The Structure of Real and Virtual Photons as measured at HERA

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AT00000590

The real photon

* kinematics
* jet cross sections
* parton densities
* uncertainties

Virtual photons

* jet cross sections
* parton densities

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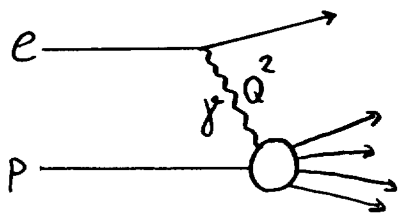
Photoproduction of jets

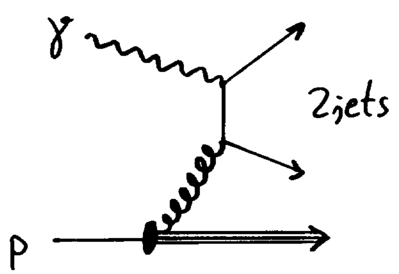
Electron - Proton scattering at HERA

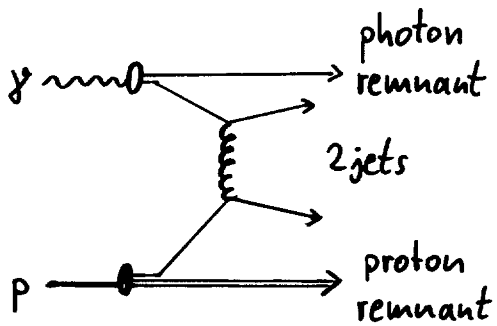


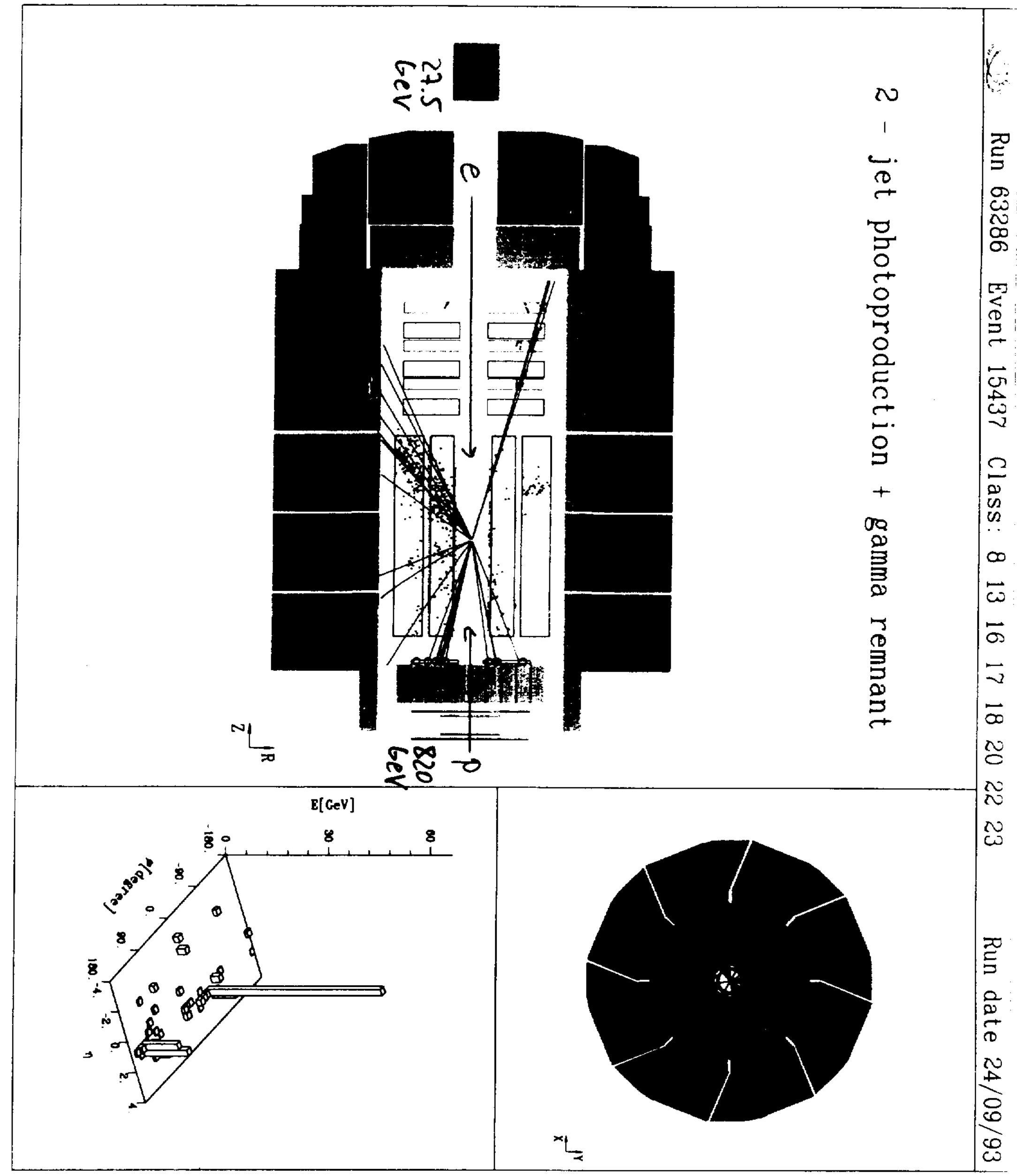
$Q^2 \approx 0$ (real photon) : " Photoproduction "

direct photon (pointlike)

resolved photon (with hadronic structure)

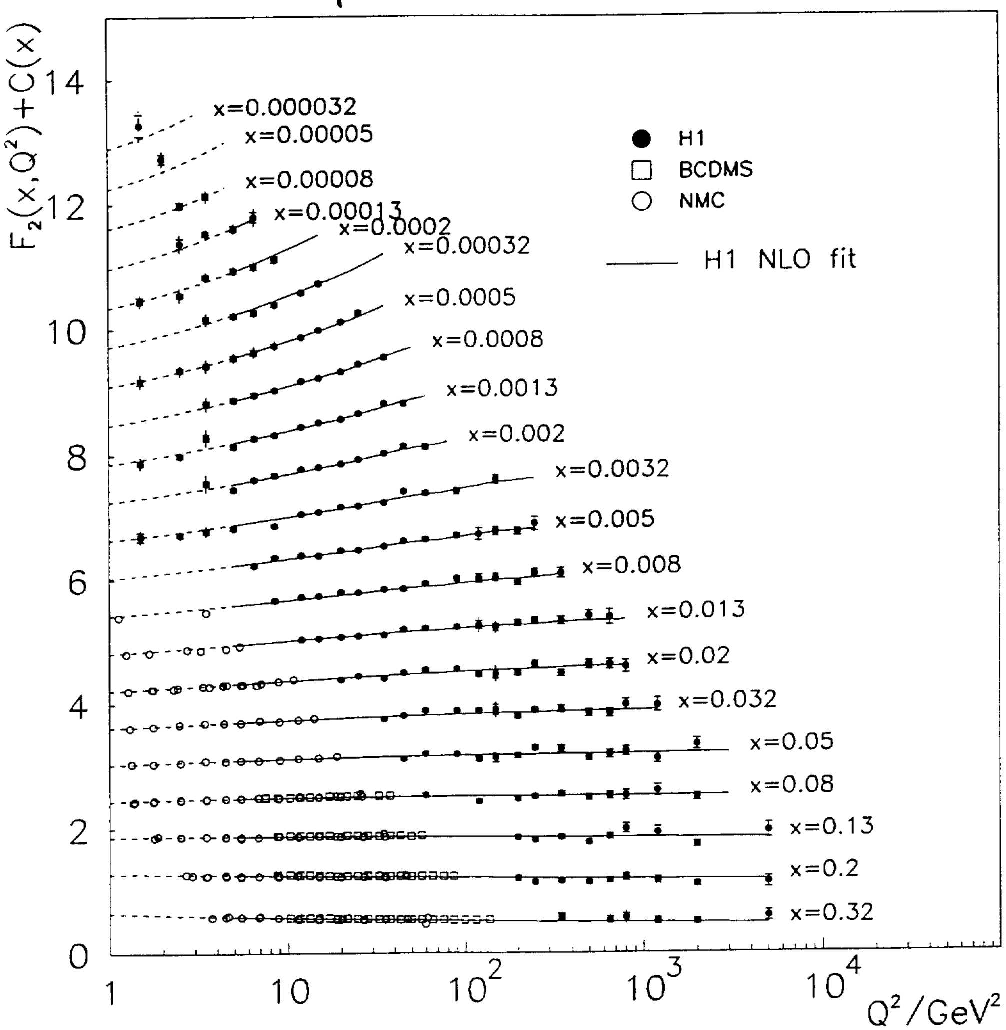






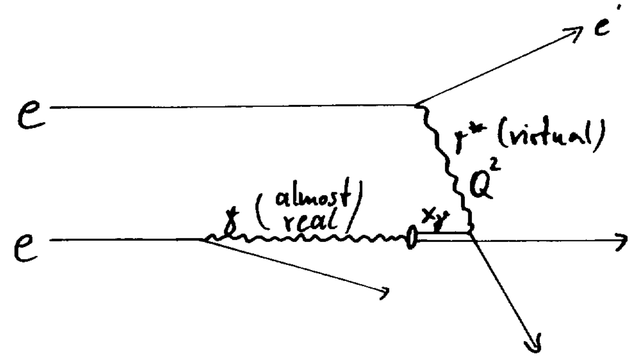
The proton structure function $F_2(x,Q^2)$

