Lecture:

Standard Model of Particle Physics

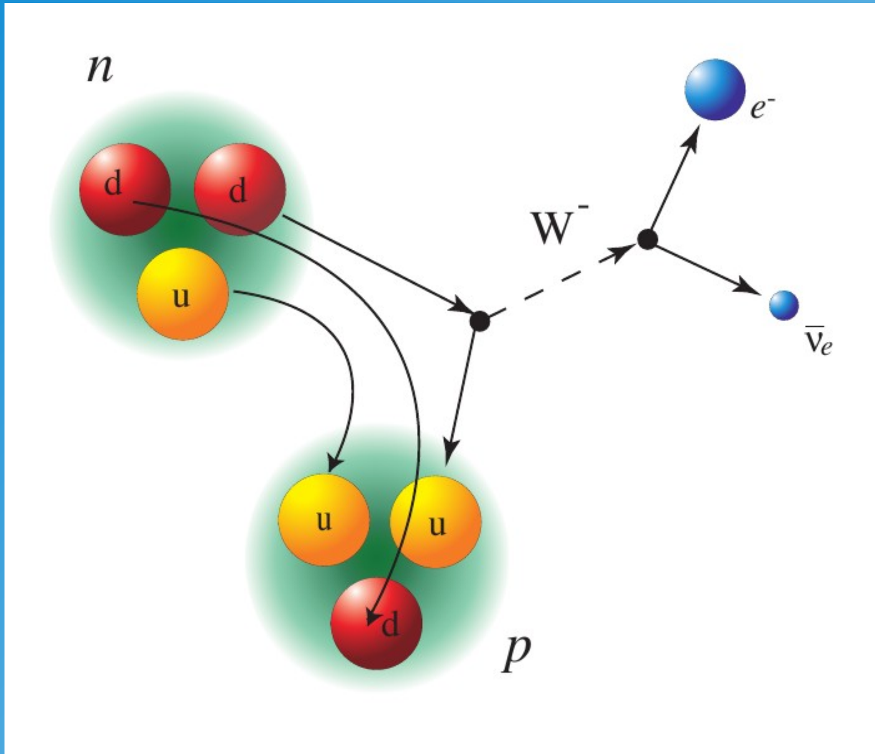
Heidelberg SS 2016

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
- Nuclear Beta Decays
- Pion Decay: branching ratios
- **Neutron Decay**
- **Neutrino Nucleon Scattering**

Neutron Decay



$n \to p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}$

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

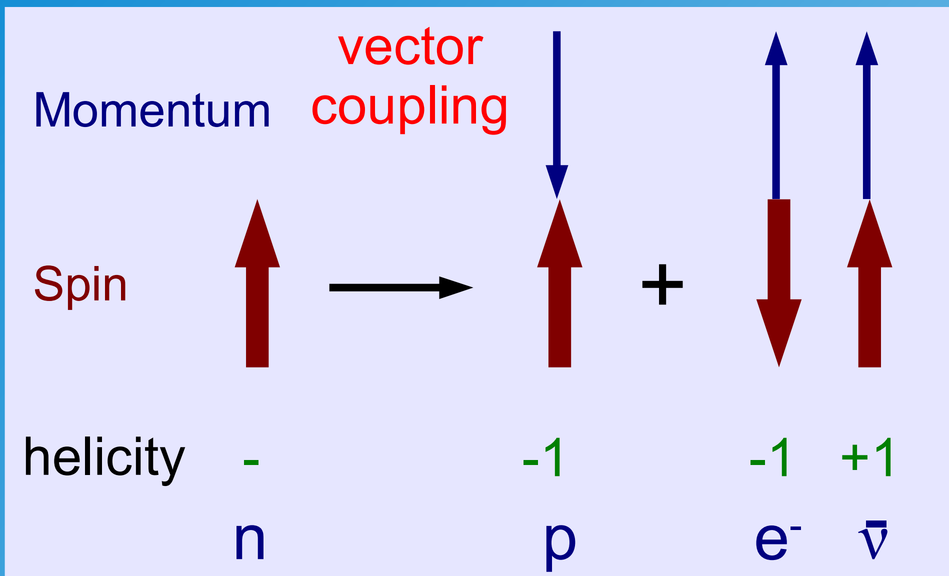
$c_1 = \cos \Theta_C$ $\Delta = 782$ keV

Note:

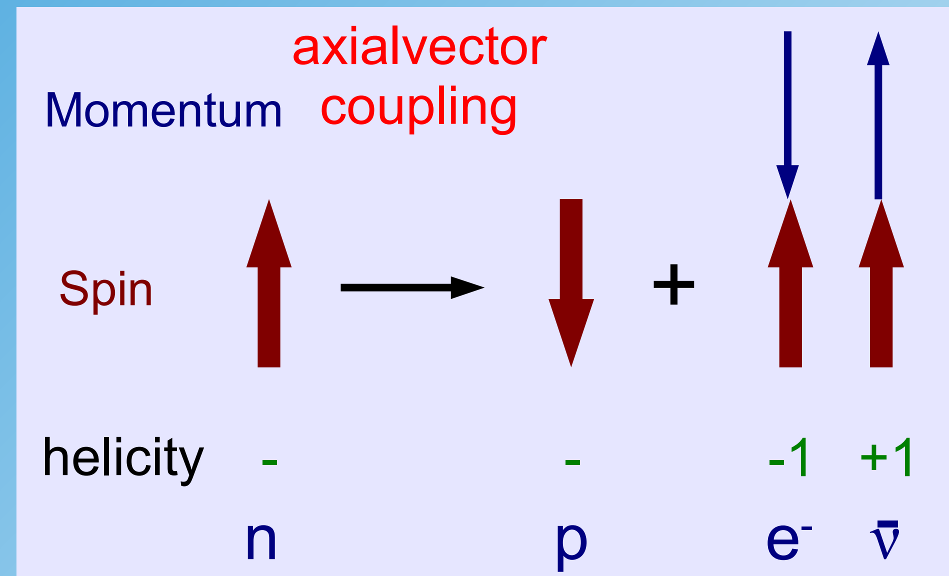
- the *d* and *u* mass eigenstates are not weak eigenstates
- the neutron decay is not a simple *d* → *u* decay (quarks are not free)

Test of Lorentz Structure

<u>Fermi transition</u>



<u>Gamov Teller transition</u>



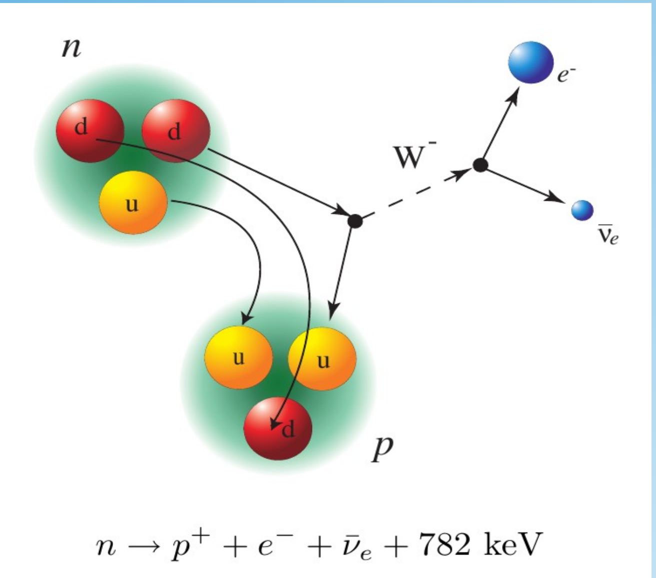
What is the relative contribution of V and A couplings in nuclear decays?

Use a more general Lagrangian:

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

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

Measurement of the Neutron Lifetime



Techniques:

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

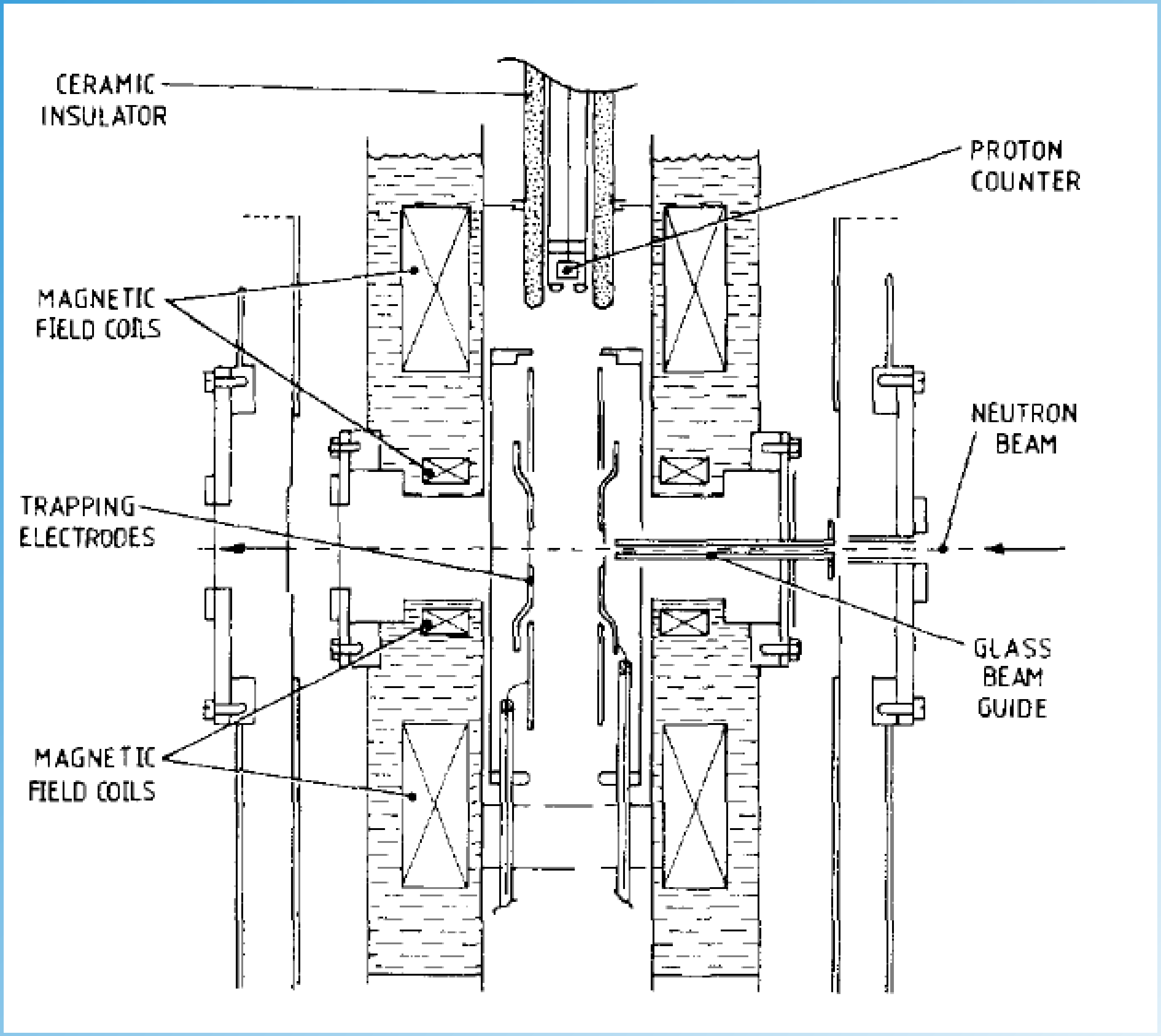
- electron detectors
- proton detectors
- electron-proton coincidence method

