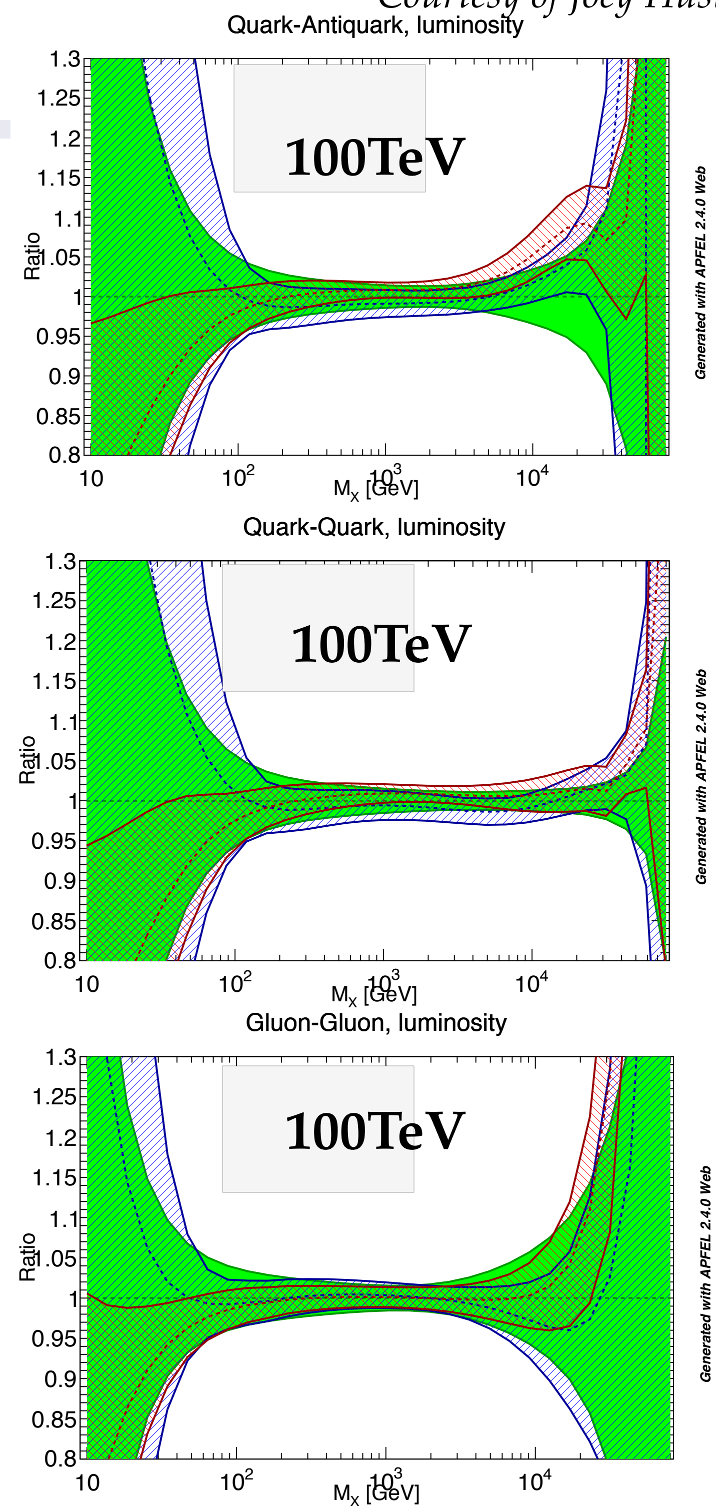
PDFs in LHC era (& beyond)

- Precise knowledge on PDF is crucial for new physics discovery at hadron colliders

Proton PDFs, today



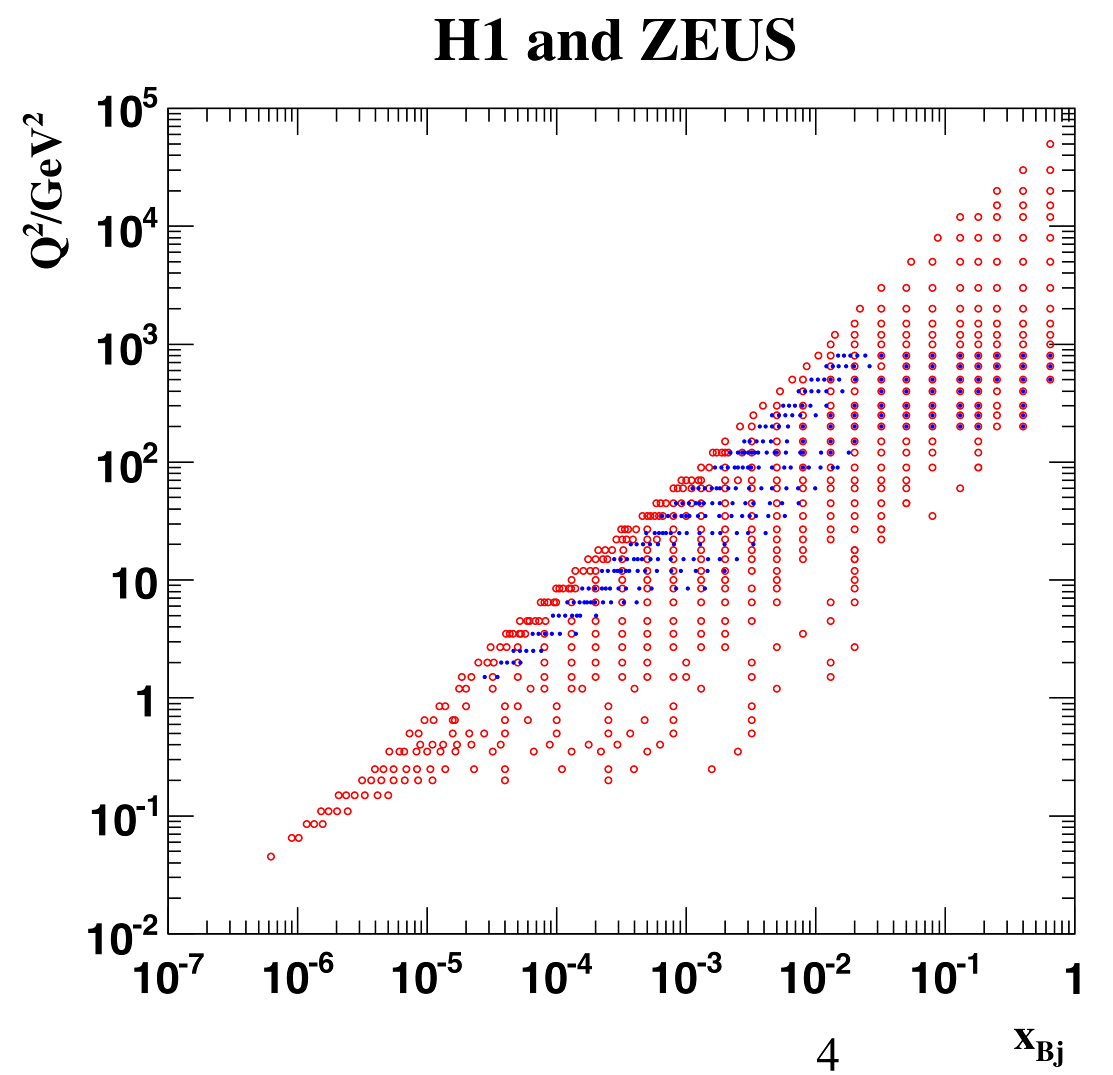
Courtesy of Joey Huston



- **need to know PDFs much better than today, for:** nucleon structure; q-g dynamics; Higgs; BSM searches; future colliders, FCC-pp; development of QCD; ..
- LHC will provide further constraints, but cannot resolve precisely (shown are latest global PDFs, also including available LHC data)

HERAPDF 2.0

- PDF set extracted from only HERA data
  - no nuclear correction (no fixed-target data)
  - no isospin symmetry assumption (no deuteron data)
- Use final H1+ZEUS combined cross sections
  - NC/CC, e^+p/e^-p
  - special runs (low Ep, shifted vertex)
- HERAPDF 1.0 from HERA-I, HERAPDF 1.5 from prel. HERA-II measurements
- Available in LO/NLO/NNLO



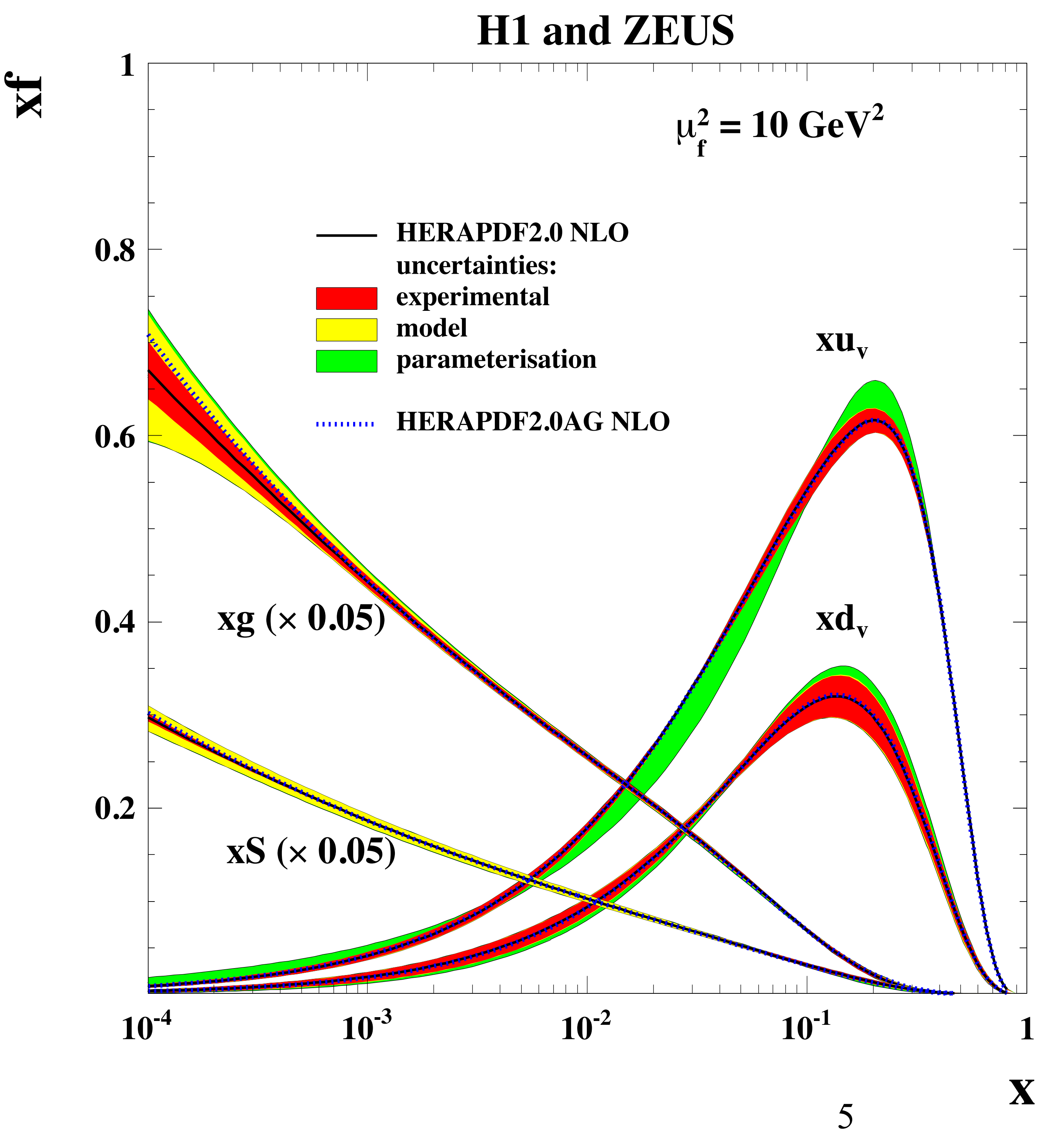
PDF parametrization

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

$$x\bar{U} = x\bar{u} \text{ and } x\bar{D} = x\bar{d} + x\bar{s}$$

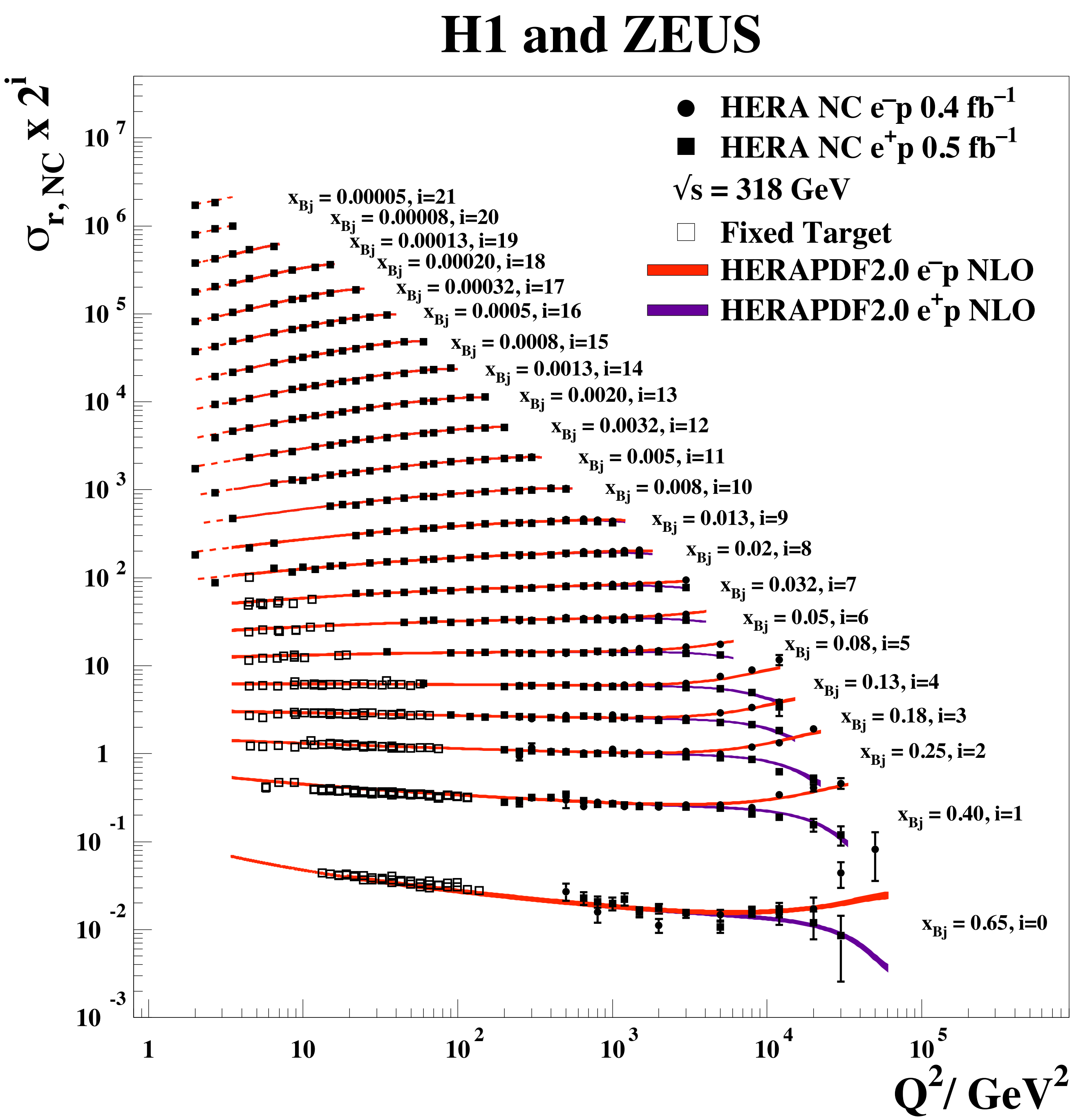
$$xS = 2x(\bar{U}+\bar{D})$$

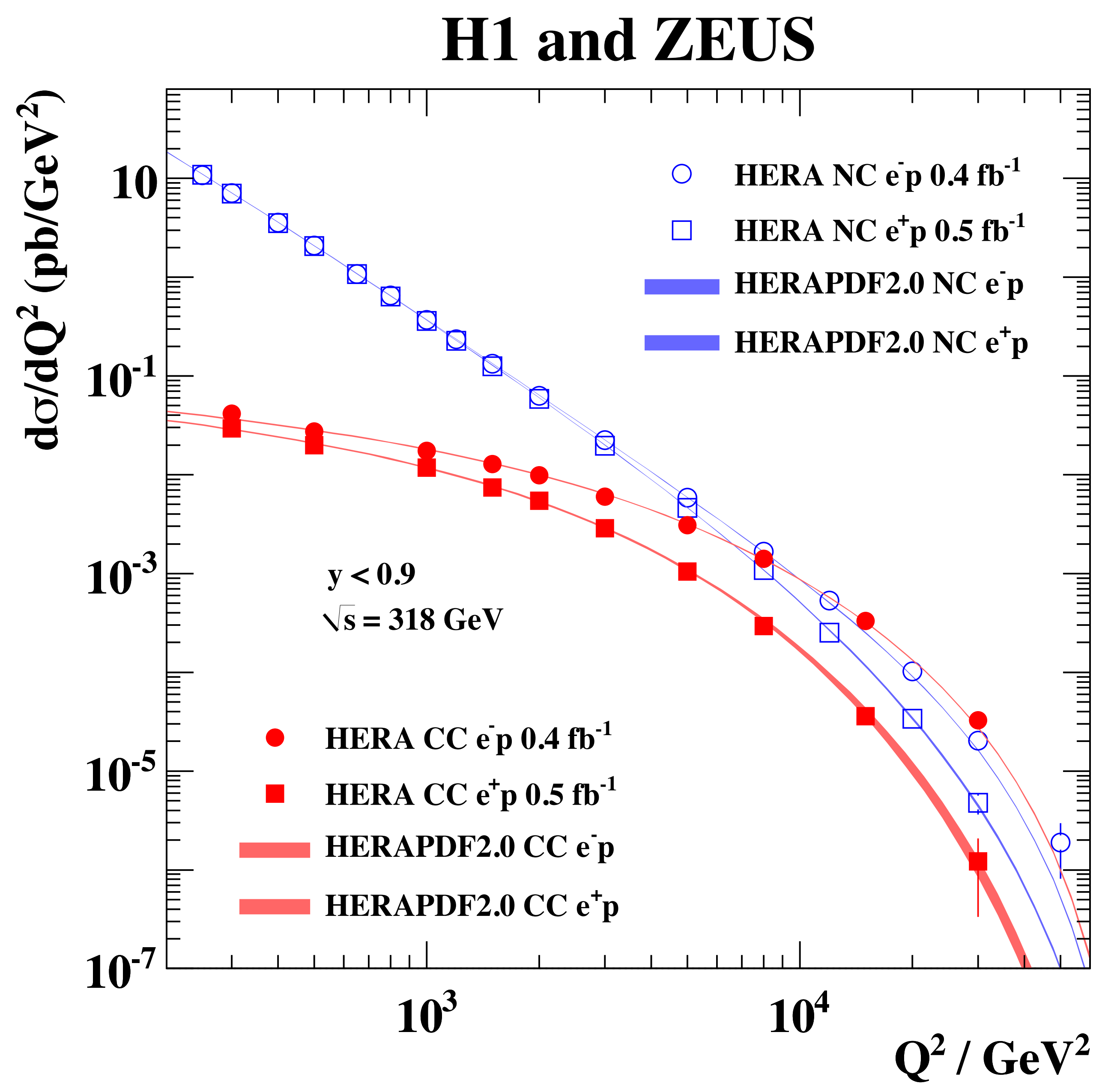
Eur. Phys. J. C75 (2015) 580



M(charm) = 1.47 GeV (NLO)
1.43 GeV (NNLO)
M(bottom) = 4.5 GeV
$\alpha_S(M_Z^2)$ = 0.118 (NLO/NNLO)
0.130 (LO)

Q^2 evolution





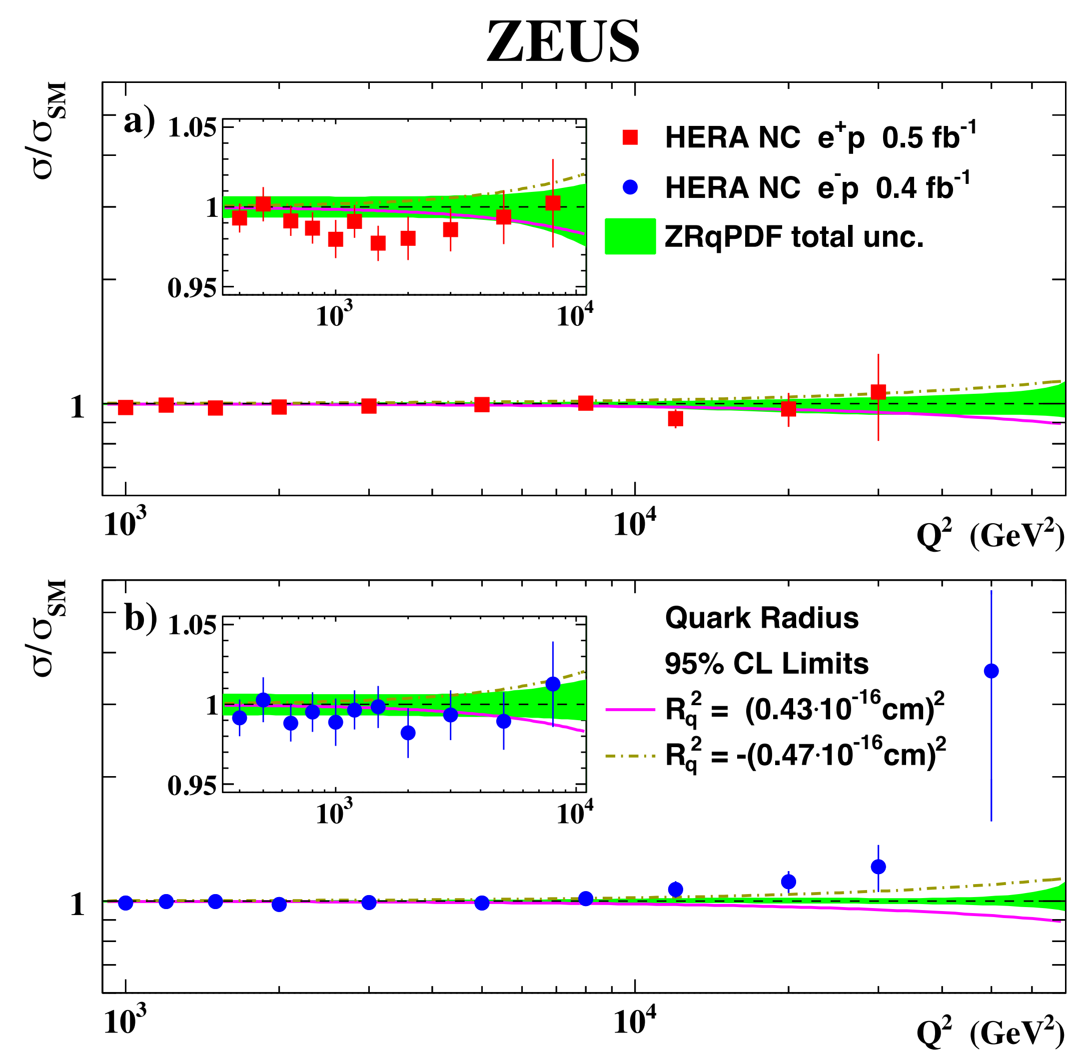
- Scaling violation at low-x, Z-exchange at high Q^2
- Electroweak unification: NC~CC at high Q^2

Limit on quark radius

- Traditionally, tests of beyond-SM physics were made by comparing HERA high-Q^2 data with PDF sets obtained from fixed-target and small portion of HERA data (eg CTEQ5D)
- Now, with HERAPDF obtained from full data set from HERA, a conceptual problem is that effect of BSM physics could be absorbed in the PDF
- New approach from ZEUS: do the simultaneous fit of PDF including the BSM term (quark form factor)
- from full H1+ZEUS data:

  $R_q < 0.43\times 10^{-18}$ m

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_q^2}{6}Q^2\right)^2$$

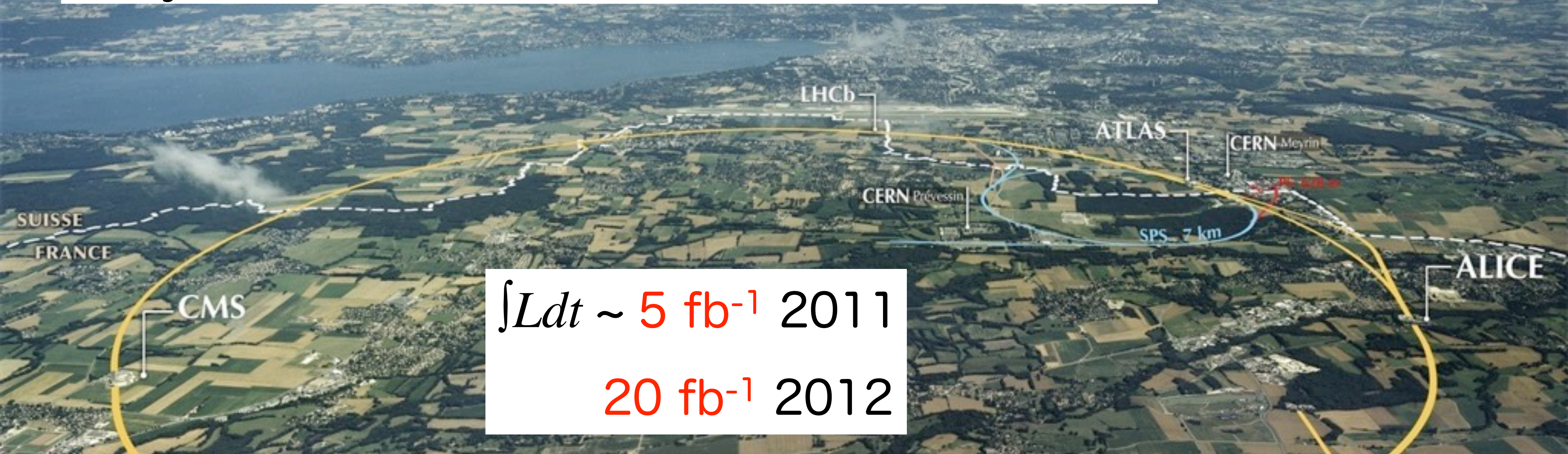


arXiv:1604.01280

accepted by Phys. Lett. B

The Large Hadron Collider

- Completed in 2008, CERN, Geneva
- Physics runs in 2010 - 2012 (Run 1)



