Testing QCD at the LHC and the Implications of HERA

DIS 2004

Štrbské Pleso, High Tatras, Slovakia 14 - 18 April 2004

Jon Butterworth

- Impact of the LHC on QCD
- Impact of QCD (and HERA data) at the LHC

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QCD will provide the beams, the background, the beauty... we had better understand it.

Impact of QCD at the LHC

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HERA is a precision QCD machine, as well as a QCD "discovery" machine. Data from HERA are needed to fully exploit the LHC.

The focus of this talk.

Areas of Impact

- Precision measurement of QCD inputs
  - α_s : from jet rates, jet substructure, event shapes, PDF fits, fragmentation fits...
  - Parton distributions from structure functions, jets and charm.
  - Fragmentation parameters: strange, charm, beauty, leading particles.

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  - Fragmentation parameters: strange, charm, beauty, leading particles.
- Testing ground for non- or semi-perturbative models
  - Underlying events; minijets, multiparton interactions, saturation
  - Soft underlying events, rescattering, forward neutrons & protons.
  - Diffractive structure functions, gaps between jets, survival probability.

Areas of Impact

- Testing ground for calculational techniques
  - Very forward jets, low x.
  - Multijets, matrix element/parton showers.
  - Evaluation of theoretical uncertainties.
  - Beauty & charm production cross sections and dynamics.
  - DIS/photoproduction transition; multiscale QCD
  - "Intrinsic" transverse momentum, k_T factorization

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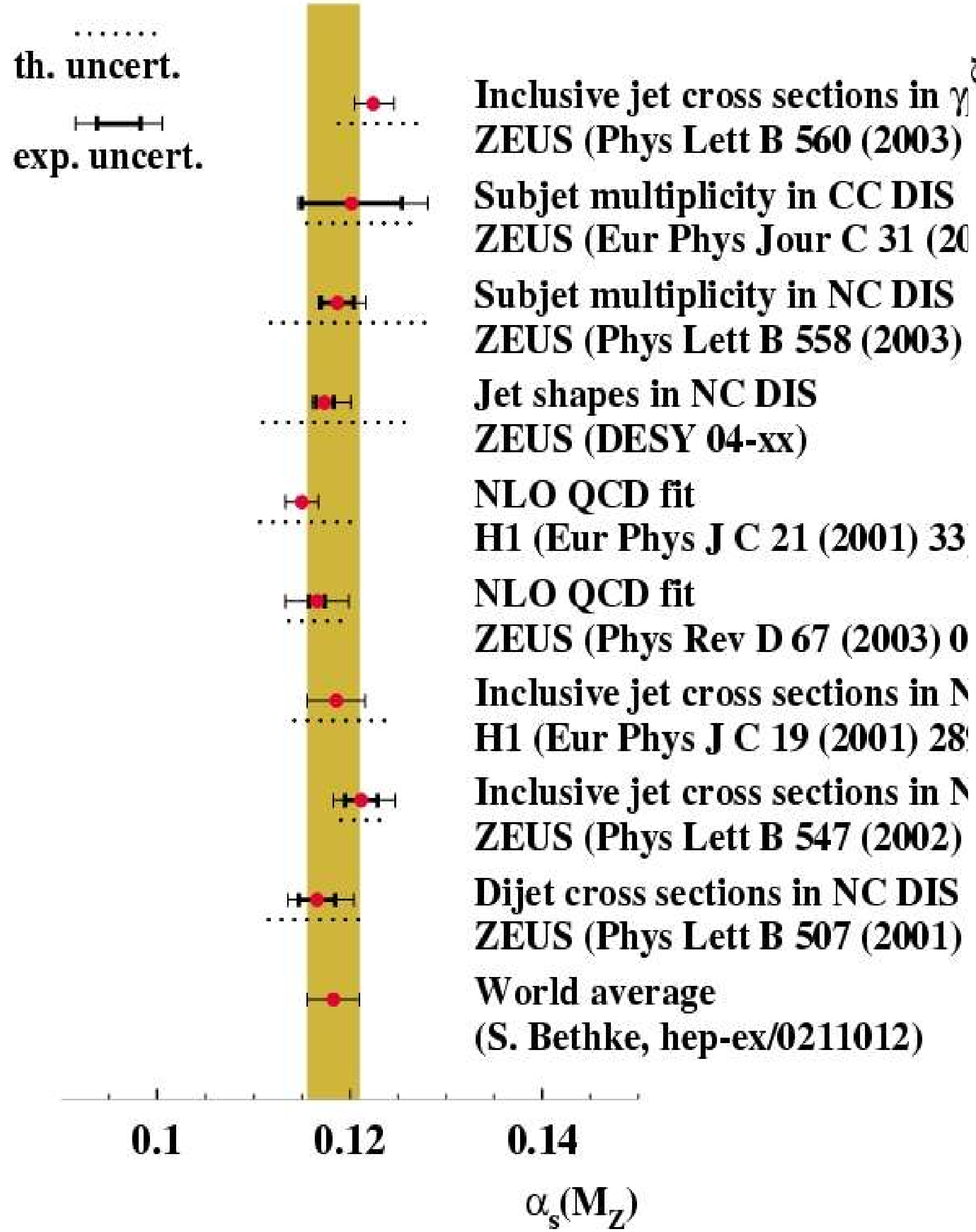
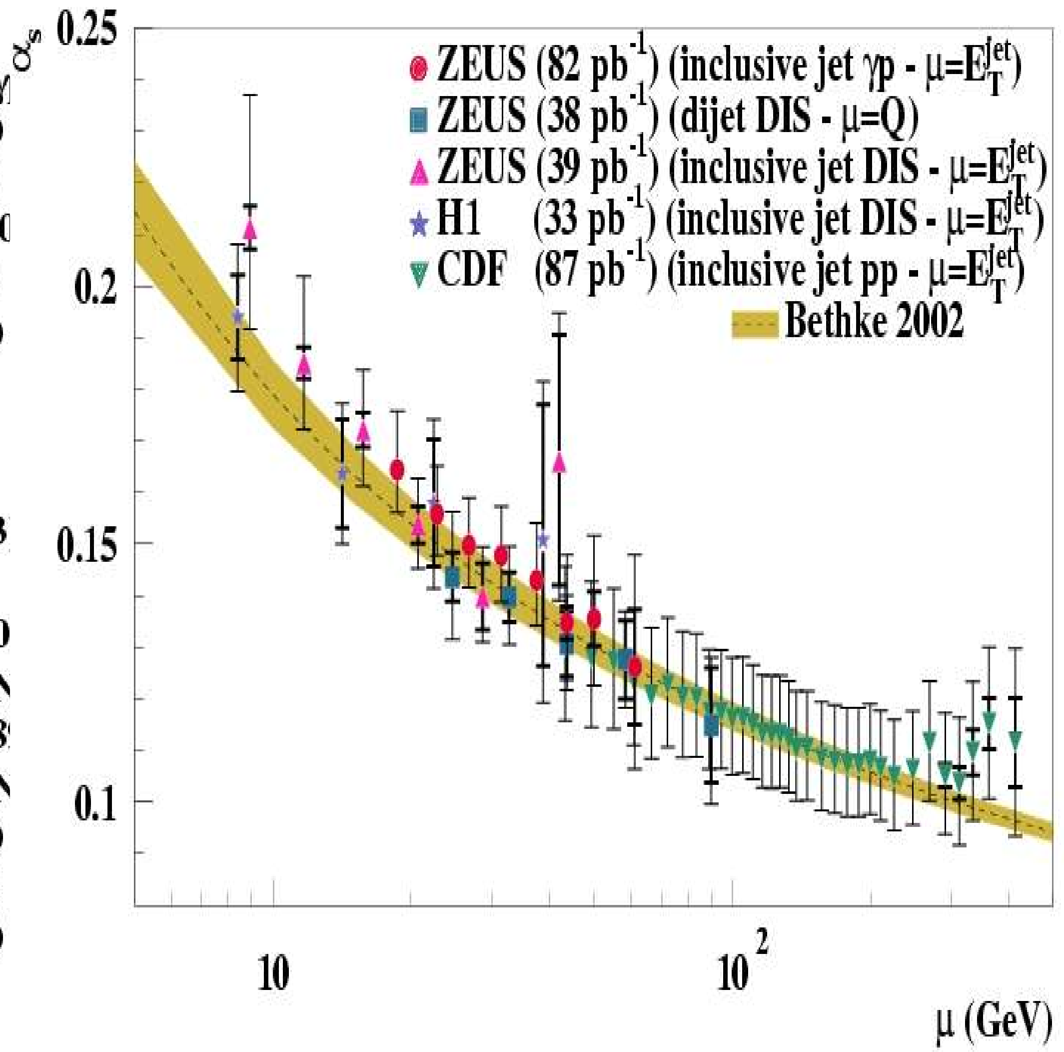
Gain a *quantitative* understanding of hadronic production mechanisms at high energies.

Only time for a few examples.

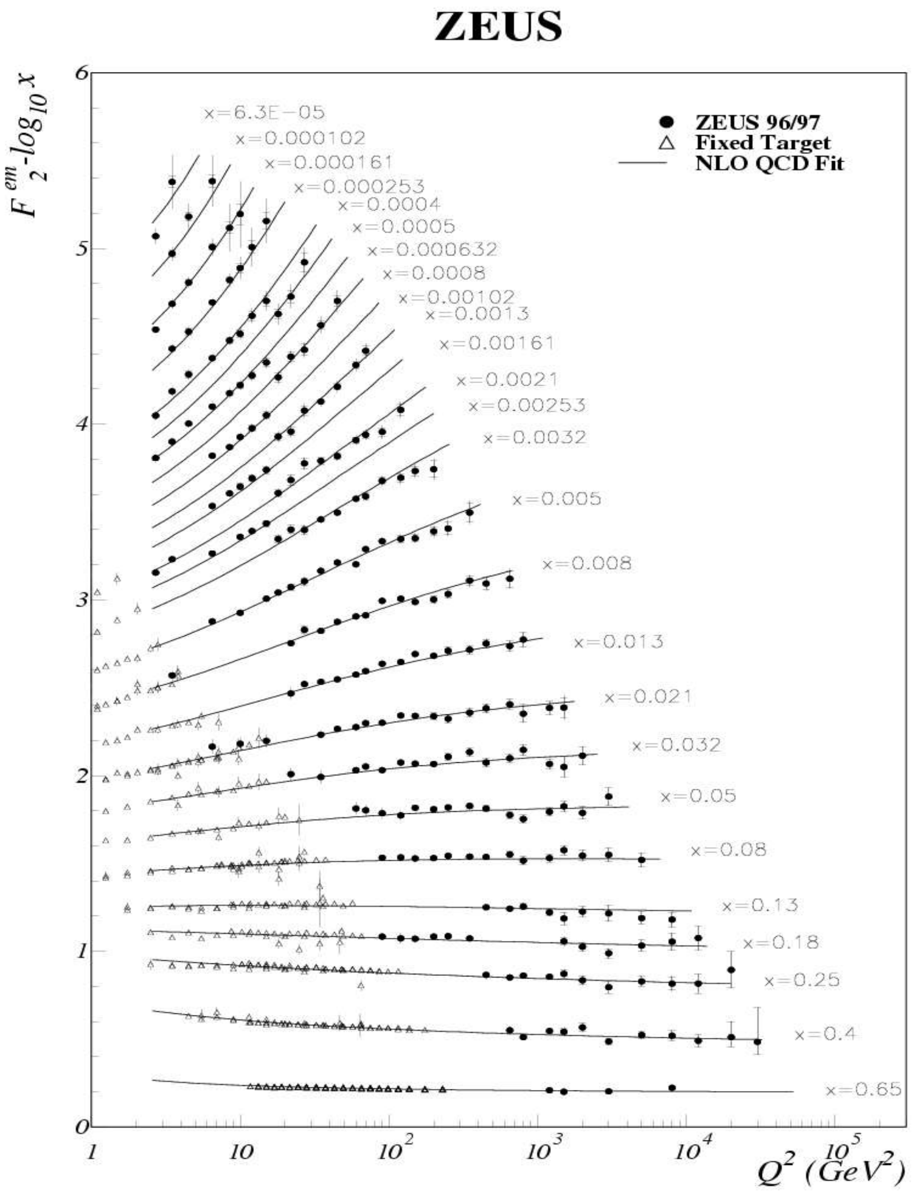




Precision jet physics in a hadronic environment

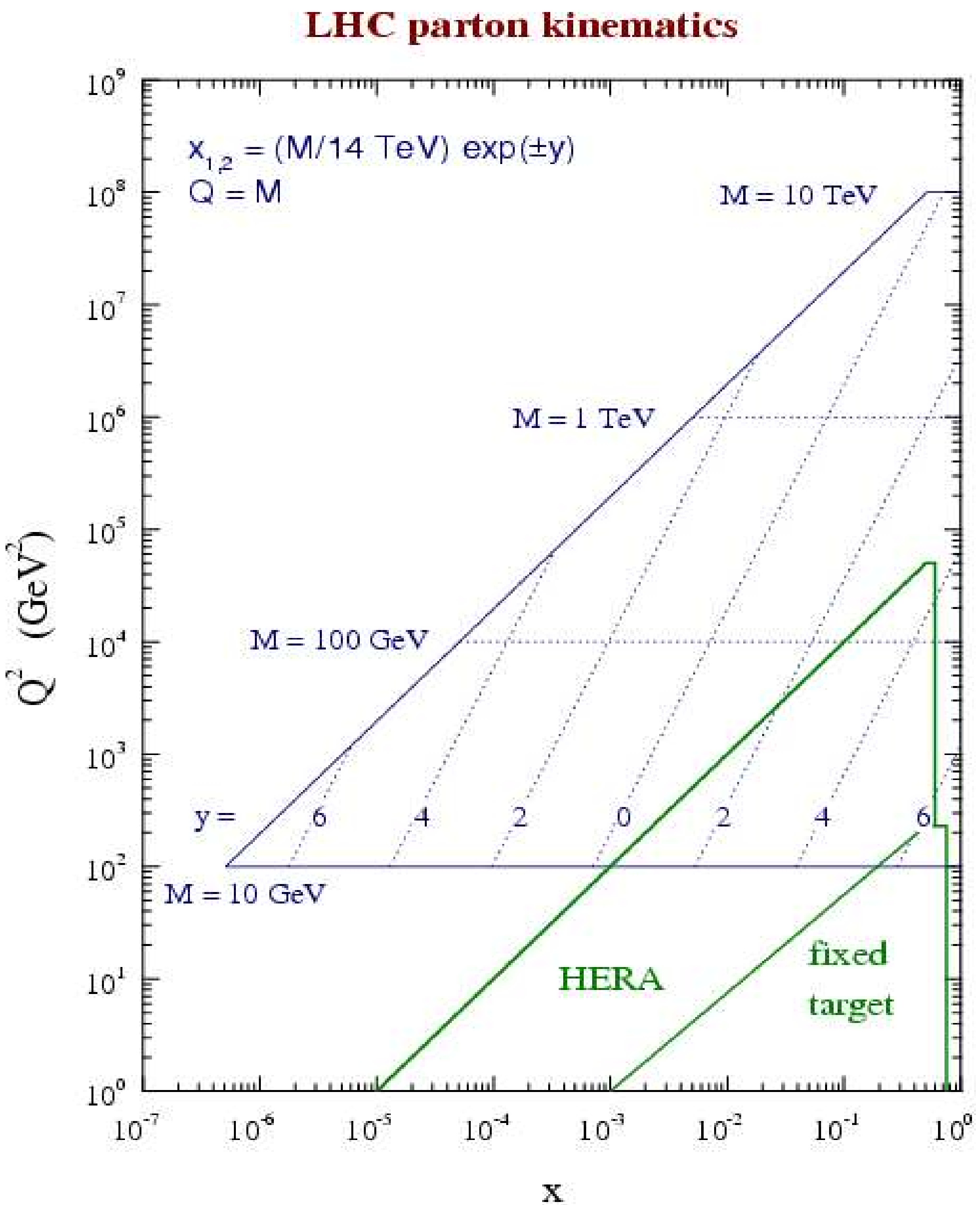
Parton Distributions in Proton

- HERA data drives the global fits.



