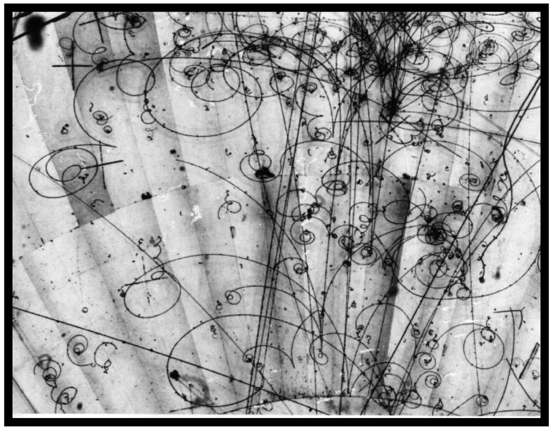
Neutrino Interaction Cross Sections

Sam Zeller
LANL

INSS

July 8, 2009



- for the most part, in the context of ν oscillation experiments
- which neutrino interaction cross sections do we need to know and how well do we know them (both theoretically & experimentally)?

Goals of This Talk

- describe the **important physical processes** necessary to understand ν interactions across a broad energy range

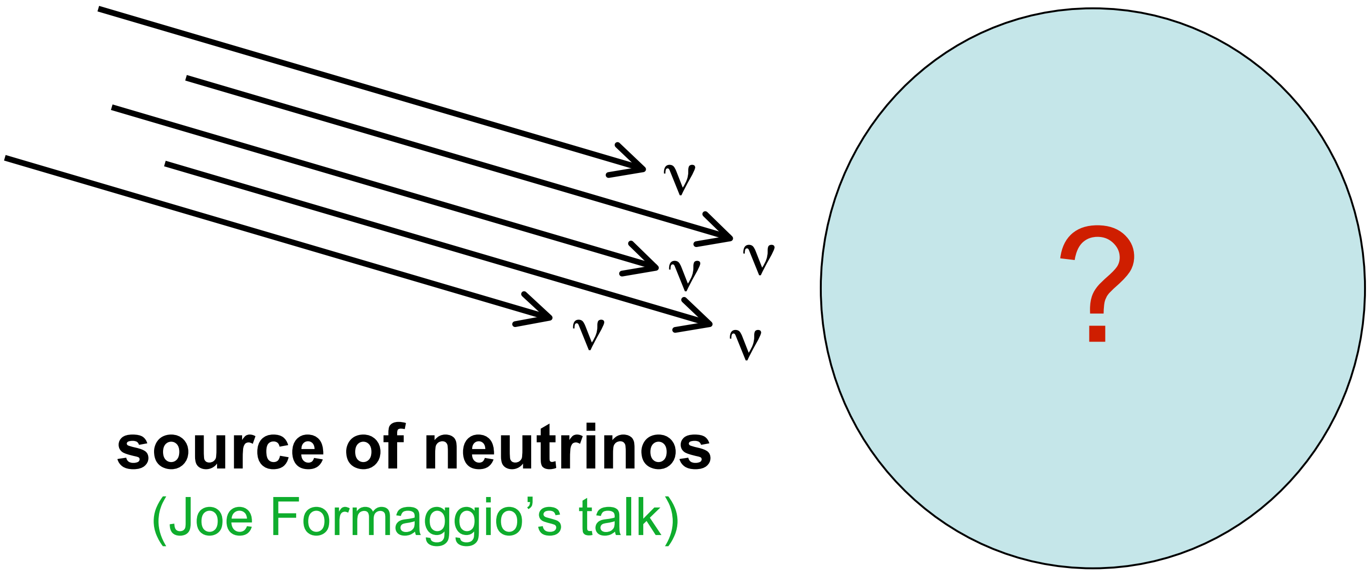
  - we will survey σ_ν's **from MeV to TeV**

- give a sense of **how well we know** the ν interaction cross sections at each of these energies

- highlight ways in which these cross sections have **importance** to recent and future ν experiments

Starting Point

- imagine you're building a ν experiment to measure ν oscillations or look for some other exciting ν physics …



source of neutrinos

(Joe Formaggio's talk)

reactor, particle accelerator,
sun, atmosphere,
supernova, galactic, extra-galactic

neutrino detector

(Mark Messier's talk)

- how many ν interactions should I expect to see?
- and what will they look like?

Number of ν Events

- neutrino interaction cross section plays a critical role in determining number of ν interactions expect to collect

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)
depends on your ν source

at 1 GeV $\sigma(\nu N) \sim 10^{-38}$ cm^2,
compare to $\sigma(pp) \sim 10^{-26}$ cm^2

ν cross section

tiny ($\sim 10^{-38}$ cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

Number of ν Events

- neutrino interaction cross section plays a critical role in determining number of ν interactions expect to collect

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

make this large!

detector

(# targets)

make this large!

ν cross section

tiny (~10^{-38} cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

go to higher energies

Number of ν Events

- neutrino interaction cross section plays a critical role in determining number of ν interactions expect to collect

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

make this large!

detector

(# targets)

make this large!

ν cross section

tiny ($\sim 10^{-38}$ cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

go to higher energies

this talk

Measuring σ_ν

- BTW, if you turn this around, can readily see how you would measure σ_ν from observed event yield in detector:

count events

$$\sigma_\nu(E) \sim \frac{N_\nu(E)}{\Phi_\nu(E) \times \text{target}}$$

- absolute σ_ν is a delicate measurement as it implies precise knowledge of normalization of incoming ν flux

- this is usually the dominant uncertainty in σ_ν measurements

Importance of σ_ν

- ν interaction cross section important for telling you:

(1) how many ν events you should expect → N_ν

(2) also, **what** you should observe in your detector → final state

(can't observe ν's directly, only detect products of their interactions)

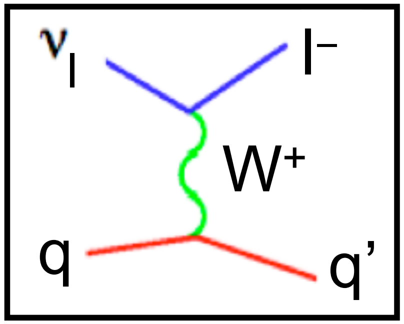
will depend on:

- type of ν interaction (NC or CC)
- ν target (nucleus, nucleon, electron)
- ν energy (MeV, GeV, or TeV)

} next in this talk

Los Alamos

Two Types of Interactions



Charged Current (CC)

- neutrino in
- charged lepton out

this is how we detected neutrinos in the first place

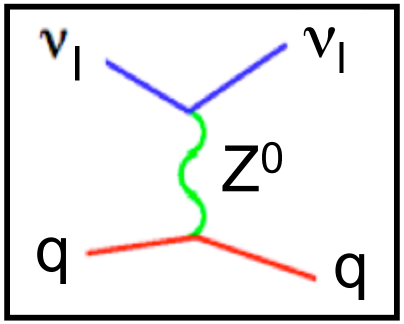
$\nu_e \rightarrow e^-$ $\quad \overline{\nu_e} \rightarrow e^+$

$\nu_\mu \rightarrow \mu^-$ $\quad \overline{\nu_\mu} \rightarrow \mu^+$

$\nu_\tau \rightarrow \tau^-$ $\quad \overline{\nu_\tau} \rightarrow \tau^+$

- flavor of outgoing lepton “tags” flavor of incoming neutrino

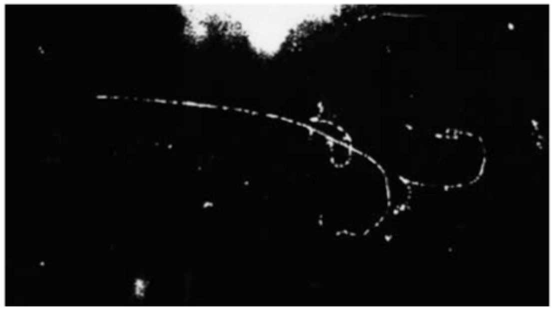
- charge of outgoing lepton determines whether ν or anti-ν



Neutral Current (NC)

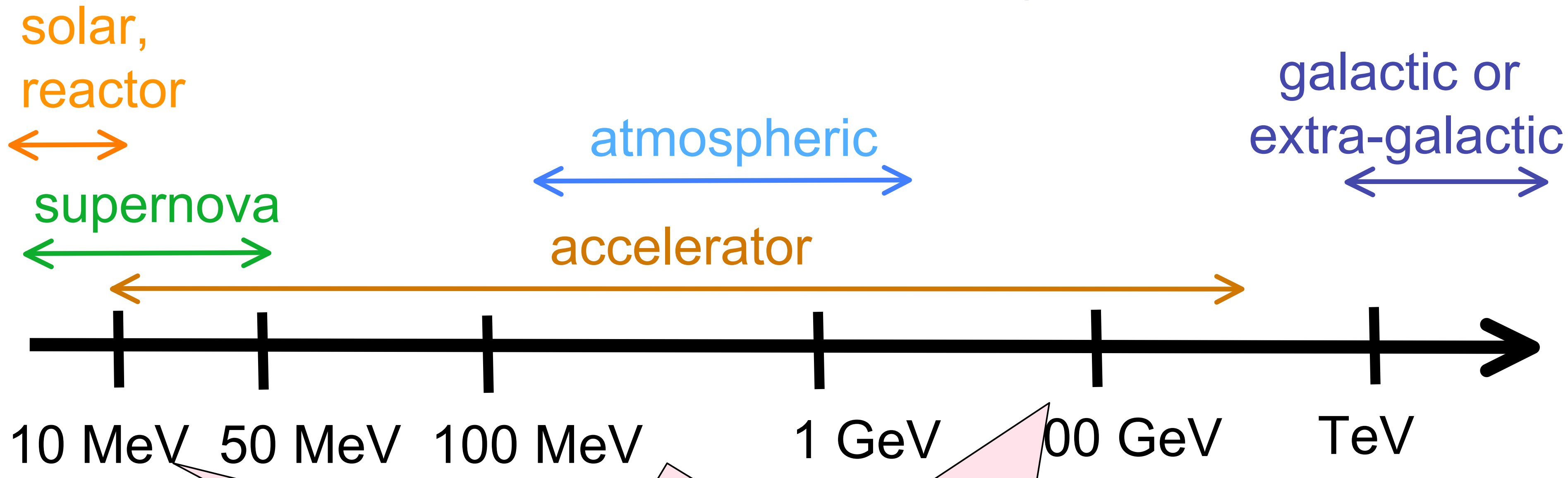
- neutrino in
- neutrino out

1st observed in 1972



$\nu_\mu \, e^- \longrightarrow \nu_\mu \, e^-$

Neutrino Energies



solar,
reactor

supernova

atmospheric

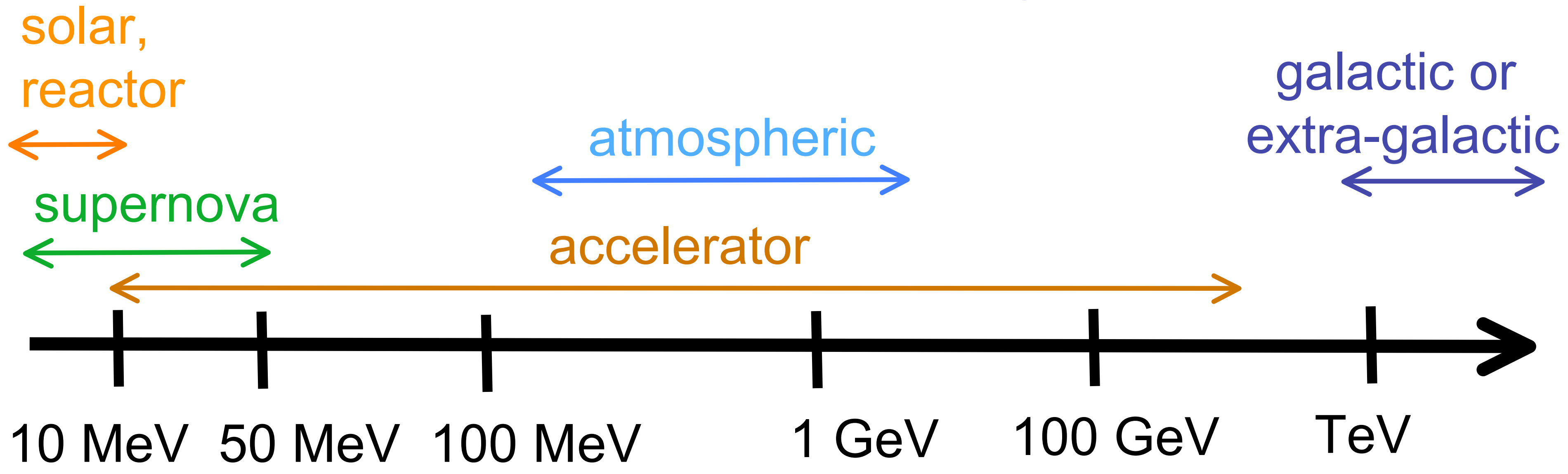
accelerator

galactic or
extra-galactic

10 MeV 50 MeV 100 MeV 1 GeV 00 GeV TeV

need to predict ν cross sections
over a broad energy range

Neutrino Energies



solar,
reactor

supernova

atmospheric

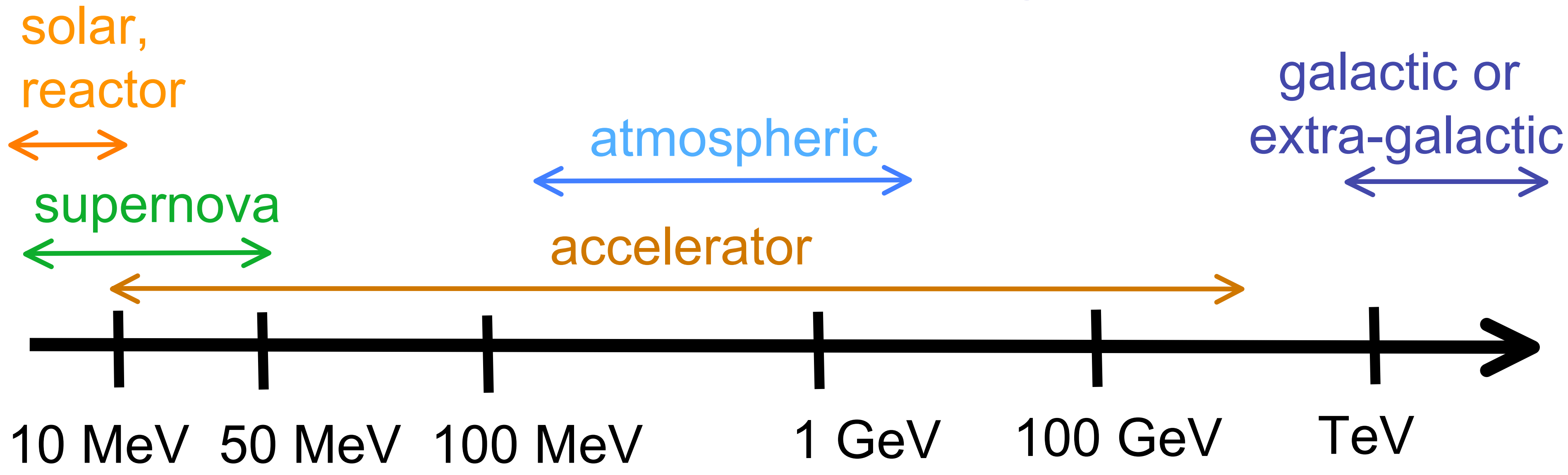
accelerator

galactic or
extra-galactic

10 MeV 50 MeV 100 MeV 1 GeV 100 GeV TeV

- ideally one would like to have a relatively simple, universal recipe valid for all energies & ν targets; but this does not exist

Neutrino Energies



- **target description** is different depending on the ν energy

ν-nucleon ……→ **ν-quark**

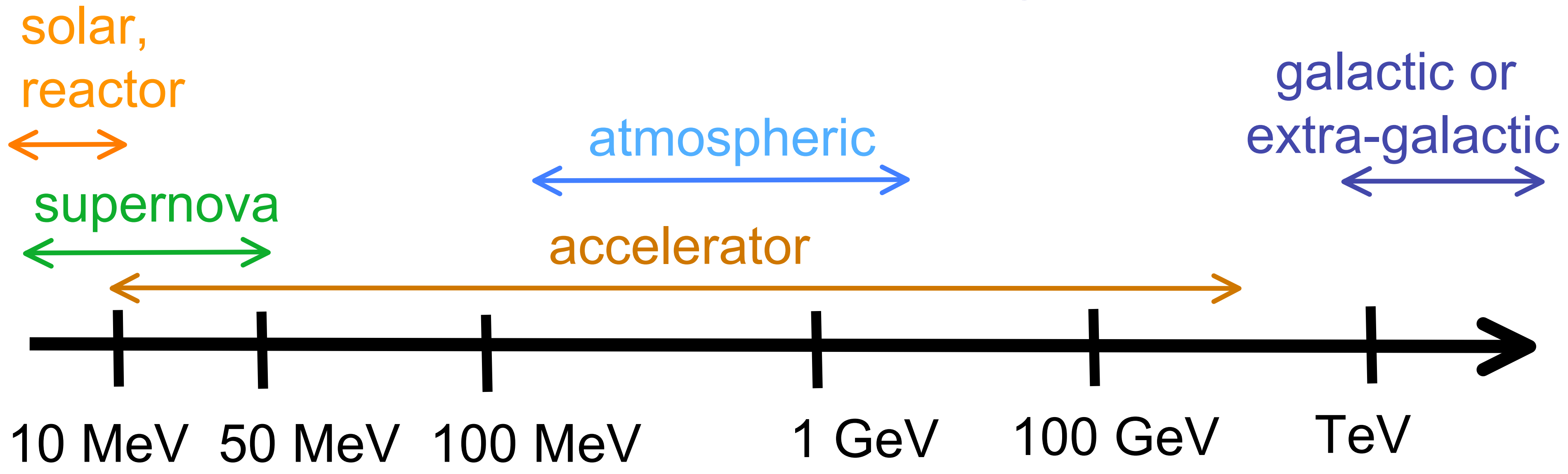
elastic scattering
(nucleon form factors)

can also create
resonances
(another type of inelastic interaction)

inelastic scattering
(parton density functions)

Los Alamos

Neutrino Energies



solar,
reactor

supernova

atmospheric

accelerator

galactic or
extra-galactic

10 MeV

50 MeV

100 MeV

1 GeV

100 GeV

TeV

- **target description** is different depending on the ν energy

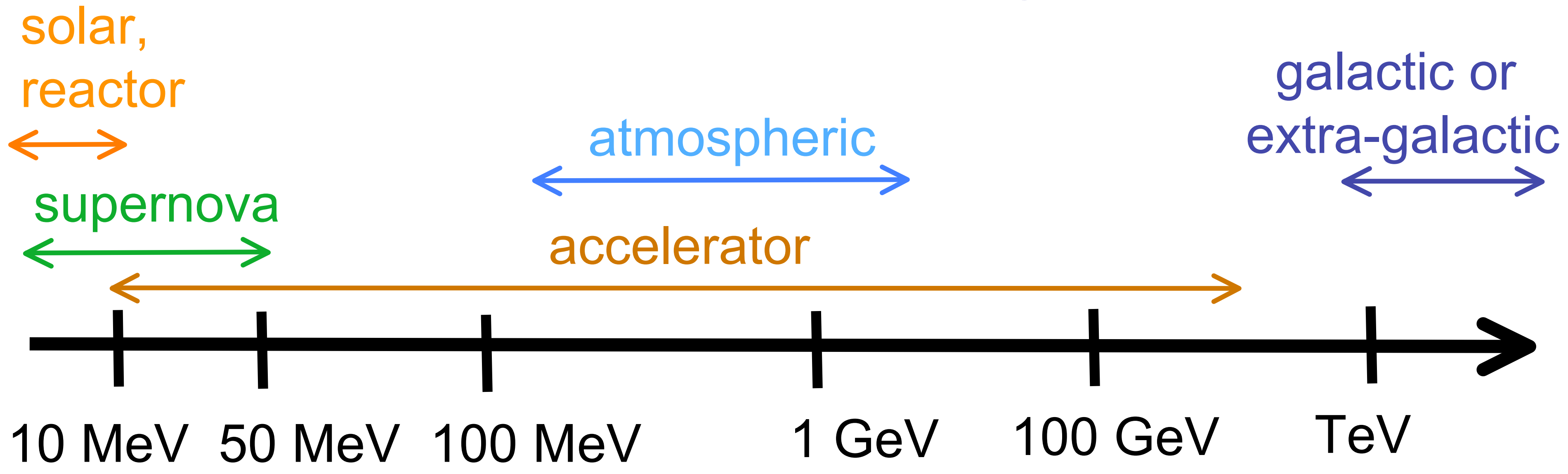
ν-nucleon → **ν-quark**

elastic scattering → inelastic scattering

(nucleon form factors) → (parton density functions)

- there is no clear cut division & both types of reactions can occur in the middle region

Neutrino Energies



solar,
reactor

supernova

atmospheric

accelerator

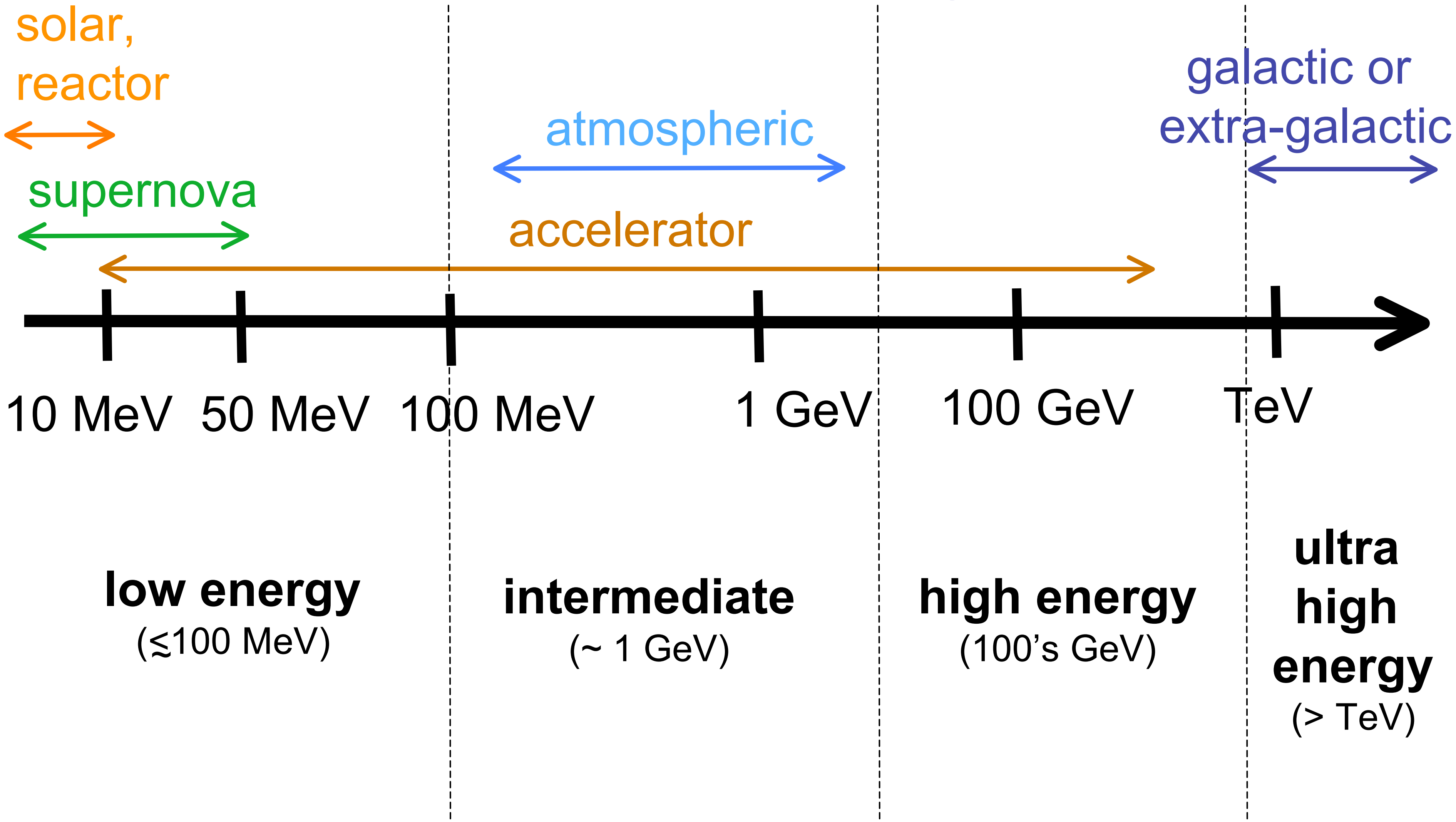
galactic or
extra-galactic

10 MeV 50 MeV 100 MeV 1 GeV 100 GeV TeV

- also, treatment of **nuclear effects** is energy dependent …

shell model,
RPA, EFT ⇢ impulse
approximation
(Fermi Gas, spectral functions, etc.) ⇢ quark parton
model

Neutrino Energies



solar,
reactor

supernova

atmospheric

accelerator

galactic or
extra-galactic

10 MeV 50 MeV 100 MeV 1 GeV 100 GeV TeV

low energy
(≲100 MeV)

intermediate
(~ 1 GeV)

high energy
(100’s GeV)

ultra high energy
(> TeV)

Structure of Rest of Talk

(1) **low energy**
($\lesssim$ 100 MeV)

(2) **intermediate energy**
(~ 1 GeV)

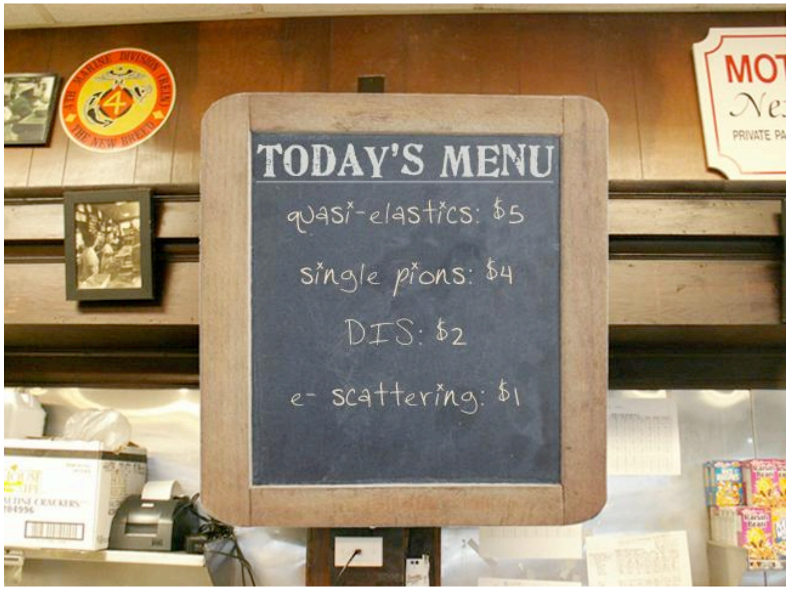
(3) **high energy**
(100's GeV)

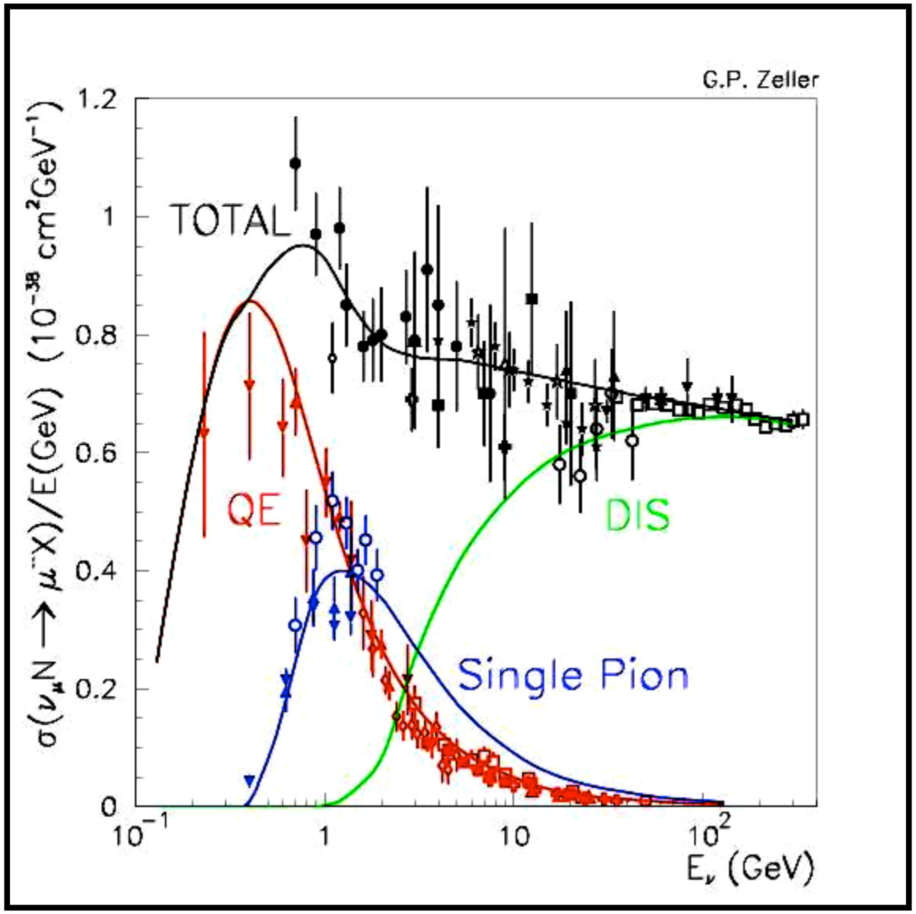
(4) **ultra high energy**
(> 1 TeV)

- which ν process dominates?
- how well is σ_ν known?
  (has it been measured experimentally?)
- why is it important to neutrino experiments?

