Neutrino Physics

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CTEQ Summer School
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Outline

Part I: Introduction and Neutrinos as Probes

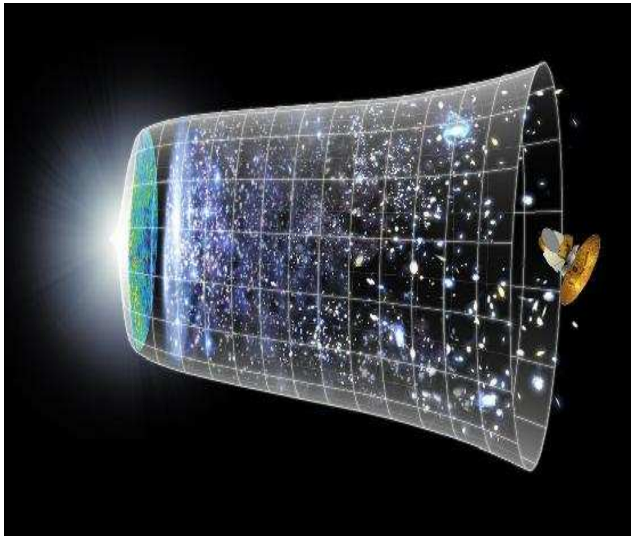
- Neutrinos in the SM, brief introduction.
- Neutrino experiment challenges
- ν as Probes : Electroweak
- ν as Probes: Nucleon structure and QCD

Part II: Neutrino oscillations beyond the SM

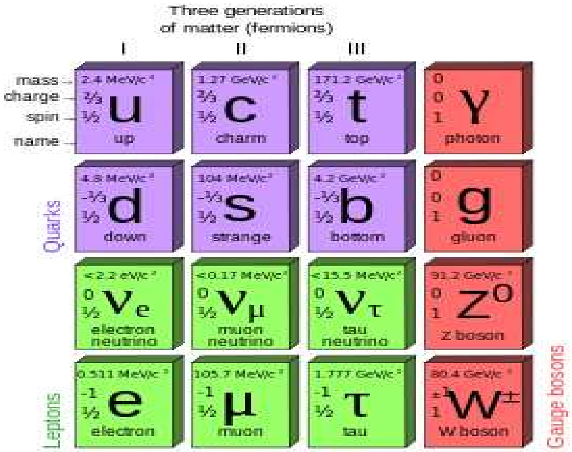
- Neutrino mass and oscillations.
- The story of neutrino oscillations.
- Some remaining questions and future

Neutrinos in Context

"It's nothing, almost nothing, it is the most tiny quantity of reality ever imagined by a human being". ***- F.Reines, (detected the first neutrino).***



- Neutrinos and photons are by far the most abundant particles in the universe. (340 ν/cm^3)
- Stable and abundant ⇒ important role in the evolution of the universe.
- Important for stellar dynamics ⇒ key role in fusion and supernovae processes.



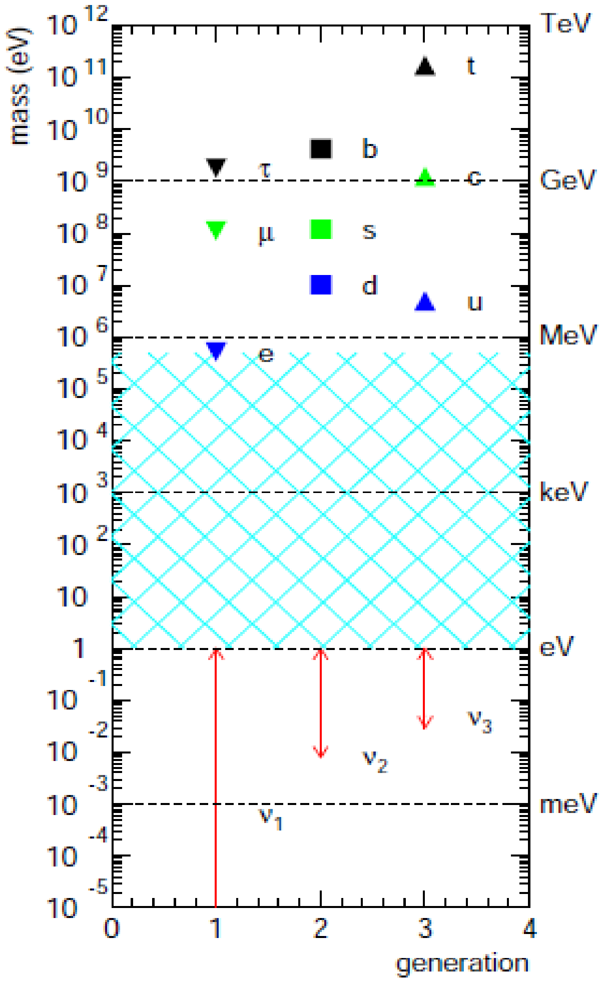
Three generations of matter (fermions)

		I	II	III	
	mass charge spin name	2.4 MeV/c² ⅔ ½ u up	1.27 GeV/c² ⅔ ½ c charm	171.2 GeV/c² ⅔ ½ t top	0 0 1 γ photon
Quarks		4.8 MeV/c² -⅓ ½ d down	104 MeV/c² -⅓ ½ s strange	4.2 GeV/c² -⅓ ½ b bottom	0 0 1 g gluon
		<2.2 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<15.5 MeV/c² 0 ½ ν_τ tau neutrino	91.2 GeV/c² 0 1 Z^0 Z boson
Leptons		0.511 MeV/c² -1 ½ e electron	105.7 MeV/c² -1 ½ μ muon	1.777 GeV/c² -1 ½ τ tau	80.4 GeV/c² ±1 1 $W^\pm$ W boson Gauge bosons

- They have unique properties.
- Recently, neutrinos have surprised us with discoveries of mixing and masses.
  - ▷ Perhaps more surprises...

Neutrino Properties

	Fundamental Particles			Force Carriers	Force
quarks	u	c	t	γ	electro−magnetic
	d	s	b	g	strong
leptons	ν_e	ν_μ	ν_τ	Z	weak
	e	μ	τ	W	



Neutrinos have unusual properties:

- The only *neutral* fermions.
- They only interact via Weak force.
- Masses very small (exact values unknown).

Neutrino Properties (cont'd)

- Every charged fermion has a charge conjugate partner. →*Dirac fermions*

particle ↔ antiparticle

$$f \leftrightarrow f^c$$

$$e^- \leftrightarrow e^+$$

$$u \leftrightarrow \overline{u}$$

- Neutral particles can be *majorana* → no distinct antiparticle exists.

$$\gamma,\, \pi^o = \frac{1}{\sqrt{2}}(u\overline{u} + d\overline{d})$$

- Neutrinos may be *majorana* fermions.

Majorana neutrino

- Neutrino is its own charge-conjugate partner.

$$(\nu)^C = \nu$$

Dirac neutrino

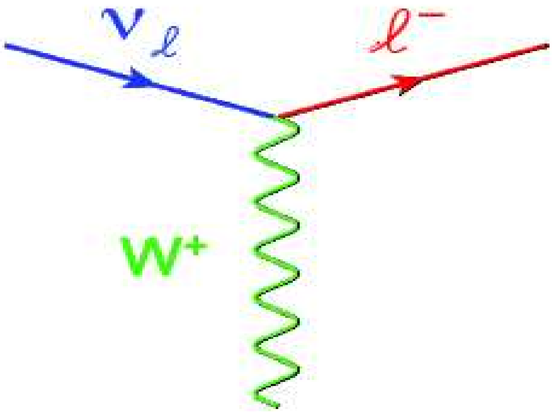
- ν and $\overline{\nu}$ are distinct particles.

$$(\nu)^C \neq \nu$$

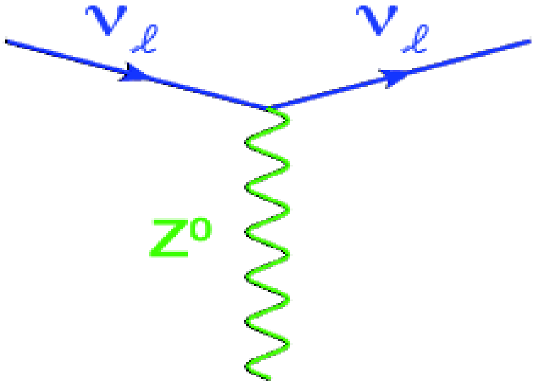
Neutrino Interactions

- Neutrinos participate in the SM only through weak interactions.

charged-current



neutral-current

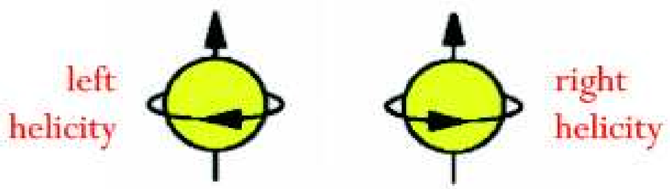


CC weak interactions → maximally violate parity symmetry.

$$\boxed{\Gamma(\pi^+ \rightarrow \mu^+ \nu_L) \neq \Gamma(\pi^+ \rightarrow \mu^+ \nu_R) = 0}$$

- Determined from experiment and built in to SM as (V-A) form.

$$J^{(CC)\mu}(f \rightarrow f') = \overline{u}_{f'} \gamma^\mu \tfrac{1}{2}\left(1 - \gamma^5\right) u_f$$



Helicity frame dependent for $m > 0$.
Chirality lorentz-invariant version.
High energy, $E >> m$
helicity ⇔ chirality.

Only ν_L and $\overline{\nu}_R$ participate in SM.

Challenges of Experimenting with ν's

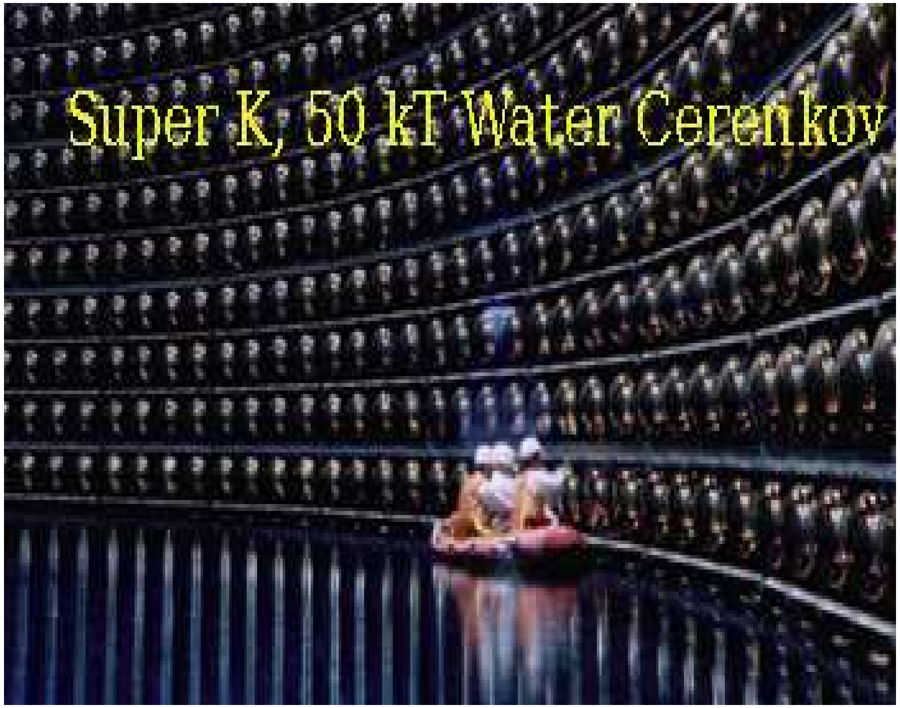
- They are difficult to produce and directly detect via the *weak* interaction.
  - Interaction cross section for 1 GeV neutrino in matter $\sim 10^{-38} cm^2$

    (Compare with pp scattering $\sigma \approx 10^{-25} cm^2$)
    - ⋆ A neutrino can pass through a light-year of steel without interacting.

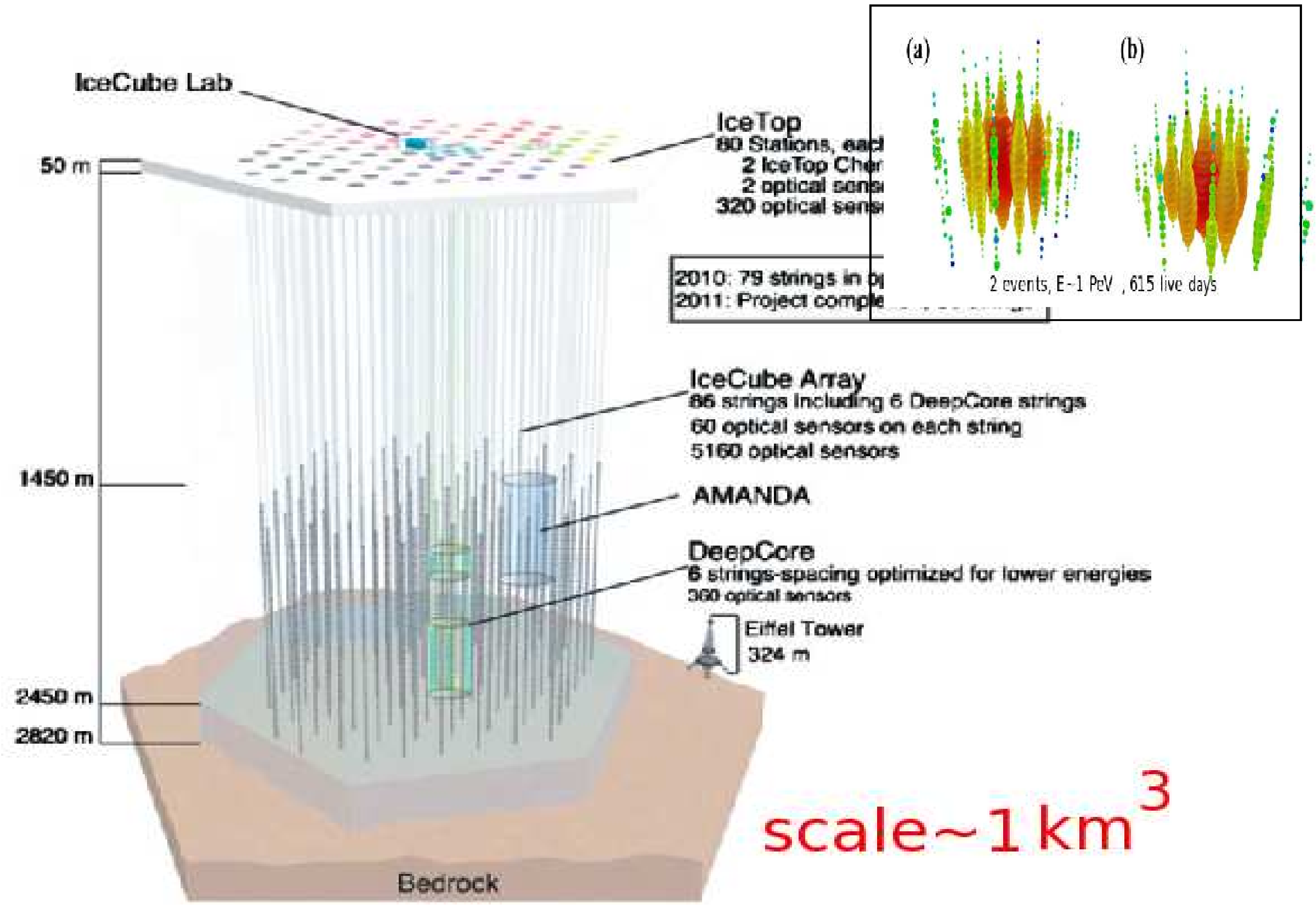
Experiments designed to overcome limitations of small interaction cross sections.

General features

- Intense neutrino sources (Reactors, high-intensity neutrino beams, sun, etc.)
- Massive detectors (sometimes in remote locations; mines, etc...)
- and patience...



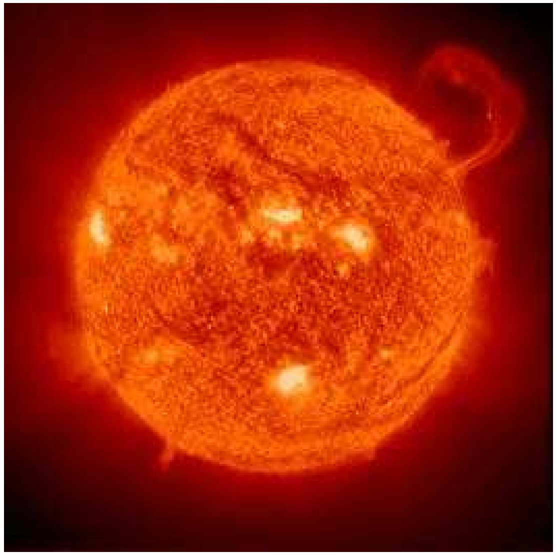
IceCube ...remote, patient and massive



scale~1 km^3

Neutrino Sources

Astrophysical sources (Part 2)

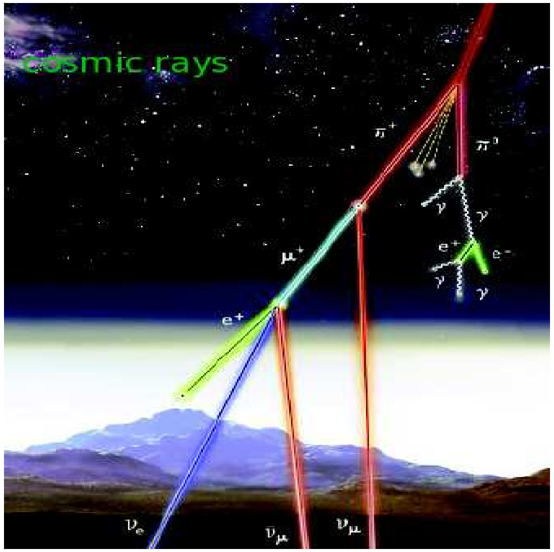


Solar

- ▶ $\nu_e <$ few MeV

Atmospheric

- ▶ few GeV $\nu_\mu \& \nu_e$



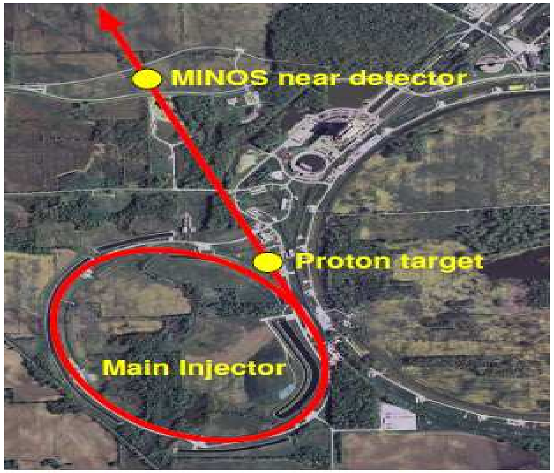
Manmade Sources: First Direct Detection + ν as Probes

Reactors

- ▶ Point source $<$10 MeV $\overline{\nu}_e$.

