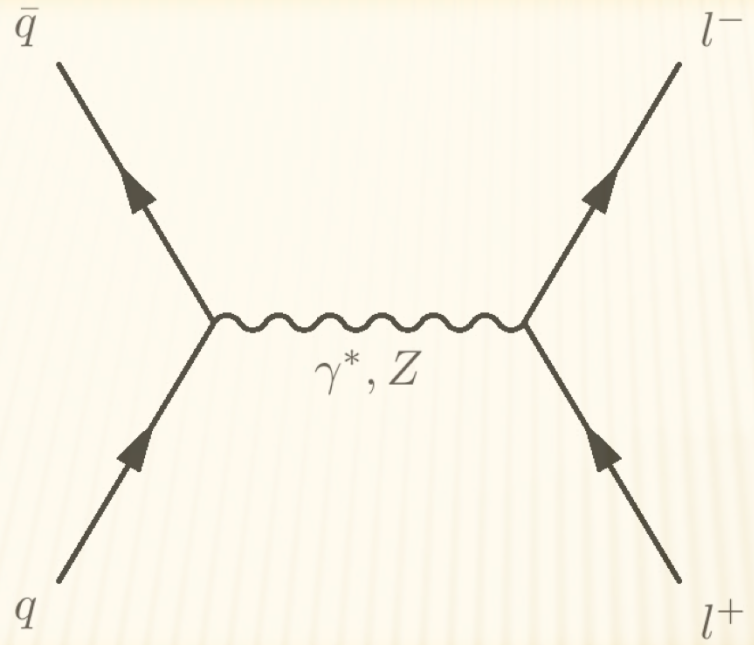


VECTOR BOSON PRODUCTION AT CMS (AND ELSEWHERE)

Michael Schmitt (Northwestern University)

LOOPFEST 13: June 18, 2014

TOPICS

- Inclusive *W* and *Z* cross sections
- Drell-Yan production
- Transverse momentum distributions
- *W* charge asymmetry
- *W*+*c* production
- W + jets differential cross sections
- W and Z + b jets

INCLUSIVE *W* AND *Z* PRODUCTION

- Important benchmark process since turn-on in 2010.
- Must master techniques for reconstructing W and Z bosons before one can do electroweak physics.
- Starting point for constraints on parton distribution functions (PDFs).

Amazing progress has been made in the precision of the measurements.
Here is an illustration:

$$R_{W/Z} = \frac{\sigma(pp \to WX)\, B(W \to \ell\nu)}{\sigma(pp \to ZX)\, B(Z \to \ell^+\ell^-)}$$

CMS: R = 10.54 ± 0.07 (stat) ± 0.08 (syst) ±0.16 (th)
ATLAS: R = 10.893 ± 0.079(stat) ± 0.110 (syst) ±0.116 (th)

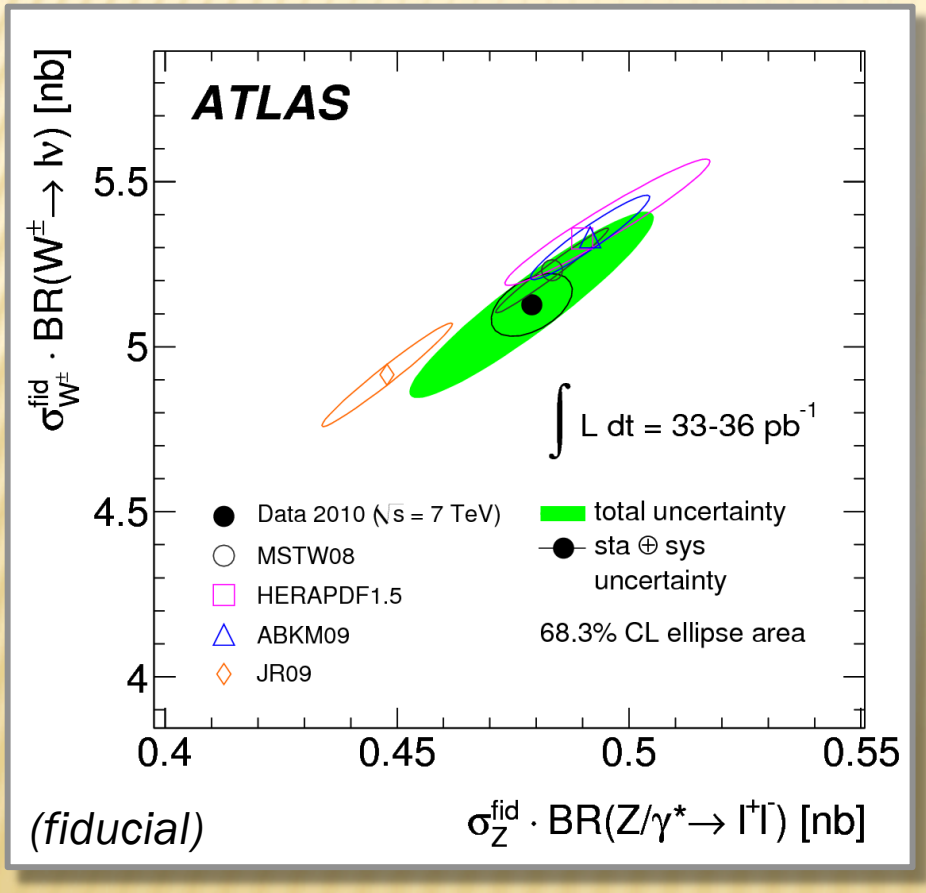
7 TeV , 35 fb^{-1}

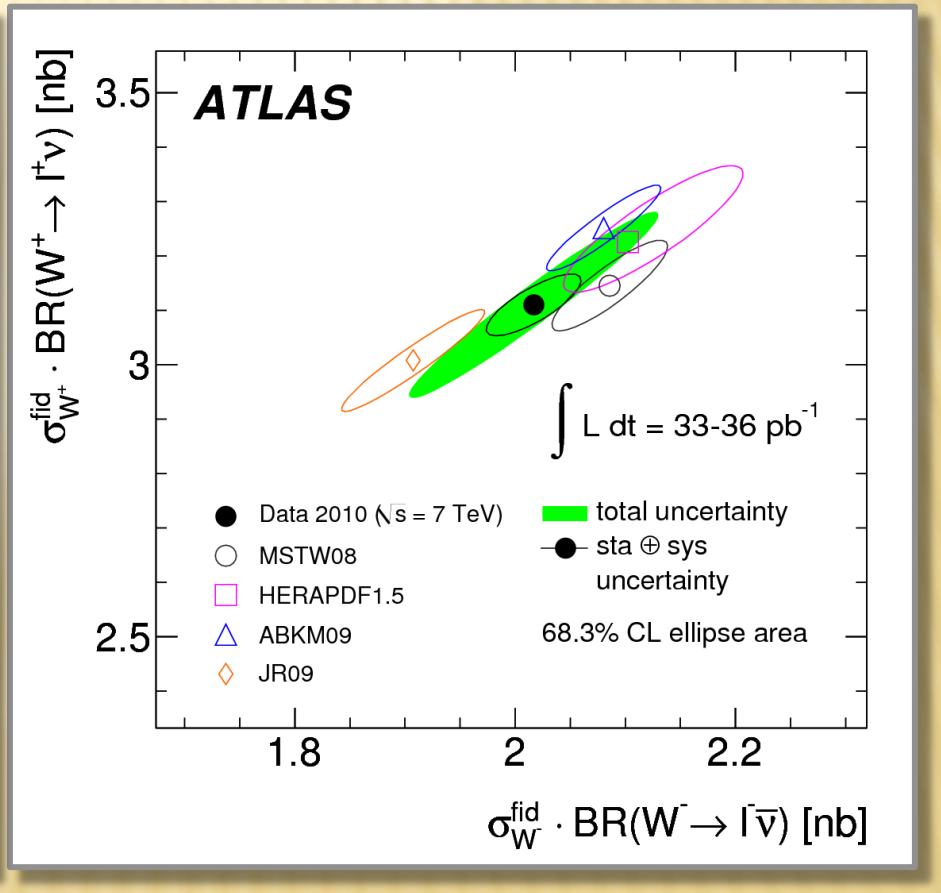
typical precision:

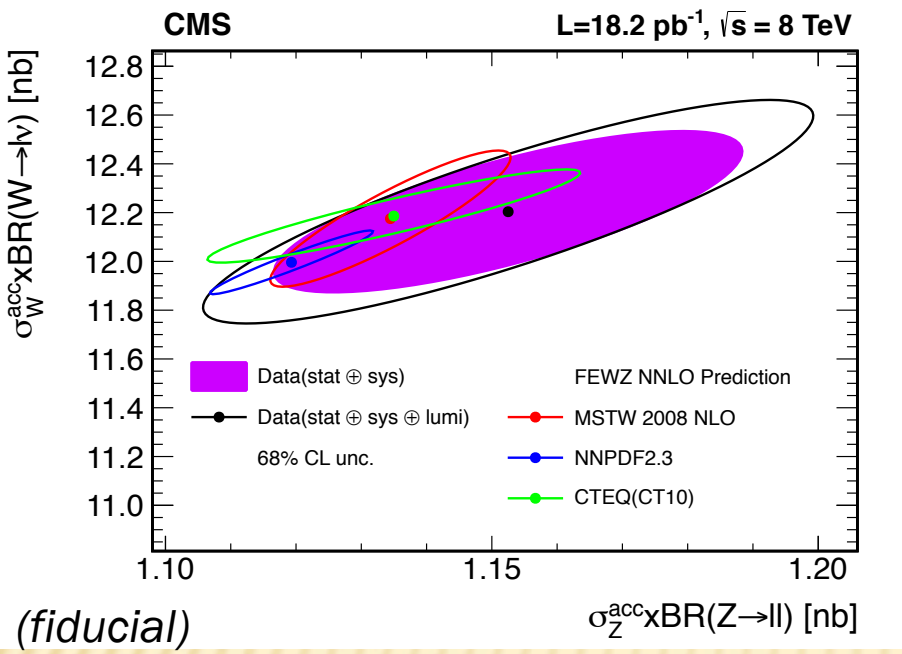
- statistical uncertainty << 1%
- experimental systematic uncertainty 1 – 1.5%
- luminosity uncertainty 3 – 4 %

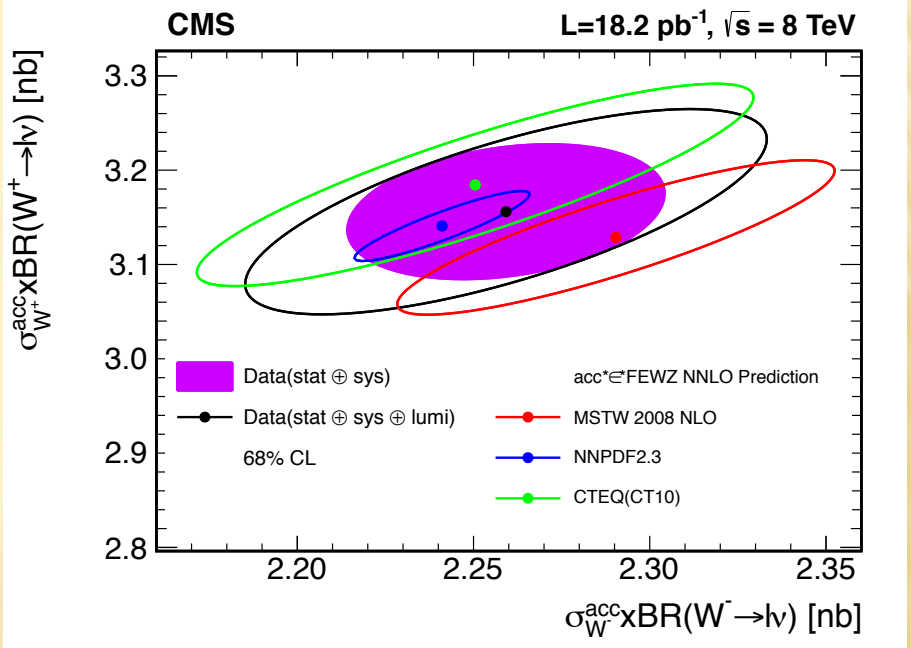
Direct comparison of data to theory predictions, displaying correlations:

- $W^{\pm}$ vs. Z is relatively insensitive to PDFs (though depends on s-quark density)
  theoretical predictions are tightly packed together
- W^{+} vs. W^{-} is sensitive to the d/u ratio at x ≈ 0.1
  greater spread in theoretical predictions due to PDF differences







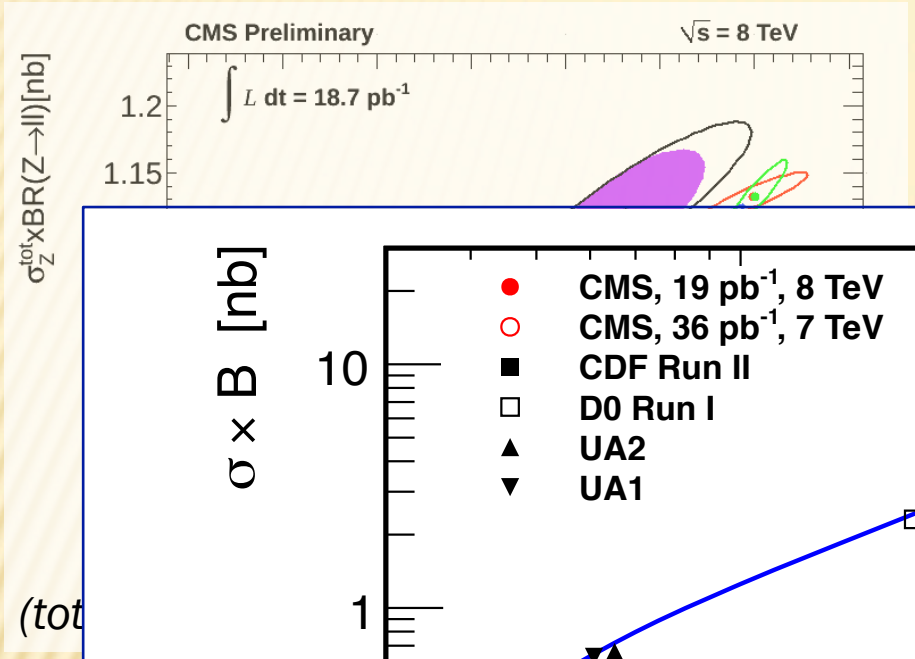


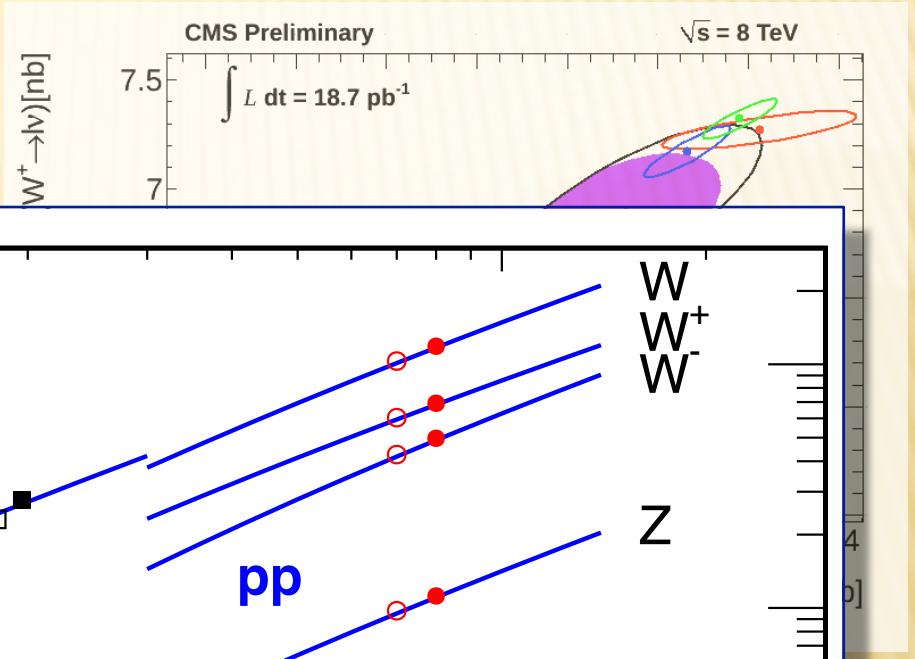
CMS have reported new measurements with 8 TeV data.

- special running conditions to reduce pile-up
- direct comparison to 7 TeV measurements is possible.

CMS 7 TeV: R = 10.54 ± 0.07 (stat) ± 0.17 (syst)
CMS 8 TeV: R = 13.26 ± 0.15 (stat) ± 0.21 (syst)

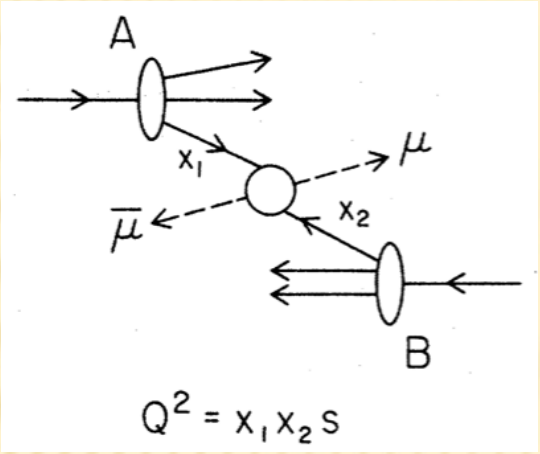
PRL 112 191802


CMS Preliminary
√s = 8 TeV
∫ L dt = 18.7 pb-1
σ^tot_Z xBR(Z→ll)[nb]
1.2
1.15

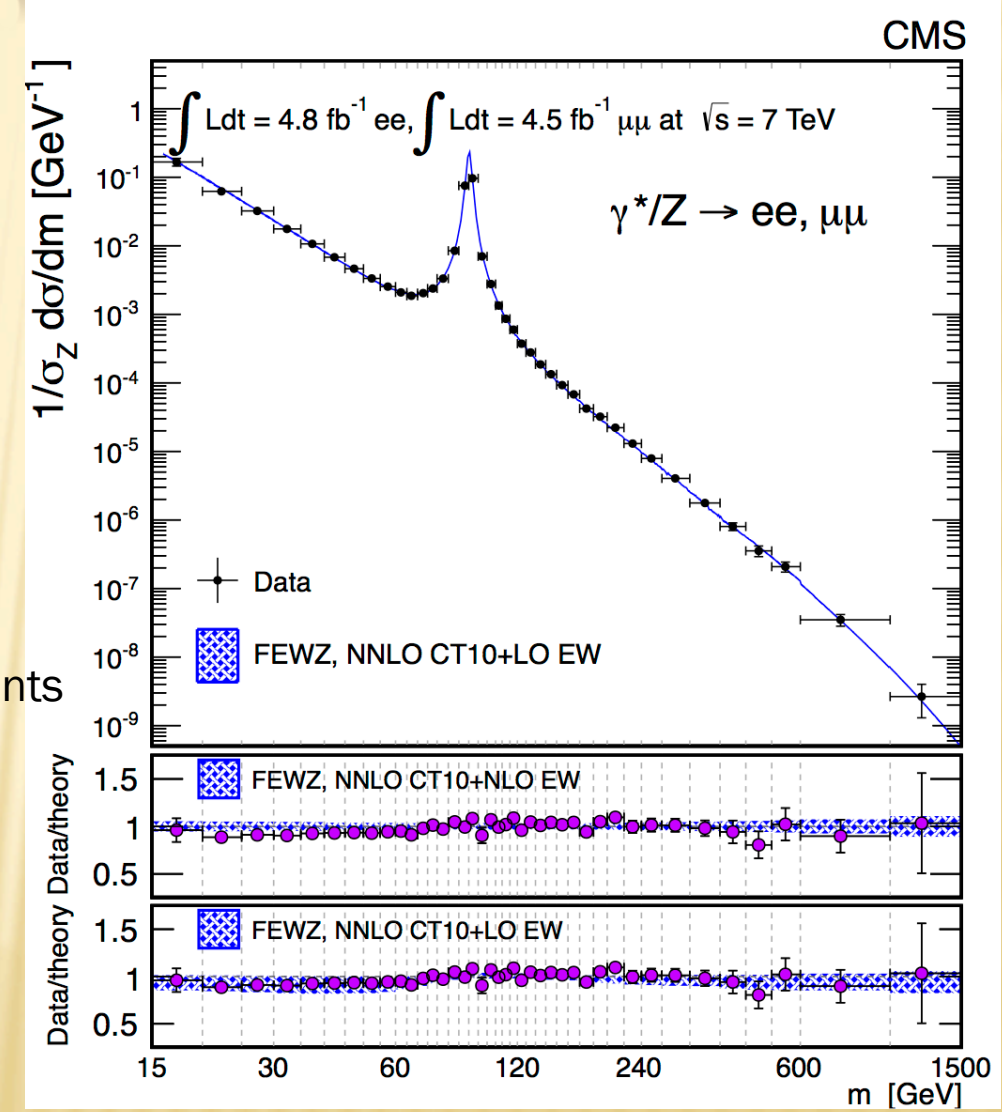

CMS Preliminary
√s = 8 TeV
∫ L dt = 18.7 pb-1
W+→lν)[nb]
7.5
7

σ × B [nb]
CMS, 19 pb-1, 8 TeV
CMS, 36 pb-1, 7 TeV
CDF Run II
D0 Run I
UA2
UA1
W
W+
W-
Z
pp
pp̄
Theory: NNLO, FEWZ and MSTW08 PDFs
10
1
10-1
0.5
1
2
5
7
10
20
Collider Energy [TeV]

Drell-Yan Production

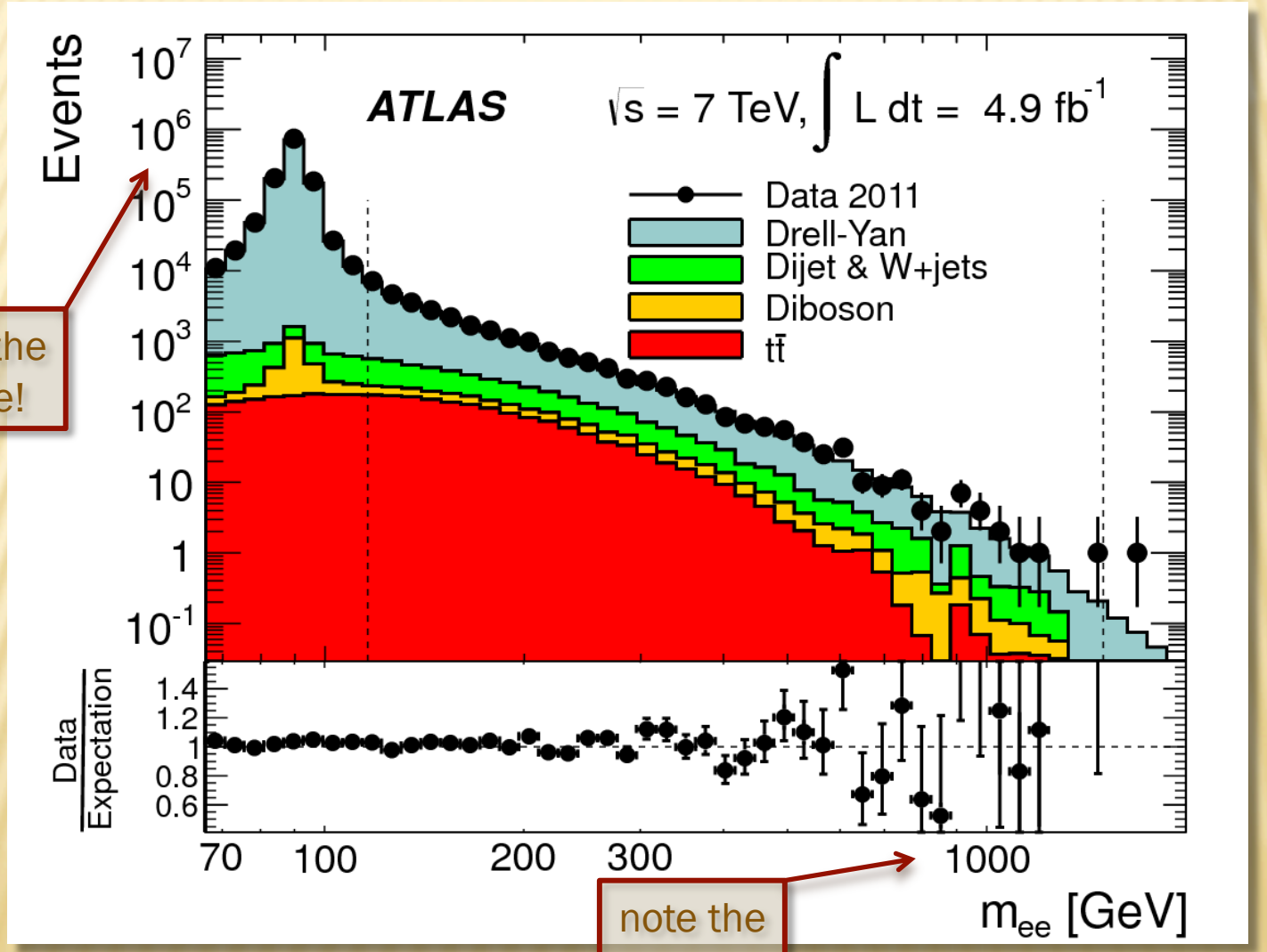


- understood since the 1970s
- 40 years later, very precise measurements
- wide range of mass: wide range of *x*
  → constrain PDFs
- higher-order corrections needed
  → tests of theory are still relevant



