(157)

Cours/Lecture Series

1985-1986 ACADEMIC TRAINING PROGRAMME

SPEAKER : F. EISELE / DESY
TITLE : Lepton-hadron scattering – past and future
DATES : 16, 17 and 18 October
TIME : 11.00 to 12.00 hours
PLACE : Auditorium

ABSTRACT

Lepton-hadron scattering experiments have played a key role for the development and verification of the standard model. The lectures will summarize the main ideas and experimental results concerning the substructure of the nucleon, the structure of the weak currents and the production of new particles. In a second step it will be discussed how experiments at e-p colliders like HERA can lead beyond the standard model by studying the substructure of quarks and leptons, the existence of new kinds of interactions and/or new particles.

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lepton-nucleon scattering: past + future

F.E. 85

2

electrons, muons | **neutrinos**

① fundamental interactions : electroweak

electroweak theory (I)

QED refused to be violated!

eD (78)
μC
} el. magn. weak interference

62 2ν
73 neutral current ☆☆
GIM
hist

structure of neutral + charged weak currents

(II) ② structure of hadronic matter : quarks

elastic eA-scattering: nuclear + nucleon charge distributions

☆☆ DIS: Partons SLAC-MIT 69

quasielastic vector + axial Formfactors

Partons = quarks ; early expt. (GGM, CITF)

flavour decomposition

$F_2^{\mu N}$, $F_2^{\mu p}$, $F_2^{\mu n}$

xu_v, xd_v, $\bar{u}$, $\bar{d}$, $\bar{s}$
$q_c(x)$

82 EMC-Effect; nuclear dependence

③ fragmentation $D_u^{\pi^+}$, $D_u^{\pi^-}$

baryon fragmentation (EMC)

$D_u^{\pi^+}$, $D_u^{\pi^-}$, $D_d^{\pi^+}$, $D_d^{\pi^-}$ } very short

(II) ④ QCD-tests : (short)

• big historical impact !

⑤ future: e-p-colliders : HERA ≥ 1990

true electroweak machine,
combines strength of charged lepton physics
and $\nu, \bar{\nu}$-physics

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today:

wednesday a) some history: ① establishment of QPM
② the way to electroweak theory
sorting out the standard model

monday b) tests of electroweak theory in ℓ-N
NC + CC
present status

c.) flavour decomposition of the nucleon:
→ determination of parton distributions
– something on QCD-tests (little)

friday d.) e-p-physics : – physics interest
– HERA
– detectors for HERA

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not covered due to lack of time: + (interest?)
- ν-oscillations, reactor ν-physics
- beam dump results
- final states in DIS ← thats a pity (little)

⑦ charged lepton nucleon scattering:

best method to measure nuclear and nucleon structure due to pointlike probe with known interaction!

phases: ① e⁻-scattering on nuclei $E_e \lesssim 600$ MeV

mainly: charge distributions of nuclei and the proton from elastic scattering (~50-62,

② e^-p, eD scattering at high energies

CEA, DESY; $E_e \leq 6$ GeV early 60'es

SLAC $E_e \leq 20$ GeV mid 60'es

CEA, DESY: emphasis on resonance production hadronic final states

SLAC: inclusive measurements
elastic → proton + neutron Formfact.
inelastic → partons! (68)

③ muon scattering experiments

FNAL, CERN

'QCD' QPM
- ⟹ first evidence for scaling violations at high Q^2 (FNAL, Chang et. al.)
- → precise measurements on H_2, D_2, Fe, C over large Q^2-range

⟹ EMC-effect: quark distributions depend on nucleon surrounding!

④ future: e–p storage rings

HERA ≥1990: electroweak machine
combines: $(e, \mu, \nu, \bar{\nu})$-experiments!

⑦ differential cross-sections + form factors (reminder)

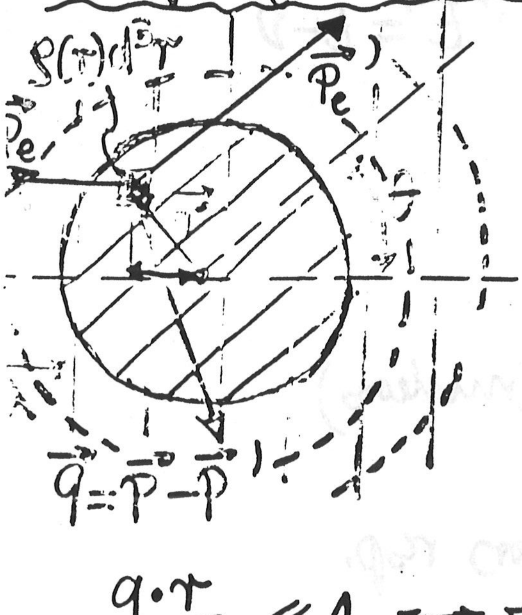
e⁻-scattering

target	cross-section for pointlike target	extended target
nucleus (M) spin 0 'elastic'	$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \underbrace{\frac{(2mZe^2)^2}{q^4}}_{Rutherford} \cdot \frac{\cos^2\theta/2}{1+\frac{2E}{M}\underset{recoil}{\uparrow}}$ ~ $\vec{s}_e$	$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \lvert F(q^2)\rvert$
nucleon (M) spin 1/2 'elastic'	$\left(\frac{d\sigma}{d\Omega}\right)_{Dirac} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left[1 + \underbrace{\frac{q^2}{2M^2}\tan^2\frac{\theta}{2}}_{nucleon\ magn.\ moment}\right]$	$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left[F_E^2(q^2)\cdot 1 + F_M^2(q^2)\cdot\tan^2\frac{\theta}{2}\right]$
nucleon (M) spin 1/2 inelastic: energy + momentum transfer independent!		$\frac{d^2\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[W_2(\nu, q^2)\cdot 1 + W_1(\nu, q^2)\cdot\tan^2\frac{\theta}{2}\right]$

hadronic structure: measure deviation from "pointlike" cross-section

$$\boxed{\text{Formfactors } F_i(q^2) \text{ contain all information!}}$$

example of non-relativistic scattering: spatial resolution and q^2



$$F(q^2) = \int_0^R e^{i\vec q\cdot\vec r/\hbar}\,\rho(r)\,d^3r$$

$$\simeq 1 - 1/6\,\frac{q^2\langle r^2\rangle}{\hbar^2} + \dots$$

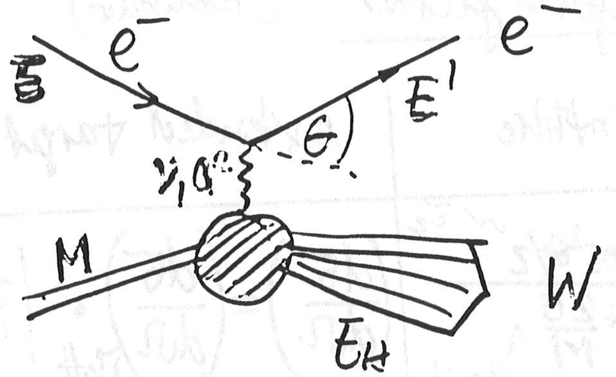
$$\frac{\vec q\cdot\vec r}{\hbar} = 2\pi\cdot\frac{r\cdot\sin\theta}{\lambda} \text{ : phase difference}$$

$$\vec q = \vec p' - \vec p$$

$$\boxed{\Delta r \simeq \frac{.2\,GeV\cdot fm}{q}}$$

$\frac{q\cdot r}{.2\,GeV fm} \ll 1$ ⟷ target appears pointlike!

① [illegible]



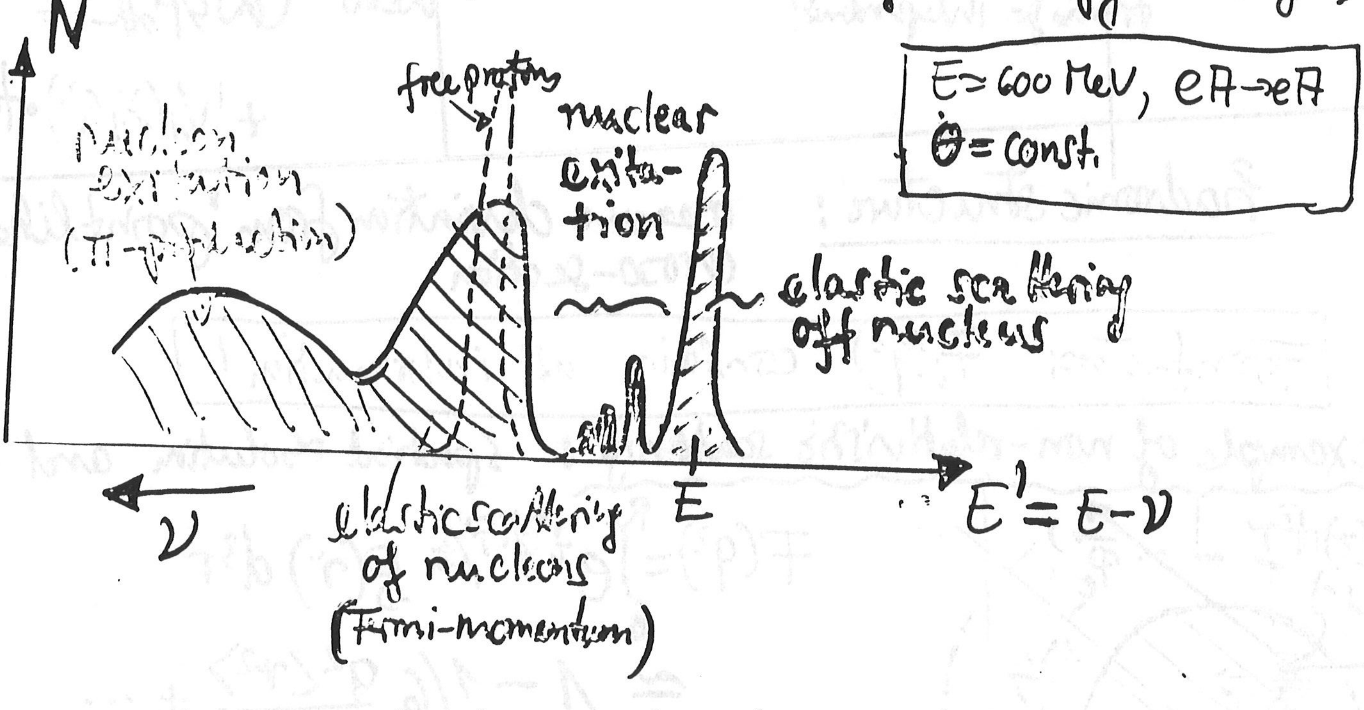
$$Q^2 = 4EE'\sin^2\theta/2$$
$$\nu = E - E' = E_H - M$$

$$\boxed{\begin{gathered} Q^2 = 2m\nu \cdot x \\ x = 1 - \frac{(W^2 - M^2)}{2m\nu} \end{gathered}}$$

$Q^2 = 2m\nu$: elastic $\rightsquigarrow$
$x = 1$

Q^2 and ν not independent for specific final state of fixed mass W! → (described by FF: $F(Q^2)$)

elastic + inelastic measurements: elastic scattering is not prominent at high energy transfer!

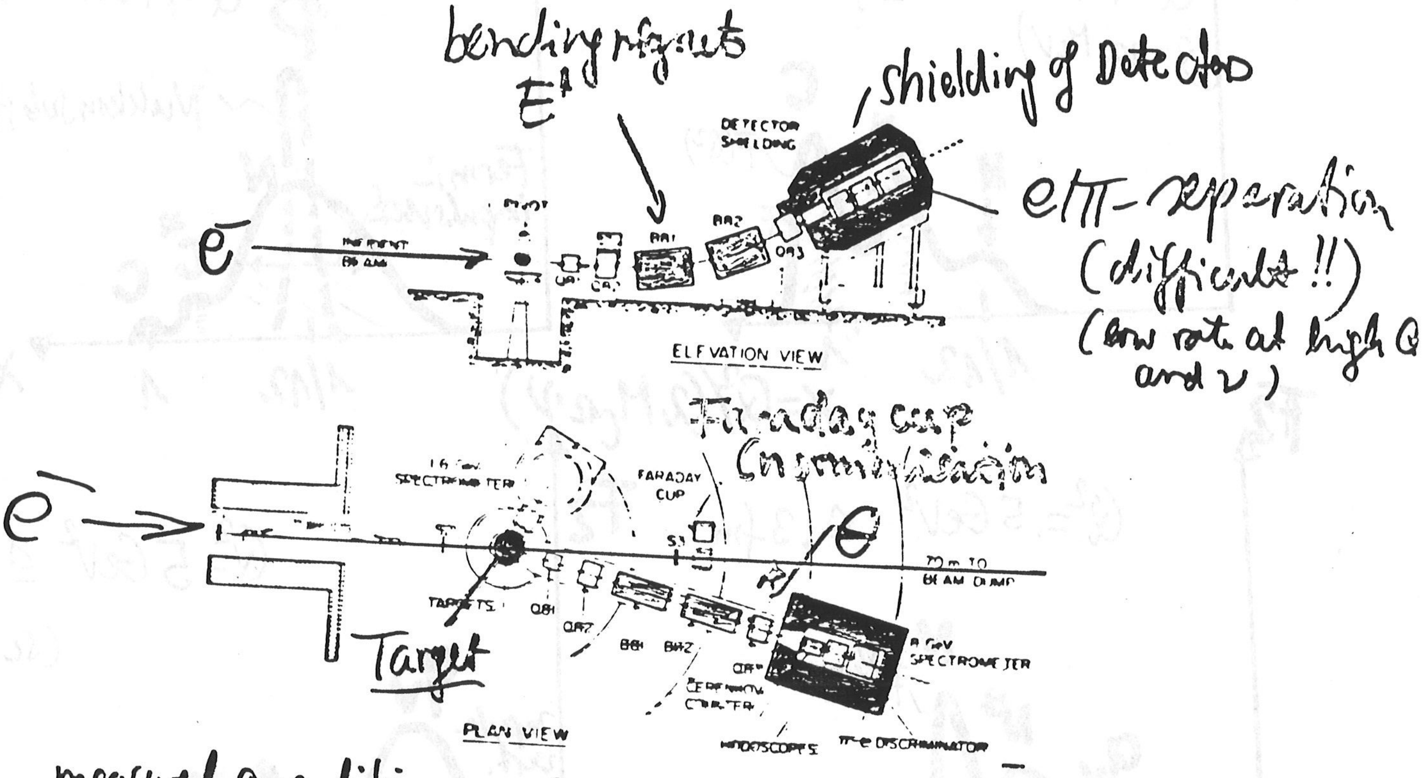


evidence for hadronic structure:

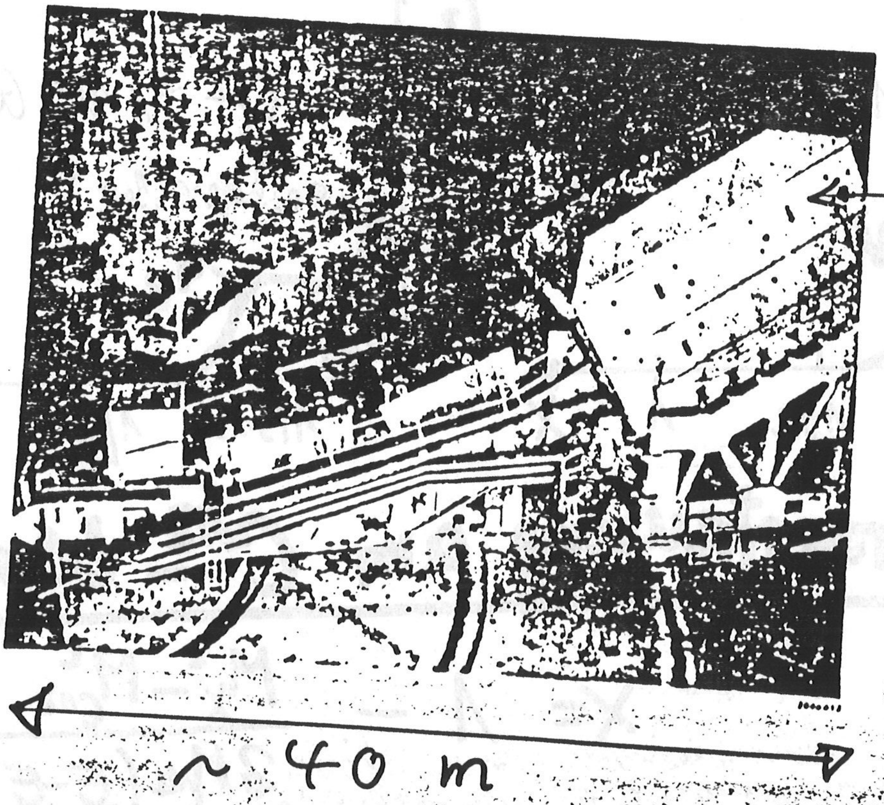
① nuclear exitation
② scattering from constituents (nucleons)
③ exitation of nucleons

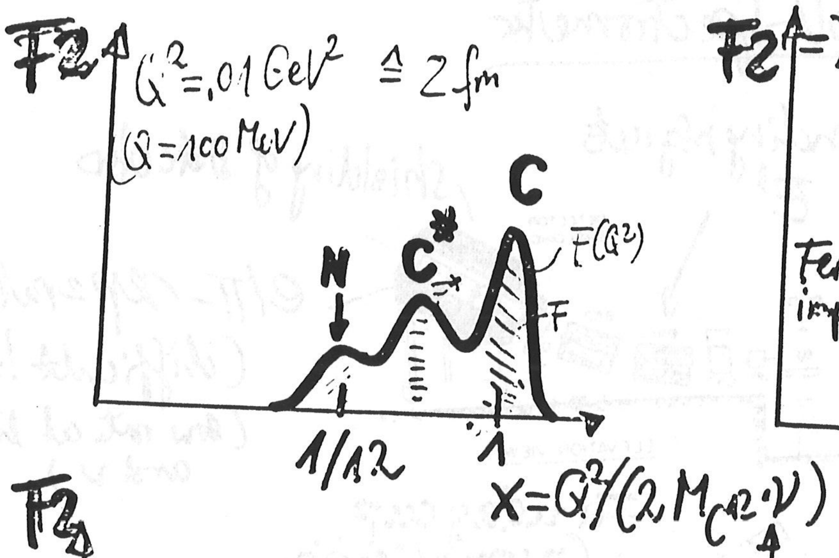
‖ + Q^2-dependence of formfactors resp. structure functions

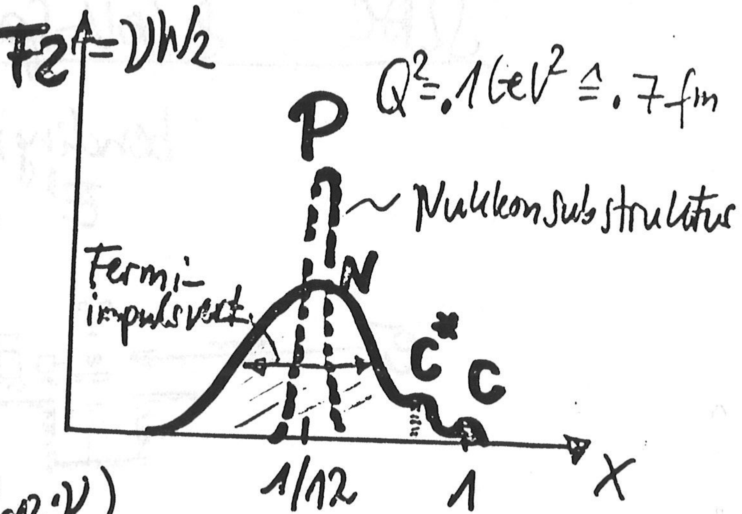
SLAC : 8 GeV-Spectrometer

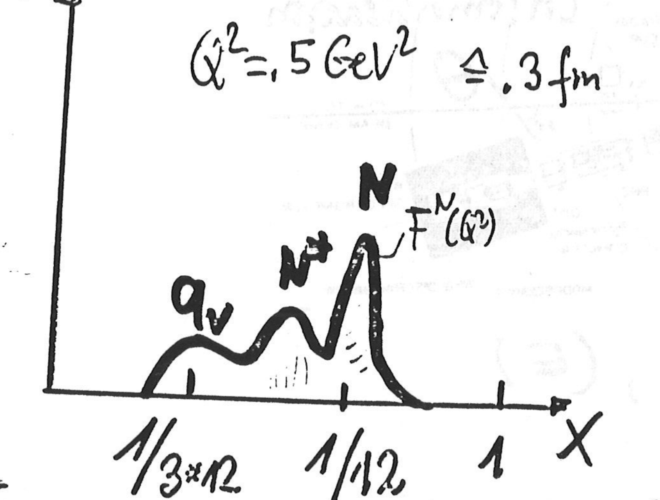


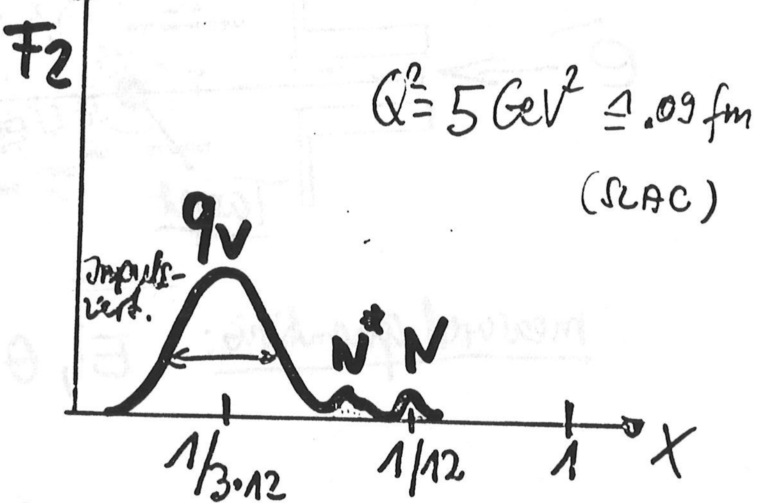
measured quantities: $E', \theta, (E)$

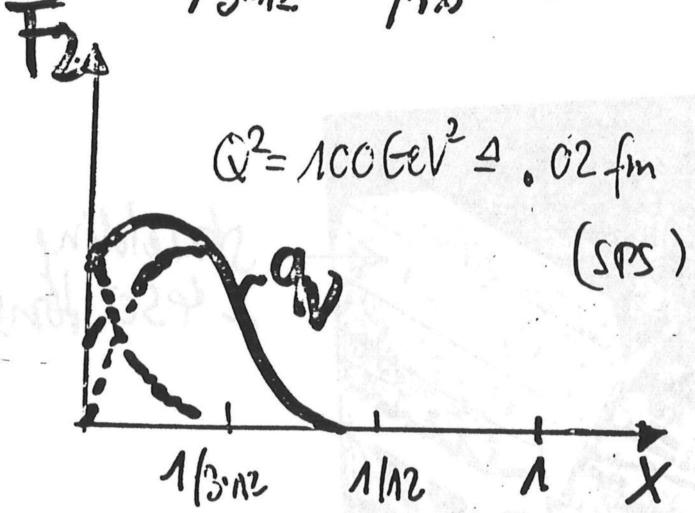


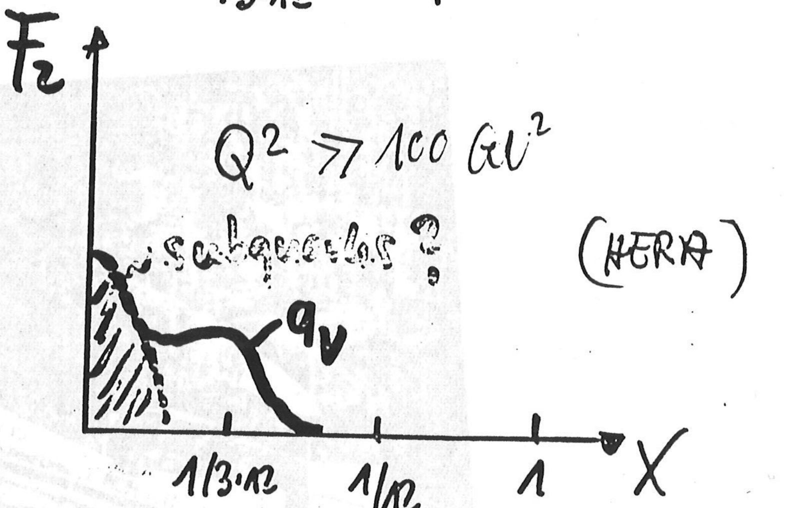












inkl. Elektronstreuung am C¹²-Kern

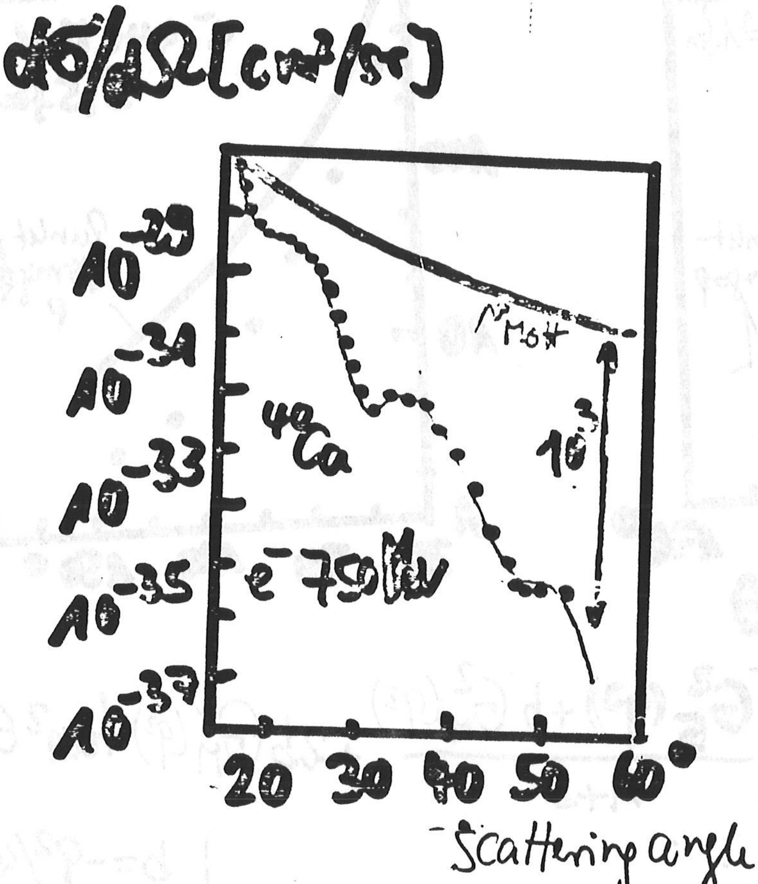
$$x = 1 - \frac{M_X^2 - M_{C^{12}}^2}{2M_{C^{12}}(E-E')} = \frac{Q^2}{2M_{C^{12}}\cdot\nu}$$

$$\frac{d^2\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + 2\tan^2\theta/2\,\frac{xF_1(x,Q^2)}{M}\right]$$

I elastic scattering on nuclei :

→ 'charge distribution' in the nucleus

(e.g. Hofstadter et al.
Stanford ...)



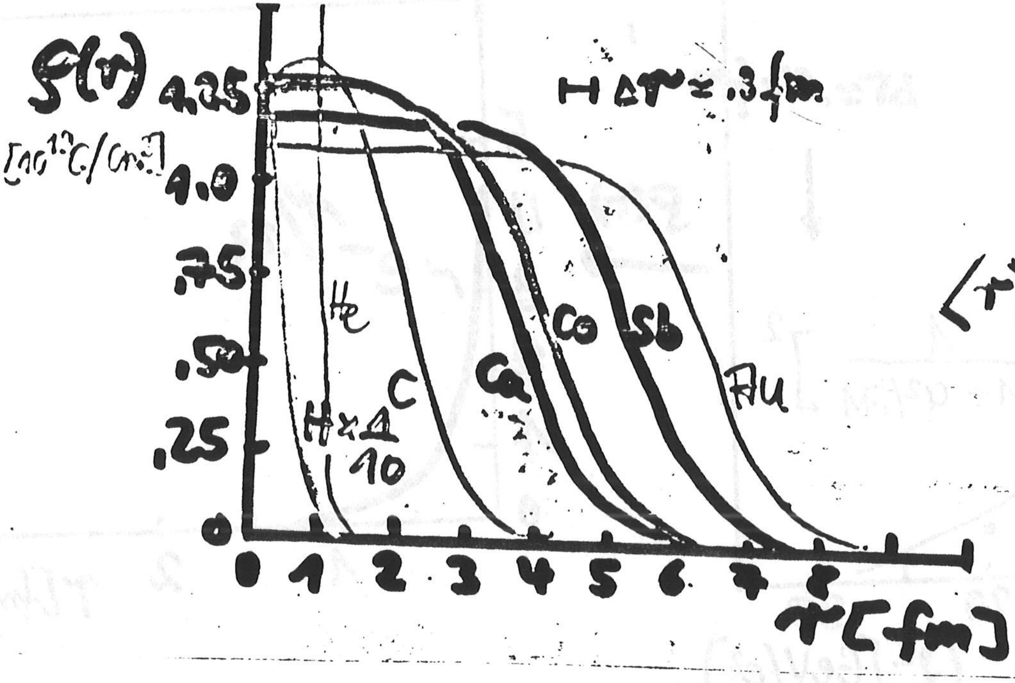
diffraction pattern:

position of minima: given by ⟨radius⟩

depth of minima: width of opaque area at the surface

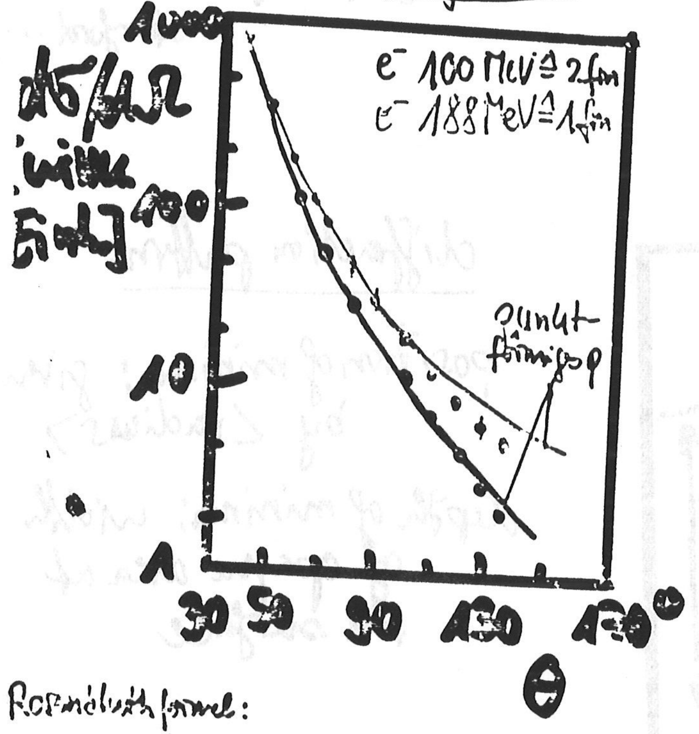
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left|F(q^2)\right|^2$$

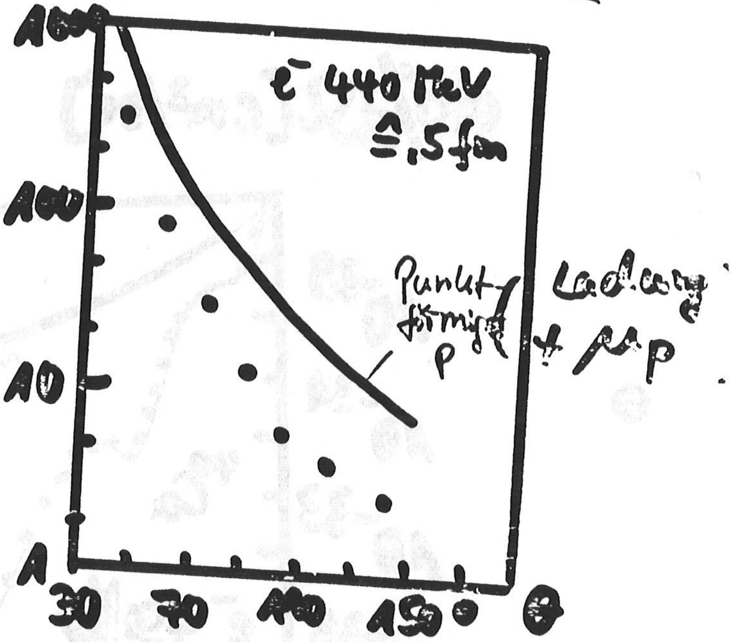
→ $\rho(r)$ (Fourier transform)



$\langle r \rangle \sim A^{1/3}$

II free nucleons: charge + magnetic moment





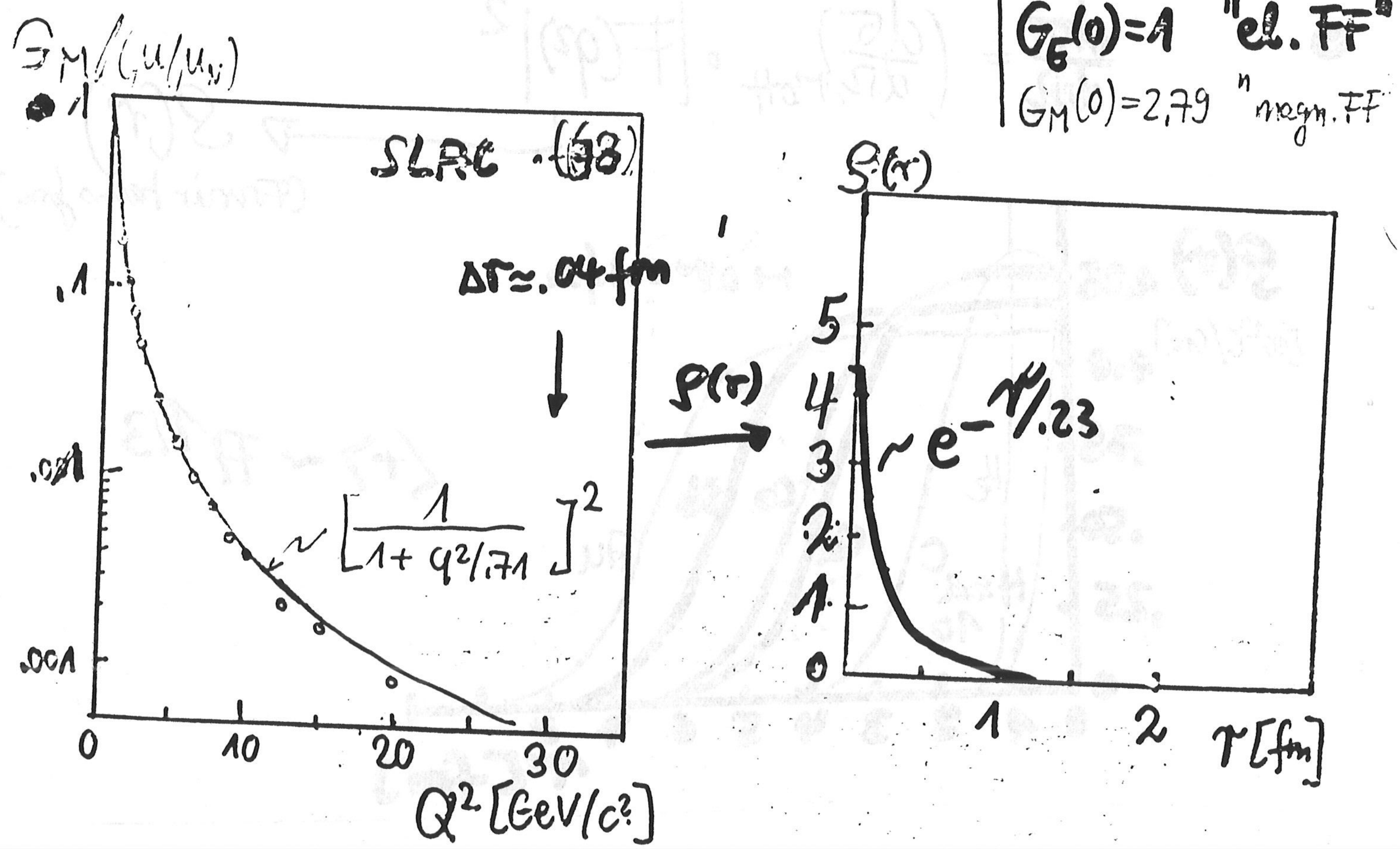
Rosenbluth formel:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{G_E^2(q^2)+b\,G_M^2(q^2)}{1+b} + 2b\,G_M^2(q^2)\tan^2\theta/2\right]$$

$b = -q^2/4m^2c^2$

$G_E(0) = 1$ "el. FF"

$G_M(0) = 2{,}79$ "magn. FF"



Partons appear on the scene

'decade of the leptons'

l-N scattering is best probe for seeing the quark and antiquark substructure of the nucleon

also true for next generation of accellerators

- practically all scattering processes occur at the parton level (in contrast to hadronic collisions not involving leptons!)
- incident particle is 'pointlike' and has well known interaction

SLAC-MIT e-p-scattering

: evidence f[illegible]

- 20 GeV Linac → large kine[illegible]c range above resonance re[illegible]
- Spectrometer specialized on inclusive measurements
  "measure only scattered electron"
  (partially motivated + enforced by short o[illegible]

inelastic measurements started summer 1967 (elastic scattering was [illegible]
first results at Vienna meeting (not in conference proceedings)

inelastic scattering above resonance region ($W \geq 2$ G[illegible]
shows much weaker q^2-dependence [illegible] elastic
scattering (this was completely un

68

Summary by Panofsky: " Theoretical
focussed on the possibility +
evidence on the behaviour of
structures in the nucleon"

67 : Bjorken: scaling for $Q^2, \nu \to \infty$
68 : Feynman: Partons
Bjorken, Paschos:

69 Lepton-photon symposium ([illegible]

all essential features are there:

① very weak Q^2-dependence for $W > 2$ [illegible]
compared to elastic scattering ← poi[illegible] scattering

② $\sigma_L / \sigma_T \ll 1$ (SLAC-MIT + DESY) (← [illegible] spin 1/2)

③ νW_2 scales in $\omega = 1/x$ f[illegible] $W > 2$ GeV
to ≈ 10% accuracy

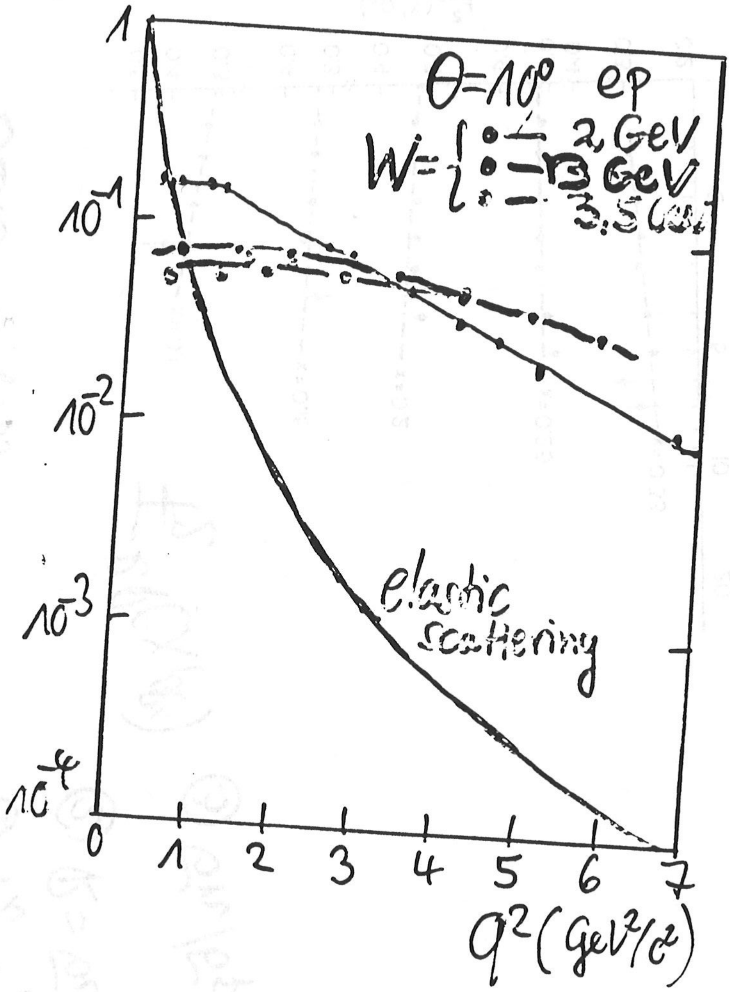
④ $\int_1^\infty \frac{d\omega}{\omega^2}(\nu W_2) = \int_0^1 F_2^{ep} dx = .16 \pm .001$ ([illegible])

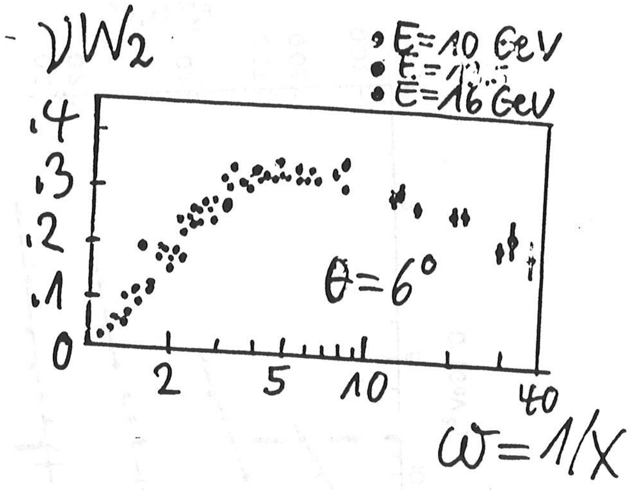
Conclusion:

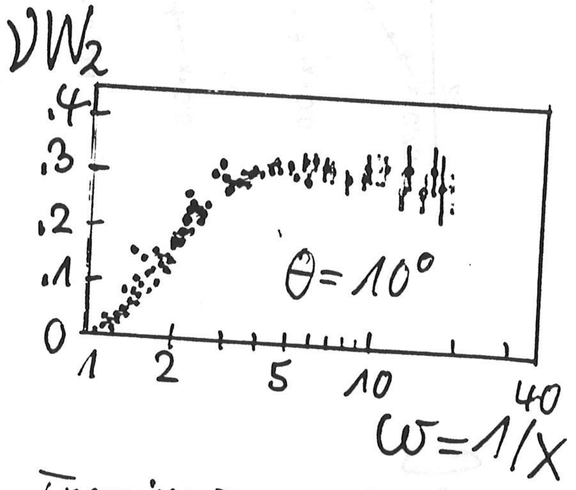
"both 'diffraction' models (vector meson dominance) and 'Parton' models fit the data

R. Taylor

$$\sigma/\sigma_{Mott} = W_2(q^2,\nu) + 2\,tg^2\,\theta/2\; W_1(q^2,\nu)$$



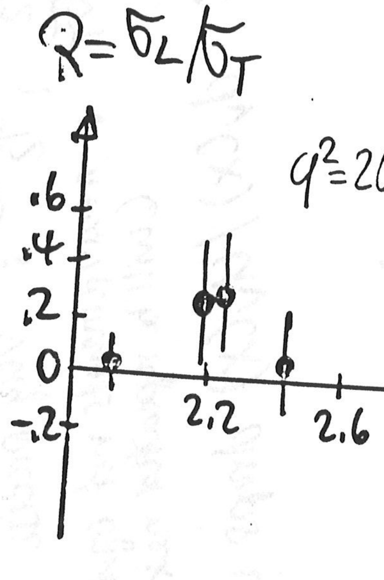


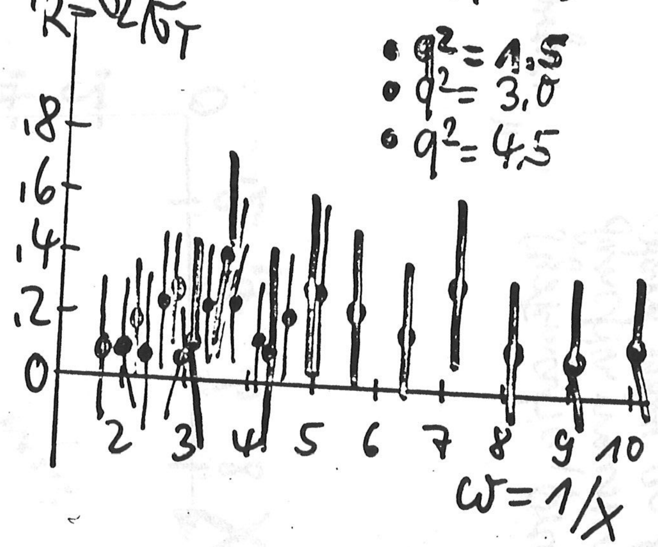


Energies: 7, 11, 13.5, 15.2, 17.7 GeV

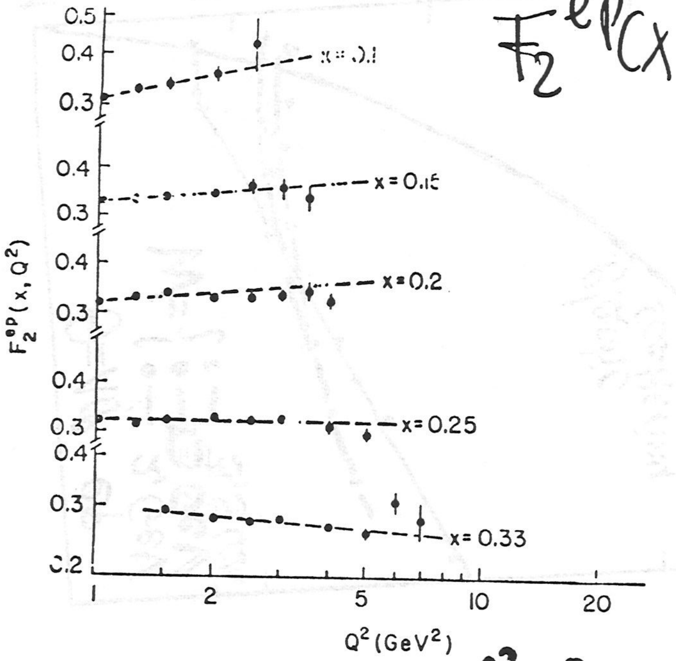
SLAC-MIT (prel.)

(DESY + SLAC)

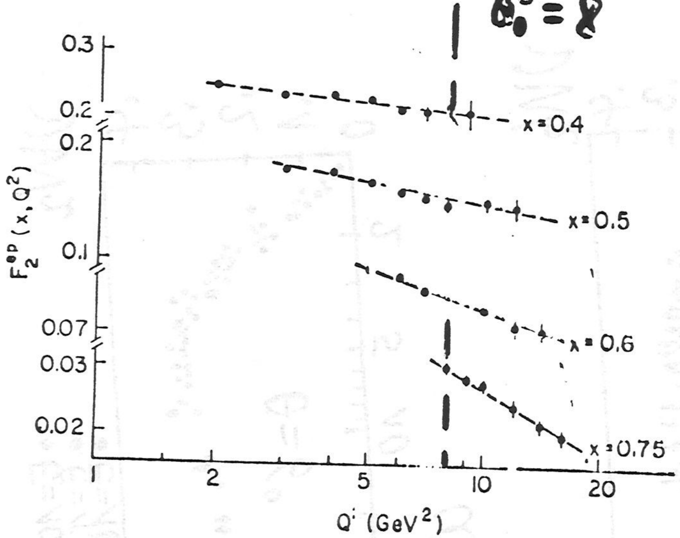




SLAC-MIT



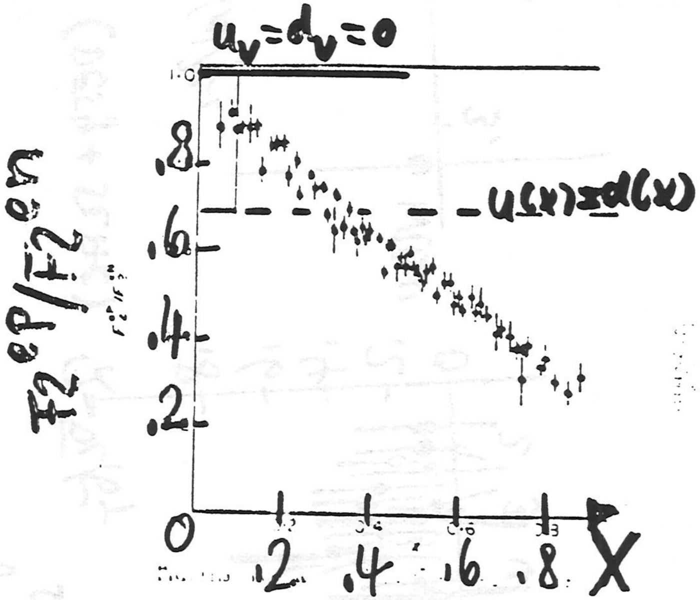
$F_2^{ep}(x, Q^2)$



① F_2^{ep}, F_2^{en}, F_2^{ed} : very precise data, Q^2 too low to dem scaling violati

② $R = \sigma_L/\sigma_T$: measurements not optimized for R (will be repeated next year!!)

③ σ_n/σ_p : $d_v(x)/u_v(x)$ drops with x !



J. Steinberger: "... systematic, precise structure function measurements, which stand today as landmarks of reliable experimentation"

Further important steps to establish QPM

Partons = Quarks

① $\sigma_T(\nu N)$ rises linearly with E_ν

$\int_0^1 F_2^{\nu N} dx \Big/ \int_0^1 F_2^{eN} dx = \frac{18}{5}$; charge 1/3 } GGM 72

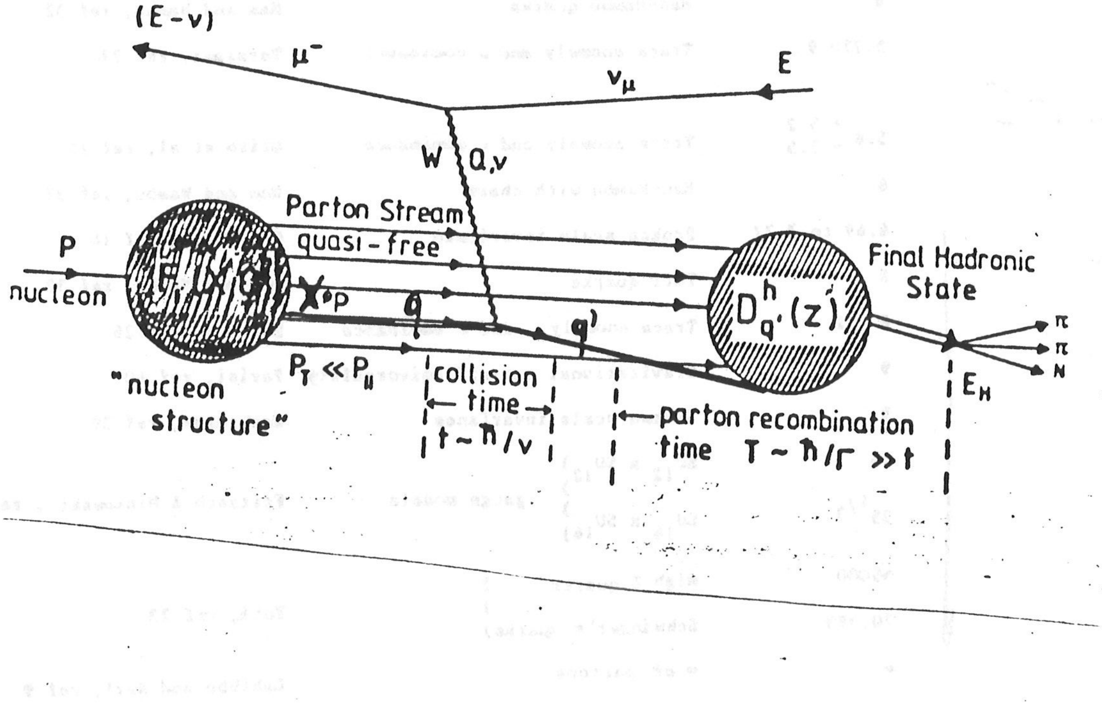
③ number of valence quarks = 3 ! { GGM, CITF } 74
sea quarks (small) GGM

④ jet structure in e^+e^- ; Spear (MARK I) 75

! CHARM ! (Ψ: Nov. 74) established 75

but: near catastrophy (London 74!)

QPM-picture for DIS

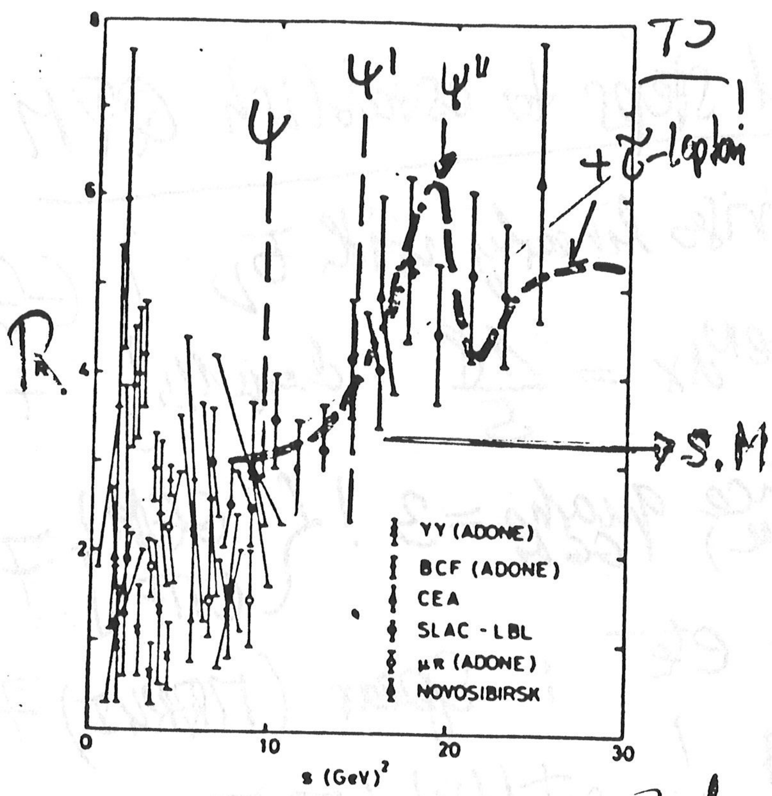


[illegible]

near catastrophy for quark model:

$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} \overset{!}{=} 3\sum e_q^2$$

nice linearity !! [illegible]



John Ellis: 22 theoretical explanations most of them fatal for standard model.

predicted values of R

Table of Values of R

Value	Model	Source
0.36	Bethe-Salpeter bound quarks	Bohm et al, ref 42
2/3	Gell-Mann-Zweig quarks	
0.69	Generalized vector meson dominance	Renard, ref 49
~1	Composite quarks	Raitio, ref 43
10/9	Gell-Mann-Zweig with charm	Glashow et al, ref 31
2	Coloured quarks	
2.5 to 3	Generalized meson dominance	Greco, ref 30
2 to 5	" " " "	Sakurai, Gounaris, ref 47
$3^1/_3$	Coloured charmed quarks	Glashow et al, ref 31
4	Han-Nambu quarks	Han and Nambu, ref 32
5.7±0.9	Trace anomaly and ρ dominance	Terazawa, ref 27
$5.8^{+3.2}_{-3.5}$	Trace anomaly and ε dominance	Orito et al, ref 25
6	Han-Nambu with charm	Han and Nambu, ref 32
6.69 to 7.77	Broken scale invariance	Choudhury, ref 18
8	Tati quarks	Han and Nambu, ref 32
8 ± 2	Trace anomaly and ε dominance	Eliezer, ref 26
9	Gravitational cut-off, universality	Parisi, ref 40
9	Broken scale invariance	Nachtmann, ref 39
16	$SU_{12} \times SU_{12}$) gauge models	Fritzsch & Minkowski, ref 34
$35^1/_3$	$SU_{16} \times SU_{16}$)	
~5000	High Z quarks)	
70,383	Schwinger's quarks)	Yock, ref 73
∞	∞ of partons	
		Cabibbo and Karl, ref 9
		Matveev and Tolkachev, ref 35
		Rozenblit, ref 36

S.M.

Ⓑ neutrino experiments : why?

① ⇒ study of weak interaction at high energy

12. Minutes of the 108th SPSC Meeting held on 5-6 November 1985, SPSC 85-72, SPSC 108(*).

i) allways full of surprises!

******P, CP, 2ν, ...

ii) no consistent theory was available

13. Minutes of the 13th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-38, LEPC 15(*).

(in contrast to QCD, which refused to be violated)

Vogue for discoveries!

later:

② ⇒ ideal probe to determine the quark content of the nucleon: separate, sea and valence quarks
(only after high intensity beams and massive detectors became available)

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field had dramatic development:

discoveries! fundamental for standard model

1. area: 62–65: low fluxes, low mass detectors } ν_μ !

