Multi Parton Interactions at HERA

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On behalf of H1 and ZEUS Collaborations

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Outline

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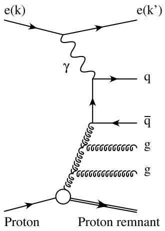
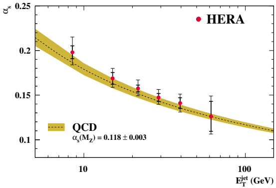
Hard scattering

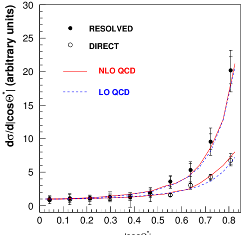
- Usual hard process qq or γq
- Partons hadronize $\rightarrow$ form jets
- Well described by pQCD



- Diverse aspects of pQCD studied experimental data, e.g.:



Precision measurement: α_{QCD} **from inclusive jets**

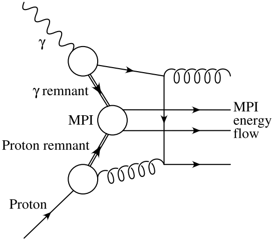


Colour dynamics: $\cos(\theta*)$ **in dijets**

Multi Parton Interaction

from hard processes

- If more than one initial parton interact?
- Two hard interactions on the event
- May lead to formation of multi-jets

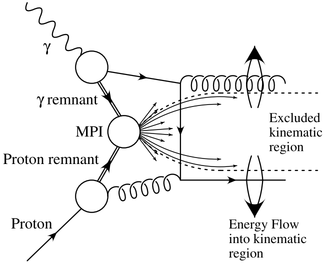


Outline

Underlying event

Soft interaction, but closely related to MPIs

- Do not form jets
    - on the contrary, it is "everything other than jets" on the event
    - Includes: initial and final state radiation
    - Soft interactions between partons spectators and beams remnants
- Energy flow between jets
    - Measure jet pedestal

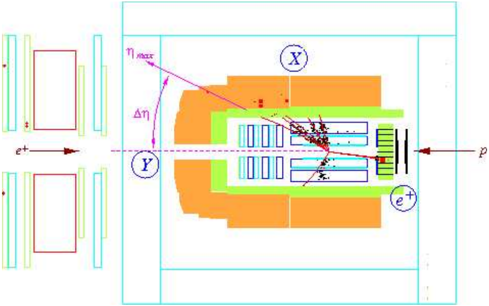


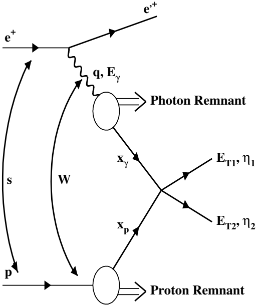
Outline

HERA physics

HERA collides $e^{\pm}p$

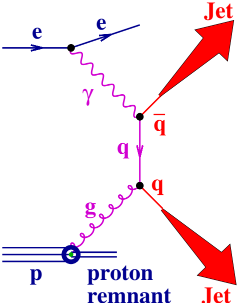
- $e^{\pm}$ at 27.5 GeV, p at 920 GeV
- $W = \gamma p$ cms energy
- $\sqrt{s} = 320$ GeV (ep cms energy) $\qquad Q^2 = -q^2$ (photon virtuality)
- $y = W^2/s =$ momentum fraction of e carried by γ



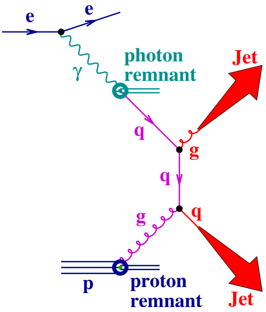


Multi-Parton interactions at HERA

- MPIs: two colliding particles are source of partons
- in **resolved photoproduction**: “hadron-like” photon
- x_γ fraction of photon momentum in hard scattering



$$x_\gamma^{\mathrm{obs}} = \sum_i^n \frac{E_{T,i}\exp(-\eta_i)}{2yE_e}$$



Direct photon ($x_\gamma \approx 1$)

Resolved photon ($x_\gamma < 1$)

Why is it important?

