Lecture:

Standard Model of Particle Physics

Heidelberg SS 2012

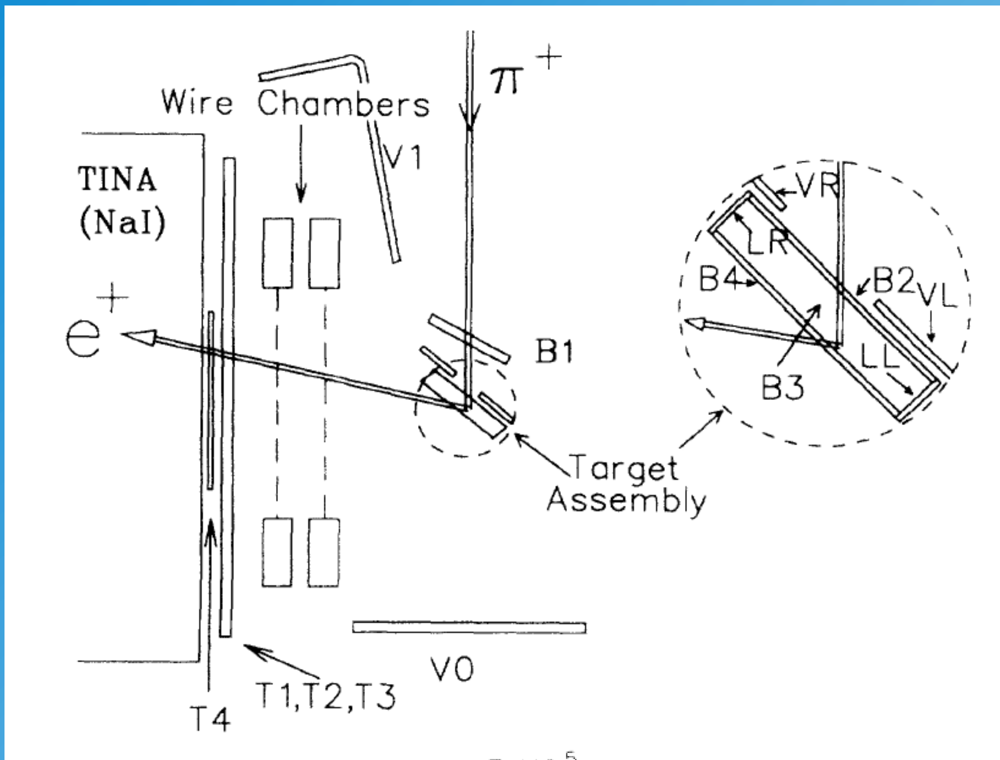
Weak Interactions II

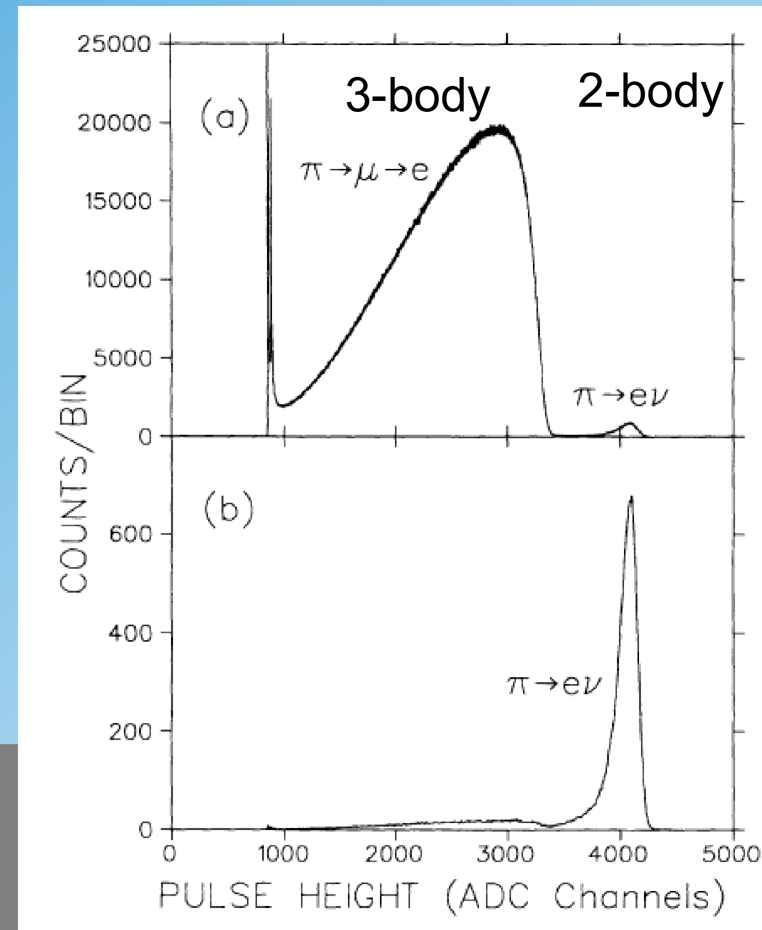
Important Experiments

- Wu-Experiment (1957): radioactive decay of Co^{60}
- Goldhaber-Experiment (1958): radioactive decay of Eu^{152}
- Muon Decay: Michel spectrum
- Pion Decay: branching ratios
- **Nuclear Beta Decays**
- **Neutrino-Nucleon Scattering (neutrino ↔ antineutrino)**

Measurement of $\pi^+ \rightarrow e^+ \nu$

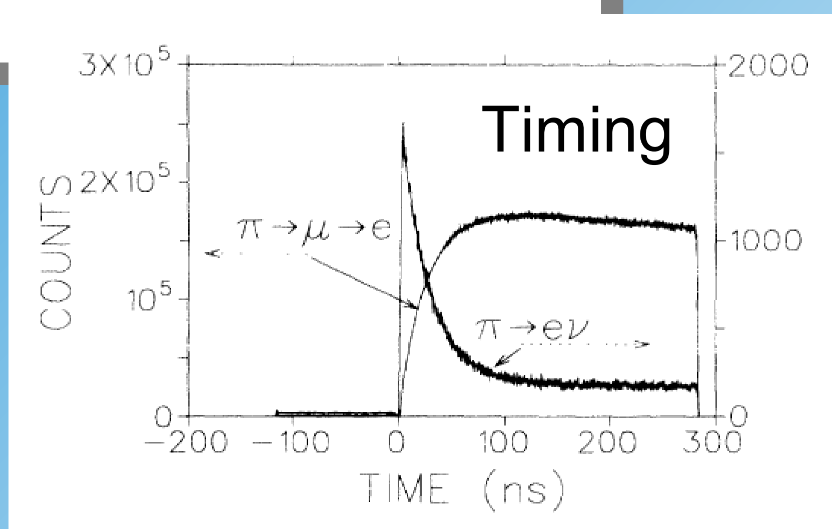
(Britton PRL 68, 20, 1992, 3000)





Pion lifetime 25 ns

Muon lifetime 2 μs



- Result:

$B(\pi^+ \rightarrow e^+ \nu) = 1.23 \cdot 10^{-4}$

Conclusion: no scalar coupling!

Measurement of $\pi^+ \to e^+ \nu$

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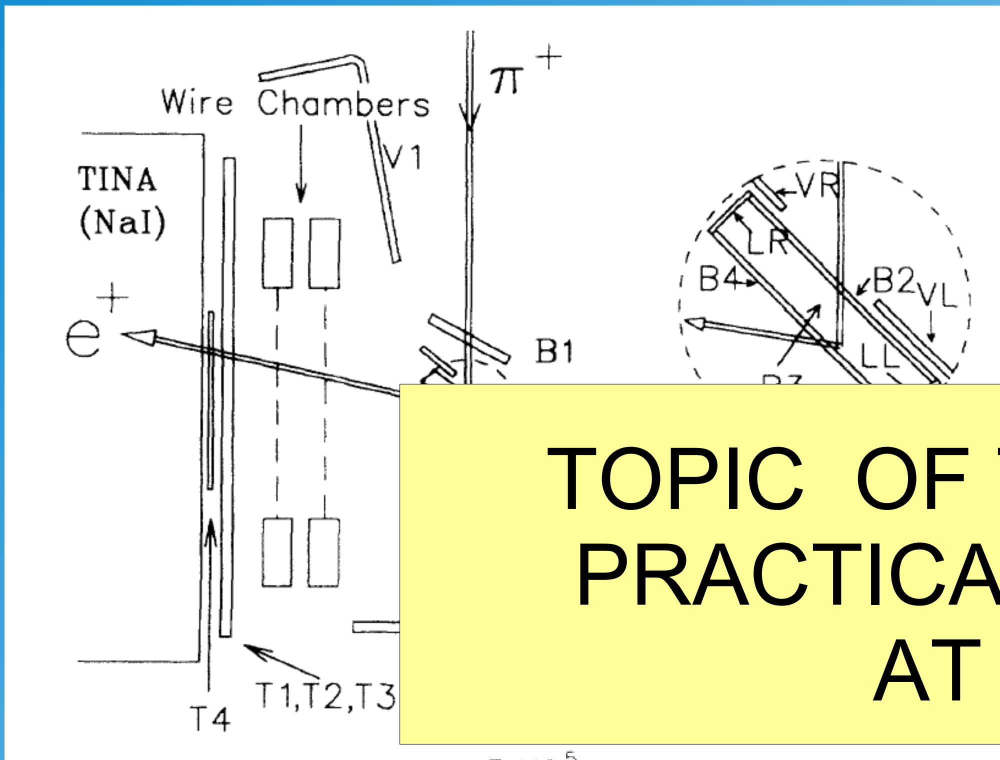
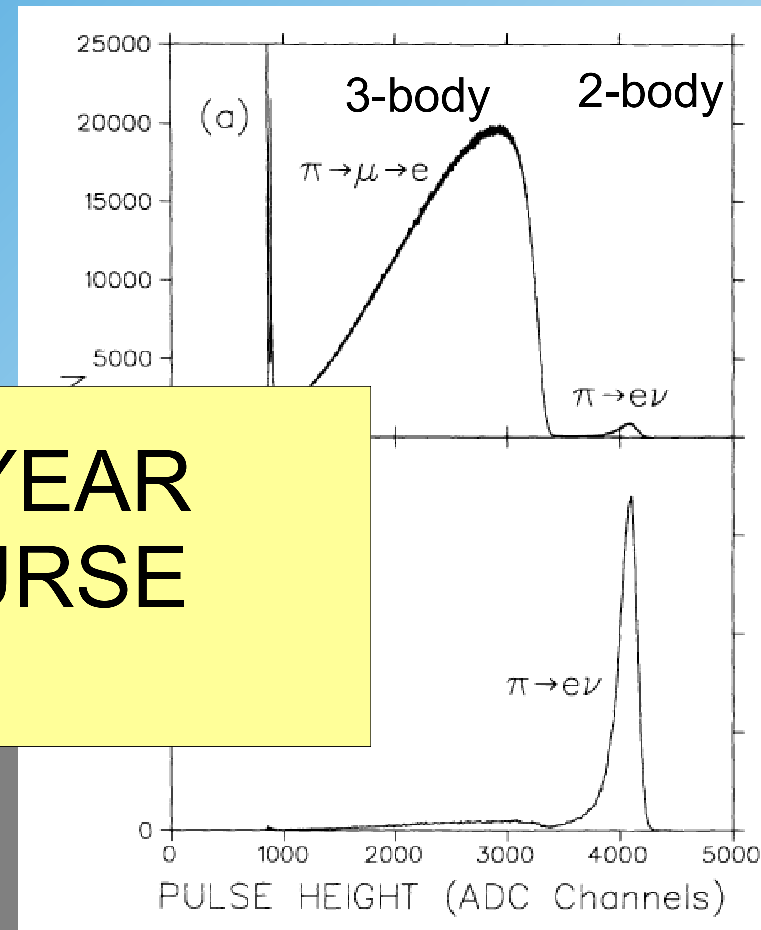
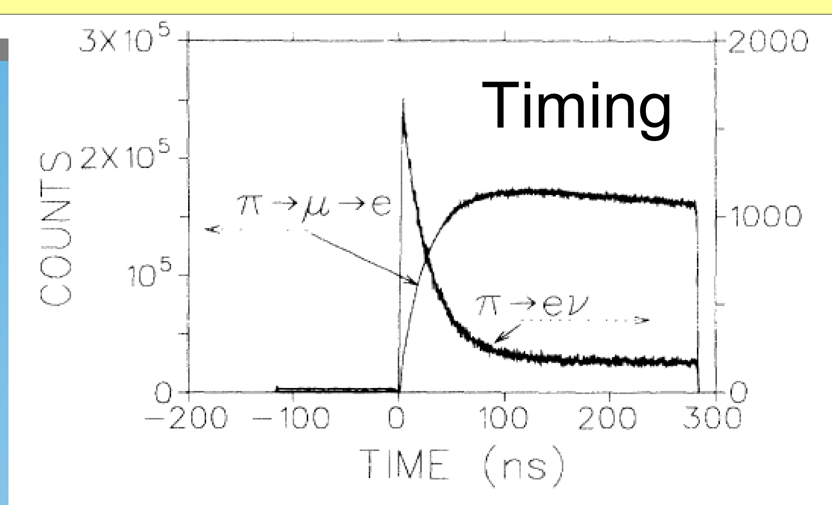




TOPIC OF THIS YEAR PRACTICAL COURSE AT PSI



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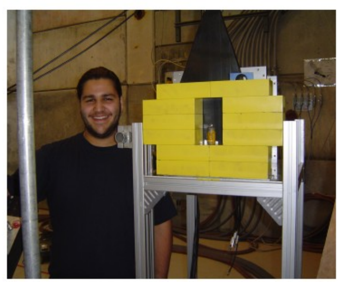
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Particle Physics

Particle Physics Practical Course at PSI (Switzerland) 2012

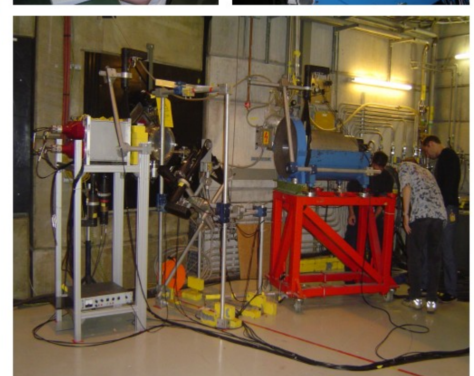
What's up ?

- During the semester break in summer we perform at the Paul Scherrer Institute (Switzerland) a real beam-line experiment to teach students in experimental particle physics.
- About 10-12 students from the ETH Zurich and the Universities Zurich and Heidelberg spend three weeks at PSI to perform an experiment. The course includes lectures about several topics of experimental techniques. Main emphasis, however, is put on the practical work and “hands on”.
- Students plan and construct a small experiment from unused detector components. After commissioning the real fun starts: data taking all day and night (7/24) using one of the beamlines at PSI. During and after data taking a full analysis of the data is performed and summarised in a written document.



Examples from previous measurements:

- Branching Ratio: $B(\pi\to\mu\nu)/B(\pi\to e\nu)$
- Panofski Ratio: $B(\pi p\to n\pi)/B(\pi p\to n\gamma)$
- Lifetime and Muon-decay parameters



Date of next course:

28. August - 15. September 2012

Contact Persons:

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A.Schöning: schoning@physi.uni-heidelberg.de
P.Robmann: peter@physik.uzh.ch

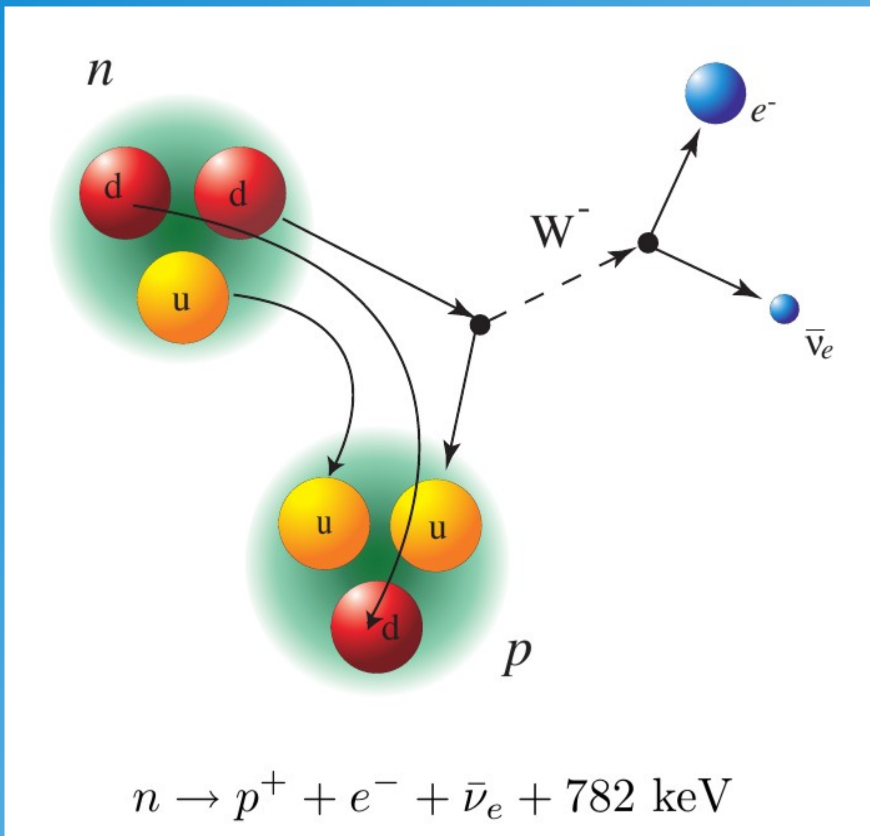
Limited number of places, please register!

