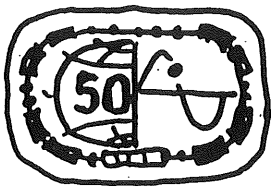


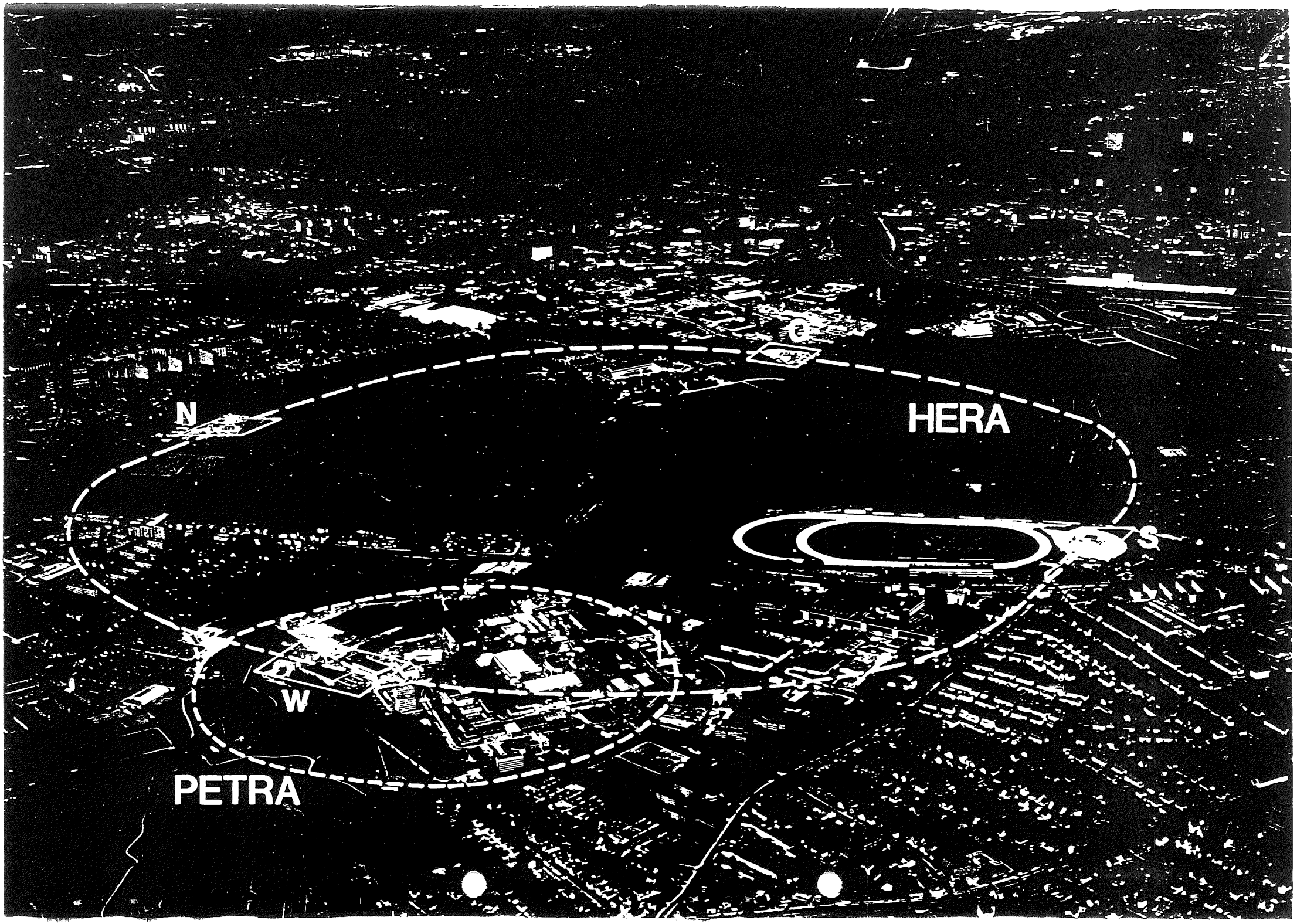
DUBNA – MOSCOW
12-15 July 1994

PHYSICS at HERA

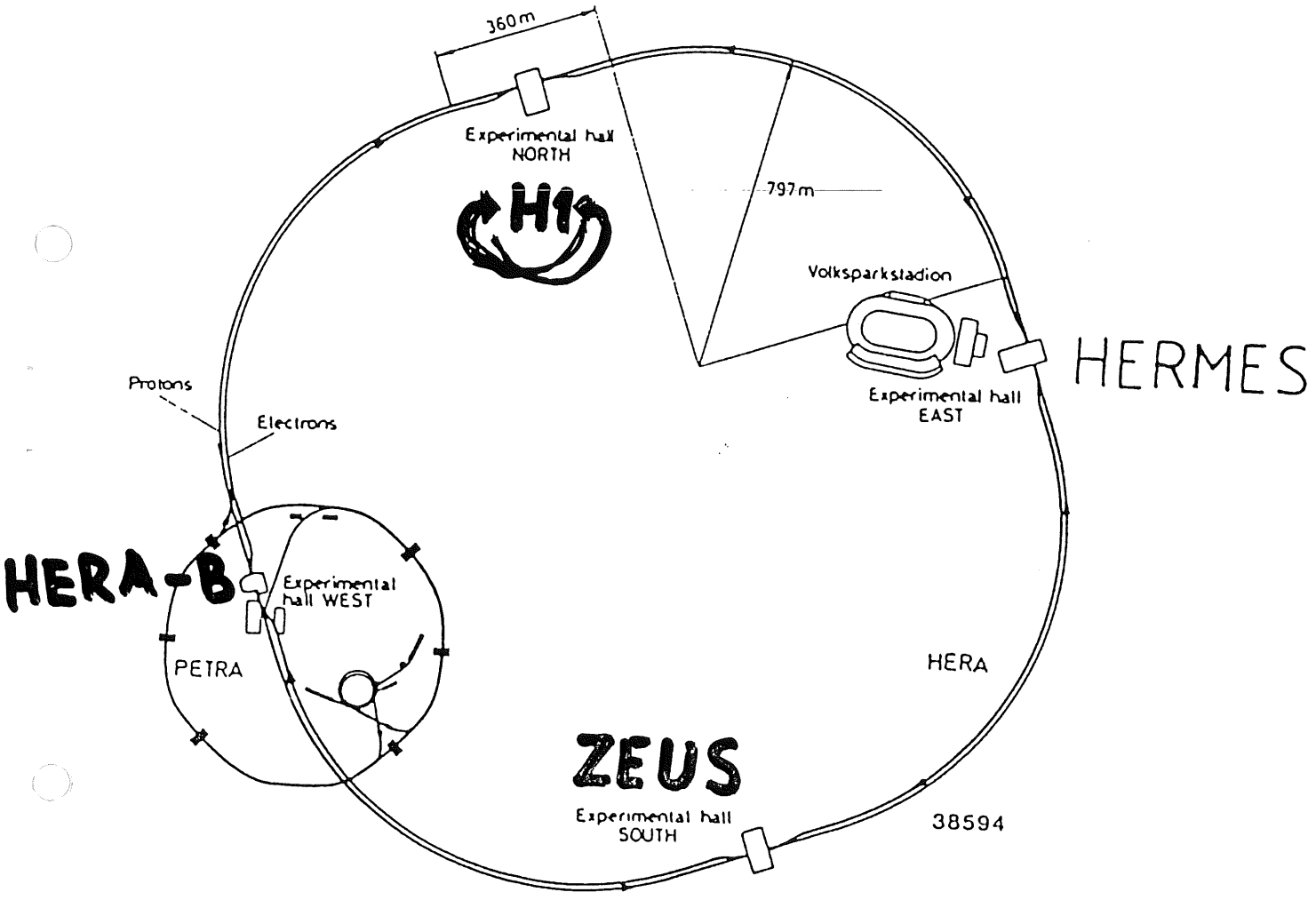
SERGEY LEVONIAN
DESY, Hamburg / LPI, Moscow

RECENT results from the first ep-collider

- **Introduction**
- **HERA and the Experiments**
- **DIS results:**
  - CC cross section
  - F_2^p
  - Hadronic final states
- **Photoproduction**
  - From particles to jets
  - Gluon distribution in the photon
- **Summary and Outlook**


N
HERA
S
W
PETRA

THE HERA COLLIDER

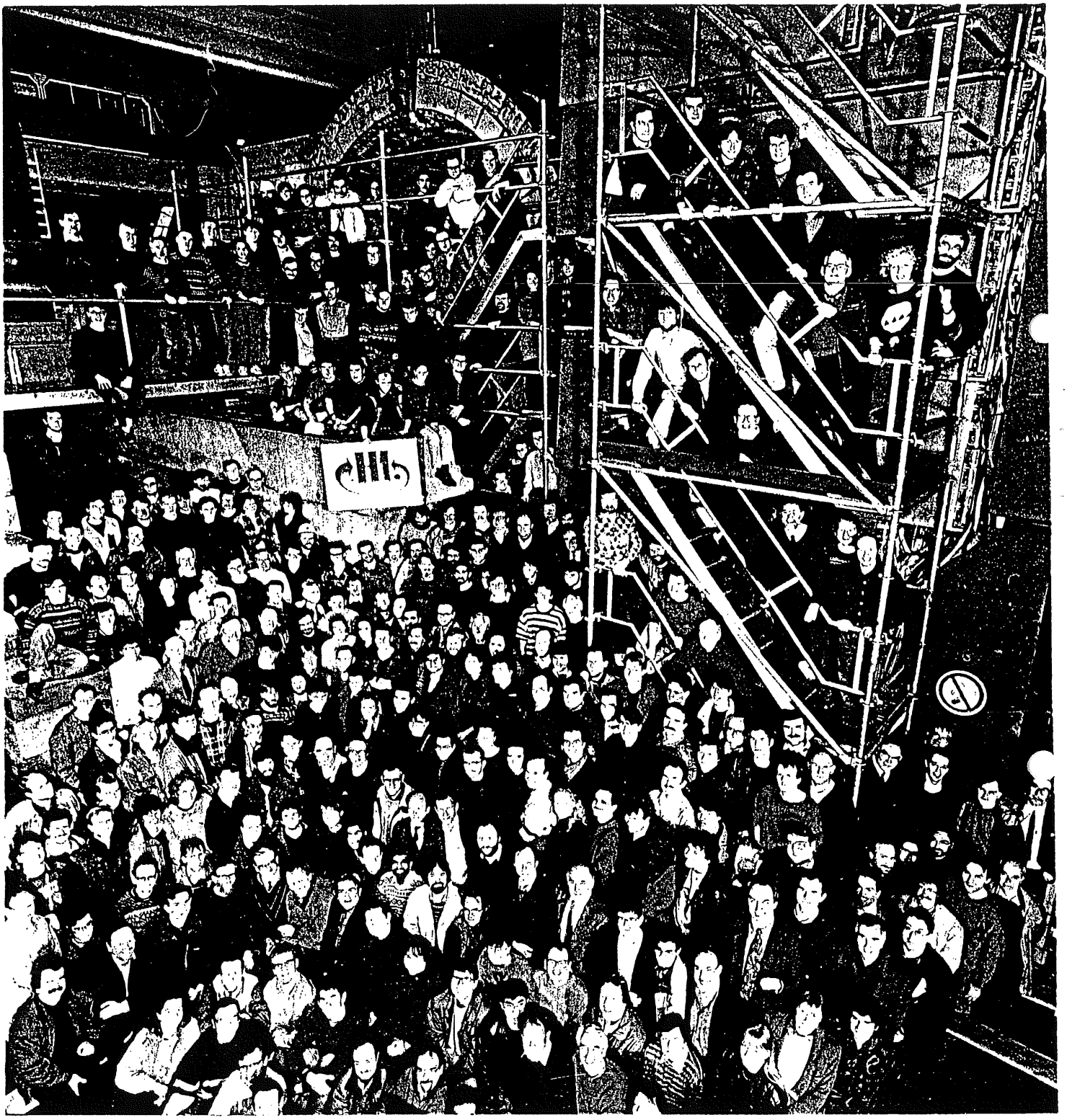


H1 in operation since 1991
ZEUS (ep-physics since 1992)

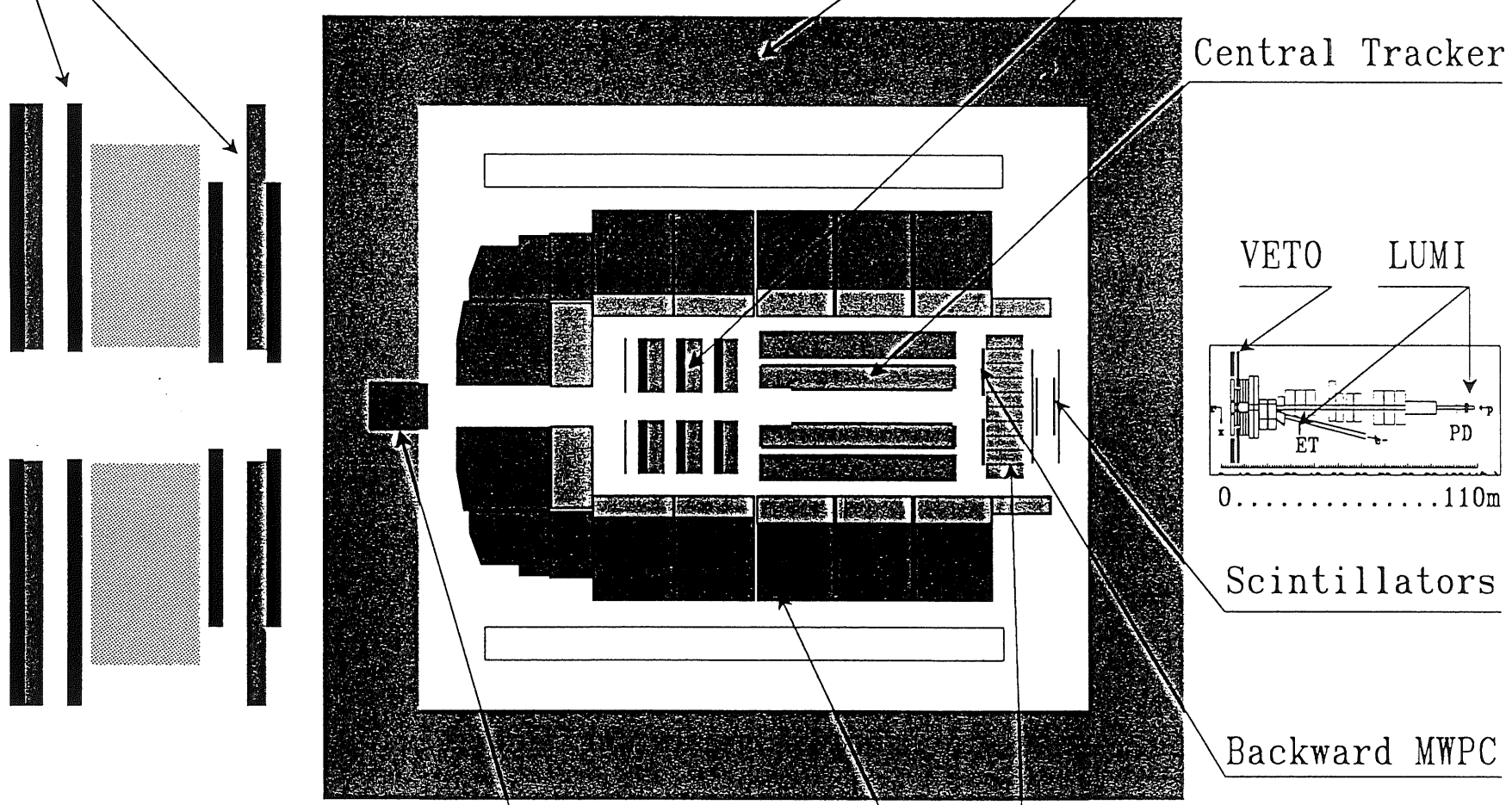
HERMES spin physics (1995 →)

HERA-B approved in May '94; data taking starts in 1998 ($pA \to B\bar{B}\ldots$)

