

Vector Meson and Final State Session I

THE UNDERLYING EVENT AND MULTIPARTON INTERACTIONS AT HERA

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Low-x Workshop
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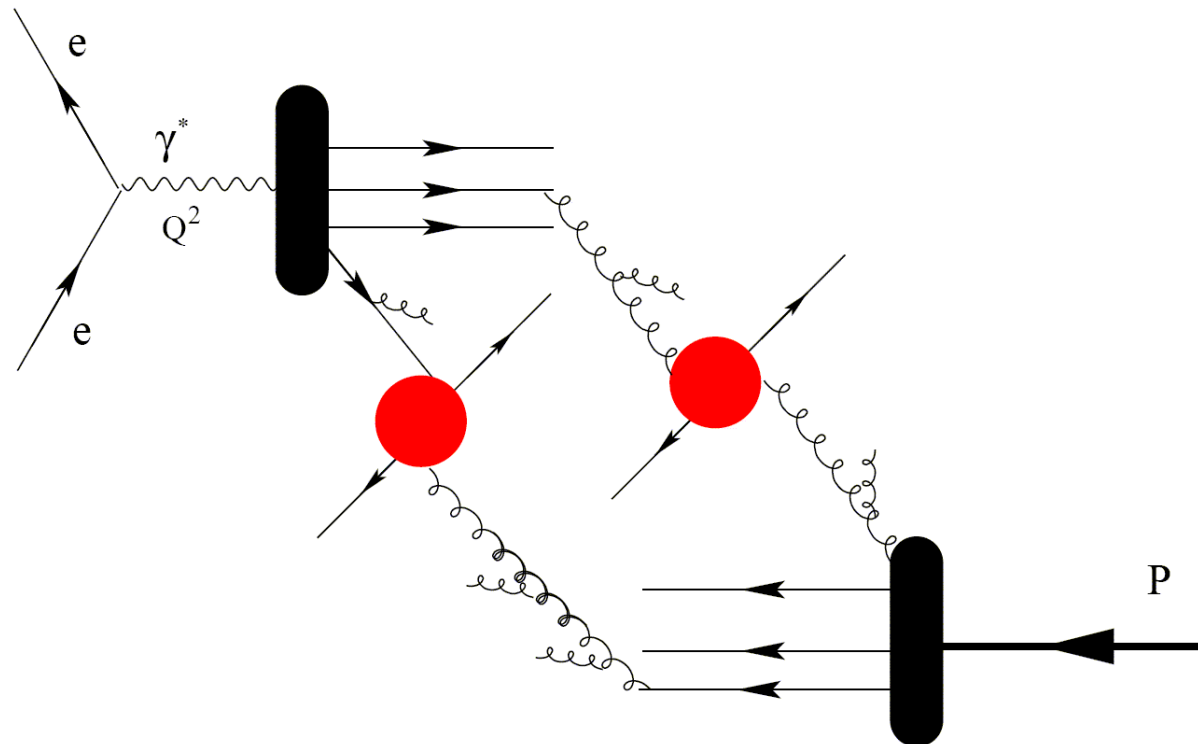
OVERVIEW

- ¶ Underlying event (UE) and multiparton interactions (MPI)
 - Definition
 - Necessity of UE and MPI
 - Tests of UE and MPI
 - Implementation of UE and MPI in MC models
- ¶ H1: Minijets in deep-inelastic scattering
- ¶ ZEUS: Multijet cross-sections in photoproduction
- ¶ Conclusion, outlook, and complaints 😊

UE (AND MPI): DEFINITIONS

¶ UE constituents: Everything except first hard interaction

- (soft) beam remnant interactions
- additional (semi)hard constituent scatterings (multi-parton interactions, MPI)
- initial and final state radiation
- ...



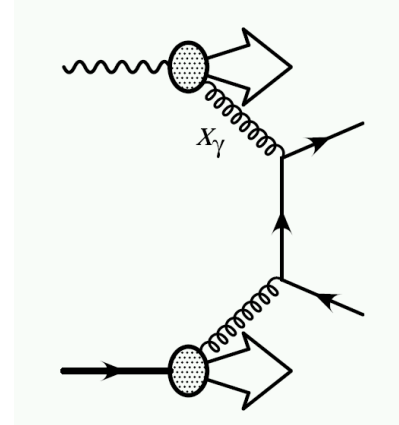
➔ UE / MPI lead to additional activity in hadronic final state

- affects measurements in hadron-hadron collisions (jets, QCD backgrounds, ...)
- theoretically interesting and challenging (mechanism not understood)

UE AND MPI: EXPERIMENTAL TESTS

¶ Multijet cross-sections (in PHP and DIS)

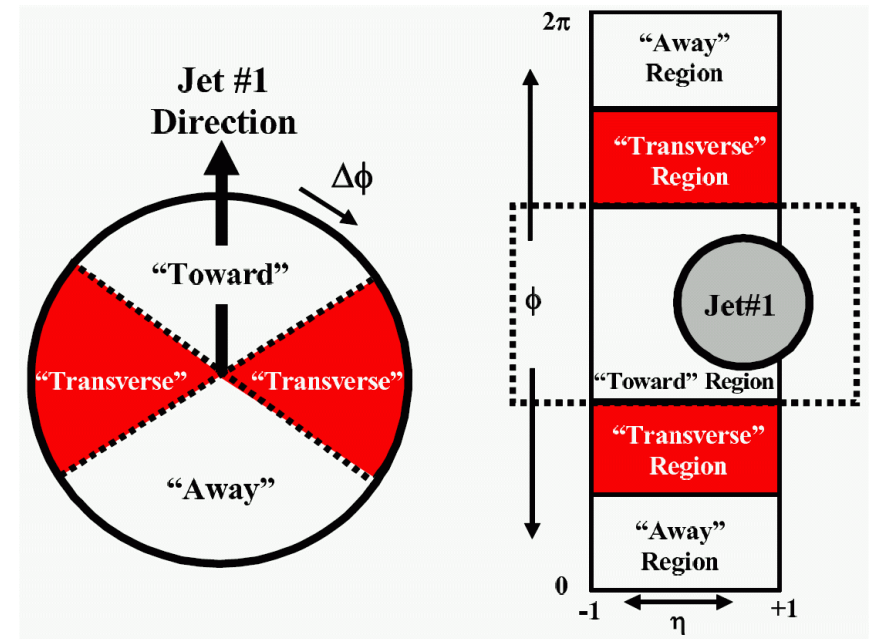
- Which model fills gap between data and MC (mainly resolved-photon regime defined by observable x_γ , hadron-hadron-like!)
- Origin of third, fourth jet: Radiation? MPI?
- If ≥ 3 jets used, sample dominated by resolved events.



¶ Define different azimuthal regions

- “**towards**” and “**away**”: hard interaction!
- **transverse**: higher orders, radiation, UE.
- “**high-activity**”: I/FSR, higher-orders, UE.
- “**low-activity**” mainly UE?
(UE uncorrelated to hard interactions?).

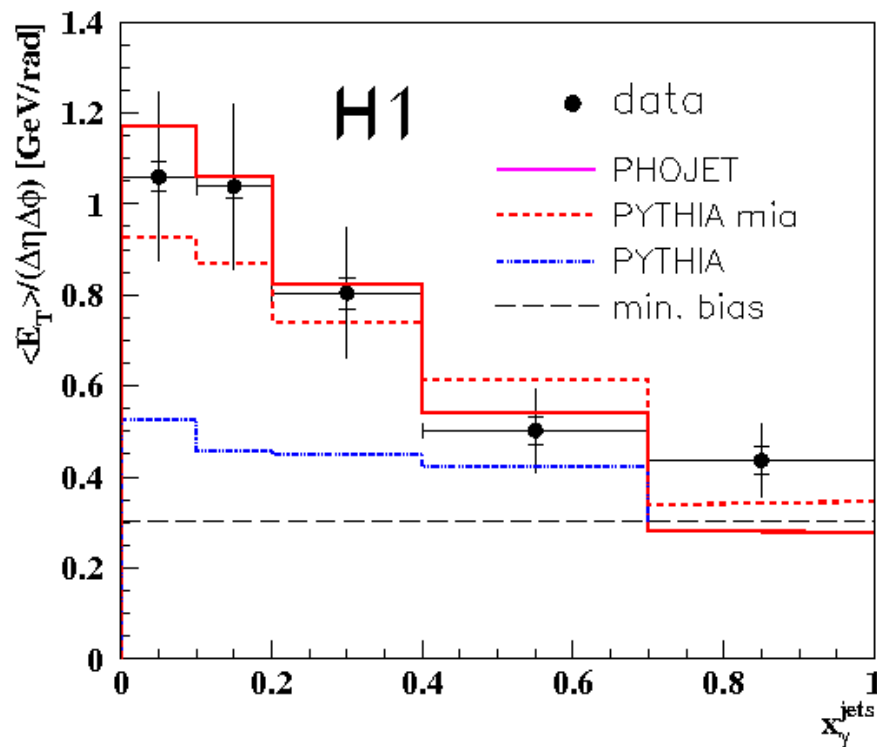
→ Study particle flow, transverse energy, mini-jet multiplicity in various regions!



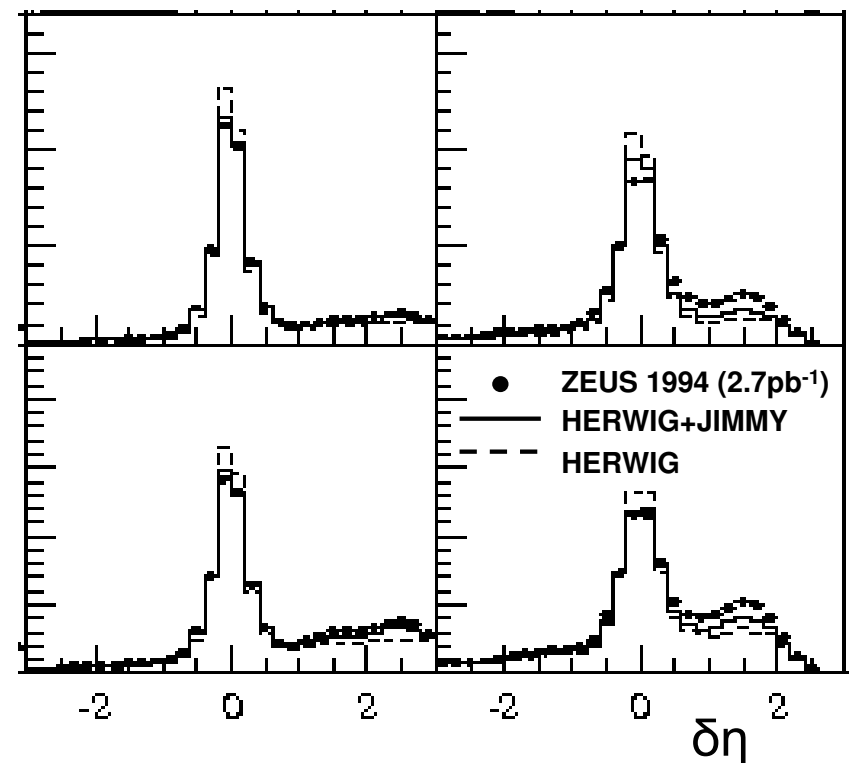
UE/MPI NECESSITY 1

¶ Various measurements demonstrate necessity of UE/MPI

- Photoproduction dijets at HERA,
 - H1: ZP C70 (1996) 17
 - ZEUS: EPJ C1 (1998) 109



