PDF uncertainties and LHC physics

A M Cooper-Sarkar

UCL- 30 March 2009

STANDARD MODEL

- There are W/Z ‘calibration’ measurememts: Z/W ratio is the best
- W and Z cross-sections should first test our understanding and then contribute to our knowledge at greater precision
- W asymmetry should bring something new
- Beware that NEW low-x physics could compromise this.

BEYOND STANDARD MODEL

- There are discovery channels – high ET jets- which could be obscured by PDF uncertainties
- But Jet Energy Scale Uncertainties could be more of a problem
- Be smart - look at ratios W+n-jets/Z+n-jets

The Standard Model is not as well known as you might think

In the QCD sector the PDFs limit our knowledge - transport PDFs to hadron-hadron cross-sections using QCD factorization theorem for short-distance inclusive processes

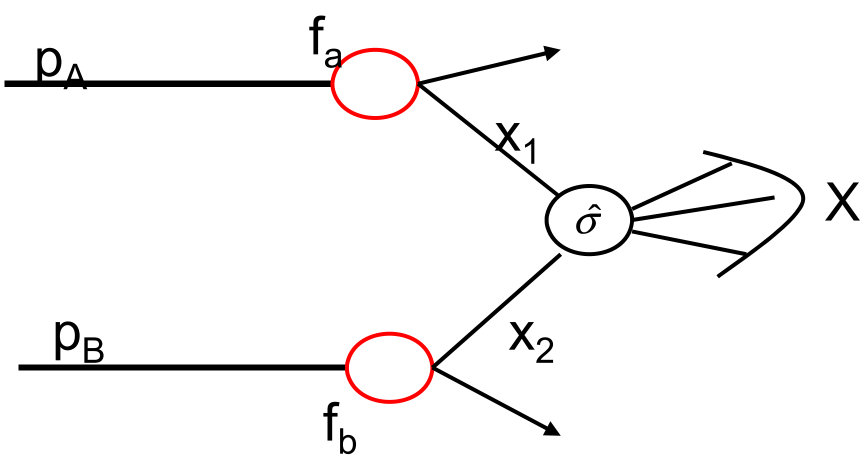
$$\sigma_X = \sum_{a,b} \int_0^1 \mathbf{dx_1 dx_2\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)}$$

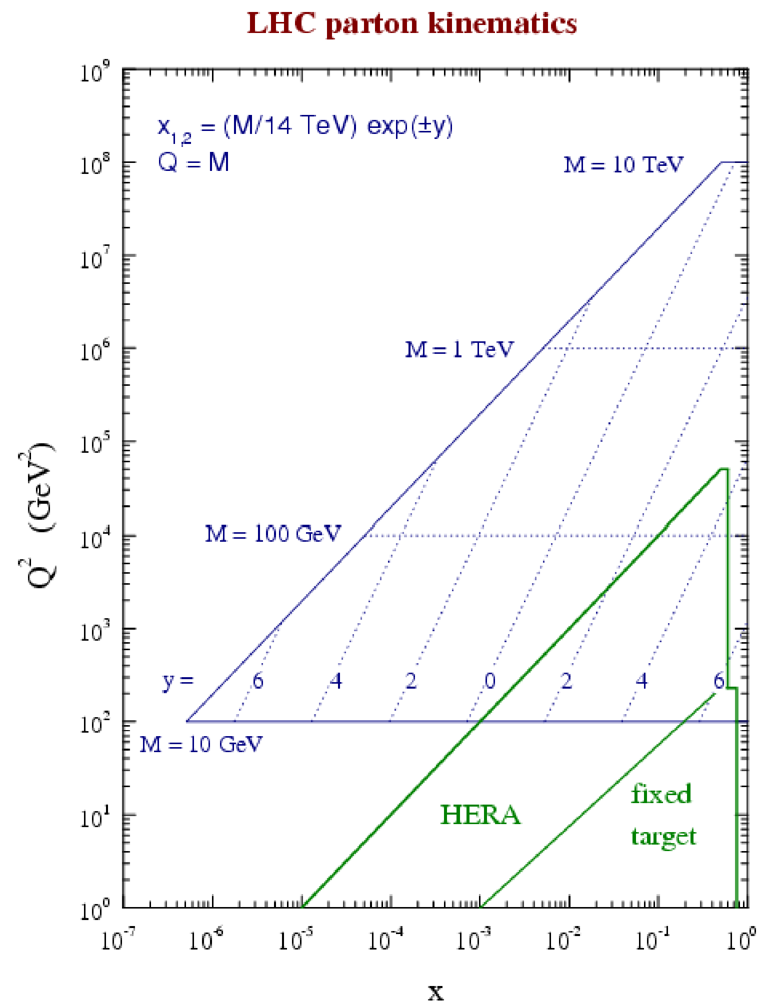
$$\times \quad \hat{\sigma}_{\mathbf{ab \to X}} \left(\mathbf{x_1, x_2, \{p_i^\mu\}}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{\mathbf{Q}^2}{\mu_R^2}, \frac{\mathbf{Q}^2}{\mu_F^2} \right)$$

where X=W, Z, D-Y, H, high-E_T jets, prompt-γ

and $\hat{\sigma}$ is known

- to some fixed order in pQCD and EW
- in some leading logarithm approximation (LL, NLL, …) to all orders via resummation





The central rapidity range for W/Z production AT LHC is at low-x

(6×10^{-4} to 6×10^{-2}) at 14 TeV

(8.5×10^{-4} to 8.5×10^{-2}) at 10 TeV

The general trend of PDF uncertainties is that

The u quark is much better known than the d quark

The valence quarks are much better known than the gluon/sea at high-x

The valence quarks are poorly known at small-x but they are not important for (most) physics in this region (except W asymmetry)

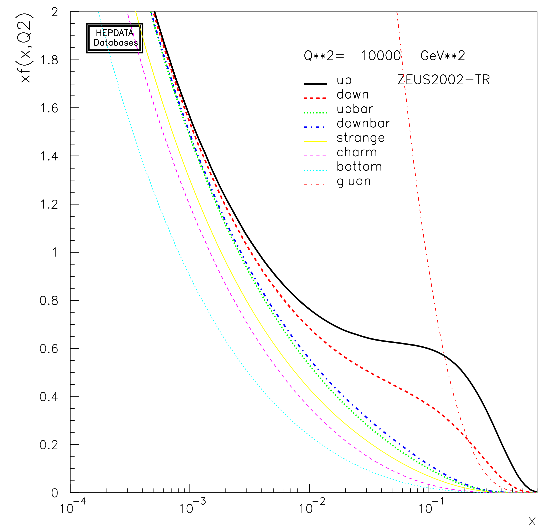
The sea and the gluon are reasonably well known at low-x- but there is always room for improvement for precision measurements

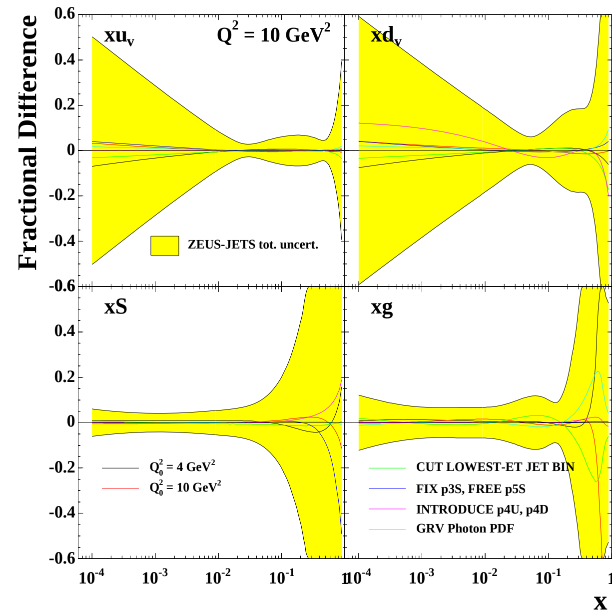
The sea is poorly known at high-x, but the valence quarks are more important in this region

The gluon is poorly known at high-x

And it can still be very important for physics e.g.– high ET jet xsecn

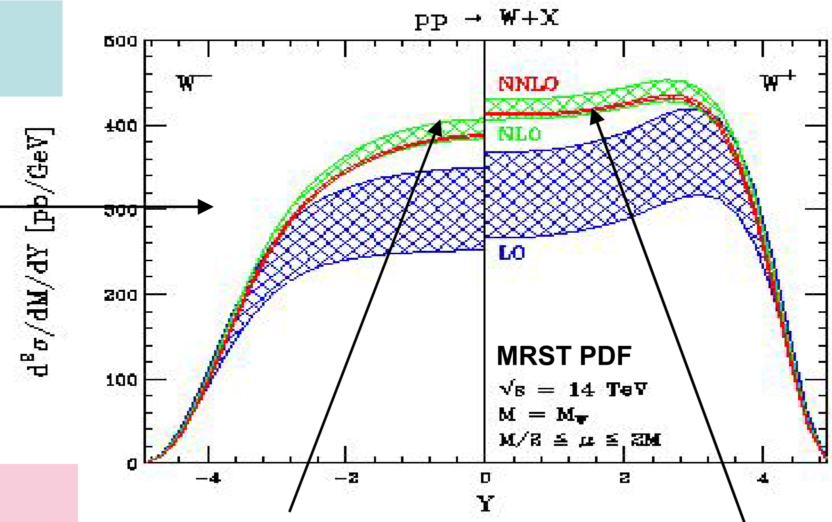
For Q2=10000 the gluon is the dominant parton until VERY high-x





WHAT DO WE KNOW WELL?

W/Z production have been considered as good standard candle processes with small theoretical uncertainty.



NNLO corrections small ~ few%
NNLO residual scale dependence < 1%

PDF uncertainty is THE dominant contribution and most PDF groups quote (68% uncertainties) <~3% (note HERAPDF ~1%)

Re do at 10 TeV

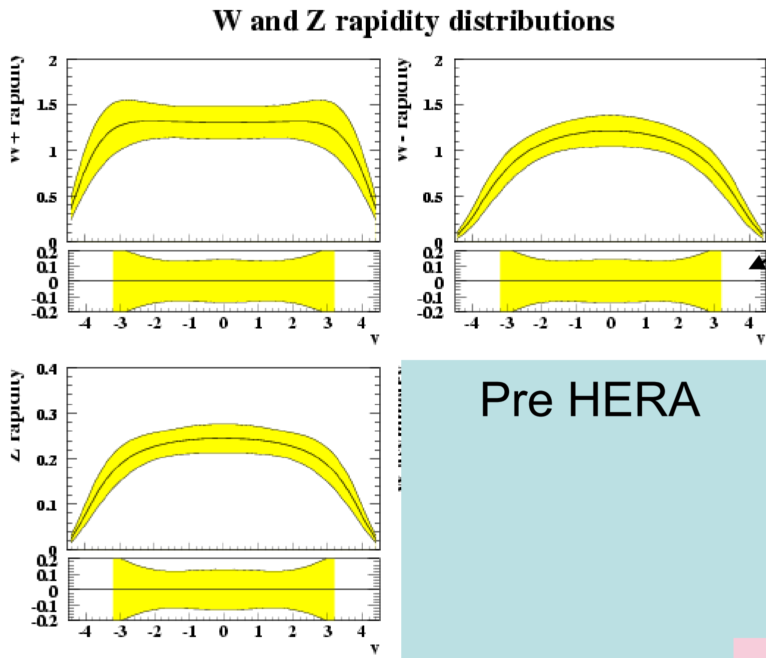
PDF set	$\sigma_{W+} B_{W\to l\nu}$ (nb)	$\sigma_{W-} B_{W\to l\nu}$ (nb)	$\sigma_Z B_{Z\to ll}$ (nb)
ZEUS-2005	8.51±0.30	6.08±0.20	1.36±0.04
MSTW08	8.55±0.15	6.25±0.12	1.38±0.025
CTEQ66	8.77±0.18	6.22±0.14	1.40±0.027
HERAPDF	**8.64±0.10**	**6.27±0.11**	**1.38±0.02**
CTEQ61	8.29±0.22	5.90±0.17	1.32±0.030
NNPDF1.0	11.83±0.26	8.41±0.20	1.95±0.04

BUT **the central values can differ by more than some of the uncertainty estimates→ uncertainty~5%. Could be useful as luminosity monitor?**

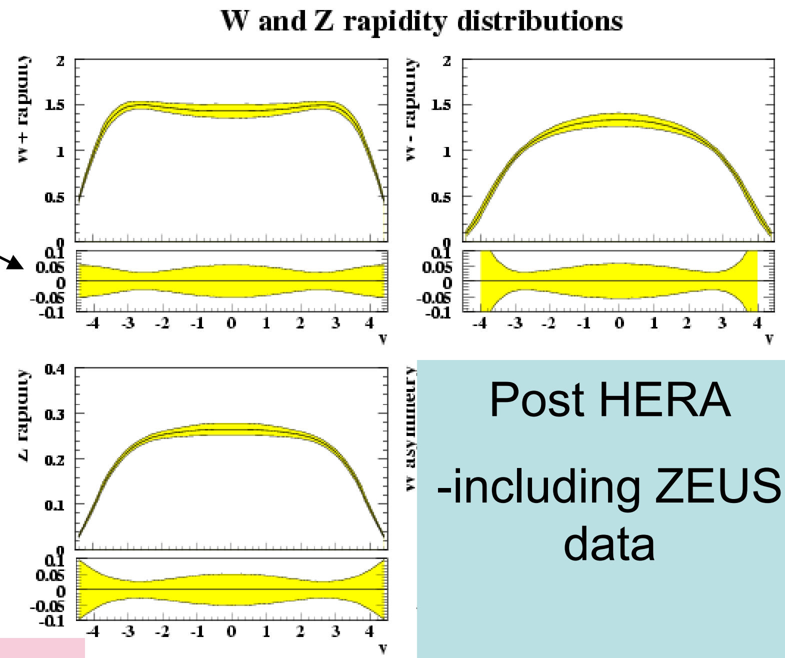
Beware Massless heavy quark treatment

With massive treatement heavy quarks are more suppressed at low-scale so light-quarks increase to compensate when fitting same low-scale data. Consequence is larger W/Z cross-sections at high-scale (CTEQ61 to 66)

WHY DO WE KNOW IT SO WELL? BECAUSE OF HERA.
Look in detail at predictions for W/Z rapidity distributions: Pre- and Post-HERA



Note difference in scale for fractional errors

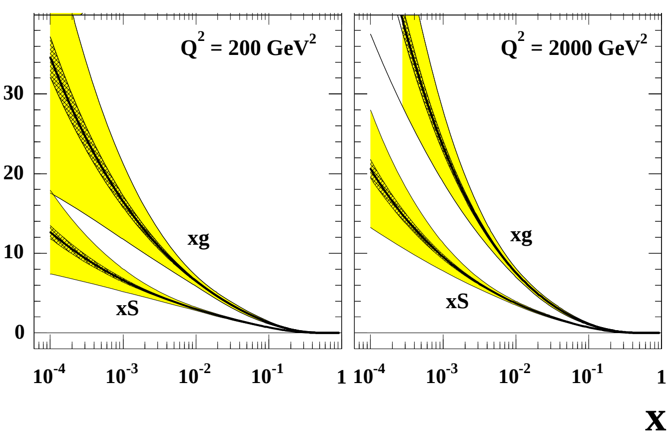


Pre HERA

Why such an improvement ?

