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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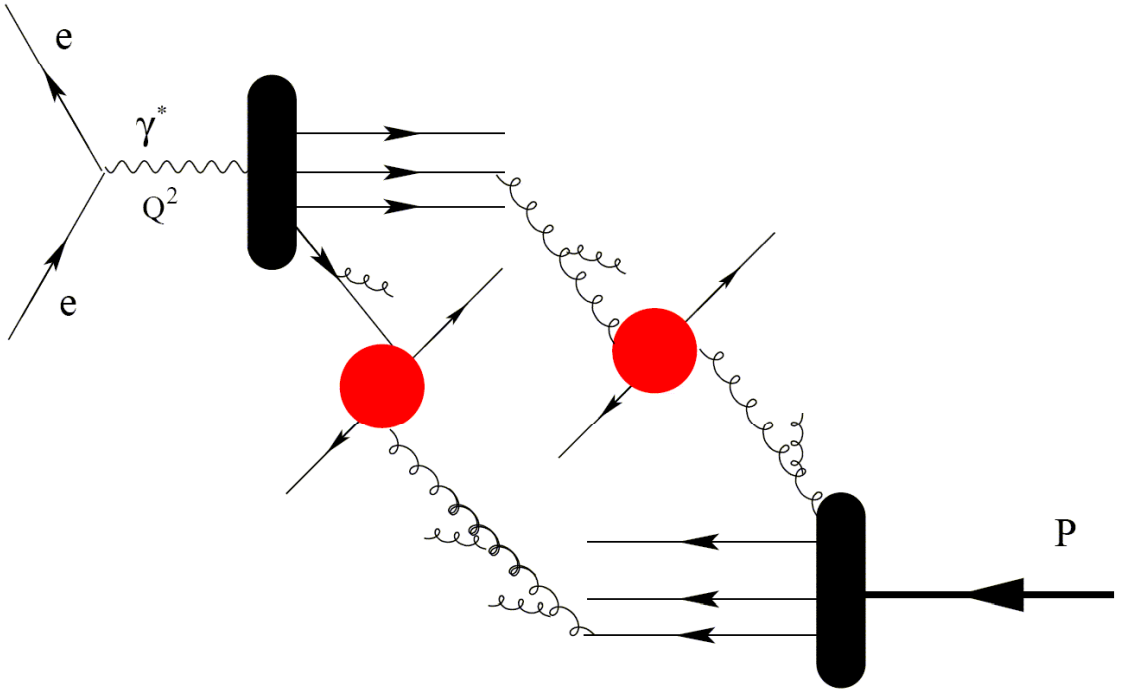
OVERVIEW

- 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
- …

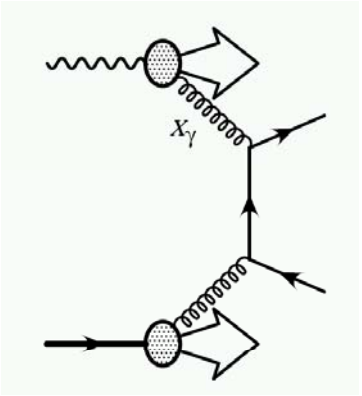


➔ UE / MPI lead to additional activity in hadronic final state
- affects measurements in hadron-hadron collisions (jets, QCD backgrounds, …)!
- theoretically interesting and challenging (mechanism not understood)!

UE AND MPI: EXPERIMENTAL TESTS

¶ Multijet cross-sections (in PHP and DIS)

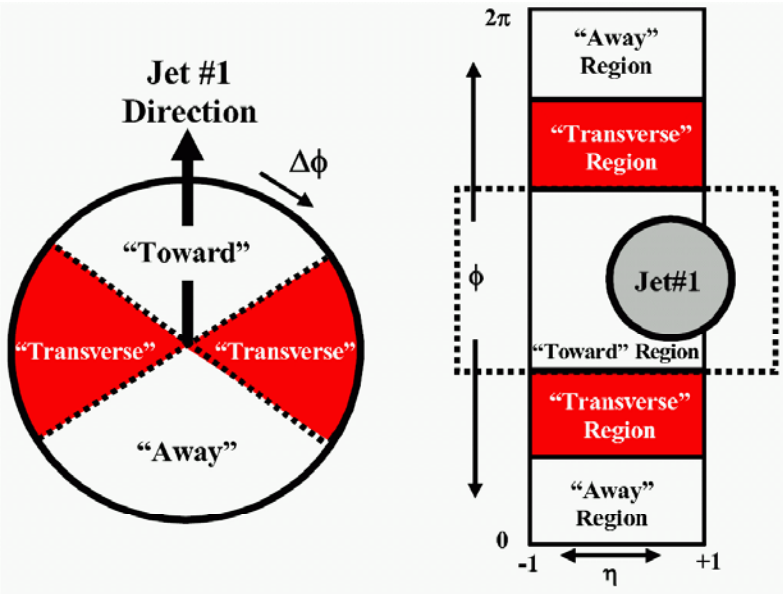
- Which model fills gap between data and MC (mainly resolved-photon regime defined by observable x_γ, hadron-hadron-like!)
- Origin of third, fourth jet: Radiation? MPI?
- If ≥3 jets used, sample dominated by resolved events.



¶ 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!

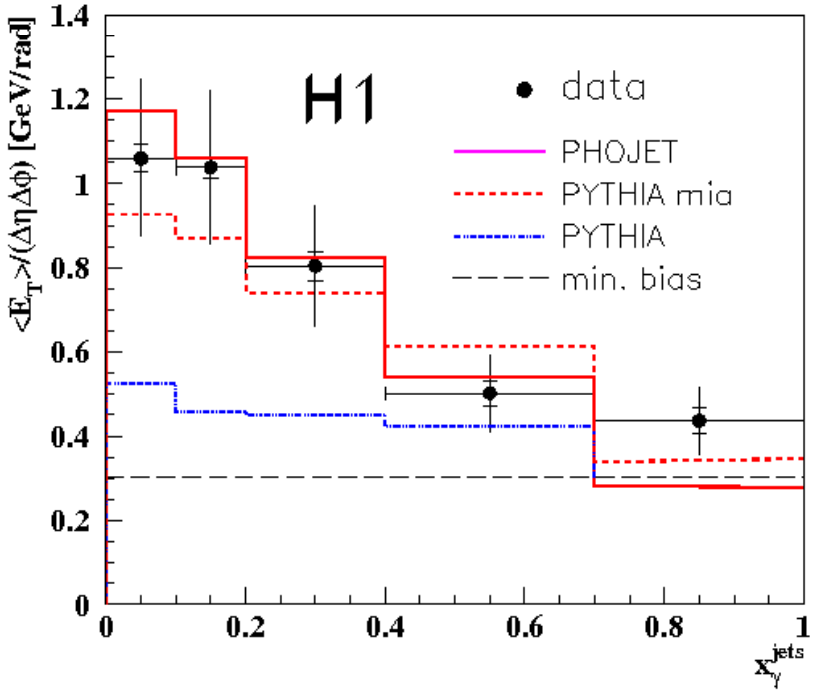


UE/MPI NECESSITY 1

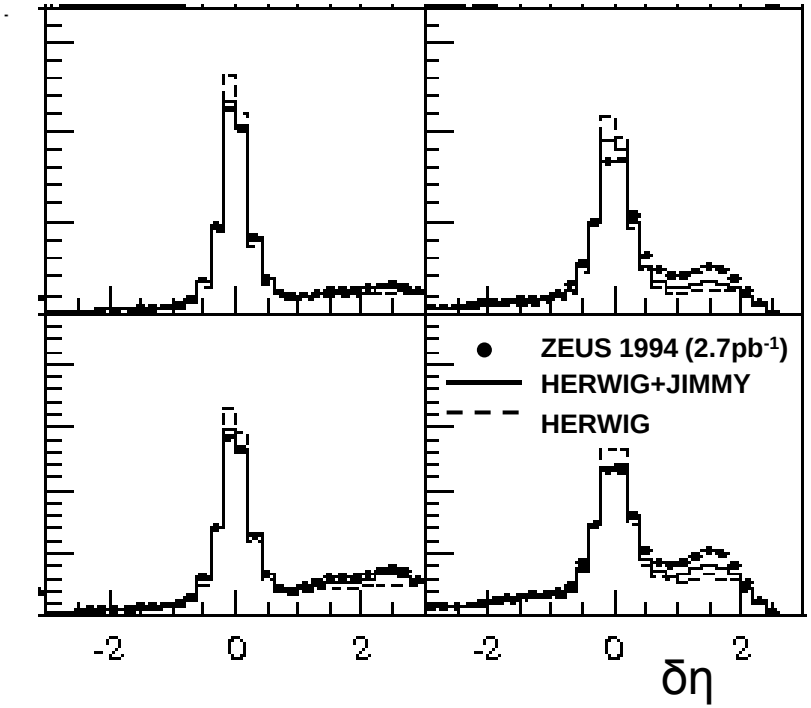
¶ Various measurements demonstrate necessity of UE/MPI

– Photoproduction dijets at HERA,

- H1: ZP C70 (1996) 17
- ZEUS: EPJ C1 (1998) 109



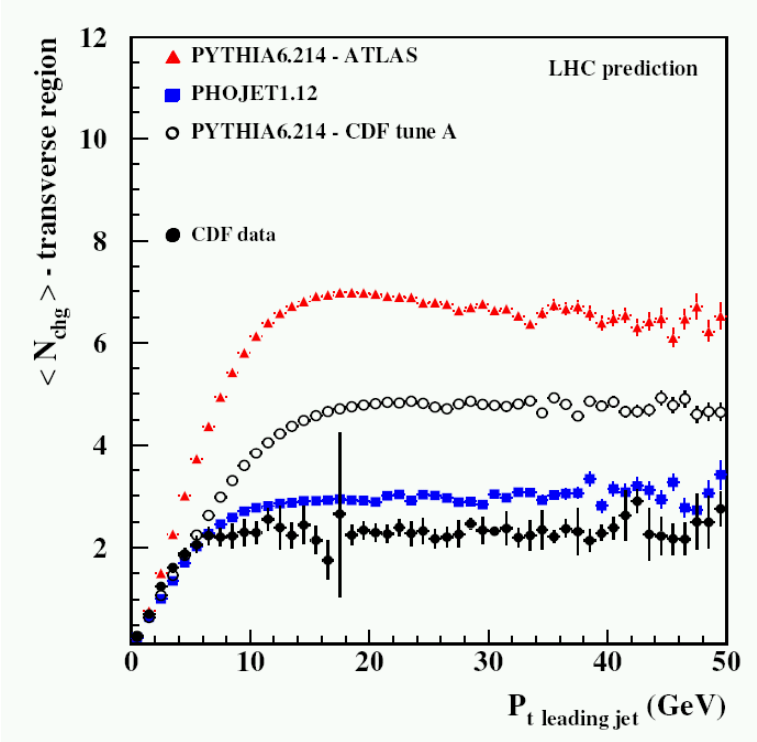
$$x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2E_\gamma}$$

