Factorization and factorization breaking in non-diffractive scattering at HERA

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- When Should Factorization Apply?
- Tests of Factorization
  - Parton Densities: Can NLO QCD fits describe $\mathbf{ep}$, $\gamma\mathbf{p}$ and $\mathbf{p\bar{p}}$?
  - Fragmentation Functions: Compare NC DIS (Breit frame) and $\mathbf{e^+e^-}$
- Factorization Breaking
  - Underlying event studies in tagged photoproduction
  - Forward Neutron Production
- Sketch of the Dipole Model of DIS
- Conclusions

When Should Factorization Apply?

- Incident particles have high momentum
  - Hadrons are Lorentz contracted along the direction of flight, so the interaction time is decreased.
  - Interactions internal to hadrons are time dilated, so the lifetime of the partonic state is increased.
  - Long distance interactions of partons within the hadron can be neglected during the (short-distance) hard interaction, so the partons can be treated as free particles.
  - The partons can be assigned a fraction $\mathbf{x}$ of the hadron's longitudinal momentum. The momentum distribution of parton species $\mathbf{i}$ within hadron $\mathbf{H}$ in $\mathbf{x}$ can be described by a universal parton density $\mathbf{f_{i/H}(x)}$ with $\mathbf{0 < x < 1}$.
- The density of partons should not be too high, so that the collision can be described by a single hard scattering

Factorized Cross Sections

- The Neutral Current DIS cross section can be factored into a sum over quark densities and a hard scattering cross section

$$\frac{d^2\sigma(ep)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4}(1+(1-y)^2)\sum_i e_i^2 f_{i/p}(x,Q^2)$$

- The direct $\gamma \mathbf{p}$ cross section can be written

$$\sigma_{\mathrm{dir}}(ep \to e + N\mathrm{jets} + X) = \int_\Omega f_{\gamma/e}(y,Q^2)\sum_i f_{i/p}(x,\mu^2)d\hat{\sigma}(\gamma i \to N\mathrm{jets})$$

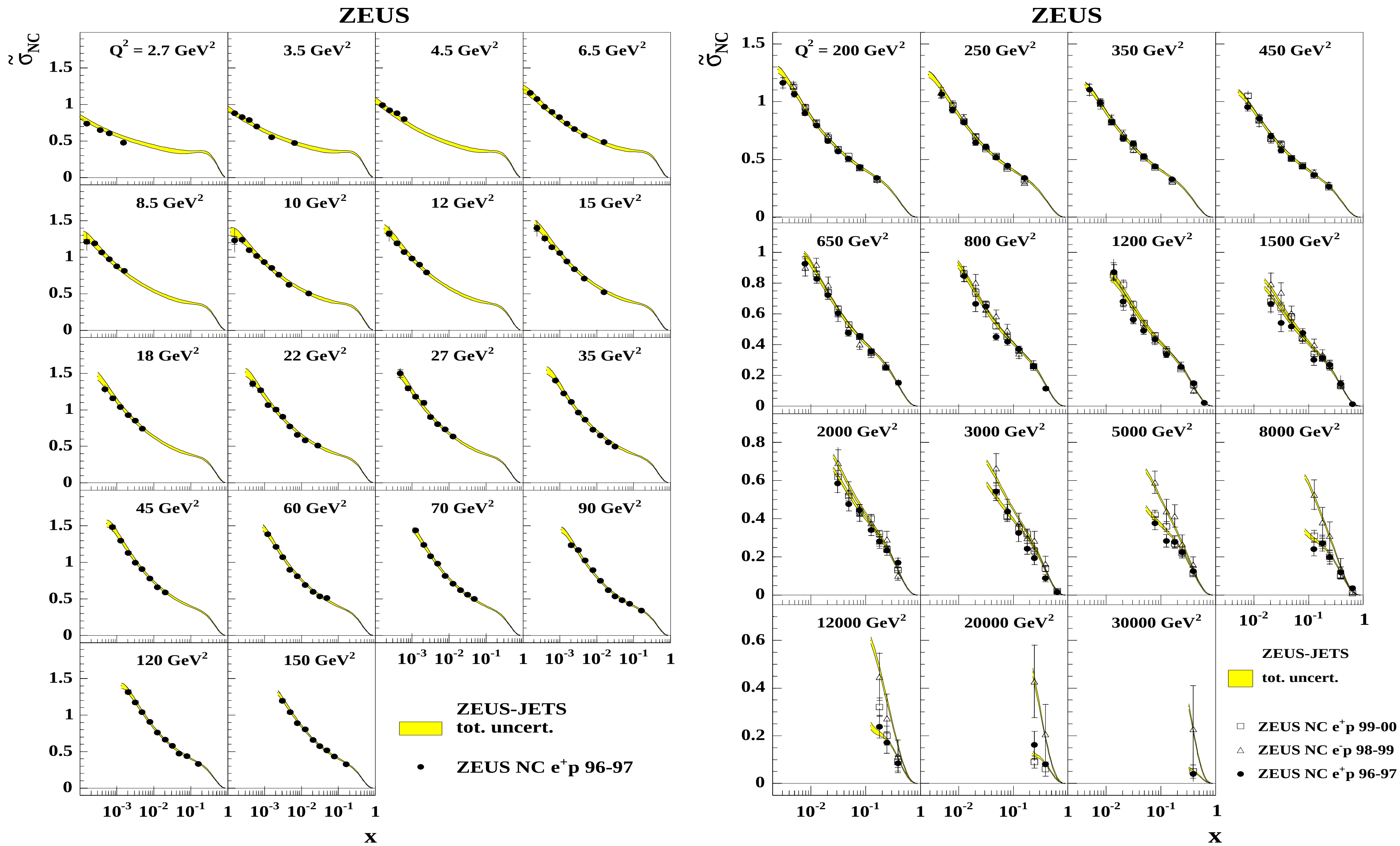
- The resolved $\gamma \mathbf{p}$ cross section can be written

$$\sigma_{\mathrm{res}}(ep \to e{+}N\mathrm{jets}{+}X) = \int_\Omega f_{\gamma/e}(y,Q^2)\sum_{ij} f_{i/p}(x,\mu_p^2)f_{j/\gamma}(x_\gamma,\mu_\gamma^2)d\hat{\sigma}(ij \to N\mathrm{jets})$$

Factorization in the Final State

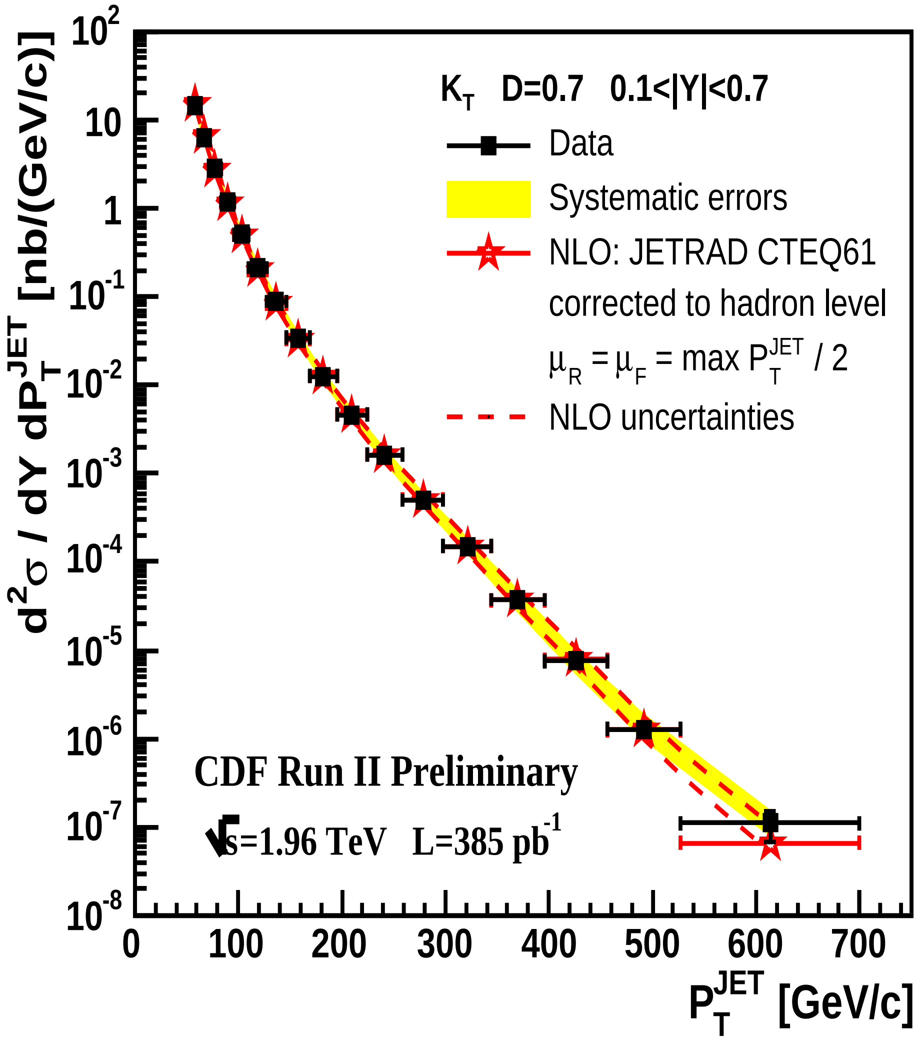
- After the hard scatter, hadron formation occurs over a much longer time scale, so it can be described independently of the hard process, again by a universal function $g_{H/i}(z)$ which gives the density in z, the fraction of the parton momentum carried by the hadron for hadrons of species H produced in the fragmentation of parton species i.

