The relevance of $\gamma^*_{\rm L}$ in hard collisions of virtual photons

Jiří Chýla, Marek Taševský
Institute of Physics, Prague

- **Virtual photon and its "structure"**
- **PDF of γ^*_L in QED**
- **QCD improved PDF of γ^*_L**
- **Relevance of γ^*_L in hard collisions**
- **Future**
- **Conclusions**

Related work:

Contributions of γ_L^*:

J. Ch., M. T.: Eur. Phys. J. C 16 (2000), hep-ph/0003300, phenomenology with $\gamma_L^{\rm QED}$

J. Ch.: Phys. Lett. B, QCD corrections to QED formulae for PDF of γ_L^*

J. Ch., M. T.: in preparation, partly in this talk phenomenology with QCD improved PDF of γ_L^*

General aspects of virtual photon interactions:

J. Ch., J. Cvach: in *Future Physics at HERA*

J. Ch., M. T.: in *MC Generators for HERA*, hep-ph/9905444

J.Ch., M. T.: in *PHOTON'99*, hep-ph/9906552

J. Ch., M. T.: hep-ph/9912514,

M. Taševský: PhD Thesis, H1 data vs NLO JETVIP calculations including the resolved γ_T^*

C. Friberg, T. Sjöstrand: Eur. Phys. J. C13 (2000), 151 also emphasizes the relevance of γ_L^*

Structure of the virtual photon

Data relevant to the concept of γ^* "structure"

PLUTO: 1984, $F_{\rm eff}^{\gamma}(x,P^2,Q^2)$ for $\langle P^2\rangle = 0.35$ GeV^2
H1 - dedicated analyses:

1. **Phys. Lett. B415 (1997), 418:** $\sigma^{\rm res}$ from single jets in the range $0 \le P^2 \le 49$ GeV^2
2. **Eur. Phys. J. C13 (2000), 397:** $D_{\rm eff}(x,P^2,Q^2)$ from dijets in the range $1.6 \le P^2 \le 80$ GeV^2
3. **M. Taševský's PhD Thesis:** dijets vs **JETVIP**, **NLO QCD** calculations including the resolved γ_T^* contributions, $1.44 \le P^2 \le 25$ GeV^2. The most detailed NLO QCD analysis of data on γ^*

H1 - several other papers (R_2, forward jets) use the concept of virtual photon structure to improve the agreement of LO MC with data
ZEUS: $r(Q^2) \equiv \sigma^{\rm res}/\sigma^{\rm dir}(P^2)$ for $0 \le P^2 \le 4$ GeV^2, claims failure of JETVIP, **but $r(Q^2)$ unsuitable** for comparison with parton level QCD!
TPC/2γ:, $\sigma_{tot}(\gamma\gamma^*(P^2))$, $0.2 \le P^2 \le 60$ GeV^2
TOPAZ: $\sigma_{tot}(\gamma\gamma^*(P^2))$, $1 \le P^2 \le 37$ GeV^2
L3: $F_{\rm eff}^{\gamma}(x,P^2,Q^2)$ for $0 \le P^2 \le 6$ GeV^2, exhibits very **puzzling P^2 dependence!!**

Basic concepts and formulae

Fluxes of photons from incoming electron

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

$$f_{\gamma_L/e}(y,P^2) = \frac{\alpha}{2\pi}\frac{2(1-y)}{y}\frac{1}{P^2}, \quad P^2_{\min}=\frac{m_e^2y^2}{1-y}$$

The difference at **large** y crucial for separation of γ^T,γ^L

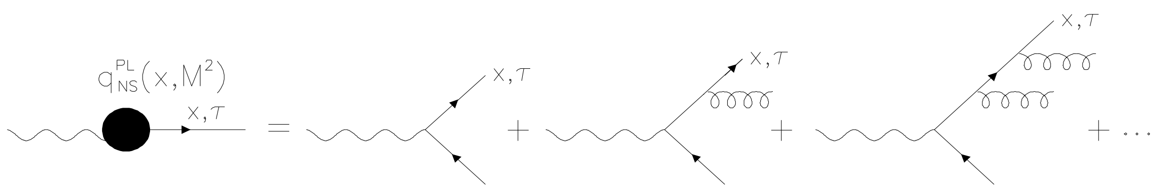
Cross sections of hard collisions of virtual photons

$$\sum_{k=T,L} f_{\gamma_k/e}\otimes \sum_{i=q,\overline{q},G} f_{i/\gamma_k}\otimes\sigma_i$$

PDF f_{i/γ^k} of the photon can be written as sums of **hadronic** (HAD) and **pointlike** (PL) parts

$$f(x,P^2,Q^2)=f^{\rm HAD}(x,P^2,Q^2)+f^{\rm PL}(x,P^2,Q^2)$$

This separation is, however, **ambiguous**!
Pointlike part of NS quark distribution function results from the resummation



describing QCD corrections to QED. In units of $3e_q^2\alpha/2\pi$

$$q_k^{\rm QED}=f_k(x)\ln\left(\frac{Q^2}{xP^2+m_q^2/(1-x)}\right)-f_k(x)+\frac{g_k(x)m_q^2+h_k(x)P^2}{xP^2+m_q^2/(1-x)}$$

$$f_T(x) = x^2 + (1-x)^2, \quad g_T(x) = \frac{1}{1-x}, \quad h_T(x) = 0,$$

$$f_L(x) = 0, \quad g_L(x) = 0, \quad h_L(x) = 4x^2(1-x)$$

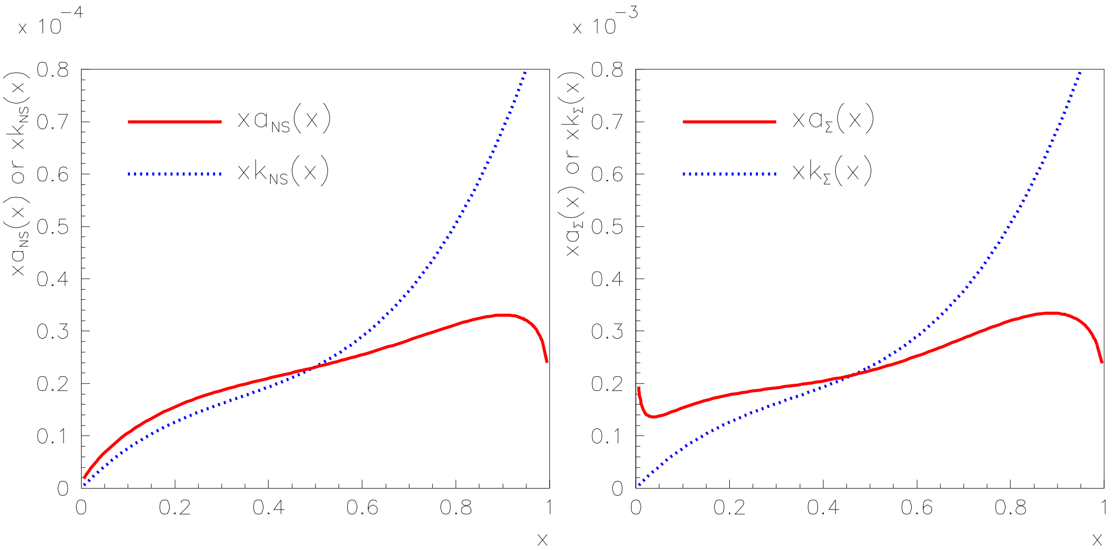
$$q_T^{\mathrm{QED}} \to (x^2+(1-x)^2)\ln\frac{Q^2}{xP^2}+8x(1-x)-2, \qquad x(1-x)P^2 \gg m_q^2$$

$$q_L^{\mathrm{QED}} = \frac{4x^2(1-x)^2P^2}{x(1-x)P^2+m_q^2} \to 4x(1-x); \qquad x(1-x)P^2 \gg m_q^2$$

$$\to \frac{P^2}{m_q^2}4x^2(1-x)^2; x(1-x)P^2 \ll m_q^2$$

QCD corrections **soften quarks** and **generate** gluons.

at large Q^2 : $\quad q_T^{\mathrm{QCD}}(x,Q^2) \to a(x)\ln Q^2$



Points on γ_T^* to keep in mind:

- $\ln Q^2$ rise is a purely **QED effect!**
- **QCD** effect: the difference $\left[a(x) - (x^2 + (1-x)^2)\right]$
- f^{HAD} drop with P^2 **much faster** than f^{PL} and for $P^2 \gtrsim 2$ GeV^2 become practically **negligible**.

