QCD Physics and HERA - Lecture III

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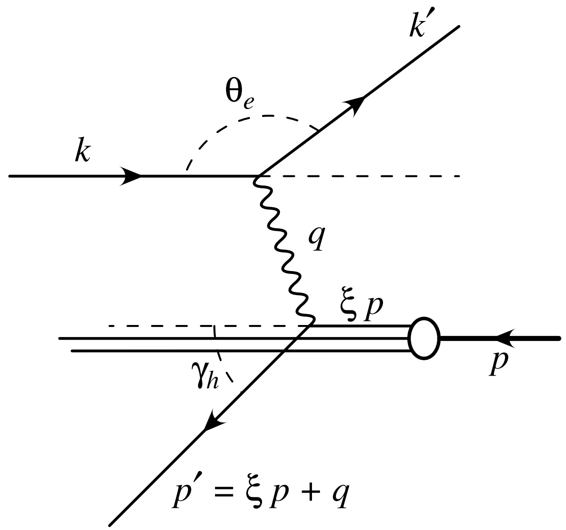
10/2/2005.

- *QCD Introduction.*
- *HERA Accelerator.*
- *Experiments.*
- *Deep Inelastic Scattering.*
- *Proton Structure.*
- *Photon Structure.*
- α_S *measurements.*
- *Beyond the SM.*

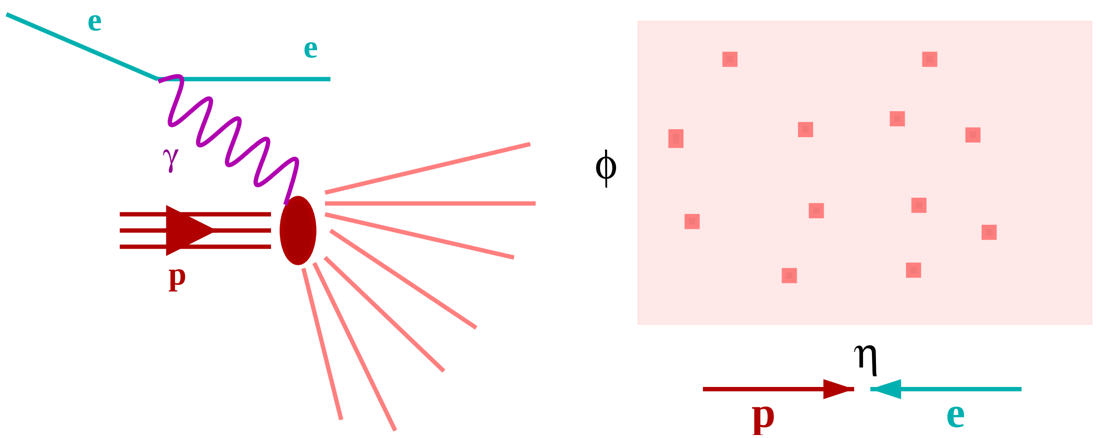


Photoproduction I

- *ep scattering at HERA is dominated by γp interactions in which a quasi-real photon ($Q^2 \approx 0$) emitted by the electron interacts with a parton from the proton.*
- *The total photoproduction cross section has been measured at HERA:*

$$\sigma_{\gamma p}^{\rm tot} = 143 \pm 4({\rm stat}) \pm 17({\rm syst})\mu{\rm b}$$

- *However at large γp CMS energies available at HERA, $100 < W_{\gamma p} < 300$ GeV, a fraction of the γp interactions are expected to produce high transverse energy jets.*



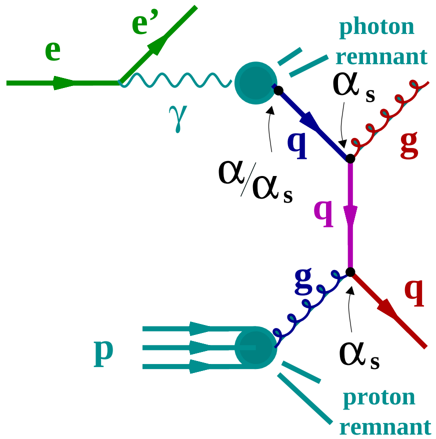
- *Most of the photoproduction cross section is due to soft processes.*
- *The main source of jets at HERA is hard scattering in γp interactions.*

Photoproduction II

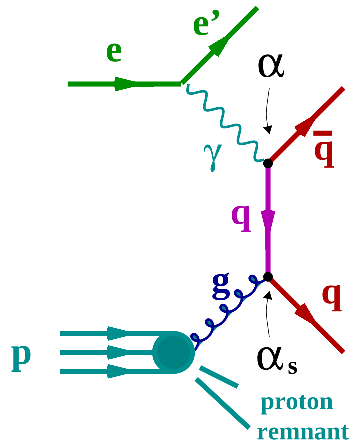
- *The photon at $Q^2 \approx 0$ displays dual behaviour:*
  - *It can couple directly in a $\gamma q\bar{q}$ vertex (normal QED gauge boson behaviour).*
  - *Can fluctuate into an intermediate vector meson state which interacts via its partonic structure.*

- *So 2 processes contribute to the photoproduction cross section:*

A) Resolved:



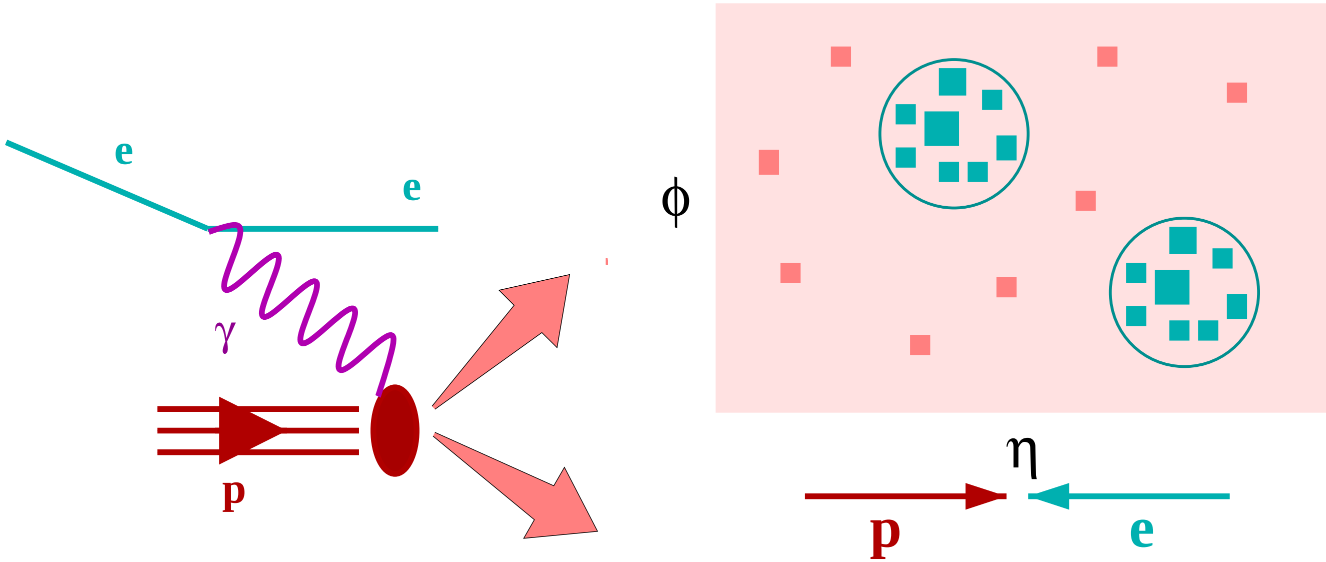
b) Direct:



  - *The resolved coupling allows the study of the parton content of the photon.*
  - *The direct coupling allows study of the parton content of the proton.*

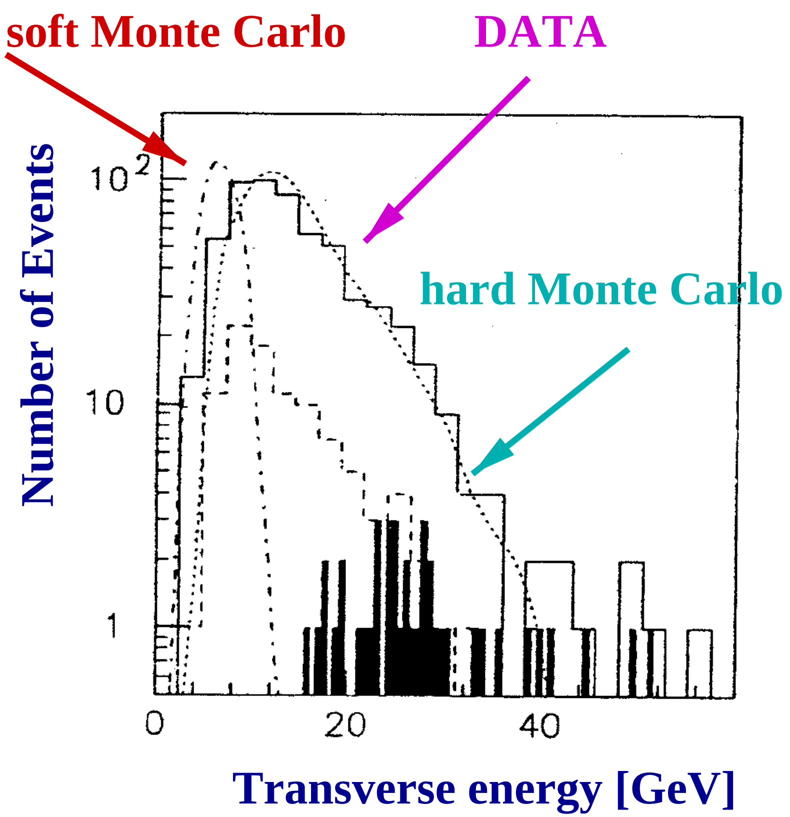
Jet production in Photoproduction.

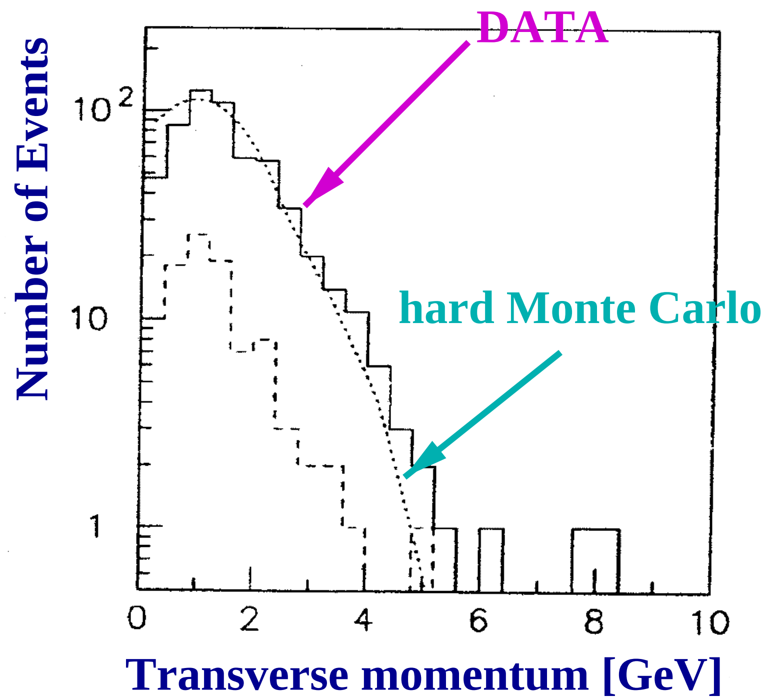
- *Evidence for hard photon scattering has been observed in* $\gamma\gamma$ *interactions in* e^+e^-
- *CMS Energy was too low to observe jet production.*
- *At HERA the CMS energies available provide a wider phase space, enabling the observation of hard scattering in photoproduction.*



Hard Scattering In Photoproduction

- *In Photoproduction, the outgoing electron is scattered at small angles.*
- *Hard Scattering processes in photoproduction are characterised by a large total transverse energy coming from jets, combined with a small total transverse momentum. This implies hard scattering between photon constituents and proton constituents.*





Jet Production in Photoproduction

- *If the data sample consists of events coming from the hard scattering of the constituents of the photon and proton, jet structure should be observed.*
- *In this type of final state jets are usually reconstructed using a cone algorithm.*
- *Experimentally jets are searched for in the pseudorapidity($\eta = -\ln\tan(\theta/2)$)-azimuth($\phi$) plane, using the transverse energy flow of the event*
- *Definition of jet variables: Snowmass Convention*