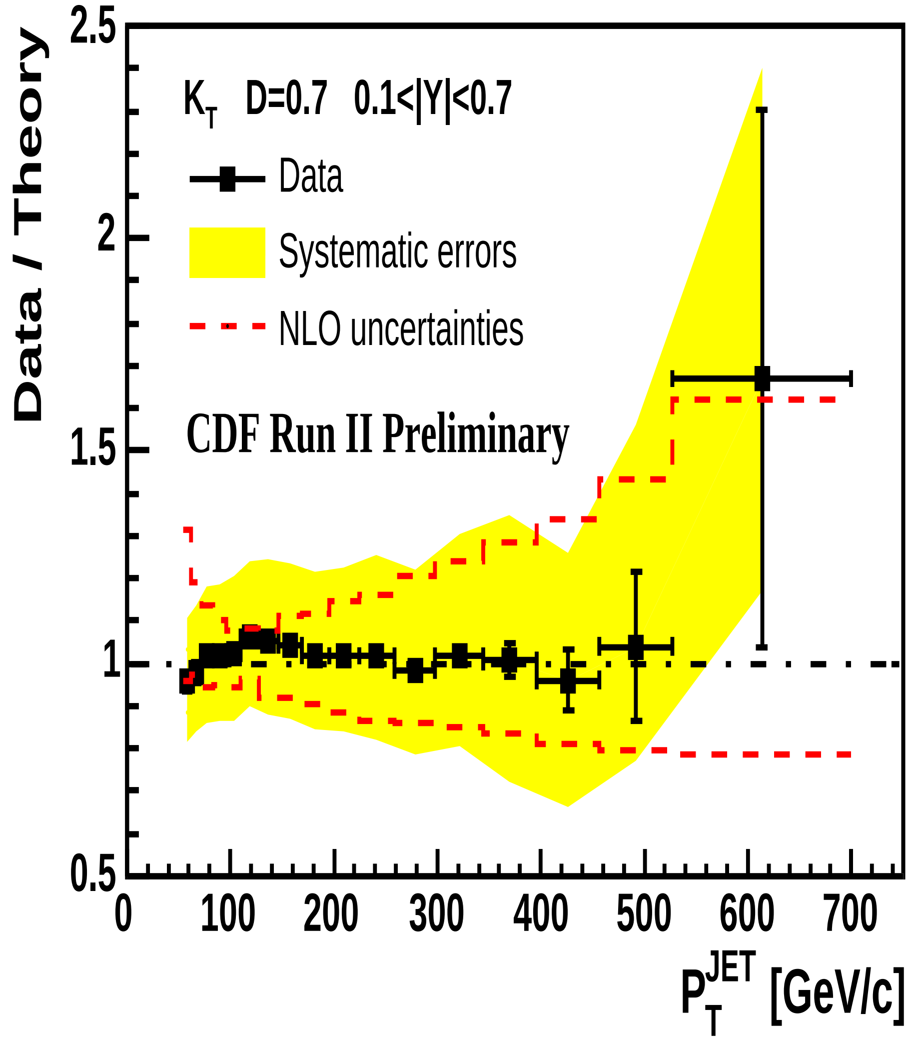
ZEUS NLO QCD Fit Compared to ZEUS NC DIS Data