Post HERA

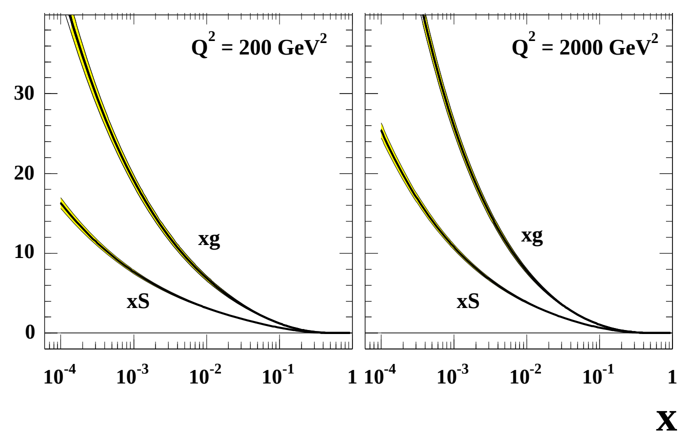
-including ZEUS data



It's due to the improvement in the low-x sea and gluon

At the LHC the q-qbar which make the boson are mostly sea-sea partons

And at $Q^2 \sim M_Z^2$ **the sea is driven by the gluon**



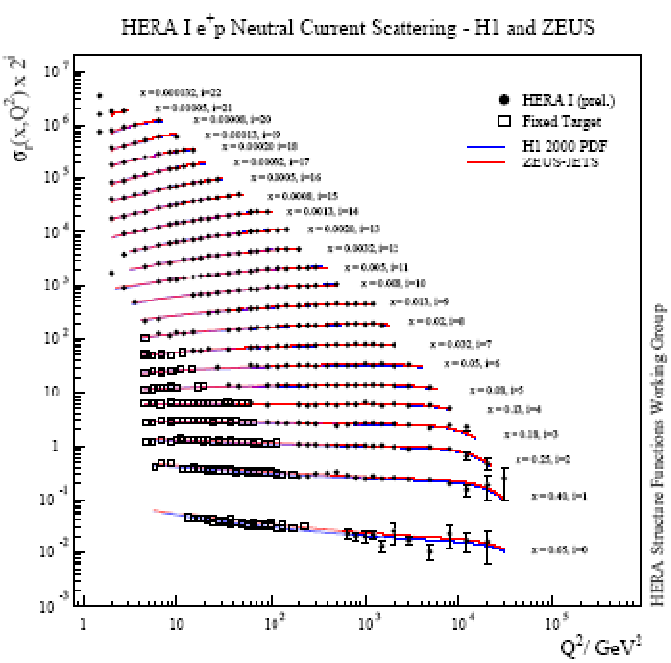
Of course global fits like CTEQ/MSTW include data from BOTH HERA experiments BUT you can do this in a very ‘smart’ way

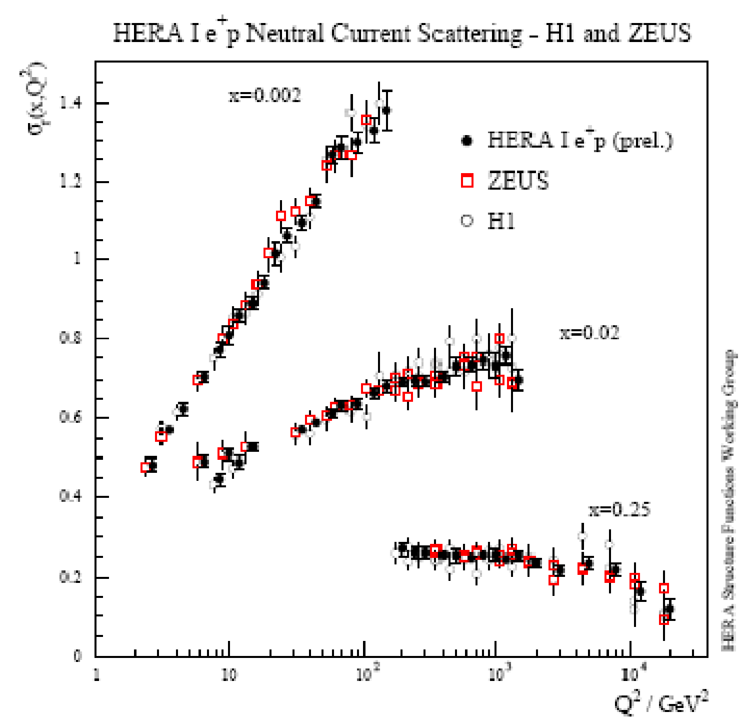
Recent development: Combining ZEUS and H1 data sets

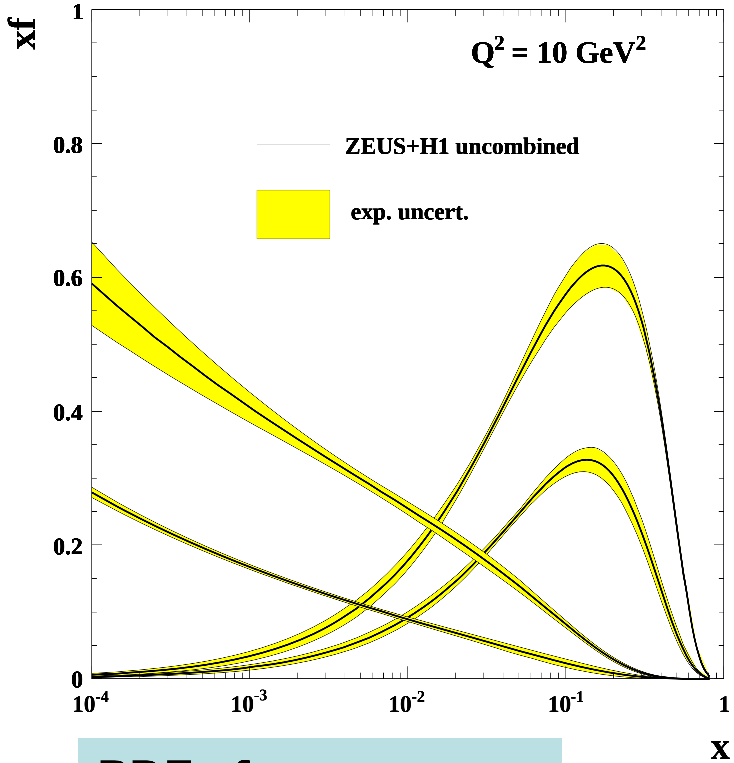
Not just statistical improvement. Each experiment can be used to calibrate the other since they have rather different sources of experimental systematics

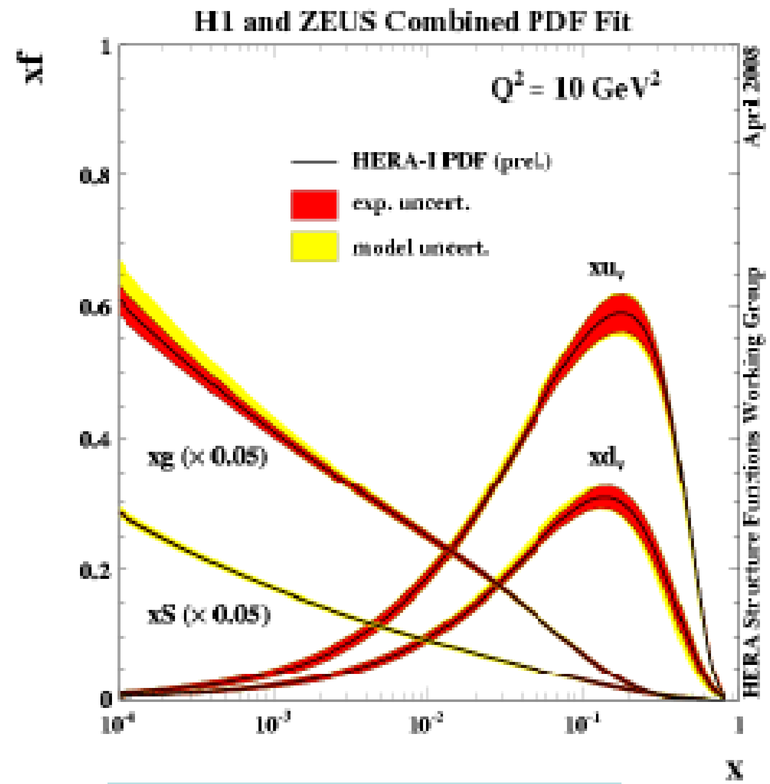
- Before combination the systematic errors are ~3 times the statistical for Q2< 100
- After combination systematic errors are < statistical
- → very consistent HERA data set can be used as sole input to PDF fits with Δχ2=1

HERAPDF0.1









PDFs from same QCD analysis of separate ZEUS and H1 data sets - before 'smart' combination

Experimental error only

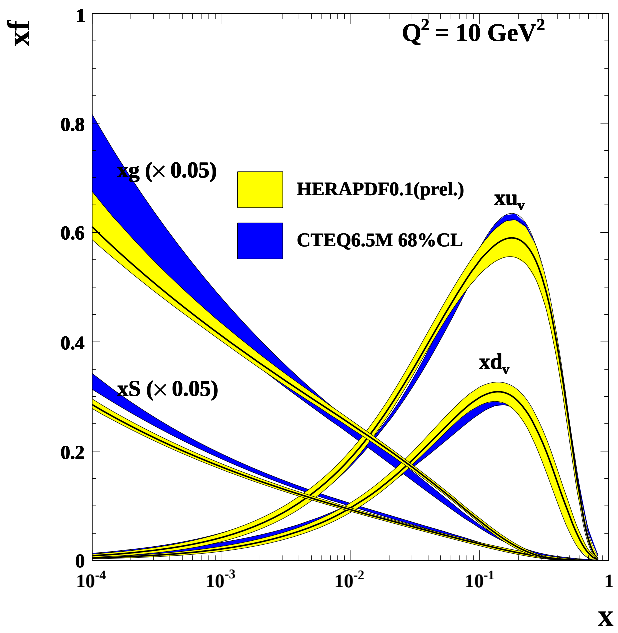
PDFs from same QCD analysis of combined HERA data - after 'smart' combination

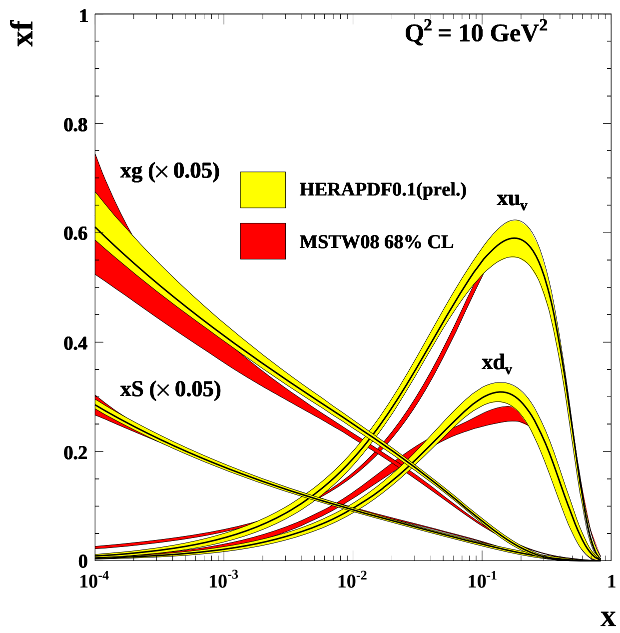
HERAPDF0.1 has small experimental errors and modest model errors

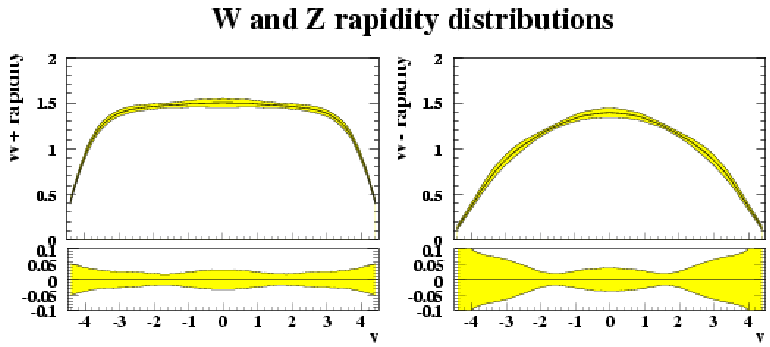
Compare HERAPDF to CTEQ6.5 and MSTW08 PDFs

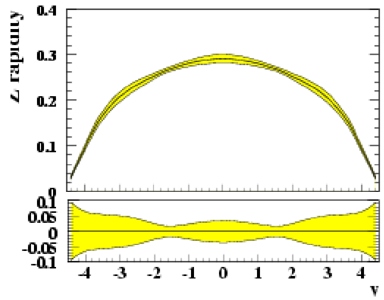
HERAPDF0.1 experimental errors and model errors all included in the yellow band

CTEQ6.5 and MSTW08 uncertainty bands are done at 68%CL for direct comparability

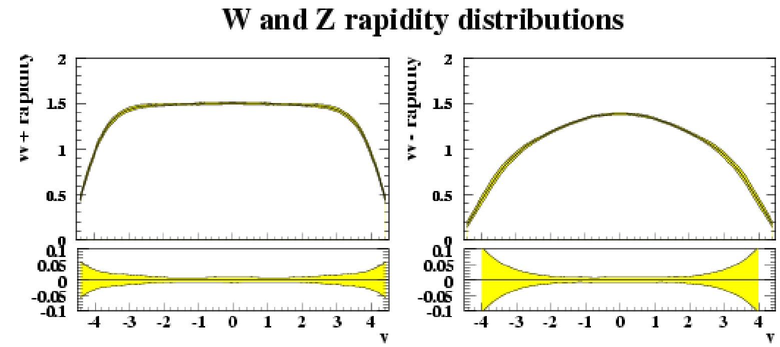


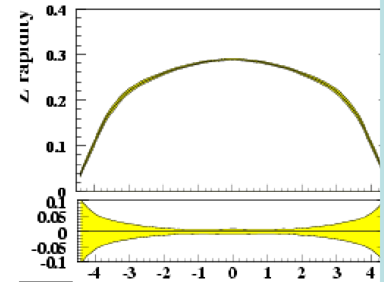




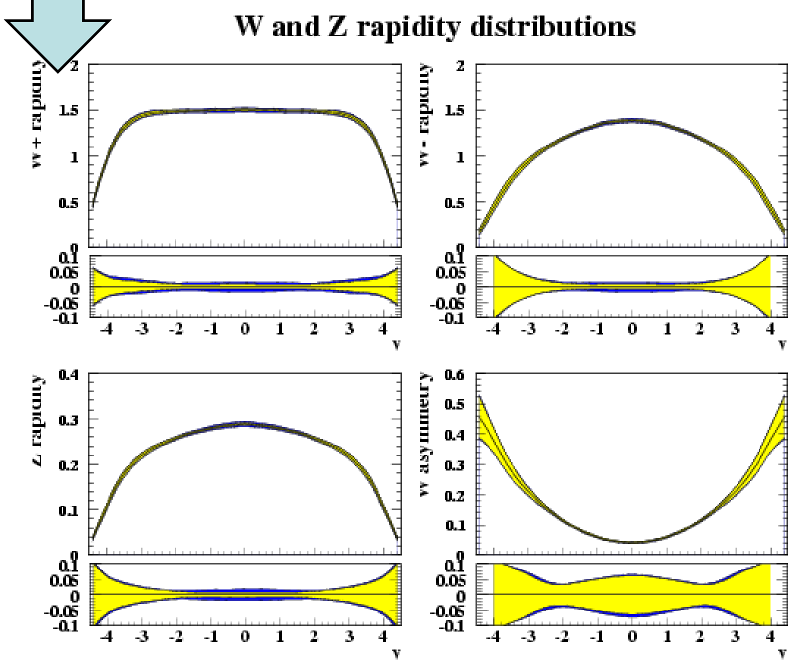


Predictions for WZ prodn from including HERA data in PDF fit **before 'smart' data combination**



