

# Jet production in virtual photon collisions at HERA and LEP

Jiří Chýla

*Institute of Physics, Prague*

1. Nature of the photon
2. Tools to investigate it
3. Equivalent Photon Approximation
4. Jets in danger: the associated soft activity
5. Structure of the real photon
6. Jets in virtual photon collisions
7. Comparison with NLO calculations
8. Is there a need for virtual photon structure?
9. Prospects for future

## 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”?
- what is meant under “photon fluctuates”?
- if photon is without intrinsic structure, quarks too?
- if  $\gamma \approx \text{VM}$ , why  $\sigma_{\gamma^*p}(W, Q^2)$  grows faster than  $(W^2)^{0.08}$  already at  $Q^2 = 2 \text{ GeV}^2$ ?

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

It makes sense to talk about particles corresponding to fields appearing in the basic lagrangian **fundamental particles** and those that have no such correspondence **composite particles** but even fundamental particles have properties closely resembling those of the composite ones. **Structure** is among them.

## Tools to investigate it

- **DIS** on  $\gamma$  (LEP)
- **JET** (or heavy quark) production (HERA and LEP)

**Jets** as:

- objects of study via jet
  - **profiles**
  - **shapes**

$$\psi(r) \equiv \frac{1}{N} \sum_{evts} \frac{\sum_i E_T^{(i)}(r' \leq r)}{E_T(R)}$$

- tools for investigation of other phenomena

These two aspects are closely related but only the latter aspect covered in this talk

DIS on  $\gamma$  and jet production are complementary

So far, most of the data and analyses on jet production from comes from HERA, but LEP catches on

In virtual photon collisions there are in general **two scales**: photon virtuality  $P^2$  and  $Q_{\text{hard}}^2 \sim E_T^2$ .

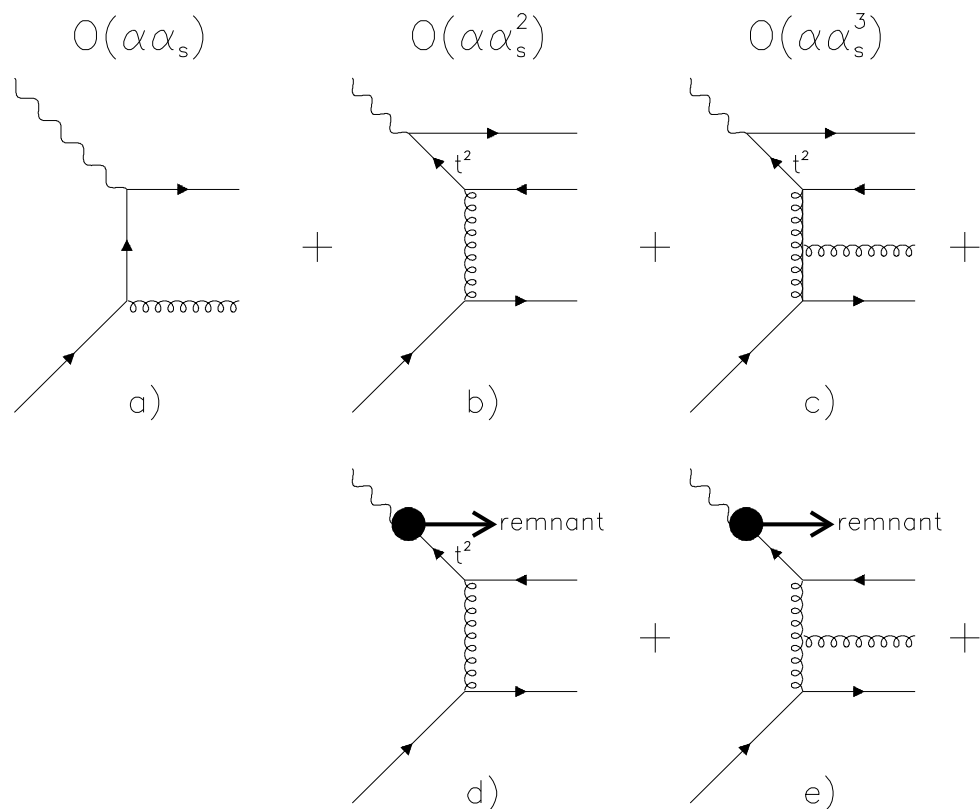
Depending on their relation we distinguish

$P^2 \gg Q_{\text{hard}}^2$ : **“DIS”**  $\Leftrightarrow \gamma^*$  structureless

$P^2 \sim Q_{\text{hard}}^2$ : theoretically least transparent

$P^2 \ll Q_{\text{hard}}^2$ : **“Photoproduction”**  $\Rightarrow \gamma^*$  structure

General picture: **direct** and **resolved** contributions



The concept of the **resolved  $\gamma^*$**  implies the use of **Equivalent Photon Approximation**

## Equivalent Photon Approximation

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

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

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

Generic expression for hadron level cross-sections in **resolved**  $\gamma^*$  hard processes in ep collisions ( $k = T, L$ )

$$\sigma^h = \sum_{i,j,k} f_{\gamma^k/e}(P^2) \otimes f_{i/\gamma^k}(P^2, Q^2) \otimes \sigma_{ij}(P^2, Q^2) \otimes f_{j/p}(Q^2)$$

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

$$\begin{aligned} \Delta(P^2, Q^2) &\equiv \sigma(P^2, Q^2) - \sigma(0, Q^2) \\ &= \sum_{i,j} \Delta_i(P^2, Q^2) \otimes \sigma_{ij}(P^2, Q^2) \otimes f_{j/p}(Q^2) \end{aligned}$$

$$\Delta_i(P^2, Q^2) = \frac{P^2}{\mu_T^2} f_{\gamma^T/e} \otimes f_{i/\gamma^T}^{(1)} + \frac{P^2}{\mu_L^2} f_{\gamma^L/e} \otimes f_{i/\gamma^L}^{(1)}$$

$\mu_k^2$  determine small  $P^2$  behaviour of  $\gamma^{*k}$

$\gamma^{*L}$  in principle as important as  $\gamma^{*T}$ .

