Measurement of the γp Cross Section with a Leading Proton at HERA

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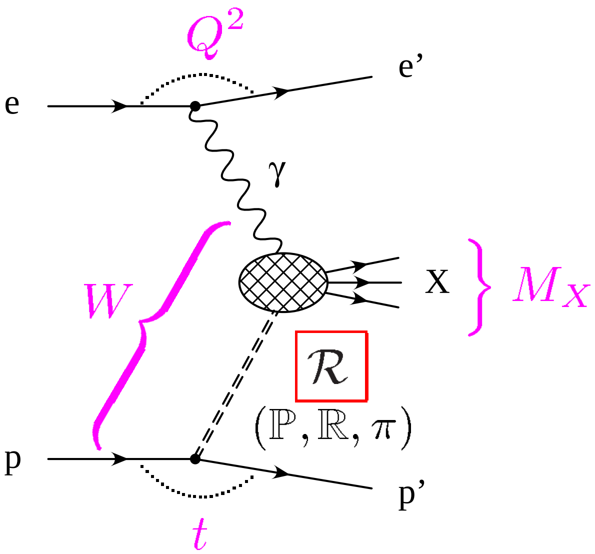
- Photoproduction with a Leading Proton
  - Measurement of $\mathrm{d}\sigma_{\gamma p \to p' X}(W)/\mathrm{d}z$
  - Fraction of Leading Proton Events r_{LP}
- Transition from DIS to Photoproduction in Leading Proton Reactions
- Summary

The process $\gamma p \to X p'$



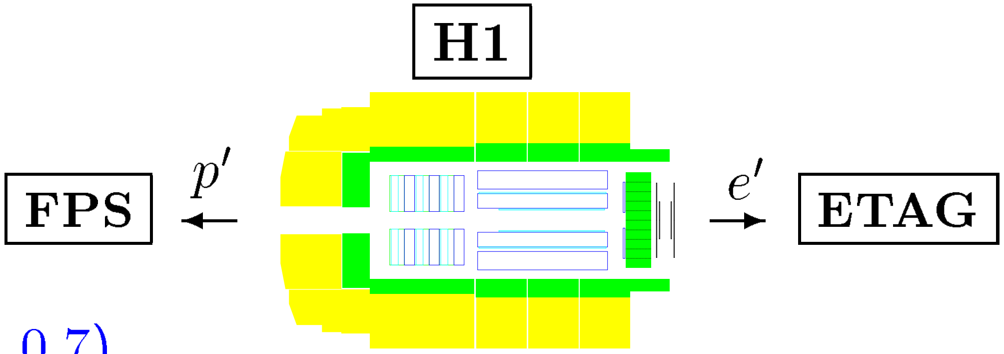
CM energy	$s = (p_e + p_p)^2$
4momentum transfer	$Q^2 = -(p_e - p'_e)^2$
inelasticity	$y = 1 - E'_e/E_e$
invariant mass of γp system	$W = \sqrt{ys}$
4momentum transfer	$t = (p_p - p'_p)^2$
energy fraction kept by p'	$\boxed{z} = E'_p/E_p = 1\text{-}x_{\mathbb{P}}$
invariant mass of $\gamma\mathcal{R}$ system	$M_X = \sqrt{(1-z)ys}$

Photoproduction ($Q^2 \approx 0\,\mathrm{GeV}^2$):

$$\underbrace{\frac{\mathrm{d}^2\sigma_{ep\to e'p'X}(W)}{\mathrm{d}y\,\mathrm{d}z}}_{\text{measurement}} = \underbrace{\mathcal{F}_{\gamma/e}(y)}_{\gamma\text{ flux factor}} \frac{\mathrm{d}\sigma_{\gamma p\to p'X}(W)}{\mathrm{d}z}$$

electron as a source of collinear photons, parametrization: flux factor (WWA)