The concept of γ^* structure in QCD

In QCD the extent to which the effects of γ^* are included depends on particular theoretical framework adopted. Questions we have often encountered:

a) **Why** to introduce the concept of γ^* **structure** when we have exact NLO QCD programs like **DISENT, MEPJET, DISASTER**, which dispense with this concept?

b) Is there **any evidence** for the usefulness of this concept in available data?

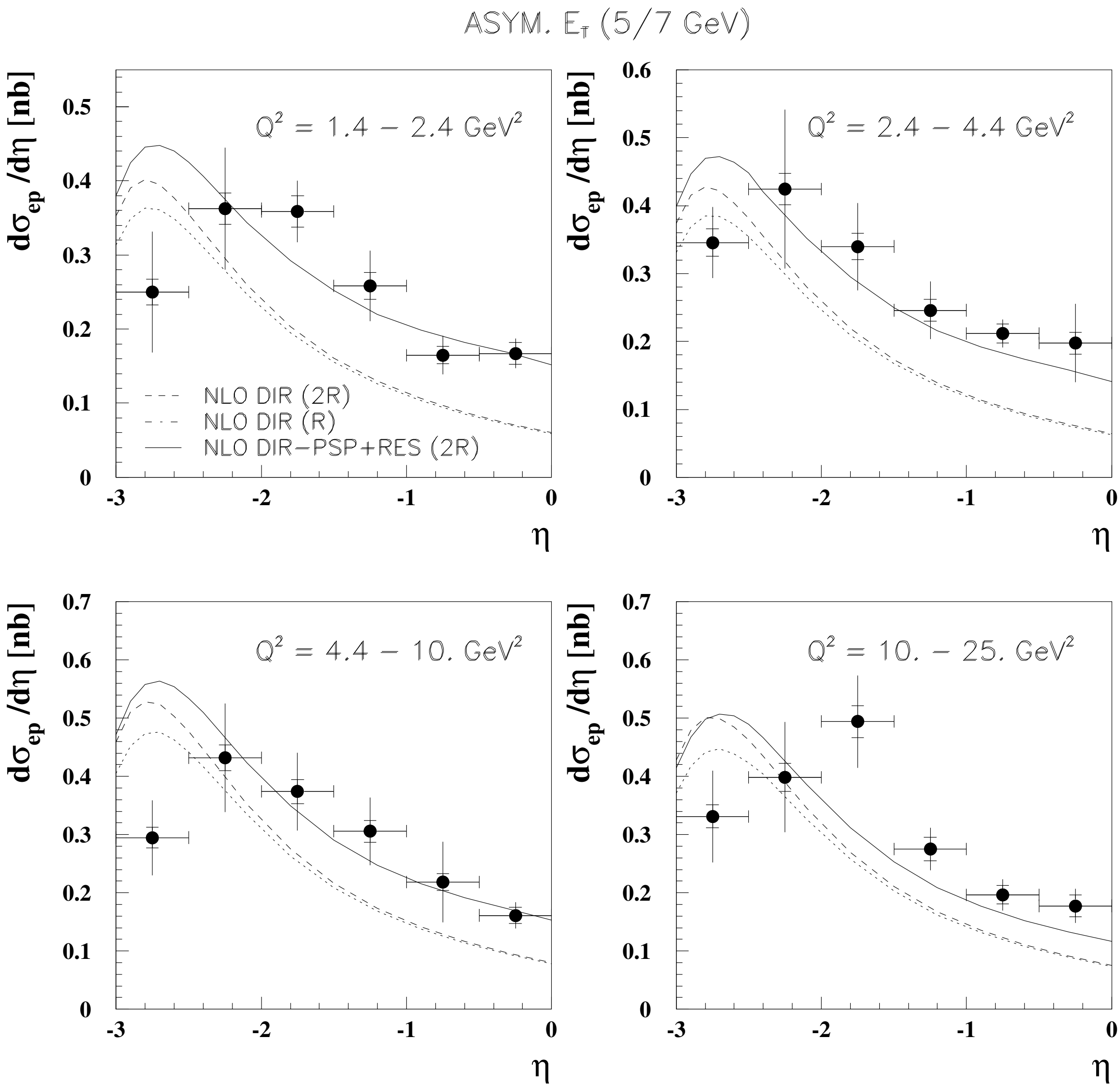
ad a) There is a **large difference** in part of the phase space accessible at HERA between the results of NLO calculations **with and without** the resolved γ^* contributions.

ad b) **YES!** NLO calculations without the resolved γ^* contribution are **significantly below** the data in the region of moderate $P^2 \ll Q^2 \simeq E_T^2$ and $\eta^* \simeq 0$

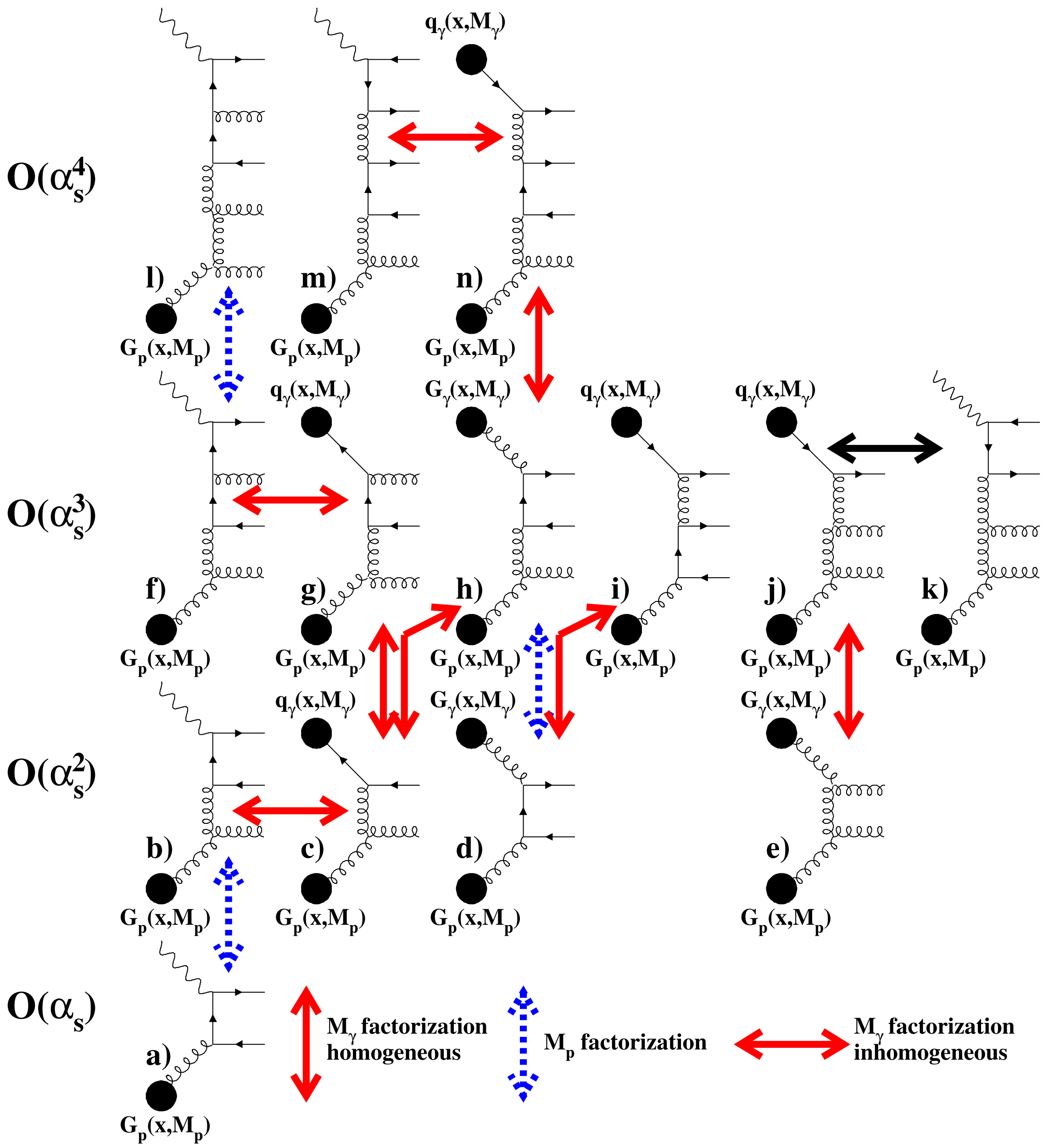
Summary: *in principle* the concept of γ^* structure **need not be introduced** but *in practice* it is **extremely useful** as a way of approximately including part of **higher order** perturbative QCD corrections