This course (MVPSI) is part of the Master Programme at the Faculty of Physics and Astronomy in Heidelberg!

PAUL SCHERRER INSTITUT PSI

ETH Institute for Particle Physics

Neutron Decay



Lagrangian d → u:

$$L = \frac{G}{\sqrt{2}} \left(\bar{d}\ \gamma^{\mu}(1-\gamma^5) u\right) \left(\bar{\nu}\ \gamma_{\mu}(1-\gamma^5)\ e\right)$$

Decay Width

$$\Gamma = \frac{G_F^2 c_1^2 \Delta^5}{15\pi^3}$$

with

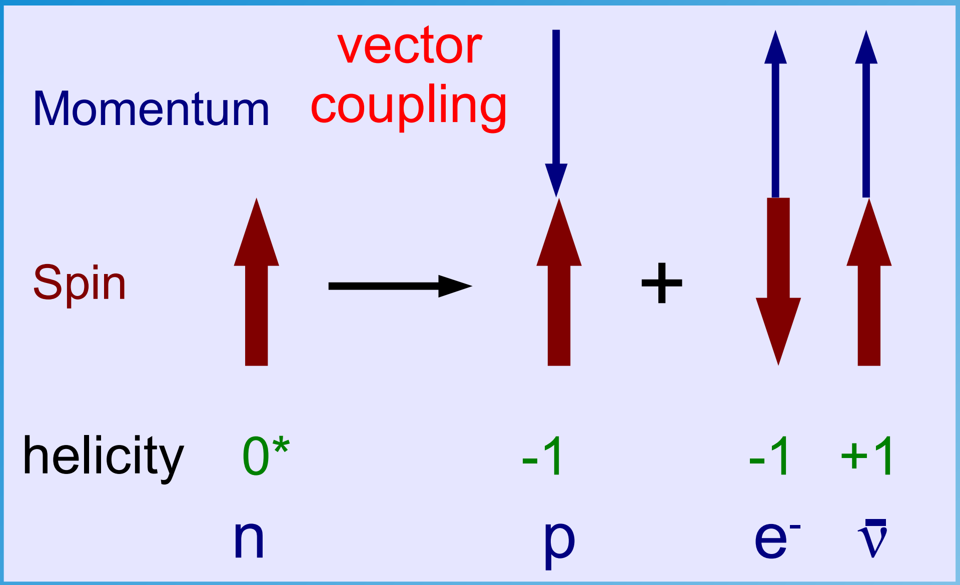
$c_1 = \cos \Theta_C$ $\Delta = 782$ keV

Problem:

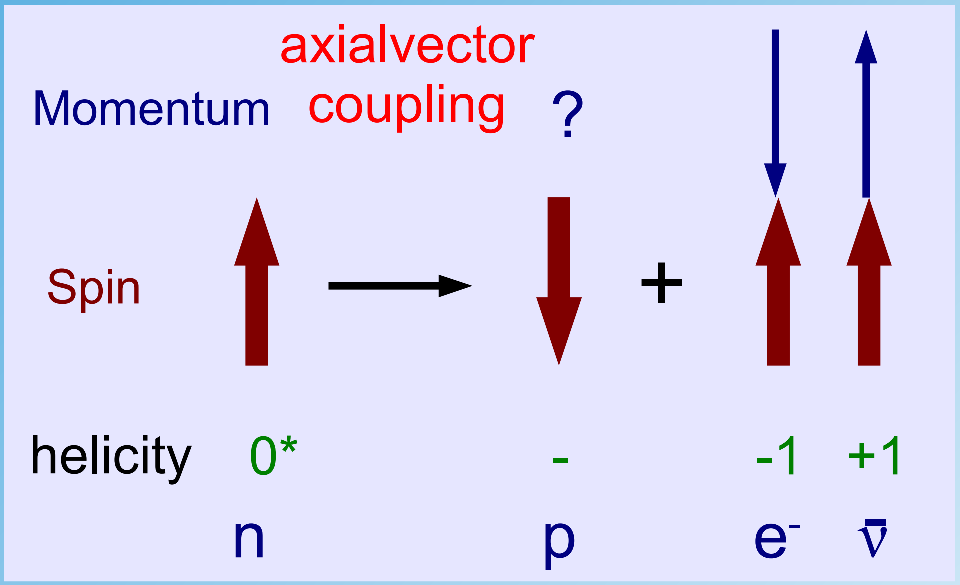
the neutron decay is not a *d* → *u* decay (quarks are not free)

Test of Lorentz Structure?

<u>Fermi transition</u>



<u>Gamov Teller transition</u>



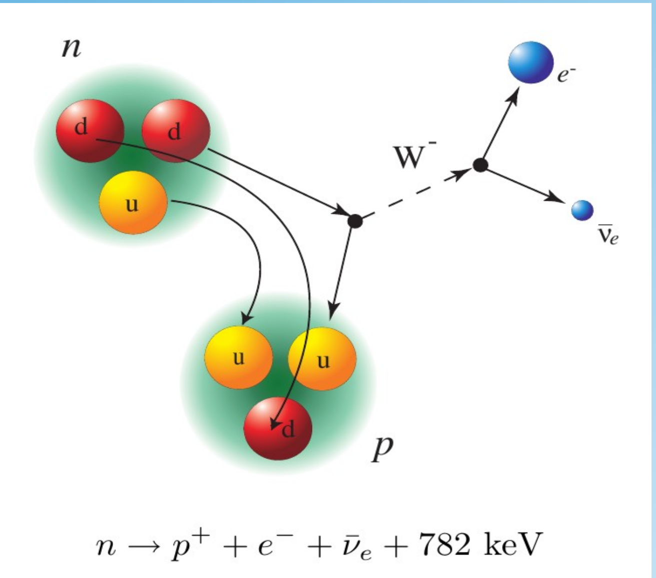
What is the relative contribution of V and A couplings in nuclear decays?

Use a more general Lagrangian:

$$L = \frac{G}{\sqrt{2}} \left(\bar{n}\ \gamma^{\mu}\left(1-\alpha\gamma^{5}\right)p\right)\left(\bar{\nu}\ \gamma_{\mu}\left(1-\gamma^{5}\right)e\right) \qquad \text{with } \alpha = \frac{c_A}{c_V}$$

The strength of the axial-coupling is related to the neutron lifetime!

Measurement of the Neutron Lifetime



$$n \rightarrow p\, e^- \nu_e$$

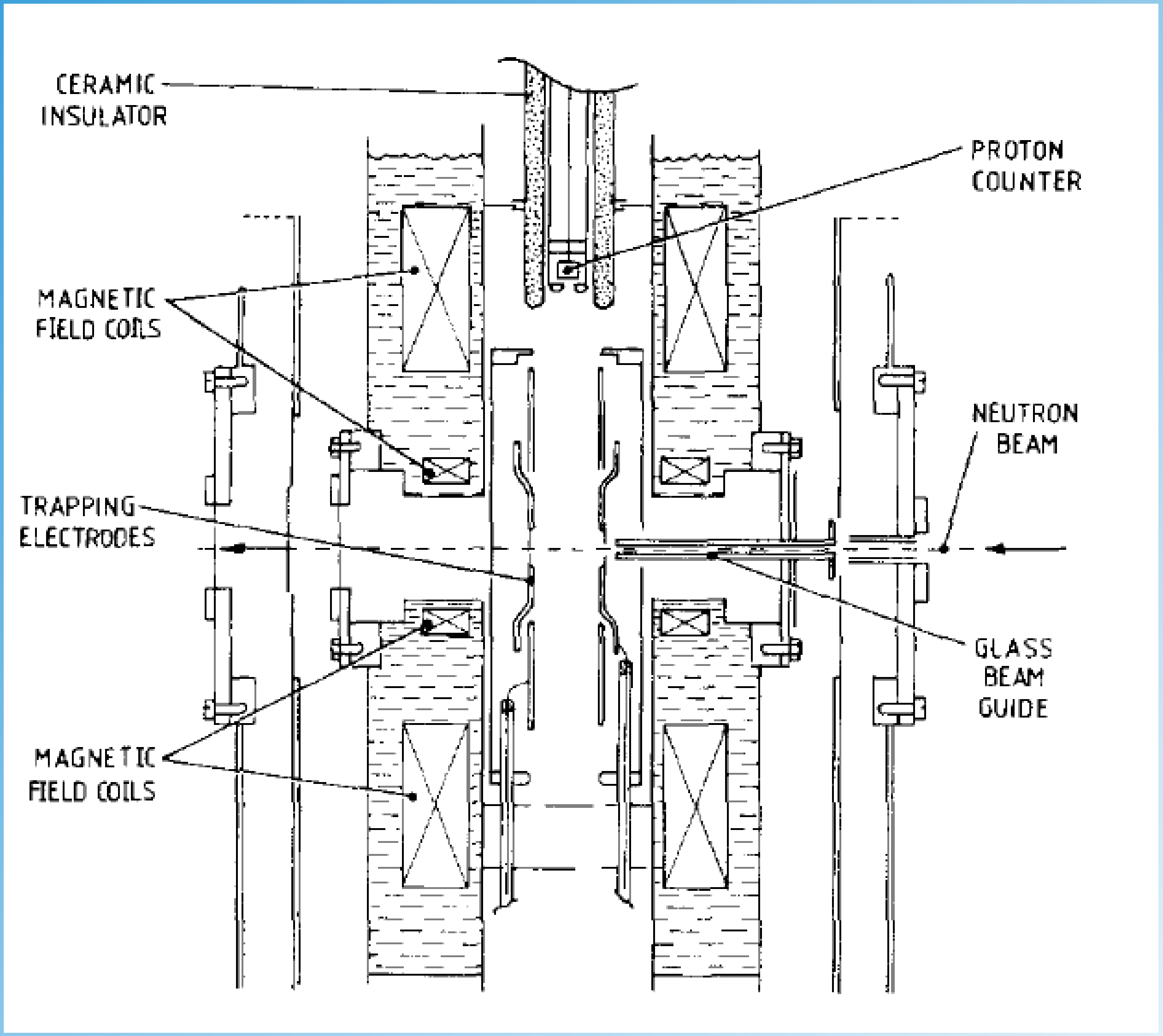
<u>Techniques</u>:

- (ultra) cold neutron traps
- in-beam decays

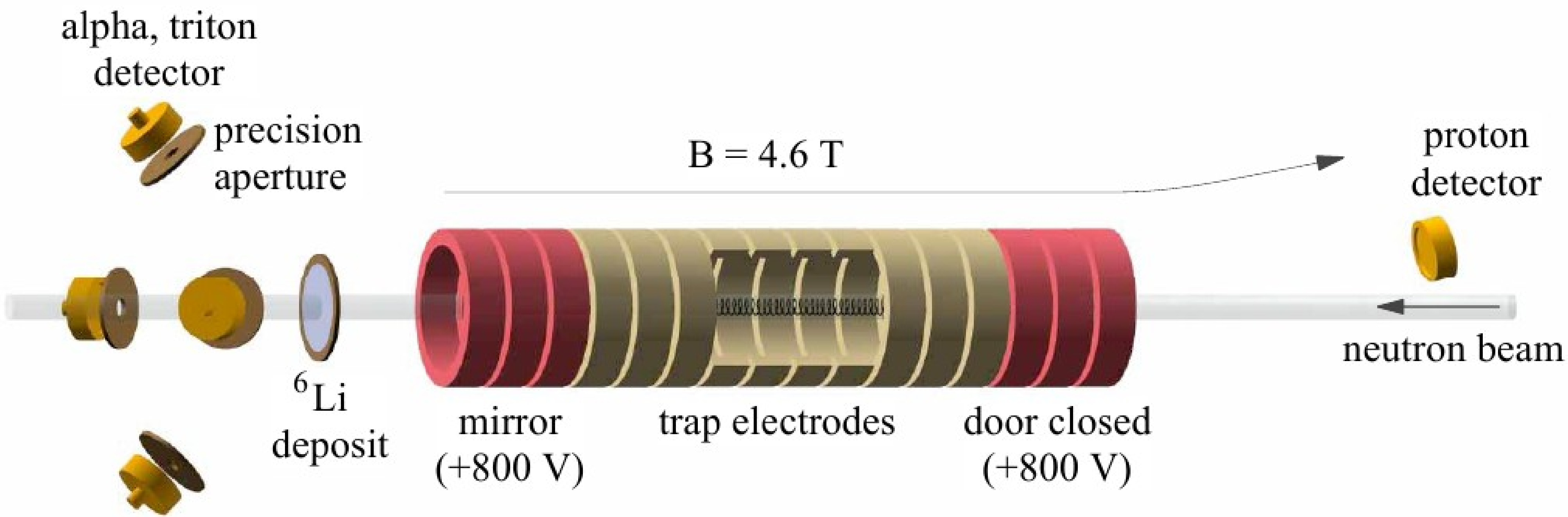
- electron detectors
- proton detectors
- electron-proton coincidence method

Neutron Lifetime Trap I

J.Byrne et al. Phys.Lett. 92B 3 (1980)

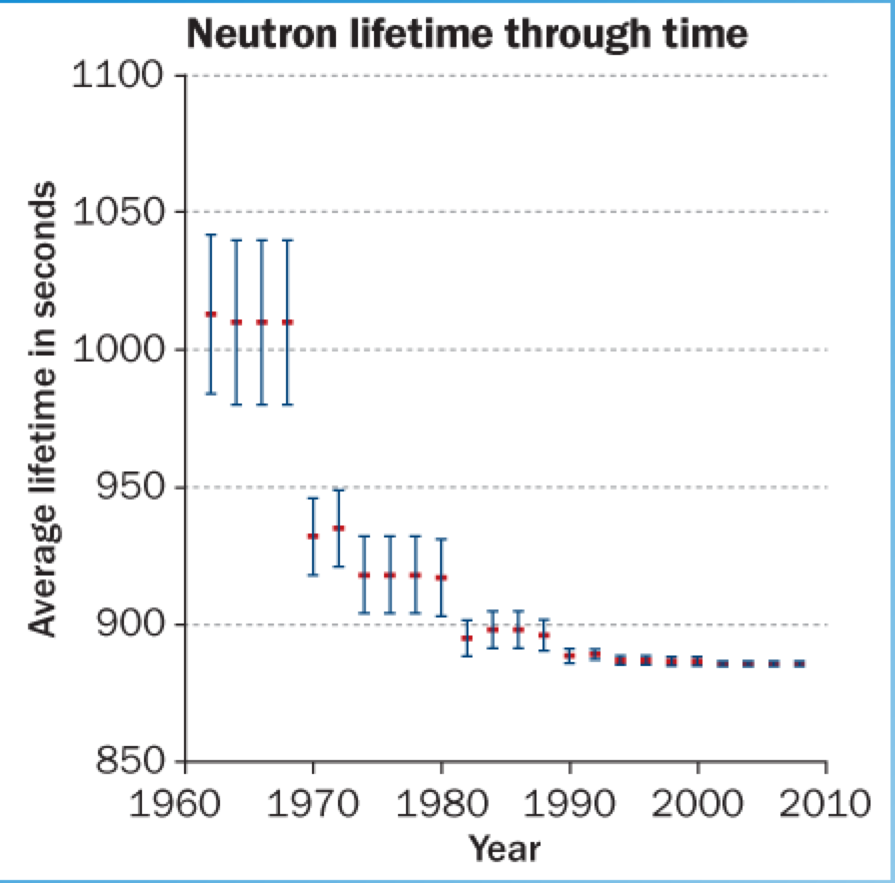


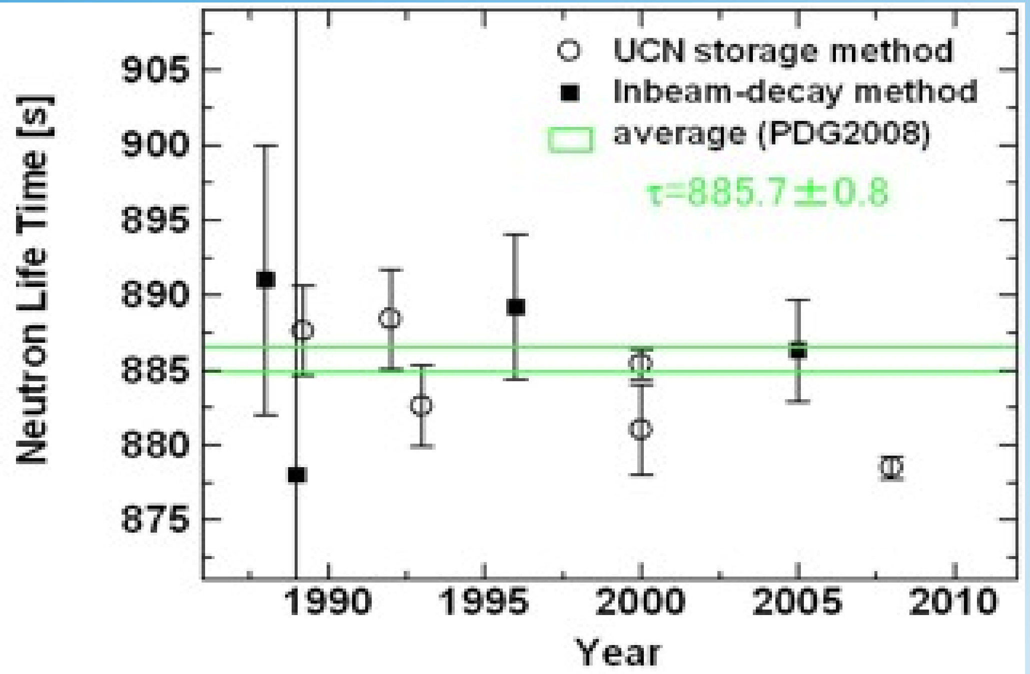
Neutron Trap II



J. Byrne *et al.*, Phys. Rev. Lett. 65, 289 (1990)

Results Neutron Lifetime





Significant tensions between experiments!