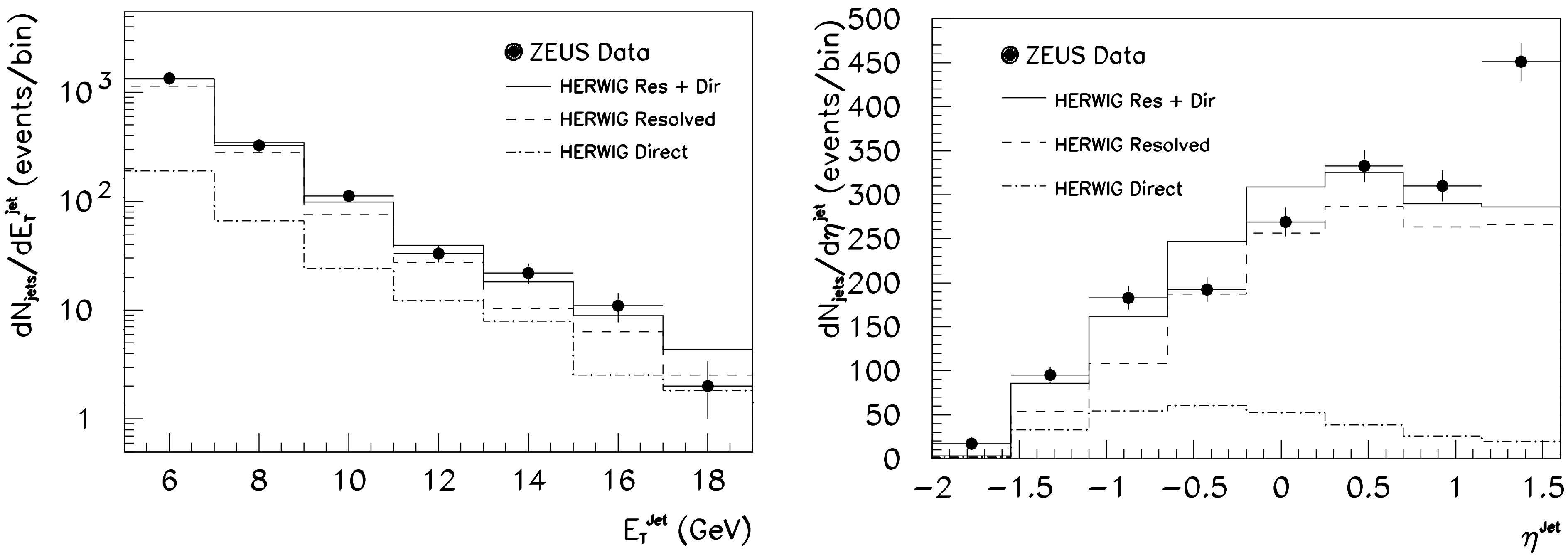
$$E_T^{\mathrm{jet}} = \sum_i E_T^i, \quad \eta^{\mathrm{jet}} = \frac{\sum_i E_T^i \eta_i}{E_T^{\mathrm{jet}}} \quad \phi^{\mathrm{jet}} = \frac{\sum_i E_T^i \phi_i}{E_T^{\mathrm{jet}}}$$

- *Iterative cone algorithm: jets are searched by maximising summed E_T within a cone of radius R for every particle such that:*

$$R_{\mathrm{jet}}^2 = (\eta - \eta_{\mathrm{jet}})^2 + (\phi - \phi_{\mathrm{jet}})^2 \leq R^2$$

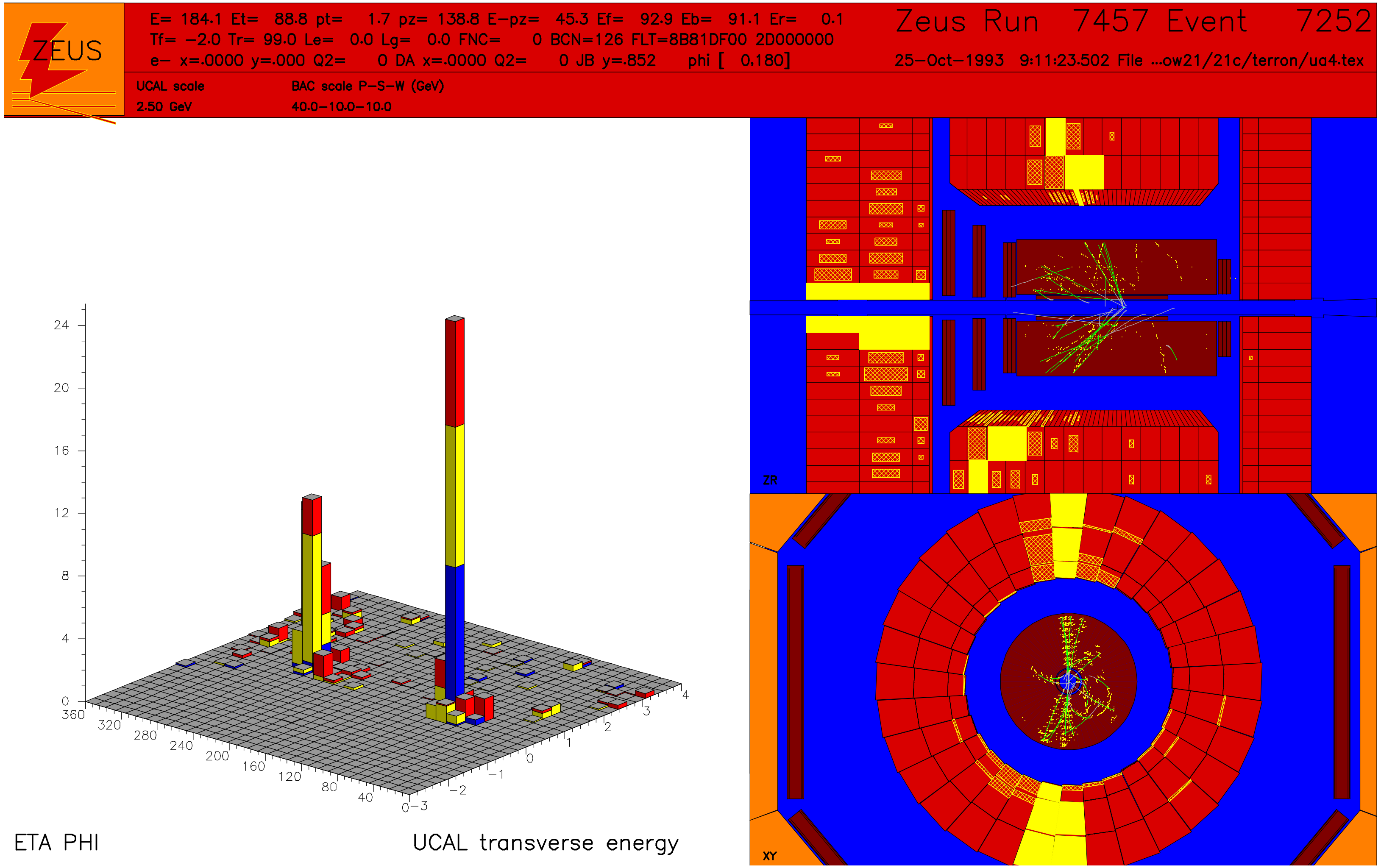
Observation of Jet Structure in Photoproduction

- *Clusters are classified as jets if* $E_T^{\rm jet} \geq 5$ *GeV and* $\eta^{\rm jet} \leq 1.6$*:*



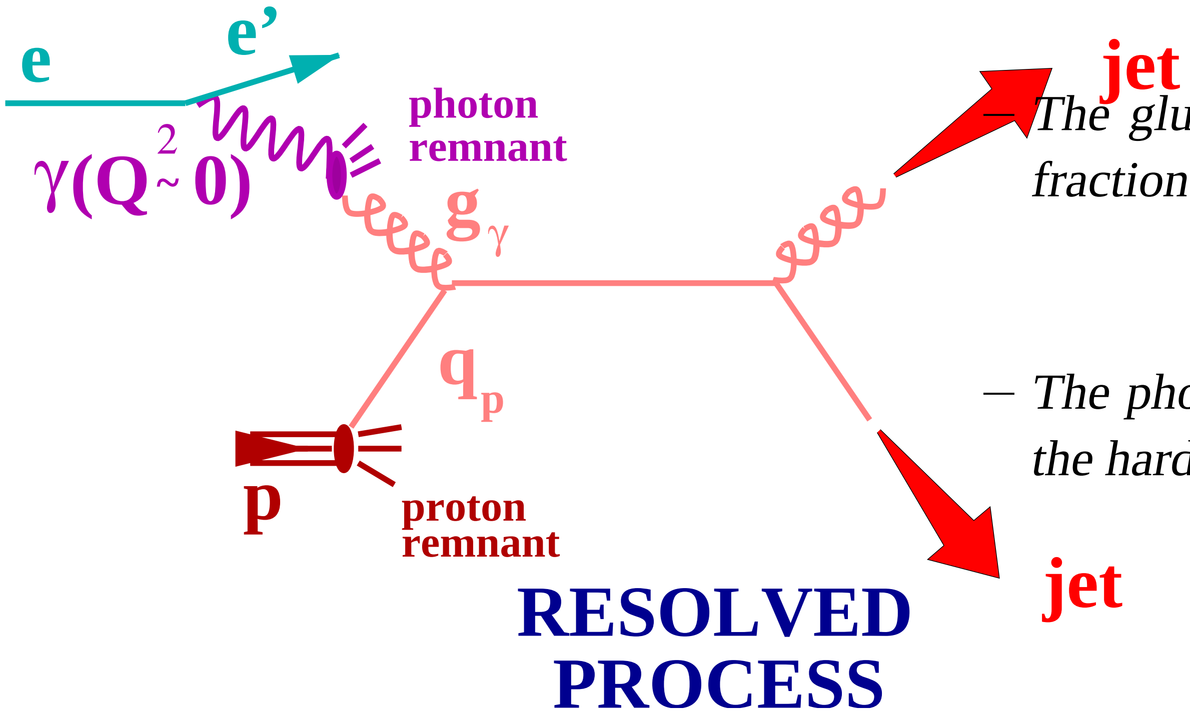
- *QCD based Monte Carlo models which include resolved and direct processes give a reasonable description of the data, except at high* $\eta_{\rm jet}$*.*