Accelerator

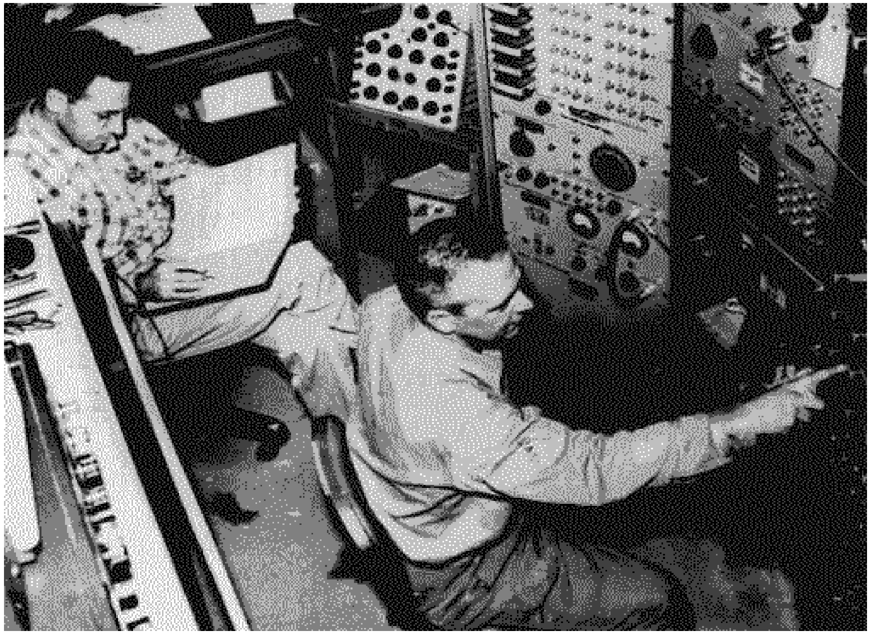
- ▶ Collimated beam (mainly ν_μ)
- ▶ Energies 0.5-500 GeV.



“Seeing” Neutrinos (1956)

First Direct Detection

- ∼25 years after Pauli’s proposed existence of the neutrino.
- Reactor source: Savannah River (11m away,12m underground).
- Technique
  - Neutrino target: cadmium doped water
  - Detector: liquid scintillator + PMTs

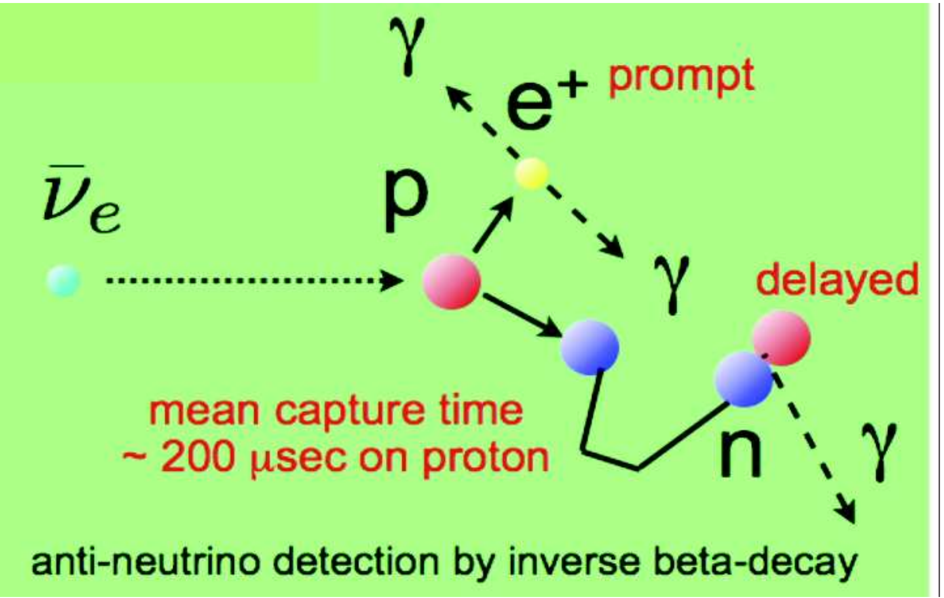


Reines and Cowan 1956, Nobel prize 1995

Inverse β-decay: $\boxed{\overline{\nu}_e + p \rightarrow n + e^+}$

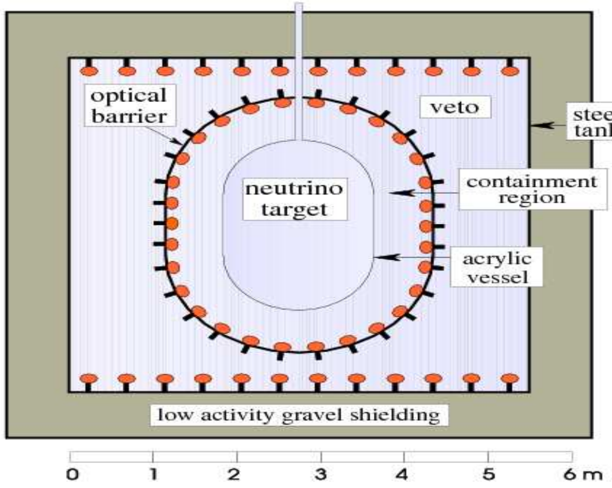
Cross section $\sigma \approx 10^{-43} cm^2$

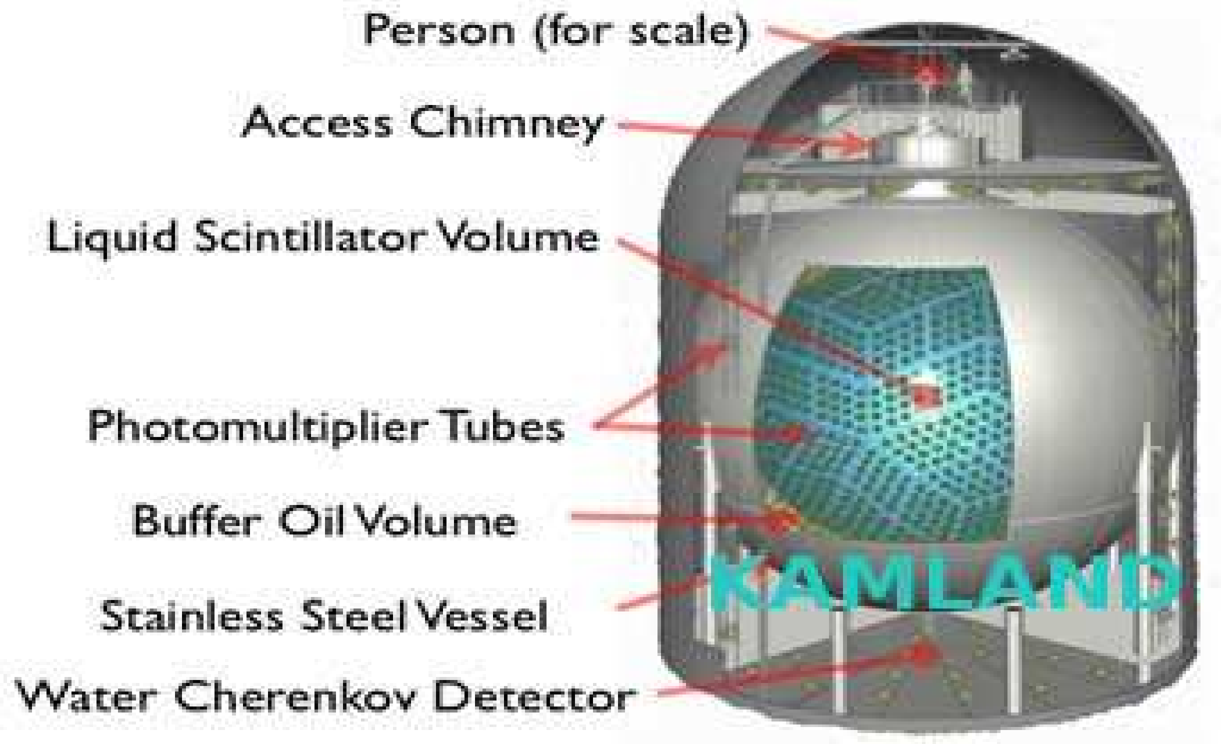
- Prompt signal from e^+ annihilation (2γs, 0.5 MeV)
- Delayed γ signal from n capture on cadmium.



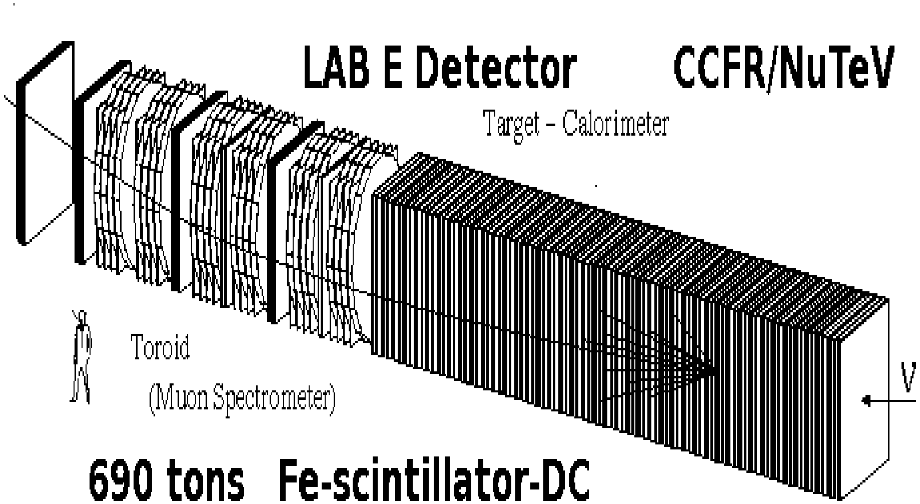
Reactor Neutrino Experiments

- Modern reactor expts use same technique (Gd for neutron capture).
- Larger targets & better background rejection methods.





Accelerator Neutrino Experiments



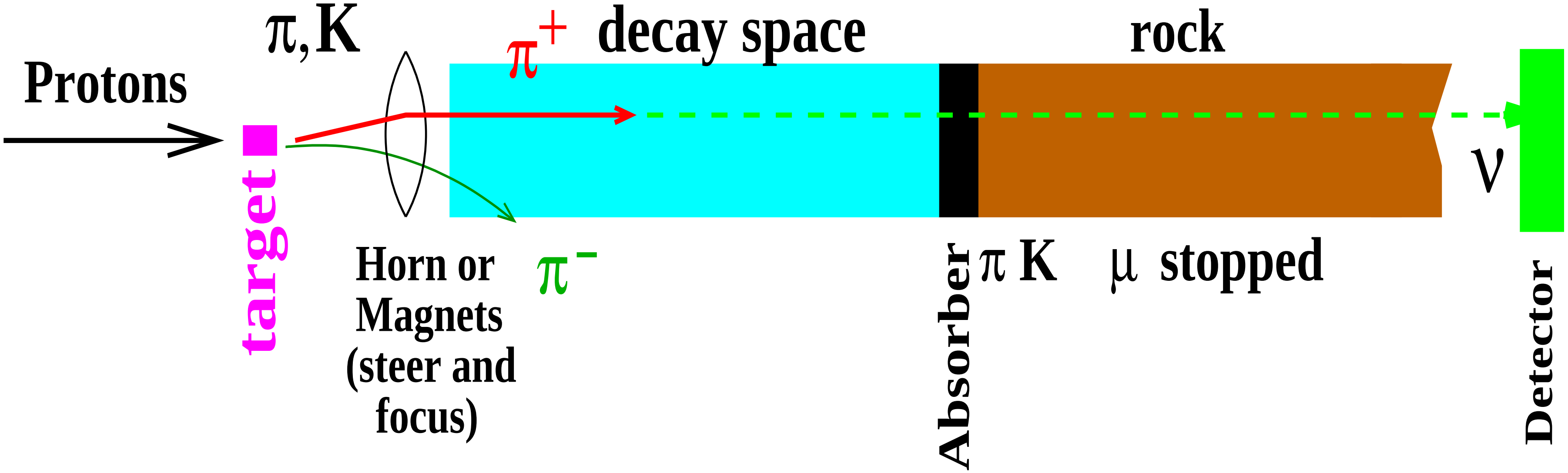
Features

- \+ High-energy, collimated, high-flux source of ν_μ
- \+ Flexibility: tunable energy.
- \- Large flux prediction uncertainties.

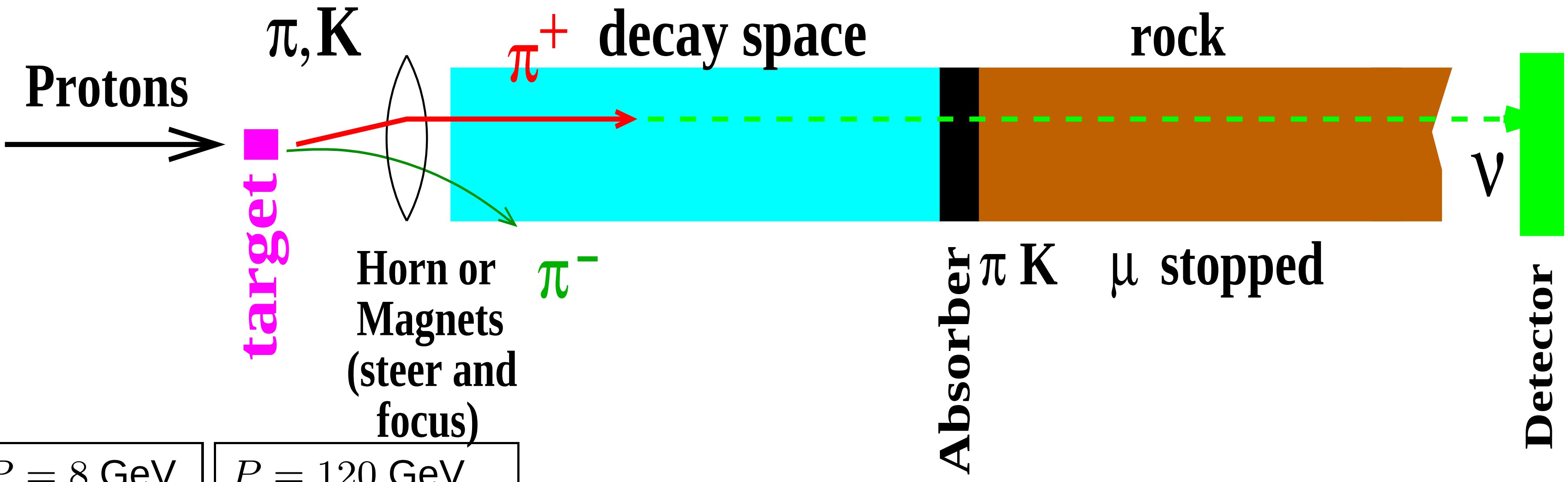
Features

- \+ High-statistics
- \- Details of the final-state are obscured.

A Neutrino Beam Primer



A Neutrino Beam Primer



Protons

π,K

target

Horn or Magnets (steer and focus)

