Lecture:

Standard Model of Particle Physics

Heidelberg SS 2013

(Weak) Neutral Currents

Contents

- Theoretical Motivation for Neutral Currents
- NC Processes
- Experimental Discovery
- Measurement of the Weinberg Angle
- NC Fermion couplings

Recap: Weinberg-Salam Theory

Left handed fermions (doublets): $\psi_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L \begin{pmatrix} c \\ s' \end{pmatrix}_L \begin{pmatrix} t \\ b' \end{pmatrix}_L$

Right handed fermions (singlets):

$\psi_2 = \nu_{e,R} \quad \nu_{\mu,R} \quad \nu_{\tau,R} \quad u_R \quad c_R \quad t_R$

$\psi_3 = e^-_R \quad \mu^-_R \quad \tau^-_R \quad d_R \quad s_R \quad b_R$

Gauge Transformations:

$$\psi_j(x) \rightarrow \psi'_j(x) = \exp\left(i\vec{\alpha}(x)\frac{\vec{\tau}}{2}\right) \cdot \exp\left(i\beta(x)\frac{Y_j}{2}\right)\psi_j(x)$$

SU(2) U(1)

τ: Pauli matrices Y_j: hypercharge

Smallest gauge group representation with >1 gauge boson is SU(2):

W^+, W^- representated by $\tau^\pm = \frac{1}{2}(\tau_1 \pm i\tau_2)$

additional W_3 field represented by: τ_3 (→4th gauge boson)

Recap: Weinberg-Salam Theory

Left handed fermions (doublets):

$$\psi_1 = \begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L \qquad \begin{pmatrix}u\\ d'\end{pmatrix}_L \quad \begin{pmatrix}c\\ s'\end{pmatrix}_L \quad \begin{pmatrix}t\\ b'\end{pmatrix}_L$$

Right handed fermions (singlets):

$$\psi_2 = \quad \nu_{e,R} \quad \nu_{\mu,R} \quad \nu_{\tau,R} \qquad u_R \quad c_R \quad t_R$$

$$\psi_3 = \quad e^-_R \quad \mu^-_R \quad \tau^-_R \qquad d_R \quad s_R \quad b_R$$

Gauge Transformations:

$$\psi_j(x) \rightarrow \psi'_j(x) = \exp\left(i\vec{\alpha}(x)\,\frac{\vec{\tau}}{2}\right)\cdot\exp\left(i\beta(x)\frac{Y_j}{2}\right)\psi_j(x)$$

SU(2) U(1)

τ: Pauli matrices Y_j: hypercharge

Note:

- SU(2) fields W_1, W_2, W_3, and U(1) field B (hypercharge) correspond to **massless** bosons!
- fields W_3 (V-A coupling) and B (hypercharge) can/do **mix**!

Electroweak Symmetry Breaking

$$\begin{pmatrix} Z \\ A \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W_3 \\ B \end{pmatrix} \quad \leftrightarrow \quad \begin{pmatrix} W_3 \\ B \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z \\ A \end{pmatrix}$$

$$L_{ew} = g\, j_L^3 W_3 + \frac{1}{2} g'\, j^Y B$$

$$\Big\downarrow \text{ symmetry breaking}$$

$$L_{elm} = g\, j_L^3 \sin\theta_W A + \frac{1}{2} g'\, j^Y \cos\theta_W A$$

$$L_{NC} = g\, j_L^3 \cos\theta_W Z - \frac{1}{2} g'\, j^Y \sin\theta_W Z$$

Electromagnetic Interaction

$$L_{elm} = g\, j_L^3 \sin\theta_W A + \frac{1}{2} g'\, j^Y \cos\theta_W A$$

Left-Handed Current:

Pauli matrix τ_3: $\tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ $\qquad j_L^3 = \frac{1}{2}\left(\bar{U}_L U_L - \bar{D}_L D_L\right)$

isospin up isospin down

Hypercharge Current:

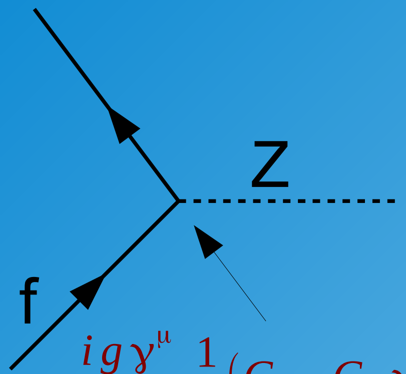
$$j_Y = \bar{\psi}\hat{Y}\psi = Y_{doublet}\bar{U}_L U_L + Y_{doublet}\bar{D}_L D_L + Y_{singlet}\bar{D}_R D_R$$

only "down" component here (leptons)!

Photon field: vector current and coupling to electric charges:

1. $e = g\sin\theta_W = g'\cos\theta_W \quad \rightarrow \quad j_{elm} = j_L^3 + \frac{1}{2} j^Y \quad \rightarrow \quad Q = I + \frac{1}{2}Y$ Gell-Mann Nishijima
2. Leptons: $Y_{doublet} = -1,\ Y_{singlet} = -2 \quad \rightarrow \quad j_{elm} = -\bar{D}_L D_L - \bar{D}_R D_R$ (e,μ,τ)
3. Quarks: $Y_{doublet} = \frac{1}{3},\ Y_{u-singlet} = \frac{4}{3},\ Y_{d-singlet} = -\frac{2}{3}$

Weak Neutral Current



$$\frac{i g \gamma^\mu}{\cos\theta_W}\frac{1}{2}(C_V - C_A\gamma_5)$$

$$L_{NC} = g\, j_L^3 \cos\theta_W Z - \frac{1}{2} g'\, j^Y \sin\theta_W Z$$

$$\propto \left(\frac{g}{\cos\theta_W}\right)\cos^2\theta_W \qquad \propto g'\sin\theta_W = \left(\frac{g}{\cos\theta_W}\right)\sin^2\theta_W$$

$$(j_{NC})^\mu = \overline{\Psi}\gamma^\mu \frac{1}{2}\left[c_L(1-\gamma^5) + c_R(1+\gamma^5)\right]\Psi_e$$

	$I_3 = -1/2$	$I_3 = +1/2$
$c_L =$	$-1/2 - Q_f\sin^2\Theta_W$	$+1/2 - Q_f\sin^2\Theta_W$
$c_R =$	$-Q_f\sin^2\Theta_W{}'$	$-Q_f\sin^2\Theta_W{}'$

no pure V-A coupling for non-zero Weinberg angle!

$$(j^e_{NC})^\mu = \overline{\Psi}_e\gamma^\mu \frac{1}{2}(C_V - C_A\gamma_5)\Psi_e$$

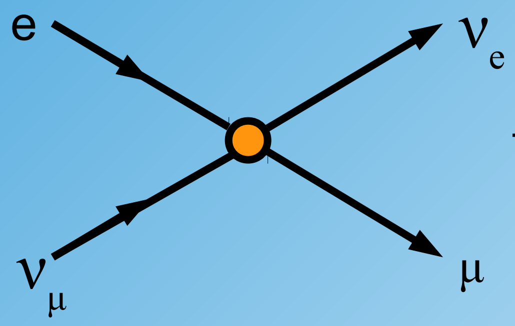
	$I_3 = -1/2$	$I_3 = +1/2$
$C_A =$	$-1/2$	$+1/2$
$C_V =$	$-1/2' - 2Q_f\sin^2\Theta_W$	$+1/2' - 2Q_f\sin^2\Theta_W$

Unitarity in SU(2) Gauge Group

Recall:

divergent behavior at high energies

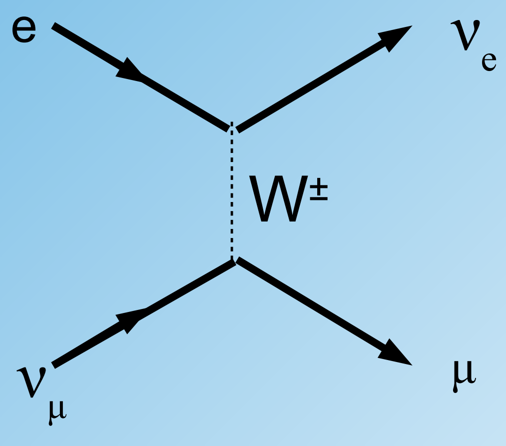
$$\sigma\left(\nu_\mu e \rightarrow \mu \nu_e\right) \propto G_F^2 s$$



four-fermion interaction

fixed by introducing the W-boson

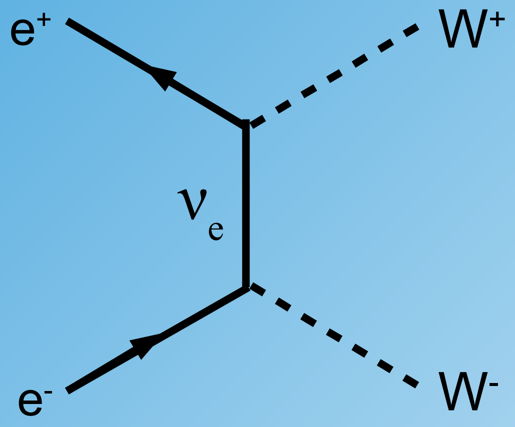
$$\sigma\left(\nu_\mu e \rightarrow \mu \nu_e\right) \propto G_F^2$$



W-exchange

Unitarity in SU(2) Gauge Group

Fermion W-boson Scattering

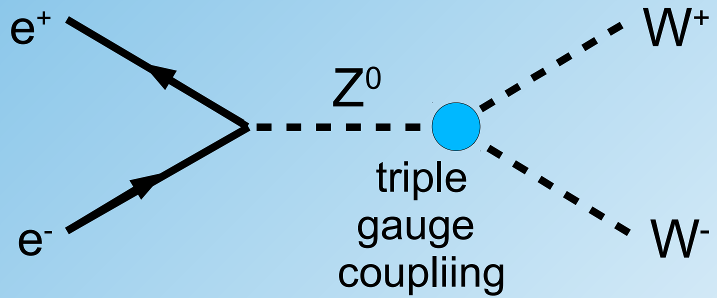


e.g. W-pair production

$$\sigma\left(e^- e^+ \rightarrow W_0^- W_0^+\right) \propto G_F^2 s$$

divergent high energy behavior
of longitudinal ($J_3=0$) spin component

fixed by introducing the Z boson (predicted by non-abelian SU(2))



$$\sigma\left(e^- e^+ \rightarrow W_0^- W_0^+\right) \propto G_F^2$$

General Rule (1970, t'Hooft, Veltmann):