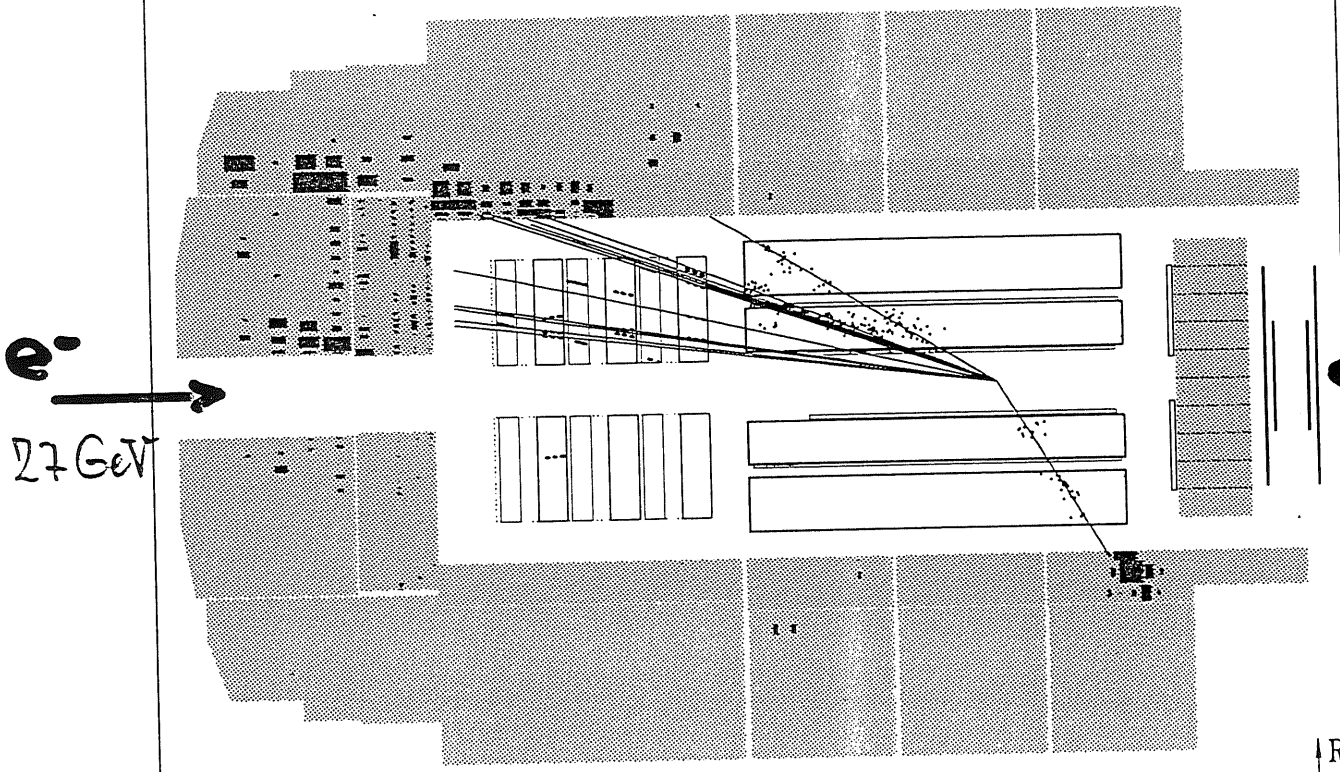
12 countries, 37 institutions,
~400 physisists

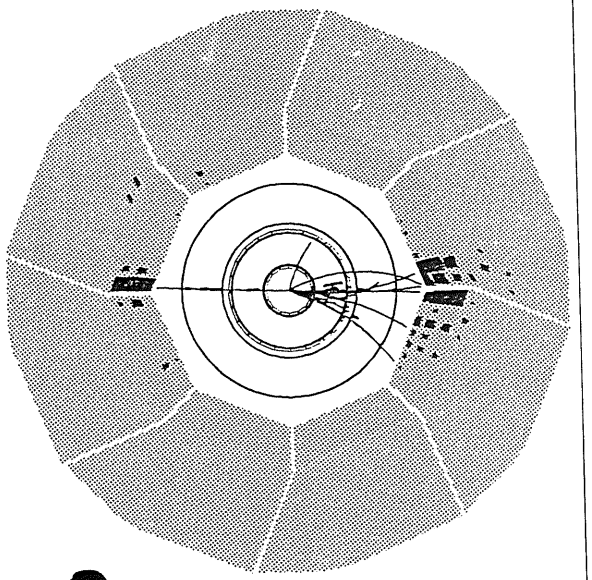


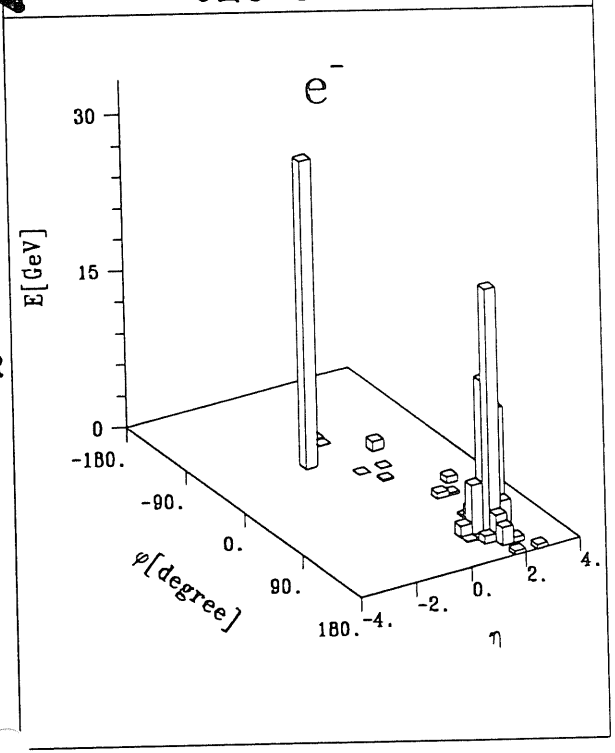
THE H1 DETECTOR



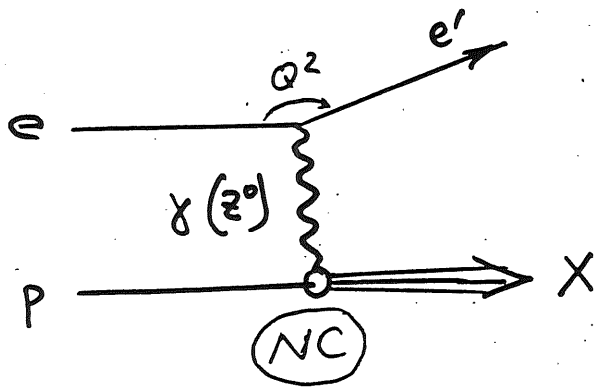
H1 Run 51435 Event 7798. Q^2 = 740 GeV^2 x = 0.05 Date 1/07/1993

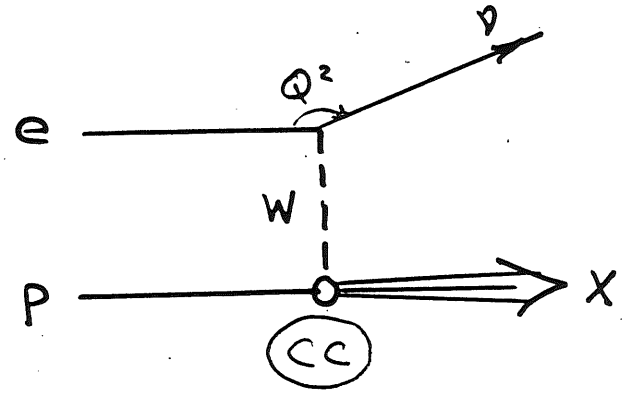


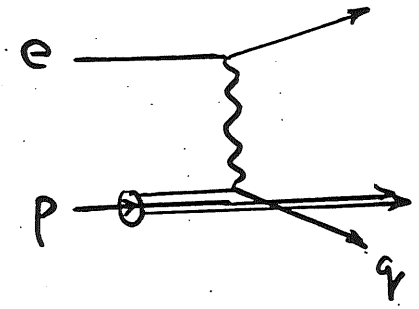




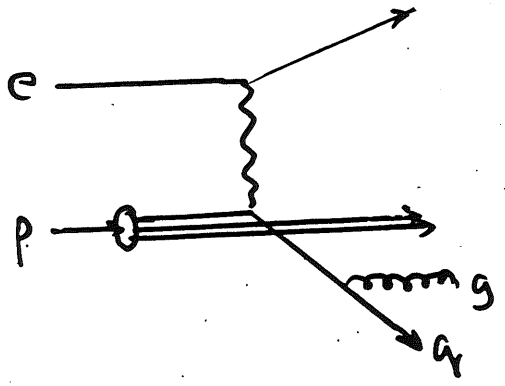
SM

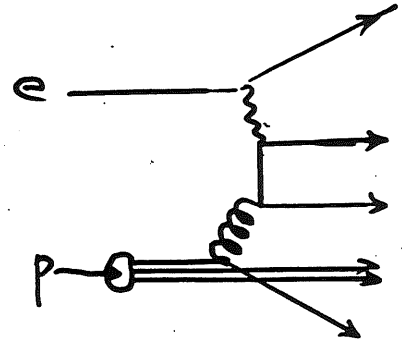






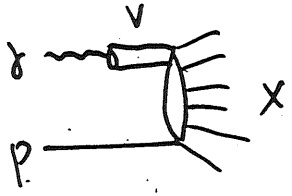
L.O.

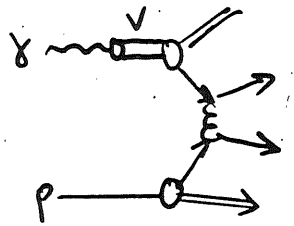


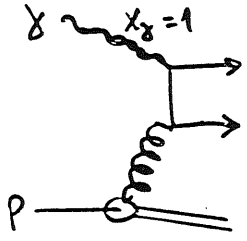


N. L. O.

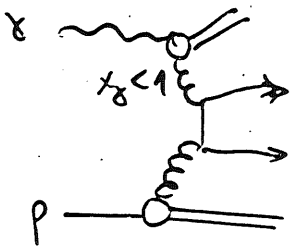
Photoproduction at HERA





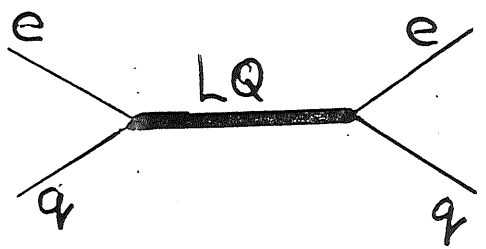


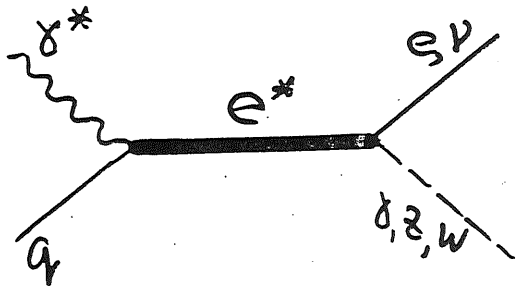
"Direct"



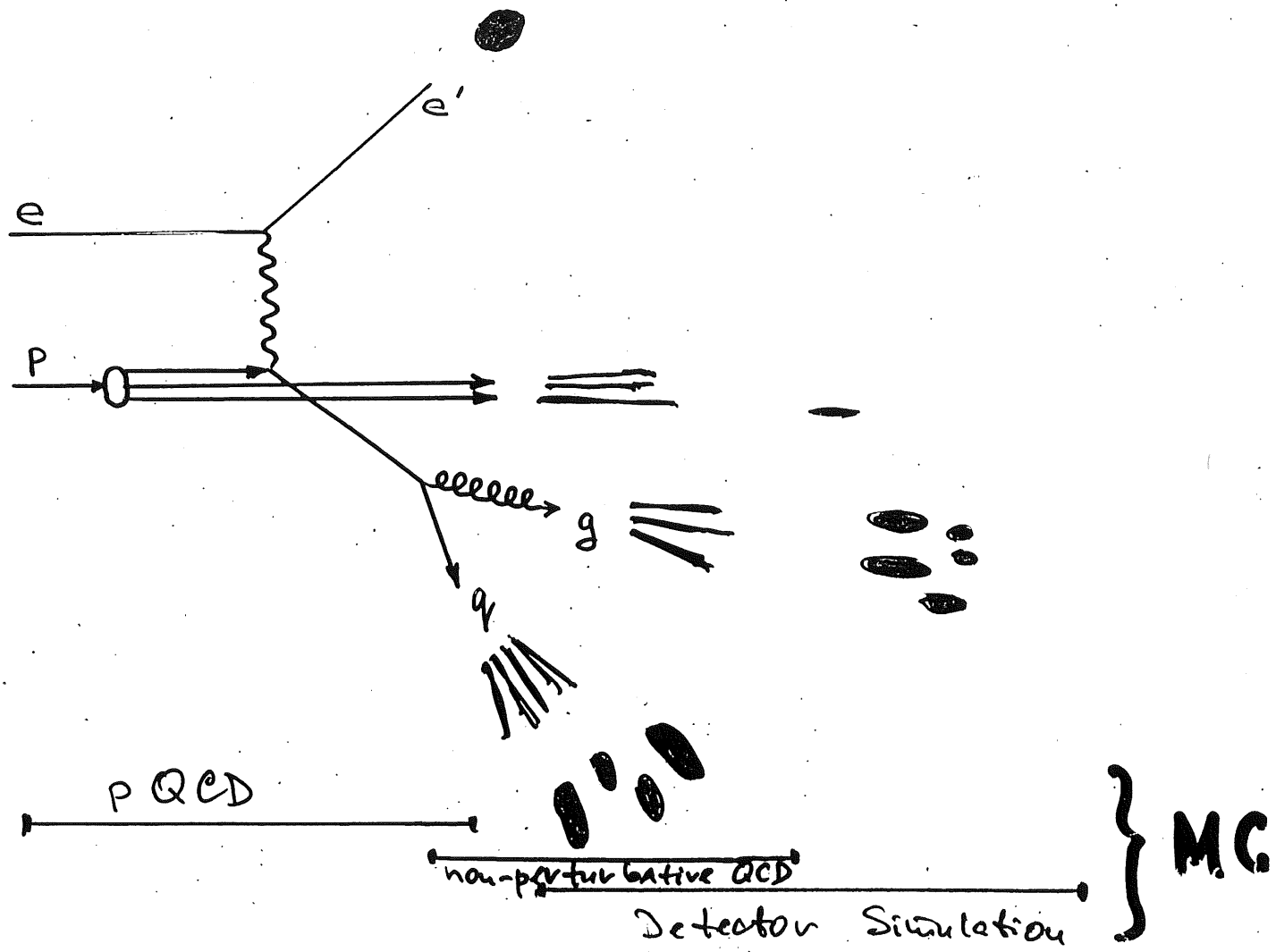
"Resolved"

