Low Q^2 Physics at HERA

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On Behalf of the H1 and ZEUS Collaborations

- **Introduction**
- **High E_T dijets in photoproduction ($Q^2 \sim 0$)**
- **Low E_T dijets in low Q^2 region**
- **Summary**

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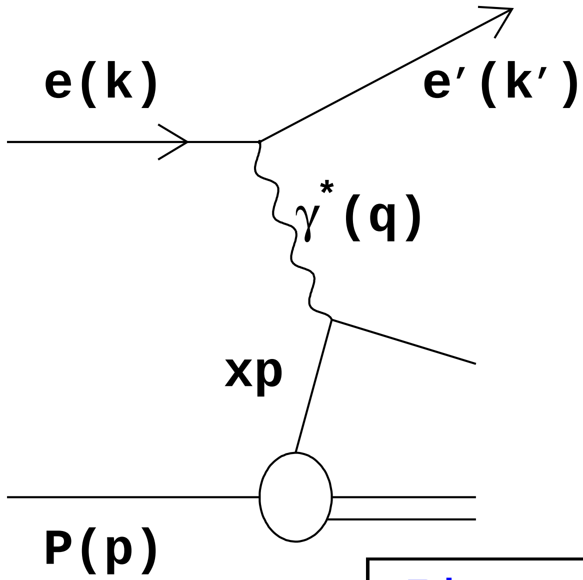
Deep Inelastic Scattering

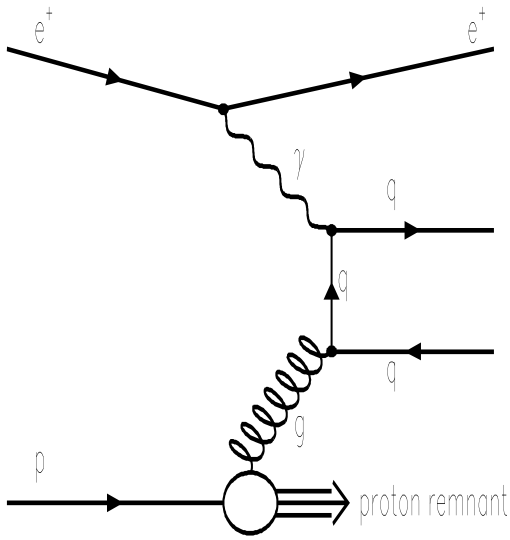
$Q^2 >> 1 GeV^2$: probing proton structure via pointlike virtual photons



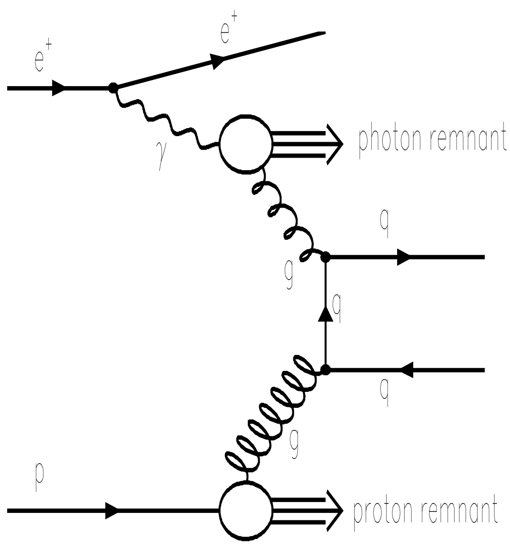
$$Q^2 = -q^2$$
$$y = \frac{q \cdot p}{k \cdot p}$$
$$Q^2 = sxy$$
$$W^2 = Q^2 \left(\frac{1-x}{x}\right)$$

Photoproduction

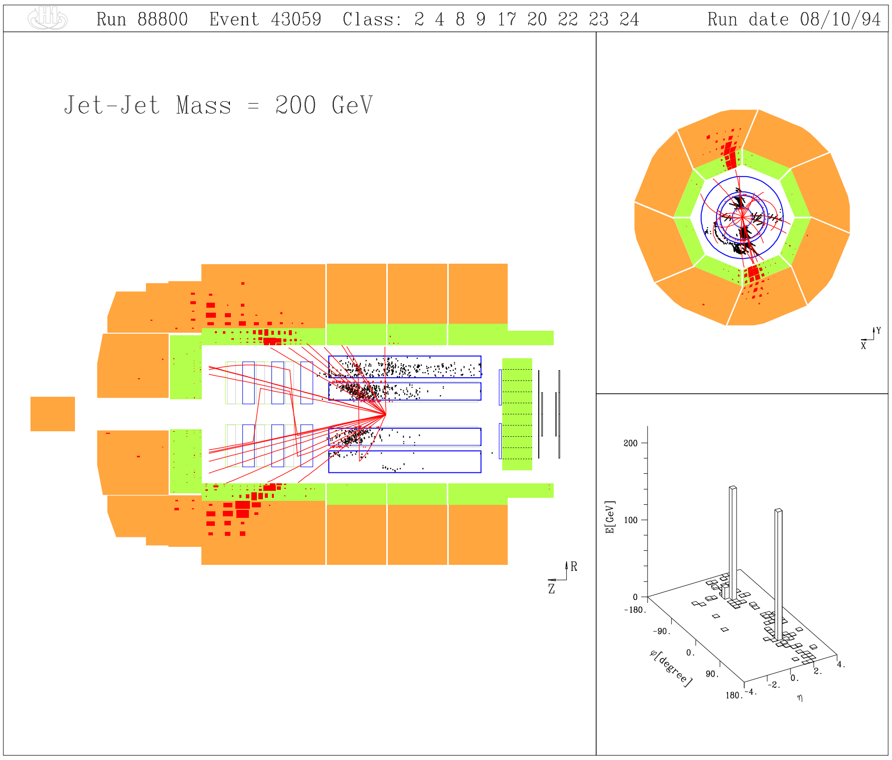
$Q^2 \simeq 0$: probing photon structure via dijet system



