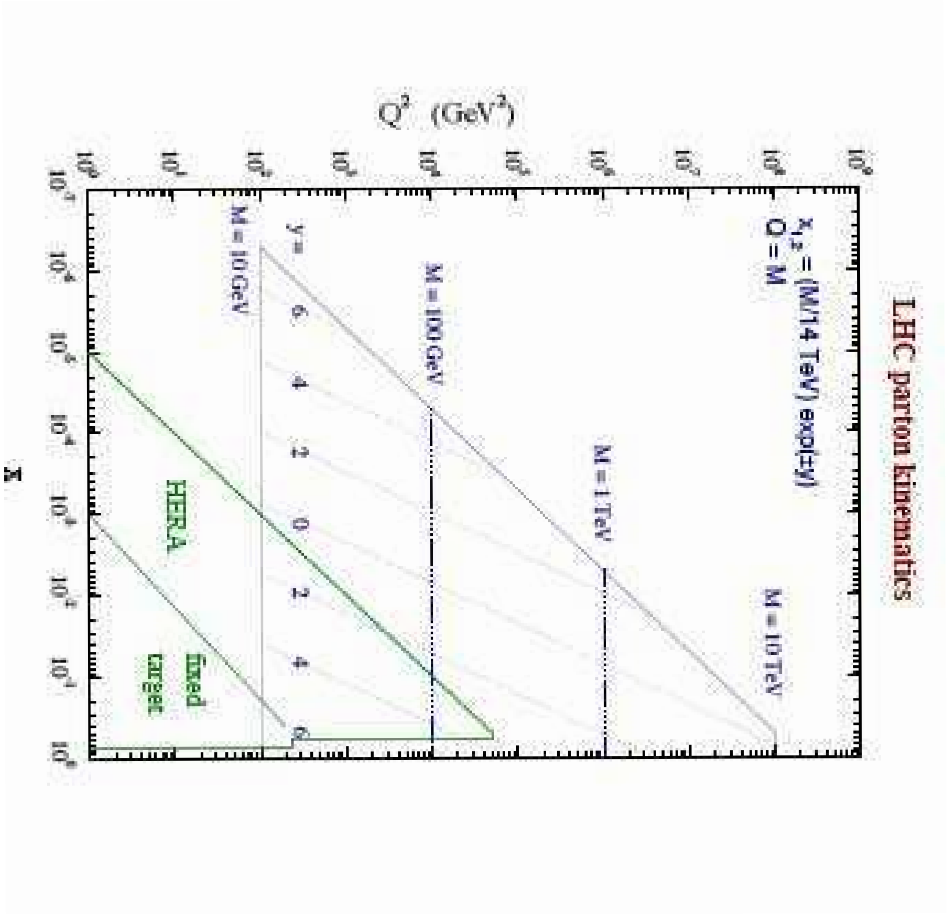
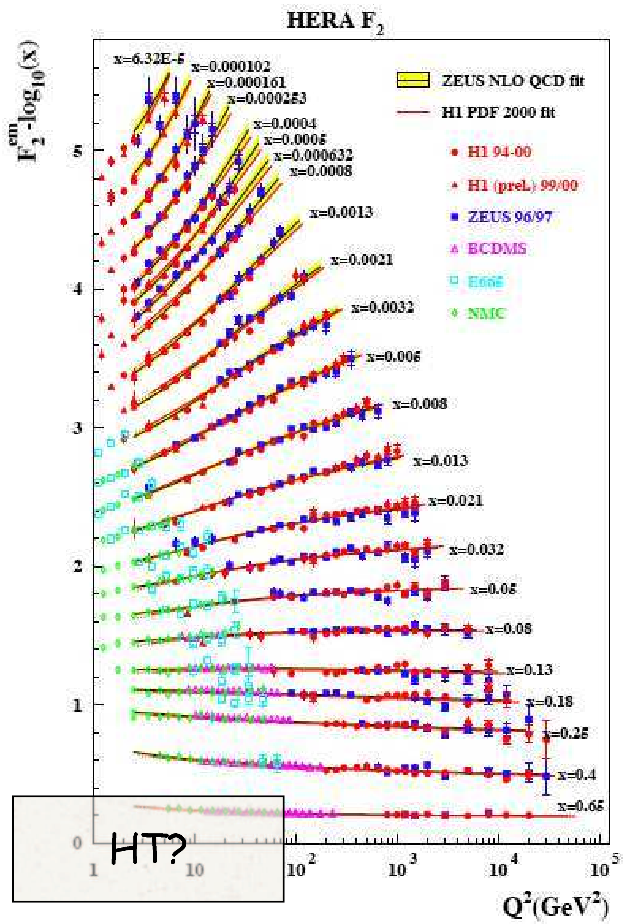
II: FUTURE PROSPECTS: THEORY AND EXPERIMENT

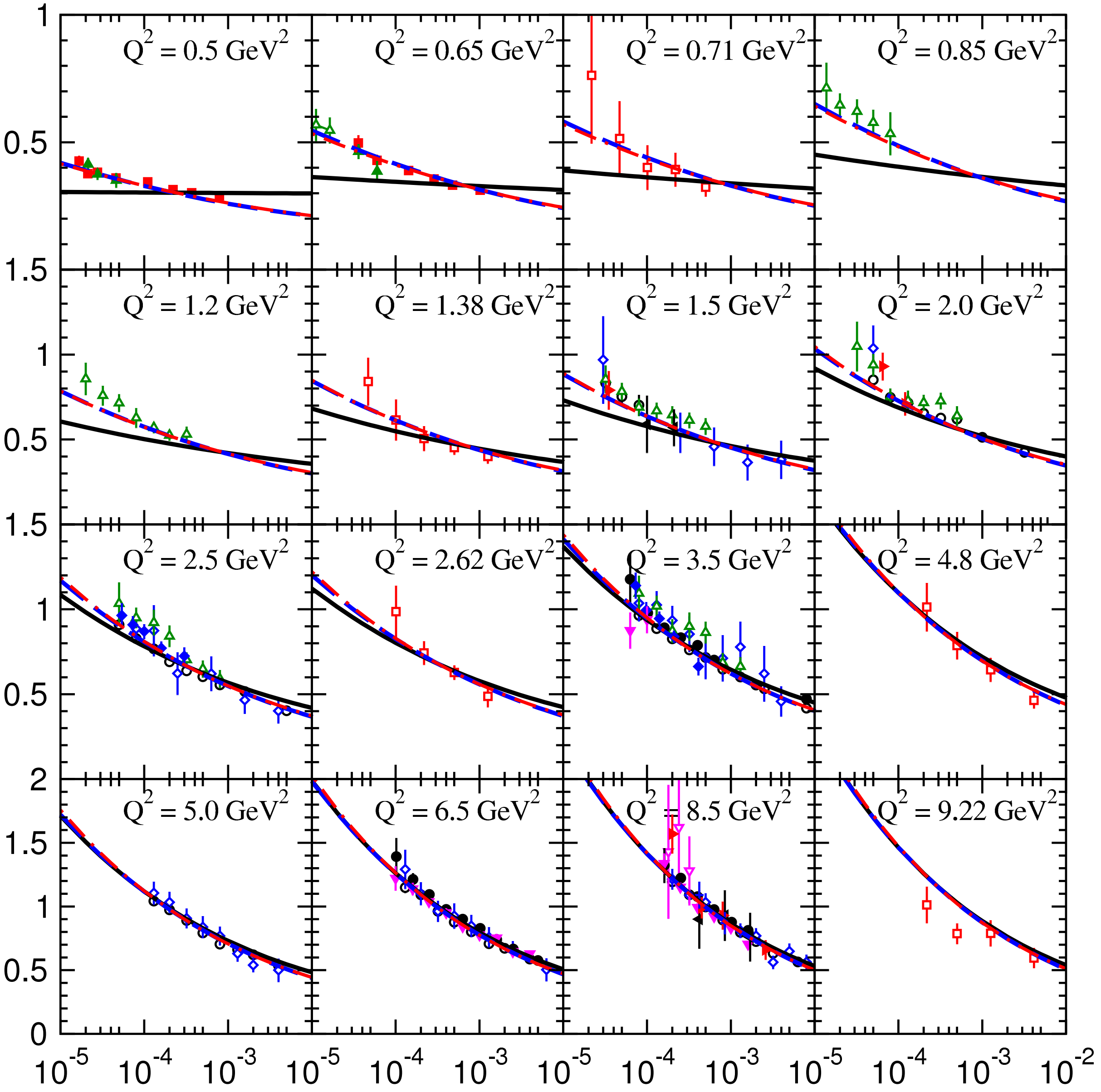
FROM HIGHER ORDERS TO RESUMMATION

PERTURBATIVE SUCCESS!





FITS INCLUDING HIGHER TWISTS...



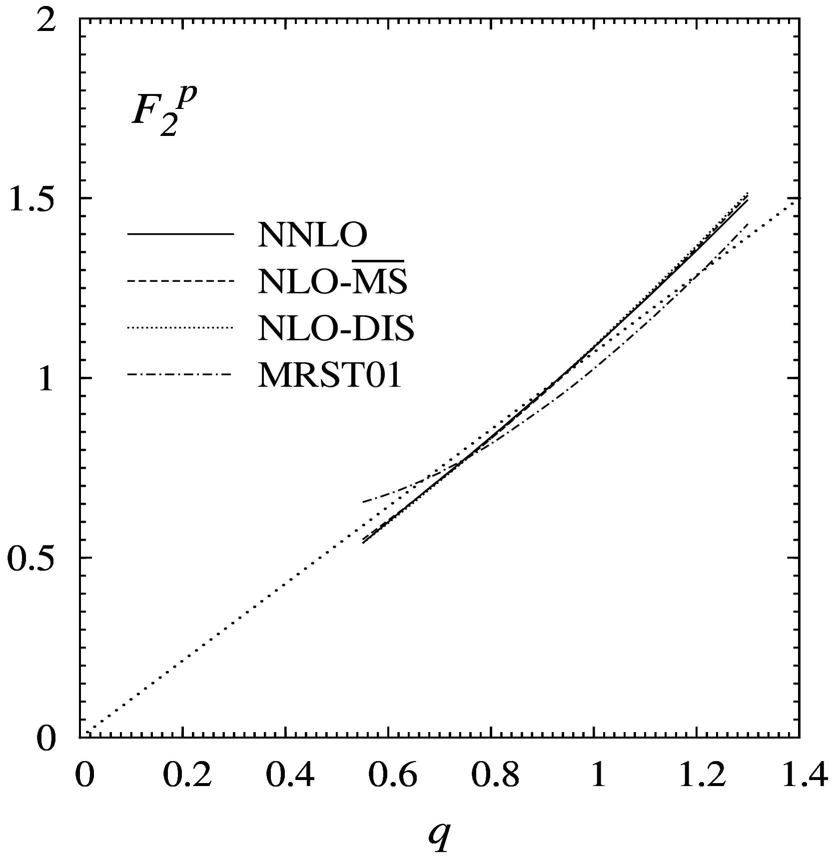
A. KOTIKOV

Curvature test of F_2

- At $x = 10^{-4}$ most measurements lie along a straight (dotted) line, if plotted versus

$$q = \log_{10}\left(1 + \frac{Q^2}{0.5\,\mathrm{GeV}^2}\right)$$

D. Haidt, EPJ C35, 519 (2004)



[illegible]
the valence–like input gluon distribution at $Q_0 = 1$ GeV

…CAN REPRODUCE PECULIAR SCALING OF THE DATA…

C. Pisano

...NNLO MOMENTS OF PDFS COMPARED TO LATTICE...