**What determines  $\mu_k^2$ ?**

To assess the accuracy of EPA in **resolved**  $\gamma^*$  jet production **HERWIG** was used to compare exact ME of the  $2 \rightarrow 3$  subprocesses

$$e + q \rightarrow e + q + G$$

$$e + G \rightarrow e + q + \bar{q}$$

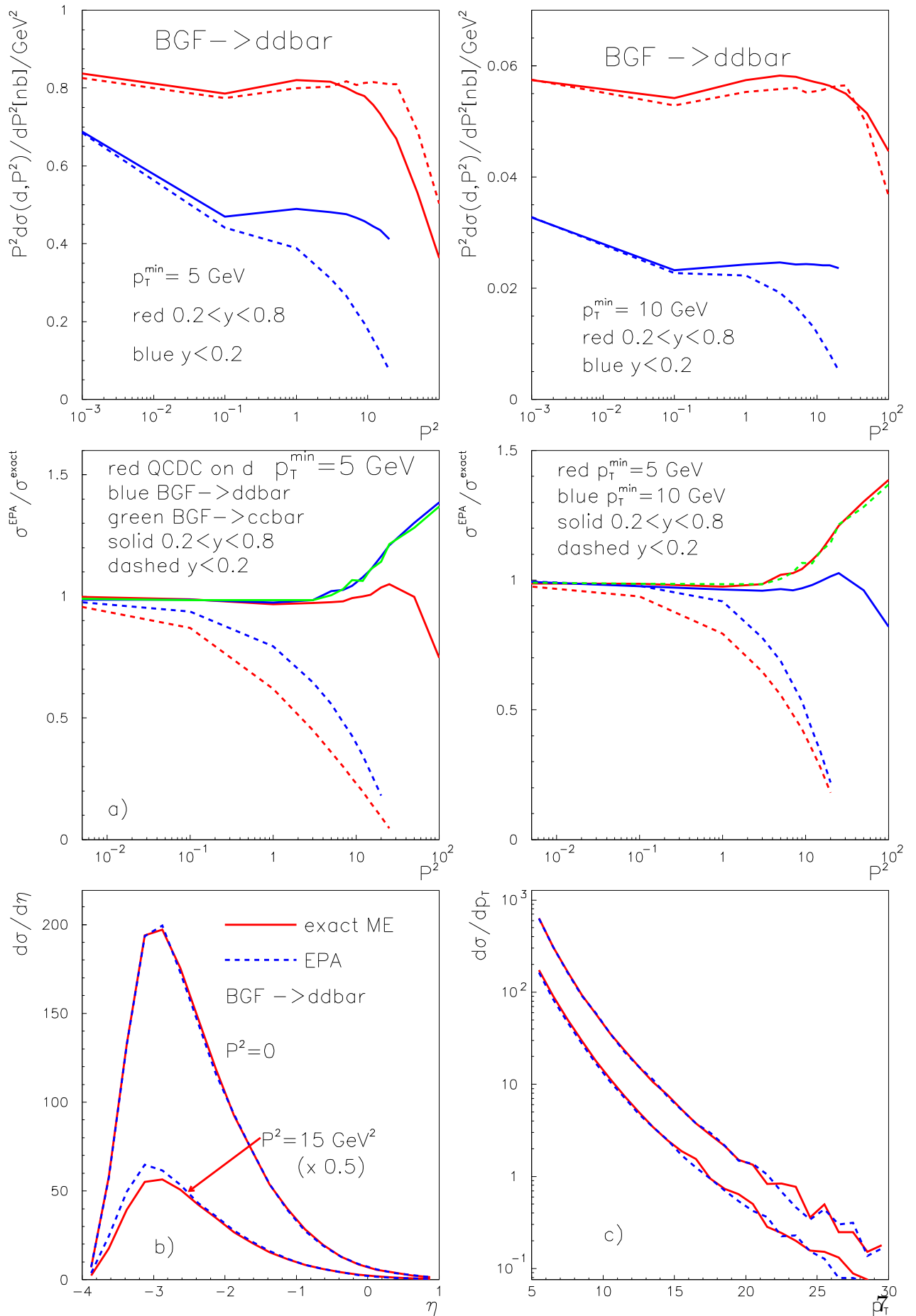
with convolutions of EPA with ME of binary processes

$$\gamma^* + q \rightarrow q + G, \quad \gamma^* + G \rightarrow q + \bar{q}$$

where, however, **only**  $\gamma^{*\mathbf{T}}$  was included.

Results depend in principle on

- photon virtuality  $P^2$
- hard scale  $Q^2$
- jet  $E_T$  and  $\eta$
- photon energy. e.g.  $y$
- subprocess type