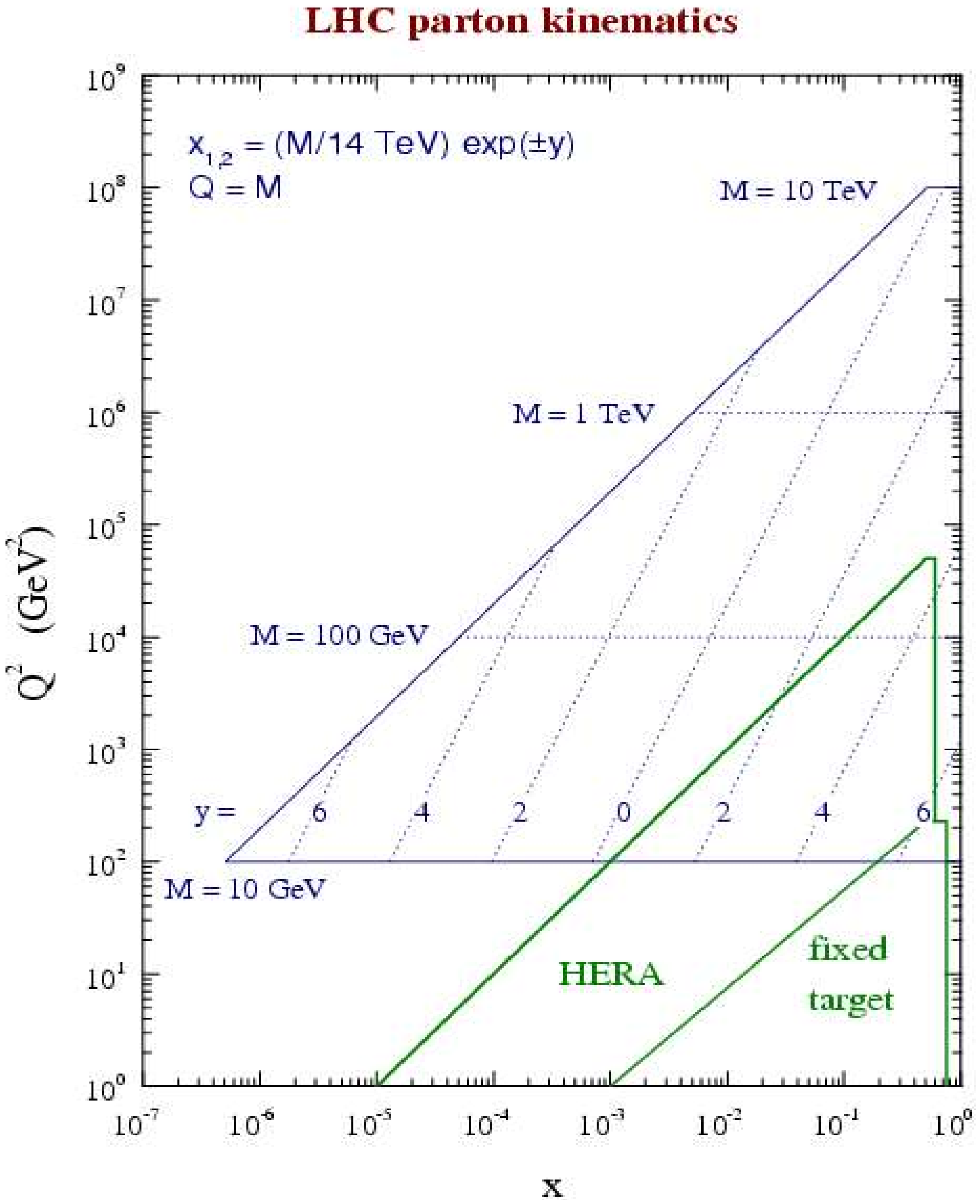
Parton Distributions in Proton

- Small overlap with LHC region
- Use DGLAP to evolve up in Q^2



Parton Distributions in Proton

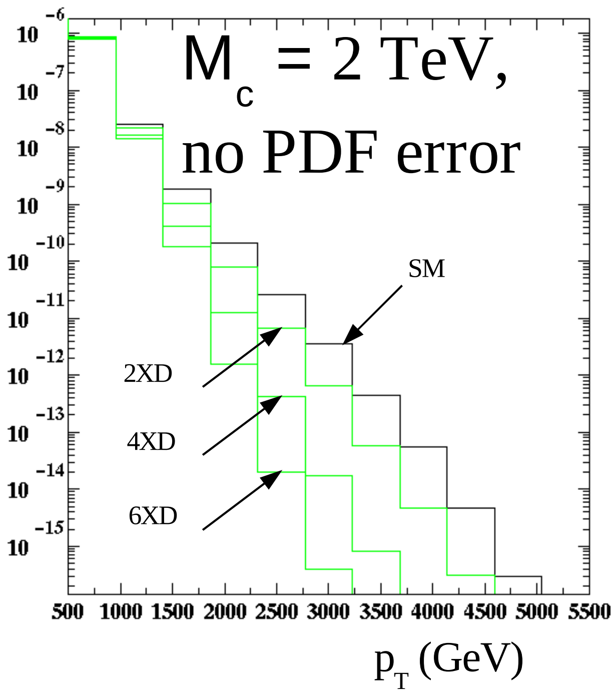
- Small overlap with LHC region
- Use DGLAP to evolve up in Q^2
- LHC will be able to measure parton luminosities using W, Z production
- Cannot do high x at intermediate Q^2.
- Badly need high x information from elsewhere.

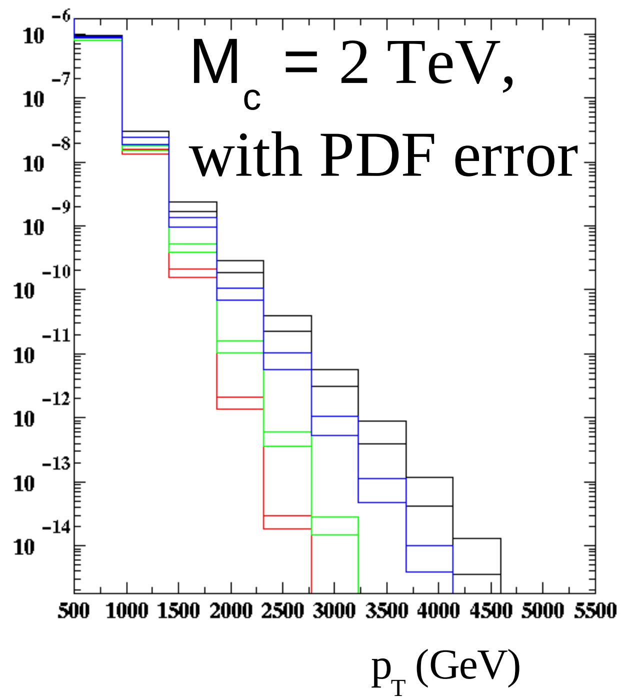


PDFs versus new physics...

- Example: Absolute level and shape of cross sections approaching kinematic limit (new physics or just PDFs?)

Ferrag et al: Dijet cross section potential sensitivity to compactification scale of extra dimensions (M_c) reduced from ~5 TeV to 2 TeV.





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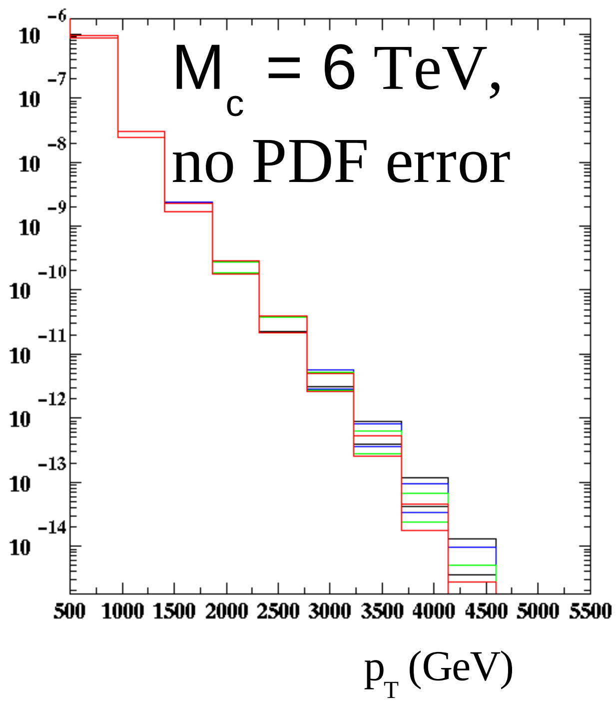
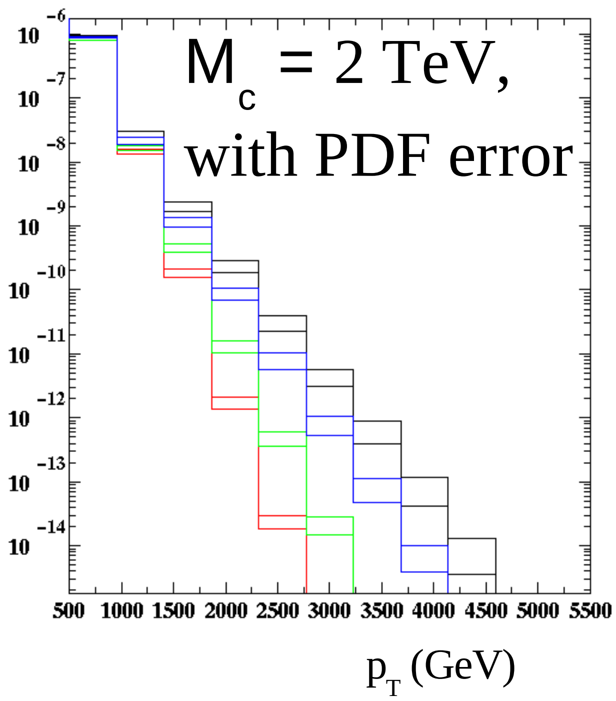
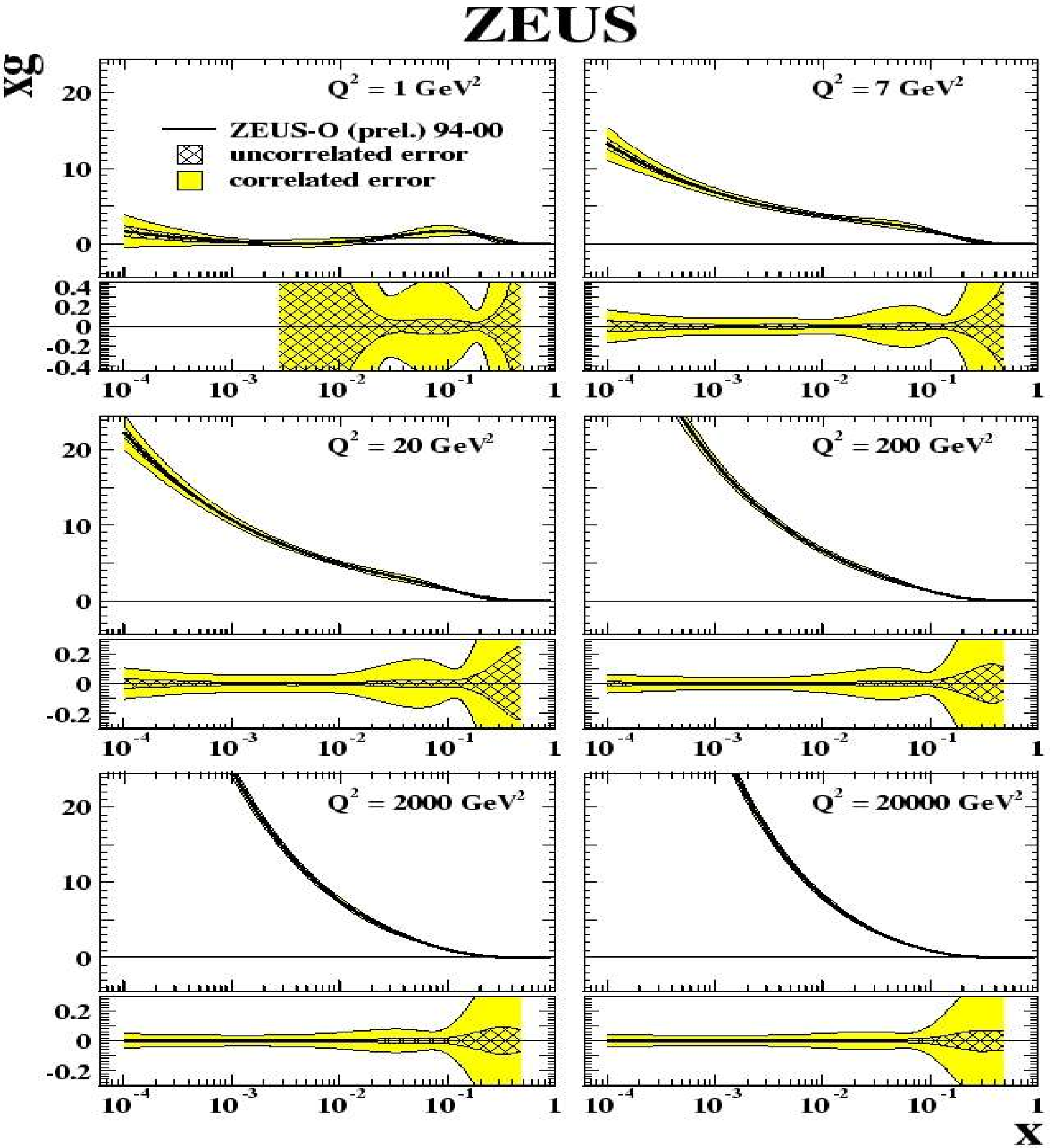




Parton Distributions in Proton

- Uncertainty in high x (>0.1) gluon is very large, even at high Q^2
- Dominant uncertainty in production rates for many processes at LHC.



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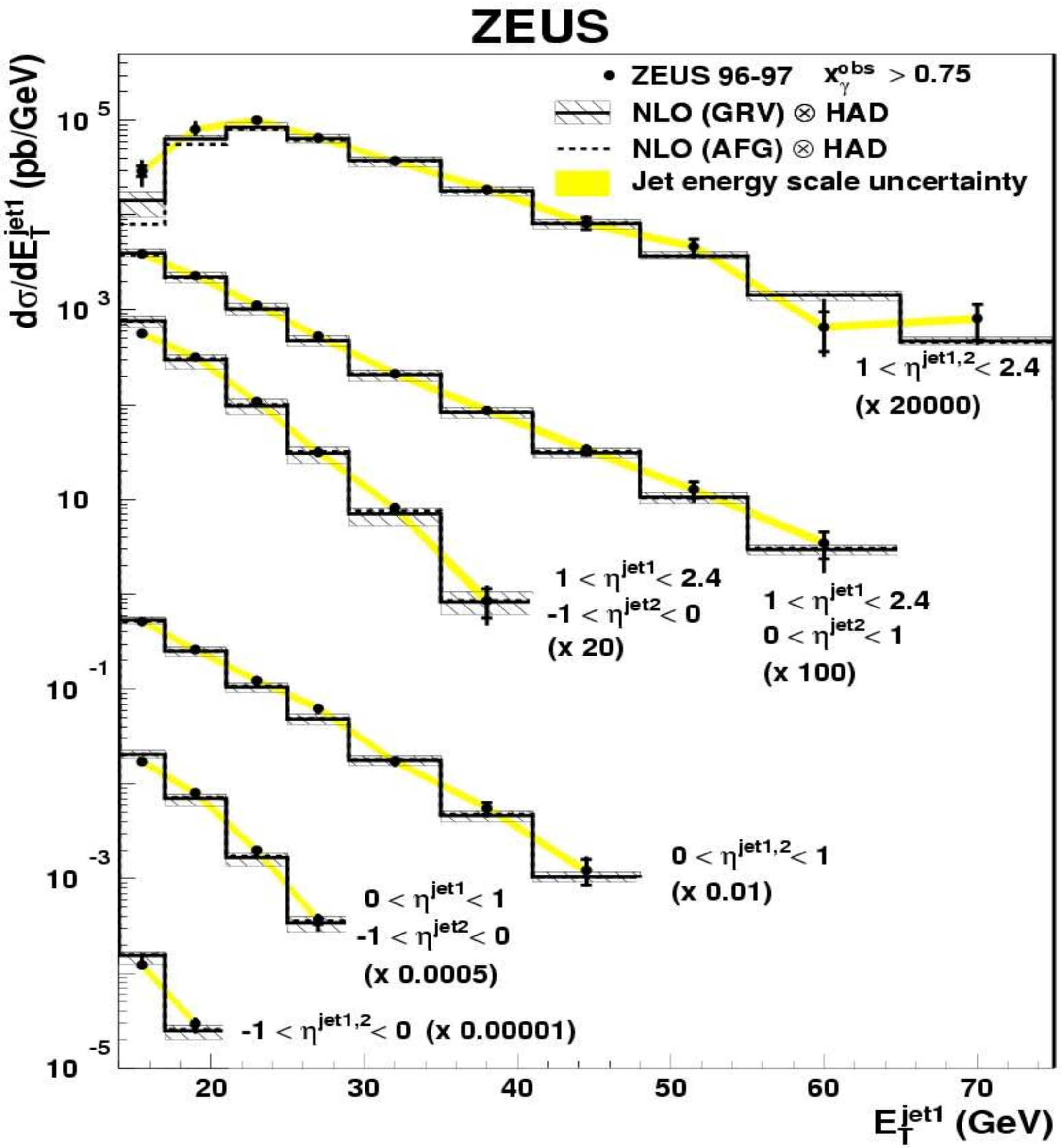