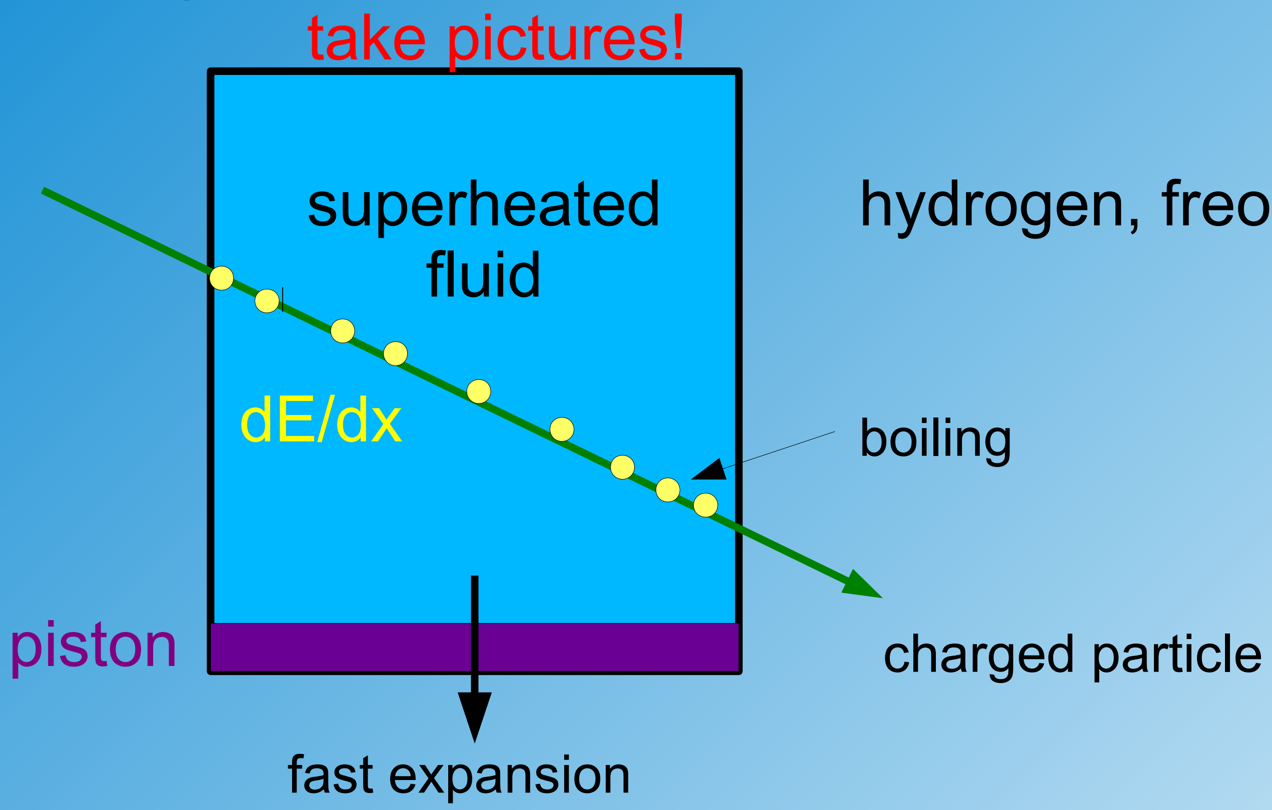
UV-divergences vanish only in gauge invariant theories

Neutrino-Nucleon Scattering Experiments

Experimental Discovery of NC

in early 70ties bubble chambers where used to study particle interactions

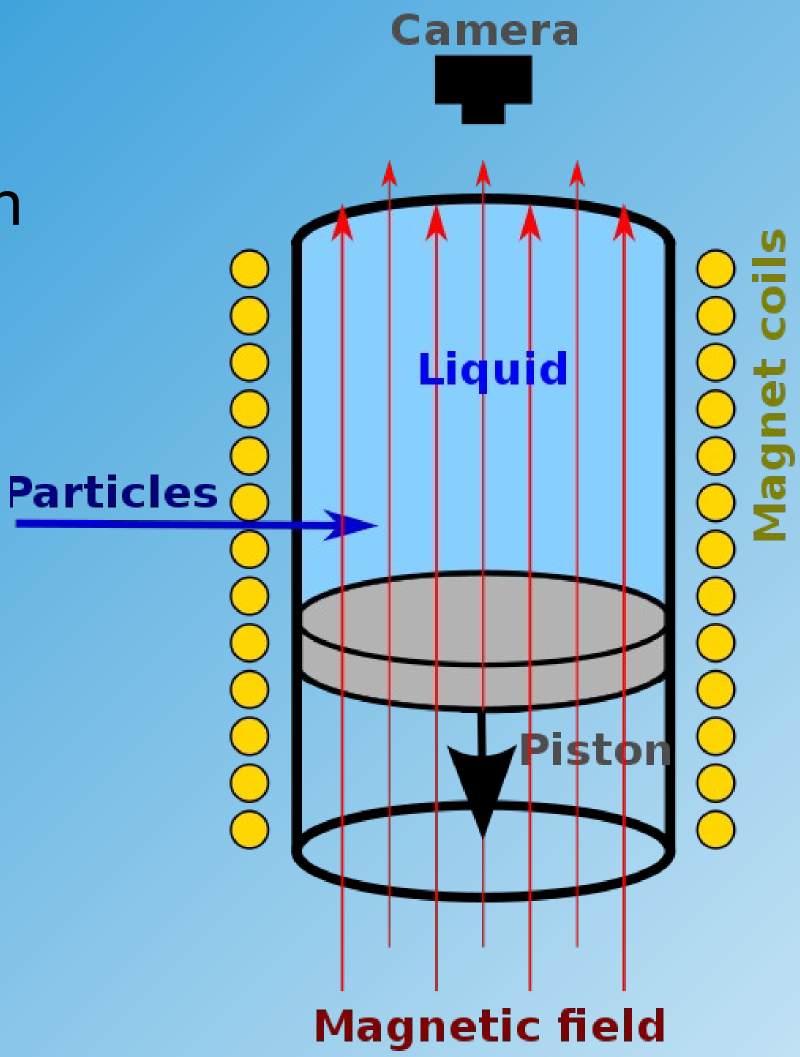
Principle:



- reconstruction of all charged particles!
- problem: low repetition rate, difficult analysis

BEBC principle

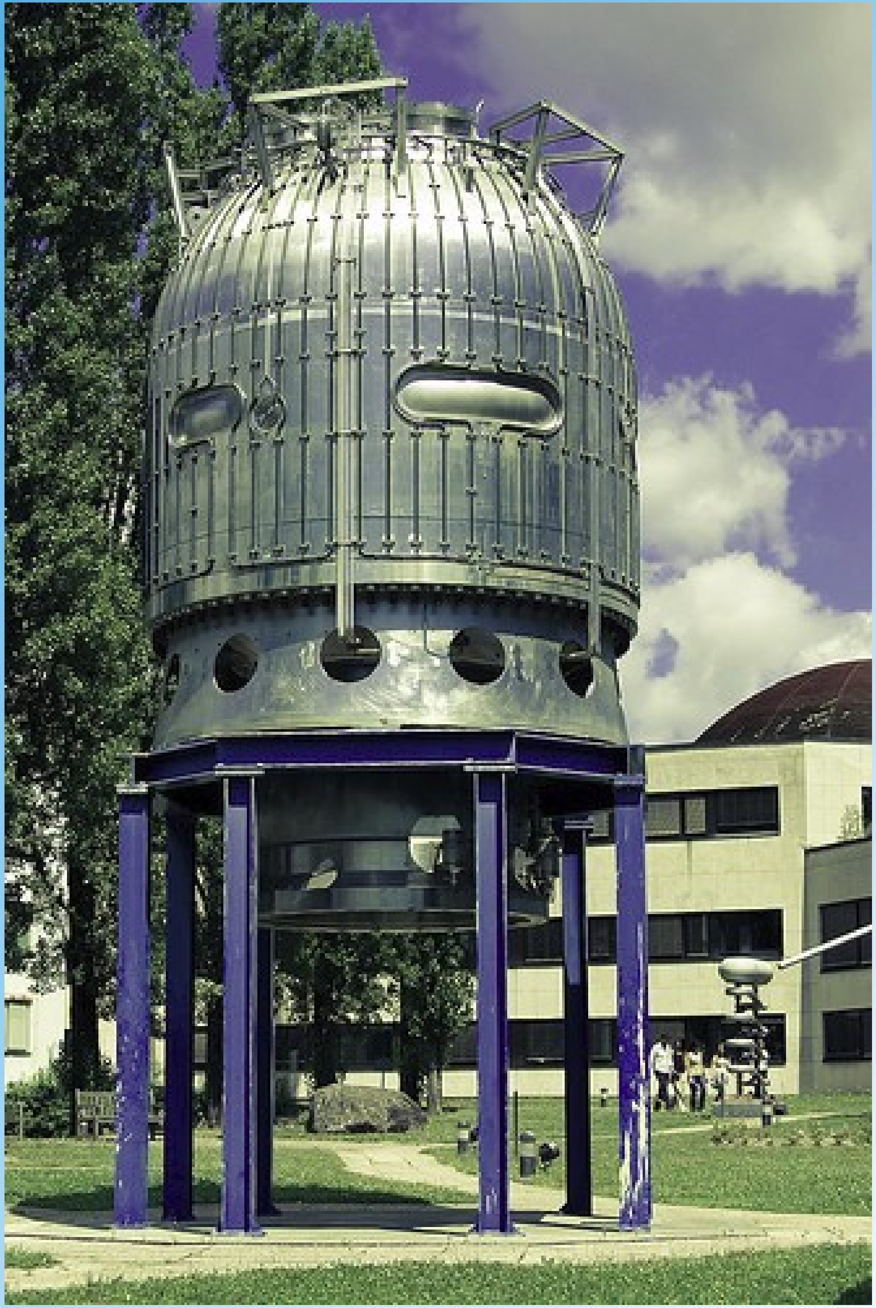
Liquid = hydrogen

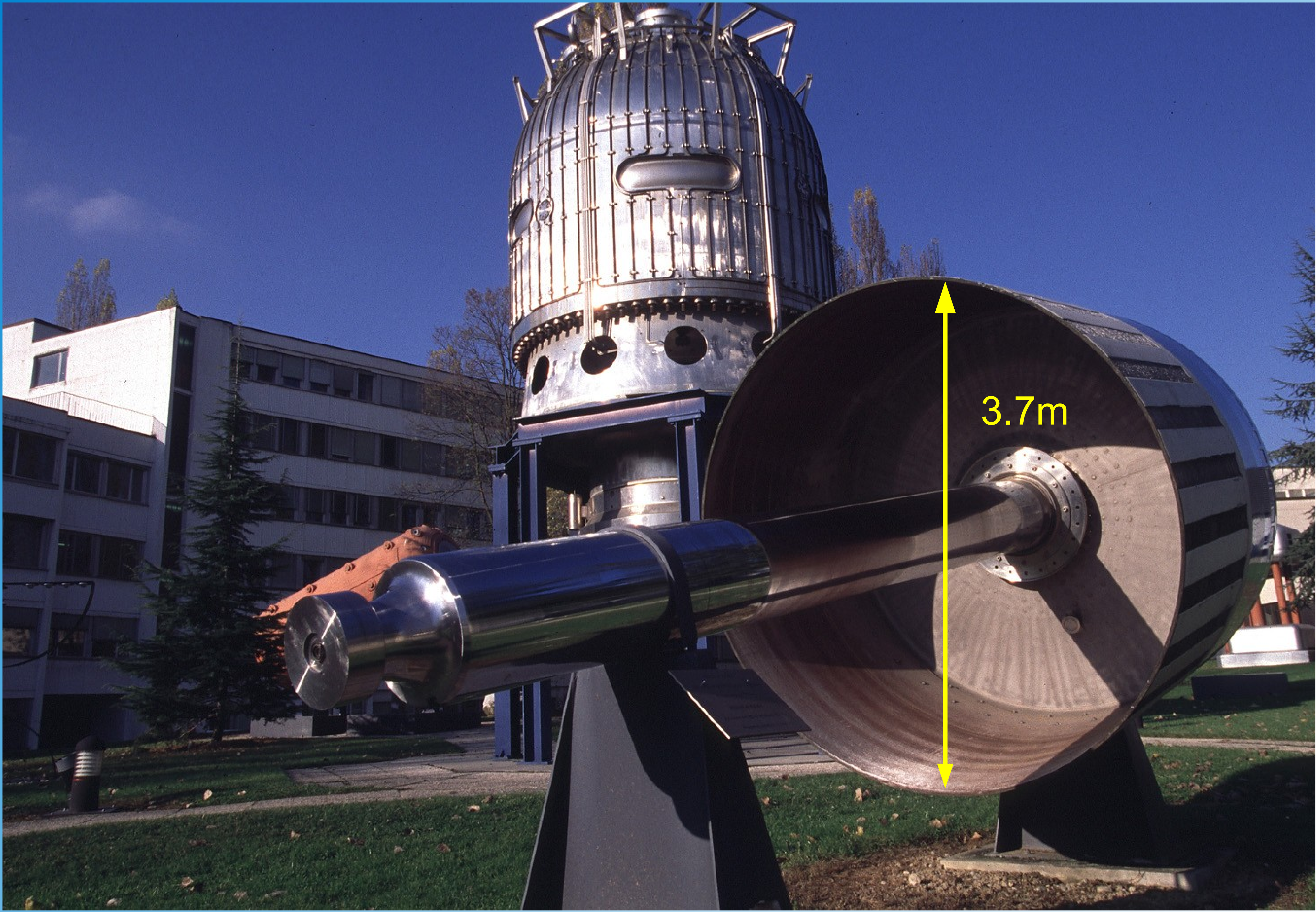


BEBC (CERN, 1967-1984)