Results - α_s, Λ_{QCD} and PDF moments

α_s determination

	$\alpha_s(M_Z^2)$	expt	theory
NNLO			
MRST03	0.1153	±0.0020	±0.0030
A02	0.1143	±0.0014	±0.0009
SY01(ep)	0.1166	±0.0013	
SY01(νN)	0.1153	±0.0063	
BBG	**0.1134**	$+0.0019$ -0.0021	
World Average	**0.1182**	**±0.0027**	

PDF moments

f	n	**BBG**(NNLO)	**MRST04**	**A02**
u_v	2	0.2986 ± 0.0029	0.285	0.304
	3	0.0871 ± 0.0011	0.082	0.087
	4	0.0333 ± 0.0005	0.032	0.033
d_v	2	0.1239 ± 0.0026	0.115	0.120
	3	0.0315 ± 0.0008	0.028	0.028
	4	0.0105 ± 0.0004	0.009	0.010
$u_v - d_v$	2	0.1747 ± 0.0039	0.171	0.184
	3	0.0556 ± 0.0014	0.055	0.059
	4	0.0228 ± 0.0007	0.022	0.024

Comparison with lattice results

BBG	Lattice
N^{3}LO - $\Lambda_{QCD}^{(4)}$ MeV	Alpha Collaboration - $\Lambda_{QCD}^{(2)}$ MeV
231 ± 26	$245 \pm 16 \pm 16$

[M. Della Morte, *et al.*,Nucl.Phys.B713,(2005),378]

		BBG	Lattice
f	n	NNLO	QCDSF
$u_v - d_v$	2	0.1747 ± 0.0039	0.191 ± 0.012

[G. Schierholz, *private communication*]

A. GUFFANTI

DOES IT WORK ALSO AT SMALL x?

HERA and the LHC- transporting PDFs to hadron-hadron cross-sections

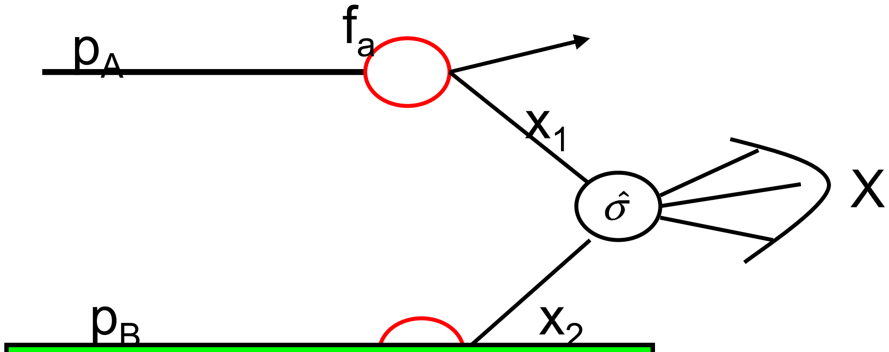
QCD factorization theorem for short-distance inclusive processes

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

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

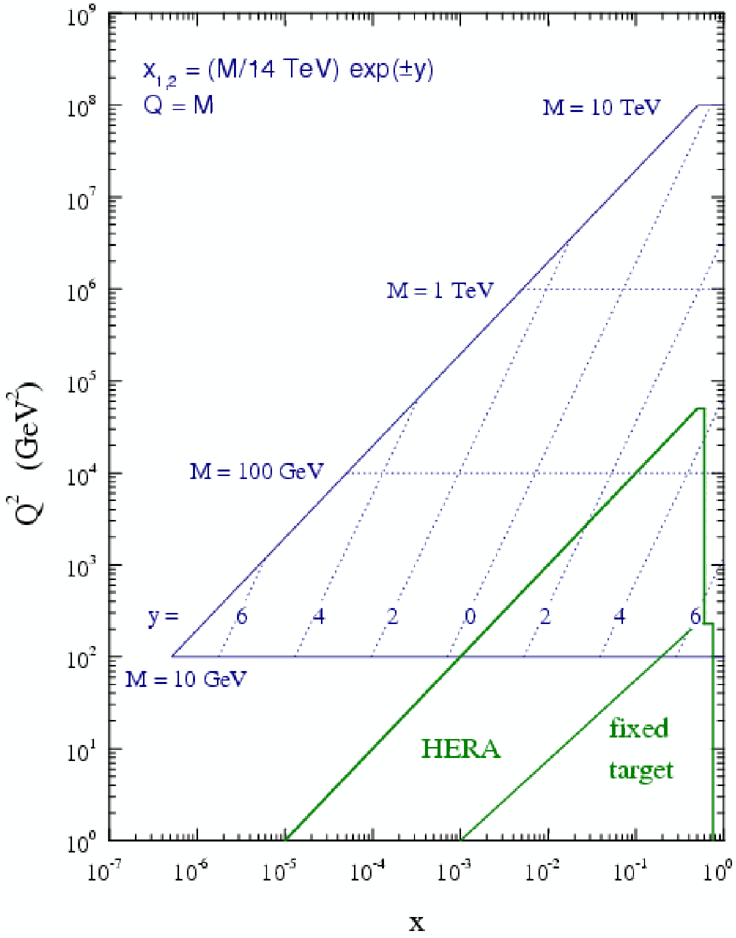
and σ is known

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



A. COOPER-SARKAR

LHC parton kinematics



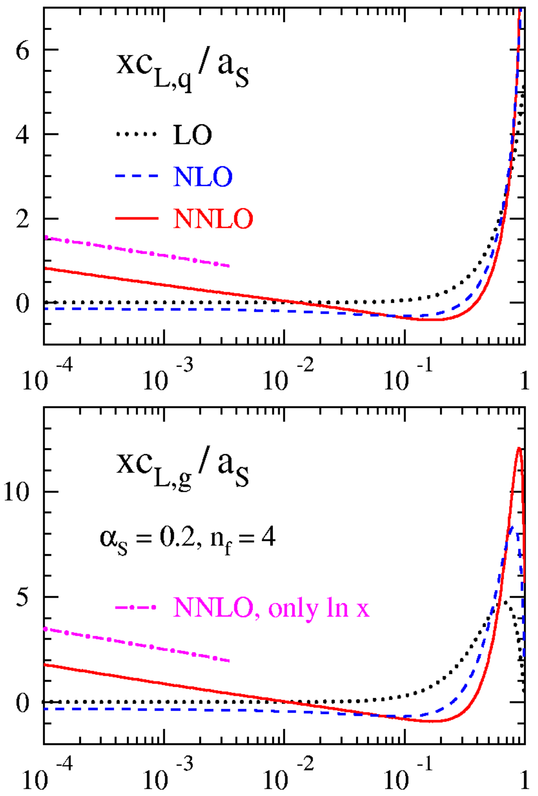
The central rapidity range for W/Z production AT LHC is at low-x (5 ×10-4 to 5 ×10-2)

Knowledge of the PDFs is vital

A PROBLEM: NNLO CORRECTIONS PERTURBATIVE INSTABILITY AT SMALL x

THEORY

- Perturbation theory unstable
- leading log approx no good

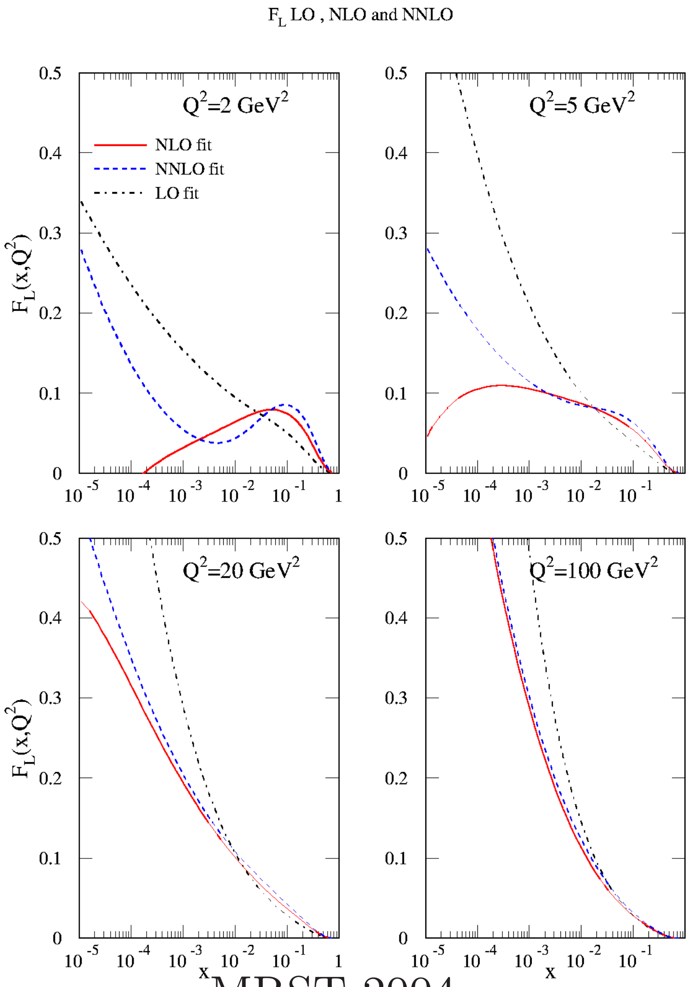


the coefficient function C_L

Moch, Vermaseren, Vogt 2005

PHENOMENOLOGY

F_L FIT



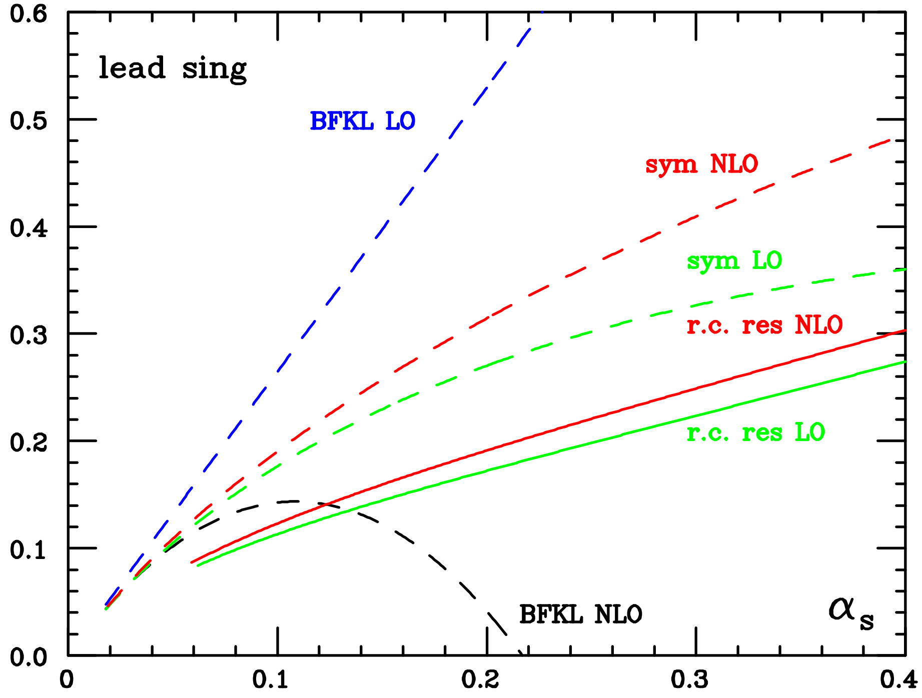
MRST 2004

SOLUTION: RESUMMATION:
$n_f = 0$ QUALITATIVE FEATURES

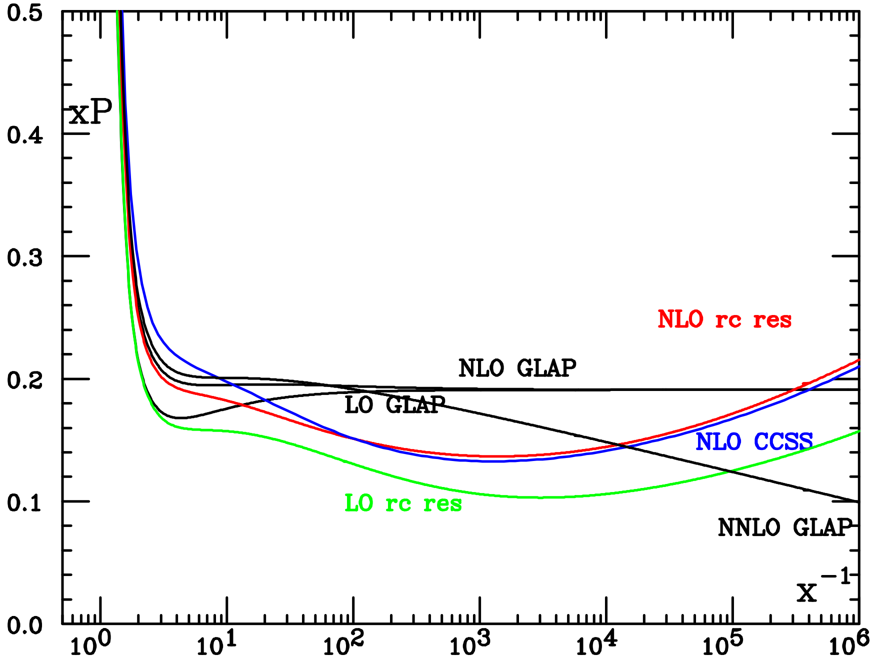
HERALHC 2005

SINGULARITY IN ANOM. DIM. AT $N = \alpha \Rightarrow$ ASYMPT. SMALL-x POWER $G \sim x^{-\alpha}$