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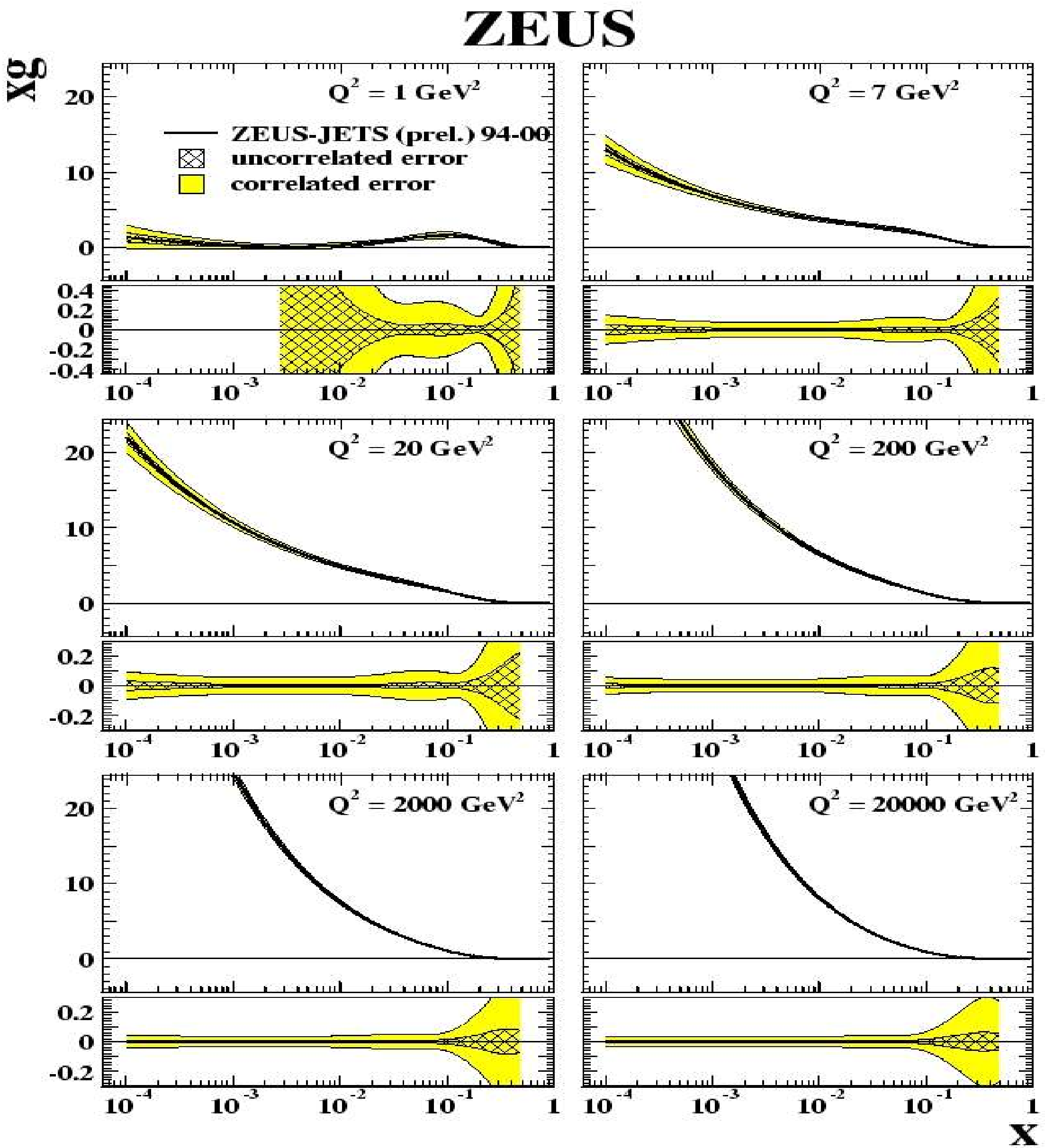

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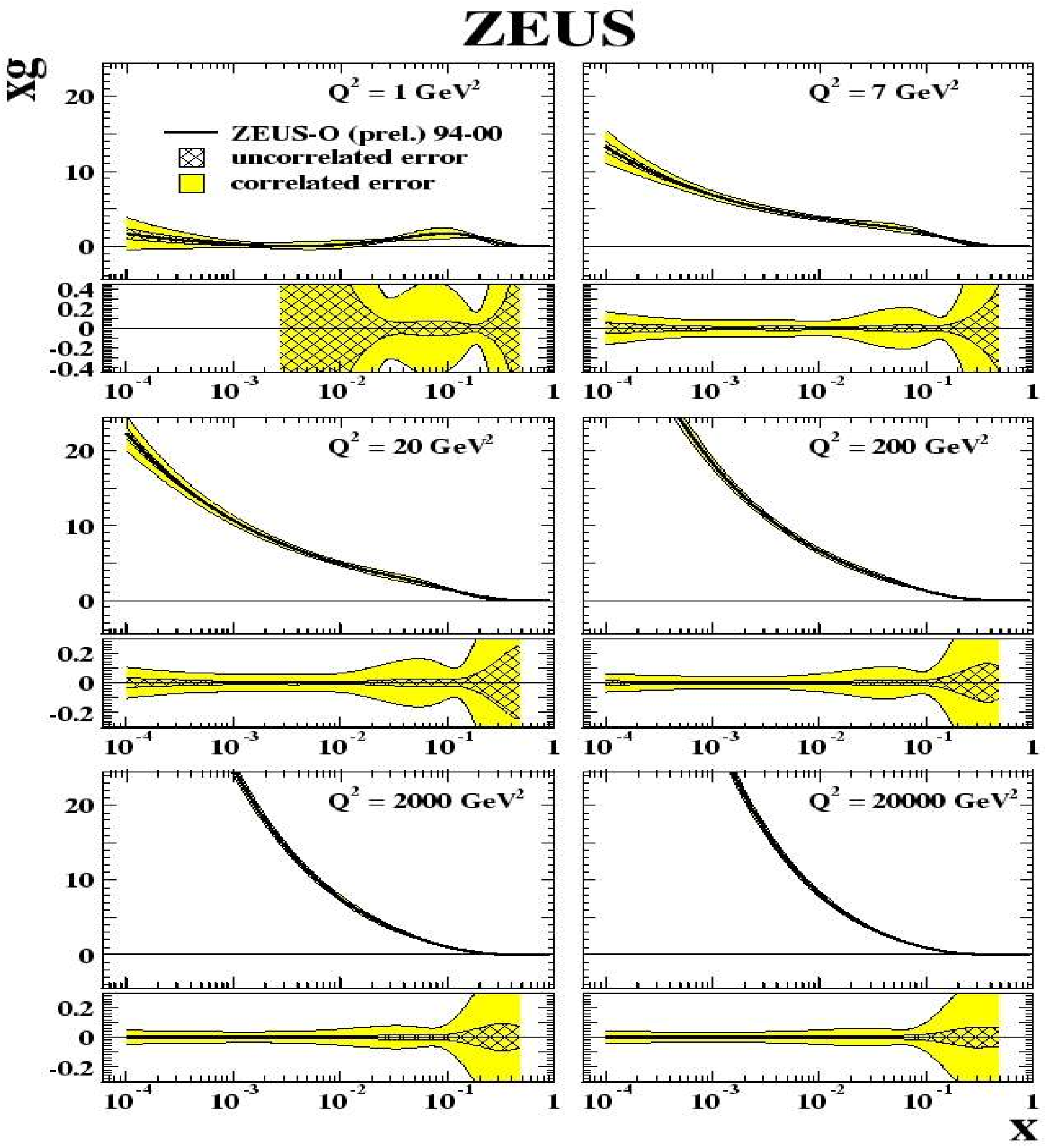
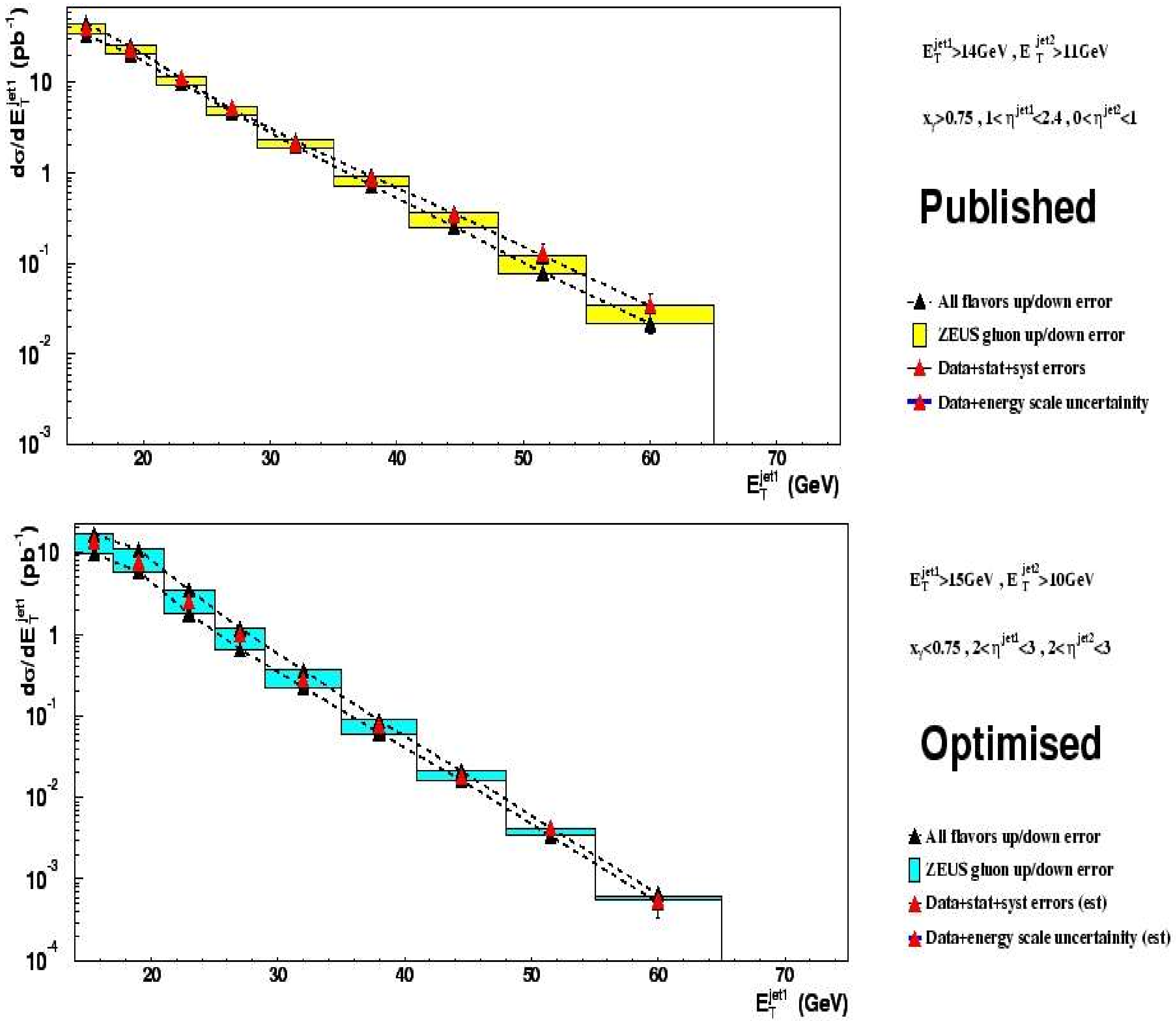


Parton Distributions in Proton

- That was only ZEUS 1996-1997 data.
- Statistically limited at high E_T = high x
- Cross sections not optimised for sensitivity to high x gluon.
- Can do much better with the rest of HERA I + HERA II



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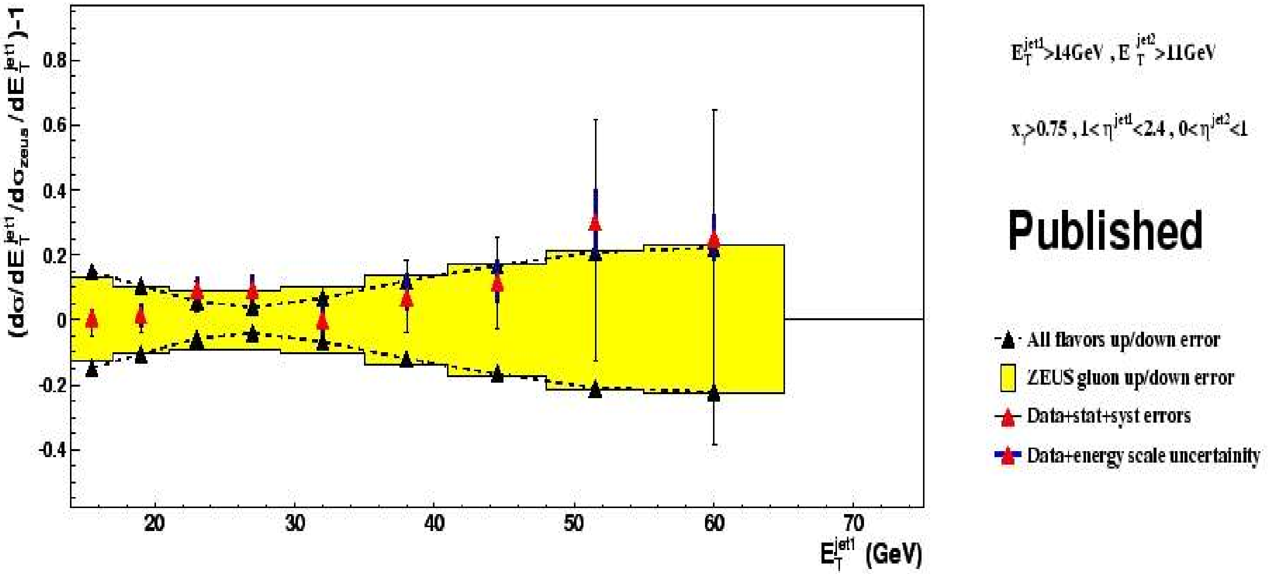
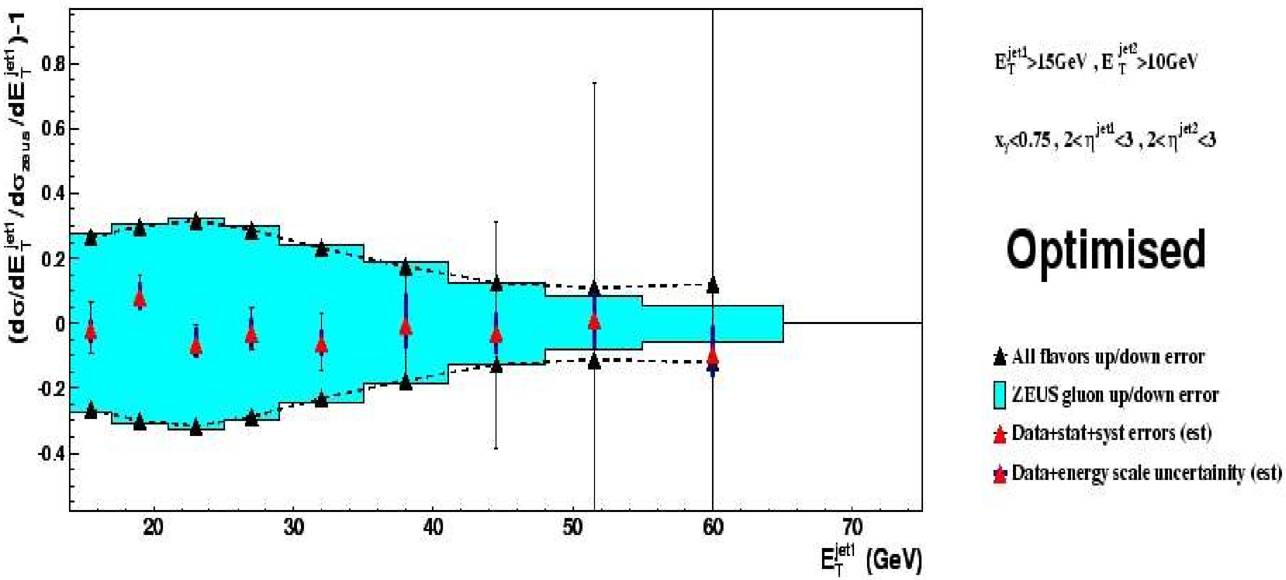
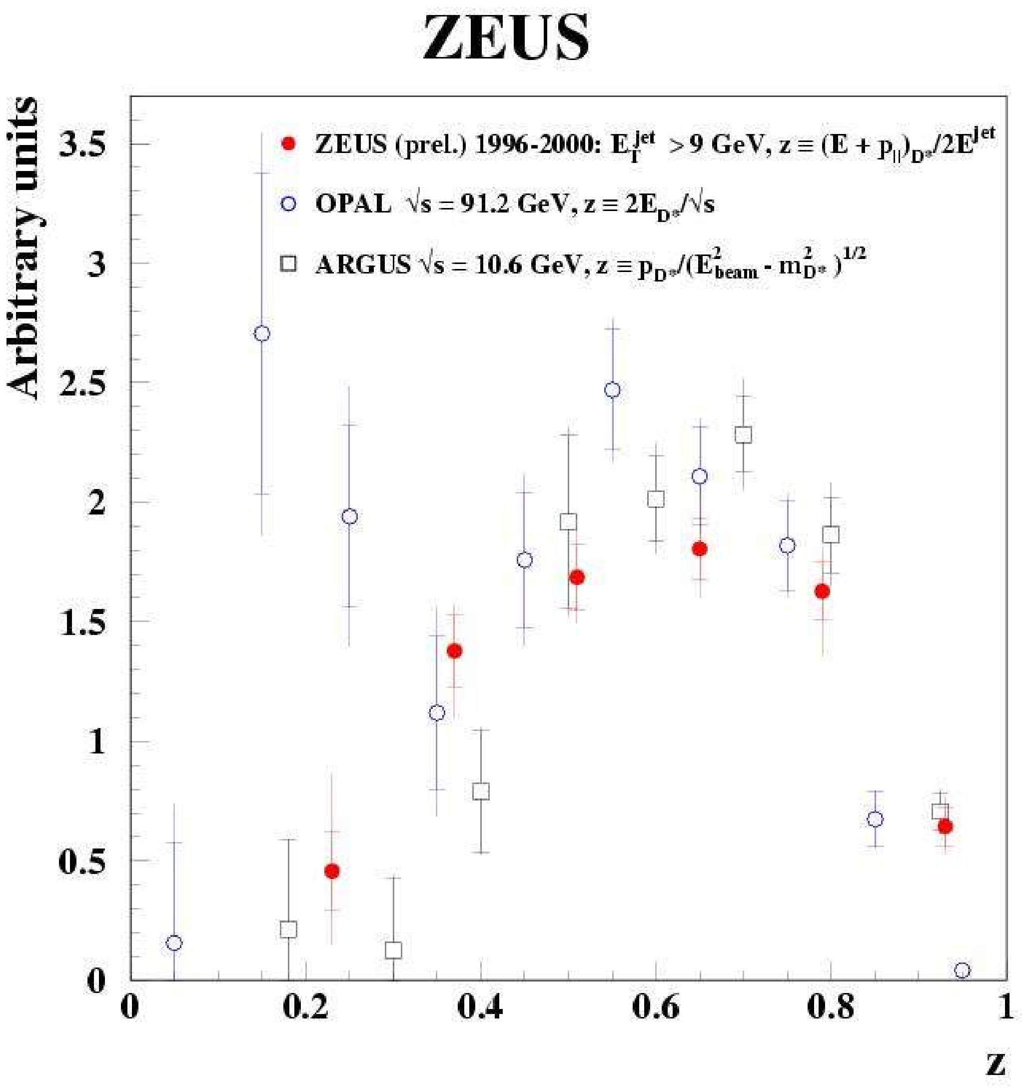