Example of a Dijet Event



Resolved Events

- *Observation of resolved processes:*



  – *The gluon from the proton carries only a fraction of the photon's energy:*

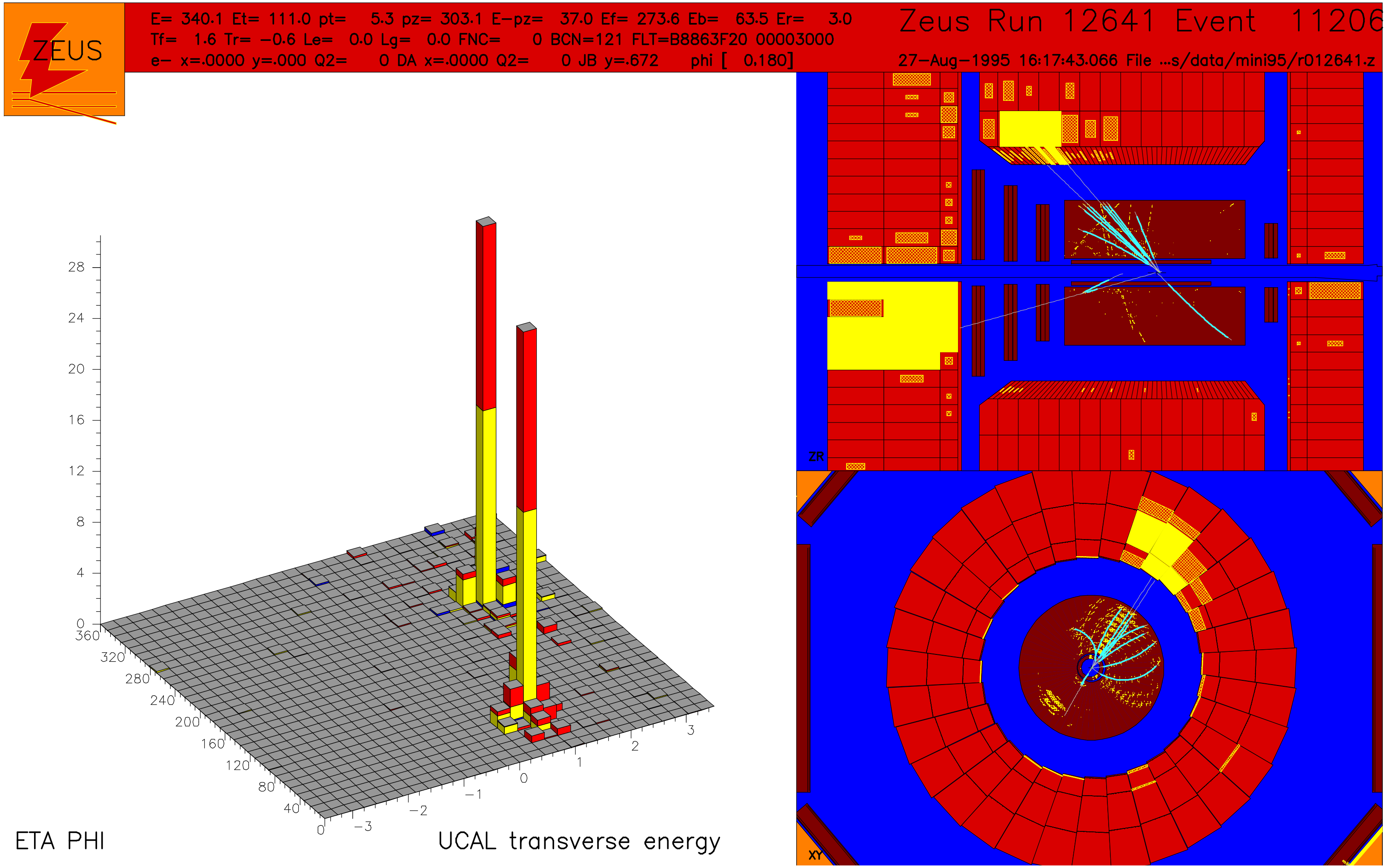
$$P_{g\gamma} = x_\gamma p_\gamma$$

  – *The photon energy is not invested fully in the hard collision:*

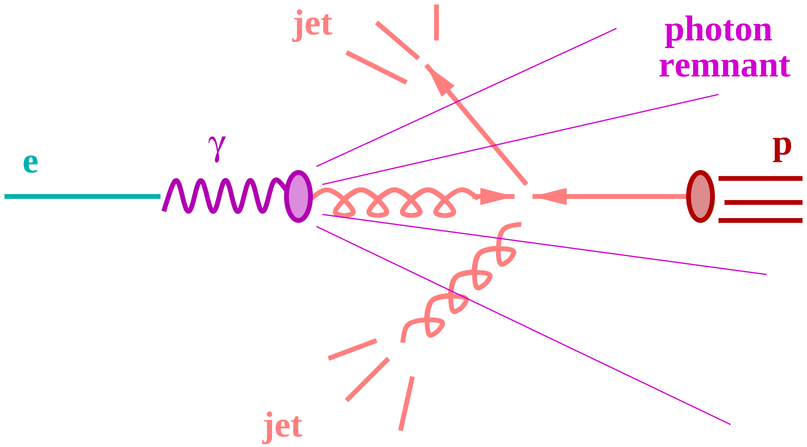
$$x_\gamma < 1$$

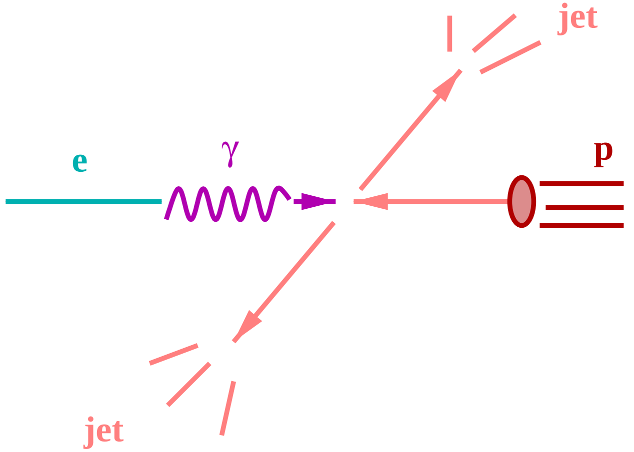
- *Outgoing jets are boosted in the proton direction.*
- *a hadronic photon remnant is expected in the electron direction.*

Example of a Resolved Photoproduction Event



Direct Events





Resolved:

- *Photon remnant.*
- $x_\gamma \ll 1$

Direct:

- *No photon remnant.*
- *All photon energy in interaction* $x_\gamma \to 1$

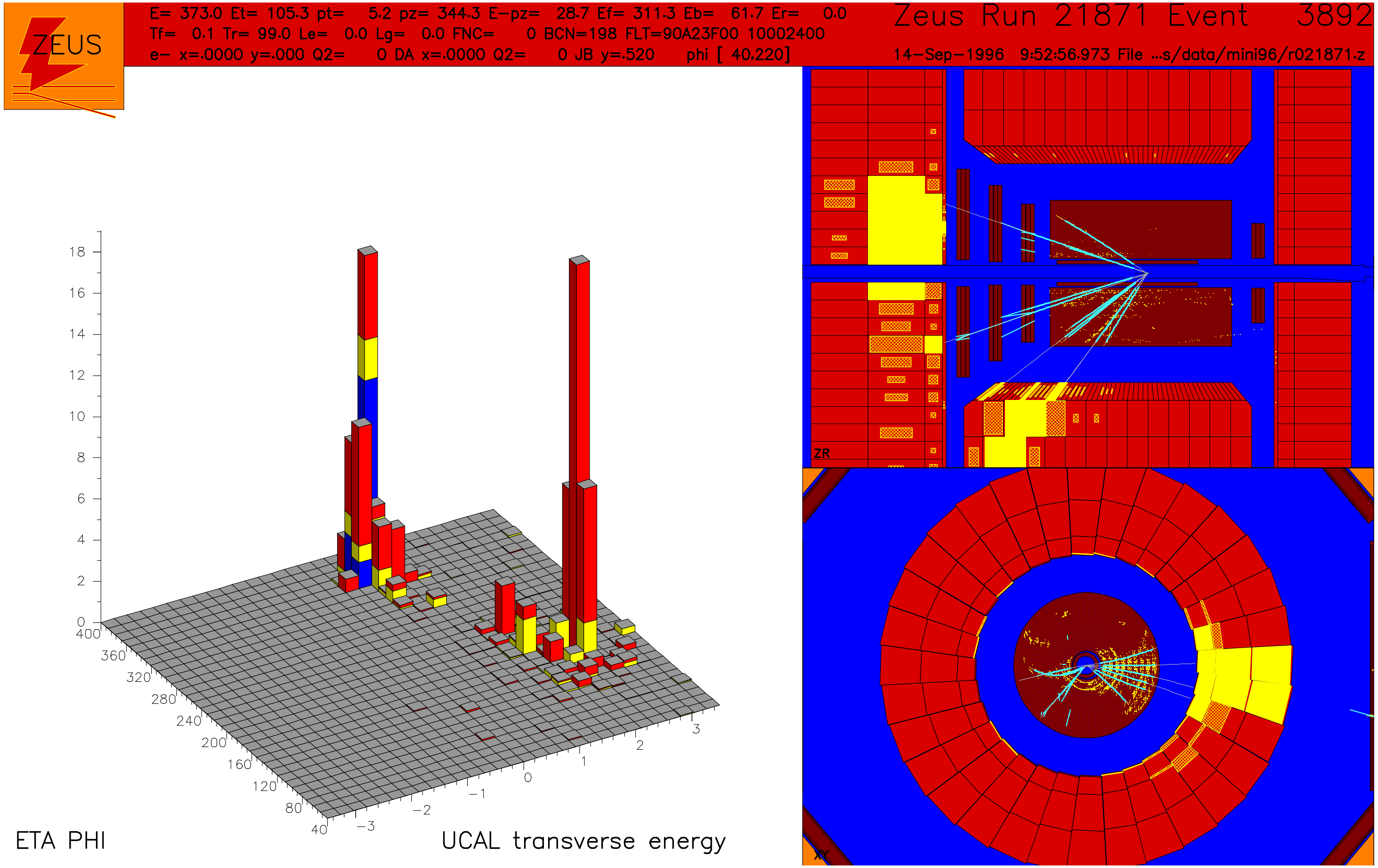
$$x_\gamma p_\gamma + x_p p_p = p_L^{\text{jet1}} + p_L^{\text{jet2}} \quad (1)$$

$$-x_\gamma p_\gamma + x_p p_p = E^{\text{jet1}} + E^{\text{jet2}} \quad (2)$$

$$p_y = yE_e \quad (3)$$

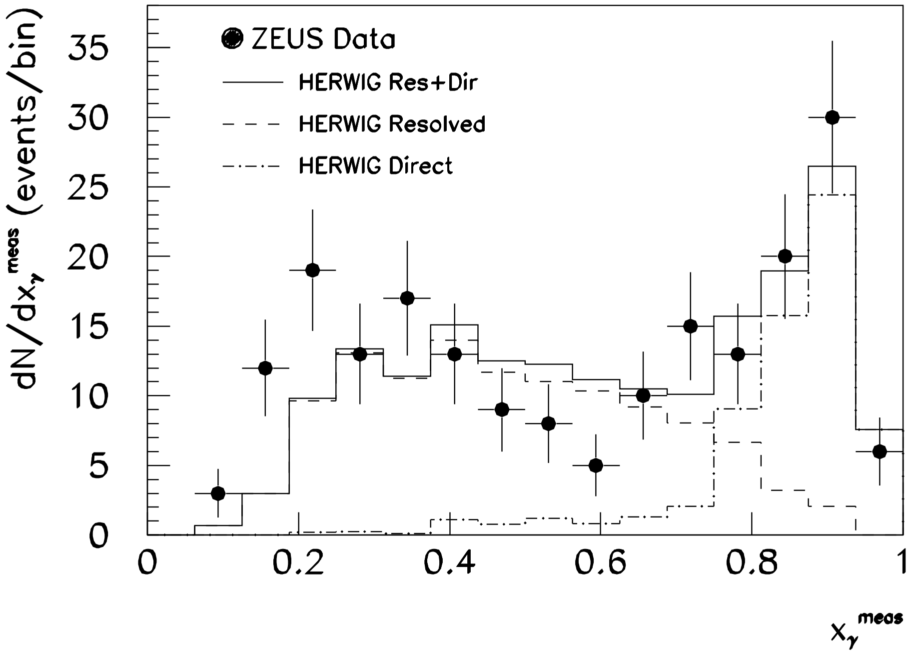
$$\to x_\gamma^{\text{obs}} = \frac{1}{2yE_e}(E^{\text{jet1}} e^{-\eta^{\text{jet1}}} + E^{\text{jet2}} e^{-\eta^{\text{jet2}}})$$

Example of a Direct Photoproduction Event



Direct and Resolved Photoproduction in Dijet Data

$$x_\gamma^{\rm obs} = \frac{1}{2yE_e}(E^{\rm jet1}e^{-\eta^{\rm jet1}} + E^{\rm jet2}e^{-\eta^{\rm jet2}})$$

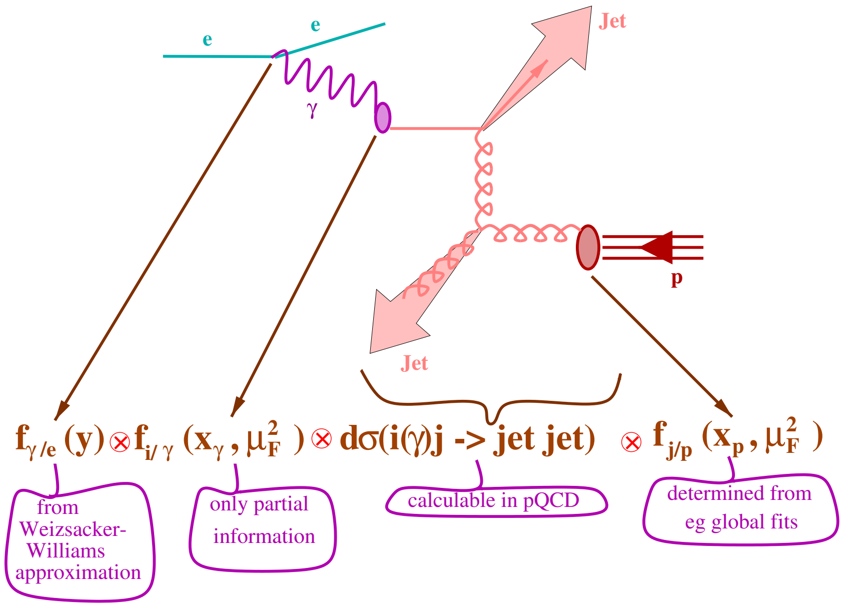


First observation of dijet structure in direct photoproduction data.