Event Selection



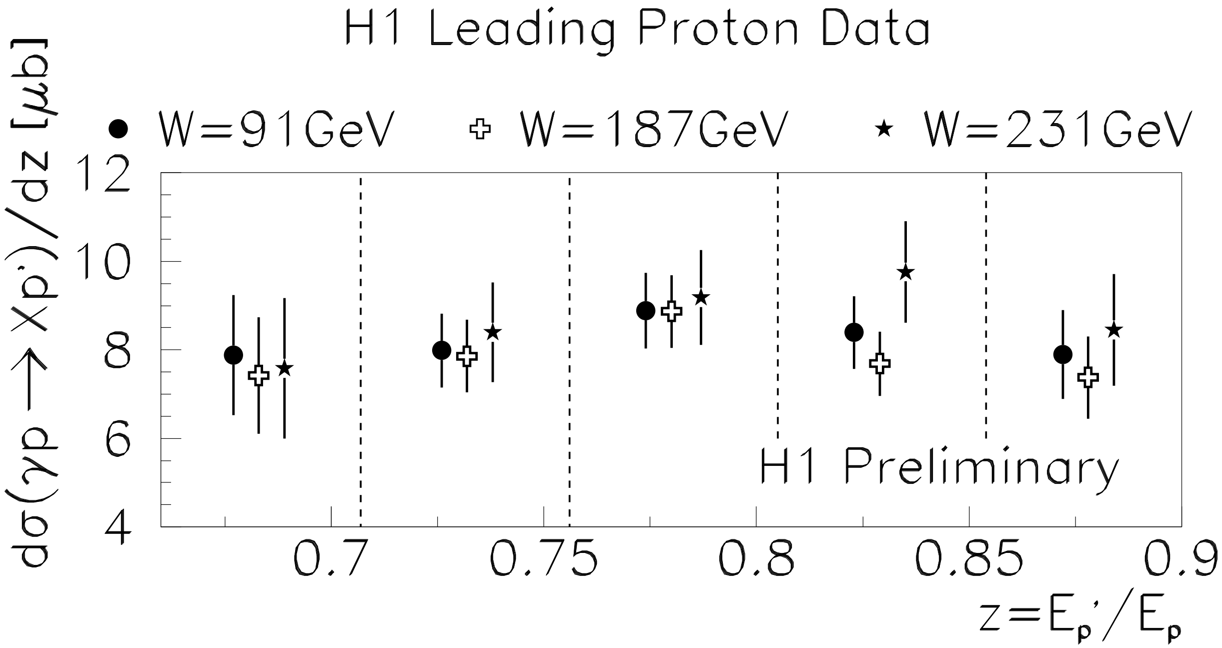
Identification of quasi real photon:
- Electron candidate in small angle electron detector ETAG($y \approx 0.03 \ldots 0.7$)

Identification of scattered proton:
- track in Forward Proton Spectrometer($E'_p \approx 500 - 750\,\mathrm{GeV}$)

Identification of hadronic final state X:
- ≥ 1 track of $p_t > 500\,\mathrm{MeV}$ in central detector

Kinematic range: $s = 300\,\mathrm{GeV}$,
$W = 60 \ldots 250\,\mathrm{GeV}$, $Q^2 < 0.01\,\mathrm{GeV}^2$, $z = 0.7 \ldots 0.9$, $p_t < 200\,\mathrm{MeV}$
Size of data sample: $\sim$ 23000 events 1996, e^+p
Integrated luminosity: $\int \mathcal{L}\,\mathrm{d}t = 3.3\,\mathrm{pb}^{-1}$ after all corrections

The differential cross section $\mathrm{d}\sigma_{\gamma p \to Xp'}(W)/\mathrm{d}z$



- independent of z
- independent of γp CM energy
- $\approx 7.7\,\mu$b per unit z

$\mathrm{d}\sigma/\mathrm{d}z[\,\mathbf{mb}]$ in pp scattering

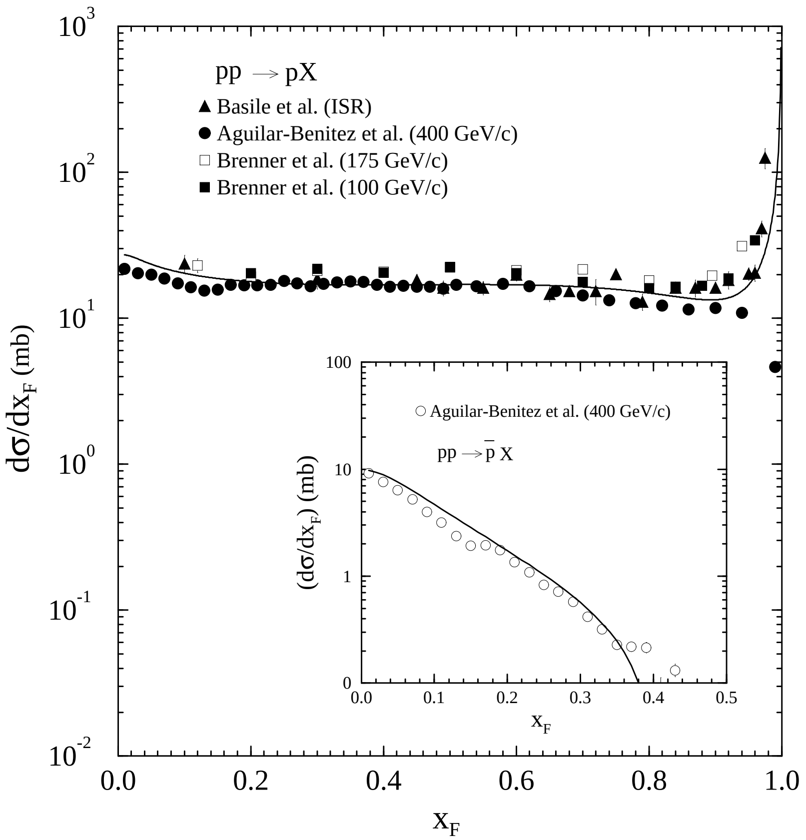


Figure 1: Inclusive spectrum for the reactions $pp \to pX$ and $pp \to \bar{p}X$ (in the insert). Data from [1, 21, 22]. The solid curves are the results of the fit described in the text calculated for 400 GeV/c.

hep-ph/9811425

Fraction of leading proton events

Enlarge the kinematic range in order to compare with ZEUS:

- p_T limit: $|p_T| < 200\,\text{MeV} \Rightarrow |p_T| < 707\,\text{MeV}$
  extrapolate using $b = 6.8\,\text{GeV}^{-2}$ (ZEUS at ICHEP98, Vancouver)

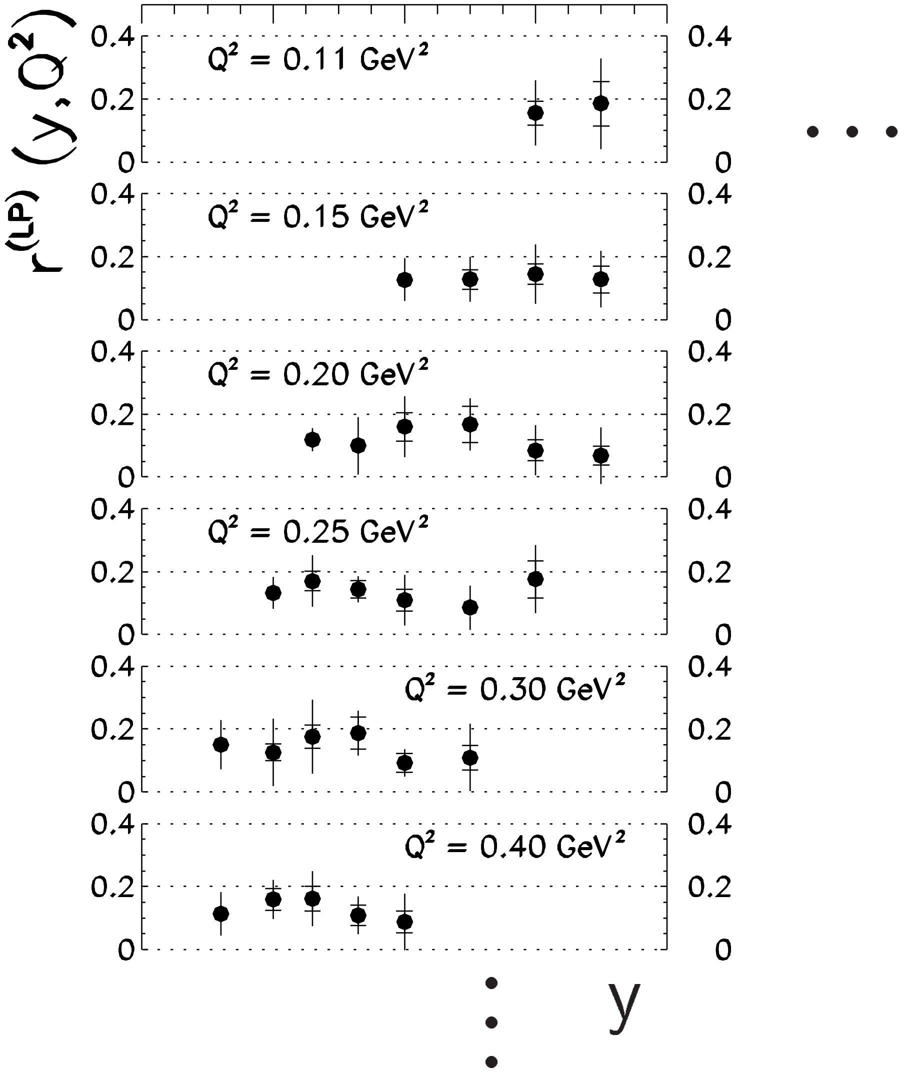
- different z range: $0.66 \ldots 0.90 \Rightarrow 0.60 \ldots 0.97$
  cross section independent of z in this range

Using $\sigma^{tot}_{\gamma p \to X}(W = 200\,\text{GeV}) = 165 \pm 2.3 \pm 10.9 \pm 1.3\,\mu\text{b}$
(H1 Collab., T. Ahmed et al, Z. Phys. C 69 (1995) 27-38):

$$\boxed{\frac{\sigma_{\gamma p \to p' X}}{\sigma_{\gamma p \to X}}(\text{extrapolated}) = (7.0 \pm 1.4)\%}$$

▶ Comparison with ZEUS...

ZEUS PRELIMINARY 1995



r_{LP}:
fraction of events with a leading proton out of all events for $Q^2 = 0.11 \ldots 100\,\text{GeV}^2$
(ZEUS at ICHEP99, Tampere)