2. area: Gargamelle: PS — just at the right moment
NC, QPM-support

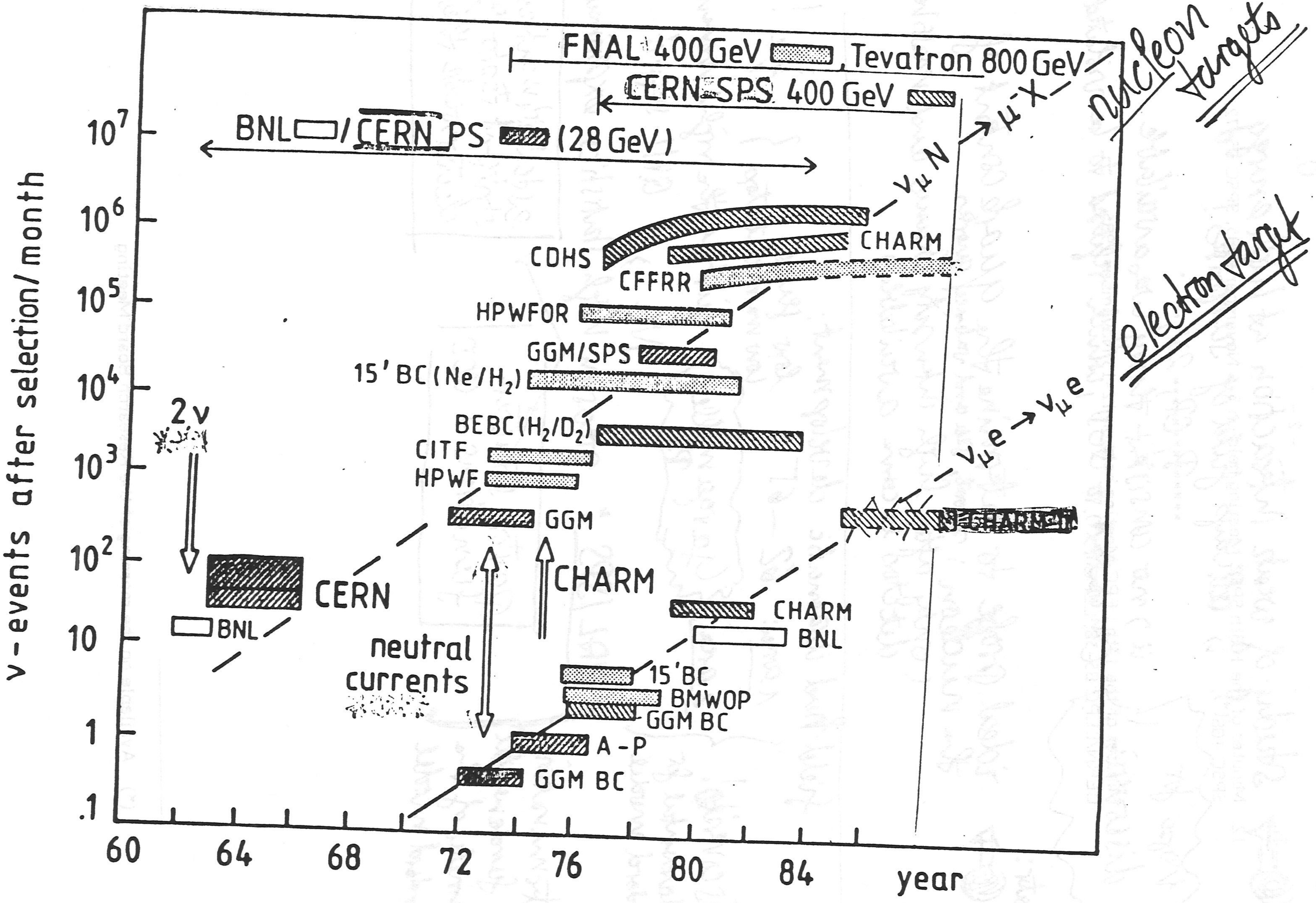
determination of fundamental parameters of the standard model

NAL/SPS: precision high statistics experiments

parton structure functions + QCD

establishment and stringent tests of electroweak theory

(*) Available on the morning of the Research Board Meeting


FNAL 400 GeV
Tevatron 800 GeV
CERN-SPS 400 GeV
BNL / CERN PS (28 GeV)
$\nu_\mu N \rightarrow \mu^- X$
nucleon targets
electron target
CHARM
CDHS
CFFRR
HPWFOR
GGM/SPS
15' BC (Ne/H_2)
BEBC (H_2/D_2)
CITF
HPWF
GGM
2 ν
CERN
BNL
CHARM
neutral currents
$\nu_\mu e \rightarrow \nu_\mu e$
II CHARM II
CHARM
BNL
15'BC
BMWOP
GGM BC
A - P
GGM BC
10^7
10^6
10^5
10^4
10^3
10^2
10
1
.1
ν - events after selection / month
60
64
68
72
76
80
84
year

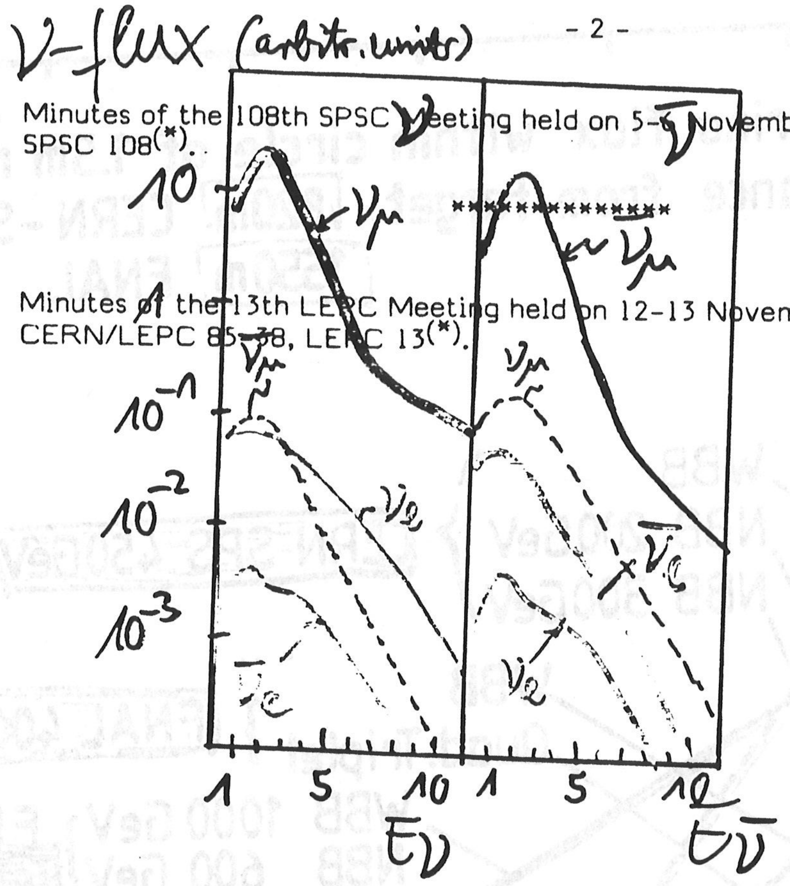
ν-beams for Gargamelle

19

PS 72 ($E_p = 25$ GeV

12. Minutes of the 108th SPSC Meeting held on 5-6 November 1985, SPSC 85-72, SPSC 108(*).

13. Minutes of the 13th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-38, LEPC 13(*).

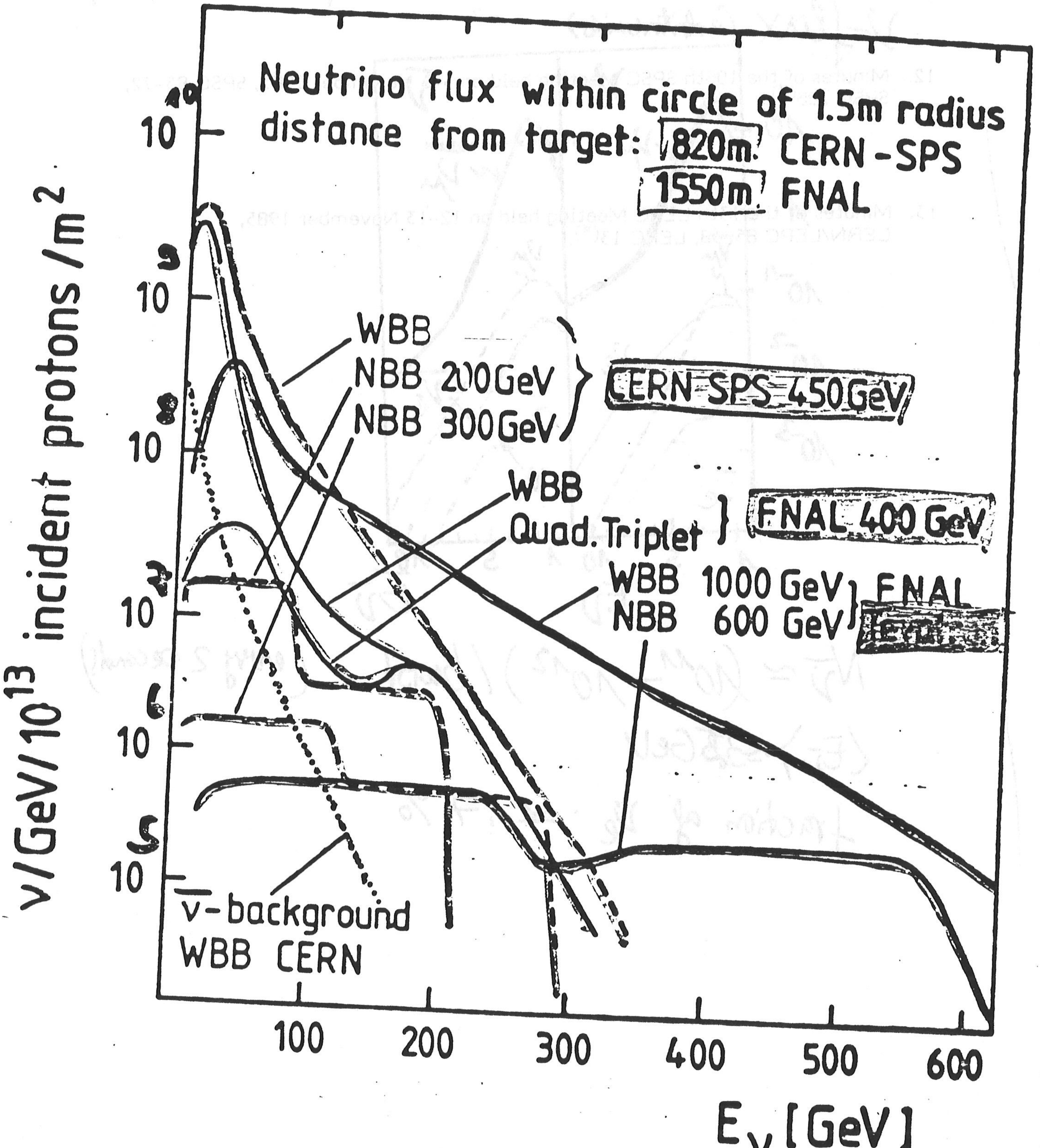


$N_\nu \simeq (10^{11} \div 10^{12})$ / burst (every 2 seconds)

$\langle E_\nu \rangle \simeq 3.5$ GeV

fraction of ν_e $\simeq .7\%$

(*) Available on the morning of the Research Board Meeting



<u>narrow band beam:</u> momentum selected π and K of one sign: — very low background of wrong polarity
— hard spectrum
— "easy" to monitor

<u>wide band beam:</u> sign selection by focussing Horn with little momentum dependence
→ maximum flux
→ low average energy
→ background [illegible] 4.6

Detectors for ν-physics

	BC (H_2, D_2)	BC heavy liquid	electronic detectors high Z iron	 low Z
target mass	1 to	~10 to	~1000 to	~100 to
muon ident.	good	good	excellent	good
electron ident ~~of~~ measurement	—	good **	no —	possible $\Delta\theta_e \simeq \frac{30\,mr}{\sqrt{E_e}}$
total hadronic energy	poor	[illegible]	good	good
jet angle	poor	possible	—	possible ~22 mrad *
hadron exclusive measurements	good for charged, 1° V^0's, ..	good	—	—
main use + strength	inclusive CC+NC: o — parton distr o — NC couplings o — fragmentation — exclusive channels	$\nu_\mu e \to \nu_\mu e$ search for rare processes: charm : exclusive channels	inclusive NC+CC — structure functions — NC ($\sin^2\theta_W$) — σ_{TOT} rare processes: — multimuon	$\nu_\mu e \to \nu_\mu e$ NC — x-distribution y — " +
examples	BEBC 15' BC	GGM 15' BC BEBC	CDHS, CITF CCFRR	* CHARM I + II BNL-E734 A-P FNAL-E594

note: construction of electronic detector depends on kind of physics one wants to do

— interest in physics changed drastically after NC + charm discovery

- What were design criteria for early experiments?
  HPWF, CITF, CDHS

- 2 -

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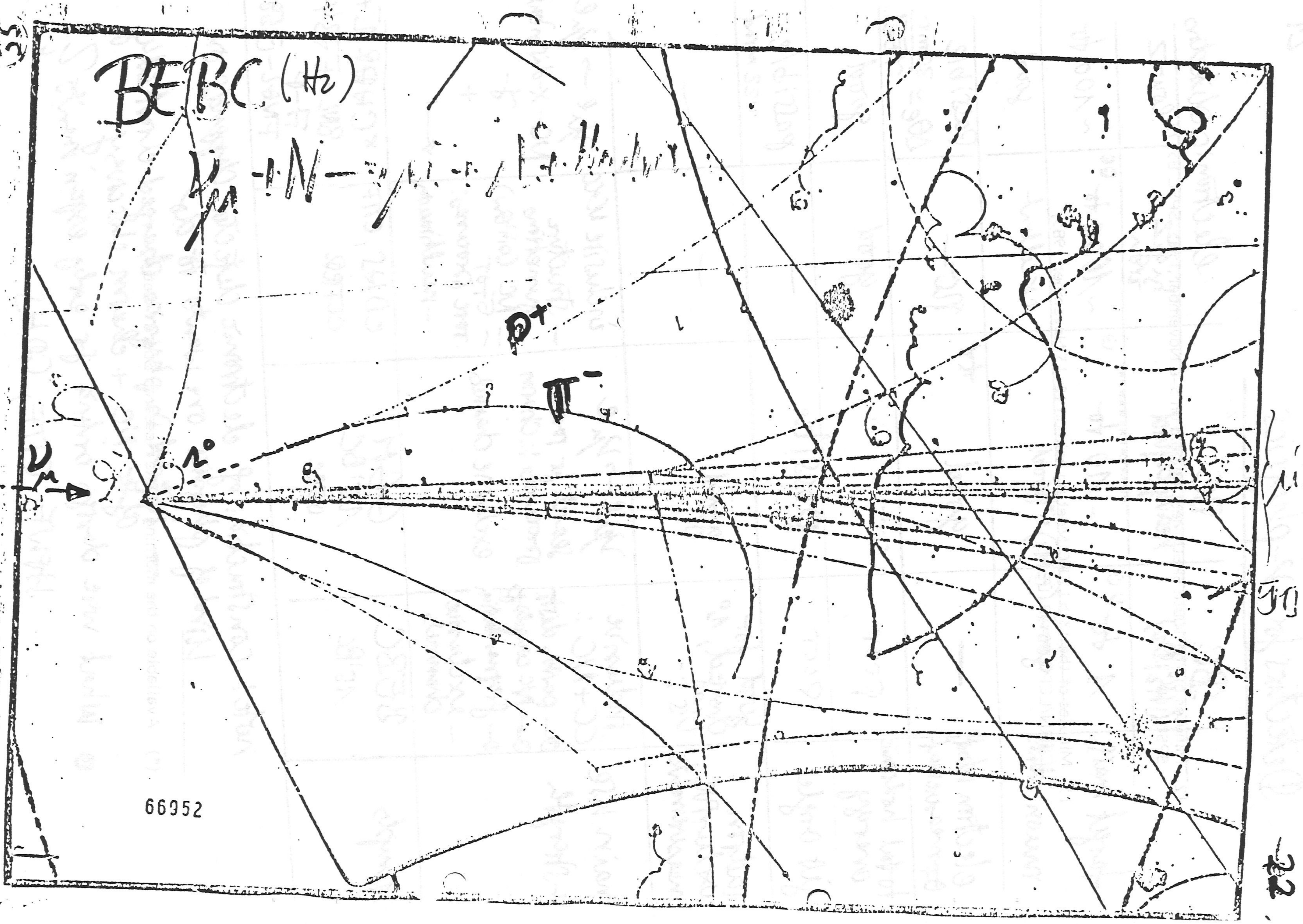
BEBC (H2)
ν_μ + N → μ⁻ + D⁺ + Hadrons
D⁺
π⁻
1°
ν_μ
μ
66952

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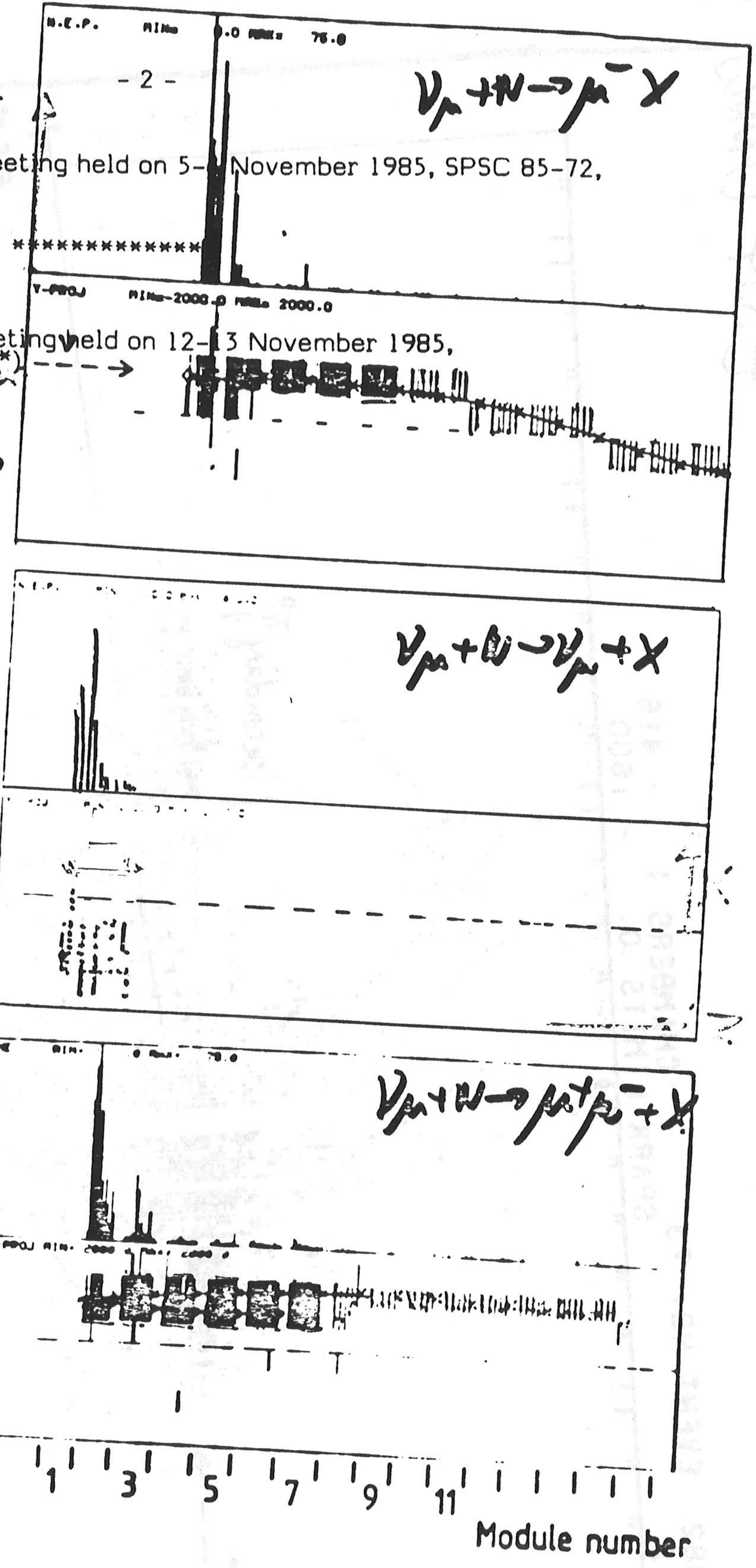
iron detector
(CDHS)



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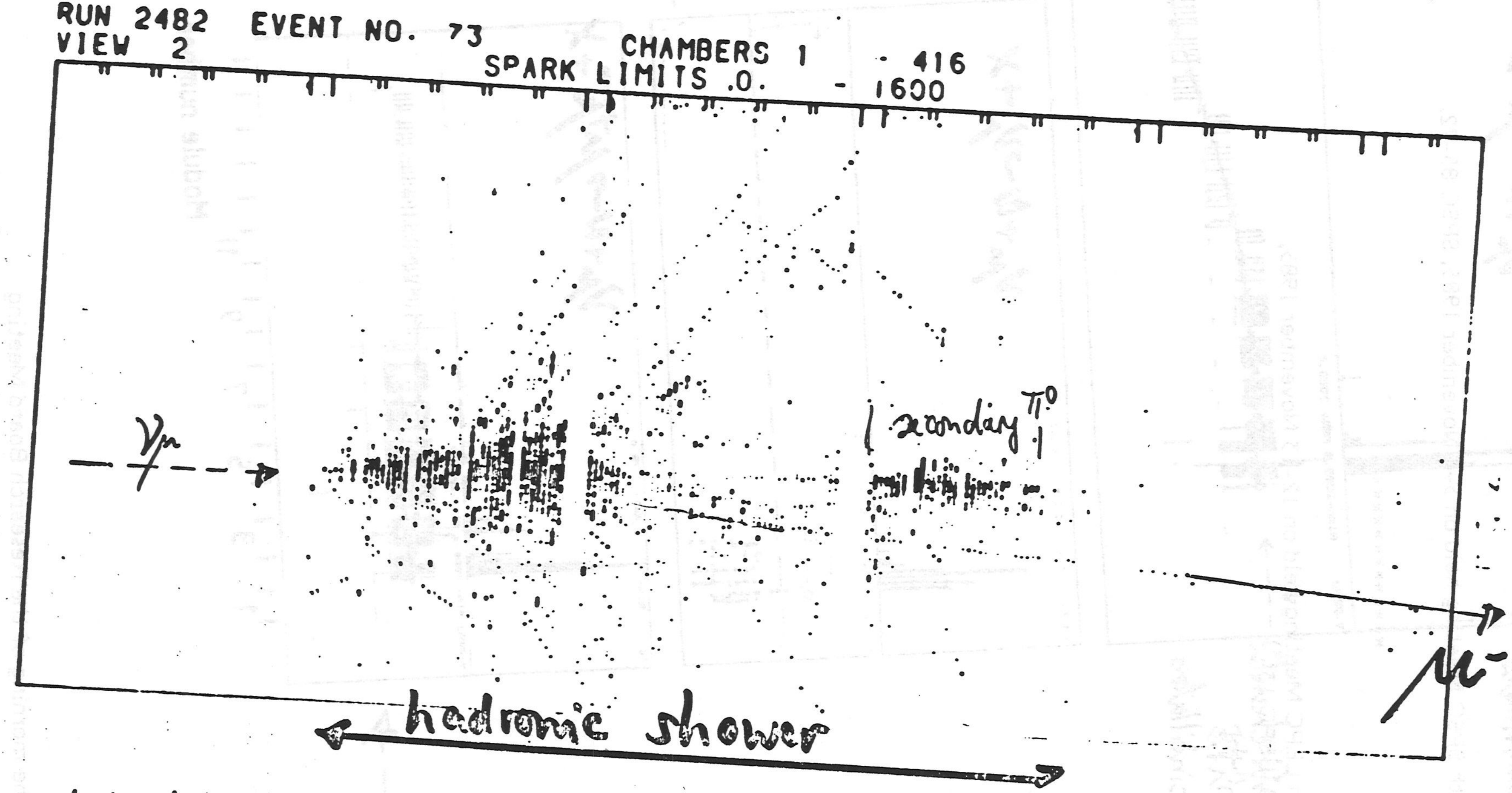
E594 (FNAL)



Low Z-detector!

fine grained calorimetric measurement of a neutrino interaction

- trace muon, inside shower
- recognize electrons: el.magn. + hadronic showers different!

liquid scintillator

spark chambers

iron toroids

HPWF

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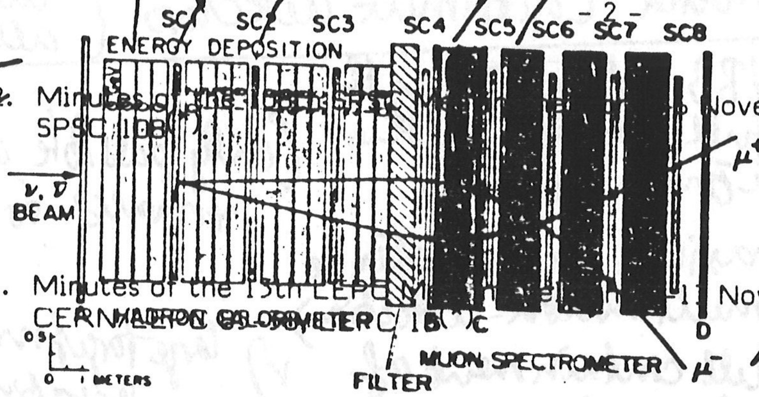
SPSC/108[illegible].



13. Minutes of the 13th LEPC M[illegible] 11 November 1985,
CERN/LEPC 85-[illegible] LEPC/ 1[illegible](*)

1m

'WBB'

$\nu_\mu + Z \rightarrow \nu_\mu \mu^+ \mu^-$

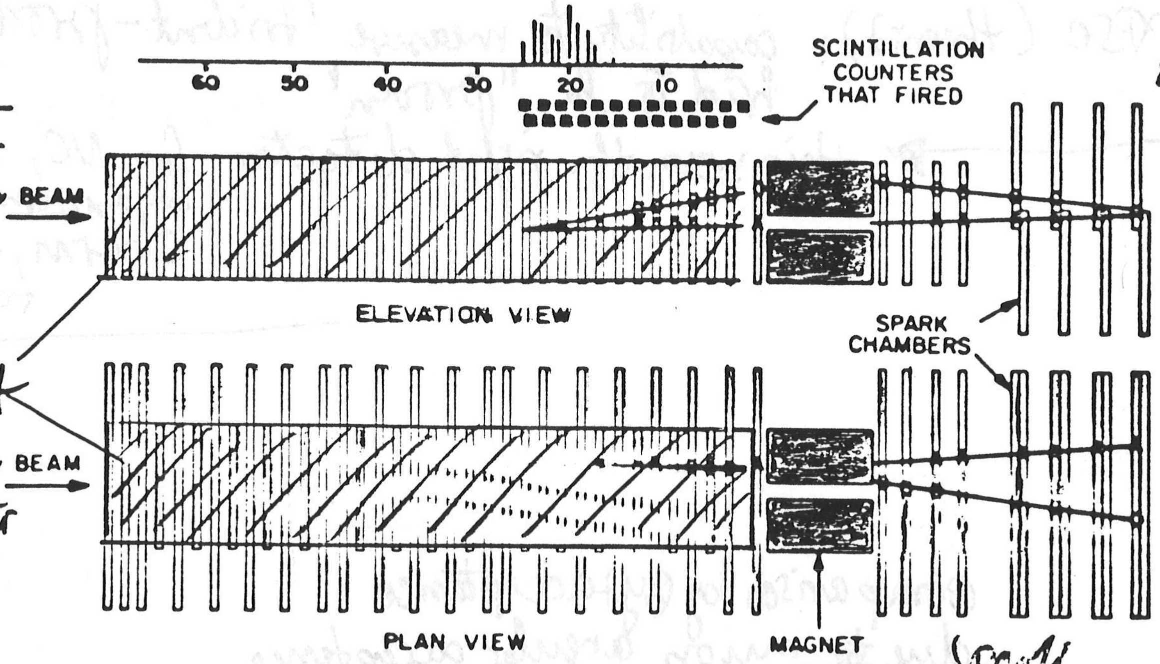
** heavy lead target

HPWF

C 1. stage detector: no

no hadron energy measurement for E_H [illegible]

- low mass



CITF

Steel target + liquid scintillator

Toroid

Spark chambers

1.7m

NBB!
"wrong sign leptons"
$\nu_\mu + N \rightarrow \mu^+ + X$

- very precision acceptance,
- bad for multimuon
- CC structure functions
- (NC)

---

explains partially the big impact of the CERN SPS ν-program!

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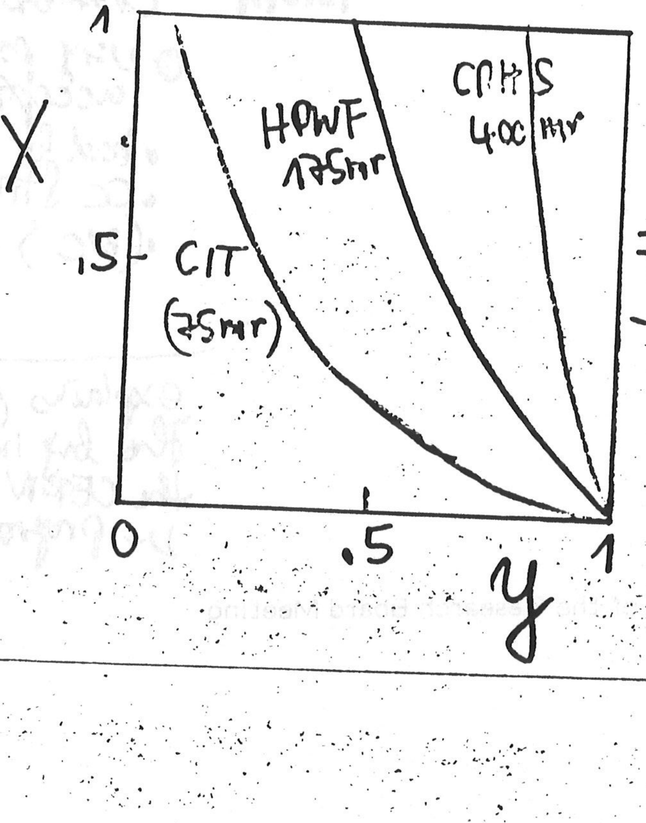
FNAL experiments pioneered calorimeter detectors (was followed all others

CDHS: (72) experimentes
i) NBB-detector with full coverage of the ν-energy spectrum (only possible at CERN! thanks to BEBC !
ii) maximal μ-acceptance (multimuon-detection)
iii) full containment of calorimeter
v) large target mass: 2. generation experiment

SPSC (theorist?): capability to measure 'trident'-production had to be "proven"

→ this was the right detector for NC, inclusive measurements charm, ... too late!

comparison of (x,y) acceptance due to muon angular acceptance



$E_\nu = 50$ GeV

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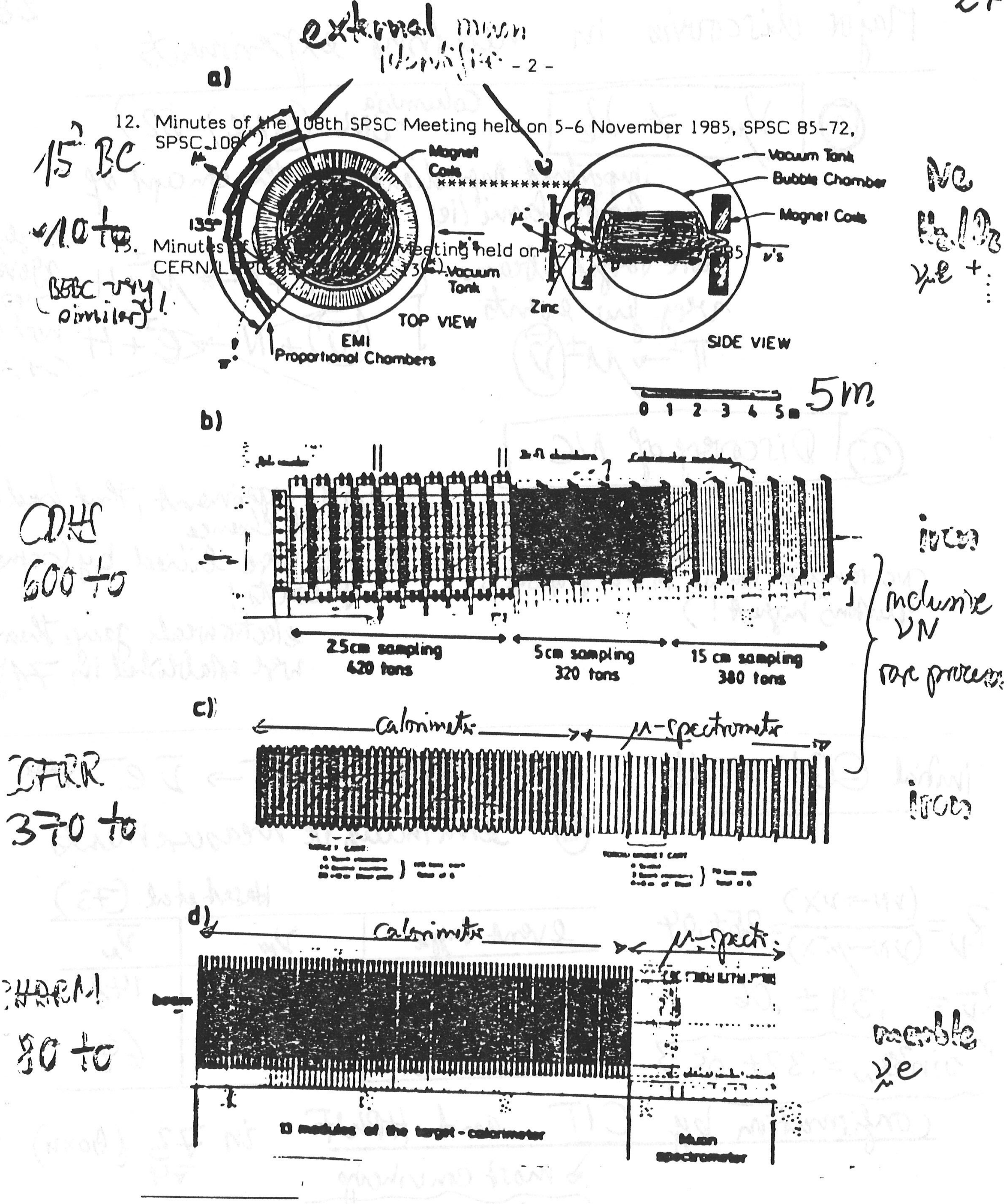

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Some major neutrino detectors (same scale)

Major discoveries in neutrino experiments:

① $\boxed{\nu_\mu \neq \nu_e}$ Columbia-BNL (BNL) 62)

important ingredient for the concept of lepton families

bare target beam
very few events
$\pi^\pm \to \mu^\pm \overset{(-)}{\nu}$ } $\overset{(-)}{\nu} + N \to \mu^\pm + H$

$\cancel{\overset{(-)}{\nu} + N \to e^\pm + H}$

(single
29 even
>40 e
not o
[illegible]

② $\boxed{\text{Discovery of NC}}$

why Gargamelle? → i) first experiment, that had a real chance
ii) NC were liked by (some) theorists!
electroweak gauge theories were established in 71!

(NC ranked lowest in their proposal, "partons" highest!)

---

initial GGM results: ① 2 events $\bar{\nu} e^- \to \bar{\nu} e^-$ ☆☆
② semi inclusive measurements

$$R_\nu = \frac{(\nu N \to \nu X)}{(\nu N \to \mu^- X)} = .25 \pm .04$$

$$R_{\bar{\nu}} = .39 \pm .06$$

$$\boxed{\sin^2\theta_W \simeq .32 \pm .05}$$

Hasert et al. (73)

event type	ν_μ	$\bar{\nu}_\mu$
# events with μ	428	148
# events without μ	102	64

confirmation by CIT and HPWF in 73/74 (Bonn)
→ most convincing
$\boxed{\sin^2\theta_W \simeq .33 \pm .07}$

Gargamelle : $\left\{ \begin{array}{l} \nu_\mu N \to \text{hadrons} + \text{'unvisible'} \\ \bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^- \end{array} \right.$

① first experiment which had a good chance to discover NC:

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① large chamber: ************* $L \simeq 4.8\,m$, $W = 18\,t$

13. Minutes of the 13th LEPC Meeting held on 12 ... November 198... CERN/LEPC 85-38, LEPC 13(*).

② large ν-flux: $> 10^{18}\ \nu$ through chamber

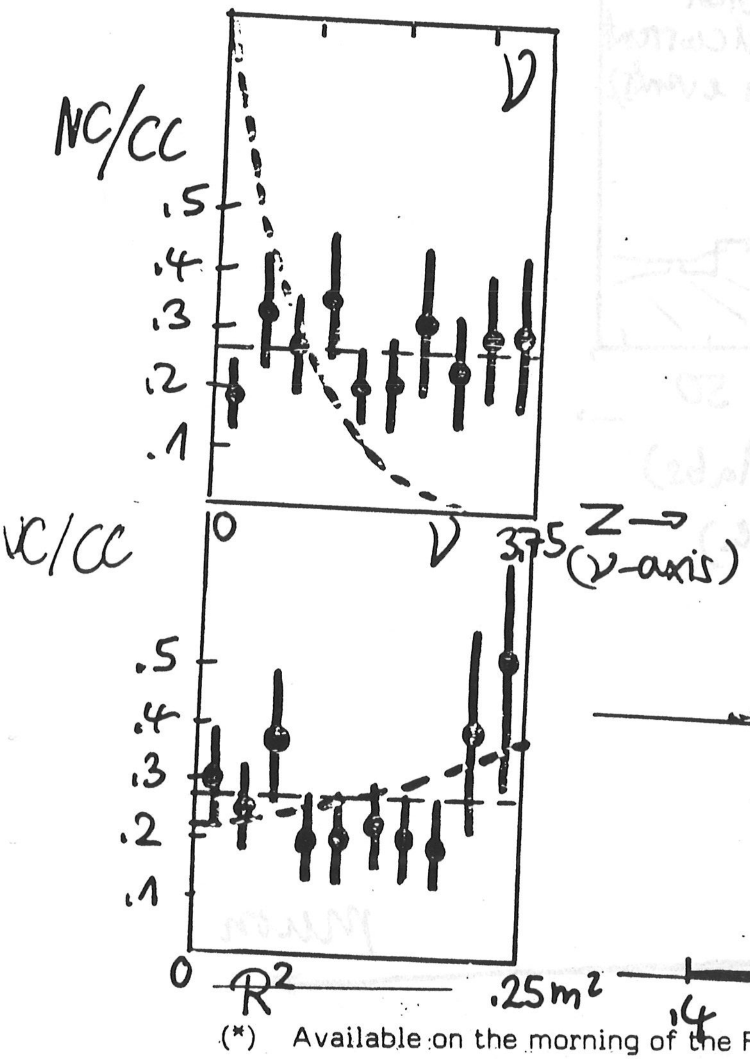
② $L \gg$ absorbtion length for n and $\pi^\pm$

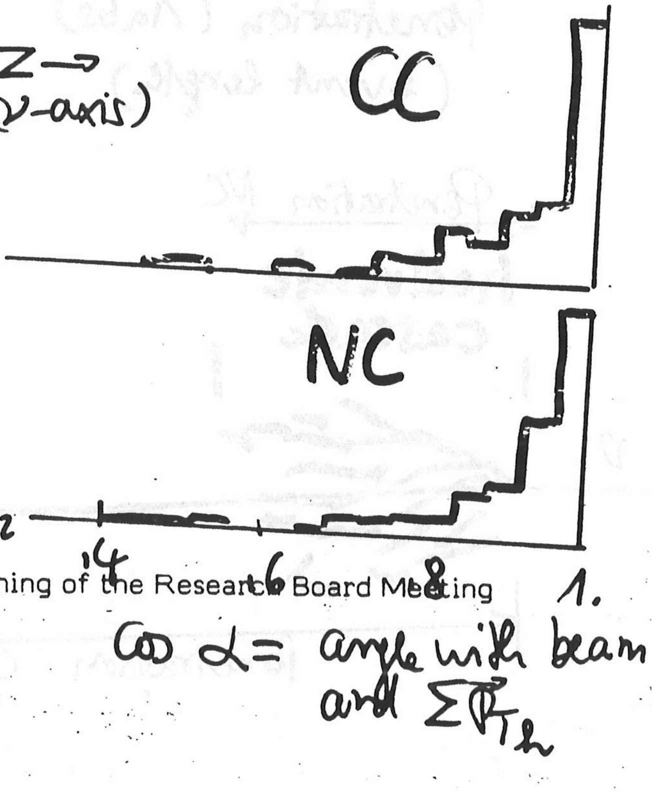
↳ neutron background can be distinguished

↳ large fraction of $\pi^\pm$ interact ↔ muon identified

③ $\bar{\nu}_\mu e$ was visible
first event found Dec. 72 !

they didnt miss !





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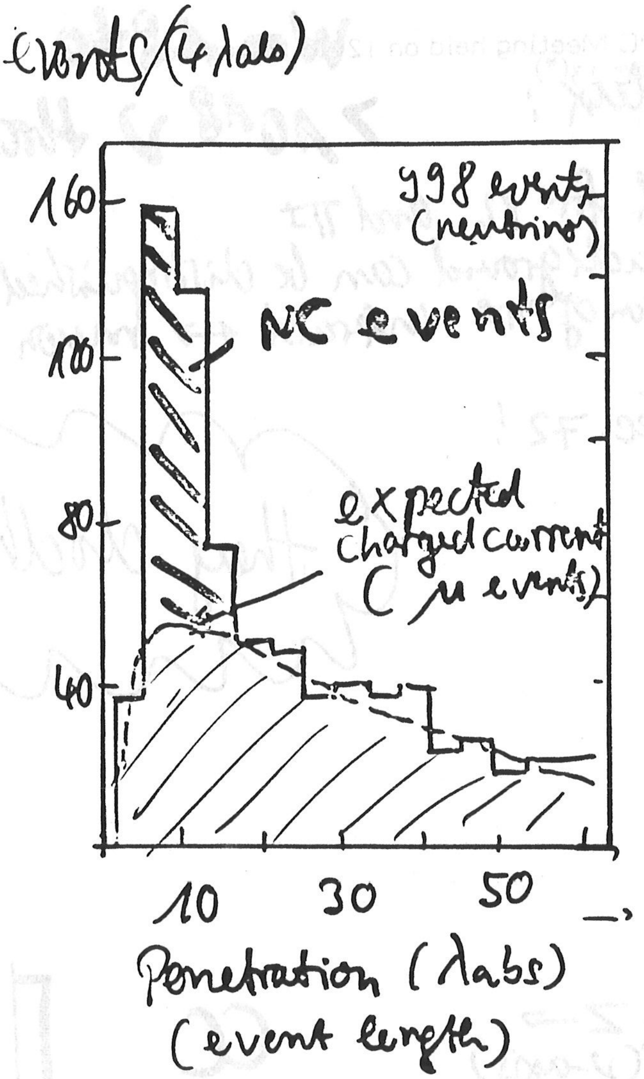
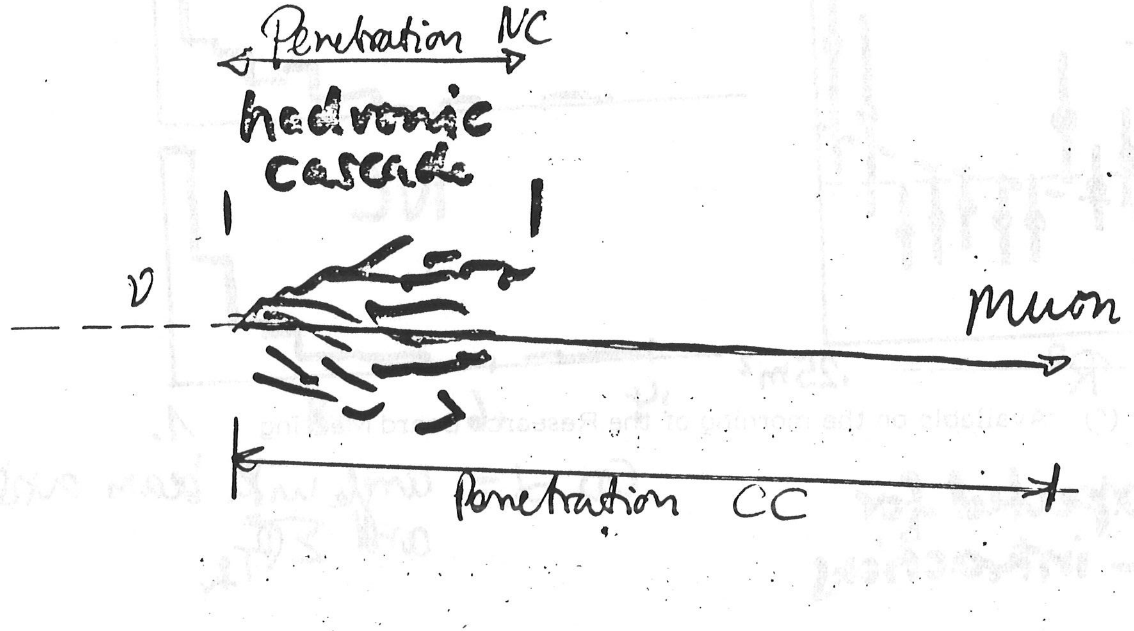
--- expected for n-interactions

$\cos\alpha$ = angle with beam axis and ΣP_{Th}

CITF- NC-result based on event length (penetration)
(present day technique)





impact of NC discovery on "standard model"

why important?

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exp. point of view: ① something qualitatively new after 40 years of ν physics (Sakurai)

Fermi point interaction (33) survived with few modifications

$V \to V-A$

$p, n \to u, d_c = d\cos\theta_c + s\sin\theta_c$

$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \to \begin{pmatrix} e \\ \nu_e \end{pmatrix} + \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$

what is the structure of this new interaction?

② It gave a strong boost to electroweak gauge theories!
(note: NC not really required, just one good option)

see: J. Illiopoulos, Int. Conference London 74 (very recommendable reading!)

ⓐ gauge theories are there and theoretically beautiful:

Yang-Mills theories 60
spontaneous symm. breaking 64
Higgs mechanism (Weinberg) 67
GIM 70
gauge theories are respectable! [illegible] and beautiful ⟹ 't Hooft: they are renormalizable 71

ⓑ NC: we are on the right track!

Illiopoulos (74): "I have won several bottles of wine for betting on NC. This time I am willing to bet a whole case on the discovery of charm before summer 75!"

ⓒ: within gauge theories: NC imply charm!!
⟹ charm discovery will make the case for gauge theories

d) best place: neutrinos! nobody talked about hidden charm

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ⓔ further content of this talk:

- QCD
- GUT's + prediction of $\sin^2\theta_W \simeq .2$
  proton decay
-
- SUSY

comment of Bjorken (on this talk) (FERMILAB-Conf-85/58 "The november revolution")

"... Everything was there, what we call the standard model: proton decay, charm, GIM, QCD, the SU(2) x U(1) electroweak theory, SU(5) grand unification, Higgs, etc. It was all presented with absolute conviction and sounded at the time just a little mad, at least to me (I am a conservative)

– recall John Ellis: $R = \frac{e^+e^- \to h}{e^+e^- \to \mu^+\mu^-}$

④ CHARM and neutrinos:

- actually 2 opposite dimuons events were presented by HPWF at the London conference 74

present wisdom: first experimental sign of charm!

75 lepton-photon symposium:
charm was clearly established in neutrino interactions by opposite sign dimuon events (HPWF)

end of "historic" section

II: electroweak theory

III: QPM, structure functions and QCD

early Confirmation of charm in ν- interactions

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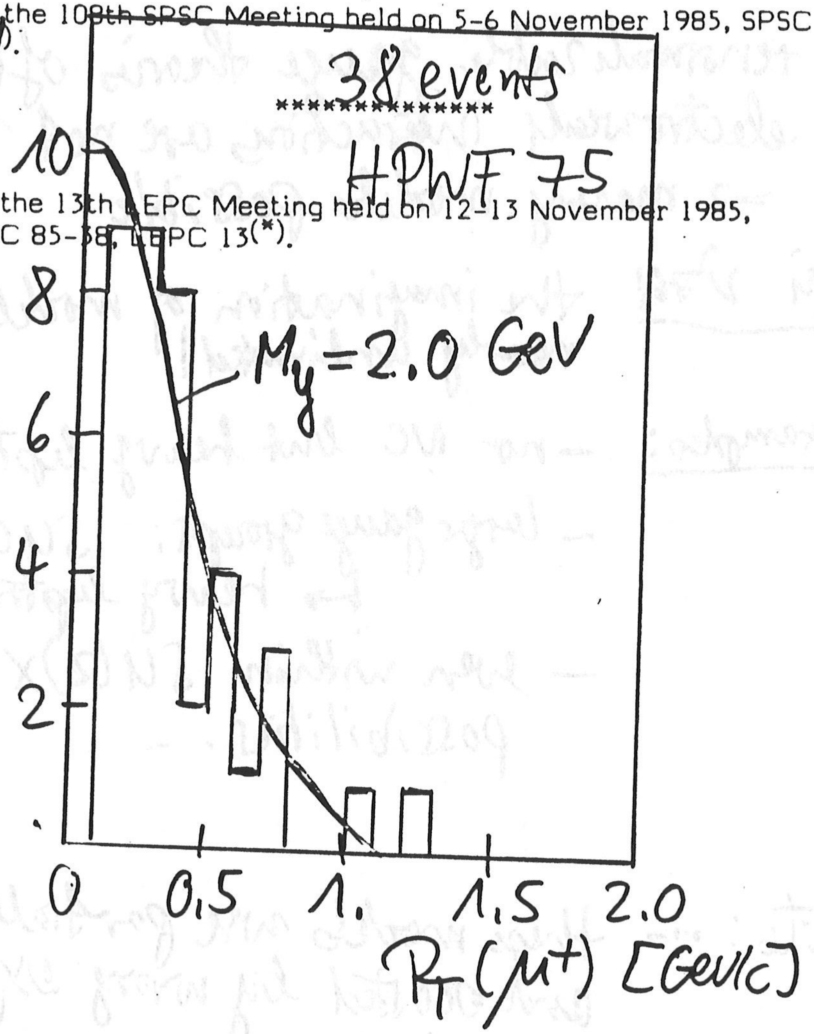

① $\frac{(\nu_\mu N \to \mu^- \mu^-)}{(\nu_\mu N \to \mu^- \mu^+)} \leq .1$

② hadronic origin: wrong sign muon correlated with hadronic shower

③ momentum asymmetry compatible with charm but not with heavy leptons

---

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III Electroweak theory

a) sorting out the standard model

note: renormalizable gauge theories of the electroweak interactions are not very restrictive:
⇒ many models possible

Sakurai ν'76! the imagination of model builders is nearly unlimited!

examples:
- no NC but heavy leptons (e^-, E^+)
- larger gauge groups: $SU(3) \times U(1)$
  ↳ heavy leptons..
- even within $SU(2) \times U(1)$ several possibilities. ..

note: -- these models were partially inspired and boosted by wrong experimental results!

35

Four possible gauge theories (Harari 75)

simplest vec
by it means
all possible

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	"Standard"	"Vector"	"Asymmetric" (Hybrid)	"Left-right
gauge group	$SU(2)\times U(1)$	$SU(2)\times U(1)$	$SU(2)\times U(1)$	$SU(2)_L\times SU(2)_R\times U($
Bosons	$W^\pm\, Z\, \gamma$	$W^\pm\, Z\, \gamma$	$W^\pm\, Z\, \gamma$	$W^\pm_L, W^\pm_R, Z_V, Z_A,$
left-handed fermions	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \begin{pmatrix}d\\ u\end{pmatrix}_L$	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \begin{pmatrix}d\\ u\end{pmatrix}_L$	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \begin{pmatrix}d\\ u\end{pmatrix}_L$	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \begin{pmatrix}u\\ d\end{pmatrix}_L$
right-handed fermions	$(e^-)_R\,(u)_R\,(d)_R$	$\begin{pmatrix}N_e\\ e^-\end{pmatrix}_R \begin{pmatrix}u\\ b\end{pmatrix}_R \begin{pmatrix}t\\ d\end{pmatrix}_R$	$\begin{pmatrix}N_e\\ e^-\end{pmatrix}_R (u)_R\,(d)_R$	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_R \begin{pmatrix}u\\ d\end{pmatrix}_R$
Boson-mass relations	$M_Z^2(1-\sin^2\theta) = M_W^2$	$M_W^2 \geq (1-x) M_Z^2$	$M_W^2 \geq (1-x) M_Z^2$	$M_{W_R}^\pm > M_{W_L}^\pm = M_{Z_A}$ $M_{Z_V}^2(1-2x) = M_{Z_A}^2$
$\frac{\sigma(\bar\nu_\mu e)}{\sigma(\nu_\mu e)}$	$\frac{1-4x+16x^2}{3-12x+16x^2}$	1	1	"Standard"
$\frac{\sigma(\bar\nu N\to\bar\nu N)}{\sigma(\nu N\to\nu N)}$	$\frac{(3-8)(1-2x)+\frac{16}{9}x^2}{(3+8)(1-2x)+\frac{16}{9}x^2} \neq 1$	$\cancel{1}$ ①	"standard"	"standard"
Parity violation in atoms	yes ④	no	no ②	no
Asymmetry in e D-scattering	yes ③	NO	yes	yes

[illegible] V_L [illegible] $= V_1$ [illegible] $= V$!

favoured   unfavoured $x = \sin^2\theta_W$

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6 questions to ask to neutral currents: (following Salvardi,

① are ordinary neutrinos involved? $\nu N \to \nu' X$

check: $\frac{d\sigma}{dy}(\nu) = \frac{d\sigma}{dy}(\bar{\nu})$ $\nu = \nu'$?

(hermiticity of the current)

② is S,P,T ruled out?

→ V,A does <u>not</u> allow rising y-distribution ($\sim y^2$)

but: confusion theorem: all V,A y-distributions can be faked by combination of S,P,T,

③ what is the V,A-structure of NC? (e.g. pure V possib

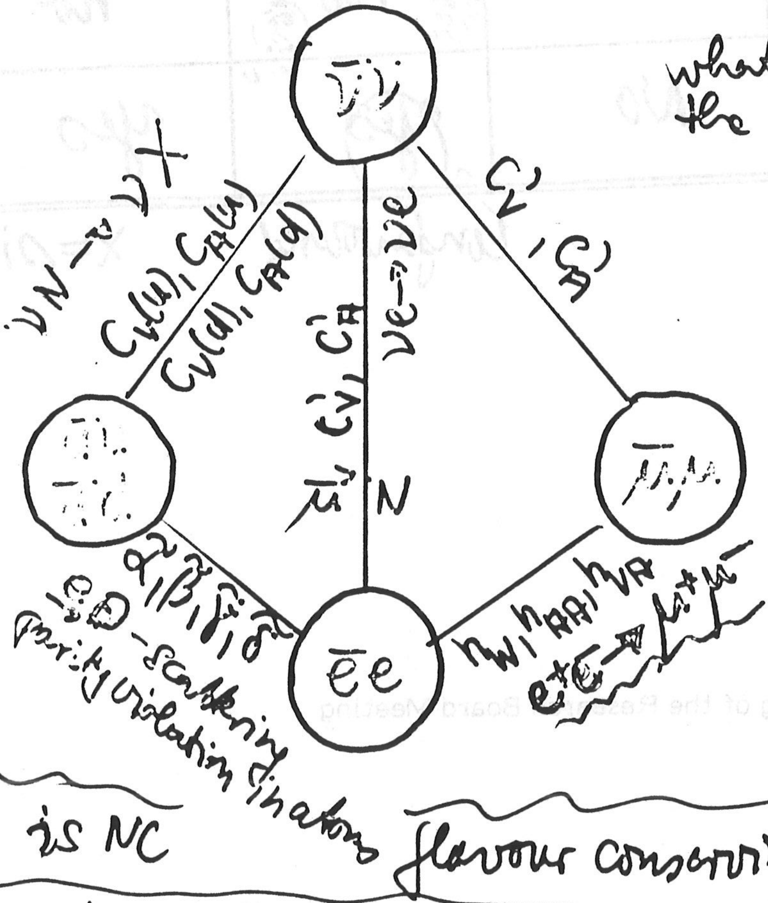
– y-distributions, $\sigma^{\nu}/\sigma^{\bar{\nu}}$; (V·A-interference)

– ~~mx.~~

④ what are the isospin and SU(3) properties of the current

u, d, s, c – couplings : measure couplings separately

⑤ universality of neutral currents?



what are the relations between the $(q\bar{q})$, $(\nu\bar{\nu})$, $(e\bar{e})$, $(\mu\bar{\mu})$ .. curren

↳ study all processes separately also those not involving neutrinos

⇩

mostly by eN instead

(note: all couplings given by $\sin^2\theta_W$ in GWS)

⑥ is NC flavour conserving? $\Delta C = 0$? $\frac{\text{CDHS } 7\mu}{\nu}$

⑦ test of GIM (K-M) structure in CC

Structure of neutral and charged current interactions

assumptions:

① interactions mediated by spin 1 bosons with $m_B \gg \sqrt{s}$
(effective pointlike interaction) (V, A !)

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② two component neutrino hypothesis

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③ $e\mu$ - universality

I νe-scattering: leptonic interactions

$$\mathcal{L} = -\frac{4G}{\sqrt{2}}\left[j_\alpha^{(C)+} j_\alpha^{(C)-} + \rho\, j_\alpha^{(N)} j_\alpha^{(N)} \right]$$

charged current

$$j_\alpha^{(C)+} = \bar{e}\,\gamma_\alpha \frac{(C_V + C_A\gamma_5)}{2}\nu_e + \bar{\mu}\,\gamma_\alpha \frac{(C_V + C_A\gamma_5)}{2}\nu_\mu$$

neutral current

$$j_\alpha^{(N)} = \bar{\nu}_e\gamma_\alpha \frac{(1-\gamma_5)}{2}\nu_e + \bar{\nu}_\mu\gamma_\alpha\frac{(1-\gamma_5)}{2}\nu_\mu + \bar{e}\,\gamma_\alpha\frac{(C_V' + C_A'\gamma_5)}{2}e + \bar{\mu}\,\gamma_\alpha\frac{(C_V' + C_A'\gamma_5)}{2}\mu$$

II semileptonic ν-q interactions

$$\mathcal{L} = -\frac{4}{\sqrt{2}}\left[J_\alpha^{(C)+} j_\alpha^{(C)-} + \rho\, J_\alpha^{(N)} j_\alpha^{(N)} \right]$$

④ generation universality of weak couplings
⑤ flavour conservation for the neutral current } GIM idea generalized by Kobayashi-Maskawa

$$J_\alpha^{(C)+} = (\bar{u}, \bar{c}, \bar{t})\,(U_{ij})_{3\times3}\,\gamma_\alpha\frac{(C_V + C_A\gamma_5)}{2}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$J_\alpha^{(N)} = \frac{1}{2}\Big[\bar{u}\gamma_\alpha(C_V(u) + C_A(u)\gamma_5)u + \bar{c}\gamma_\alpha(C_V(u) + C_A(u)\gamma_5)c + \bar{t}\gamma_\alpha(C_V(u) + C_A(u)\gamma_5)t - \bar{d}\gamma_\alpha(C_V(d) + C_A(d)\gamma_5)d - \bar{s}\gamma_\alpha(C_V(d) + C_A(d)\gamma_5)s - \bar{b}\gamma_\alpha(C_V(d) + C_A(d)\gamma_5)b\Big]$$

(U_{ij}): unitary 3x3 matrix: generation mixing

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<u>comments:</u>

ρ : relative strength of CC and NC couplings

C_V, C_A : relative strength of vector and axial vector currents.

(U_{ij}) : (3×3) unitary matrix : generation mixing of charged currents
(Kobayashi-Maskawa-matrix)

unitary: each flavour couples with same strength!

e.g.: $$J_\alpha^{(C)+}(\underset{\sim}{u}) = \bar{u}\gamma_\alpha \frac{(C_V + C_A\gamma_5)}{2}\left[U_{ud}\, d + U_{us}\, s + U_{ub}\, b\right]$$

$$|U_{ud}|^2 + U_{us}^2 + U_{ub}^2 = 1 \ !$$

---

righthanded couplings: $C_R = \frac{C_V + C_A}{2}$ $(V+A)$

lefthanded couplings: $C_L = \frac{C_V - C_A}{2}$ $(V-A)$

experimental answers:

① + ② : not well tested! CHFF excludes large y^2-term (76)
CDHS, BEBC : consistent with V, A

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③ V, A structure : fool!

a,) hadronic current (quarks)

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① semi inclusive measurements on iso scalar targets:

$$R^N_\nu =: \frac{(d\sigma^\nu/dy)^{NC}}{(d\sigma^\nu/dy)^{CC}} \quad ; \quad R^N_{\bar\nu} = \frac{(d\sigma^{\bar\nu}/dy)^{NC}}{(d\sigma^{\bar\nu}/dy)^{CC}}$$

these ratios are best measured!

QPM:

L.H. coupling
$$\rho^2[C_L^2(u)+C_L^2(d)] = (R^N_\nu - r^2 R^N_{\bar\nu})/(1-r^2) \quad + \text{corr.}$$

R.H.
$$\rho^2[C_R^2(u)+C_R^2(d)] = (R^N_{\bar\nu} - R^N_\nu/(1/r - r) \quad + \text{corr.}$$

$$r = \sigma^{\bar\nu}_{cc}/\sigma^{\nu}_{cc}$$

results: (3 most precise published expts.)

experiment	E_H	R^N_ν	$R^N_{\bar\nu}$	$R^N_\nu - R^N_{\bar\nu}$	(V−A) L-H	(V+A) R-H
* CDHS 77	>12 GeV	.293±.010	.35±.03	.057±.032	.29±.02	.036±.02
CHARM 81	>2 GeV	.320±.010	.377±.02	.057±.022	.305±.013	.036±.013
CDHS 82	>10 GeV	.300±.007	.357±.015	.057±.017	.292±.010	.036±.011

r = .48±.0

$$\Rightarrow \boxed{\begin{aligned} \rho^2[C_L^2(u)+C_L^2(d)] &= .296 \pm .008 \\ \rho^2[C_R^2(u)+C_R^2(d)] &= \underline{.036 \pm .008} \end{aligned}}$$

V+A component non-zero!