BSM





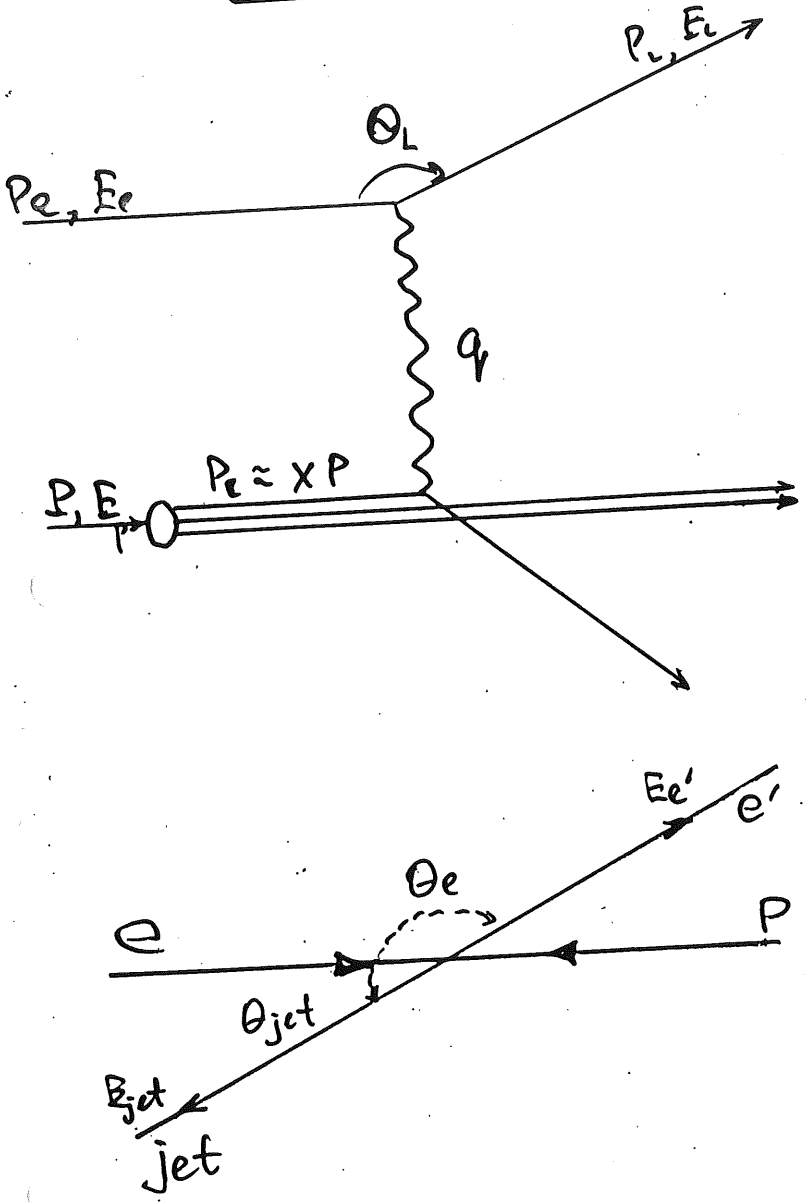
• • •



Energy deposit → Clusters
hits → Tracks
→ jets

→ partons

HERA specifics



KINEMATICS :

* $Q^2 = -q^2$
* $x = \frac{Q^2}{2pq} \approx \frac{P_e}{P}$
* $y = \frac{pq}{p \cdot p_e}$

$$S = 4E_eE_p = \frac{Q^2}{xy}$$

$$W^2 = (q+p)^2 - Q^2 \frac{(1-x)}{x}$$

$$\underset{Q^2 \to 0}{\simeq} sy$$

① 2 degrees of freedom ; 4 variables measured → redundancy in x, Q^2 (y) determination

② $\sqrt{s} \approx 300$ GeV → $x \leq 10^{-4}$ and $Q^2 \approx 10^4$ GeV^2 can be reached ("resolution" of HERA ~ 10^{-16} cm)

③ Photoproduction ($Q^2 \approx 1$ GeV^2)

→ Equivalent $E_\gamma \approx 20 \div 35$ TeV

Basic cross sections at HERA

Photoproduction : $\sigma_{\gamma p} \approx 20\,\mu b = 2 \cdot 10^{4}\,nb$

NC DIS ($Q^2 > 5\,GeV^2$) : $\sigma_{NC}^{DIS} \approx 100\,nb = 10^{2}\,nb$

CC DIS : $\sigma_{CC} \approx 100\,pb = 10^{-1}\,nb$

Exotics (BSM) : $\sigma < 10\,pb = 10^{-2}\,nb$

$\mathcal{L}$ accumulated by experiments

July '92 : $\mathcal{L} = 1.5\,nb^{-1}$ → Dallas HEP's

Fall '92 : $= 25\,nb^{-1}$ → Published in PL,

1993 : $\approx 500\,nb^{-1}$ → final status at Glasgow

1994 : $= ?$

Charged Current Cross Section Measurement

HERA : $e^- p \to \nu + \text{hadrons}$ ($E_{\text{"}\nu\text{"}} \approx 50$ TeV)

Fixed target : $\nu N \to e(\mu) X$ ($E_\nu \leq 250$ GeV)

$$\sigma \sim S \frac{1}{\left(1 + \frac{Q^2}{M_W^2}\right)^2}$$

H1 : $P_t^{miss} > 25$ GeV

$\mathcal{L} = 348 \pm 17$ nb^{-1} $\Rightarrow$ 14 events

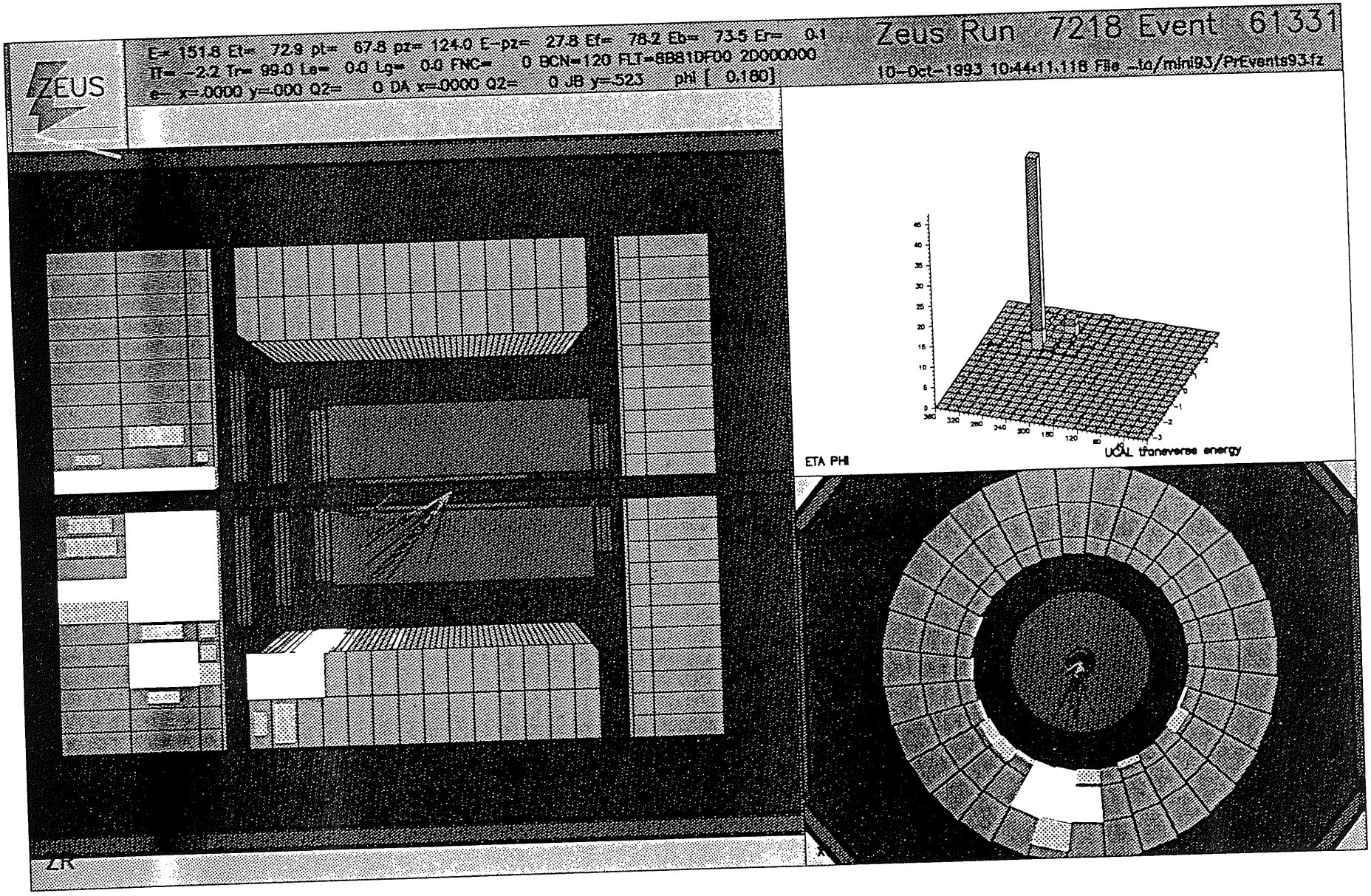
$\sigma_{cc}(p_t > 25\,\text{GeV}) = 55 \pm 15 \pm 6$ pb

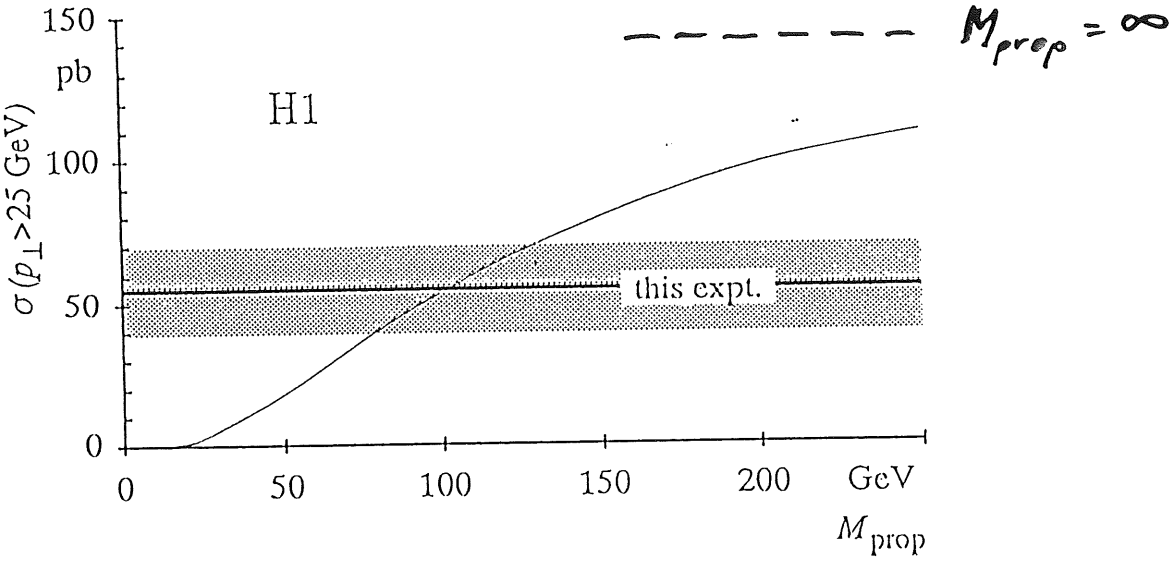
$R = \frac{\sigma^{NC}}{\sigma_{CC}} = 7.2 \pm 2.1 \pm 1.2$ ($R_{th} = 7.7$)

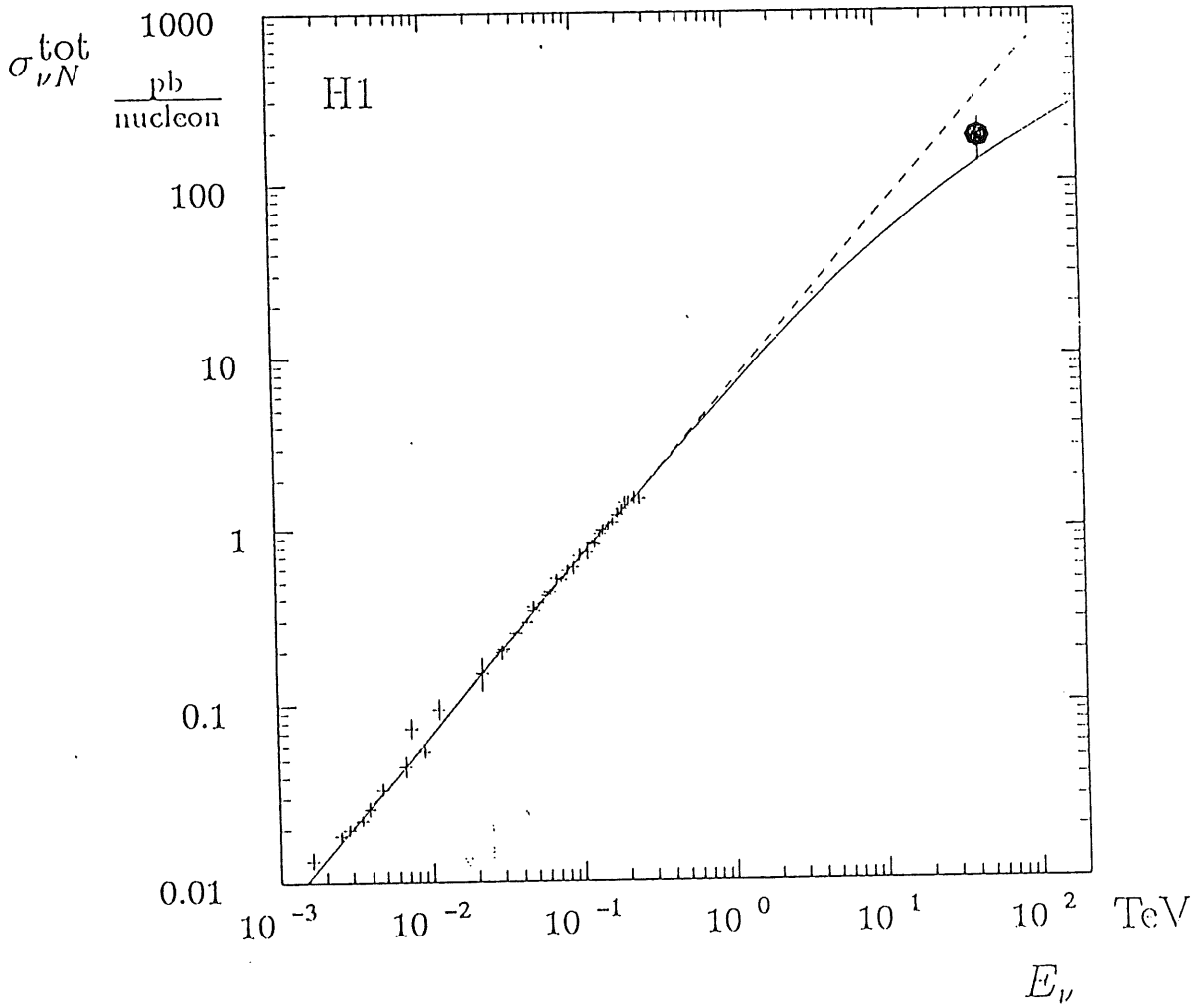
ZEUS: $E_T^{miss} > 20$ GeV

$\mathcal{L} = 550$ nb^{-1} $\Rightarrow$ 24 events

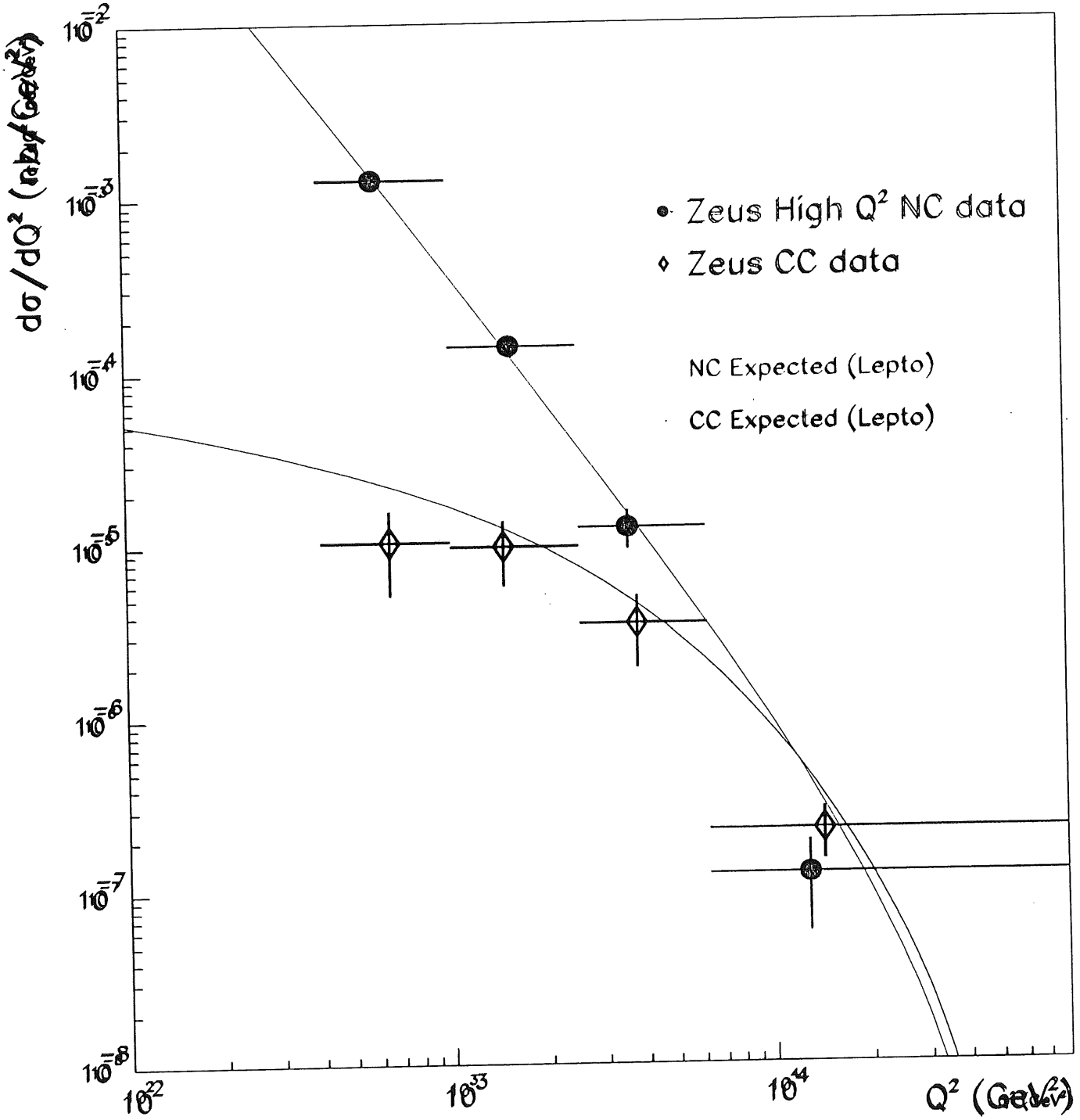
↳ Still limited by statistics. Better results are expected in 94 and later.