π^+ decay space

π^-

rock

Absorber

π K μ stopped

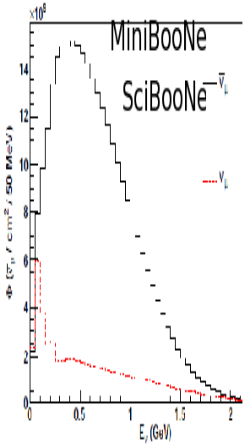
ν

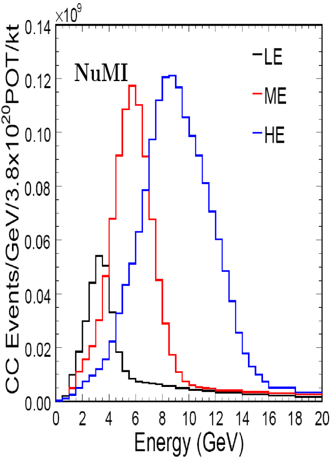
Detector

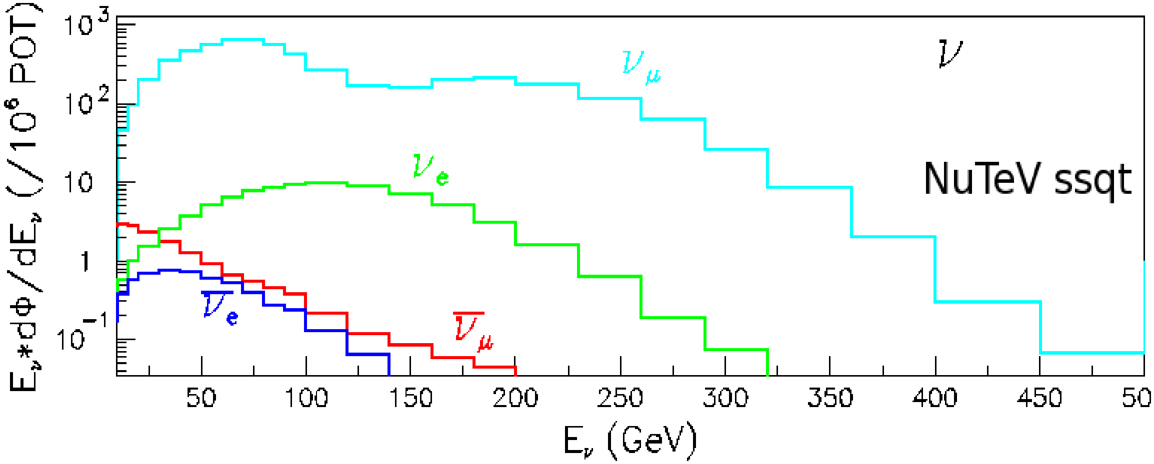
$P = 8$ GeV
Booster

$P = 120$ GeV
Main Injector

$P = 800$ GeV Tevatron

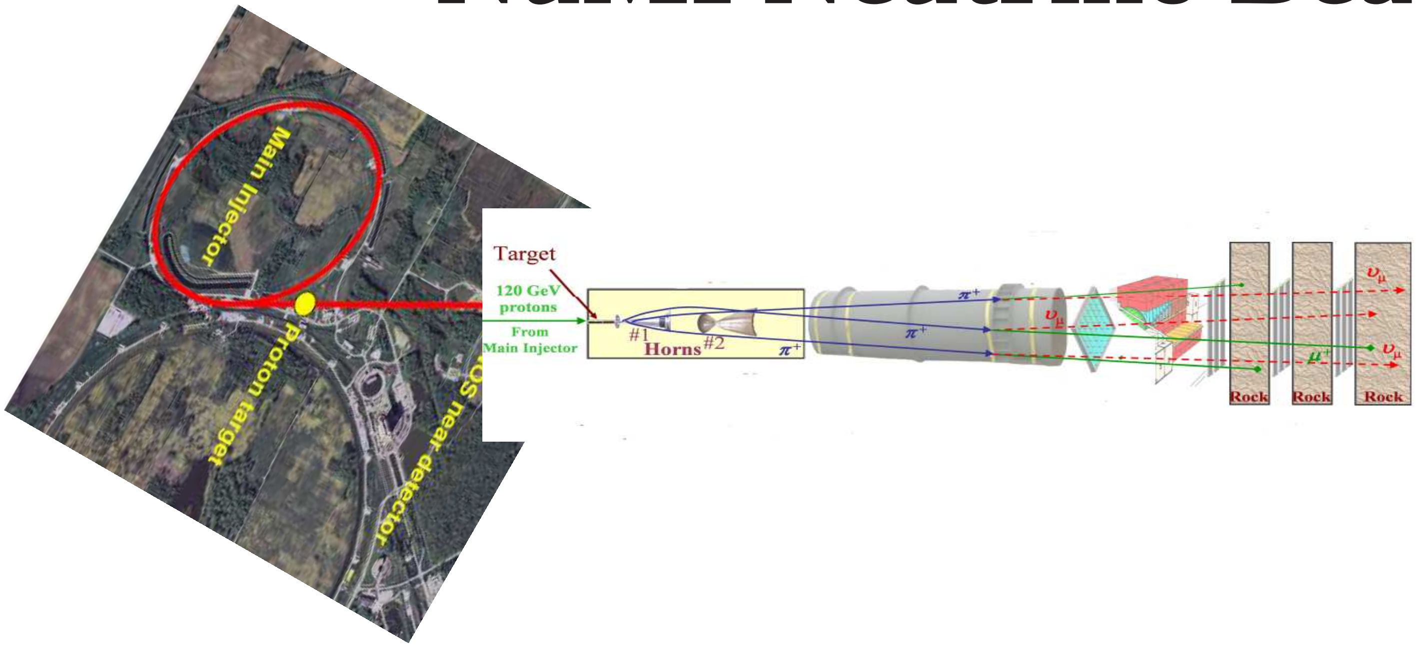




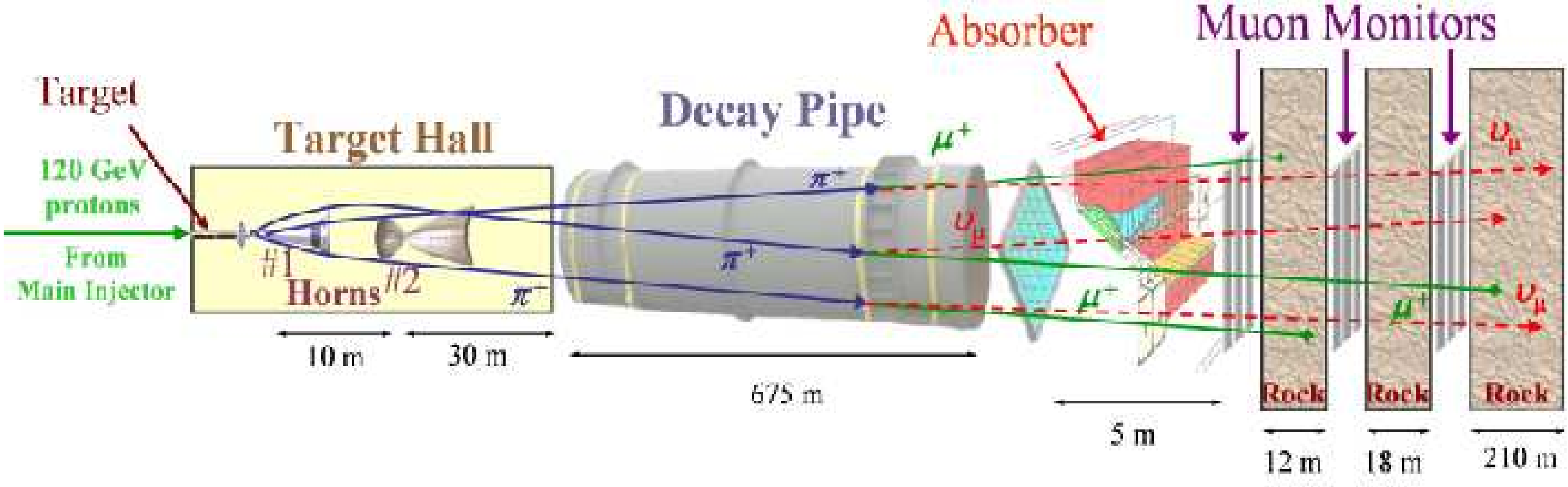


0.5 3 **Neutrino Energy (GeV)** 500

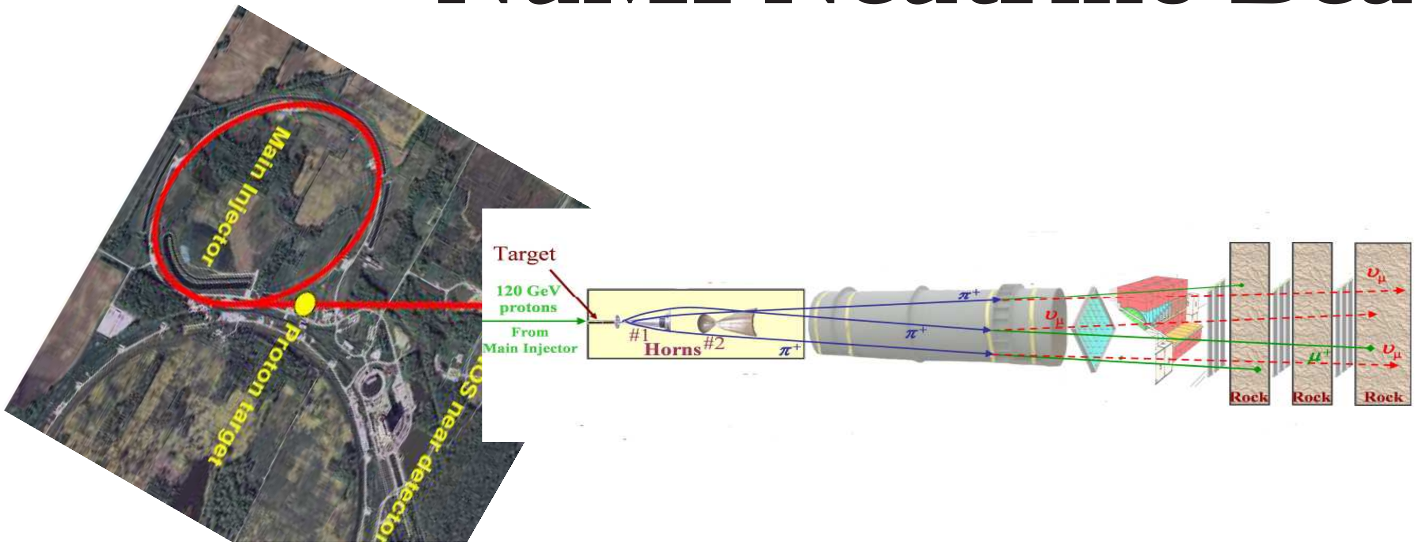
NuMI Neutrino Beam



≈10 billion neutrinos/m^2/sec produced



NuMI Neutrino Beam



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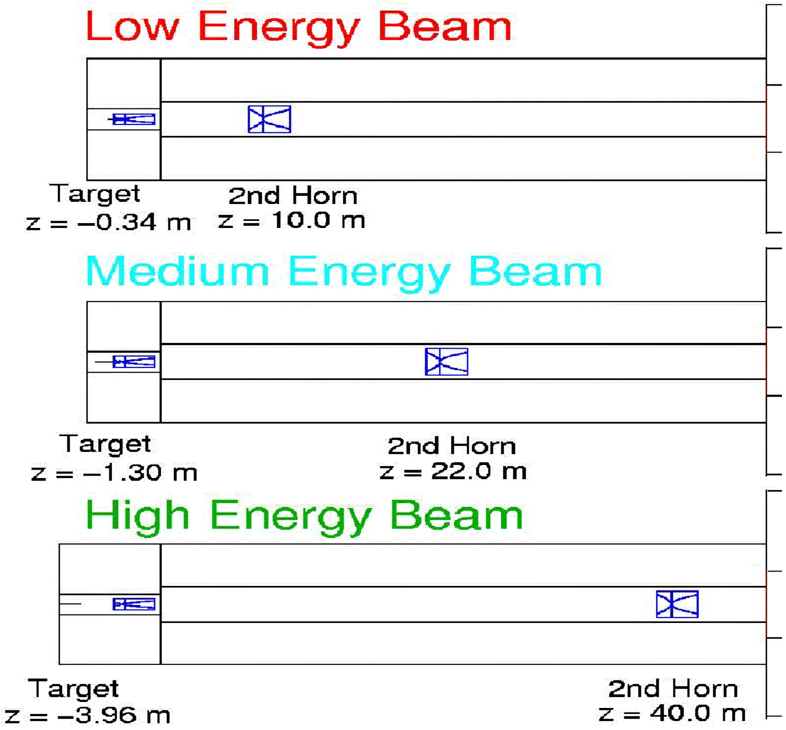
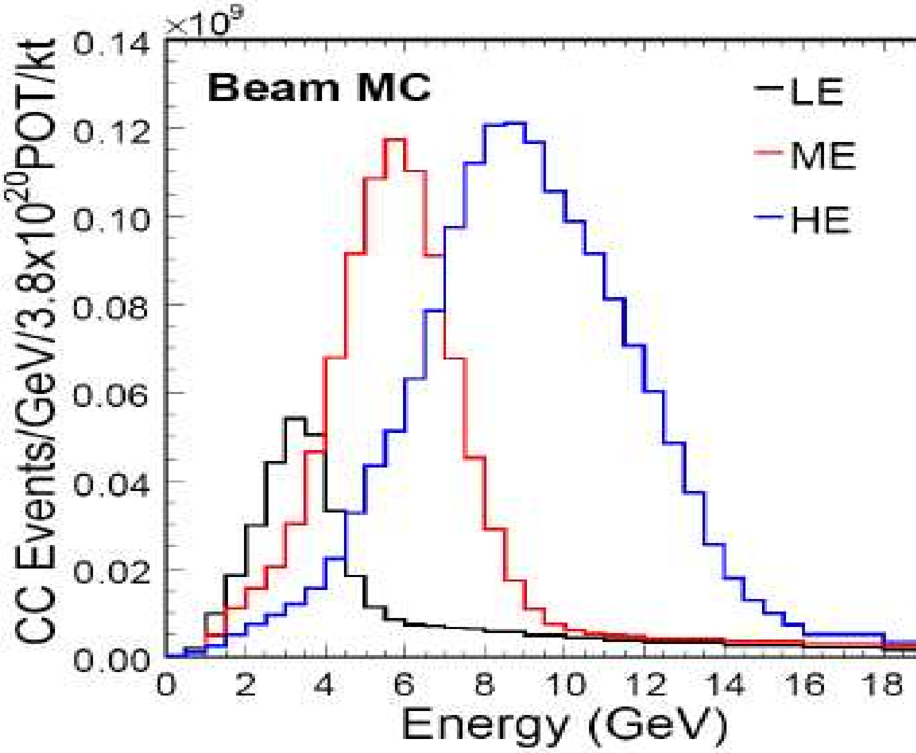
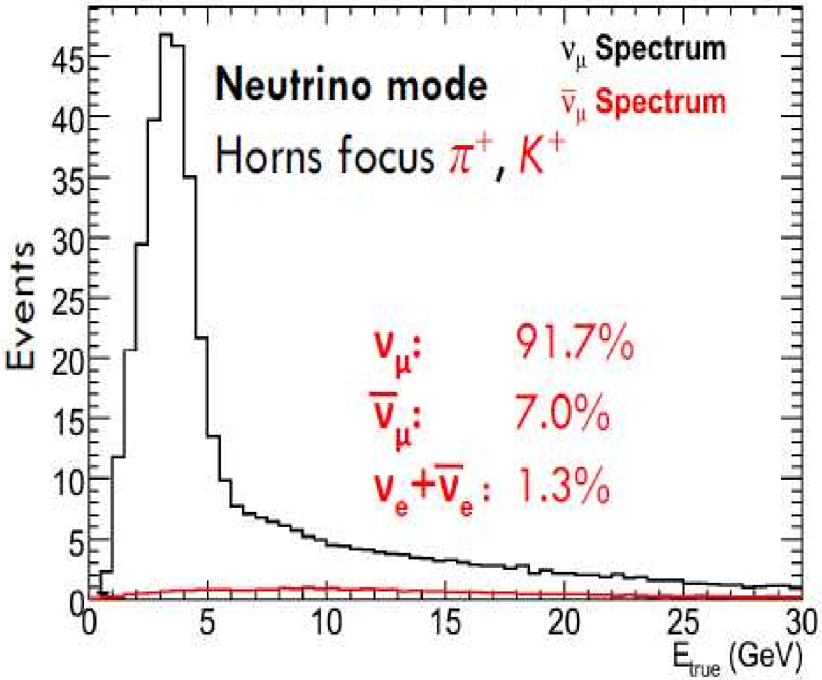
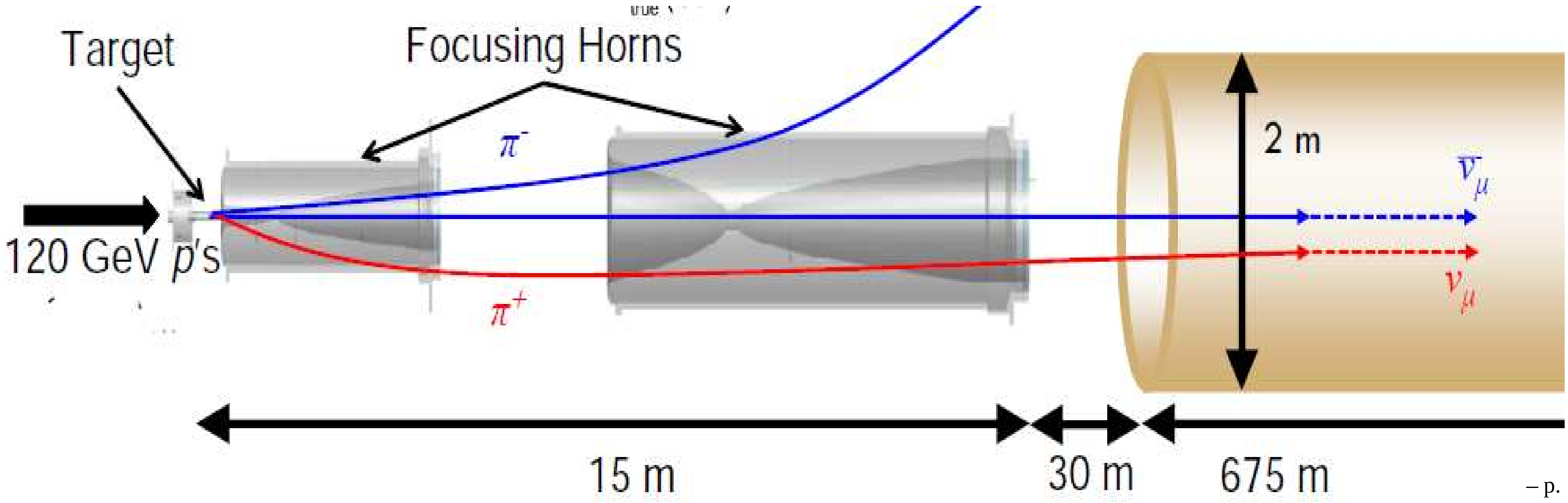




NuMI Beam ν_μ and $\overline{\nu}_\mu$ Modes



- Horns focus π^+,K^+ which decay into ν_μ
- Small fraction of $\overline{\nu}_\mu$ at higher energy from very forward π^-.
- Antineutrino beams have lower rate and lower purity.
  - Fewer π^- from protons.
  - $\sigma^{cc}(\overline{\nu}) \approx 0.5\sigma^{cc}(\nu)$



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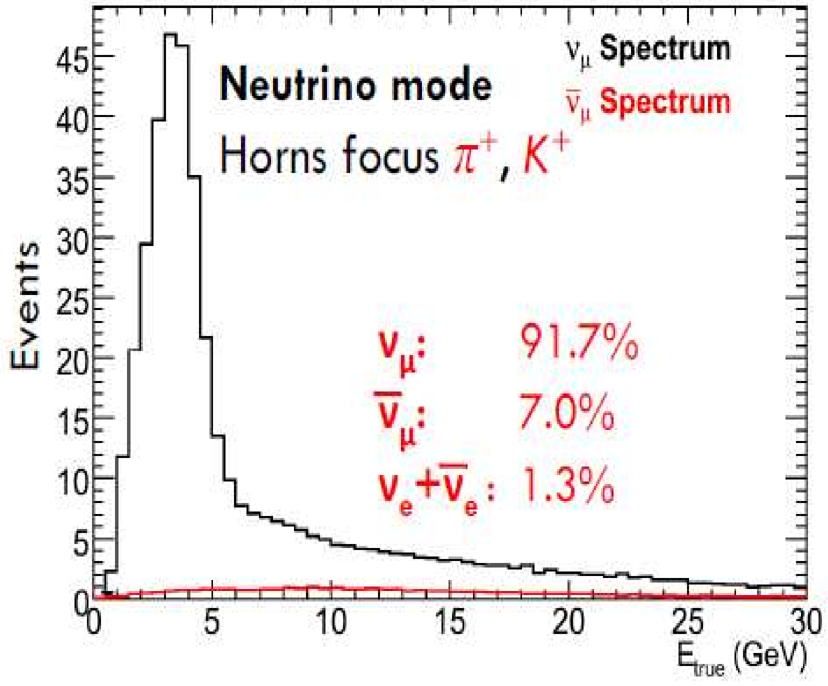
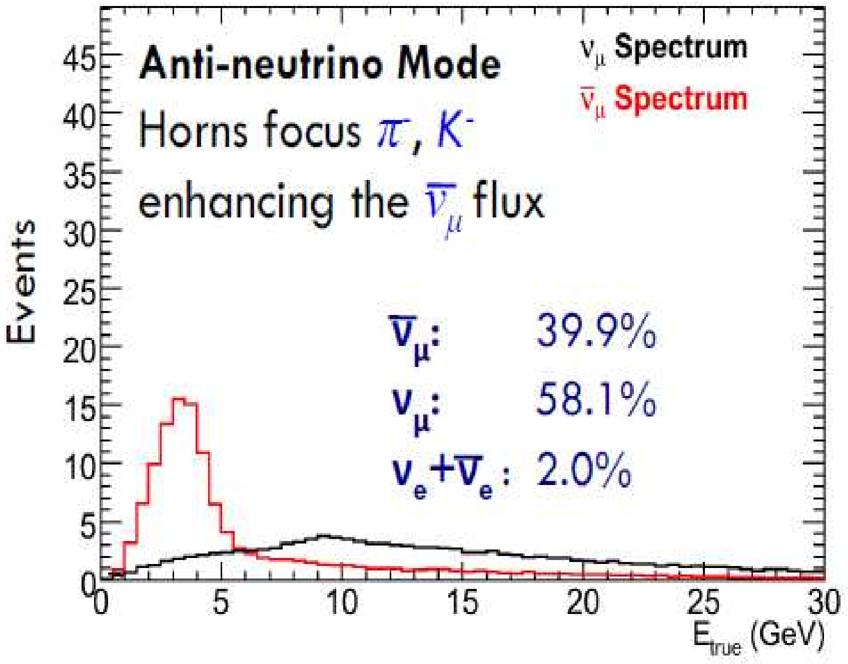
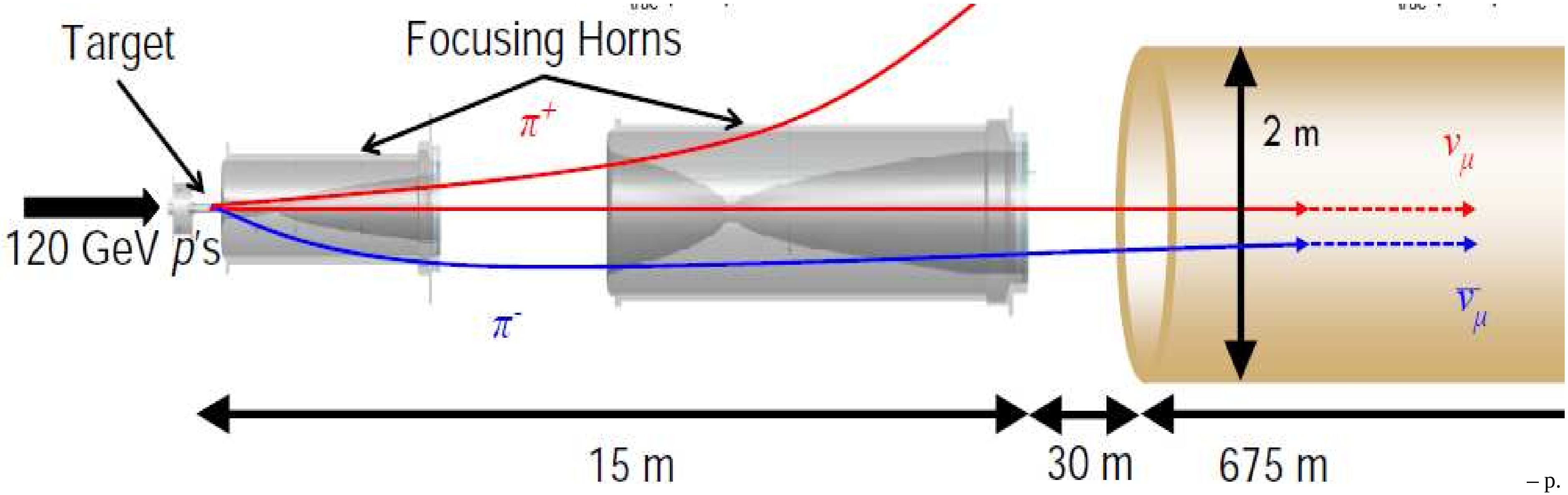
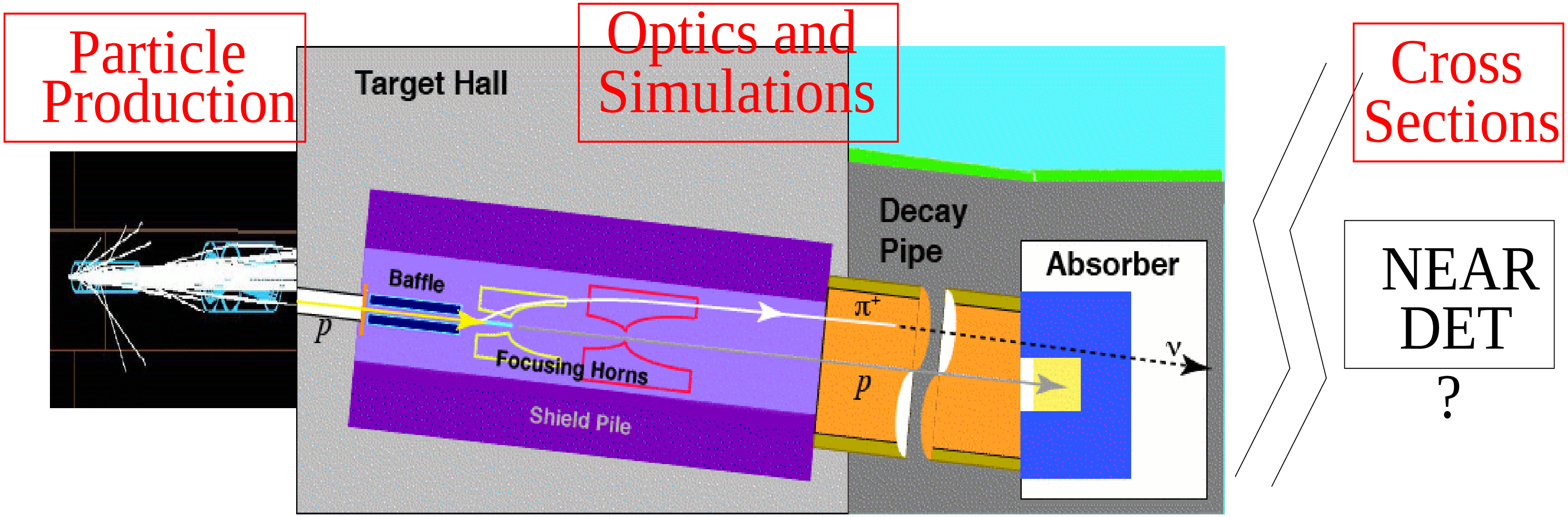