SMALL-x POWER VS. α_s



SPLITTING FUNCTION



- RESUMMED EXPANSION CONVERGES RAPIDLY
- SMALL x INTERCEPT & CURVATURE DETERMINE RESUMMED BEHAVIOUR
- RESSUMMED RESULTS OBTAINED BY DIFFERENT GROUPS AGREE WELL

PROGRESS: EXTENSION TO QUARKS (CCSS)

The Matrix Kernel

$$\mathcal{K}_0 = \begin{pmatrix} \Gamma^0_{qq}(\omega)\chi^\omega_c(\gamma) & \Gamma^0_{qg}(\omega)\chi^\omega_c(\gamma)+\Delta_{qg}(\gamma,\omega) \\ \Gamma^0_{gq}(\omega)\chi^\omega_c(\gamma) & [\Gamma^0_{gg}(\omega)-\frac{1}{\omega}]\chi^\omega_c(\gamma)+\frac{1}{\omega}\chi^\omega_0(\gamma)+\Delta_{gg}(\gamma,\omega) \end{pmatrix}$$

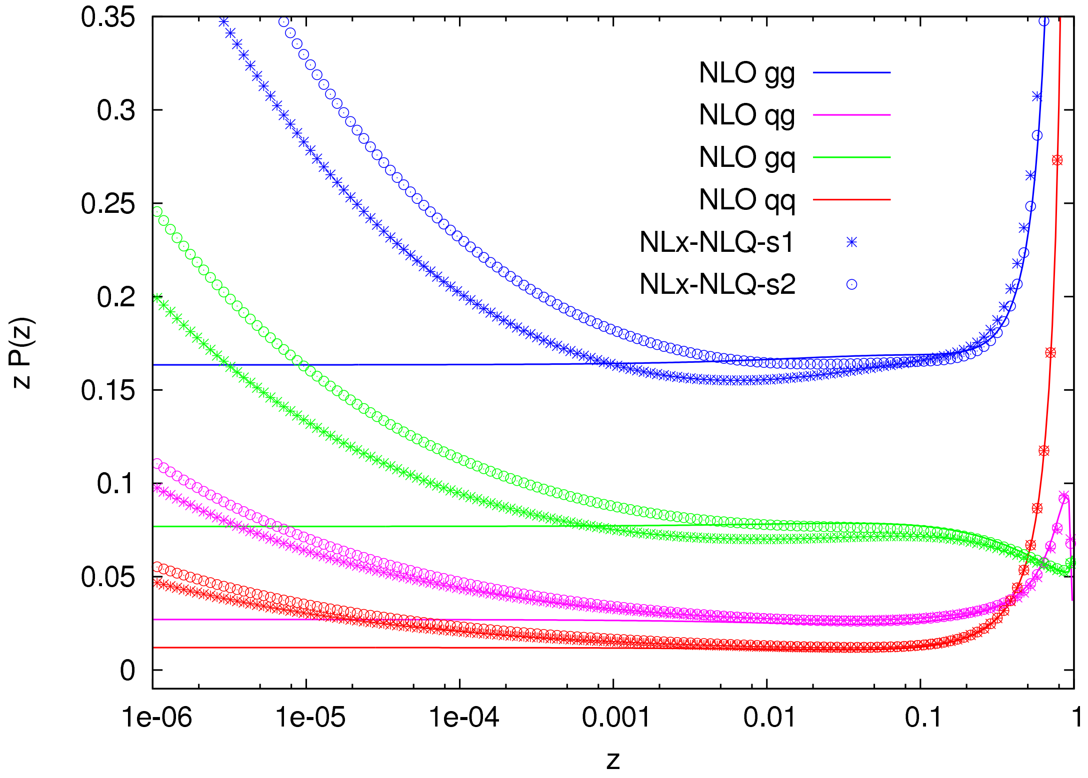
- $\mathcal{K}_0$ has at most simple poles in γ and simple poles in ω in the gluon row
- No ω-poles are present in the quark row, consistently with LO DGLAP and reggeization of the quark at $\omega = -1$;
  We'll keep this structure also in $\mathcal{K}_1$
- At NLO Γ^1_{qq} and Γ^1_{qg} contain $\frac{\bar{\alpha}_s^2}{\omega}$. Instead of adding such terms in $\mathcal{K}_1$ (see above) we add a proper non-singular $\Delta_{qg}(\gamma,\omega)$ term
- Momentum Sum Rule: restored by adding a non-singular subleading $\Delta_{gg}(\gamma,\omega)$ term
- $\mathcal{K}_1$: we add NLO DGLAP matrix Γ_1 and NLLx BFKL kernel χ_1 in $\mathcal{K}_{1,gg}$ with subtractions to avoid double-counting
- Running coupling: introduced in $(\boldsymbol{k}, x)$ space (analytic double inverse Mellin transf.)

$$\mathcal{K}(\boldsymbol{k},\boldsymbol{k}';x) = \bar{\alpha}_s(\boldsymbol{k}^2_>)\mathcal{K}_0(\boldsymbol{k},\boldsymbol{k}';x) + \bar{\alpha}_s^2(\boldsymbol{k}^2_>)\mathcal{K}_1(\boldsymbol{k},\boldsymbol{k}';x)$$

($\mathcal{K}_1$ depends on the choice of run.coupl. scale $\boldsymbol{k}_> \equiv \max(\boldsymbol{k},\boldsymbol{k}')$)

Frozen Coupling Features

Resummed $\overline{\mathrm{MS}}$ splitting functions $z\,P(\alpha_s, z)$ for $\alpha_s = 0.2$



- at large-x fixed order and resummed splitting functions overlap
- at moderate-x resummed splitting functions show a small dip
- final rise sets in at very small-x
- resummation scheme uncertainty is small

EXTENSION TO QUARKS (ABF)

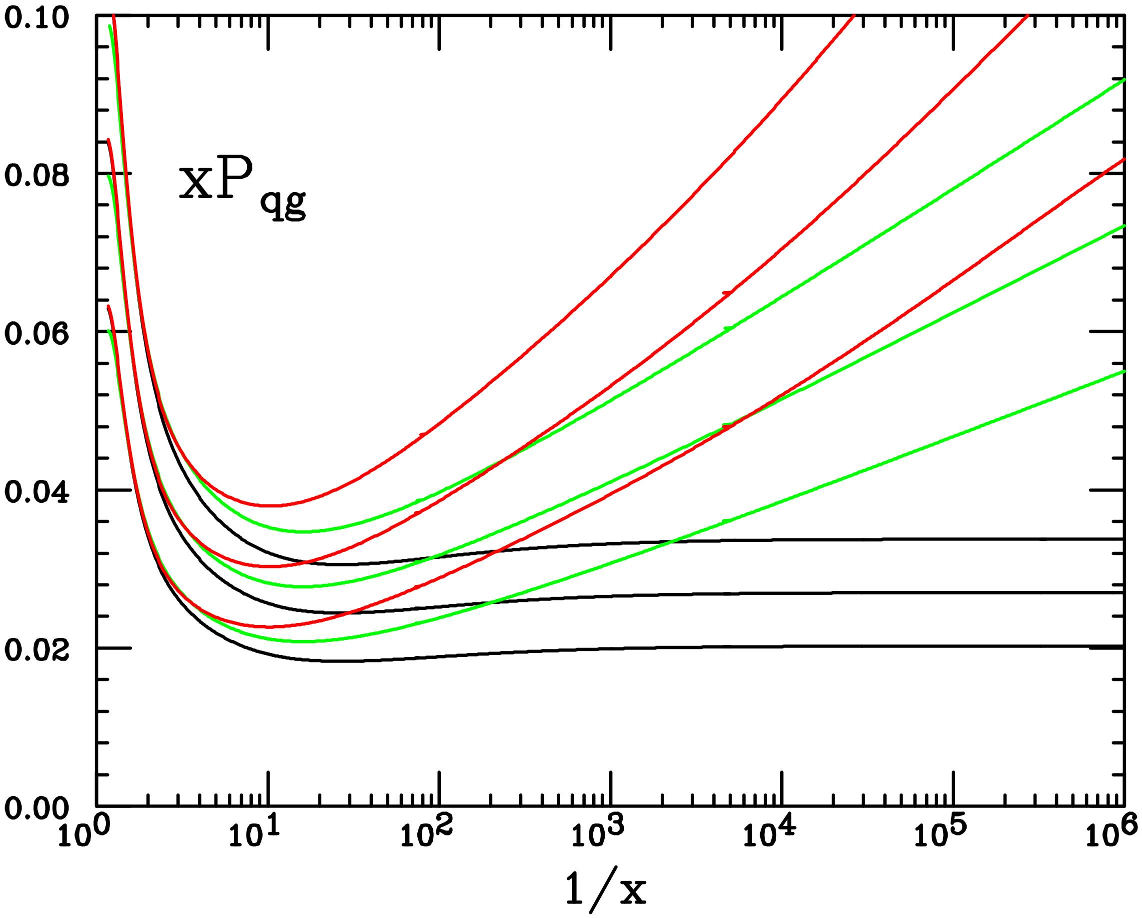
USE $Q_0\overline{\mathrm{MS}}$ SCHEME: (Ball, Forte, 2005)

COINCIDES WITH $\overline{\mathrm{MS}}$ AT LARGE x (NLO) BUT SMALL x R.C. SINGULARITIES IN GLUON SECTOR

- γ_{qg} SAME AS IN $\overline{\mathrm{MS}}$
- γ_+ SAME AS IN Q_0
- CAN DETERMINE RESUMMED γ_{qg} (Catani & Hautmann)