500 pb^{-1}. C. Targett-Adams

Fragmentation Parameters

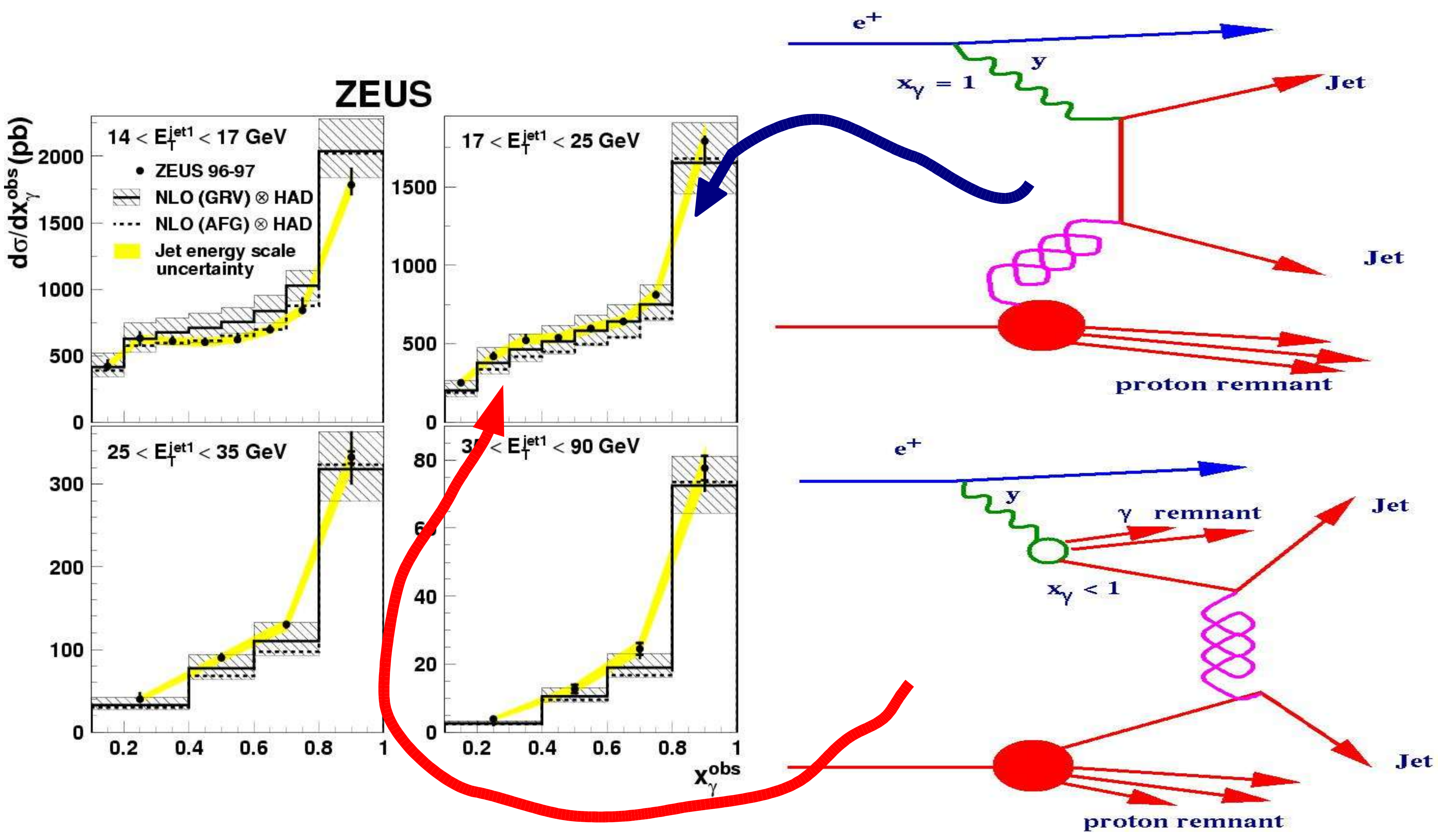
- e.g. Measure charm fragmentation function in *hadronic* events.
- Needed for beauty jet rates; minimise extrapolation uncertainties.
- Should be more precise after ugrade (CST, MVD).
- Should also be done for beauty.
- Also measured fragmentation fractions.



Testing Models and Calculational Techniques

- HERA as a 'hadron-hadron' collider
  - Almost on-shell photons come along with the electron beam & collide with protons.
  - These photons can fluctuate to acquire a hadron-like structure.
- HERA can look like a hadron-hadron machine (hadronic photon vs proton)
  - can also do "simpler" measurements with a pointlike photon (in Deep Inelastic Scattering or direct photoproduction).

HERA as a 'hadron-hadron' collider

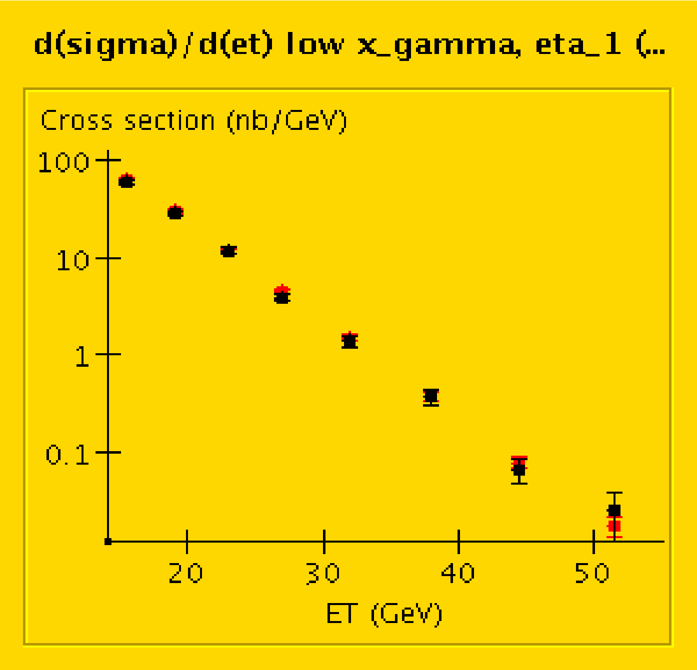


Parton Showers & Matrix Elements

Matching of (N)NLO Matrix elements to parton showers is important for multijet final states at LHC (See Frixione, Monday: several presentations this week in HFS sessions)

W+jets, WW+jets, top+jets, Higgs+jets....Sophisticated topological cuts to identify signals at LHC.

How well do fixed-order matrix element programs and LL partons shower simulations do compared to current jet data?



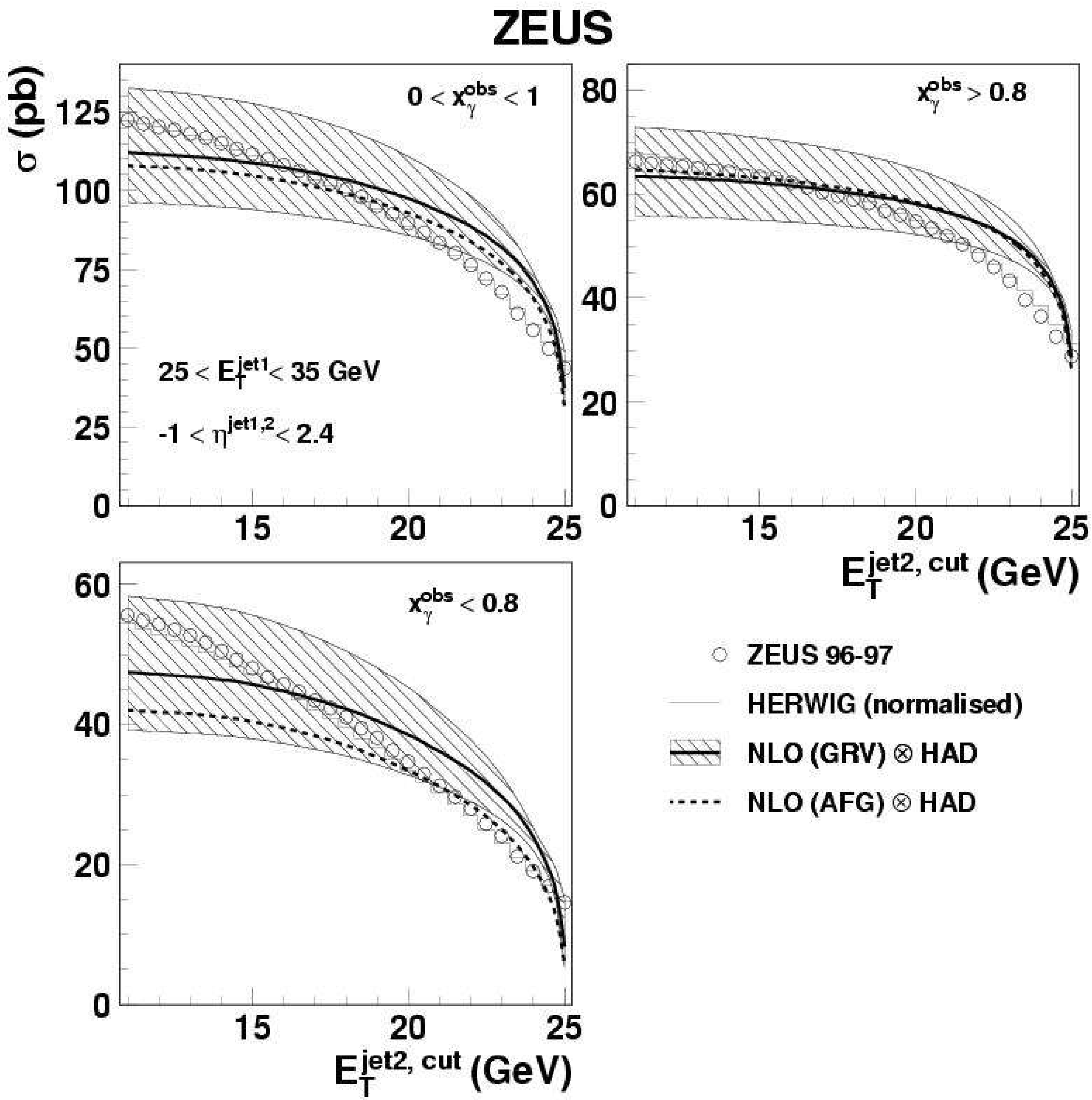
ZEUS dijet cross section for hadonic photon events as a function of the leading jet transverse energy.
Data vs Herwig x 1.6.

Matrix Elements & Parton Showers

Dijet cross section defined in terms of highest E_T jet and the rapidities of the two jets.

What happens when we vary the the E_T of the second jet?

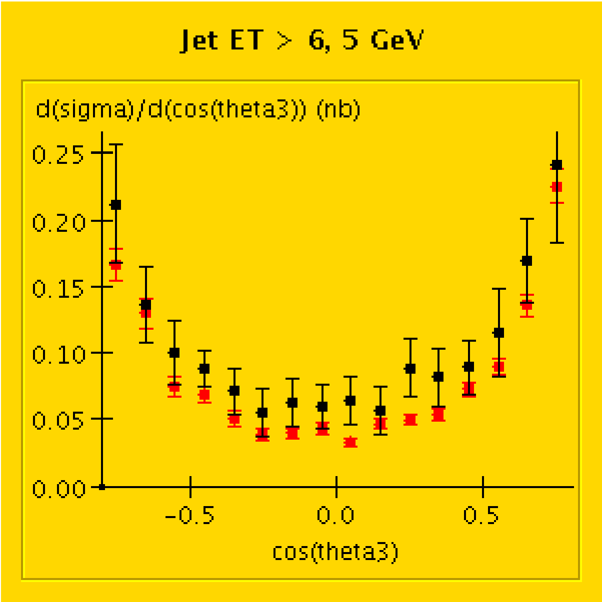
Shape well modelled by HERWIG, not by fixed order NLO.

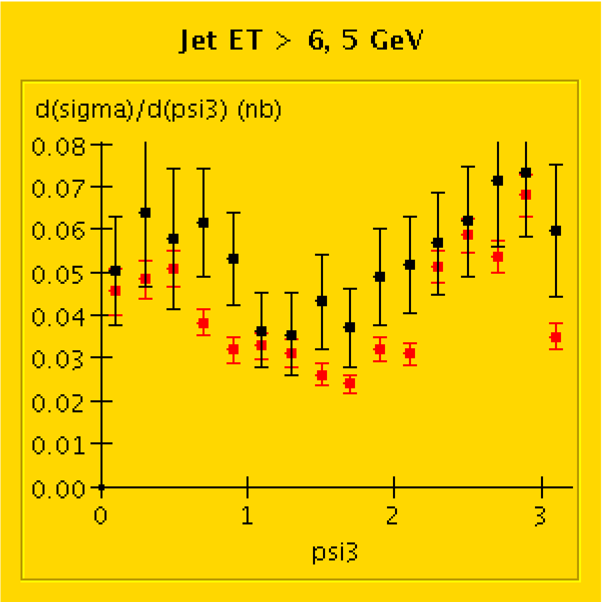


Three-Jet Cross Sections

Three-jet cross sections for Mjjj>50 GeV

Colour Coherence in initial & final state radiation.



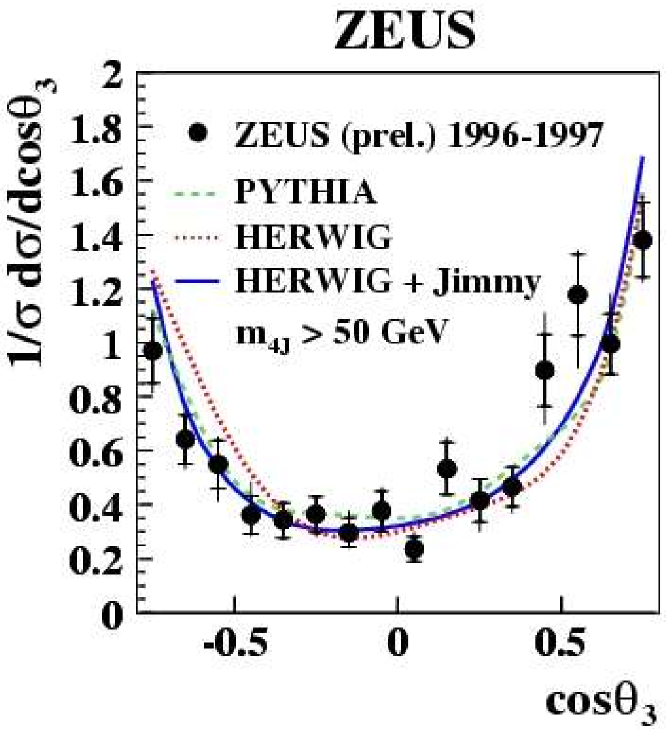


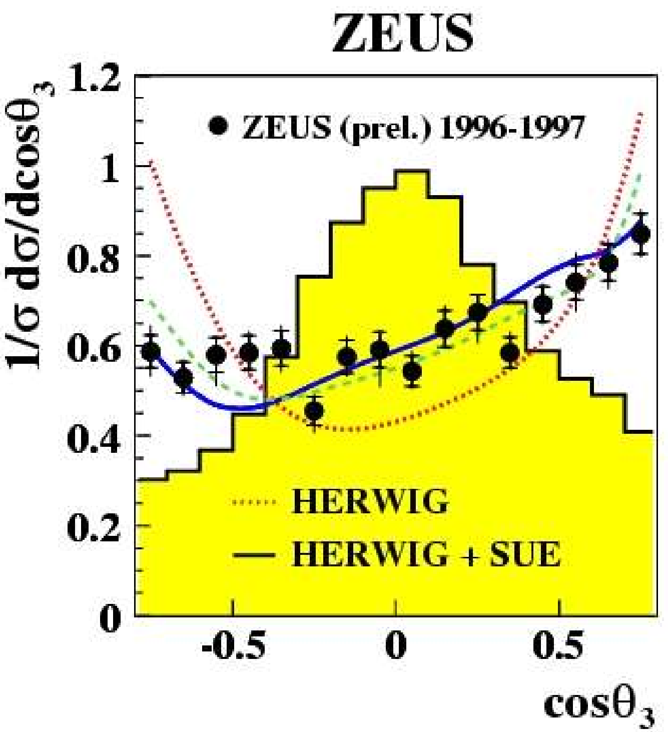
Data vs Herwig.

NB: HERWIG normalisation factor of 1.6x, determined by the high E_T dijet data. Parton showers do very well.

Four-jet cross sections

Photoproduction, jet transverse energy > 6 (5) GeV. No mass cut.





Four jet Mass > 50 GeV. QCD (LO+PS) doing well.

No mass cut. Need something else. Multiparton interaction models are favoured.

Why care about underlying events

- Inevitable property of hadronic collisions. Impact on jet energies and profiles, energy flow, isolation of photons...
- Natural consequence of eikonalisation of the parton model in high density PDF region. Related to saturation and total cross sections.