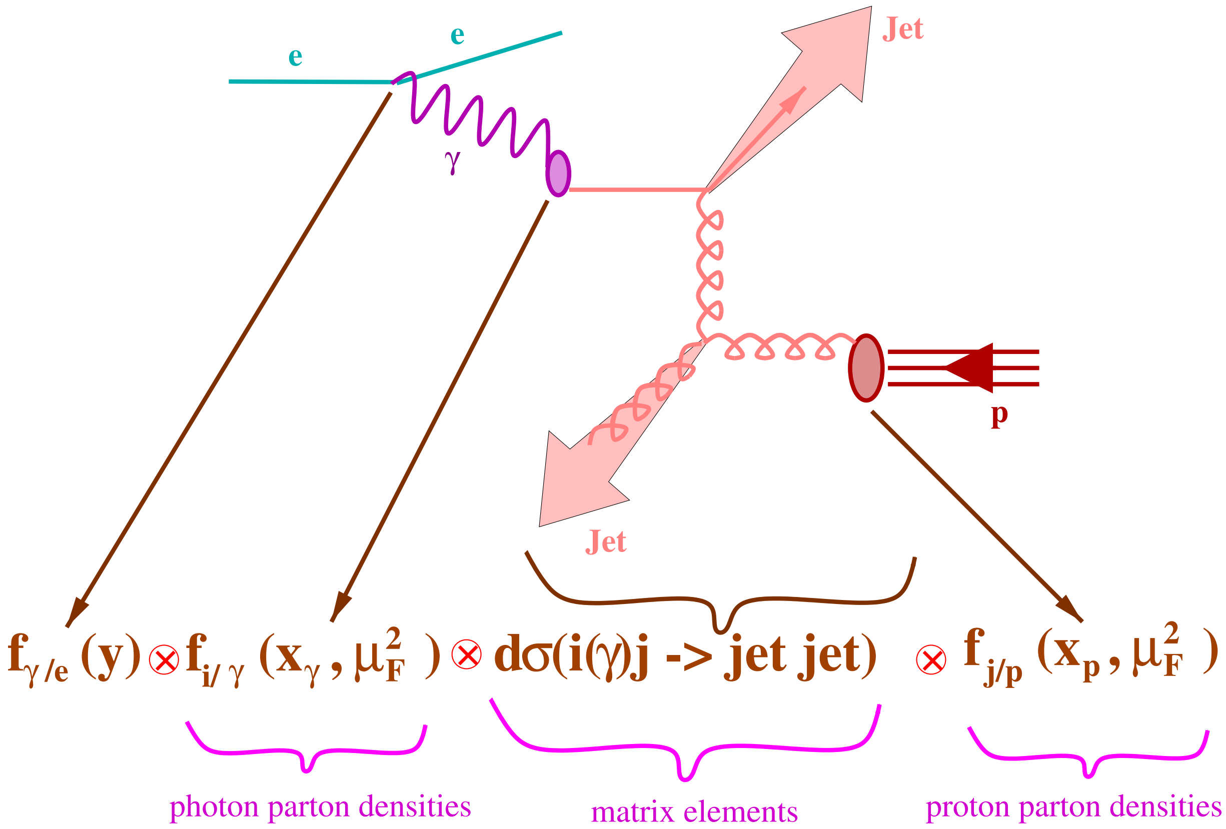
Jet Cross sections in γp I

$$\sigma_{\mathrm{LO}}^{\mathrm{dijet}} = \Sigma \int f_{\gamma/e}(y) f_{j/p}(x_p, \mu_F^2) f_{i/\gamma}(x, \mu^2) d\sigma(i(\gamma)j \rightarrow \mathrm{dijet})$$

- $f_{\gamma/e}(y)$: *Flux of photons from* e.
- $f_{j/p}(x_p, \mu_F^2)$: *parton* j *density in* p.
- $f_{i/\gamma}(x, \mu_F^2)$: *parton* i *density in* γ.
- $d\sigma(i(\gamma)j \rightarrow \mathrm{dijet})$ *subprocess cross section.*

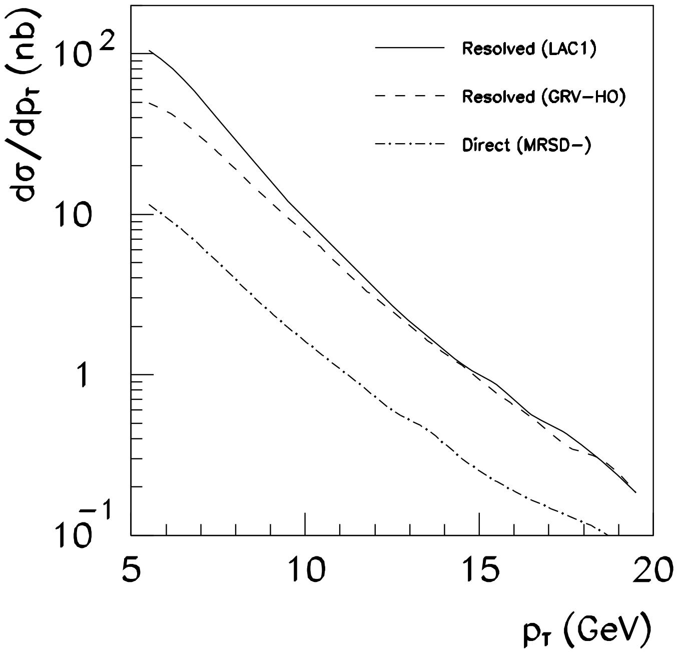


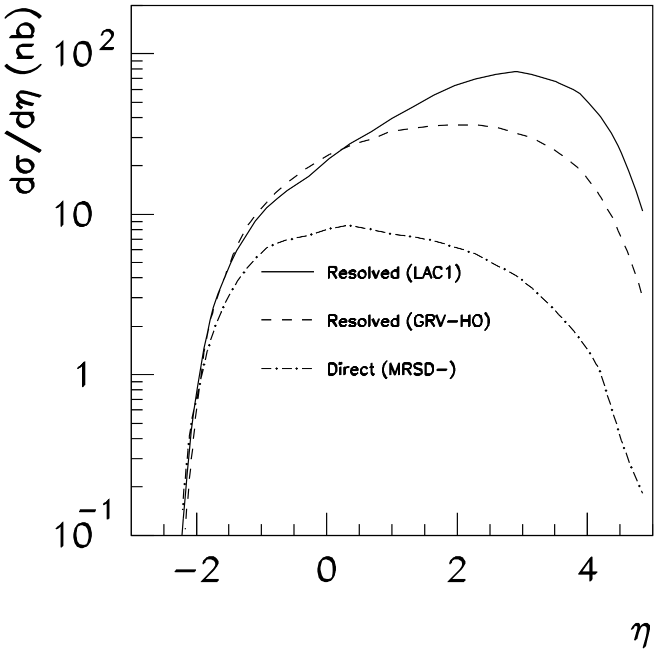
Jet Cross sections in γp II



- *measurements of jet cross sections in γp allow study of:*
  - *photon structure.*
  - *proton structure.*
  - *perturbative QCD.*

Jet Cross Sections at LO

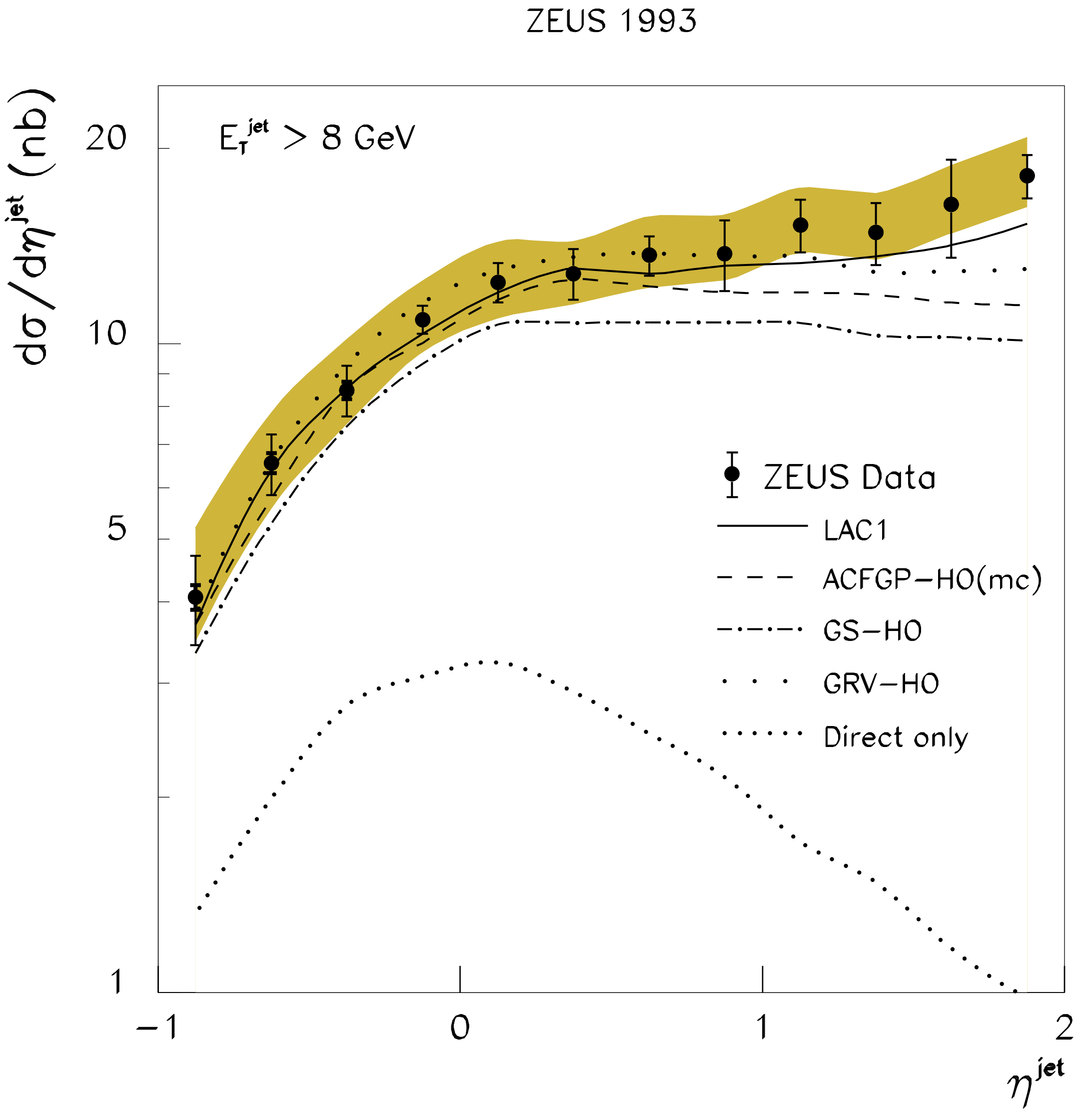




- *resolved processes dominate for a wide range of p_T.*
- *Direct processes are significant only in the tails of the distribution.*
- *The η distribution for resolved processes is boosted in the proton direction.*
- *the η distribution for direct processes is more central.*

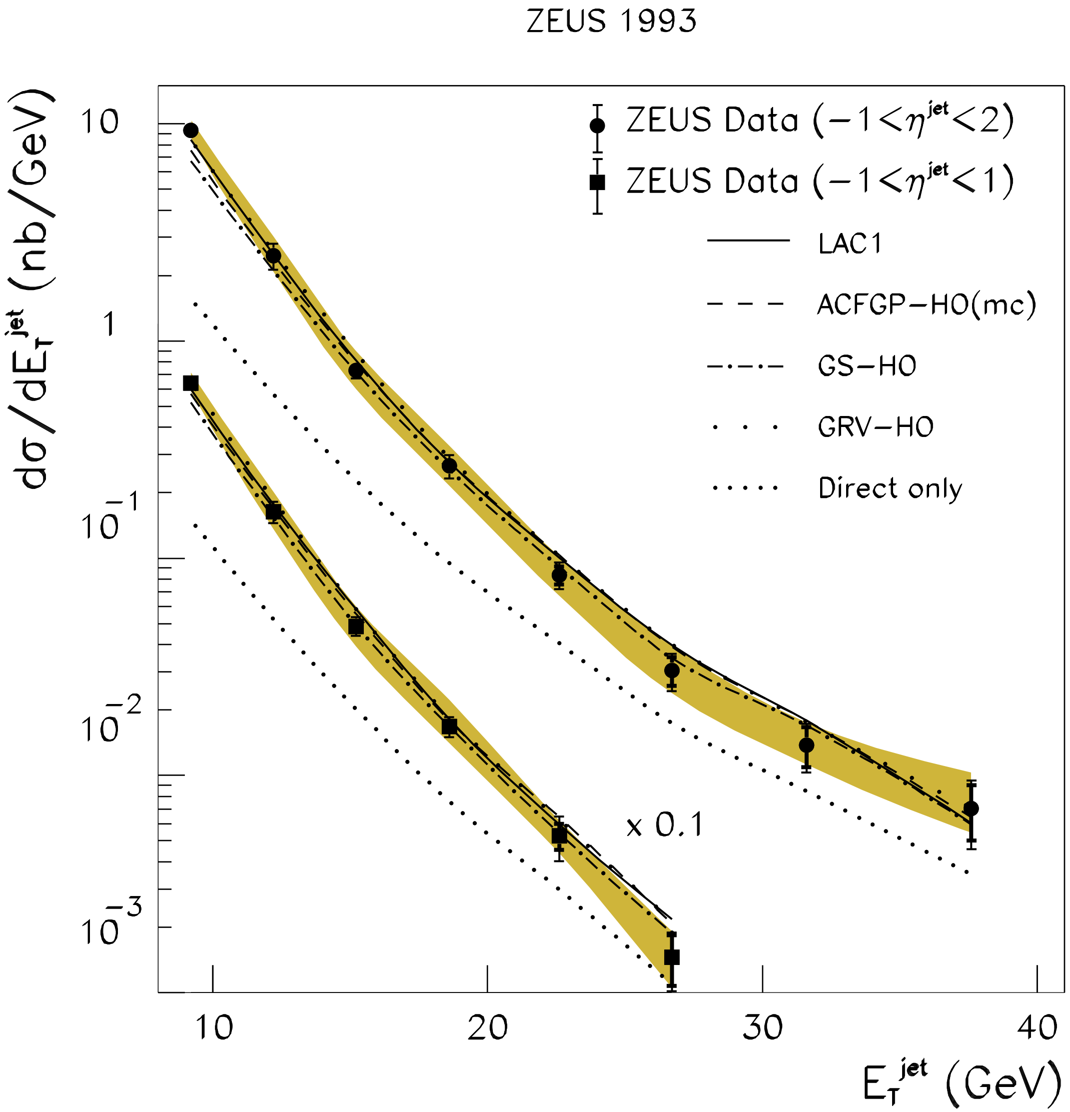
Measurement of $\mathrm{d}\sigma/\mathrm{d}\eta^{\mathrm{jet}}$