Example: **J. Cvach**: Talk at DIS99:

H1 Preliminary



Factorization scale dependence and the relation between direct and resolved photon contributions:



Resolved $\gamma^*_{T,L}$ in QCD calculations

- **LO MC event generators:**

  Contributions of γ^*_L included exactly in the **direct** channel. In the resolved one

  PYTHIA: since version 6.12 $f_{\gamma^*_T/e}$ as well as $f_{\gamma^*_L/e}$ with exact kinematics at the eγ^*e vertex and SaS PDF of γ^*_T. γ^*_L treated via **rescaling ansatz**.

  HERWIG:

  official version: γ^*_T only

  my version: γ^*_L as well with QCD improved PDF

  PHOJET: only γ^*_T

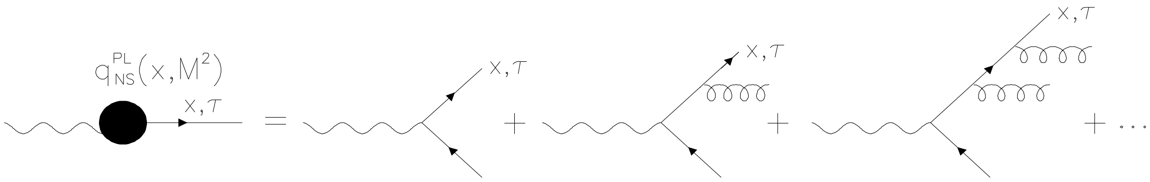
- **NLO parton level calculations:**

  DISENT, MEPJET, DISASTER: $\gamma^*_{T,L}$ treated exactly up to order $\alpha\alpha_s^2$, but only **unsubtracted direct** contributions taken into account

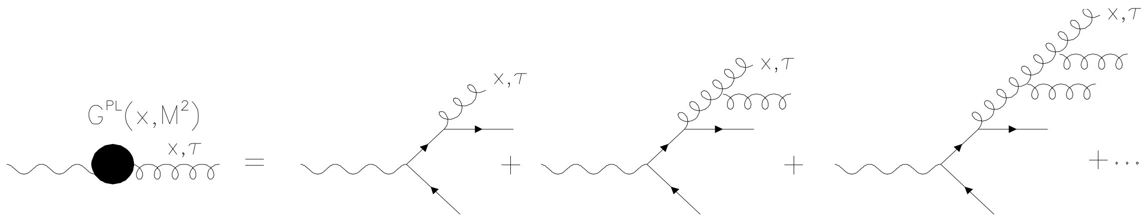
  JETVIP: includes the **resolved photon** channel with γ^*_T convoluted with cross sections up to α_s^3 recently we have added (with help from Bjorn Pötter) the **resolved** γ^*_L contributions (see below)

QCD improved PDF of γ_L^*

Resummation of diagrams



in **leading-log approximation** (i.e. in powers of $\alpha_s \ln M^2$) and similarly for quark singlet and gluons



leads for

$$m_q^2 \ll P^2 \ll M^2$$

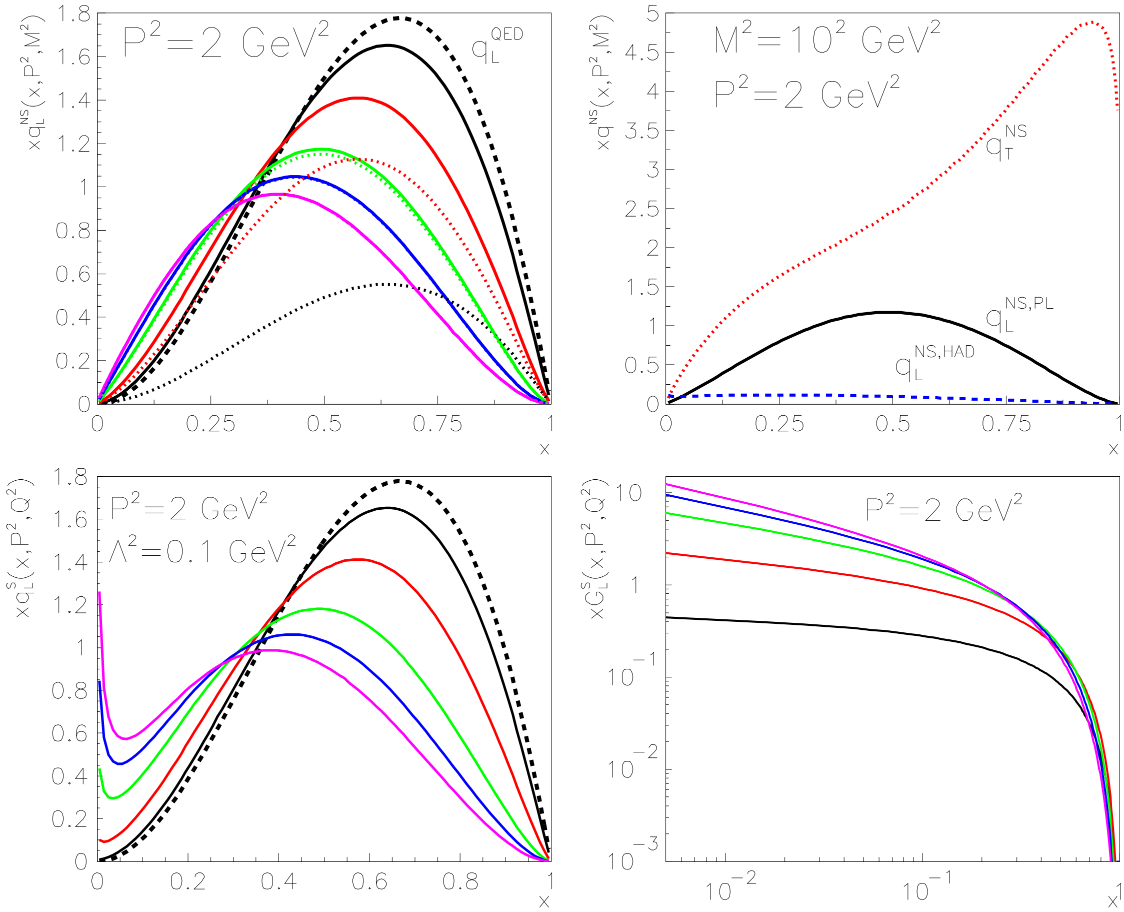
to typical **hadron-like scale dependence** even for the **pointlike parts!**

$$q_L^{\rm NS}(n, P^2, M^2) = k_L(n) \left[\frac{\alpha_s(M^2)}{\alpha_s(P^2)}\right]^{-2P_{qq}^{(0)}(n)/\beta_0},$$

where

$$k_l(x) = 12x(1-x), \qquad s \equiv \frac{\ln(M^2/\Lambda^2)}{\ln(P^2/\Lambda^2)}$$

Examples:



Hadronic part of q_L^{QCD} **negligible** for $P^2 \gtrsim 2\ \mathrm{GeV}^2$

Parameterization of PDF of γ_L^* available for

$$0.001 \le x \le 0.995, \qquad 1 \le s \le 3.9$$

Question: **what is** m_q or, generally, **what governs** the onset of PDF of γ_L^*?