independent of

- Q^2, x, y

compatible with $(7 \pm 1)\%$

$\gamma^{(*)}p \to X$ at different virtualities Q^2

Deep inelastic scattering:
dominantly direct γ

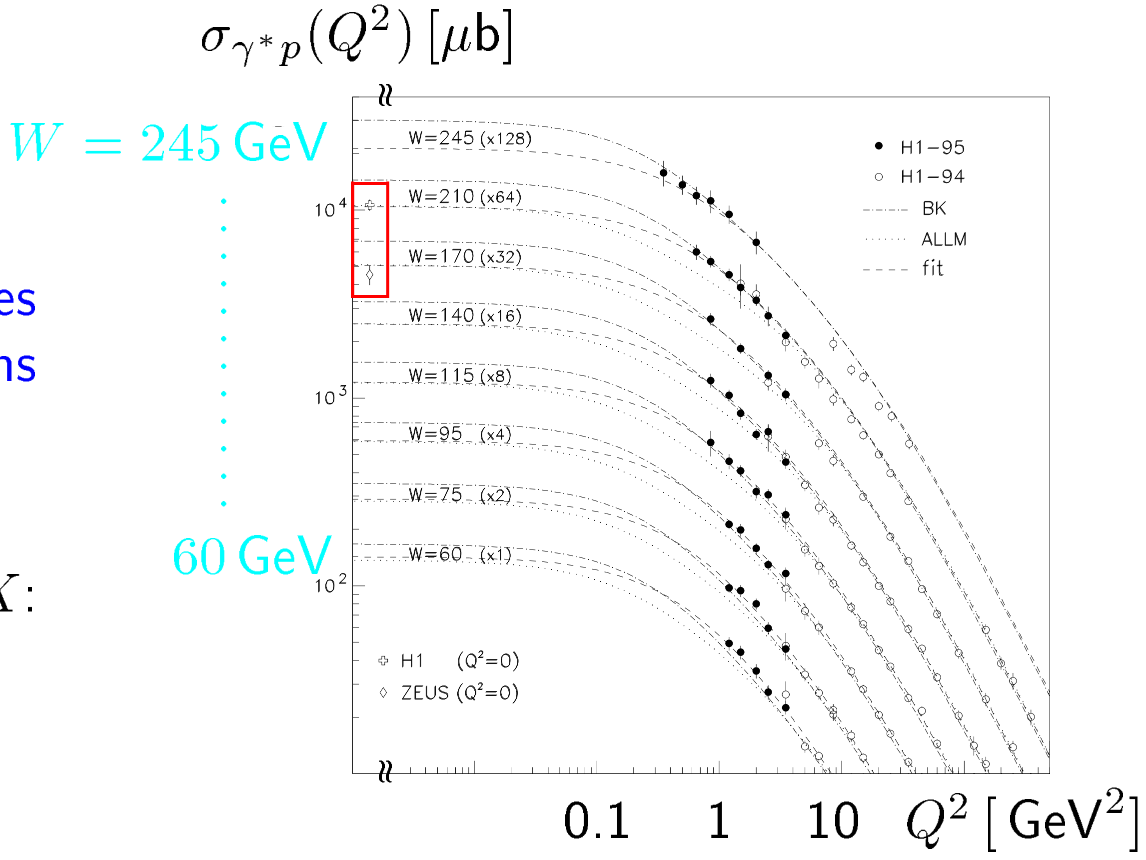
Photoproduction:
dominantly hadronic γ coupling

Study transition between both regimes by measuring γp and DIS reactions with medium and small Q^2

For small $x = Q^2/(sy)$ in $\gamma^{(*)}p \to X$:

$$\sigma^{tot}_{\gamma^* p}(W) = \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2)$$

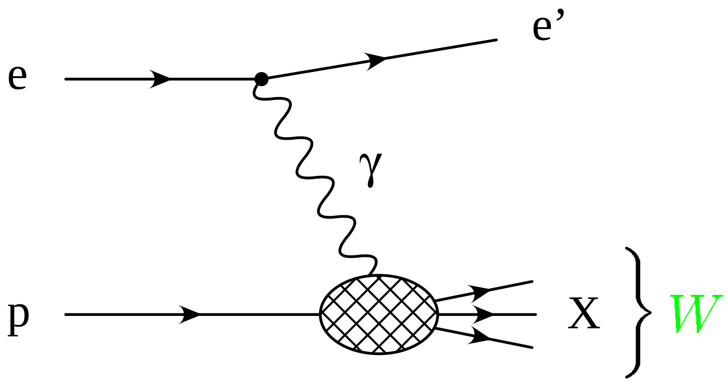
$$W^2 = Q^2(1-x)/x$$



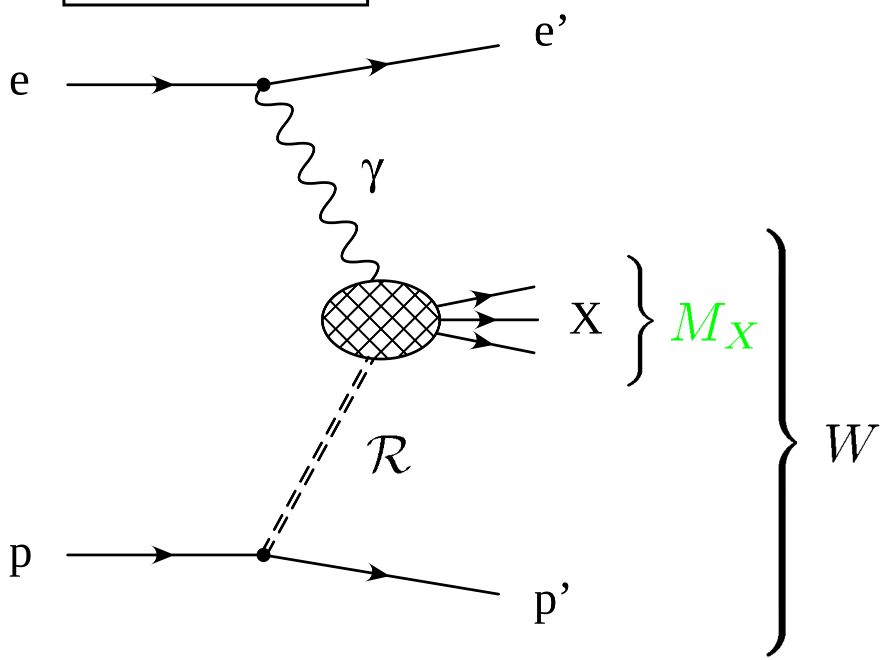
H1 Collab., C. Adloff et al.,
Nucl. Phys. B 497 (1997) 3-30