Neutrino Cross Sections

- this will be our template





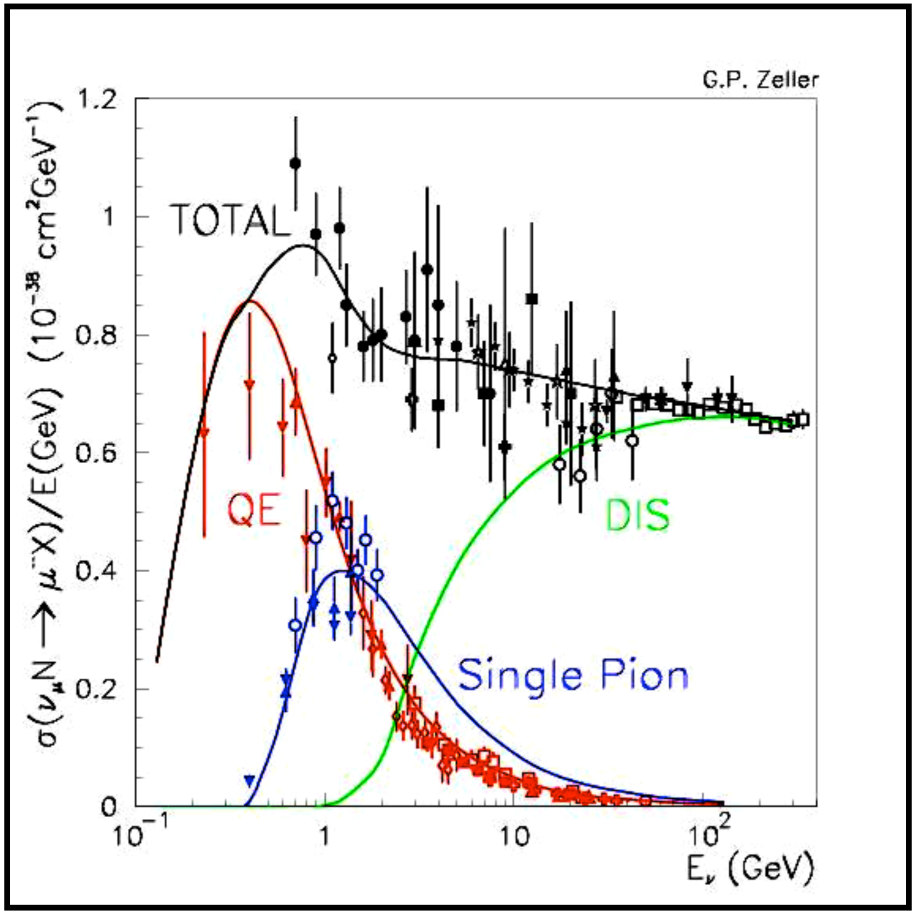
Neutrino Cross Sections

- quasi-elastic scattering
  $\nu_\mu\ n \rightarrow \mu\ p$

- single π production
  $\nu_\mu\ N \rightarrow \mu\ N'\ \pi$

- deep inelastic scattering (DIS)
  $\nu_\mu\ N \rightarrow \mu\ X$

- elastic ν-electron scattering
  $\nu_\mu\ e^- \rightarrow \nu_\mu\ e^-$ (not shown)



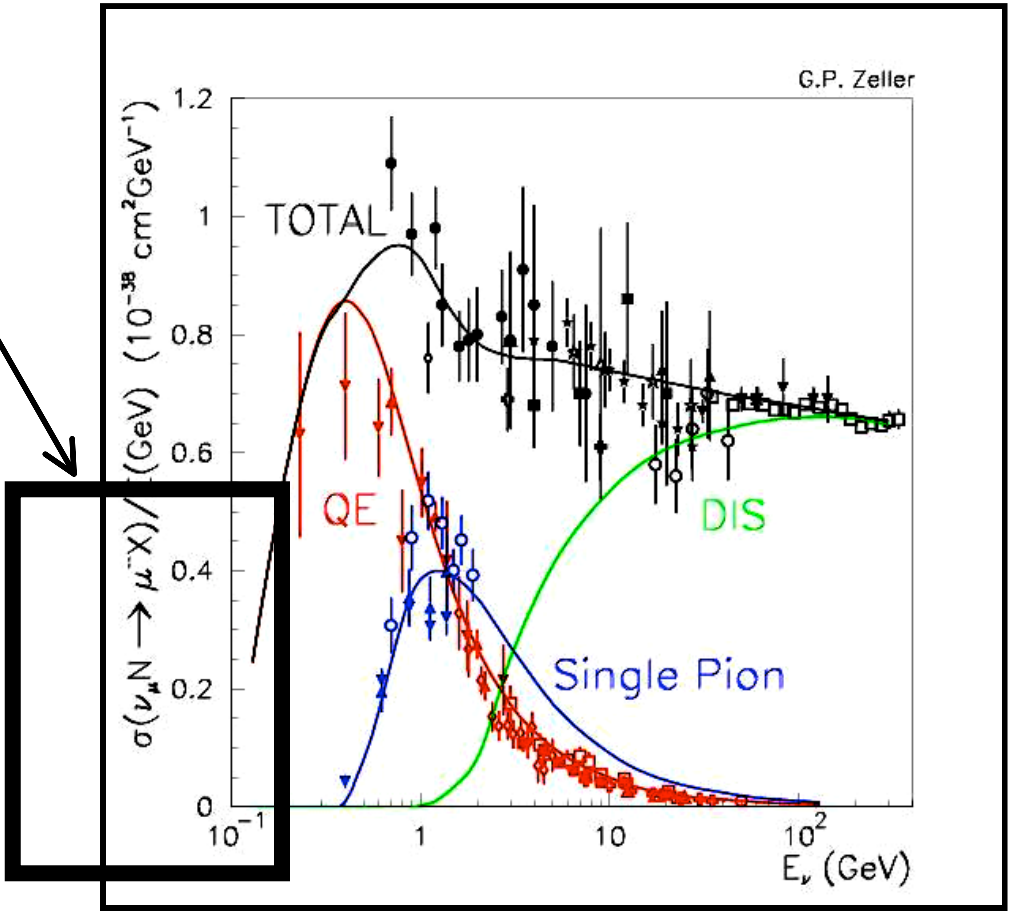
- we'll talk about each of these in the region in which they are relevant

Low Energy

- zoom in on left hand side
  $E_\nu \lesssim 100$ MeV

- where σ is rising rapidly
- dominated by QE

- solar, reactor, and
  supernova ν's are
  all in this energy range

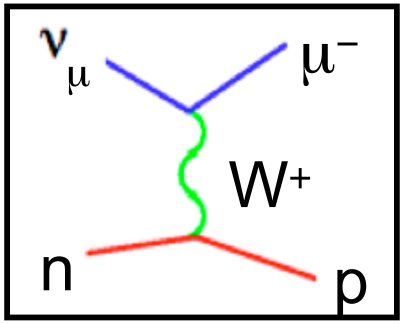


solar, reactor (< 10 MeV)

supernova ($\lesssim$ 50 MeV)

(off the plot)

Quasi-Elastic Scattering



- **simple 2-body interaction**

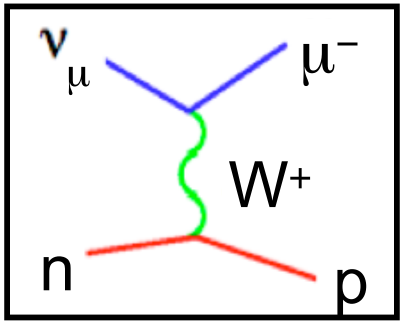
$$\nu_\mu\, n \rightarrow \mu^-\, p \qquad \bar{\nu}_\mu\, p \rightarrow \mu^+\, n$$

$$\nu_e\, n \rightarrow e^-\, p \qquad \bar{\nu}_e\, p \rightarrow e^+\, n$$

elastic
(nucleon
stays
Intact)

in CC case, called "quasi-elastic" … target changes but does not break up

Quasi-Elastic Scattering



- **simple 2-body interaction**

$\nu_\mu \, n \rightarrow \mu^- \, p$	$\overline{\nu}_\mu \, p \rightarrow \mu^+ \, n$
$\nu_e \, n \rightarrow e^- \, p$	$\overline{\nu}_e \, p \rightarrow e^+ \, n$

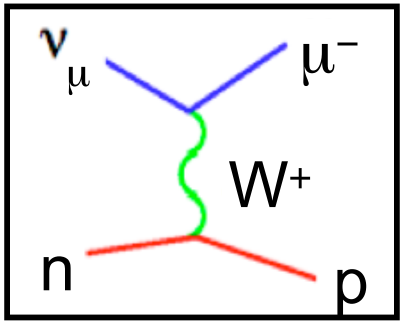
elastic
(nucleon
stays
Intact)

- appealing signal channel for ν oscillation exps because:
  - charged lepton tags flavor of ν ($\mu \Rightarrow \nu_\mu$, $e \Rightarrow \nu_e$)
  - can reconstruct E_ν from outgoing lepton kinematics
  - straightforward to calculate (especially if ν scattering off free nucleons)

let's talk about simplest case where scattering off free nucleon …

low E
(< 100 MeV)

At Low Energy



- **simple 2-body interaction**

$\xcancel{\nu_\mu\, n \rightarrow \mu^-\, p}$ $\xcancel{\bar{\nu}_\mu\, p \rightarrow \mu^+\, n}$ ← threshold > 100 MeV

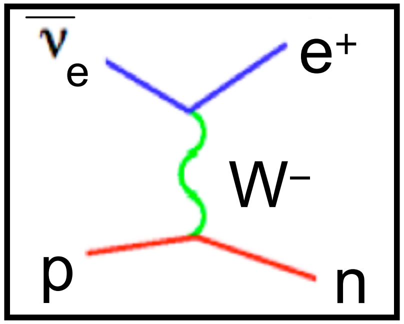
$\xcancel{\nu_e\, n \rightarrow e^-\, p}$ $\bar{\nu}_e\, p \rightarrow e^+\, n$

no free neutrons

(but can scatter off neutrons bound in nuclei
… we'll talk about this later)

low E
(< 100 MeV)

At Low Energy



- **simple 2-body interaction**

$\cancel{\nu_\mu\, n \to \mu^-\, p}$ $\cancel{\bar{\nu}_\mu\, p \to \mu^+\, n}$ ← threshold > 100 MeV

$\cancel{\nu_e\, n \to e^-\, p}$ $\boxed{\bar{\nu}_e\, p \to e^+\, n}$ — old workhorse of ν physics (IBD)

Reines-Cowan discovery signal

no free neutrons

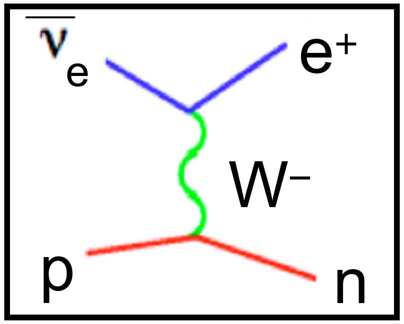
called “inverse beta decay”

remember this is historically the 1^{st} reaction we observed with ν’s

it is still important today!

low E
(< 100 MeV)

At Low Energy



- **simple 2-body interaction**

$\xcancel{\nu_\mu n \to \mu^- p}$ $\xcancel{\bar{\nu}_\mu p \to \mu^+ n}$ ← threshold > 100 MeV

$\xcancel{\nu_e n \to e^- p}$ $\bar{\nu}_e p \to e^+ n$ — old workhorse of ν physics (IBD)

Reines-Cowan discovery signal

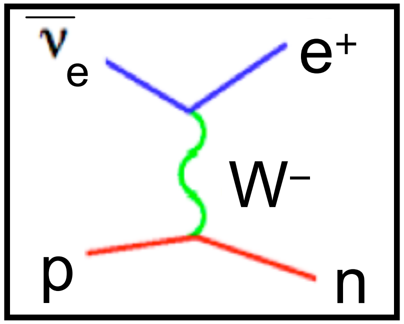
no free neutrons

- **reaction of choice for detection of reactor & SN ν's**

IMB & Kamiokande both observed
SN ν's with this reaction channel

low E
(< 100 MeV)

At Low Energy



- **simple 2-body interaction**

$\cancel{\nu_\mu\, n \to \mu^-\, p}$	$\cancel{\bar{\nu}_\mu\, p \to \mu^+\, n}$
$\cancel{\nu_e\, n \to e^-\, p}$	$\bar{\nu}_e\, p \to e^+\, n$

threshold
> 100 MeV

old workhorse
of ν physics
(IBD)
Reines-Cowan
discovery signal

no free neutrons

- **reaction of choice for detection of reactor & SN ν's**
  - dominant σ at these energies
  - low threshold ~ $(m_n - m_p) + m_e = 1.8$ MeV
  - e^+ energy strongly correlated with $\bar{\nu}_e$ energy ($E_\nu \sim T_e + 1.8$ MeV)
  - materials rich in free protons are cheap (water, hydrocarbon) so can build large detectors; plus in scintillator can tag neutron
  - σ can be accurately calculated (1st estimates done in 1934)

Quasi-Elastic Scattering

- today, general formula for QE scattering on free nucleons that is routinely used: C.H. Llewellyn Smith, Phys. Rep. **3C**, 261 (1972)

$$\mathrm{d}\sigma = \frac{G_F^2 \cos^2 \vartheta_c}{2} \, 2\pi \, L^{\mu\nu} \, W_{\mu\nu} \, \frac{\mathrm{d}^3 k}{(2\pi)^3}$$

you should recognize some familiar quantities

Fermi constant

$G_F = 1.16639 \times 10^{-11}$ MeV^{-2}

(responsible for small σ)

Cabibbo angle

$\cos\theta_c \sim 0.97$

Quasi-Elastic Scattering

- today, general formula for QE scattering on free nucleons that is routinely used: C.H. Llewellyn Smith, Phys. Rep. **3C**, 261 (1972)

$$d\sigma = \frac{G_F^2 \cos^2 \vartheta_c}{2}\, 2\pi\, L^{\mu\nu}\, W_{\mu\nu}\, \frac{d^3 k}{(2\pi)^3}$$

leptonic tensor

$$L^{\mu\nu} = \frac{1}{2\varepsilon_i \varepsilon} \mathrm{Tr}\left[\gamma \cdot k\, \gamma^\mu\, (1 \mp \gamma^5)\, \gamma \cdot k_i\, \gamma^\nu\right]$$

easy to calculate, well-known

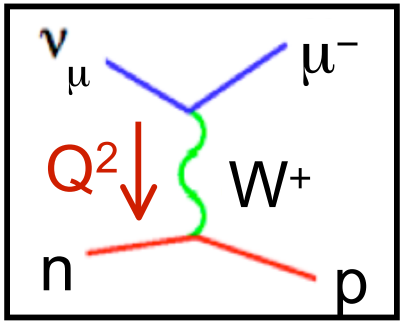
Quasi-Elastic Scattering

- today, general formula for QE scattering on free nucleons that is routinely used: C.H. Llewellyn Smith, Phys. Rep. **3C**, 261 (1972)

$$d\sigma = \frac{G_F^2 \cos^2 \vartheta_c}{2} \, 2\pi \, L^{\mu\nu} \, W_{\mu\nu} \, \frac{d^3 k}{(2\pi)^3}$$

hadronic tensor

$$W^{\mu\nu}(\omega, q) = \sum_f \langle \Psi_f \,|\, J^\mu(\boldsymbol{q}) \,|\, \Psi_0 \rangle \times \langle \Psi_0 \,|\, J^{\nu\dagger}(\boldsymbol{q}) \,|\, \Psi_f \rangle \, \delta(E_0 + \omega - E_f)$$



form factors contains all of the information on the target

$$j^\mu = [F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M} F_2^V(Q^2)\sigma^{\mu\nu} q_\nu - F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2) q^\mu \gamma^5] \tau^\pm$$

- form factors are functions of Q^2/M^2 (M~1 GeV), so can safely neglect this variation at low energy ($E_\nu \lesssim 10$ MeV)

low E
(< 100 MeV)

Inverse Beta Decay

- at low energy, form factors are constant & σ reduces to:

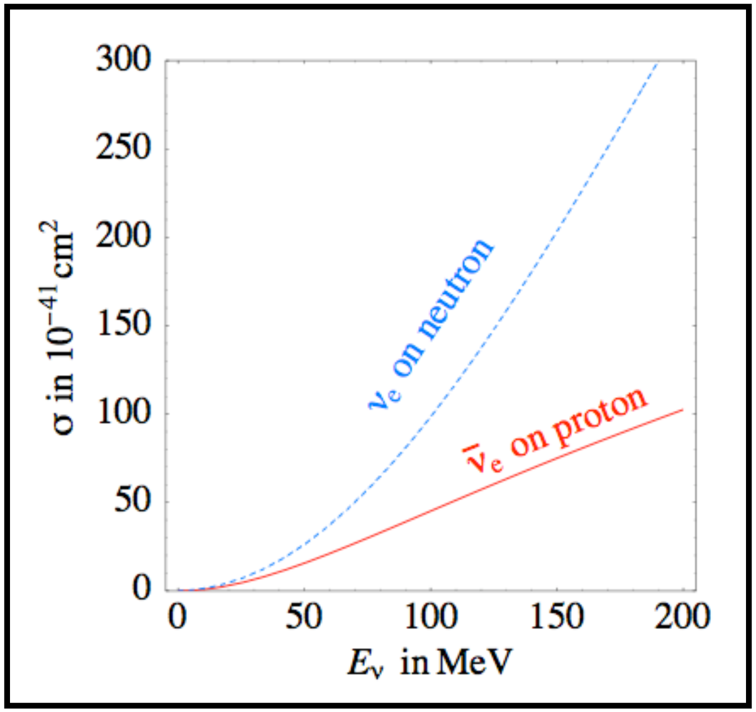
$$\sigma\,(\overline{\nu}_e\, p \rightarrow e^+ n) = \frac{G_F^2\, E_\nu^2}{\pi} \cos^2\theta_c \left(F_V^2 + 3F_A^2\right)$$

$(F_A \sim 1.267,\ F_V \sim 1.0)$

- parameters well constrained by neutron lifetime

- radiative & final state corrs further modify this
  (are small, calculable, follow from EM, QM)

- σ can be accurately computed
  uncertainty <0.5% at low E
  (uncertainty increases at higher energies)



Strumia, Vissani, PLB **564**, 42 (2003)

Sam Zeller, INSS, 07/08/09

low E
(< 100 MeV)

Inverse Beta Decay

- at low energy, form factors are constant & σ reduces to:

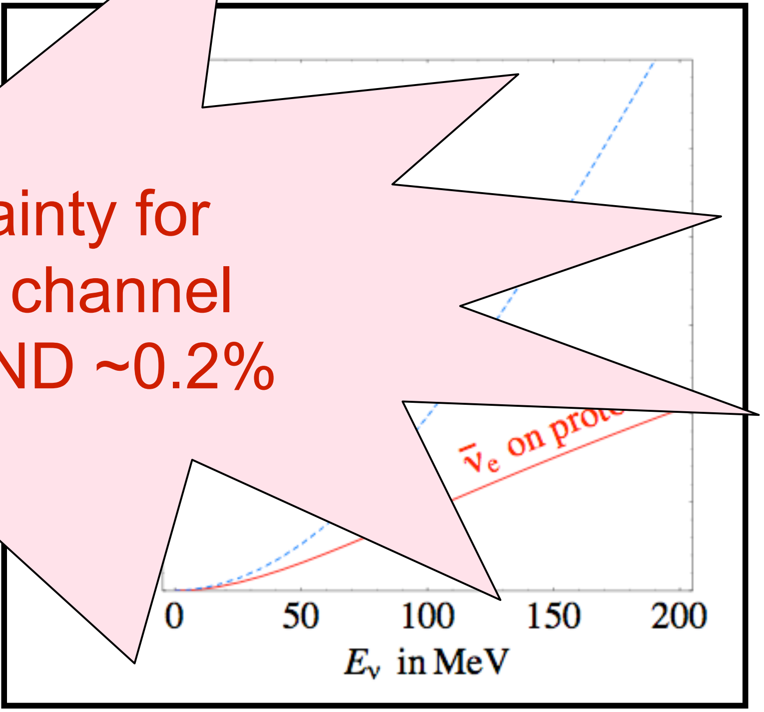
$$\sigma\,(\overline{\nu}_e\, p \to e^+ n) = \frac{G_F^2\, E_\nu^2}{\pi} \cos^2\theta_c \left(F_V^2 + 3F_A^2 \right)$$

(F_A ~ 1.267, F_V ~ 1.0)

- parameters well constrained
  by neutro fetime

- radiative & fina
  further r
  (are small, calcula

- σ can be accurate
  uncertainty <0.5% at low
  (uncertainty increases at higher en gies)



Strumia, Vissani, PLB **564**, 42 (2003)

σ_ν uncertainty for
IBD signal channel
for KAMLAND ~0.2%

low E
(< 100 MeV)

Los Alamos

Has This Been Measured?

- σ_{IBD} has been checked in reactor experiments
  (a short distance from the reactor where possible oscillation effects are negligible)

$$\overline{\nu}_e\, p \rightarrow e^+ n$$

- measurements at few-% level, consistent with prediction

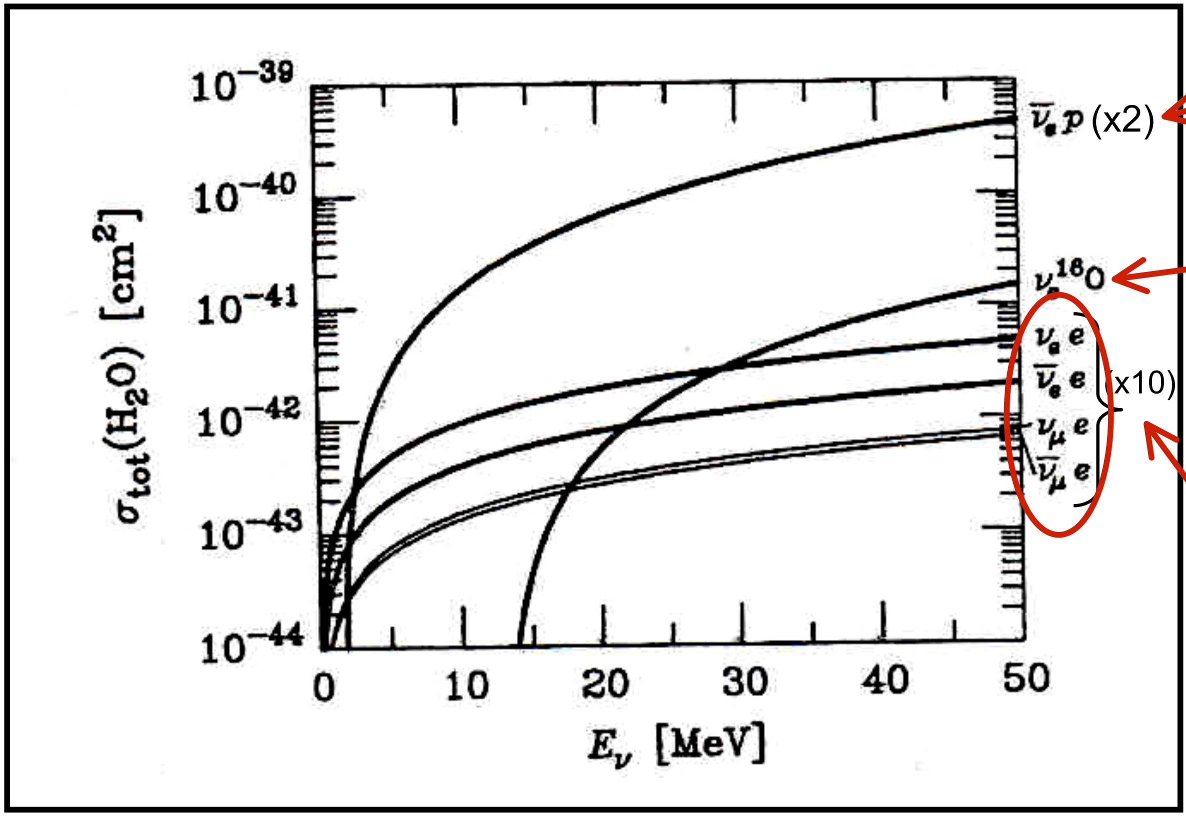
	Goesgen PRD **34**, 2621 (1986)	Krasnoyarsk JETP Lett **54**, 2225 (1991)	Bugey PLB **338**, 383 (1994)
σ_{exp}	3.0%	2.8%	1.4%

- theory is ahead here, σ_ν measurements limited by how well know reactor neutrino flux

low E
(< 100 MeV)

Low Energy σ_ν

- neutrinos scatter off more than free protons (IBD)
- for ex., what if you want to detect SN ν's in Super-K (H_2O)?