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

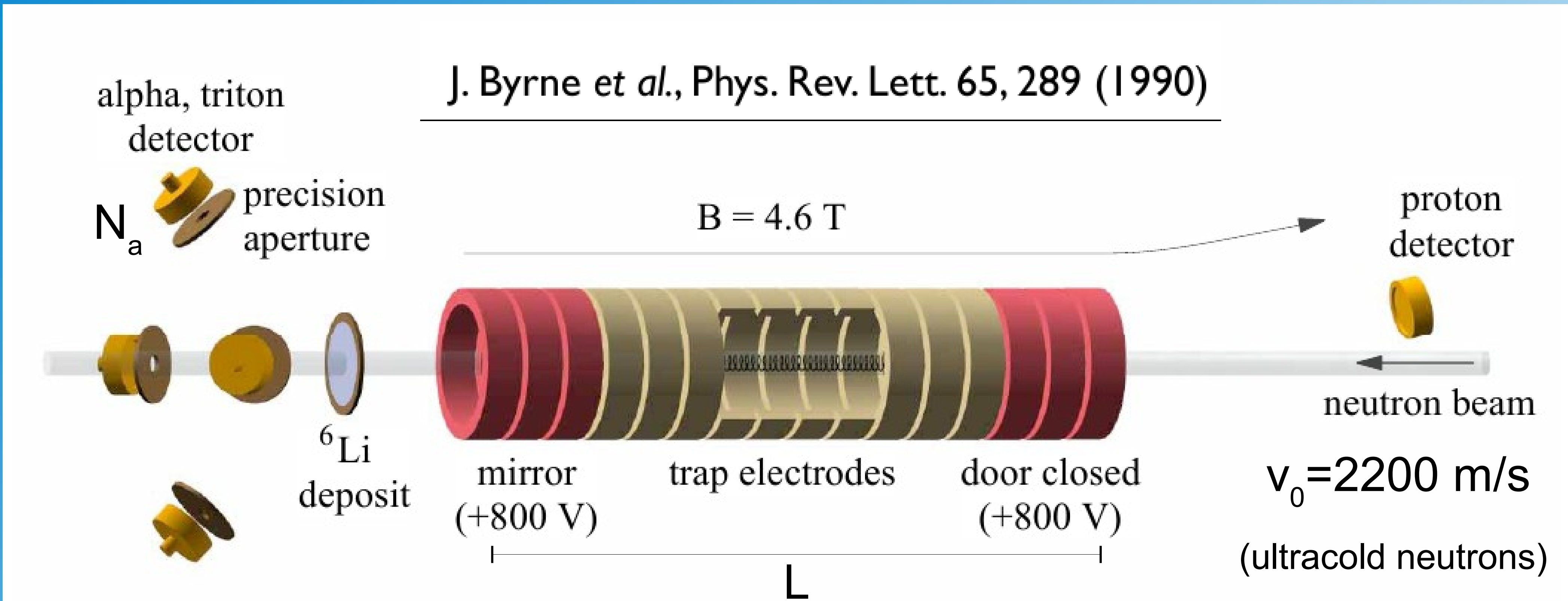
Neutron Lifetime via Proton Trap I

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

“in beam” method



Neutron Lifetime via Proton Trap II



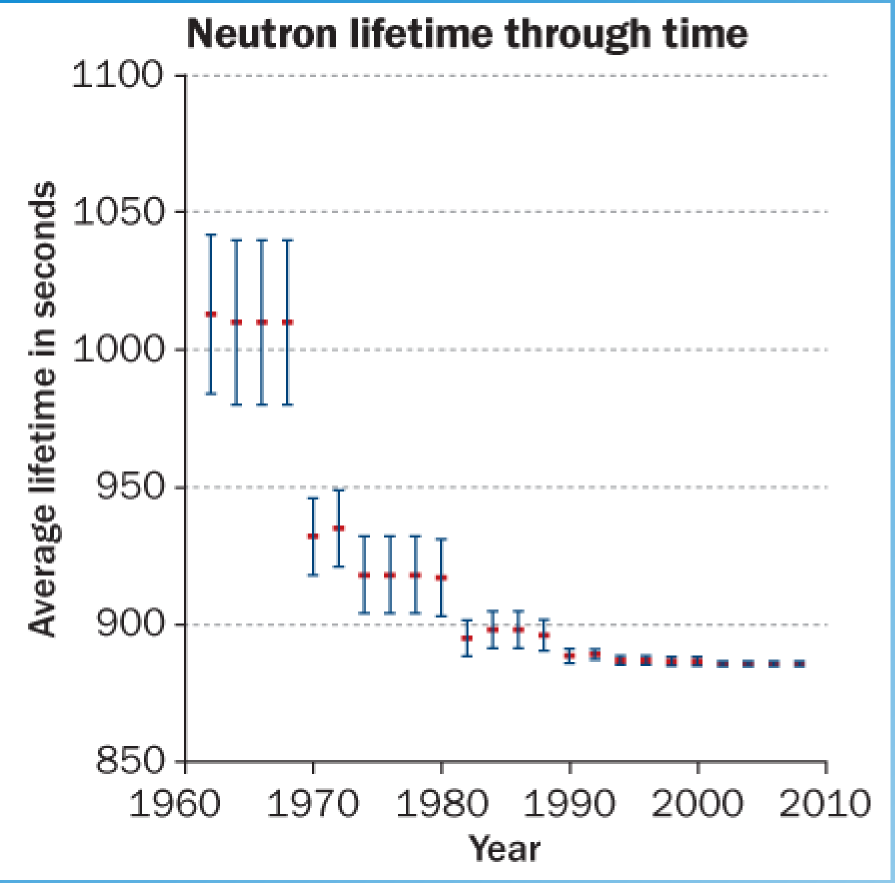
neutron detection:

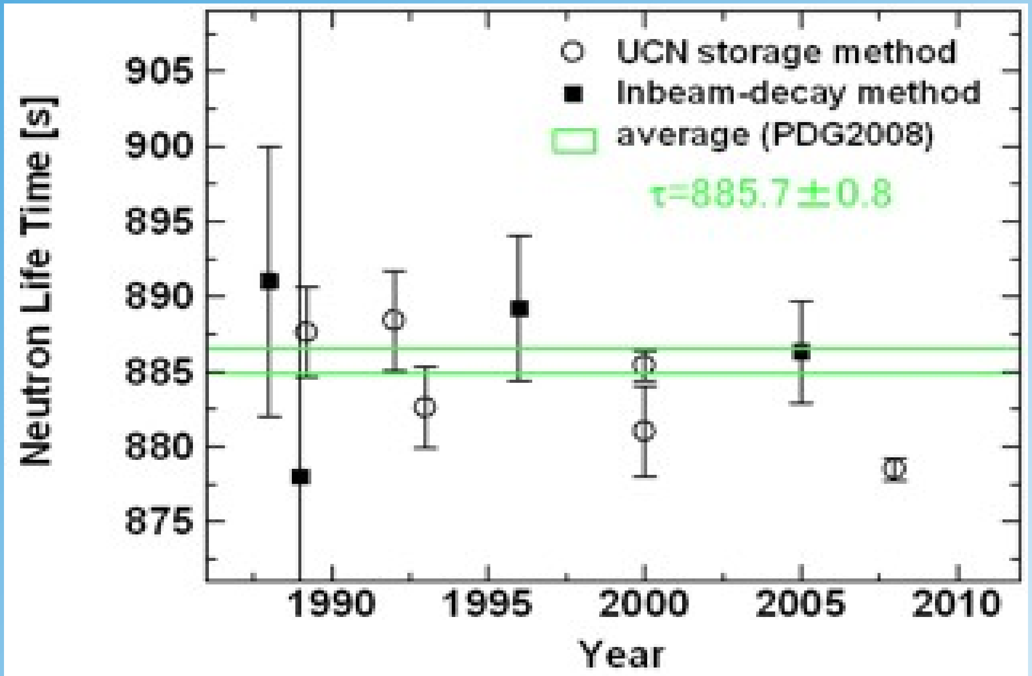
$^{10}B\ n \rightarrow\ ^7Li\ \alpha$

$^6Li\ n \rightarrow\ \alpha\ ^3H$

$$\tau_n = \left(\frac{N_a}{\epsilon_0}\right)\left(\frac{\epsilon_p}{N_p}\right)\left(\frac{L}{v_0}\right)$$

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

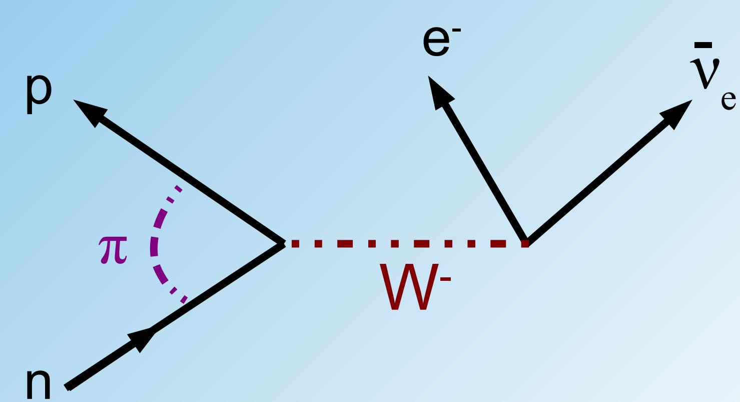
- Valence quark wave function of the neutron :

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

- Naive 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



QCD corrections modify axial-coupling

Prediction for c_A/c_v

- Valence quark wave function of the neutron :

$$
\begin{aligned}
|n\rangle = \frac{1}{\sqrt{18}}\big(&-2|d\uparrow u\downarrow d\uparrow\rangle - 2|d\uparrow d\uparrow u\downarrow\rangle - 2|u\downarrow d\uparrow d\uparrow\rangle \\
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\end{aligned}
$$

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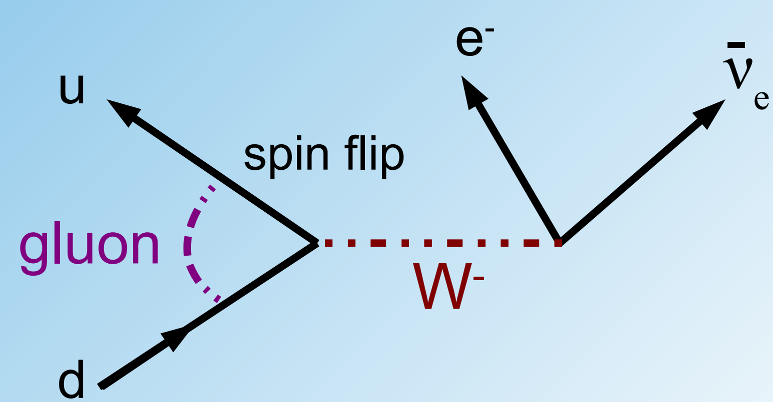


QCD corrections modify axial-coupling

Summary Neutron Decay

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

$c_V = 1$: conserved vector currents (CVC)

$c_A = 1.2694 +- 0.0028$ (experiment)

pion exchange calculation: $c_A \sim 1.29$ (Golberger-Treiman)

Axial currents are NOT conserved!

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)
$Q \to q W^\pm$	hadronic + semileptonic 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)