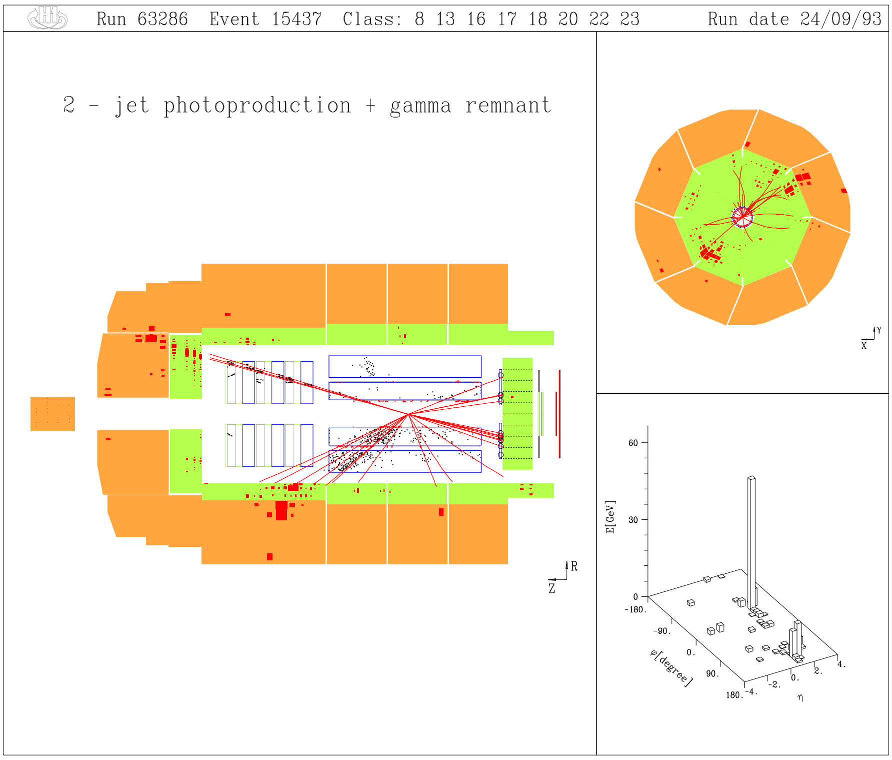
$x_\gamma = 1$



$x_\gamma < 1$



direct photon event



resolved photon event

σ_{ep} is convolution of partonic cross sections and pdf's:

$$\frac{d\sigma_{ep}}{dQ^2} = \gamma_{flux}(y, Q^2) \otimes PDF_{\gamma}(x_{\gamma}, Q^2, \mu) \otimes PDF_p(x_p, \mu) \otimes d\sigma_{ij}(\theta^*, Q^2, \mu)$$

- x_γ (x_p) - fraction of γ^*'s (proton's) momentum in hard subprocess

$$x_\gamma = \frac{\sum_{jets} E_{T,i} e^{-\eta_i}}{2yE_e} \quad \text{or} \quad \frac{\sum_{jets}(E_i - p_{z,i})}{\sum_{had}(E_h - p_{z,h})}$$

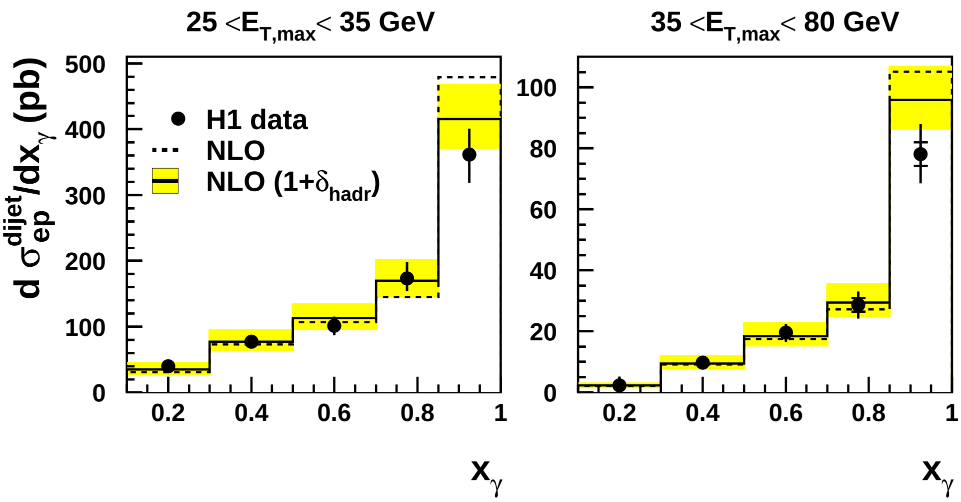
$$x_p = \frac{\sum_{jets} E_{T,i} e^{\eta_i}}{2E_p}$$

- Q^2 - virtuality of γ^* and y - inelasticity
- E_T, η - transverse momentum and pseudorapidity of jets
- θ^* angle of dijet system in 2–jet CMS
- $\mu \rightarrow E_T$ is the hard scale

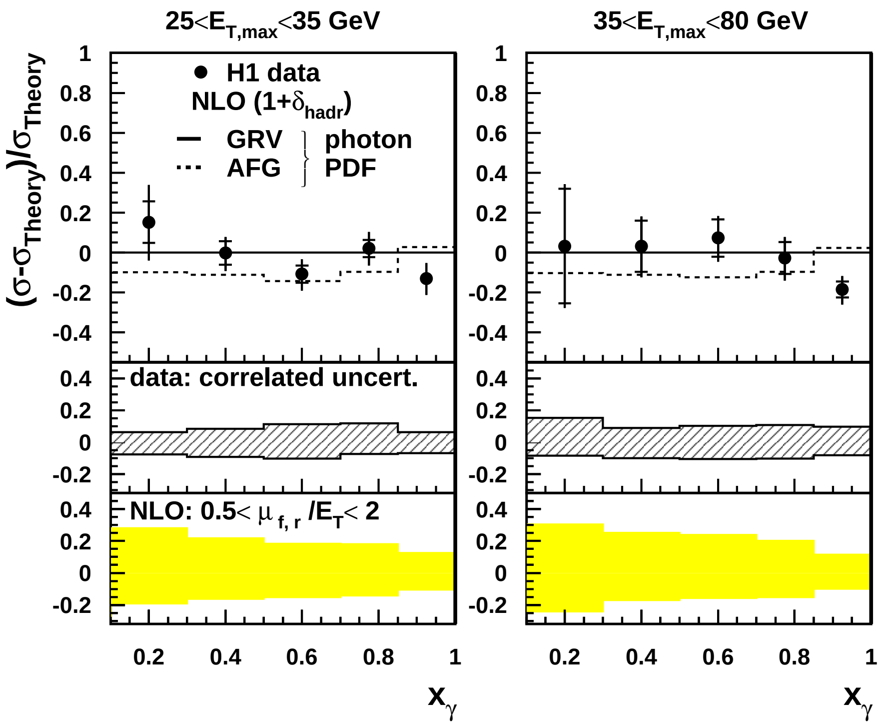
High E_T dijets → motivation

- high E_T jets provide hard scale for perturbative QCD calculations
- soft physics suppressed (hadronization corrections small)
- test perturbative QCD at NLO
- test parametrizations of proton pdf
  → gluon in the proton, 0.05< x_p <0.6
- test parametrizations of photon pdf
  → q/g in the photon, 0.1< x_γ <1
  gluon poorly constrained by F_2^γ,
  jets at HERA sensitive to gluons already at LO

