INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.762 - 29

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

13 June - 29 July 1994

HERA - RECENT RESULTS AND FUTURE PLANS

ALBRECHT WAGNER
DESY
Hamburg
GERMANY

Please note: These are preliminary notes intended for internal distribution only.

HERA

RECENT RESULTS

&

FUTURE PLANS

ALBRECHT WAGNER

- Physics Case
- HERA Detectors
- HERA machine & performance
- Physics results
- Future plans = 2. generation experiments

Lepton - Nucleon Scattering

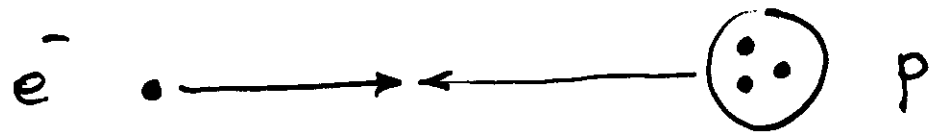
probes - electron
- neutrino

1965 - 1994
Cornell, DESY, SLAC : $\sqrt{s} \sim 4-6$ GeV
CERN, Fermilab : ~ 20 GeV
since 1992
HERA (DESY) : ~ 300 GeV

Results from "deep inelastic scattering":

- partons in nucleus
- partons → point like
  spin 1/2
  fractional charge
- momentum distribution of partons
- valence
  sea
  quarks
- gluons
- weak neutral current

HERA



30 GeV (26.6 GeV) 820 GeV

- Center of mass energy range:

$\sqrt{s} = \sqrt{4 E_e E_p} = 314$ GeV

today's fixed target experiments:) 15

$\sqrt{s} = \sqrt{2 E_e m_p} \approx 20$ GeV

HERA corresponds to fixed target exp. with $E_e \approx 50$ TeV

- sensitivity to substructure:

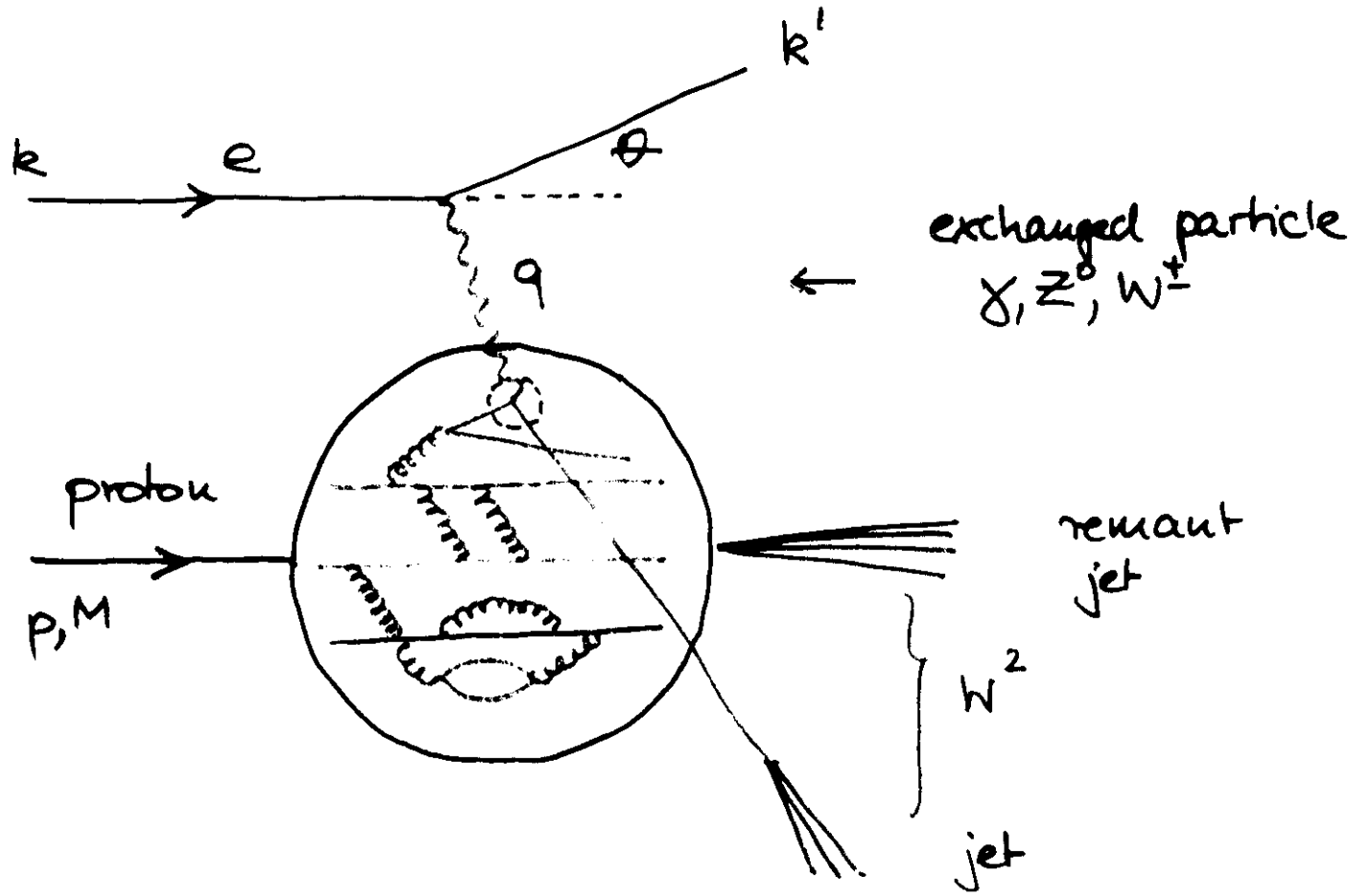
  - proton 1 fm

  - $\lambda = \frac{\hbar c}{\sqrt{s}} = \frac{0.2 \text{ fm GeV}}{314 \text{ GeV}} = 0.0006 \text{ fm}$) $\frac{1}{1000}$

  - at fixed target exp.

    $\lambda = 0.01$ fm

    ↘ HERA as microscope



- $Q^2 = -q^2 = -(k-k')^2$ 4-momentum transfer

  $\simeq 4 E_e E_e' \sin^2\theta/2$

  Q defines volume probed by photon $r \propto \frac{1}{Q}$

- $x = \frac{Q^2}{2 p \cdot q}$ fraction of nucl. mom. carried by struck quark

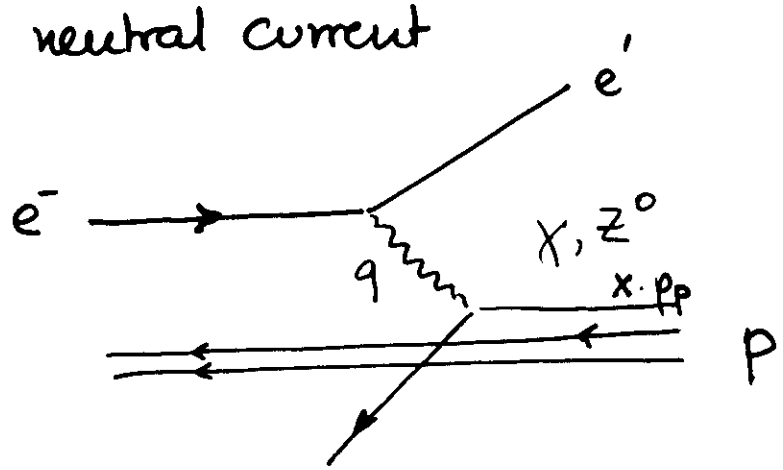
→ deep inelastic scattering

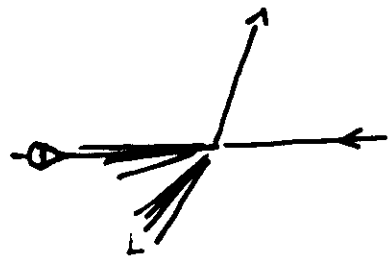
$Q^2 \gg M^2$ $W^2 \gg M^2$

Physics at HERA

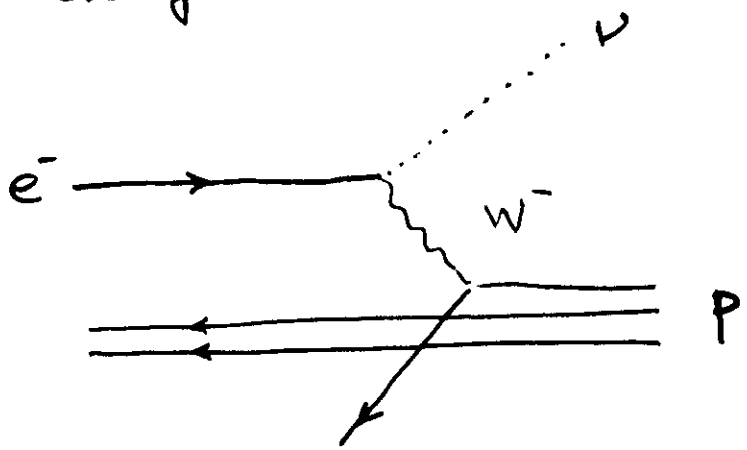
1) Deep Inelastic Scattering DIS

neutral current





charged current



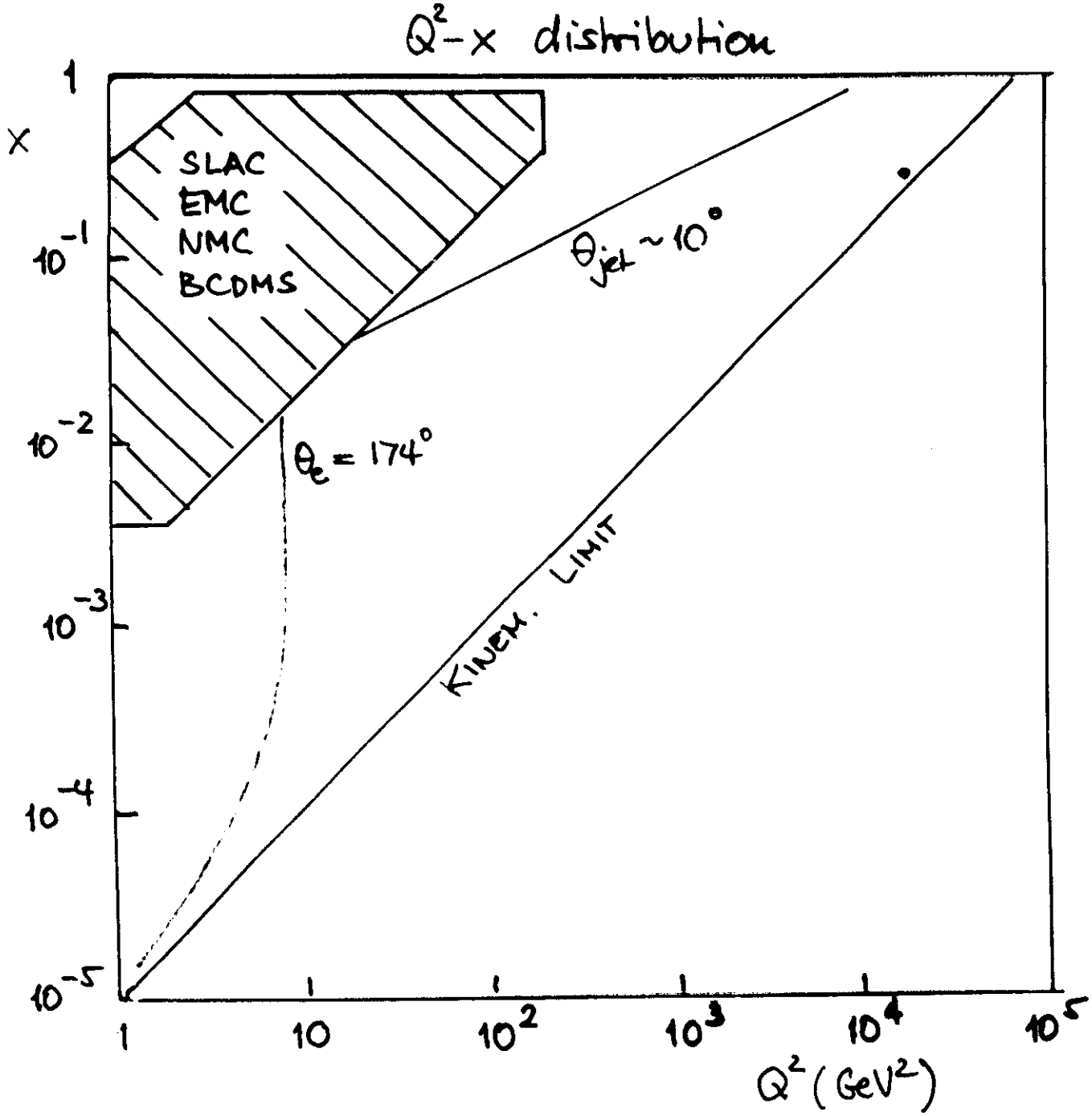
Kinematic quantities →

$Q^2 \geq 100\ GeV^2$ → continuation of (e, μ, ν)-Experiments at high energies

$x \geq 10^{-2}$

- range of Q^2 extended by 100
- 15 times better resolution for substruct.

→ new domains in x, Q^2 accessible



- measure $\frac{d\sigma}{dx}(Q^2)$ density of quarks with energy fraction x inside proton

- cross section described by structure functions

of special interest:

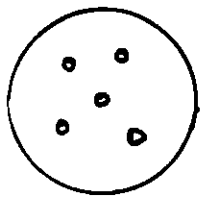
Physics at low x and high Q^2

Ryskin
Levin
Gribov

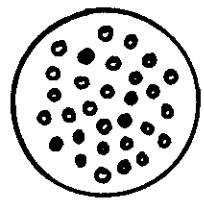
$10^{-4} < x < 10^{-2}$

$Q^2 > 10 \quad GeV^2$

→ Test of QCD at high parton densities

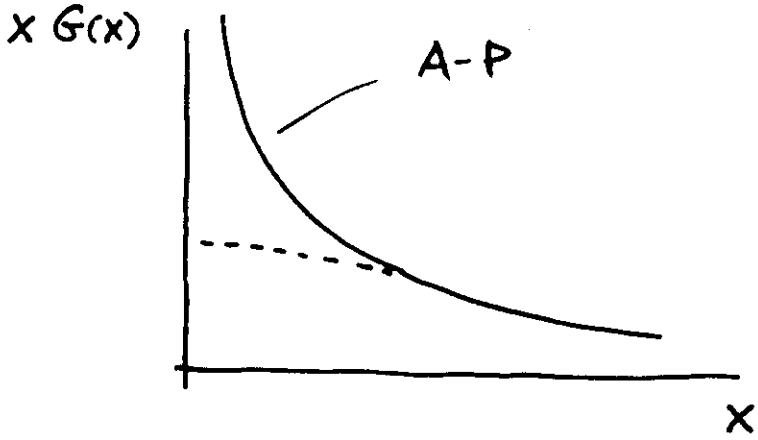


$x > 10^{-2}$



$x < 10^{-2}$

parton density rises for small x, large Q^2



screening ?
"hot spots"

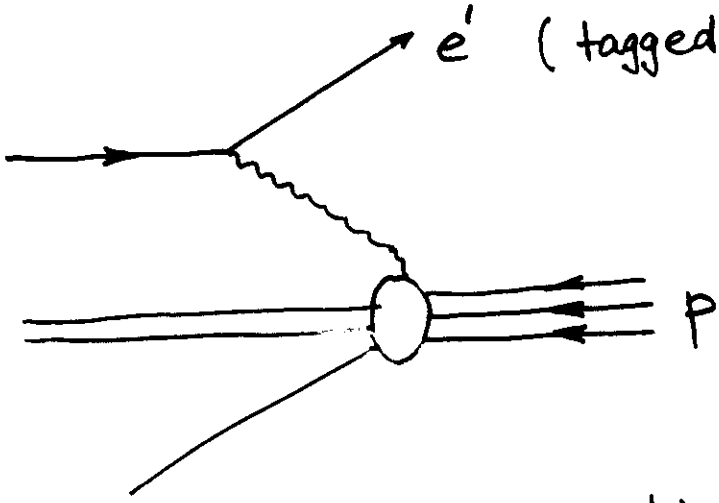
→ important testing ground for QCD in transition from perturbative → non-perturbative region

→ important for $p\bar{p}$ cross section

2) Physics at low x and low Q^2

$Q^2 < 4\ GeV^2$ → quasi real photon

Photoproduction



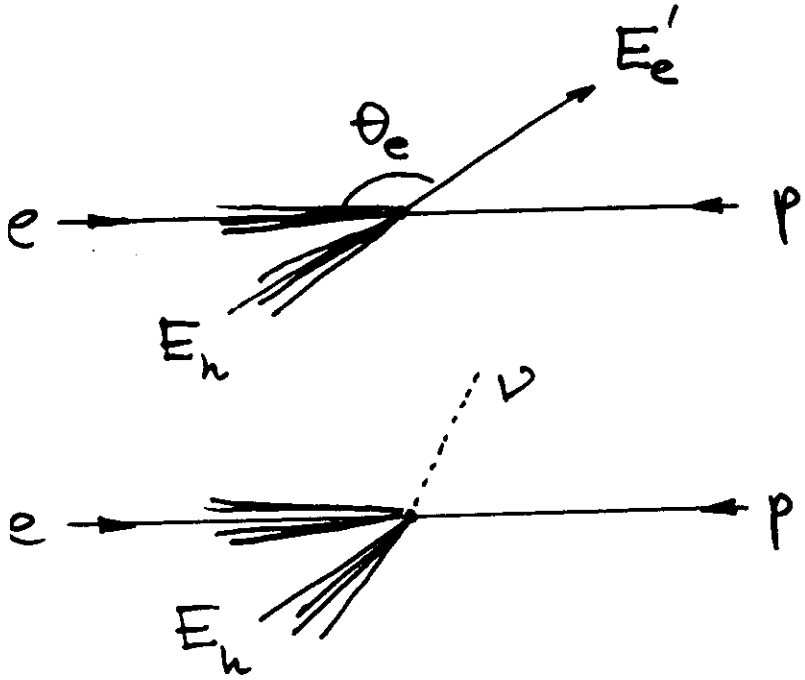
measure : . cross section
. final state topology
...

↘
- study γ - p coupling
- does γ interact as a hadron
- measure gluon density in γ

3) Search for new physics

The HERA Experiments

Task: measurement of the kinematic quantities of the scattering process



measure

E_e', θ_e

$\delta E_e \sim 1\% E_e$

$$y_h = \sum_h \frac{E_h - p_{zh}}{2E_e}$$

$\delta E_h \sim 2\% E_h$

↓ very stringent requirement on calorimetry:

- absolute calibration
- energy resolution

basic elements of detectors

1) measurement of directions & momenta of charged particles

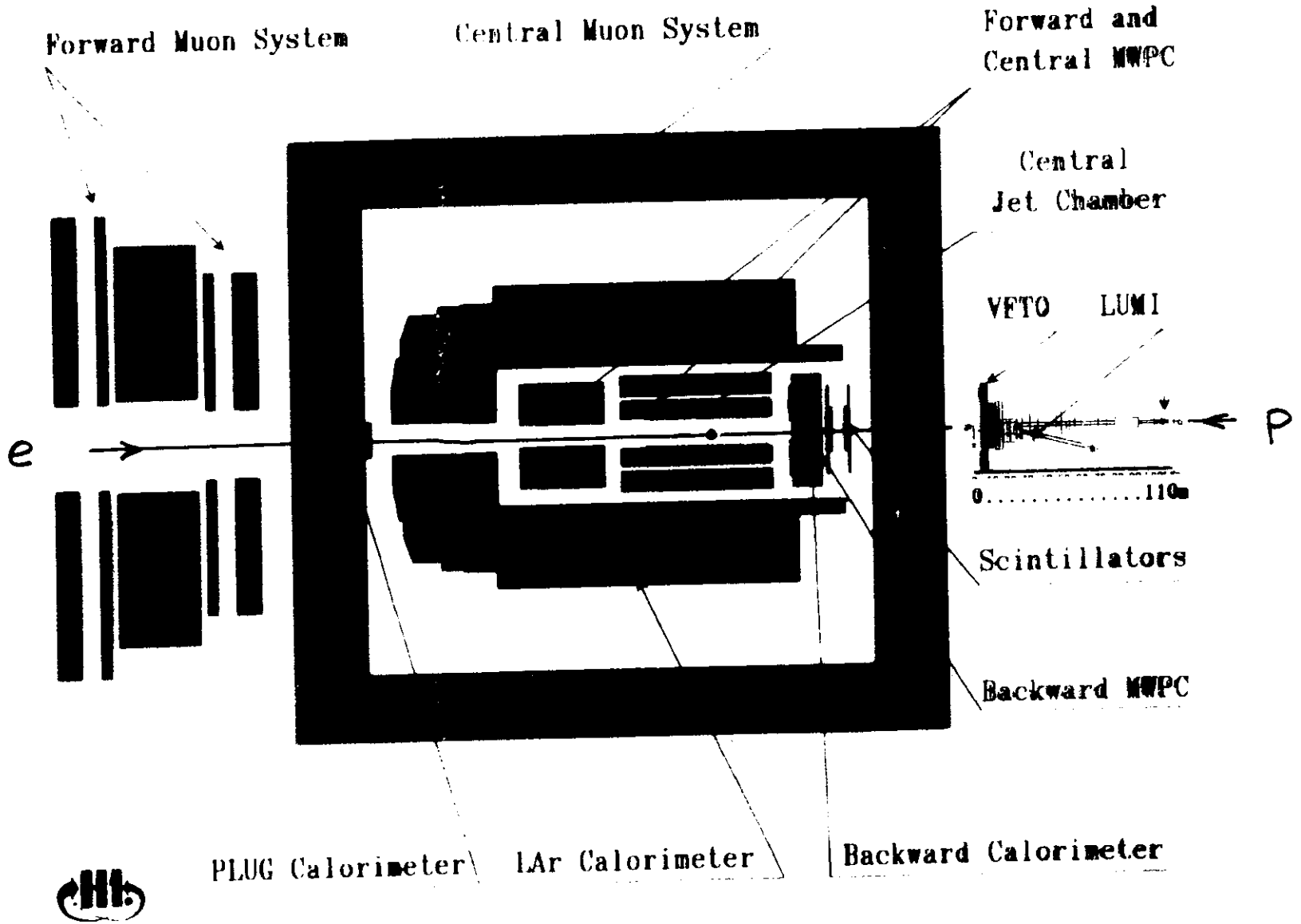
- magnetic field (solenoid)
- tracking detectors