*) first established by CDHS (77) c

② separation of u and d-couplings

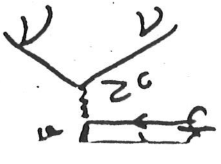
ⓐ single pion production (first done by GGM)
ⓑ data on neutrons and protons

→ ~~unique~~ solution for all 4 couplings by (1978)

(*): Available on the morning of the Research Board Meeting.

in excellent agreement with standard model

- weak ^{NC} coupling of strange quark (not really measured)
- Charmed quark: rough estimate by CDHS using
ν Fe → ν_μ + ψ + X : ψ-production by



NC inclusive measurement: $R^N_\nu, R^N_{\bar\nu}$

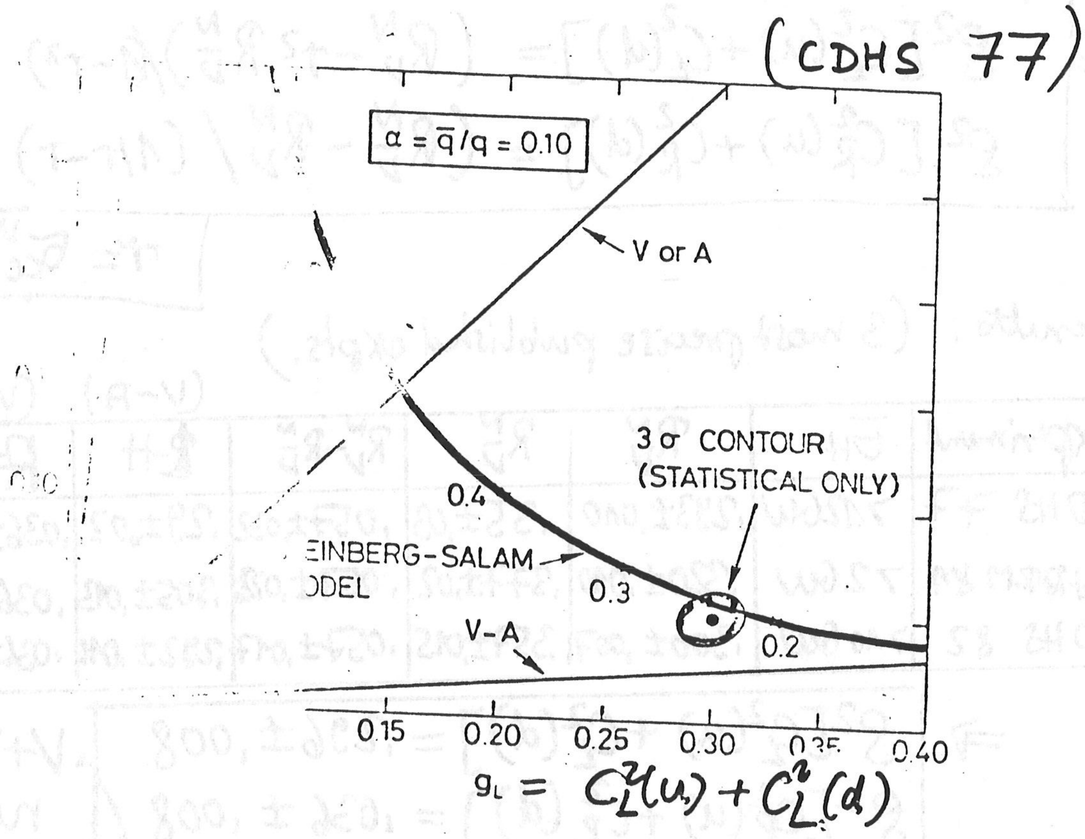


Fig. 32: Comparison of model predictions and the CDHS result on g_L and g_R. The relative amount of the sea is assumed to be 0.10.

V+A - component established

separation of lefthanded couplings

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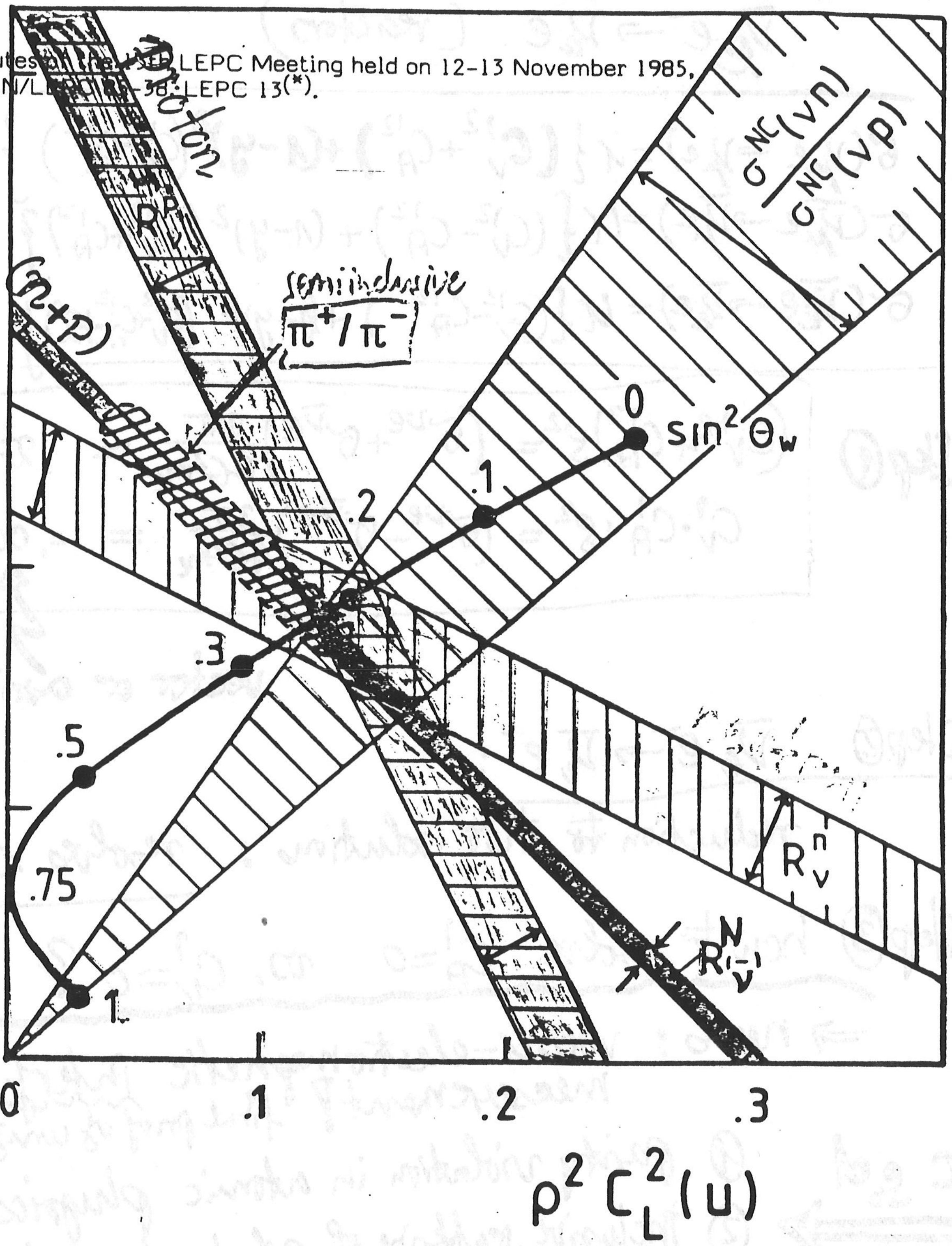
****

13. Minutes of the 15th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-38, LEPC 13(*).

status '84



$C_L(u) = .39 \pm .014$ $C_R(u) = -.17 \pm .014$
$C_L(d) = -.37 \pm .015$ $C_R(d) = .04 \pm .027$
} Panman ν'84

(*) Available on the morning of the Research Board Meeting.

ⓑ neutral weak couplings of the electron

① $\nu_\mu e^- \rightarrow \nu_\mu e^-$

$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$

$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ (reactors)

$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) = K\left\{ \left(C_V'^2 + C_A'^2\right) + (1-y)^2 \left(C_V'^2 - C_A'^2\right) \right\}$$

$$\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e) = K\left\{ \left(C_V'^2 - C_A'^2\right) + (1-y)^2 \left(C_V'^2 + C_A'^2\right) \right\}$$

$$\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e) = K\left\{ \left(C_V'^2 - C_A'^2\right) + (1-y)^2 \left(C_V'^2 + C_A'^2 + 2\right) \right\}$$

Step ①

$$\boxed{\begin{aligned} \left(C_V'^2 + C_A'^2\right)\rho^2 &= \left(\sigma^{\nu e} + \sigma^{\bar{\nu} e}\right)\frac{3\pi}{4G^2 m_e} = .27 \pm .04 \\ C_V' \cdot C_A' \cdot \rho^2 &= \left(\sigma^{\nu e} - \sigma^{\bar{\nu} e}\right)\frac{3\pi}{4G^2 m_e} = -.002 \pm .04 \end{aligned}}$$

vector or axial vector = 0

Step ② $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$:

reduction to two solutions: resolves sign ambiguity

Step ③ how to reduce $C_A' = 0$ vs. $C_V' = 0$?

⇒ needs: weak-electromagnetic interference measurement! final proof of unification!!

AC g.d! ⟹

① parity violation in atomic physics

② inclusive scattering of polarized electrons

③ $e^+e^- \rightarrow \mu^+\mu^-$ asymmetry

νe-scattrig results at accellerators

- 2 -

11. Minutes of the 108th SPSC Meeting held on 5-6 November 1985, SPSC 85-
SPSC 108(*).

I $\nu_\mu e \to \nu_\mu e$ [10^{-42} cm²/GeV]

Experiment	Detector	$\langle E_\nu \rangle$	νe events	background	S/B	σ^ν/E
Gargamelle PS 73	BC	2.2 GeV	1	.3±.1		< 3 (90% C.L
Aachen-Padua PS 75	Spark chamber	2.2 GeV	11	3	1.8	1.1±.6
Gargamelle SPS (78)	BC	25 GeV	9	0.5±.2	18	$2.4^{+1.2}_{-.9}$
BNL-Columbia FNAL (78)	15' BC	30 GeV	11	0.5±.2	18	1.8±.8
BMWOP (FNAL)	Spark chamber	20 GeV	40	12	2.8	1.4±.3±.2
CHARM (SPS)	counter exp. marble	31 GeV	46±12	64±10	.72	1.8±.3±.4
BNL E734	counter Liquid scint.	2.2 GeV	51±9	25±3	2.0	1.6±.29±.26
World average		165 events				1.53±.18

13. Minutes of the 13th LEPC Meeting held on 12-13 November 1985,
CERN/LEPC 85-38, LEPC 13(*).

II $\bar\nu_\mu e \to \bar\nu_\mu e$

		$\langle E_\nu \rangle$	νe events	background	S/B	σ^ν/E [10^{-42} cm²/GeV
Gargamelle PS 73	BC	3.2	3	0.4±.1	7.5	$1.0^{+.9}_{-.5}$
Aachen Padua B	Spark chamber	2.2	8	1.7	4.7	2.2±1
CHARM (SPS)	counter	31 GeV	77±19	146	.44	1.4±.3±.3
BEBC (TST)	BC		0.5	0.5		<3.4 (90% C.L.)
world average			80 events			1.42±.28

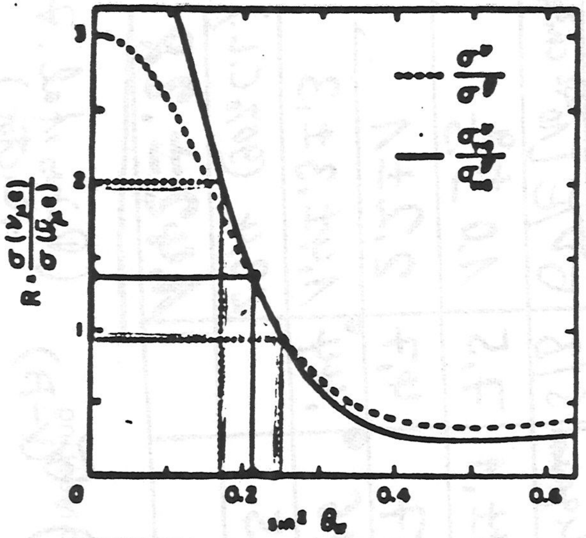
III $\bar\nu_e e \to \bar\nu_e e$

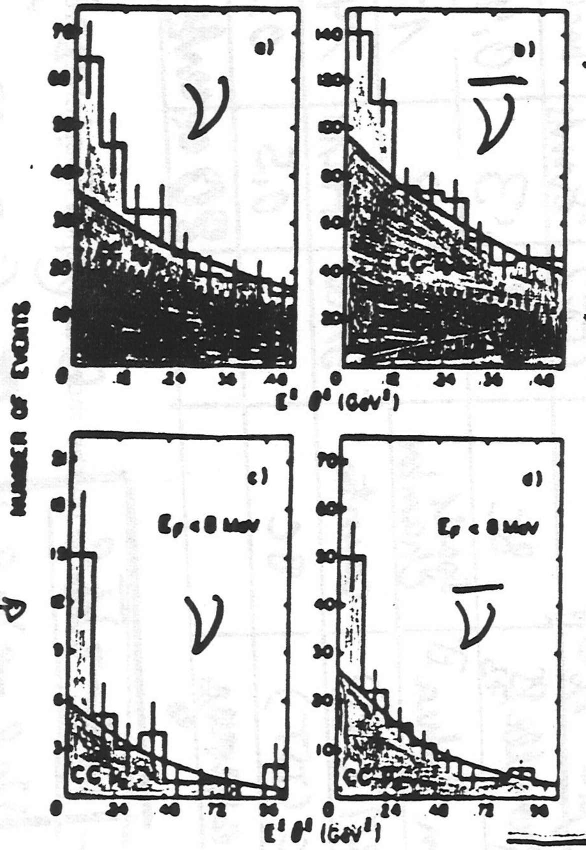
$\sigma = (1.07 \pm .22)\,\sigma_{(V-A)}$ (Reines et al. 76 reactor)

$\nu_e e \to \nu_e e$: $\sigma = (9.5 \pm .37 \pm 1.8)\,E_\nu \cdot 10^{-42}$ cm²/GeV (LAMPF prel. V'84)

(*) Available on the morning of the Research Board Meeting

$\nu e \to \nu e$





signal

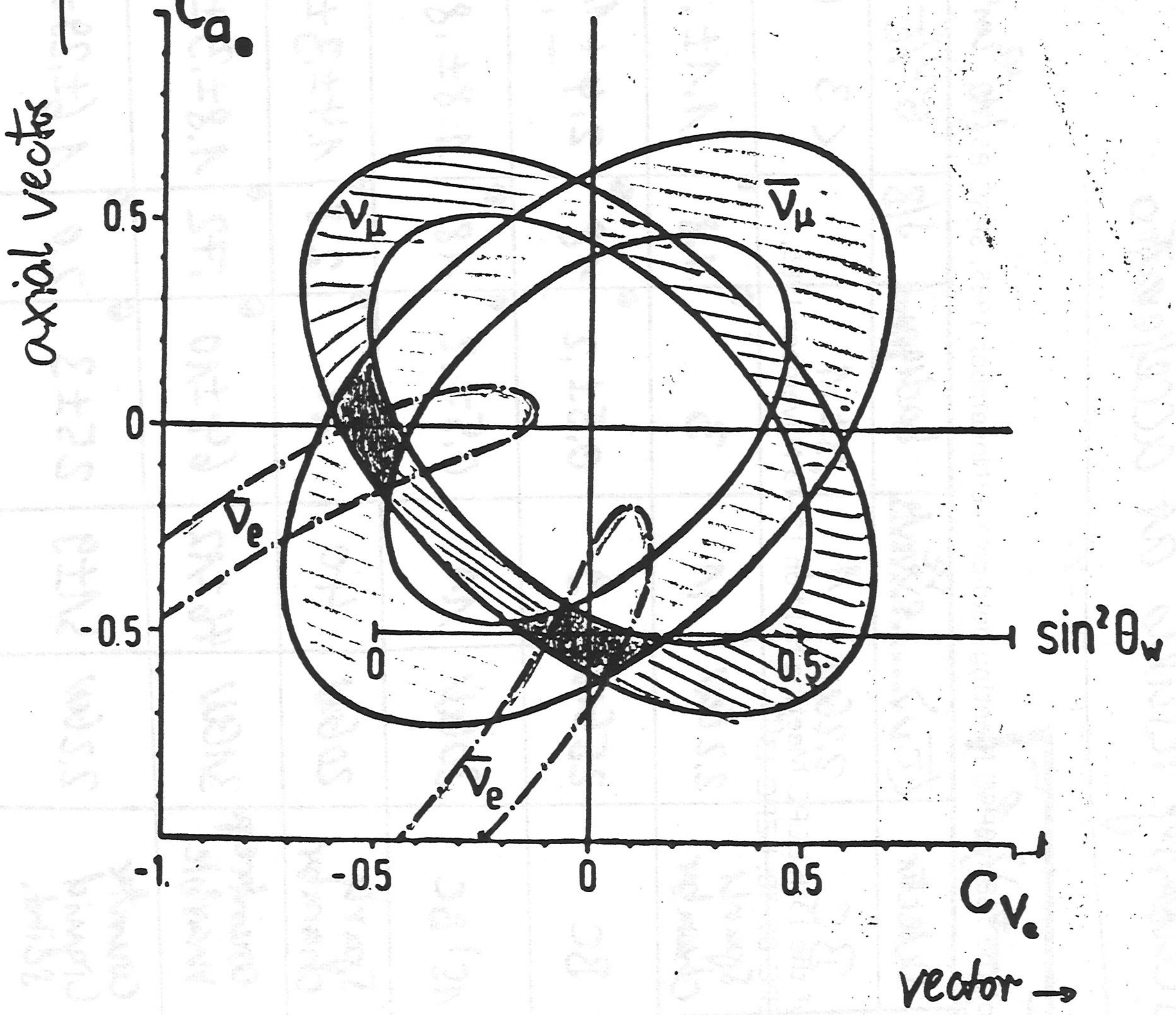
ν_e(CC)

ν_μ(NC)

eject
e^- pairs
t beginning

$\longrightarrow E_e^2\theta_e^2$

example: CHARM



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neutral currents:

sorting out the standard model

12. Minutes of the 108th SPSC Meeting held on 5-6 November 1985, SPSC 85-72, SPSC 108(*).

① semileptonic interactions

$$R_\nu^N = \frac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to \mu X)} \; ; \; R_{\bar\nu}^N$$

} a) not pure V or A!
b) significant but small (V+A)-component

13. Minutes of the 13th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-18, LEPC 13(*).

$$\hookrightarrow \quad g^2\{C_L^2(u) + C_L^2(d)\}$$

$$g^2\{C_R^2(u) + C_R^2(d)\}$$

② measurements on free nucleons (H_2, D_2)
separation of u and d couplings

↳ all couplings uniquely determined! (first in $\bar{\nu}e$)

③ $\overset{(-)}{\nu}_\mu e \to \overset{(-)}{\nu}_\mu e$ scattering + $\nu_e e \to \nu_e e$

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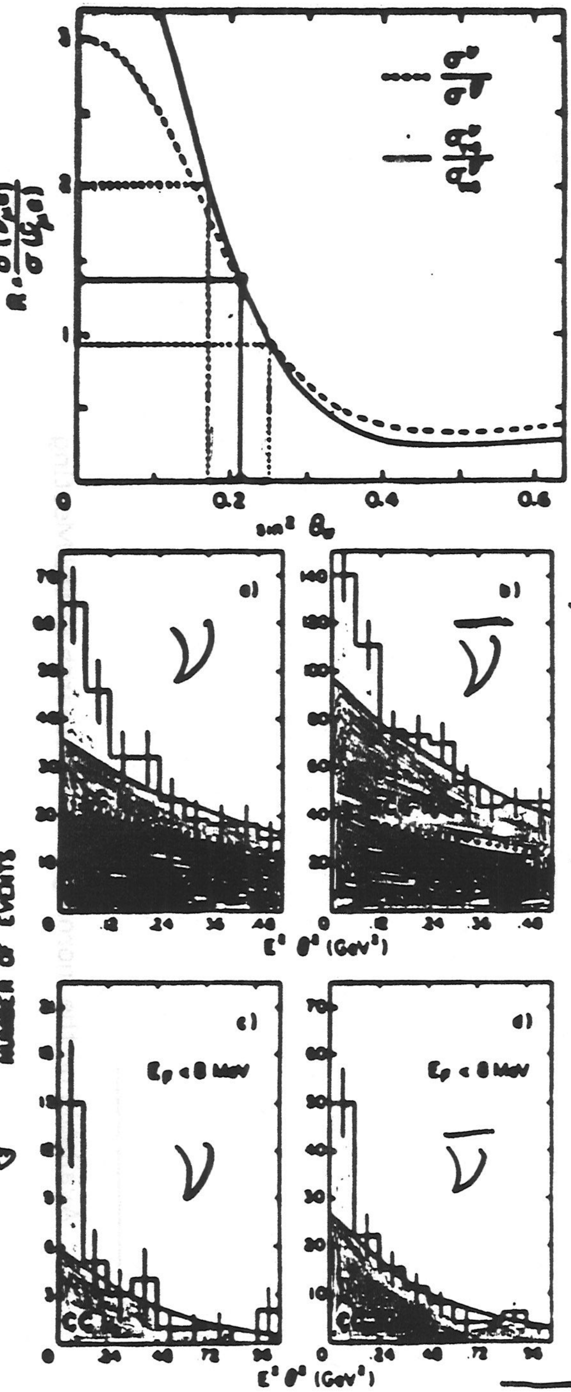


Signal

ν_e (CC)

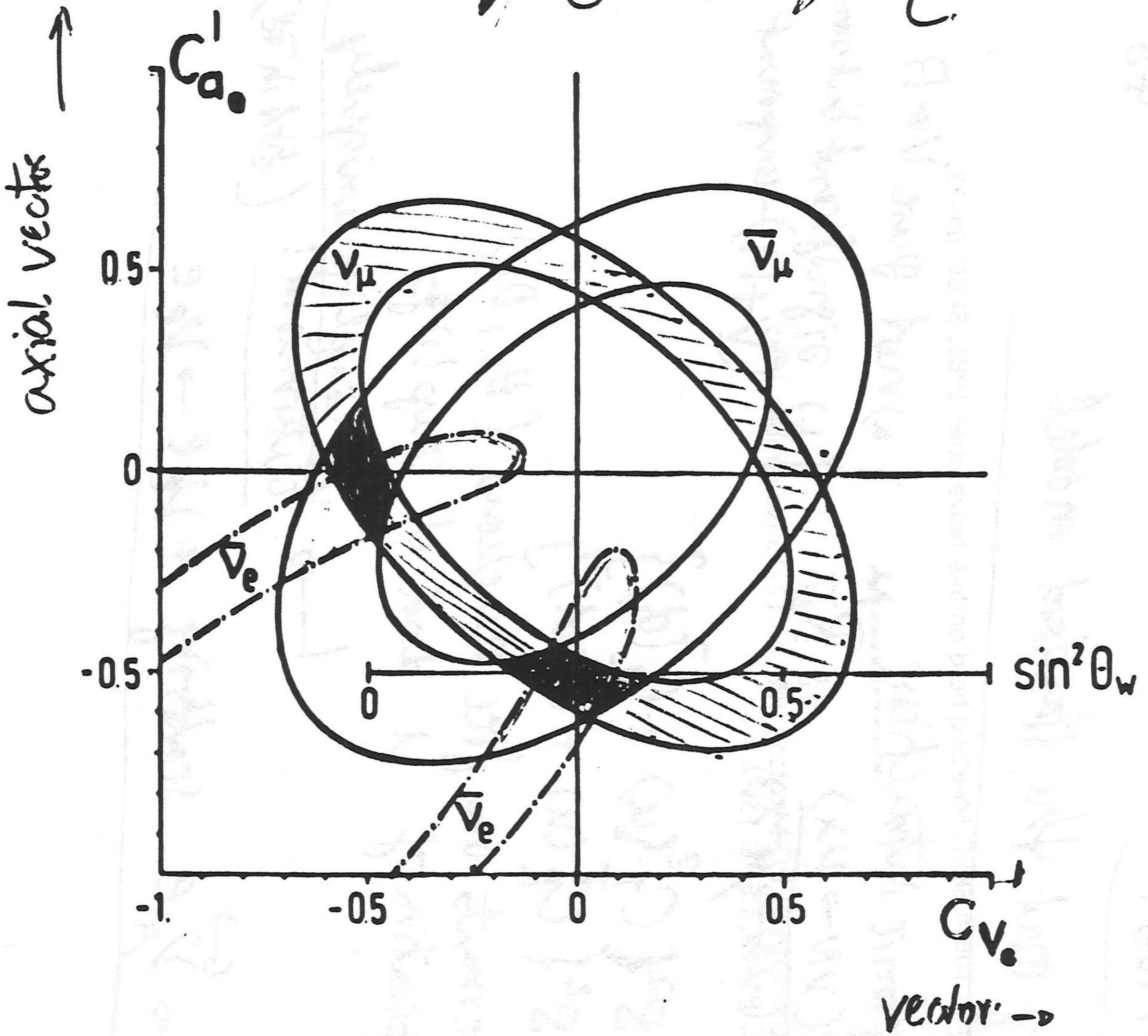
ν_μ (NC)

reject
e^+e^- pairs
at beginning

$\rightarrow E_e^2\,\theta_e^2$

example: CHARM

$\nu\, e \rightarrow \nu\, e$



$$\boxed{C_V' \cdot C_A' = -.002 \pm .04}$$

↳ electron NC either pure vector
or pure axial vector

<u>Needs:</u> measurement of pseudoscalar

SLAC $\underset{\rightarrow}{e}D$-experiment ($\gamma Z$): inelastic scattering of polarized electrons

measured quantity:

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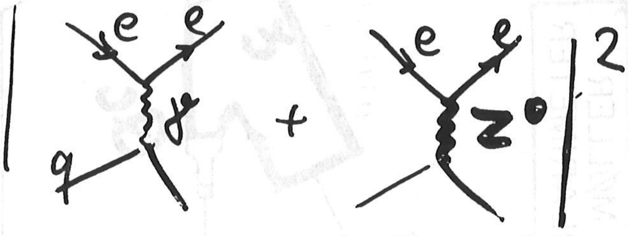
$$A = \frac{\sigma_R(e\uparrow D \to ex) - \sigma_L(e\downarrow D \to ex)}{\sigma_R(e\uparrow) + \sigma_L(e\downarrow)}$$

13. Minutes of the 13th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-38, LEPC 13(*).

$\sigma \sim$



parity violating

$$A = \frac{A_{weak} \cdot A_{el.magn.}}{|A_W + A_{el.magn}|^2} \simeq \boxed{\frac{A_{weak}}{A_{el.magn}}} \simeq \frac{G_F}{4\pi} \cdot \frac{Q^2}{\alpha} = 10^{-4}$$

for $Q^2 = 1\,GeV^2$

$$= a_1(x) + a_2(x)\left[\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$\left.\begin{array}{|ll} a_1(x)\,(\sigma_R + \sigma_L): & C_A^1 \cdot C_V(q) \\ a_2(x)\,(\sigma_R + \sigma_L): & C_V^1 \cdot C_A(q) \end{array}\right\}$$ y-dependence!

e.g.: $C_V^1 = 0 \Rightarrow$ $A = $ const. (independent of y)

$C_A^1 = 0 \Rightarrow$ $A = 0$ for $y = 0$; varies with y!

---

note: similar experiment done by BCDMS with polarized muons!

measures muon coupling and e-μ universality

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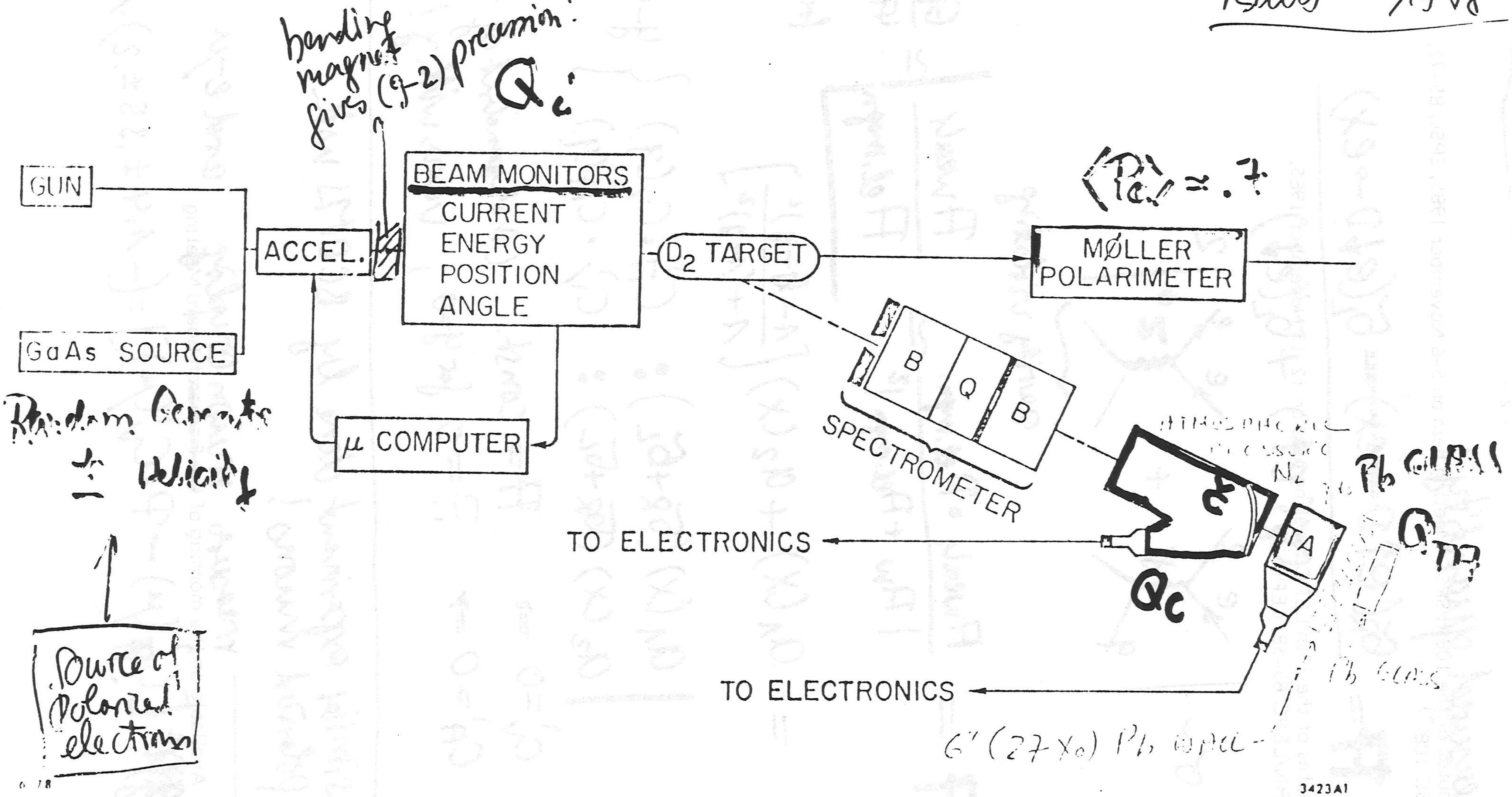
$$A_\mu = -g\,Q^2\left[C_A^1(\mu) - P \cdot C_V^1(\mu)\right] = (-1.4 \pm .35 \pm .2) \cdot 10^{-4}\,GeV^{-2} \cdot g(y) \cdot Q^2$$

proposed 1970
results 1978



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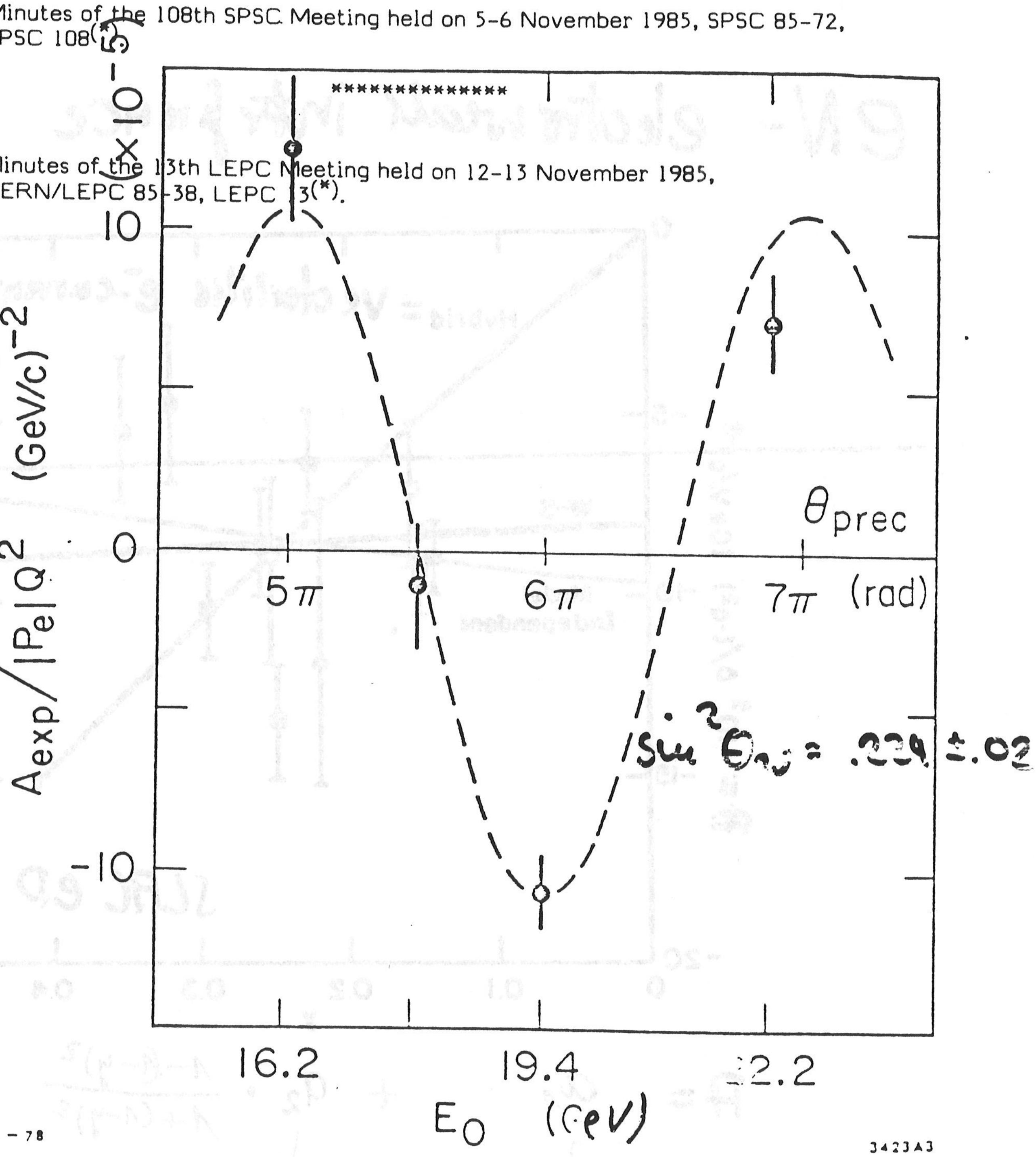
13. Minutes of the 13th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-38, LEPC 13(*).



$\sin^2\theta_w = .229 \pm .02$

$\theta_{prec} \sim (g-2) \cdot E_0$

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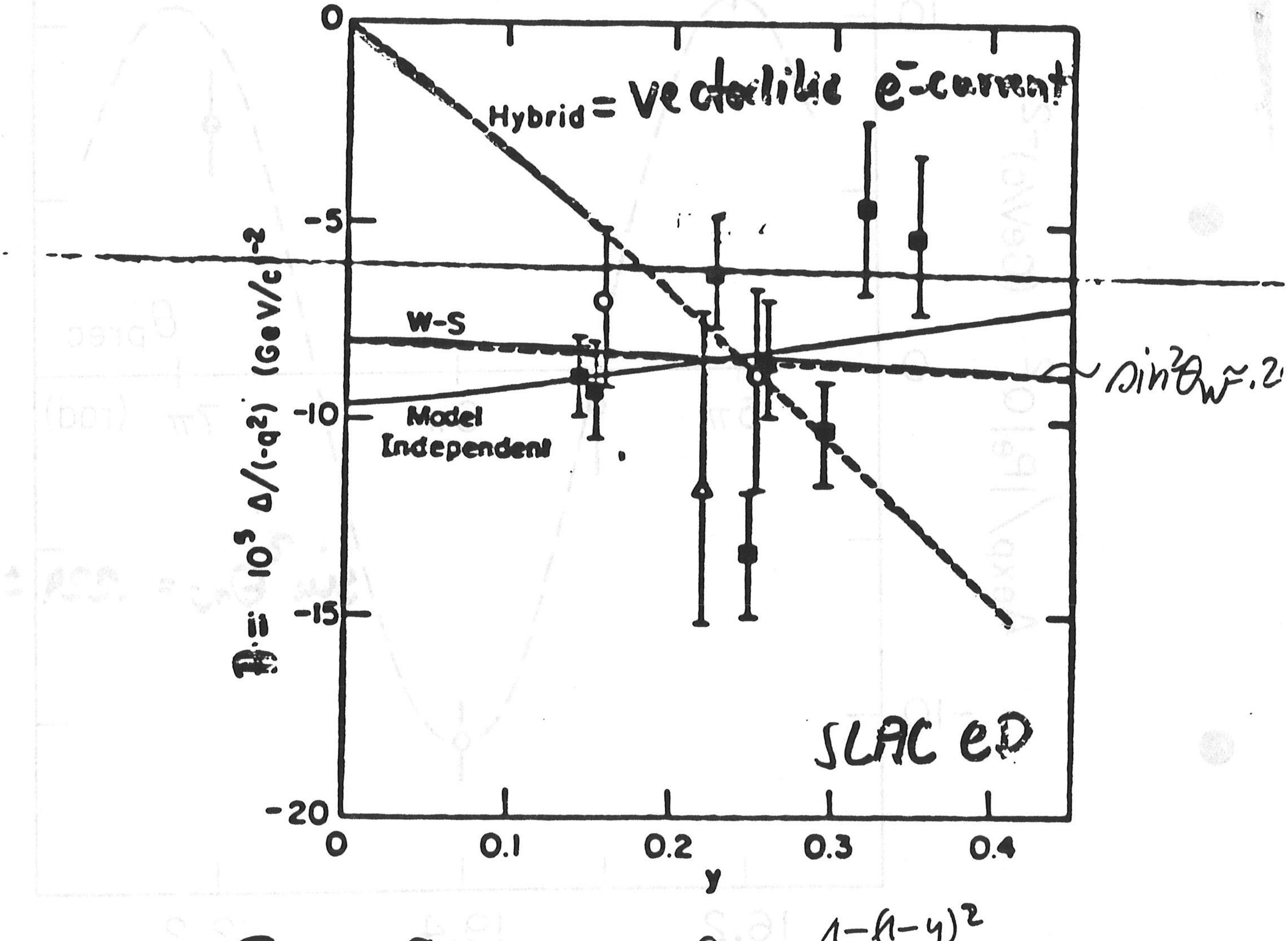
eN- electroweak interference



$$A = \underset{\downarrow \atop G_A(e)\cdot G_V(q)}{a_1} + \underset{\downarrow \atop G_V(e)\cdot G_A(q)}{a_2} \cdot \frac{1-(1-y)^2}{1+(1-y)^2}$$

SLAC e, D expriment: (78)

① showed el.magnetic-weak interference for the first time ▼ (essential ingredient of standard model)

② gave precise value of $\sin^2\theta_W$:

$\sin^2\theta_W = .20 \pm .03$ SLAC(78)

$\sin^2\theta_W = .24 \pm .02$ CDHS(77)

giving strong support to the universality of the coupling.

(model dependent)

③ it excluded vectorlike electron currents which were favoured at that time by atomic physics expts.

↳ ▼ standard model was established (apart from $W^\pm, Z^0$, Higgs ...)

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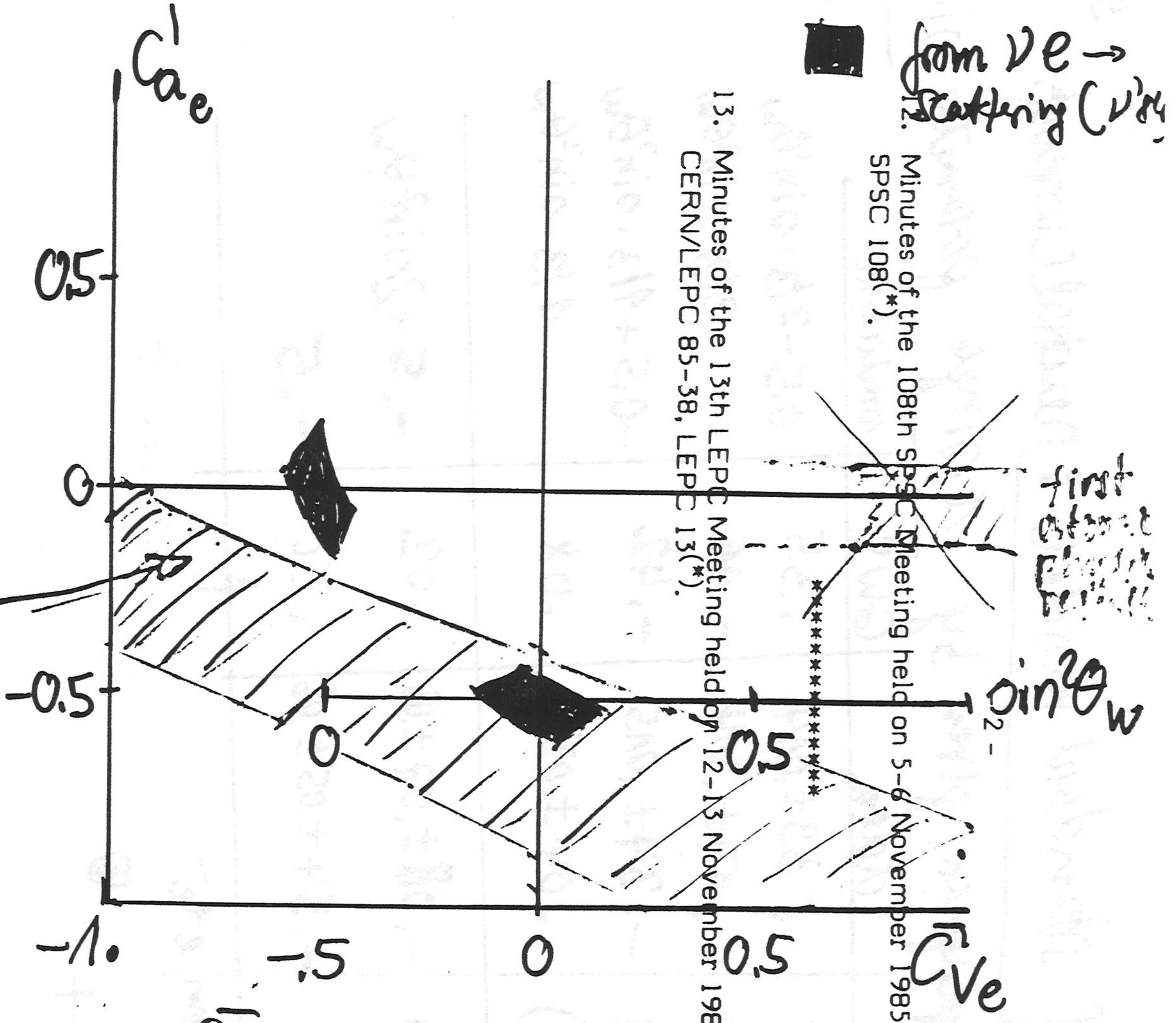
Sakurai 78': "Despite the almost unbounded imagination of the model builders, the only model that has survived, is the least imaginative, standard model"



e^- ν'84

$C'_V = -0.08 \pm .07 \pm .03$

$C'_A =$ [illegible]$.54 \pm .05 \pm .06$

$C'_V(\mu) = -.17 \pm .36$	using C'_A from e^+e^-	BCDMS

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13. Minutes of the 13th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-38, LEPC 13(*).

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ⓑ Tests of standard model : neutral currents

i) all couplings are given by 1 single parameter $\sin^2\theta_W$

		data	GWS	prediction
(νq)	$C_L(u)$	$.39 \pm .014$	$.35$	$0.5 - 2/3 \cdot \sin^2\theta_W$
	$C_R(u)$	$-.17 \pm .014$	$-.16$	$-2/3 \cdot \sin^2\theta_W$
	$C_L(d)$	$-.37 \pm .015$	$-.42$	$-0.5 + 1/3 \cdot \sin^2\theta_W$
	$C_R(d)$	$.04 \pm .027$	$.08$	$1/3 \cdot \sin^2\theta_W$
νe	$C_V'(e)$	$-.08 \pm .07 \pm .13$	$.02$	$-.5 + 2\sin^2\theta_W$
	$C_A'(e)$	$-.54 \pm .05 \pm .06$	$.50$	$-.5$

from e^+e^-

↑ for $\sin^2\theta_W = .23$

$e\mu$
$(e\tau)$
$(e\,b)$
$(e\,c)$

\+ ⊙

ii) determination of ρ : relative strength of neutral and charged currents

$\rho \equiv 1$ in standard model (1 Higgs doublet + ···)

best values from inclusive νN scattering

$$\boxed{\nu N \qquad \rho = 1.01 \pm .02}$$ $\nu' + \nu$

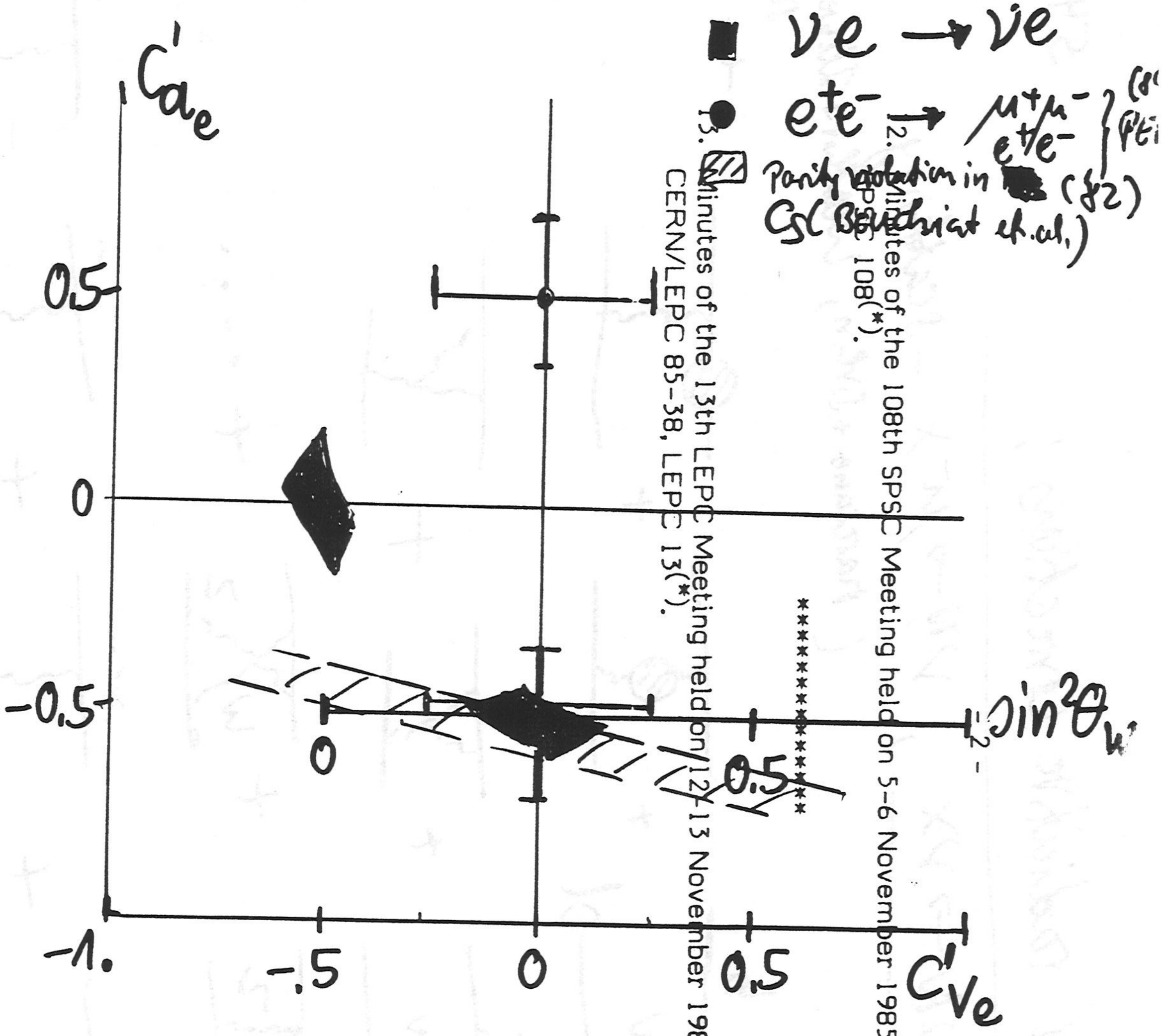
iii) consistency of $\sin^2\theta_W$ for all processes ?

tested from $Q^2 \simeq 10^{-6}$ up to $Q^2 \simeq 10^3$

⇒ needs el.weak radiative corrections $O(\alpha)$ to be meaningful : $\sin^2\theta_W$ depends on Q^2 !!
$\longrightarrow \sin^2\theta_W(M_Z)$: running coupling constant

test of standard model:

electron couplings



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3. Minutes of the 13th LEPC Meeting held on 12-13 November 1985, CERN/LEPC 85-38, LEPC 13(*).

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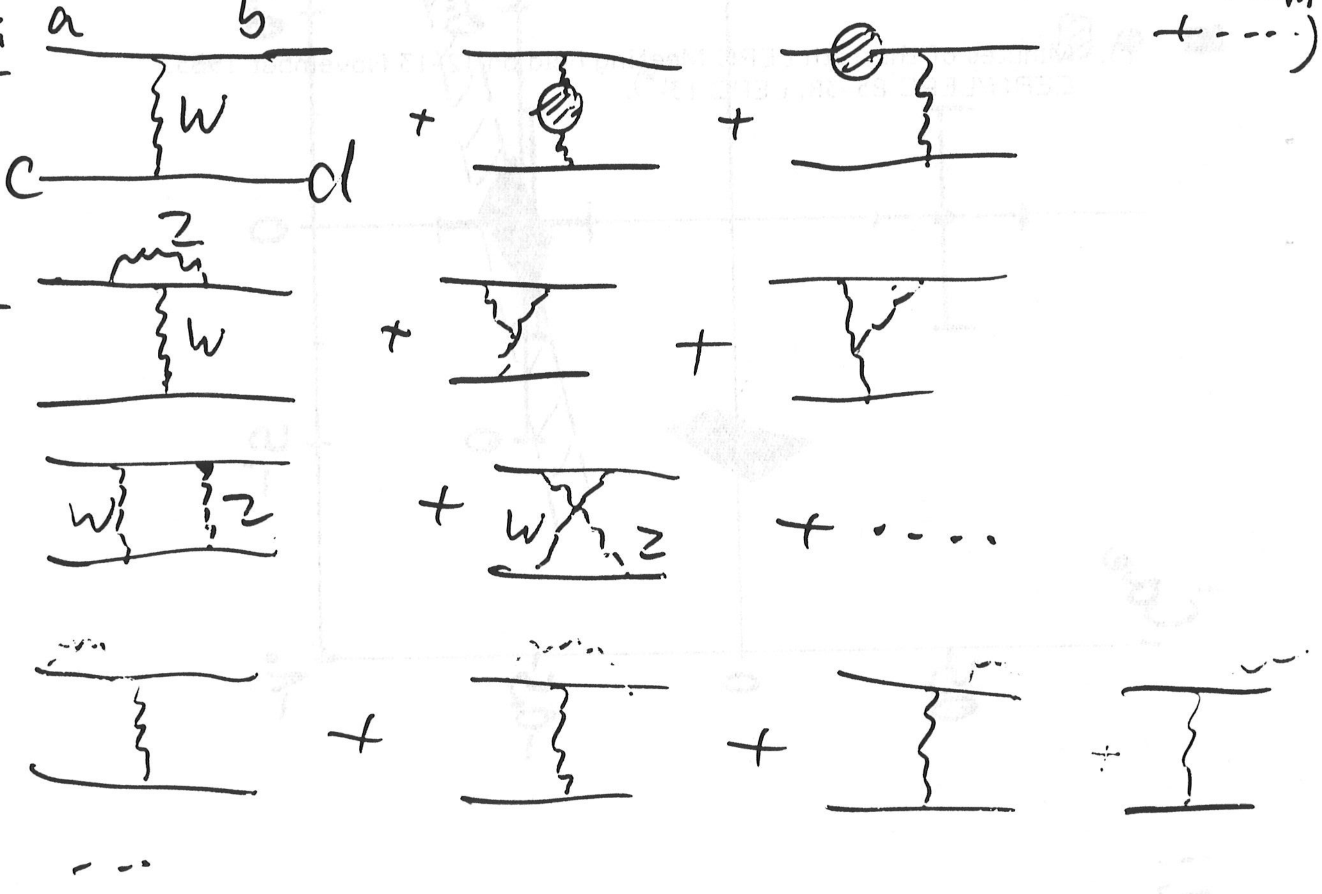
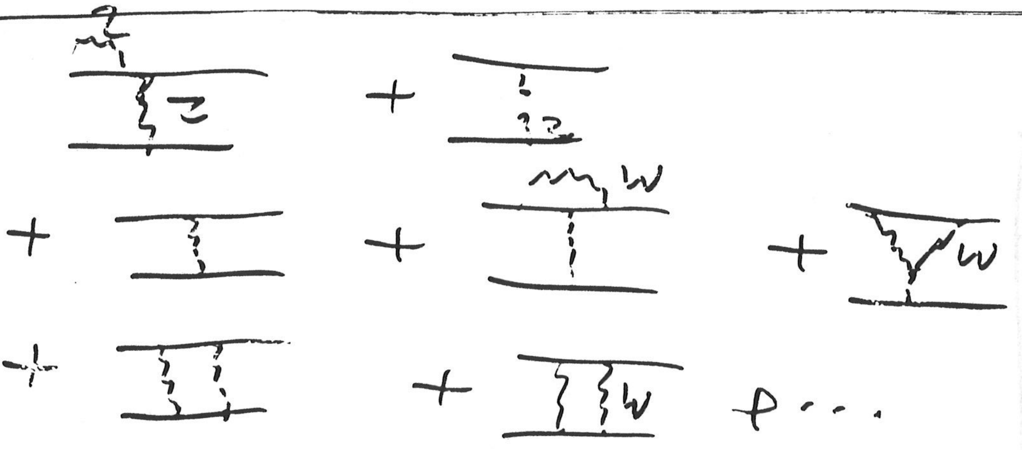
electroweak radiative corrections:

example: $\nu N \to \nu X$, $\nu N \to \mu^- X$ - scattering
(Marciano + Sirlin, Weather + Llewellyn-Smith + ...)

CC:



NC:



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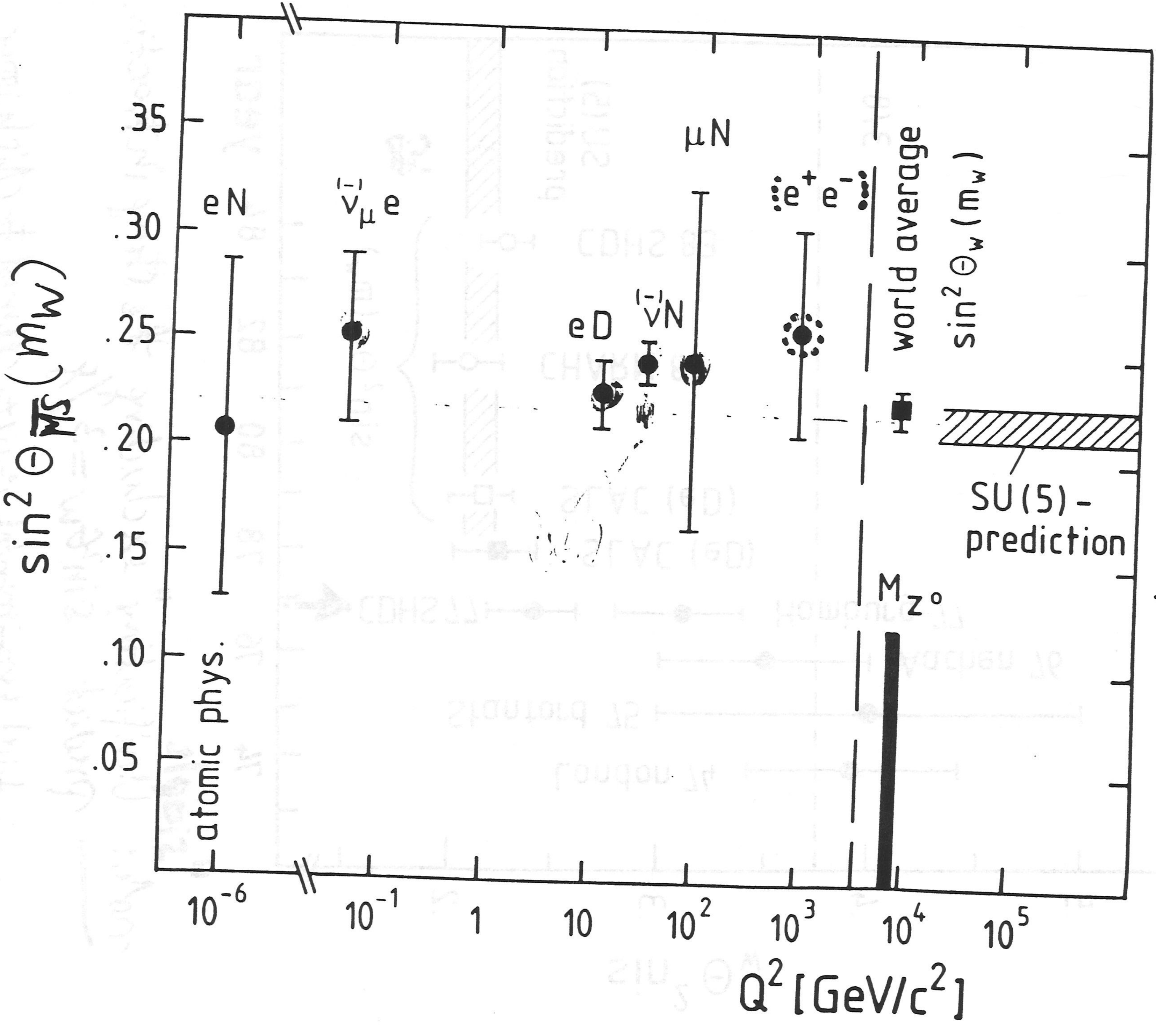
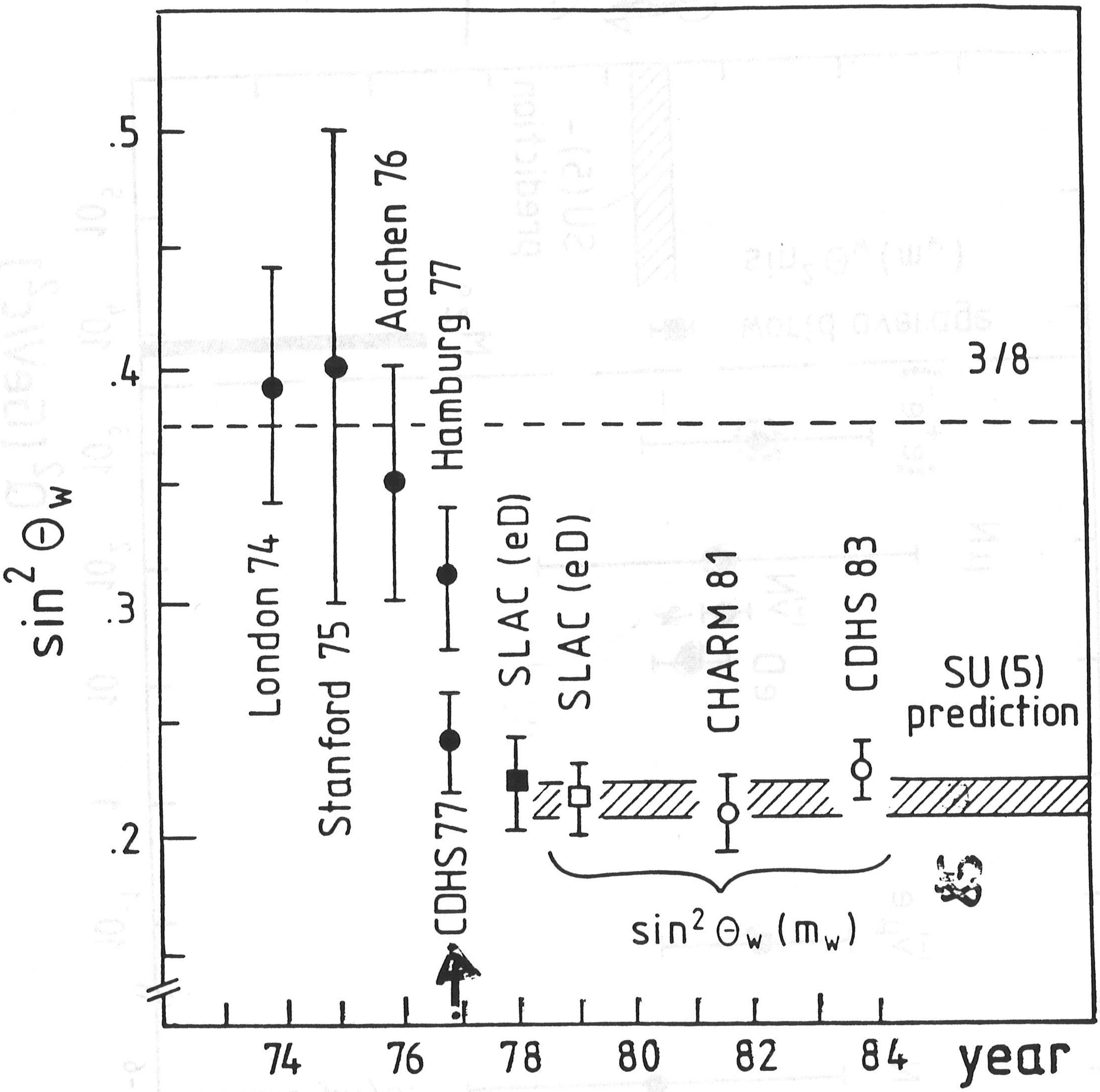
note: purely electromagnetic corrections dominate!
but:
||| corrections finite <u>only</u> within gauge theories!



