# Three-Jet Production in DIS and gamma-P

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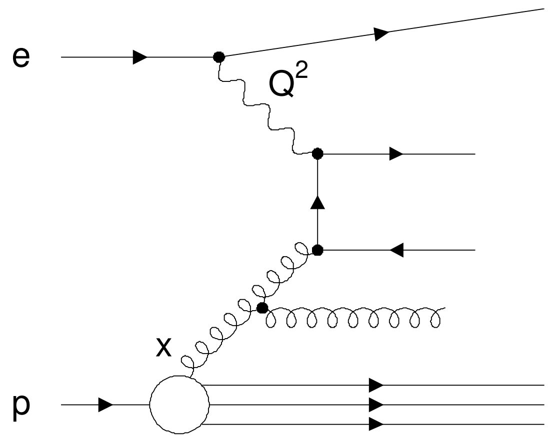
on behalf of the H1 and ZEUS Collaborations

Topics:

- Why are three-Jet events interesting?
- Production mechanisms in DIS and gamma-P
- Discussion of the measured data
- What have we learned until now?
- What could be interesting in the future?

# Why are three-Jet events interesting?




3-Jet production is an important phenomenon in hadron-hadron and electron-hadron colliders (HERA) :

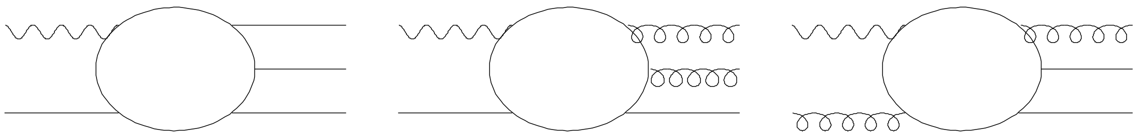
- Large rates and rich final state structure
  $\Rightarrow$ excellent testing ground of pQCD
- $\sigma_{ep\to 3Jets} \propto O(\alpha_s^2)$
  $\Rightarrow$ could be used e.g. for additional $\alpha_s$ measurement
- Background to various new physics signals

# Production mechanism of 3-Jets in DIS

Hadronic 3-Jet Cross section can be calculated from ME with factorisation theorem:

Direct: Photon couples direct to quark or gluon (e.g. $\gamma$+q $\Rightarrow$ q+$\overline{q}$+q)

$$\sigma^{dir,LO}_{eP\rightarrow 3Jets} = \sum_i \int dx\, f_{i/P}(x,\mu)\times$$
$$\sigma_{ei\rightarrow 3Jets}(x,\mu)$$



- Direct contribution dominates in DIS down to moderate photon virtualities $Q^2$
- Calculations done for 3-Jet Production in LO $O(\alpha_s^2)$
- LO Cross section depends on factorisation $\mu_f$ and renormalisation $\mu_r$ scale and on Proton Parton densities $f_{i/P}$

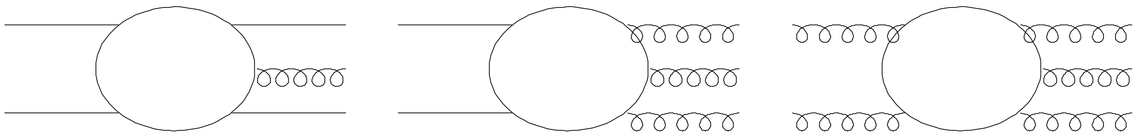
# Production mechanism of 3 Jets in $\gamma$P

Direct AND Resolved contributions

Resolved: Photon splits in partons which couple to quarks or gluons (e.g. q+q' $\Rightarrow$ g+g+g)

$$\sigma^{res,LO}_{eP \to 3Jets} = \sum_{j,i} \int dx_\gamma f_{j/\gamma}(x_\gamma, \mu) f_{\gamma/e}(y) \times$$

$$dx f_{i/P}(x) \sigma_{ij \to 3Jets}(x, x_\gamma, \mu)$$



- Resolved contribution dominates at low $x_\gamma$. ($x_\gamma$ is fraction of photon momentum carried by the interacting parton)
- Resolved contribution needed for low $Q^2$ region.
- Calculations done for 3-Jet Production to LO $O(\alpha_s^2)$
- Cross section depends on factorisation $\mu_f$ and renormalisation $\mu_r$ scale, on the Proton Parton densities $f_{i/P}$ and Photon Parton densities $f_{j/\gamma}(x_\gamma)$

