PDF uncertainties and LHC physics

-using ATLAS examples

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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.

HIGGS

BEYOND STANDARD MODEL

- Z' channels
- 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
- Other ways to get at high-x gluon?

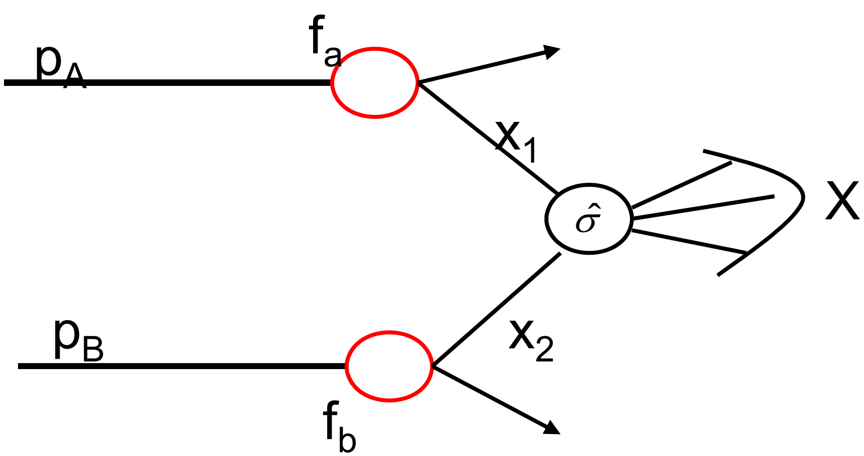
The Standard Model is not as well known as you might think

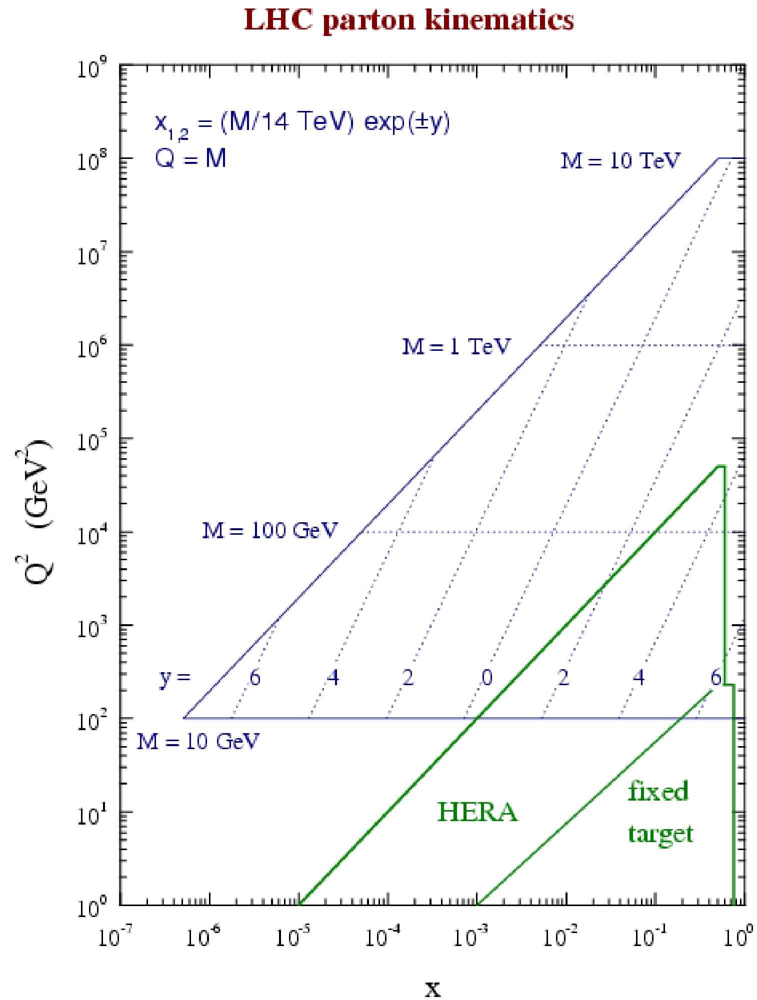
In the QCD sector the PDFs limit our knowledge - transport PDFs to hadron-hadron cross-sections using QCD factorization theorem for short-distance inclusive processes

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) \, f_b(x_2, \mu_F^2)$$
$$\times \quad \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

where X=W, Z, D-Y, H, high-E_T jets, prompt-γ
and σ is known

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





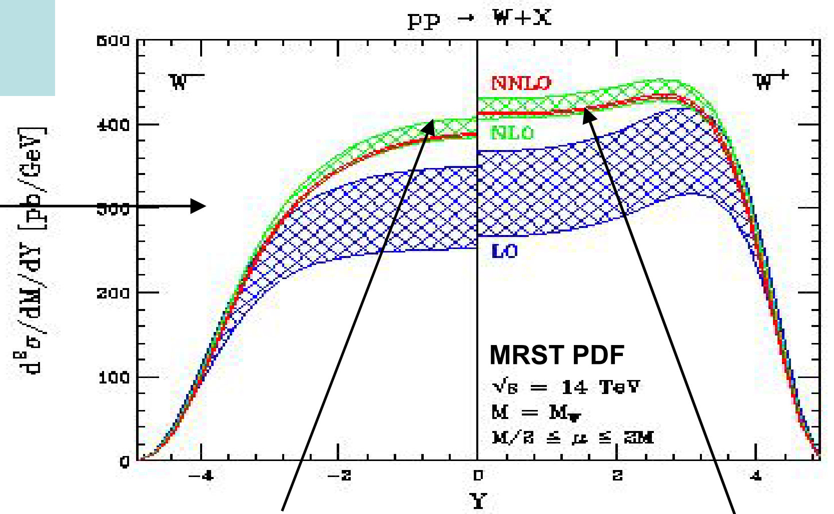
The central rapidity range for W/Z production AT LHC is at low-x

(6×10^{-4} to 6×10^{-2}) at 14 TeV

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

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 uncertainties ~3-4%

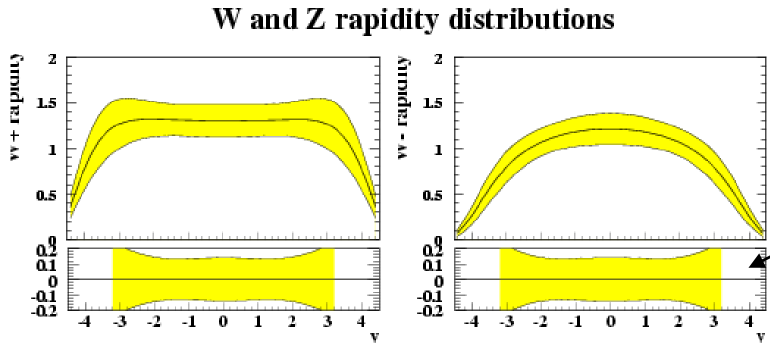
W Z cross-sections at 10 TeV

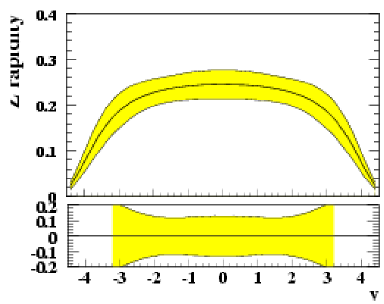
PDF set	$\sigma_{W+} B_{W\to l\nu}$ (nb)	$\sigma_{W-} B_{W\to l\nu}$ (nb)	$\sigma_{Z} B_{Z\to ll}$ (nb)
ZEUS-2005	8.51±0.30	6.08±0.20	1.36±0.04
MSTW08	8.55±0.25	6.25±0.20	1.38±0.04
CTEQ66	8.77±0.30	6.22±0.23	1.40±0.044
HERAPDF02	**8.69±0.07** **±0.16±0.16**	**6.31±0.04** **±0.13±0.13**	**1.40±0.01** **±0.03 ±0.02**

Agreement between PDFs has improved in recent years –only consider those which include massive heavy quark treatment.
Can be used as a luminosity monitor?

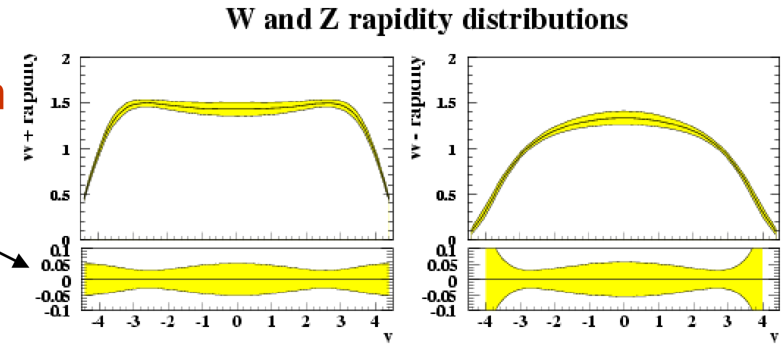
10 TeV cross-sections are ~70% of 14 TeV cross-sections- there will still be millions of events

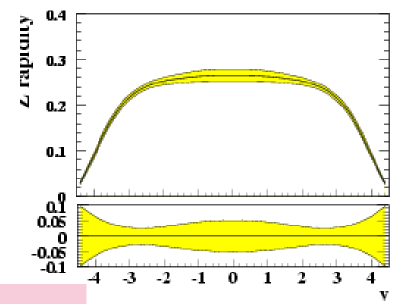
WHY DO WE KNOW IT SO WELL? BECAUSE OF HERA.
Look in detail at predictions for W/Z rapidity distributions: Pre- and Post-HERA





Note difference in scale for fractional errors





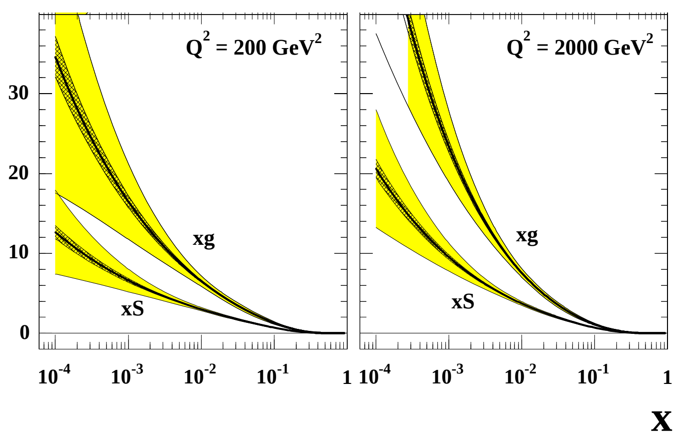
Pre HERA

~15% errors

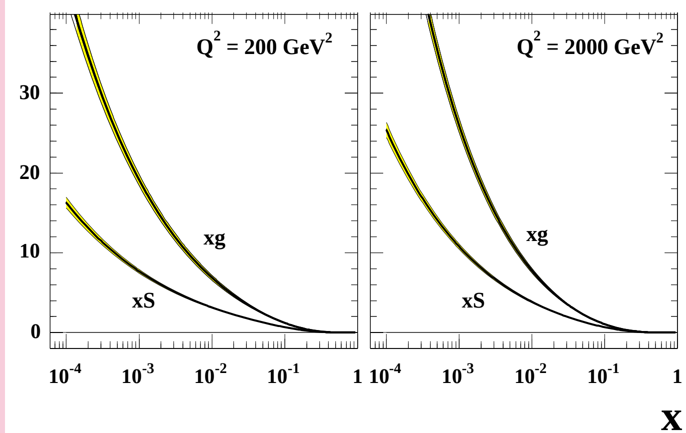
Why such an improvement ?

