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

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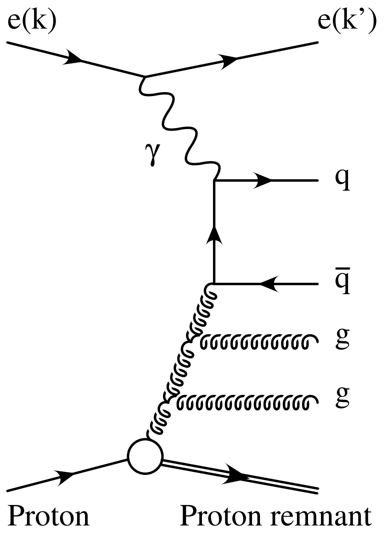
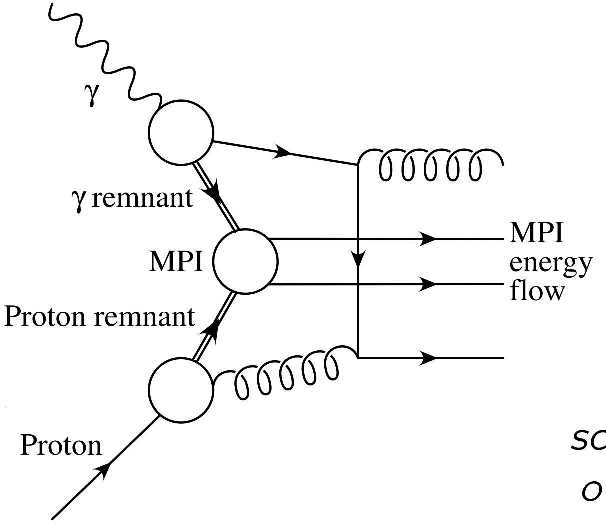
  - *compared to* $\mathcal{O}(\alpha\alpha_s^2)$ *pQCD*
- *Summary*

Motivation

- 7.5× 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 α_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
- Test of parton showers (LLA) used to simulate multi-jet states in (LO ME+PS) Monte Carlos.
- Appear sensitive to MPIs ⟶ test/tune MPI models.



4-jet direct (tree-level)



schematic of a MPI

- Multi-jet HFS and MPIs will be abundant at the LHC & next generation colliders.