At the LHC:

- Larger $\sqrt{s}$, can see partons at very low x
- Many interactions between spectators
- QCD must be completelly under control to observe new phenomena
- HERA data good training ground for tuning models/MCs

Outline

Event selection (121 pb^{-1} of data)

Jets selection (LAB frame)

- $E_T^{jet_{1,2}} > 7$ GeV
- $E_T^{jet_{3,4}} > 5$ GeV
- $|\eta^{jet}| < 2.4$
- selected with inclusive k_T algorithim & massless

Kinematic region

- 0.2< y <0.85
- $Q^2 < 1$ GeV^2
- Two mass regions studied:
  - semi-inclusive ($M_{nj} \geq 25$ GeV)
  - high-mass ($M_{nj} \geq 50$ GeV)

$$M_{nj} = \sqrt{(\sum_i^n p_i)^2}$$

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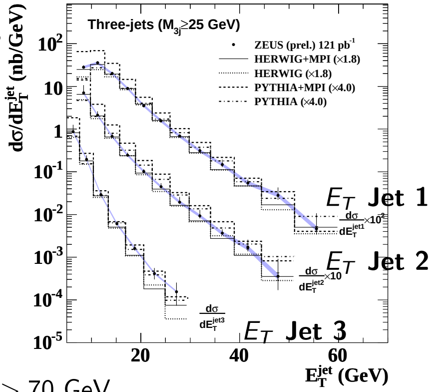
Monte Carlo samples

- PYTHIA 6.2
  - without MPI
  - with MPIs from simple model, tuned to collider data (JETWEB)
- HERWIG 6.5
  - without MPI
  - with MPIs from JIMMY 4.0 (eikonal model), tuned to ZEUS multi-jet data
- normalization
  - DATA/(MC no MPIs) at $M_{nj} > 70$ GeV

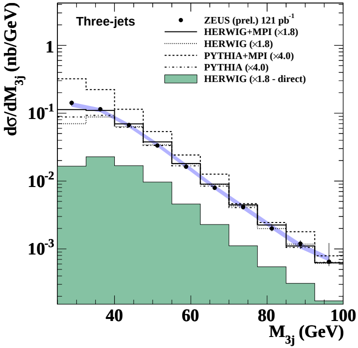


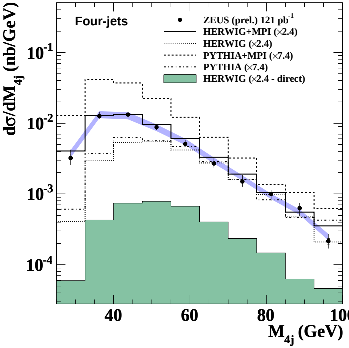
Outline

Comparison with Monte Carlo

Three and four-jets M_{nj} distribution

- PYTHIA MPI: excessive contribution but tuned to hadron collider data
- HERWIG MPI: good description tuned for HERA data
- No MPI for $M_{3j} > 50$ and $M_{4j} > 70$ GeV (where MC is normalized)