ATLAS published measurements of high-mass Drell-Yan:

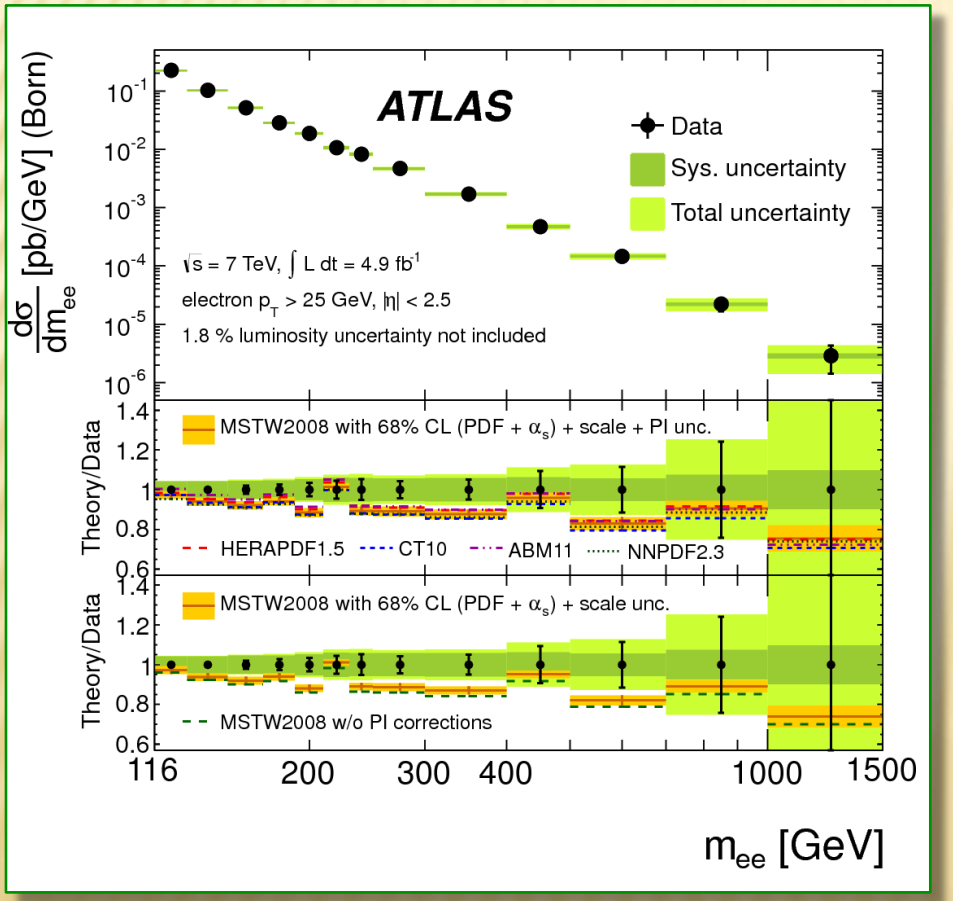
- high-mass region is amenable to pQCD calculations

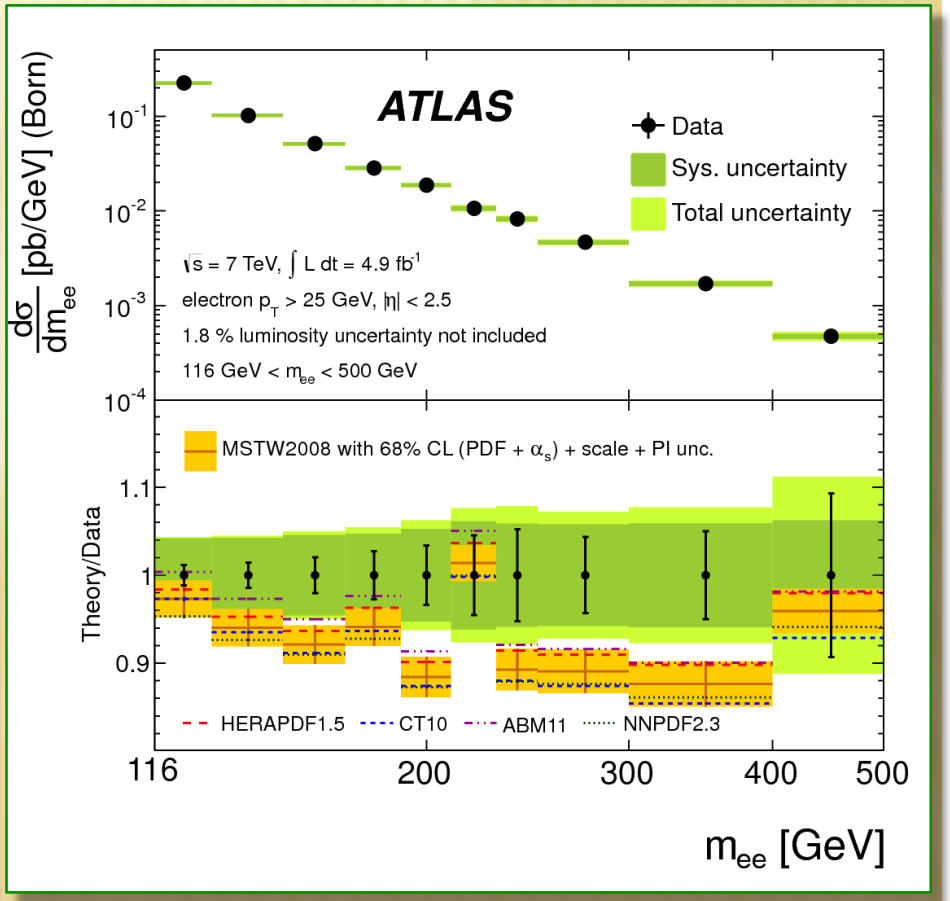


Phys. Lett. B725 (2013) 223

ATLAS published measurements of high-mass Drell-Yan:

- high-mass region is amenable to pQCD calculations
- sensitive to PDFs – even to $q \rightarrow q+\gamma$ splitting (a source of background)
- agreement is adequate, though data show excess in 120 < M < 400 range.

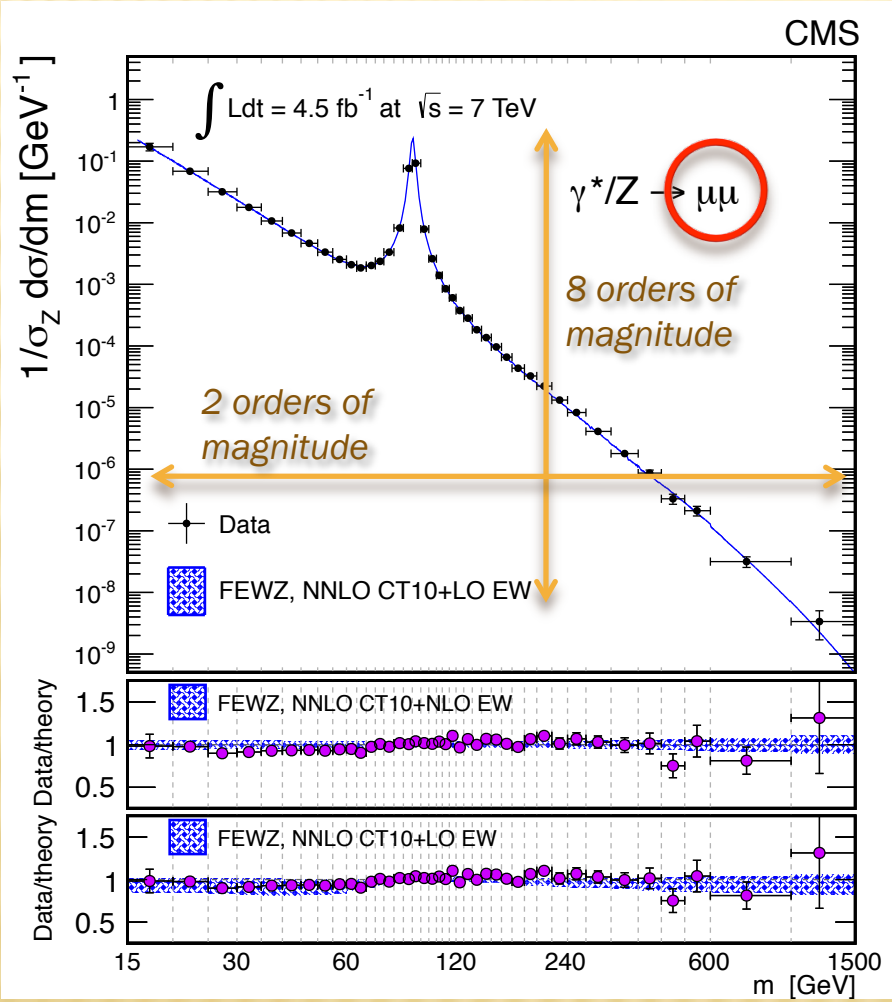


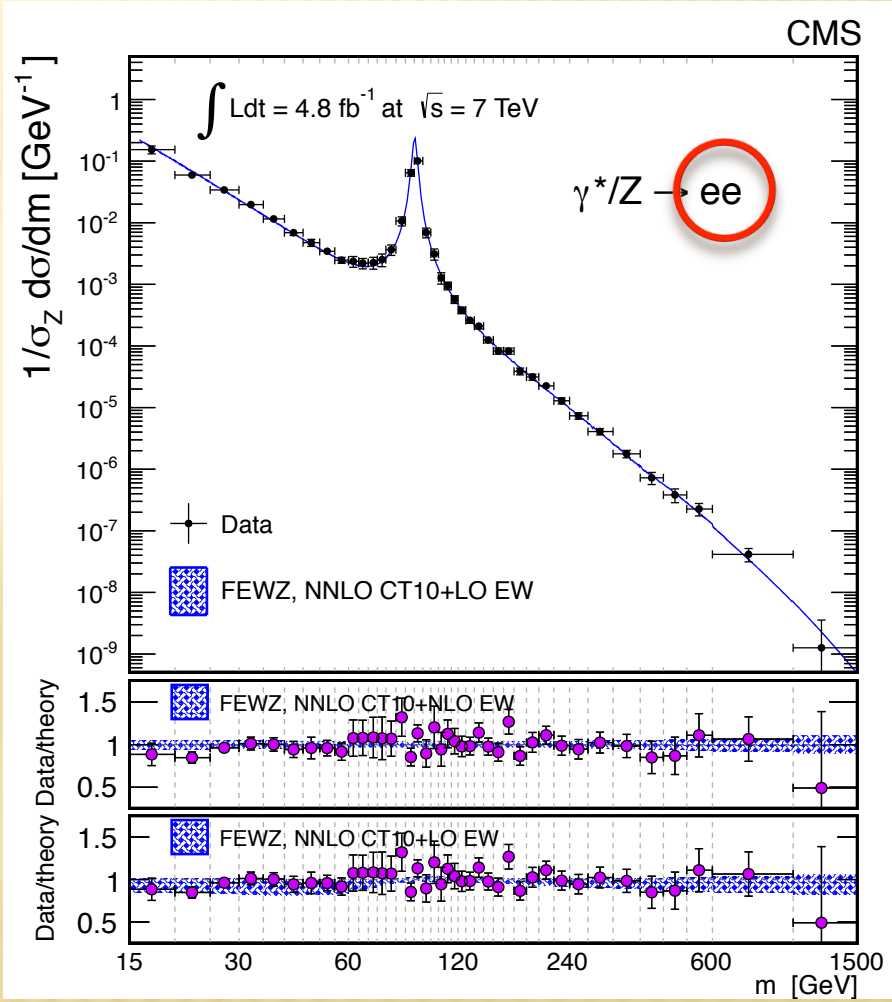


Phys. Lett. B725 (2013) 223

CMS has published a double-differential cross section measurement: $\frac{1}{\sigma_Z}\frac{d^2\sigma}{dM\,dY}$

- The integrated mass distribution is measured in both $\mu^+\mu^-$ and e^+e^- channels.



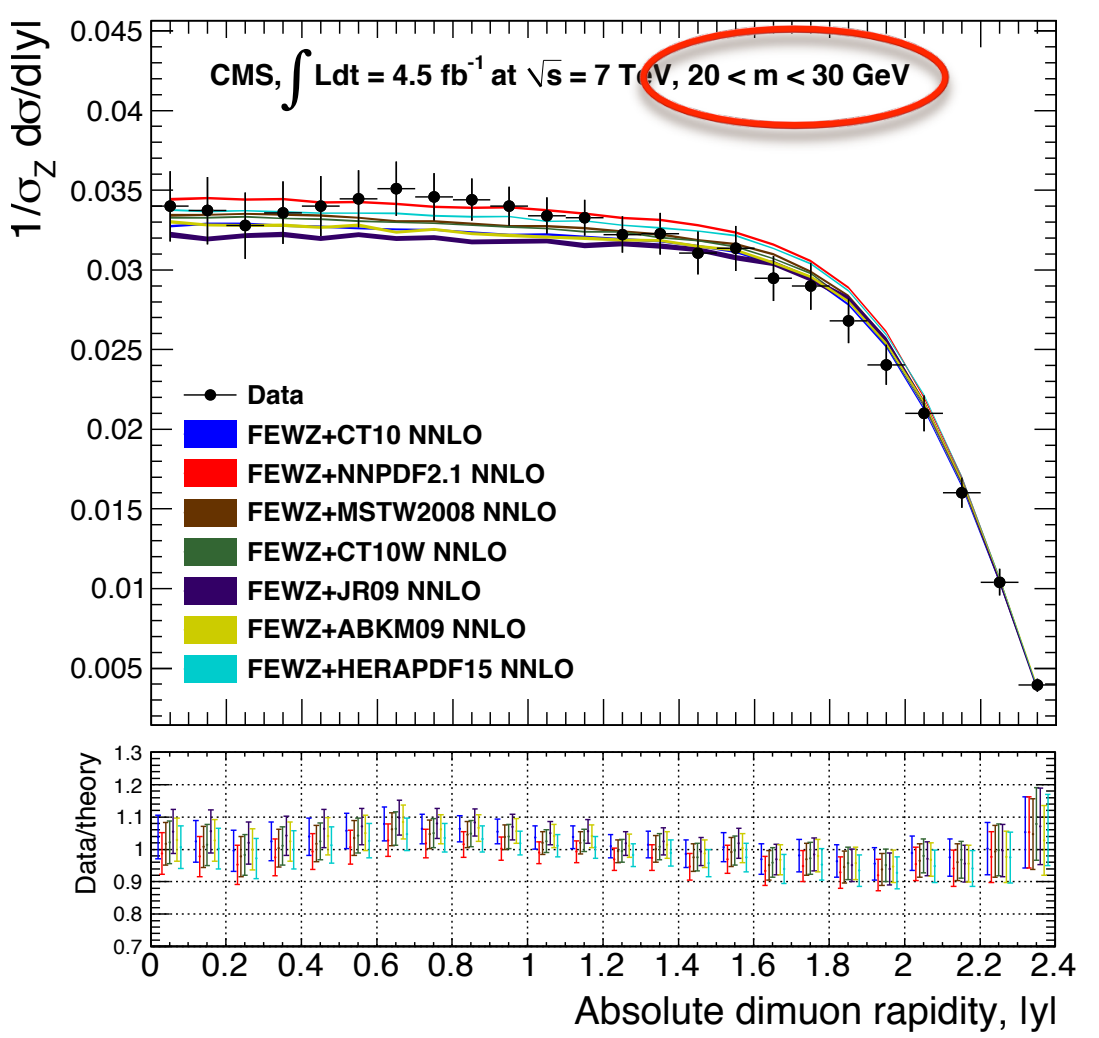


JHEP12 (2013) 030

(Combined e & μ plot shown earlier.)

CMS is publishing a double-differential cross section measurement: $\frac{1}{\sigma_Z}\frac{d^2\sigma}{dM\,dY}$

- There is enough data to measure $d\sigma/dY$ in several bins of mass.



Even in this low mass bin, experimental error bars about same size as spread coming from PDFs...

JHEP12 (2013) 030

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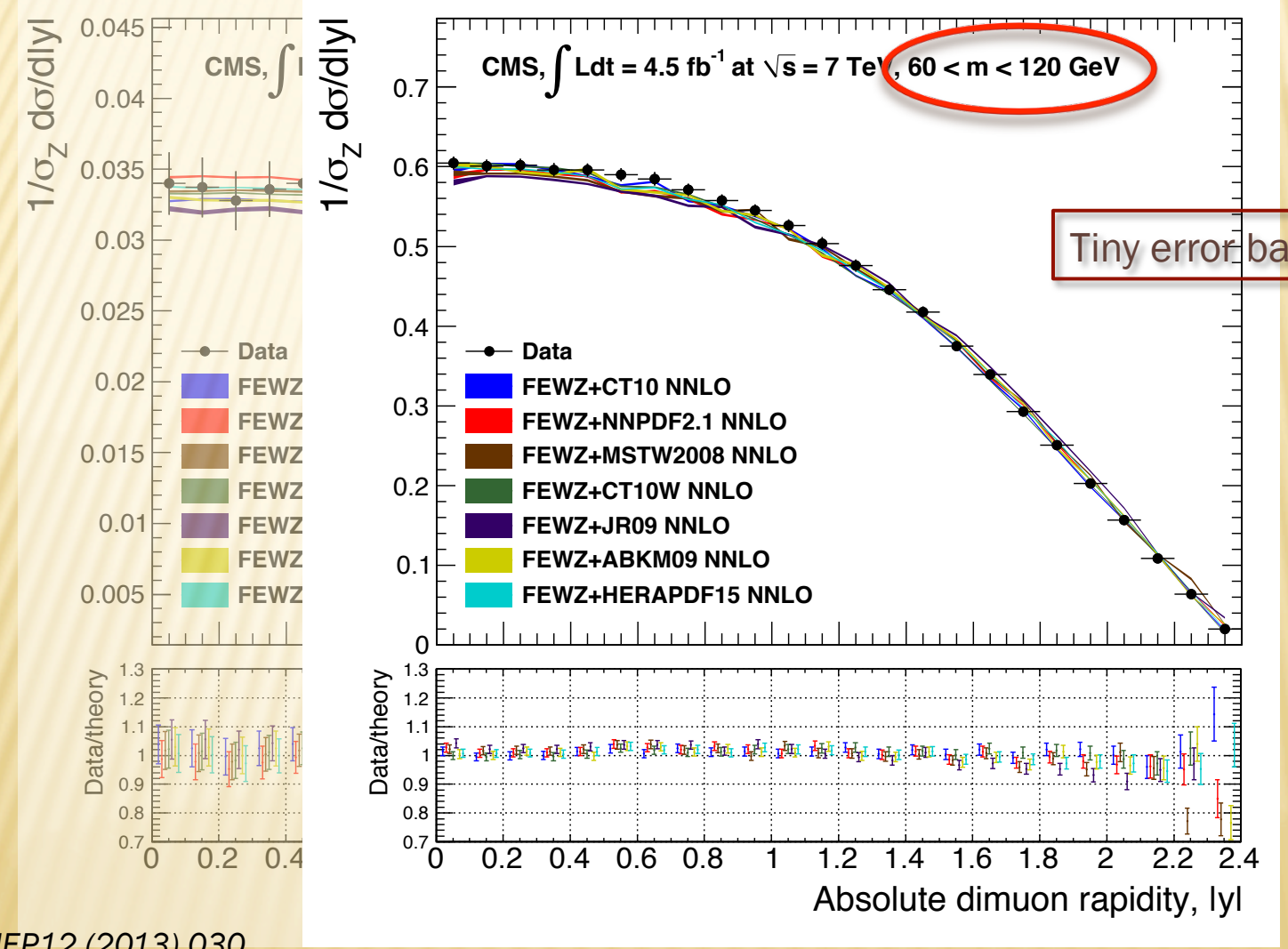