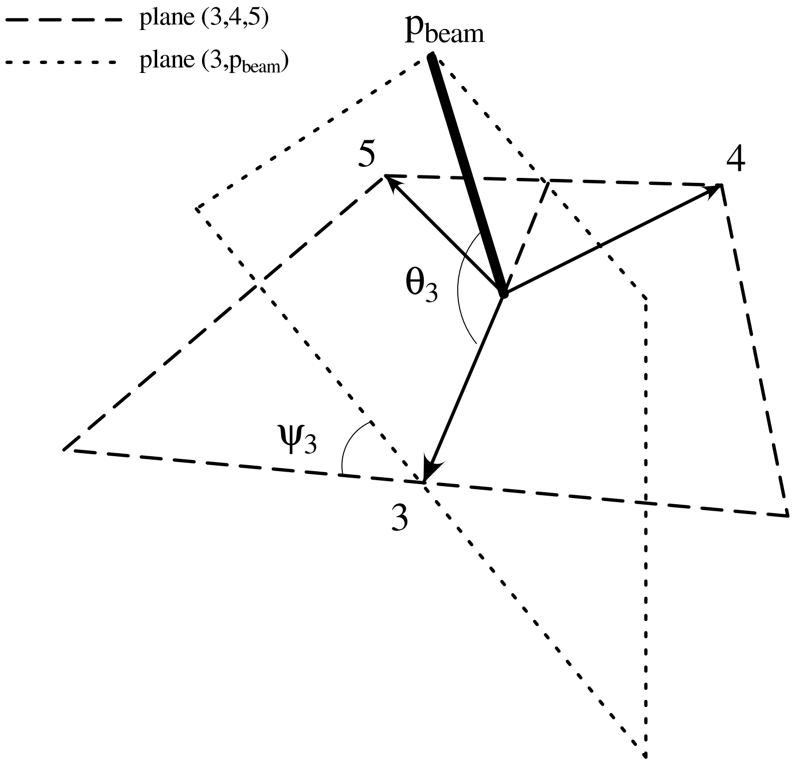
Variable definitions

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

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
- $\cos(\Psi_{3(')}) = \frac{(\mathbf{p}_{\mathrm{beam}} \times \mathbf{p}_{3(')}) \cdot (\mathbf{p}_{4(')} \times \mathbf{p}_{5(')})}{|\mathbf{p}_{\mathrm{beam}} \times \mathbf{p}_{3(')}||\mathbf{p}_{4(')} \times \mathbf{p}_{5(')}|}$
- $\cos(\theta_{3(')}) = \frac{\mathbf{p}_{\mathrm{beam}} \cdot \mathbf{p}_{3(')}}{|\mathbf{p}_{\mathrm{beam}}||\mathbf{p}_{3(')}|}$
- $X_{\mathrm{j(')}} = \frac{2E_{\mathrm{j(')}}}{E_{3(')}+E_{4(')}+E_{5(')}}$

schematic of 3-jet angles



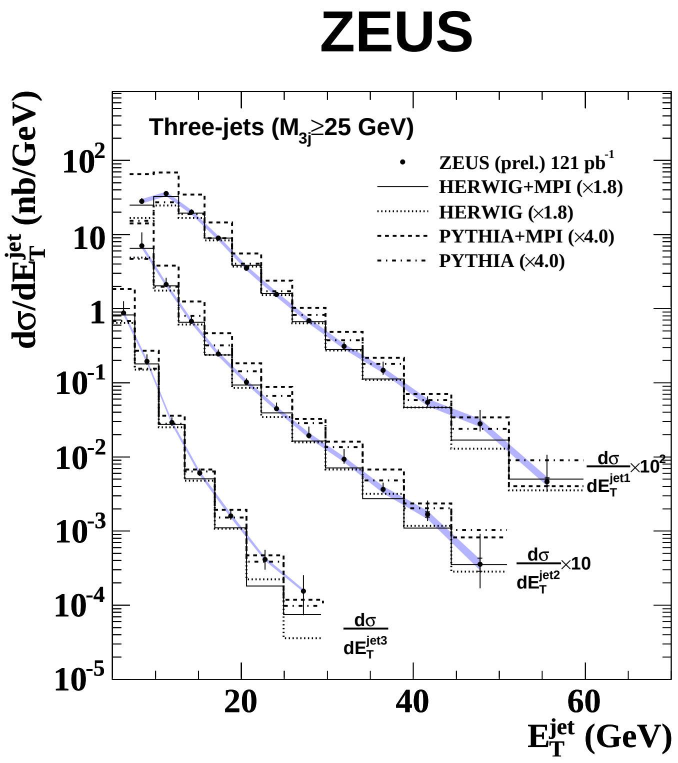
$$\mathbf{p}_{\mathrm{beam}} = \mathbf{p}_{\mathrm{elec}} - \mathbf{p}_{\mathrm{prot}}$$

Cross section definition

- **Jet requirements** (lab frame)
  - $E_T^{\mathrm{jet}_{1,2}} > 7\ \mathrm{GeV}$
  - $E_T^{\mathrm{jet}_{3,4}} > 5\ \mathrm{GeV}$
  - $|\eta^{\mathrm{jet}}| < 2.4$
- **Kinematic region**
  - $0.2 < y < 0.85$
  - $Q^2 < 1.0\ \mathrm{GeV}^2$
  - $\cos(\theta_{3^{(\prime)}}) < 0.95$
  - $X_{3^{(\prime)}} < 0.95$
- **Jets**: inclusive k_T algorithm & massless
- Two mass regions studied:
  - semi-inclusive ($M_{\mathrm{nj}} \geq 25\ \mathrm{GeV}$)
  - high mass ($M_{\mathrm{nj}} \geq 50\ \mathrm{GeV}$)

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.