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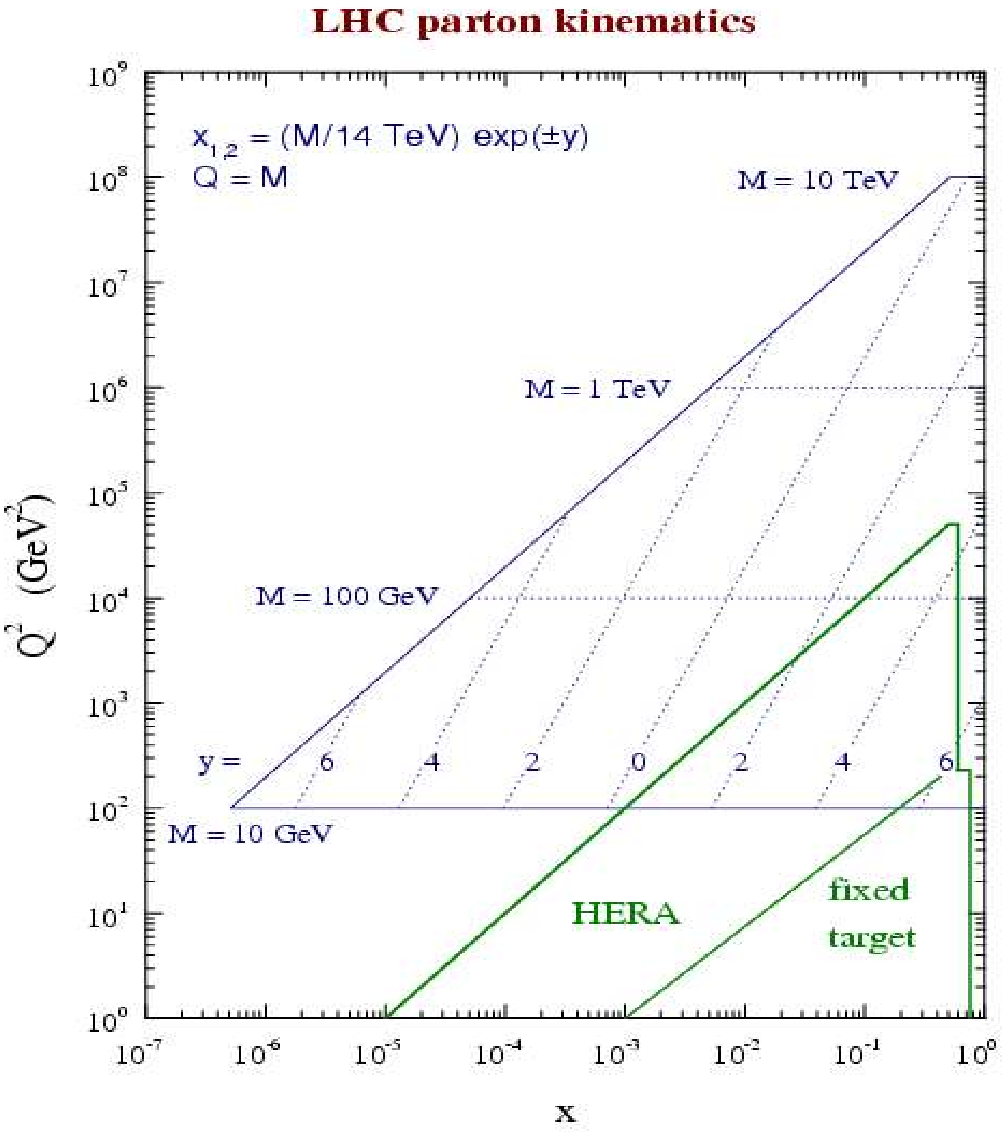

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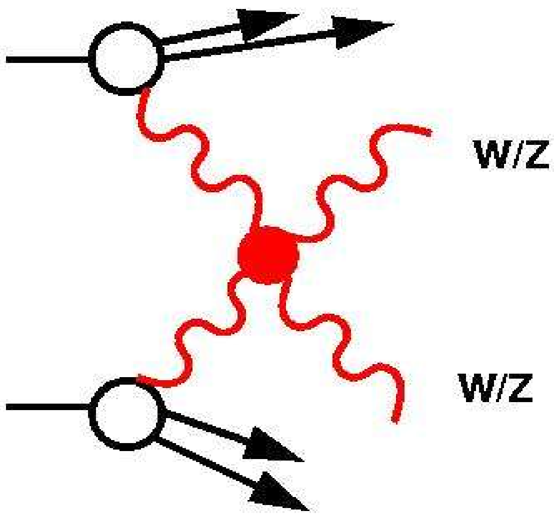
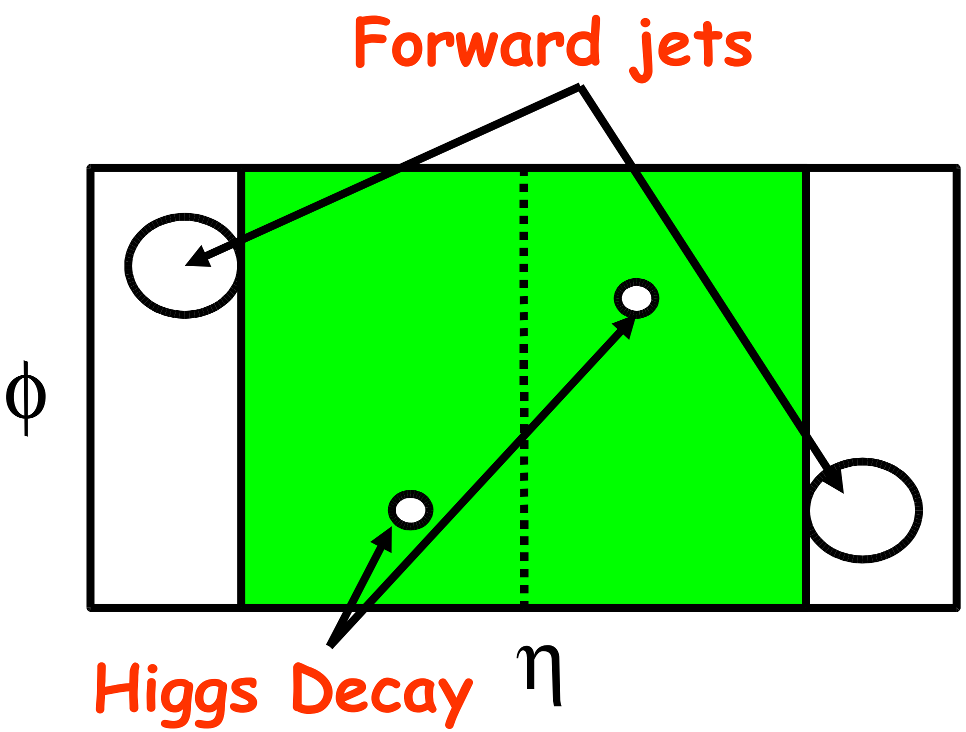
- Natural consequence of eikonalisation of the parton model in high density PDF region. Related to saturation and total cross sections.
- Responsible for diffractive factorisation breaking/gap survival probability
- Related to absorption/rescattering corrections to forward proton and neutron production.

Vector Boson Fusion at LHC

Commonly used minijet veto in WW events.





Les Houche Higgs Working group:
Minijet veto at 20-30GeV
(hep-ph/0203056).

Great sensivity to choice of underlying event model.

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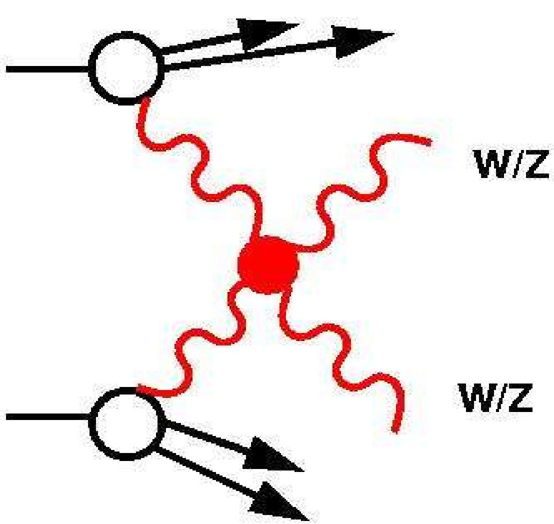

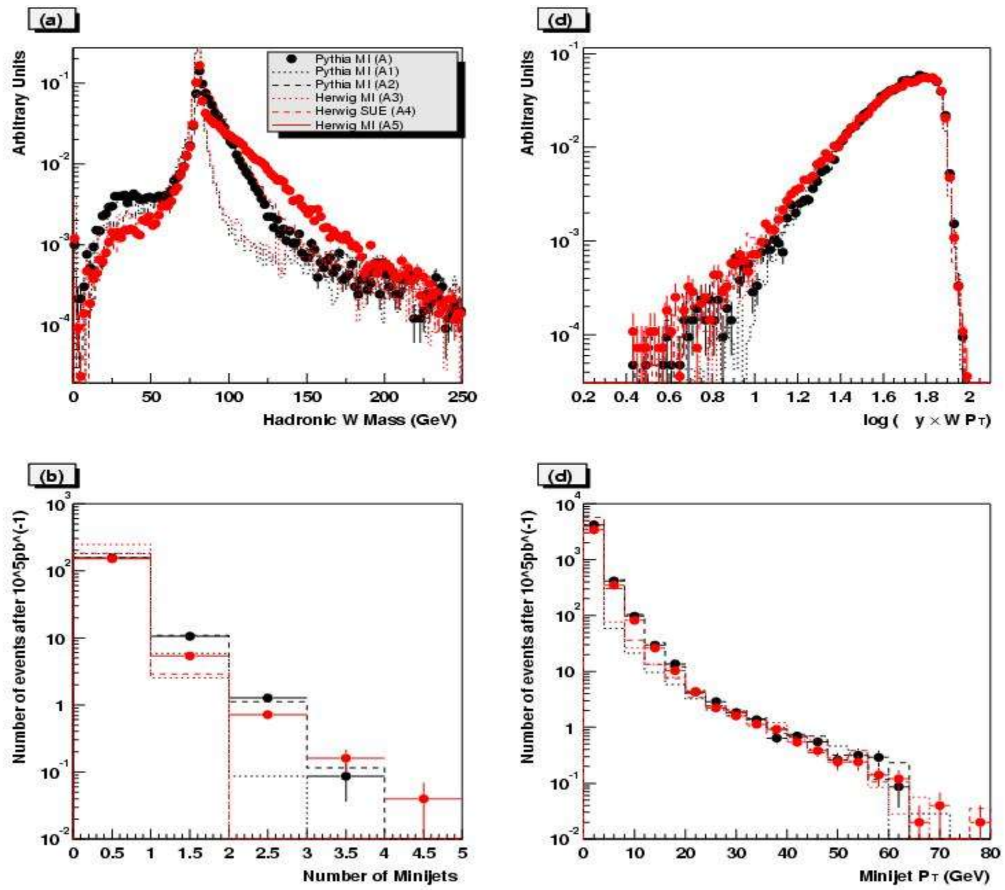

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Great sensivity to choice of underlying event model.

Also determines 'survival probability' in diffractive events.

Double Pomeron Scattering as a Search Channel at LHC

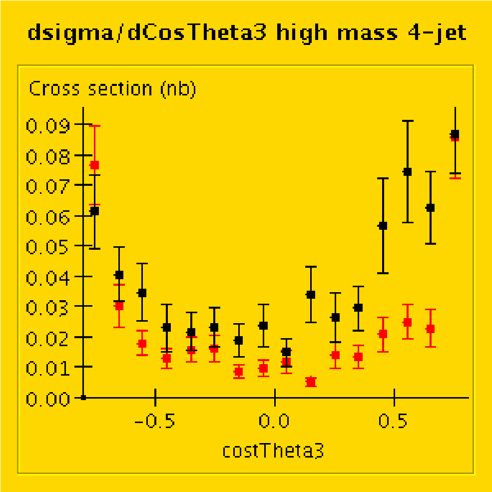
- An area of increasing interest. Much phenomenological progress in the past year. Several talks in the diffractive sessions this week.
- Possibly the cleanest way see a low-mass Higgs at LHC. Other search channels also possible.
- Requires leading proton tagging, triggered with central detector
- Would also do some excellent diffractive QCD physics
- Predictions require a good understanding of diffractive processes, particularly diffractive PDFs and factorization breaking/ survival probabilities/ rescattering

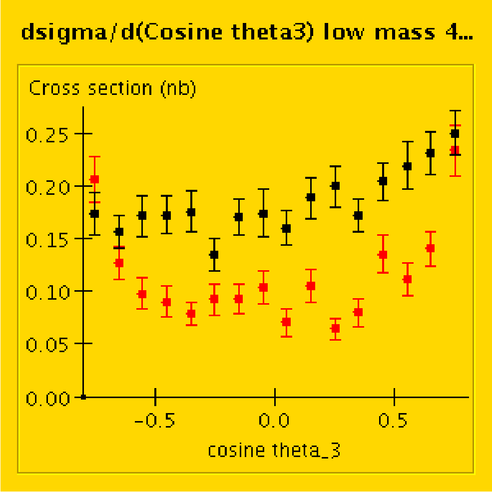
What might we learn from HERA about underlying events

- Learn about energy dependence and target dependence of models by comparing γp, pp(bar) and $\gamma\gamma$.
- Learn about proton PDFs at low x -> input to multiparton interaction models.
- Look at behaviour of jet finding for the same kinematics but with & without an underlying event.
- Test models which predict both minimum bias & underlying event by studying tagged photoproduction.
- Look at forward neutron and proton rates in photoproduction vs DIS.

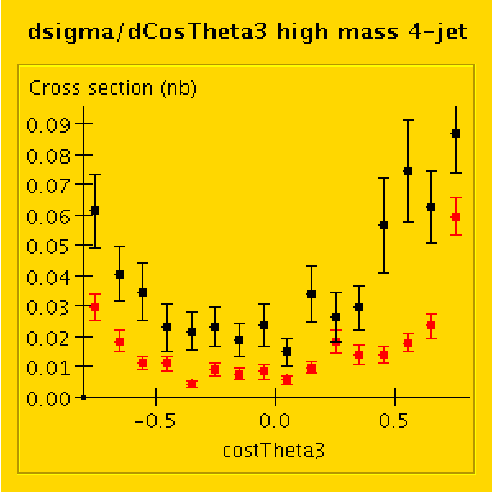
Four-jet cross sections

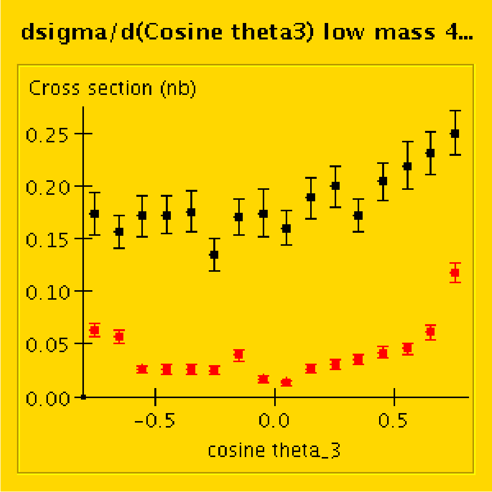
Same data: compare absolute cross sections.





HERWIG+JIMMY, as tuned to Tevatron data minimum bias data.



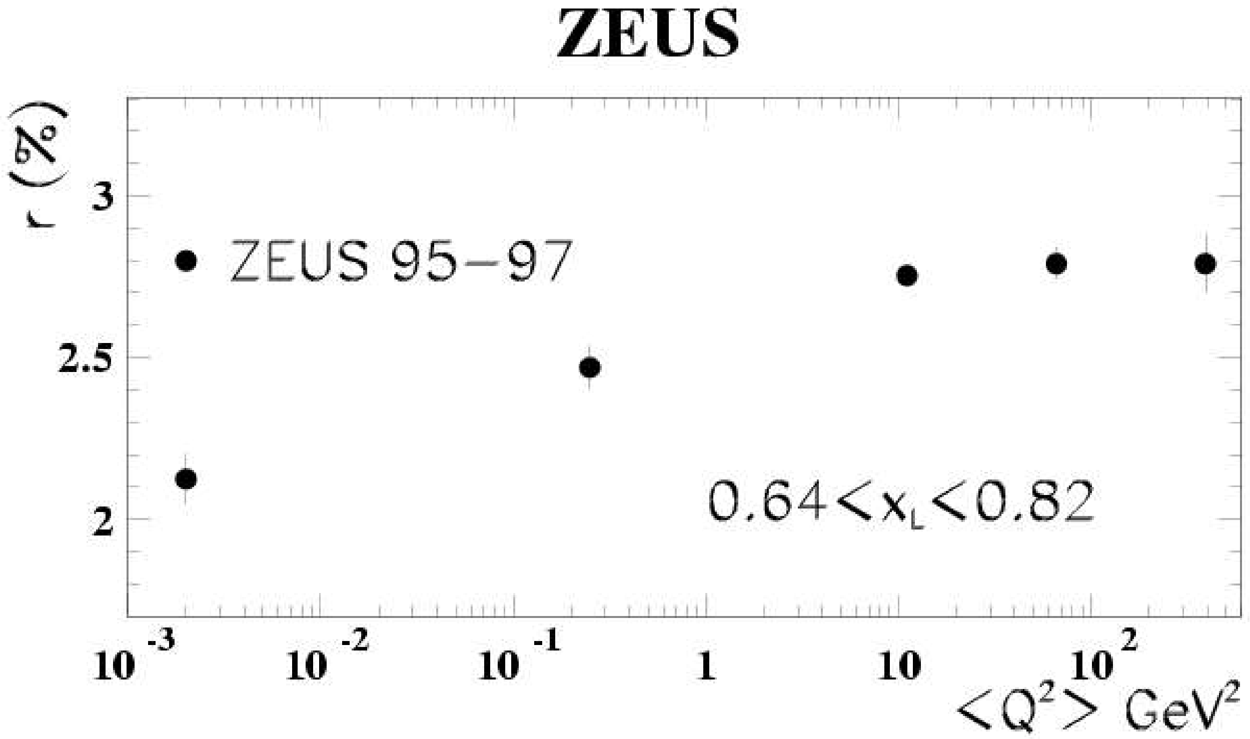


HERWIG default.