$$F_2^p \sim x \sum_q e_q^2 \, q^p$$



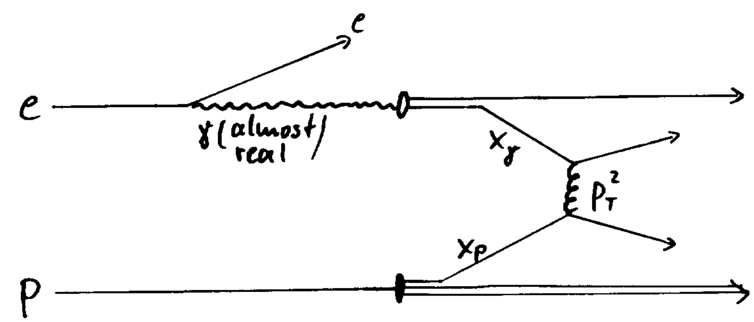
Measuring photon parton distributions

a) deep inelastic scattering at e^+e^- experiments



$$F_2^\gamma(x_\gamma,Q^2) = x_\gamma \sum_q e_q^2 \left(q(x_\gamma,Q^2) + \bar{q}(x_\gamma,Q^2)\right)$$

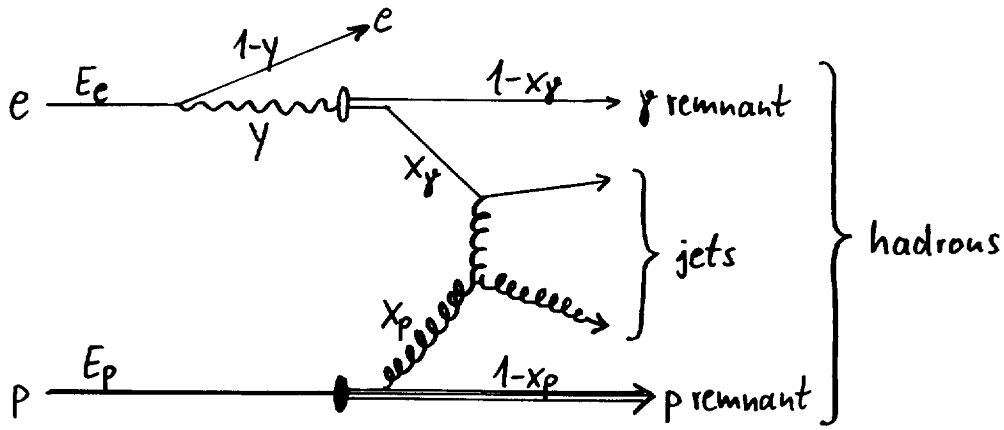
b) photoproduction at HERA (ep collisions)



hadronic scattering, both quark and gluon content of the photon contribute:

$$f_{eff}^\gamma(x_\gamma,p_T^2) = \sum_q \left(q(x_\gamma,p_T^2) + \bar{q}(x_\gamma,p_T^2)\right) + \frac{9}{4}\, g(x_\gamma,p_T^2)$$

The di-jet cross section



4 independent kinematic variables, e.g.:

$$y = \frac{E_\gamma}{E_e} = \frac{1}{2E_e} \sum_{hadrons} (E - p_z) \qquad x_\gamma = \frac{1}{2E_\gamma} \sum_{jets} (E - p_z)$$

$$\cos\theta^* = \tanh \frac{\Delta\eta_{jets}}{2} \qquad x_p = \frac{1}{2E_p} \sum_{jets} (E + p_z)$$

4 fold differential di-jet cross section:

$$\frac{d^4\sigma}{dy\, dx_\gamma\, dx_p\, d\cos\theta^*} = \frac{1}{32\pi s_{ep}} \frac{f_{\gamma/e}(y)}{y} \sum_{i,j} \frac{f_{i/\gamma}(x_\gamma, p_T^2)}{x_\gamma} \frac{f_{j/p}(x_p, p_T^2)}{x_p} \left| M_{ij}(\cos\theta^*) \right|^2$$

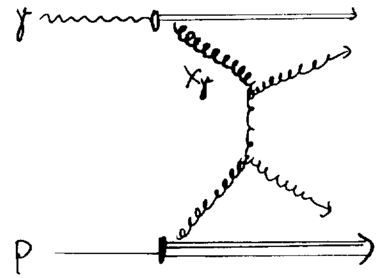
transverse momentum of the partons: $p_T^2 = \frac{1}{4} s_{ep}\, y\, x_\gamma\, x_p \sin^2\theta^*$

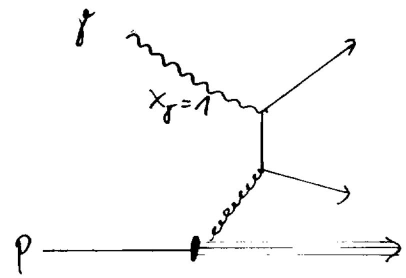
with $s_{ep} = (300\ \mathrm{GeV})^2$

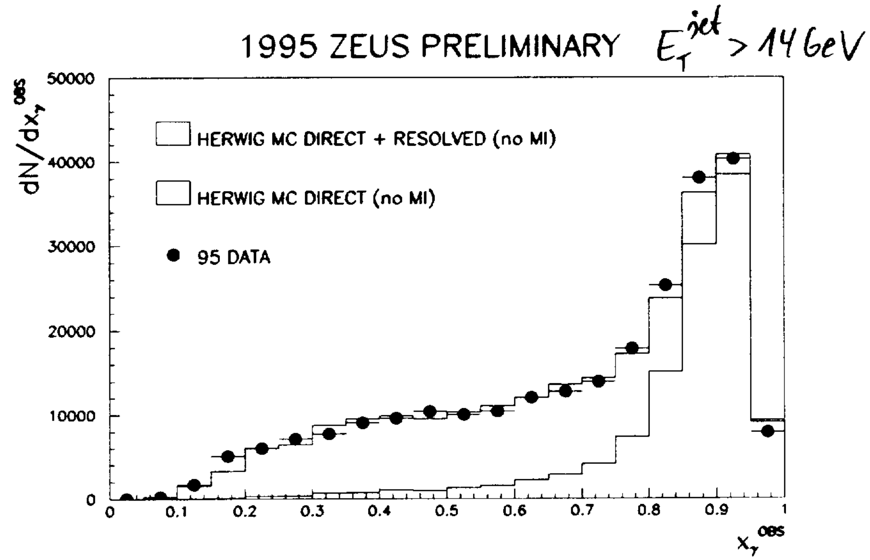
Direct and resolved contributions in real photoproduction