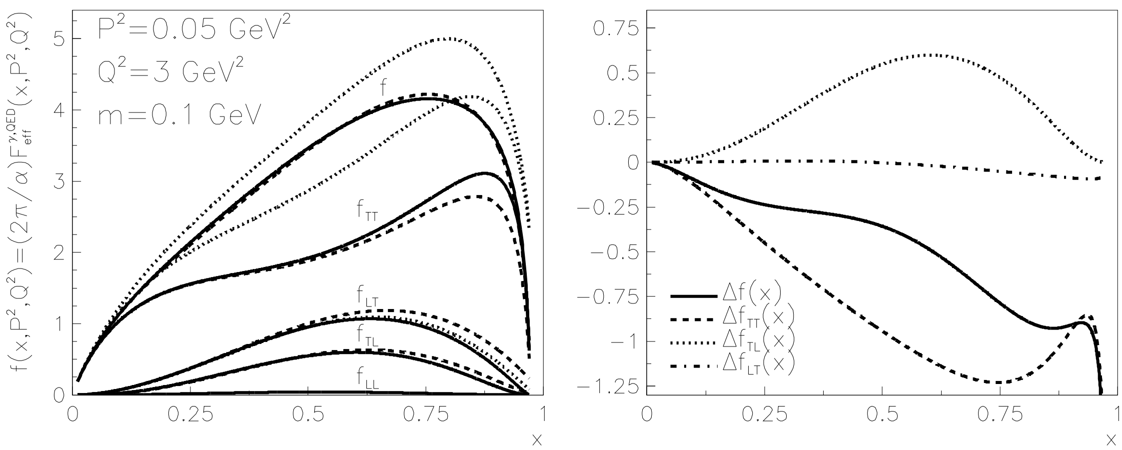
The relevance of γ_L^*

Claim: whenever the variations of contributions of $\gamma_T^*(P^2)$ with P^2 are taken into account, so **must** be those of $\gamma_L^*(P^2)$!

Illustration: at LEP one measures the combination

$$F_{\rm eff}^{\gamma}(x,P^2,Q^2) \equiv \frac{Q^2}{4\pi^2\alpha}\left(\sigma_{TT}+\sigma_{LT}+\sigma_{TL}+\sigma_{LL}\right)$$

The QED structure function $F_{\rm eff}^{\rm QED}$, measurable using $\mu^+\mu^-$ pairs, is fully calculable. For **OPAL** data the individual contributions σ_{ij} look as follows



The data clearly require the contributions of target γ_L^*. The same for **L3** data.

