Rapidity gaps and energy flow between jets in photoproduction at HERA

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On behalf of the ZEUS Collaboration

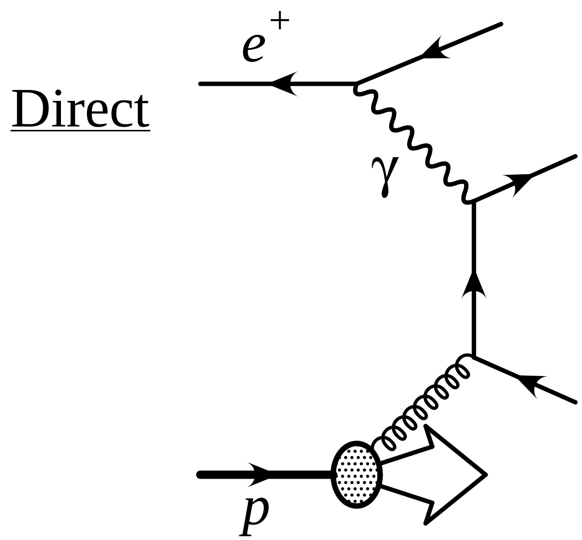
Introduction

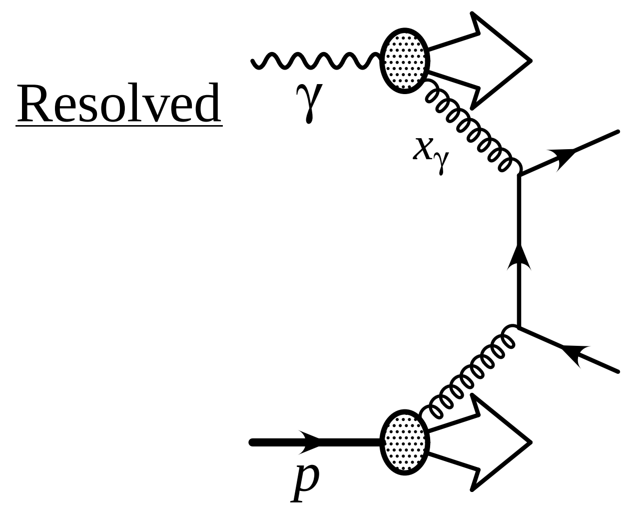
- QCD IS the theory of the strong interaction, describes hard processes very well, but not total hadronic cross sections.
- However, Regge phenomenology describes total hadronic cross sections very well, using colour singlet (Pomeron) exchange, but not so well processes with a hard scale.
- For QCD to be considered the "complete" theory of the strong interaction, it must be able to reproduce Regge behaviour in the high energy limit
  ⇒ need understanding of the Pomeron within the framework of perturbative QCD.

Introduction – jet photoproduction

- In photoproduction at HERA, the photon has a very low virtuality $\sim 10^{-3}$ GeV^2
  ⇒ perturbatively calculable when there is a hard scale provided by high transverse energy jets.

- To $\mathcal{O}(\alpha\alpha_s)$, two types of process contribute to high E_T jet production.

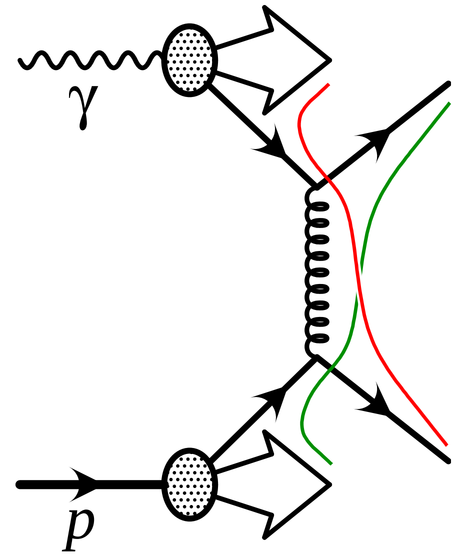


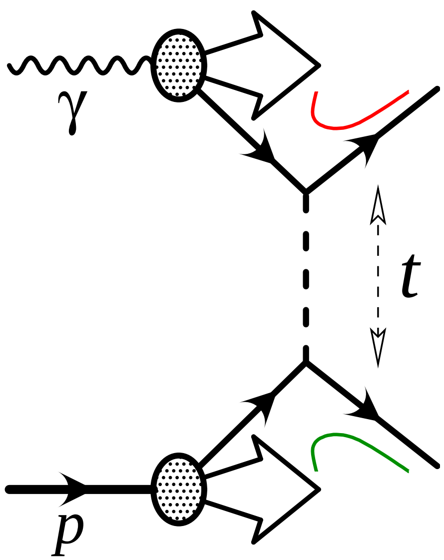


- At Leading Order picture, two jets, balanced in E_T, back-to-back in ϕ.

Events with and without gaps

- In standard QCD dijet production, jets are colour connected across gap
  ⇒ energy flow between jets, gaps exponentially suppressed.