Heidelberg -Saclay-CERN

6.3 million photographs

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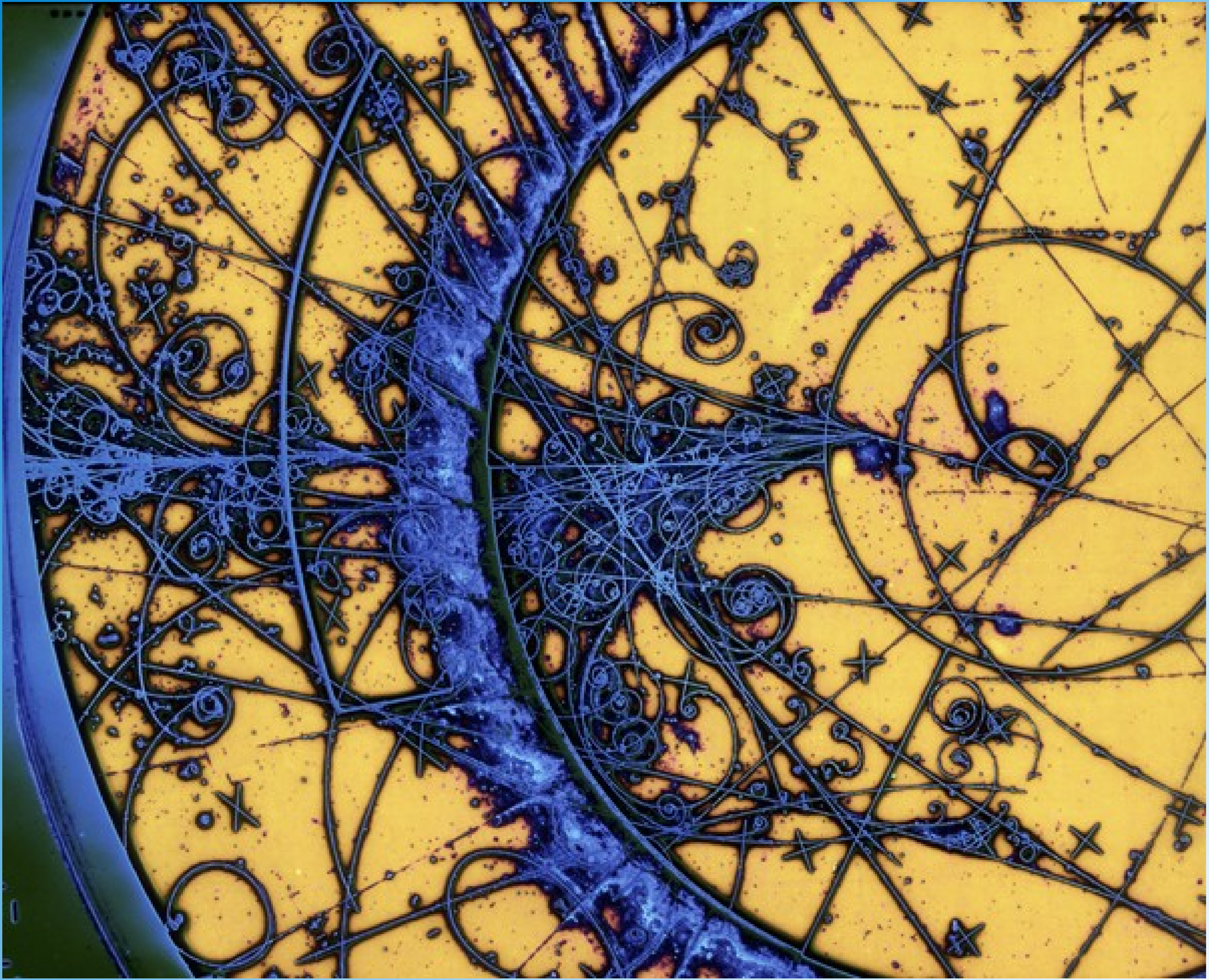
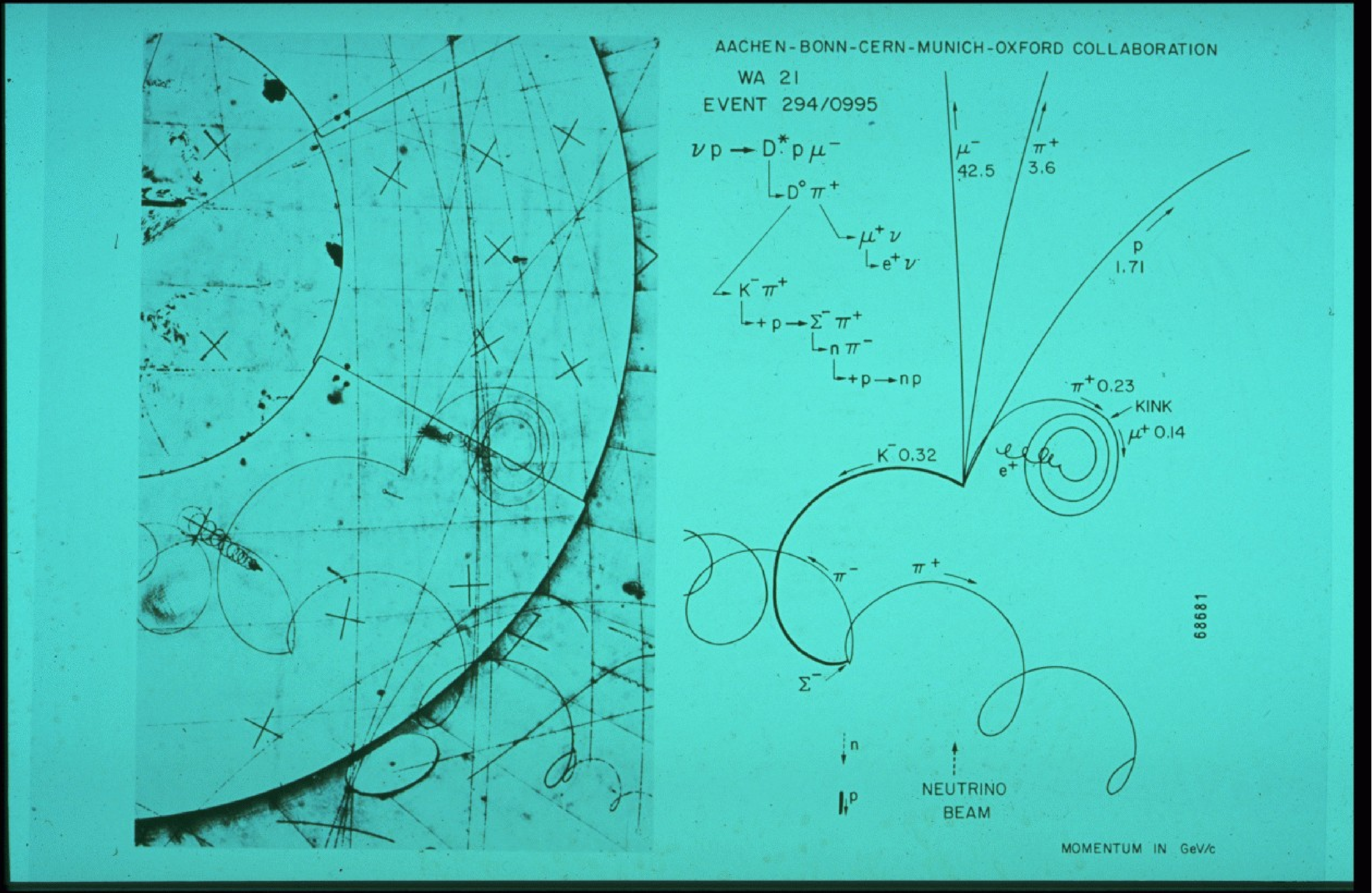


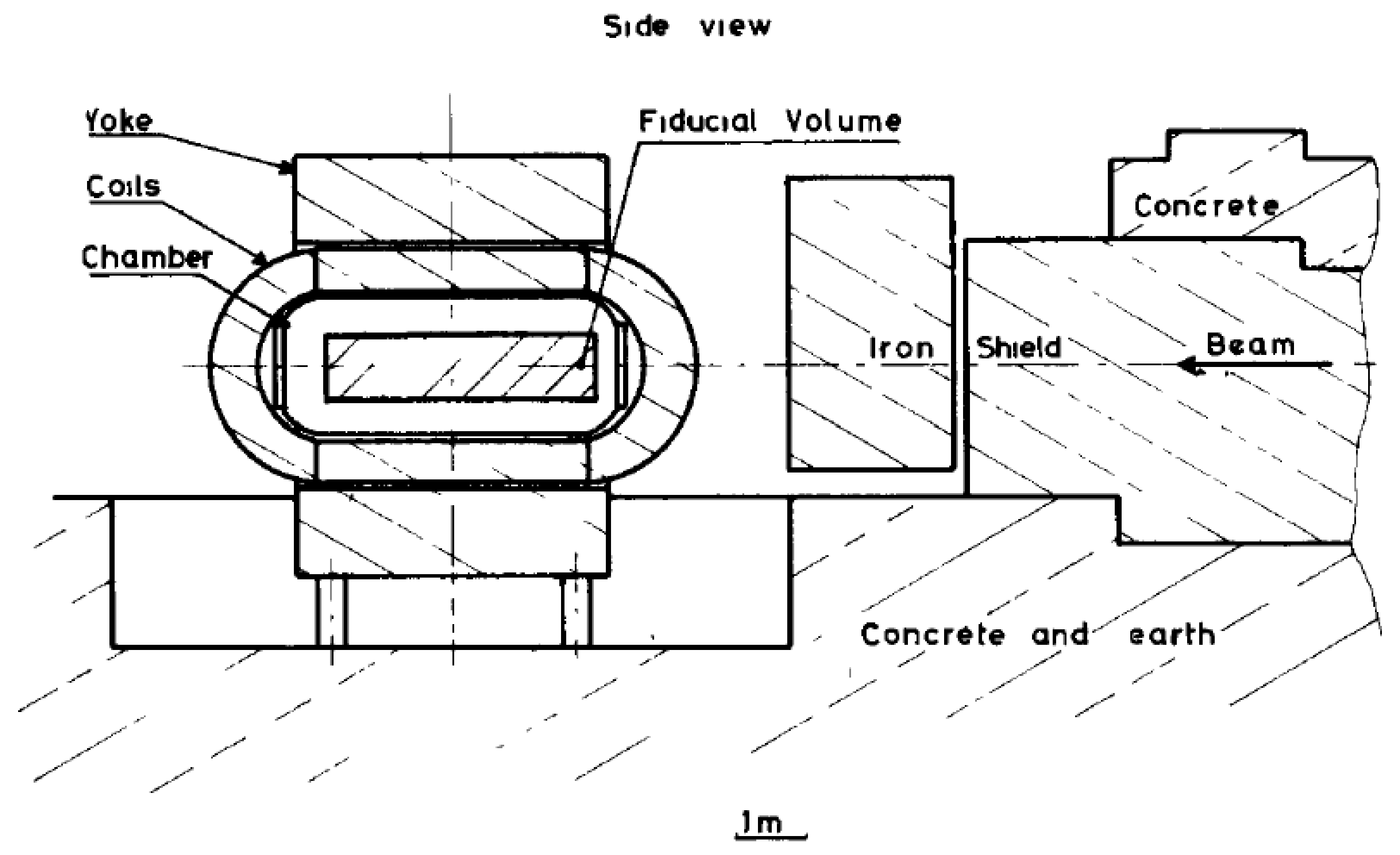
Neutrino-Proton Scattering (Charged Current)