Tiny error bars for the Z peak

JHEP12 (2013) 030

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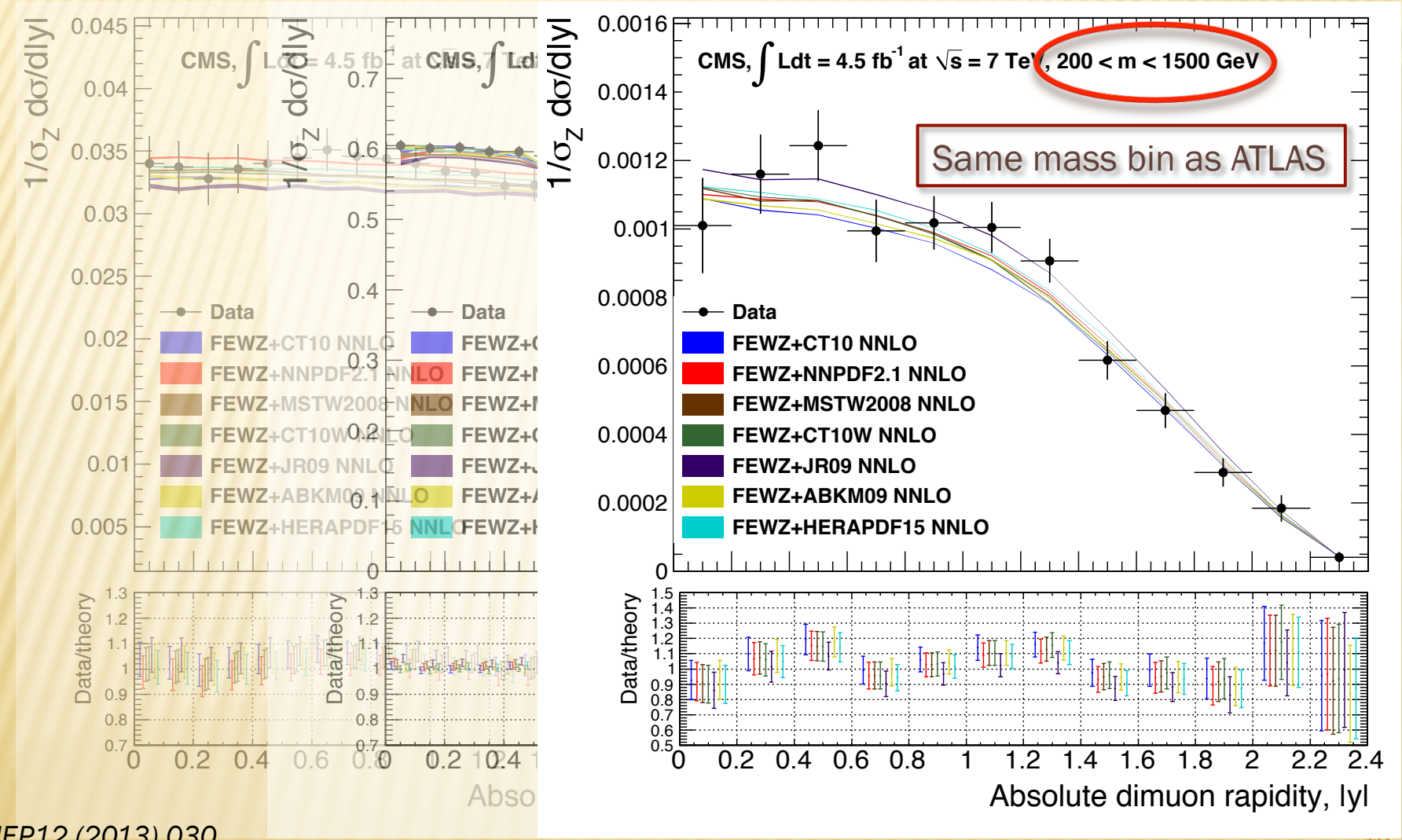
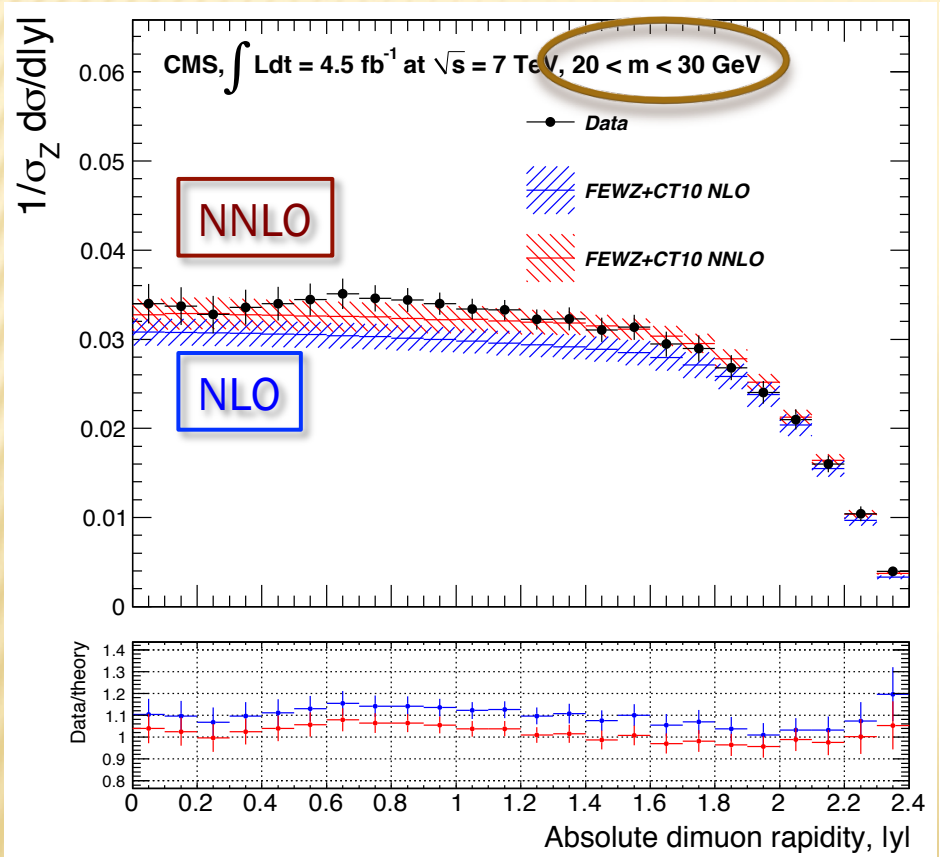
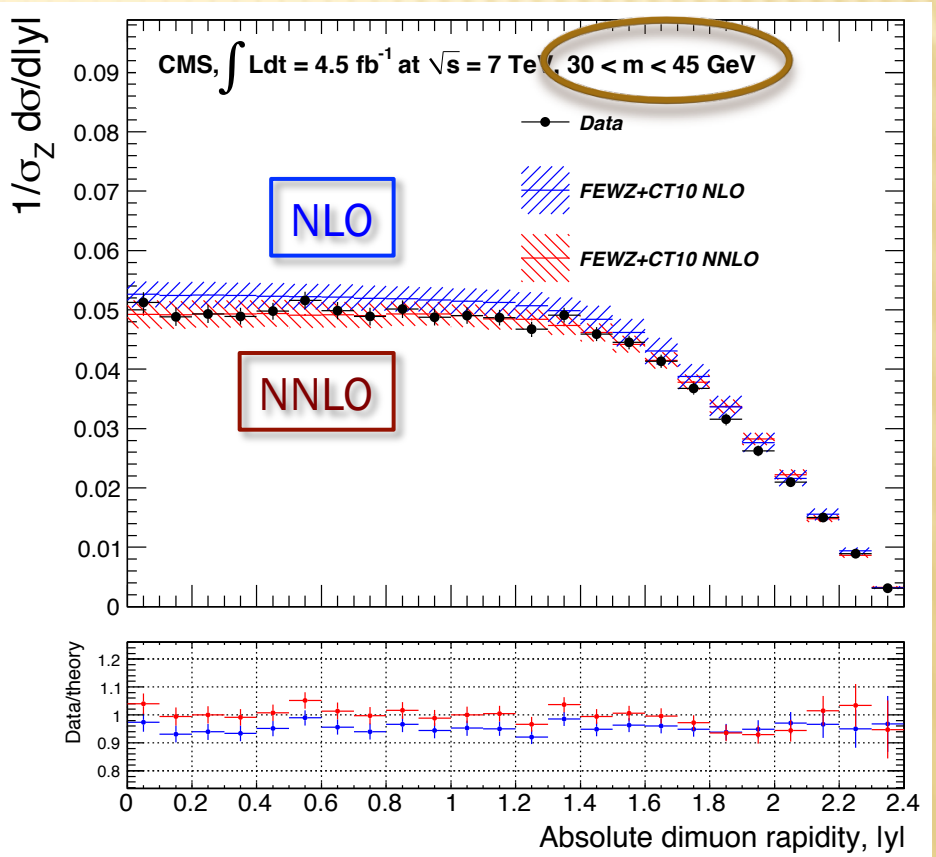


JHEP12 (2013) 030

CMS is publishing a double-differential cross section measurement: $\frac{1}{\sigma_Z}\frac{d^2\sigma}{dM\,dY}$

- The lower mass bins show an interesting sensitivity to higher-order corrections:





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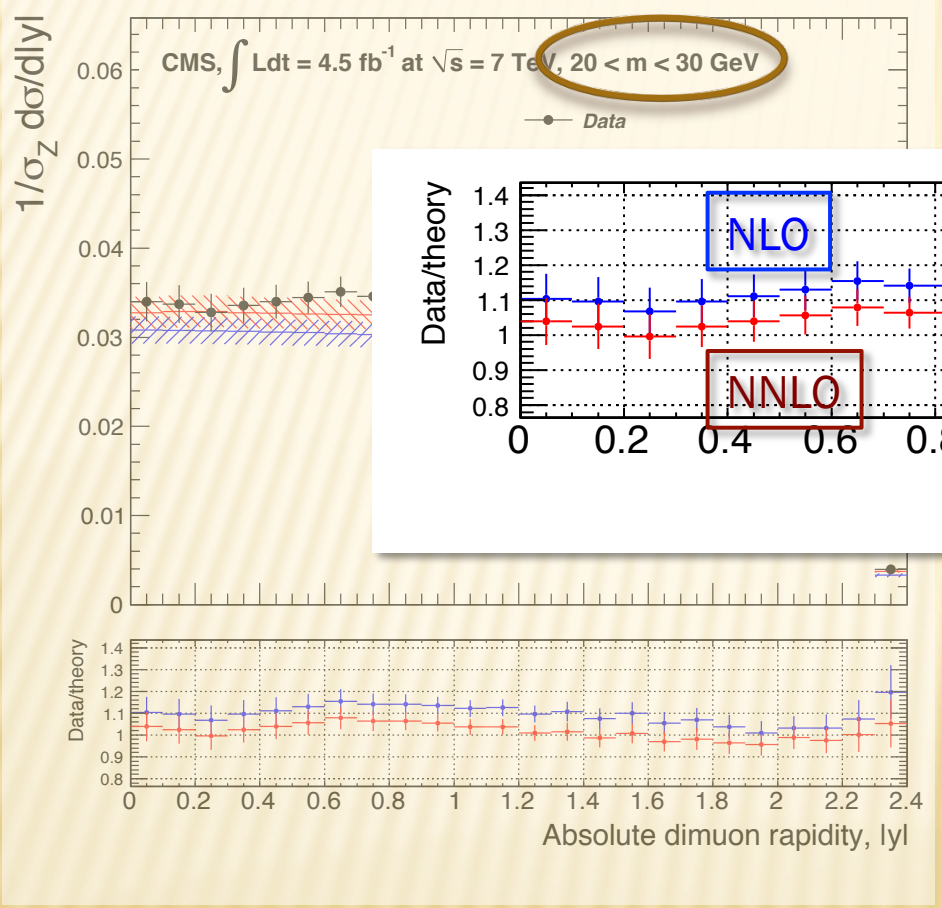
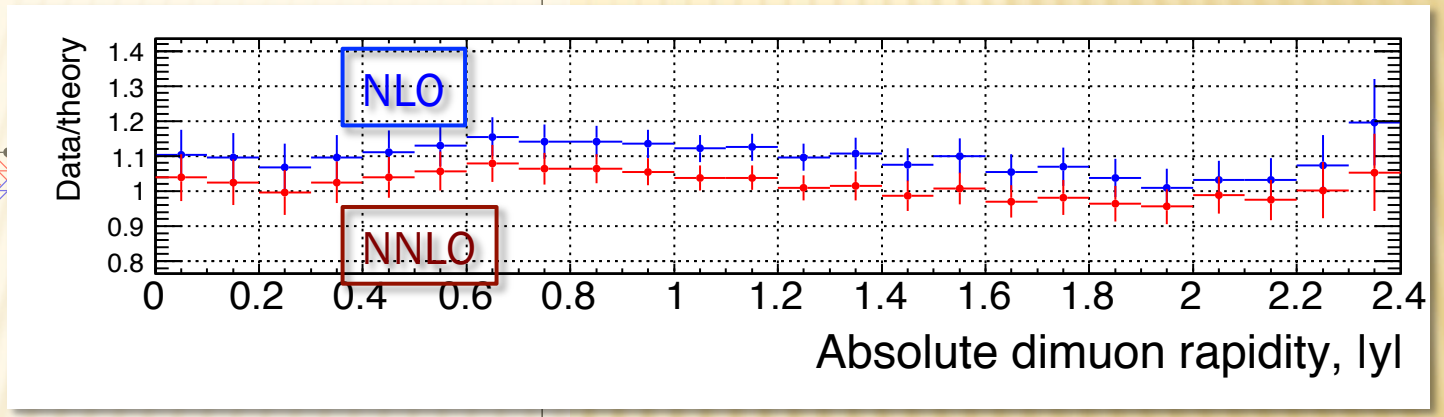


Closer look at NLO vs NNLO



JHEP12 (2013) 030

Transverse Momentum Distributions $\frac{d\sigma}{dq_T}$

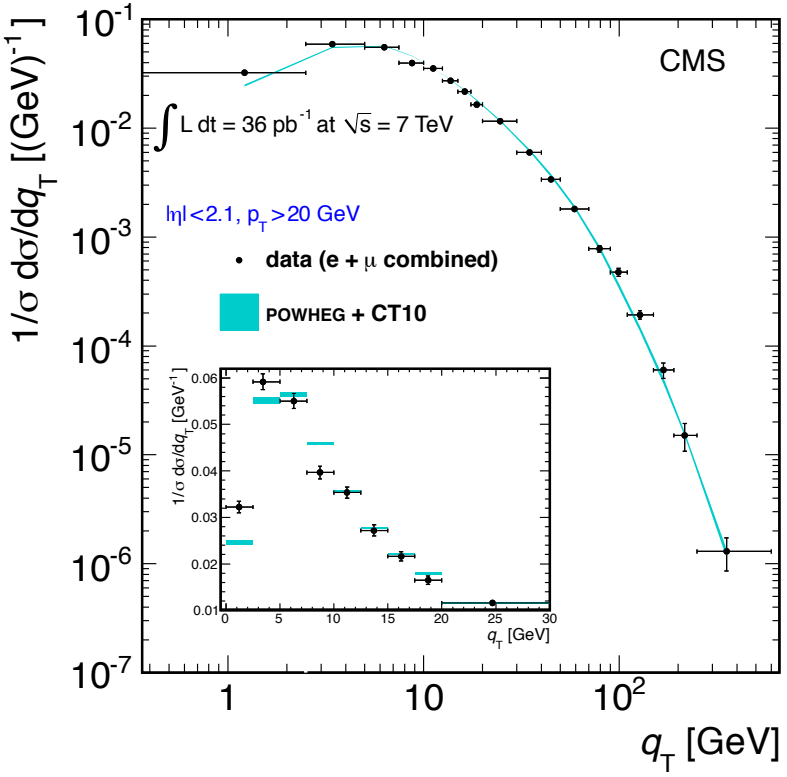
Two regimes:

1. low – q_T : dominated by multi-gluon emission : essentially non-perturbative
   depends on details of showering scheme
   gives information on the underlying event
   two theoretical scales: q_T and M which can be very different
   angular variables – an experimental improvement

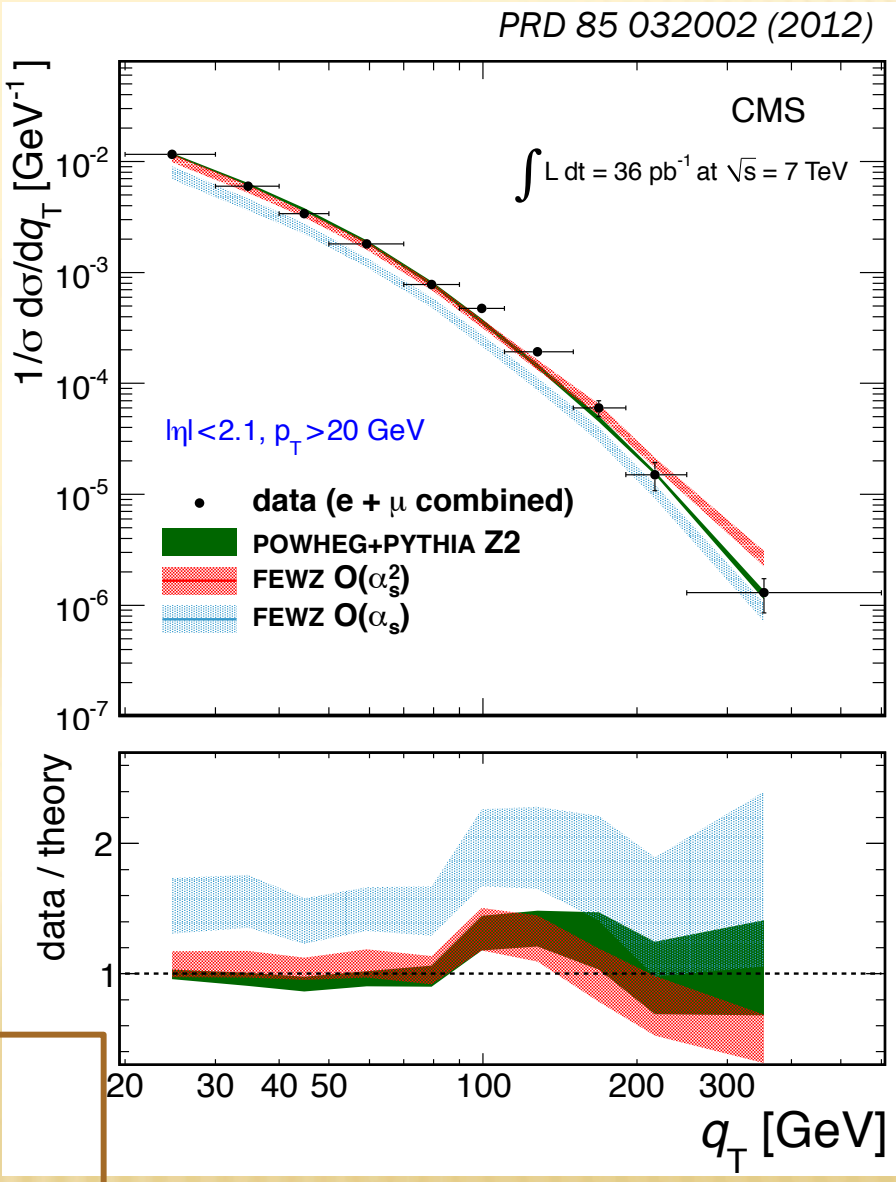
2. high – q_T : dominated by one or two hard parton emission: pQCD
   gluons in initial state start to be important
   matrix element calculations needed

CMS measurements at low and high q_T :

7 TeV



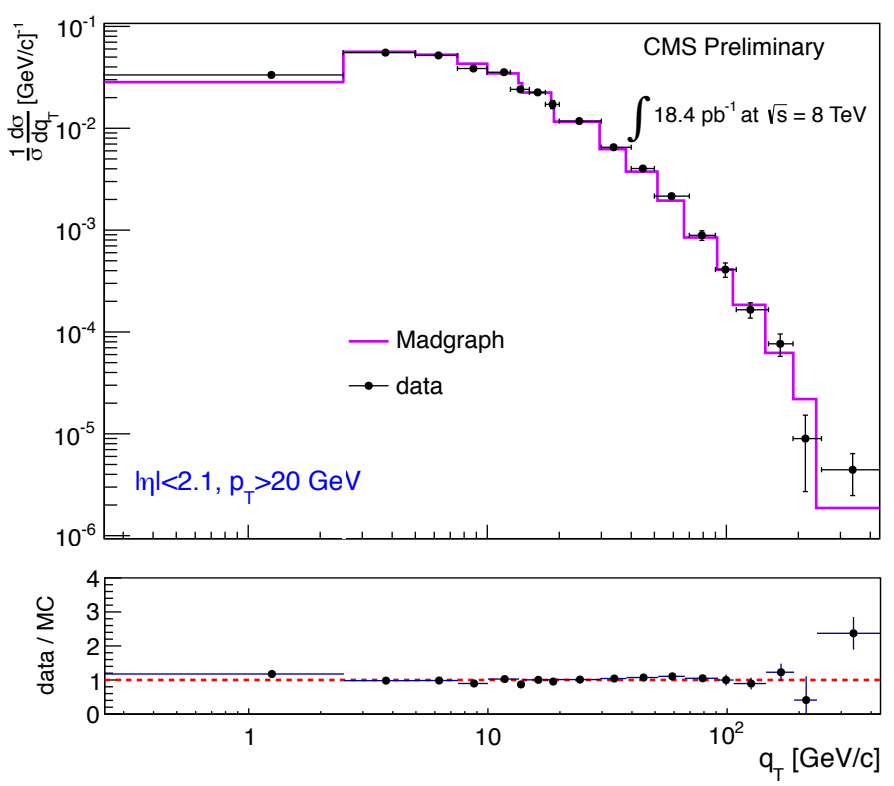
PRD 85 032002 (2012)

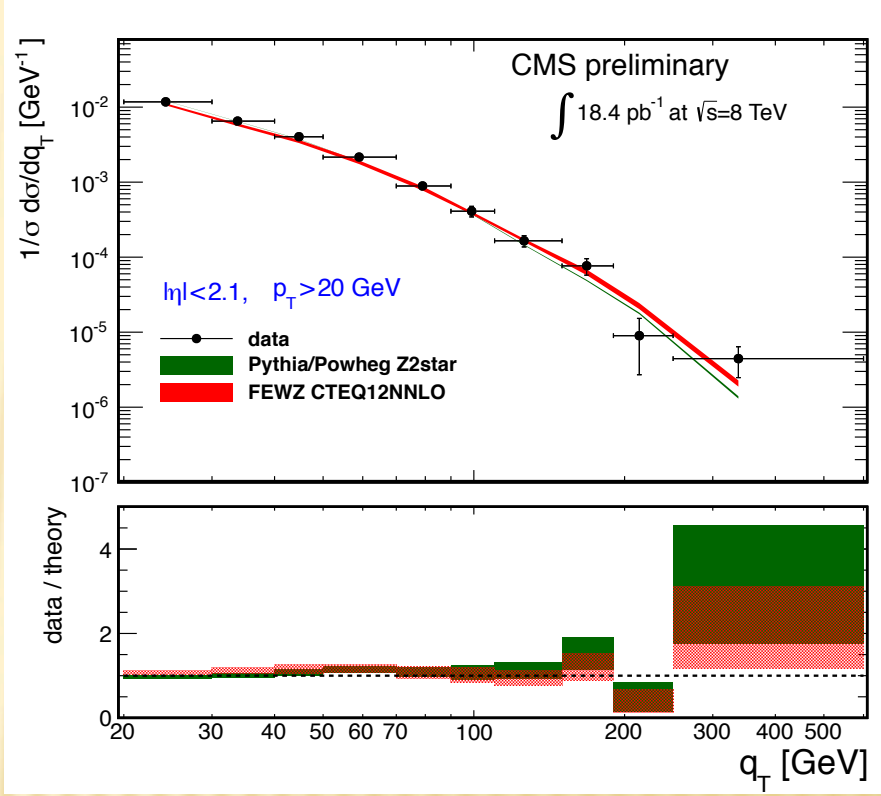


- disagreement at low – q_T indicates need for tuning underlying event model
- agreement at high – q_T is achieved with FEWZ at $O(\alpha^2_S)$ .... and POWHEG/PYTHIA/Z2

See also ATLAS: *PLB 725 (2013) 223*

CMS preliminary measurements: 8 TeV



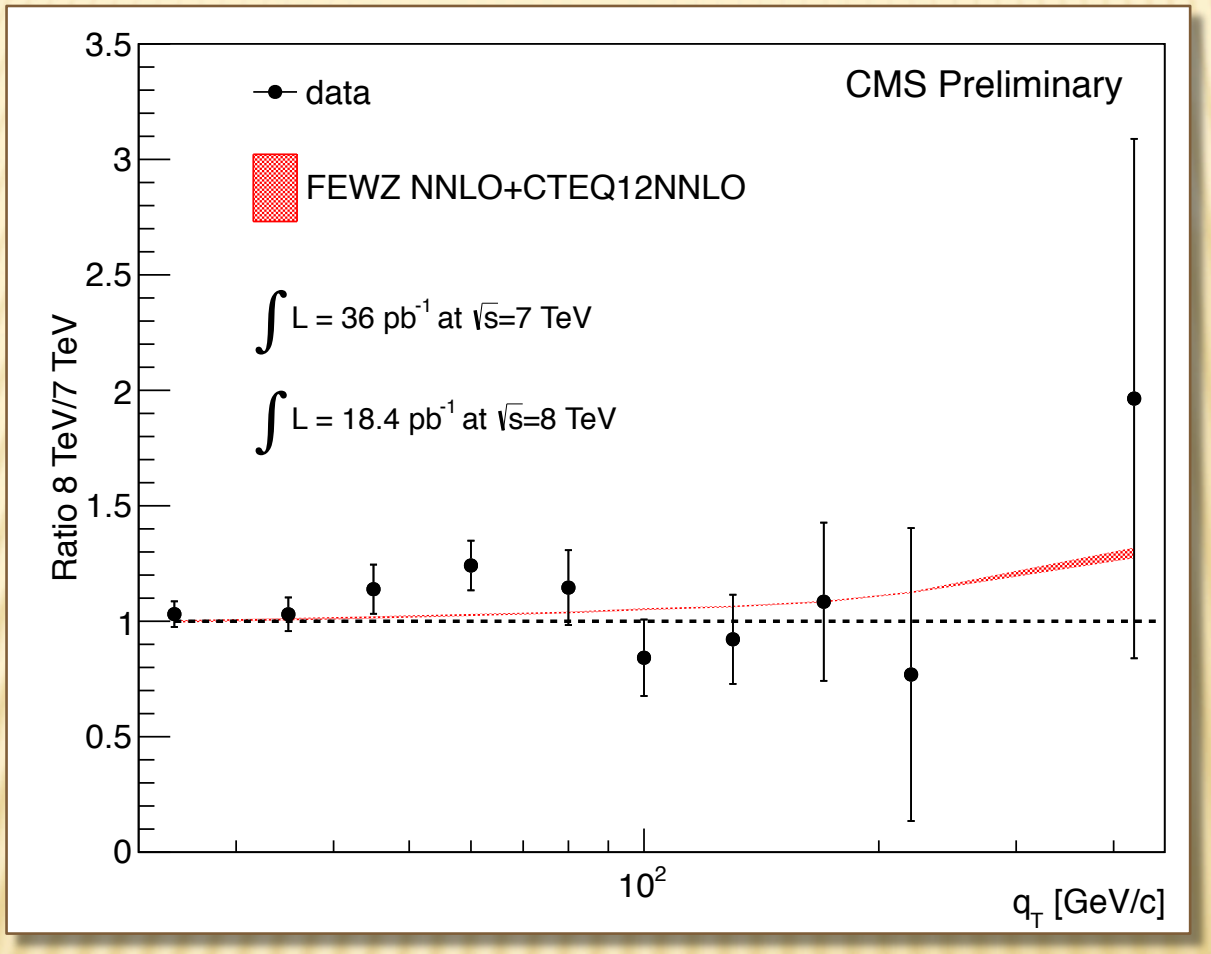


- best overall agreement achieved with ResBos, which uses two scales (q_T & M)
- agreement at high – q_T is achieved with FEWZ at $O(\alpha^2_S)$ …. and POWHEG/PYTHIA/Z2*

SMP-12-025

CMS compares 7 TeV and 8 TeV directly:

CMS PAS SMP-12-025



Data seem to agree with the prediction from FEWZ but statistical uncertainties are large.