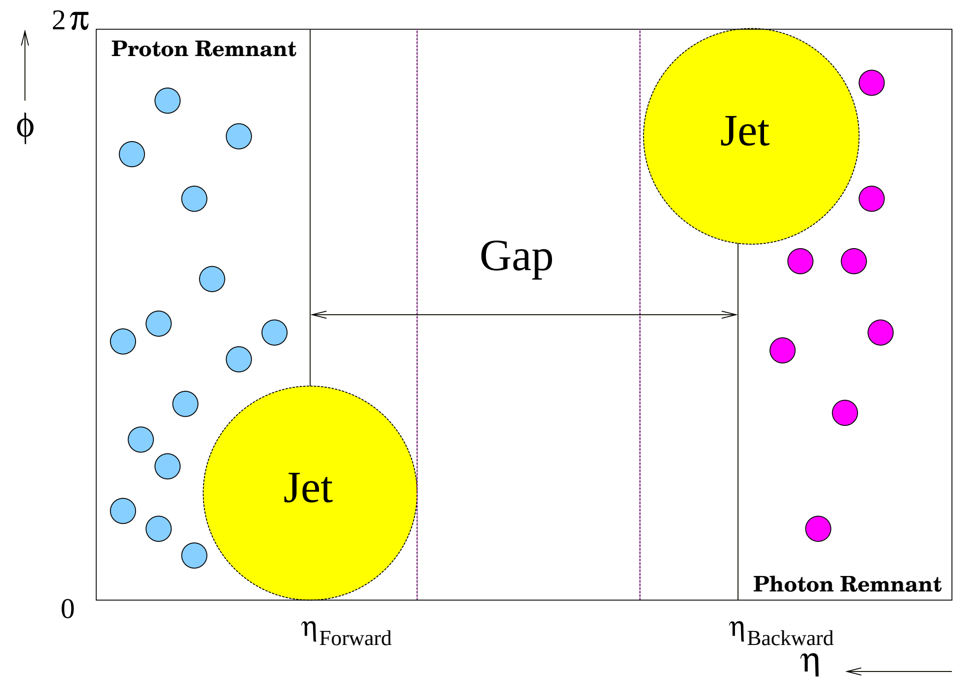




- At large, negative t, colour singlet exchange (CSE) would result in gaps between the jets with little or no energy flow across the gap
  ⇒ not exponentially suppressed.

Experimental signature and gap fraction

- Longitudinally invariant $k_\perp$ algorithm ➡ all objects assigned to jets.



- Two highest transverse energy jets, separated in pseudorapidity,

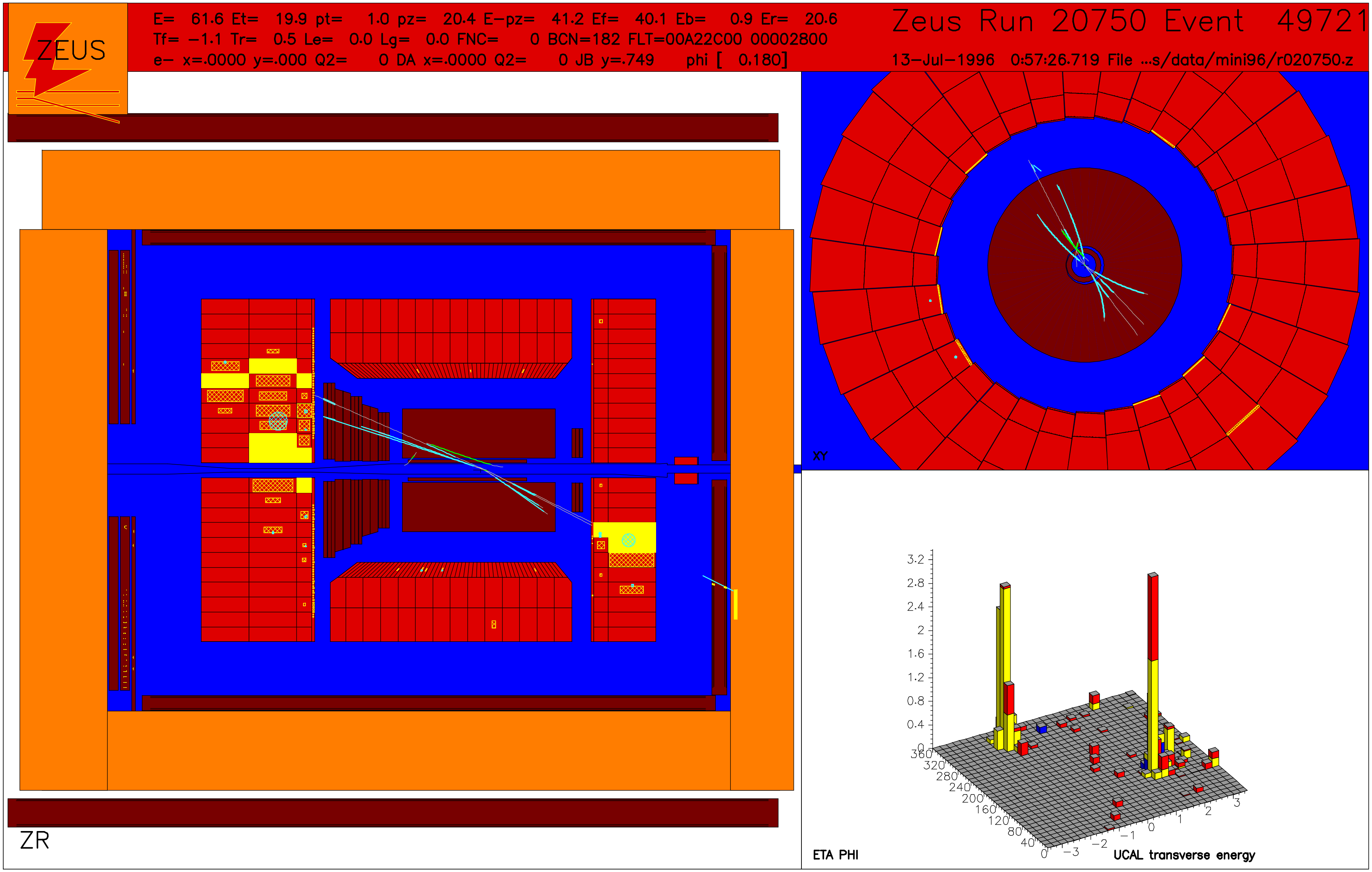
$$\Delta\eta = \eta^{\text{jet}}_{\text{forward}} - \eta^{\text{jet}}_{\text{backward}}$$

