# Three- and four-jet states in photoproduction at HERA and the $\gamma p$ underlying event.

**Tim Namsoo** (University of Bristol)

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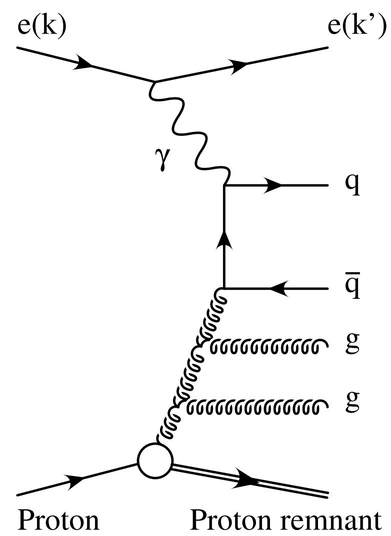
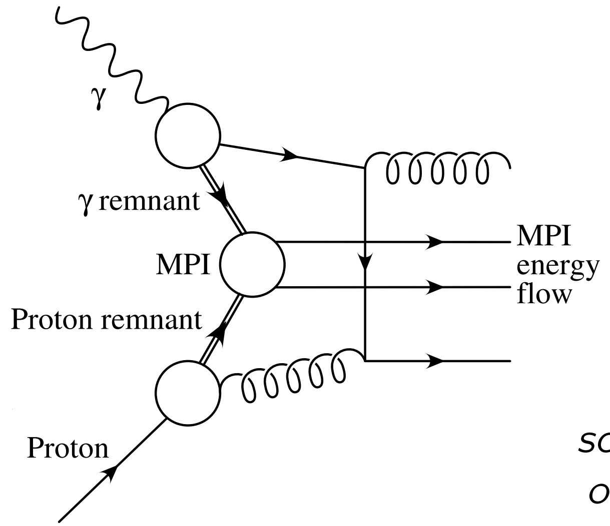
- *Motivation*
- *Variable definitions*
- *Cross section definition*
- *JIMMY MPI tune*
- *Results:*
  - *compared to Monte Carlo*
  - *compared to* $\mathcal{O}(\alpha\alpha_s^2)$ *pQCD*
- *Summary*

# Motivation

- ...more lumi, more inclusive phase-space region, $1^{st}$ 4-jet results at HERA... BUT why multi-jets?
- Test of pQCD in PHP at high orders of $\alpha_S$:
  - n-jet direct PHP is $\mathcal{O}(\alpha\alpha_s^{(n-1)})$ (tree-level)
  - highest order PHP theory is $\mathcal{O}(\alpha\alpha_s^2)$ (3-jet)
  - in anticipation of $\mathcal{O}(\alpha\alpha_s^3)$ pQCD in PHP
  - highest order process studied at HERA
  - PHP - $Q^2$ not a hard scale & possibility of MPIs
- MPIs not present in pQCD calculations $\Rightarrow$ use MC
- LO ME+PS MC relies on PS to generate multi-jets
- Can test this approach & look for sensitivity to MPIs $\longrightarrow$ test/tune MPI models.
- Multi-jet HFS and MPIs will be abundant at the LHC & next generation colliders.




*4-jet direct (tree-level)*




*schematic of a MPI*

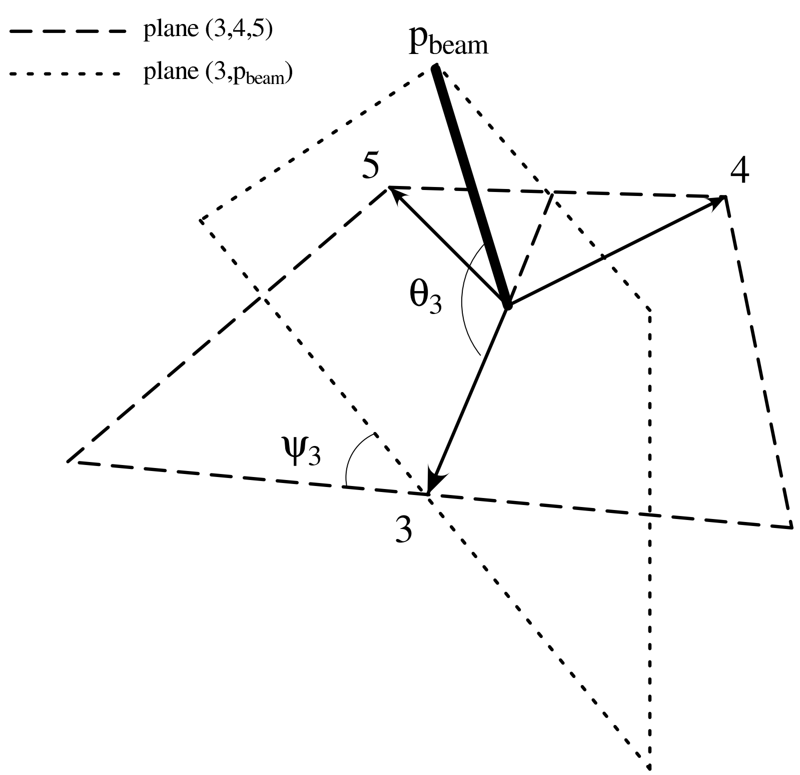
# Variable definitions

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

**multi-jet variables:**

- S. Geer & T. Asakawa (Phys. Rev. D53, 4793 (1996))
- evaluated in n-jet COM frame with multi-jet numbering
- n-jet state collapsed into pseudo-3-jet state
- $\cos(\Psi_{3^{(\prime)}}) = \frac{(\mathbf{p}_{\mathrm{beam}} \times \mathbf{p}_{3^{(\prime)}}) \cdot (\mathbf{p}_{4^{(\prime)}} \times \mathbf{p}_{5^{(\prime)}})}{|\mathbf{p}_{\mathrm{beam}} \times \mathbf{p}_{3^{(\prime)}}||\mathbf{p}_{4^{(\prime)}} \times \mathbf{p}_{5^{(\prime)}}|}$
- $\cos(\theta_{3^{(\prime)}}) = \frac{\mathbf{p}_{\mathrm{beam}} \cdot \mathbf{p}_{3^{(\prime)}}}{|\mathbf{p}_{\mathrm{beam}}||\mathbf{p}_{3^{(\prime)}}|}$
- $X_{\mathrm{j}^{(\prime)}} = \frac{2E_{\mathrm{j}^{(\prime)}}}{E_{3^{(\prime)}} + E_{4^{(\prime)}} + E_{5^{(\prime)}}}$

