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Measurement of the Proton structure function F_2 and the Total $\gamma^* p$ cross-section at low Q^2 and low x

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For the
ZEUS-collaboration

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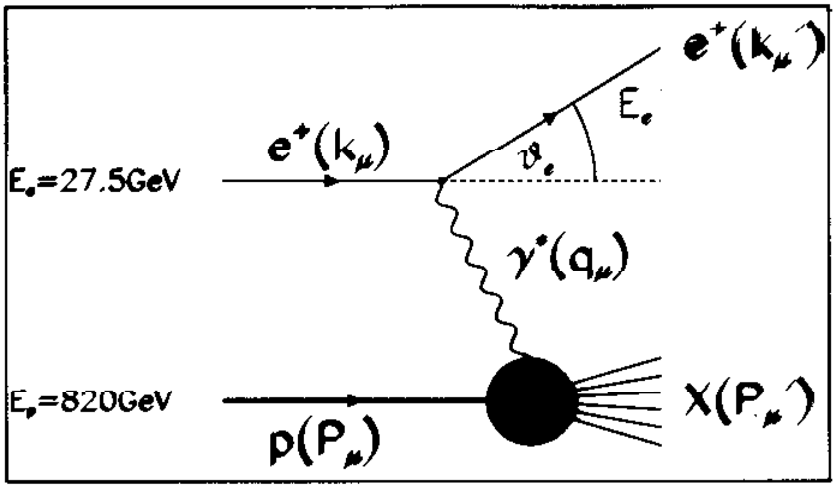
- $\sigma_{tot}(\gamma^* p)$-measurement

6 Summary

1 Introduction

- HERA Kinematics



$$Q^2 = -q^2 = -(k-k')^2 = 4E_eE_e' \cdot sin^2\frac{\vartheta_e}{2}$$ 4-momentum transfer

$$x = \frac{Q^2}{2P\cdot q}$$ fractional momentum carried by the struck quark $0 < x < 1$

$$y = \frac{P\cdot q}{P\cdot k}$$ fractional energy transfer $0 < y < 1$

$$W^2 = (q+P)^2 \simeq \frac{Q^2\cdot(1-x)}{x}$$ center of mass energy of the $\gamma^* p$-system

$$s = (k+P)^2 \simeq 4E_eE_p$$ $\sqrt{s}$ = center of mass energy $\simeq 300 GeV$

$$Q^2 = x \cdot y \cdot s$$

- The NC differential e^+p cross section

$$\frac{d^2\sigma(e^+p\rightarrow e^+X)}{dy\,dQ^2} =$$

can be expressed:

A) in terms of the Proton structure functions F_2 and F_L:

$$= \frac{2\pi\alpha^2}{yQ^4}\left[(1+(1-y)^2)F_2(y,Q^2) - y^2F_L(y,Q^2)\right](1+\delta_r(y,Q^2))$$

B) in terms of the total cross section for virtual transverse (T) and longitudinal (L) photons:

$$= \Gamma\left[\sigma_T(y,Q^2) + \epsilon\,\sigma_L(y,Q^2)\right](1+\delta_r(y,Q^2))$$

whereas $\Gamma = \alpha(1+(1-y)^2)/(2\pi Q^2 y)$ and $\epsilon = 2(1-y)/(1+(1-y)^2)$.

- The total cross section $\sigma_{tot}^{\gamma^*p}$ for the scattering of virtual photons on protons is given by:

$$\sigma_{tot}^{\gamma^*p} \equiv \sigma_T(y,Q^2) + \sigma_L(y,Q^2)$$

- The expression for F_2 in terms of $\sigma_T(y,Q^2)$ and $\sigma_L(y,Q^2)$ is:

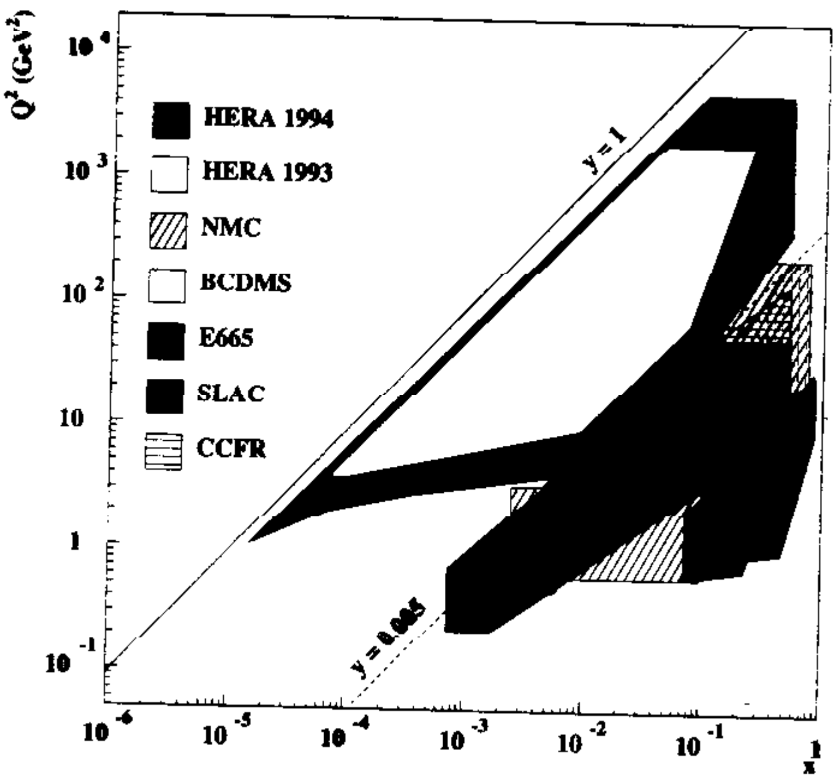
$$F_2(x,Q^2) = \frac{Q^2(1-x)}{4\pi^2\alpha}\,\frac{Q^2}{Q^2+4m_p^2x^2}\left[\sigma_T(y,Q^2) + \sigma_L(y,Q^2)\right]$$

$\Rightarrow$ **At small values of x one finds:**

$$\sigma_{tot}^{\gamma^*p} \approx \frac{4\pi^2\alpha}{Q^2}F_2(x,Q^2)$$

2 Physics Motivation

- Kinematic $Q^2 - x$-plane (until 1994)



⇒ **What we know experimentally:**

- $Q^2 \geq 1.5\, GeV^2$

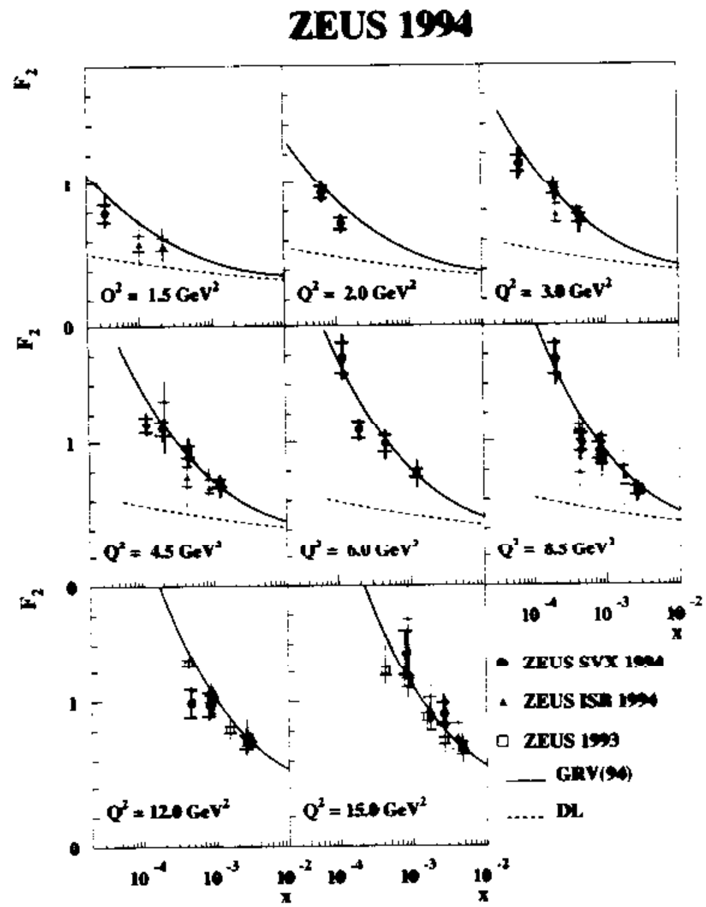
  ⇒ Well described by perturbative QCD (partonic behaviour)

- $Q^2 \simeq 0\, GeV^2$

  ⇒ Mostly soft hadron-physics-type behaviour (Regge-phenomenology

  ⇒ non-perturbative QCD)

