Jets (γ) in photoproduction at HERA

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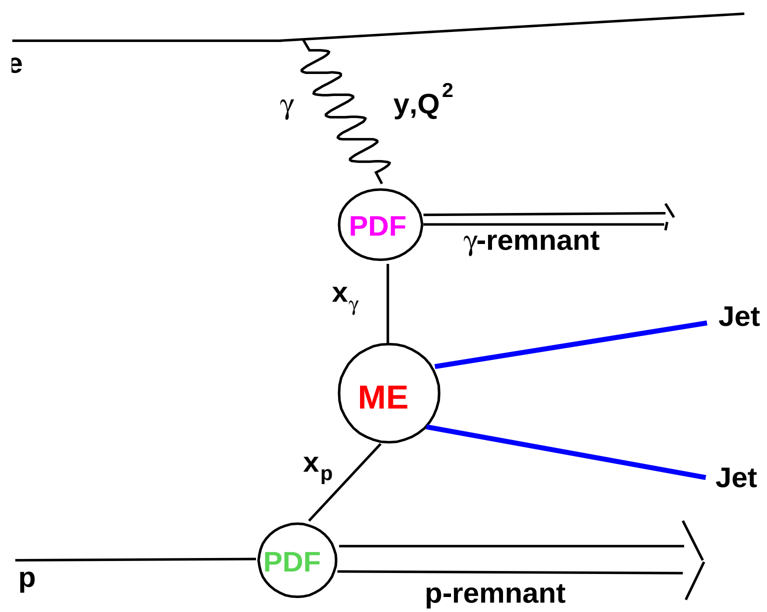
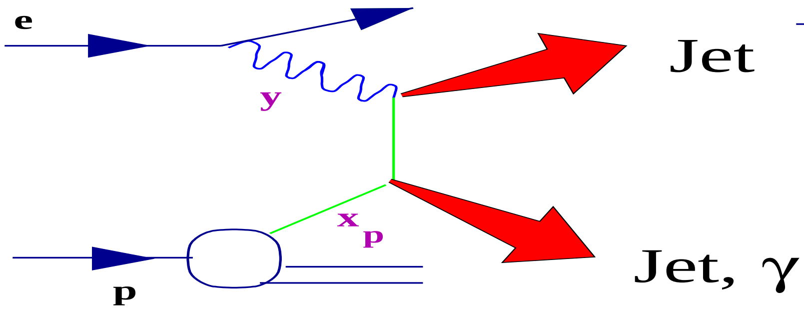
- **Inclusive jets**
- **Dijets**
- **Multijets**
- **Prompt photons**
- **Summary**

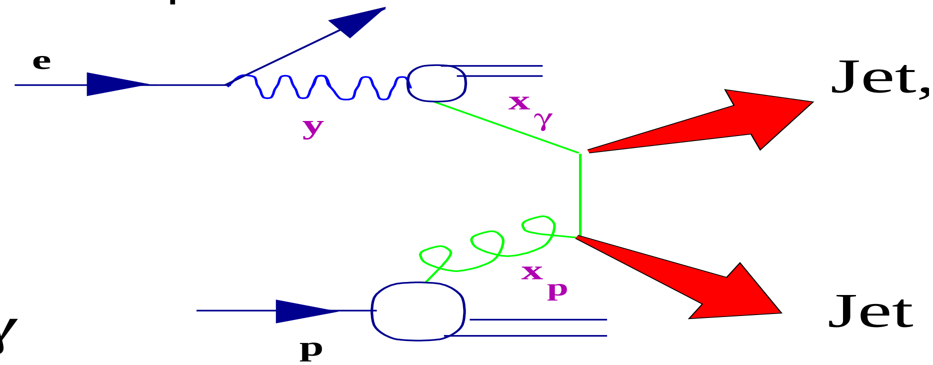


Basics

In LO in α_s we have direct and resolved processes:

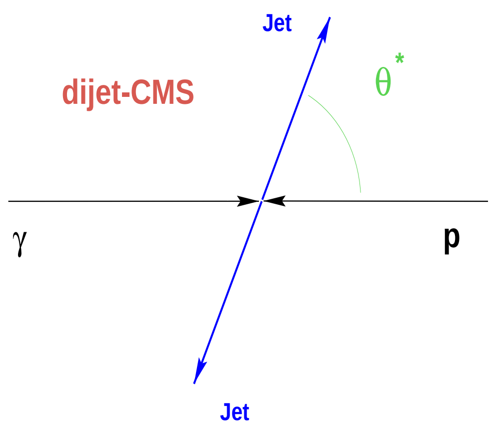


$x_\gamma \approx 1$



$x_\gamma < 1$

$$\sigma_{\mathrm{JJ}(\gamma)} = f_{\gamma/e}(y) \otimes f_{i/\gamma}(x_\gamma, \mu) \otimes f_{j/p}(x_p, \mu) \otimes \sigma_{ij}(\theta^\star, \mu)$$



- $x_\gamma = \frac{E_{\mathrm{T,jet1}} \exp^{-\eta_{\mathrm{jet1}}} + E_{\mathrm{T,jet2}} \exp^{-\eta_{\mathrm{jet2}}}}{2yE_e}$
- $x_p = \frac{E_{\mathrm{T,jet1}} \exp^{+\eta_{\mathrm{jet1}}} + E_{\mathrm{T,jet2}} \exp^{+\eta_{\mathrm{jet2}}}}{2E_p}$
- $\cos\theta^\star = \tanh\frac{\eta_{\mathrm{jet1}} - \eta_{\mathrm{jet2}}}{2}$