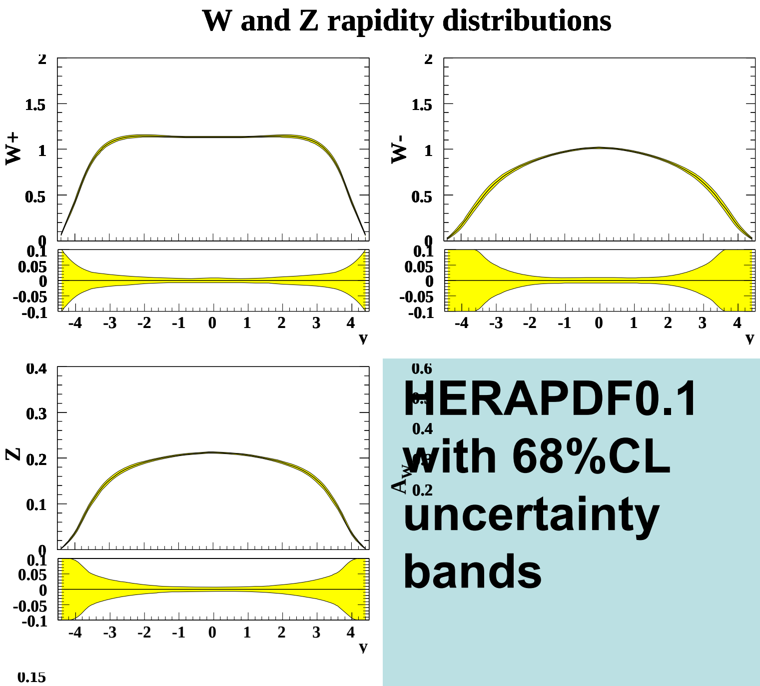


Predictions for WZ prodn from HERAPDF0.1 **after 'smart' data combination**

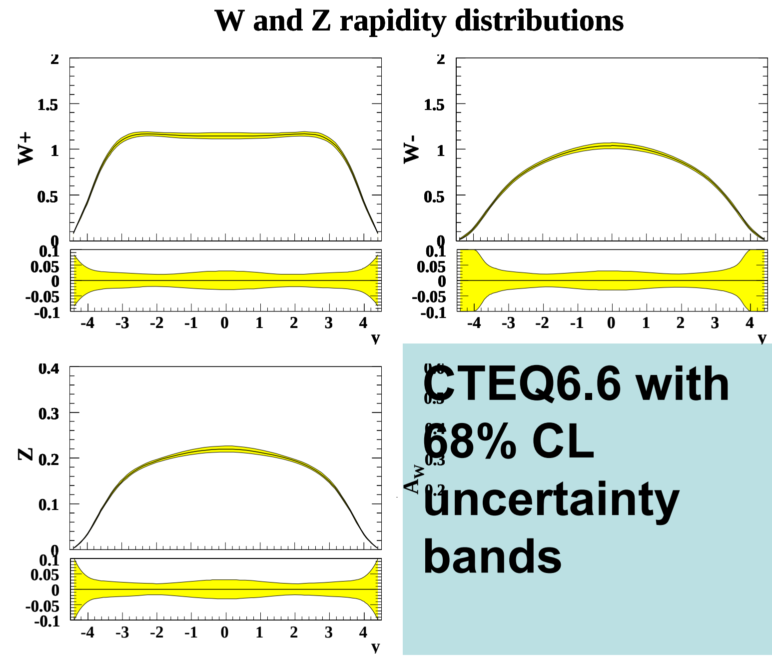


Experimental uncertainties are becoming so small that model dependence assumes greater importance- here **add model errors to HERAPDF0.1 from input assumptions to PDF fitting**

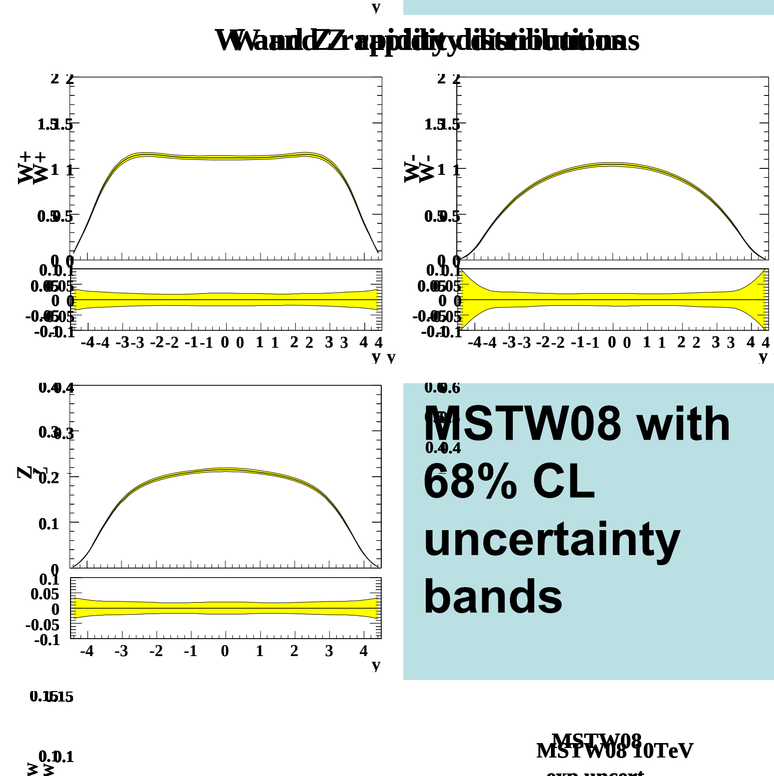
Compare HERAPDF to CTEQ6.6 and MSTW08 for W/Z predictions for 10TeV



HERAPDF0.1 with 68%CL uncertainty bands



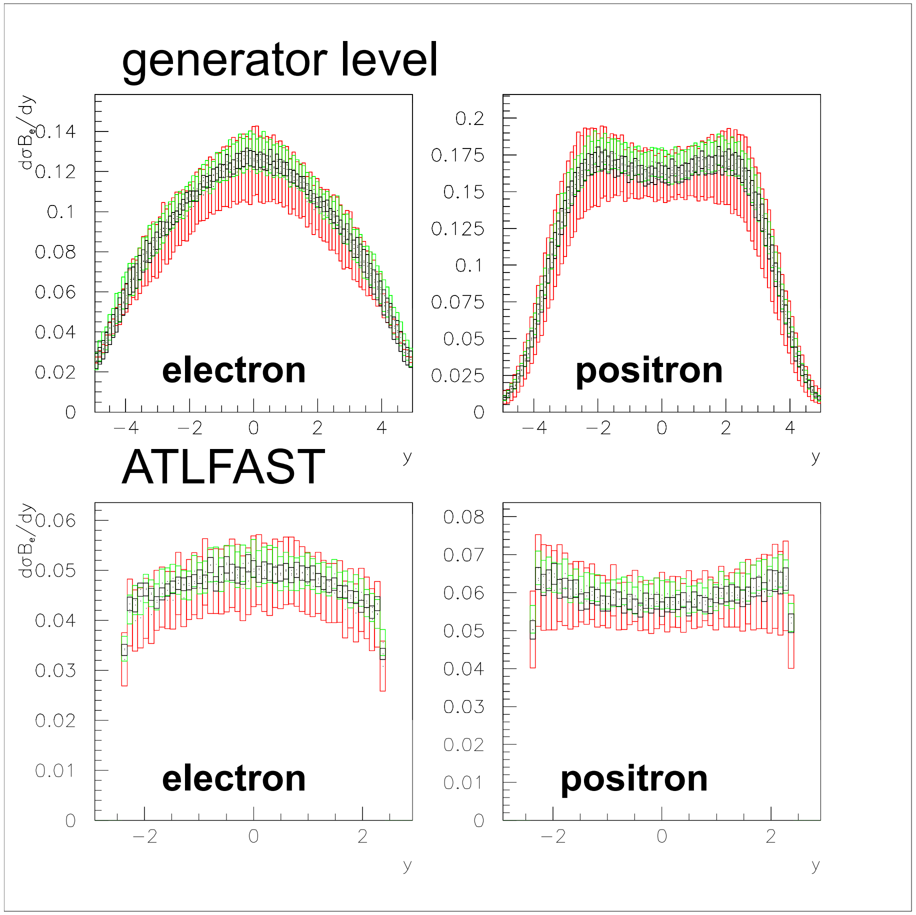
CTEQ6.6 with 68% CL uncertainty bands



MSTW08 with 68% CL uncertainty bands

The new HERA combined data reduce the uncertainty in the central region- should be fed into CTEQ/MSTW fits

Can we improve our knowledge of PDFs using LHC data itself?



We actually measure the decay lepton spectra

Generate pseudodata at 14TeV corresponding to 100pb^{-1}- using CTEQ6.1M ZEUS_S MRST2001 PDFs with full uncertainties

At y=0 the total uncertainty is

~ ±6% from ZEUS

~ ±4% from MRST01E

~ ±8% from CTEQ6.1

To improve the situation we NEED to be more accurate than this:**~4%**

Statistics are no problem there will be millions of W's

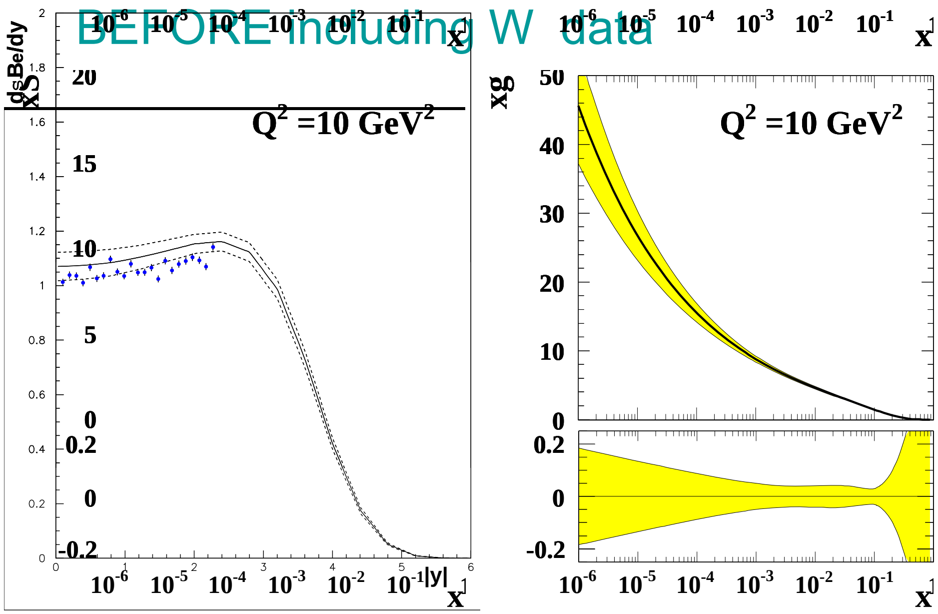
We need to control the systematic uncertainty

AMCS + A Tricoli

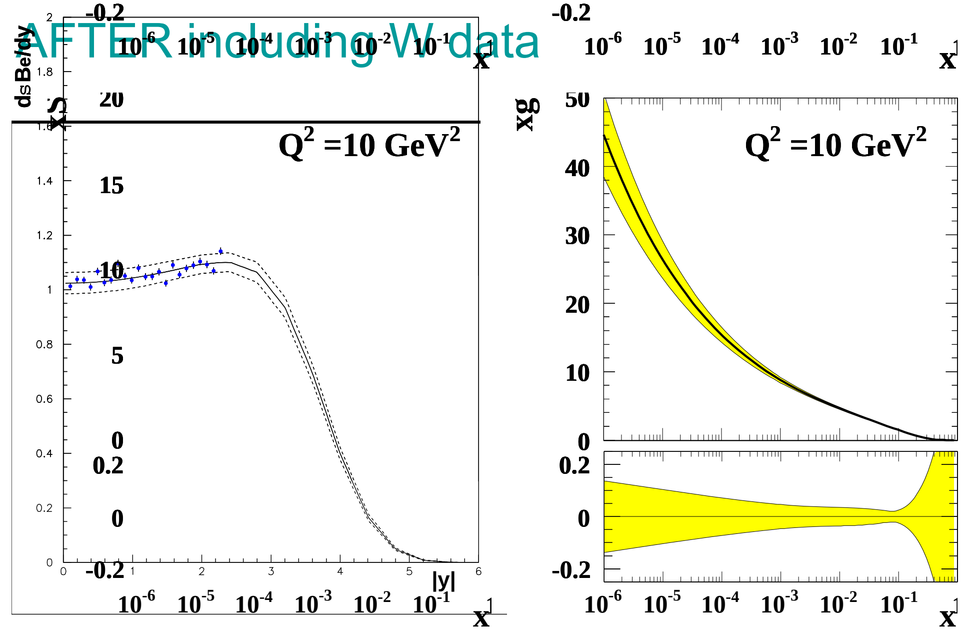
Can we improve the situation with early LHC data?

Generate W^+/W^- data with 4% error using CTEQ6.1 PDF, pass through ATLFAST detector simulation and then include this pseudo-data in the global ZEUS PDF fit (actually use the decay lepton spectra) **Central value of prediction shifts and uncertainty is reduced**

BEFORE including W data



AFTER including W data

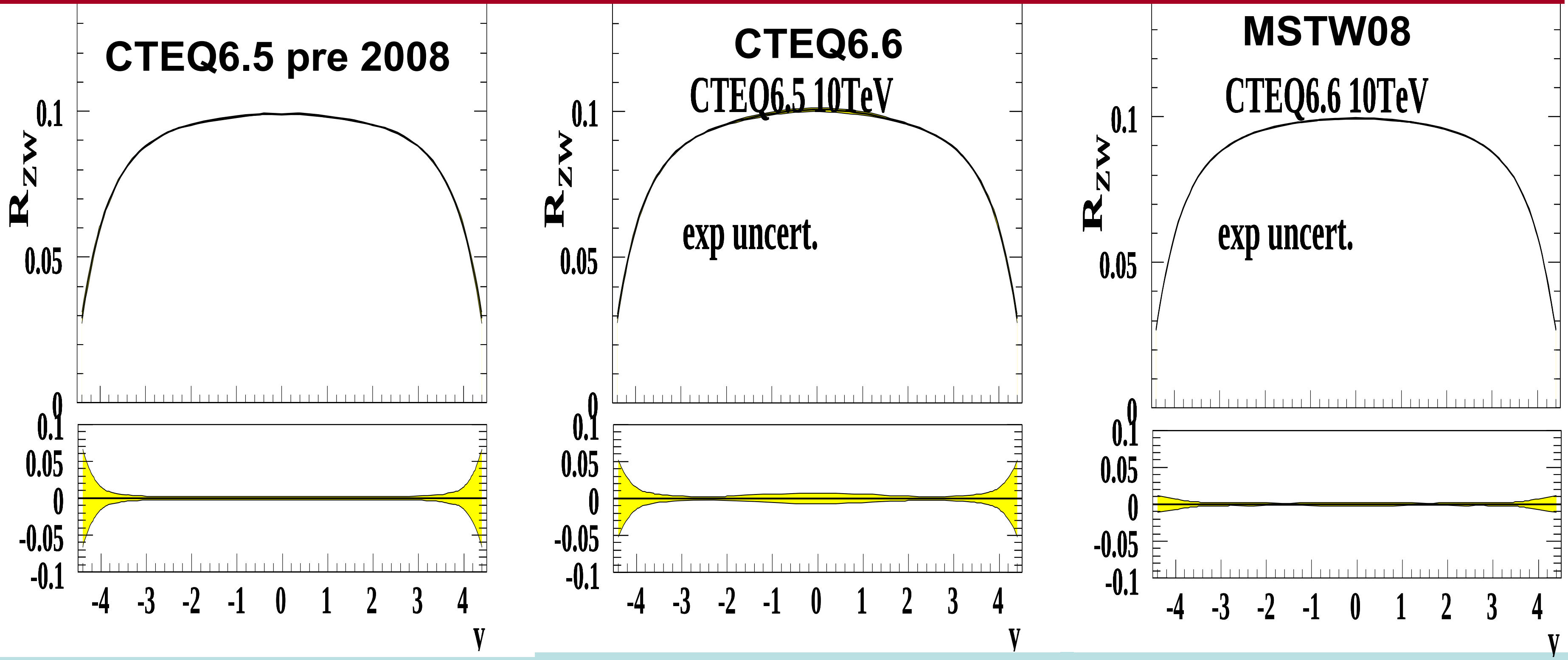


e+ rapidity spectrum and gluon PDF BEFORE these data are included in the PDF fit

e+ rapidity spectrum and gluon PDF AFTER these pseudodata are included in the PDF fit