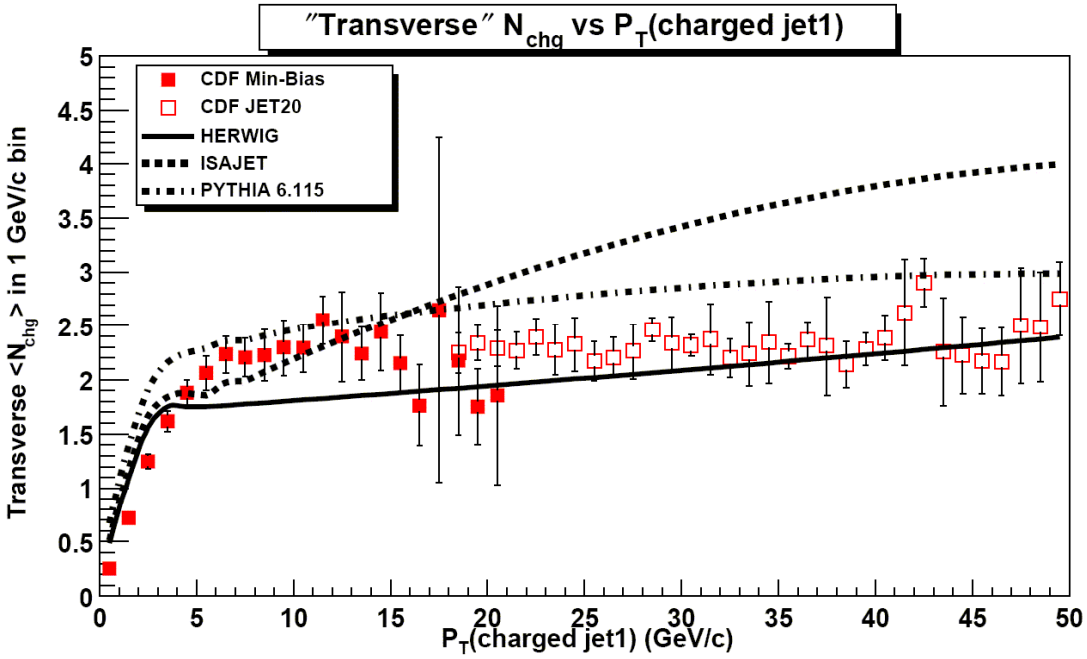


Jet profiles: energy flow relative to jet axis in different η regions

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→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→2 cross-section to all events, choose number of interactions according to precalcuted 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: $5 < Q^2 < 100$ GeV^2, $0.1 < y < 0.7$, $W > 200$ GeV.

– Jets: $-1.7 < \eta^{lab}_{1(,2)} < 2.79$ $p_{T1(,2)} > 5$ GeV ($|\varphi_1 - \varphi_2| > 140^o$).

– Mini jets: $-1.7 < \eta^{lab}_{1(,2)} < 2.79$ $p_T > 3$ GeV

¶ Data compared to various models

– PYTHIA with MPI (simple scenario without impact-parameter dependence)

– ARIADNE (CDM)

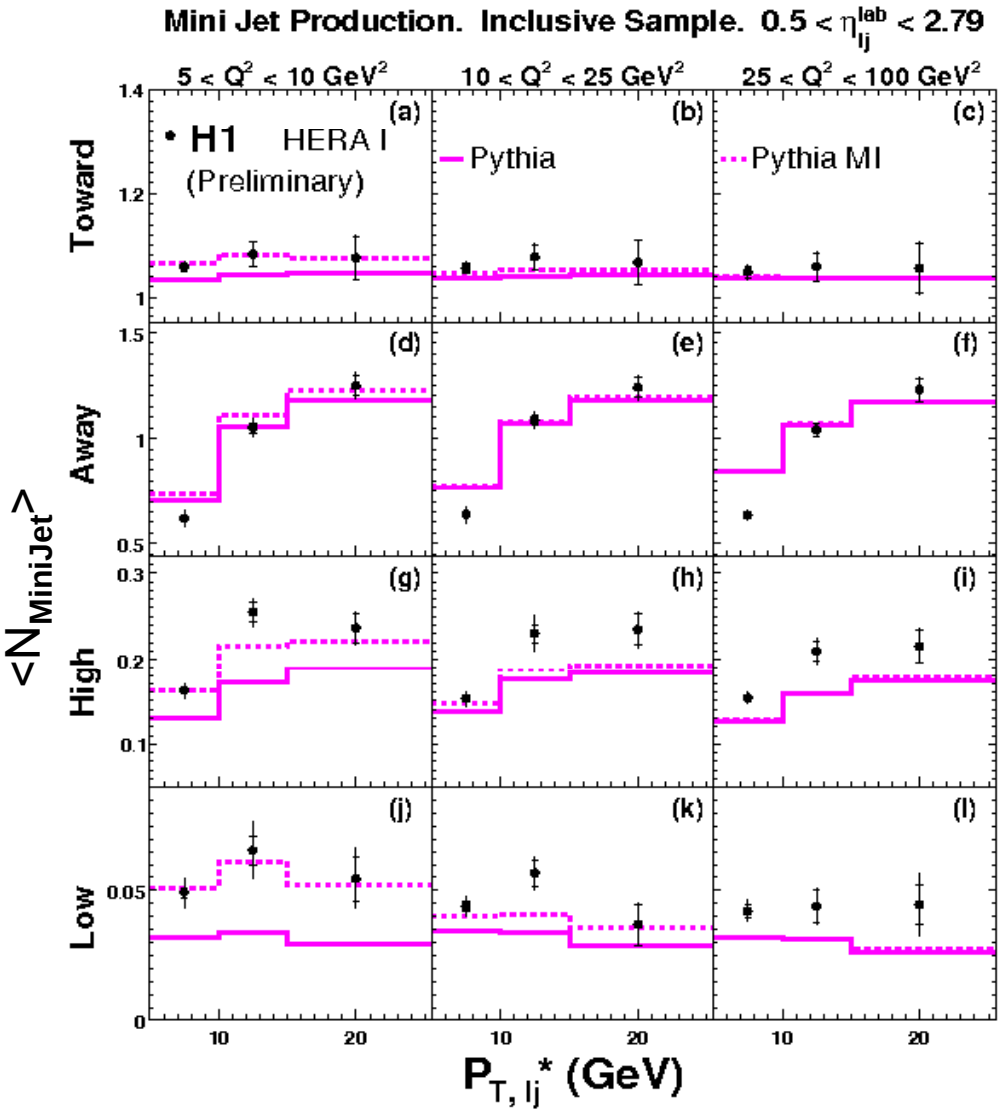
– RAPGAP direct and direct+resolved γp interactions

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.

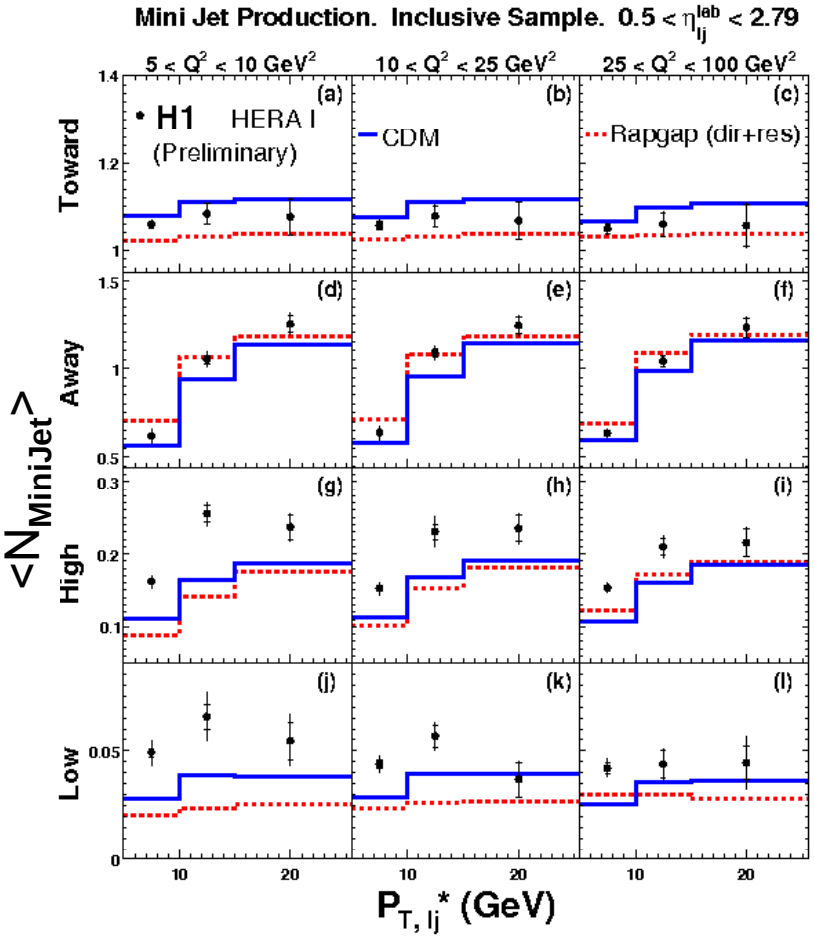
¶ High activity transverse region
- no MPI/SUE: MC too low.
- PYTHIA + MPI: okay at low Q^2. (at high Q^2 missing contributions)

¶ Low activity transverse region
- no UE/MPI: MC too low (low Q^2!).
- PYTHIA+MPI: okay.