Dijets in photoproduction: H1



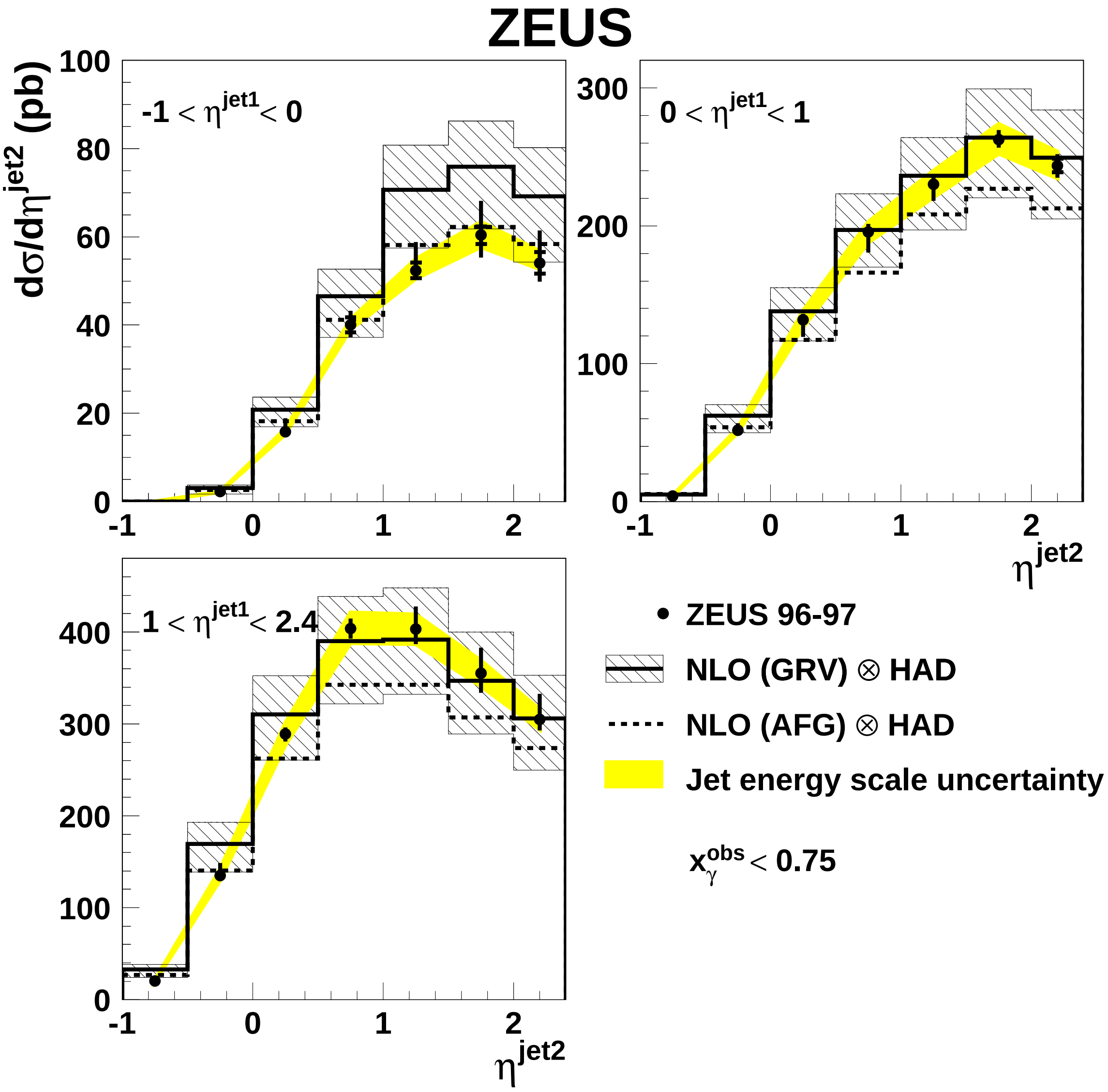
- $E_T^{jet1} > 25$, $E_T^{jet2} > 15$ GeV