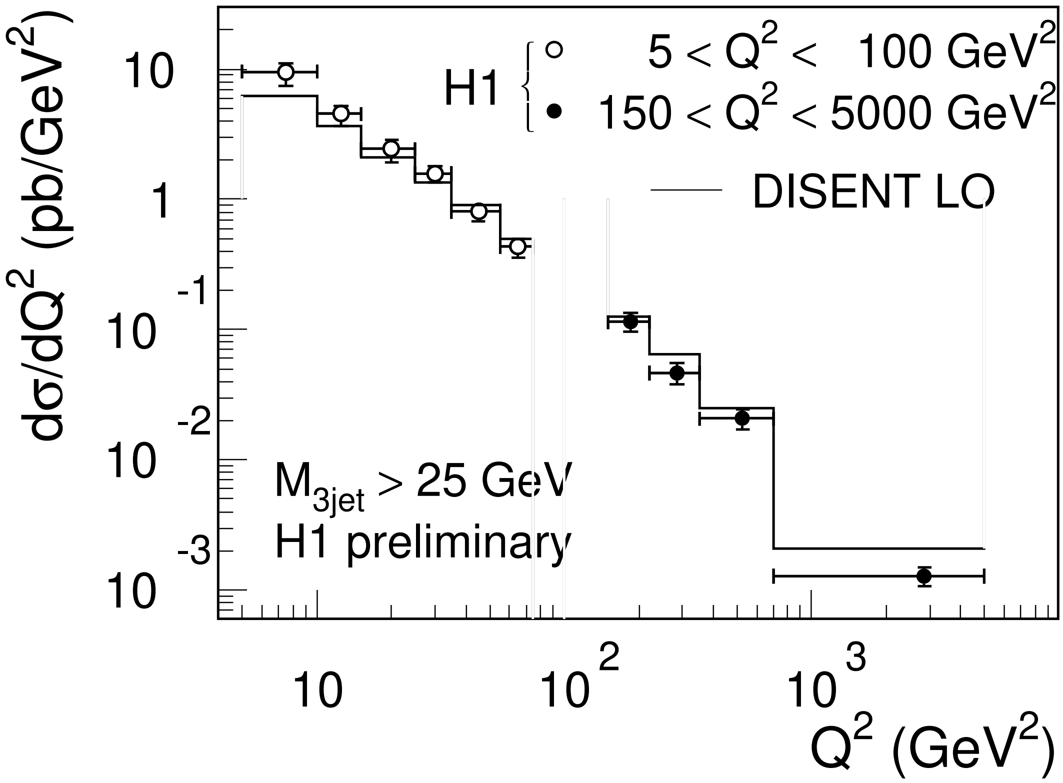
# Production mechanism of 3 Jets in DIS and $\gamma$P

- Higher integrated Luminosities allows measurements of 3-Jet events. $\Rightarrow$ Measurements are made at low ($Q^2 < 4GeV^2$), moderate ($5 < Q^2 < 100GeV^2$) and high photon virtualties $Q^2$ ($100 < Q^2 < 5000GeV^2$).
- Range of measurered Jet $E_T$ in 3-Jet events goes from 5 GeV up to 75 GeV.
  $\Rightarrow$ Possible to use the Jet $E_T$ for renormalisation and factorisation scale
- NLO 3-Jet calculations not available
  $\Rightarrow$ large renormalisation and factorisation scale uncertainties
- Compare with 3 Jet predictions of Parton Shower Models (only Born Level QCD ME ($O(\alpha_s)$) + Parton Showers to simulate higher order QCD radiation)
- How to classify a 3-Jet event?
  $\Rightarrow$ Used Jetalgorithm: inclusive $k_\perp$ (KTCLUS package):
  Define 3 Jet events with $p_T^{Jet}$ and $\eta$ cuts on Jet candidates in Laboratory (Photoproduction) or Breit-System (DIS).
  Breit-System: spacelike virtual photon collides head-on with the proton

# Measured data at high and moderate $Q^2$

H1: $5 < Q^2 < 100 GeV^2$ and $150 < Q^2 < 5000 GeV^2$
Jets defined in the Breit frame, $E_{T,Breit} > 5 GeV$ for each Jet is required