Comparison inclusive / semi-inclusive Reaction

$\boxed{\gamma p \to X :}$



$\boxed{\gamma p \to X p' :}$



Photon reacts with

$$p \leftrightarrow \mathcal{R}$$

invariant mass of hadronic final state:

$$W \leftrightarrow M_X$$

relevant momentum fraction

$$x \leftrightarrow \beta = x/(1-z)$$

additional degree of freedom:

$$z = \frac{E'_p}{E_p}!$$

$\sigma_{\gamma^{(*)}p}$ in $\boxed{\gamma^{(*)}p \to Xp}$

Data on DIS with a leading proton:

H1 Collab., C. Adloff et al., Eur. Phys. C 6 (1999) 587-602

$$\frac{d^3\sigma_{ep\to e'p'X}}{dx\,dQ^2\,dz} = \frac{2\pi\alpha^2}{Q^4 x}\left(2 - 2y + y^2\right) F_2^{\mathrm{LP}(3)}(x, Q^2, z)$$

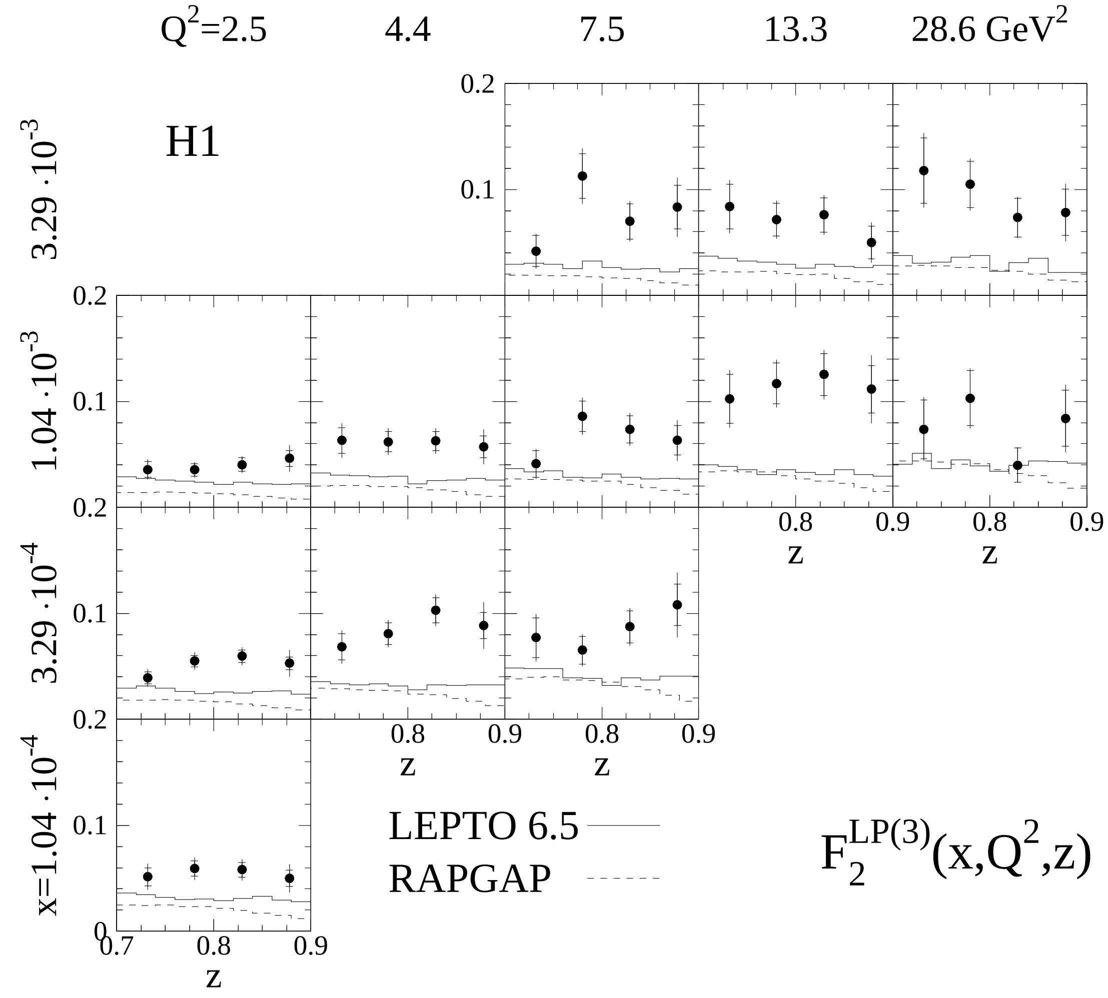
$2\,\mathrm{GeV}^2 \leq Q^2 \leq 50\,\mathrm{GeV}^2$, $6 \cdot 10^{-5} \leq x \leq 6 \cdot 10^{-3}$, $|p_T^{\mathrm{Proton}}| < 200\,\mathrm{MeV}$, $0.71 \leq z \leq 0.90$