$$x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2E_\gamma}$$

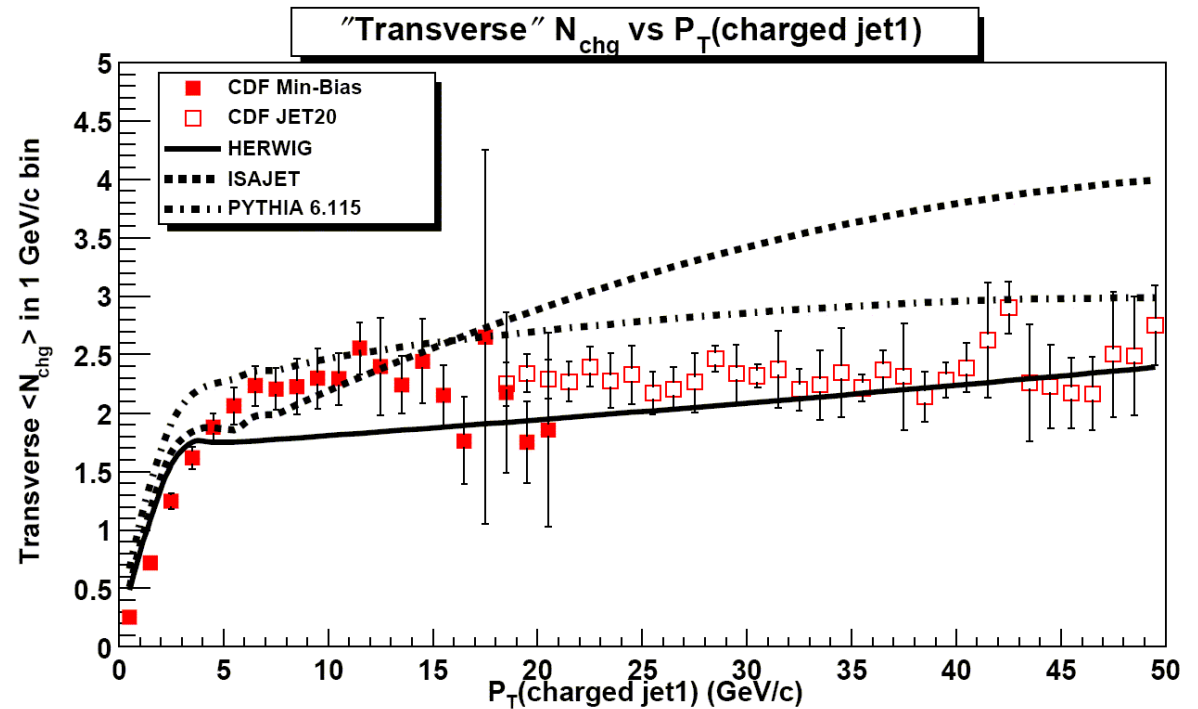


Jet profiles: energy flow relative to jet axis in different η regions

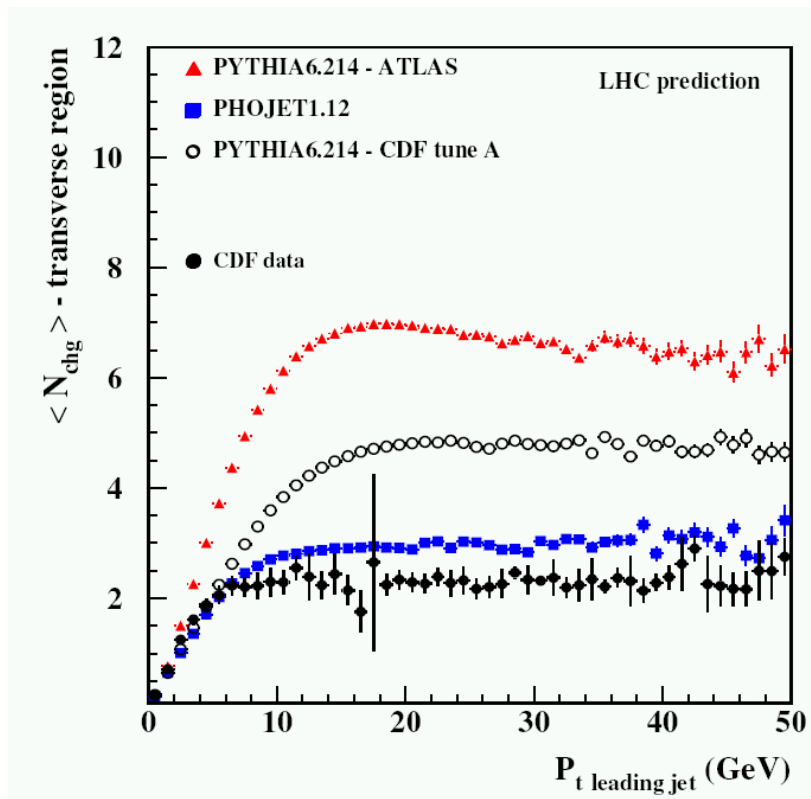
UE/MPI NECESSITY 2

TEVATRON jets:

- PRD 65 (2002) 092002
- charged-particle multiplicity in transverse region as function of leading-jet p_T .



- Predictions for LHC notoriously difficult
- extrapolations of various programs to 14 TeV differ by up to factor of 4 (HERWIG+JIMMY not shown)!



UE MODEL IMPLEMENTATIONS

¶ PYTHIA + MPI

- Various models (old / intermediate / new): differ wrt color flow, remnant treatment, showering initiators, shower mode, interleaving of ISR and MPI, ...
- simple overlap of hadrons or impact-parameter dependence
- Average number of interactions per event derived from regularised $2 \rightarrow 2$ cross-section and total cross-section; secondary interactions Sudakov-suppressed.

¶ HERWIG + JIMMY

- Based on eikonal model assuming matter distributions in colliding particles and an overlap function $A(b)$.
- Assign $2 \rightarrow 2$ cross-section to all events, choose number of interactions according to precalculated probability distribution.

¶ SHERPA

- similar assumptions as in PYTHIA, module AMISIC++ simulates MPIs.
- independent Q^2 -evolution of initial/final state partons in each scatter via APACIC++.

¶ PHOJET

- Not part of general purpose generator, limited use for HEP.

H1 ANALYSIS: MINIJETS IN DIS

¶ Measure for UE

- average number of low- p_T jets (“mini jets”, $E_T > 3$ GeV) in different azimuthal regions as function of p_T of leading jet.

¶ Inclusive sample

- in bins of Q^2 and in bins of η^{lab} of leading jet
- forward region in η^{lab} : enhanced in resolved photon processes

¶ Dijet sample

- in bins of x_γ (separation of direct- / resolved-enhanced samples)

$$x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2E_\gamma}$$

¶ Selection: 57.4 pb^{-1} from 1999-2000

- **low- Q^2 DIS**: $5 < Q^2 < 100 \text{ GeV}^2$, $0.1 < y < 0.7$, $W > 200 \text{ GeV}$.
- **Jets**: $-1.7 < \eta_{1(2)}^{\text{lab}} < 2.79$, $p_{T1(2)} > 5 \text{ GeV}$ ($|\varphi_1 - \varphi_2| > 140^\circ$).
- **Mini jets**: $-1.7 < \eta_{1(2)}^{\text{lab}} < 2.79$, $p_T > 3 \text{ GeV}$

¶ Data compared to various models

- PYTHIA with MPI (simple scenario without impact-parameter dependence)
- ARIADNE (CDM)
- RAPGAP direct and direct+resolved γp interactions

H1: INCLUSIVE SAMPLE FORWARD: PYTHIA

¶ Towards (and Away)

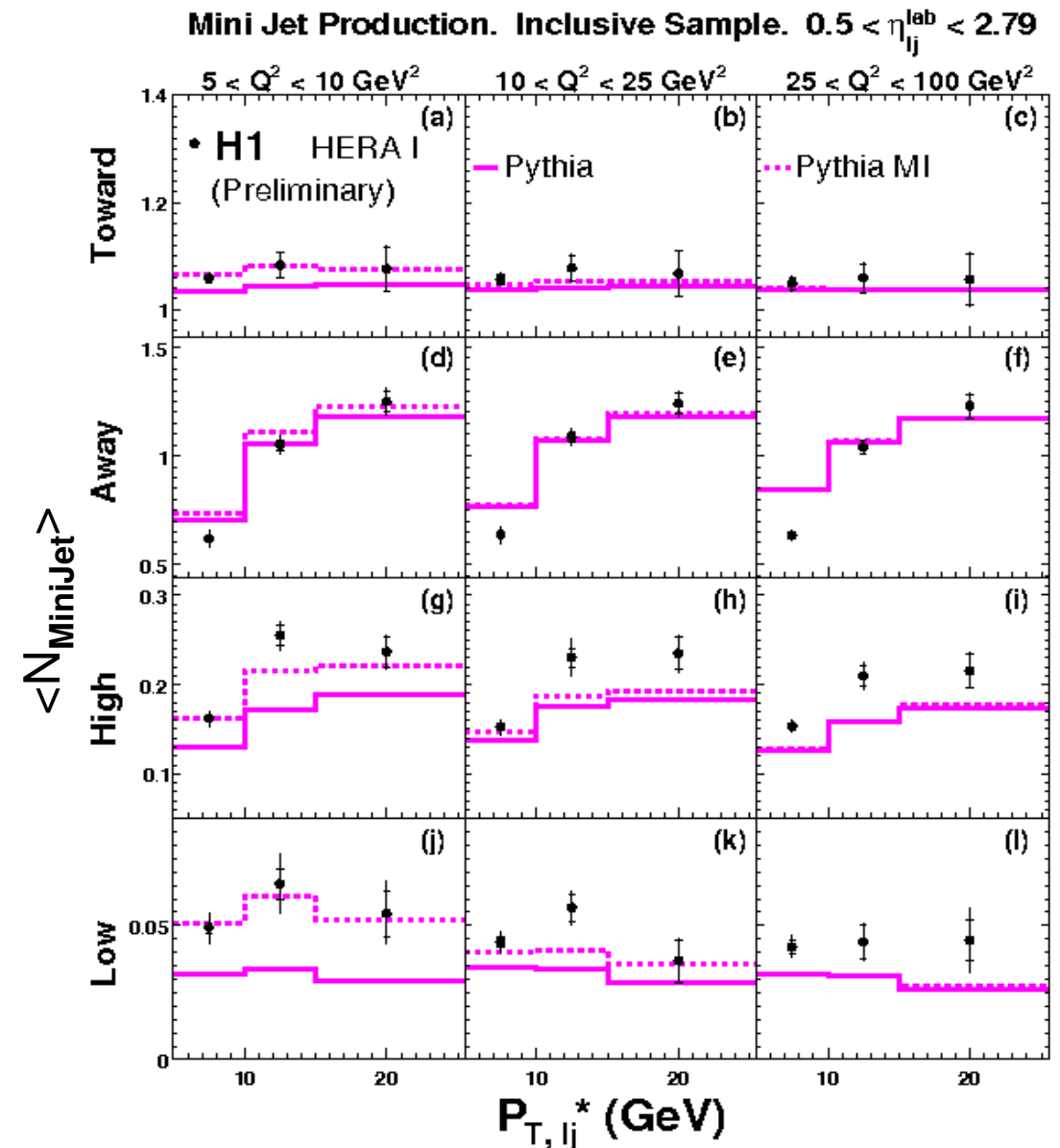
- PYTHIA with and without MPI describes the data.
- Dominated by hard interaction, UE contributions not relevant here.

¶ High activity transverse region

- no MPI/SUE: MC too low.
- PYTHIA + MPI: okay at low Q^2 .
(at high Q^2 missing contributions)

¶ Low activity transverse region

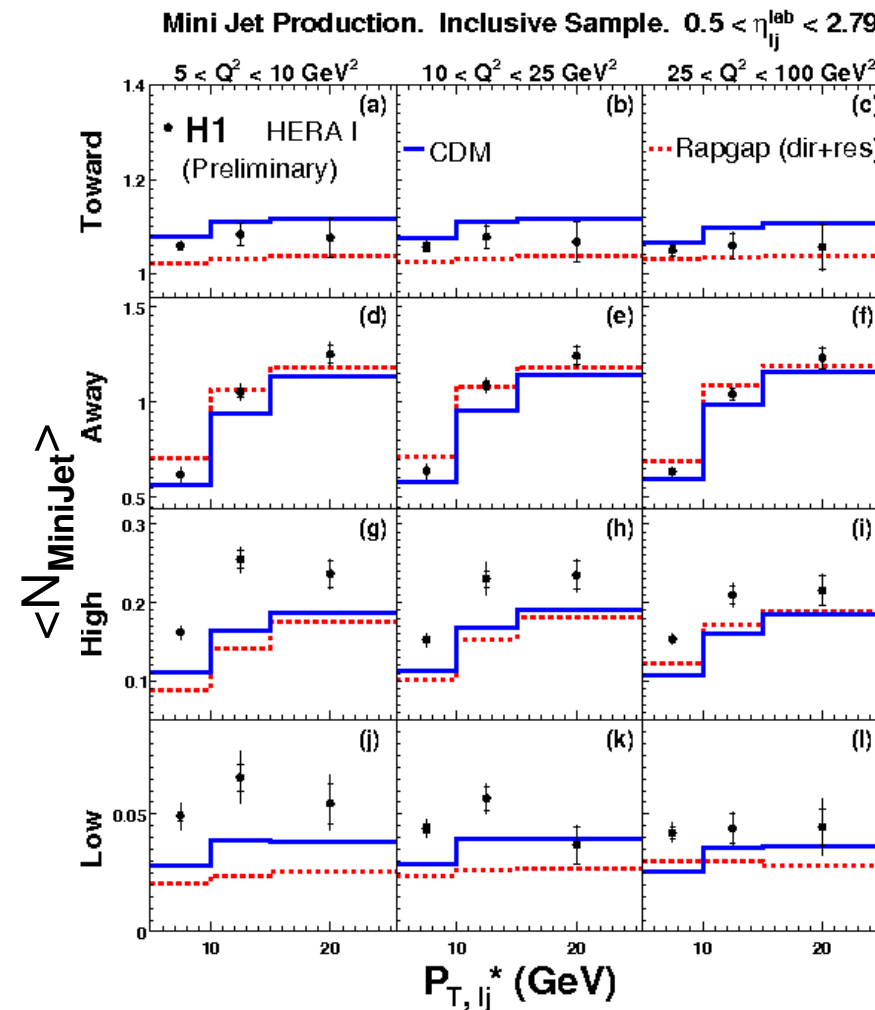
- no UE/MPI: MC too low (low Q^2 !).
- PYTHIA+MPI: okay.