resolved
photon with hadronic structure

direct
pointlike photon

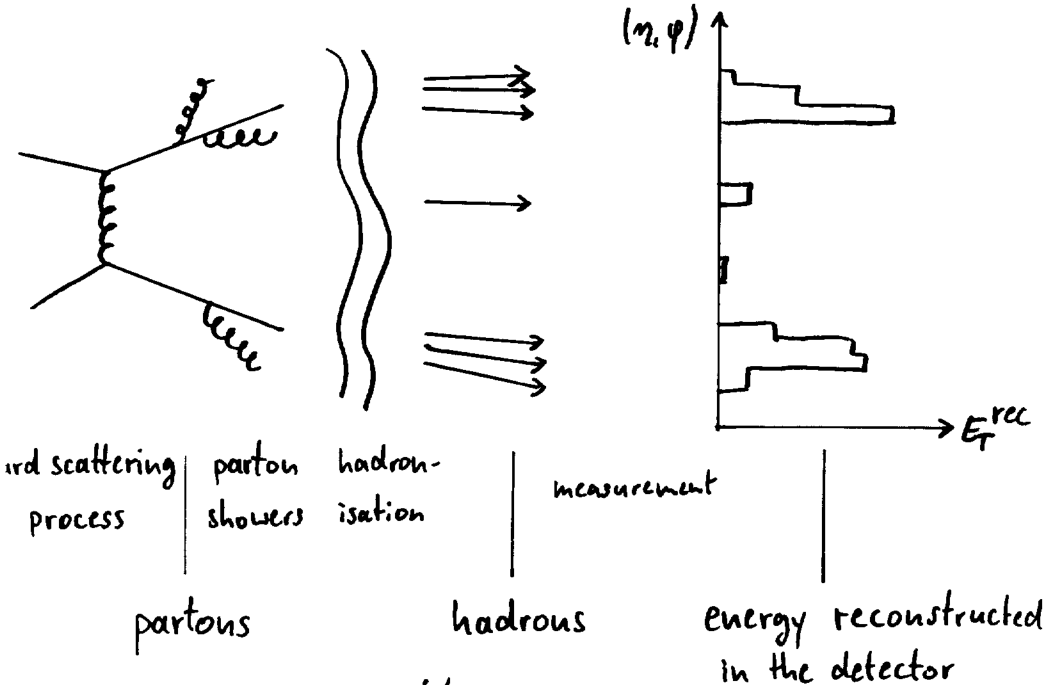


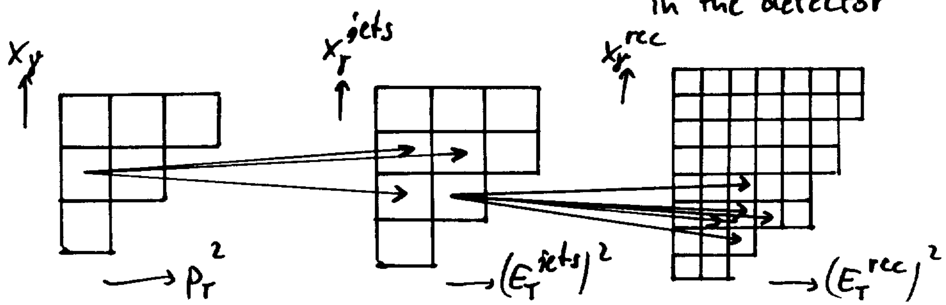




→ reconstructed momentum fraction x_γ

Correction of the di-jet cross section





Migrations determined by:

MC model with parton showers and fragmentation — detector simulation

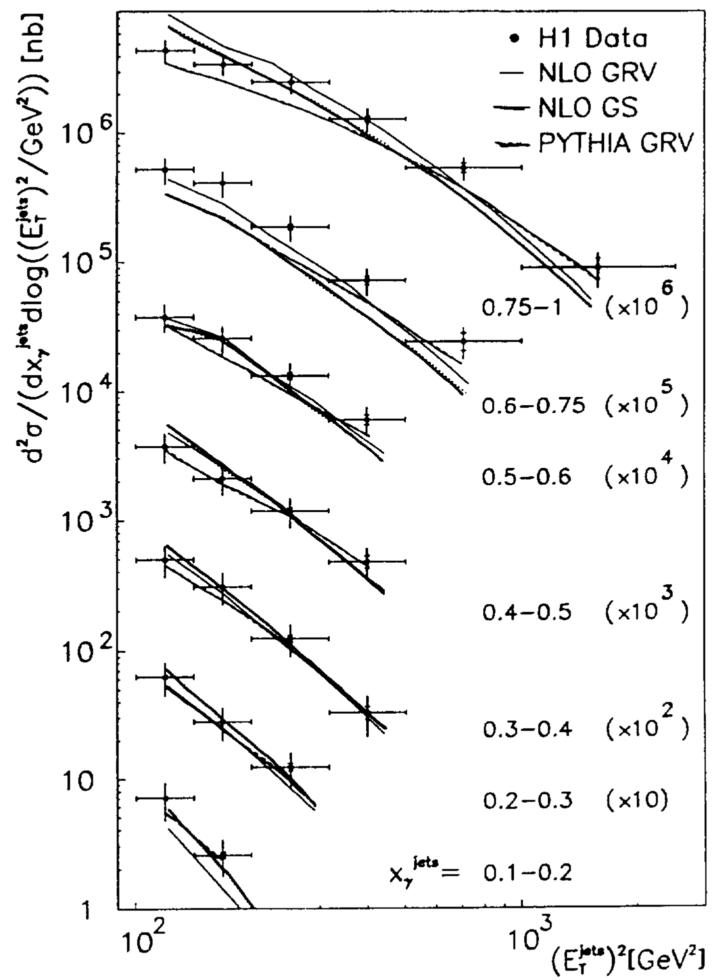
$\Longrightarrow$ 2-step unfolding procedure

Inclusive double-differential di-jet cross section

valid for: $Q^2 < 4\,\mathrm{GeV}^2$ $\quad 0.2 < y < 0.83$

$$\frac{|E_{T1}^{jet} - E_{T2}^{jet}|}{E_{T1}^{jet} + E_{T2}^{jet}} < \frac{1}{4} \qquad 0 < \frac{1}{2}(\eta_1^{jet} + \eta_2^{jet}) < 2 \qquad |\eta_1^{jet} - \eta_2^{jet}| < 1$$

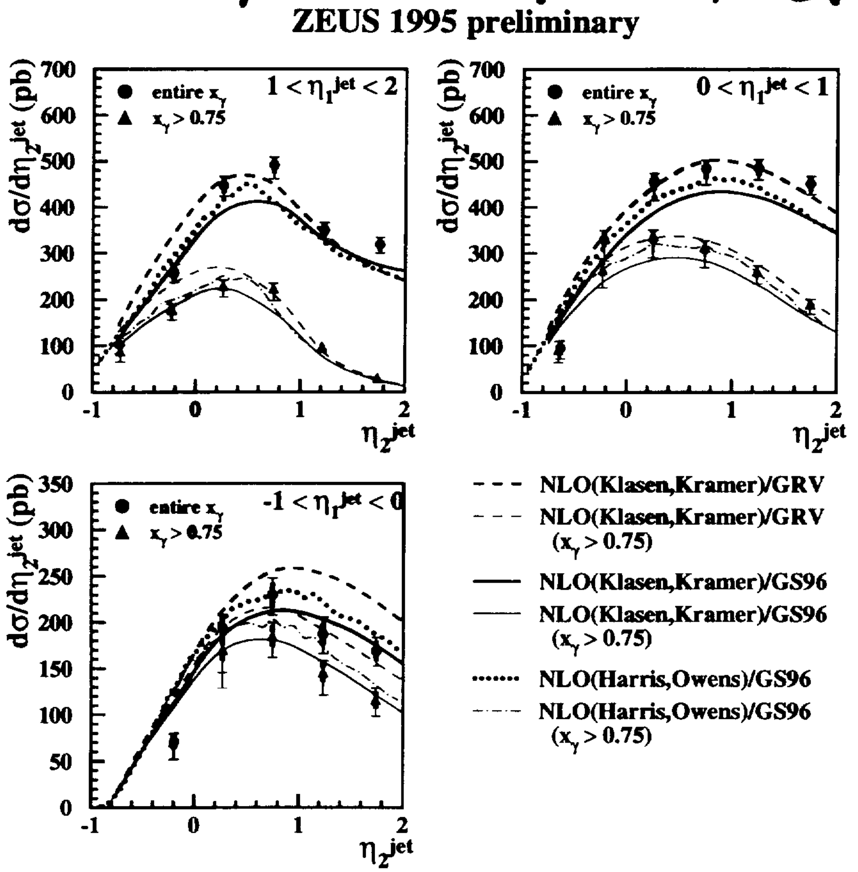
jets defined by cone algorithm, $R = 0.7$