2) measurement of energy (energy flow) of <u>all</u> particles (charged & neutral)

- 'calorimeters'

3) Identification of particles

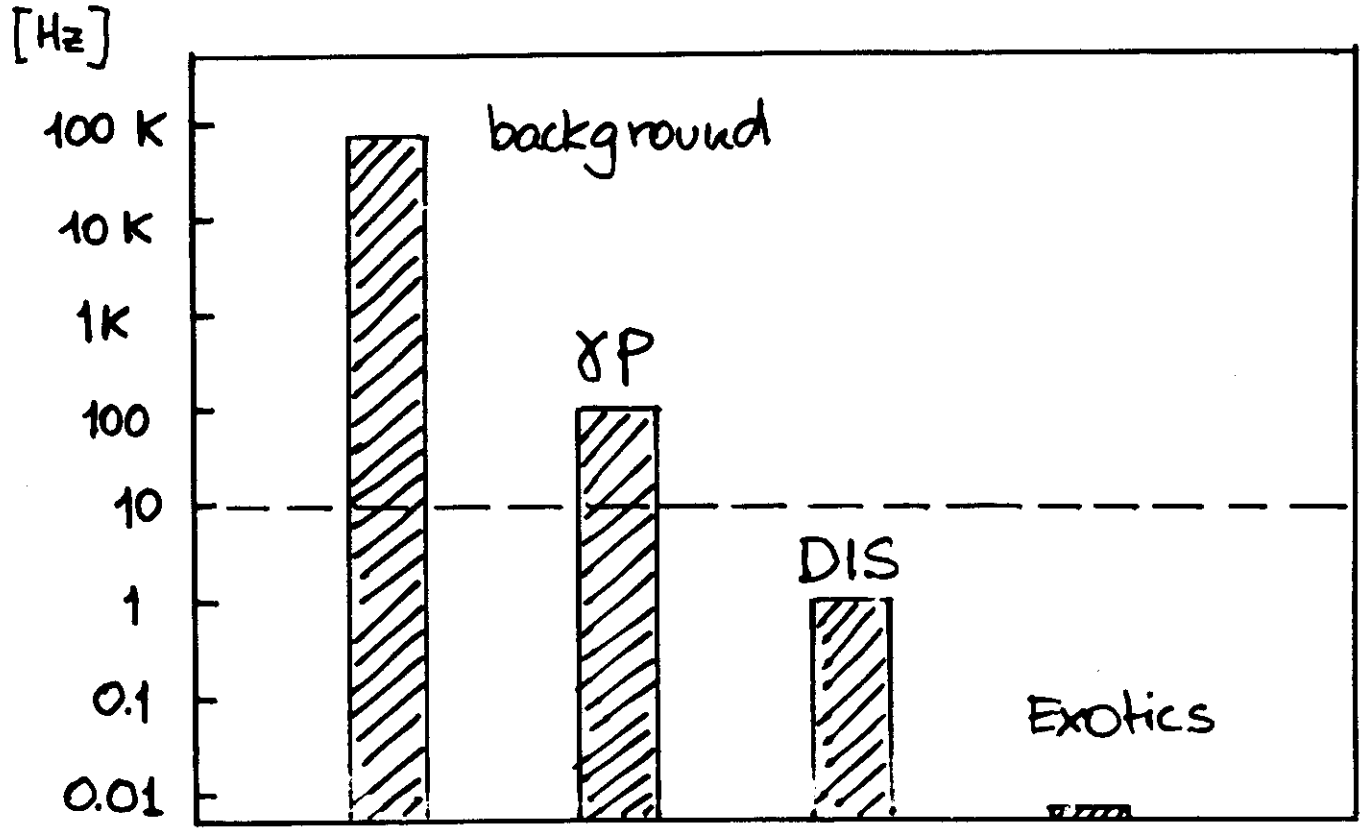
- energy loss in gas of tracking chambers
- energy loss & interactions in iron shielding

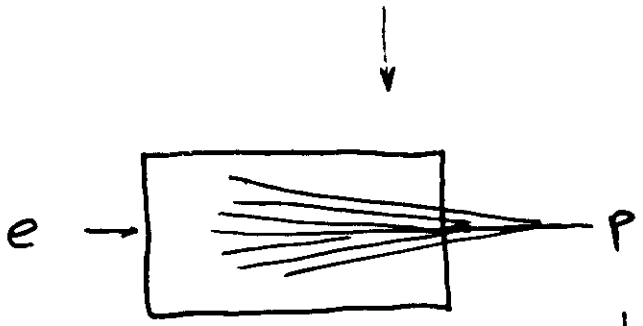

Forward Muon System
Central Muon System
Forward and
Central MWPC
Central
Jet Chamber
VETO
LUMI
e
p
0.....110m
Scintillators
Backward MWPC
PLUG Calorimeter
LAr Calorimeter
Backward Calorimeter

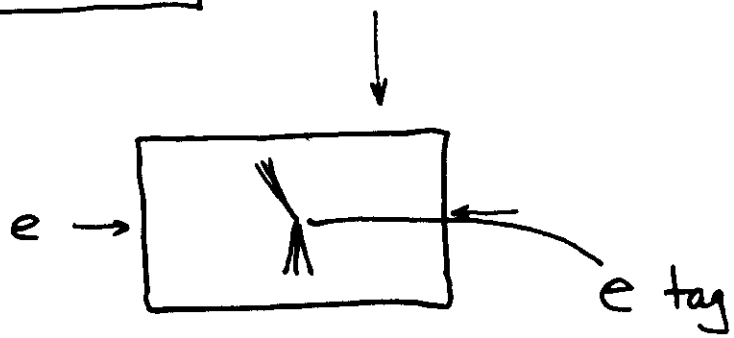
ZEUS

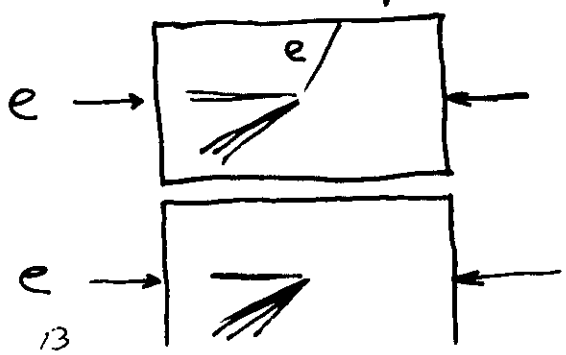
ypical Rates at HERA

for nominal Luminosity









cross section

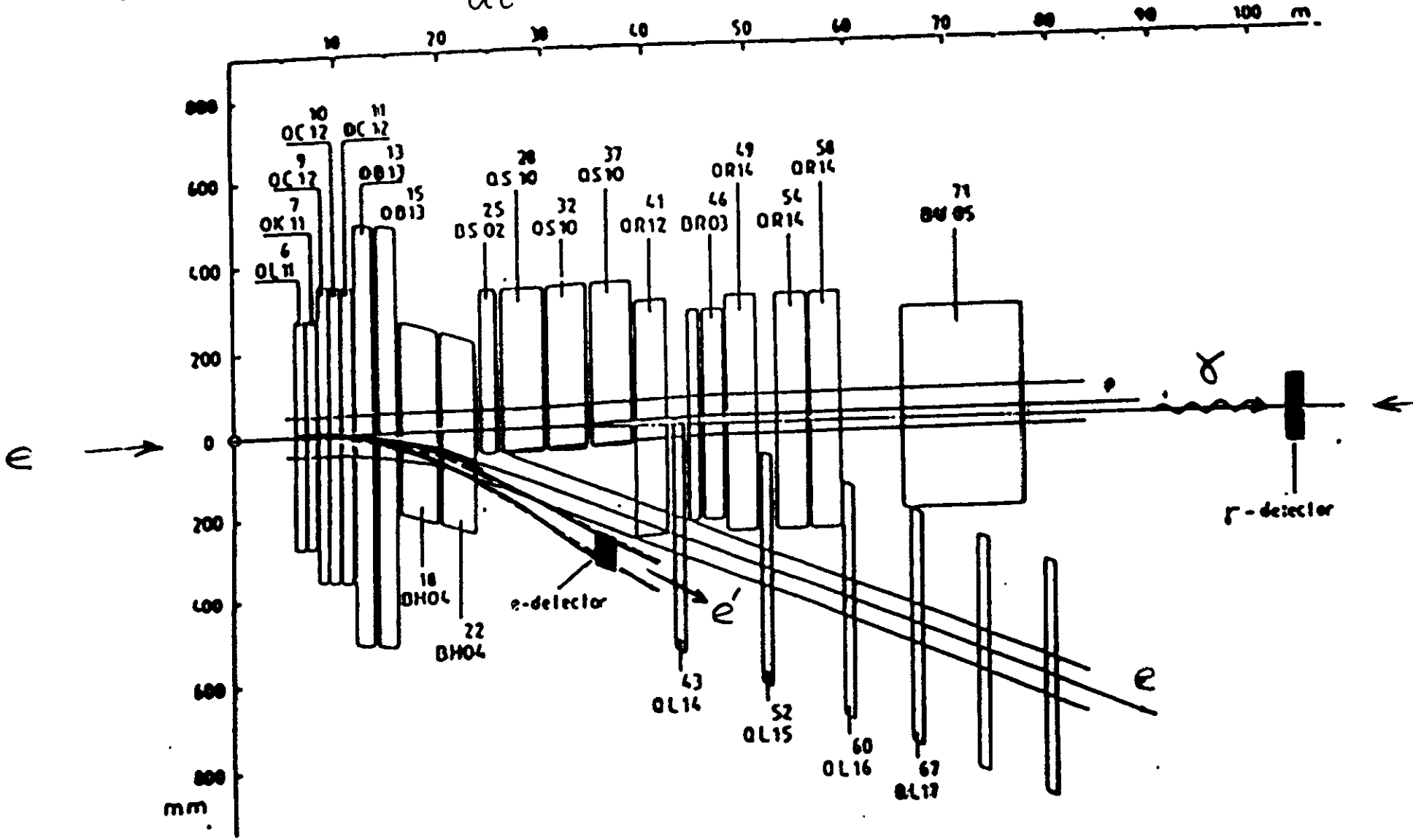
15000 nb

100 nb

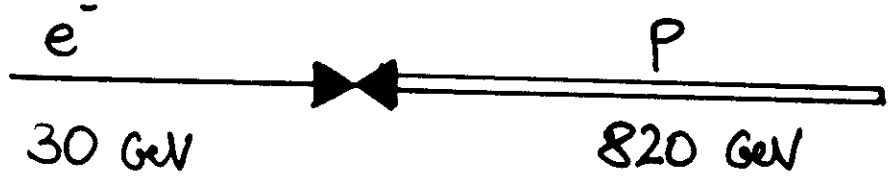
0.1 nb

The Luminosity detector setup

$$\frac{dN}{dt} = L \cdot \sigma$$



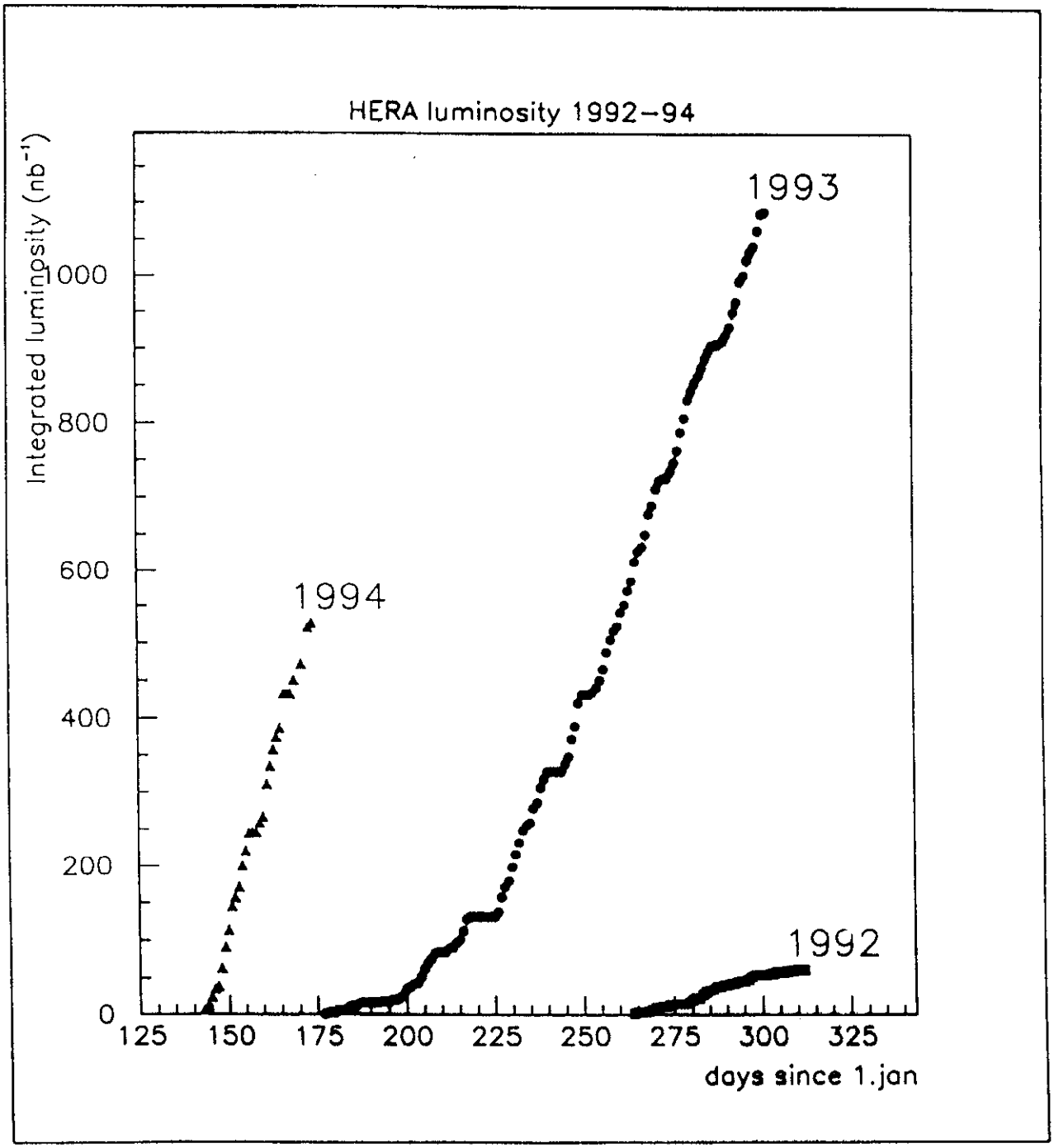
The HERA Storage Rings



	Electrons	Protons
Energy	30 GeV	820 GeV
Injection En.	13 GeV	40 GeV
N_{bunch}	210	210
$\langle I \rangle$	60 mA	150 mA
ΔE/turn	127 MeV	2 eV
Magn. Field	.165 T	4.65 T
Circumference	6336 m	
Luminosity	$1.5 \cdot 10^{31}$ $cm^{-2} s^{-1}$	

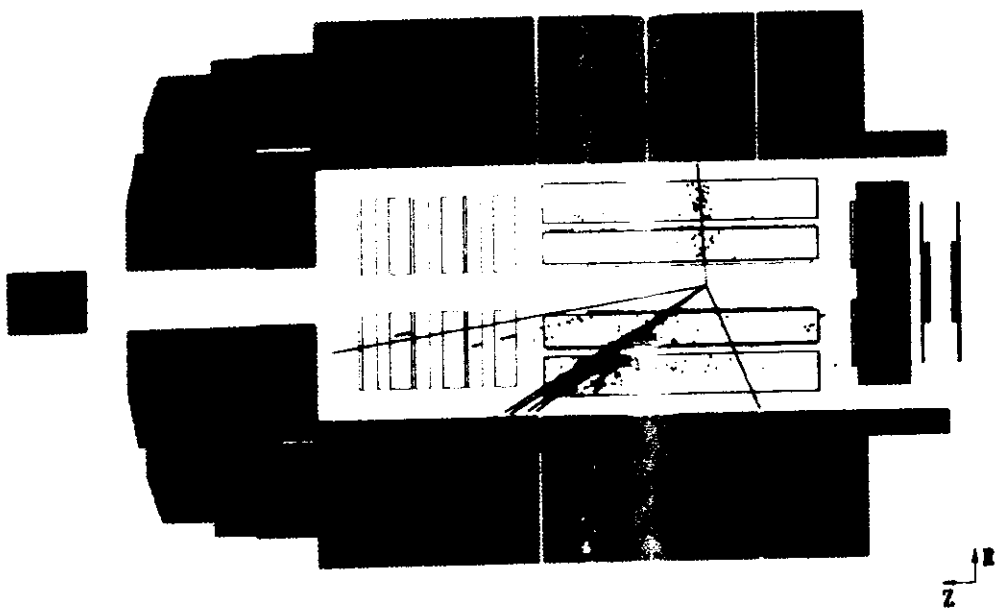
Authorisation	4.84
Construction complete	11.90
first ep collision	10.91
first data	7.92

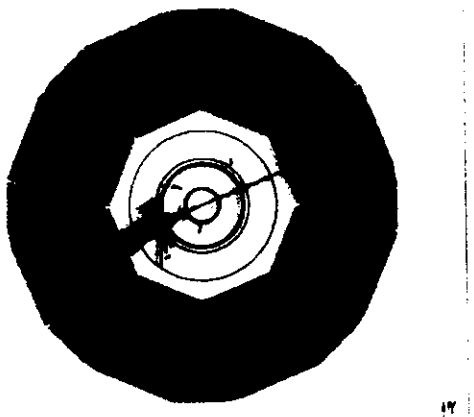
Luminosity history

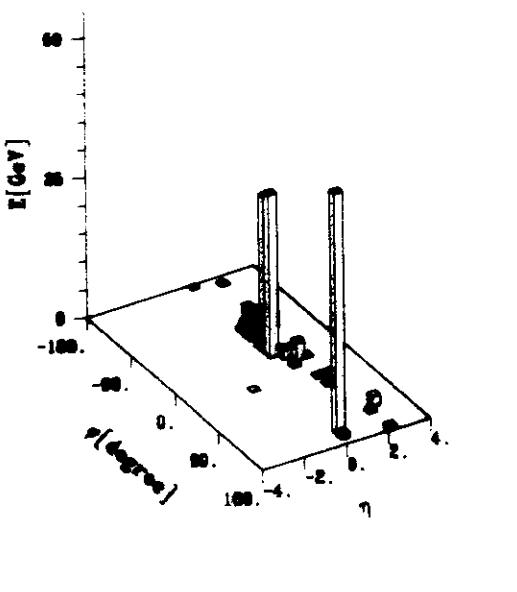


Run 59416 Event 3357 Class: 8 9 12 14 16 20 22 23 28 Date 21/09/1993

$Q^2 = 2470\ GeV^2$ $x = 0.13$ $y = 0.22$

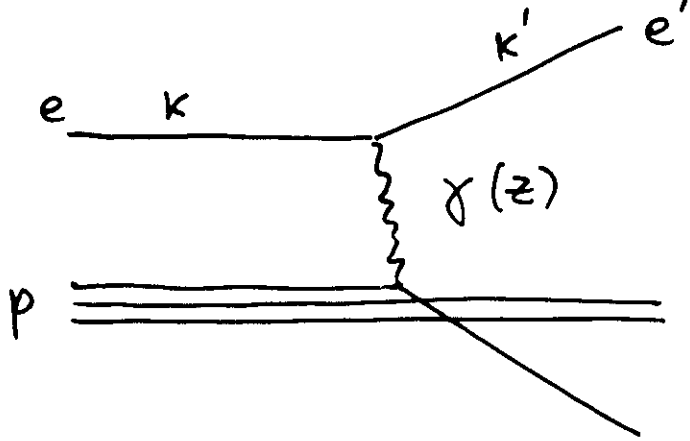






Measurement of the Structure Function $F_2(x,Q^2)$

DESY reports by ZEUS, H1 / Aug 93
analyses based on ~ 25 nb^{-1} / Exp



$$Q^2 = -q^2 = -(k-k')^2$$

$$x = \frac{Q^2}{2pq}$$

$$y = \frac{Q^2}{xs}$$

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

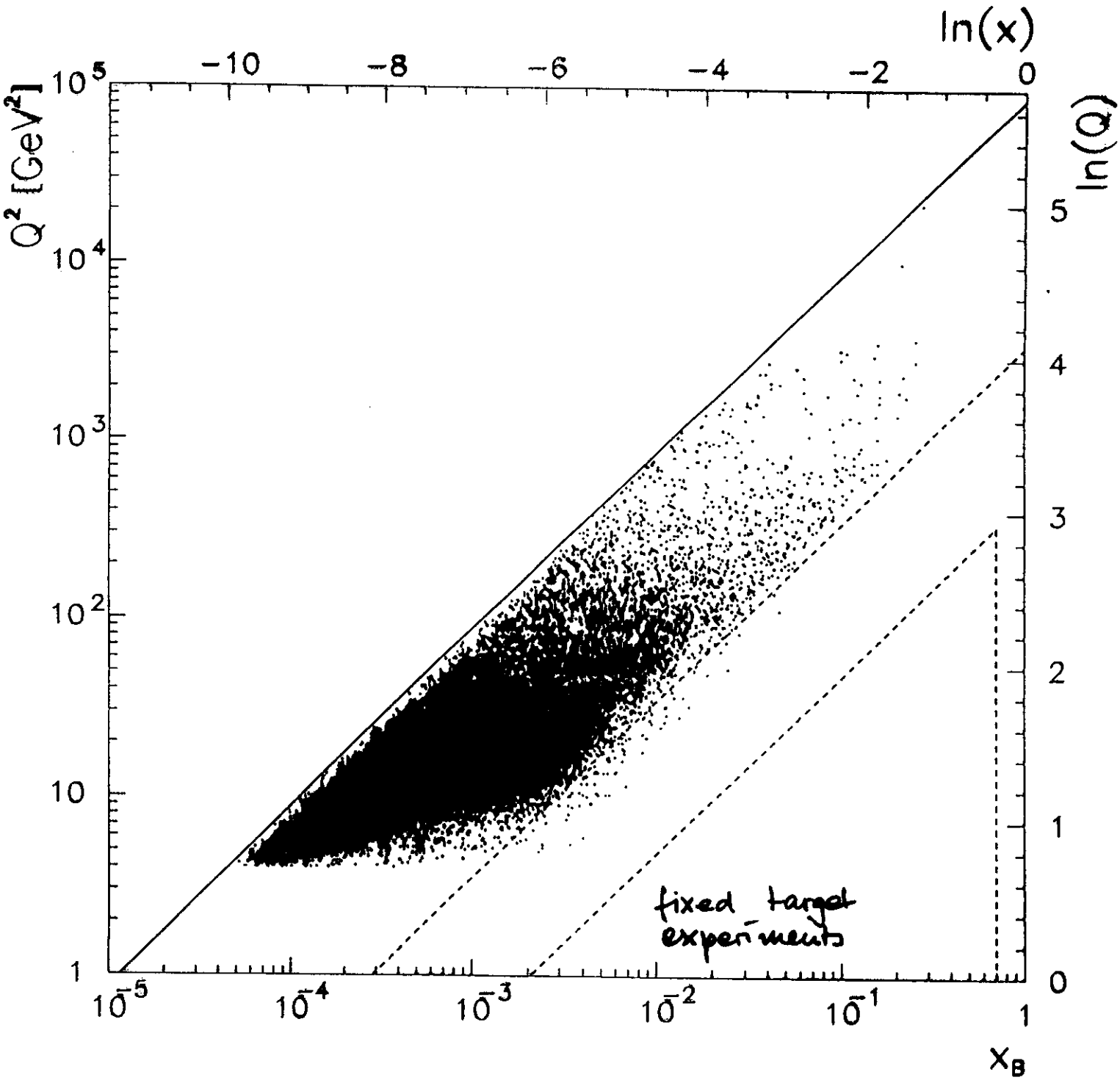
- $R = \frac{\sigma_L}{\sigma_T}$ photo absorption X section for long / transv polarised γ