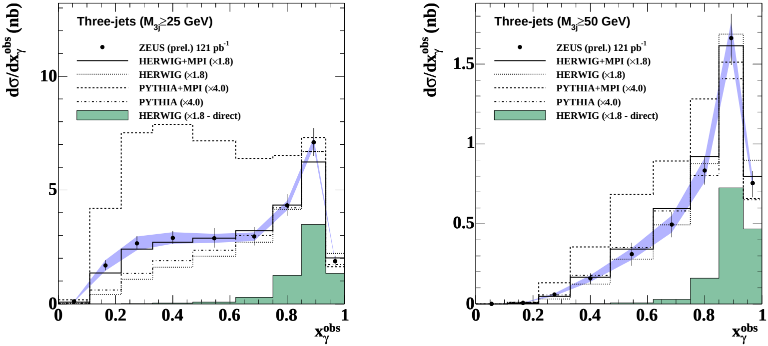




Comparison with Monte Carlo

Three-jets x_γ distribution

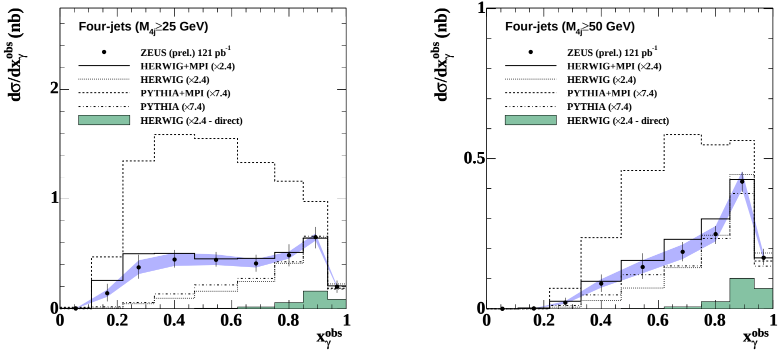
- MC no MPIs: missing component at low x_γ, low mass
- PYTHIA MPI: excessive contribution
- HERWIG MPI: good description



Comparison with Monte Carlo

Four-jets x_γ distribution

- MC no MPIs: larger missing component at low x_γ
- MPIs needed also at higher mass

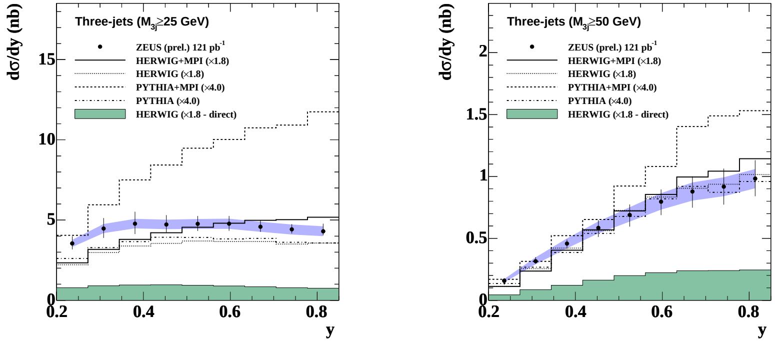


Comparison with Monte Carlo

Three-jets y distribution (Similar results for 4-jets case)

$>>>>>>$ **Here MPI models FAIL!!!** $<<<<<<$

- $W = \sqrt{sy}$ (γp cms energy)
- Shapes slightly better described by MC without MPIs
- Good ground to tune/test MPI models



Outline

Fixed order pQCD calculation

- **Theory does NOT include MPIs**
- Only calculations up to $O(\alpha\alpha_s^2)$ are available in literature
- Lowest order for 3-jet process, not comparable to 4-jets
- $E_T^{jet_1}$ used for renormalization and factorization scales (and varied by $\times 2,\ 1/2$ to evaluate theoretical uncertainty)
- to compare with data theory convoluted with:
  - hadronisation corrections ($\mathcal{C}_{HAD} = \frac{\sigma_{\mathrm{hadrons}}}{\sigma_{\mathrm{partons}}}$)
  - MPI corrections ($\mathcal{C}_{MPI} = \frac{\sigma_{\mathrm{MPI}}}{\sigma_{\mathrm{NO\ MPI}}}$)

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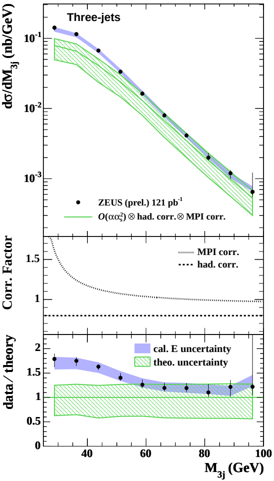
Comparison with theory

- Good agreement at high mass
- Possible sources of discrepancy
  - incorrect hadronization
  - incorrect MPIs modelling
- hadr. corrections: *flat*
  - unlikely to be the cause
- MPIs understimated (??)