- *LO calculations give a good description of the data for* $-1 < \eta^{\mathrm{jet}<1}$
- *Direct processes alone cannot describe the data*
- *Resolved processes dominate over the whole* η *range.*

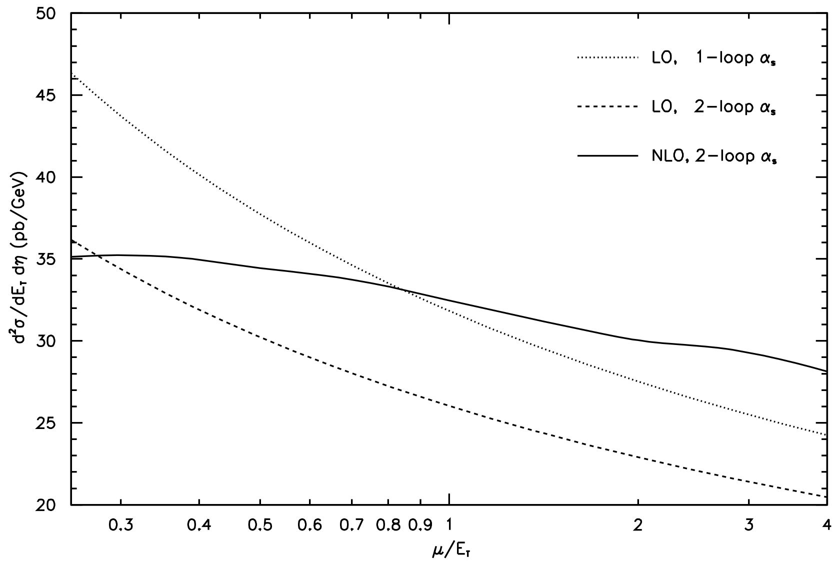


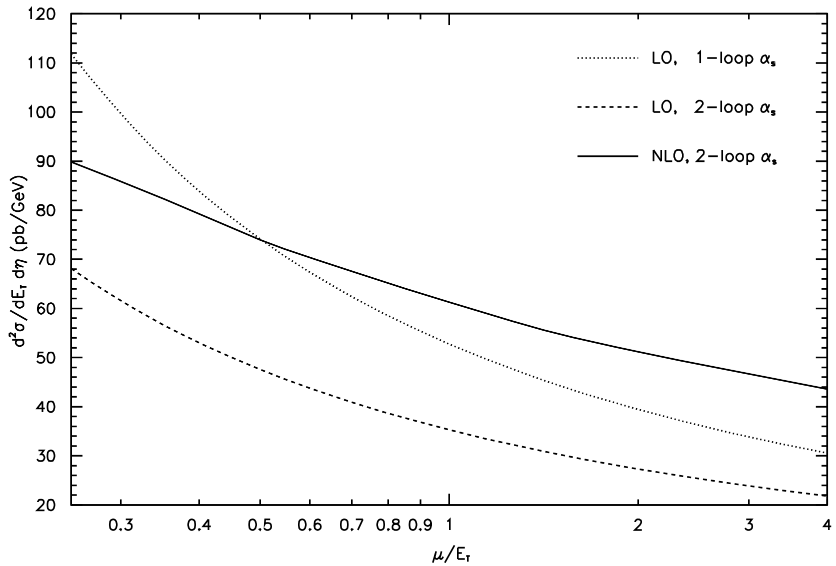
Measurement of $d\sigma/dE^{jet}$

- *LO calculations give a good description of the data.*
- *Direct processes cannot describe the data alone.*
- *Direct processes become more important as E_T increases.*



Renormalisation Scale Dependence of Calculations I



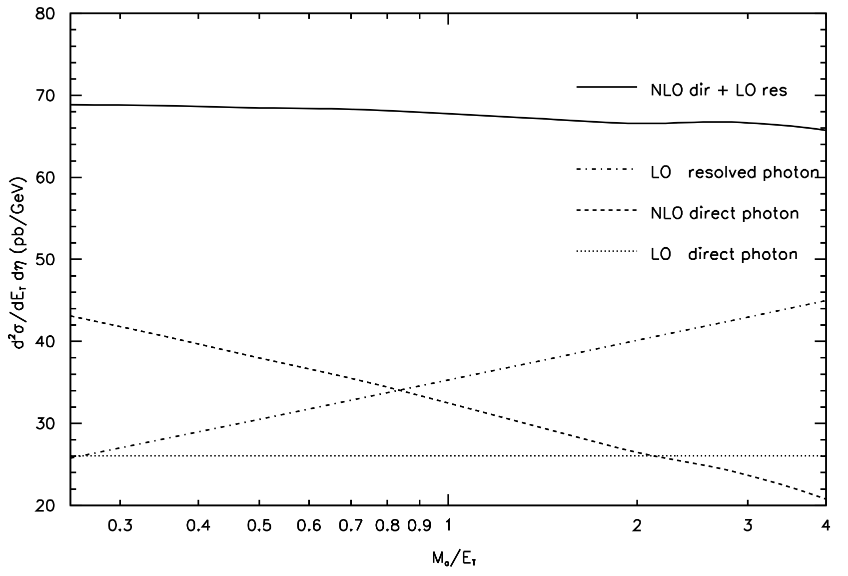


- *One Loop approximation:*

$$\alpha_S(\mu_R^2) = \frac{12\pi}{(33-2N_f)\ln\frac{\mu_R^2}{\Lambda^2}}$$

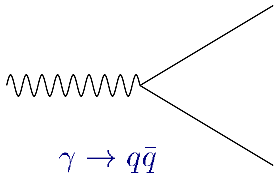
- *Scale dependence of α_S different in 2 loop calculation*
- *Large scale dependence in LO calculations.*
- *Reduced scale dependence at NLO.*

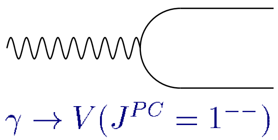
Renormalisation Scale Dependence of Calculations II



- *μ_F separates the soft parton content in the photon PDF from the hard partonic cross section.*
- *The Direct PDF at LO is simply a δ function and does not depend on scale.*
- *The resolved PDF at LO depends strongly on μ_F*
- *The direct PDF at NLO depends on the scale but with opposite sign to the resolved part, so contributions cancel to some degree.*
- *Direct and resolved processes are separable only at LO.*
- *Addition of NLO terms reduces scale depenced of calculations.*

Photon Structure I

- *The interactions of the photon are classified according to the way it takes part in the hard interaction:*
  - *In the 'direct' case, the photon as a whole takes part in the interaction and we cannot discern any structure.*
  - *In the 'resolved' case, where the photon fluctuates into an hadronic system, structure functions can be defined. The resolved photon contains 2 contributions:*
    - 

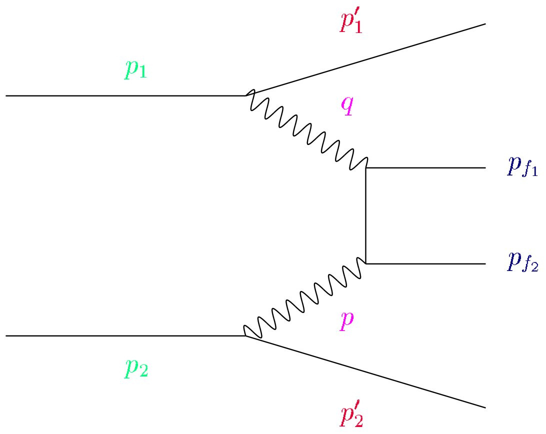
anomalous (perturbatively calculable).
    - 

hadronic (non-perturbative)

$$f_{i/\gamma}(x,\mu) = f_{i/\gamma^{\mathrm{had}}}(x,\mu^2) + f^{\mathrm{anom}}_{i/\gamma}(x,\mu^2)$$

Photon Structure II

- *The structure of the quasi-real photon γ is probed by a highly virtual photon $\gamma*$ emitted by the electron in deep inelastic scattering.*



- *In high energy scattering of $e^{\pm}$ off $e^{\pm}$:*
  $q = p_1 - p_1'; p = p_2 - p_2'; Q^2 = q^2 \gg 0$
  $P^2 = -p^2 \approx 0; x = \frac{Q^2}{2p.q}; y = \frac{q.p}{p_1.p}$

- *Structure functions, which parametrise the structure of the real photon are defined in terms of the scattering cross section:*

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left\{\left[1+(1-y)^2\right]F_1^\gamma + \frac{(1-y)}{x}(F_2^\gamma - 2xF_1^\gamma)\right\}$$

The longitudinal structure function $F_L^\gamma = F_2^\gamma - 2xF_1^\gamma$ is non-zero even in QPM.

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left\{\left[1+(1-y)^2\right]F_1^\gamma + y^2F_L^\gamma\right\}$$

At LO: $F_2^\gamma(x,Q^2) = \sum_{q,q} e_q^2 x f_{q/\gamma}(x,Q^2)$

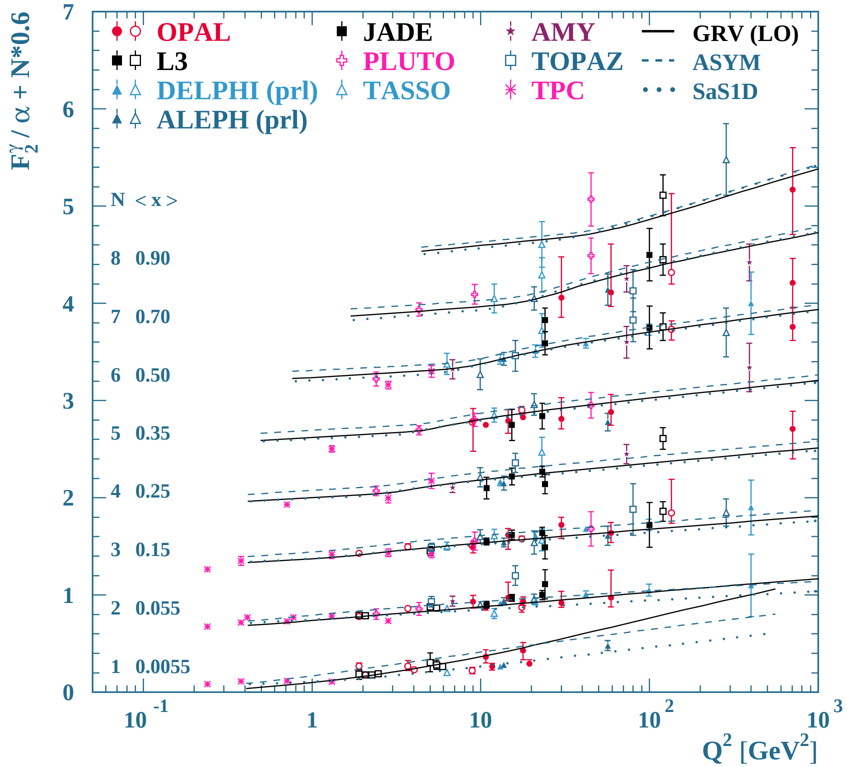
Photon Structure III

- *the DGLAP evolution equations for the proton are given by:*

$$\frac{\mathrm{d}f_{\gamma/\gamma}(x,q^2)}{\mathrm{d}Q^2} = 0$$

$$\frac{\mathrm{d}f_{q/\gamma}(x,q^2)}{\mathrm{d}Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{\mathrm{d}z}{z}\left[P_{qq}\left(\frac{x}{z}\right) f_{q/\gamma}(z,Q^2) + P_{gq}\left(\frac{x}{z}\right) f_{g/\gamma(z,Q^2)}\right] + \frac{\alpha}{2\pi}P_{q\gamma}(x)$$

$$\frac{\mathrm{d}f_{g/\gamma}(x,q^2)}{\mathrm{d}Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{\mathrm{d}z}{z}\left[P_{qg}\left(\frac{x}{z}\right) f_{q/\gamma}(z,Q^2) + P_{gg}\left(\frac{x}{z}\right) f_{g/\gamma(z,Q^2)}\right]$$