*schematic of 3-jet angles*



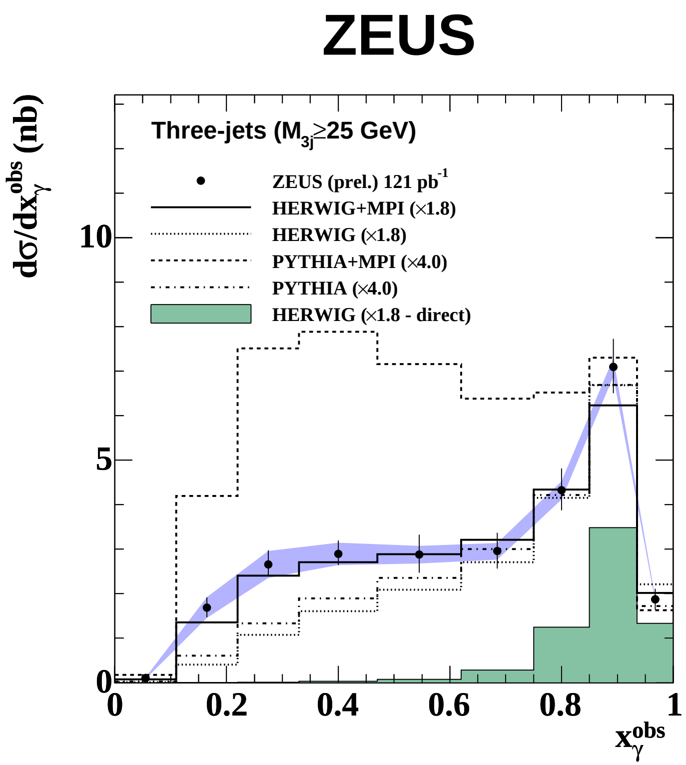

$\mathbf{p}_{\mathrm{beam}} = \mathbf{p}_{\mathrm{elec}} - \mathbf{p}_{\mathrm{prot}}$

## 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$^2$
  - $\cos(\theta_{3^{(\prime)}}) < 0.95$
  - $X_{3^{(\prime)}} < 0.95$
- **Jets**: inclusive $k_T$ algorithm & massless
- Two mass regions studied:
  - semi-inclusive ($M_{\text{nj}} \geq 25$ GeV)
  - high mass ($M_{\text{nj}} \geq 50$ 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.



# JIMMY MPI tune - the strategy

- Fix "$k$-factor": the (hypothetical) ratio of the data divided by the LO+PS MC, if there were no MPIs.
- Assume LO+PS MC describes energy dependences etc. of hard interaction perfectly - i.e. same $k$-factor applies at all energies - not correct but no additional info to refine assumption.
- Once $k$-factor applied to MC, the remaining differences are therefore assumed to be due to something either non-perturbative (e.g. could be incorrect PDFs) or something absent from the simulation - assume the latter, assume MPIs.
- Thus, the question is, what MPI model/tune will augment the LO+PS$\times k$-factor MC till it agrees with the measured cross section and its dependences on observables e.g. $x_\gamma^{obs}$?
- Could (simultaneously) tune to any number of measured differential cross sections but chose $d^2\sigma/dx_\gamma^{\text{obs}}dM_{nj}$, binned finely in $x_\gamma^{\text{obs}}$ (shape v. sensitive to MPIs) and coarsely in $M_{nj}$ (to ensure correct energy dependence).
- Also, tune parameters simultaneously to 3- and 4-jet data.

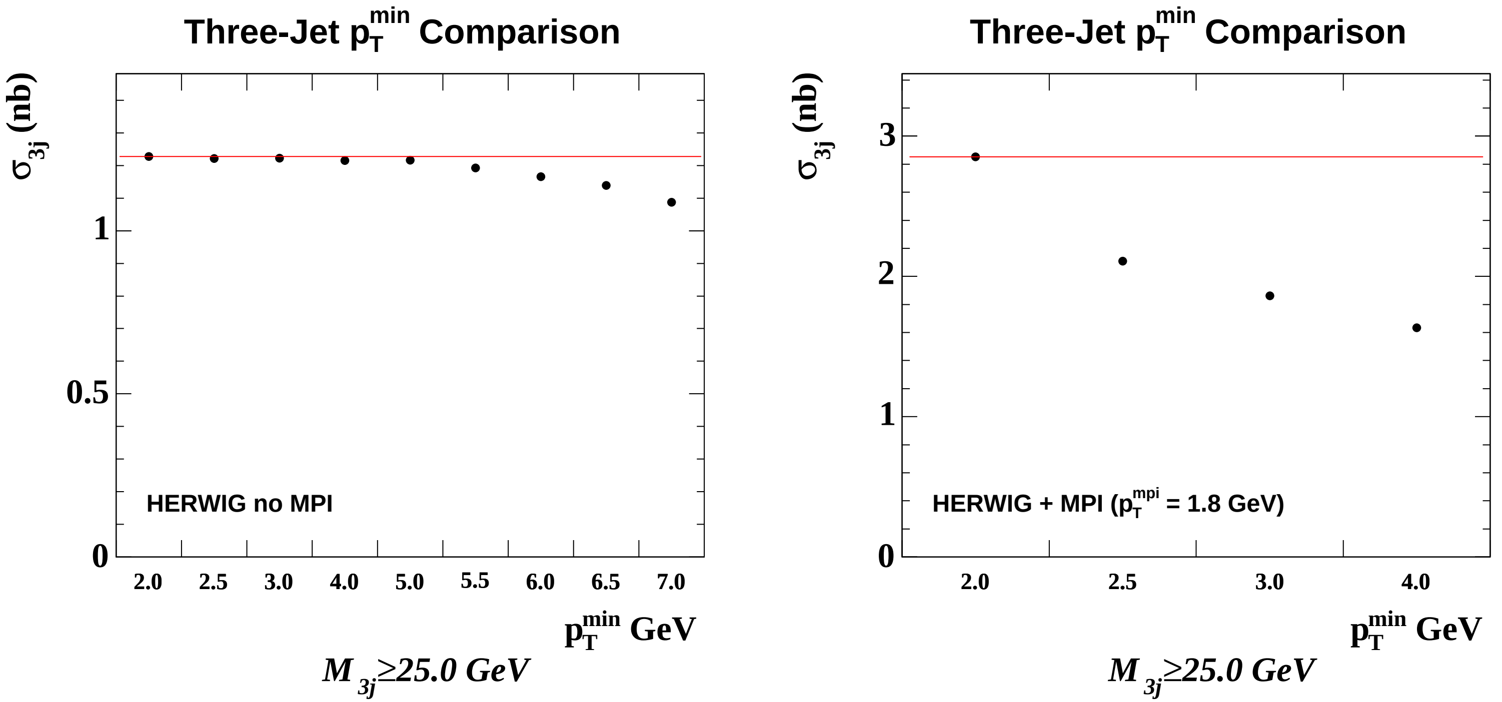
# JIMMY MPI tune - the tuning parameters