Predicting Neutrino Flux

- Unlike charged particle beams → cannot directly measure ν fluxes.



Particle Production

Optics and Simulations

Cross Sections

NEAR DET

?

Multi-stage modeling process: (particle production, optics and particle transport, material and tertiary interactions, etc.)

- Leads to large energy-dependent uncertainties in flux predictions (10-20%)

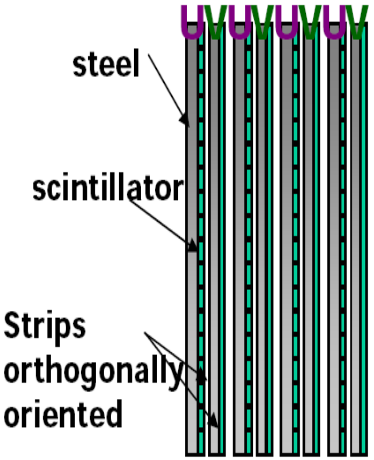
Techniques for dealing with flux uncertainties

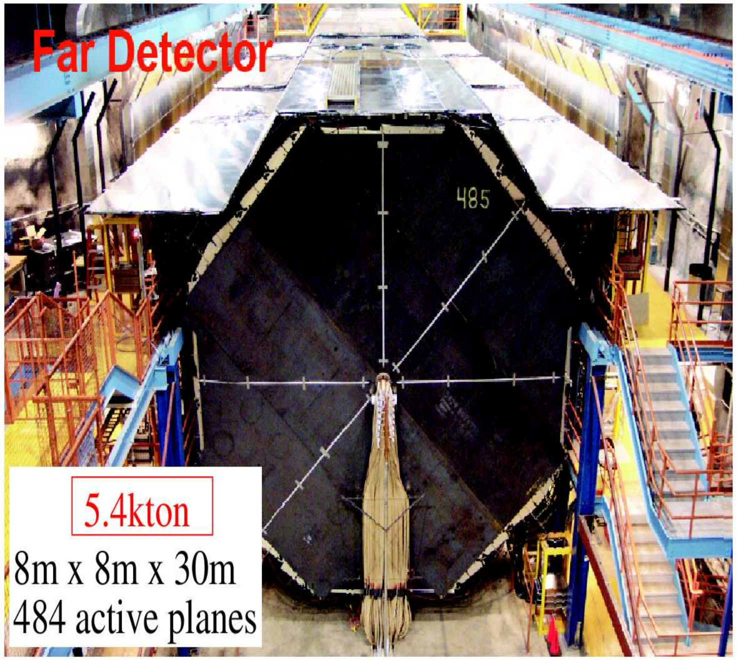
- *ex-situ and in-situ* dedicated experiments to measure particle production.
- Standard candle cross sections
  $$\Phi(E) = \frac{Measured\ Rate(E)}{\sigma^{known}(E)}$$
- Experimental technique
  - ▹ Measure ratios (Fluxes cancel).
  - ▹ Near Detectors for flux monitoring.

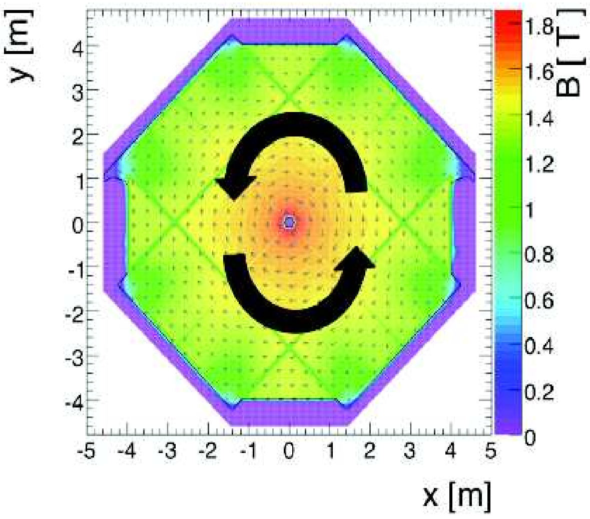
MINOS Neutrino Detector

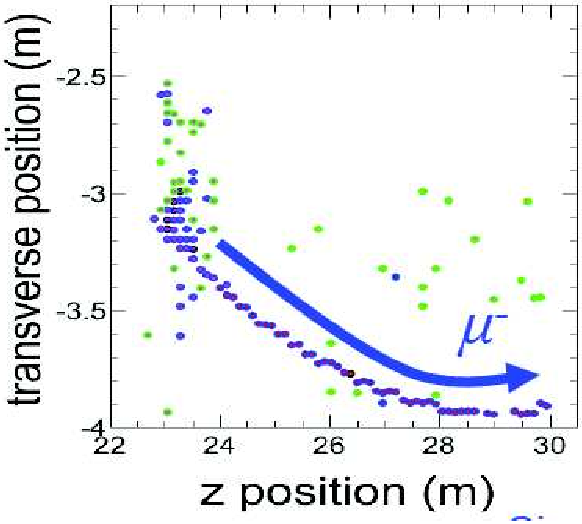
magnetized tracking-calorimeter

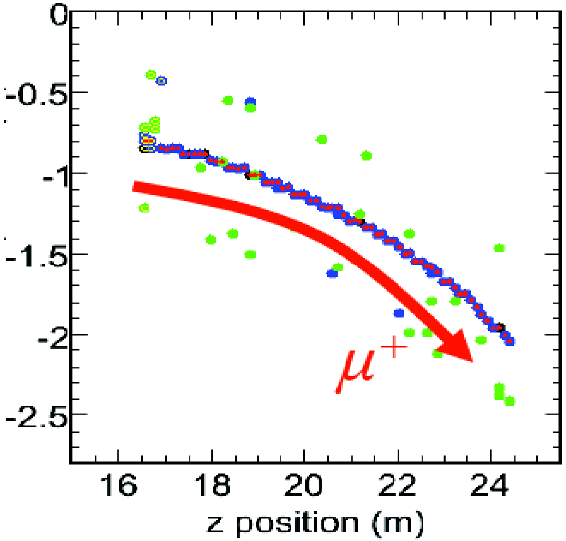
- TRACKING: scintillator planes (4.1cm wide strips).
- SHOWER ENERGY/CONTAINMENT: Sampling calorimeter (alternating 1” thick Iron planes)
- AZIMUTHAL **B** FIELD (coil magnetizes the steel)
  - track momentum and sign.





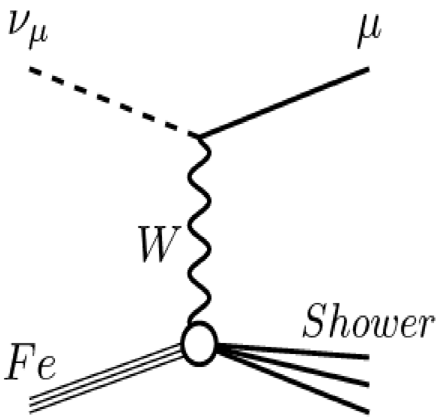


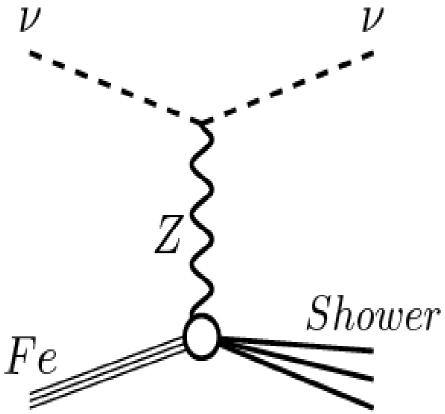


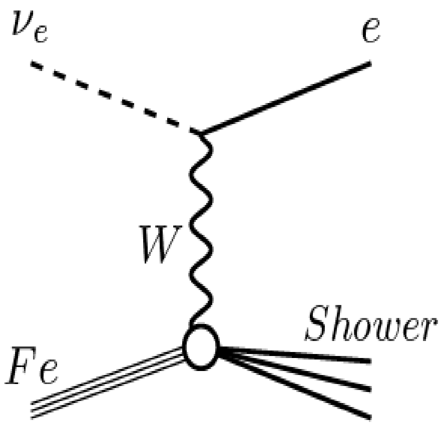


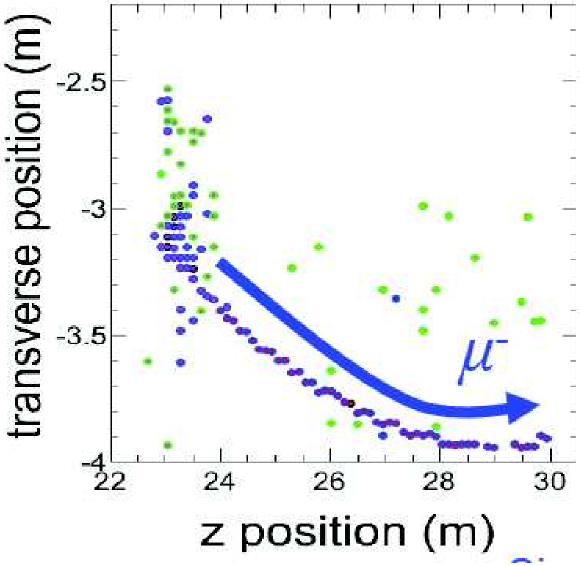
Coarse-grained Neutrino Detectors

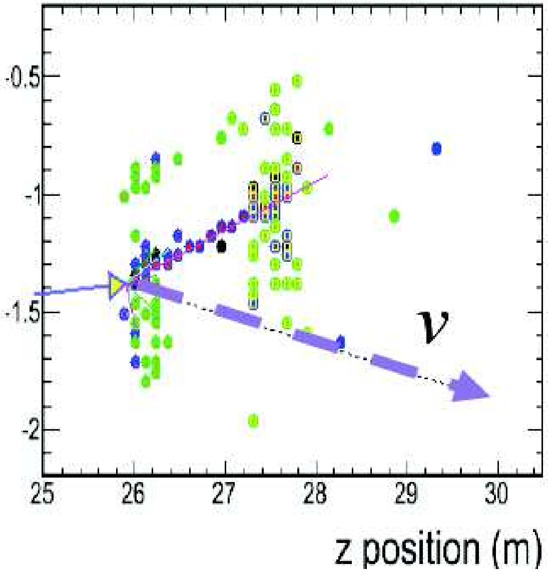
- Good for tagging high energy final state μ, and measuring high energy shower.
- Other detectors needed for low energy processes or other final state leptons (e, τ)

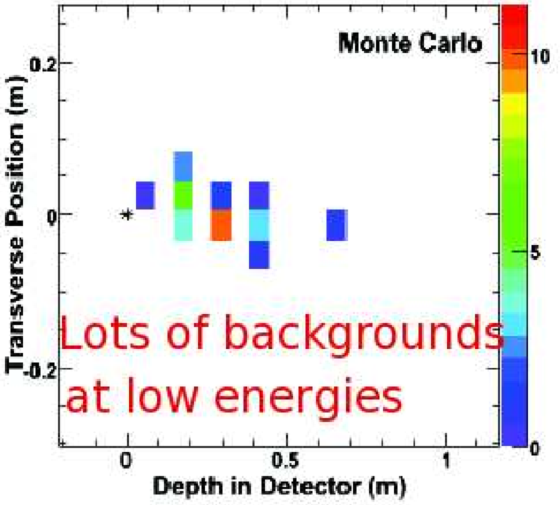






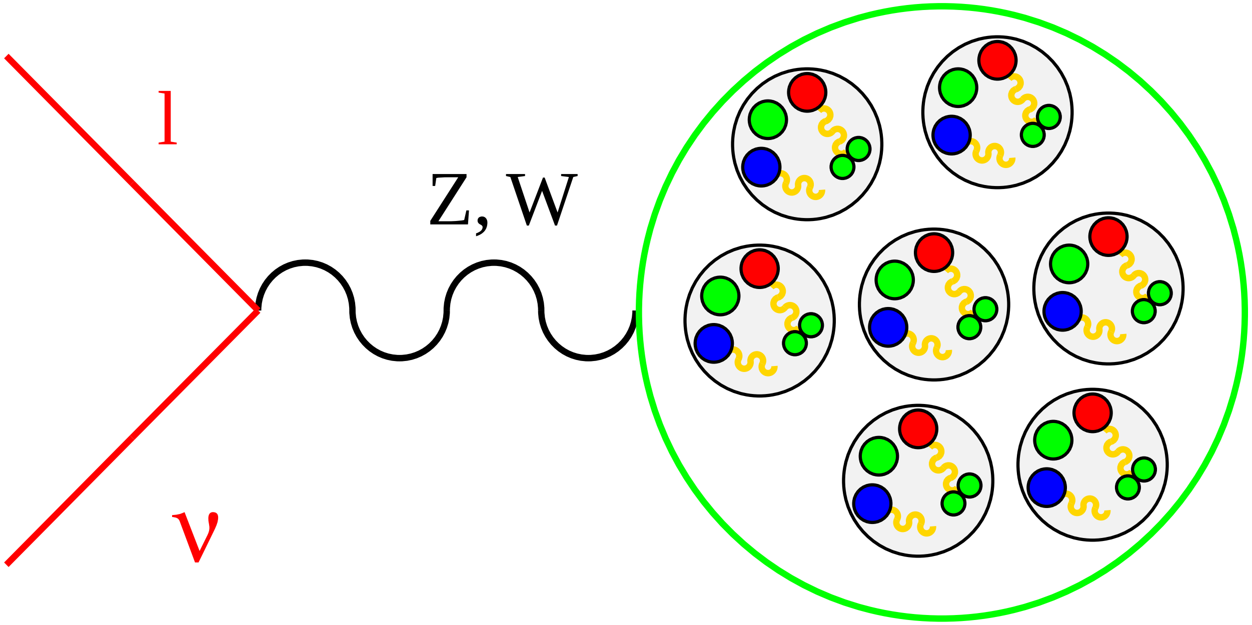






Lots of backgrounds at low energies

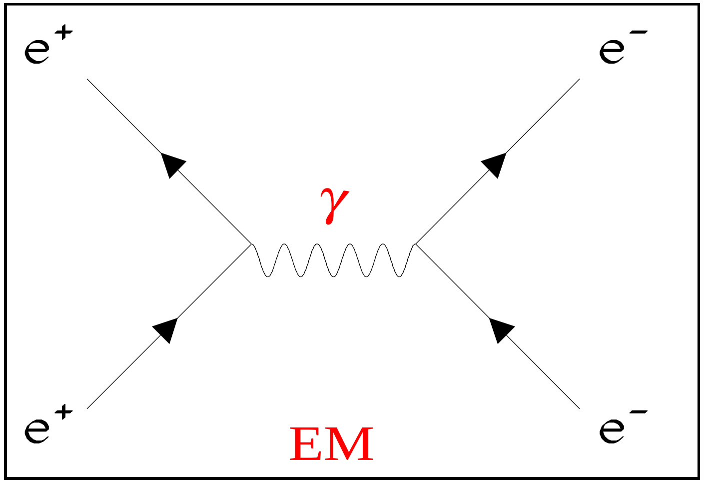
ν as Probes

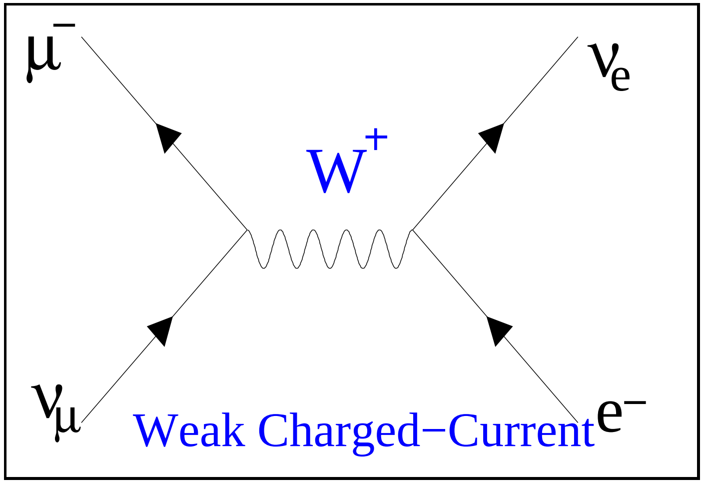


- Electroweak
  - Discovery of the weak neutral current
  - Measurement of weak-mixing angle.
- Neutrino charged-current scattering
  - DIS Probing nucleon structure
  - Neutrino cross sections

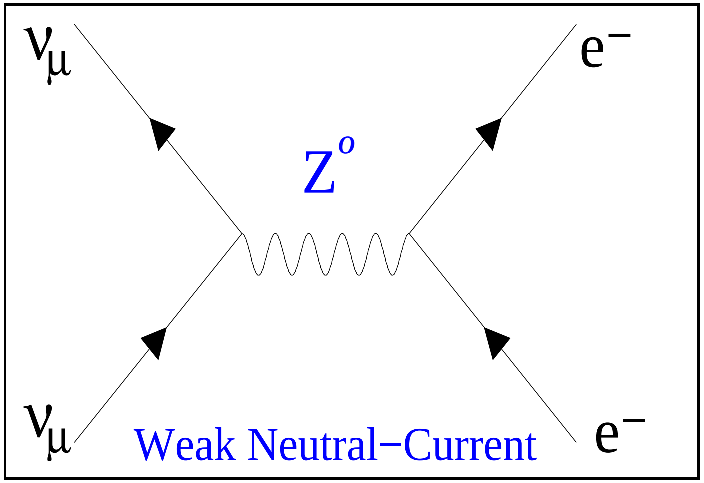
Electroweak Unification

- **Standard Model**: SU(2) $\otimes$ U(1) Gauge theory unifying EM and weak interactions. (Weinberg-Salam, 1967).