Differential di-jet cross sections

as a function of η_1, η_2, x_γ

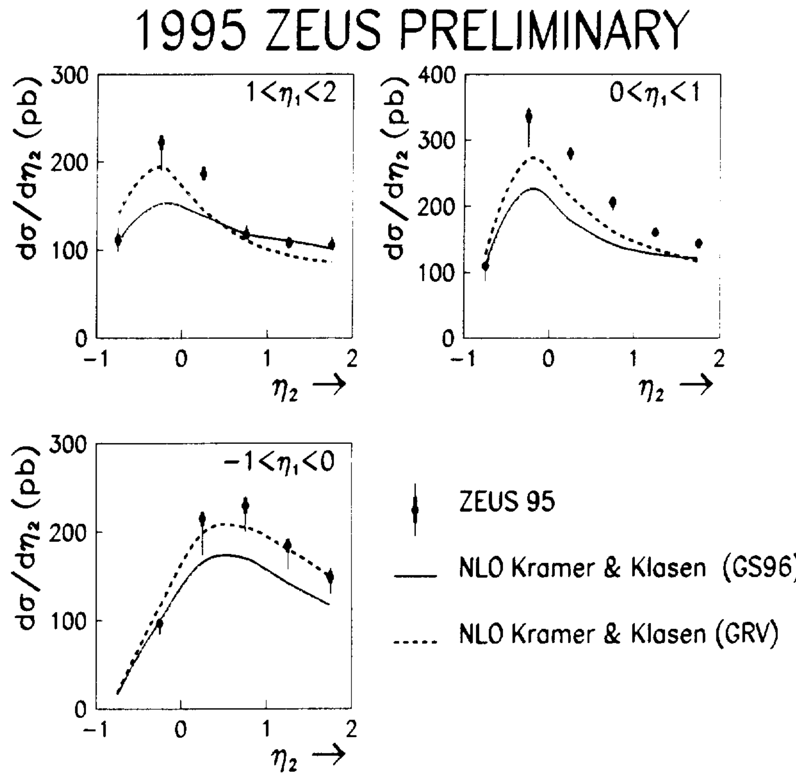
$0.2 < y < 0.85, \; E_T^{jet} > 14$ GeV



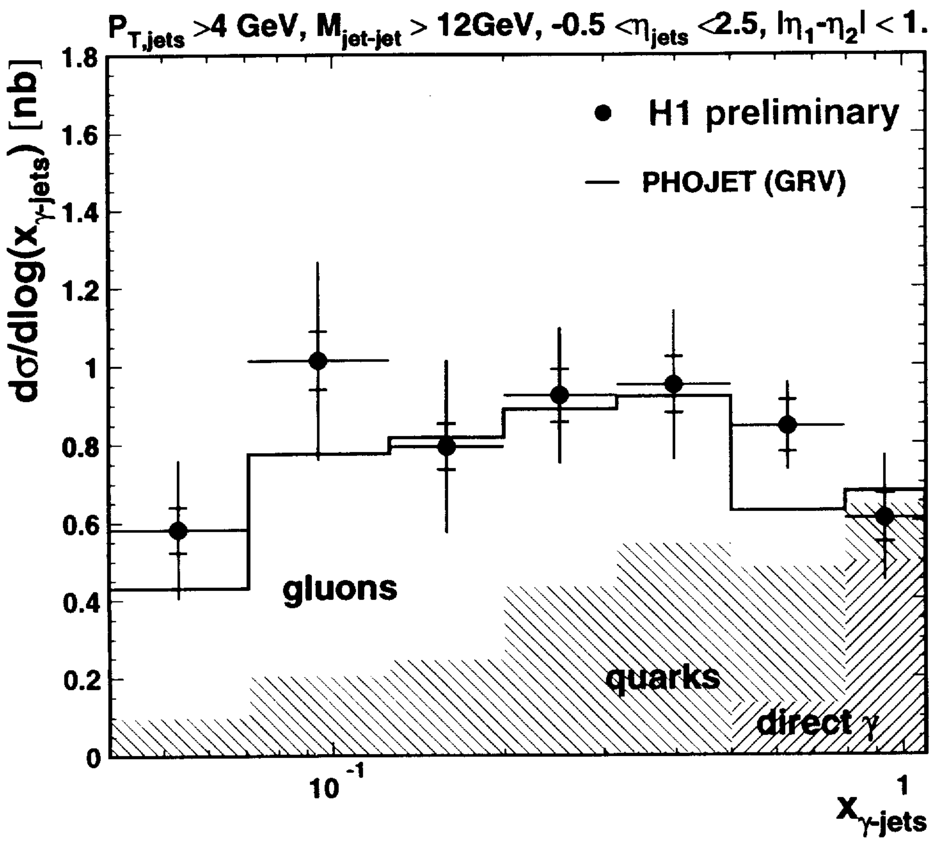
Di-jet cross sections in real photoproduction

at large center of mass energies:

$0.5 < y < 0.85 \; , \; E_T^{jet} > 14$ GeV



Di-jet cross sections at small x_γ

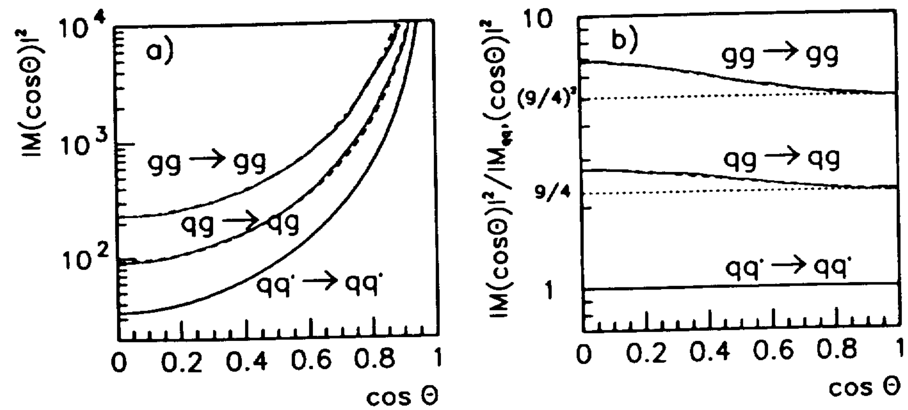


⇒ The contribution from gluons in the photon is essential to describe the observed cross section, especially at small x_γ.

The effective subprocess

Idea (Combridge/Maxwell 1983):

The angular distributions of the most important partonic scattering processes are similar:



$$|M_{qq'\to qq'}|^2 : |M_{qg\to qg}|^2 : |M_{gg\to gg}|^2 \approx 1 : \frac{9}{4} : \left(\frac{9}{4}\right)^2$$

With the definition of effective parton densities

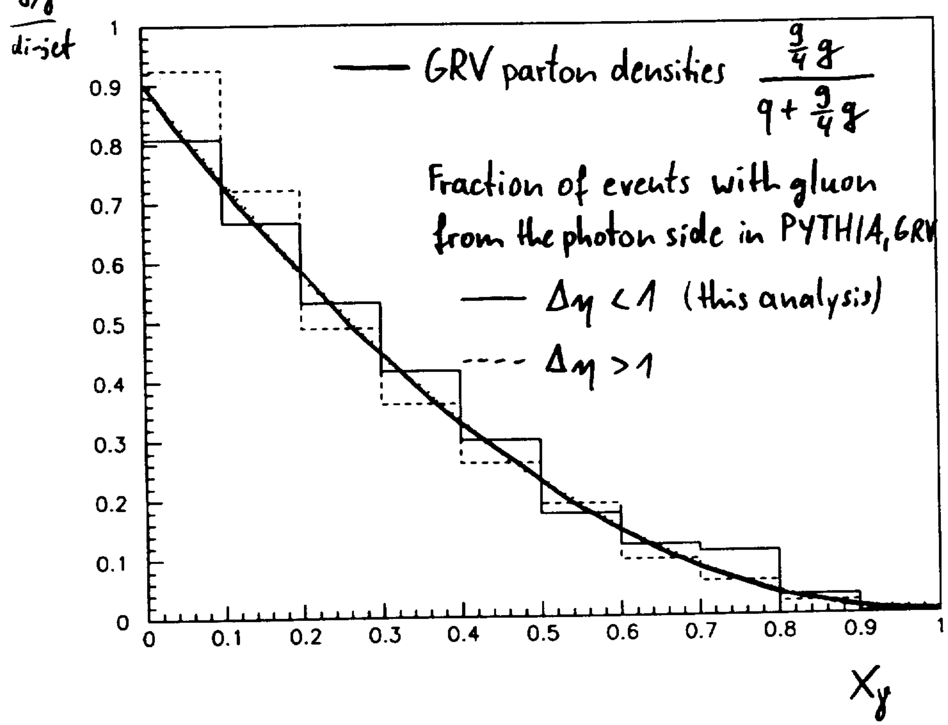
$$f_{eff}(x,p_T^2) = \sum_q \left(q(x,p_T^2) + \bar{q}(x,p_T^2)\right) + \frac{9}{4} g(x,p_T^2)$$

the cross section factorizes like a single effective subprocess:

$$\frac{d^4\sigma}{dy\,dx_\gamma\,dx_p\,d\cos\theta^*} = \frac{1}{32\pi s_{ep}} \frac{f_{\gamma/e}(y)}{y} \frac{f^\gamma_{eff}(x_\gamma,p_T^2)}{x_\gamma} \frac{f^p_{eff}(x_p,p_T^2)}{x_p} |M_{eff}(\cos\theta^*)|^2$$

Precision of the SES approximation

relative gluon contribution to the di-jet cross section



Can we verify the factorisation of the di-jet cross section?

$$\frac{d\sigma}{dx_\gamma dx_p} \sim \frac{f^\gamma_{eff}(x_\gamma, p_T^2)}{x_\gamma} \cdot \frac{f^p_{eff}(x_p, p_T^2, \cancel{x_\gamma})}{x_p}$$

The proton part should be independent of x_γ

⟹ compare x_p-distribution for different x_γ bins

however: $x_\gamma^{jets} \sim \frac{p_T}{y} e^{-\bar\eta}$

$x_p^{jets} \sim p_T e^{\bar\eta}$; $p_T^2 = \frac{1}{4} s_{ep} \, y x_\gamma \, x_p \sin^2\theta$

we need to keep $y \cdot x_\gamma$ constant in order to preserve the shape of the x_p-distribution

Therefore: fix $0.1 < y_{JB} \cdot x_\gamma^{jets} < 0.2$

and compare x_p for the following $(y_{JB}, x_\gamma^{jets})$ bins:

a) $0.2 < y_{JB} < 0.28$, $0.35 < x_\gamma^{jets} < 1$, $\langle x_\gamma^{jets} \rangle = 0.69$