DESY-05-71, submitted to European Physical Journal C

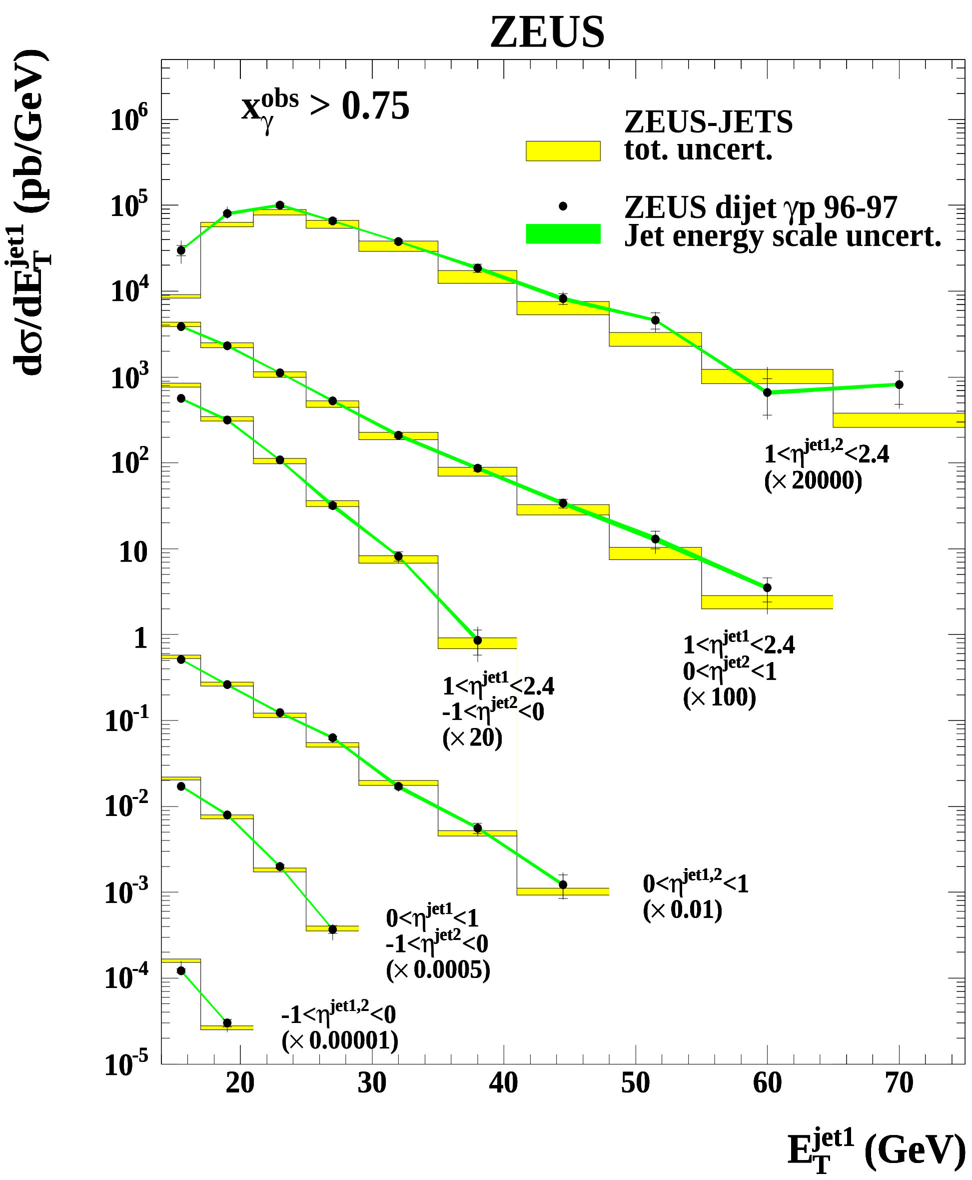
CTEQ61 Compared to CDF Jet Data

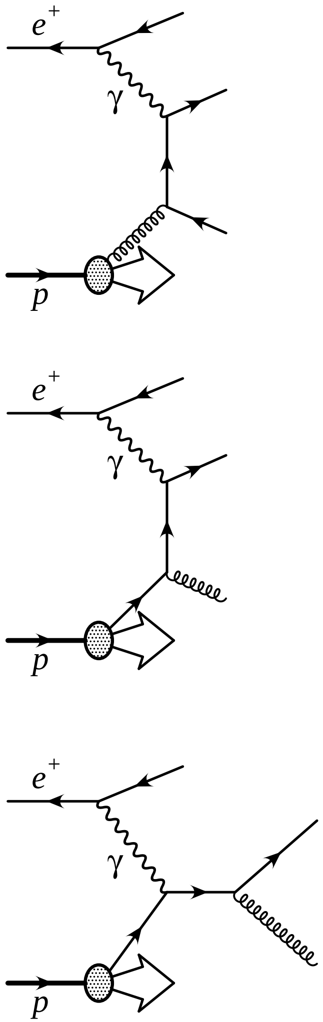




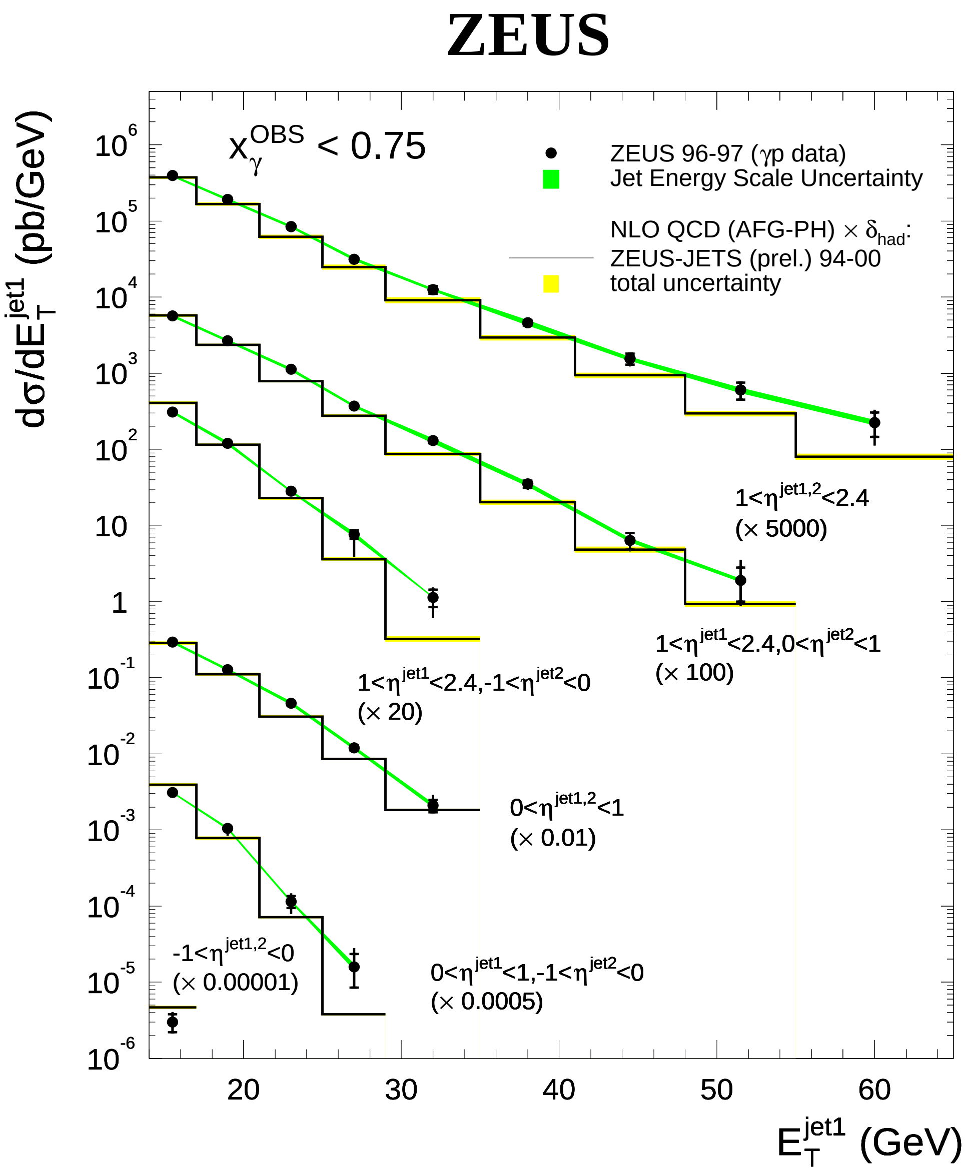
CTEQ61 also gives an excellent description of the HERA DIS data

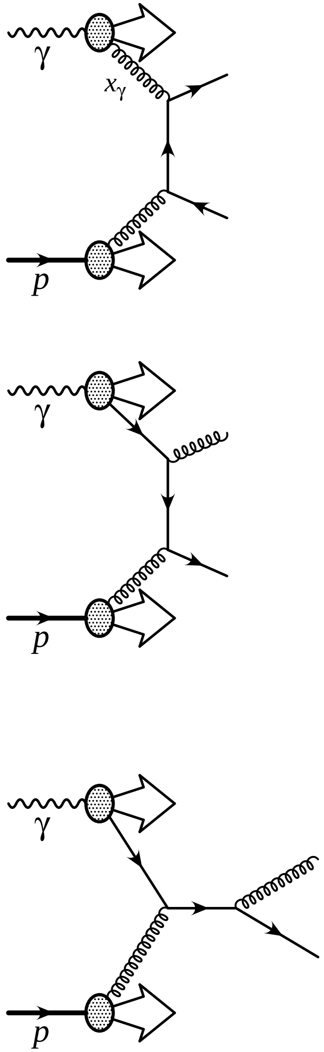
ZEUS NLO QCD Fit Compared to Direct Photoproduction Data





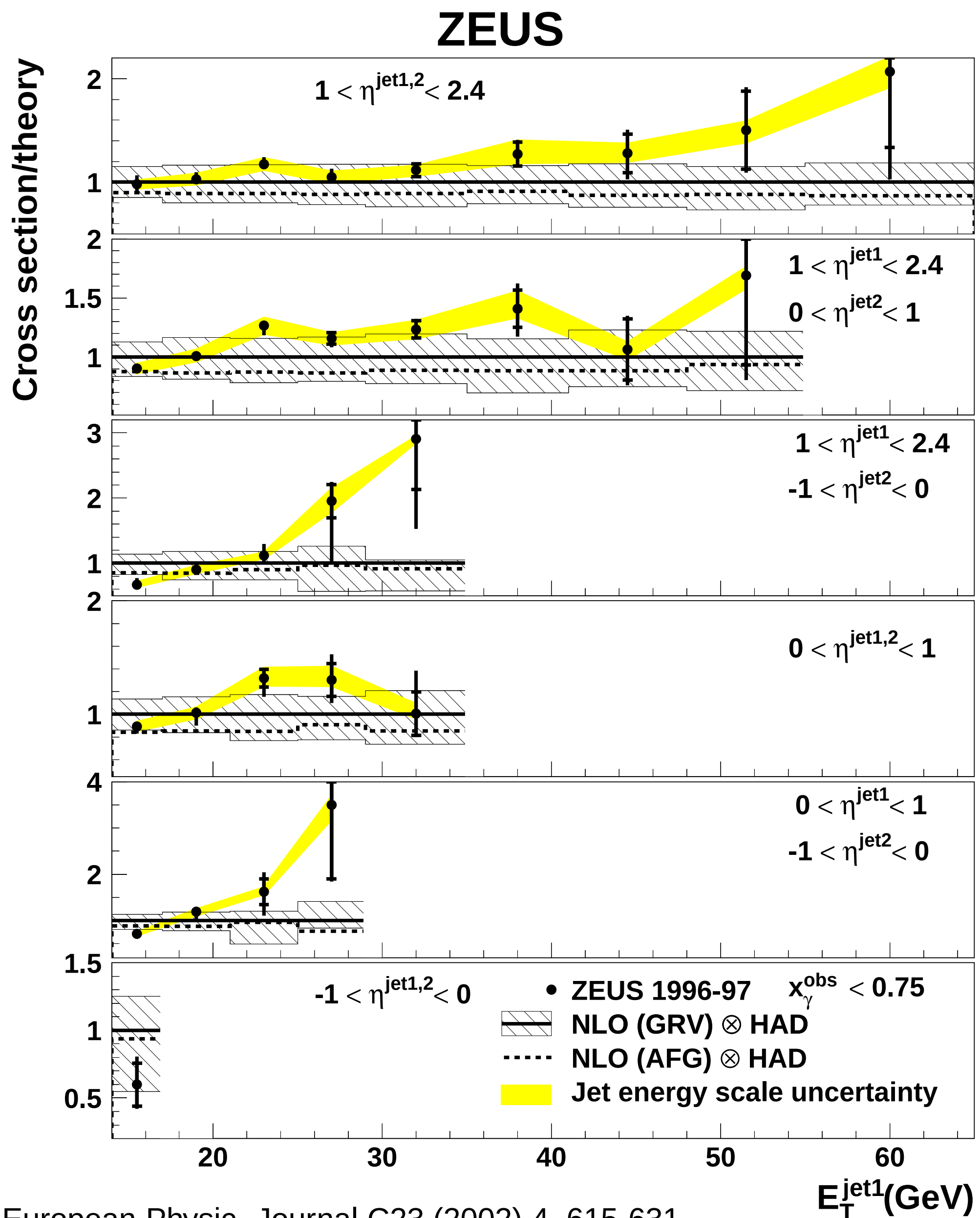
ZEUS NLO QCD Fit Compared to Resolved Photoproduction Data





The data lies above the NLO QCD calculations, especially at high $\mathbf{E_T}$

Resolved Photoproduction Data Compared to NLO Predictions



European Physic. Journal C23 (2002) 4, 615-631

CTEQ5M1 parton densities for the proton

The hatched theory error band includes:

· Renormalization and factorization scales μ varying between $E_T/4$ and E_T

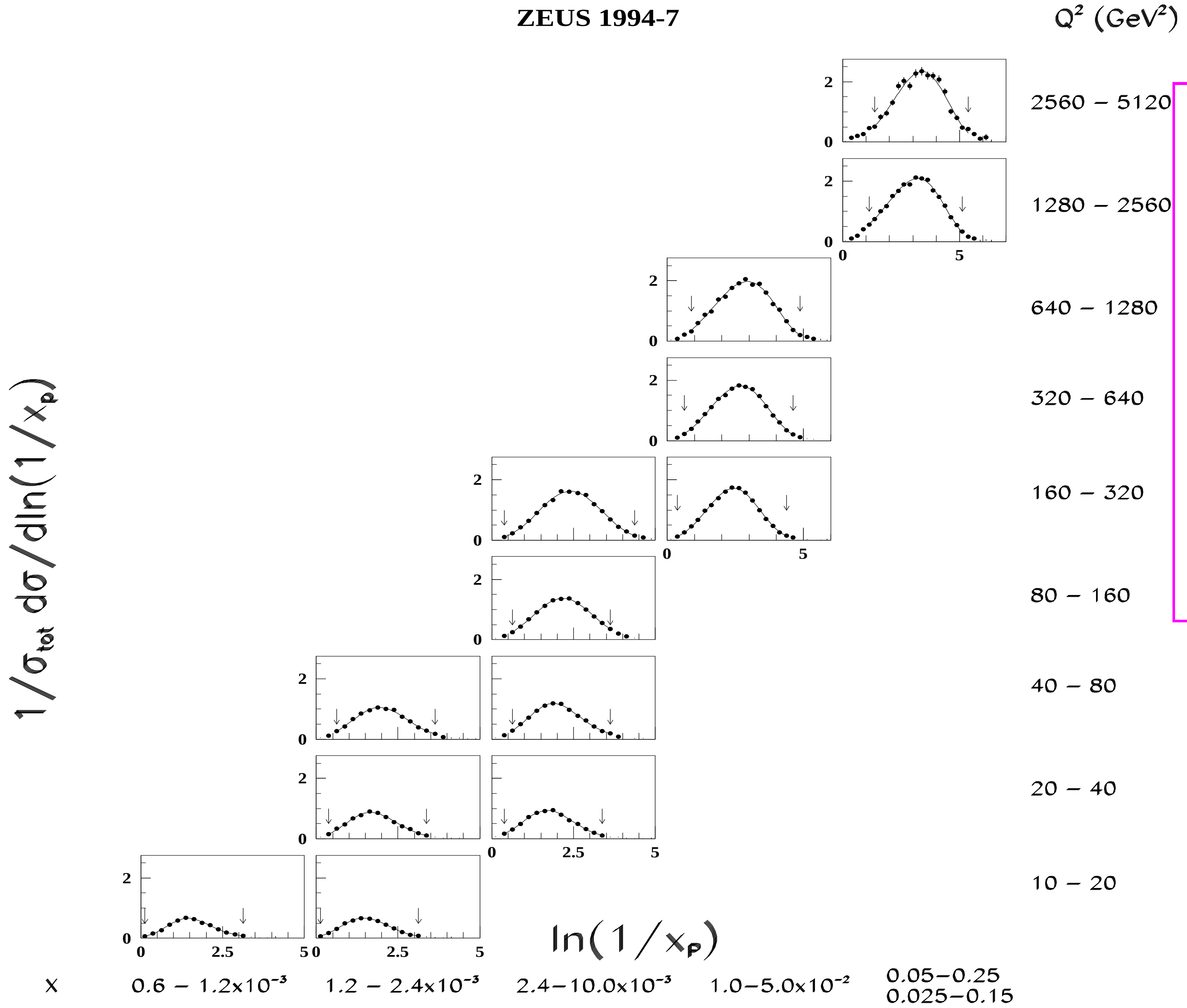
· Hadronization uncertainty

· $\alpha_s(M_z) = 0.116 \pm 0.003$

High E_T excess especially pronounced for forward jets

NC DIS Breit Frame Current Region Scaled Momentum Spectra

European Physical Journal C 11 (1999) 2, 251-270

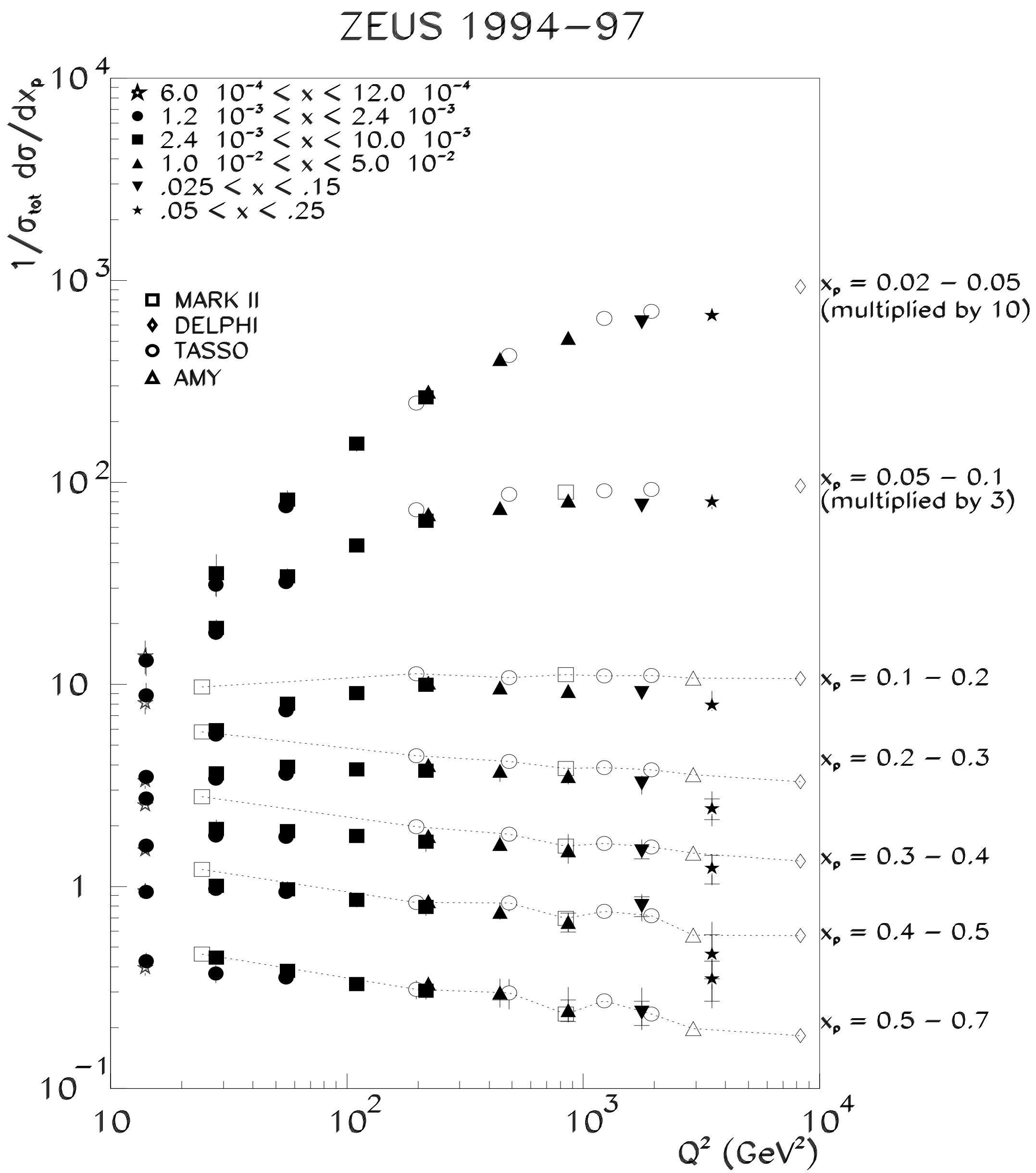


$q = (0, 0, 0, -Q)$ is the virtual photon momentum.