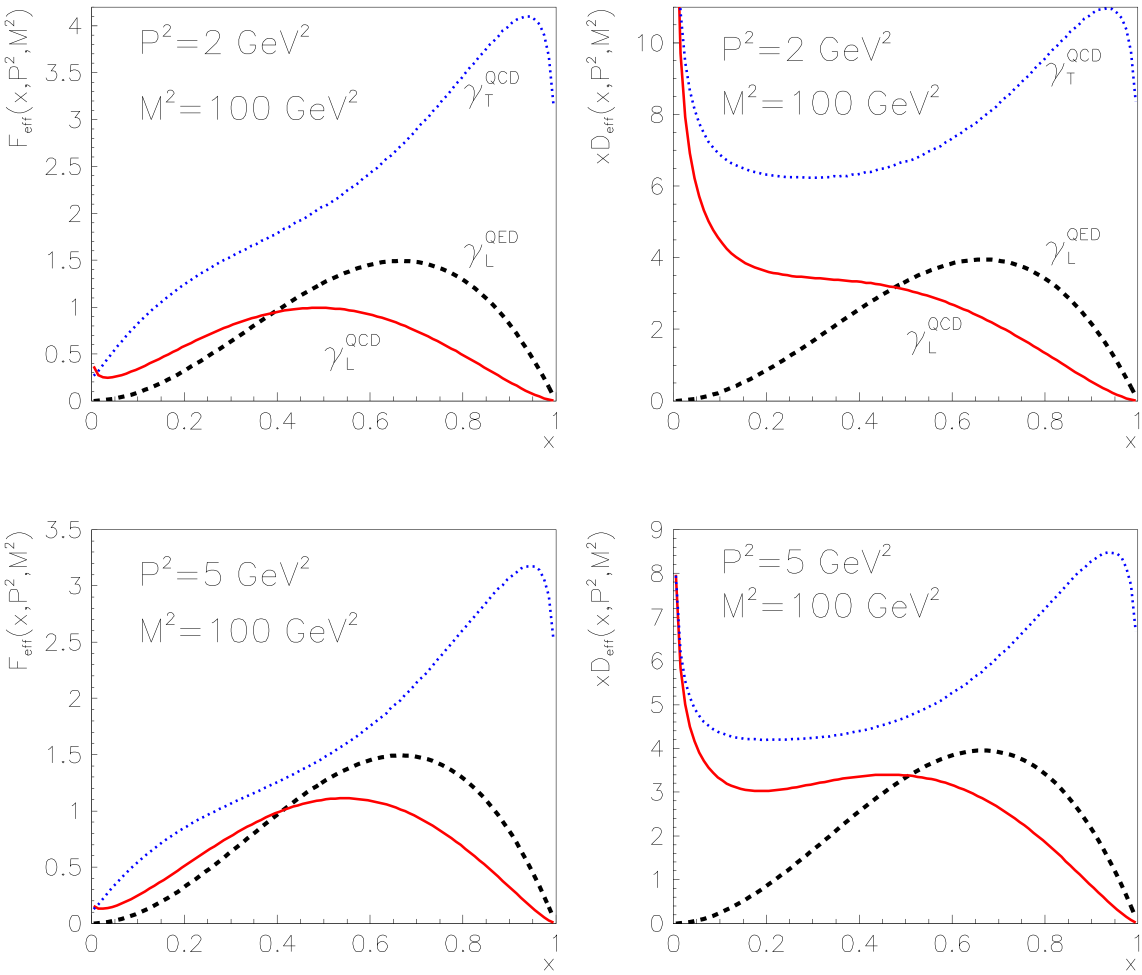
Resolved γ_L^* in LO calculations

The relative contributions of γ_L^* depend on

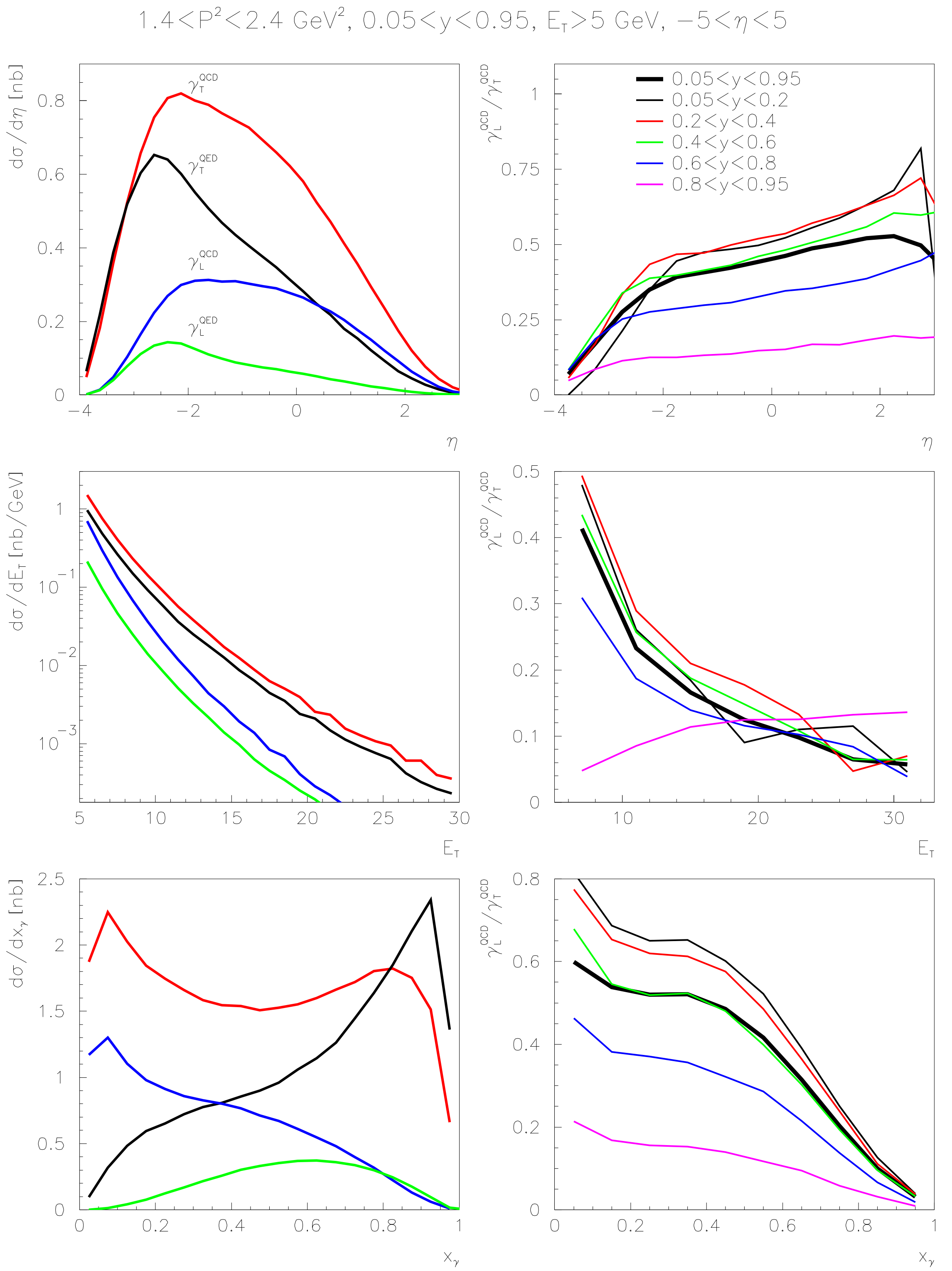
- electron variables y and P^2
- jet variables E_T, η and x_γ.

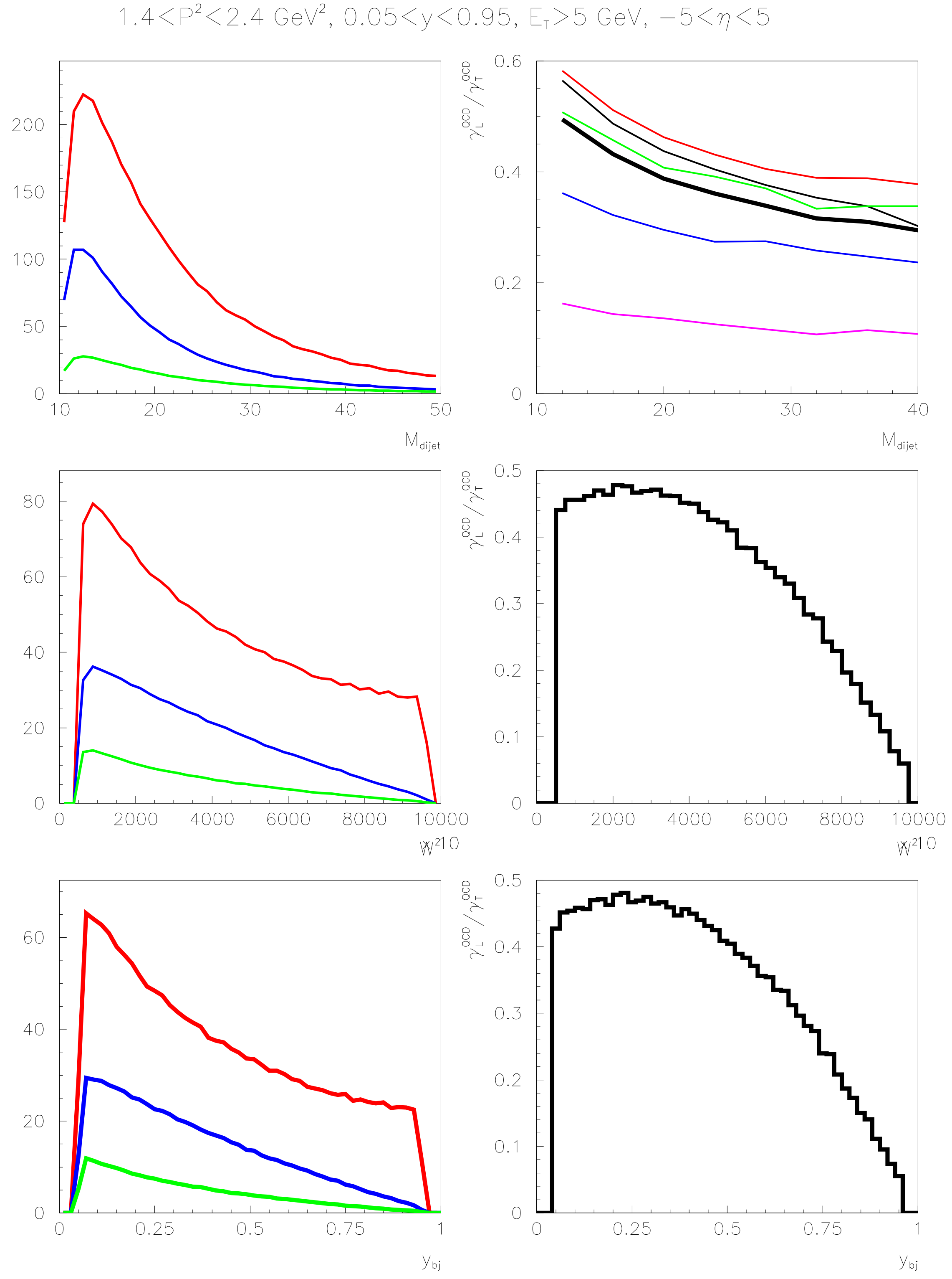
Analytical evaluation of $F_{\rm eff}(P^2, M^2)$ and

