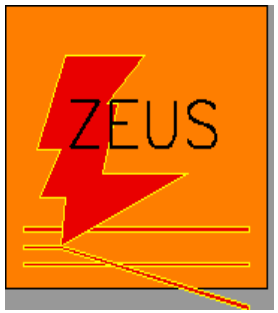
Multi-Jet Photoproduction using the ZEUS Detector at HERA



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Outline

- Introduction
- Multi-Jet Photoproduction
- Multi-Jet Results
- Conclusions & Outlook

Motivation

- Tests of perturbative QCD at intrinsically higher orders
- Study the dominant jet production mechanisms
- Study the effects of photon structure on the final state
- Search for signatures of "multi-parton interactions"

- Recent precision measurements of inclusive dijet photoproduction show that NLO cross-sections cannot describe the distribution of the data (*Europ. Phys. Journal;* ***DOI*** *10.1007/s100520200936*)

  $\rightarrow$ higher order corrections important; probed by studying events with > 2 jets

In order to maximise the physics potential both at HERA and other current and future hadron colliders (e.g. Tevatron/LHC) it is essential to study the dynamics of QCD sub-processes with large numbers of partons in the final state and to attempt to understand the nature of the "underlying event" and model it correctly

HERA Kinematics

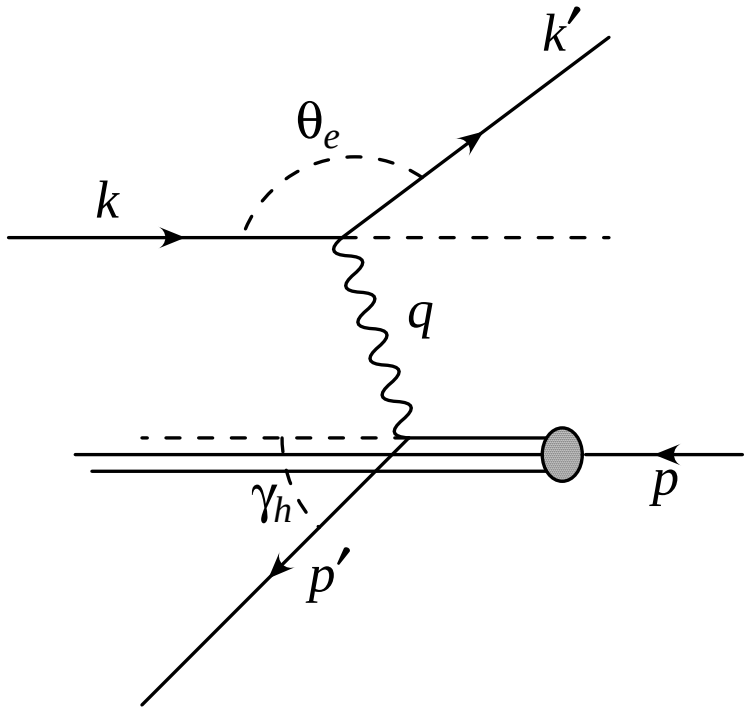
- ep collider, cms energy $\sqrt{s} \approx 300$ GeV
- measurements with the ZEUS detector

$$Q^2 = -q^2 = -(k - k')^2$$

$$x_p = \frac{Q^2}{2p.q}$$

$$y = \frac{q.p}{k.p}$$

$$\eta = -\ln(\tan\theta/2)$$



Photoproduction

- very low virtuality photon ($Q^2 \sim 0$ GeV^2)

  → long lifetime compared to characteristic time of hard subprocess

For perturbative expansion an alternative hard scale is required

- photoproduction with hard scale given by high E_T partons ($O(\alpha\alpha_s)$ at LO)

  → high E_T jets in the final state (perturbatively calculable for 2+ jets)

Hard Photoproduction

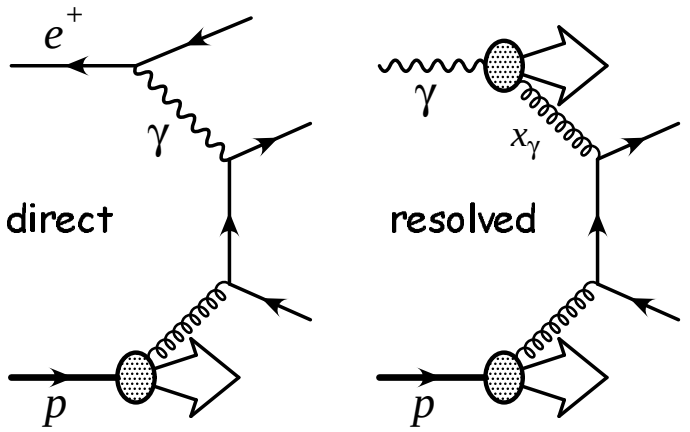
(i) "Direct" Photoproduction

- γ acts as a point-like particle (γp interaction)

(ii) "Resolved" Photoproduction

- long lifetime $\rightarrow$ γ can develop complex "hadronic" structure

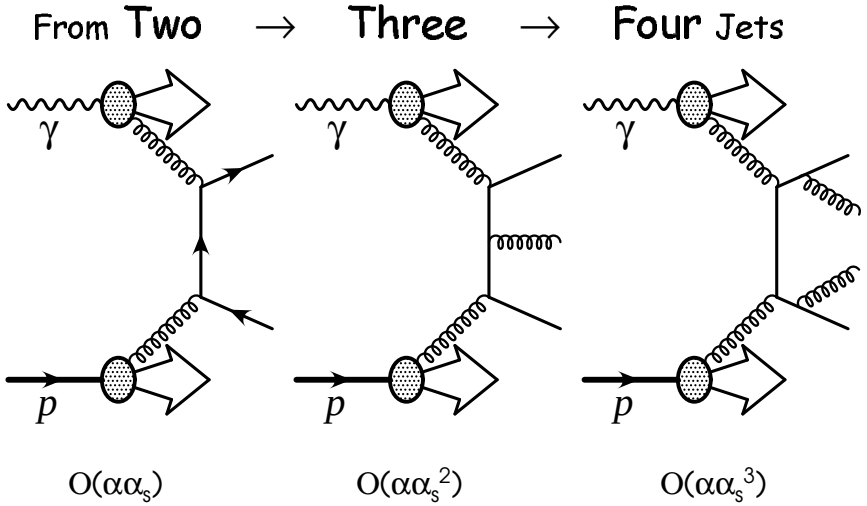
  $\rightarrow$ interacts via parton from γ carrying fraction $x_\gamma < 1$ of total γ momentum



LO Dijet Photoproduction Picture

- Use jets (k_T algorithm) to reconstruct dynamics of initial QCD subprocess

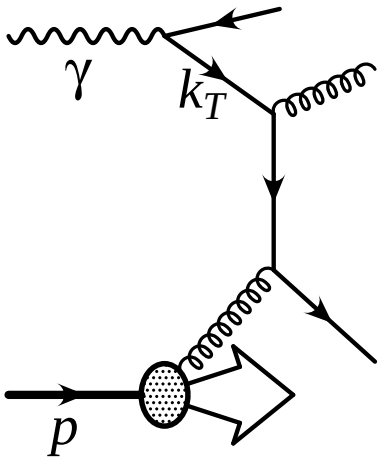
- Dynamics of multi-jet production studied by requiring at least 3 hard jets $\rightarrow$ $E_T^2 >> Q^2$



Jet Photoproduction at Higher Orders

Resolved/direct not clearly distinguished beyond LO

→ interpretation as NLO direct or LO resolved depends on virtuality, k_T^2 and factorisation scheme