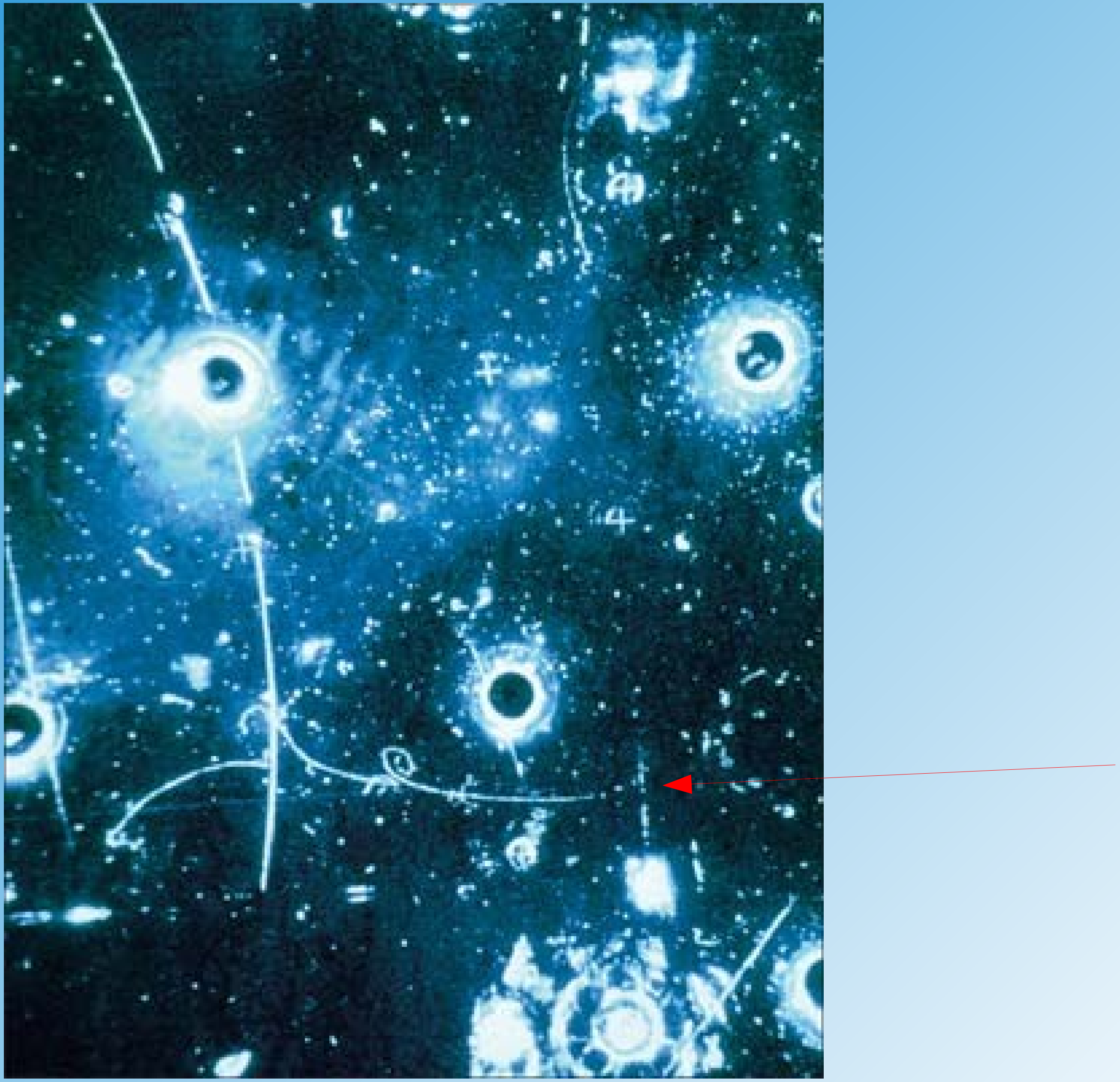
Gargamelle

Liquid: freon (CF3Br).

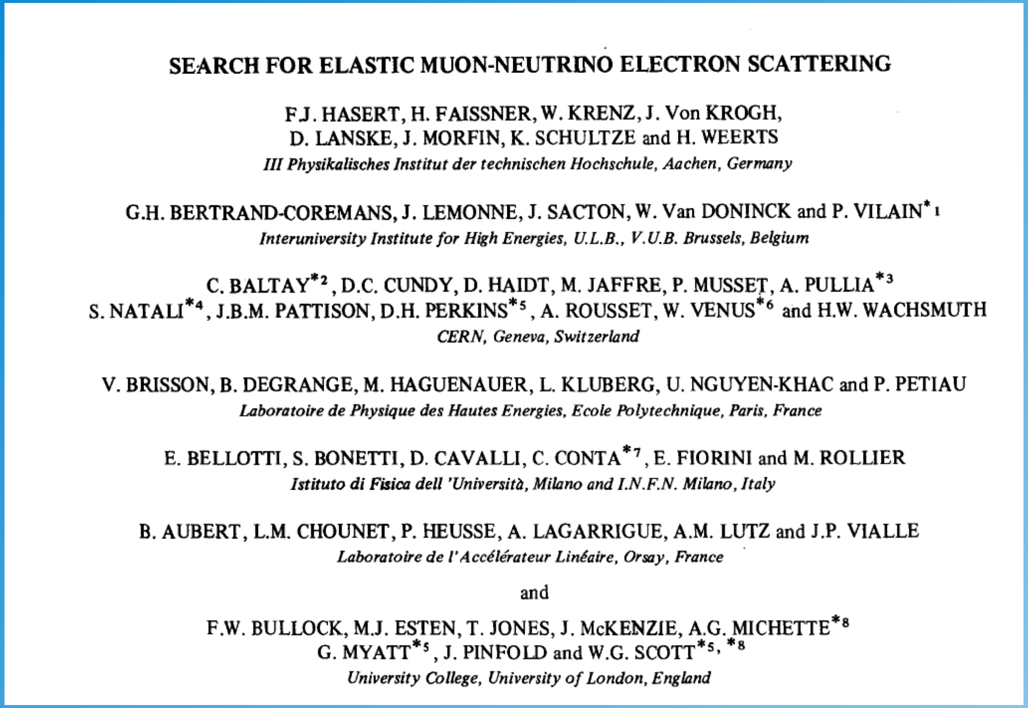
Cross Section of Experiment



Eleastic Neutral Current $\nu e \rightarrow \nu e$



Discovery of Neutral Currents



SEARCH FOR ELASTIC MUON-NEUTRINO ELECTRON SCATTERING

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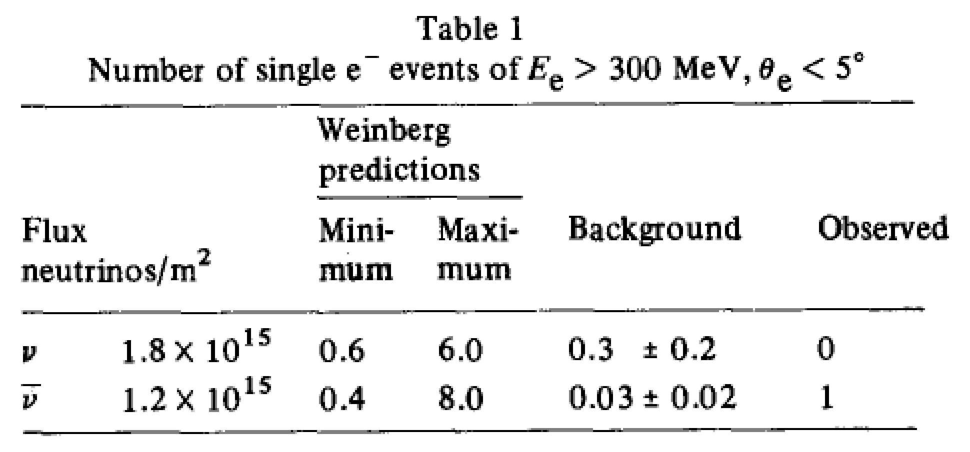
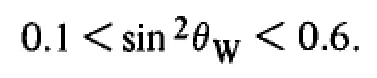


Table 1
Number of single e^- events of $E_e > 300$ MeV, $\theta_e < 5°$

	Flux neutrinos/m^2	Weinberg predictions Minimum	Weinberg predictions Maximum	Background	Observed
ν	1.8×10^{15}	0.6	6.0	0.3 ± 0.2	0
$\bar{\nu}$	1.2×10^{15}	0.4	8.0	0.03 ± 0.02	1



$$0.1 < \sin^2\theta_W < 0.6.$$

Hasert et al.

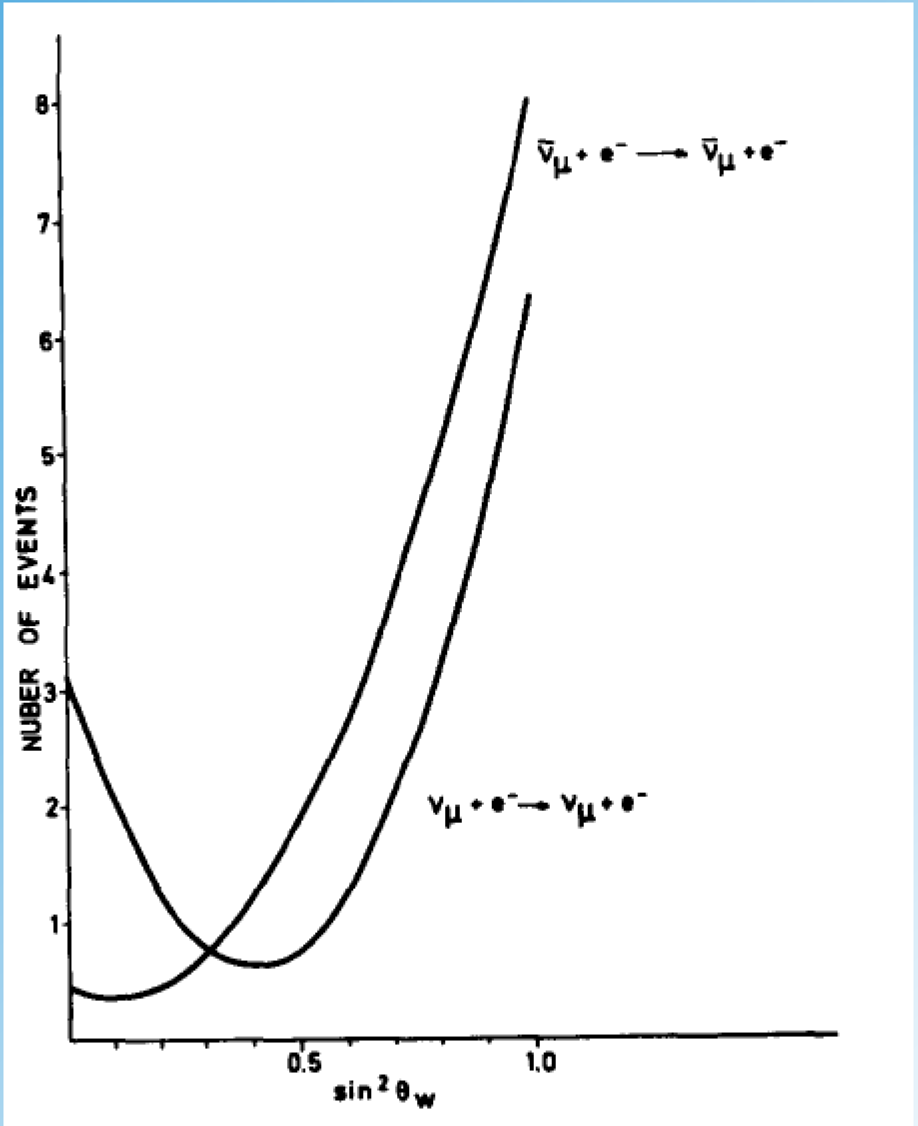


Fig. 2. Expected event rate as a function of the Weinberg parameter.