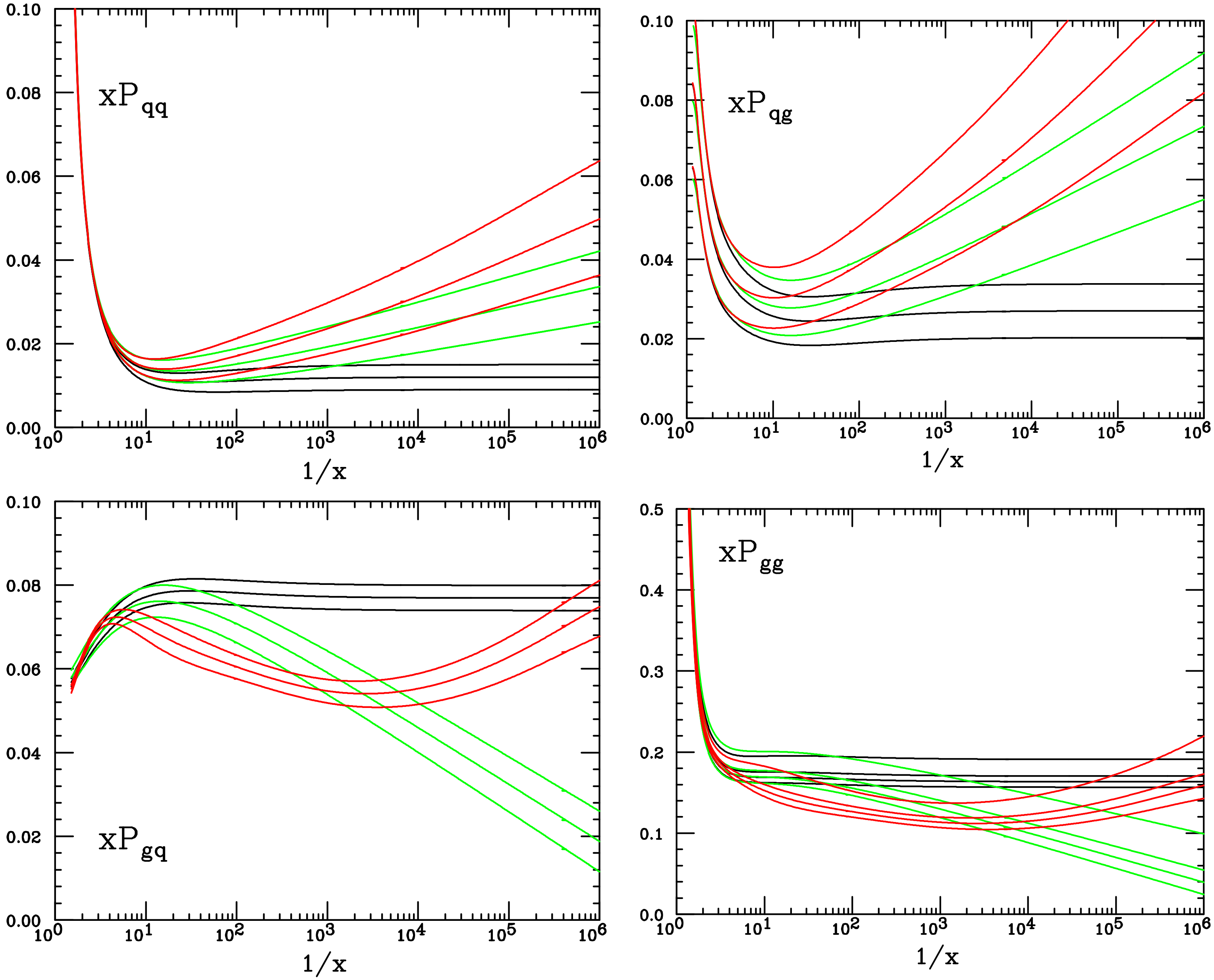
P_{qg}, $n_f = 3, 4, 5$ (top to bottom)

NLO, NNLO, RESUMMED



THE SPLITTING FUNCTION MATRIX (ABF)

NLO, NNLO, RESUMMED

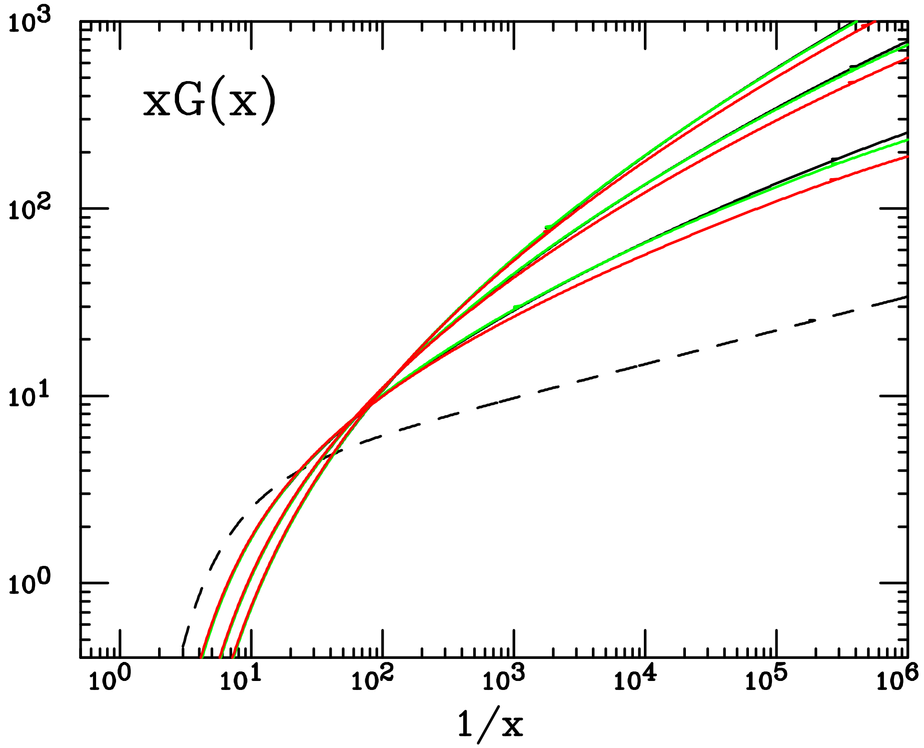


QUARK AND GLUON EVOLUTION (ABF)

evolve toy $G = (x, Q_0) = x^{-0.18}(1-x)^5$, $Q(x, Q_0) = \frac{1}{3}G(x, Q_0)$, $Q_0 = 2$ GeV

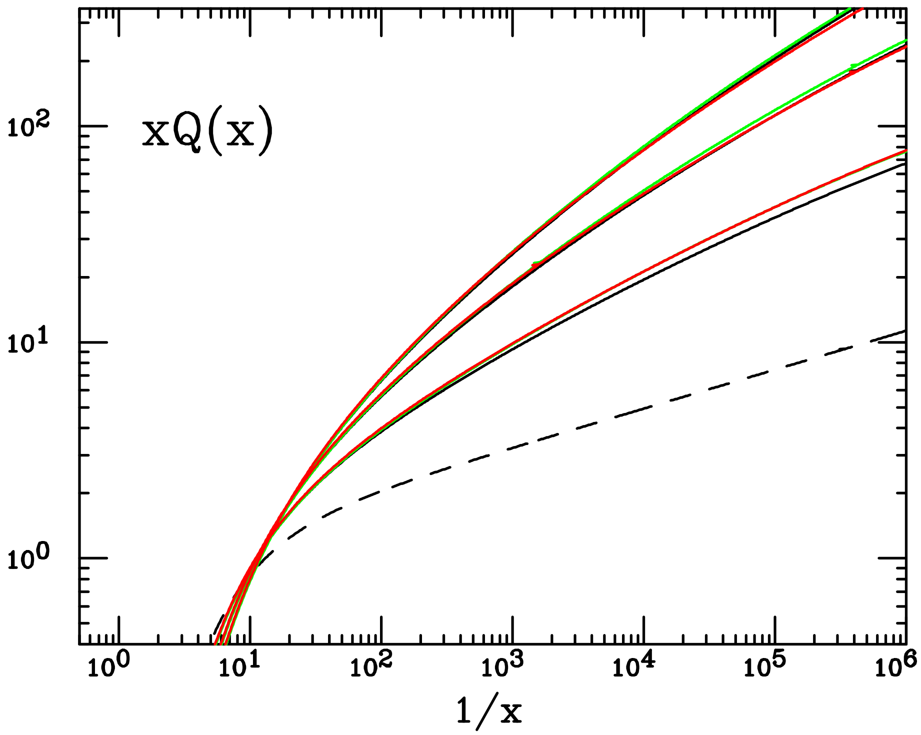
GLUON

$Q = 2,\ 10,\ 100,\ 1000$ GeV (bottom to top)



QUARK

NLO, NNLO, RESUMMED

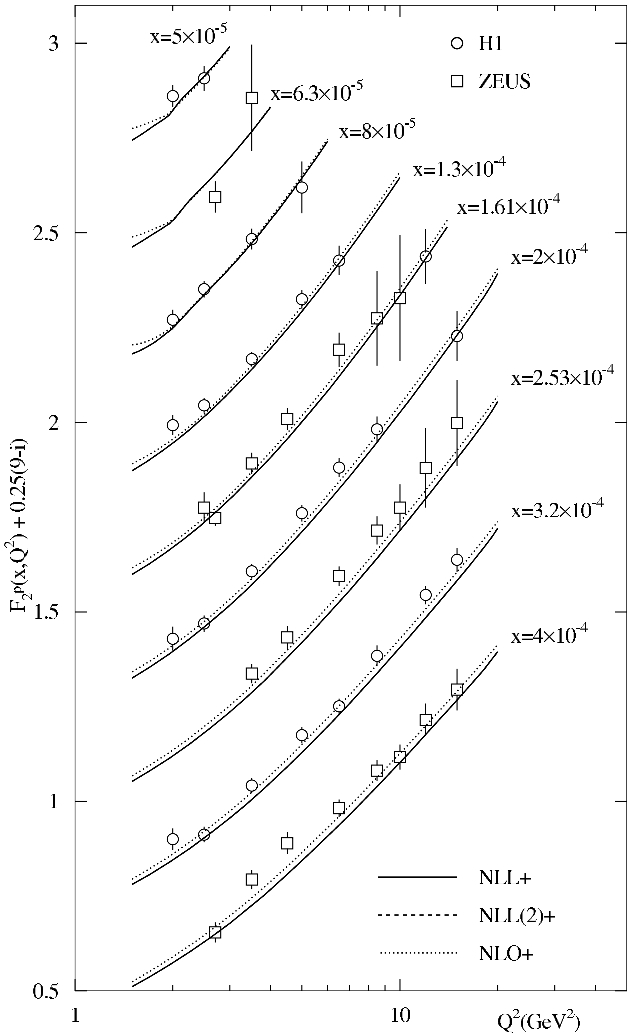


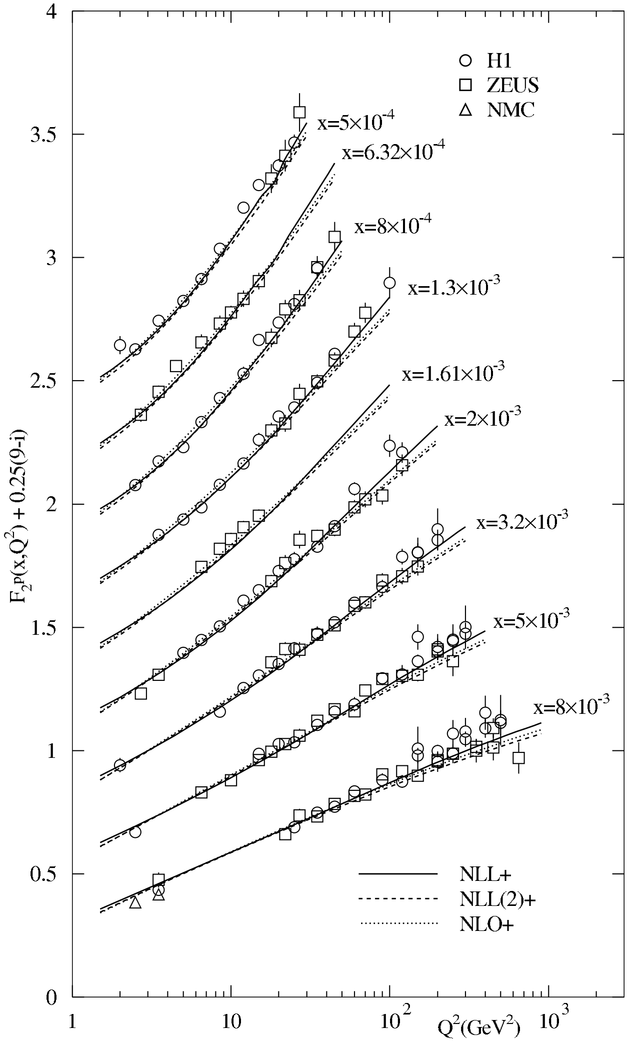
- LO VS NLO DIFFERENCE LARGER THAN FIXED VS RESUMMED
- RESUMMED GLUON BELOW UNRESUMMED, QUARK JUST BELOW

A FIRST RESUMMED FIT (THORNE-WHITE)