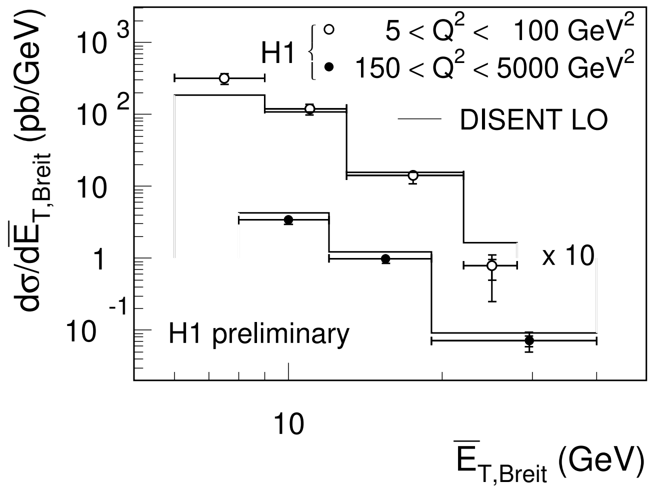
Hadronisation Correction would lower pQCD predictions by 20-40 percent



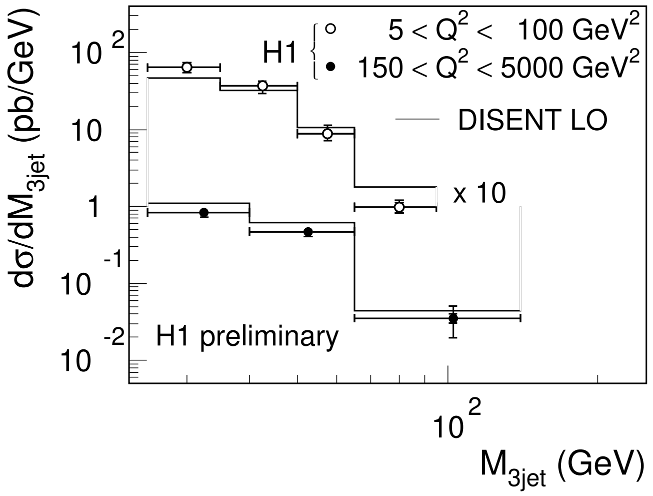

- Direct LO $O(\alpha_s^2)$ pQCD (Disent with CTEQ5L, $\mu = E_{T,mean}$) gives describtion of data down to $Q^2$ of 40 $GeV^2$

# Measured data at high and moderate $Q^2$

Hadronisation Correction would lower pQCD predictions by 20-40 percent




$\Rightarrow$ $O(\alpha_s^2)$ pQCD undershoots the data at $\overline{E}_{T,Breit} < 10GeV$

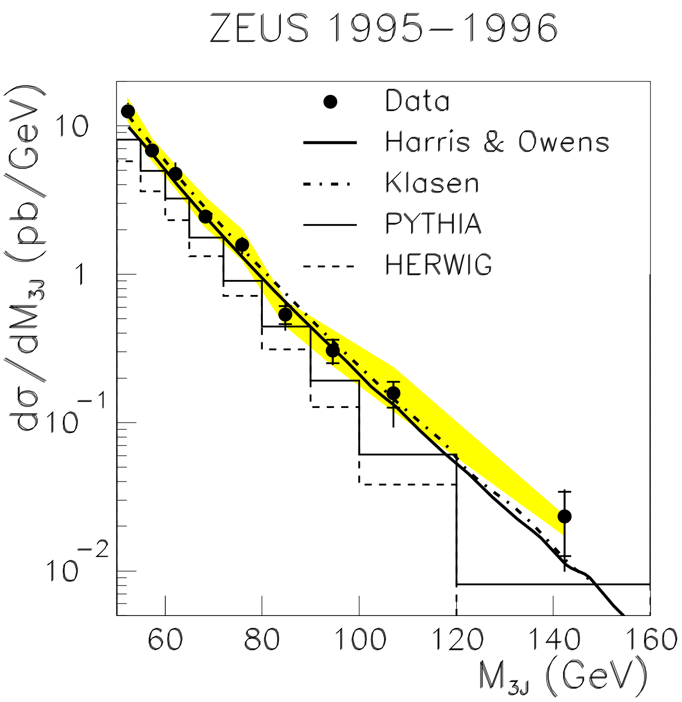



$\Rightarrow$ $O(\alpha_s^2)$ pQCD undershoots the data at $M_{123} < 50GeV^2$

$\Rightarrow$ Description of the data by LO pQCD at high masses and $p_T$ in DIS (but high scale uncertainties)