- NLO with GRV and AFG pdf's describe data
- NLO scale uncertaintes dominate

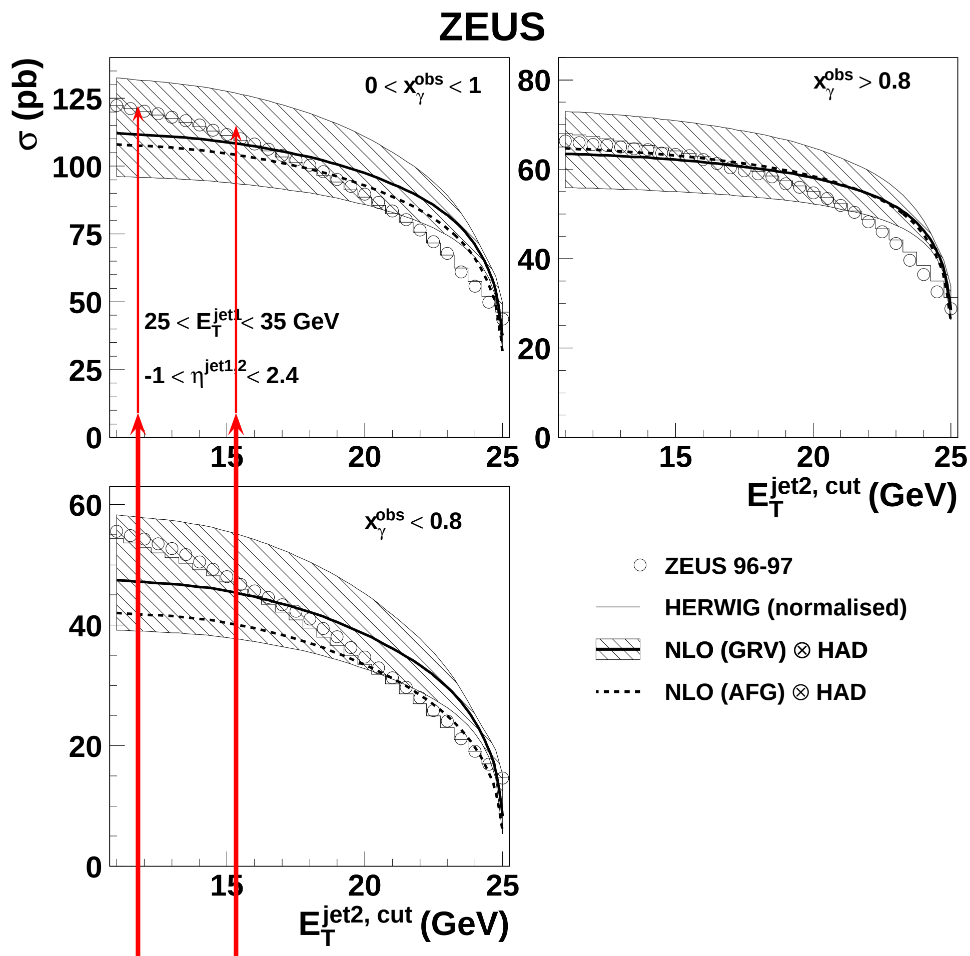
Dijets in photoproduction: ZEUS

- $E_T^{jet1} > 14$, $E_T^{jet2} > 11$ GeV



- NLO describes the data not too bad overall
- neither GRV nor AFG pdf's provide a perfect description everywhere

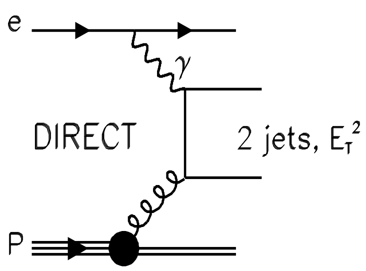
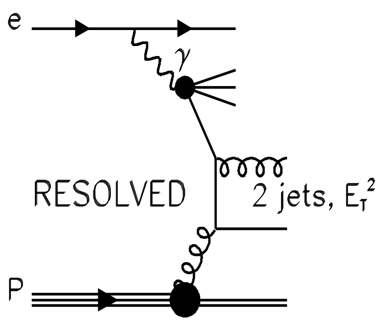
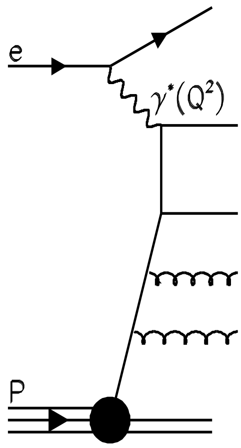
Dijets in photoproduction: ZEUS



ZEUS: E_T^{jet2} >11 GeV
H1: E_T^{jet2} >15 GeV

- assymetric E_T^{jet1}/E_T^{jet2} cuts to avoid infrared sensitivity of NLO calculations
- dependence on E_T^{jet2} significantly different for data and NLO prediction, HERWIG describes dependence well
- comparison data & NLO depends on the cut value, theoretical progress needed!!

Different regimes and scales at HERA

PHOTOPRODUCTION $E_T^2 >> Q^2 \sim 0$	LOW Q^2 $E_T^2 > Q^2 > 0$	D.I.S. ON PROTON $Q^2 >> m_p^2$
 	?	

- what are possible concepts in the region where $E_T^2 > Q^2 > 0$?

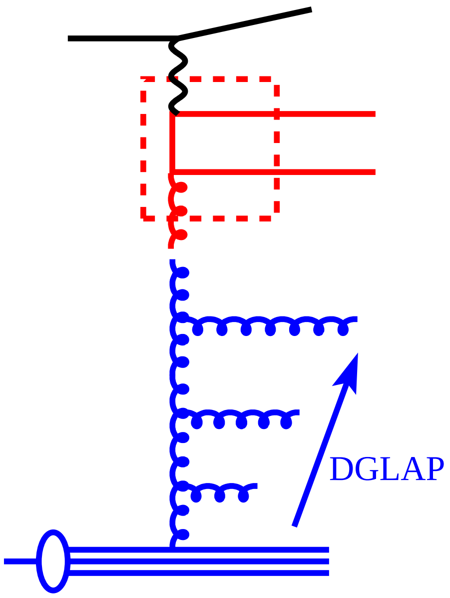
Low E_T jets in low Q^2

Concepts and questions

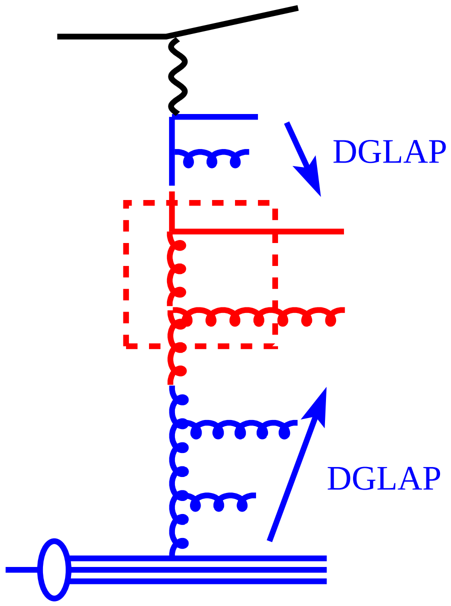
- Experimentally more challenging than study of high E_T jets (soft underlying event, hadronization corrections)
- Formally, when $Q^2 < E_T^2$ photon can be considered to have resolved structure
- Possible contribution of longitudinally polarized resolved photons?
- What are the scales in NLO calculations? E_T^2 or $E_T^2 + Q^2$ or Q^2?
  Are the data described by NLO?
- Is the concept of the resolved photons with the photon structure function the only possibility how to describe the data?