Classification of Inelastic Events

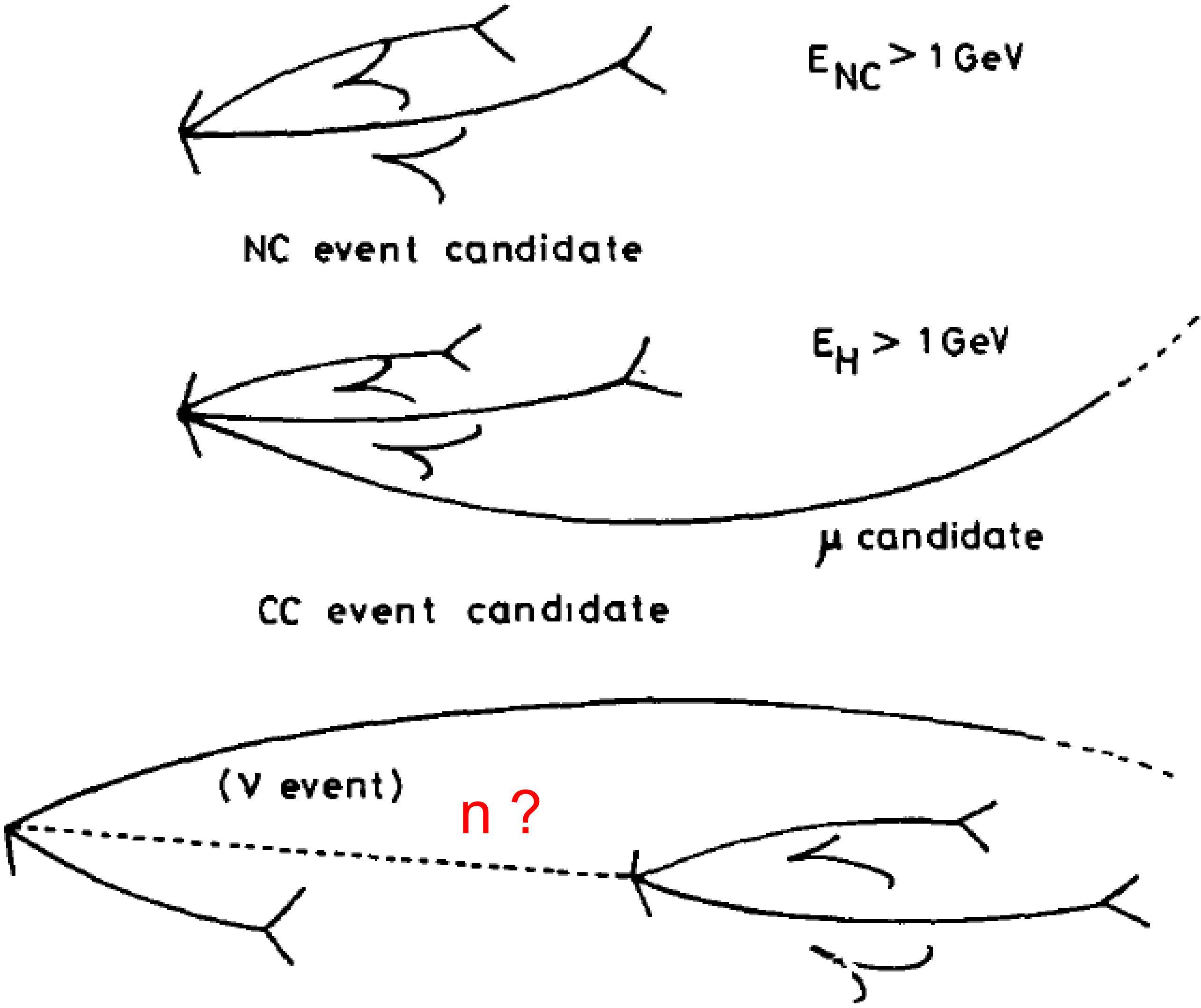
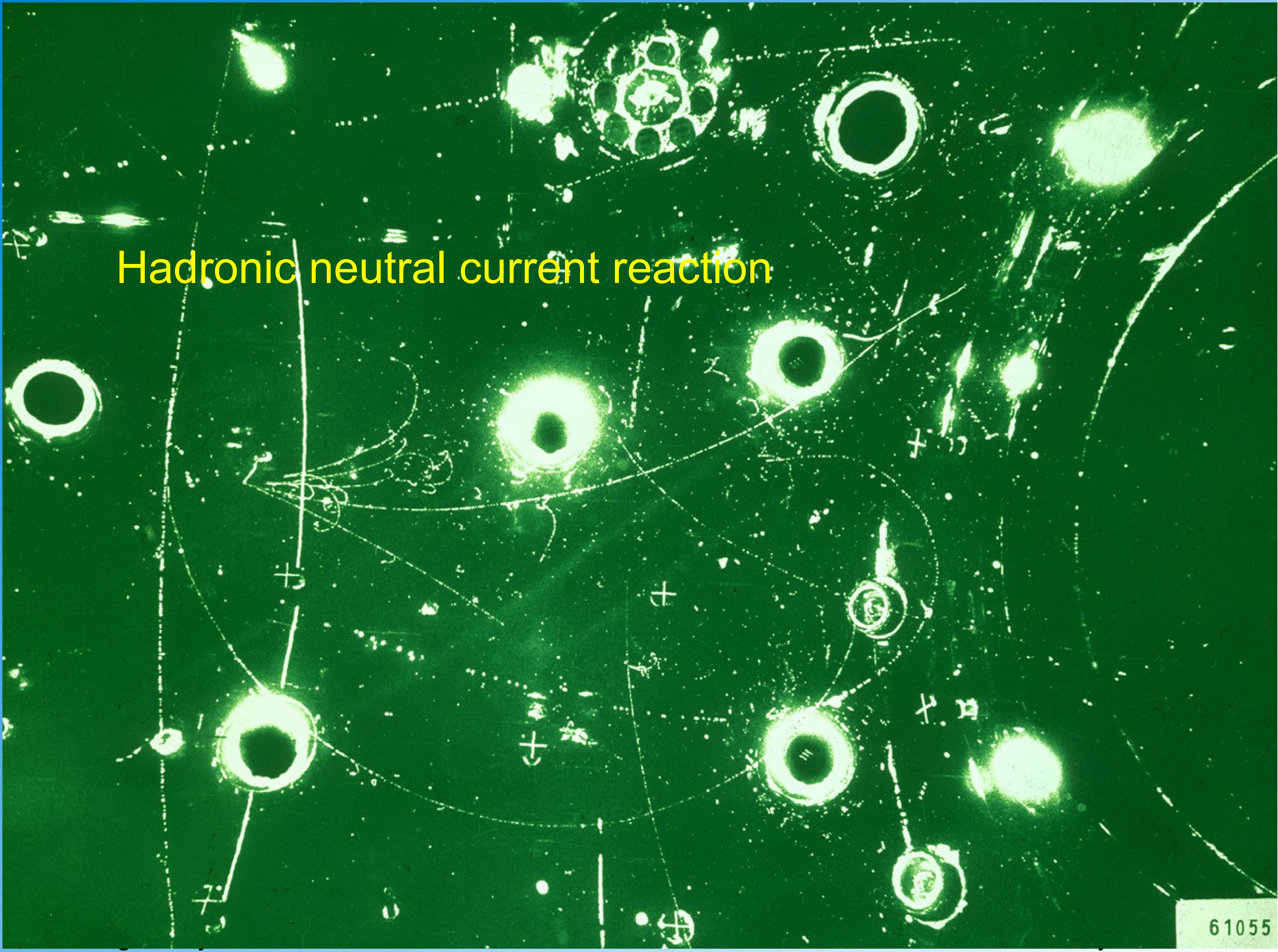


Fig. 4. Diagrammatic representations of NC, CC and AS events.