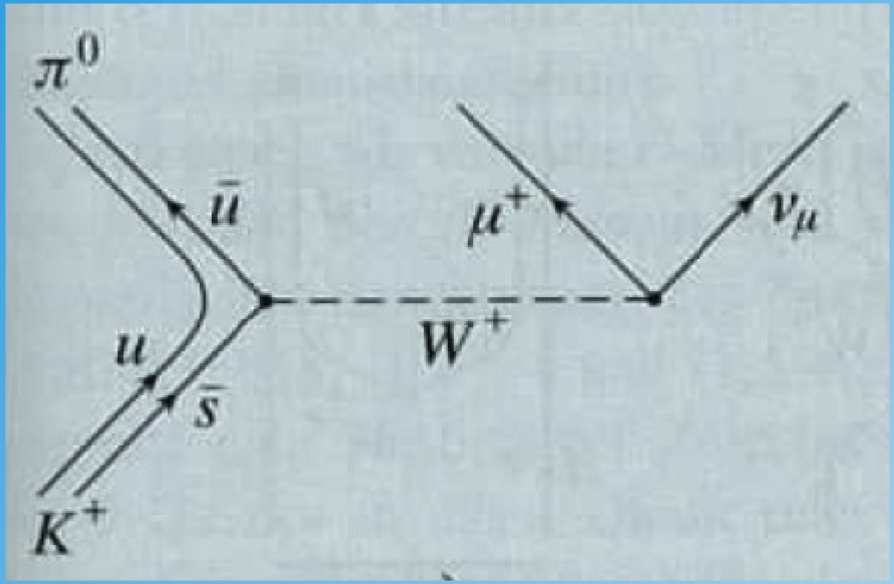
K-Meson Decays

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

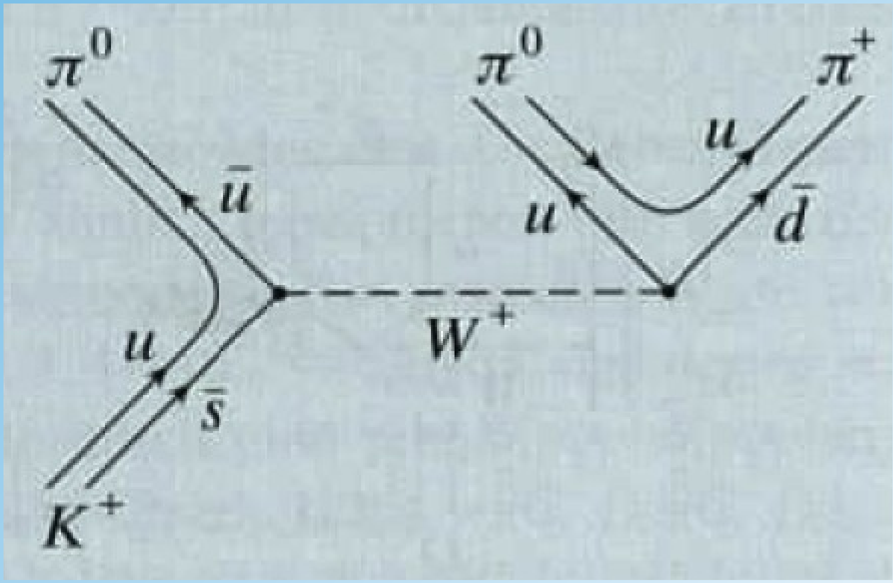
$m_s \approx 150\ MeV$

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

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



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



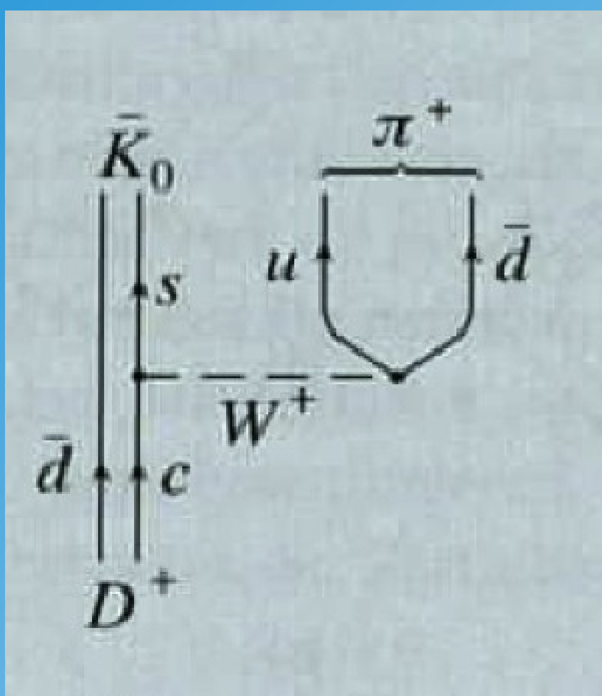
Hadronic Decays of D-mesons

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

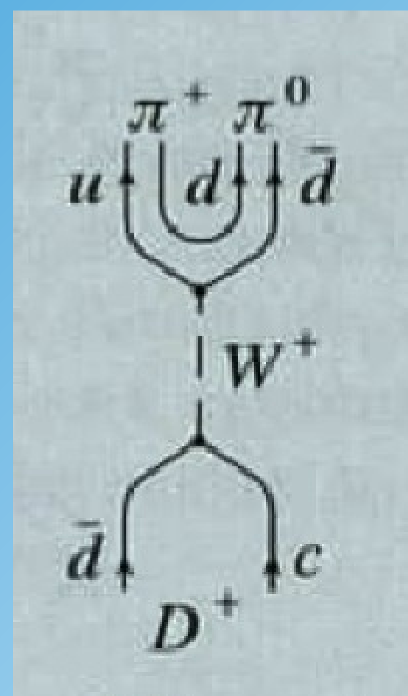
$m_c \approx 1.5\ GeV$

Lifetime $\tau \sim 0.5$ ps

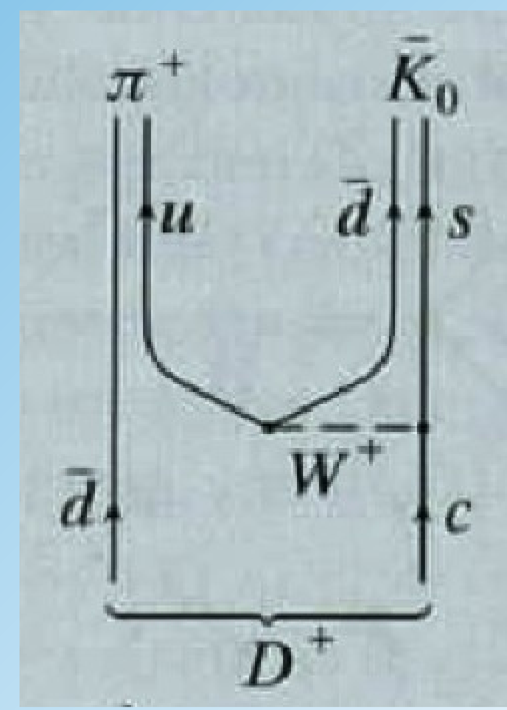
$D^+ \rightarrow K^0 \pi^+$



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



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



Weak Decays of B-mesons

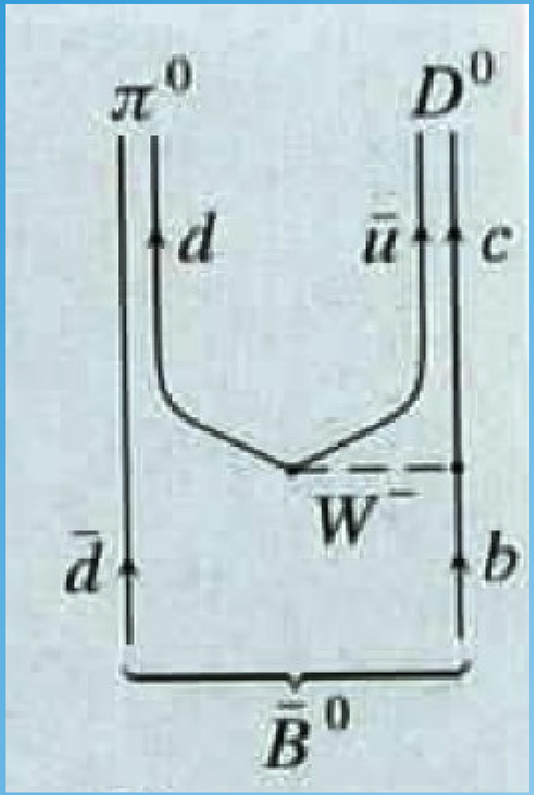
$\Gamma \propto G_F^2 m_b^5$

$m_b \approx 4.5\ GeV$

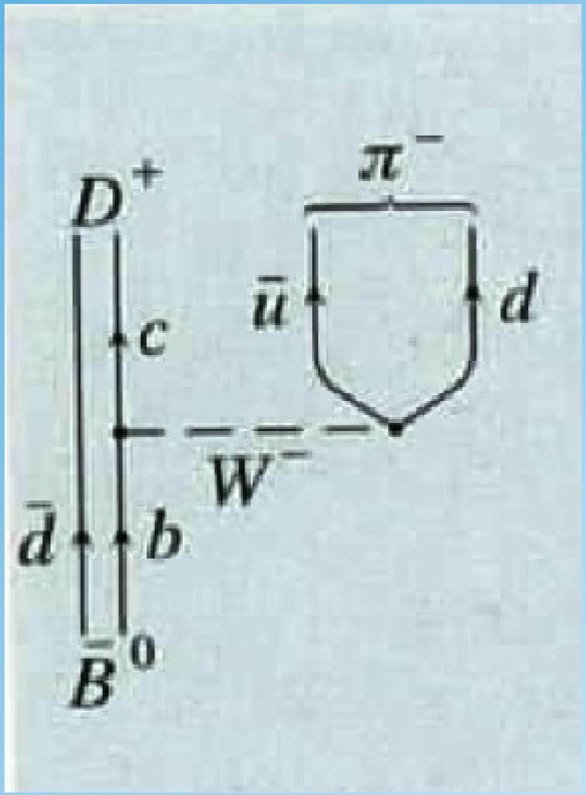
Lifetime $\tau \sim 1.5$ ps

why so large?

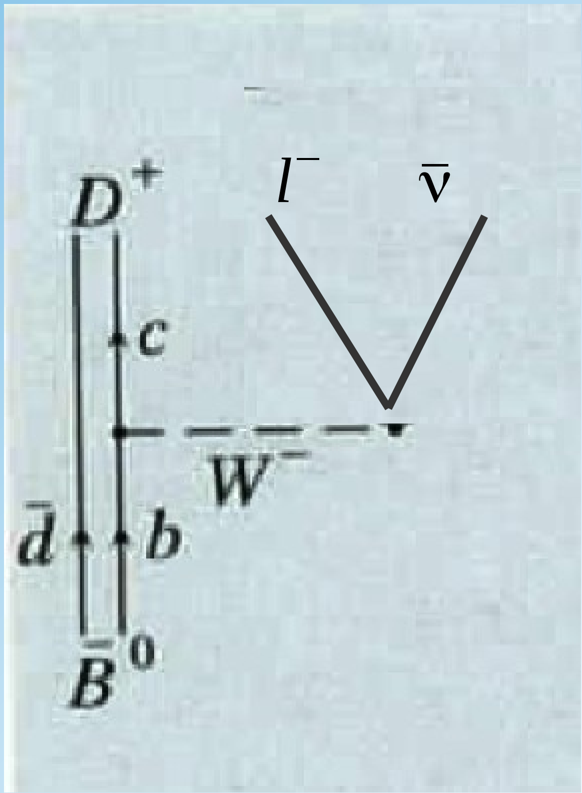
$\bar{B}^0 \rightarrow D^0 \pi^0$



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



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

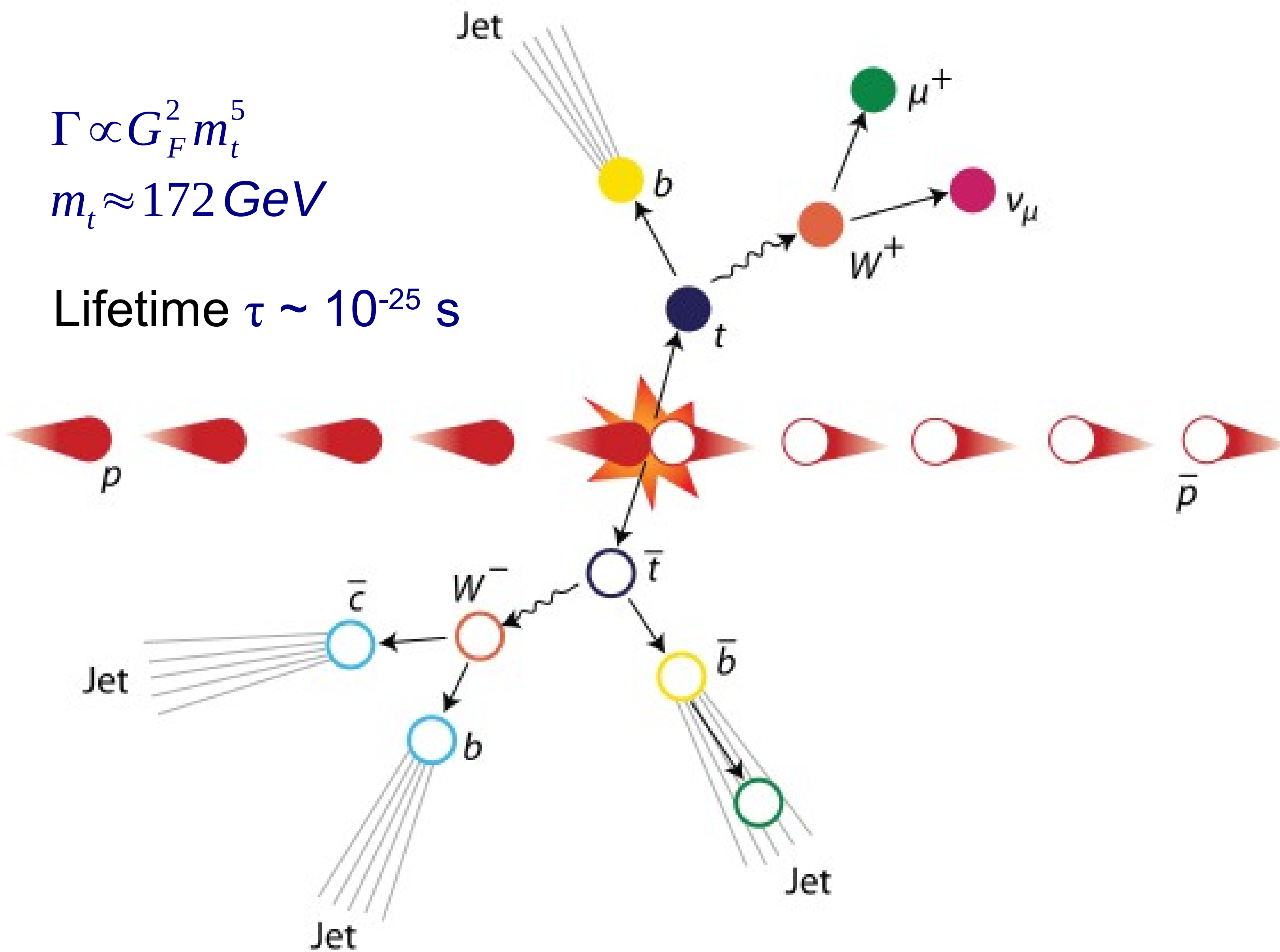


Decay of the Top quark

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

$$m_t \approx 172\,GeV$$

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



Isospin and 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: $I_3=0$

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

e^-_R μ^-_R τ^-_R d_R s_R b_R

W-bosons couple only on fermions with weak isospin, i.e. left-handed particles !

Weak Scattering Experiments

Question:

What is the difference between:

A) scattering experiments electrodynamics

B) scattering experiments in weak interactions?

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A) scattering experiments electrodynamics

B) scattering experiments in weak interactions?

Answer:

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

Video of a classical scattering experiment

Strength of Weak Interaction

Question:

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

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Answer:

	elm. IA	weak IA
1. Coupling	$e \ (\approx 0.3)$	$g \ (\approx 0.65)$ $\quad (e, g = \sqrt{4\pi\alpha})$

Strength of Weak Interaction

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Answer:

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

Strength of Weak Interaction

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

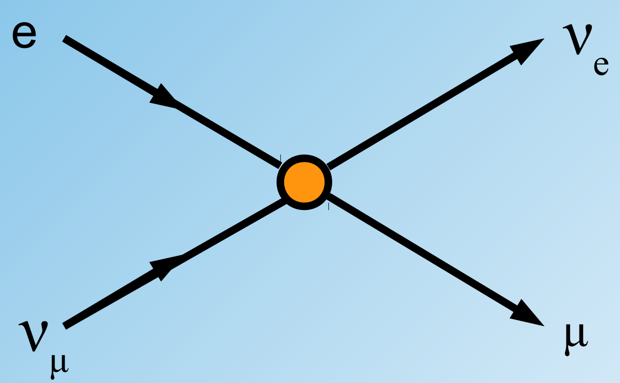
Neutrino-nucleon scattering experiments require neutrino beams of about **E_ν ~100 GeV** to test weak interactions at reasonable rates **$\sigma \sim$ O(1pb)** because of the propagator effect

at low energies:

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

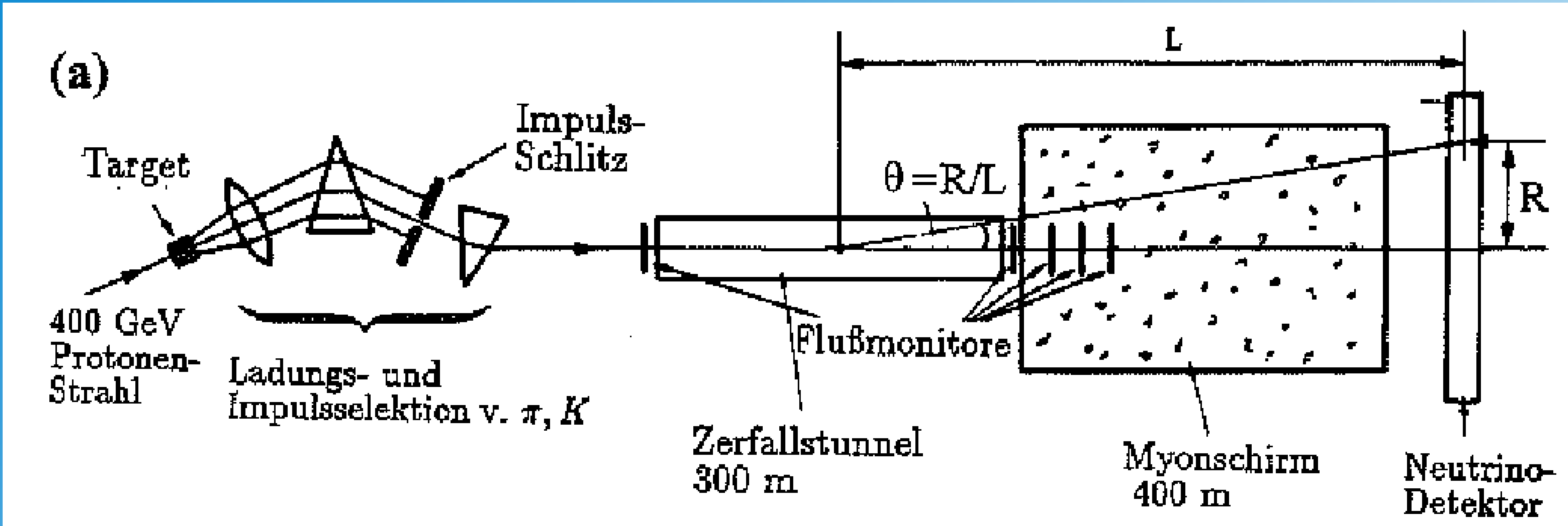
at very high energies:

$$\sigma\left(\nu_\mu e \rightarrow \mu \nu_e\right) \propto 1/s$$



neutrino-electron scattering

Production of (Myon) Neutrino Beams



Production reactions:

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

M=meson

CHARM Detector

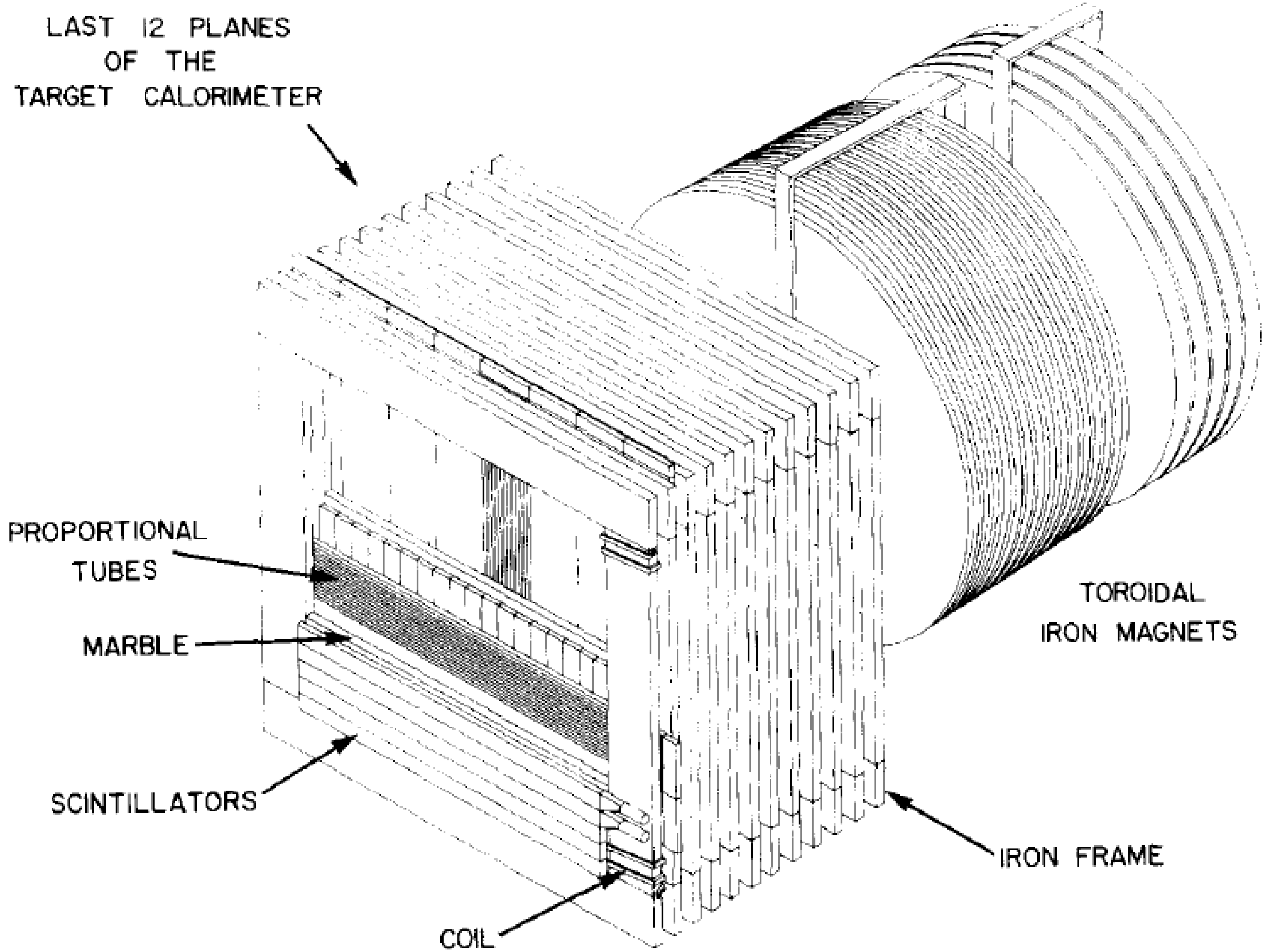
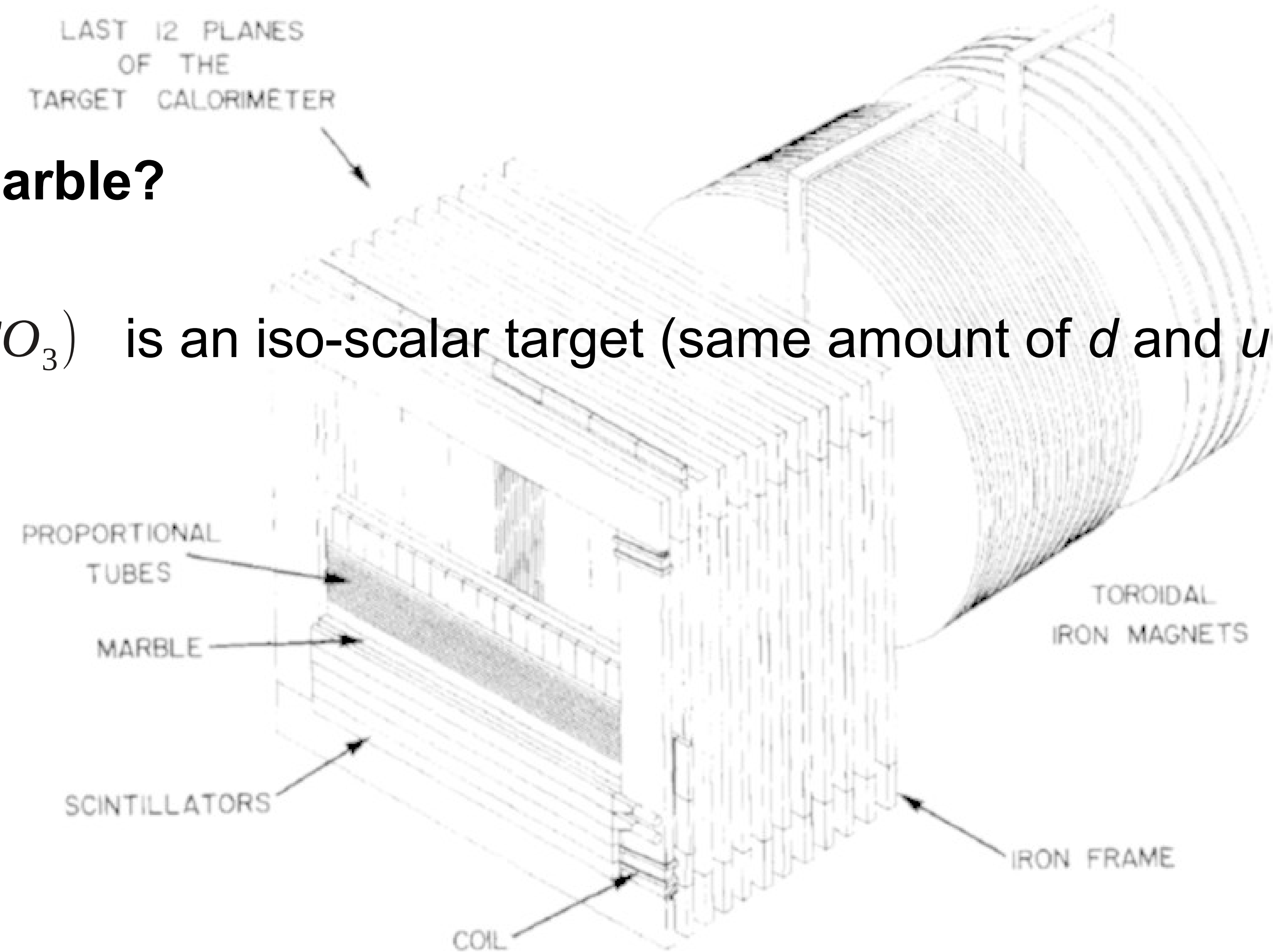


Fig. 1. Partial view of the fine-grain calorimeter and the muon spectrometer. Each subunit is composed of a marble plate of $3 \times 3\ m^2$ surface area and 8 cm thickness, a layer of 20 scintillators 15 cm wide and 3 m long, and a layer of 128 proportional drift tubes 3 cm wide and 4 m long. The calorimeter 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?

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



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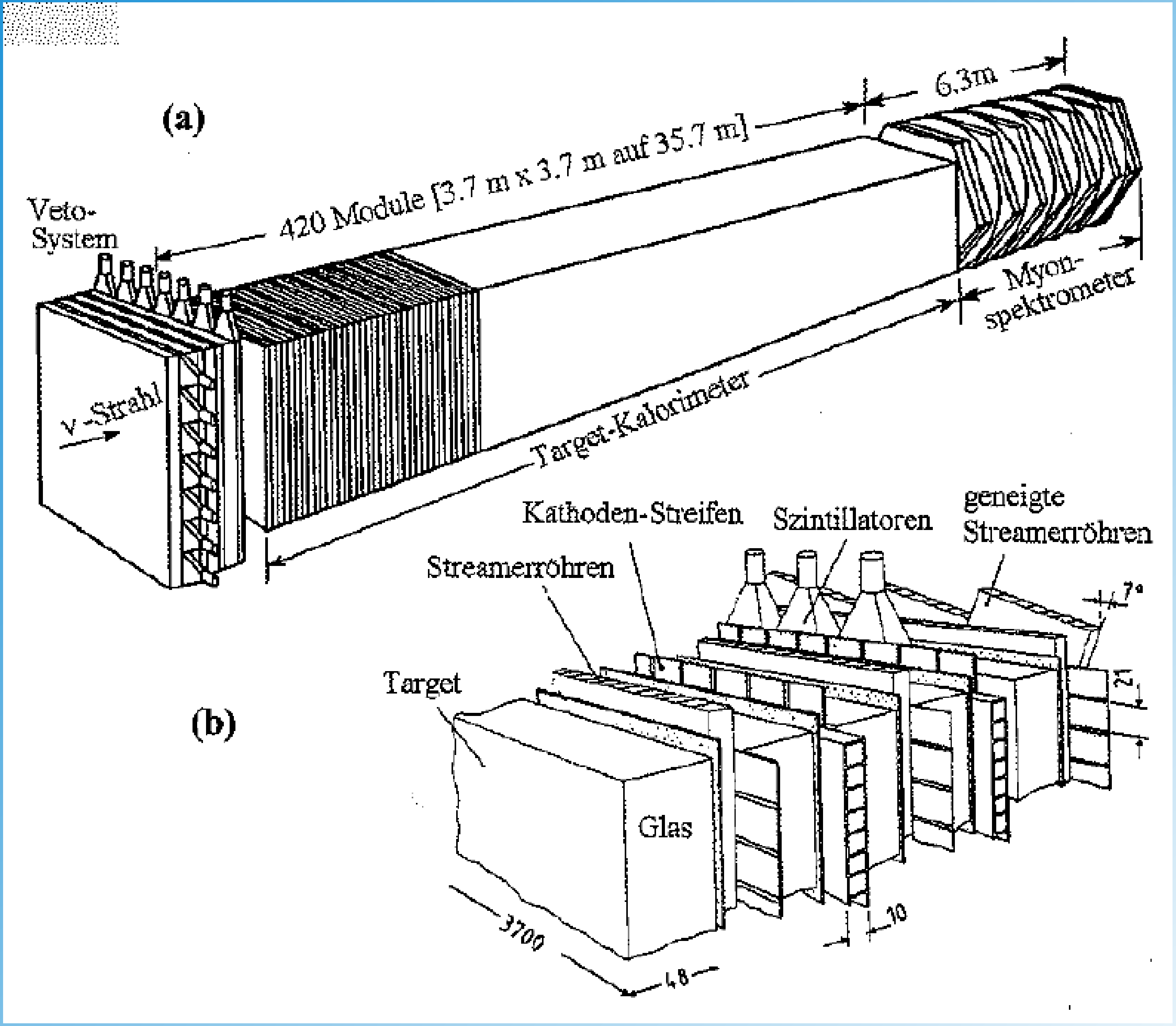
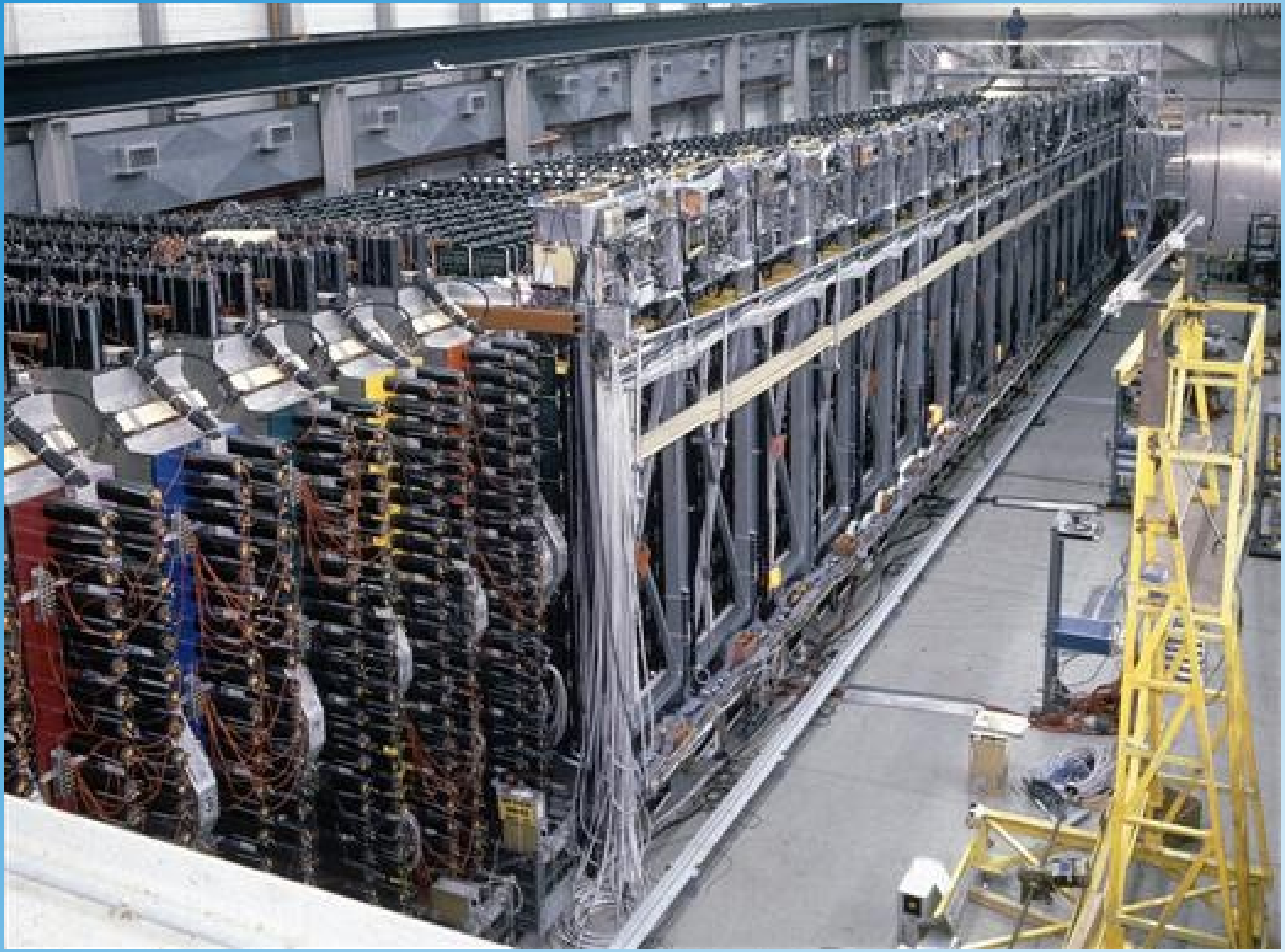
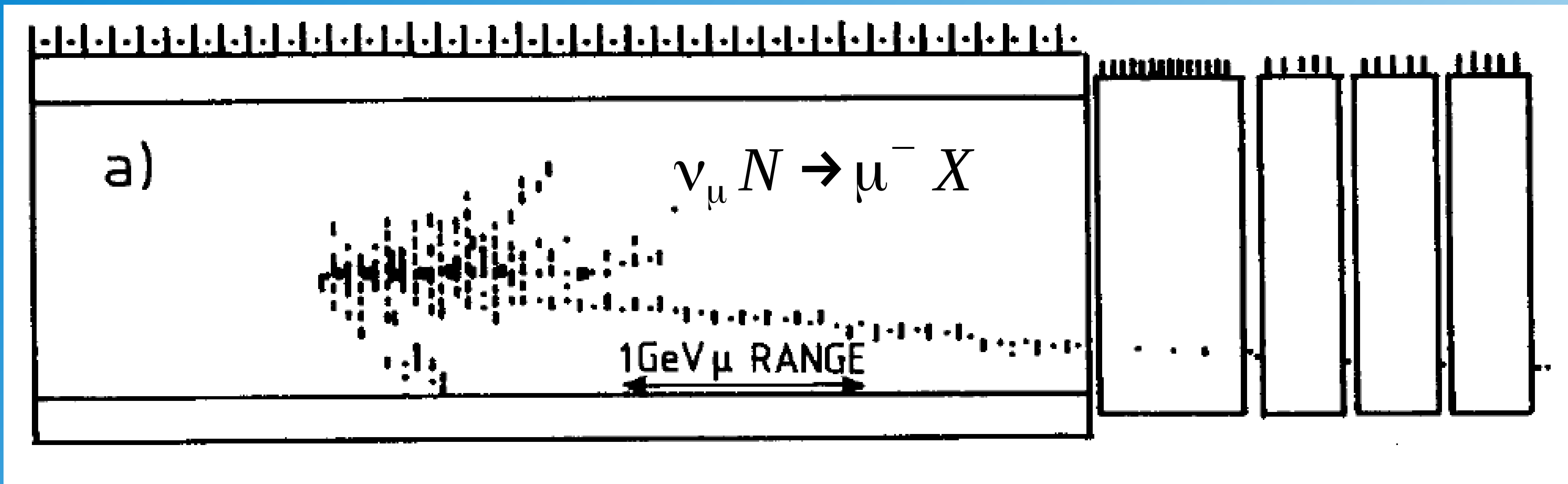
CHARMII Detector