CCFM approach, DGLAP → BFKL

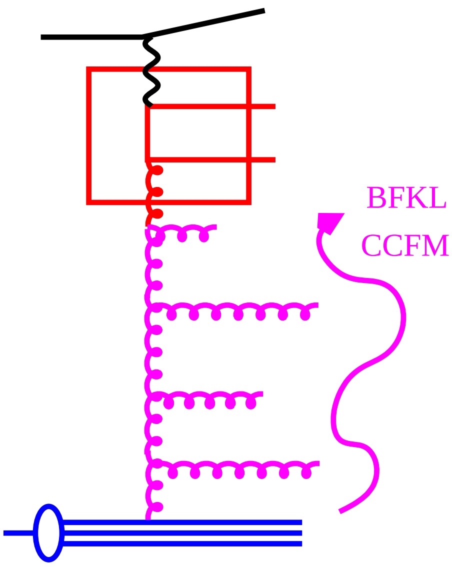
DGLAP
single ladder ordered in E_T
LO



DGLAP
2 ladders each ordered in E_T
resolved photon



BFKL CCFM
ordered in energy/angle
k_t – factorization



Unordered parton evolution allows the two highest E_T jets in an event to come from anywhere along the ladder.
Similar to resolved photon but without explicit photon structure

Theoretical tools

- **NLO calculations:**
  without resolved component → DISASTER, DISENT,
  with the resolved component → JETVIP
- **CASCADE Monte Carlo model with the conception of CCFM approach**
- **HERWIG, RAPGAP Monte Carlo models (direct + resolved contributions)**
- **HERWIG with longitudinal component of γ^* pdf**

Resolved Processes: Difference between γ_T^* and γ_L^*

- Photon fluxes:

$$f_{\gamma^T/e}(y,Q^2) = \frac{\alpha}{2\pi}\left[\frac{2(1-y)+y^2}{y}\frac{1}{Q^2} - \frac{2m_e^2 y}{Q^4}\right]$$
$$f_{\gamma^L/e}(y,Q^2) = \frac{\alpha}{2\pi}\left[\frac{2(1-y)}{y}\frac{1}{Q^2}\right]$$

Note that for $Q^2 \gg m_e$:

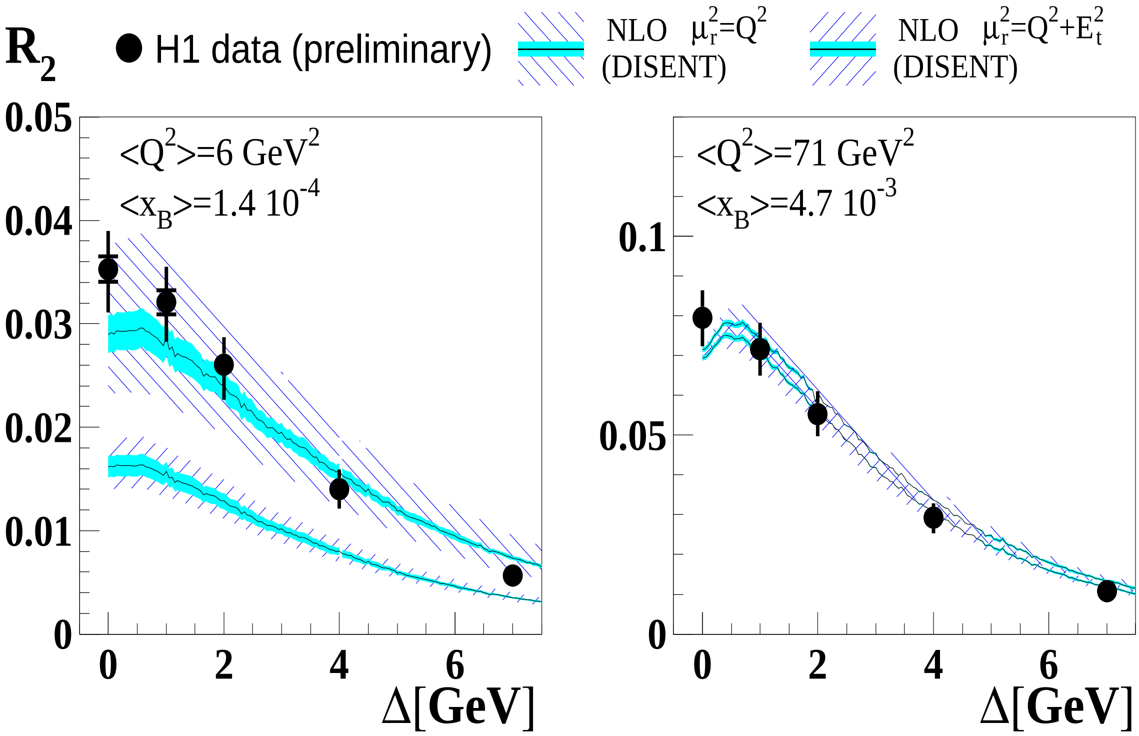
$$y = 0 \implies f_{\gamma^L/e} = f_{\gamma^T/e}$$
$$y = 1 \implies f_{\gamma^L/e} = 0$$

- **adding of longitudinal component → different dependence of cross section on inelasticity y**

Dijet rates in low Q^2 - H1

- dependence of dijet rate $R_2 = \sigma_{2jets}/\sigma$ on Δ, $E_T^{jet1} > (5+\Delta)$GeV
- two scales in NLO calculations: $E_T^2 + Q^2$ and Q^2