Best value (PDG 2010): $\tau_n = 885.7$ s

derived from this value: $\alpha = \frac{c_A}{c_V} = 1.2694 \pm 0.0028$

Prediction for c_A/c_v

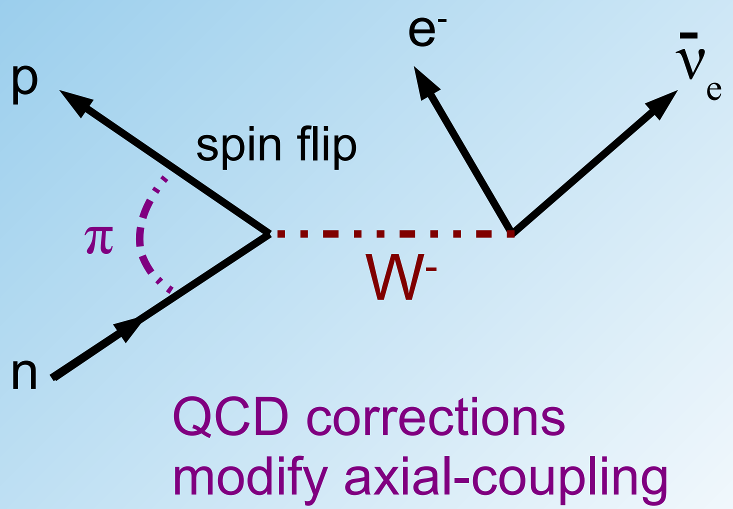
- Valence quark wave function of the neutron :

$$|n\rangle = \frac{1}{\sqrt{18}}(-2|d\uparrow u\downarrow d\uparrow\rangle - 2|d\uparrow d\uparrow u\downarrow\rangle - 2|u\downarrow d\uparrow d\uparrow\rangle + |u\uparrow d\downarrow d\uparrow\rangle + |d\downarrow u\uparrow d\uparrow\rangle + |d\uparrow u\uparrow d\downarrow\rangle + |d\uparrow d\downarrow u\uparrow\rangle + |u\uparrow d\uparrow d\downarrow\rangle + |d\downarrow d\uparrow u\uparrow\rangle)\ .$$

- Detailed calculation of vector/axial-vector contributions gives:

  $c_A/c_v = 5/3$

- Mismatch between experiment and prediction due to:
  - Relativistic corrections
  - Neglected sea quarks in the neutron
  - QCD corrections



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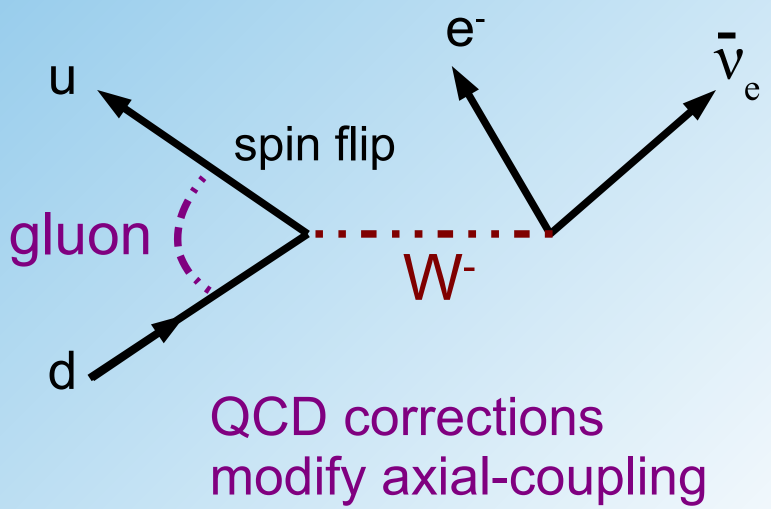


Overview Weak Decay Processes

Weak decays of quarks and leptons (fermions)

$\mu^- \to e^- \nu_\mu \bar{\nu}_e$	leptonic decay
$n \to p e^- \nu_e$	semileptonic decays
$\Lambda \to p e^- \nu_e$	semileptonic decays (ΔS=1)
$\Lambda \to p \pi^-$	hadronic weak decays (ΔS=1)
$Q \to q W^\pm$	heavy quark decays (ΔC=1, ΔB=1, ΔT=1)

W-Boson decays:

$$W \to l^- \nu_l$$
$$W \to q \bar{q}'$$

Charged currents can mediate interactions between different lepton and quark generations (mixing)