Max momentum of particles in the current region is $Q/2$

For particle with momentum p,
$x_p = 2p/Q$

Breit Frame Current Region Multiplicity in Bands of Scaled Momentum

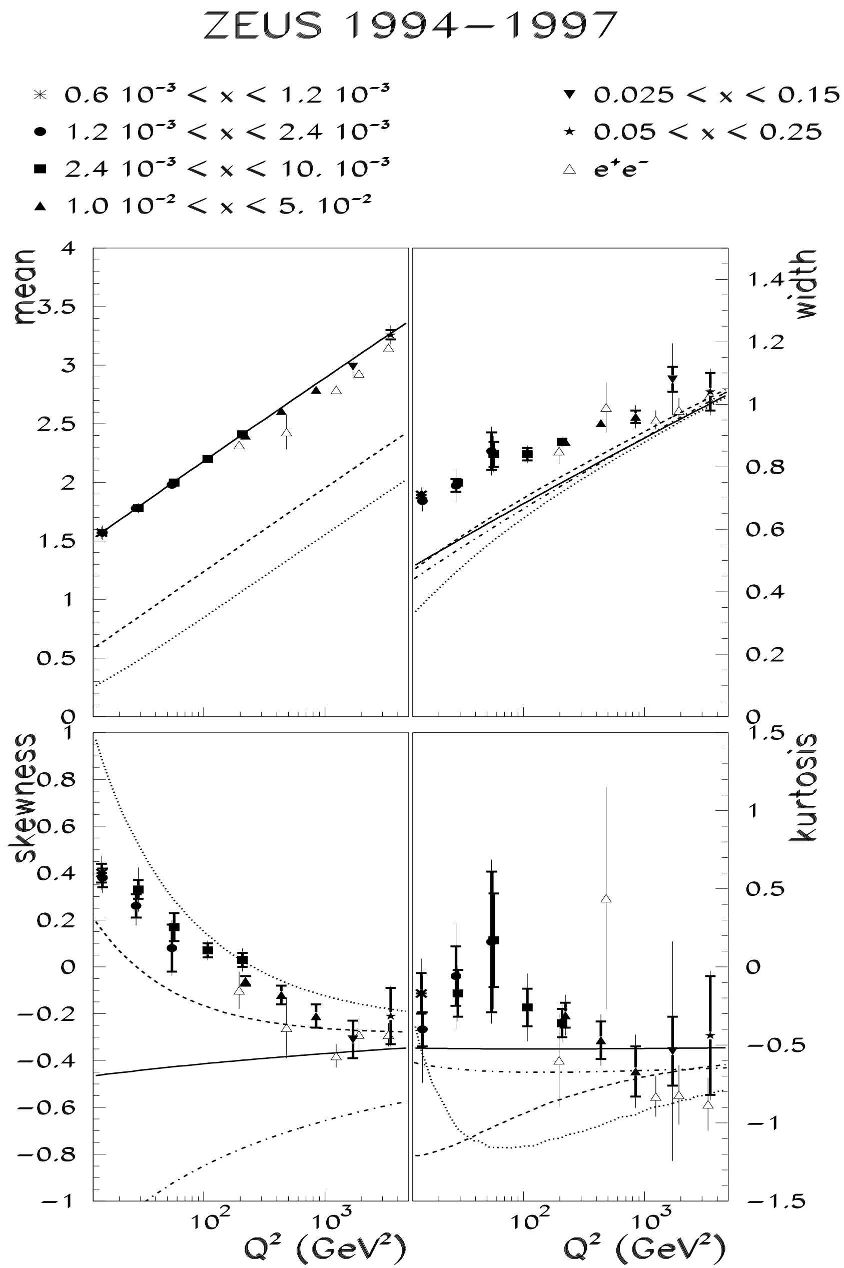


Open Symbols are e^+e^- multiplicities (divided by 2) plotted at $Q^2 = s$

Q^2 variation = scaling violation

e^+e^- and NC DIS data agree well

Compare Shape of the NC DIS Scaled Momentum Spectra to $\mathrm{e^+e^-}$



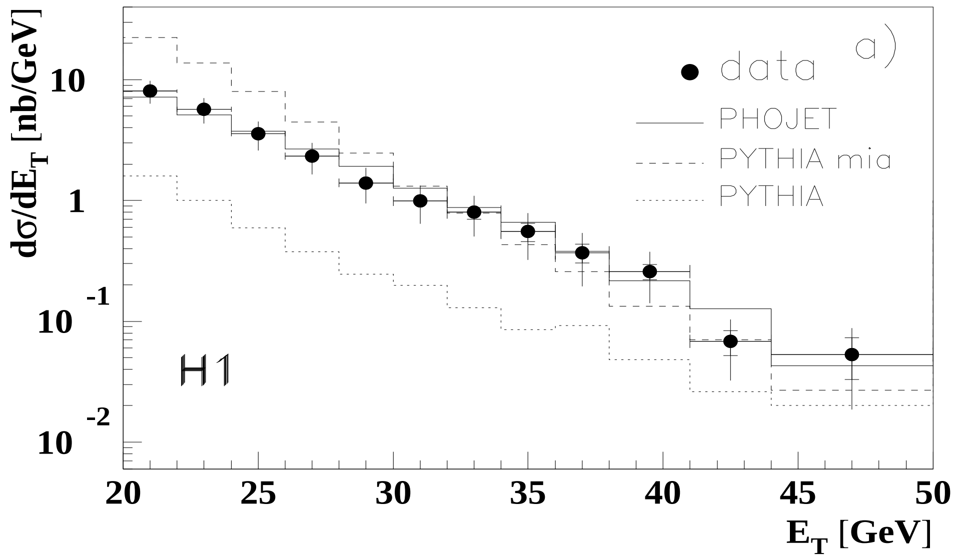
Parameterize the $\ln(1/x_p)$ distribution with mean l and width w as a distorted Gaussian in $\delta = (\ln(1/x_p) - l)/w$:

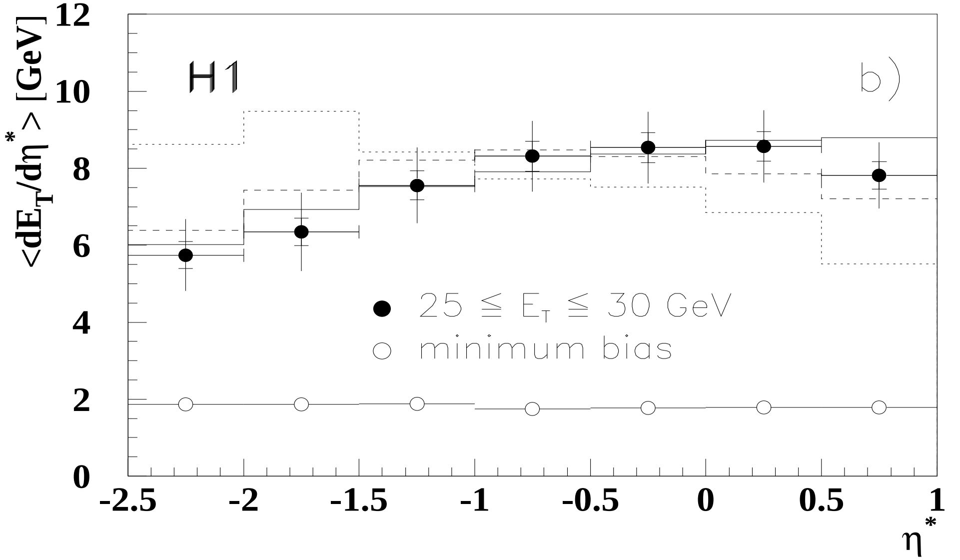
$$f(\delta) = \exp\left(\frac{k}{8} - \frac{s\delta}{2} - \frac{(2+k)\delta^2}{4} + \frac{s\delta^3}{6} + \frac{k\delta^4}{24}\right)$$

e^+e^- and NC DIS data agree well

Event Characteristics for Tagged Photoproduction

Z. Phys. C70 (1996) 17





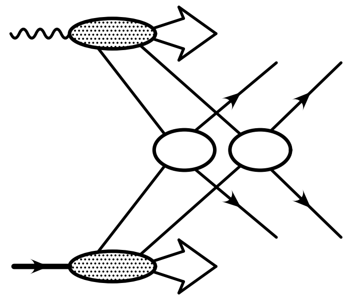
$Q^2 < 0.01\,\text{GeV}^2$

Tagged electron with $8 < E'_e < 20\,\text{GeV}$

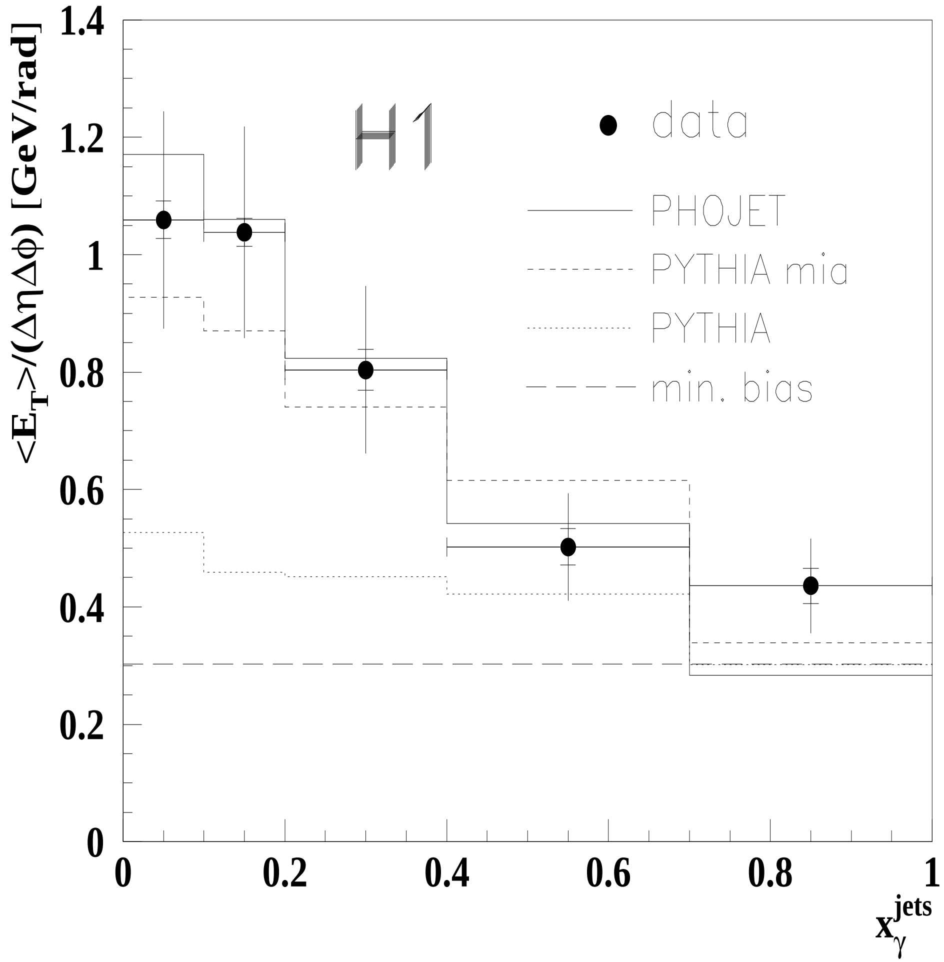
$0.25 < y < 0.7$

$150 < W < 251\,\text{GeV}$

Better description using simulations with multiple interactions (PHOJET, PYTHIA mia)