# What about Photoproduction?

ZEUS: $Q^2 < 1GeV^2$, $0.2 < y < 0.8$
Jets defined in the Laboratory frame $E_{T,Jet1} > 6GeV$, $E_{T,Jet2} > 6GeV$ ,$E_{T,Jet3} > 5GeV$
$|\eta_{jet}| < 2.4$
integrated Luminosity= 16 $pb^{-1}$




$\Rightarrow$ $O(\alpha_s^2)$ pQCD (CTEQ4LO and GRVLO with $E_{T,Jet1}$ choosen as scale) describes the data in Photoproduction up to the highest masses

$\Rightarrow$ $O(\alpha_s^2)$ pQCD calculations by different goups agree up to 10 percent

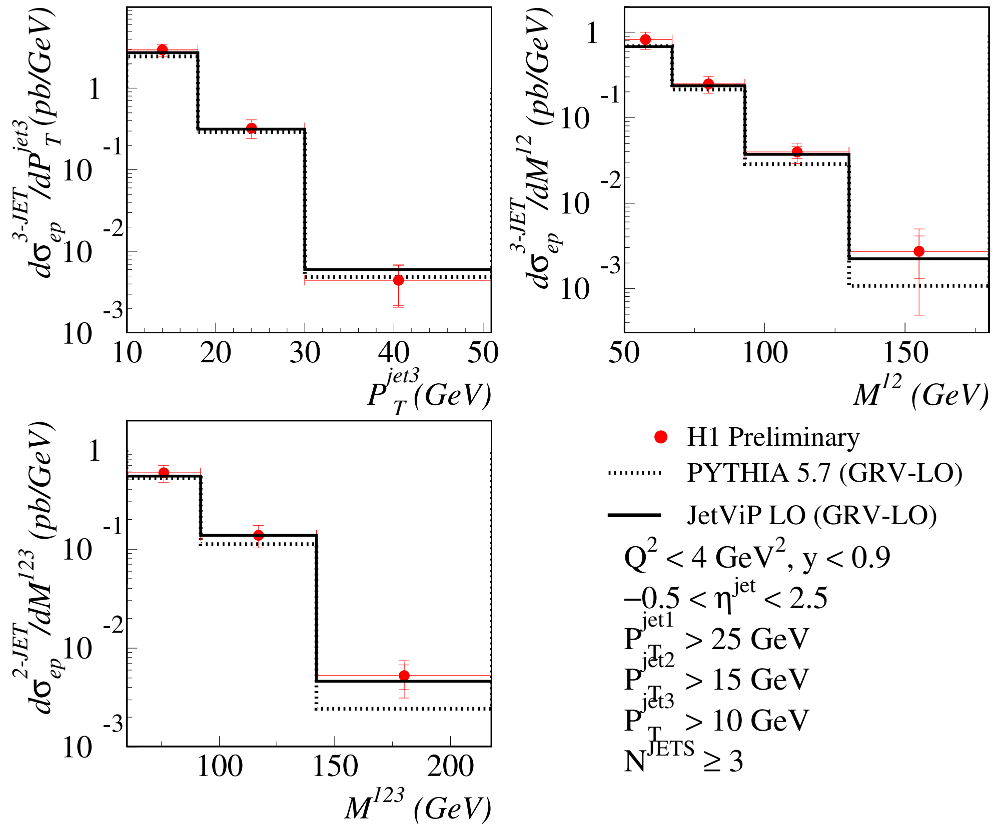
$\Rightarrow$ Uncertainty by the choice of scale is large

$\Rightarrow$ Parton shower models are always too low

How far can we go in $M_{3Jet}$?
$M_{3Jet} \propto x_{Bj} * x_\gamma * y * \sqrt{s_{eP}}$

