QCD Physics - Lecture 6

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Outline

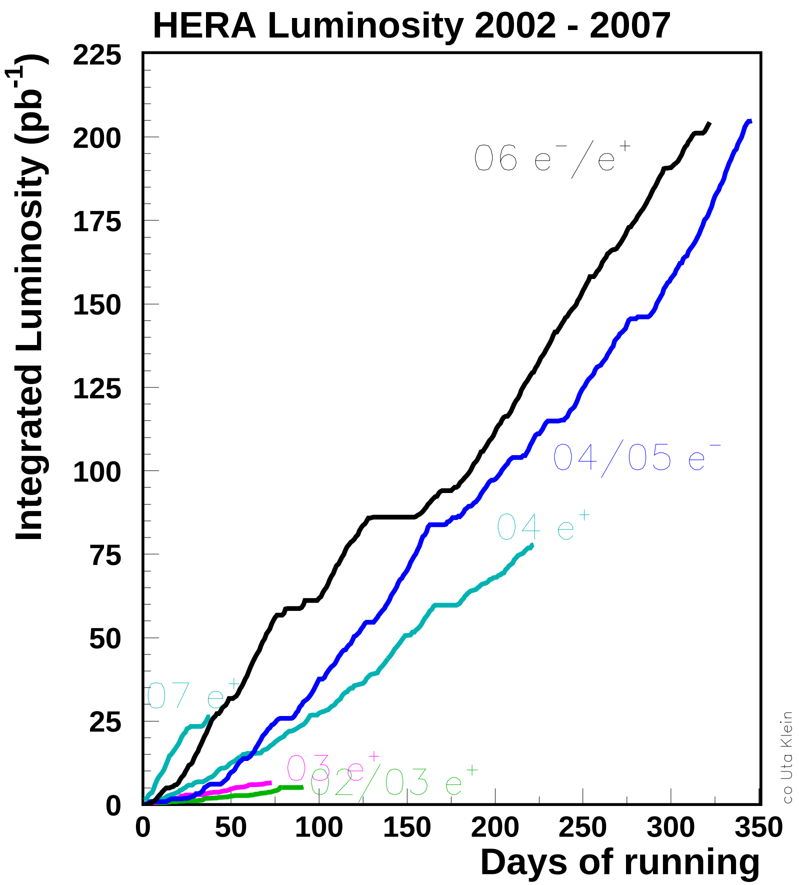
http://www.desy.de/∼heralhc

- Identify & prioritise measurements to be made at HERA with an impact on the physics reach of the LHC.
- Encourage and stimulate knowledge transfer between communities + establish ongoing interaction.
- Encourage & stimulate theory and phenomenological efforts.
- Examine & improve theoretical & experimental tools.
- Increase quantitative understanding of the implications of HERA measurements on LHC physics.

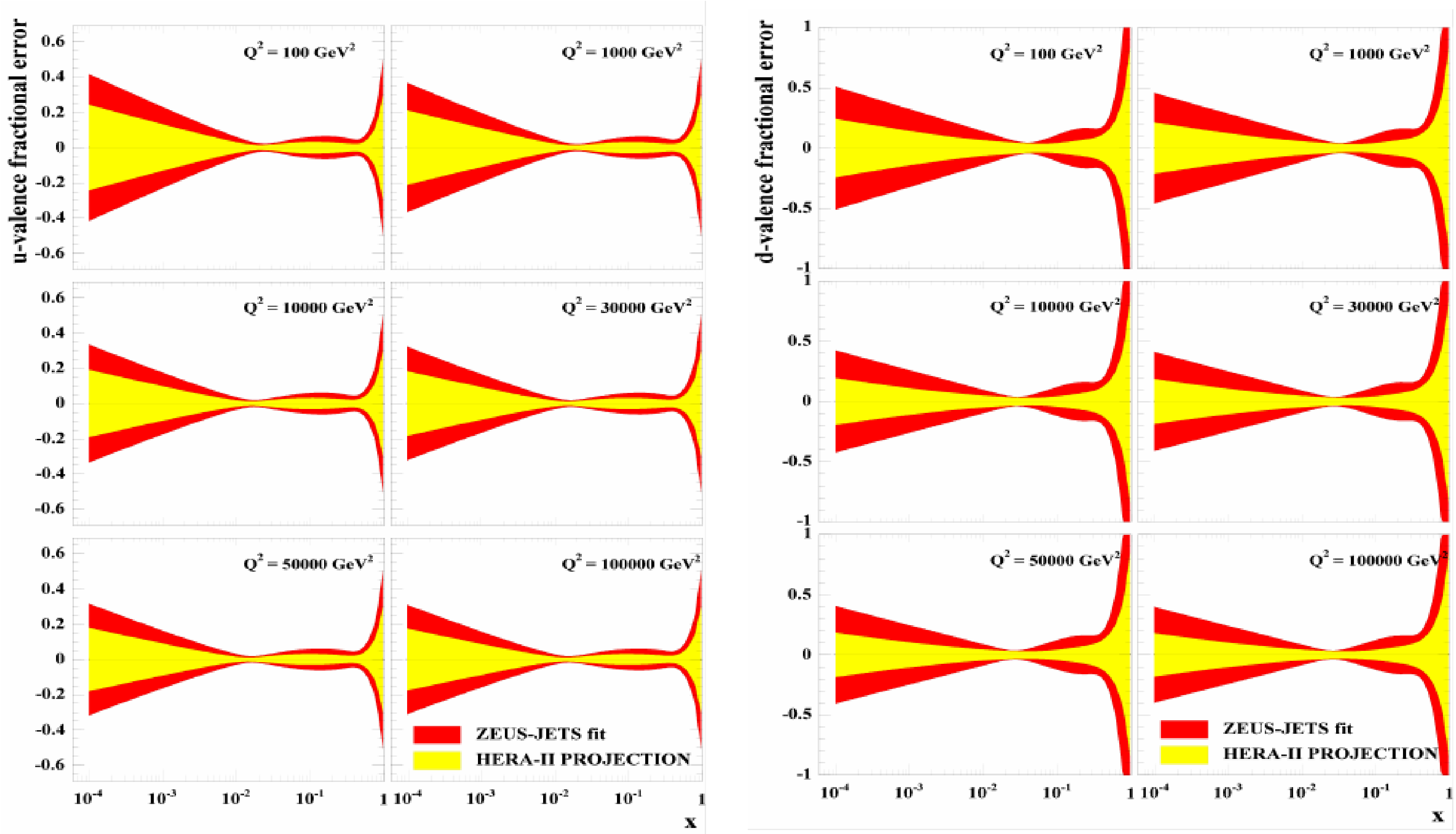
Work on understanding how to use Tevatron data to improve event modelling and theoretical understanding of cross sections for the signals and backgrounds at the LHC

HERA will run until mid 2007

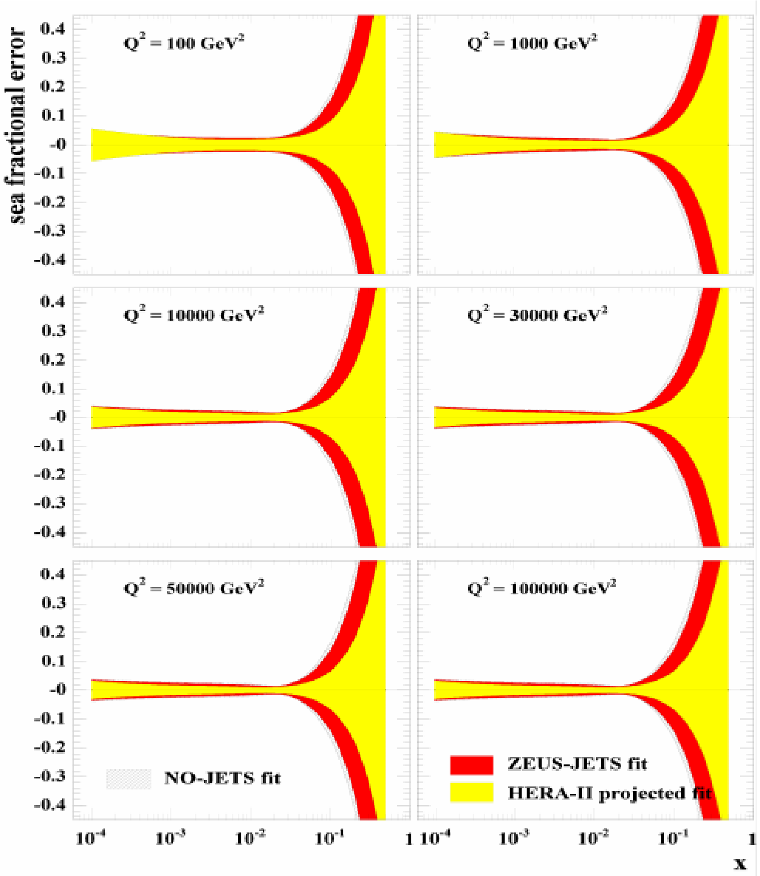
- Will collect a large amount of new data
- Can expect significant improvement before LHC turns on