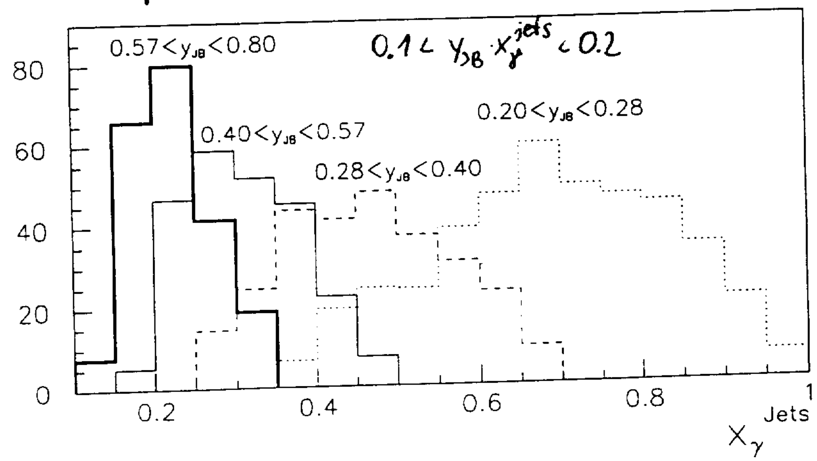
b) $0.28 < y_{JB} < 0.4$, $0.25 < x_\gamma^{jets} < 0.7$, $\langle x_\gamma^{jets} \rangle = 0.46$

c) $0.4 < y_{JB} < 0.57$, $0.18 < x_\gamma^{jets} < 0.5$, $\langle x_\gamma^{jets} \rangle = 0.31$

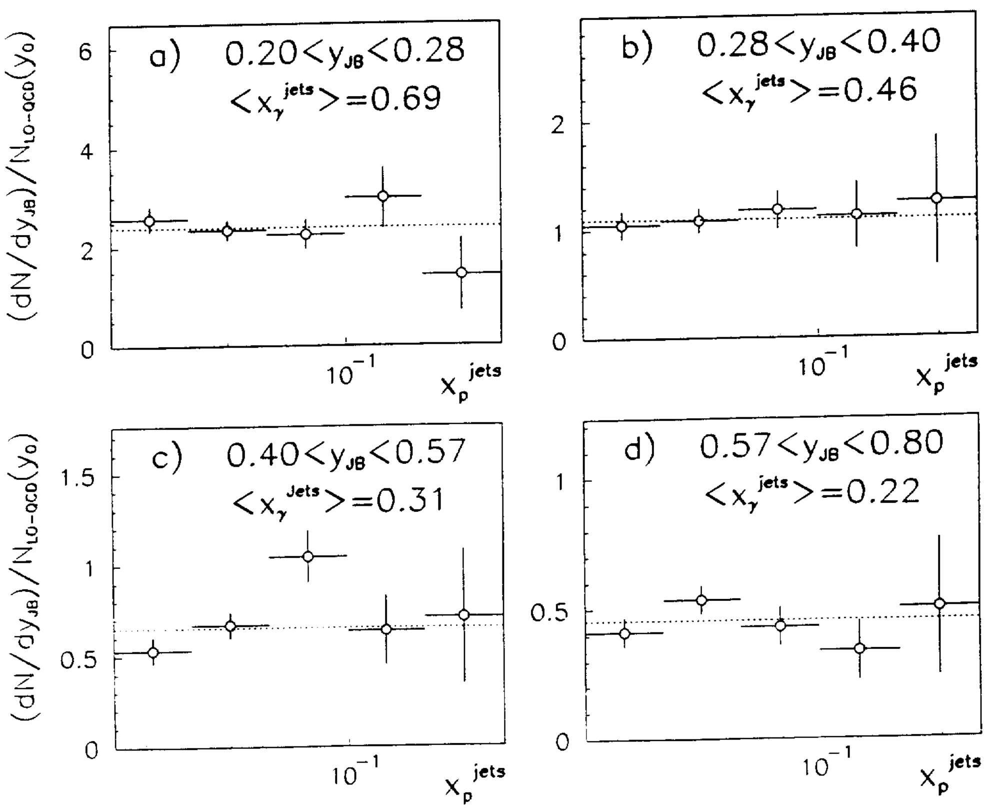
d) $0.57 < y_{JB} < 0.8$, $0.12 < x_\gamma^{jets} < 0.35$, $\langle x_\gamma^{jets} \rangle = 0.22$

Factorisation of the di-jet cross section

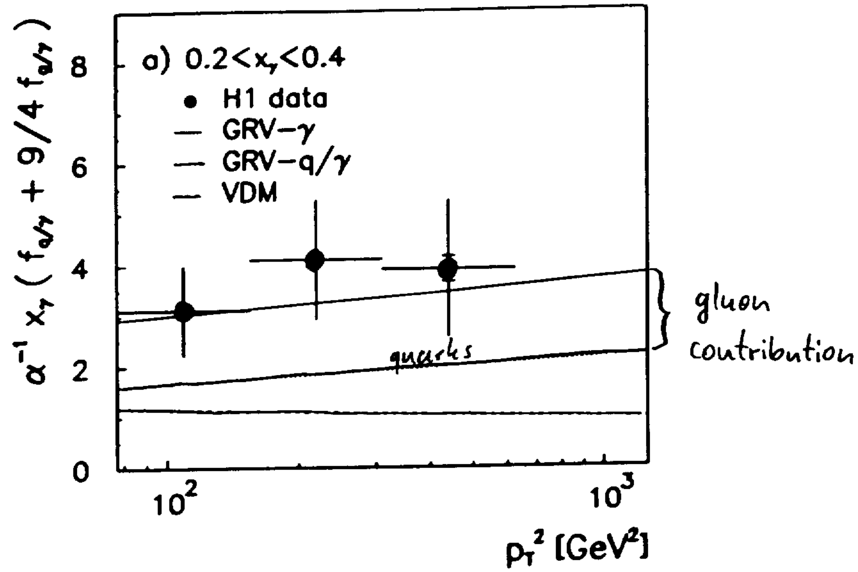
into photon- and proton-dependent parts

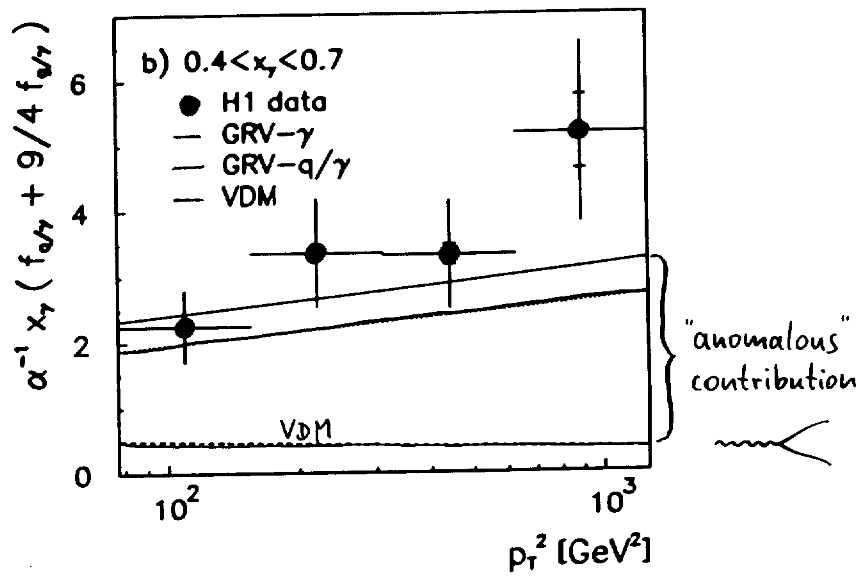


H1 preliminary, uncorrected data

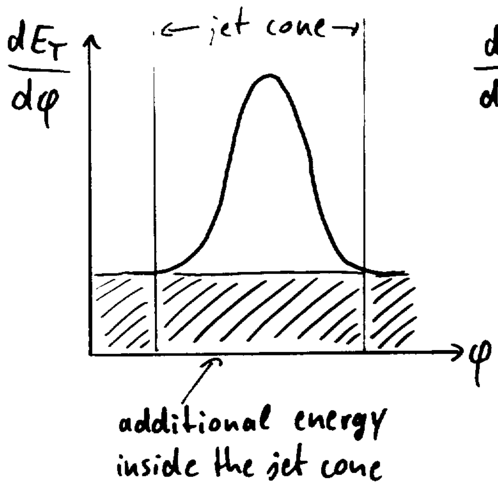


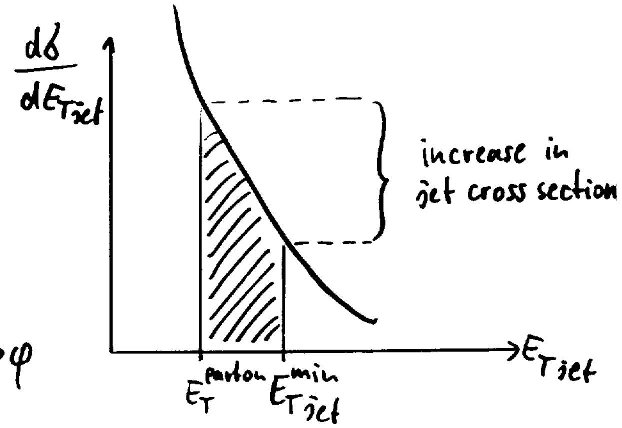
The effective parton distribution of the photon.