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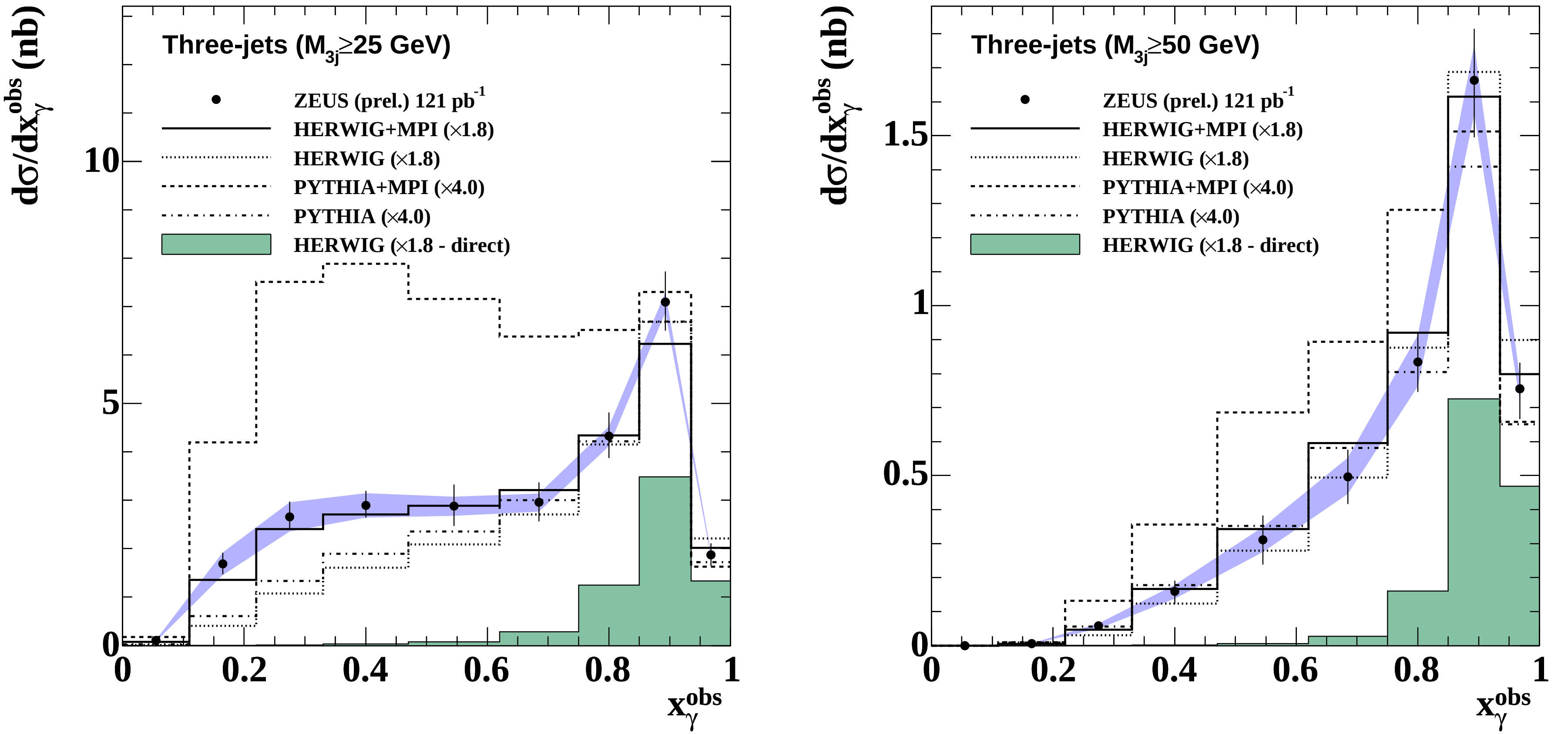