- Theory Predicted Weak NC mediated by massive neutral Z^o Boson.
- Physical parameters related through a mixing parameter for the couplings $g = g' \tan\theta_W$.



Electroweak Unification (cont'd)

- Three measured parameters are required to define the theory (tree level).

- $W^{\pm}$ coupling, $G_F = \frac{g^2\sqrt{2}}{8M_W^2}$
- $\alpha_{em} = \frac{e^2}{4\pi} = \frac{g^2 \sin^2\theta_W}{4\pi}$
- One among M_W, M_Z, or $\sin^2\theta_W$ related by $\frac{M_W}{M_z} = \cos\theta_W$

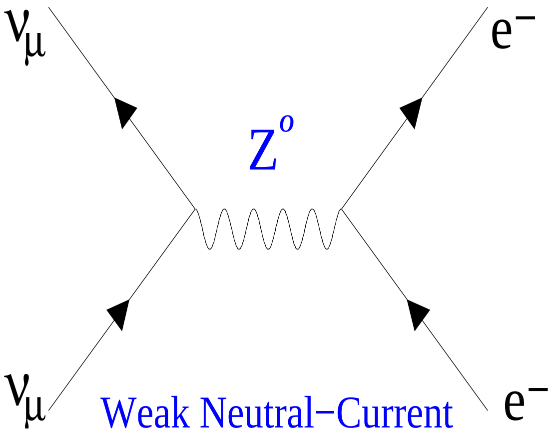
- Z-boson couplings to leptons and quarks depend on *weak mixing angle*.
- Neutrinos only have (left-handed) weak interactions.
  - Mediated by $W^{\pm}$ *(or undiscovered)* Z-boson.

Z coupling	g_L	g_R
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	0
e, μ, τ	$-\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$
u, c, t	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$	$-\frac{2}{3}\sin^2\theta_W$
d, s, b	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$

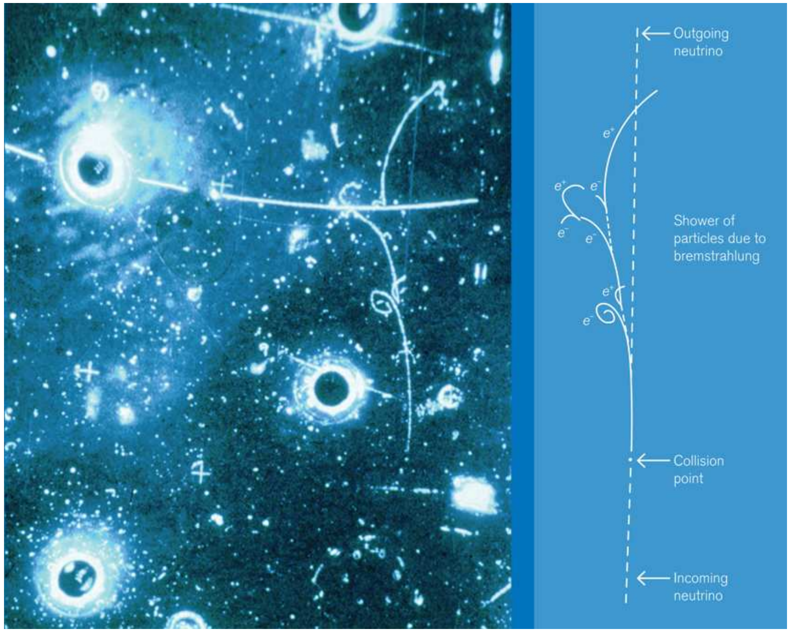
- **Good probe for discovering new Z-mediated interaction.**

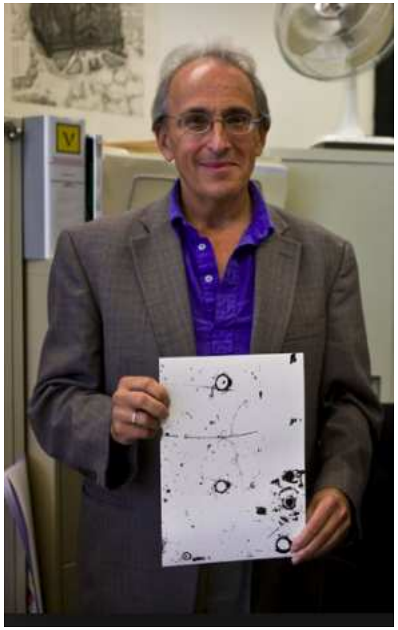
ν's as Probes: Proving ground for the SM

Gargamelle, CERN (summer 1973): Discovery of the weak neutral current



(Leptonic neutral currents only 3/10^6 Events)

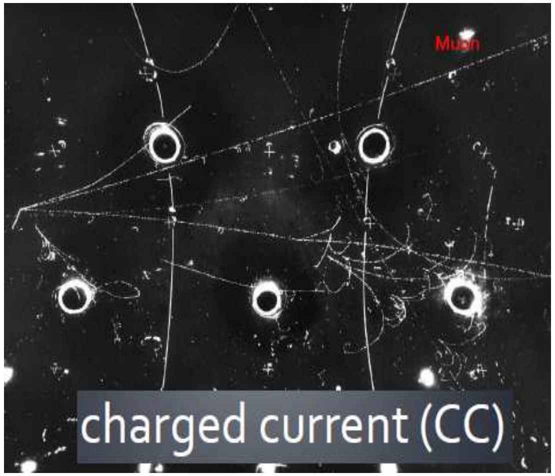




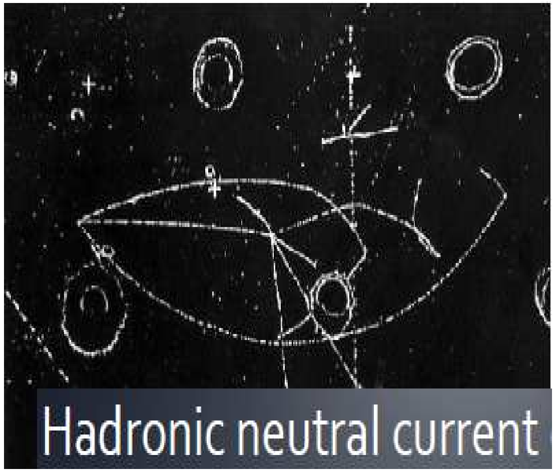
Successful prediction of EW theory

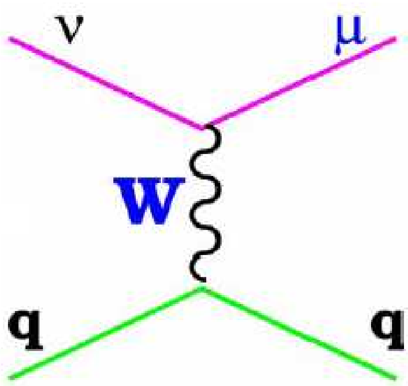
Measure NC/CC Ratios

muon

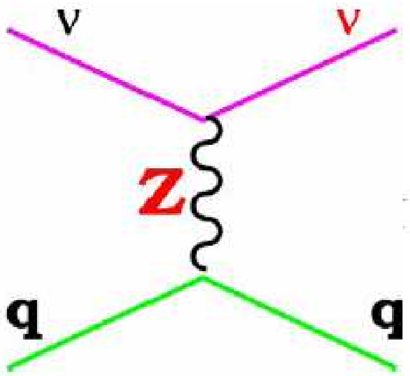


No muon





$$Coupling \propto J^{(3)}_{weak}$$



$$Coupling \propto \left(J^{(3)}_{weak} - Q_{em} \sin^2 \theta_W\right)$$

Bubble chamber sees details but limited statistics!

	ν	$\overline{\nu}$
NC	102	64
CC	428	148
n-BKG	15	12

$$R^{\nu} = 0.21 \pm 0.03\ (stat)$$

$$R^{\overline{\nu}} = 0.45 \pm 0.09\ (stat)$$

$\sin^2 \theta_{\mathrm{w}}$ range 0.3-0.4

$$R^{\nu(\overline{\nu})} = \frac{\sigma^{\nu(\overline{\nu})}_{NC}}{\sigma^{\nu(\overline{\nu})}_{CC}} = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1 + \frac{\sigma^{\overline{\nu}(\nu)}_{CC}}{\sigma^{\nu(\overline{\nu})}_{CC}}\right)$$

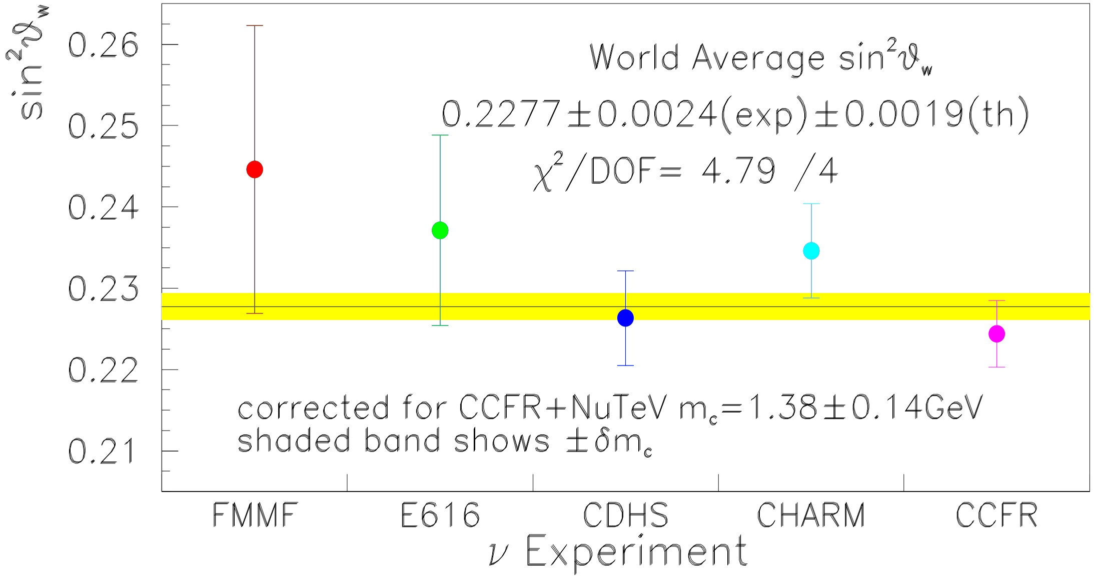
ν's and the Weak Mixing Angle

- **First generation** experiments (precision ∼10%) narrowed in on the value:

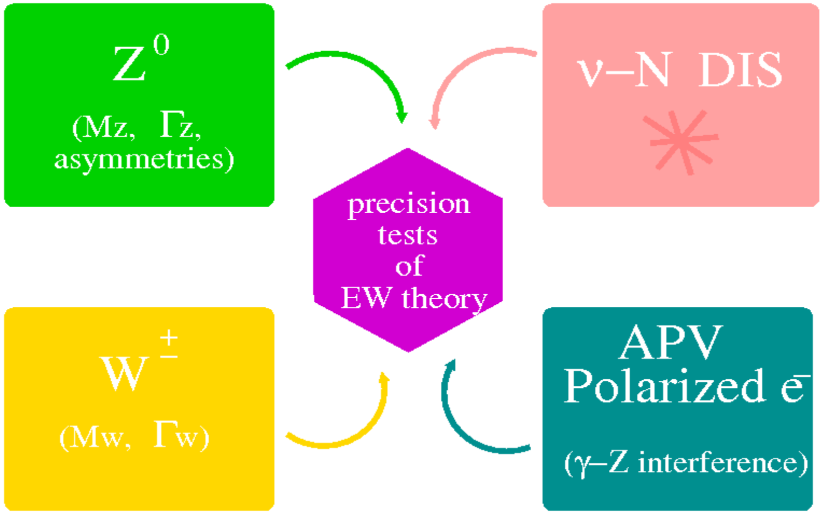
$$\boxed{\sin^2\theta_{\rm w} = 0.23} \Rightarrow \text{Prediction for } M_{\rm w} = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_{\rm w}} = \frac{37GeV}{\sin\theta_{\rm w}} \approx 77\ {\rm GeV}$$

- **Second Generation** experiments (late 1980's) with precision 1-5%.

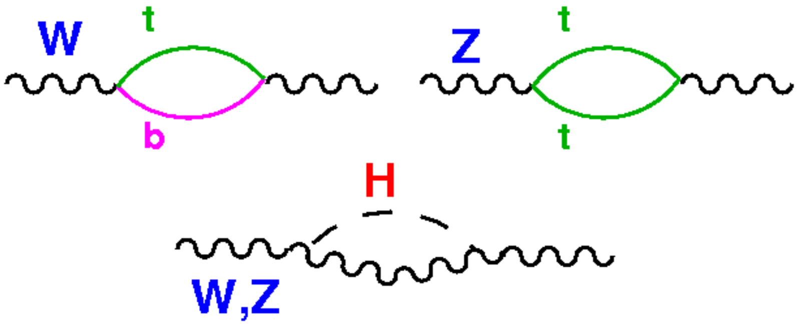
$$\sin^2\theta_W^{\rm on-shell} \equiv 1 - \frac{M_{\rm w}^2}{M_{\rm z}^2} = 0.2277 \pm 0.0036 \Rightarrow M_{\rm W} = 80.14 \pm 0.19 GeV$$



Precision Electroweak Tests



- Internal consistency → search for new physics
- Within the Standard Model:
  Radiative corrections sensitive to m_t, m_H



- Global electroweak fit (including e^+e^- and νN) predicted $M_{top} = 178 \pm 8^{+17}_{-20}$ before it was measured in 1995.

  LEP Electroweak Working Group, (1995), CERN-PPE-95-172.

- Push precision below second generation level (1-5%) for νN → need new technique with reduced systematic uncertainty.

Neutrino WMA Measurement Techniques

Purely leptonic channel $\boxed{\nu_\mu e^- \rightarrow \nu_\mu e^-}$

Rate suppressed by e^- target mass : $s = m_e^2 + 2m_e E_\nu$

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_{\mathrm{W}} + \frac{4}{3}\sin^4\theta_{\mathrm{W}}\right)$$

CHARM II

$\sim$ 2700 evts for each ν and $\overline{\nu}$.

$\sin^2\theta_{\mathrm{W}} = 0.232 \pm 0.008$

ν-quark scattering: Llewellyn Smith Relation

$$R^{\nu(\overline{\nu})} = \frac{\sigma_{NC}^{\nu(\overline{\nu})}}{\sigma_{CC}^{\nu(\overline{\nu})}} = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1 + \frac{\sigma_{CC}^{\overline{\nu}(\nu)}}{\sigma_{CC}^{\nu(\overline{\nu})}}\right)$$

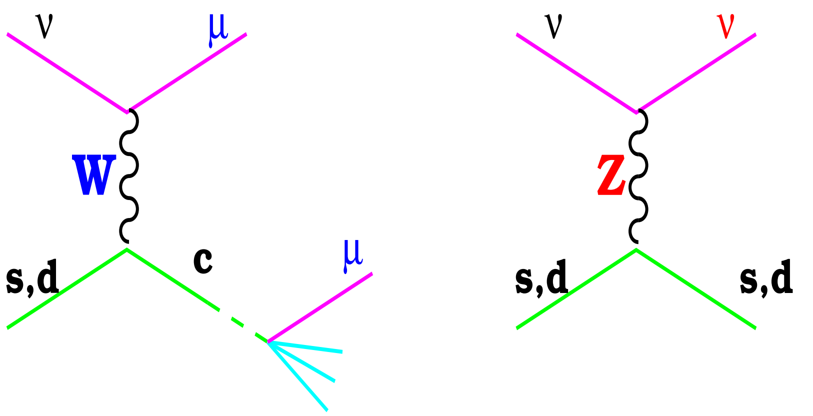
Assumes:

- ▶ isoscalar tgt of light-quarks
- ▶ leading-order.

CCFR, CDHSW (syst. limited).

Must correct for

- ▶ higher-order cross section effects: R_L, target mass, etc.
- ▶ radiative corr.
- ▶ non-isoscalarity ($N_p \neq N_n$)
- ▶ **heavy quark effects.**
  - ▷ Large theoretical uncertainty.



- ▶ Suppression of CC cross section for interactions with massive charm quark in final state → must be modeled.

NuTeV WMA Measurement

Paschos-Wolfenstein Relation

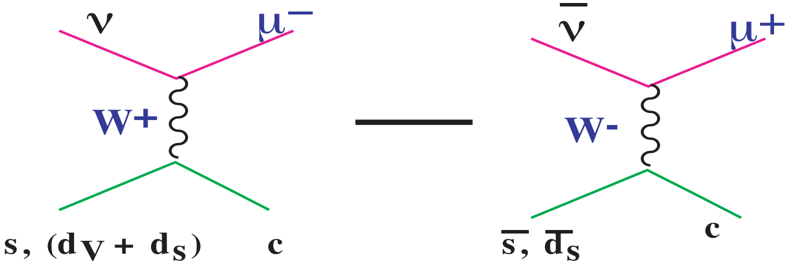
$$R^{-} = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}} = \frac{1}{2} - \sin^2\theta_W$$

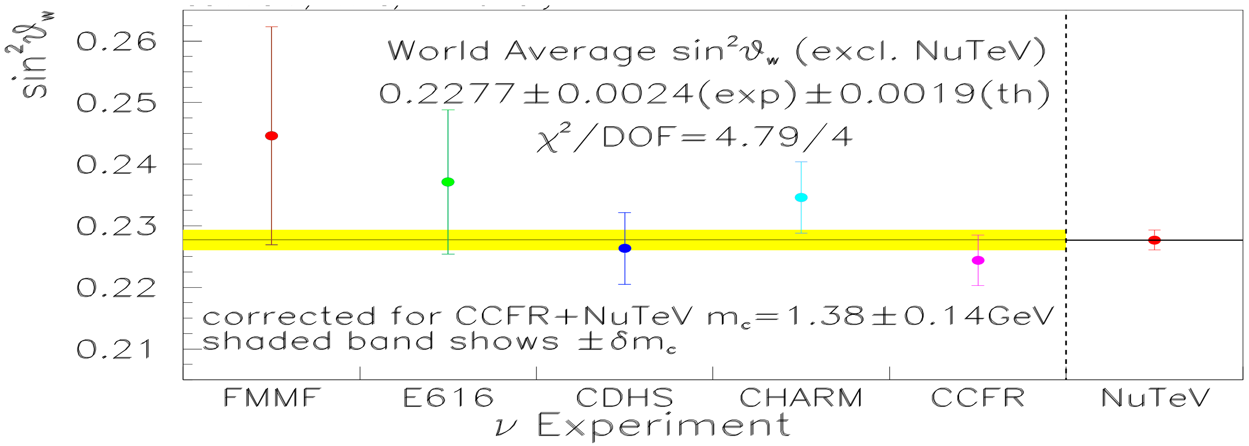
- ▶ R^{-} insensitive to sea quarks

Requires high-purity ν or $\overline{\nu}$ beams

NuTeV employed this technique $< 1\%$ precision.