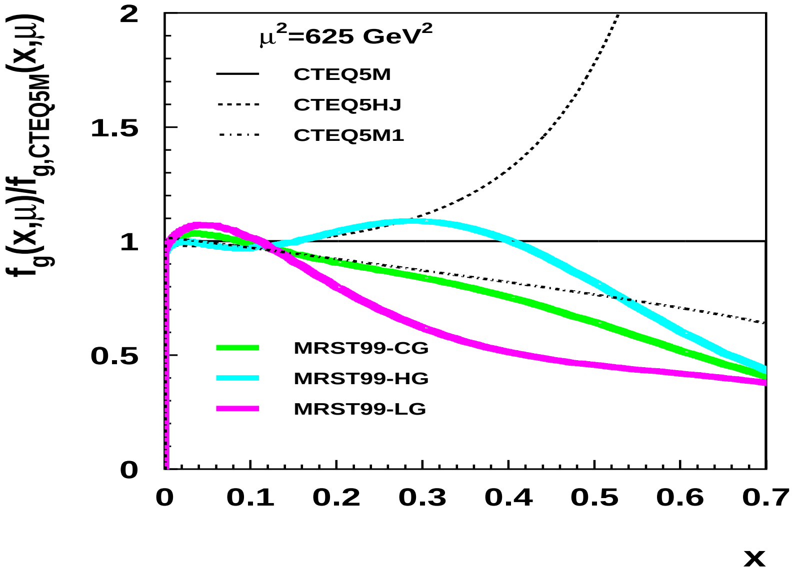
Motivation

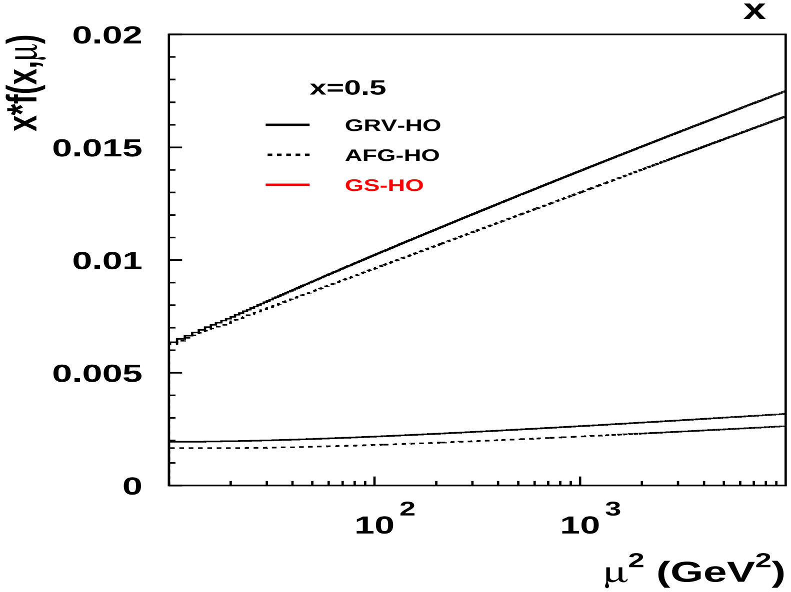
The aim is to test QCD calculations for jets and prompt photons involving:

- NLO matrix elements ($\cos\theta^{\star}$) and higher order corrections (e.g. 4-jets)
- PDFs of the photon and the proton (x_γ, $\eta_{\rm jet}$, $E_{\rm T,jet}$, x_p)

Soft 4-jet events also allow to test our understanding of models of multi-parton interactions (mpi) and soft underlying event (sue) in resolved photon interactions.

Testing PDFs: g in the Proton, q/g in the Photon





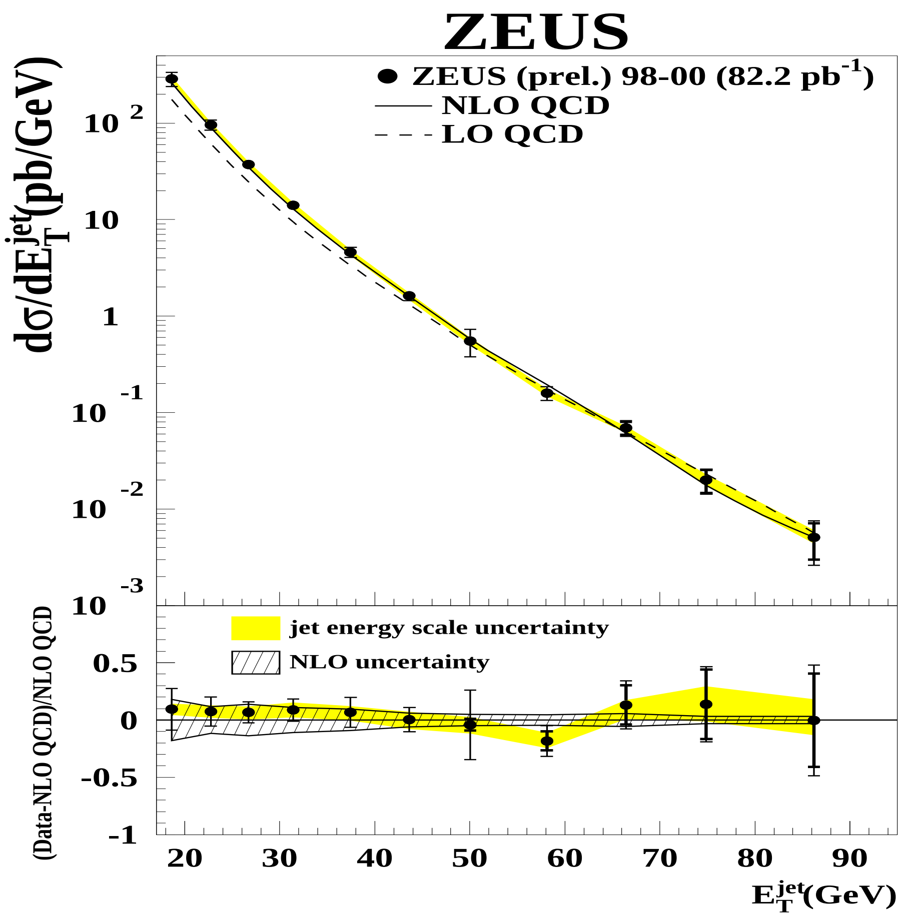
- probe partons in proton for $0.05 < x_p < 0.6$
- for large x_p gluon density uncertain by 10-50 %
- probe partons in photon for $0.1 < x_\gamma < 1.$
- $x_\gamma < 0.5$, quarks constrained by F_2^γ
- gluon poorly constrained by F_2^γ, jets at HERA sensitive to gluon already in LO
- probe scales between 25 and 75 GeV

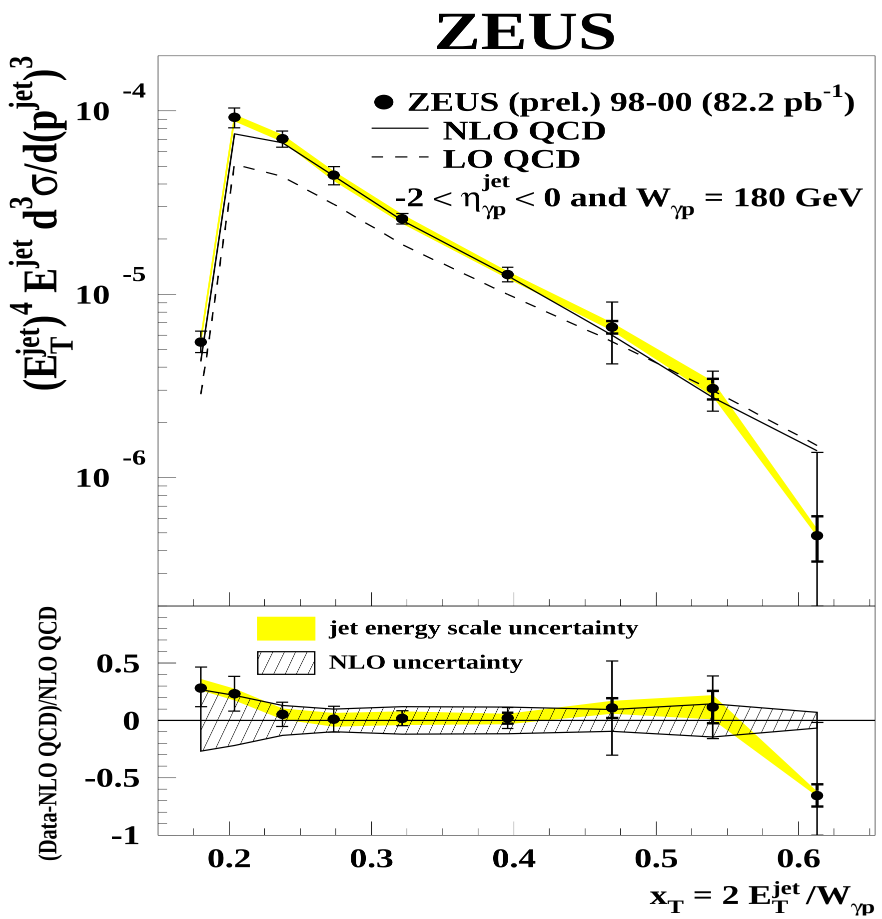
NLO Calculations

NLO calculations by Frixione and Ridolfi, by Klasen, Kramer, Kleinwort, and by Fontannaz, Guillet, Heinrich have been used for comparison with data. Typically they use the following settings:

- $N_f = 5$
- $\mu = \mu_{\rm R} = \mu_{\rm F} = \mu_\gamma = \mu_p = 1/2 \sum_{\rm partons} E_T$ or $= E_{\rm T,jet}$
- $\alpha_s(M_Z) = 0.118$
- proton pdf: CTEQ5M, MRST99, photon pdf: GRV-HO, AFG-HO
- scale dependence: vary μ up and down by factor of 2 $\rightarrow$ 10-20 % change in cross section
- NLO predictions usually corrected for hadronization effects; at high $E_{\rm T,jet}$ typically $\leq$ 10 %

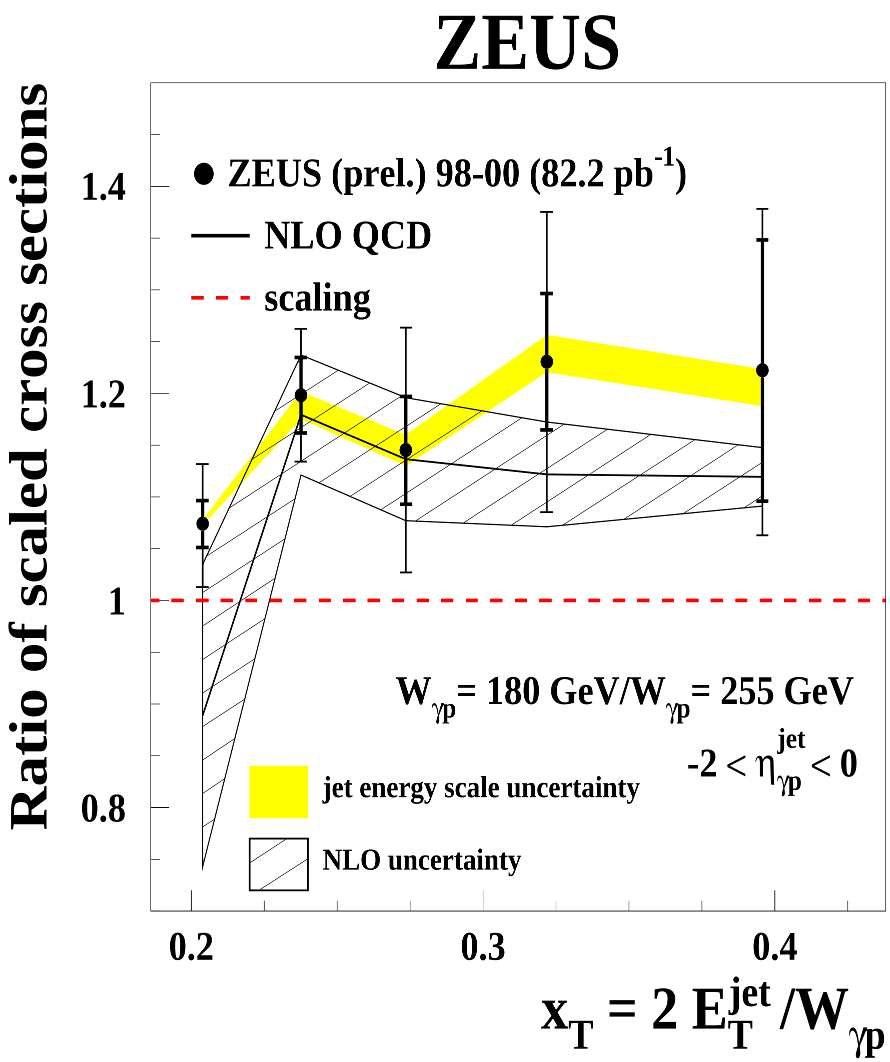
Inclusive Jets: Cross Sections vs. $E_{T,\text{jet}}$ and $x_T = \frac{2E_{T,\text{jet}}}{W_{\gamma p}}$





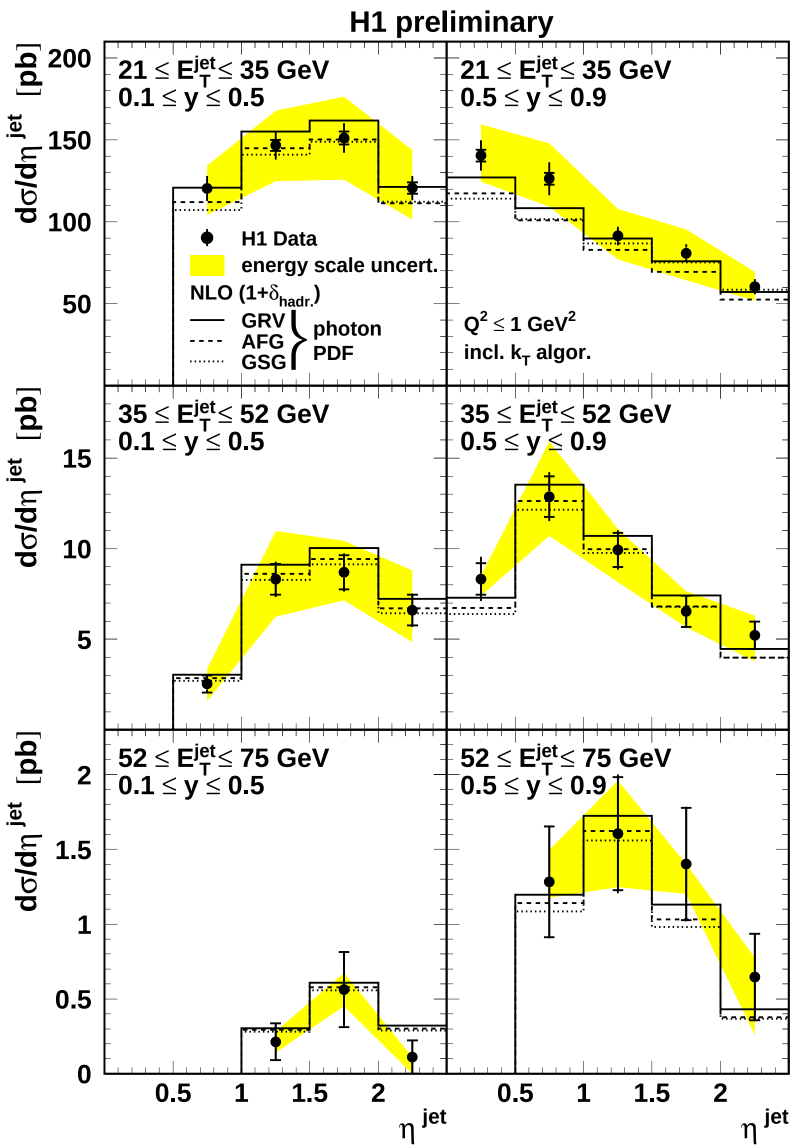
NLO QCD gives excellent description of data. Energy scale uncertainty of jets of 1 % $\rightarrow$ 5 % error on cross section. NLO uncertainty from $18 \rightarrow 3$ %.