NB: Both these options give a decent fit to the high ET data.

Look at leading neutron rates

- Shown to be well described by pion exchange.
- Different rates of forward neutrons for different central events. Modelled by rescattering (absorption) of the neutron in the photon remnant.



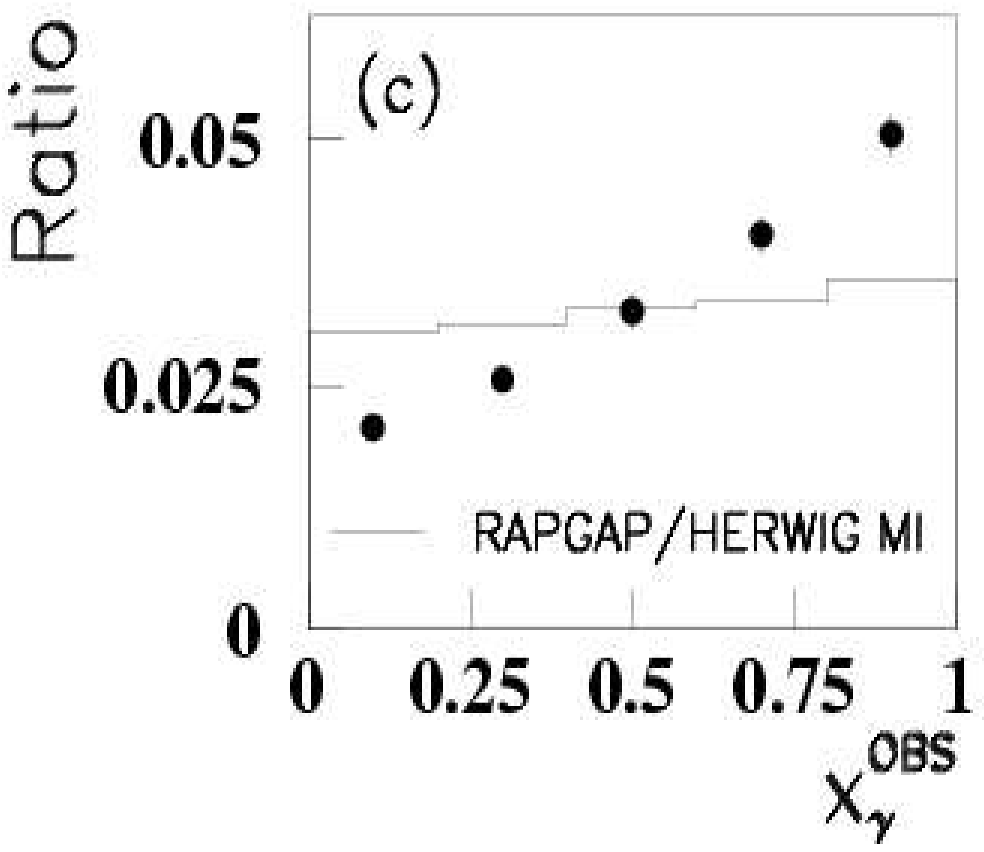
Uncorrected rate – real rate is ~8%

Look at leading neutron rates

- Inclusive photoproduction (Nucl. Physics B637 (2002) 3-56) :
  - No hard scale; Dominated by hadronic photon; Rescattering similar to hadron-hadron (?)
- DIS (same paper):
  - Hard scale; Pointlike photon; No rescattering
- Charm Photoproduction (DESY 03-221):
  - Hard scale; Some hadronic photon, but suppressed w.r.t. Inclusive case. No rescattering (rate ~9+/-1% agrees with DIS, not inclusive photoproduction).

Look at leading neutron rates

- Dijet Photoproduction : (Nucl. Phys. B596 (2001) 3)
  - Hard scale; can select between pointlike and hadronic photons.
  - Suggestive trend vs x_γ.



Look at leading neutron rates

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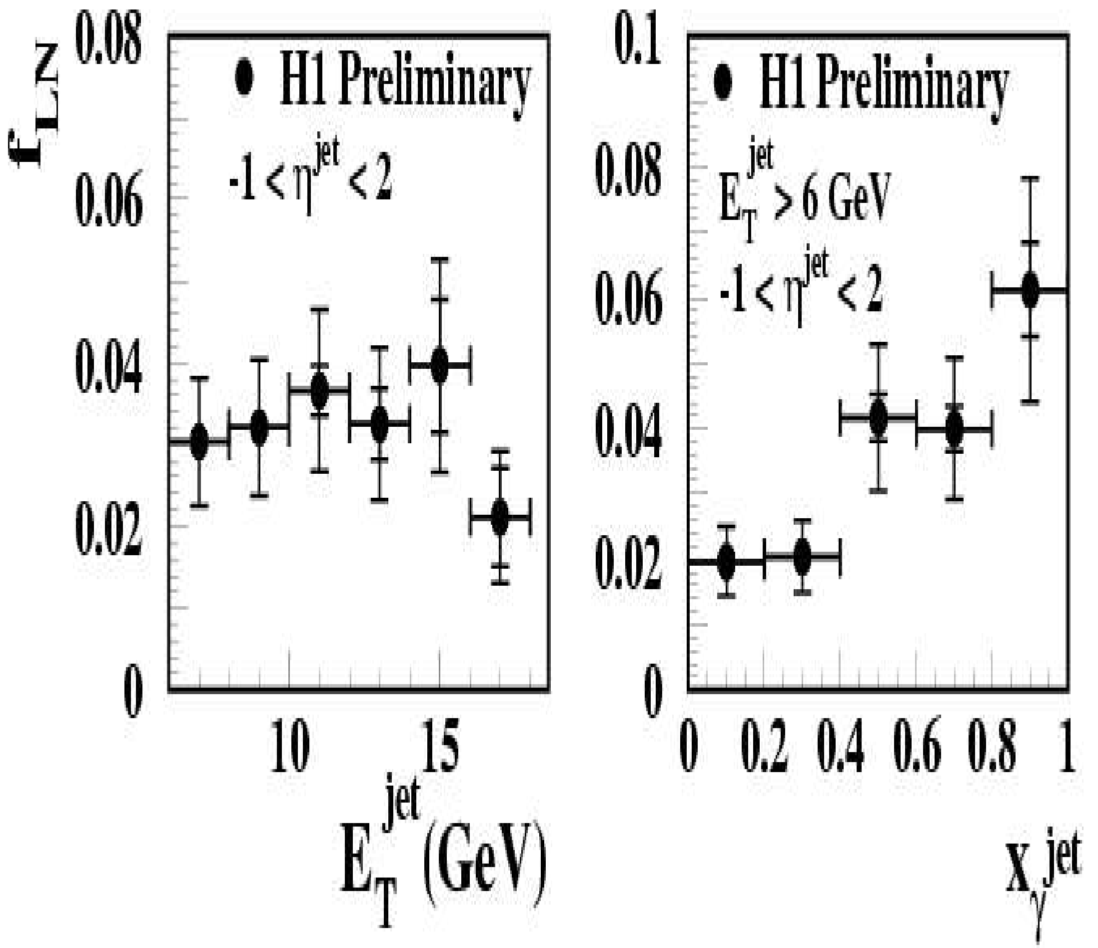
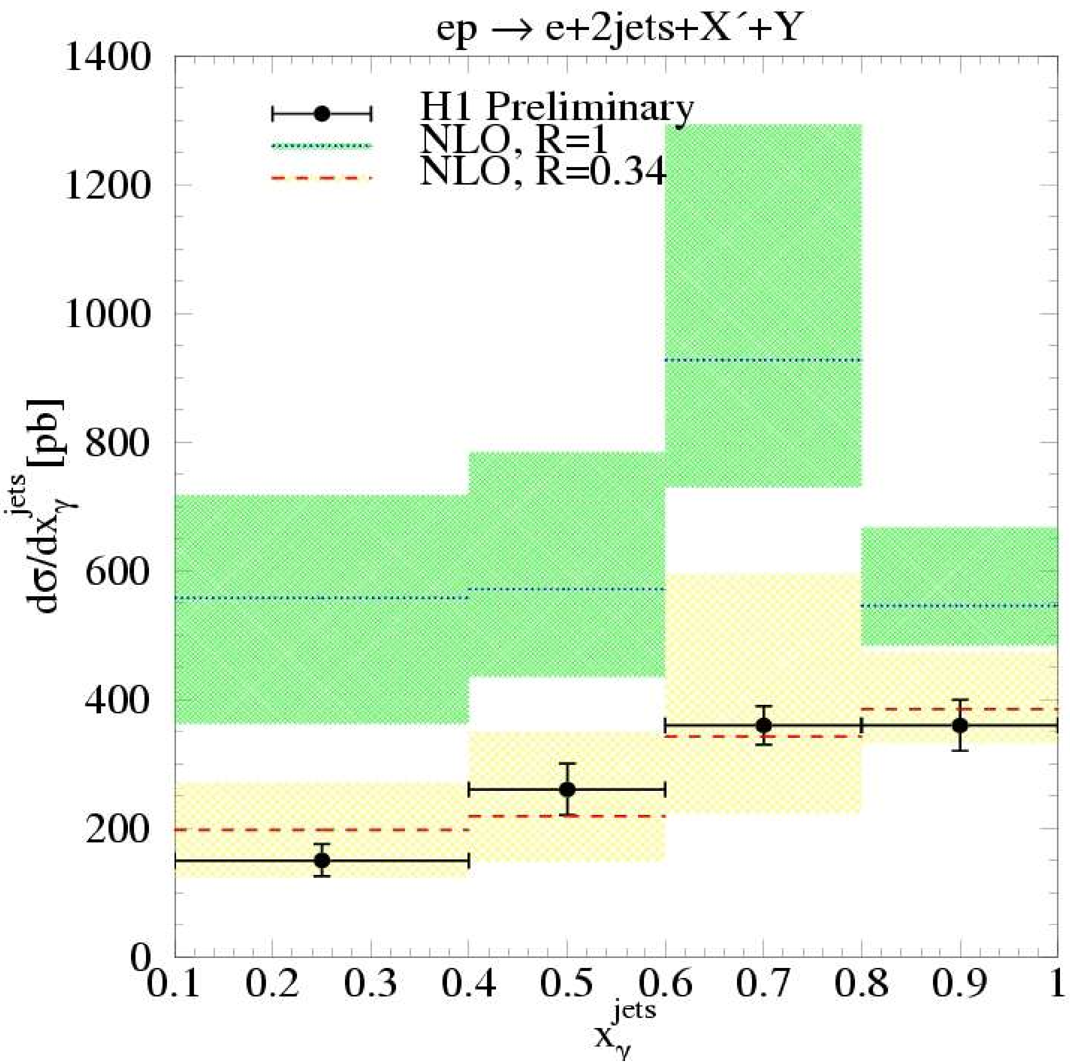


- Compare with diffractive dijets- underlying event, survival probability.

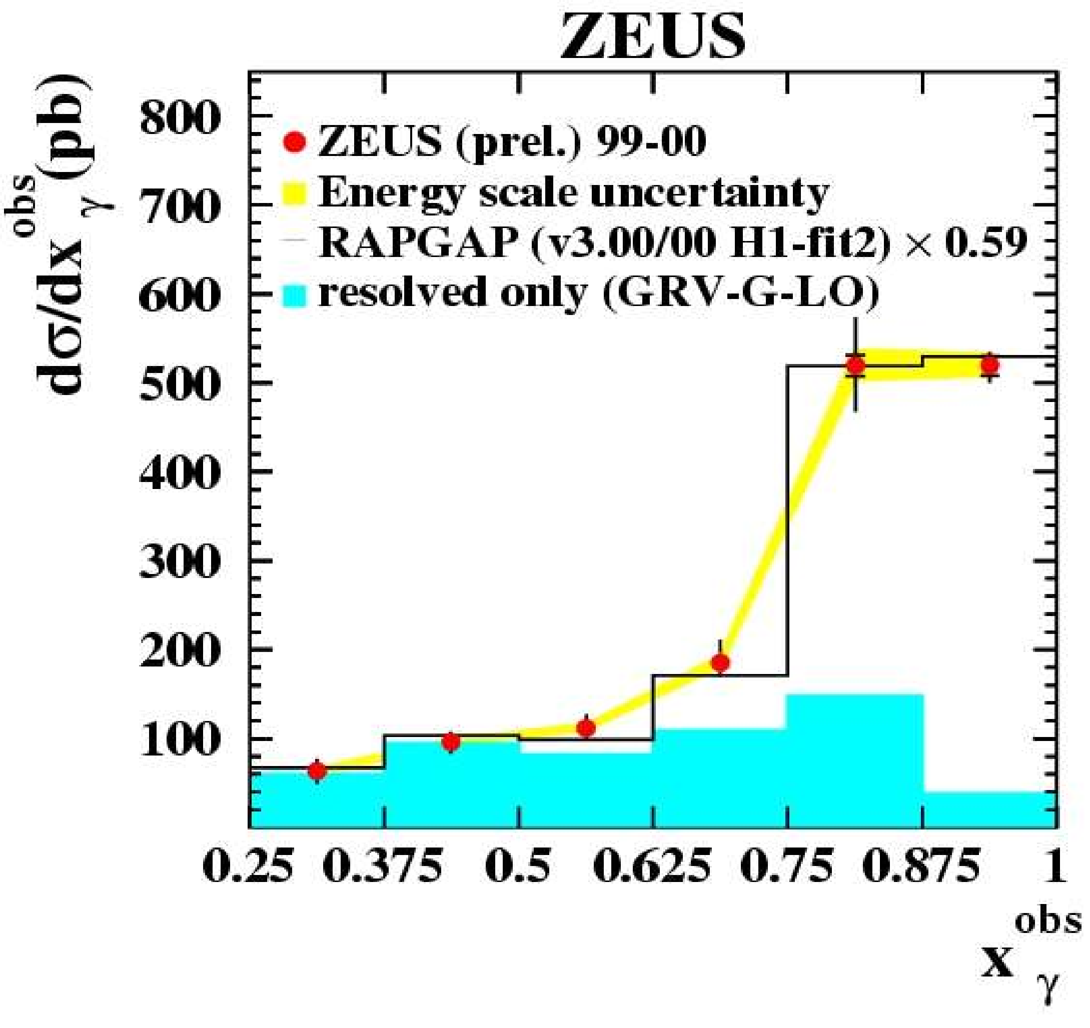
Look at leading proton rates

- Dijet Photoproduction : H1, NLO from Klasen & Kramer
  - H1 vs NLO: Agreement if resolved scaled by factor 0.34 (from Kaidalov et al).



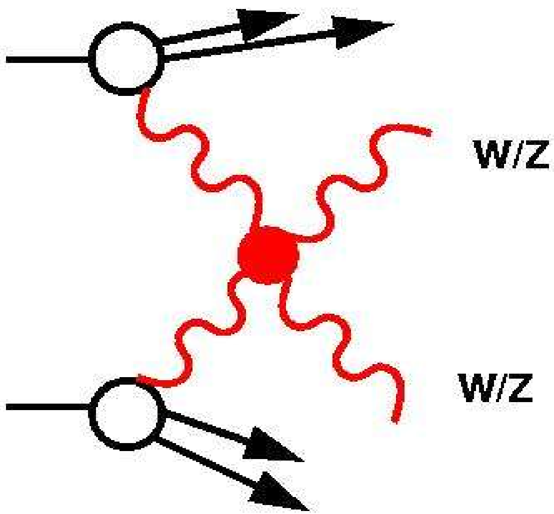
Look at leading proton rates

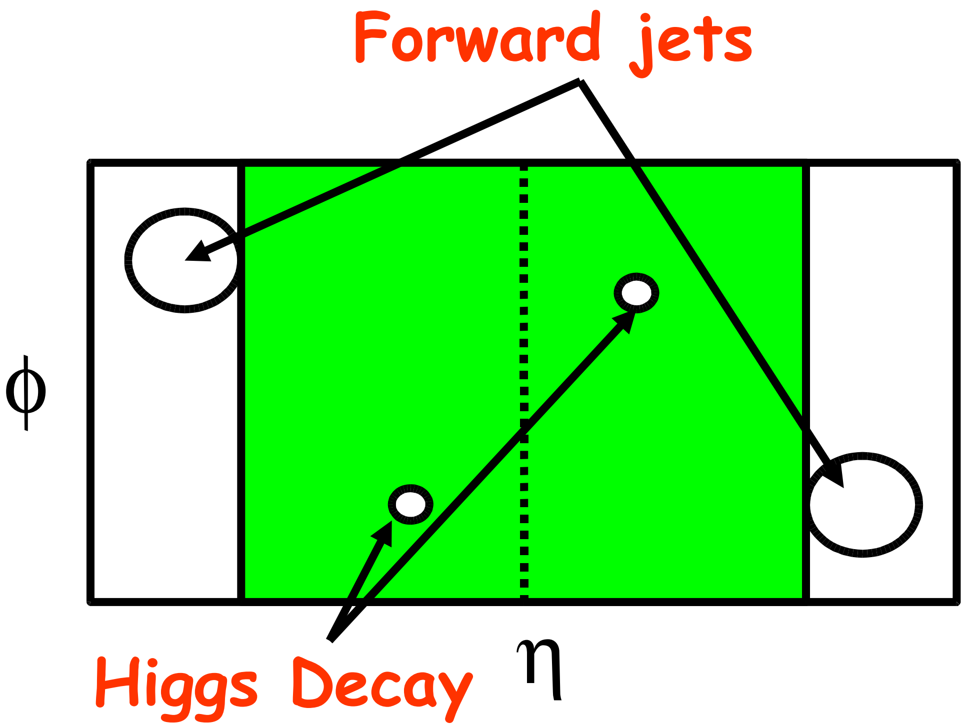
- Dijet Photoproduction :
  - H1 vs NLO: Agreement if resolved scaled by factor 0.34
  - ZEUS (LO PS) agreement without a separate scale factor for resolved (also true for H1 data!).
  - Can we understand what's going on?