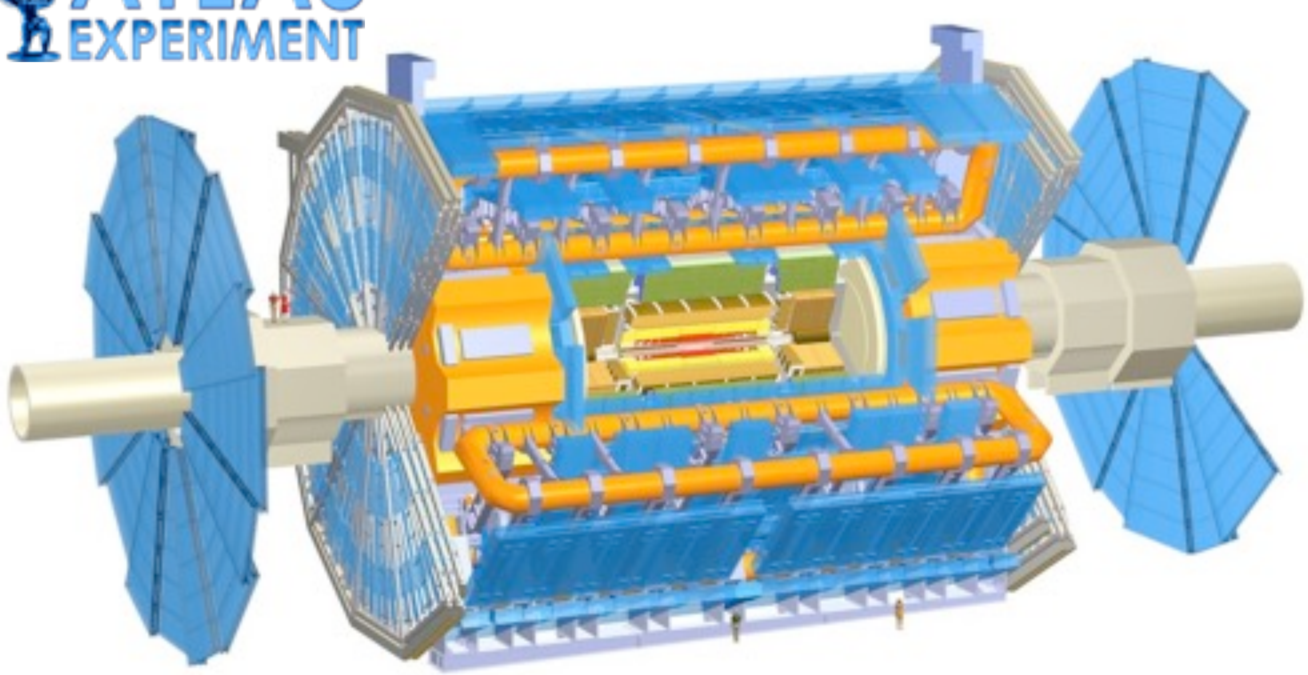
$\int L dt \sim$ 5 fb^{-1} 2011

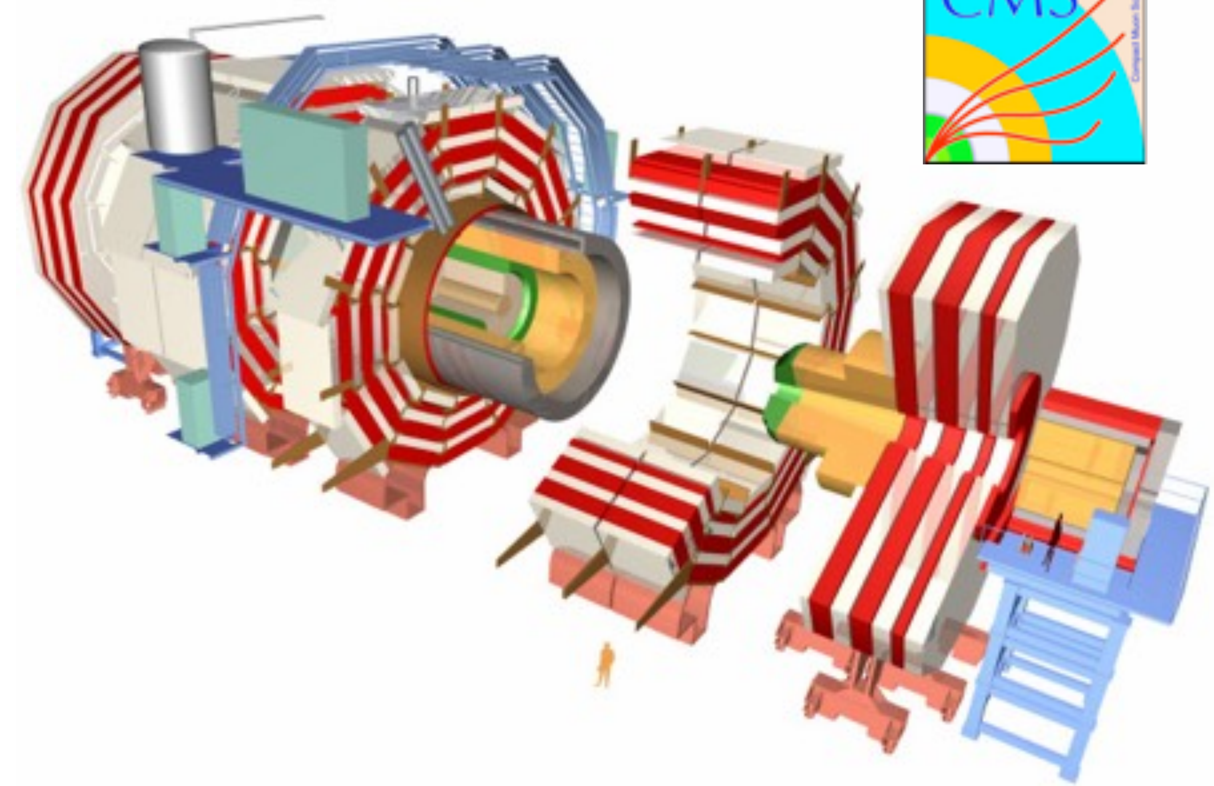
20 fb^{-1} 2012

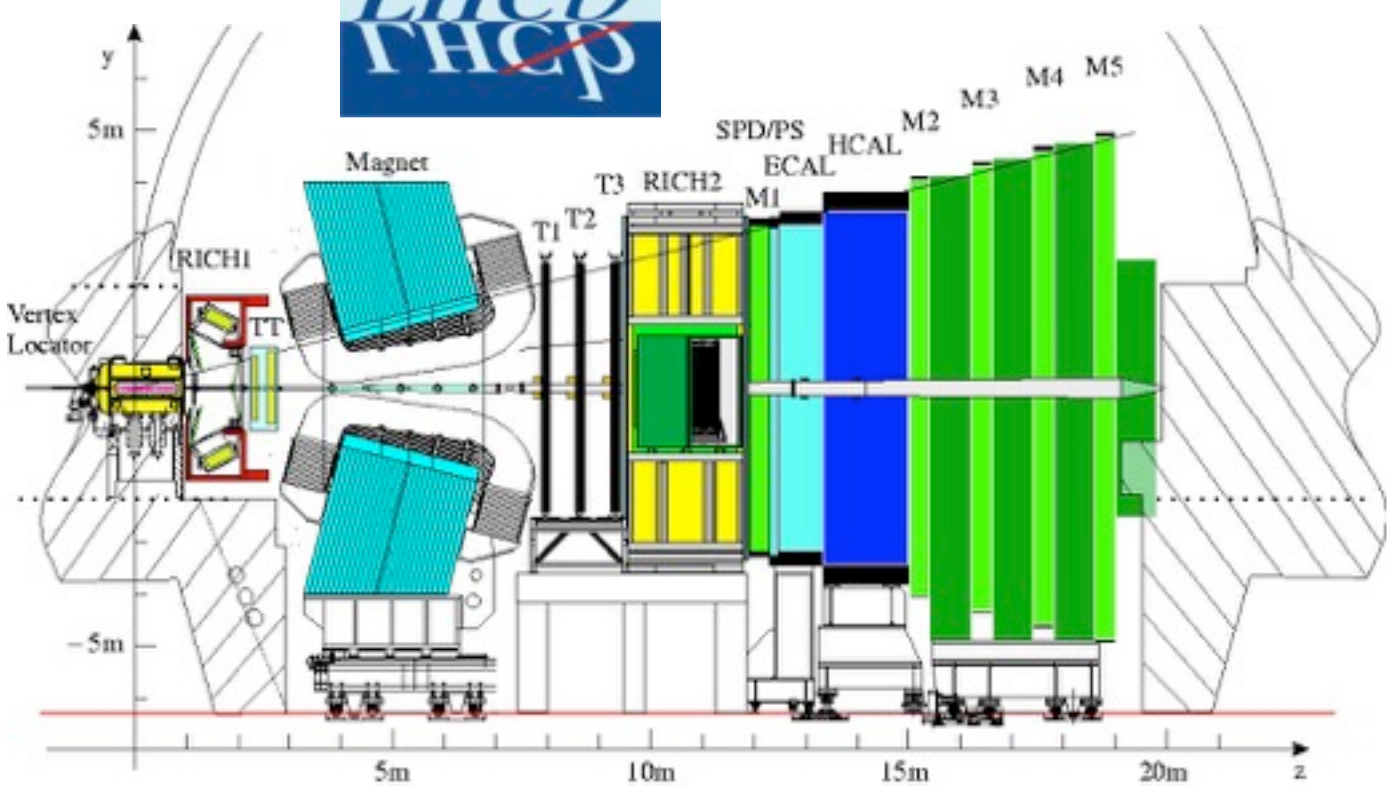
- pp collisions at
  $\sqrt{s}$ = 7 TeV (3.5 + 3.5) for 2010-11
  $\sqrt{s}$ = 8 TeV (4 + 4) for 2012
- also Pb+Pb, p+Pb (not covered here)
- Long Shutdown (LS1) 2013-2014

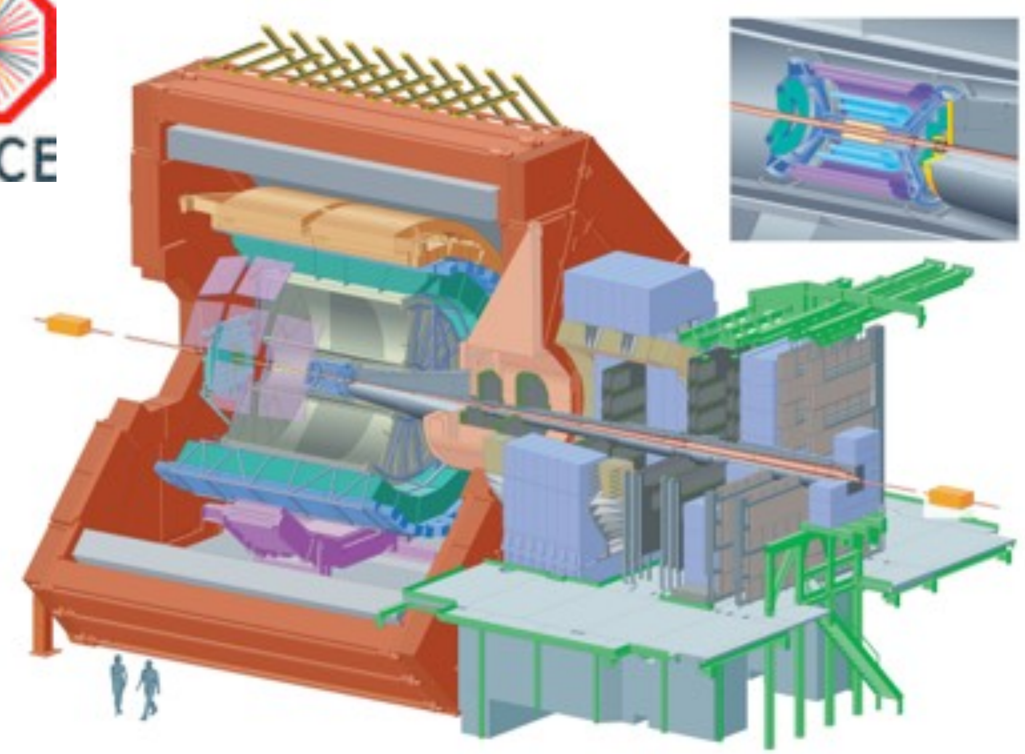
- Run 2 from 2015
  started @ $\sqrt{s}$ = 13 TeV
  (design 14 TeV)
- Recorded ~4 fb^{-1} in 2015
  2016 run to start soon!

The experiments

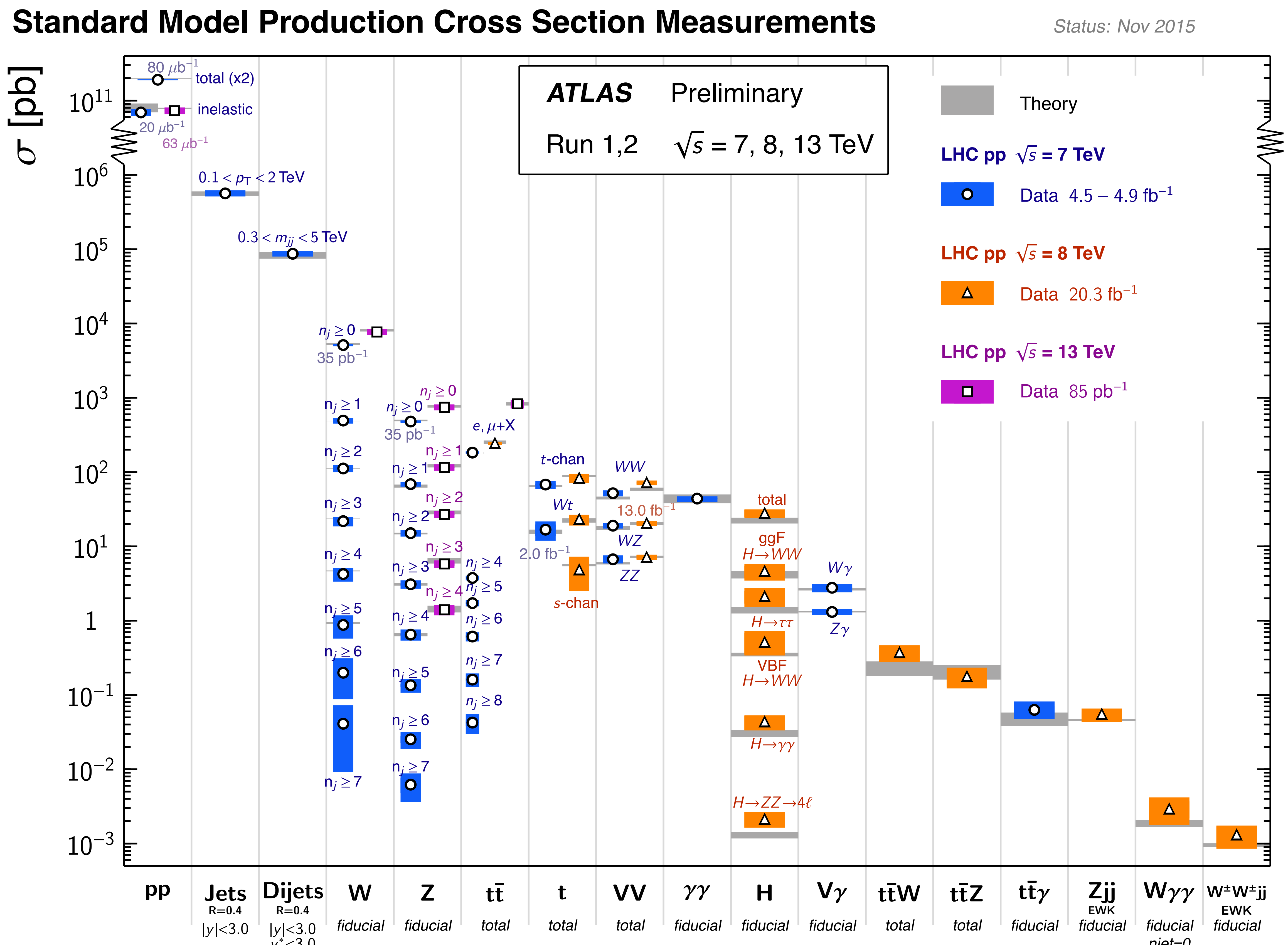




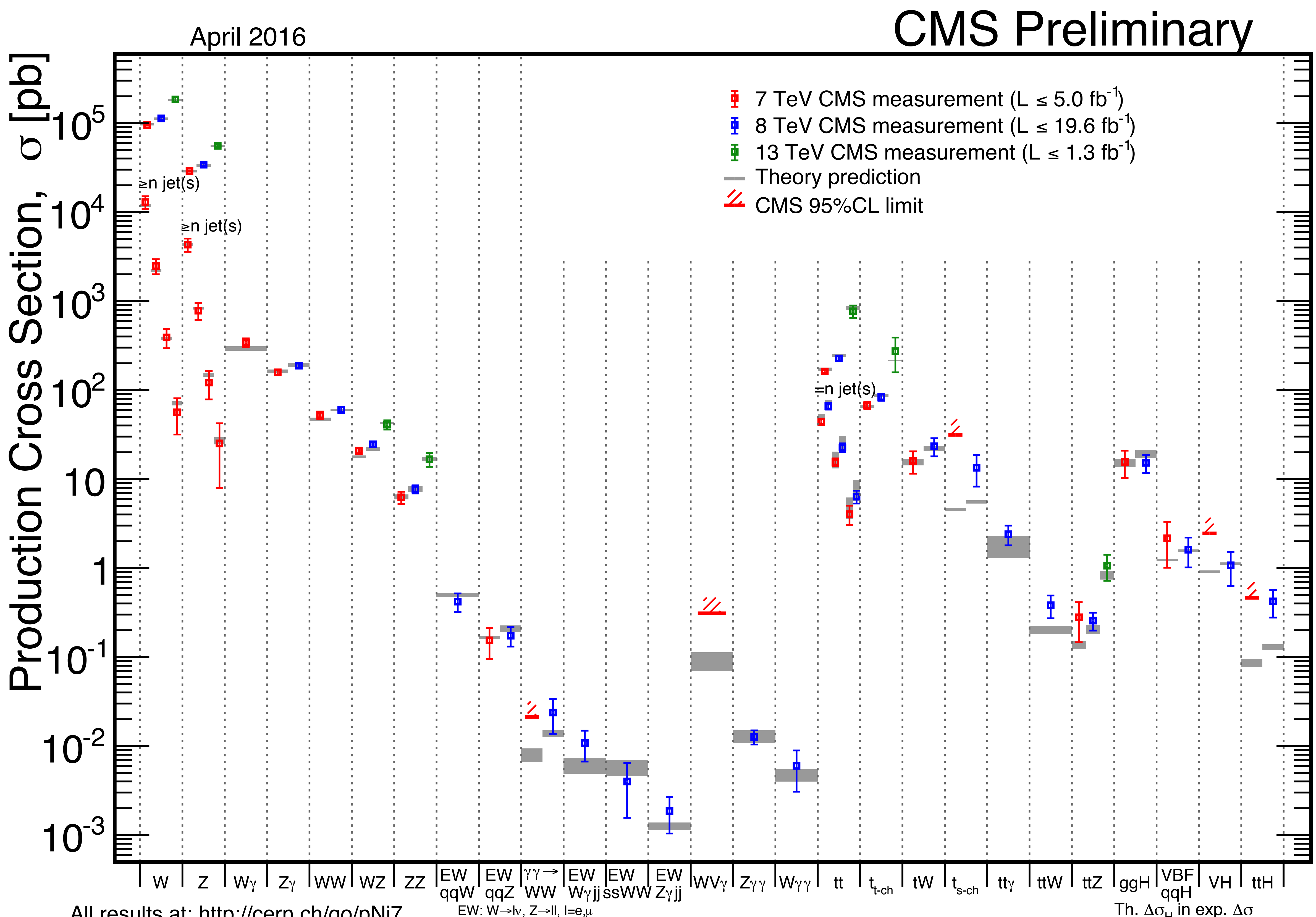




SM measurements - ATLAS



SM measurements - CMS



PDF sensitivity at LHC

- W/Z cross section, W asymmetry, W/Z p_T, W/Z+jets
- Drell-Yan $\gamma^*/Z \to$ lepton pair
- Inclusive jets, dijets, trijets, prompt photons
- Heavy quark production (especially top pair)
- W/Z + heavy quark (eg. W+c for strange quark)

arXiv:1507.00556

REACTION	OBSERVABLE	PDFS	x	Q
$pp \to W^\pm + X$	$d\sigma(W^\pm)/dy_l$	$q, \bar{q}$	$10^{-3} \lesssim x \lesssim 0.7$	$\sim M_W$
$pp \to \gamma^*/Z + X$	$d^2\sigma(\gamma^*/Z)/dy_{ll}dM_{ll}$	$q, \bar{q}$	$10^{-3} \lesssim x \lesssim 0.7$	$5 \text{ GeV} \lesssim Q \lesssim 2 \text{ TeV}$
$pp \to \gamma^*/Z + \text{jet} + X$	$d\sigma(\gamma^*/Z)/dp_T^{ll}$	q, g	$10^{-2} \lesssim x \lesssim 0.7$	$200 \text{ GeV} \lesssim Q \lesssim 1 \text{ TeV}$
$pp \to \text{jet} + X$	$d\sigma(\text{jet})/dp_T dy$	q, g	$10^{-2} \lesssim x \lesssim 0.8$	$20 \text{ GeV} \lesssim Q \lesssim 3 \text{ TeV}$
$pp \to \text{jet} + \text{jet} + X$	$d\sigma(\text{jet})/dM_{jj}dy_{jj}$	q, g	$10^{-2} \lesssim x \lesssim 0.8$	$500 \text{ GeV} \lesssim Q \lesssim 5 \text{ TeV}$
$pp \to t\bar{t} + X$	$\sigma(t\bar{t}), d\sigma(t\bar{t})/dM_{t\bar{t}}, ...$	g	$0.1 \lesssim x \lesssim 0.7$	$350 \text{ GeV} \lesssim Q \lesssim 1 \text{ TeV}$
$pp \to c\bar{c} + X$	$d\sigma(c\bar{c})/dp_{T,c}dy_c$	g	$10^{-5} \lesssim x \lesssim 10^{-3}$	$1 \text{ GeV} \lesssim Q \lesssim 10 \text{ GeV}$
$pp \to b\bar{b} + X$	$d\sigma(b\bar{b})/dp_{T,c}dy_c$	g	$10^{-4} \lesssim x \lesssim 10^{-2}$	$5 \text{ GeV} \lesssim Q \lesssim 30 \text{ GeV}$
$pp \to W + c$	$d\sigma(W + c)/d\eta_l$	$s, \bar{s}$	$0.01 \lesssim x \lesssim 0.5$	$\sim M_W$

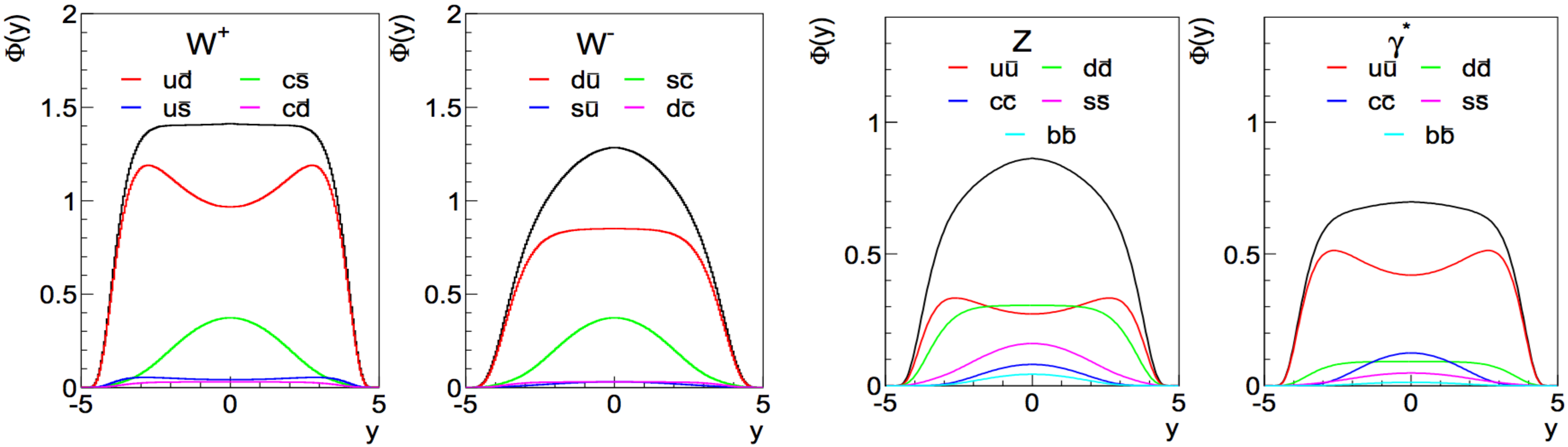
Vector bosons at LHC

Flavour decomposition at LHC (EW bosons)

Additional constraints on PDFs come from DY and jet data at the LHC probe a bi-linear combination of quarks

$$x_1 = \frac{M}{\sqrt{s}} e^{+y}$$
$$x_2 = \frac{M}{\sqrt{s}} e^{-y}$$

$$W^+ \quad \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \quad \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$
$$Z \quad \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$
$$\gamma^* \quad \sim 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$

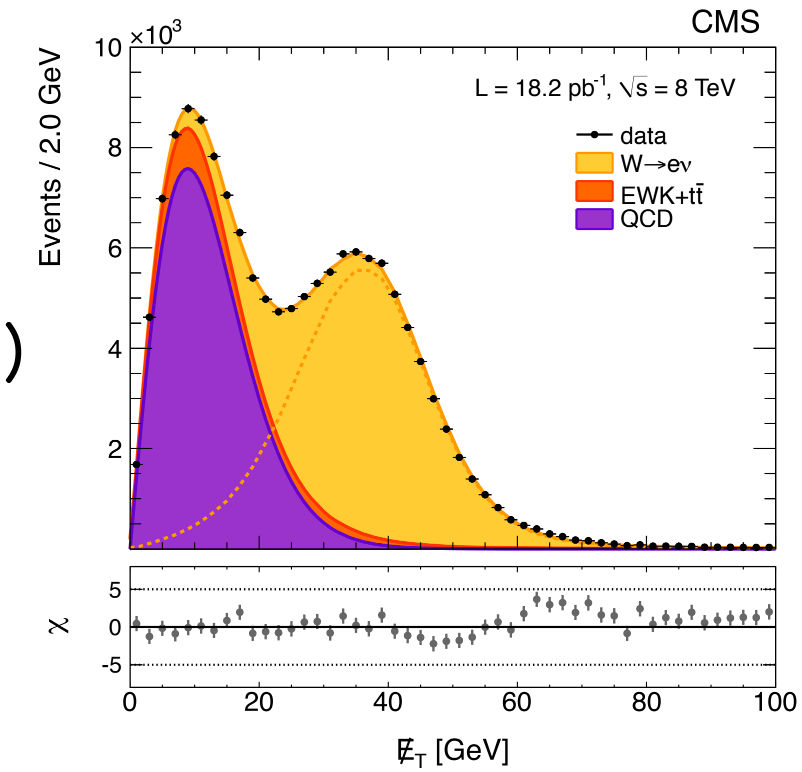


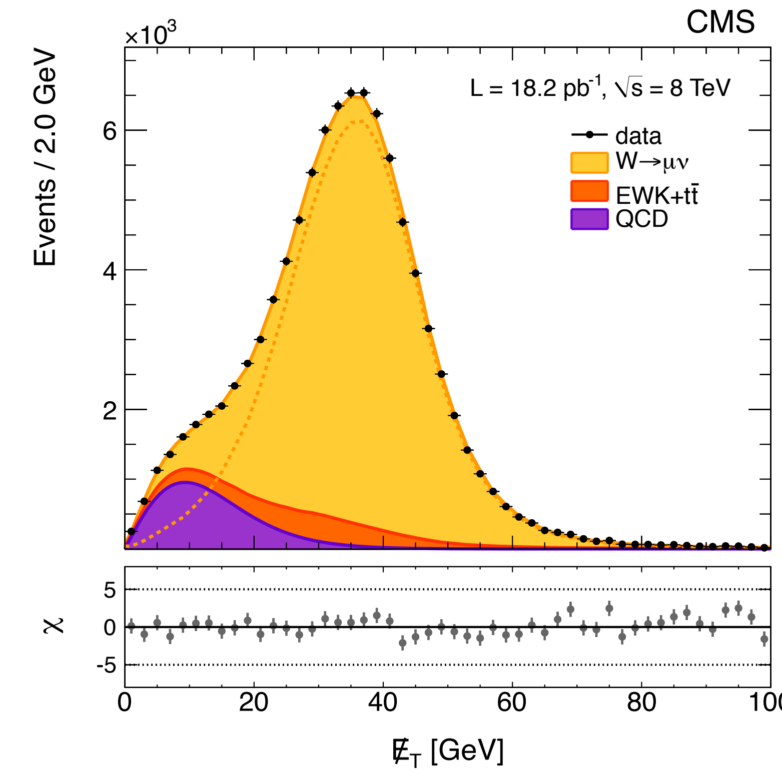
Measurements of W, Z production differentially in y_Z and η_ℓ provide information on light sea decomposition