- ▶ Charm production uncertainty reduced.
- ▶ $s/\overline{s}$ and $d/\overline{d}$ seas cancel in $\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}$. (assuming symmetric quark-antiquark seas in an isoscalar target).



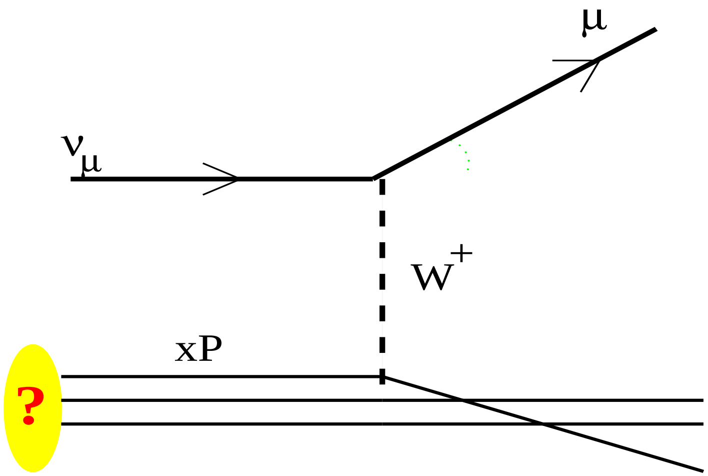


Agrees with previous ν measurements.

$$\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2277 \pm 0.0013\ (\mathrm{stat}) \pm 0.0009\ (\mathrm{syst})$$

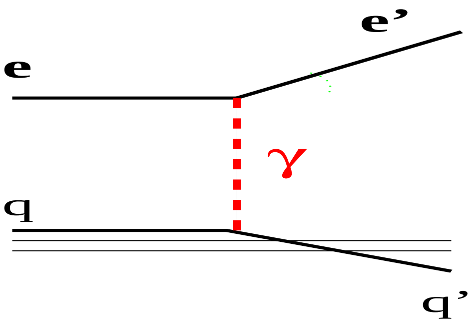
... a discrepancy of 3σ from SM prediction.

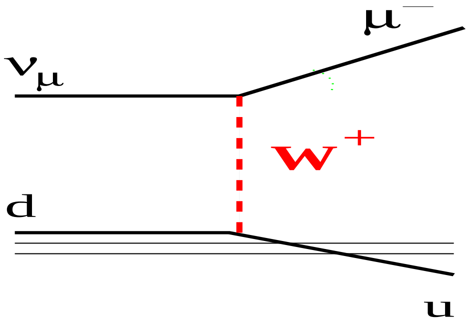
Charged-current νN DIS



QCD tells you about Q^2 evolution,

but structure functions must be measured!

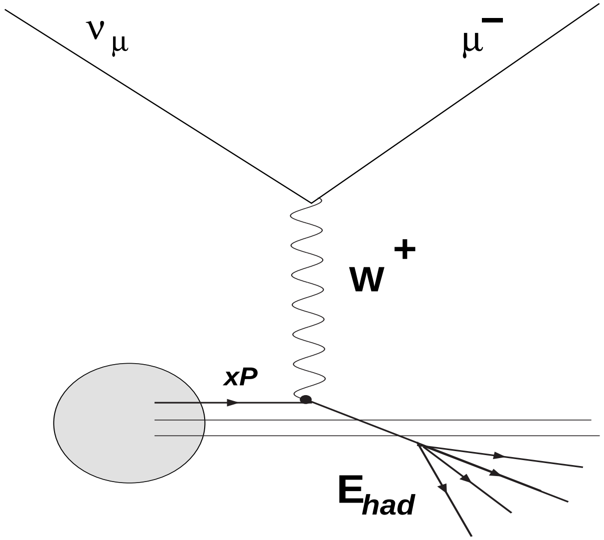




- In charged-lepton scattering, photons couple to quark charges $F_2 = x\Sigma_q e_q^2 q(x)$
- Two structure functions: F_2 and $2xF_1$ (or R_L) measured.

- ν probes use weak interaction.
  - Sensitive to quark flavor.
- Parity violating character of weak interaction gives access to $xF_3(x, Q^2)$.

Neutrino-Nucleon DIS



Lorentz-invariant quantities in terms of measured $E_\mu,\ \theta_\mu,\ E_{had}$:

$$\left\{\begin{array}{ll} Q^2 = 4(E_\mu + E_{had})E_\mu sin^2\frac{\theta_\mu}{2} & \longrightarrow \text{Squared 4-momentum transfer} \\ x = \frac{Q^2}{2ME_{had}} & \longrightarrow \text{Fractional struck quark momentum} \\ y = \frac{E_{had}}{E_\mu + E_{had}} & \longrightarrow \text{Inelasticity} \\ W^2 = M^2 + 2ME_{\mathrm{HAD}} - Q^2 & \longrightarrow \text{Squared invariant final state mass} \\ \nu = E_{had} & \longrightarrow \text{Energy transfered to hadronic syste} \end{array}\right.$$

Neutrino CC Scattering Cross-Section:

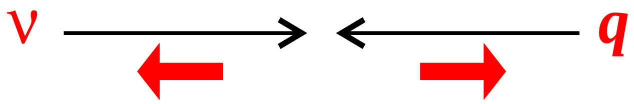
$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\left[\left(1 - y - \frac{Mxy}{2E_\nu}\right) F_2^{\nu(\overline{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\overline{\nu})} \pm y(1-\frac{y}{2})xF_3^{\nu(\overline{\nu})}\right]$$

(neglects final-state lepton mass terms).

ν-quark Scattering

- Parity violation in CC weak-interactions ⇒ Imposes constraints on angular dependence of ν-quark and ν-antiquark scattering.

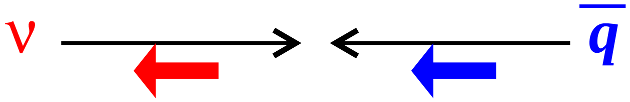
$$\boxed{\nu_L + q_L}$$



S=0

$$\boxed{\frac{d\sigma}{d\cos\theta^*} \propto \frac{1}{2}}$$

$$\boxed{\nu_L + \bar{q}_R}$$



S=1

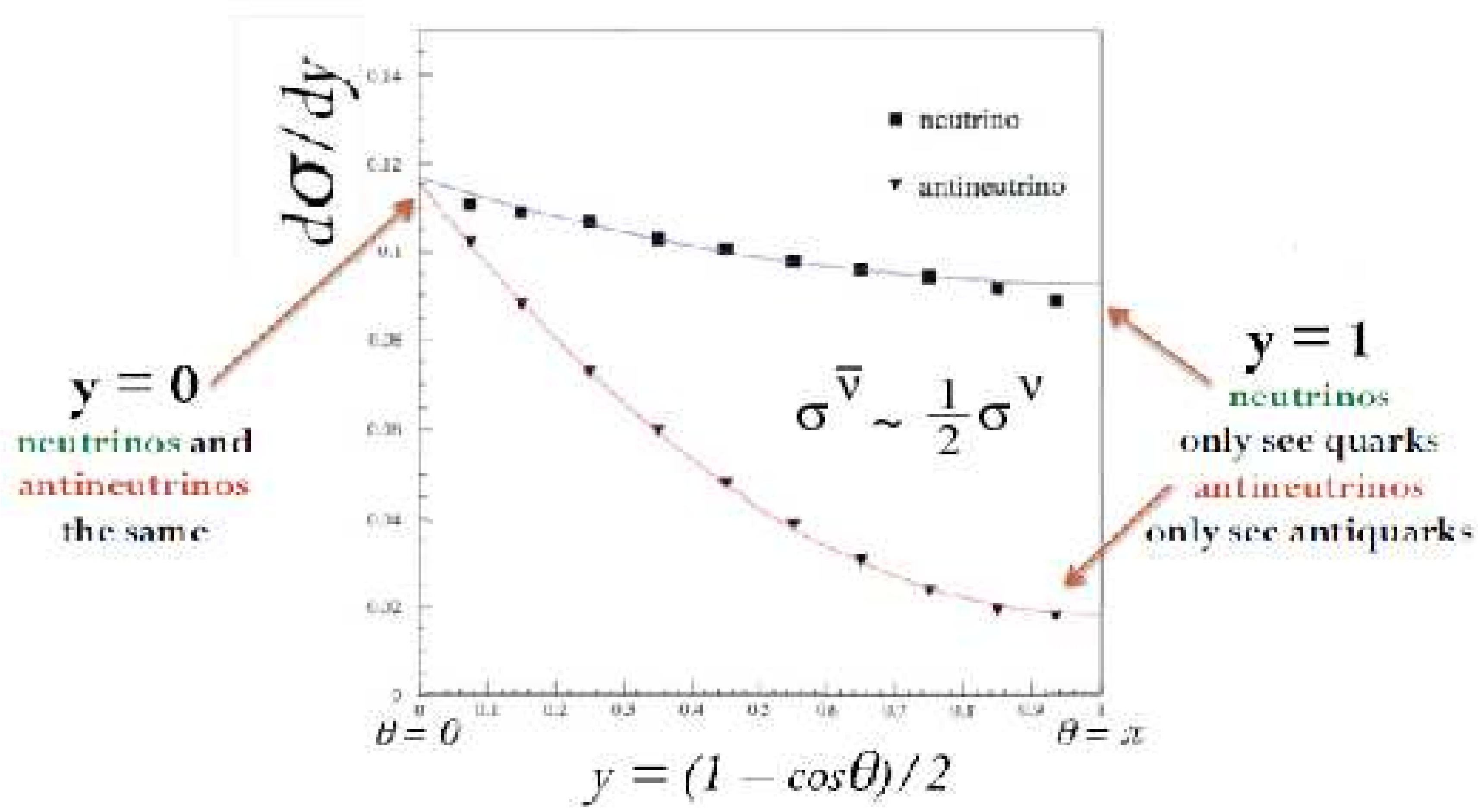
$$\boxed{\frac{d\sigma}{d\cos\theta^*} \propto \frac{1}{2}\left(\frac{1+\cos\theta^*}{2}\right)^2}$$

Relate to inelasticity, y $\boxed{1-y=\frac{1}{2}(1+cos\theta^*)}$

	q	$\bar{q}$
ν	1	$(1-y)^2$
$\bar{\nu}$	$(1-y)^2$	1

Y-Dependence ν vs. $\overline{\nu}$ Cross Sections

$$\boxed{\begin{aligned} \frac{d^2\sigma^{\nu}}{dxdy} &= \frac{G^2 sx}{\pi}\left[\mathrm{q(x)} + \overline{\mathrm{q}}\mathrm{(x)}(1-y)^2\right] \\ \frac{d^2\sigma^{\overline{\nu}}}{dxdy} &= \frac{G^2 sx}{\pi}\left[\overline{\mathrm{q}}\mathrm{(x)} + \mathrm{q(x)}(1-y)^2\right] \end{aligned}}$$



$\sigma^{\overline{\nu}} \sim \frac{1}{2}\sigma^{\nu}$

$y = 0$

neutrinos and antineutrinos the same

$y = 1$

neutrinos only see quarks

antineutrinos only see antiquarks

Neutrino SFs in the Parton Model

QPM: scattering off the nucleon is the incoherent sum of elastic scattering off the constituents.

- Assume no spin 0 constituents: Callan-Gross relation (R=0) $F_2(x) = 2xF_1(x)$.
- Relate SFs to PDFs by matching y-dependence in cross section terms.

Neutrino Structure Functions

$$F_2(x) = 2\Sigma x\,(q(x) + \overline{q}(x))$$

$$xF_3(x) = 2\Sigma x\,(q(x) - \overline{q}(x))$$

Flavor sensitivity: lepton number and charge conservation.

ν selects: $d, s, \overline{u}, \overline{c}$ $\quad q^{\nu p}(x) = d^p(x) + s^p(x) \quad \overline{q}^{\nu p}(x) = \overline{u}^p(x) + \overline{c}^p(x)$

$\overline{\nu}$ selects: $u, c, \overline{d}, \overline{s}$ $\quad q^{\overline{\nu} p}(x) = u^p(x) + c^p(x) \quad \overline{q}^{\overline{\nu} p}(x) = \overline{d}^p(x) + \overline{s}^p(x)$

Neutrino Structure Functions

More practical: *isoscalar* target ($N_n = N_p$)

- *(Neutrino experiments use nuclear target/detectors)*.
- Isospin symmetry $$\begin{aligned} u(x) &\equiv u^p(x) = d^n(x) & d(x) &\equiv d^p(x) = u^n(x) \\ \overline{u}(x) &\equiv \overline{u}^p(x) = \overline{d}^n(x) & \overline{d}(x) &\equiv \overline{d}^p(x) = \overline{u}^n(x) \end{aligned}$$
- Assume symmetric heavy quark seas $s = \overline{s}$ and $c = \overline{c}$

$$\begin{aligned} F_2^{\nu N} = F_2^{\overline{\nu} N} &= x\left(u + \overline{u} + d + \overline{d} + 2\overline{s} + 2c\right) \\ xF_3^{\nu N} &= x\left(u + d - \overline{u} - \overline{d} + 2s - 2\overline{c}\right) \\ xF_3^{\overline{\nu} N} &= x\left(u + d - \overline{u} - \overline{d} + 2\overline{s} - 2c\right) \end{aligned}$$

$F_2^{\nu N}$	all quarks
xF_3	valence quarks
ΔxF_3	$= 4x(s - c)$
	heavy quark seas.

Measuring ν Cross Sections and SFs

- Cross sections and structure functions measurements require a precise method to determine ν and $\overline{\nu}$ beam fluxes.

$$\boxed{\frac{\mathrm{d}^2\sigma}{\mathrm{dxdy}}^{\nu(\overline{\nu})} = \frac{1}{\Phi(\mathrm{E})}\frac{\mathrm{d}^2\mathrm{N}}{\mathrm{dxdy}}^{\nu(\overline{\nu})} .}$$

Low-ν Flux extraction technique

- ν **(energy transferred to hadronic system)** is related to inelasticity $\nu = yE(= E_{\mathrm{HAD}})$

$$\frac{\mathrm{d}^2\sigma^{\nu,\overline{\nu}}}{\mathrm{dxd}\nu} = \frac{\mathrm{G}^2\mathrm{M}}{\pi}\left[\left(1 - \frac{\nu}{\mathrm{E}} - \frac{\mathrm{Mx}\nu}{2\mathrm{E}^2} + \frac{\nu^2}{2\mathrm{E}^2}\,\frac{1+2\mathrm{Mx}/\nu}{1+\mathrm{R}}\right)\mathrm{F}_2(\mathrm{x}) \pm \frac{\nu}{\mathrm{E}}\left(1 - \frac{\nu}{2\mathrm{E}}\right)\mathrm{xF}_3(\mathrm{x})\right]$$

Integrate $d^2\sigma/dxd\nu$ over x

$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

$$\begin{cases} A = \dfrac{\mathrm{G}^2\mathrm{M}}{\pi}\displaystyle\int F_2(x,Q^2)dx \\ B = -\dfrac{\mathrm{G}^2\mathrm{M}}{\pi}\displaystyle\int \left[F_2(x,Q^2) \mp xF_3(x,Q^2)\right]dx \\ C = B - \dfrac{\mathrm{G}^2\mathrm{M}}{\pi}\displaystyle\int F_2(x,Q^2)\left(\dfrac{1+\frac{2Mx}{\nu}}{1+R(x,Q^2)} - \dfrac{Mx}{\nu} - 1\right)dx \end{cases}$$

Low-ν Flux (cont'd)

$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\,\frac{\nu}{E} - \frac{C}{A}\,\frac{\nu^2}{2E^2}\right)$$

- ▶ At low ν and high $E \Rightarrow (\frac{\nu}{E})$ and $(\frac{\nu}{E})^2$ terms are small.

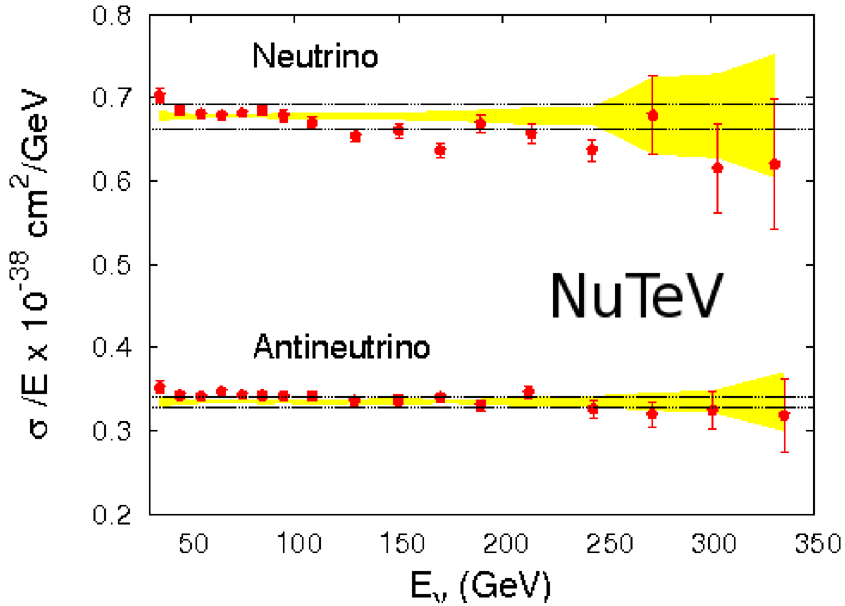
$\frac{d\sigma}{d\nu}^{\nu}_{\lim \nu\to 0} = \frac{d\sigma}{d\nu}^{\overline{\nu}}_{\lim \nu\to 0} = A$ *constant, independent of* E_ν.