IBD
dominates

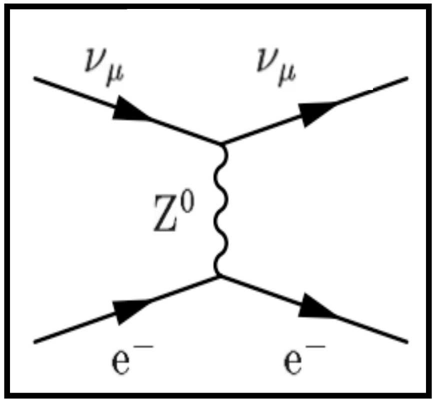
ν's can also
transfer a lot of
energy to a nucleus
(higher threshold than IBD,
~10-15 MeV)

ν's can scatter off
electrons in the target

K. Zuber, Neutrino Physics, IOP, 2004

$\nu+e^- \rightarrow \nu+e^-$ Scattering

- process in which we 1st discovered NC's!
- purely-leptonic process, so σ calculation is very straightforward (no form factors!)



$$\sigma = \frac{2G_F^2 m_e}{\pi}\left[\left(g_L^2 + \frac{g_R^2}{3}\right)E_\nu - g_L g_R \frac{m_e}{2}\right]$$

$$g_L = \sin^2\theta_W \underset{\mu,\tau}{\overset{e}{\pm}} \frac{1}{2}$$

$$g_R = \sin^2\theta_W$$

some facts

- σ is ~ linear with E_ν (generic feature of point-like scattering)
- $\sigma(\nu_e\, e^-) > \sigma(\nu_{\mu,\tau}\, e^-)$ (ν_e can scatter both by NC & CC)
- σ is small:

$$\sigma \sim s = (E_{CM})^2 = 2m_{target}E_\nu$$

4 orders of magnitude less likely than scattering off nucleons at 1 GeV!

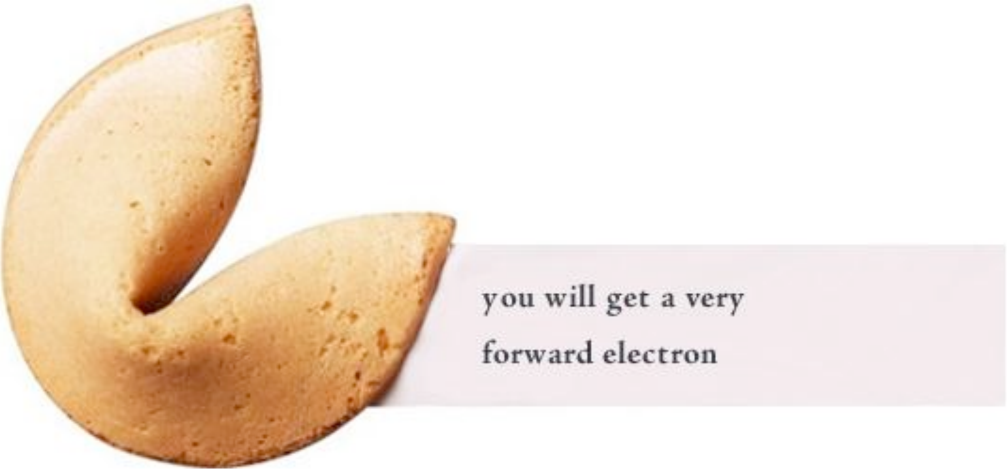
$\nu + e^- \rightarrow \nu + e^-$ Scattering

- appealing to use for **SN and solar ν** detection because it is directional! (e⁻ emitted at a very small angle wrt incoming ν direction)

$$E_e\,\theta_e^2 < 2\,m_e$$

can derive from simple E, mom conservation

- recoiling e⁻ preserves knowledge of incident ν direction (compared to e⁺ from IBD which is essentially isotropic for low E_ν)



$\nu + e^- \rightarrow \nu + e^-$ Scattering

- appealing to use for **SN and solar** ν detection because it is directional! (e^- emitted at a very small angle wrt incoming ν direction)

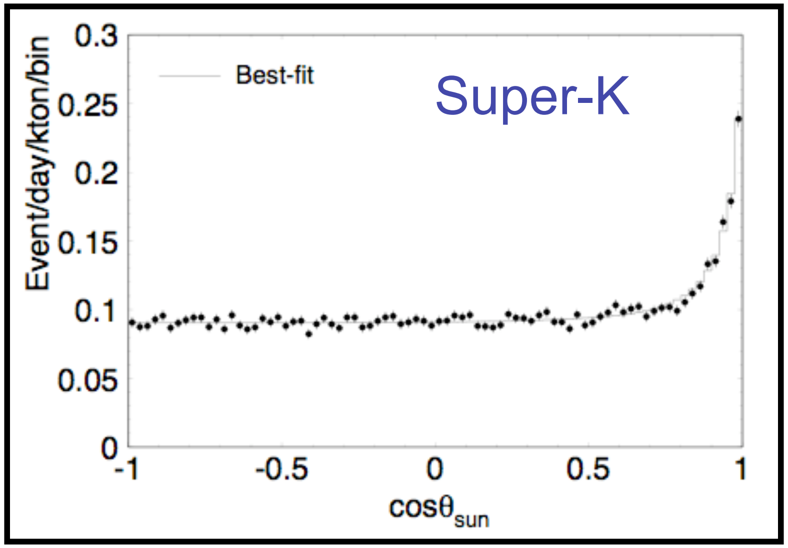
$$E_e\, \theta_e^2 < 2\, m_e$$

can derive from simple E, mom conservation

- recoiling e^- preserves knowledge of incident ν direction
  (compared to e^+ from IBD which is essentially isotropic for low E_ν)

- Kamiokande was the 1st to point back to the sun
  also Super-K, SNO, Borexino

- tend not to use for reactor exps
  ($\bar{\nu}_e\, e^- \rightarrow \bar{\nu}_e\, e^-$)
  single e^- difficult to distinguish from background caused by radioactivity



Fukuda *et al.*, PRL **81**, 1158 (1998)

$\nu + e^- \rightarrow \nu + e^-$ Scattering

things to remember here …

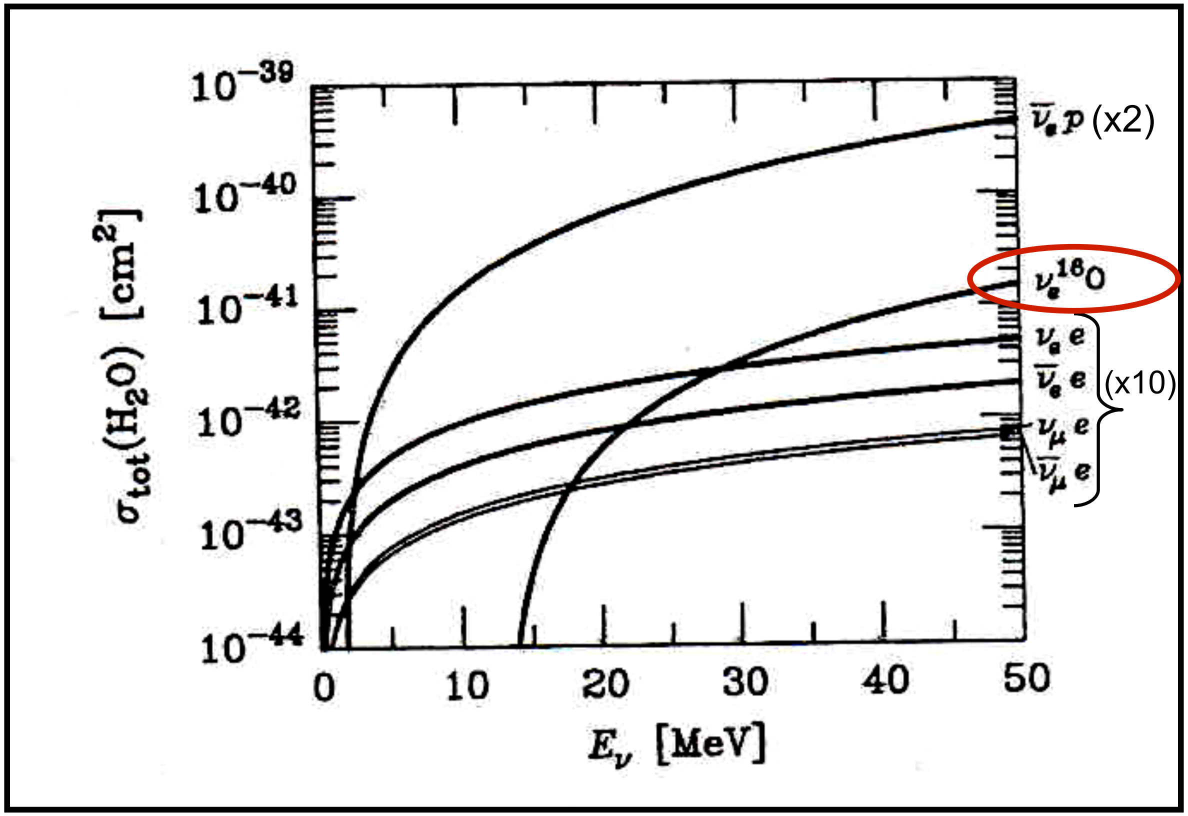
disadvantage → σ is small (small rates)

advantages
- directional (very forward emitted e^-)
- σ extremely well known (no strongly interacting particles involved)

low E
(< 100 MeV)

Low Energy σ_ν

- let's go back to our example …



K. Zuber, Neutrino Physics, IOP, 2004

low E
(< 100 MeV)

Nuclear Targets

- nature of observables depends on the nuclear physics of the specific nucleus (add'l ejected nucleons or nuclear de-excitation γ's)

examples of CC interactions

$\nu_e\, d \rightarrow e^-\, pp$

$\bar{\nu}_e\, d \rightarrow e^+\, nn$

→ deuteron breakup in heavy water (SNO)

$\nu_e\, {}^{16}O \rightarrow e^-\, {}^{16}F$

$\bar{\nu}_e\, {}^{16}O \rightarrow e^+\, {}^{16}N$

→ interactions with ${}^{16}O$ in water

$\nu_e\, {}^{12}C \rightarrow e^-\, {}^{12}N$

$\bar{\nu}_e\, {}^{12}C \rightarrow e^+\, {}^{12}B$

→ interactions with ${}^{12}C$ in oil, scintillator

low E
(< 100 MeV)

Nuclear Targets

- nature of observables depends on the nuclear physics of the specific nucleus (add'l ejected nucleons or nuclear de-excitation γ's)

examples of CC interactions

$\nu_e\, d \rightarrow e^-\, pp$

$\bar{\nu}_e\, d \rightarrow e^+\, nn$

deuteron breakup in heavy water (SNO)

$\nu_e\, {}^{16}O \rightarrow e^-\, {}^{16}F$

$\bar{\nu}_e\, {}^{16}O \rightarrow e^+\, {}^{16}N$

$\nu_e\, {}^{12}C \rightarrow e^-\, {}^{12}N$

$\bar{\nu}_e\, {}^{12}C \rightarrow e^+\, {}^{12}B$

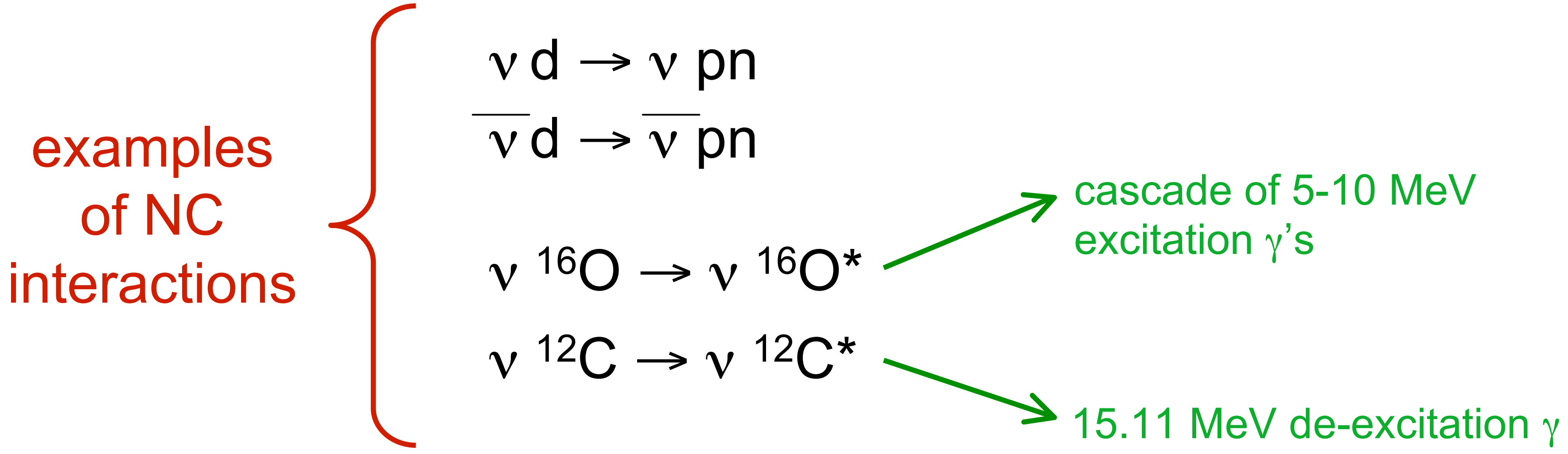
higher thresholds
(10's MeV)
and theoretically
less clean

- $\nu_e\, {}^{37}Cl \rightarrow e^-\, {}^{37}Ar$ was 1st reaction used to detect solar ν (Ray Davis)

low E
(< 100 MeV)

Nuclear Targets

- nature of observables depends on the nuclear physics of the specific nucleus (add’l ejected nucleons or nuclear de-excitation γ’s)



examples of NC interactions

$\nu\, d \rightarrow \nu\, pn$

$\bar{\nu}\, d \rightarrow \bar{\nu}\, pn$

$\nu\, {}^{16}O \rightarrow \nu\, {}^{16}O^*$

$\nu\, {}^{12}C \rightarrow \nu\, {}^{12}C^*$

cascade of 5-10 MeV excitation γ’s

15.11 MeV de-excitation γ

- let’s start with simplest nucleus, deuteron (deuterium nucleus=1n+1p)

low E
(< 100 MeV)

Deuteron

- even though σ's are more than order of magnitude smaller than IBD reaction on protons, important because both CC & NC

- ν-d interactions used by SNO, $\bar{\nu}_e$-d by Bugey

CC
$\nu_e\, d \rightarrow e^-\, pp$ (threshold ~ $m_p+m_e-m_n+E_B$ = 1.4 MeV)
$\bar{\nu}_e\, d \rightarrow e^+\, nn$ (threshold ~ $m_n+m_e-m_p+E_B$ = 4.0 MeV)

NC
$\nu\, d \rightarrow \nu\, pn$ (threshold ~ E_B = 2.2 MeV)
$\bar{\nu}\, d \rightarrow \bar{\nu}\, pn$

Deuteron

- even though σ's are more than order of magnitude smaller than IBD reaction on protons, important because both CC & NC

- ν-d interactions used by SNO, $\bar{\nu}_e$-d by Bugey

CC

$$\nu_e\, d \rightarrow e^-\, pp$$
$$\bar{\nu}_e\, d \rightarrow e^+\, nn$$

sensitive to ν oscillations

NC
(flavor blind)

$$\nu\, d \rightarrow \nu\, pn$$
$$\bar{\nu}\, d \rightarrow \bar{\nu}\, pn$$

measures total flux of active ν's
independent of oscillations

- number of groups have very carefully computed these σ's

low E
(< 100 MeV)

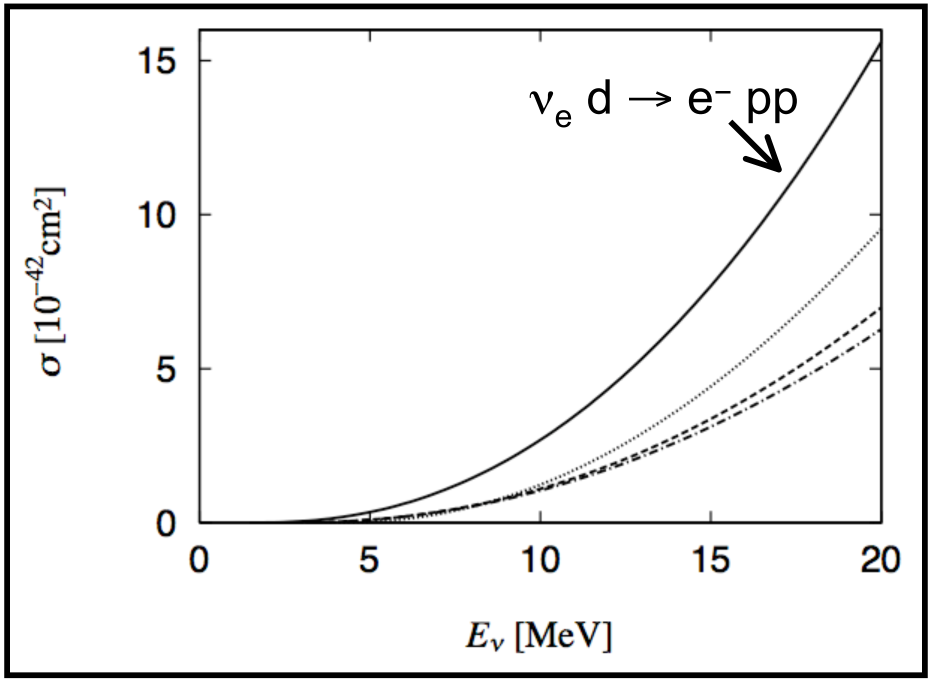
Deuteron

- at low E's, know a lot because deuteron is so weakly bound
  (almost free neutron & proton, so almost same as IBD)

  - nucleon is almost free
  - deuteron is stable
  - know neutron lifetime
  - constraints from γ+d

- σ rather well determined, theoretical uncertainty is ~1% at lowest E's
  (sufficient to interpret SNO results)

- more uncertain at higher energies ($\lesssim$ 10% at 100 MeV)



Nakamura *et al.*, PRC **63**, 034617 (2001)

low E
(< 100 MeV)

Deuteron

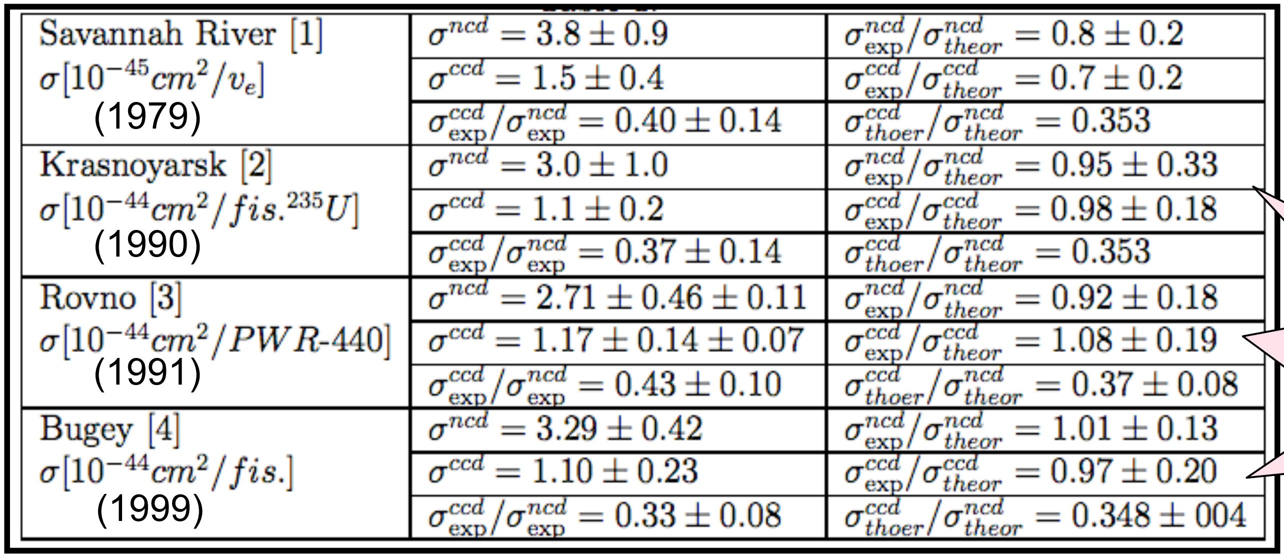
- only one experimental measurement of CC ν_e d cross section

Willis *et al.*, Phys. Rev. Lett. **44**, 522 (1980), LAMPF stopped π^+ beam

$$\sigma(\nu_e\, d \rightarrow e^-\, pp) = (0.52 \pm 0.18\,) \times 10^{-40}\ \mathrm{cm}^2$$

35%
measurement

- several reactor measurements of CC, NC $\overline{\nu}_e$ d cross sections



Savannah River [1] $\sigma[10^{-45} cm^2/\nu_e]$ (1979)	$\sigma^{ncd} = 3.8 \pm 0.9$	$\sigma^{ncd}_{\exp}/\sigma^{ncd}_{theor} = 0.8 \pm 0.2$
	$\sigma^{ccd} = 1.5 \pm 0.4$	$\sigma^{ccd}_{\exp}/\sigma^{ccd}_{theor} = 0.7 \pm 0.2$
	$\sigma^{ccd}_{\exp}/\sigma^{ncd}_{\exp} = 0.40 \pm 0.14$	$\sigma^{ccd}_{thoer}/\sigma^{ncd}_{theor} = 0.353$
Krasnoyarsk [2] $\sigma[10^{-44} cm^2/fis.^{235}U]$ (1990)	$\sigma^{ncd} = 3.0 \pm 1.0$	$\sigma^{ncd}_{\exp}/\sigma^{ncd}_{theor} = 0.95 \pm 0.33$
	$\sigma^{ccd} = 1.1 \pm 0.2$	$\sigma^{ccd}_{\exp}/\sigma^{ccd}_{theor} = 0.98 \pm 0.18$
	$\sigma^{ccd}_{\exp}/\sigma^{ncd}_{\exp} = 0.37 \pm 0.14$	$\sigma^{ccd}_{thoer}/\sigma^{ncd}_{theor} = 0.353$
Rovno [3] $\sigma[10^{-44} cm^2/PWR\text{-}440]$ (1991)	$\sigma^{ncd} = 2.71 \pm 0.46 \pm 0.11$	$\sigma^{ncd}_{\exp}/\sigma^{ncd}_{theor} = 0.92 \pm 0.18$
	$\sigma^{ccd} = 1.17 \pm 0.14 \pm 0.07$	$\sigma^{ccd}_{\exp}/\sigma^{ccd}_{theor} = 1.08 \pm 0.19$
	$\sigma^{ccd}_{\exp}/\sigma^{ncd}_{\exp} = 0.43 \pm 0.10$	$\sigma^{ccd}_{thoer}/\sigma^{ncd}_{theor} = 0.37 \pm 0.08$
Bugey [4] $\sigma[10^{-44} cm^2/fis.]$ (1999)	$\sigma^{ncd} = 3.29 \pm 0.42$	$\sigma^{ncd}_{\exp}/\sigma^{ncd}_{theor} = 1.01 \pm 0.13$
	$\sigma^{ccd} = 1.10 \pm 0.23$	$\sigma^{ccd}_{\exp}/\sigma^{ccd}_{theor} = 0.97 \pm 0.20$
	$\sigma^{ccd}_{\exp}/\sigma^{ncd}_{\exp} = 0.33 \pm 0.08$	$\sigma^{ccd}_{thoer}/\sigma^{ncd}_{theor} = 0.348 \pm 004$

Kozlov *et al.*, Phys. Atom. Nucl. **63**, 1016 (2000)

20-30%
measurements

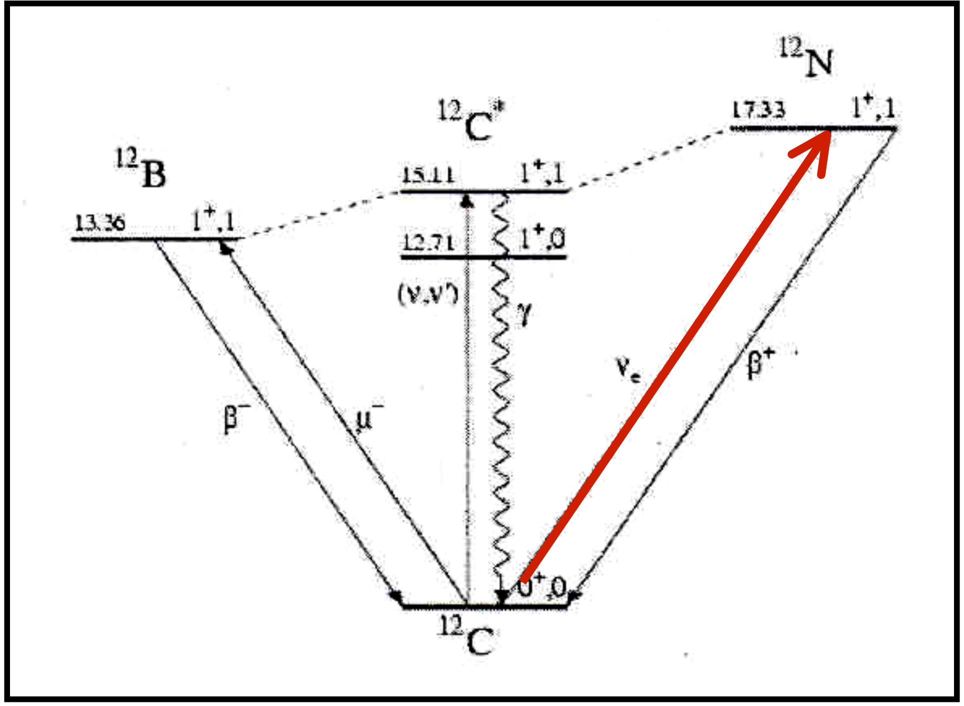
not at all
competitive
with theory

low E
(< 100 MeV)

^{12}C

- one nucleus that has been closely studied is ^{12}C (abundantly contained in ordinary liquid scintillators)