- $p_T^{\text{min}}$ : min $p_T$ of primary int.
- $p_T^{\text{mpi}}$ : min $p_T$ of secondary int's.
- $R_p^{-2}$ : inversely scales proton transverse area
- $P_{\text{had}}^{-1}$ : inversely scales prob that $\gamma$ resolves

## - evaluate the $k$-factor

- Evaluate $k$-factor as ratio of data/(MC no MPIs) at high mass ($\geq$ 70 GeV) where MPIs are expected to be negligible - would go higher if possible but start to run low on stats.
- Using this approach it is clearly apparent that $k$-factor for 3-jets ($k_{3j} = 1.8$) is different to that of 4-jets ($k_{4j} = 2.4$). These numbers are generator/tune dependent.
- Surprising? LO 3-jet process $\mathcal{O}(\alpha\alpha_s^2)$ whereas 4-jet $\mathcal{O}(\alpha\alpha_s^3)$, so probably related to order of process and order dependence in LO+PS MC. Also possible that MPIs affect the 4-jet data beyond $M_{4j} = 70$ GeV.

# JIMMY MPI tune - the $p_T^{min}$ & $p_T^{mpi}$ parameters

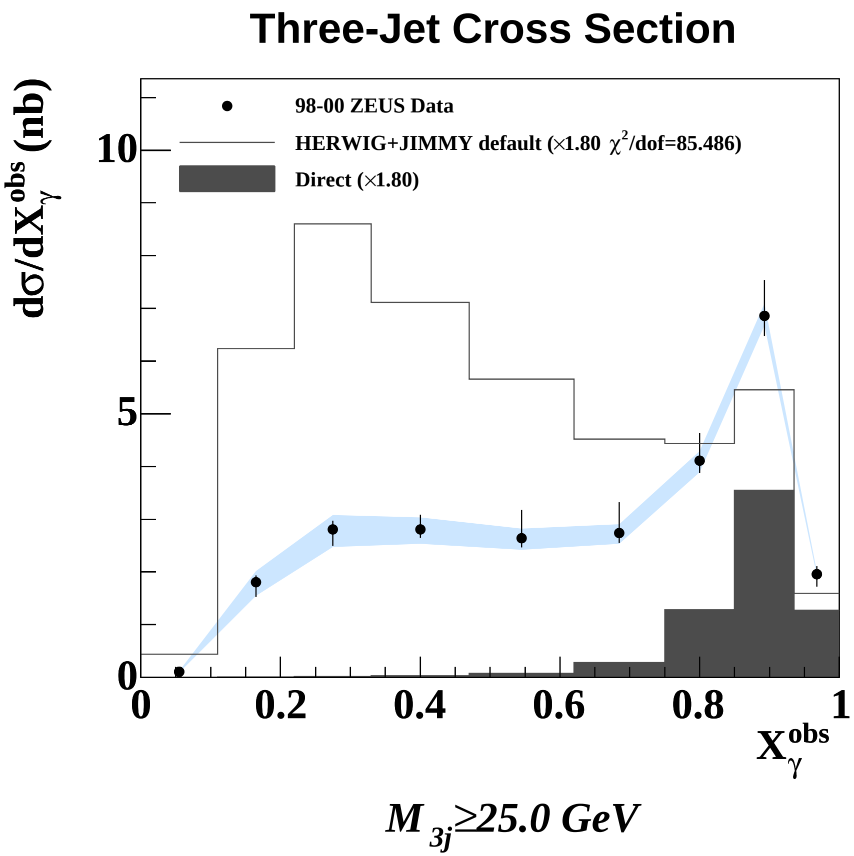


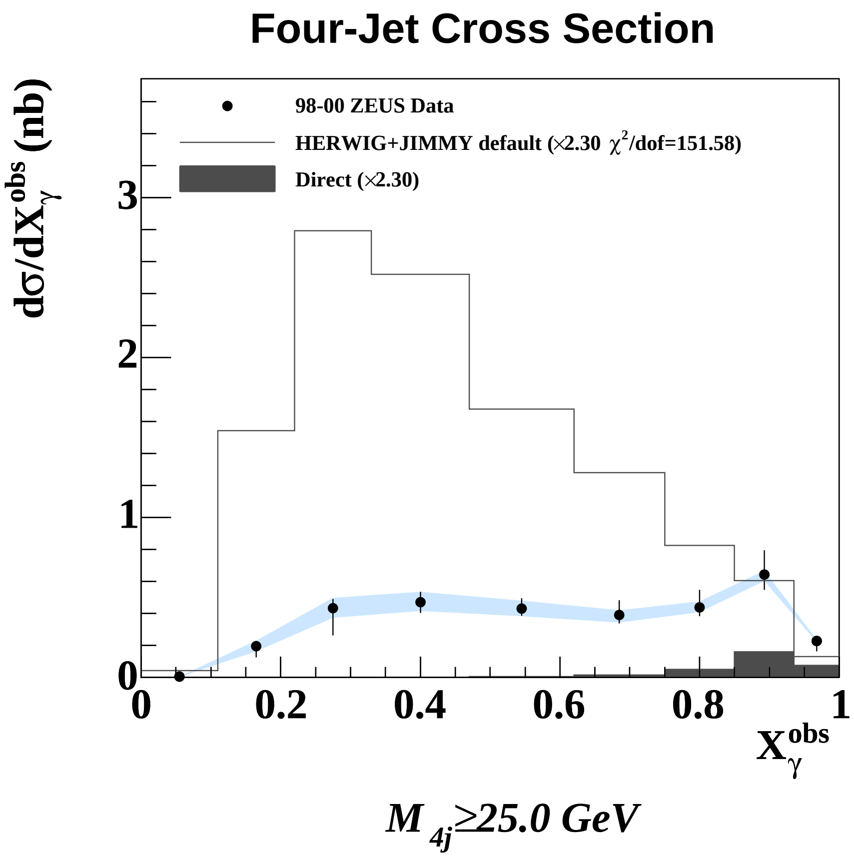

- Want $\sigma$ to be independent of $p_T^{\text{min}}$ around value chosen.
- MPIs can affect the $\sigma$ by supplementing the energy of soft primary interaction jets, pushing them into the kinematic region of study.
- If $p_T^{\text{min}}$ too high, the soft primary jets are not present and MPIs have less impact on $\sigma \quad \Rightarrow \quad p_T^{\text{mpi}}$ dependent on $p_T^{\text{min}}$.