Investigate separately for each interval in z:

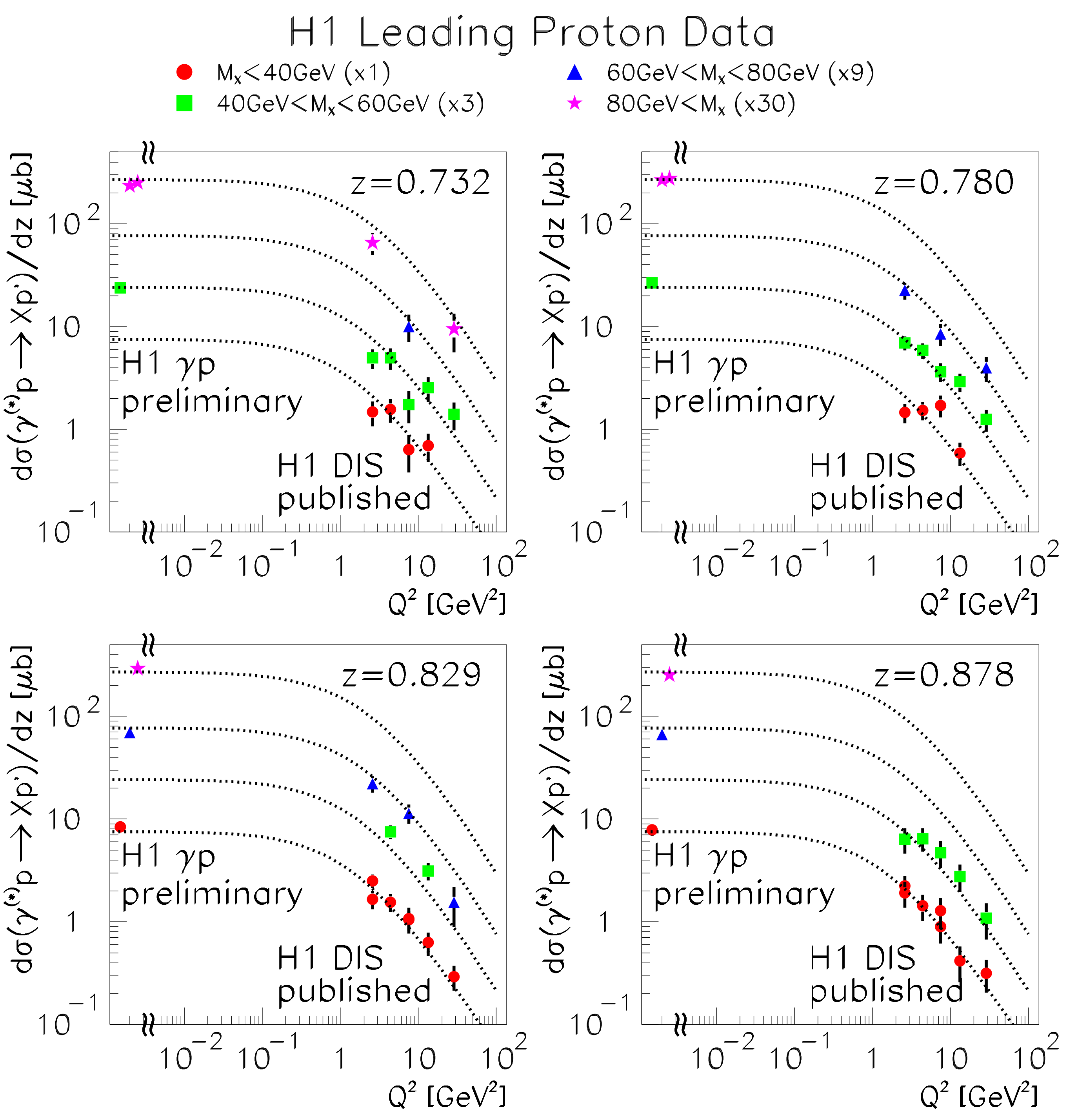
$$\boxed{\frac{d\sigma_{\gamma^{(*)}p\to p'X}(M_X)}{dz} = \frac{4\pi^2\alpha}{Q^2} F_2^{\mathrm{LP}(3)}(\beta, Q^2, z)}$$