K. Zuber, ν Physics, IOP, 2004



CC interactions

$\nu_\mu\ ^{12}C \rightarrow \mu^-\ ^{12}N_{gs}$

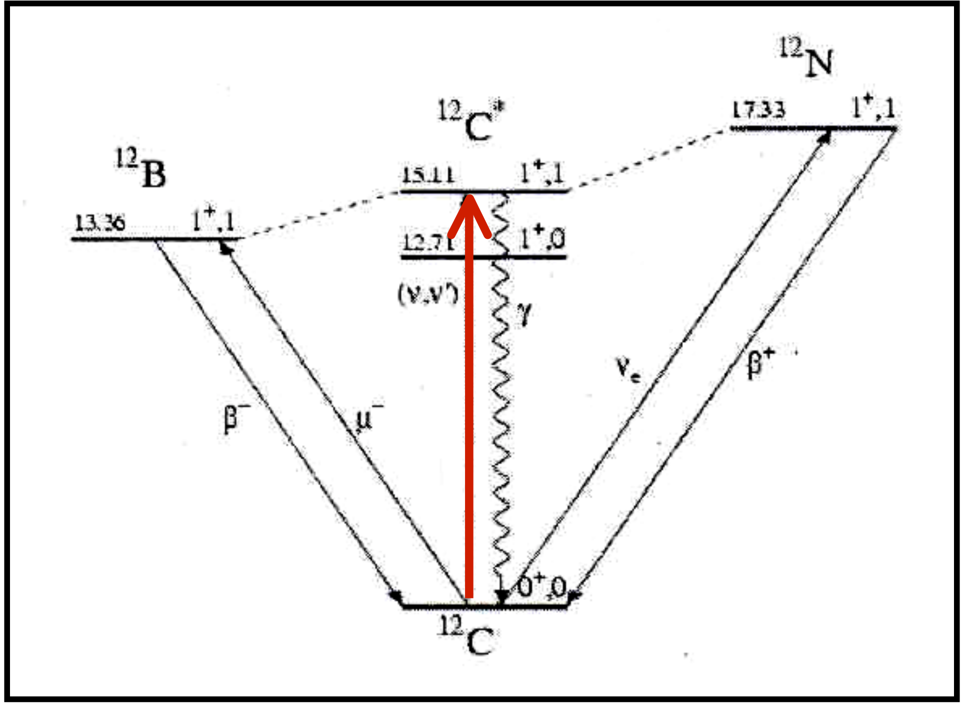
$\nu_e\ ^{12}C \rightarrow e^-\ ^{12}N_{gs}$

(note: also written as $^{12}C(\nu_\mu,\mu^-)^{12}N_{gs}$ and $^{12}C(\nu_e,e^-)^{12}N_{gs}$)

^{12}C

- one nucleus that has been closely studied is ^{12}C (abundantly contained in ordinary liquid scintillators)

K. Zuber, ν Physics, IOP, 2004



NC interactions

$\nu\ ^{12}C \rightarrow \nu\ ^{12}C^{*}$(15.11 MeV)

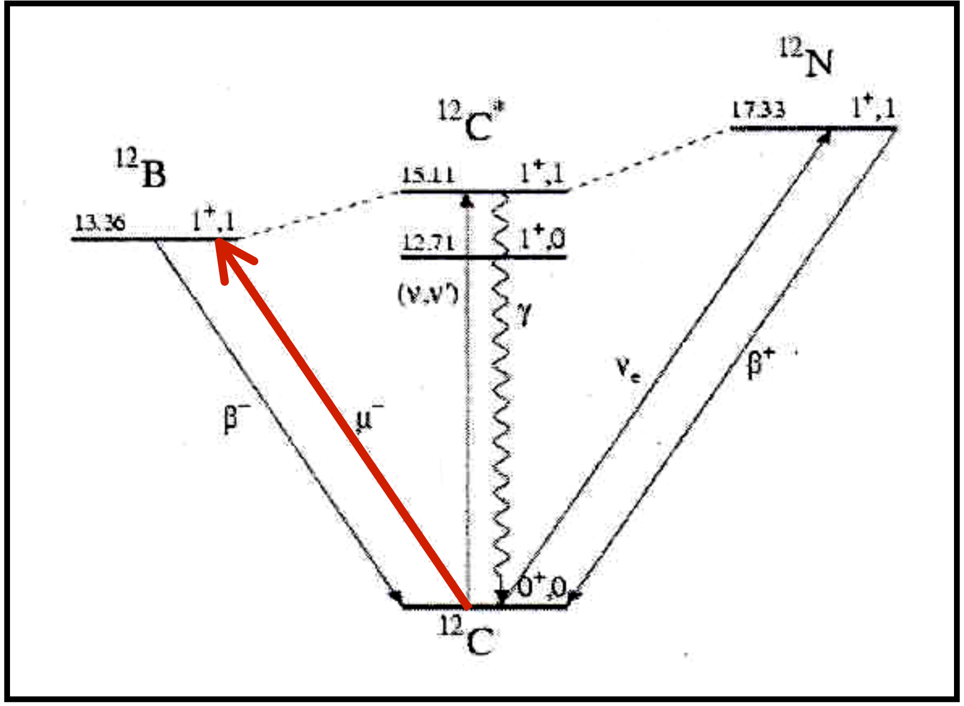
(note: also written as $^{12}C(\nu,\nu)^{12}C^{*}$)

low E
(< 100 MeV)

^{12}C

- one nucleus that has been closely studied is ^{12}C (abundantly contained in ordinary liquid scintillators)

K. Zuber, ν Physics, IOP, 2004



ex. muon capture

& can also relate to measured lifetimes of these isotopes

- σ's constrained by the obvious requirement that the same method and parameters must describe related processes

low E
(< 100 MeV)

^{12}C

- intensive program of beam dump ν experiments at Los Alamos & Rutherford lab (10-20% measurements)

flux-averaged σ in units of cm^2	$^{12}C(\nu_e, e^-)^{12}N_{gs}$ decay at rest	$^{12}C(\nu_\mu, \mu^-)^{12}N_{gs}$ decay in flight	$^{12}C(\nu, \nu')^{12}C(15.11)$ decay at rest
KARMEN	9.1 ± 0.5 ± 0.8	-	10.4 ± 1.0 ± 0.9
LSND	8.9 ± 0.3 ± 0.9	66±10 ± 10	-
E225	10.5 ± 1.0 ± 1.0	-	-
Shell model [10]	9.1	63.5	9.8
CRPA [4,5]	8.9	63.0	10.5
EPT [11]	9.2	59	9.9

- predictions agree with experimental measurements

- σ for $^{12}N_{g.s.}$ can be predicted with accuracy of ~5%

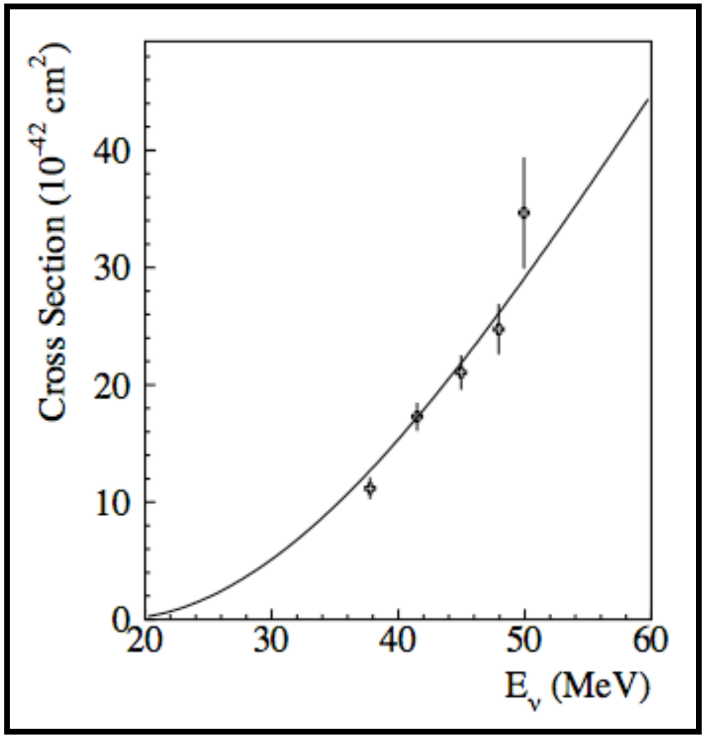
(have to rely on nuclear theory but can take advantage of a # of constraints from related processes like β decay transitions of various isotopes, μ^- capture, etc.)

low E
(< 100 MeV)

^{12}C

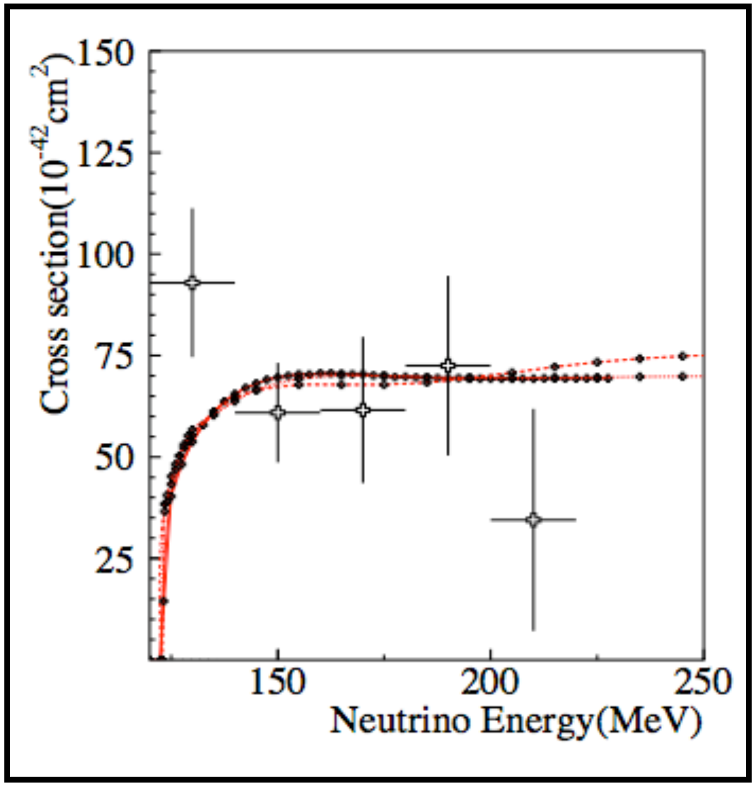
- also measured energy dependence of the cross sections

$\nu_e\ ^{12}C \rightarrow e^-\ ^{12}N_{g.s.}$



Auerbach *et al*., PRC **64**, 065001 (2001)
LSND, DAR of stopped π^+ and μ^+

$\nu_\mu\ ^{12}C \rightarrow \mu^-\ ^{12}N_{g.s.}$

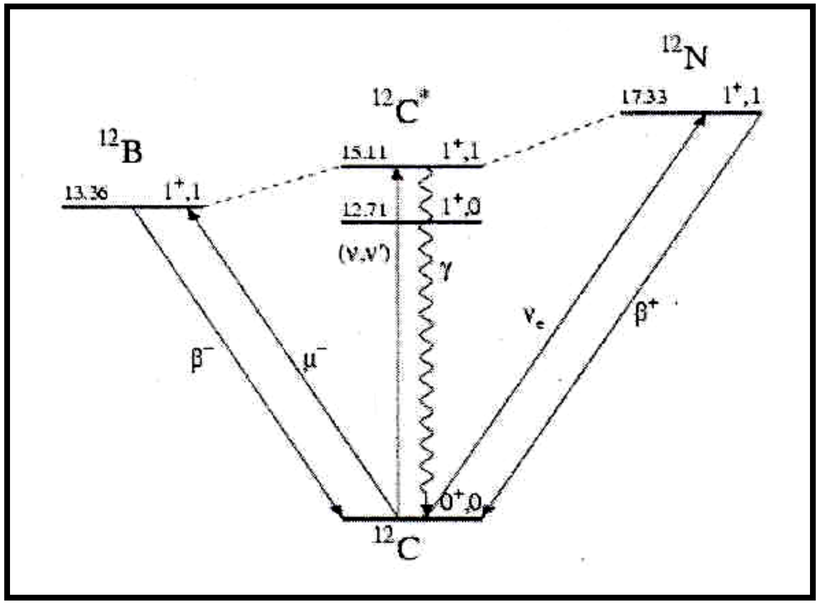


Auerbach *et al*., PRC **66**, 015501 (2002)
LSND, π^+ DIF

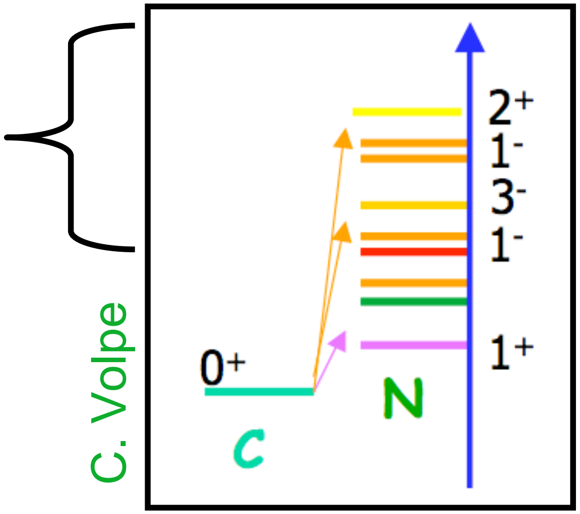
low E
(< 100 MeV)

^{12}C

- for higher energy ν's, populate not only g.s. but also continuum states …



K. Zuber, ν Physics, IOP, 2004



C. Volpe

$\nu_\mu\ ^{12}C \rightarrow \mu^-\ ^{12}N^*$

(final state includes all E levels)

- calculation of σ to excited states is a less certain procedure
  (need to model more complex nuclear dynamics)
- there are model-dependent uncertainties not present in $^{12}N_{g.s.}$

low E
(< 100 MeV)

Low Energy Scorecard

process	**σ uncertainty**	**exp'l meas**	**importance**
IBD $\bar{\nu}_e\, p \rightarrow e^+ n$	<0.5%	1.4-3% reactor $\bar{\nu}_e$	main reaction channel for detecting **reactor, SN ν's**
ν-deuteron	~1% (<10 MeV) less certain higher E	25-30% one ν_e, several $\bar{\nu}_e$	**solar ν's** (SNO) **reactor ν's** (Bugey)
ν-^{12}C	~5% ($^{12}N_{gs}$) less certain ^{12}N*	10-20% KARMEN, LSND	**SN + atmospheric ν's** (threshold too high for solar or reactor, unless pick diff nucleus)

- theory is in better shape than exp'l measurements
- σ's are well known because can tie them to other processes

low E
(< 100 MeV)

What I Didn't Talk About

solar ν's
(Homestake, GALLEX, SAGE)

ICARUS

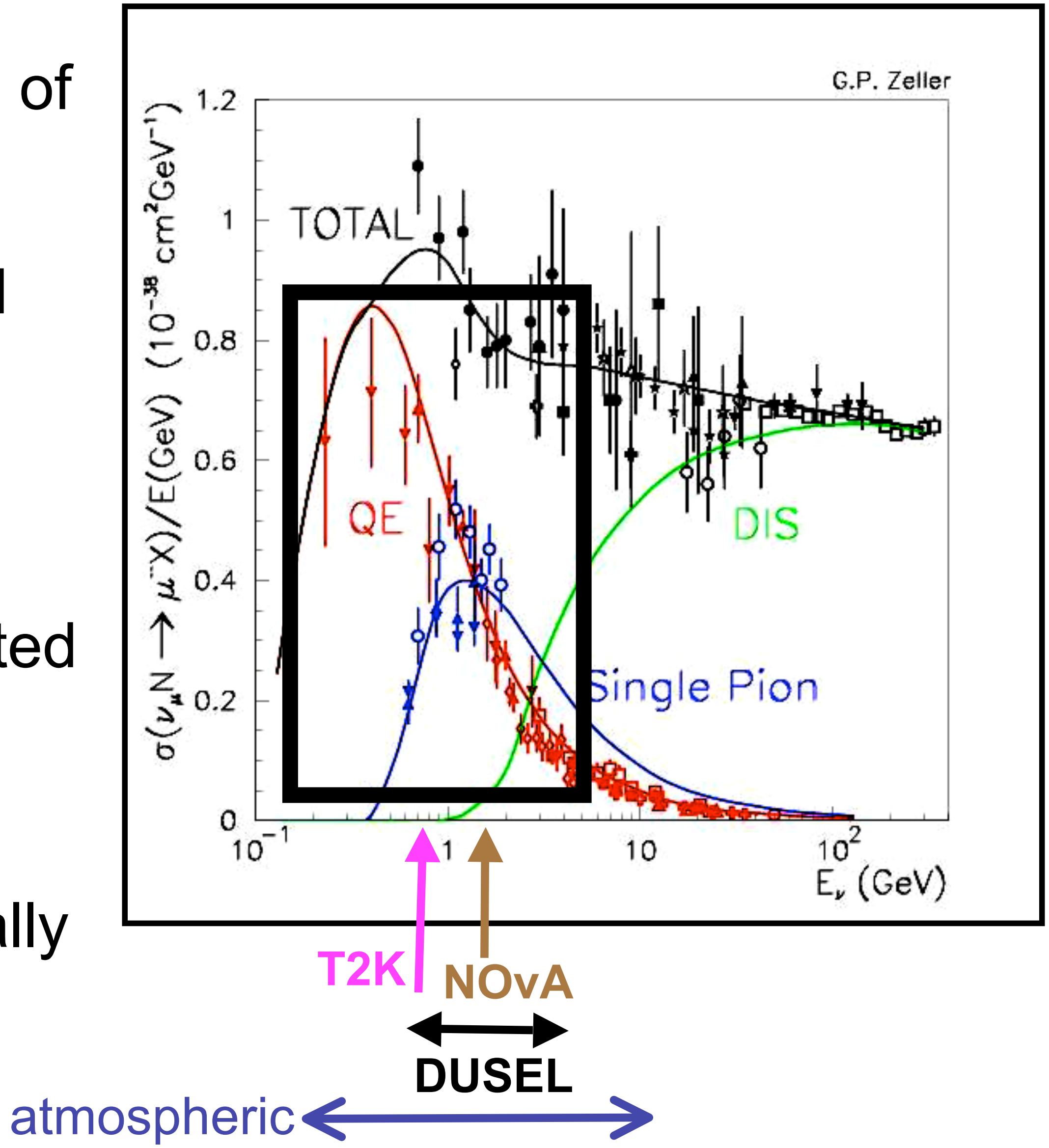
- **radio-chemical transitions** (^{37}Cl ,^{71}Ga,^{40}Ar)
  - complicated nuclear physics (need to now nuclear matrix elements)
  - showed you one of simplest cases with $^{12}C \rightarrow {}^{12}N_{g.s.}$
  - ground state transitions generally well known because can be tied to other processes, but larger uncertainties for excited states

- **coherent elastic νA → νA scattering** (J. Wilkerson's talk)
  - larger σ than IBD at low energy, but difficult to observe
  - very small nuclear recoil (keV)

intermediate
(~ 1 GeV)

Intermediate Energies

- important for studies of **atmospheric ν's**
- future **accelerator-based** ν experiments will all be operating in this E range
- things get more complicated (multiple processes contribute!)
- need to describe each of these processes individually (each has their own σ model)



T2K

NOvA

DUSEL

atmospheric

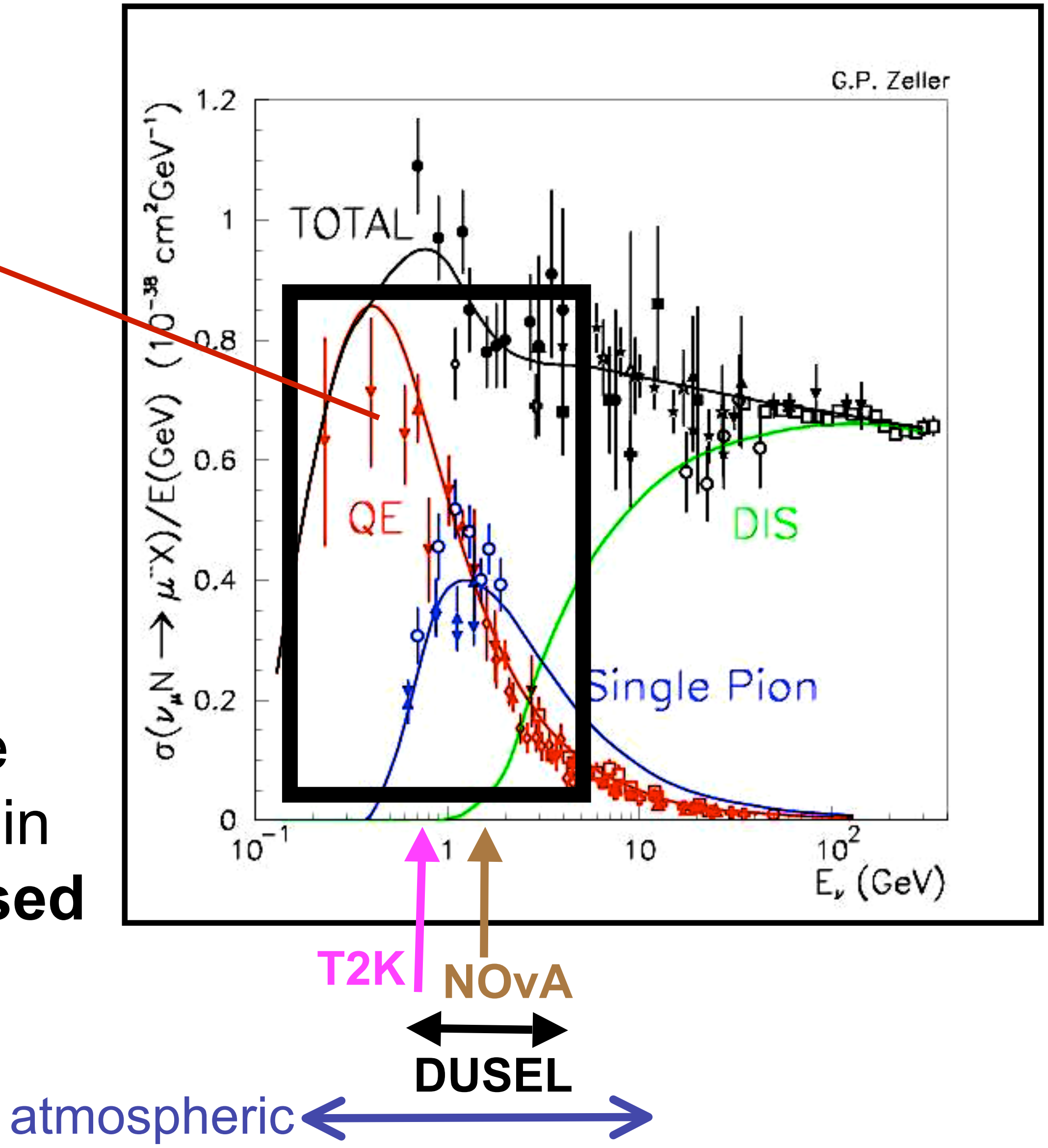
intermediate
(~ 1 GeV)

Intermediate Energies

QE scattering

at higher energies
E_ν ~ 1 GeV

$$\left(\begin{array}{l} \nu_\mu\, n \rightarrow \mu^- p \\ \nu_e\, n \rightarrow e^- p \end{array}\right)$$



T2K

NOvA

DUSEL

atmospheric

- important because it is the dominant **signal channel** in **atmospheric & accel-based** ν oscillation experiments

intermediate
(~ 1 GeV)

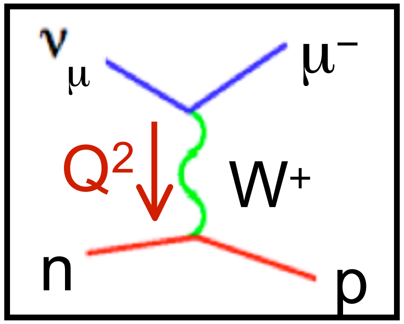
QE Scattering at 1 GeV

oday, general formula for QE scattering on free nucleons that is routinely used: C.H. Llewellyn Smith, Phys. Rep. **3C**, 261 (1972)

$$d\sigma = \frac{G_F^2 \cos^2 \vartheta_c}{2} \, 2\pi \, L^{\mu\nu} \, W_{\mu\nu} \, \frac{d^3 k}{(2\pi)^3}$$

hadronic tensor

$$W^{\mu\nu}(\omega, q) = \sum\!\!\!\!\!\!\int_{f} \langle \Psi_f \mid J^{\mu}(\boldsymbol{q}) \mid \Psi_0 \rangle \times \langle \Psi_0 \mid J^{\nu\dagger}(\boldsymbol{q}) \mid \Psi_f \rangle \, \delta(E_0 + \omega - E_f)$$



remember: form factors encapsulate info about the structure of the object are scattering from

$$j^{\mu} = \left[F_1^V(Q^2)\gamma^{\mu} + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_{\nu} - F_A(Q^2)\gamma^{\mu}\gamma^5 + F_P(Q^2)q^{\mu}\gamma^5\right]\tau^{\pm}$$

- as move up in E_ν, Q^2 dependence of FFs becomes important

QE Scattering at 1 GeV

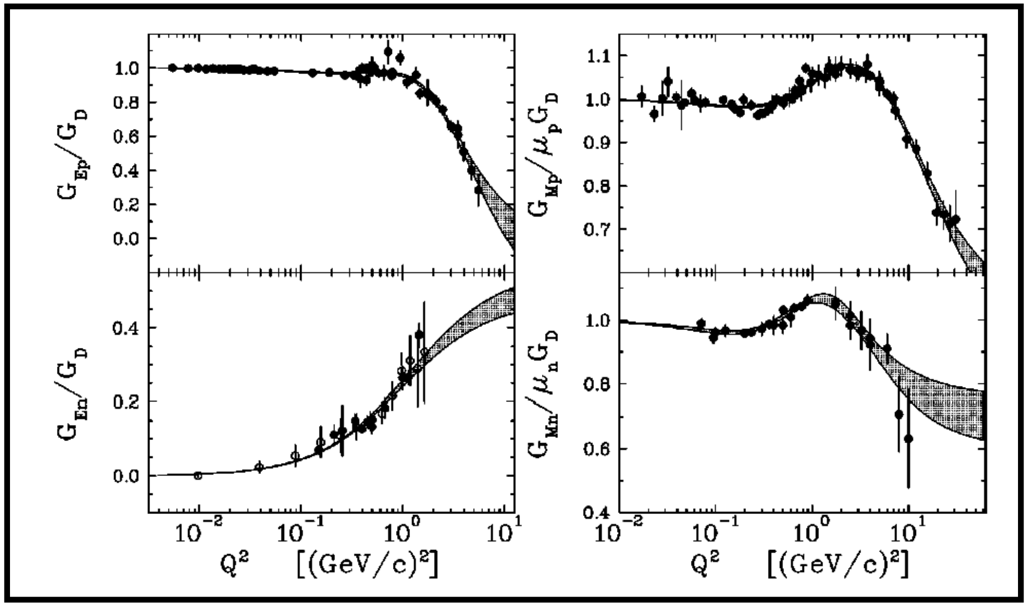
- FFs are not calculable, need to measure experimentally

$$j^\mu = \left[F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_\nu - F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)q^\mu\gamma^5\right]\tau^\pm$$

vector form factors

- proton is not point-like but is an extended object with some charge distribution