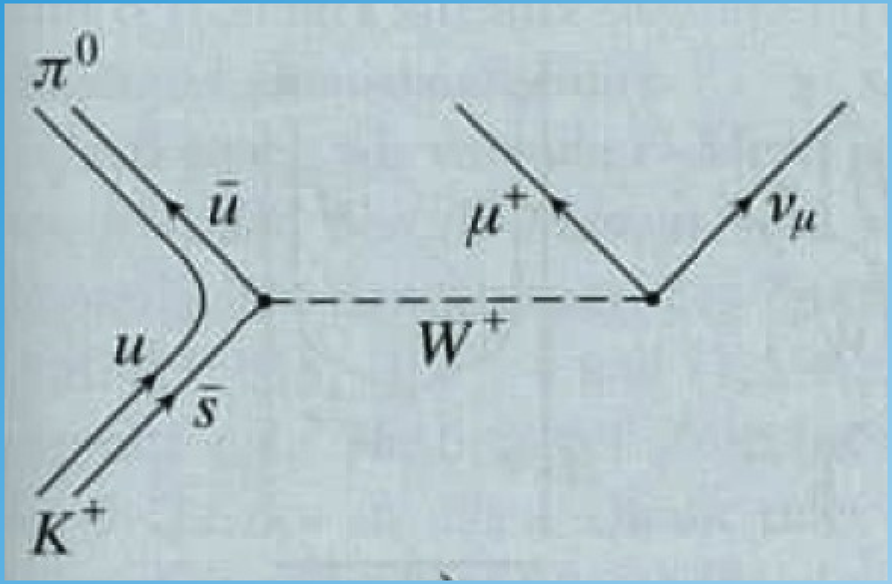
K-Meson Decays

$\Gamma \propto G_F^2 m_s^5$

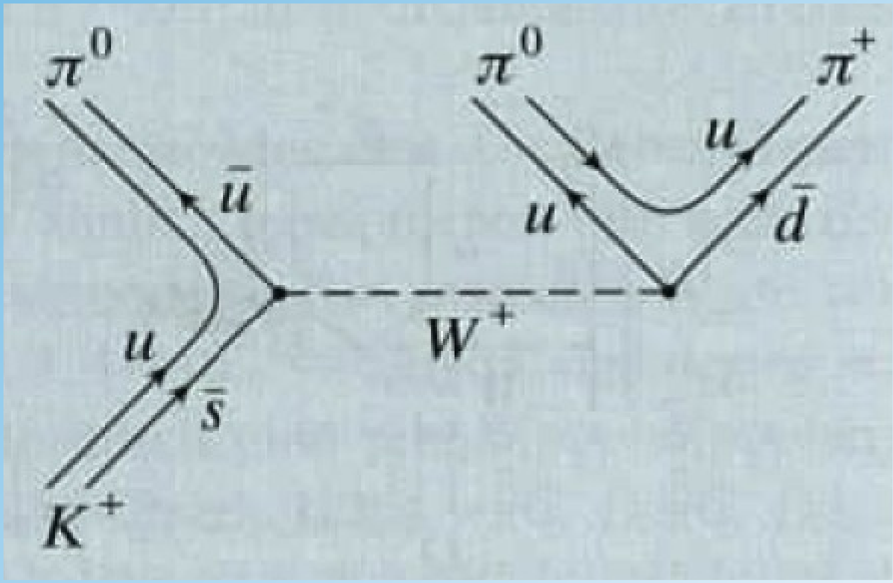
$m_s \approx 150\ MeV$

Lifetime $\tau \sim 10^{-8}$ s

$K^+ \to \pi^0 l^+ \nu$



$K^+ \to \pi^0 \pi^0 \pi^+$



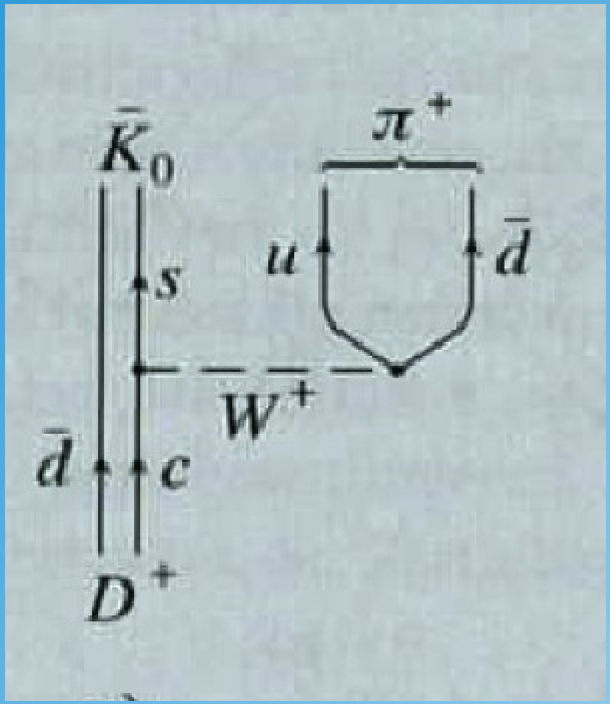
Hadronic Decays of D-mesons

$\Gamma \propto G_F^2 m_c^5$

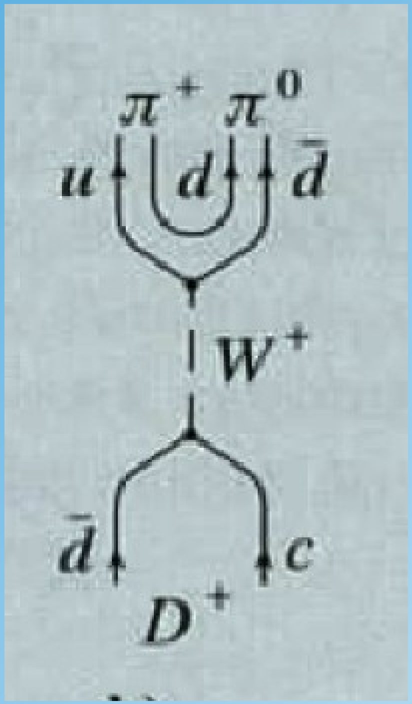
$m_c \approx 1.5\ GeV$

Lifetime τ ~ 0.5 ps

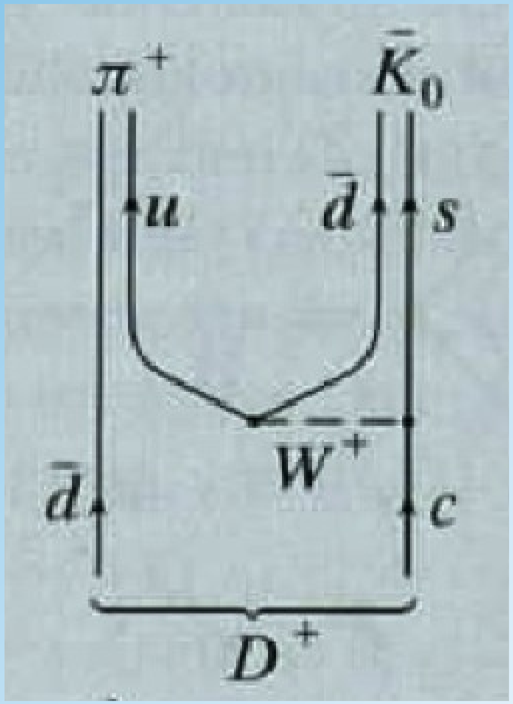
$D^+ \rightarrow K^0 \pi^+$



$D^+ \rightarrow \pi^+ \pi^-$



$D^+ \rightarrow \pi^+ \bar{K}_0$



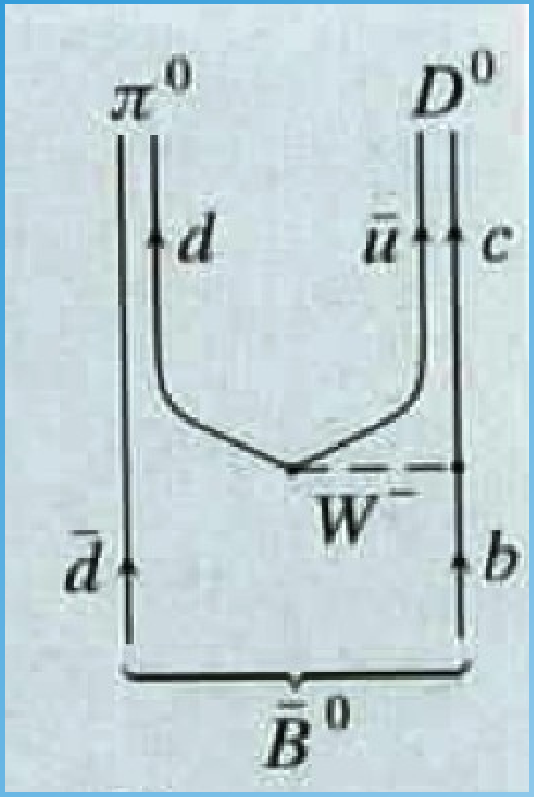
Weak Decays of B-mesons

$\Gamma \propto G_F^2 m_b^5$

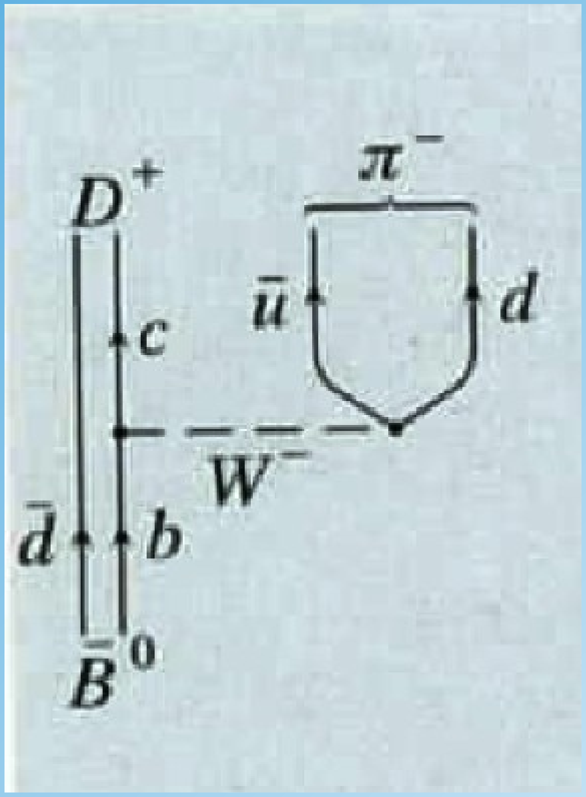
$m_b \approx 4.5\ GeV$

Lifetime $\tau \sim 1.5$ ps

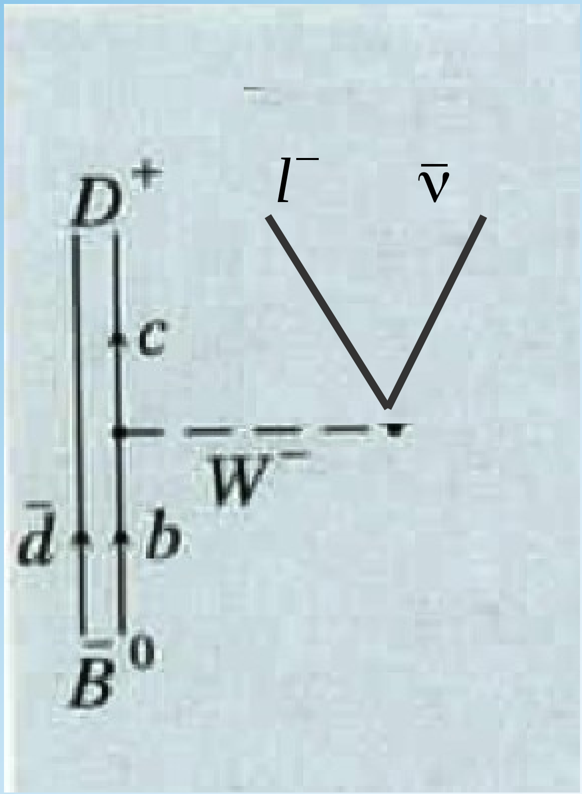
$\bar{B}^0 \to D^0 \pi^0$



$\bar{B}^0 \to D^+ \pi^-$



$\bar{B}^0 \to D^+ l^- \bar{\nu}$

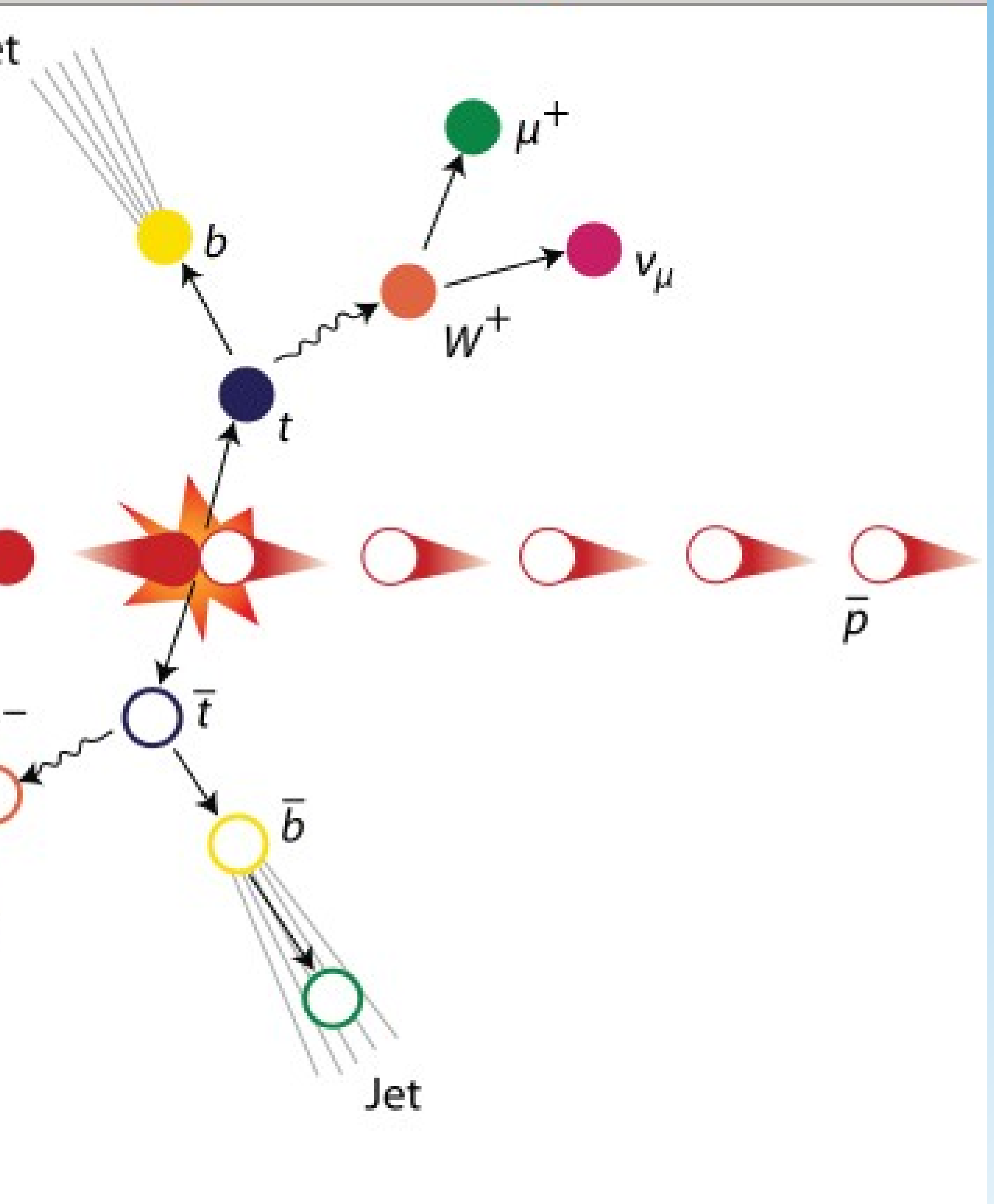


Decay of the Top quark

$\Gamma \propto G_F^2 m_t^5$

$m_t \approx 172\, GeV$

Lifetime $\tau \sim 10^{-25}$ s



Summary Weak Interaction

left handed fermions: $\begin{pmatrix} I_3 = +1/2 \\ I_3 = -1/2 \end{pmatrix}$ $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ $\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$ $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $\begin{pmatrix} u \\ d' \end{pmatrix}_L$ $\begin{pmatrix} c \\ s' \end{pmatrix}_L$ $\begin{pmatrix} t \\ b' \end{pmatrix}_L$

right handed fermions: $I_3 = 0$ $\begin{matrix} \nu_{e,R} \\ e_R^- \end{matrix}$ $\begin{matrix} \nu_{\mu,R} \\ \mu_R^- \end{matrix}$ $\begin{matrix} \nu_{\tau,R} \\ \tau_R^- \end{matrix}$ $\begin{matrix} u_R \\ d_R \end{matrix}$ $\begin{matrix} c_R \\ s_R \end{matrix}$ $\begin{matrix} t_R \\ b_R \end{matrix}$

W-bosons couple only on fermions with weak isospin!

Weak Scattering Experiments

Question:

What is the difference between:

A) scattering experiments in classical mechanics

B) weak scattering experiments?

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A) scattering experiments in classical mechanics

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Answer:

Despite the fact that α_{em}=1/127 is much smaller than α_{weak}~1/30 electromagnetic interactions (A) are much more dangerous than weak interactions (B)

Video of a classical scattering experiment

Strength of Weak Interaction

Question:

Why is the weak interaction so weak if α_{weak}~1/30 much stronger than α_{em}=1/127 ?

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	elm. IA	weak IA	
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Strength of Weak Interaction

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Answer:

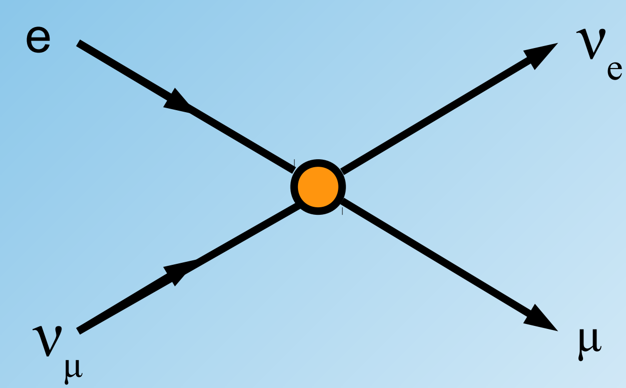
	elm. IA	weak IA
1. Coupling	$e \; (\approx 0.3)$	$g \; (\approx 0.65)$ $\quad (e, g = \sqrt{4\pi\alpha})$
2. Propagator	$\frac{-i g^{\mu\nu}}{q^2}$	$\frac{-i g^{\mu\nu} + q^\mu q^\nu / m_W^2}{q^2 - m_W^2} \xrightarrow{\text{low energy}} \frac{i g^{\mu\nu}}{m_W^2} = \frac{8 G_F}{\sqrt{2}}$
$Q^2 = 1\ eV^2$ $Q^2 = 1\ MeV^2$ $Q^2 = 1\ TeV^2$	Ratio(elm./weak)	$\approx (\frac{1}{q^2}) / (\frac{1}{m_W^2}) \approx$ $0.64 \cdot 10^{22}$ $0.64 \cdot 10^{10}$ $0.64 \cdot 10^{-2}$ m_W ~ 80 GeV

Strength of Weak Interaction

At high mass scales E~100 GeV the weak interaction is stronger than the electromagnetic interaction

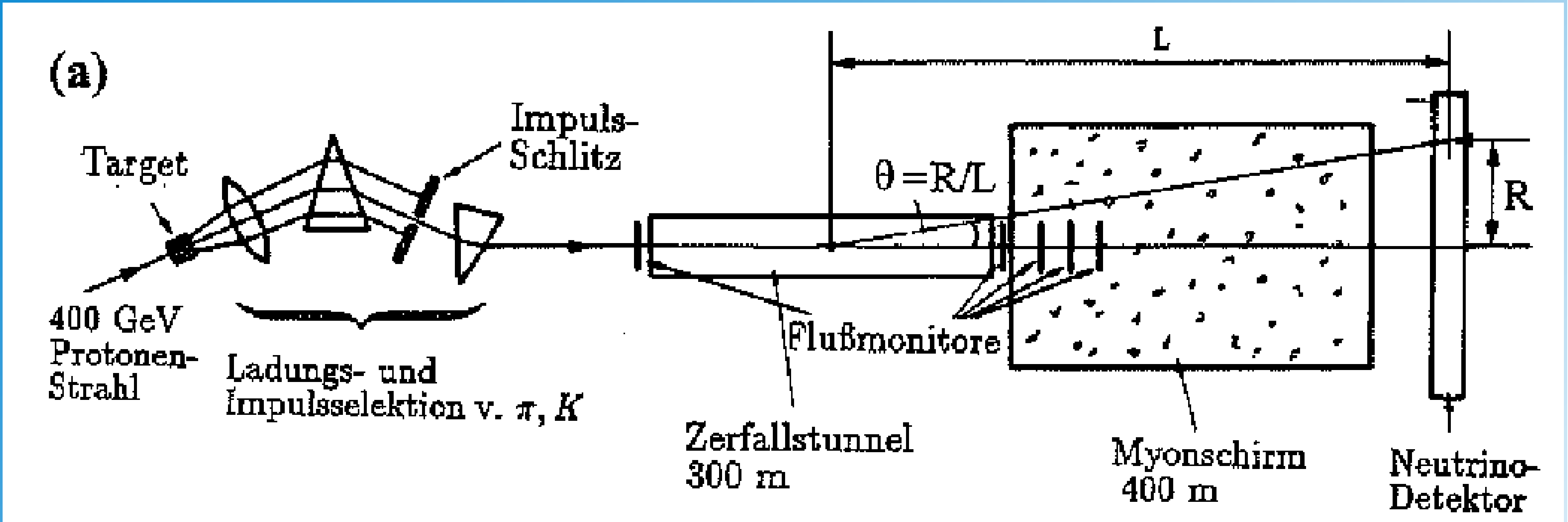
Because of the propagator effect in neutrino-nucleon scattering experiments require neutrino beams of about **E_ν ~100 GeV** to test weak interactions at reasonable rates **$\sigma \sim O(1pb)$**

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



neutrino-electron scattering

Production of (Myon) Neutrino Beams



Production reactions:

$$M^+ \to \mu^+ + \nu_\mu \quad (M^+ = \pi^+, K^+)$$

CHARM Detector

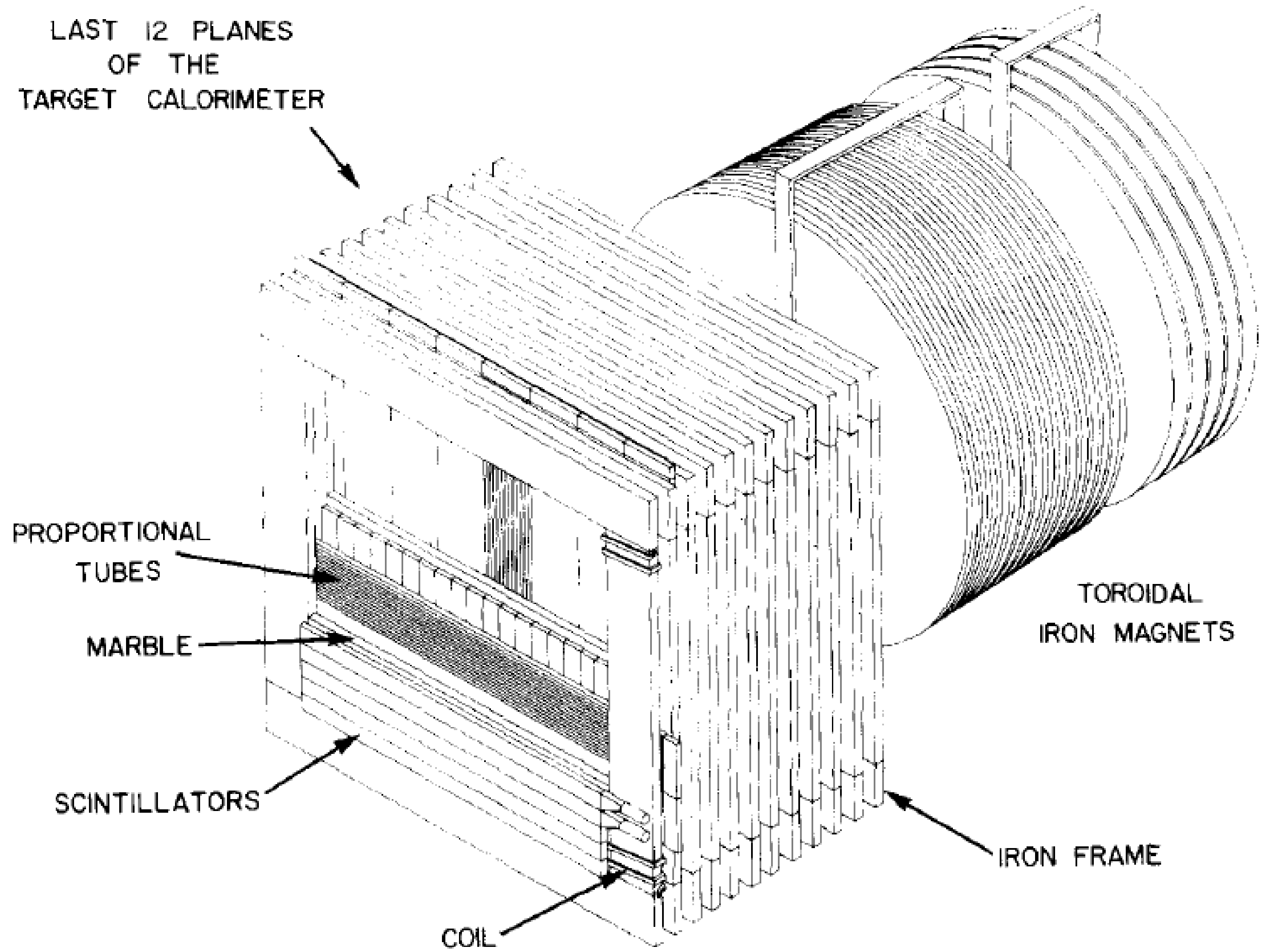
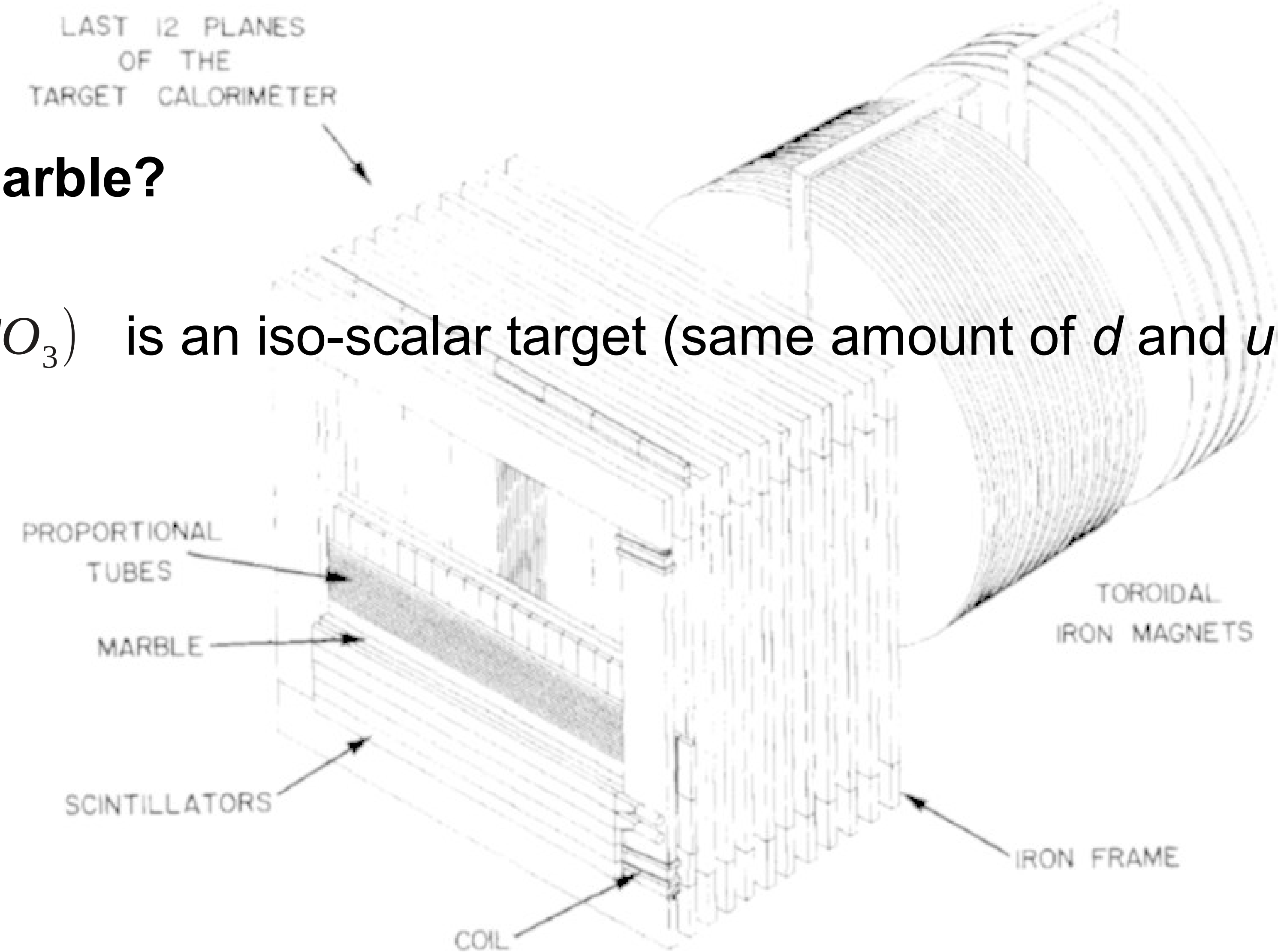


Fig. 1. Partial view of the fine-grain calorimeter and the muon spectrometer. Each subunit is composed of a marble plate of $3 \times 3\ m^2$ surface area and 8 cm thickness, a layer of 20 scintillators 15 cm wide and 3 m long, and a layer of 128 proportional drift tubes 3 cm wide and 4 m long. The calorimeter is surrounded by a frame of magnetized steel and followed by four toroidal iron magnets of 3.7 m diameter, each 75 cm thick.