Post HERA

-including ZEUS data ~5% errors



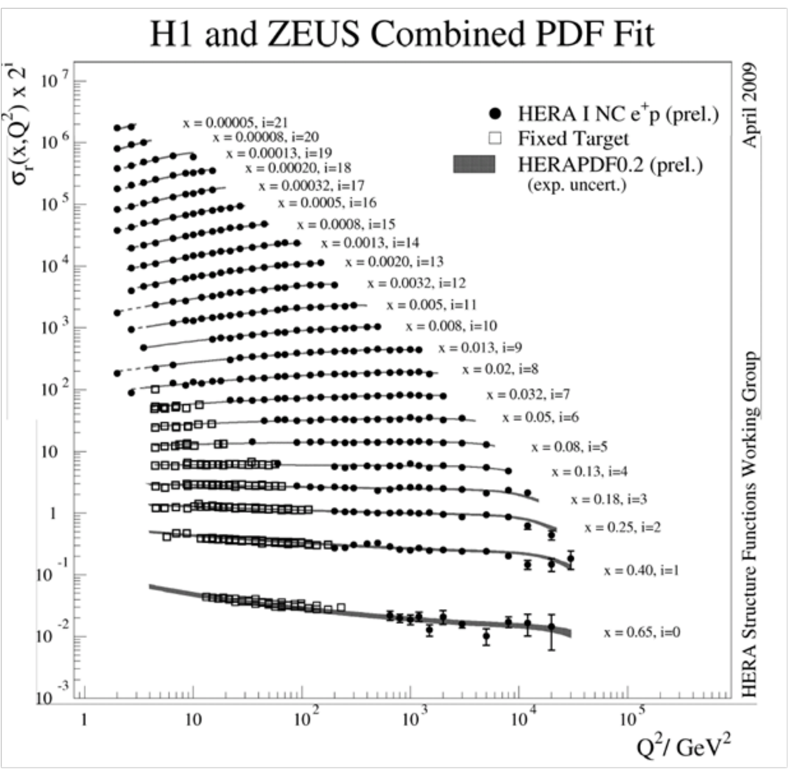
It's due to the improvement in the low-x sea and gluon
At the LHC the q-qbar which make the boson are mostly sea-sea partons
And at $Q^2 \sim M_Z^2$ **the sea is driven by the gluon**



Recently this has improved dramatically due to the combination of ZEUS and H1 data sets

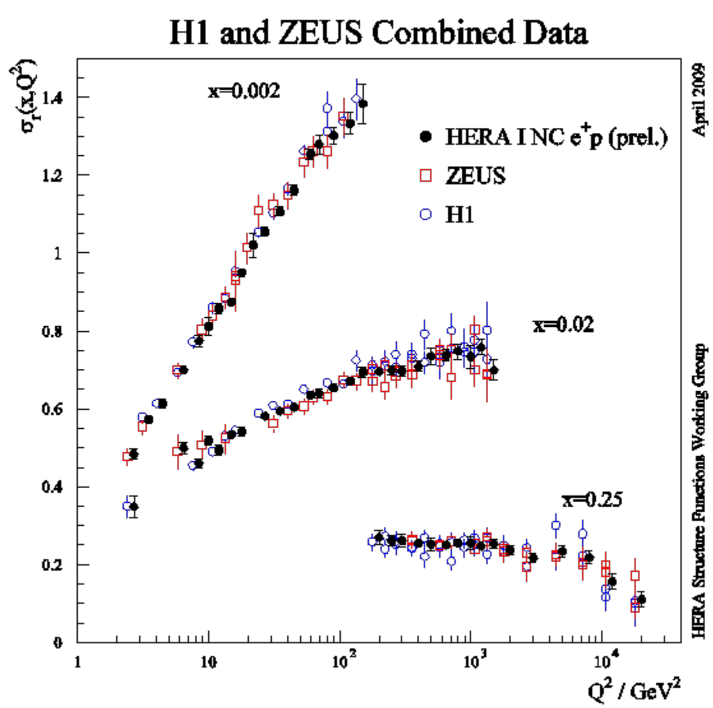
Not just statistical improvement. Each experiment can be used to calibrate the other since they have rather different sources of experimental systematics

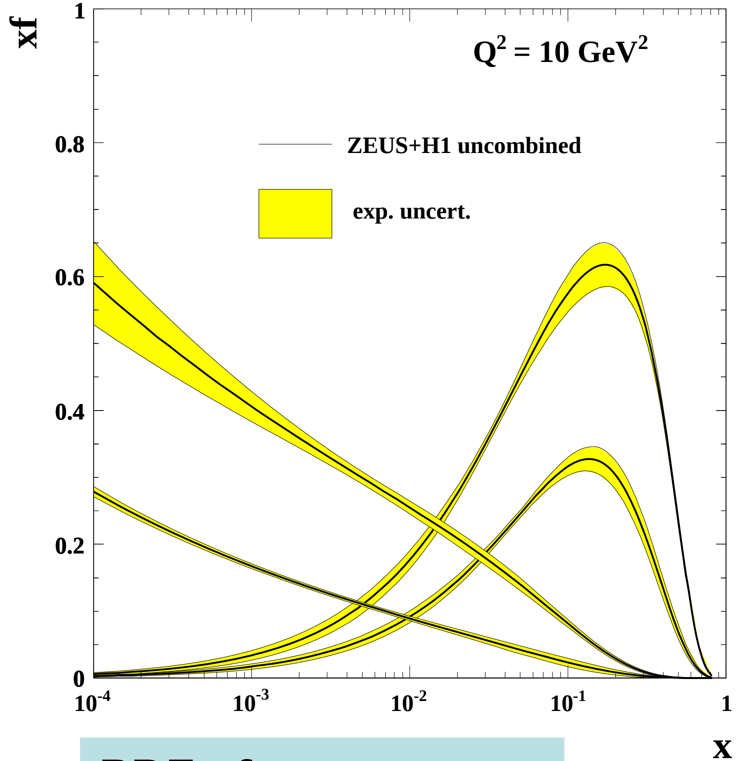
- Before combination the systematic errors are ~3 times the statistical for Q2< 100
- After combination systematic errors are < statistical
- → very consistent HERA data set can be used as sole input to PDF fits with Δχ2=1

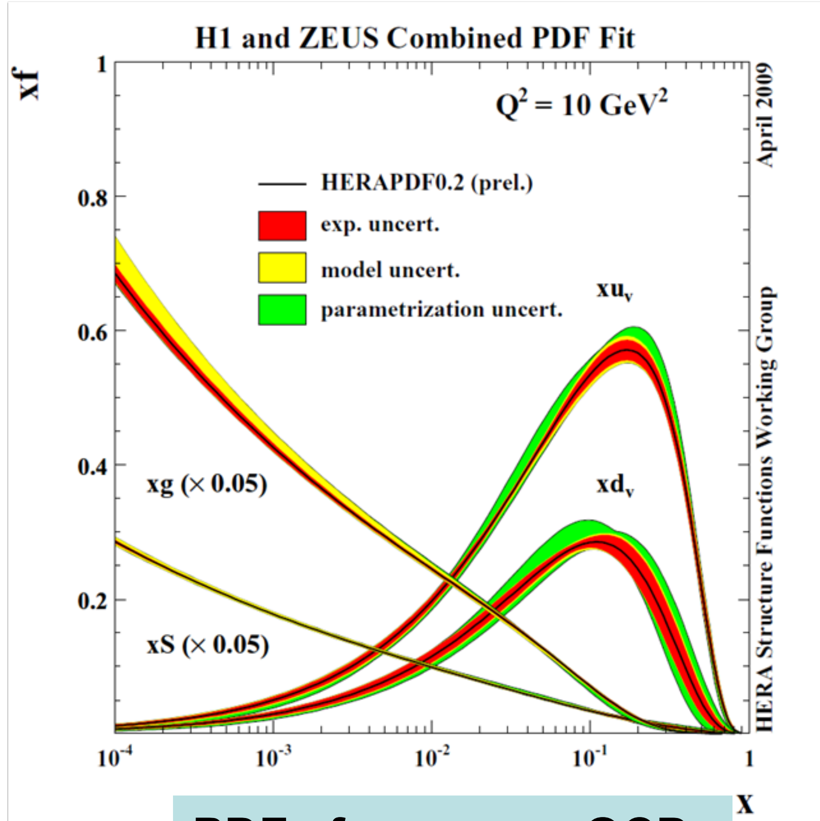


HERAPDF0.2
2009

also has new and very precise H1 data sets included







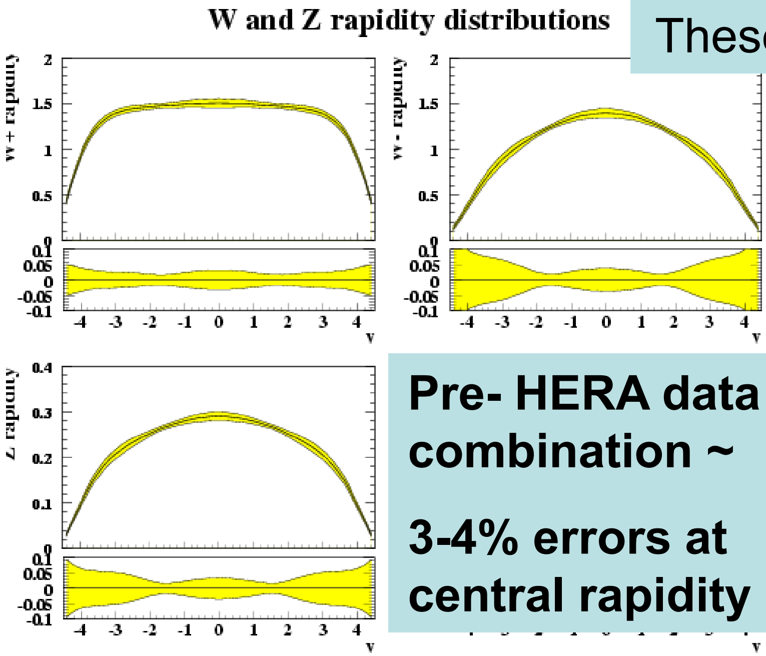
PDFs from same QCD analysis of separate ZEUS and H1 data sets - before combination

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

Experimental error only

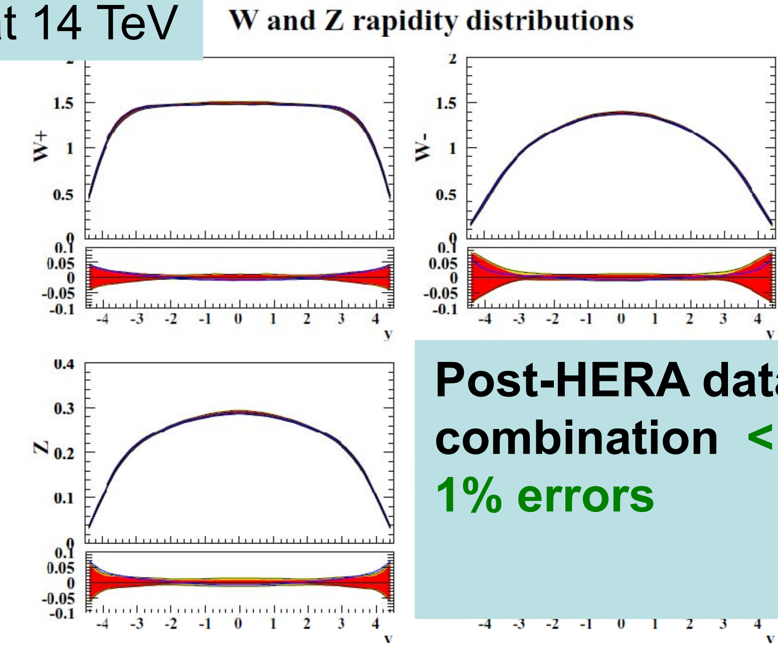
Compare experimental errors

These illustrations at 14 TeV



Pre- HERA data combination ~

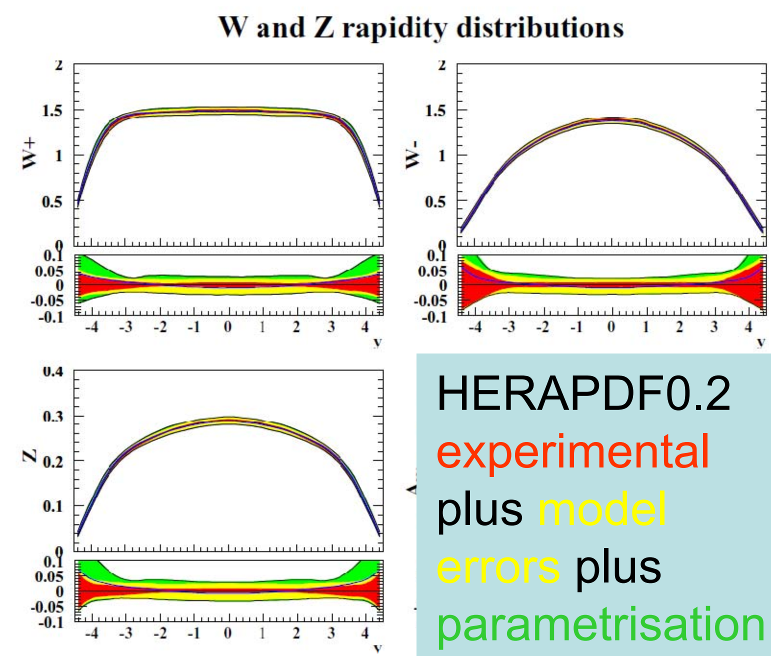
3-4% errors at central rapidity



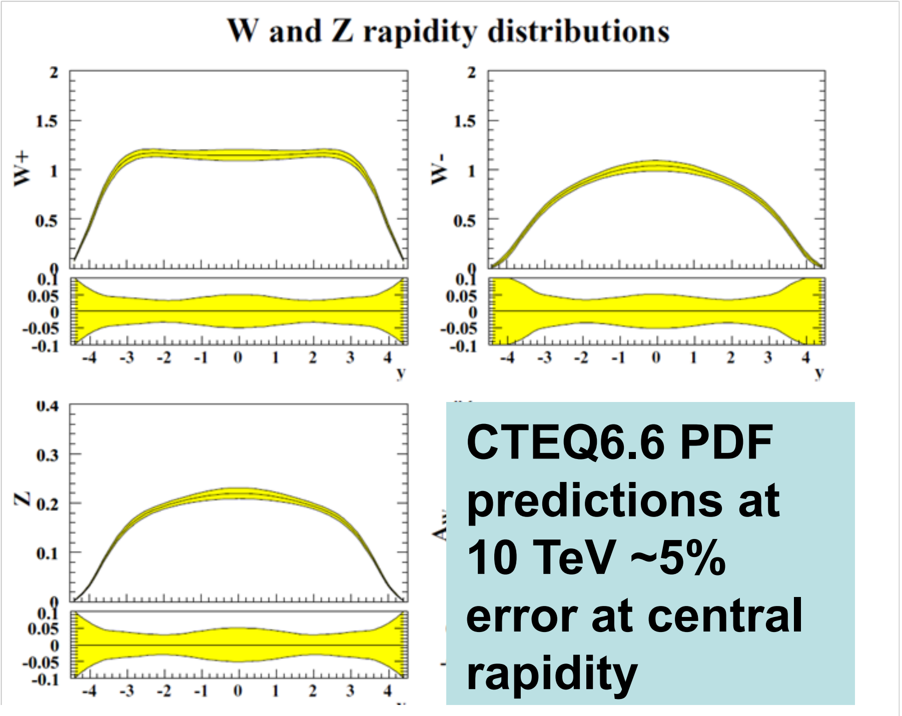
Post-HERA data combination < **1% errors**