Define experimental observable correlated to x_γ

→ defined to all orders of perturbation theory

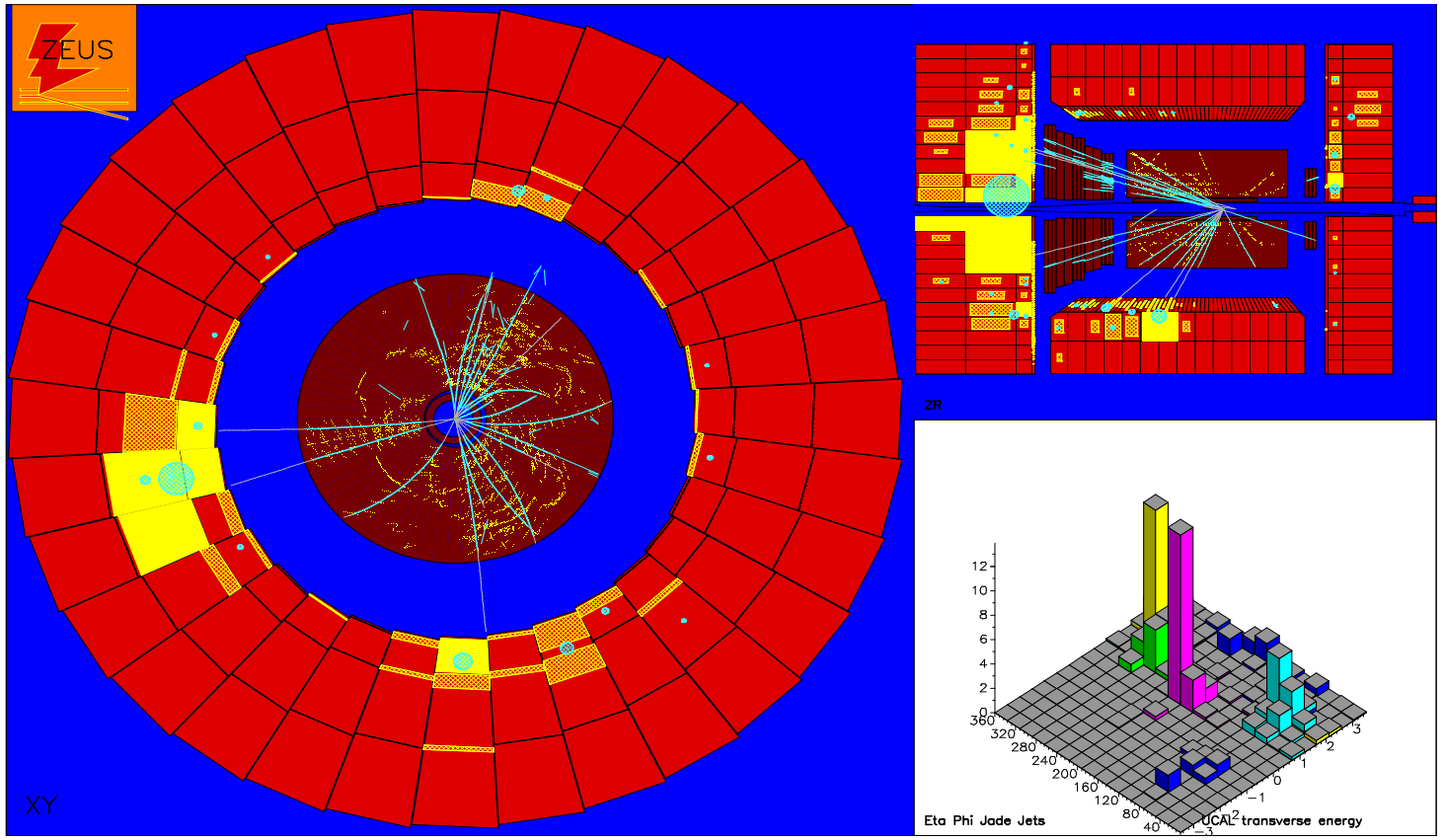
$$x_\gamma^{OBS} = \frac{\sum E_T^{Jet} \exp(-\eta^{Jet})}{2yE_e}$$

Experimentally define:

- Direct enhanced region by: $x_\gamma^{OBS} > 0.75$
- Resolved enhanced region by: $x_\gamma^{OBS} < 0.75$

where the sum is over the N jets in the event

A Four-Jet Event in ZEUS



A selected **resolved** four-jet event in the ZEUS detector, from the ZEUS Event Display Program, LAZE

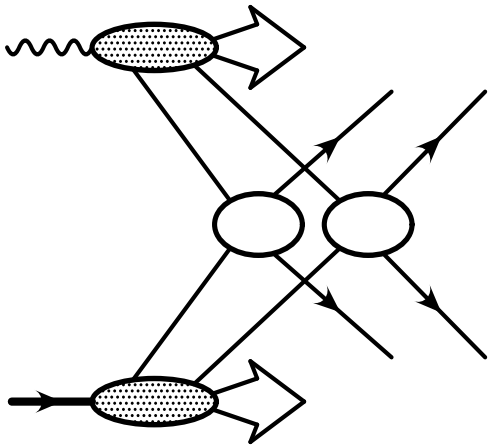
- four high E_T jets, separated by $R = \sqrt{(\Delta\eta^{jet})^2 + (\Delta\phi^{jet})^2} > 1$
- p remnant in the forward direction; γ remnant in the backward direction