- Energy flow in the gap

$$E_T^{\text{gap}} = \sum_{\text{jet } i} E_T^{\text{jet } i} \quad \text{where} \quad \eta^{\text{jet}}_{\text{backwards}} < \eta^{\text{jet } i} < \eta^{\text{jet}}_{\text{forward}}$$

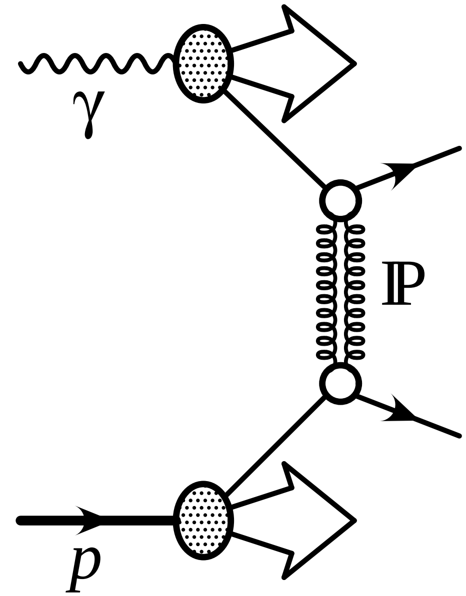
- Gap event where $E_T^{\text{gap}} < E_T^{\text{cut}}$.
- Infrared safe, perturbatively calculable when $E_T^{\text{cut}} \gg \Lambda_{\text{QCD}}$
- Define gap fraction, $f(E_T^{\text{cut}}, \Delta\eta)$, for a given pseudorapidity interval $\Delta\eta$, as the fraction of events where $E_T^{\text{gap}} < E_T^{\text{cut}}$.

Experimental signature and gap fraction



What is the mechanism of gap formation?

- QCD has no fundamental colour singlet object.
- The large momentum transfer $-t \gg \Lambda^2_{\rm QCD}$ ensures a hard scale at both ends of the exchange ⇒ perturbative QCD.
- Can construct perturbative colour singlet using two gluons.
  ⇒ Leading Log BFKL approximation colour singlet exchange, two gluons including resummation of $\ln 1/x$ terms (LLA BFKL).
- Calculation from Mueller and Tang,

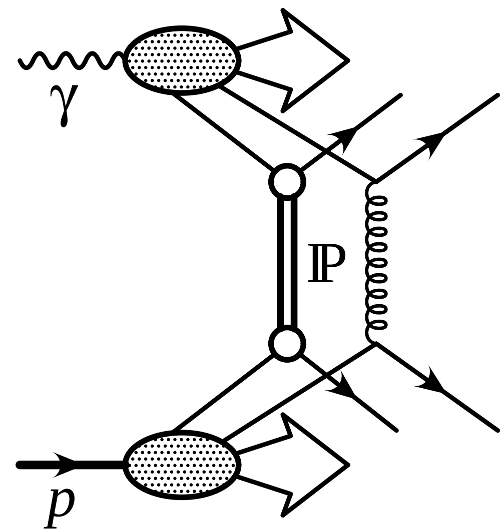


$$\frac{d\sigma(qq \to qq)}{dt} = (\alpha_s^{\rm pre.} C_F)^4 \frac{2\pi^3}{t^2} \frac{\exp(2\omega_0 \Delta\eta)}{(7\alpha_s^{\rm den.} C_A \zeta(3) \Delta\eta)^3}$$

- Hard Pomeron intercept, $1 + \omega_0$ with $\omega_0 = (\alpha_s C_A/\pi) 4 \ln 2$, couplings $\alpha_s^{\rm pre.}$ and $\alpha_s^{\rm den.}$ free along the ladder.
- Implemention in HERWIG + LLA BFKL, $\omega_0 = 0.45$ ($\alpha_s = 0.17$).