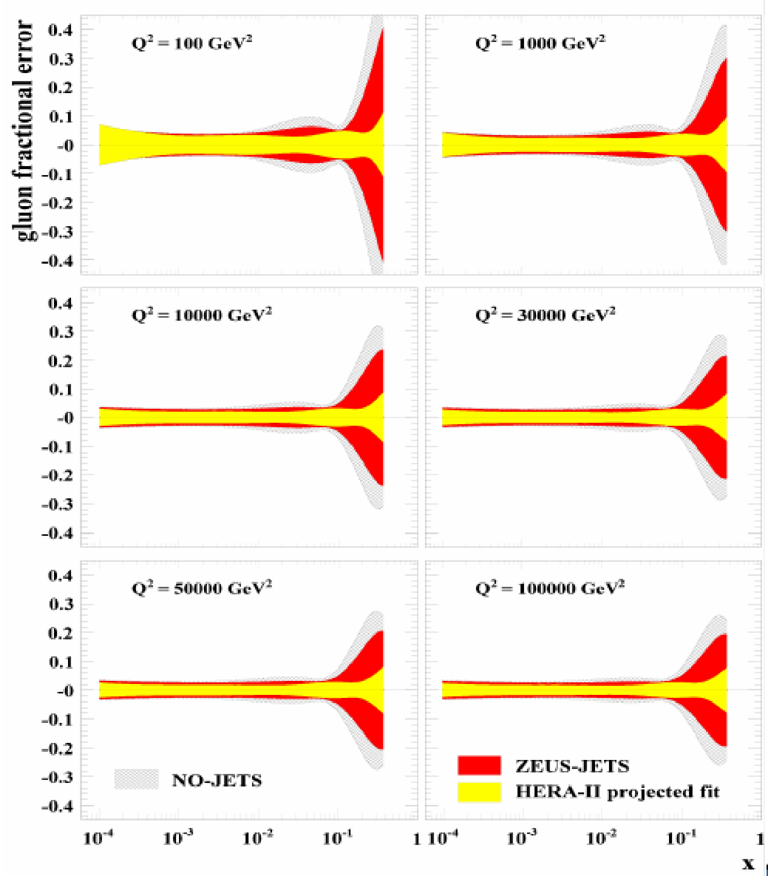


How much improvement can we expect in PDFs?



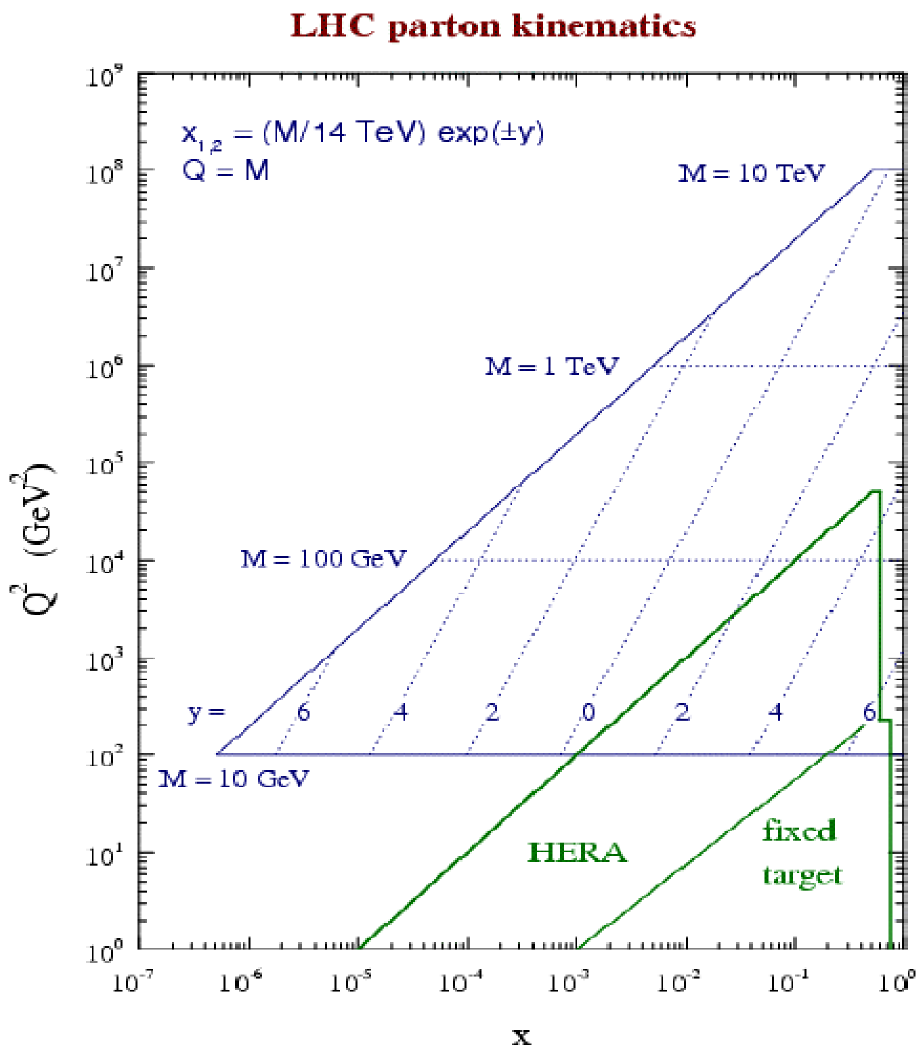
Valence quark distributions expected to improve in HERA II





Sea quark and Gluon expected to improve from HERA II, relevant for LHC processes

W and Z production at the LHC I



Already seen that W/Z production occurs via $q\bar{q} \rightarrow W/Z$ at LO

Momentum fraction of particles taking part in the process is $x_{1,2} = \frac{M}{\sqrt{s}} exp(\pm y)$