Forward Jets and Low x

Back to vector boson fusion





Background rates and efficiencies critical.

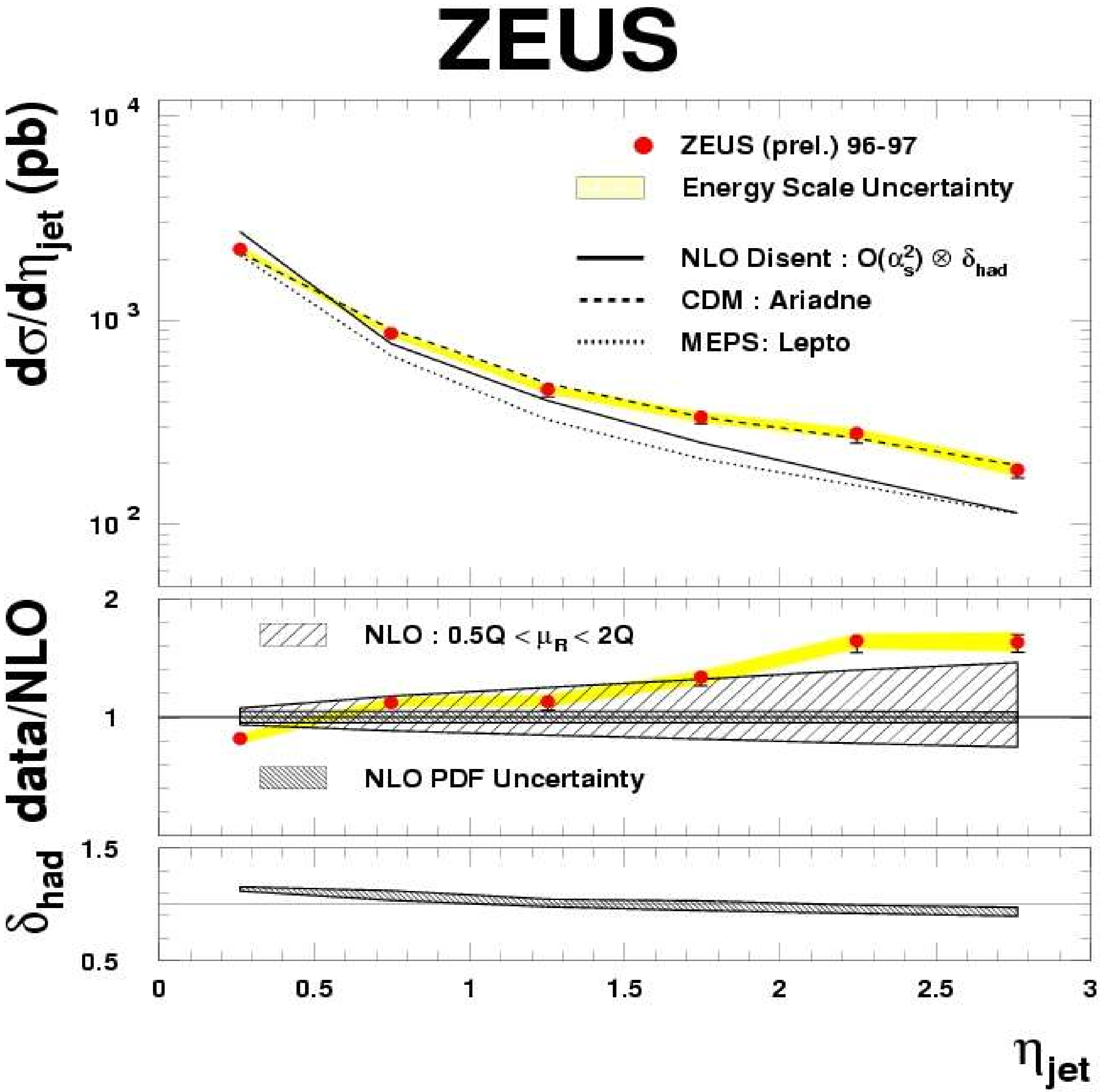
Also possible to use as a trigger at LHCb?

(E.Rodrigues, HERA-LHC wkshp)

Forward Jets and Low x

How well is the rate predicted?

Uncertainties blowing up at high rapidities.



Forward Jets and Low x

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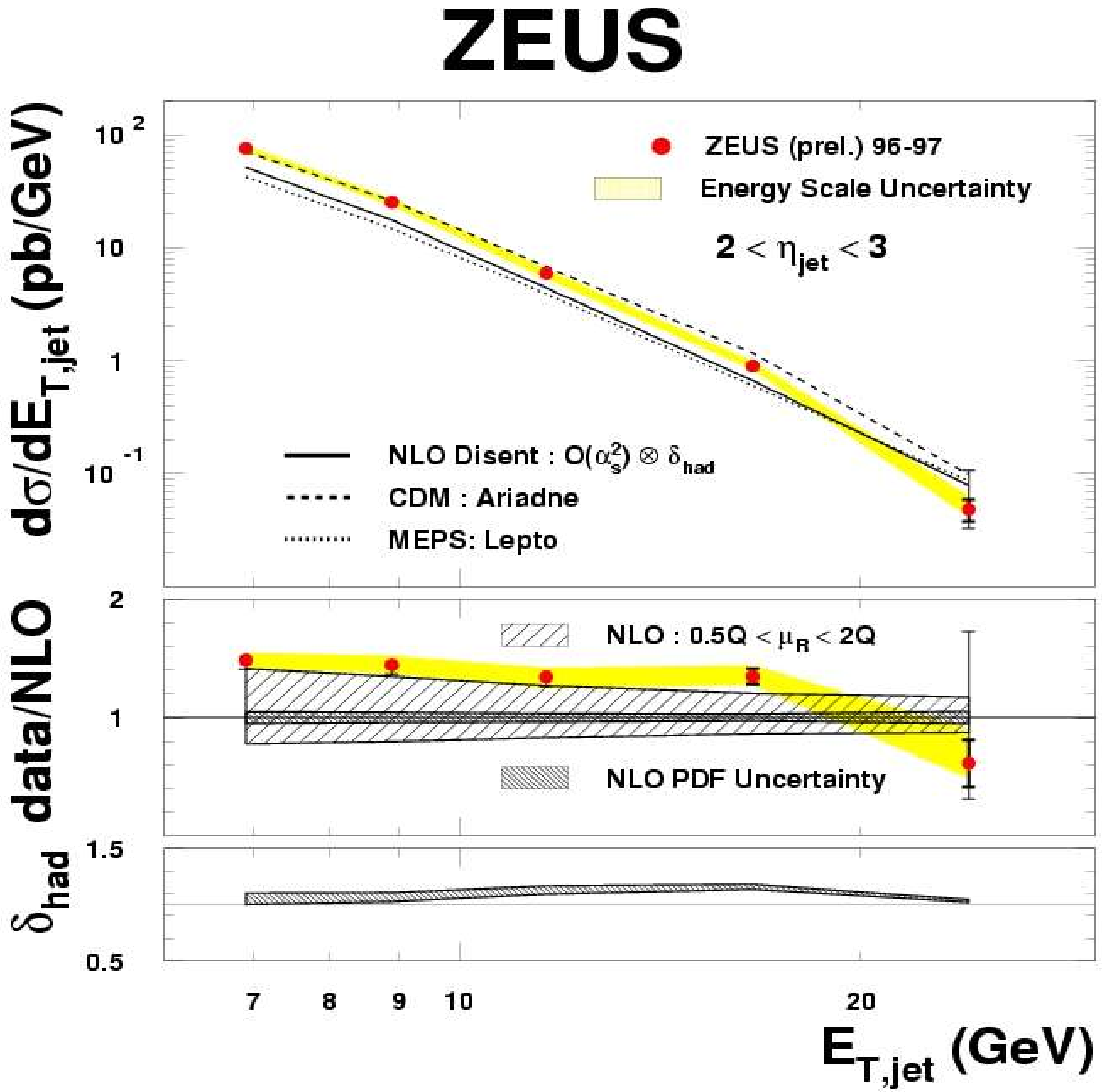
Not particularly a low E_T effect.



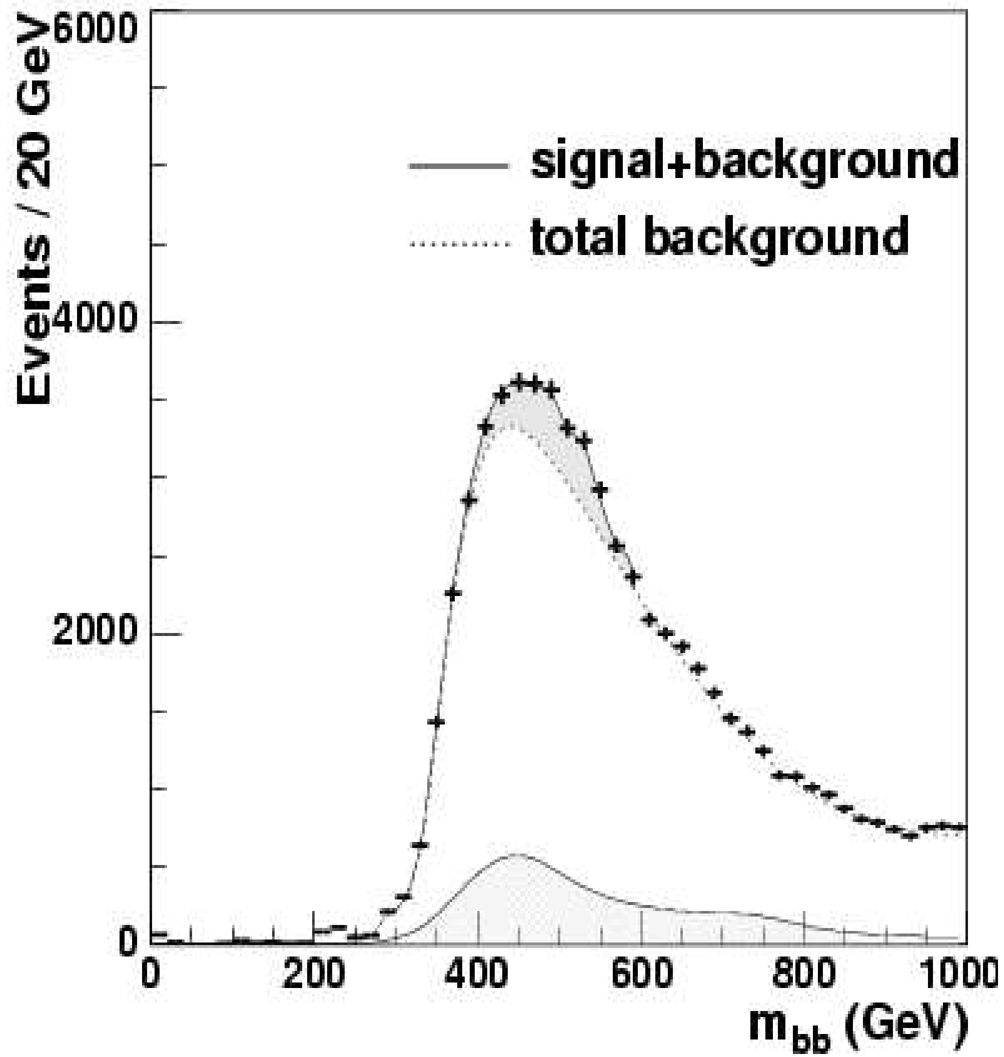
Charm and Beauty Production

- How are heavy flavours produced in hadronic collisions?
  - Challenging multiscale problem in QCD (Transverse energy, Quark mass, Photon Virtuality).
  - Obviously important to understand these processes for LHC (b-tagging for searches)...

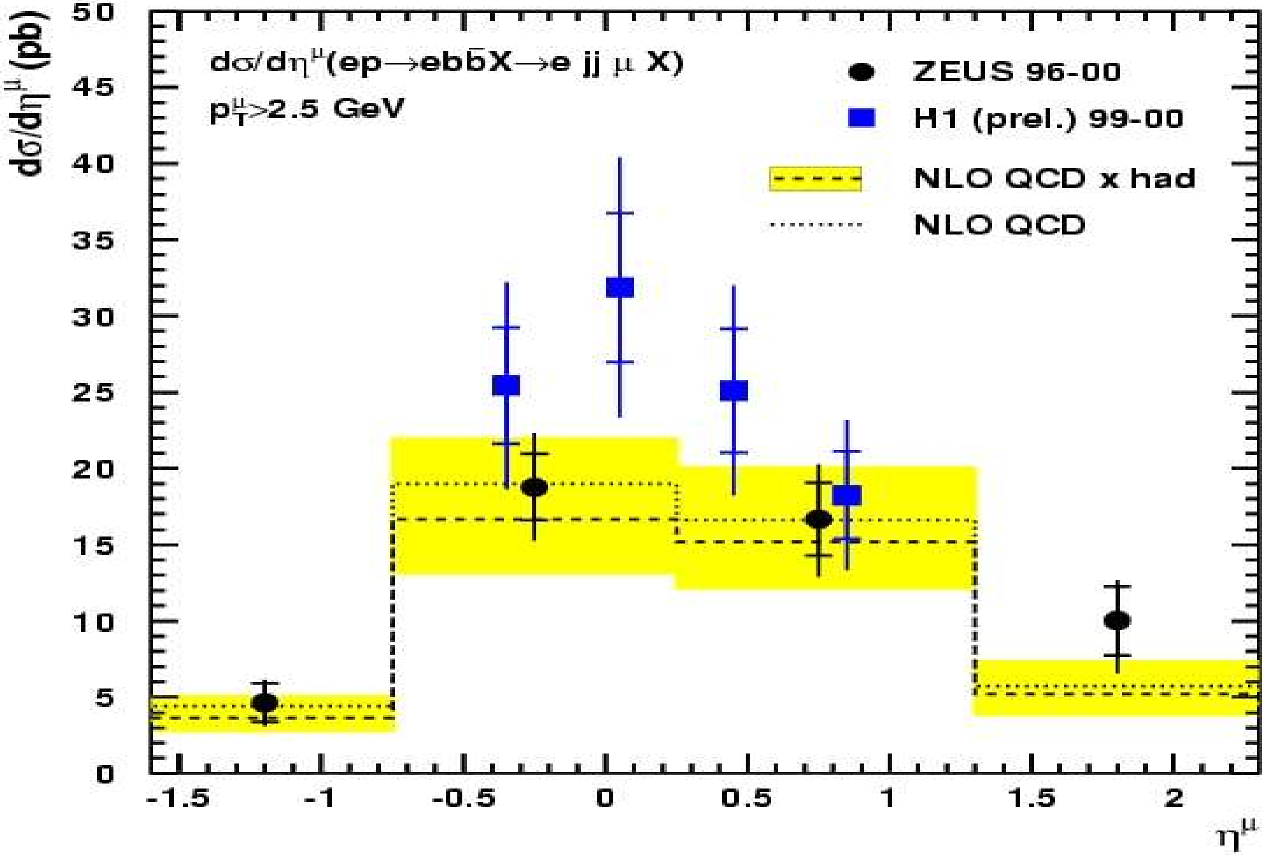
Beauty Production

Example: Higgs or A production with bb pairs; H/A -> bb

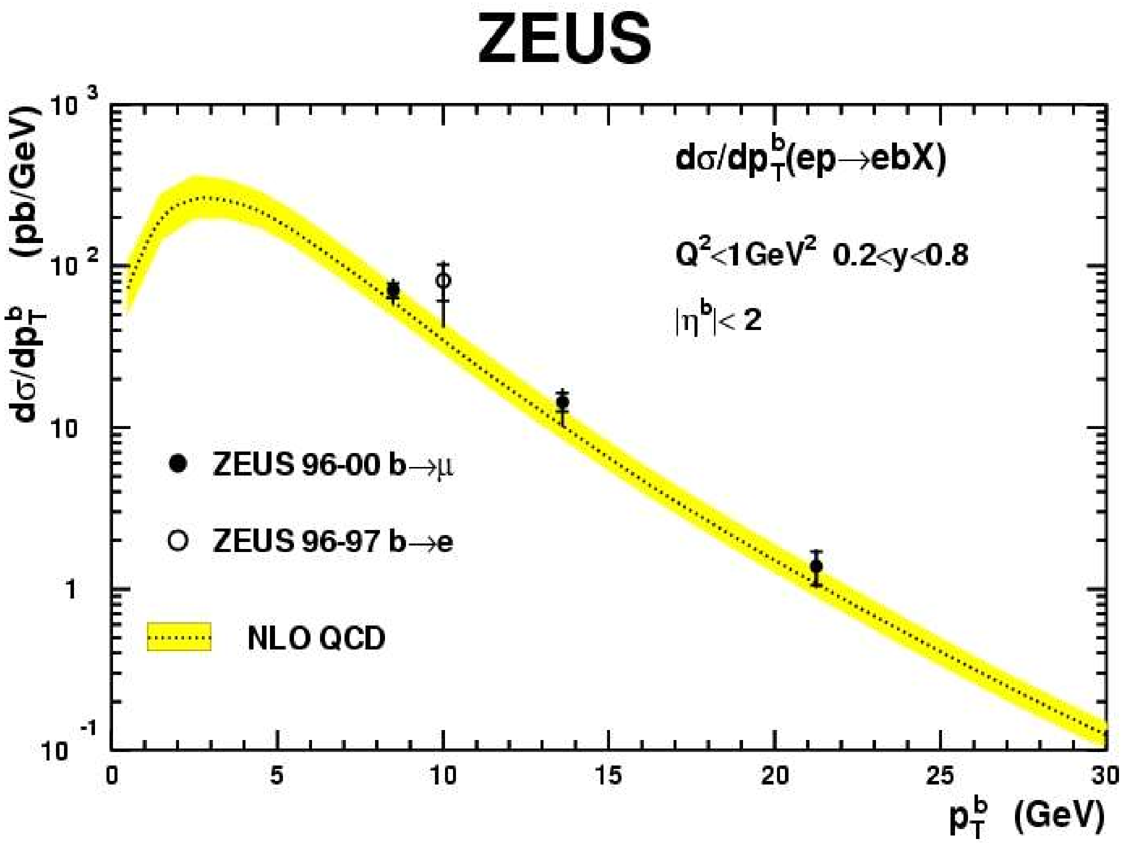
(ATLAS TDR)



Beauty Production



Beauty Production



See also: New DIS measurements this week from H1; CST

Summary

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  - hadroproduction of jets, photons, rapidity gaps.
  - precise heavy flavour data to come.