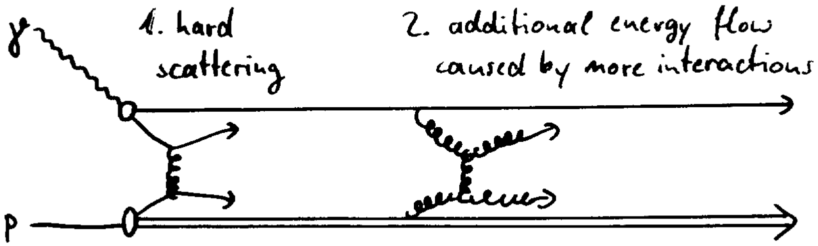


The energy flow problem





The solution: multiple parton interactions ?

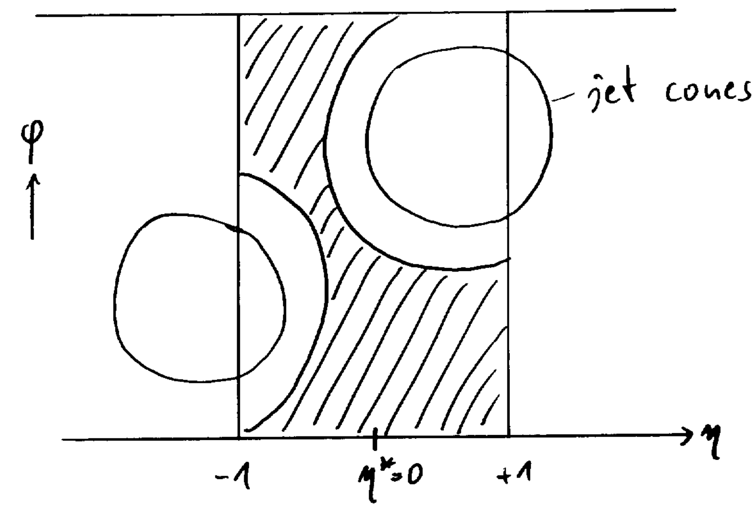


Monte Carlo models

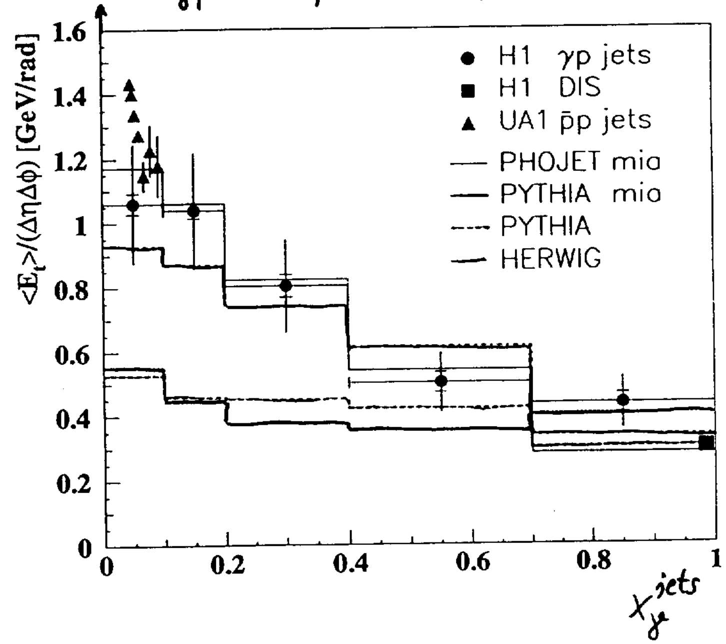
PYTHIA "mia" : multiple hard interactions,
lower p_T-cutoff for 2nd interaction

PHOJET : smooth transition between soft and
hard processes, includes multiple
soft and hard interactions

Transverse energy flow outside of jets



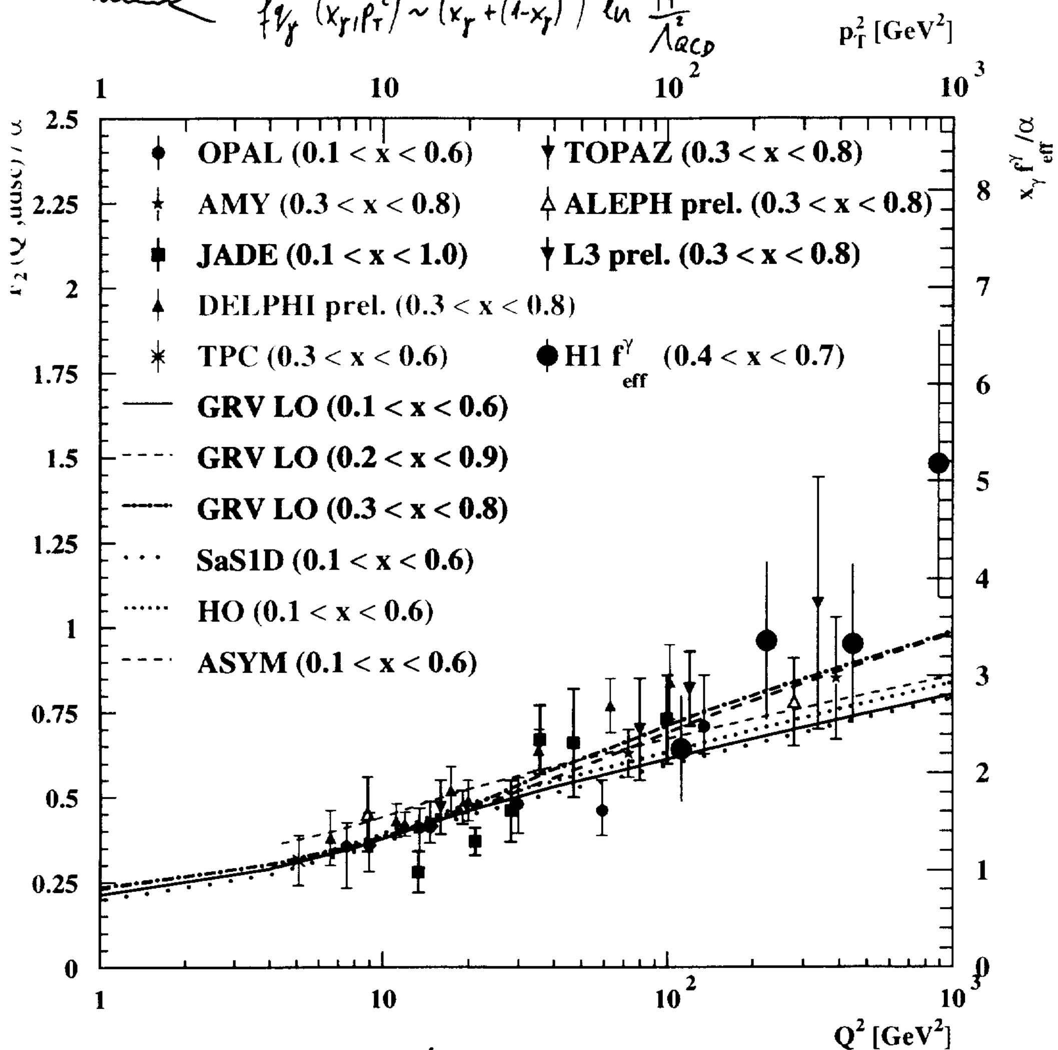
transverse energy density outside of jets



The scale dependence of photon parton distributions

The photon differs from typical hadrons by its electromagnetic coupling to quark pairs:

$$f_{q/\gamma}^{QPM}(x_\gamma, p_T^2) \sim (x_\gamma^2 + (1-x_\gamma)^2) \ln \frac{p_T^2}{\Lambda_{QCD}^2}$$



In GRV-LO: $\frac{x_\gamma f_{eff}^\gamma}{F_2^\gamma} \approx 3.5$

The structure of virtual photons

Classical application of virtual photons:

Deep-inelastic scattering, $Q^2 \gg E_{T\,jet}^2$

$\Rightarrow$ pointlike photon probes proton structure, purely 'direct' process

Photoproduction:

$Q^2 \approx 0$

$\Rightarrow$ direct pointlike scattering as well as hadronic scattering of the resolved photon

Virtual photon-proton scattering:

$Q^2 \lesssim E_{T\,jet}^2$

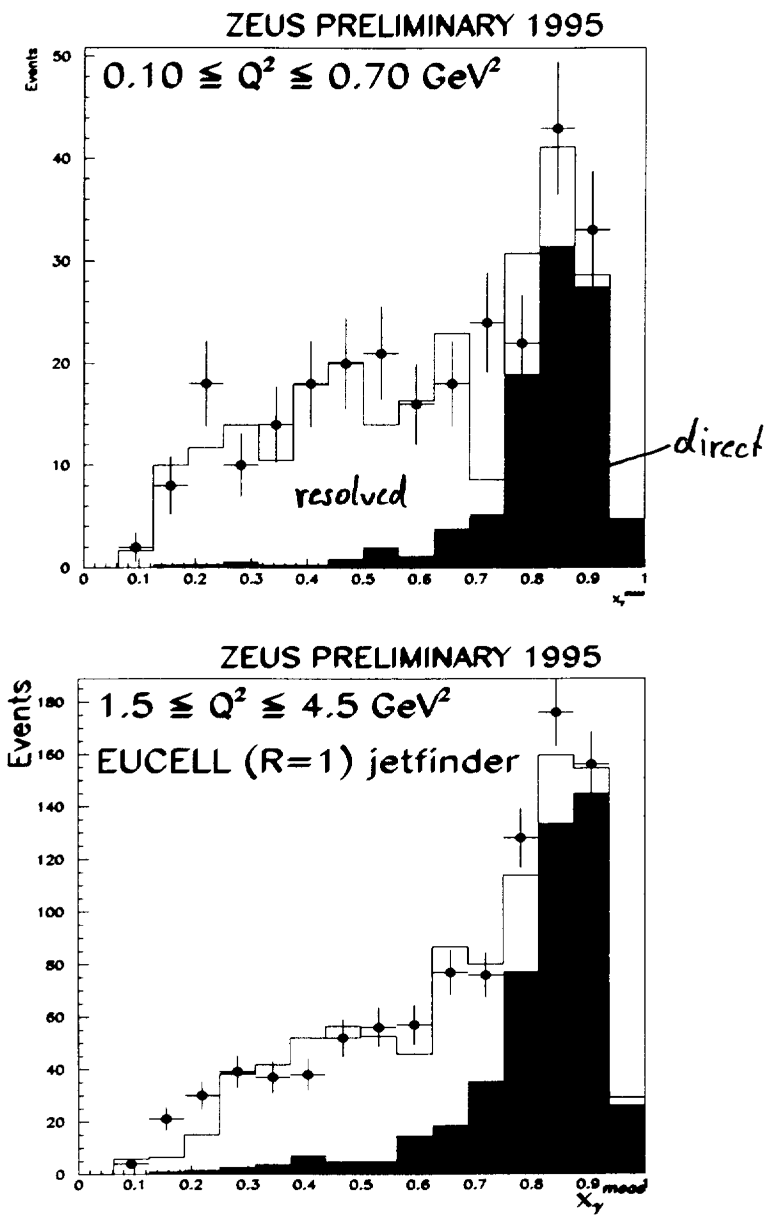
$\Rightarrow$ structure of resolved photon still visible for $Q^2 > 0$

Expect resolved photon contribution to be suppressed with increasing Q^2, f.ex. Drees-Godbole-Model:

$$\frac{f^\gamma(Q^2)}{f^\gamma(Q^2=0)} \sim \frac{\ln \frac{p_t^2+\omega^2}{Q^2+\omega^2}}{\ln \frac{p_t^2+\omega^2}{\omega^2}}$$

with free parameter ω

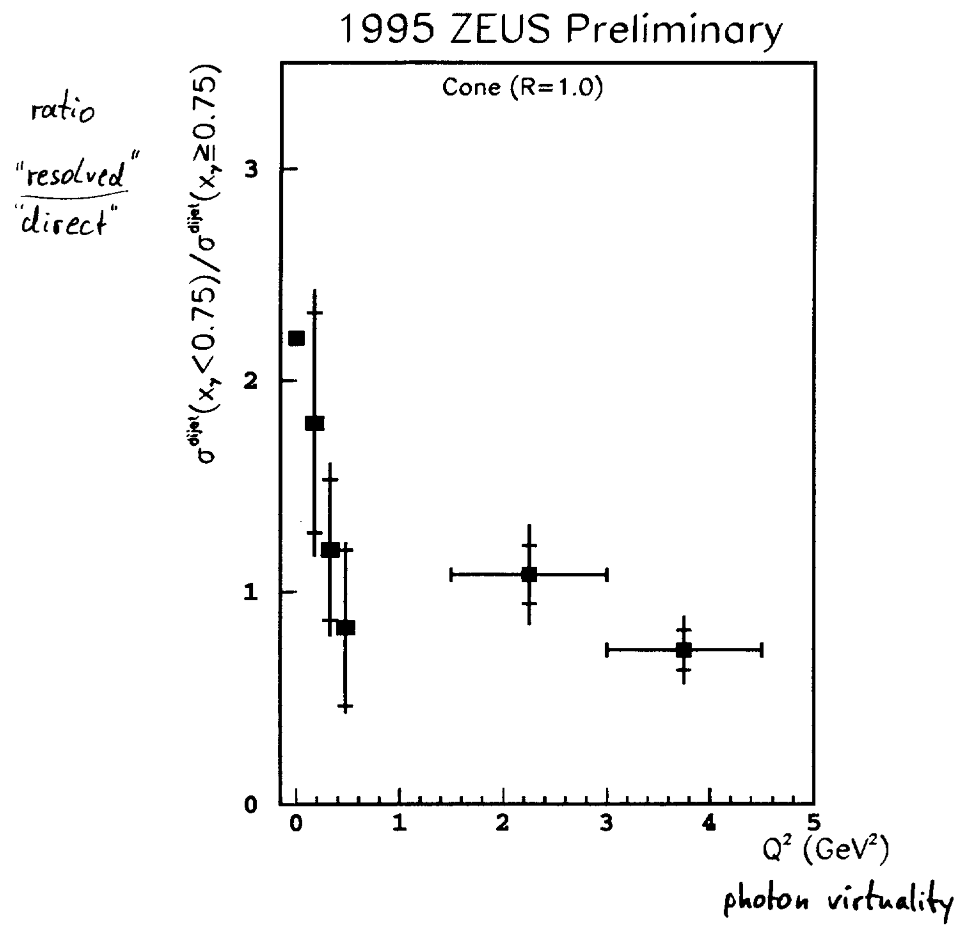
Virtual photon-proton scattering



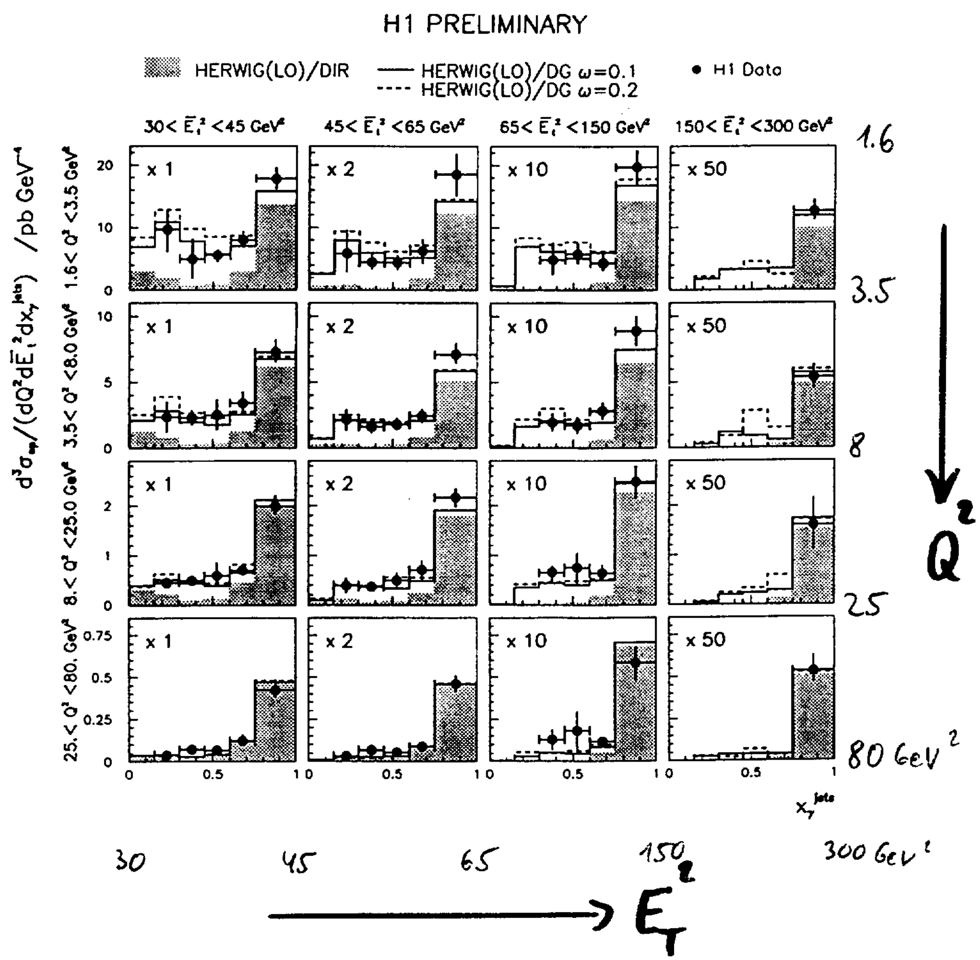
Suppression of the resolved photon component with Q^2