Global Fit - Results

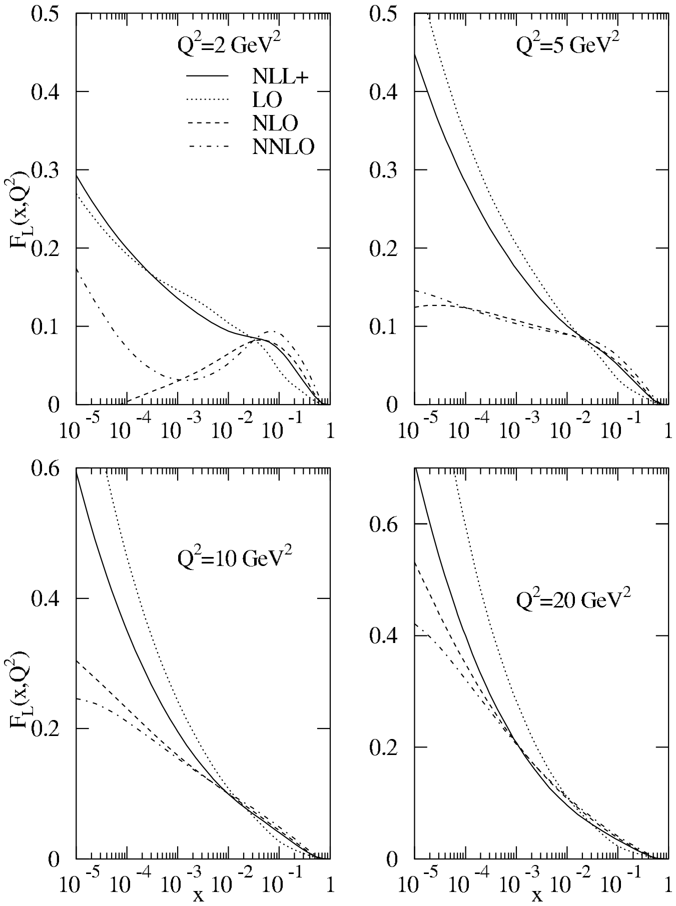
Results - F_2





C. WHITE

Longitudinal Structure Function

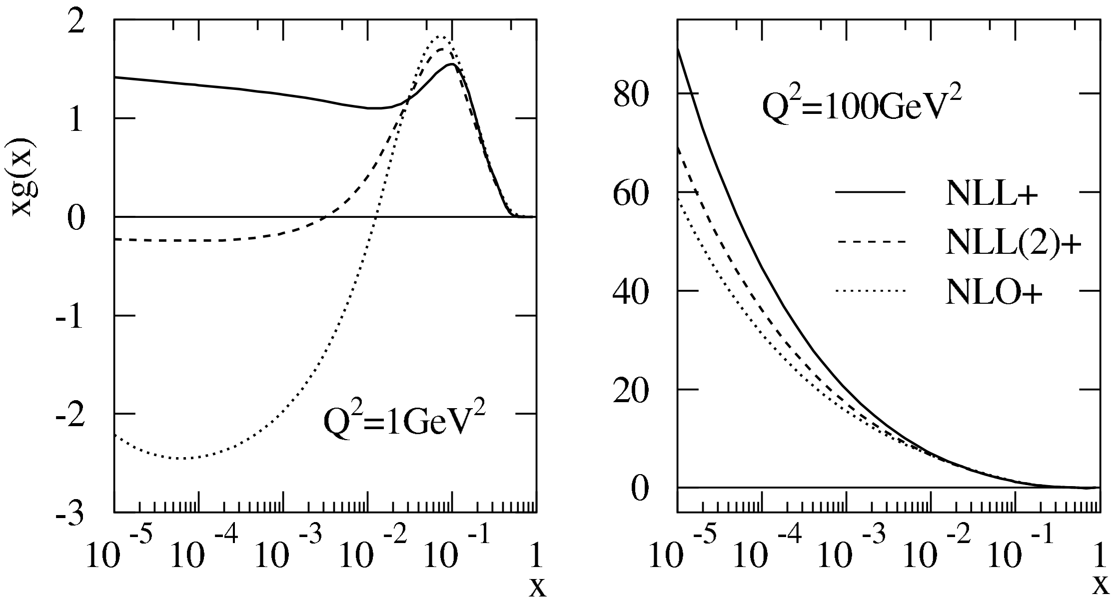


- Clearly see perturbative instability in fixed order results.
- This is cured by the resummation.

NNLO INSTABILITY REMOVED FROM F_L

C. WHITE

Gluon Distribution



- Gluons differ for $x \lesssim 10^{-2}$.
- NLL resummed gluon positive and growing at small x!
- Not true at fixed order

HIGHER INITIAL GLUON (LESS EVOLUTION)

- See this in e.g. F_L...

C. WHITE

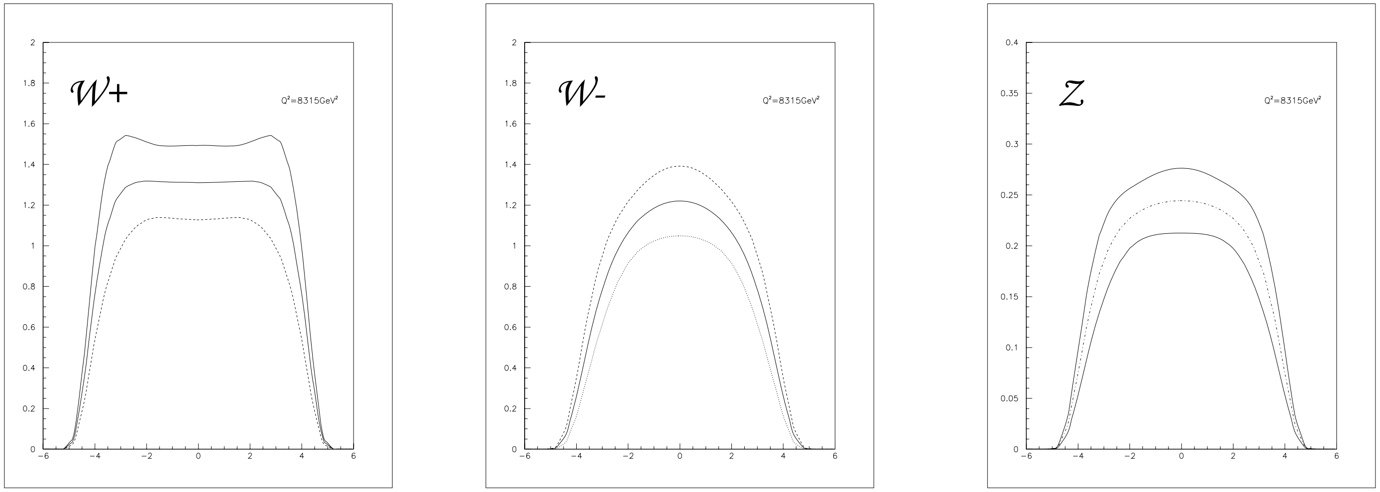
RESUMMATION: SUMMARY

- FULL RESUMMED EVOLUTION SOON AVAILABLE IN VARIOUS APROACHES
- DIFFERENT APPROACHES MUST BE BENCHMARKED
- NNLO INSTABILITY REMOVED
- SOME CRITICAL ASPECTS OF FITS MIGHT IMPROVE (NEGATIVE GLUON?)

TOWARDS LHC

EXPERIMENTAL SUCCESS!

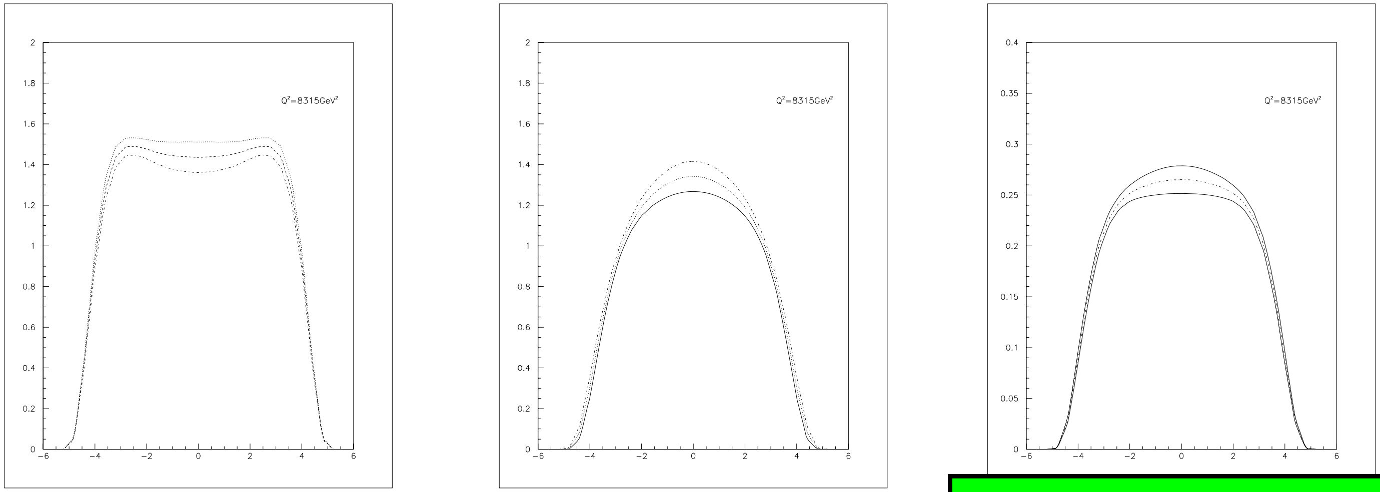
What has HERA data ever done for us?



Pre-HERA W+/W-/Z rapidity spectra ~ ± 15% uncertainties become!

NO WAY to use these cross-sections as a good luminosity monitor

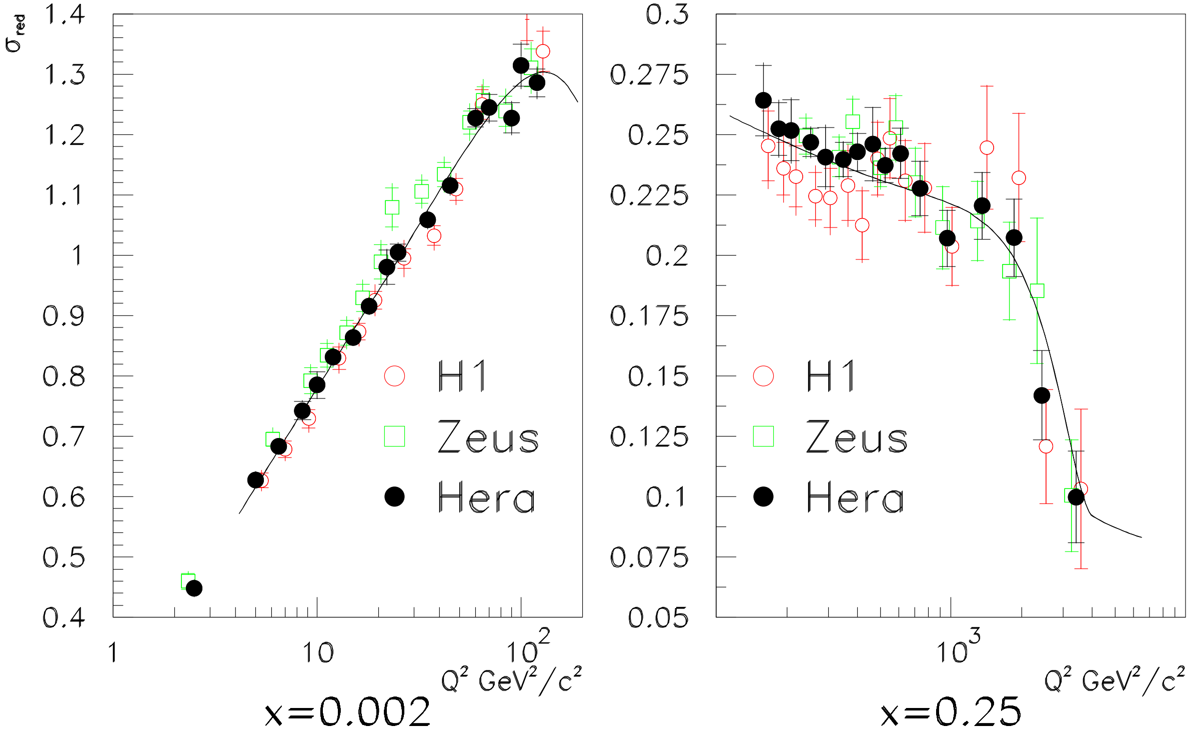
Post-HERA W+/W-/Z rapidity spectra ~ ± 5% uncertainties



A. COOPER-SARKAR

...STILL NOT OVER!