  - not yet measured at HERA
  - calculate according to QCD prescription using MRS D_ parton distribution

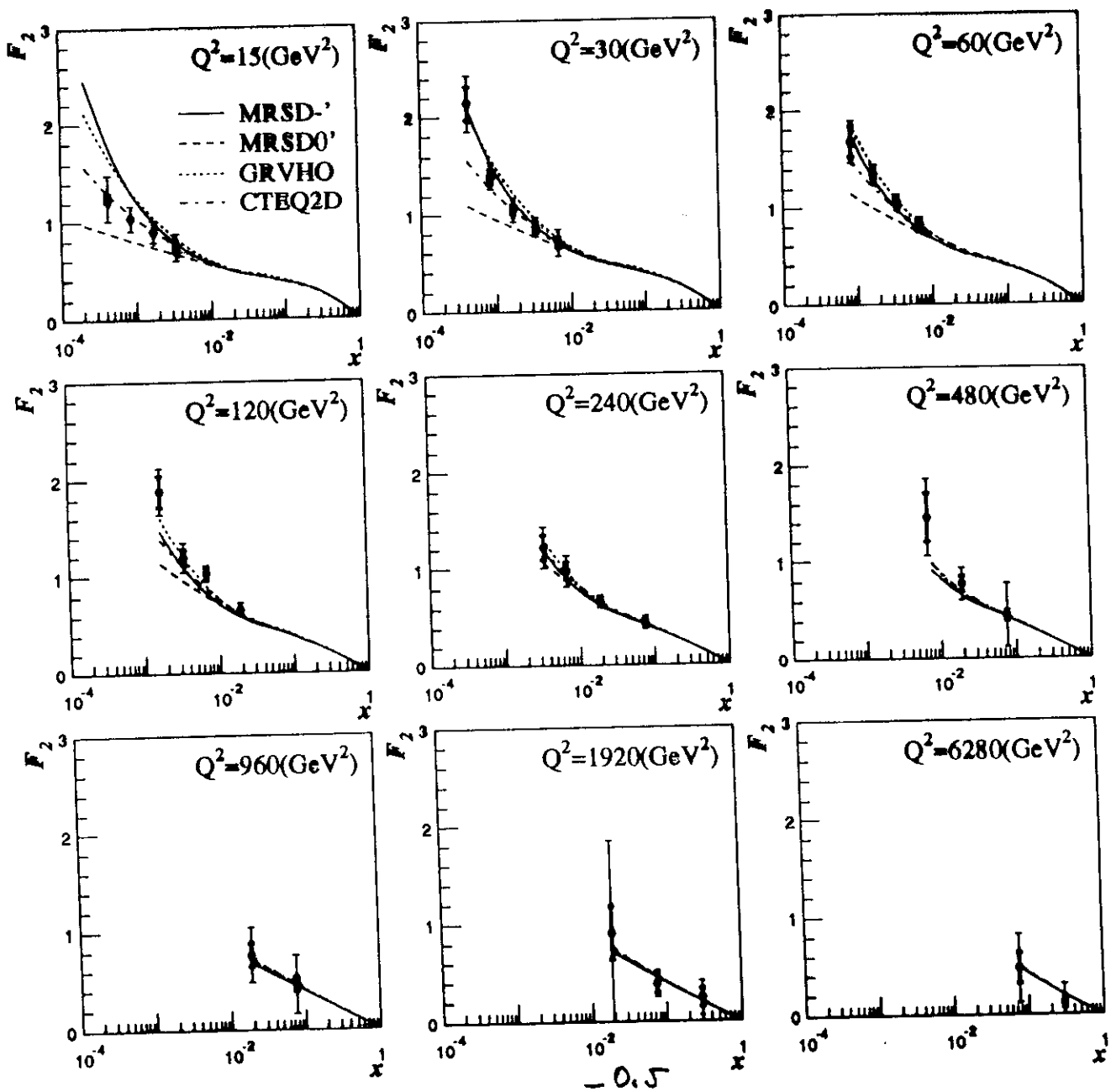
$\frac{\delta\sigma}{\sigma} \lesssim 7\%$ due to R

→ To measure F_2 :

- identify clean well measured events
- calculate kinematic variables
- unfold detector resolution → MC
  radiative corrections


ln(x)
−10
−8
−6
−4
−2
0
Q^2 [GeV^2]
10^5
10^4
10^3
10^2
10
1
ln(Q)
5
4
3
2
1
0
fixed target experiments
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x_B

Measurement of $F_2(x)$ for different Q^2



-0.5

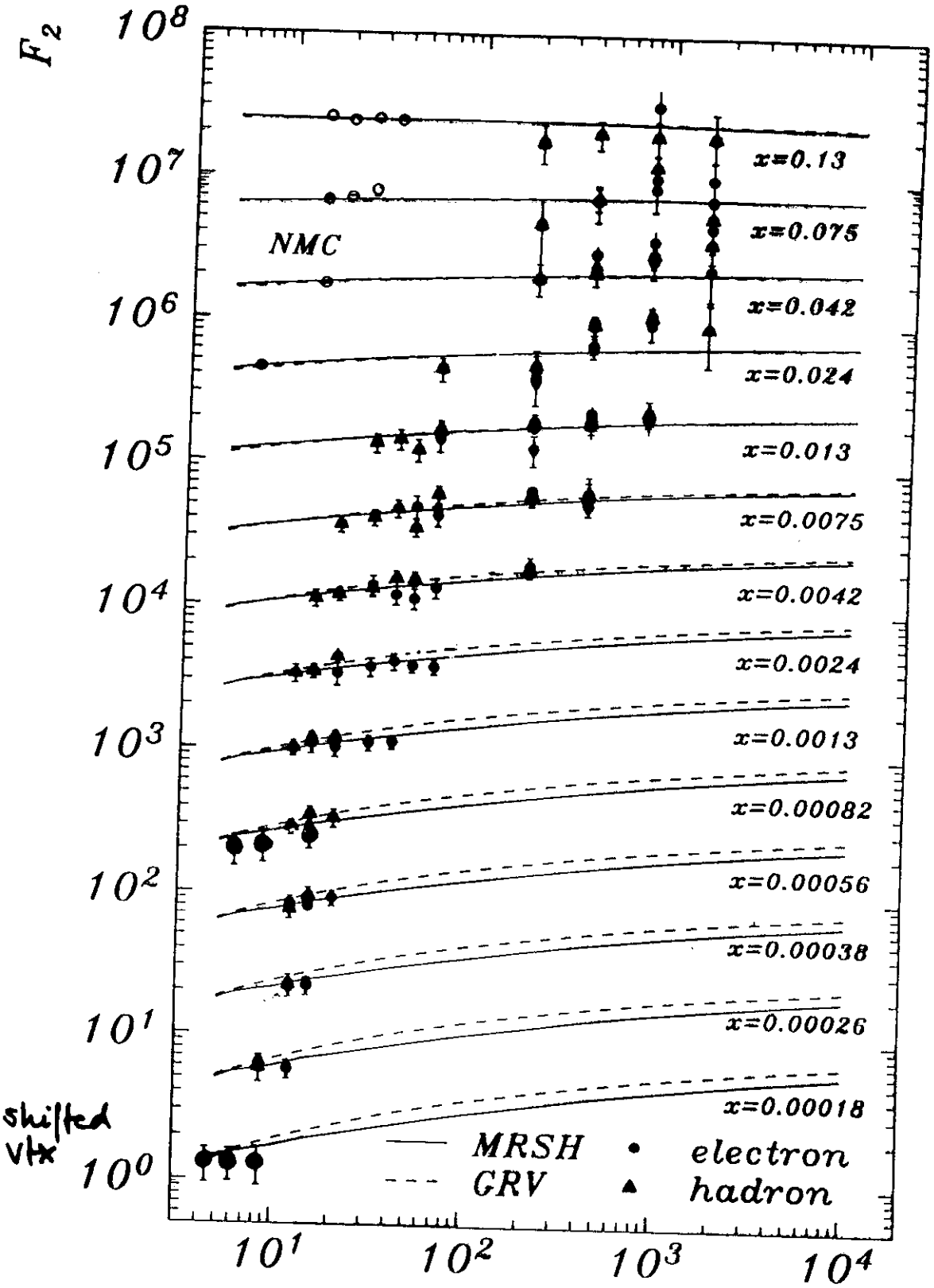
MRSD$^-$: $G(x) \propto x$

DO : $G(x) \propto$ Const

GRV : start from "valence like" q, g at $Q^2 = 0.3$ GeV^2
higher order QCD partons → GLAP evol.

↘ strongly rising gluon density

preliminary



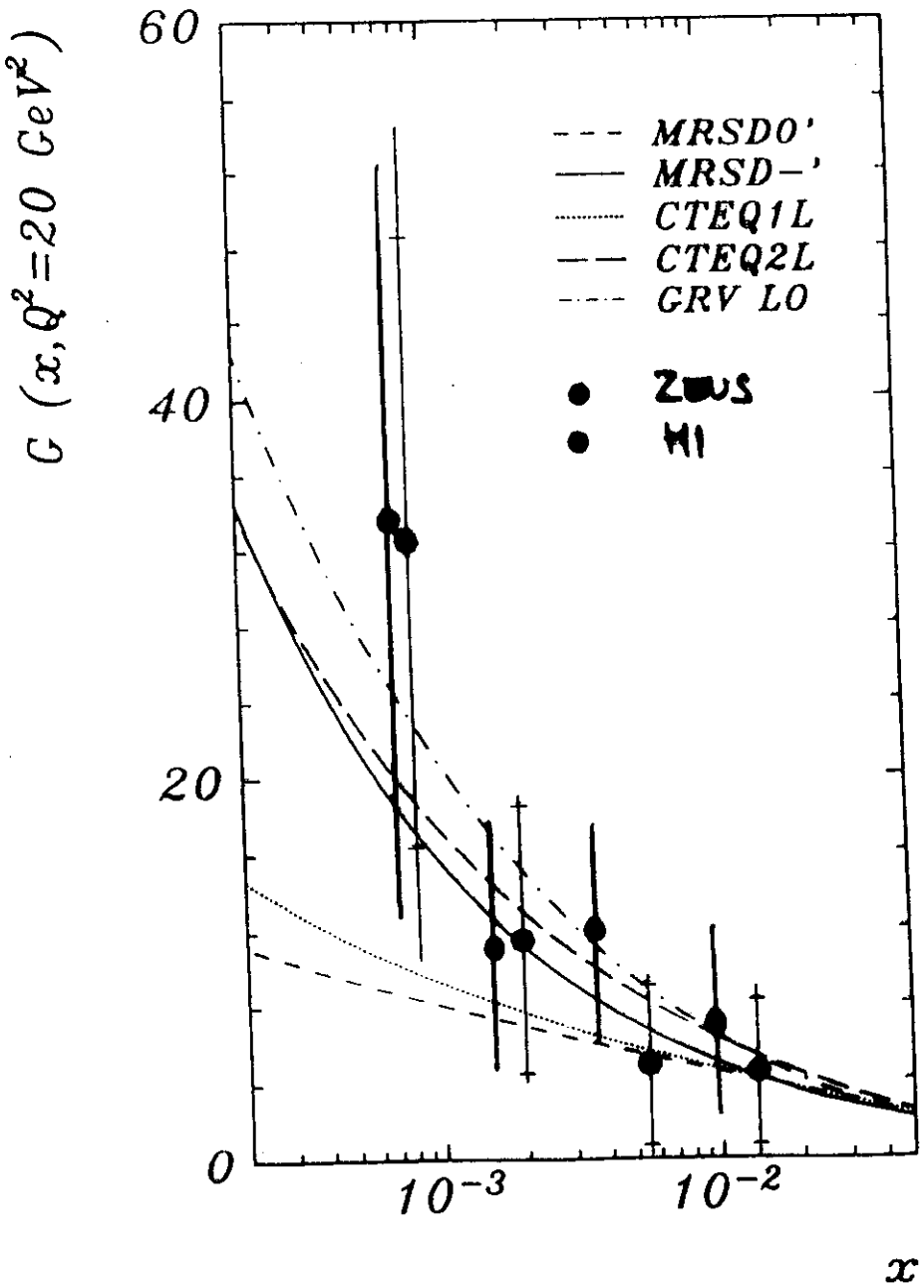
o = shifted Vtx

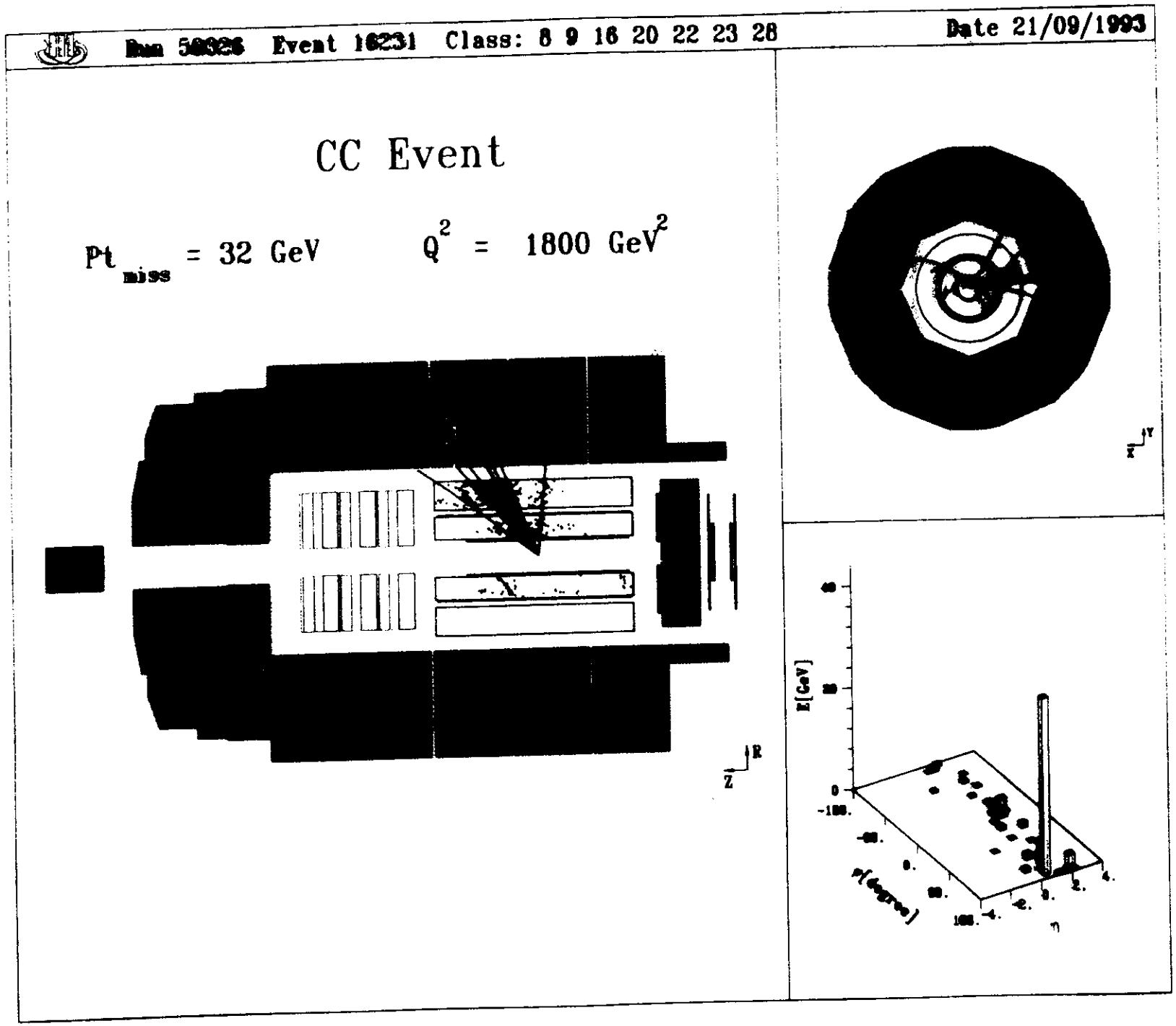
Q^2 dependence agrees with logarithmic scaling violation

Gluon structure function

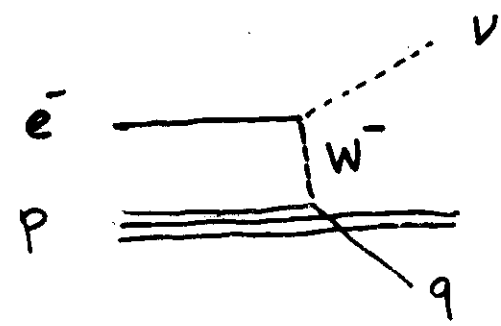
study of method → scaling viol of F_2^p at small x

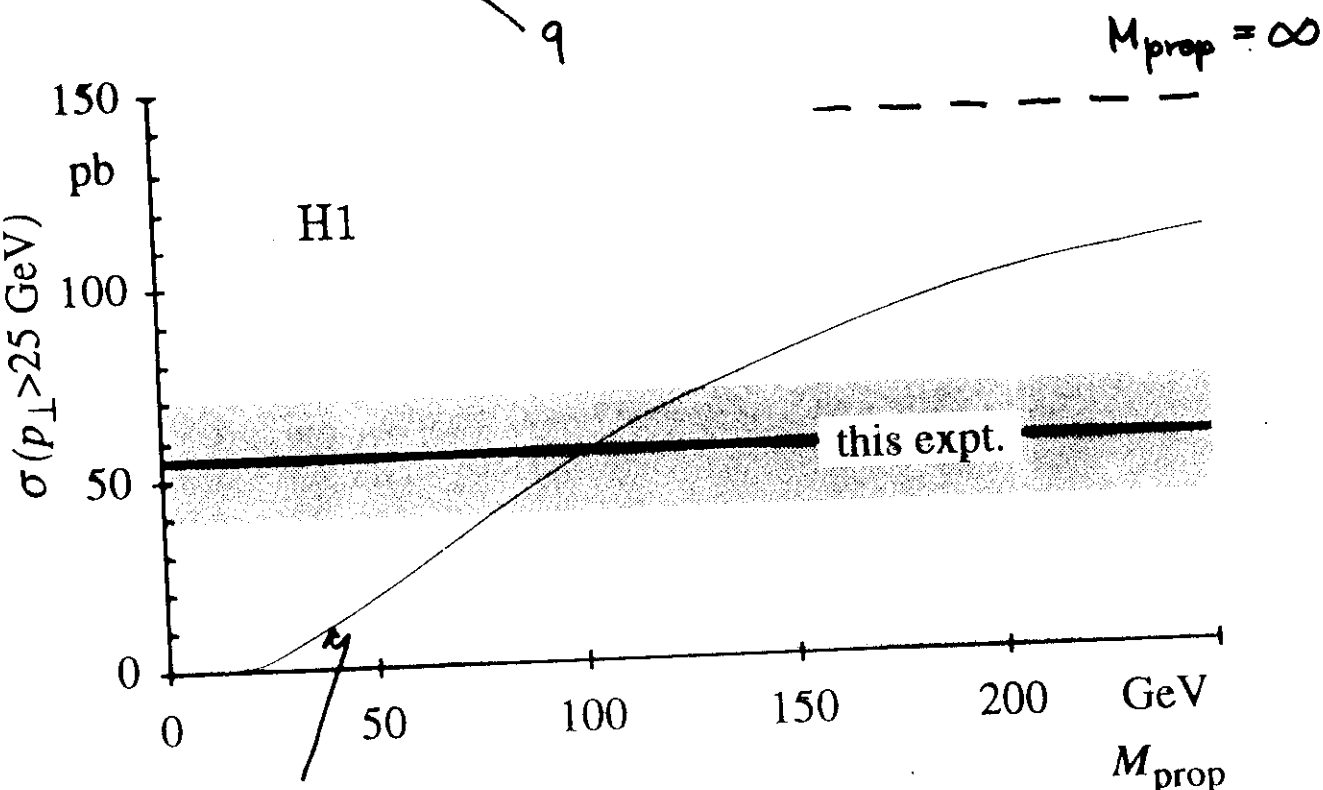
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \simeq \frac{10\,\alpha_s(Q^2)}{27\pi} \cdot G(x,Q^2)$$