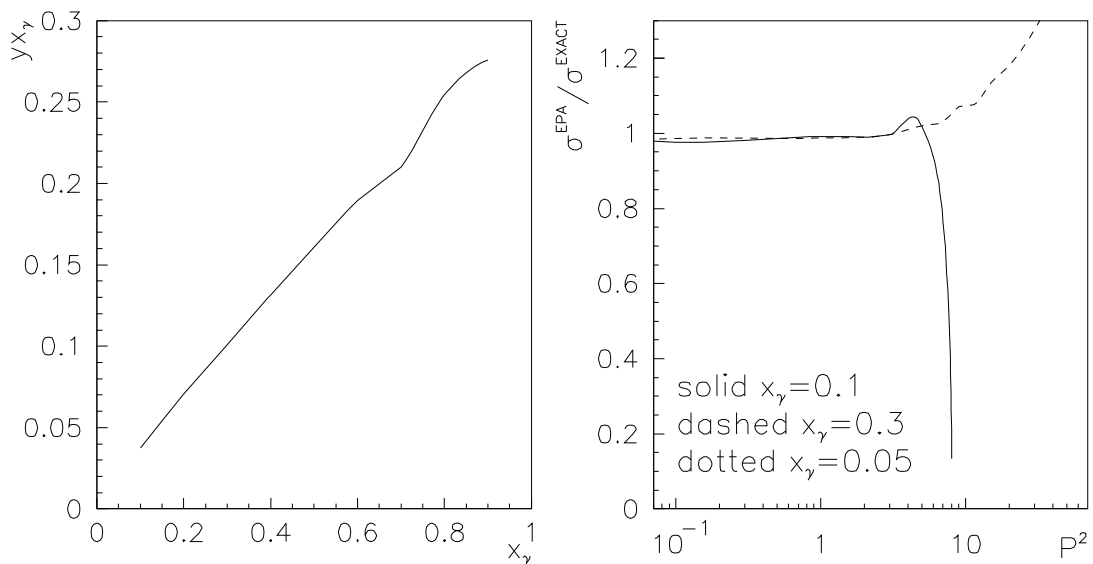


Conclusions from the comparison:

- a) **Strong** dependence on  $y$
- **good** agreement for **standard** cuts on  $y$
  - **poor** agreement for **low**  $y$ , e.g. low photon energy
- b) Little dependence on  $E_T^{jet}$
- c) Some, but small, dependence on the process type
- d) For  $0.2 \leq y \leq 0.8$  **very good** agreement also differentially in both  $\eta$  and  $E_T^{jet}$

**what does it imply for the resolved  $\gamma^*$ ?**

Plot  $\langle yx_\gamma \rangle(x_\gamma)$



EPA expected to apply down to  $x_\gamma \sim 0.1$



## Jets in danger: the associated soft activity

Properties of jets and their cross-sections require and are influenced by the **associated soft activity**, unrelated to jet production dynamics. Two models for its origin

### **Multiple parton interaction:**

additional **parton level** collision via LO QCD, implemented in **PYTHIA**, governed by  $p_T^{\min}$ , data require very low  $p_T^{\min} \sim 1 - 2$  GeV! Does it make sense to use PQCD for such low scale?

### **Soft underlying event:**

additional soft collision of **colorless remnant clusters**, implemented in **HERWIG**, governed by parameter (PRSOFT) specifying its frequency, data (H1) require moderate value  $\text{PRSOFT} \approx 0.1$ .

Good understanding of event structure **outside jets** is crucial for proper interpretation of jet data in term of photon (and proton) structure

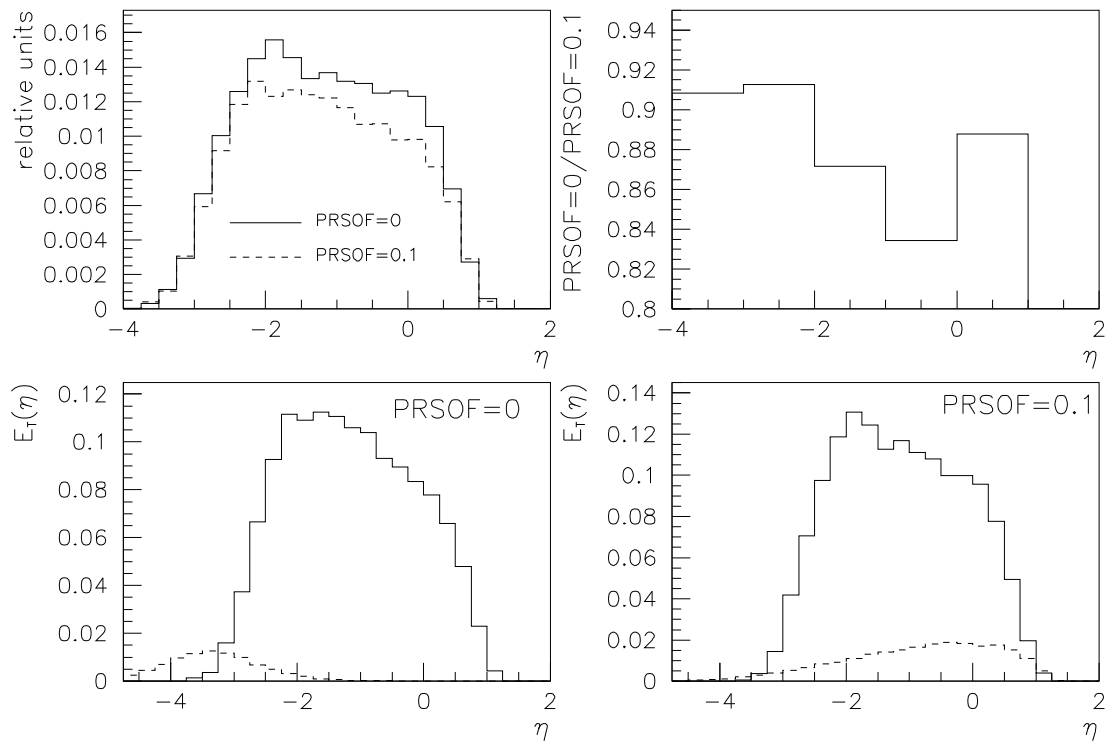
Corresponding parameters must be determined from comparison of data with theory in this region, not by fitting the jet cross-sections. Measures:

**jet pedestals**: characterize immediate vicinity of jets  
**transverse energy flow** outside jets in a fixed  $\eta$  range

Data as well as MC suggest their dependence on  $P^2$  – weak

$E_T^{\text{jet}}$  – weak  
 $\eta^{\text{jet}}$  – strong!