Gap survival probability

- QCD Colour singlet exchange only relevant in resolved photoproduction.
- Secondary hard scatters from spectator partons lead to multi-parton interactions (MPI).
- Additional soft (or hard) interactions ⇒ gap destroyed by energy flow into gap region.
- Mechanisms of multi-parton interactions and underlying event not completely understood.



- Models of multi-parton interactions included in both HERWIG (JIMMY) and PYTHIA ⇒ used for all comparisons here.

Kinematic region

- Photoproduction region, virtuality and inelasticity,

$$Q^2 < 1\text{GeV}^2, \quad 0.2 < y < 0.85$$

- Require at least two high transverse energy jets,

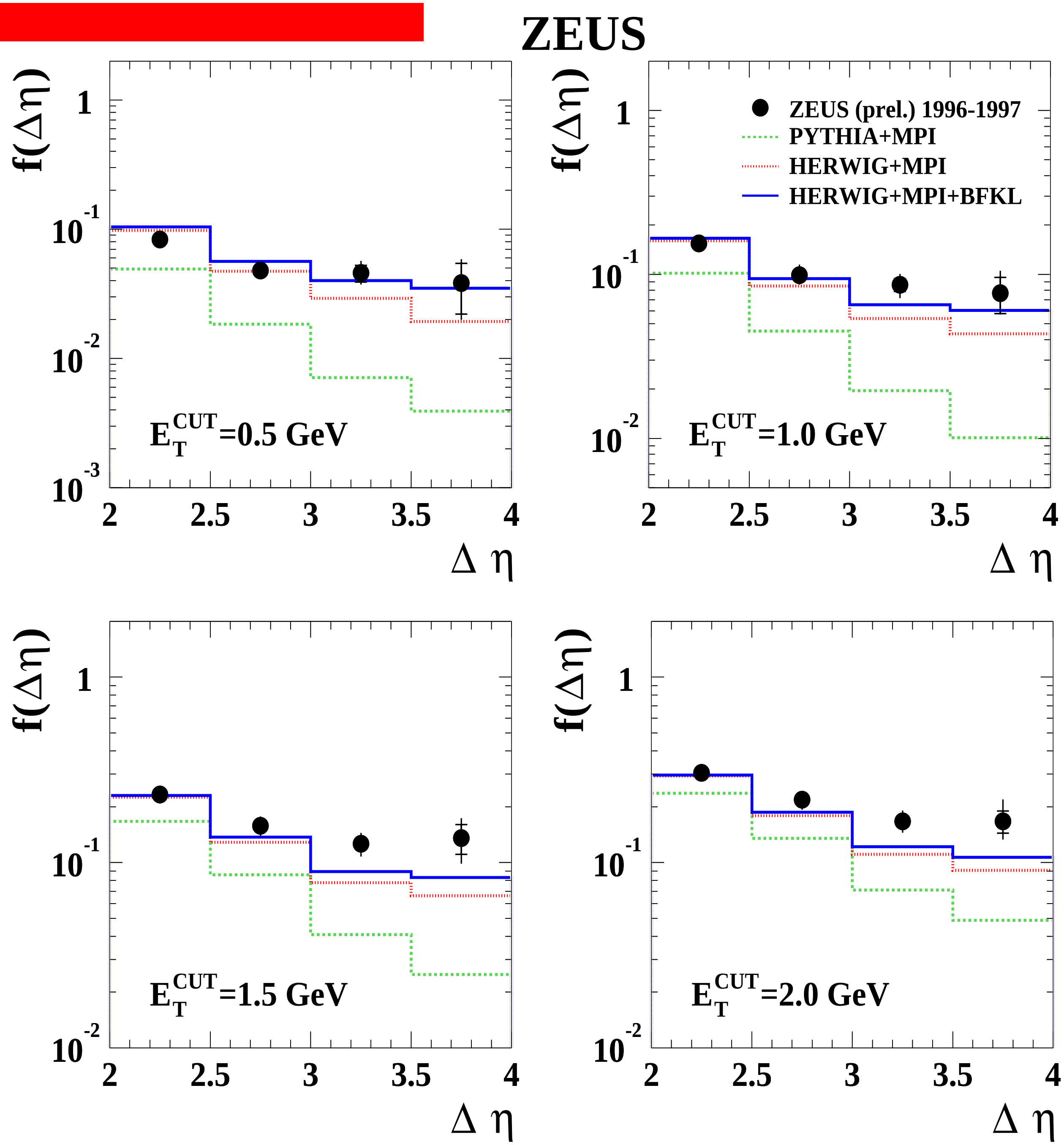
$$E_T^{\text{jet1}} > 6 \text{ GeV}, \; E_T^{\text{jet2}} > 5 \text{ GeV}, \qquad |\eta^{\text{jet1,2}}| < 2.4,$$
$$|\frac{1}{2}(\eta^{\text{jet1}} + \eta^{\text{jet2}})| < 0.75.$$
$$2.0 < \Delta\eta \equiv |\eta^{\text{jet1}} - \eta^{\text{jet2}}| < 4.0$$