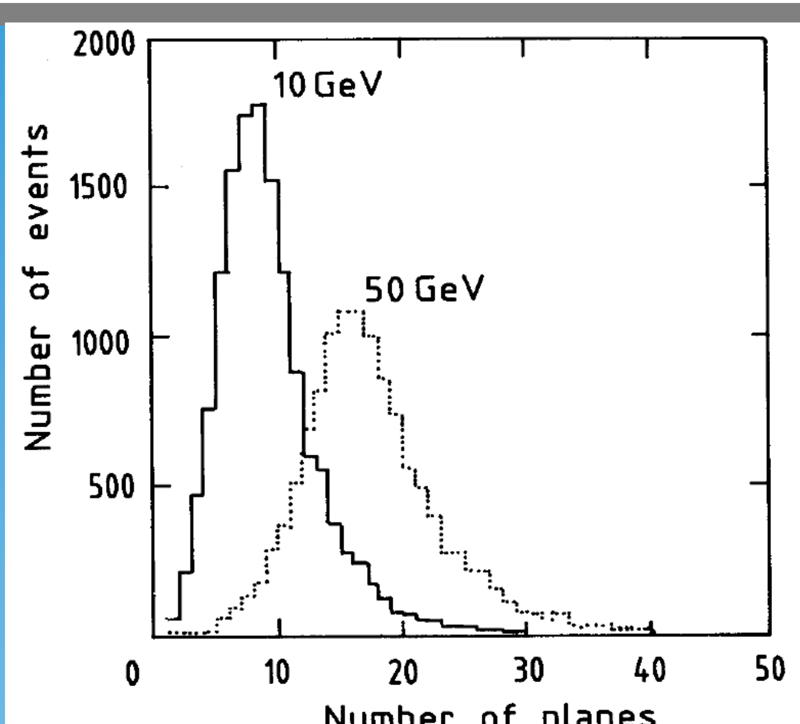


CHARMII Detector



Detection of Myon Neutrinos in CC





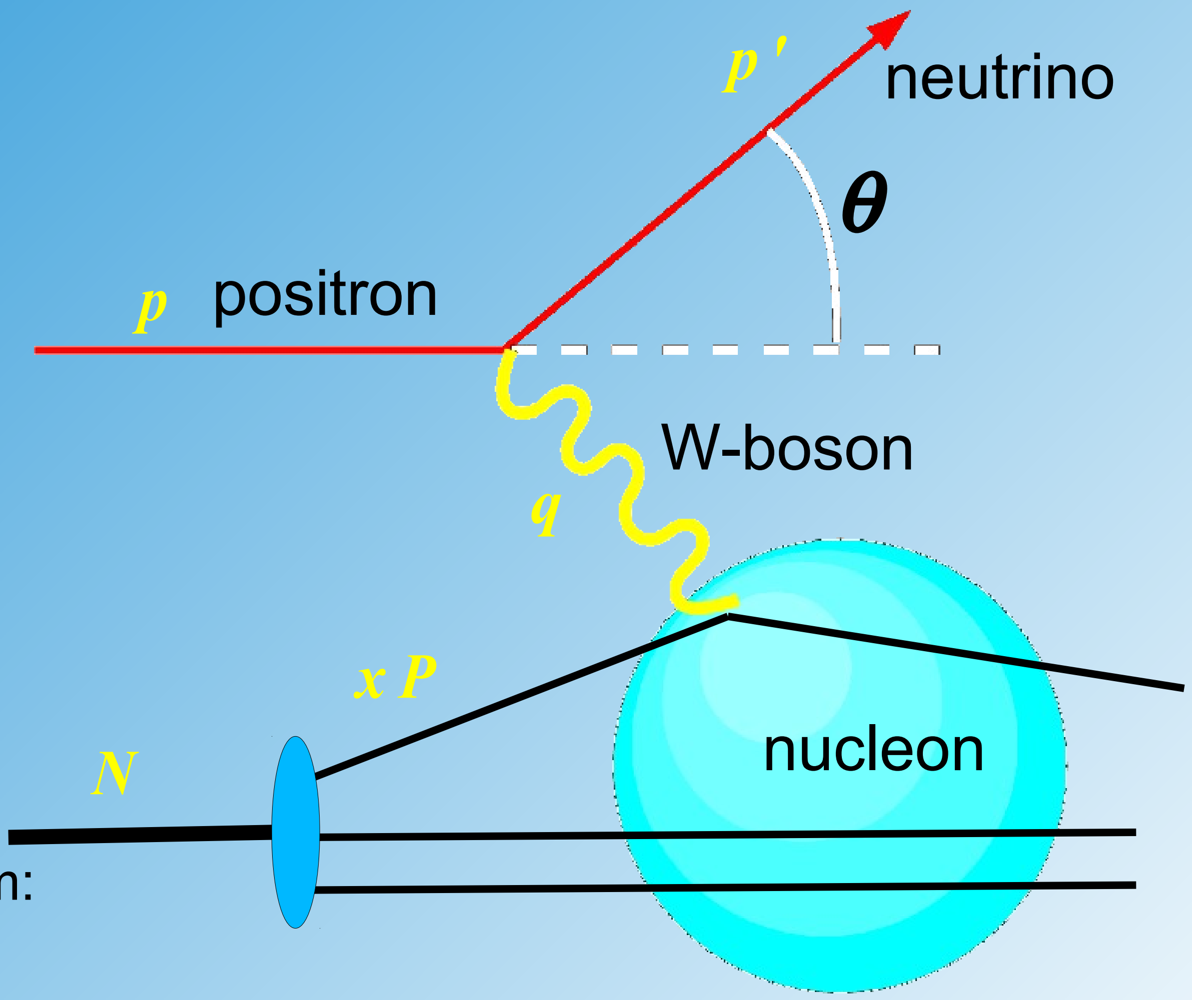
- long track identified as muon (minimum ionising particle)
- length of track is a measure of the muon energy

Lorentz Invariant Kinematics of the Deep Inelastic Scattering Process

The virtuality of the exchanged boson 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:

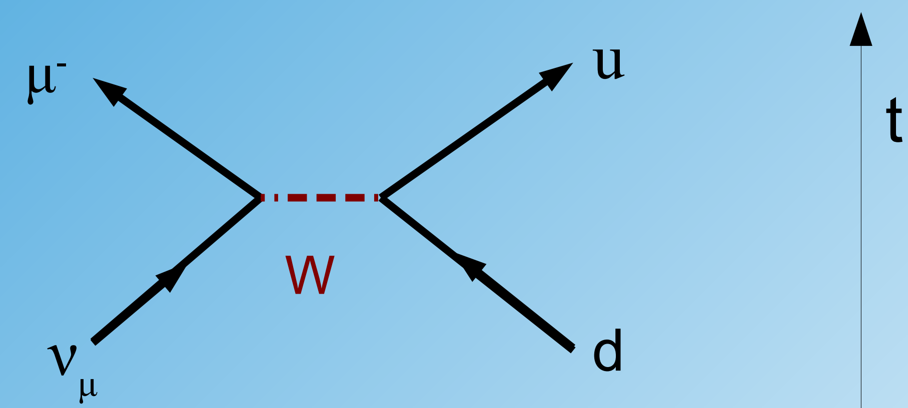
$$x = \frac{q^2}{2\,q\,P} = \frac{Q^2}{S\,y}$$

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

(Anti-) Neutrino-Nucleon Scattering

Neutrino-Nucleon:

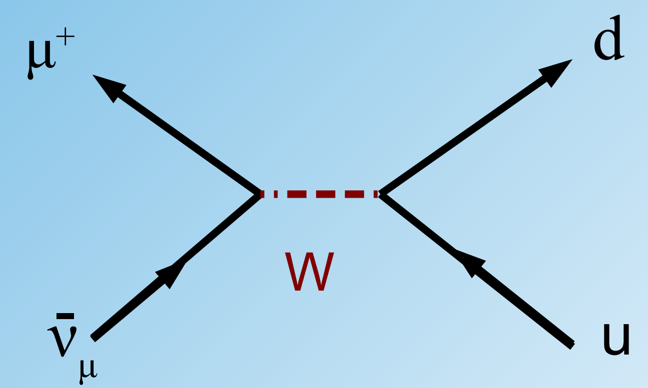
$$\frac{d\sigma}{d\Omega}(\nu_\mu d \rightarrow \mu^- u) = \frac{G_F^2}{4\pi^2} s$$



neutrino-nucleon scattering

Anti-Neutrino-Nucleon:

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



antineutrino-nucleon scattering

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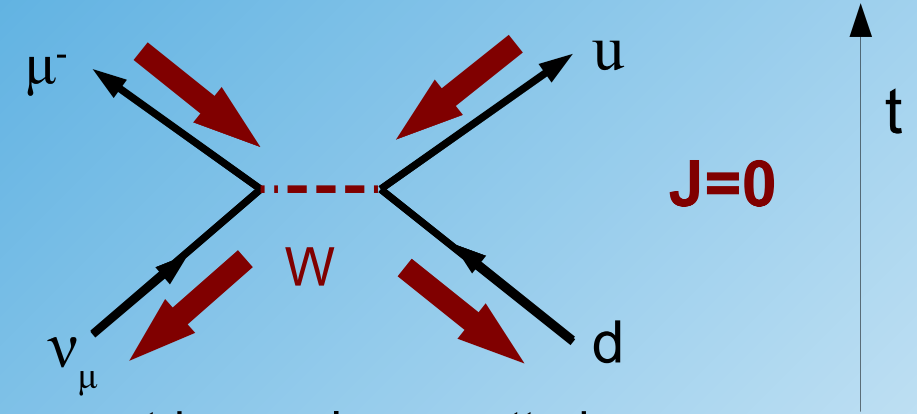
in CMS



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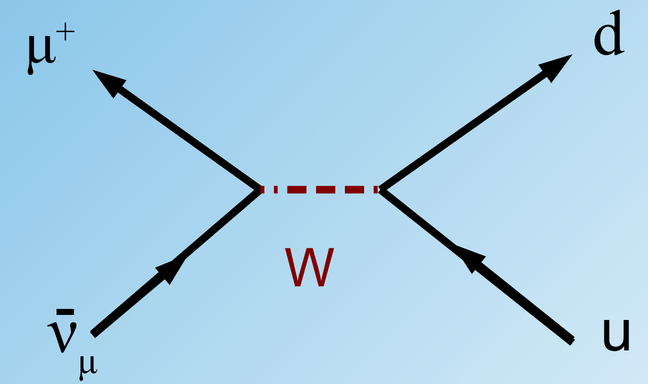

antineutrino-nucleon scattering

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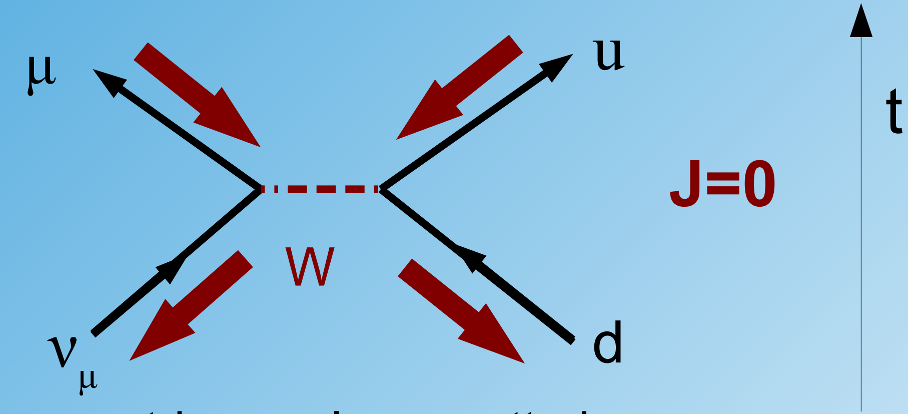