Example of a benign influence:  $d\sigma/d\eta$  distribution for  $E_T^{(1)} \geq 7$  GeV,  $E_T^{(2)} \geq 5$  GeV as given by HERWIG



but much worse scenario possible!

## Structure of the real photon

Described, as for hadrons, by **parton distribution functions** (PDF), satisfying evolution equation (EE) with **inhomogenous term** in the quark channel

For quarks the solution is written as as a sum

$$f_{q/\gamma}(x, M^2) = f_{q/\gamma}^{\text{PL}}(x, M^2) + f_{q/\gamma}^{\text{HAD}}(x, M^2)$$

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

Conventional viewpoint:

- **hadronic** part necessary for consistency and containing nontrivial information, while
- **pointlike** part calculable, i.e. “trivial”

**BUT:** the separation is **ambiguous** as there is infinite number “pointlike” solutions, differing by the initial condition

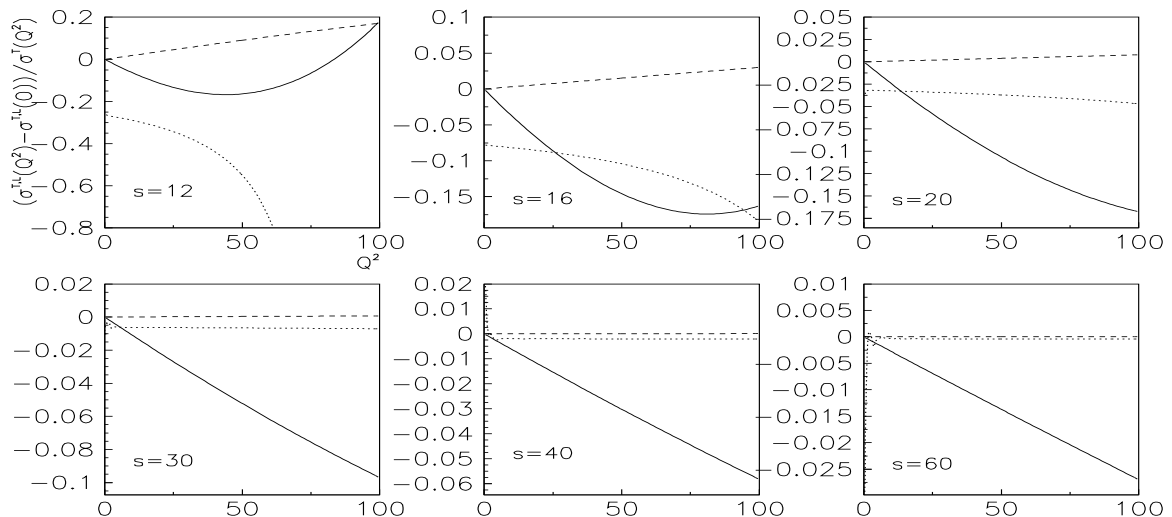
$$f_{q/\gamma}^{\text{PL}}(x, M_0^2) = 0$$

Example: SaS1 ( $M_0^2 = 0.36 \text{ GeV}^2$ ), SaS2 ( $M_0^2 = 2 \text{ GeV}^2$ )

## Jets in virtual photon collisions

Several sources of complications with respect to real  $\gamma$ :

1. Terms in EPA with no probabilistic interpretation  
Difficult to quantify, probably small effects,  $\mu^2 \approx S^2$
2. off-shell ME for  $\gamma$ -parton collisions  
explicit calculations give  $\mu^2 \approx s^2 \Rightarrow$  negligible
3. virtuality dependence of photonic PDF:
  - in QED:  $\mu^2 \sim m_q^2 \rightarrow$  important for heavy Q
  - in QCD:  $\mu^2$  expected to be a parameter characterizing **large distance** properties of strong interactions
4. contribution of the longitudinal photon: probably important, almost entirely **unexplored**



Models of the  $P^2$ -dependence of photonic PDF

**Drees–Godbole:** simple suppression factor

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

governed by  $\omega \Rightarrow \mu^2 \approx \omega^2 \ln(M^2/\omega^2)$

data suggest  $\omega \sim 0.1$  GeV

**Glück,Reya,Stratman:**  $P^2$  dependent initial condition

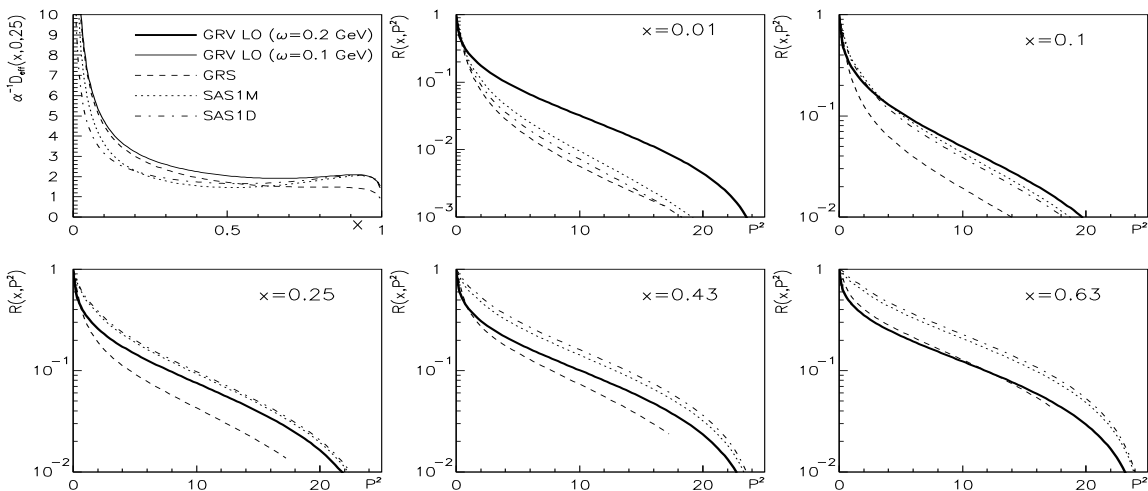
**Schuler–Sjöstrand:** based on dispersion relations in  $P^2$