Run 58326 Event 16231 Class: 8 9 16 20 22 23 28
Date 21/09/1993
CC Event
Pt miss = 32 GeV
Q2 = 1800 GeV2
R
Z
E[GeV]

First measurement of the charged current cross section at HERA





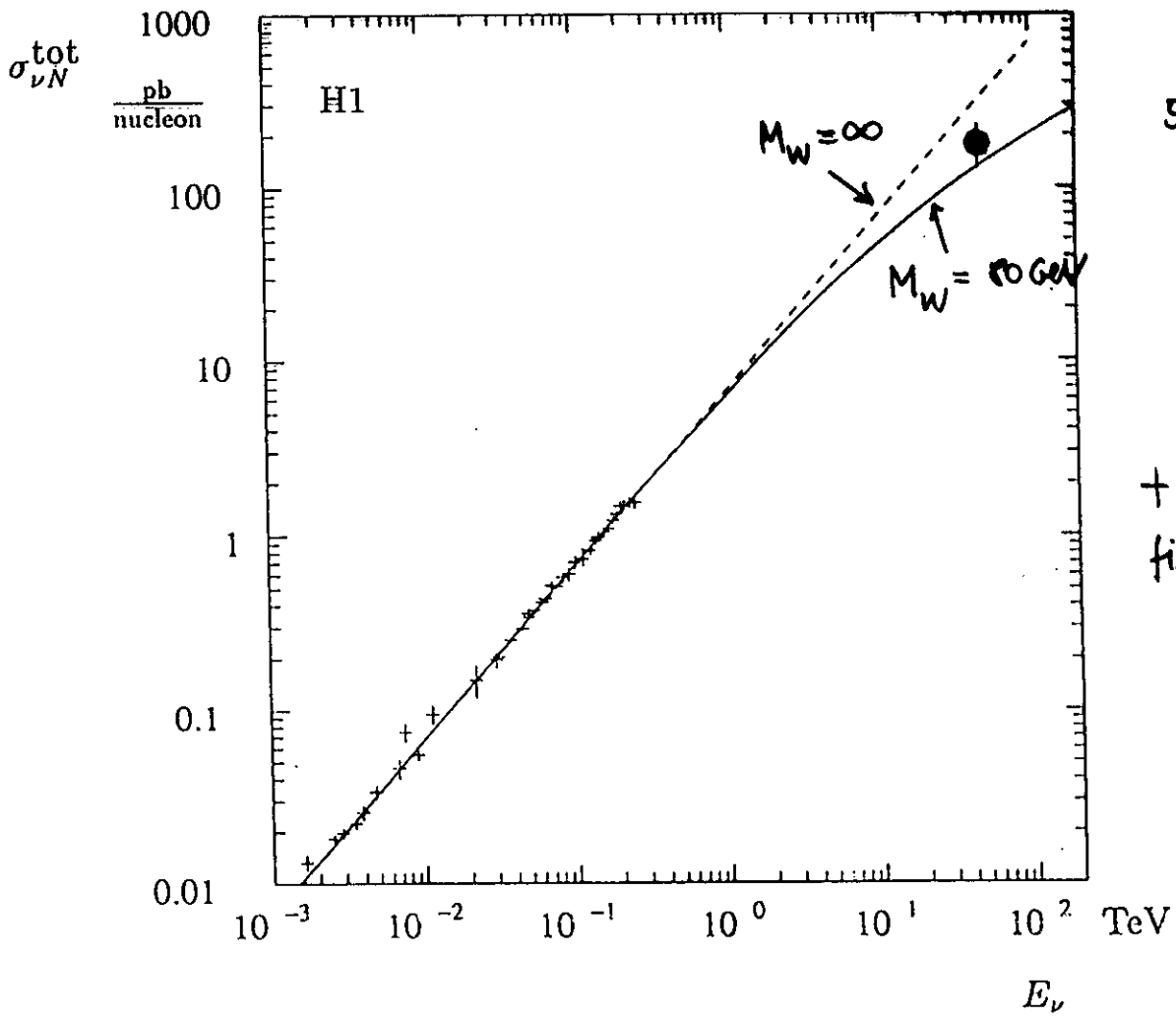
σ_{cc} as function of propagator mass

$\sigma(p_\perp > 25\ GeV) = 55 \pm 15 \pm 6$ pb

N = 14 events

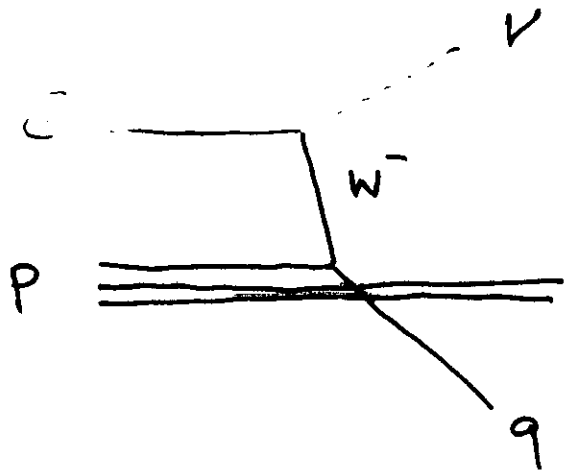
1983 first direct observation of W

1994 first observation of influence of W on weak interaction



5σ

+ - ν-Exp. fixed target

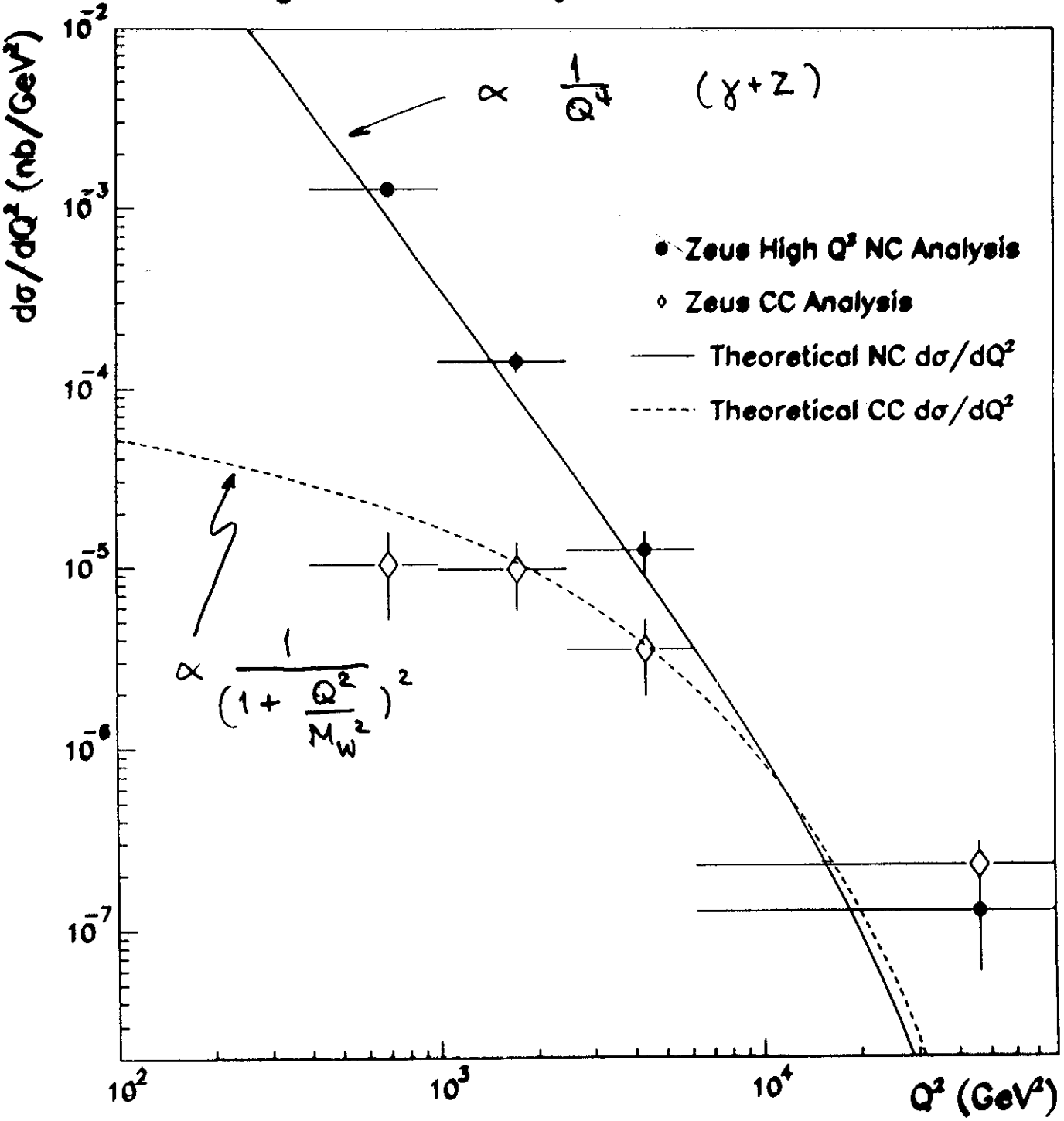


$$\sigma \propto S \cdot \frac{1}{\left(1 + \frac{Q^2}{M_W^2}\right)^2}$$

convert measured cross section to ν cross section

extrapolate to $p_T = 0$

ZEUS preliminary DIS Cross sections



at high Q^2: $\sigma_{weak} \approx \sigma_{el.magn}$

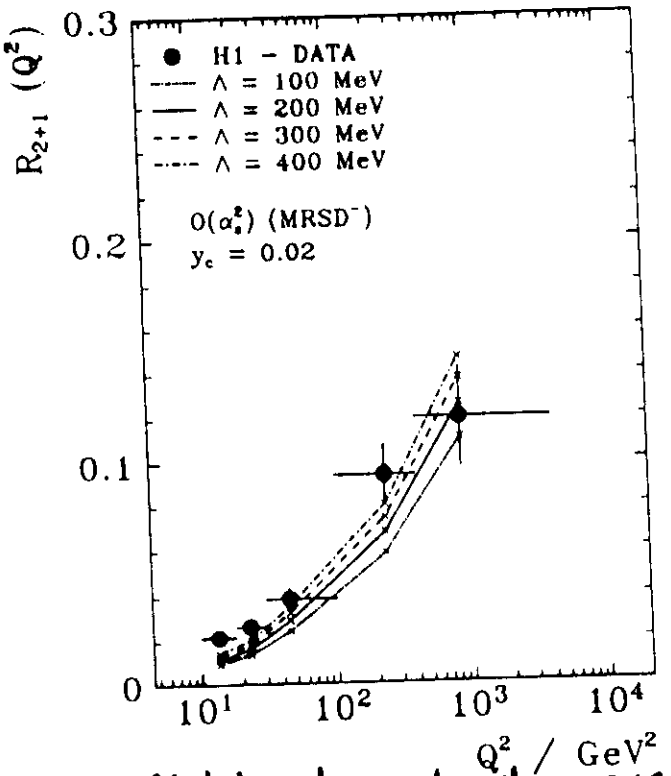
The α_s Measurement

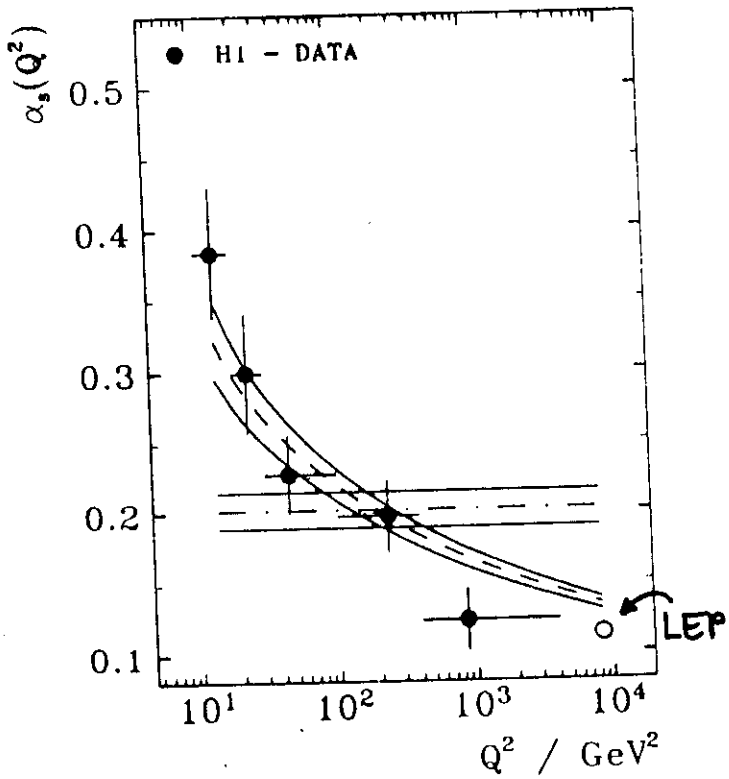
$$y_c = 0.02$$

Fit using $MRSD^-$

measure jets in hadronic final states

$R_{2+1} = \frac{\sigma_{2+1}}{\sigma_{all}}$, corrected at parton level



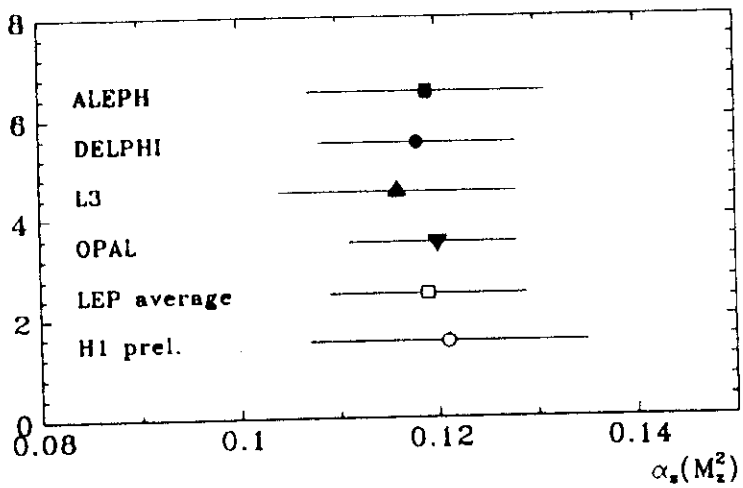


→ Matrix element decrease
→ Phase space increase

- running of α_s seen in <u>one</u> experiment
- study sensitive to parton density at very low x → require $x_p > 10^{-2}$

The α_s Measurement compared to LEP

! preliminary !



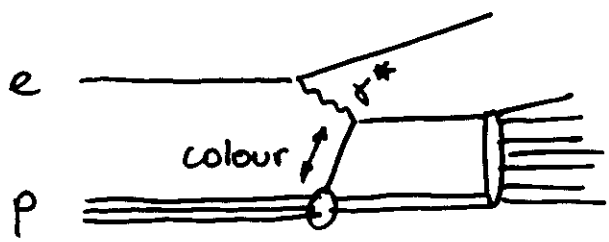
central value	0.121
stat. data + corr factors	± 0.009
y_c dependence	± 0.003
$p^*_{t,jet}$ dependence	± 0.003
hadronic energy scale	$^{+0.006}_{-0.007}$
Parton Densities	± 0.005
Renormalisation scale	± 0.006

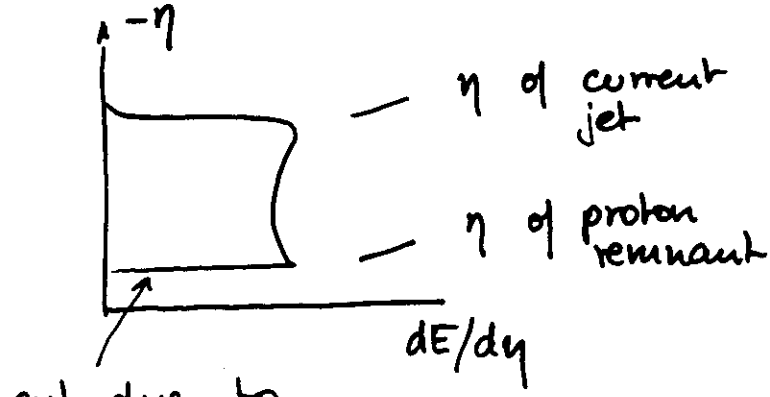
errors not yet final

DIS off colour-neutral objects

Events with "large rapidity gap"

Hadronic energy flow:





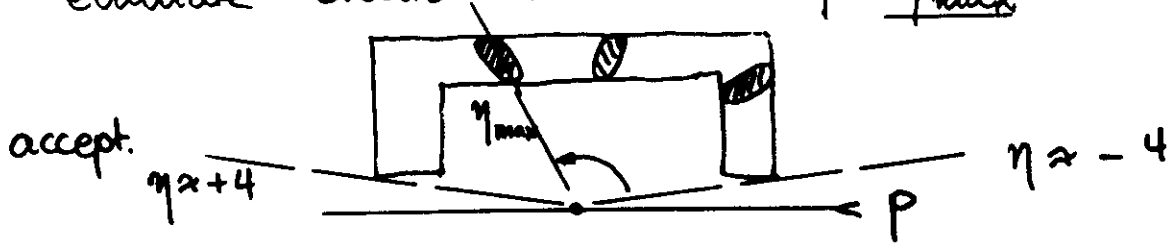
Pseudo rapidity:

$\eta = -\ln \tan \frac{\theta}{2}$

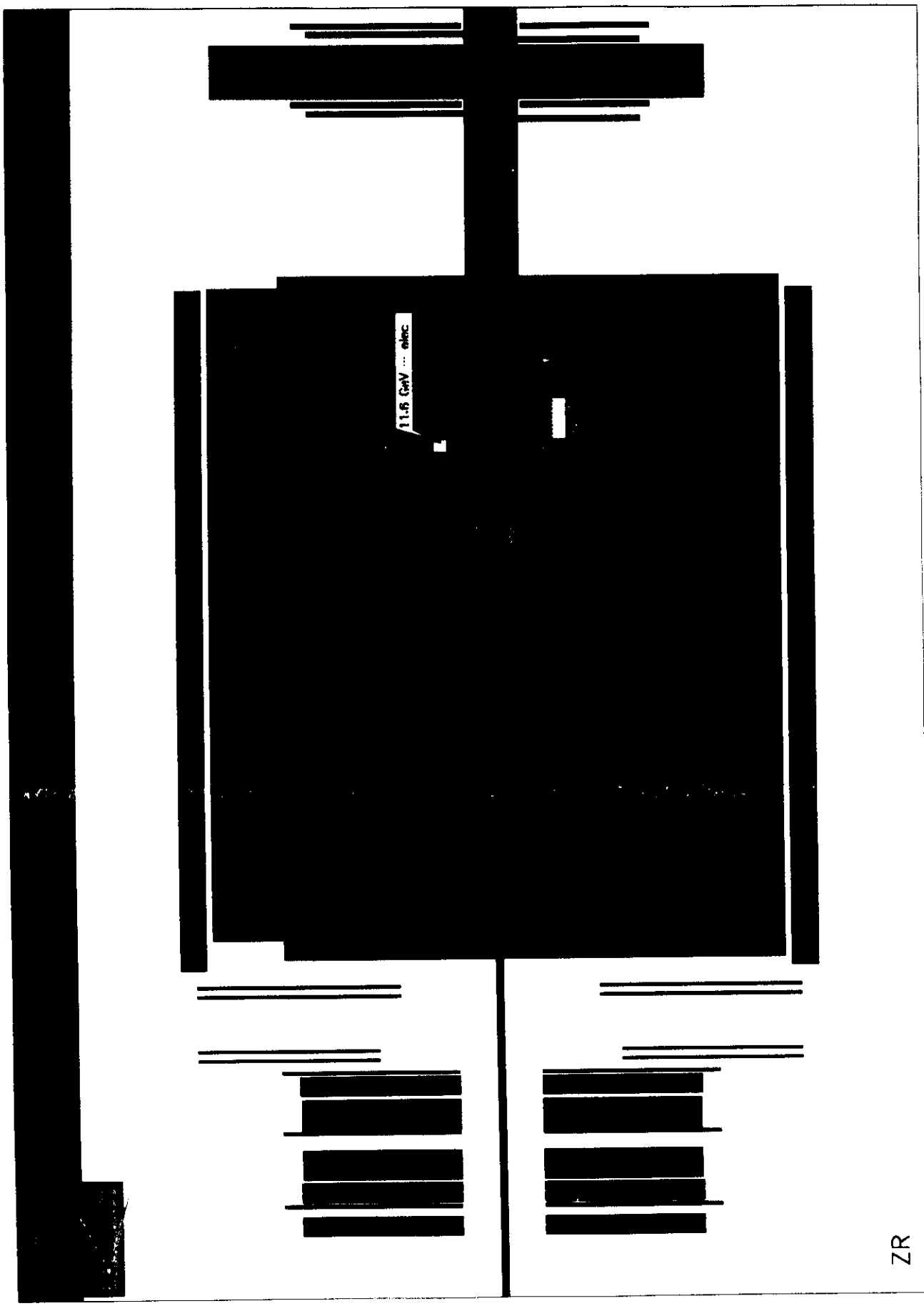
- most events have, due to colour exchange, hadronic activity between current jet and proton remnant

ZEUS / H1 observe events without particles between current jet and p-remnant →

evaluate events in terms of η_{max}:



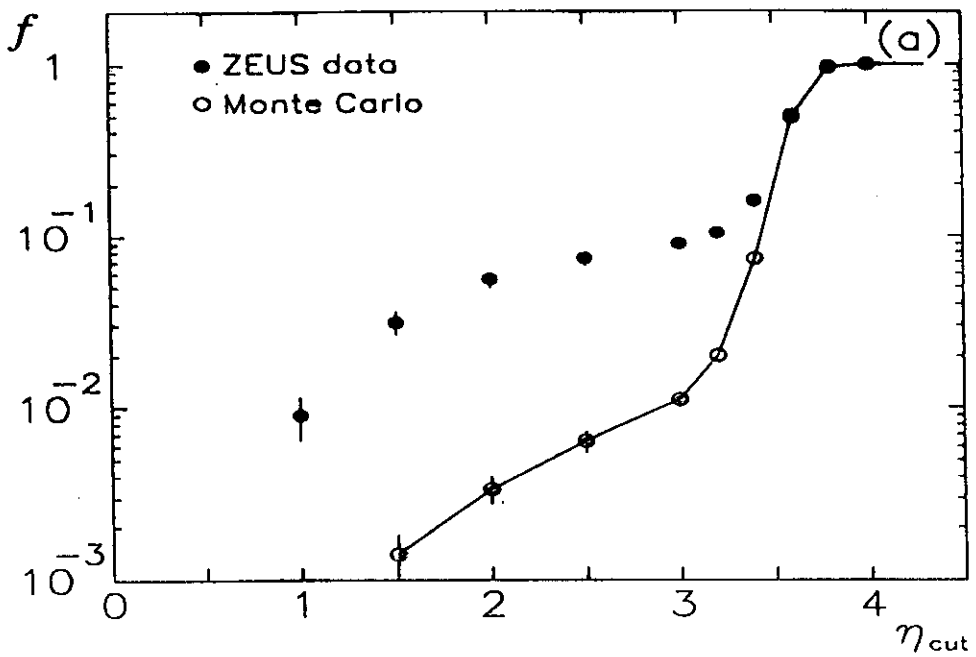
→ $dN/d\eta_{max}$

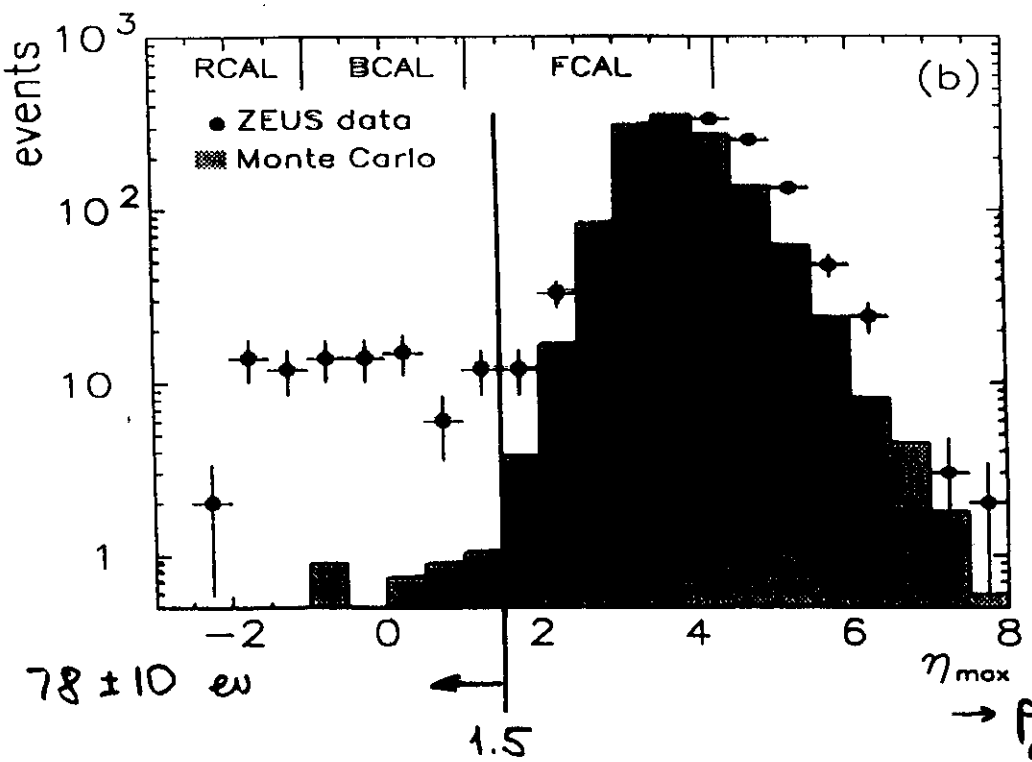

11.6 GeV ... elec
ZR
$Q^2 \gtrsim 65\ GeV^2$

Evidence for events with large rapidity gap

Data vs Monte Carlo:

↳ HERACLES
ARIADNE
LUND
Detector

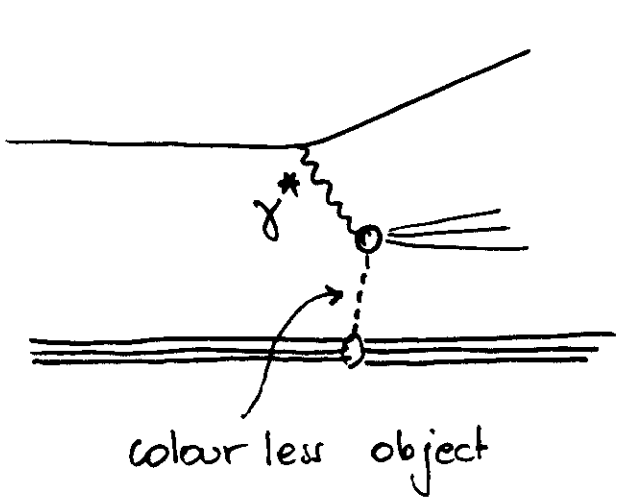


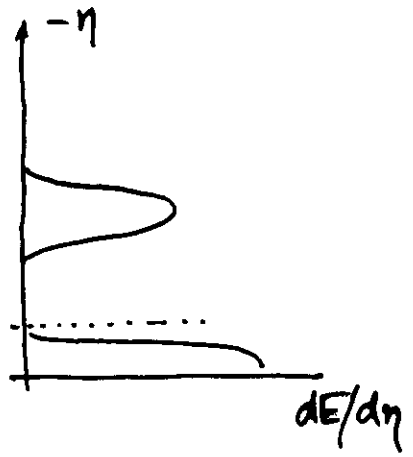


signal: 78 ± 10 ev

→ proton direction

Event topology suggests diffractive-like process

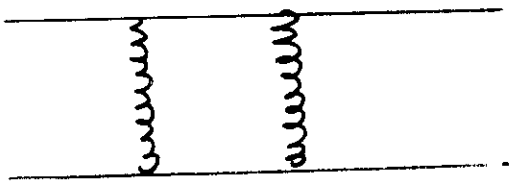




→ diffract. dissociation of a highly virtual γ →

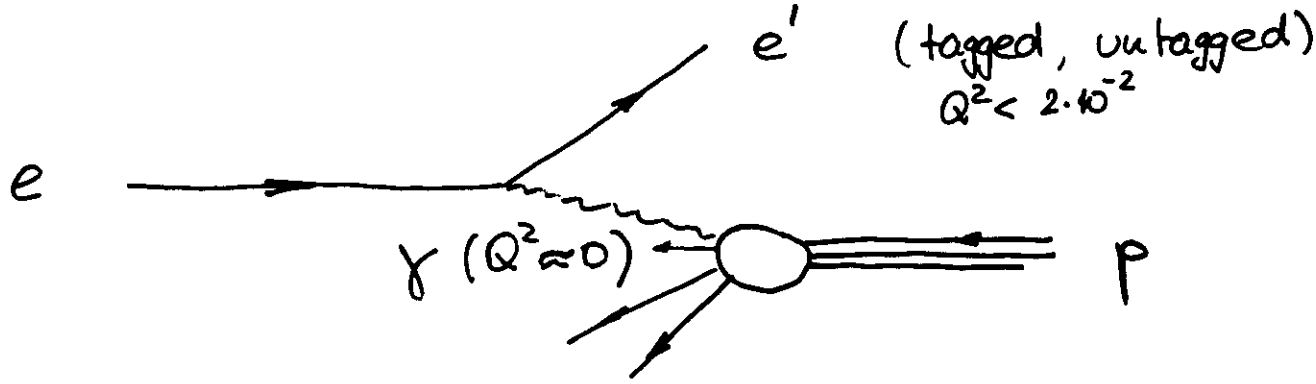
mechanism:

Pomeron exchange = non perturb. gluon exchange



- UA8: Pomeron behaves like hadron or photon
  → hard diff. scattering in
  $\bar{p}p \rightarrow p + jet + X$
- This type of events was predicted
- observed event fraction: ~ 5%

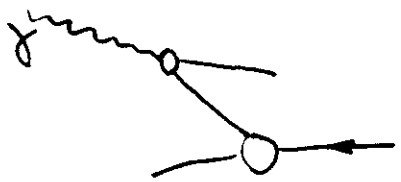
Photoproduction at HERA



2 mechanisms:

- γ - parton (p) electrodyn "direct"

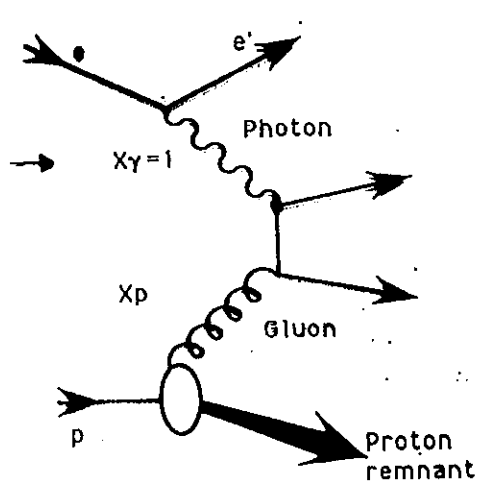
- parton (γ) - parton (p) hadron "resolved" VMD



Energy domain: $\sqrt{s_{\gamma p}} \simeq 200$ GeV
previous: 20 GeV

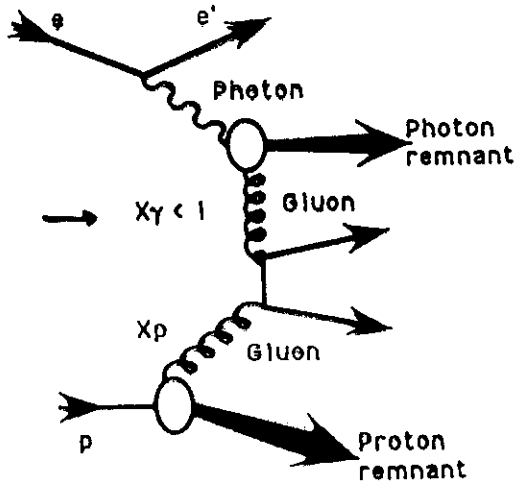
<u>Study</u>:
- total cross section
- quark, gluon } content of photon
- test of QCD
- future: heavy flavour prod.

Observation of direct processes in Photo prod.



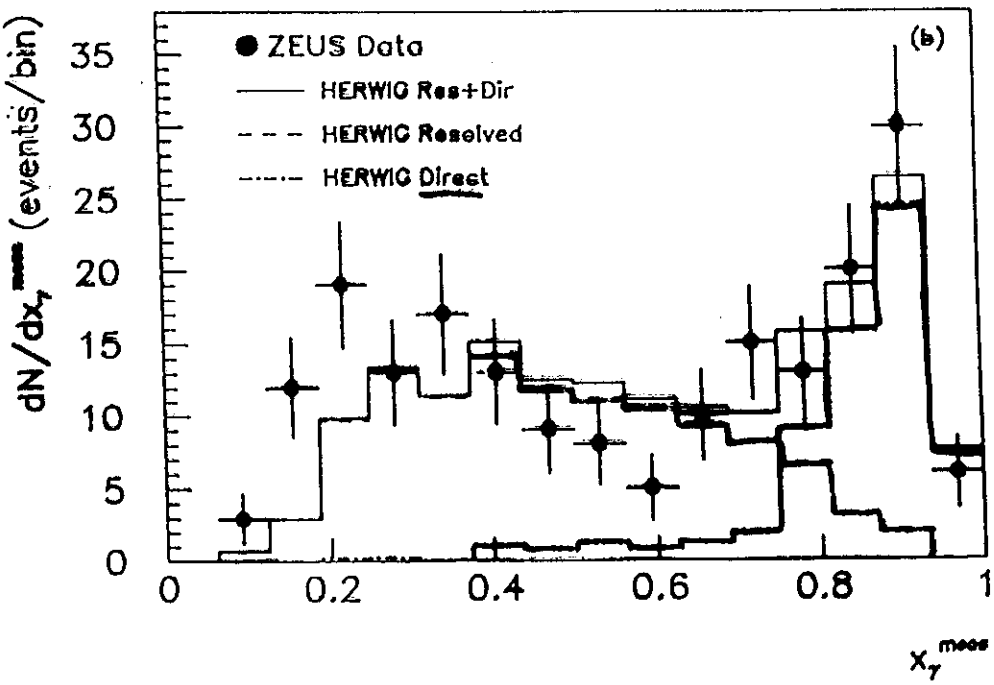
(a)

direct



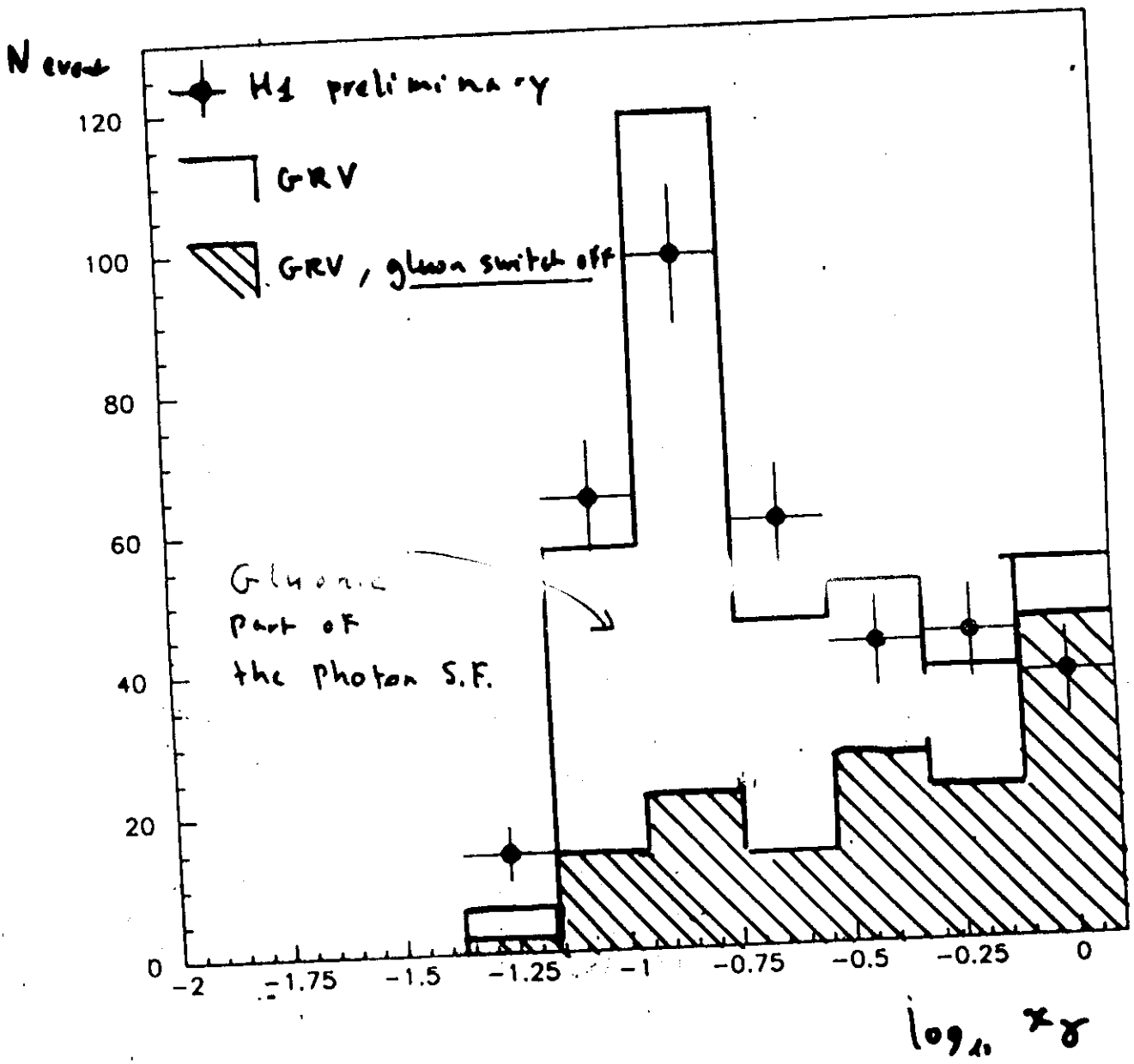
(b)

resolved



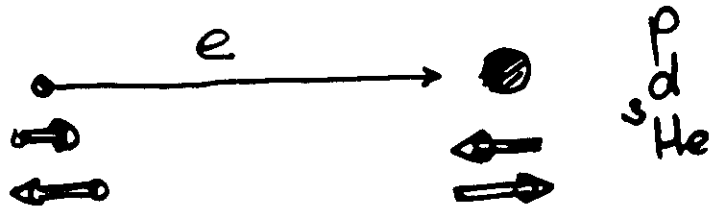
evidence for gluon contribution to photon structure function

350 evts, e- tagged, $E_T > 7$ GeV, $\Delta\eta < 1.5$



$$x_\gamma = \frac{(E - P_z)\ \text{jets}}{2E_e\ y_{\text{tag}}}$$

The Spin of the nucleon



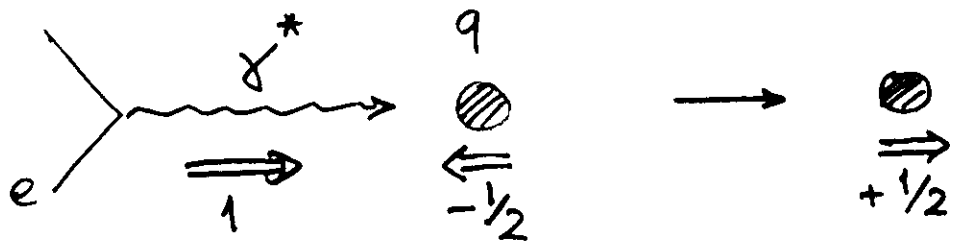
internal gas target (storage cell)
10^{14} nuclei / cm^2

$P_e > 50\%$

$P_p \gtrsim 90\%$

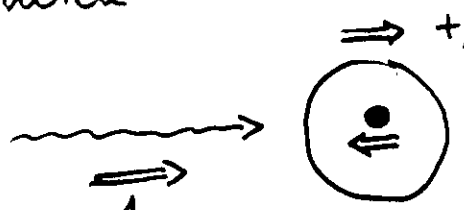
→ measure contribution of quarks to the nucleon spin

- Photon - quark interaction

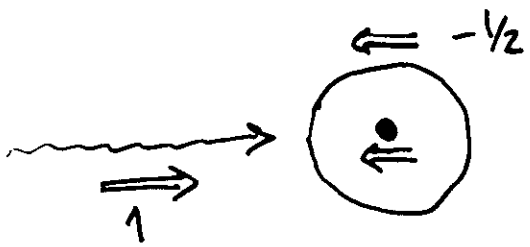


no interaction

- Photon - nucleon interaction



$$\sigma_{3/2} \sim \sum_i e_i^2 \, q_i^-$$



$$\sigma_{1/2} \sim \sum e_i^2 q_i^+$$

$q_i^{\pm}$: probab to find quark with spin parallel / antipar to

measure : $A = \dfrac{\sigma^{\rightleftarrows} + \sigma^{\Rightarrow}}{\sigma^{\rightleftarrows} + \sigma^{\Rightarrow}}$

$$\approx \frac{g_1(x)}{F_1(x)}$$

$$g_1 = \frac{1}{2} \sum e_i^2 (q_i^+ - q_i^-)$$ spin depend. structure function

$$F_1 = \frac{1}{2} \sum e_i^2 (q_i^+ + q_i^-)$$

Sum rules:

QPM: $$\int_0^1 g_1(x)\,dx = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{4}{9}\Delta s\right)$$

Δu = contribution of u-flavor to nucleon spin

Bjorken: $$\int_0^1 [g_1^p - g_1^n]\,dx = \frac{1}{6}\frac{g_A}{g_V}\cdot\left(1 - \frac{\alpha_s(Q^2)}{\pi}\ldots\right)$$

$$= .189 \quad \text{in } O(\alpha_s^3) \text{ @ 10 GeV}$$
$$\pm .002$$

Ellis-Jaffe: $$\int_0^1 g_1^p\,dx = \frac{1}{2}\left(F - \frac{1}{9}D\right)\cdot\{\text{QCD corr}\}$$

$$\int_0^1 g_1^n\,dx = \frac{1}{3}\left(F - \frac{2}{3}D\right)\cdot\{\text{QCD corr}\}$$