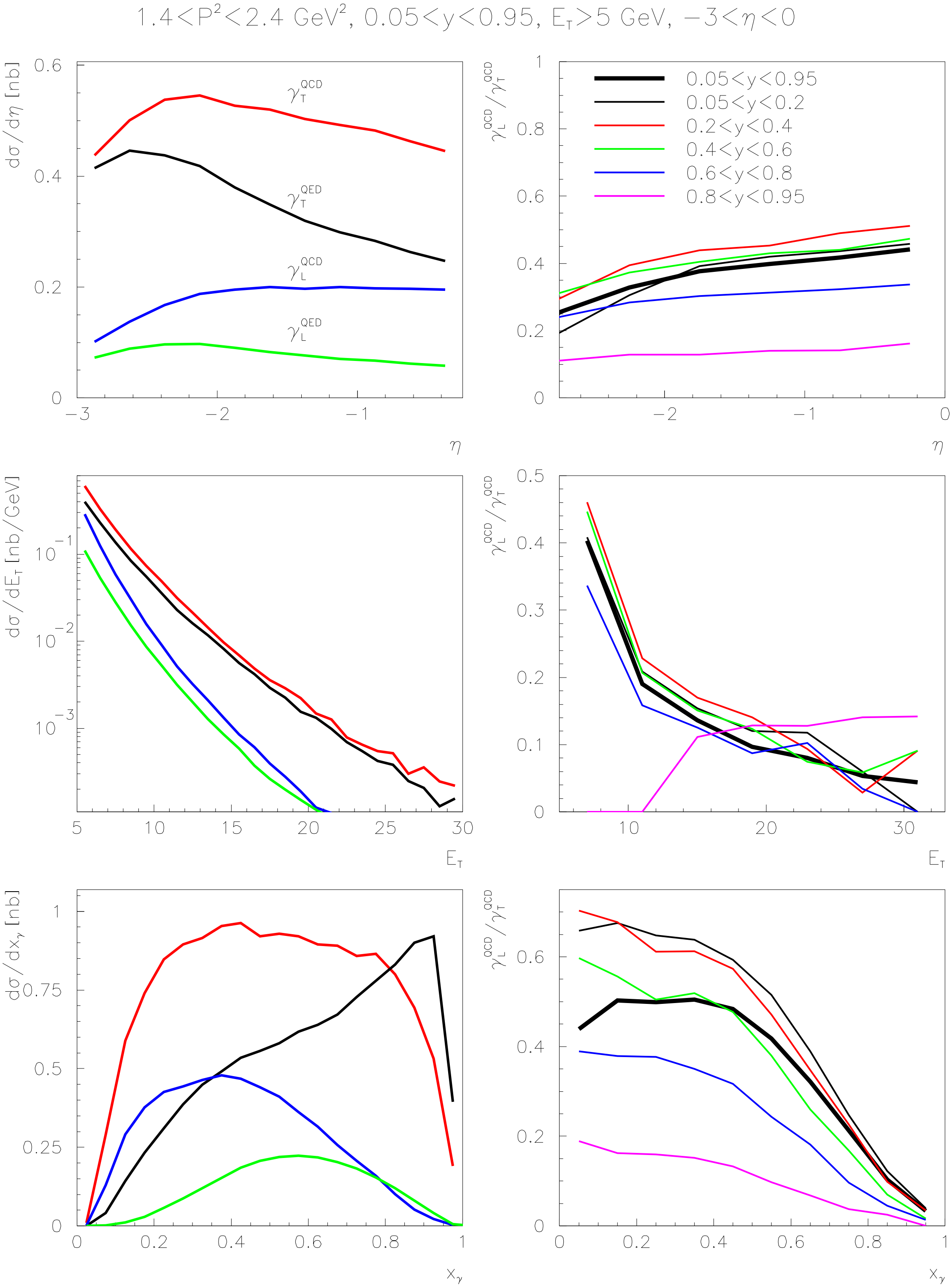
$$D_{\rm eff}(x, P^2, M^2) \equiv \sum_{i=1}^{n_f} (q_i + \overline{q}_i) + \frac{9}{4}G$$



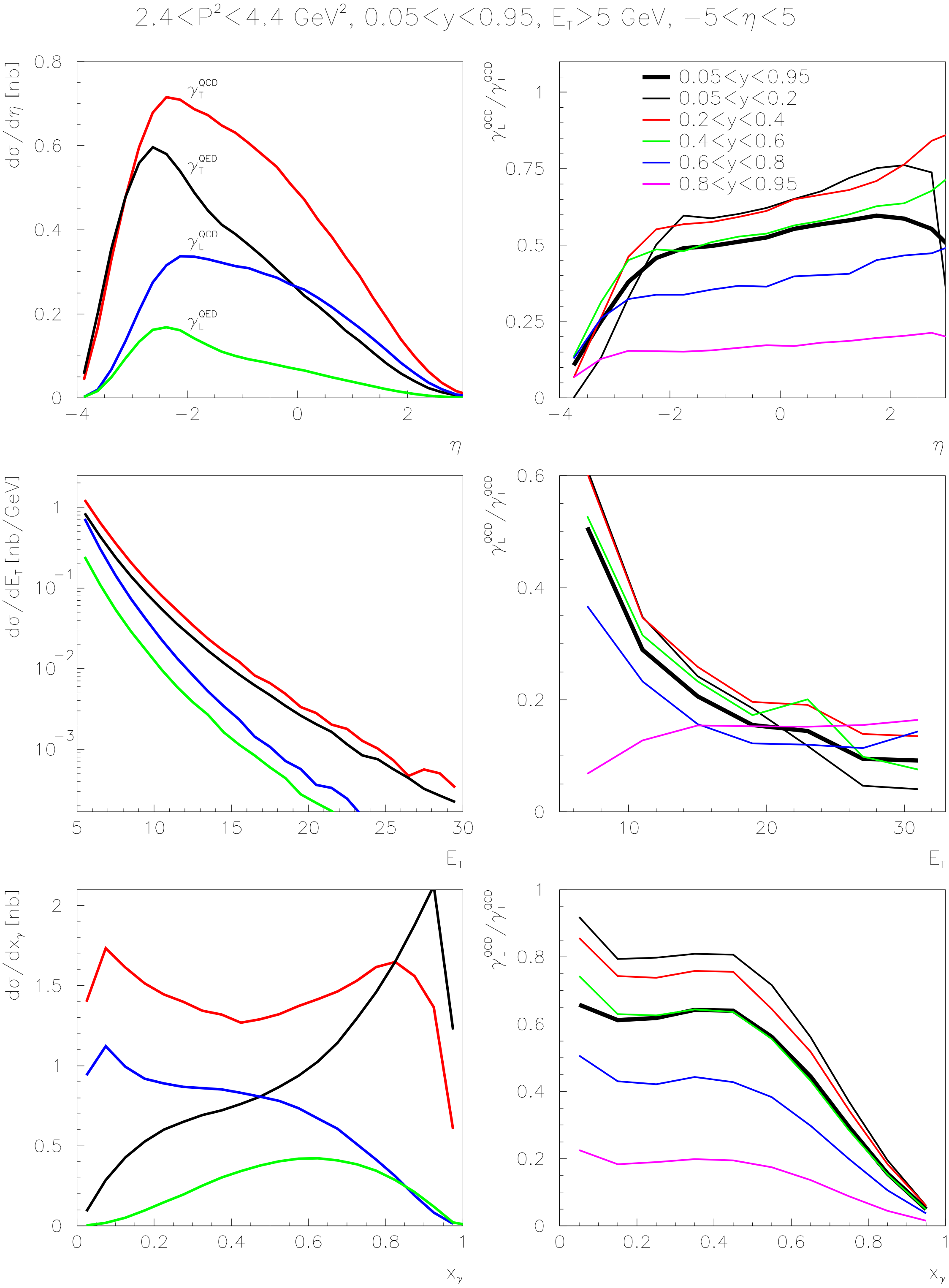
HERWIG MC simulations:

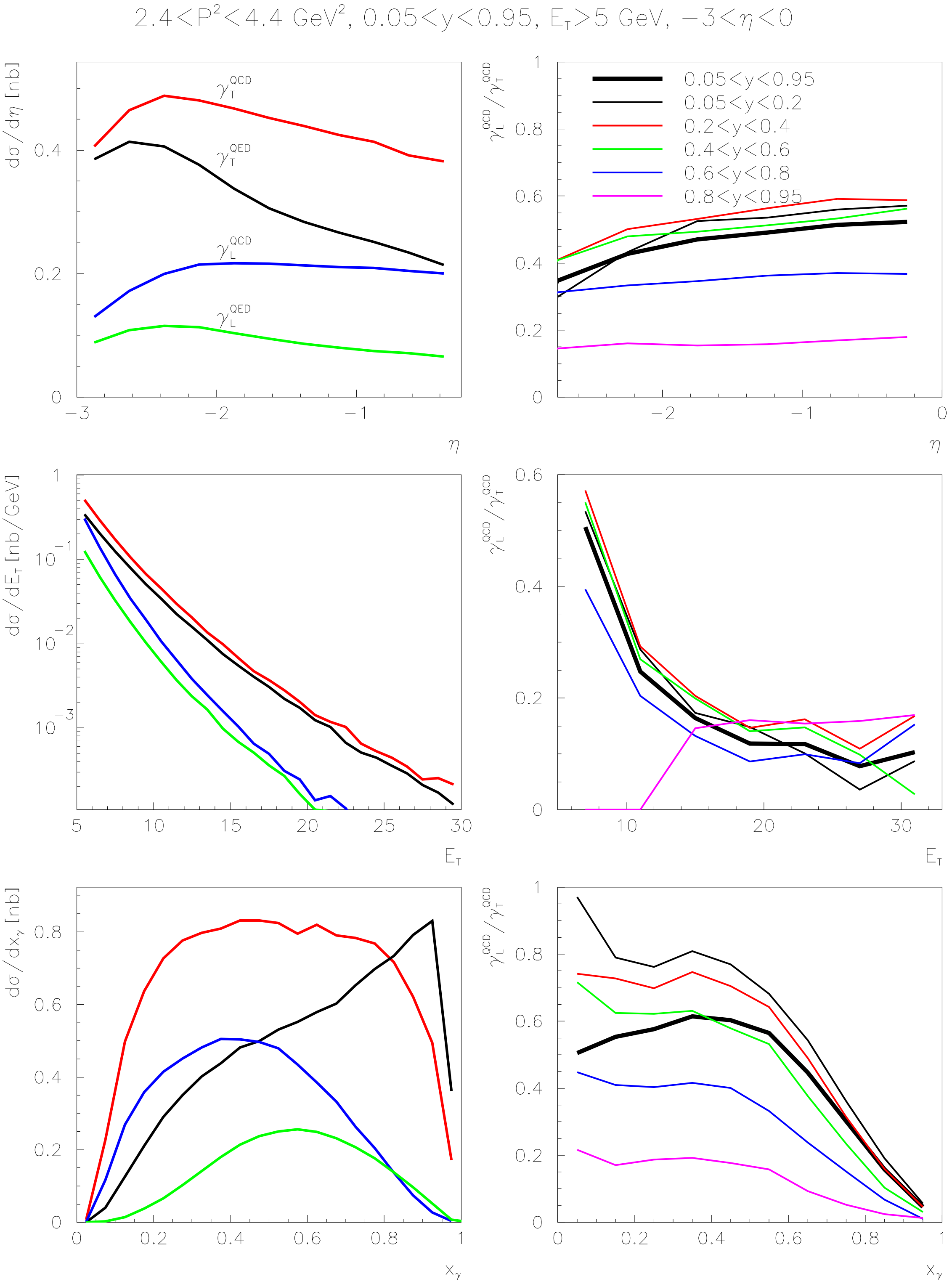



1.4<P²<2.4 GeV², 0.05<y<0.95, E_T>5 GeV, −5<η<5
M_dijet
M_dijet
W²
W²
y_bj
y_bj
γ_L^QCD / γ_T^QCD
γ_L^QCD / γ_T^QCD
γ_L^QCD / γ_T^QCD



1.4<P²<2.4 GeV², 0.05<y<0.95, E_T>5 GeV, −3<η<0
dσ/dη [nb]
γ_T^QCD
γ_T^QED
γ_L^QCD
γ_L^QED
η
γ_L^QCD/γ_T^QCD
0.05<y<0.95
0.05<y<0.2
0.2<y<0.4
0.4<y<0.6
0.6<y<0.8
0.8<y<0.95
dσ/dE_T [nb/GeV]
E_T
dσ/dx_γ [nb]
x_γ


2.4<P²<4.4 GeV², 0.05<y<0.95, E_T>5 GeV, −5<η<5
dσ/dη [nb]
γ_T^QCD
γ_T^QED
γ_L^QCD
γ_L^QED
η
γ_L^QCD/γ_T^QCD
0.05<y<0.95
0.05<y<0.2
0.2<y<0.4
0.4<y<0.6
0.6<y<0.8
0.8<y<0.95
dσ/dE_T [nb/GeV]
E_T
dσ/dx_γ [nb]
x_γ


2.4<P²<4.4 GeV², 0.05<y<0.95, E_T>5 GeV, −3<η<0
dσ/dη [nb]
η
dσ/dE_T [nb/GeV]
E_T
dσ/dx_γ [nb]
x_γ
γ_L^QCD/γ_T^QCD
0.05<y<0.95
0.05<y<0.2
0.2<y<0.4
0.4<y<0.6
0.6<y<0.8
0.8<y<0.95

Message from the comparisons

In the kinematical region

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

accessible at HERA and conventionally considered as part of **DIS** region the contributions of γ_L^* are **substantial**, particularly

- at **small** y,
- close to E_T **threshold**,
- for **small** x_γ,
- i.e. **large** η

The cuts enforced by H1 and ZEUS acceptances reduce the sensitivity to contributions of γ_L^*, but in parts of accessible kinematical range they are typically $\gtrsim 50\%$ and can be identified by their

characteristic y and P^2 dependence.

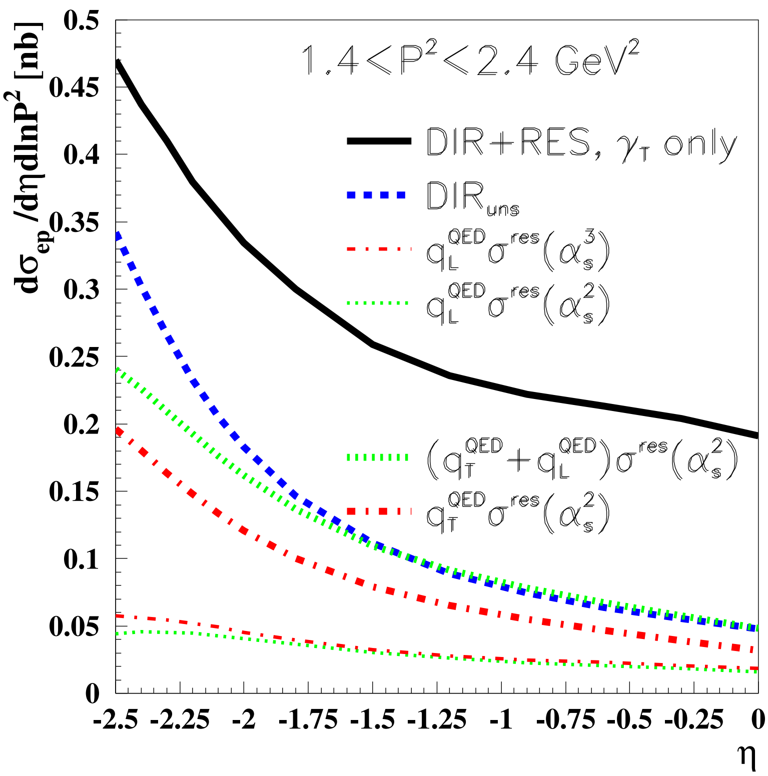
Resolved γ_L^* in JETVIP calculations of dijet production at HERA