ATLAS has published measurements of a special angular variable:

$$\phi_\eta^* = \tan\left(\frac{\varphi_{\text{acop}}}{2}\right)\sin(\theta_\eta^*)$$

where:

$$\varphi_{\text{acop}} = \pi - \Delta\varphi$$

$$\cos(\theta_\eta^*) = \tanh\left[\tfrac{1}{2}\left(\eta^{(-)} - \eta^{(+)}\right)\right]$$

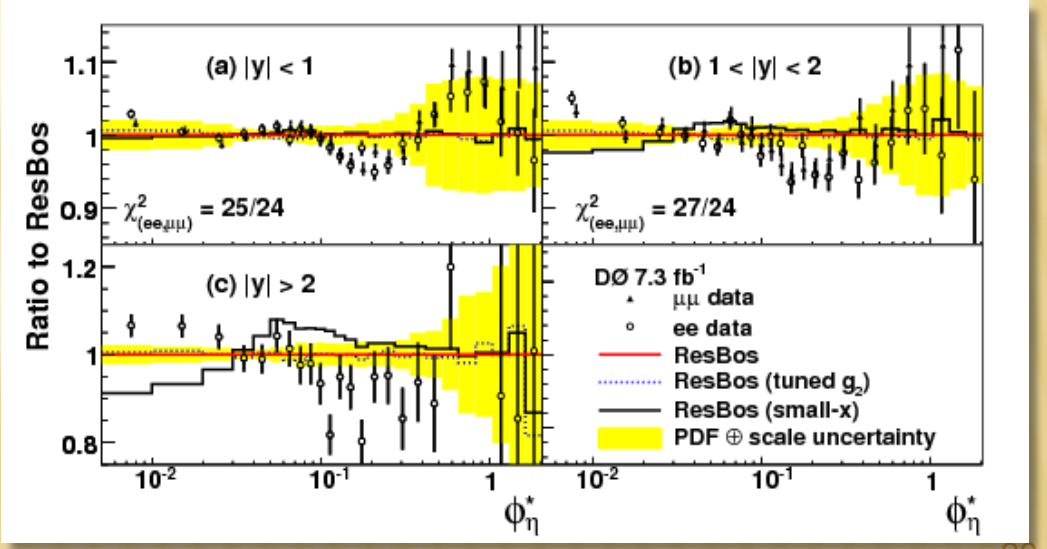
- For a back-to-back configuration, the resolution of q_T is not very good.
- The quantity ϕ^*_η depends only on the angles of the muon trajectories.
- Roughly speaking,

$$\phi_\eta^* \approx \frac{q_T}{M_{\ell\ell}}$$

- $\phi^*_\eta \rightarrow 0.1$ corresponds to $q_T \rightarrow$ *10 GeV*
- The small – q_T region is better studied with ϕ^*_η .

PRL 106 122001 (2011)

DØ published the first study of ϕ^*_η showing deviations from ResBos predictions at moderate q_T.



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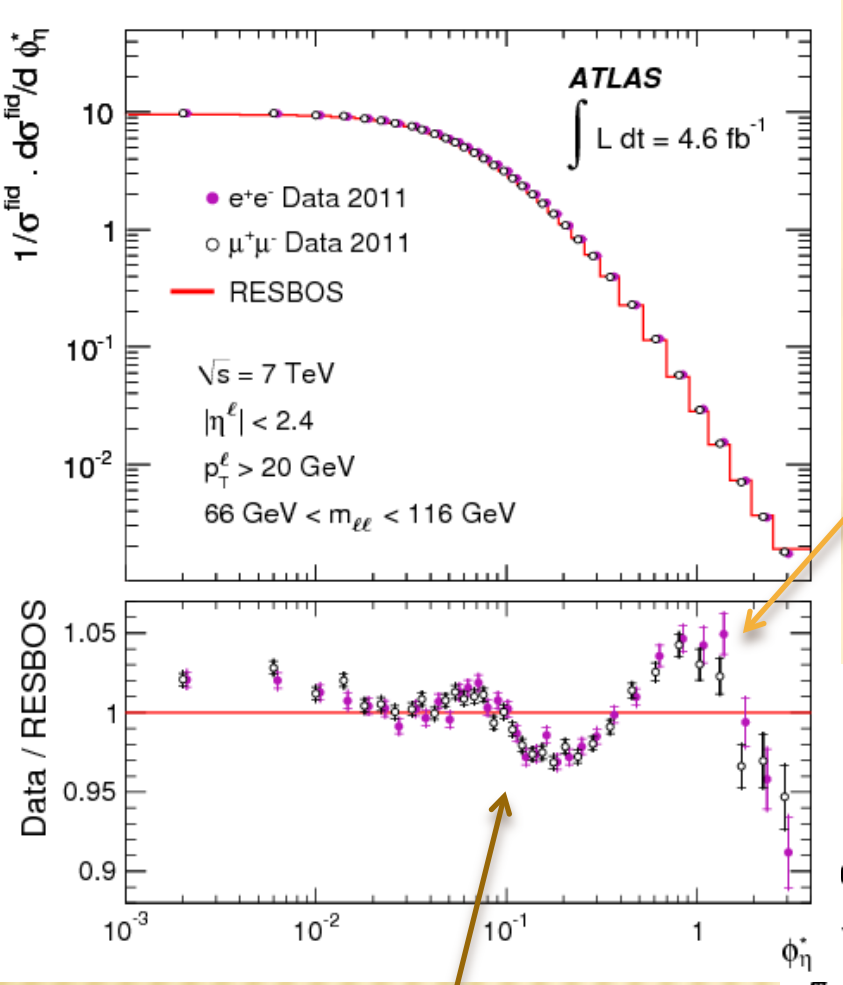
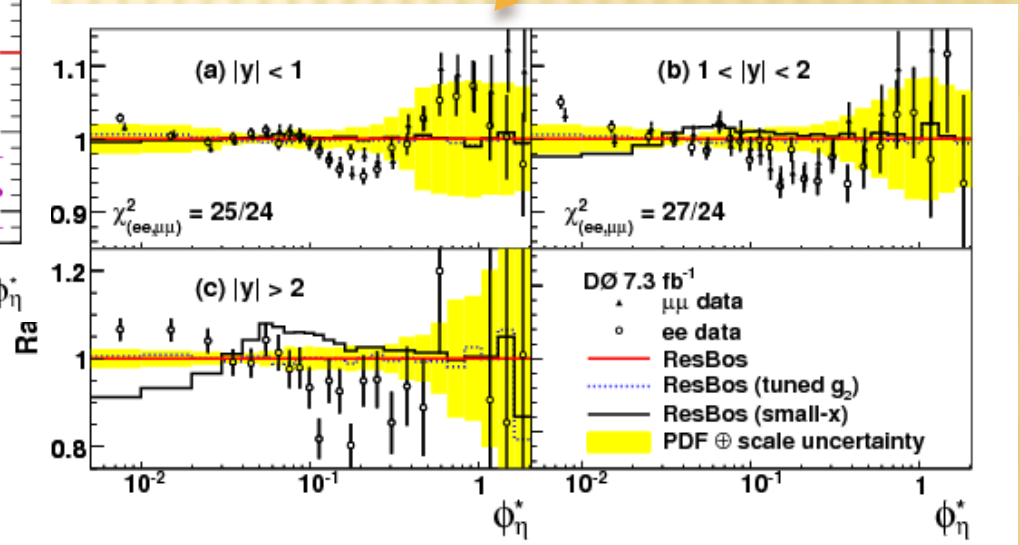


Phys. Lett. B720 (2013) 32

ATLAS confirms trends seen by DØ

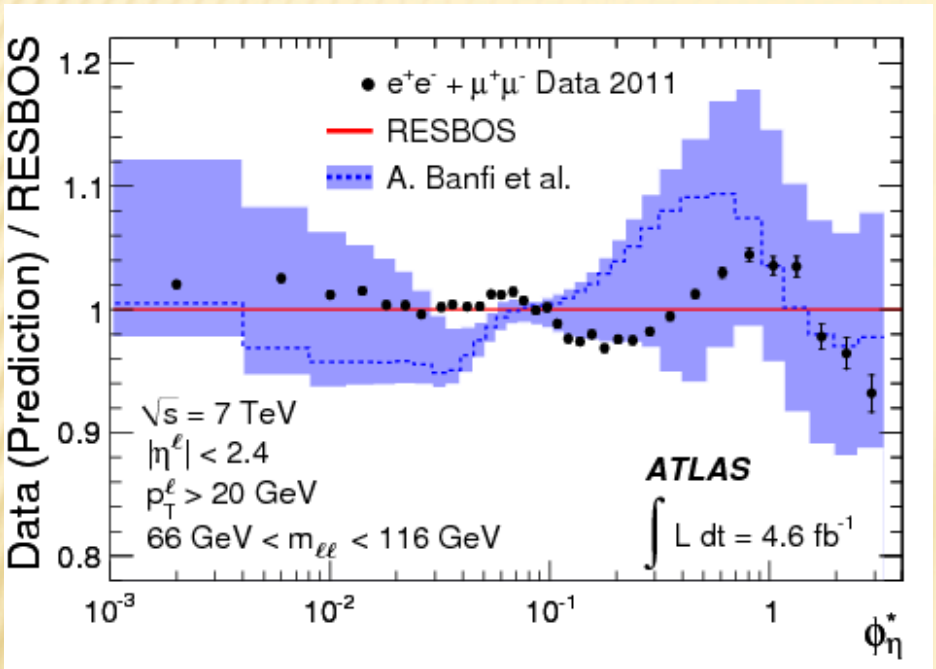
PRL 106 122001 (2011)

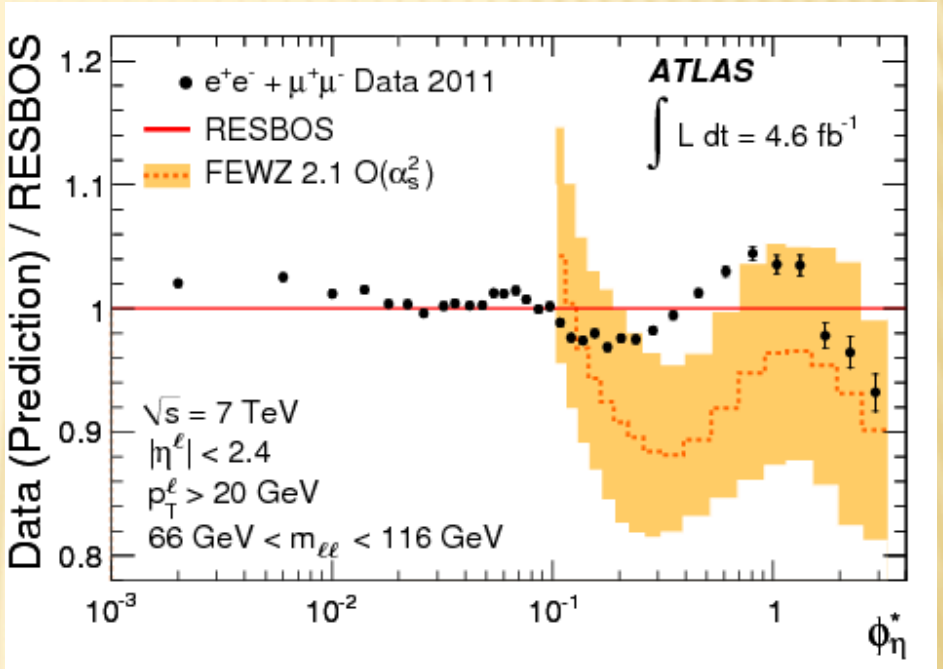


e^+e^- and $\mu^+\mu^-$ agree very well

ATLAS comparisons to theoretical predictions:

Phys. Lett. B720 (2013) 32





Banfi *et al.* [Phys. Lett. B715 (2012) 152]

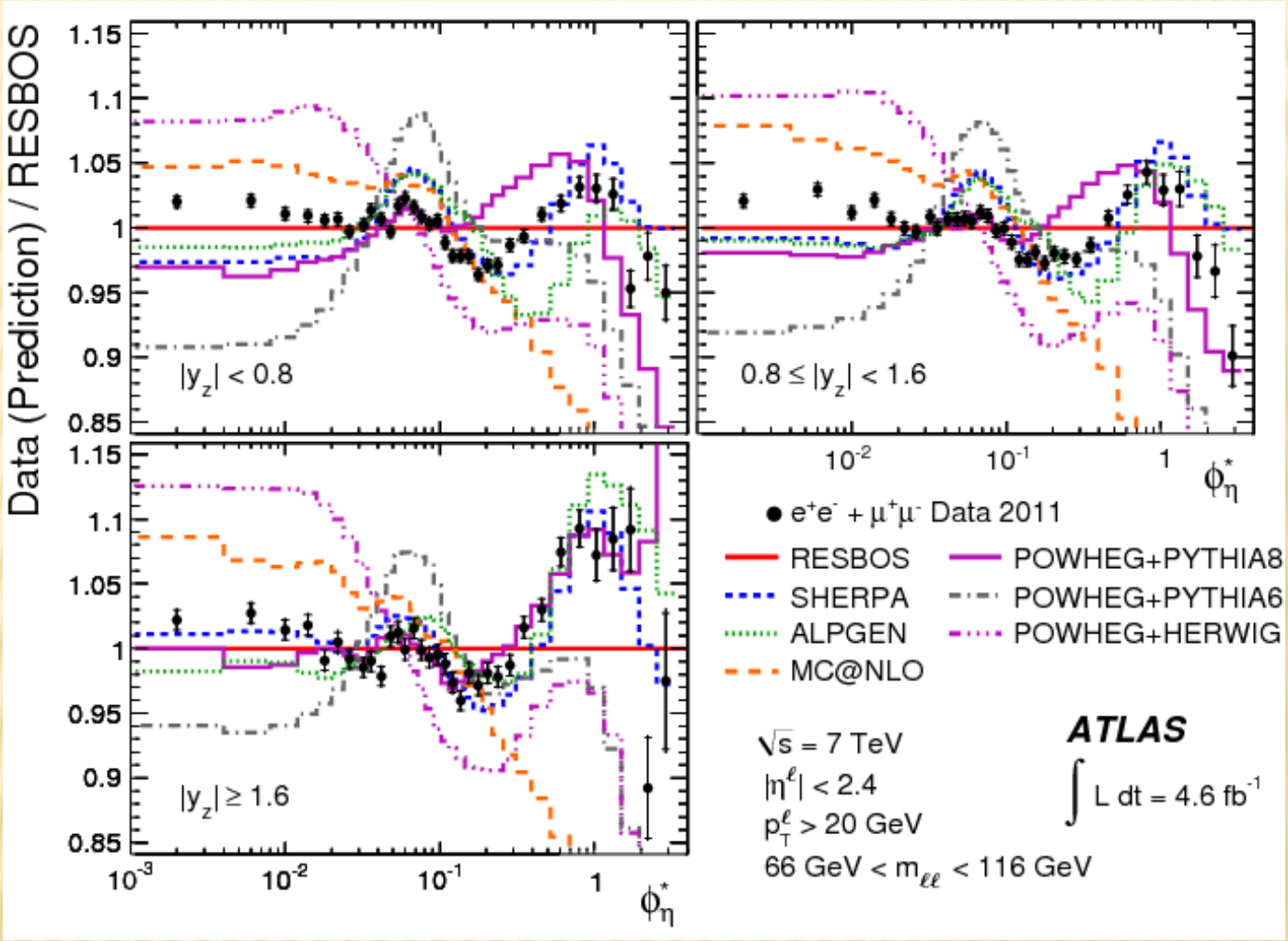
- employ q_T – resummation technique
- match to fixed-order calculation in MCFM
- good results for LHC $d\sigma/dq_T$ data

FEWZ (F. Petriello *et al.*)

- fixed-order (α^2_S)
- not good in non-perturbative regime
- good agreement with other observables

ATLAS comparisons to theoretical predictions in $|Y|$ bins:

Phys. Lett. B720 (2013) 32

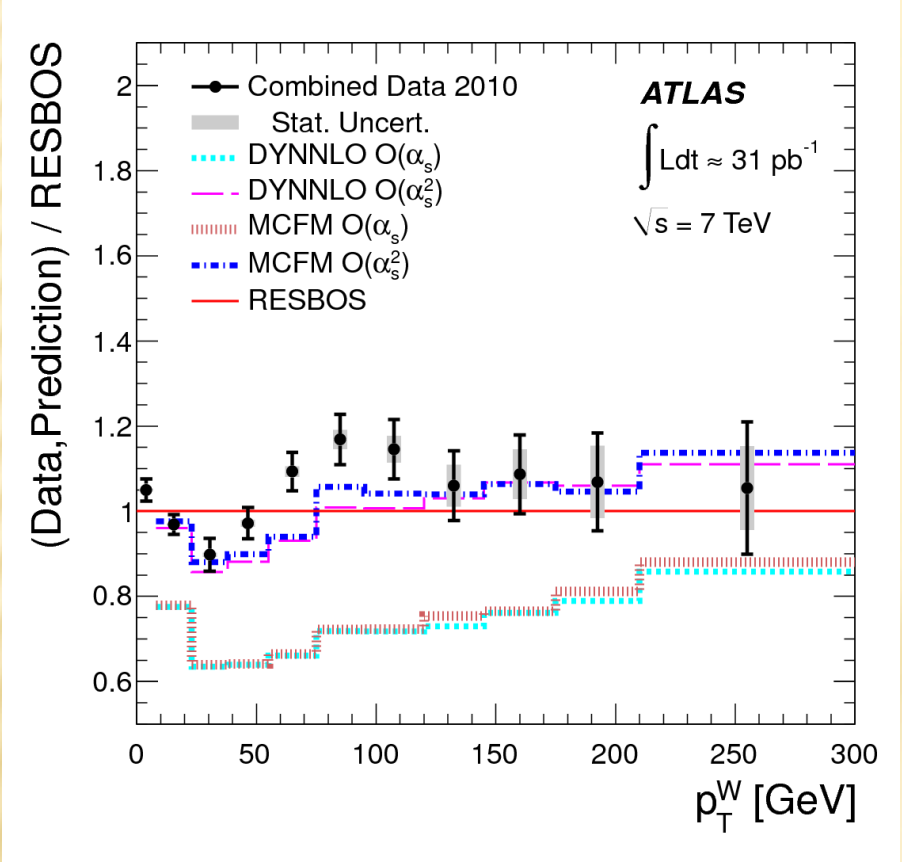


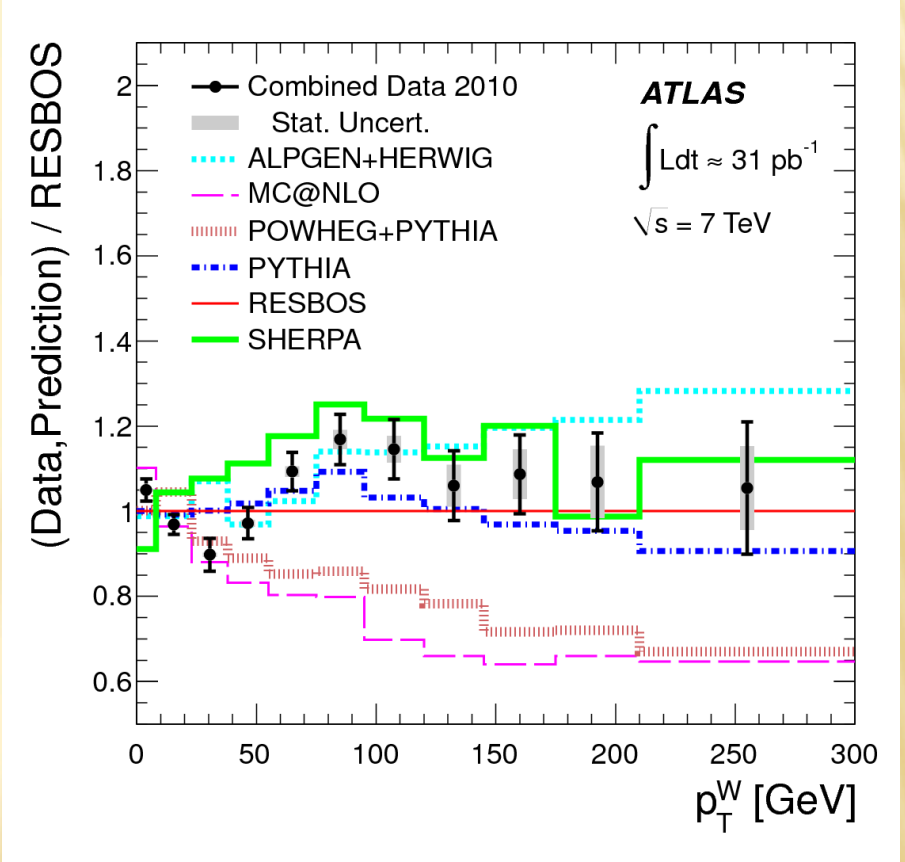
SHERPA does best

ALPGEN is OK

ATLAS have also measured the q_T distribution of W bosons:

PRD 85 012005 (2012)



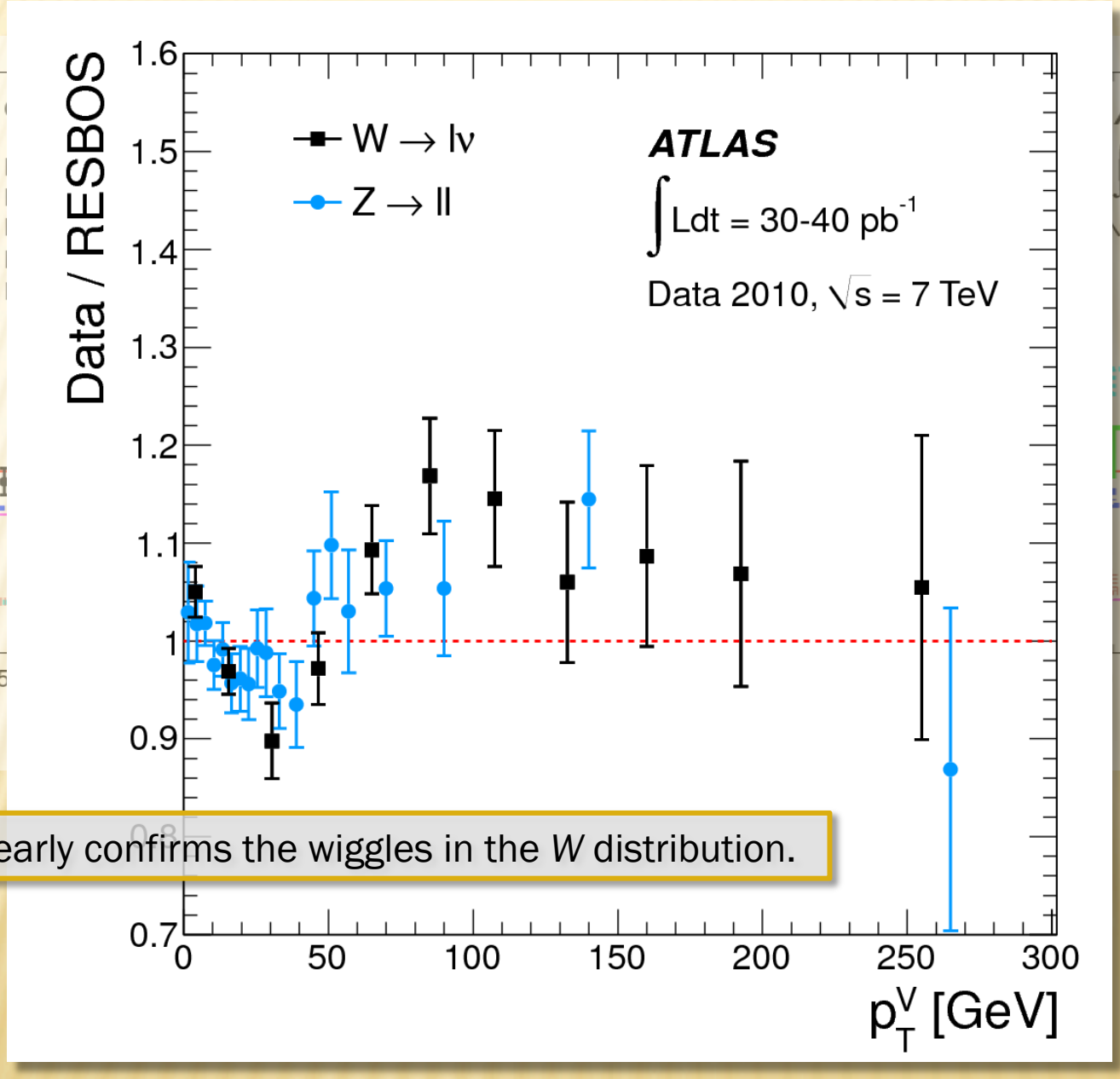


$O(\alpha^2_S)$ calculation is clearly needed.