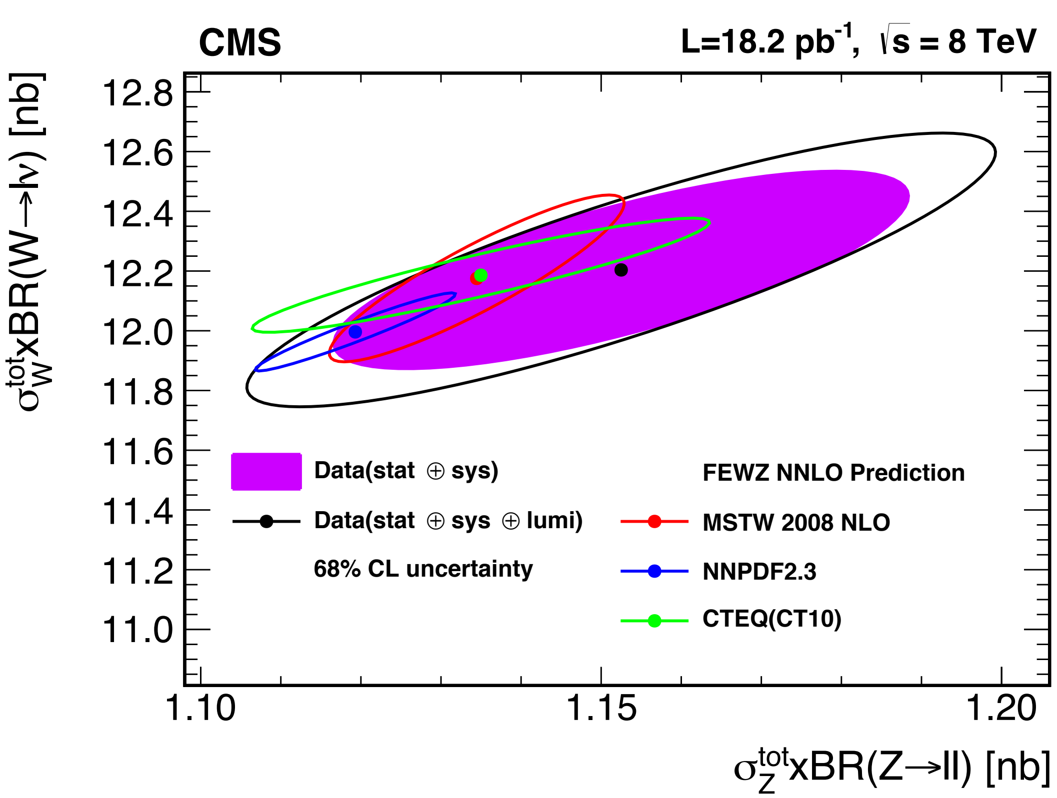
Inclusive W/Z at 8 TeV

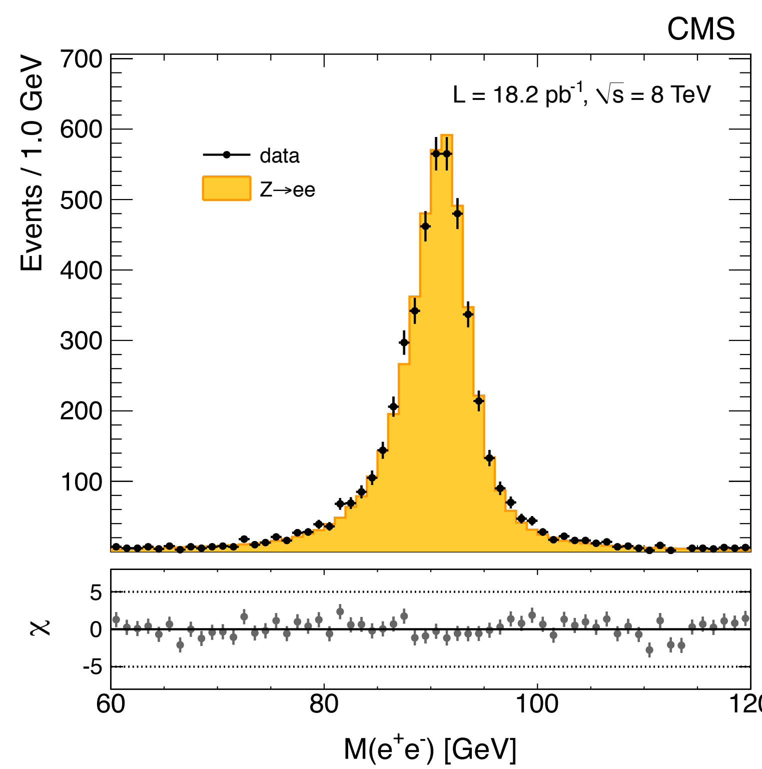
arXiv:1402.0923 PRL112 (2014) 191802

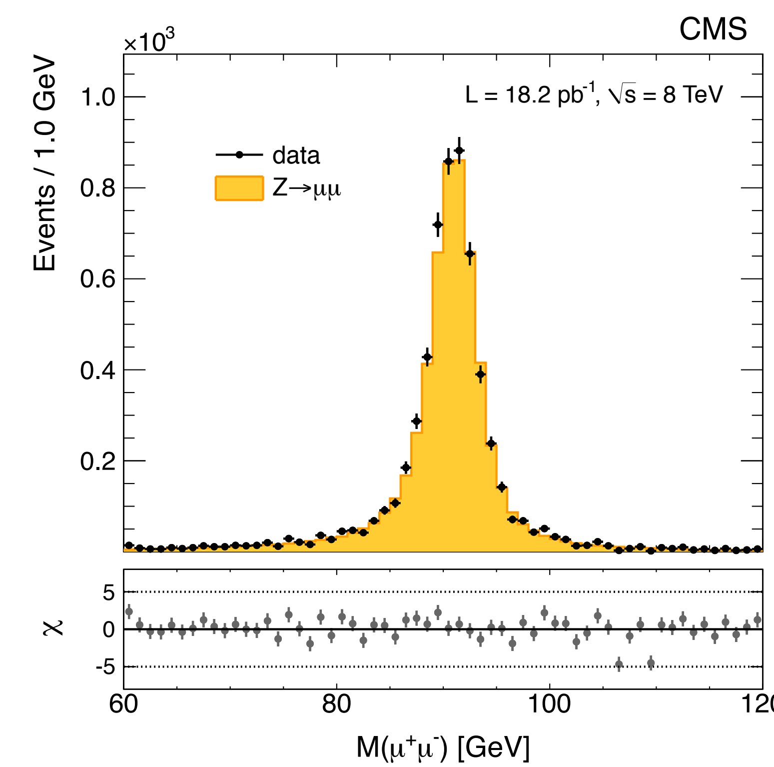
- Special data set with low pile-up
  - $R_{W/Z}$ = 10.63±0.11(stat.)±0.25(syst.) (FEWZ NNLO: 10.74±0.04)
  - R_{W^+/W^-} = 1.39±0.01(stat.)±0.02(syst.) (FEWZ NNLO: 1.41±0.01)







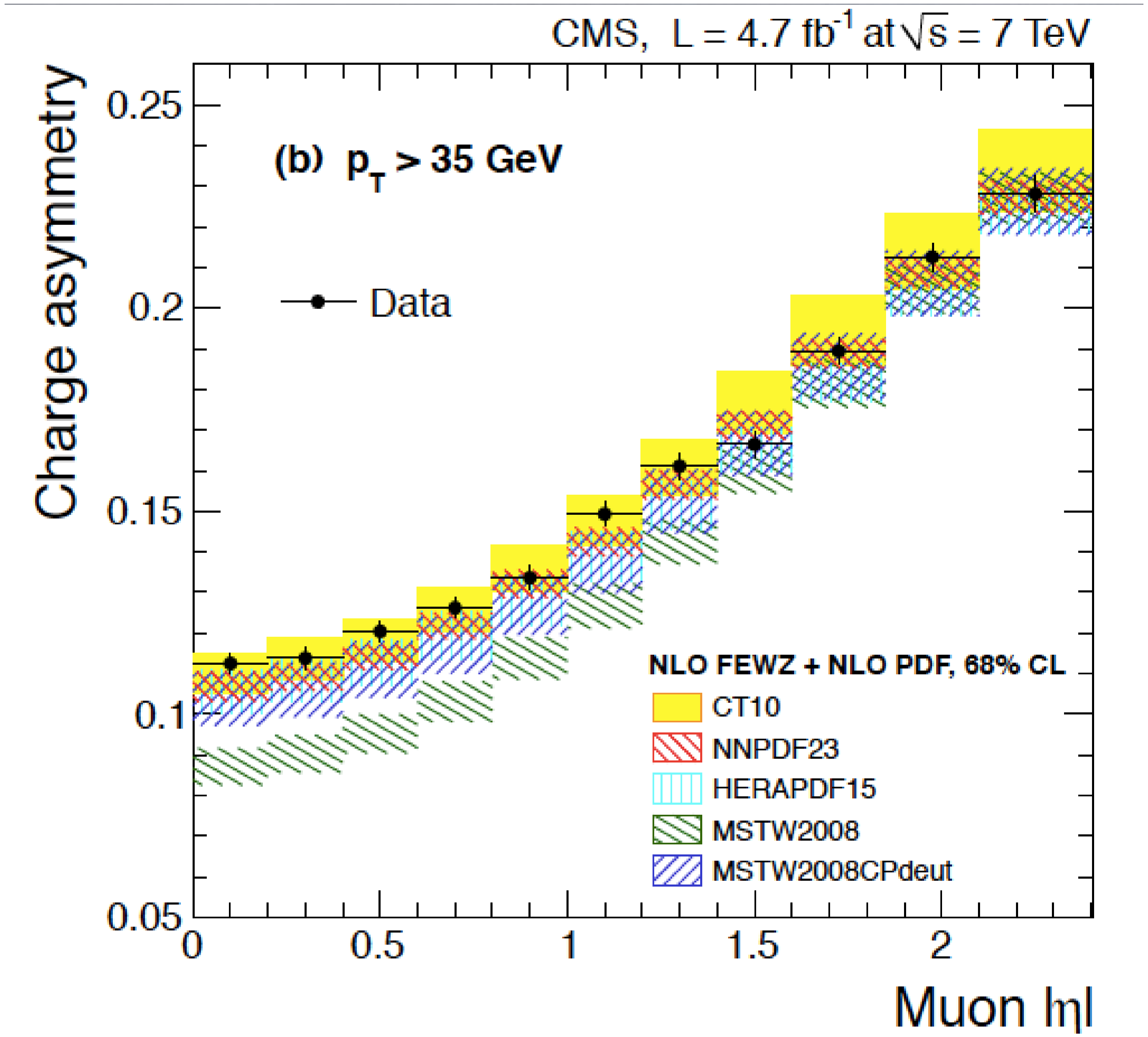


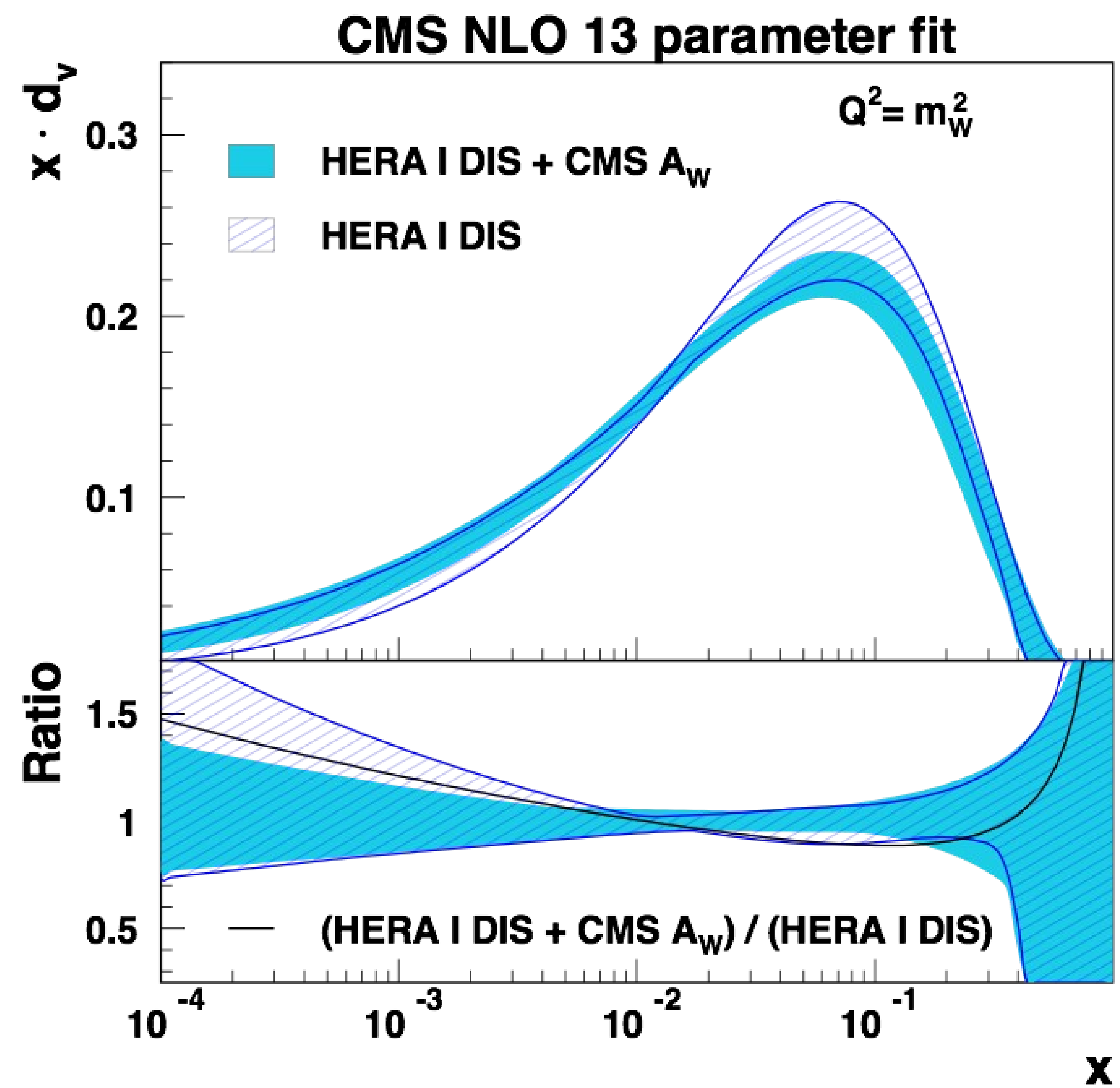


W charge asymmetry

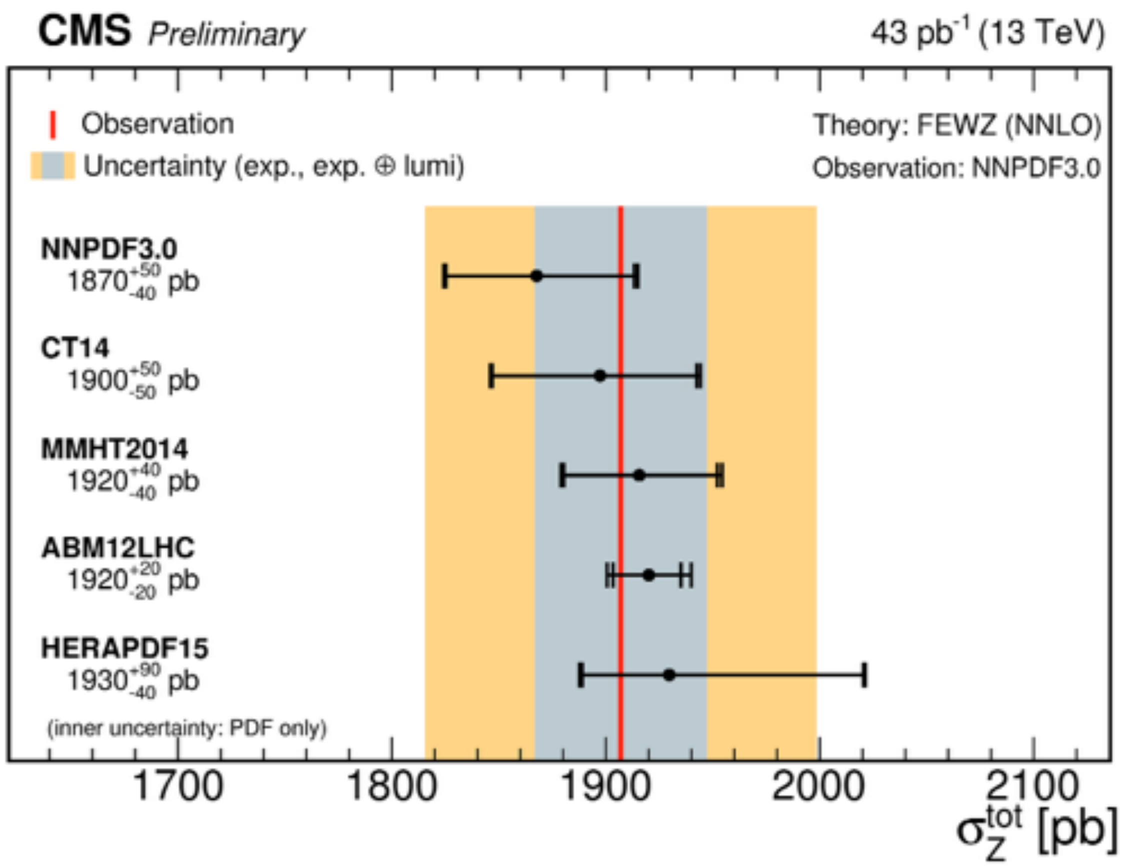
- $A=(\sigma^{+}-\sigma^{-})/(\sigma^{+}+\sigma^{-})$ as a function of lepton η
- Impressive improvement on valence PDF (u and d)