dangerous background from neutrons

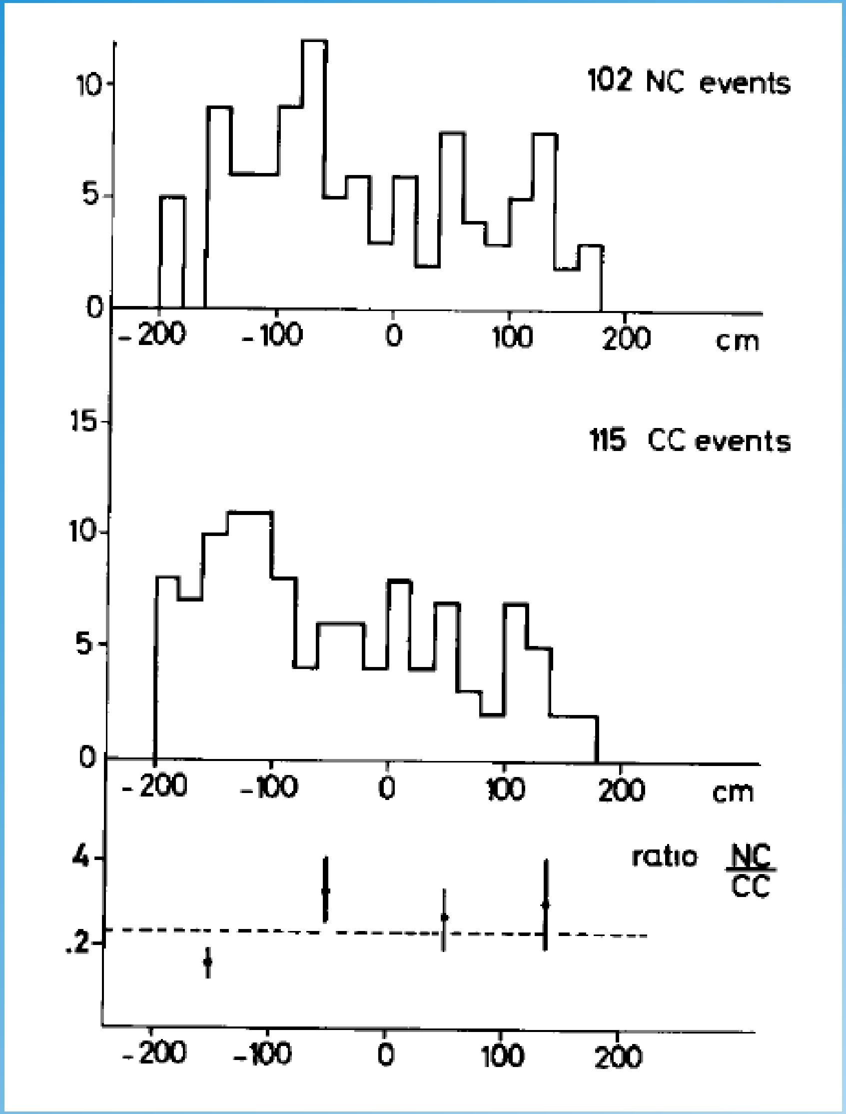
Hadronic neutral current reaction



NC/CC Ratio

Neutrino-Nucleon Scattering

Anti-neutrino Beam



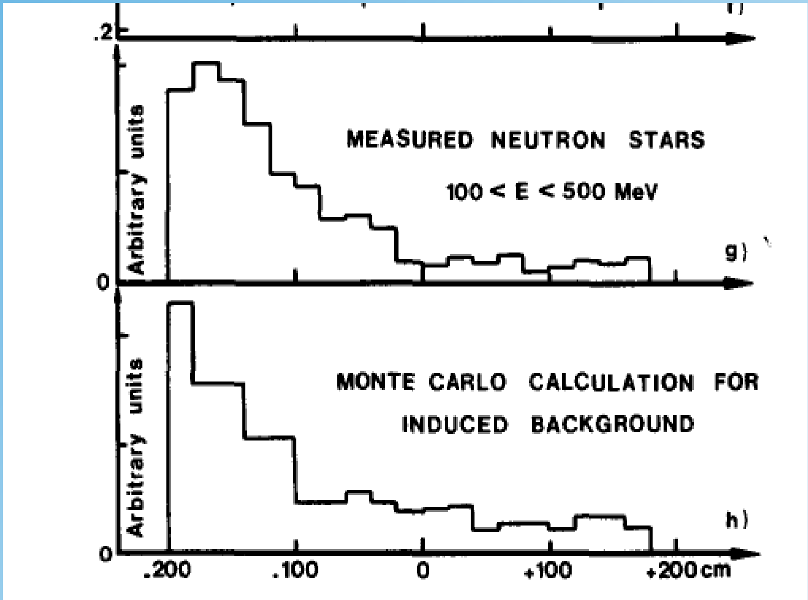
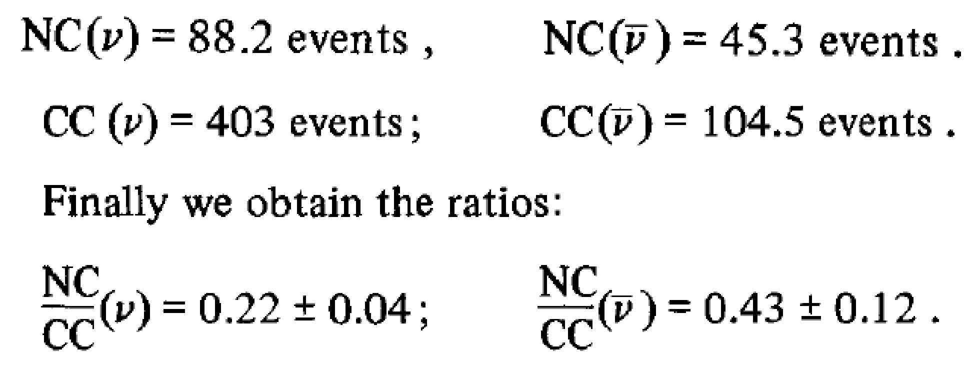


Fig. 1. Distributions along the ν-beam axis. a) NC events in ν. b) CC events in ν (this distribution is based on a reference sample of ~ 1/4 of the total ν film). c) Ratio NC/CC in ν (normalized). d) NC in $\bar{\nu}$. e) CC events in $\bar{\nu}$. f) Ratio NC/CC in $\bar{\nu}$. g) Measured neutron stars with $100 < E < 500$ MeV having protons only. h) Computed distribution of the background events from the Monte-Carlo.

R-Measurements in Gargamelle

Neutrino-Nucleon Scattering

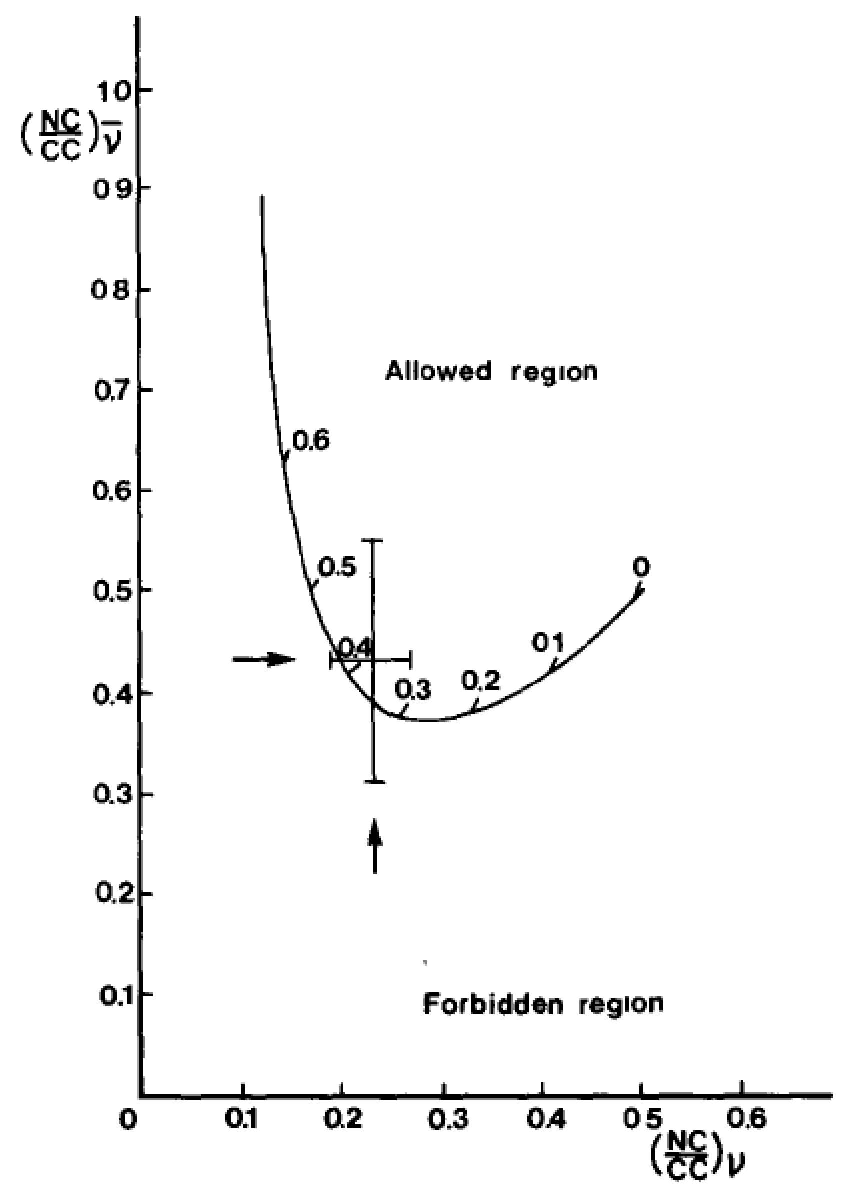


$NC(\nu) = 88.2$ events , $NC(\bar{\nu}) = 45.3$ events .

$CC(\nu) = 403$ events; $CC(\bar{\nu}) = 104.5$ events .

Finally we obtain the ratios:

$\frac{NC}{CC}(\nu) = 0.22 \pm 0.04$; $\frac{NC}{CC}(\bar{\nu}) = 0.43 \pm 0.12$.