H1: INCL. SAMPLE FORWARD: CDM, RAPGAP

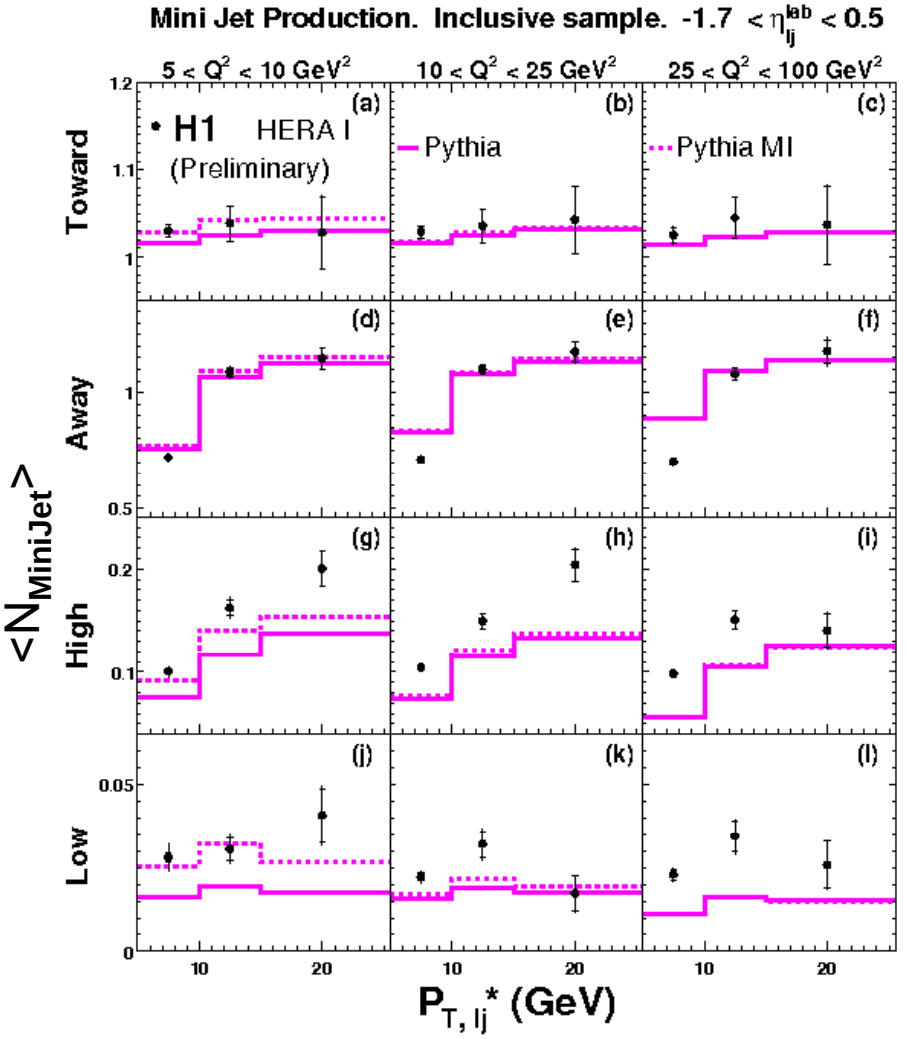
¶ towards+away fine like PYTHIA
- … but too low in transverse regions.



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.

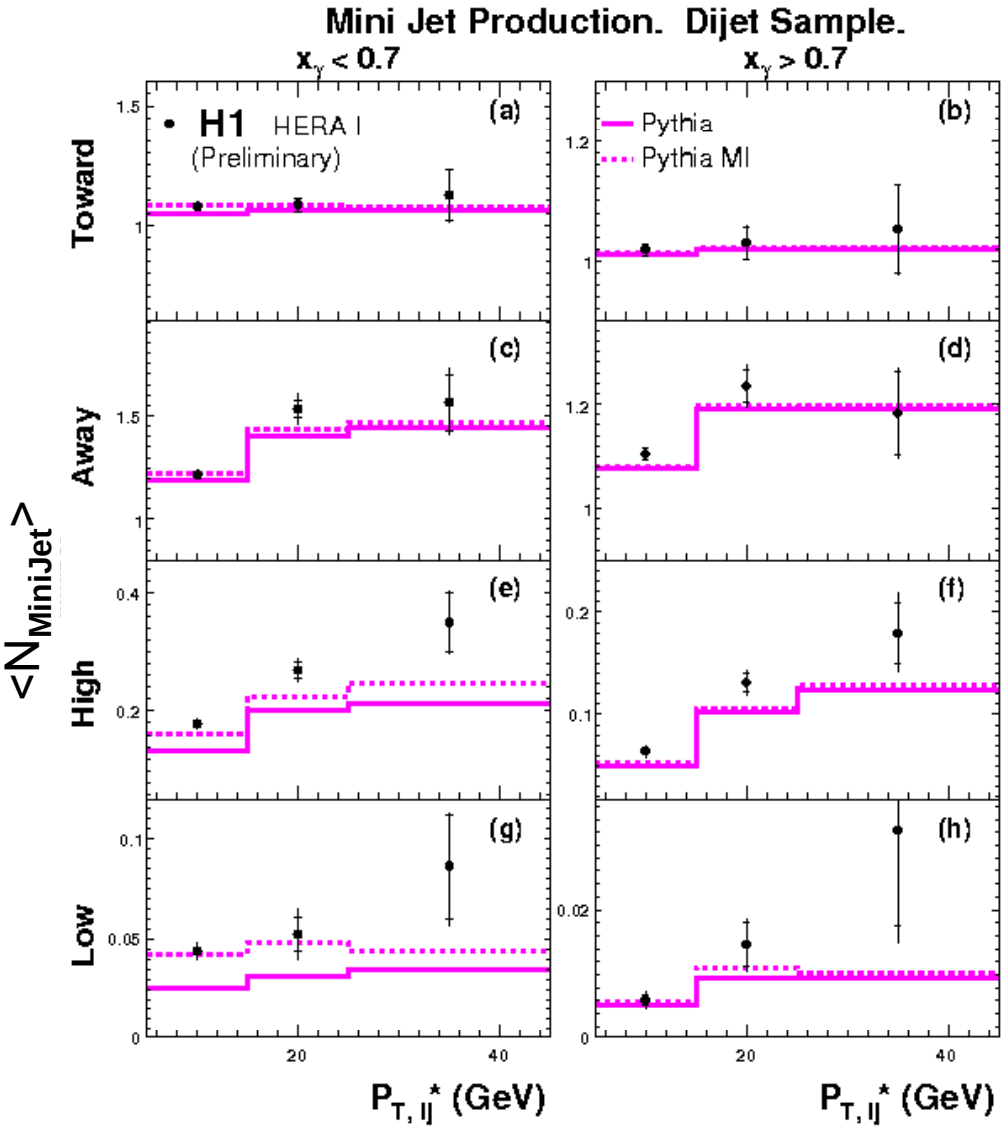


H1: DIJET SAMPLE: PYTHIA

¶ Towards and Away regions
- all models with and without UE/MPI can describe the data.

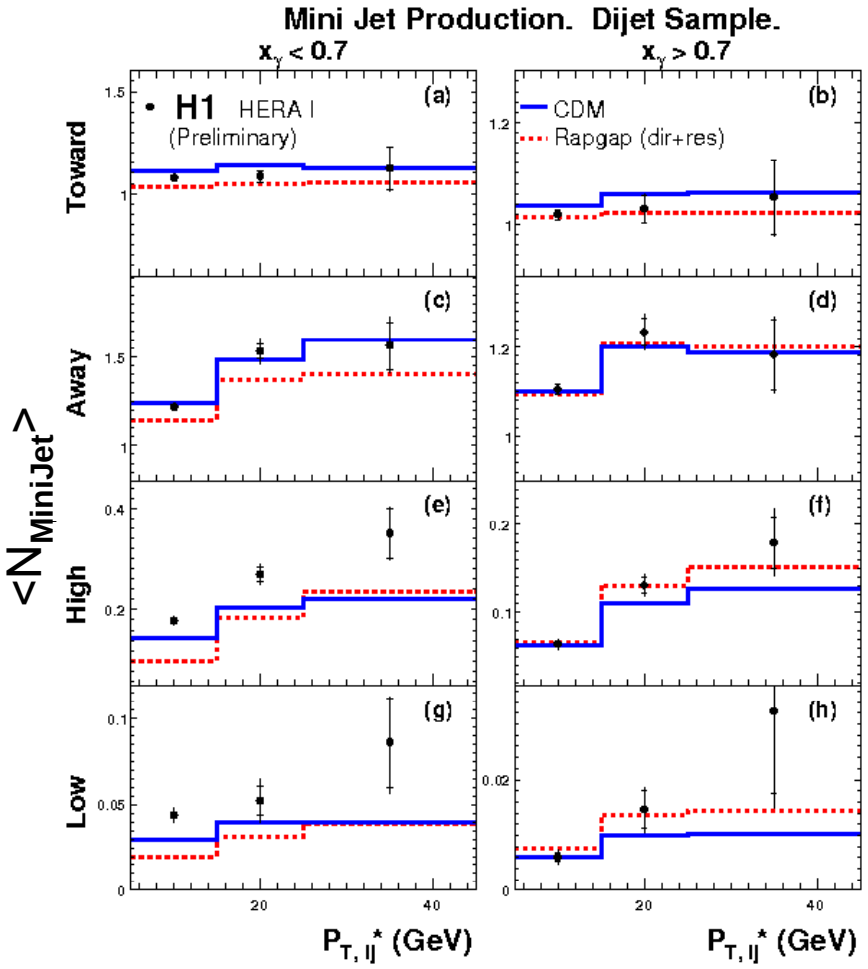
¶ High-activity region
- data generally above the models
- PYTHIA similar for direct and resolved; little UE influence

¶ 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, $\eta_{leading}$.