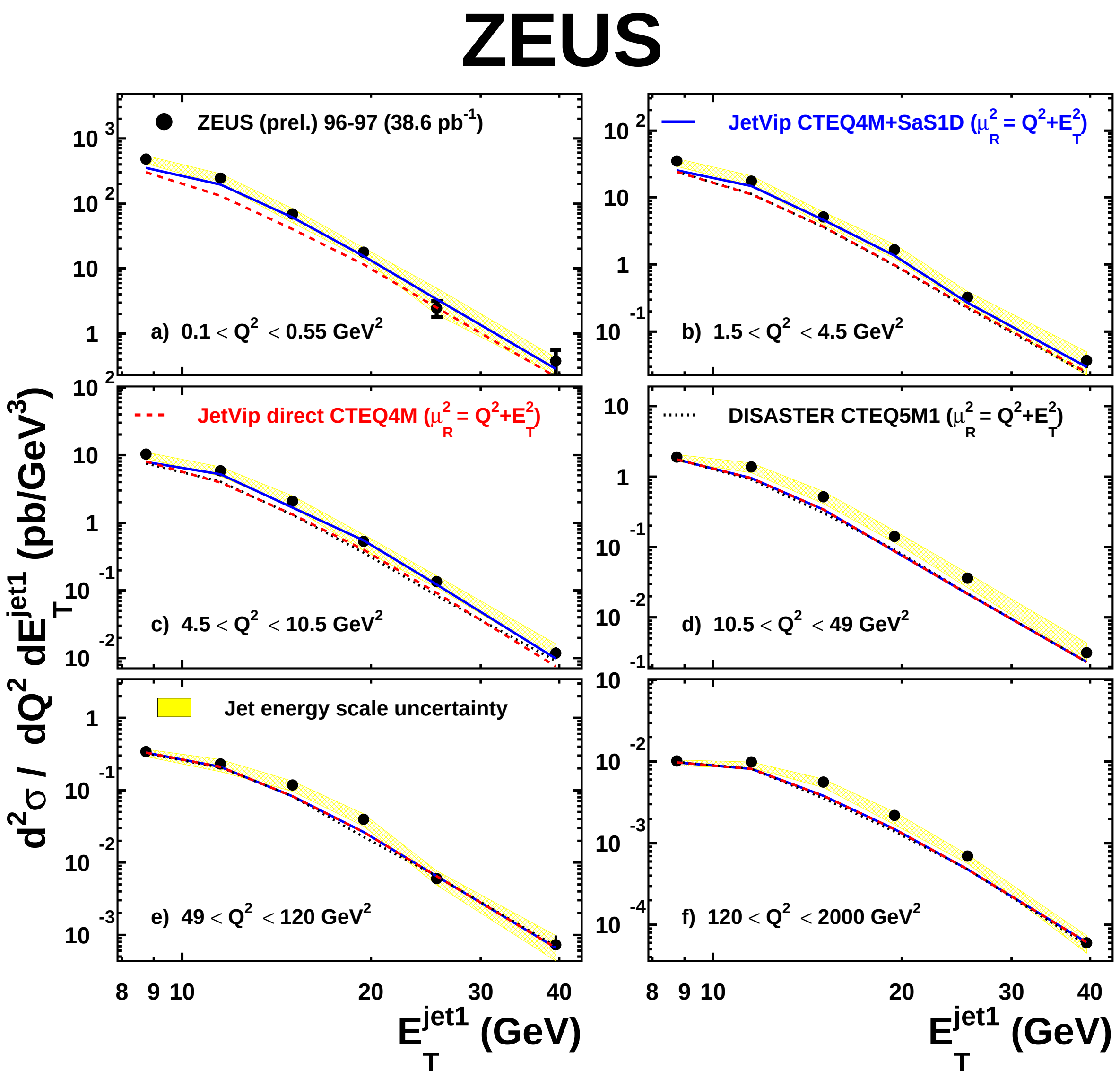
Δ dependence of R_2 for two bins of x_B and Q^2



- for $\Delta \to 0$ NLO calculations infrared sensitive
- dijet rate is described by NLO only with Q^2 scale

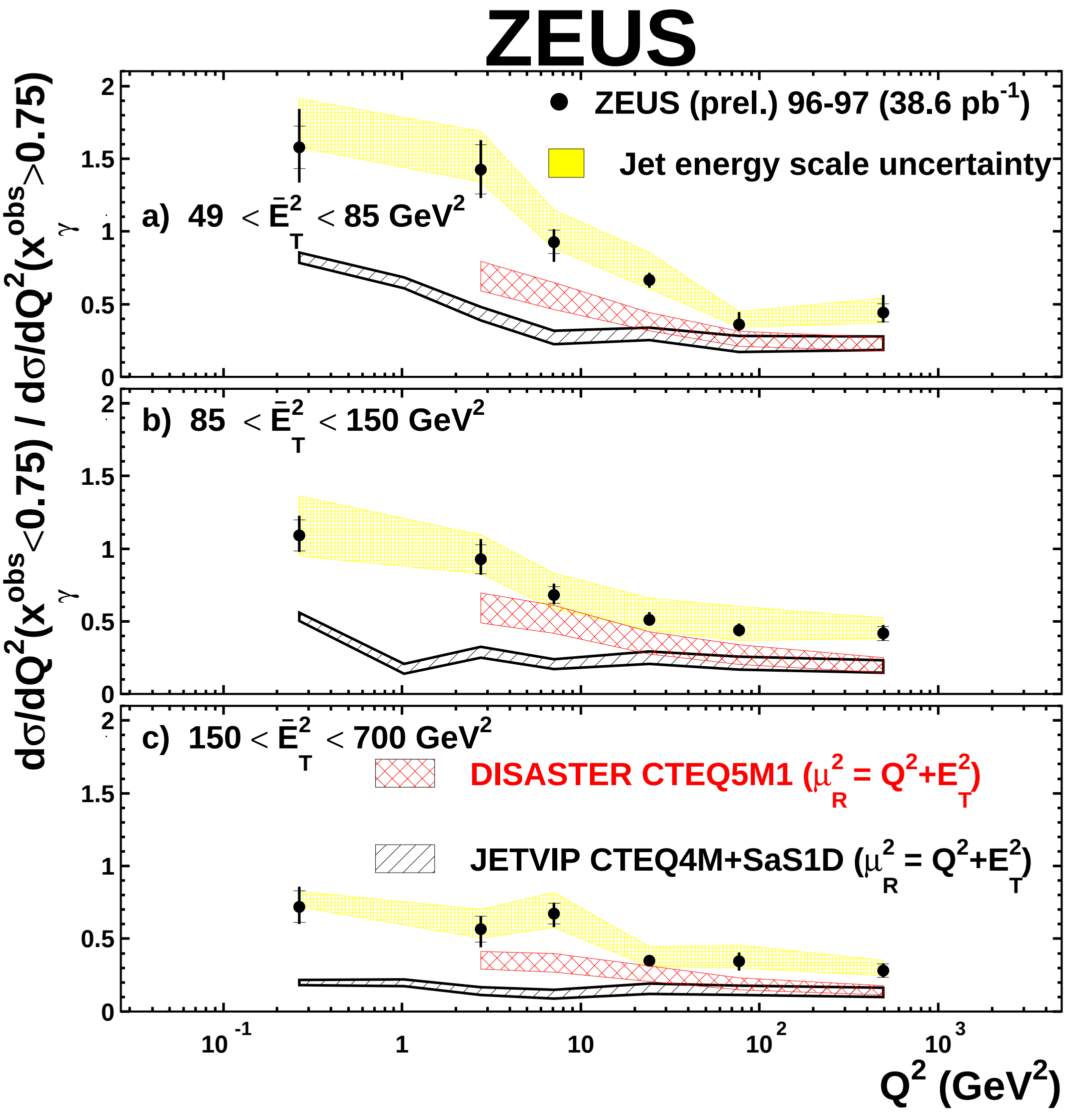
Dijets in low Q^2 - ZEUS

- $E_T^{jet1} > 7$ GeV, $E_T^{jet2} > 5$ GeV, -2.5< η <0
- NLO calculations: scale $E_T^2 + Q^2$



- NLO calculations underestimate the data
- the predictions of JETVIP with resolved comp. are closer to data than DISASTER and JETVIP direct especially for low Q^2 region