SHERPA is OK

ALPGEN does best

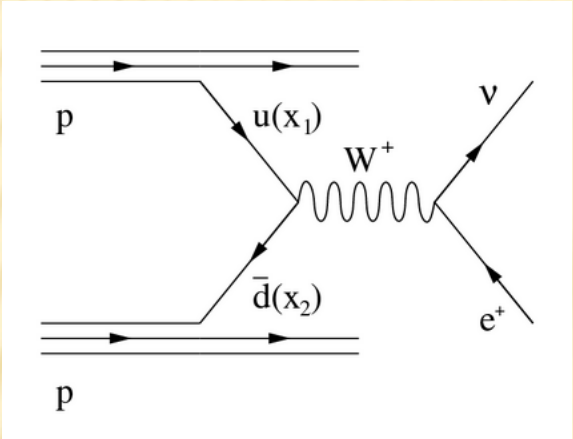
ATLAS have also measured the q_T distribution of W bosons: *PRD 85 012005 (2012)*

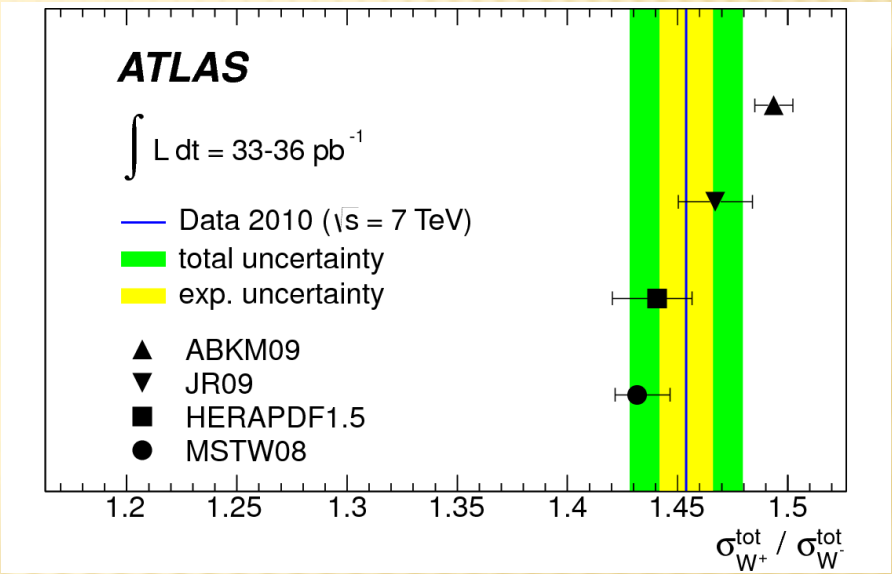


Z clearly confirms the wiggles in the *W* distribution.

W Charge Asymmetry

- More W^+ are produced than W^- because u predominates over d.
  → possibility to constrain d/u ratio





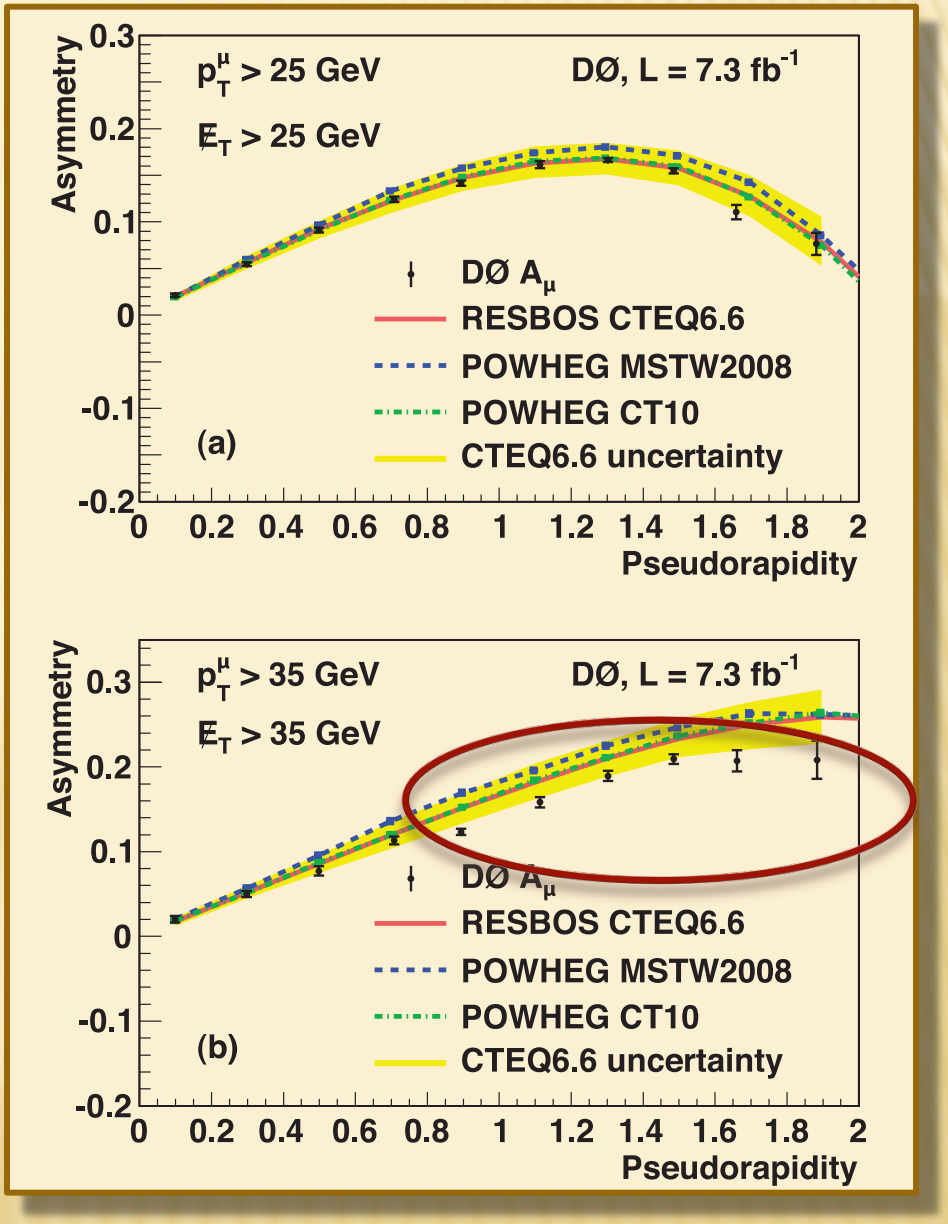
- The asymmetry will be more pronounced at larger Y_W (corresponds to larger x)
  → but Y_W is difficult to measure

- We can use the lepton η instead of Y_W but the asymmetry is more complicated.
  → and very small errors means dealing with very difficult systematics

$$A_\ell = \frac{\sigma(\eta^{(+)}) - \sigma(\eta^{(-)})}{\sigma(\eta^{(+)}) + \sigma(\eta^{(-)})}$$

DØ have a new measurement:

- There has been tension between CDF & DØ measurements.
- Measurements from p pbar colliders are complimentary.
- New DØ measurements are precise and do not agree with theory.
- Interpretation: *d/u* should be increased.

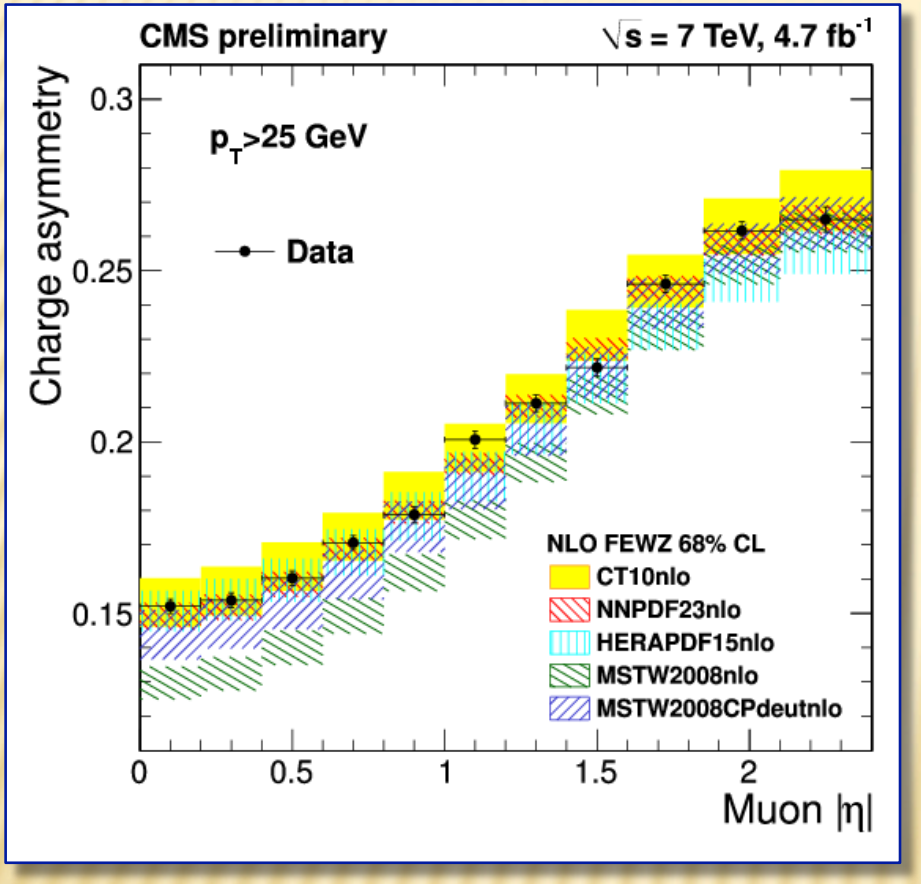


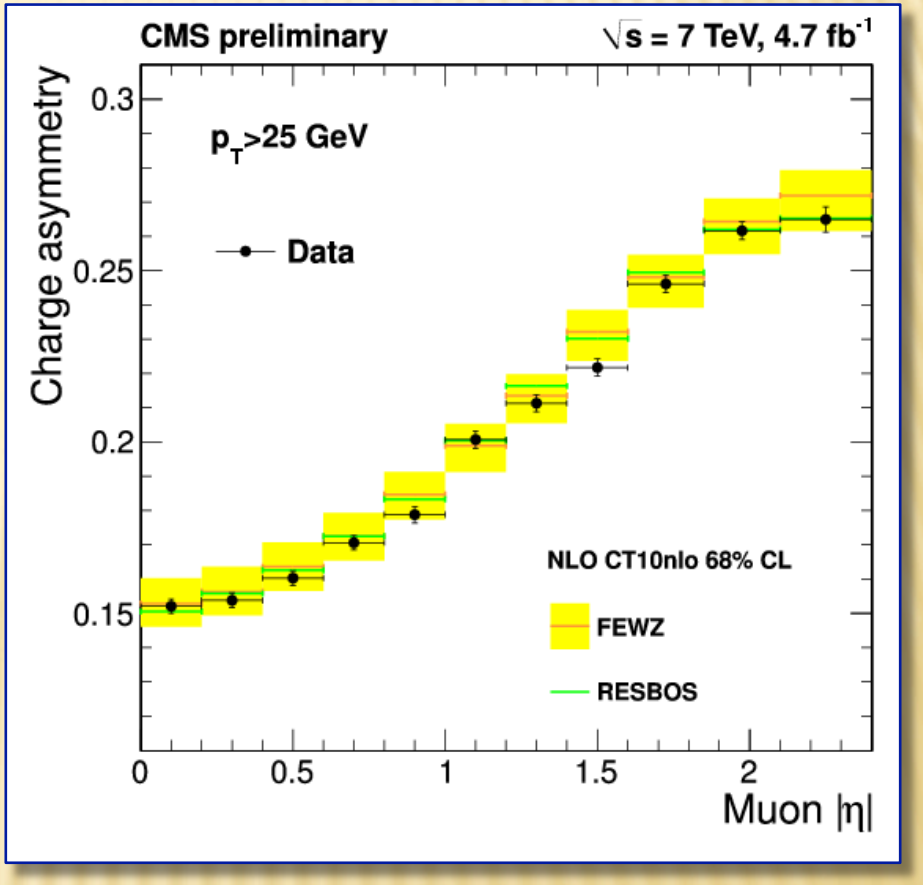
Phys. Rev. D88 091102(R) (2013)

CMS have a new measurement:

arXiv:1312.6283

full data set at 7 TeV, muon channel, $p_T > 25$ GeV, and also $p_T > 35$ GeV

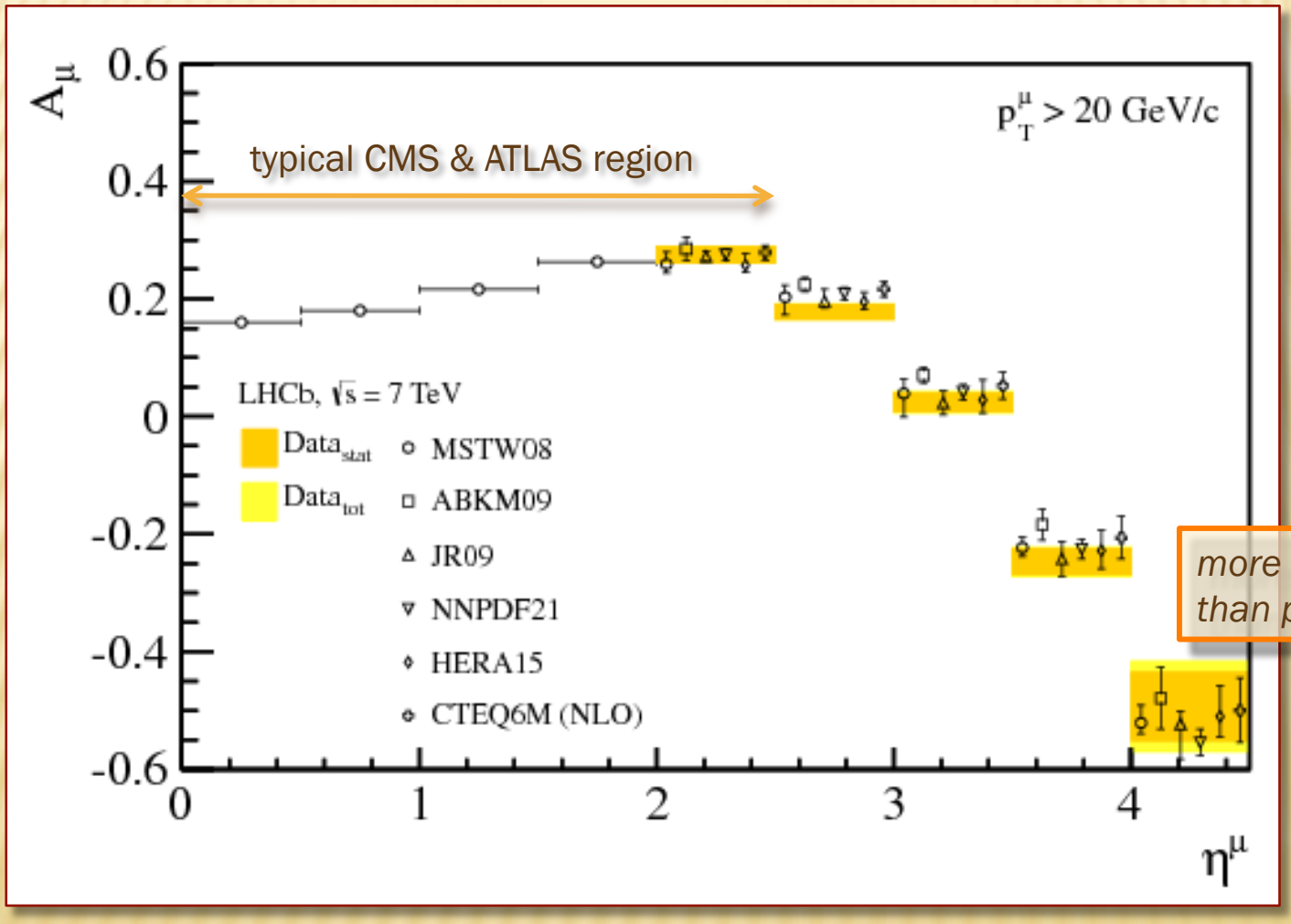




- tremendous power to distinguish & constrain PDFs
  - MSTW2008CPdeut clearly improves upon MSTW2008 but not as good as CT10nlo
- FEWZ and RESBOS are equally good at predicting the asymmetry.

LHCb have a made a very nice measurement in the far-forward region:

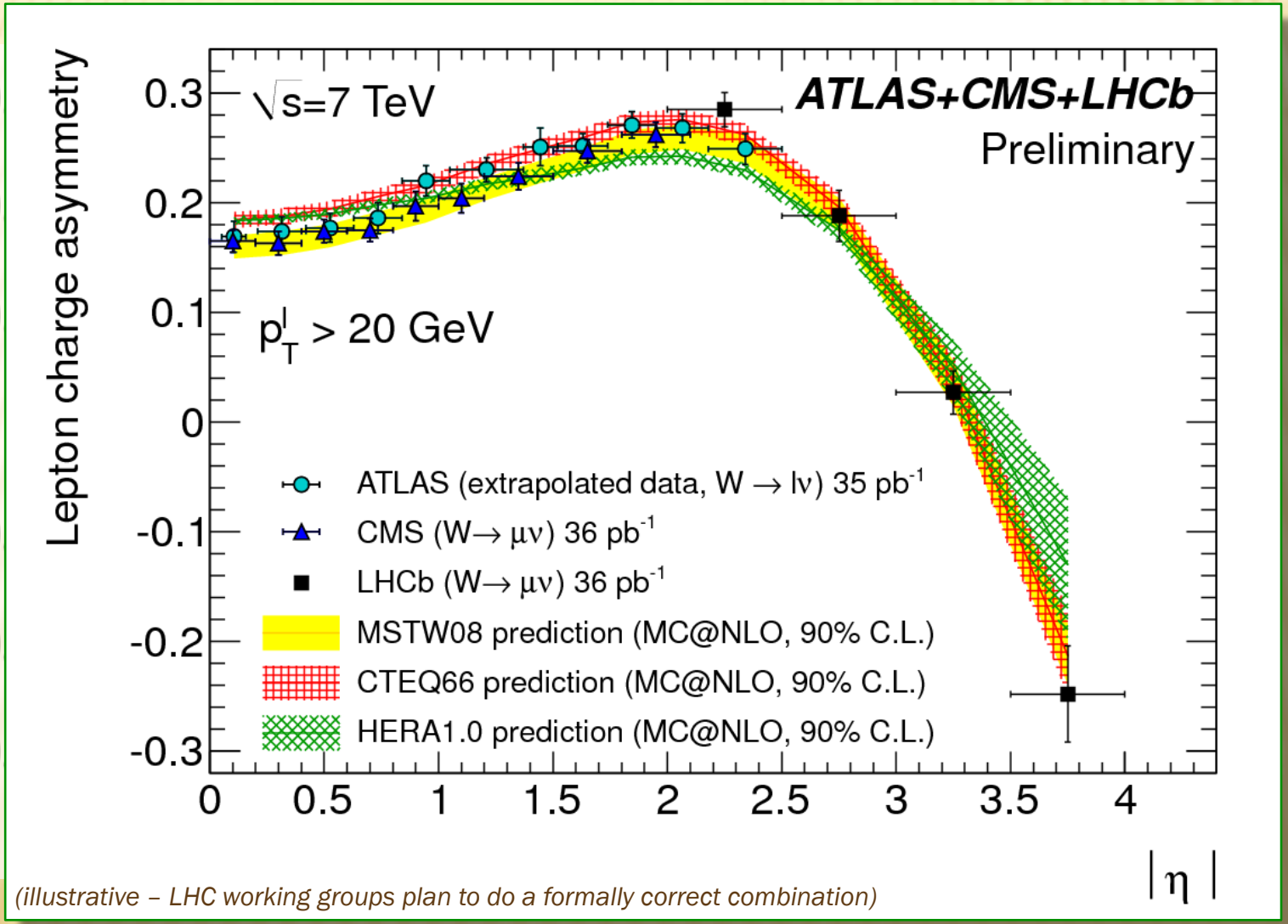
JHEP1206 (2012) 058



more negative muons than positive muons!

LHCb have a made a very nice measurement in the far-forward region:

JHEP1206 (2012) 058



(illustrative – LHC working groups plan to do a formally correct combination)

W + CHARM

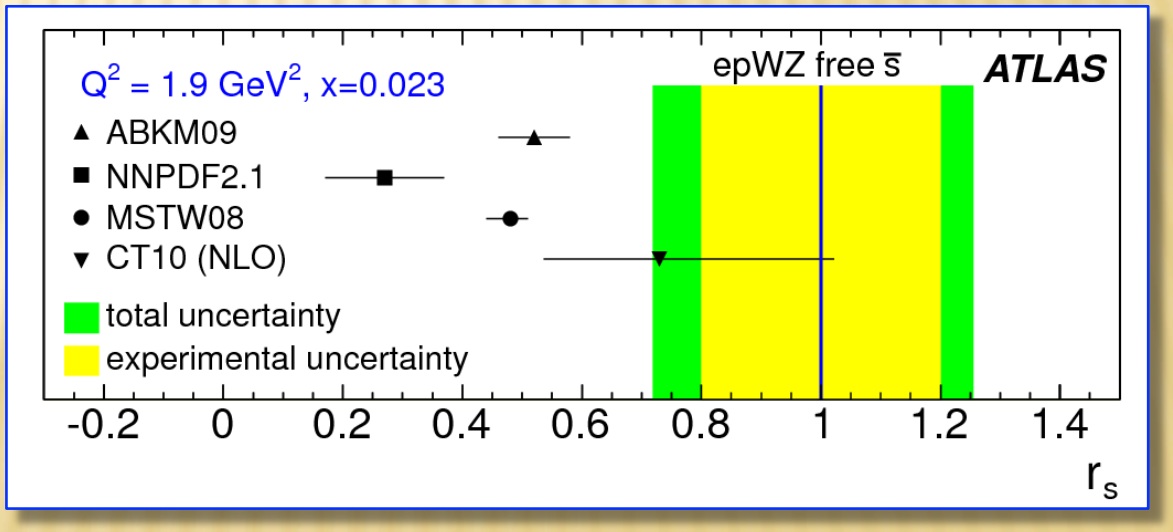
- A central question in PDFs: is $SU(3)_F$ a good symmetry or bad?
  (e.g. due to s-quark mass)
- $x\Sigma = 2x(ubar+dbar+sbar)$ cannot be wholly determined by DIS (e.g. F_2)
- ν-scattering probes s through $W^+s \rightarrow c$ and $W^-sbar \rightarrow cbar$,
  but results can be difficult to interpret (c-fragmentation, nuclear corrections, etc.)
- $R_W = (W^+ + W^-)/Z$ complements DIS b/c couplings are weak, not electromagnetic.
- R_W is very well measured by ATLAS & CMS (& LHCb)

PRL 109 12001 (2012)

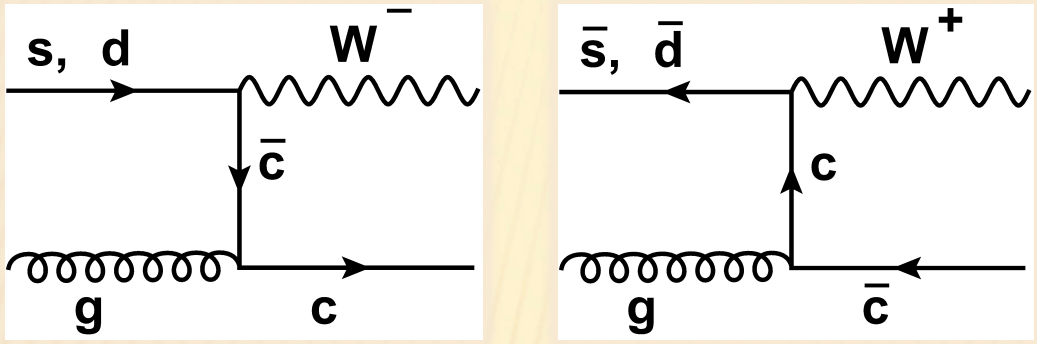
ATLAS inferred relative size of s from their cross section data:

- HERA data + W/Z $d\sigma/dY$
- flexible PDF parametrization allows s normalization free
- quantify s/d contributions:

$$r_s \equiv \frac{0.5(s+\bar{s})}{d}$$



CMS have measured *W*+*c* which gives direct information about *s(x)*.



$$R_c^{\pm} = \frac{\sigma(W^+\bar{c})}{\sigma(W^-c)} \cong \frac{\bar{s} + |V_{dc}|^2 \bar{d}}{s + |V_{dc}|^2 d}$$