Chose to use as low a values as poss:

- $p_T^{\text{min}} = 2.0$ GeV
- $p_T^{\text{mpi}} = 1.8$ GeV

# JIMMY MPI tune - the $p_T^{min}$ & $p_T^{mpi}$ parameters



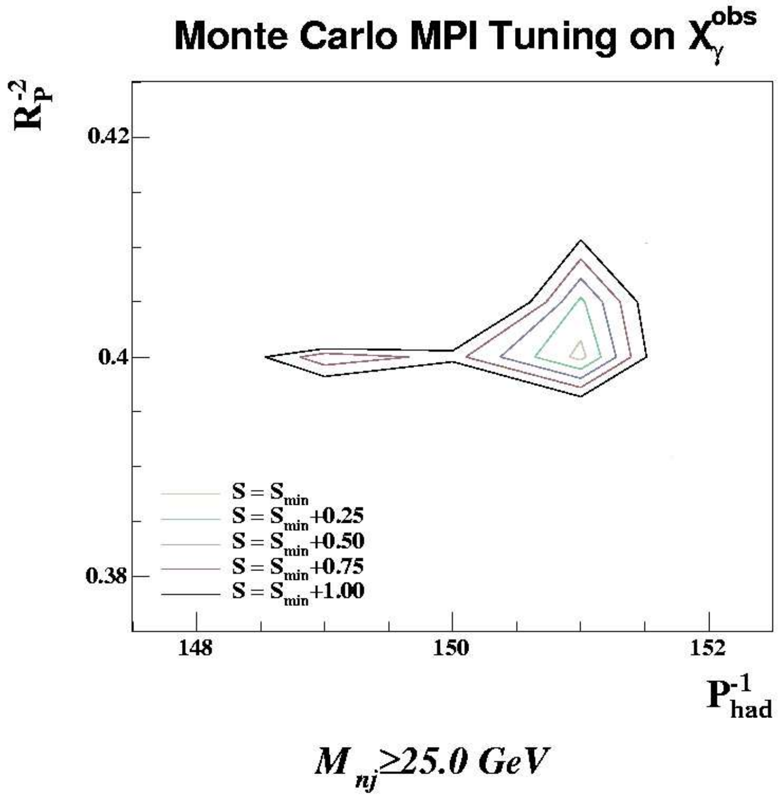

- If $p_T^{\text{min}} = 2.0$ & $p_T^{mpi} = 1.8$ and $R_p^{-2}$ & $P_{\text{had}}^{-1}$ set to default, JIMMY grossly overestimates MPI affect.
- default values are: $R_p^{-2} = 1$ & $P_{\text{had}}^{-1} = 300$

# JIMMY MPI tune - in the $R_p^{-2}$ & $P_{\text{had}}^{-1}$ phase space

- contours on the surface in the $(R_p^{-2}, P_{\text{had}}^{-1})$ plane marked out by the $\chi^2$ difference between the $x_\gamma^{\text{obs}}$ distribution in the data and different MC sets.
- best tune values relate to the minimum, $S_{\text{min}}$, and uncertainty roughly estimated using projection of contour at $S_{\text{min}} + 1$ onto either axis.

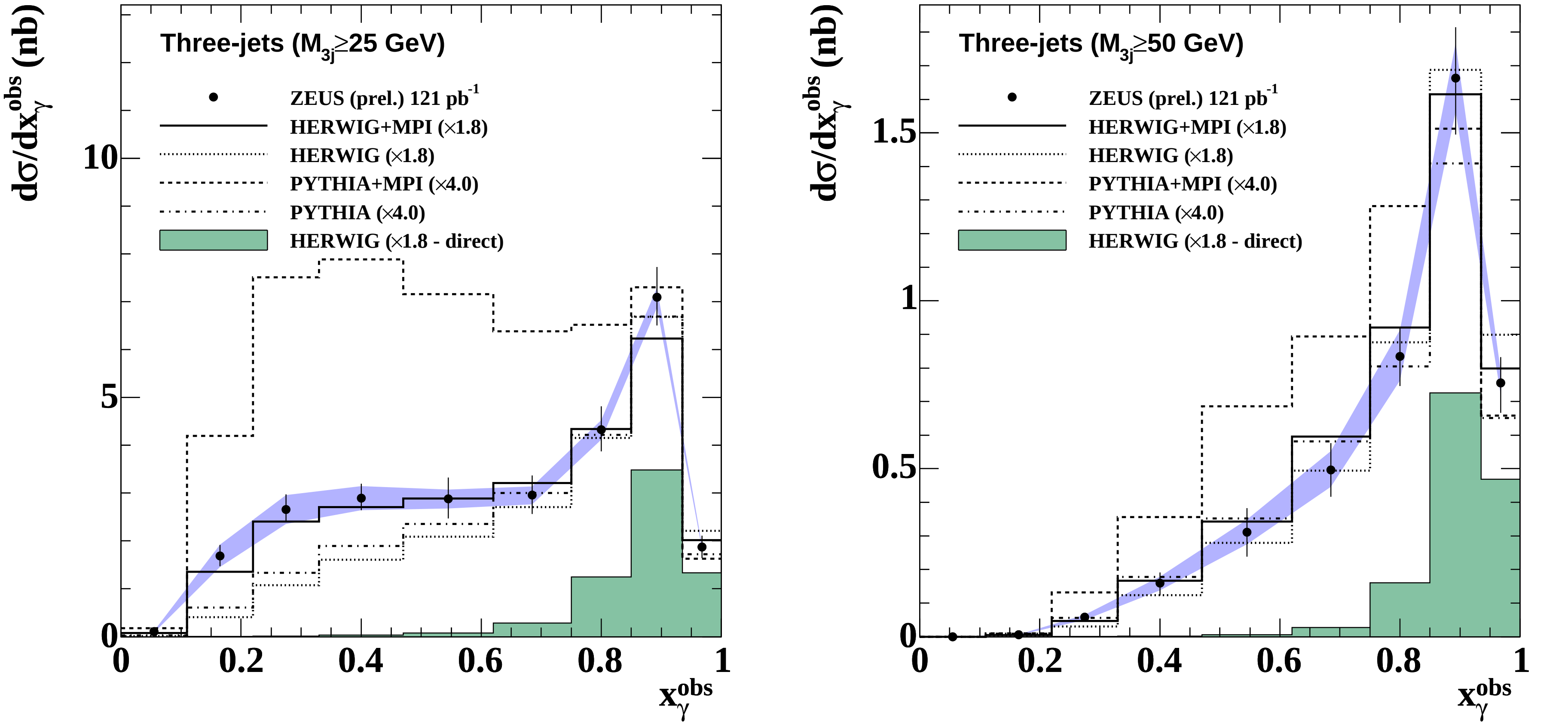
$$R_P^{-2} = 0.400 \begin{array}{l} +0.012 \\ -0.005 \end{array}$$

