Structure of the virtual photon

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Nature of the photon

The photon is one of the fundamental gauge bosons of the Standard Model without selfcouplings and without intrinsic structure. However, at high energies photon–hadron interactions are dominated by quantum fluctuations of the photons into fermion–antifermion pairs and into vector mesons which have the same spin–parity as the photon. This is called photon structure. (**S. Söldner–Rembold in LP97**)

- what is meant under "intrinsic structure"?
- "structure" $\neq$ "intrinsic structure"?
- what is meant under "photon fluctuates"?
- if $\gamma \approx$ VM, why $\sigma_{\gamma^* p}(W, Q^2)$ grows faster than $(W^2)^{0.08}$ already at $Q^2 = 2$ GeV^2?

In QFT it is difficult to distinguish between the effects coming from **structure** from those due to **interaction**.

Fundamental particles: those in the basic $\mathcal{L}_{\rm QCD}$

Composite particles: everything else

BUT: even fundamental particles have properties closely resembling those of the composite ones. **Structure** is among them.

Why virtual photon?

Recall: because real on–shell hadrons have infinite time to develop their structure :

- Parton **interactions** at **short** distances, are calculable within perturbative QCD, but
- internal structure at short distances, i.e. **parton distribution functions**, is not! $\Rightarrow$ **nonperturbative** input needed

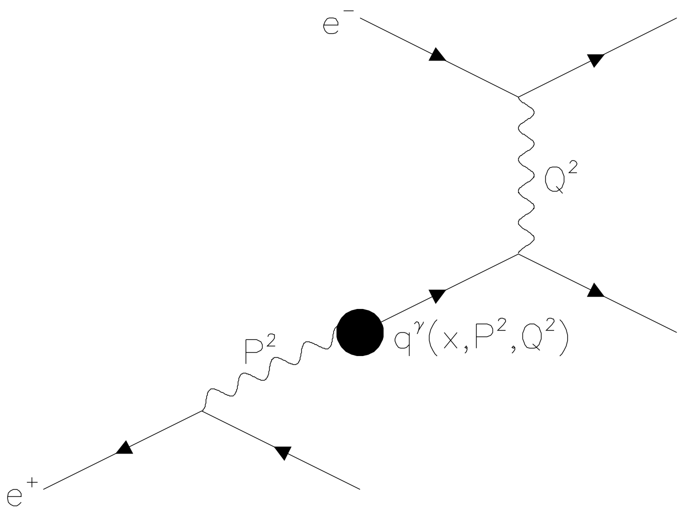
Hope:
for large photon virtualities its "lifetime" is short and its structure may therefore be calculable by perturbation means. By studying virtuality dependence of photonic PDF we may learn about the transition between perturbative and nonpeturbative QCD.

Questions:

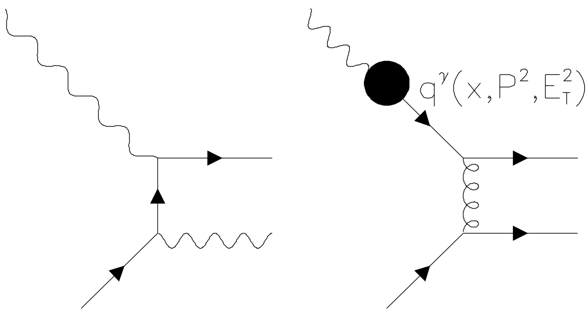
- How large must photon virtuality be for perturbative dynamics to dominate?
- How to describe the nonperturbative features?

Tools to investigate it

- **DIS** on γ (LEP)



- **JET** (or heavy quark) production (HERA and LEP)



So far, most of the data and analyses on jet production from comes from HERA, but LEP catches on.
DIS on γ and jet production are complementary

The concept of the **resolved photon** implies the use of

Equivalent Photon Approximation

$$f_{\gamma^T/e}(x,P^2) = \frac{\alpha}{2\pi}\left(\frac{1+(1-x)^2}{x}\frac{1}{P^2}-\frac{2m_e^2x}{P^4}\right)$$

$$f_{\gamma^L/e}(x,P^2) = \frac{\alpha}{2\pi}\frac{2(1-x)}{x}\frac{1}{P^2}$$

- Similar P^2 dependences, but for <u>different</u> reasons
- $f_{\gamma^L/e}$ vanishes at $x=1$, but equals $f_{\gamma^T/e}$ at $x=0$

Generic LO expression for DIS cross–section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}P^2} = e_q^2\sum_{k=T,L} f_{\gamma^k/e}(P^2)\otimes f_{q/\gamma^k}(P^2,Q^2)+C_q^\gamma$$

$$f_{i/\gamma^k}(P^2,Q^2) = \underbrace{f_{i/\gamma^k}(0,Q^2)}_{=0 \text{ for k=L by g.i.}} + \frac{P^2}{\mu_k^2}\underbrace{f^{(1)}_{i/\gamma^k}(P^2,Q^2)}_{\text{finite at } P^2=0}$$

- μ_k^2 determine small P^2 behaviour of f_{q/γ^k}
- if we are interested in virtuality dependence of $f_{q/\gamma}$ γ^L in principle as important as γ^T.
- What determines μ_k^2?
- How accurate is EPA? (very much in current experimental conditions)
- Only γ^T used so far in most analysis!

Description of photon structure

Parton distribution functions (PDF) satisfy *inhomogenus* evolution equations (EE). For quarks they are written as a sum

$$f_{q/\gamma}(x,P^2,M^2) = f^{\rm PL}_{q/\gamma}(x,P^2,M^2) + f^{\rm HAD}_{q/\gamma}(x,P^2,M^2)$$

of a particular solution of the full inhomogenous EE, **pointlike** part, and general solution of the corresponding homogenous EE, **hadronic** part.