- Fraction of photon energy contributing to the production of the two highest E_T jets,

$$x_\gamma^{\text{OBS}} \equiv \frac{\Sigma_{i=1,2} E_T^{\text{jet } i} \exp -\eta^{\text{jet } i}}{2yE_e},$$

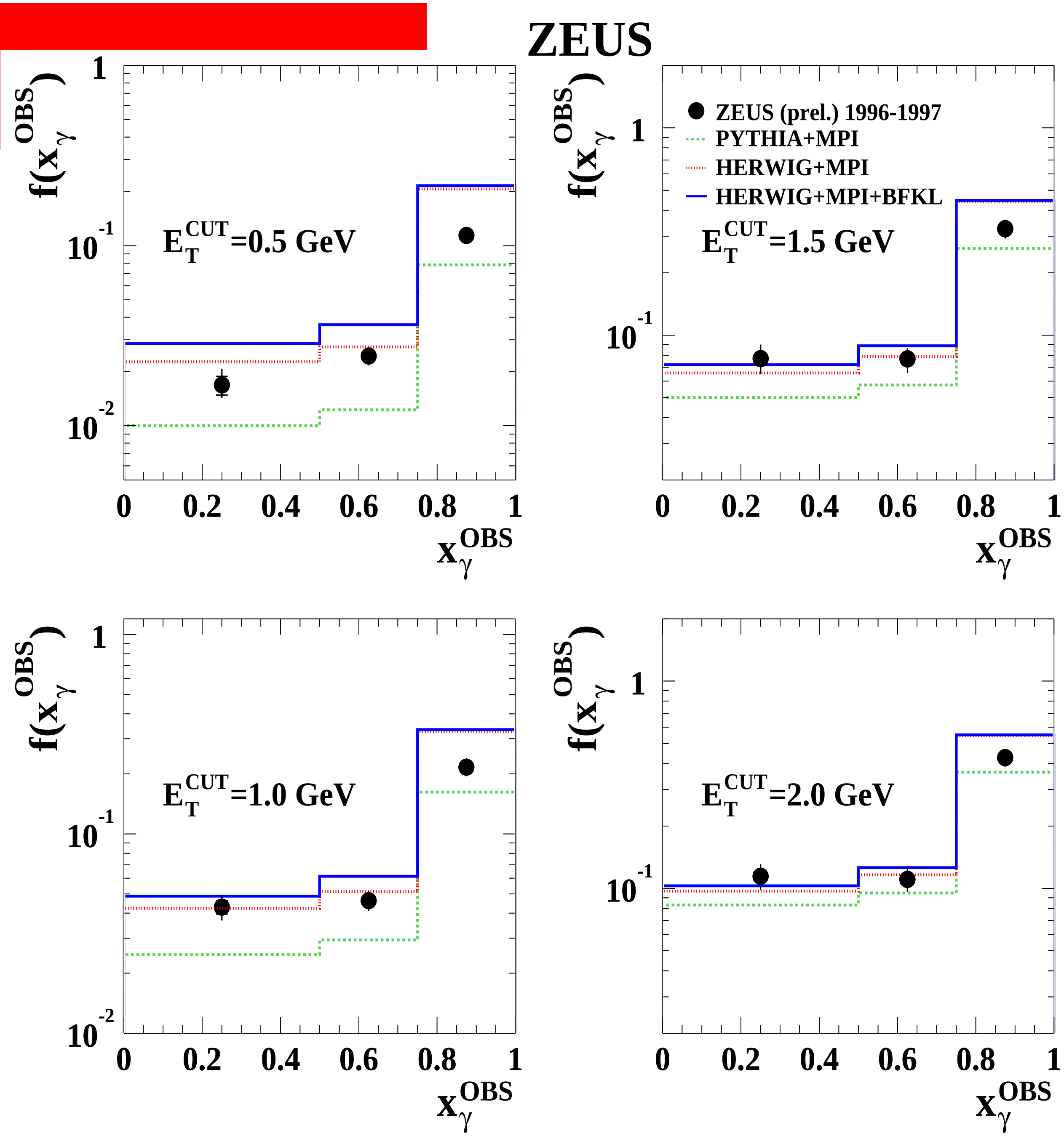
- Resolved enhanced region with $x_\gamma^{\text{OBS}} < 0.75$.