- vector part can be checked in e⁻ elastic scattering (well known, under control)



J.J. Kelly, Phys. Rev. **C70**, 068202 (2004)

intermediate
(~ 1 GeV)

Los Alamos

QE Scattering at 1 GeV

- FFs are not calculable, need to measure experimentally

$$\begin{aligned} j^\mu &= [F_1^{\mathrm{V}}(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^{\mathrm{V}}(Q^2)\sigma^{\mu\nu}q_\nu \\ &- \mathrm{F_A}(Q^2)\gamma^\mu\gamma^5 + F_{\mathrm{P}}(Q^2)q^\mu\gamma^5]\tau^\pm \end{aligned}$$

pseudoscalar form factor

contribution enters as $(m_l/M)^2$
small for ν_e, ν_μ

- since F_P is small and know F_V from e^- scattering, σ is then determined at these energies … except for F_A …

QE Scattering at 1 GeV

- FFs are not calculable, need to measure experimentally

$$
\begin{aligned}
j^{\mu} &= [F_1^{\rm V}(Q^2)\gamma^{\mu} + i\frac{\kappa}{2M}F_2^{\rm V}(Q^2)\sigma^{\mu\nu}q_{\nu} \\
&\quad - F_A(Q^2)\gamma^{\mu}\gamma^5 + F_{\rm P}(Q^2)q^{\mu}\gamma^5]\tau^{\pm}
\end{aligned}
$$

axial form factor

$$\boxed{F_A(Q^2) = \frac{1.267}{(1+Q^2/M_A^2)^2}}$$

$F_A(Q^2=0)$
determined from
β decay
(same value saw earlier
for IBD)

intermediate
(~ 1 GeV)

QE Scattering at 1 GeV

- FFs are not calculable, need to measure experimentally

$$
\begin{aligned}
j^\mu &= [F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_\nu \\
&\quad - F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)q^\mu\gamma^5]\tau^\pm
\end{aligned}
$$

axial form factor

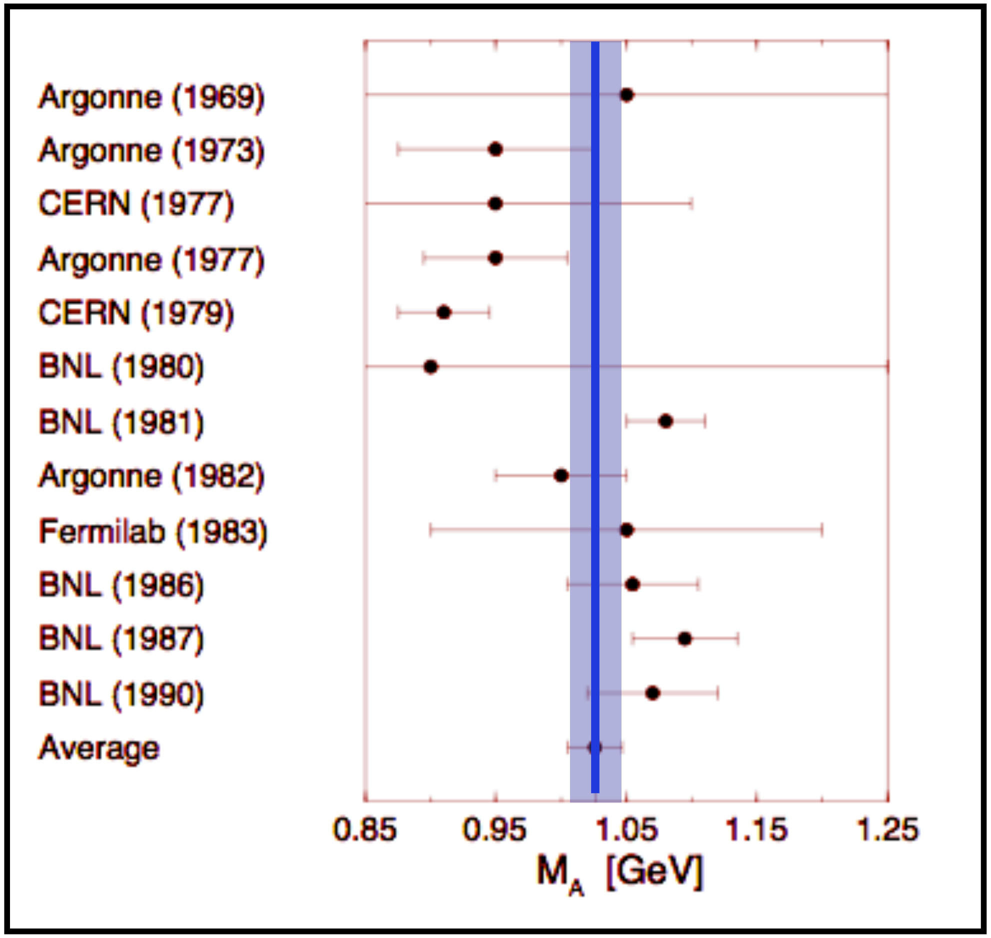
$$\boxed{F_A(Q^2) = \frac{1.267}{(1+Q^2/M_A^2)^2}}$$

- Q^2 dependence can only be measured in ν scattering
- not as well measured
- assumed to have dipole form

(function of a single parameter
"axial mass" = M_A)

must be measured experimentally!

M_A Measurements



past world average:

M_A = 1.03 ± 0.02 GeV

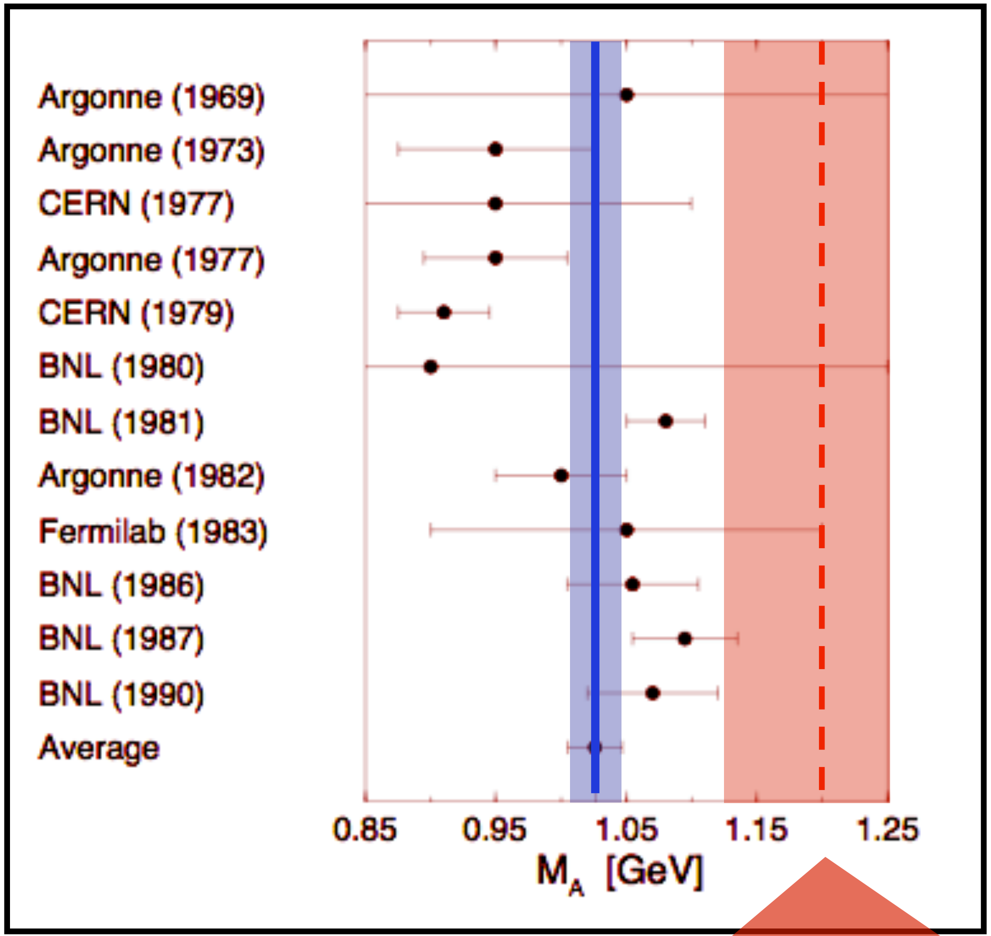
- was the focus of many early bubble chamber exps

- mostly QE data on D_2 (1969-1990)

$$\nu_\mu\, n \rightarrow \mu^-\, p$$

- because plays such a crucial role in σ, a lot of interest in this & attempts to re-measure this recently

Modern M_A



past world average:

$M_A = 1.03 \pm 0.02$ GeV

- **K2K SciFi** (^{16}O, $Q^2>0.2$)

  Phys. Rev. **D74**, 052002 (2006)

  $M_A=1.20 \pm 0.12$ GeV

- **K2K SciBar** (^{12}C, $Q^2>0.2$)

  AIP Conf. Proc. **967**, 117 (2007)

  $M_A=1.14 \pm 0.11$ GeV

- **MiniBooNE** (^{12}C, $Q^2>0$)

  paper in preparation

  $M_A=1.35 \pm 0.17$ GeV

- **MINOS** (Fe, $Q^2>0.3$)

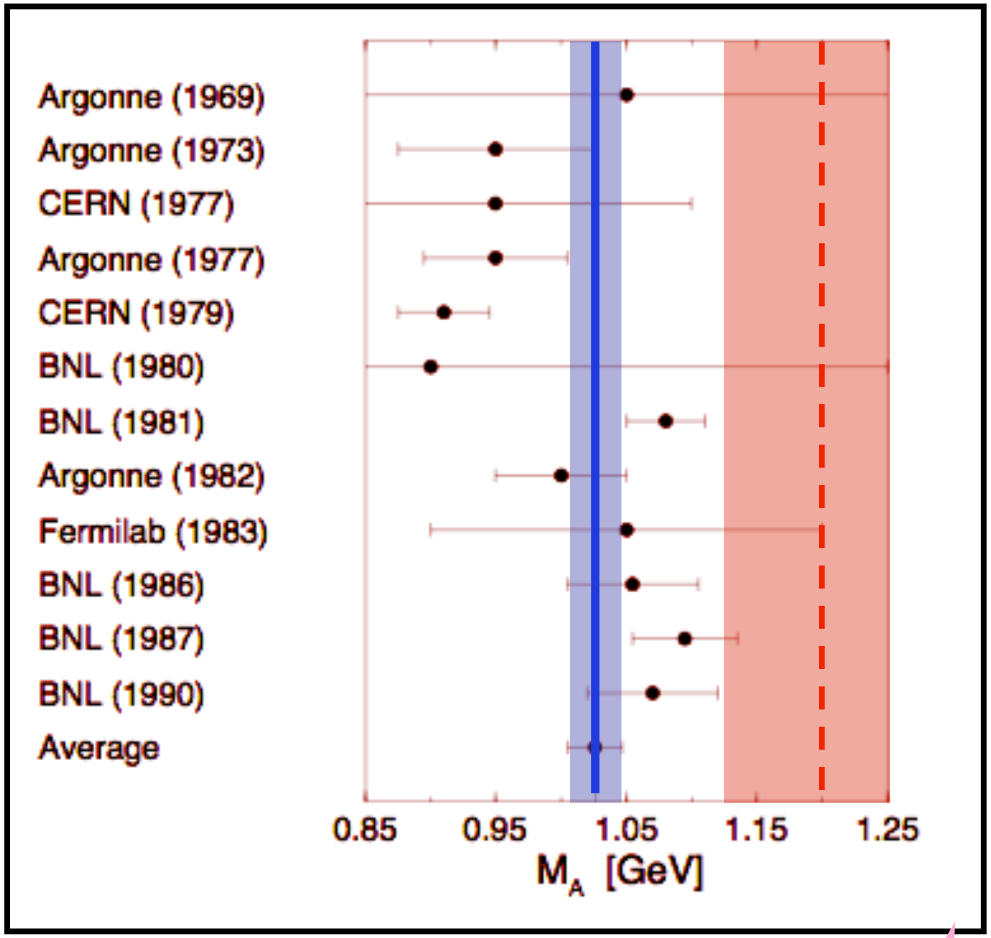
  NuInt09, preliminary

  $M_A=1.26 \pm 0.17$ GeV

? not sure why

Sam Zeller, INSS, 07/08/09

Modern M_A



past world average:

$M_A = 1.03 \pm 0.02$ GeV

?

- **K2K SciFi** (^{16}O, $Q^2>0.2$)
  Phys. Rev. **D74**, 052002 (2006)
  $M_A=1.20 \pm 0.12$ GeV

- **K2K SciBar** (^{12}C, $Q^2>0.2$)
  AIP Conf. Proc. **967**, 117 (2007)
  $M_A=1.14 \pm 0.11$ GeV

- **MiniBooNE** (^{12}C, $Q^2>0$)
  paper in preparation
  $M_A=1.35 \pm 0.17$ GeV

- **MINOS** (Fe, $Q^2>0.3$)
  NuInt09, preliminary
  $M_A=1.26 \pm 0.17$ GeV

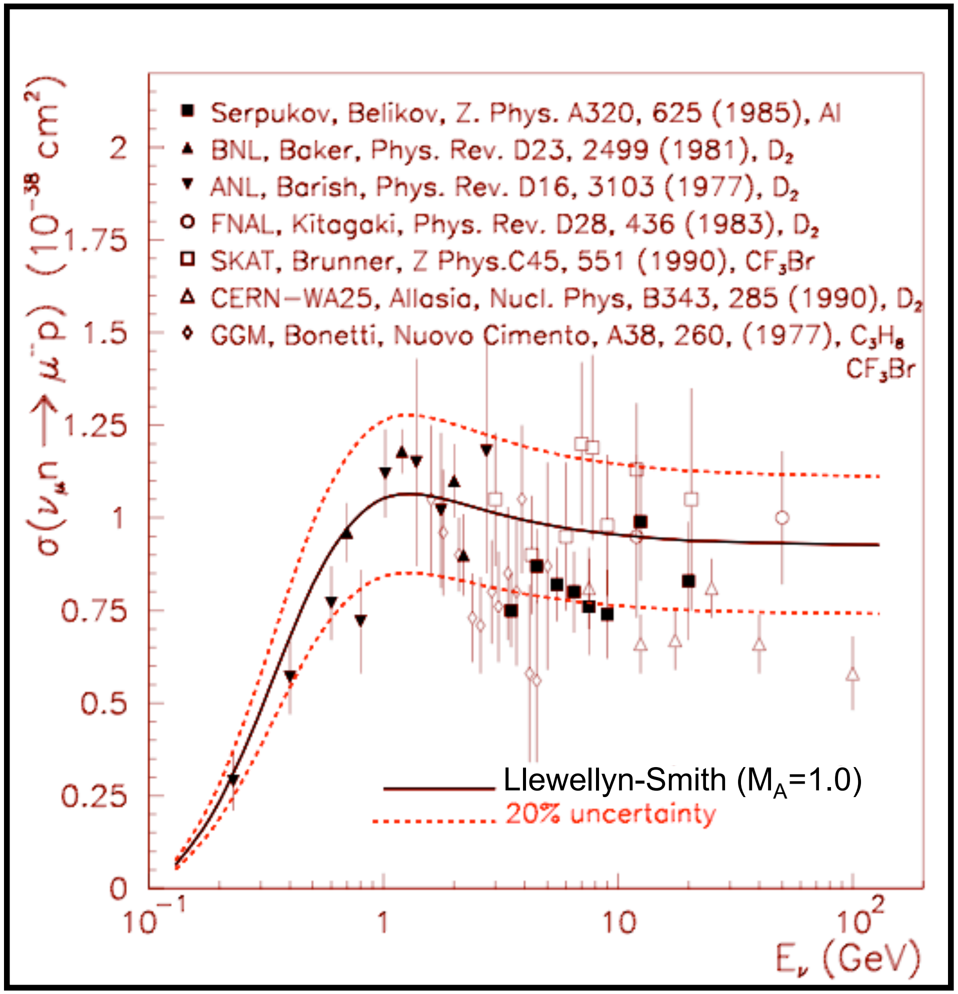
- **NOMAD** (^{12}C, $Q^2>0$)
  arXiv:0812.4543 [hep-ex]
  $M_A=1.07 \pm 0.07$ GeV

intermediate
(~ 1 GeV)

QE Cross Section

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

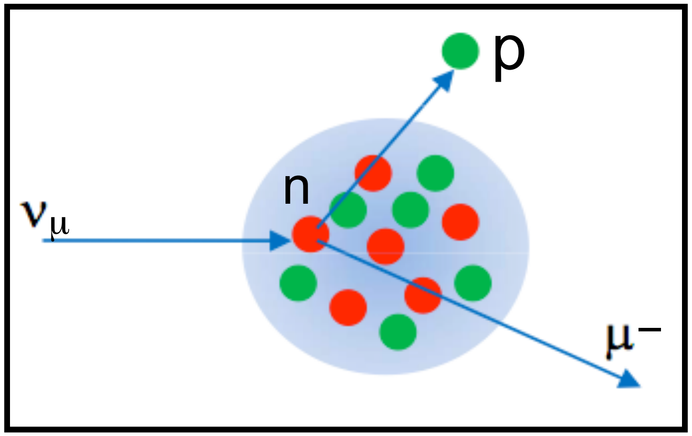
- large span at any given E_ν
- typically assign
  ~20% σ uncertainty
  at these energies
  (recall: known to <0.5% E_ν<10 MeV)
- most of the data on D_2
- oscillation experiments use heavier targets!



intermediate
(~ 1 GeV)

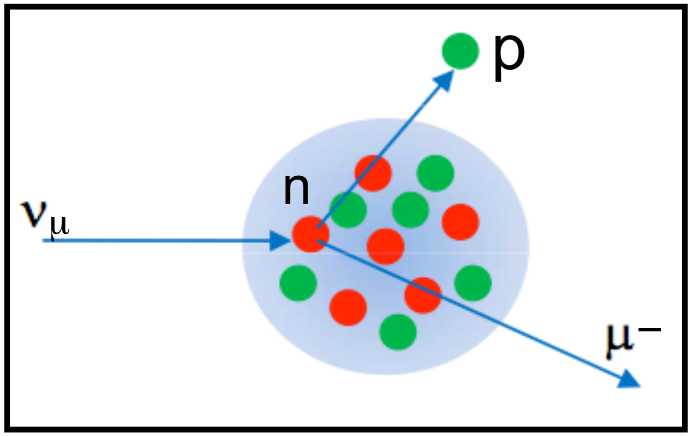
Nuclear Effects

- for ν scattering off heavier targets (^{12}C, ^{16}O, ^{56}Fe, etc,), need to account for fact that nucleons are in fact part of a nucleus



intermediate
(~ 1 GeV)

Nuclear Effects

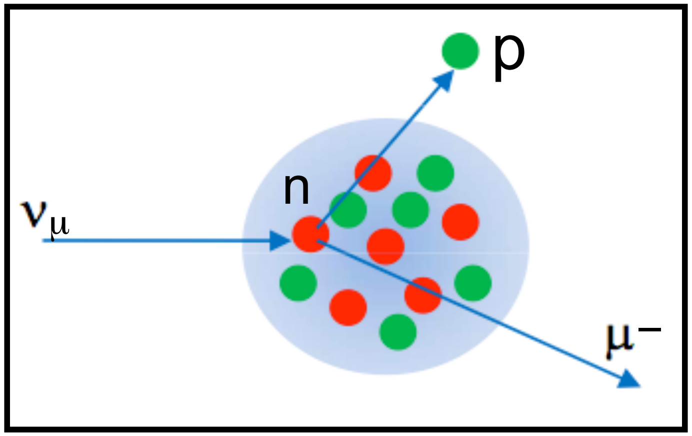


- in a nucleus, target nucleon has some initial momentum which modifies the observed scattering

intermediate
(~ 1 GeV)

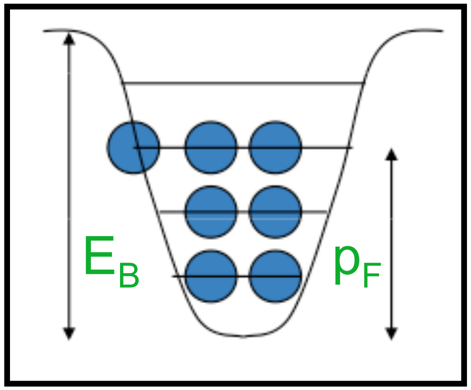
Nuclear Effects

- in a nucleus, target nucleon has some initial momentum which modifies the observed scattering



- hadronic tensor now an integral over initial nucleon states

$$W_A^{\mu\nu} = \frac{1}{2}\int d^3p\,dE\,P(\mathbf{p},E)\,\frac{1}{4\,E_{|\mathbf{p}|}\,E_{|\mathbf{p}+\mathbf{q}|}}\,W^{\mu\nu}(\tilde{p},\tilde{q})$$



- simplest: **Fermi Gas model**
  (2 free parameters)

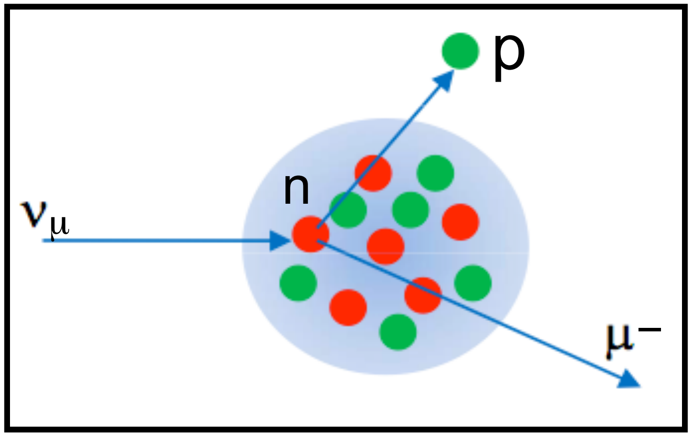
p_F=220 MeV/c (^{12}C)
E_B =25 MeV

$$P_{RFGM}(\mathbf{p},E) = \left(\frac{6\,\pi^2\,A}{p_F^3}\right)\theta(p_F - \mathbf{p})\,\delta(E_{\mathbf{p}} - E_B + E)$$

intermediate
(~ 1 GeV)

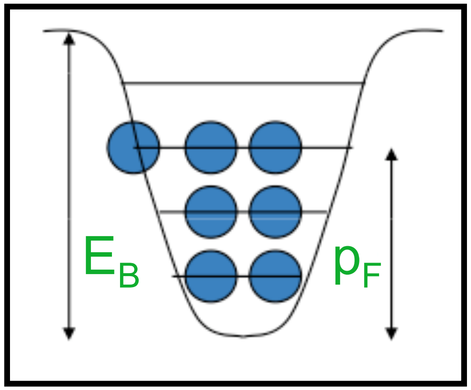
Nuclear Effects

- in a nucleus, target nucleon has some initial momentum which modifies the observed scattering



- hadronic tensor now an integral over initial nucleon states

$$W_A^{\mu\nu} = \frac{1}{2}\int d^3p\, dE\, \boxed{P(\mathbf{p},E)}\, \frac{1}{4\, E_{|\mathbf{p}|}\, E_{|\mathbf{p}+\mathbf{q}|}}\, W^{\mu\nu}(\tilde{p},\tilde{q})$$



- simplest: **Fermi Gas model**

(2 free parameters)

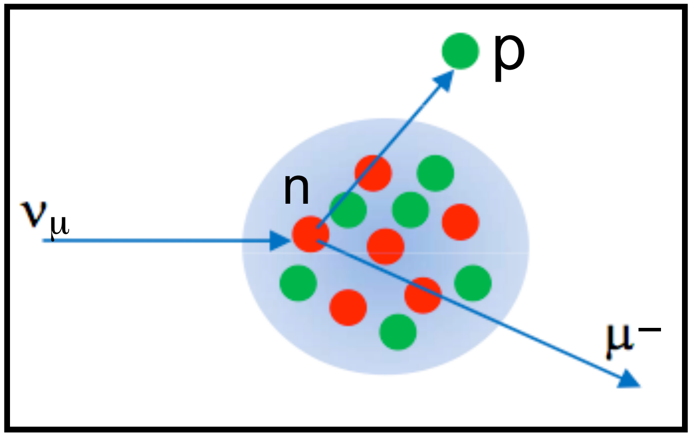
p_F=220 MeV/c (^{12}C)
E_B =25 MeV

- energy transfer > E_B
- final state: p_p > p_F (Pauli blocking)

intermediate
(~ 1 GeV)

Nuclear Effects

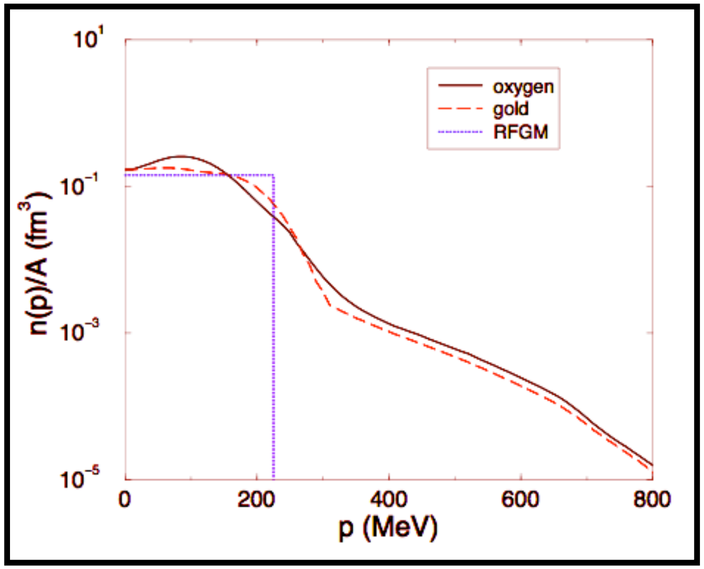
- in a nucleus, target nucleon has some initial momentum which modifies the observed scattering



- hadronic tensor now an integral over initial nucleon states

$$W_A^{\mu\nu} = \frac{1}{2}\int d^3p\, dE\, \boxed{P(\mathbf{p}, E)}\, \frac{1}{4\, E_{|\mathbf{p}|}\, E_{|\mathbf{p}+\mathbf{q}|}}\, W^{\mu\nu}(\tilde{p}, \tilde{q})$$