¶ Models without UE/MPI contributions
- work well in towards / away regions → 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: $0.2 < y < 0.85$, $p_{T,miss}/\sqrt{ET} < 2$ $GeV^{1/2}$, no electron cand.
– Jets: 3 or 4 jets with $E_T \geq 6$ GeV, $\eta < 2.4$
– low-mass region: $25 \leq M_{njet} \leq 50$ GeV, high-mass region: $M_{njet} \geq 50$ GeV

¶ Models for comparison:

– HERWIG 6.505 + JIMMY 4.0
– PYTHIA 6.206 + “simple” MPI model

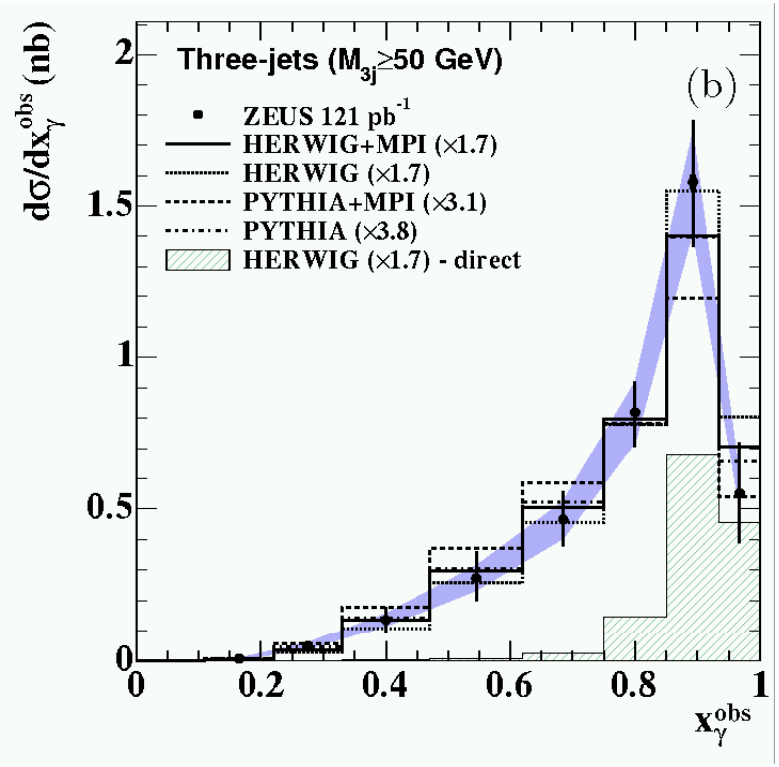
→ Both MC underestimate cross-section → scale to match total cross-section or high-mass part of distribution, depending on observable!

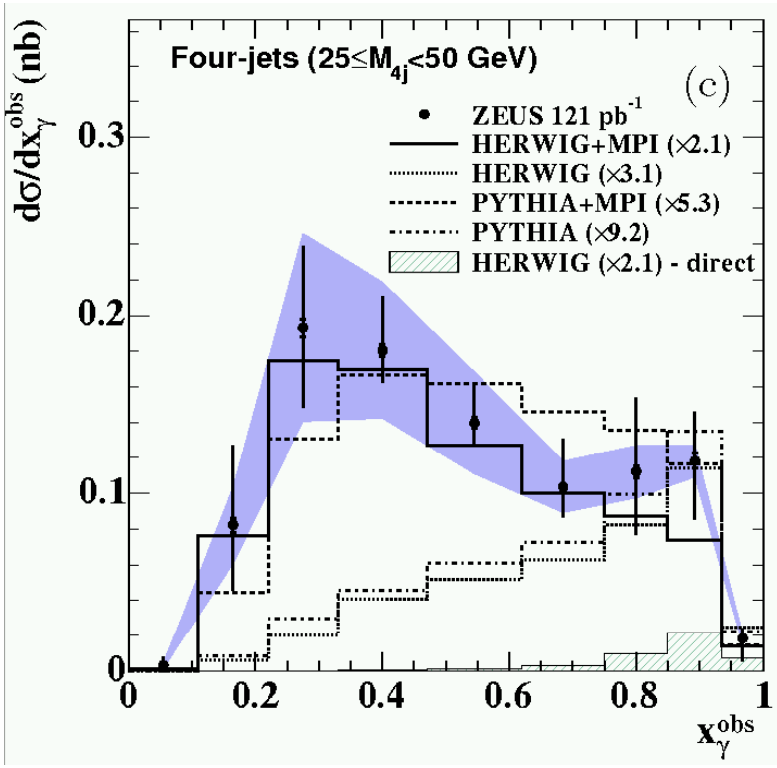
In addition: NLO QCD calculation from Klasen et al. for the three-jet case.
(effectively LO since NLO for dijet case!)

$d\sigma/dx_\gamma$

¶ 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 (↔dijets!).
- Especially HERWIG+JIMMY describes data well.
- Note large systematic uncertainties: Model dependence

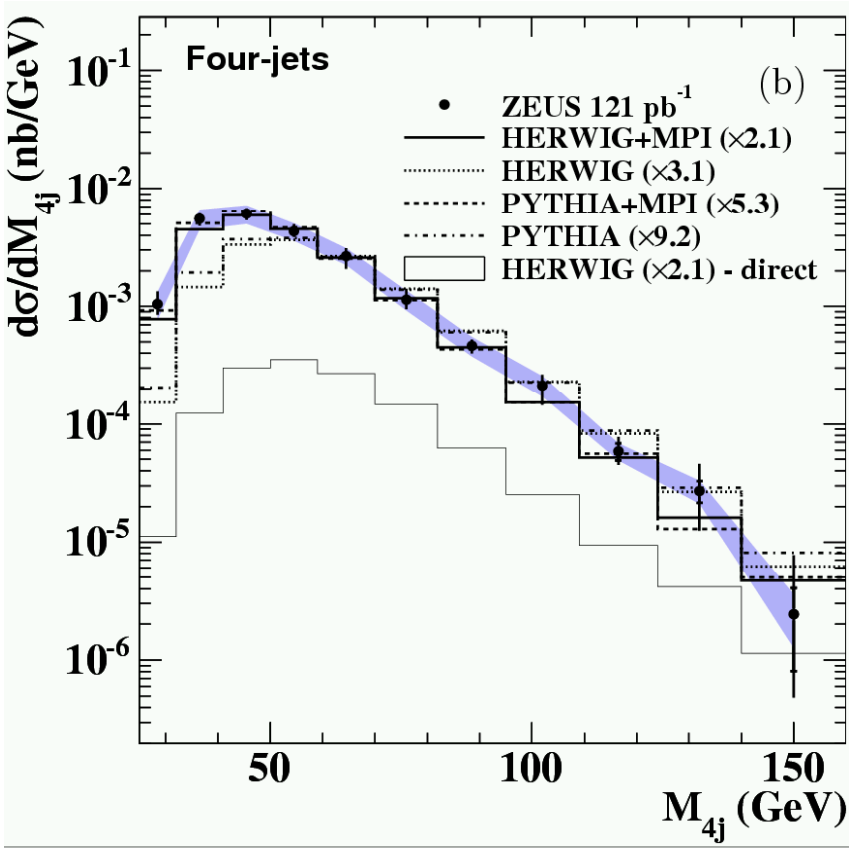




$d\sigma/dM_{njet}$ (4-jet events)

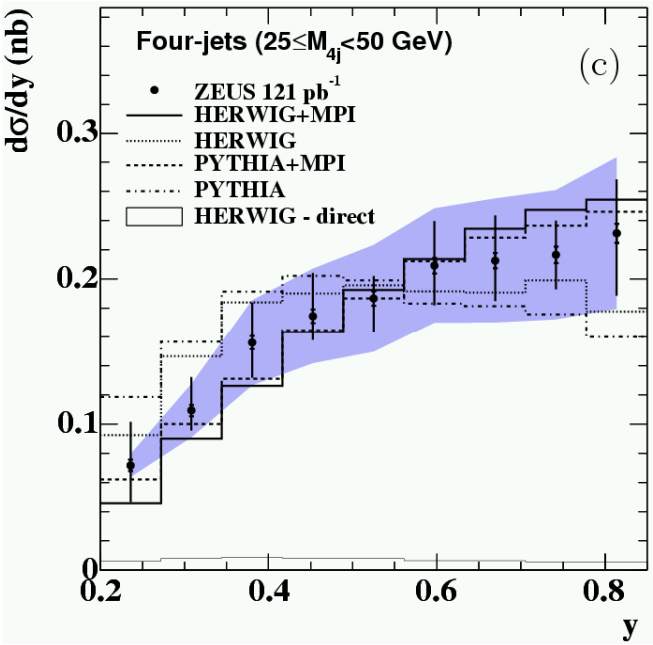
¶ Need MPI/UE simulations to correctly describe the data:

- 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)



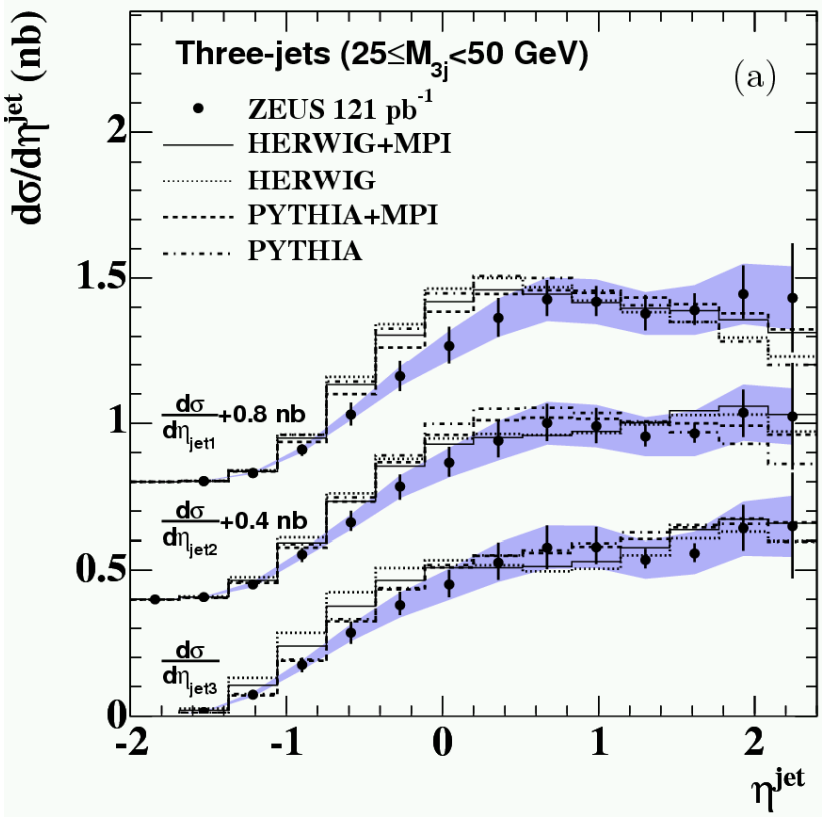
dσ/dy

- … 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.



dσ/dη

- 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.