# What about Photoproduction?

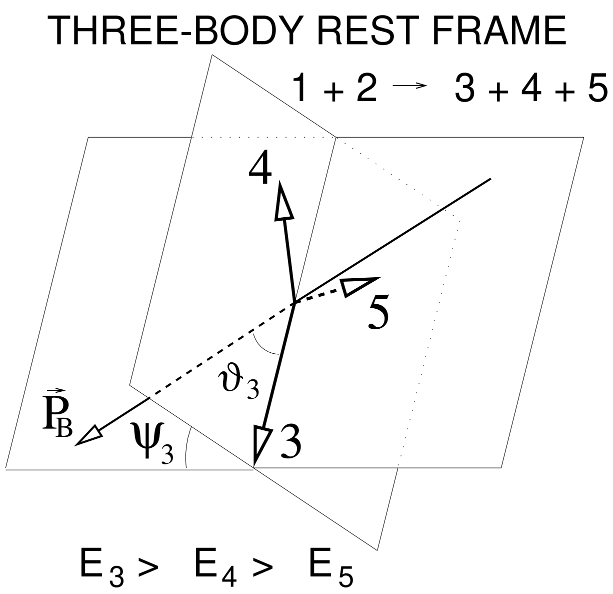
H1: Jets defined in the Laboratory frame
integrated Luminosity$= 35.7\ pb^{-1}$




$\Rightarrow$ $O(\alpha_s^2)$ pQCD (JetViP with GRV-LO PDFs, $\mu = E_{T,leading}$) describes the data in Photoproduction up to masses of 180 GeV $\Rightarrow$ No significant deviations seen so far in highest transverse momentum and invariant masses in 3-Jet production

# CMS Variables

Process 1+2 $\longrightarrow$ 3+4+5 (with respect to their energies in 3 Jet CMS)




Five variables fully characterize the 3 Jet properties:

Dalitz energy fractions specify the energy sharing:

$X_1 = \frac{2E_{1.Jet}}{M_3}$

$X_2 = \frac{2E_{2.Jet}}{M_3}$

$(X_1 + X_2 + X_3 = 2)$

2 variables specify the orientation:

$\cos\theta_3 = \frac{\vec{P}_B \vec{P}_3}{|\vec{P}_B||\vec{P}_3|}$

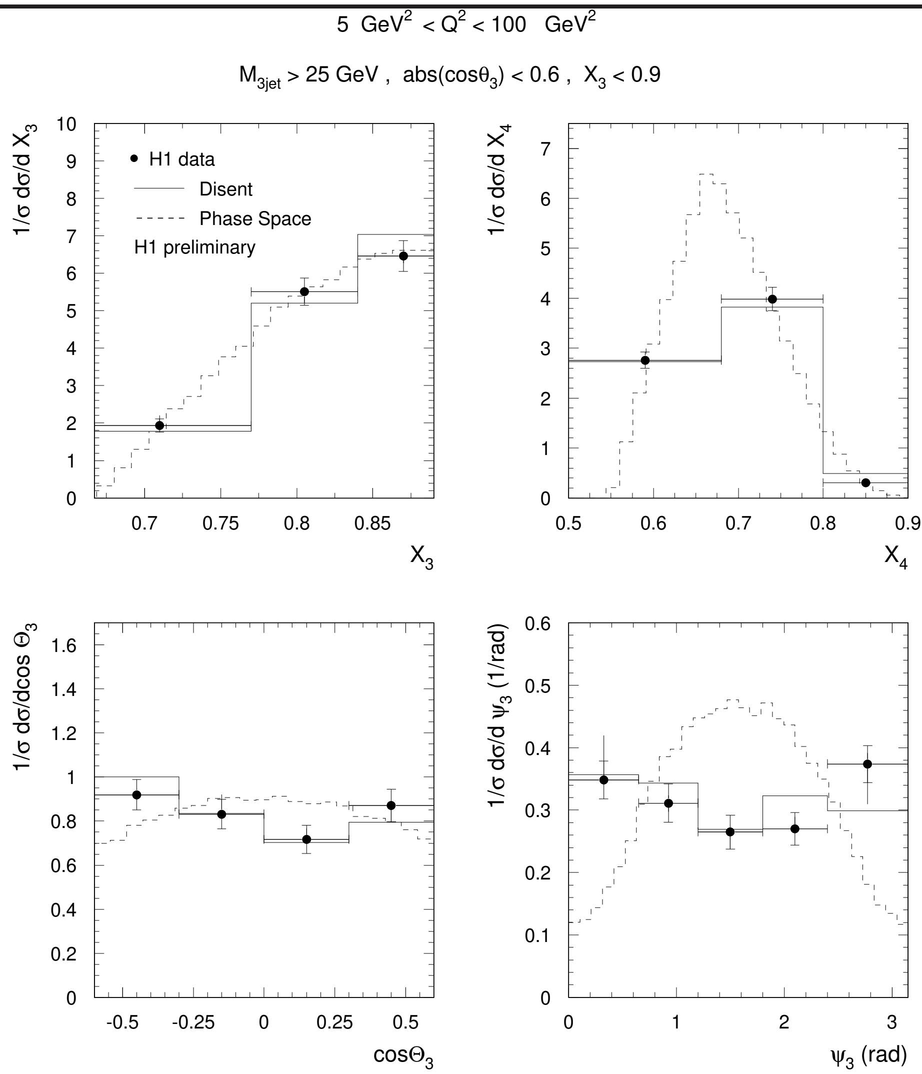
$\cos\psi_3 = \frac{(\vec{P}_3 \times \vec{P}_B)(\vec{P}_4 \times \vec{P}_5)}{|\vec{P}_3 \times \vec{P}_B||\vec{P}_4 \times \vec{P}_5|}$