$$y = \frac{1}{2}\frac{E+p_l}{E-p_l}$$

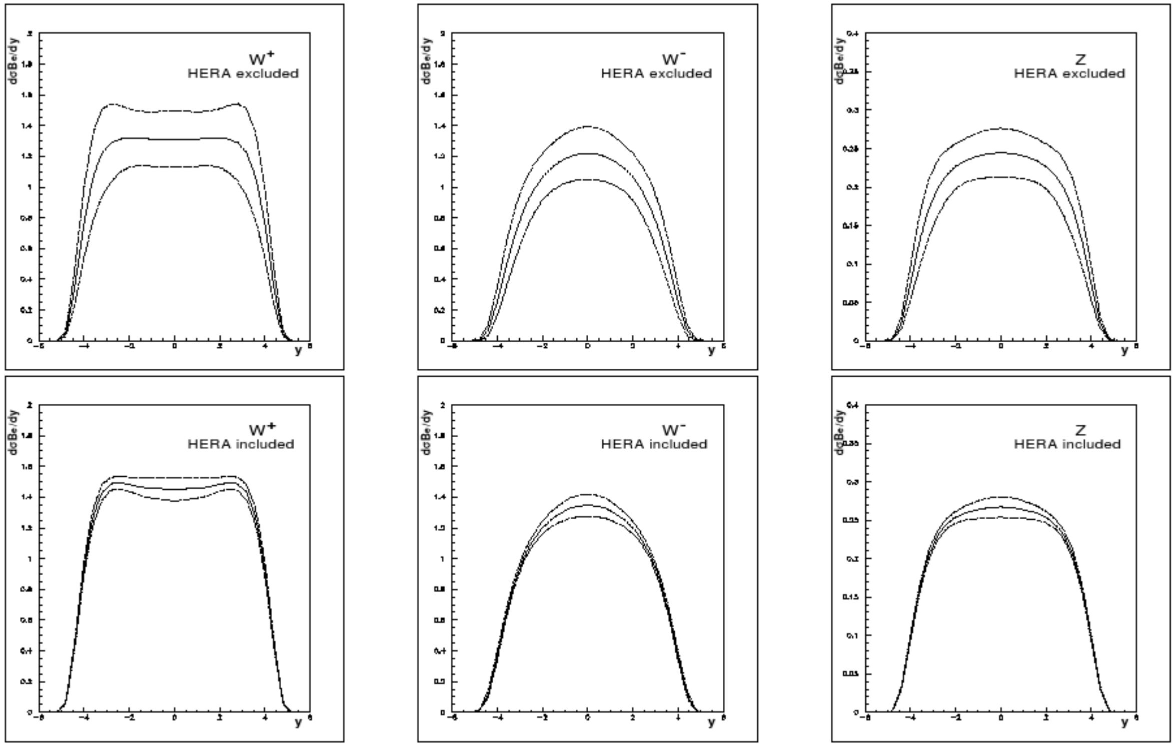
at central rapidity $x \sim 0.005$

$|y| < 2.5 \rightarrow 10^{-4} < x < 0.1$

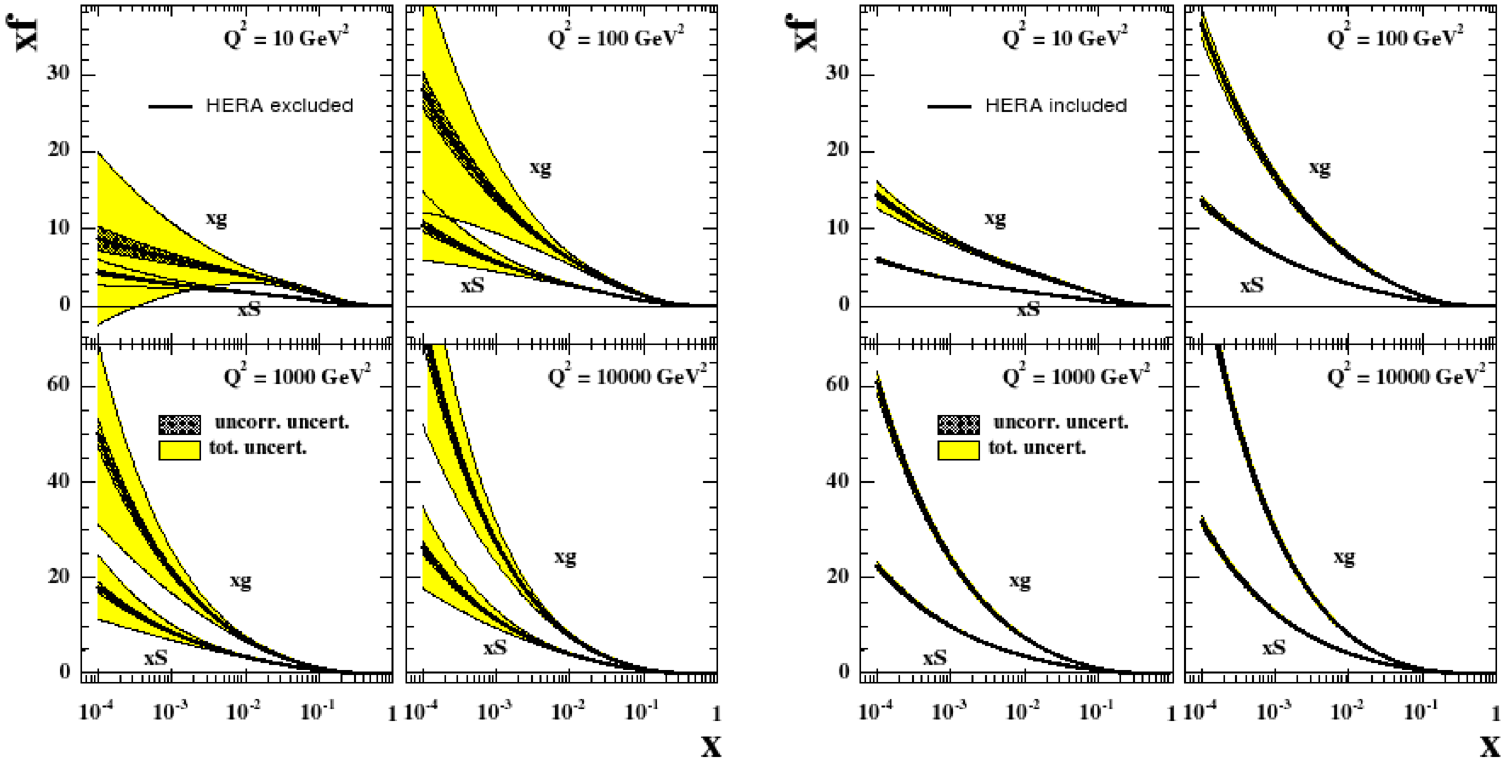
Unlike TeVatron u_v, d_v not involved

$Q^2 \approx M_W^2 \rightarrow g$ dominant

W and Z production at the LHC II



- Before HERA I uncertainty in g and sea q was $\sim 16\%$
- Post HERA I uncertainty improves to e $\sim 3.5\%$
- Will improve from HERA II measurements



Huge improvement in sea-q and g uncertainties from HERA data

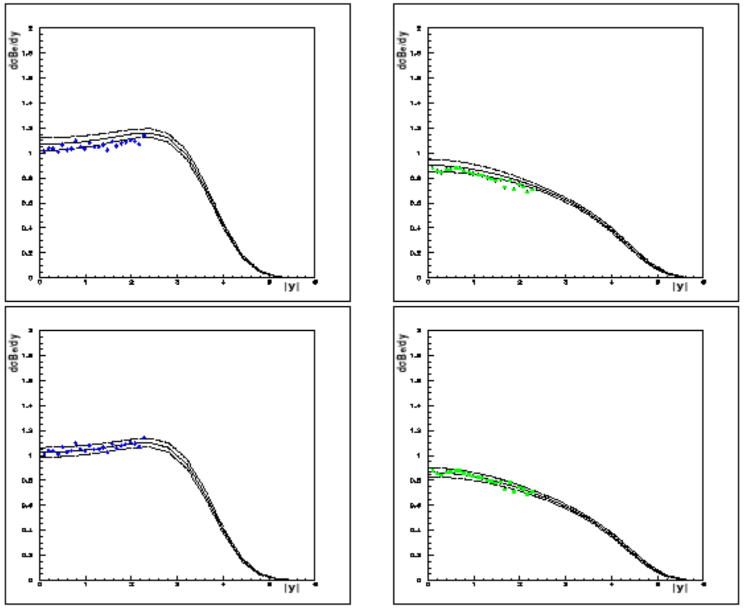


Fig. 14: Top row: e^+ and e^- rapidity spectra generated from CTEQ6.1 PDFs, which have been passed through the ATLFAST detector simulation and corrected back to generator level using ZEUS-S PDFs, compared to the analytic prediction using ZEUS-S PDFs. Bottom row: the same lepton rapidity spectra compared to the analytic prediction AFTER including these lepton pseudo-data in the ZEUS-S PDF fit.

Small improvement on uncertainties indicated by simulated data

- In the QPM F_L is zero.
- In DGLAP QCD to lowest order F_L is given by:

$$F_L(x, Q^2) = \frac{\alpha_S}{4\pi} x^2 \int_x^1 \frac{\mathrm{d}z}{z^3} \cdot \left[\frac{16}{3} F_2(z, Q^2) + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) zg(z, Q^2)\right]$$

which can be, approximately solved to give a measurable gluon quantity:

$$xg(x) = 1.8 \left[\frac{3\pi}{2\alpha_S} F_L(0.4x) - F_2(0.8x)\right] \simeq \frac{8.3}{\alpha_S} F_L$$

(determined by measurements of F_2 and F_L)

Extraction of F_L

Recall that for unpolarised $e^{\pm}p$ scattering:

$$\frac{\mathrm{d}^2\sigma^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha_2}{xQ^4}[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) \mp Y_-xF_3(x,Q^2)]$$

$Y_{\pm} = 1 \pm (1-y)^2$

For $Q^2 < 50$ we can neglect xF_3 and write an expression of the reduced cross section (σ_r)