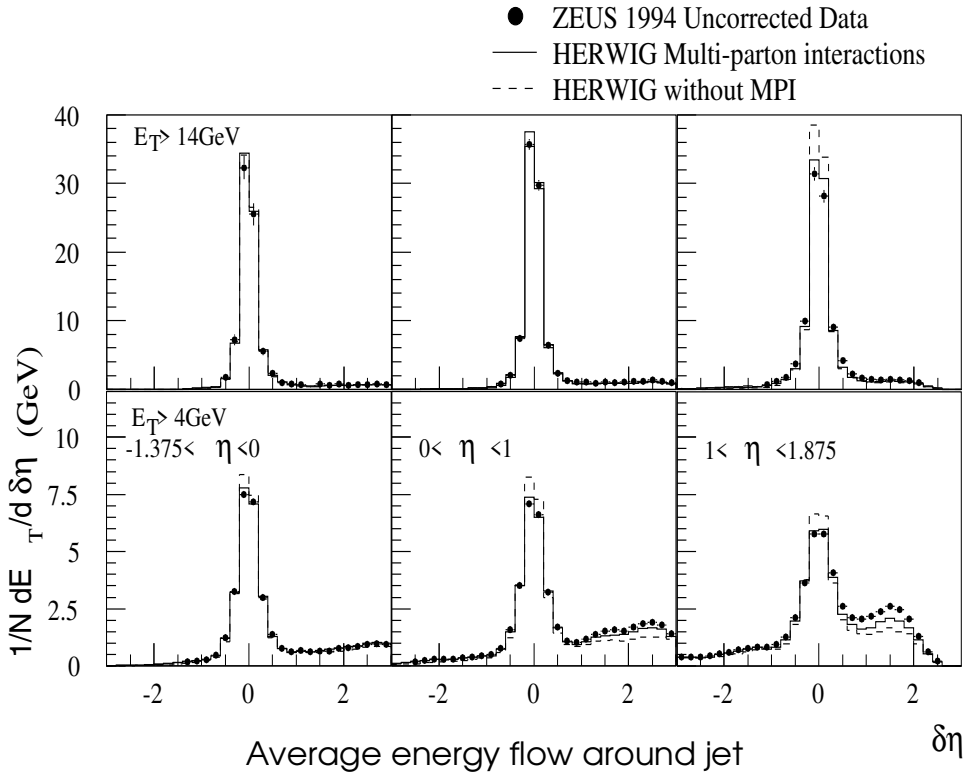
Multi-Parton Interactions

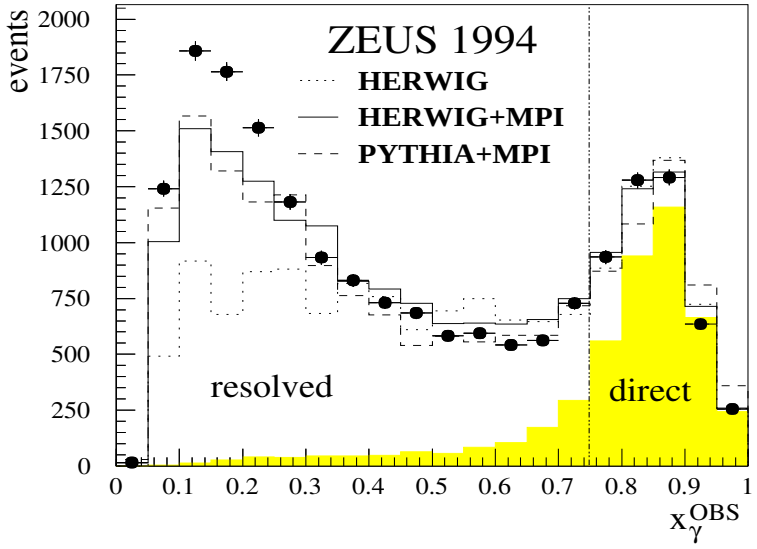
In resolved events, secondary scatters between p and γ remnant possible (multi-parton interactions)

→ most significant at low x_γ^{OBS}

→ increased energy flow in event







Multi-Jet Variables

Scheme of S.Geer & T.Asakawa
(*Phys. Rev.* ***D53*** *(1996) 4793*)

- variables defined in multi-jet rest-frame

  $1+2 \rightarrow 3+4+5+(6)$

  $E_3 > E_4 > E_5 > (E_6)$

- invariant mass of jet system: m_{NJ}

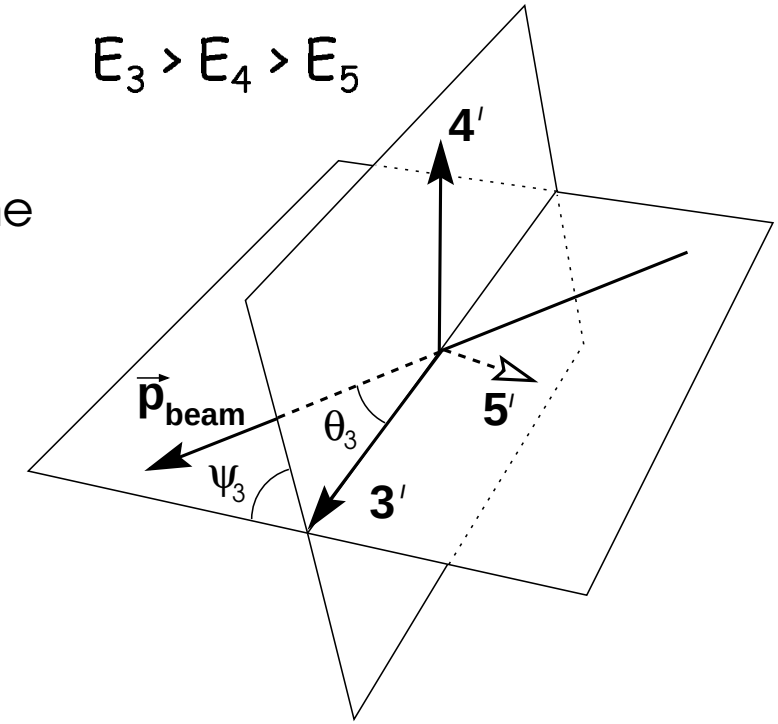
- energy fractions of jets: X_3 X_4

$$X_i \equiv \frac{2E_i}{m_{NJ}} \quad i = 3,4,5$$

- angular variables: $\cos\theta_3$ ψ_3

$$\cos\psi_3 \equiv \frac{(\vec{p}_{beam} \times \vec{p}_3).(\vec{p}_4 \times \vec{p}_5)}{|\vec{p}_{beam} \times \vec{p}_3| \, |\vec{p}_4 \times \vec{p}_5|}$$

$$\cos\theta_3 \equiv \frac{\vec{p}_{beam}.\vec{p}_3}{|\vec{p}_{beam}| \, |\vec{p}_3|}$$



Modification for four jets

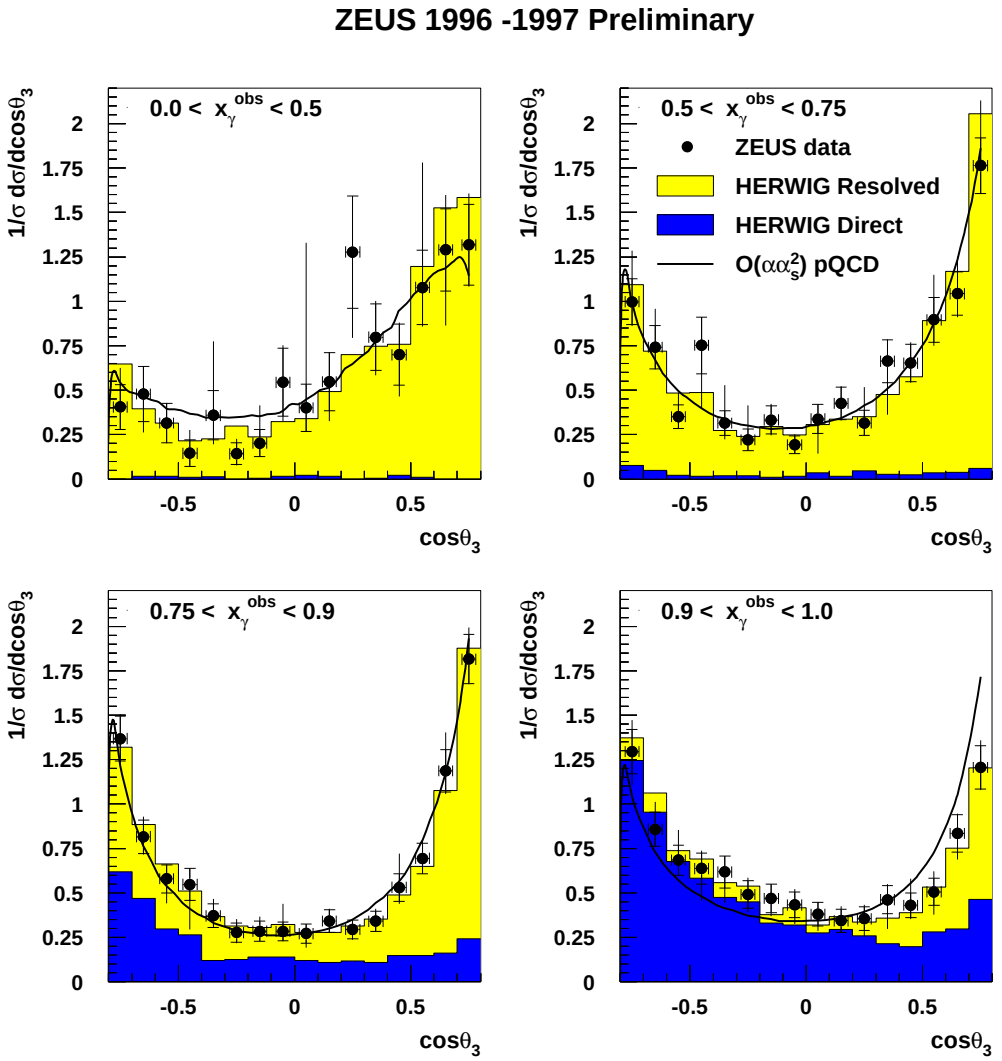
Two jets of lowest dijet invariant mass combined to form single pseudo-"jet"