$\Rightarrow$ $\theta_3$ is sensitive to orientation of highest energetic jet and to the spin of the exchanged particle

$\Rightarrow$ $\psi_3$ and $\theta_3$ is influenced by the orientation of the least energetic jet

$\psi_3 = 0$ or $= \pi$ : $Jet_5$ tends to lie in the plane of beam and highest energetic Jet

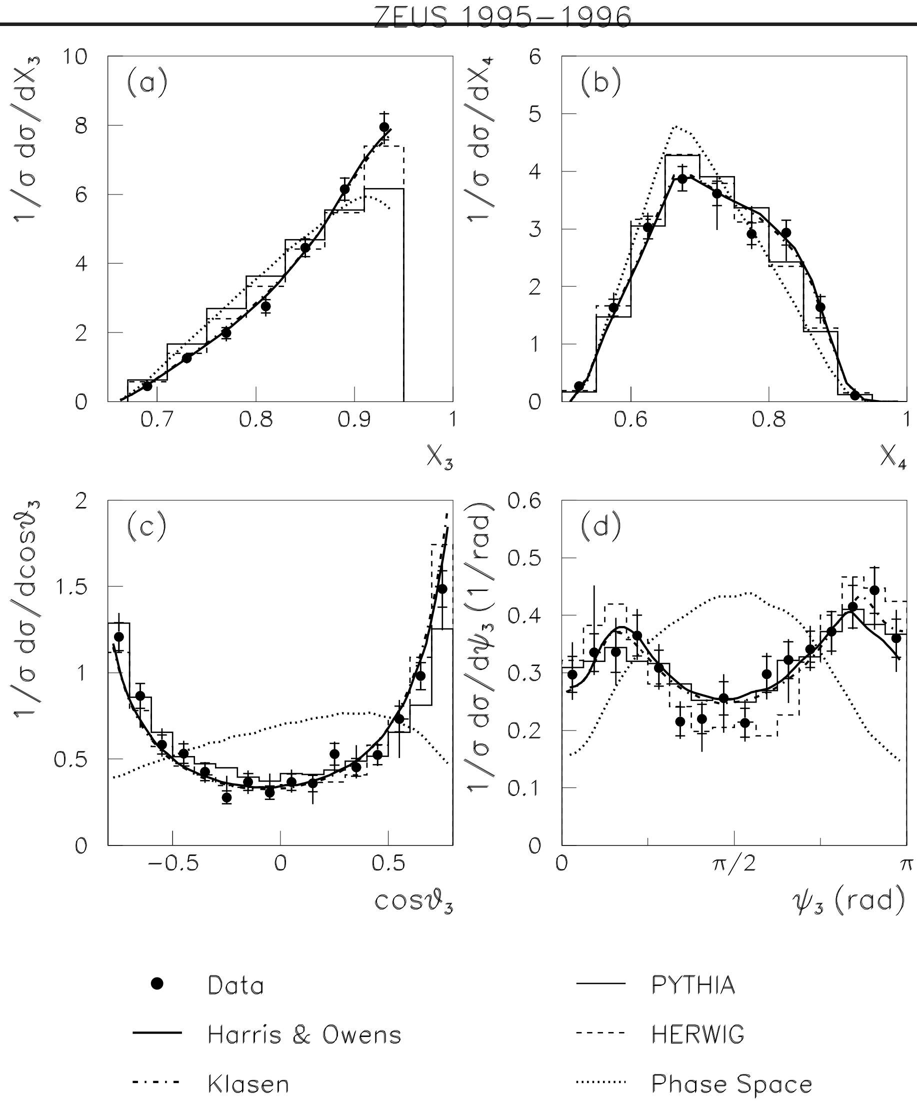