CHARM Detector

Why marble?

$^{40}_{20}Ca(CO_3)$ is an iso-scalar target (same amount of *d* and *u* quarks)



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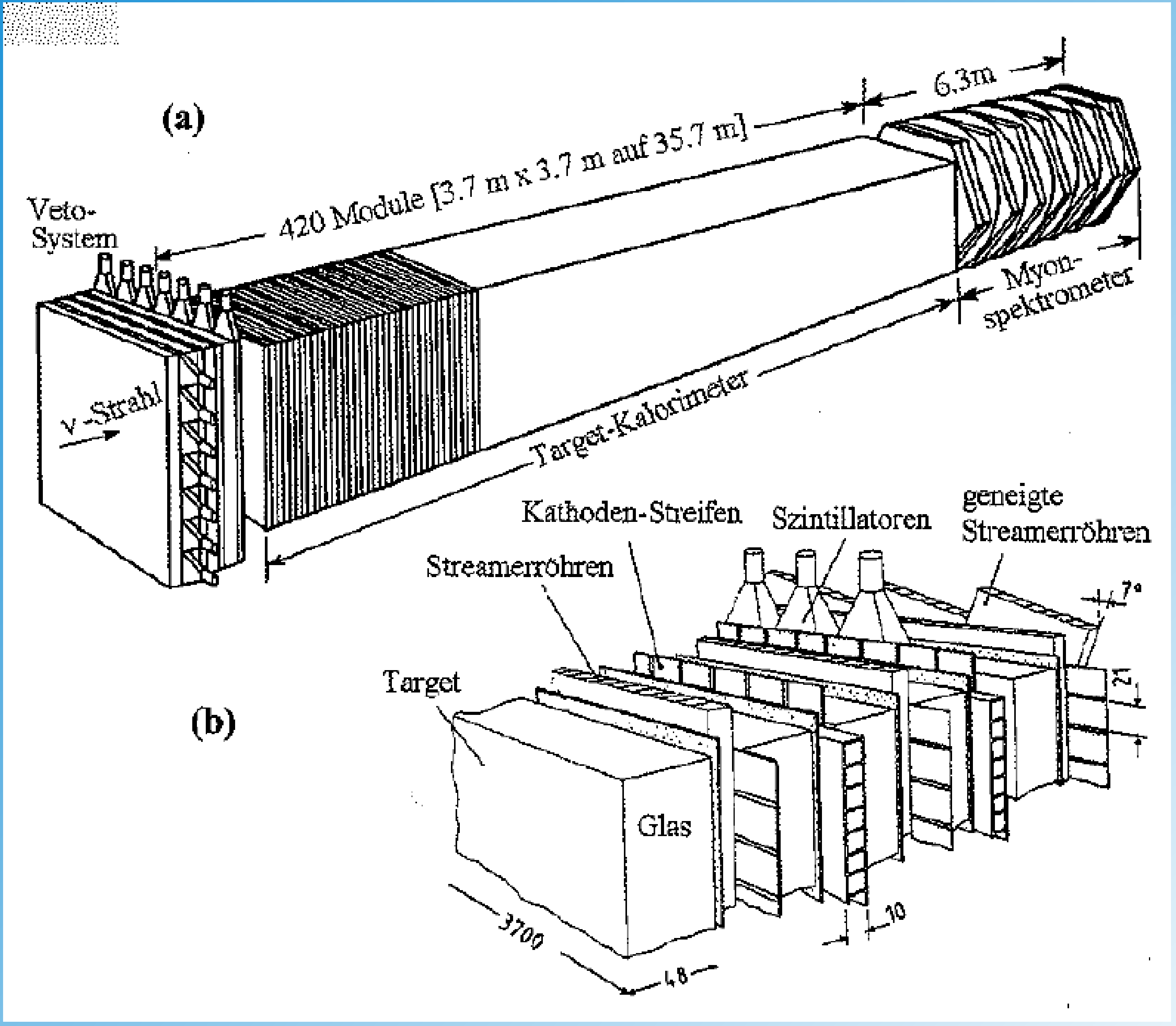
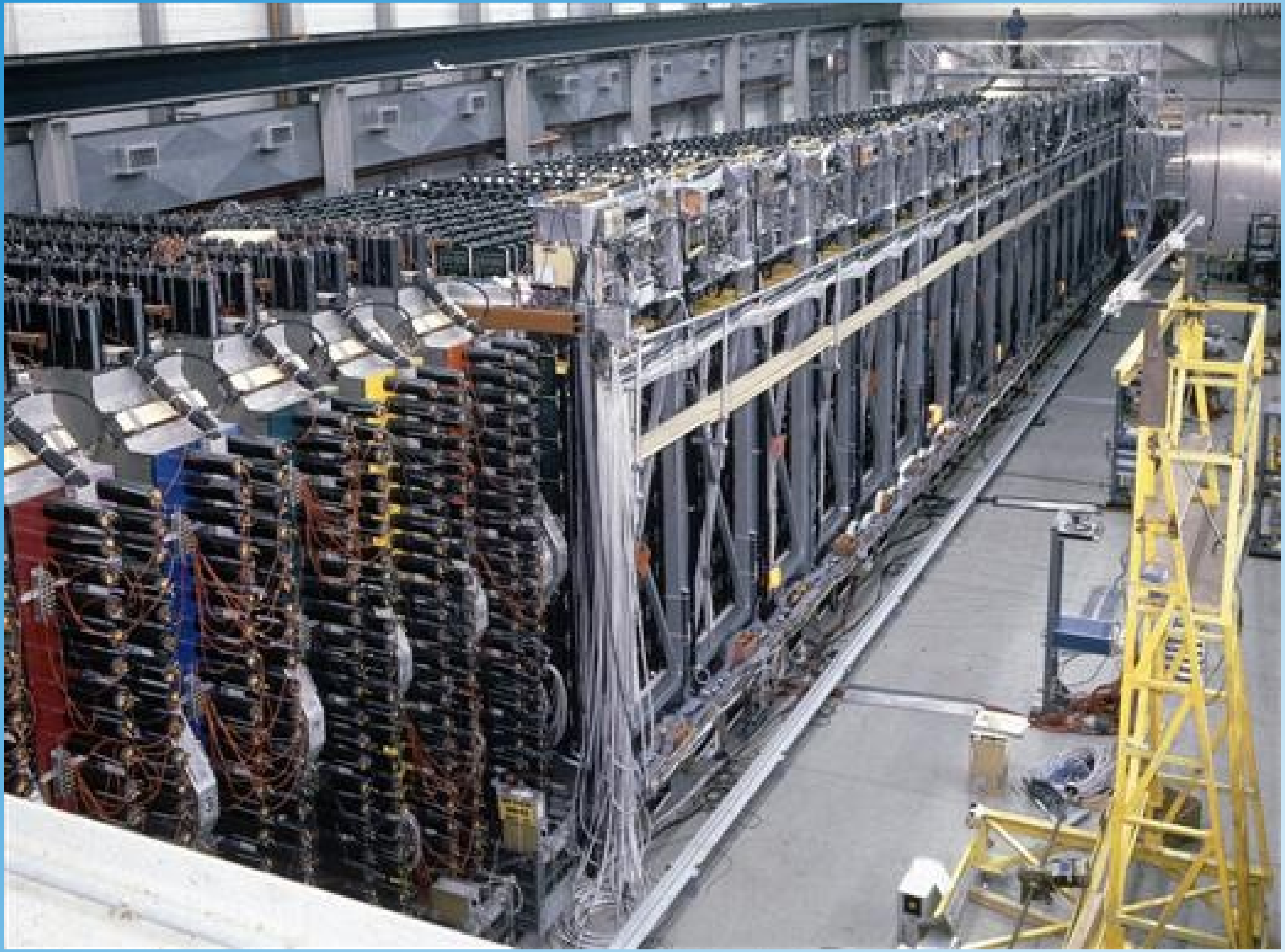
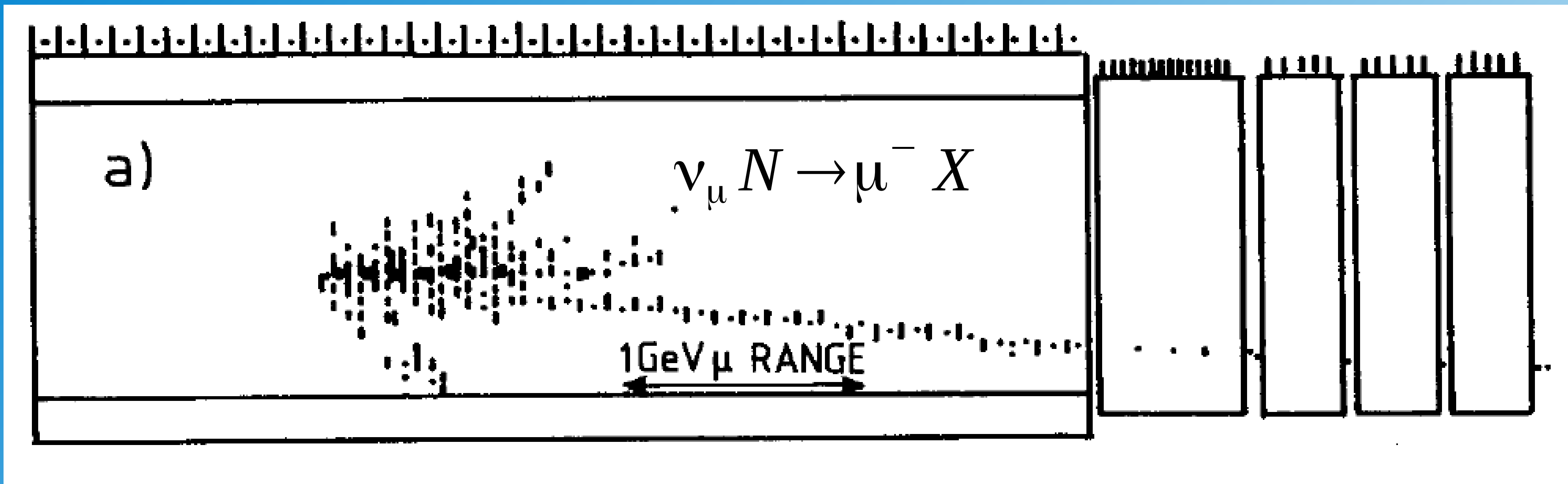
CHARMII Detector

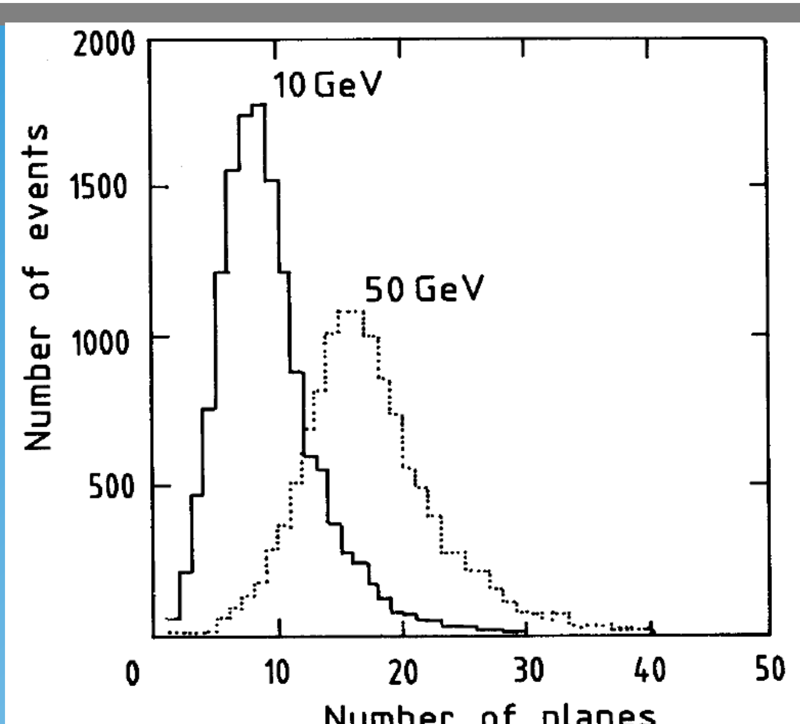


CHARMII Detector



Detection of Myon Neutrinos in CC



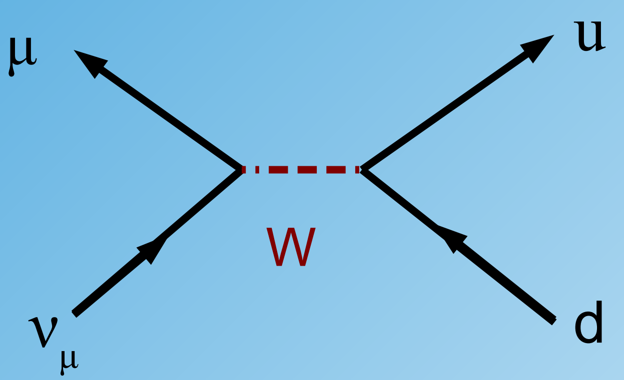


- long track identified as muon (minimum ionising particle)
- length of track is a measure of the muon energy

(Anti-) Neutrino-Nucleon Scattering

Neutrino-Nucleon:

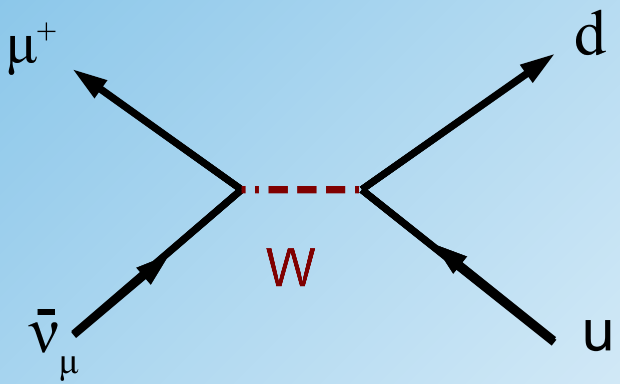
$$\frac{d\sigma}{d\Omega}(\nu_\mu d \to \mu^- u) = \frac{G_F^2}{4\pi^2} s$$



neutrino-nucleon scattering

Anti-Neutrino-Nucleon:

$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu u \to \mu^+ d) = \frac{G_F^2}{4\pi^2} t$$



antineutrino-nucleon scattering

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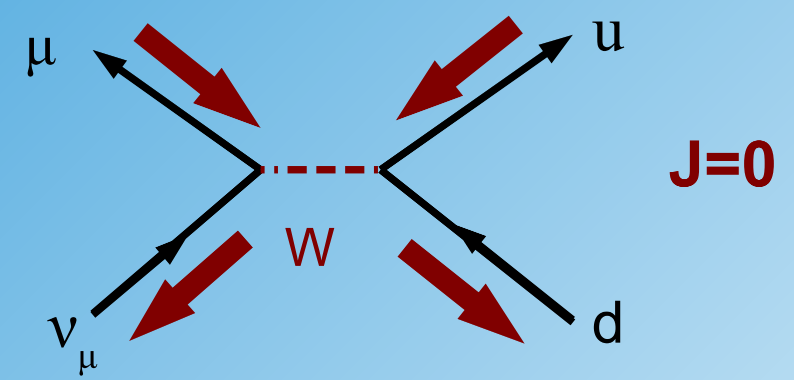