- re-order in energy $E_{3'} > E_{4'} > E_{5'}$

Remaining system described exactly the same way as for three jet case

Review of Three-Jet Results

- Highest energy jet tends to lie along or against beam
  - ▹ forward peaked for low x_γ^{OBS}
  - ▹ transition to backward peaked with increasing x_γ^{OBS}
- Asymmetries can be explained by the changing contribution from direct and resolved events
- $O(\alpha\alpha_s^2)$ predictions agree with data for $x_\gamma^{OBS} < 0.9$
- Hadronisation corrections large for $x_\gamma^{OBS} > 0.9$



Definition of the Cross-Section

Inclusive Sample

Photoproduction region

- $Q^2 < 1$ GeV^2
- $0.2 < y < 0.85$

Jets found with k_T algorithm

→ inclusive mode of Ellis & Soper (*Phys. Rev.* ***D48*** *(1993) 3160*)

- $E_T^{Jet3,4} > 6$ GeV
- $E_T^{Jet5,6} > 5$ GeV
- $-2.4 < \eta^{Jet} < 2.4$

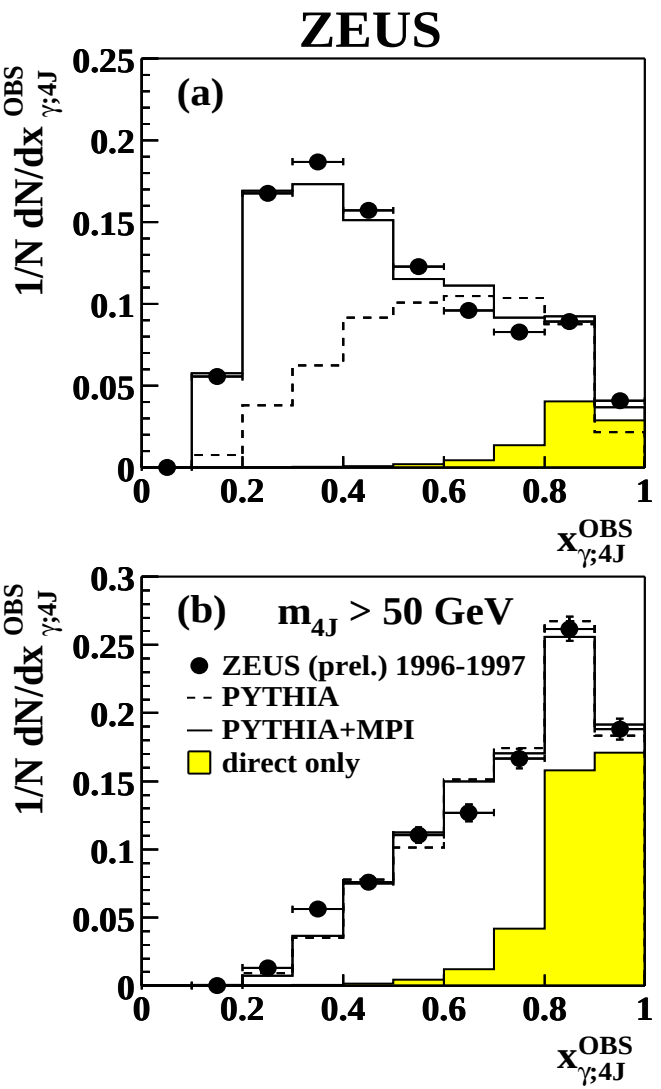
Variable cuts

- $|\cos\theta_3| < 0.8$
- $X_3 < 0.95$

High Mass

Additional cut to define more "highly perturbative" region

- $m_{4J} > 50$ GeV



Model Comparisons

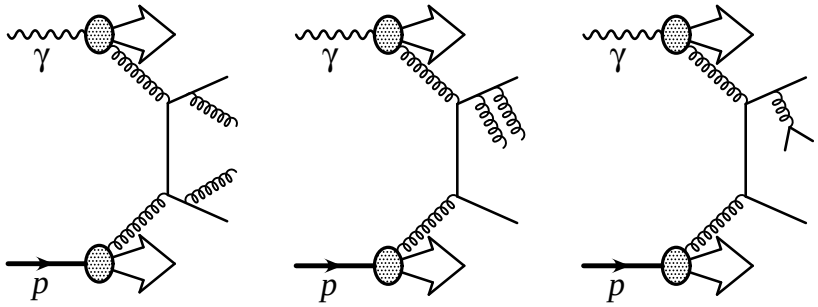
No $O(\alpha\alpha_s^3)$ QCD calculation yet available → BUT look forward to one coming soon

PYTHIA 6.1		LL parton shower model
PYTHIA 6.1	+MPI	Multi-parton Interaction model
HERWIG 6.1		LL parton shower model
HERWIG 6.1	+Jimmy	Multi-parton Interaction model
HERWIG 6.1	+SUE	"Soft Underlying Event" model

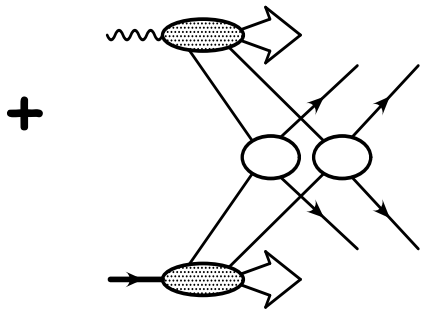
HERWIG + Jimmy model parameters tuned to CDF data

Fits by I. Borozan (UCL/RAL) on data from CDF Collaboration (data from **hep-ph/0201192**)