Using the HERA combined data (2008) and then improving the HERA combined data (2009) leads to smaller and smaller experimental uncertainties on the predictions for W/Z production at central rapidity, because the HERA data improve the low-x sea and gluon PDFs

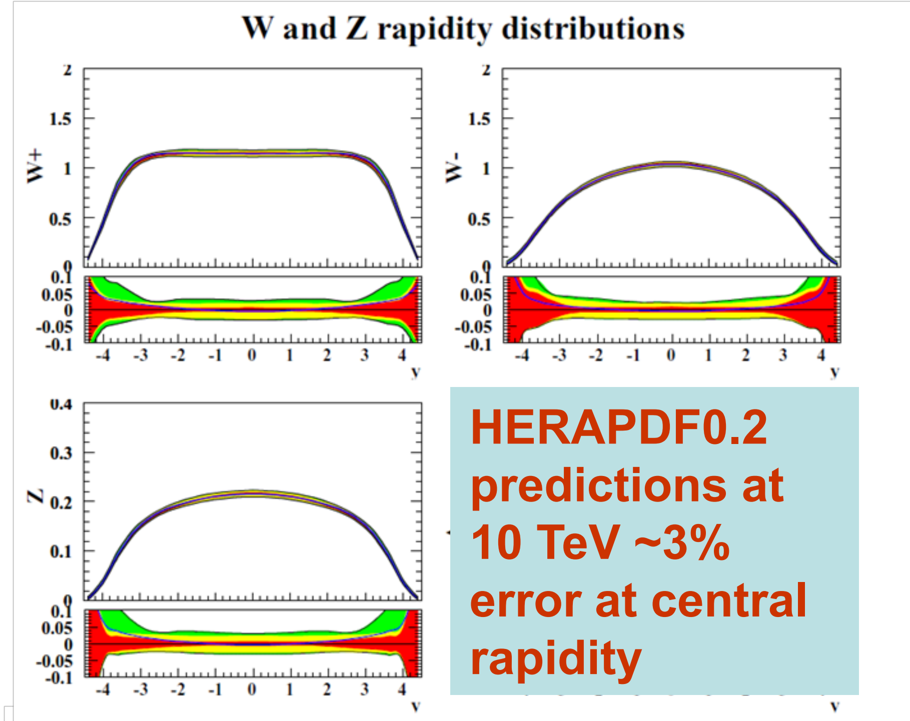
However PDF fitting should also include consideration of model errors and parametrisation errors



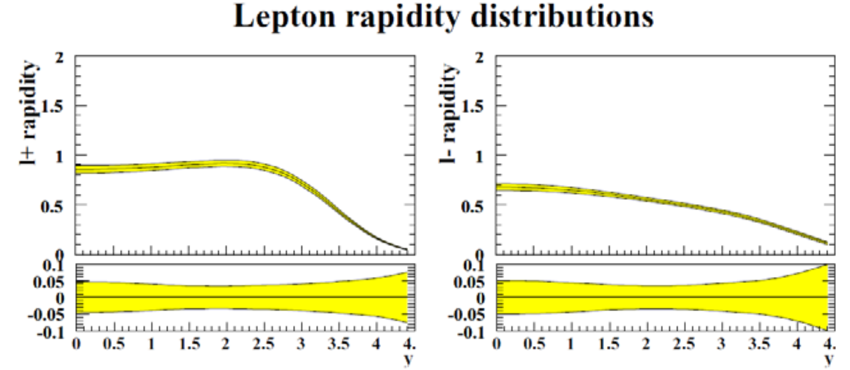
HERAPDF0.2 experimental plus model errors plus parametrisation

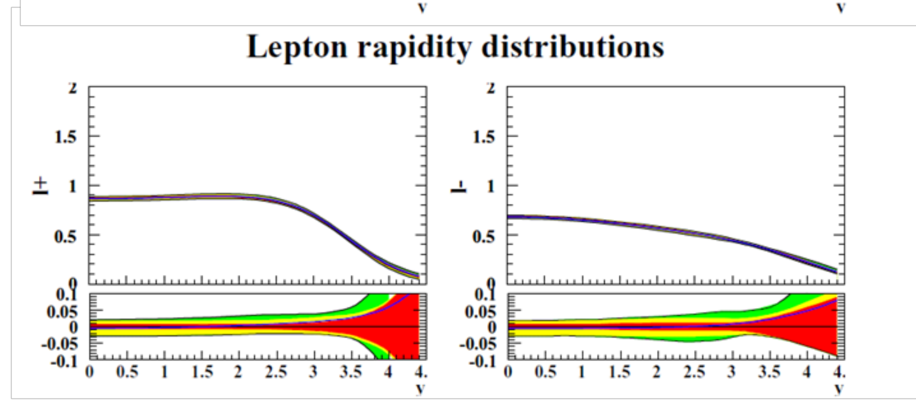


CTEQ6.6 PDF predictions at 10 TeV ~5% error at central rapidity



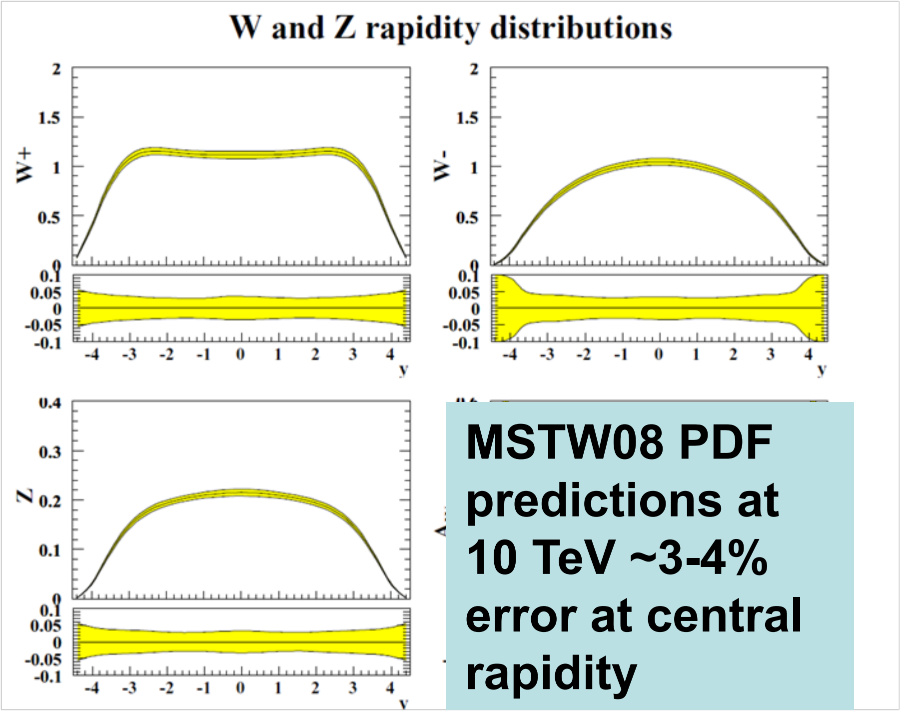
HERAPDF0.2 predictions at 10 TeV ~3% error at central rapidity



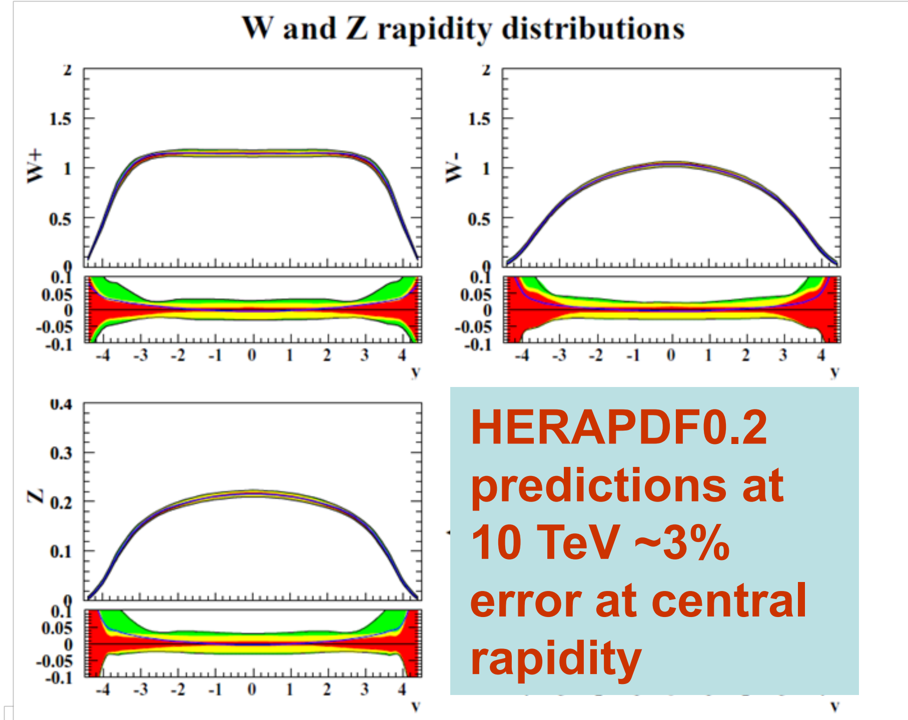


Now go to 10 TeV and compare to CTEQ66, including lepton decay distributions

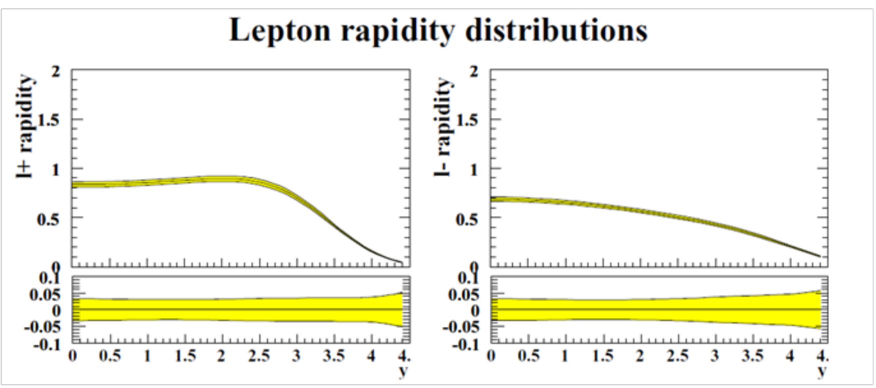
Note blue line on HERAPDF plots from variation of $\alpha_s(M_Z)$=0.1176 (standard) up to 0.1196