# CMS Variables at moderate $Q^2$




H1: $E_T > 6GeV$ for 1st and 2nd Jet is required, $E_T > 5GeV$ for the 3rd Jet

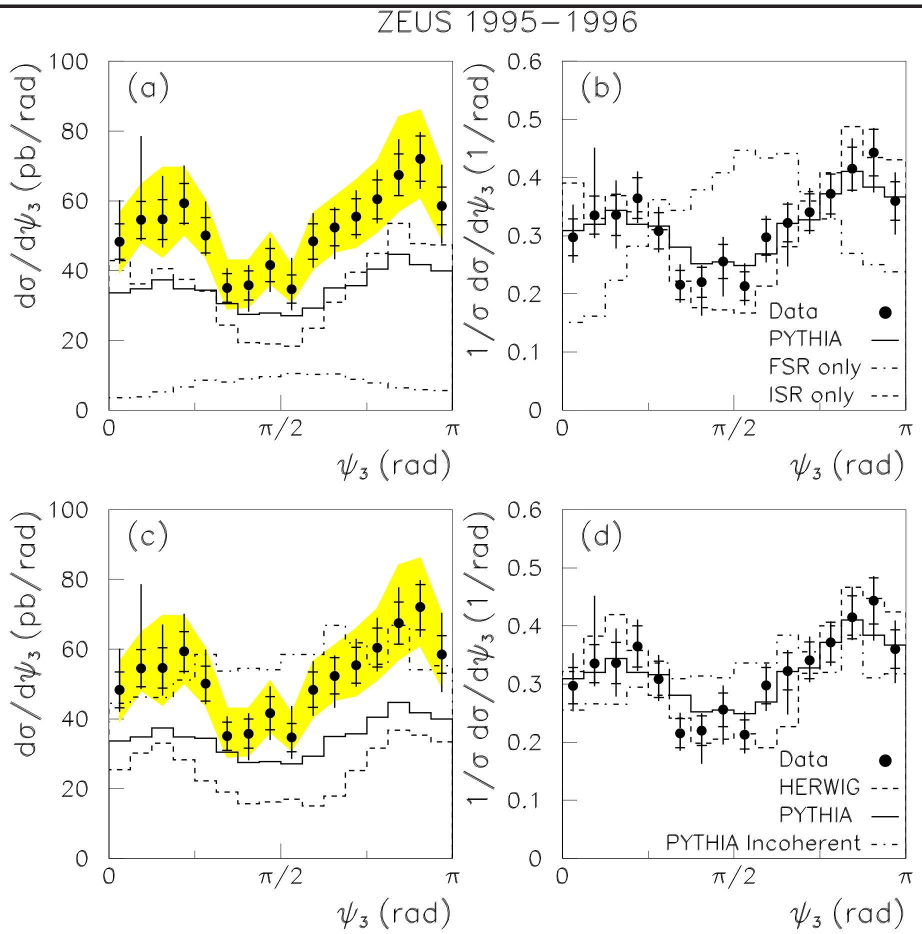
- Influence of Phasespace reduced by additional cuts
- Shape normalised LO $O(\alpha_s^2)$ pQCD (Disent) gives description for orientation of 3 Jet events in DIS