Leading log parton shower models

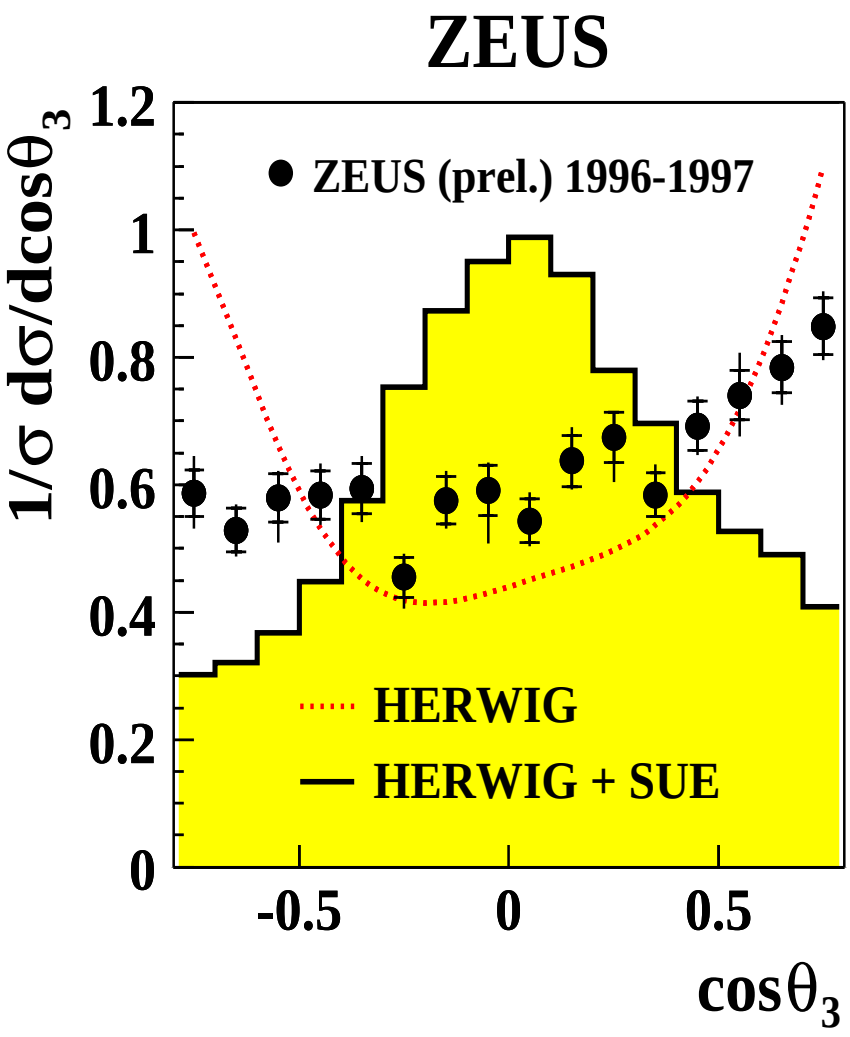


+ MPI/Jimmy



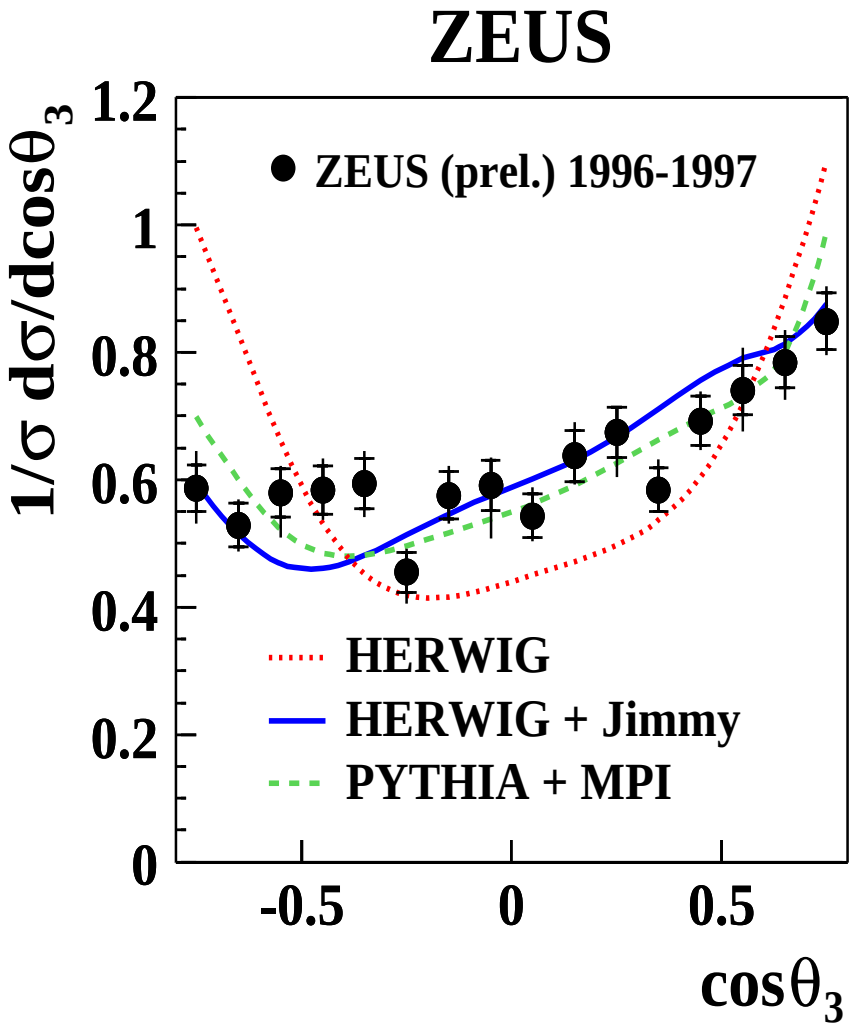
Four-Jet $\cos\theta_3$ - Inclusive Sample

- $\cos\theta_3$ expected to be sensitive to dynamics of multi-jet production
- Enhancement in forward direction
  $\rightarrow$ contribution from low x_γ partons
- "Standard" parton shower models unable to describe shape of data
- "Soft Underlying Event" (min. bias) model strongly disfavoured