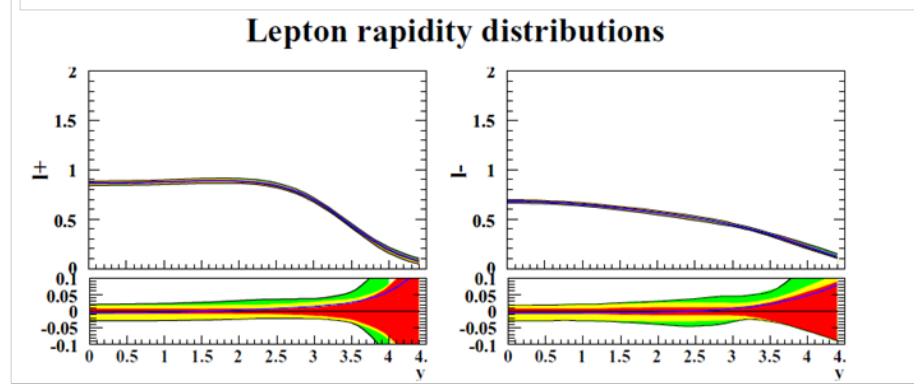


MSTW08 PDF predictions at 10 TeV ~3-4% error at central rapidity



HERAPDF0.2 predictions at 10 TeV ~3% error at central rapidity

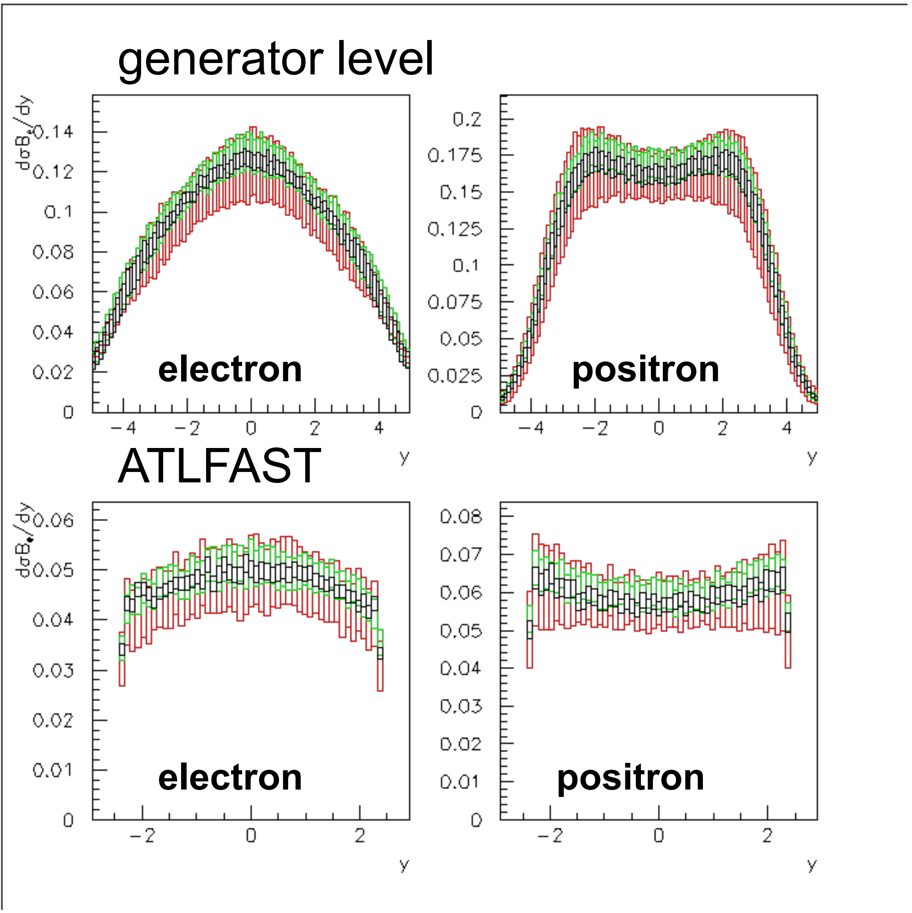




Now go to 10 TeV and compare to MSTW08, including lepton decay distributions

There is still potential for PDF predictions to improve before LHC

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

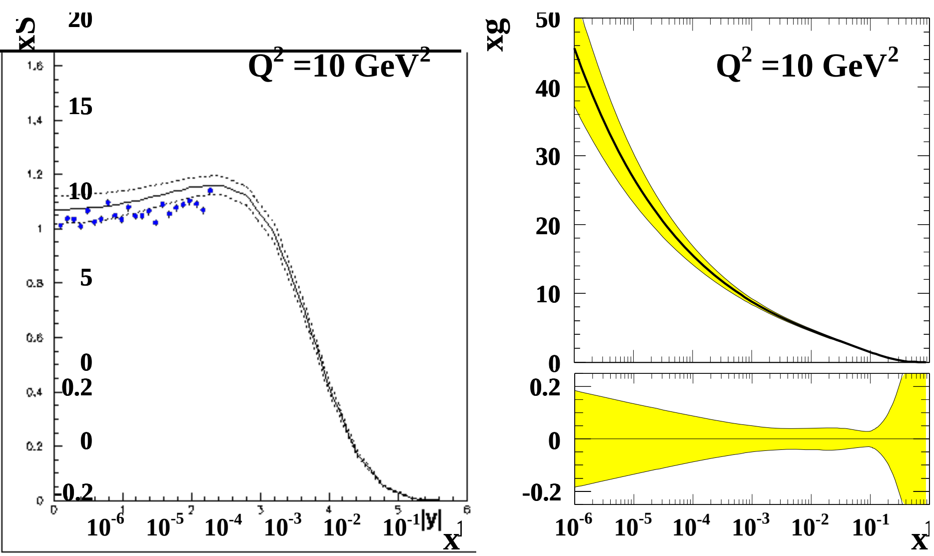
To improve the situation we NEED to be more accurate than this:**~4%**
Statistics are no problem there will be millions of W's
We need to control the systematic uncertainty

AMCS + A Tricoli

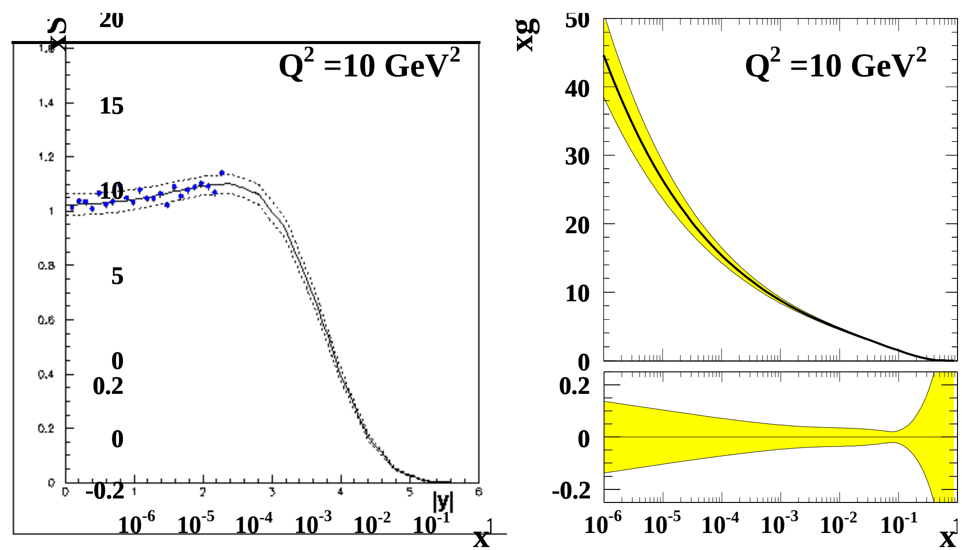
Can we improve the situation with early LHC data?

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

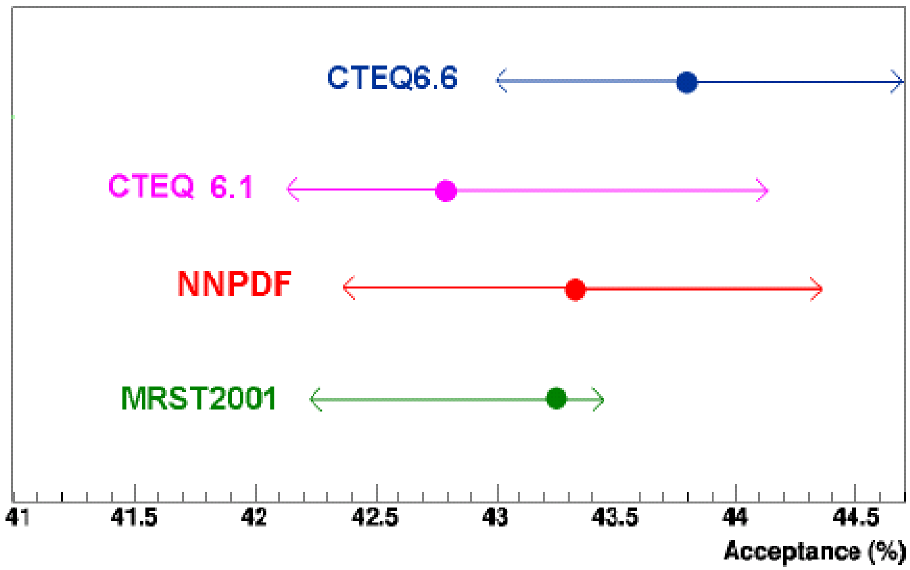
Gluon PDF uncertainties are reduced

IS achieving a 4% systematic possible? And how soon?

After the first fb-1 Δσ will be dominated by acceptance uncertainty

Dependence of ATLAS acceptance for Z on PDFs

Study done in the muon channel: pt > 20 GeV, η < 2.5

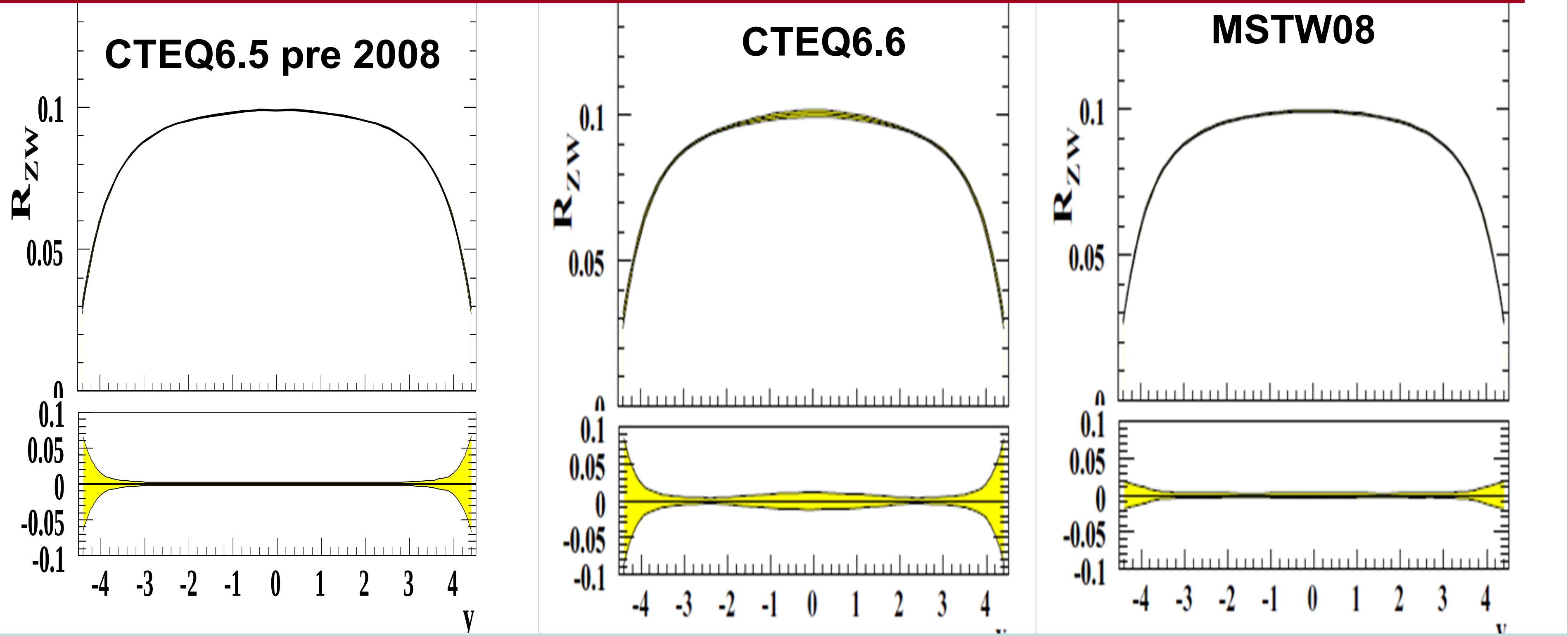


Difference in acceptance between CTEQ6.6 to 6.1 only 2% ---whereas there is a 6% difference in cross-section predictions

Seems possible to achieve < 2% systematic on acceptance when considering up to date PDf sets which differ by only 3% in xsecn predictions.