Inclusive Jets: Test of Feynman Scaling



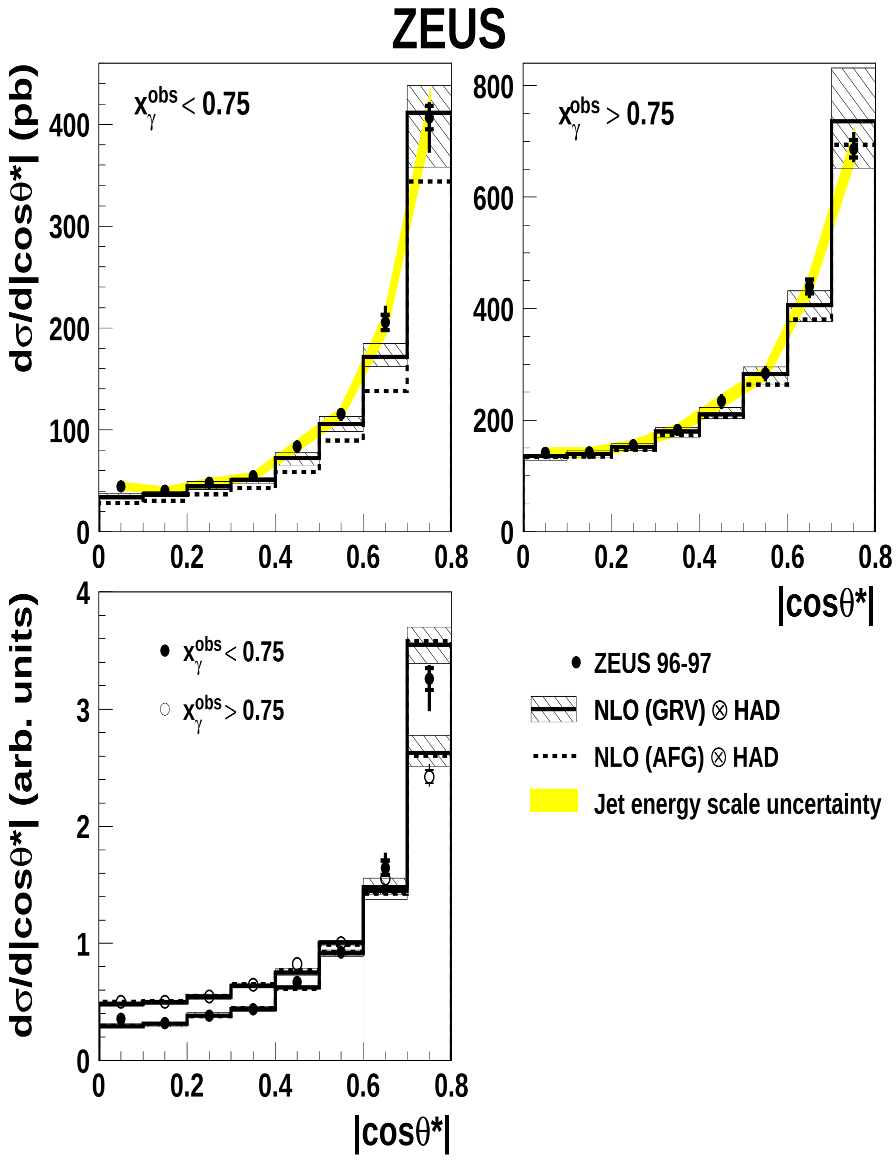
- Ratio of scaled invariant cross section as a function of x_{T} for two values of $W_{\gamma p}$
- Naive parton model predicts that the dimensionless quantity $E^4_{\mathrm{T,jet}} E_{\mathrm{T,jet}} d^3\sigma/d^3p_{\mathrm{jet}}$ as a function of x_{T}should be independent of $W_{\gamma p}$
- Data show clear violation of scaling in agreement with expectations from NLO QCD

Inclusive Jets: Cross Sections as a Function of $\eta_{\rm jet}$



- $E_{\rm T,jet} \geq 21$ GeV
- $x_\gamma = (\sum E_T \exp^{-\eta})/(2yE_e)$
- differences in photon pdfs and therefore in x_γ should be visible in $\eta_{\rm jet}$ for restricted ranges in y and $E_{\rm T,jet}$
- divide data in two y regions and three $E_{\rm T,jet}$ regions
- NLO QCD with GRV-HO gives best description of the data

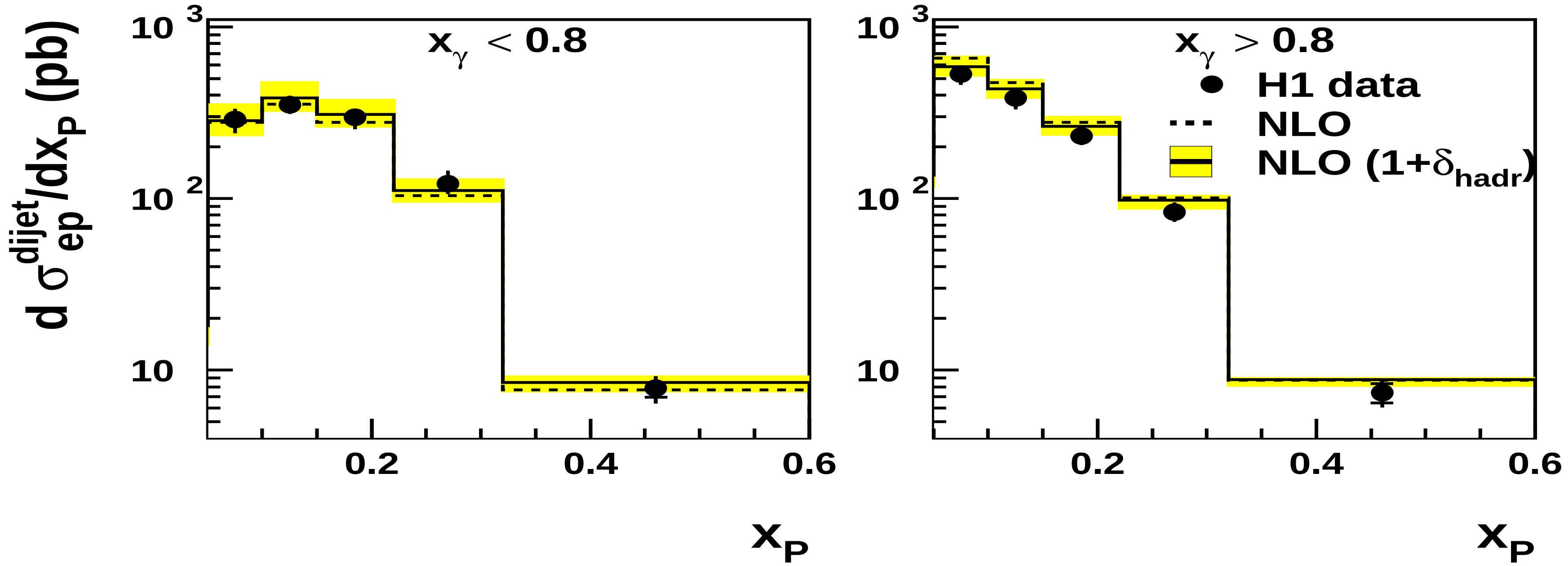
Dijets: Cross Sections as a Function of $|\cos\theta^\star|$