F, D = weak decay const

p: $= .171 \pm .005$

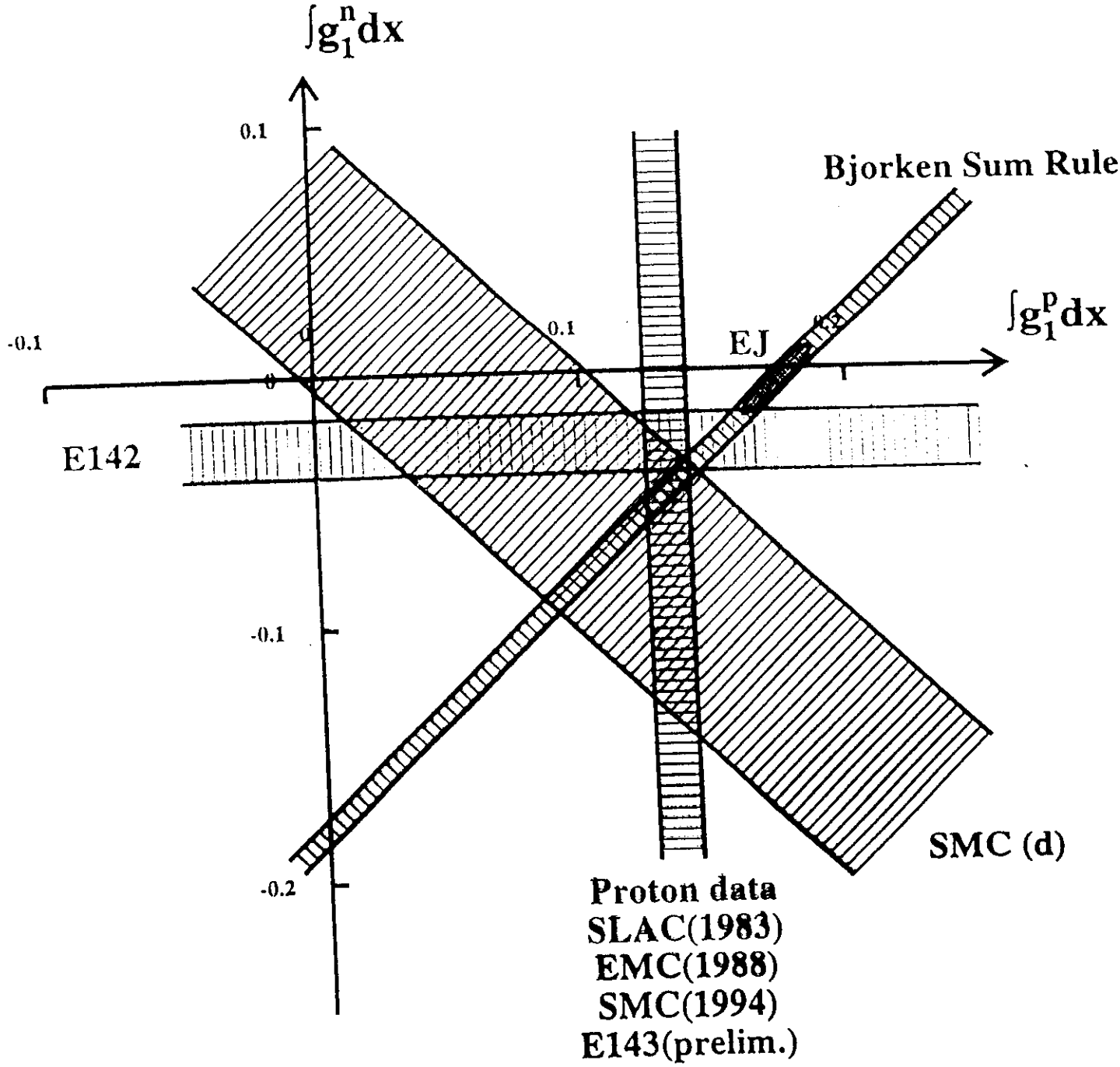
n: $= -.018 \pm .005$

EMC & SLAC (1988):

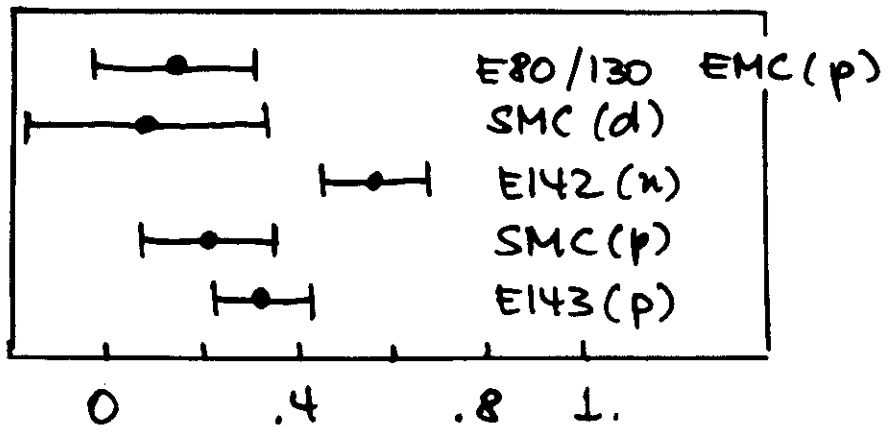
$\langle S \rangle_q \approx 12\%\ S_{proton}$

"spin crisis"

↝ new activities

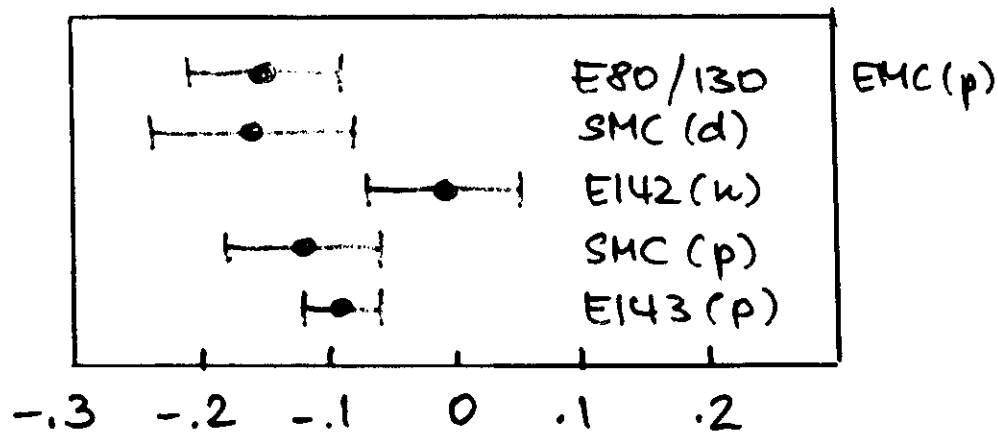


Status of measurements



$\Delta S = \Delta u + \Delta d + \Delta s$

= quark contribution to nucleon spin (fraction of 1/2)



Δs = s-quark contribution to nucleon spin

↝ spin "crisis" persists

syst. uncertainties ?

THE HERMES EXPERIMENT

The experimental programme:

- spin structure functions of proton and neutron $g_1^{p,n}(x)$
  - $0.02 < x < .8$
  - Test Bjorken Sum rule to 5-10%
  - Targets: $\vec{p}$, $\vec{d}$, $\vec{^3He}$

- transverse structure functions $g_2^{p,n}(x)$
  - → quark-gluon correlations
  - → Burkhardt-Cottingham SR to $\pm .017$

with deuteron target: ($S=1$)

- new structure functions $b_1(x)$, $\Delta_d(x)$

  related to quadrupole quark, gluon distributions

Coincident hadron production in pol. DIS:

- new leading twist structure function from transverse π-Asymmetry $h_1(x)$

Special features of HERMES:

- high target polarisation
- high beam polarisation
- no dilution factor
- high statistics
- analyse hadronic final state

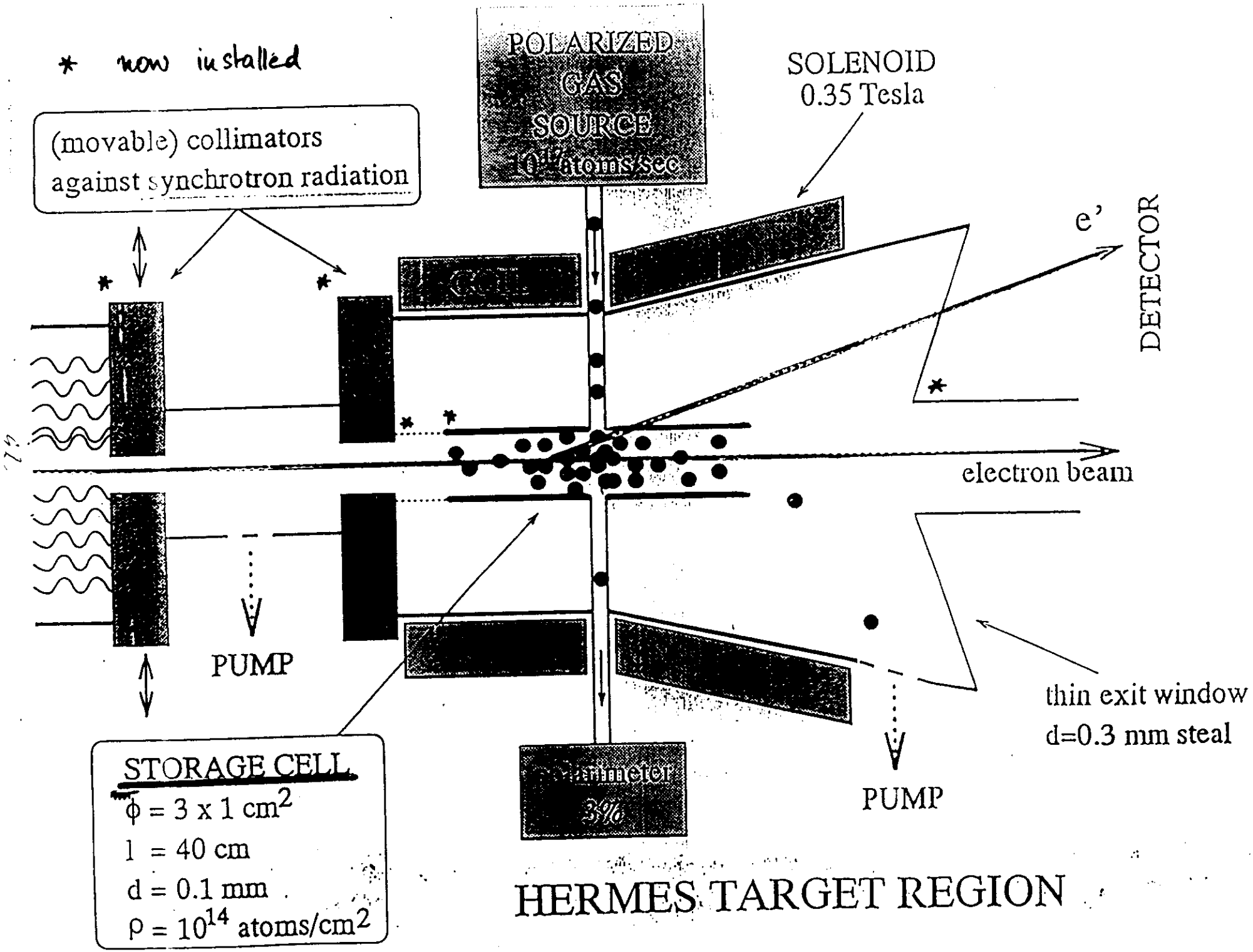
↑ high precision (stat + syst) →

Tools:

- Atomic beam source for pol. targets
- storage cell as target
- use electron beam of HERA → (Xing rate 10 MHz) + self polaris.
- forward spectrometer →

Status:

- approved (summer 93)
- install spin-rotators & test experiment (93/94 shut-down)
- install experiment (94/95 shut down)
- start measurements (95)

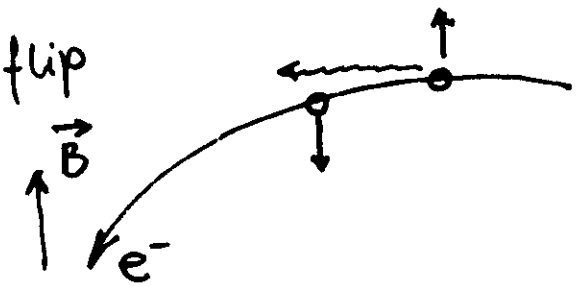

* now installed
POLARIZED GAS SOURCE
SOLENOID
0.35 Tesla
(movable) collimators
against synchrotron radiation
e'
DETECTOR
electron beam
PUMP
PUMP
thin exit window
d=0.3 mm steal
STORAGE CELL
ϕ = 3 x 1 cm^2
l = 40 cm
d = 0.1 mm
$\rho = 10^{14}$ atoms/cm^2
3%
HERMES TARGET REGION

Polarization of the HERA e^--beam

1) Radiative Selfpolarization (Sokolov, Ternov)

syn. radiation cause spin flip

$$R_{\uparrow\downarrow} > R_{\downarrow\uparrow}$$



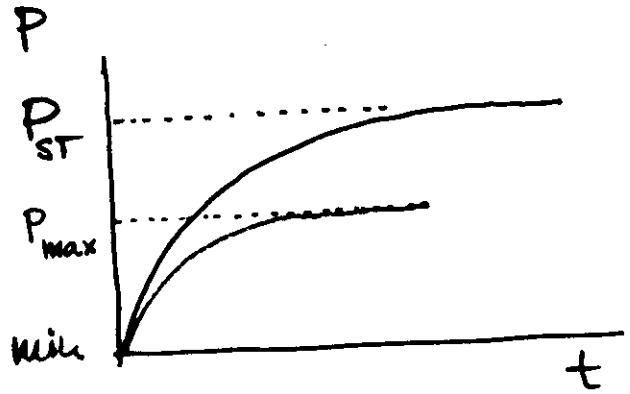
↘ for flat machine:

$$P_{ST} = 92.4\%$$

with build-up time

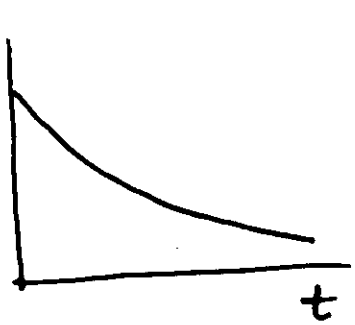
$$\tau_p \propto \frac{\rho^3}{\gamma^5}$$

HERA at 26.6 GeV: → 42 min



2) Depolarization Effects

stochastic motion of e^-
→ spin diffusion, if $B_{horiz} \neq 0$

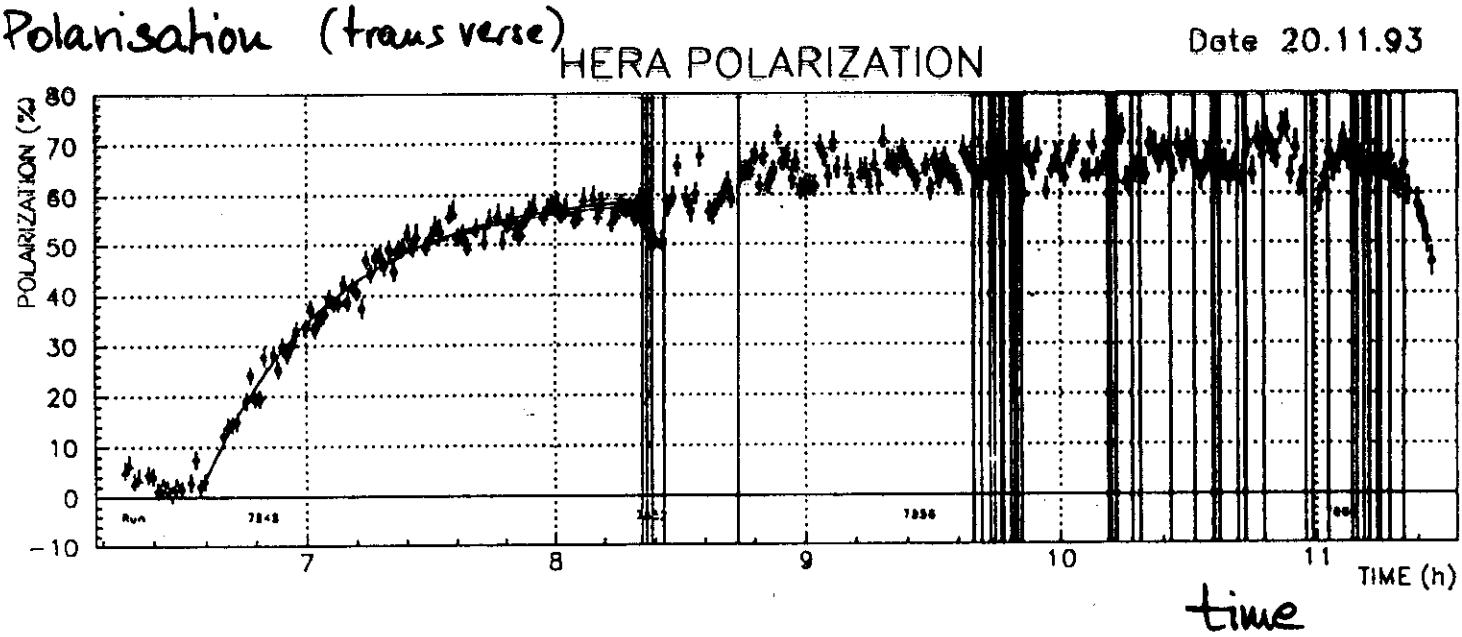


1) and 2) compete:

$$P(t) = P_{ST} \cdot \frac{\tau_D}{\tau_p + \tau_D} \cdot \left(1 - e^{-\frac{\tau_p + \tau_D}{\tau_p \cdot \tau_D} \cdot t}\right)$$

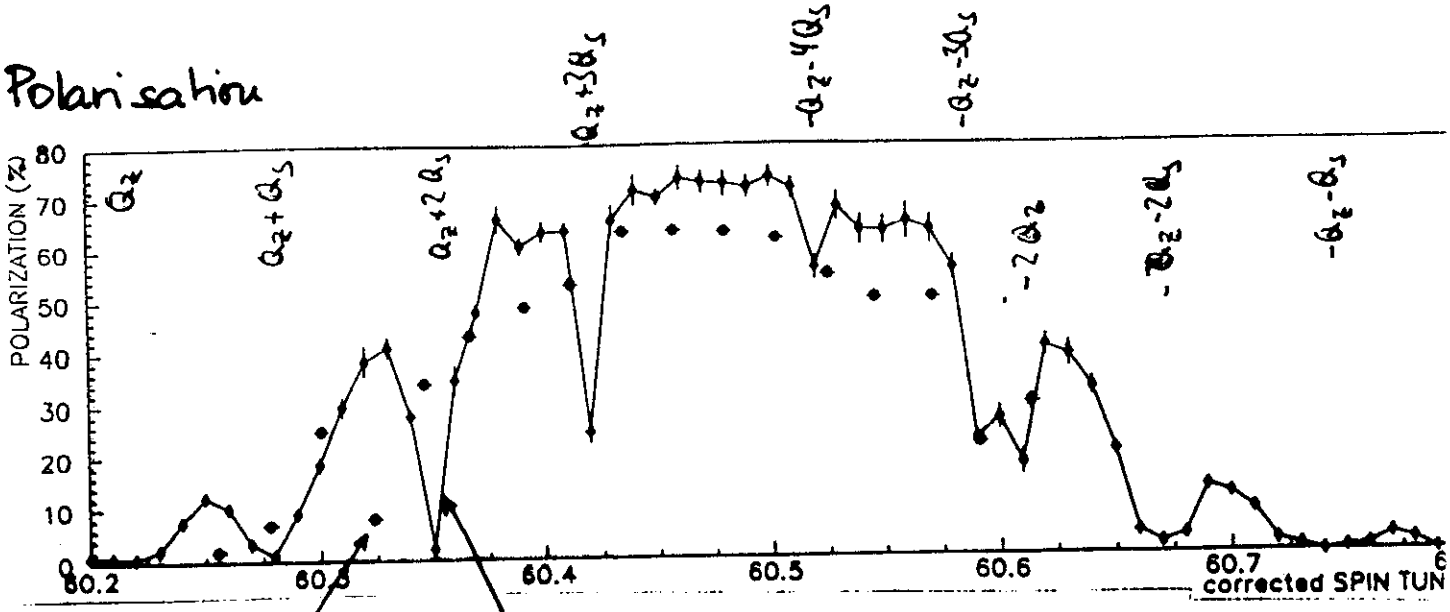
P_{max} $\quad$ $1/\tau$

Polarisation (transverse)