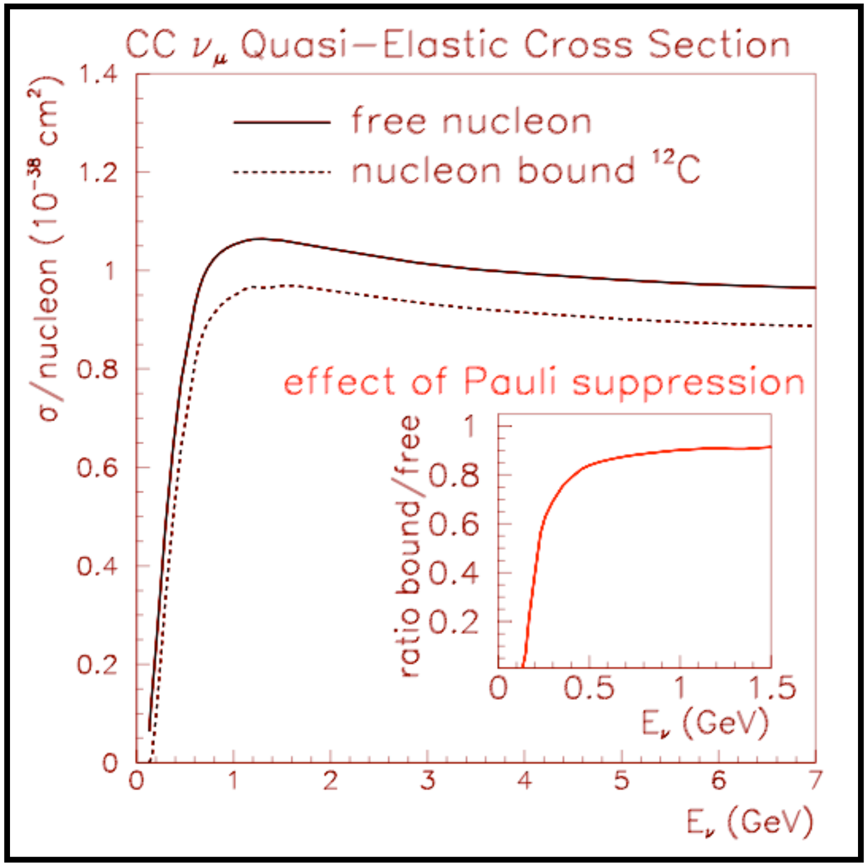
- simplest: **Fermi Gas model**
- more realistic: **spectral functions**
  superscaling



intermediate
(~ 1 GeV)

Nuclear Effects

- this gives a different σ for scattering off nucleons bound in nuclei than for scattering off free nucleons

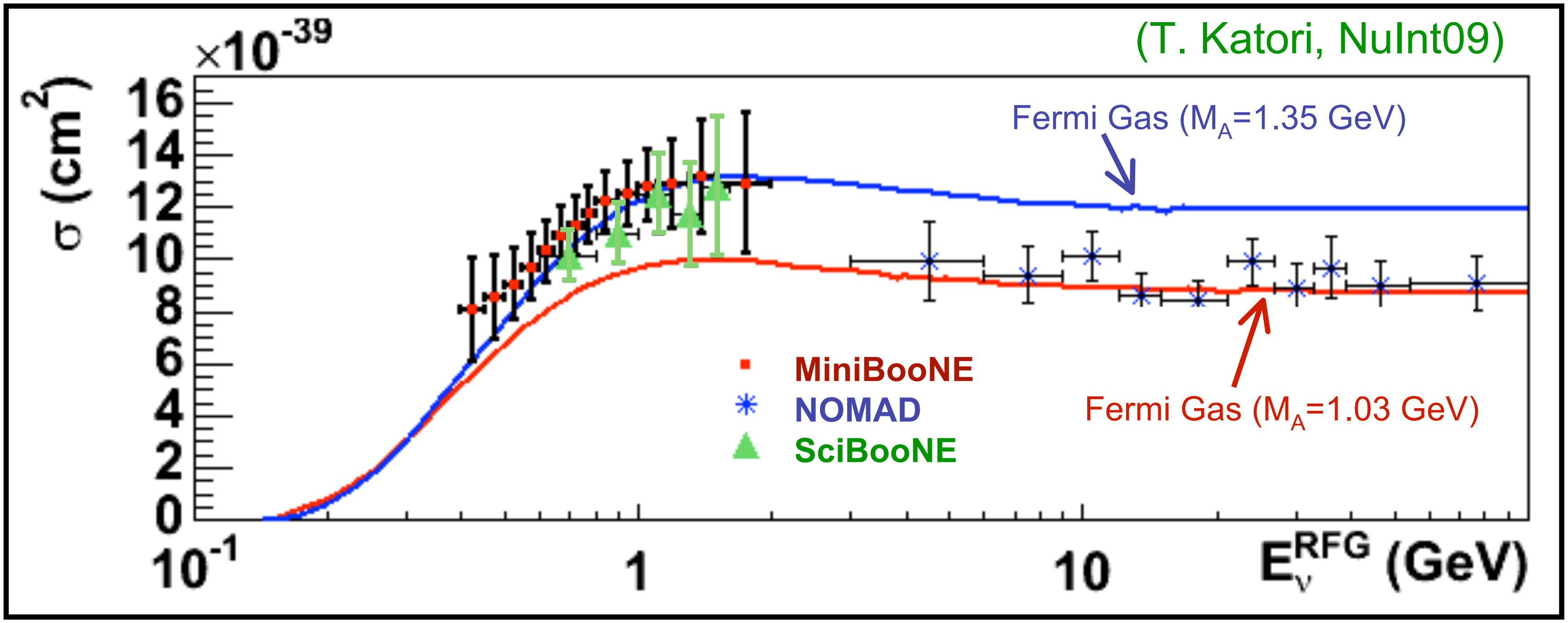


- significant suppression at low E_ν (and low Q^2) if the target is ^{12}C, ^{16}O, etc.

intermediate
(~ 1 GeV)

ν_μ QE Scattering on ^{12}C

- modern measurements of QE σ at these energies


(T. Katori, NuInt09)

- ~ 30% difference between QE σ measured at low & high E both on ^{12}C ?!

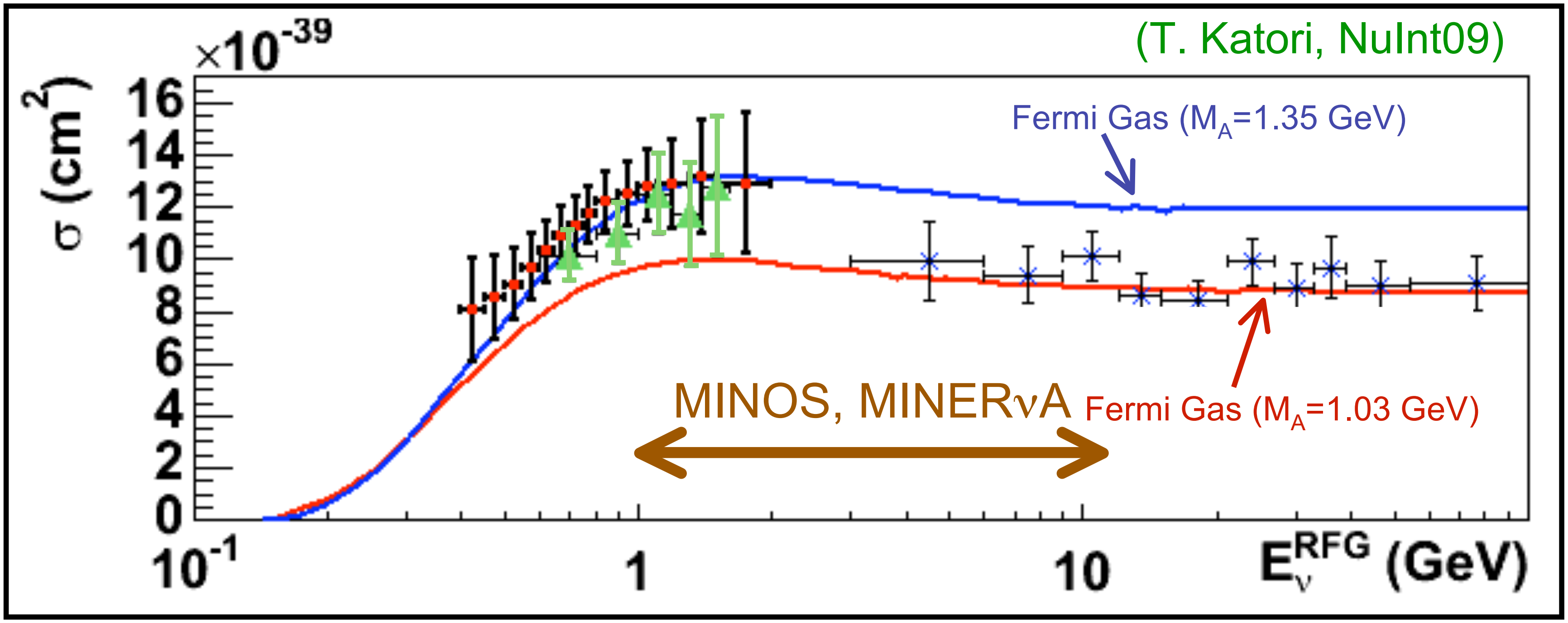
?

who ordered this?

intermediate
(~ 1 GeV)

ν_μ QE Scattering on ^{12}C

- modern measurements of QE σ at these energies



- good news is that will have results soon from NuMI experiments here at Fermilab

intermediate
(~ 1 GeV)

ν_μ QE Scattering on ^{12}C

M_A & nuclear effects important for accurate prediction of ν QE scattering at ~1 GeV

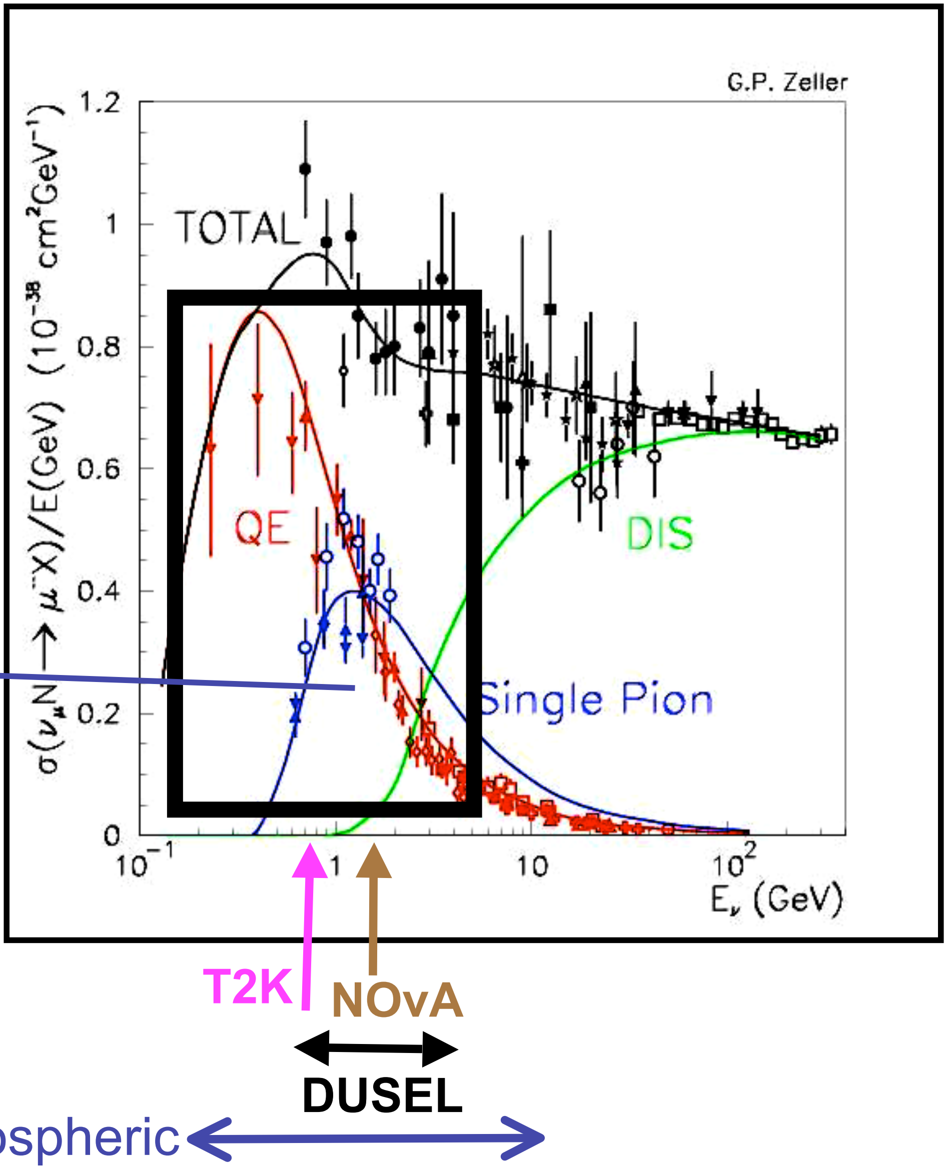
(atmospheric, accelerator)

intermediate
(~ 1 GeV)

Intermediate Energies

- as ν energy increases, other channels open up & QE process becomes less important

single pion production

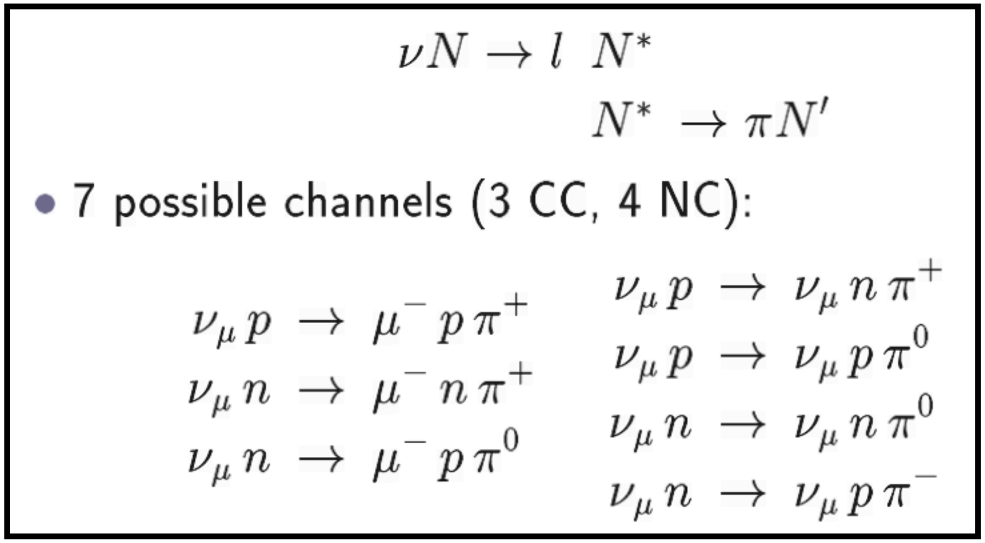


atmospheric

intermediate
(~ 1 GeV)

Resonance Production

- if have enough E, can excite the nucleon to a baryonic resonance



$$\nu N \rightarrow l \;\; N^*$$

$$N^* \;\rightarrow \pi N'$$

- 7 possible channels (3 CC, 4 NC):

$$\begin{aligned} \nu_\mu\, p &\rightarrow \mu^-\, p\, \pi^+ \\ \nu_\mu\, n &\rightarrow \mu^-\, n\, \pi^+ \\ \nu_\mu\, n &\rightarrow \mu^-\, p\, \pi^0 \end{aligned}$$

$$\begin{aligned} \nu_\mu\, p &\rightarrow \nu_\mu\, n\, \pi^+ \\ \nu_\mu\, p &\rightarrow \nu_\mu\, p\, \pi^0 \\ \nu_\mu\, n &\rightarrow \nu_\mu\, n\, \pi^0 \\ \nu_\mu\, n &\rightarrow \nu_\mu\, p\, \pi^- \end{aligned}$$

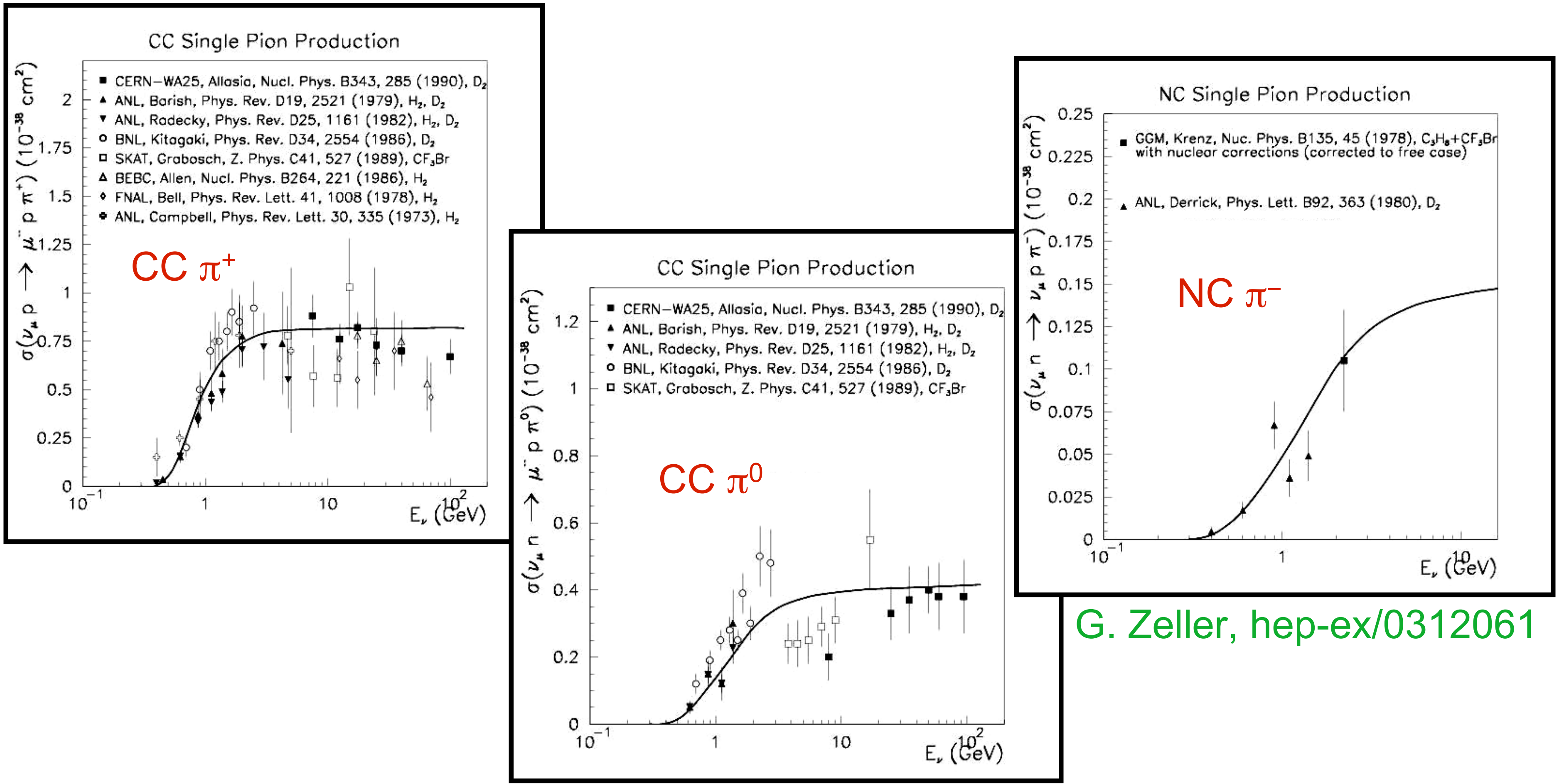
nucleon
+ pion(s)
final state

- main contribution is from Δ(1232) → Nπ
- most widely used model (Rein, Sehgal, Annals Phys **133**, 179 (1981))
- experiments typically simulate ~18 different resonances (Δ,N*) including their single-π & multi-π decay modes, also Δ → Nγ!

intermediate
(~ 1 GeV)

Single π Cross Sections

- variety of σ measurements, mostly bubble chamber experiments (1970's-80's), 25-40% level uncertainties



G. Zeller, hep-ex/0312061

intermediate
(~ 1 GeV)

NC π^0 Production

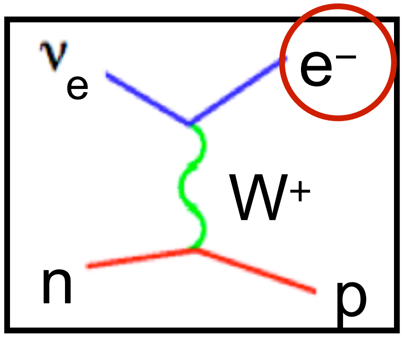
- many channels, let's pick one important example …

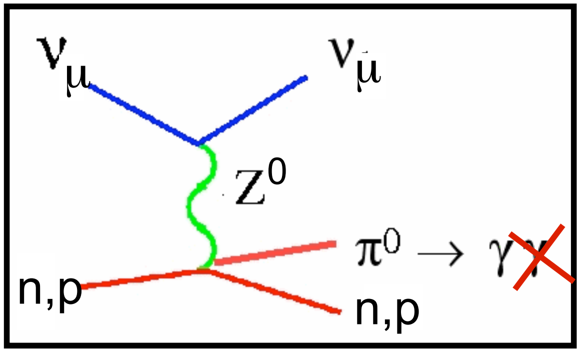
$$\nu_\mu\ N \rightarrow \nu_\mu\ N\ \pi^0$$

- **important for neutrino oscillation experiments**
  - important background for experiments looking for $\nu_\mu \rightarrow \nu_{e}$, θ_{13}

(final state can mimic a QE ν_e interaction, $\pi^0 \rightarrow \gamma\ \cancel{\gamma}$)

signal

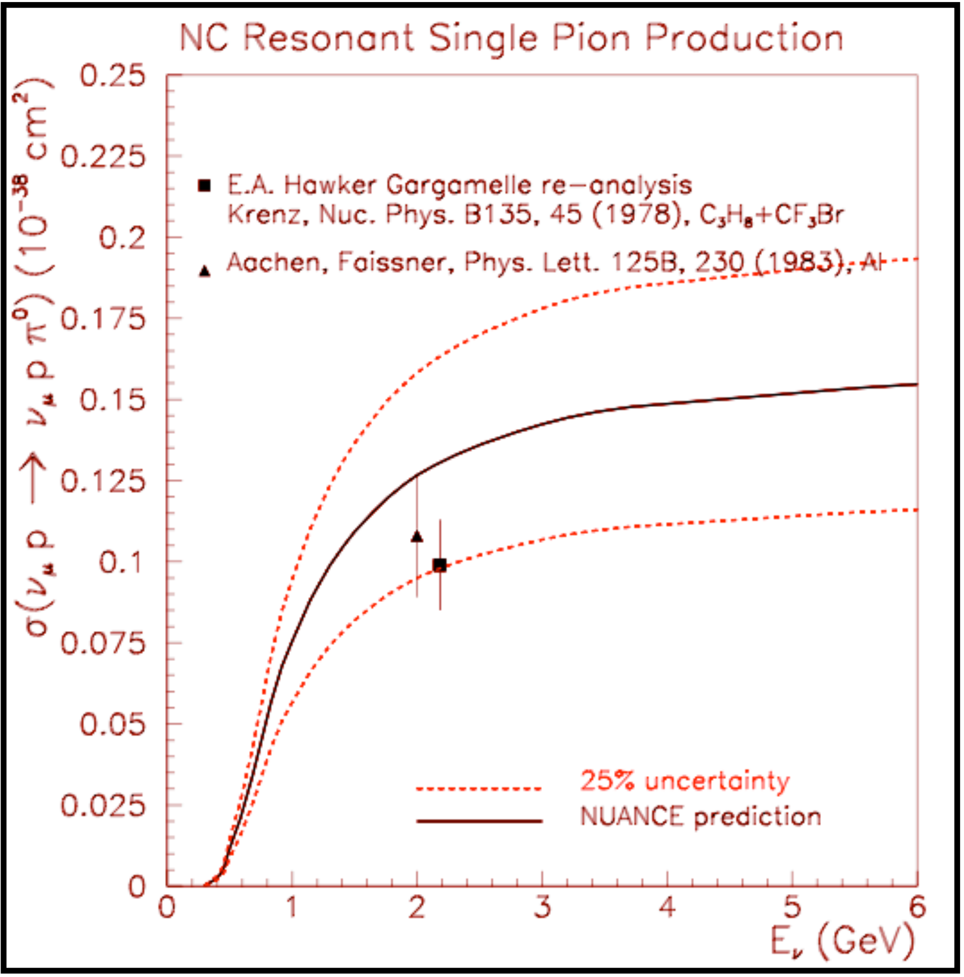




background

intermediate
(~ 1 GeV)

NC π^0 Production



- historically, only two existing measurements of ν_μ NC π^0 production (1978 and 1983)
- together < 500 events

this σ tells you how many π^0 background events should expect to have

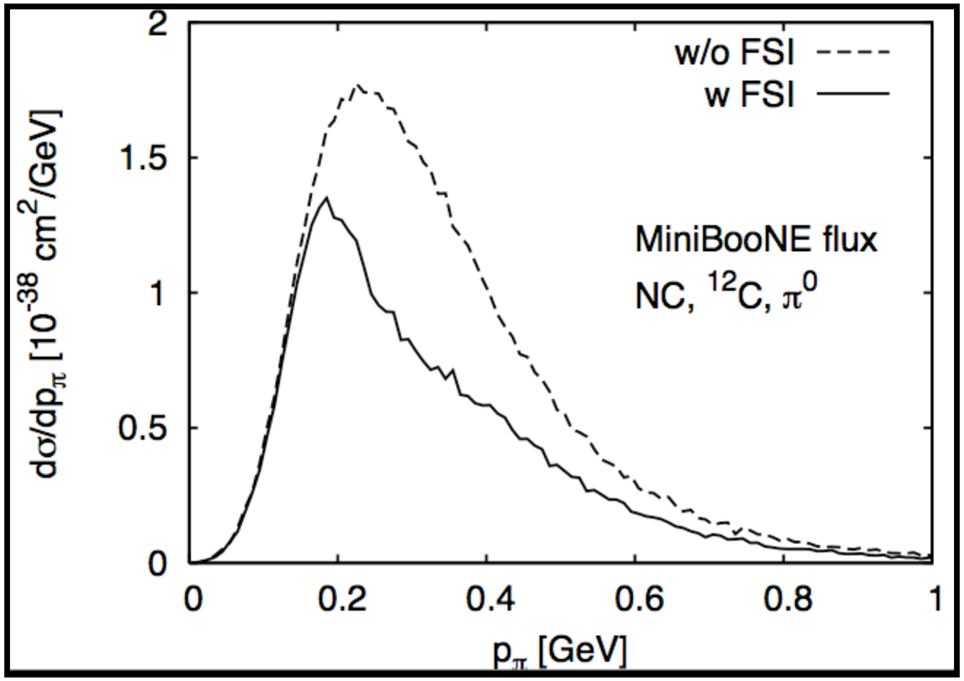
ν osc exps typically assign 25-40% uncertainties to initial interaction σ

intermediate
(~ 1 GeV)

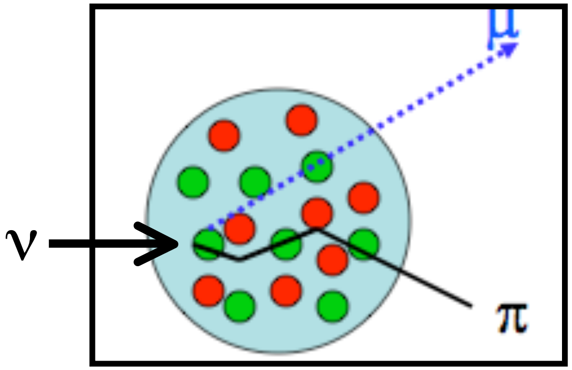
Final State Interactions

- nuclear effects further complicate this description

(once produce π^0, has to get out of nucleus, FSI alter π^0 kinematics!)