$$P_{had}^{-1} = 151.0 \begin{array}{l} +0.5 \\ -2.5 \end{array}$$



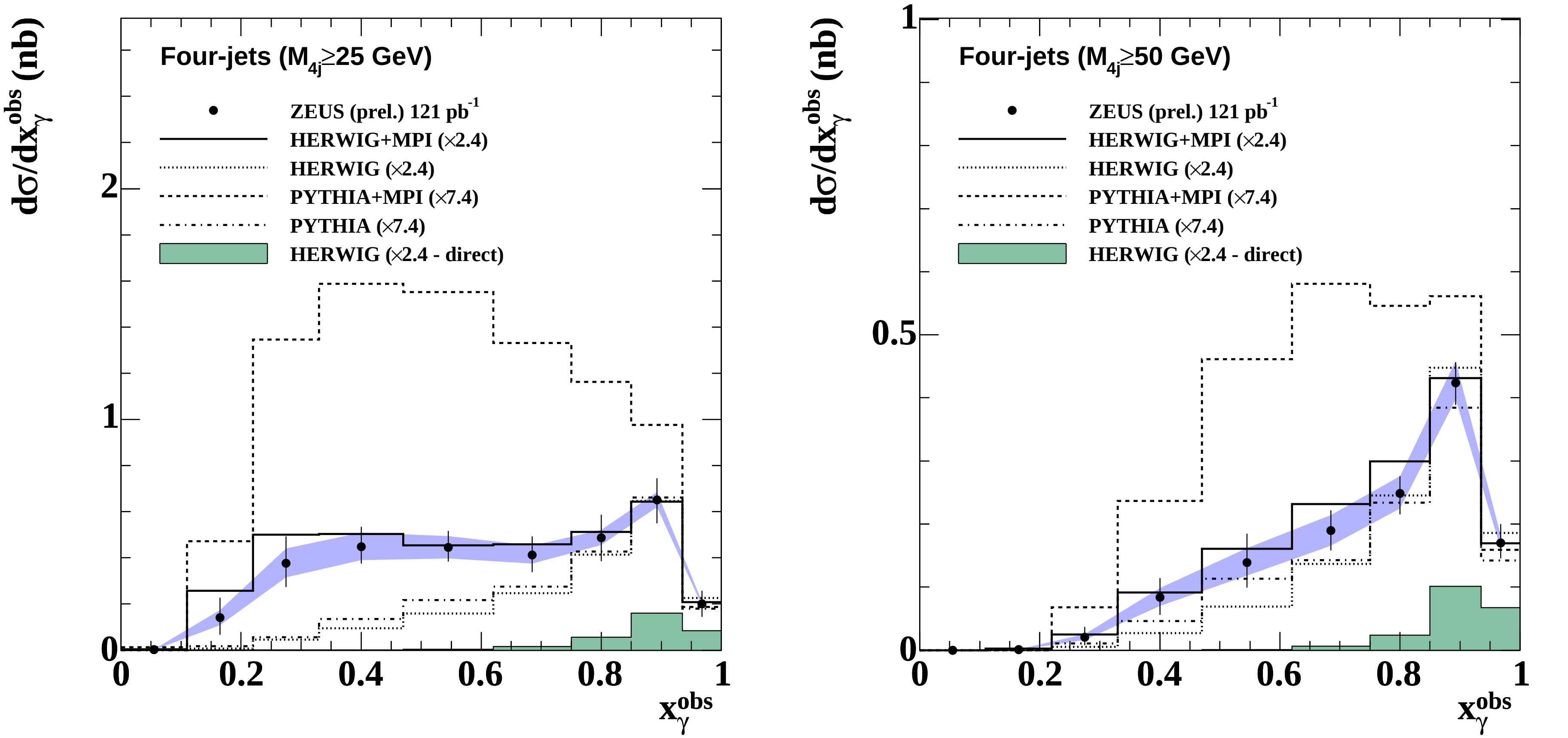

- would be interesting to see how the value of $R_P^{-2}$ compares to that from a similar $p\bar{p}$ tune - would suggest the validity of the model and scope for extrapolating to different beams/energies.