Gluon PDF uncertainties are reduced

Now let's look at ratios: Z/W ratio is a golden benchmark measurement - 10TeV



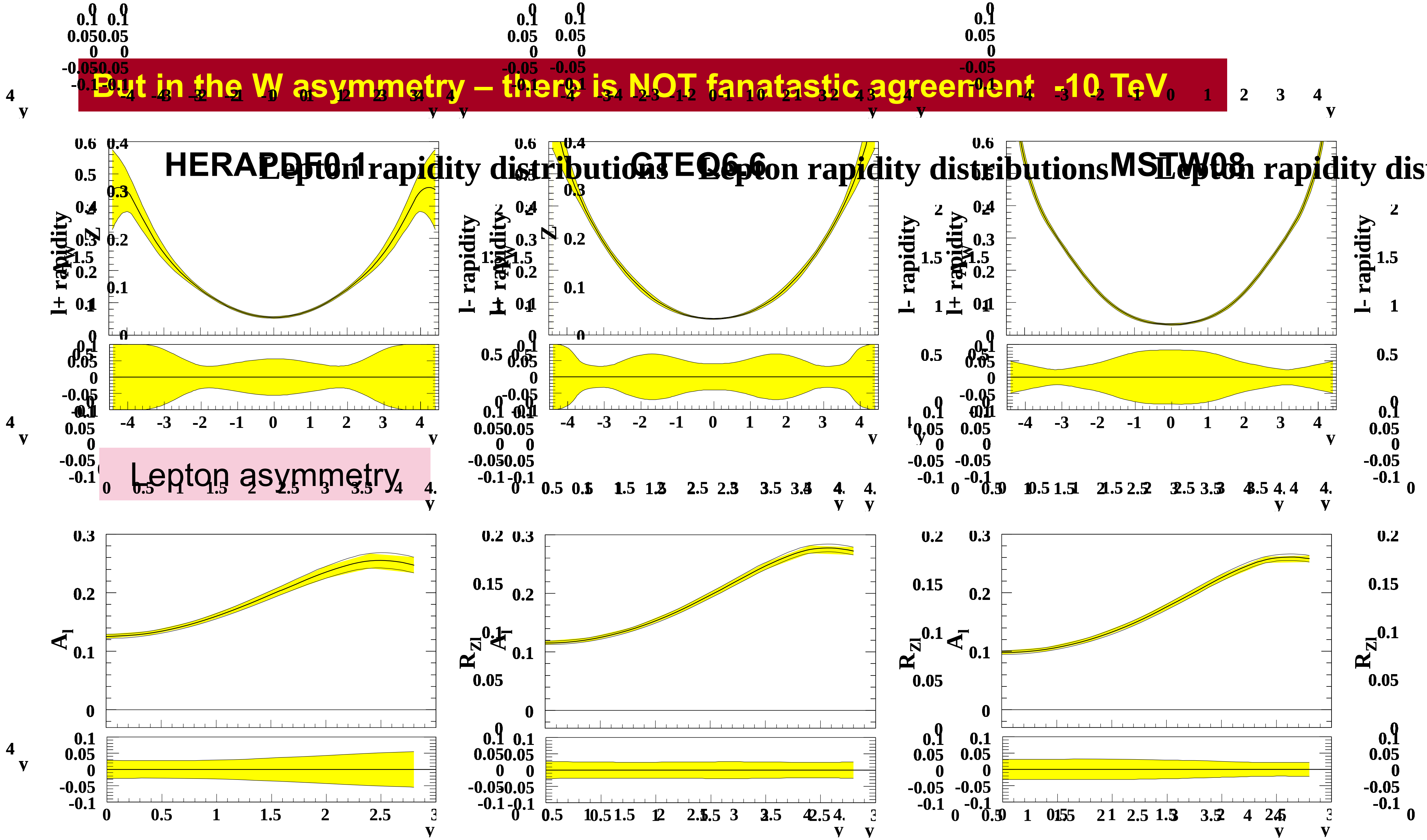
ZOOM in on Z/W ratio – there is fantastic agreement between PDF providers
PDF uncertainty from the low-x gluon and flavour symmetric sea cancels out- and so do luminosity errors BUT there is somewhat more PDF uncertainty than we thought before 2008 (~1.5% rather than <1% in the central region)

There is uncertainty in the strangeness sector that does not cancel out between Z and (W^+ + W^-)… it was always there we just didn't account for it

$$\frac{Z}{W^+ + W^-} = \frac{\text{uubar + ddbar + ssbar +ccbar +bbar}}{\sim \text{(udbar + csbar) + (dubar+scbar)}}$$

YES this does translate to the Z/lepton ratio

But in the W asymmetry – there is NOT fanatastic agreement -10 TeV



Further sources of PDF uncertainty from the valence sector are revealed.

And note that when it comes to W asymmetry CTEQ do not have the most conservative errors at central rapidity - MRST/MSTW do

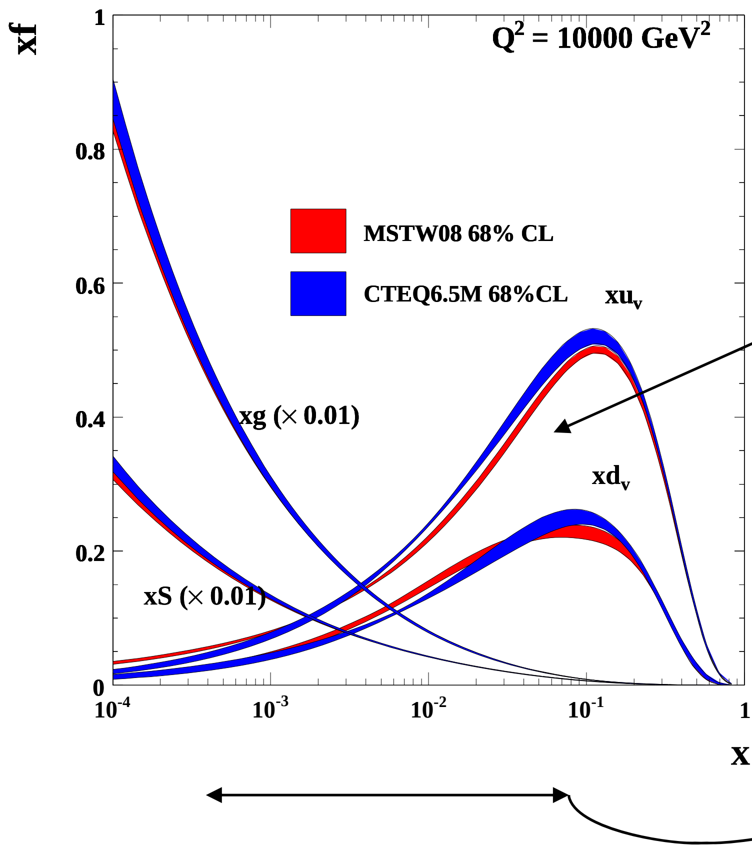
Dominantly, at LO $\quad Aw = \dfrac{(u\,dbar - d\,ubar)}{(u\,dbar + d\,ubar)}$

And ubar ~ dbar ~ qbar at small x

So $Aw \sim \dfrac{(u - d)}{(u + d)} = \dfrac{(u_v - d_v)}{(u_v + d_v + 2\,qbar)}$

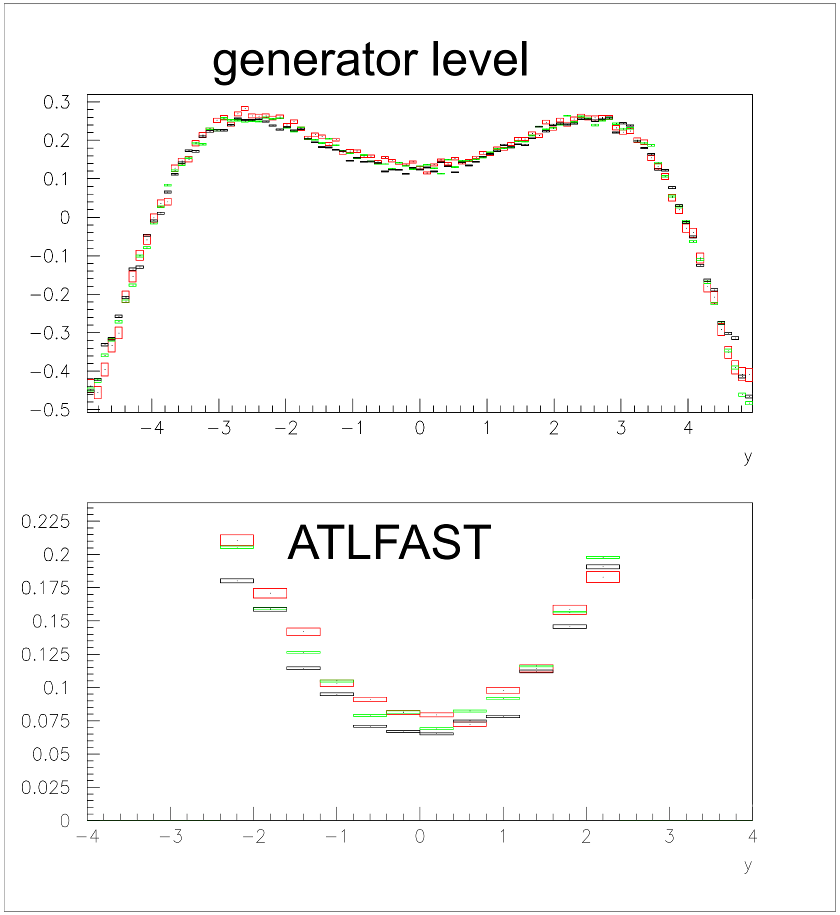
Predictions for AW are different in the central region- because predictions for valence distributions at small-x are different

Actually this LO approx. is pretty good even quantitatively
The difference in valence PDFs you see here does explain the difference in A_W between MRST and CTEQ



x- range affecting W asymmetry in the measurable rapidity range at ATLAS (10TeV)

Can we improve our knowledge of PDFs using ATLAS data itself?



We actually measure the decay lepton spectra

Generate pseudodata at 14TeV corresponding to 100pb^{-1}- using CTEQ6.1M ZEUS_S MRST2004 PDFs with full uncertainties

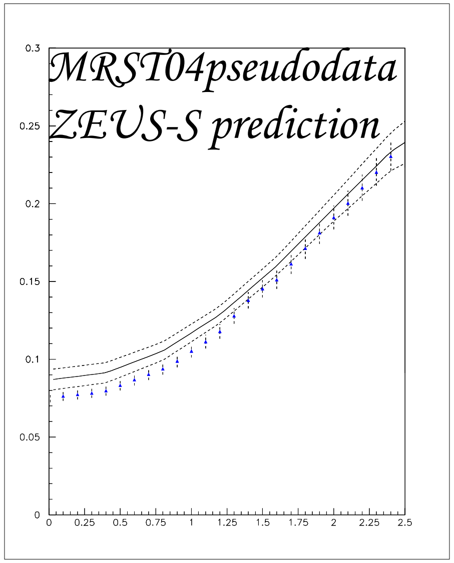
Generate data with ~4% systematic error on the asymmetry

AMCS + A Tricoli

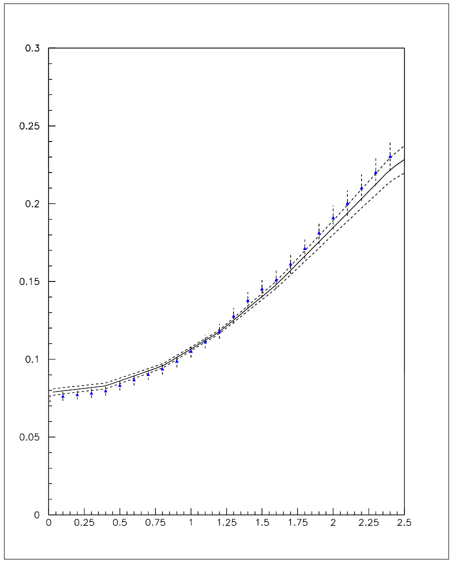
Generate data with 4% error using MRST04 PDF and then include this pseudo-data in the global ZEUS PDF fit (actually use the lepton asymmetry data)

The PDF uncertainty of the valence distributions is improved by the input of such data

BEFORE including A_e pseudo-data

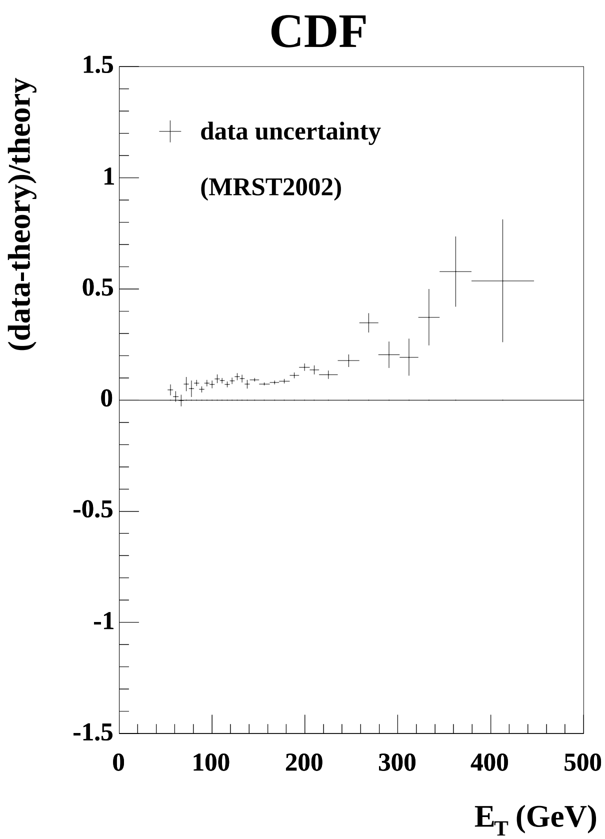


AFTER including A_e pseudo-data



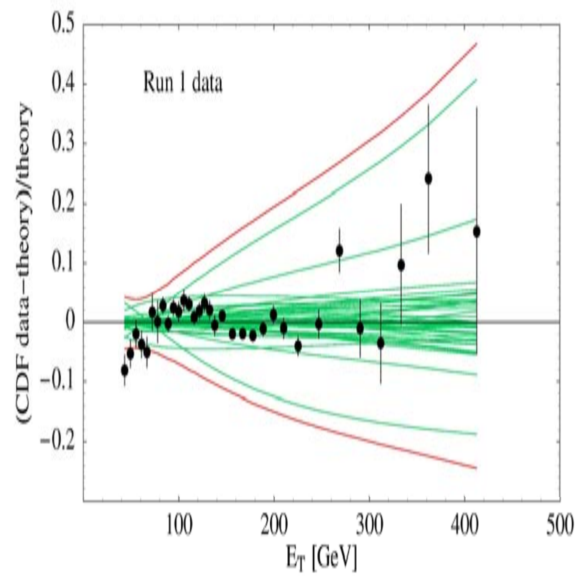
Result is improved accuracy of and change of shape of the valence PDFs

ATLAS/CMS LHC asymmetry data can measure valence distributions at x~0.005



And what is not well known?

Example of how PDF uncertainties matter for BSM physics– Tevatron jet data were originally taken as evidence for new physics--



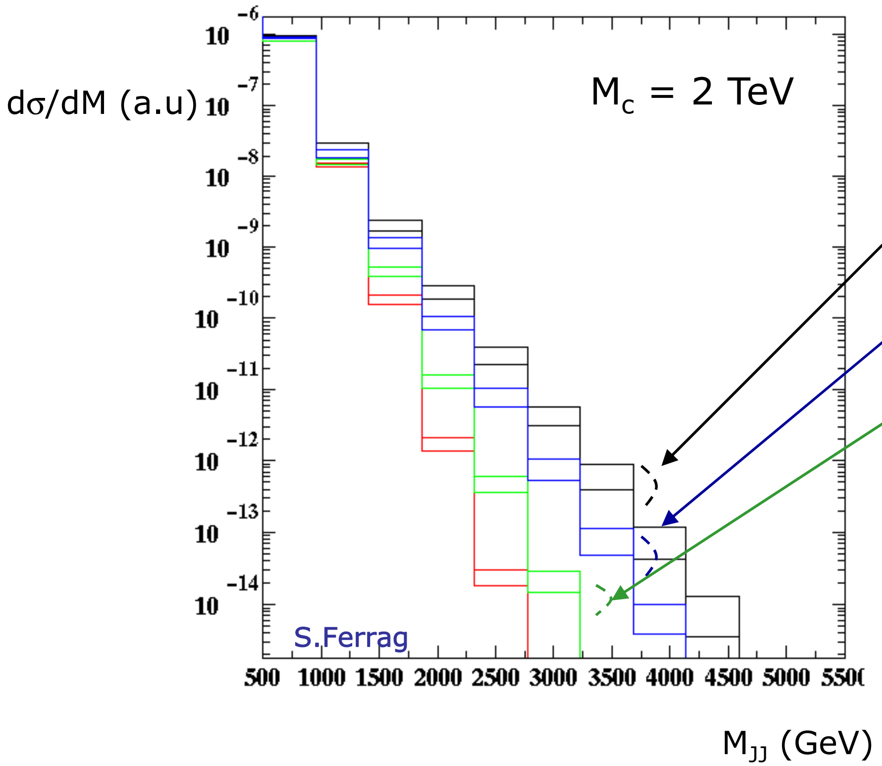
Theory CTEQ6M

These figures show inclusive jet cross-sections compared to predictions in the form (data - theory)/ theory

Today Tevatron jet data are considered to lie within PDF uncertainties
And the largest uncertainty comes from the uncertainty on the high x gluon

And what consequences might this have?