- cross sections peak at $x_\gamma^{\mathrm{obs}} \approx 0.9$, and are kinematically suppressed at low x_γ^{obs}.
- MC predicts peaks partly due to direct (LO definition) but significant resolved PHP contributions.
- MCs without MPIs fail to describe low x_γ^{obs} region at low M_{3j} - MC requires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

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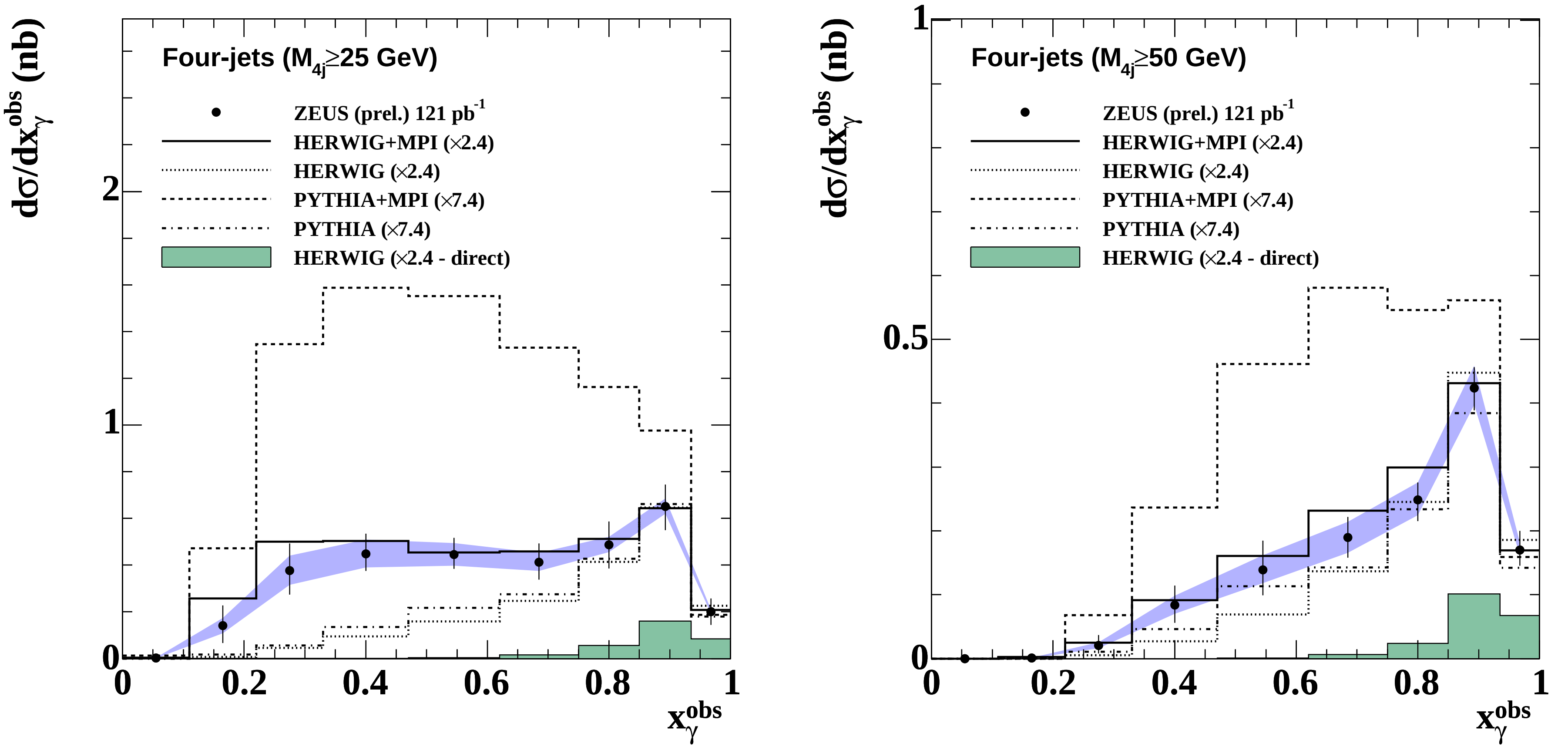

- again, cross sections peak at $x_\gamma^{\rm obs} \approx 0.9$ and low $x_\gamma^{\rm obs}$ kinematically suppressed... BUT...
- ...smaller direct contribution and less suppression even though four-jet HFS more tightly constrained.
- MCs predict that differences at low $x_\gamma^{\rm obs}$ are due to larger missing component/more MPIs... BUT...
- ...high $x_\gamma^{\rm obs}$ 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.