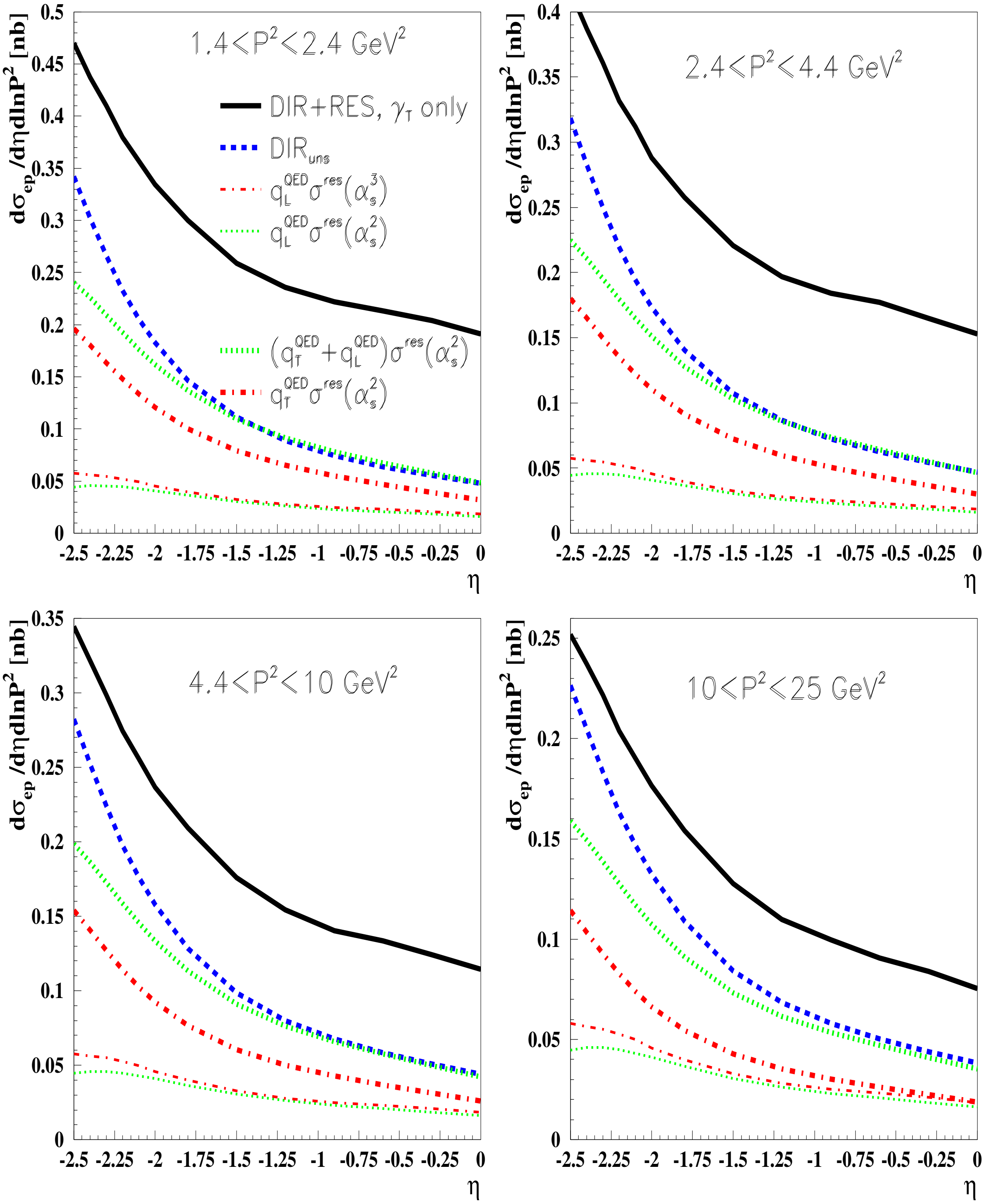
Standard formulation: γ_L^* included **exactly in direct unsubtracted calculations** (LO as well as NLO) but **not in the resolved photon** contributions.
Schematically:

$$\sigma(\mathrm{TOT}) = \sigma(\mathrm{DIR_{uns}}) - \sigma_T(\mathrm{PSP}) + \sigma_T(\mathrm{RES}) - \sigma_L(\mathrm{PSP}) + \sigma_L(\mathrm{RES})$$

Calculations performed for **asymmetric E_T cuts:**

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



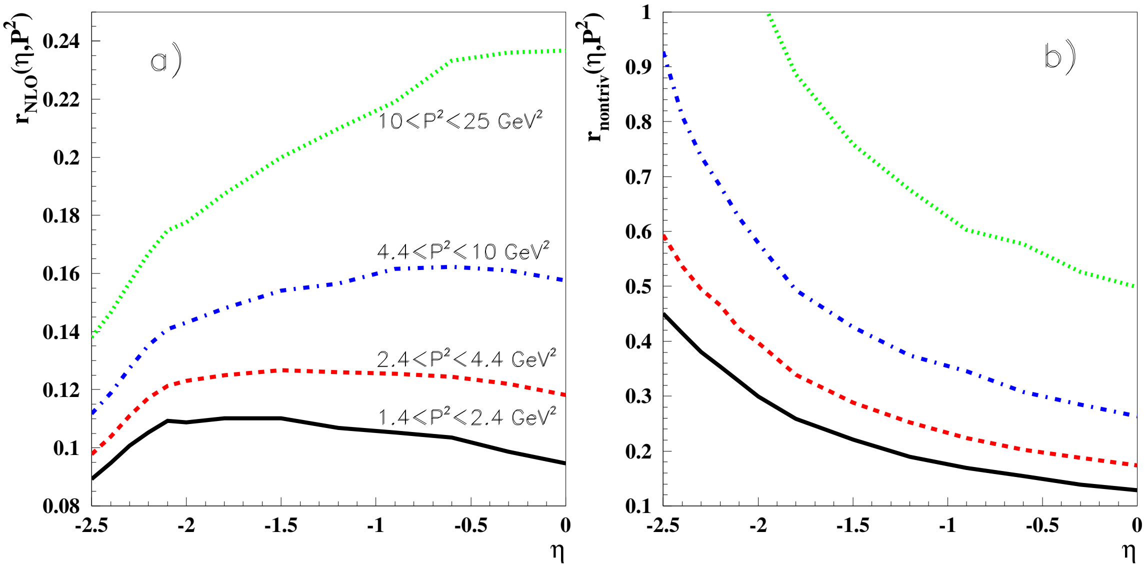

1.4<P²<2.4 GeV²
DIR+RES, γT only
DIRuns
qL QED σres(αs3)
qL QED σres(αs2)
(qT QED+qL QED)σres(αs2)
qT QED σres(αs2)
2.4<P²<4.4 GeV²
4.4<P²<10 GeV²
10<P²<25 GeV²
dσep/dηdlnP² [nb]
η

Nontrivial effect of introducing the concept of PDF of γ_L^* into JETVIP measured by the ratia

$$r_q^{\rm NLO} \equiv \frac{(q_L^{\rm QCD} - q_L^{\rm QED}) \otimes \sigma_q^{\rm res}(\alpha_s^2) + q_L^{\rm QCD} \otimes \sigma_q^{\rm res}(\alpha_s^3)}{\sigma^{\rm DIR+RES}(\gamma_T)}$$

$$r_G^{\rm NLO} \equiv \frac{G_L^{\rm QCD} \otimes \left(\sigma_G^{\rm res}(\alpha_s^2) + \sigma_G^{\rm res}(\alpha_s^3)\right)}{\sigma^{\rm DIR+RES}(\gamma_T)}.$$

Effects of $q_L^{\rm QED}$:



We wanted to present first NLO JETVIP results with $q_L^{\rm QCD}$ and $G_L^{\rm QCD}$ but failed because of other duties. Hope to have them for the Proceedings.

Future

Experiment: ongoing analysis of **H1** dijet data (31 pb^{-1}, $1.4 \leq P^2 \leq 50$ GeV^2, $0.1 \leq y \leq 0.9$)

$E_T^{\rm min}$	N$_{tot}$	1.4–2.4	2.4–4.4	4.4–10	10–25
5 GeV	123000	18400	25500	31800	30700
6 GeV	80000	12300	16500	20400	20000
7 GeV	53000	7600	11200	13000	13000
10 GeV	17500	2400	3200	4300	4300

offers a chance to

- perform the comparison with QCD calculations in the kinematical region $P^2 \ll Q^2$ in greater detail
- identify the contributions of γ_L^* by measuring $D_{\rm eff}^{\gamma_L}(x, P^2, Q^2)$

For the second task one has to separate γ_L^* by measuring the dependence of dijet cross sections on

- y: $\sigma_L \propto (1-y) \Rightarrow$ broad range in y necessary
- P^2: $\sigma_L \propto P^2 \Rightarrow$ **VLQ** ($P^2 \simeq 0.1 - 0.2$) vital!
- E_T: **hadronic** scaling violations of $q_L(x, P^2, M^2)$

Theory: detailed studies using **JETVIP** with QCD improved PDF of γ_L^*

Conclusions

1. The concept of **resolved** γ_L^* is phenomenologically **very useful**.
2. Contributions of resolved γ_L^* **must be included** whenever virtuality dependence of PDF γ_T^* is taken into account.
3. Numerically these contributions are **quite large** in parts of phase space accessible at HERA.
4. QCD improved PDF of γ_L^* are **available** but more theoretical work needed, in particular concerning the question of their threshold behavior.
5. There is a good chance to **extract** PDF of γ_L^* from recent HERA data.