$d\sigma/dM_{jj}$ versus NLO

¶ Theory: $O(\alpha\alpha_S^2)$

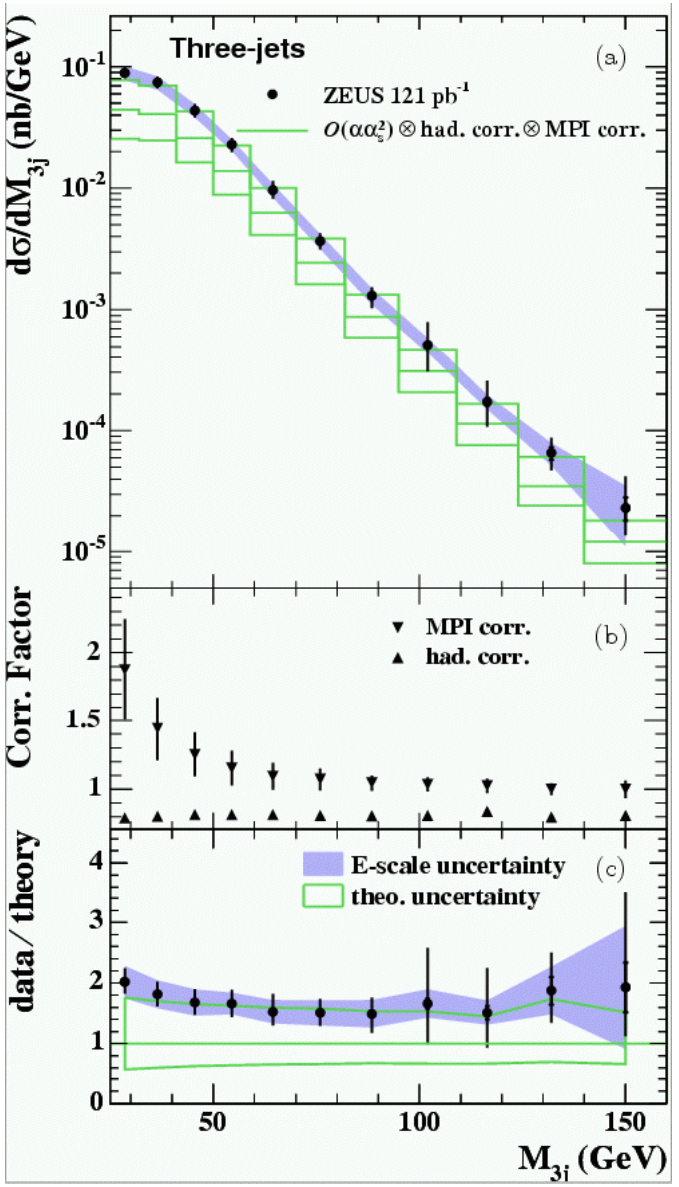
- NLO for dijets in photoproduction
- effective LO for three-jets
- no calculation of MPI effects (need to be corrected for)

¶ 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

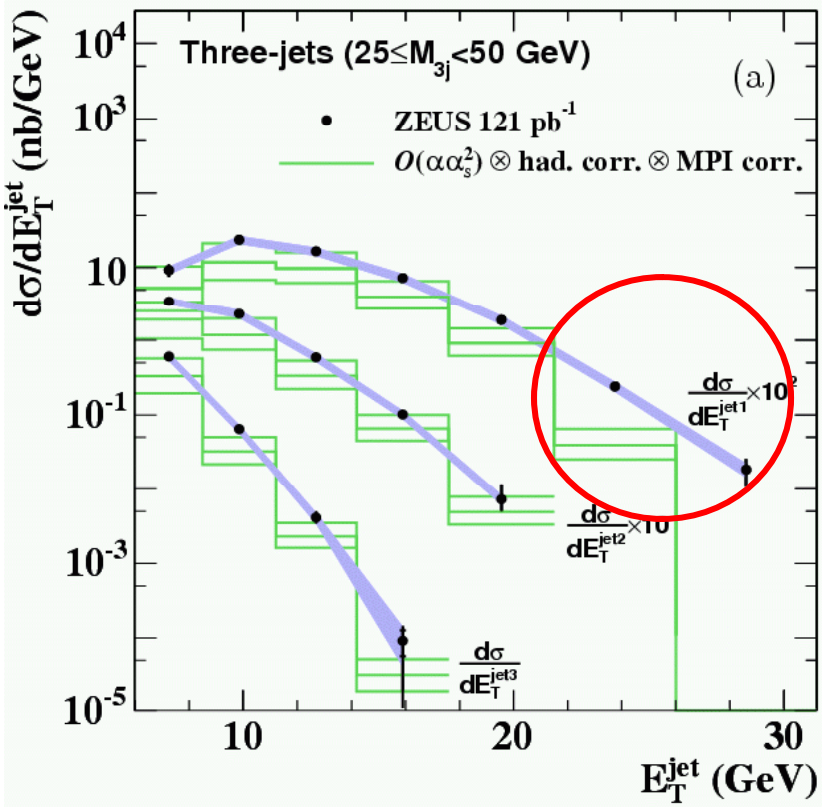
- Without MPI, discrepancy between data and theory would be significantly larger !
- With MPI shape and (within large theory errors!) normalisation correct!

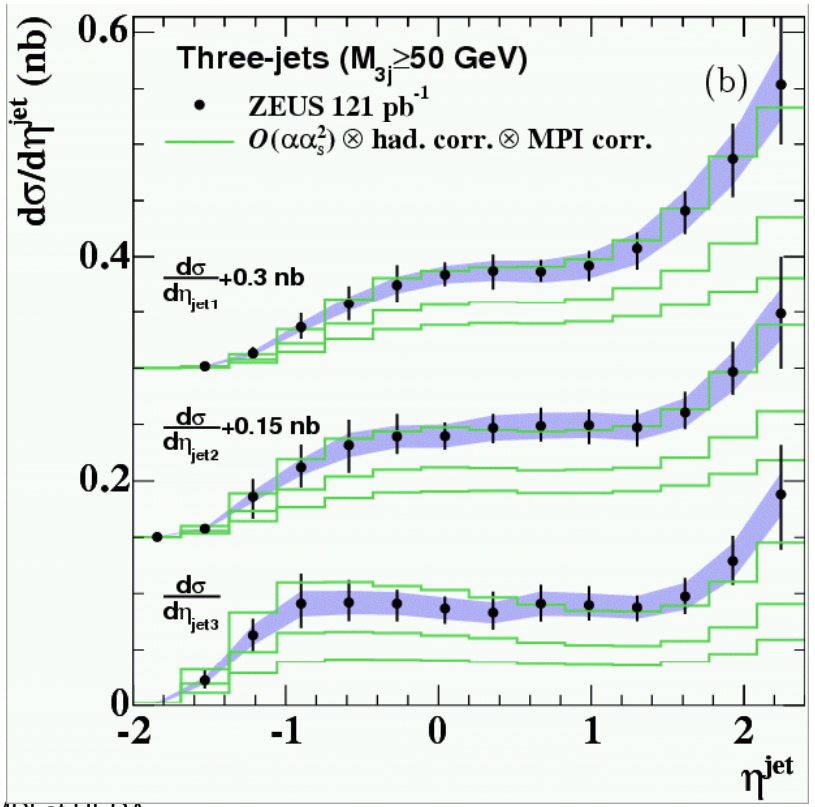


$d\sigma/dE_T$ and $d\sigma/d\eta$ versus NLO

¶ $d\sigma/dE_T$: 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.

¶ $O(\alpha\alpha_S^2)$ 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)!

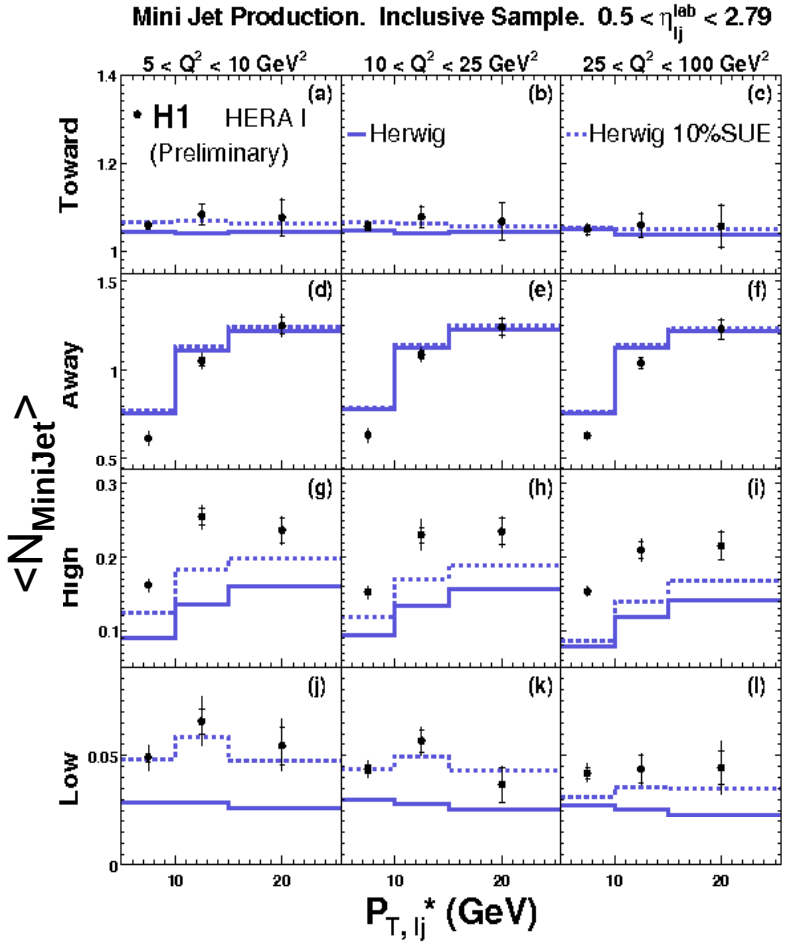
BACKUP

H1 ANALYSIS: INCL. SAMPLE: FORWARD

¶ HERWIG + 10% SUE (~minimum bias)