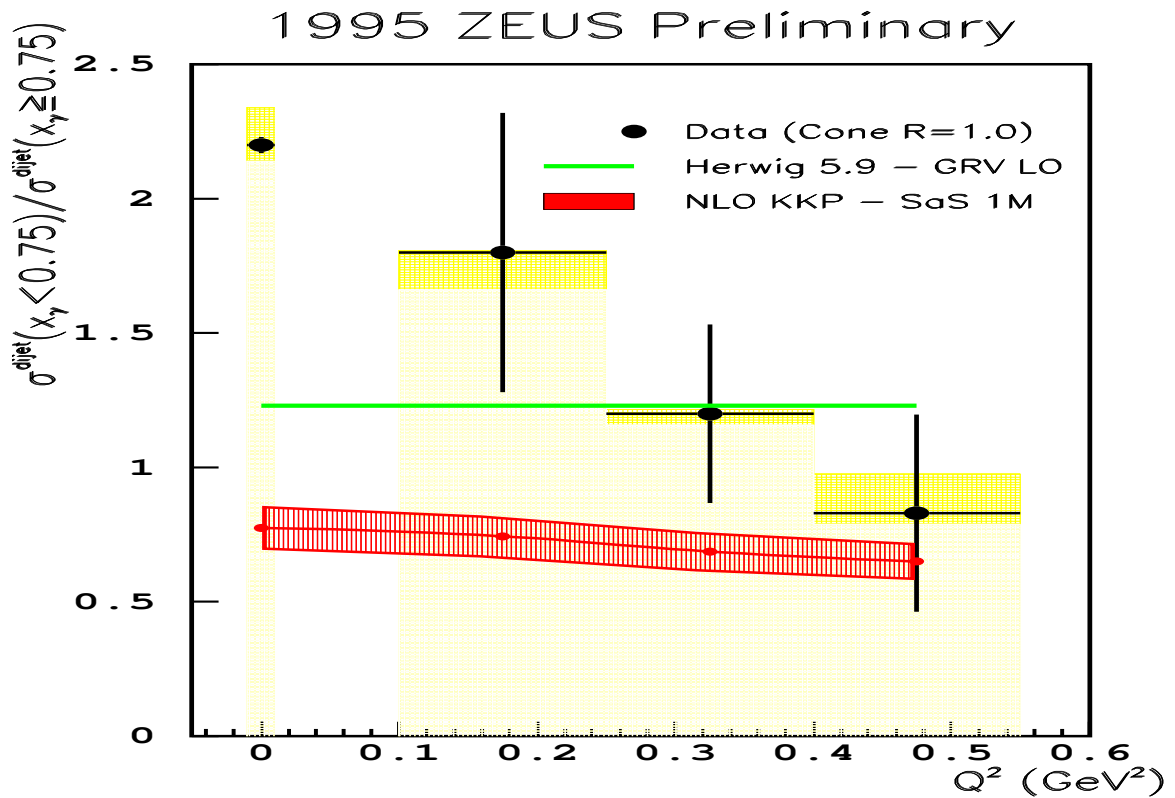
$$q_\gamma^{\text{HAD}}(M^2, P^2) \propto \left( \frac{m_V^2}{m_V^2 + P^2} \right)^2 \rightarrow 1 - 2 \left( \frac{P^2}{m_V^2} \right)$$

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

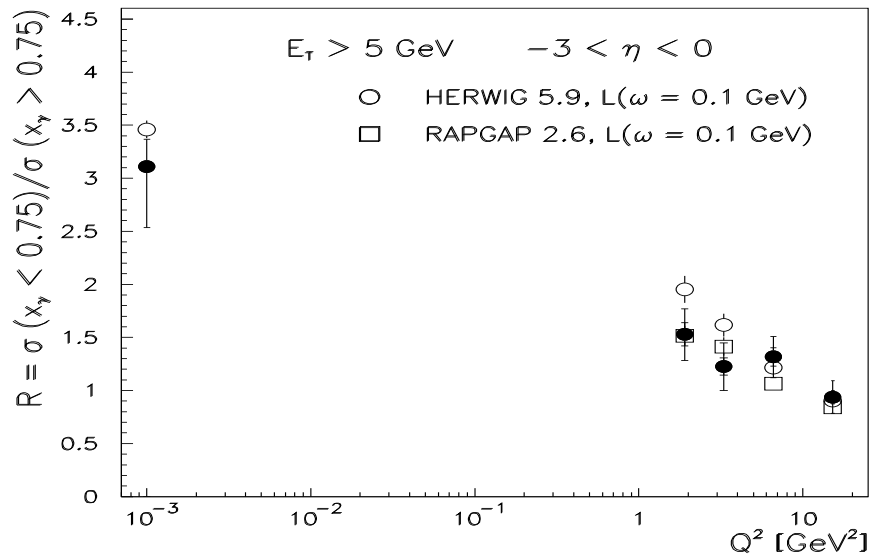
$$\rightarrow \ln \frac{M^2}{M_0^2} - 2 \left( \frac{P^2}{M_0^2} \right)$$

$$q_\gamma(M^2, P^2) \doteq q_\gamma(M^2, 0) - 2 \left( \frac{P^2}{m_V^2} + \frac{P^2}{M_0^2} \right)$$