Higher order calculation may help



Outline

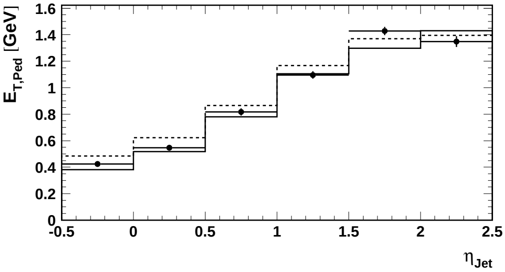
Energy flow between jets

Dijet sample (cone algorithm)

- $E_T^{jet_{1,2}} > 4$ GeV
- $M_{1,2} > 12$ GeV
- $-0.5 < \eta < 2.5$

Energy flow

- sum outside jets cone R=1
- $-1 < \eta - \eta_{jet} < 1$
- $-\pi < \phi - \phi_{jet} < \pi$



• H1 Collaboration

MC: PYTHIA with MPI

PHOJET with MPI

$$\boxed{E_{T,ped} = \frac{1}{A} \sum E_T}$$

Energy flow between jets

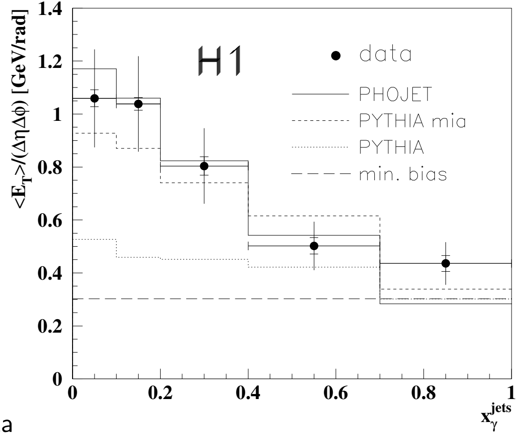
Another dijet sample

- $E_T^{jet_{1,2}} > 7$ GeV
- $-1 \leq \eta^{jet_{1,2}} \leq 2.5$

Minimum bias (data):
"almost there" for direct γ

Add ISR on γ side
(g emission): not enough

Add MPIs:
good description of the data



Outline

Transverse energy correlations

High-E_T sample (results unchanged when a jet is required)

$$\boxed{\Omega(\eta^*) = \frac{1}{N_{ev}} \sum_{i=1}^{N_{ev}} \frac{(<E_{T,\eta^*=0}> - (E_{T,\eta^*=0,i}))(<E_{T,\eta^*}> - (E_{T,\eta^*,i}))}{(E_T^2)_i}}$$

- $E_T > 20$ GeV
- $-0.8 \leq \eta \leq 3.3$ (lab frame)
- $\eta^* \rightarrow \gamma p$ cms

- Ω in small η^* bins

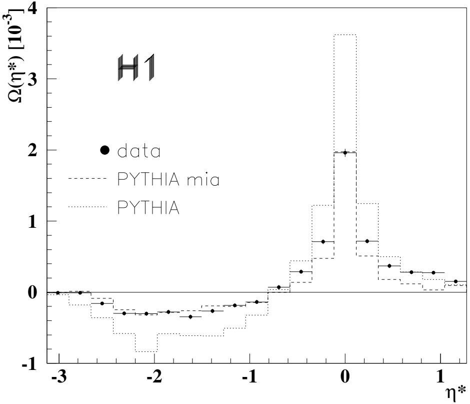
PYTHIA without MPIs:

· too much correlation close to reference bin

· too much anti-correlation on the photon side

PYTHIA with MPIs:

· correlations well described



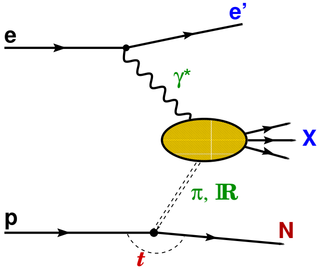
Outline

Absorption in leading baryon production

- Leaving pQCD regime
  $\longrightarrow$ Approach from soft physics
- Leading baryons (leading neutrons/leading protons)
  - contain characteristics of both soft and hard interactions
  - data is best described by Regge theory (essentially soft)
  - excellent ground to study the interplay between hard-soft physics

Leading neutron production at HERA

The process:



One-Pion-Exchange Model:

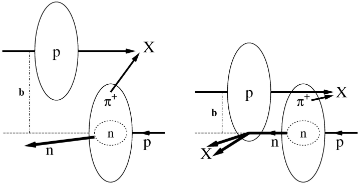
- $p \longrightarrow \pi n$
- $\frac{d\sigma_{ep\rightarrow e' nX}}{dx_L\, dt} = f_{\pi/p}(x_L, t)\sigma^{e\pi}((1-x_L)s))$
- $x_L = \frac{E_n}{E_p}$

Parameters from low energy hadron collisions (soft physics)

How does it relate multi-parton interactions?

Absorption: secondary interactions

d'Alesio and Pirner, EPJ A7 (2000) 109
(resembles MPI implementation in JIMMY)



Nikolaev, Speth and Zakharov, hep-ph/9708290

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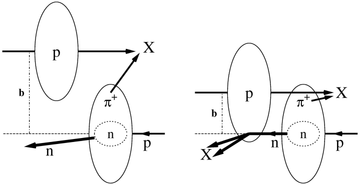

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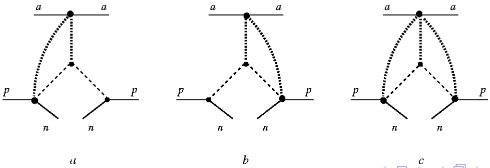
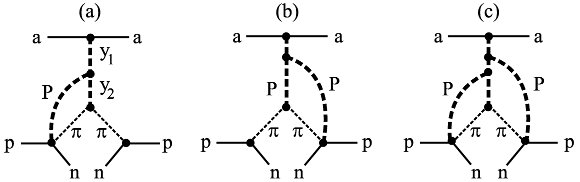


Absorption

Kaidalov, Khoze, Martin, Ryskin, hep-ph/062215



- absorption from additional pomeron exchange
- (a)-(c) contribute to the dominant process

Similar case, different approach

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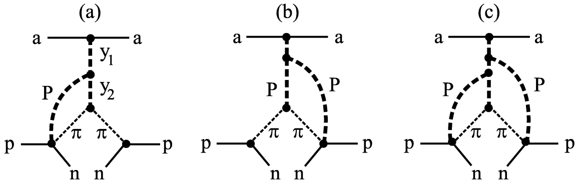

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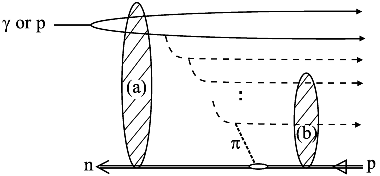