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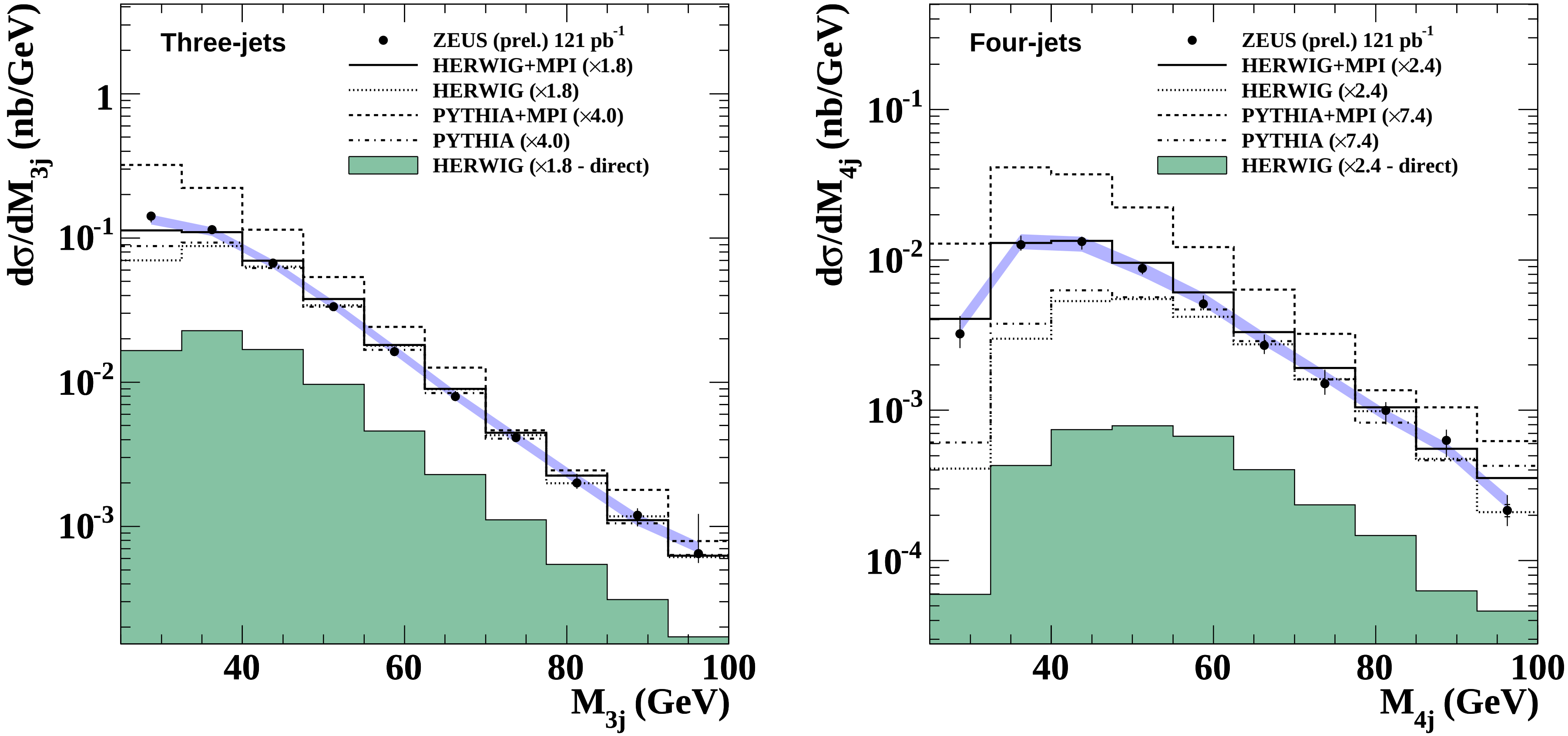
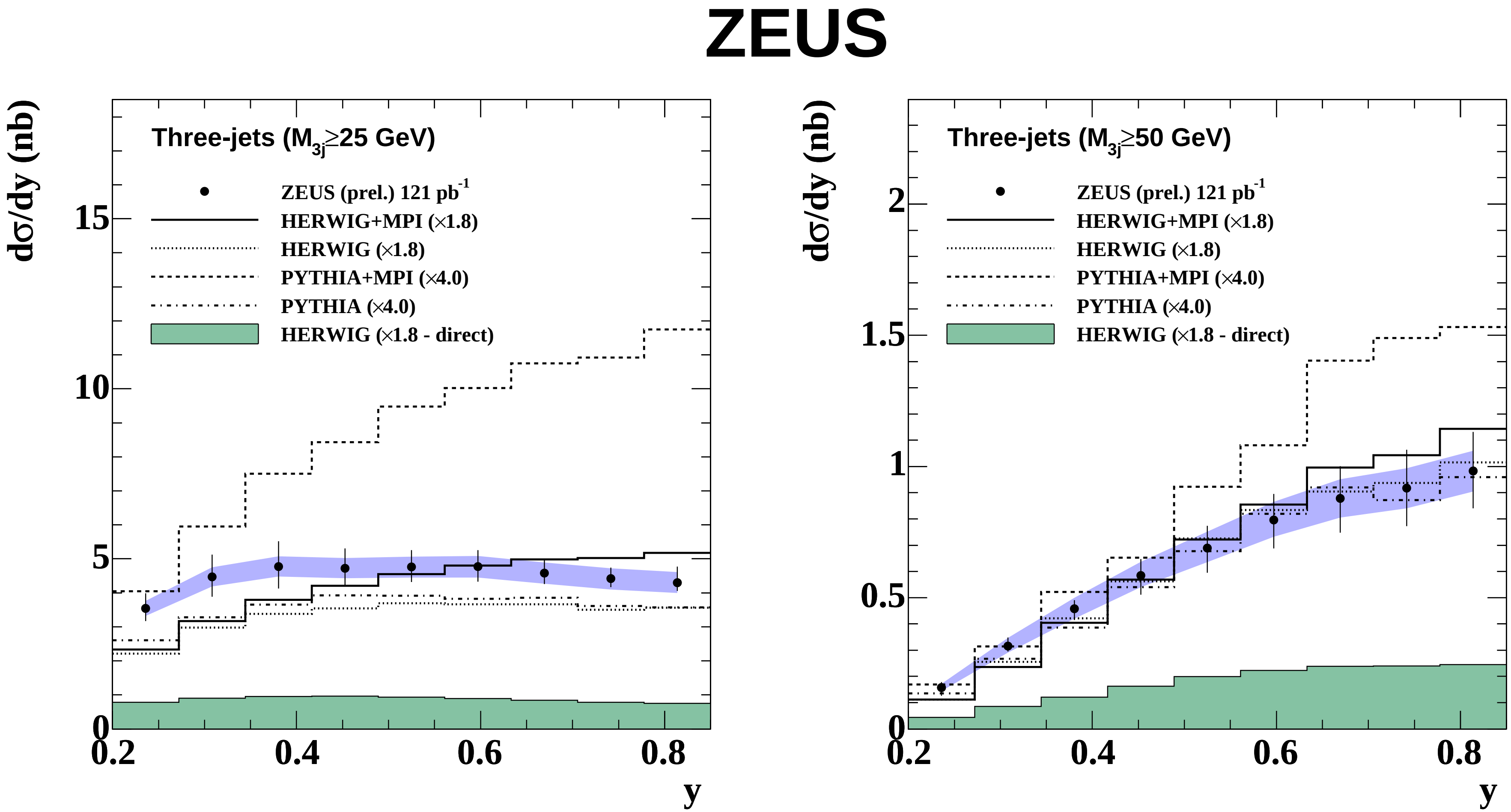