time

Polarisation



data

Simulation

Energy

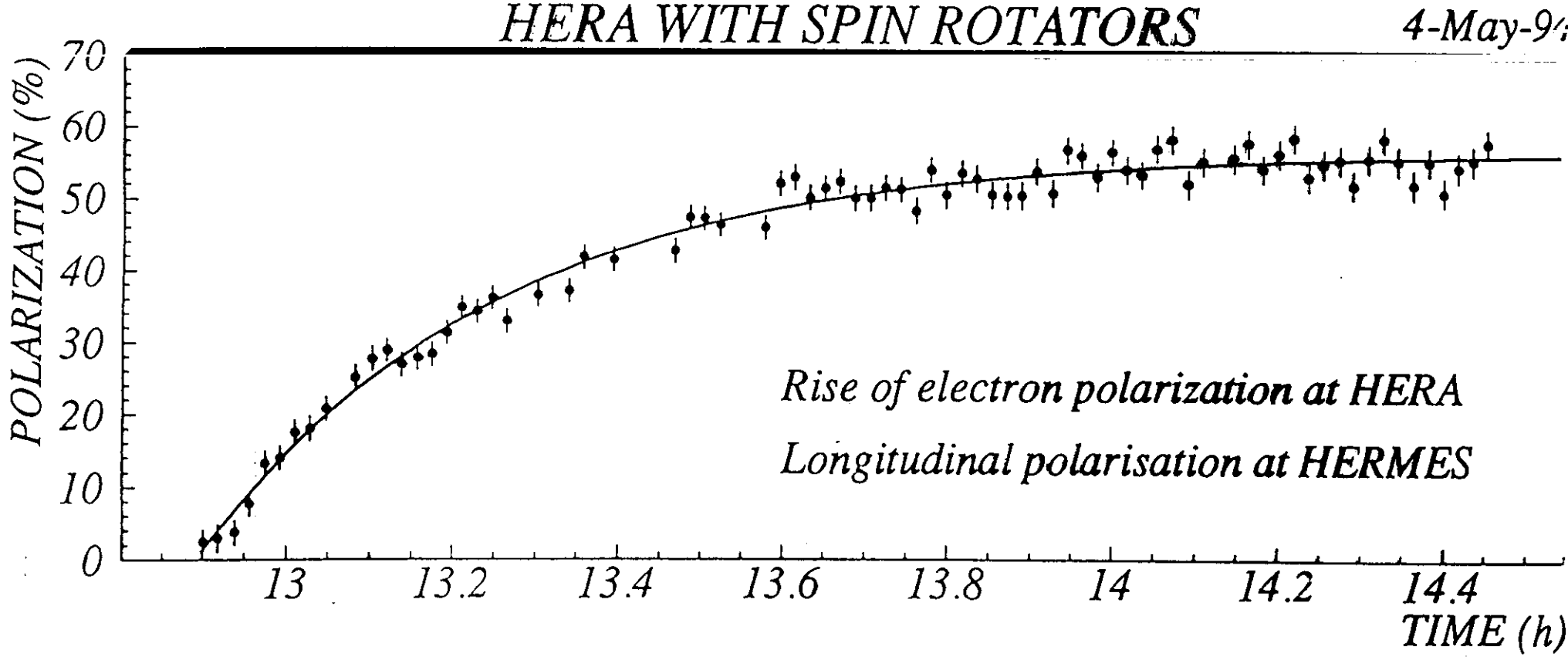
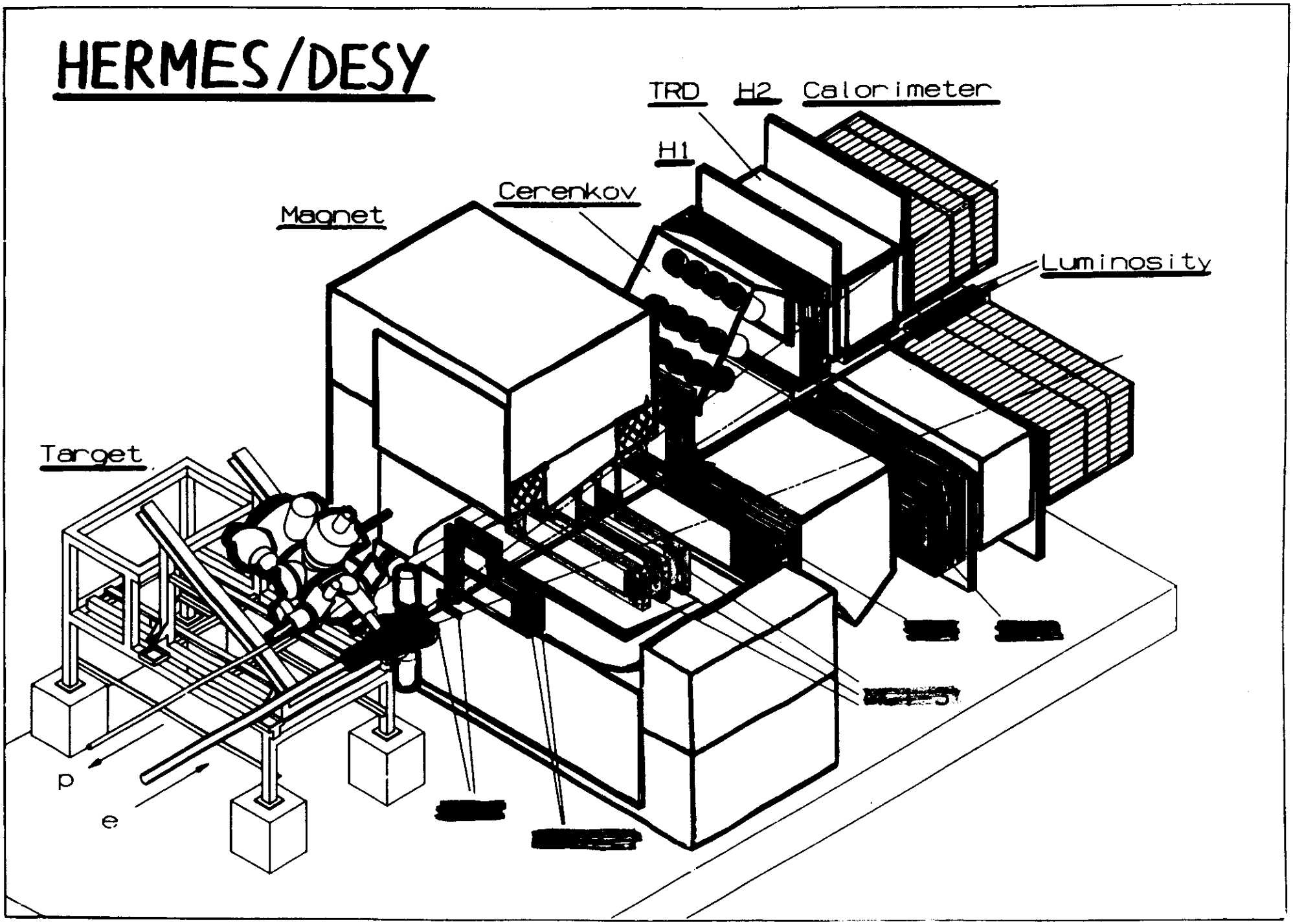


Fig 2: First observation of polarization with activated spin-rotators.

Fit: $P(t) = P_0 \left(1 - e^{-\frac{t-t_0}{\tau}}\right)$ $P_0 = 57 \pm 1\%$ $\tau = 22 \pm 1$ min

$\hookrightarrow P_0^{\tau} = \frac{89\%}{36\,\text{min}} \cdot \tau = 54 \pm 2\%$

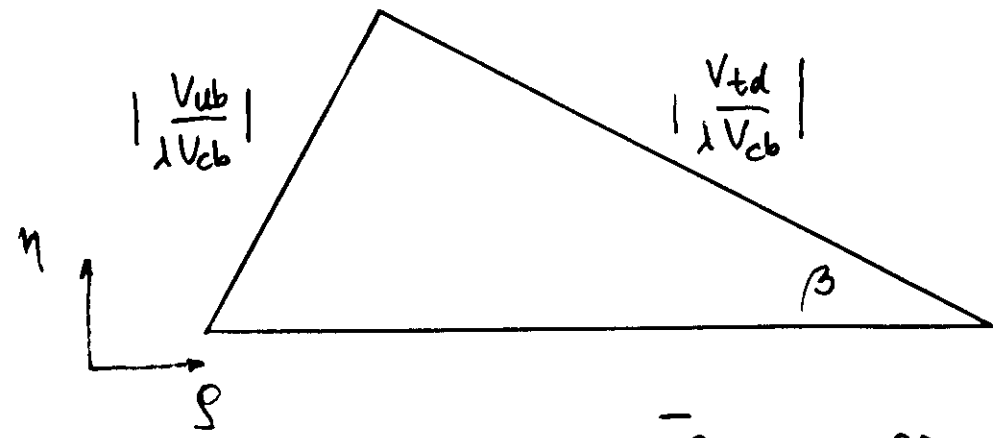

HERMES/DESY
TRD
H2
Calorimeter
H1
Cerenkov
Magnet
Luminosity
Target
p
e

A B- PHYSICS EXPERIMENT using an INTERNAL TARGET in the HERA PROTON RING

- Goal: use high rate of b-production from internal target to study CP-violation in B-meson decay

- Status: LoI (Oct 92)
  Progress Report (March 93)
  → Pre-Collaboration
  cond. Approval (June 94)

- measure: sin (2β)



$$A_{CP} = \frac{N(B^0 \to J/\psi K_s^0) - N(\bar{B}^0 \to J/\psi K_s^0)}{+}$$

$\propto \sin(2\beta)$

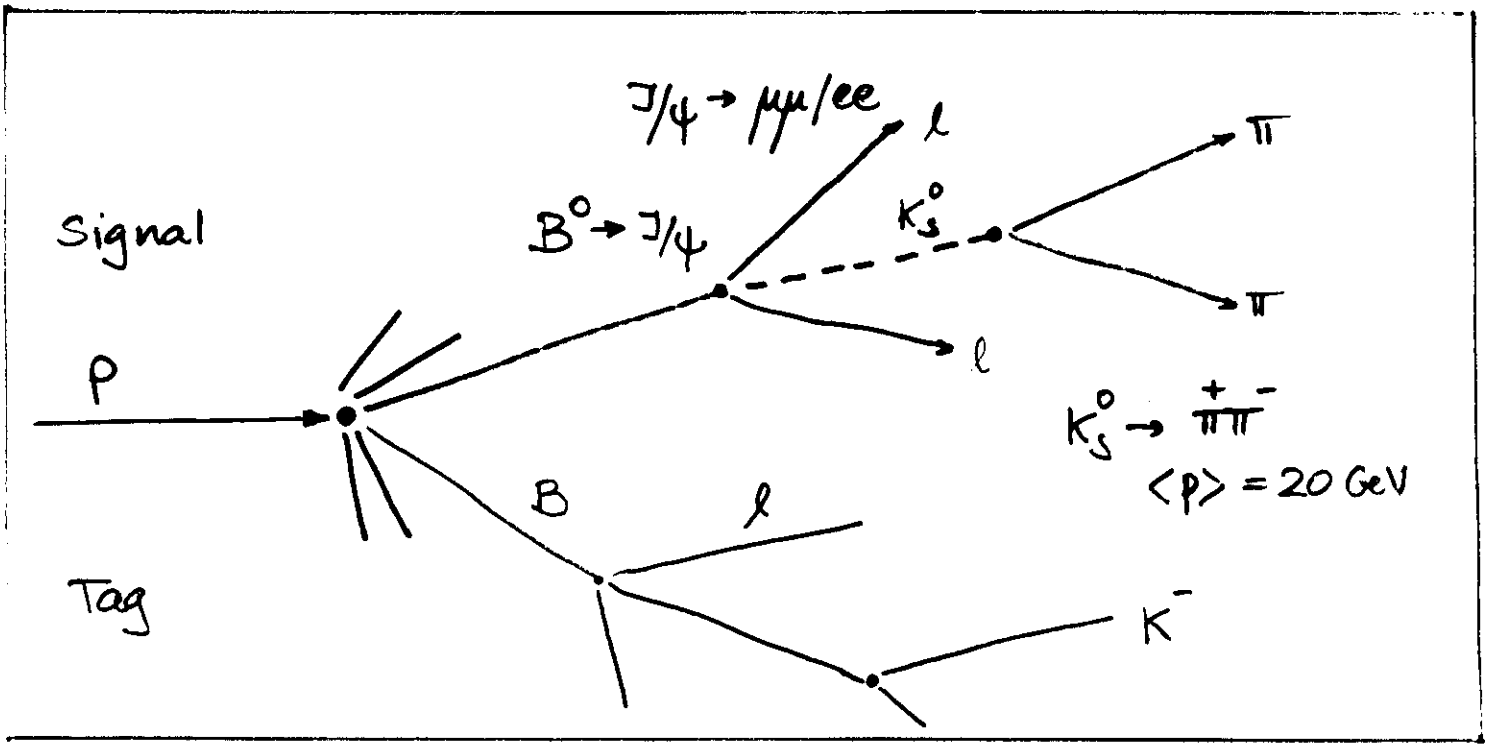
no uncertaint due to hadr matrix elemen

expected range: $\sin 2\beta = .16 \ldots . .98$

similar proposals exist e.g. for LHC
LHCC/93-45
GAJET
CODEX

- measurement principle:

trigger only on events with 2 leptons



$B \to J/\psi\, K^0_S$ CP violating

$B_s \to D_s^{*-}\, l\, \nu$ B_s mixing

$\vdots$

To tag $B/\bar{B}$:

use decay of second b

lepton tag $\epsilon \sim 10\%$

K^- tag $\epsilon \sim 50\%$

• Quantitative evaluation

- statistical requirements

$$\Delta \sin(2\beta) = \frac{1}{D}\sqrt{\frac{K}{N}}$$

$D \approx 0.5$ dilution
$K \approx 1.5$ sec. vtx cut

$\Delta \sin(2\beta) \approx 0.05 \rightarrow$ requires 3000 events which are tagged

- Event rates

$\sigma_{b\bar{b}} / \sigma_{inel}$	$\sim 10^{-6}$	→
$2 P_{b \to B^0}$	0.8	
$Br(B^0 \to J/\psi K_S)$	$4 \cdot 10^{-4}$	
$Br(J/\psi \to ee/\mu\mu)$	0.12	
$Br(K_S \to \pi\pi)$	0.69	
		$3 \cdot 10^{-11}$

- Efficiencies

reconstruction	.5	
trigger	.7	
vertex cut	.5	
tagging ϵ	.5	
		$\sim 3 \cdot 10^{-12}$

↘ need 10^{15} interactions → 3000 events
$\hat{=}$ $3 \cdot 10^7$ sec @ 30 MHz

- HERA

Bunch Xing rate	10 MHz
natural beam loss	$\approx$ 60 MHz

↘ need multiple interactions
+ efficient target

- detector elements and challenges

Requirements:

- reconstruct multiple events at 10 MHz (ϵ!)
  trk multiplicity ~ 50
- reconstruct B decay vertices
- identify leptons & Kaons
- provide fast, efficient, selective trigger for J/ψ
- stand high radiation dose

Possible techniques:

- forward spectrometer →
- Si Vertex detector (need for exchange)
- high granularity tracker
  - Si, MSGC, straws, honey comb DC
- Particle ID
  - RICH
  - TRD
  - El. mag calorimeter
  - Muon system
- Three level pipeline trigger & read out
  - m_{ll} - cut at level 1 !

↘ profit from detector R&D for LHC

Non CP-related b-physics

- Determination of V_{cb} (Th. Ost) →
- $B_s - \bar{B}_s$ mixing (O. Mai) →
- Determination of V_{ub} (Yu. Zaitsev) ↘

- rare B-decays
  $B^0 - \bar{B}^0$ mixing
  B_c production + decay
  } (A. Ali)
- b-baryons (A. Fridman)
- Angular distributions in $\Lambda_c \to \Lambda J/\psi$ (H. Simma)
- Production of $J/\psi\, J/\psi\, X$ (S Baranov)

V_{ub}

so far only feasibility study:

present situation:

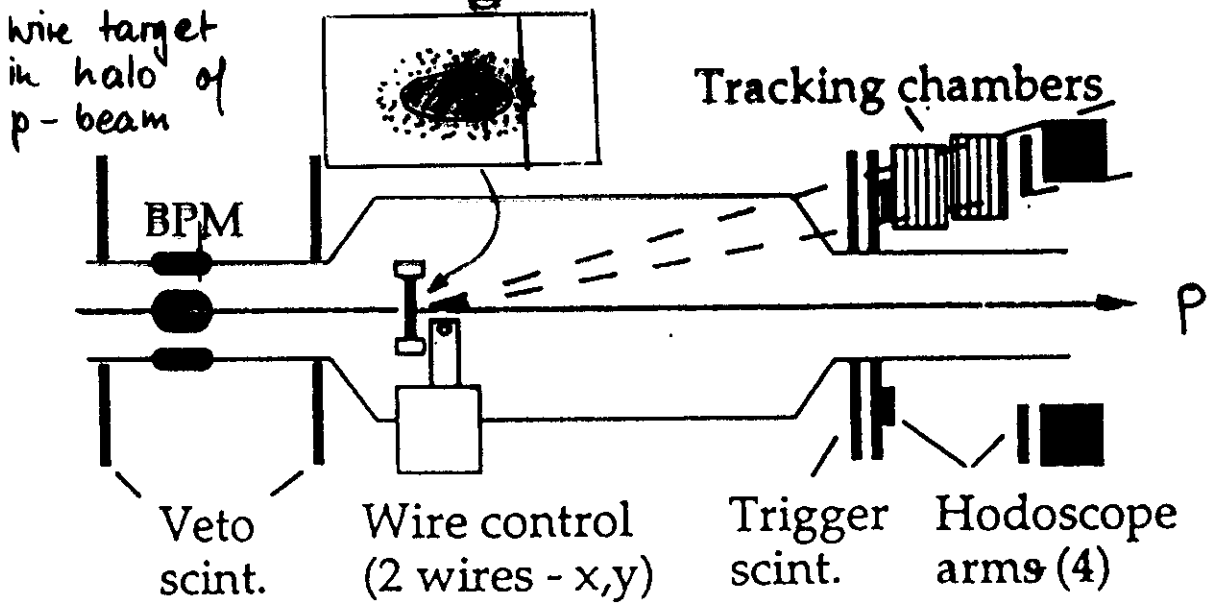
$$|V_{ub}| / |V_{cb}| = .08 \pm .02$$
$$\hat{=} \; 25\%$$
$$\downarrow$$

possible: $< 5\%$

- result strongly dependent on performance of vtx detector
- needs further study

new measurements of target efficiency

93 HERA Target Test (near West Hall)



2 horizontal wires (Cu, Al)
2 vertical wires

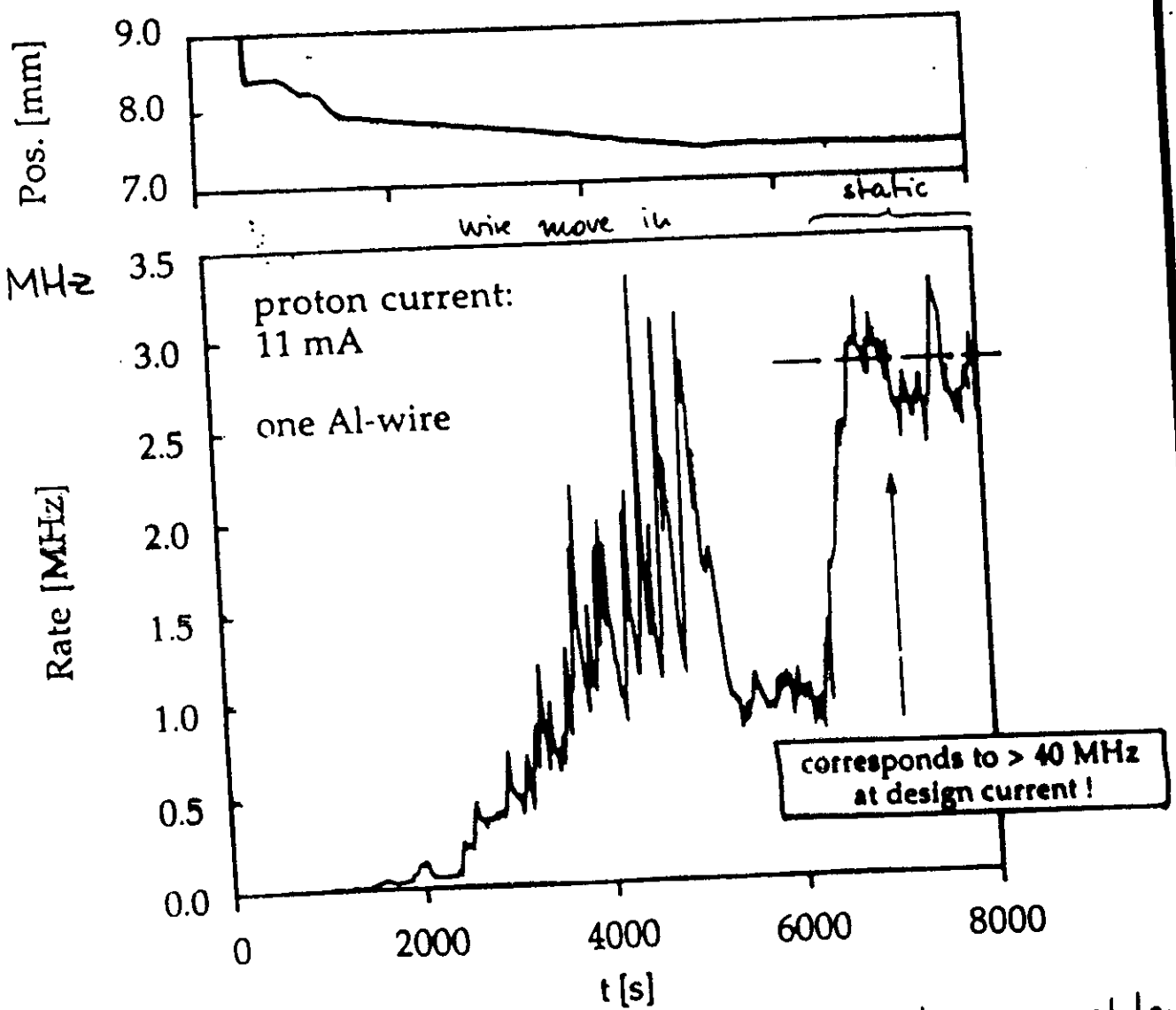
each wire ≈ equivalent to final target

so far, only one Al wire in beam

$$\text{Target } \epsilon = \frac{\text{frac of p interacting in wire}}{\text{frac of p leaving machine}}$$

Target Test Sept. 7 *(preliminary)*

- **Only one wire - rate should be higher with two orthogonal wires**
- **Large β**
- **HERA-p at ≈ 7% of design current**