$\boxed{\Phi(\mathrm{E}) \propto \mathrm{N}(\mathrm{E}, \nu < \nu_o)}$ (up to corrections of order $\frac{\nu_o}{E}$, $(\frac{\nu_o}{E})^2$)

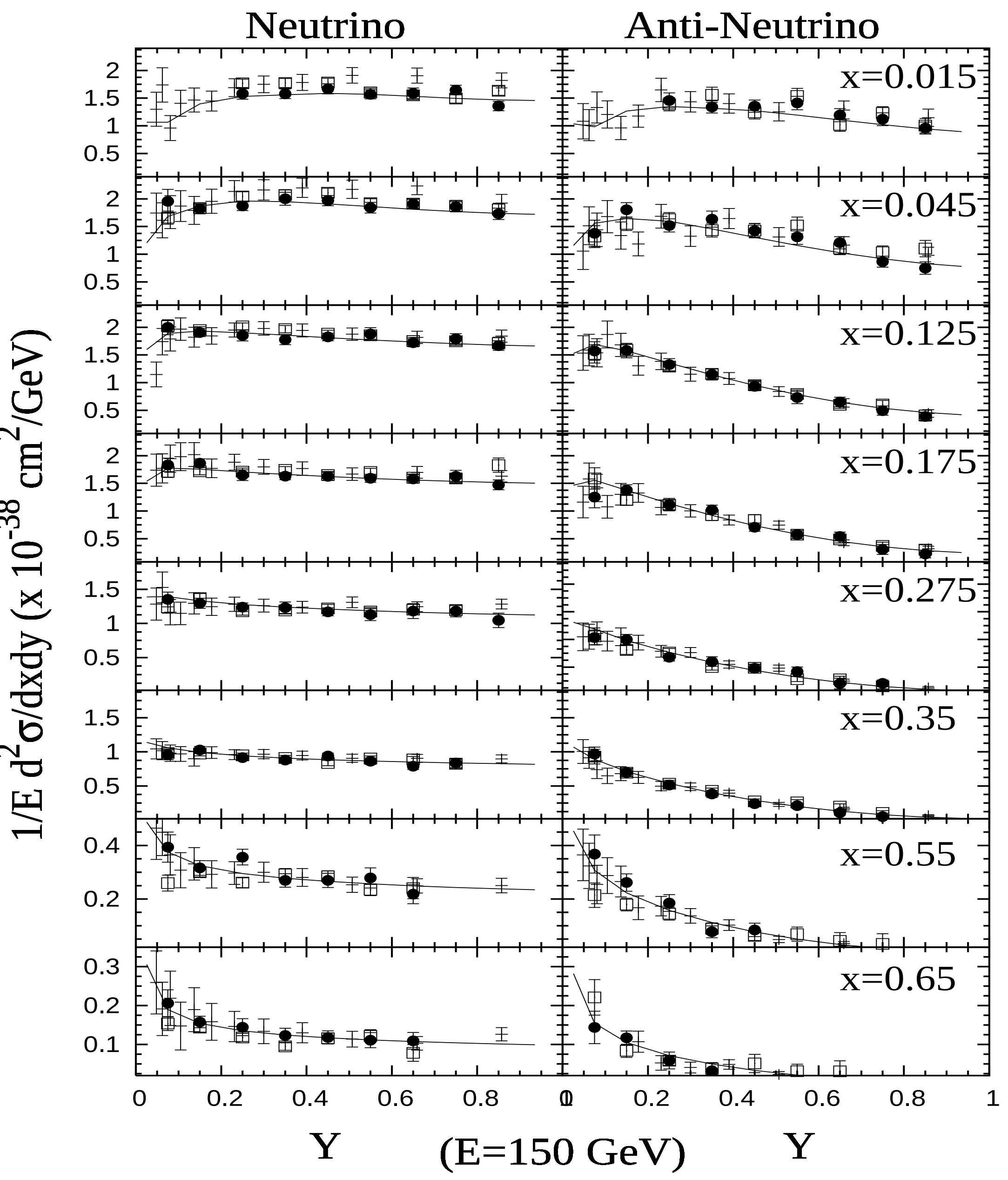
- ▶ Correct for small energy dependent terms (using $\frac{dN}{d\nu}$ data or model).
- ▶ Determines the flux shape with energy → must use external normalization.
  - ▷ World average (30-200 GeV): $\frac{\sigma^\nu}{\mathrm{E}} = 0.677 \pm 0.014 \times 10^{-38}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}}$

Test of flux → Measure σ_{TOT}

- ▶ $\frac{\sigma^\nu}{E_\nu}$ for DIS is flat as function of E_ν
- ▶ $\frac{\sigma^{\overline{\nu}}}{\sigma^\nu} \sim 0.5$ agrees with world average ($r = 0.499 \pm 0.007$).



Differential Cross Sections



- Measured $\nu(\overline{\nu}) - Fe$ differential cross sections at $\boxed{\mathrm{E}_\nu = 150\ \mathrm{GeV}}$

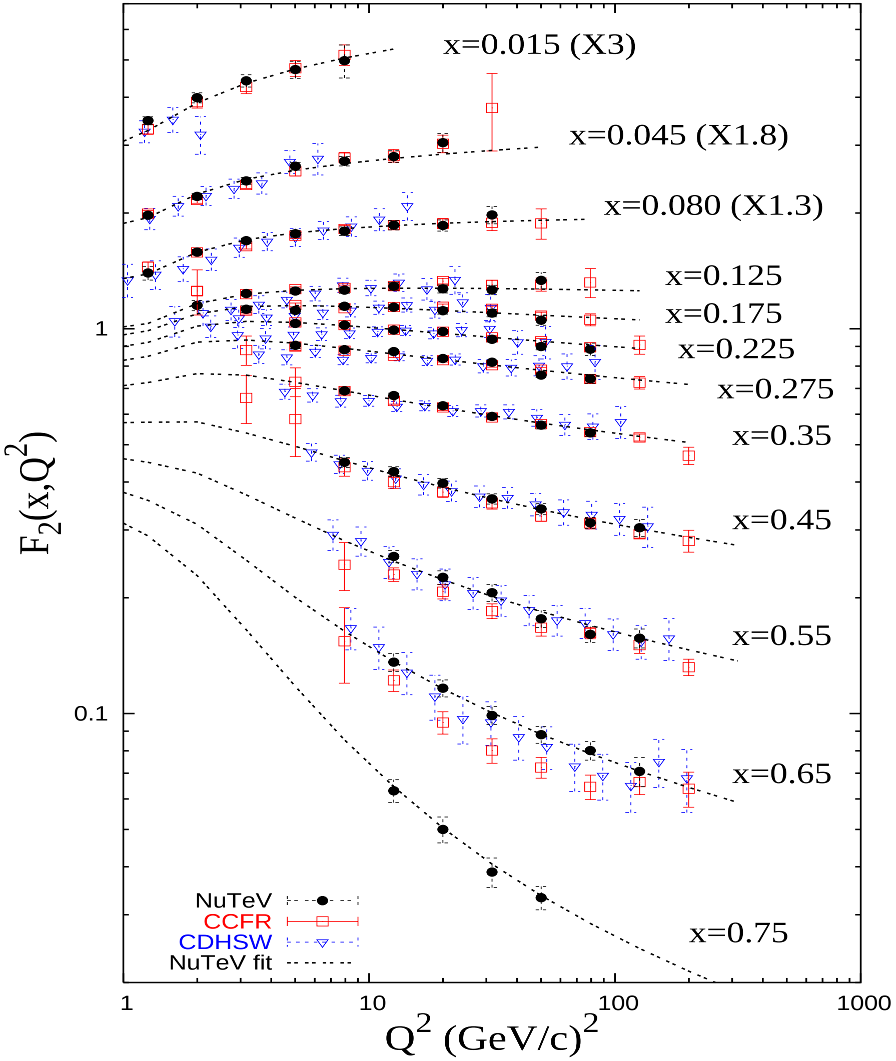
NuTeV ●
CCFR □
CDHSW +

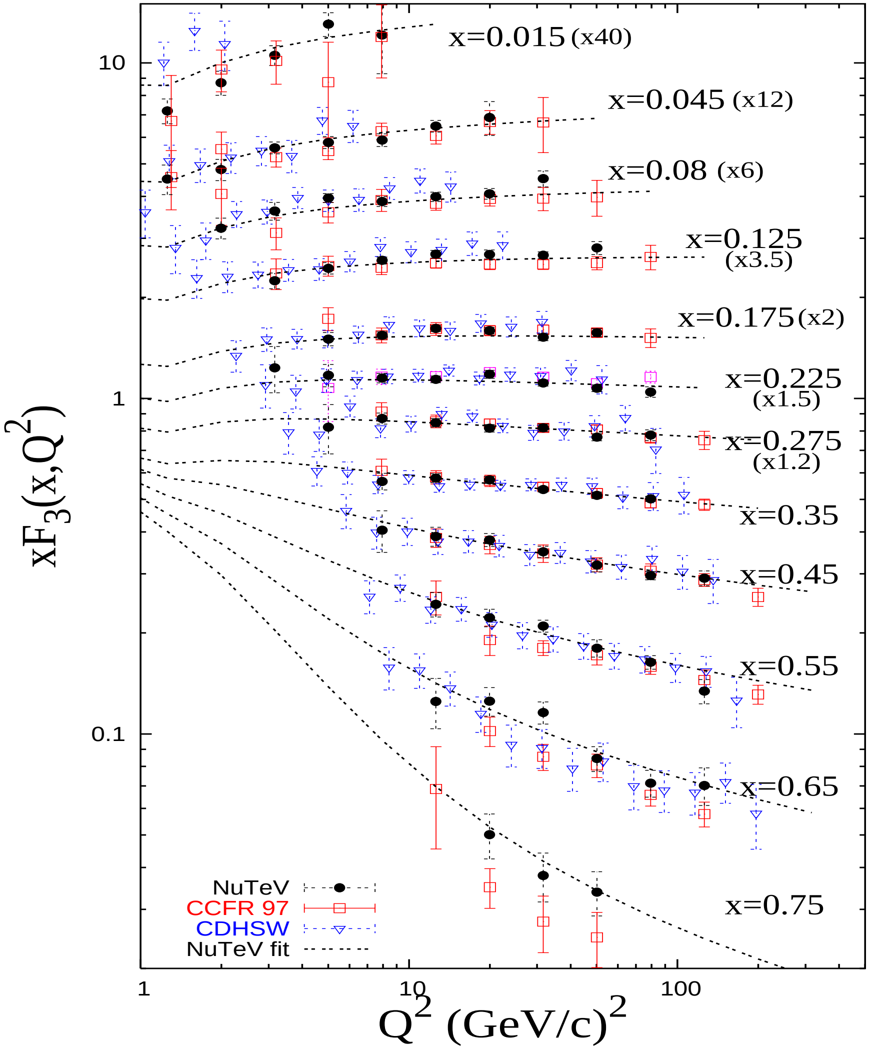
	E_μ scale	E_{had}	E_ν range
CDHSW	2%	2.5%	20-200 GeV
CCFR	1%	1%	30-400 GeV
NuTeV	0.7%	0.43%	30-350 GeV

Neutrino-Iron Structure Functions

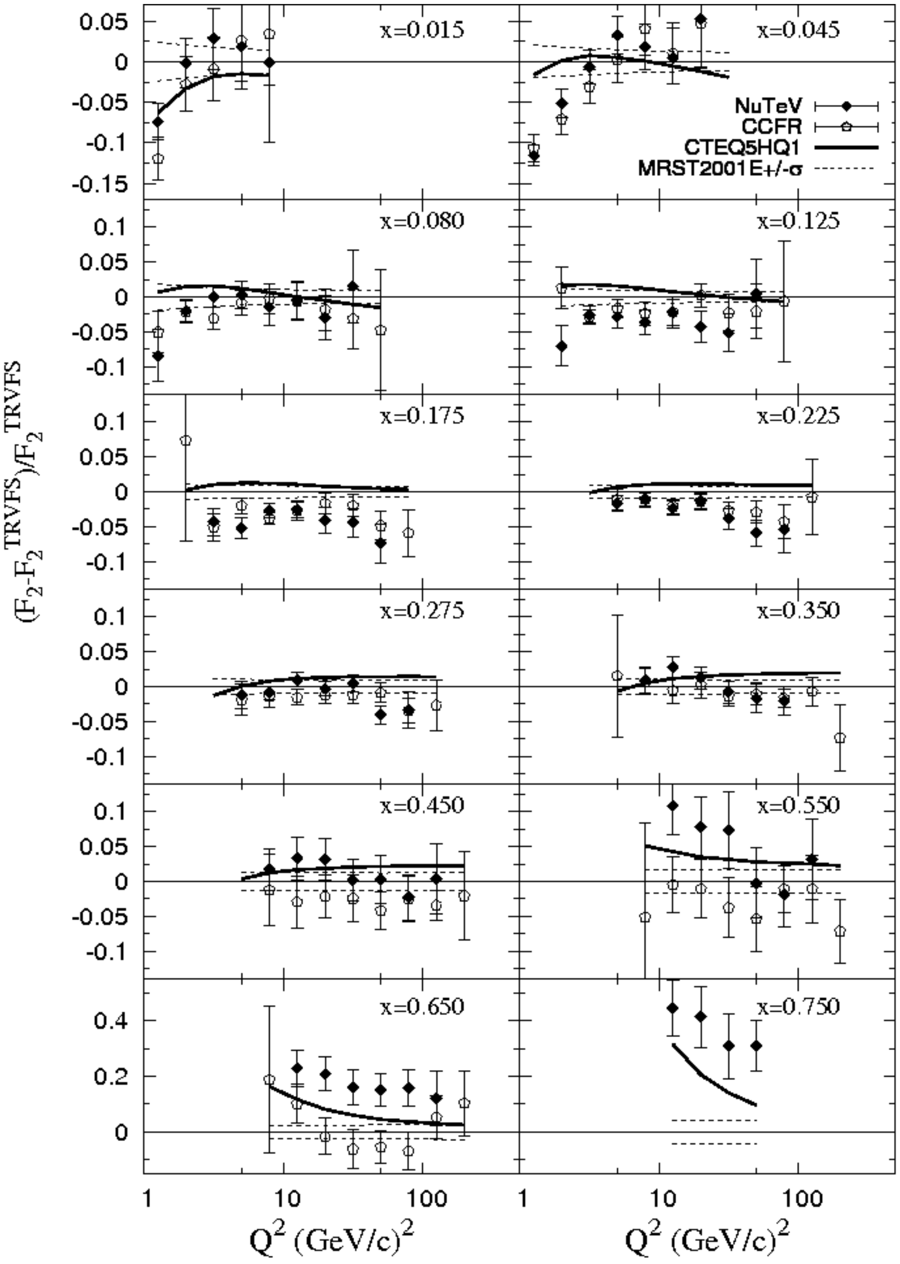
$$\left[\frac{d^2\sigma^\nu}{dxdy} + \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right] \frac{\pi}{2MG^2E_\nu} \approx \left(1-y+\left(\frac{1}{1+R_L}\right)\frac{y^2}{2}\right)F_2 + y\left(1-\frac{y}{2}\right)\Delta xF_3$$

$$\left[\frac{d^2\sigma^\nu}{dxdy} - \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right] \frac{\pi}{2MG^2E_\nu} = \left(y-\frac{y^2}{2}\right)x\overline{F}_3$$

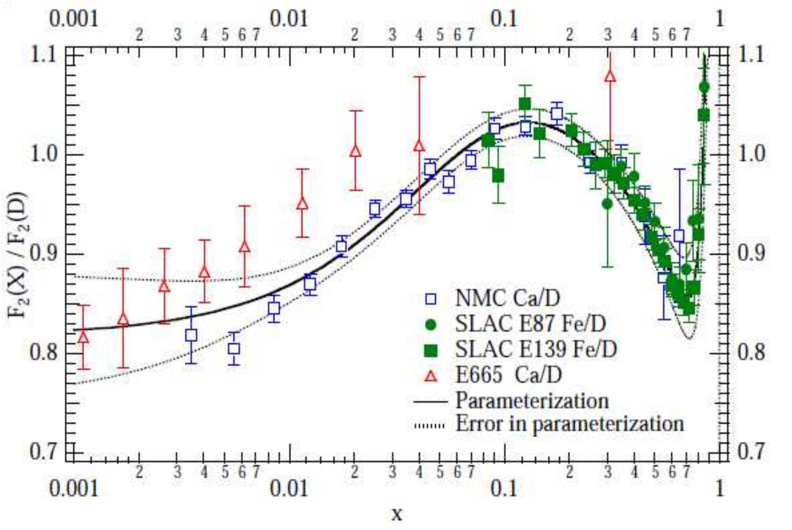




Massive Detectors ⇒ Nuclear Effects

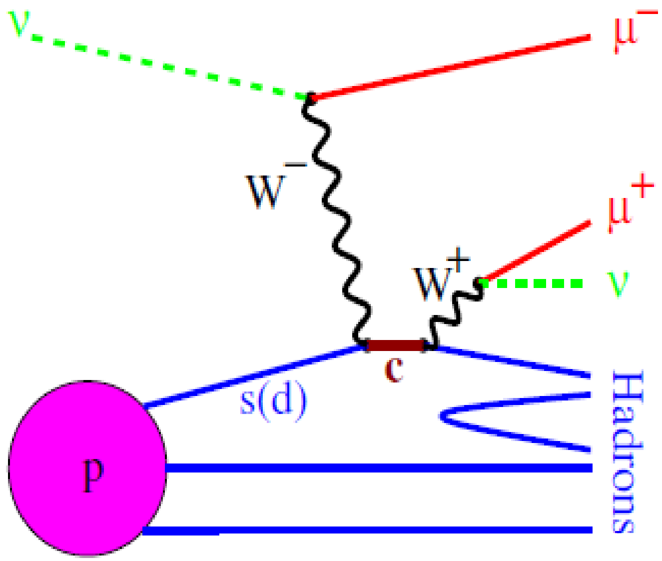


- ▶ Neutrinos are scattering off of nucleons embedded in a nuclear target.
- ▶ To compare with theory → Nuclear corrections must be applied *(from charge-lepton scattering)*.