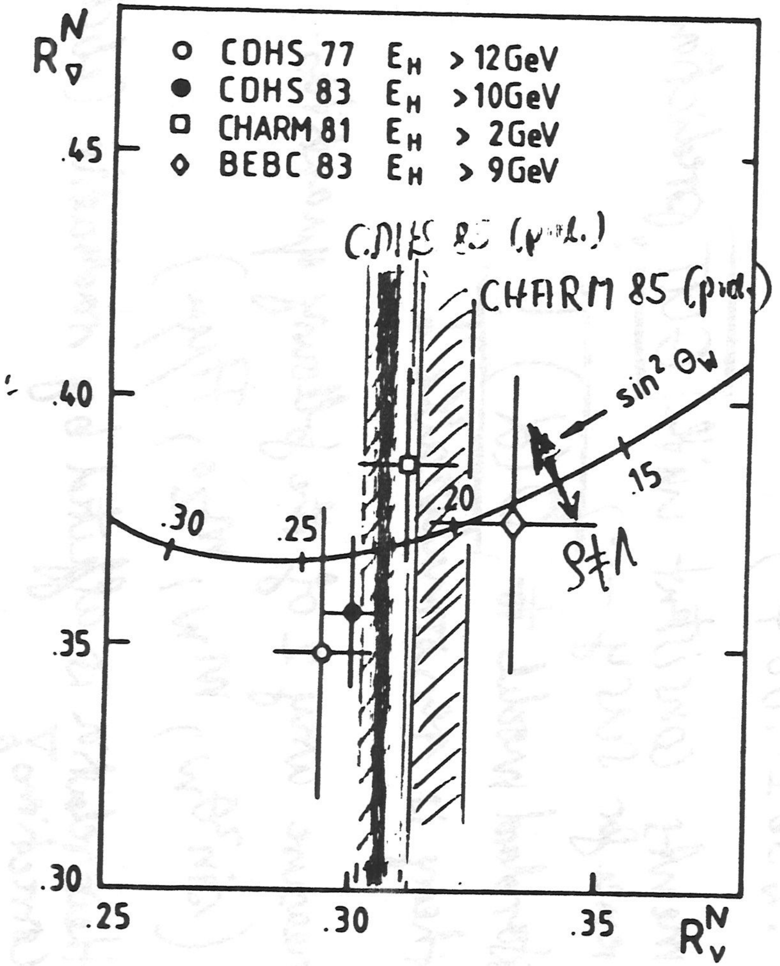
Grand unified theories need $\sin^2\Theta_W \simeq .2$.

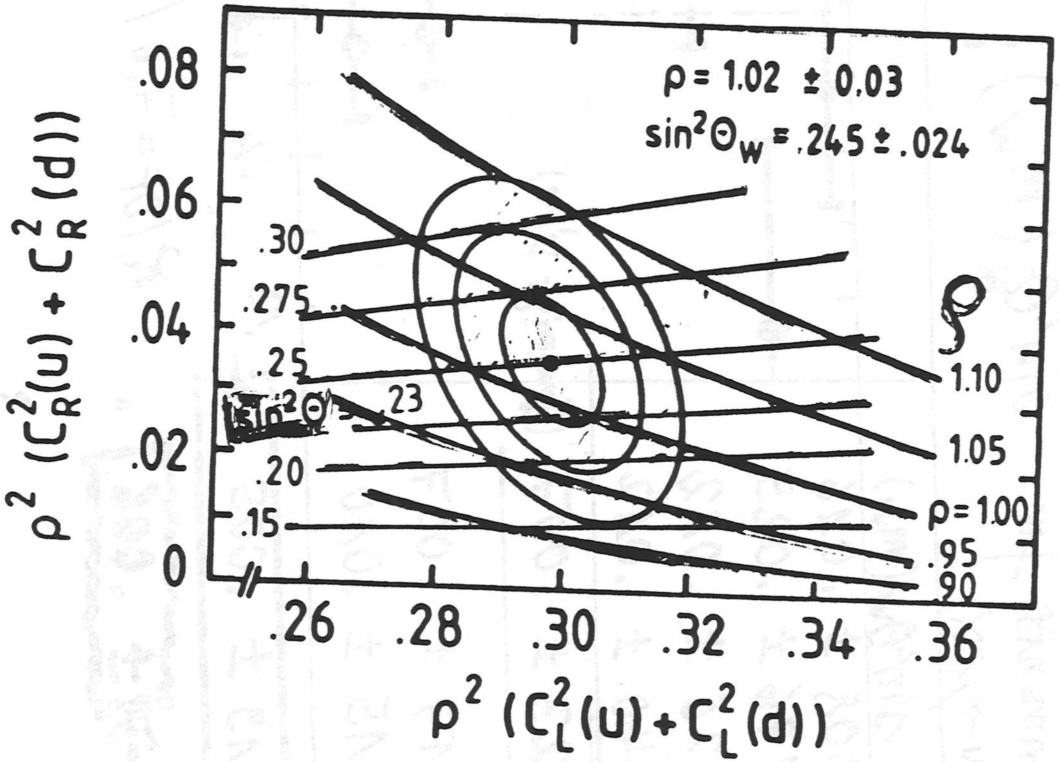
history of $\sin^2\theta_W$



"simple
note: Unification" excluding the strong interaction
predict $\sin^2\theta_W = 3/8$

first experimental results seemed to disfavour GUT's





isoscalar targets

master equations

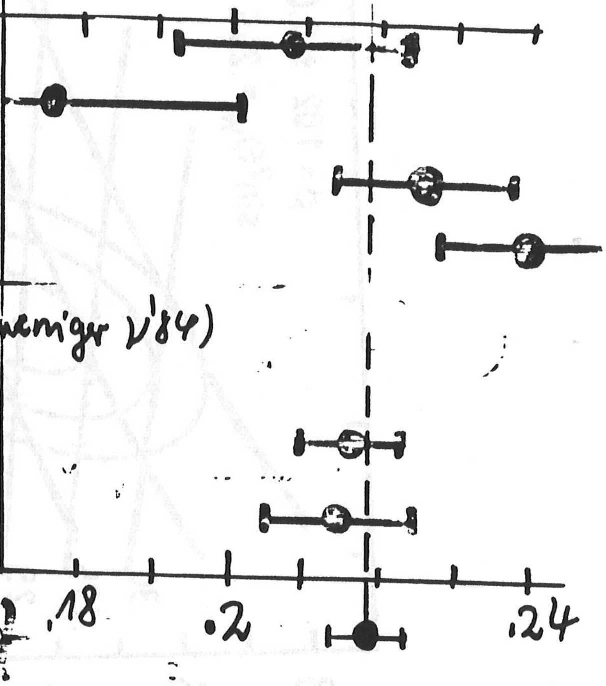
$$\varrho^2[C_L^2(u)+C_L^2(d)] = (R_\nu^N - r^2 R_{\bar\nu}^N)/(1-r^2) + \text{corr}$$

$$\varrho^2[C_R^2(u)+C_R^2(d)] = (R_{\bar\nu}^N - R_\nu^N)(1/r - r) + \text{corr}$$

Precision experiments for $\sin^2\theta_{\overline{MS}}(m_W)$:

$R_\nu^N = (\nu N \to \nu X)/(\nu N \to \mu^- X)$

	$\sin^2\theta_W(m_W)$
CHARM 81	.208 ± .016
ABCDLOS 83	.176 ± .025
CDHS 83	.226 ± .012
CCFRR 84	.240 ± .012
average 84	.223 ± .007 (Gueniger ν'84)
CDHS 85	.217 ± .007
CHARM 85	.215 ± .010
world average 85:	.219 ± .005



- theoretical uncertainty → $\pm$ .006 . $\chi^2/DF = 7.6/6$

(mainly charm mass effect)

SU(5) prediction: .213 ± .004 } (Marciano, Sirlin)$_{85}$

(minimal susy GUT's ⋯→ .236 ± .004)

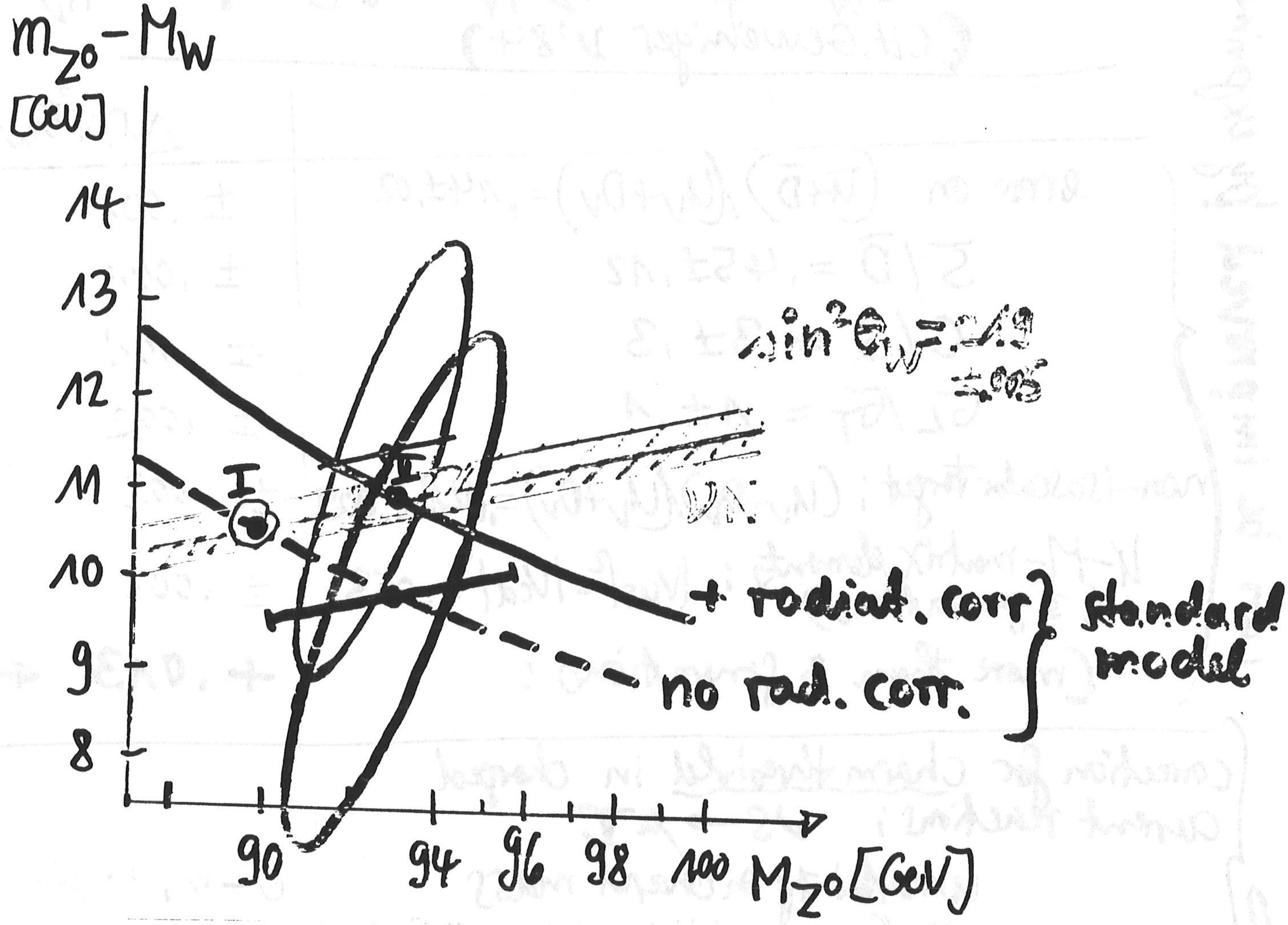
⇒ ① measurements consistent with GUT prediction
(no preference for susy ⋯)

⇒ ② test of standard model to $O(\alpha)$!
theory is renormalizable !

idea: measure any 2 of the following quantities:
$(\sin^2\theta_W, m_W, m_{Z^0}, A_{\mu\mu})$

⇒ their relation is affected by radiative (electroweak) corrections!

② consistency with $m_{Z^0}, m_{W^\pm}$ and electroweak radiative corrections:



correction for νN : ~ 4% on $\sin^2\theta_W (m_W)$

$$m_W = \frac{37.281\ \mathrm{GeV}}{\sin\theta_W \sqrt{1-\Delta r}} = \frac{38.8\ \mathrm{GeV}}{\sin\theta_W}$$

rad. corr: $\Delta r = 1 - \left(\frac{37.281\ \mathrm{GeV}}{M_W \cdot \sin\theta_W}\right)^2 = .077$ predicted!

expt.: $\boxed{\Delta r = .08 \pm .05}$ (νN + $m_W{}^c$)

$\downarrow$ $\delta(\Delta r) \simeq .02$!

conclusion: standard model tested to $O(\alpha)$ within ~2σ. Neutrino experiments are not now the limiting factor ! ⇒ LEP!

theoretical uncertainties in the determination of $\sin^2\theta_W$ from νN − DIS : R_ν^N

(CH. Geweniger ν'84)

can be improved by experimentalists

	$\Delta \sin^2\theta_W$
error on $(\overline{U}+\overline{D})/(U_V+D_V) = .14 \pm .02$	± .001
$\overline{S}/\overline{D} = .45 \pm .12$	± .001
$C/S = .3 \pm .3$	± .001
$\sigma_L/\sigma_T = .1 \pm .1$	± .002
non-isoscalar target: $(U_V-D_V)/(U_V+D_V) = .028 \pm .009$	± .003
K-M-matrix elements (3 generations): $\lvert V_{us}\rvert^2 = \lvert V_{cd}\rvert^2 = .053$	± .000
(more than 3 generations:	+ .013 ←)
correction for <u>charm threshold</u> in charged current reactions: $\nu s \to \mu^- c$	
uncertainty in charm mass m_c [illegible] → m_c [illegible]	0 − .[illegible]
highest twists ??	± .00[illegible]

theorists needed, can they help? total $\boxed{\pm .[illegible]}$

'conservative' estimate!

note: theoretical uncertainties dominate allready!

way out: $\boxed{\begin{array}{l}\text{precision measurement of } \nu_\mu e \to \nu_\mu e \\ \text{CHARM II}: \ \Delta \sin^2\theta_W = \pm .005\end{array}}$

c) test of standard model: charged currents

→ • V−A structure : $C_L = \frac{C_A + C_V}{2}$, $C_R = \frac{C_A - C_V}{2}$

→ • GIM-mechanism

• U_{cs}, U_{ds} − couplings (parameters)

(i) partial differential cross-section for the reaction $\nu + q_i \to l + q_j$:

$$\Rightarrow \quad \frac{d^2\sigma^{ij}}{dx\,dy} = \frac{G^2 M E_\nu}{\pi}\left[U_{ij}\, q_i(x)\, \delta_{ij}\, (A + B(1-y)^2)\right]$$

$\delta_{ij} = 1$ for [illegible] $\Big\}$ threshold suppression of heavy quark production
$\delta_{ij} \neq 1$ for e.g. $s \to c$

---

table!

$$\frac{d^2\sigma^{\nu}}{dx\,dy} = \frac{G^2 M E_\nu}{\pi}\left\{C_L^2\, q^{\nu}(x) + C_R^2\, \bar{q}^{\nu}(x) + (1-y)^2\left[C_L^2\, \bar{q}^{\nu}(x) + C_R^2\, q^{\nu}(x)\right]\right\}$$

$$\frac{d^2\sigma^{\bar\nu}}{dx\,dy} = \frac{G^2 M E_\nu}{\pi}\left\{\underbrace{C_L^2\, \bar{q}^{\bar\nu}(x) + C_R^2\, q^{\bar\nu}(x)}_{\text{flat: right-handed partons } q_L(x)} + (1-y)^2\underbrace{\left[C_L^2\, q^{\bar\nu}(x) + C_R^2\, \bar{q}^{\bar\nu}(x)\right]}_{(1-y)^2\text{: left-handed partons } q_R(x)}\right\}$$

simplify: i) neglect coupling to 3. generation (ok)
ii) neglect charm threshold effects ← quite large!

	$q(x)$	$\bar{q}(x)$
$\nu p \to \mu^- X$	$2x(d+s)$	$2x(\bar{u}+\bar{c})$
$\bar\nu p \to \mu^+ X$	$2x(u+c)$	$2x(\bar{d}+\bar{s})$
$\nu N \to \mu^- X$	$q(x) + x(s-c)$	$\bar{q}(x) - x(s-c)$
$\bar\nu N \to \mu^+ X$	$q(x) - x(s-c)$	$\bar{q}(x) + x(s-c)$

$$q(x) = x(u+d+s+c)$$
$$\bar{q}(x) = x(\bar{u}+\bar{d}+\bar{s}+\bar{c})$$

Table 5.4a) Elementary quark cross-sections leading to light and charmed quarks

I. charged current reactions

reaction	U_{ij}^{*}	y-distribution		ξ_{ij} ‡	$q_i(x)$		
		A	B		proton	neutron	isoscalar targe
$\nu_\mu + d \to \mu^- + u$ $\mu^- + c$	$U^2_{du} = .94$ $U^2_{dc} = .06$	C_L^2	C_R^2	1 ξ_{cd}	$2xd(x)$ $2xd(x)$	$2xu(x)$ $2xu(x)$	$x(u+d)$ $x(u+d)$
$\nu_\mu + s \to \mu^- + c$	$U^2_{sc} = .94$	C_L^2	C_R^2	ξ_{cs}	$2xs(x)$	$2xs(x)$	$2xs(x)$
$\to \mu^- + u$	$U^2_{su} = .06$	C_L^2	C_R^2	1	$2xs(x)$	$2xs(x)$	$2xs(x)$
$\nu_\mu + \bar{u} \to \mu^- + \bar{d}$ $\to \mu^- + \bar{s}$	$U^2_{ud} = .94$ $U^2_{su} = .06$	C_R^2 C_R^2	C_L^2 C_L^2	1 1	$2x\bar{u}(x)$	$2x\bar{d}(x)$	$x(\bar{u}+\bar{d})$
$\nu_\mu + \bar{c} \to \mu^- + \bar{d}$ $\to \mu^+ + s$	$U^2_{dc} = .06$ $U^2_{sc} = .94$	C_R^2 C_R^2	C_L^2 C_L^2	1 1	$2x\bar{c}(x)$	$2x\bar{c}(x)$	$2x\bar{c}(x)$
$\bar{\nu} + u \to \mu^+ + d$ $\to \mu^+ + s$	$U^2_{du} = .94$ $U^2_{us} = .06$	C_R^2 C_R^2	C_L^2 C_L^2	1 1	$2xu(x)$	$2xd(x)$	$x(u+d)$
$\bar{\nu} + c \to \mu^+ + d$ $\to \mu^+ + s$	$U^2_{dc} = .06$ $U^2_{sc} = .94$	C_R^2 C_R^2	C_L^2 C_L^2	1 1	$2xc(x)$	$2xc(x)$	$2xc(x)$
$\bar{\nu}\bar{d} \to \mu^+ + \bar{u}$ $\to \mu^+ + \bar{c}$	$U^2_{ud} = .94$ $U^2_{cd} = .06$	C_L^2 C_L^2	C_R^2 C_R^2	1 ξ_{cd}	$2x\bar{d}(x)$ $2x\bar{d}(x)$	$2x\bar{u}(x)$ $2x\bar{u}(x)$	$x(\bar{u}+\bar{d})$ $x(\bar{u}+\bar{d})$
$\bar{\nu}\bar{s} \to \mu^+ + \bar{c}$ $\to \mu^+ + \bar{u}$	$U^2_{cs} = .94$ $U^2_{su} = .06$	C_L^2	C_R^2	ξ_{cs} 1	$2x\bar{s}(x)$ $2x\bar{s}(x)$	$2x\bar{s}(x)$ $2x\bar{s}(x)$	$2x\bar{s}(x)$ $2x\bar{s}(x)$

* see chapter 8 ‡ ξ_{ij} depends on the energy spectrum of the experiment

example: $\nu N \to \mu^- X$:

horrible $\Bigg\{$ $$q_L^{\nu N}(x) = C_L^2\big[\,[illegible]\, x(u+d) \;[illegible]\; x(u+d) \;[illegible]\; 2xs(x)$$
$$+ [illegible]\; 2xs(x)\;[illegible]$$
$$+ C_R^2\big[\,[illegible]\; x(\bar{u}+\bar{d}) + [illegible]\; 2x\bar{c}(x)\big]$$

+ coupling to 3. generation!

but fortunately

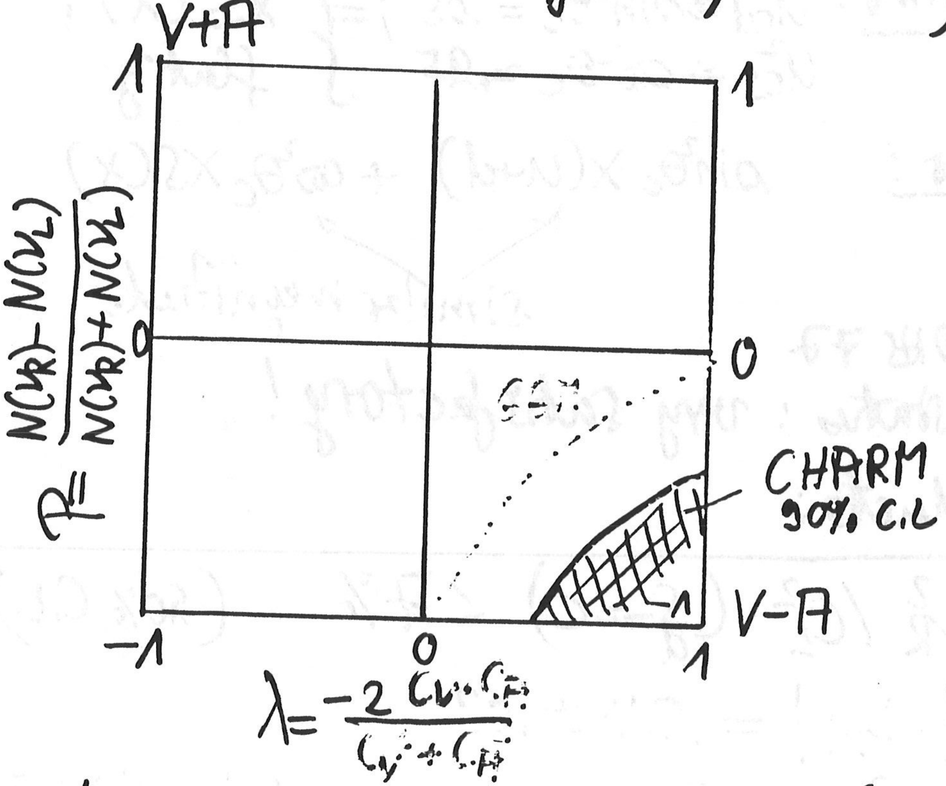
(V−A)−structure of CC

① measurement of muon polarization in $\bar{\nu}_\mu + N \rightarrow \mu^+ + X$
CHARM 82 (some help by CDHS): only sufficient to rule out S, P, T

$$\boxed{\frac{\sigma_{S,P}}{\sigma_{TOT}} \leq .07 \quad (95\%\ C.L.)}$$

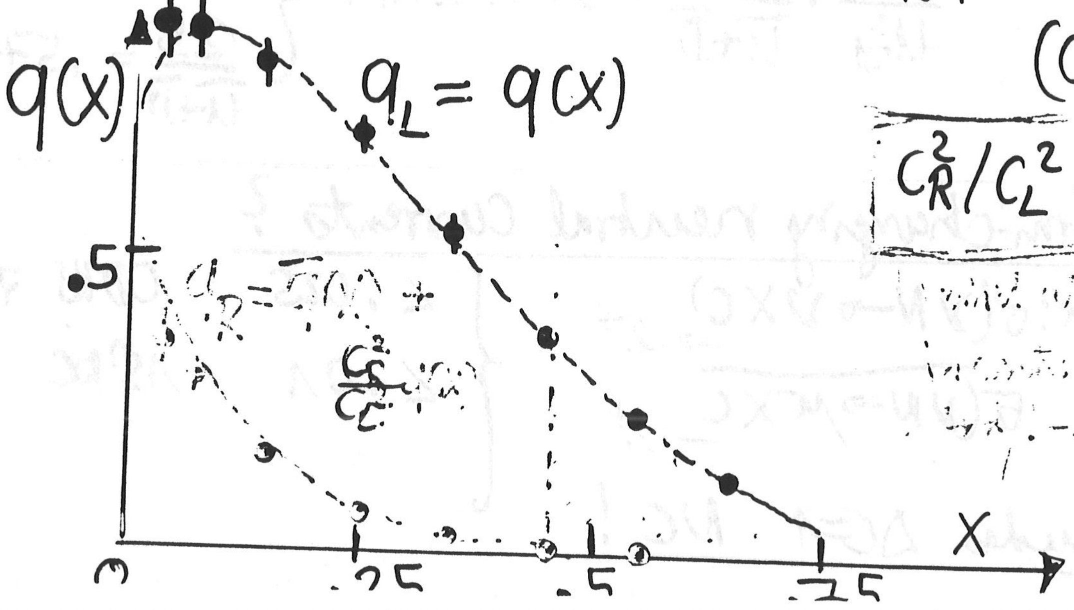
$$\boxed{H_{\mu^+} = .82 \pm .07 \pm .12\,(\text{syst})}$$ = 1 for V−A!
= −1 for S, P, T

② inverse muon decay: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$



① resolves sign ambiguity of μ decay
② 5 times larger CME
(③ incoming neutrinos are left handed)

③ inclusive measurements: measure q_R, q_L : limit on righthanded couplings!



(CDHS 82)

$$\boxed{C_R^2/C_L^2 < .009}$$

[illegible]

⑦ test of GIM-mechanism : undispensable ingredient of standard model

a) single charm production:

$$\frac{d^2\sigma}{dx\,dy}\left(\overset{(-)}{\nu} N \to \mu^\pm X \overset{(-)}{c}\right) = \frac{G^2 M E_\nu}{\pi}\left\{ \overset{\overset{\sin^2\theta_C \simeq .05}{\downarrow}}{U_{cd}^2}\, x(\overset{(-)}{u}+\overset{(-)}{d})_{\to c} + \overset{\overset{\cos^2\theta_C \simeq .95}{\downarrow}}{U_{cs}^2}\, 2x\overset{(-)}{s}_{\to c} \right\}$$

$\hookrightarrow \ell^\pm \overset{(-)}{s} \nu$

exp. signatures: i) dileptons opposite charge $\mu^+\mu^- / e^+\mu^-$

ii) strange hadrons in final state!

antineutrino: $U_{cd}^2 \simeq \sin^2\theta_C = .05$; $U_{cs}^2 = \cos^2\theta_C = .95$ $\Rightarrow x\bar{s}(x)$! flat y

neutrino: $\sin^2\theta_C\, x(u+d) + \cos^2\theta_C\, xs(x)$

similar magnitude

1. test: CDHS 77

present status: very satisfactory!

byproducts:

CDHS 82

$C_R^2 / C_L^2 \;(s_d \to c) < 7\%$ (90% C.L.)

$|U_{cd}| = .24 \pm .03$

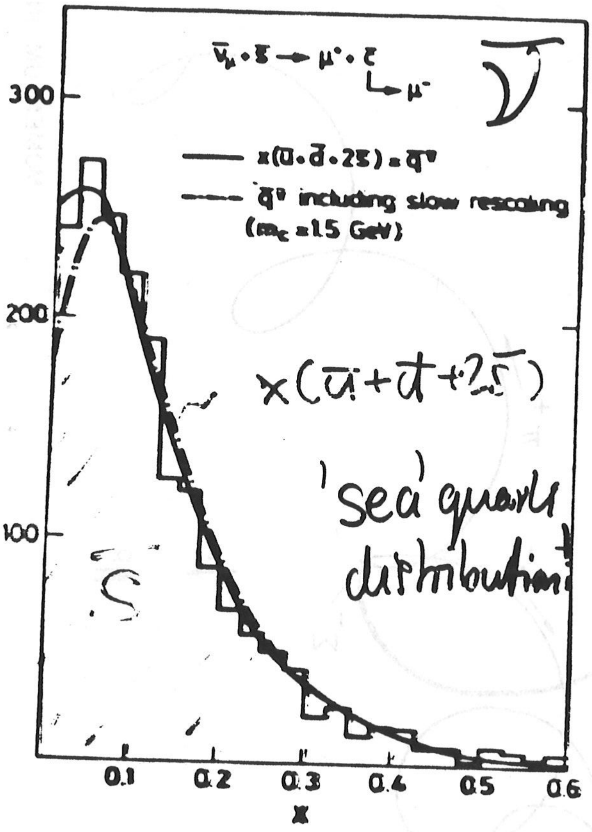
$$\frac{U_{cs}^2}{U_{cd}^2}\cdot\frac{2\,S}{U+D} = 10.4 \pm 1.7 \left\{ \begin{array}{l} |U_{cs}| > .59 \\ \frac{2S}{U+D} = .57 \pm .10 \end{array}\right.$$

ⓑ charm-changing neutral currents?

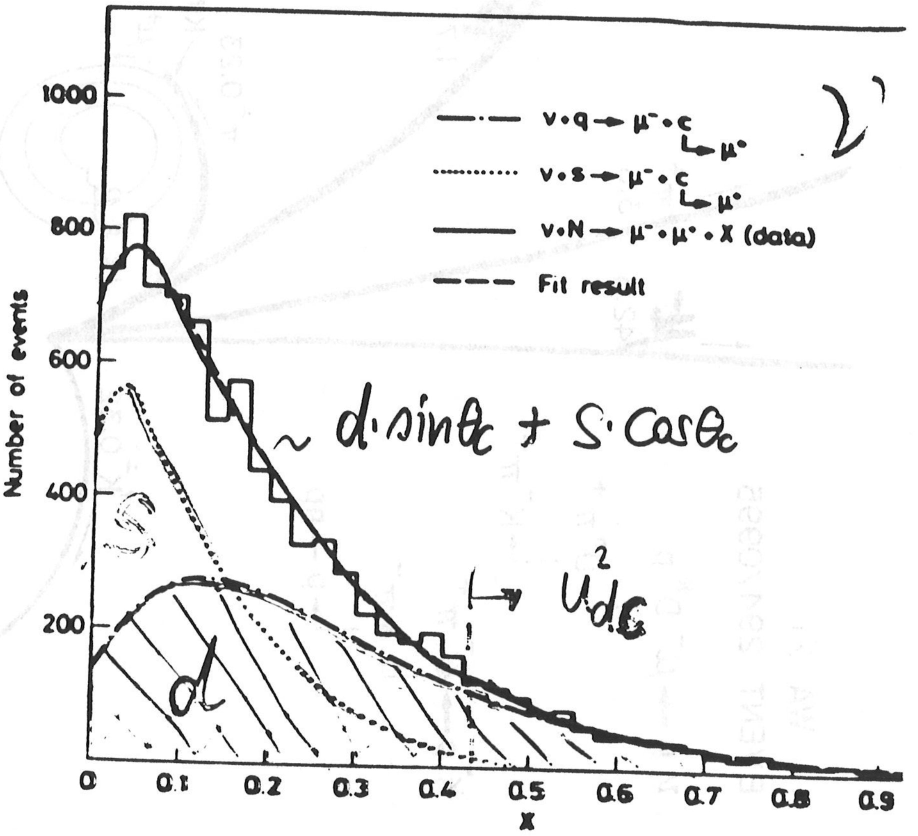
search for: $\dfrac{\sigma(\nu N \to \nu X C)_{\to \mu^+}}{\sigma(\nu N \to \mu^- X C)_{\to \mu^+}}$ $\left\{ \begin{array}{ll} < .025 & \text{CDHS 77} \\ < .01 & \text{15' BC 77} \end{array}\right.$

excludes $\Delta C = 1$ NC!

① CDHS 82



a)



b)

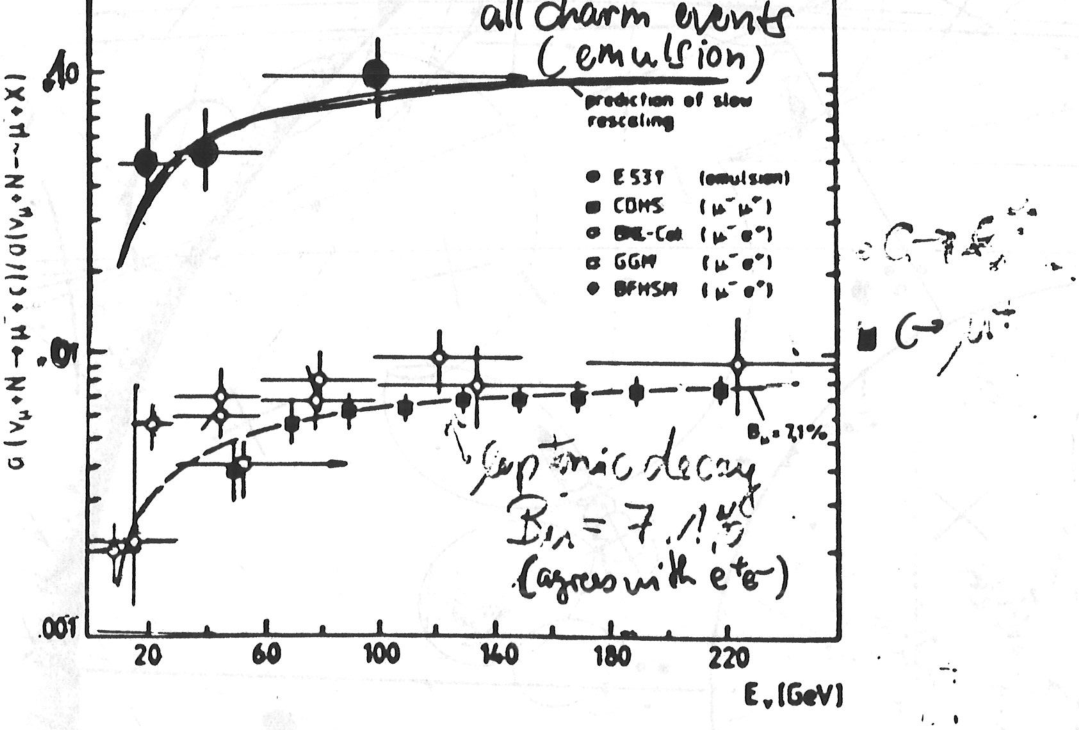
$\bar\nu_\mu + s \to \mu^+ + \bar c$ ↳ μ^-

$\nu_\mu + \binom{d}{s} \to \mu^- + c$ ↳ μ^+

(10 000 events)

② (2000 events)

$\sigma(\nu_\mu N \to \mu^- + c) / \sigma^\nu(cc)$



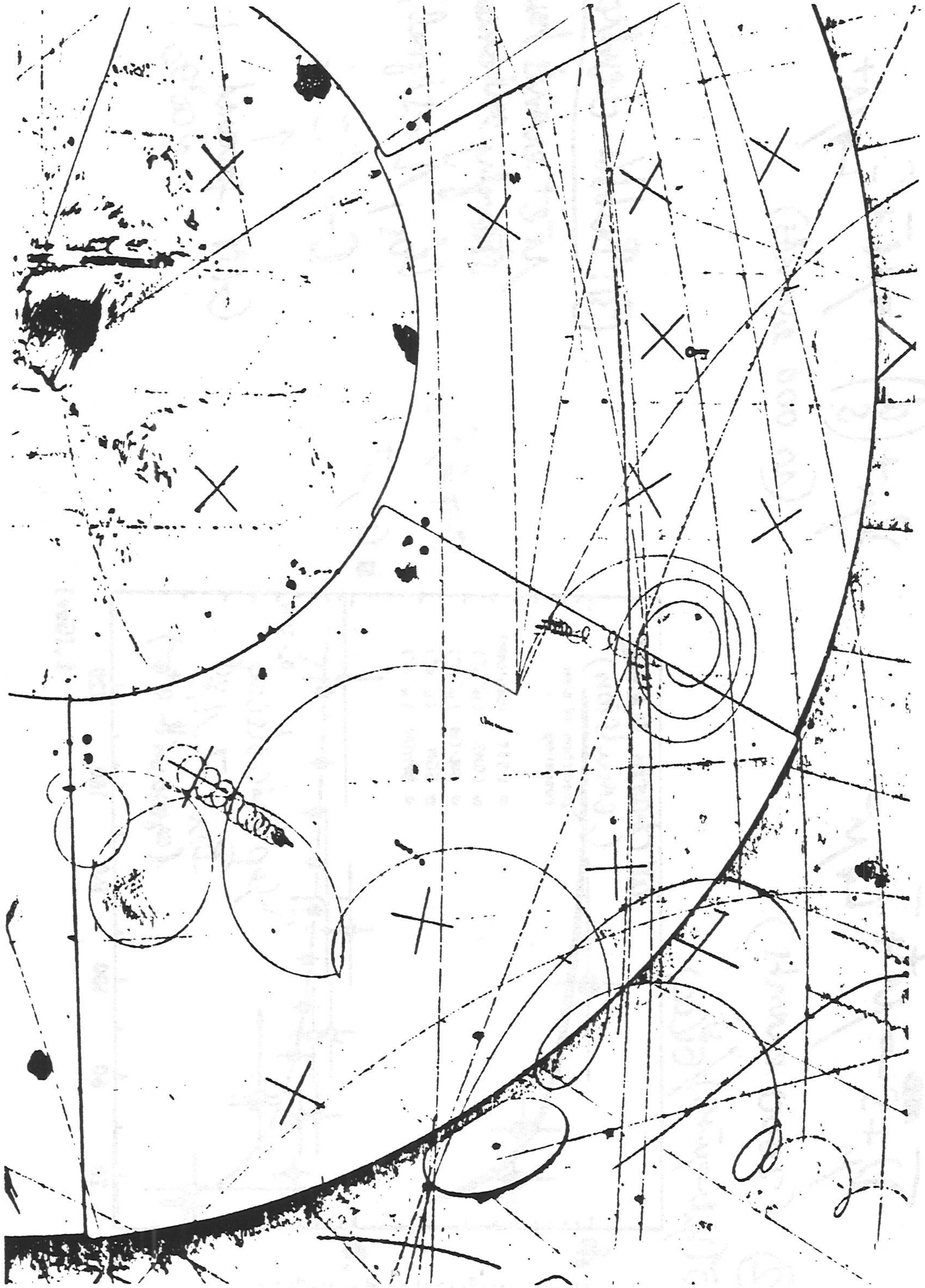
③: Bubble chamber:

$\mu^- e^+$ events have strongly enhanced V_{0s}, Λ-signal!

$c \to$ [illegible]

↑

GIM favoured $\sim \cos^2\theta_c$!



WA 21

EVENT 294/0995

$\nu\, p \rightarrow \mu^{-}\, D^{*} p$

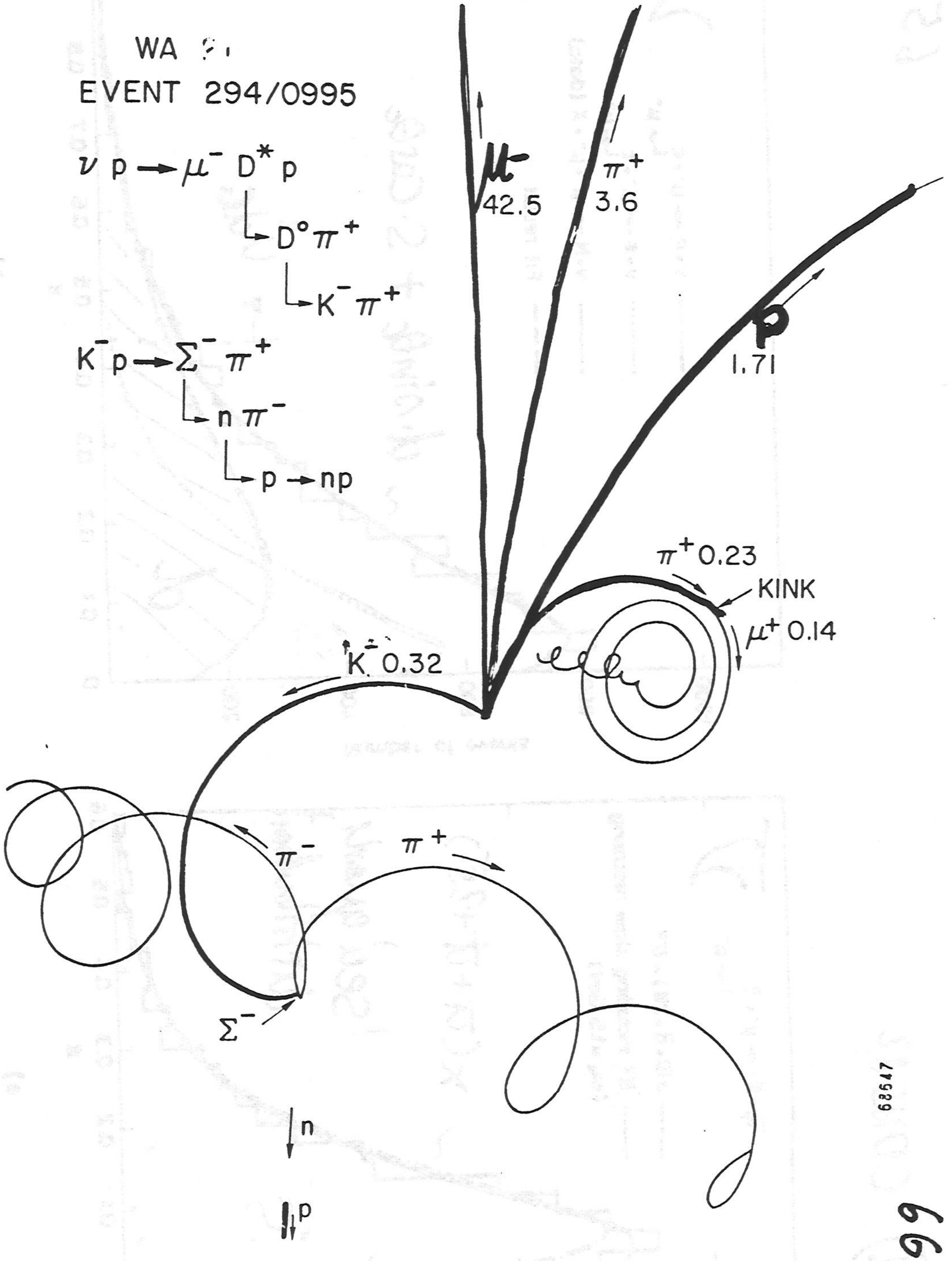
$\quad\quad \llcorner\!\rightarrow D^{\circ}\pi^{+}$

$\quad\quad\quad\quad \llcorner\!\rightarrow K^{-}\pi^{+}$

$K^{-}p \rightarrow \Sigma^{-}\,\pi^{+}$

$\quad\quad \llcorner\!\rightarrow n\,\pi^{-}$

$\quad\quad\quad\quad \llcorner\!\rightarrow p \rightarrow np$



MOMENTUM IN GeV/c

68547

IV Parton distributions + QCD

$$① \quad F_2^{\mu}(x,Q^2)\left[1+(1-y)^2\right] = \frac{Q^4}{8\pi\alpha^2 M E_\mu}\cdot\frac{d^2\sigma^{\mu}}{dx\,dy} + q_L(x,Q^2)\cdot y^2$$

$$② \quad F_2^{\nu}(x,Q^2)\left[1+(1-y)^2\right] = \frac{\pi\,(1+Q^2/m_W^2)^2}{G^2 M E_\nu}\,\frac{d^2(\sigma^{\nu}+\sigma^{\bar\nu})}{dx\,dy} + q_L(x,Q^2)\cdot y^2$$

$$+ \mathrm{corr}(s-c)$$

$$③ \quad xF_3(x,Q^2)\left[1-(1-y)^2\right] = \frac{\pi(1+Q^2/m_W^2)^2}{G^2 M E_\nu}\cdot\frac{d^2(\sigma^{\nu}-\sigma^{\bar\nu})}{dx\,dy}$$

$$④ \quad \bar q^{\bar\nu}(x,Q^2)\left[1-(1-y)^4\right] = \frac{\pi(1+Q^2/m_W^2)^2}{G^2 M E_\nu}\left[\frac{d^2\sigma^{\bar\nu}}{dx\,dy} - (1-y)^2\frac{d^2\sigma^{\nu}}{dx\,dy}\right] - q_L(x,Q^2)\left[(1-y)-(1-y)^3\right]$$

$R = \dfrac{q_L(x,Q^2)}{F_2 - q_L} \approx \dfrac{\sigma_L}{\sigma_T}$ accessible using relation ① μ or ② and ④ for neutrinos

⇒ measure y-dependence at fixed (x, Q^2)

QPM-relations:

$$F_2^{\nu} = q + \bar q + q_L \; ; \quad F_2^{\mu} = \sum_{\text{quarks}} e_i^2 \cdot q_i(x)$$

$$xF_3 = q - \bar q = q_{\text{valenz}}$$

most important example: isoscalar targets

$$F_2^{\nu N} = x(u+d+s+c+\bar u+\bar d+\bar s+\bar c) \leftarrow \text{after correction for strange suppression!!}$$

$$F_2^{\mu N} = \frac{5}{18}\cdot x(u+d+s+c+\bar u+\bar d+\bar s+\bar c) \quad - 6/5\; x(s-c)$$

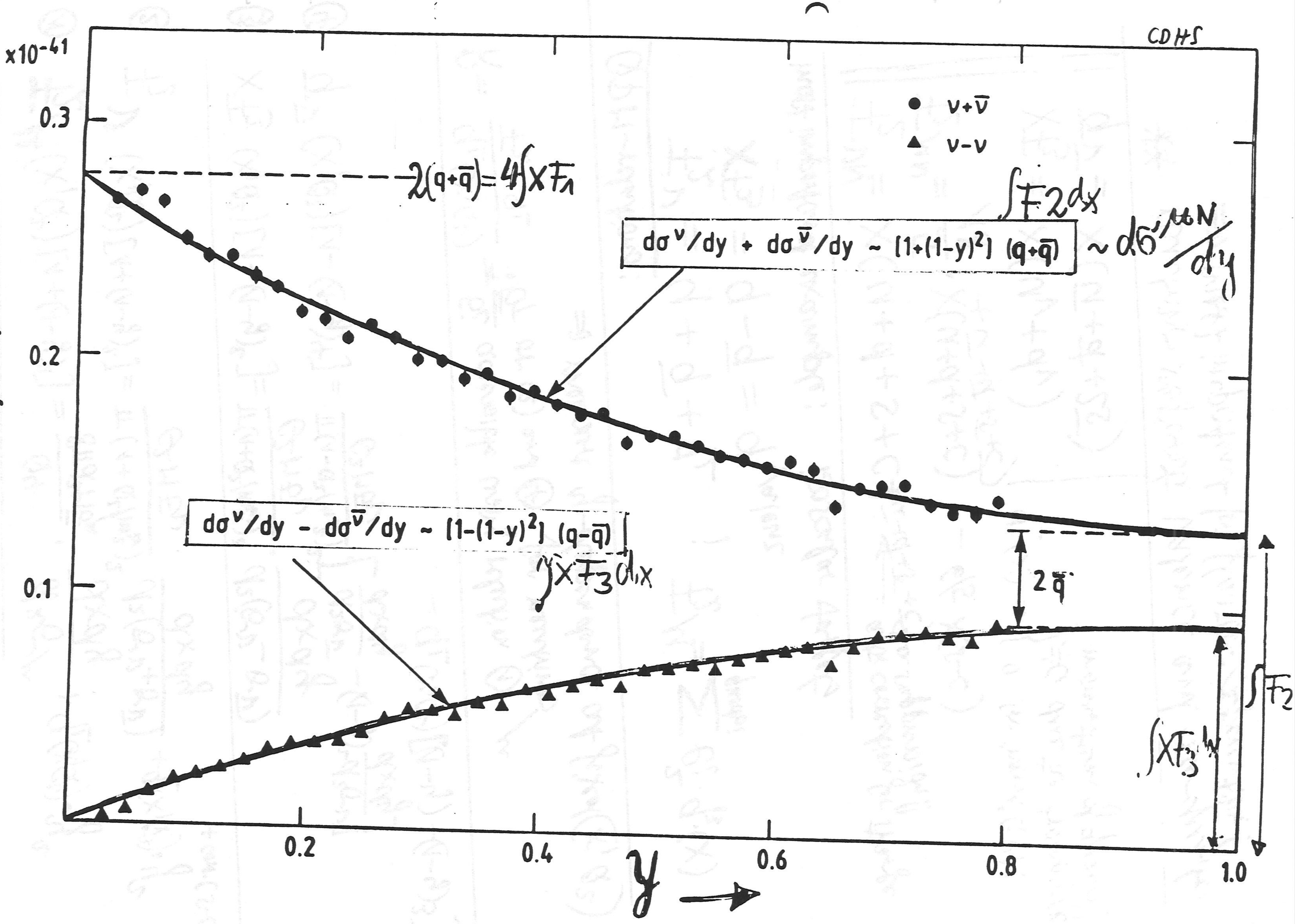
$$xF_3 = x(u_v + d_v)$$

$$\bar q^{\bar\nu} = x(\bar u + \bar d + 2\bar s)$$

$$q_L(x) = \begin{cases} 0 & \text{for "naive" QPM} \\ \neq 0 & \text{due to transverse momentum of quarks!} \end{cases}$$

** neutrinos separate valence and sea-quarks

⇒ most important for flavour separation!


x10^-41
CDHS
● ν+ν̄
▲ ν−ν
0.3
0.2
0.1
dσ/dy [cm²]
2(q+q̄)=4∫xF1
∫F2dx
dσ^ν/dy + dσ^ν̄/dy ~ [1+(1−y)²] (q+q̄)
~dσ^μN/dy
dσ^ν/dy − dσ^ν̄/dy ~ [1−(1−y)²] (q−q̄)
∫xF3dx
2q̄
∫F2
∫xF3 dx
0.2
0.4
0.6
0.8
1.0
y →

② flavour decomposition of the nucleon

determine: $q_L(x)$

$xu_v(x)$, $xd_v(x)$, $xs(x)$, $xc(x)$

$x\bar{d}(x)$, $x\bar{u}(x)$

mainly neutrino since sea and valence must be separated!

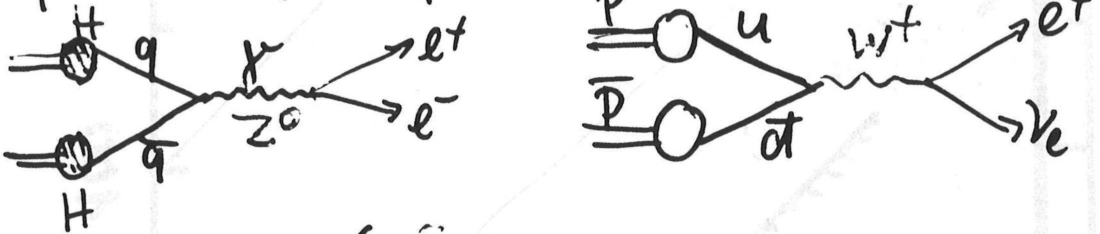
+ gluon-distribution $xG(x)$ ← no direct access apart from

$$\int_0^1 xG(x)dx = 1 - \int_0^1 F_2(x)dx$$

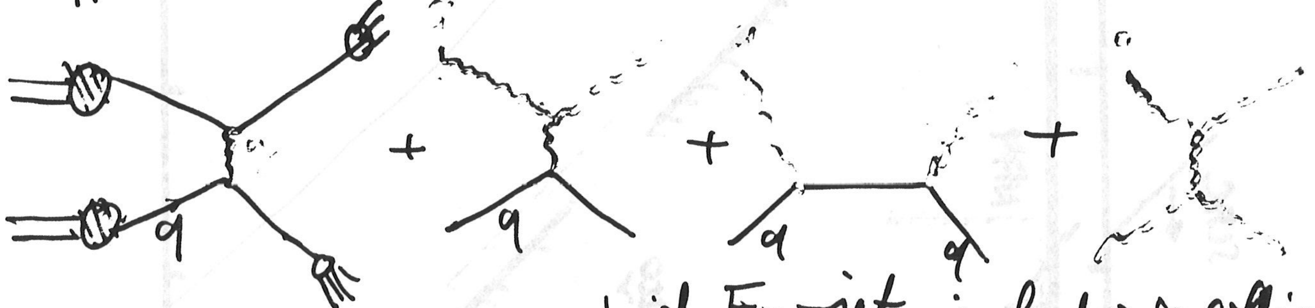
---

why do we want parton distributions?

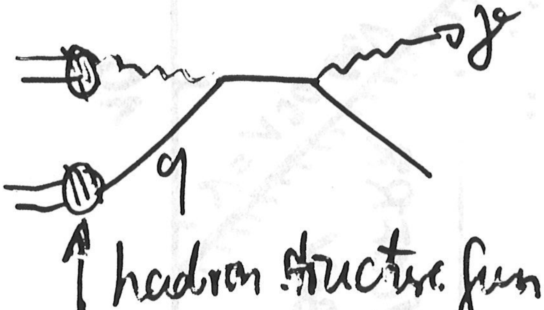
phenomenological input for all hard scattering processes / QCD-phenomenology:



} Drell-Yan



high E_T-jets in hadronic collisions



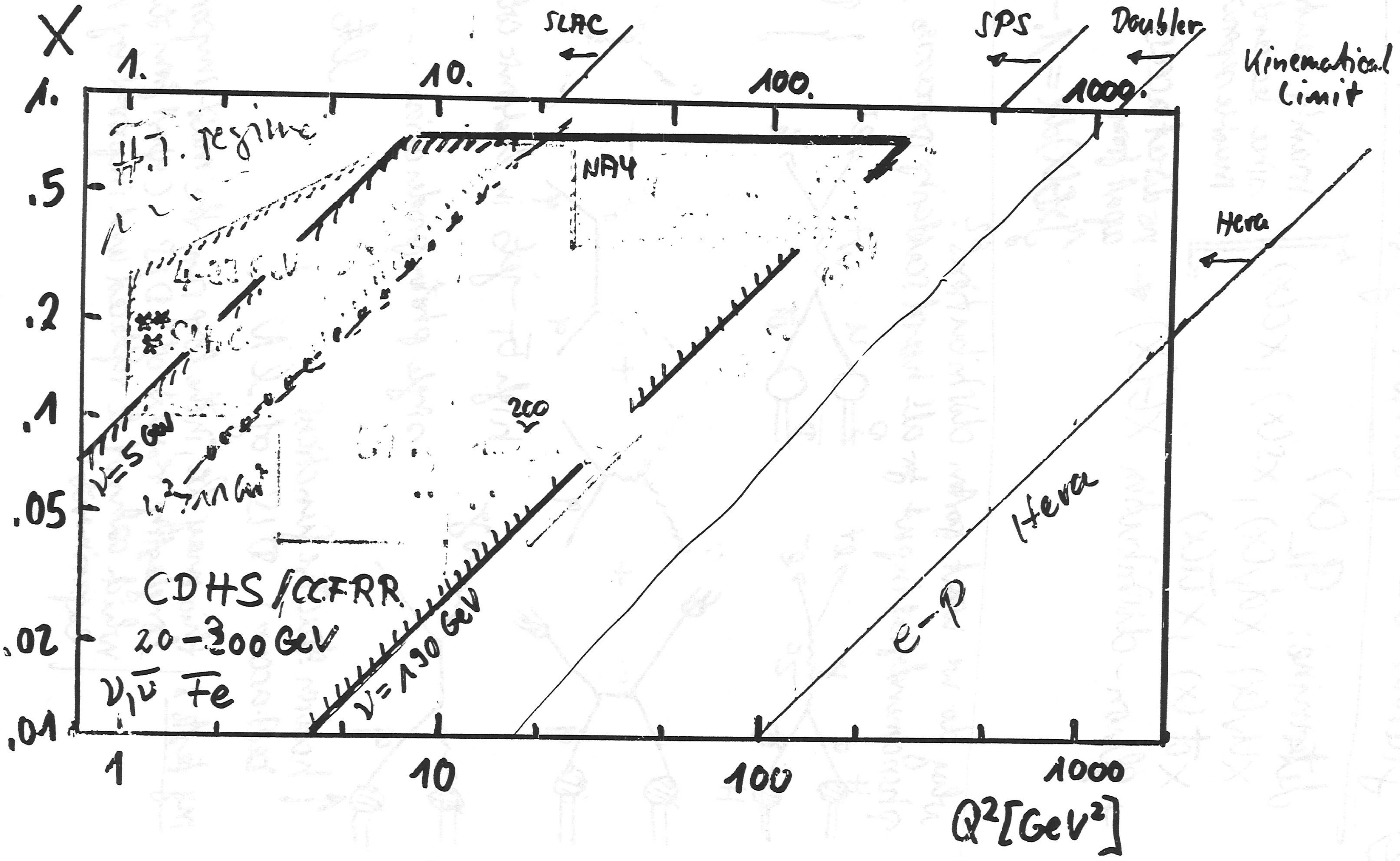
single photon production ...

etc.

↑ hadron structure functions
best access: DIS of lN!

my taste: | this may be, in the long run the most important longlasting result of DIS (apart from the discoveries) which cannot be replaced and improved by new experiments!