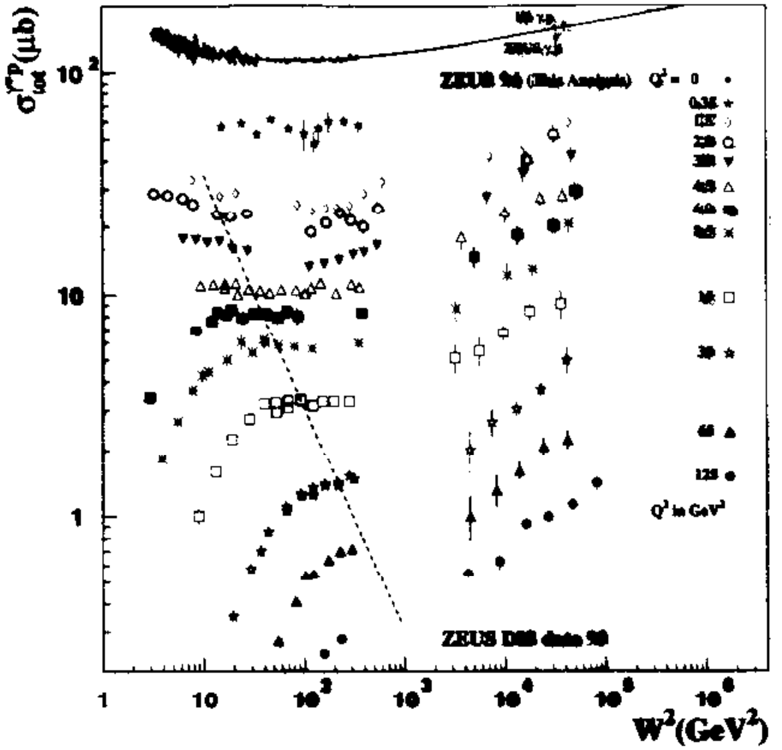
- Results and open questions from 1994 Data
  - $F_2(x, Q^2)$ versus x
  - $\sigma_{tot}^{\gamma^* p}$ versus W^2



$\Rightarrow$ Rapid rise of $F_2(x, Q^2)$ with decreasing x down to $Q^2 = 1.5\ GeV^2$

$\Rightarrow$ pQCD-model of GRV(94) describes data for $Q^2 \geq 1.5 GeV^2$

$\Rightarrow$ Non-perturbative QCD-model of DL (prediction in the framework of Regge theory for $\gamma^* p$-scattering) fails to describe data for $Q^2 \geq 1.5 GeV^2$



$\Rightarrow$ Modest rise **of** $\sigma_{tot}^{\gamma^* p} \sim W^{2\Delta}$ (high W^2) **with** W^2 for $Q^2 \simeq 0\, GeV^2$ **whereas** $\Delta = 0.0808$ (soft) **(well described by the Regge-model of DL)**

$\Rightarrow$ Rapid rise **of** $\sigma_{tot}^{\gamma^* p} \sim W^{2\Delta}$ (high W^2) **with** W^2 for $Q^2 \geq 1.5\, GeV^2$ whereas $\Delta > 0.2$ (hard) (equivalent to the rapid **rise of** F_2 **as** $x \to 0$)

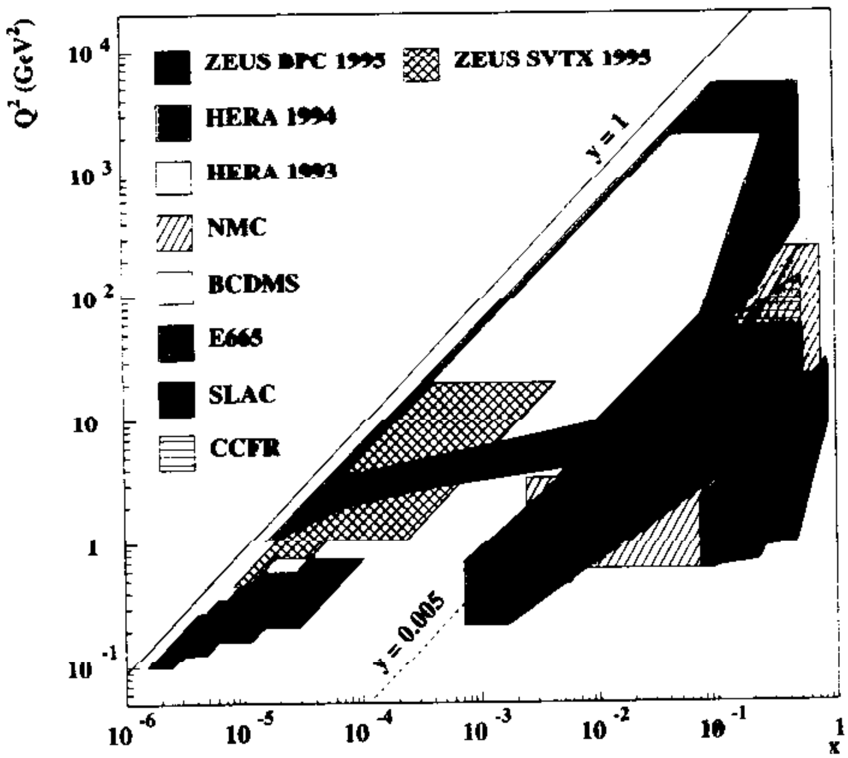
$\Rightarrow$ What about **the** transition region ?

- Where and how does **energy dependence** change from soft to **hard?**
- Where does pQCD break down **and** therefore non-perturbative **contributions** become **dominant?**
- Gap in Q^2: $0\, GeV^2 < Q^2 < 1.5 GeV^2 \Rightarrow$ (**ZEUS 1995**)

- Kinematic $Q^2 - x$-plane until 1995

⇒ Two major upgrades in 1995:

  - Installation of the BPC
  - Movement of two Rear-Calorimeter modules + SRTD towards the beam pipe



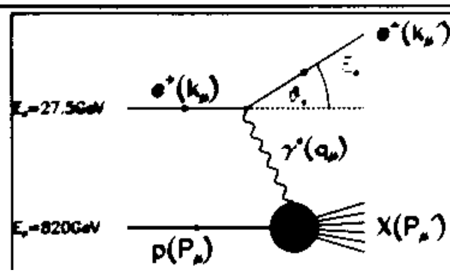
⇒ Enhanced Q^2-acceptance in 1995 towards very low values ($Q^2 \geq 0.1\ GeV^2$)

⇒ Measure transition region with 1995 Data!

3 ZEUS-detector

- Experimental approach to explore the low Q^2-region

$$Q^2 = 4E_eE'_e \cdot sin^2\frac{\vartheta_e}{2}$$



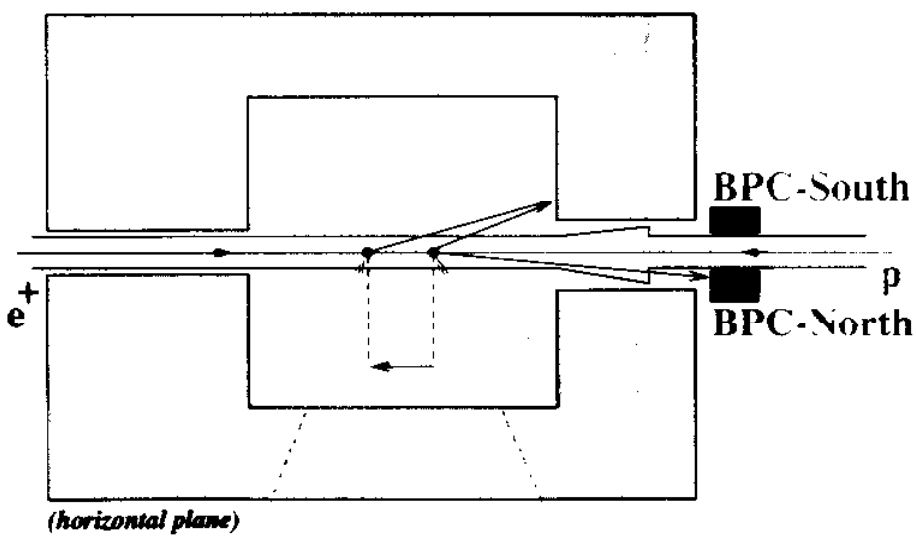
Method A: extend acceptance for small ϑ_e

⇒ **Tag scattered electrons in e^+p-collisions under very small angles with the** BPC ($17 - 35\,mrad$)

⇒ **Tag scattered electrons in e^+p-collisions with smaller angles compared to 94-run by moving** two RCAL-modules + SRTD **towards the re-configured beam pipe**