- from now on will assume that the missing component from the MCs without MPIs is due to MPIs.
- cross sections fall exponentially with increasing M_{nj} - low M_{nj} suppression due to selection criteria.
- MC predicts MPIs augment low M_{nj} cross section - reduce the effects selection criteria.
- 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

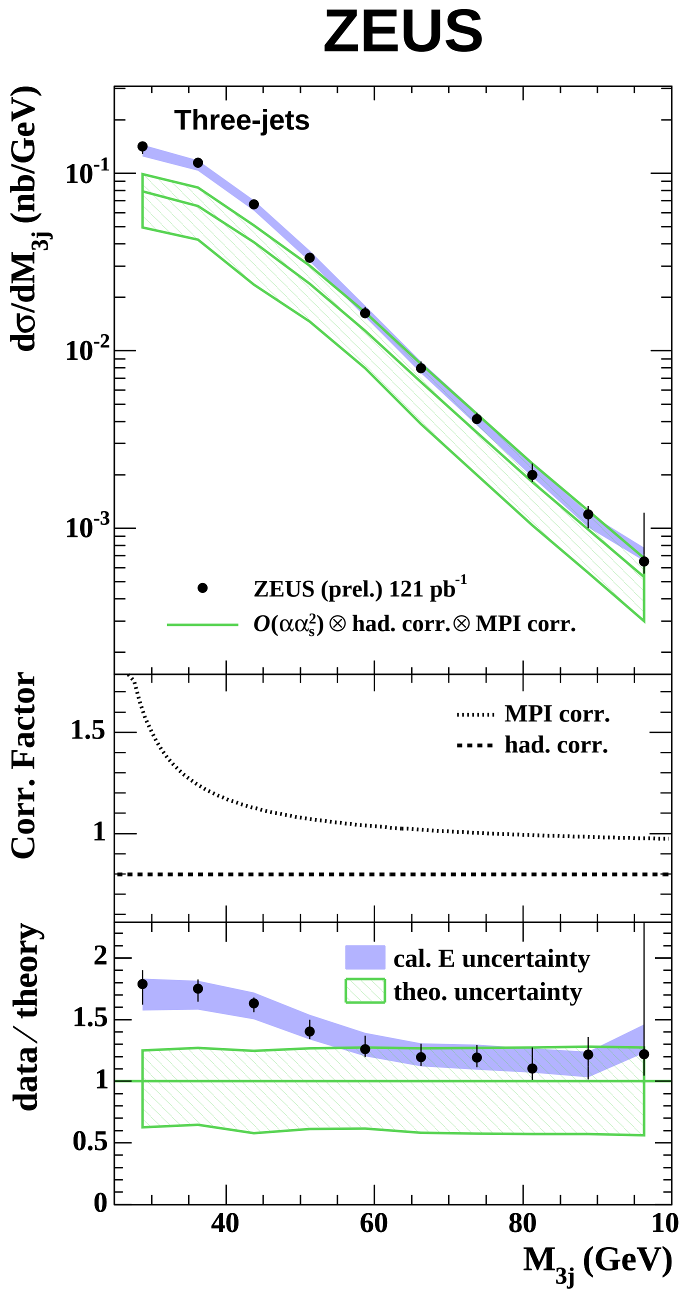
- $\mathcal{O}(\alpha\alpha_s^2)$ pQCD is lowest order for 3-jet process.
- E_T^{jet1} used for renormalisation & factorisation scales.
- theoretical uncertainty evaluated using $2^{\pm 1}E_T^{\text{jet1}}$ for scales.
- α_s calculated with one loop precision & five active flavours

  - 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:

