Three- and four-jet states in photoproduction at HERA.

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- Monte Carlo curves
- Results:
  - compared to Monte Carlo
  - compared to $\mathcal{O}(\alpha\alpha_s^2)$ pQCD
- Summary
Motivation

- 7.5$\times$ more lumi than existing 3-jet PHP results.
- 3-jets studied in more inclusive phase-space region.
- No published 4-jet PHP results by ZEUS or H1.
- Test of pQCD in PHP at high orders of $\alpha_s$:
  - n-jet direct PHP is $O(\alpha_s^{n-1})$ (tree-level)
  - highest order PHP theory is $O(\alpha_s^2)$ (3-jet)
  - in anticipation of $O(\alpha_s^3)$ pQCD in PHP
  - highest order process studied at HERA
- Test of parton showers (LLA) used to simulate multi-jet states in (LO ME+PS) Monte Carlos.
- Appear sensitive to MPIs $\rightarrow$ test/tune MPI models.
- Multi-jet HFS and MPIs will be abundant at the LHC & next generation colliders.

Motivation

Test of parton showers (LLA) used to simulate multi-jet states in (LO ME+PS) Monte Carlos.

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Variable definitions

- $M_{nj} = \sqrt{\left(\sum_i^n p_i\right)^2}$
- $x^{\gamma \text{obs}} = \sum_i^{n_{\text{jet}}} \frac{E_{t,i} \exp(-\eta_i)}{2yE_e}$

multi-jet variables:

- evaluated in n-jet COM frame with multi-jet numbering
- n-jet state collapsed into pseudo-3-jet state

- $\cos(\psi_{3(i)}) = \frac{(p_{\text{beam}} \times p_{3(i)}) \cdot (p_{4(i)} \times p_{5(i)})}{|p_{\text{beam}} \times p_{3(i)}||p_{4(i)} \times p_{5(i)}|}$
- $\cos(\theta_{3(i)}) = \frac{p_{\text{beam}} \cdot p_{3(i)}}{|p_{\text{beam}}||p_{3(i)}|}$
- $X_{i(i)} = \frac{2E_{i(i)}}{E_{3(i)} + E_{4(i)} + E_{5(i)}}$

schematic of 3-jet angles

$p_{\text{beam}} = p_{\text{elec}} - p_{\text{prot}}$
Cross section definition

- **Jet requirements** (lab frame)
  - \( E_T^{\text{jet}_{1,2}} > 7 \) GeV
  - \( E_T^{\text{jet}_{3,4}} > 5 \) GeV
  - \( |\eta^{\text{jet}}| < 2.4 \)

- **Kinematic region**
  - \( 0.2 < y < 0.85 \)
  - \( Q^2 < 1.0 \) GeV\(^2\)
  - \( \cos(\theta_{3(0)}) < 0.95 \)
  - \( X_{3(0)} < 0.95 \)

- **Jets**: inclusive \( k_T \) algorithm & massless

- Two mass regions studied:
  - semi-inclusive (\( M_{nj} \geq 25 \) GeV)
  - high mass (\( M_{nj} \geq 50 \) GeV)

Monte Carlo curves

- PYTHIA 6.2 & HERWIG 6.5 both with & without MPIs
  - PYTHIA MPIs from simple model.
  - HERWIG MPIs from JIMMY 4.0 model.
- PYTHIA MPIs tuned to collider data (JETWEB).
- HERWIG MPIs tuned to ZEUS multi-jet data.
- MC scale factors = data/(MC no MPIs) at \( M_{nj} > 70 \) GeV.

**ZEUS**

![Graph showing three-jet cross section data]
• cross sections peak at $x_{\gamma}^{\text{obs}} \approx 0.9$, and are kinematically suppressed at low $x_{\gamma}^{\text{obs}}$.
• MC predicts peaks partly due to direct (LO definition) but significant resolved PHP contributions.
• MCs without MPIs fail to describe low $x_{\gamma}^{\text{obs}}$ region at low $M_{3j}$ - MC requires additional component.
• MC predicts MPIs augment low $x_{\gamma}^{\text{obs}}$ but don’t affect high $x_{\gamma}^{\text{obs}}$ - are MPIs the missing component?
• PYTHIA MPI model predicts excessive contribution - HERWIG+MPI describes $x_{\gamma}^{\text{obs}}$ very well.
again, cross sections peak at $x_{\gamma}^{\text{obs}} \approx 0.9$ and low $x_{\gamma}^{\text{obs}}$ kinematically suppressed... BUT...