AVERAGING OF HERA DATA



Cross calibration of systematic uncertainties leads to better than $1/\sqrt{2}$ improvement for systematic errors dominated regions. Simple $1/\sqrt{2}$ improvement for stat. error dominated domain.

CAN WE USE HERA/TEVATRON WISDOM @ LHC?

- W/Z cross sections serve as precision physics monitors
  - all cross sections at Tevatron/LHC could be normalized to W/Z
  - Tevatron is a *W factory*

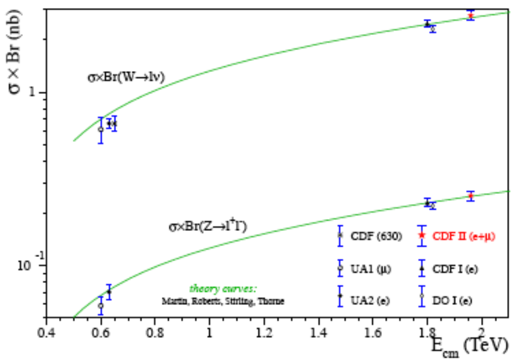
W Factory	Mode	Events/Week/Exp. (after trigger & cuts)
	$W \to e\nu$	~ 15,000
	$Z \to ee$	~ 1,500

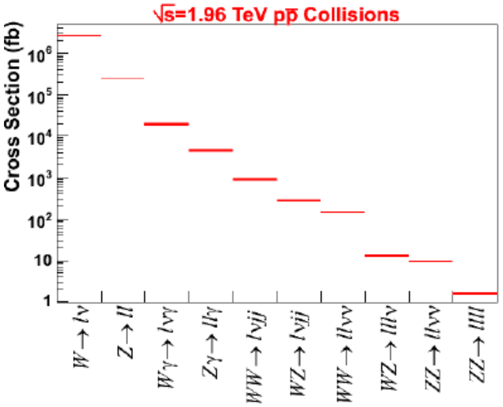
- Both experimental and theoretical errors are under control
  - NNLO a small (positive) correction to NLO

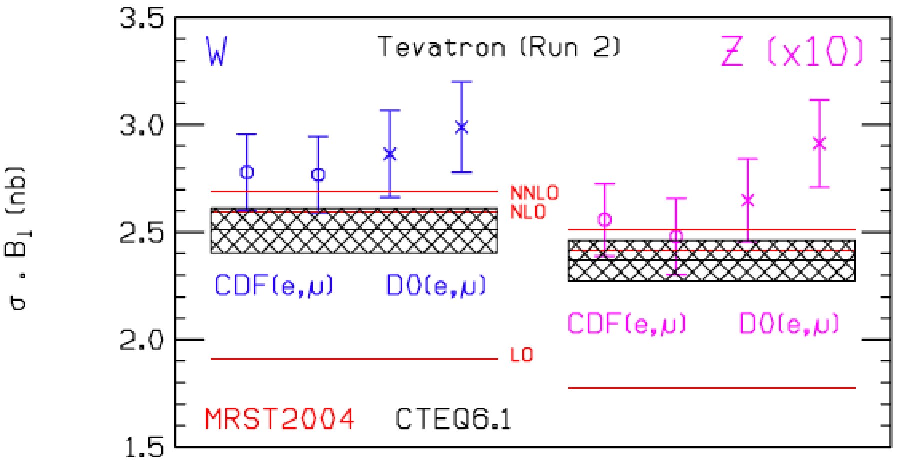
$$\boxed{\frac{\sigma(L)}{L} = 2.5\% \oplus 5.5\%}$$

dominated by experimental uncertainty

$\sigma_{\rm TOT}(p\bar{p})$ $\sigma_{\rm EXP}$ (lumi detector acceptance)







- Note that CTEQ and MRST NLO predictions agree within CTEQ6.1 pdf errors (but MRST at edge of CTEQ6.1 error band)

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Precision benchmarks: W/Z cross sections at the LHC

- CTEQ and MRST NLO predictions in good agreement with each other →
- NNLO corrections are small and negative
- NNLO mostly a K-factor; NLO predictions adequate for most predictions at the LHC

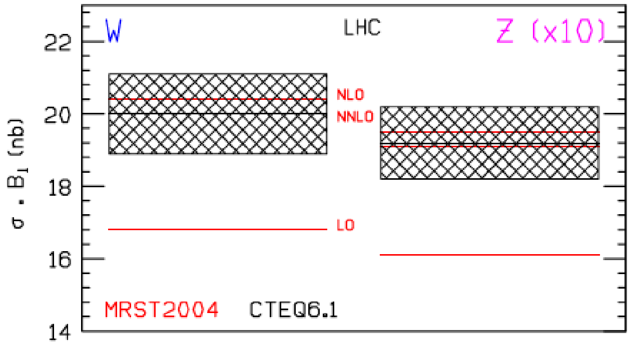
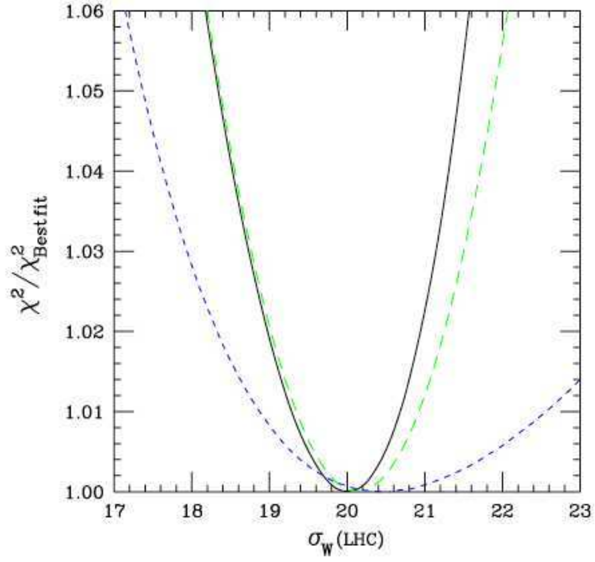
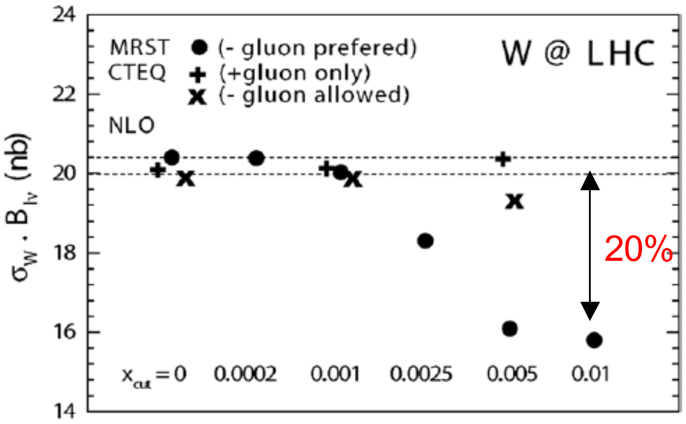


Figure 80. Predicted cross sections for *W* and *Z* production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.



removing low x data from global fits increases uncertainty but does not significantly move central answer

Figure 82. Lagrange multiplier results for the *W* cross section (in nb) at the LHC using a positive–definite gluon. The three curves, in order of decreasing steepness, correspond to three sets of kinematic cuts, standard/intermediate/strong.



MRST found a tension between low x and high x data; not present in CTEQ analysis

Figure 81. Predicted total cross section of $W^+ + W^-$ production at the LHC for the fits obtained in the CTEQ stability study, compared with the MRST results. The overall pdf uncertainty of the prediction is ~5%, as observed in figure 77.

J. HUSTON

EXAMPLE OF APPLICATION

LUMINOSITY MEASUREMENT

$$pp \to W \to \ell \nu$$

$$pp \to Z \to \ell^+ \ell^-$$

Clean signature of leptonic final state.
High rate: O (10 Hz) at $L = 10^{34}$ cm^{-2} s^{-1}.
$\Delta L/L$ = 1% in 20 min.

The increasing precision of the QCD calculation of W and Z production cross section makes the counting of the W and Z leptonic decays an attractive means to measure the luminosity at the LHC (ref. G. Polesello)

$$L = \frac{N_{W/Z} - N_{background}}{A \cdot \varepsilon \cdot \sigma_{W/Z}}$$

$N_{W/Z}$	Number of identified bosons
$N_{background}$	Number of background events
A	Geometrical acceptance
ε	Reconstruction efficiency
$\sigma_{W/Z}$	Theoretical cross section

Largest uncertainties: theoretical estimate of $\sigma_{W,\,Z}$ and detector mo

A. SBRIZZI

Uncertainty on luminosity from W/Z decays

In *pp* collision, $\sigma_{W,Z}$ is the convolution of the PDF and the partonic cross section

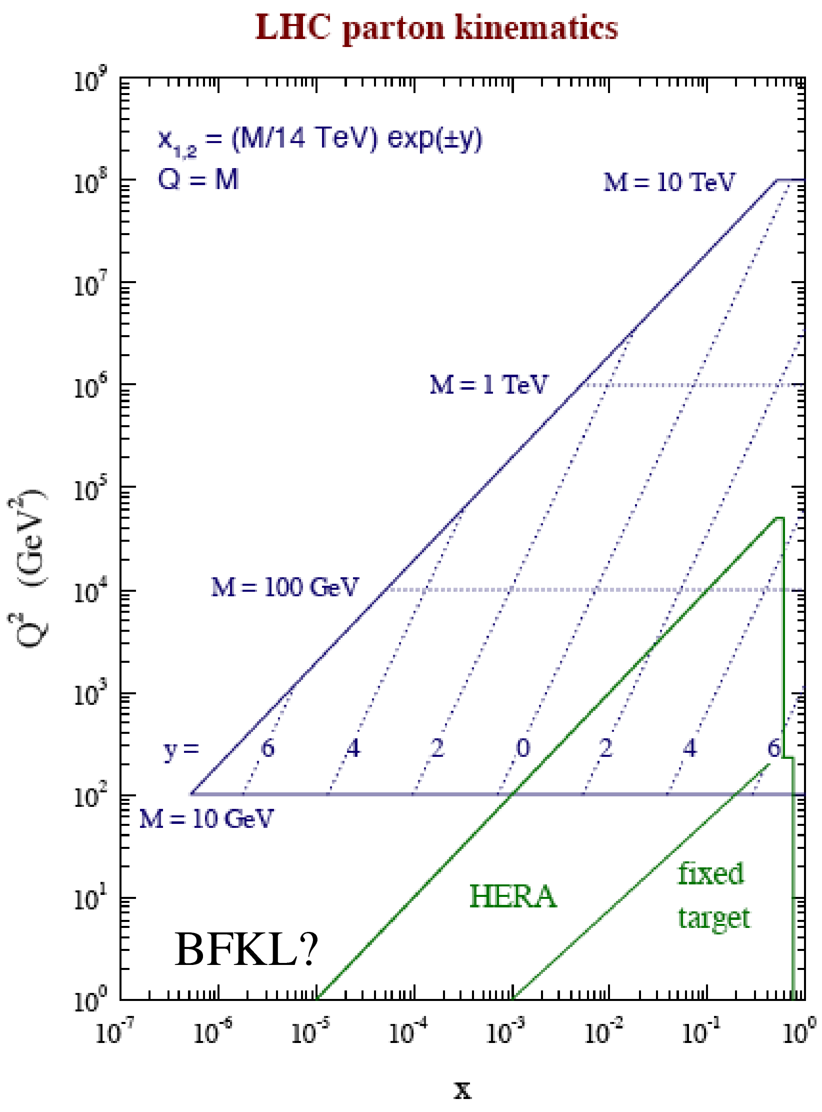
$$\sigma_{W/Z} = \sum_{i,j} \int dx_i dx_j \, f_1(x_i) \, f_2(x_j) \, \hat{\sigma}_{ij \to W/Z}\left(S_{\max} x_i x_j\right)$$