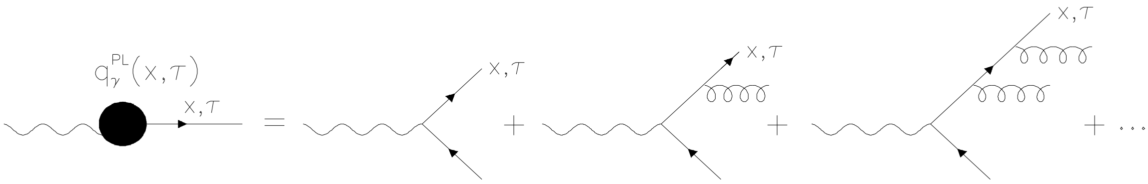
Conventional viewpoint:

- Evolution equations can be used for $P^2 > 0$ as well but the whole framework based on PDF is applicable only so long as (Q^2 is in general a hard scale)

$$P^2 \ll Q^2$$

- **hadronic** part is necessary for theoretical consistency and contains <u>nontrivial</u> information on **nonperturbative** properties of hadrons, while
- **pointlike** part is <u>calculable</u> in perturbation theory and thus essentially "trivial"
- hadronic part important only at **low** P^2 and x.

BUT: the separation is **ambiguous** as there is infinite number "pointlike" solutions, resulting from resummation



$$f_{q/\gamma}^{\rm PL}(x,M^2) \quad = \quad \frac{\alpha}{2\pi}(x^2+(1-x)^2)\ln\frac{M^2}{M_0^2}+\cdots$$

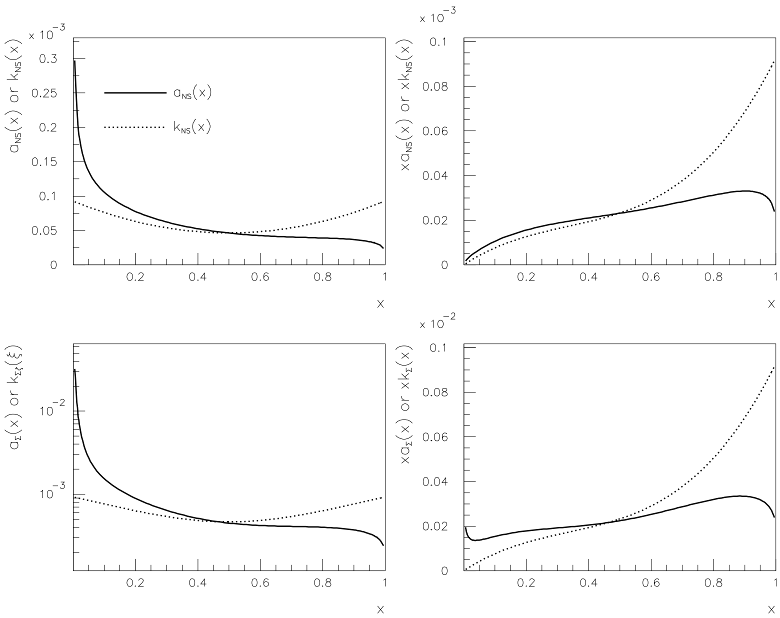
$$= \quad \frac{\alpha}{2\pi}a(x,M)\ln\frac{M^2}{M_0^2}$$

but differing by initial condition: $f_{q/\gamma}^{\rm PL}(x,M_0^2)=0$

Example: SaS1 ($M_0^2 = 0.36$ GeV^2), SaS2 ($M_0^2 = 4$ GeV^2)

Asymptotic pointlike (Witten)

$$a^{\rm AP}(x) = \lim_{M\to\infty} a(x,M)$$



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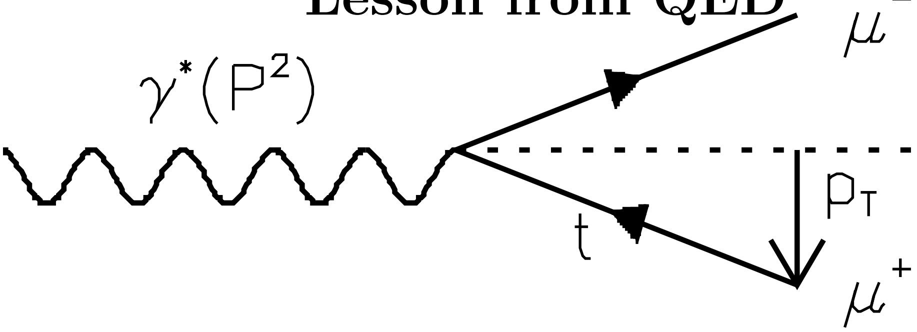
nontrivial & substantial effects of resummation!

Virtuality dependent PDF

Lesson from QED



$$f_{\mu/\gamma^*}(x, m^2, P^2, Q^2) \equiv \frac{\alpha}{2\pi}\int_{-Q^2}^{t_{max}} \frac{W(x, m^2, P^2)}{(t-m^2)^2}\mathrm{dt}$$

In general in collinear kinematics

$$W(x, m^2, P^2) = f(x)\frac{p_T^2}{1-x} + g(x)m^2 + h(x)(-P^2)$$

Integrating over dt we get (in units of $\alpha/2\pi$)

$$\begin{aligned} f_{\mu/\gamma}(x, m^2, P^2, Q^2) \quad = \quad & f(x)\ln\frac{Q^2}{\kappa^2} - f(x)\left(1-\frac{\kappa^2}{Q^2}\right) + \\ & \frac{g(x)m^2 - h(x)P^2}{\kappa^2}\left(1-\frac{\kappa^2}{Q^2}\right) \end{aligned}$$

where $\kappa^2 \equiv -xP^2 + m^2/(1-x)$ and

$$f_T(x) = x^2 + (1-x)^2, \quad g_T(x) = \tfrac{1}{1-x}, \quad h_T(x) = 0$$
$$f_L(x) = 0, \quad g_L(x) = 0, \quad h_L(x) = 4x^2(1-x)$$

transition between real and virtual γ governed by

$$\tfrac{P^2}{m^2} \Rightarrow \mu^2 = m^2 \Rightarrow \text{quark masses } \textbf{essential!}$$