- choice of W fixes M_X in each interval
- use β instead of x

DIS data with a leading proton: $F_2^{\mathbf{LP(3)}}$



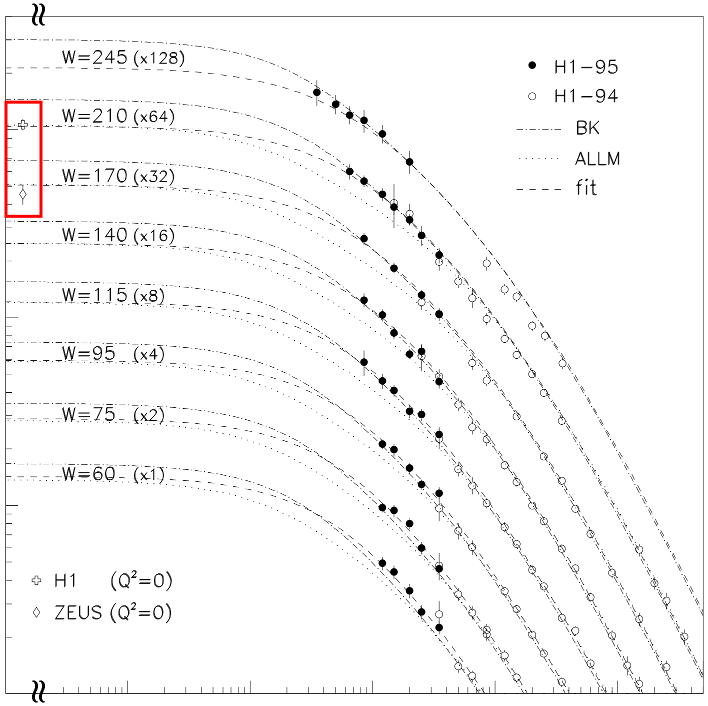
independent of z
in all (x, Q^2) bins


H1 Leading Proton Data
M_x<40GeV (x1)
40GeV<M_x<60GeV (x3)
60GeV<M_x<80GeV (x9)
80GeV<M_x (x30)
z=0.732
z=0.780
z=0.829
z=0.878
H1 γp preliminary
H1 DIS published
$d\sigma(\gamma^{(*)}p \rightarrow Xp')/dz$ [μb]
Q^2 [GeV^2]

Once more back to the inclusive case. . .

$\sigma_{\gamma^* p}(Q^2)$ [μb]

W = 245 GeV



60 GeV

0.1 1 10 Q^2 [GeV^2]

H1 Collab., C. Adloff et al., Nucl. Phys. B 497 (1997) 3-30

BK:

"Electroproduction structure function F_2 in the low x, low Q^2 region",
B. Badełek, J. Kwieciński,
Phys. Lett. B 295 (1992) 263-268

fit:

(slight) modification of BK model by H1

Model by Badełek and Kwieciński for $\gamma^{(*)}p \to X$

$$F_2^{\mathrm{BK}}(x,Q^2) = C_{\mathrm{VM}} F_2^{\mathrm{VDM}}(x,Q^2) + \frac{Q^2}{Q^2+Q^2_{\mathrm{VM}}} F_2^{\mathrm{part}}(\bar{x}, Q^2+Q^2_{\mathrm{VM}})$$

$$F_2^{\mathrm{VDM}}(x,Q^2) = \frac{Q^2}{4\pi}\sum_V \frac{M_V^4 \boxed{\sigma_{Vp}(W)}}{\gamma_V^2 (Q^2+M_V^2)^2}$$

$$F_2^{\mathrm{part}}(x,Q^2) = F_2^{\mathrm{H1QCD}}(x,Q^2) \text{ from measurement}$$

C_{VM}	relative normalization of VM term; introduced by H1 to reproduce HERA γp data $(C_{\mathrm{VM}} = 0.77)$
Q^2_{VM}	meson mass cut-off $(Q^2_{\mathrm{VM}} = 0.45\ \mathrm{GeV}^2)$
$\sum_V$	runs over the low mass vector mesons