M Venturi

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



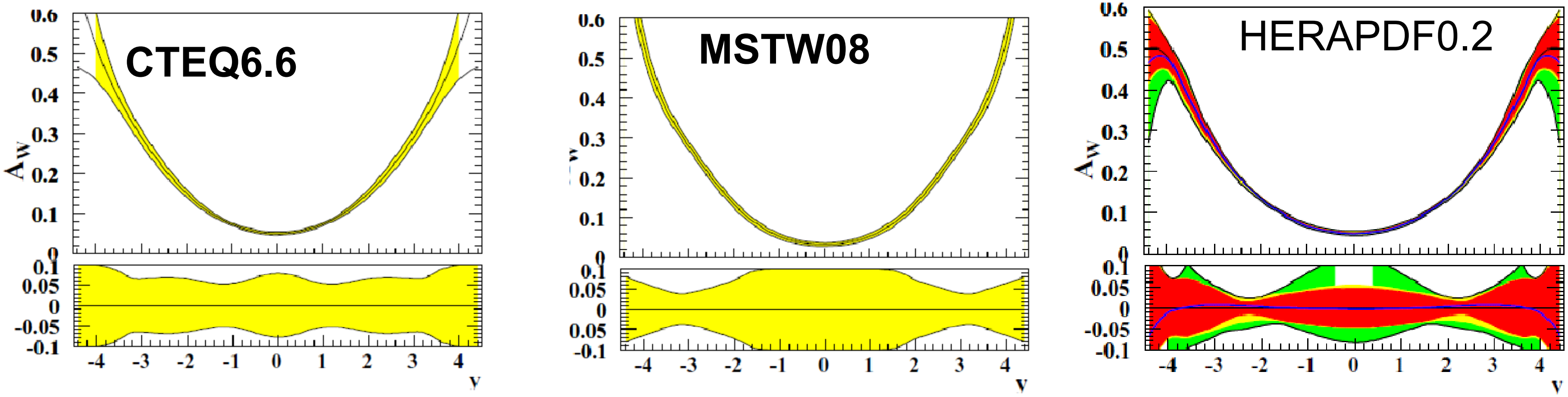
ZOOM in on Z/W ratio – **there is fantastic agreement between PDF providers**
PDF uncertainty from the low-x gluon and flavour symmetric sea cancels out- **and so do luminosity errors** BUT there is somewhat more PDF uncertainty than we thought before 2008 (~1.5% rather than <1% in the central region)

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

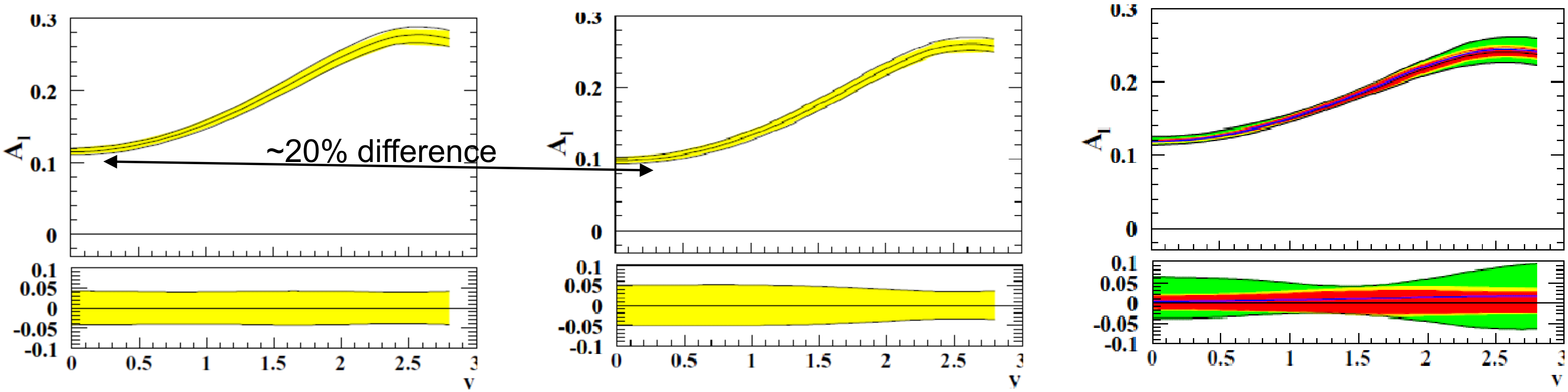
$$\frac{Z}{W^+ + W^-} = \frac{\text{uubar + ddbar + ssbar +ccbar +bbar}}{\sim \text{(udbar + csbar) + (dubar+scbar)}}$$

YES this does translate to the Z/lepton ratio

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



Lepton asymmetry



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 $A_W = \frac{u(x_1)\,\bar{d}(x_2) - d(x_1)\,\bar{u}(x_2)}{u(x_1)\,\bar{d}(x_2) + d(x_1)\,\bar{u}(x_2)}$

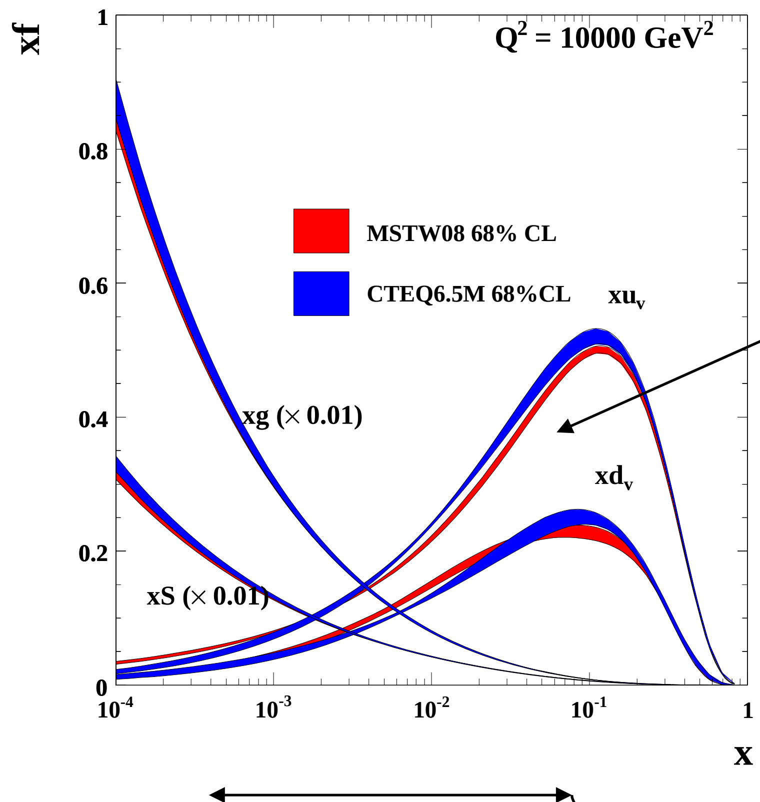
Predictions for AW are different in the central region- because predictions for valence distributions at small-x are different

And at central rapidity $x_1 = x_2$

and ubar ~ dbar ~ qbar at small x

So $A_W \sim \frac{(u - d)}{(u + d)} = \frac{(u_v - d_v)}{(u_v + d_v + 2\,\bar{q})}$

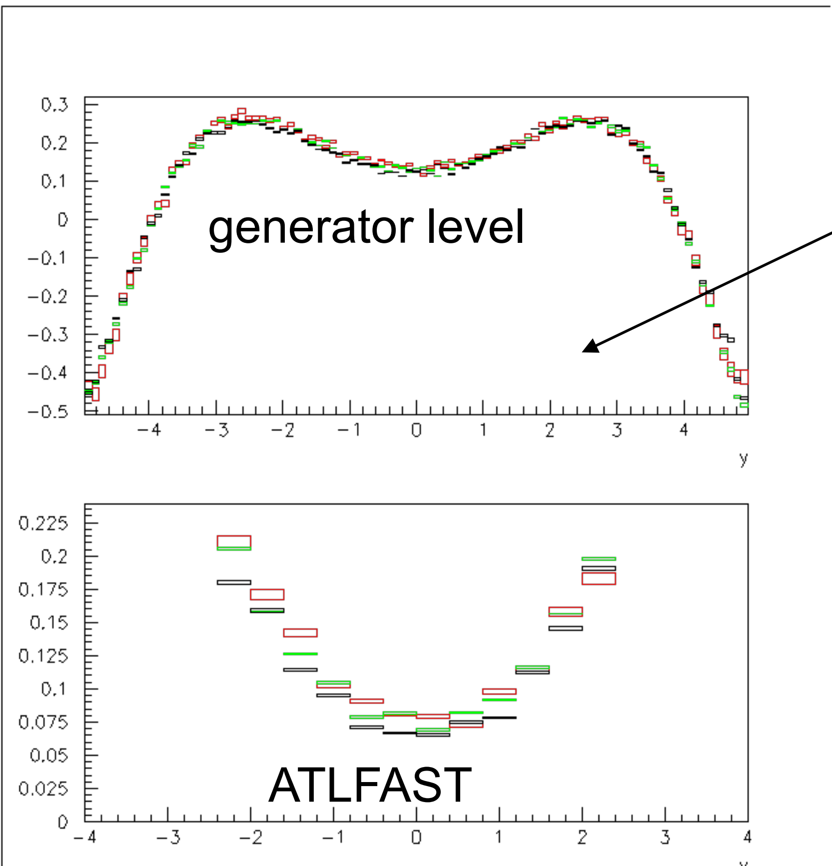
Actually this LO approx. is pretty good even quantitatively
The difference in valence PDFs you see here does explain the difference in A_W between MRST and CTEQ



As we move away from central rapidity: as x_1 increases (decreases) the larger (smaller) difference is weighted by larger (smaller) sea distributions at smaller x_2

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

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



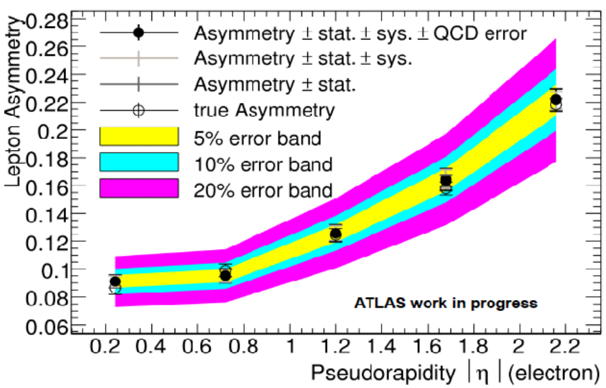
AMCS + A Tricoli

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

Recent study with full detector simulation AND QCD di-jet background estimation

W Asymmetry: Prospects for $100pb^{-1}$ data

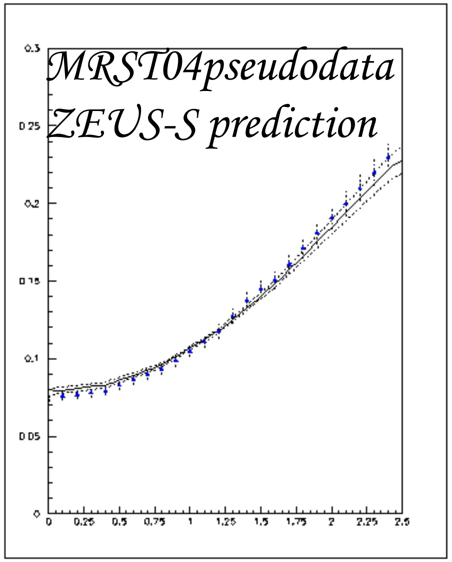


- 47 ± 12 % QCD background assumed (25% uncertainty)
- combined +/- η (weighted with errors)

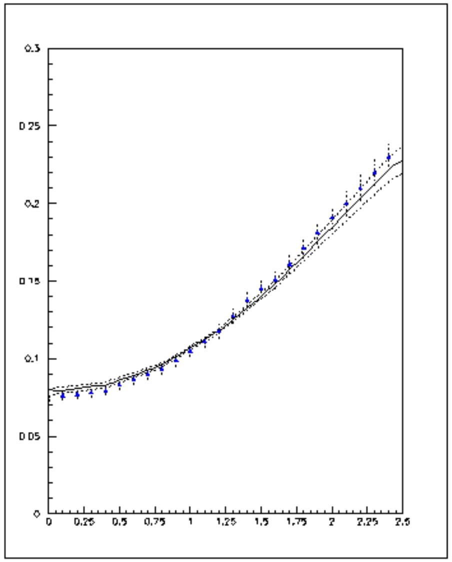
5-10% uncertainty K Lohwasser

So be optimistic and 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)