$E_{\mathrm{T,jet1}} > 14$ GeV, $E_{\mathrm{T,jet2}} > 11$ GeV, $M_{\mathrm{JJ}} > 42$ GeV

- errors on data 5 to 10 %
- errors on NLO QCD 5 to 10 %
- NLO QCD can describe angular dependence
- shapes consistent with expectations from dominant propagators "gluon" $\sim (1 - |\cos\theta^\star|)^{-2}$ and "quark" $\sim (1 - |\cos\theta^\star|)^{-1}$

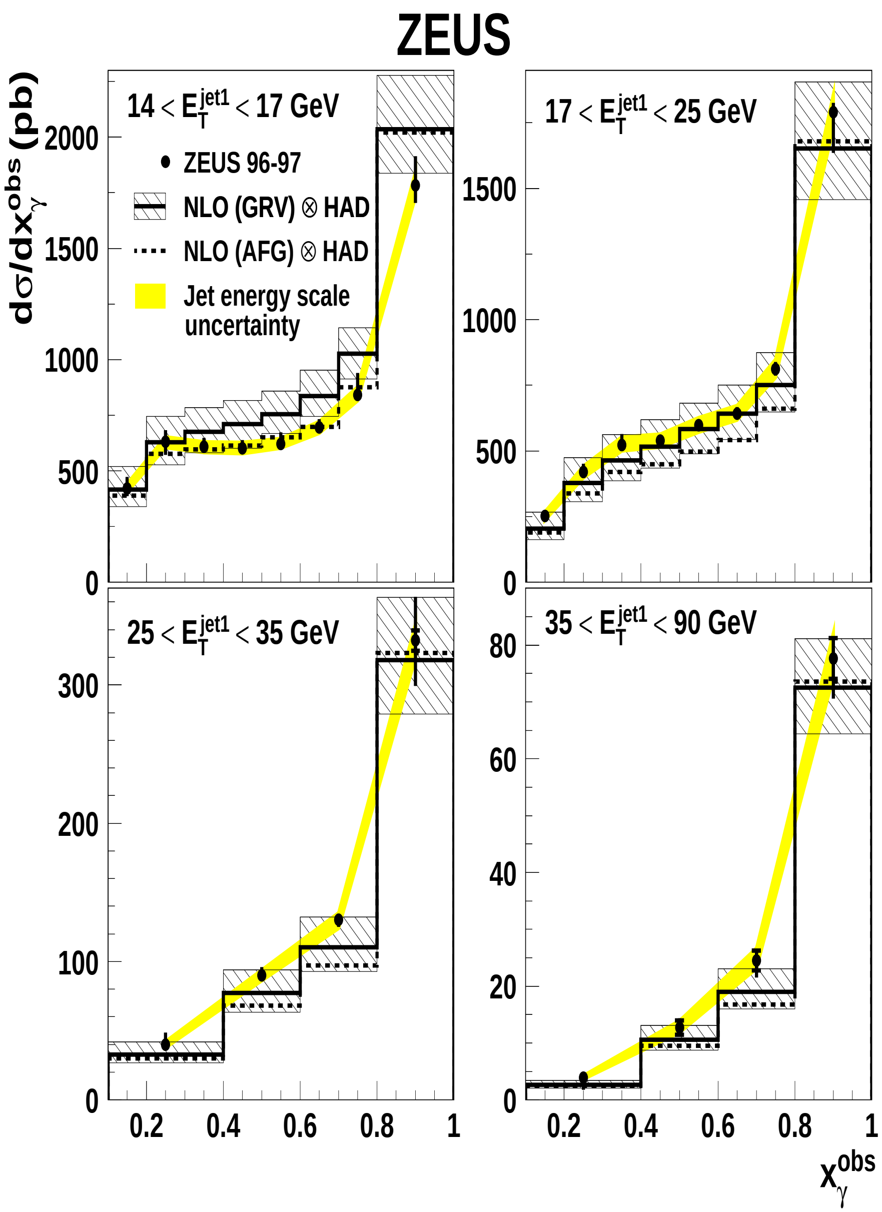
Dijets: Cross Sections as a Function of x_p



- $E_{\mathrm{T,jet1}} > 25$ GeV, $E_{\mathrm{T,jet2}} > 15$ GeV
- ≈ 35 % gluon induced at $x_p \approx 0.4$
- $x_p < 0.1$: <5 % diff. between CTEQ5M and MRST ($g \uparrow, g \downarrow$)
- $x_p > 0.1$: 15 % diff. between CTEQ5M and MRST ($g \uparrow, g \downarrow$)
- NLO scale uncertainty dominant

$\Rightarrow$ data sensitive to high x_p gluon in proton; interesting for future high luminosity at HERA

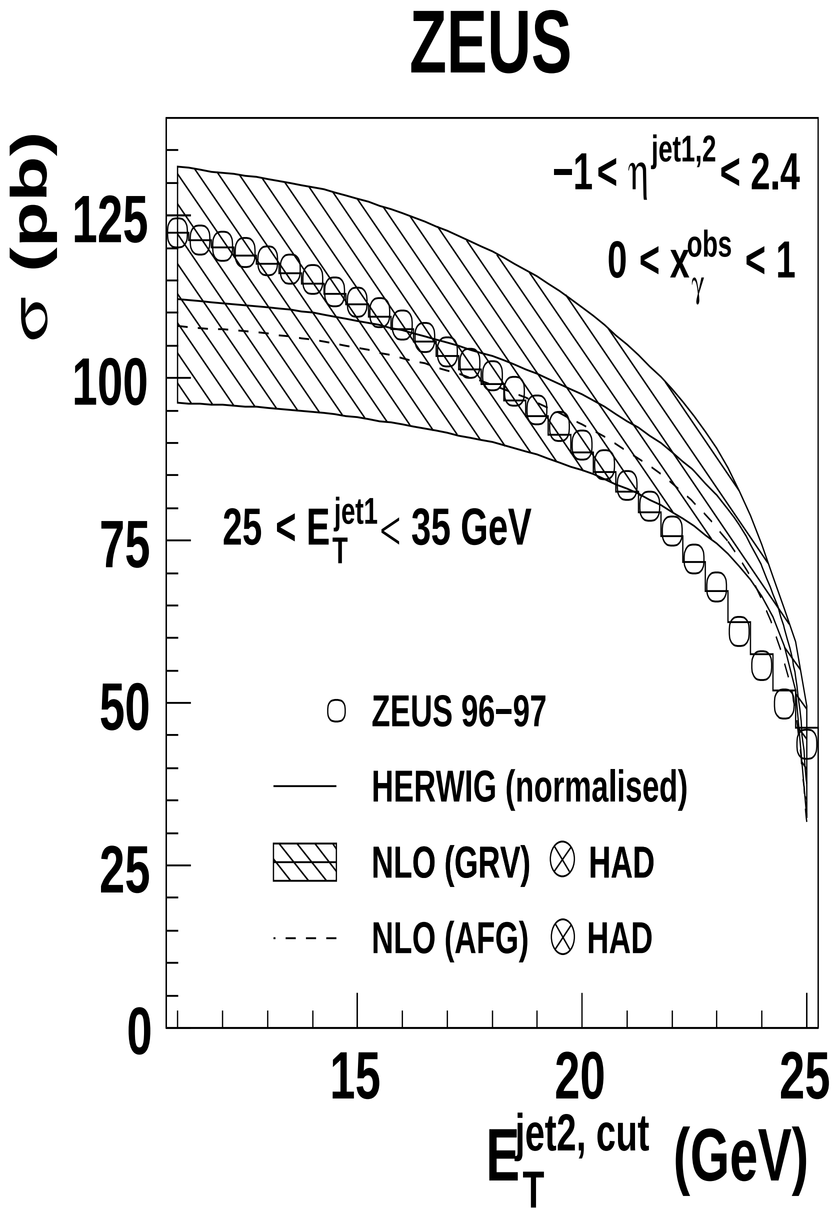
Dijets: Cross Sections as a Function of x_γ