Such PDF uncertainties in the jet cross sections compromise the LHC potential for discovery of any new physics which can written as a contact interaction
E.G. Dijet cross section has potential sensitivity to compactification scale of extra dimensions (M_c)



Up to ~50% at high mass :

SM + structure function uncertainty band

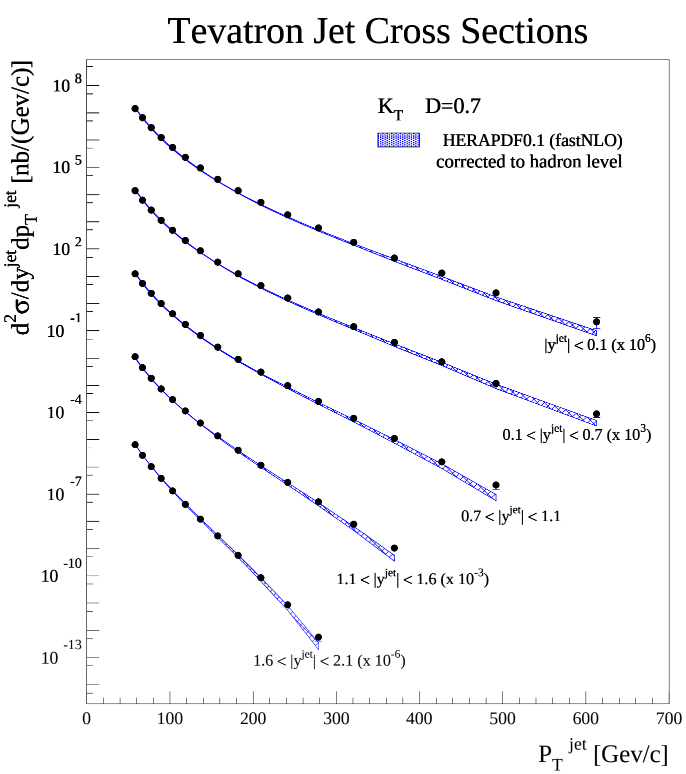
2XD + structure function uncertainty band

4XD + structure function uncertainty band

→Enough to lose sensitivity to higher compactification scales

S. Ferrag + A Djouadi

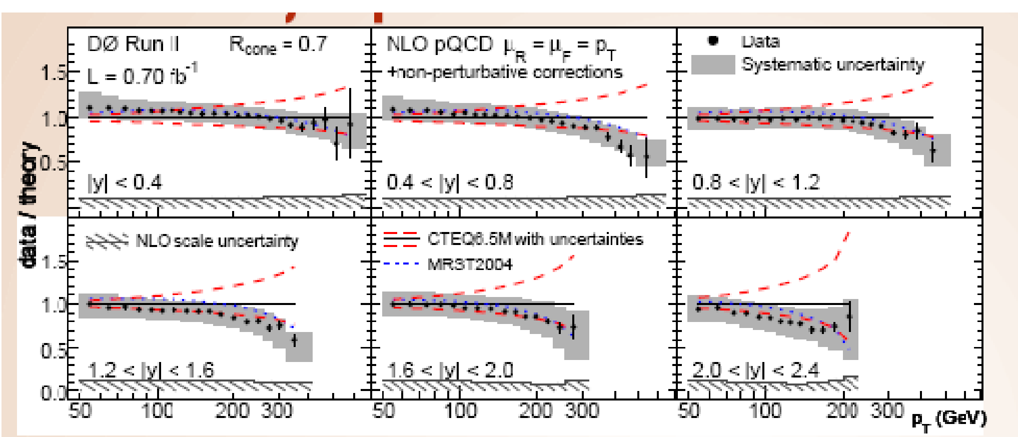
CDF Run-II jet data compared to HERAPDF0.1



Note there is now new Tevatron Run-II jet data

Has been used in MSTW08 PDFs

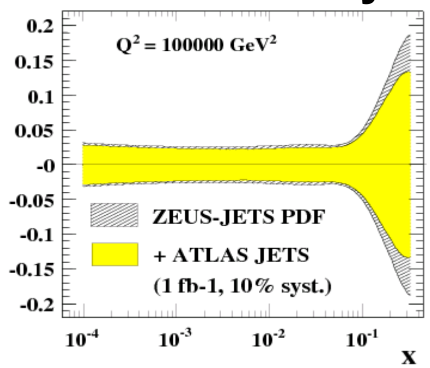
It does not make MUCH difference to the level of high-x gluon PDF uncertainty



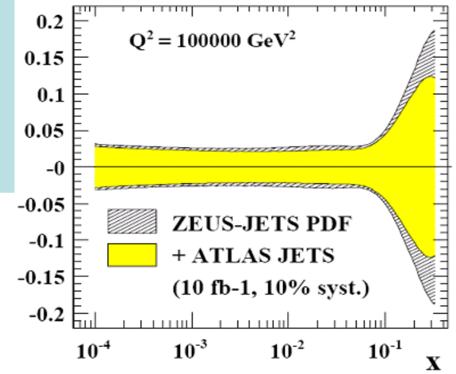
D0 jet data compared to CTEQ6.5 seem to be less hard than Run-I

(CTEQ6.5 fitted Run-I)

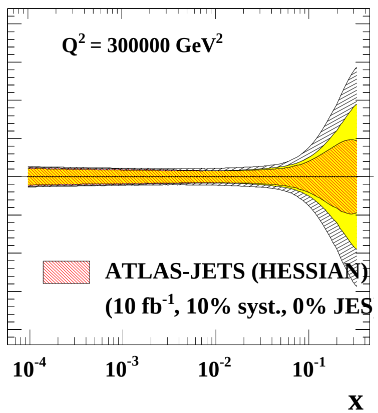
And will we be able to use LHC data itself to improve the situation?- study of including ATLAS pseudodata in PDF fit



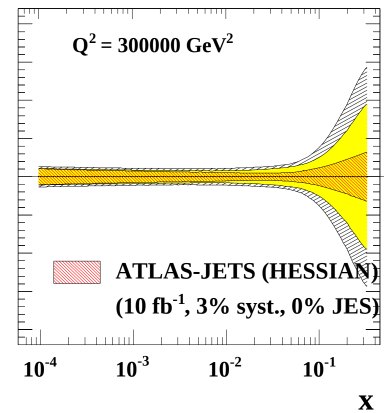
Use data at higher η > 1 and lower pt < 3TeV to avoid new physics!

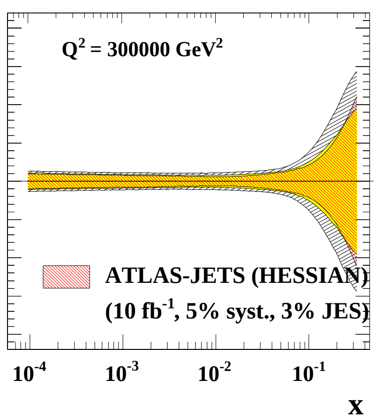


Impact of increasing statistics



Impact of decreasing experimental systematic uncertainty

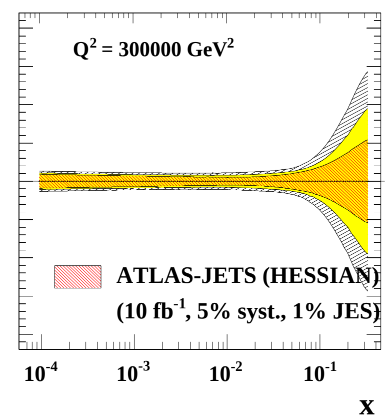




Impact of decreasing experimental correlated systematic uncertainty

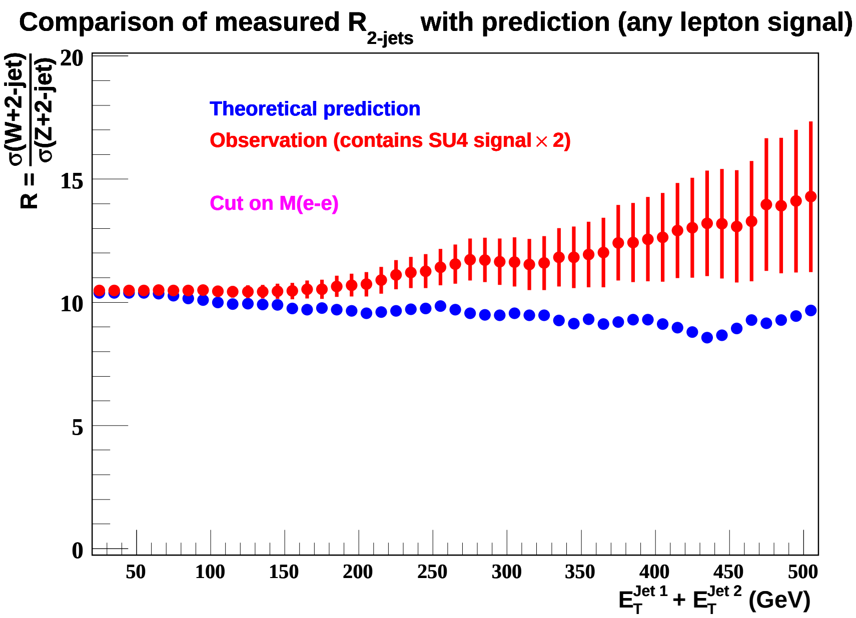
Challenging!

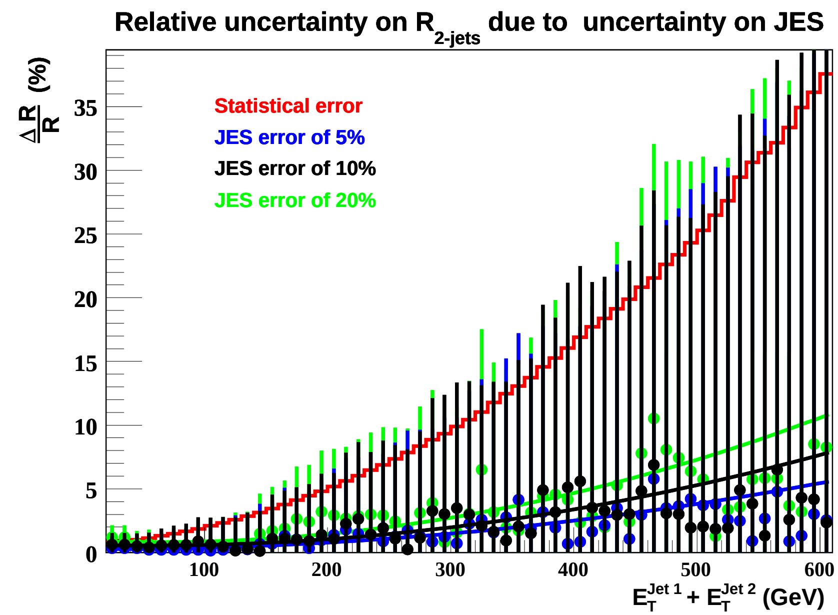
Can we decrease Jet Energy Scale systematic to 1%?



C Gwenlan
D Clements

Jet energy scale also a problem in W/Z+jets channel, where SUSY signals may show up – Jet Energy Scale of 5% gives uncertainties 5-12% on the W + (1-6) jet cross-sections. This is larger than the PDF uncertainty (3-8%)





However BSM signals should be more obvious in the R=(W+n jet) / (Z+n jet) ratio

Illustrated is MSugra SU(4) compared to Standard Model for 200pb^{-1} of data in the W/Z +2 jets channel

The jet energy scale is less of a problem in the ratio

JES of 5% gives < 5% uncertainty on the ratio –very much less than the statistical error

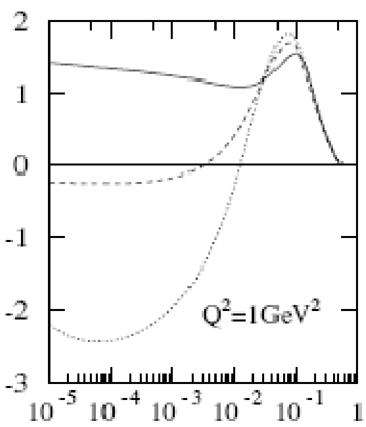
H Beauchemin

BEWARE of different sort of 'new physics'

What if low-x behaves very differently?

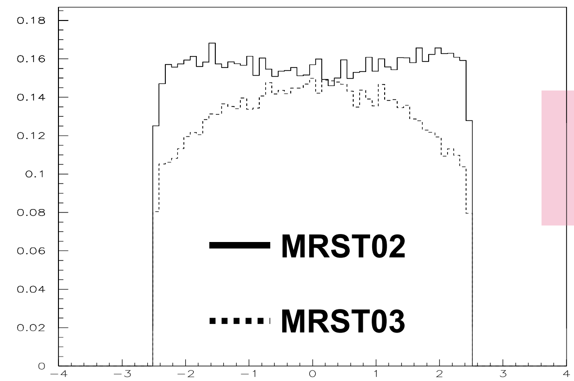
LHC is a low-x machine (at least for the early years of running) Is NLO (or even NNLO) DGLAP good enough for $x < 10^{-2}$. The QCD formalism may need extending at small-x. What is SAFE x?

- BFKL ln(1/x) resummation would change the deduced shape of the gluon



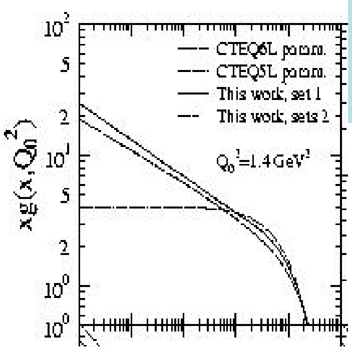
Thorne and White

MRST03 PDFs were a TOY PDF which distrusted all $x < 10^{-3}$. This would affect the central region for W production.



Central rapidity

High density non-linear effects may induce gluon saturation this also affects the deduced shape of the gluon

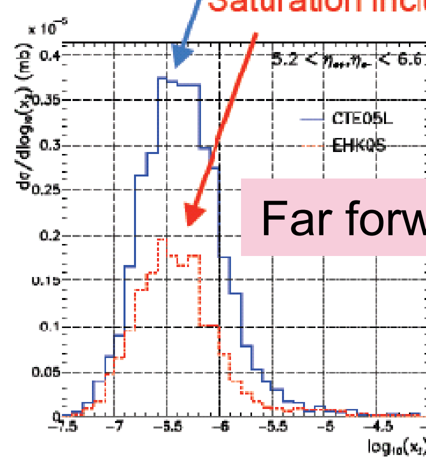


Eskola et al

Drell-Yan M(ee) = 4GeV

No saturation

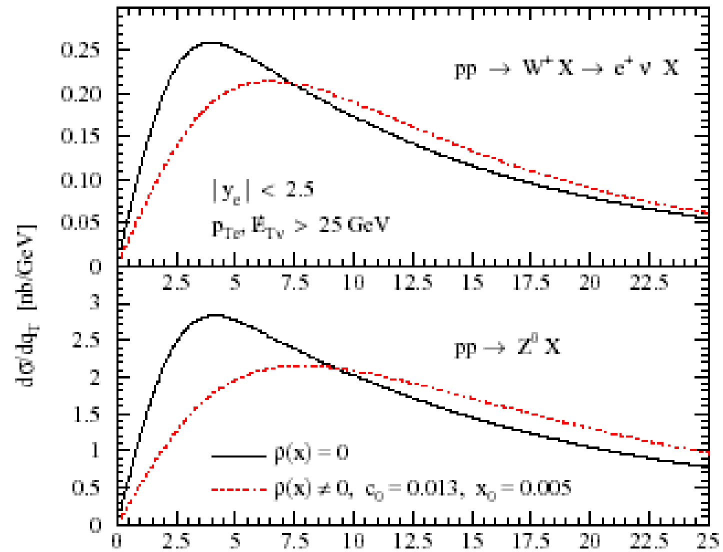
Saturation included



Far forward

But the TOY PDFs are unlikely to be realistic - a better way could be to look at pt spectra for W and Z production

Lack of pt ordering at low-x is a further consequence BFKL resummation AND most non-linear treatments. This would affect the pt spectra for W and Z production at the LHC
(See hep-ph/0508215)



Conventional

Unconventional

And if any of this is true the W/Z cross-sections are very different - cannot be used as a luminosity monitor until we thoroughly understand low-x physics

PDF set	$\sigma_{W+} B_{W\to l\nu}$ (nb)	$\sigma_{W-} B_{W\to l\nu}$ (nb)	$\sigma_Z B_{Z\to ll}$ (nb)
MSTW08	8.55±0.15	6.25±0.12	1.38±0.025
MRST03	6.88	5.23	1.18

Summary

STANDARD MODEL

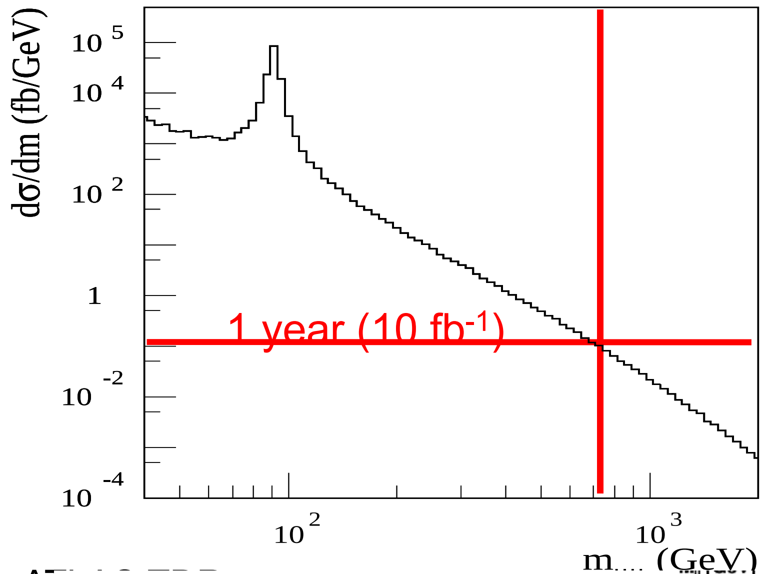
- There are W/Z standard candle measurememts: Z/W ratio is the best
- W and Z cross-sections should first test our understanding- then contribute to our knowledge at greater precision
- W asymmetry should bring something new
- Beware that NEW low-x physics could compromise this.