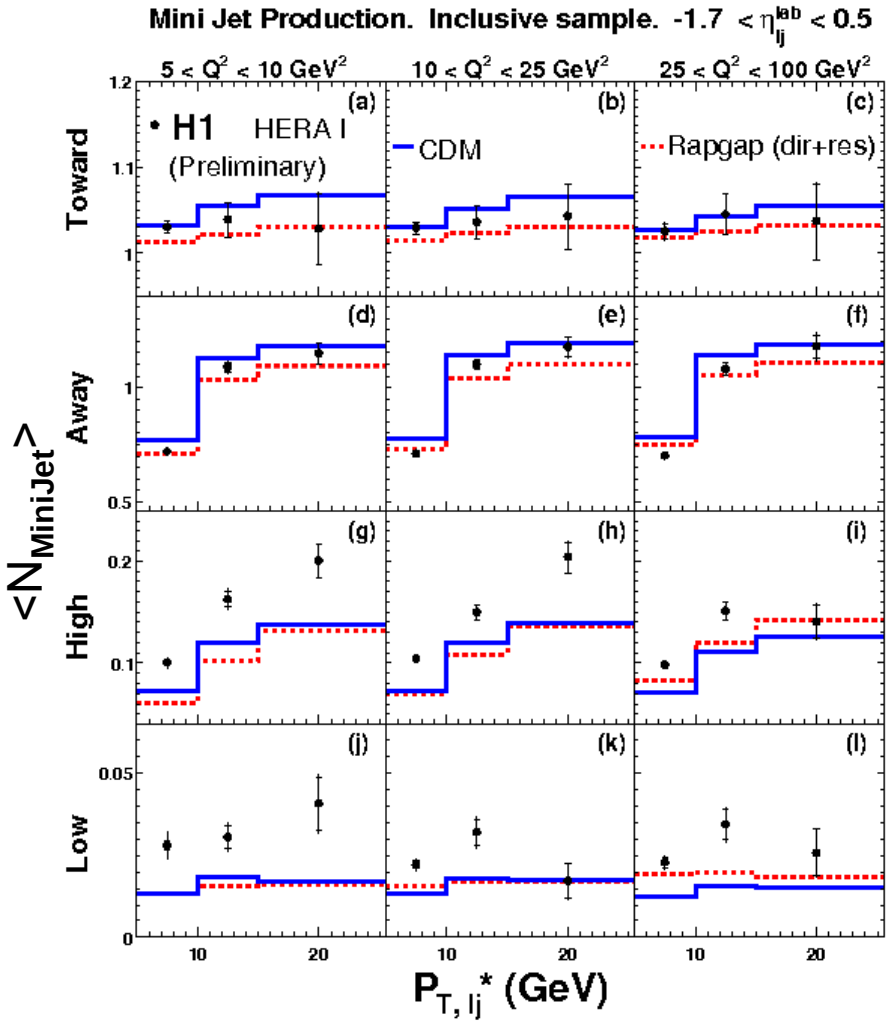
– No real physics justification for the `model' (UA5).

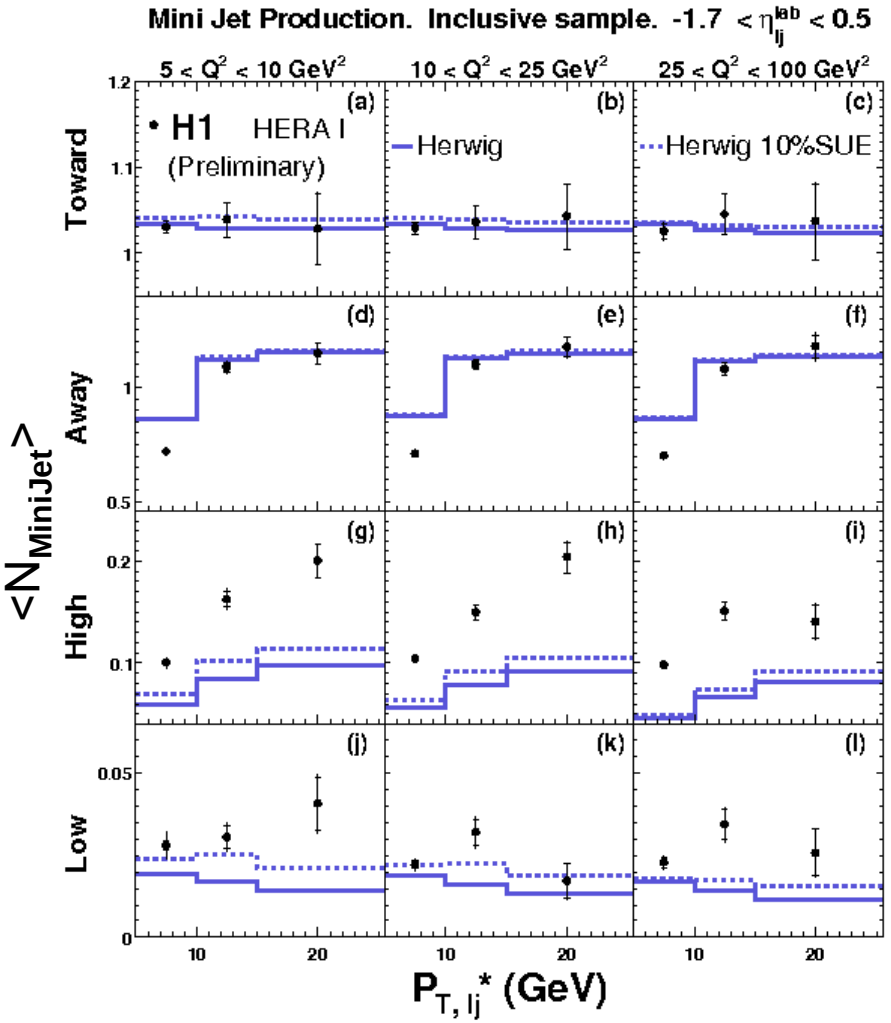
– Increases predictions at low Q^2, low-activity region.



H1 ANALYSIS: INCL. SAMPLE: BACKWARD

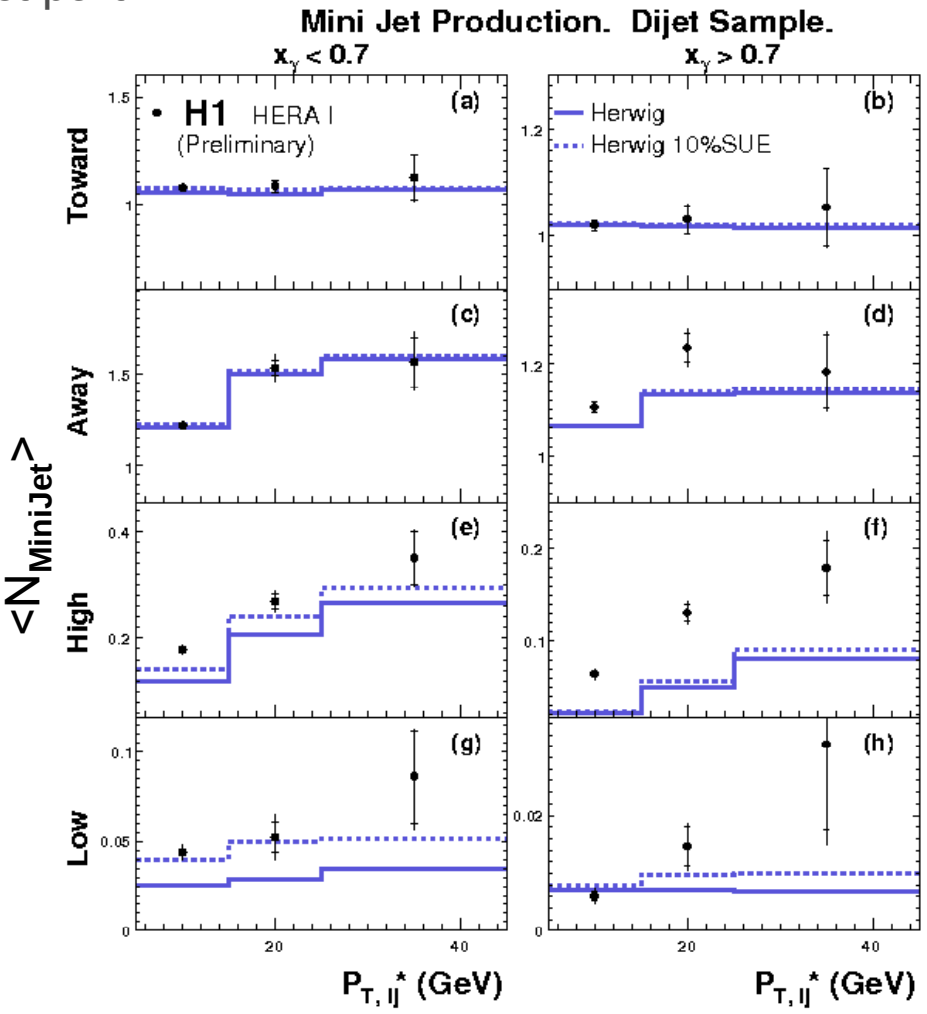
¶ CDM, RAPGAP, HERWIG+SUE: Problems for high-activity region





H1 ANALYSIS: DIJET SAMPLE: HERWIG+SUE

¶ HERWIG + 10% SUE
- Problems for direct part.



$d\sigma/dx_\gamma$

¶ x_γ separates resolved- from direct-dominated subsamples:

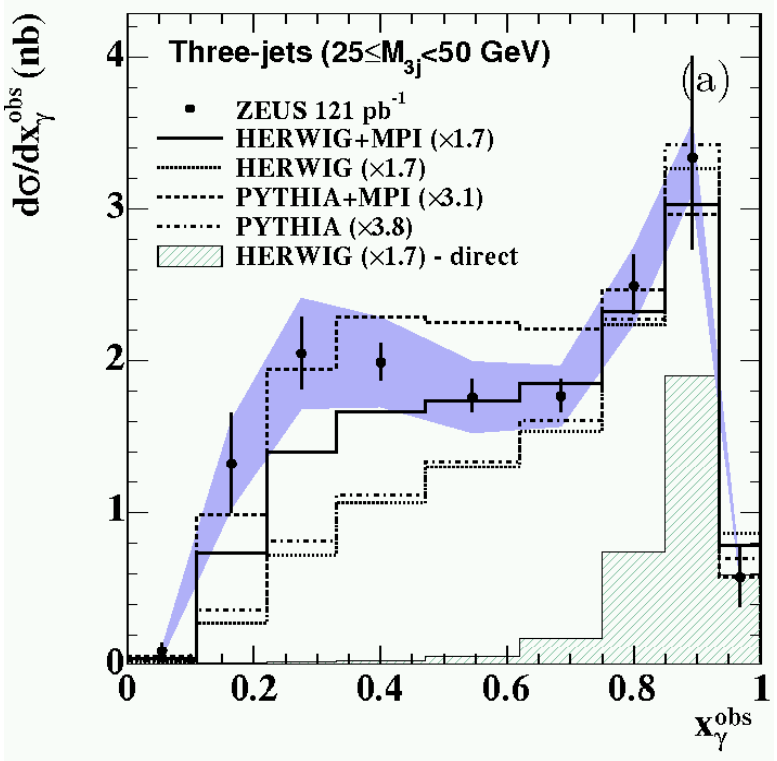
– Models without MPI suggest decreasing cross-sections with decreasing x_γ.