resolved: $x_\gamma^{obs} < 0.75$

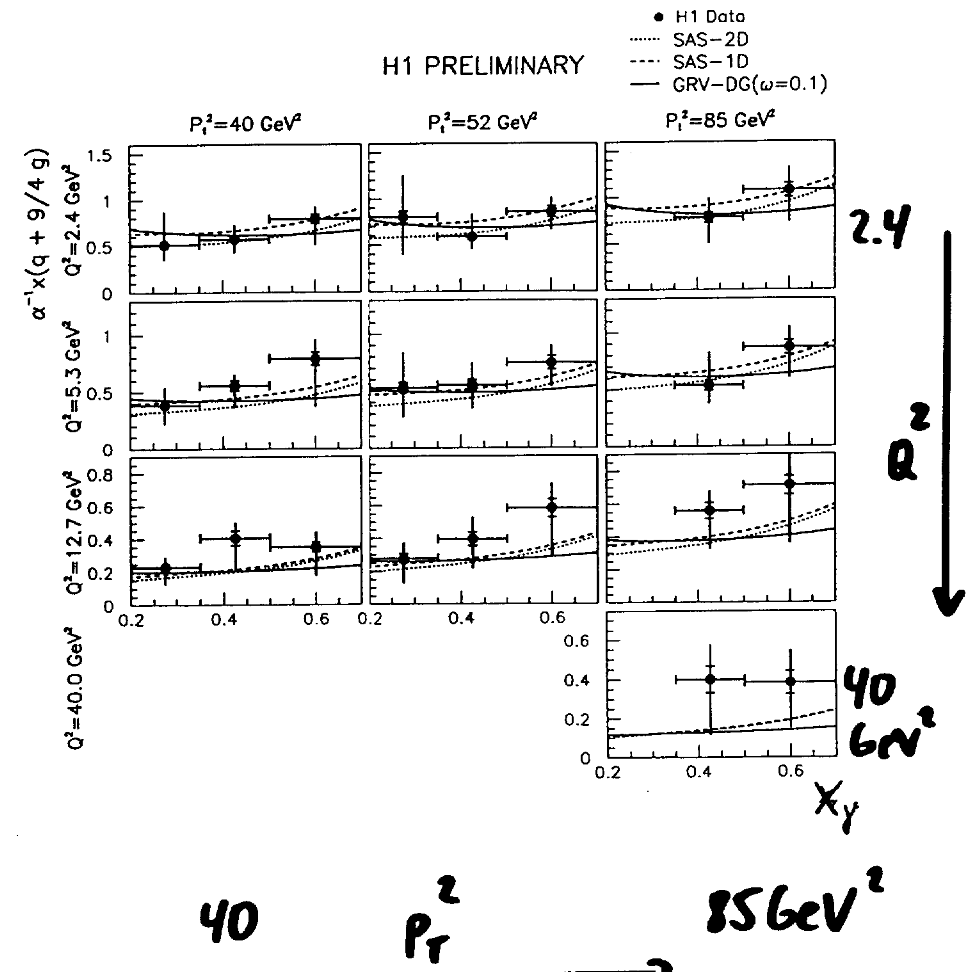
direct: $x_\gamma^{obs} > 0.75$



Triple differential di-jet cross section for virtual photon-proton scattering



The effective parton density of the virtual photon



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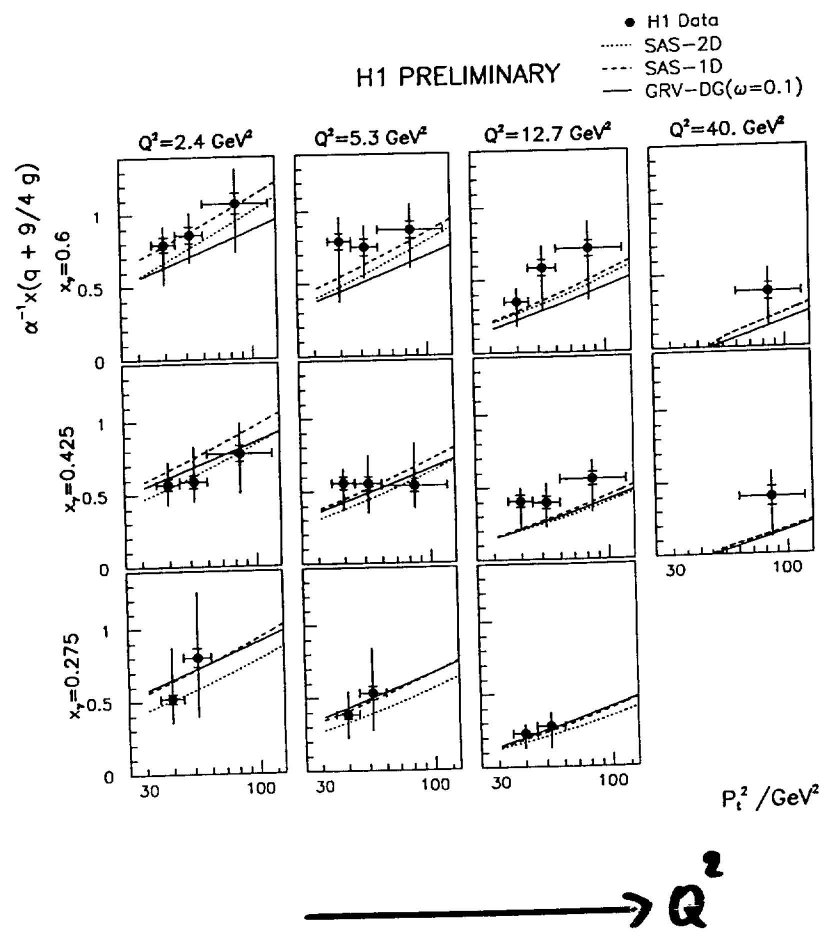
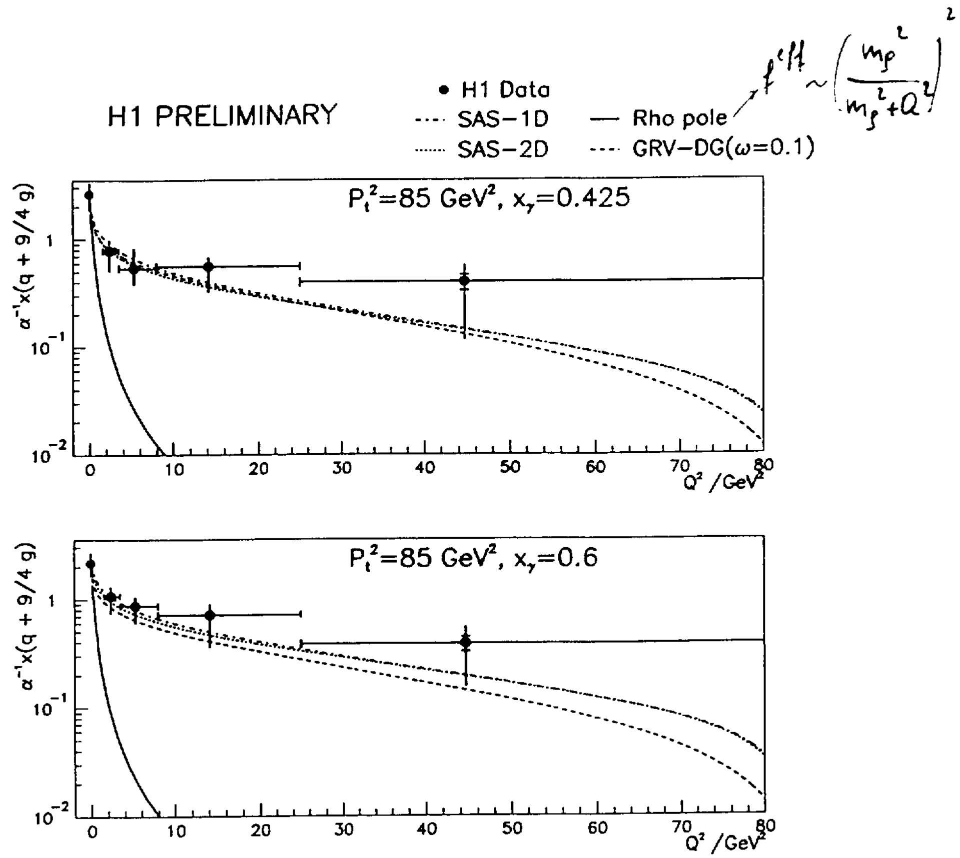


Q^2 dependence of the virtual photon parton density



Summary

* Jet cross section measurements at HERA constrain the parton density of real and virtual photons, complementing and extending photon structure function measurements at e^+e^- experiments.

* The precision of the data starts to get good enough to distinguish between different parton density parameterizations and to access the gluon content of the photon.

* The effective parton density of the virtual photon has been measured for the first time.

* The resolved photon parton density shows the expected scaling behaviour:

  - rising with the scale P_T^2
  - suppressed with increasing virtuality Q^2