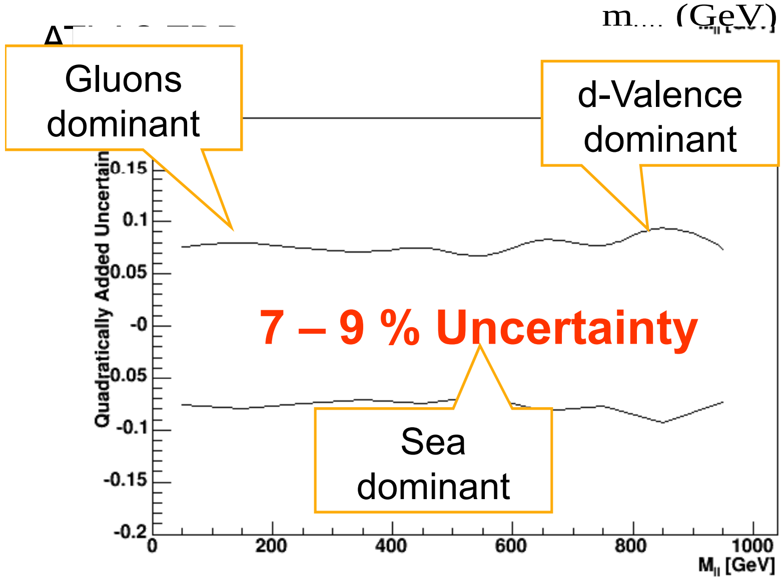
BEYOND STANDARD MODEL

- There are discovery channels – high ET jets- which could be obscured by PDF uncertainties
- But Jet Energy Scale Uncertainties could be more of a problem
- Be smart - look at ratios W+n-jets/Z+n-jets

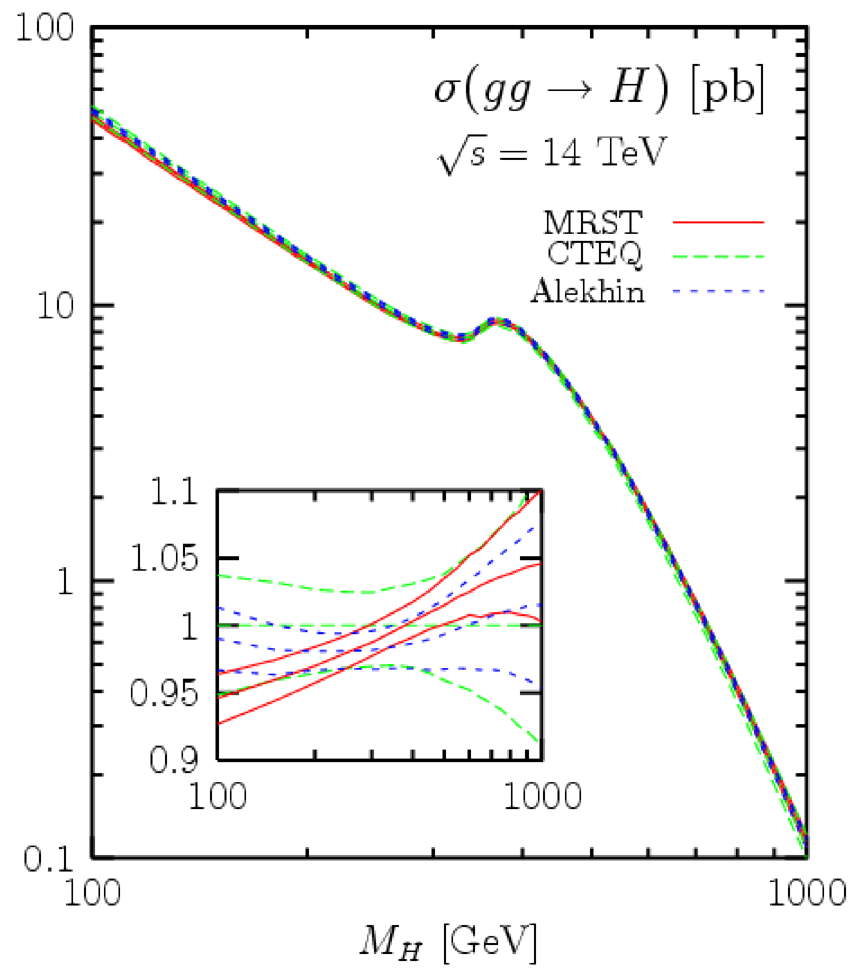
extras

But not all discovery physics is strongly compromised: e.g PDF Uncertainty in High-mass Drell-Yan- won't stop us seeing Zprimes





and PDF uncertainties don't affect the Higgs discovery potential too badly

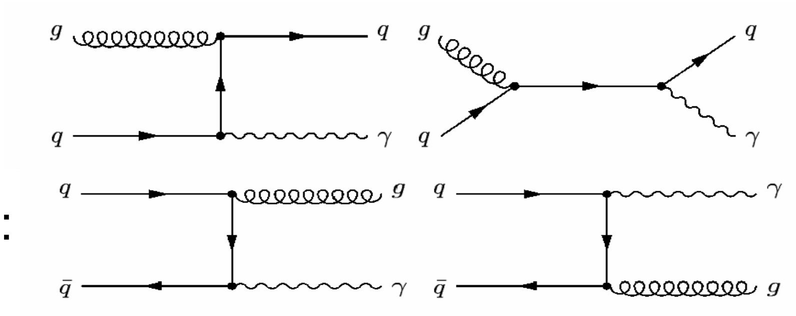


What other processes will be useful?

Direct photon production for the high-x gluon

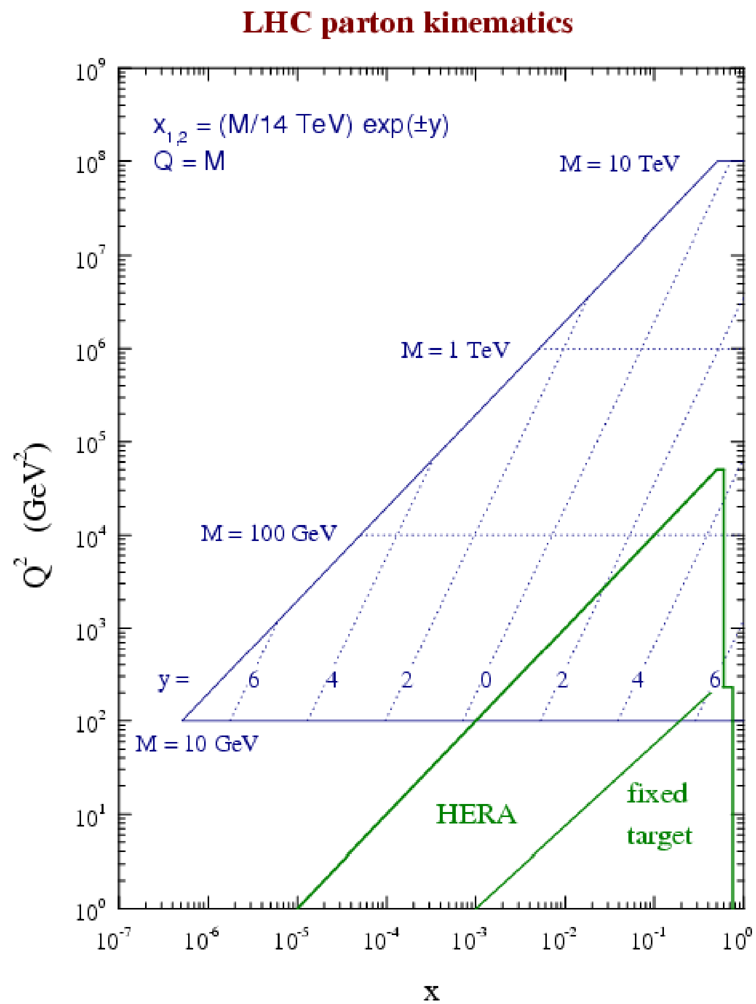
Compton:
(~90%)

Annihilation:
(~10%)

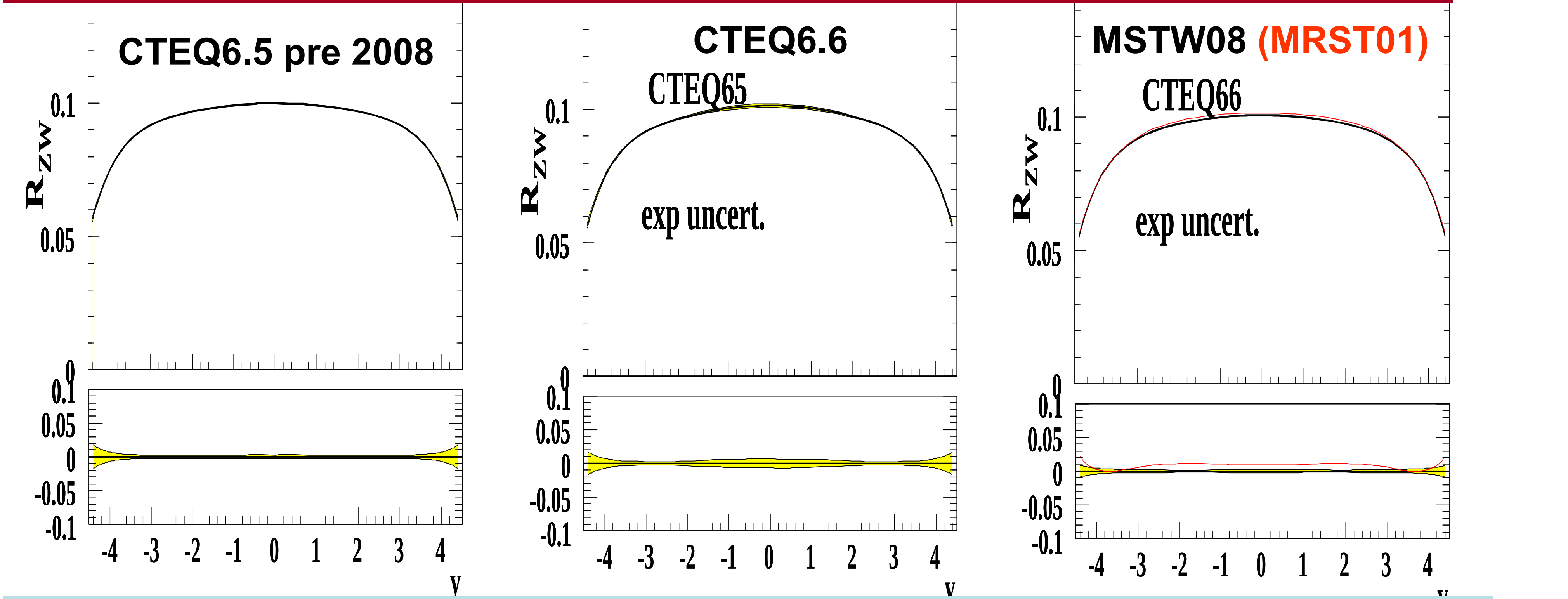


- **Z+ b-jet for Measurement of the b-quark PDF**

Low-mass Drell-Yan will probe low-x partons but also low-x calculations – LHCb can look at this



Now let's look at ratios: Z/W ratio is a golden benchmark measurement – 14TeV



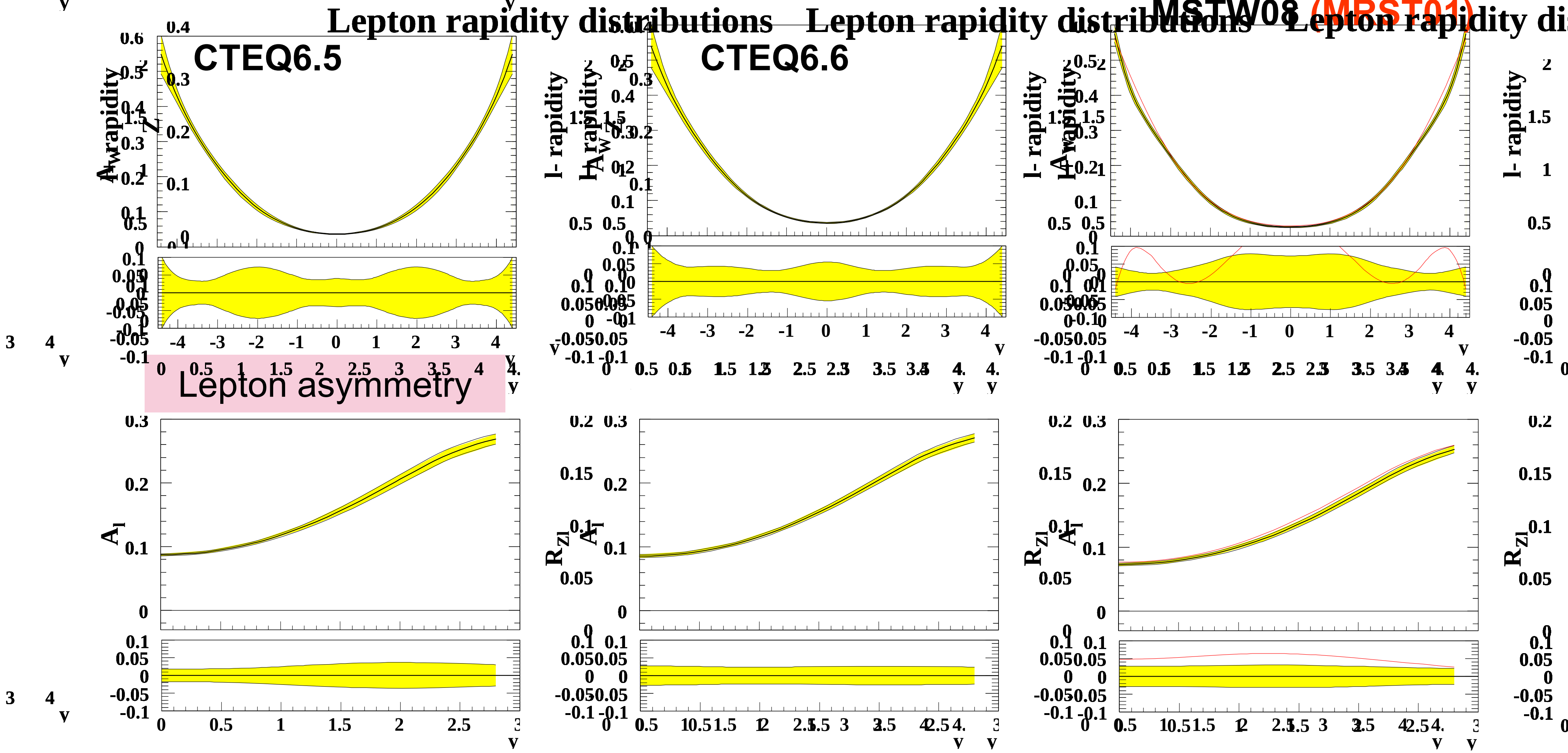
ZOOM in on Z/W ratio – there is fantastic agreement between PDF providers PDF uncertainty from the low-x gluon/ flavour symmetric sea cancels out- and so do luminosity errors BUT there is somewhat more PDF uncertainty than we thought before 2008 (~2% rather than 1% in the central region)

There is uncertainty in the strangeness sector that does not cancel out between Z and (W^+ + W^-)… it was always there we just didn't account for it

$$\frac{Z}{W^+ + W^-} = \frac{\text{uubar + ddbar + ssbar + ccbar + bbar}}{\sim \text{(udbar + csbar) + (dubar+scbar)}}$$

YES this does translate to the Z/lepton ratio

But in the W asymmetry – there is NOT fanatastic agreement 14TEV



Further sources of PDF uncertainty from the valence sector are revealed. And note that when it comes to W asymmetry CTEQ do not have the most conservative errors at central rapidity - MRST/MSTW do

But what about valence PDFs at high-x?