Tagged Photoproduction Underlying Event E_T density *vs.* x_γ



Require 2 jets with $E_T^{\rm jet} > 7$ GeV and $-2.5 < \eta^* < 0.5$

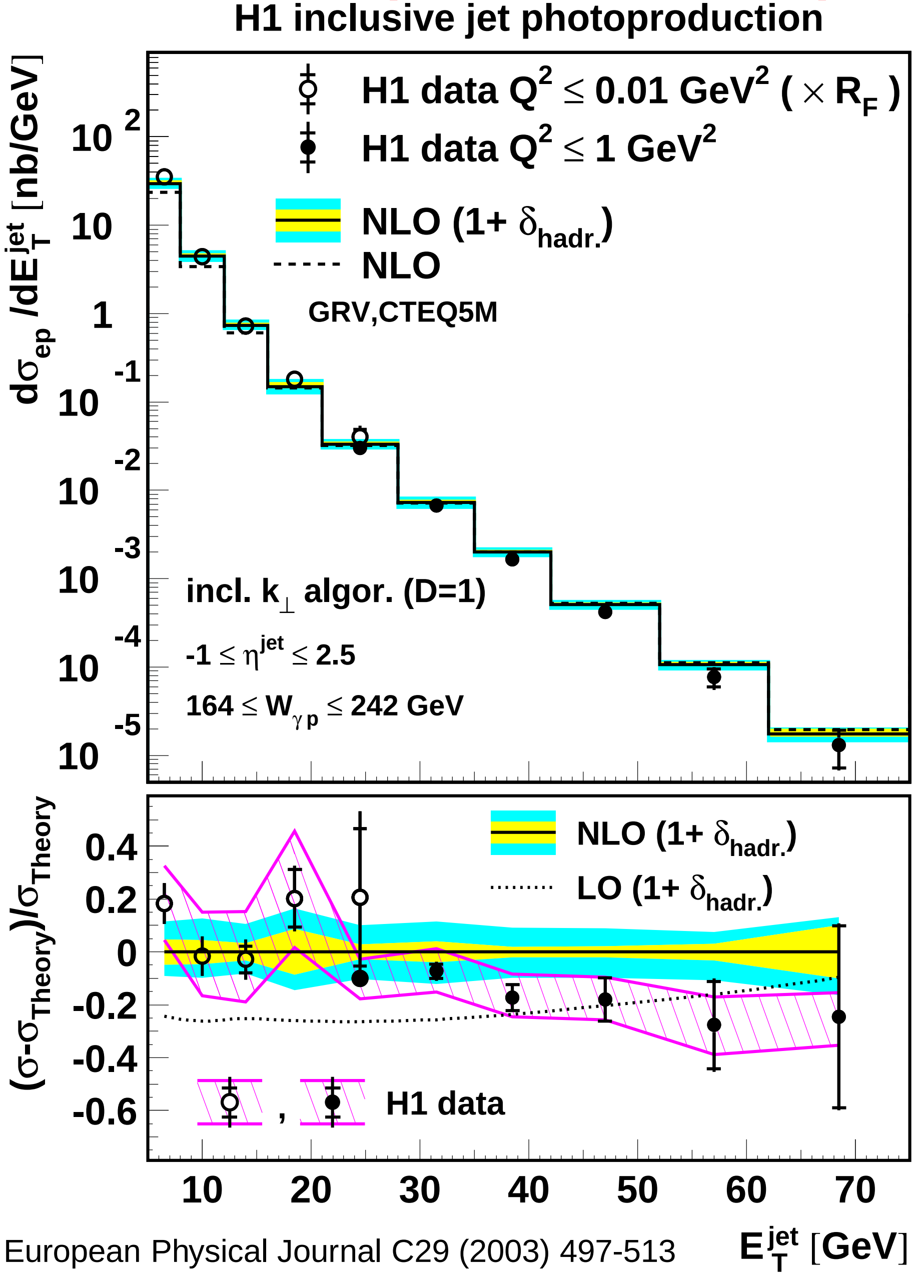
$x_\gamma^{\rm jets}$ is the fraction of the photon's longitudinal momentum carried by the dijet system

$$x_\gamma^{\rm jets} = \frac{(E - P_z)_{\rm jet1} + (E - P_z)_{\rm jet2}}{(E - P_z)_\gamma}$$

Plot shows the (η, ϕ) E_T density in the central region $|\eta^*| < 1$ excluding cones of radius 1.3 centered on the 2 highest E_T jets

Low $x_\gamma^{\rm jets}$ (resolved) γp interactions have $\sim 2\times$ as much E_T density as direct γp.

Photoproduction E_T Spectrum Compared to NLO QCD

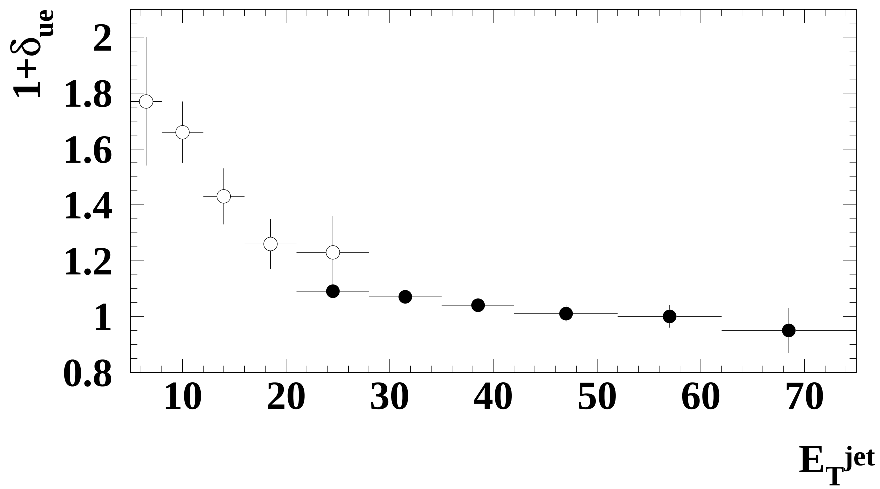


European Physical Journal C29 (2003) 497-513

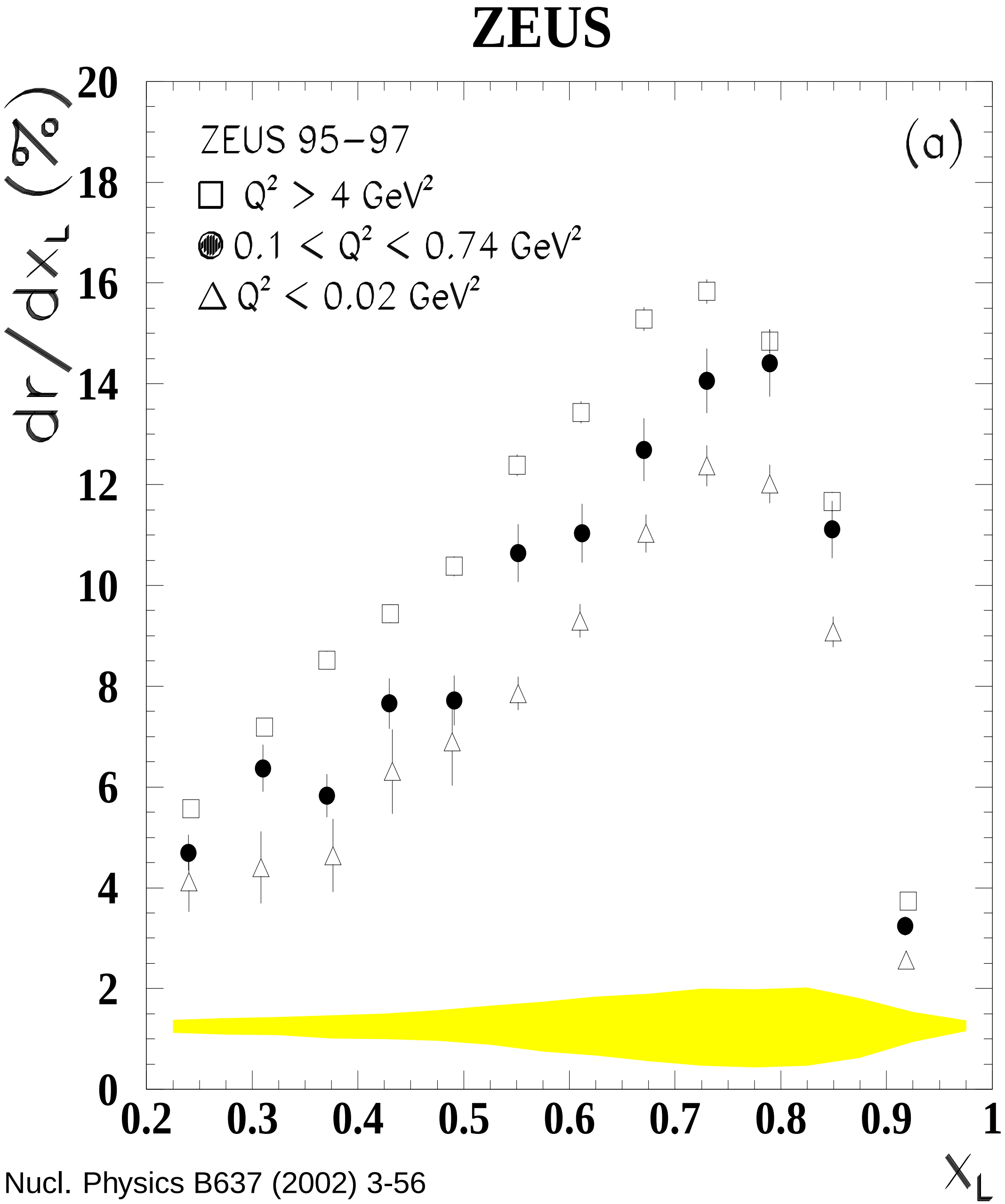
NLO results corrected by $1 + \delta_{\mathrm{hadr}} = (1 + \delta_{\mathrm{frag}})(1 + \delta_{ue})$