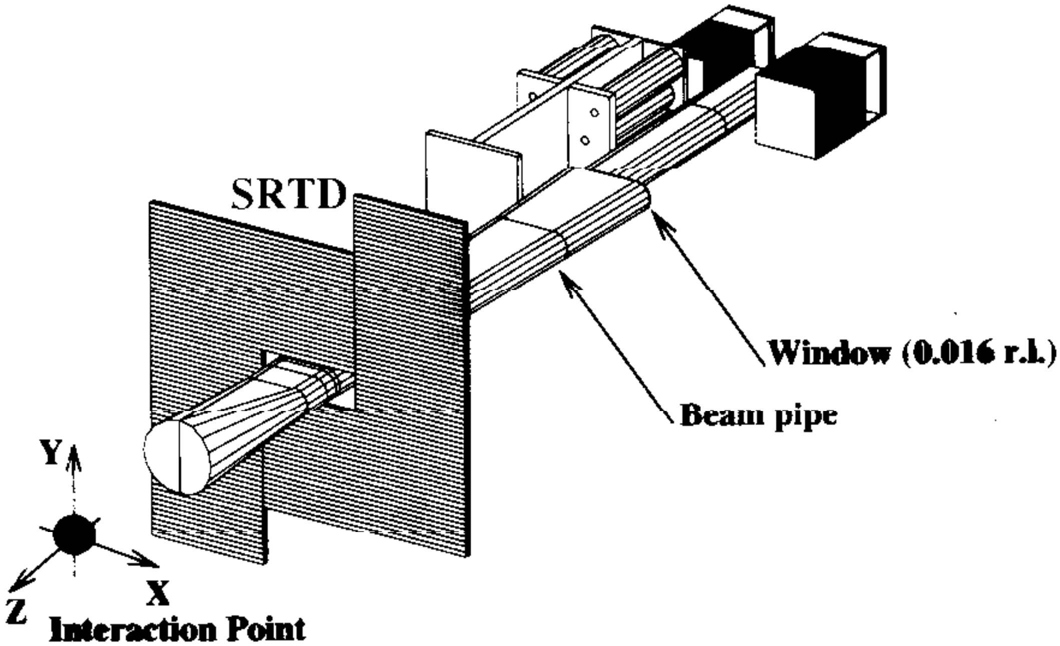
Method B: shift event vertex ($+70cm$)

⇒ **Achieve effectively smaller angles ϑ_e and therefore smaller Q^2-values**



shifted vertex **nominal vertex**

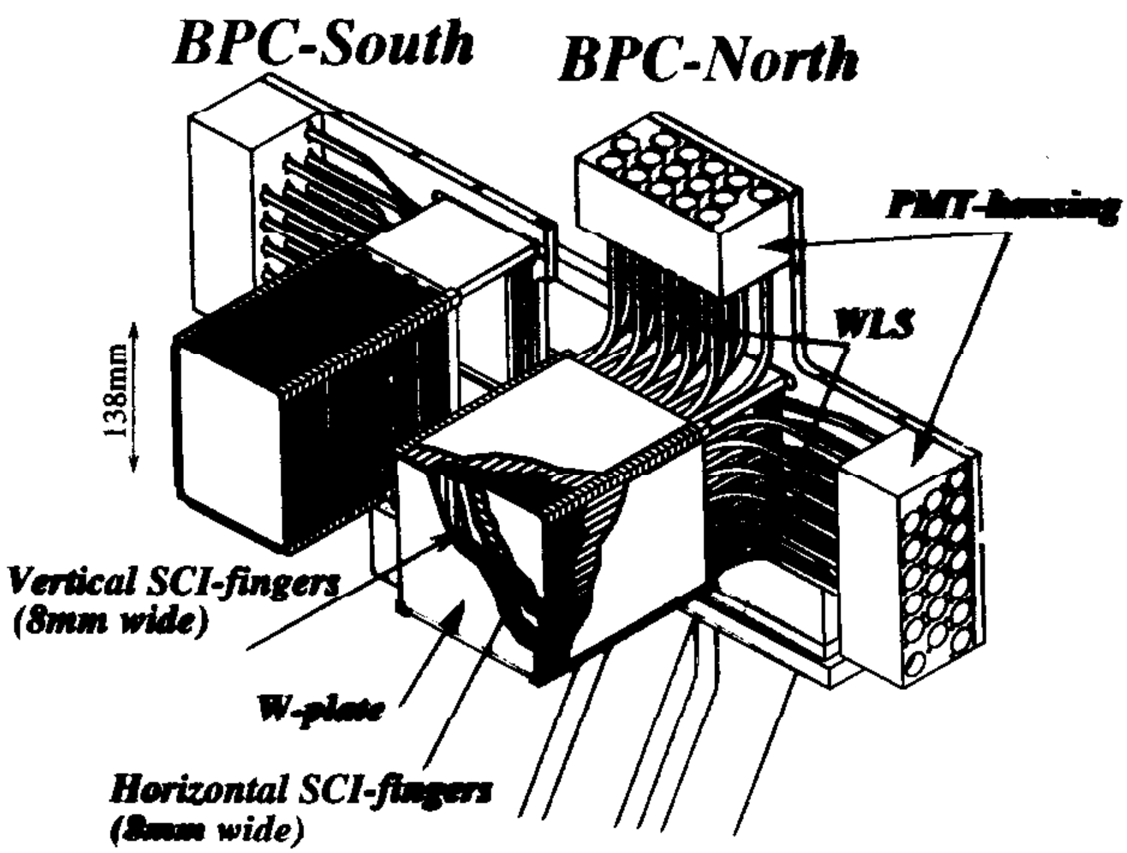
• The SRTD/RCAL at ZEUS



SRTD/RCAL

- The Small Rear Tracking Detector consists of two planes of $10mm$-wide scintillator strips arranged in orthogonal directions
- The SRTD allows a more precise determination of the scattered positron's impact positon (position resolution: [illegible]) and hence the scattering angle
- Alignment accuracy: [illegible] mm
- A presampler type energy correction can be applied to the measured electron energy
- Accuracy of energy scale: [illegible]
- SRTD/RCAL-arrangement together with shifted vertex runs allows to study e^+p-scattering down to $Q^2 =$ [illegible]

- The BPC at ZEUS
  - Tungsten-scintillator "EM-sampling" **calorimeter**
  - **Depth:** $\approx$ 24 X_0
  - **Alternating horizontal and vertical** oriented 8 mm-wide SCI-fingers
  - **Energy resolution:** 17 $\%/\sqrt{E}$
  - **Accuracy of energy calibration:** 0.5 %
  - Uniformity: 0.5 %
  - Position resolution: $<$ 1 mm
  - Alignment **accuracy**: 0.5 mm
  - Time resolution: $<$ 1 ns
  - Q^2**-range:** $0.11 GeV^2 \leq Q^2 \leq 0.65 GeV^2$



4 Details on the analysis

- Data sample

  ⇒ SVTX-F_2-analysis

  – luminosity: $235\,nb^{-1}$ 1995-run

  – shifted vertex: +70 cm

  ⇒ BPC-F_2-analysis

  – luminosity: $1.65\,pb^{-1}$ 1995-run

  – nominal vertex

- MC sample

  ⇒ Physics simulation

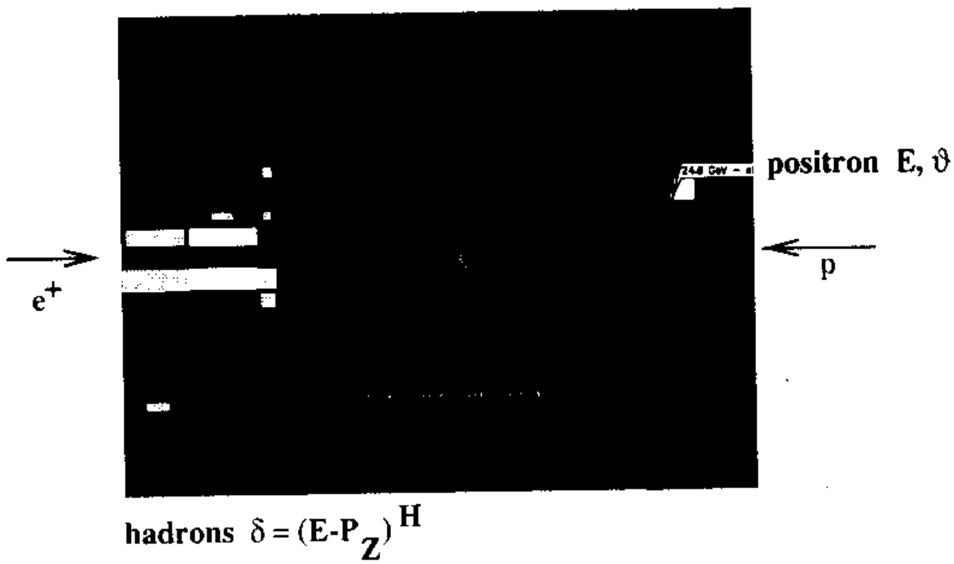
  – used to determine radiative corrections and the acceptance of the detector

  – Simulation of e^+p - collisions with the DJANGO-program which interfaces HERACLES, ARIADNE and LEPTO

  ⇒ Detector simulation

  – based on the GEANT-program

- Selection cuts (SVTX 1995 and BPC 1995)