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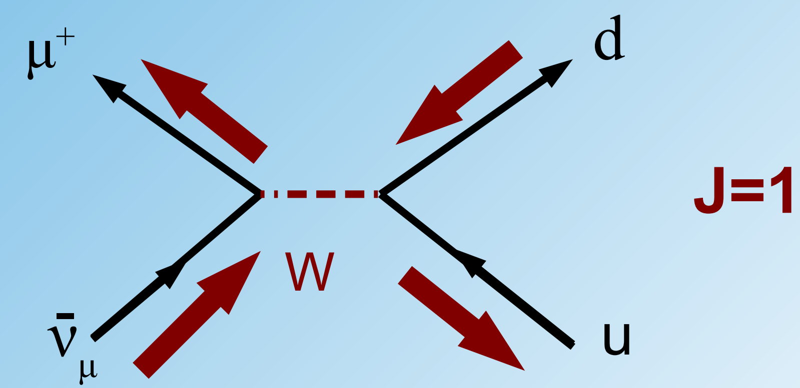


antineutrino-nucleon scattering

$$t/s = (1+\cos\Theta^*)^2/4 = (1-y)^2$$

(Anti-) Neutrino-Nucleon Scattering

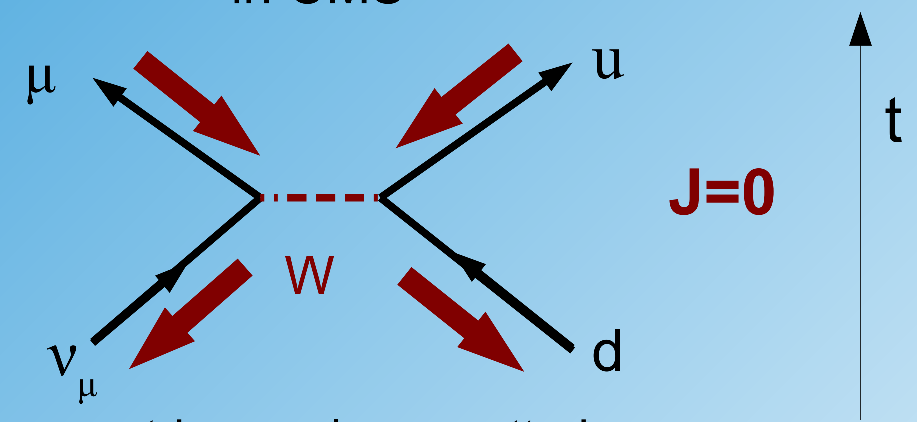
in CMS

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



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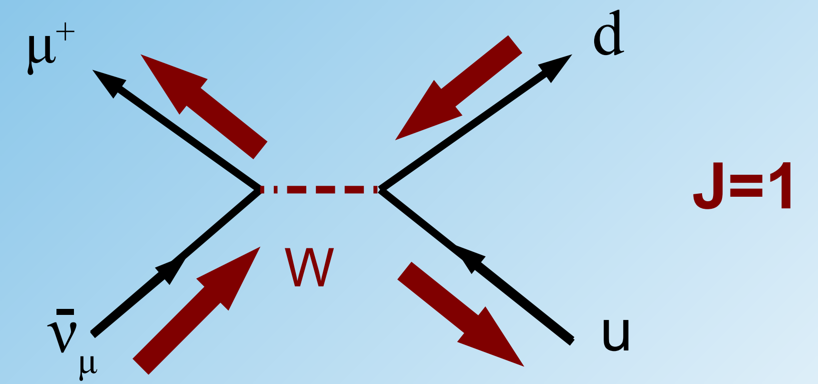


antineutrino-nucleon scattering

$$t/s = (1+\cos\Theta^*)^2/4 = (1-y)^2$$

Measurement of the Differential νN and anti-νN Cross Section

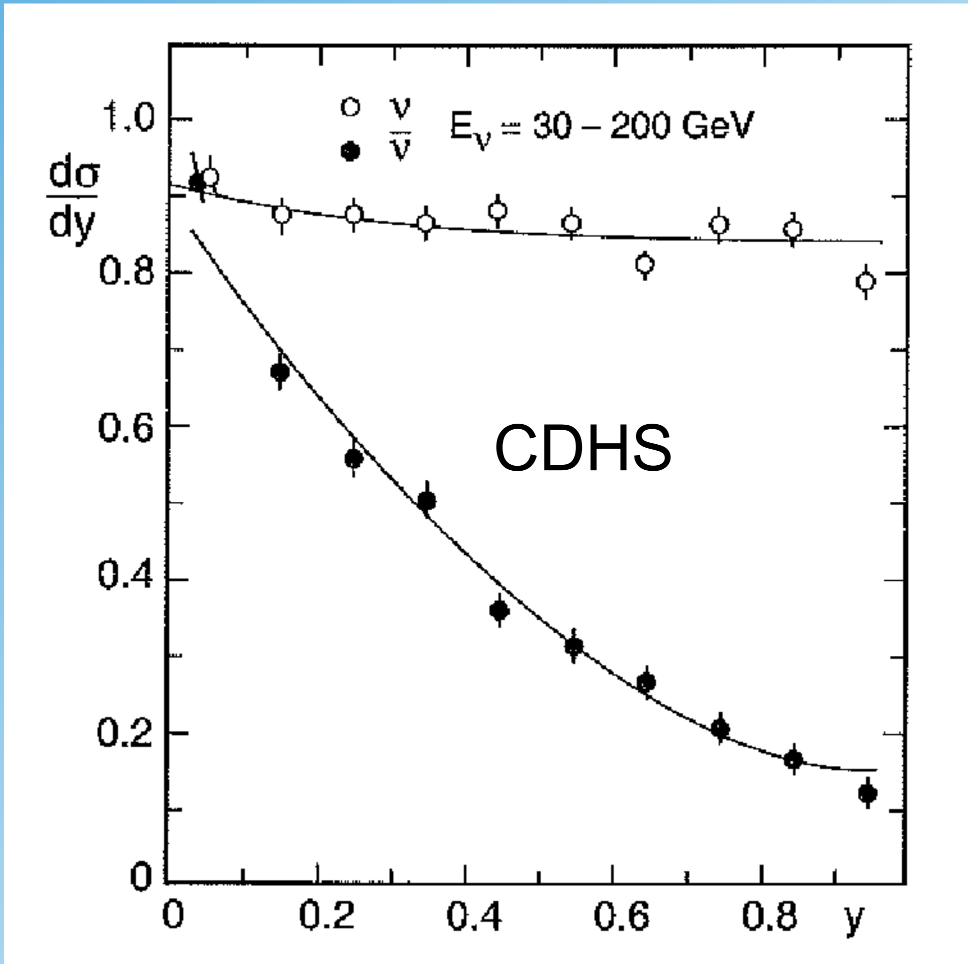
Neutrino-Nucleon:

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

isoscalar target

Anti-Neutrino-Nucleon:

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



why are experimental results not exact?

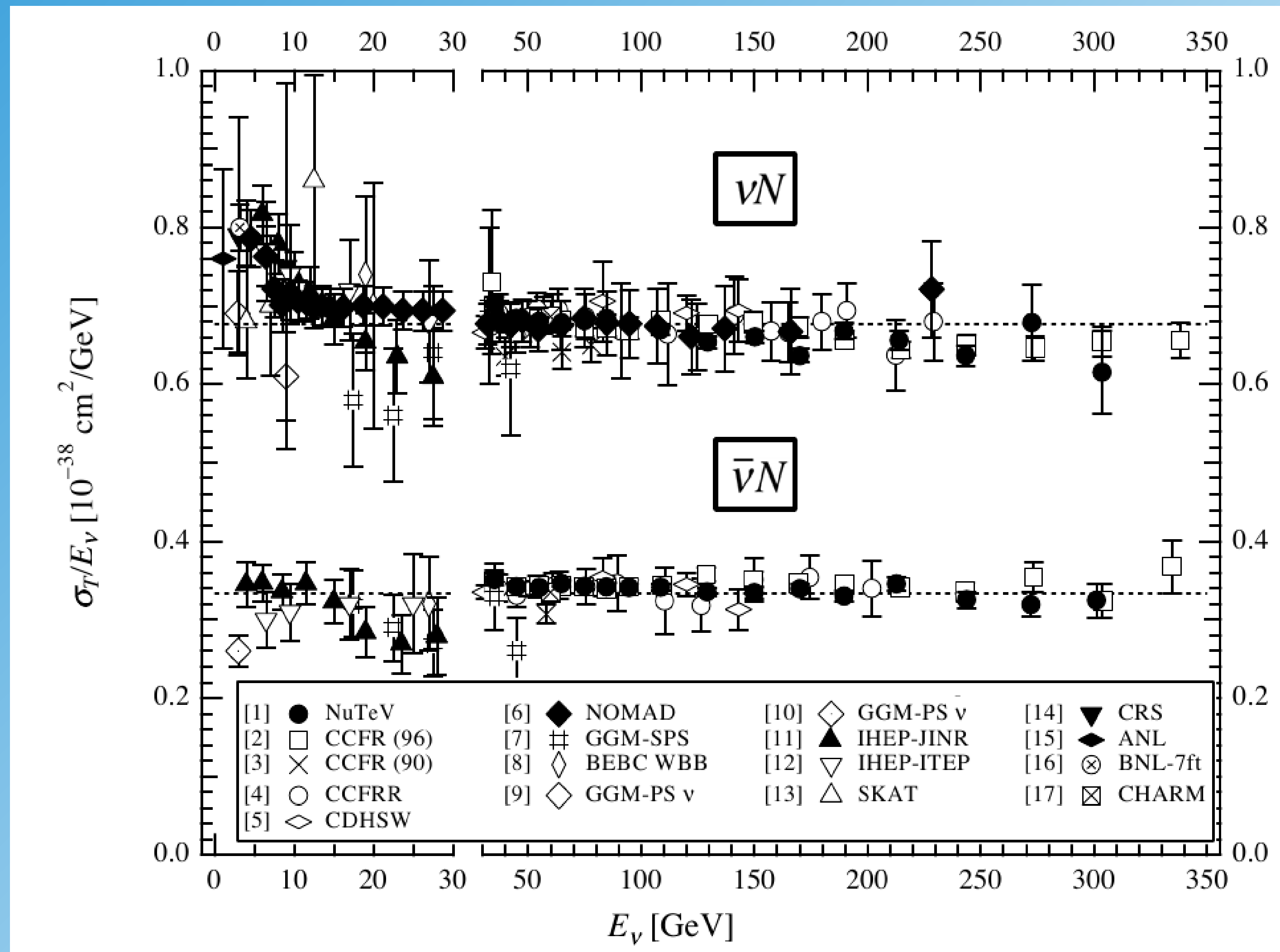
Measurement of the Total νN and anti-νN Cross Section

From simple quark counting:
(isoscalar target)

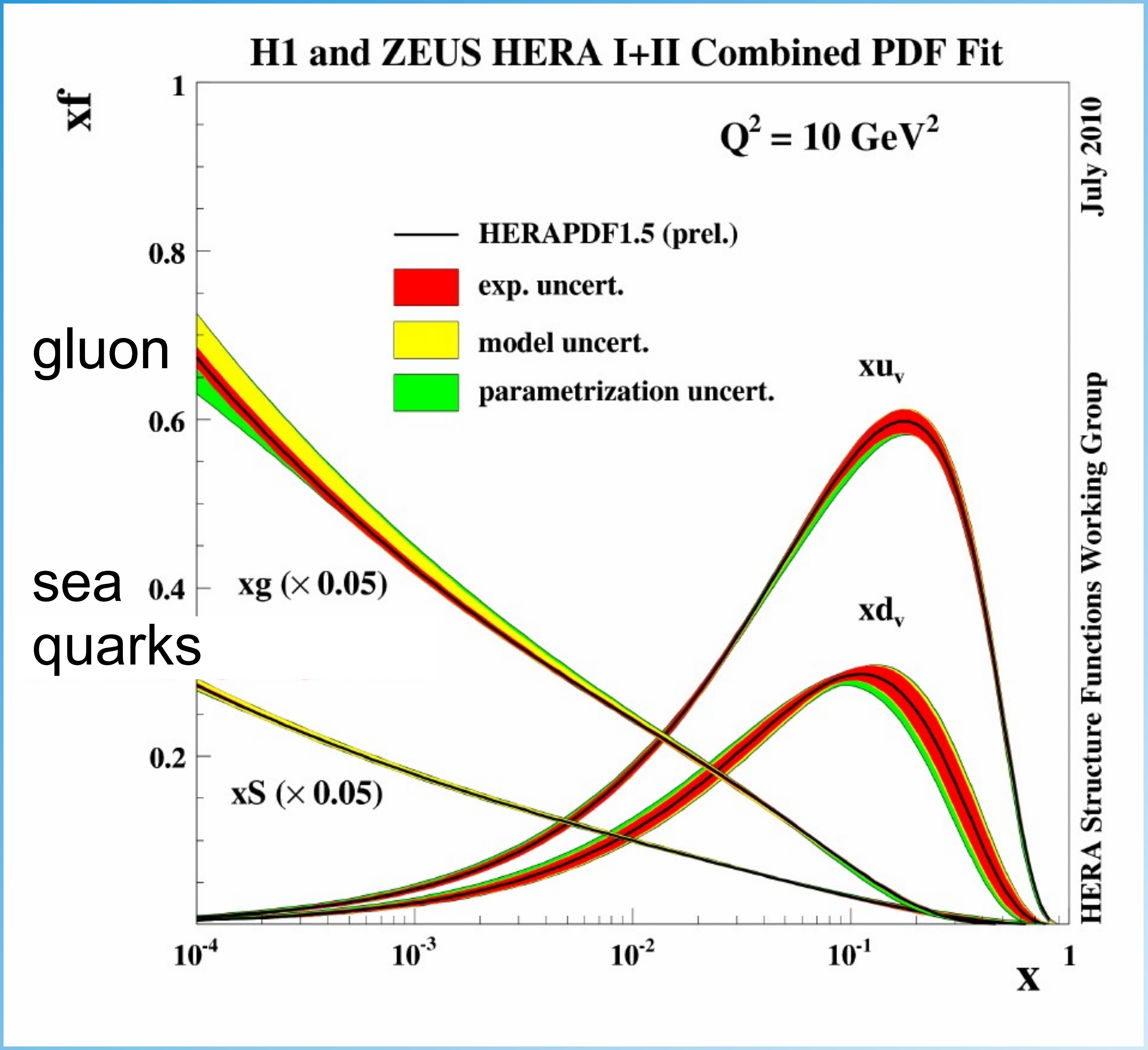
$$\frac{\sigma(\nu_\mu N)}{\sigma(\bar{\nu}_\mu N)} = 3$$

measured value ~2
is significantly smaller!