$1 + \delta_{\mathrm{frag}}$ corrects for fragmentation.

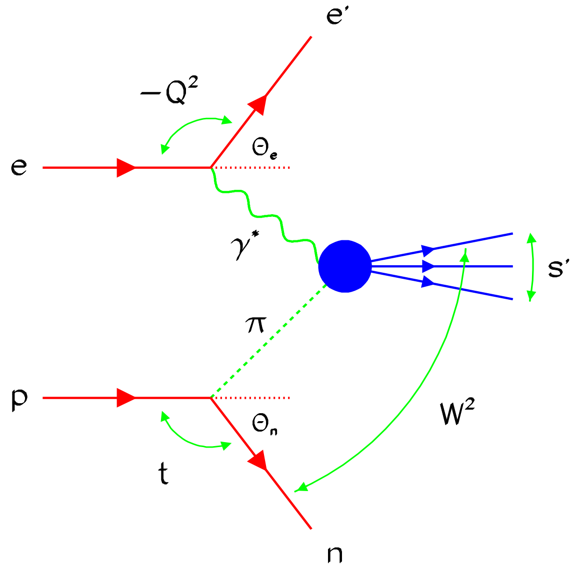
The underlying event correction $1 + \delta_{ue}$ is defined as the ratio of cross sections with and without a simulated underlying event which was tuned to describe the energy flow between jets.



Forward Neutron Production in DIS and γP



Nucl. Physics B637 (2002) 3-56

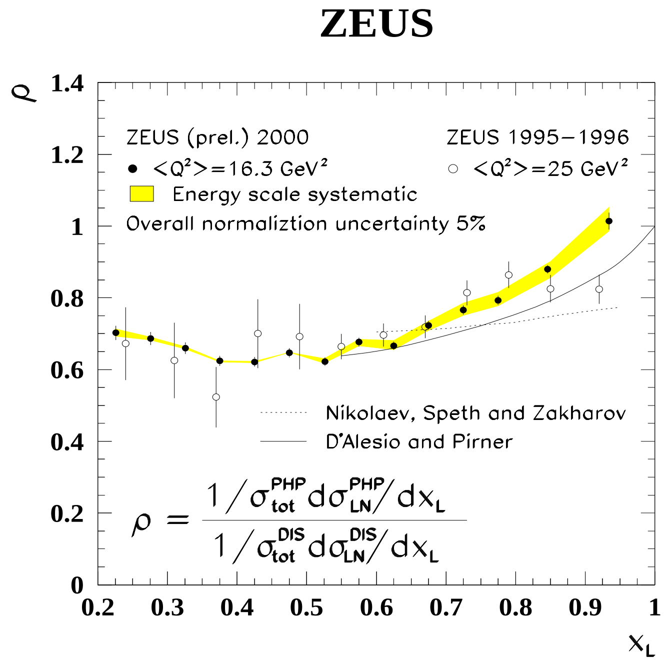


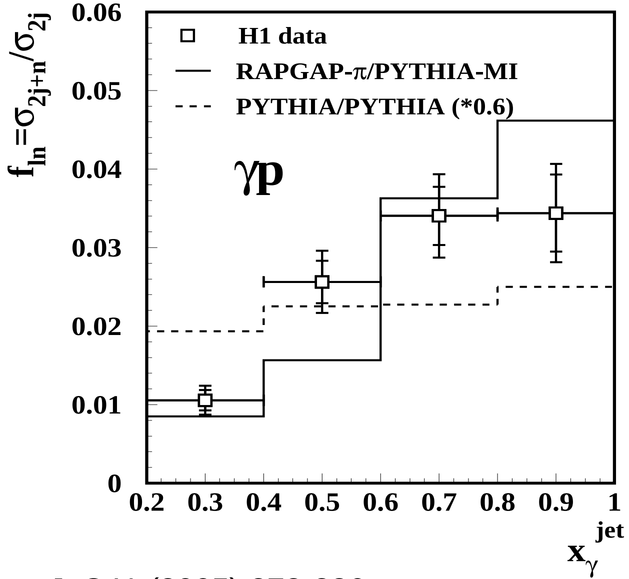
$x_L = P_n/P_p$

Probability of producing a neutron is about $1/2$ that observed in pp collisions at the ISR.

γp collisions are 20-30% less likely to produce a neutron compared to NC DIS, although no Q^2 dependence is observed for $Q^2 > 4$.

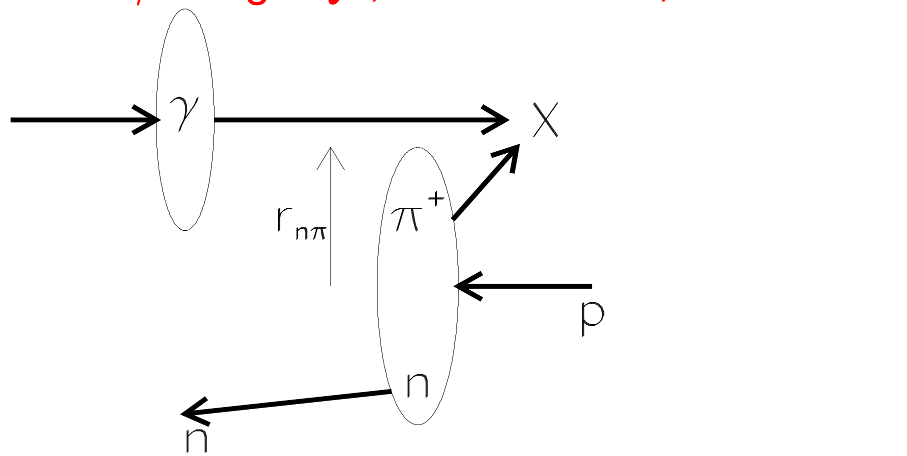
Forward Neutron Production in DIS and γP