H1: INCL. SAMPLE FORWARD: CDM, RAPGAP

¶ towards+away fine like PYTHIA

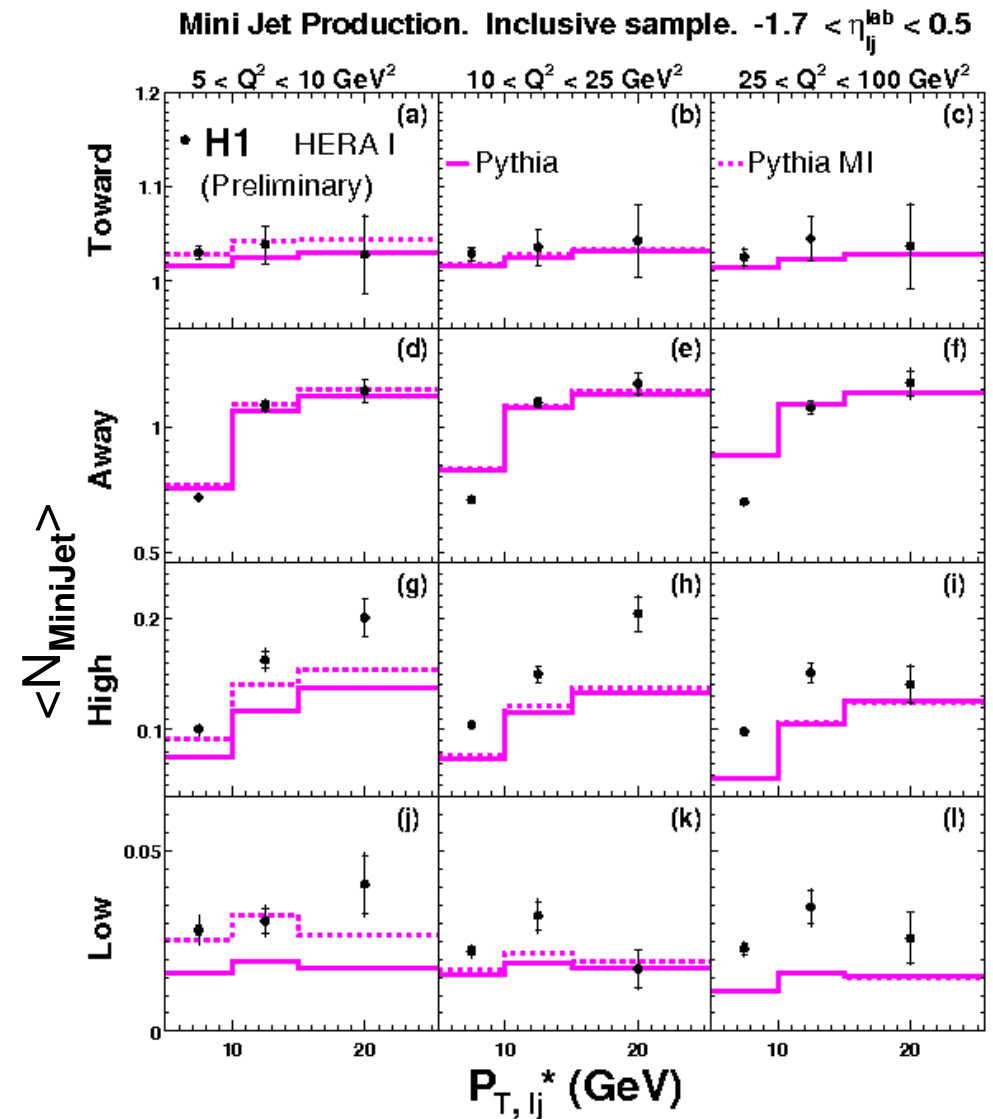
– ... but too low in transverse regions.



H1: INCLUSIVE SAMPLE BACKWARD

Messages like in forward region

- towards + away: UE/MPI not relevant
- less difference between description in low- and high-activity region than for forward sample.
- inclusion of UE/MPI improves transverse regions slightly.



H1: DIJET SAMPLE: PYTHIA

¶ Towards and Away regions

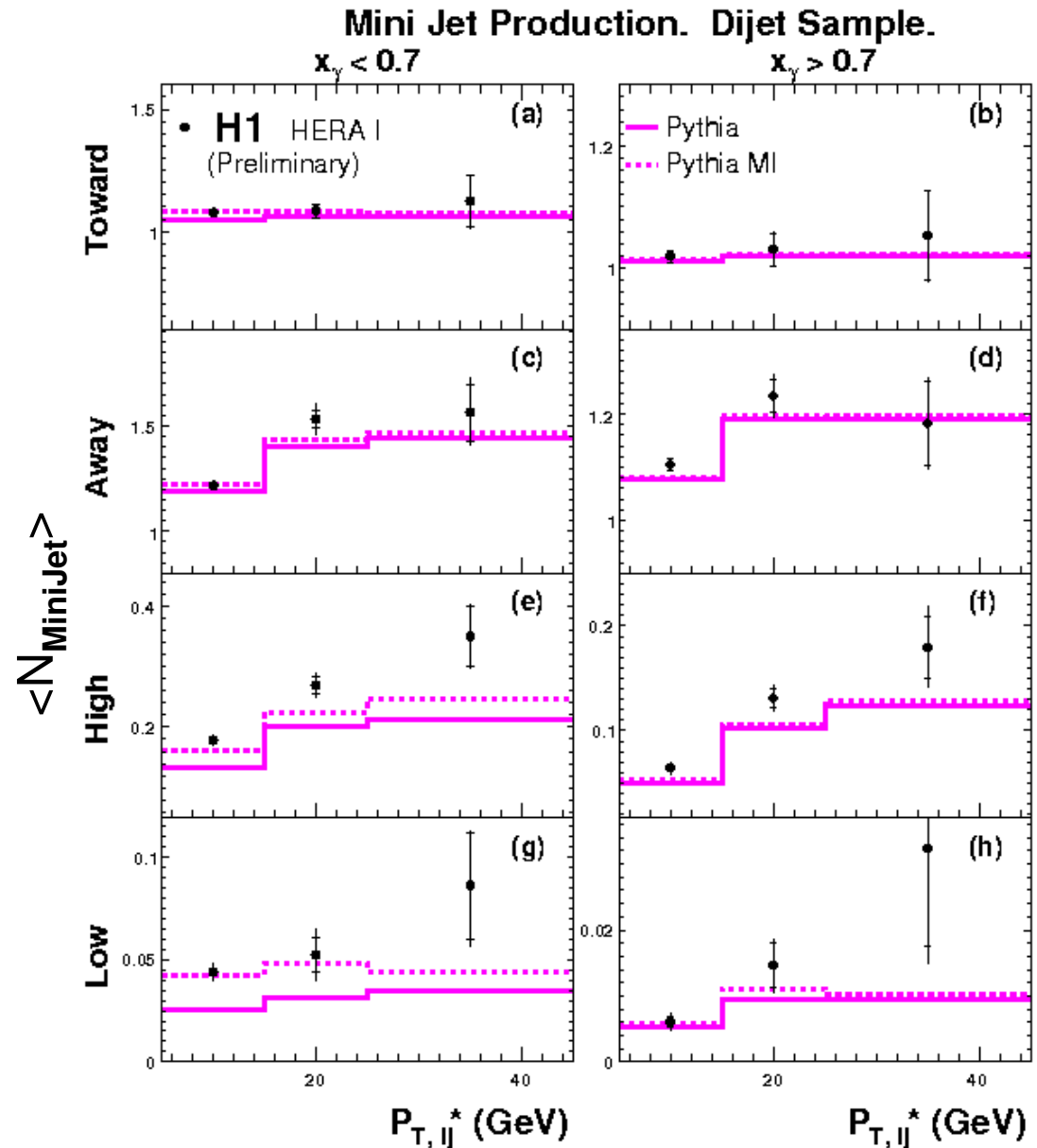
- all models with and without UE/MPI can describe the data.

¶ High-activity region

- data generally above the models
- PYTHIA similar for direct and resolved; little UE influence

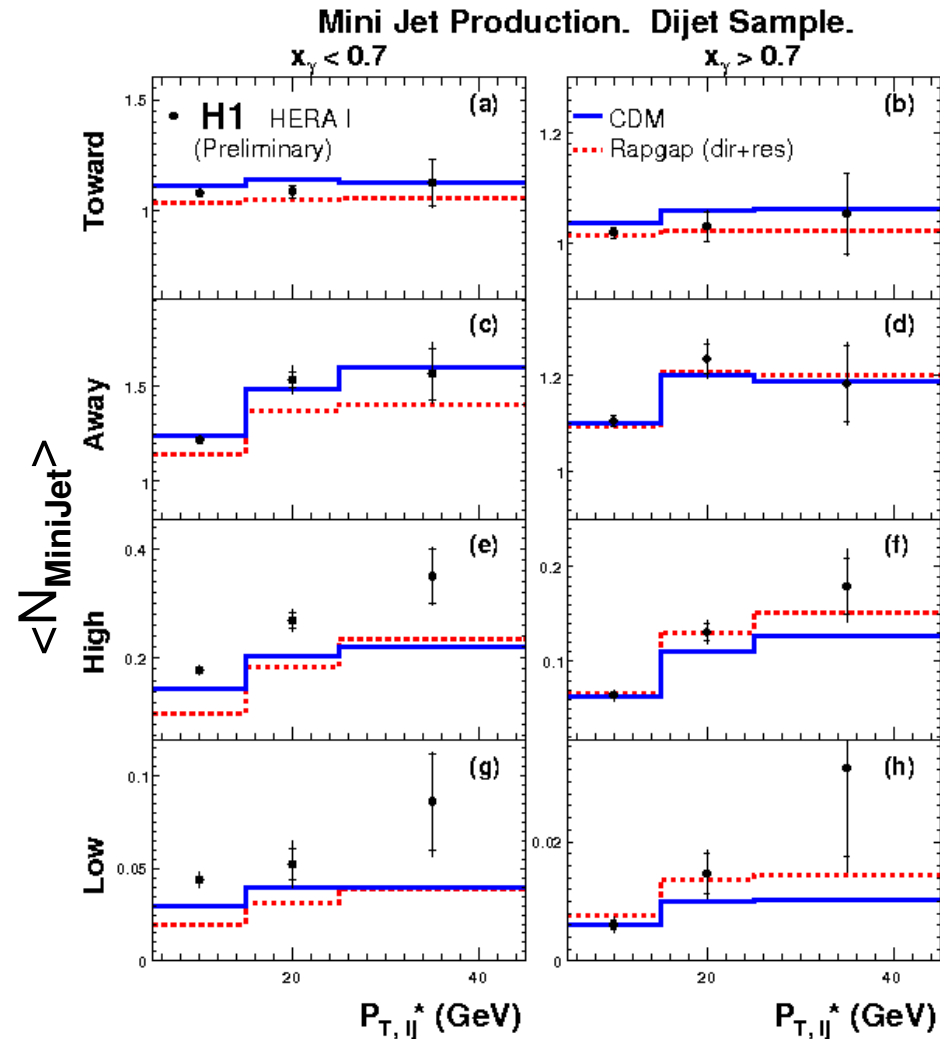
¶ Low-activity region

- larger influence of UE for resolved than for direct.
- PYTHIA+MPI describes both resolved and direct parts.



H1: DIJET SAMPLE: CDM, RPGAP

¶ ... similar to PYTHIA



SUMMARY: H1 MINIJETS IN DIS

¶ Measurement of average minijet ($E_T > 3$ GeV) multiplicities

- as function of the leading-jet p_T in different azimuthal regions
- in leading-jet and dijet samples
- in different regions of Q^2 , x_γ , η_{leading} .

¶ Models without UE/MPI contributions

- work well in towards / away regions \rightarrow dominated by hard interaction
- work less well or fail completely in transverse regions, especially
 - in the low-activity region
 - at low x_γ and low Q^2 (increased contribution from resolved events, UE)

¶ Models with UE/MPI contributions

- help improve the situation, especially in the low-activity, UE-dominated region.

Conclusions:

- **Something in addition to normal MC models missing in transverse regions.**
- But difficult to tell what precisely! Can HERA help pin down the effect further?
- **Note:** This is DIS – not a priori clear that MPI relevant here at all!

ZEUS: MULTIJETS IN γ^*p

¶ Measure for UE:

- 3- and 4-jet cross-sections in photoproduction
- Jets 3 and 4 generated by hard QCD radiation? Additional scatterings (MPI)?