Advantage : successful model with few parameters

Adaption of BK model to $\gamma p \to p' X$

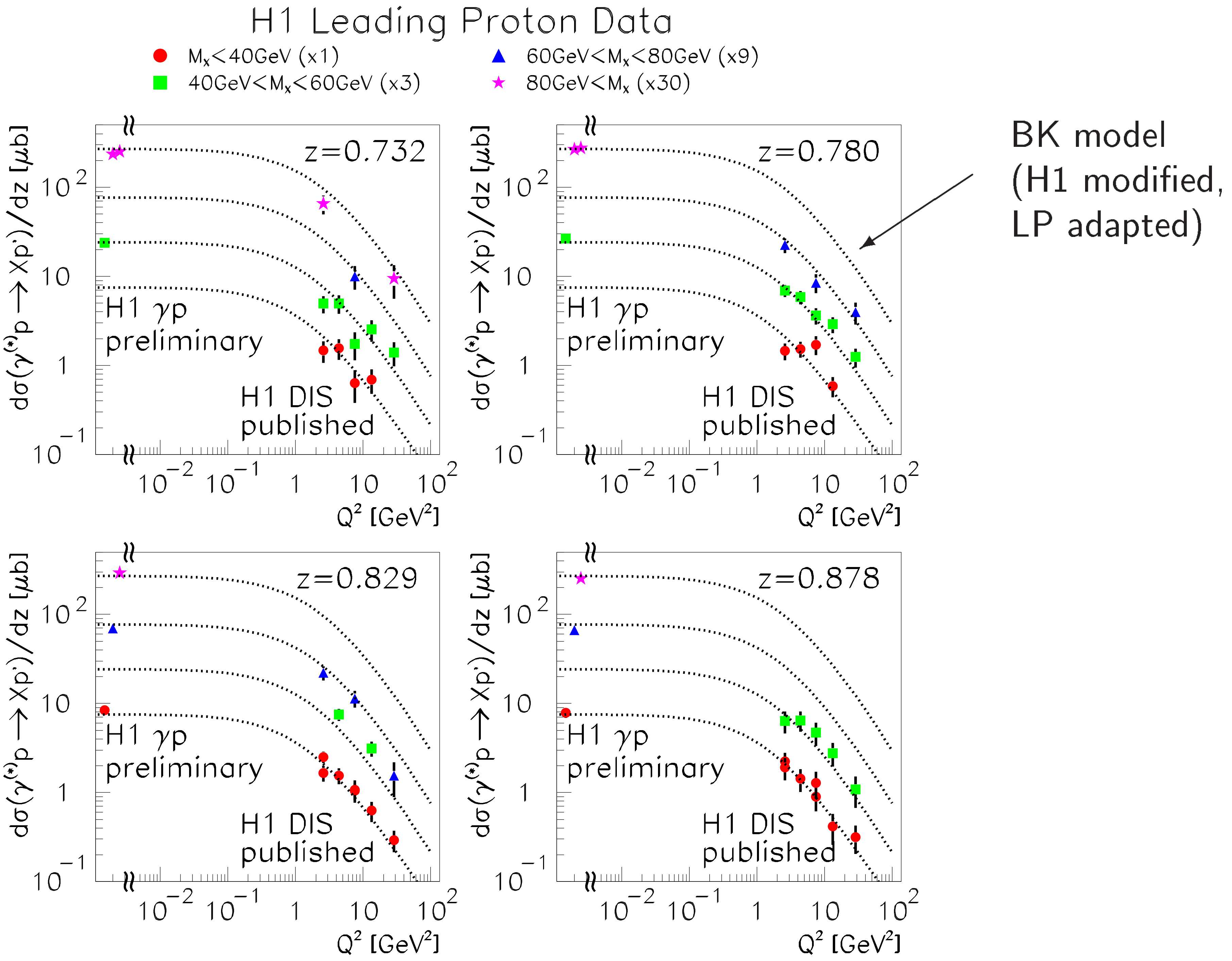
Why? Photon scattering on hadronic, quark dominated object $\mathcal{R}$!

$$F_{2LP}^{\mathrm{BK}} = F \left(C_{\mathrm{VM}} \frac{Q^2}{4\pi} \sum_V \frac{M_V^4}{\gamma_V^2} \frac{C_{\mathrm{VM}}^{\mathrm{LP}} \sigma_{Vp}(M_X)}{(Q^2 + M_V^2)^2} + \frac{Q^2}{Q^2 + Q_{\mathrm{VM}}^2} F_2^{\mathrm{part}} \right)$$

Set of variables for $\gamma\mathcal{R}$ scattering: (β, M_X) instead of (x, W)
Two new parameters: Common normalization F,
relative normalization $C_{\mathrm{VM}}^{\mathrm{LP}}$ (keep $C_{\mathrm{VM}} = 0.77, Q_{\mathrm{VM}}^2 = 0.45$ GeV^2)

- Determine common scale factor F with DIS data alone

- Using $F = 0.12 \pm 0.02$, fit relative normalization $C_{\mathrm{VM}}^{\mathrm{LP}}$.
  Result: $C_{\mathrm{VM}}^{\mathrm{LP}} = 0.23 \pm 0.10$ (cf. $\frac{\mathrm{d}\sigma(\pi p \to \pi X)/\mathrm{d}z}{\mathrm{d}\sigma(pp \to pX)/\mathrm{d}z} = 0.4 \pm 0.04 < \frac{2}{3}$)



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dσ(γ(*)p → Xp')/dz [μb]
Q² [GeV²]
BK model
(H1 modified,
LP adapted)

Summary

- Photoproduction data with a leading proton analyzed with $0.66 < z < 0.90$, $p_T < 200\,\text{MeV}$ for $W = 91, 187$, and $231\,\text{GeV}$:
  - Cross section $\mathrm{d}\sigma_{\gamma p \to p' X}(W)/\mathrm{d}z \approx 7.7\,\mu\text{b}$ independent of z or W. After extrapoloation, it is compatible with the ratio r_{LP} measured by ZEUS.

- Combine leading proton γp with DIS data: DIS data for $z = 0.71 \ldots 0.90$ used together with the photoproduction data separately for each bin in z:
  - The Q^2 dependence of $\sigma_{\gamma^{(*)}p}$ in $\gamma^{(*)}p \to p'X$ is observed to be similar as in $\gamma^{(*)}p \to X$.
  - A model describing the transition from DIS to the photoproduction regime by means of a partonic component, dominant at higher Q^2, plus a VDM component, dominant for low Q^2, $F_2 = F_2^{\text{VDM}} + F_2^{\text{part}}$, was adapted to the situation with a leading proton and fitted to the LP data.

  The relative contribution of the VDM part was found to be only 23% of the value obtained in inclusive reactions.