BEFORE including A_e pseudo-data



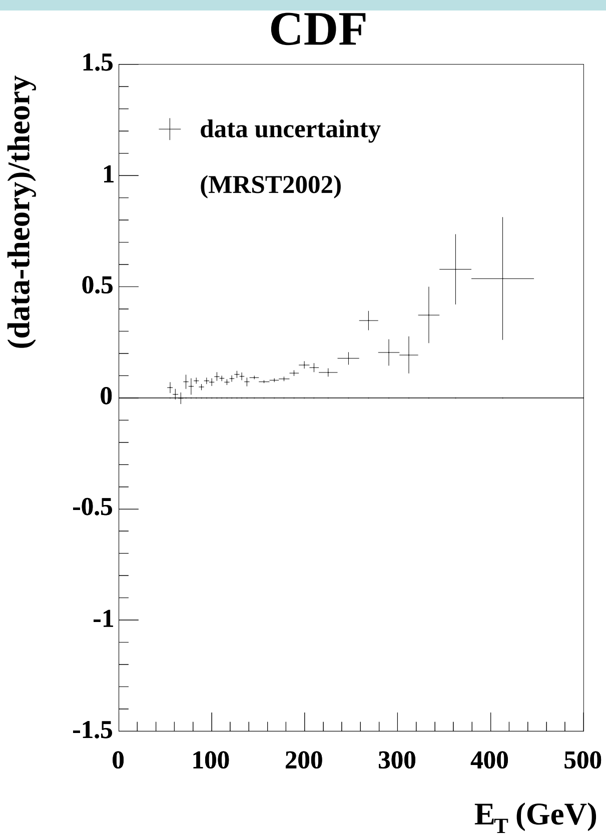
AFTER including A_e pseudo-data



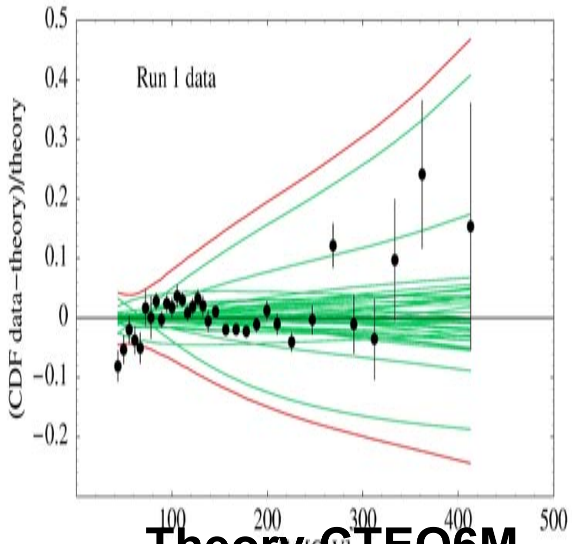
Result is improved accuracy of and change of shape of the valence PDFs

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

WHAT DO WE NOT KNOW WELL?



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



Theory CTEQ6M

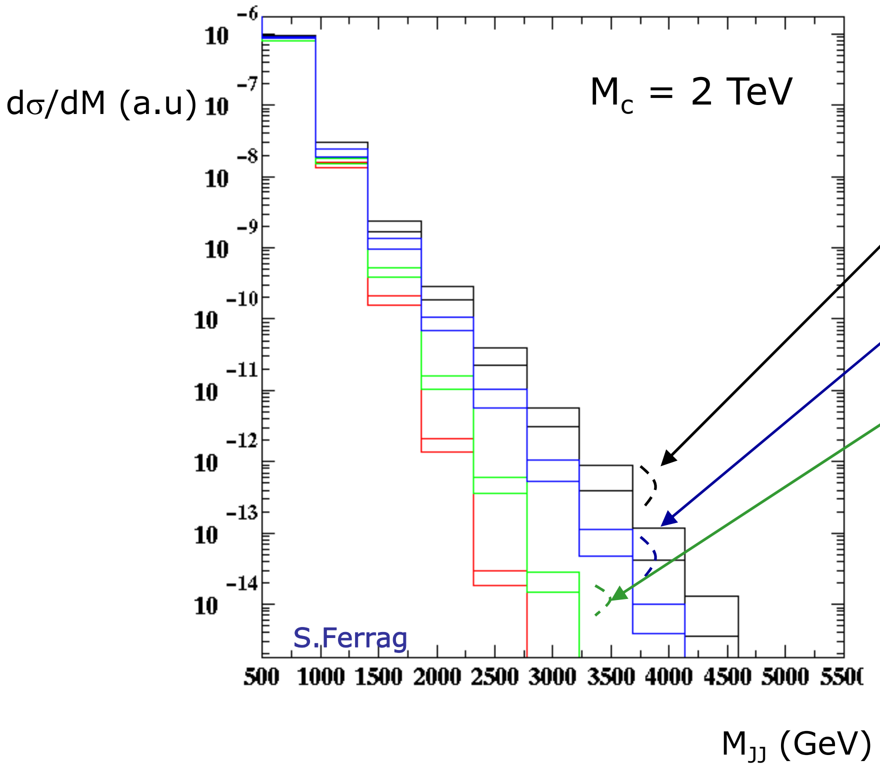
i

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

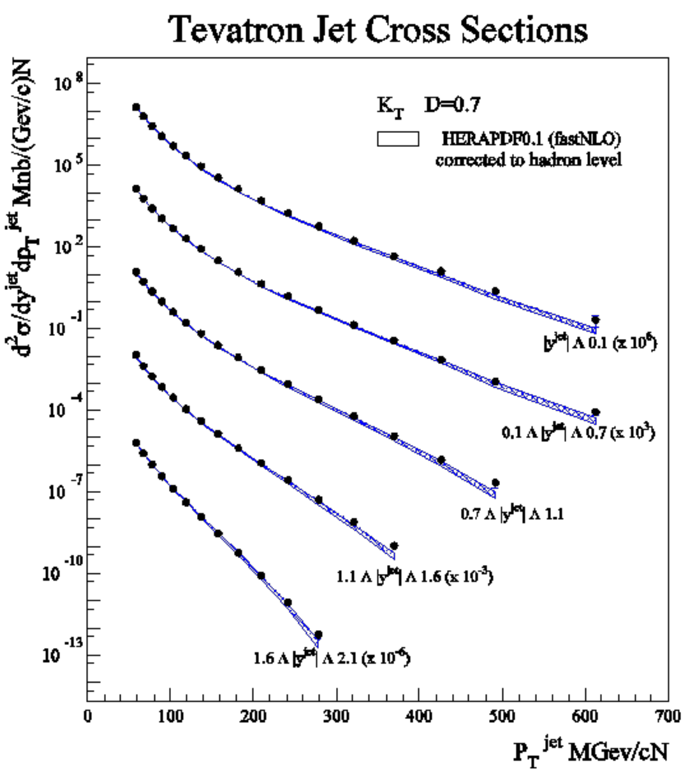
2XD + structure function uncertainty band

4XD + structure function uncertainty band

→Enough to lose sensitivity to higher compactification scales

S. Ferrag + A Djouadi

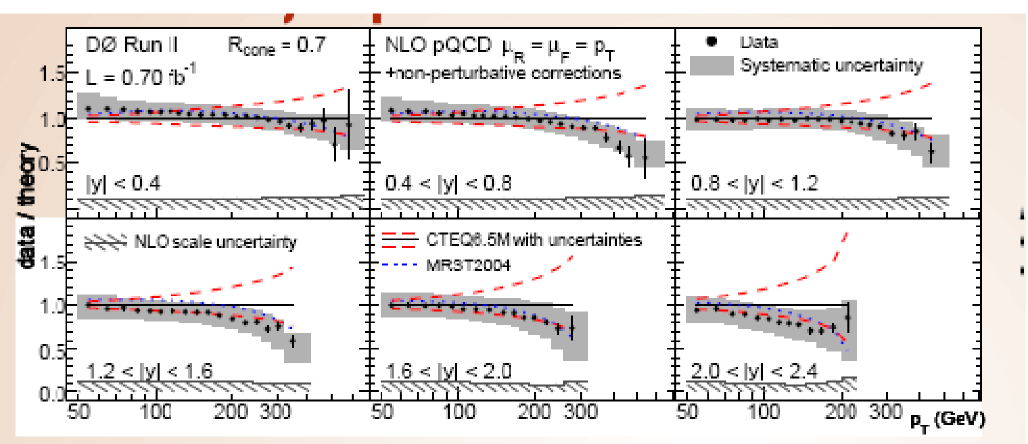
CDF Run-II jet data compared to HERAPDF0.1



Note there is now new Tevatron Run-II jet data

Has been used in MSTW08 PDFs

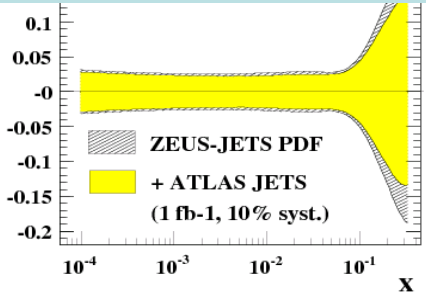
It does not make MUCH difference to the level of high-x gluon PDF uncertainty



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

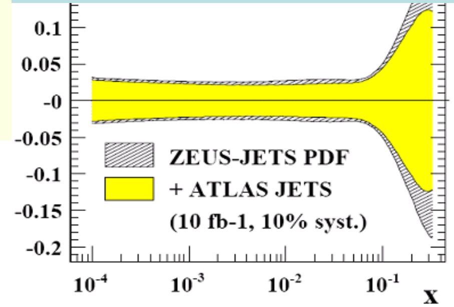
(CTEQ6.5 fitted Run-I)

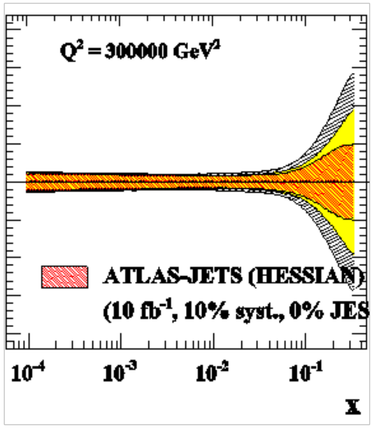
And will we be able to use LHC data itself to improve the situation?- study of impact on gluon PDF uncertainties from including ATLAS pseudodata in PDF fit



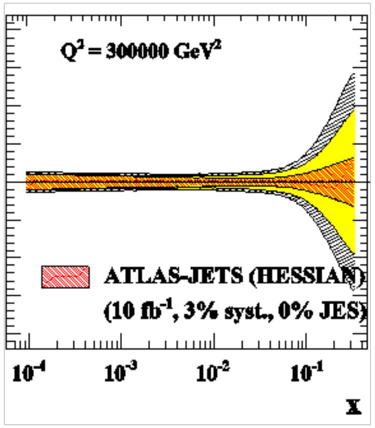
Use data at higher η > 1 and lower pt < 3TeV to avoid new physics!

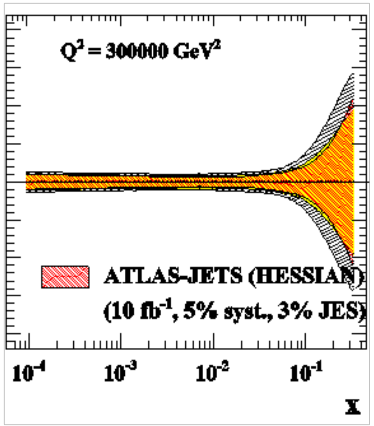
Impact of increasing statistics





Impact of decreasing experimental systematic uncertainty

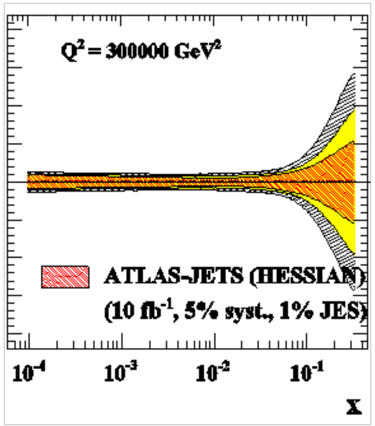




Impact of decreasing experimental correlated systematic uncertainty

Challenging!

Can we decrease Jet Energy Scale systematic to 1%?