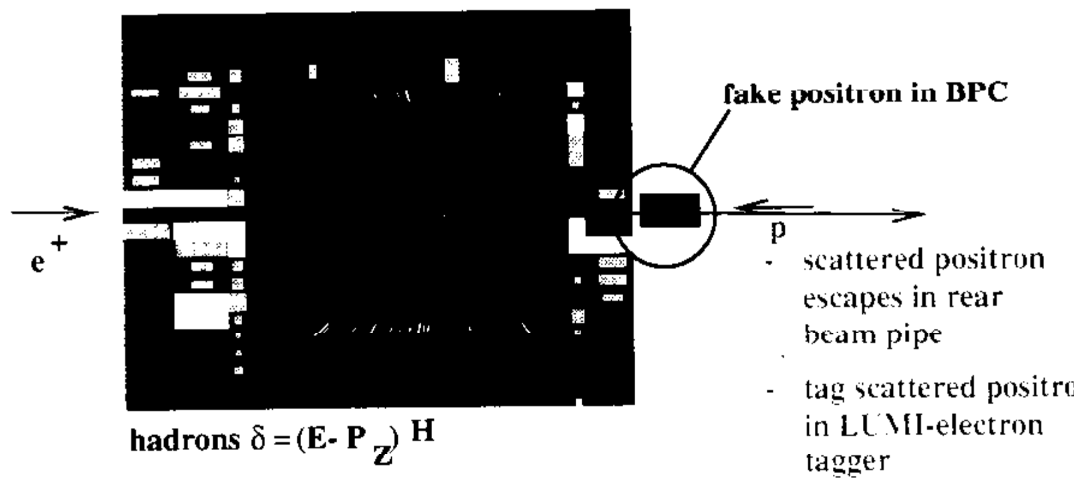
⇒ Cuts on the final state positron

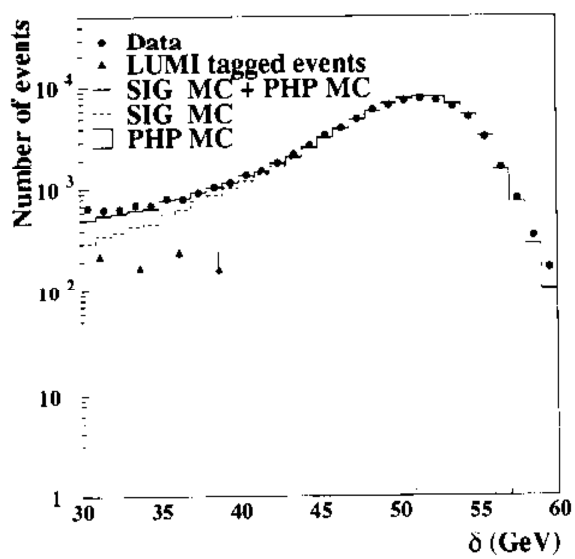
- good timing from e^+p-collisions
- positron energy cut
- positron identification criteria
- fiducial volume cut

⇒ Cuts involving the main detector

- $35\,GeV < (E - P_z) < 60\,GeV$ (where $(E - P_z) = (E - P_z)^H + (E - P_z)^{positron}$)
- cut on $y_{JB} = \frac{(E-P_z)^H}{2E_e}$
- vertex cut on well reconstructed events

- Photoproduction background study (BPC)



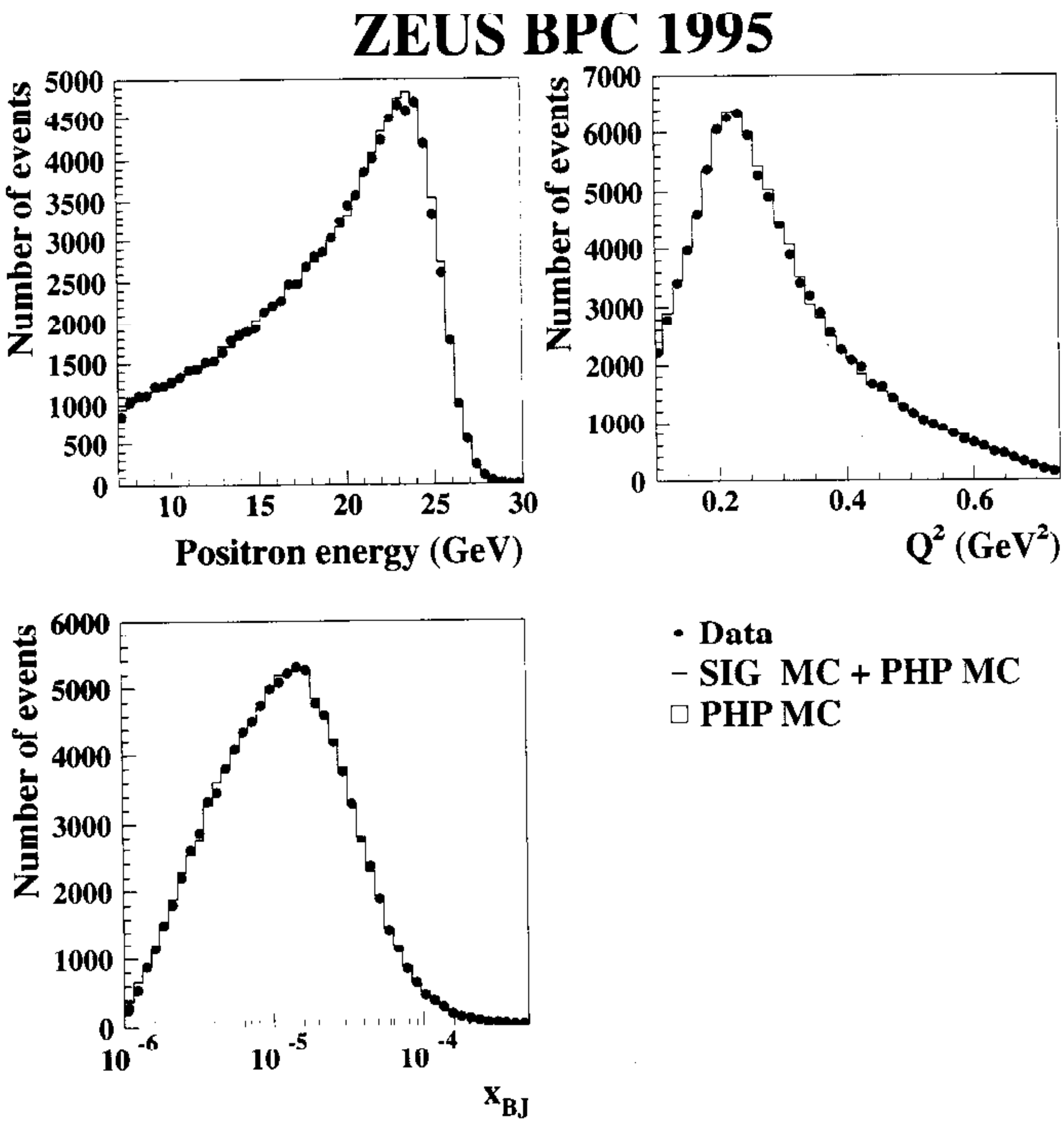


⇒ Photoproduction background events were generated using the PYTHIA program and used to subtract photoproduction events statistically from the data sample

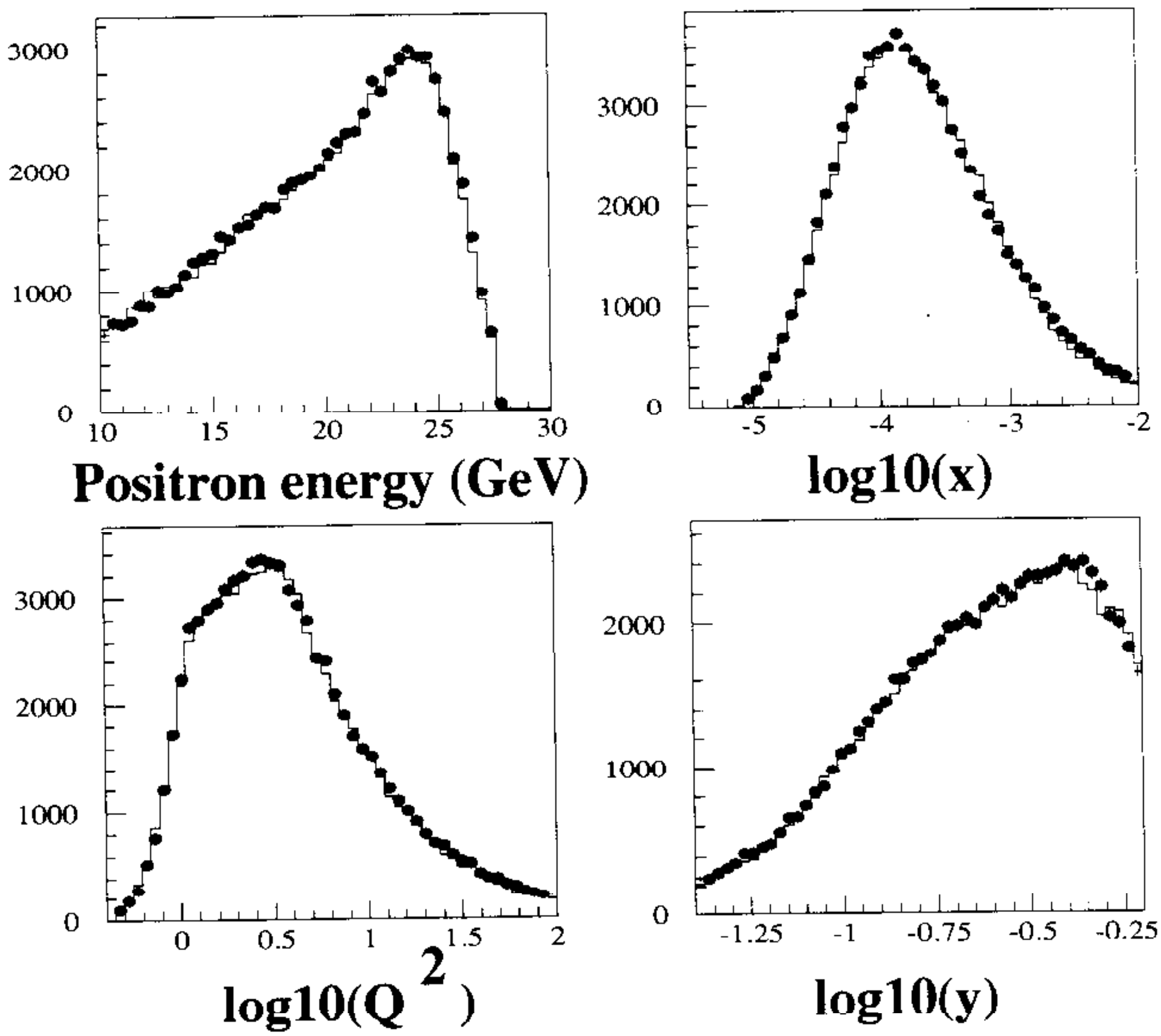
⇒ Good agreement between Data and MC (SIG MC + PHP MC)