# ZEUS



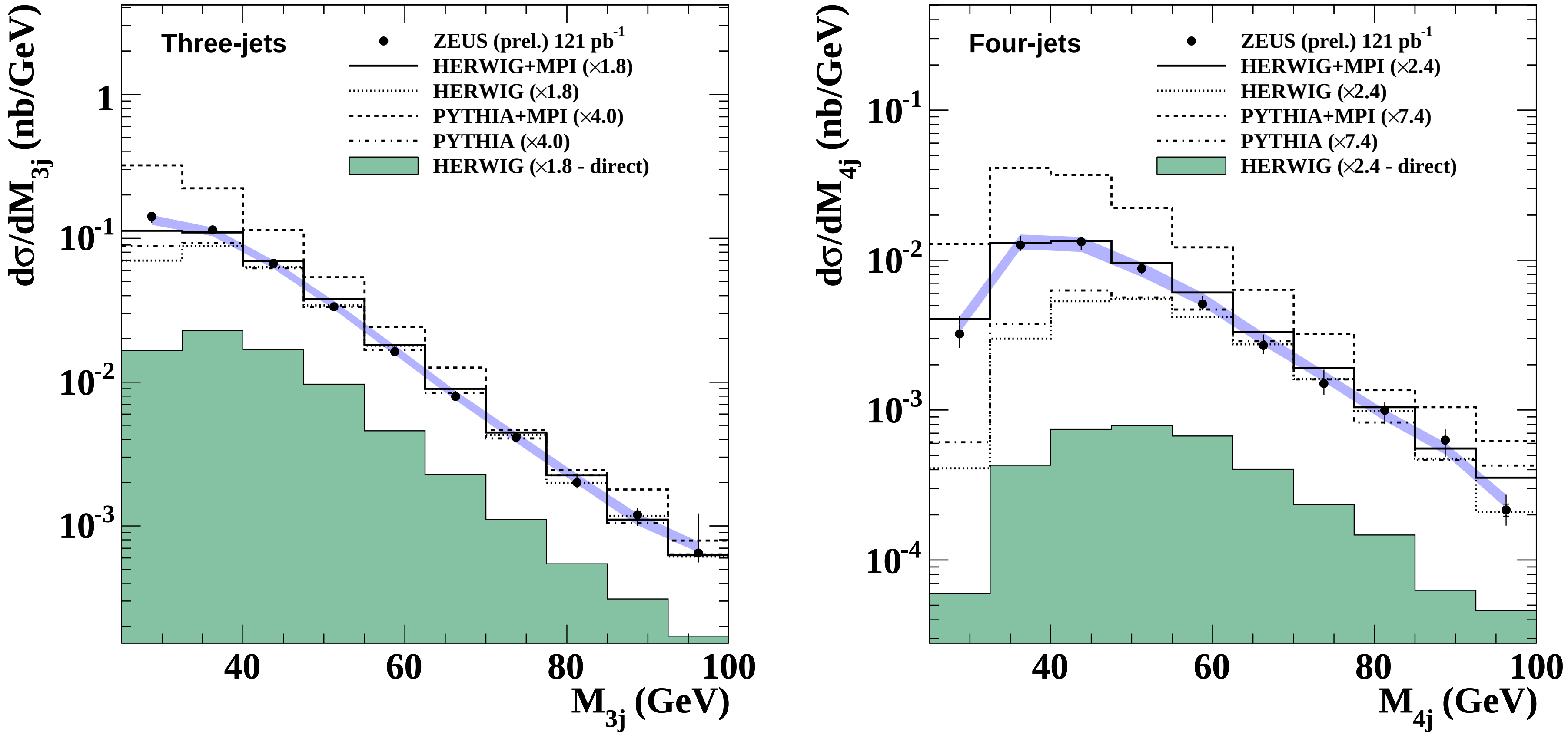

- MCs without MPIs describe $d\sigma/dx_\gamma^{\rm obs}$ at high $M_{3j}$
- MCs without MPIs fail to describe low $x_\gamma^{\rm obs}$ region at low $M_{3j}$ - MC requires additional component.
- MC predicts MPIs augment low $x_\gamma^{\rm obs}$ but don't affect high $x_\gamma^{\rm obs}$ - are MPIs the missing component?
- PYTHIA MPI model prediction excessive - tuned HERWIG+MPI describes $x_\gamma^{\rm obs}$ very well.
- MC predicts peaks partly due to direct (LO definition) but significant resolved PHP contributions.

# ZEUS



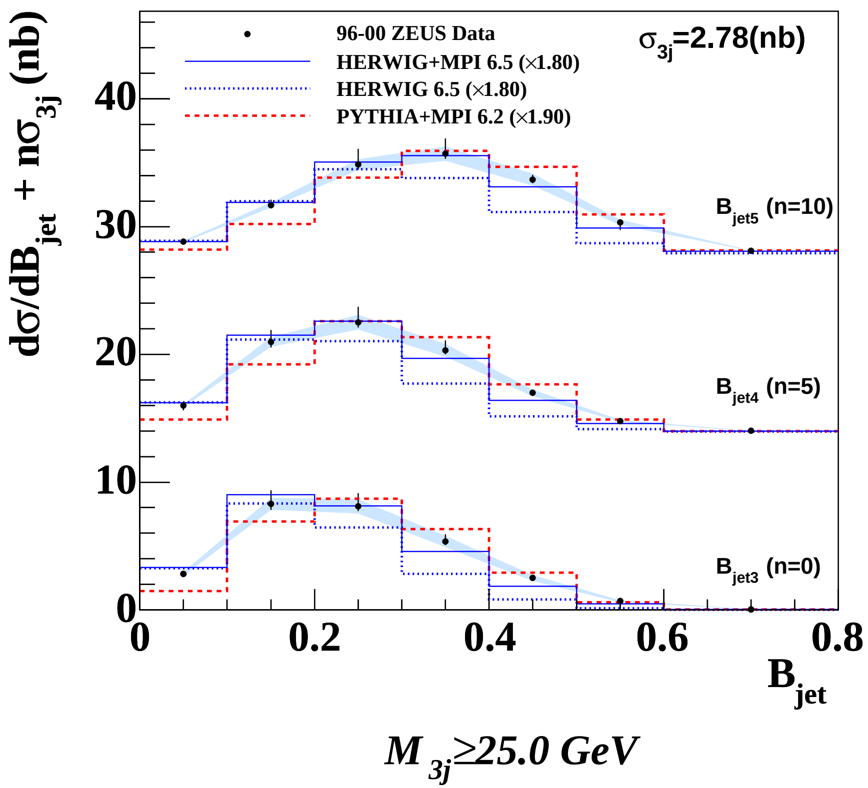

- MCs without MPIs significantly underestimates low $x_\gamma^{\text{obs}}$ region at low $M_{4j}$.
- MC without MPIs also slightly underestimates low $x_\gamma^{\text{obs}}$ region at high $M_{4j}$
- PYTHIA MPI model prediction v. excessive - tuned HERWIG+MPI describes $x_\gamma^{\text{obs}}$ very well.
- 4-jet data more sensitive to missing component - sensitivity stretches to higher mass - MPIs?

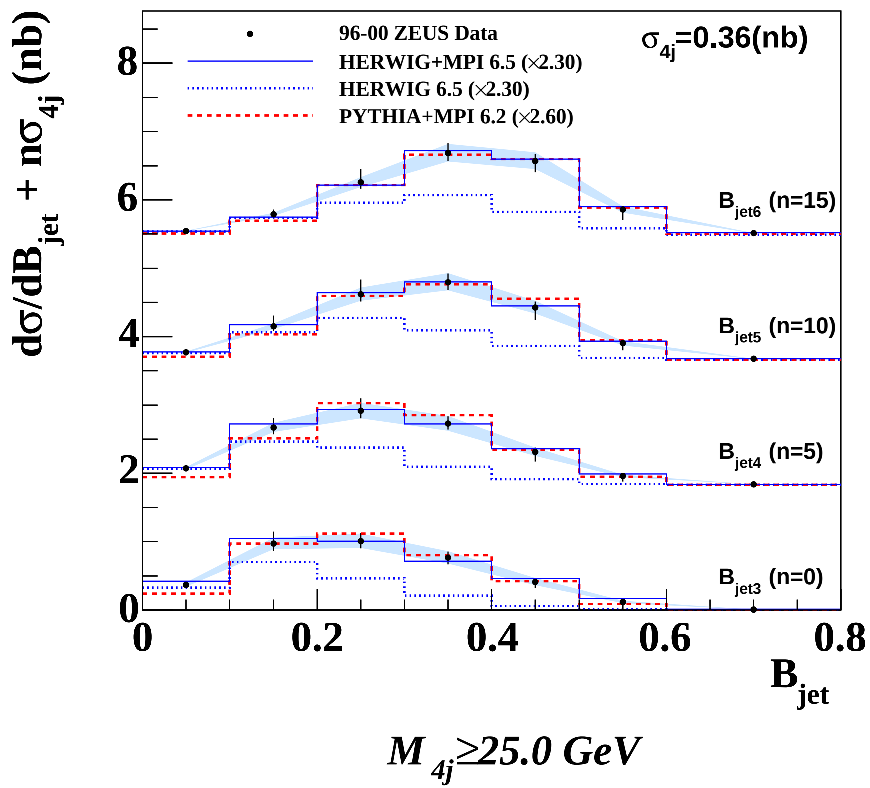
# ZEUS




- 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 - pad out phase-space reduced by selection cuts
- PYTHIA MPI excess still apparent. HERWIG MPIs good - no MPIs for $M_{3j} \gtrsim 50$ & $M_{4j} \gtrsim 70$ GeV.