- Parton dynamics more complex
- Sea Quarks!

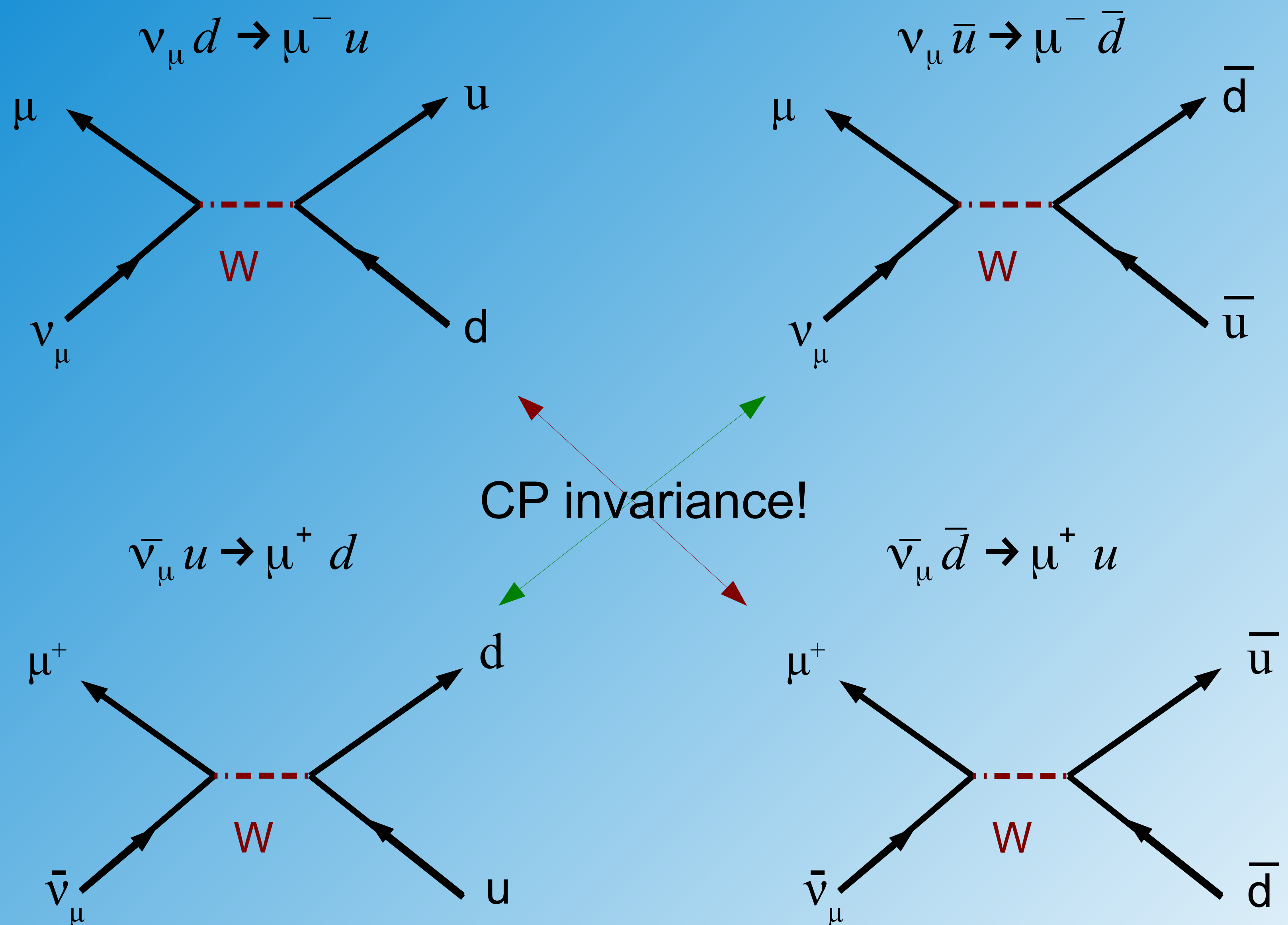


Proton Parton Densities



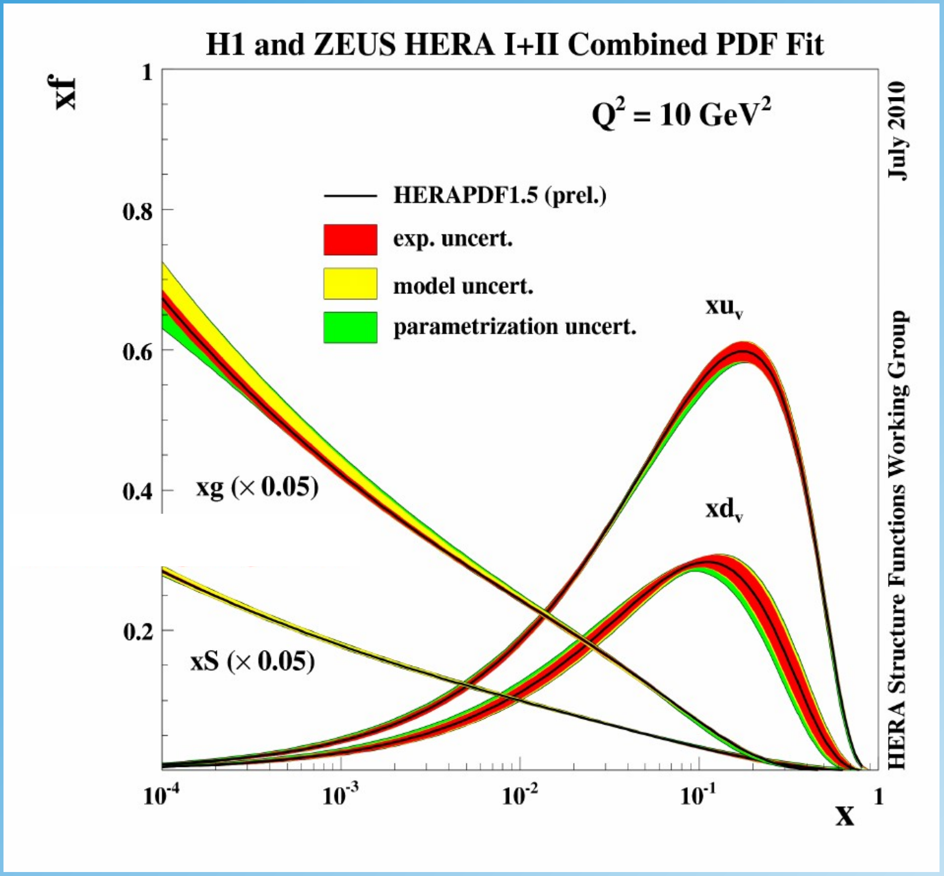
Significant component from sea quarks!

(Anti-) Neutrino-Nucleon Scattering



Neutrino-Nucleon Scattering

• tool for measuring parton densities of nucleons:



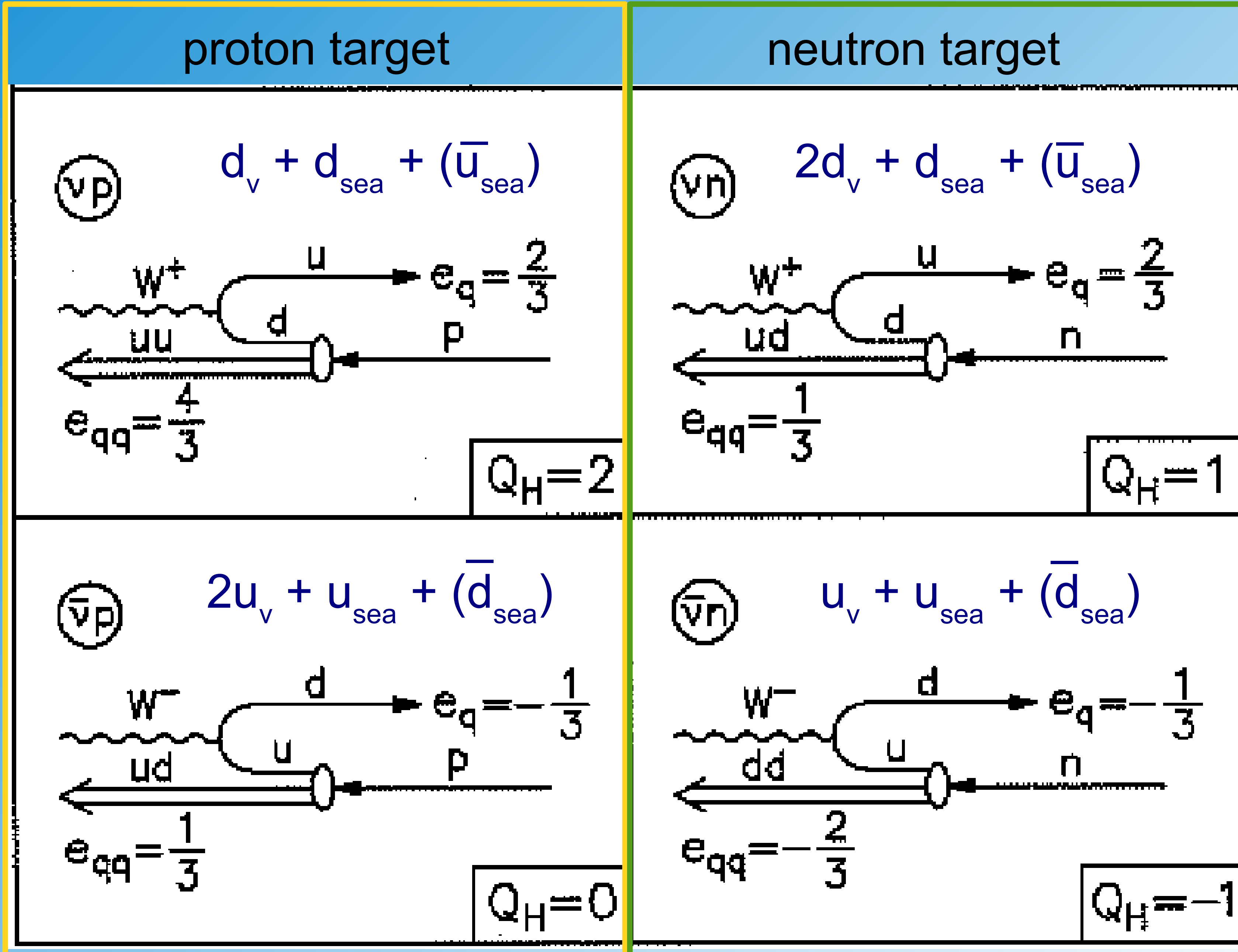
Unfolding the Valence Quark Distributions

neutrinos produce W^+

$\rightarrow$ d quarks

neutrinos produce W^-

$\rightarrow$ u quarks



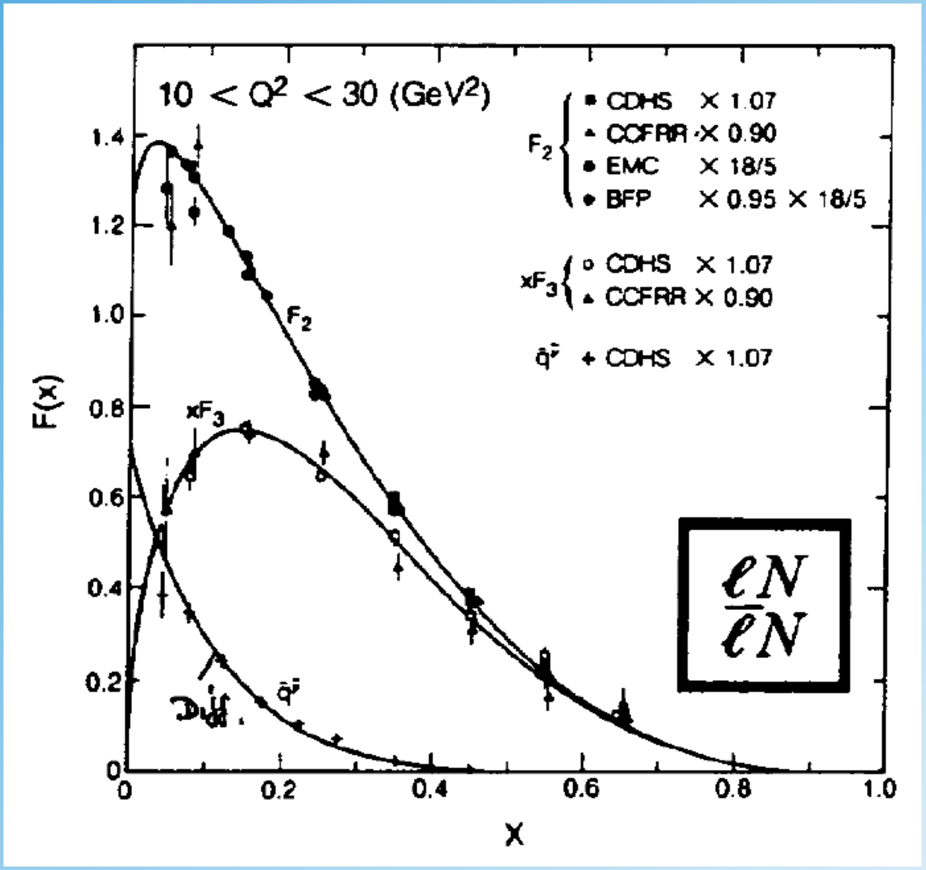
Structure Functions

Relations:

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

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

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



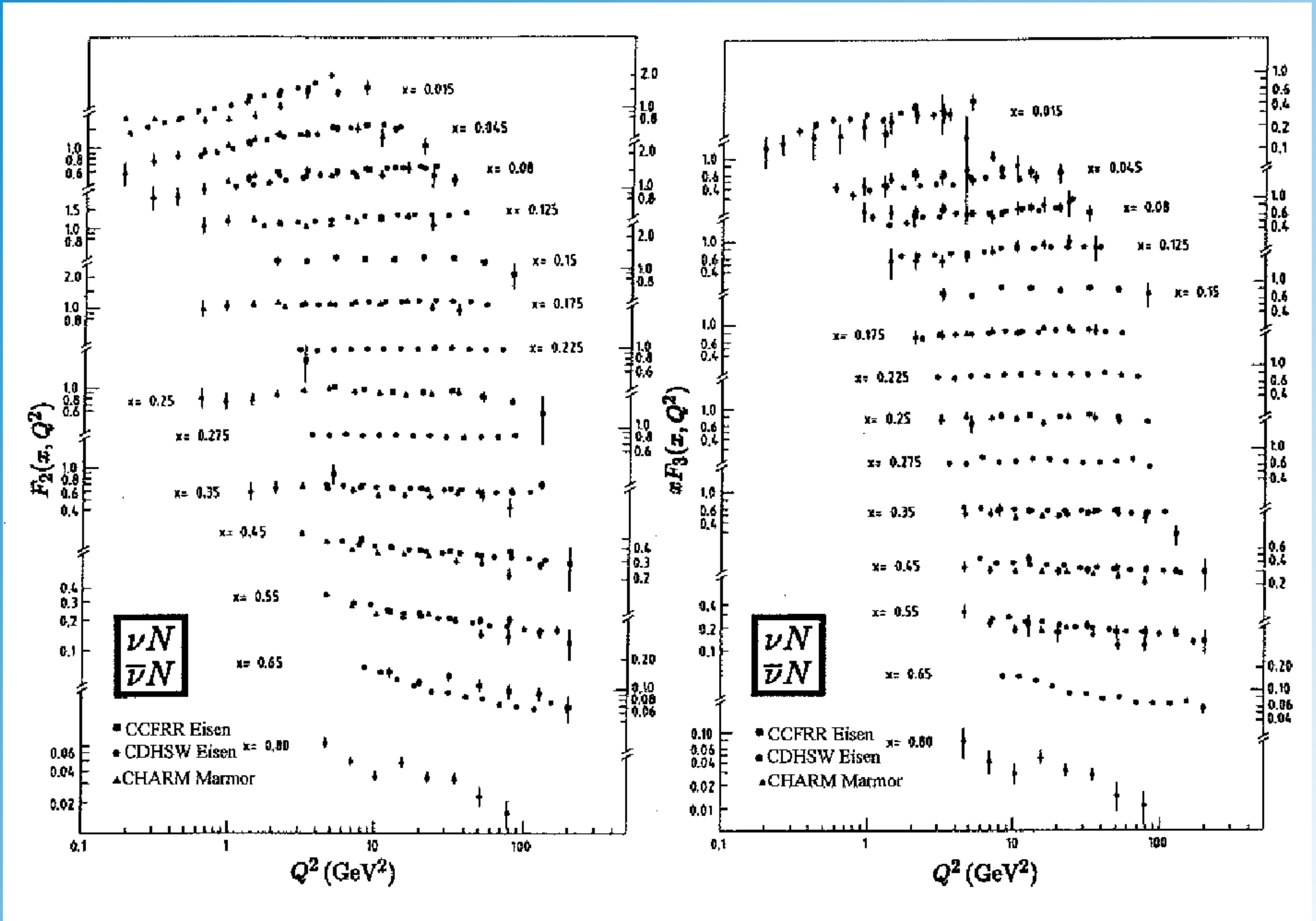
Measurement:

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

Extraction of parton densities:

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

F_2 Results xF_3 Results

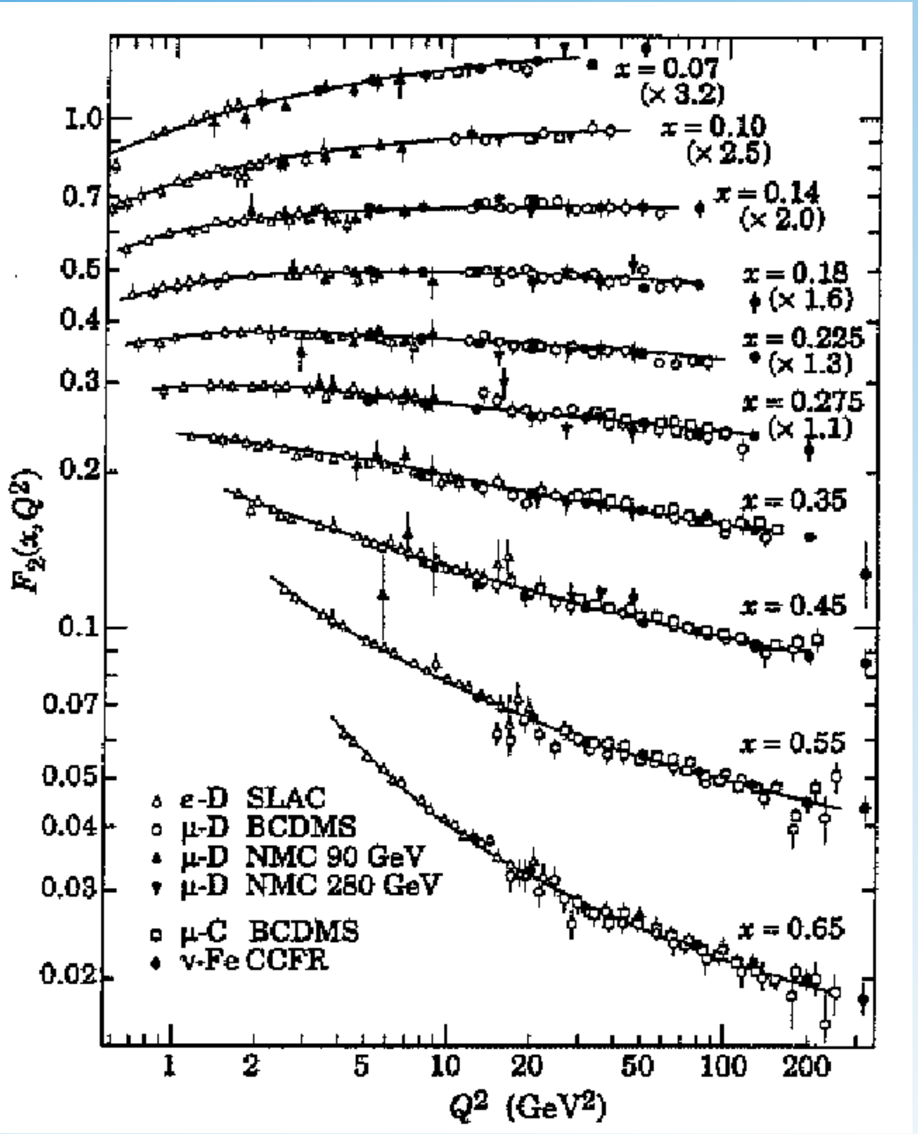


Comparison νN versus lepton-N Scattering

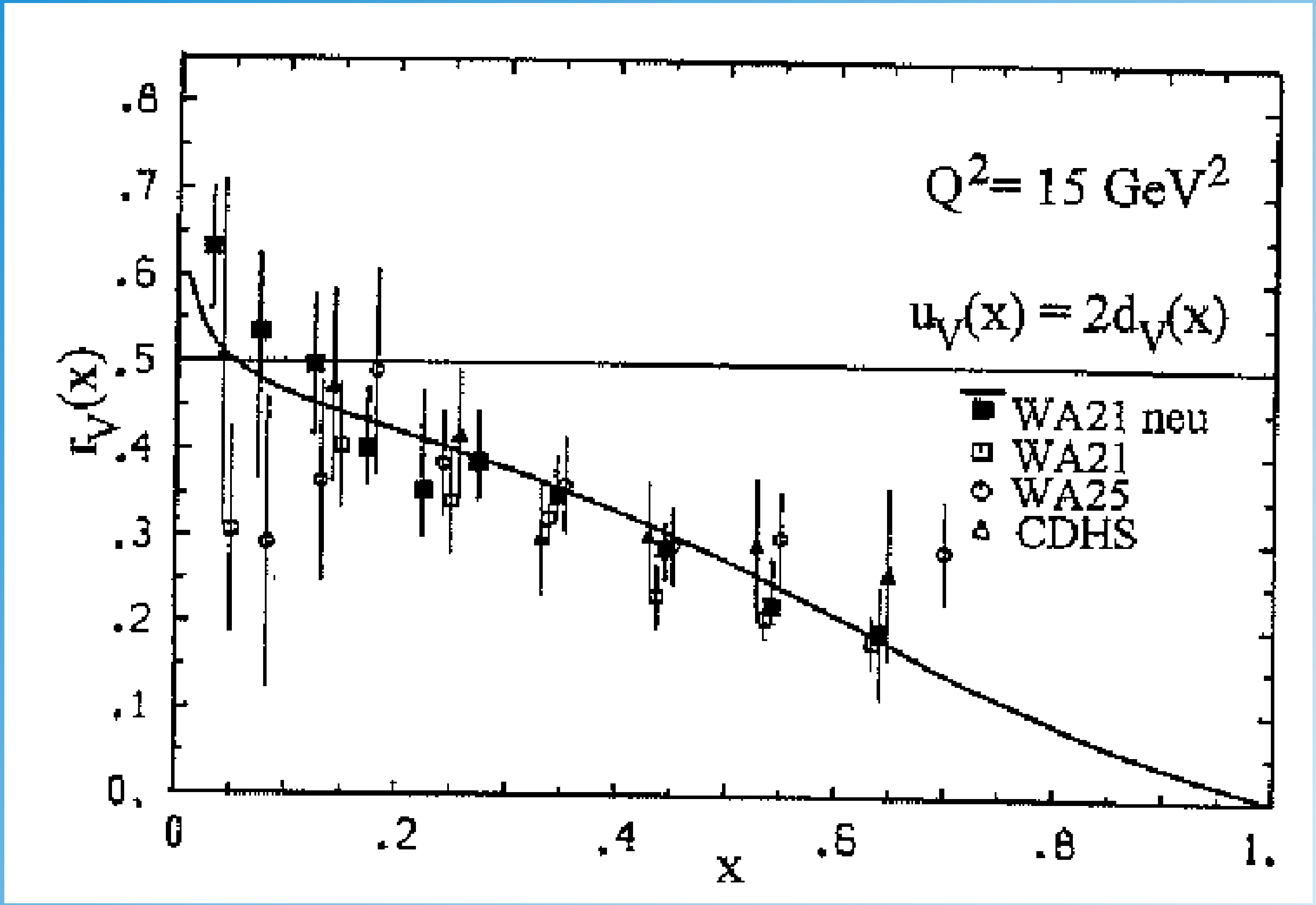
Due to different couplings:

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

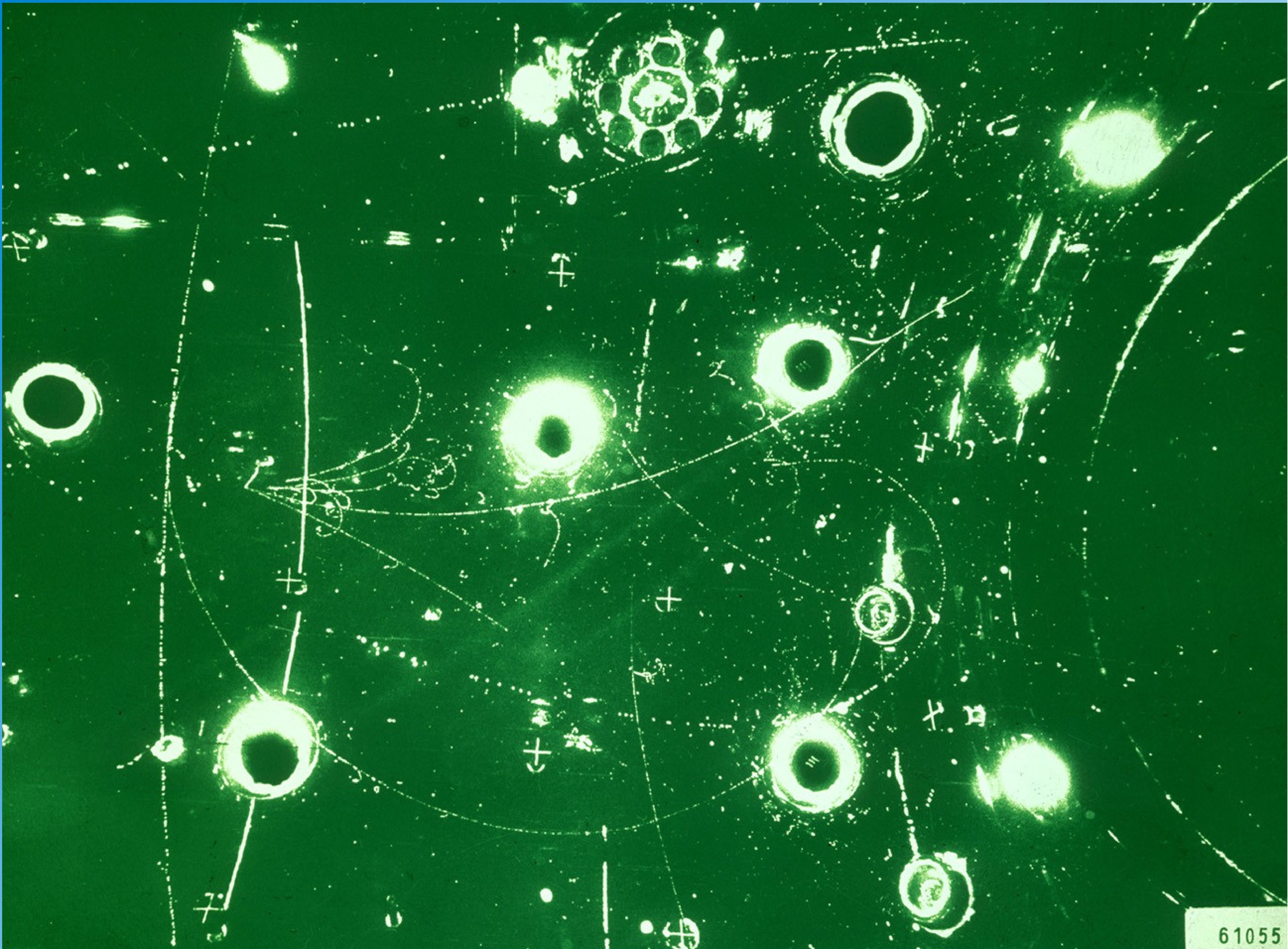
Structure function results obtained in **weak interactions** agree well with result obtained in **electromagnetic interactions**!



Ratio of d_v/u_v



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