⇒ Good agreement between generated MC-background (PHP MC)

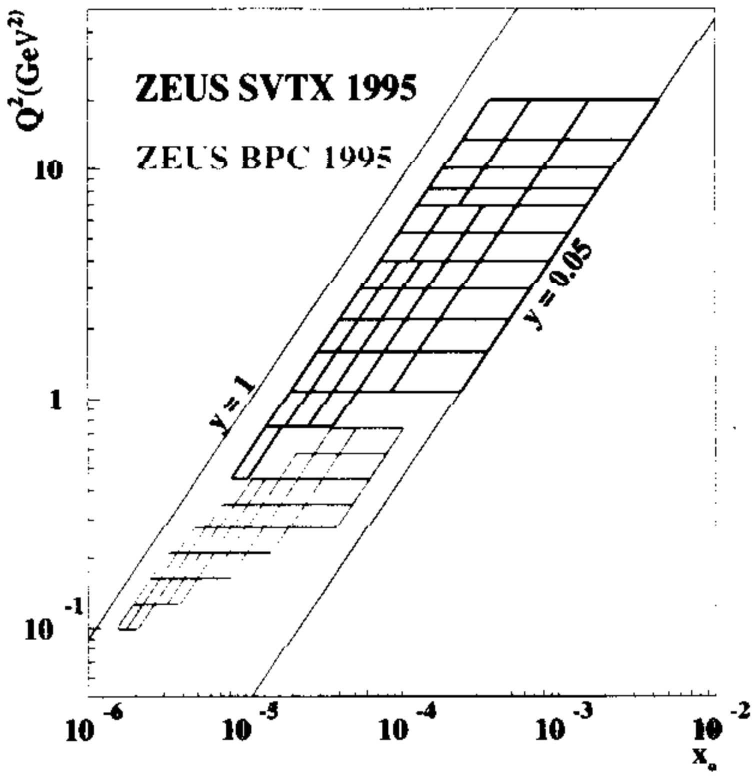
- Comparison DATA and MC



ZEUS SVTX 1995



- Extracting F_2 (SVTX 1995 and BPC 1995)
  - Bin data in (y, Q^2)-bins



  - Background subtraction (beam-gas; photoproduction ⇒)
  - Measure $\sigma_T + \epsilon\sigma_L$ via:

$$\frac{d^2\sigma}{dy\,dQ^2} = \Gamma(\sigma_T + \epsilon\sigma_L)(1 - \ldots$$

With

F_L-ansatz

calculate

F_2 and $\sigma_{\gamma^* p} \approx \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2)$

5 Results

- Systematic checks on $F_2/\sigma_{tot}(\gamma^* p)$-analysis
- Models for the low-x and low-Q^2 region
- F_2 versus x
- $\sigma_{tot}(\gamma^* p)$ versus W^2

- Systematic checks on $F_2/\sigma_{tot}(\gamma^* p)$-analysis

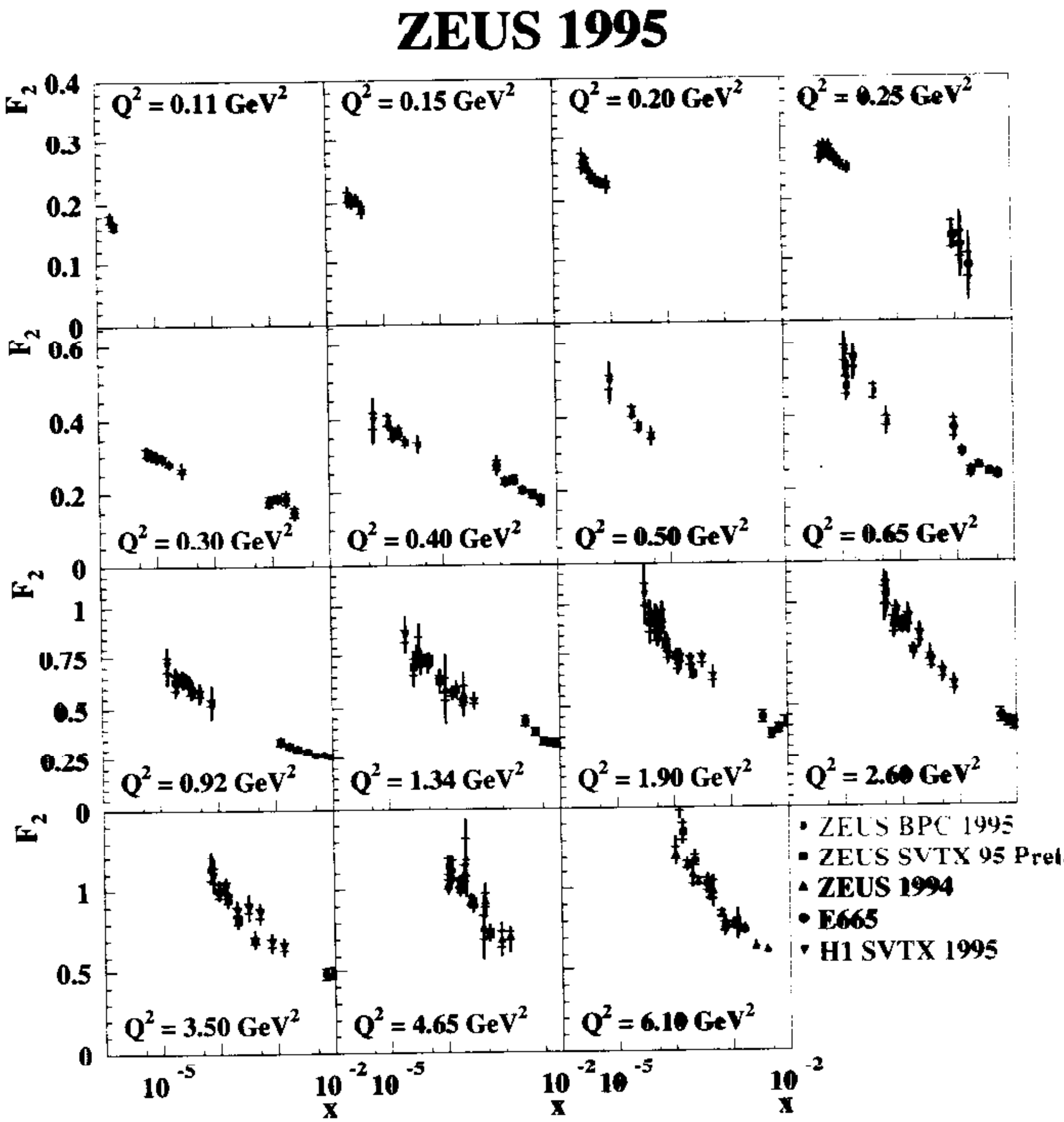
⇒ BPC-F_2-analysis:

total statistical errors:	2...4 %
total systematic errors:	3...10 % dominated by:
low y:	UCAL energy scale; y_{JB}-cut
medium y:	BPC-reconstruction
high y:	Photoproduction background

⇒ SVTX-F_2-analysis:

total statistical errors:	3...7 %
total systematic errors:	3...14 % dominated by:
low - medium y:	SRTD/RCAL-reconstruction
high y:	Photoproduction background