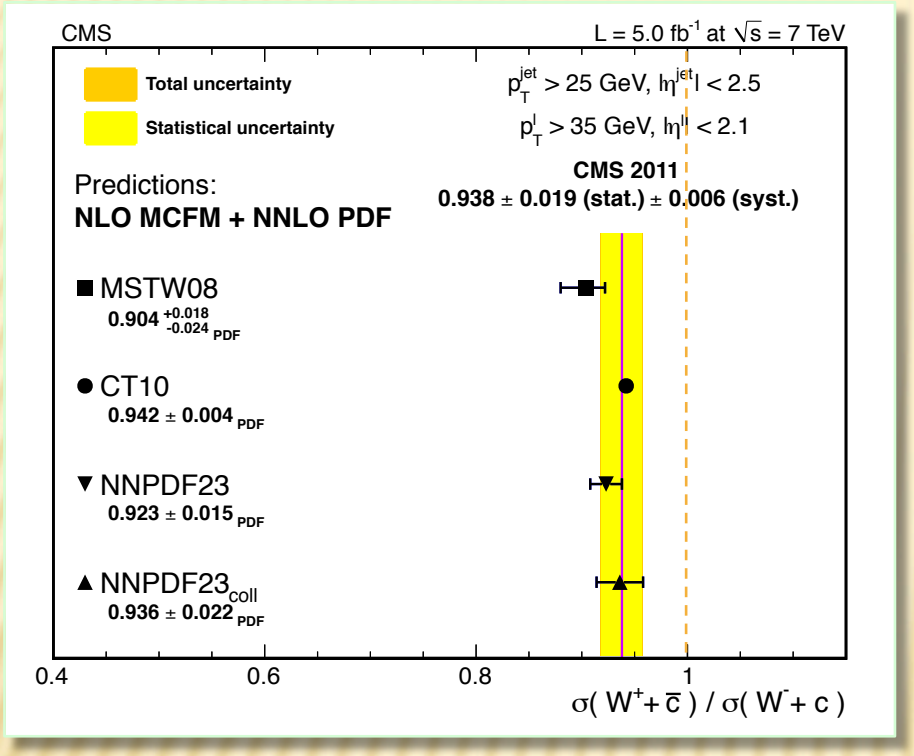
- examine the $W^- c$ / $W^+ \bar{c}$ asymmetry
  - $d \rightarrow c$ is Cabibbo-suppressed though *d*-quarks are relatively plentiful
  - $s \rightarrow c$ is Cabibbo-favored and makes a 3% contribution, depending on *s(x)*
  - $\bar{d}/d$ constrained by the *W* charge asymmetry
  - important to have smallest uncertainties possible

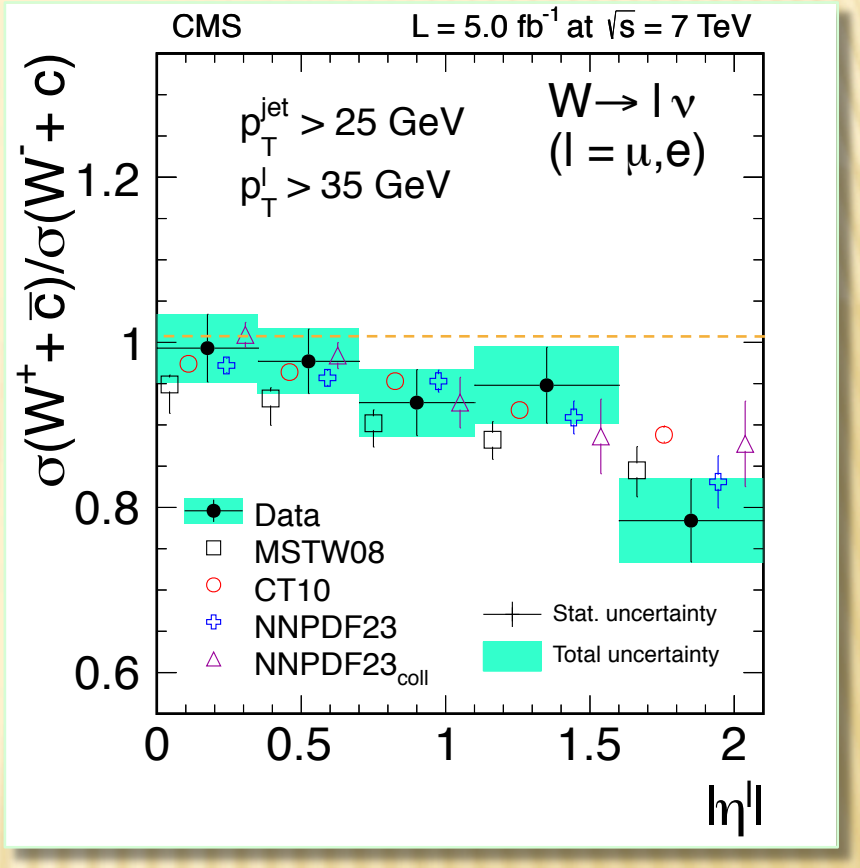
$$|V_{dc}|^2 \approx 0.225$$

- theoretically, ratio is not sensitive to higher-order corrections, but is sensitive to *s(x)*
- reconstruct the charm jet three ways:
  - exclusive *D*-meson decays to charged particles
  - inclusive charm decays to muons
  - semi-inclusive *D*-meson decays
- key feature: opposite-sign – same-sign (OS-SS) subtraction
  - removes backgrounds, and removes gluon splitting $g \rightarrow c\bar{c}$

CMS: *W+c*

arXiv:1310.1138 (subm.)



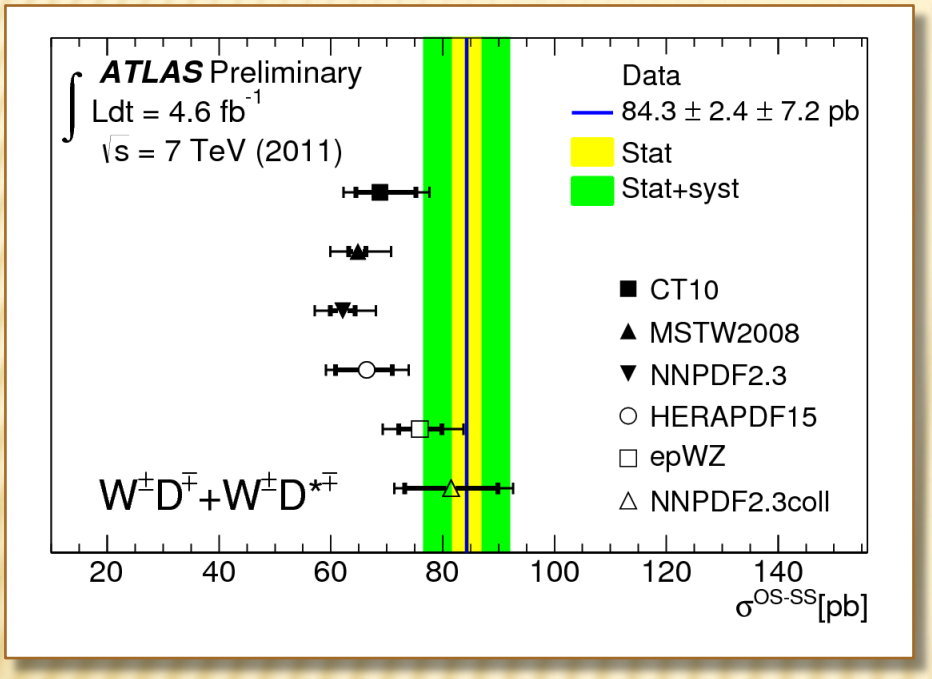


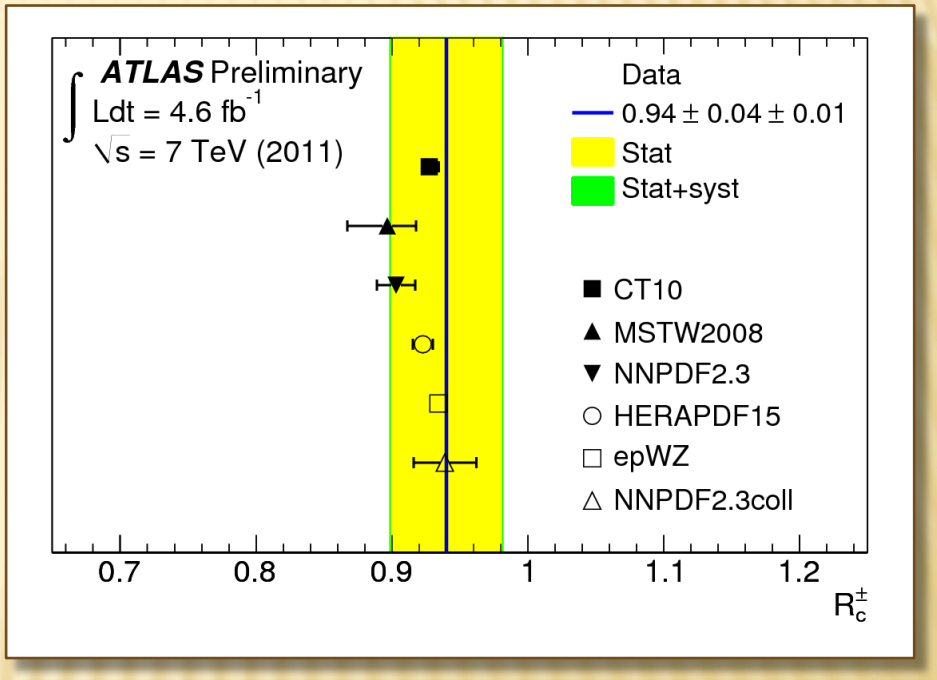
- distinct asymmetry is observed & measured precisely (more than 3 s.d. from unity)
- theoretical calculations agree well (especially CT10 & NNPDF23coll)
- data seem to decline more rapidly with η but not really precise enough yet

ATLAS has a preliminary measurement:

- reconstruct exclusive *D*-mesons only (in many channels)

ATLAS-CONF-2013-045



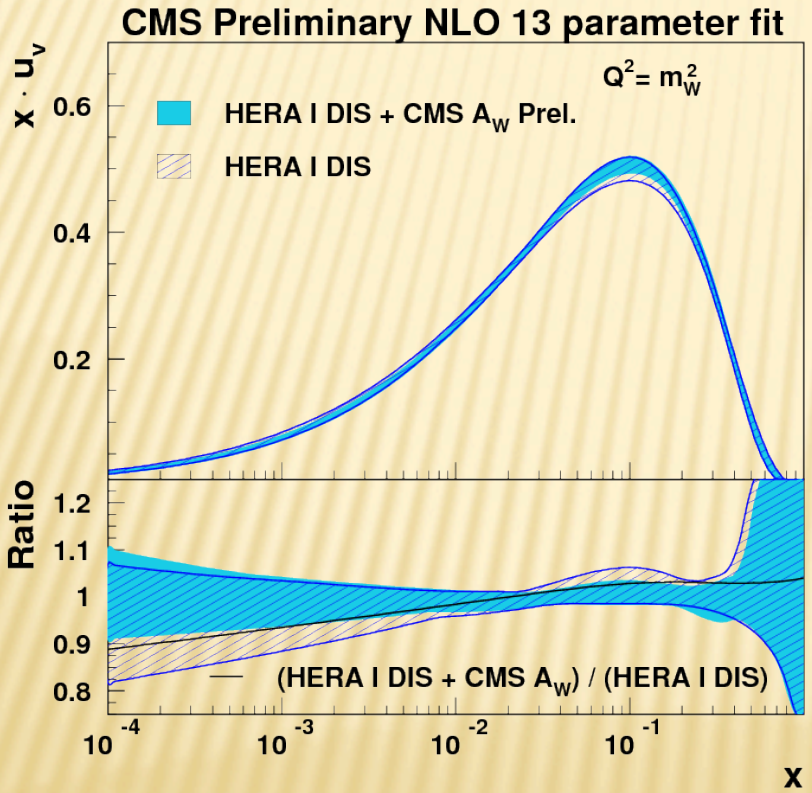


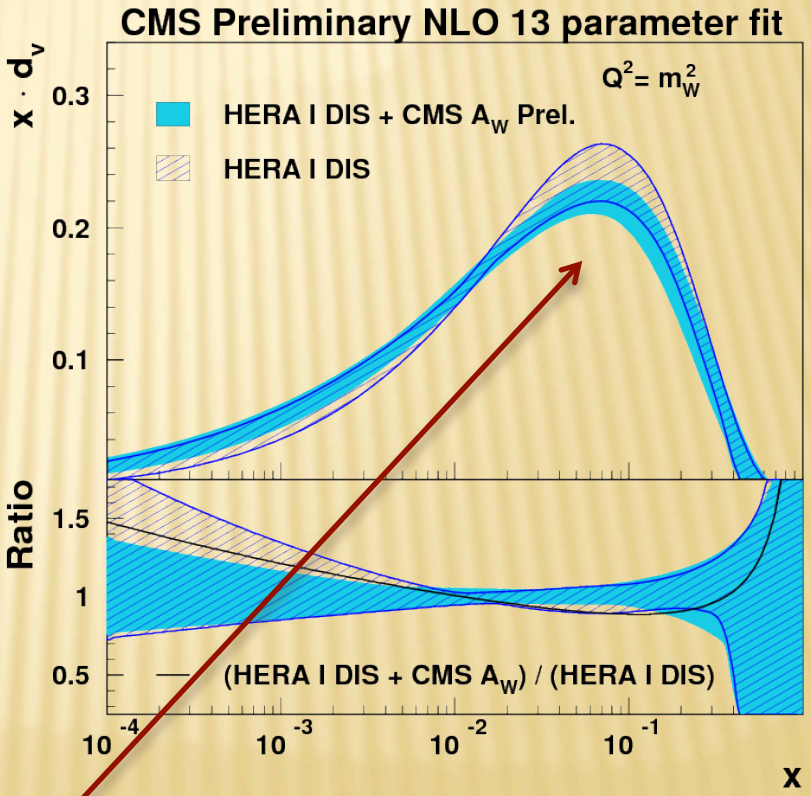
- conclusions are similar to what CMS found
- not yet at the same precision

arXiv:1312.6283 (subm. to PRD)

CMS have carried out a QCD analysis to explore PDF constraints:

- Use HERA DIS, CMS *W* asymmetry & CMS *W+c* data
- Like ATLAS, consider fixed-s and free-s fits.



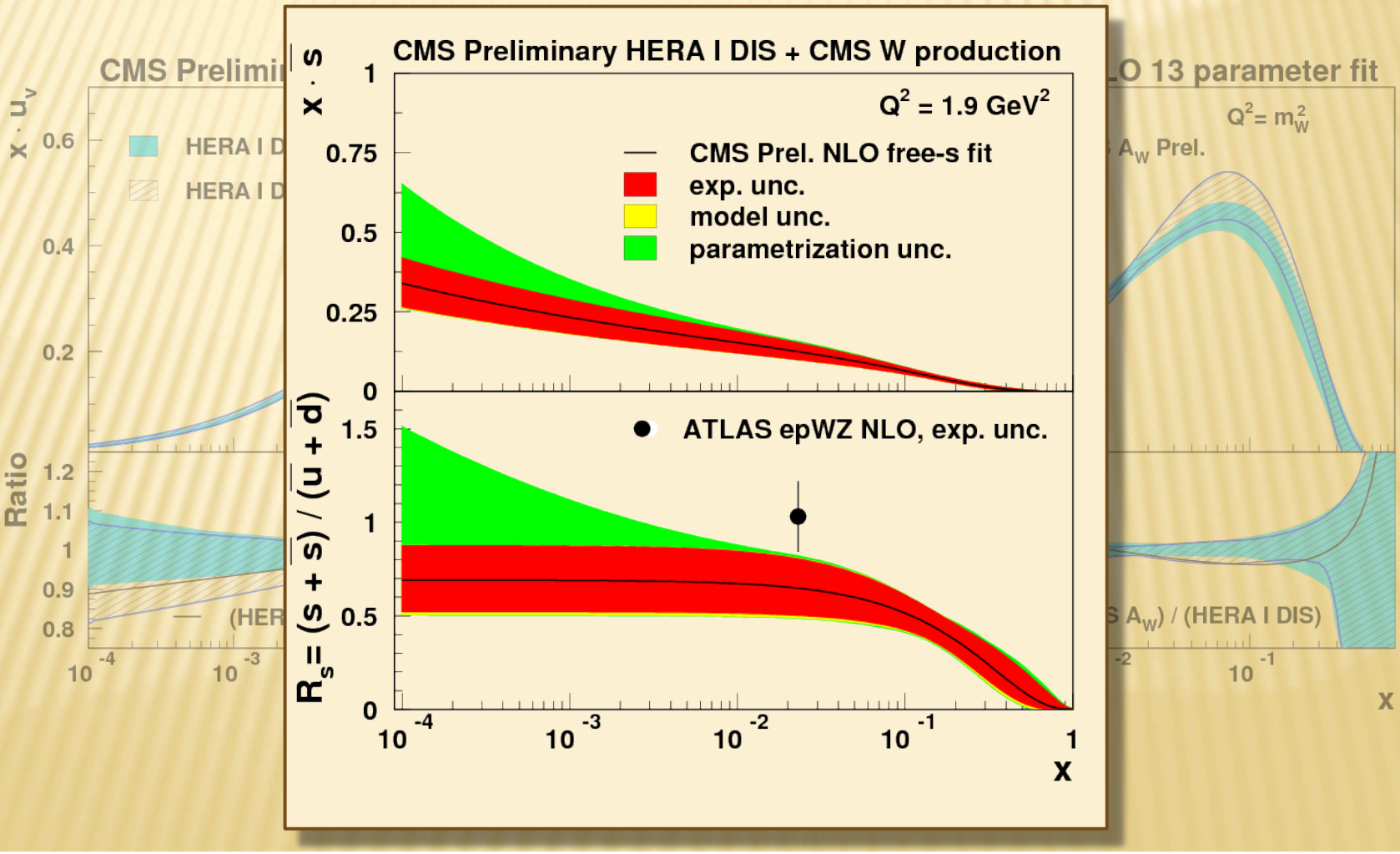


Notice that $xd_v(x)$ is reduced. (D⊘ data want d/u increased.)

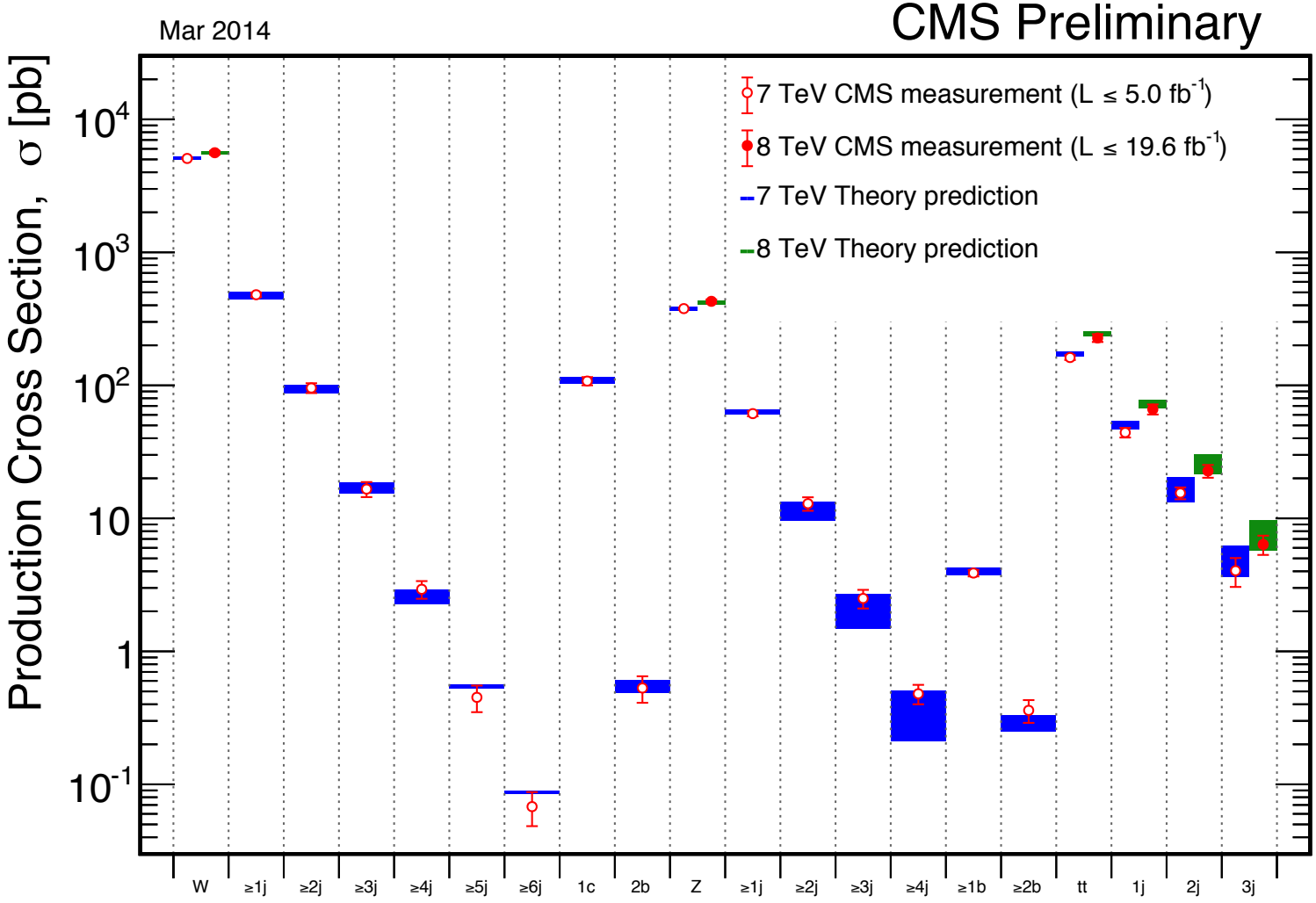
arXiv:1312.6283 (subm. to PRD)

CMS have carried out a QCD analysis to explore PDF constraints:

Maybe some tension between CMS & ATLAS results on *s(x)* ?