- The partonic cross section is known at NNLO at 1% level (PRD 094008)
- The PDF contribution controversial (commonly set at 3%) (hep-ph/0307219)
- Currently available tools are NLO + parton shower (see also CMS 2004/056)
- Uncertainty on background simulation to be studied
  - QCD and heavy quarks (difficult to simulate, real data needed)
  - Leptonic decays of top quark pairs
  - $W \to \tau \to l$ decays
- Uncertainty on acceptance determination at 2% level (hep-ph/0405130)
  - Variation of NLO QCD scale 1%
  - PDF contribution 1%
  - Improvement are expected by better fixing PDF by looking at W/Z data
  - EW effect of multiple photon radiation to be studied

A. SBRIZZI

A WORD OF CAUTION

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x in many key searches
  - dominance of gluon and sea quark scattering
    - where HERA experience comes in handy
  - large phase space for gluon emission and thus for production of extra jets
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



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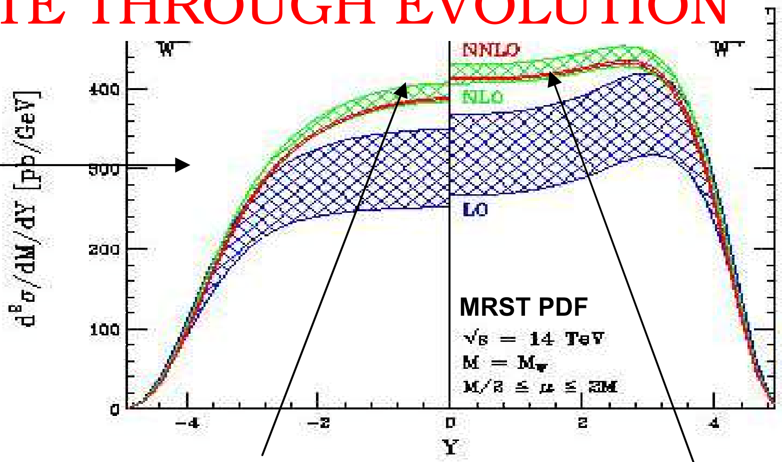
PARTON UNCERTAINTIES PROPAGATE THROUGH EVOLUTION



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

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

BUT- there are also QED effects to be considered of a similar size to NNLO QCD

PDF uncertainty has been considered as a dominant contribution and most PDF groups quote uncertainties <~5%

PDF Set	$\sigma_{W^+}\cdot B_{W\to l\nu}$ (nb)	$\sigma_{W^-}\cdot B_{W\to l\nu}$ (nb)	$\sigma_Z\cdot B_{Z\to ll}$ (nb)
ZEUS-S	12.07 ± 0.41	8.76 ± 0.30	1.89 ± 0.06
CTEQ6.1	11.66 ± 0.56	8.58 ± 0.43	1.92 ± 0.08
MRST01	11.72 ± 0.23	8.72 ± 0.16	1.96 ± 0.03

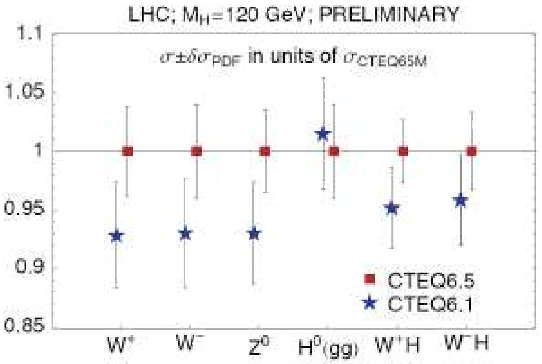
BUT **the central values differ by more than some of the uncertainty estimates.**

AND the situation just got dramatically worse. The new CTEQ6.5 estimate is 8% higher

MRST-CTEQ QUARK AGREEMENT AT LOW SCALE

⇒ DISAGREEMENT AT HIGH SCALE

monitor

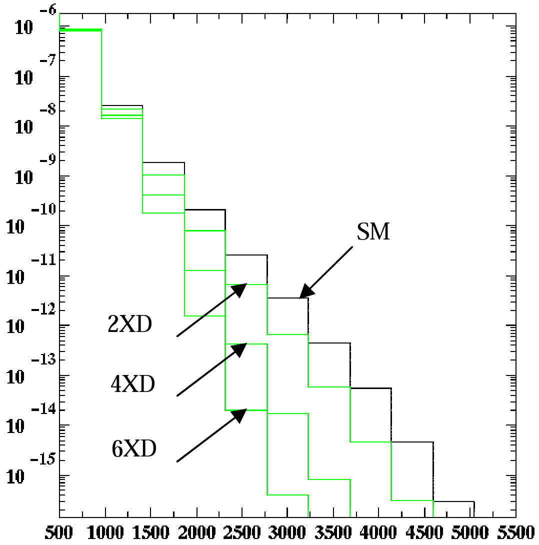


A. COOPER-SARKA

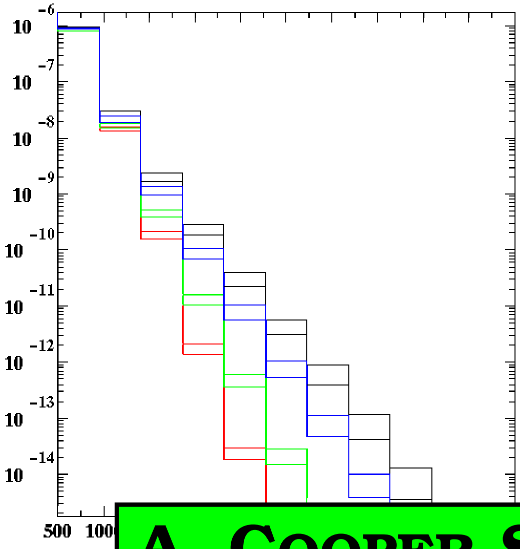
LHC LIMITED BY PDFS (J. HUSTON)

Such PDF uncertainties the jet cross sections compromise the LHC potential for discovery.
E.G. Dijet cross section potential sensitivity to compactification scale of extra dimensions (M_c) reduced from ~6 TeV to 2 TeV. (Ferrag et al)

M_c = 2 TeV,
no PDF error



M_c = 2 TeV,
with PDF error



A. COOPER-SARKAR

TURNING THE QUESTION AROUND…

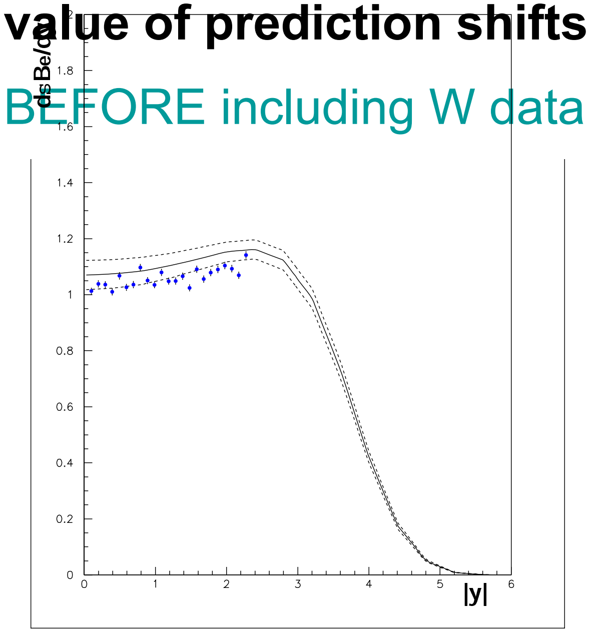
by how much can we reduce the PDF errors with early LHC data?

EXAMPLE I: SMALL x GLUON

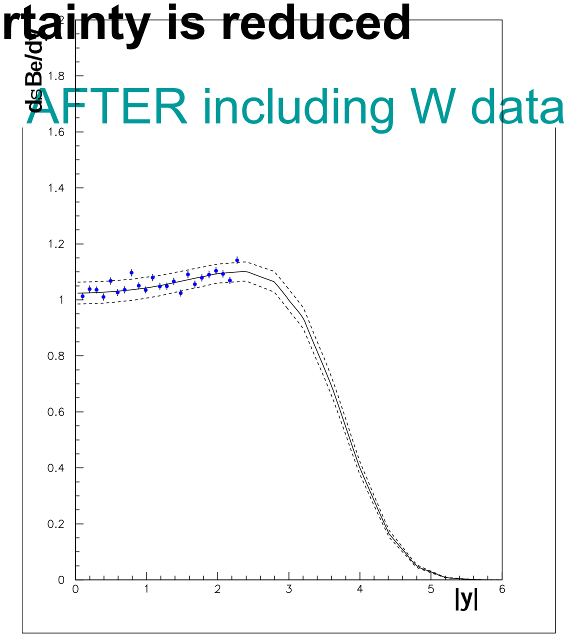
Generate data with 4% e hrough ATLFAST detector simulation and then include this pseudo-data in the global ZEUS PDF fit **Central value of prediction shifts and uncertainty is reduced**

BEFORE including W data

AFTER including W data



Lepton+ rapidity spectrum data generated with CTEQ6.1 PDF compared to predictions from ZEUS PDF



Lepton+ rapidity spectrum data generated with CTEQ6.1 PDF compared to predictions from ZEUS PDF AFTER these data are included in the fit

Specifically the low-x gluon shape parameter λ, $xg(x) = x^{-\lambda}$, was
λ = -.199 ± .046 for the ZEUS PDF before including this pseudo-data
It becomes λ = -.181 ± .030 after including the pseudoda