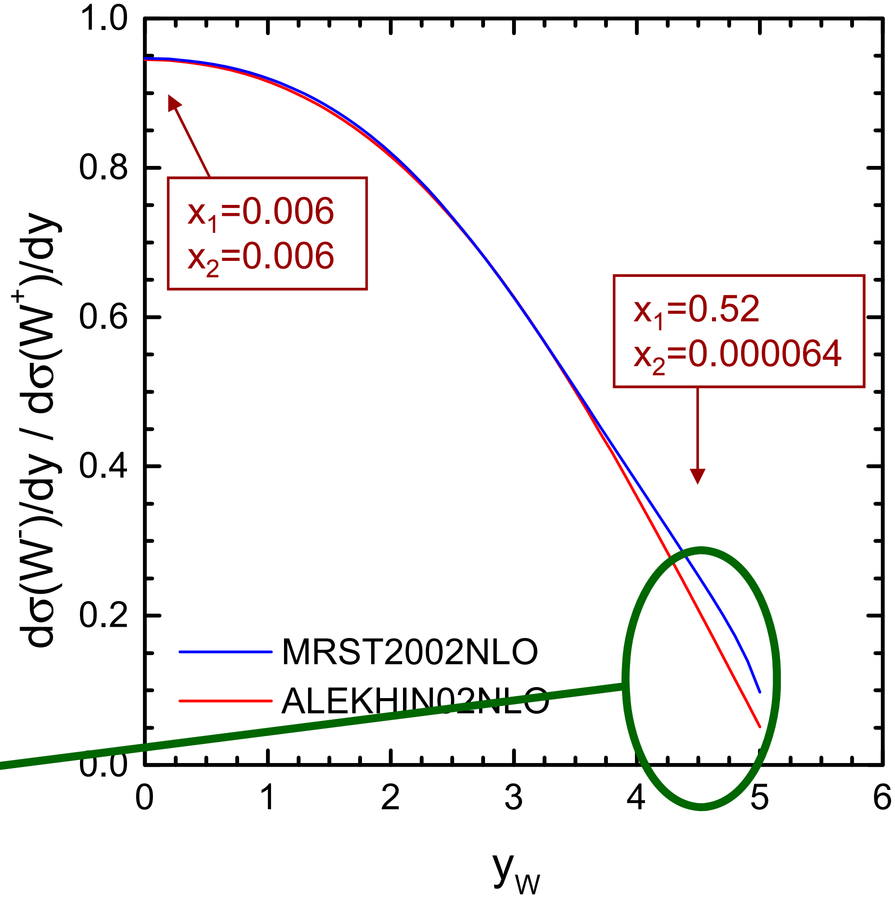
Look at W-/W+ ratio at large rapidity

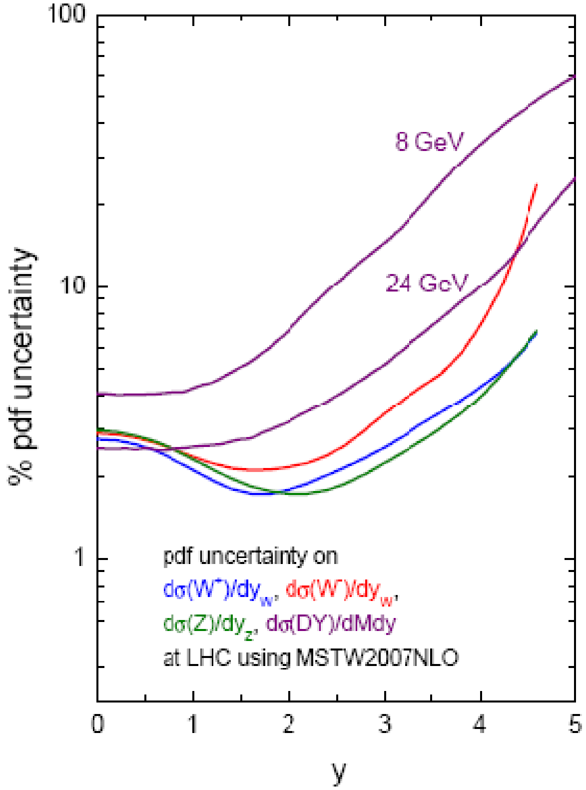
$$\frac{W^-}{W^+} = \frac{u\,\bar{d}}{d\,\bar{u}}$$

Not possible for main LHc detectors BUT LHCb rapidity range 1.9 to 4.9

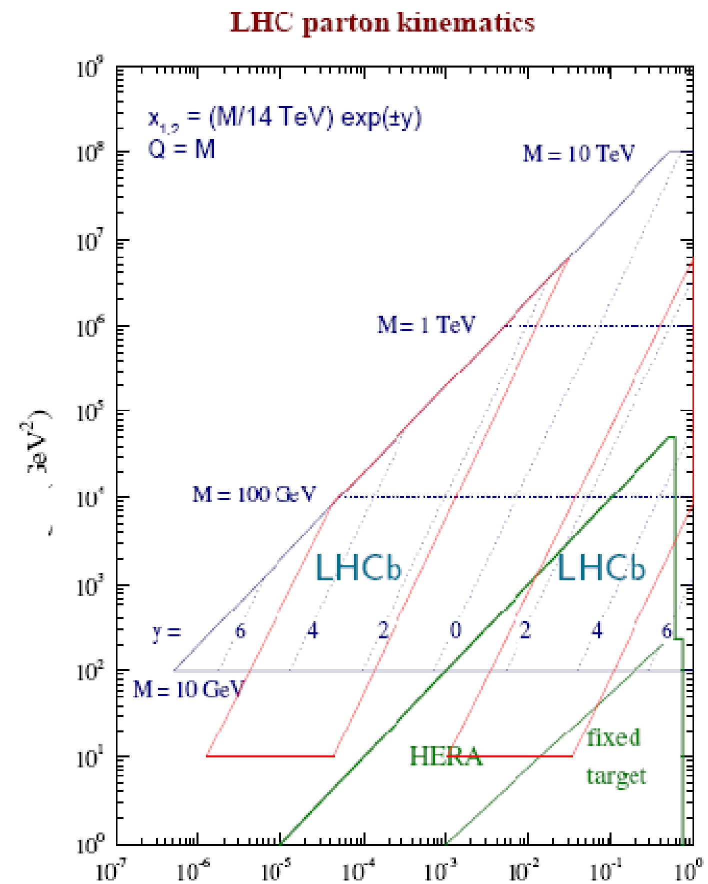
There is a proposal ro look at this in LHCb

sensitive to large-x d/u

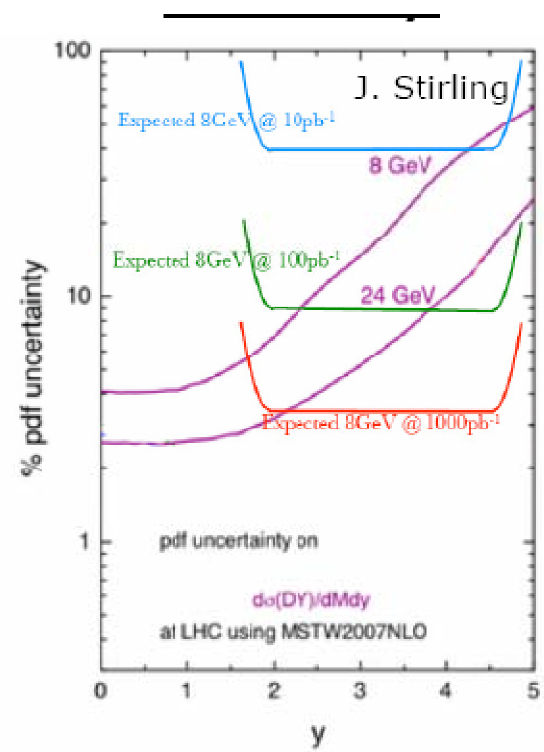




% pdf uncertainty
y
8 GeV
24 GeV
pdf uncertainty on
dσ(W+)/dyw, dσ(W-)/dyw,
dσ(Z)/dyz, dσ(DY)/dMdy
at LHC using MSTW2007NLO



LHC parton kinematics
x1,2 = (M/14 TeV) exp(±y)
Q = M
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
LHCb
LHCb
y = 6 4 2 0 2 4 6
HERA
fixed
target



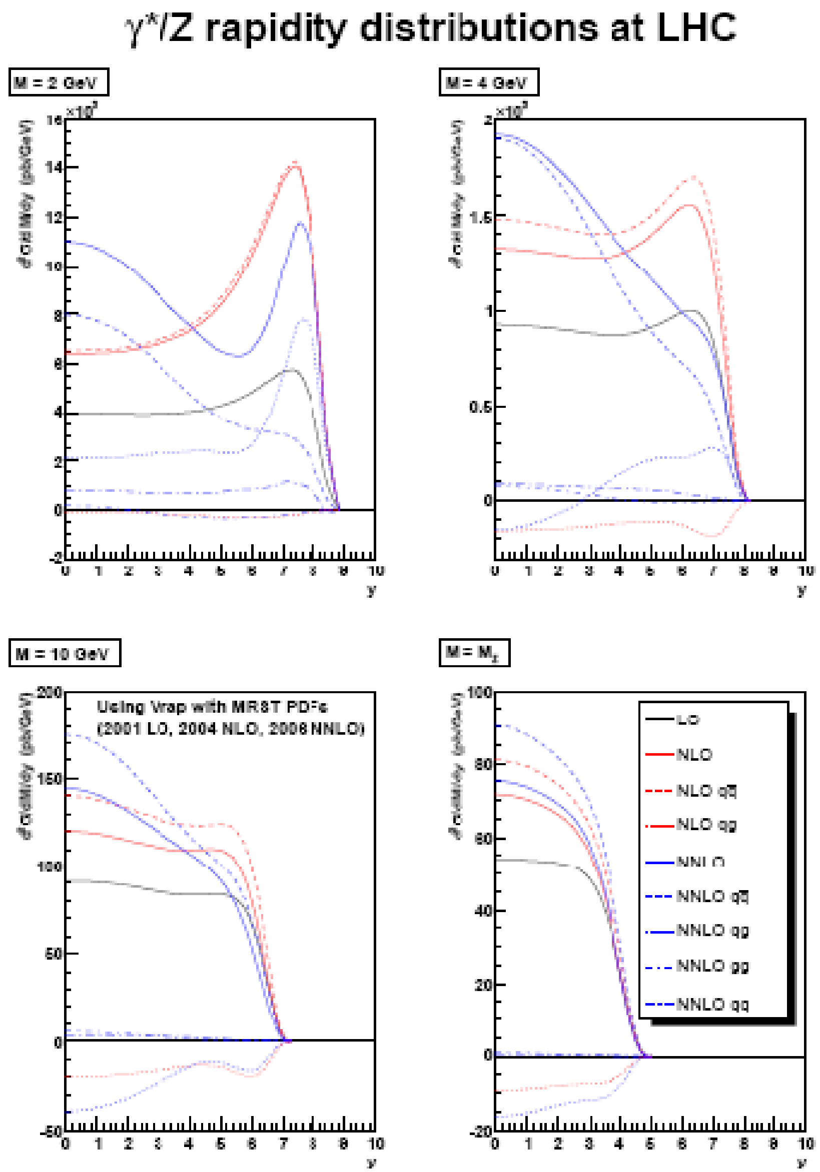
J. Stirling
Expected 8GeV @ 10pb-1
Expected 8GeV @ 100pb-1
Expected 8GeV @ 1000pb-1
8 GeV
24 GeV
% pdf uncertainty
y
pdf uncertainty on
dσ(DY)/dMdy
at LHC using MSTW2007NLO

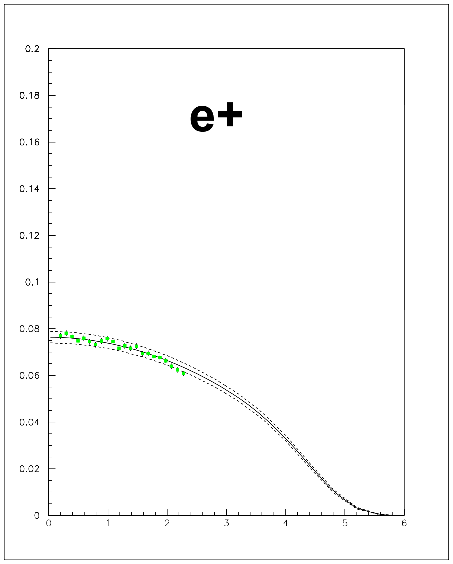
However, this assumes perturbative prediction of Drell-Yan production is reliable.

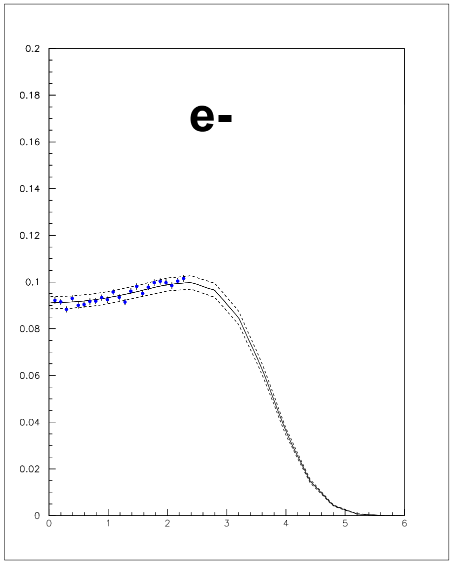
As seen very large change in prediction from order to order, particularly for low M and high y.

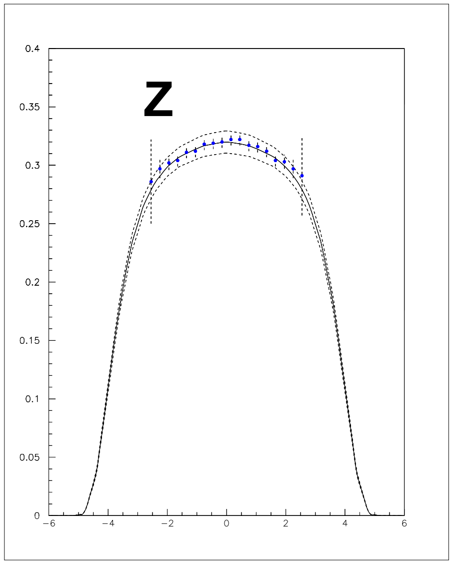
Problem with perturbative stability. Is this due to partons or cross-sections?

Cross-section may be sensitive to resummations (high and low z) at lowest M and highest y. In region where measurements can be made?









In fact I have included e+/e- from W+/W- decay as well as the Z data in the fit

The Z is from CSC muons whereas the e+/e- are from the earlier ATLFAST study (for now).

The plots show only statistical/uncorrelated errors: ~4% for W+/W-

~1% for Z BUT there is also a correlated systematic 4% for the Z data

If you are looking at this in detail beware that the normalisation of the e+/e- plots have a bin width included

W+jets: PDF vs JES Uncertainty

PDF vs Jet Scale Uncertainty (**Δ JS**)

with **10%** (**5%**) jet energy miscal.

(Note: results with tight EF cuts samples)

2.9% < **Δ PDF** < 7.3%

5.8% < **Δ JS** (10%)< 23.6%

3.6% < **Δ JS** (5 %) < 11.9%

↓

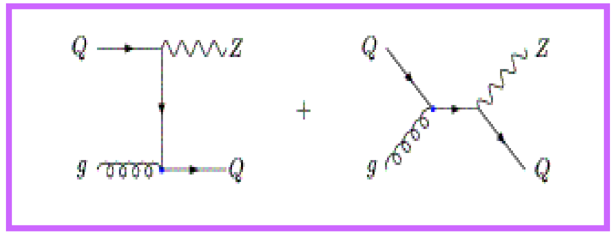
PDF Uncert < Expt. Syst. Uncert

Next: When is JES < PDF Unc?

Try with 1,2,3% jet energy miscal.