### H1 1995



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

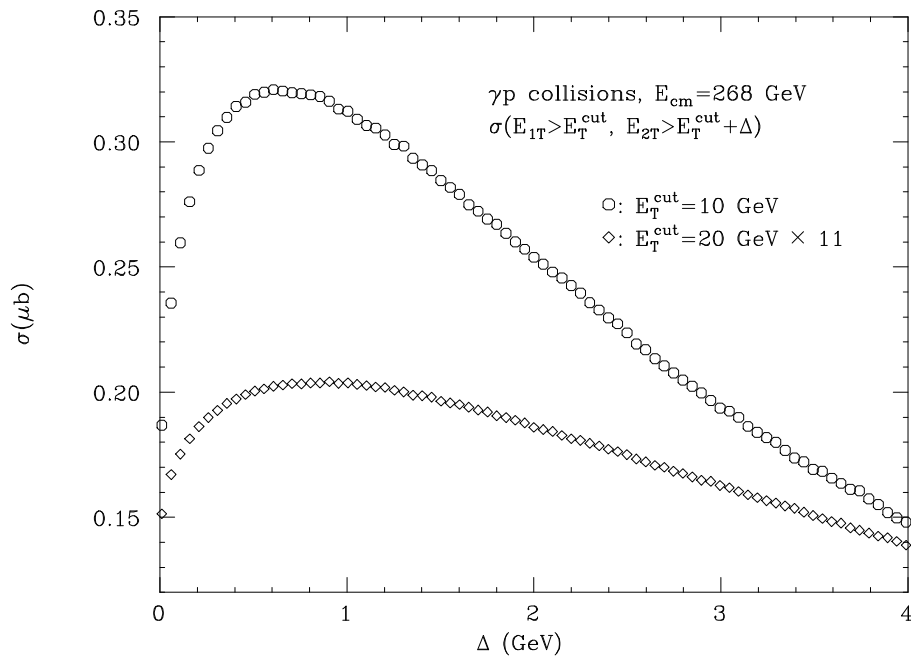
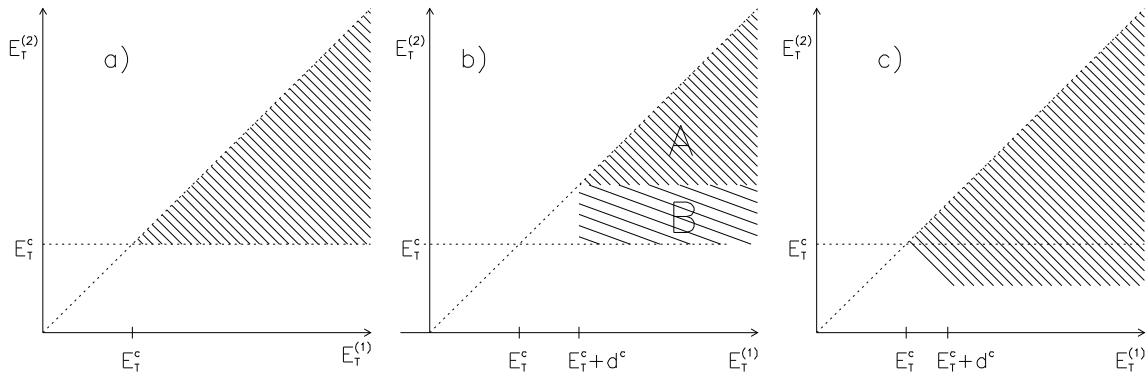
## Comparison with NLO calculations

Complications concerning the cuts on jet  $E_T$ . Three classes of  $E_T$  cuts:

**Symmetric:**  $E_T^{(1)}, E_T^{(2)} \geq E_T^c$

**Asymmetric:**  $E_T^{(1)} \geq E_T^c + d^c, E_T^{(2)} \geq E_T^c$

**Hybrid:**  $E_T^{(1)} + E_T^{(2)} \geq 2E_T^c, E_T^{(2)} \geq E_T^c - d^c$



**real photon:** several NLO parton level calculations

Kramer, Klasen, Kleinwort

Owens, Harris

Aurenche, Fontannaz,...

Frixione, Ridolfi

**virtual photon:** only one so far

Kramer, Klasen, Pötter (hep-ph/9804352, DESY 98-046)

Interpretation of the comparisons with data nontrivial  
even at large  $E_T^{\text{jet}}$  because of the

- the influence of additional soft activity
- the dependence on jet parameters

Note:

for  $P^2 > 0$  **no mass singularities** in the direct  
contribution requiring subtraction  $\Rightarrow$

**unsubtracted direct contribution** can alone be  
compared to data

Alternative:

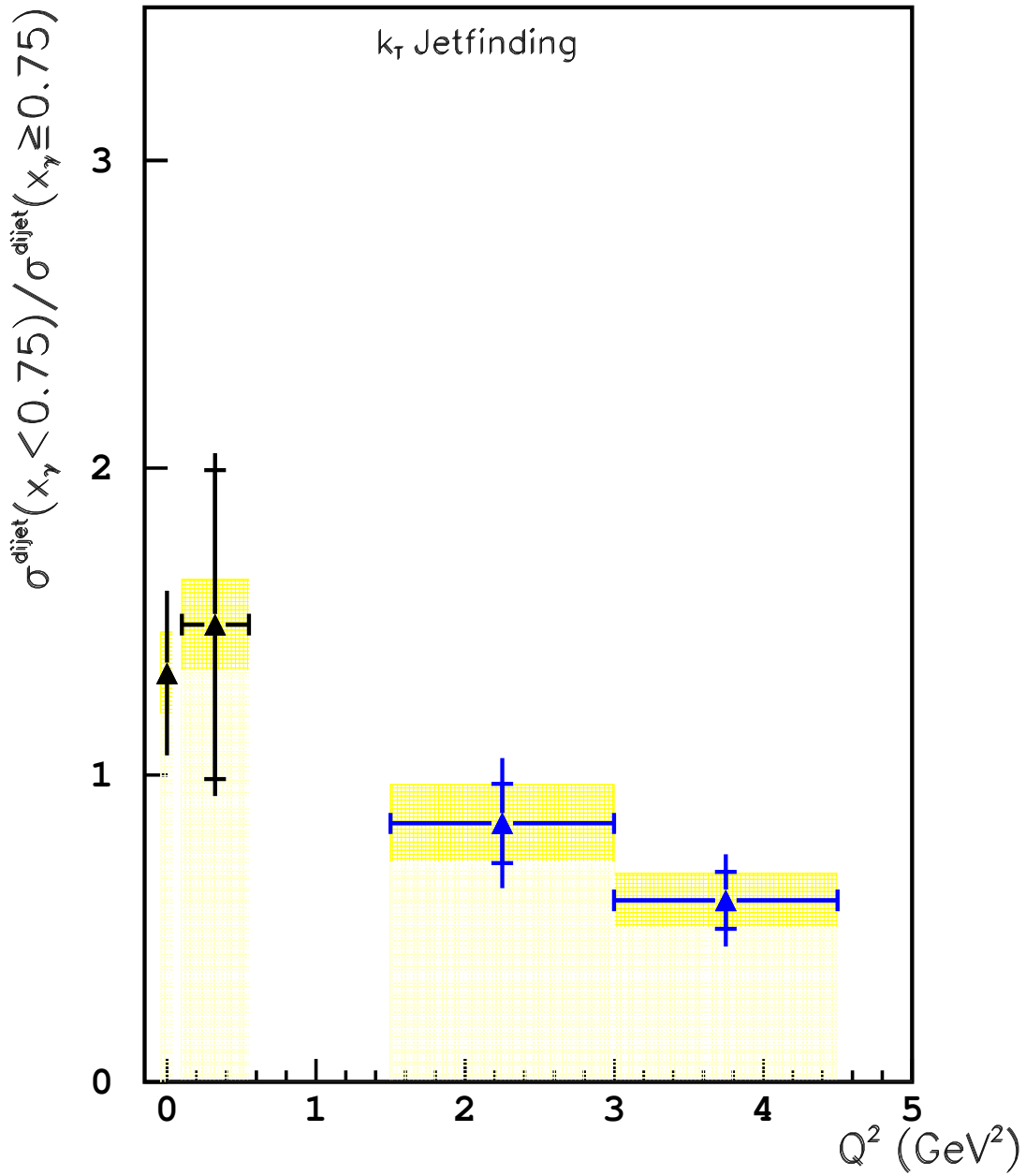
subtract terms

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

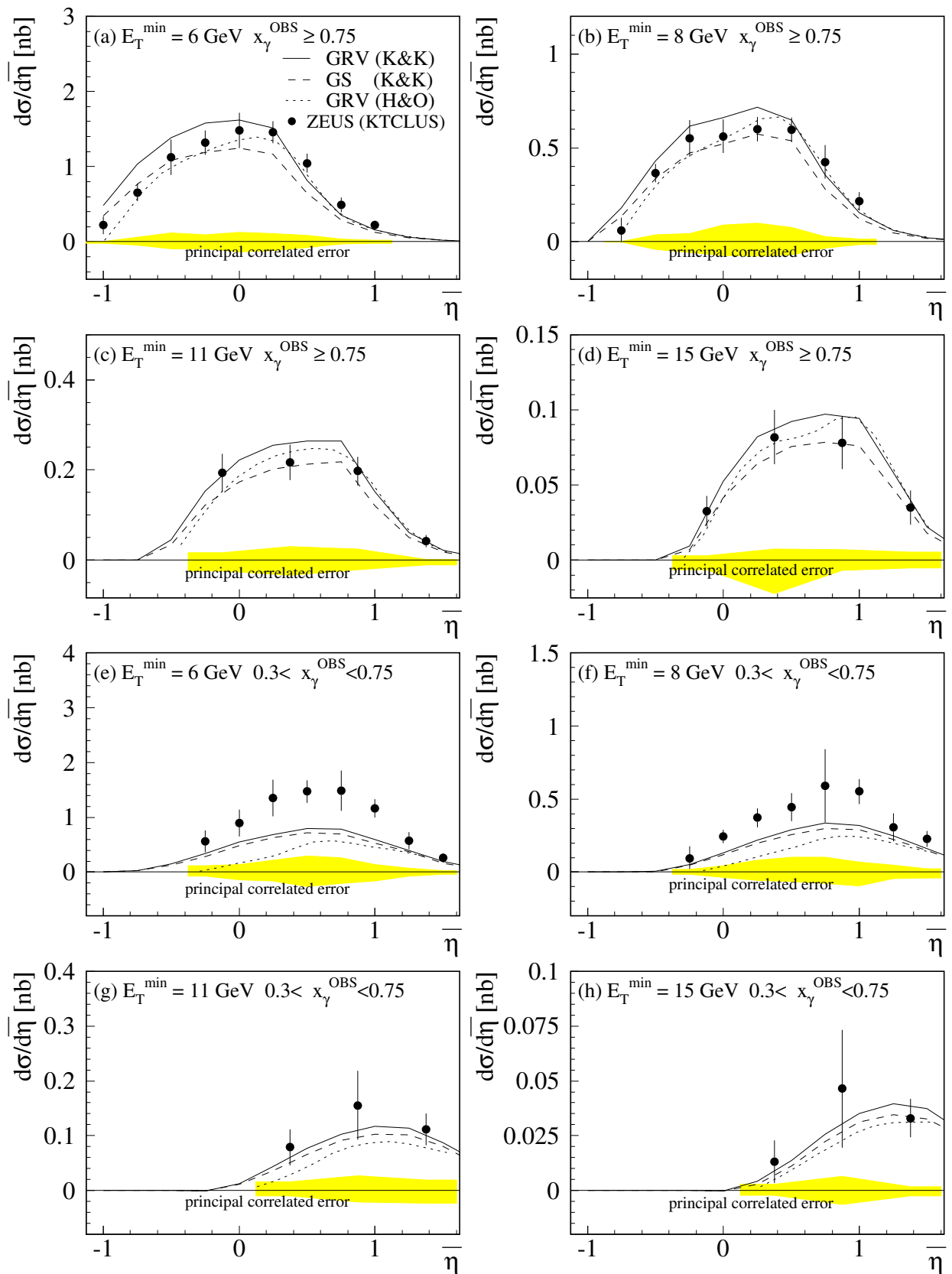
by including them in  $q_\gamma(M^2, P^2)$  and define, as for the  
real photon, the **subtracted direct contribution**