VECTOR BOSONS + JETS

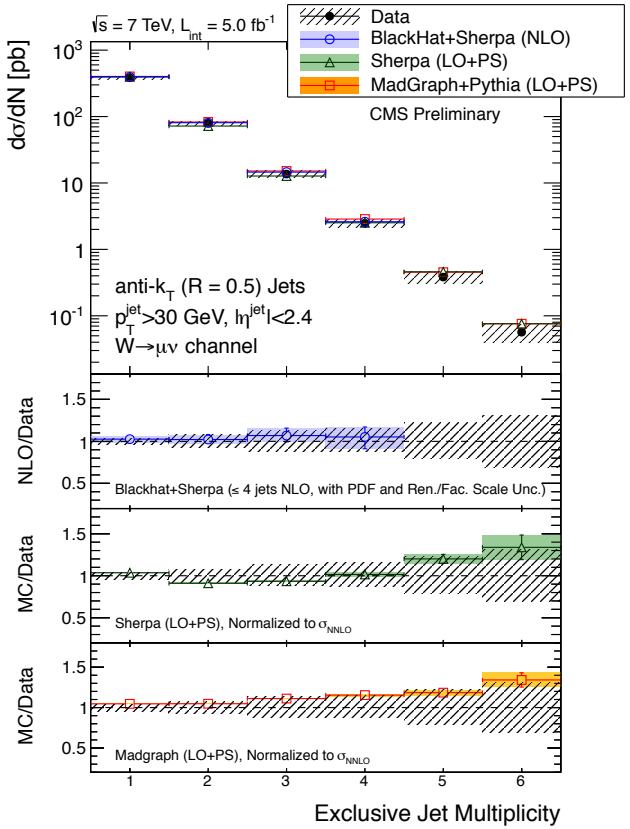


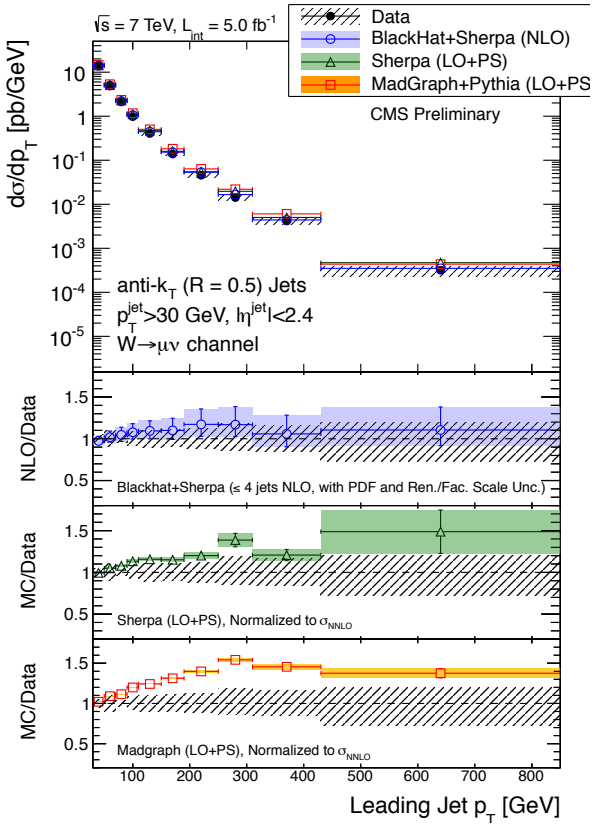
CMS PAS SMP-12-023

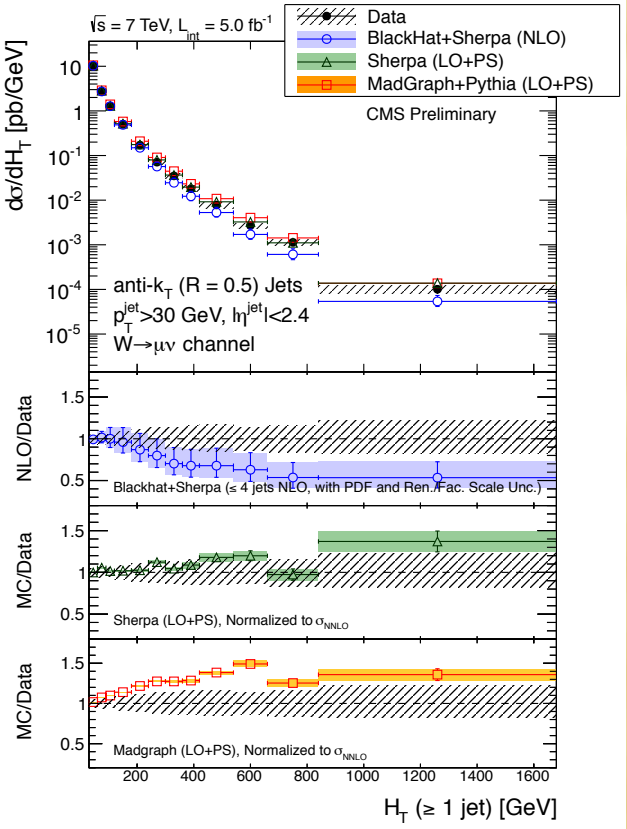
CMS preliminary results on differential cross sections of W + jets

- all distributions unfolded and corrected to the particle level
- small experimental errors allow real distinctions of theoretical models

[NLO] BLACKHAT+SHERPA SHERPA MADGRAPH







A parallel analysis with Z + jets: *CMS PAS SMP-12-017*

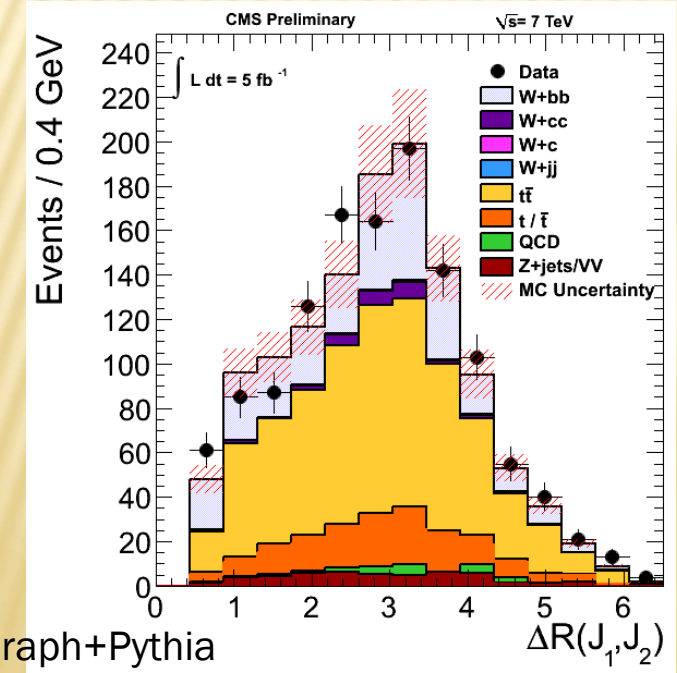
arXiv:1312.6608

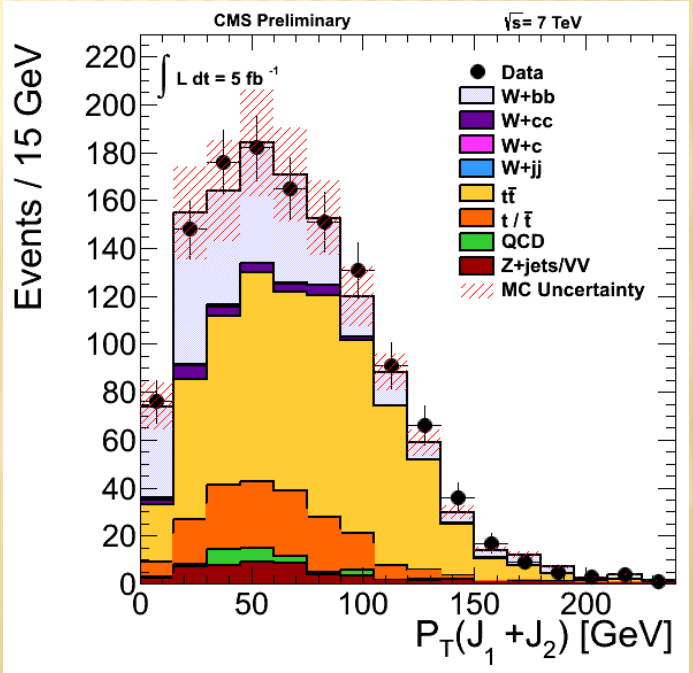
CMS measurement of W + 2b jets

- previous measurements show varying levels of agreement with theory
- W + 1b, or nearly-collinear b-jets, present the worst difficulties
- This analysis investigates *exclusive 2 b-jet final state* – complements prior studies
- the b-jets are well separated from each other: $\Delta R > 0.5$
- NLO MCFM calculation adjusted for DPS and parton – particle differences

$$\sigma(pp \to W + bb) \times B(W \to \mu\nu) = 0.53 \pm 0.05(stat) \pm 0.09(syst) \pm 0.06(th) \pm 0.01(lum)\ pb$$

Standard Model: $0.55 \pm 0.03(MCFM) \pm 0.01(had) \pm 0.05(DPS)\ pb$





MadGraph+Pythia

arXiv:1402.1521

CMS measurement of Z + 1b jet and Z + ≥2b jets

- Z + 1b sensitive to b-quark content of the proton
- Z + 2b (inclusive) test of QCD calculations

} non-overlapping

- MADGRAPH and aMC@NLO:
  - 4-flavor (4F) scheme with massive b-quarks
  - 5-flavor (5F) scheme with massless b-quarks
- careful unfolding of 1b and ≥2b samples

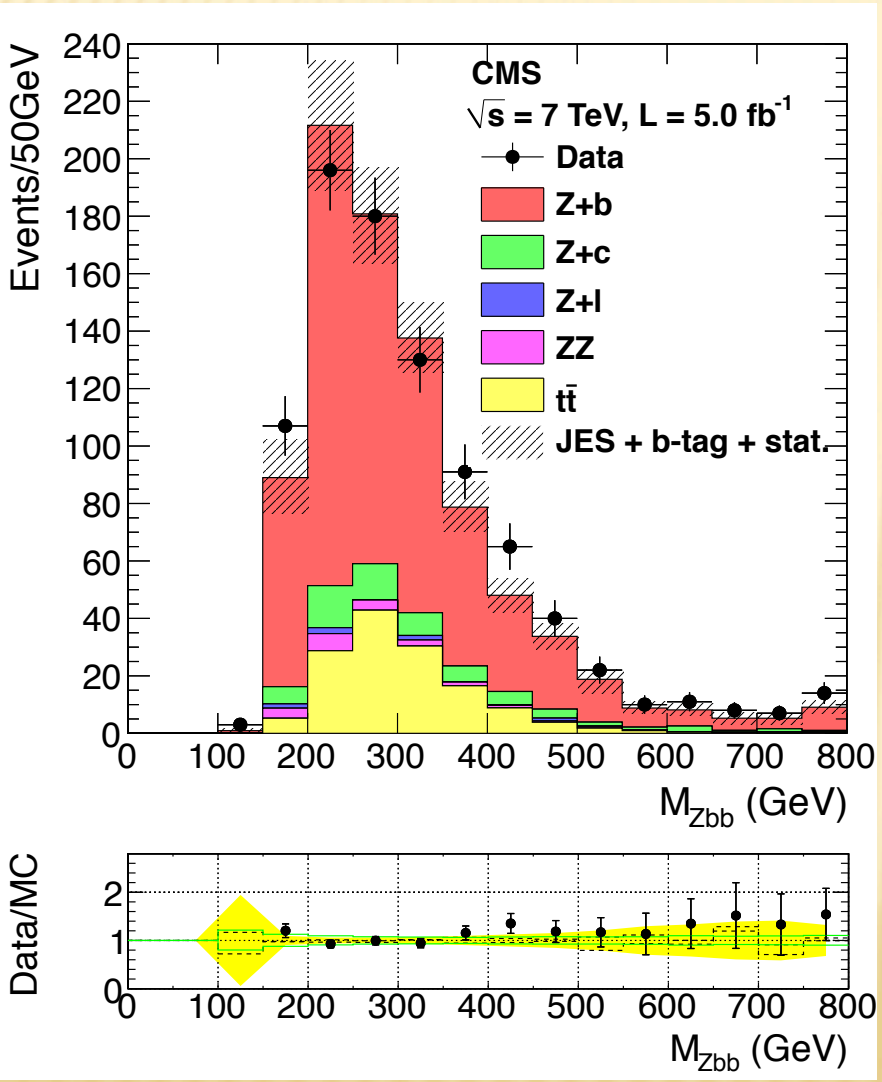
Cross section	Measured	MADGRAPH (5F)	aMC@NLO (5F)	MCFM (parton level)	MADGRAPH (4F)	aMC@NLO (4F)
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.07	$0.29^{+0.04}_{-0.04}$	$0.29^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.08}_{-0.06}$
σ_{Z+b} (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.24	$3.99^{+0.25}_{-0.29}$	$3.23^{+0.34}_{-0.40}$	$3.49^{+0.52}_{-0.91}$	$2.71^{+0.52}_{-0.41}$
$\sigma_{Z+b/Z+j}$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.11	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

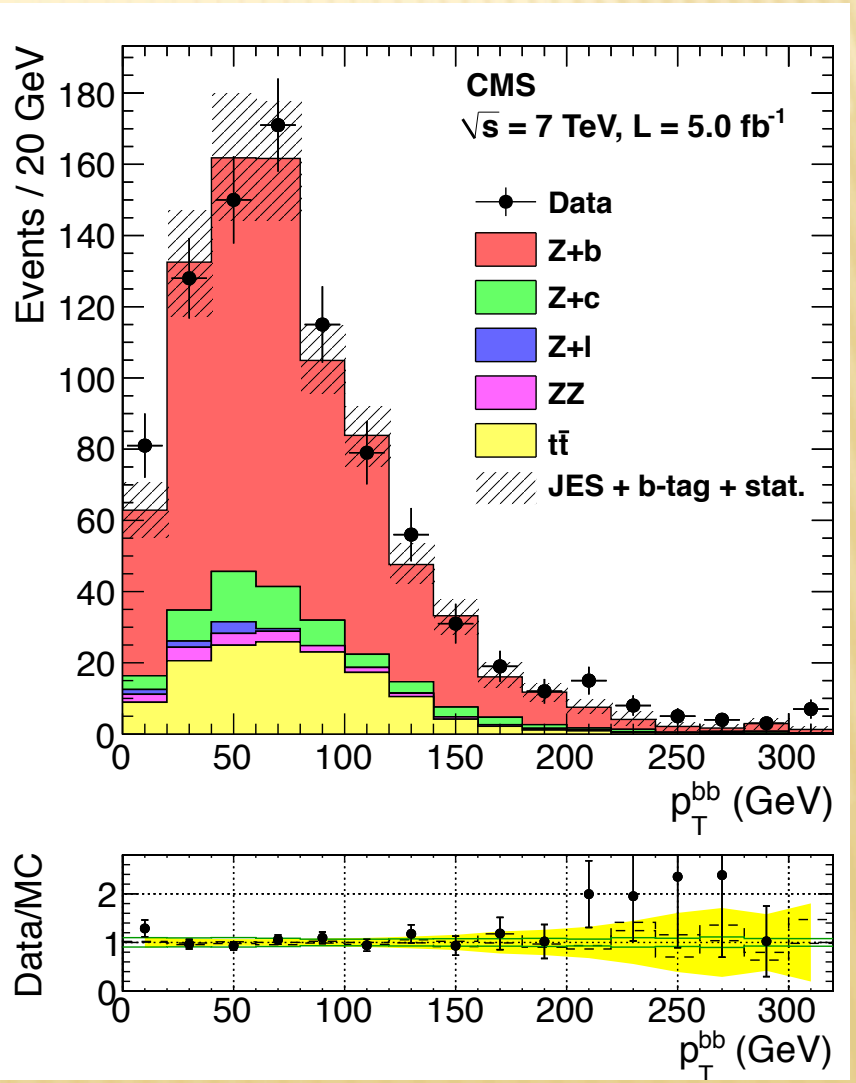
- 5F predictions agree better with data than 4F predictions do.
- MCFM at parton level does not agree with data well: not even Z+b/Z+j

MadGraph+Pythia

arXiv:1402.1521

CMS measurement of Z + 1b jet and Z + ≥2b jets



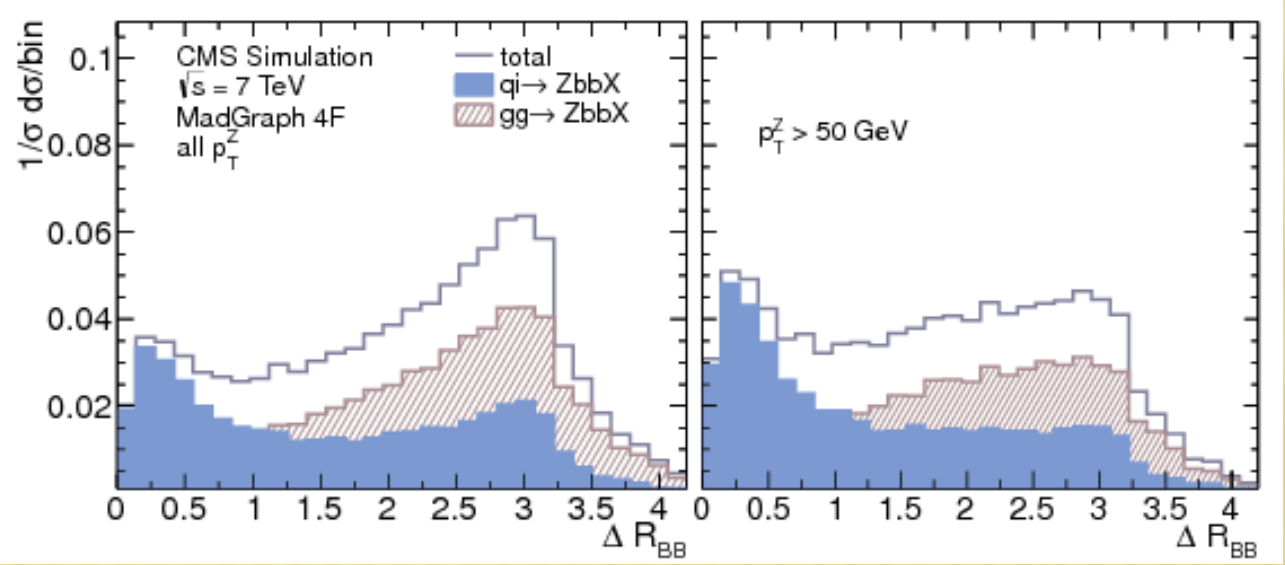


JHEP12 (2013) 039

Z + 2b jets : angular correlations

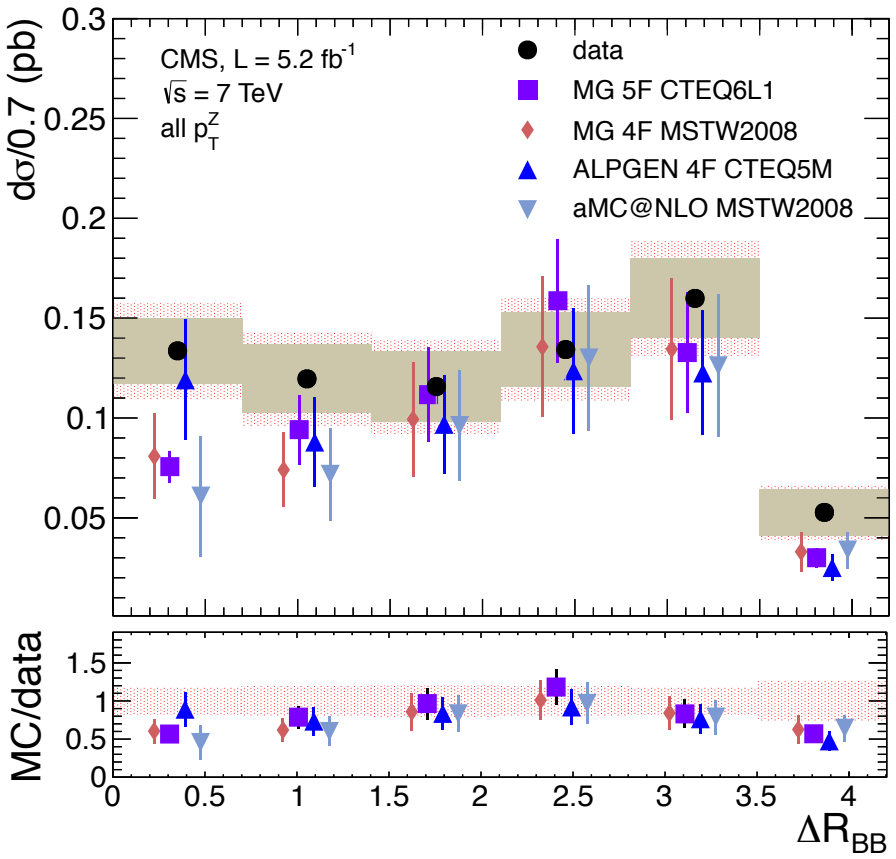
- differential cross sections : angular separation between b hadrons & Z boson
- special interest: angular correlations of the b hadrons
- tree-level calculations allowing for many extra partons in the matrix elements:
  MADGRAPH ALPGEN SHERPA
- four-flavor and five-flavor scheme
- MCFM is NLO for 5F aMC@NLO is NLO
- Comparisons done for ranges of Z boson p_T
- illustration of how q-initiated and g-initiated processes can be distinguished:

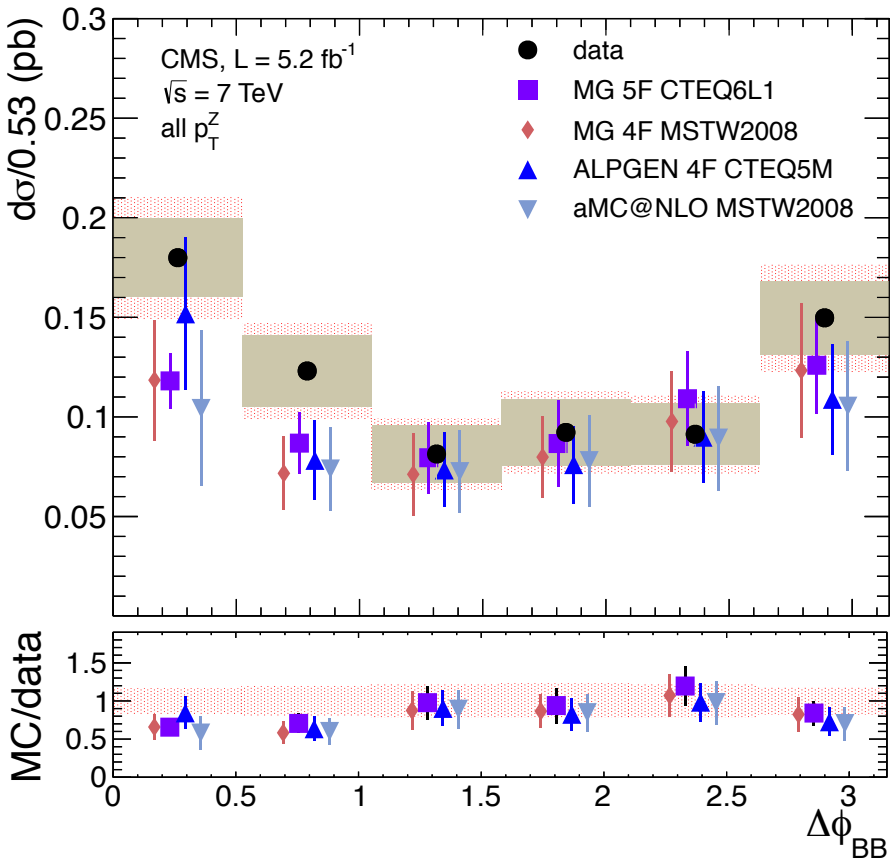
simulation



JHEP12 (2013) 039

Z + 2b jets : angular correlations





- ALPGEN with 4F does the best job describing the data
- all generators agree with data well, for p_T^Z > 50 GeV

Conclusion

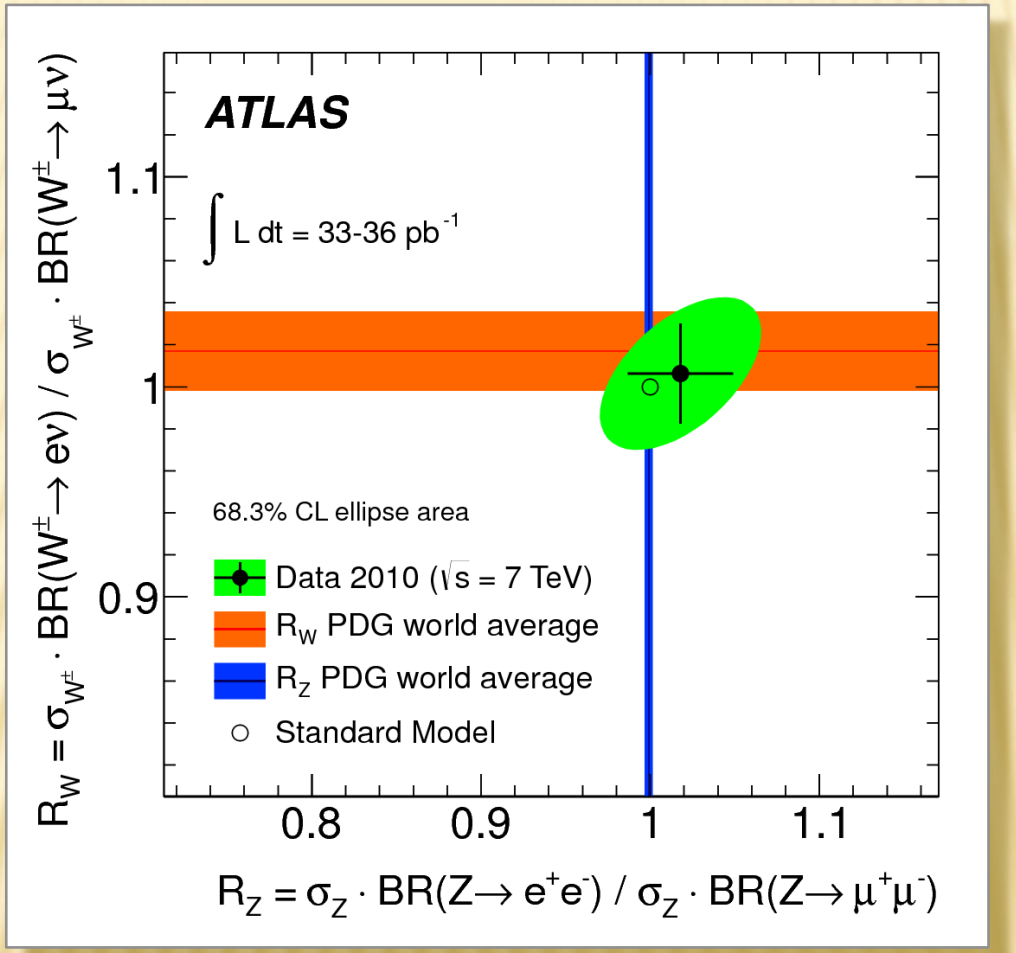
- This summary is woefully incomplete – I regret I could not cover more.
- Precision of the studies of vector boson production is unprecedented and will continue to improve.
- Theoretical calculations (in the form of MC simulations) stand up well, in general, though clear discrepancies are visible in select kinematic distributions.

Thank you to the organizers & City Tech!