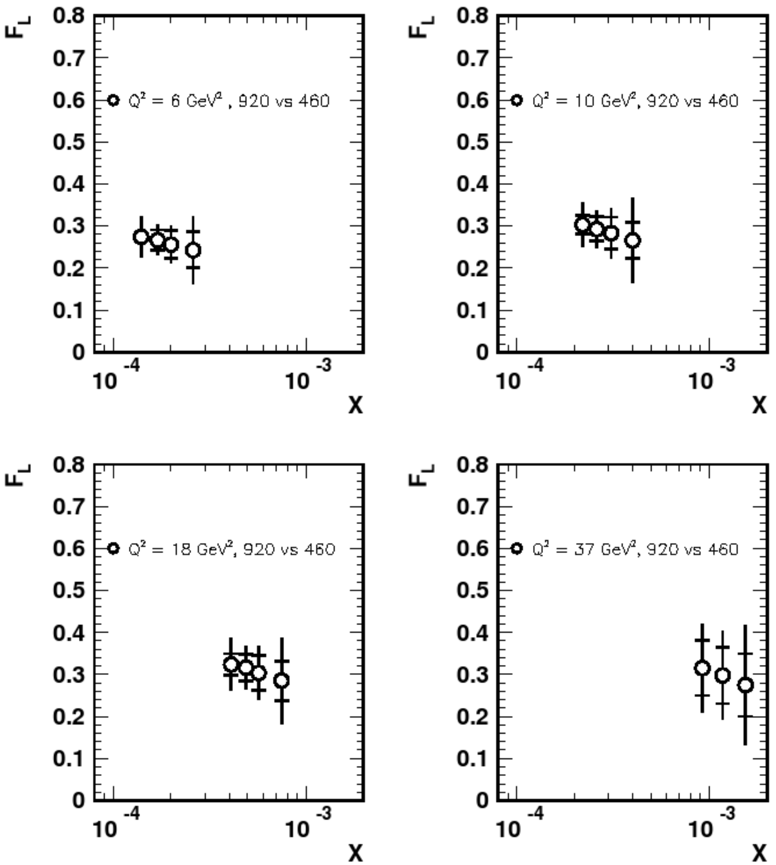
$$\sigma_r = \left(\frac{xQ^4}{2\pi\alpha^2 Y_+}\right)\frac{\mathrm{d}^2\sigma^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2} = \left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right]$$

Measurements at different y for the same x, Q^2 required.

Solution? Use different beam energies

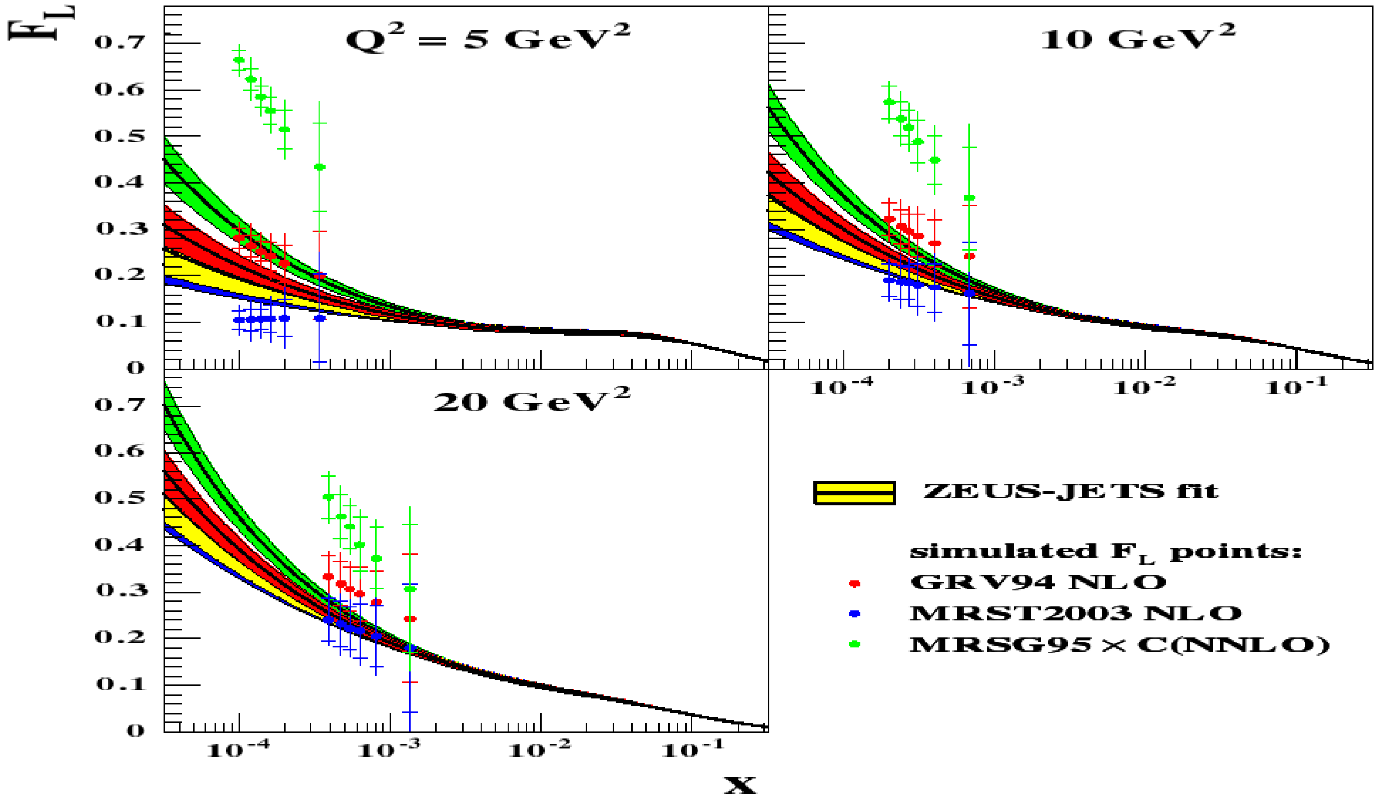
Choice of energies is made to maximise difference in $\frac{y^2}{Y_+}$

Scenario	$E_P = 920$	$E_P = 460$ GeV	$E_P = 690$ GeV
1	30 pb^{-1}	10 pb^{-1}	0 pb^{-1}
2	30 pb^{-1}	5 pb^{-1}	5 pb^{-1}



The ZEUS and H1 experiments have proposed several low-energy running scenarios to enable HERA data to be used to measure F_L.
Scenarios require approx 3 months of running, and may take place later this year. 15 % of the nominal energy running luminosity would be sacrificed for this important measurement.

Impact of F_L on PDF uncertainties

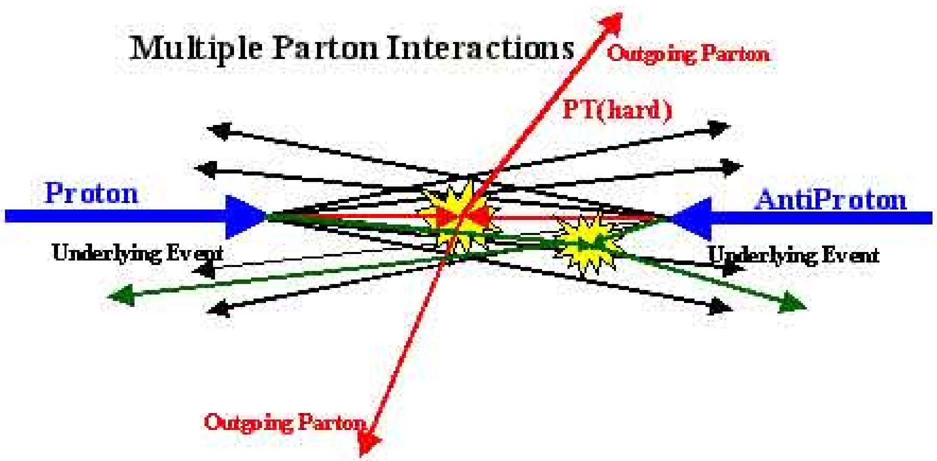


Impact is very small except at low Q^2

- Inelastic hadron-hadron collisions are dominated by soft (low p_T) interactions. Occasionally we see a hard scatter
- Important to model both the soft and hard components in MCs so that:
  - The impact on physics backgrounds can be assesed
  - The impact on detector performance can be evaluated
- We also expect the effects of multiple parton interactions (MPI) to become significant at the LHC
- Perturbative QCD is very succesful when applied to hard processes but cannot be applied to the soft interactions.