Dijets in low Q^2 - ZEUS

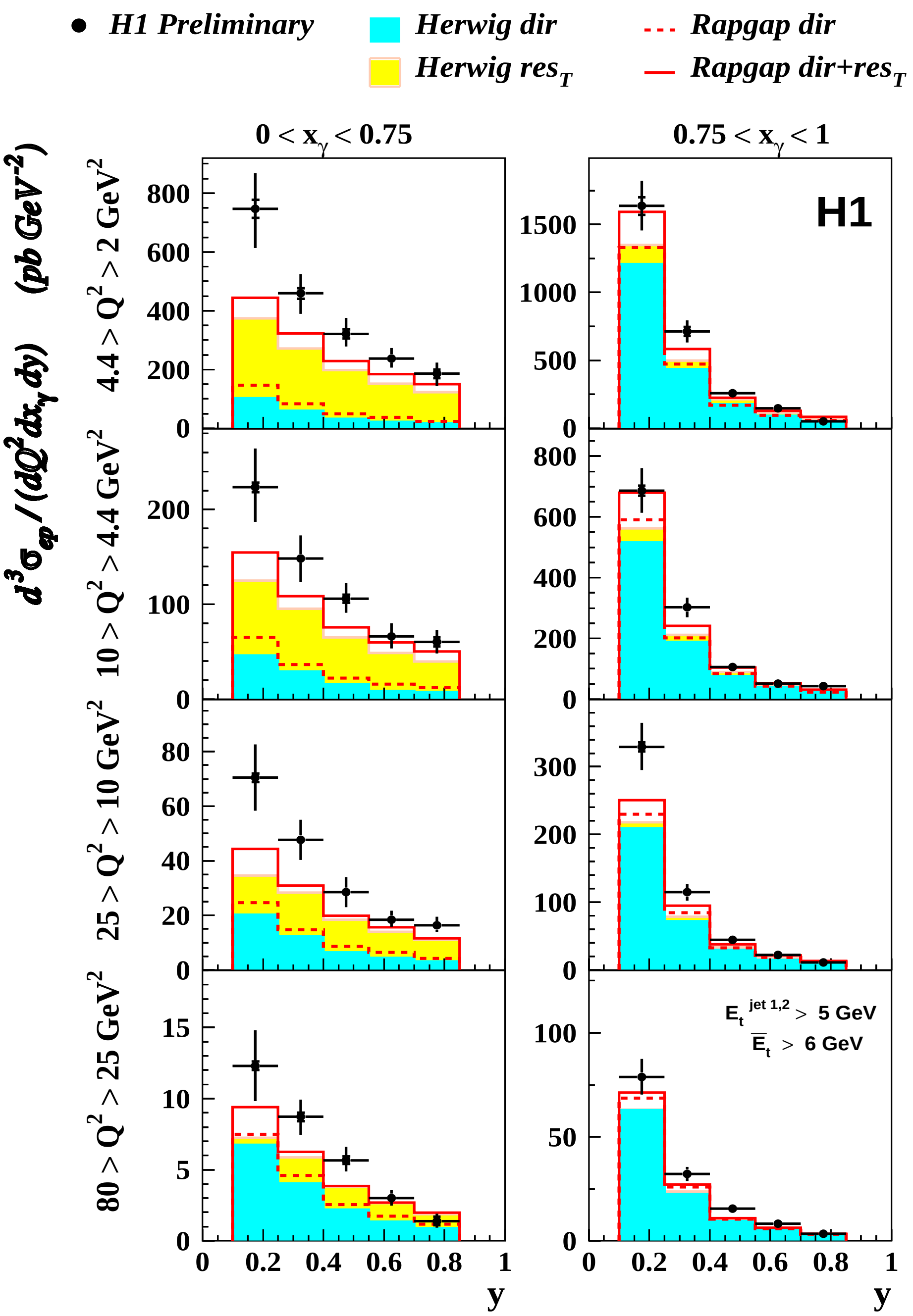


- calculations significantly underestimate measured R for $Q^2 < E_T^2$
- JETVIP with resolved component describes data less well than DISASTER (moreover JETVIP slicing method has some problems – see for example DIS2000)

Dijets in low Q^2 - H1

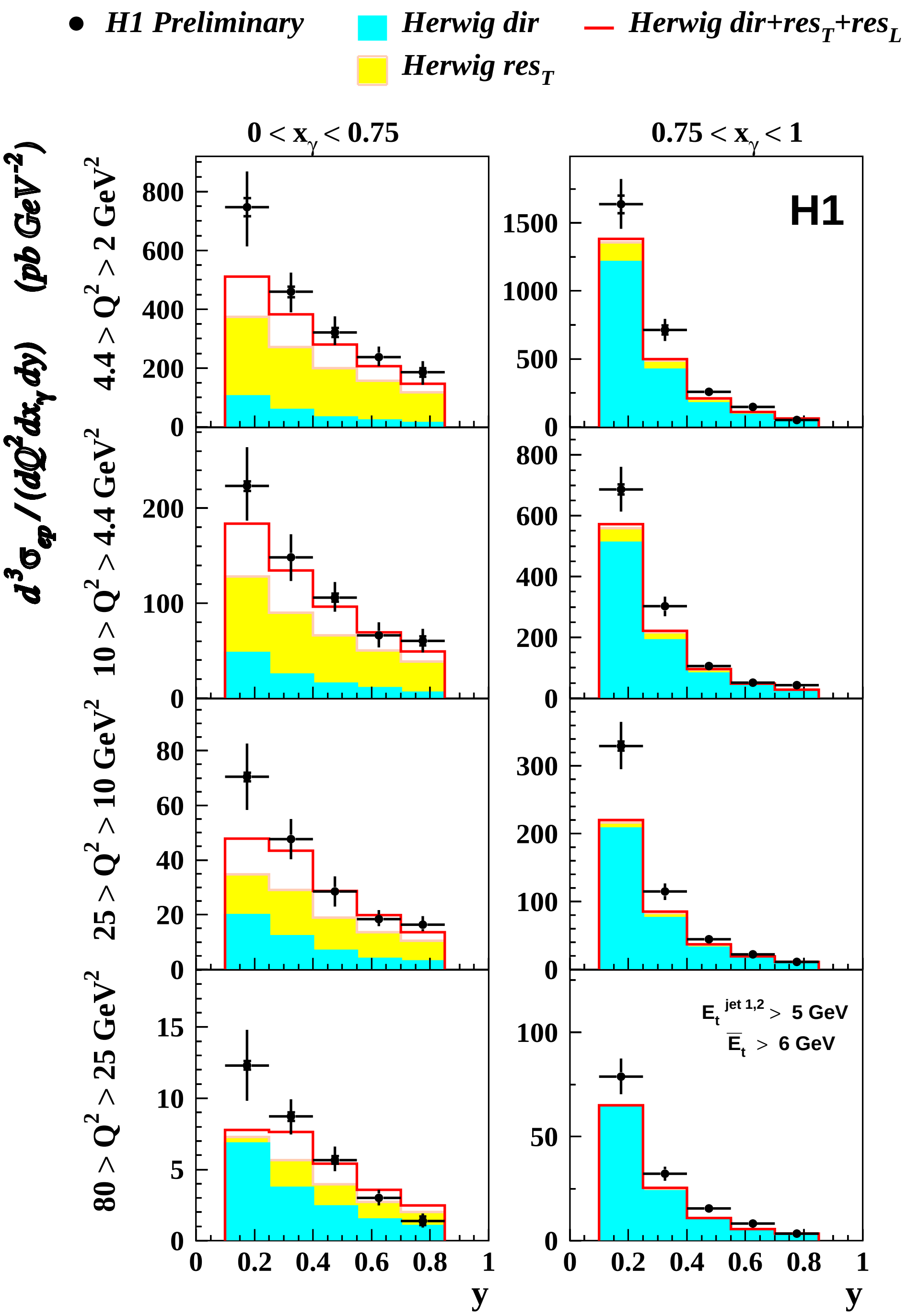
- $E_T^{jet1,2} > 5$ GeV, $\bar{E}_T > 6$ GeV, -2.5< $\eta^{jet1,2}$ <0