The gap fraction versus $\Delta\eta$



- Gradient less steep with larger $\Delta\eta$.
- Models without CSE, exponentially falling.
- Large difference between models without CSE (hadronisation?).
- Smaller LLA BFKL contribution with increasing $E_T^{\rm cut}$.

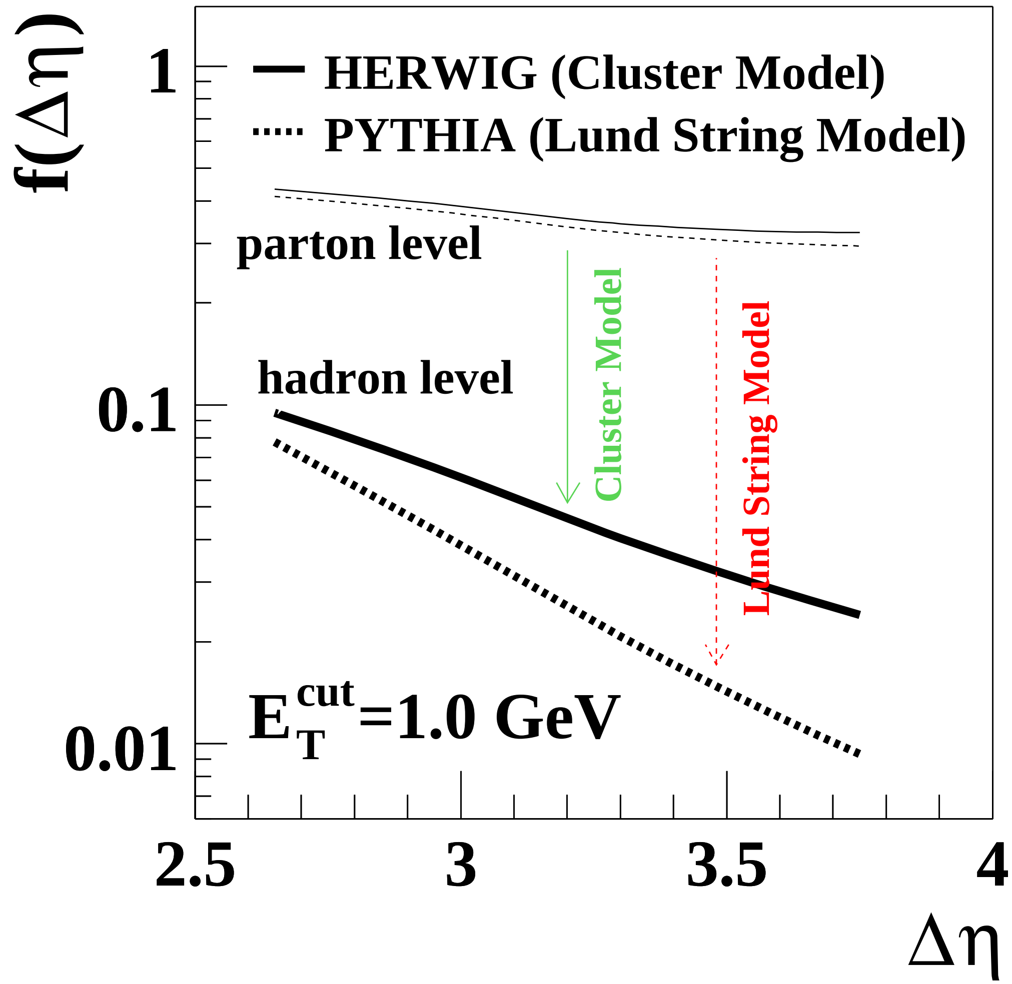
The gap fraction versus $x_\gamma^{\rm OBS}$