(T. Leitner, E_ν beam ~ 1 GeV)



- example, at E_ν=1 GeV

~20% of π^0 get absorbed
~10% charge exchange ($\pi^0 \rightarrow \pi^{+,-}$)

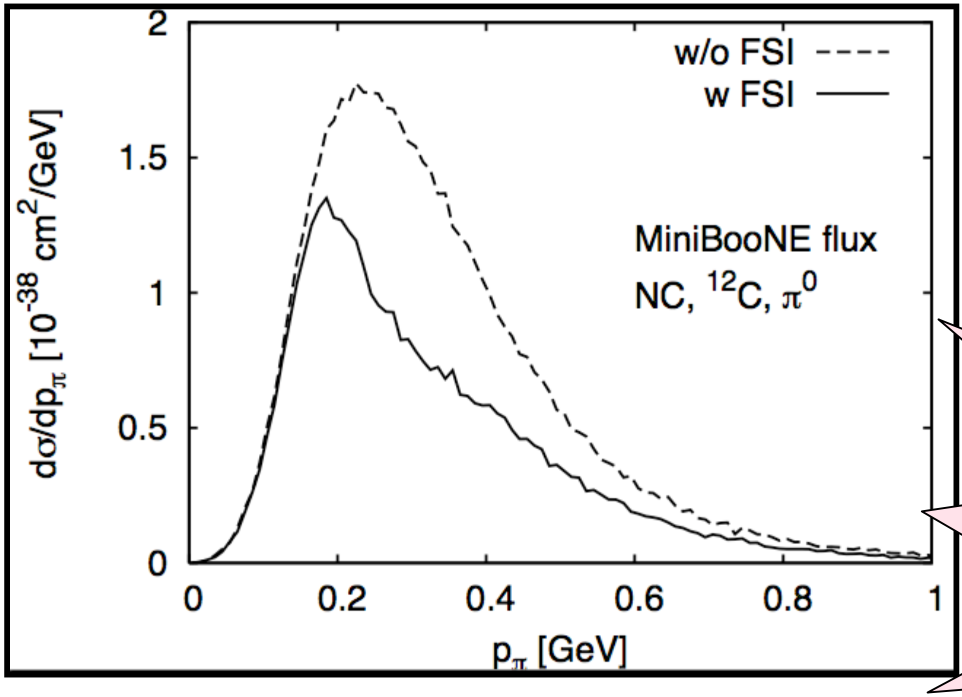
- need to predict initial interaction σ and final state effects

intermediate
(~ 1 GeV)

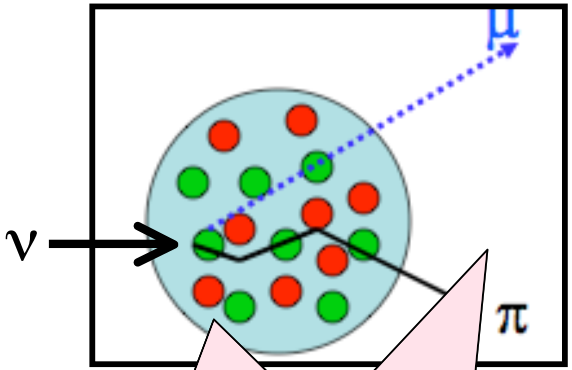
Final State Interactions

- nuclear effects further complicate this description

(once produce π^0, has to get out of nucleus, FSI alter π^0 kinematics!)



(T. Leitner, E_ν beam ~ 1 GeV)



- exa

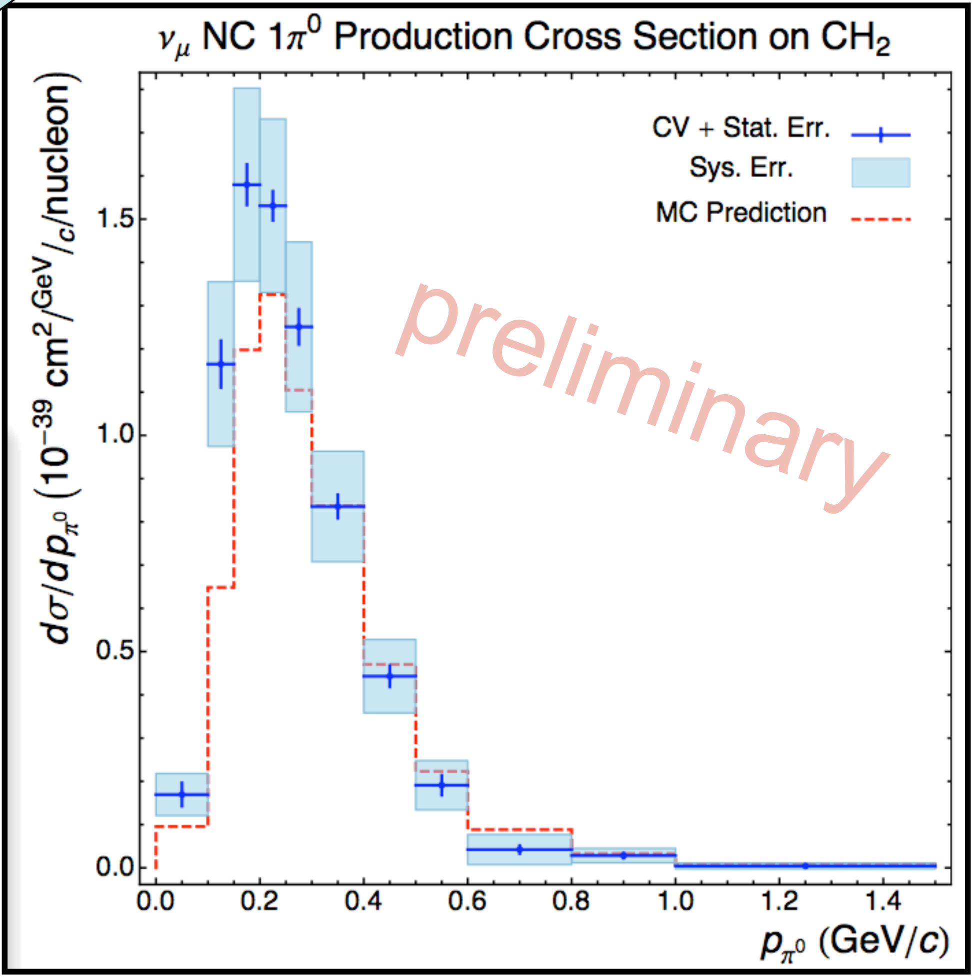
~1)

must measure to predict ν_e backgrounds!

- need to predict initial interaction σ and fin state effects

intermediate
(~ 1 GeV)

NC π^0 Production in Nuclei



- ν experiments are just starting to take a careful look at this

- 21,542 ν_μ NC π^0 events measured in MiniBooNE (^{12}C)

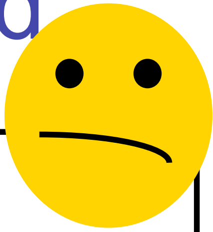
(C. Anderson, NuInt09, May 2009)

(16% measurement)

intermediate
(~ 1 GeV)

Los Alamos

Intermediate Energy Scorecard



process	σ uncertainty	importance
QE	~20-30% (M_A? nuclear effects?)	signal channel for **atmospheric** & **accelerator-based** ν osc exps
π production	~25-40% + FSI uncertainties	background channels for **atmos** & **accelerator-based** ν osc exps

- σ's about an order of magnitude less well known than what we saw at low energy … complex region
- nuclear effects & FFs create added complications & uncertainty

intermediate
(~ 1 GeV)

What I Didn't Talk About

- **coherent π production** ($\nu_\mu A \rightarrow \nu_\mu A\pi^0$, $\nu_\mu A \rightarrow \mu^- A\pi^+$)

  - small fraction of total π production
  - large uncertainties in its contribution at ~ 1 GeV
  - still trying to sort out experimentally

- **NC elastic scattering** ($\nu p \rightarrow \nu p$, $\nu n \rightarrow \nu n$)

  - NC analogue of QE scattering
  - follows exact same description as QE (add $\sin^2\theta_w$, Δs)
  - can use to measure M_A, Δs

- **extrapolation of DIS into intermediate energy region**

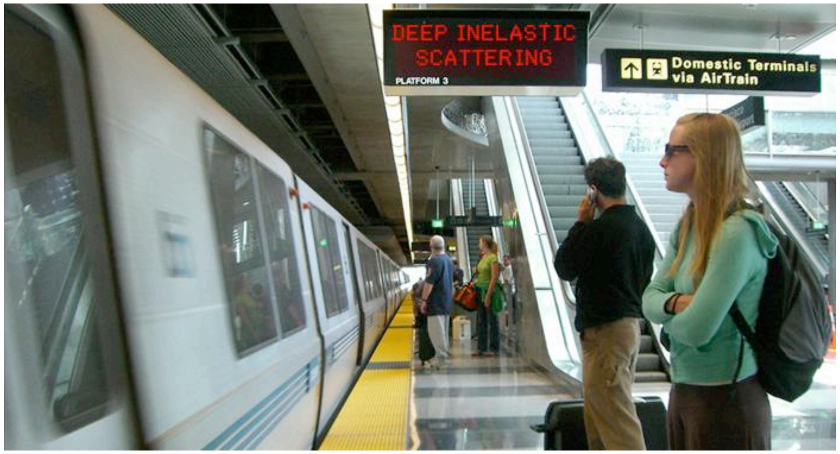
  - feed-down into low energy region
  - will talk about DIS next …

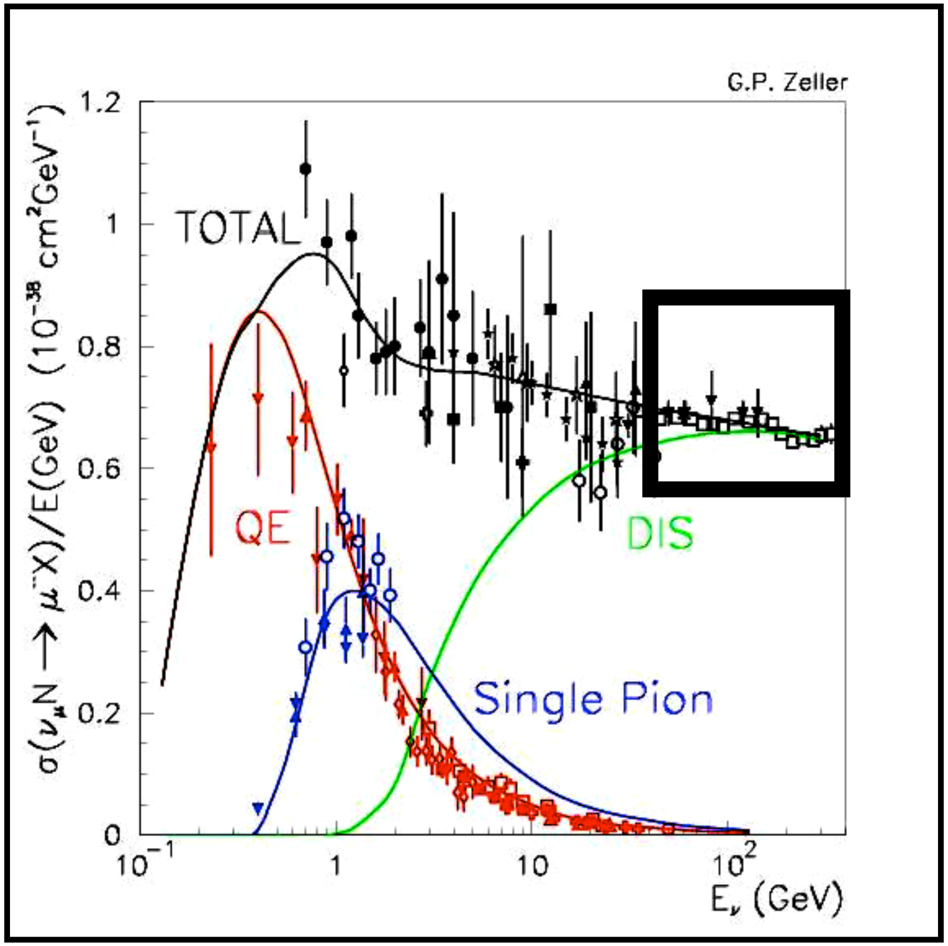
high E
(100's GeV)

ν DIS Cross Sections

- let's move up to an energy range where safely in deep inelastic scattering (DIS) regime

- dominant process at these energies





high E
(100's GeV)

ν DIS Cross Sections

nucleons

↓

pions

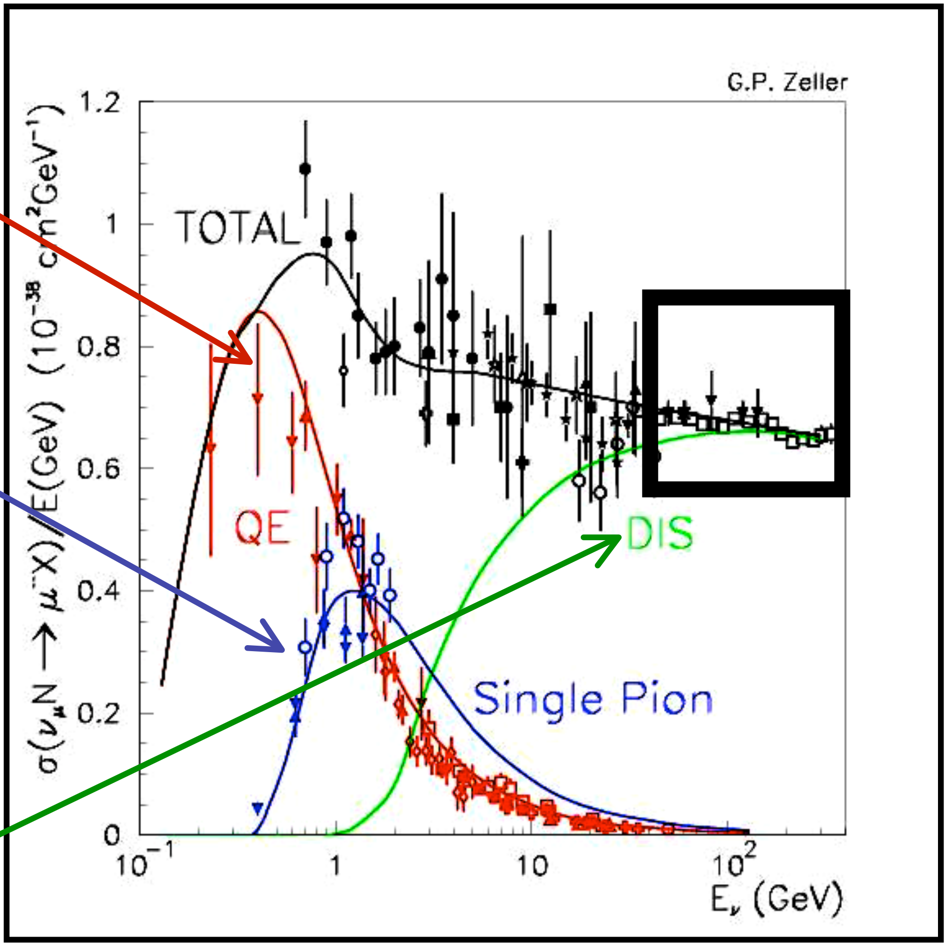
↓

hadronic shower

nucleon stays intact
$(\nu_\mu\ n \rightarrow \mu^-\ p)$

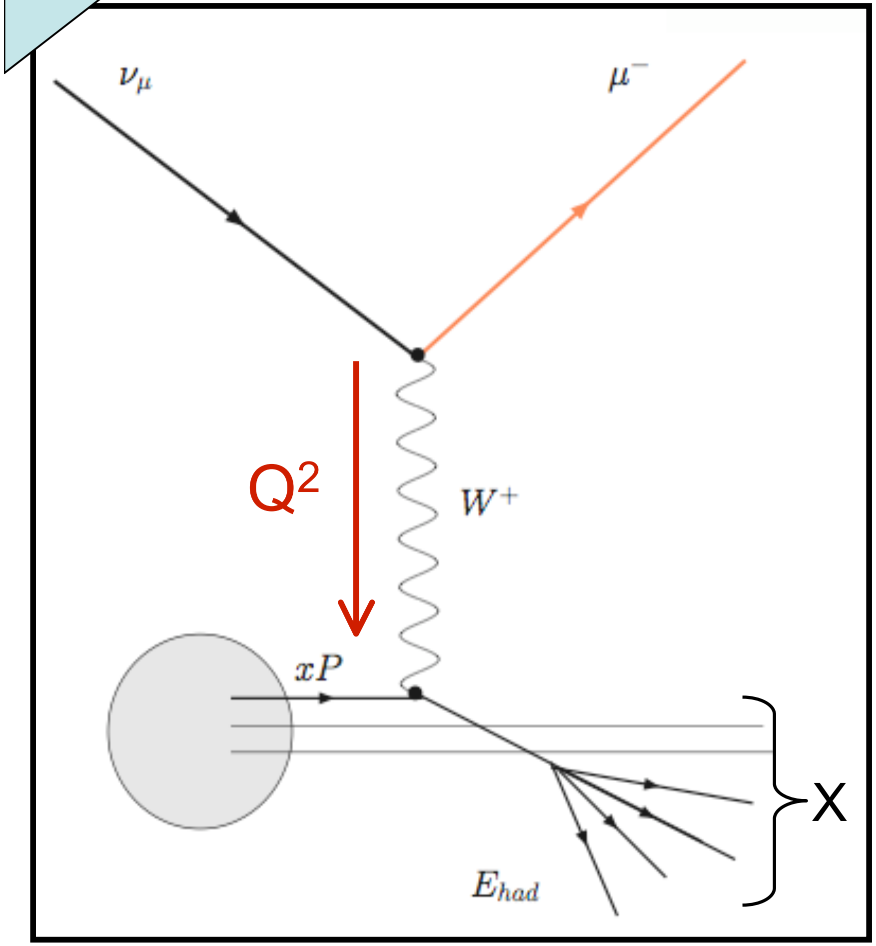
nucleon goes to excited state
$(\Delta \text{ or } N^* \rightarrow N\ \pi)$

nucleon breaks up
$(\nu_\mu\ N \rightarrow \mu^-\ X)$



high E
(100's GeV)

Deep Inelastic Scattering



$$\nu_\mu \, N \to \mu^- \, X$$

- in the quark parton model, these reactions are described as the scattering of ν's from q (and $\bar{q}$) constituents in nucleon

$$Q^2 = 4(E_\mu + E_{had})E_\mu \sin^2\frac{\theta_\mu}{2}$$ (4-momentum transfer squared)

$\nu = E_{had}$ (energy transfer)

$y = E_{had}/E_\nu$ (inelasticity)

$$x = \frac{Q^2}{2M\nu}$$ (fraction of the nucleon momentum carried by struck quark, i.e. Bjorken x)

high E
(100's GeV)

ν DIS Cross Section

- written in its simplest form …

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2\,y}{16\pi}\frac{1}{(1+Q^2/M_{W,Z}^2)^2}\,\underline{L_{\mu\nu}W^{\mu\nu}}$$

vector boson propagator

just like
in QE case

ν DIS Cross Section

- written in its simplest form …

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2\,y}{16\pi}\,\frac{1}{(1+Q^2/M_{W,Z}^2)^2}\,L_{\mu\nu}W^{\mu\nu}$$

leptonic tensor

$$L_{\mu\nu} = 2\,\mathrm{Tr}[(\not{k}'+m)\gamma_\mu(1-\gamma_5)\,\not{k}\,\gamma_\nu]$$

hadronic tensor

$$\begin{aligned} W^{\mu\nu} = & -\; g^{\mu\nu}\,W_1(x,Q^2) + \frac{p^\mu p^\nu}{M^2}\,W_2(x,Q^2) - i\epsilon^{\mu\nu\lambda\sigma}\frac{p_\lambda q_\sigma}{2M^2}\,W_3(x,Q^2) \\ & +\; \frac{q^\mu q^\nu}{M^2}\,W_4(x,Q^2) + (p^\mu q^\nu + p^\nu q^\mu)\,W_5(x,Q^2) \end{aligned}$$

W_i called
“structure functions”
rather than “form factors”
(but idea is the same)

(contains all of the information about nucleon structure)

high E
(100's GeV)

ν DIS Cross Section

- for simplicity, the W_i usually replaced by dimensionless F_i

$$F_1(x,Q^2) = W_1(x,Q^2)$$
$$F_2(x,Q^2) = \frac{\nu}{M} W_2(x,Q^2)$$
$$F_3(x,Q^2) = \frac{\nu}{M} W_3(x,Q^2)$$
$$F_4(x,Q^2) = \frac{\nu}{M} W_4(x,Q^2)$$
$$F_5(x,Q^2) = W_5(x,Q^2)$$

- at LO, neglecting lepton mass terms, the DIS σ reduces to:

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

F_1, F_2, F_3 contain direct information on nucleon structure;
they are functions of x, Q^2

high E
(100's GeV)

Los Alamos

ν DIS Cross Section

- for simplicity, the W_i usually replaced by dimensionless F_i

$$F_1(x,Q^2) = W_1(x,Q^2)$$
$$F_2(x,Q^2) = \frac{\nu}{M} W_2(x,Q^2)$$
$$F_3(x,Q^2) = \frac{\nu}{M} W_3(x,Q^2)$$
$$F_4(x,Q^2) = \frac{\nu}{M} W_4(x,Q^2)$$
$$F_5(x,Q^2) = W_5(x,Q^2)$$

- at LO, neglecting lepton mass terms, the DIS σ reduces to:

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

- unique to neutrino scattering
- absent for e, μ scattering because it is parity violating
- flips sign in case of $\overline{\nu}$

high E
(100's GeV)

ν DIS Cross Section

- for simplicity, the W_i usually replaced by dimensionless F_i

$$F_1(x,Q^2) = W_1(x,Q^2)$$
$$F_2(x,Q^2) = \frac{\nu}{M} W_2(x,Q^2)$$
$$F_3(x,Q^2) = \frac{\nu}{M} W_3(x,Q^2)$$
$$F_4(x,Q^2) = \frac{\nu}{M} W_4(x,Q^2)$$
$$F_5(x,Q^2) = W_5(x,Q^2)$$

- at LO, neglecting lepton mass terms, the DIS σ reduces to:

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

SFs
expressed in terms
of quark composition
of the target
(PDFs)

$$F_2^{\nu,\overline{\nu}} = 2\sum_i x(Q_i(x) + \overline{Q}_i(x))$$

→ measures density distribution of all quarks & antiquarks in the nucleon

$$xF_3^{\nu,\overline{\nu}} = 2\sum_i x(Q_i(x) - \overline{Q}_i(x))$$

→ measures the valence distribution

high E
(100's GeV)

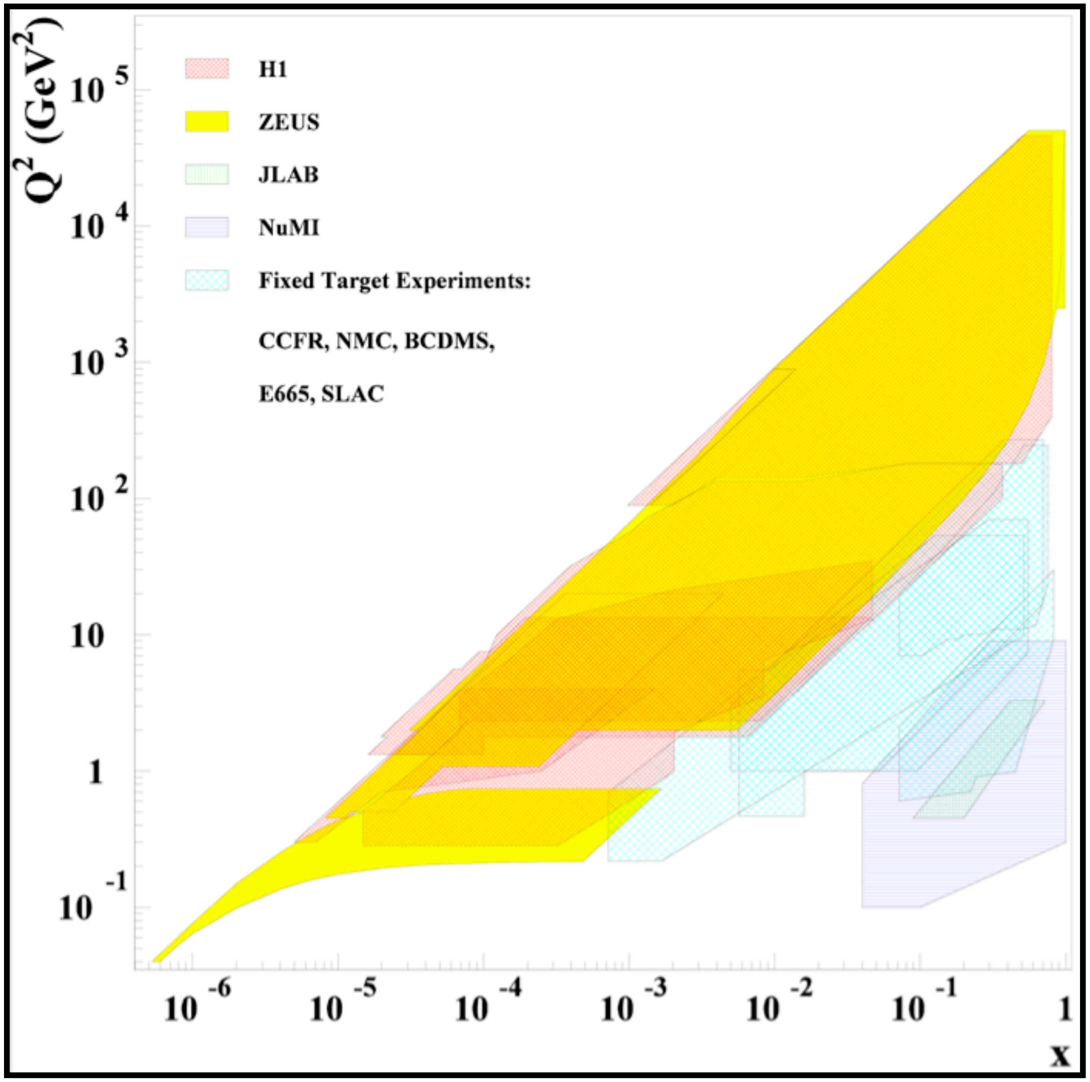
Los Alamos

Experimental Coverage

- structure functions (PDFs) have been measured across an extremely large kinematic range