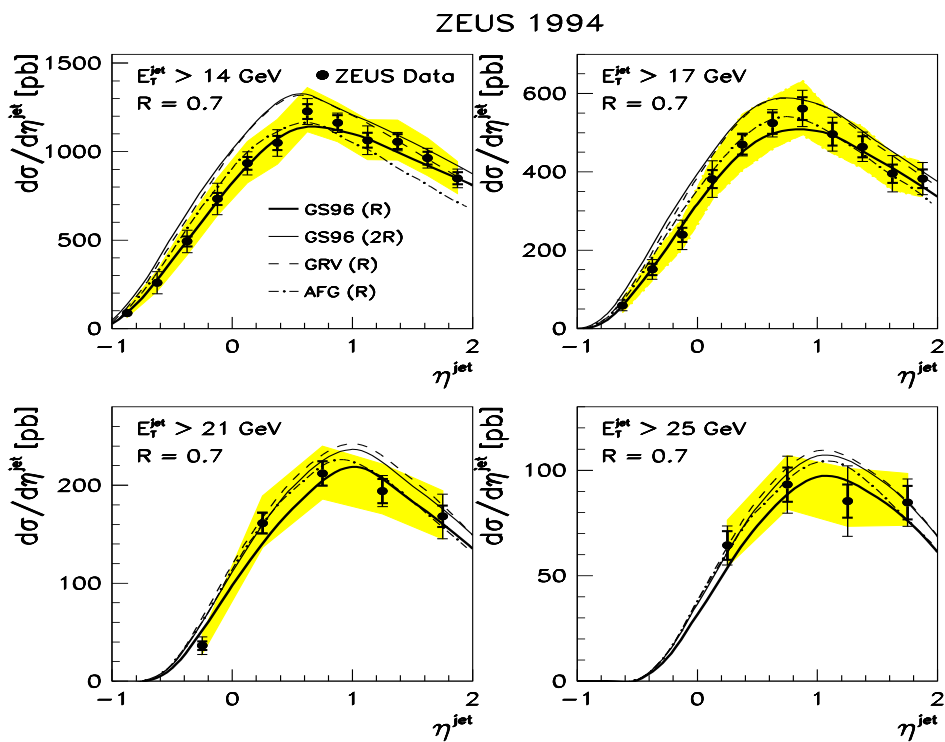
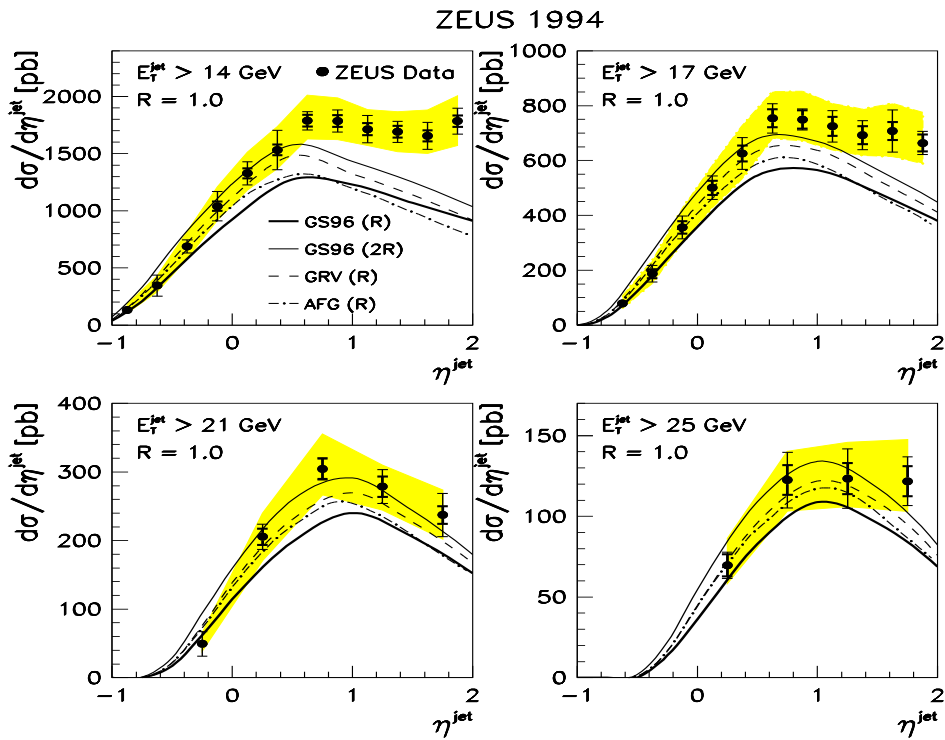


### 1995 ZEUS Preliminary



# ZEUS 1994





**Is there a need for virtual photon structure?**

Question:

**For which  $P^2$  do we need the hadronic component?**

Answer:

Difficult because of ambiguity in the separation of **pointlike** and **hadronic** components. Despite this uncertainty my personal answer is **YES**.

## Prospects for future

Ongoing analyses at LEP 2 by

**DELPHI**: “window of opportunity” in the range  
 $P^2 \in (0.3, 1) \text{ GeV}^2$

**OPAL**:?

and HERA by both

**H1** (talk by M. Taševský)

**ZEUS**:

will extend the region of accessible  $P^2$ ,  $x_\gamma$  and  $E_T$  and provide more statistics for detailed investigations of the photon structure