LO Monte Carlo HERWIG and RAPGAP



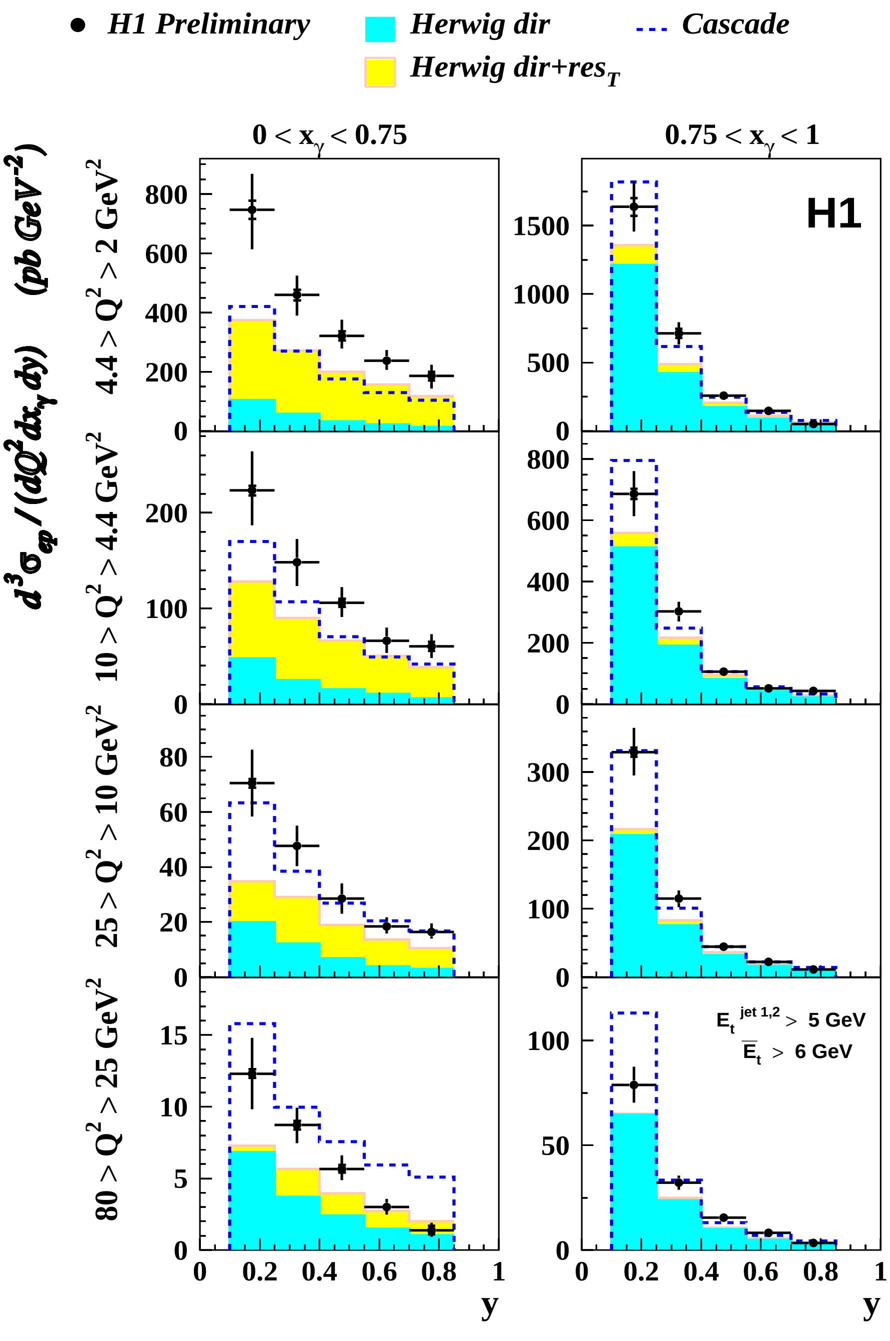
- The slope of y dependence is different in data compared to HERWIG or RAPGAP.

Adding Longitudinal Photon



- The slope of y distribution in HERWIG comes closer to data γ_L^* is added.

CCFM Prediction (CASCADE)



- CASCADE MC (with k_T unordered parton evolution and no concept of photon structure) much closer to data than standard DGLAP direct.

Low Q^2 – summary

- **High E_T dijets in photoproduction:**
  - data agree with NLO QCD calculations
  - theoretical uncertainty is dominating!
  - interpretation of results seems to be dependent on the cut of E_T of the second jet
- **Dijets in low Q^2:**
  - existing NLO calculations not able to describe data
  - reliable NLO calculations in this region not available
  - LO MC models (HERWIG,RAPGAP) underestimate the data cross sections (addition of longitudinally polarized photons brings HERWIG closer to data)
  - CCFM approach gives better agreement than LO MC models

$\longrightarrow$ theoretical progress needed!