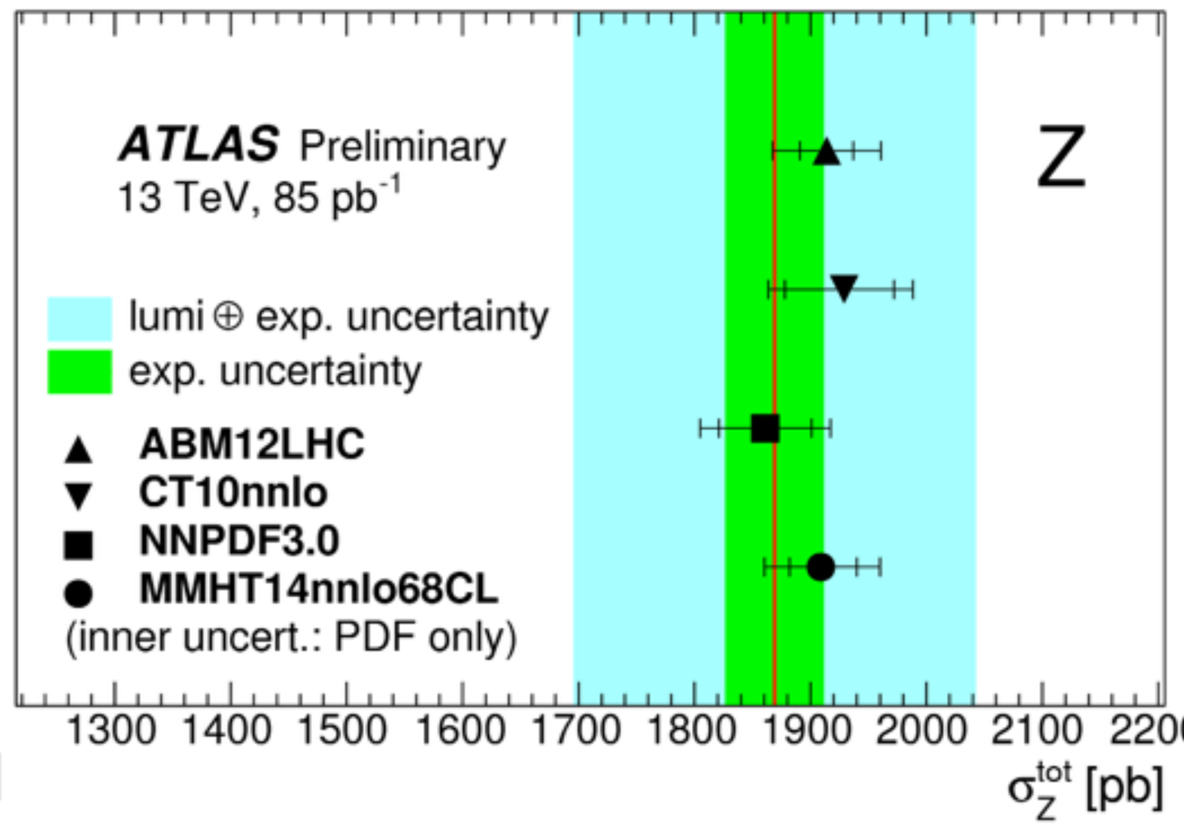
PRL109(2012)111806

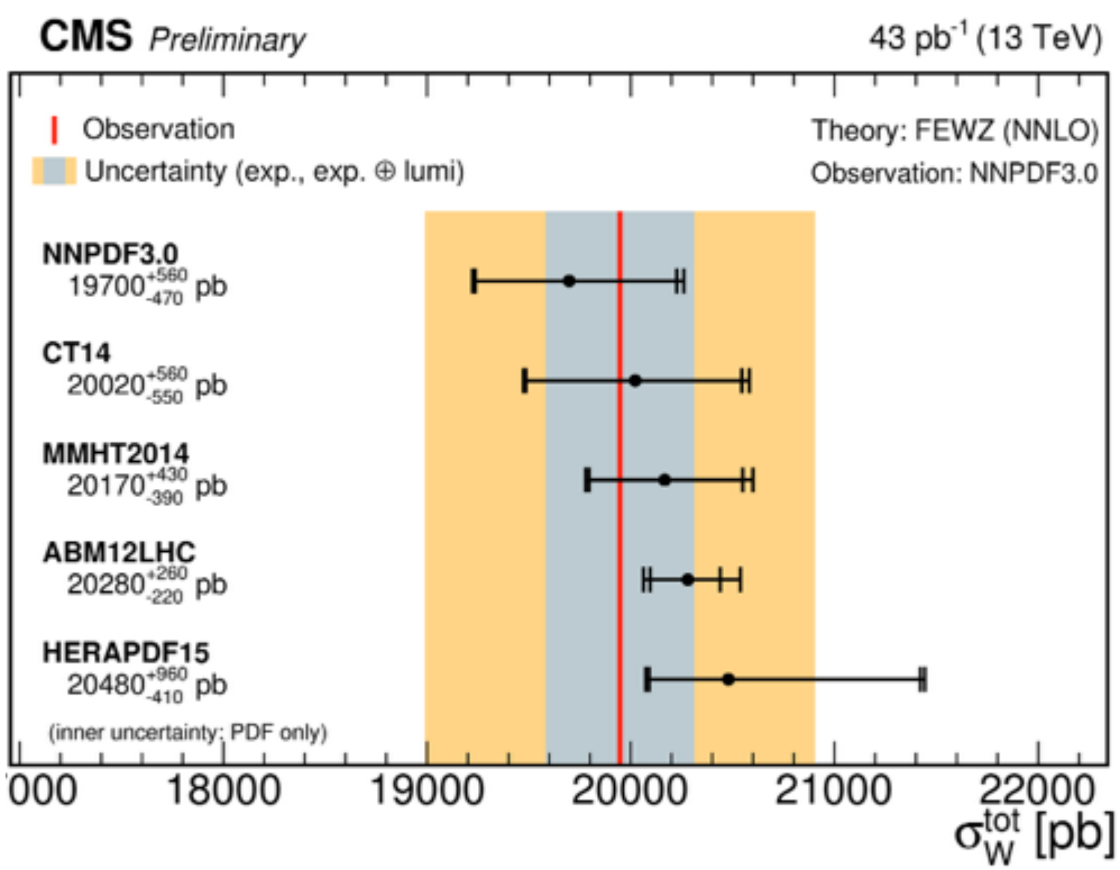


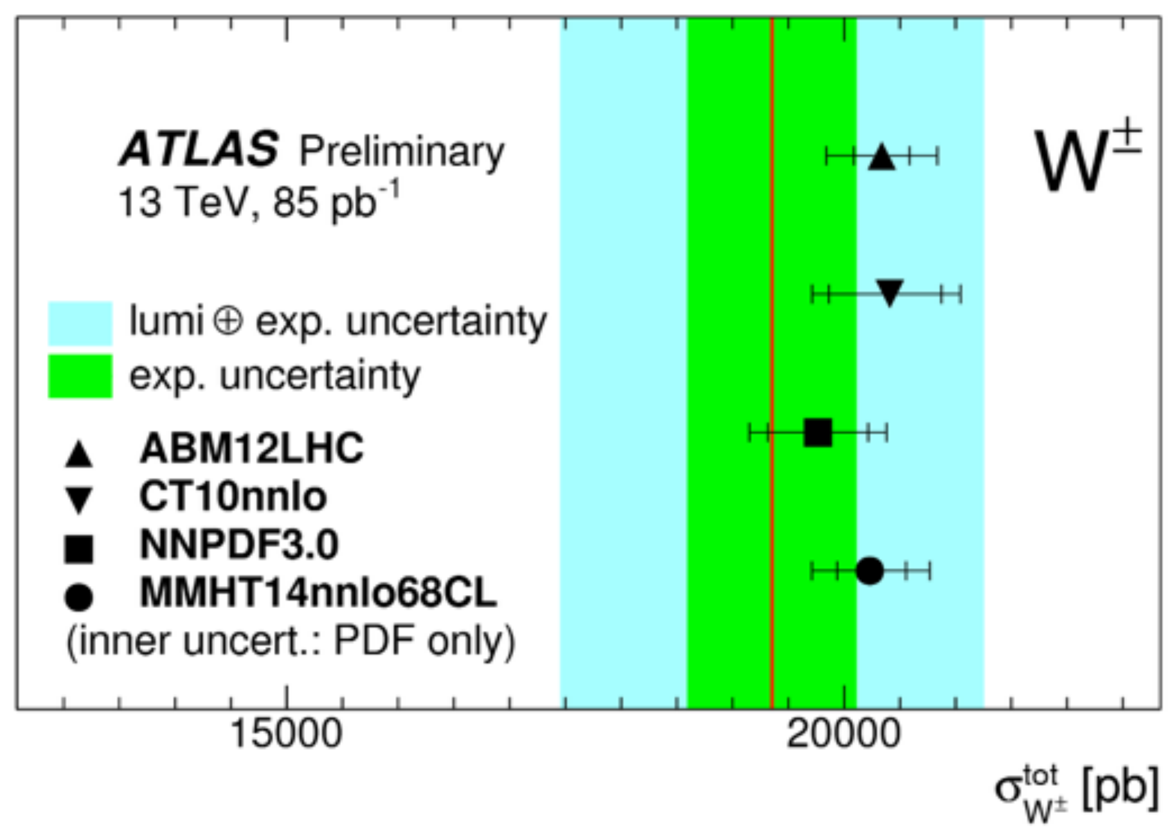


13TeV results @Moriond

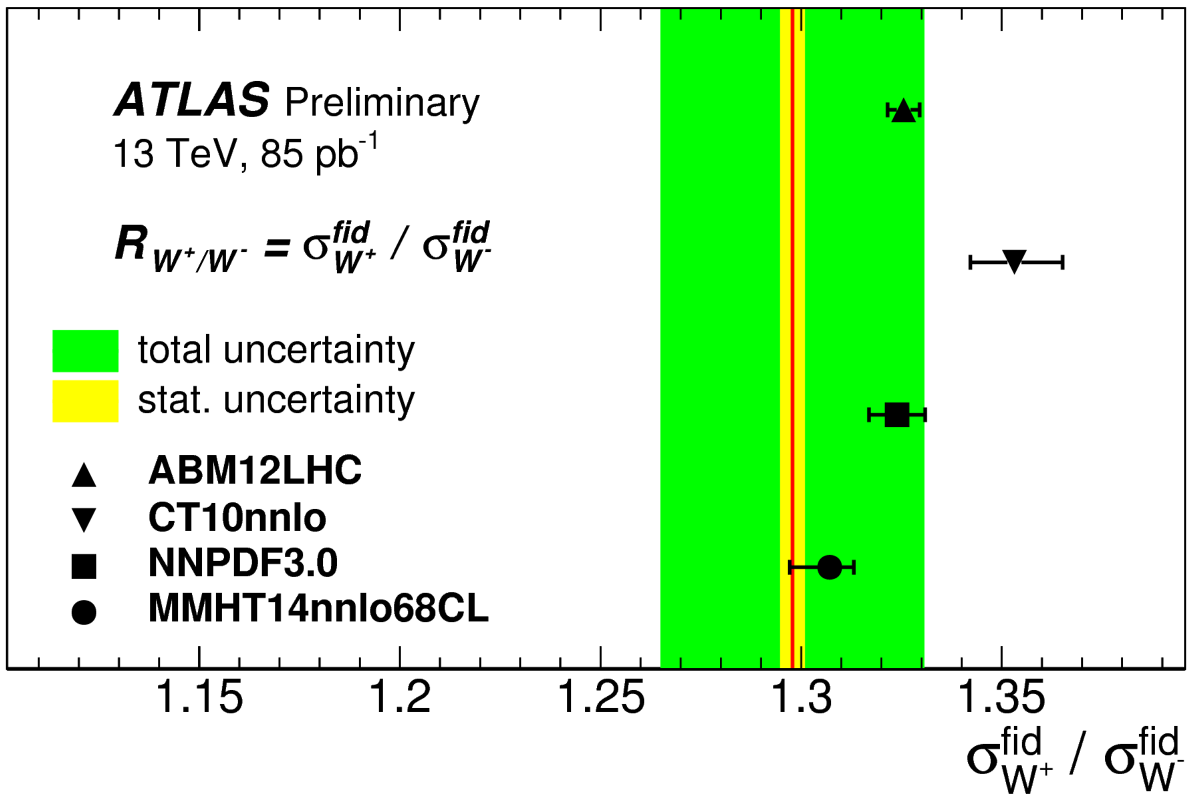


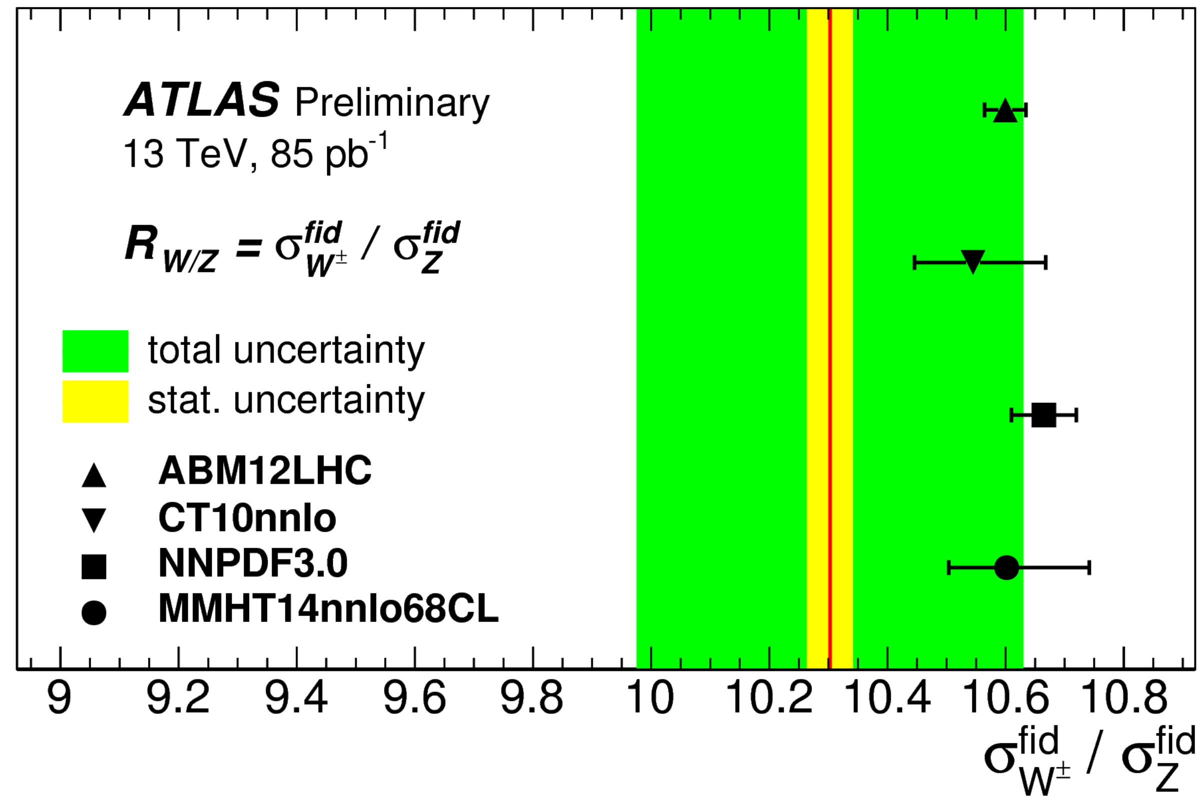


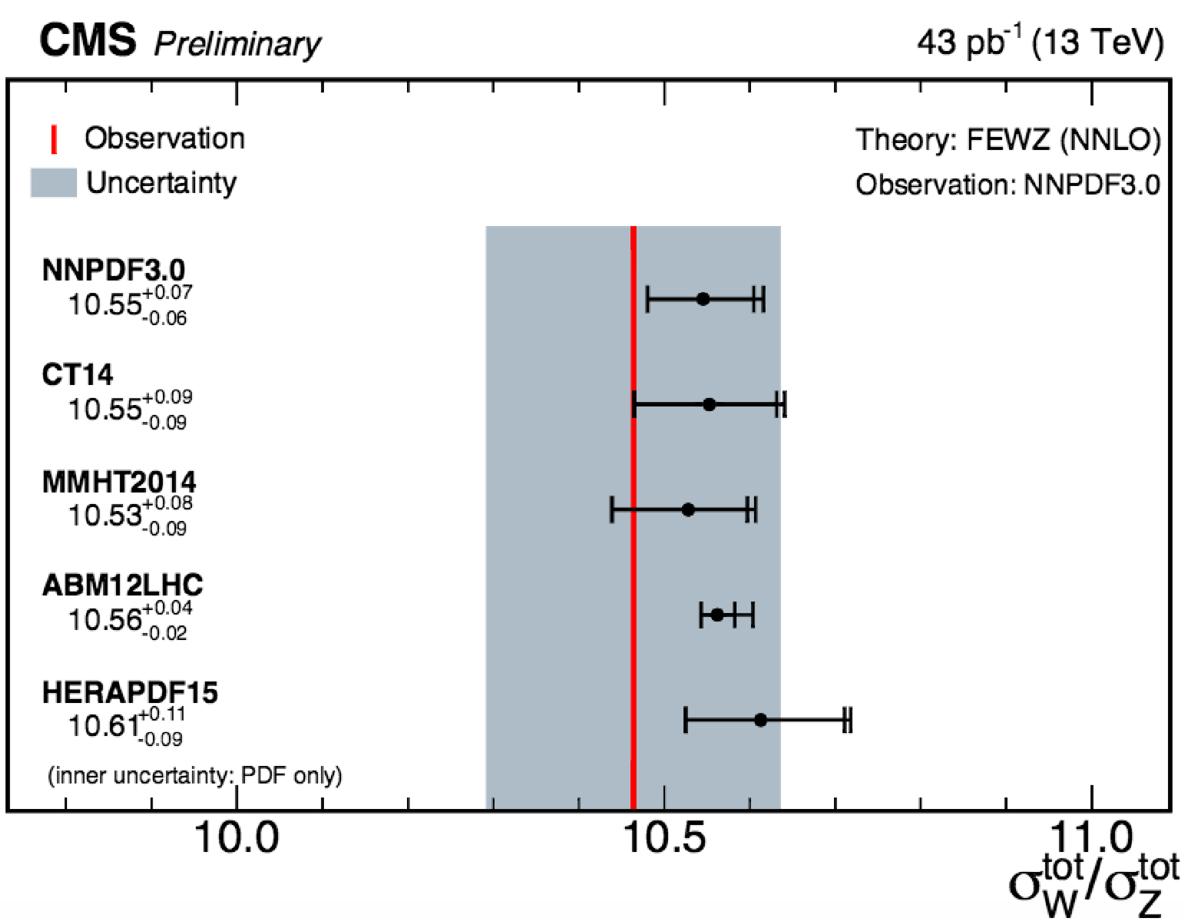


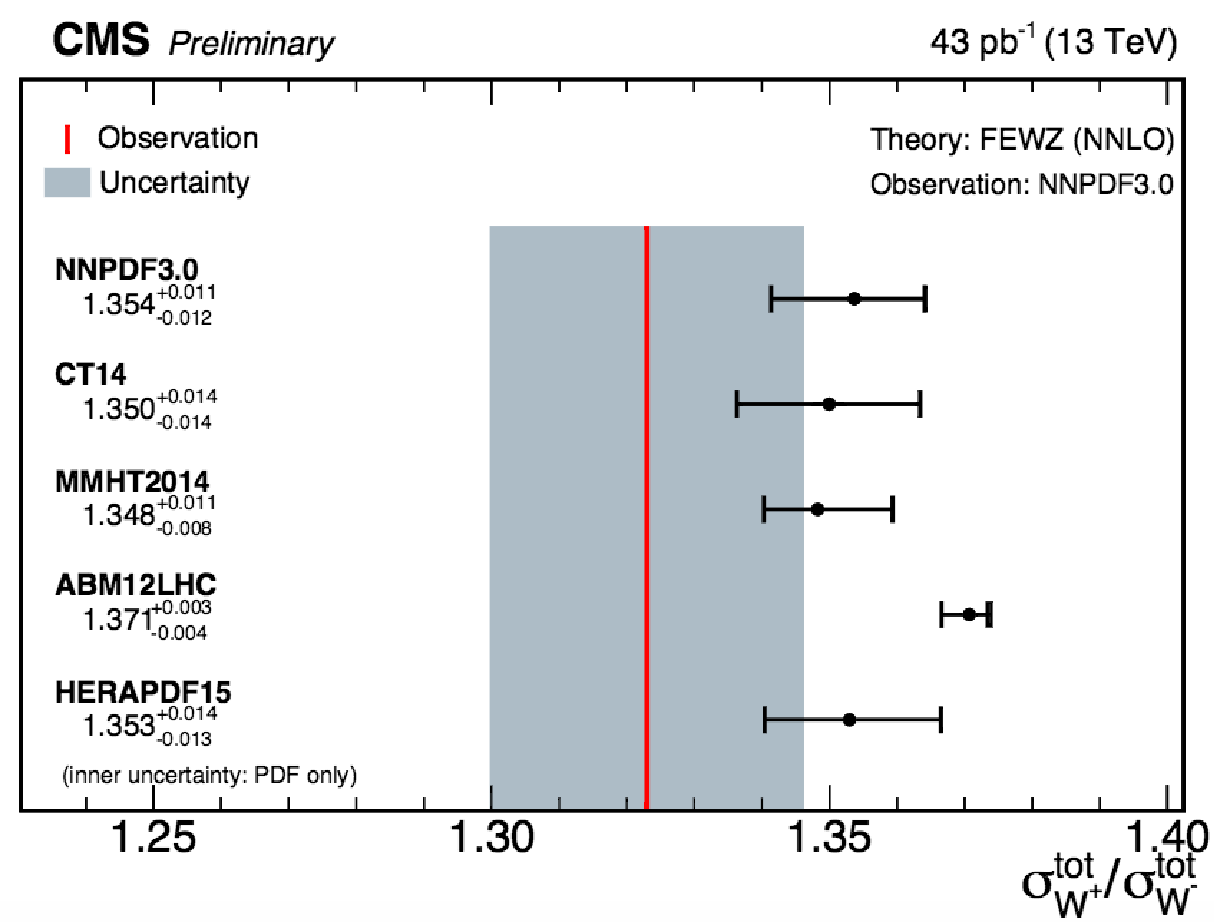


13TeV results - ratios



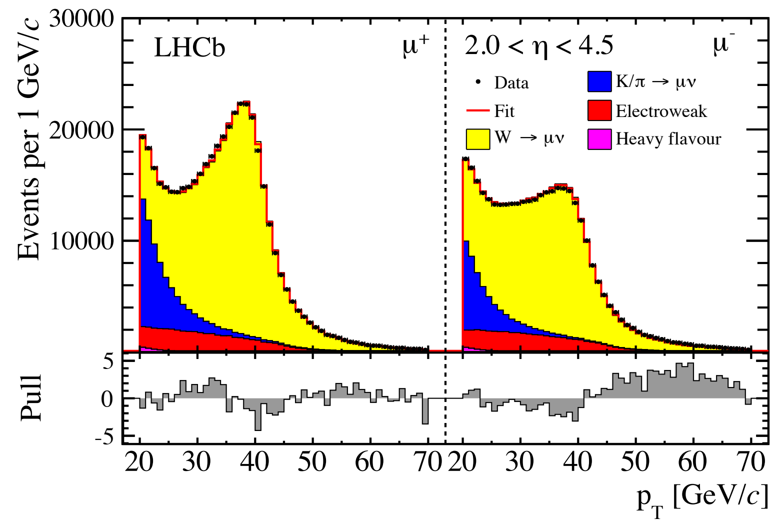


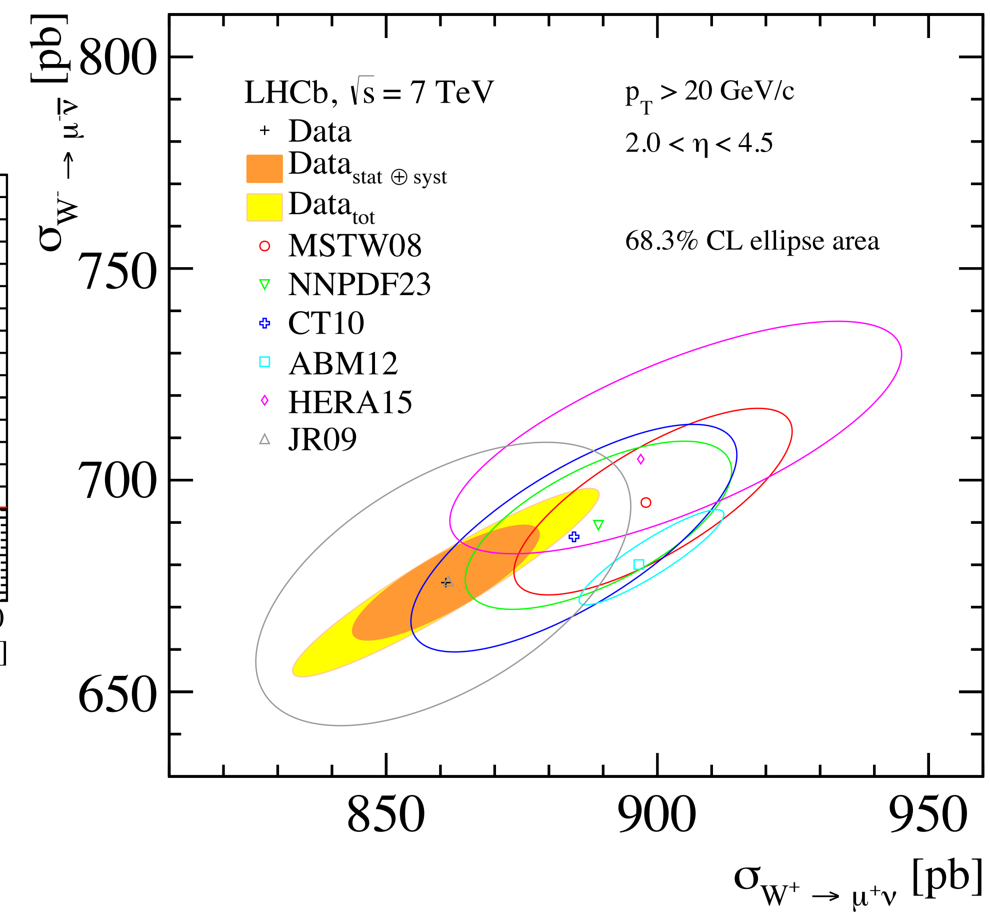




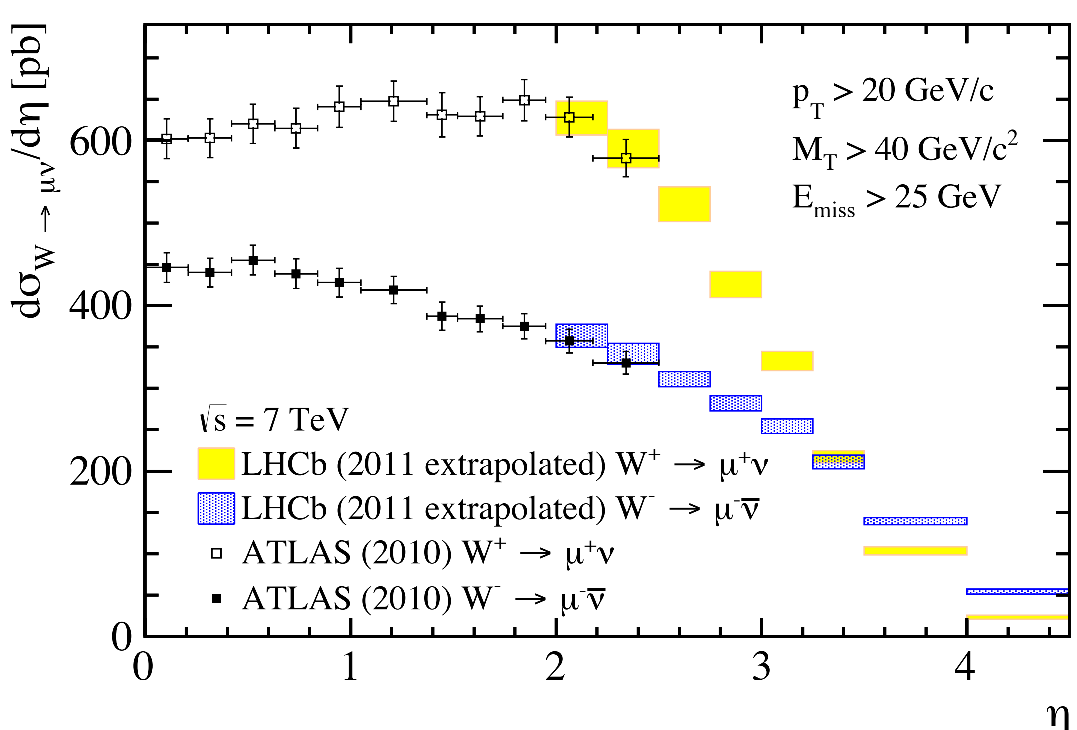
Forward W in LHCb

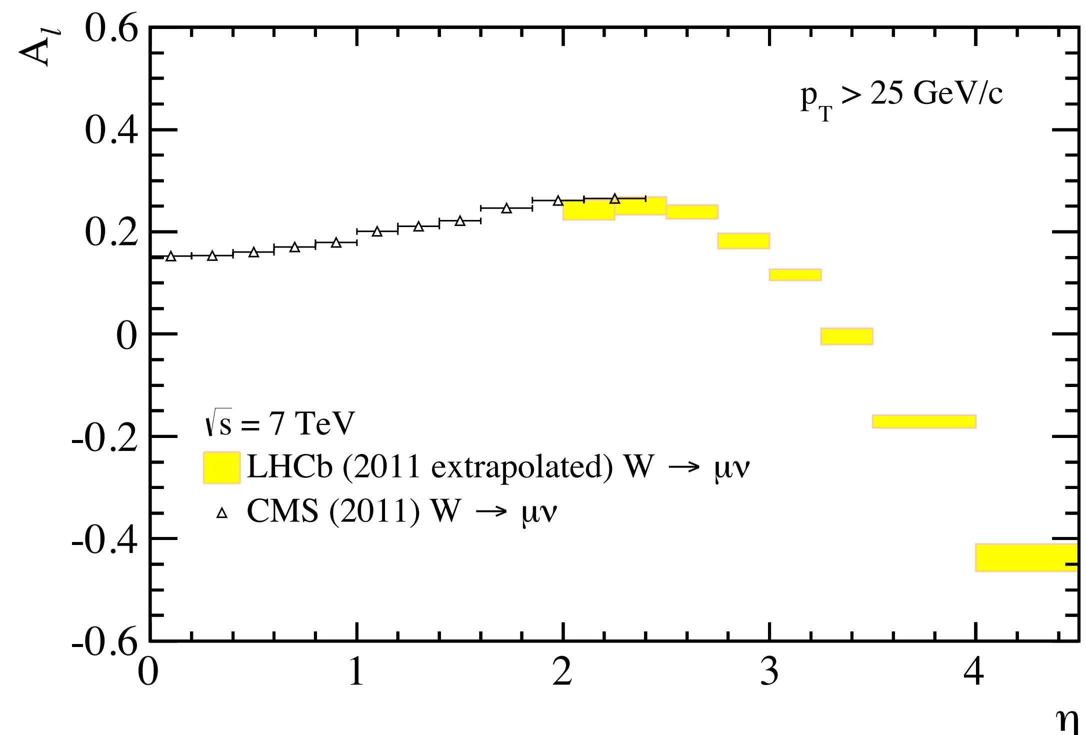
- Acceptance in 2<η(μ)<5 (η=-ln tan θ/2)
- Sensitive to PDF
- Nicely extends ATLAS/CMS measurements to larger η





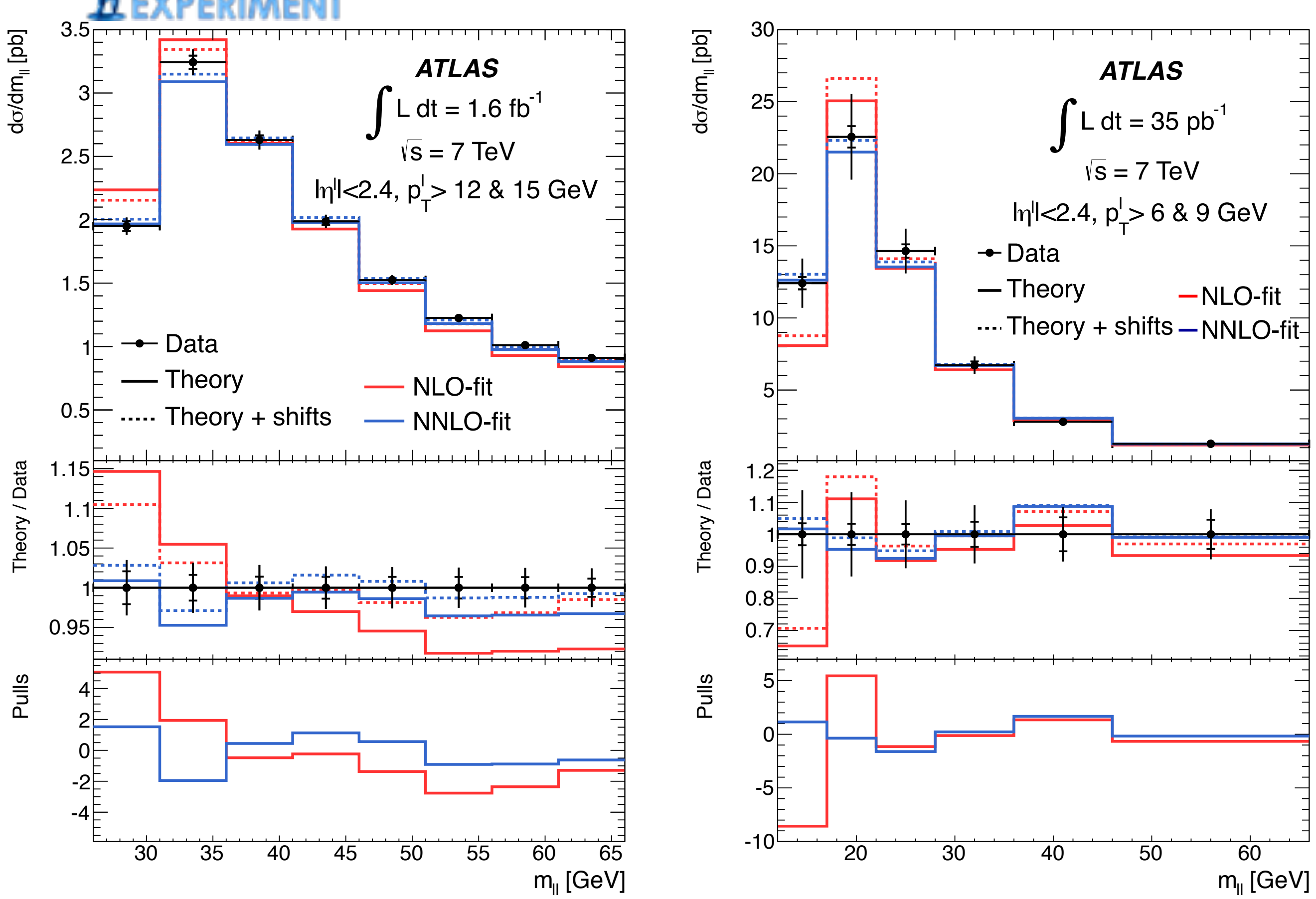
arXiv:1408.4354



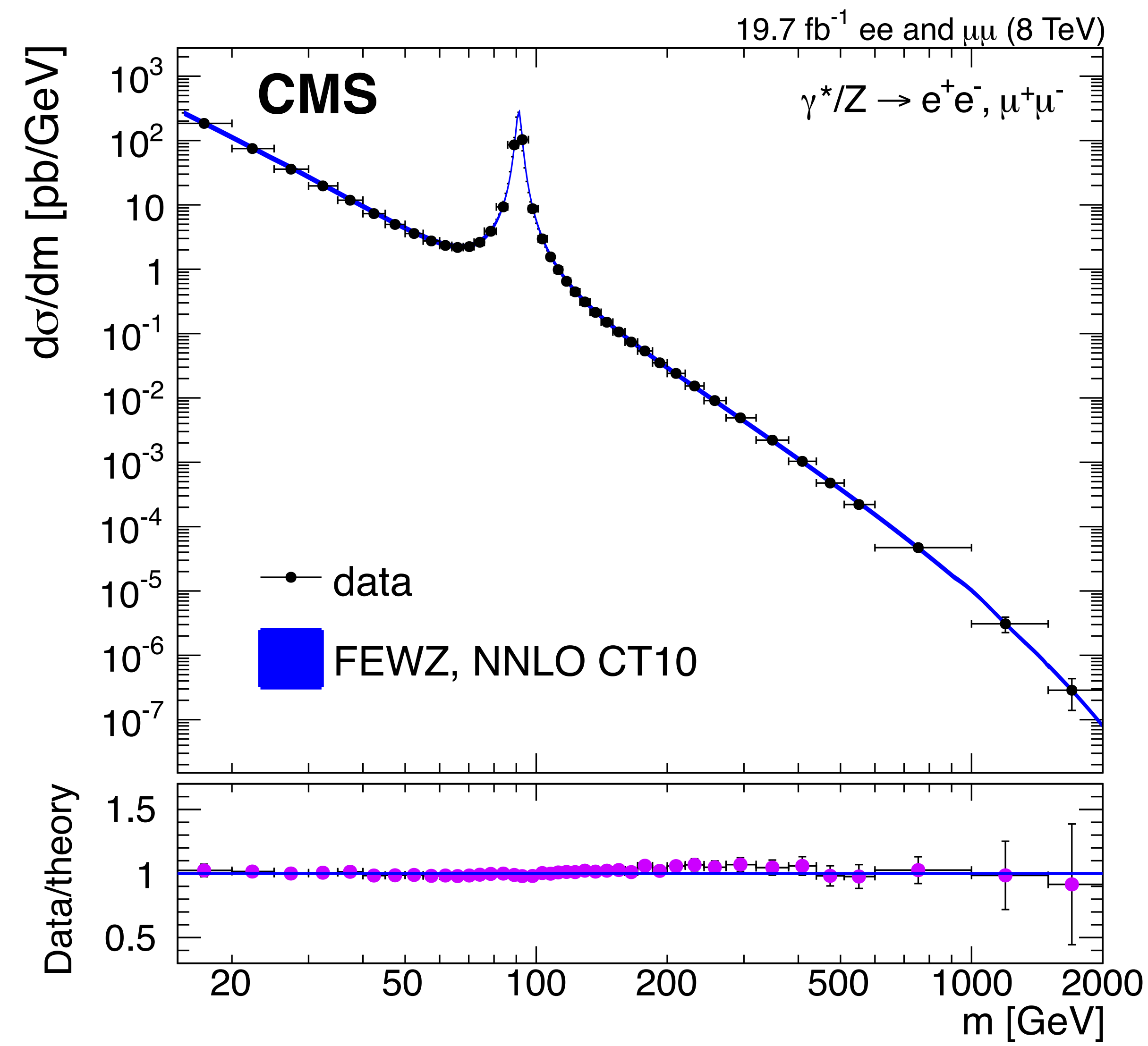


Drell-Yan cross sections

- $q\bar{q} \rightarrow \gamma^*/Z \rightarrow e^+e^-,\ \mu^+\mu^-$
  - ATLAS paper @low-mass (incl. low-p_T events in 2010)
  - CMS results @8TeV (double diff. $d^2\sigma/dm\,d|y|$)
- NNLO describes data