ZEUS
E= 151.8 Et= 72.9 pt= 67.8 pz= 124.0 E-pz= 27.8 Ef= 78.2 Eb= 73.5 Er= 0.1
It= -2.2 Tr= 99.0 La= 0.0 Lg= 0.0 FNC= 0 BCN=120 FLT=8B81DF00 2D000000
e- x=.0000 y=.000 Q2= 0 DA x=.0000 Q2= 0 JB y=.523 phi [0.180]
Zeus Run 7218 Event 61331
10-Oct-1993 10:44:11.116 File ../d/mini93/PrEvents93.fz
ETA PHI
UCAL transverse energy
ZR


150
pb
100
50
0
$\sigma(p_\perp > 25\ \mathrm{GeV})$
H1
this expt.
0
50
100
150
200
GeV
M_{prop}
$M_{prop} = \infty$


$\sigma^{\mathrm{tot}}_{\nu N}$
1000
pb
nucleon
100
10
1
0.1
0.01
H1
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
TeV
E_ν

Zeus 1993 preliminary DIS cross sections



Measurement of the Proton Str. Function F_2

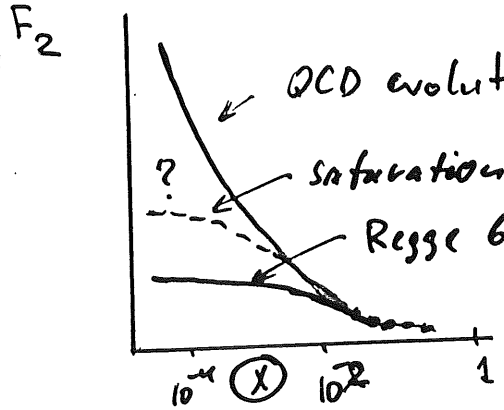
$$\frac{d\sigma^{BORN}}{dQ^2\,dx} = \frac{2\pi\alpha^2}{Q^4 x}\left[2(1-y) + \frac{y^2}{1+R(x,Q^2)}\right] F_2(x,Q^2)$$

where $R(x,Q^2) = \frac{\sigma_L}{\sigma_T}$ (here: $R^{D^-}_{QCD} \sim 0.5$)

$F_2(x,Q^2)$ related to the parton distributions in the proton ("proton structure")

$$= \sum_{\text{flavours}} e_i^2 \times [q_i(x,Q^2) + \bar{q}_i(x,Q^2)] \qquad (L.O.)$$

MOTIVATION



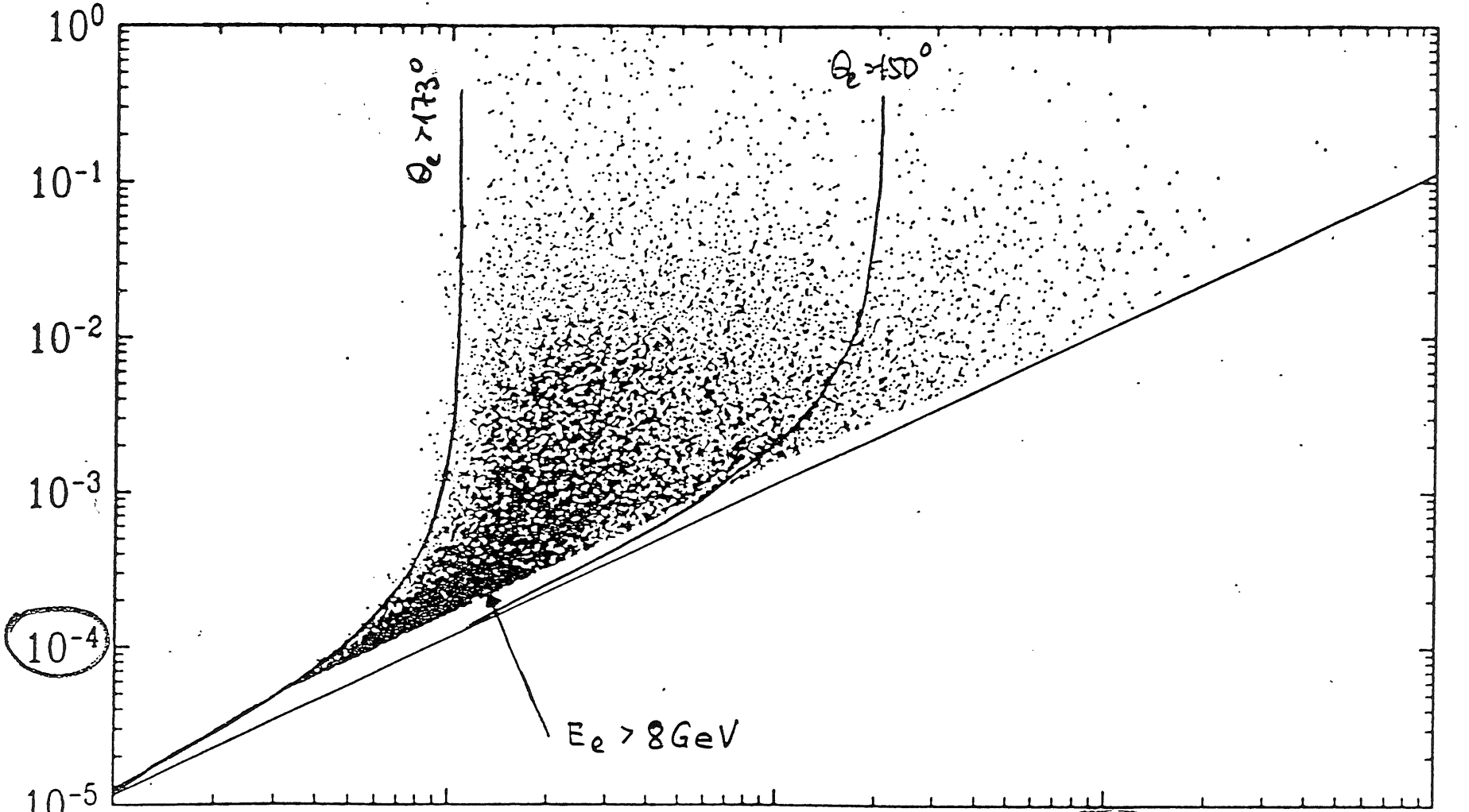
QCD: $F_2(x,Q^2) \Rightarrow F_2(x',Q'^2)$ by evolution equations (DGLAP (Q^2) or BFKL (x))
B.g. "BFKL" expects $xG(x) \sim x^{-\frac{1}{2}}$

Low-x: "hot spots" in p ?
parton recombination ?

H1 DATA 93

~ 10^4 events

Date 11/03/1994



X

Q^2 [GeV^2]

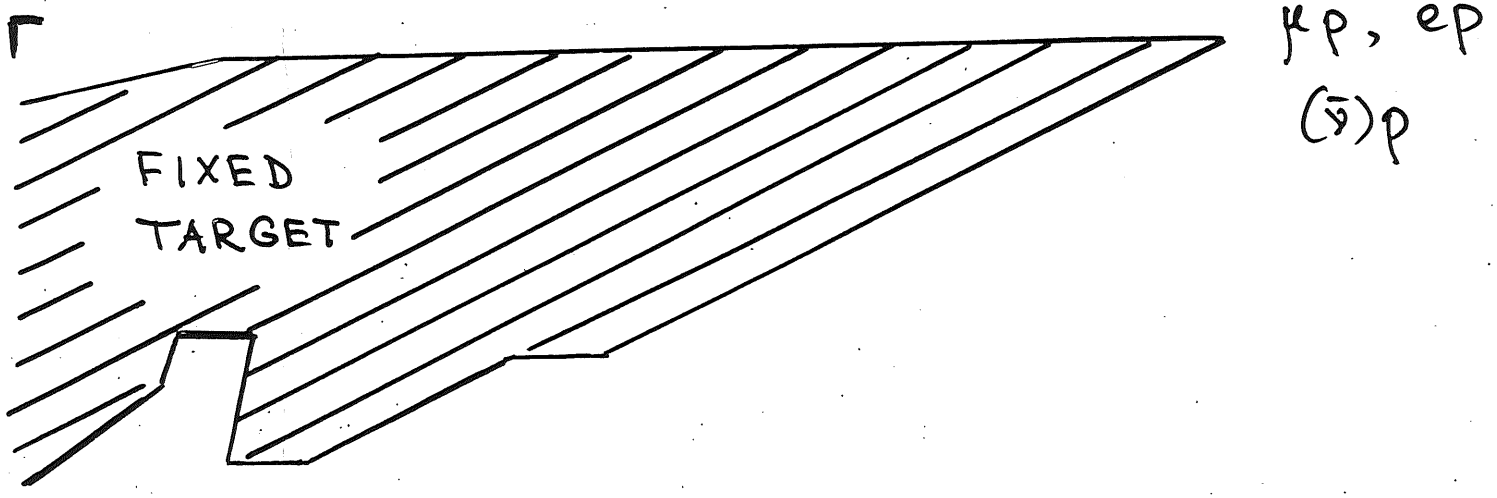
EXPERIMENTAL LIMITATIONS

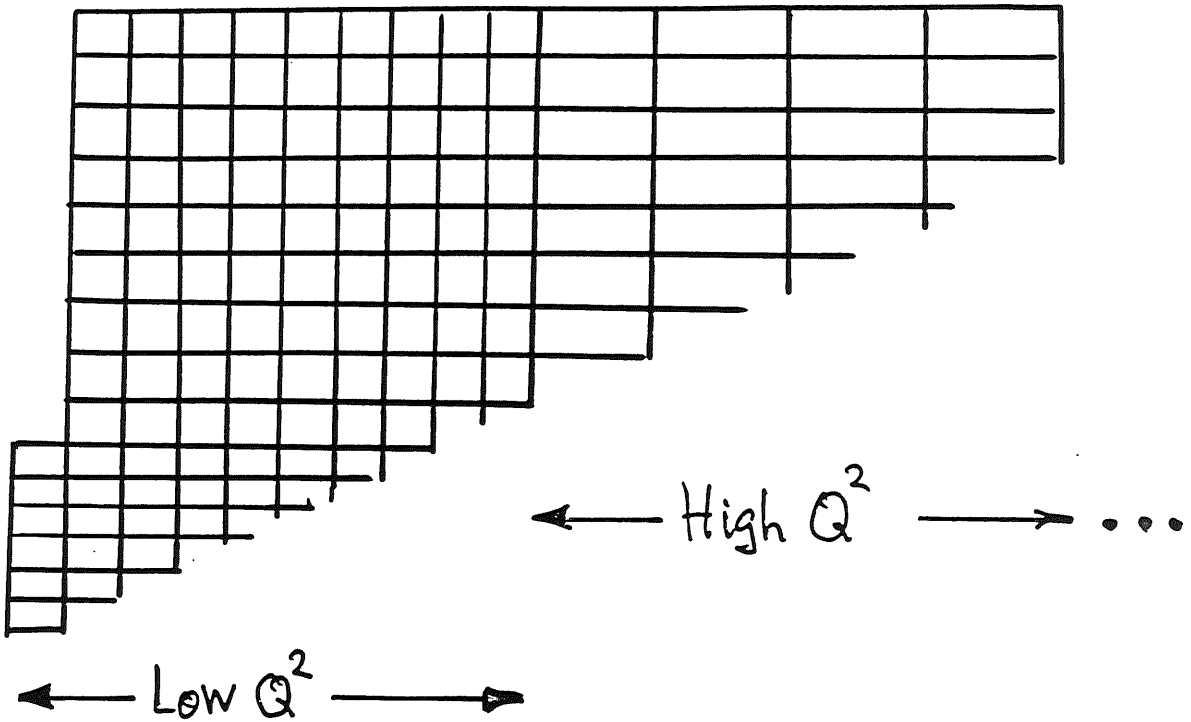
ELECTRON RESOLUTION
HADRON ACCEPTANCE

STATISTICS

DETECTOR ACCEPTANCE

ELECTRON MISIDENTIFICATION


FIXED
TARGET
μp, ep
(ν̄)p


High Q^2
Low Q^2

Systematics on F_2

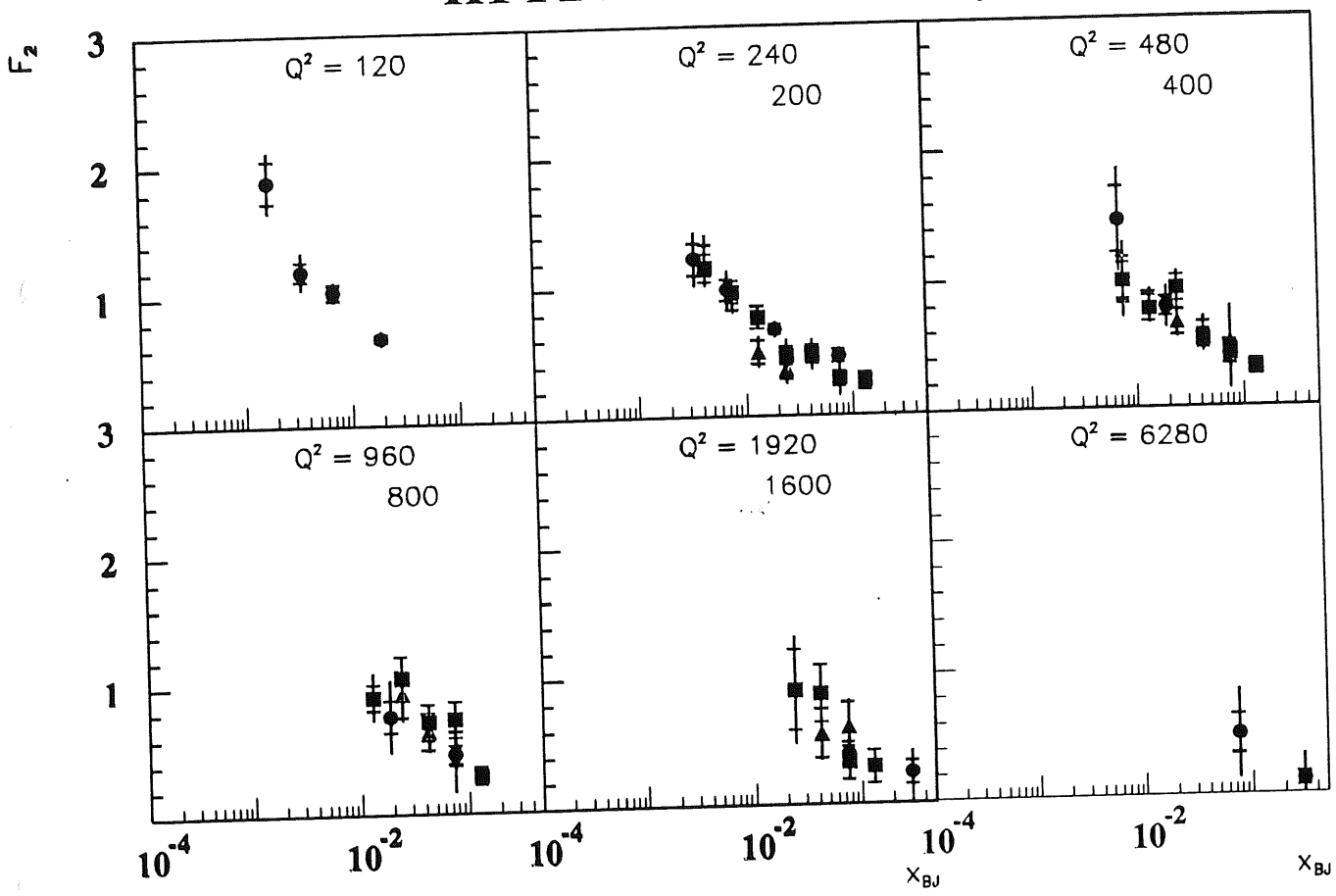
Kinematical variables:

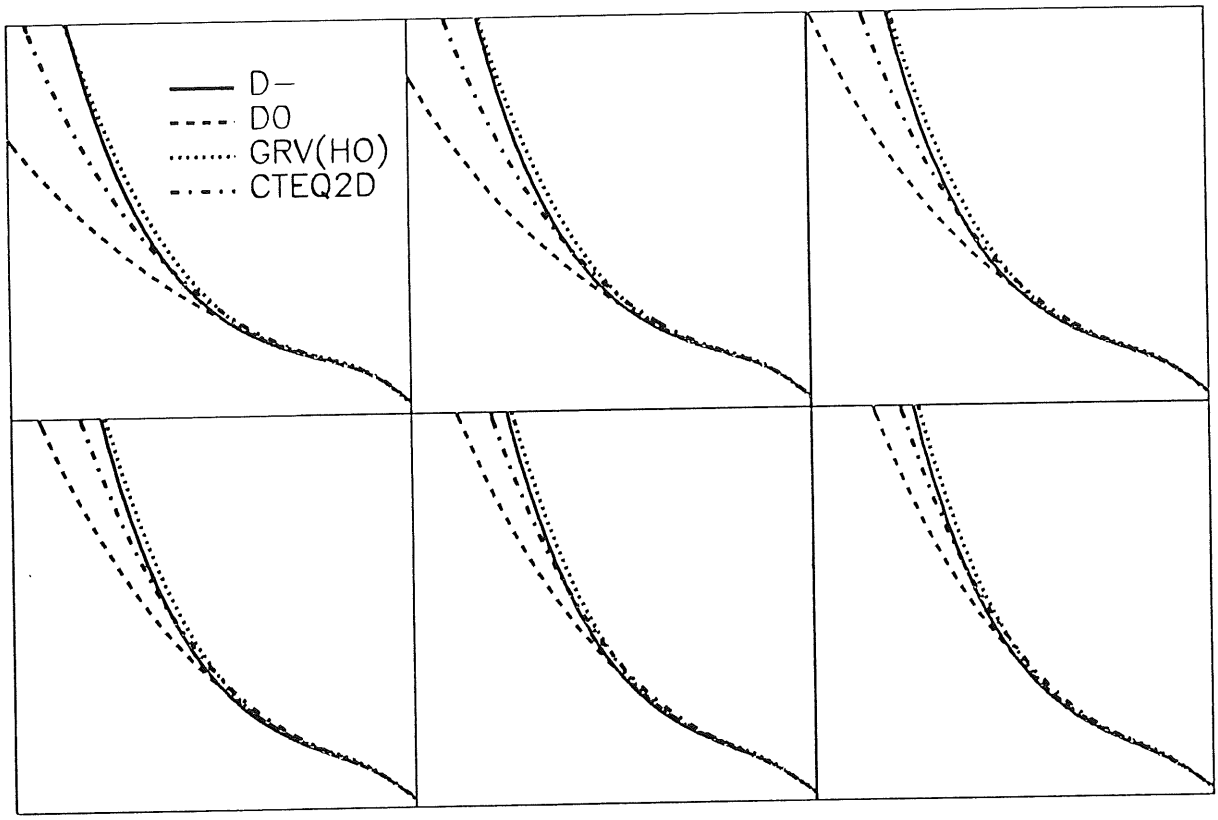
ΔE_{e^-}	$2 \div 15\%$
$\Delta \theta_{e^-}$	$2 \div 8\%$
y_{hadron}	$2 \div 12\%$
Fragmentation	$3 \div 10\%$
Bgr. rejection eff.	$2 \div 5\%$
Remaining background (fp)	$< 3\%$
Radiative corrections	$3 \div 5\%$
e^- - identification	$< 3\%$
Bin center corrections	$< 2\%$
Luminosity	$\leq 5\%$

Typical values:

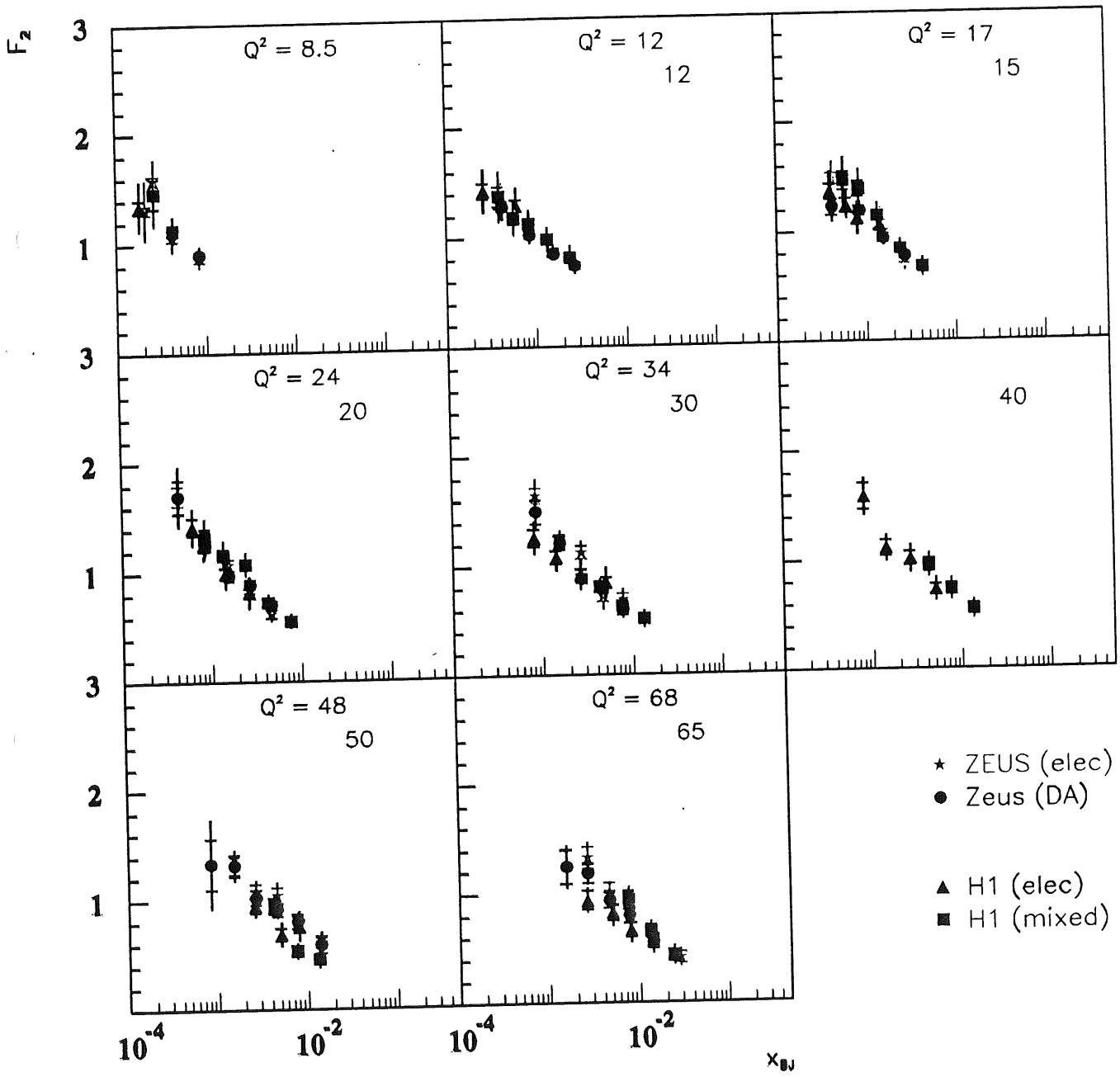
statistical error :	$(3 \div 7)\%$	- low Q2
	$(6 \div 30)\%$	- high Q2
systematical error:	$(8 \div 24)\%$	

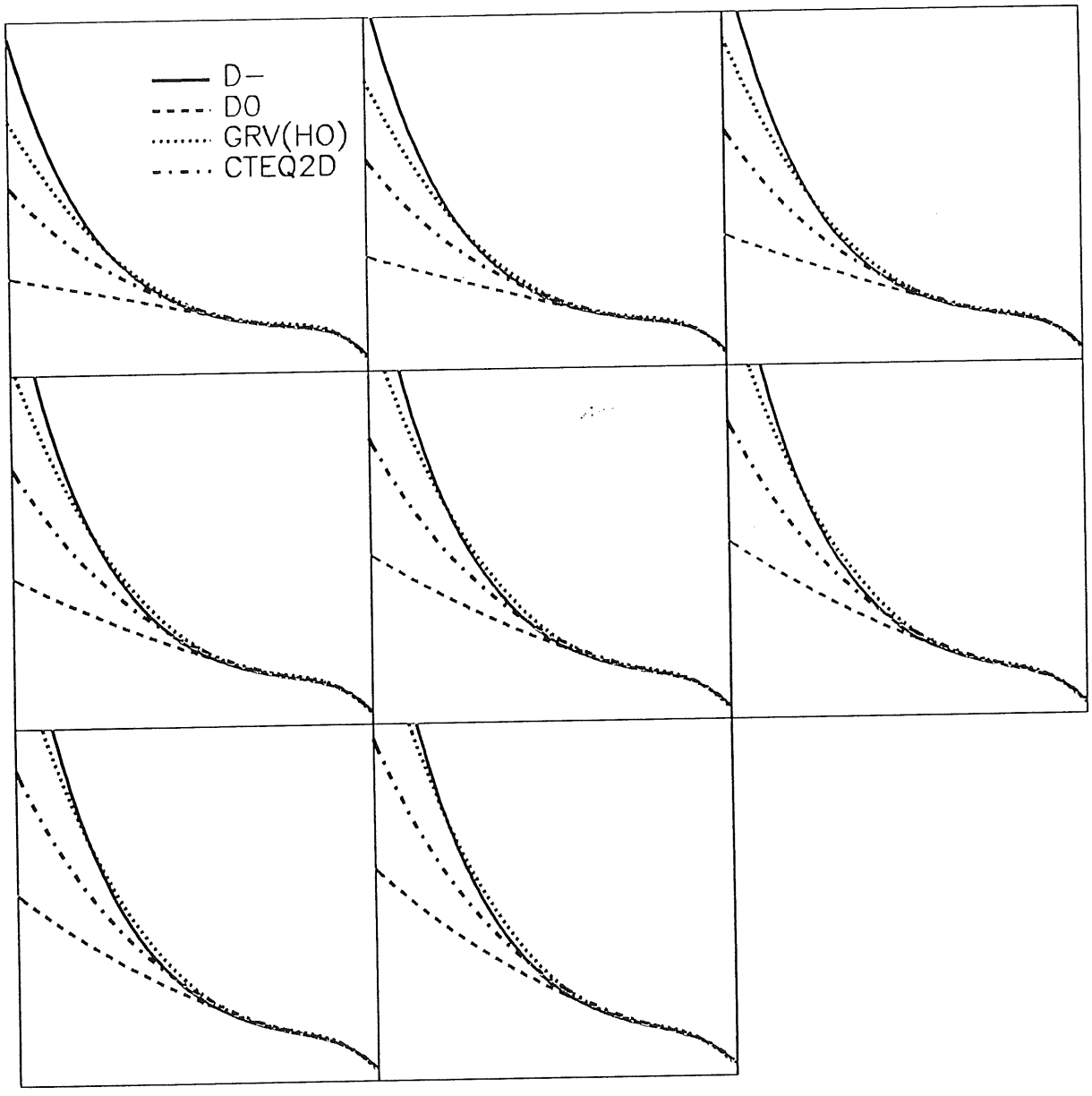
ZEUS F2 1993 Preliminary
H1 F2 1993 Preliminary




D−
D0
GRV(HO)
CTEQ2D

ZEUS F2 1993 Preliminary
H1 F2 1993 Preliminary




D−
D0
GRV(HO)
CTEQ2D

Hadronic final states in DIS

- QCD coherence observation
- E_T-flow and jets in forward region at small x
  → new ("Lipatov") dynamics?
- multi jet events in DIS:
  α_s determination
  gluon density in the proton

QCD coherence effect

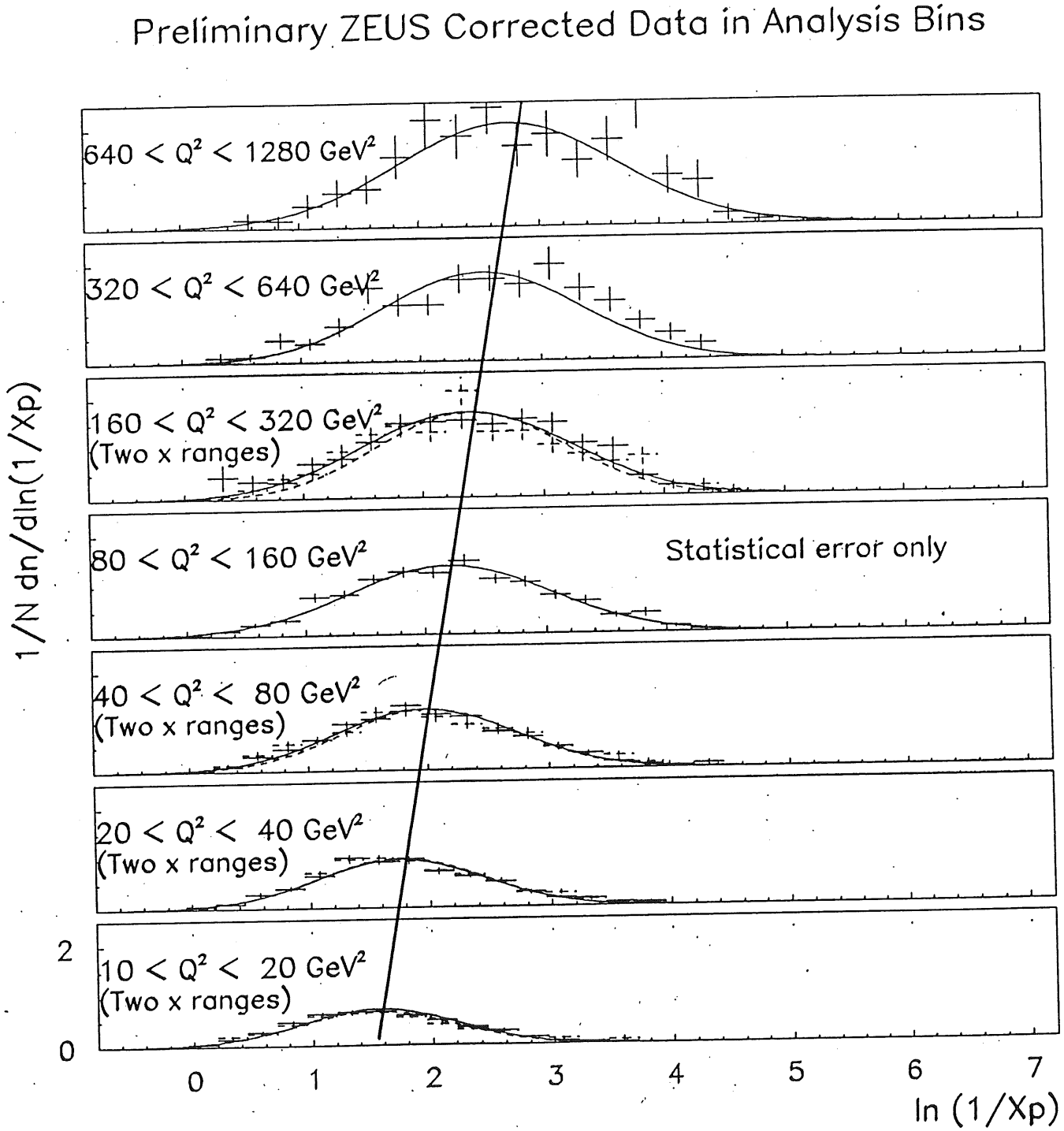
- pQCD predicts the reduction of the available phase space for soft gluon emission due to destructive interference.
- Observed in e^+e^-