¶ Selection: 121 pb^{-1} from 1996-2000

- **Photoproduction:** $0.2 < y < 0.85$, $p_{T,\text{miss}}/\sqrt{ET} < 2 \text{ GeV}^{1/2}$, no electron cand.
- **Jets:** 3 or 4 jets with $E_T \geq 6 \text{ GeV}$, $\eta < 2.4$
- **low-mass** region: $25 \leq M_{\text{njet}} \leq 50 \text{ GeV}$, **high-mass** region: $M_{\text{njet}} \geq 50 \text{ GeV}$

¶ Models for comparison:

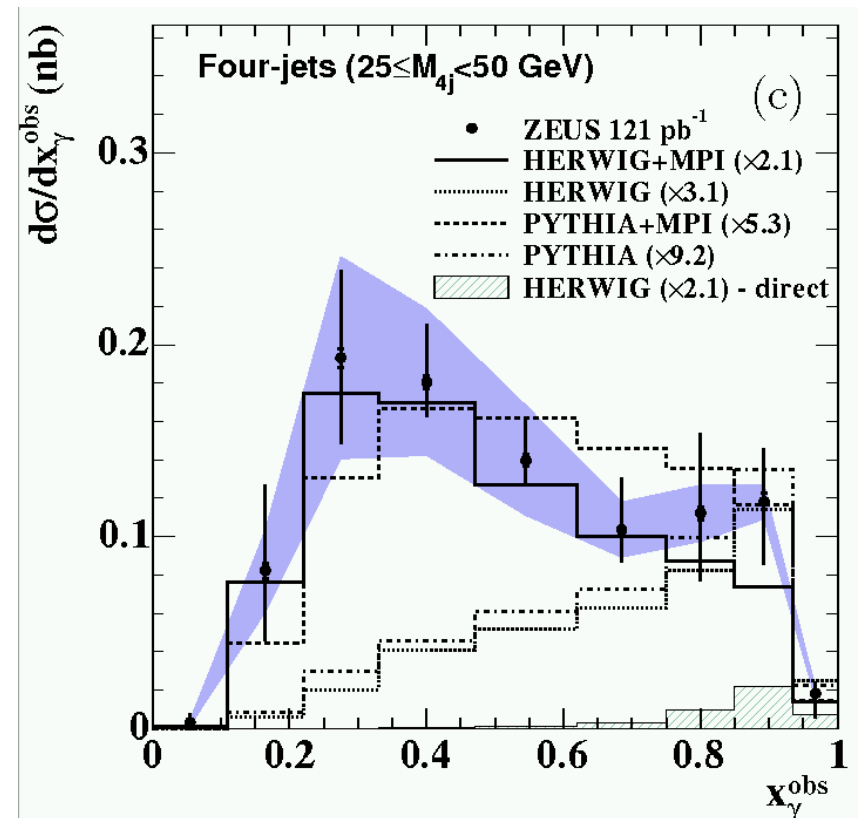
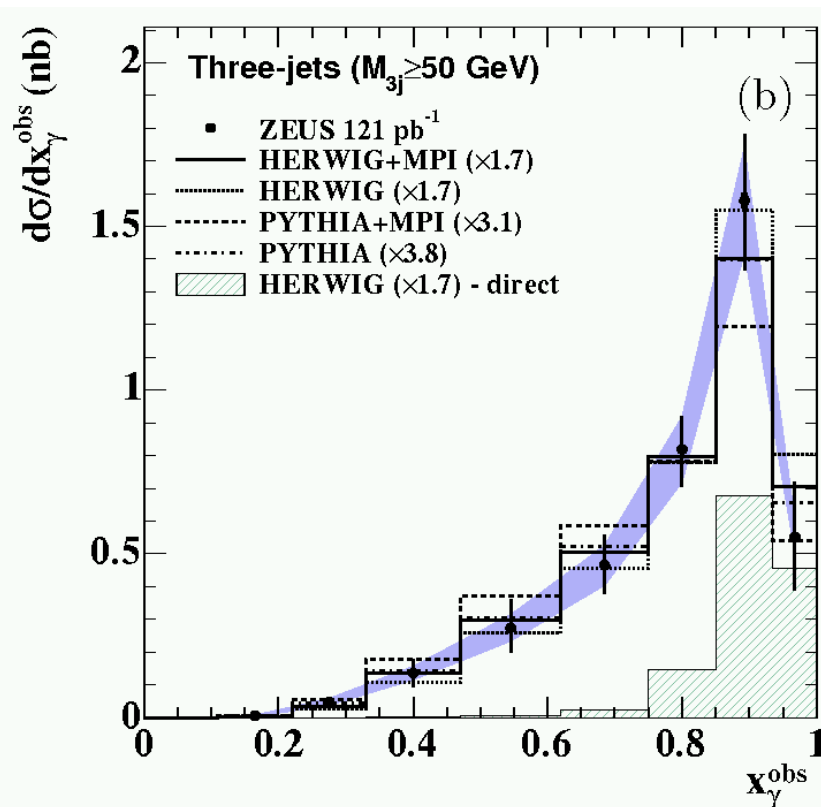
- HERWIG 6.505 + JIMMY 4.0
 - PYTHIA 6.206 + “simple” MPI model
- Both MC underestimate cross-section → scale to match total cross-section or high-mass part of distribution, depending on observable!

In addition: NLO QCD calculation from Klasen et al. for the three-jet case.
(effectively LO since NLO for dijet case!)

$d\sigma/dx_\gamma$

¶ x_γ separates resolved- from direct-dominated subsamples:

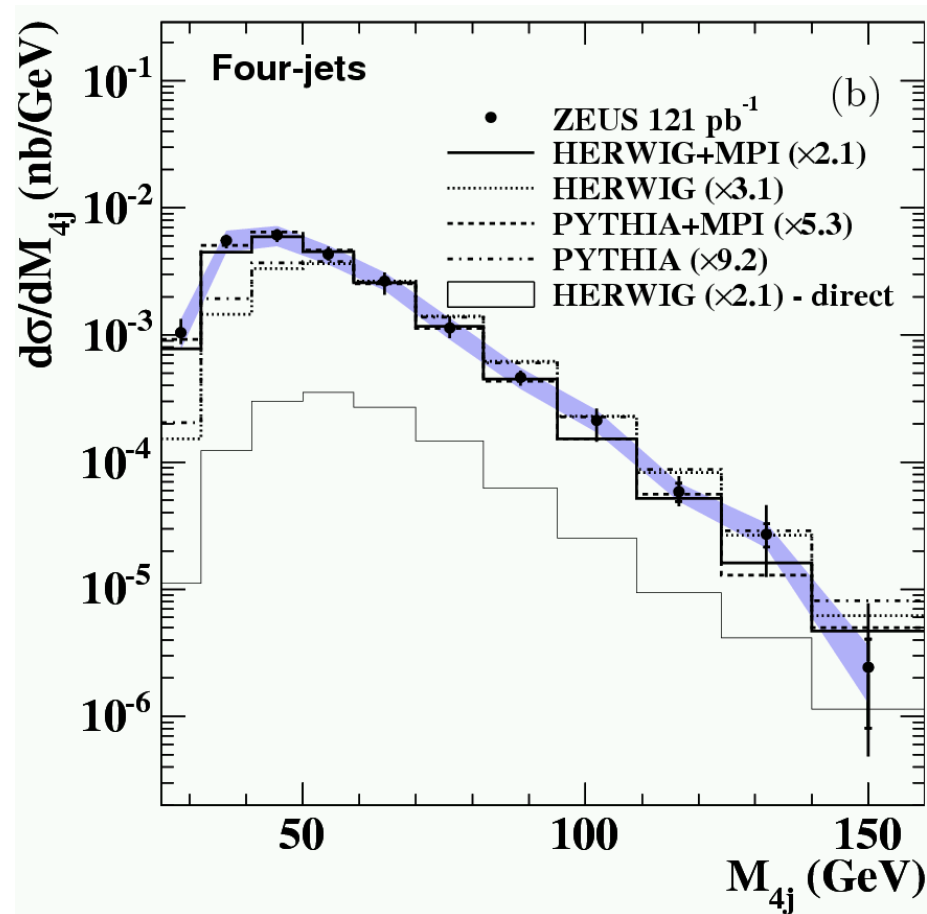
- Models without MPI suggest decreasing cross-sections with decreasing x_γ .
- But for low masses large discrepancy with INCREASING data
 - mechanism beyond direct+resolved as modelled in MC necessary.
- Even “direct” region ($x_\gamma > 0.75$) dominated by resolved events (\leftrightarrow dijets!).
- Especially HERWIG+JIMMY describes data well.
- Note large systematic uncertainties: Model dependence



$d\sigma/dM_{njet}$ (4-jet events)

¶ Need MPI/UE simulations to correctly describe the data:

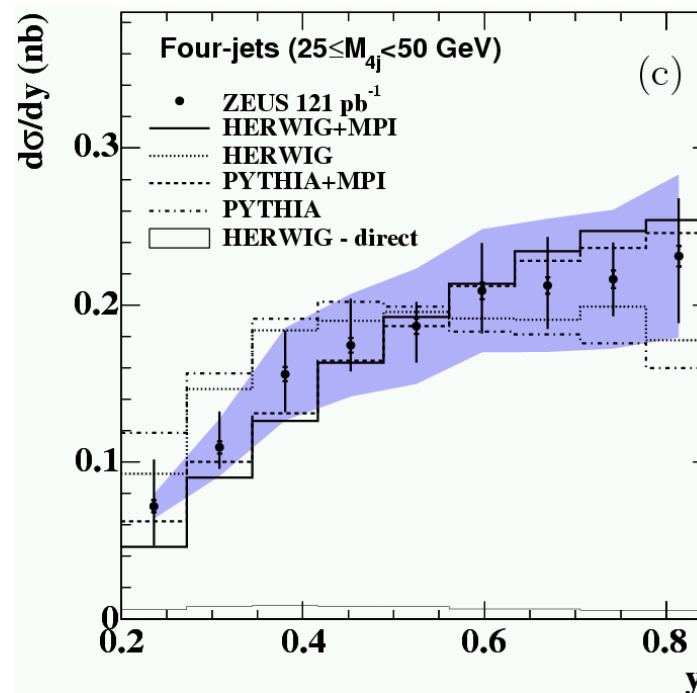
- HERWIG and PYTHIA without UE/MPI fail to describe the data at low masses
- Effect larger for four-jets than for three-jets.
- Here MC normalised to data in high-mass region (unaffected by UE/MPI)



$d\sigma/dy$

¶ ... for low-mass four-jets sample.

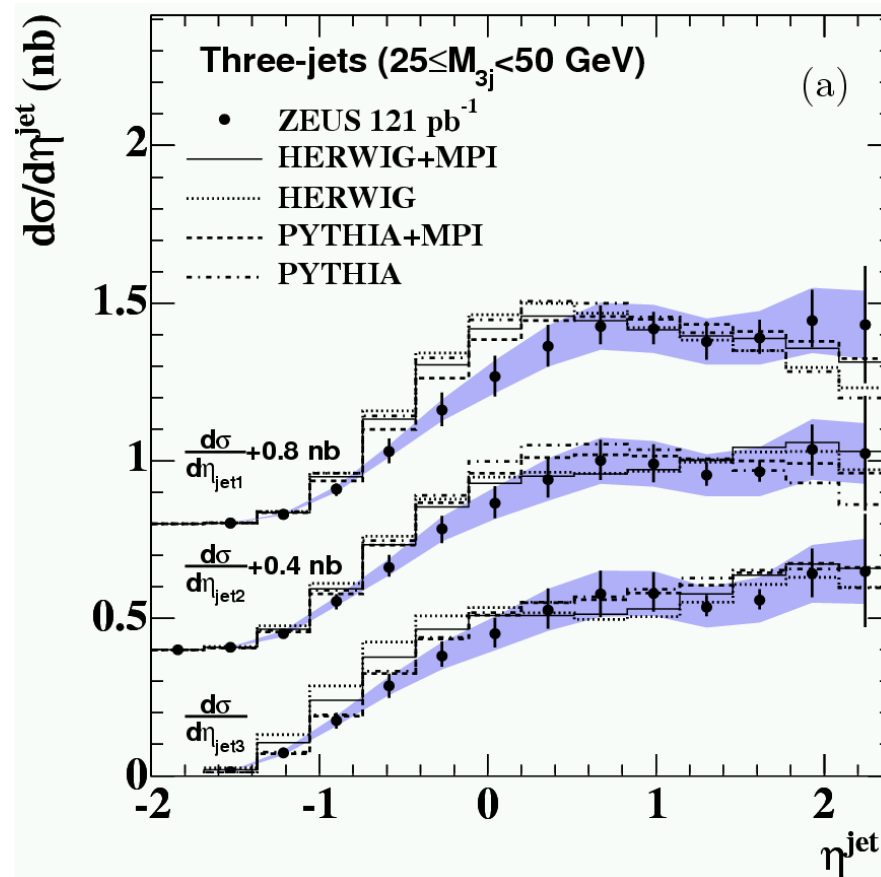
- Behaviour dictated by phase-space and photon flux energy distribution.
- At high masses only small differences between models with and without MPI.
- At low masses, MPI models predict steeper rise of distribution.