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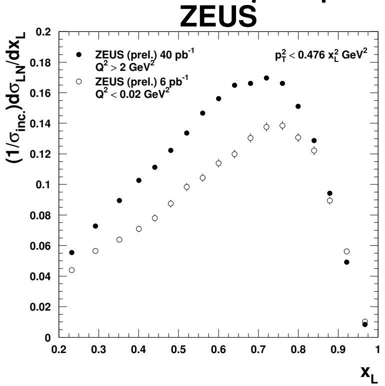
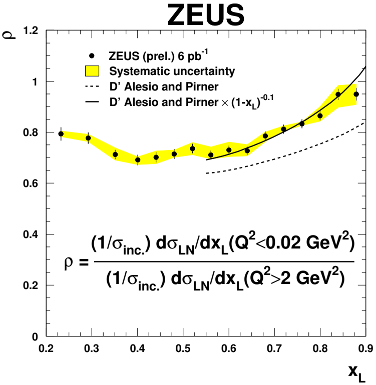
Leading neutrons

Photoproduction and DIS samples, $0.2 < x_L < 1$, $\theta_n < 0.75$ mrad

Fewer neutrons seen in photoproduction



Model: d'Alesio and Pirner



data in agreement with absorption hypothesis

Leading neutrons

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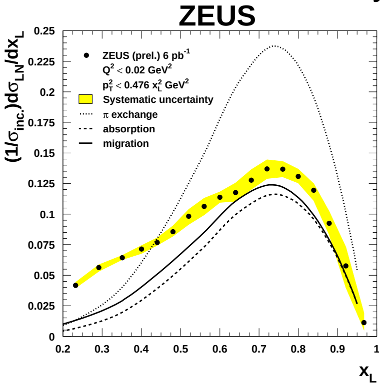

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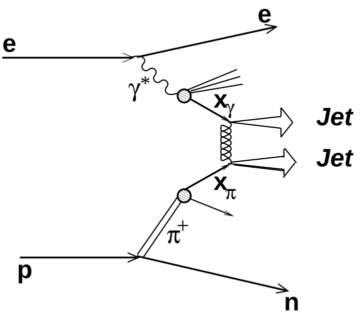
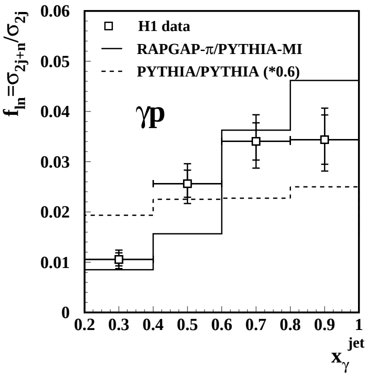
Leading Neutrons - ratios dijets+n/inclusive dijets

Dijet photoproduction sample, $0.488 < x_L < 1$, $\theta_n < 0.75$ mrad





- Neutron production suppressed in resolved-photon enriched region
- Shape well described by RAPGAP (π-exchange MC) and PYTHIA-MPI

Summary

Results from Multi-Jets (3 and 4 jets photoproduction)

- First measurement of 4-jets in γp at HERA is presented
- pQCD alone (LO matrix elements + parton shower) not able to describe the data (3 and 4 jets)
  - Additional component missing at low M_{nj} and low x_γ^{OBS}
- Data much better described by MC+tuned MPIs
  - HOWEVER, introduction of MPI in MCs spoils good description of the y distribution
  - $d\sigma/dy$ is a good quantity for tuning/testing MPI models
  - MPI may be not the only missing component
- Data is ahead of theory
  - Higher order pQCD calculations would contribute

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- In dijet events, energy measured outside of cone jets ($E_T^{jets} > 4$ GeV) is as high as 1.4 GeV
  - Effect caused by soft multi-parton interations
  - Results in agreement with PYTHIA and PHOJET MPI´s
- Transverse energy correlations studied
  - A big ammount of uncorrelated energy need to be added to describe the data
  - Similar results when jet is required

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- Coming from soft-physics approach
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  - ... provided that secondary interactions are included

  - Effects of absorption via additional pomeron-exchange was quantified
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Conclusion

- MPIs and underlying event must be understood and quantified for they are expected to play an important role on LHC
- We looked at Multi Parton Interactions from the very hard (multi-jets) to the quasi-soft (leading baryon) regime processes at HERA
- HERA provides good quality data to help understanding the problem