Real world of QCD

Drees–Godbole: simple suppression factor

$$L \equiv \frac{\ln((M^2+\omega^2)/(Q^2+\omega^2))}{\ln((M^2+\omega^2)/\omega^2)} \doteq 1 - \frac{P^2}{\omega^2 \ln(M^2/\omega^2)}$$

$\Rightarrow \mu^2 \approx \omega^2 \ln(M^2/\omega^2)$ (data: $\omega \sim 0.1$ GeV)

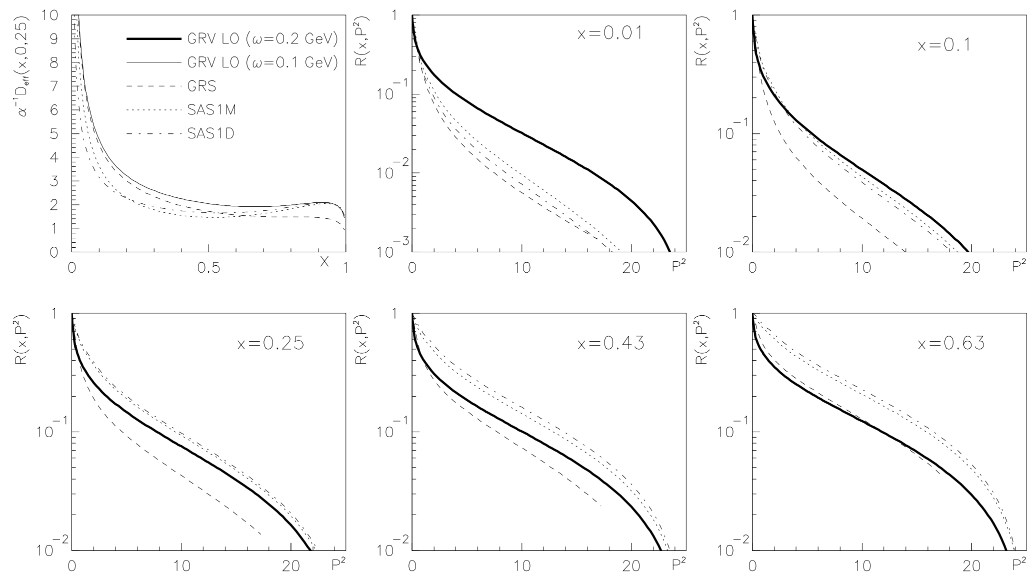
Glück,Reya,Stratman: P^2–dependent initial cond.

Schuler–Sjöstrand: dispersion relations in P^2

$$q_\gamma^{\rm HAD}(M^2,P^2) \quad \propto \quad \left(\frac{m_V^2}{m_V^2+P^2}\right)^2 \to 1-2\left(\frac{P^2}{m_V^2}\right)$$

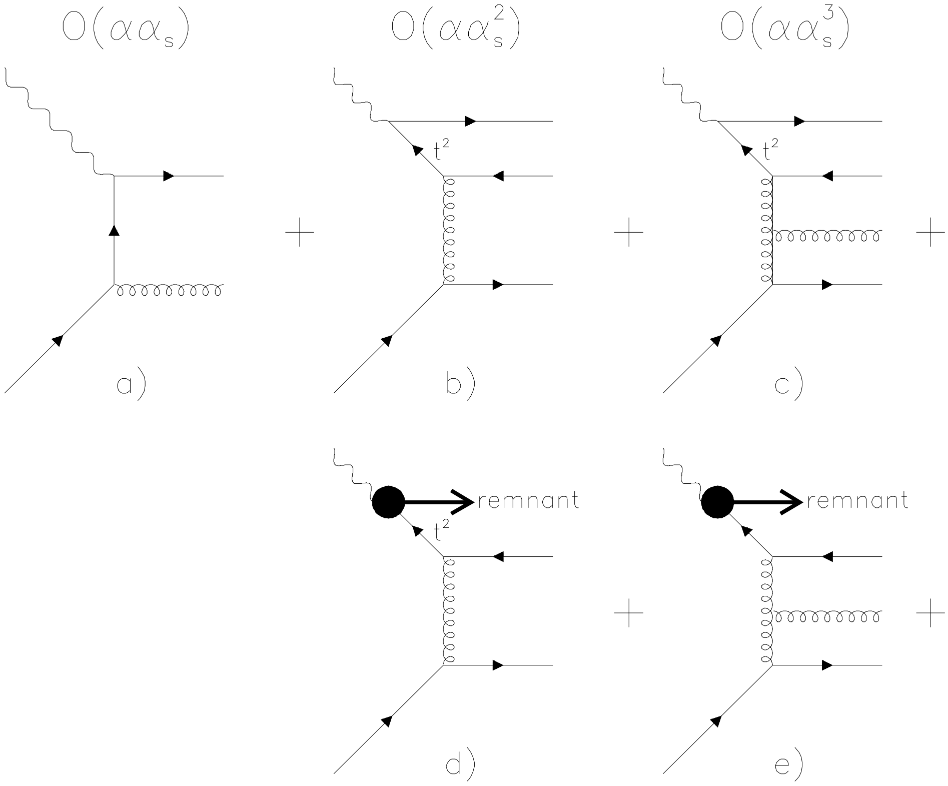
$$q_\gamma^{\rm PL}(M^2,P^2) \quad \propto \quad \int_{M_0^2}^{M^2} {\rm d}k^2 \frac{k^2}{(k^2+P^2)^2}$$

$$\to \quad \ln\frac{M^2}{M_0^2} - 2\left(\frac{P^2}{M_0^2}\right)$$



What do the jet data tell us about virtual photon structure?