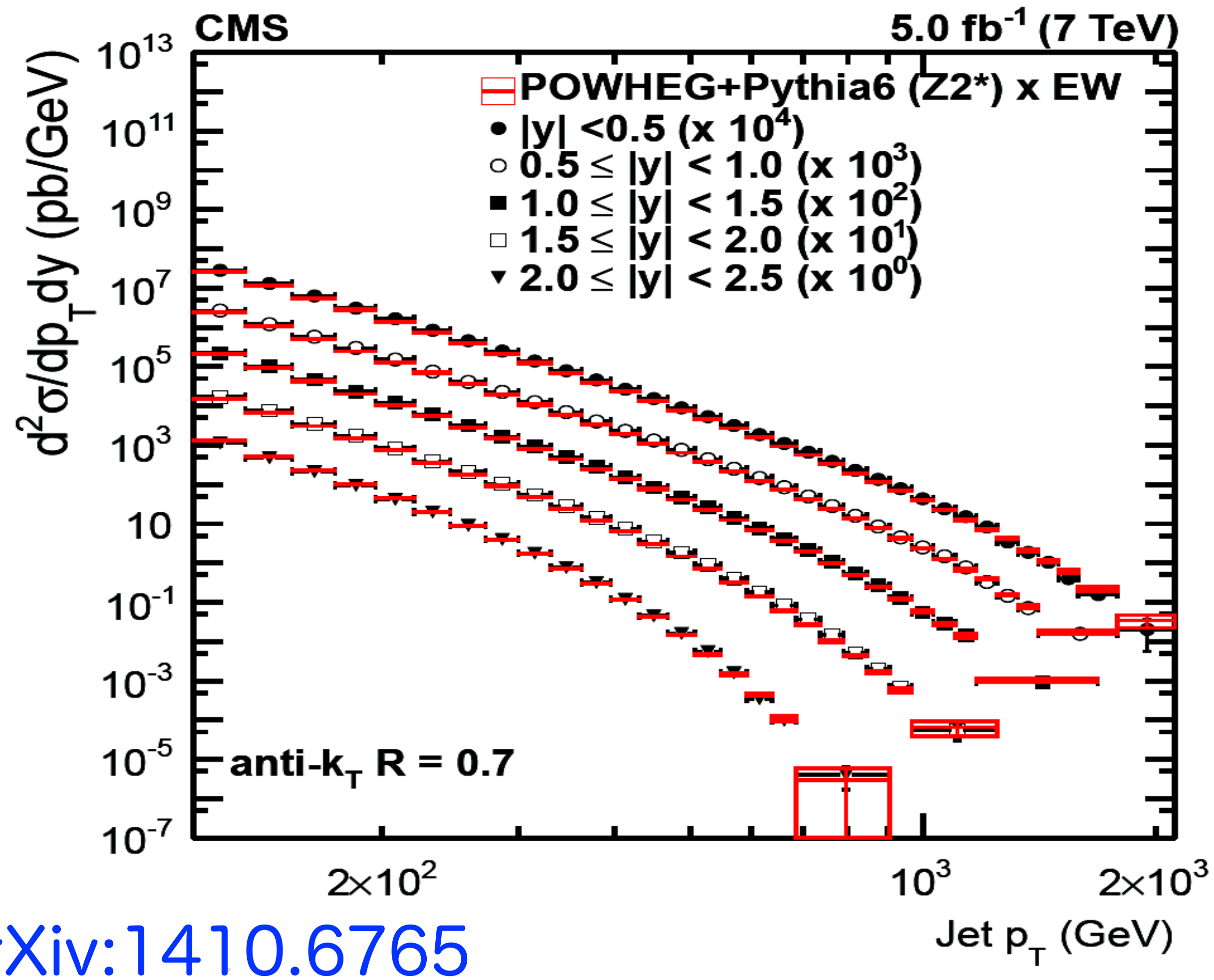


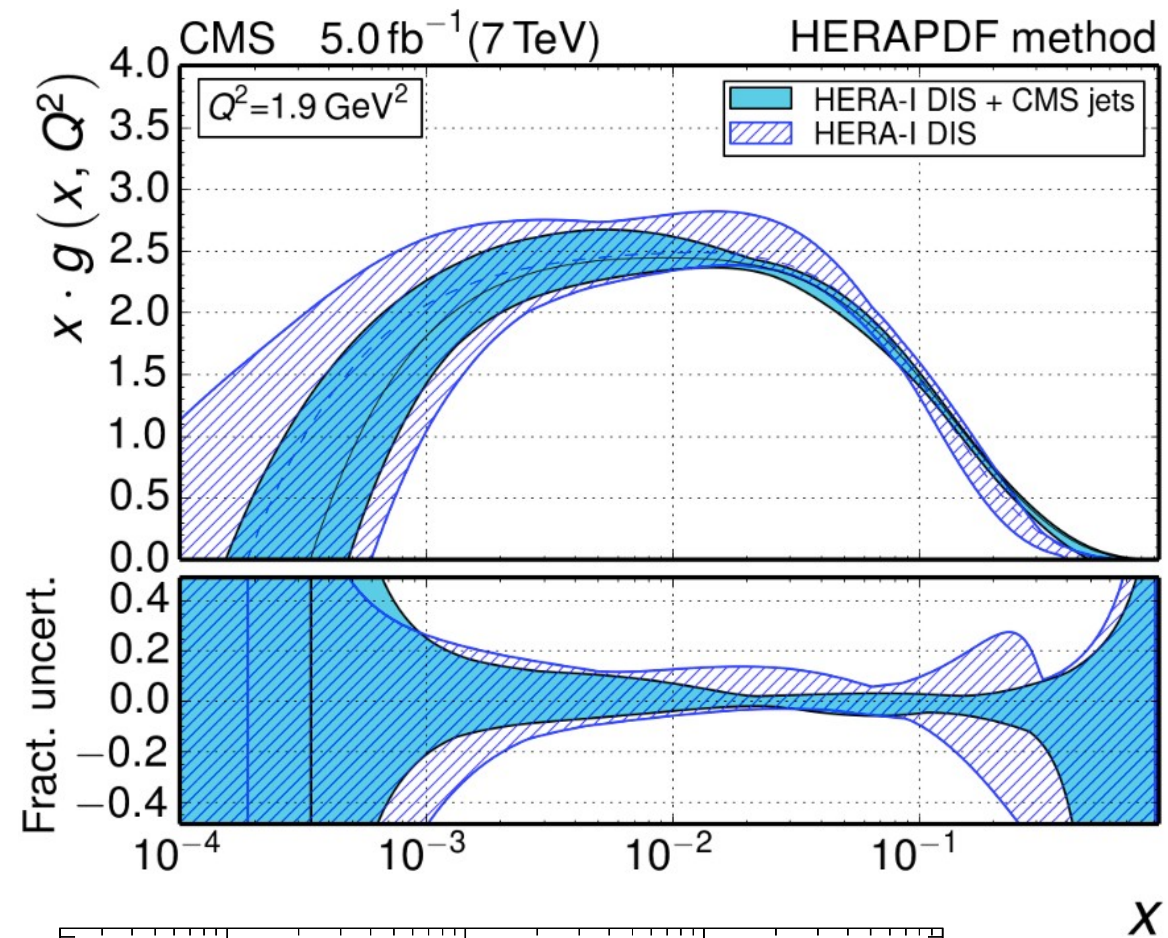
arXiv:1404.1212 JHEP06 (2014) 112



arXiv:1412.1115 EPJC 75 (2015) 147

Inclusive jet production



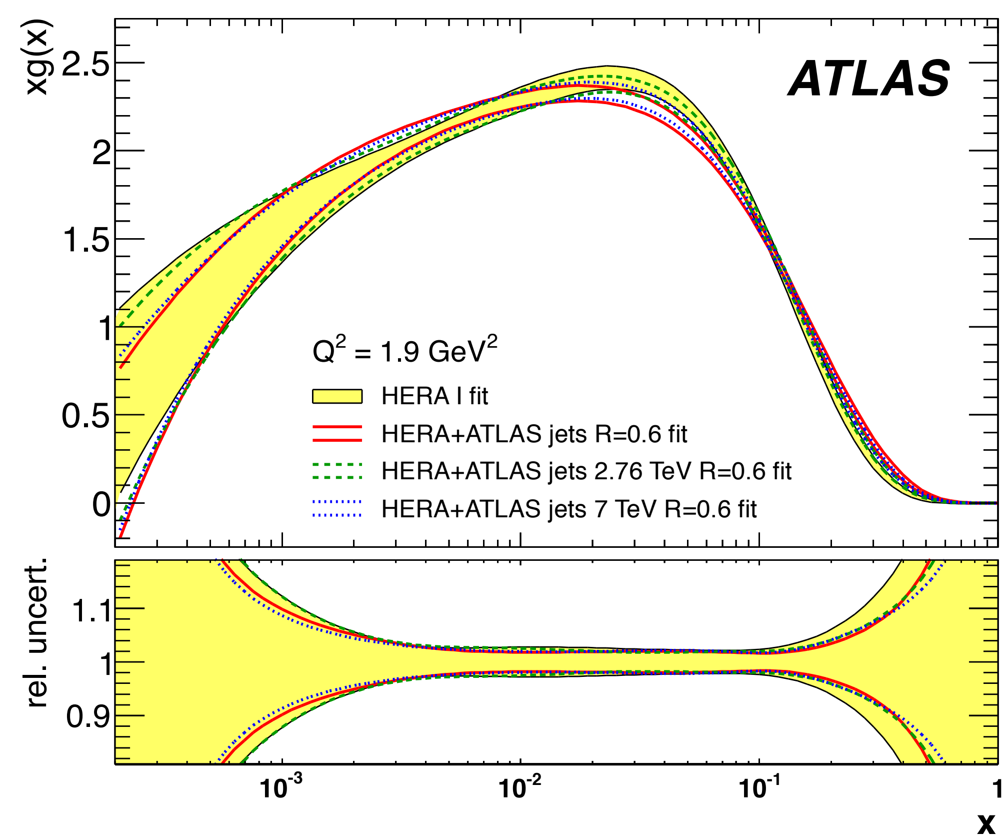


arXiv:1410.6765

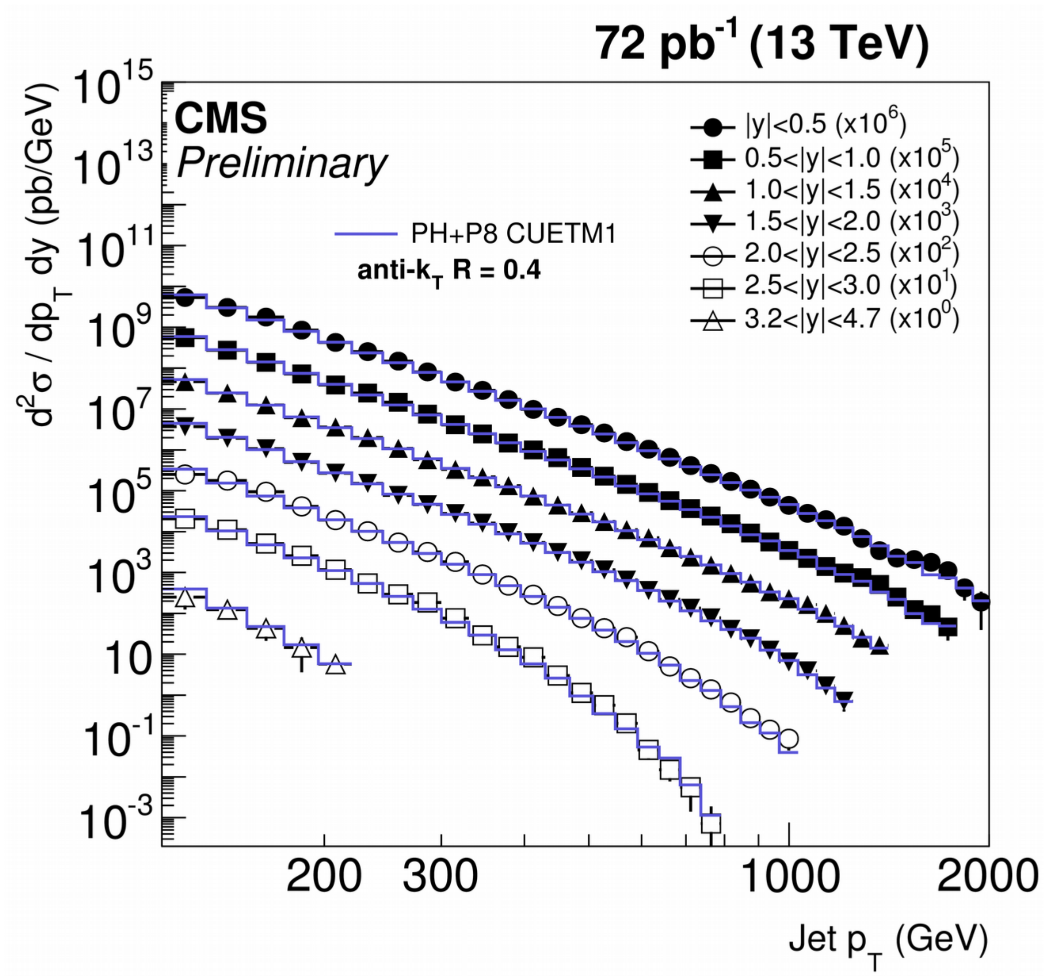
- up to jet pT~2TeV
- improves gluon PDF

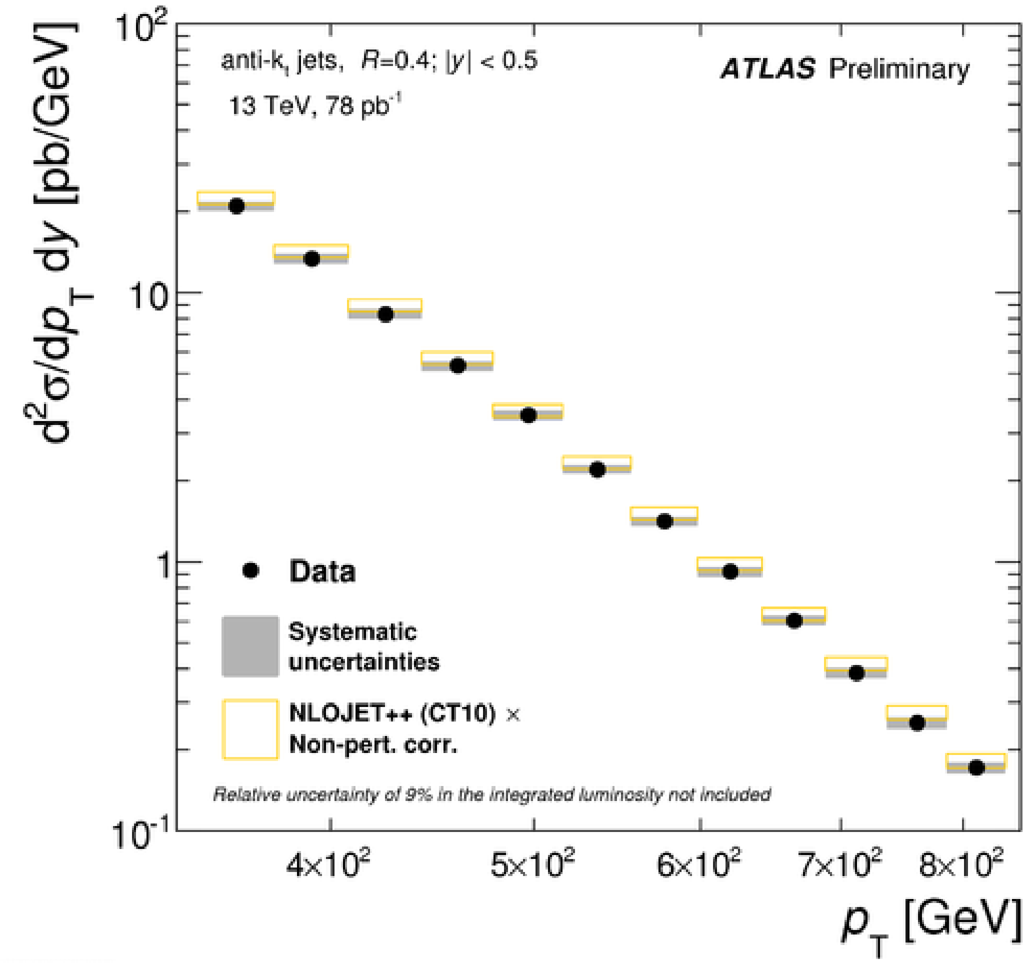
EPJC 73(2013)2509

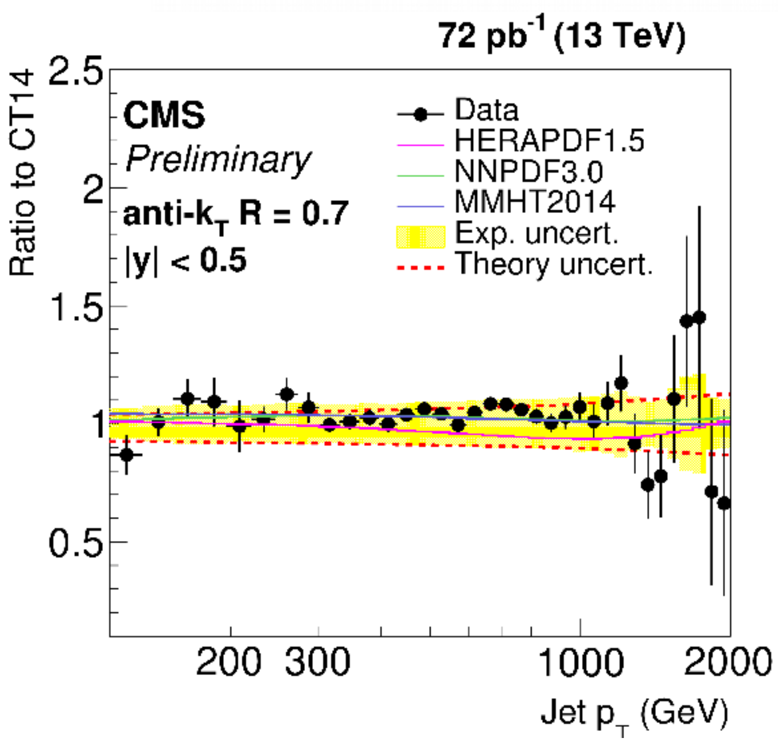
- ATLAS: ratio of 2.76TeV and 7TeV

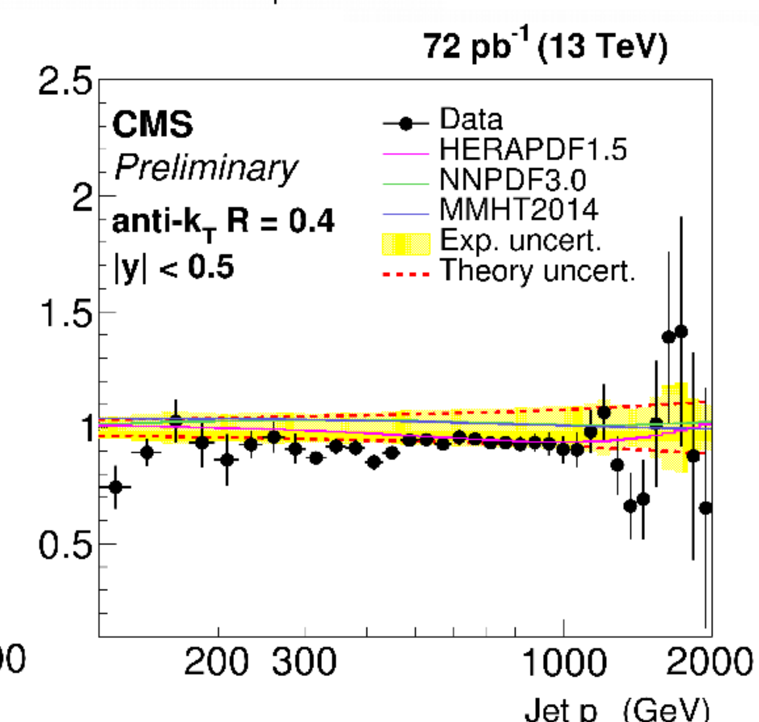


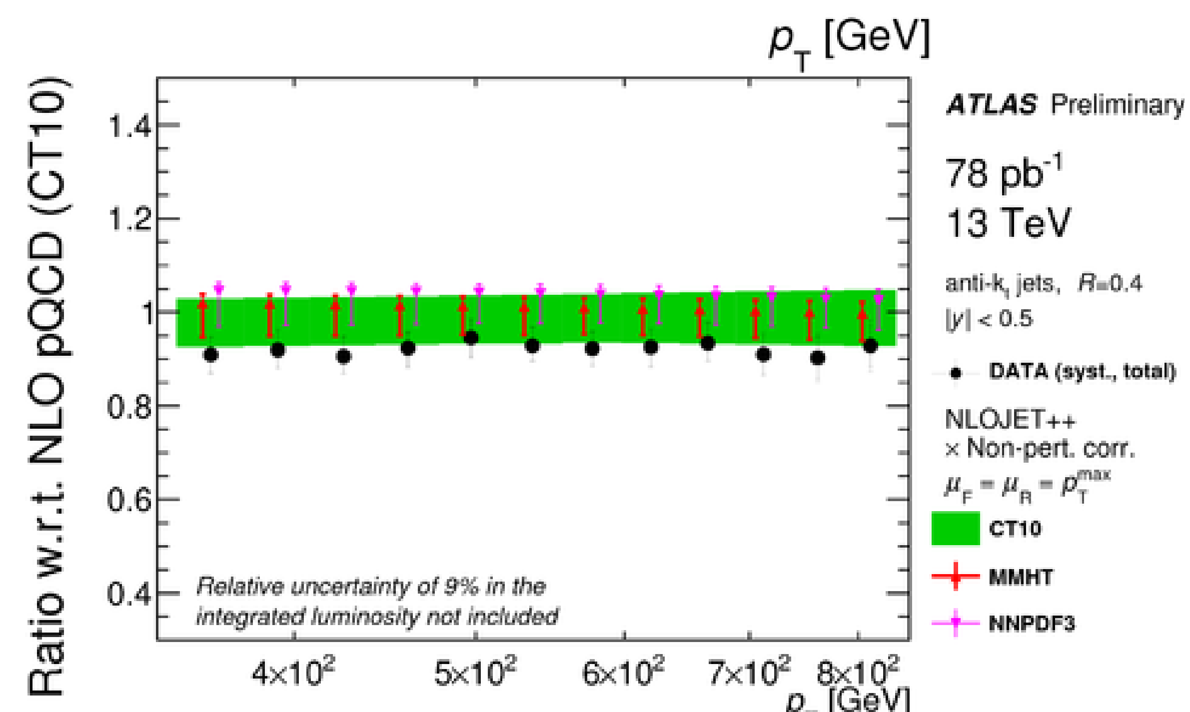
Inclusive jets @13TeV









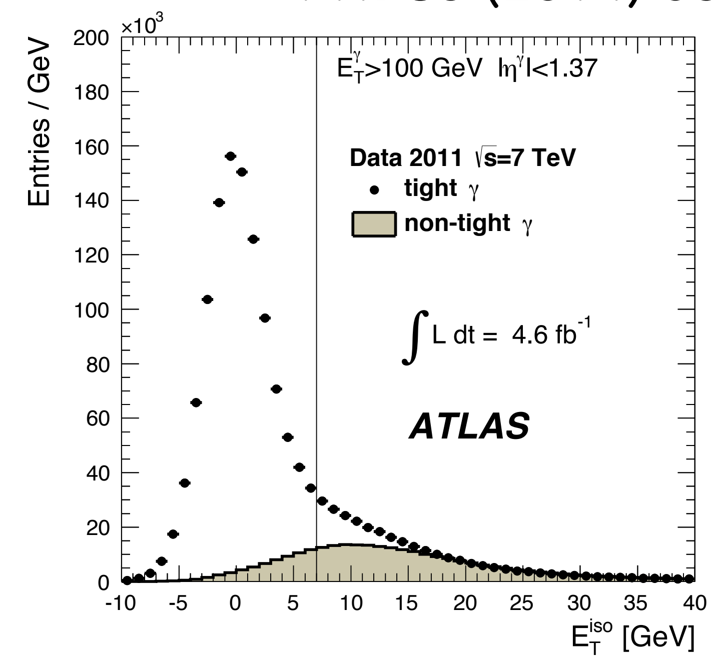


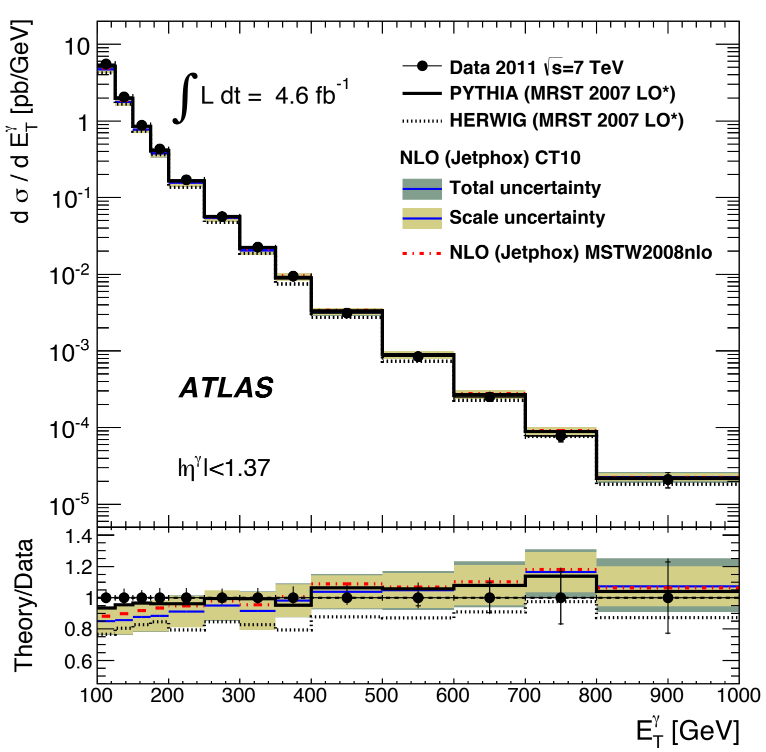
Prompt γ

arXiv:1311.1440

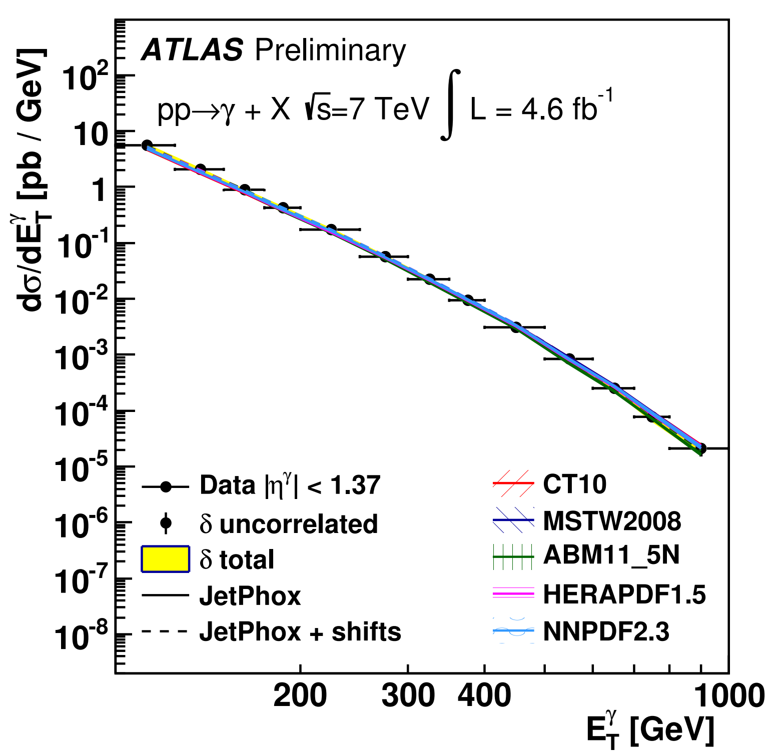
PRD89 (2014) 052004

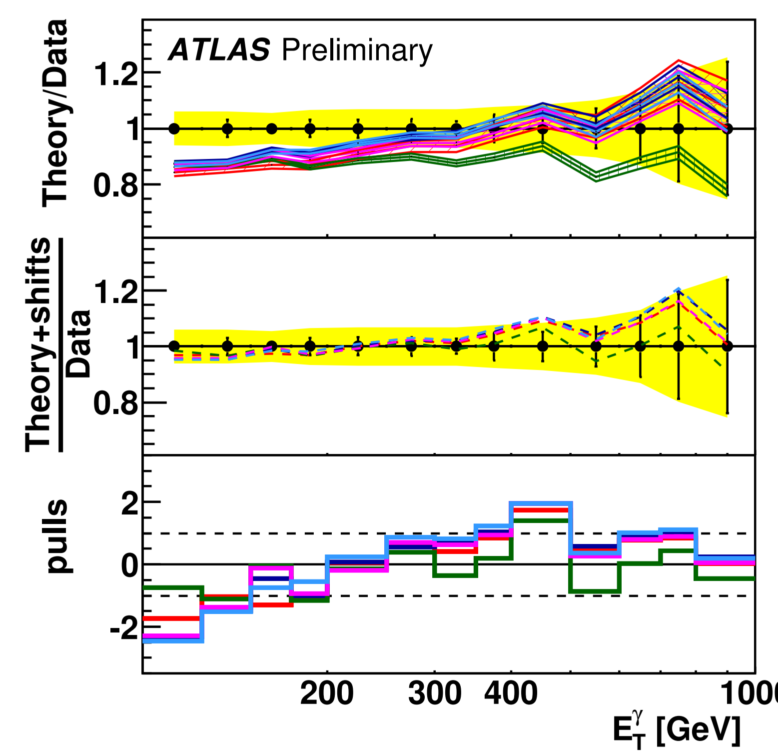
- $qg \to q\gamma$, $q\bar{q} \to g\gamma$
- Sensitive to gluon PDF
- Signal extraction using isolation E
- Compared to NLO calculations with various PDF sets
- $100 < E_T^{\gamma} < 1000$ GeV, $|\eta^{\gamma}|<2.37$