Photon Structure IV

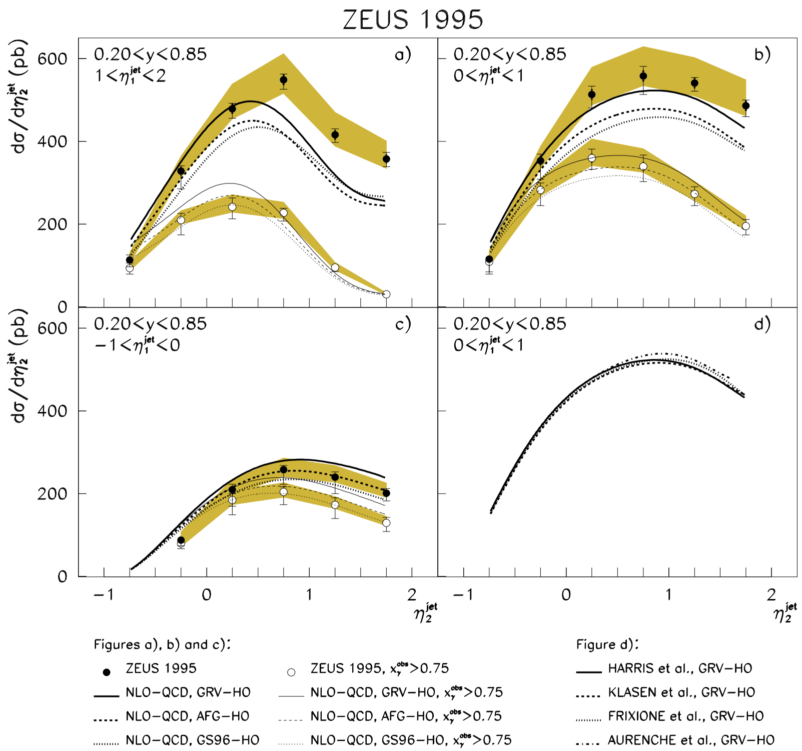
- *fitting the data to obtain parameterisation of the γ parton densities is not so easy as for the proton:*
  - *No momentum sum rule applies for photon parton densities.*
  - *Cross section is small, leading to large statistical errors.*
  - *Since electron escapes undetected, photon + electron energy can only be determined form the hadronic system (large systematics) on F_2^γ*
- *There are several paramaterisations obtained from fits to the data*
- *Parameterisations from HERA used in other experiments to test universality of photon structure.*

Photon Structure at HERA

- *At HERA, photon structure is investigated by measuring jet cross sections sensitive to the* γ *PDFs such as* $\mathrm{d}\sigma/\mathrm{d}\eta^{\mathrm{jet}}$ *or* $\mathrm{d}\sigma/\mathrm{d}x_{\gamma}^{\mathrm{obs}}$
- *Measurements are compared to NLO QCD predictions based on different parameterisations of the* γ *PDFs.*
- *Models assumed in obtaining the parameterisations can be favoured or disfavoured.*

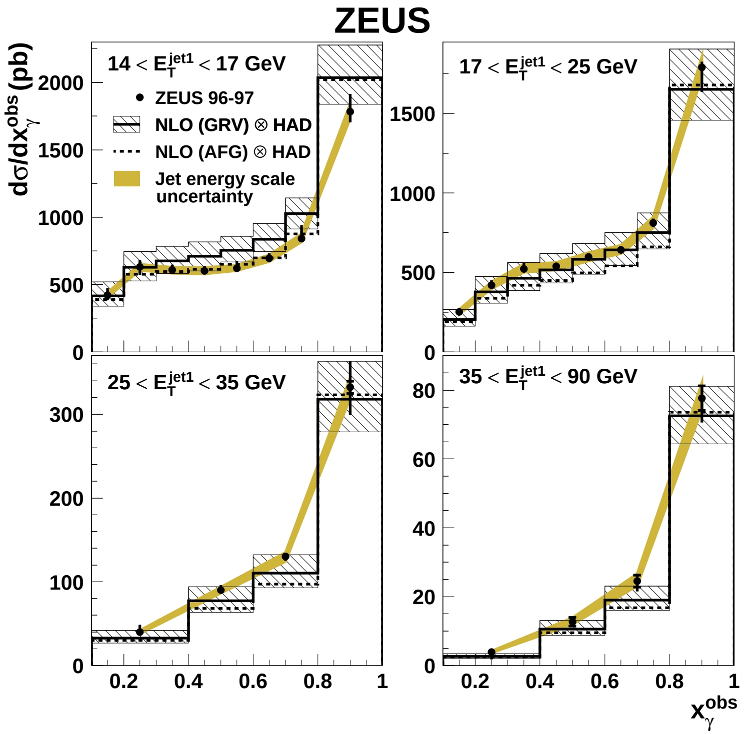
$\mathrm{d}\sigma/\mathrm{d}\eta^{\mathrm{jet}}$ in dijet γp

- *The measured cross sections are higher than the predictions in a region where the theoretical uncertainties are small.*
- *Current parameterisations of the photon parton densities are inadequate.*

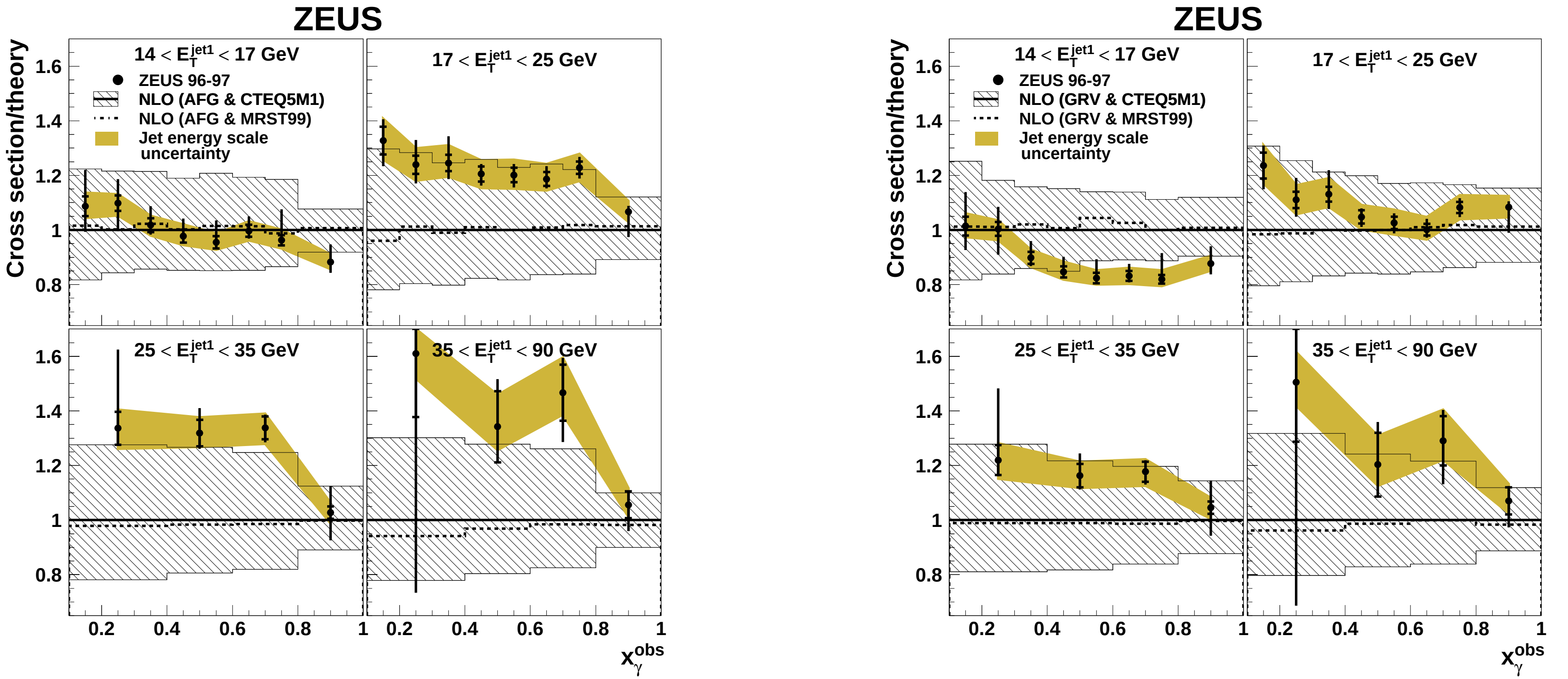


$\mathrm{d}\sigma/\mathrm{d}x_\gamma^{\mathrm{obs}}$ in dijet γp I

- *The NLO calculations using GRV-HO lie significantly above the data for* $14 < E^{\mathrm{jet}} < 27$ *GeV for* x_γ^{obs} *are increasingly below the data for values higher than 17 GeV.*
- *The predictions using AFG-HO agree with the data at low* E_T^{jet1}*, but lie below the data for high* E_T^{jet1}



$\mathrm{d}\sigma/\mathrm{d}x_\gamma^{\text{obs}}$ in dijet γp II



- *Discrepancies between data and NLO calculations cannot be accounted for by uncertainties (Theory* $\sim 17\%$ *, Syst* $\sim 8\%$ *)*
- *The inclusion of higher-order contributions would have to significantly change the shape of the distribution as a function of* E_T^{jet} *and* x_γ^{obs} *to describe data.*
- *Photon Structure is not as well described as proton structure.*

Inclusive Jet Production in DIS

$$\mathrm{d}\sigma_{\text{jet}} = \sum_{a=q,\bar{q},g} \int \mathrm{d}x f_a(x, \mu_F^2) \mathrm{d}\hat{\sigma}_a(x, \alpha_S(\mu_R^2)), \mu_R^2, \mu_F^2)$$

f_a: *parton* α *density in the proton, determined from experiment.*
$\hat{\sigma}_a$: *subprocess cross section, calculable in pQCD.*

- *Jet cross sections in NC and CC interactions provide a test of pQCD calculations, measurements of* α_S *constrain parton densities and are sensitive to the production of new particles and new interactions.*
- *HERA experiments have reported an excess of NC events over the SM at high* x *and* Q^2 *and TeVatron an excess over QCD at high* E_T^{jet}
- *These observations are possible evidence for anomalies in PDFs or of physics beyond the SM.*
- *New particles or resonances that decay into* e+*jets(s) would lead to deviations in the differential cross sections for inclusive jet production from the SM expectation.*
- *A Jacobian Peak would be observed in the differential cross section as a function of* E_T^{jet} *in the LAB frame.*

Jacobian Peak in the $E_T^{\rm jet}$ distribution I

- *For the process* $eq \rightarrow Y \rightarrow \mathcal{L}q'$ *the matrix elements are proportional to:*

$$\mathcal{M} = M_Y^2 \frac{[\bar{\nu}(q)\Omega^{\alpha}u(e)][\bar{u}(\mathcal{L})\Omega'_{\alpha}\nu(q')]}{\hat{s}-M_Y^2+iM_Y\Gamma_Y}$$

where $\hat{s} = (p_e + p_q)^2$; $\hat{u} = (p_e - p_{q'})^2$; $\hat{t} = (p_e + p_{\mathcal{L}})^2$

- *Assuming EW interaction:* $\Omega_\alpha = \gamma_\alpha(1-\gamma_5)$
- *After squaring and summing spins, the spin averaged cross section in the rest frame is given by:*

$$\frac{d\hat{\sigma}}{dt} \propto \overline{\Sigma\,|\mathcal{M}|} \propto M_Y^4 \frac{\hat{u}^2}{(\hat{s}-M_Y^2)^2+(M_Y\Gamma_Y)^2}$$

$$\hat{u} = -\frac{1}{2}\hat{s}(1+\cos\theta^*);\hat{t} = -\frac{1}{2}\hat{s}(1-\cos\theta^*)$$

then:

$$\frac{d\hat{\sigma}}{dcos\theta^*} \propto M_Y^4\hat{s}\frac{(1+\cos\theta^*)^2}{(\hat{s}-M_Y^2)^2+(M_Y\Gamma_Y)^2}$$

where θ^* *is the scattering angle between* q *and* q' *in the* $\mathcal{L}q'$ *rest frame.*