Break the activity in an event into two separate groups

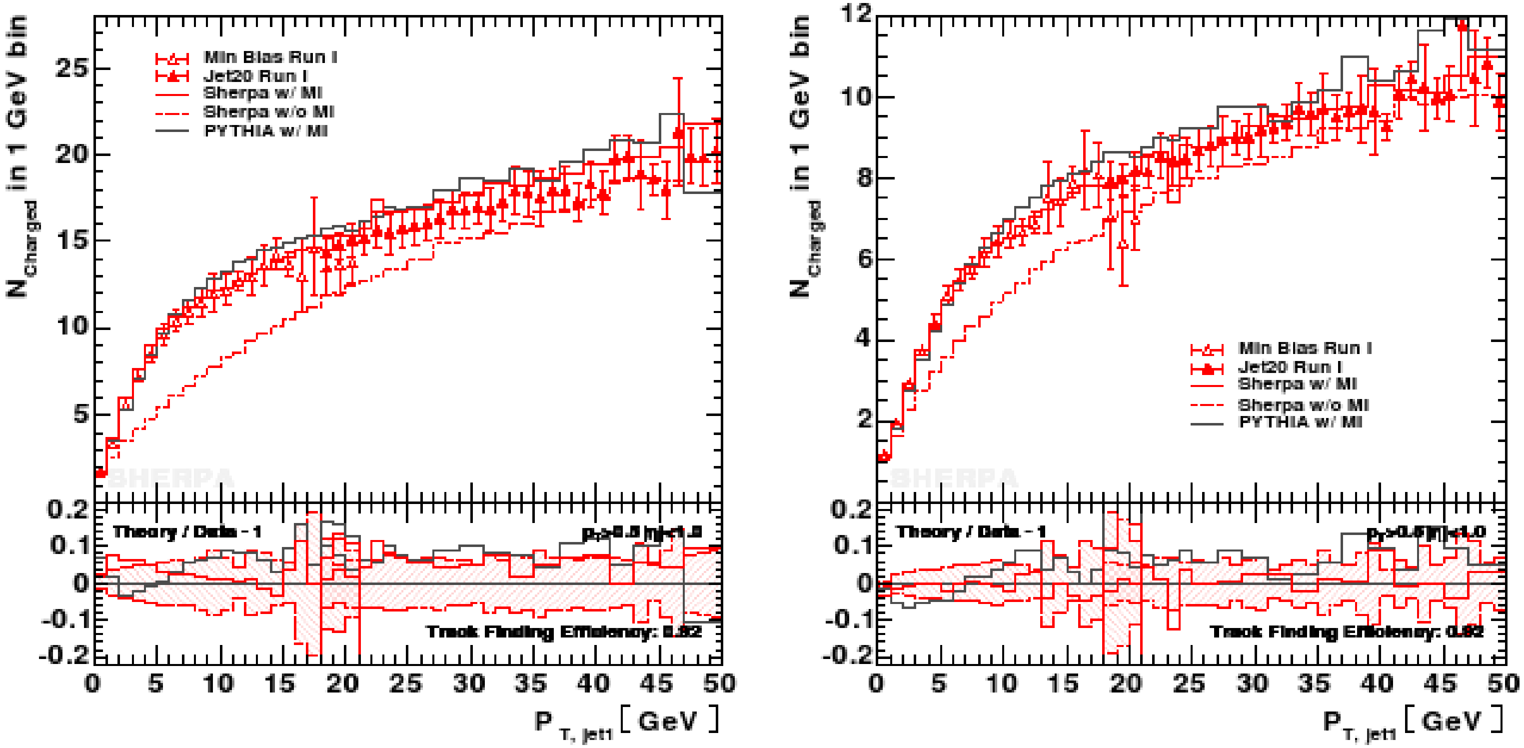
- The hard scattering component which consists only of the high transverse energy jets arising from the hard interaction itself and containing the information about the underlying subprocess
- The Underlying Event which incorporates all remaining hadronic activity



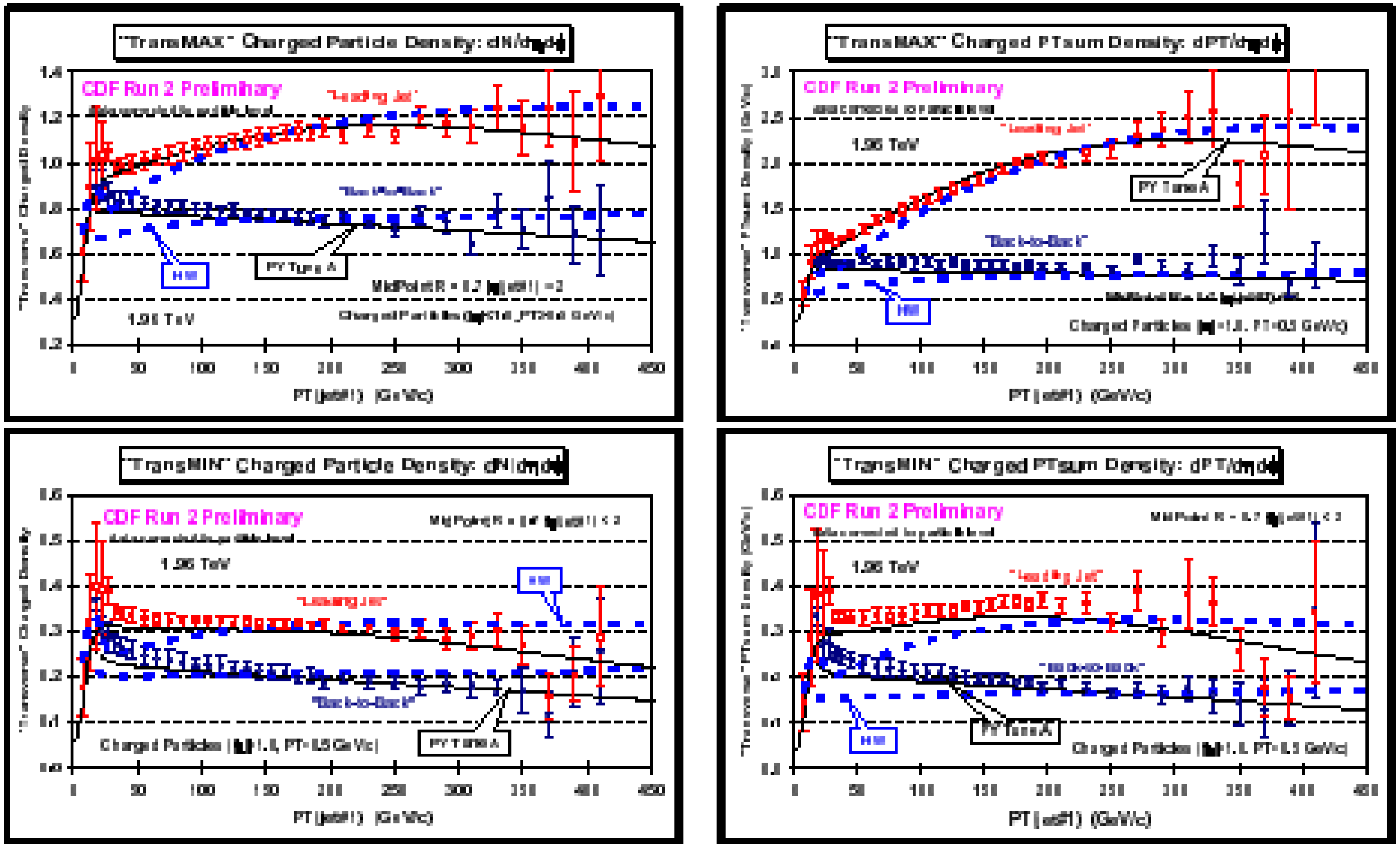
Multiple Parton Interactions

Becuase hadrons are composite objects it is possible for secondary scatters to take place between partons in beam remnants in hadronic collisions. This phenomenon is called Multiple Parton Interactions

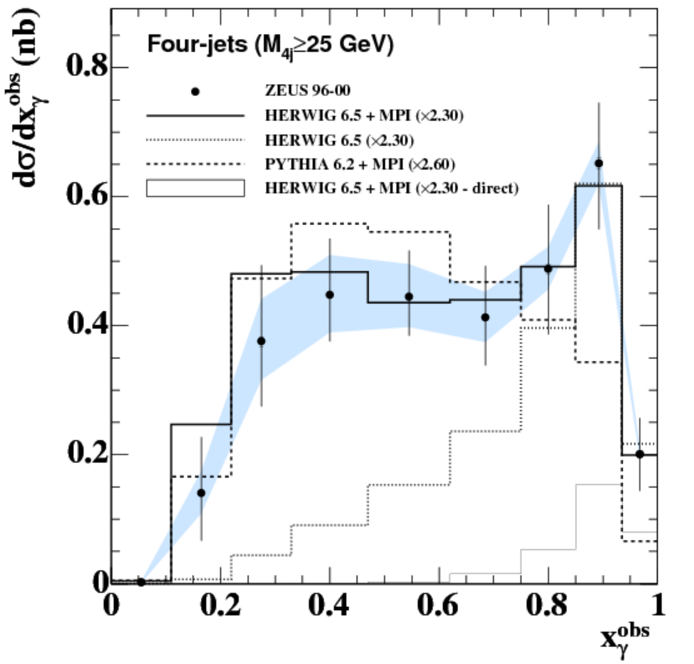
- The existence of MPI has a direct impact on the hadronic final state
- The increased energy flow can form a hard partonic scattering component to the underlying event
- Jet energies in hard scatter may be increased and other jet quantities may be altered