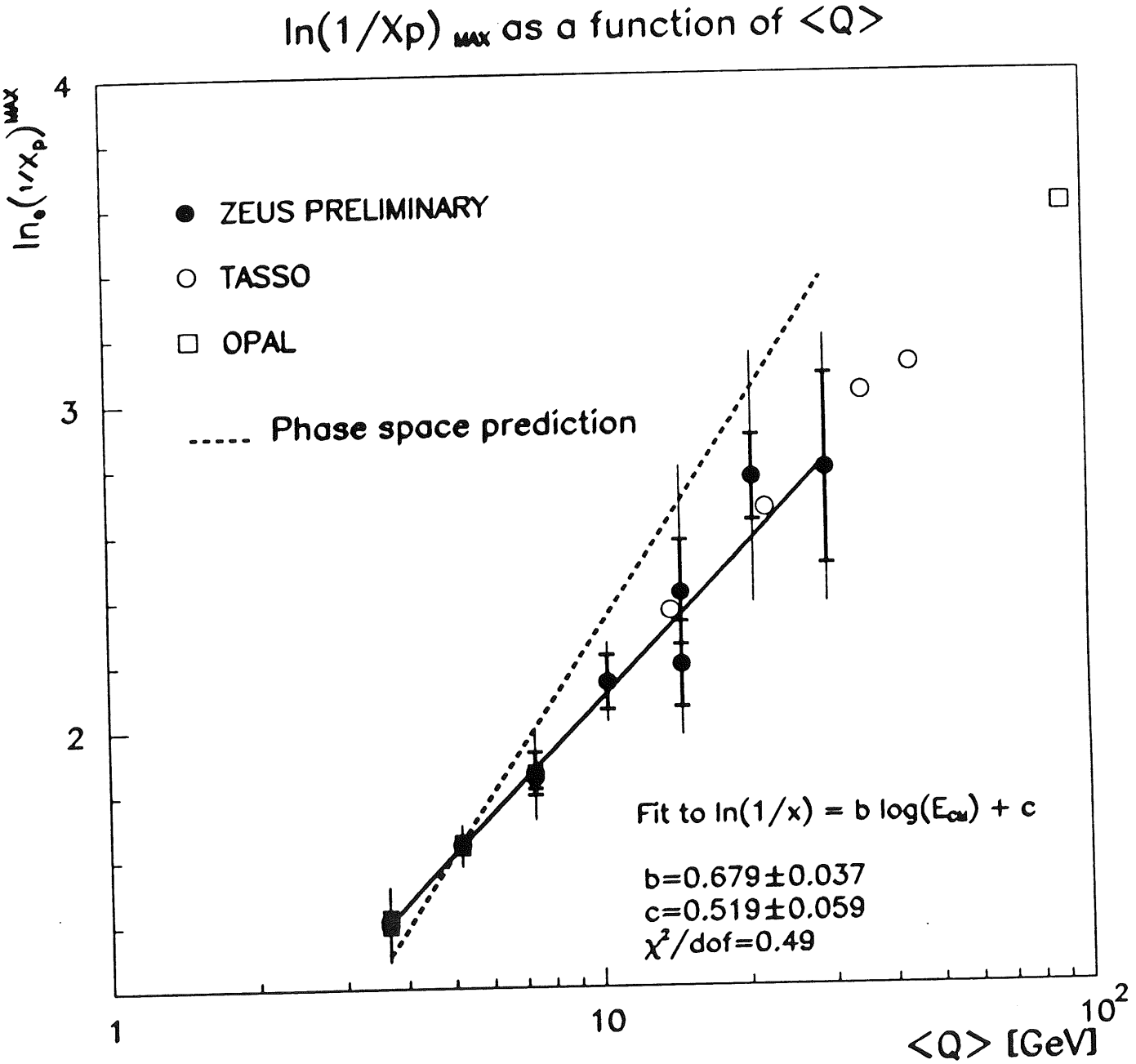
$$\frac{dn}{d\ln\left(\frac{1}{x_p}\right)} \quad ; \quad x_p = \frac{2E}{E_{CM}} \quad \text{(scaled momentum)}$$

$\ln\left(\frac{1}{x_p}\right)$ evolves with

$\sqrt{s}$ for e^+e^-

Q for DIS


Preliminary ZEUS Corrected Data in Analysis Bins
640 < Q² < 1280 GeV²
320 < Q² < 640 GeV²
160 < Q² < 320 GeV²
(Two x ranges)
80 < Q² < 160 GeV²
Statistical error only
40 < Q² < 80 GeV²
(Two x ranges)
20 < Q² < 40 GeV²
(Two x ranges)
10 < Q² < 20 GeV²
(Two x ranges)
1/N dn/dln(1/Xp)
2
0
0
1
2
3
4
5
6
7
ln (1/Xp)

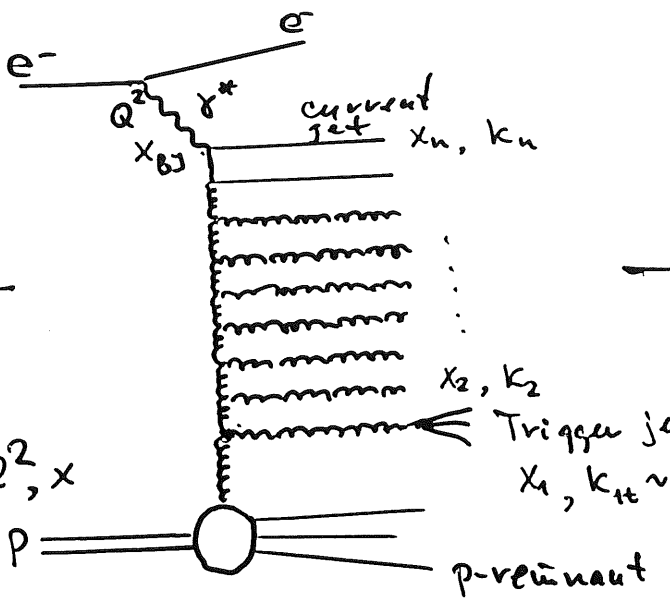

ln(1/Xp) max as a function of <Q>
ln(1/Xp)max
4
3
2
ZEUS PRELIMINARY
TASSO
OPAL
----- Phase space prediction
Fit to ln(1/x) = b log(Ecm) + c
b=0.679±0.037
c=0.519±0.059
χ²/dof=0.49
1
10
10²
<Q> [GeV]

FORWARD JETS in DIS

Dokshitser
Gribov
Lipatov
Altarelli
Parisi

$\alpha_s \ln(Q^2/Q_0^2)$

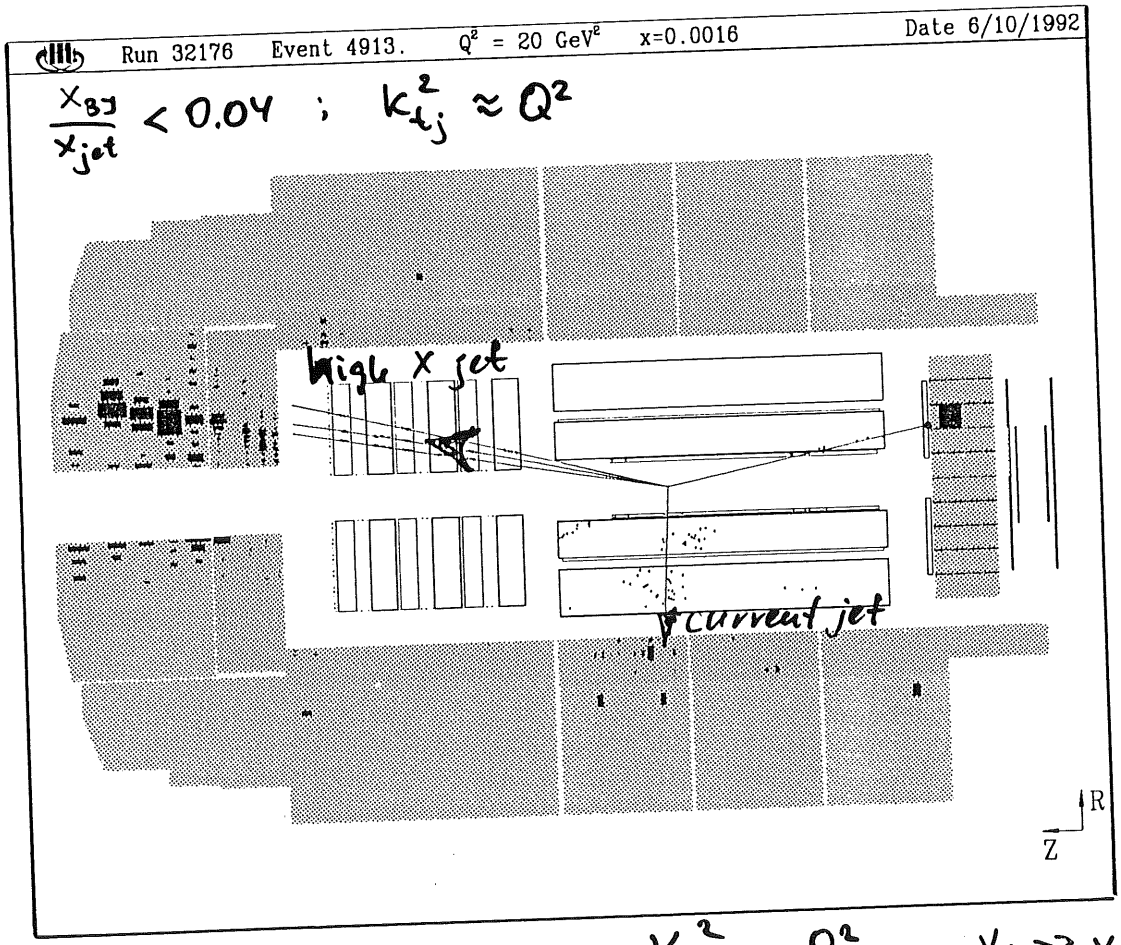
strong ordering in Q^2, x



Balitsky
Fadin
Kuraev
Lipatov

$\alpha_s \ln(1/x)$

strong ordering in x, but not in k_t



Mueller: "forward" jets with $K_{tjet}^2 \simeq Q^2$, $x_j \gg x_{BJ}$

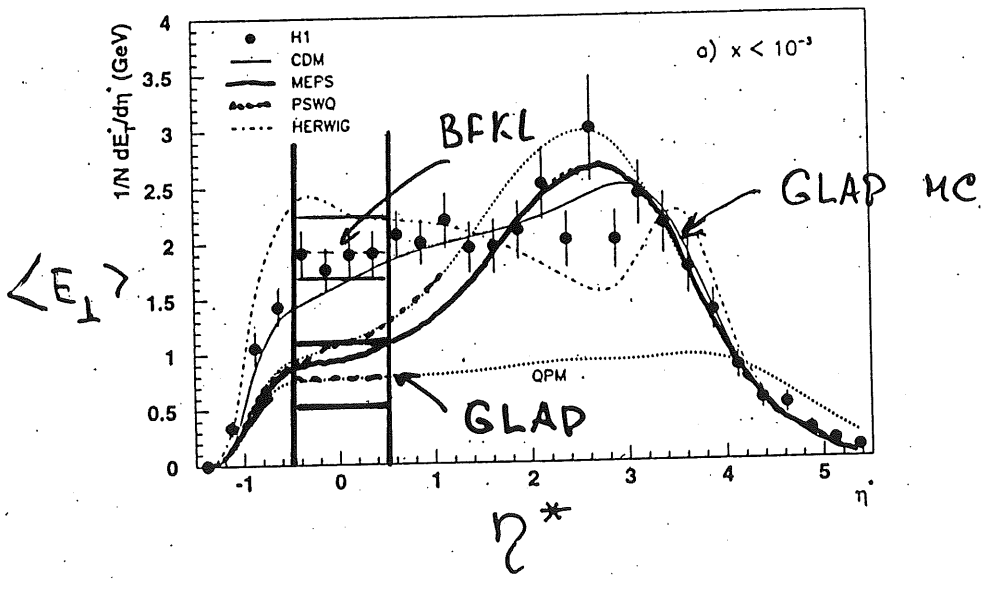
x_{BJ}	DATA	MC (≡DGLAP)	Analytical calculations* BFKL	no BFKL
$2\cdot10^{-4}-2\cdot10^{-3}$	128	69	111	45
$2\cdot10^{-4}-10^{-3}$	85	37	75	25
$10^{-3}-2\cdot10^{-3}$	43	32	36	20

(*) Martin, Kwiecinski, Sutton, NP B298 (1992), 67

↘ hint for Lipatov evolution (?)

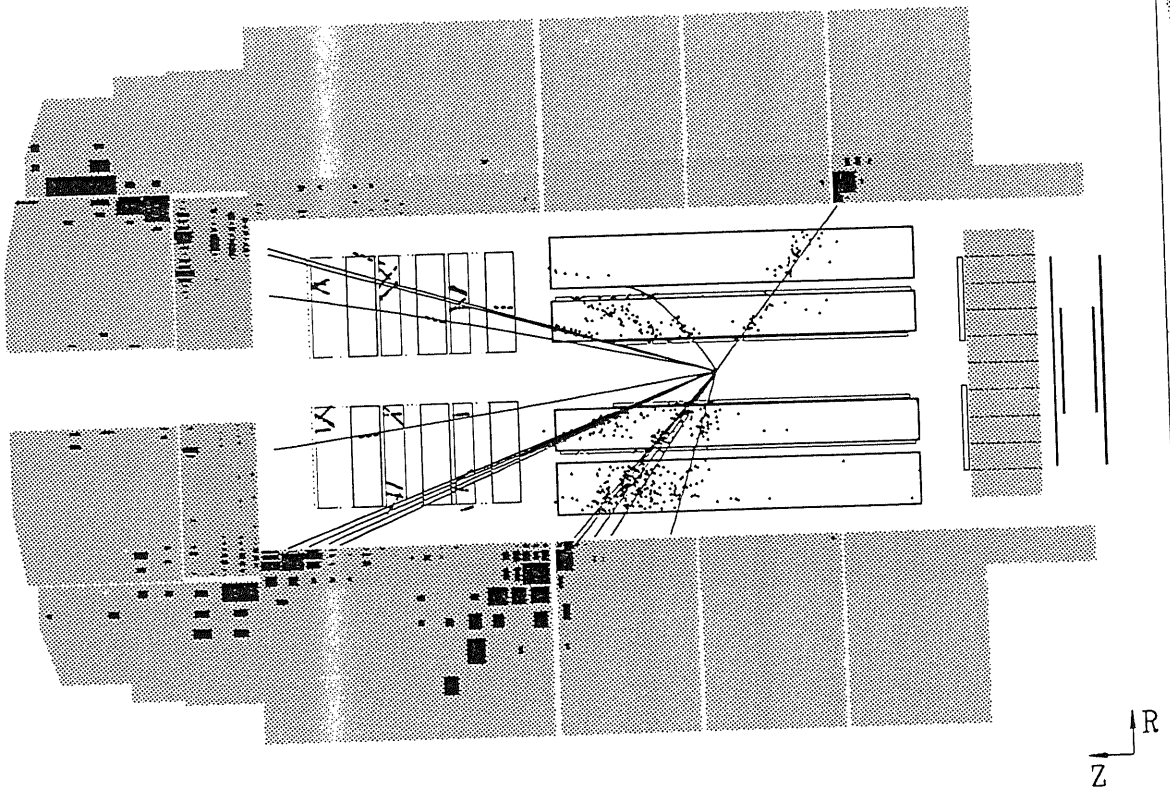
Work in progress on systematics improvement.