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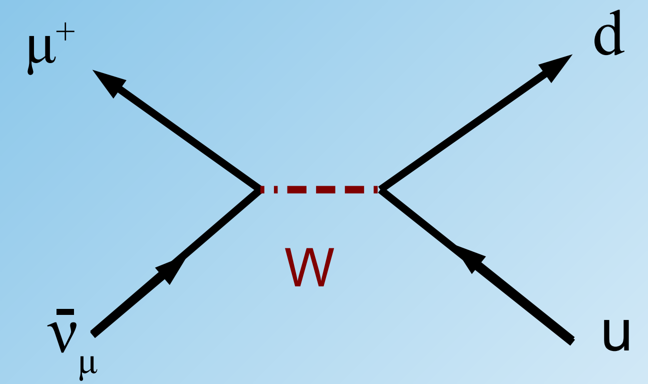

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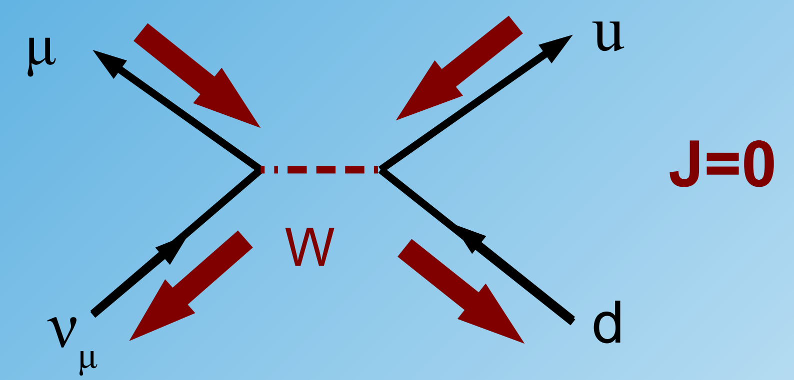

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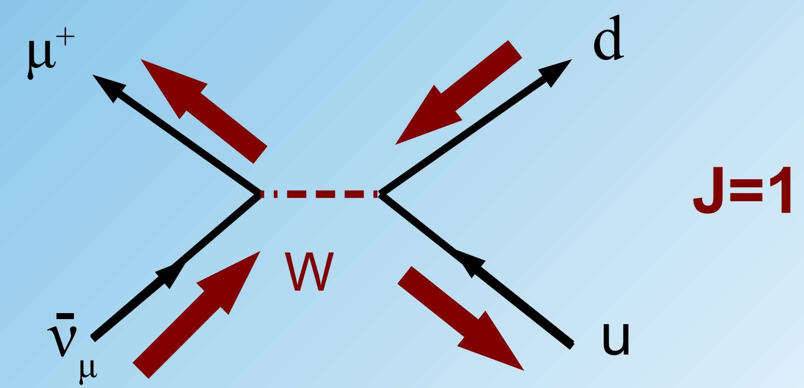
Anti-Neutrino-Nucleon:

$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu u \to \mu^+ d) = \frac{G_F^2}{4\pi^2} t$$



antineutrino-nucleon scattering

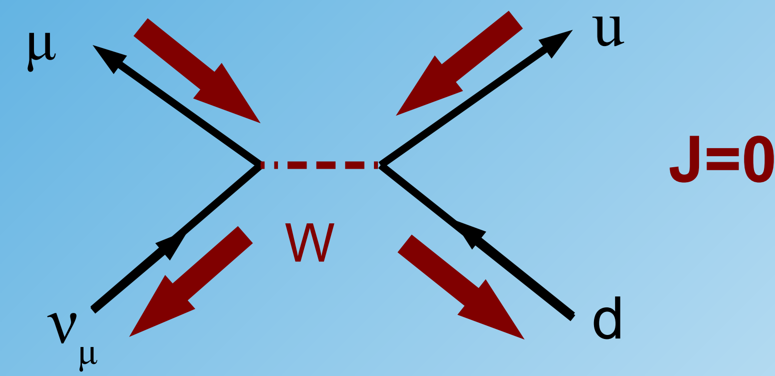
(Anti-) Neutrino-Nucleon Scattering

Neutrino-Nucleon:

$$\frac{d\sigma}{d\Omega}(\nu_\mu d \to \mu^- u) = \frac{G_F^2}{4\pi^2} s$$

$$\frac{d\sigma}{d\Omega}(\nu_\mu N \to \mu^- X) \propto \frac{1}{2} \frac{G_F^2}{4\pi^2} x S$$

isoscalar target

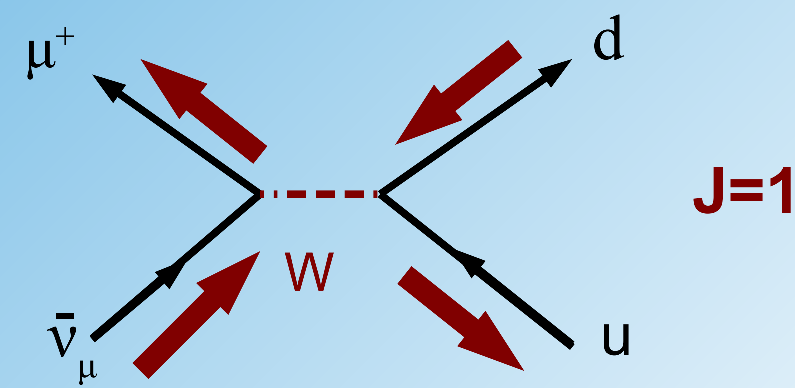


neutrino-nucleon scattering

Anti-Neutrino-Nucleon:

$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu u \to \mu^+ d) = \frac{G_F^2}{4\pi^2} t$$

$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu N \to \mu^+ X) \propto \frac{1}{2} \frac{G_F^2}{4\pi^2} x t$$



antineutrino-nucleon scattering

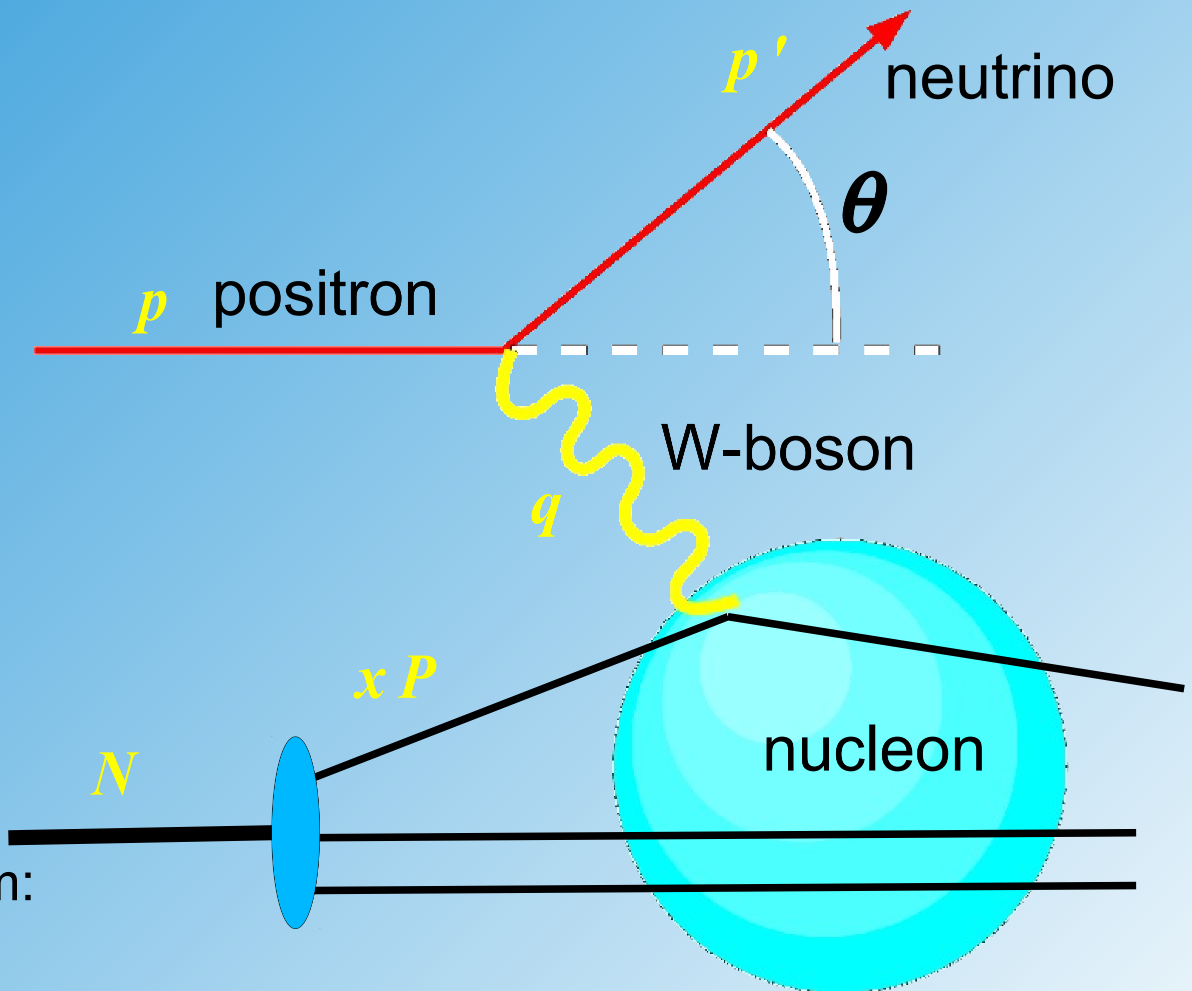
$$t = s(1-\cos\theta^*)^2 = s(1-y)^2$$

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: $S = 2 p P$

Measurement of the Differential νN and anti-νN Cross Section

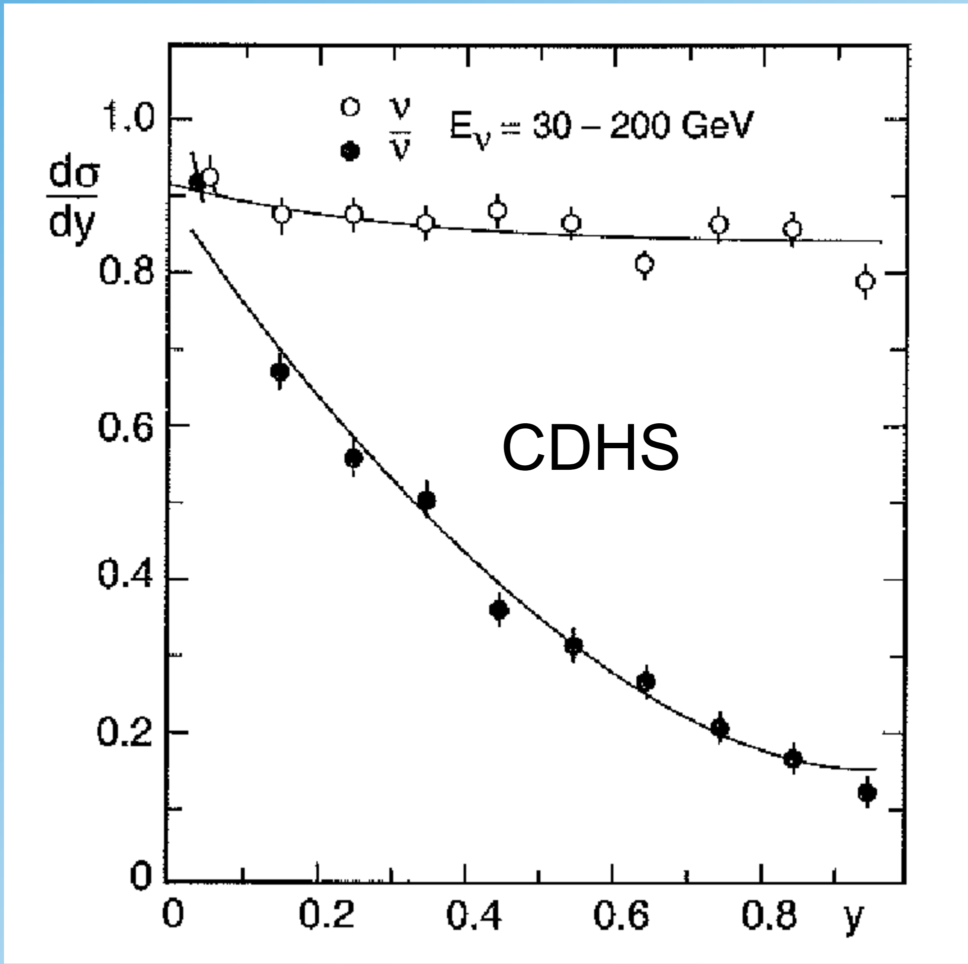
Neutrino-Nucleon:

$$\frac{d\sigma}{dy}(\nu_\mu N \to \mu^- X) \propto \frac{1}{2}\frac{G_F^2}{\pi} x S$$

isoscalar target

Anti-Neutrino-Nucleon:

$$\frac{d\sigma}{dy}(\bar{\nu}_\mu N \to \mu^+ X) \propto \frac{1}{2}\frac{G_F^2}{\pi} x S (1-y)^2$$



small deviations from above equations due to x-dependence!

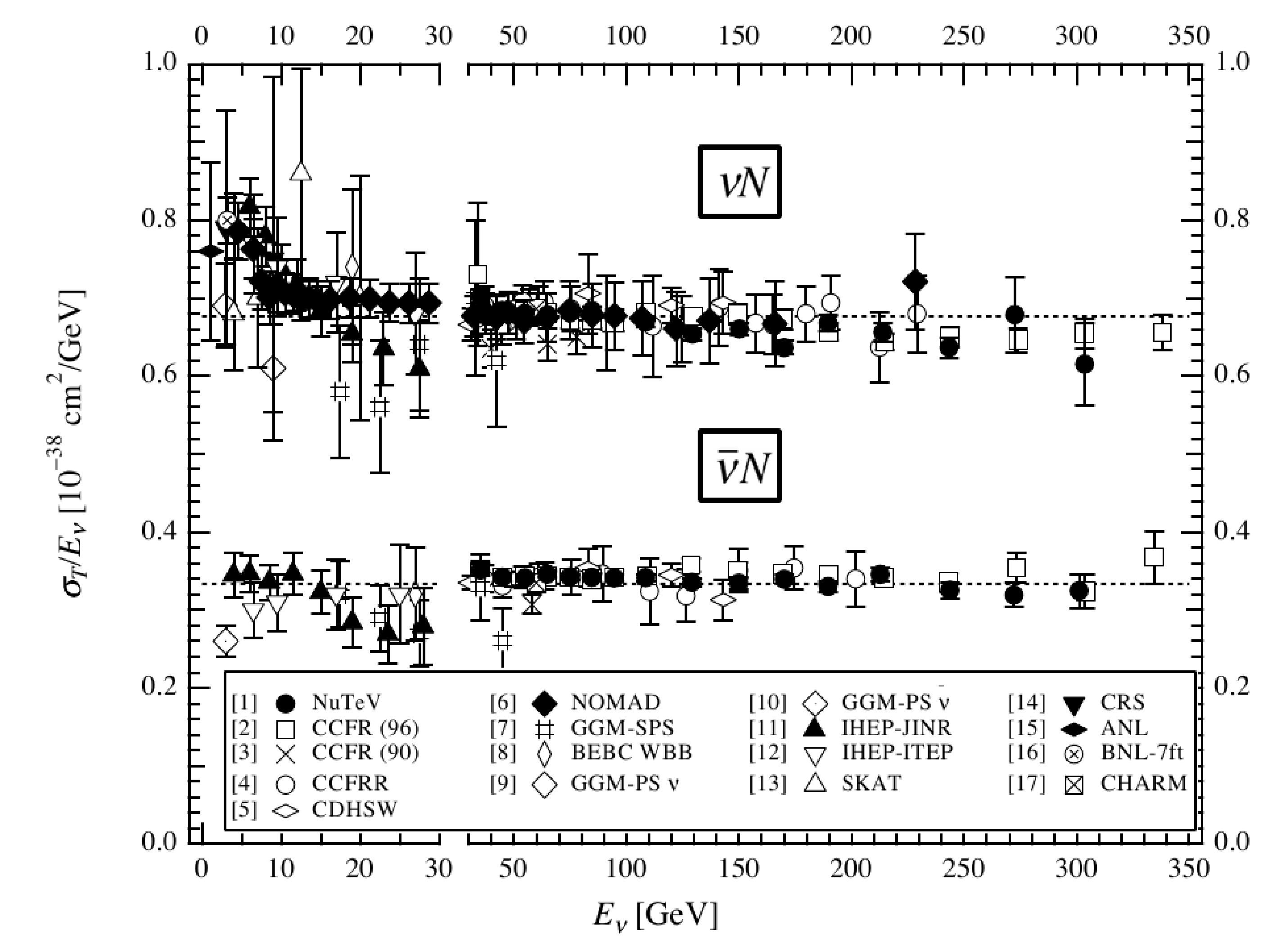
Measurement of the Total νN and anti-νN Cross Section