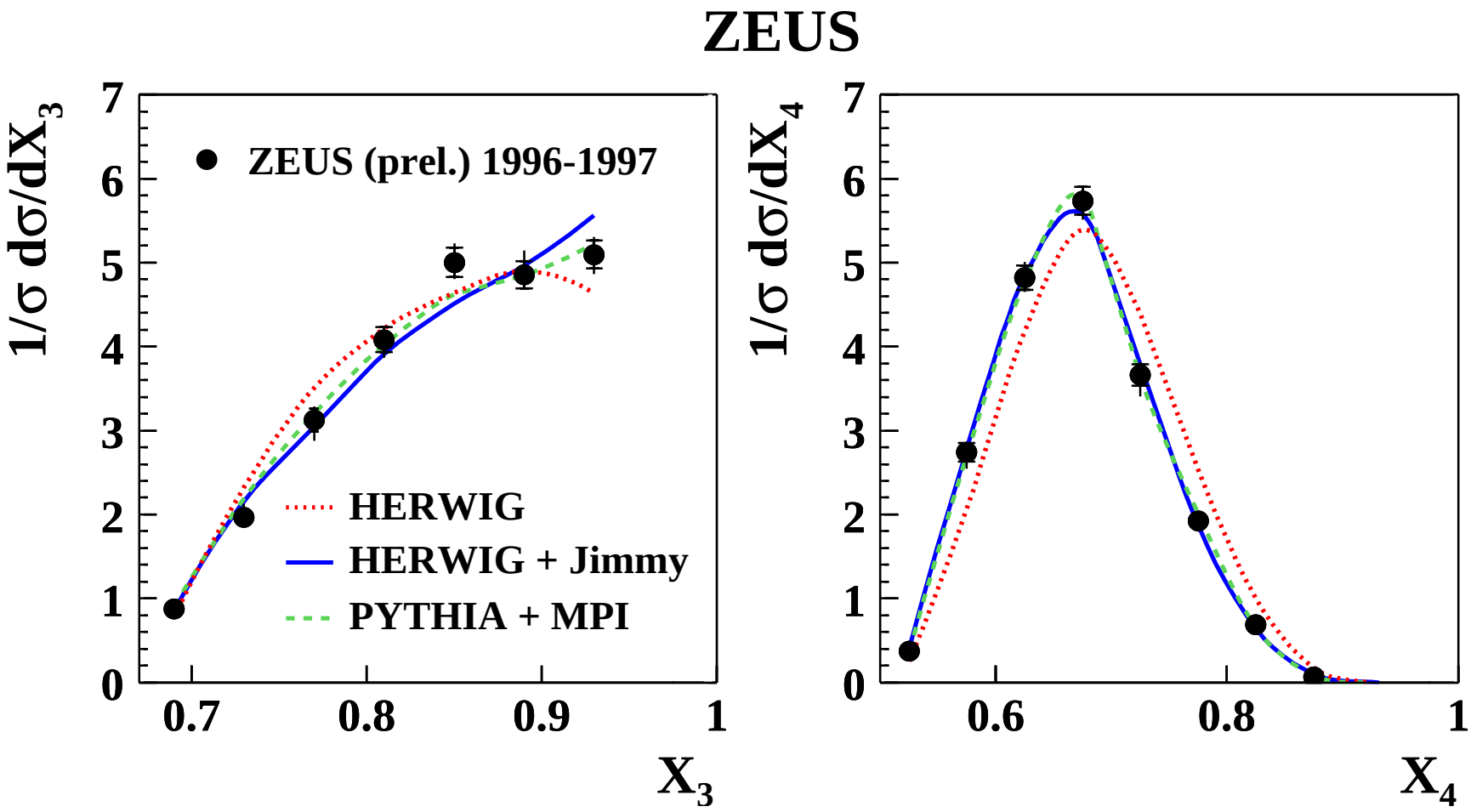


Four-Jet $\cos\theta_3$ - Multi-Parton Interaction Models

- MPI models enhanced in the forward direction
- PYTHIA and HERWIG models indicate similar trends
- Data favours MPI contribution in this kinematic region



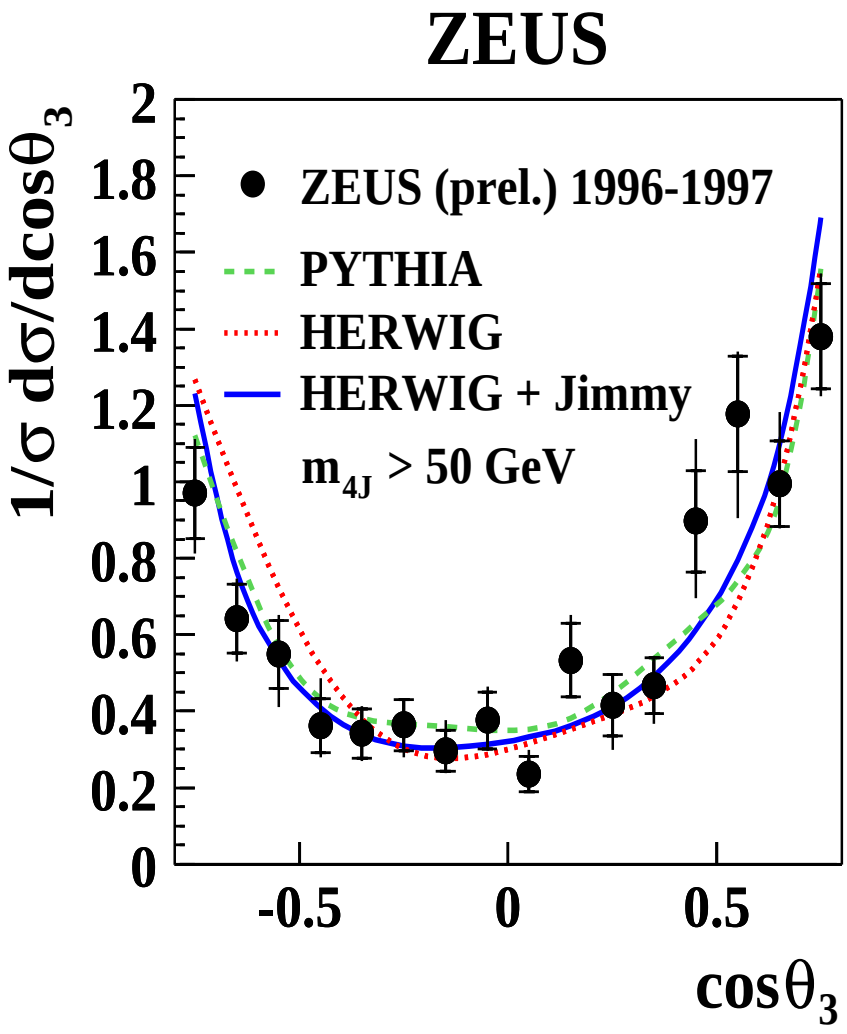
Four-Jet Energy Fractions – Inclusive Sample



- Reasonable description of energy sharing quantities by MPI models
  - ▹ good agreement between PYTHIA and HERWIG models

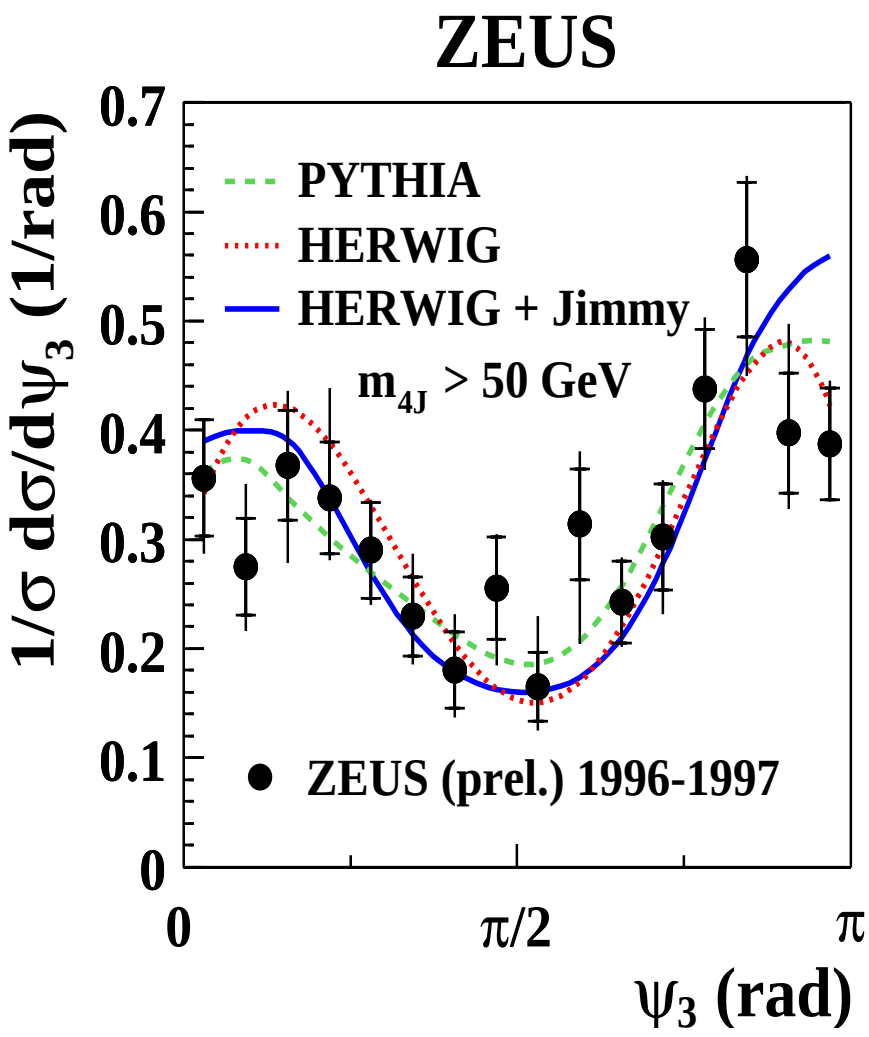
Four-Jet $\cos\theta_3$ Distribution - $m_{4J} > 50$ GeV

- Strongly peaked in both forward and backward direction (c.f. inclusive sample)
- Little sensitivity to MPI in the models
  - ▹ jets arise predominantly from the parton shower and not from MPI in this kinematic region