Multipl	Δ+ PDF (%)	Δ- PDF (%)	Δ+ JS (%)	Δ- JS (%)
W+ ≥1 jets	3.2	2.9	10.7 (5.2)	10.7 (5.2)
W+ ≥2 jets	3.2	2.9	10.2 (5.1)	10.7 (5.2)
W+ ≥3 jets	3.3	2.9	5.8 (3.6)	9.0 (4.0)
W+ ≥4 jets	5.0	3.9	14.7 (7.8)	15.6 (7.0)
W+ ≥5 jets	5.9	4.8	20.8 (9.5)	20.5 (10.7)
W+ ≥6 jets	7.3	5.9	22.2 (10.4)	23.6 (11.9)

Also studying Z+ b-jet

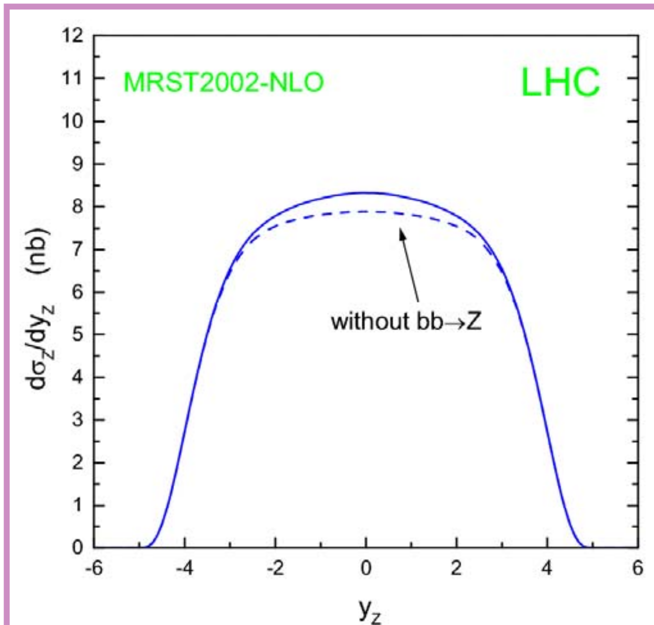


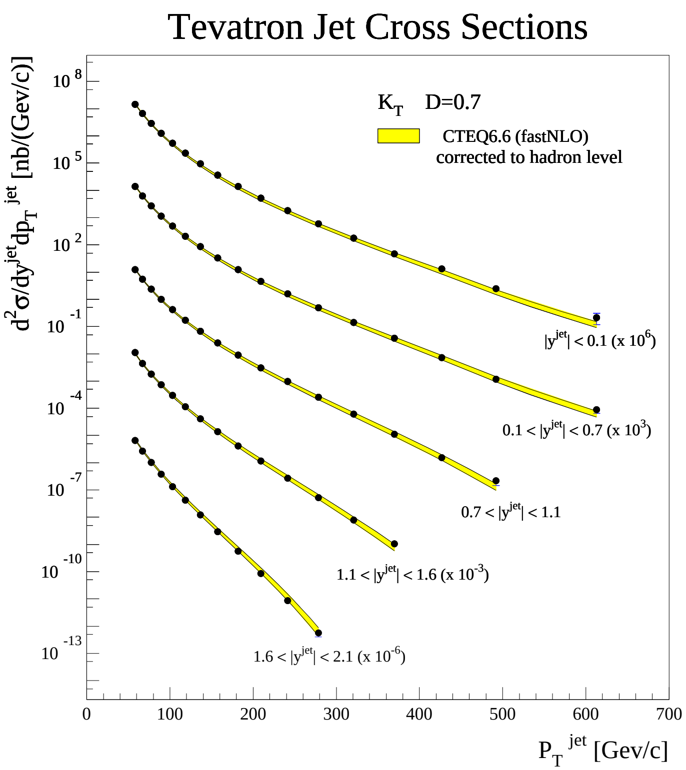
- Measurement of the b-quark PDF
  - Process sensitive to b content of the proton
- Differences in total Z+b cross-section from current PDFs are of the order of 5%

The measurement of Z+b should be more interesting at LHC than at Tevatron:
Signal cross-section larger (x80), and more luminosity
Relative background contribution smaller (x5)

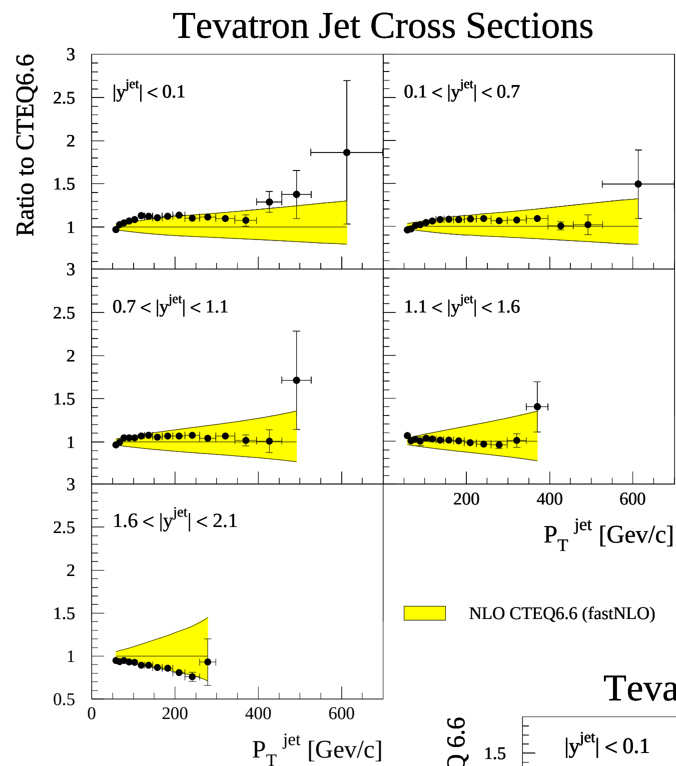
bb->Z @ LHC is ~5% of entire Z production -> Knowing σZ to about 1% requires a b-pdf precision of the order of 20%

Z+b measurement in ATLAS will be possible with **high statistics** and **good purity** of the selected samples with two independent b-tagging methods:

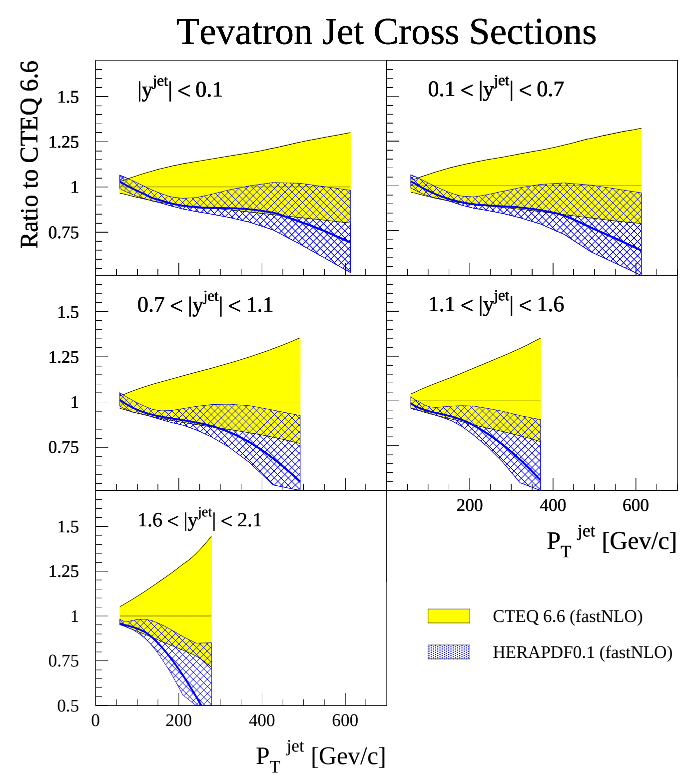




Tevatron Jet Cross Sections
K_T D=0.7
CTEQ6.6 (fastNLO) corrected to hadron level
$d^2\sigma/dy^{jet}dp_T^{jet}$ [nb/(Gev/c)]
$|y^{jet}| < 0.1$ (x 10^6)
$0.1 < |y^{jet}| < 0.7$ (x 10^3)
$0.7 < |y^{jet}| < 1.1$
$1.1 < |y^{jet}| < 1.6$ (x 10^{-3})
$1.6 < |y^{jet}| < 2.1$ (x 10^{-6})
P_T^{jet} [Gev/c]

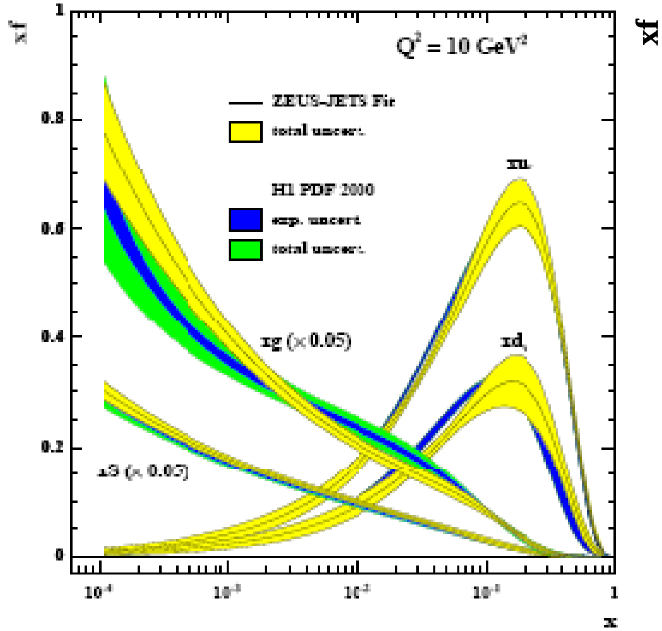


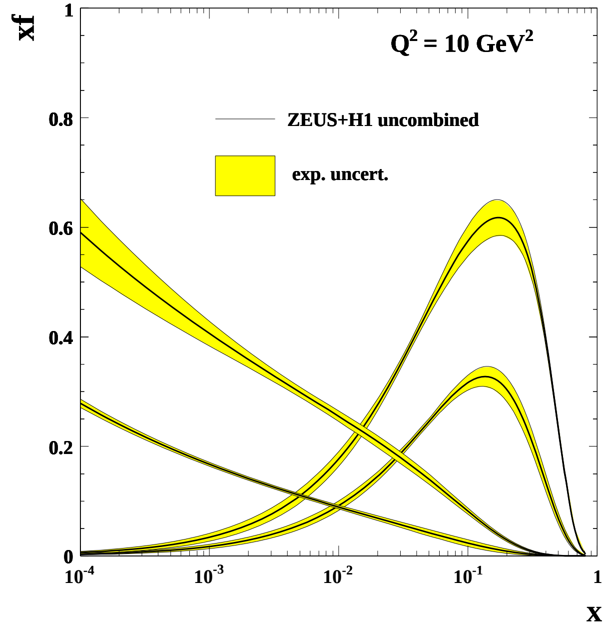
Tevatron Jet Cross Sections
Ratio to CTEQ6.6
$|y^{jet}| < 0.1$
$0.1 < |y^{jet}| < 0.7$
$0.7 < |y^{jet}| < 1.1$
$1.1 < |y^{jet}| < 1.6$
$1.6 < |y^{jet}| < 2.1$
NLO CTEQ6.6 (fastNLO)
P_T^{jet} [Gev/c]

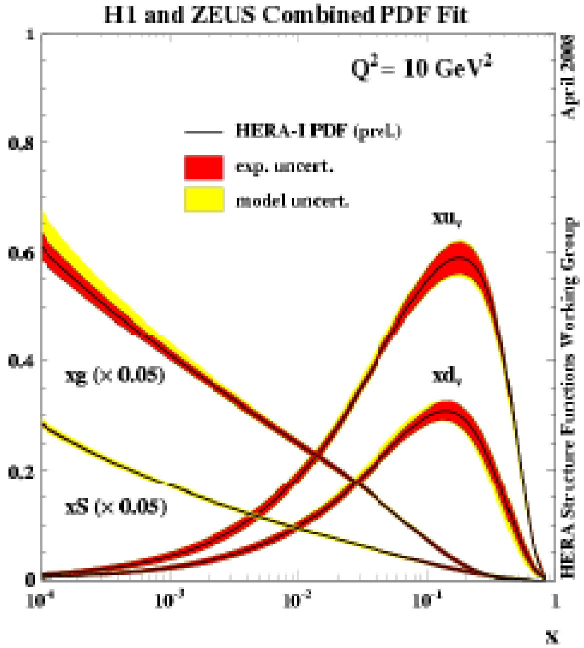


Tevatron Jet Cross Sections
Ratio to CTEQ 6.6
$|y^{jet}| < 0.1$
$0.1 < |y^{jet}| < 0.7$
$0.7 < |y^{jet}| < 1.1$
$1.1 < |y^{jet}| < 1.6$
$1.6 < |y^{jet}| < 2.1$
CTEQ 6.6 (fastNLO)
HERAPDF0.1 (fastNLO)
P_T^{jet} [Gev/c]

does not.







PDFs from separate QCD analyses of separate ZEUS and H1 data

PDFs from same QCD analysis of separate ZEUS and H1 data sets - before 'smart' combination

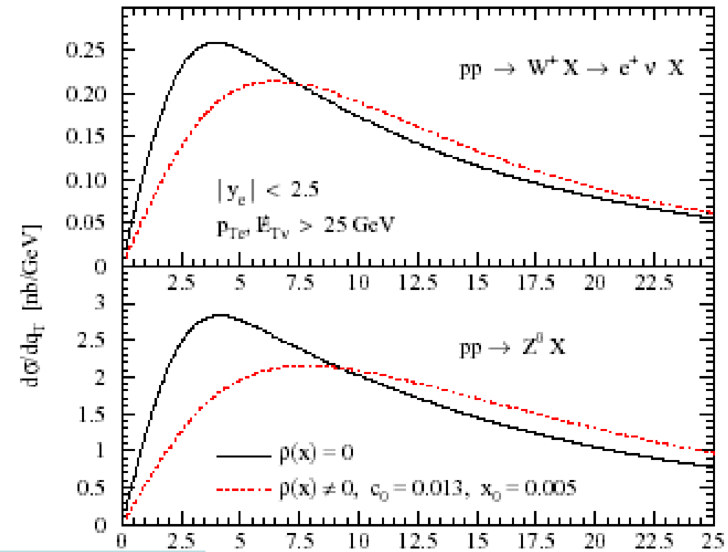
Experimental error only

PDFs from same QCD analysis of combined HERA data - after 'smart' combination

HERAPDF0.1 has small experimental errors and modest model errors

But the TOY PDFs are unlikely to be realistic - a better way could be to look at pt spectra for W and Z production

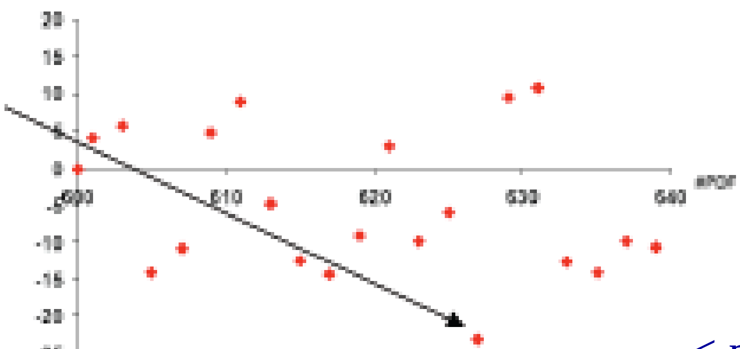
Lack of pt ordering at low-x is a further consequence BFKL resummation AND most non-linear treatments. This would affect the pt spectra for W and Z production at the LHC (See hep-ph/0508215)



Conventional

Unconventional

Pt spectra are also used to measure M_W -- dM_W from PDF uncertainties, using pt(e), is ~20 MeV

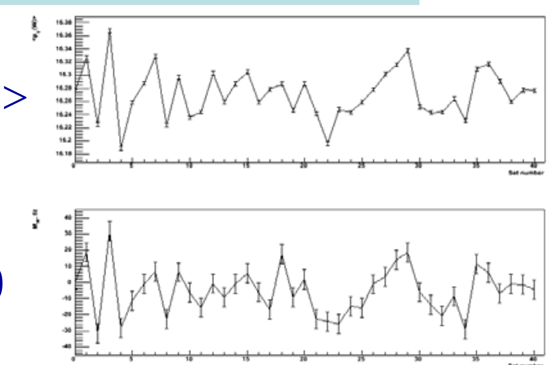


Note largest shift ~25 MeV

So we'd better be sure we've got the calculations for Pt spectra right

$< p_T(W) >$

$\delta M_W(\text{fit})$



Same pattern