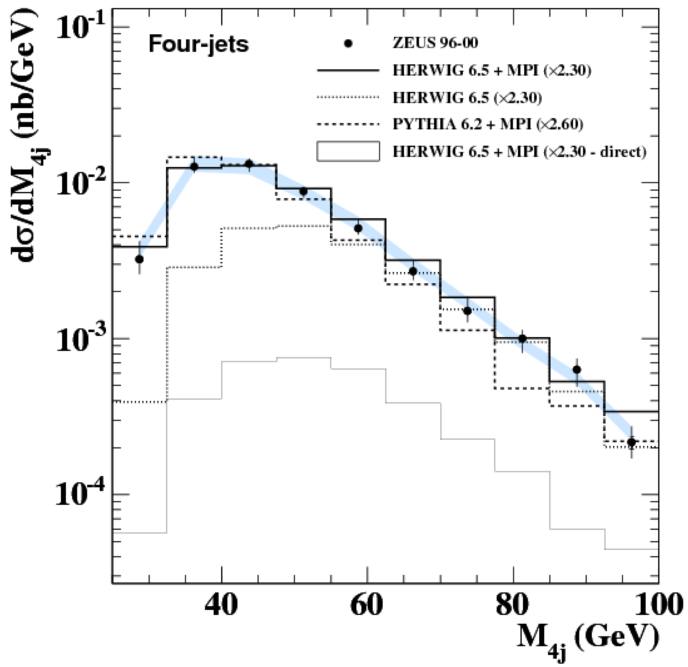


CDF run1 data already gave evidence for MI



Tunes to CDF run2 data already being done. Progress will certainly affect Tevatron MC





Can HERA help us to understand the underlying event?

- Resolved γp at HERA is a hadron-hadron collision
- Sensitivity to MPI has been observed at HERA
- Fits to HERA data have been used to predict the LHC final state, results are close to CDF tune and stable.

- The production of Heavy Quarks in hadron-hadron collisions (and DIS) is directly sensitive to the gluon content of the hadron.
- Heavy quarks will be copiously produced at future colliders as a background to the more exotic processes expected
- A precise description of the production properties in QCD will aid in discovery of phsyics beyond the SM. An example of this from the ATLAS TDR...

Irreducible background to supersymmetric Higgs production arises from QCD. Dominant processes are gg and gb. Discovery in this channel only possible with precise knowledge of this QCD process

ATLAS detector and physics performance *Volume II*
Technical Design Report *25 May 1999*

Table 19-41 Expected signal and background rates inside the signal mass window as a function of m_A, for $H/A \to b\bar{b}$ decays for $b\bar{b}H$ and $b\bar{b}A$ production with tanβ = 30, after applying an optimised selection procedure. The numbers are given for integrated luminosities of 30 fb^{-1} and 300 fb^{-1}(without and with the LVL1 trigger thresholds applied).

m_A(GeV)	200	300	500	700	900
$\sigma \times$ BR (pb)	107.0	29.0	3.5	0.9	0.2
		Integrated luminosity of 30 fb^{-1}			
Signal	2 550	630	200	50	16
Background	43 000	24000	6100	1800	520
S/B	5.9%	2.6%	2.8%	2.8%	3.0%
$S/\sqrt{B}$	12.4	4.1	2.6	1.2	0.7

Recall hadron-hadron lecture. for generic collision between hadrons with heavy quark production:

$$H_a + H_b \rightarrow Q\bar{Q} + X$$

cross section at centre of mass energy S can be written as:

$$\sigma(S) = \sum_{i,j} \int \mathrm{d}x_1 \int \mathrm{d}x_2 \hat{\sigma}_{ij(x_1 x_2 S, m^2, \mu^2)} f_i^{H_a}(x_1, \mu) f_i^{H_b}(x_2, \mu)$$

$\hat{\sigma}_{ij}$ is the short distance cross section

Short Distance Cross Section

The short-distance cross section is calculable in QCD and is a perturbative expansion in the mass of the heavy quark m:

$$\hat{\sigma}_{ij}(s, m^2, \mu^2) = \frac{\alpha_S^2(\mu^2)}{m^2}\left[f_{ij}^{(0)}(\rho) + 4\pi\alpha_S(\mu^2)\left[f_{ij}^{1)}(\rho) + f_{ij}^{(1)}(\rho)\log(\mu^2/m^2)\right] + \mathcal{O}(\alpha_S)\right]$$

and $\rho = 4m^2/s$

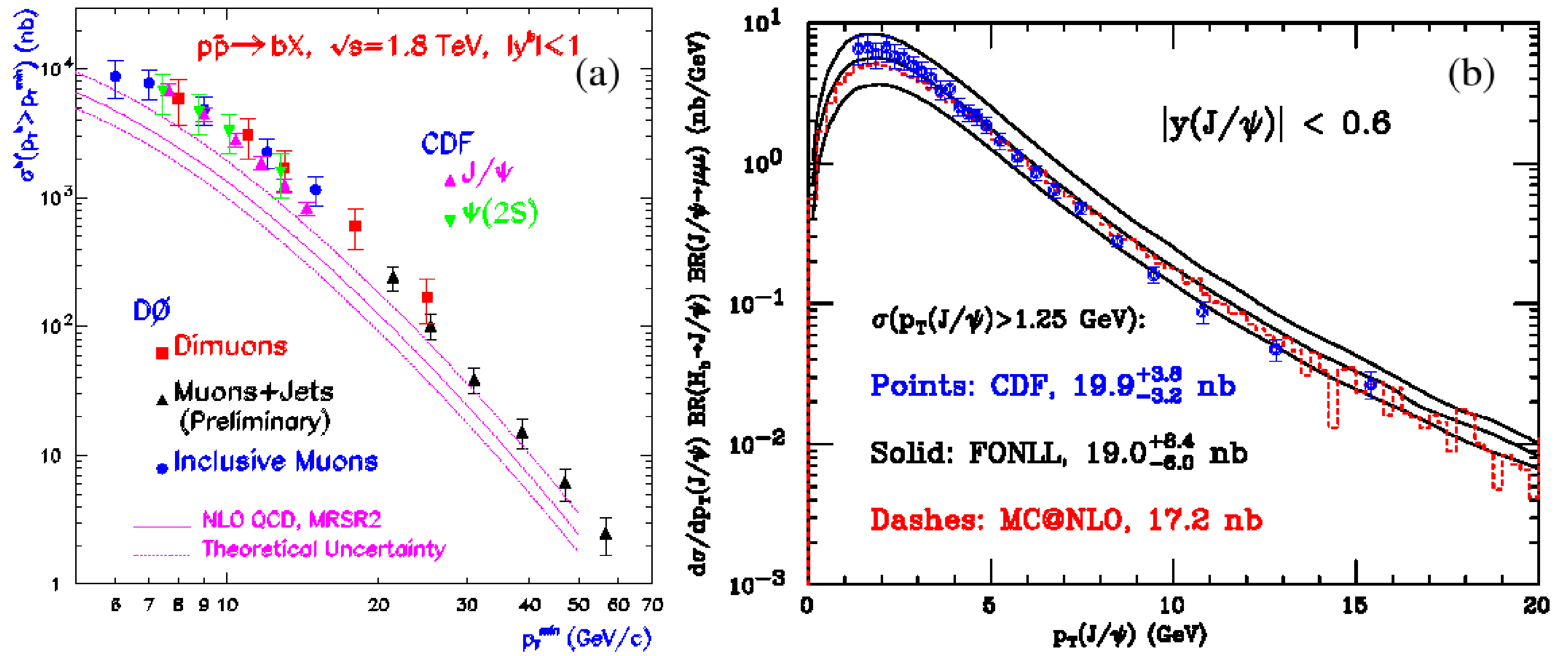
The larger the mass the faster the convergence $\longrightarrow$ predictions for beauty production should be more accurate than those for charm.