# CMS Variables in Photoproduction



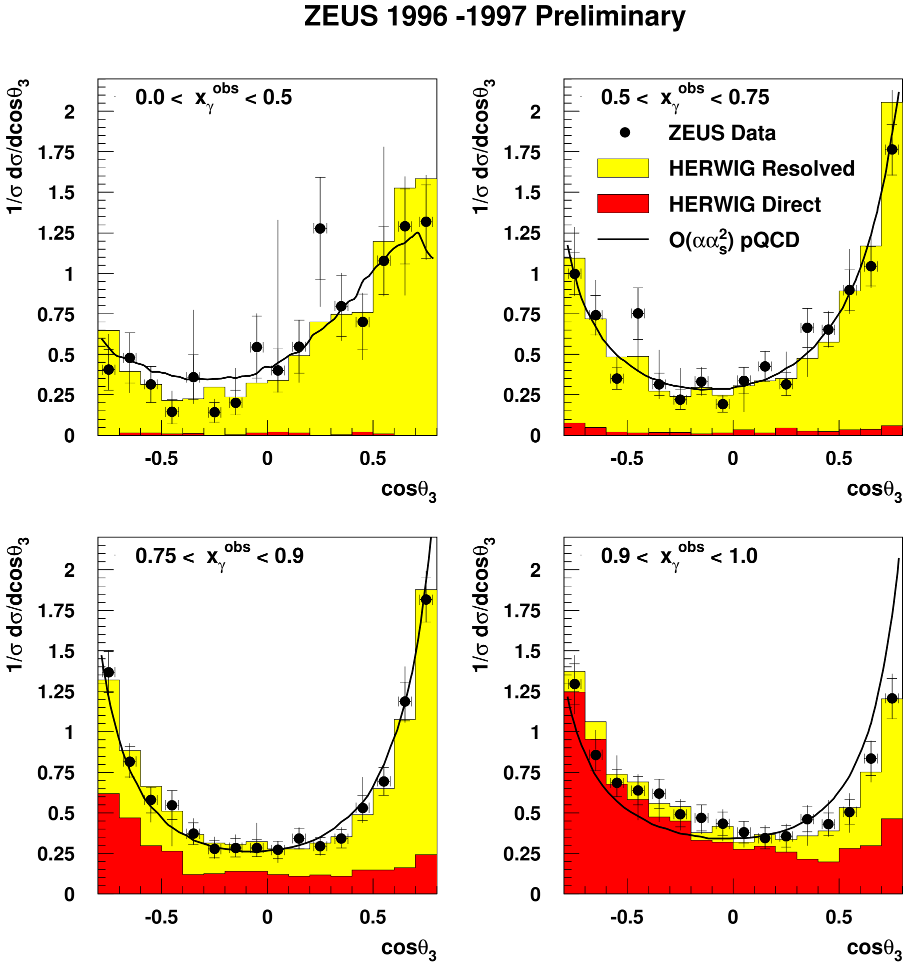

- Influence of Phasespace reduced by $M_{3Jet} > 50 GeV$, $|\cos\theta_3| < 0.8$ and $X_3 < 0.95 \Rightarrow$ Sensitivity to pQCD ME
- Shape normalised LO $O(\alpha_s^2)$ pQCD gives a good description for orientation of 3 Jet events

# Measurement of $\psi_3$ in Photoproduction




- Normalisation and shape indicates that observed 3-Jet production occurs by ISR (initial state radiation)
- Colour coherence in the parton shower models needed to describe the shape

# Measurement of $\cos\theta_3$ in Photoproduction




- Influence of Phasespace reduced by $M_{3Jet} > 50GeV$,$|\cos\theta_3| < 0.8$ and $X_3 < 0.95$
- Highest energetic jets tends to go in proton direction for small $x_\gamma$
- Shape normalised LO $O(\alpha_s^2)$ pQCD gives a good description except for highest $x_\gamma$

# Conclusions and Outlook

- With increasing integrated Luminosities 3-Jet data becomes available with high statistics at HERA

- Rich final state structure of 3 Jet events is explored from photoproduction to DIS

- Data shows no significant deviations to LO pQCD , even at highest inv. masses and transverse momenta $\Rightarrow$ But large scale uncertainties due to LO calculations

- NLO QCD for 3 Jet production will allow additional measurements for $\alpha_s$ (e.g. $R_{2/3} = \frac{\sigma_{2-Jet}}{\sigma_{3-Jet}}$)