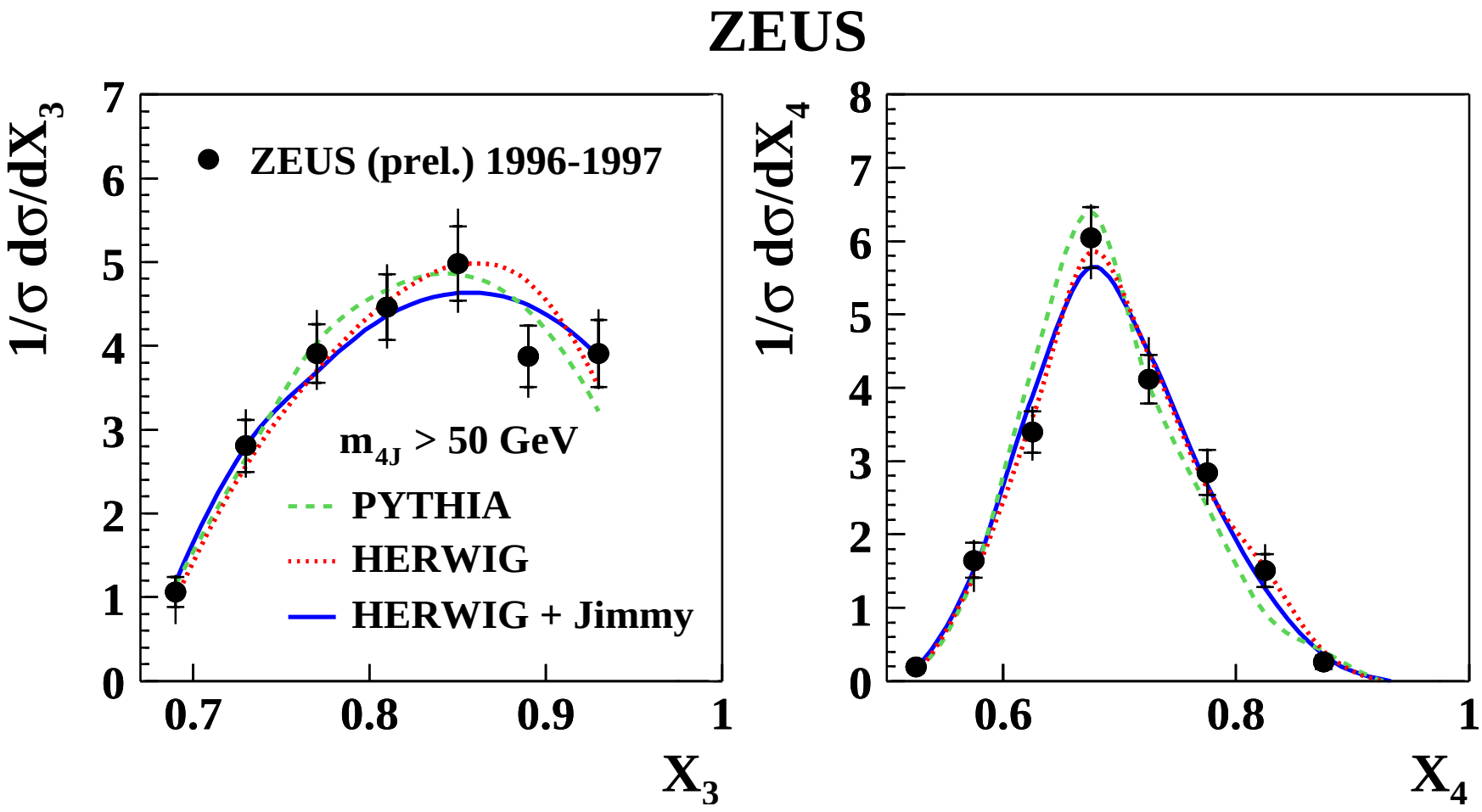


Four-Jet ψ_3 Distribution - $m_{4J} > 50$ GeV

- Lowest energy "jet" tends to lie close to the plane containing the beam and the highest energy "jet" (*Phys. Lett.* ***B443*** *(1998) 394-408*)
  - ▹ consequence of colour coherence
  - ▹ depletion at 0 and π due to phase space
- Parton shower models show reasonable agreement
  - ▹ cannot distinguish between HERWIG and PYTHIA with current statistics



Four-Jet Energy Fractions - $m_{4J} > 50$ GeV



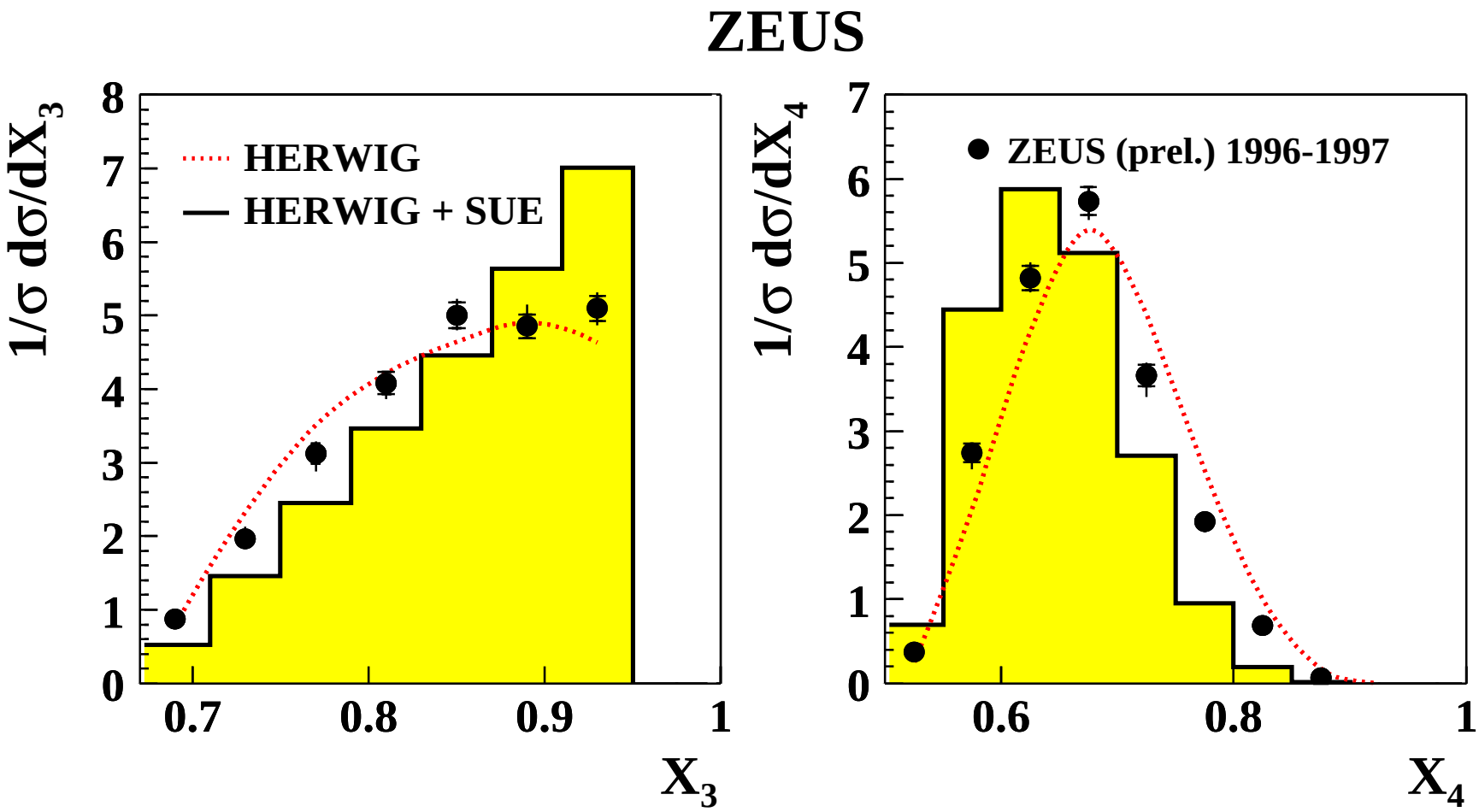
- Reasonable description of high mass energy fractions by all models