From simple quark counting:
(isoscalar target)

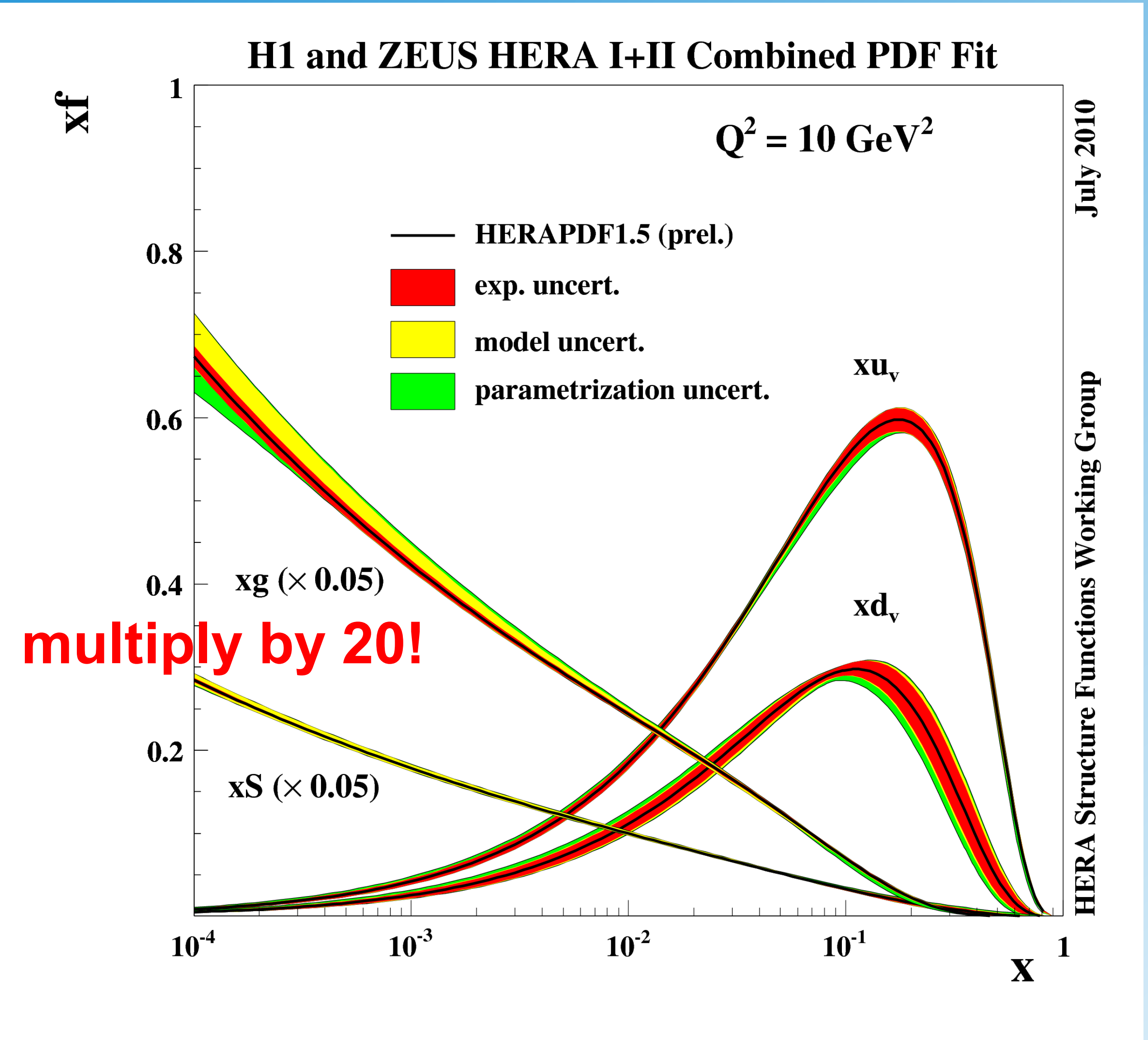
$$\frac{\sigma(\nu_\mu N)}{\sigma(\bar{\nu}_\mu N)} = 3$$

measured value ~2
is significantly smaller!

- Parton dynamics more complex
- Sea Quarks!



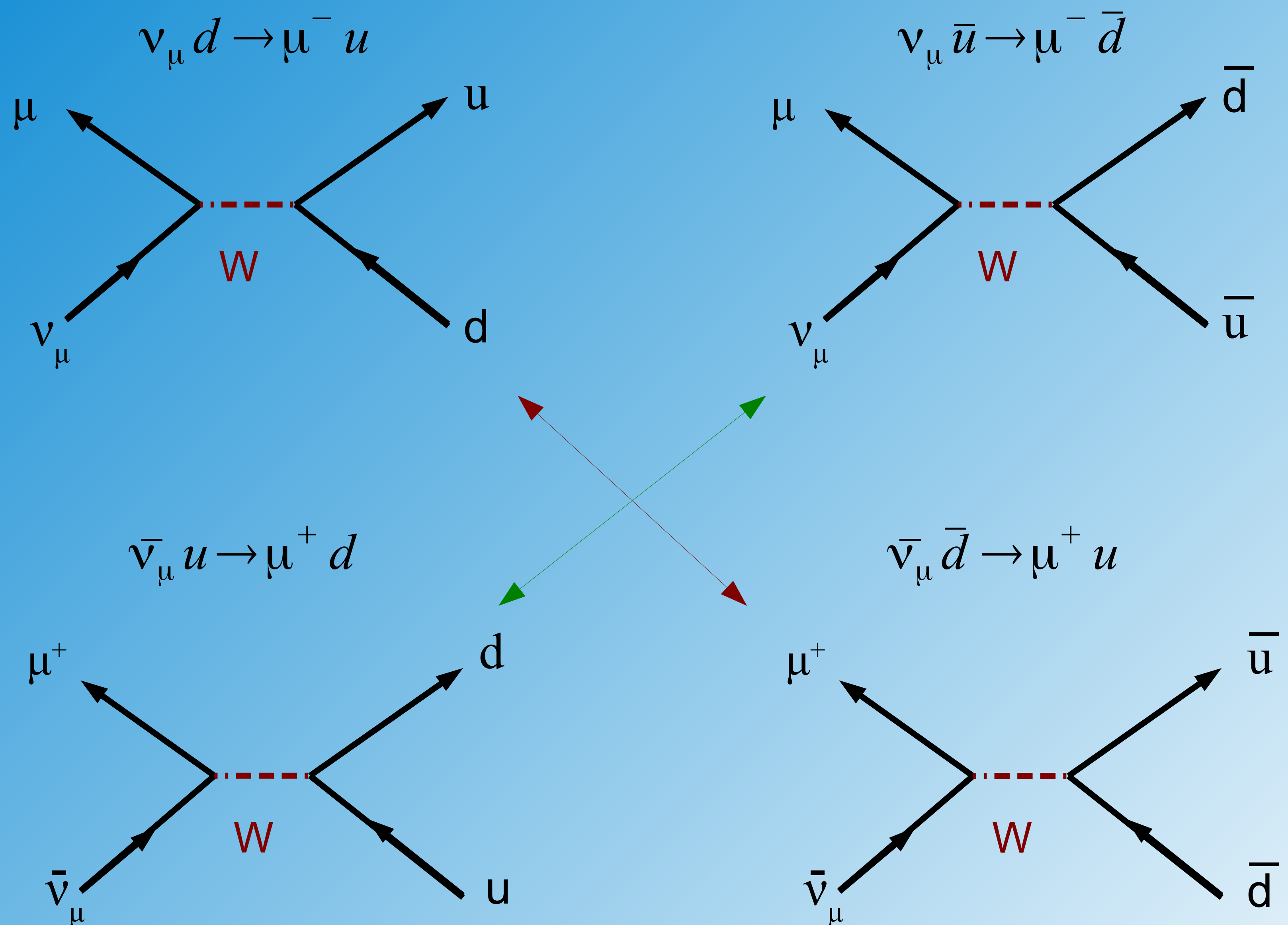
Example: Proton Parton Densities



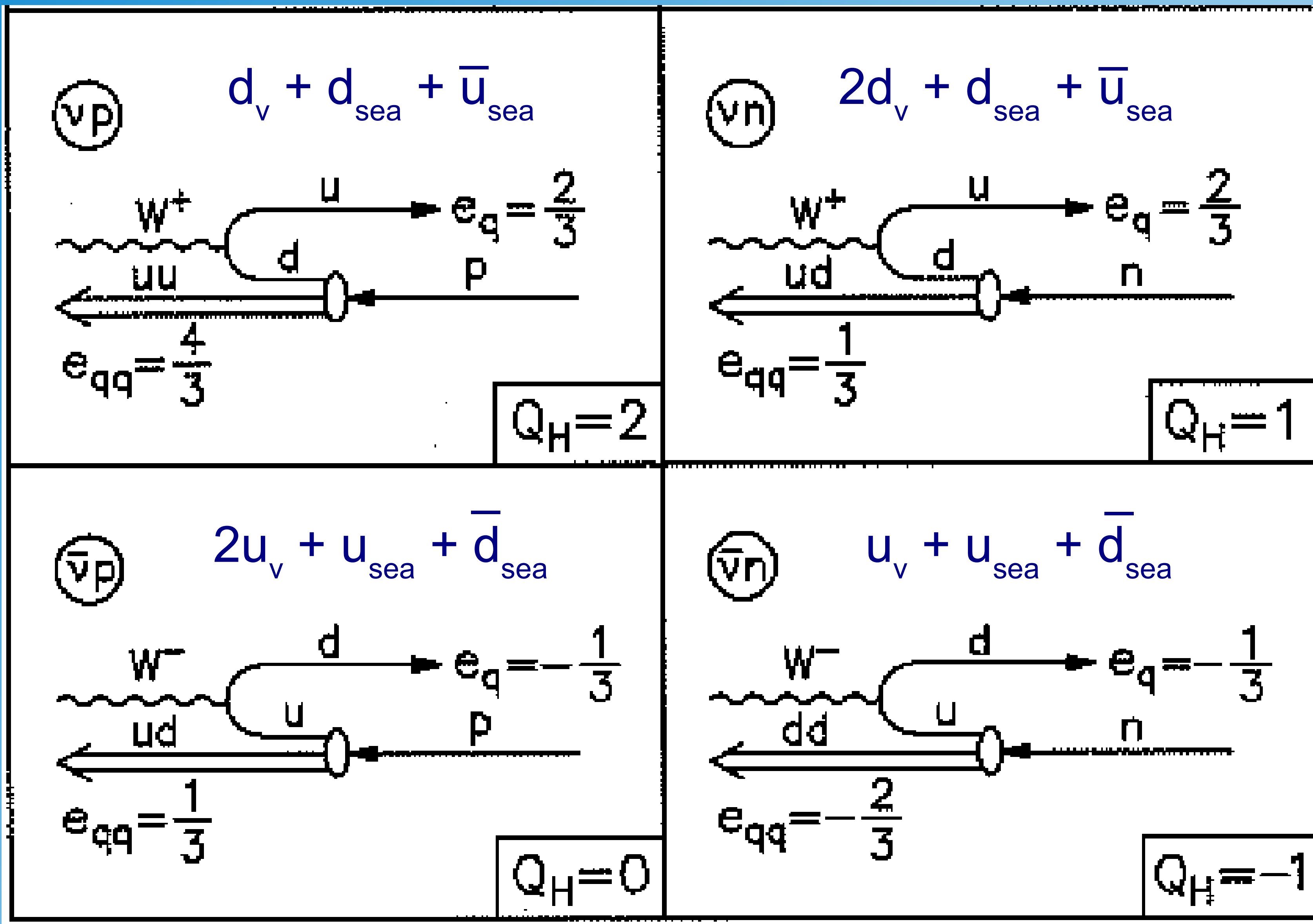
multiply by 20!

Significant component from sea quarks!

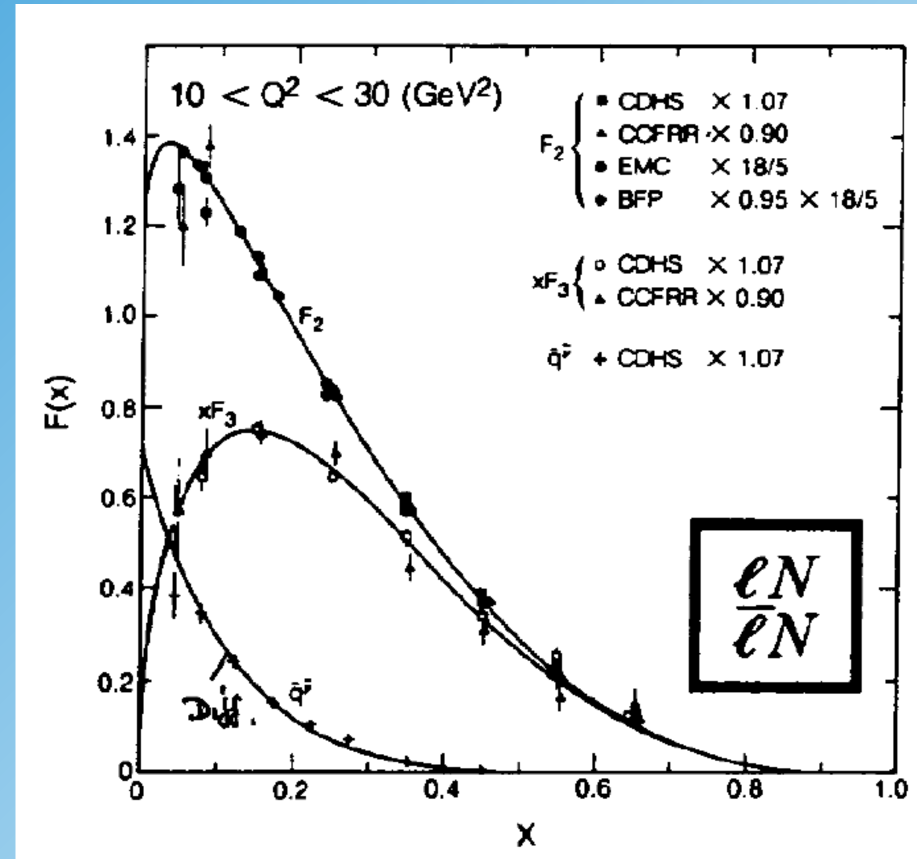
(Anti-) Neutrino-Nucleon Scattering



Unfolding the Valence Quark Distributions



Structure Functions



Relations:

$$F_2 - xF_3 = 4x\,\overline{d}(x)$$
$$F_2 + xF_3 = 4x\,u(x)$$

$$F_2^{\overline{\nu}p} = 2x\left[u(x) + \overline{d}(x)\right]$$
$$xF_3^{\overline{\nu}p} = 2x\left[u(x) - \overline{d}(x)\right]$$

$$F_2^{\overline{\nu}n} = 2x\left[d(x) + \overline{u}(x)\right]$$
$$xF_3^{\overline{\nu}n} = 2x\left[d(x) - \overline{u}(x)\right].$$