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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%)

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%

↓

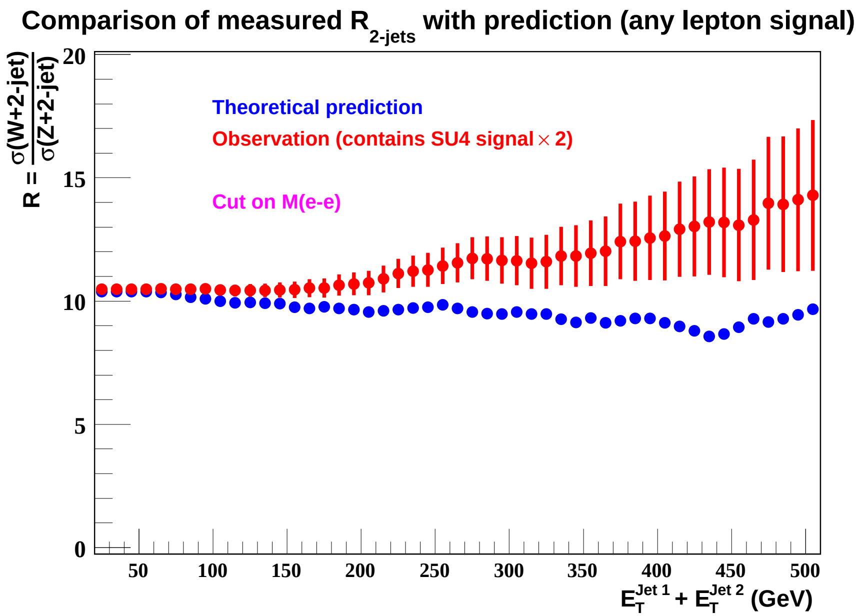
PDF Uncert < Expt. Syst. Uncert

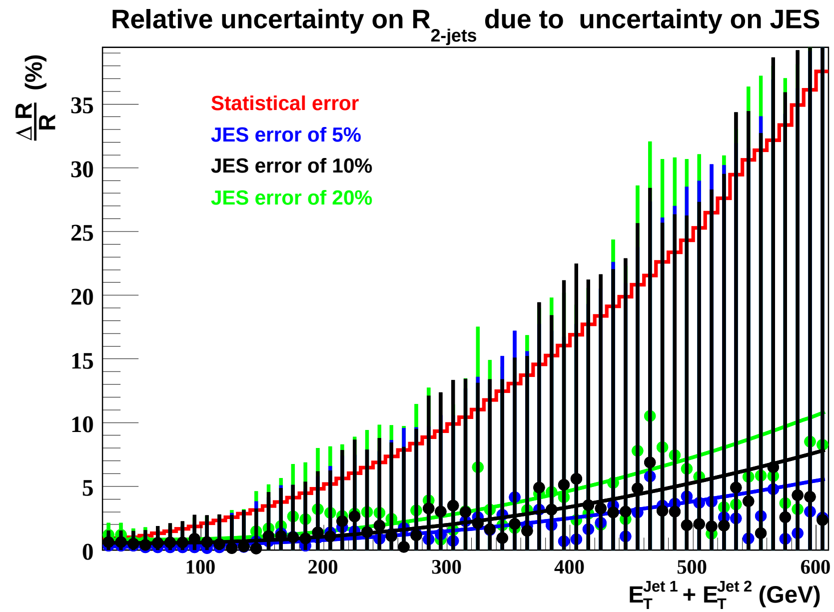
Next: When is JES < PDF Unc?
Try with 1,2,3% jet energy miscal.

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)

M Fiascaris

However BSM signals can show up in the R=(W+n jet) / (Z+n jet) ratio and the jet energy scale is less of a problem in the ratio



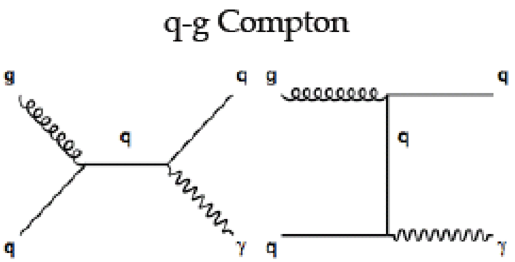


Illustrated is MSugra SU(4) compared to Standard Model for 200pb^{-1} of data in the W/Z +2 jets channel

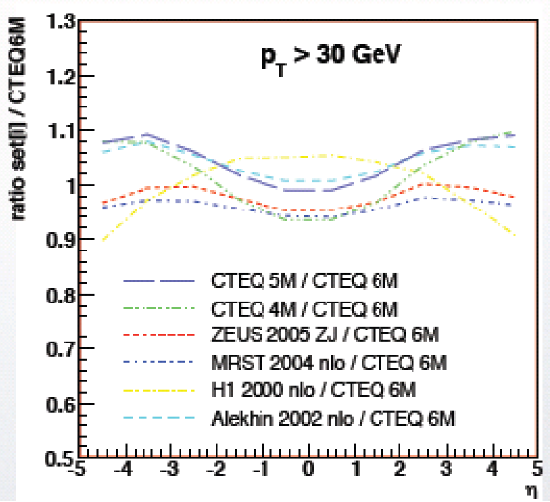
JES of 5% gives < 5% uncertainty on the ratio –very much less than the statistical error

H Beauchemin

Other ways of getting at high-x gluon – direct photon production?



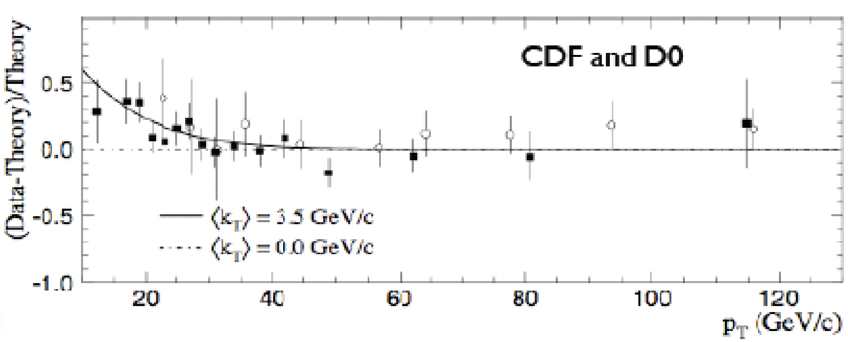
Cross-sections are Compton dominated so there is a chance of some information on the gluon



η spectra of the direct-photons differ significantly for different PDFs so there could be new information from a measurement with ~few % experimental errors

However there is a known discrepancy between data at low-pt and the NLO cross-section predictions. This could be due to kt of initial state gluons and is expected to be negligible for pt > 60 GeV.

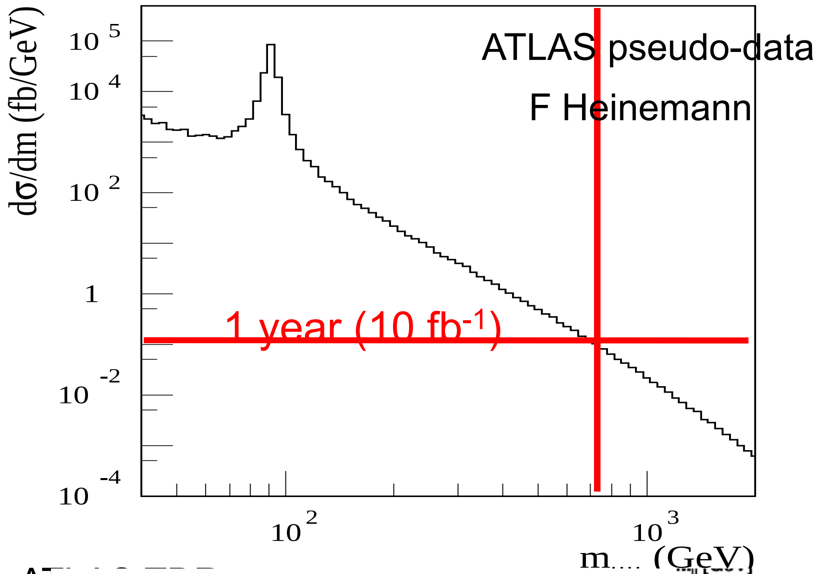
Confirm this and then use high pt data.

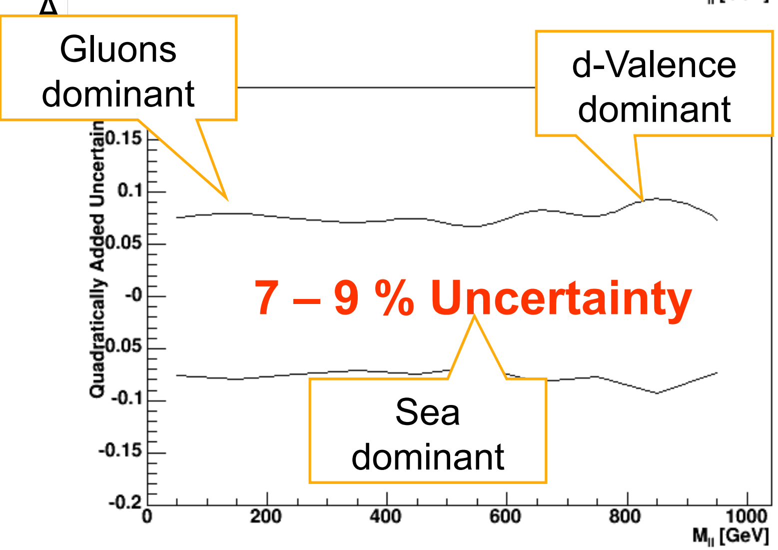


P Newman M Stockton

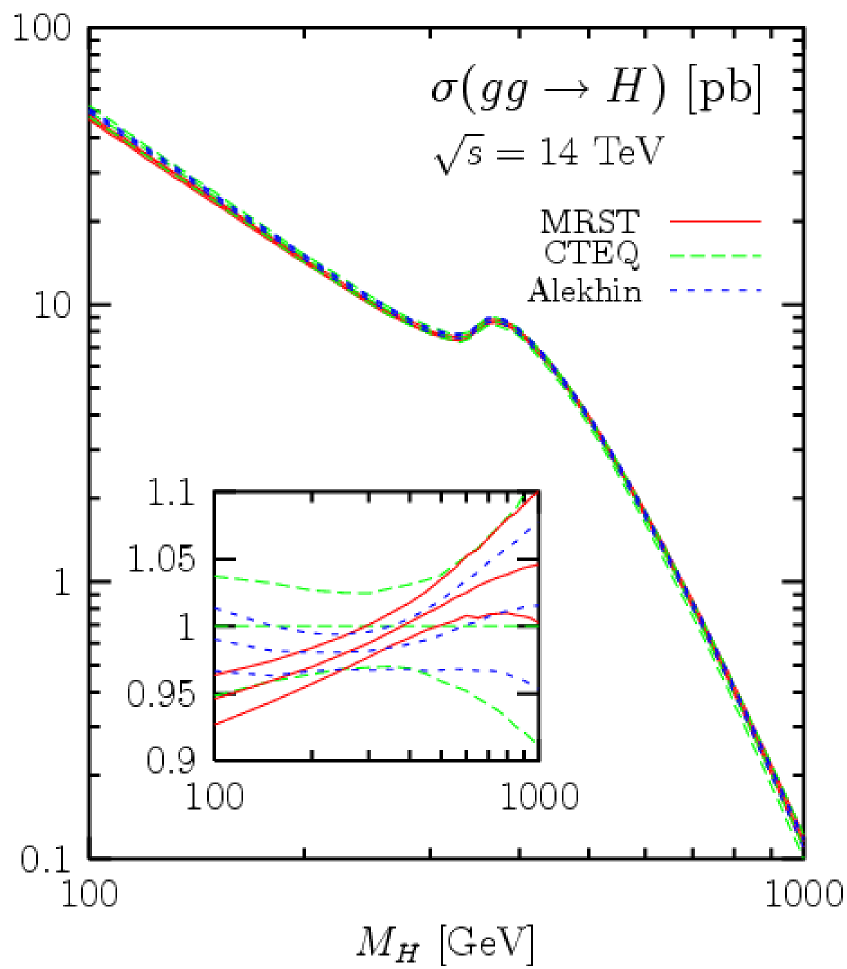
For what discoveries do PDF uncertainties not hamper us (much)

PDF Uncertainty in High-mass Drell-Yan- won't stop us seeing Zprimes





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



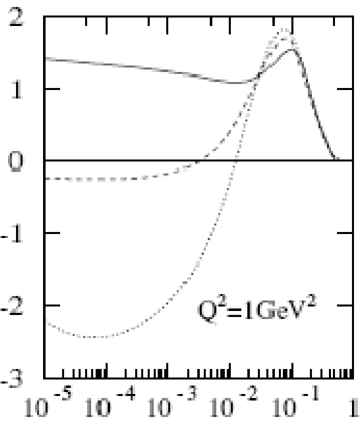
S. Ferrag + A Djouadi

BEWARE of different sort of 'new physics'

What if low-x behaves very differently?

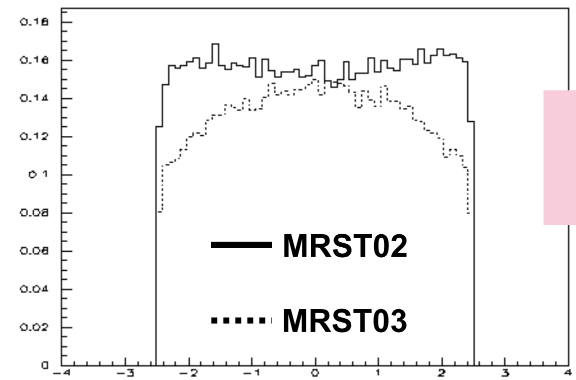
LHC is a low-x machine (at least for the early years of running) Is NLO (or even NNLO) DGLAP good enough for $x < 10^{-2}$. The QCD formalism may need extending at small-x. What is SAFE x?