3 Schemes for mass treatment

- Fixed Order (FO) - valid for $p_T \approx m_Q$
- Resummed ot next-to-leading order (NLL) a.k.a. "massless" for $p_T \gg m_Q$
- Matched FONLL valid for all scales

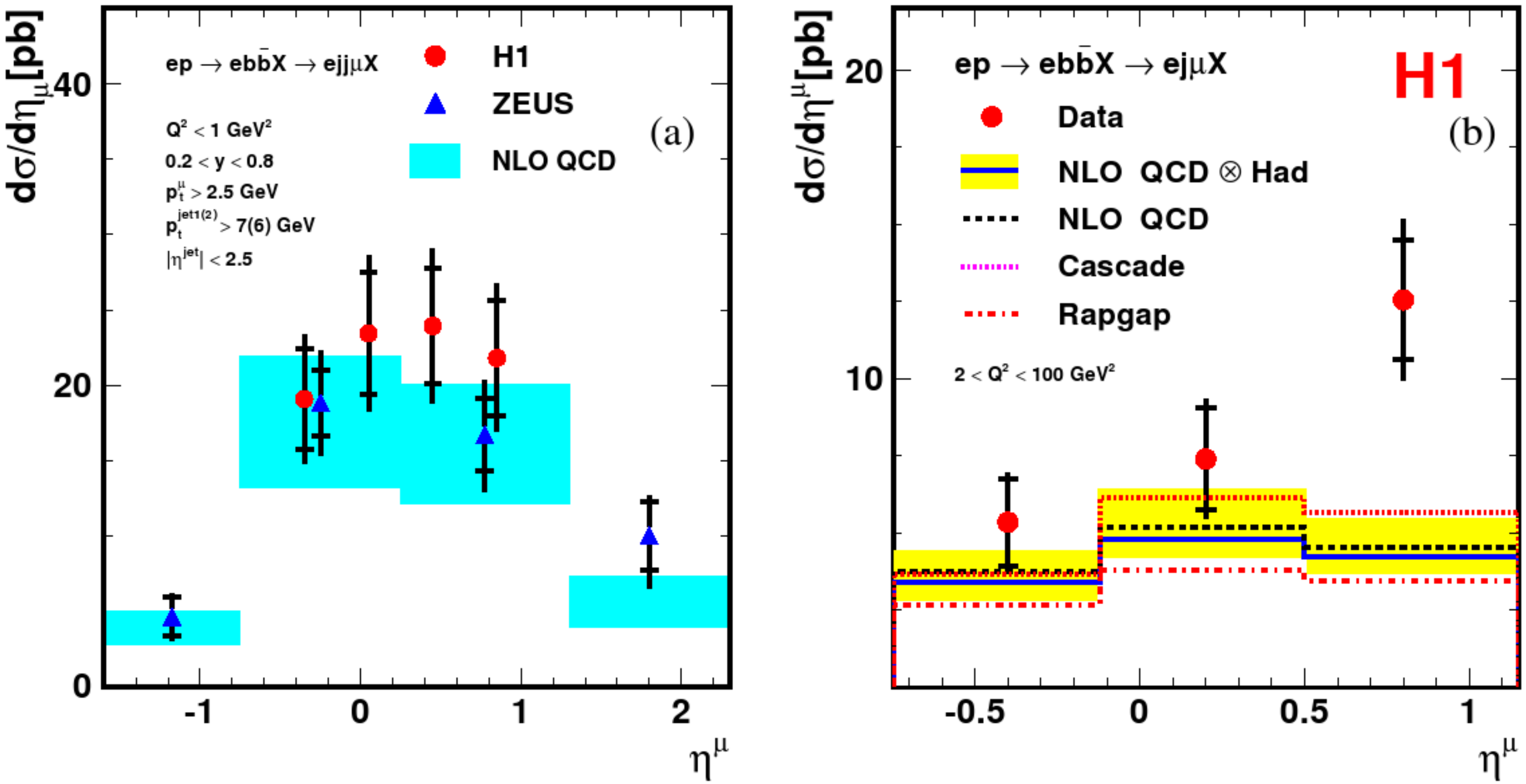
The information for LHC which can be provided by running experiments is:

- The state of the description of heavy quark production by theoretical predictions.
- The gluon and heavy quark content of the proton PDFs
- Details of hadronic fragmentation
- Effect of the underlying event in heavy quark processes
- HERA results (for example) can provide general information on event and jet topologies which will be useful for designing algorithms or triggers at the LHC



Remember from previous lecture that B production is now well described at TeVatron.

- FONLL and MC@NLO (Fixed Order) describe the measured quantities well



Beauty production well described in most of the kinematic regions

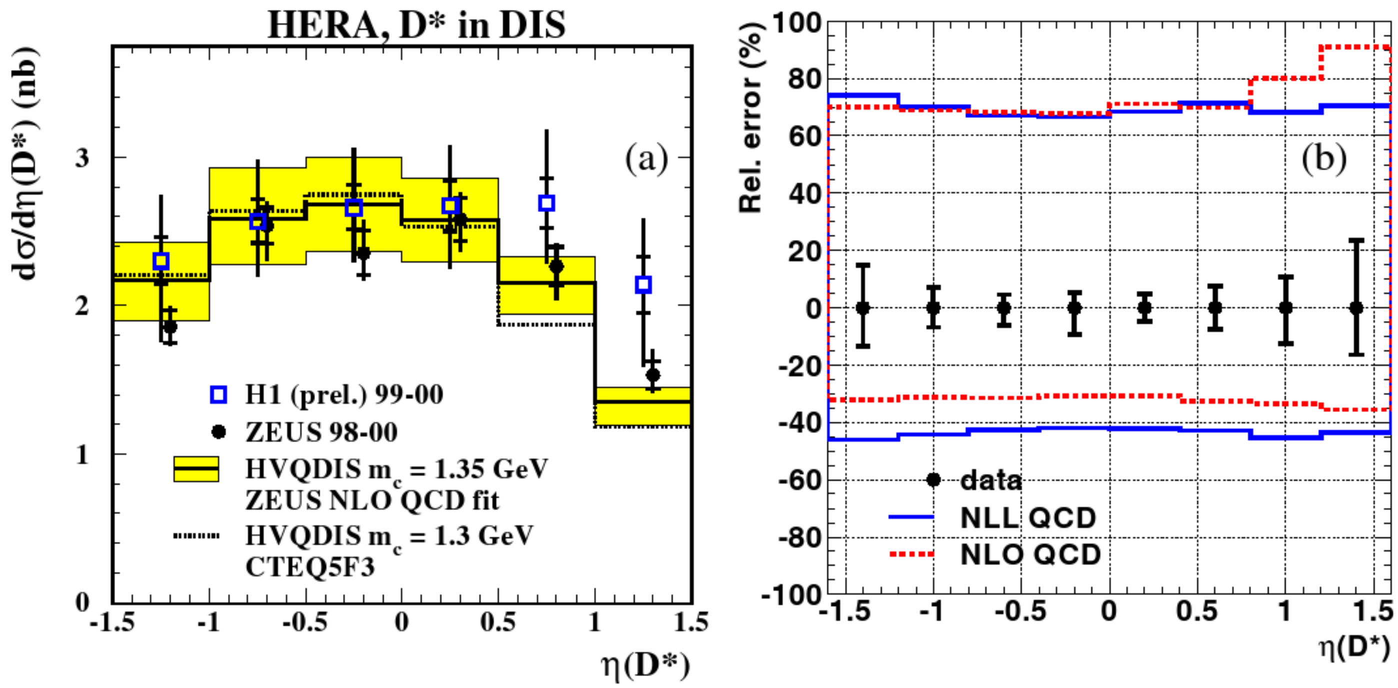
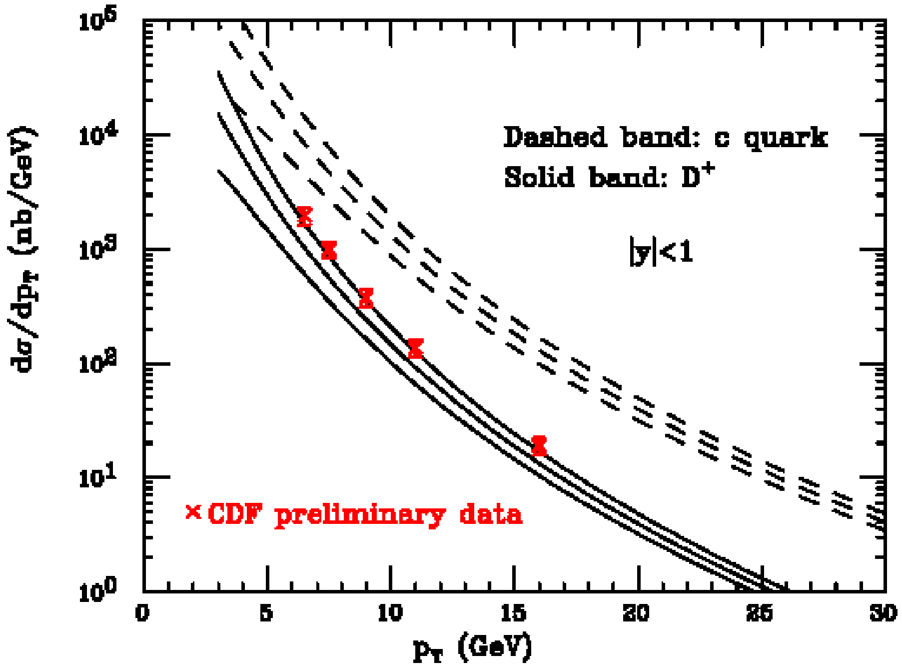


Fig. 4: Measurement of D^* production compared with NLO QCD predictions: (a) the differential cross section in deep inelastic scattering and (b) the relative uncertainty in data and theory in photoproduction.