$E_{T,jet1} > 14$ GeV,
$E_{T,jet2} > 11$ GeV

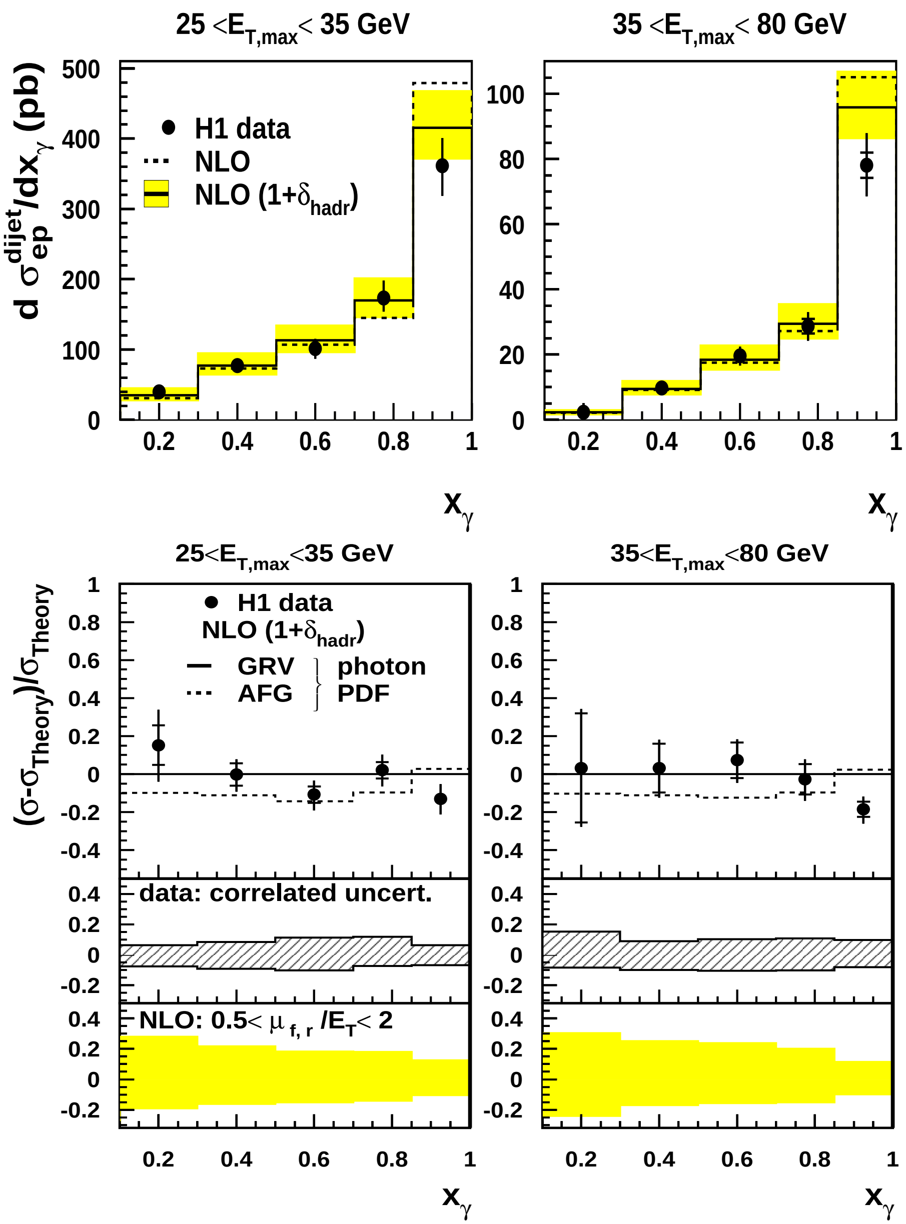
- NLO QCD descibes the data not too badly overall
- neither GRV nor AFG pdfs provide a perfect description everywhere
- are the existing pdfs inadequate?

Dijets: Sensitivity of NLO Calculations to $E_{\mathrm{T,jet}}$ Cuts



- asymmetric $E_{\mathrm{T,jet1}}/E_{\mathrm{T,jet2}}$ cuts to avoid IR sensitivity of NLO calc.
  - ZEUS: $E_{\mathrm{T,jet2}} > 11$ GeV
  - H1: $E_{\mathrm{T,jet2}} > 15$ GeV
- dependence on $E_{\mathrm{T,jet2}}$ significantly different for data and NLO prediction
- HERWIG (LO + LL parton showers) describes dependence quite well
- theoretical progress needed

Dijets: Cross Sections as a Function of x_γ



$E_{\mathrm{T,jet1}} > 25$ GeV,
$E_{\mathrm{T,jet2}} > 15$ GeV

- NLO descibes the data well
- GRV or AFG pdfs can describe the data everywhere
- existing pdfs are adequate to describe the data
- NLO scale uncertainties are the dominant errors

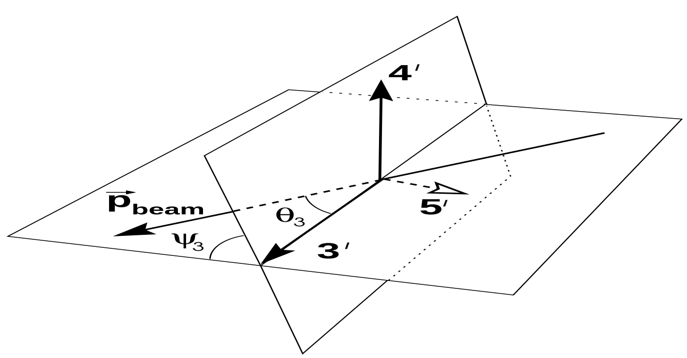
Multijets - 4 Jets

- events with 4 jets from a hard interaction are of $O(\alpha_s^3)$ in LO

- in resolved events they may arise from additional interactions between partons of the p and γ remnant (multi-parton interactions (mpi))