Jacobian Peak in the E_T^{jet} distribution II

- *The inclusive jet cross section for the process* $ep \to Y + X \to \mathcal{L}\,\mathrm{jet}\,X$

$$\mathrm{d}\sigma(ep \to YX \to \mathcal{L}\,\mathrm{jet}\,X \propto \sum_q \Sigma\, \mathrm{d}x_q q(x_q)\mathrm{d}\hat{\sigma}(eq \to \mathcal{L})q')$$

where x_q *is the momentum fraction of the quark* q *and the sum runs over all possible quarks in the proton.*

- *In the* $eq' \to \mathcal{L}q'$ *subprocess COM frame, the transverse momentum* $\hat{p}_T$ *of the* $\mathcal{L}$ *and* q' *are back to back with the same magnitude:*

$$p_T^2 = \left(\frac{\widehat{\sqrt{s}}}{2}\sin\theta^*\right)^2 = \frac{\hat{s}}{4}\sin^2\theta^* = \frac{\hat{t}\hat{u}}{\hat{s}} \to \cos\theta^* = \left(1 - \frac{4\hat{p}_T^2}{\hat{s}}\right)^{\frac{1}{2}}$$

- *Make a change of variables:* $\frac{\mathrm{d}\cos\theta^*}{\mathrm{d}p_T^2} = -\frac{2}{\hat{s}}\left(1 - \frac{4\hat{p}_T^2}{\hat{s}}\right)^{-\frac{1}{2}} = \frac{2}{\hat{s}\cos\theta^*}$

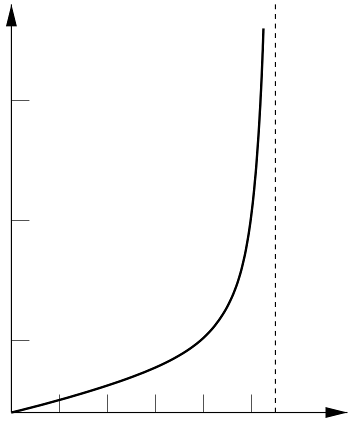
$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{p}_T^2} \propto \frac{2}{\hat{s}|\cos\theta^*|} M_Y^2 \hat{s} \frac{1+\cos^2\theta^*}{(\hat{s}-M_Y^2)^2 + (M_Y\Gamma_Y)^2}$$

Jacobian peak in the E_T^{jet} distribution III

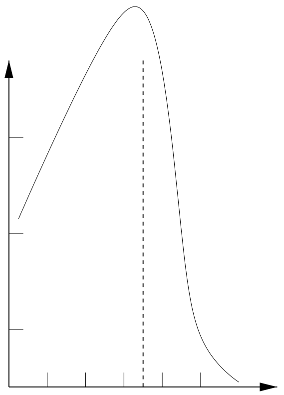
- *Therefore:*

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{p}_T^2} \propto \frac{\hat{\sigma}(1+\cos^2\theta^*)}{\hat{s}|\cos\theta^*|} = 2\frac{\hat{\sigma}(1-\frac{2\hat{p}_T^2}{\hat{s}})}{\hat{s}(1-\frac{4\hat{p}_T^2}{\hat{s}})^{\frac{1}{2}}}$$

- *We get a divergence at* $\theta^* = \frac{\pi}{2} \longrightarrow \hat{p}_T = \frac{1}{2}\sqrt{s} \sim \frac{1}{2}M_Y$ *in the* p_T *distribution.*
- *At lowest order the incident particles are longitudinal so that* Y *is produced longitudinally in the lab frame and the LAB* $p_T = p'_q \sim E_T^{\mathrm{jet}}$
- *Peak in* $E_T^{\mathrm{jet}} \approx \frac{M_Y}{2}$ *is smeared out by higher order processes:*



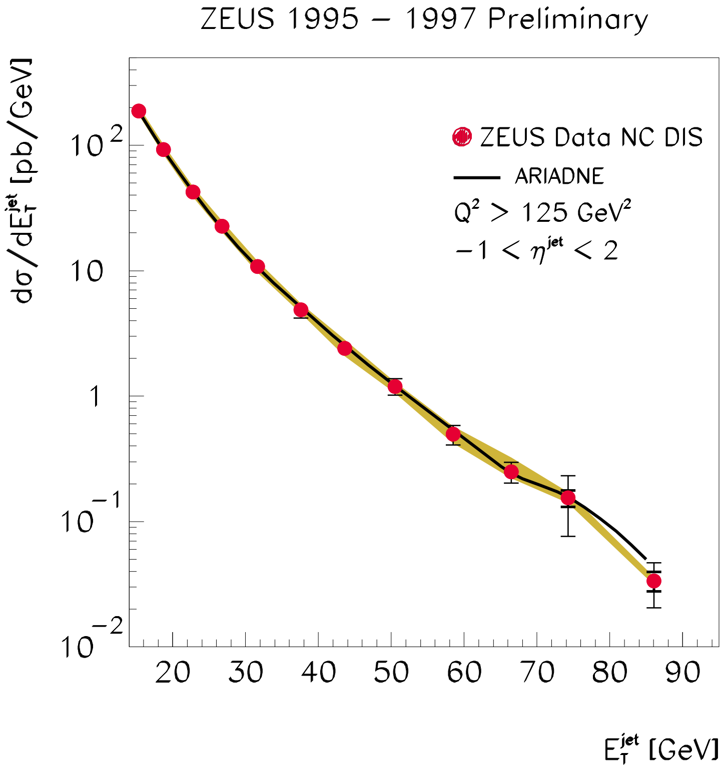
Peak in $\hat{p}_T$ *distribution.*

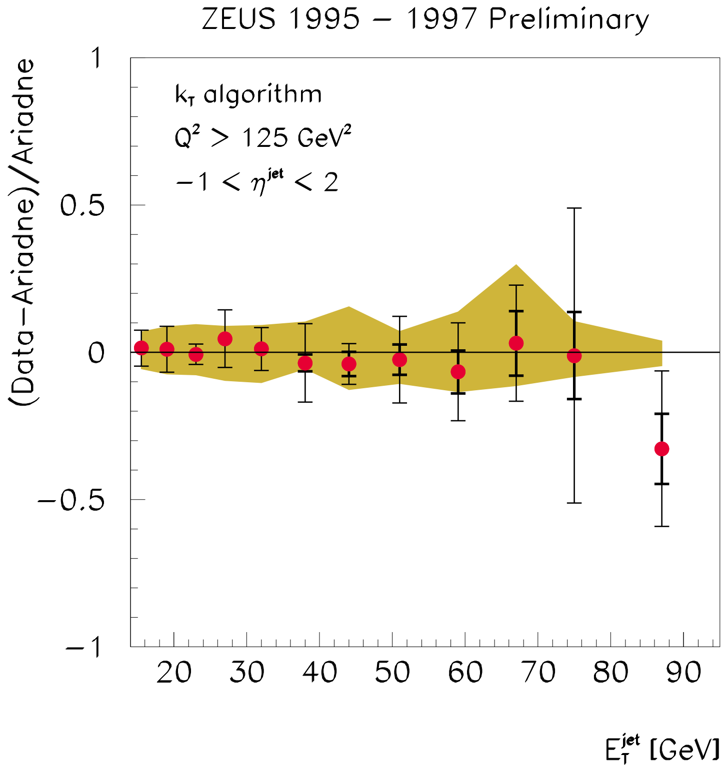


Peak in E_T^{jet} *distribution.*

$E_T^{\rm jet}$ distribution in NC DIS I

- *In NC DIS at high Q^2, the most probable final state is a jet balancing the $\mathcal{L} = e$ transverse momentum, $E_T^{\rm jet} = Q$*
- *Example of a jet search using jets found with the k_T algorithm for events with $Q^2 > 125\ \mathrm{GeV}^2$ and $E_T^{\rm jet} > 14\ \mathrm{GeV}$ and $-1 < \eta^{\rm jet} < 2$.*

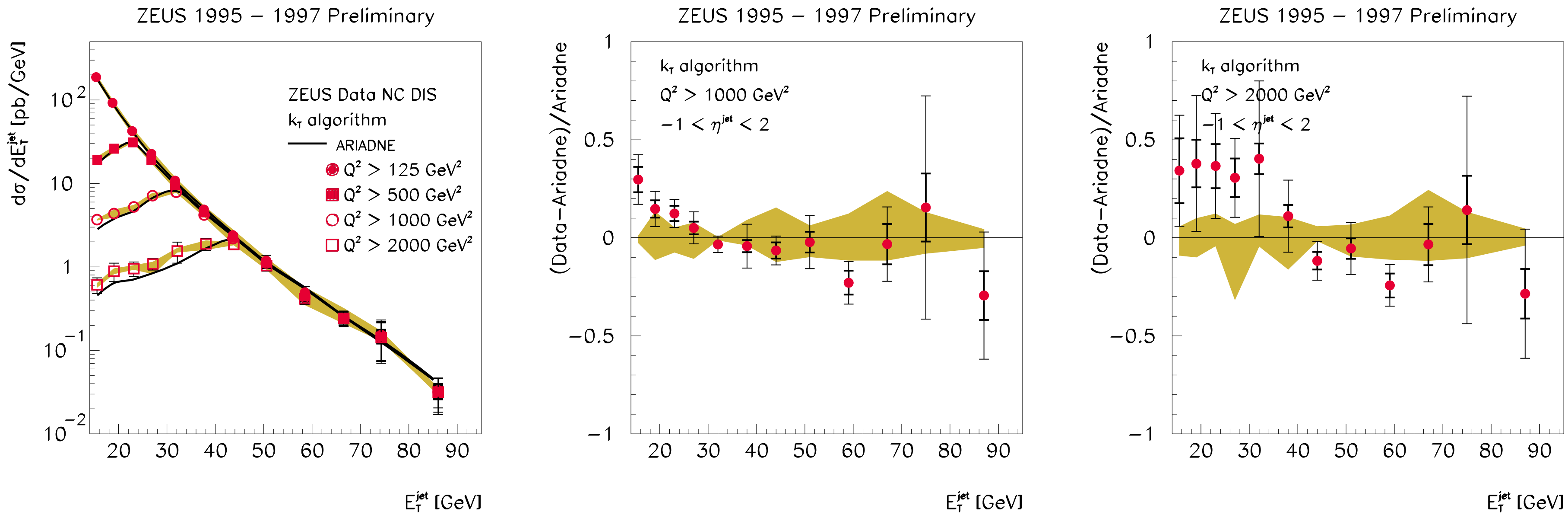




- *Shape and magnitude of the cross section is well described by the Monte Carlo.*

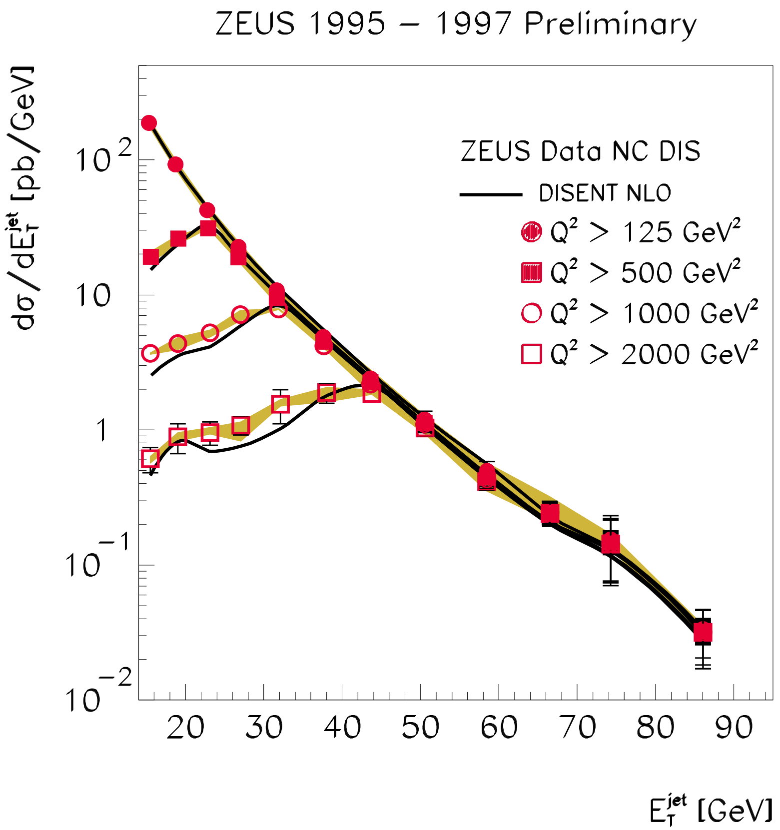
E_T^{jet} distribution in NC DIS II

- *A resonance decaying into* e *plus several jets would populate the region* $E_T^{\mathrm{jet}} \ll Q$ *where multijet production in the SM is suppressed by powers of* α_S.
- *There is a tendency for data to be above SM predictions for* $E_T^{\mathrm{jet}} < Q$.