$d\sigma/d\eta$

¶ Same shape for all jets, independent of their place in E_T ordering

- High-mass data described by all models (not shown)
- Best description of low-mass data by HERWIG+JIMMY.
- Models with MPI suggest decrease of cross-section at high η^{lab} ; MPIs reduce this effect in line with measurement.



Also E_T spectra of 3+4 jets well described by all models.

$d\sigma/dM_{3j}$ versus NLO

¶ Theory: $O(\alpha_s^2)$

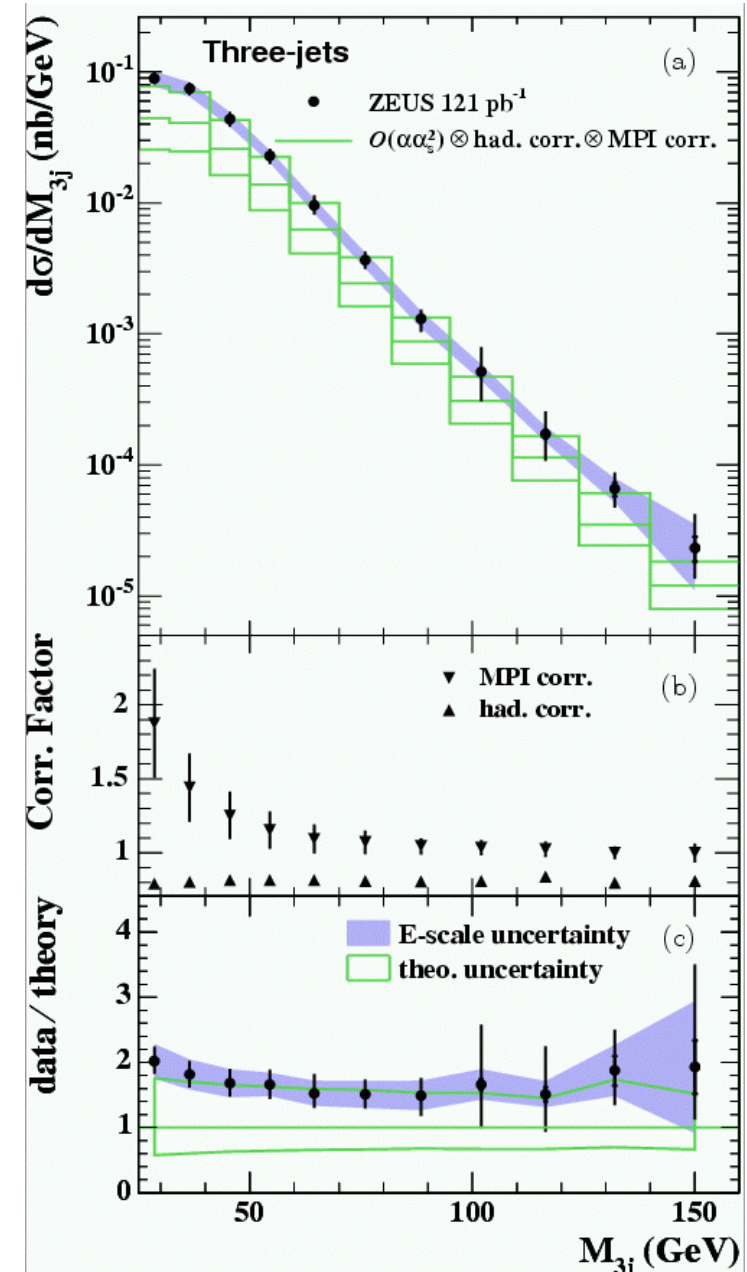
- NLO for dijets in photoproduction
- effective LO for three-jets
- no calculation of MPI effects (need to be corrected for)

¶ Corrections of theory

- hadronisation: small and flat
- MPI: rising rapidly towards low M_{3j} .
→ without NLO far too low!
- large theory uncertainties at low M_{3j} !

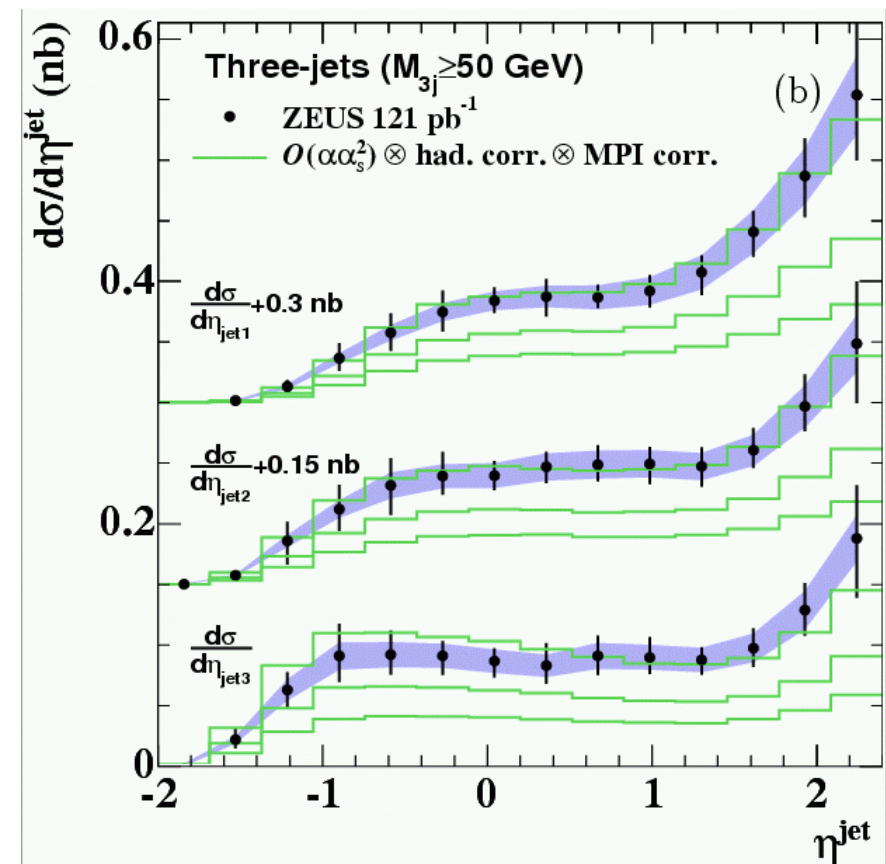
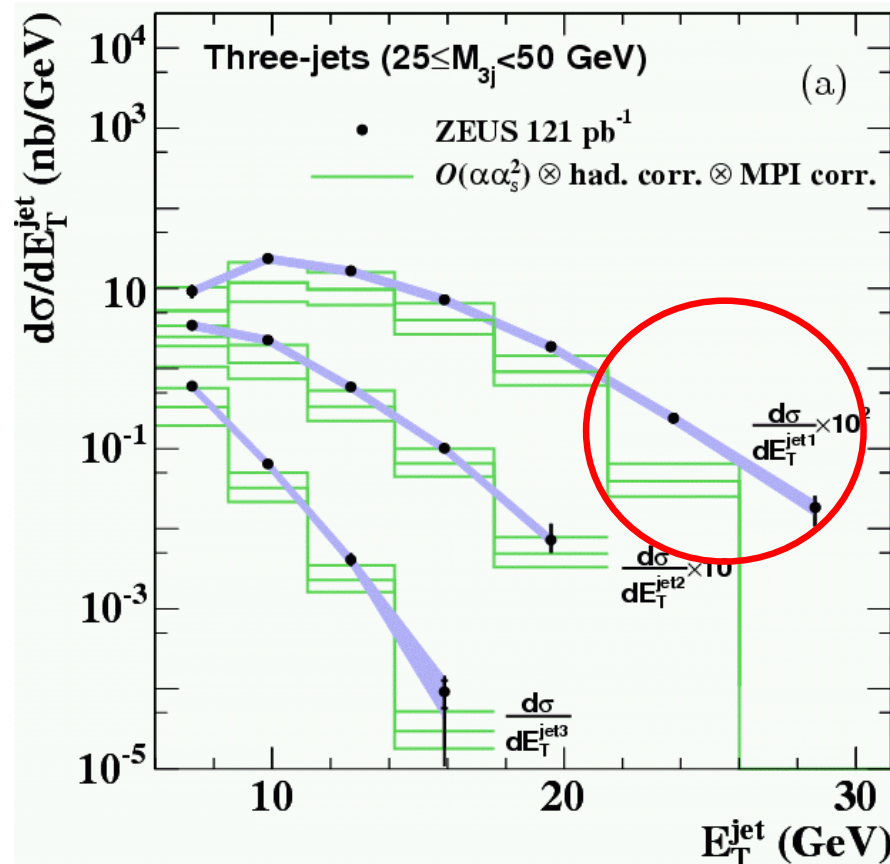
¶ Conclusion

- Without MPI, discrepancy between data and theory would be significantly larger !
- With MPI shape and (within large theory errors!) normalisation correct!



$d\sigma/dE_T$ and $d\sigma/d\eta$ versus NLO

- ¶ $d\sigma/dE_T$: Calculation essentially consistent with data (large errors).
 - Exception: rapid decrease for high E_{T1} in low-mass region (kinematics in NLO).
- ¶ $d\sigma/d\eta$ within large theory errors described by NLO QCD:
 - Description of low-mass data improved by MPI correctons of NLO.
 - especially large η^{lab} (“forward”) “on the edge”.



SUMMARY: ZEUS MULTIJETS

¶ Measurement of multijet cross-sections in photoproduction:

- 3- and 4-jet events with $E_T > 6$ GeV in low- and high-mass region ($M_{nj} <> 50$ GeV)
- 121 pb⁻¹ of ZEUS data from 1996-2000.
- first measurement of 4-jet cross-sections in photoproduction.

¶ Description of data by MC models

- In high-mass region both PYTHIA and HERWIG without MPI describe shape of data.
- In low-mass region, models without MPI undershoot data when normalised to high-mass data points.
- Inclusion of MPI in models generally improves description of data.

¶ $O(\alpha_s^2)$ QCD calculations

- effectively LO for 3-jet cross-sections.
- Theory consistent with three-jet data – within large theory errors.
- MPI corrections (determined from MC) typically improve description.

CONCLUSIONS AND OUTLOOK

¶ MPI / UE studies at HERA:

- ZEUS: multijets in photoproduction; H1: minijets in DIS
- MPI / UE contributions to MC models improves description of data.
- we need something in addition to ‘normal’ MCs – unclear what. Also at LHC there could be more than just MPI – need to study thoroughly, HERA ideal for that!

¶ Ongoing studies at HERA:

- energy flow, particle multiplicities in azimuthal regions as fct of leading jet E_T in PHP.
- Underlying event in jets + heavy quarks events.
- Minijets in PHP
- More multijet measurements in PHP and DIS

¶ Outlook, complaint and wishes:

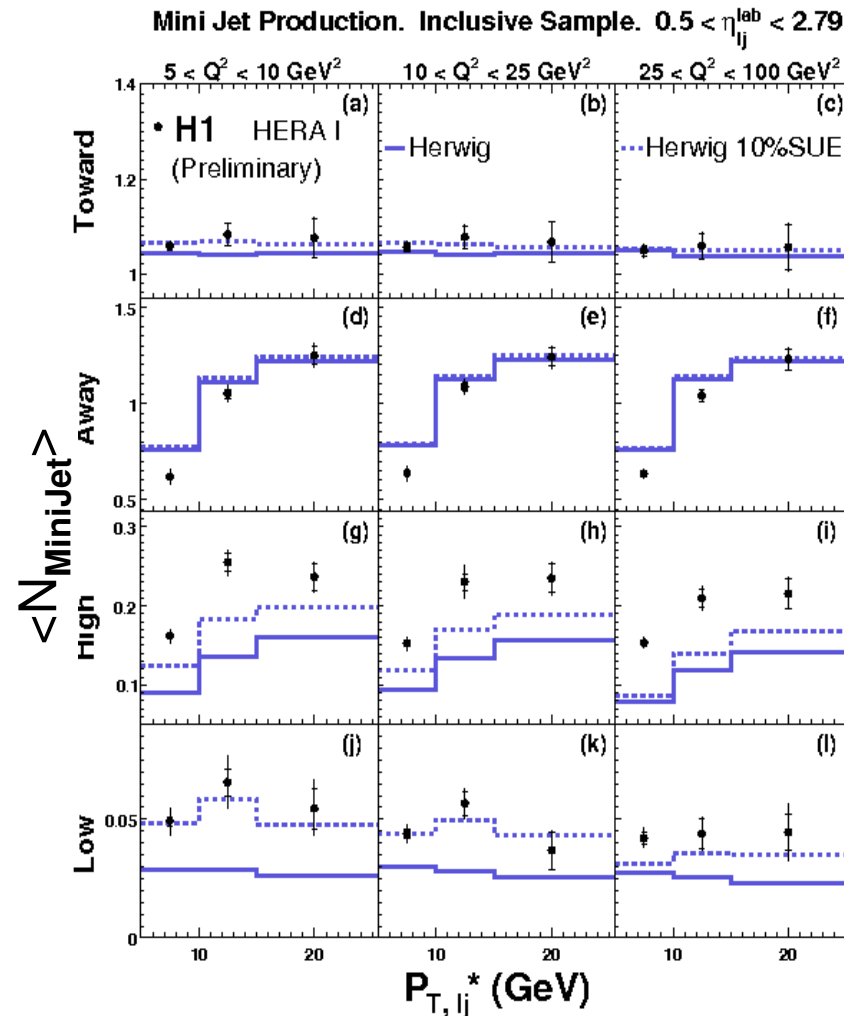
- Measurements of UE / MPI will be among the first to be carried out at the LHC.
- large extrapolation uncertainties → HERA data valuable to pin down underlying mechanisms and rule out models.
- Seemingly low interest from model makers to update MCs for ep:
 - e.g. we want the impact-parameter model also for HERA data (simple model shown to not describe the Tevatron data, and model uncertainty dominant at HERA)!