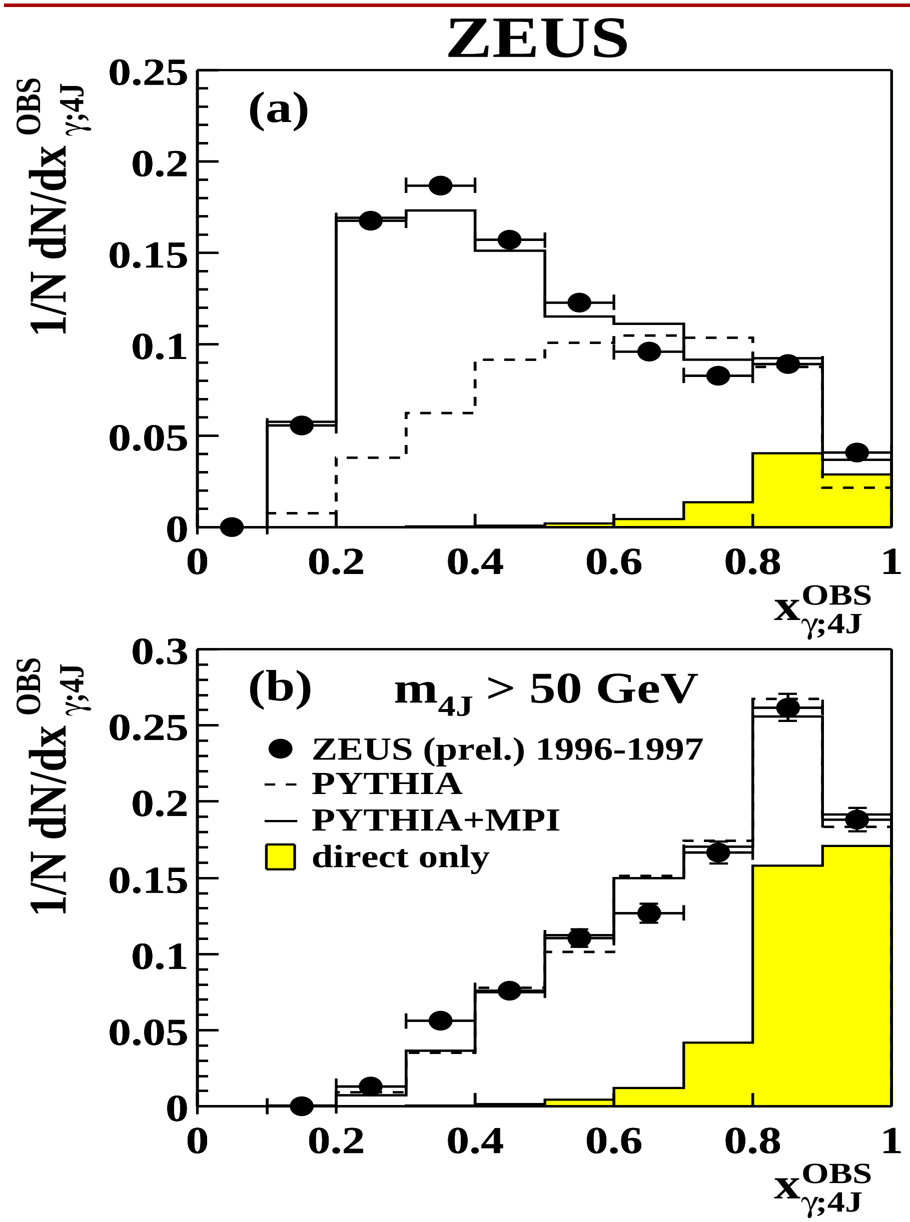
- mpi are looked for in events with 4 jets ($1+2 \rightarrow 3+4+5+6$) at low x_γ i.e. $x_{\gamma,4\mathrm{J}} = (\sum_3^6 E_{\mathrm{T,jet}} \exp^{-\eta_{\mathrm{jet}}})/(2yE_e)$

- for simplicity, the 4 jets are mapped onto three by combining the two jets of lowest invariant mass into one jet; the remaining three jets are relabelled 3', 4', and 5' in order of decreasing energy



- resulting "3-jet" system described by two angles, $\cos\theta_3$ and ψ_3, and energy fractions $X_{3'} = 2E_{3'}/M_{4J}$ and $X_{4'} = 2E_{4'}/M_{4J}$

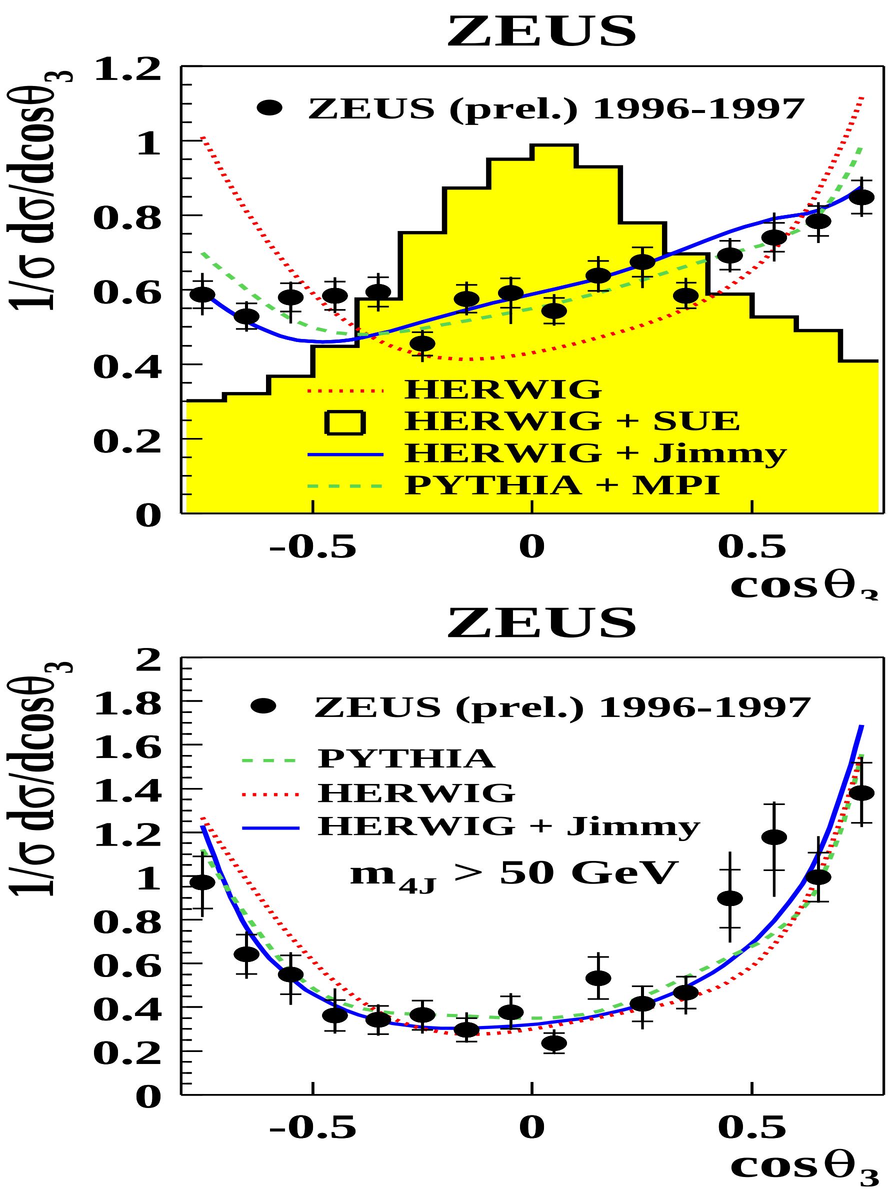
Multijets: x_γ Distribution



$E_{T,jet}^{3,4} > 6$ GeV, $E_{T,jet}^{5,6} > 5$ GeV

- the inclusive data show a clear enhancement at low x_γ and can be better described with the inclusion of multi-parton interactions
- the high mass data sample shows little difference between PYTHIA with or without mpi, indicating that mpi have little effect in this highly perturbative region