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- Systematic efforts to make best use of this data are underway and should intensify.
  - http://www.desy.de/~heralhc/
  - (Thanks to speakers from the opening meeting)

Summary

- HERA is a great lab for testing the standard model, particularly QCD
  - hadroproduction of jets, photons, rapidity gaps.
  - precise heavy flavour data to come.
- Systematic efforts to make best use of this data are underway and should intensify.
  - http://www.desy.de/~heralhc/
  - (Thanks to speakers from the opening meeting)
- Working out what we need to know from current colliders should be a priority for LHC physicists *now,* while new measurements can still be proposed.

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  - ha…
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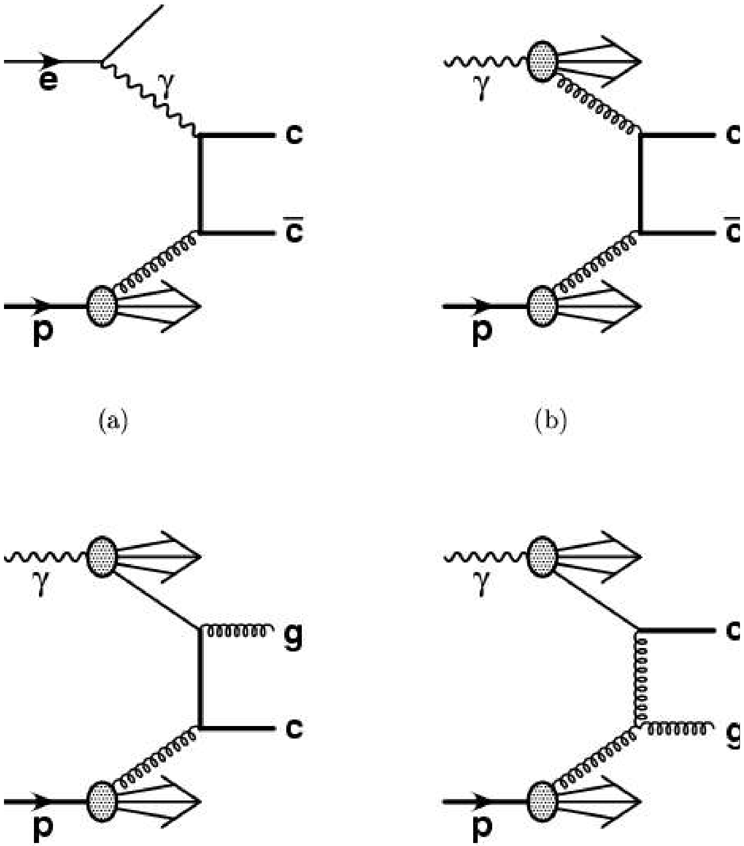
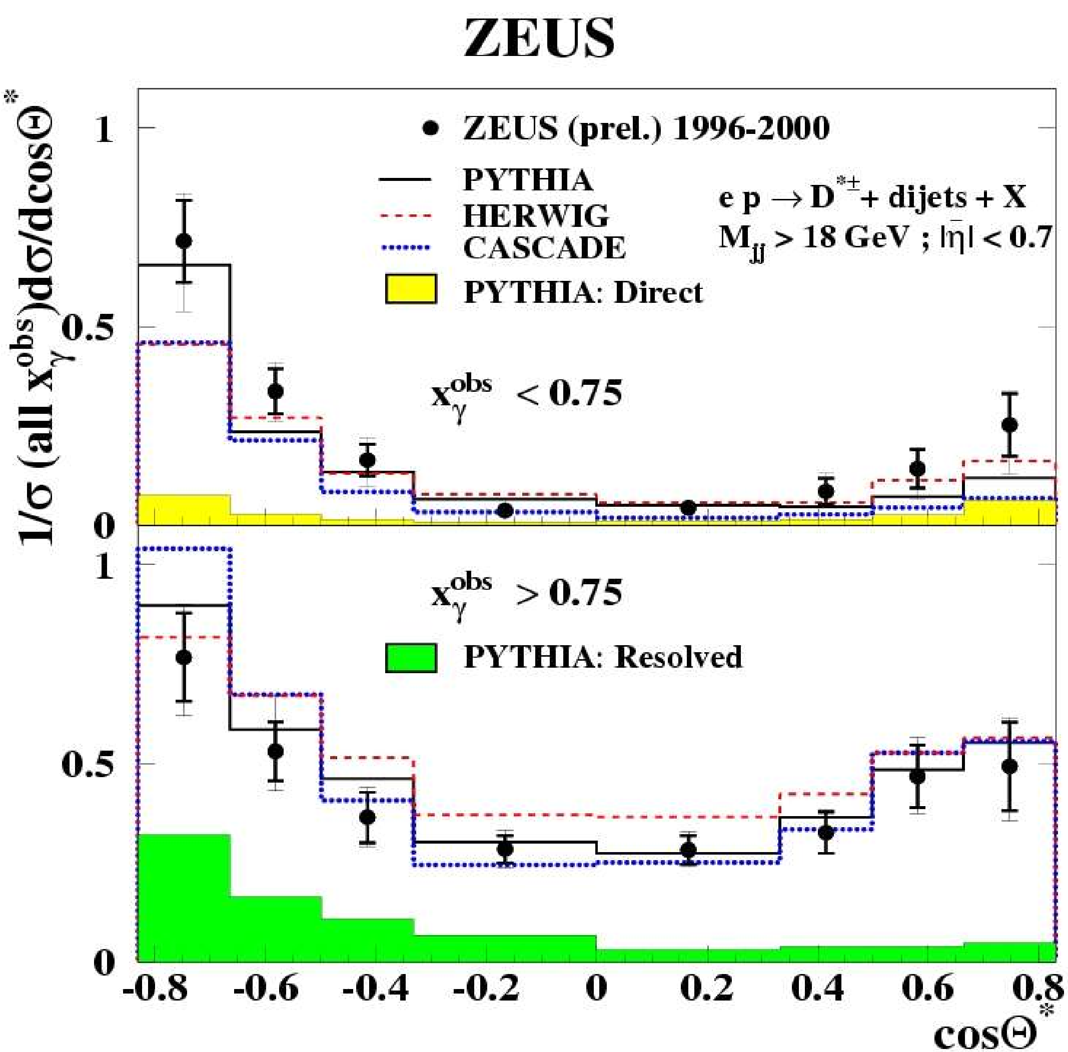
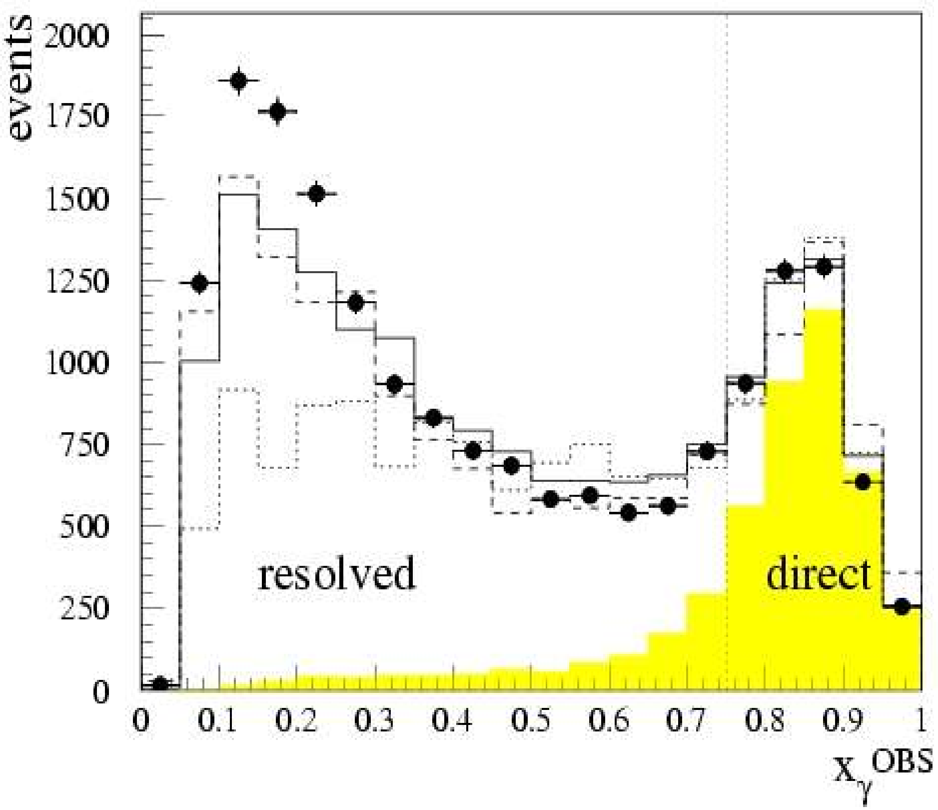
- Work… …nt collic… …s *now,* while… .

Charm production dynamics

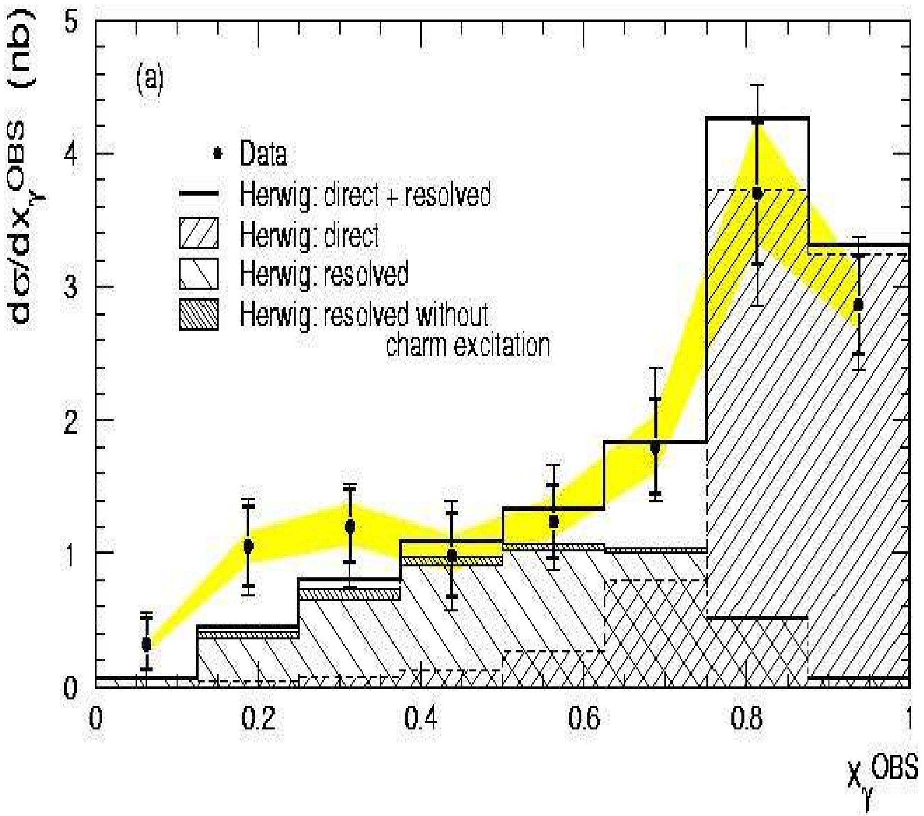




Charm Photoproduction



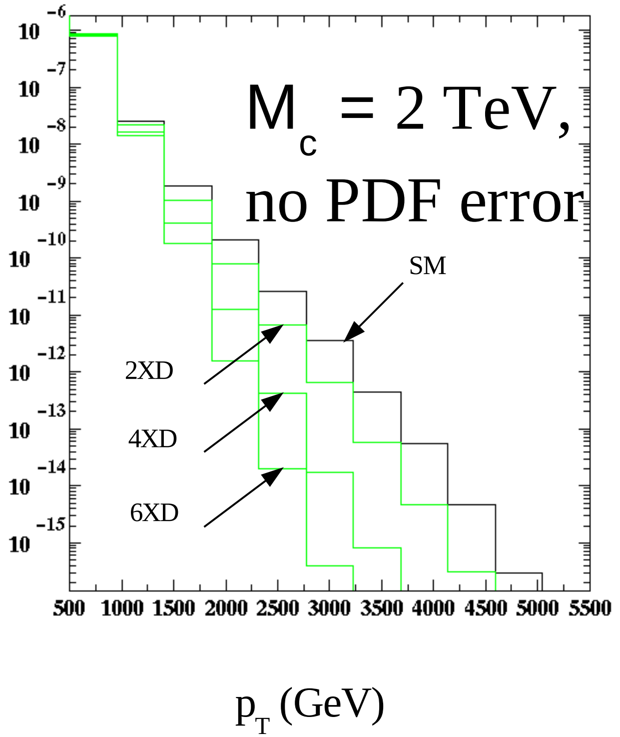
ZEUS, Eur.J.Phys C1(1998) 109

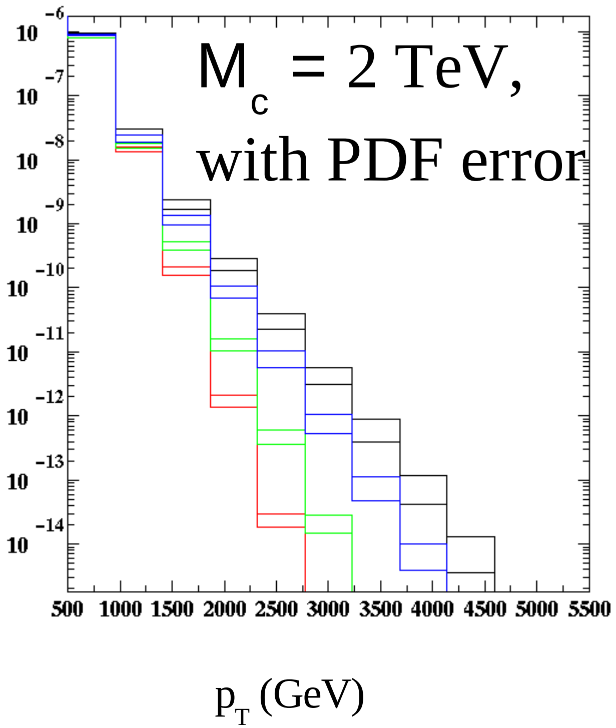


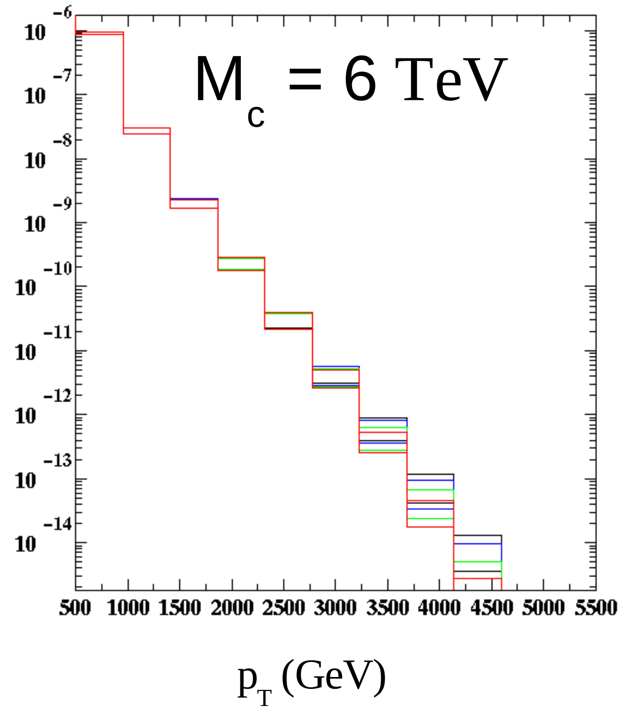
ZEUS, Eur.J.Phys C6(1999) 67

PDFs versus new physics...

- Example: Absolute level and shape of cross sections approaching kinematic limit (new physics or just PDFs?)







S.Ferrag: Dijet cross section potential sensitivity to compactification scale of extra dimensions (M_c) reduced from ~5 TeV to 2 TeV.

Charm Production as a function of photon virtuality

- Charm + jets.

Suppression due to photon virtuality and suppression due to charm mass are not independent.

One example of many multiscale problems which have been or will be precisely studied.