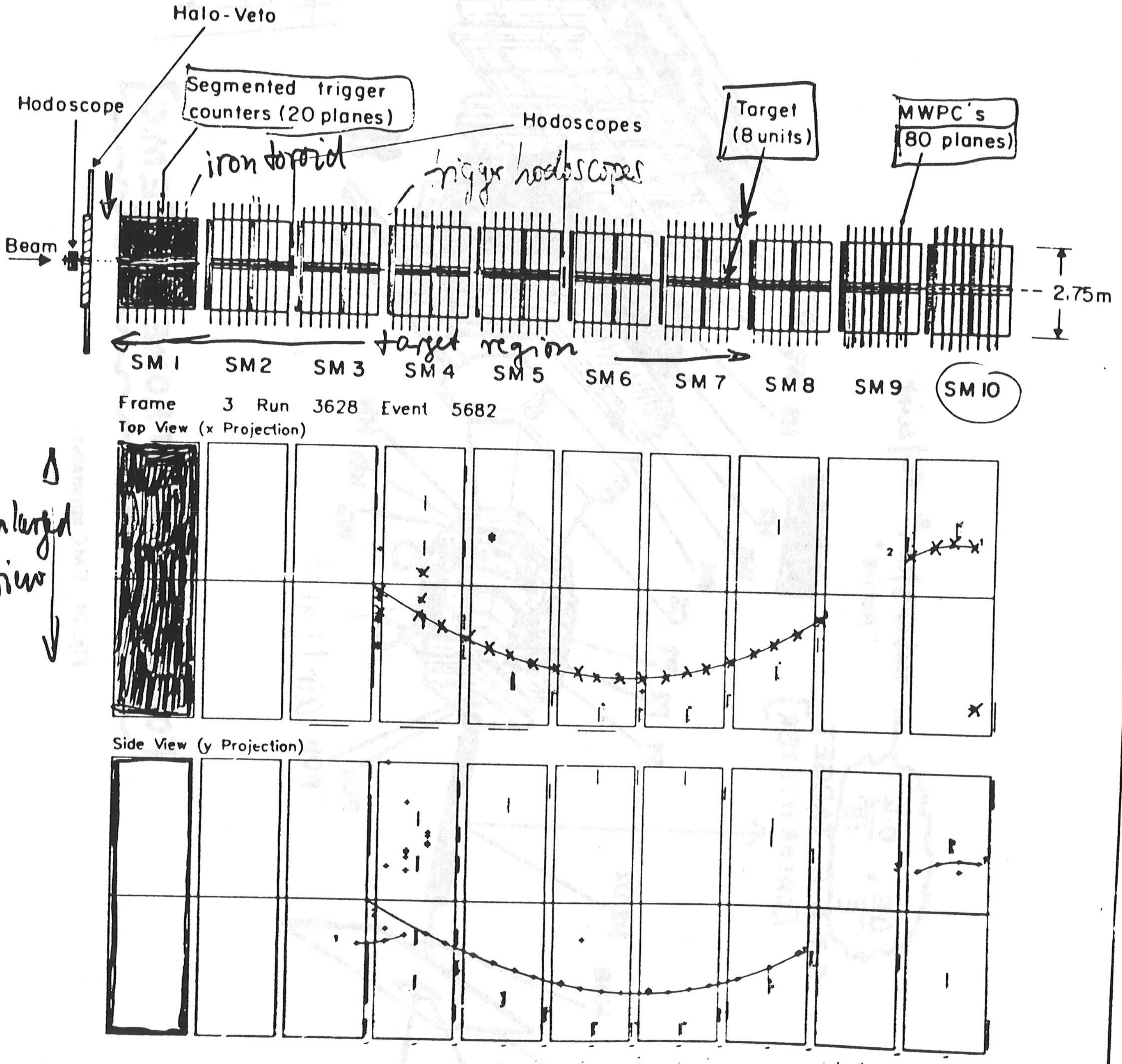
I.1 : DIS : Expriments



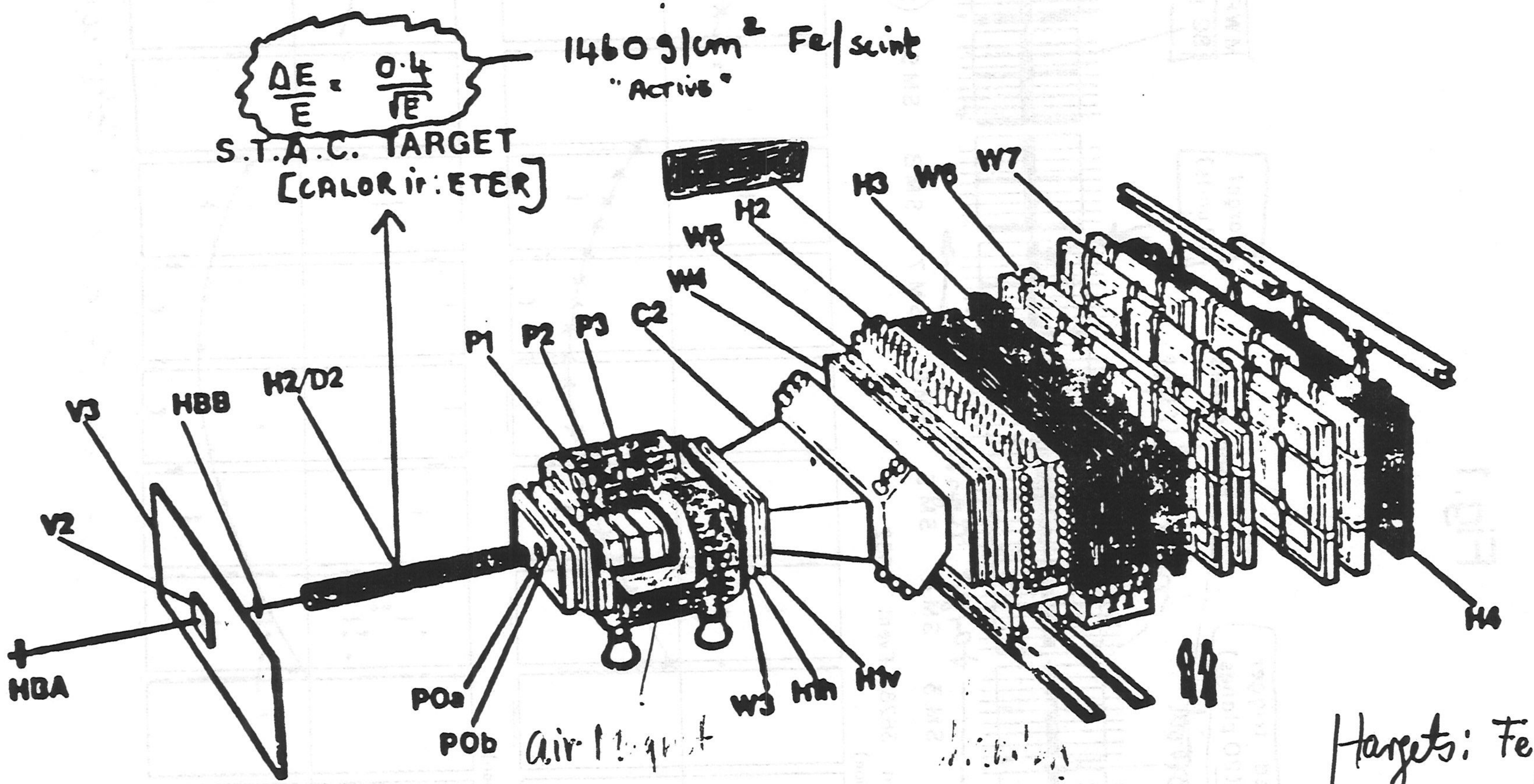
BCDMS (NA4)

(mainly heavy targets: C^{12})

Fig. 1



[illegible] hodoscopes



FORWARD SPECTROMETER [E.M.C]

Fig. 29 EMC apparatus.

Targets: Fe $\boxed{H_2, D_2}$
forward particle identification,
muon spectrometer

Strategy for flavour separation

0) fix normalisation, $\sigma^{\bar\nu}/\sigma^{\nu}$ ✓

1) measure $xF_3(x,Q^2) = \boxed{x(u_v + d_v)}$ (no problem)

2) measure $\boxed{q_L(x,Q^2)}$ equiv. to $R = \sigma_L/\sigma_T$

→ no further progress without or smaller assumptions

3.) check consistency of data by measuring $F_2(x,Q^2)$

$$F_2^{\mu n} + \frac{6}{5}(s-c) = \frac{8}{15} F_2^{\nu N}$$

correction for strange sea suppression [illegible]

4.) measure strange sea and threshold suppression $\boxed{xs(x,Q^2)}$ (dimuon events, CDHS 82)

5.) measure $\bar q^{\bar\nu}(x,Q^2) = x(\bar u + \bar d + 2\bar s)$

6.) estimate of $xc(x)$ $\Rightarrow x(\bar u + \bar d)$

isoscalar target (Fe, marble) (good statistics)

7.) measure $d(x)/u(x)$ (large x)

$F_2^{\mu p}/F_2^{\mu n}$

$\left.\begin{matrix} \nu p, & \nu n \\ \bar\nu p, & \bar\nu n \end{matrix}\right\}$ all can be done in $(\nu,\bar\nu)$ D_2 exposure

$$\boxed{\begin{matrix} x\,u_v(x),\ x\,d_v(x) \\ x(\bar u + 3/4\,\bar s) \\ x(\bar d + 3/4\,\bar s) \end{matrix}}$$

H_2, D_2 targets

---

⑧ Synthesis: combine data from isoscalar targets and free nucleon targets ?

would give: Q^2-dependence
much better accuracy

Experimental results:

① total cross-section for neutrinos

$$\sigma^{\nu}_{TOT} \simeq \frac{G^2 M E_\nu}{\pi}\left[Q + \frac{1}{3}\bar{Q}\right] \qquad ; Q = \int_0^1 q(x)\,dx$$

$$\sigma^{\bar{\nu}}_{TOT} \simeq \frac{G^2 M E_\nu}{\pi}\left[\bar{Q} + \frac{1}{3}Q\right]$$

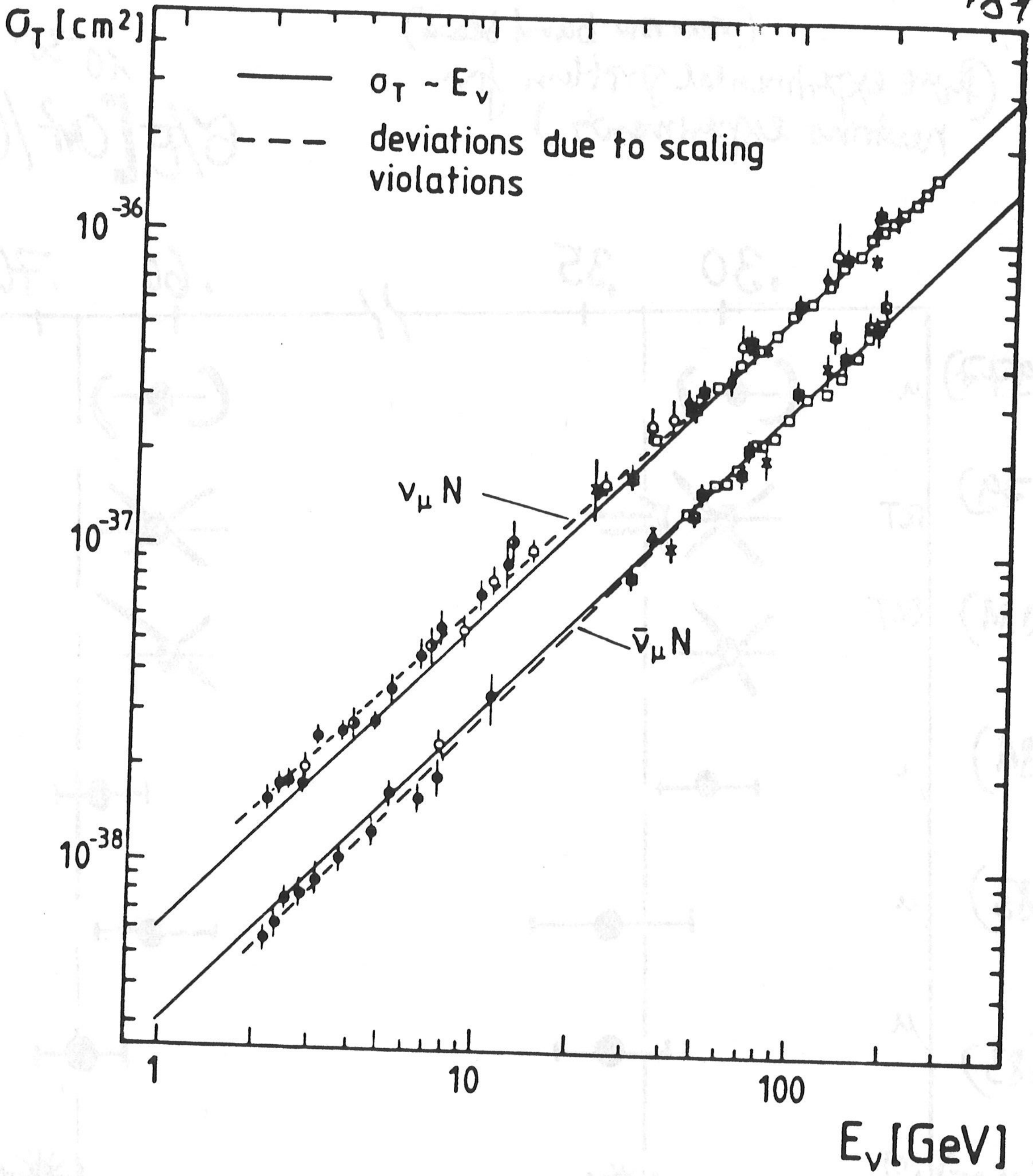
a) linear rise predicted for $Q^2 \ll m_W^2$ and **Q** independent of Q^2 (scaling)

b) momentum fractions of quarks + antiquarks

$$\boxed{\begin{aligned} (Q+\bar{Q}) &= \int_0^1 F_2\,dx = .476 \pm .015 \\ Q_V &\simeq \int_0^1 xF_3\,dx = .332 \pm .010 \\ \bar{Q} &\simeq \int_0^1 \bar{q}(x)\,dx = .072 \pm .010 \end{aligned}}$$

$\langle \nu \rangle = 50\,GeV$

sets scale for gluon momentum fraction!!



5,t

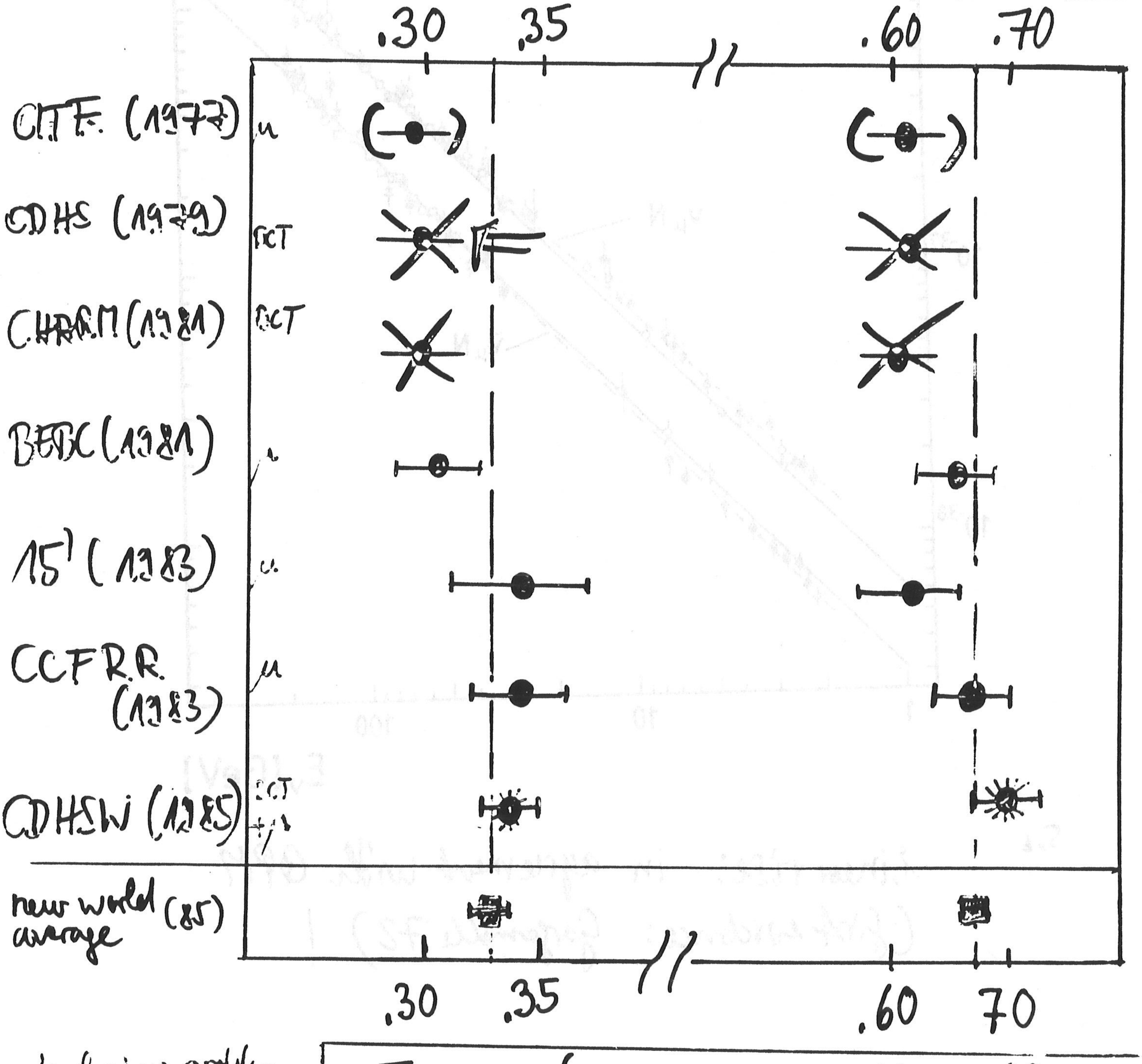
linear rise: in agreement with QPM (first evidence: Gargamelle 72) !

Neutrino + Antineutrino Cross sections

(narrow band beam)

(Severe experimental problem for neutrino experiments)

10^{-38} $\sigma/E\,[\mathrm{cm}^2/\mathrm{GeV}]$



longstanding problem is settled (my opinion)

$$\sigma^{\bar{\nu}}/E_\nu \simeq .326 \pm .008 \qquad \sigma^{\nu}/E_\nu = .680 \pm .014$$

$$r = \sigma^{\bar{\nu}}/\sigma^{\nu} = .480 \pm .009$$

[illegible] in BCT – [illegible]

Ⓐ valence quark distributions on isoscalar targets $x(u_v+d_v)$

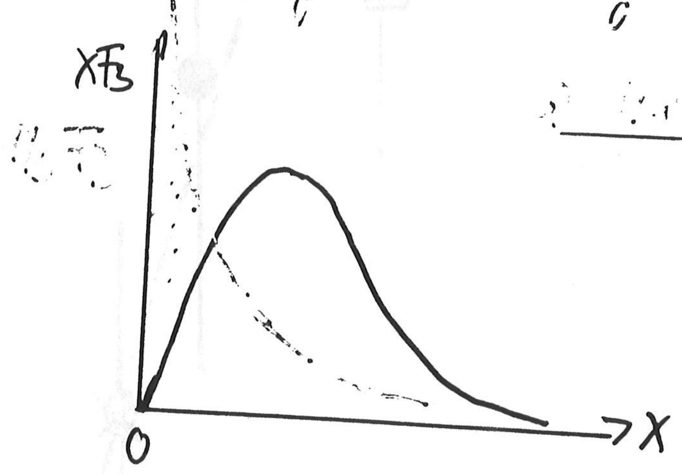
⇒ unaffected by R and sea corrections!
<u>but</u> normalisation!

- good agreement between experiments for same normalisation

$$\boxed{\int_0^1 xF_3\,dx = \int_0^1 x(u_v+d_v)\,dx = .337 \pm .010}$$

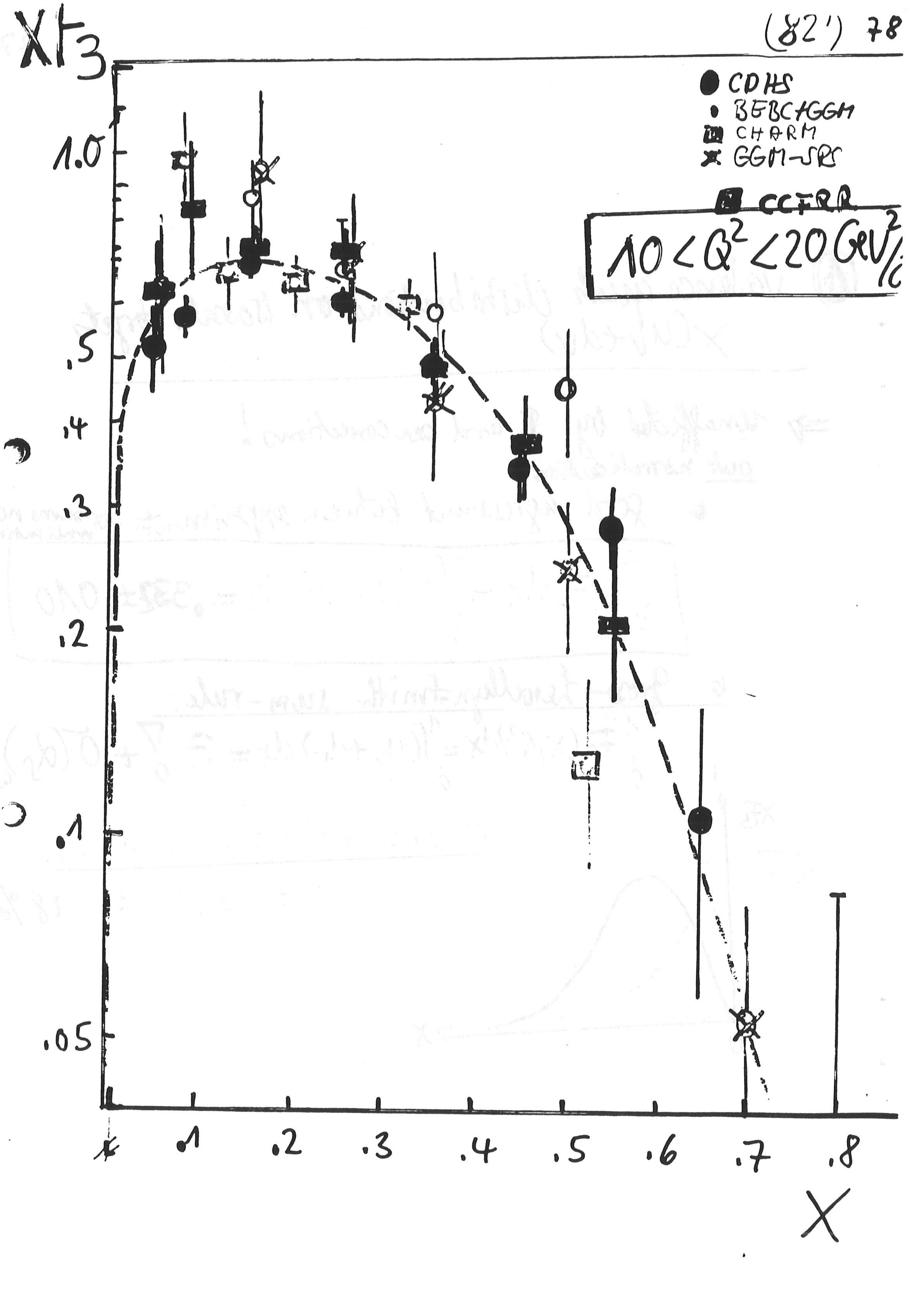
- Gross–Llewellyn-Smith sum-rule:

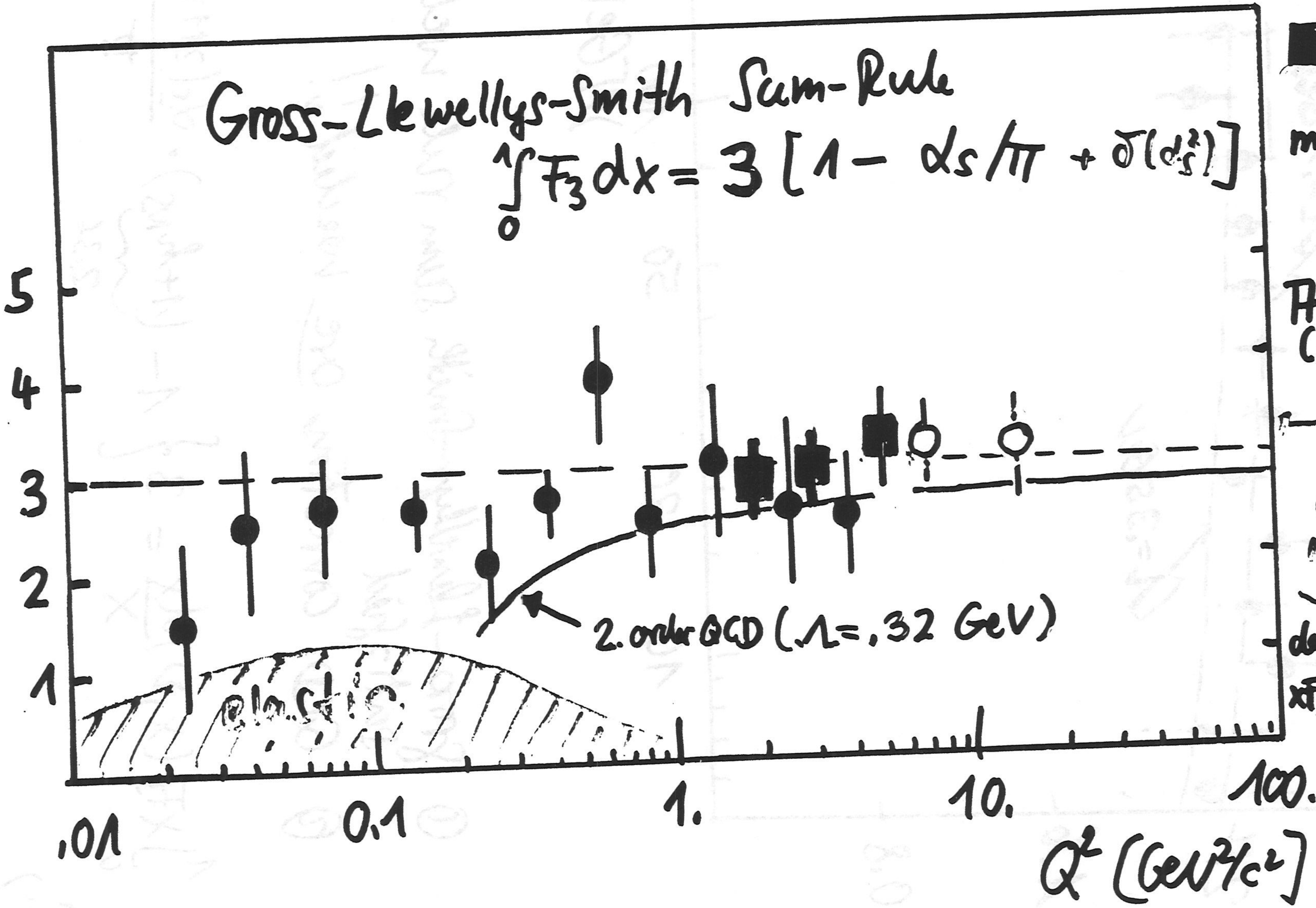
$$\int_0^1 F_3(x,Q^2)\,dx = \int_0^1 (u_v+d_v)\,dx = 3 + O(\alpha_s)_{corr.}$$



[illegible]

[illegible] : 18%!!


xF3
● CDHS
• BEBC+GGM
▣ CHARM
✻ GGM-SPS
■ CCFRR
10 < Q² < 20 GeV²/c
1.0
.5
.4
.3
.2
.1
.05
.1
.2
.3
.4
.5
.6
.7
.8
X



Gross-Llewellys-Smith Sum-Rule

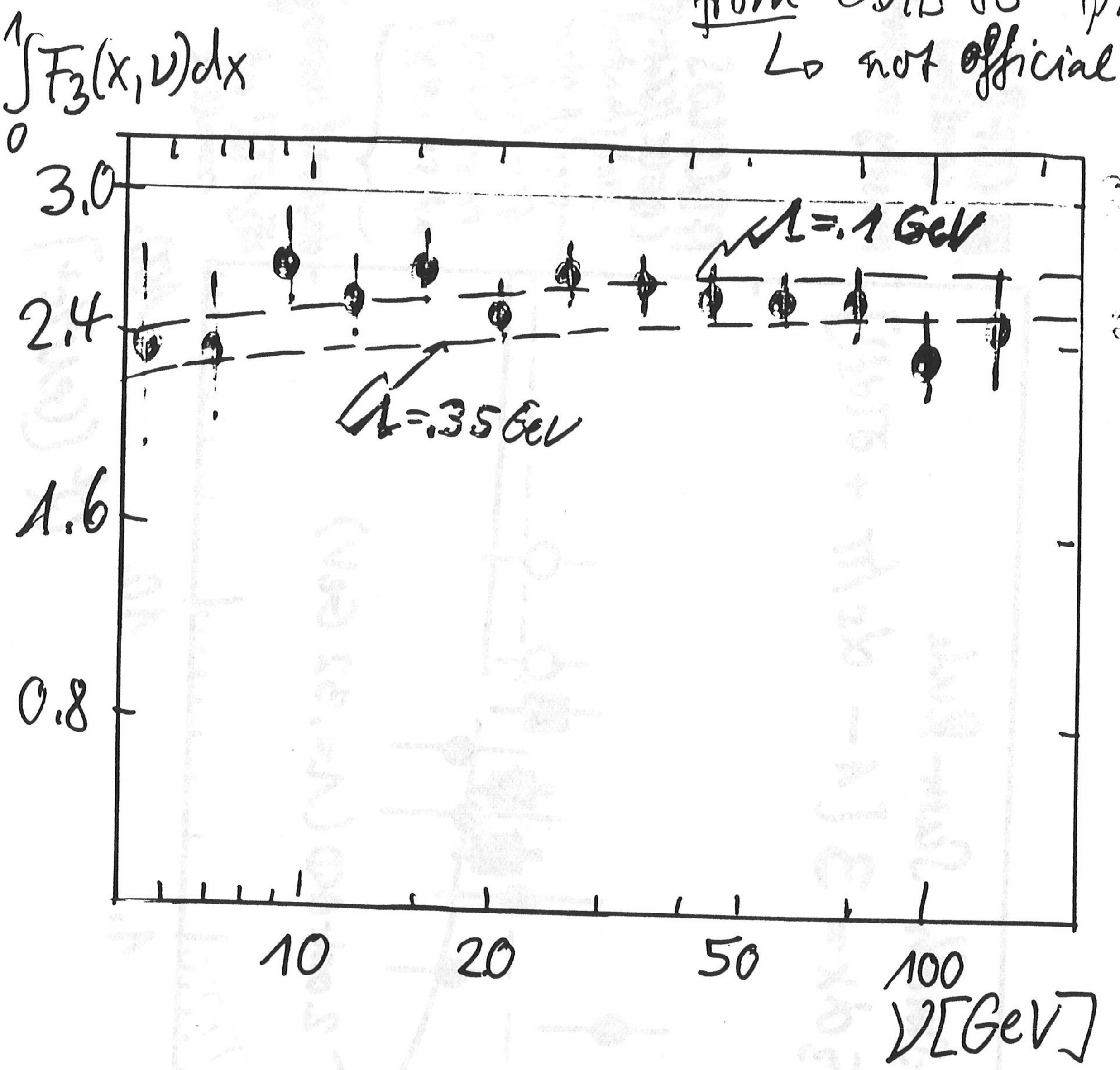
$$\int_0^1 F_3\,dx = 3\,[1 - \alpha_s/\pi + \mathcal{O}(\alpha_s^2)]$$

■ CCFRR
(prelim)
mostly measured

ABCDLOS
(BEBC/GGM-PS)
substantial
model dependent
corrections
at small x!

derived assuming
$xF_3 \sim \sqrt{x}$ at
small x

from CDHS 85 prel.
↳ not official



① Gross–Llewellyn-Smith sum rule well satisfied

② QCD corrections are needed!!

$$\int_0^1 xF_3(x,\nu)\frac{dx}{x} = 3\left\{1-\underbrace{(1+h_{NS})}_{2.36}\cdot\frac{\alpha_s(2M\nu)}{\pi}\right\}$$

(Yndurain et.al.)

② measurement of $F_L(x,Q^2)$ or $R = \sigma_L/\sigma_T$

- necessary to obtain $F_2(x,Q^2)$ and $\overline{q}(x,Q^2)$!
- longlasting experimental problem
  (several experiments made strong statements at the proposal level, but had no success)
- there is a genuine QCD-prediction for F_L !

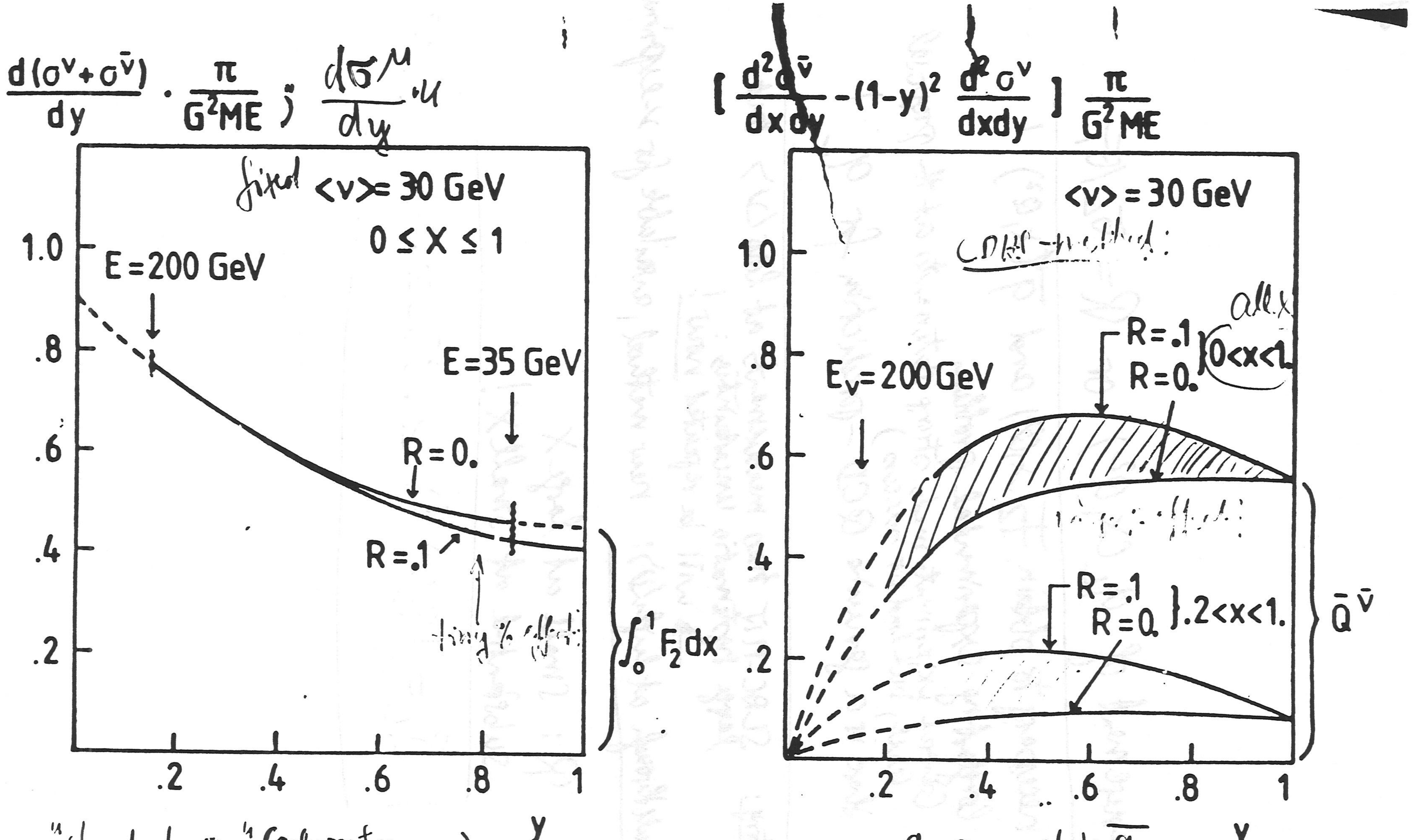
---

history: SLAC-MIT has measurements at low $\langle\nu\rangle$ but large systematic uncertainties:
→ will be repeated now!

breakthrough at high $\langle\nu\rangle$: new method, available for ν-experiment

R: small at large x
substantial at small x!

$$\boxed{S_L = \int_0 \text{[illegible]}}$$



"standard way" (only one term more)
q_L compared to $Q+\bar Q$

q_L compared to $\bar q$

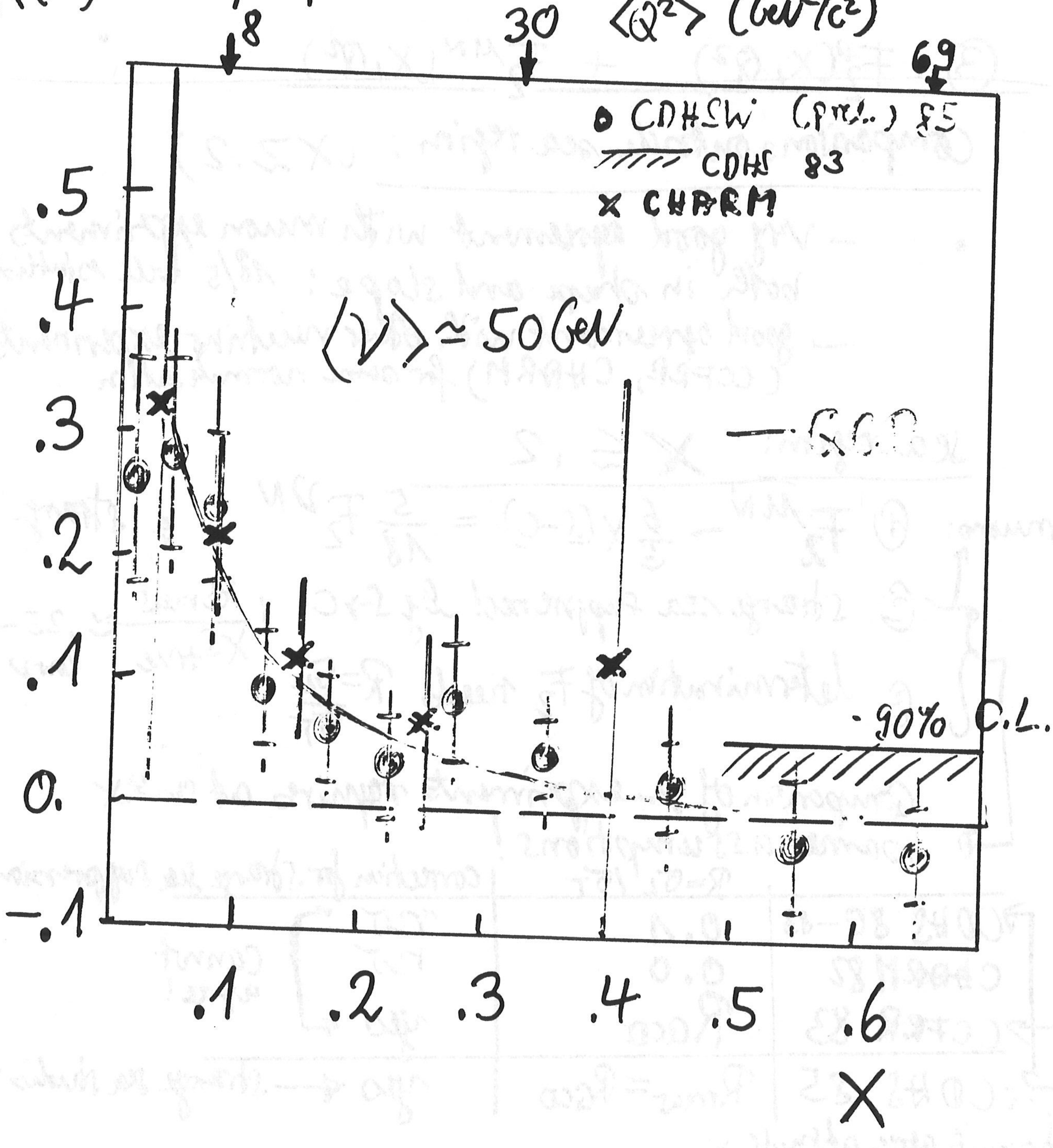
determination of $R = \sigma_L/\sigma_T$

fig 6.2

CDHS 85

WBB: $10^6\ \nu$; $\sim 10^6\ \bar{\nu}$ cont.

$$R(x) = \sigma_L / \sigma_T$$



③ $F_2^{\nu}(x, Q^2)$ + $F_2^{\mu N}(x, Q^2)$

comparison outside sea region: ($x \gtrsim .2$)

- – very good agreement with muon experiments both in shape and slope: 18/5 well established
  – good agreement with other neutrino experiments (CCFRR, CHARM) for same normalisation

sea region: $x \lesssim .2$

muons: ① $F_2^{\mu N} - \frac{6}{5} x(s-c) = \frac{5}{18} F_2^{\nu N}$: strange sea

② strange sea suppressed by $s \to c$; $\frac{xs_{meas}}{xs_{true}} \simeq .25 \to .7$ low ν high ν

③ determination of F_2 needs $R = \frac{\sigma_L}{\sigma_T}$

Comparison of ν-experiments requires at small x same assumptions!

	$R = \sigma_L / \sigma_T$	correction for strange sea suppression
CDHS 80–83	0.1	no
CHARM 82	0.0	no
CCFRR 83	R_{QCD}	yes
CDHS 85	$R_{meas} = R_{QCD}$	yes

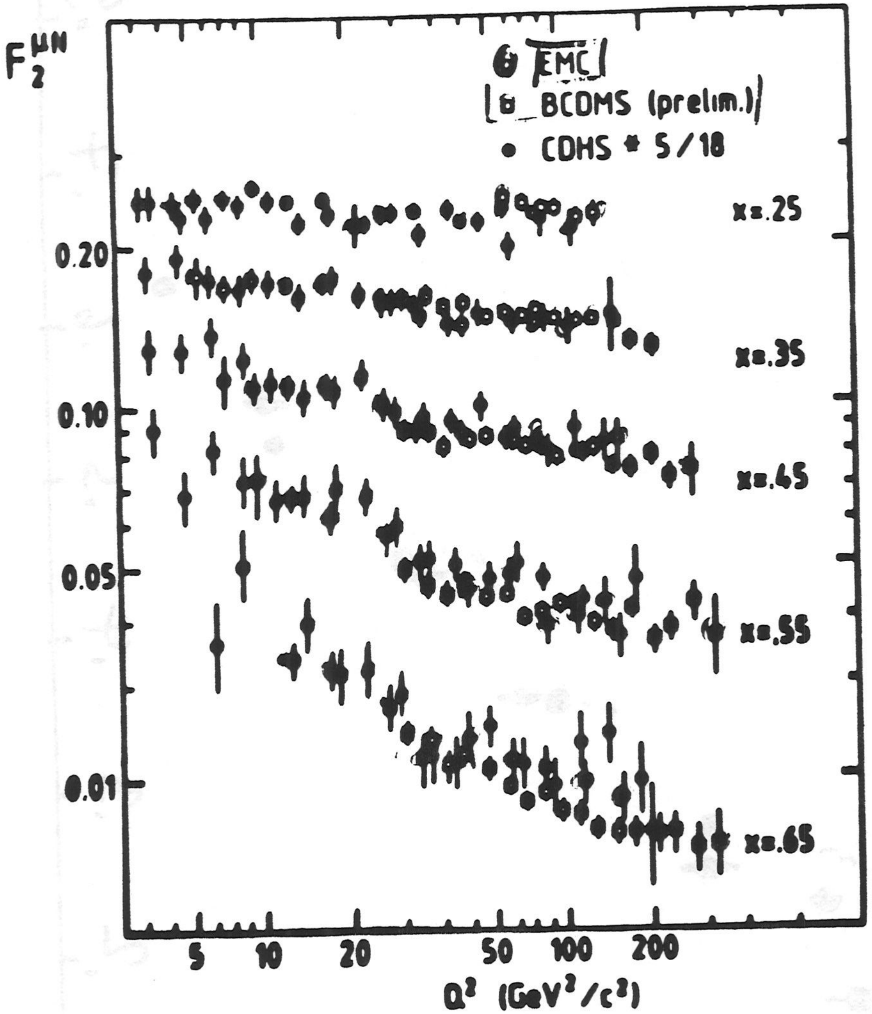
cannot agree!

yes ← strange sea studies are done

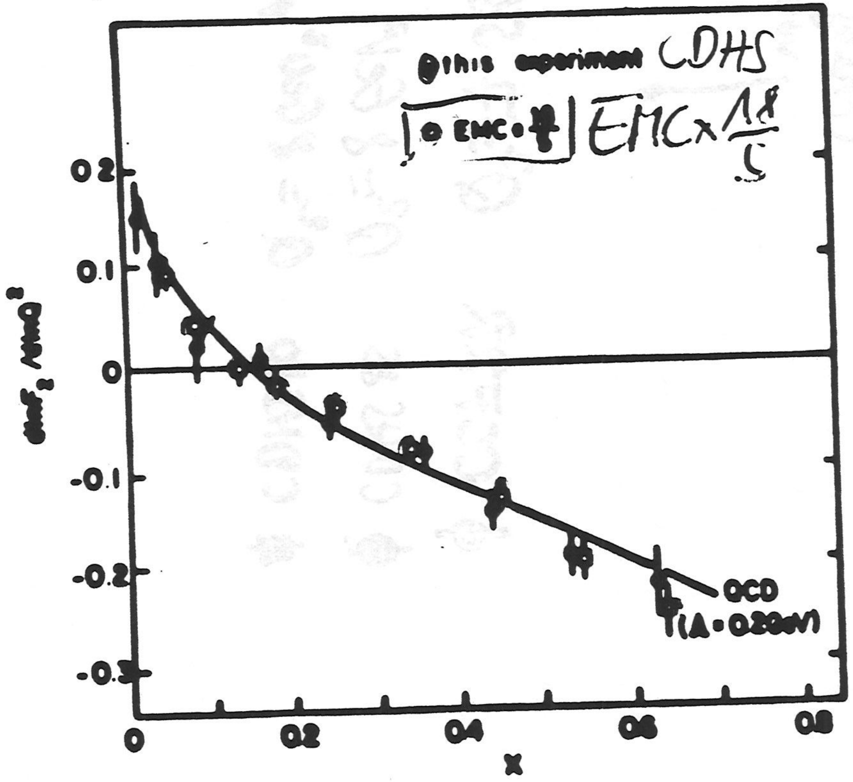
cannot agree at small x

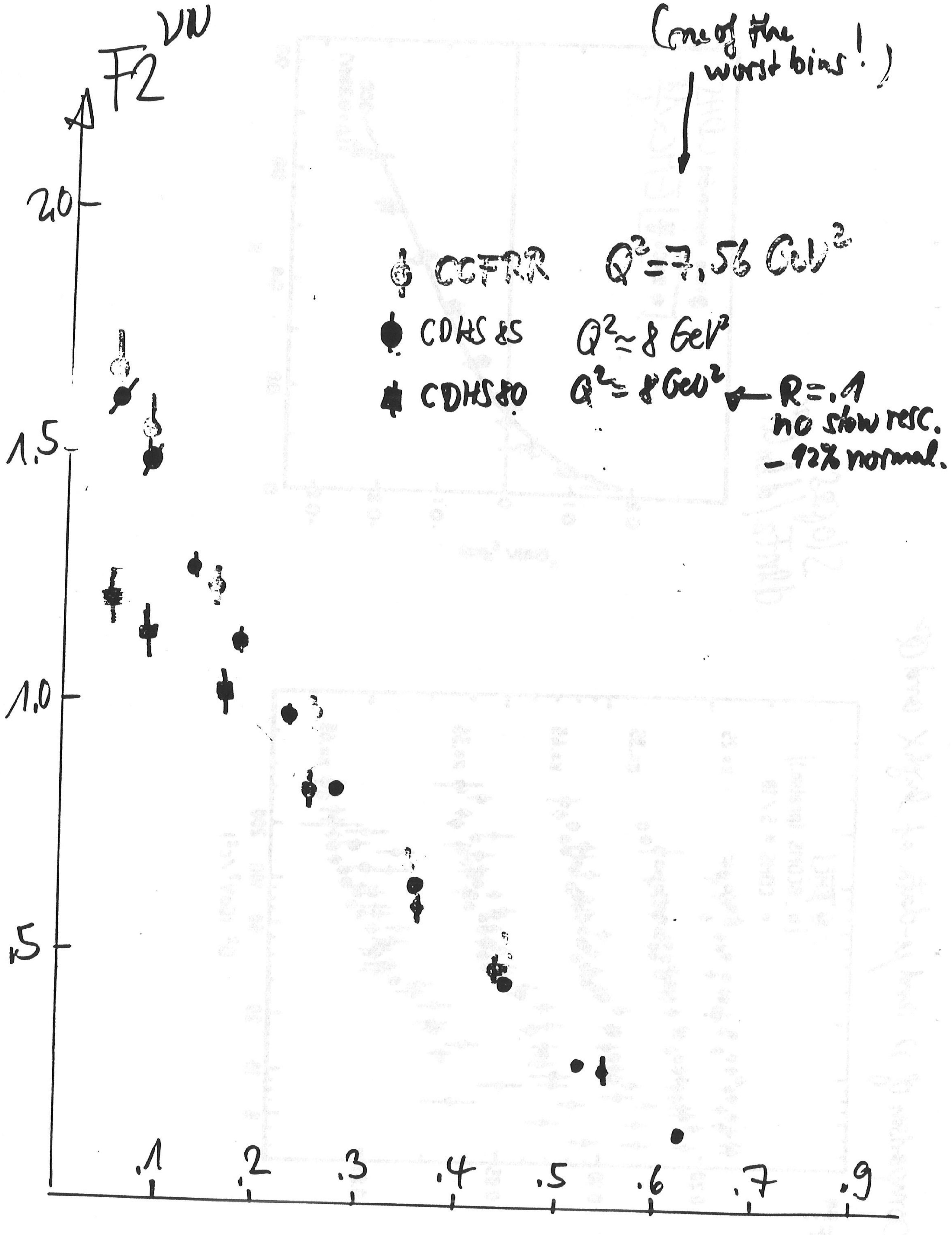
① effects are large
② well known since long time!
} see e.g. Dydak, Cornell '83
F.E. Paris 82

comparison of ν and μ-data at high x and Q^2

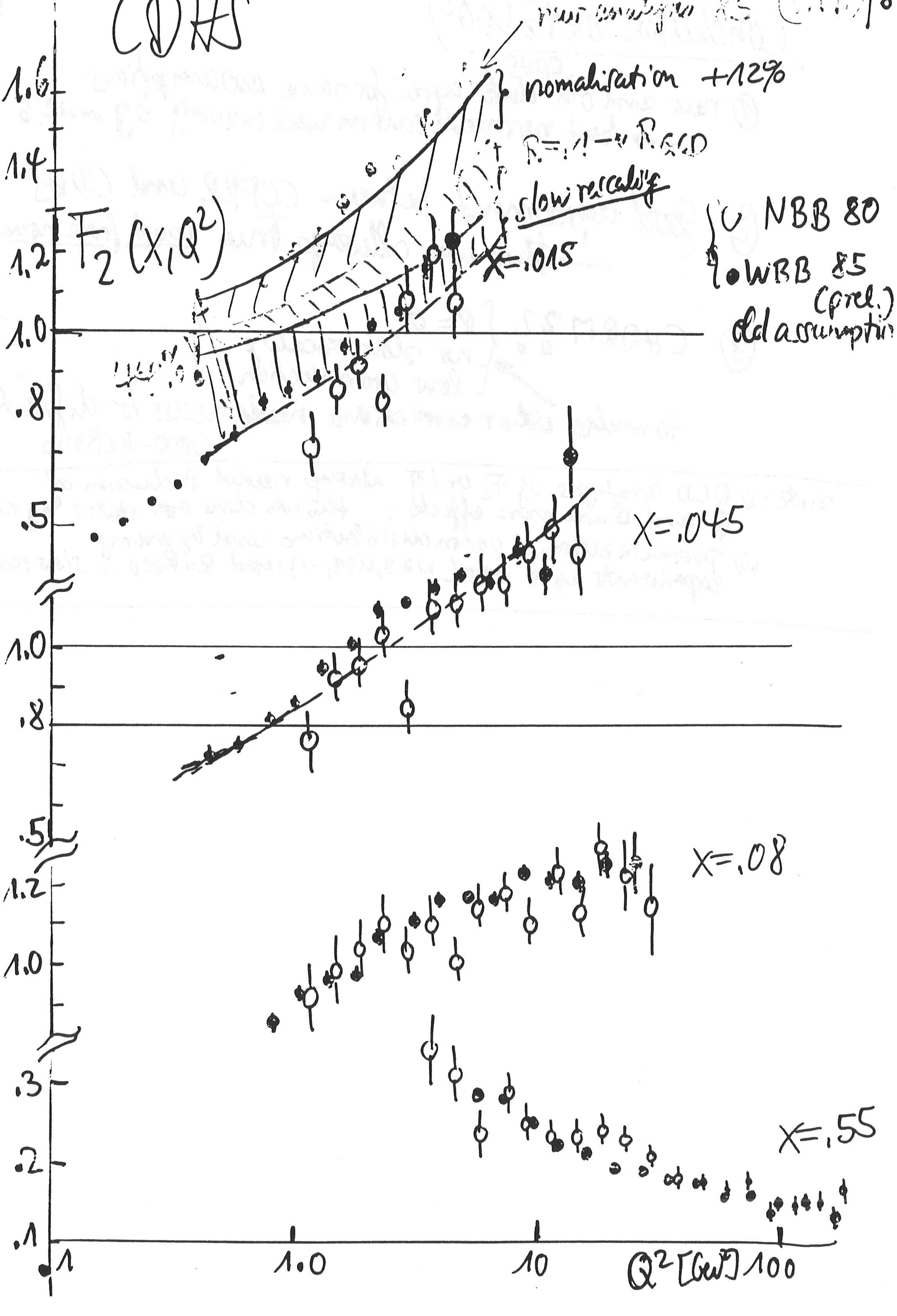


Slopes $d\ln F_2/d\ln Q^2$




F2 νN
2,0
1,5
1,0
,5
.1
.2
.3
.4
.5
.6
.7
.9
CCFRR Q² = 7,56 GeV²
CDHS 85 Q² ≃ 8 GeV²
CDHS 80 Q² ≃ 8 GeV² ← R = .1 no slow resc. − 12% normal.
(one of the worst bins!)

CDHS


new analysis 85 ([illegible])
normalisation +12%
R = .1 → R QCD
slow rescaling
X = .015
○ NBB 80
● WBB 85 (prel.)
old assumption
$F_2(X, Q^2)$
X = .045
X = .08
X = .55
1.6
1.4
1.2
1.0
.8
.5
1.0
.8
.5
1.2
1.0
.3
.2
.1
.1
1.0
10
100
Q^2 [GeV²]

Conclusions on $F_2(x,Q^2)$

① new and old CDHS data agree for same assumptions
→ but normalisation was wrong by ~2%

② Good agreement between CCFRR and CDHS
→ this was allways true apart from normalisation

③ CHARM ?? $\left\{\begin{array}{l} R=0 \\ \text{no slow rescaling} \\ \text{low cross-section} \end{array}\right\}$

to make other corrections needs access to differential cross-sections

---

note: i) QCD analysis of F_2 and q always needed inclusion of R and charm mass effects: this was done and stated by CDHS
ii) parametrisations of parton distributions used by many experiments up to now (NA3, UA1, ...) used $R = R_{QCD}$ & slow rescaling

---

⑤

$$\bar{q}^{\bar{\nu}}(x,Q^2) = x(\bar{u}+\bar{d}+2\bar{s})$$

(83')

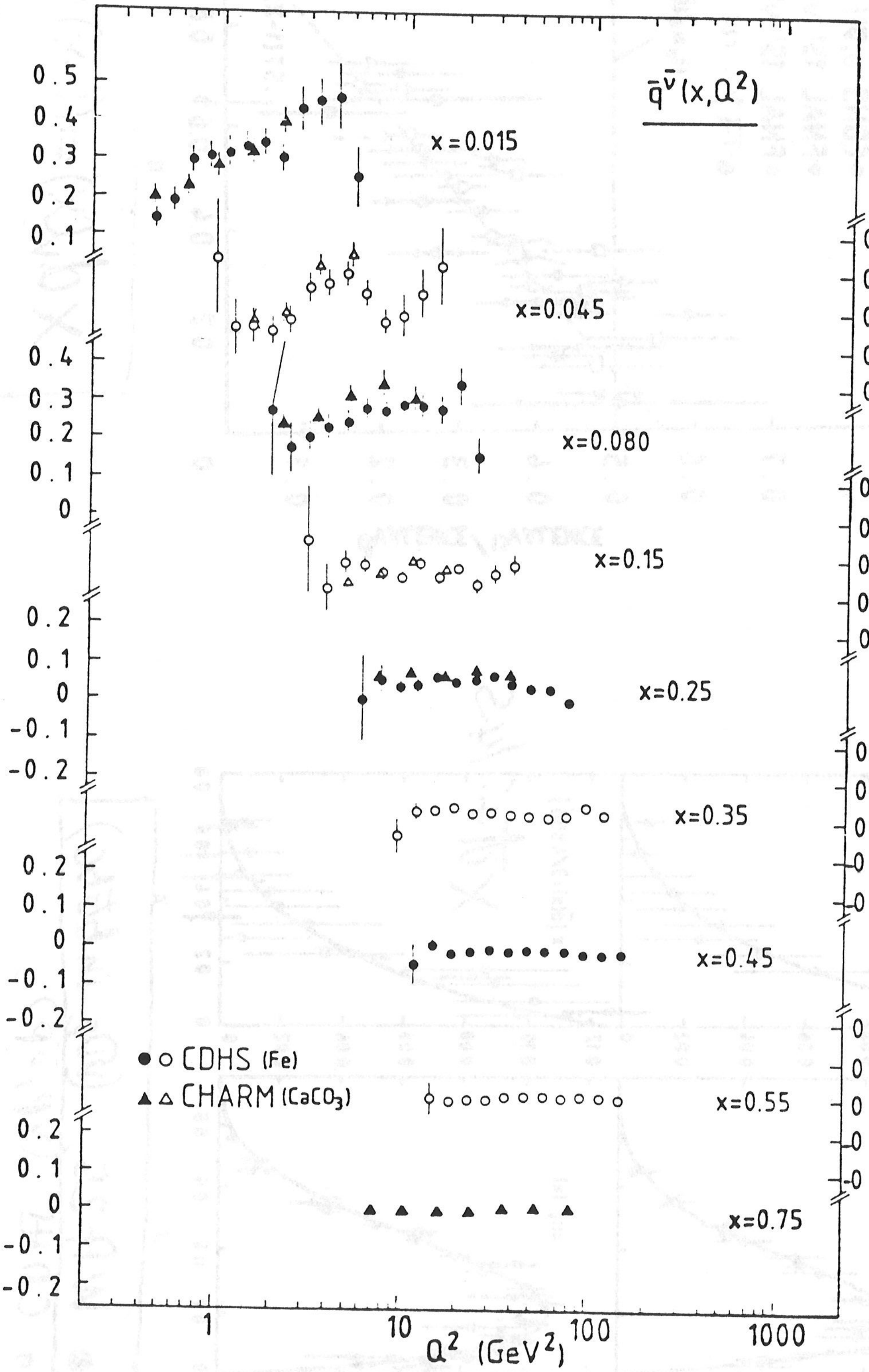
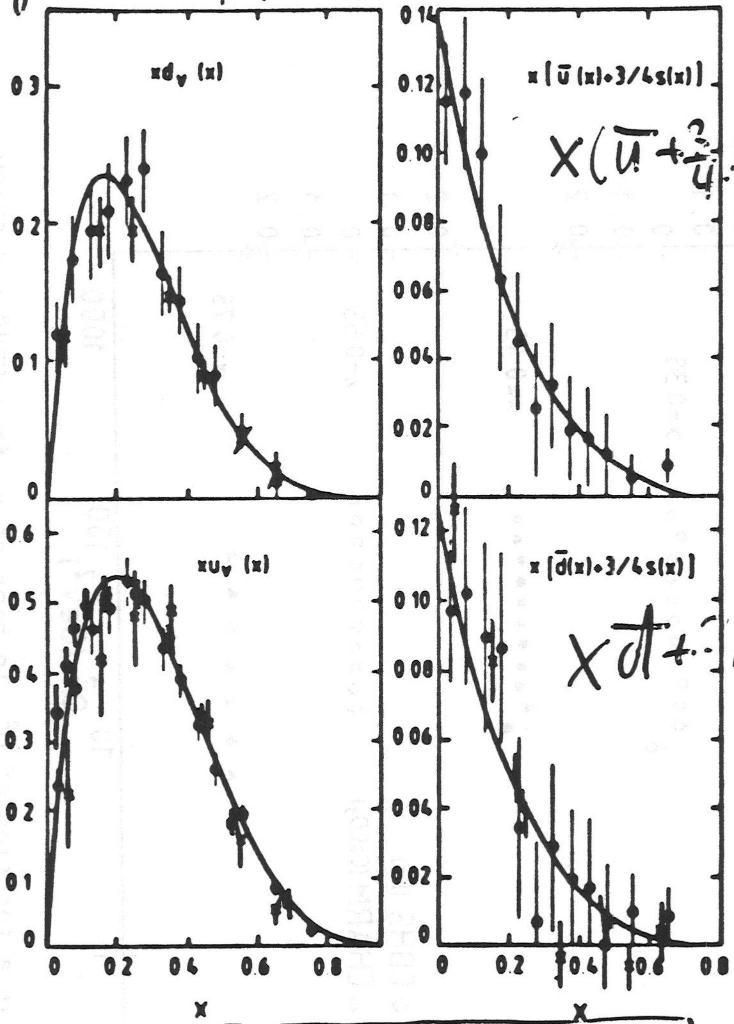


Fig. 15 $\bar{q}^{\bar{\nu}}$ as a function of Q^2, in bins of x, from CDHS and CHARM.