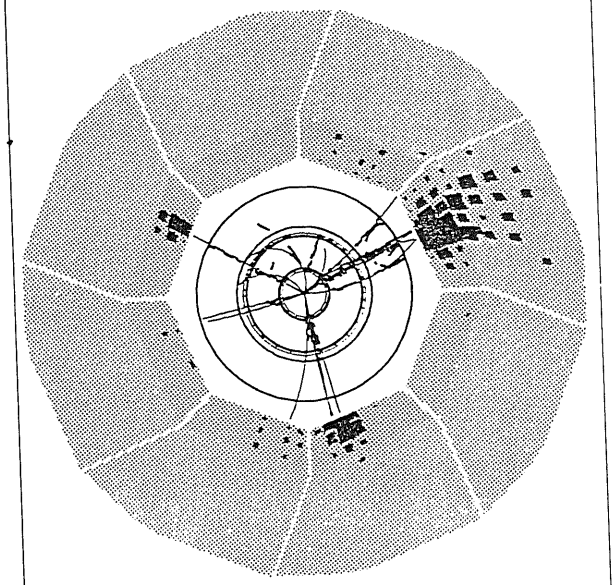
Corrected E_T-flow in $\gamma^* p$ C.M.S.

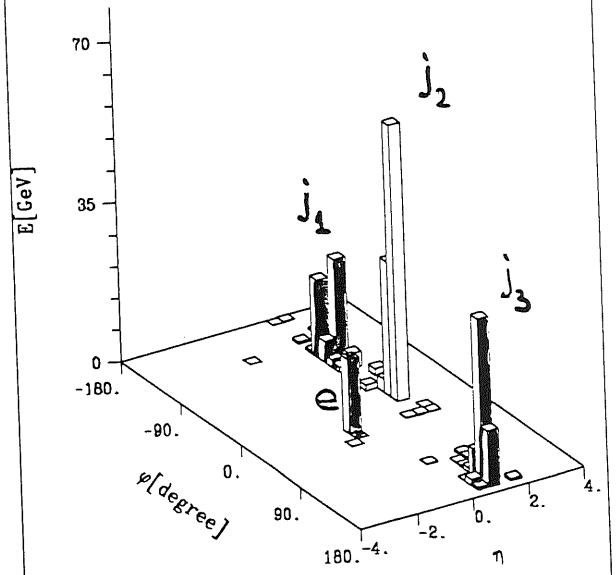


H1 Run 77369 Event 15492 Date 29/05/1994

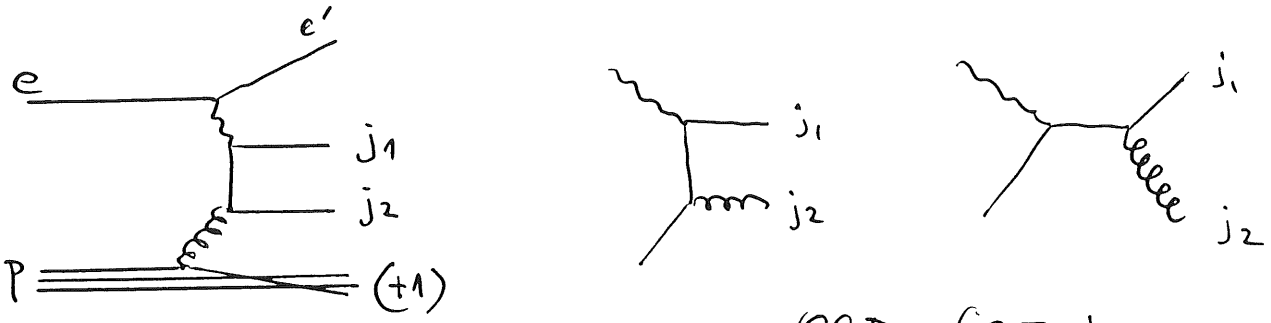
3-jet high Q^2 DIS event





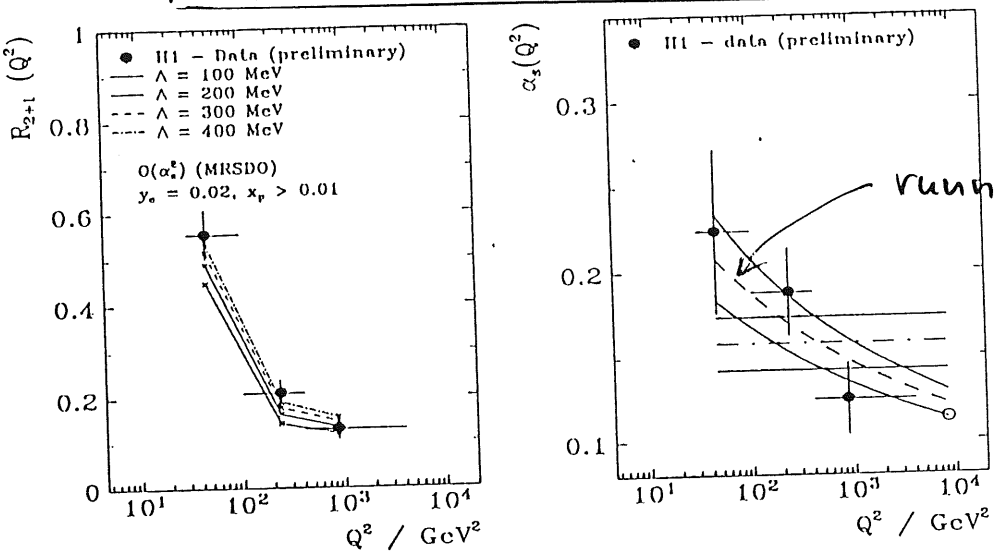


α_s measurement from multi-jet events (R_{2+1} jet)



BGF QCD Compton

$\alpha_s(M_Z^2) = 0.121 \pm 0.015$



running $\alpha_s(Q^2)$

4.5 Gluon density from (2+1) jets events in DIS

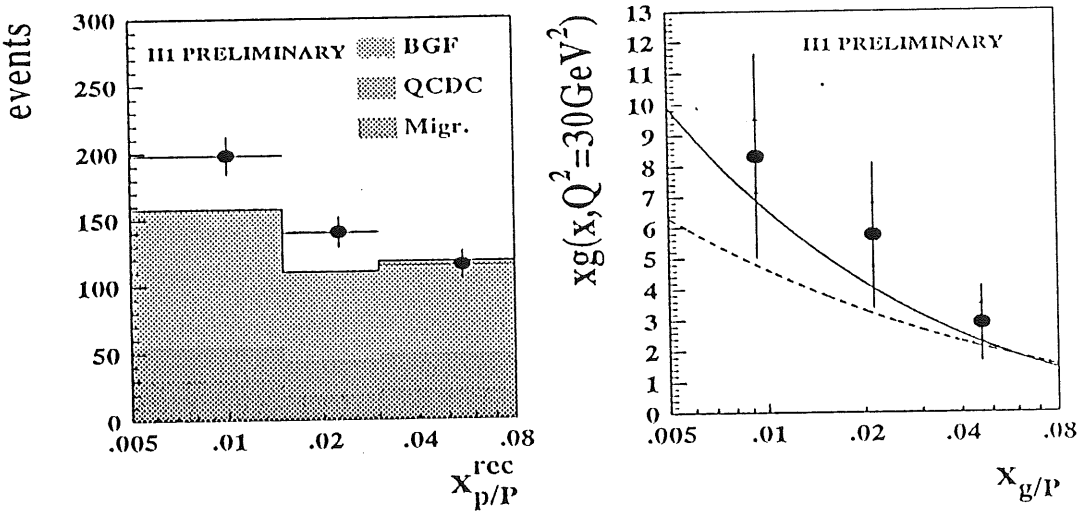


Figure 14: The uncorrected x_p^{rec} distribution (dots) compared to the MEPS expectations (solid). The predictions are broken down into the photon gluon fusion signal for $\hat{s} >$ 100 GeV^2, the QCD-Compton background (QCDC) for $\hat{s} > 100$ GeV^2 and the migrations from $\hat{s} < 100$ GeV^2 . b) The LO gluon density $xg(x, Q^2)$ compared to LO GRV (solid) and LO CTEQ2pL (dashed) parametrizations.

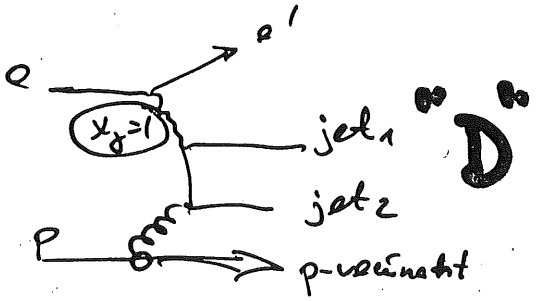
Compressed summary on γp results at HERA

From 1992 data:

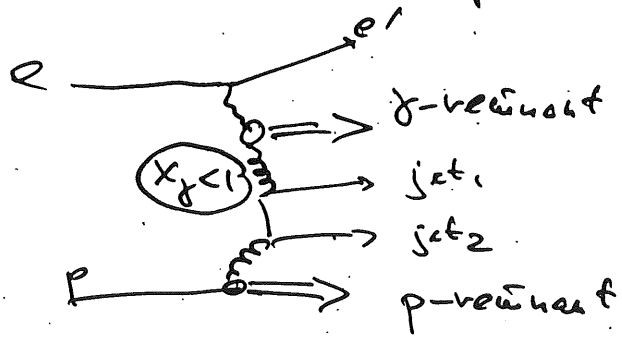
- $\sigma_{tot}^{\gamma p}$ rises smoothly, in agreement with Regge motivated picture
- Hard γp-scattering (jets) observed
- Resolved processes have been seen

New results:

- charged particle spectra:
  γp is harder than hp
- inclusive jet cross section in E_T and η have been measured in γp events (sensitive to the "γ structure function")
- for the first time gluon density in the photon has been measured (preliminary)



"D"



"R"

- hard γp-diffraction observed

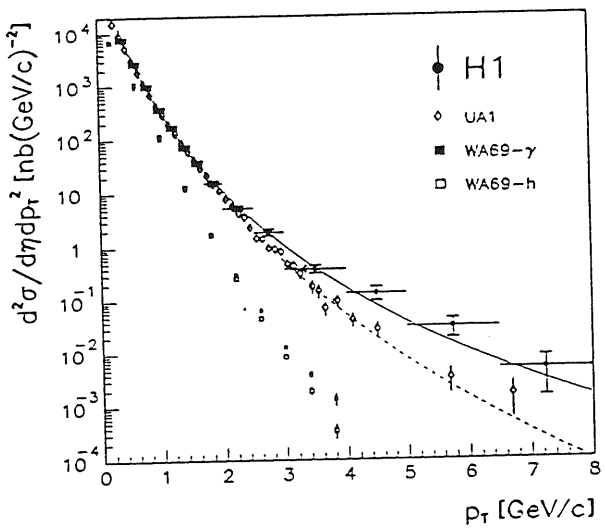


Figure 2: The inclusive ep cross section for charged particles in photoproduction (full circles) measured in the kinematical region $|\eta| < 1.5$, $Q^2 < 10^{-2}$ GeV^2 and $0.3 < y < 0.7$, at an average $E_{CMS}(\gamma p) \approx 200$ GeV. The error bars indicate the quadratic sum of statistical and systematic errors. An overall uncertainty of 7% from the luminosity measurement is not included in the figure. Also shown are cross sections measured by the UA1-collaboration (open diamonds) at $E_{CMS} \approx 200$ GeV for $|\eta| < 2.5$, normalized to the H1-data at $p_T = 1.5$ GeV/c. The curves indicate the power-law fit, as described in the text.
The rectangles show the shape of the cross section measurements by the WA69-collaboration at $E_{CMS} \approx 18$ GeV, for γp (filled rectangles) and for *hadron* p data (open rectangles).