BACKUP

H1 ANALYSIS: INCL. SAMPLE: FORWARD

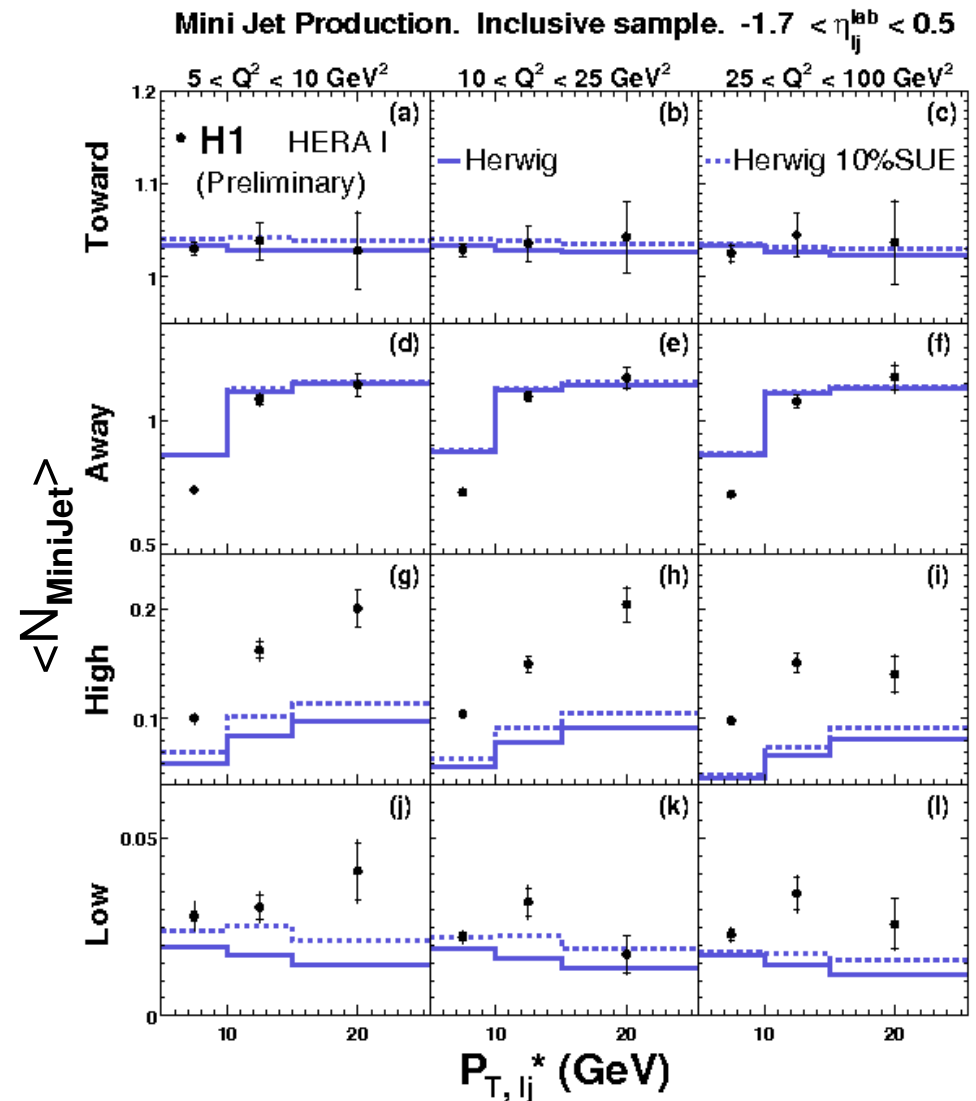
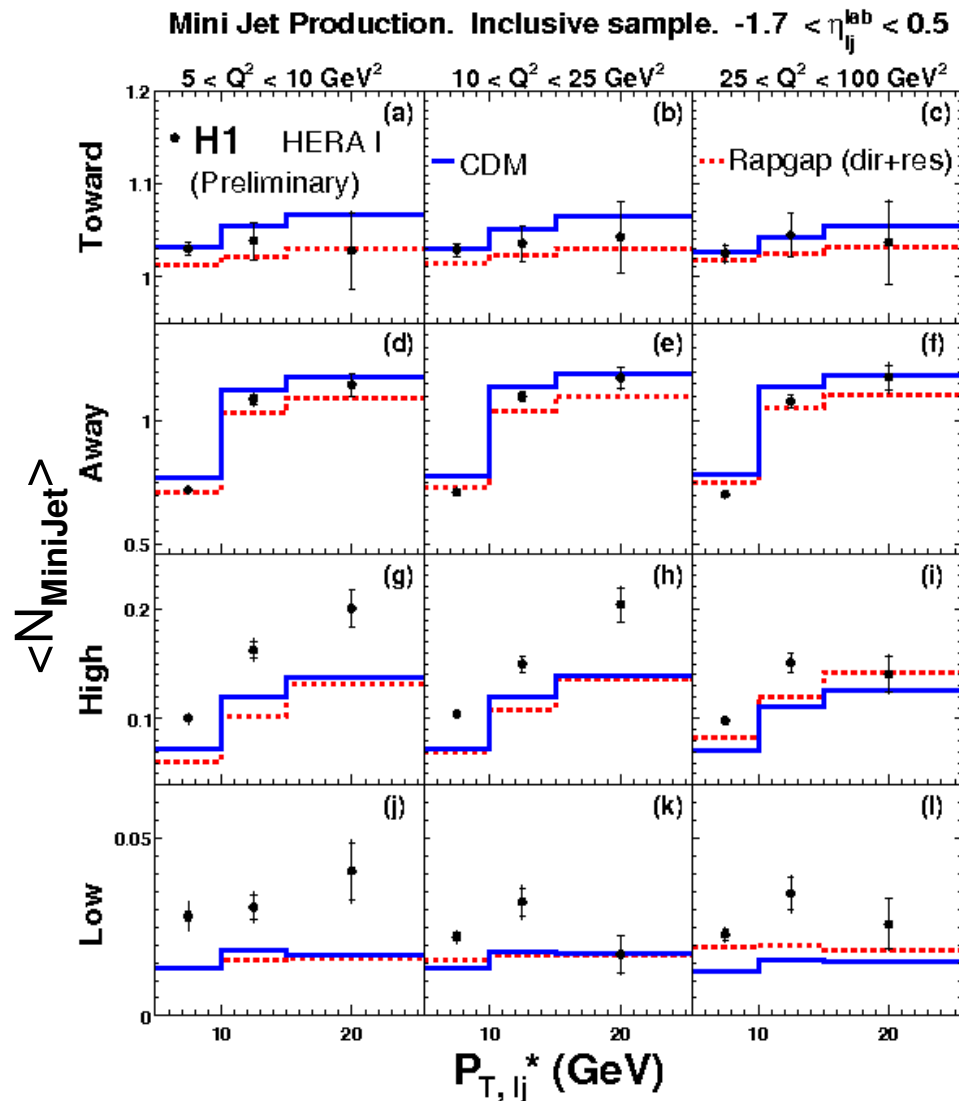
¶ HERWIG + 10% SUE (~minimum bias)

- No real physics justification for the 'model' (UA5).
- Increases predictions at low Q^2 , low-activity region.



H1 ANALYSIS: INCL. SAMPLE: BACKWARD

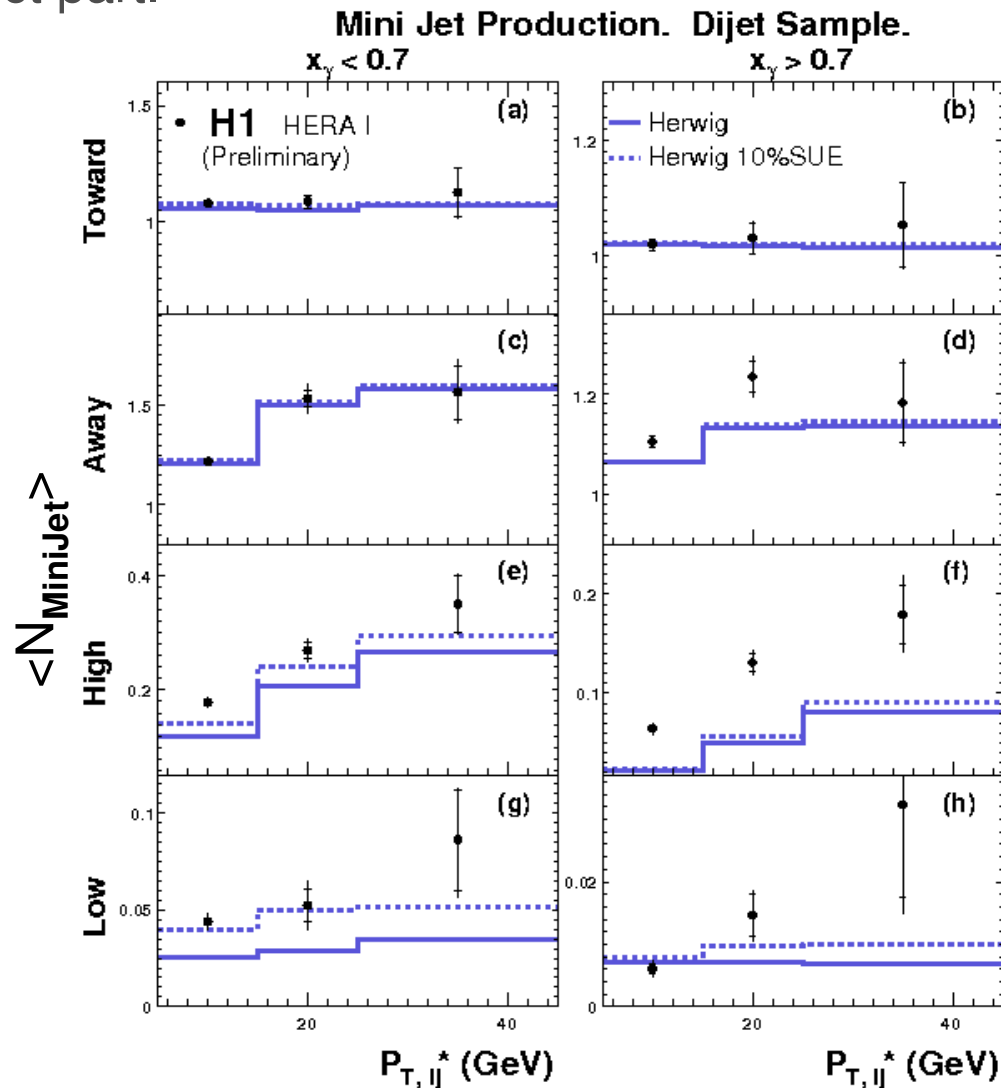
¶ CDM, RAPGAP, HERWIG+SUE: Problems for high-activity region