- Calculations less precise than in beauty
- Theoretical precision much worse than experimental data



- Calculations less precise than in beauty
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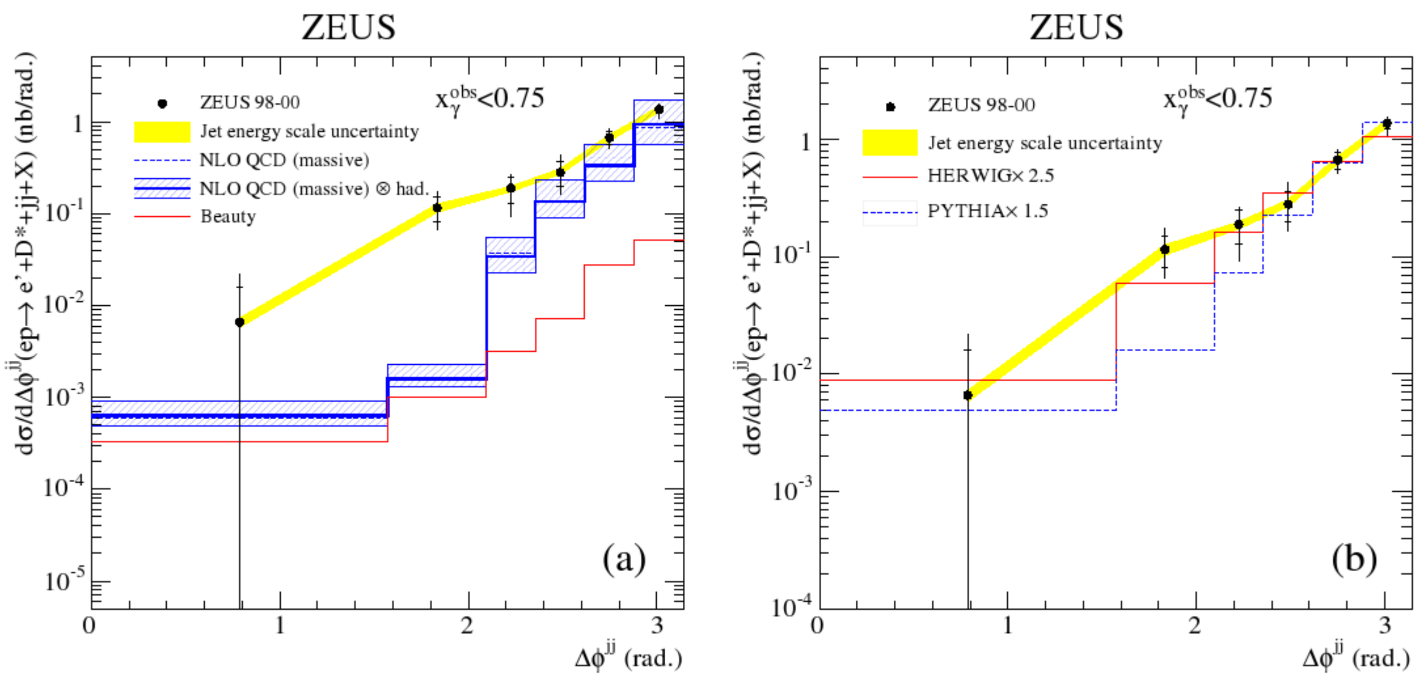
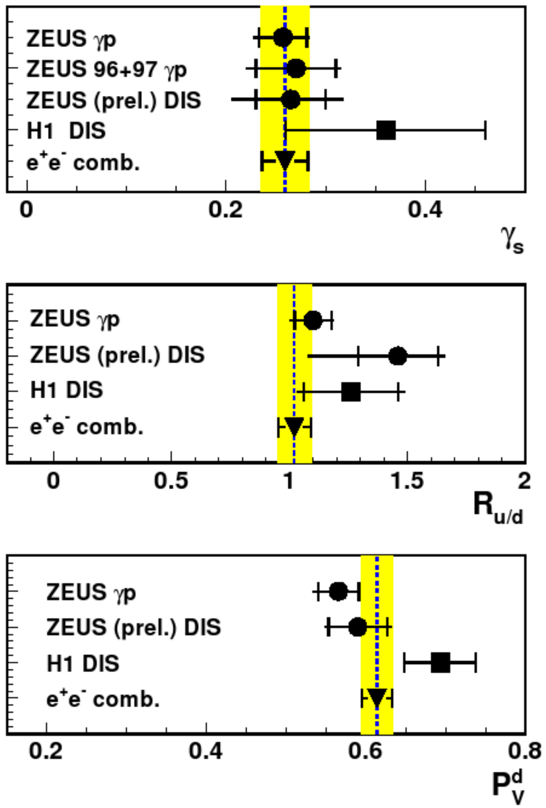
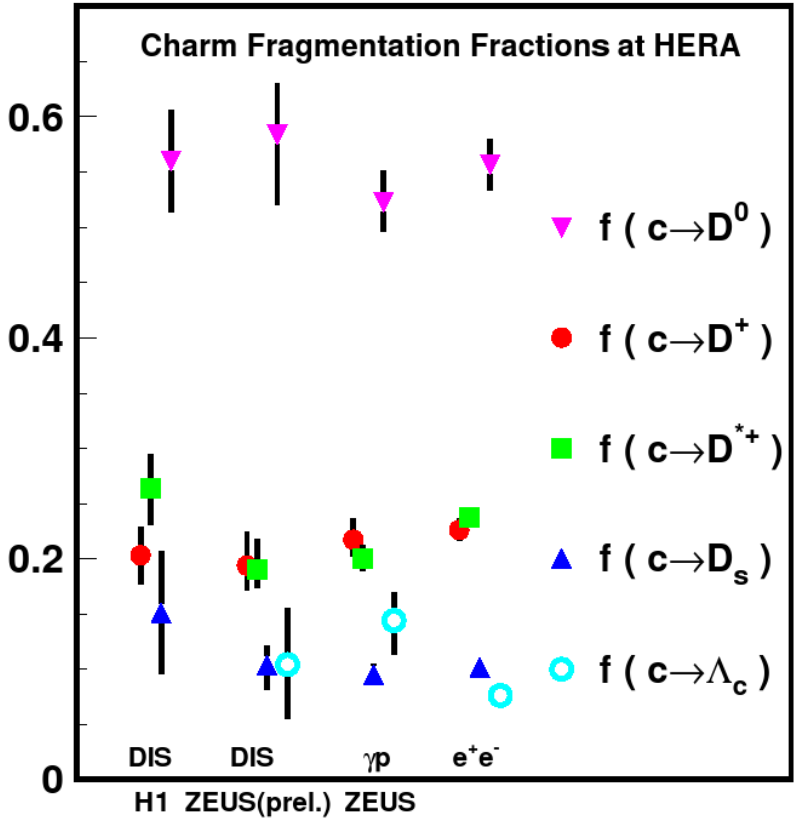
Measurements of charm photoproduction accompanied with jets pose a challenge for theory due to the extra scale of the jet transverse energy. Such complicated states will be commonplace at the LHC $\rightarrow$ verification of theory with HERA data will aid in understanding these high rate QCD events.
Dijet correlations in charm events have been measured, which (as in the D0 result shown in previous lecture) are sensitive to higher order effects.
At LO the two jets are back to back.



- For resolved events description by NLO poor
- HERWIG describes the shapes well
- Indicates that higher order calculations or implementation of additional parton showers in current NLO needed

- Heavy quark fragmentation has been extensively studied in e^+e^-
- LEP was the ideal environment for such studies (clean with back-to-back jets)
- The accurate measurements of fragmentation functions etc/ are used as input to models and NLO calculations of hadron collisions.
- The validity of these functions in the hadronic environment needs to be verified
- Measurements at HERA and the TeVatron are therefore very interesting to establish the universality of the fragmentation functions





Results from different types of collisions are consistent.

Summary

- As we near the turn on date for the LHC,much work is underway to bridge the gap from the personnel of running experiments with experience of data analysis to the LHC experiments
- Many measurements are still to come from HERA and the Tevatron which directly affect the discovery potential at the LHC.
    - PDF (esp. gluon) uncertainties
    - Heavy Quark production
- A key issue is the production of Monte Carlo generators and tools that can accurately describe behaviour of the LHC data:
    - MPI & Underlying events
    - Definition of safe Event Shape variables
    - Survival of rapidity gaps
    - Matching of detector to hadron level jets in large jet multiplicity events