- ZEUS F_2 results



- Error bars: statistical $\oplus$ systematic errors
- F_2-results: shown using the F_L-model by BKS
- Normalization uncertainty: BPC (2.4%); SVTX (1%)

- Models for the low-x and low-Q^2 region

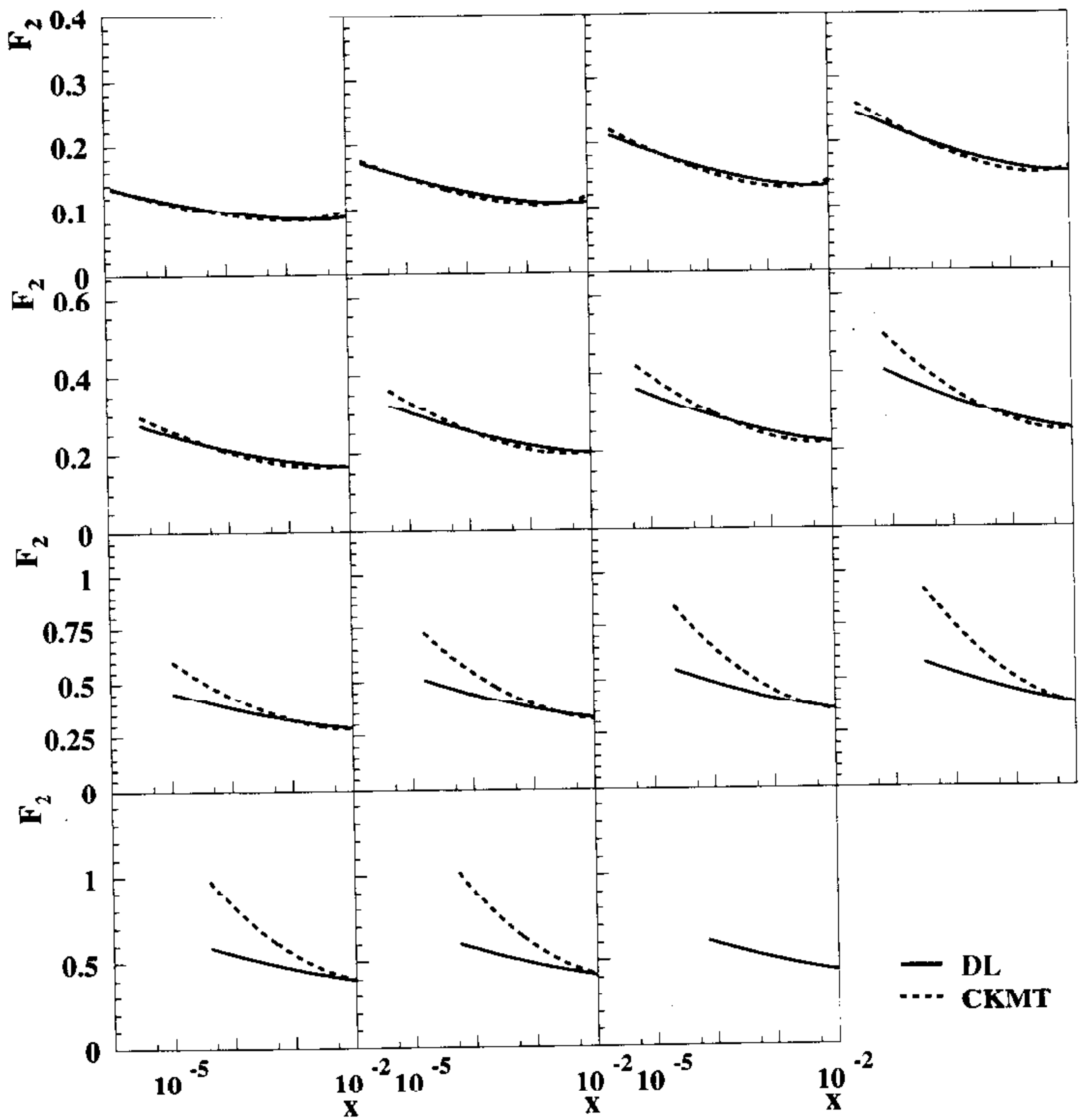
- DL (Donnachie and Landshoff)
  - found a simple Regge picture (sum of pomeron and reggeon exchange) to describe all hadron-hadron and γp cross sections
  - extension for virtual photons to see contribution of this non-perturbative mechanism for $Q^2 < 10 GeV^2$ (pomeron intercept: 1.0808)

- CKK (Cudell, Kang and Kim)
  - similar ansatz as already used by DL including
  - detailed analysis on the uncertainties of the various parameters being used (e.g. pomeron intercept: 1.07...1.11)

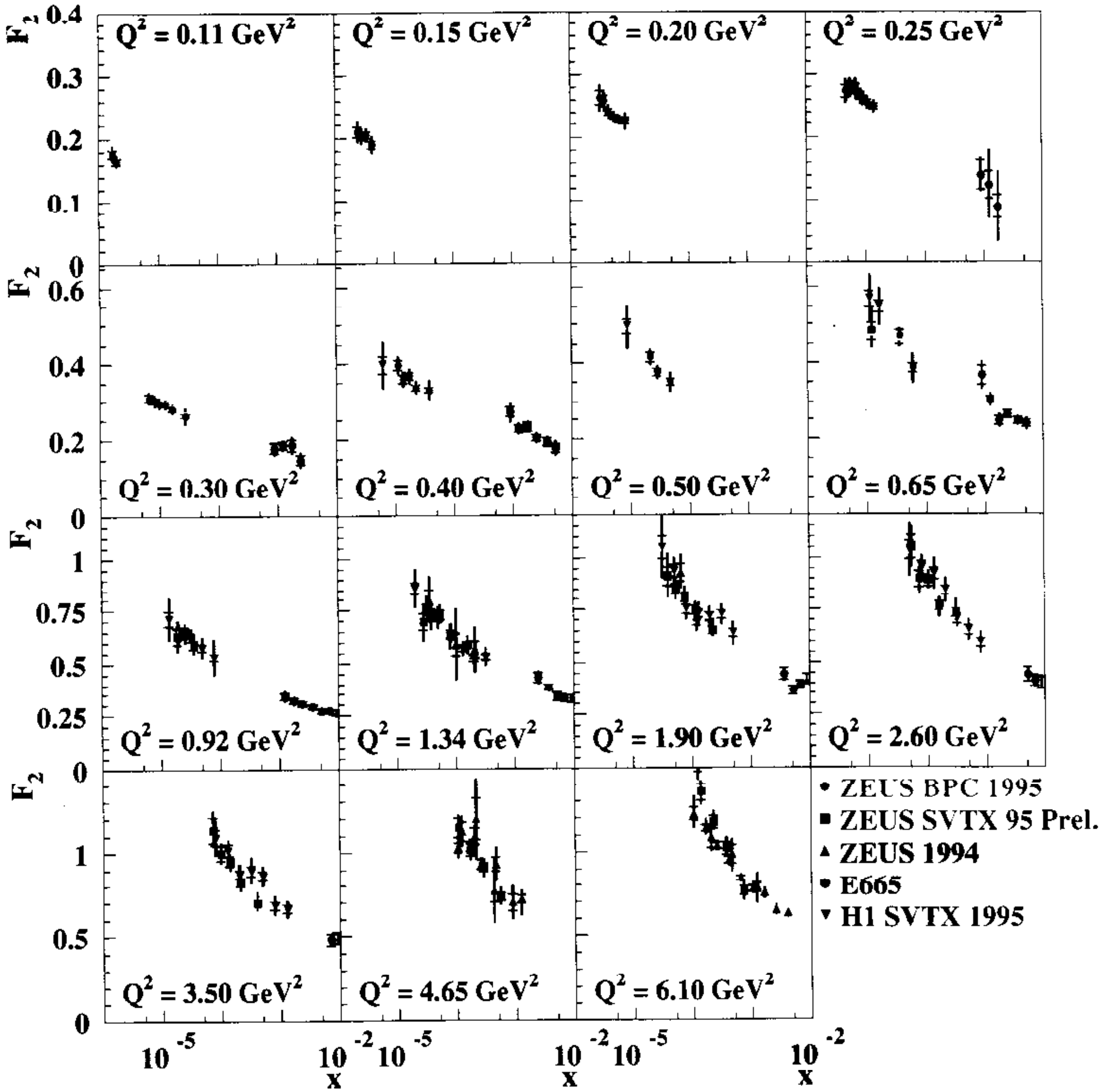
- CKMT (Capella, Kaidalov, Merino and Tran-Than-Van)
  - use in their Regge picture one bare pomeron with an intercept $1 + \Delta(Q^2)$ which interpolates between the effective soft pomeron and the effective hard pomeron
  - parametrize data with this pomeron behavior up to $Q^2 < 5 GeV^2$ and use it then as an initial condition for a pQCD evolution