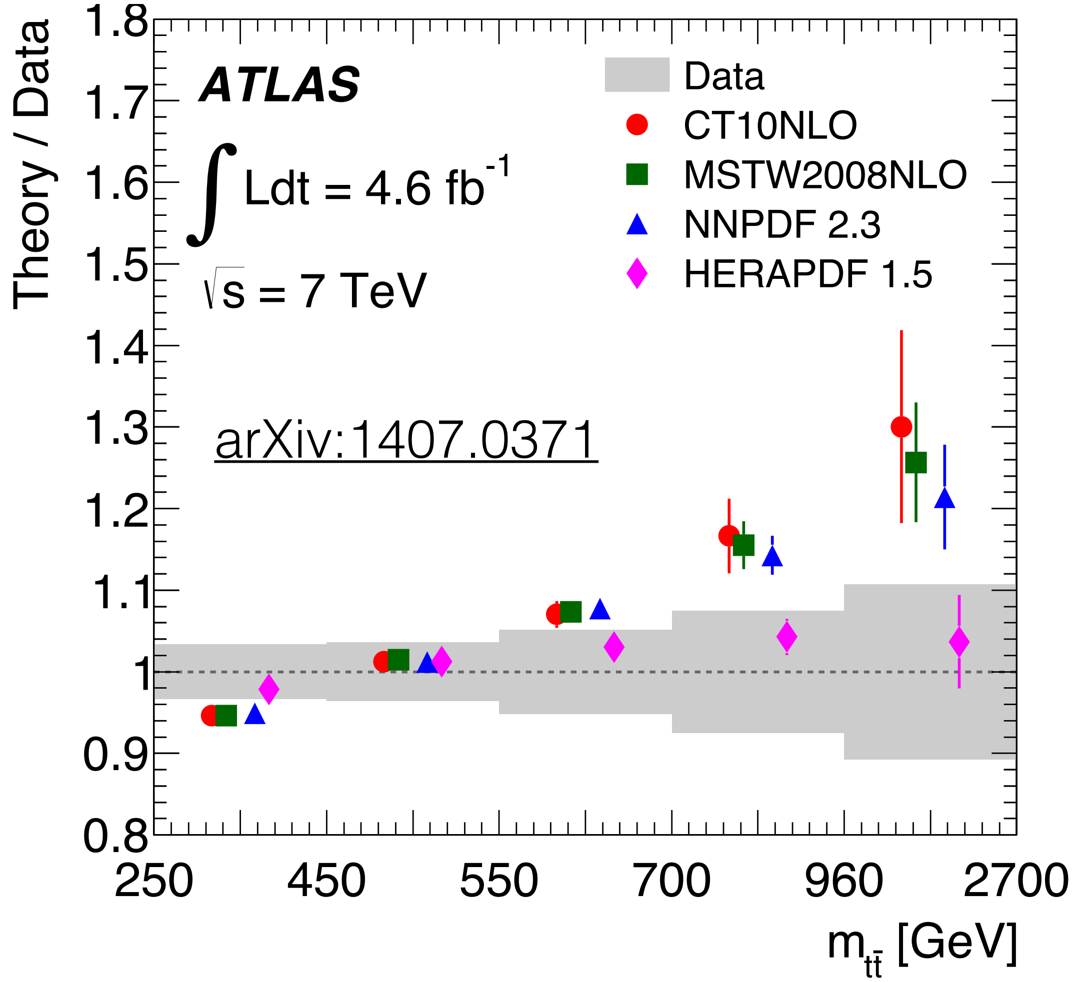


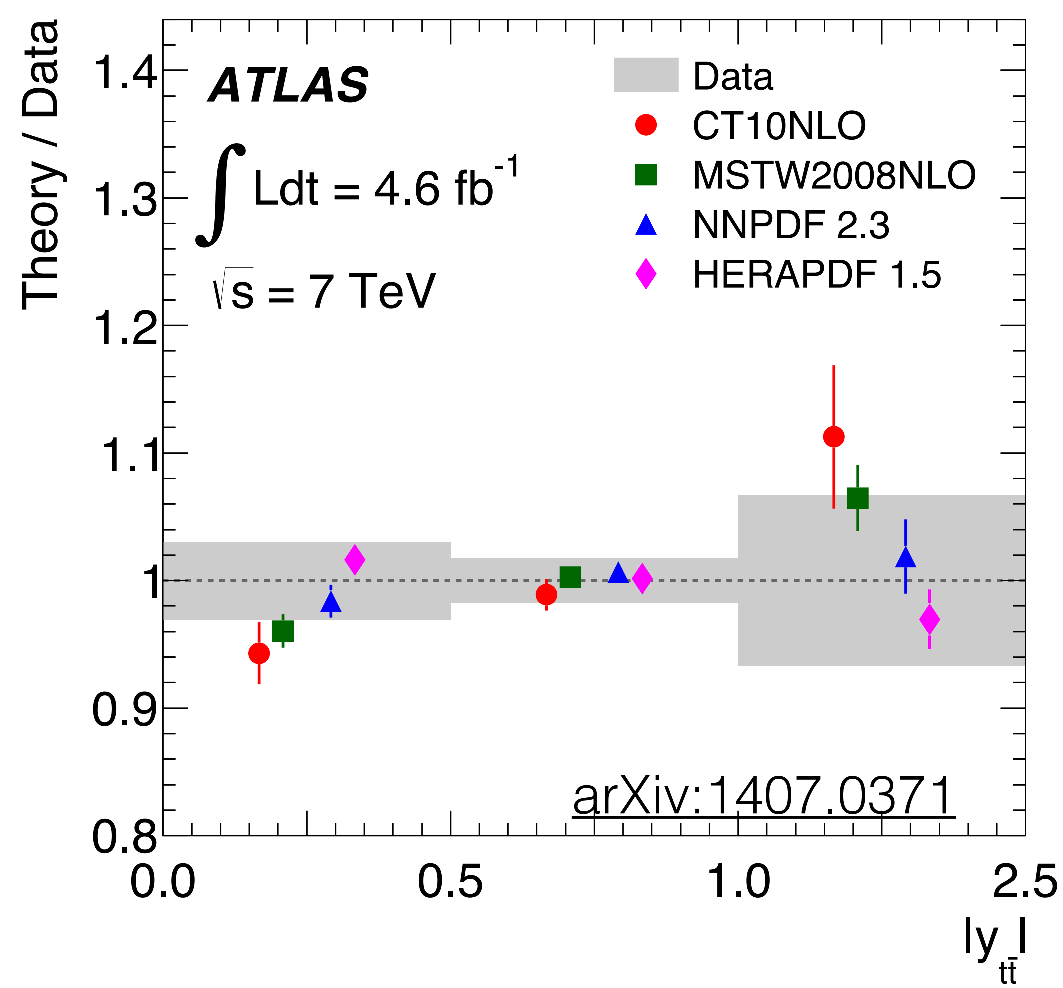
ATLAS-PUB-2013-018



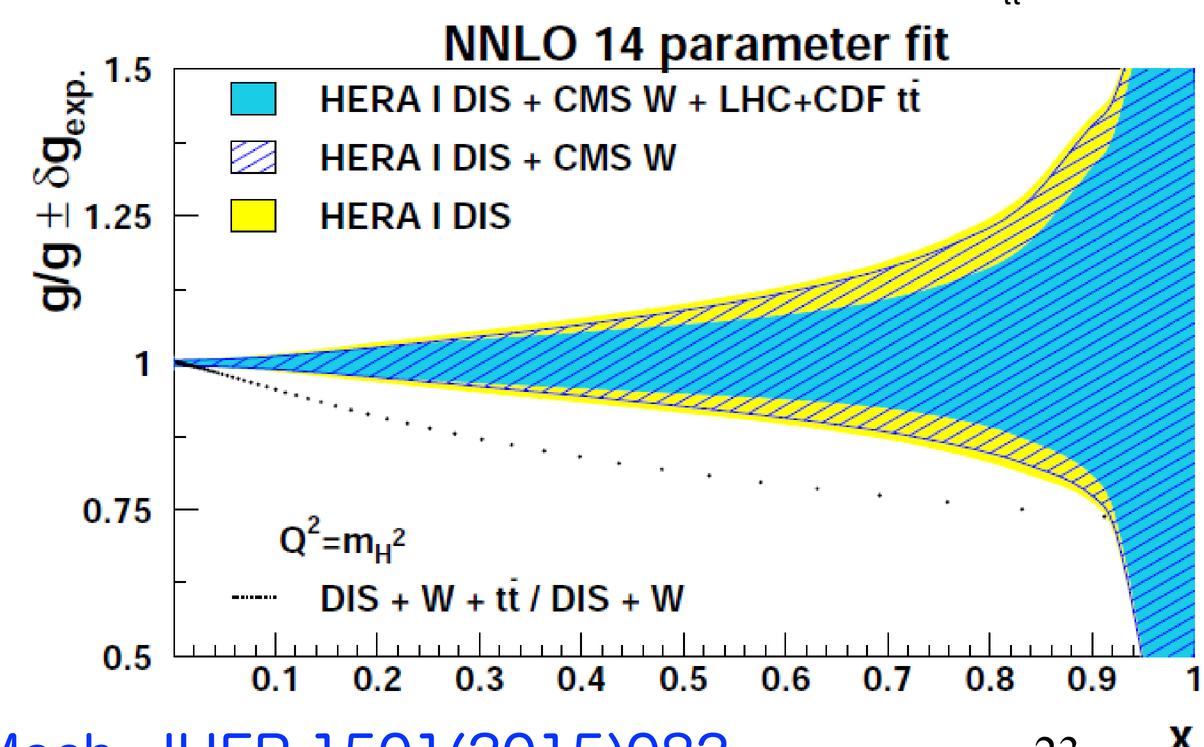


Top-quark pair production



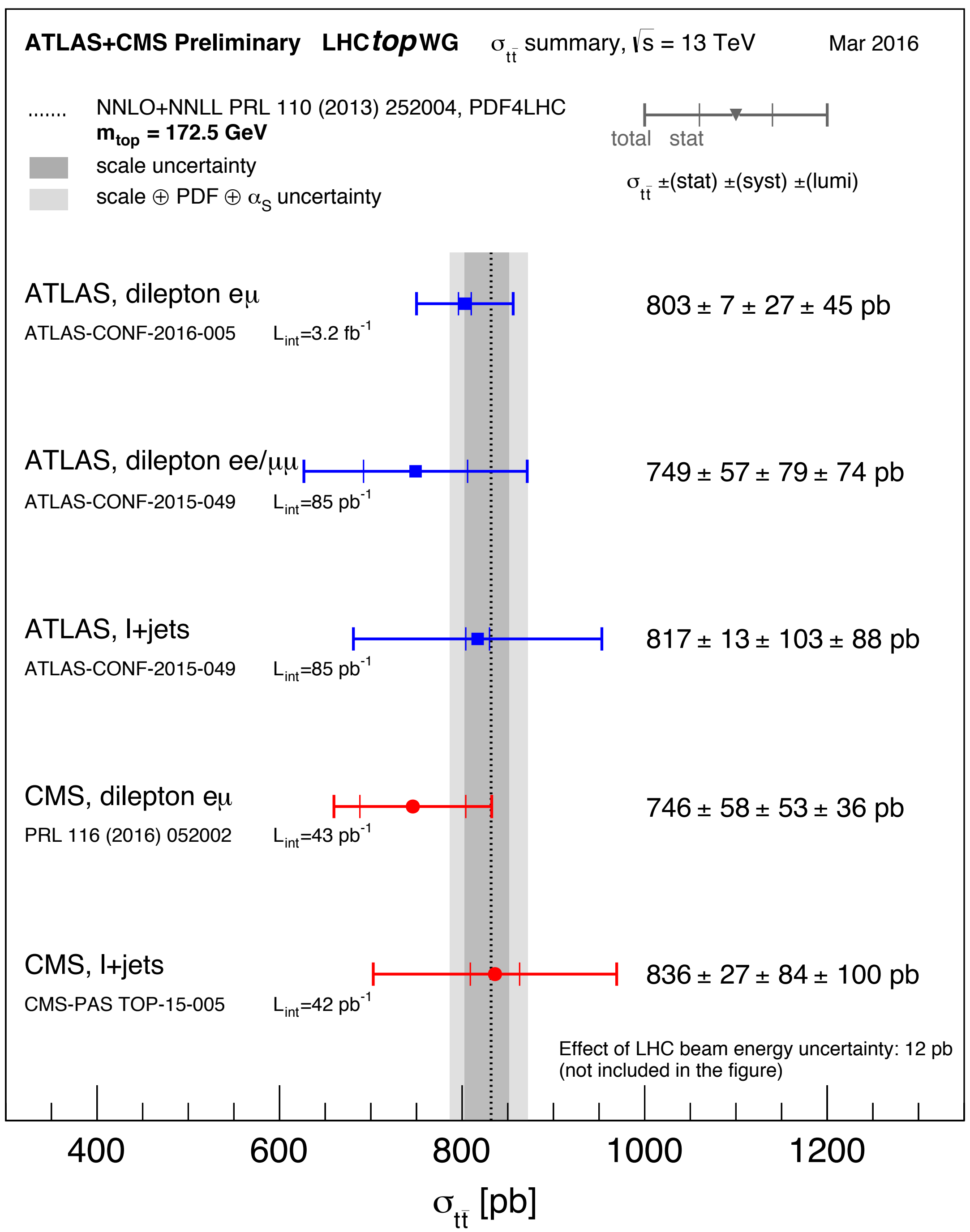


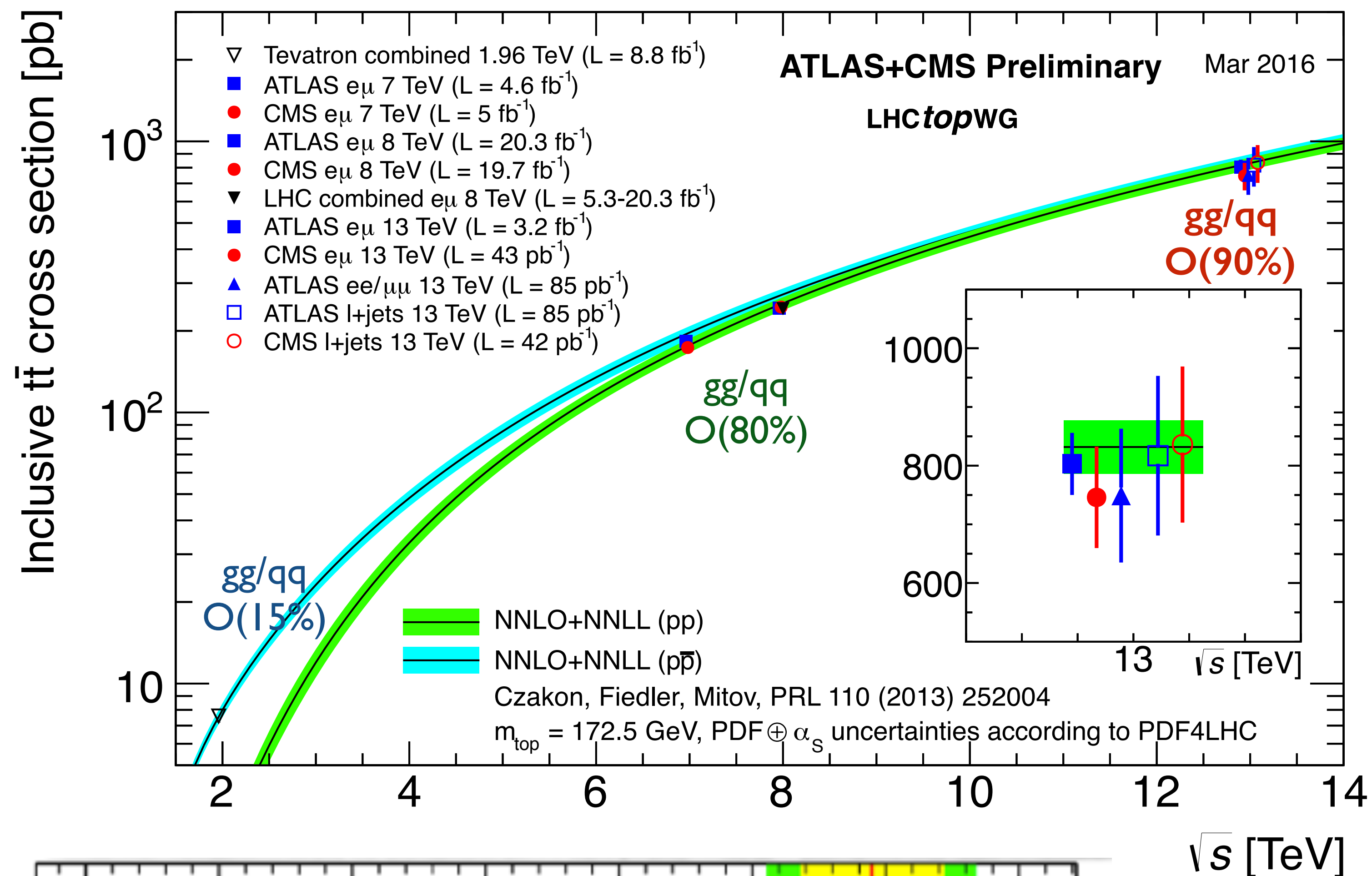
- σ~200pb: LHC is a 'top factory'
- Helps improving gluon PDF precision

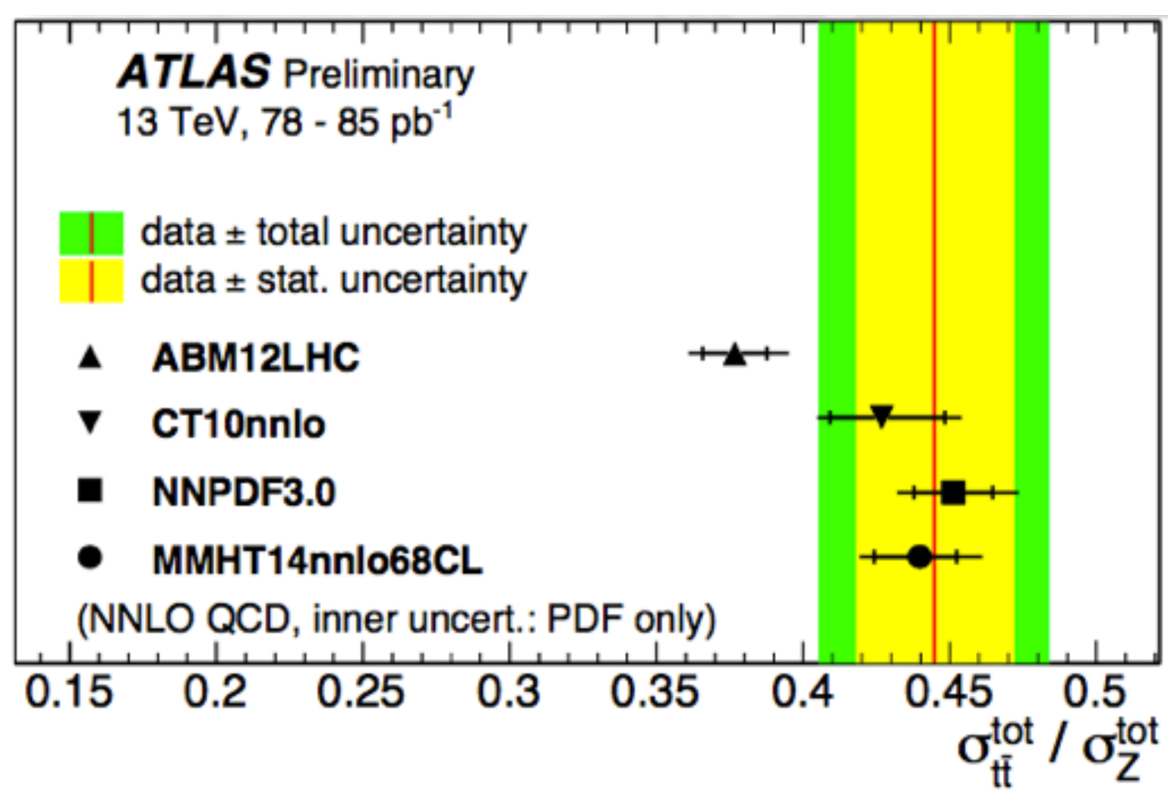


Guzzi, Lipka, Moch, JHEP 1501(2015)082

Top pair @ 13TeV



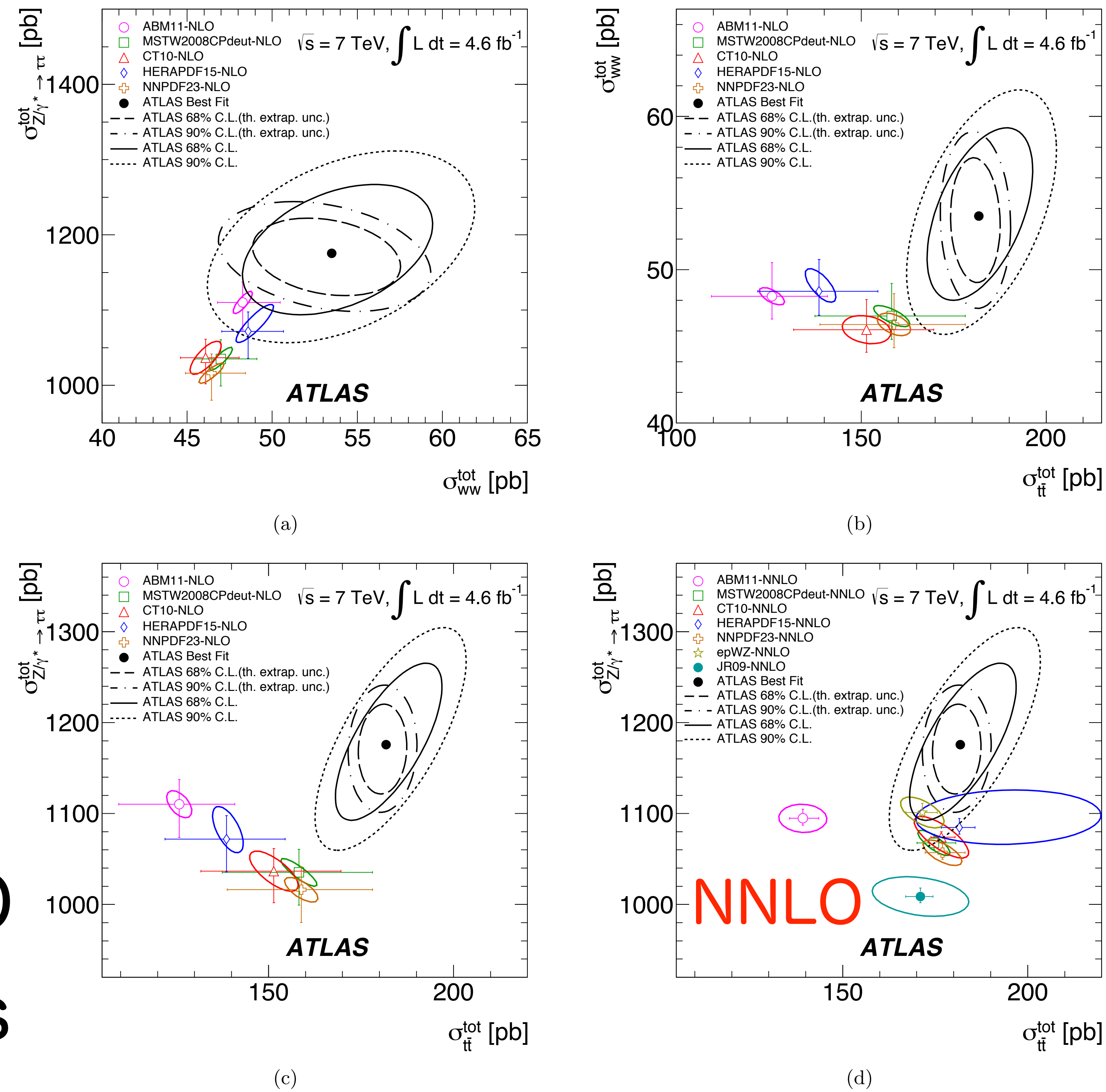




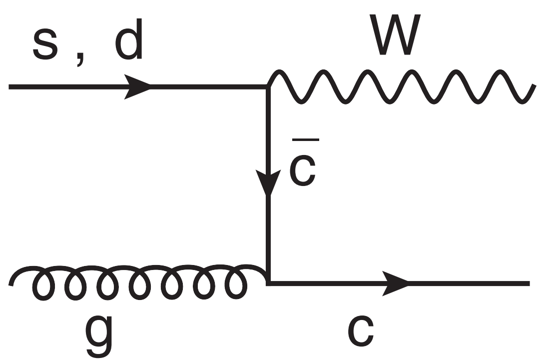
Inclusive dilepton analysis

arXiv:1407.0573

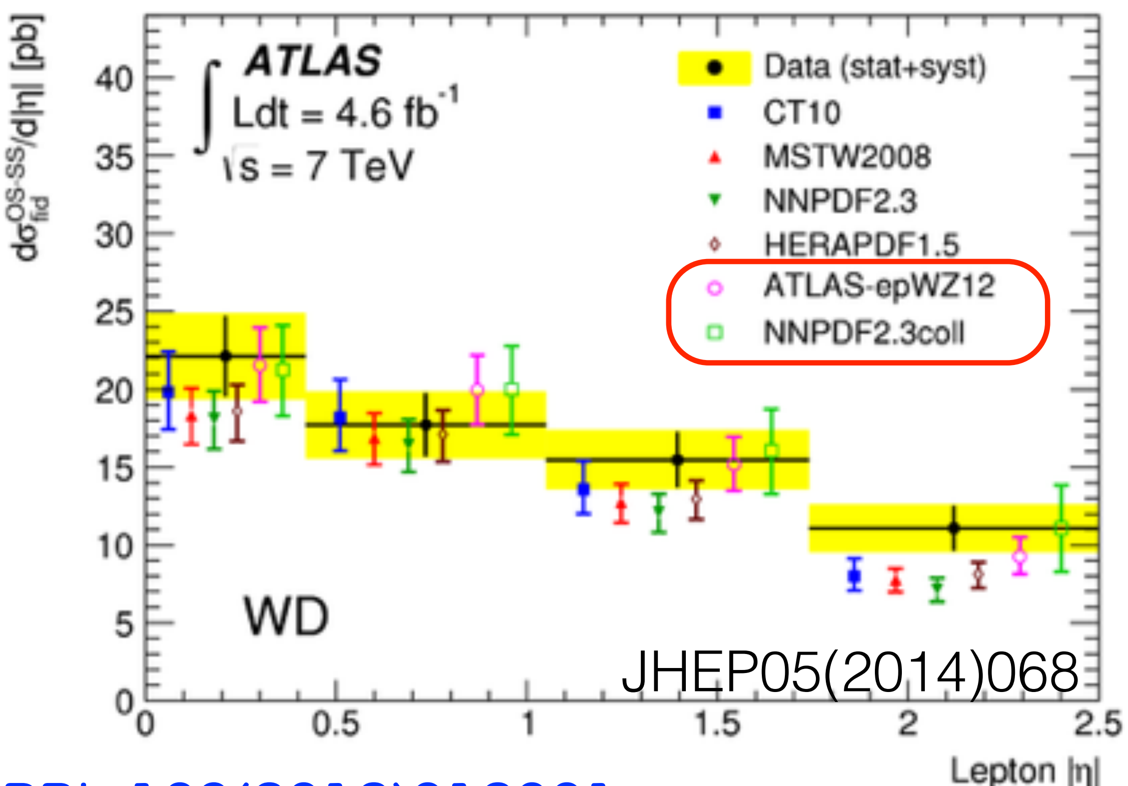
- Opposite-sign $e\mu$ events mainly from
  - ttbar
  - WW
  - $Z \to \tau\tau$
- Simultaneous measurement of 3 cross sections
- compared to N(N)LO prediction with PDFs



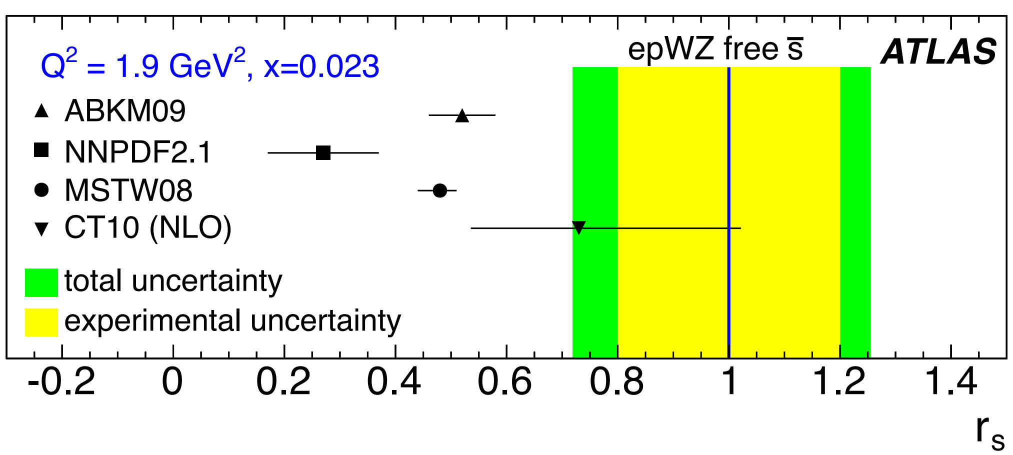
W+charm: mild tension?



- directly sensitive to strange quark
- traditionally 's-suppression' based on ν-charm data
- ATLAS data consistent with no suppression (symmetric sea)
- also consistent with ATLAS W/Z
- but CMS W+c consistent w/ sup.