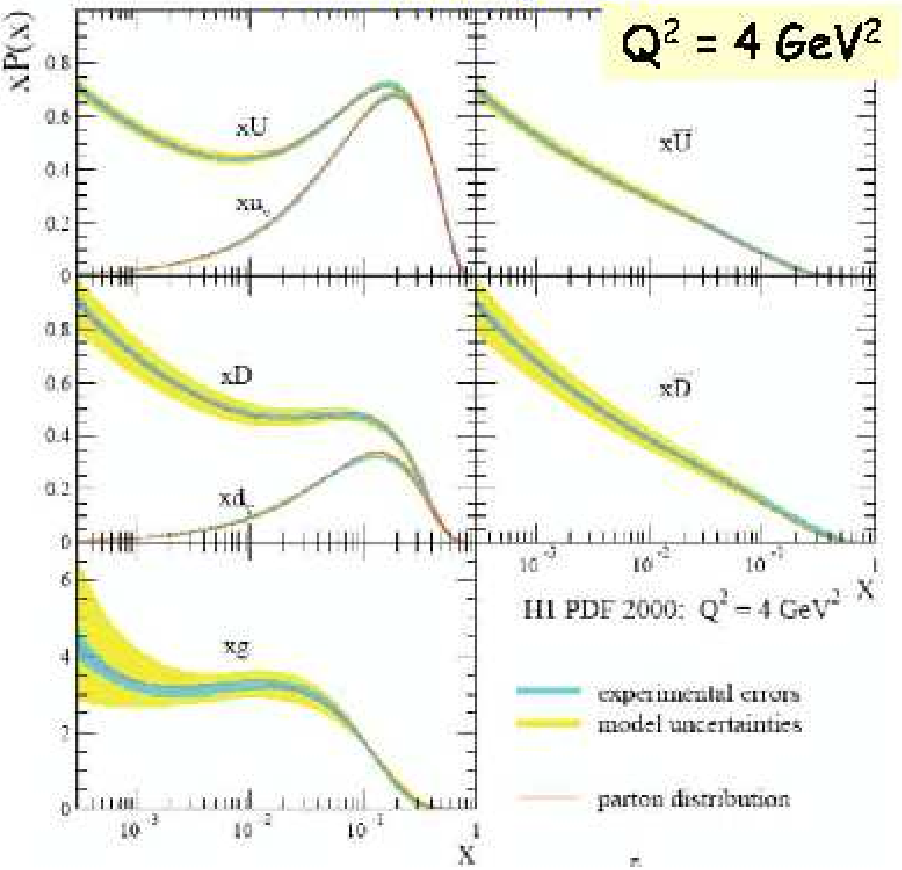
A. COOPER-SARKAR

EXAMPLE II: $\bar{u} - \bar{d}$ AT SMALL x

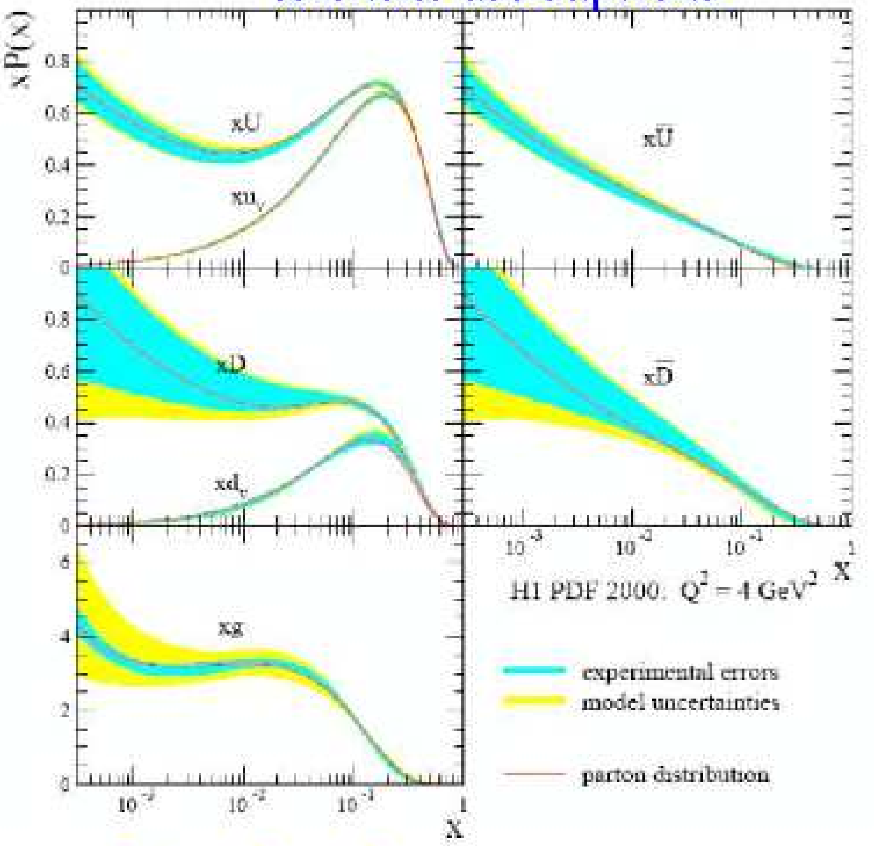
POSSIBLE NON-REGGE BEHAVIOUR

MK/BR,
March 2005

With assumptions



Without assumptions



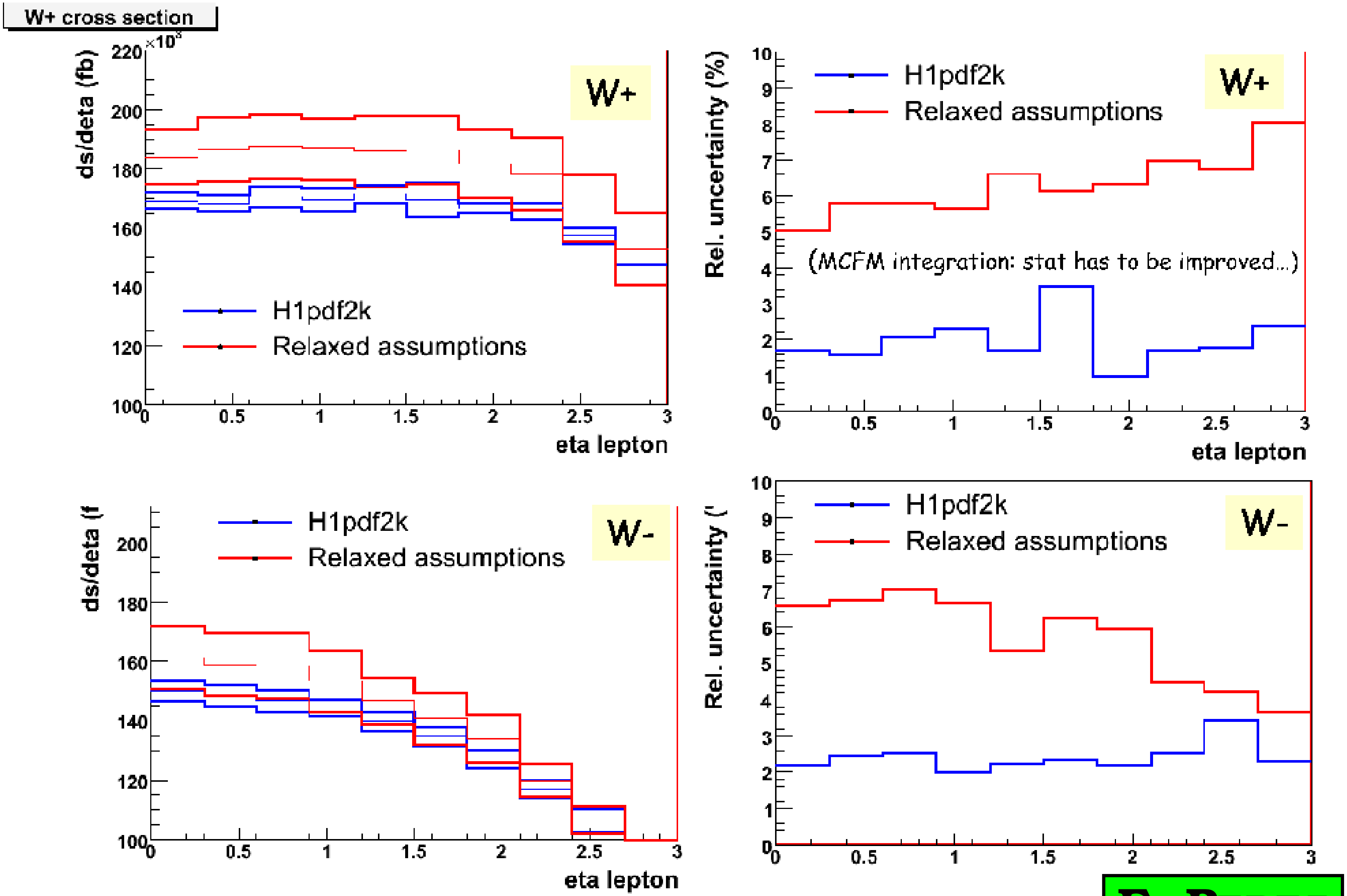
Relax $B_U = B_D$
& relation between A_U and A_D

eD at HERA would have helped a lot...

i.e. still assume u=ubar, d=dbar,
relax ubar = dbar

E. PEREZ

Uncertainties on W x-sections



(MCFM integration: stat has to be improved...)

E. PEREZ

EXAMPLE III: GLUONS AND SEA AT SMALL x

LHC is a low-x machine (at least for the early years of running)

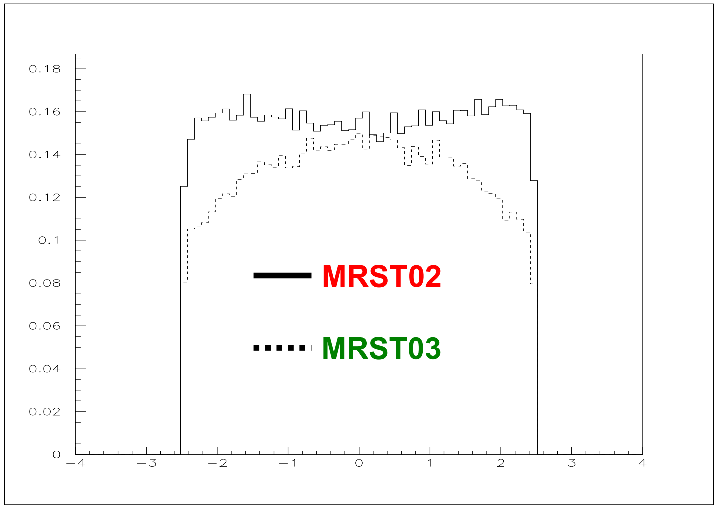
Is NLO (or even NNLO) DGLAP good enough?

The QCD formalism may need extending at small-x

MRST03 is a toy PDF set produced without low-x data

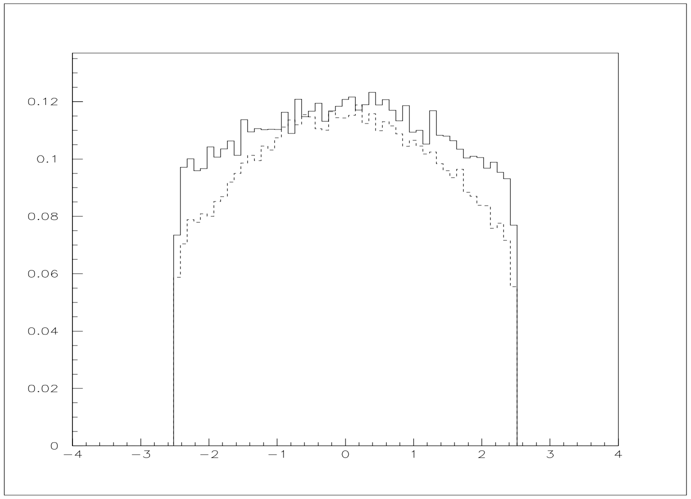
200k events of **W+- -> e+-** generated with MC@NLO using MRST03 and MRST02

Reconstructed Electron Pseudo-Rapidity Distributions (ATLAS fast simulation)



Reconstructed e^+

6 hours running



Reconstructed e^-

If something is very different about low-x behaviour it will show up in the our measurable rapidity range

A. COOPER-SARKAR

OUTLOOK

FitPDF?

NEED A JOINT EFFORT OF THEORISTS AND LHC EXPERIMENTALISTS:

- WHICH PRECISION MEASUREMENTS ARE LIMITED BY PDFS?
- WHEN DOES LACK OF PDF KNOWLEDGE HIDE/SIMULATE NEW PHYSICS?
- HOW CAN LHC MEASUREMENTS IMPROVE PDF DETERMINATION?

EXPERIMENTAL INPUT

SOME EXPECTATIONS

- HERA: F_L & COMBINED F_2
- NEUTRINO DATA: INCOMPATIBILITIES?
- JETS: WHAT IS THE IDEAL DATASET?

OPEN ISSUES

SOME EXAMPLES

- W/Z CROSS-SECTION AS STANDARD CANDLE:
  ARE UNCERTAINTIES UNDER CONTROL? (EG HEAVY QUARKS)
- $\bar{u} - \bar{d}$ FROM $W\pm$ ASYMMETRY:
  REGGE BEHAVIOUR AT SMALL X?
- OBSERVABLES SENSITIVE SMALL x PARTONS
  RESUMMATION REQUIRED AT NNLO?

THE PDF CONTROL ROOM AT LHC

Control room is operational and used during the cosmic commissioning runs integrating gradually more detector components.

Cosmic ray data is collected through segments of the full final Event Building and DAQ system