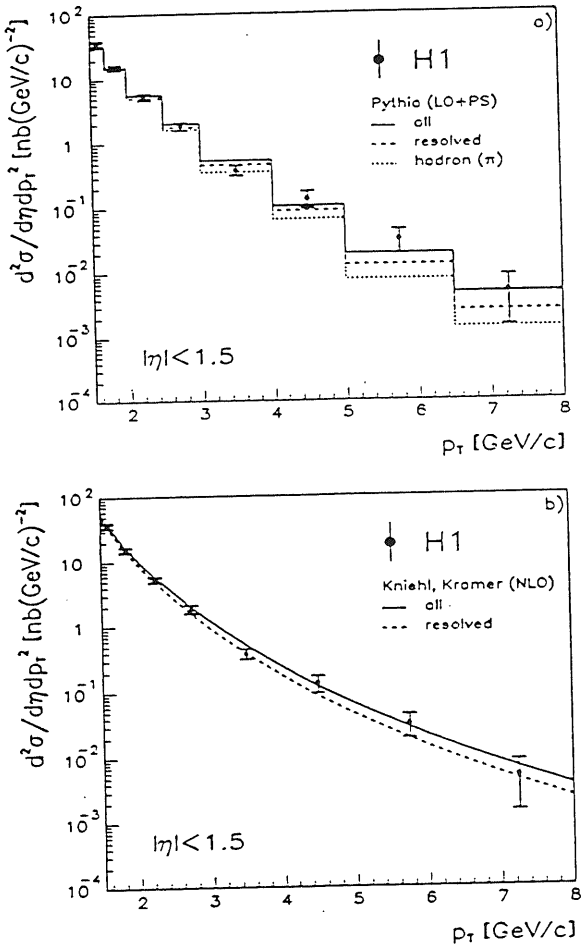
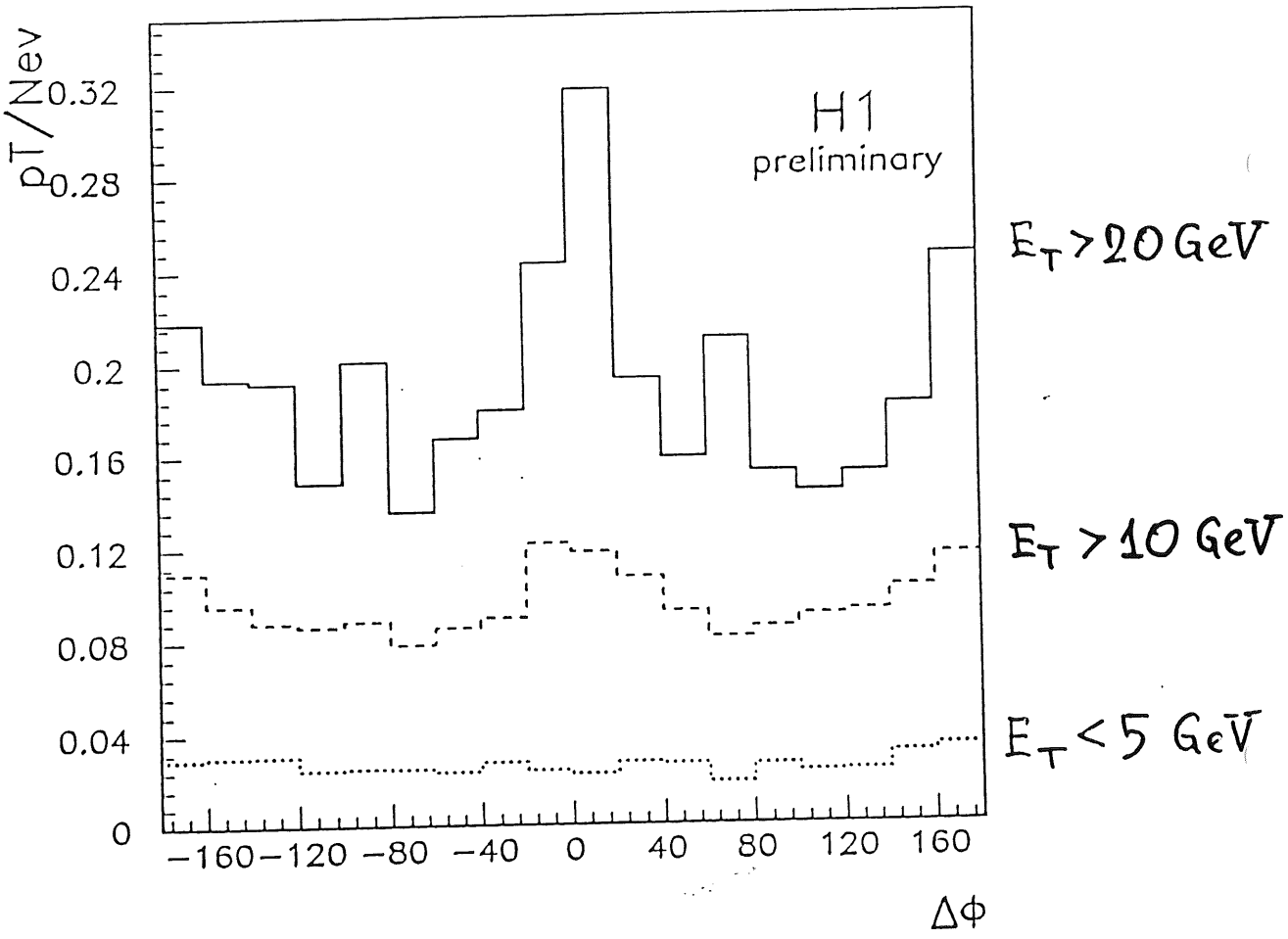
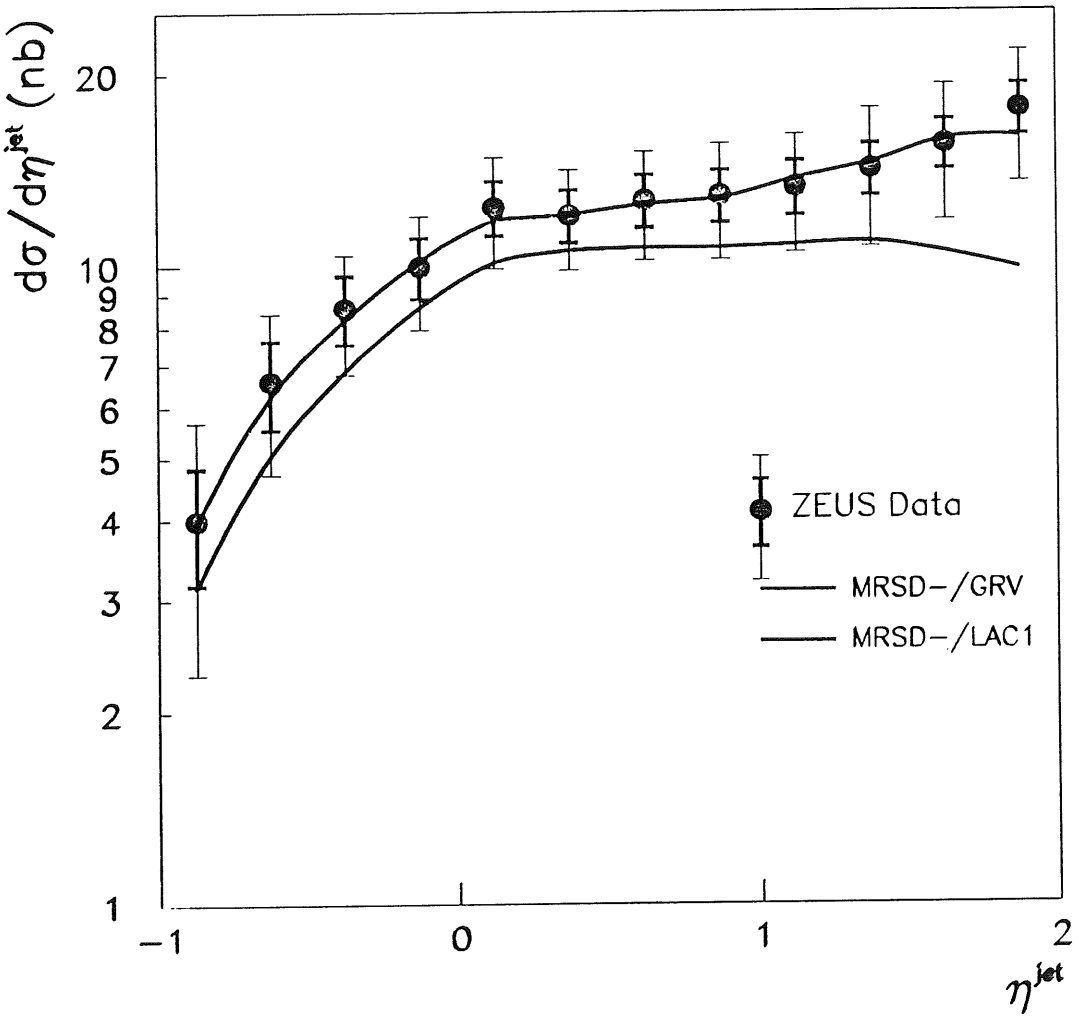
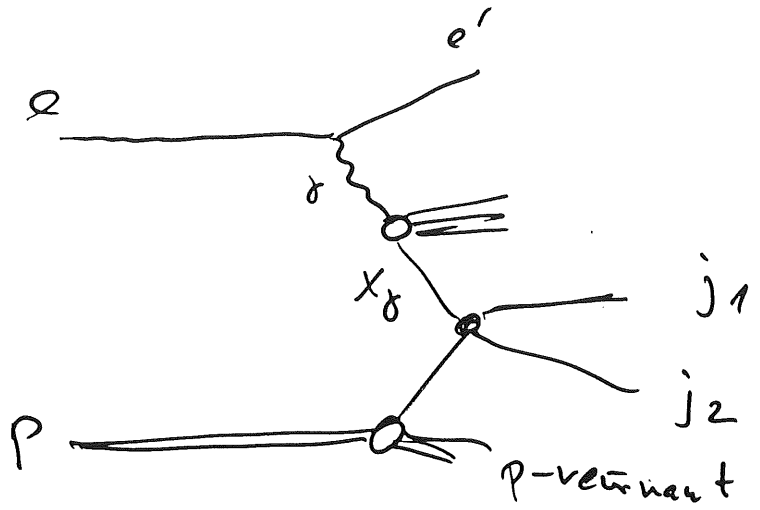


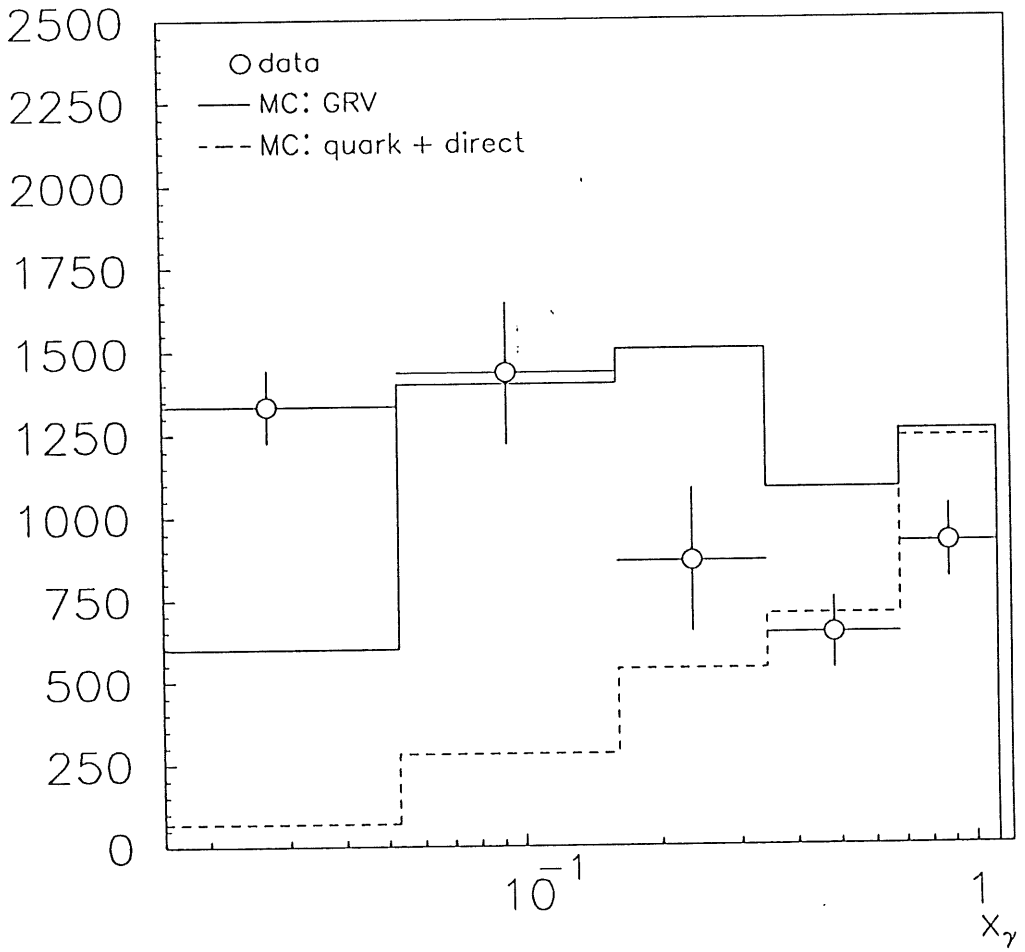
Figure 3: a) The measured cross section as depicted in fig. 2 (full circles) is compared in the $p_T > 1.5$ GeV/c region with the predictions of a LO QCD calculation (PYTHIA). The histograms indicate the different contributions to the calculation: resolved photon (dashed), all=resolved+direct (full), hadron using the pion structure function (dotted).
b) The same data points as in fig. 3a are compared with an analytical NLO QCD calculation [28]. The solid line represents the sum of the resolved (dashed line) and direct photon contributions.



φ- distance to the highest p_t particle

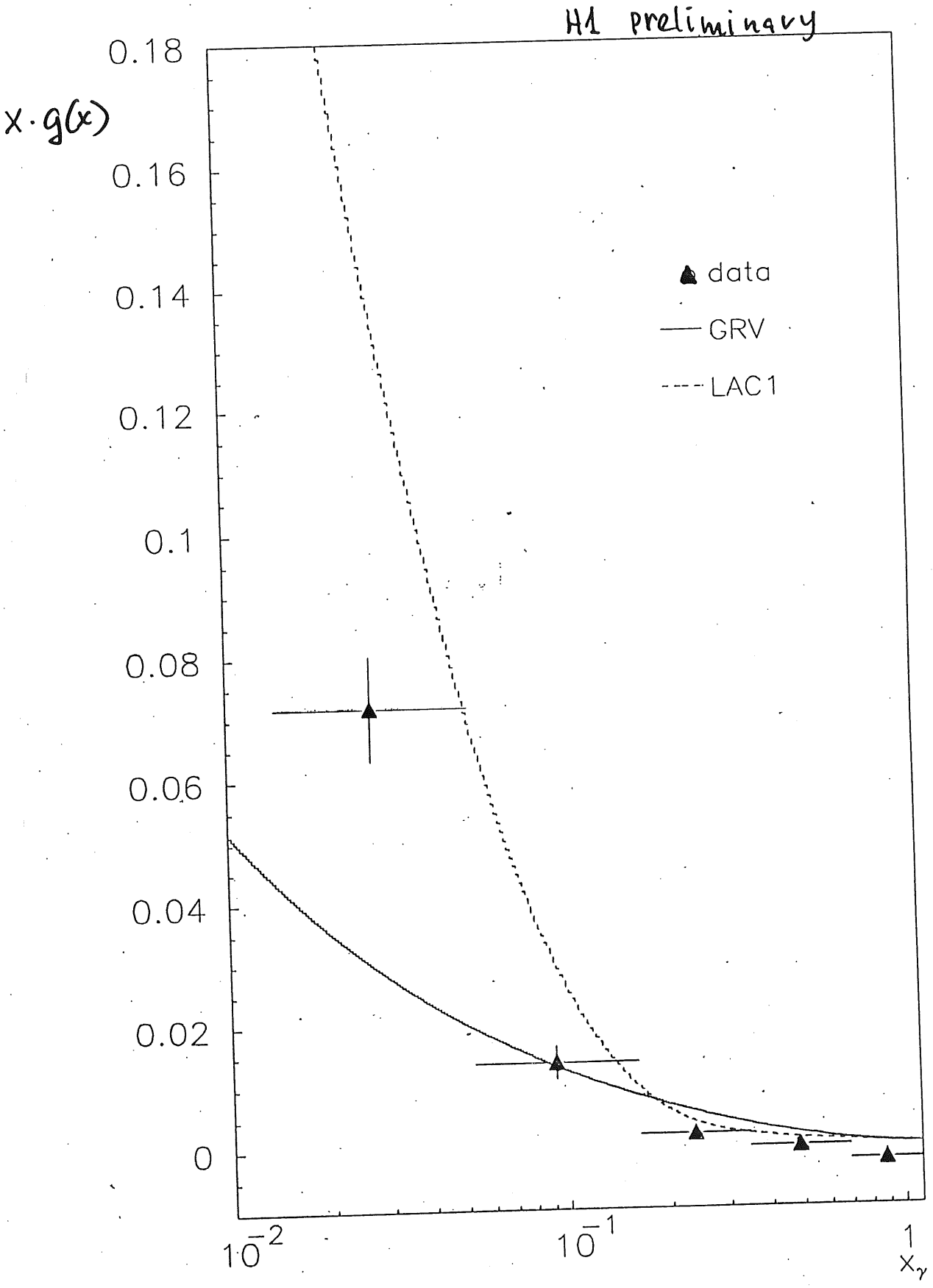

dσ/dη^jet (nb)
20
10
9
8
7
6
5
4
3
2
1
−1
0
1
2
η^jet
ZEUS Data
MRSD−/GRV
MRSD−/LAC1





$$x_\gamma = \frac{\sum_{jets} (E - p_z)}{\sum_i (E - p_z)_i}$$

Gluon density in the photon (L.O.)



SUMMARY

Already at the beginning of its physics program HERA has proven its large potential:

- for the first time $\sigma_{cc} \simeq \sigma_{NC}$ observed experimentally
- F_2^p shows fast rise at low x
- evidence of new (BFKL) dynamics at low x
- α_s has been measured as a function of Q^2:
  - running of $\alpha_s(Q)$ in one experiment
  - precision potentially comparable with LEP
- gluon density in the proton (DIS jets) and photon (γp jets) can be extracted

...

More interesting results are expected with increasing of luminosity:

- precise extraction of EW parameters
- global QCD fit of $F_2^?$
- HQ physics
- Hard diffraction → $I\!P$ structure → bridge between pQCD and soft non perturbative regime

INTEGRATED LUMINOSITY