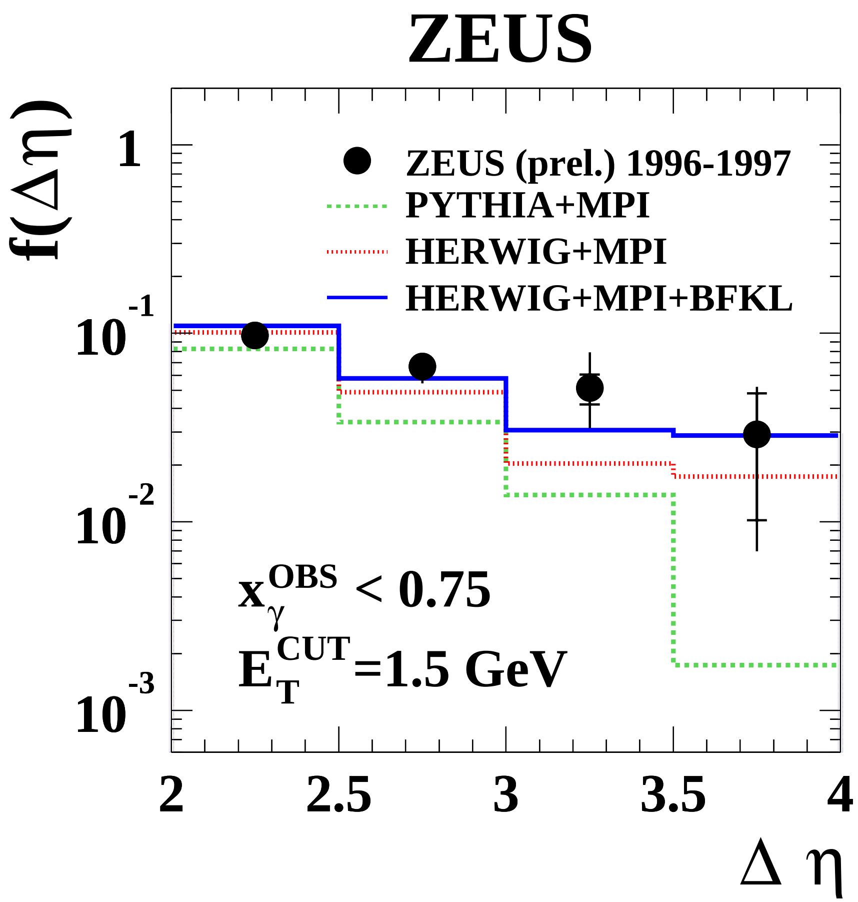
- Larger gap fraction at high $x_\gamma^{\rm OBS}$ ⇒ quark propagator.
- Models; too many gap events at high $x_\gamma^{\rm OBS}$.
- HERWIG + LLA BFKL too high at low $E_T^{\rm cut}$.

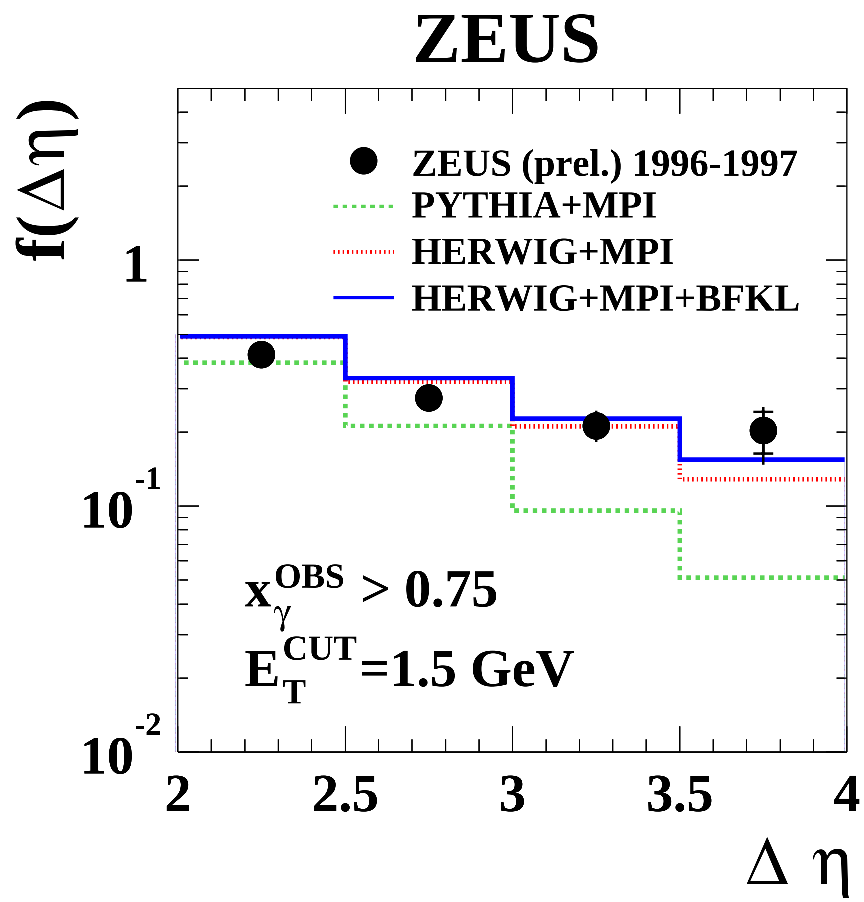
Why are the models so different?

- Small differences from different simulations of multi-parton interactions.
- Models after parton shower, but before hadronisation in good agreement.
- Models (without MPI) show large differences from hadronisation.