...smaller direct contribution and less suppression even though four-jet HFS more tightly constrained.

MCs predict that differences at low $x_{\gamma}^{\text{obs}}$ are due to larger missing component/more MPIs... BUT...

...high $x_{\gamma}^{\text{obs}}$ region is insensitive to MPIs so not the sole reason for larger resolved contribution.

resolved processes have more complex colour structure - generate multi-jet states more efficiently.
from now on will assume that the missing component from the MCs without MPIs is due to MPIs.
cross sections fall exponentially with increasing $M_{nj}$ - low $M_{nj}$ suppression due to selection criteria.
MC predicts MPIs augment low $M_{nj}$ cross section - reduce the effects selection criteria.
PYTHIA MPI excess still apparent. HERWIG MPIs good - no MPIs for $M_{3j} \gtrsim 50$ & $M_{4j} \gtrsim 70$ GeV.
direct PHP on average leads to a more massive final state as expected.
- $M_{3j} \geq 25$ GeV cross section roughly flat in $y$ - $M_{3j} \geq 50$ GeV cross section increases linearly.
- this behaviour understood from phase-space considerations & the WWA.
- Both MCs with MPIs give a poor description of $y$ - but MCs without MPIs describe shape well.
- MPI models causing the problem - $y$ cross sections good for tuning/testing MPI models.
- same observations made in the 4-jet $d\sigma/dy$ distributions.
The pQCD calculation

- $\mathcal{O}(\alpha_s^2)$ pQCD is lowest order for 3-jet process.
- $E_T^{\text{jet1}}$ used for renormalisation & factorisation scales.
- theoretical uncertainty evaluated using $2^{\pm 1} E_T^{\text{jet1}}$ for scales.
- $\alpha_s$ calculated with one loop precision & five active flavours
  - correspondingly $\Lambda_{\overline{\text{MS}}} = 181$ MeV was used.
- the CTEQ4L proton & GRV-G LO photon PDFs were used.
- theory convoluted with hadronisation and MPI corrections:
  
  \[ C_{\text{had}} = \sigma_{\text{HL}}/\sigma_{\text{PSL}} \quad \text{and} \quad C_{\text{MPI}} = \sigma_{\text{MPI}}^{\text{HL}}/\sigma_{\text{HL}}^{\text{noMPI}} \]

Comparison with the data

- theory describes high mass but fails for $M_{3j} \lesssim 50$ GeV.
- discrepancy could stem from:
  - incorrect modelling of the either corrections
  - missing higher-order processes
- the had. corrections are flat - unlikely to be the cause.
- the MPI corrections dependent on $M_{3j}$ - underestimated?
Comparison with the data

- theory again describes high mass data well...
- ... but is poor for $M_{3j} < 50 \text{ GeV}$.
- both sets of corrections are flat in $\cos(\psi_3)$
- so unlikely sole cause of problems
- therefore likely data is sensitive to $O(\alpha\alpha_s^3)$ processes.
Summary

- Three- & four-jet states in PHP measured differentially with 121 pb\(^{-1}\) in two \(M_{nj}\) regions.
- LO ME+PS MCs do not describe the data well - require an additional component.
- The magnitude of the additional component increases near the kinematic boundaries (low \(M_{nj}\) & \(x_{\gamma}^{\text{obs}}\))
- MPIs can account for this correctly (HERWIG)... BUT...
- ...MPIs tuned to general (albeit less sensitive) collider data fail dramatically (PYTHIA).
- The introduction of MPIs in both HERWIG & PYTHIA disrupts the description of \(d\sigma/dy\).
  - the MPI models overestimate the effect at high \(y\), which is away from any kinematic boundary.
  - therefore, \(d\sigma/dy\) useful for tuning/testing MPI models (if MPIs are the missing component).
- the \(\mathcal{O}(\alpha s^2)\) pQCD calculation describes 3-jet data well for \(M_{3j} \gtrsim 50\) GeV.
- the prediction is poorer for \(M_{3j} \lesssim 50\) GeV due to higher-order processes absent in the calculation.