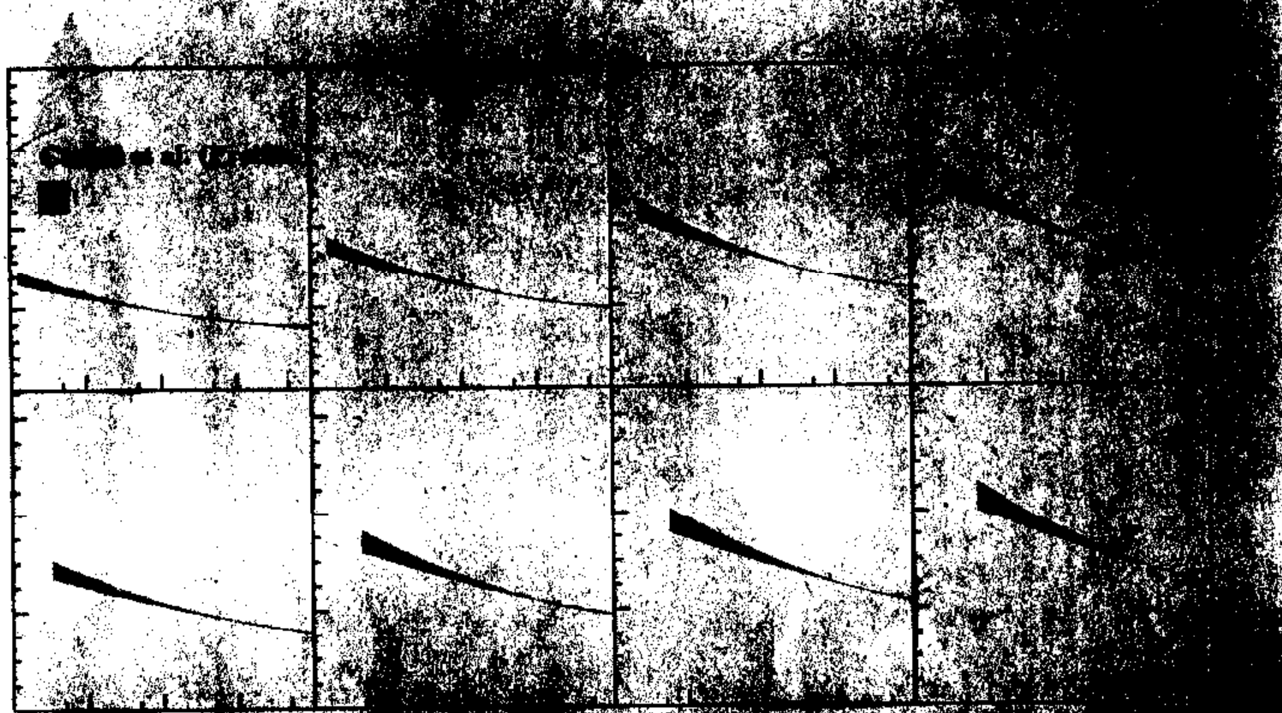
- GRV (Glück, Reya and Vogt)
  - assume valence-like input distributions at $Q_0^2 = 0.34 GeV^2$ which are then evolved using NLO DGLAP equations
  - rise of F_2 at low-x is generated dynamically
  - prediction is not valid close to the starting value Q_0^2
- BK (Badelek and Kwiecinski)
  - describe F_2 using the generalized vector meson dominance model (GVDM)
  - the low Q^2-region is controlled by the contributions of low mass vector mesons whereas the higher mass contributions are described by a standard set of structure function parametrizations, e.g. GRV(94) and are assumed to be given
- ABY (Adel, Barreiro and Ynduráin)
  - introduce to the soft behaviour of F_2 with decreasing x for $Q^2 \sim 1 GeV^2$ a harder contribution ($\sim x^{-\lambda_s}$ with $\lambda_s = 0.48$ independent of Q^2) to prevent F_2 to decrease with $x \to 0$ for $Q^2 < 1 GeV^2$
  - assume α_s to be independent of Q^2 for $Q^2 < 1 GeV^2$