$0.1 < Q^2 < 10^4$ GeV^2
$10^{-6} < x < 1$

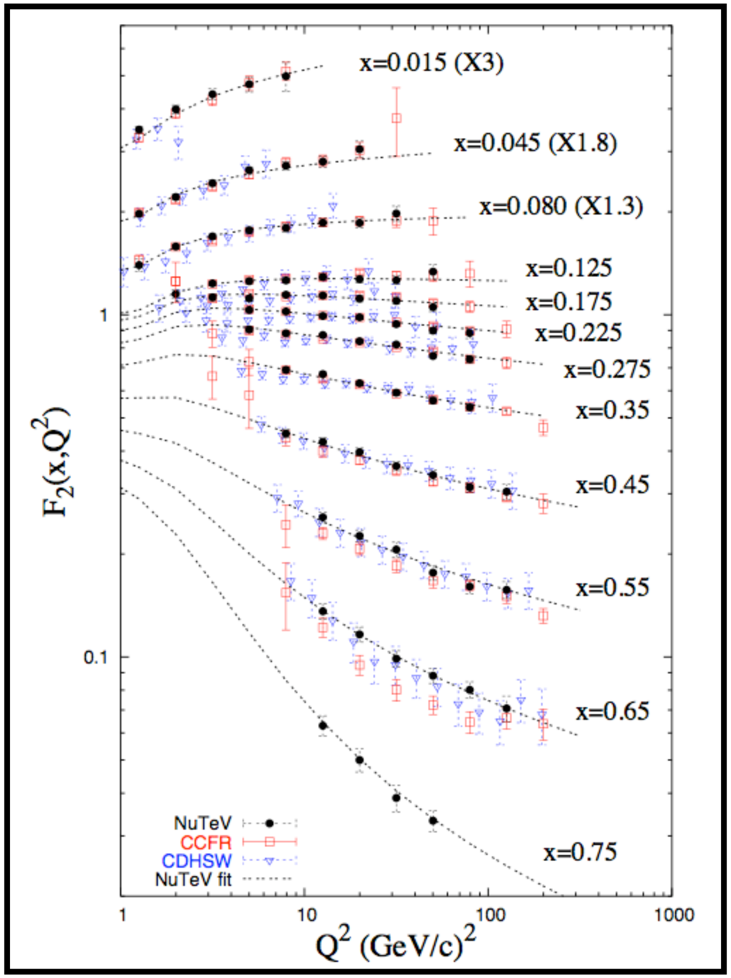
- measurements at HERA (H1, ZEUS) have extended reach to low x, high Q^2

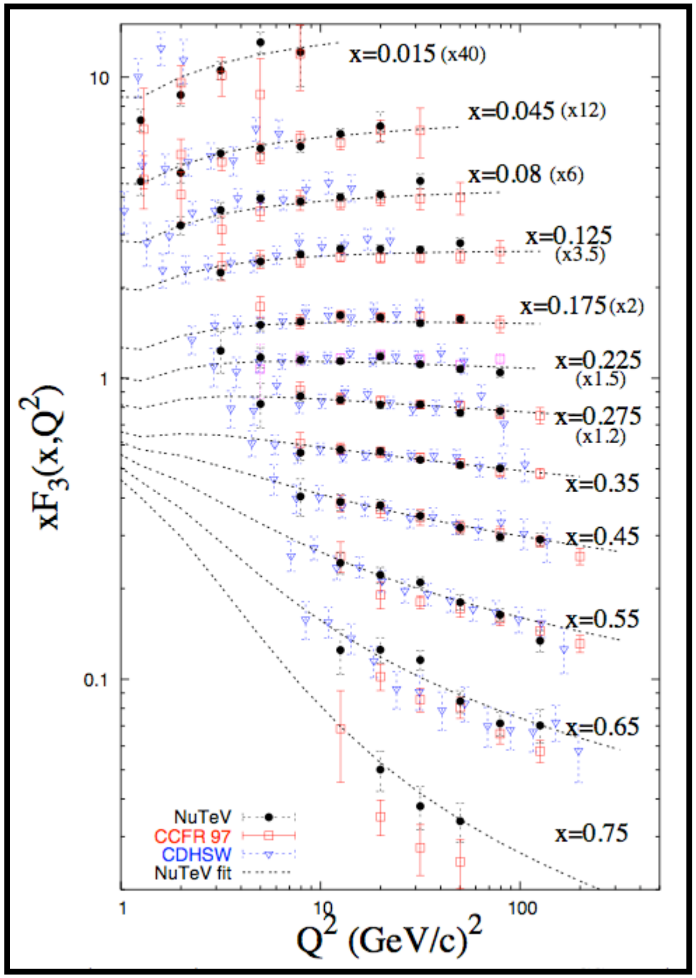


high E
(100's GeV)

Structure Functions

- example from ν DIS experiments ….



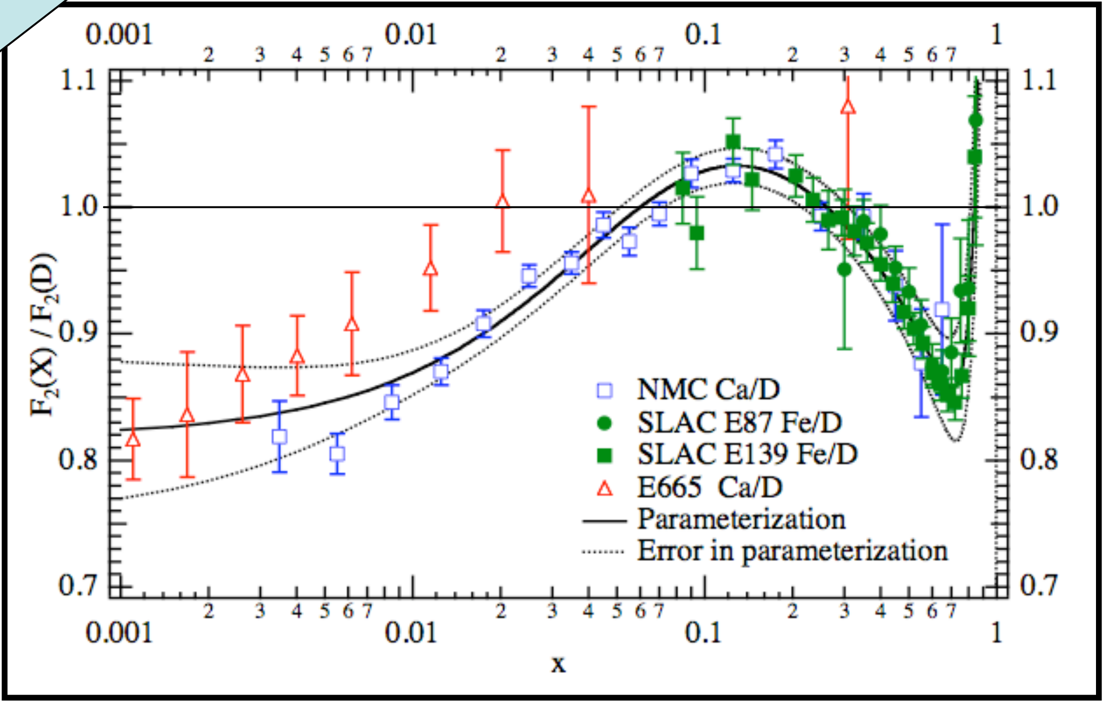


- quark model and pQCD make definite predictions for ν DIS scattering which are beautifully confirmed by experiment

Tzanov *et al.*, PRD 74, 012008 (2006)

high E
(100's GeV)

Nuclear Effects



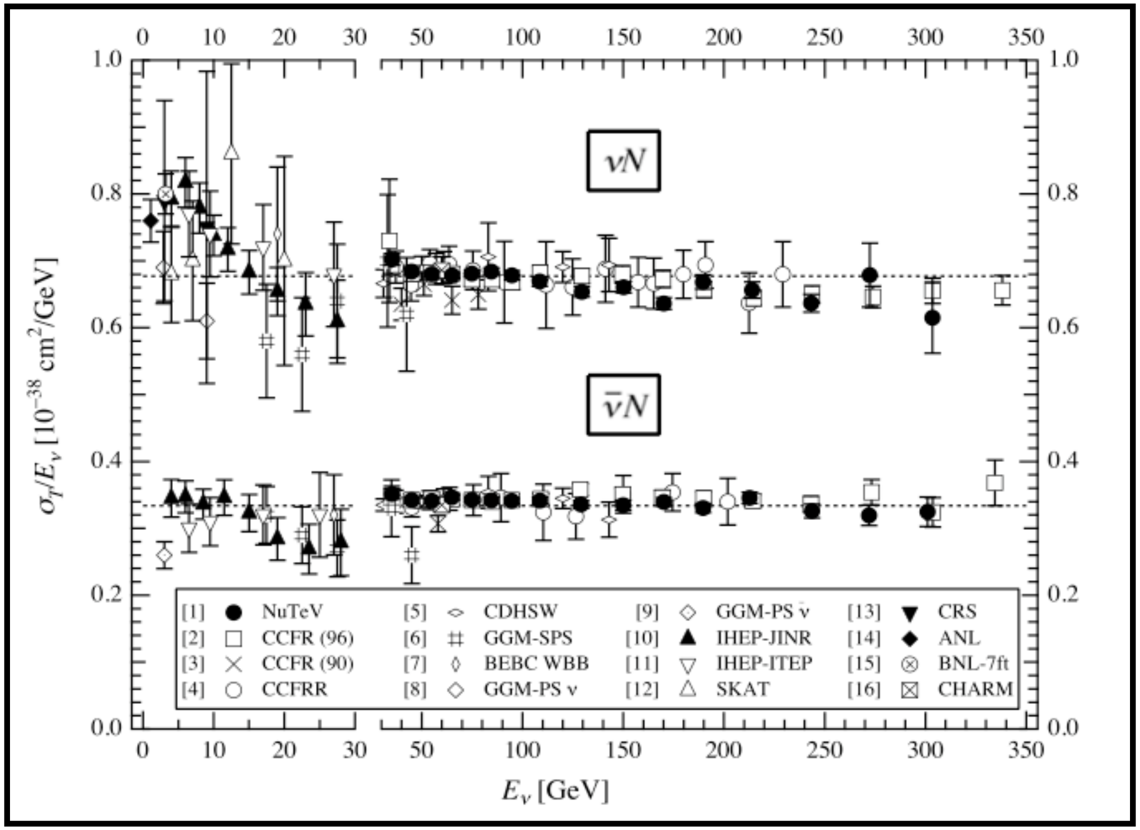
- in charged lepton scattering, observe that the SFs measured on heavy nuclei differ from those on D
- differences observed over entire x region

- if ν scattering on nucleus at these energies, the nucleon structure functions get further modified by nuclear effects
- effects are absorbed into "effective" SFs in nucleus

high E
(100's GeV)

Total νN Cross Section

- if you look in the PDG, you'll see this plot:



PDG, 2009

- the total σ has been measured to 2% level

- is the one place where the neutrino σ is this well measured

high E
(100’s GeV)

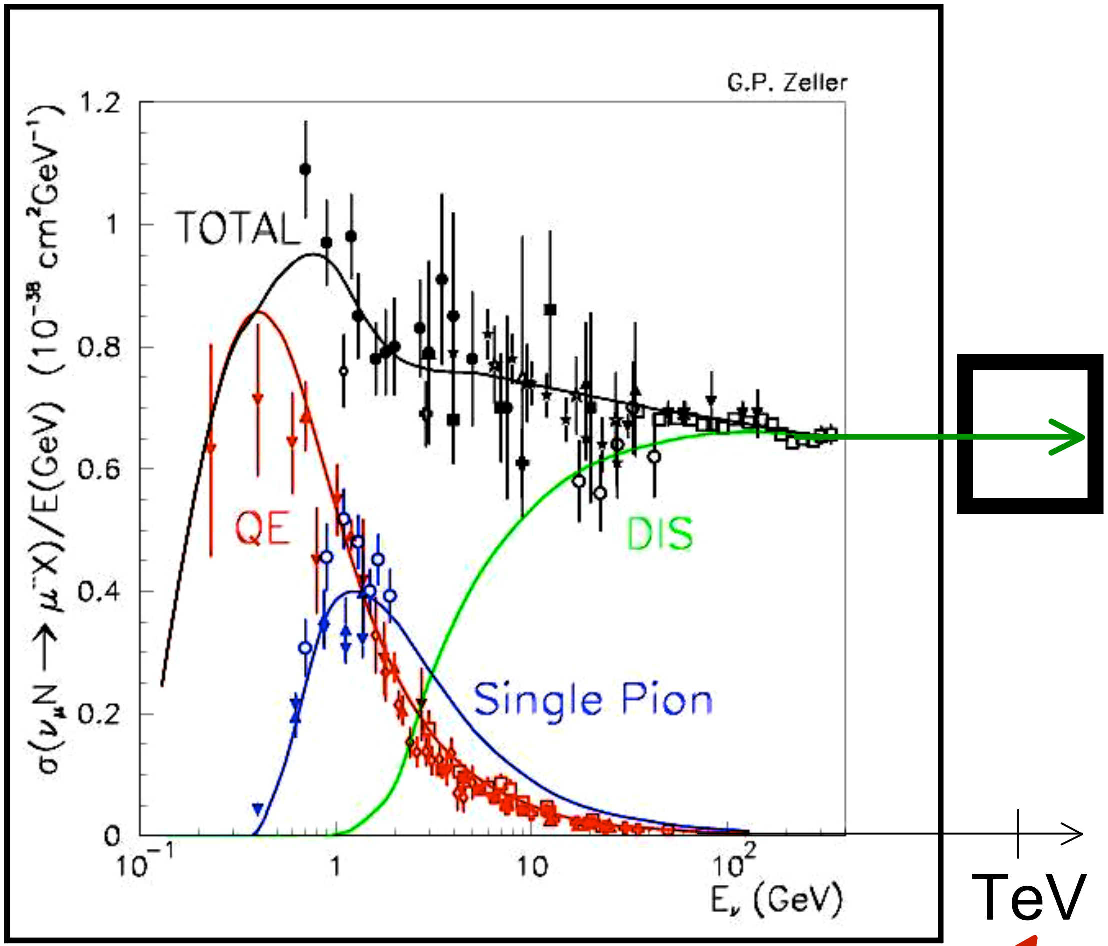
What I Didn't Talk About

- **ν_τ cross sections**
  - need to include add’l SFs that we neglected, α $(m_l)^2$
  - OPERA ($\nu_\mu \rightarrow \nu_\tau$ in CNGS beam)
- **heavy charm production** (ν_μ N $\rightarrow \mu^-$ c X)
  - σ is suppressed at low E_ν (“slow rescaling”, $x \rightarrow \xi$)
  - used to measure s and $\overline{s}$ quarks ($s \rightarrow c$)
- **NC DIS** (ν_μ N $\rightarrow \nu_\mu$ X)
  - formalism is the same ($m_l \rightarrow 0$, add’l couplings ~ $\sin^2\theta_W$)
- **added effects**
  - target mass effects, radiative corrections, NLO (gluons, R_L)

ultra high E
(> TeV)

Ultra High Energy

- ν's with E_ν > TeV
- observation of UHE cosmic rays (>10^{10} GeV) gives hope for a flux of UHE neutrinos
  (Jenni Adam's talk)
- use DIS ν_μ N → μ^- X to detect UHE ν's



AMANDA, Anita, Antares, IceCube, NESTOR, RICE, etc.

ultra high E
(> TeV)

Ultra High Energies

- no man-made machines (existing or planned) can produce particles this high in energy

- use same DIS σ_ν formula but extrapolate to very high E's, far beyond currently available data

$$\left.\begin{array}{l} Q^2 \sim M_W^2 \\ \\ x \sim \dfrac{M_W^2}{2ME_\nu} \end{array}\right\}$$

due to presence of propagator term

$$\frac{1}{(1+Q^2/M_{W,Z}^2)^2}$$

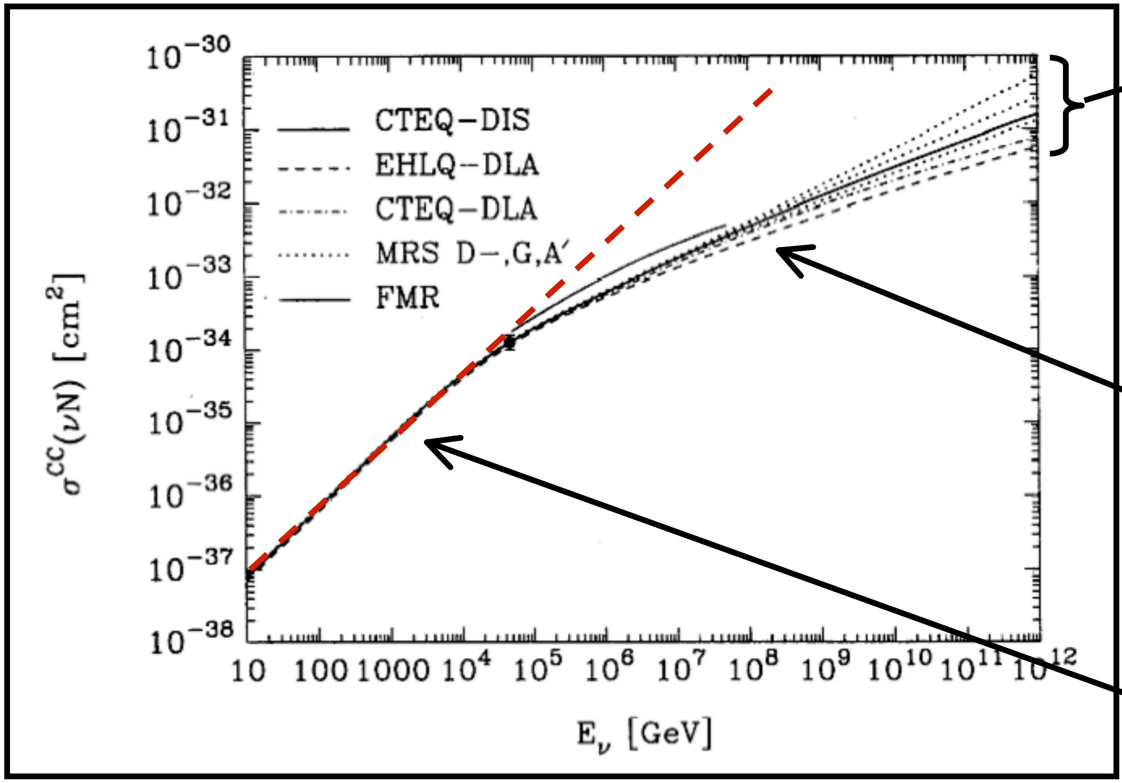
- extrapolation of PDFs to **small x** is crucial at highest energies

(ex., $E_\nu < 10^{12}$ GeV means $Q^2 \sim 10^4$ GeV^2, $x \sim 10^{-8}$ … large extrapolation!)

ultra high E
(> TeV)

Ultra High Energies

$\nu_\mu N \rightarrow \mu^- X$



Gandhi *et al.*, Astropart Phys **5**, 81 (1996)

differences only at very high energy due to differences in small x extrapolation

damping due to propagator

$$\frac{1}{(1+Q^2/M_{W,Z}^2)^2}$$

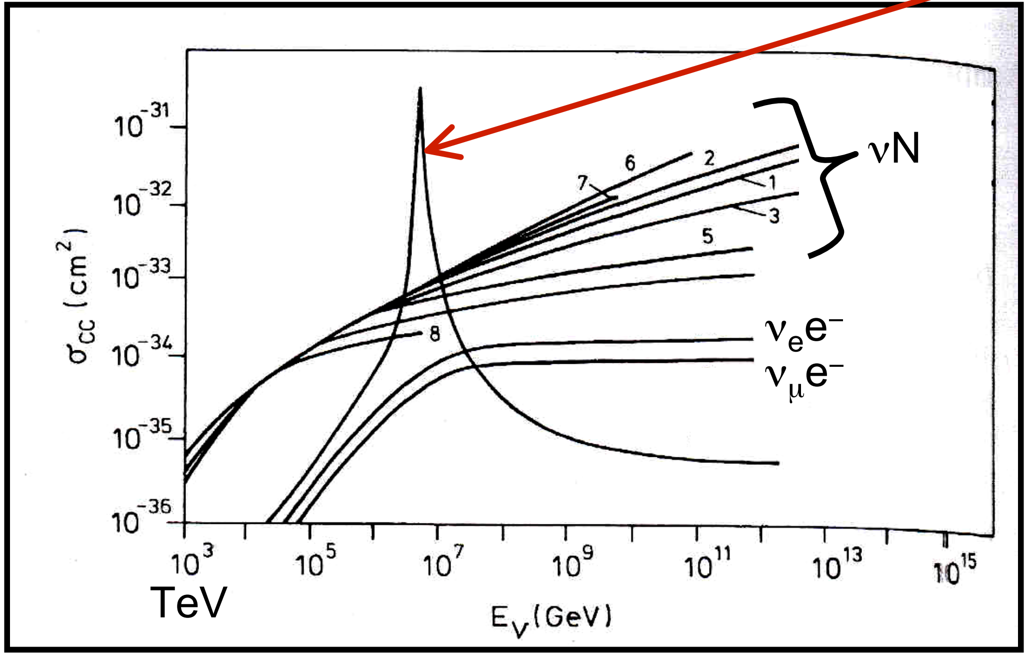
linear rise up to ~ 10^4 GeV ~ M_W^2

- impressive that can predict across 11 orders of magnitude in E_ν!

Ultra High Energy

- over E range of interest for ν astronomy, can generally neglect ν interactions with e⁻'s in earth in comparison to νN; one exception:

$$\bar{\nu}_e\, e^- \rightarrow W^-$$



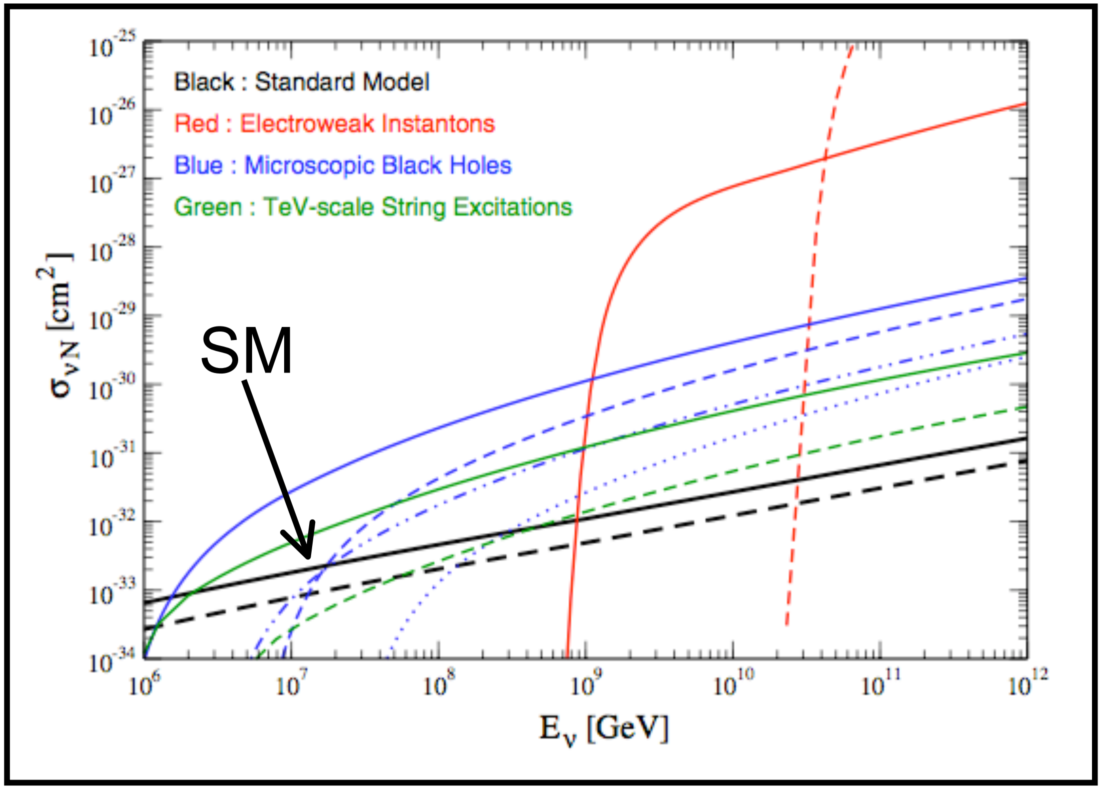
Butkevich *et al.*, Z. Phys. C **39**, 241 (1988)

- resonance at E_ν of $M_W^2/2m_e \sim 6\text{x}10^6$ GeV
- same process first suggested by Glashow (1960) as a means to directly detect W boson

ultra high E
(> TeV)

Physics Beyond SM

- why is this important to predict?



Sarcevic, TeV Astrophys Workshop, Madison ('06)

- at very high E, $\sigma(\nu N)$ can depart substantially from SM if new physics

- probes new physics at E's well beyond LHC

  - LHC ~ 14 TeV
  - UHE ν > 100 TeV

Overall Scorecard

- **low energy** (<100 MeV) inverse β decay, ν-deuteron
  - σ known to 1% or better (<10 MeV)
  - solar, reactor, SN ν's

- β beams
- SNS

- **intermediate energy** (~1 GeV) QE, single-π
  - σ typically known to 20-40%
  - more complicated region + nuclear effects
  - atmospheric, accelerator-based ν's

- MiniBooNE
- SciBooNE
- MINOS ND
- MINERνA!

- **high & ultra-high energy** (100's GeV+) DIS
  - can accurately predict σ to a few-% all the way up to ultra-high energies (~10^7 GeV!)
  - ν astronomy

What You Should Take Away

- ν σ's are small & there are multiple processes that contribute
- σ_ν are at the core of everything; absolutely critical for knowing:
  - how many ν interactions you should expect (N_ν)
  - what those ν interactions will look like (final state)
- need to know σ_ν across a large energy range (MeV to TeV)
- σ_ν well known at low and high energy, less so in the middle (nuclear effects & FFs complicate things, easier if scatter off electrons)
- the demands on our knowledge of σ_ν will be even greater in the future …

Hope You Will Play a Role

- in the future, hopefully you will play a role in either:

  - better measuring these ν cross sections
    (if you're an experimentalist)

  - developing improved theoretical calcs
    (if you're a theorist)

- there is certainly a lot more work to do!

- if you're interested, there is an entire workshop series devoted solely to this topic (NuInt)