E_T^{jet} distribution in NC DIS III

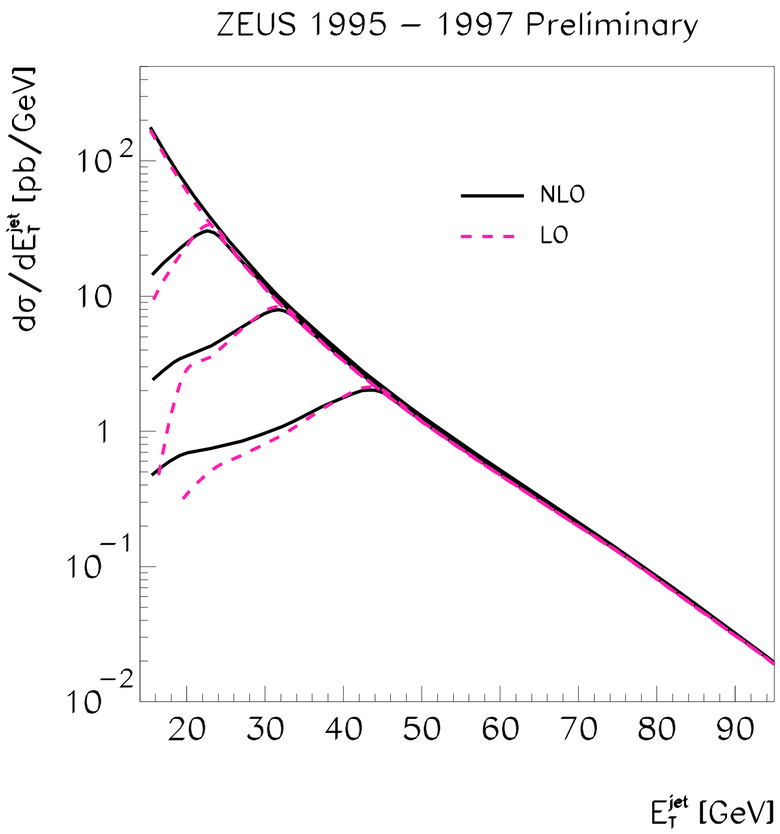
- *Can we account for differences with NLO QCD calculations (DISENT)?*

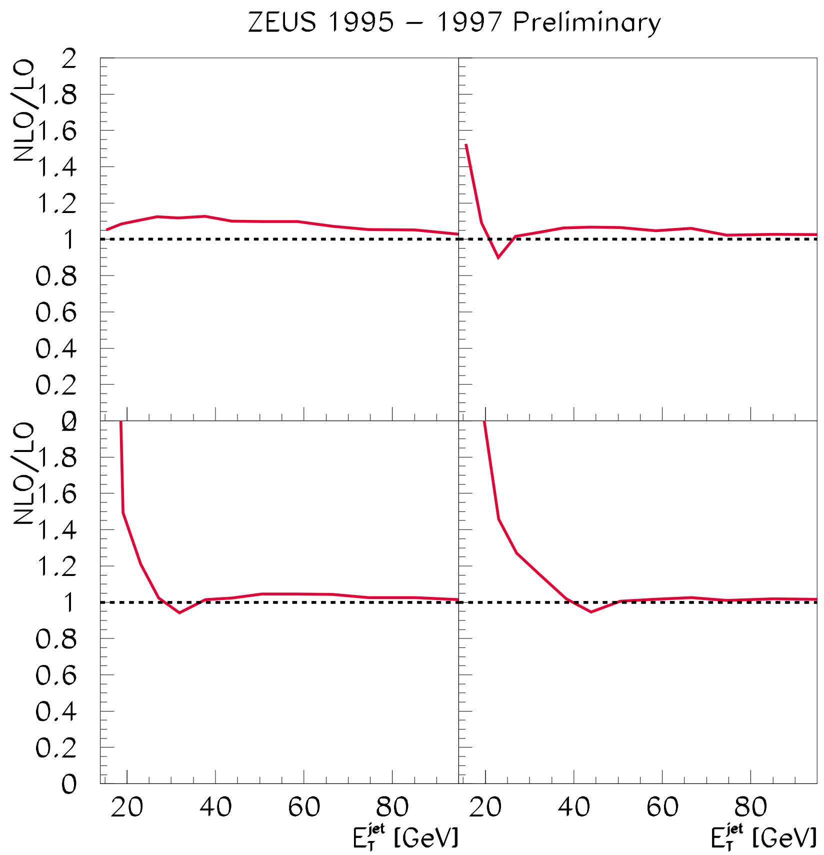


- *Cross section is reproduced well except for* $Q^2 > 1000\ \text{GeV}^2$ *at low* E_T^{jet}.

Excess = New Physics?

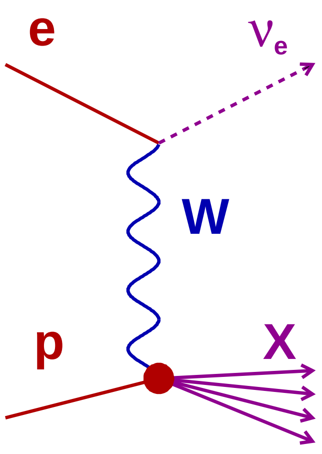
- *Excess at* $E_T^{\rm jet} \ll Q$ *for* $Q^2 > 1000\ {\rm GeV}^2$ *could be due to accuracy of QCD predictions in that region.*
- *Observe the size of the NLO QCD corrections.*





Excess = New Physics? II

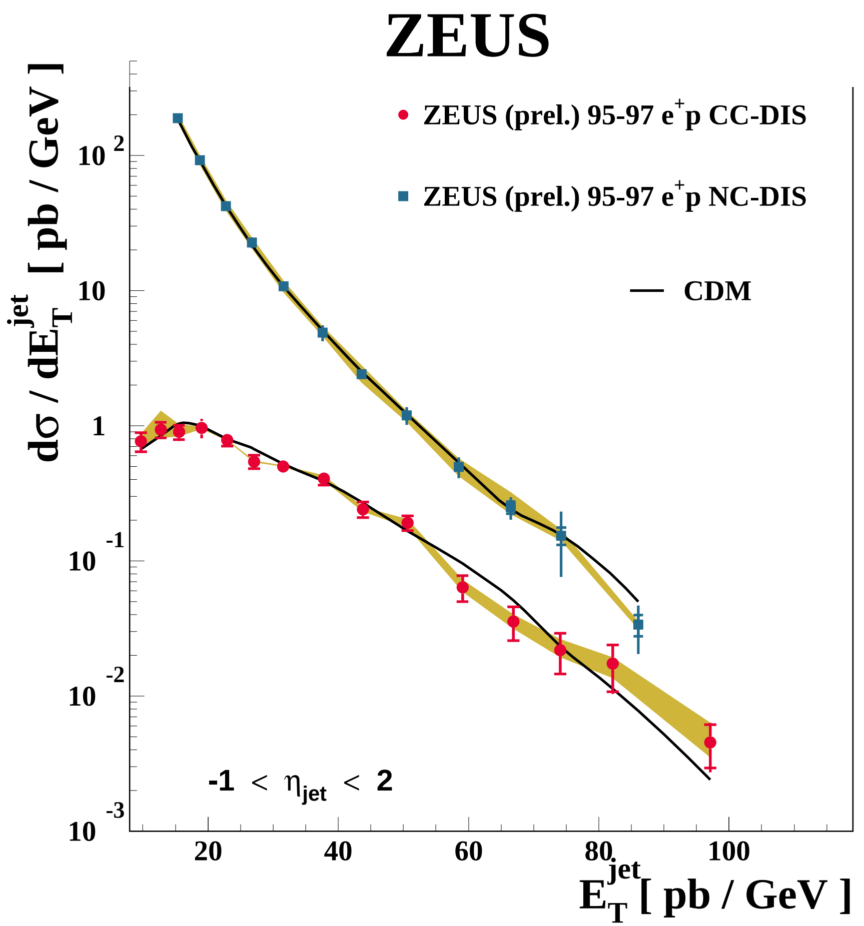
- *One can see that the NLO corrections at low-*$E_T^{\rm jet}$ *become large at high* Q^2.
- *The NLO corrections depart from unity at* $E_T^{\rm jet} \approx Q^2$.
- *The NLO corrections suggest that higher order corrections could be very large*
- *Until improved QCD calculations exist, it is not possible to be sure whether excess at low* $E_T^{\rm jet}$ *comes from new physics.*
- *Try other processes , such as CC DIS.*
- *CC is also powerful for flavour specific investigation of parton momentum distributions.*
- *CC processes are directly sensitive to the* W.



Inclusive Jet Cross Sections on NC and CC DIS

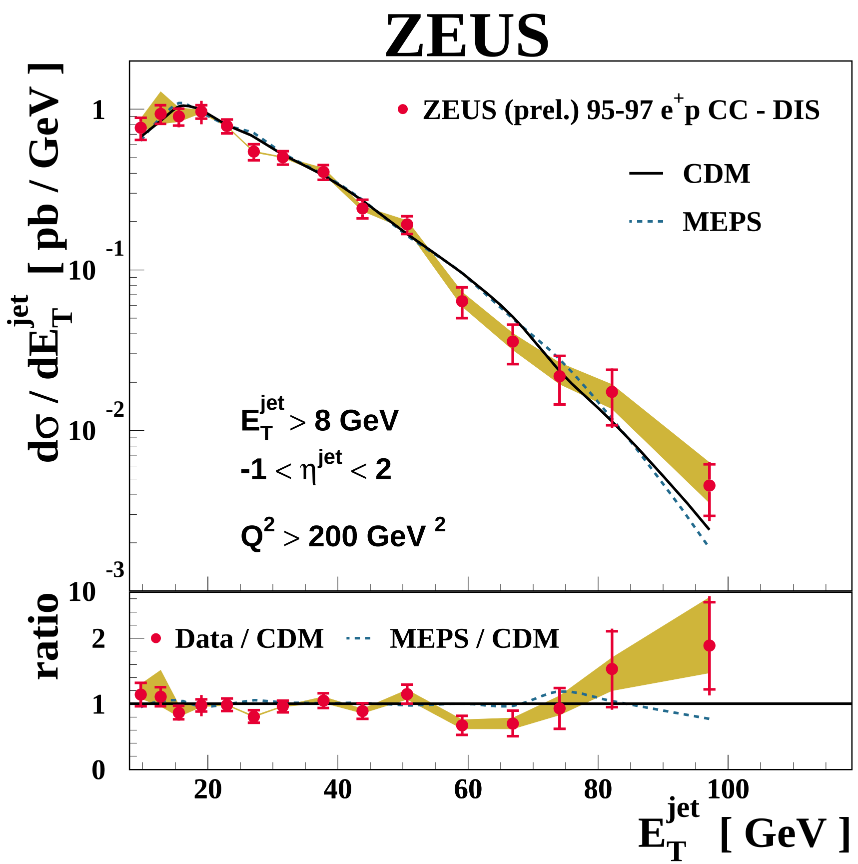
$ep \longrightarrow e(\nu) + \text{ jet } + X$

- *Jet production in CC provides a testing ground for the EW sector of the SM and for QCD. Differential cross sections for jet production are directly sensitive to the mass of the propagator* M_W, *to* α_S *and to the presence of new physics.*
- *The* $\mathrm{d}\sigma/\mathrm{d}E_T^{\rm jet}$ *in CC exhibits a fall-off of 3 orders of magnitude for* $E_T^{\rm jet} \geq 20$ *GeV and for* $8 < E_T^{\rm jet} < 20$ *GeV it displays almost no dependence on* $E_T^{\rm jet}$
- *Behaviour is very different from NC. CC is found to fall with* $E_T^{\rm jet}$ *less rapidly and to approach the NC cross section for* $E_T^{\rm jet} \sim 80$ *GeV.*
- *Independent confirmation of the presence of a massive propagator in CC events.*



Inclusive Jet Cross sections in CC DIS

- *Shape and magnitude of measured cross section is described by predictions though there is a tendency of the data to be above the calculations for* $E_T^{\rm jet} > 80$ *GeV*
- *Not conclusive evidence for new physics at high* $E_T^{\rm jet}$ *because measurements in the CC regime suffer from large statistical uncertainties. (*$\sigma_{CC}(30\text{pb}) \ll pb \ll \sigma_{NC}$ *)*
- *to fully explore this high energy regime, require much more luminosity than gathered in 1996-2000 data taking.*



Lecture III : Summary

- *Jet production in γp helps us understand:*
  - *Photon structure.*
  - *Proton structure.*
  - *Perturbative QCD.*
  - *Physics beyond the SM*
- *The Photon structure is not as well understood as proton structure.*
- *No deviation from the SM has been conclusively demonstrated by jet studies.*