Extra Slides

ATLAS reported a competitive test of lepton universality in *W* decays:

exploits the very high precision of the cross section measurements



36 pb^{-1} at 7 TeV

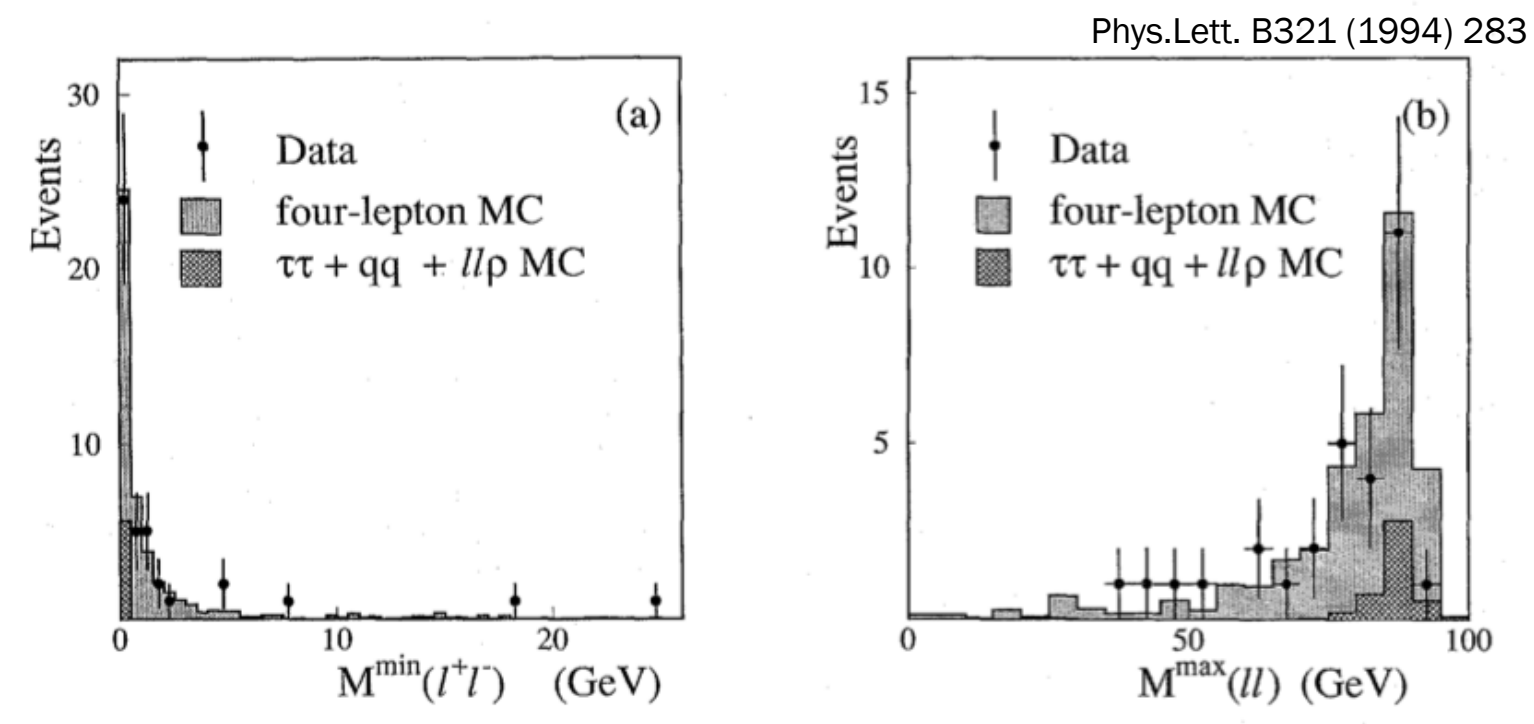
ATLAS: $\frac{B(W \to e\nu)}{B(W \to \mu\nu)} = 1.006 \pm 0.024$ PDG: 1.017 ± 0.019

Rare Decay Process $Z \rightarrow 4$ leptons

$Z \rightarrow 4\ell$ was observed at LEP in the mid-1990s.

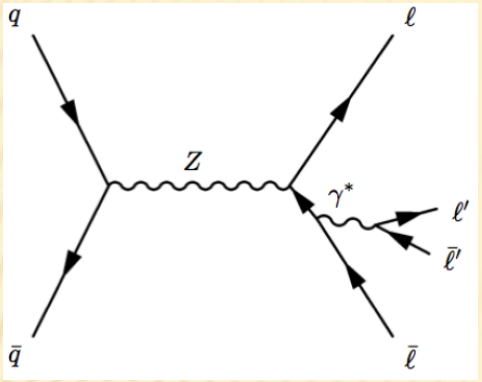
Example: L3 reported 43 events for e, μ and τ.

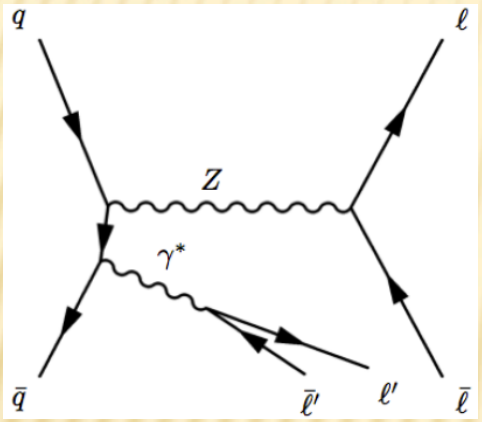
Phys.Lett. B321 (1994) 283

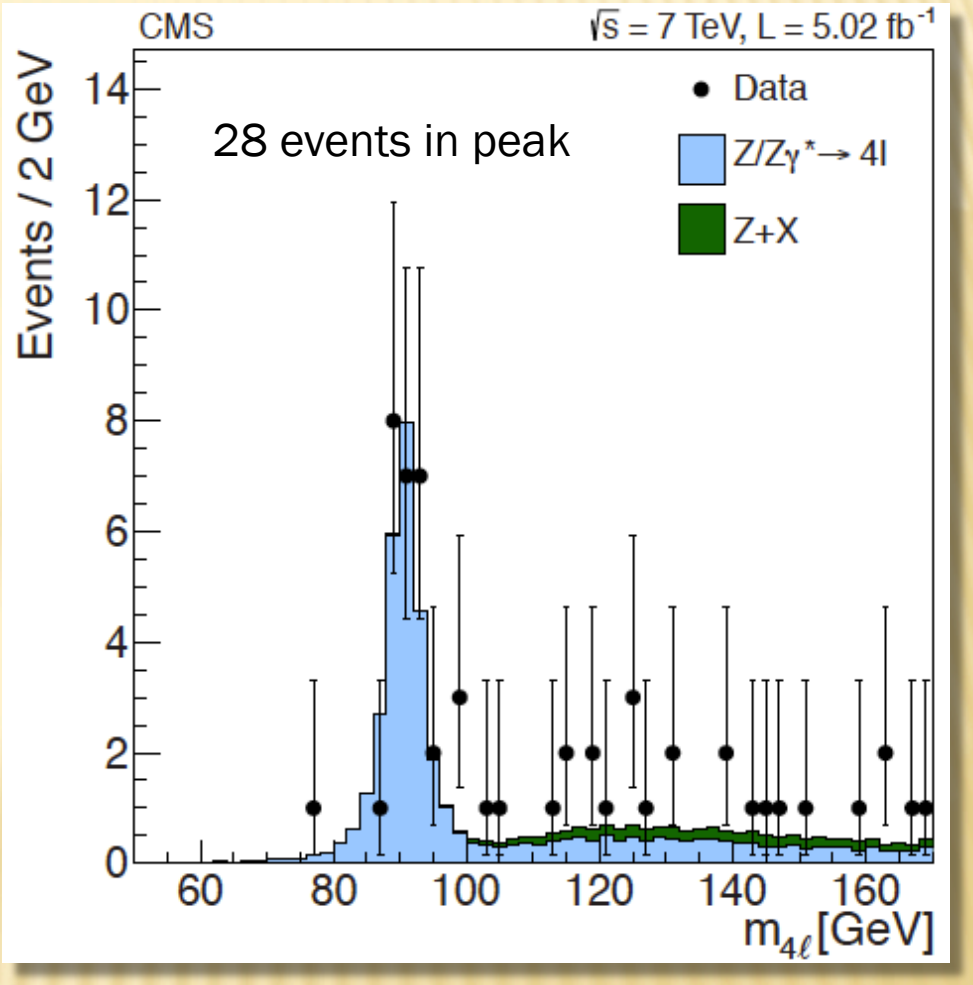


The "second pair" of leptons come mainly from virtual photon exchange.

CMS reported observation of $Z \rightarrow 4l$ in the context of the Higgs search.







- main goal: measure mass resolution
- normalize to $Z \rightarrow \mu^+\mu^-$ signal and infer:

$$B(Z \rightarrow 4\ell) = (4.2 \pm 0.9 \pm 0.2) \times 10^{-6}$$

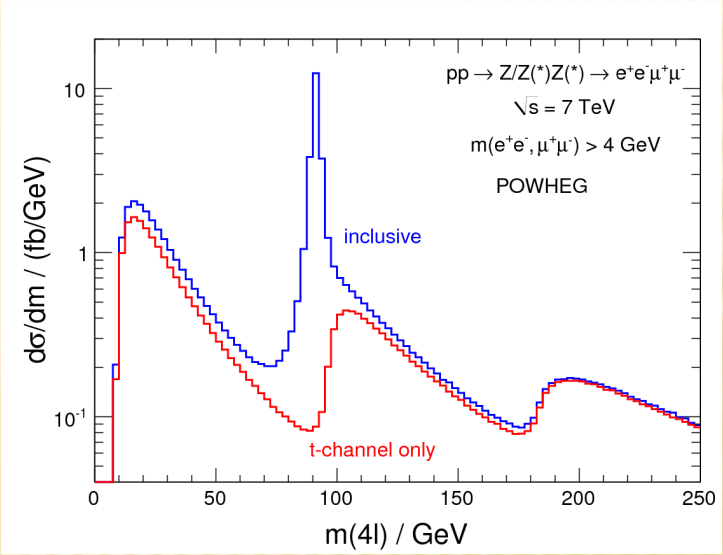
SM value: $(4.37 \pm 0.03) \times 10^{-6}$ note: $\Gamma_{4\ell} = 11\,keV$!

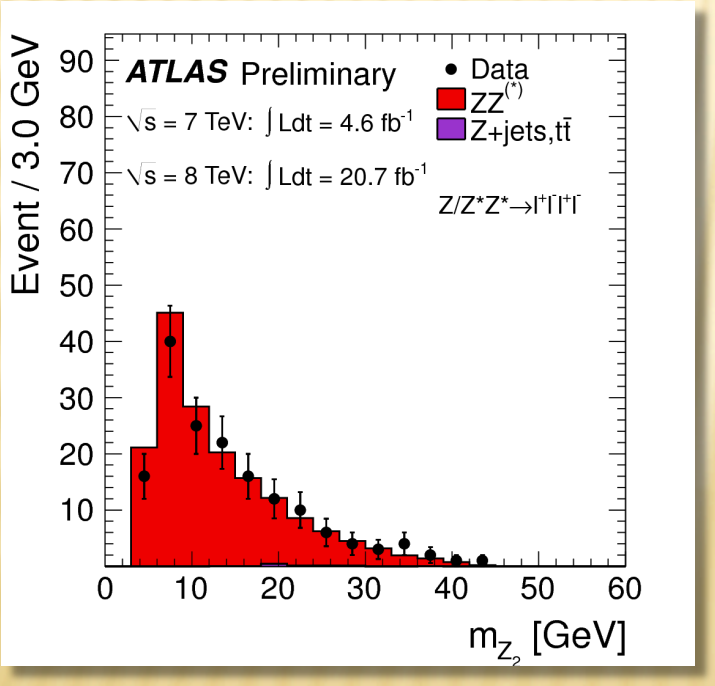
ATLAS $Z \rightarrow 4l$ signal from 7 TeV & 8 TeV

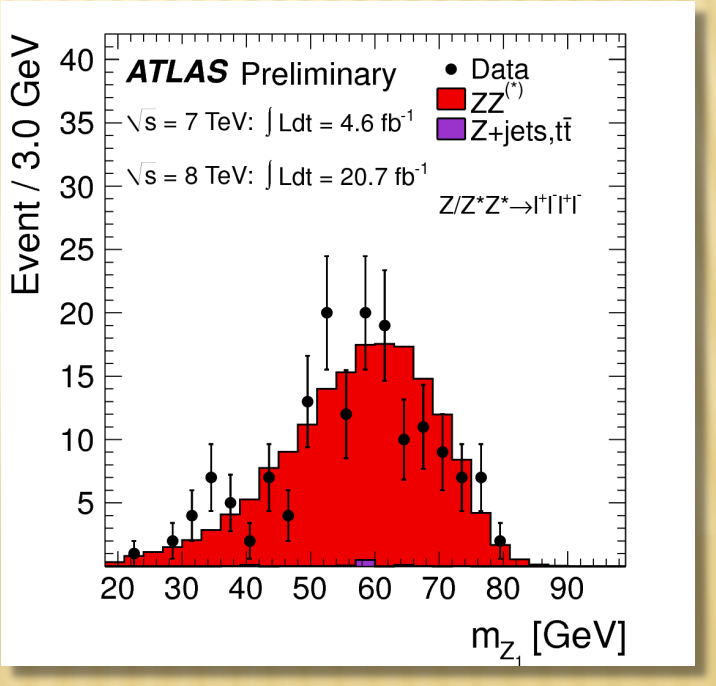
- interesting structure in t-channel
  - contributes 8% under Z-peak
  - dominates above ZZ threshold
- more than 160 candidates selected
- normalize to theoretical Z cross section:

$$B(Z \rightarrow 4\ell) = (4.2 \pm 0.4) \times 10^{-6}$$

$$(4.37 \pm 0.03) \times 10^{-6}$$

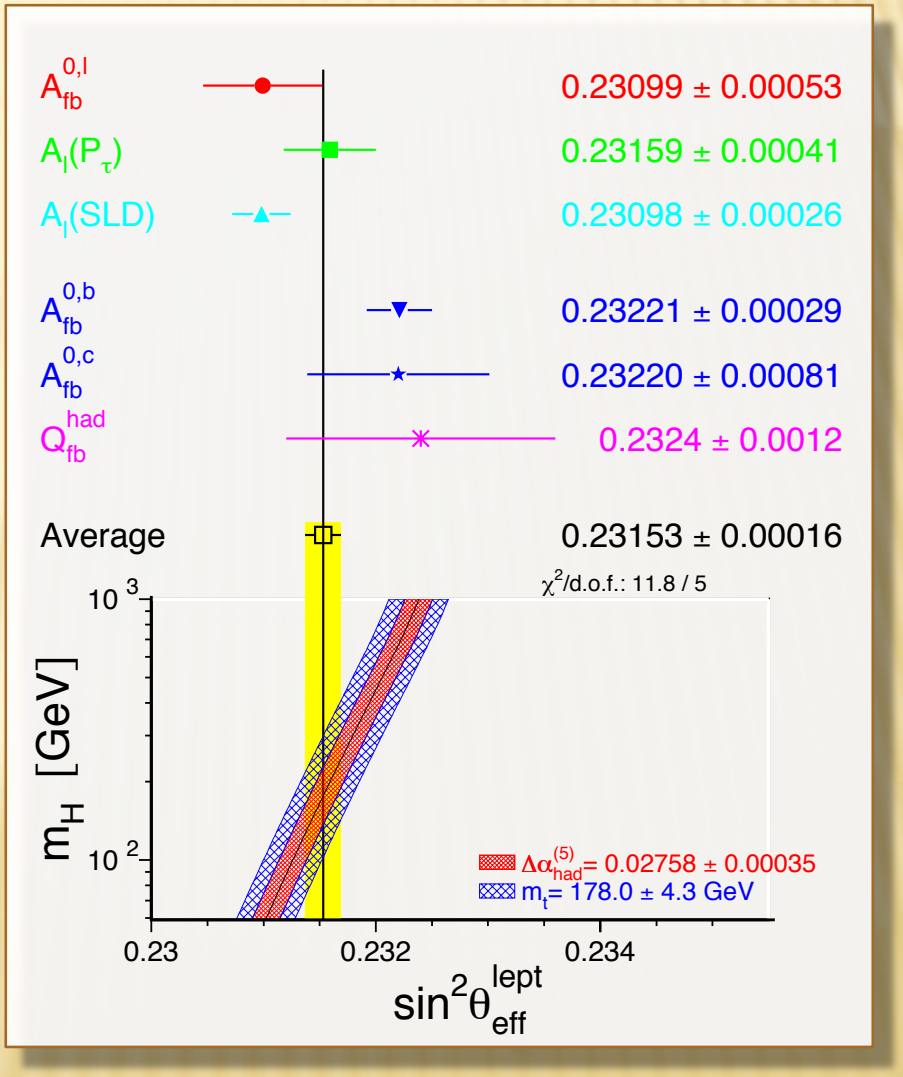






FORWARD-BACKWARD ASYMMETRY AND $SIN^2\Theta_W$

- well-known tension between "leptonic" and "hadronic" asymmetry measurements.
- lead to two very different values for $sin^2\theta_W$
- two most precise values differ by more than 3σ
- used to be a problem for estimating the SM Higgs mass.
- Clearly, a new measurements with an uncertainty of 0.0002 or better would be very useful.



Phys. Rep. 427 (2006) 257

CMS reported the first measurement of $sin^2\theta_W$ at the LHC:

- innovative: make full use of the Drell-Yan leading-order matrix element (in the past people used only A_{FB})
- A_{FB} is relatively weak at a pp collider because there is no clear "forward" direction
  - one resolves the q direction on a statistical basis:
  - the longitudinal direction of the Z indicates the likely q direction.
- The use of the full matrix element squeezes the most information and helps deal with the forward/backward direction ambiguity ("dilution")
- Gain is about 20% with respect to A_{FB} alone.

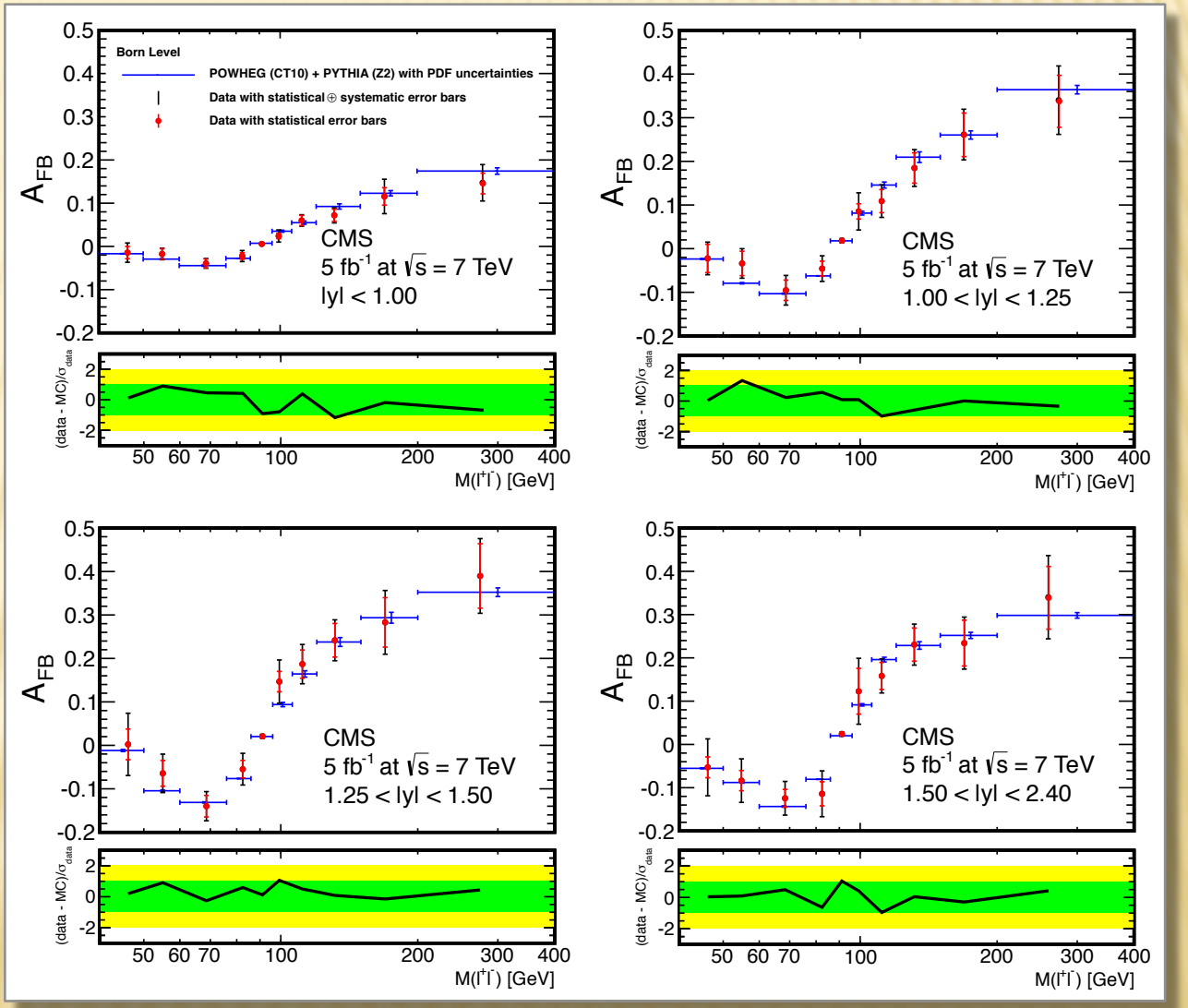
$$\sin^2(\theta_{\text{eff}}) = 0.2287 \pm 0.0020_{\text{stat}} \pm 0.0025_{\text{syst}}$$

Phys. Rev. D84 112002 (2011)

- This is a "demonstration" measurement.
  - 5 fb^{-1} at 7 TeV, $\mu^+\mu^-$ only
  - significant systematic uncertainty due to NLO corrections, momentum resolution and mis-alignment
  - speculate that systematic uncertainty could be pushed down to 0.0010?

CMS did measure A_{FB} in an independent analysis:

- combine e^+e^- and $\mu^+\mu^-$
- more than 1M events
- subtract backgrounds, unfold (F and B separately), correct for dilution…
- four bins of rapidity *Y*
- any signs of a deviation at high *M*?

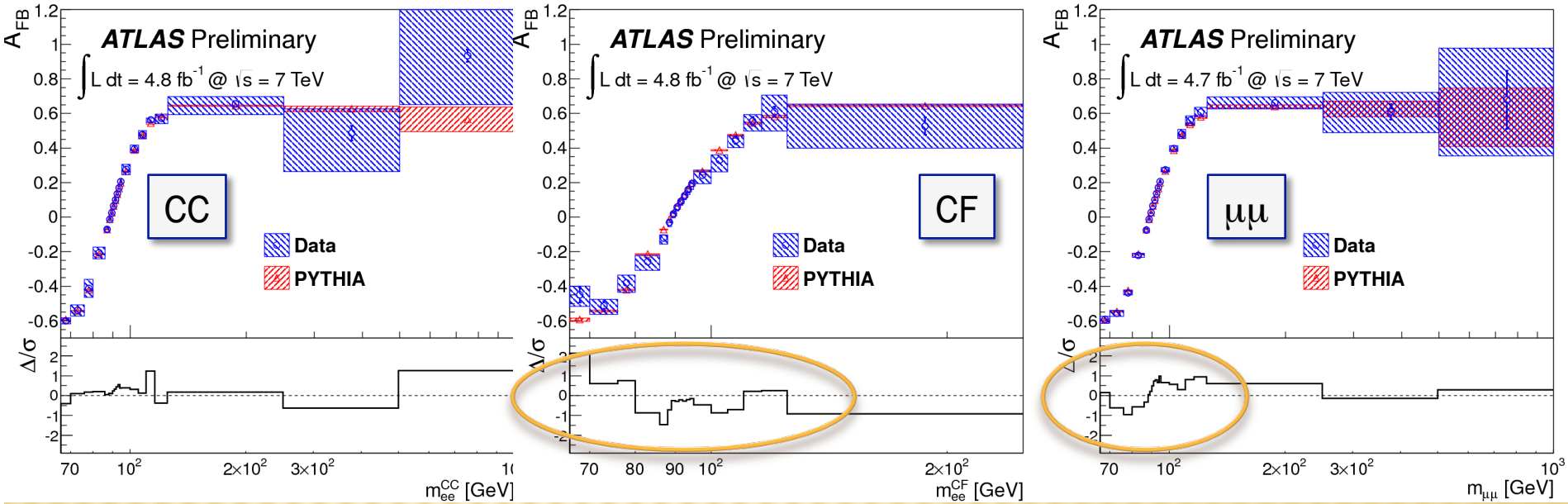


Phys. Lett. B718 (2013) 752

ATLAS-CONF-2013-043

New preliminary ATLAS measurement of A_{FB} and $sin^2\theta_W$

- same approach as CMS and the Tevatron experiments
- 5 fb^{-1} at 7 TeV, both e^+e^- and $\mu^+\mu^-$
- unfold and correct



not-quite-perfect agreement...

ATLAS-CONF-2013-043

New preliminary ATLAS measurement of A_{FB} and $sin^2\theta_W$

$$\sin^2(\theta_{\text{eff}}) = 0.2287 \pm 0.0004_{\text{stat}} \pm 0.0009_{\text{syst}}$$