ZEUS 1995

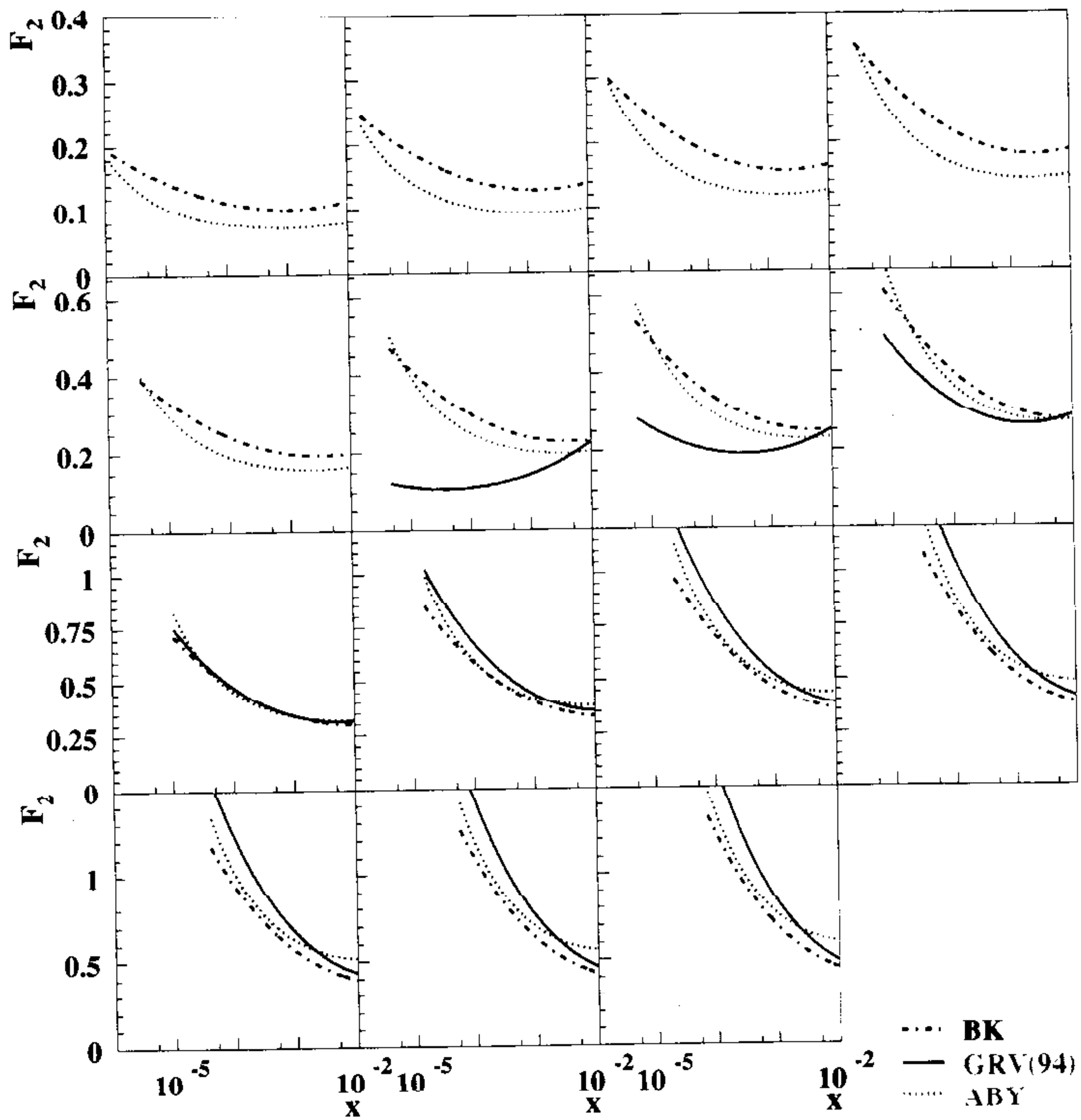


ZEUS 1995

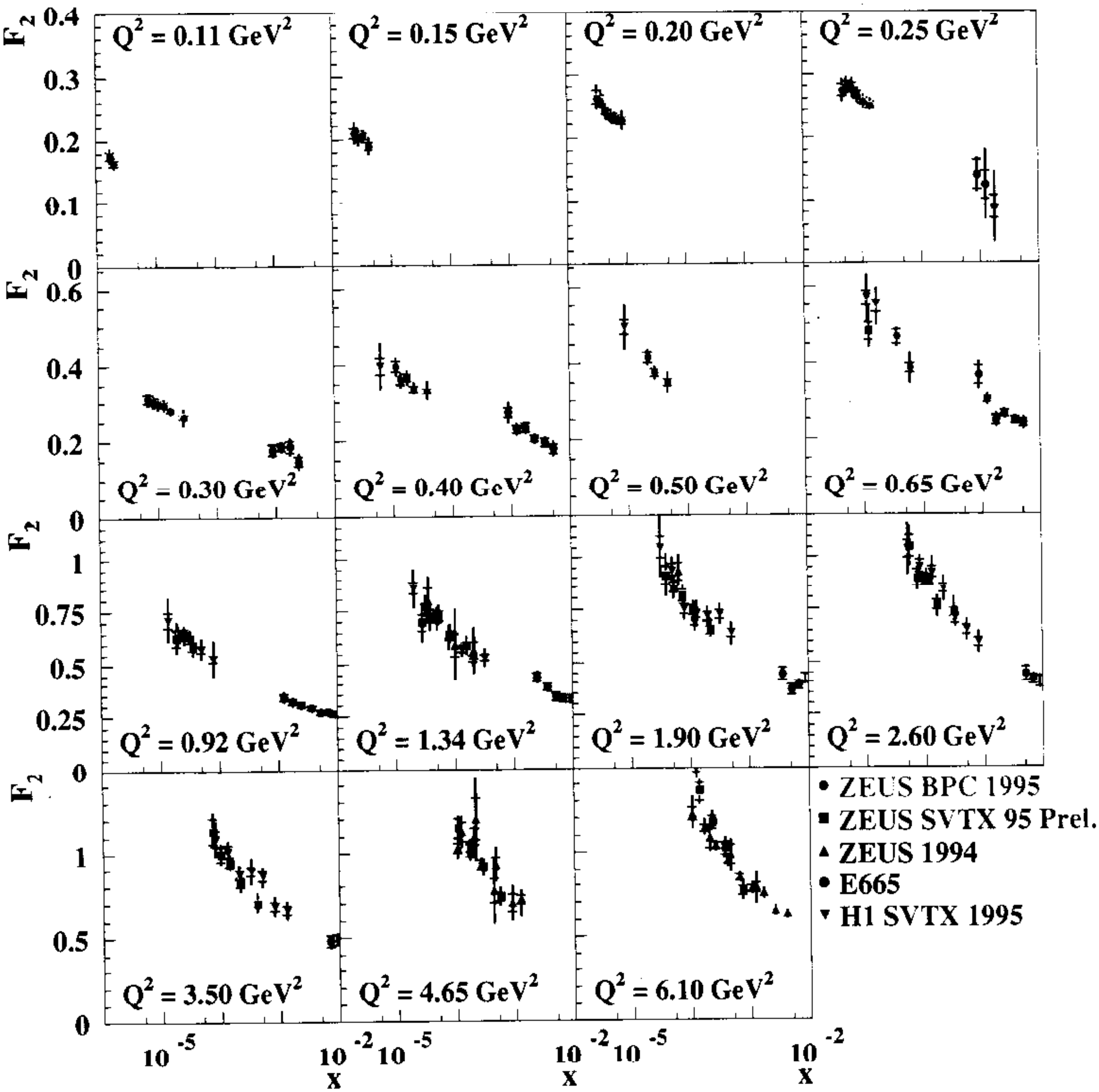

$Q^2 = 0.11$ GeV^2
$Q^2 = 0.15$ GeV^2
$Q^2 = 0.20$ GeV^2
$Q^2 = 0.25$ GeV^2
$Q^2 = 0.30$ GeV^2
$Q^2 = 0.40$ GeV^2
$Q^2 = 0.50$ GeV^2
$Q^2 = 0.65$ GeV^2
$Q^2 = 0.92$ GeV^2
$Q^2 = 1.34$ GeV^2
$Q^2 = 1.90$ GeV^2
$Q^2 = 2.60$ GeV^2
$Q^2 = 3.50$ GeV^2
$Q^2 = 4.65$ GeV^2
$Q^2 = 6.10$ GeV^2
F_2
x
ZEUS BPC 1995
ZEUS SVTX 95 Prel.
ZEUS 1994
E665
H1 SVTX 1995



ZEUS 1995



ZEUS 1995



Q² = 0.11 GeV²
Q² = 0.15 GeV²
Q² = 0.20 GeV²
Q² = 0.25 GeV²
Q² = 0.30 GeV²
Q² = 0.40 GeV²
Q² = 0.50 GeV²
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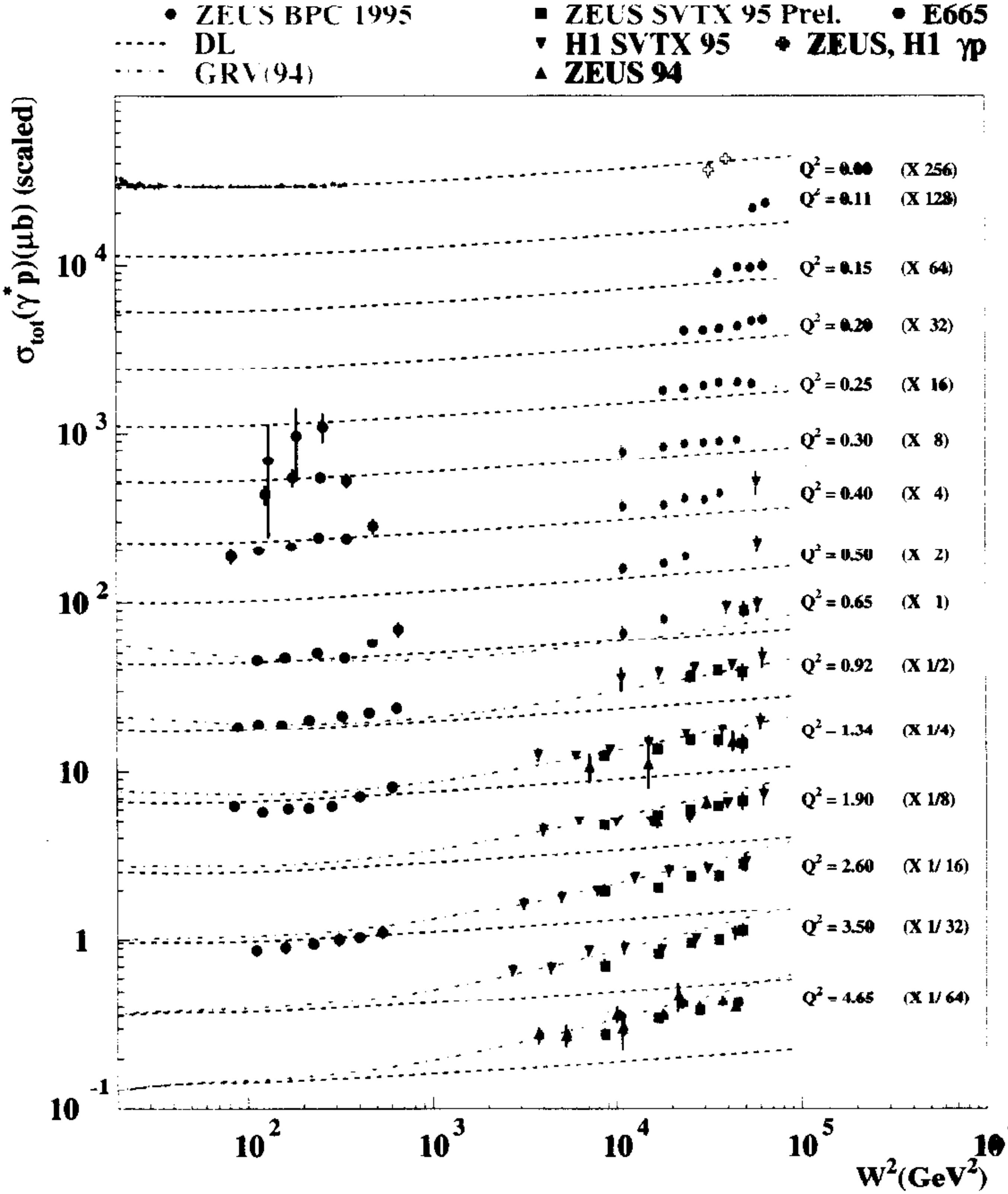
Q² = 0.92 GeV²
Q² = 1.34 GeV²
Q² = 1.90 GeV²
Q² = 2.60 GeV²
Q² = 3.50 GeV²
Q² = 4.65 GeV²
Q² = 6.10 GeV²
F2
x
ZEUS BPC 1995
ZEUS SVTX 95 Prel.
ZEUS 1994
E665
H1 SVTX 1995

- ZEUS $\sigma_{tot}(\gamma^* p)$ results



6 Summary

- $F_2/\sigma_{tot}(\gamma^* p)$-measurement was presented at low Q^2 and low x at ZEUS :

$$2 \cdot 10^{-6} < x < 7 \cdot 10^{-4}$$
$$0.11 GeV^2 < Q^2 < 6.10 GeV^2$$

  corresponding to $90GeV < W < 230GeV$

  where:

  statistical errors: 2...4% / 3...7%
  systematic errors: 3...10% / 3...14%
  from two analysis: BPC 1995 SVTX 1995 Preliminary

- Our combined results BPC 1995 and SVTX 1995 Preliminary suggest:

  "pQCD-calculations (e.g. GRV(94) using NLO DGLAP-evolution) can account for an increasing fraction of the cross-section. The transition from the region of soft processes to the perturbative region appears to be smooth within current experimental errors and occurs at a Q^2-value of approximately $1GeV^2$"