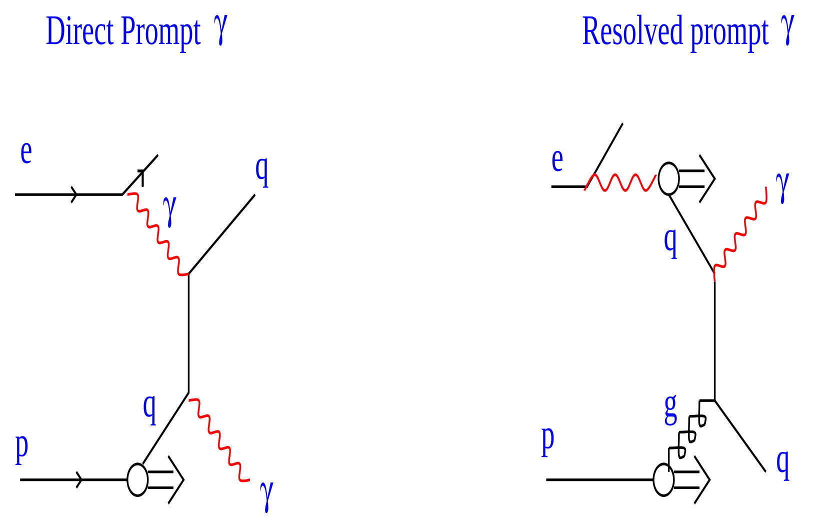
Multijets: Normalized Cross Section vs. $\cos\theta_3$



- the soft underlying event option of HERWIG fails to describe the data
- mpi must be included in models to describe the inclusive data
- including mpi makes little or no difference in describing the high mass data sample

Prompt Photons

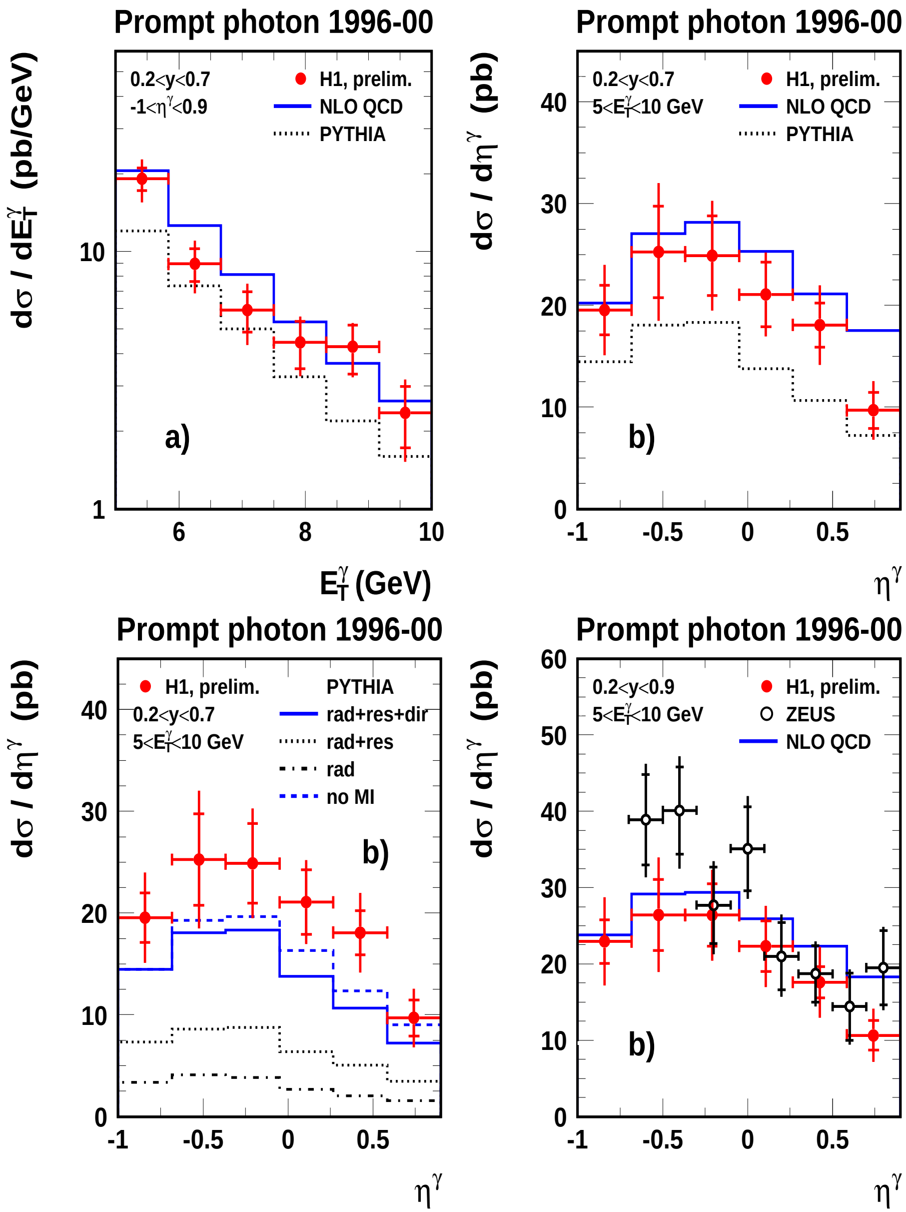
- prompt photons can be produced in direct and resolved interactions; they probe most sensitively our understanding at the parton level
- photons are also produced radiatively and in fragmentation
- photons are most copiously produced in the decays of π^0 's and η 's
- look for photons which are isolated
- use shower shape variables for photons, π^0 's, and η 's in a likelihood analysis



Prompt γ selection:

- $5 < E_T^\gamma < 10$ GeV
- $-1 < \eta^\gamma < 0.9$
- isolation cone: $E_T^{\text{cone}}/E_T^\gamma < 0.1$

Prompt Photons: Cross Sections vs. E_T^γ and η^γ



- NLO describes the data within errors
- PYTHIA: shape ok, but normalization off
- PYTHIA indicates effect of multi-parton interactions (MI) at large η^γ; would reduce NLO prediction
- comparison with ZEUS: lower at low η^γ

Summary

- Achieved good understanding of jets in γp and DIS at HERA
- NLO with photon pdfs from $\gamma\gamma^\star$ scattering able to describe jet and prompt photon data
- Experimental error now often $<$ theoretical error
- Data provide information on gluon density in the photon and proton at large x and scales
- Theoretical progress needed to match achieved experimental precision
- HERA II: much more data $\longrightarrow$ high $E_{\mathrm{T,jet}}$, high x