Important new H1 & ZEUS data on jet production in $\gamma^*(P^2)$–proton collisions

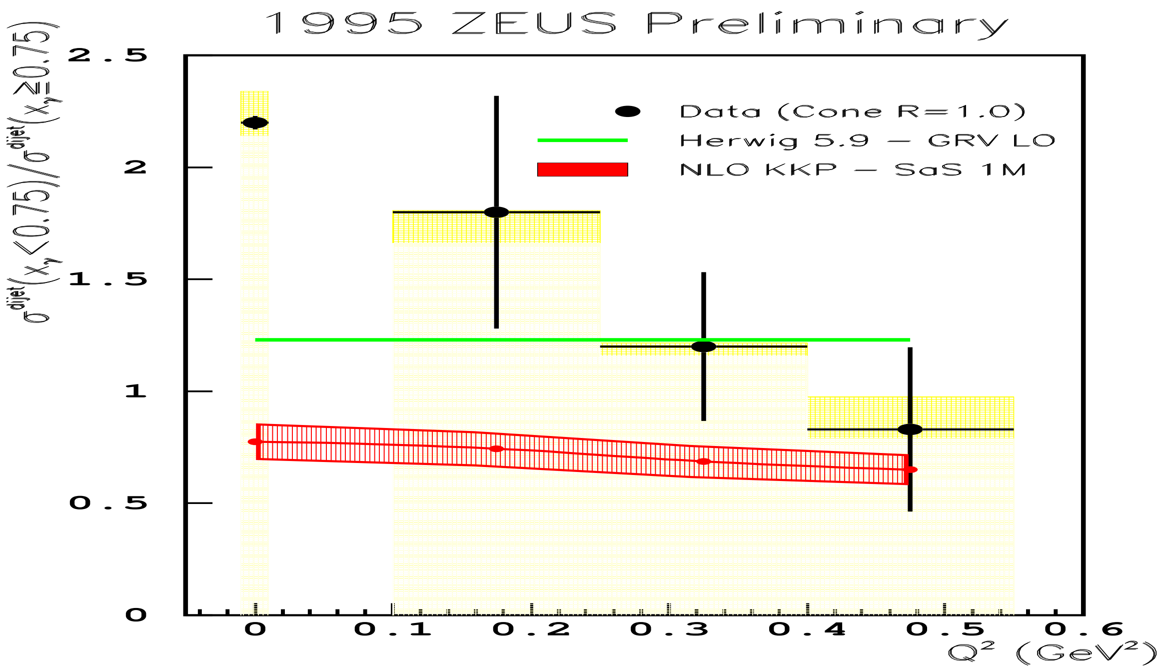


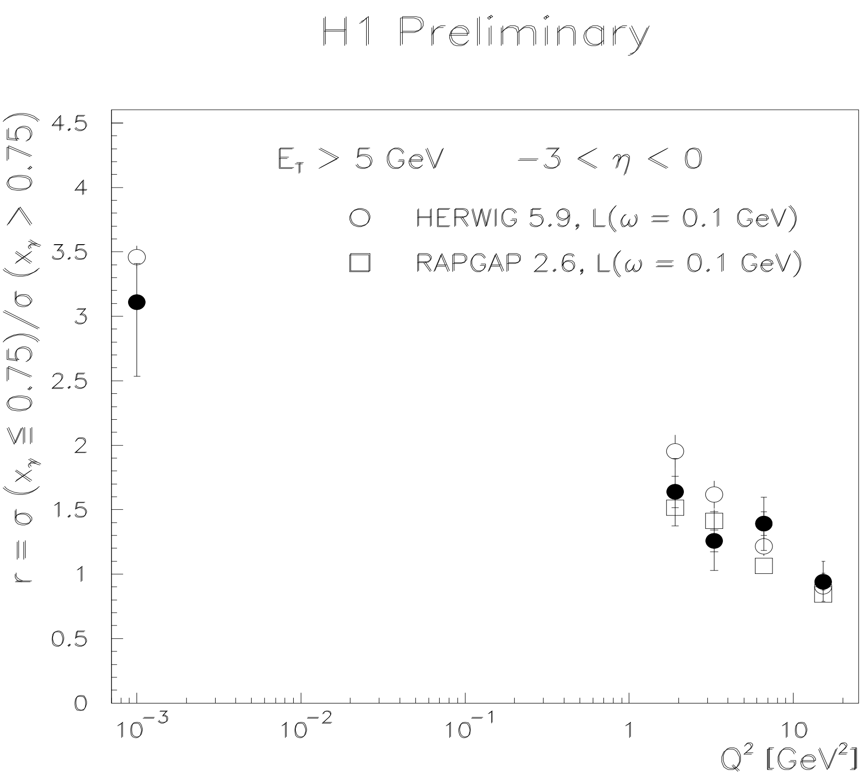
Analyses concerning two subjects:

- **Effective parton distributions functions** in γ

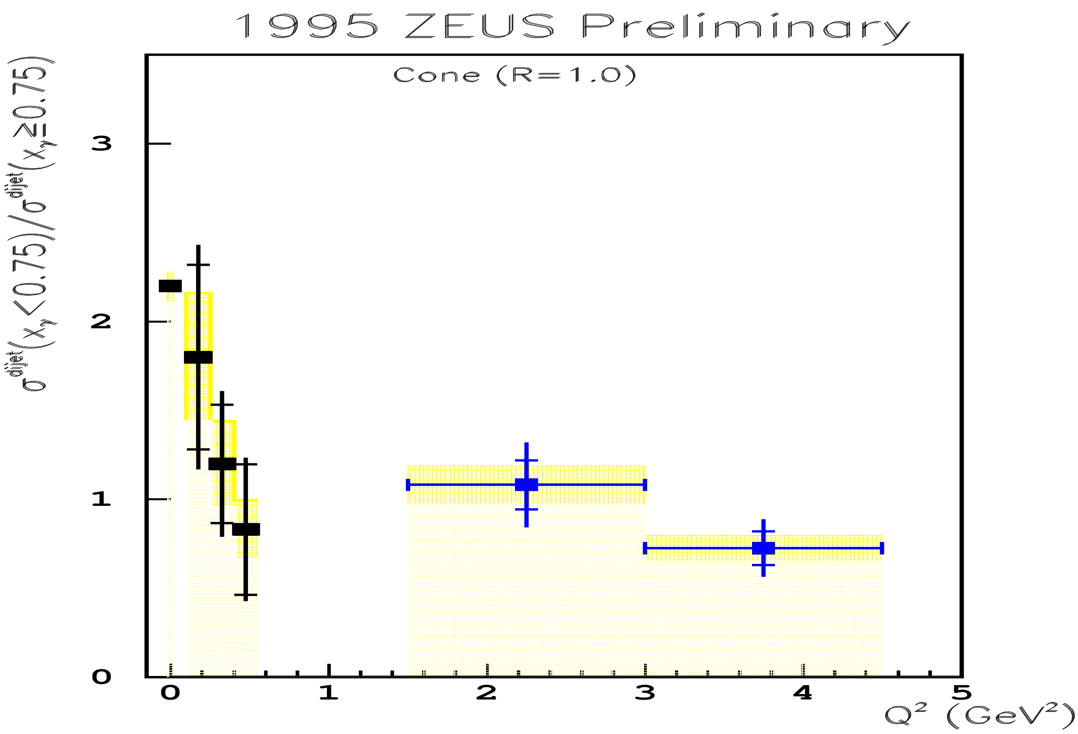
$$D_{\text{eff}}^{\gamma} \equiv (q(x,M) + \overline{q}(x,M)) + \frac{9}{4}G(x,M)$$

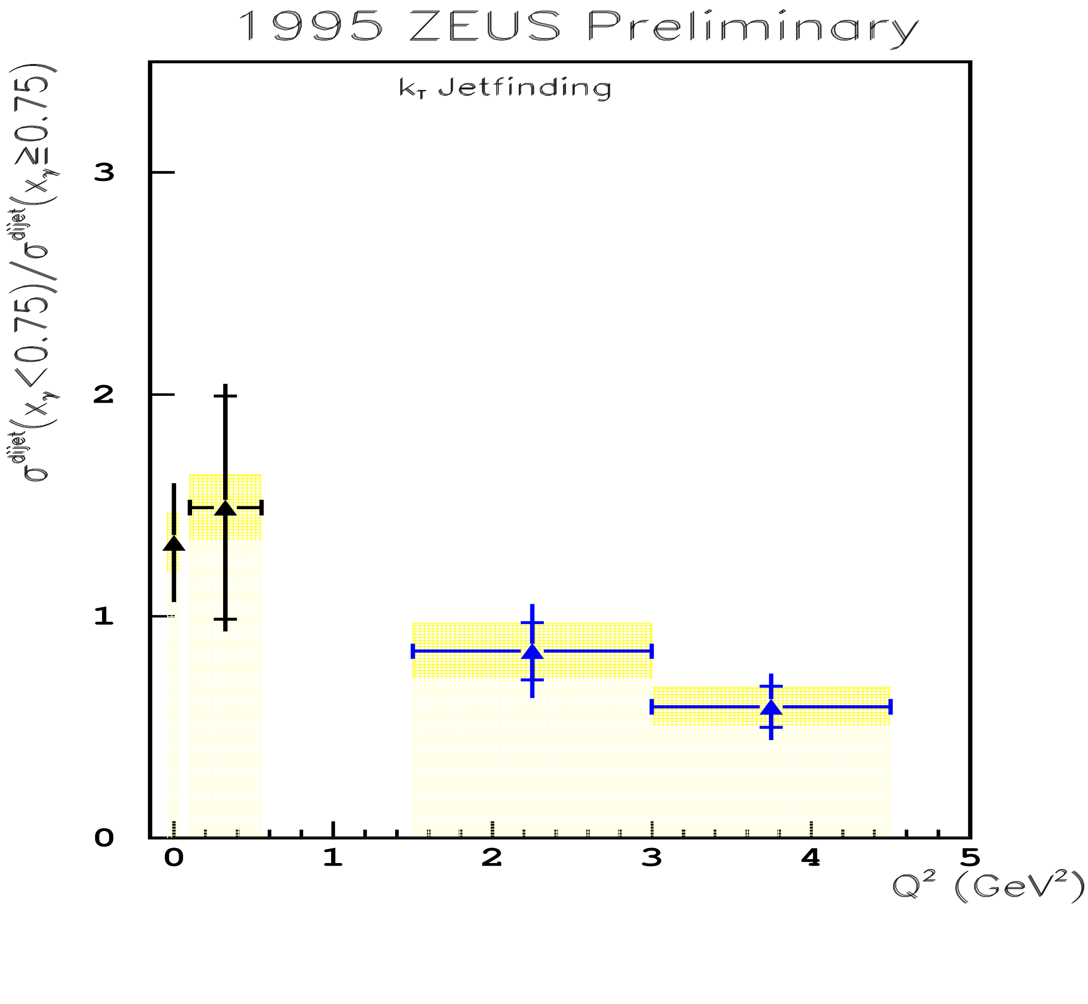
- Comparison with the **NLO** calculations by **JETVIP** (Kramer & Pötter)