H1 ANALYSIS: DIJET SAMPLE: HERWIG+SUE

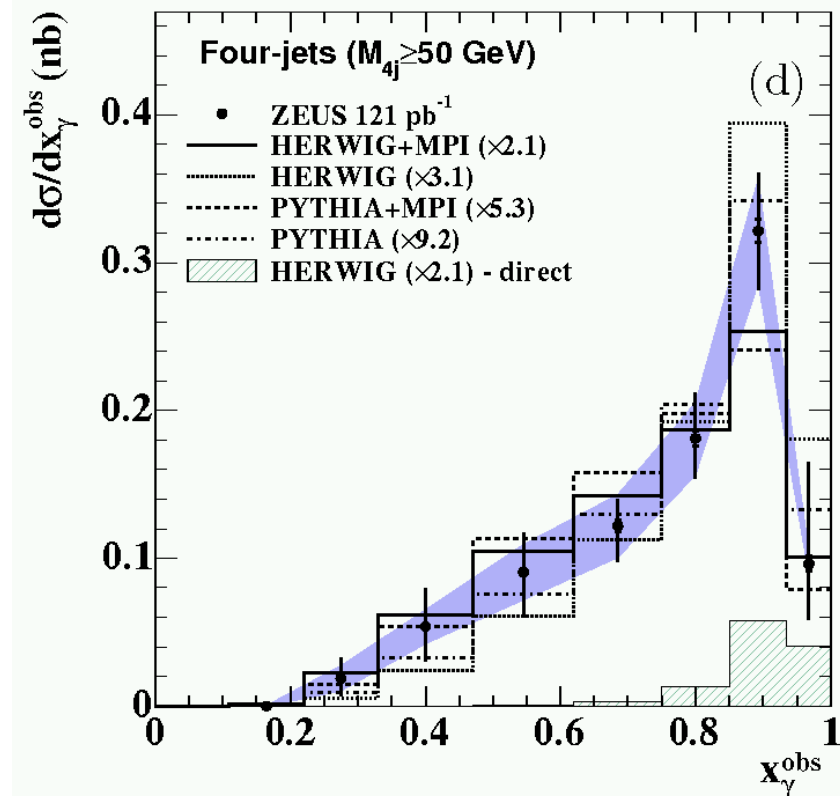
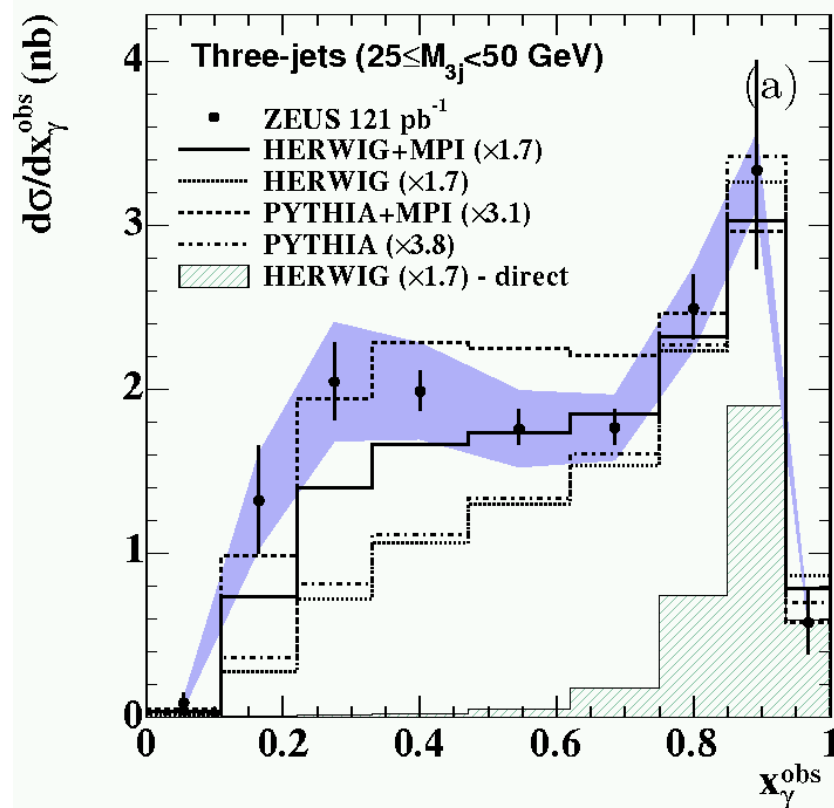
HERWIG + 10% SUE

– Problems for direct part.



$d\sigma/dx_Y$

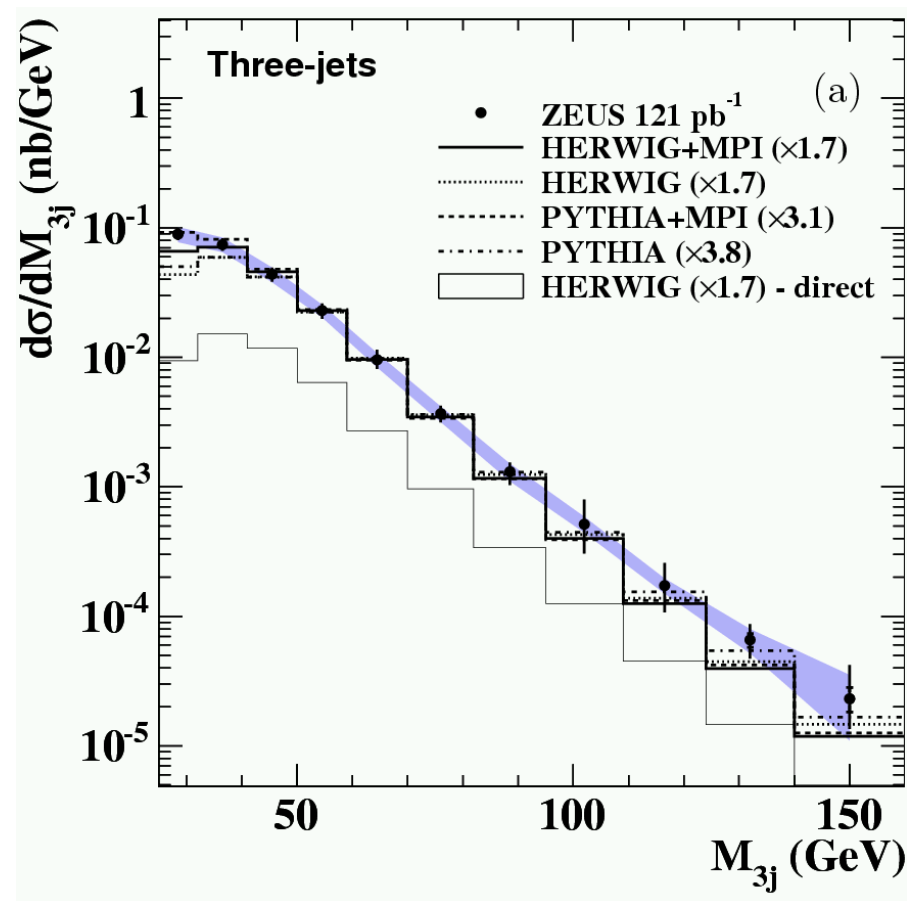
- ¶ x_Y separates resolved- from direct-dominated subsamples:
 - Models without MPI suggest decreasing cross-sections with decreasing x_Y .
 - But for low masses large discrepancy with INCREASING data
 - mechanism beyond direct+resolved as modelled in MC necessary.
 - Even “direct” region ($x_Y > 0.75$) dominated by resolved events (\leftrightarrow dijets!).
 - Especially HERWIG+JIMMY describes data well.



$d\sigma/dM_{njet}$ (3-jet events)

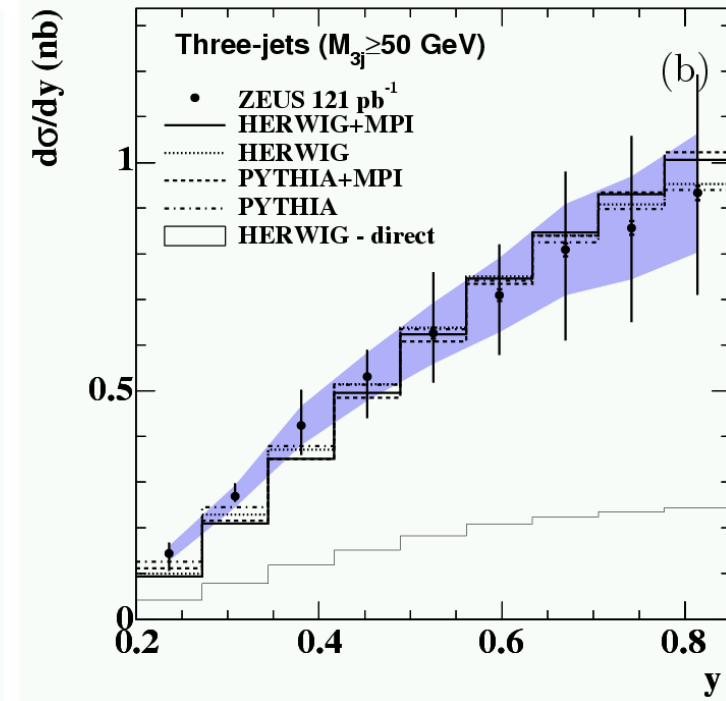
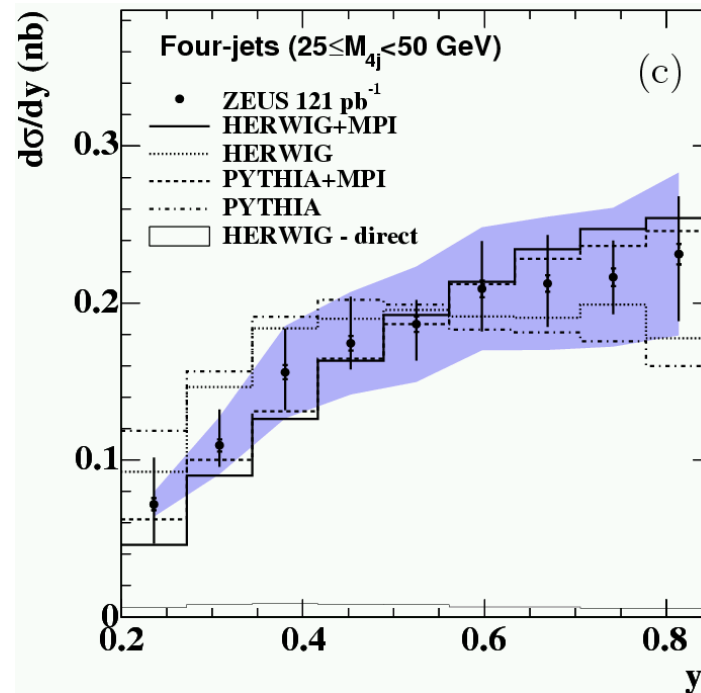
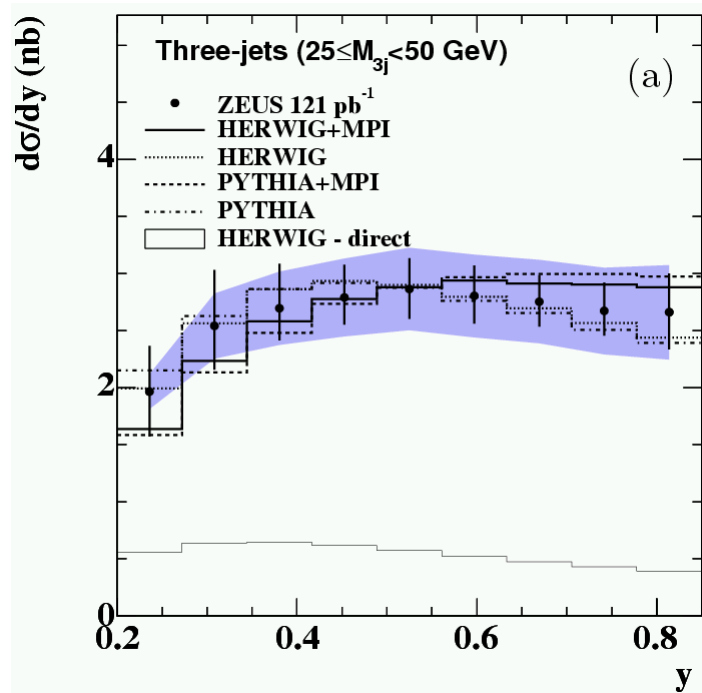
¶ Need MPI/UE simulations to correctly describe the data:

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- Effect larger for four-jets than for three-jets.