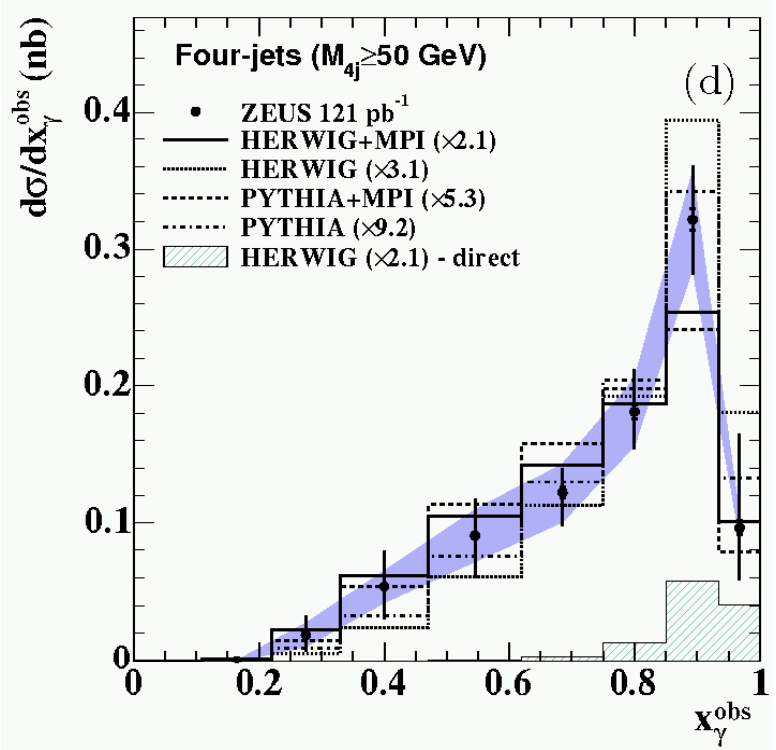
– But for low masses large discrepancy with INCREASING data

→ mechanism beyond direct+resolved as modelled in MC necessary.

– Even "direct" region ($x_\gamma > 0.75$) dominated by resolved events (↔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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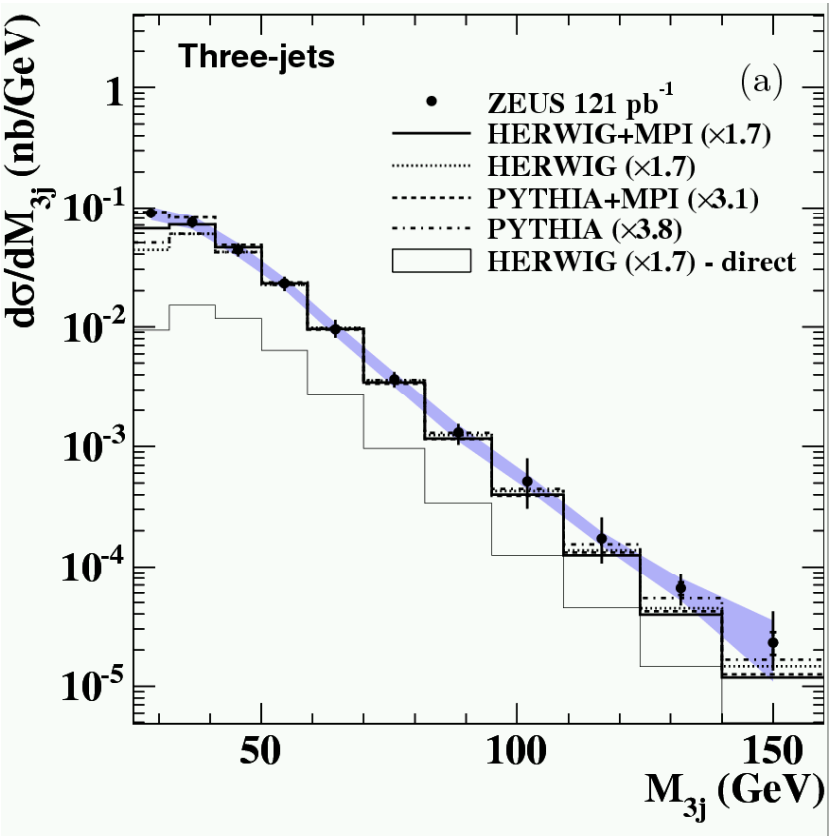
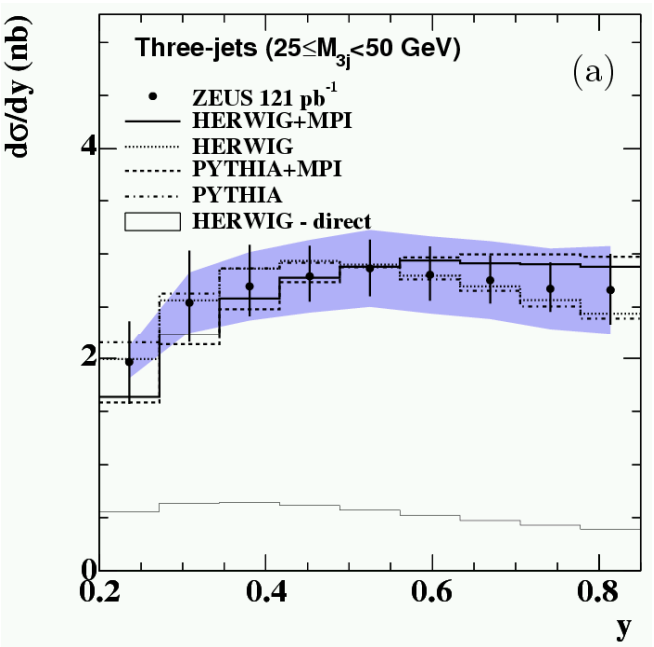
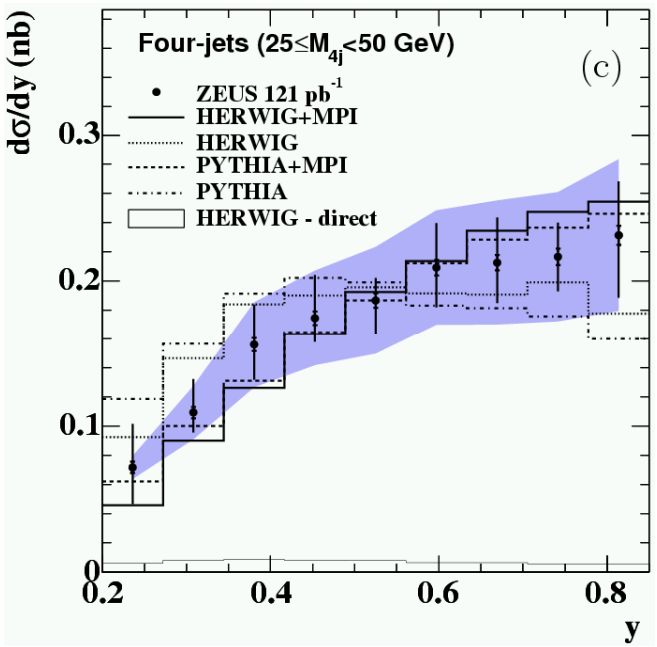
- Effect larger for fouer-jets than for three-jets.

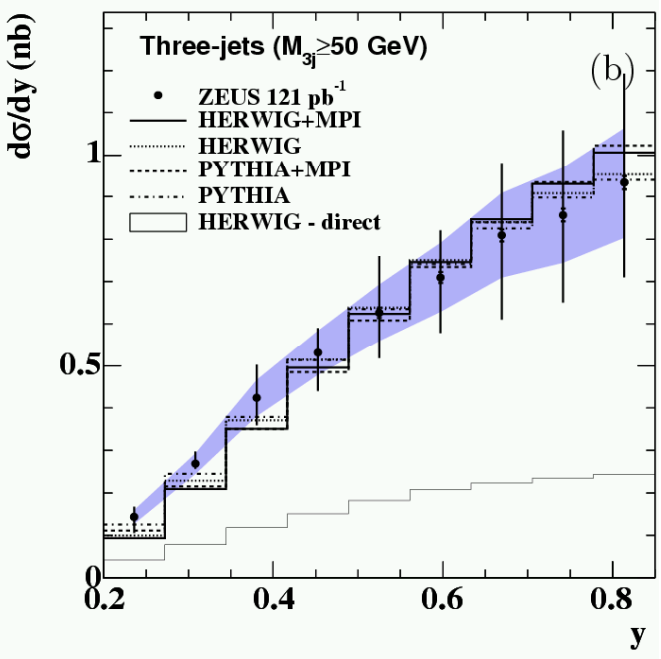


dσ/dy

- … 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.