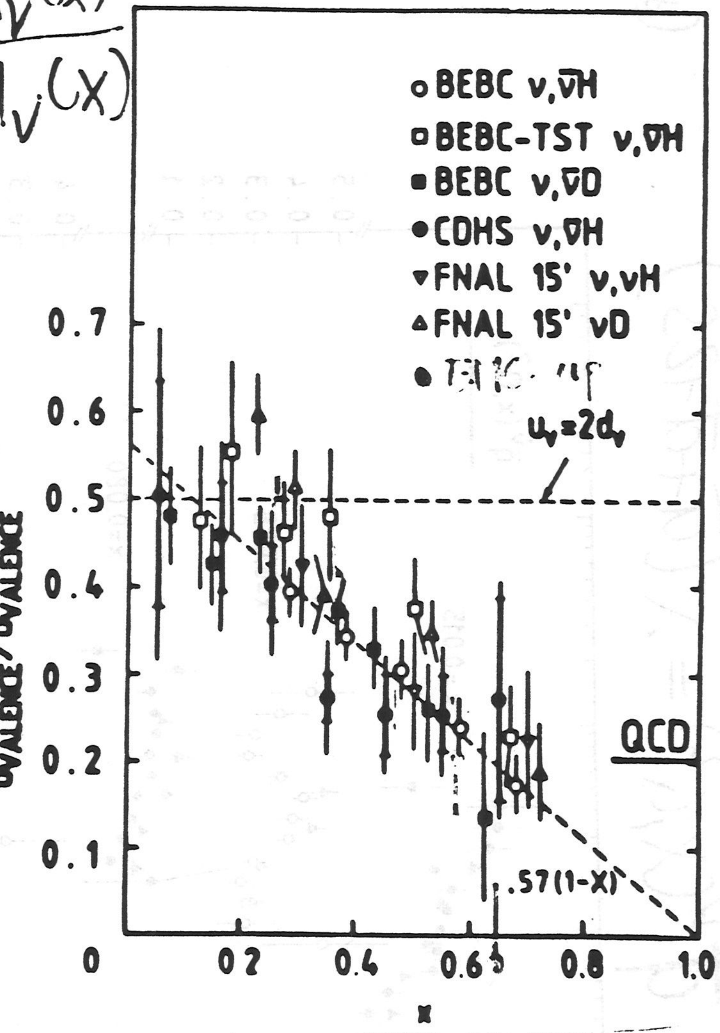
⑦' free quarks in n, p



$x(\bar{u} + \frac{3}{4} s)$

$x\bar{d} + 3/4\, s$

$$\frac{d_v(x)}{u_v(x)}$$



** ● WA 25 ($\bar{\nu}D_2$ in BEBC)

● CDHS (νp, $\bar{\nu} p$)

85 ● EMC prelim. using sea measurement of CDHS

$$\boxed{x d_v(x) \simeq (1-x)\, x\, u_v(x)}\ !$$

up quarks in proton carry higher momenta than down quarks!

antiquarks in free nucleons:

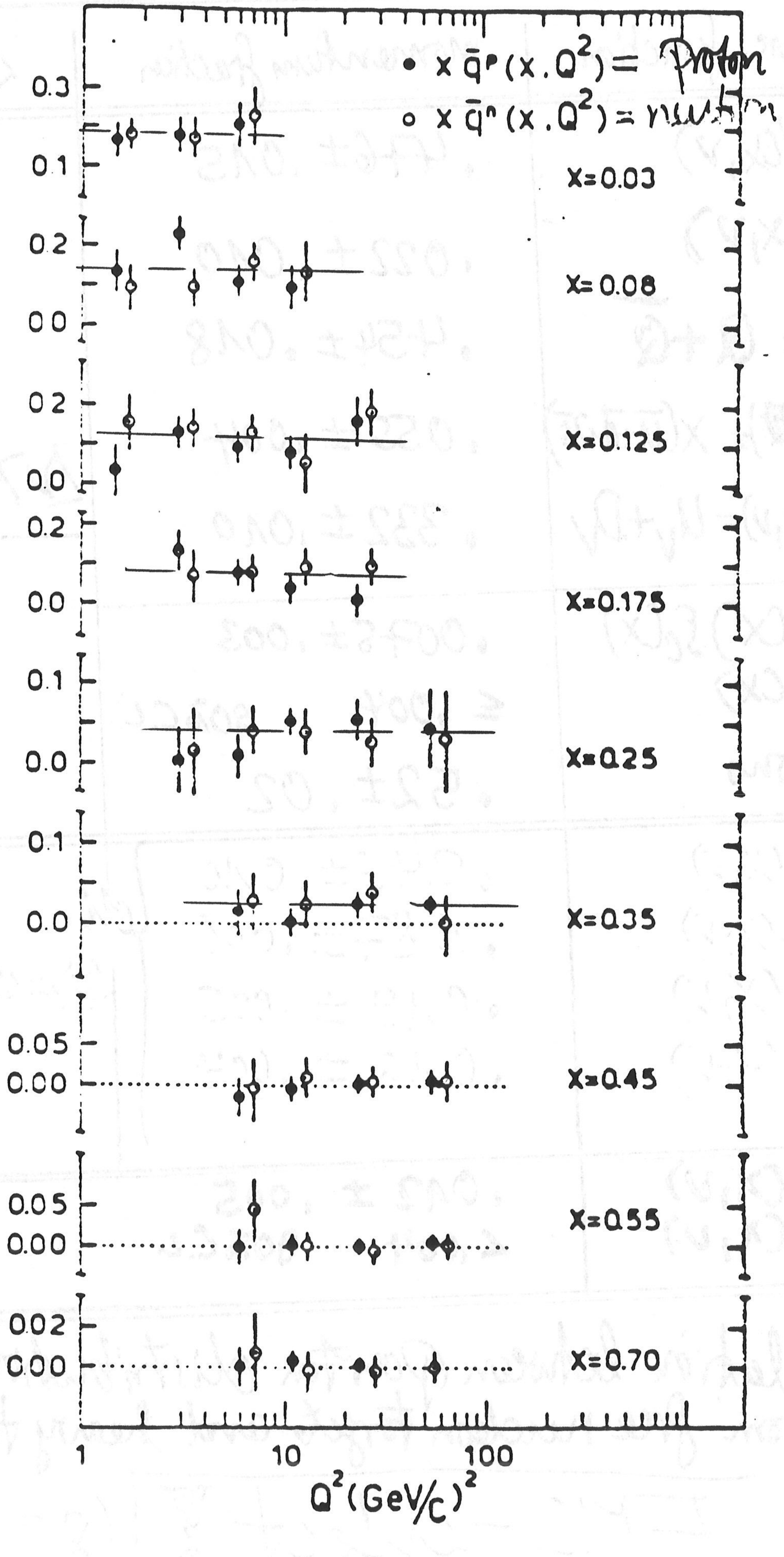


fig 2

WA25

$\left(\frac{\nu}{\nu}\right) D_2$ in BEBC

$\bar{u} = \bar{d}$!!

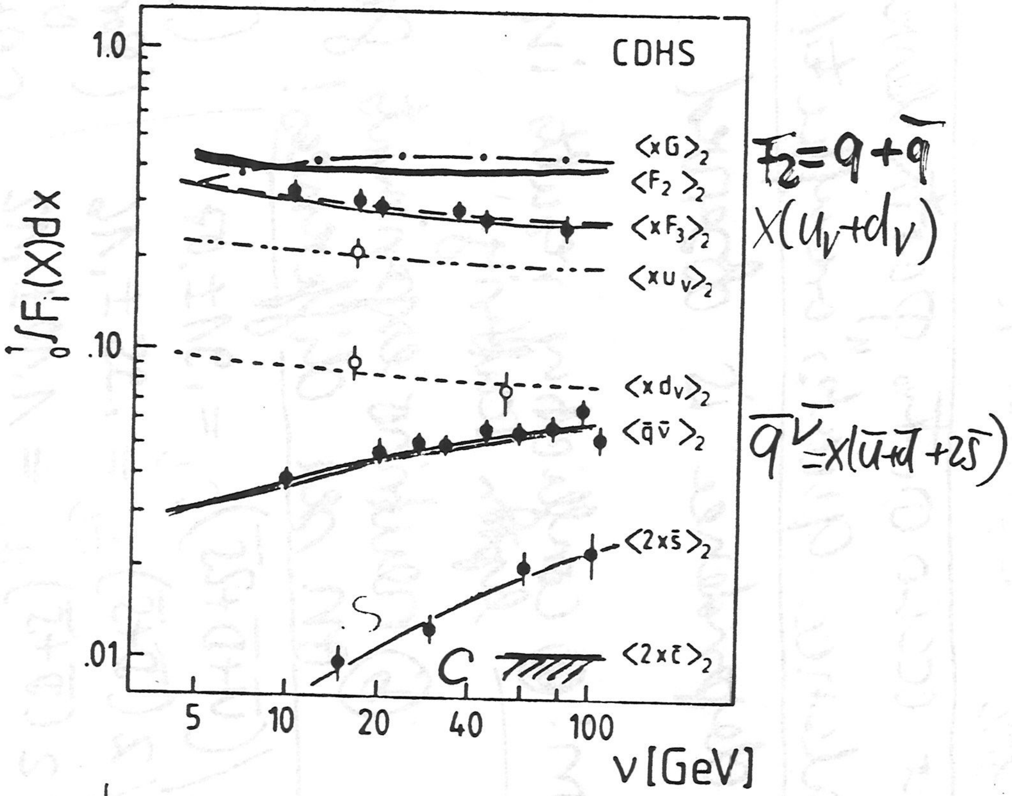
$\bar{U}/\bar{D} = 1.1 \pm .4$

momentum fractions of nucleon constituents* (85)

	structure function	momentum fraction	$\langle\nu\rangle$ *depend $\langle\nu\rangle$
heavy targets	$F_2^{\nu N}(x,\nu)$	.476 ± .015	$\langle\nu\rangle \simeq 50$ GeV
	$q_L(x,\nu)$	.022 ± .010	
	$2xF_1 = Q + \overline{Q}$	.454 ± .018	
	$\overline{q}^{\bar\nu}(x,\nu) = x(\overline{u}+\overline{d}+2\overline{s})$	.055 ± .004	
	$xF_3(x,\nu) = U_V + D_V$	.332 ± .010	
	$x\overline{s}(x)\,\xi_c(x)$	.0075 ± .003	
	$x\,c(x)$	≤ .004 90% C.L.	
	gluons	.52 ± .02	
free nucleon targets	$xu_V(x,\nu)$	.245 ± .010	ok $\langle\nu\rangle \simeq 15$ GeV
	$xd_V(x,\nu)$	.087 ± .004	
	$x\overline{u}(x,\nu)$	.019 ± .005	
	$x\overline{d}(x,\nu)$	.012 ± .004	
iron	$x\underline{S}(x,\nu)$	.042 ± .005	
	$x\overline{C}(x,\nu)$	< .004 90% C.L.	

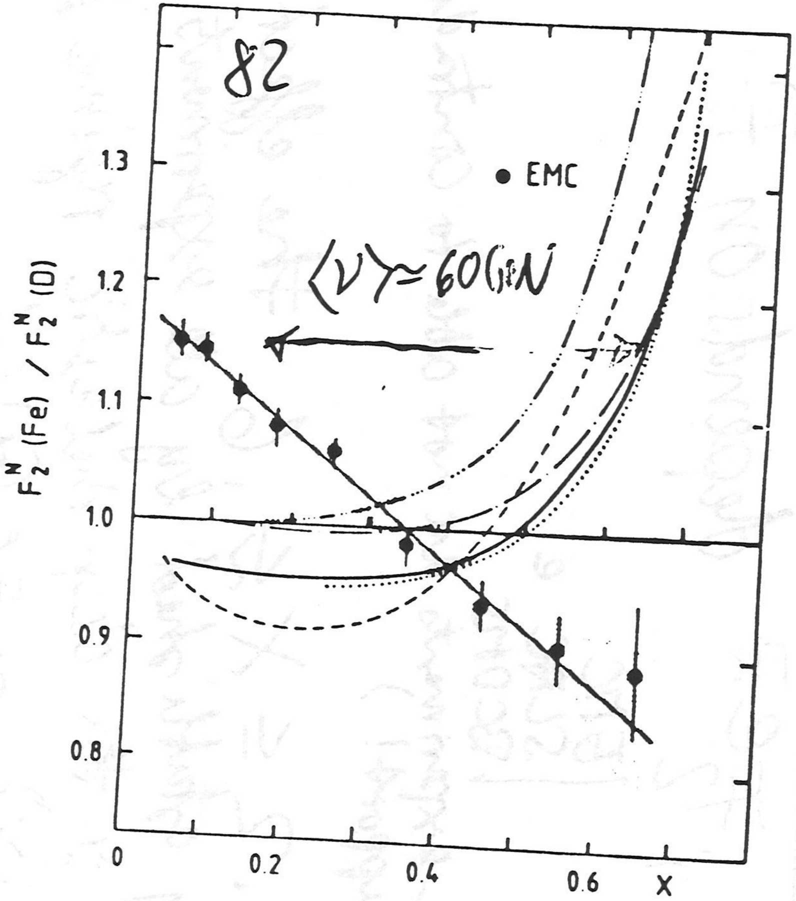
? ? relation between parton distributions from free nucleon targets and heavy targets ??

EMC-effect ! (82)



change of momentum fractions with $\langle \nu \rangle$

EMC-effect



nuclear dependence of parton distributions

<u>note</u>: $\langle \nu \rangle = 60\,\mathrm{GeV}$ is $\overset{\text{well}}{\text{on}}$ the parton scale !!

Some facts about EMC-effect

① $F_2^{\mu A}$, F_2^{eA} depends on A !

| EMC
| SLAC e
| BCDMS

(ν-experiments are not able to contradict or support!)

② for $.2 \leq x \lesssim .6$ the effect is clearly established by all experiments

this is the deep inelastic regime!

$\nu_{BEBC} > 50$ GeV!!

The effect occurs on the parton level !
"valence quarks" are affected! ☺

③ no Q^2-dependence is observed

④ Sea-region: ⓐ conflicting results in charged lepton scattering

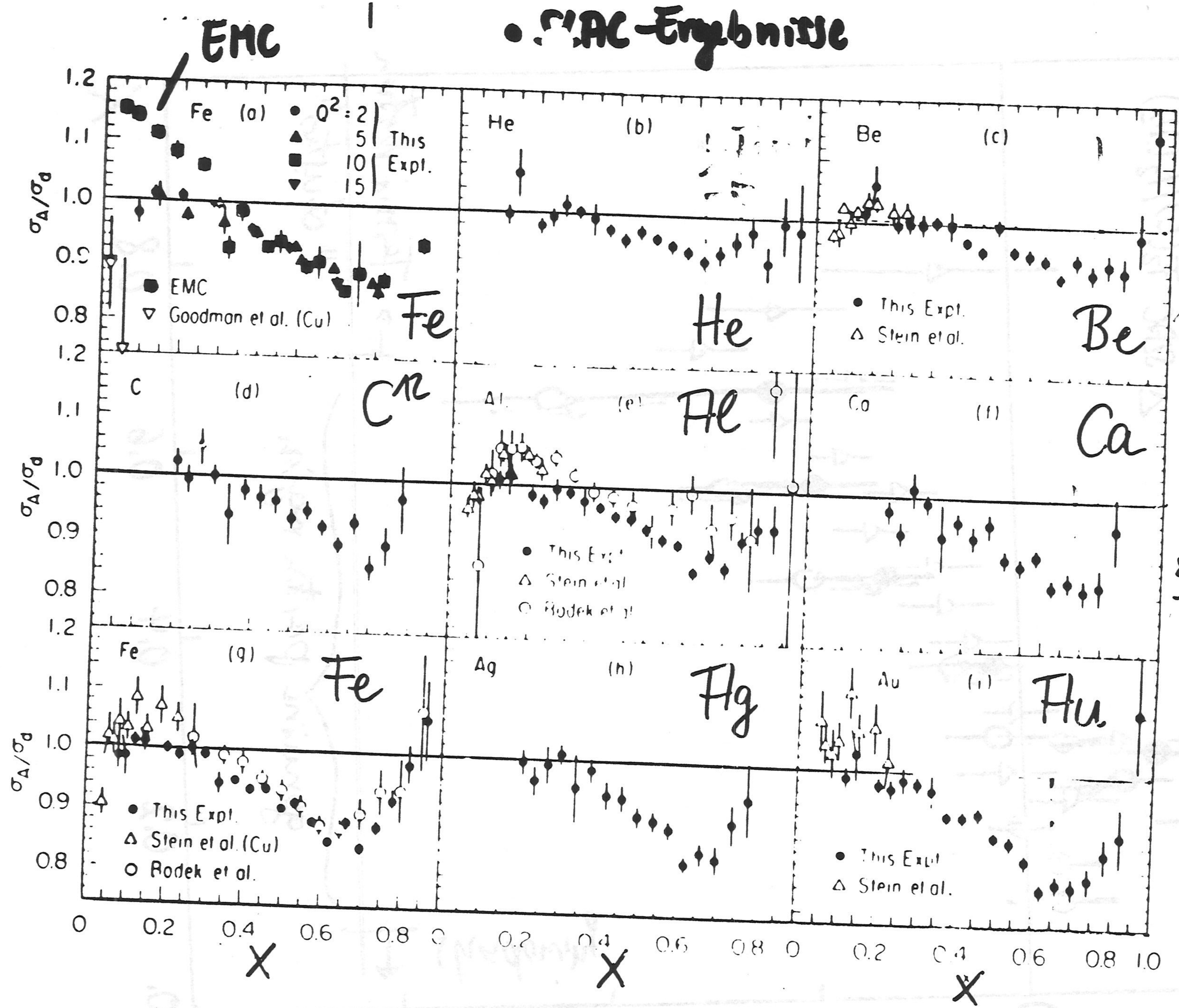
only important contribution of ν-expt! → ⓑ neutrino experiments give limits on sea differences!

$$(\overline{U}+\overline{D}+2\overline{S})_{Ne} / (\overline{U}+\overline{D}+2\overline{S})_{D_2} = .91 \pm .07$$
$$(\overline{U}+\overline{D}+2\overline{S})_{Ne} / 2(\overline{D}+\overline{S})_{H_2} = .95 \pm .16$$
$$(\overline{U}+\overline{D}+2\overline{S})_{Fe} / 2(\overline{D}+\overline{S})_{H_2} = 1.10 \pm .12$$

(Cooper et al. BEBC 84)
(Parker et al. 84 BEBC
CDHS.

no evidence for sea difference!

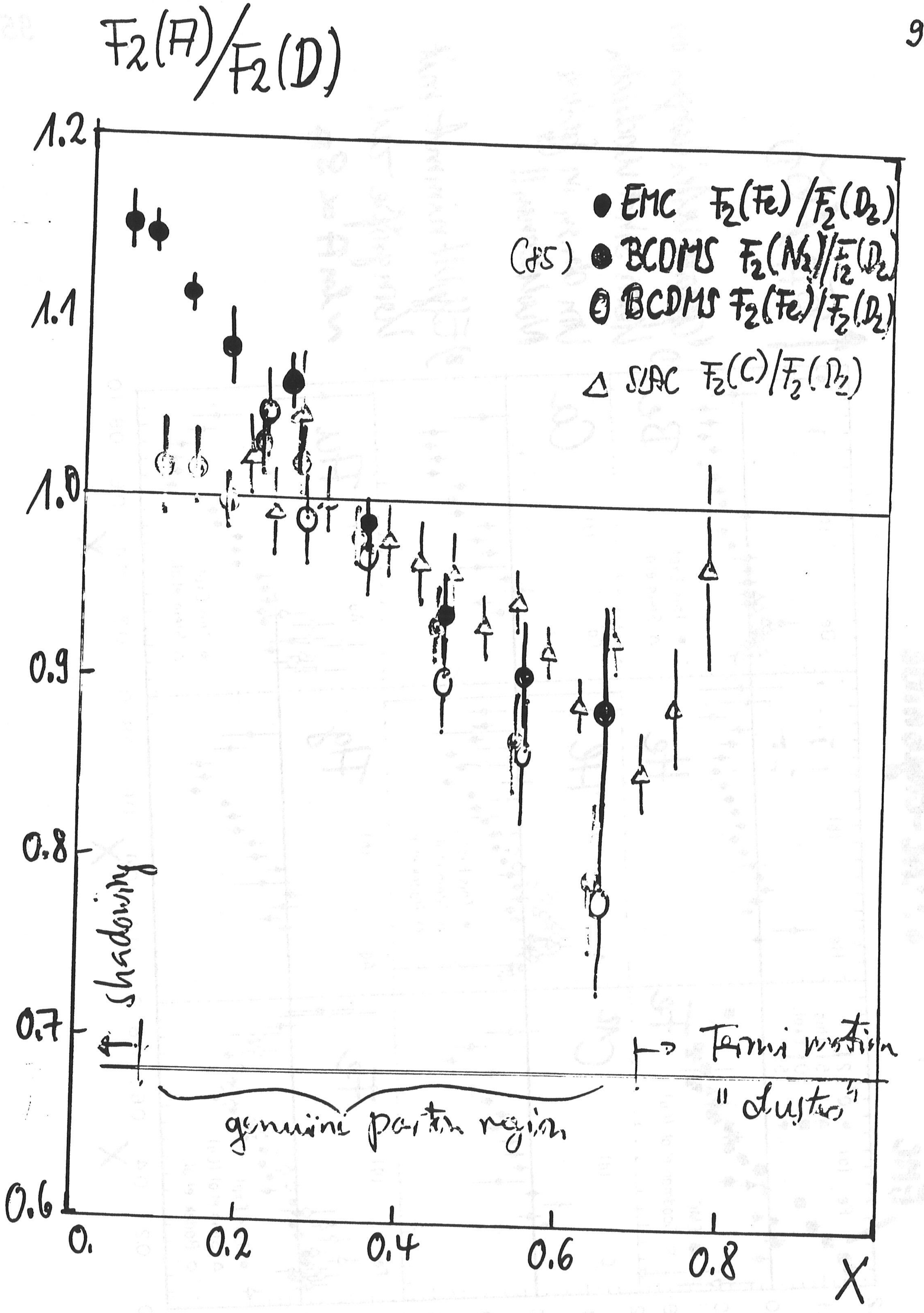
• SLAC-Ergebnisse



↑ σ_A/σ_D

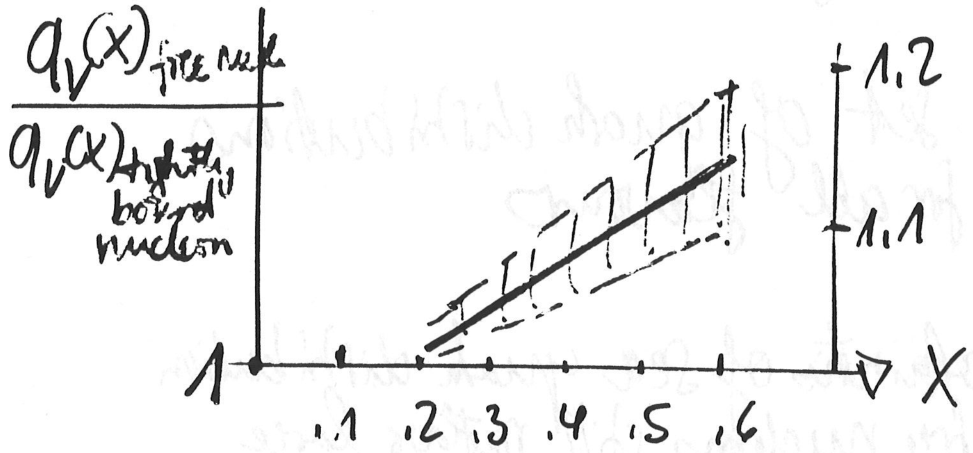
1) "Quarkverteilungen im Kern sind verschieden von denen in freien Nukleonen!!"

2) Effekt nimmt mit Kerngröße zu!
$\sim \ln A \propto \rho_A$


F2(A)/F2(D)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.
0.2
0.4
0.6
0.8
X
● EMC F2(Fe)/F2(D2)
(85) ● BCDMS F2(N2)/F2(D2)
○ BCDMS F2(Fe)/F2(D2)
△ SLAC F2(C)/F2(D2)
← shadowing
genuine parton region
→ Fermi motion
"clusters"

Summary EMC-effect: effect on flavour decomposition is rather moderate!! (not dramatic)

① effect on valence quarks established!



a) tiny effect on $\int x F_3 \, dx$

b) quarks in free nucleons carry higher momentum fraction at large x (up to 20%)

② sea-quarks:

a) not established

b) maximum effect: $\frac{(\text{sea fraction})_{\text{free nucleon}}}{(\text{sea fraction})_{\text{bound nucleon}}} = 1.05 \pm .06$ ± syst.?

≤ 10%

Conservative estimate:

sea quark momentum fractions differ by not more than 15%!
no effect favoured by data.

③ theoretial interest and explanations?

class 1: pions in heavy nucleons (extra sea!)

class 2: rescaling: $R_A > R_N$ (nucleon effective radius)

$\rightarrow F^A(x, Q^2) = F^N\left(x, Q'^2 = Q^2 \cdot \frac{r_N^2}{r_A^2}\right)$

class 3: cluster models: (

study behaviour of multiquark systems! ← QCD?

Summary on flavour decomposition

- Consistent set of quark distributions available for all flavours

- uncertainties of sea quark distribution for free nucleons still rather large due to EMC-effect : ≤ 15%

note: these differences disappear in applications at high Q^2 (SppS, HERA) due to rapid evolution of the sea-quarks + gluons

- Valence quark distributions differ for bound and free nucleons:

≲ 15% effect is quantitatively measured and can be corrected

---

2 longstanding experimental problems settled:

i) $\sigma_T^{\bar{\nu}}$, σ_T^{ν} : scale for parton distribution well known

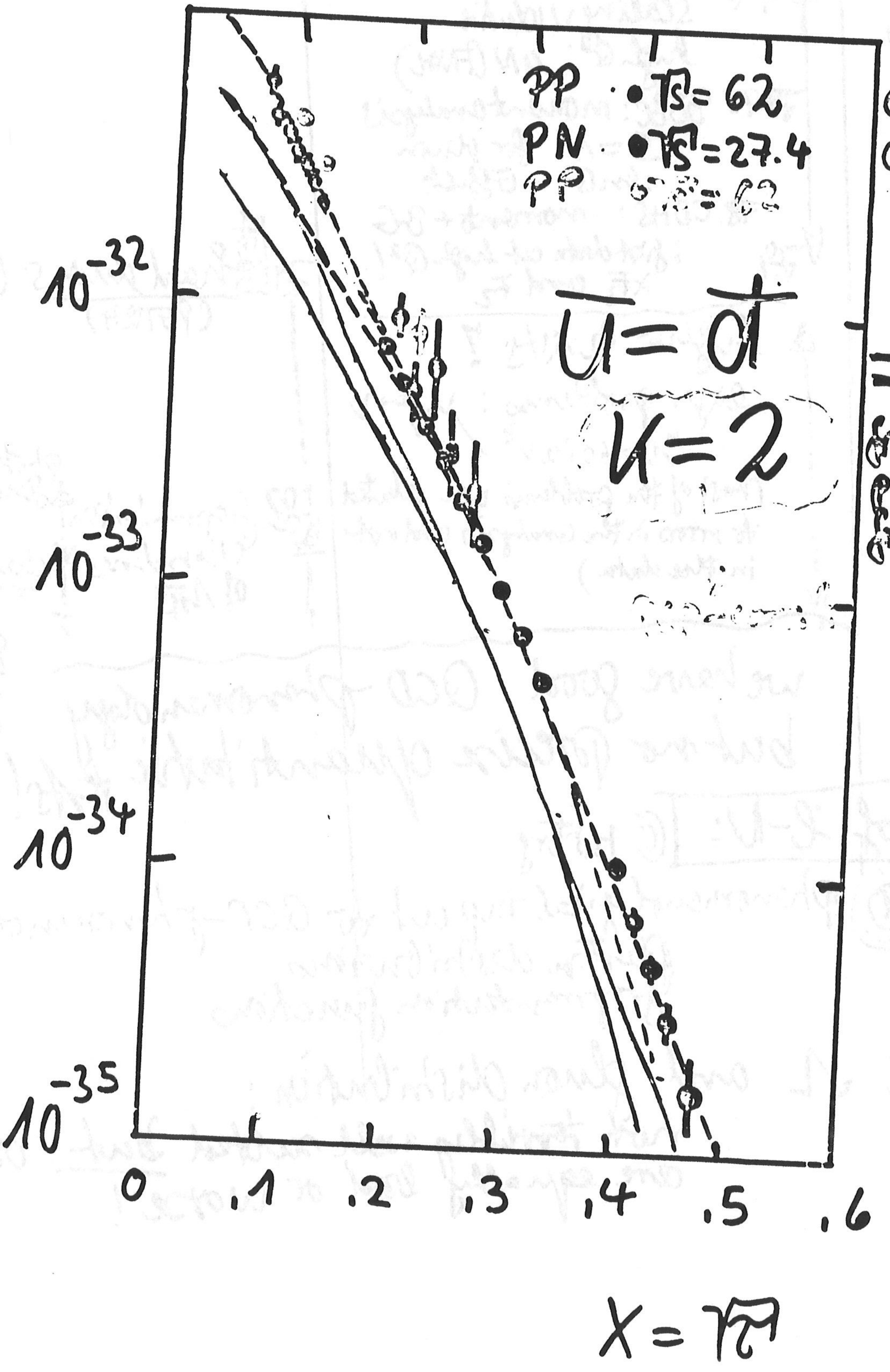
ii) $q_L(x)$ measured rather decently ($R = \sigma_L/\sigma_T$)

$\rightarrow$ μ + ν - people at the SPS can leave the field with good conscience soon (we will still learn on EMC-effect)

Application of functions to Drell-Yan

$p + N \rightarrow \mu^+\mu^- X$

$$m^3 \frac{d^2\sigma}{dm\,dx}\Big|_{x_F=0} \quad [\mathrm{cm}^2\,\mathrm{GeV}^2] \propto x\bar{u}(4u+d)$$



CHAMNP (ISR)

CFS

PP CCOR

$\bar{u} = \bar{d}$

$K = 2$

$\left.\begin{matrix}\text{——}\\ \text{——}\end{matrix}\right\}$ absolute predictions from CDHS parametrisations for u_v, d_v, $\bar{q}(x$,

③ l–N–scattering and QCD

3 phases

	lN: first testing ground of QCD;	e^+e^-
enthusiasm	77 scaling violation high Q^2: μN (FNAL) 78 BEBC: moment analysis S = 1 for gluon ln Q^2 – Effect 78 CDHS: moment + BG : first data at high Q^2! xF_3 and F_2	
frustration	79	79! hard gluons ($e^+e^- \to q\bar{q}g$) (PETRA)
	higher twist ? exp. problems: μ ↔ ν $\Lambda = 500$ MeV (most of the problems were related to errors in the analysis and not in the data)	82 (experimental) determinations of $\Lambda_{\overline{MS}}$ photon structure function charm high E_T jets $\bar{p}p$ $q\bar{q}$
accomodation		

we have good QCD-phenomenology but no precise quantitative tests!

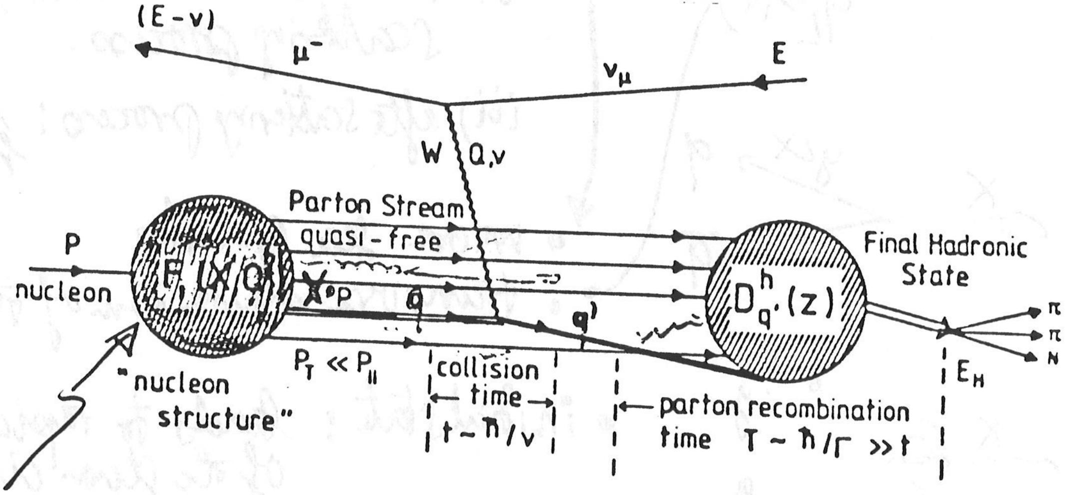
role of l-N: © history

⇒ ① phenomenological input to QCD-phenomenology
parton distributions
fragmentation functions

② Λ and gluon distribution:
not ~~terribly~~ well suited but others are equally bad or worse!

QCD-modifications of the Quark-Parton-Model

QPM-picture for DIS :



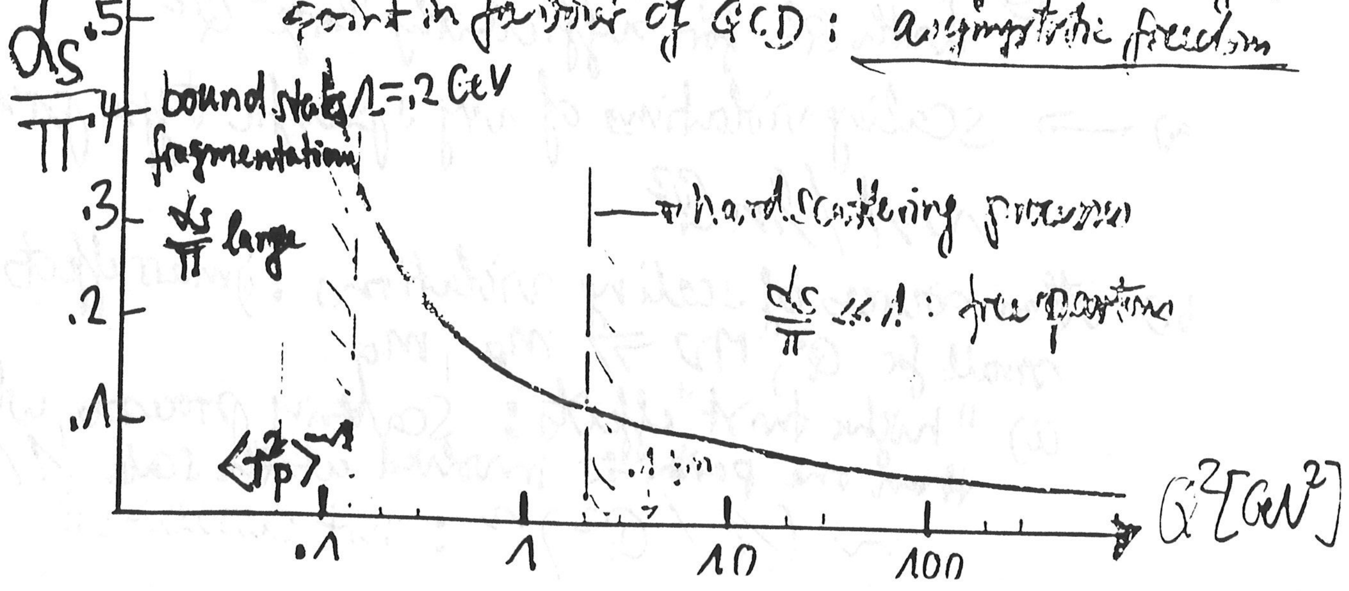
QPM

i) quarks + antiquarks are quasifree for the space-time scale of the hard scattering process
$\hookrightarrow$ scaling of structure functions

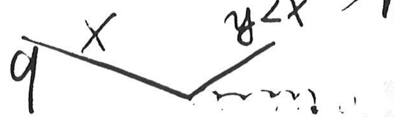
ii) they will have a transverse momentum with respect to the incident proton direction (clear from uncertainty principle)
$\hookrightarrow$ $q_L = 4\langle p_T^2\rangle / Q^2$ (intrinsic p_T)

iii) the final quarks fragment into observable hadrons, independent of the nature of the hard scattering process.

QCD : a QCD is the <u>Only</u> theoretical basis of the QPM!!
(the derivation of approximate scaling is the strongest point in favour of QCD : <u>asymptotic freedom</u>



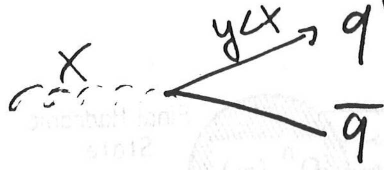
b.) radiation effects of hard field quanta : in the time scale of the hard scattering process



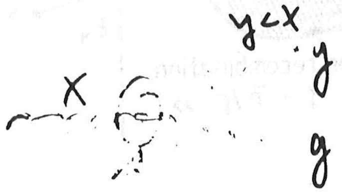
: i) loss of longitudinal momentum: → Shrinkage of parton distributions towards small X

scaling violations $q_L^{QCD}(x,Q^2)$ → ii) transverse momentum of quark before scattering process.

iii) after scattering process: broadening of hadron jet



- more sea quarks
- transverse momentum of these quarks



- initial state: leads to rapid shrinking of the gluon distribution towards small X
- final state: broadening of gluon jets

this is the basic coupling in QCD: gluons are colored ⇒ asymptotic freedom (not directly testable in DIS)

c.) gluons have to show up as partons : γ-gluon fusion ; q-g, g-g scat.

QCD predictions for DIS:

① shape of structure functions not predictable at present using perturbation theory

② prediction for the change of structure functions with Q^2 for sufficiently large Q^2

a.) ⟶ scaling violations of very specific type predicted

$\sim 1/\ln Q^2$

b.) other sources of scaling violations : i) mass effects (m_p, m_q) small for $Q^2, M\nu \gg m_p, m_q$

ii) "higher twist" effects: scattering processes, where more than one parton is involved at the scale $1/Q$!

$\sim (1/Q^2)^{n}$: not calculable!!

QCD-prediction: available for sufficiently large Q^2, W^2
since $1/\ln Q^2$-terms will dominate

are present experiments in this energy regime?

basic problem of QCD-tests

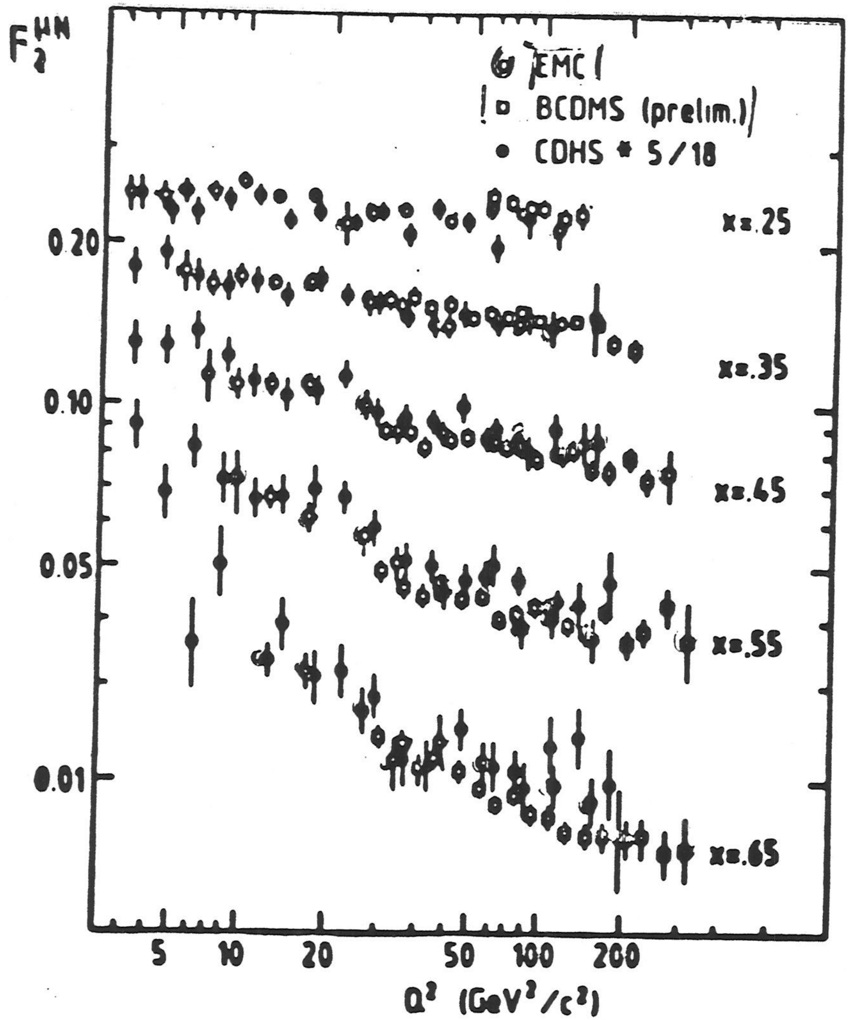
Step 1: exp. evidence for scaling violations

a) Clearly established up to highest available values of Q^2: muon and neutrino experiments

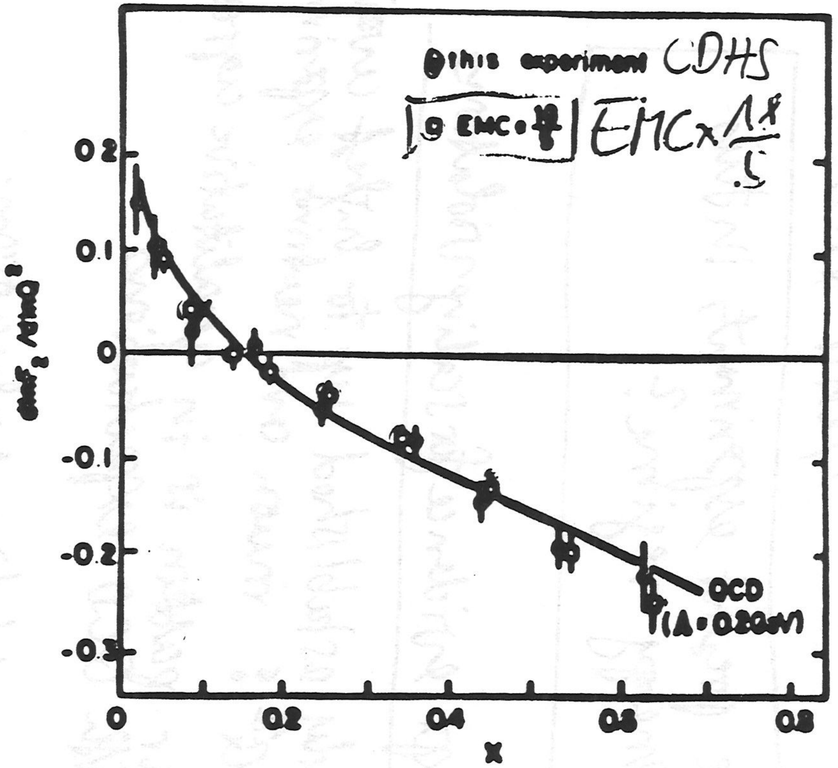
b.) their pattern is in qualitative agreement with QCD expectations

Step 2: quantitative evaluations:

comparison of ν and μ-data at high x and Q^2

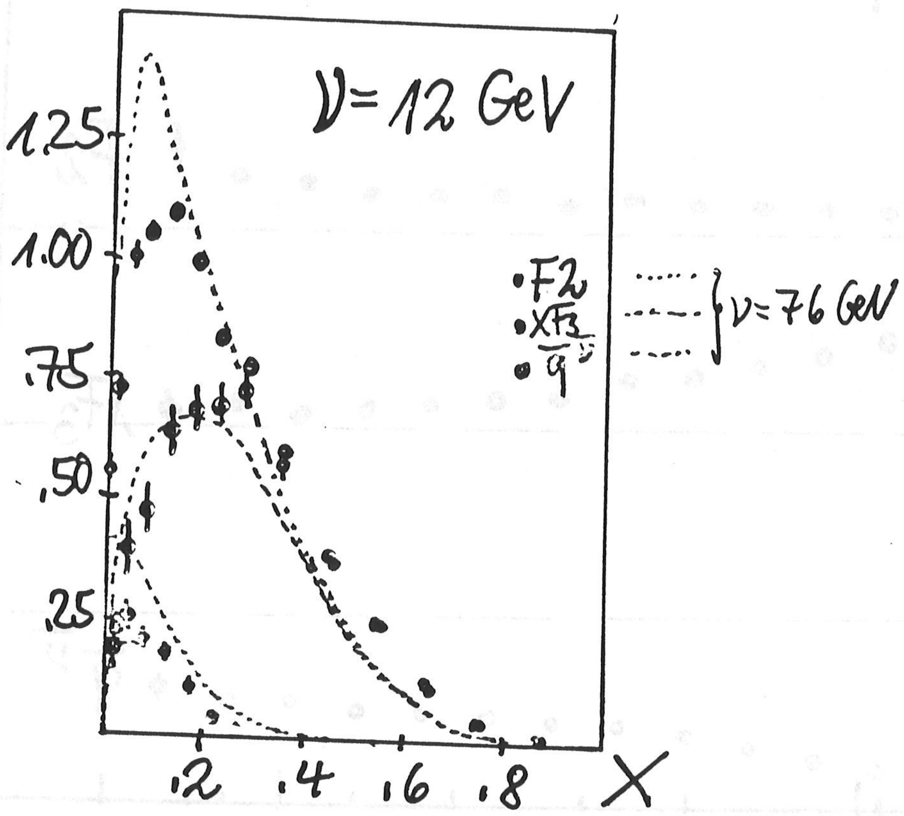


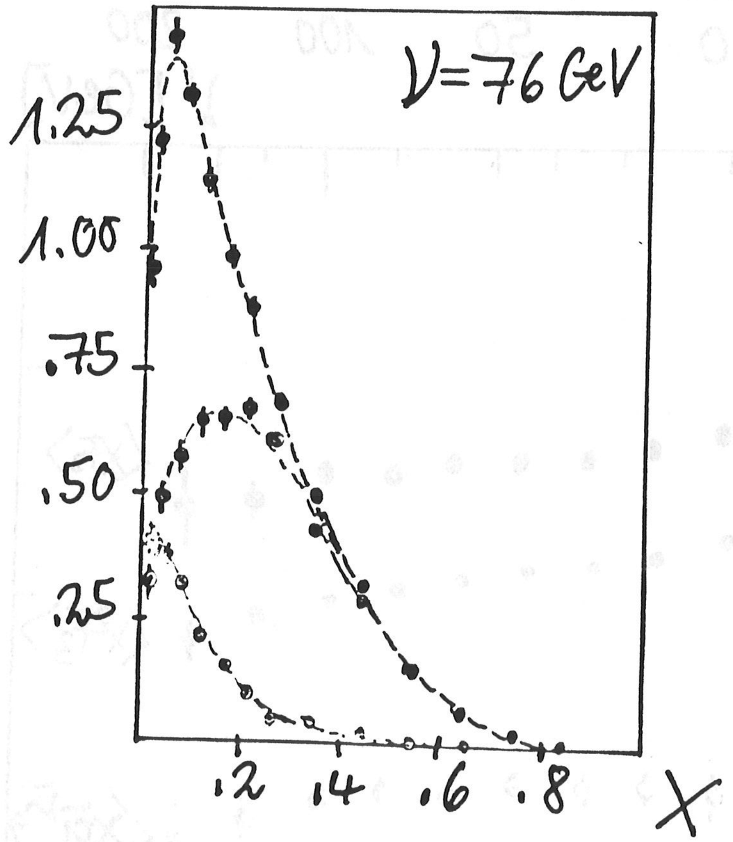
Slopes $d\ln F_2/d\ln Q^2$



Change of shape with $\nu = \frac{Q^2}{2mx}$

CDHS 85
(ν, prel.)





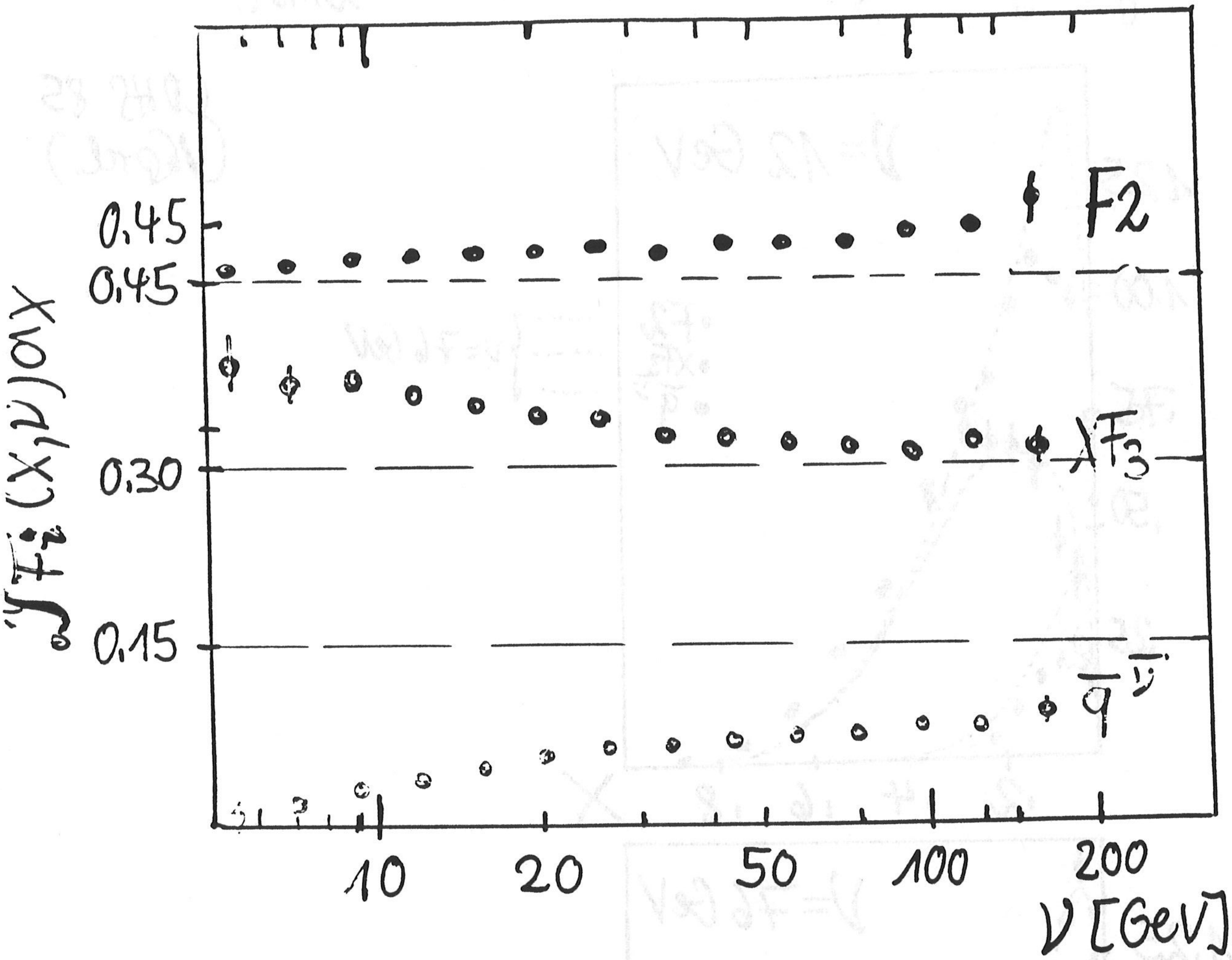
- sea (q̄) rises
- valence distribution shrinks at large x

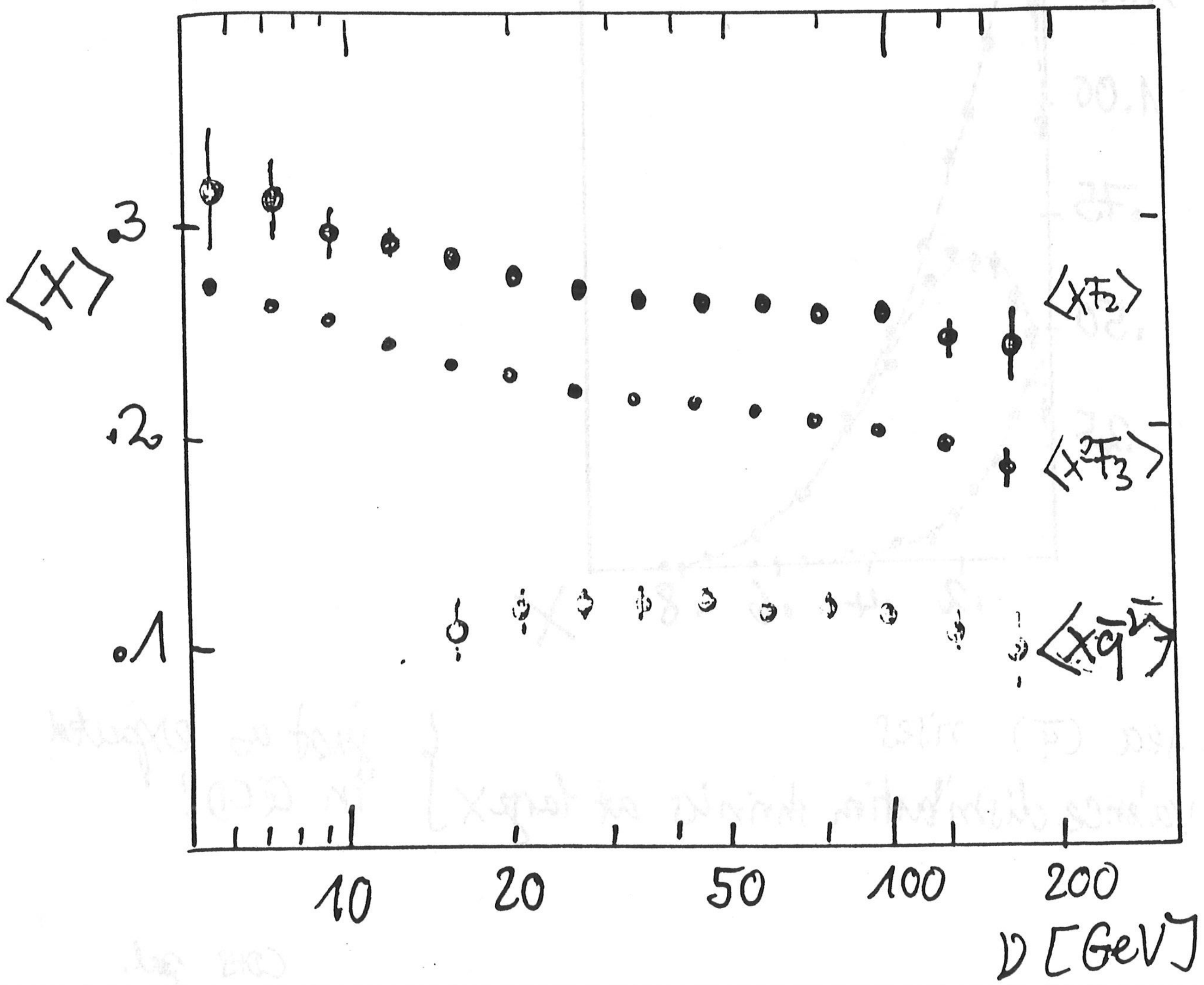
} just as expected in QCD!

CDHS prel.

"momentum fraction"

CDHS (prelim., (very)





: Scaling violations in DIS : test of QCD

- do we see QCD effects?
  - kinematic effects
  - higher twist contributions

  (→ QCD vs. other field-"theories")

yes

- determination of the gluon distribution
- what is $\Lambda_{\overline{MS}}$?

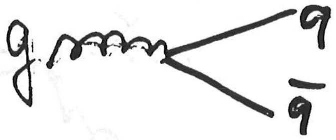
QCD-analysis:

relevant for QCD: slopes of structure functions

$$\frac{dF_i(x,Q^2)}{d\ln Q^2}$$ (scaling violations)

2 contributions:

" bremsstrahlung " : shrinking at large x



" pair production " : rise of the sea at small x

1 scale:

$$\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\,:)}$$ (L.O.)

specific QCD predictions:

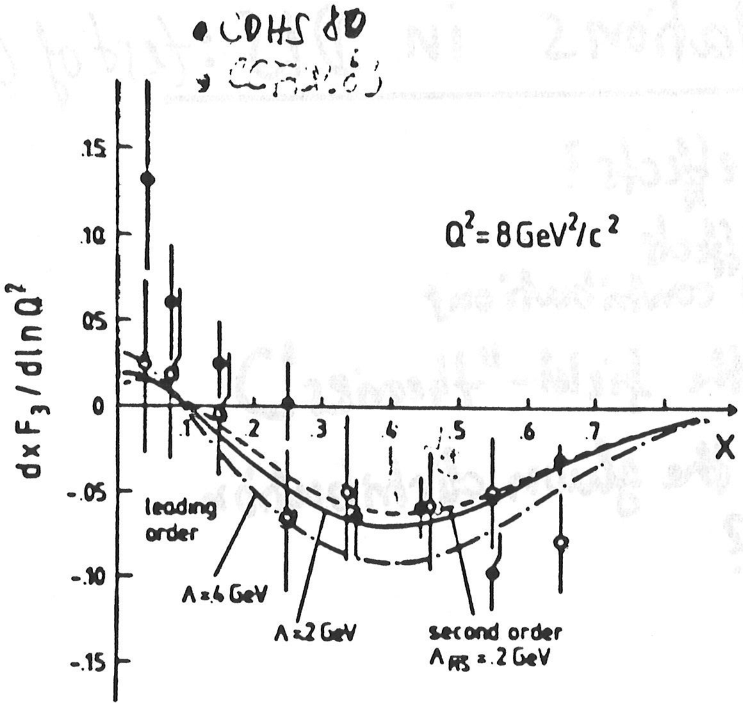
- $\alpha_s(Q^2) \sim 1/\ln Q^2$: "asymptotic freedom"

  related to

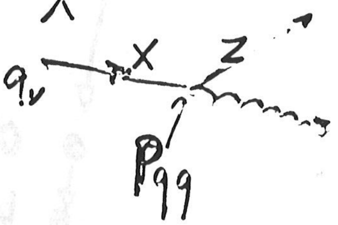
- gluons have spin 1
  → x-dependence of scaling violations

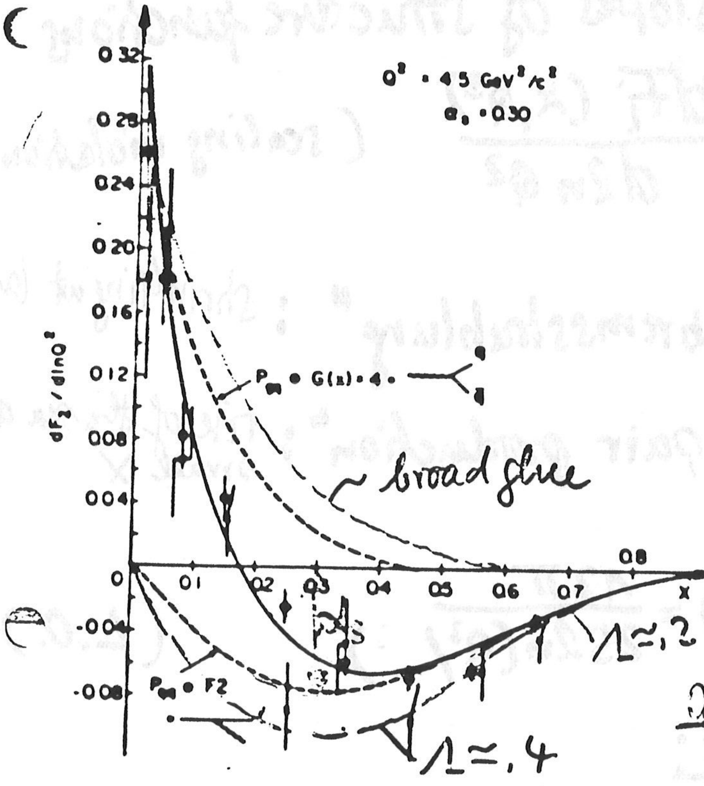
most direct access:

Altarelli-Parisi equations



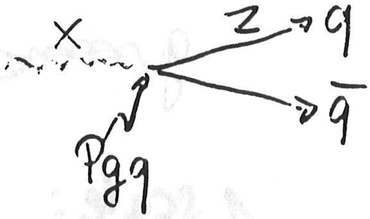
$$\frac{d\,xF_3(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1\left[P_{qq}\left(\frac{x}{z}\right)zF_3(z,\ldots)\frac{x}{z}\right.$$





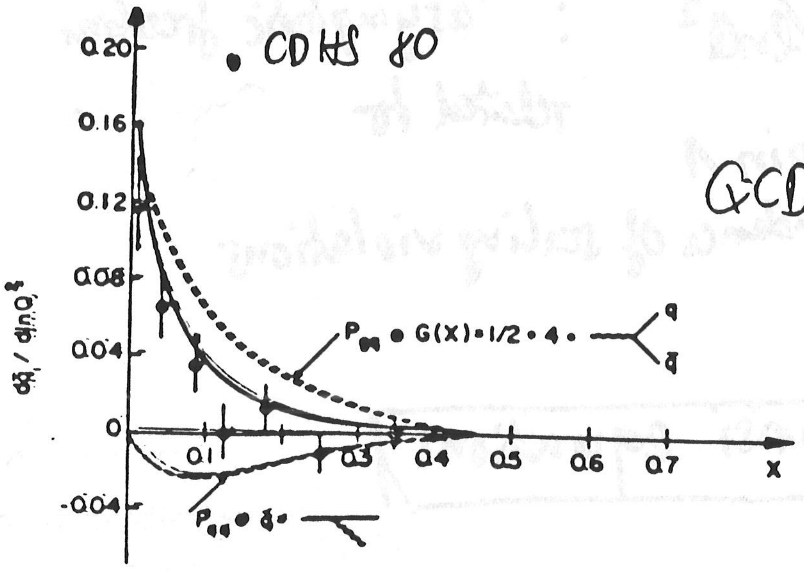
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1\left[P_{qq}\left(\frac{x}{z}\right)F_2(z,Q^2)\right.$$

$$\left.+N_f P_{gq}\left(\frac{x}{z}\right)zG(z,Q^2)\right]\frac{x\,dz}{z^2}$$



$$\frac{d\bar{q}^{\nu}(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x\left[P_{qq}\left(\frac{x}{z}\right)\bar{q}^{\nu}(z,Q^2)\right.$$

$$+N_f P_{gq}\left(\frac{x}{z}\right)zG(z,Q^2)\Big]$$



QCD → ① unknown: $\alpha_s(Q^2)/\pi = \frac{12}{(33-2N_f)\ln(Q^2/\Lambda^2)}$

② gluon distribution

③ measured: $F_i(x,Q^2)$

④ predicted by QCD: P_{ij} :

slopes are predicted !!