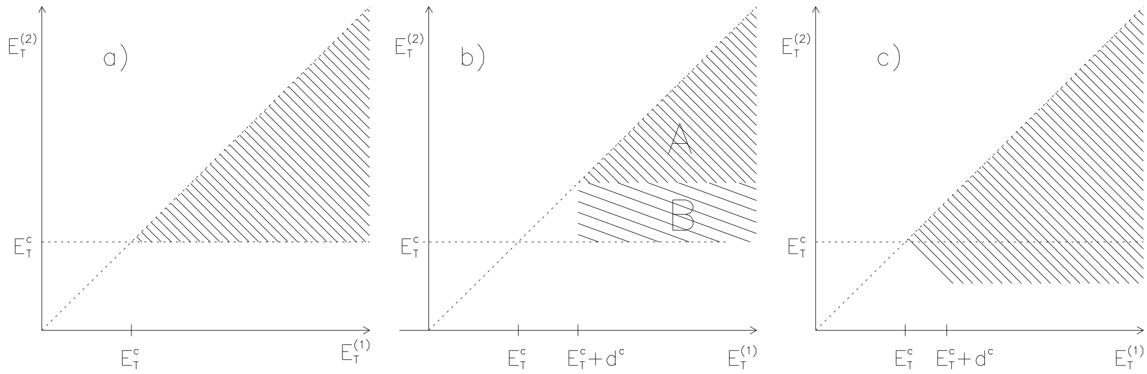
Substantial decrease already at $\mathbf{P^2} \sim \mathbf{0.5}$ GeV^2

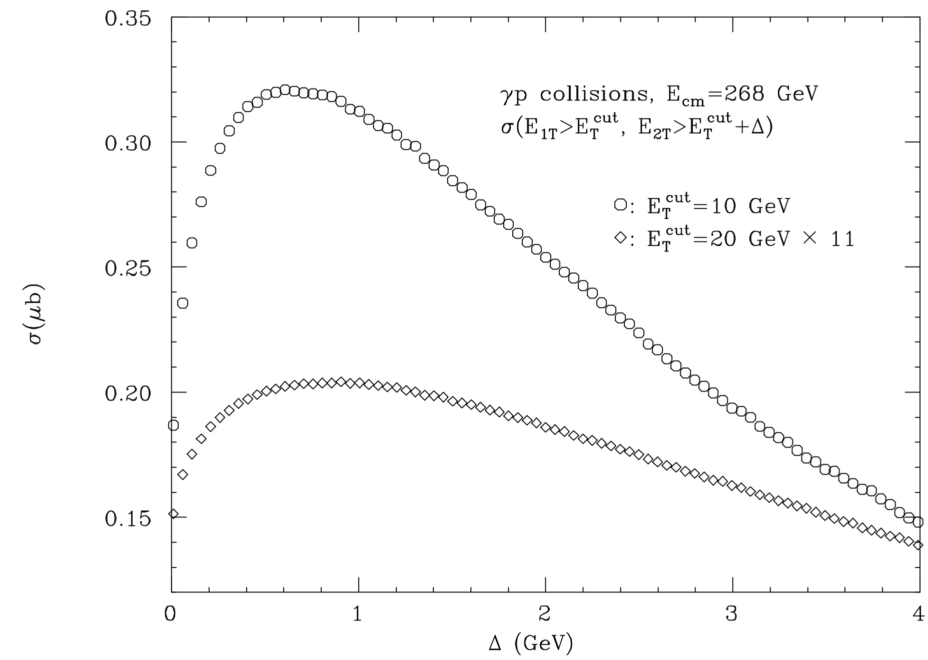

1995 ZEUS Preliminary
Cone (R=1.0)
$\sigma^{dijet}(x_\gamma<0.75)/\sigma^{dijet}(x_\gamma\geq0.75)$
0
1
2
3
0
1
2
3
4
5
Q^2 (GeV^2)


1995 ZEUS Preliminary
k_T Jetfinding
$\sigma^{dijet}(x_\gamma<0.75)/\sigma^{dijet}(x_\gamma\geq0.75)$
0
1
2
3
0
1
2
3
4
5
Q^2 (GeV^2)

Comparison with the NLO calculations

Complications concerning the cuts on jet E_T. Options:
Symmetric: $E_T^{(1)}, \quad E_T^{(2)} \geq E_T^c$
Asymmetric: $E_T^{(1)} \geq E_T^c + d^c \quad, E_T^{(2)} \geq E_T^c$
Hybrid: $E_T^{(1)} + E_T^{(2)} \geq 2E_T^c, \quad E_T^{(2)} \geq E_T^c - d^c$





Correct choice depends on the quantity considered

- **real photon**: several NLO parton level calculations (Kramer et al., Owens&Harris, Aurenche et al., Frixione&Ridolfi)
- **virtual photon**: only one calculation; Kramer, Klasen, Pötter, DESY 98-046 and Pötter's code **JETVIP**

Interpretation of the comparisons with data nontrivial even at large $E_T^{\rm jet}$ because of the influence of *additional soft activity* and dependence on *jet parameters*.
There are two **inequivalent** ways of comparing NLO calculations to data