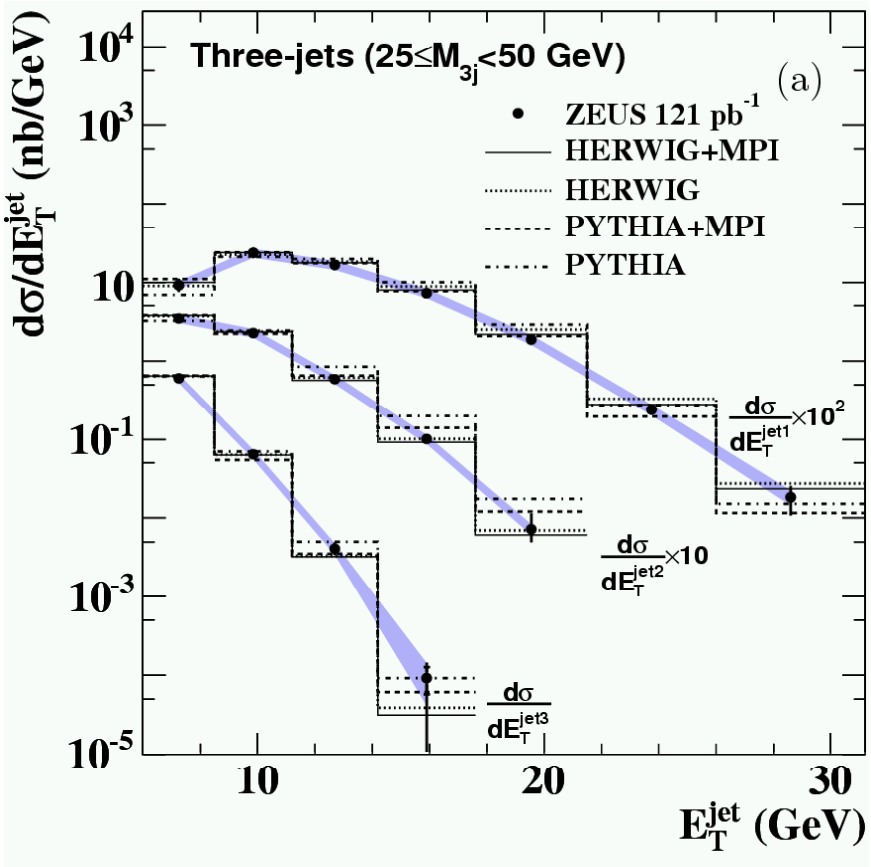


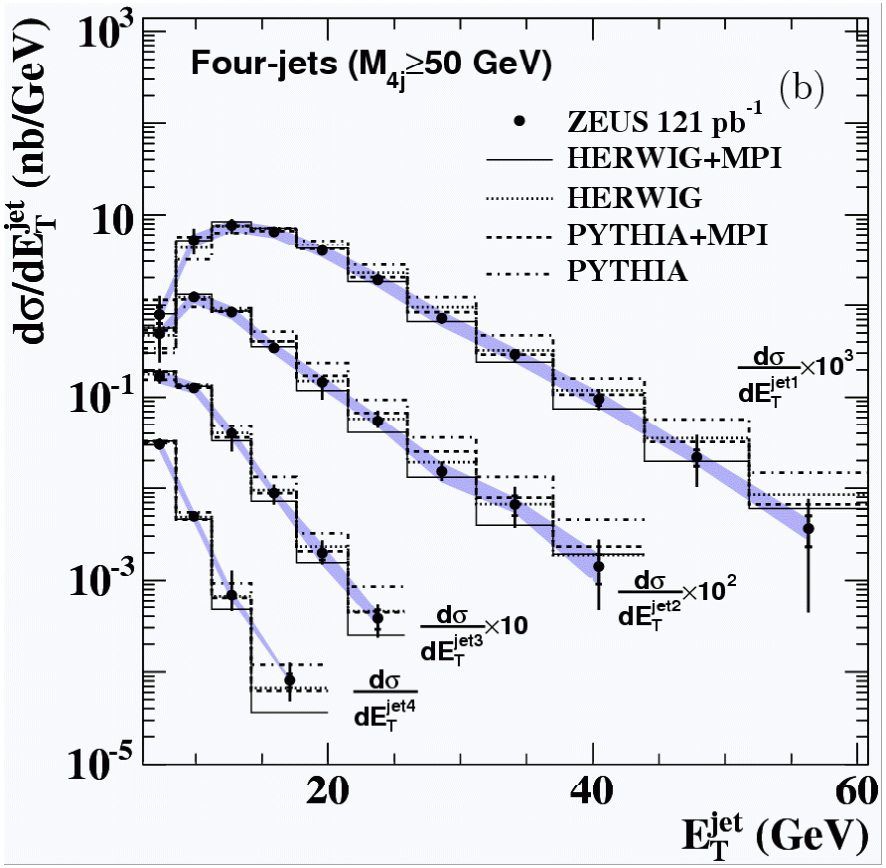
$d\sigma/dE_T$

¶ 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.





dσ/dη

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

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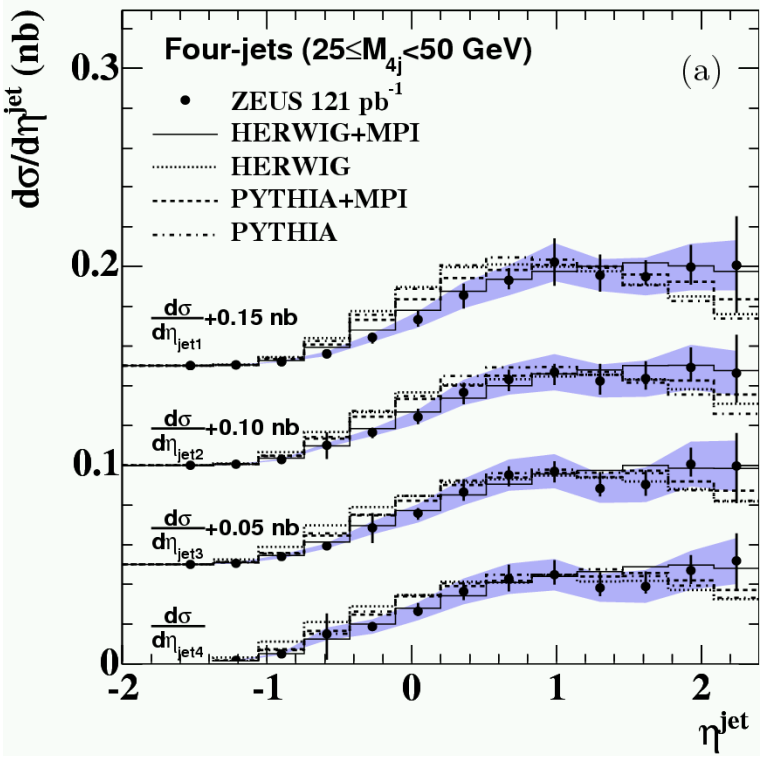
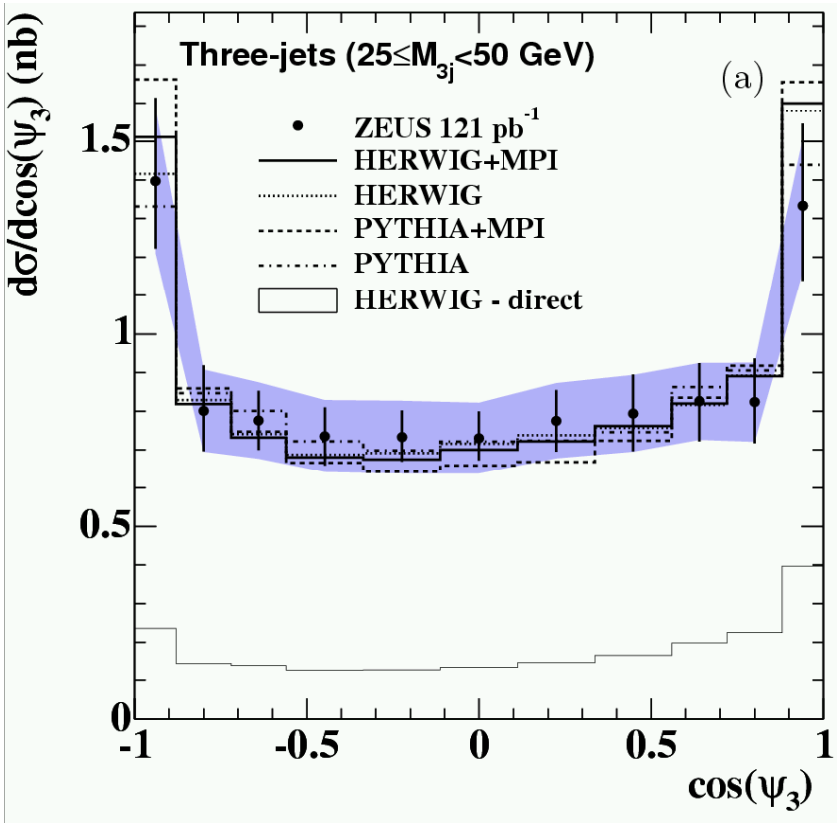
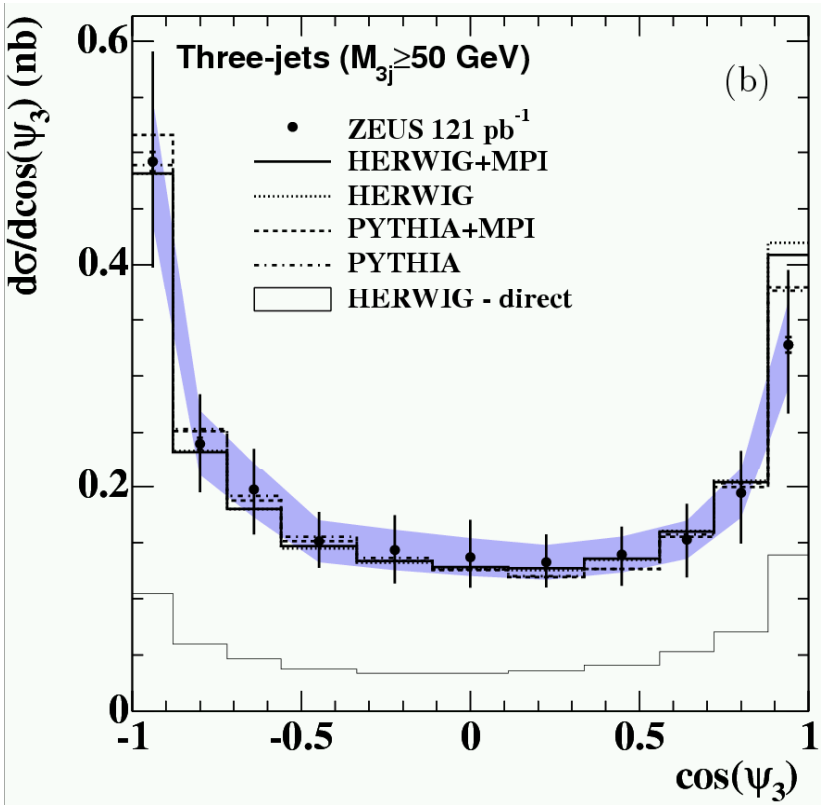
- Best description of low-mass data by HERWIG+JIMMY.
- Models with MPI suggest decrease of cross-section at high η^{lab}; MPIs reduce this effect in line with measurement.



MULTIJETS: dσ/dcosΨ_3 three-jets

¶ data well described by all MC models.





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

¶ Theory: $O(\alpha\alpha_S^2)$

¶ 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.