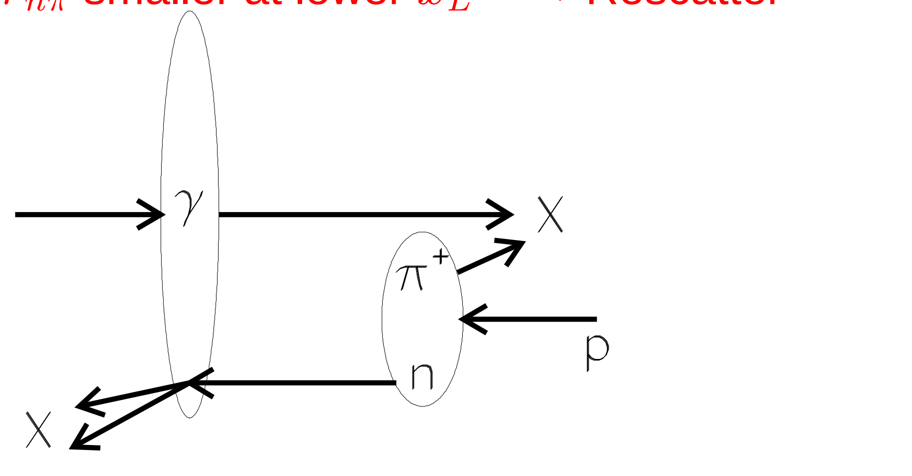
Eur. Phys. J. C41 (2005) 273-286

Small γ = High Q^2, No Rescatter, n detected

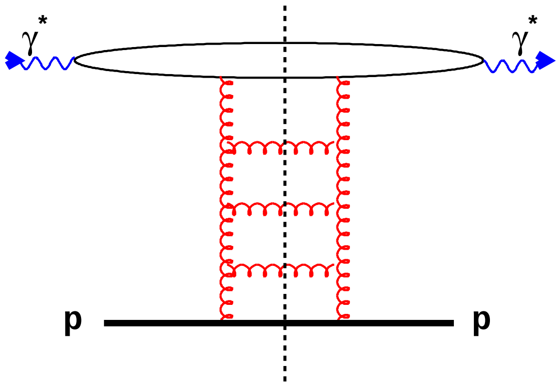


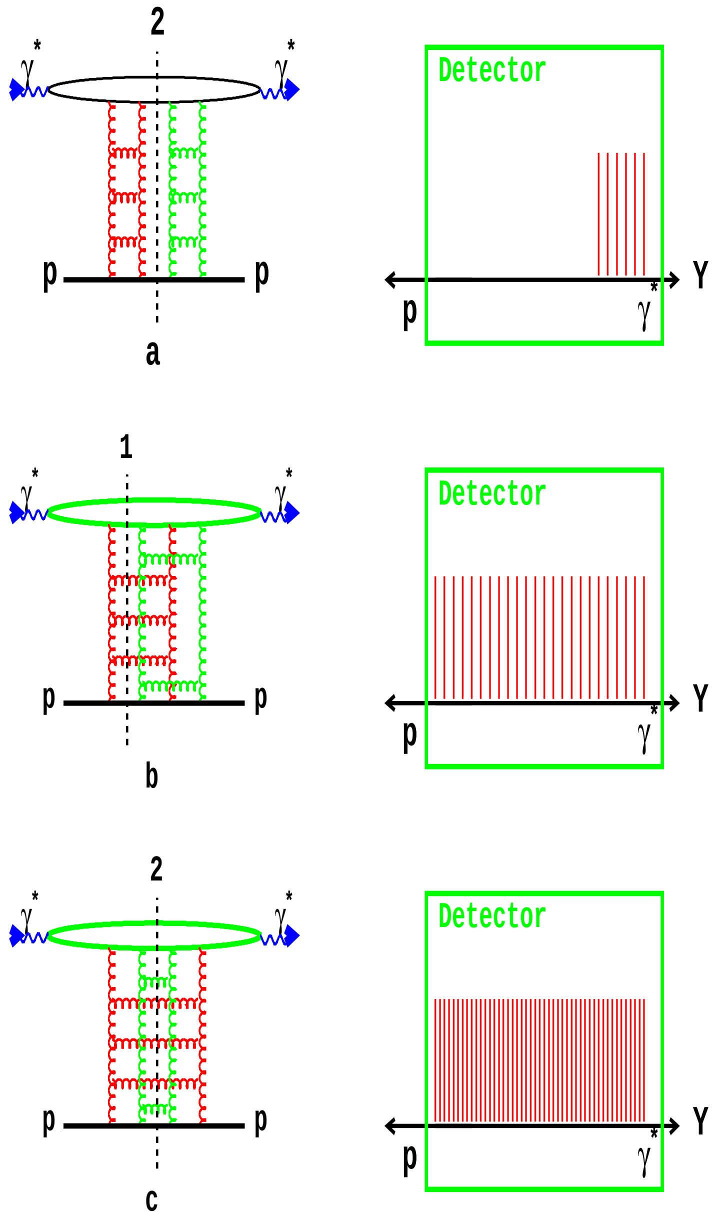
Large γ = Low Q^2 $\longrightarrow$ Rescatter.

$r_{n\pi}$ smaller at lower x_L $\longrightarrow$ Rescatter



Dipole Model of Deep Inelastic Scattering





The Optical Theorem relates the amplitude for elastic $\gamma^* p$ scattering (no cut) to the inclusive $\gamma^* p$ cross section (with the cut). The total cross section is a sum of all diagrams with all possible Pomeron (gluon ladder) exchanges. Diagram (a) above right gives the leading term to the diffractive cross section.

J.Bartels, M.Salvadore, G.P.Vacca,Eur.Phys.J. C42 (2005) 53-71

H.Kowalski, D.Teaney, Phys.Rev. D68 (2003) 114005

Dipole Model of Deep Inelastic Scattering

The $\gamma^* p$ cross section for k-cut Pomerons vs. impact parameter b is

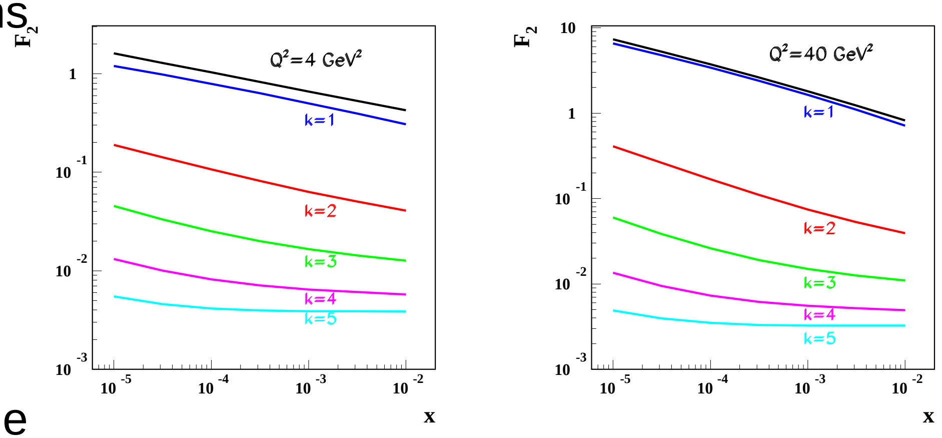
$$\frac{d\sigma_k}{d^2b} = \frac{\Omega(b)^k}{k!}\exp(-\Omega(b)), \text{ where}$$

$$\Omega = \frac{\pi^2}{N_C} r^2 \alpha_s(\mu^2)\, xg(x,\mu^2)\, T(b)$$

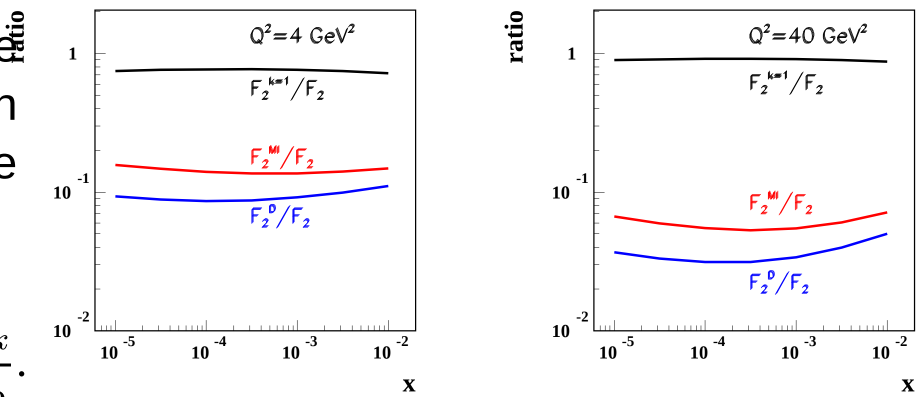
is the Opacity written in terms of the dipole radius r, the gluon density $xg(x,\mu^2)$ and the transverse shape of the proton $T(b)$.

To get the total cross section, F_2, average the dipole cross secctions over the photon wave function $\psi(r,z)$ and integrate over the impact parameter

$$F_2^k = \frac{Q^2}{4\pi^2\alpha_{em}} \int d^2r \int \frac{dz}{4\pi}\psi^*\psi \int d^2b \frac{d\sigma_k}{d^2b}.$$



Contributions to F_2 from k-cut Pomerons (H.Kowalski).



Fraction of F_2 due to single Pomeron exchange, multiple Pomeron exchange, and diffraction.

Conclusions

- Factorization holds very well in non-diffractive interactions of protons with point-like photons
- Universal parton densities can describe $\mathbf{ep}$, direct $\gamma\mathbf{p}$, and hard $\mathbf{p\bar{p}}$ interactions
- Fragmentation functions measured in DIS are quite compatible with those measured in $\mathbf{e^+e^-}$.

Conclusions

- In resolved photoproduction, which is a hadron-hadron collision, multiple-interaction models describe the data better than LO models without multiple interactions.
  - The underlying event produces about twice as much $\mathbf{E_T}$ in resolved photoproduction compared to direct
  - Resolved $\gamma\mathbf{p}$ cross sections exceed NLO QCD predictions, at high $\mathbf{E_T}$
  - HERA experiments should measure event shapes and energy flow in $\gamma\mathbf{p}$ more systematically, instead of focusing entirely on jets
- The probability to produce a forward neutron is process dependent, highest in $\mathbf{pp}$ collisions, and lowest in $\gamma\mathbf{p}$ interactions.
- The dipole model relates the cross section for multiple gluon exchange to the diffractive cross section. Even at the relatively high $\mathbf{Q^2}$ of 40 GeV^2, the model predicts that multiple gluon exchange makes up 6-8% of the DIS cross section