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

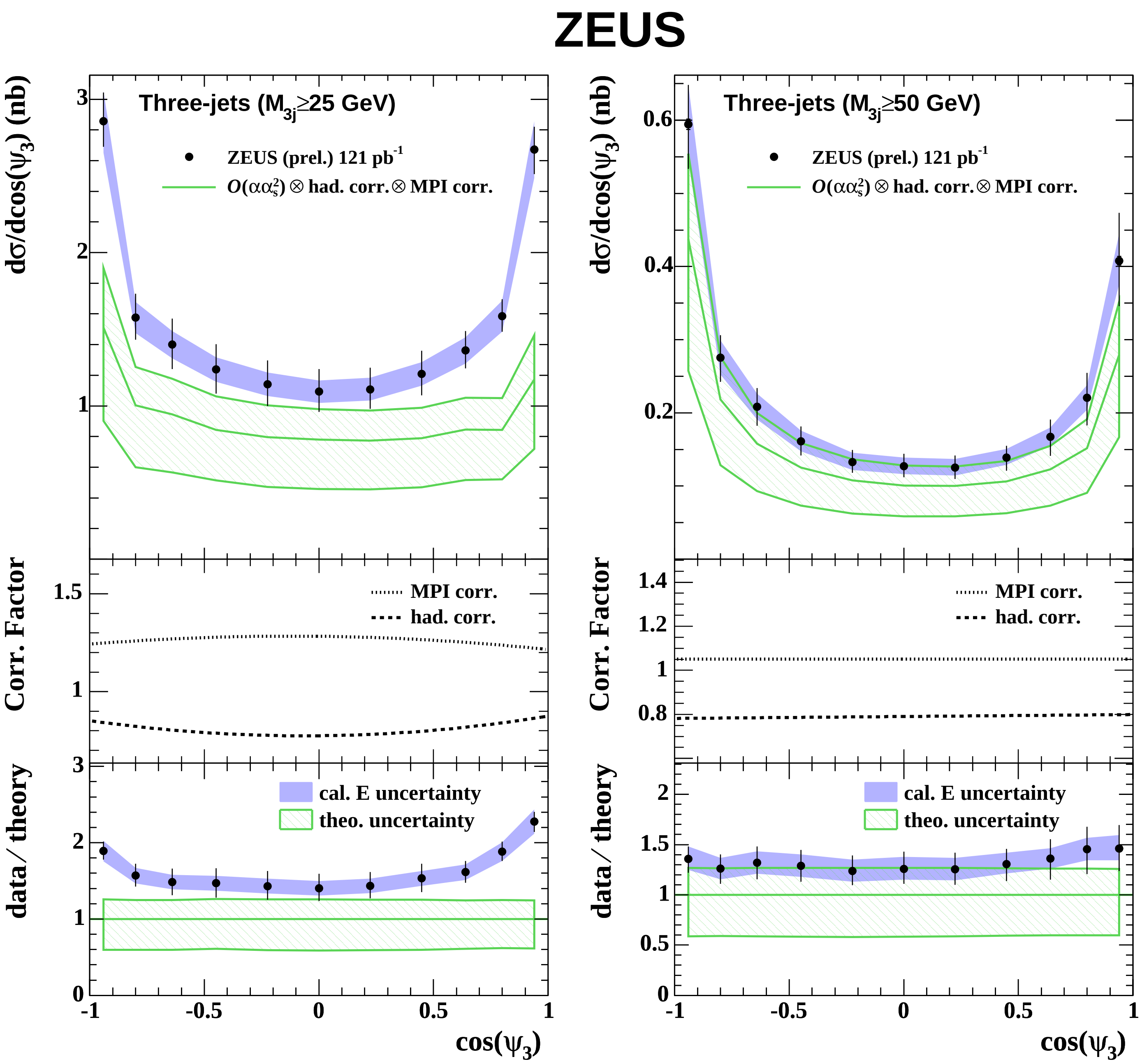
Comparison with the data

- 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?



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_{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_{γ}^{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 $\mathcal{O}(\alpha\alpha_s^2)$ 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.