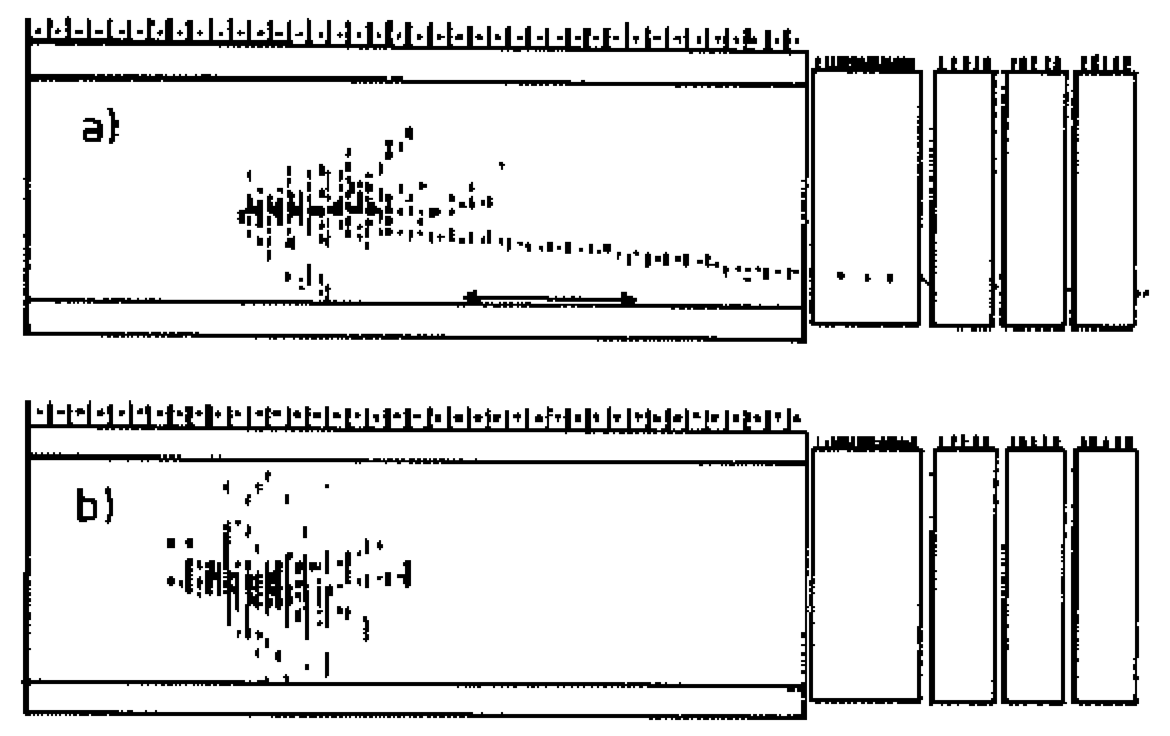
NC event in every ~1000th film

Signatures in CHARM Experiment

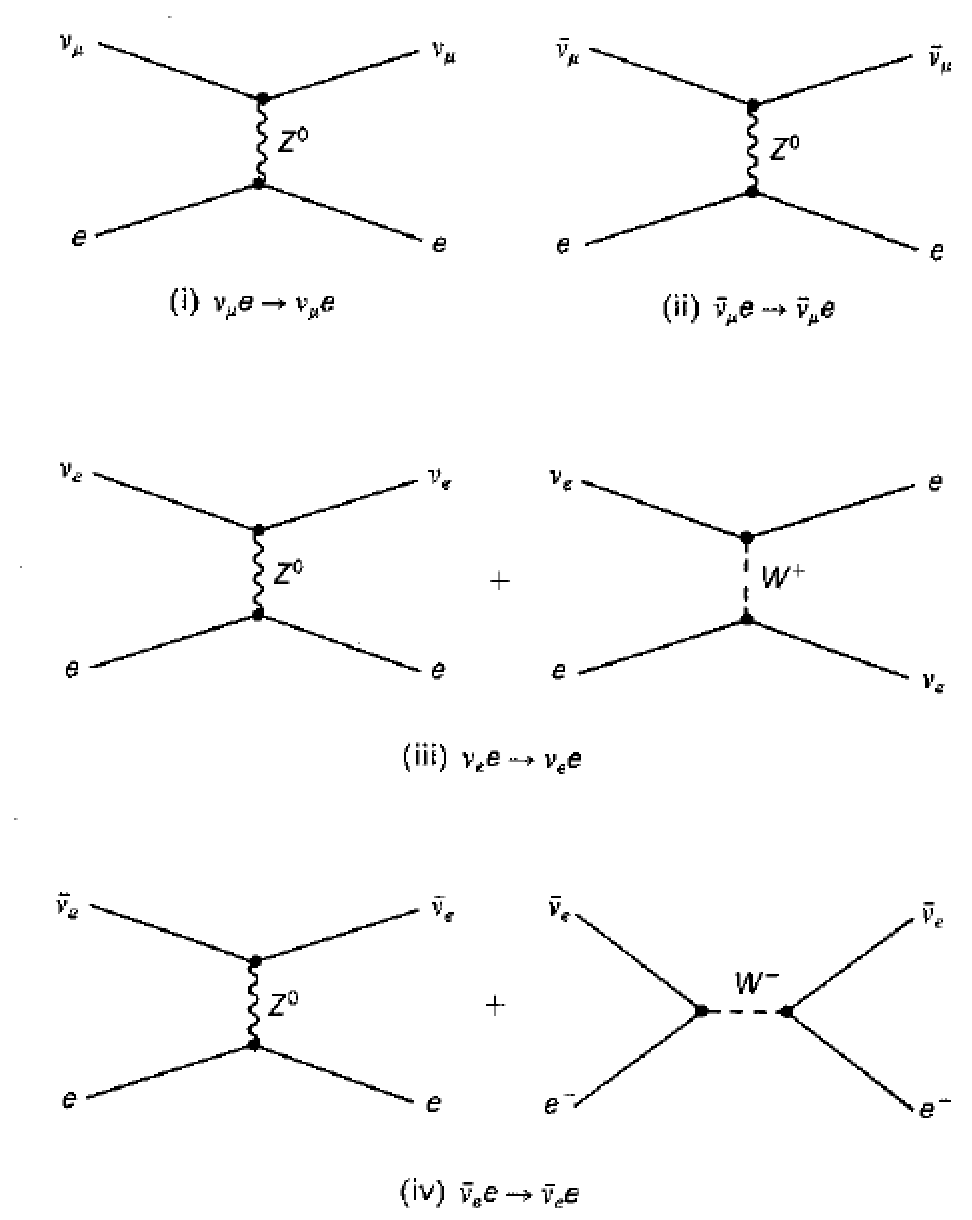
Drift Chambers:

charged currents

neutral currents



Neutrino-Electron Scattering



(i) $\nu_\mu e \rightarrow \nu_\mu e$

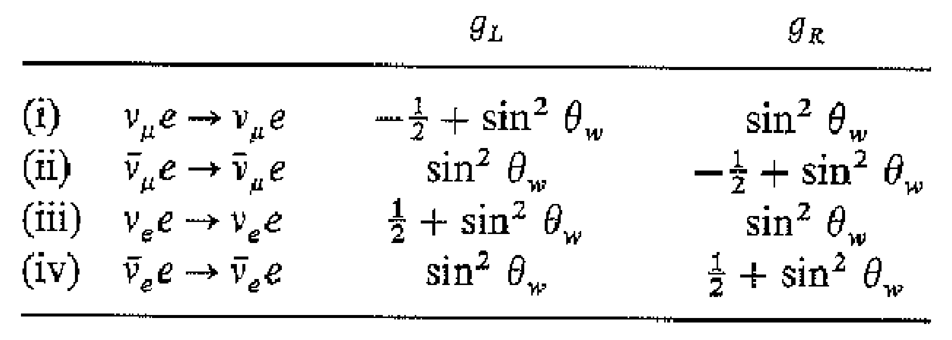
(ii) $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$

(iii) $\nu_e e \rightarrow \nu_e e$

(iv) $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$

$$\frac{d\sigma^{\nu e}(\mathrm{NC})}{dy} = \frac{2G^2 mE}{\pi}\left[g_L^2 + g_R^2(1-y)^2\right],$$

and similar for anti-neutrinos



		g_L	g_R
(i)	$\nu_\mu e \rightarrow \nu_\mu e$	$-\frac{1}{2} + \sin^2\theta_w$	$\sin^2\theta_w$
(ii)	$\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$	$\sin^2\theta_w$	$-\frac{1}{2} + \sin^2\theta_w$
(iii)	$\nu_e e \rightarrow \nu_e e$	$\frac{1}{2} + \sin^2\theta_w$	$\sin^2\theta_w$
(iv)	$\bar{\nu}_e e \rightarrow \bar{\nu}_e e$	$\sin^2\theta_w$	$\frac{1}{2} + \sin^2\theta_w$

possible to determine couplings and Weinberg angle from different reactions

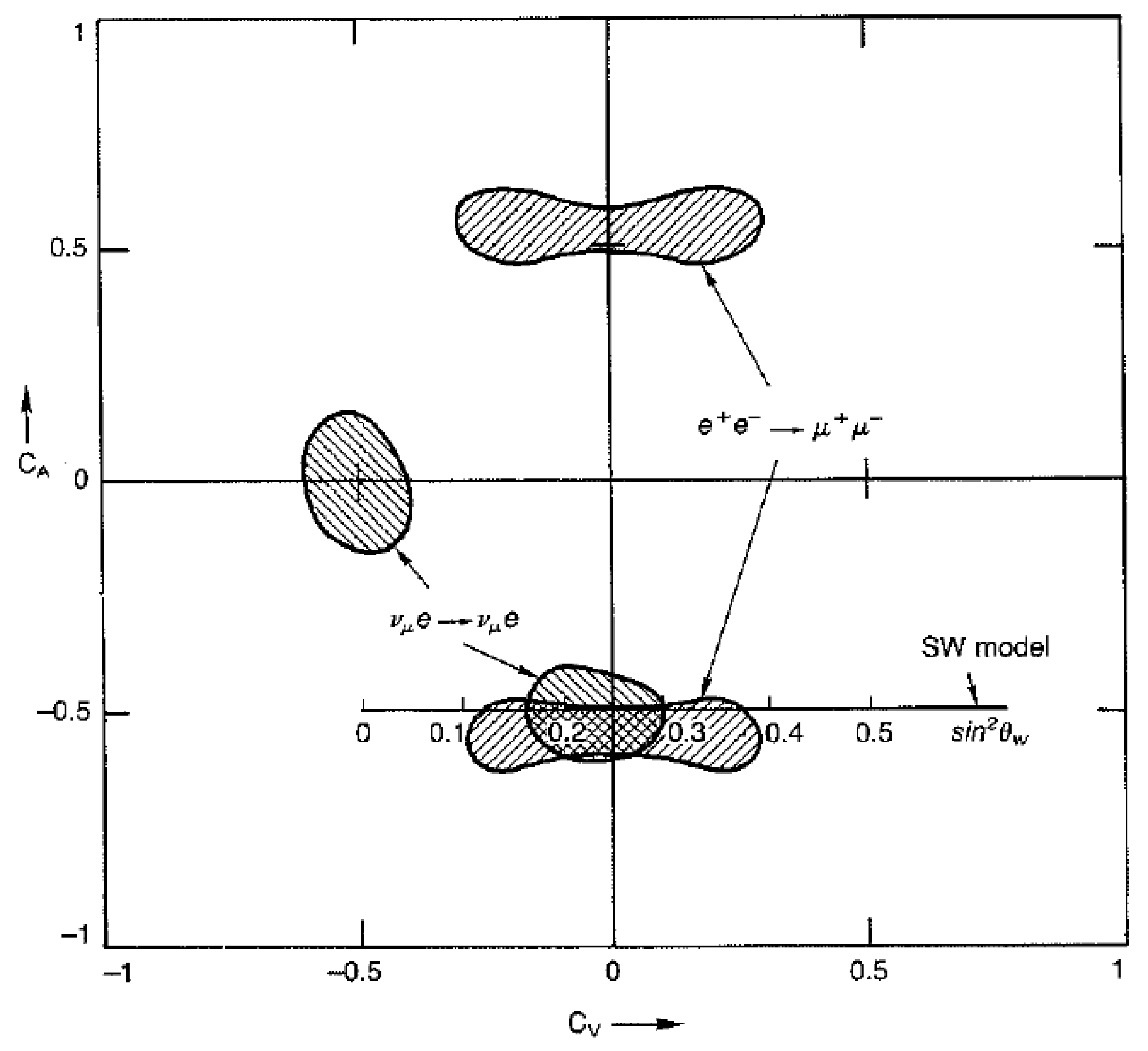
Lepton Couplings

$I_3 = -1/2$

$C_A = -1/2$

$C_V = -1/2' - 2Q_f \sin^2\Theta_W$

compilation of several experiments (Wu)



Deep Inelastic Neutrino-Lepton Scattering and Weinberg Angle

$$\frac{d^2\sigma^{\nu N}(CC)}{dx\,dy} = \frac{G^2MEx}{2\pi}[u(x)+d(x)],$$

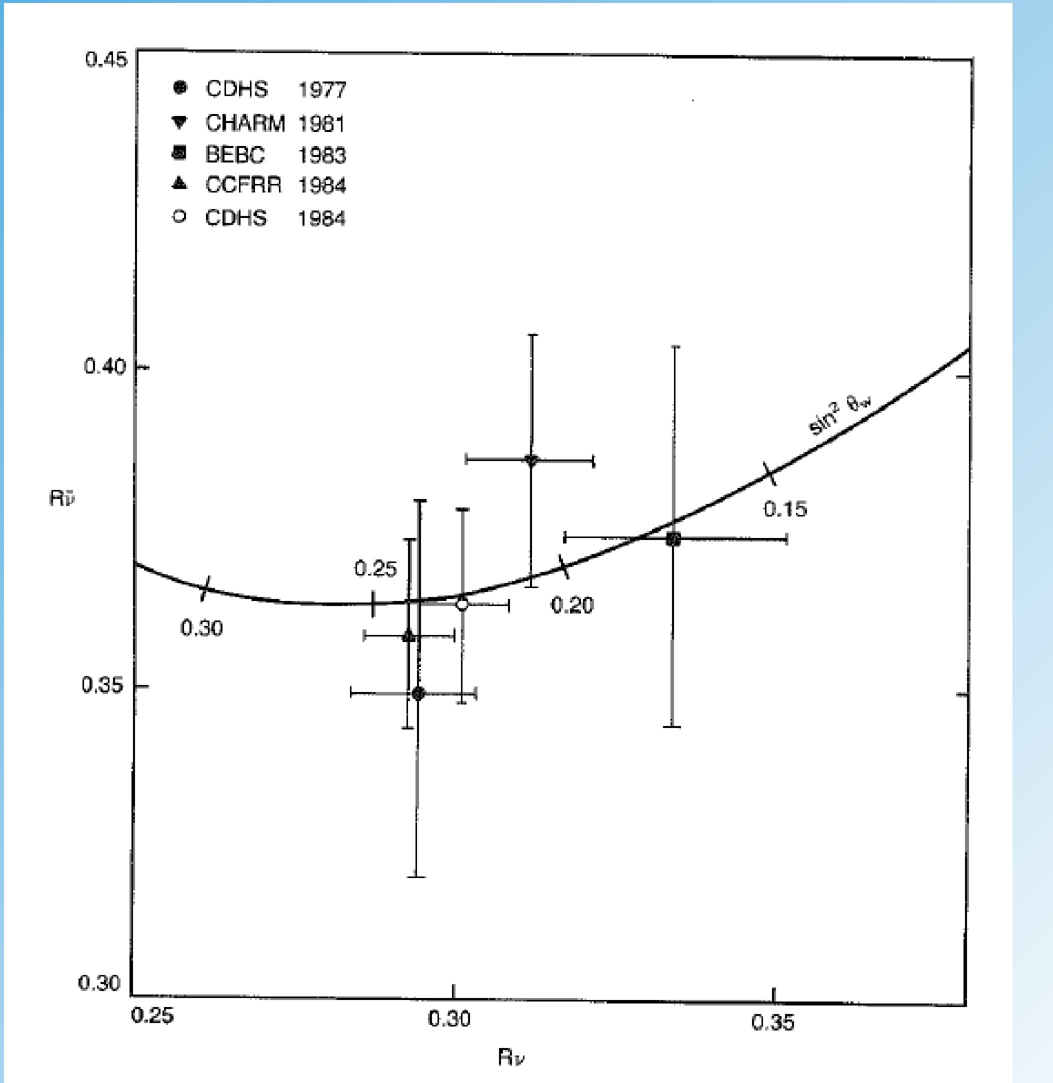
$$\frac{d^2\sigma^{\bar{\nu} N}(CC)}{dx\,dy} = \frac{G^2MEx}{2\pi}[u(x)+d(x)](1-y)^2.$$

$$R = \frac{\sigma^{\nu N}(NC)}{\sigma^{\nu N}(CC)} = \tfrac{1}{2} - \sin^2\theta_w + \tfrac{20}{27}\sin^4\theta_w,$$

$$\bar{R} = \frac{\sigma^{\bar{\nu} N}(NC)}{\sigma^{\bar{\nu} N}(CC)} = \tfrac{1}{2} - \sin^2\theta_w + \tfrac{20}{9}\sin^4\theta_w.$$