- **DIS–like:** for $P^2 > 0$ no true mass singularity in the direct part requiring subtraction $\Rightarrow$ **NLO unsubtracted direct** contribution can alone be compared to data $\Rightarrow$ **no virtual photon structure**.
- **DIR+RES:** define **subtracted direct contribution** by subtracting from the direct part the term

$$P_{q/\gamma}(z) \ln \frac{M^2}{-P^2}$$

and add the **resolved photon** contribution. It differs from DIS by

  - the presence of **hadronic component** $f_{i/\gamma}^{\rm HAD}$
  - **resummation effects** in pointlike part $f_{i/\gamma}^{\rm PL}$

Results of (almost finished) analysis of preliminary H1 data by J. Ch., J. Cvach, M. Taševský, A. Valkárová:

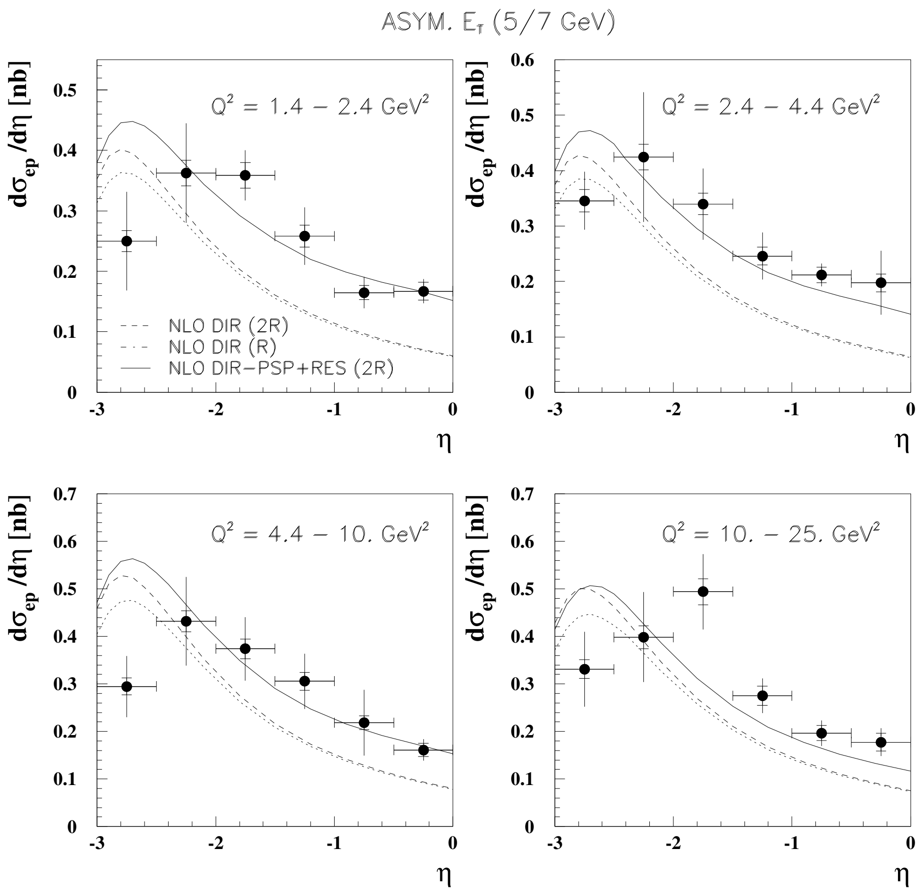
Inclusive **dijet** events in e^+p collisions at HERA analysed using **cone** algorithm with $R = 1$ in the region

$$1.4\ \mathrm{GeV}^2 \leq Q^2 \leq 25\ \mathrm{GeV}^2$$

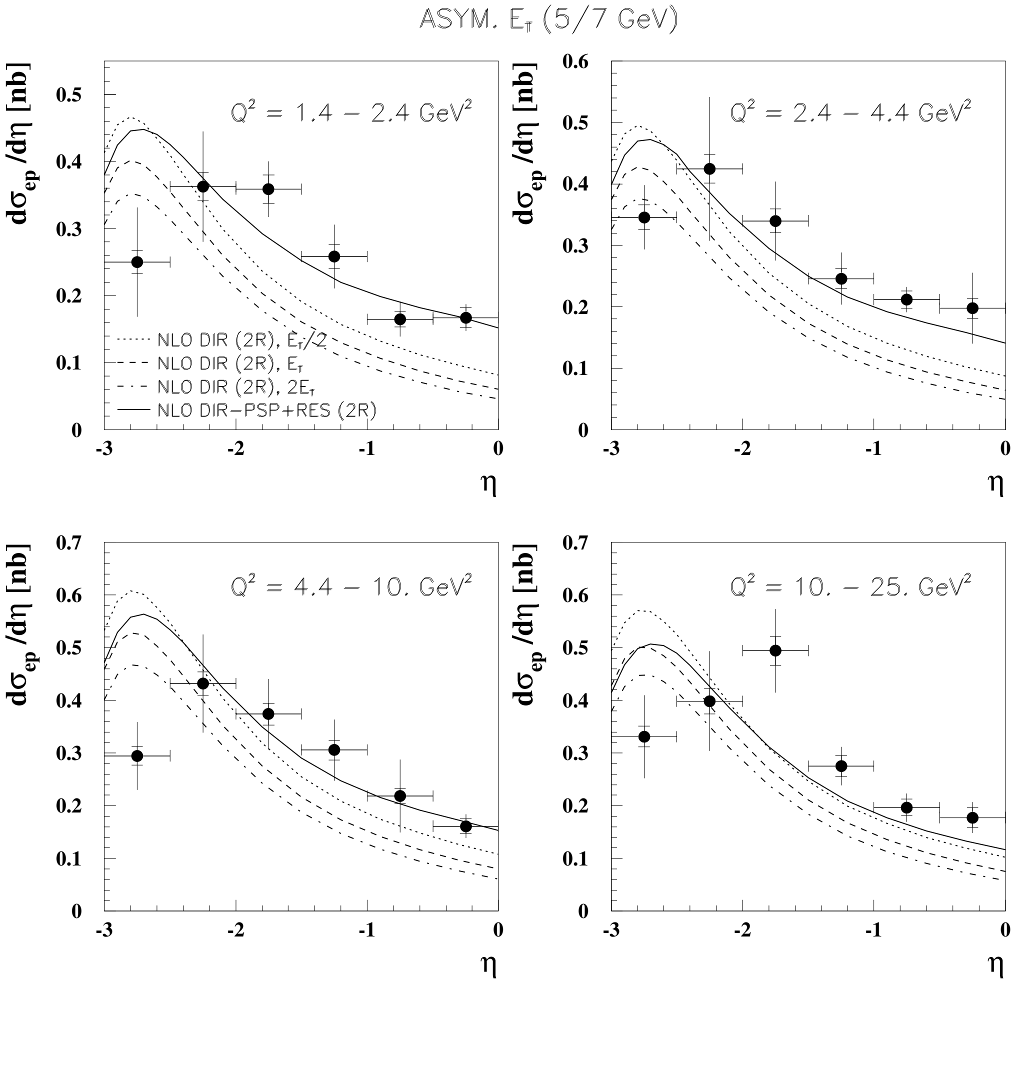
$$E_T^{(1)} \geq 7\ \mathrm{GeV}, \qquad E_T^{(2)} \geq 5\ \mathrm{GeV}$$