A few facts about scaling violations and QCD

a.) they are presently quantitatively described by QCD-effects <u>alone</u> for $Q^2 \gtrsim 2\,\text{GeV}^2$ and $W \gtrsim 3.5$ GeV

b) QCD is unable to describe low Q^2 (W^2) data (e.g. from SLAC) and high Q^2 data from SPS, FNAL simultaneously!

↳ mass or non-perturbative effects must be present! (especially for low W!)

c.) we can never proof that we see QCD-effects experim.!
A series of $(1/Q^2)^n$ can fit an elephant!
⇒ all scaling violations could be non-perturbative!
example: simple diquark models can explain a lot!

---

theoretical input: "higher twist contributions are probably small" ??
Jaffe + Soldate

<u>assume:</u> we see effects due to radiation:

<u>which QCD-ingredients are tested?</u>

gluon spin 1 ? - yes! BEBC/CDHS (77/78)

gluon-gluon coupling - no

equivalent to ↳ $\alpha_s(Q^2) \sim 1/\ln Q^2$ - no

Quantitative QCD-analysis of scaling violations

aim:
- determine $\Lambda_{\overline{MS}}$
- determine $xG(x, Q_0^2)$

warnings:

- data at low invariant mass are suspicious
  we have evidence for substantial non-perturbative effects
  $\hookrightarrow$ cut at $W^2 \gtrsim 10\ GeV^2$
- data at low Q^2 are suspicious: low order QCD-predictions will not work
  xF_3: no problem, since low x-region has no information on $\Lambda_{\overline{MS}}$
  $F_2, \bar{q}^\nu$: all information is at small x! to get $xG(x, Q_0^2)$
  $\rightarrow$ high Q^2-cut not possible $\rightarrow$ (doubt
- many technical problems: delicate analysis
  $\rightarrow$ different programs do not agree (second order)
  $\rightarrow$ analysis of $F_2, \bar{q}^\nu$ depends on assumptions
  R, sea-subtraction, ..
  $\rightarrow$ the errors due to the analysis, extracting $\Lambda_{\overline{MS}}$ have often be larger than the errors due to data

---

① $\Lambda_{\overline{MS}}$: $xF_3(x, Q^2)$ $\left\{ \begin{array}{l} \text{straightforward but statisti-} \\ \text{cally limited} \end{array} \right.$

"improve" by using $F_2(x, Q^2)$ for $x \gtrsim .3$
- necessary for muon experiments
- what value of R!
- subtract sea contribution!

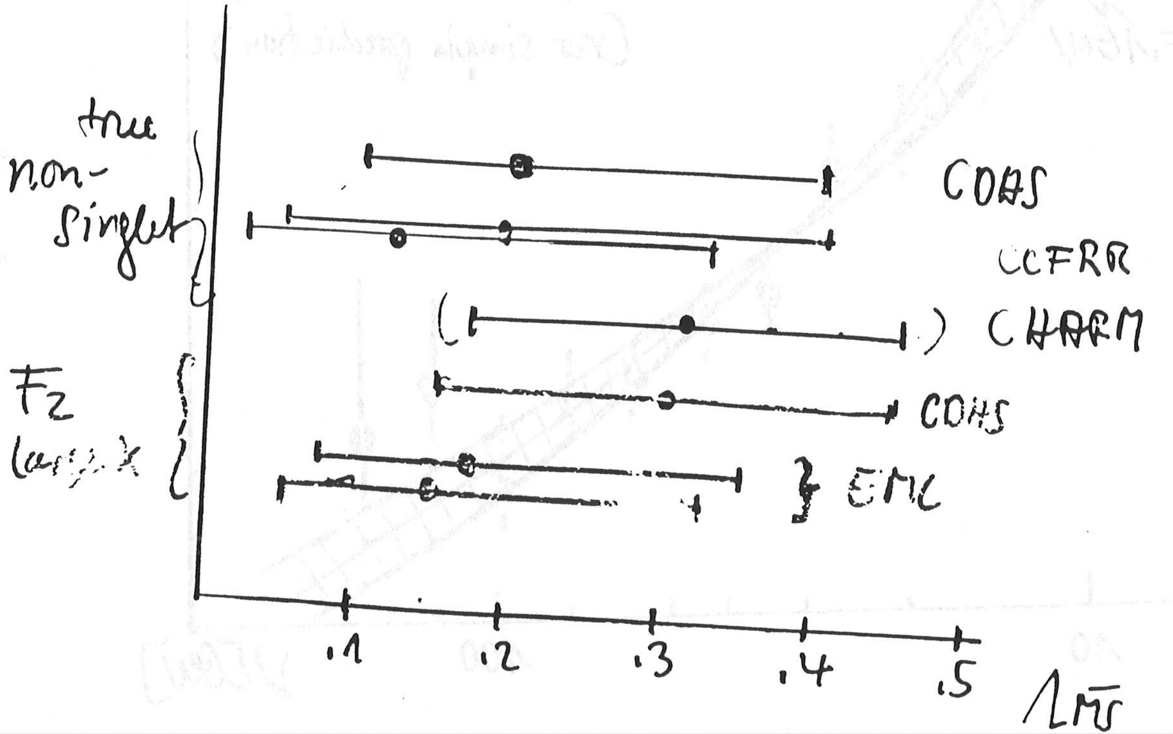
② $xG(x, Q_0^2)$: F_2 alone not sufficient. $\left\{ \begin{array}{l} + \bar{q}^\nu \\ + xF_3 \end{array} \right.$

genuine non-singlet results at high W^2 and Q^2

			$\Lambda_{\overline{MS}}$ [MeV]
CDHS (83)	xF_3	$Q^2 > 2\,GeV^2$ $W^2 > 11\,GeV^2$	200^{+200}_{-100}
CCFRR (84)	xF_3	$Q^2 > 5\,GeV^2$ $W^2 > 10\,GeV^2$	120^{+200}_{-106} (194^{+220}_{-150} second prog.) same progr.
(! CHARM	xF_3	$Q^2 > 3\,GeV^2$ no W^2 cut !	310 ± 140) !

! using F_2 at large x ! depends on R!

			$\Lambda_{\overline{MS}}$ [MeV]
CDHS (83)	F_2 ($x \geq .3$) sea subtracted as measured	$Q^2 > 2\,GeV^2$ $W^2 > 11\,GeV^2$ R_{QCD}	300 ± 150
EMC	F_2 ($x \geq .25$) sea subtracted from CDHS	$W^2 \geq 10\,GeV^2$ $Q^2 > 3$ R_{QCD}	$173\,{}^{\pm 20}_{-37}\,{}^{+158}_{-97}$ (Fe) $150\,{}^{+70}_{-60}\,{}^{+110}_{-90}$ (H_2)



Altarelli Bari '85

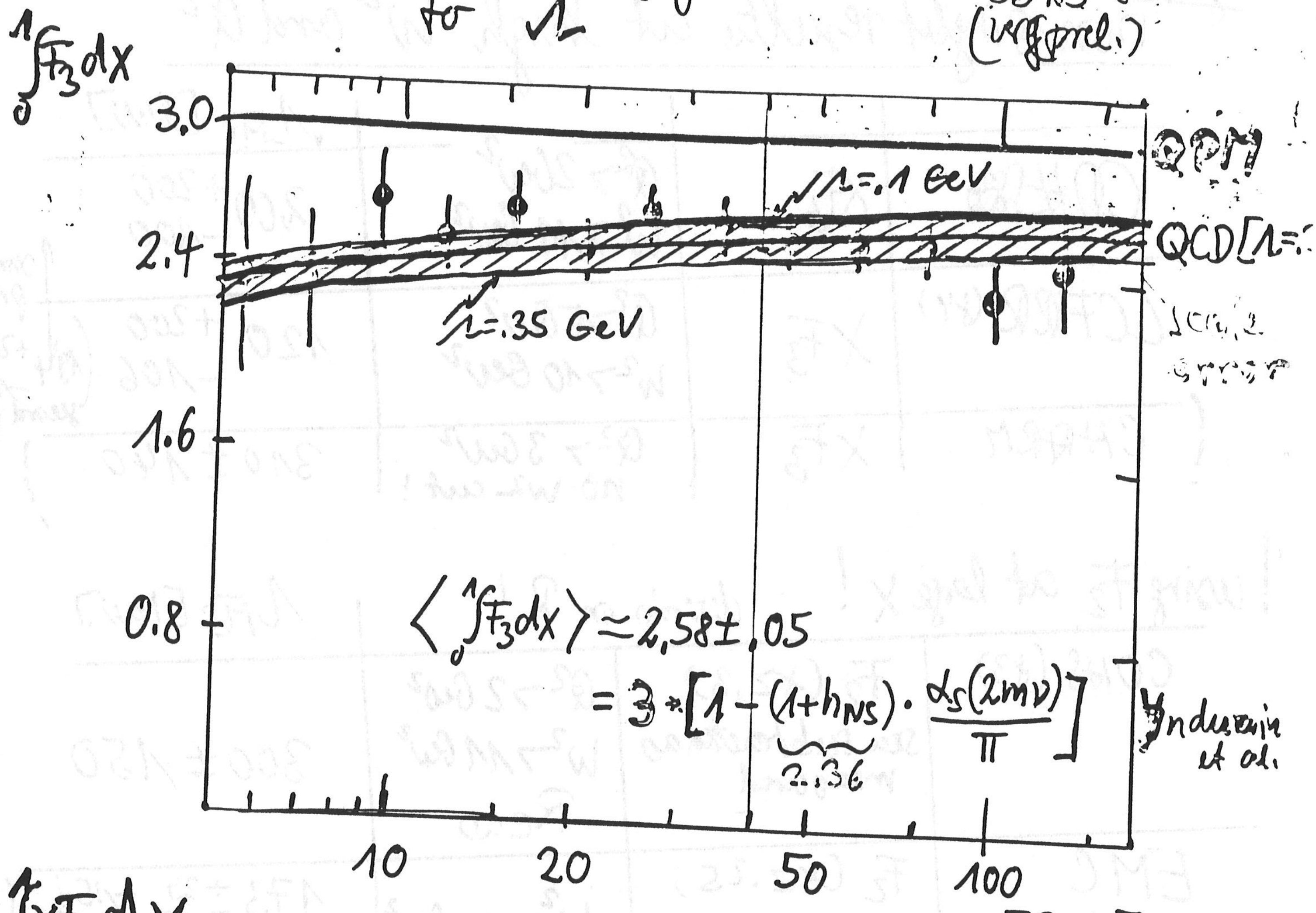
$100 \leq \Lambda_{\overline{MS}} \leq 500$!

$\alpha_s(Q^2 = 100)$

$= .165 \pm .030$

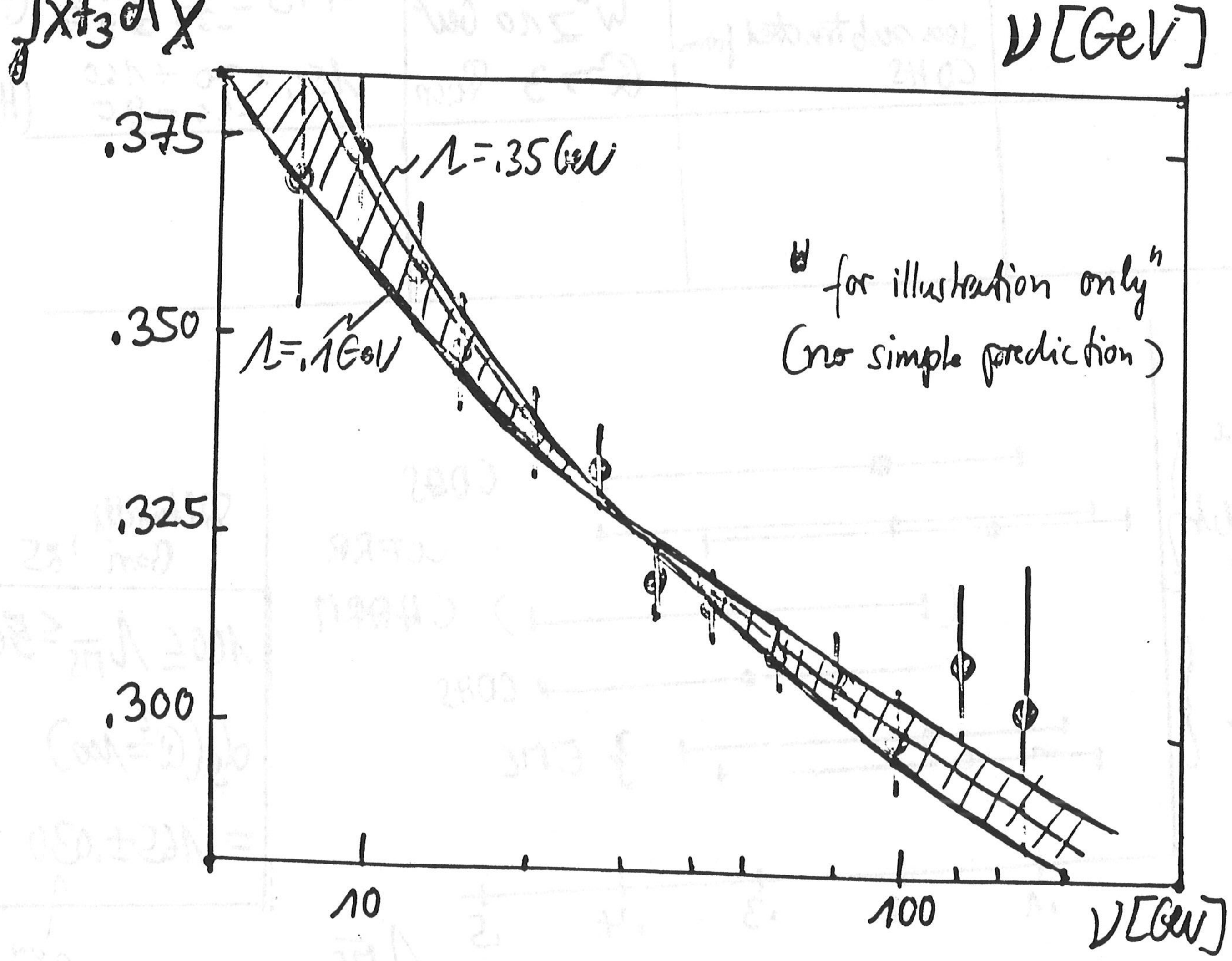
illustrates sensitivity of data to Λ

CDHS 85 (very prel.)



$$\left\langle \int_0^1 F_3 dx \right\rangle \simeq 2{,}58 \pm .05$$
$$= 3 \cdot \left[1 - \underbrace{(1+h_{NS})}_{2.36} \cdot \frac{\alpha_s(2m\nu)}{\pi} \right]$$

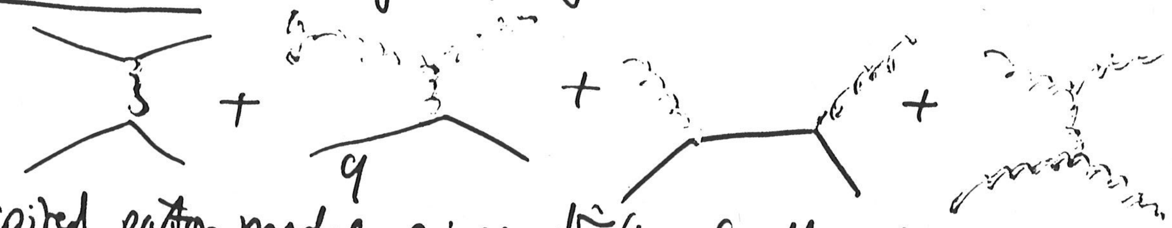
Yndurain et al.



"for illustration only" (no simple prediction)

Gluon distribution:

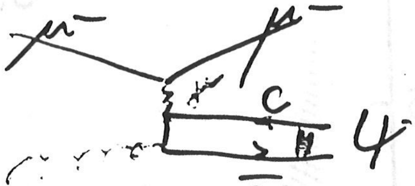
a) **direct access:** high $p_\perp$ - jets in hadronic collisions



QCD inspired parton model gives $d\hat{\sigma}/dt$ for all subprocesses + relative strength, gluon scattering dominates at present $Sp\bar{p}S$ kinematic range

but: model not yet genuine prediction

b.) **heavy flavour production:**
strong model dependence!



: γ-gluon fusion model

c.) **analysis of scaling violations** of F_2 and/or $\bar{q}^{\bar{\nu}}$

needs assumption! the bulk of scaling violations at small x is due to QCD !!

note: fractional momentum of gluons is fixed by energy momentum sum rule

$\Rightarrow$ scaling violations determine mainly the width of the gluon distribution

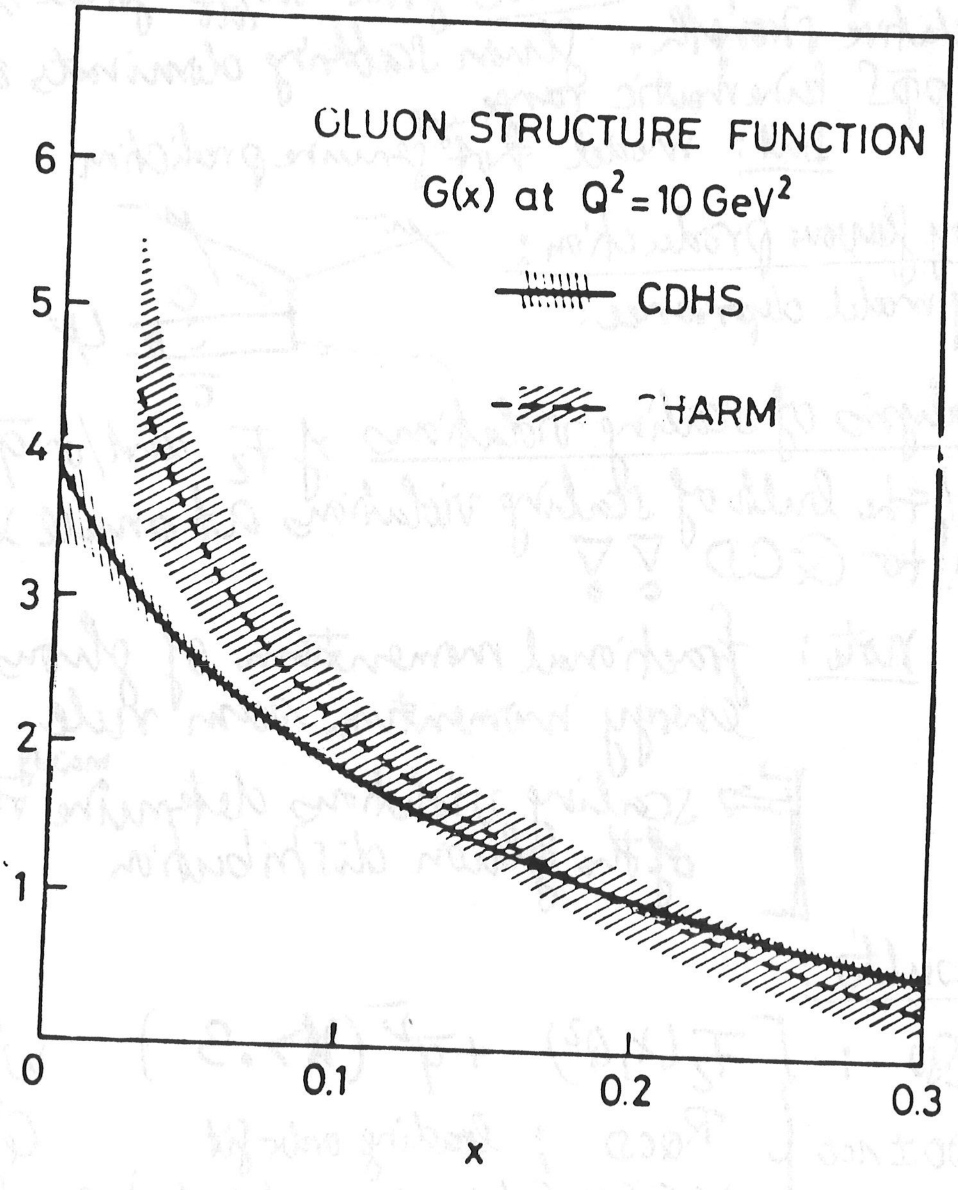
results:

i) CDHS80 : $\Lambda_{L.O} = 230 \pm 100$
- $F_2(x, Q^2)$ + $\bar{q}^{\bar{\nu}}$ ($x > .3$) $W^2 > 11\,GeV^2/c^2$
- R_{QCD} ; leading order fit $Q^2 > 2\,GeV^2/c^2$
- $xG(x, Q_0^2)$ parametrized in specific functional form

ii) CHARM82 : $\boxed{F_2(x,Q^2), xF_3(x,Q^2), \bar{q}^{\nu}(x,Q^2)}$ $Q^2 > 3\,GeV^2/c$

$\Lambda_{L.O} = 190^{+70}_{-40} \pm 70 \rightarrow R = 0.0$; $(R = 0.1)$

Furmanski, Petronzio-method: needs no parametrisation!


GLUON STRUCTURE FUNCTION
G(x) at $Q^2 = 10\ \mathrm{GeV}^2$
CDHS
CHARM
0
1
2
3
4
5
6
0.1
0.2
0.3
x

Tr. 1

reasonable agreement, "reasonably good" estimates of the gluon distribution

— defects: inprinciple: • relies on QCD interpretation of structure functions
but: it is genuine prediction of QCD
• has to make use of rather low Q^2 data (sea-region)
leading order fits only (probably ok for the purpose)

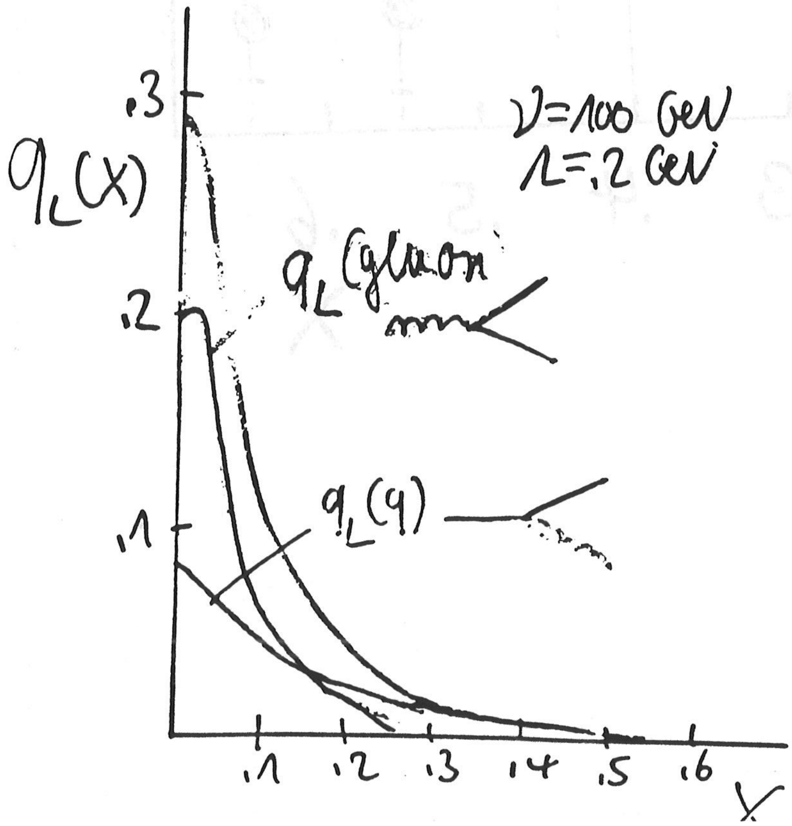
in practice:

- specific parametrisation (CDHS)
- R = 0 : inconsistent with QCD and measurements (CHARM)
- no slow rescaling corrections
→ $\bar{q}^{\nu}$ at small x is very strongly affected

further progress is possible!

---

d) $q_L(x)$ and QCD: access to gluon distribution



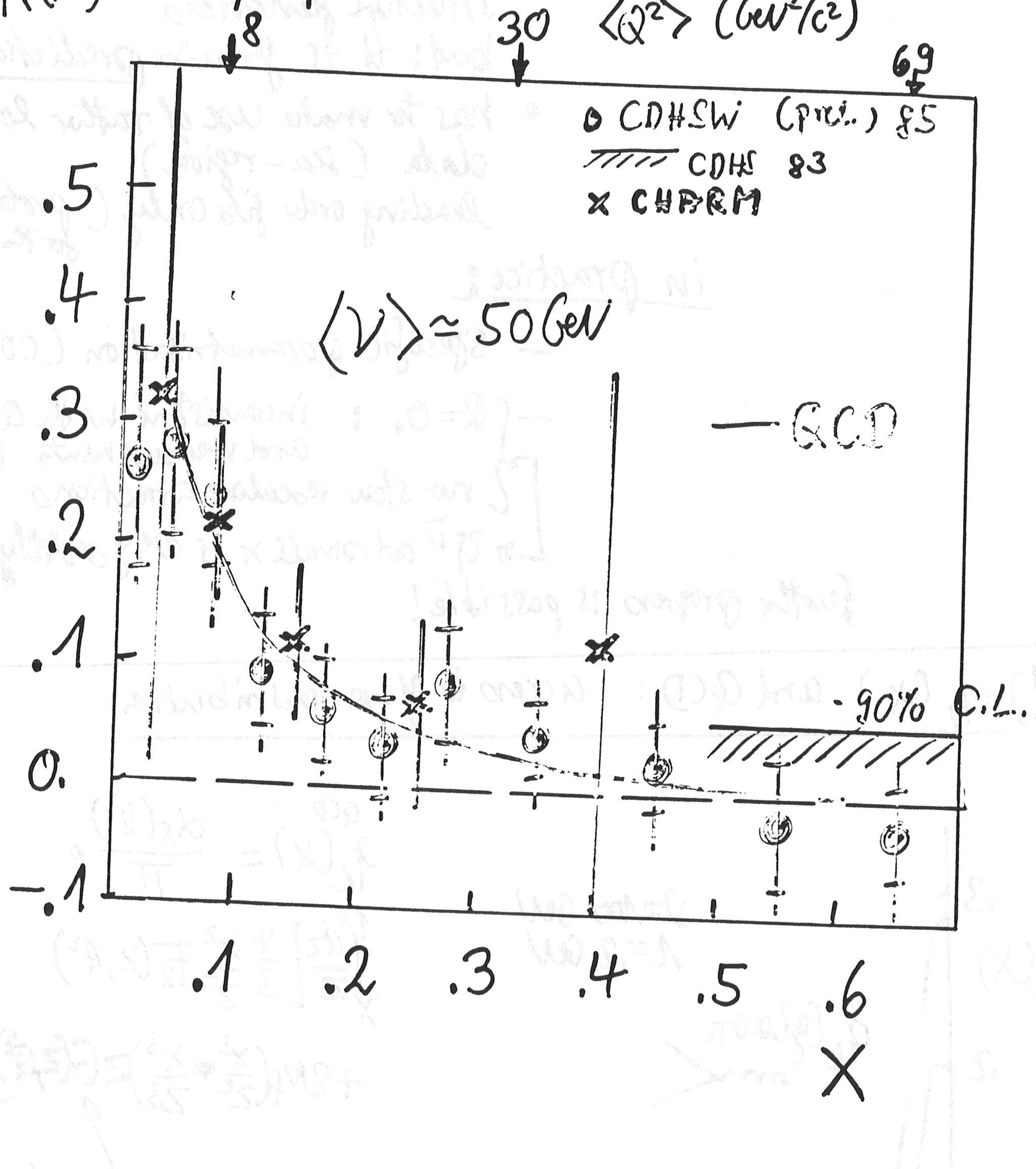
$$q_L^{QCD}(x) = \frac{\alpha_s(Q^2)}{\pi} \cdot \int_x^1 \frac{dz}{z}\left[\frac{4}{3}\frac{x^2}{z^2}F_2(z,Q^2) + 2N_f\left(\frac{x^2}{z^2} - \frac{x^3}{z^3}\right) z\,G(z,Q^2)\right]$$

dominates!

CDHS 85

WBB: $10^6\ \nu$; $\sim 10^6\ \bar{\nu}$ evts

$R(X) = \sigma_L / \sigma_T$

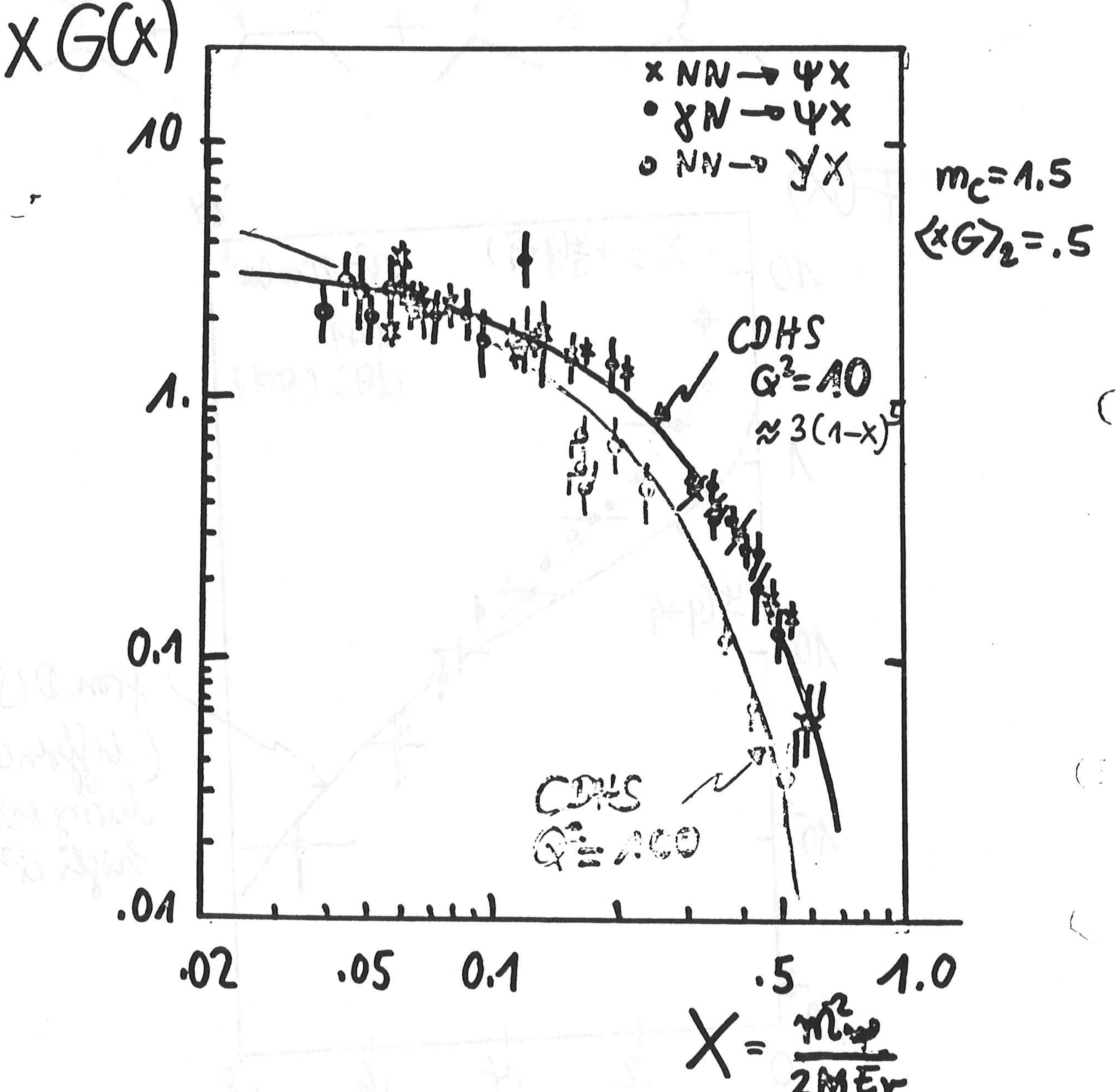


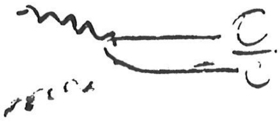
③ Hadronic ψ and Υ-production

$NN \to \binom{\psi}{\Upsilon} + X$:

[illegible]

R.J.N. Phillips
Madison conference 80

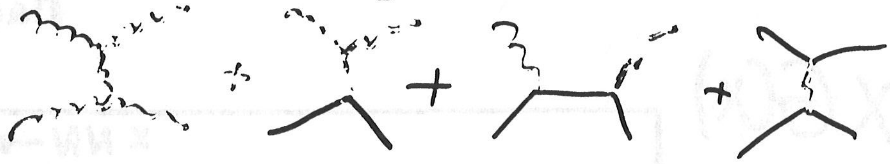


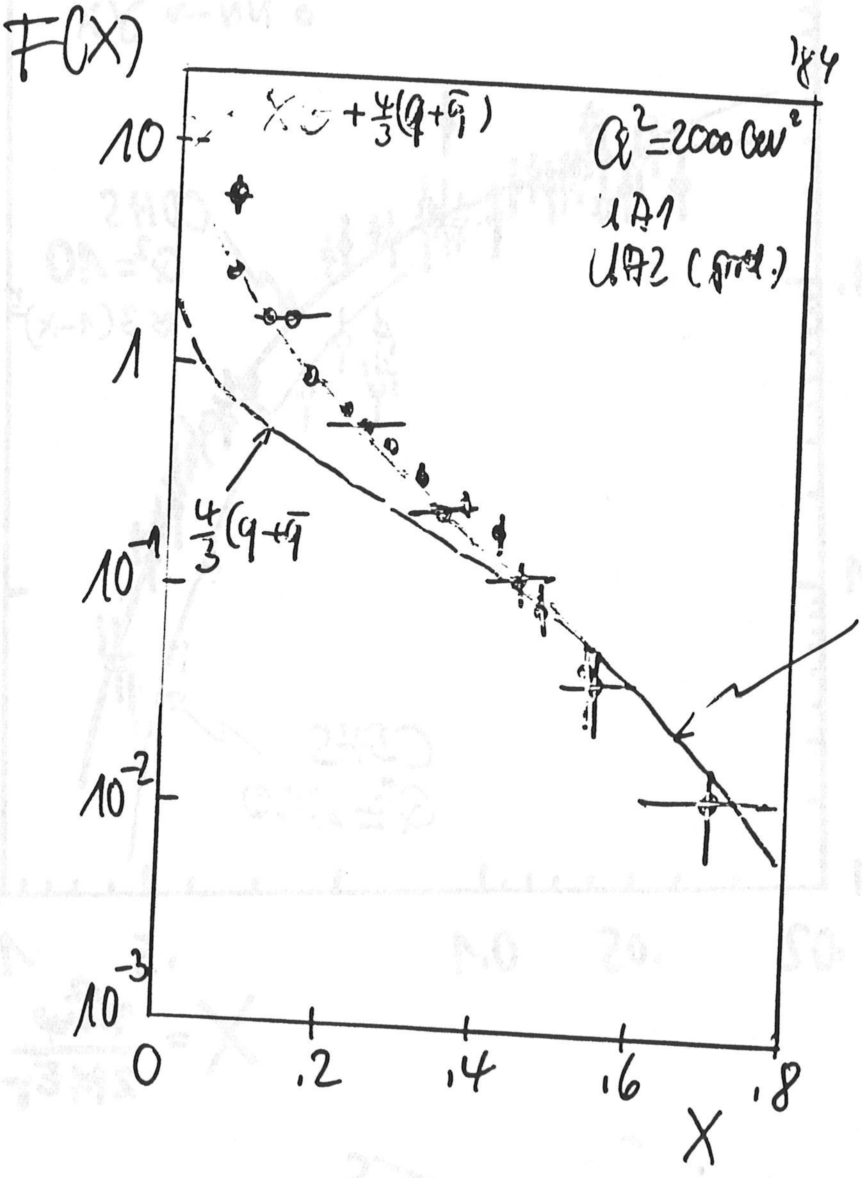


Photon-gluon fusion (γN und μN-Experimente (EMC, EMC))

$\bar{p}p$-collider: high E_T jet cross-section

$$F(x) = \text{[illegible]} + \frac{4}{9}\left(q(x) + \bar{q}(x)\right)$$



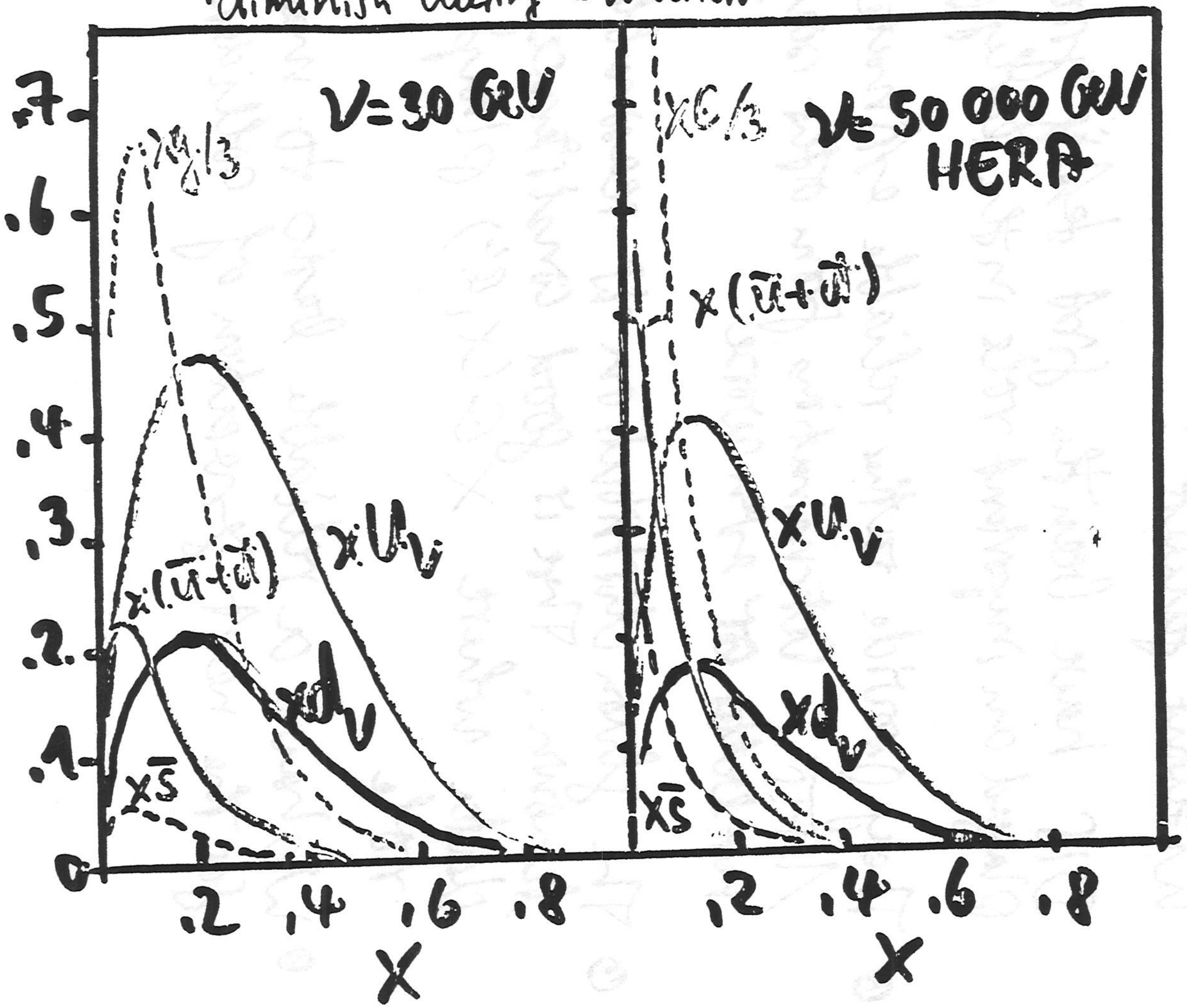


from DIS (CDHS or CHARM)
(differences disappear during evolution to higher Q^2 !)

evolution of parton distributions

QCD gives a basis for the extrapolation to next generation of accellerators!

Predictions are quite safe, since present day uncertainties in shape largely diminish during evolution.



Summary QCD:

Our trust in QCD relies on its ability to describe quantitatively, semiquantitatively and qualitatively a very large variety of processes at large mass scale without failure!

DIS have been the first testing ground and played an important role in the early phase

- They provide rather reliable estimates of $\Lambda_{\overline{MS}}$. Determinations from other sources are no better or even worse
- The gluon distribution is reasonably well known. There is good consistency of all data where $xG(x,Q^2)$ plays a dominant role
- We have a reliable basis to make prediction for the next generation of colliders

VI Future of lepton-nucleon scattering experiments

e-p-colliders

at least one will be available: HERA (DESY)
≥ 1990
$E_{CMS} \leq 370$ GeV

distant future: maybe proton ring in LEP tunnel: LHC ($E_p \simeq 5-10$ TeV)
($E_{CMS} \simeq 1-2$ TeV)

lets concentrate on HERA:

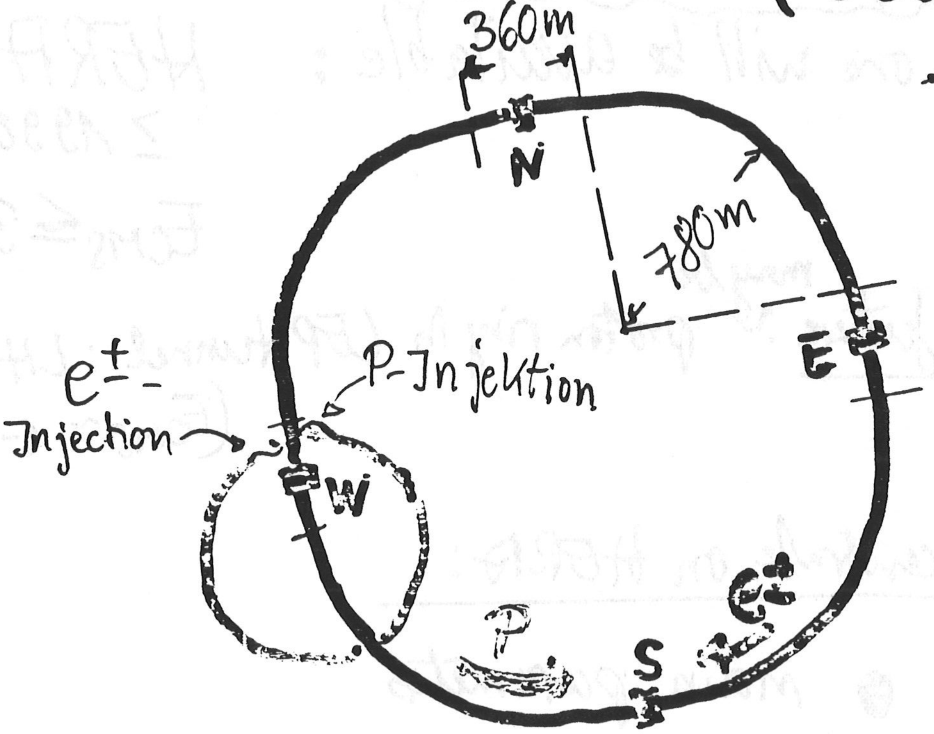
- main parameters
- physics potential (compared to other colliders)
- status of project
- detector designs

people interested should have a look to
proceedings of Genova meeting 1/8.
DESY/HERA 85/01

HERA = $e^\pm$-p collider for the 90'

(DESY, HAMBUR

+ substantial contributions from foreign countries



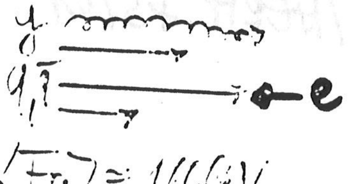
Main parameters: I. Energy

$E_p = 820$ GeV (→1TeV) $E_e = 30$ GeV (→35)

p ——————→← e

$$E_{CM} = 314 \text{ GeV } (\to 375)$$

at the constituent level: e-q-collider



$\langle E_q \rangle = 160$ GeV

$E_{CM}^{eq} \leq 200$ GeV (useful range / event rate.....)

II. Luminosity

$\mathcal{L} \simeq 2 \times 10^{31}$ cm^{-2} s^{-1} > 10 pb^{-1}/a

---

III. Polarisation

$e_L^\pm$, $e_R^\pm$ with P ≤ 80%

IV Time scale

⇒ funded + started ⟶ start of physics program A. D. 90

Physics (basics)

(I) HERA is a "weak interaction" machine

(in the interesting kinematic range; $Q^2 \approx m_{W,Z}^2$)

(unique) $\Longrightarrow$

$ep \to \nu X$ CC
$ep \to e X$ NC } comparable rate at high Q^2 (larger) *

~ 150 NC events/day with $Q^2 > 1000\ \mathrm{GeV}^2/c^2$

| Hera continues ν (and μ) program at high energies

(II) Kinematic range

compared to present DIS expts }
$1/Q$ ~ * $\frac{1}{15}$ ← substructure
W ~ * 15 ← new particles

(III) Main physics themes : unique features + strength of e-p collider

- Proton structure + e/q substructure
- •• Spectroscopy of particles with electron lepton numbers
  (scalar electrons $\tilde{e}$, e^*, $\tilde{\nu}$, ν_R ....) $M \leq 200$ G
- ••• new interactions: new gauge bosons or new effective 4-Fermion interactions with ch
  (W'_s, ν_R, $HL \leftrightarrow HQ$)
  outside $\bar{p}p$ / e^+e^--range
  or CC-mediated

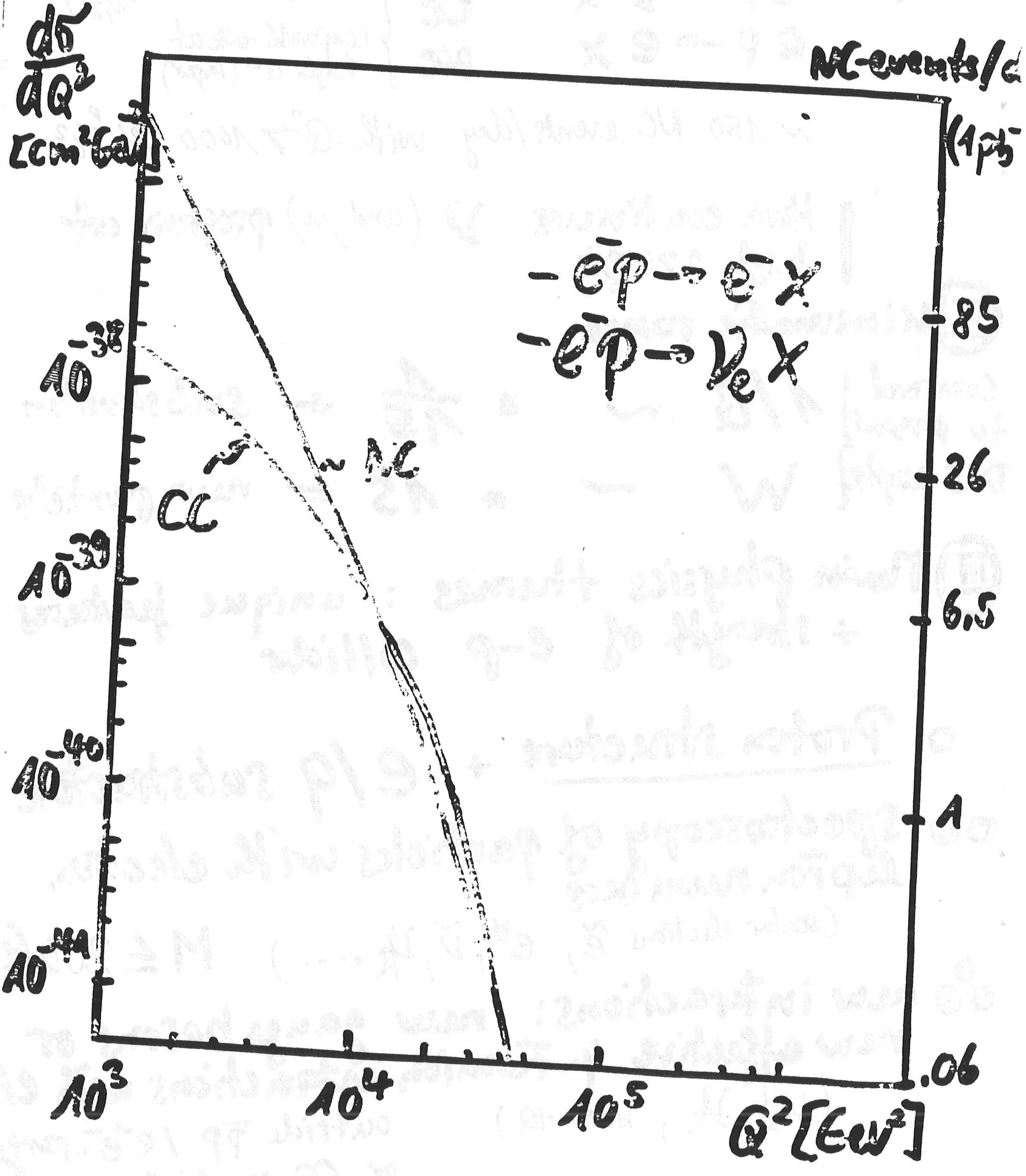
+ ○○○...

- **HERA is weak interaction machine**

(in the interesting kinematic range)

⟹ extension of νN

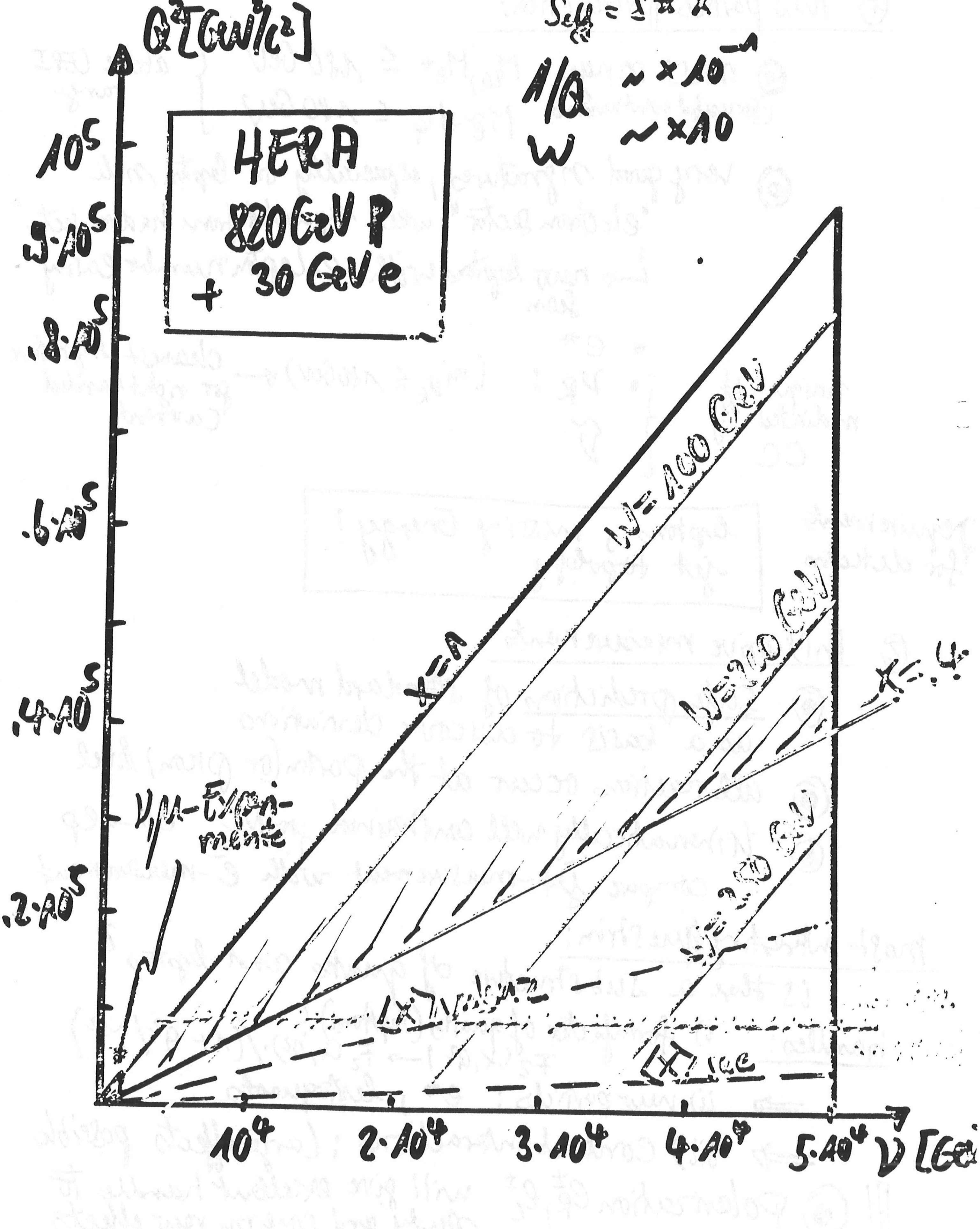
→ and μN scattering at low energies



$s_{eff} = s \cdot x$

$1/Q \sim \times 10^{-1}$

$W \sim \times 10$



specific strength of HERA

① new particle production:

- ⊙ mass range (for useful event numbers) $M_{LQ}, M_{e^*} \le 180$ GeV, $M_{\tilde{e}} + M_{\tilde{q}} \le 180$ GeV } above LEP I range
- ⊙ very good signatures, especially on lepton side
  "electron sector" well separated from hadron sector
  ↳ new leptons with e-Lepton number easily seen
  - e^*
  - ν_R : $(m_{\nu_R} \le 180\,\text{GeV})$ ← cleanest signature for right handed currents
  - $\tilde{\nu}$

unique if mediated by CC { ν_R, $\tilde{\nu}$ }

requirements for detectors

leptons, missing energy!
jet topology

② Inclusive measurements

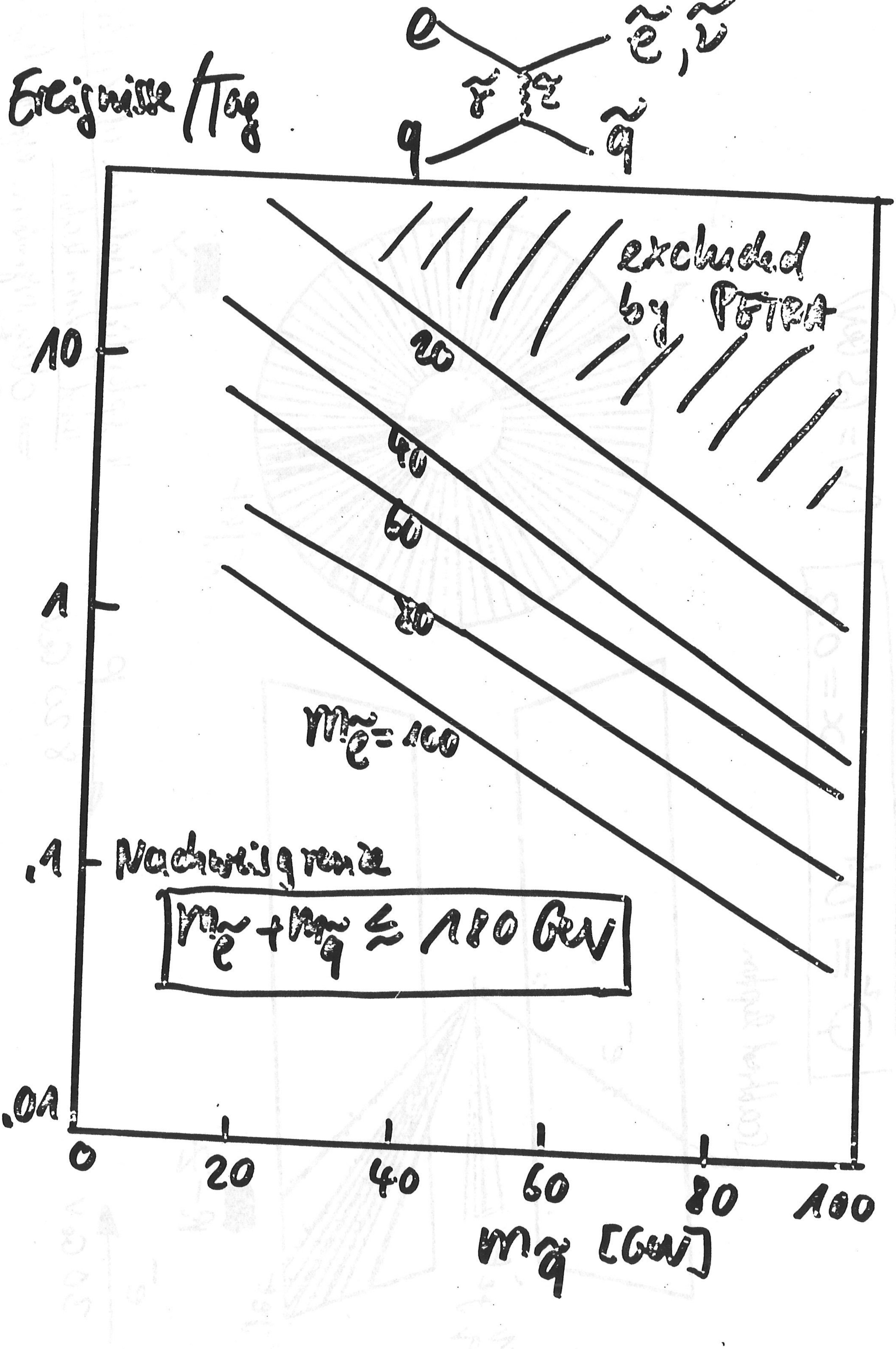
- ⊙ Safe predictions of standard model as a basis to discover deviations
- ⊙ all reactions occur at the parton (or preon) level
- ⊙ kinematically well constrained for NC $ep \to ep$
  compare jet-measurement with e^--measurement

most interesting question:

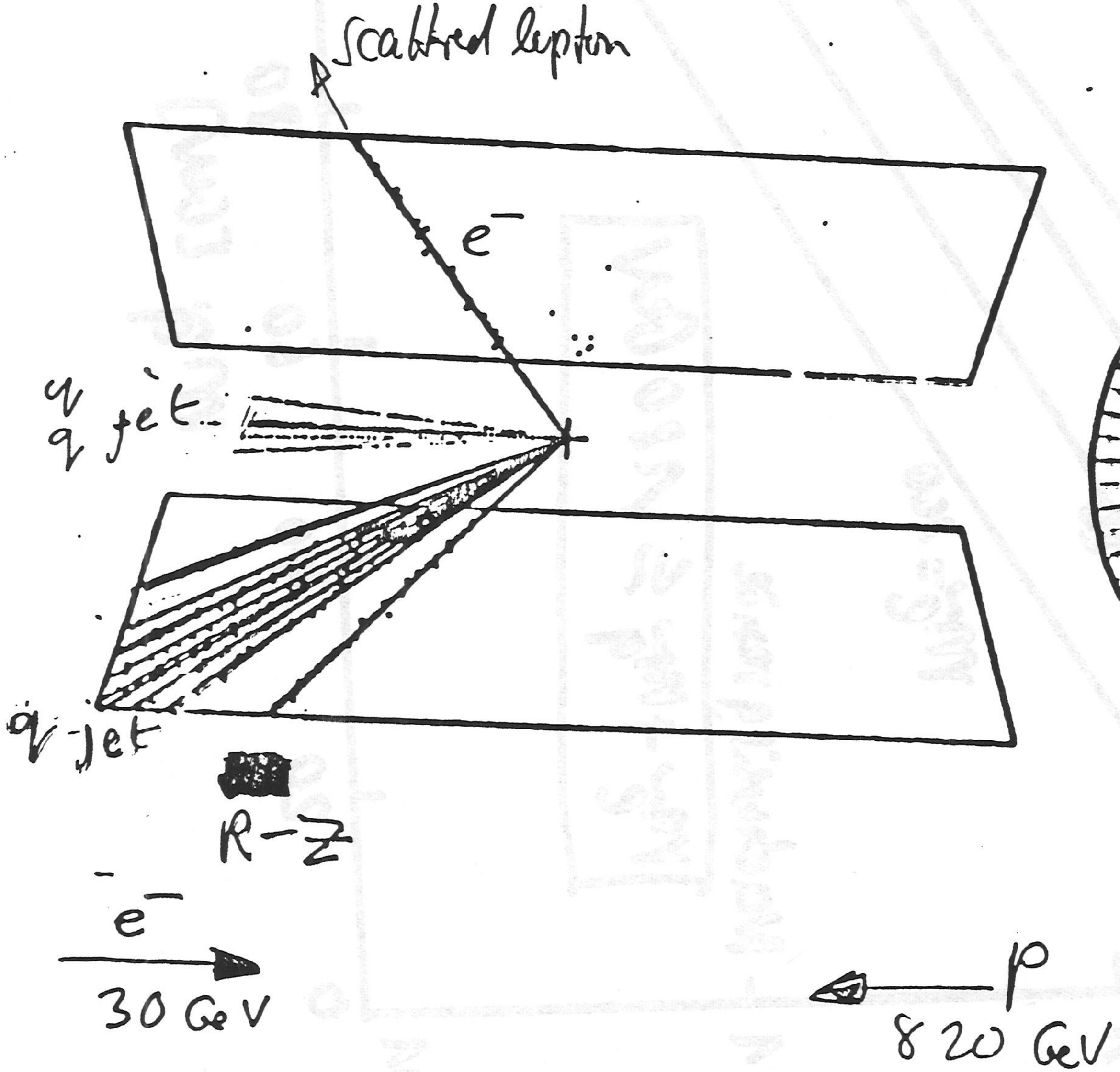
is there a substructure of quarks and leptons?