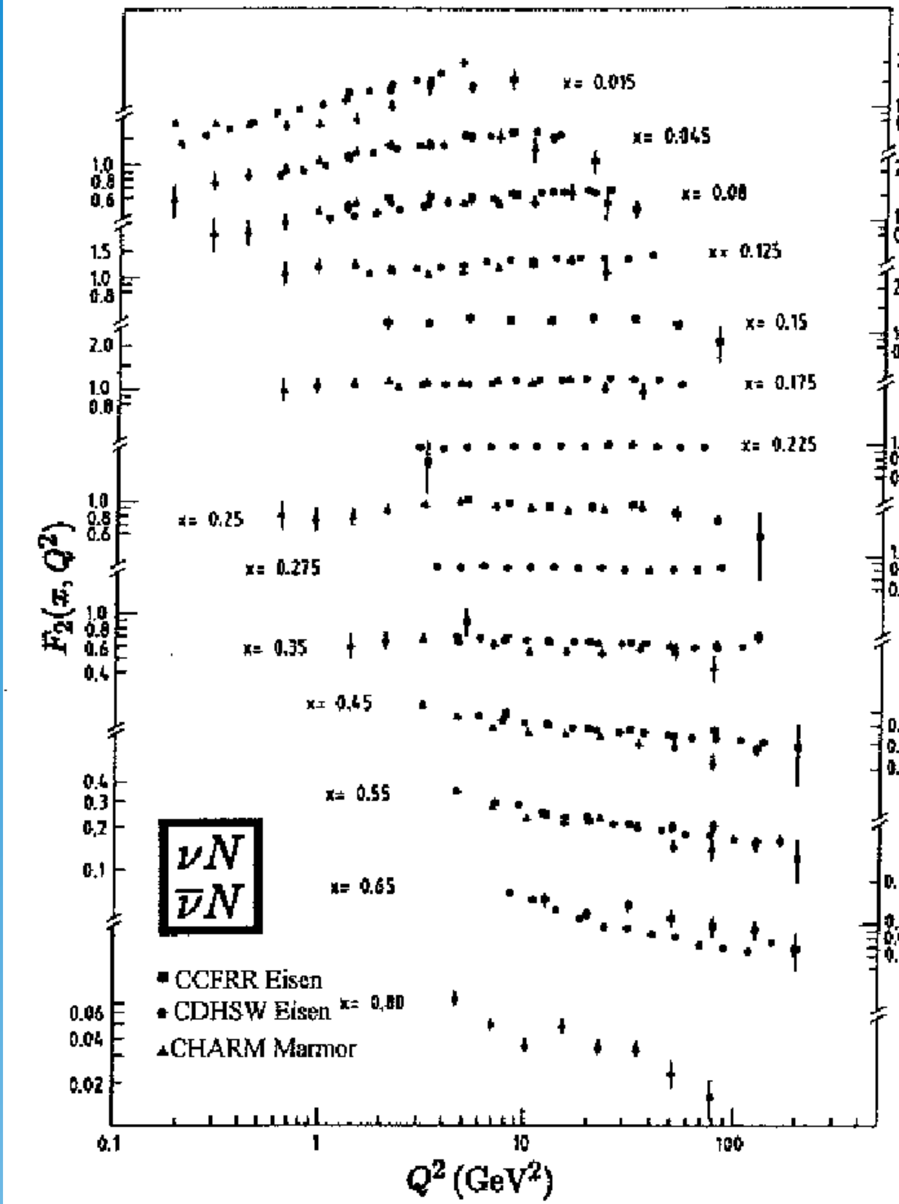
Measurement:

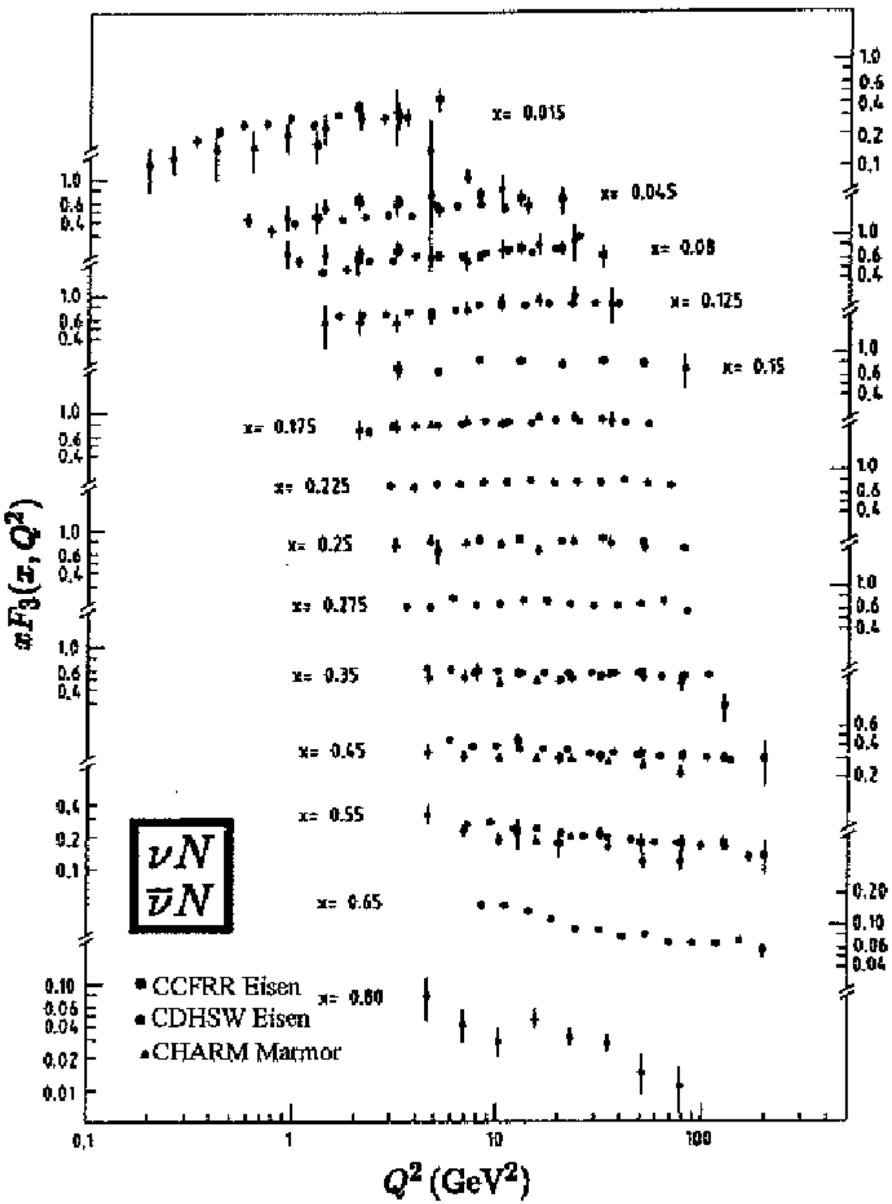
$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2}{4\pi} S\left\{[F_2^{\nu,\overline{\nu}} \pm xF_3^{\nu,\overline{\nu}}] + [F_2^{\nu,\overline{\nu}} \mp xF_3^{\nu,\overline{\nu}}](1-y)^2\right\}.$$

Extraction of parton densities:

$$x\,(u(x) + d(x)) = \frac{1}{2}\left(F_2^{\nu N} + xF_3^{\nu N}\right)$$
$$x\,(\overline{u}(x) + \overline{d}(x)) = \frac{1}{2}\left(F_2^{\nu N} - xF_3^{\nu N}\right)$$

F_2 Results xF_3 Results



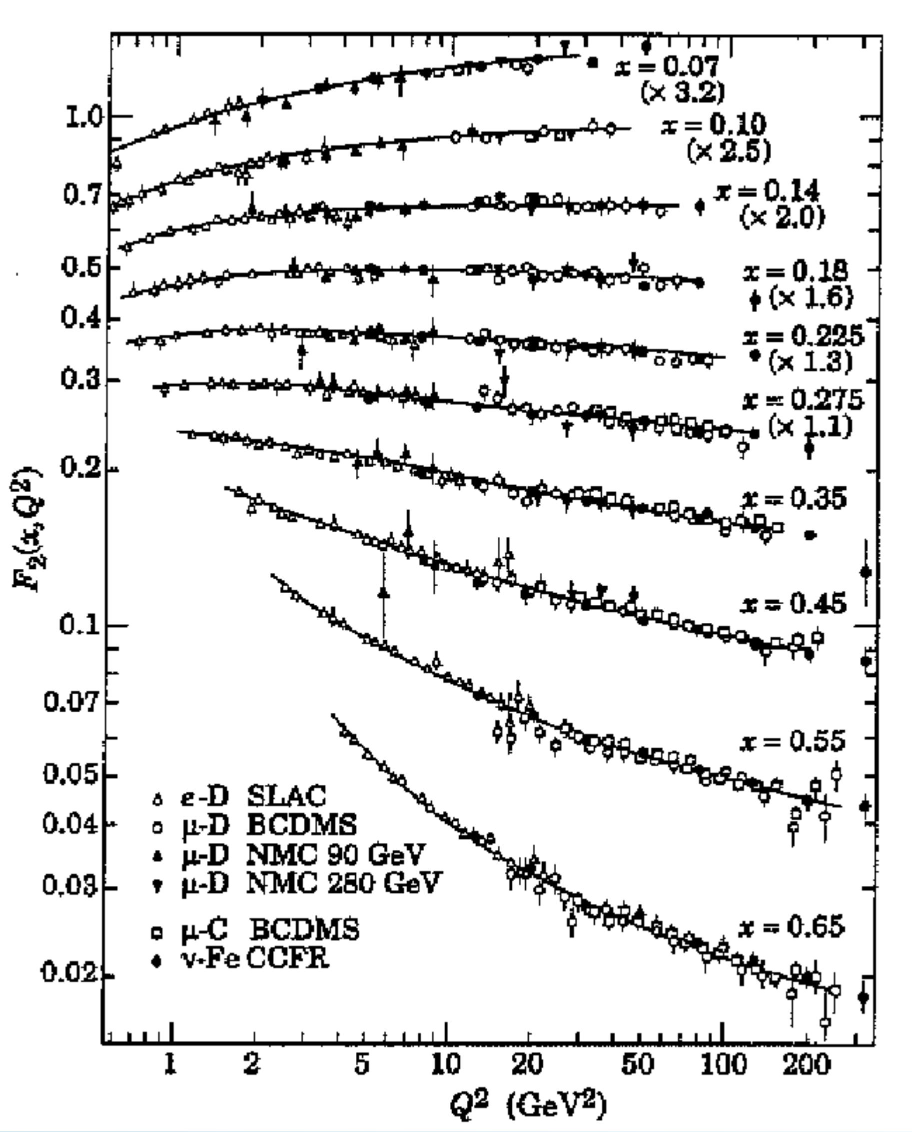


Comparison νN versus lepton-N Scattering

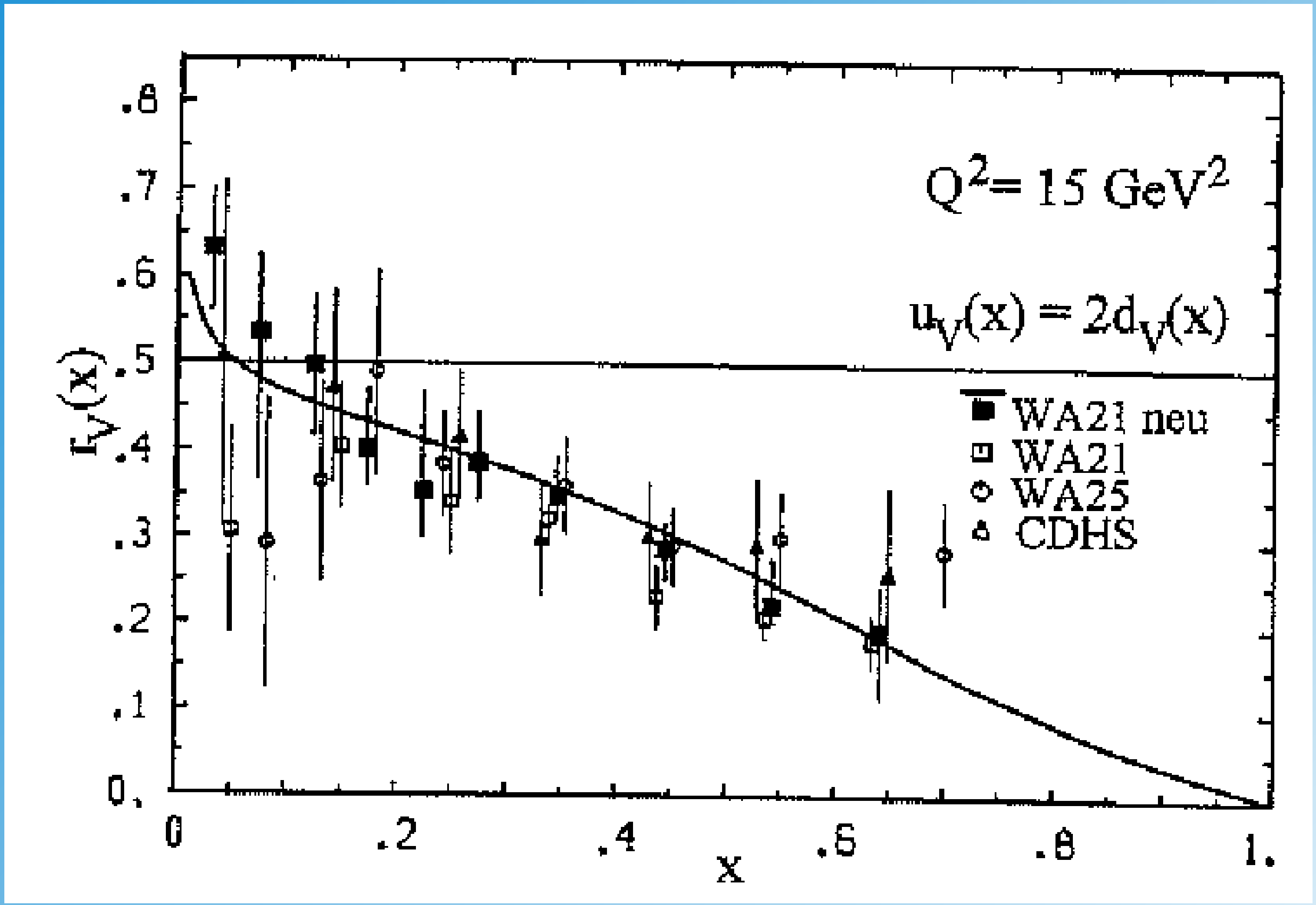
Due to different coupliings:

$$F_2^{eN} = \frac{5}{18} F_2^{\nu N}$$

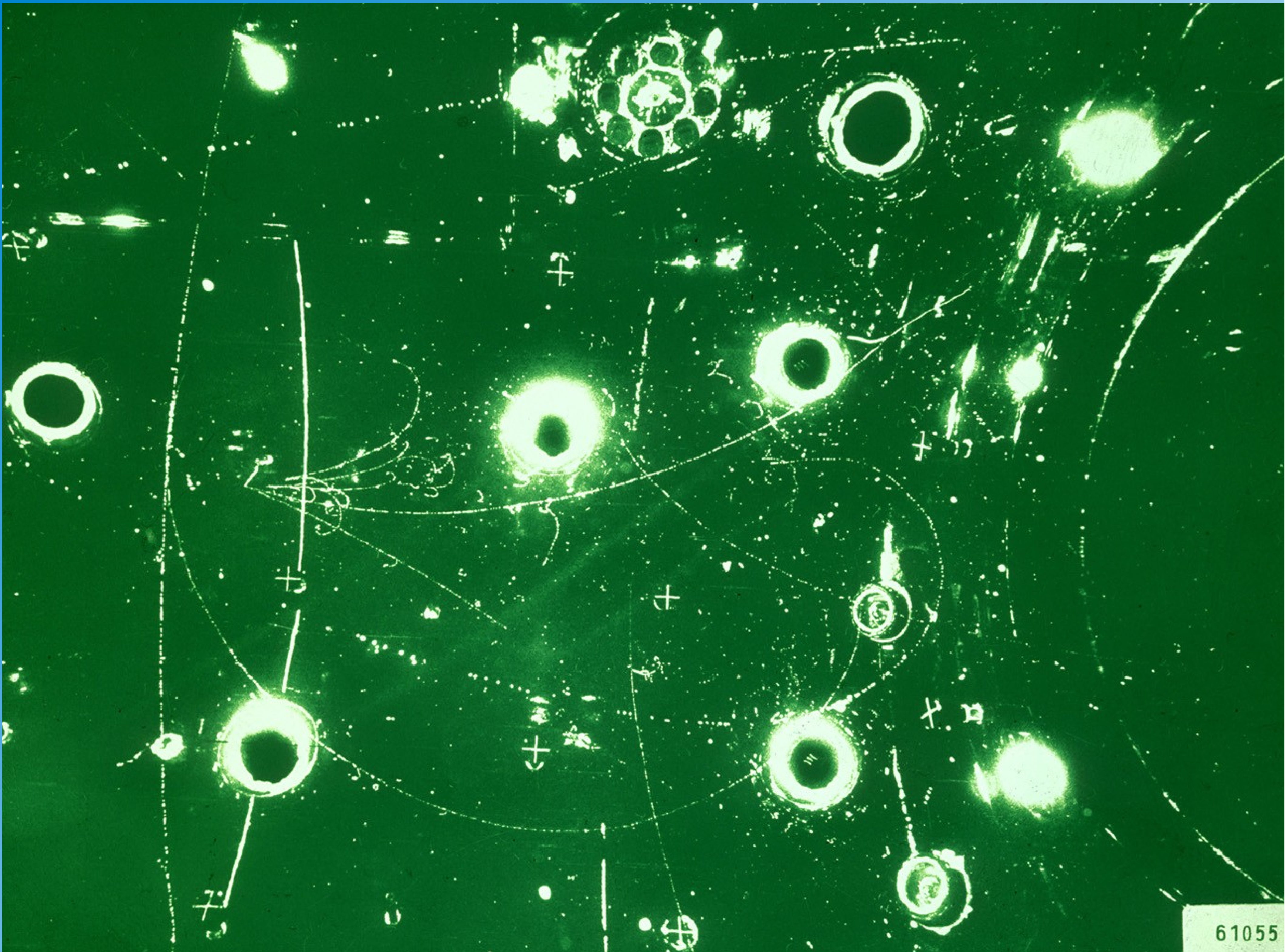
Structure function results obtained in **weak interactions** agree well with result obtained in **electromagnetic interactions**!



Ratio of d_v/u_v



Result: $d_v/u_v \rightarrow 0$ if $x \rightarrow 1$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