measured distributions $\mathrm{d}\sigma/\mathrm{d}\eta$, $\mathrm{d}\sigma/\mathrm{d}E_T$

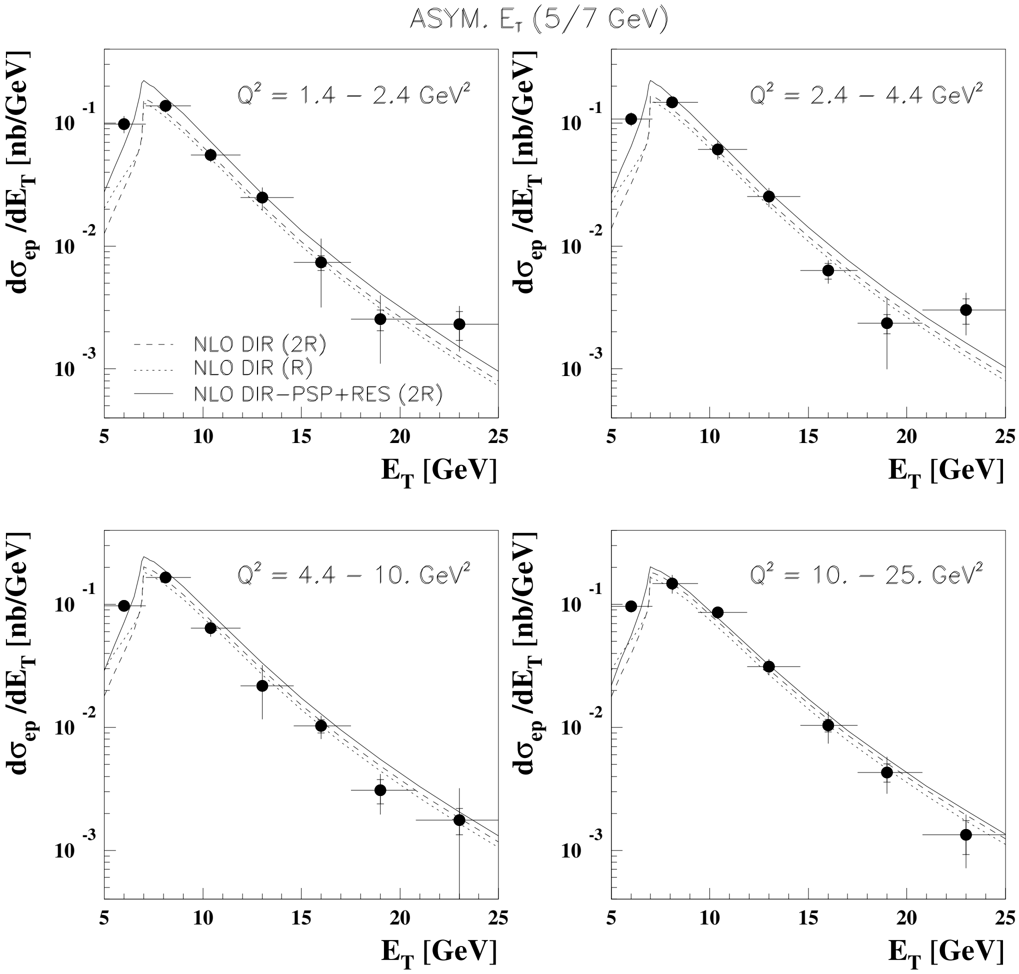
H1 Preliminary



H1 Preliminary



H1 Preliminary



Theoretical ambiguties of NLO calculations investigated:

- Dependence on the **factorization scale** $M = \kappa E_T$
- Details of jet merging, described by $R_{\rm sep}$ parameter
- Hadronization corrections

Conclusions from the comparison:

1. NLO direct unsubtraced systematically **below** data in η. In E_T the excess comes from lower edge $E_T \leq 7$ GeV
2. Pattern of Q^2 dependence consistent with expectations
3. Complete DIR+RES calculation using SaS in nice agreement with data
4. The conclusions survive theoretical ambiguities

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Does virtual photon have a structure?

In my view the answer is a resounding

YES!

but, of course, the answer depends on what exactly is meant under "structure"