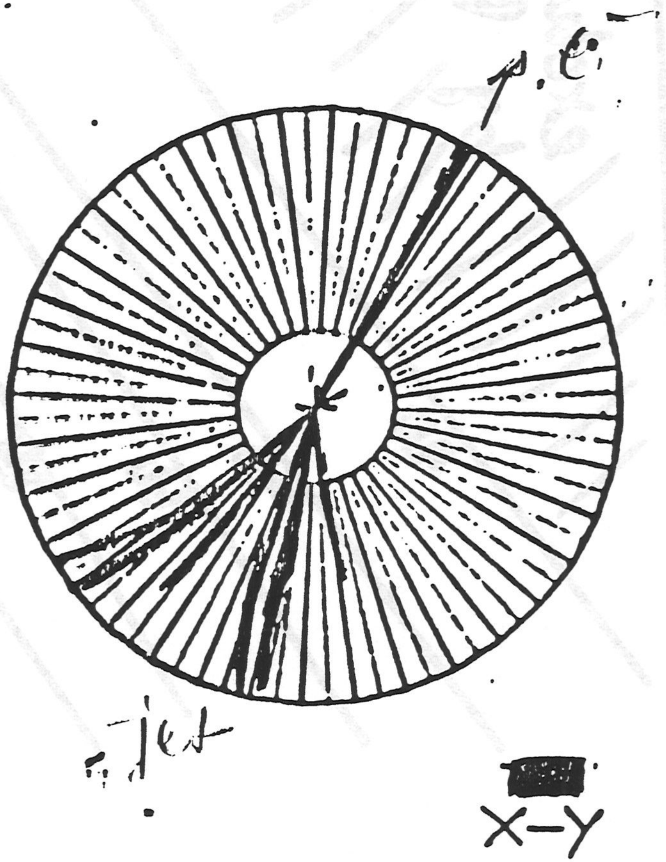
handles:
i) formfactor of quarks (leptons)?
$F_2(x, Q^2) \longrightarrow F_2(x, Q^2) \cdot / (1 + q^2/M^2)$
⟹ ii) new particles: e^*, leptoquarks
⟹ iii) contact interactions: large effects possible

!!! ⊙ Polarization $e^{\pm}_R, e^{\pm}_L$ will give excellent handle to study and confirm new effects


e
q
ẽ, ν̃
q̃
γ̃
Z̃
Ereignisse/Tag
excluded by PETRA
10
1
.1
.01
20
40
60
80
$m_{\tilde{e}} = 100$
Nachweisgrenze
$m_{\tilde{e}} + m_{\tilde{q}} \lesssim 180$ GeV
0
20
40
60
80
100
$m_{\tilde{q}}$ [GeV]

$\boxed{Q^2 = 10^4 \qquad x = 0.3}$ (W = 65 GeV)





"splendid isolation of lepton and hadron vector"

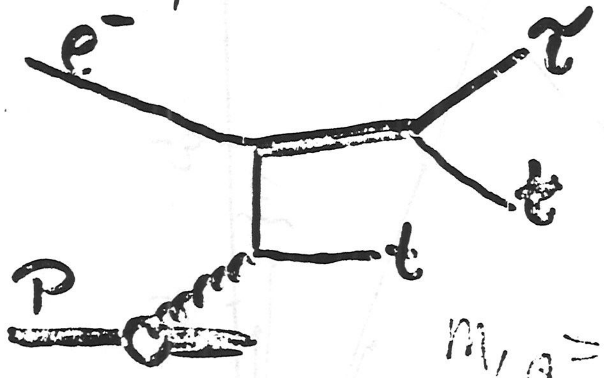
⇒ clean signatures, esp. in lepton sector

⇒ kinematically well constrained

I partons in hard collision

example:

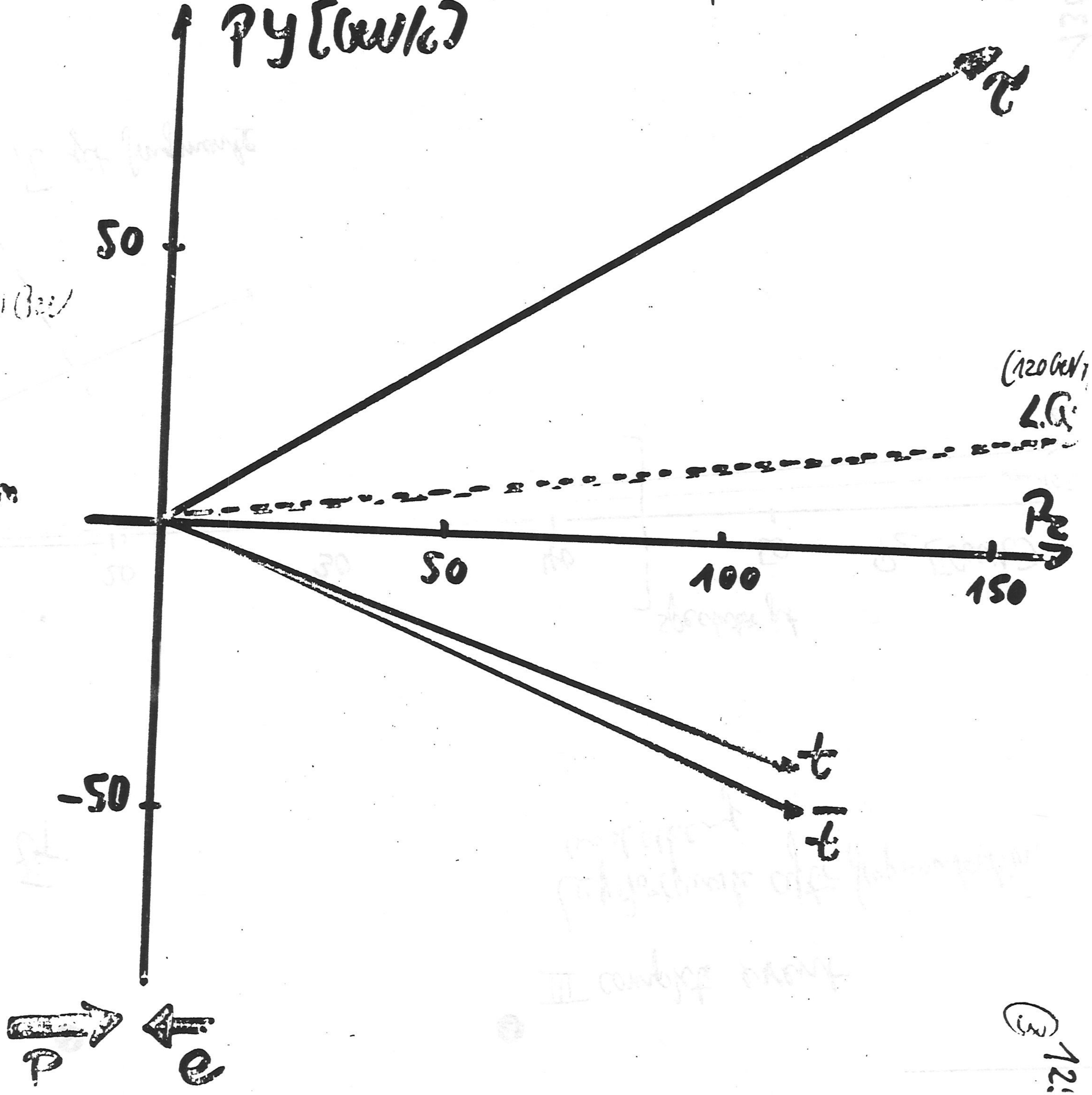
"Leptoquark-production"



$m_{LQ} = 150\ GeV$

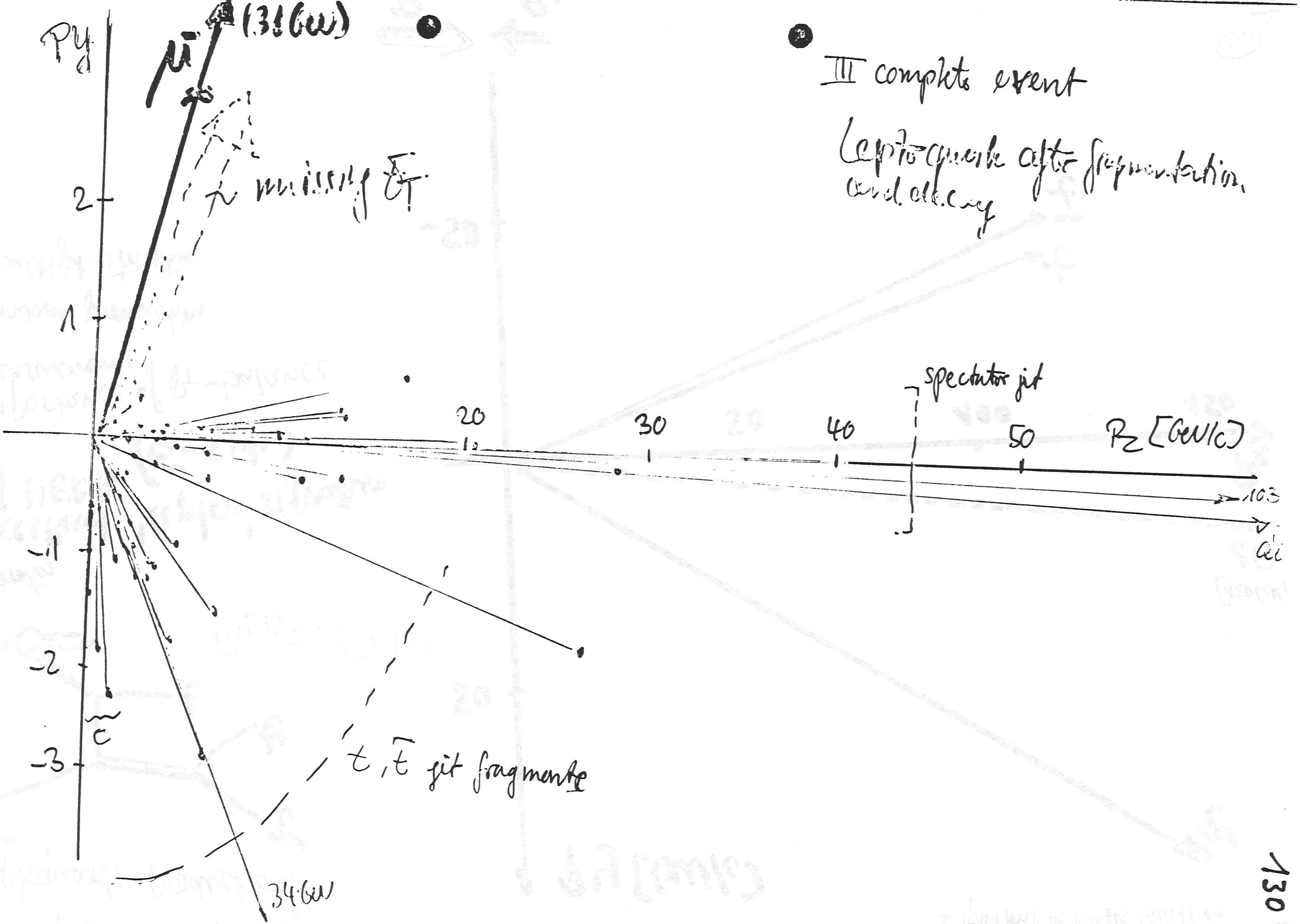
illustrates

- excellent 'lepton' signature of HERA (e^--side)
- importance of P_T-balance measurements
- "forward" production
- multijet-structure



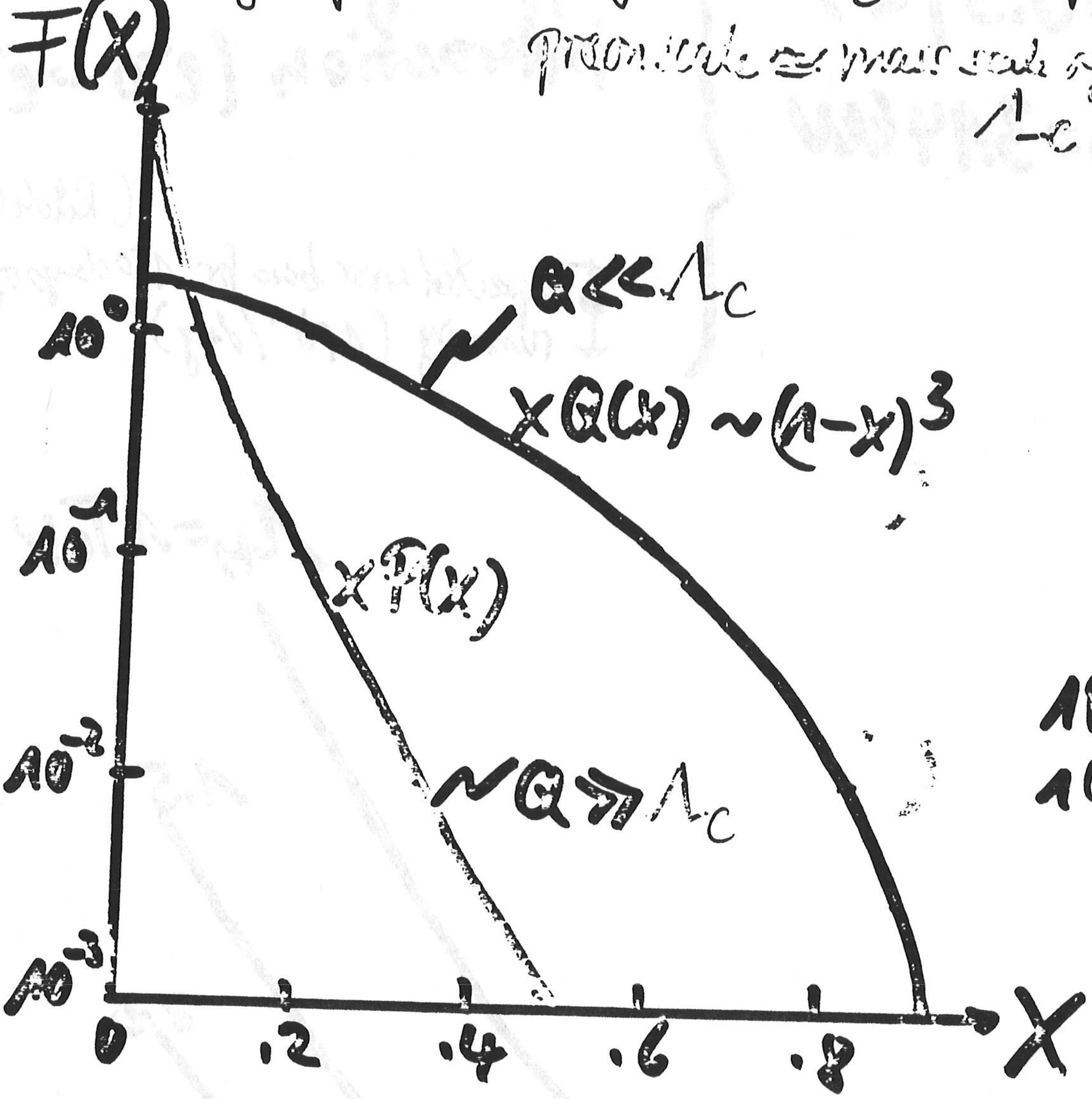
III complete event

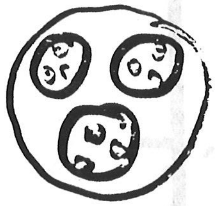
Leptoquark after fragmentation and decay



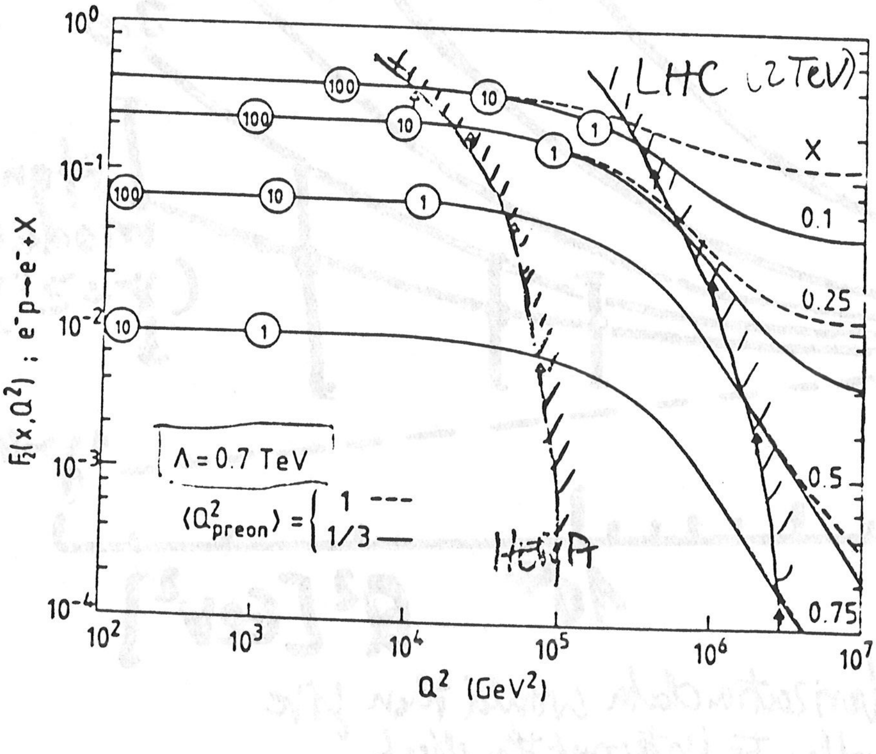
Change of structure function F_2 at preon scale

preon scale ≅ mass scale of new strong inte
$\Lambda_c \gtrsim$ TeV



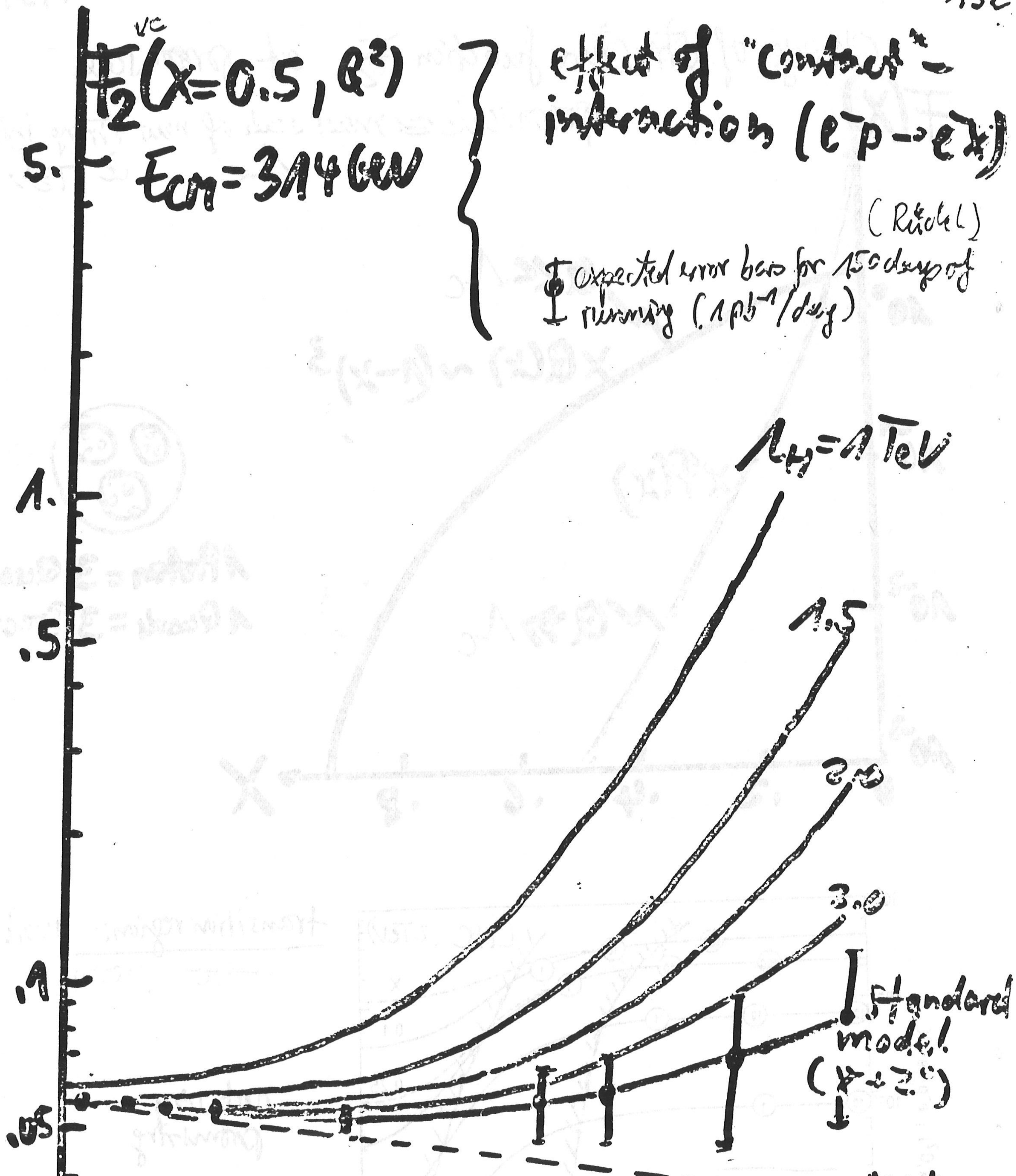


1 Proton = 3 Quar
1 Quark = 3 Preon



transition region: quarks
→ to preons

not very promising



$F_2^{NC}(x=0.5, Q^2)$
$E_{CM} = 314$ GeV

effect of "contact"-interaction ($e^-p \to e^-X$)

(Rückl)

expected error bars for 150 days of running (1 pb^{-1}/day)

note: Polarization data would then give handles to interpret the effect requirements for detector ;

good e^- identification + measurement : NC
excellent hadron flow measurements

$$x = \left(\Sigma P_x^{i\,2} + \Sigma P_y^{i\,2} \right) / y \qquad y = \Sigma \left(E^i - P_z^i \right) / 2E_e$$

} sum over all visible hadrons

excellent absolute calibration

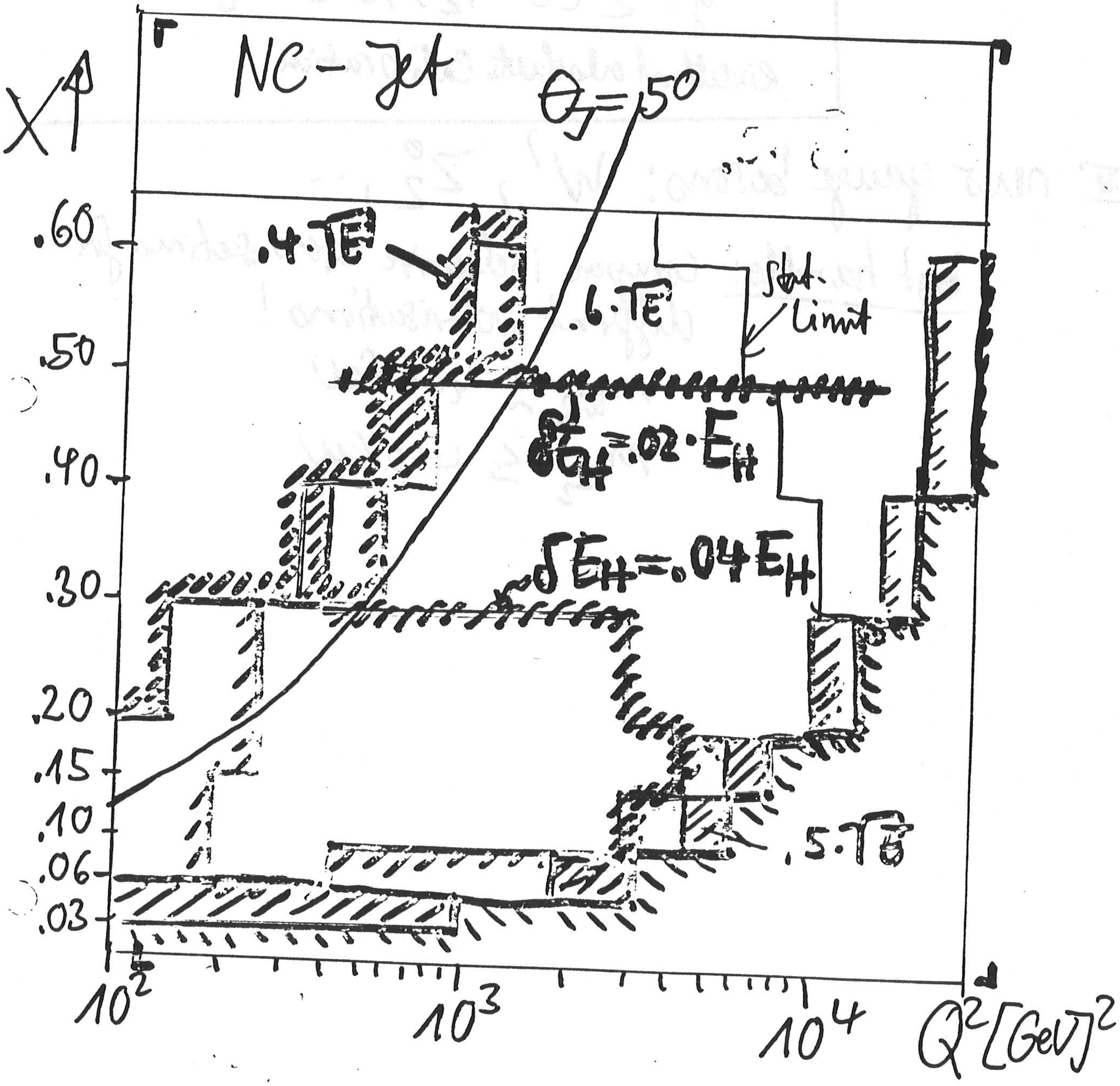
IV new gauge bosons: W', Z_2^0, ..

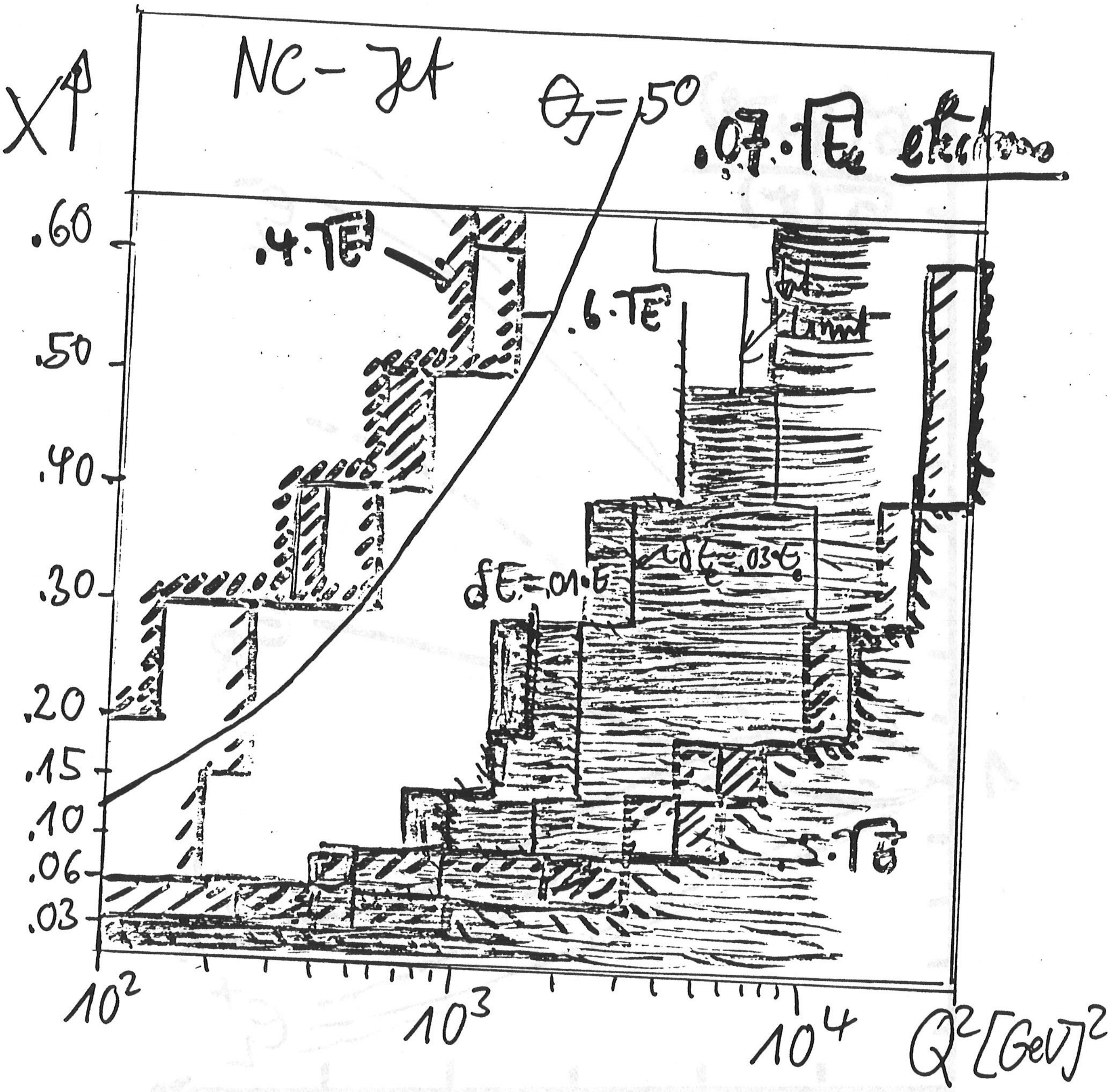
best handle: compare inclusive cross-sections for different polarisations!

$m_{W_R} \lesssim 400$ GeV

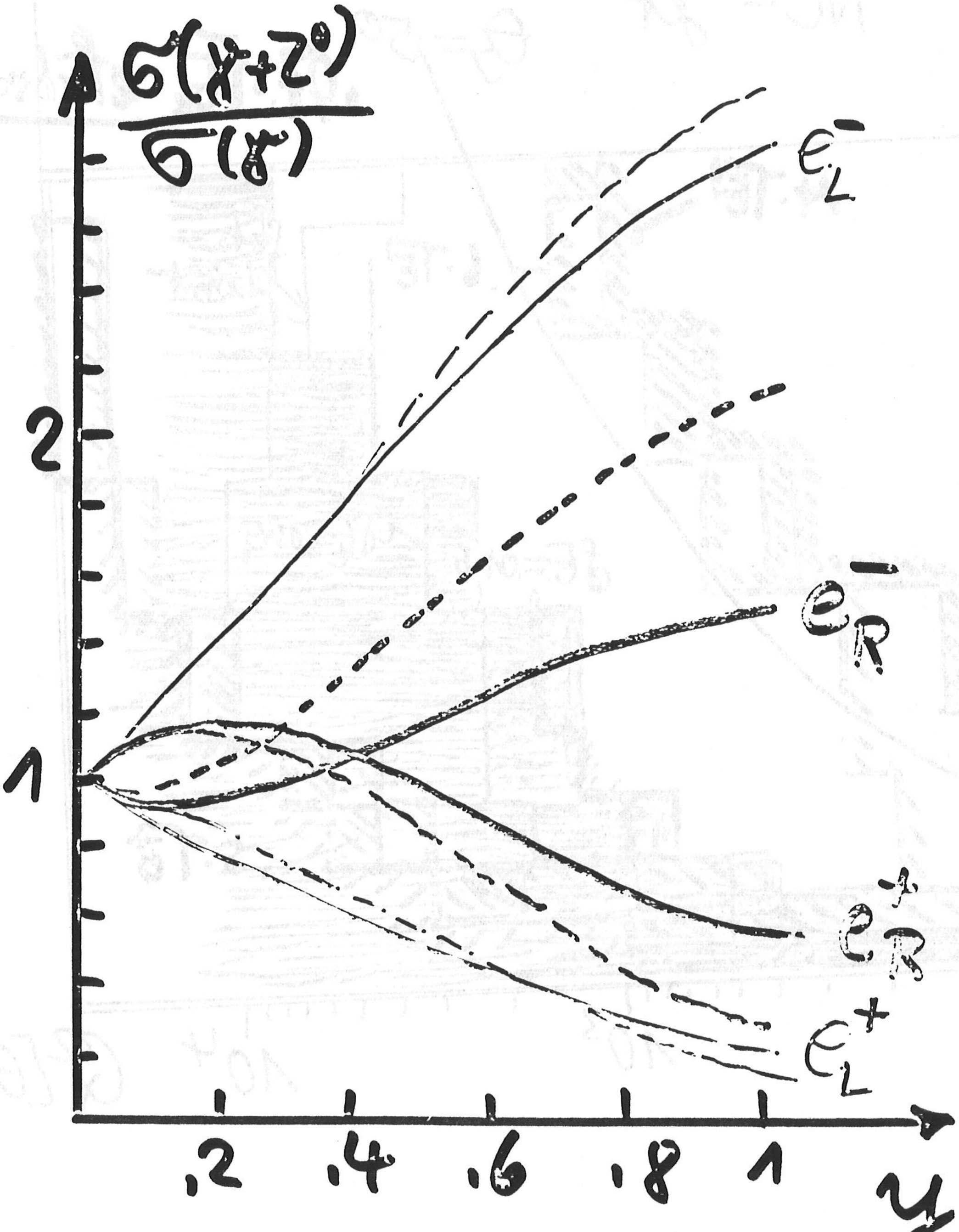
$m_{Z_2'} \lesssim 400$ GeV

$ep \rightarrow eX$




NC - Jet
X
$\Theta_J = 5^0$
$.07 \cdot \sqrt{E_e}$ electron
.60
.50
.40
.30
.20
.15
.10
.06
.03
$.4 \cdot \sqrt{E}$
$.6 \cdot \sqrt{E}$
Stat. Limit
$dE = .01 \cdot E$
$dE = .03 \cdot E$
$.5 \cdot \sqrt{E}$
10^2
10^3
10^4
$Q^2 [GeV]^2$

Struktur neutraler Ströme ($x = .25$)



== : Standardmodell ($\sin^2\theta_W = .23$)

- - - : 2 Z^0's mit $m_{Z_2^0} = 224$ GeV
($SU(2)_L \times SU(2)_R \times U(1)$)

Status of project (few comments)

①

I machine : project has started with a very impressive speed

- construction has started last year
  - halls, tunnel   ∗ 1/8 done
- $e^{\pm}$-ring : "standard", many components ordered
  - ready : 3/88
- p-ring : - superconducting magnets

BM: 6 m {— warm / — cold} iron prototypes successfully tested

easy? step : ⇒ new "hybrid" 9 m magnets
prototype tests summer 85

- large components ordered
  (cryogenic, superconducting cables, iron, ...)
- interaction regions : not finalized

aim: ready for physics end of 1989 !

II detectors : call for letter of intent, Genova 10/84

≤ 3 in first phase

for orientation only

2 new collaborations : { H1 (JADE, PLUTO, CELLO, EMC ..... USA, I, F, P, GB)
(new detectors) { ZEUS (TASSO, + ... GB, CAN, USA, I, P, ..)

+ ev: ~~use of upgraded UA1-detector~~

milestones for experiments {
Letter of intent June 85 ⇐
technical proposal March 86
decision mid 86

Start: 1/90


HERA
PETRA
DESY
DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

Detector design :

*) ⊙ emphasis on hadron energy flow measurements

H1: Liquid calorimeter

- high granularity
- good jet energy resolution ← ceramic
- good coverage for ΔE_T-measurements
- very good and stable calibration ($\leq 1\%$!)

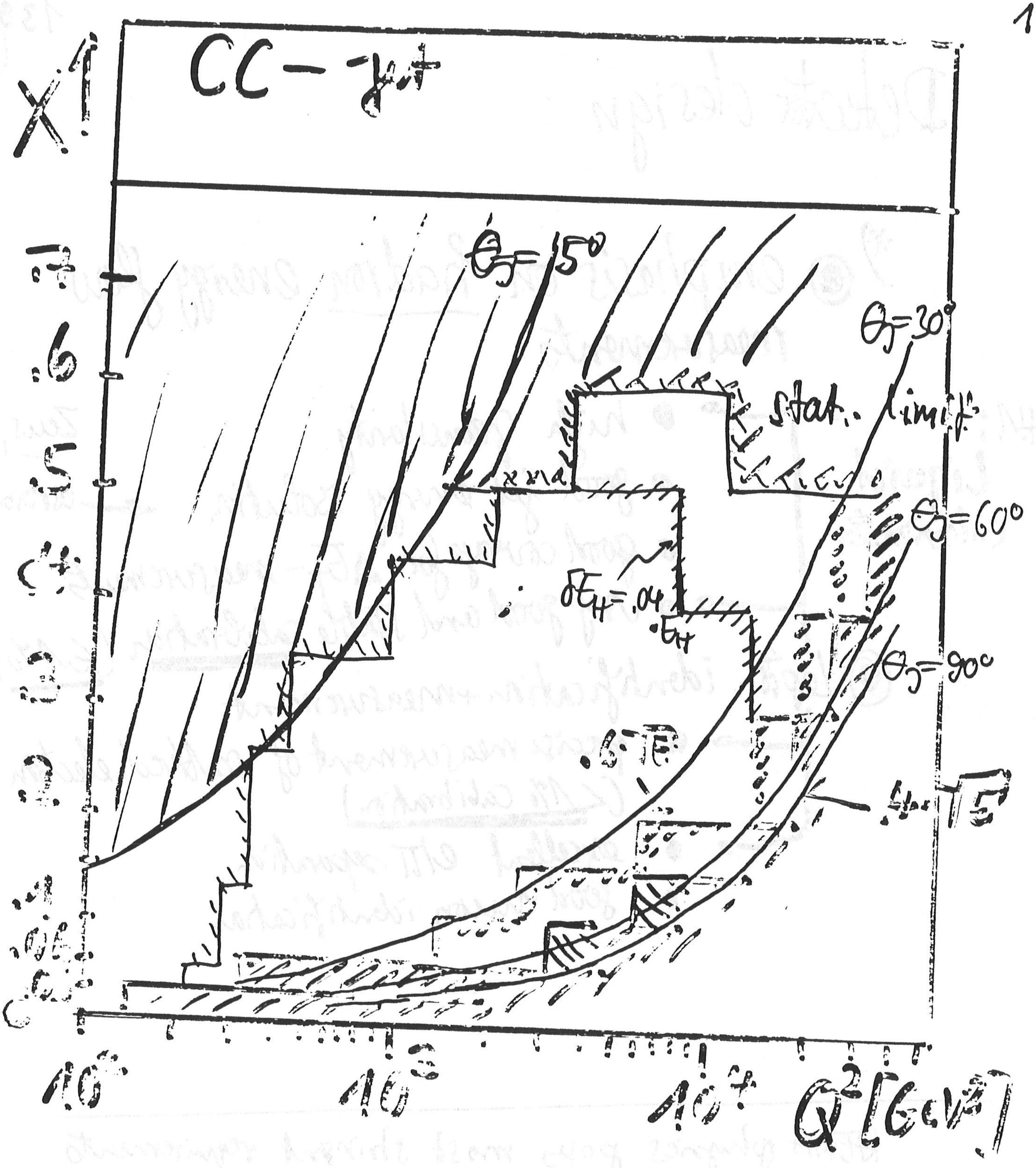
Zeus, H1

⊙ Lepton identification + measurement

- precise measurement of scattered electron ($< 1\%$ calibration)
- excellent e/π separation
- good muon identification

HERA physics poses most stringent requirements on hadron calorimeters:

- energy resolution
- angular resolution (fine granularity)
- absolute calibration to 1-2% level



$$ep \longrightarrow \nu \underbrace{X}_{\text{relies entirely on jet measurement}}$$

H1- Collaboration

main emphasis on:

$\frac{\Delta E_e}{E_e} \le \frac{10\%}{\sqrt{E_e}}$
very fine grained el. magn. calorimeter

- lepton identification (e, μ)
- missing E_T-measurements (ν, $\tilde{\gamma}$)
- NC- inclusive measurements

less ambitious on CC inclusive measurements:
Pb/Cu - LA - calorimeter : $\frac{\Delta E_H}{E_H} \gtrsim .5/\sqrt{E_H}$

technique: liquid argon calorimeter:
- stable calibration
- radiation proof
- high granularity

ZEUS-Collaboration:

main emphasis on:

aim at:
$\frac{\Delta E_H}{E_H} \simeq \frac{.35}{\sqrt{E_H}}$

- CC- inclusive measurements:
  (Uranium/scintillator-calorimeter)
- missing E_T measurements

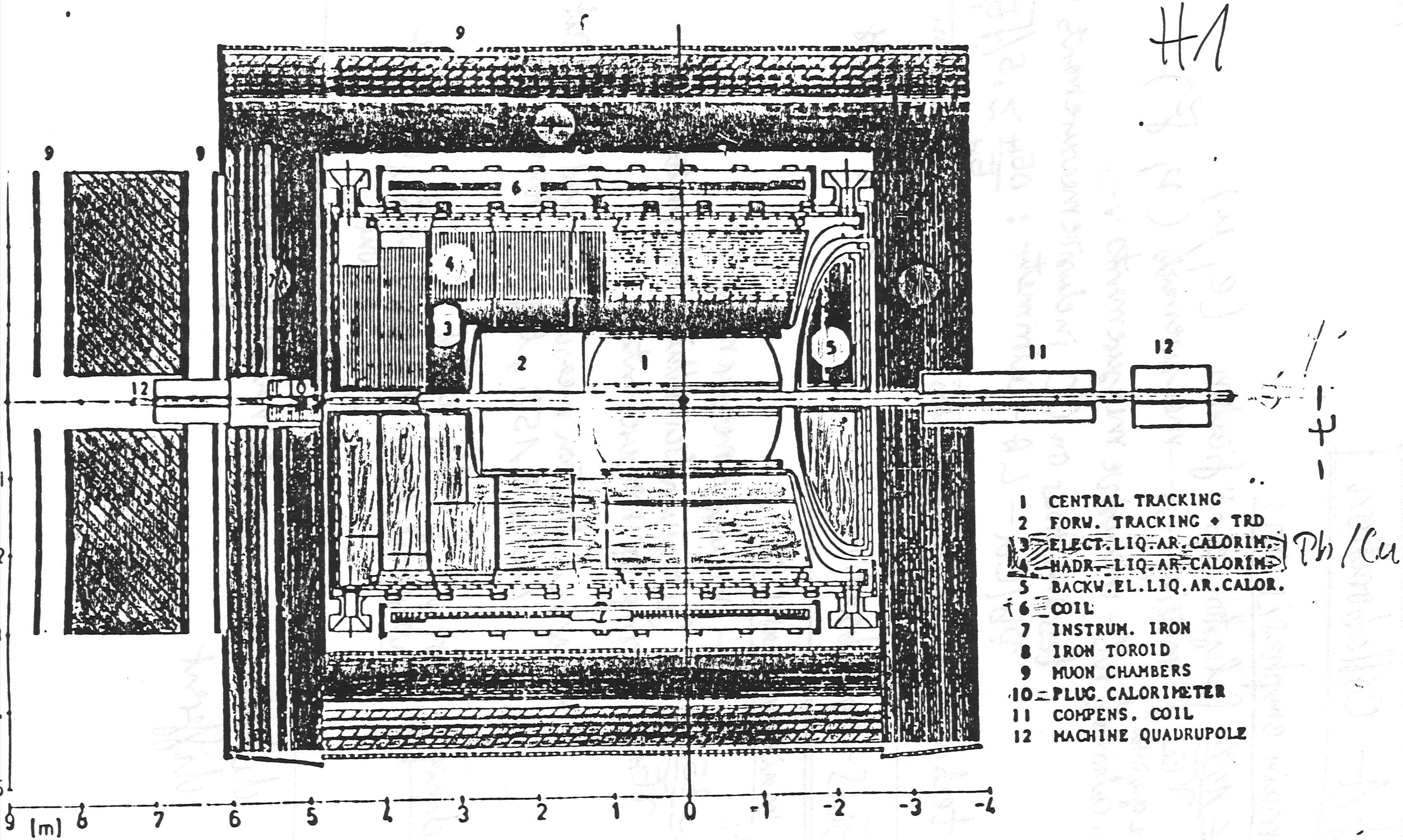
relax on electron measurement and identification;
$\Delta E_e/E_e \gtrsim 15\%$, larger size towers

technique: not yet finally settled
favoured solution: scintillator with fluorescent fibre readout.

---

detectors are complementary; and rather different

H1



Pb/Cu

Fig. 2.1 Layout of the H1 detector . Vertical cut along the beam

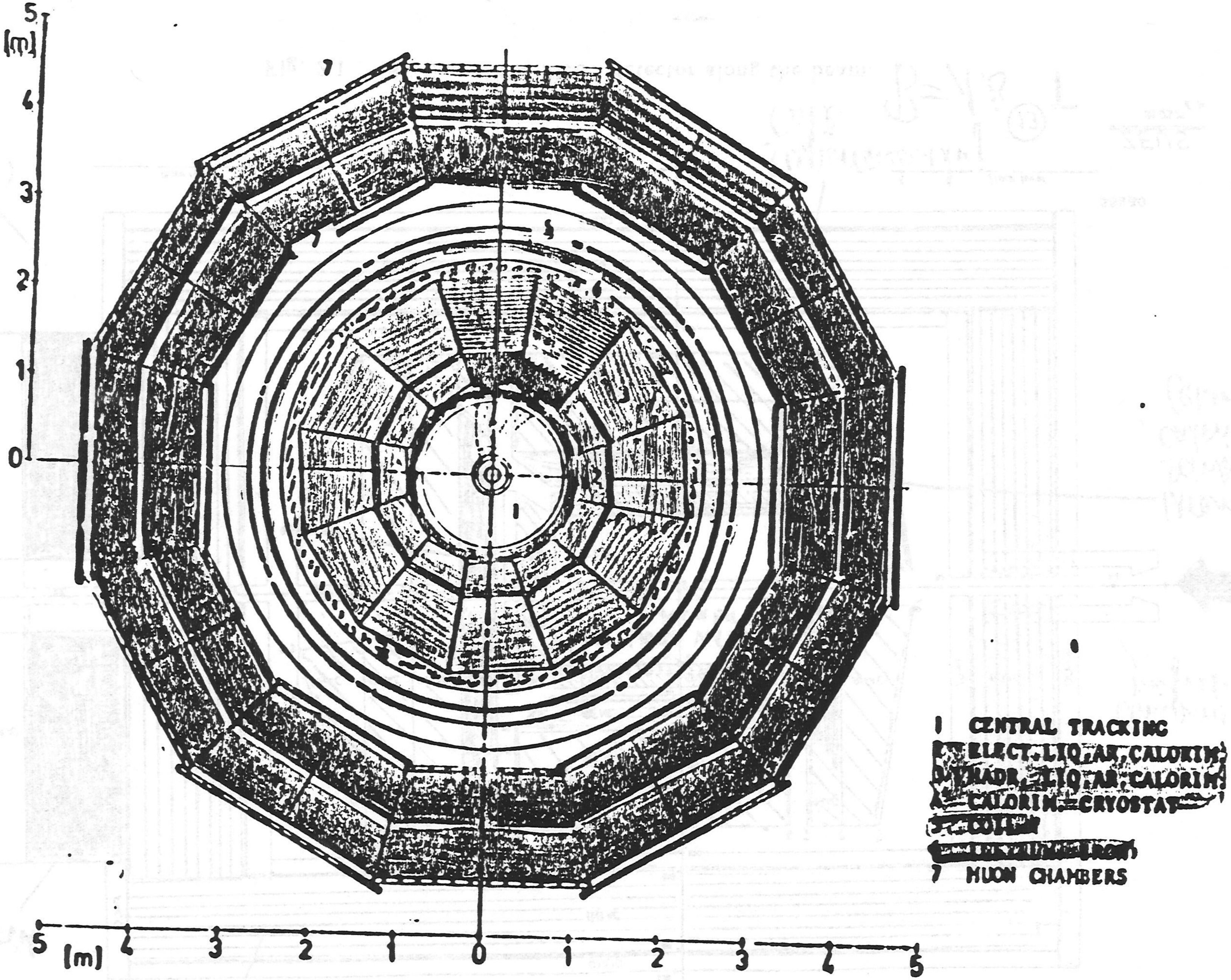


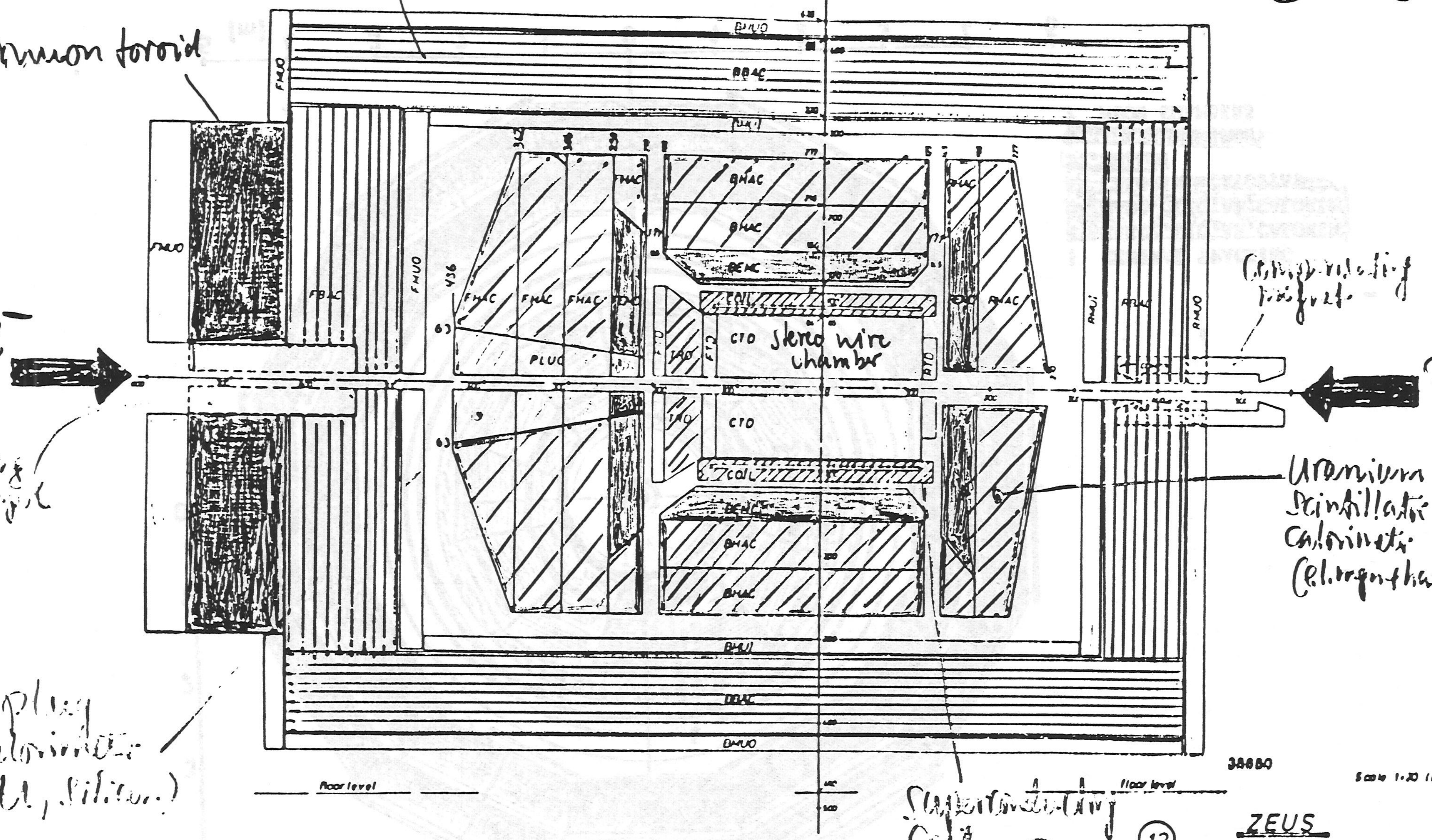
Fig. 2.2 Layout of the H1 detector. Vertical cut transverse to the beam

muon analyser + tail catcher

iron (toroidally magnetized) + instrumented with streamer tubes

ZEUS

muon toroid



e^-

stereo wire chamber

P

compensating magnet

focussing quadrupol

Uranium Scintillator Calorimeter (el.magnet + hadron)

plug Calorimeter (Cu, Silicon)

Superconducting Coil. B = 1.8 T ⑬

Fig. 2.1 Section of the ZEUS detector along the beam.

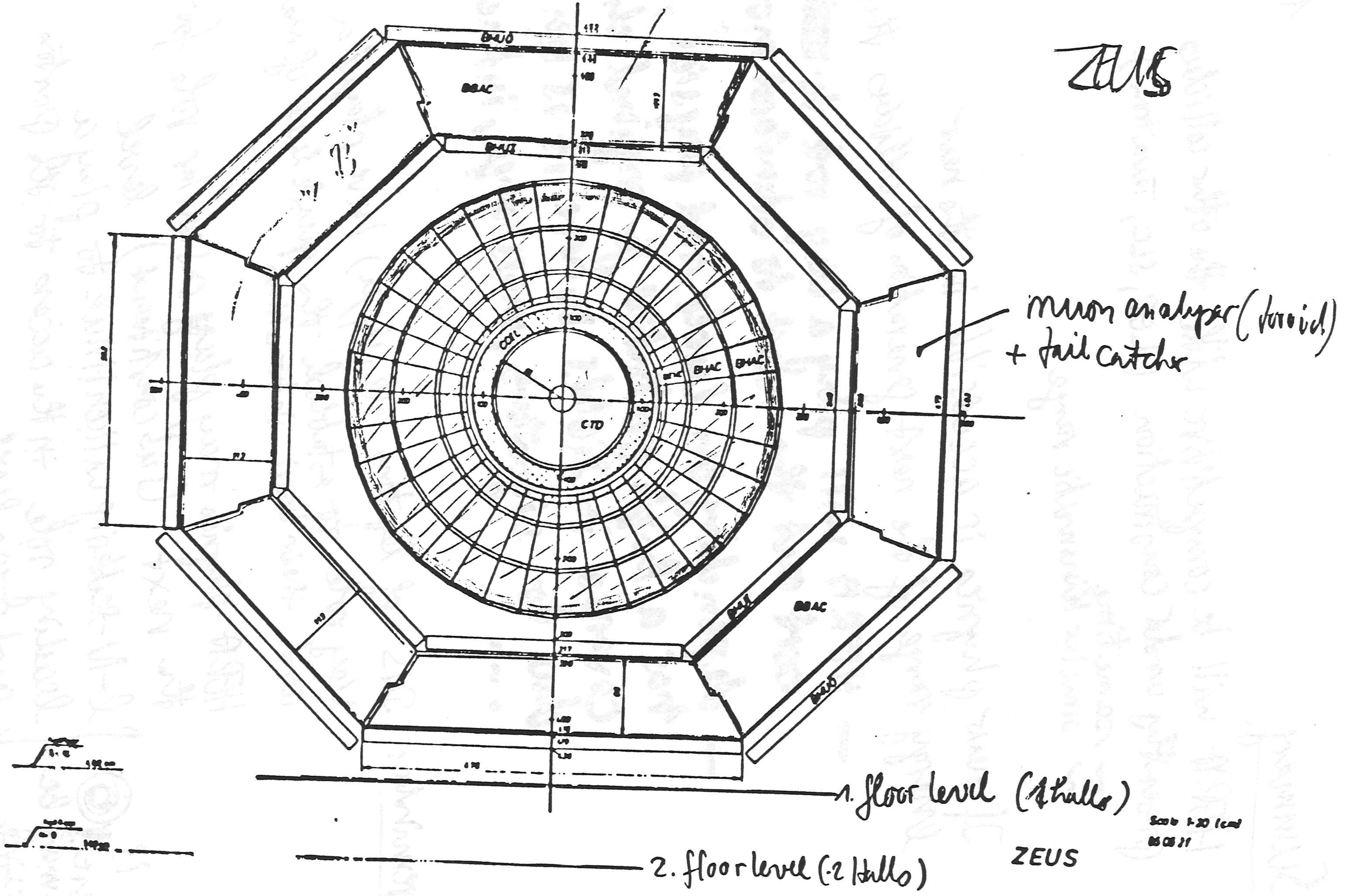


Fig. 2.2 Section of the ZEUS detector perpendicular to the beam.

Summary

HERA will be competitive with the other colliders presently under construction (LEP, SLC, Tevatron).
~ same time
~ similar kinematic range

If new physics is accessible in the new energy range of the next generation of colliders then

- HERA will play a key role to sort out the next to standard model
- depending on luck and physics, it has a high potential for original discoveries in fields where it is unique due to signatures, mass range, interaction ...

reminder: DIS of leptons (e, ν, μ) have played a key role to establish the quark level of matter and their basic interactions.

HERA-physics may play a similar role for the next (subconstituent) level

There is future ☺ and it may be exciting

{ l-N-scattering will continue to play a leading role in the access to the parton and gluon level

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