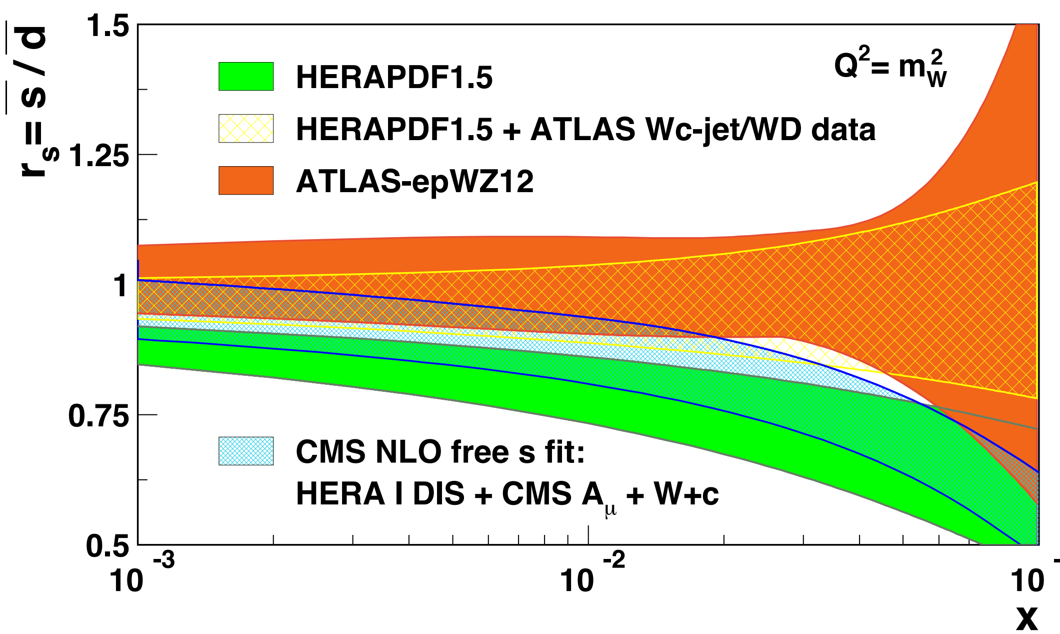


PRL 109(2012)012001



arXiv:1507.00556

J. Rojo et al.



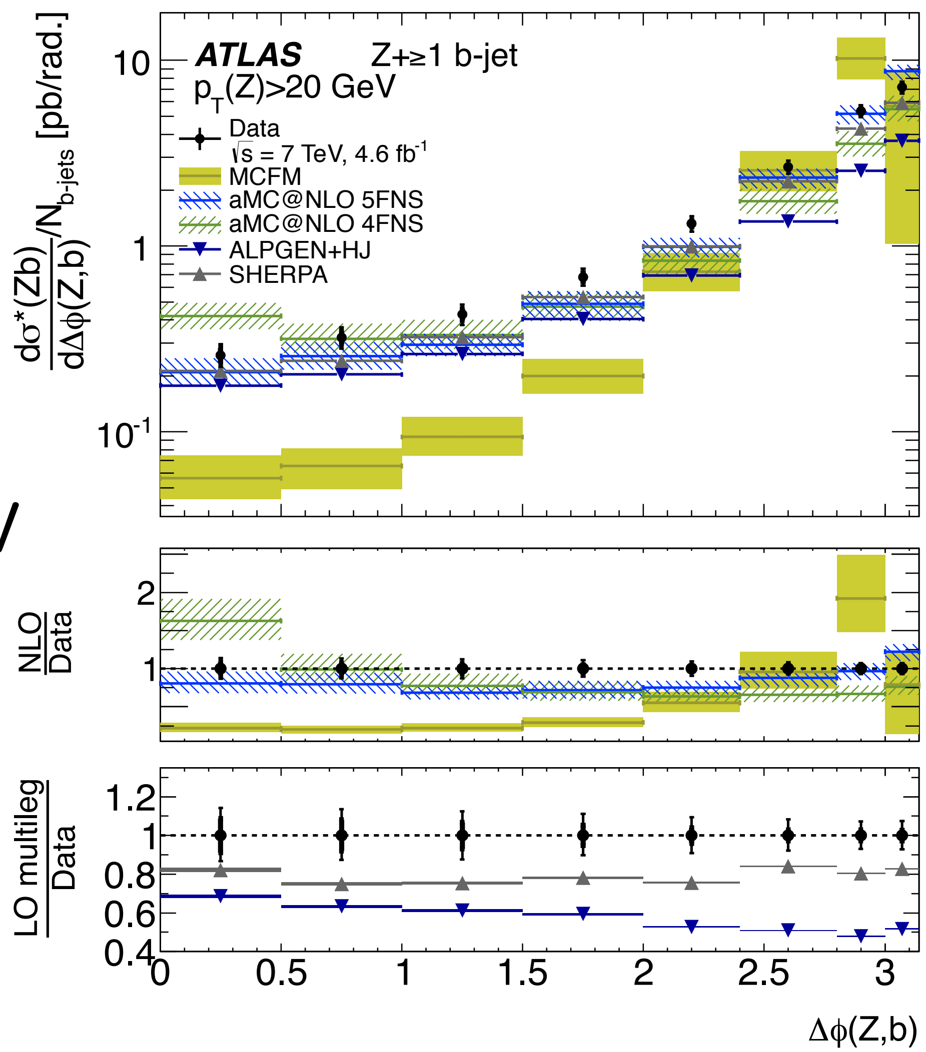
Z+b, Z+bb

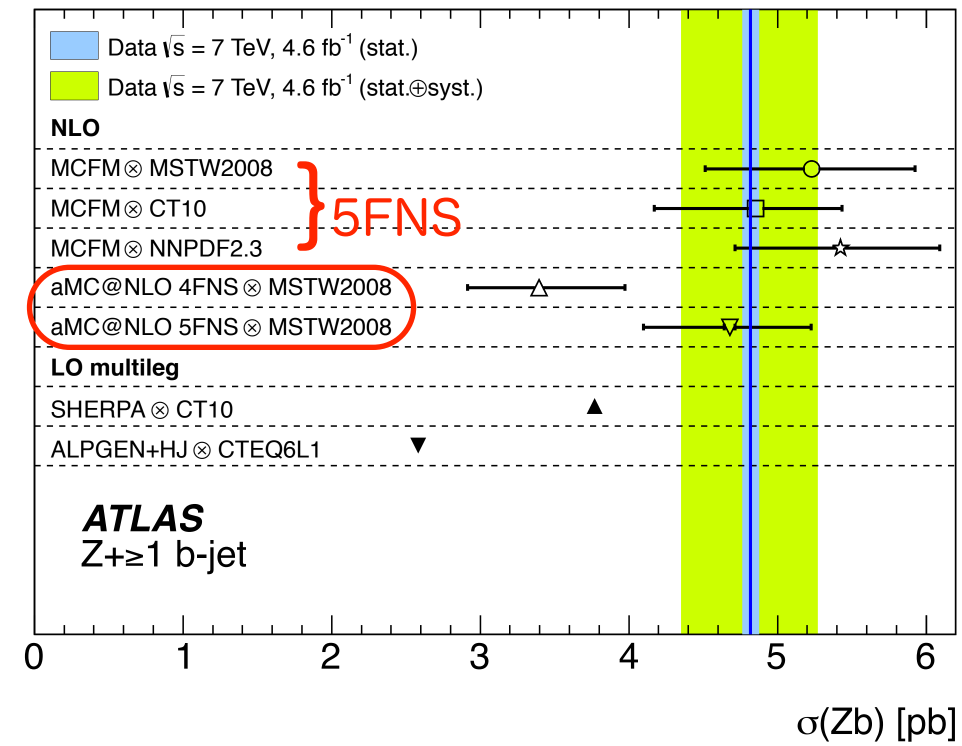
arXiv:1407.3643

- BG to ZH(WH), H→bb
- Z(W)+heavy flavor: larger theo. uncertainty than light quarks
- 4FNS, 5FNS schemes (udsc+g or udscb+g in proton)

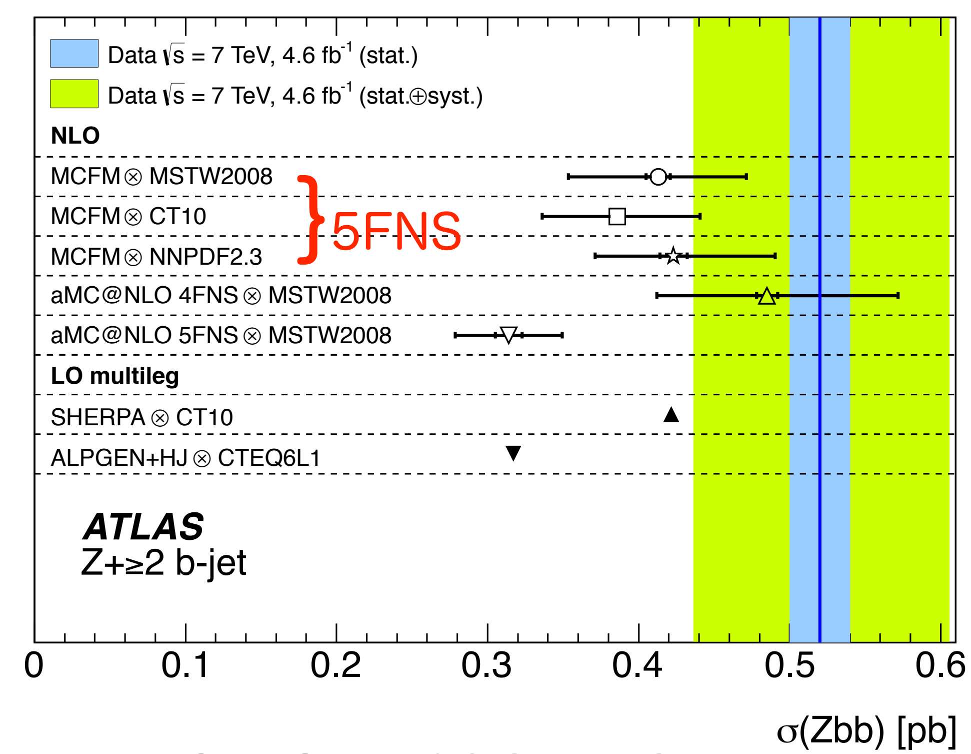
Z→e⁺e⁻, $\mu^+\mu^-$

p_T(b-jet) > 20GeV





(a)



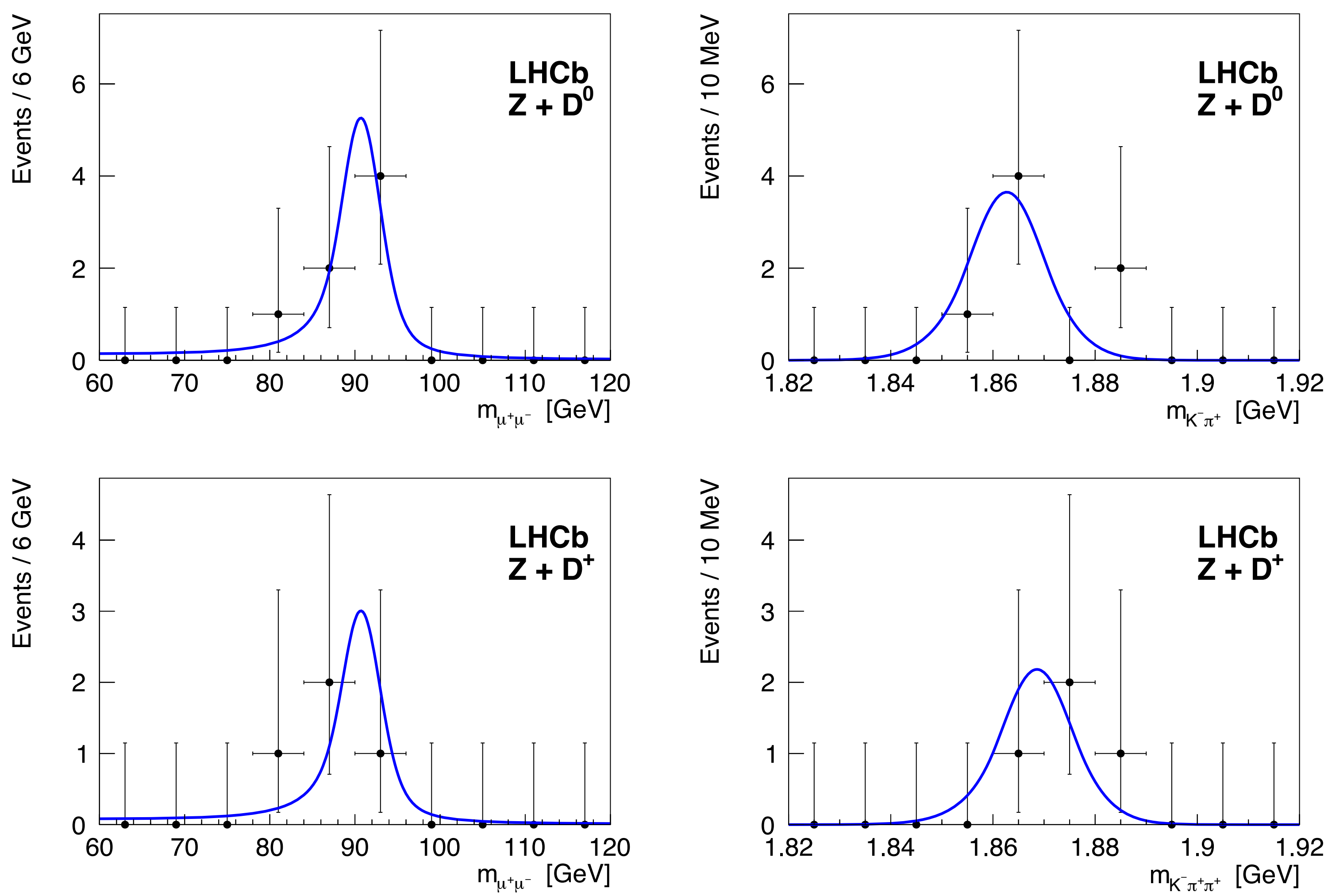
Also CMS: 1402.1521

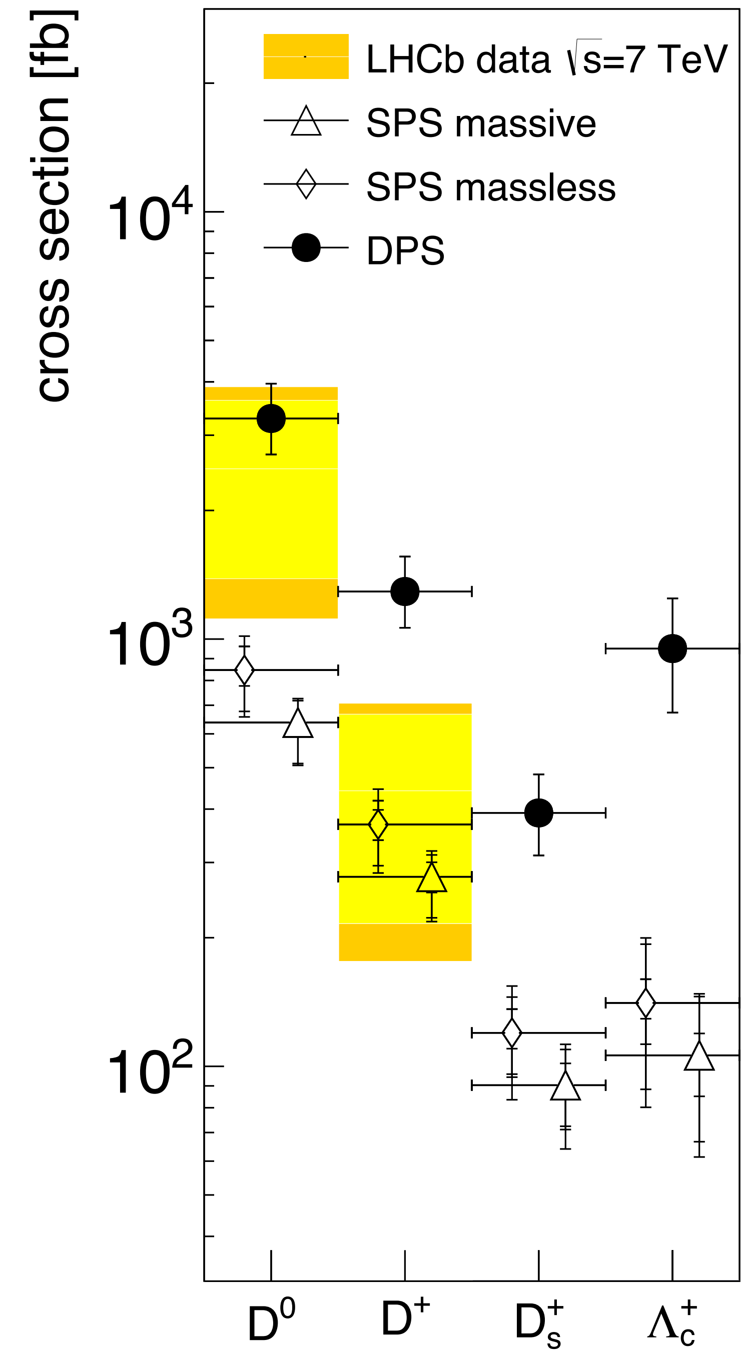
Z+D from LHCb

arXiv:1401.3245

JHEP04 (2014) 091

- Exclusive reconstruction of $Z \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ (+c.c.)
- Compared with Single Parton Scattering (one parton-parton collision creates Z & D) and Double Parton Scattering (one collision creates Z and another for D)

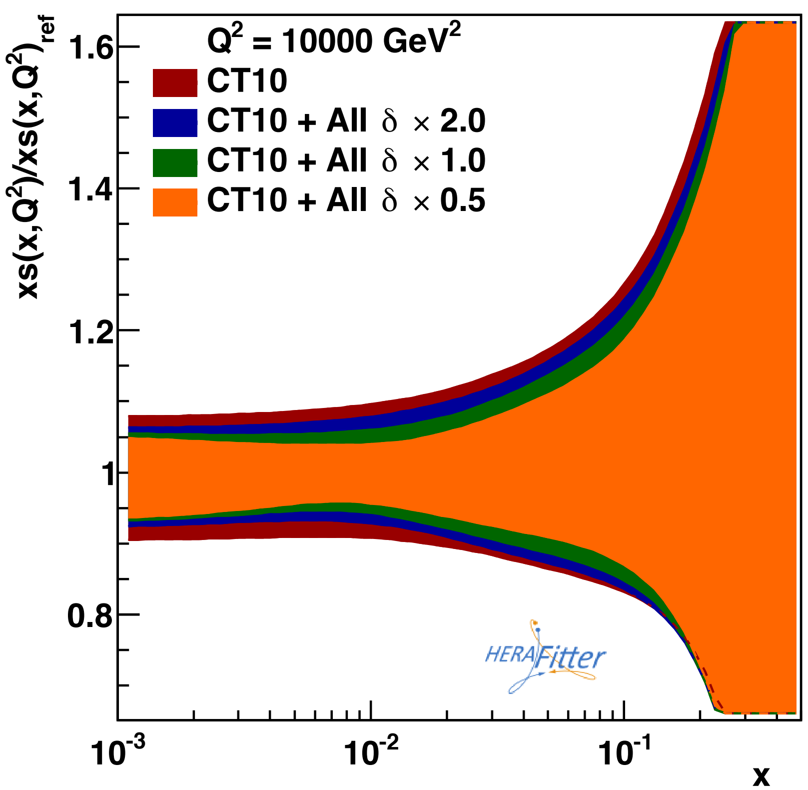




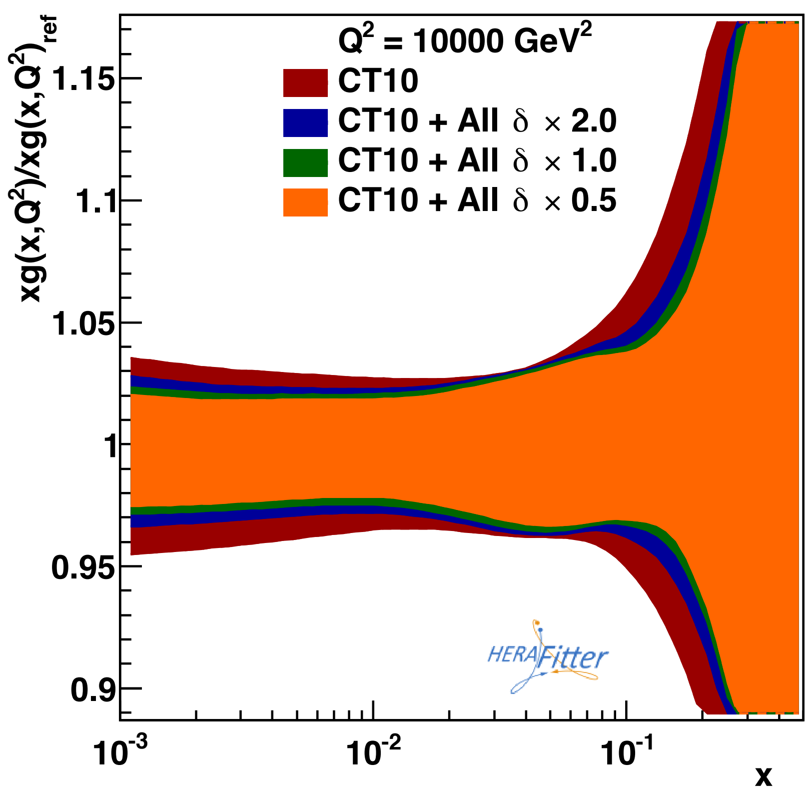
LHC Run 2 prospects

- Profiling study of Run 2 data's impact on PDF
- W/Z ratio, tt/Z ratio, W asymmetry, Z rapidity
- various assumptions on systematic uncertainty

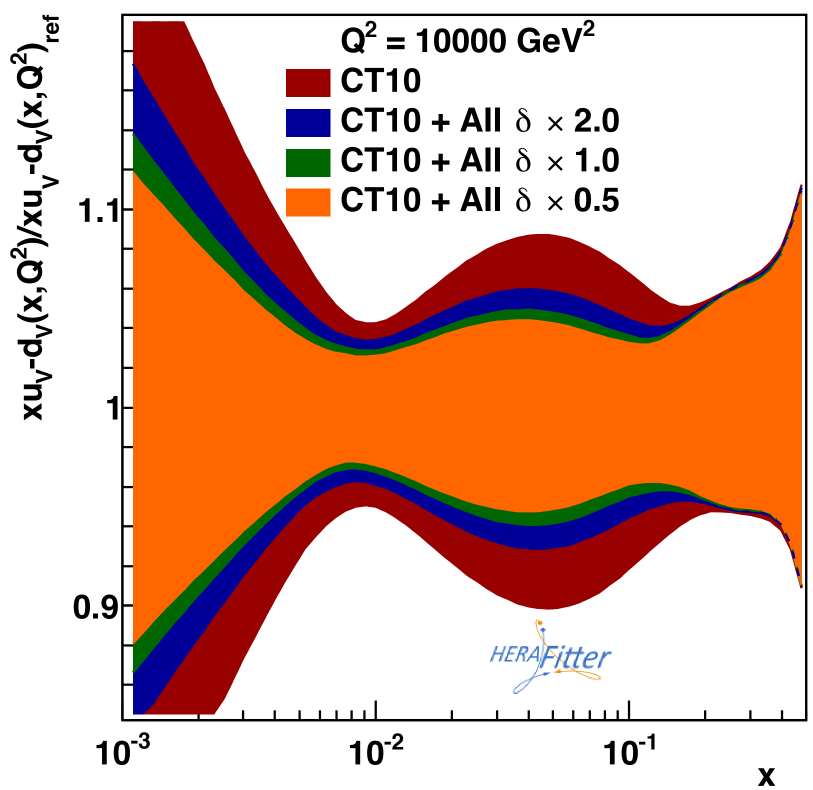
strange



gluon



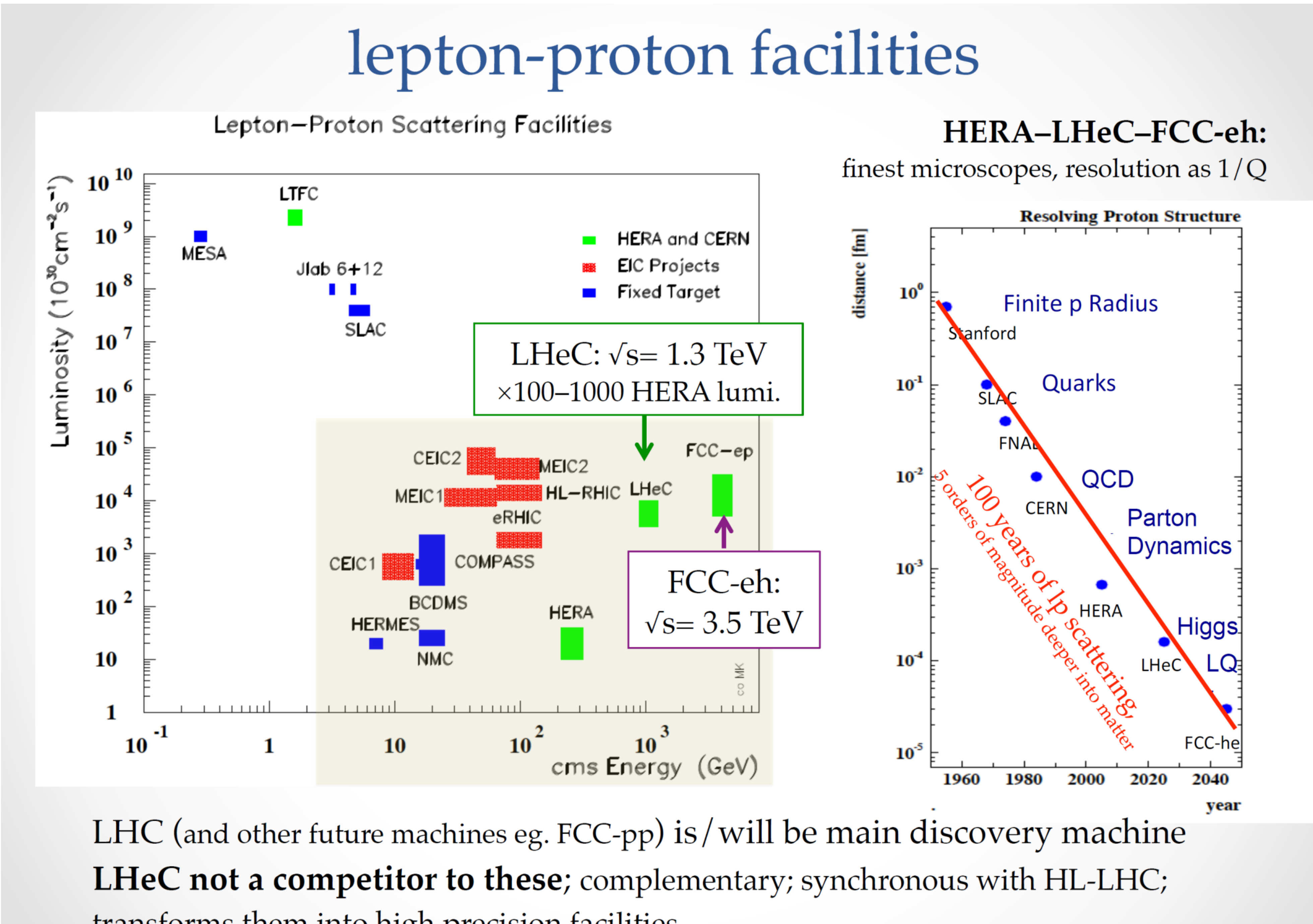
u_V-d_V



arXiv:1507.00556

(High energy) future of DIS

- LHeC project: 7TeV p in LHC × 60GeV e in ERL
- also h-e option considered in FCC (100km ring)



E_{CM}=1.3 TeV,
4 times HERA

Luminosity up to:10^{34} cm^{-2}s^{-1}

A.M. Cooper-Sarker,
LHeC workshop,
June'15

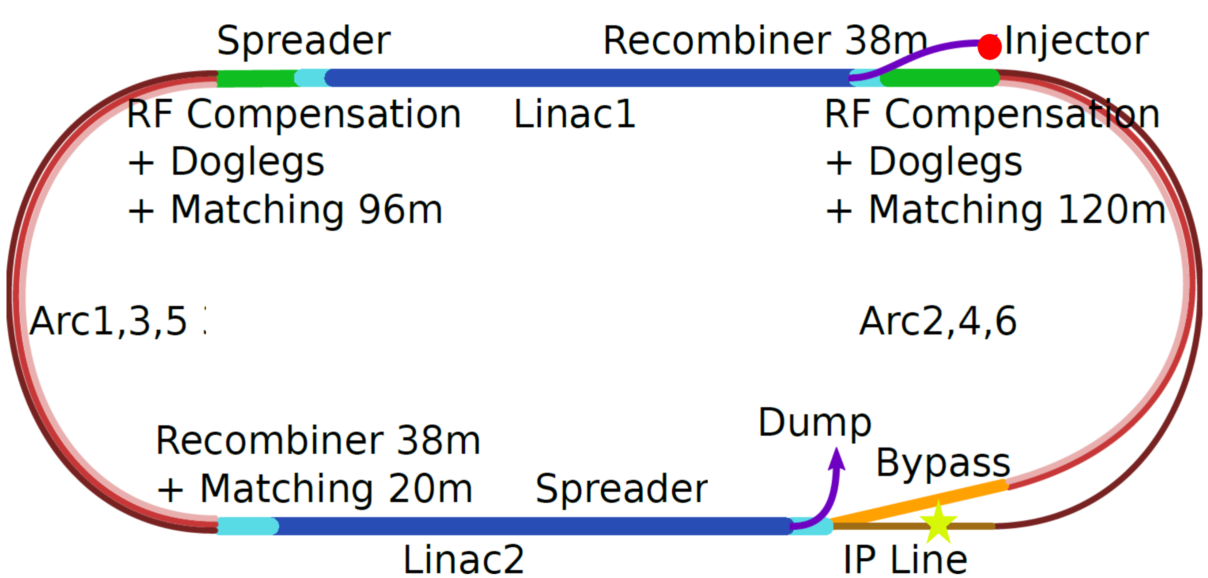
Energy Recovery Linac

- The e beam after collision is decelerated in the same linac (at the 'wrong' RF phase) to give energy to the accelerating beam

Recirculating Linac with Energy Recovery:

60 GeV acceleration with Recirculating Linacs:

Animation from A. Bogacz (JLab) @ ERL'15



➔ Three accelerating passes through each of the two 10 GeV linacs (efficient use of LINAC installation!)