Geweniger 1984:

$$\sin^2\theta_w = 0.223 \pm 0.010$$

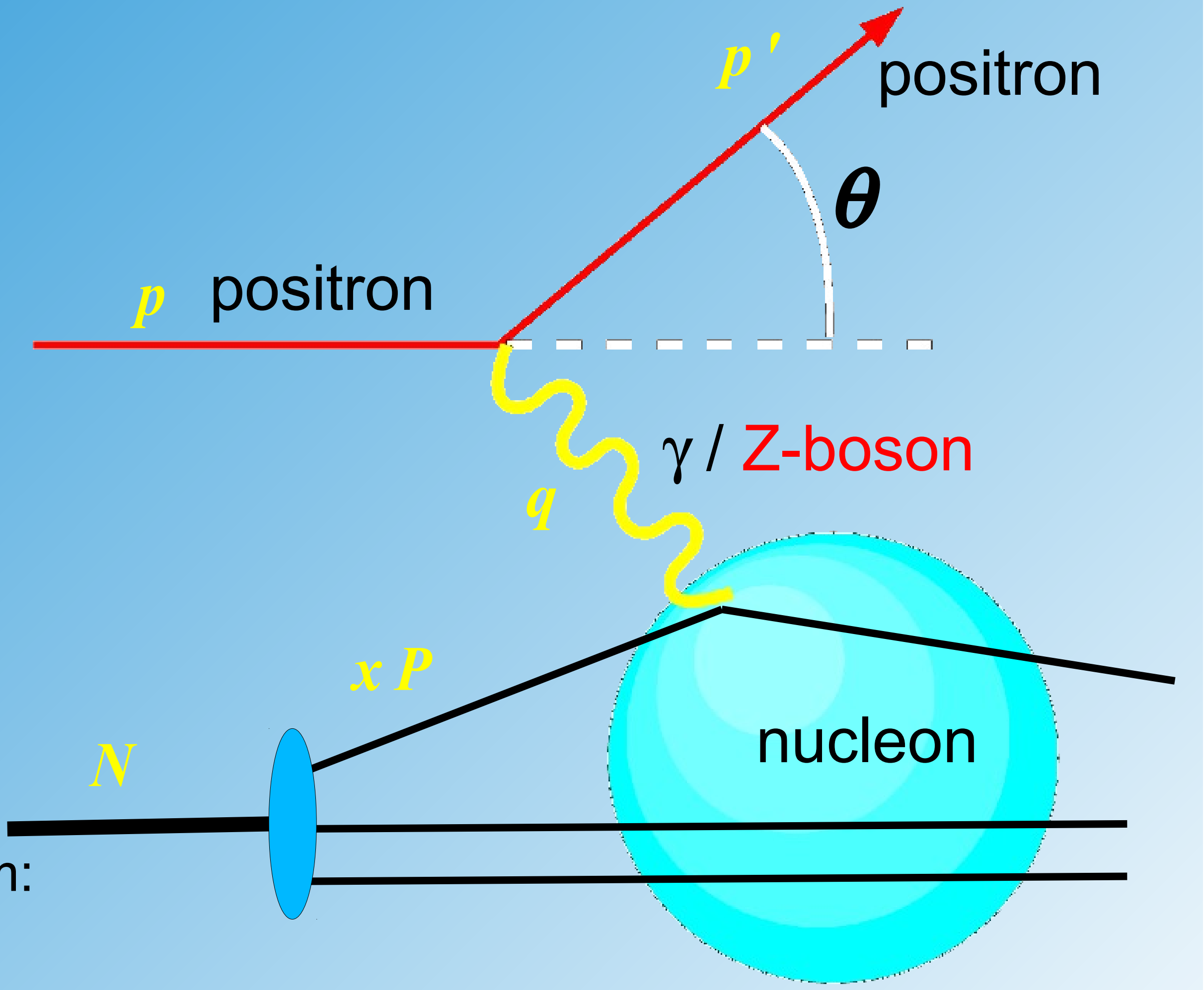


Lorentz Invariant Kinematics of the Deep Inelastic Scattering Process

The virtuality of the exchanged photon is given by:

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

$$\propto \frac{1}{\sin^4\theta/2}$$



Relative energy loss (inelasticity):

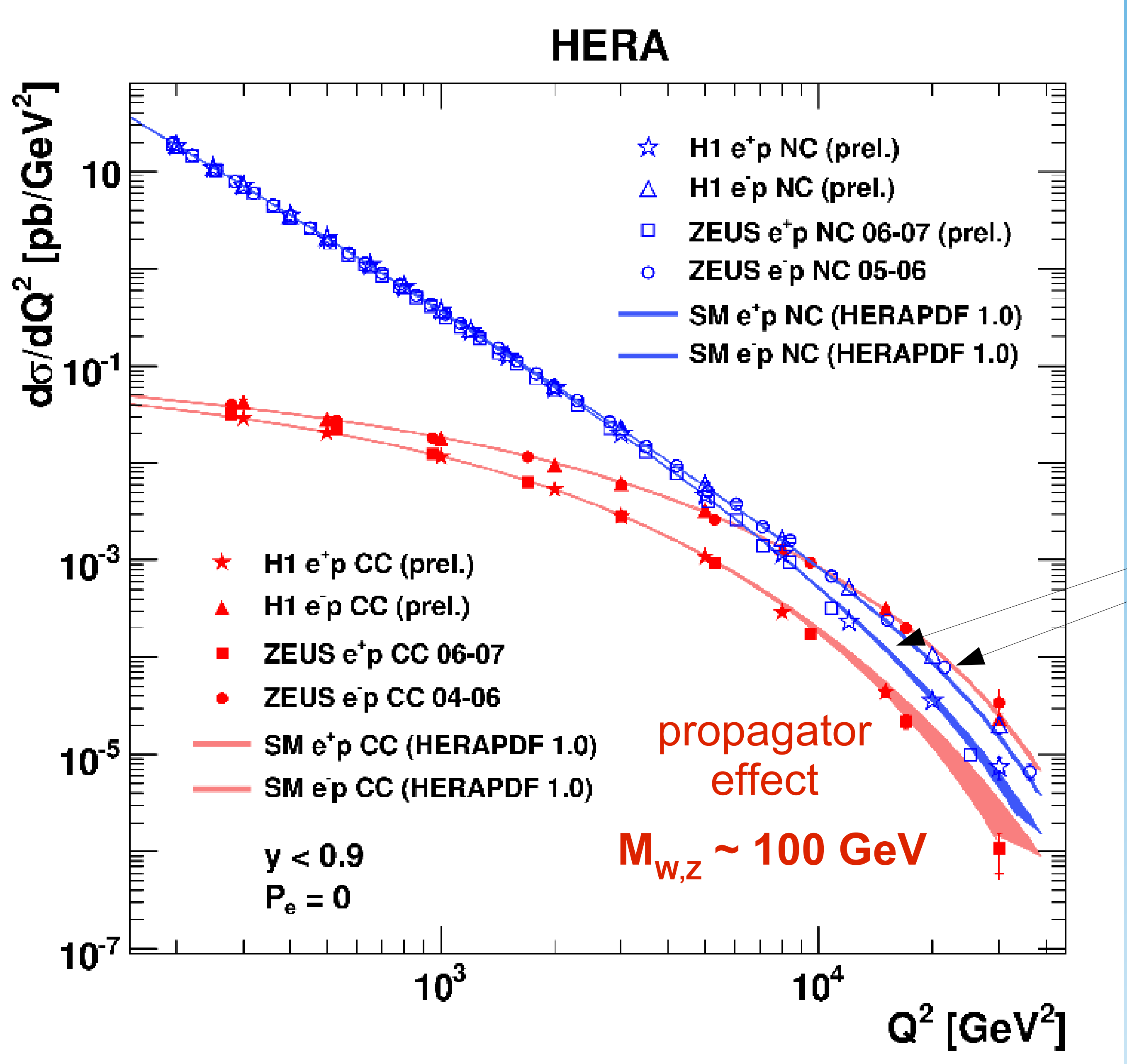
$$y = \frac{\nu}{E_\nu} = \frac{q\,P}{p\,P}$$

relative fraction of parton momentum:

$$x = \frac{q^2}{2\,q\,P} = \frac{Q^2}{S\,y}$$

with cms energy: $S = 2\,p\,P$

HERA NC (CC) Cross Sections



Difference between e^+p and e^-p cross section due to electroweak (c_V, c_A) Z-boson couplings

DIS Structure Functions at HERA

Deep Inelastic Scattering for **e±p** described by:

$$\frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L)$$

Generalised functions $\tilde{F}_2$ and $\tilde{F}_3$:

$$\tilde{F}_2^{\pm} = F_2 - (v_e \pm P_e a_e)\kappa\frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm P_e 2 v_e a_e)\kappa^2\left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\kappa\frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z} + (2a_e v_e \pm P_e[v_e^2 + a_e^2])\kappa^2\left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z$$

with $\kappa^{-1} = 4\frac{M_W^2}{M_Z^2}(1 - \frac{M_W^2}{M_Z^2})$

Structure Functions F_2 and F_3:

$$\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x\sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2](q + \bar{q})$$

$$\left[xF_3^{\gamma Z}, xF3^Z\right] = 2x\sum_q [e_q a_q, v_q a_q](q - \bar{q}) \quad ,$$

Summary

- Neutral Currents = Virtual exchange of Z-boson discovered with the Gargamelle experiment in 1973

- Electroweak Symmetry Breaking:
  - Triplet field **W** couples to left handed particles (V-A)
  - Singlet field B couples to hypercharge
  - parity violation fields W_3 and B are broken into Z and A field
  - The Photon field is massless and parity conserving (V-coupling)
  - The Z-field has V and A couplings depending on fermion type

- Electroweak Symmetry Breaking needs Higgs field to explain masses of W and Z particles

$$m_Z = \frac{m_W}{\cos\theta_W} \sim 90\,GeV$$

- Masses of W and Z particles ~ 100 GeV, precise determination in resonant production (LEP → Wednesday)