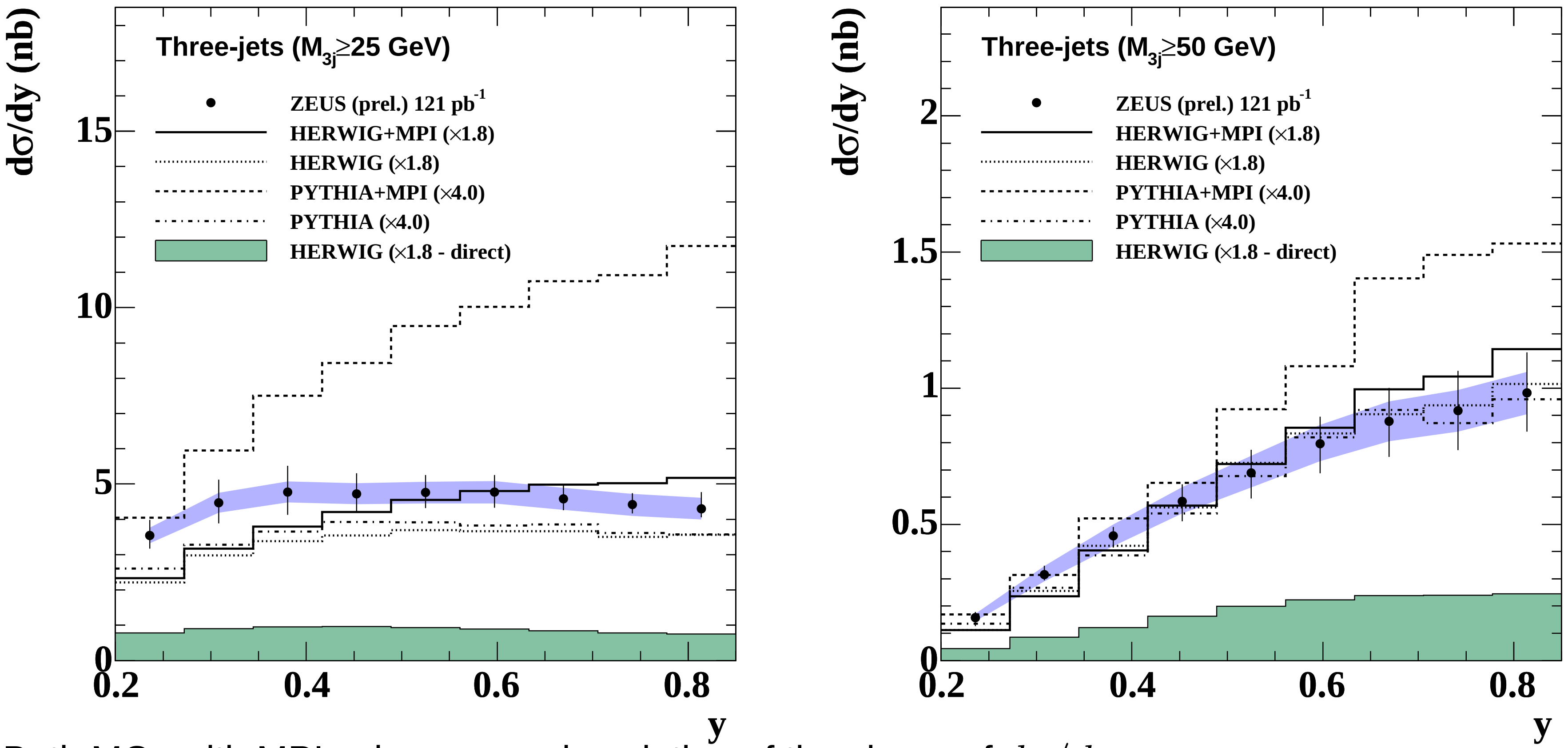
# ZEUS




- jet broadness: $B_j = \left(\sum_i |\mathbf{h}_i \times \mathbf{p}_j|\right) / \left(\sum_i |\mathbf{h}_i||\mathbf{p}_j|\right)$ (sensitive to transverse energy flow in jet)
- note: different PYTHIA $k$-factors - want to observe how each model affects the jet shape.
- clearly the MC without MPIs predicts too narrow jets - MPIs could account for the broadening
- PYTHIA simple model and JIMMY predictions very similar in 4-jet case but less so in 3-jet.