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



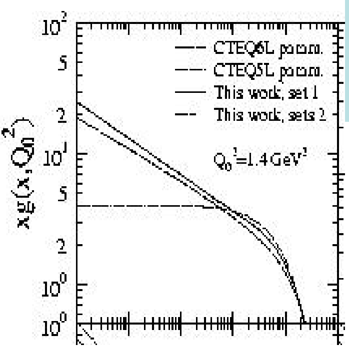
Thorne and White

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



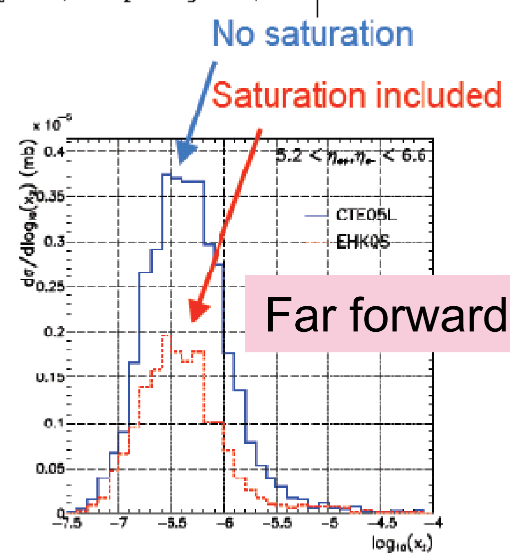
Central rapidity

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



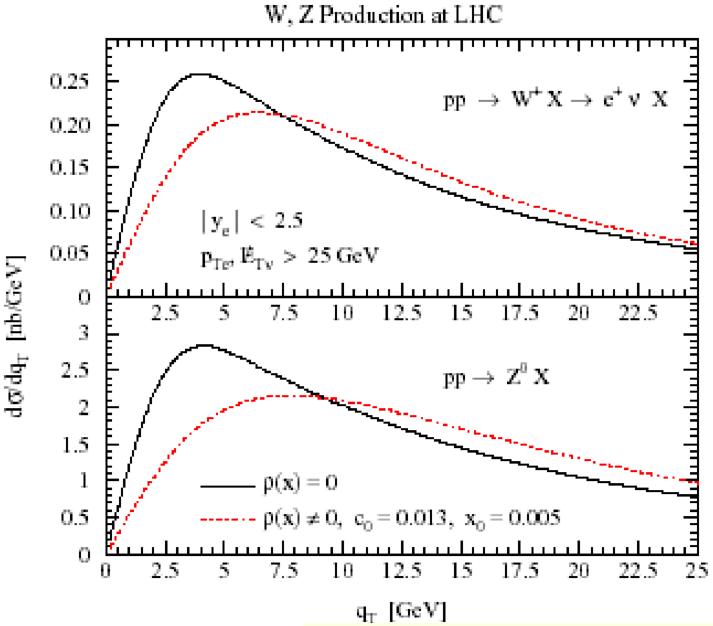
Far forward

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

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

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.

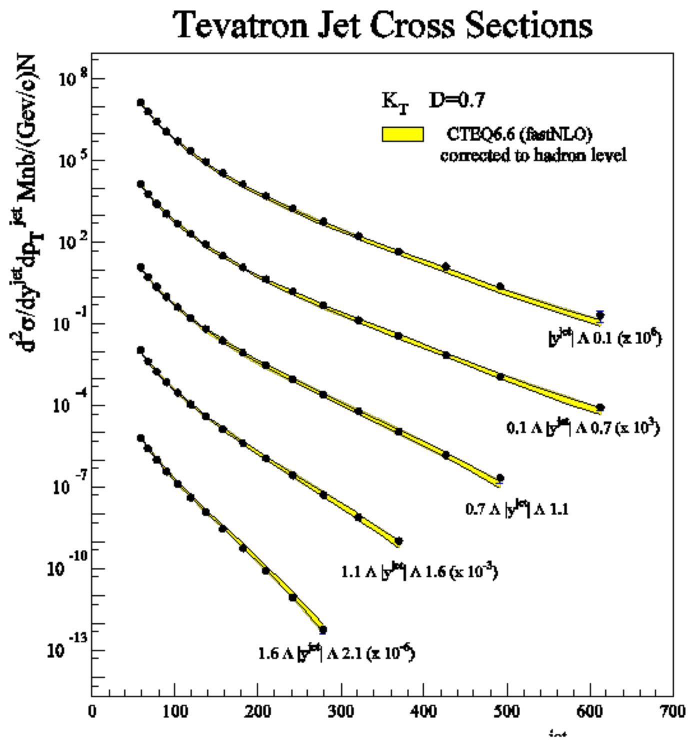
HIGGS discovery will not be compromised by PDF uncertainty

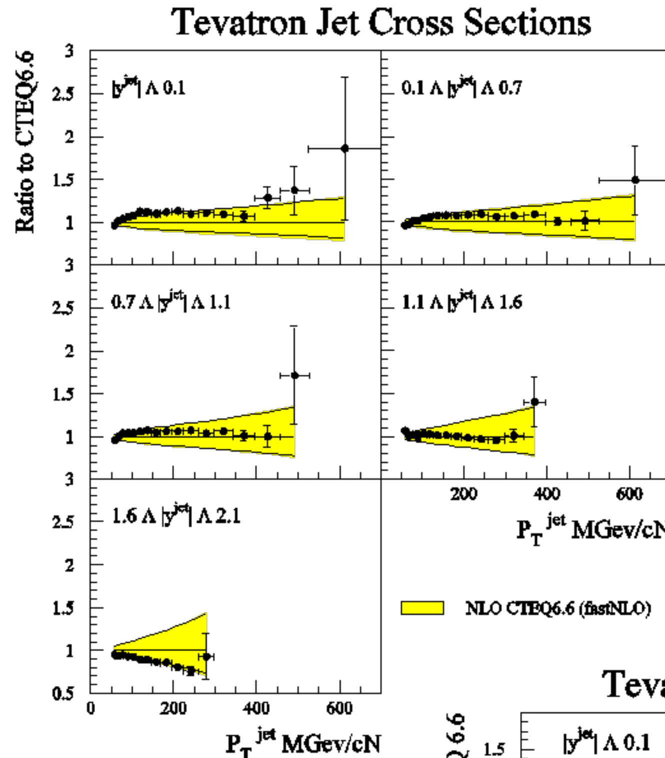
High-mass Z' will not be compromised by PDF uncertainty

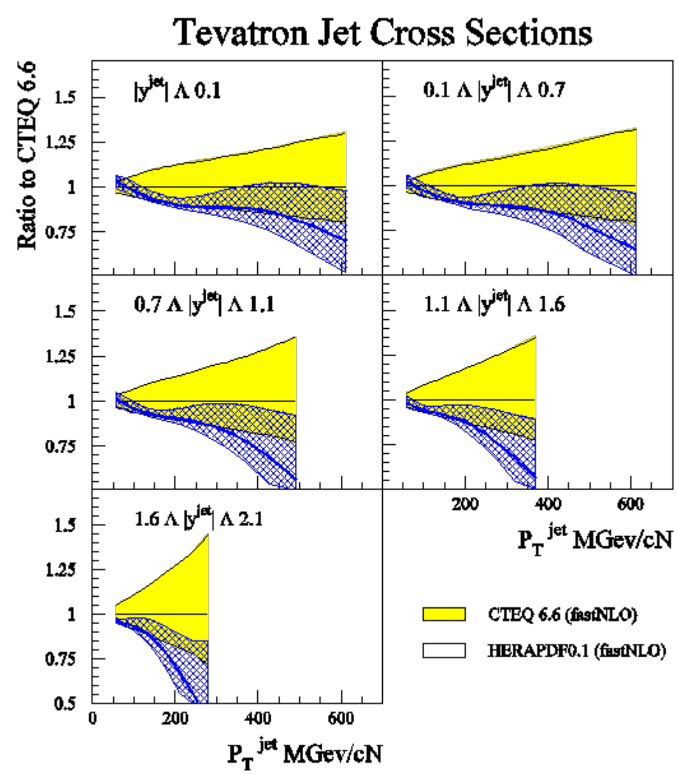
BEYOND STANDARD MODEL

- There are discovery channels – high ET jets- which could be obscured by PDF uncertainties
- PDF uncertainties could be improved by jet measurements at higher η and lower ET- but Jet Energy Scale Uncertainties must be carefully controlled
- Be smart - look at ratios W+n-jets/Z+n-jets
- Direct photon production could also help improve PDF uncertainties

extras


Tevatron Jet Cross Sections
K_T D=0.7
CTEQ6.6 (fastNLO) corrected to hadron level
|y^jet| Λ 0.1 (x 10^6)
0.1 Λ |y^jet| Λ 0.7 (x 10^3)
0.7 Λ |y^jet| Λ 1.1
1.1 Λ |y^jet| Λ 1.6 (x 10^-3)
1.6 Λ |y^jet| Λ 2.1 (x 10^-6)
d^2σ/dy^jet dp_T^jet Mnb/(Gev/c)N


Tevatron Jet Cross Sections
Ratio to CTEQ6.6
|y^jet| Λ 0.1
0.1 Λ |y^jet| Λ 0.7
0.7 Λ |y^jet| Λ 1.1
1.1 Λ |y^jet| Λ 1.6
1.6 Λ |y^jet| Λ 2.1
P_T^jet MGev/cN
NLO CTEQ6.6 (fastNLO)


Tevatron Jet Cross Sections
Ratio to CTEQ 6.6
|y^jet| Λ 0.1
0.1 Λ |y^jet| Λ 0.7
0.7 Λ |y^jet| Λ 1.1
1.1 Λ |y^jet| Λ 1.6
1.6 Λ |y^jet| Λ 2.1
P_T^jet MGev/cN
CTEQ 6.6 (fastNLO)
HERAPDF0.1 (fastNLO)

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

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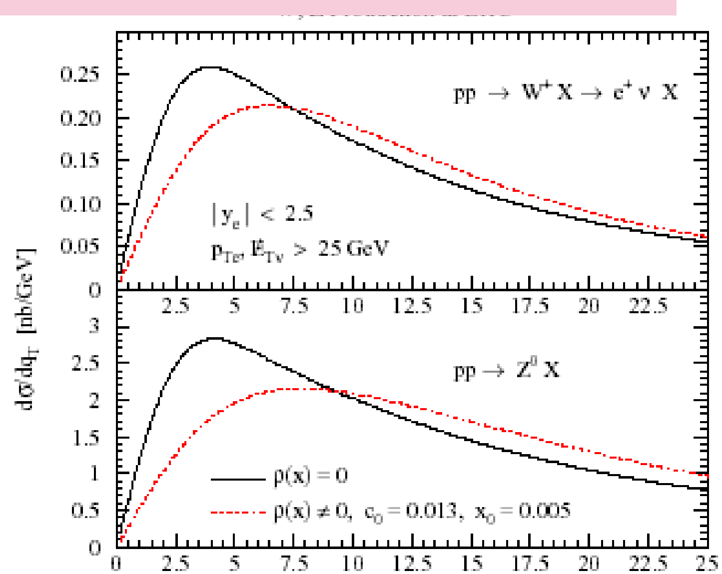
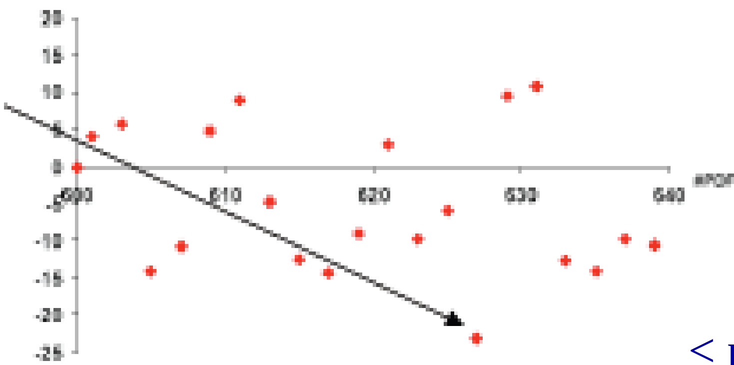


Conventional

Unconventional

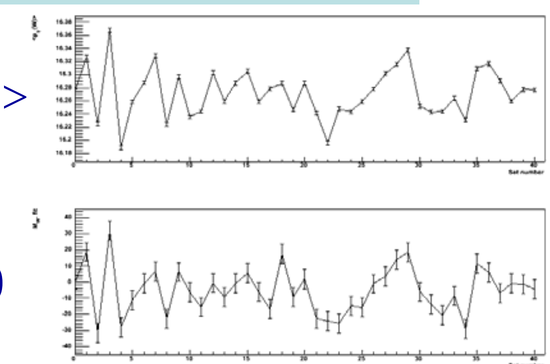
Pt spectra are also used to measure M_W -- dM_W from PDF uncertainties, using pt(e), is ~20 MeV



Note largest shift ~25 MeV

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

$< p_T(W) >$



δM_W(fit)

Same pattern