$d\sigma/dy$

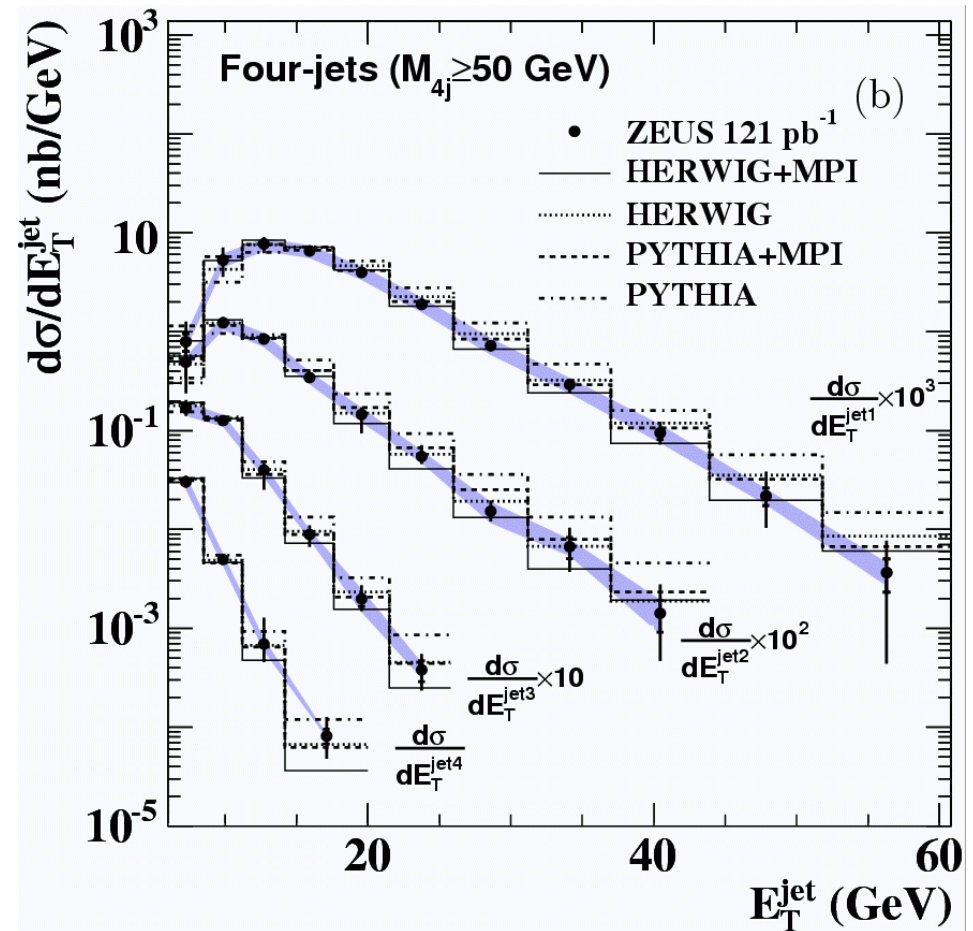
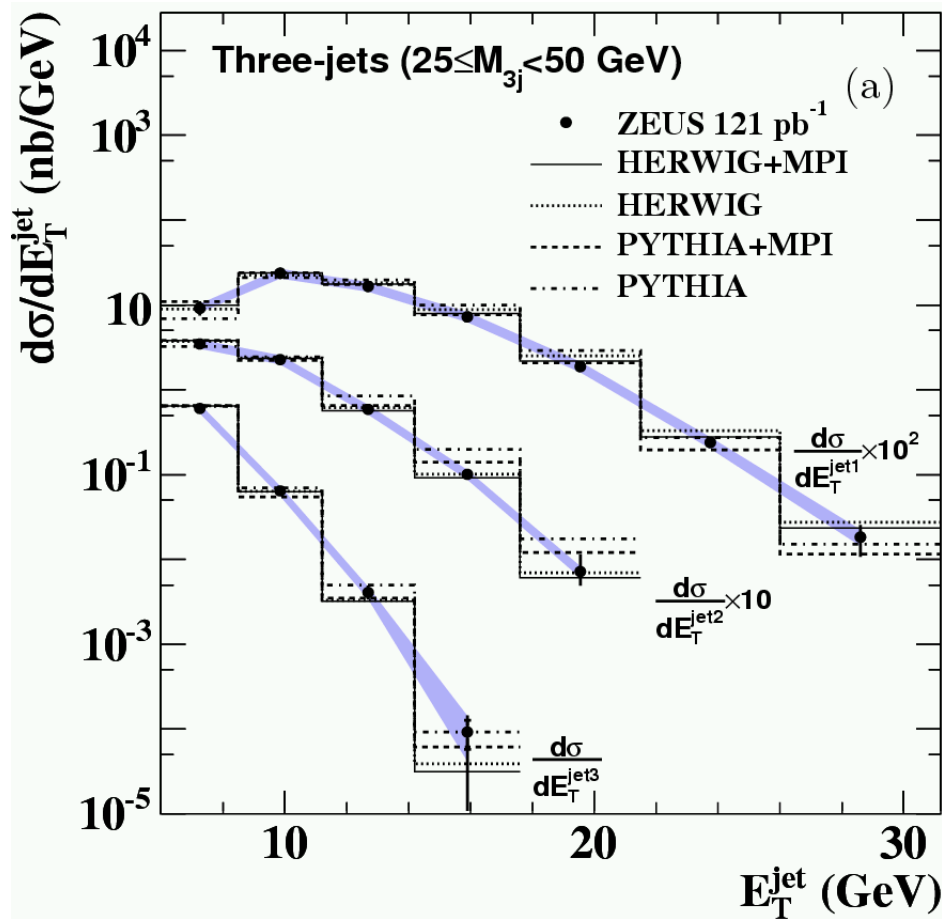
- ¶ ... for three- and four-jets and high and low multijet masses.
- Behaviour dictated by phase-space and photon flux energy distribution.
- All distributions except low-mass three-jet rise strongly with increasing y .
- At high masses only small differences between models with and without MPI.
- At low masses, MPI models predict steeper rise of distribution.



$d\sigma/dE_T$

¶ Jets are ordered in transverse energy E_T .

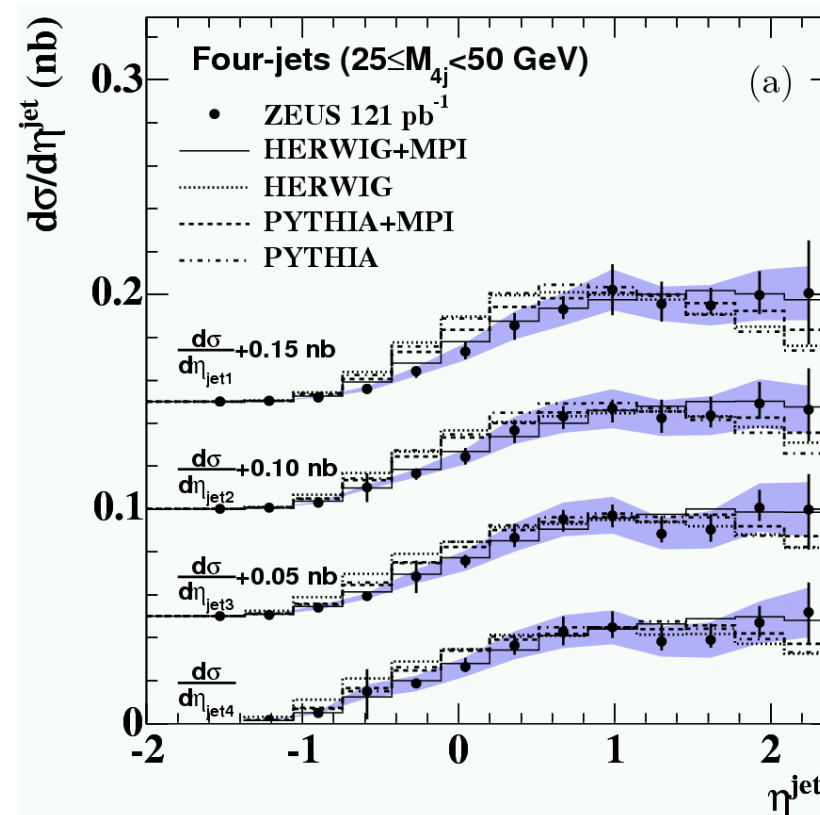
- in general all models describe the data somehow.
- Inclusion of MPI into the simulations improves the description.



$d\sigma/d\eta$

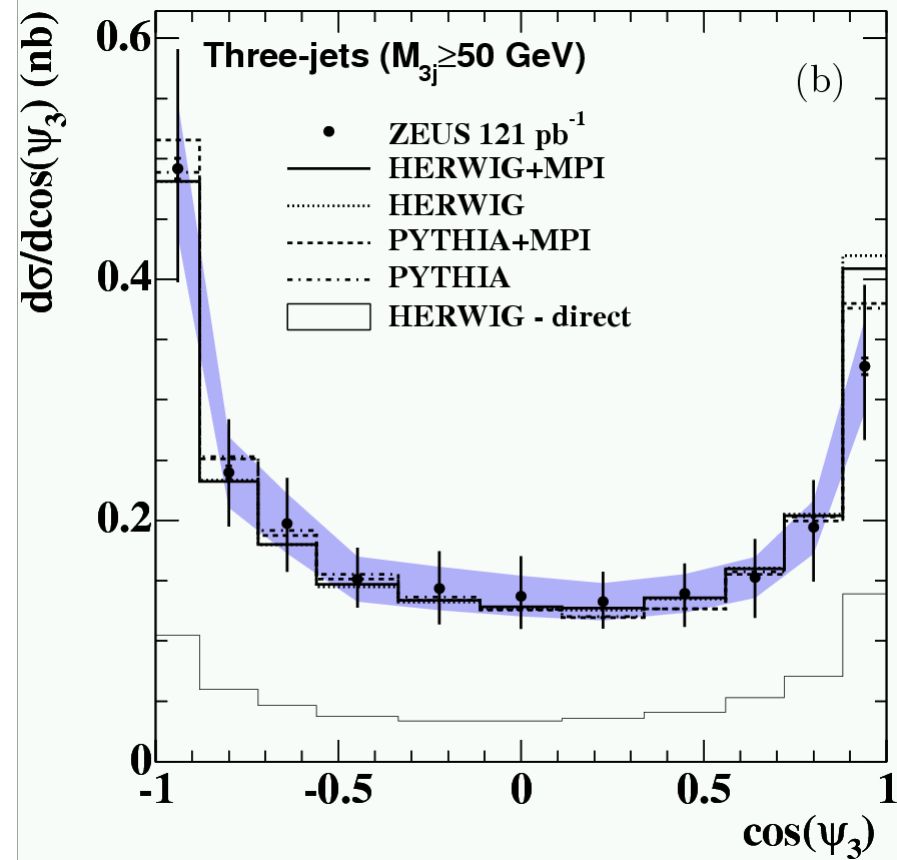
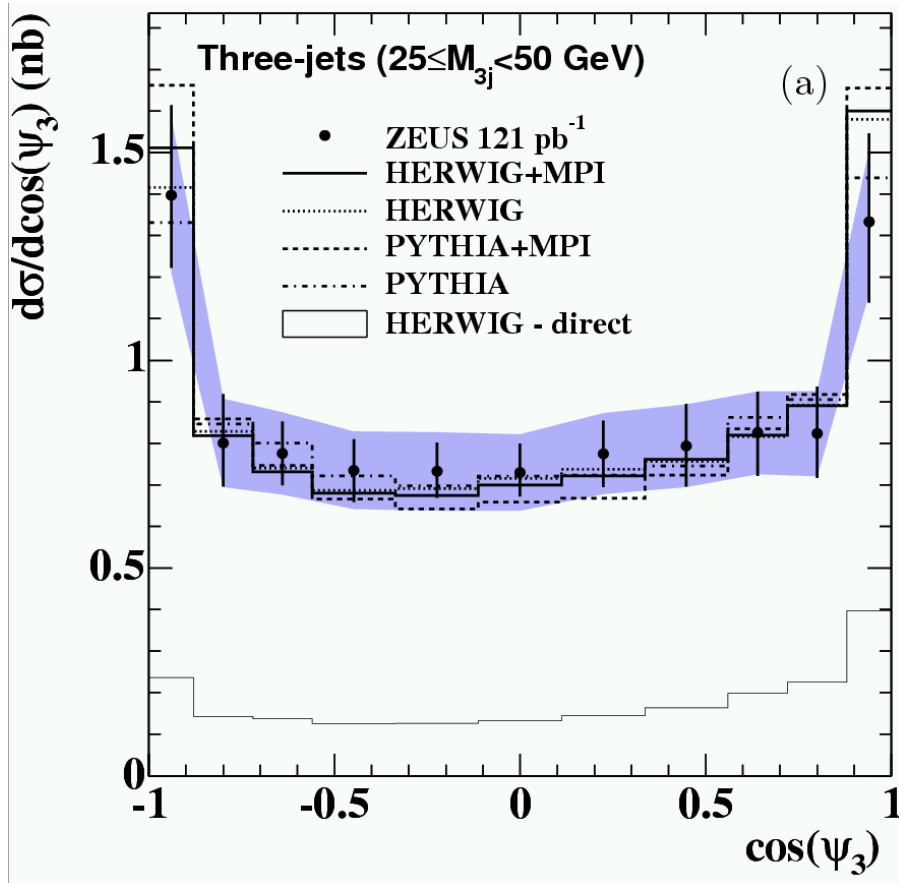
¶ Same shape for all jets, independent of their place in E_T ordering

- High-mass data described by all models (not shown)
- Best description of low-mass data by HERWIG+JIMMY.
- Models with MPI suggest decrease of cross-section at high η^{lab} ; MPIs reduce this effect in line with measurement.



MULTIJETS: $d\sigma/d\cos\Psi_3$ three-jets

¶ data well described by all MC models.



$d\sigma/d\cos\Psi_3$ versus NLO

¶ Theory: $O(\alpha_s^2)$

¶ Corrections of theory

- hadronisation: small and flat
- MPI: flat.
- smaller theory uncertainties!

¶ Conclusion

- MPI-corrected NLO calculation consistent with data in both high- and low-mass regions.