- ▶ Nuclear effects could be different for neutrino probes.
- ▶ Need to systematically measure ν-A (MinerνA)

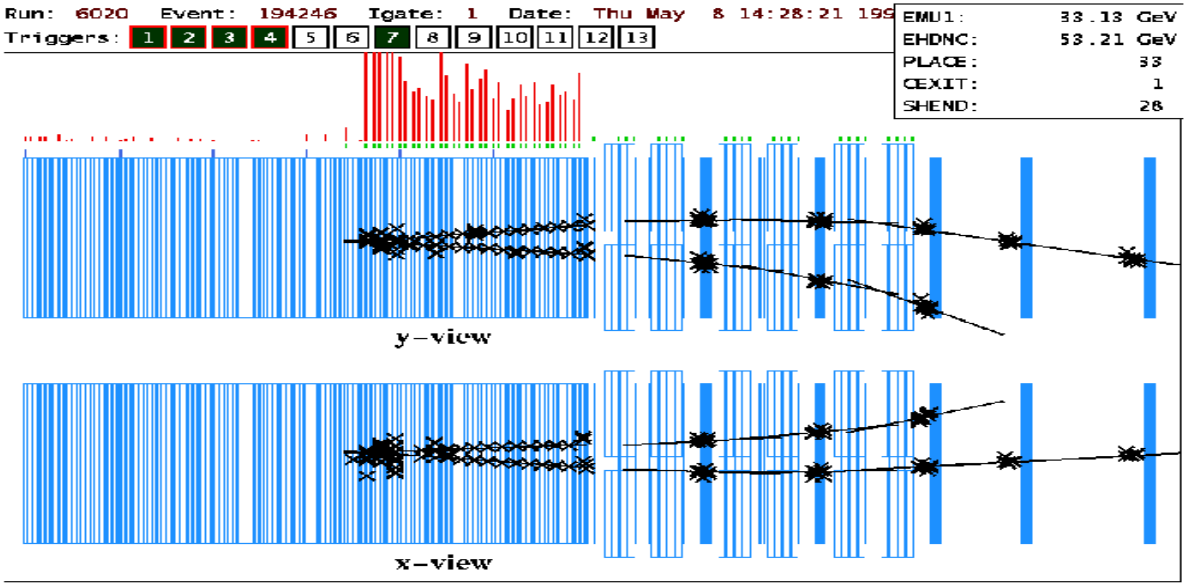
Probing the Strange Sea



- $\nu_\mu + d, s \rightarrow \mu^- + c + X$

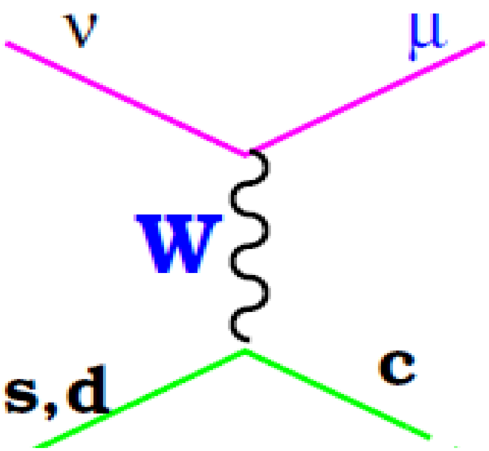
  $c \rightarrow \mu^+ + \nu_\mu + X$

  - Unique tag: opposite sign dimuons
- $s(\overline{s})$ are responsible for 50%(90%) of charm production in $\nu(\overline{\nu})$ mode.
  - Charm production from d quarks is Cabibbo suppressed $|V_{cd}|^2 \sim 0.05$



EMU1: 33.13 GeV
EHDNC: 53.21 GeV
PLACE: 33
CEXIT: 1
SHEND: 28

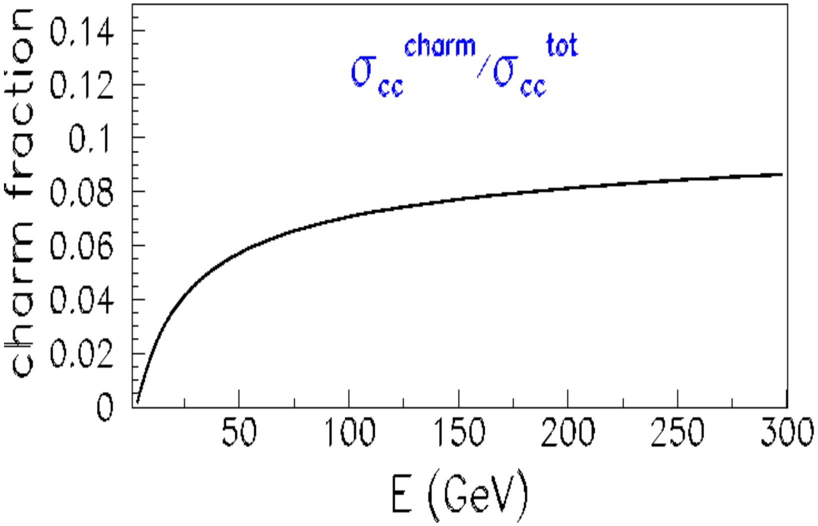
Heavy Quark Production



- LO slow-rescaling model to extract $s(x)$
  - rescaling variable depends on m_c

    $x = \frac{Q^2}{2M\nu} \longrightarrow \xi = \frac{Q^2+m_c^2}{2M\nu}$
- Kinematic suppresses of cross section due to heavy quark in final state $\left(1-\frac{m_c^2}{2ME_\nu\xi}\right)$

$$\frac{d^2\sigma(\nu_\mu N \to cX)}{d\xi\, dy} \propto \left(1-\frac{m_c^2}{2ME_\nu\xi}\right)\left[\frac{[u(\xi,Q^2)+d(\xi,Q^2)]}{2}\,|V_{cd}|^2 + \;(s(\xi,Q^2)\;|V_{cs}|^2\right]$$



- LO $s(x)$ ~40% of light quark sea.

$$s = \kappa\left(\frac{\bar{d}+\bar{u}}{2}\right)(1-x)^\alpha$$

NuTeV LO fit

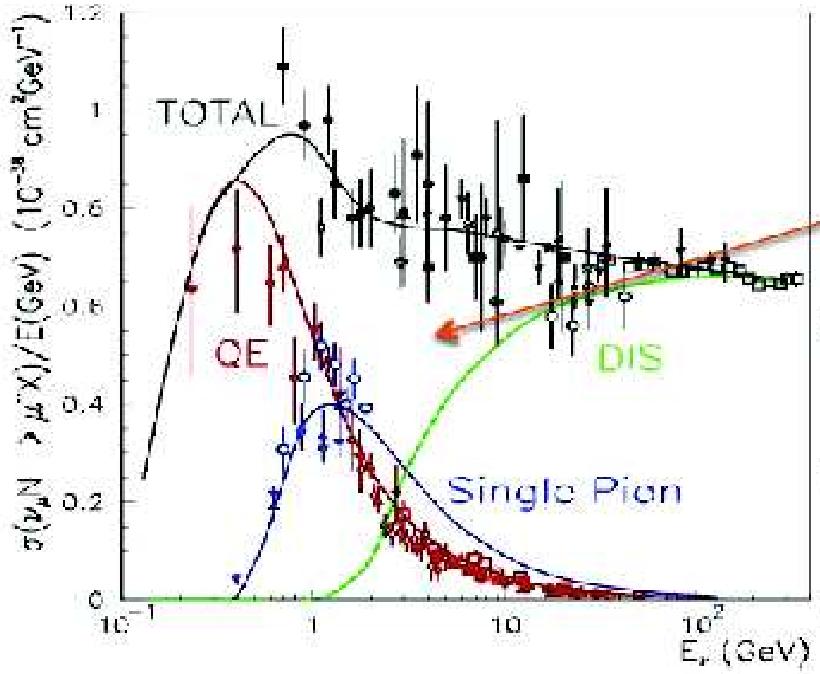
κ=0.38 ± 0.08

α= -2.07 ± 0.96

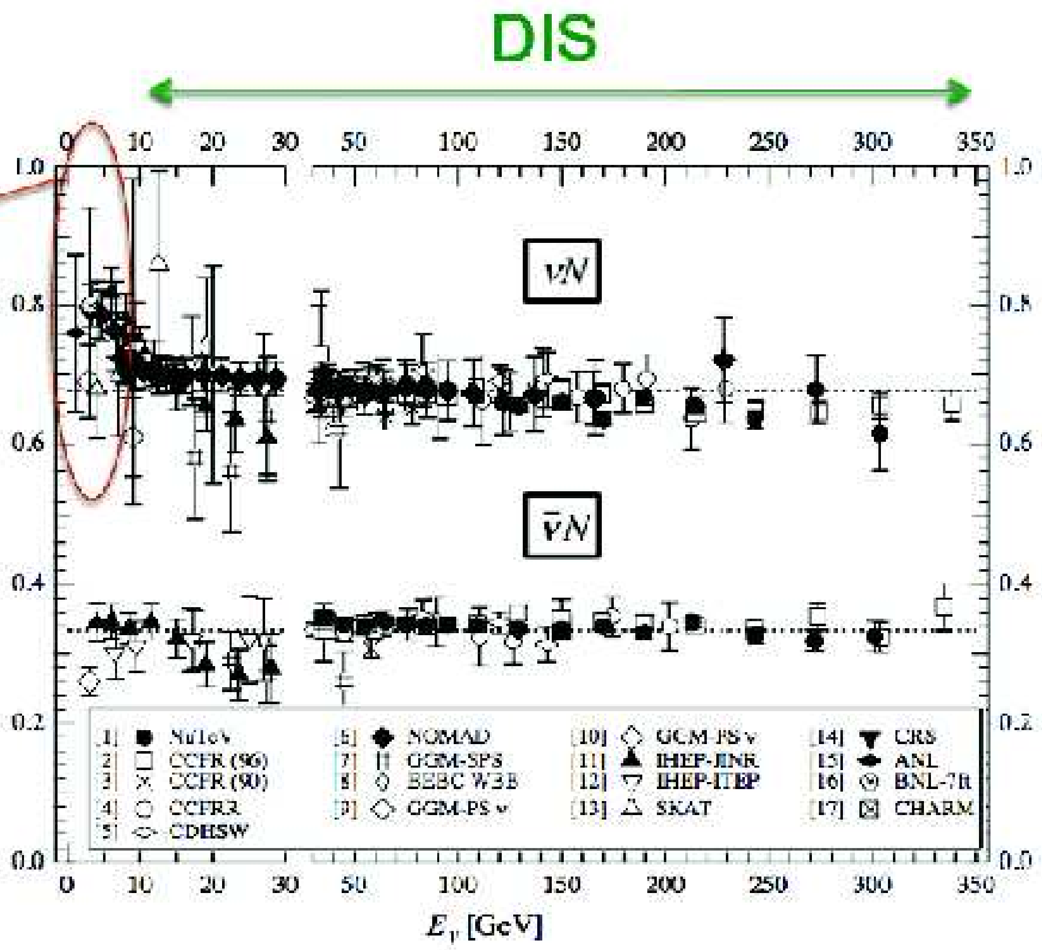
- Now experiments provide differential cross sections for NLO model fit.

Total ν-N CC Cross Section

- Dominated at high energies (> 10 GeV) by DIS $\boxed{\sigma_{TOT} \propto E_\nu}$.
- Low energy region ? $\rightarrow \frac{\sigma}{E}$ rises due to non-DIS contributions.

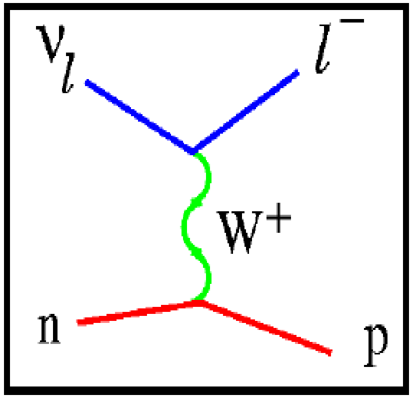


Low energies important for oscillation measurements



Neutrino Scattering Contributions

$$\boxed{\sigma_{\rm TOT} = \sigma_{\rm QE} + \sigma_{\rm RES} + \sigma_{\rm DIS}}$$

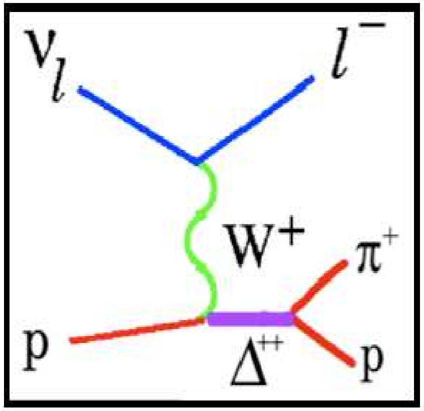


Quasi Elastic (QE)

$$\nu n \rightarrow \mu^- p$$

$$\overline{\nu} p \rightarrow \mu^+ n$$

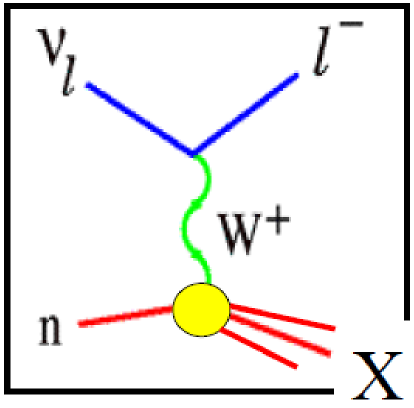
- ν scatters off an entire nucleon.



Resonance

$$\nu N \rightarrow \nu N^*$$

- Excited nucleon decays into low multiplicity final states.

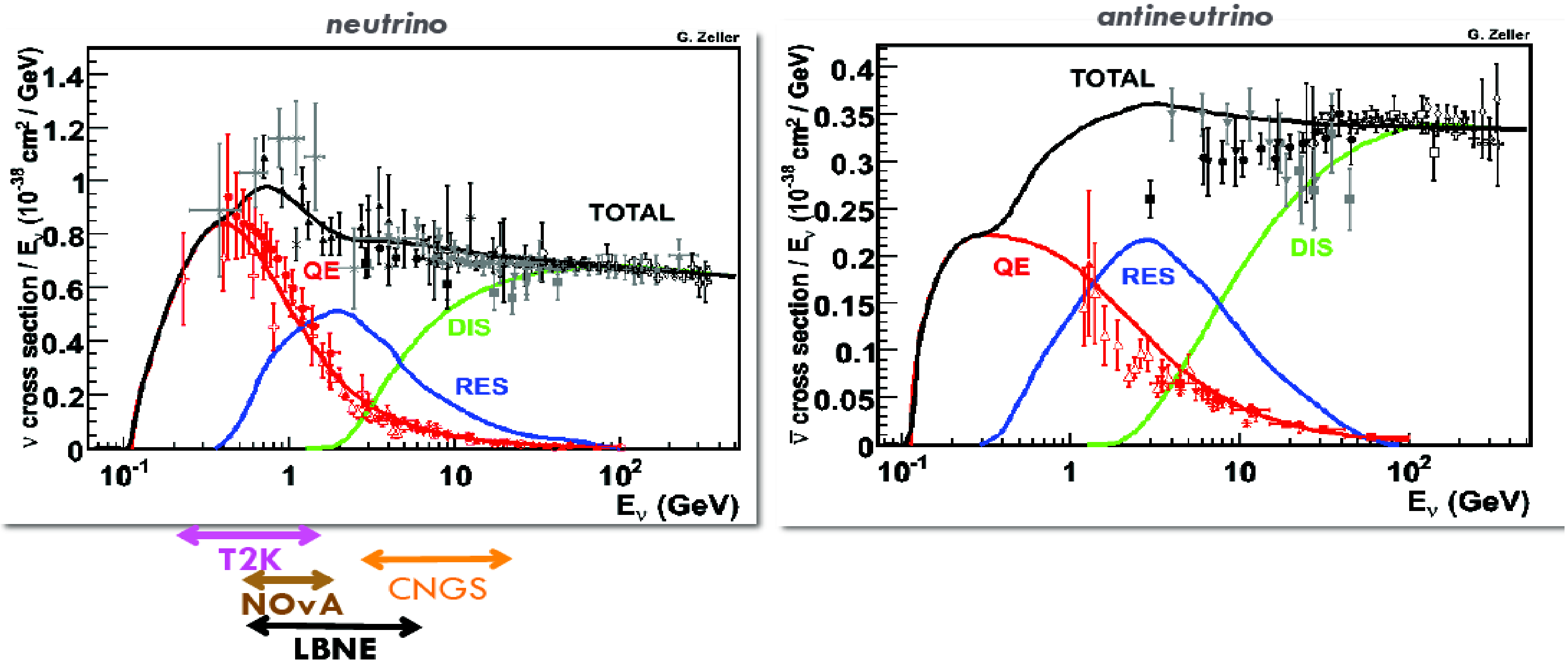


Deep Inelastic Scattering (DIS)

(W $>$ 2GeV, $Q^2 >$ 1GeV^2)

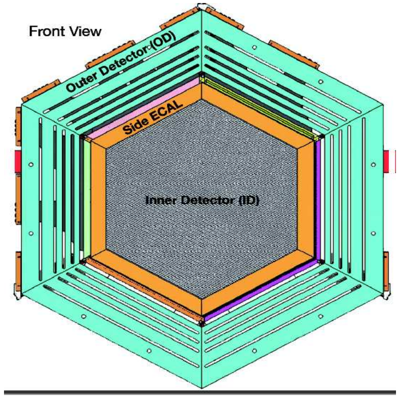
- scatters off nucleon constituents.

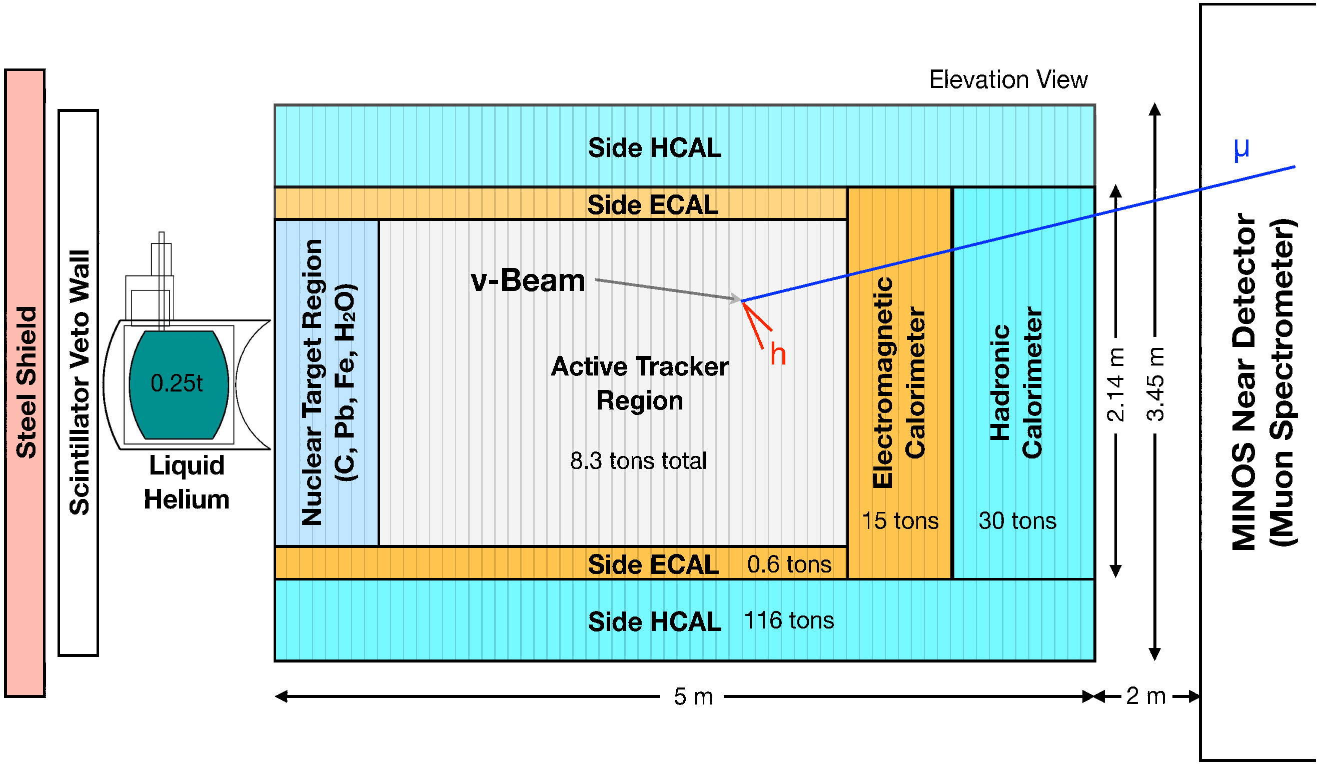
Current Status at Low-Energies



- Most data ($E < 10$ GeV) from 70's and 80's (Gargamelle, BEBC, ANL-12ft, BNL-7ft, etc.)
  - ▷ Bubble chambers *low statistics* → limited data, w/precision 10-20%
- Interest from oscillation measurements → $\boxed{\text{Revival}}$
  - ▷ New generation of experiments with *fine-grained* detectors and high statistics. (MinerνA, MiniBooNE/SciBoone, Argoneut/MicroBoone, ND280, etc.)

Example: MinerνA Experiment





- Fully-active scintillator-tracker in central region ⇒ much improved ability to identify exclusive final states.
- Shower containment (ECAL & HCAL), muon spectromenter (MINOS).
- Incorporates nuclear targets (helium, carbon, water, iron, lead).

Summary Part I

- Neutrinos have unique properties → interesting and important to study.
- Experiments need special techniques to produce and detect them → massive detectors, high-flux sources.
- They are useful as probes and have made unique contributions to understanding
  - Electroweak standard model
  - QCD and nucleon structure
- Understanding of low-energy scattering and nuclear environment is important for future oscillation measurements.