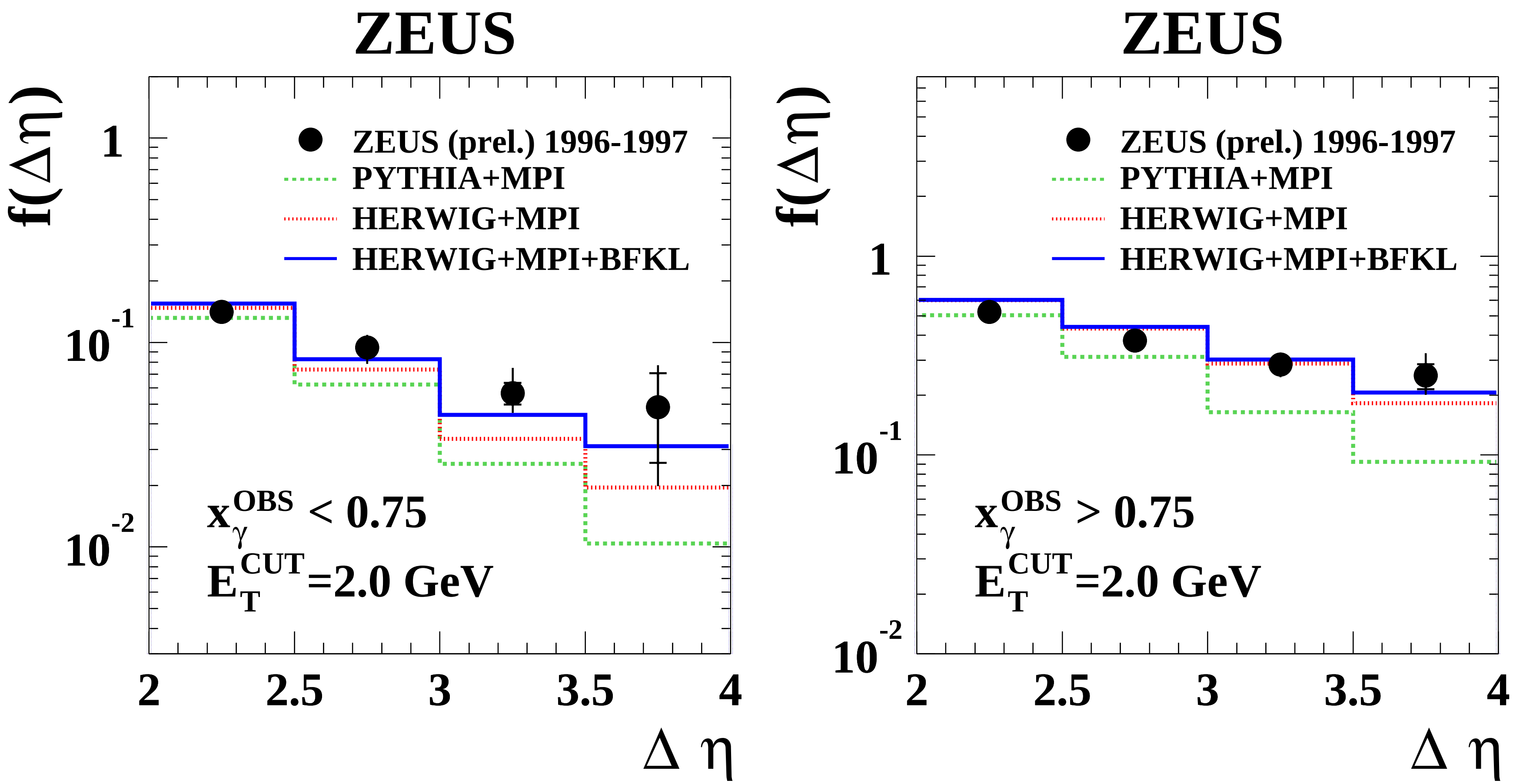
The gap fraction dependence on $x_\gamma^{\rm OBS}$





- Look at high and low $x_\gamma^{\rm OBS}$ separately.
- HERWIG prediction at high $x_\gamma^{\rm OBS}$ and low $\Delta\eta$ too high.
- Contribution from LLA BFKL smaller at higher $x_\gamma^{\rm OBS}$.

The gap fraction dependence on $x_\gamma^{\rm OBS}$



- At higher $E_T^{\rm cut}$ again LLA BFKL contribution smaller at high $x_\gamma^{\rm OBS}$.
- Difference between HERWIG and PYTHIA smaller.

Conclusions and outlook

- High transverse energy photoproduction events with a large rapidity gap between the two highest E_T jets have been measured with high experimental precision.
- Fraction of events with small energy flow between the jets shows a clear excess with respect to models without QCD colour singlet exchange.
- Larger contribution from colour singlet exchange for resolved type events ⇒ Clear evidence for BFKL processes?
- Differences between models without colour singlet exchange is large, ⇒ Difficult to draw firm conclusions about size of possible contribution from BFKL processes.
- Data at larger rapidity separations limited by statistical precision, ⇒ Look forward to analysis of the complete HERA I data set, and data from the upgraded HERA II machine.