→ wire induced background → not a problem

newly tested: steering of wire by feedback syst

HERA-b vs e^+e^- factories

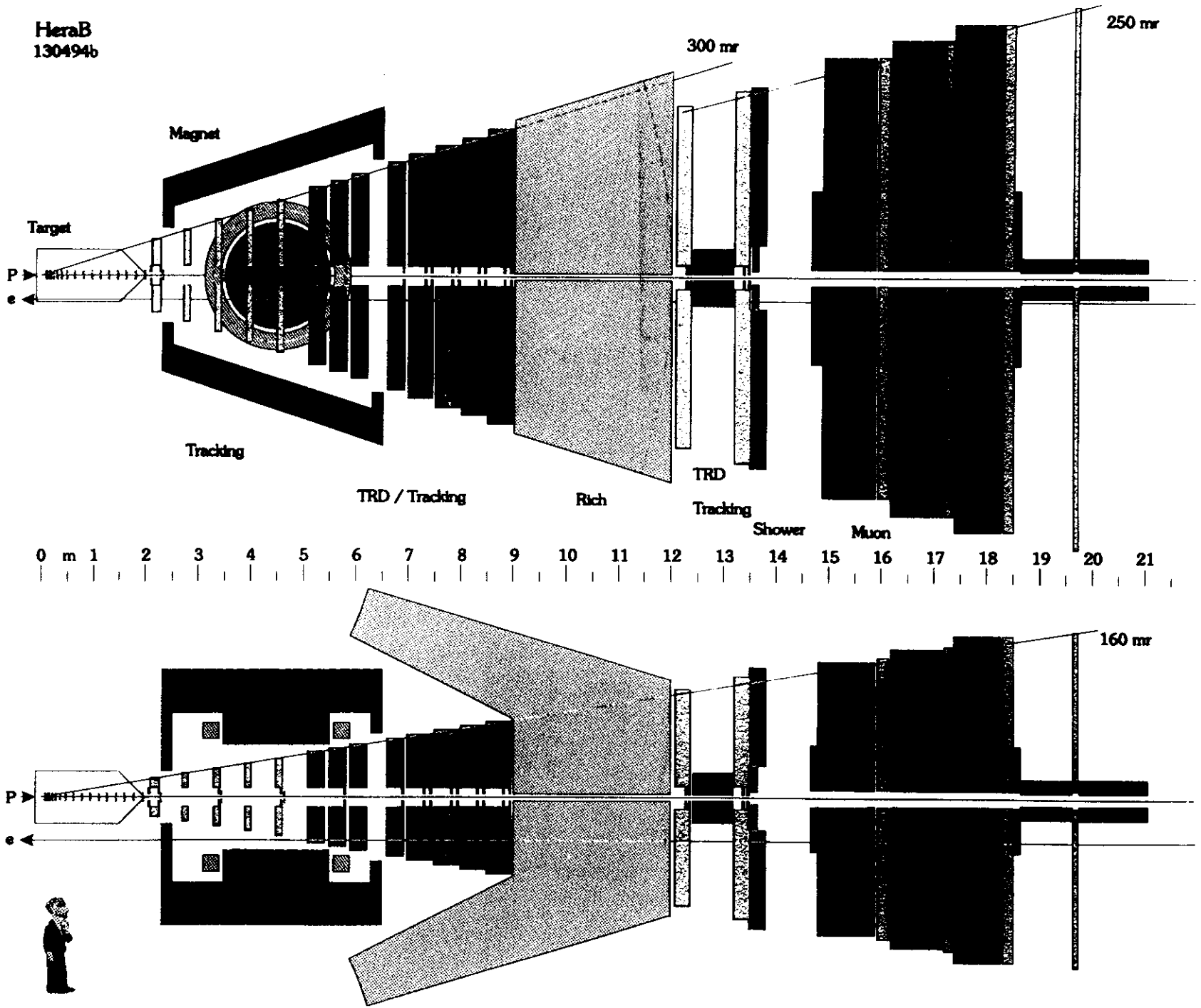
J. Jaros

- Physics Potential

	HERA b	e^+e^-
CP	$\sin 2\beta$	$\sin 2\beta$ $\sin 2\alpha$ several modes
CKM	V_{cb} ($\gtrsim 5\%$) V_{ub} ($< 5\%$) x_s (< 17)	V_{cb} ($\sim 2\%$) V_{ub} ($\sim 10\%$) x_s (< 15)
B	τ (B^0, $B^\pm$, B_s) some rare decays	τ (B^0, $B^\pm$, B_s) f_B ($B \to \tau\nu$) rare decays

- critical areas (experimental)

• trigger
• efficiencies
  • reconstruction
  • tag
• (b cross section)
	• Luminosity

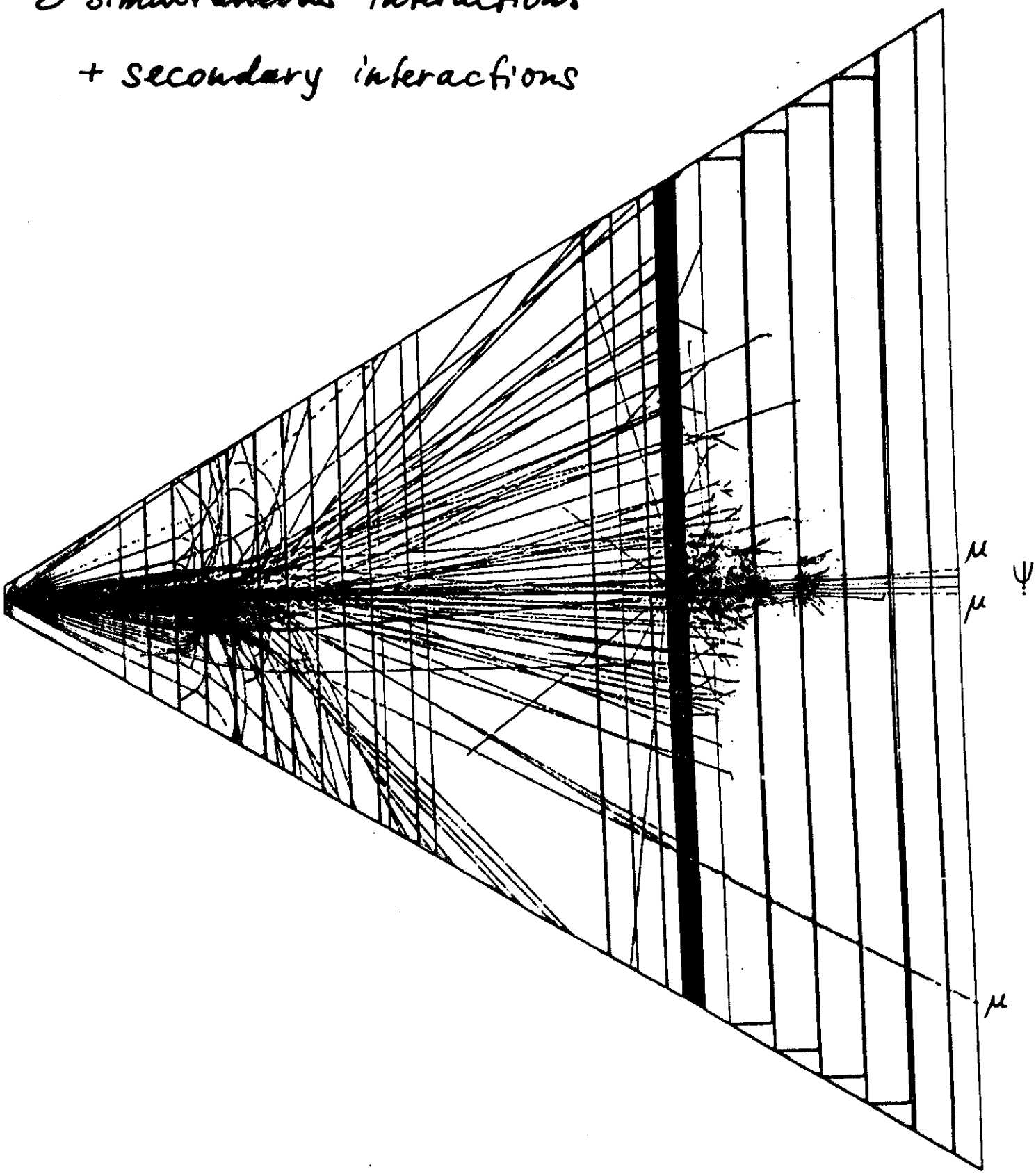

HeraB
130494b
300 mr
250 mr
Magnet
Target
P
e
Tracking
TRD / Tracking
Rich
TRD
Tracking
Shower
Muon
0 m 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
160 mr
P
e

Defector Optimization by GEANT Simulation

"typical" B - event

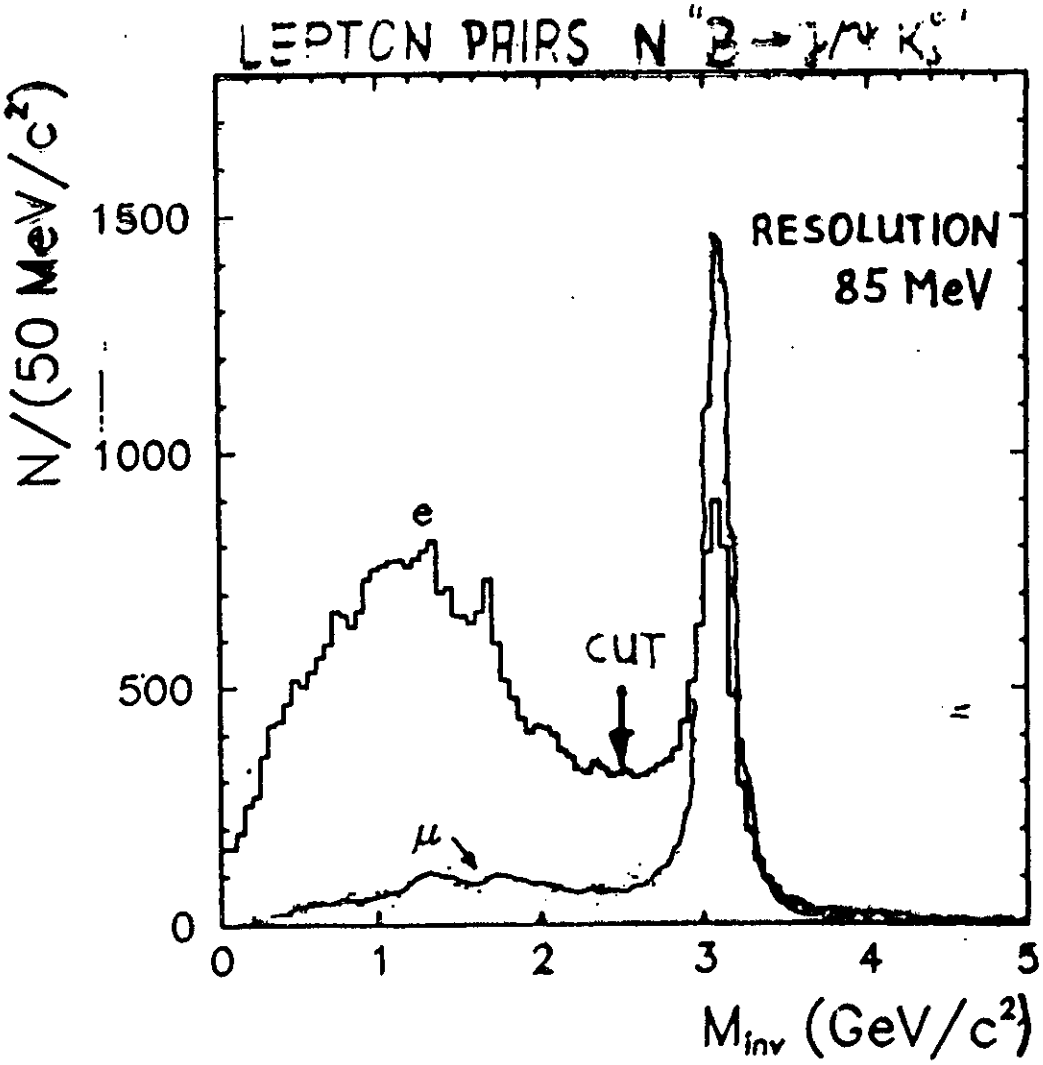
3 simultaneous interactions

+ secondary interactions



Trigger Performance

1. Efficiency for signal



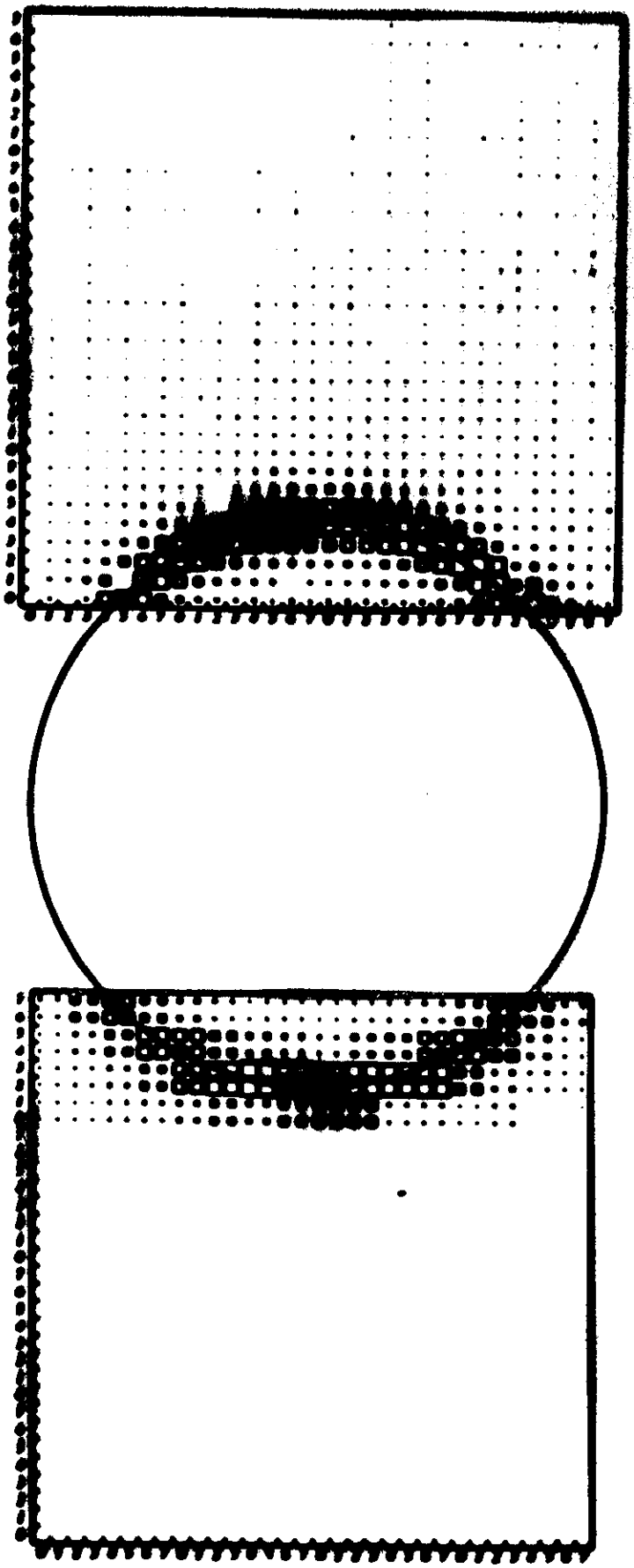
$\varepsilon_{geom} * \varepsilon_{cuts} * \varepsilon_{trig} =$ 60% for $\mu^+\mu^-$

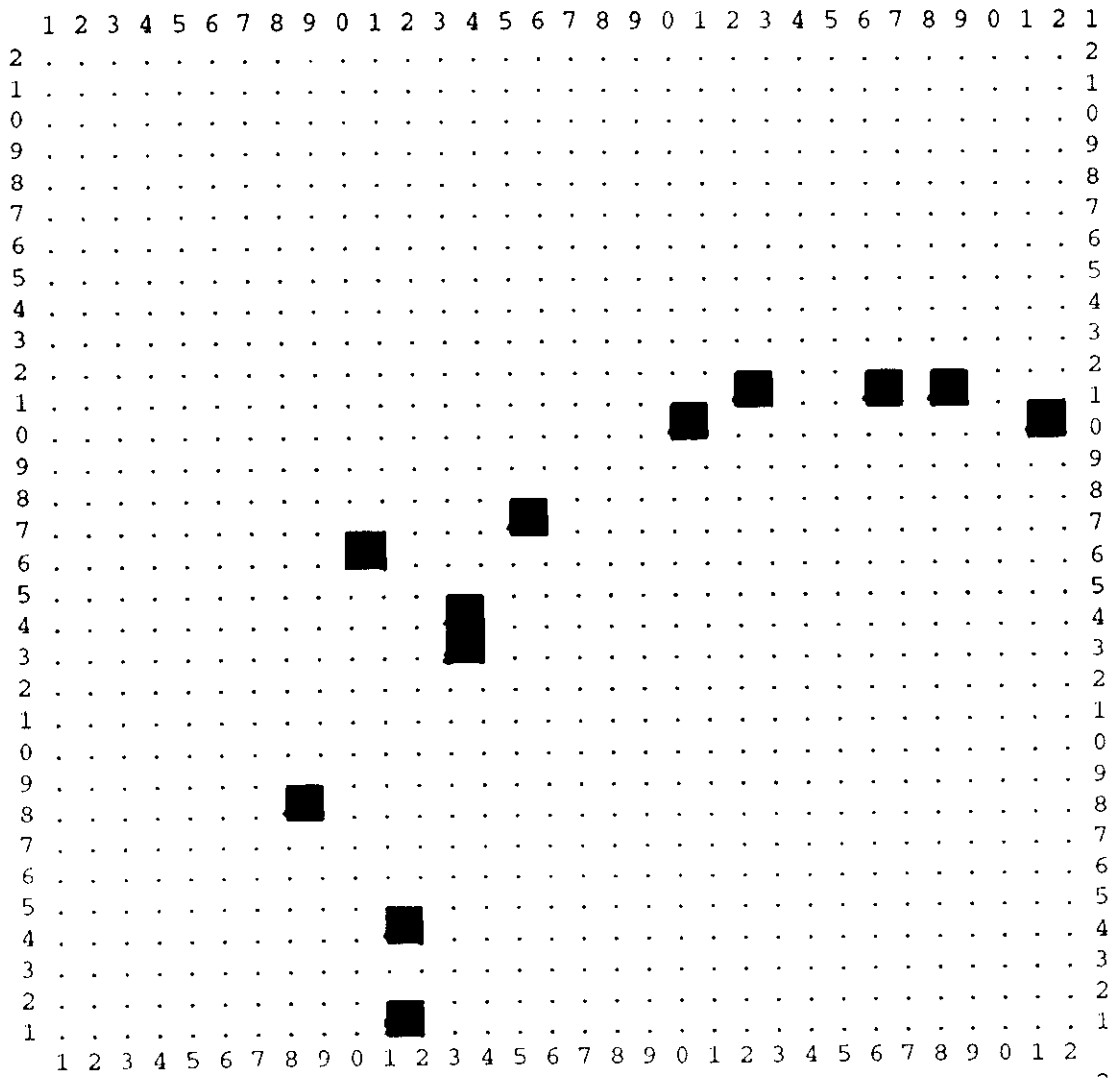
47% for e^+e^-

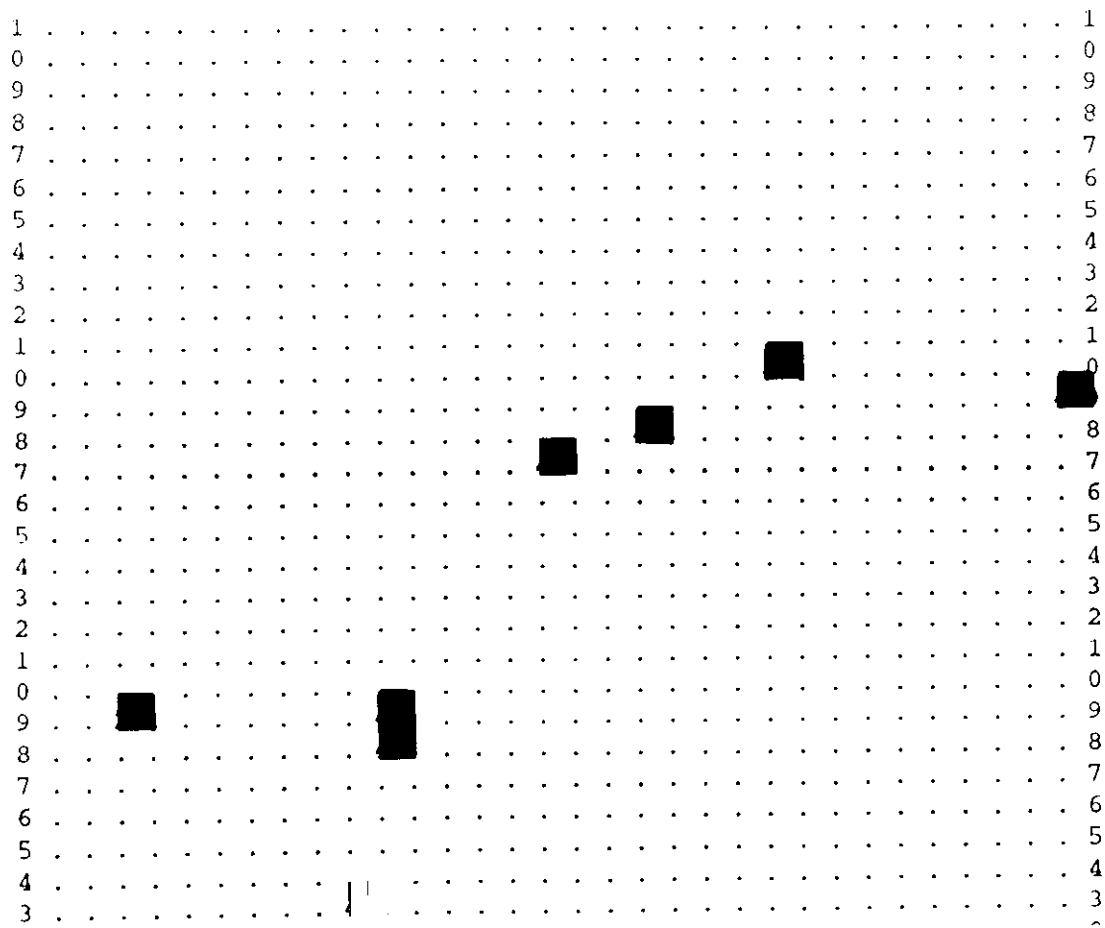
better than specified ✔

2. Rate: **30 kHz for 5 interactions per BX**
< 10 kHz for 3 interactions

required: < 50 kHz ✔




1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 1
2 1 0 9 8 7 6 5 4 3 2 1 0 9 8 7 6 5 4 3 2 1 0 9 8 7 6 5 4 3 2 1
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2


1 0 9 8 7 6 5 4 3 2 1 0 9 8 7 6 5 4 3 2 1 0 9 8 7 6 5 4 3 2 1 0 9 8 7 6 5 4 3

Summary

HERA:
- supraconducting p-ring and e-ring work well
- beam-beam interaction as calculated
- Lumi (93) = 20 · Lumi (92)
- full Lumi obtainable

PHYSICS:
- new kinematic region
- Photo production
  - σ_{TOT} measured
  - hard scattering process = import.
  - multi jet events
  - subprocesses can be identified
- Deep Inelastic Scattering
  - new region in (x, Q^2) accesible
  - first measurement of F_2 at low x → strong rise → QCD
  - jet structure observed
  - scattering of colourless objects observed
- Searches
  - new limits

FUTURE:
- exp. to study polarised struct. fu.
- can CP violation be measured at HERA?