Summary & Outlook

- Four jet photoproduction cross-sections measured for the first time at HERA using the ZEUS detector
- Strong sensitivity to underlying event model observed for **low** m_{4J}
  - $\rightarrow$ soft underlying event model disfavoured
  - $\rightarrow$ data shows reasonable agreement with MPI models
- For **high** m_{4J} (>50 GeV), shape of four-jet distributions reasonably described by leading log parton shower models
  - $\rightarrow$ apparently little sensitivity to MPI in this kinematic region
  - $\rightarrow$ need more statistics to distinguish between models

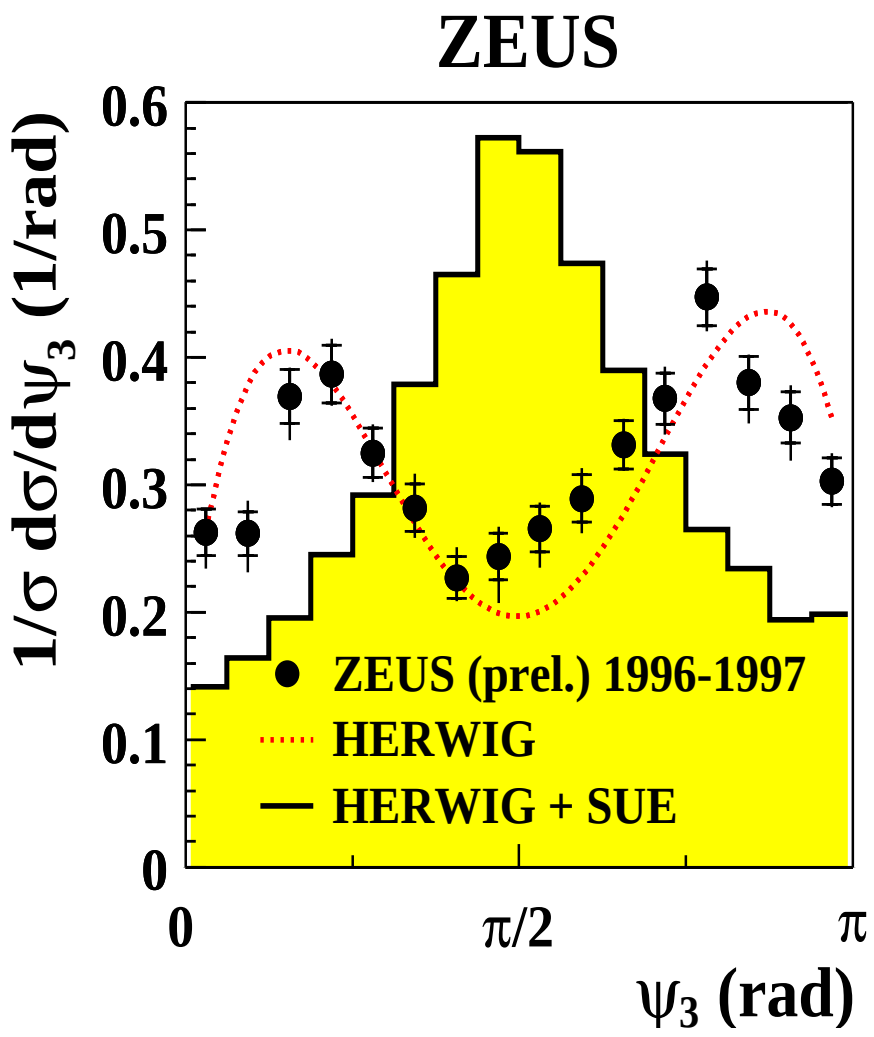
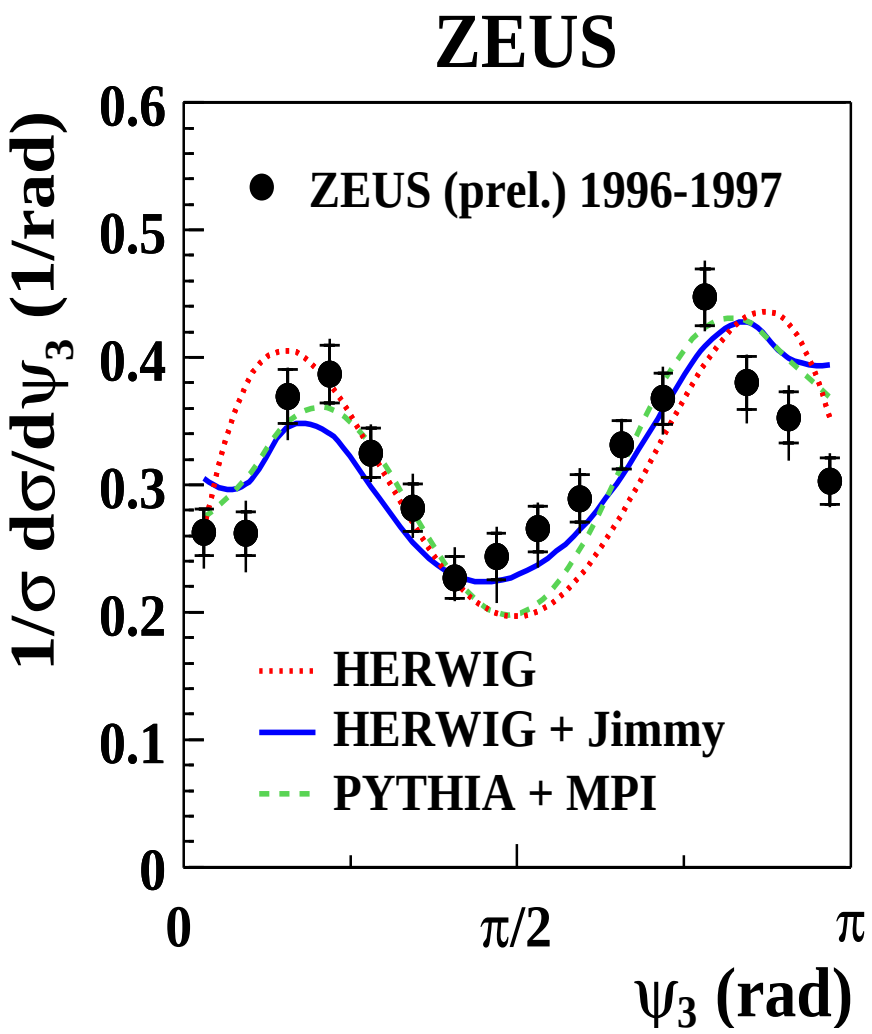
- $\mathcal{O}(\alpha\alpha_s^3)$ perturbative QCD calculation expected soon
  - $\rightarrow$ NLO for three jets; LO for four jets
- Higher luminosity from HERA upgrade will allow precision measurements of these and even higher order QCD sub-processes

Four-Jet Energy Fractions – Inclusive Sample



- Neither "standard" parton shower model nor "soft underlying event" model gives good description of the data

Four Jet ψ_3 - Inclusive Sample



Four Jet ψ_3 - Inclusive Sample