# ZEUS

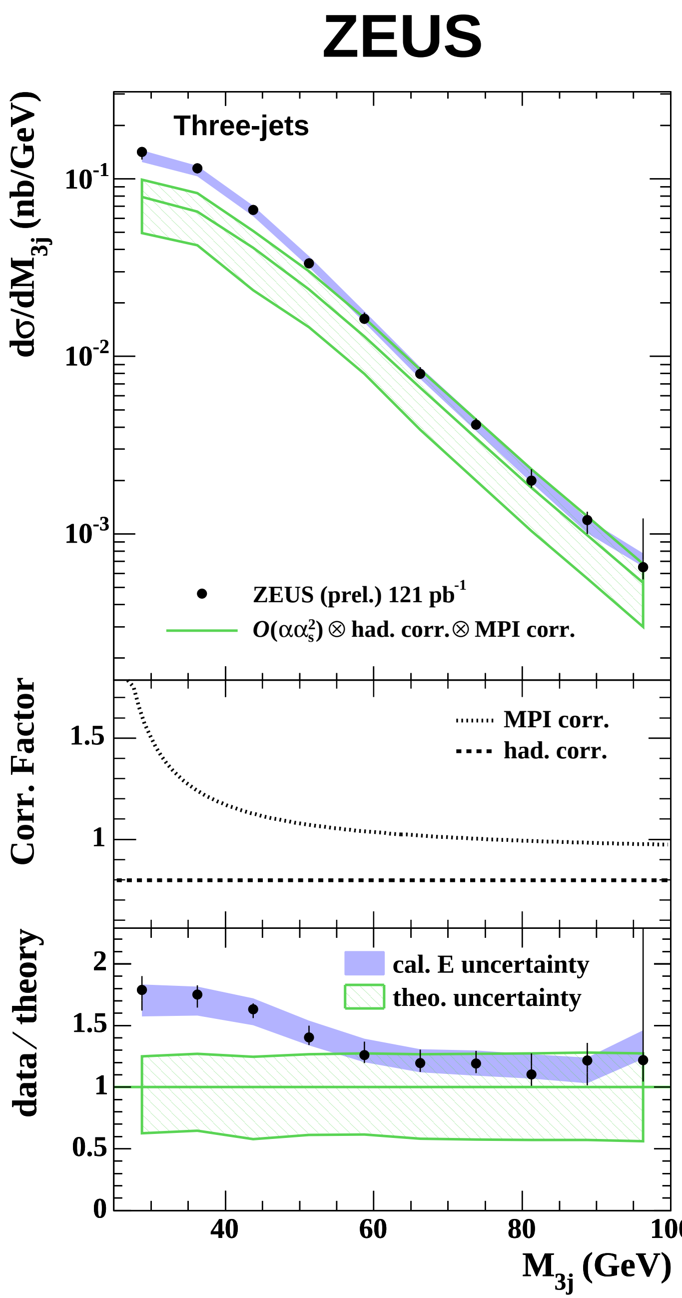



- Both MCs with MPIs give a poor description of the shape of $d\sigma/dy$...
- ...but MCs without MPIs describe shape well. MPI models causing the problem?
- if so, $d\sigma/dy$ good for tuning/testing models but hard not to imagine MPIs not (slightly) $y$ dependent.
- suggests MPIs not the only problem?
- same observations made in the 4-jet $d\sigma/dy$ distributions.

# The pQCD calculation

- $\mathcal{O}(\alpha\alpha_s^2)$ pQCD is lowest order for 3-jet process.
- $E_T^{\text{jet1}}$ used for renormalisation & factorisation scales.
- theoretical uncertainty evaluated using $2^{\pm1}E_T^{\text{jet1}}$ for scales.
- the CTEQ4L proton & GRV-G LO photon PDFs were used.
- theory convoluted with hadronisation and MPI corrections:

$$\mathcal{C}_{\text{had}} = \sigma_{\text{HL}}/\sigma_{\text{PSL}} \qquad \& \qquad \mathcal{C}_{\text{MPI}} = \sigma_{\text{HL}}^{\text{MPI}}/\sigma_{\text{HL}}^{\text{noMPI}}$$

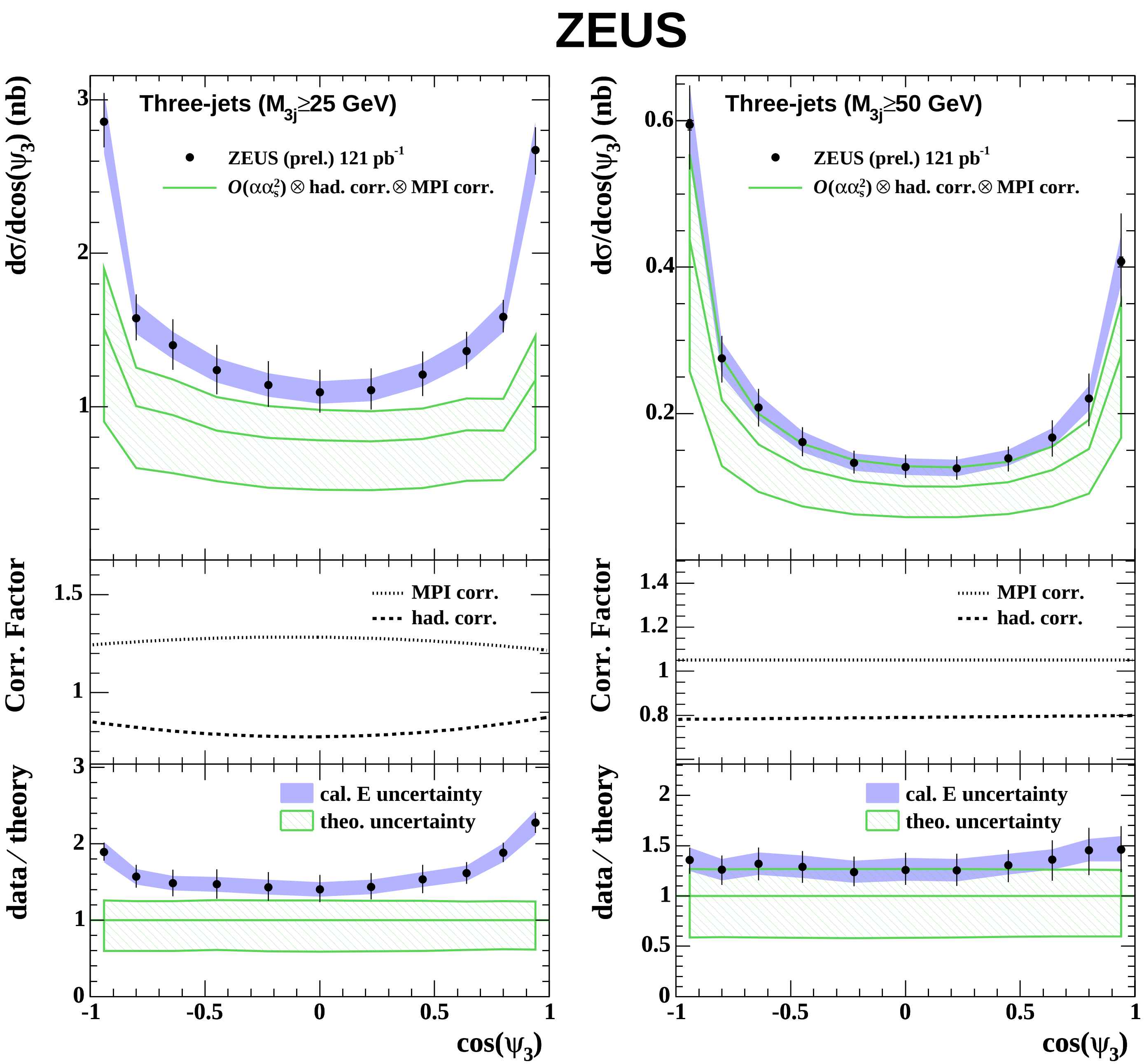



# Comparison with the data

- 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?
- an NLO calculation could help a lot - if NLO$\otimes\mathcal{C}_{\text{had}}\otimes\mathcal{C}_{\text{MPI}}$ describes data well, would have more faith in $\mathcal{C}_{\text{MPI}}$

# Comparison with the data

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



# Summary

- Three- & four-jet states in PHP measured differentially with 121 $pb^{-1}$ in two $M_{\text{nj}}$ 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 $M_{\text{nj}}$ & $x_{\gamma}^{\text{obs}}$) and with jet multiplicity
- MPIs can account for this correctly ...
- ...this has been shown by tuning JIMMY (in HERWIG) to the data ... 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).
  - although possibly indicative that MPIs are not the sole cause
- the $\mathcal{O}(\alpha\alpha_s^2)$ pQCD calculation describes 3-jet data well for $M_{\text{3j}} \gtrsim$ 50 GeV.
- the prediction is poorer for $M_{\text{3j}} \lesssim$ 50 GeV due to higher-order processes absent in the calculation.