➔ 60 GeV beam energy

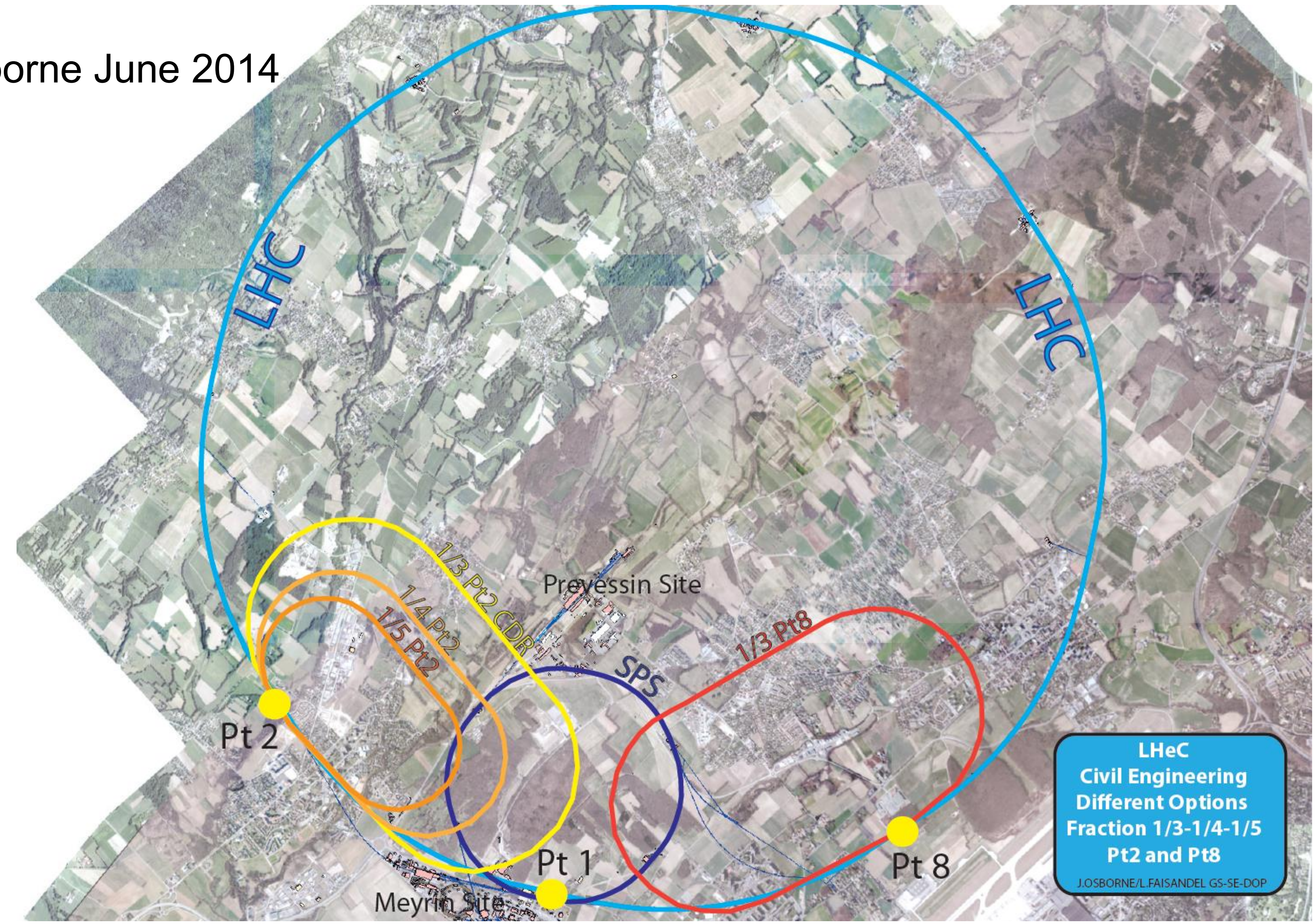
LHeC footprints

- P2/P8 options evaluated (runs concurrently with ATLAS/CMS)

Site Considerations:

LHeC

John Osborne June 2014



PDF precision at LHeC

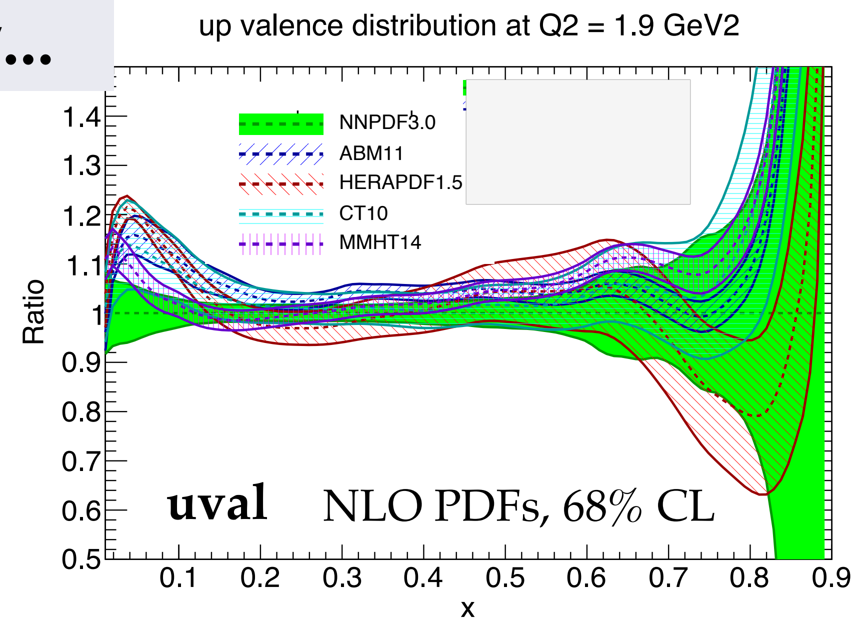
Valence quarks

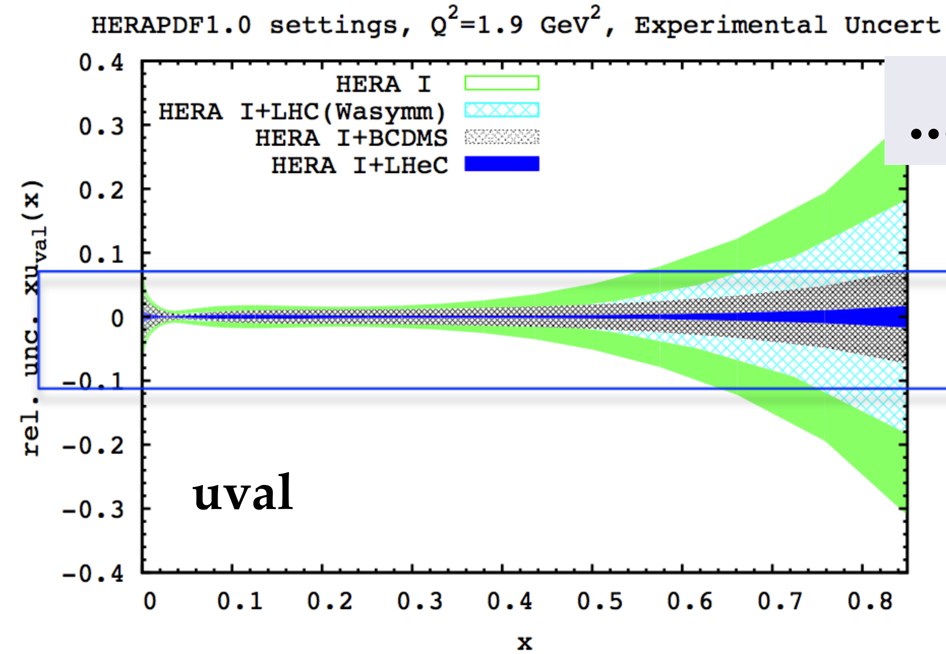
• LHeC CDR: arXiv:1206.2913

CDR study: LHeC simulated NC, CC e±p, P=±0.4, including projected systematics

HERAfitter framework with HERAPDF1.0 NLO settings

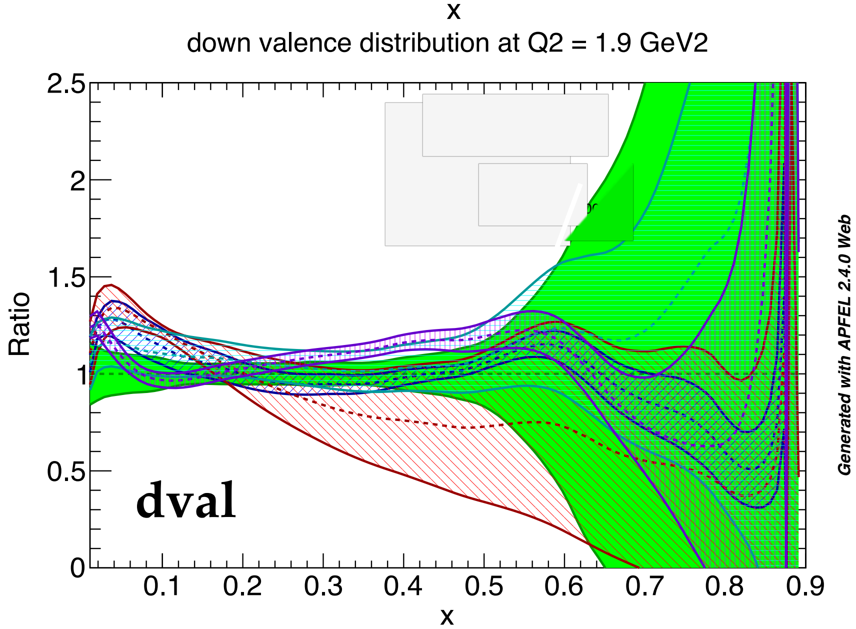
now…

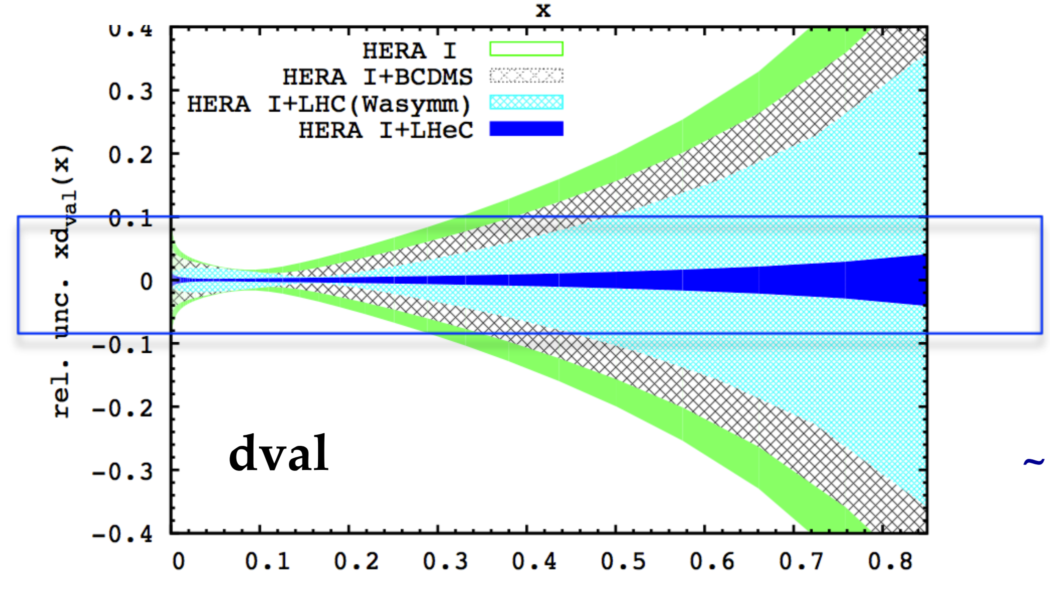




…then

~ 2%





~ 4%

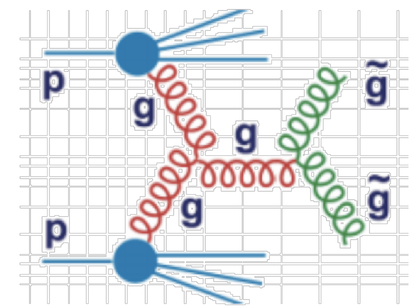
precision determination, free from higher twist corrections and nuclear uncertainties

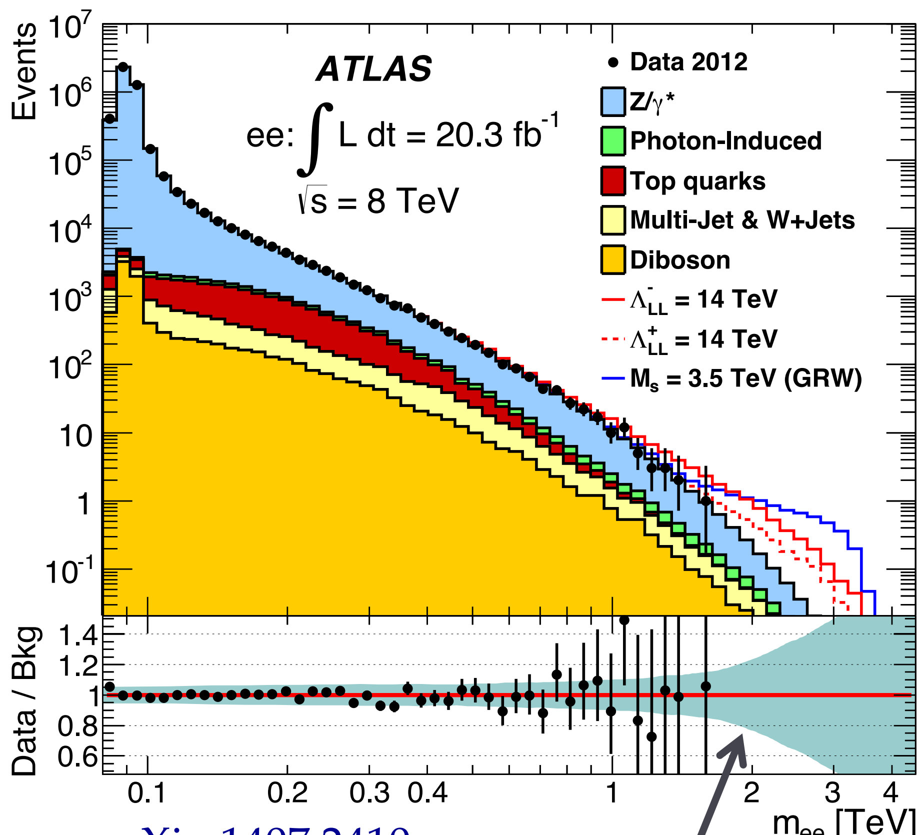
High-x valence, sea, gluon

High x PDFs: link to LHC

- large uncertainties in high x PDFs limit searches for new physics at high scales

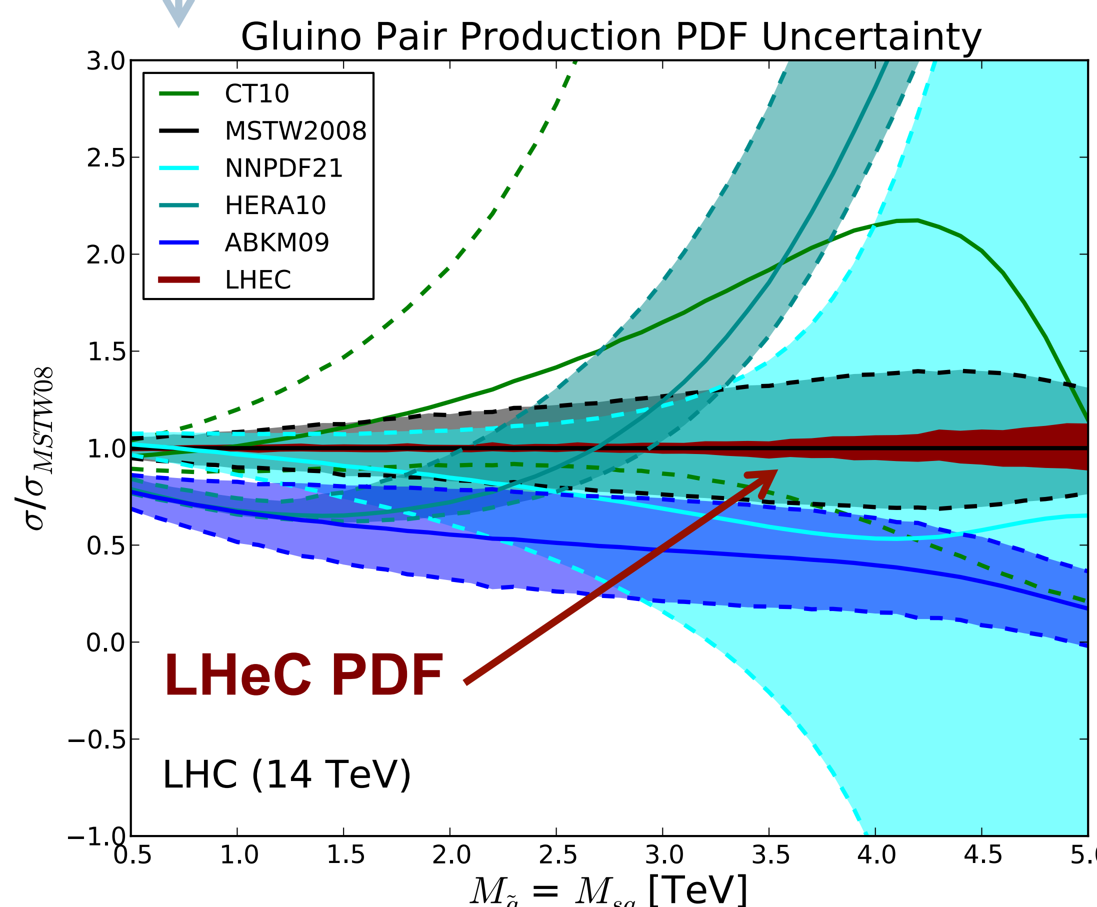
many interesting processes at LHC are gluon-gluon initiated:
top, Higgs, … and BSM processes, such as gluino pair production





arXiv:1407.2410

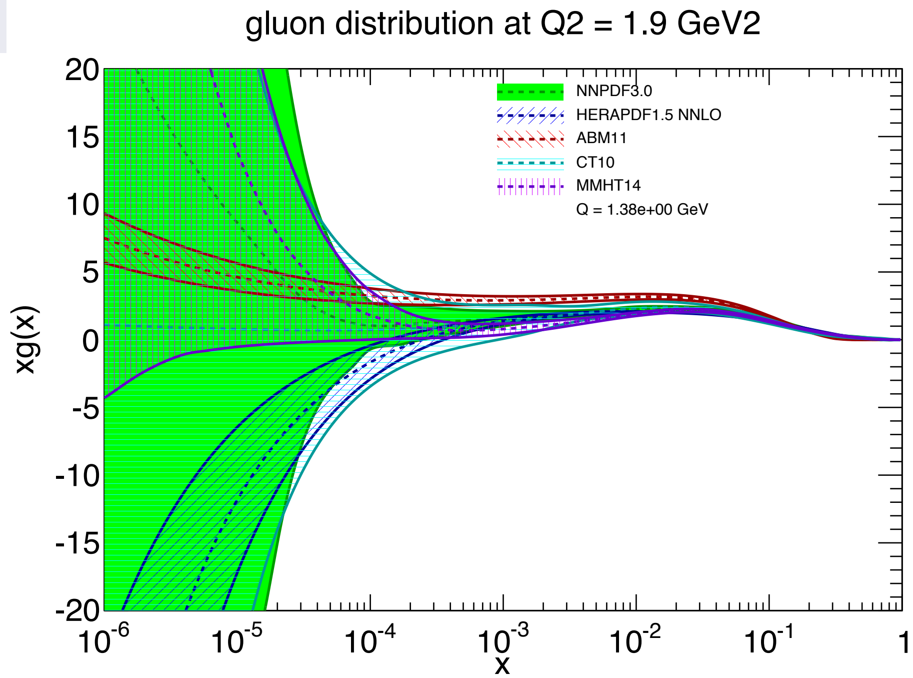
current BSM search in dilepton final state;
uncertainties on high-x (anti)quarks dominate



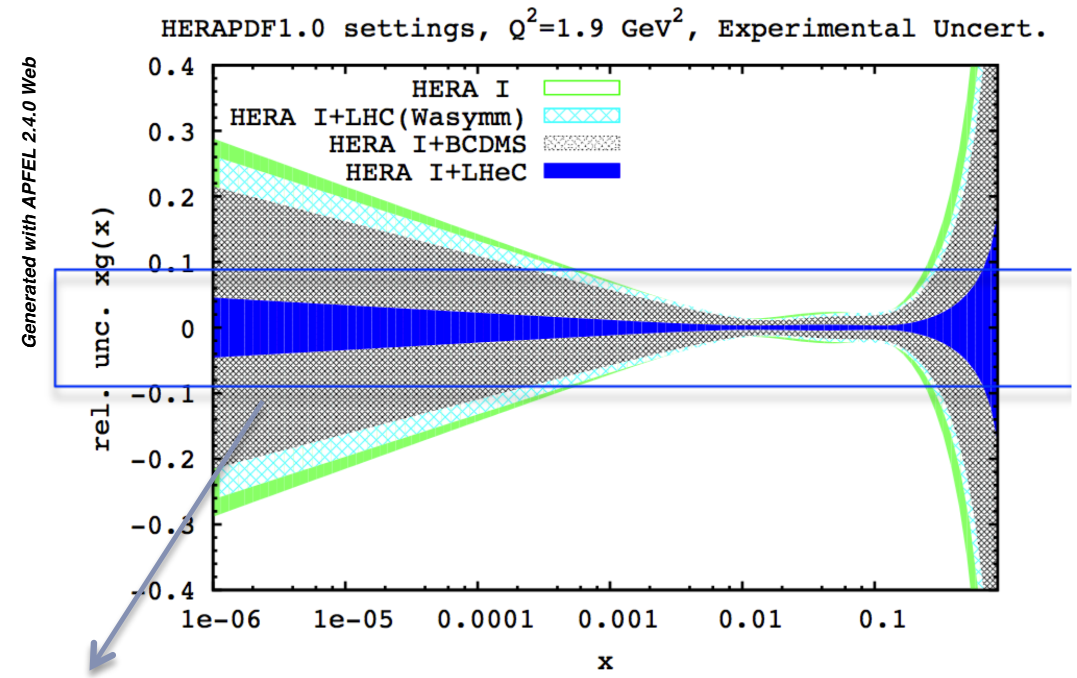
arXiv:1211.5102

Low x and gluon saturation

now…



then…



gluon measurement down to $x=10^{-6}$ → < 5%

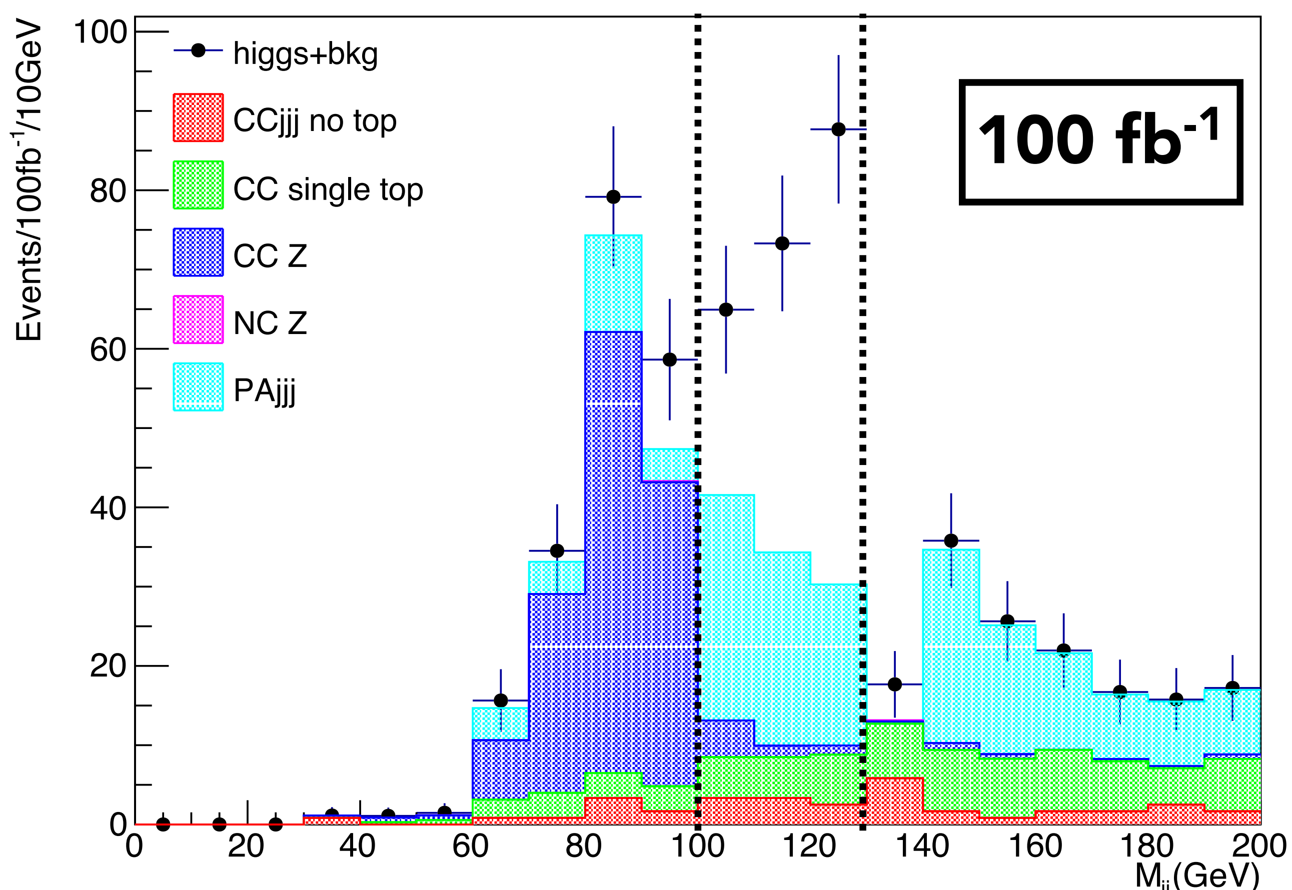
- F_L measurements would improve further
- Allow understanding of possible non-linear evolution (not accommodated by DGLAP fits) leading to saturation at low x (tension between F_2 and F_L)
- Important for high energy neutrino cross sections
  - → E.g. essential input for ICECUBE observations

Higgs studies at LHeC

Result

• $100 fb^{-1}$/year

- Mass reconstructed with 1st and 2nd minimum η b-jets.
- Signal region is defined as [100,130] GeV.



Events in signal region

Signal H->bb	119±2
CCjjj no top	9±3
CC single top	17±2
CC Z	7±1
NC Z	0
PAjjj	73±17
CCbkg total	33±4
NCbkg total	73±17

photoproduction multijets

- Errors are weighted

$S/\sqrt{B}$ = 11.5

- We can detect H->bb signal in good efficiency.
- Peak around 80 GeV is Z boson from CC background.
- PAjjj background has large statistical error due to small statistics.
- Electron tagging of Photo-production events could further suppress BG under peak.

M. Tanaka (Tokyo Tech), LHeC workshop

Conclusions

- Precise PDF knowledge stays to be crucial in LHC and post-LHC era in search for new physics.
- Scale uncertainty of theoretical calculation needs to improve as well. NLO, NNLO, NNNLO ...
- HERAPDF2.0 recently released using (only) final full cross sections from H1+ZEUS.
- LHC measurements also sensitive to PDF, giving added precision - good prospects for Run 2.
- Ultimate big jump would be a new ep collider: LHeC (and FCC-he).