

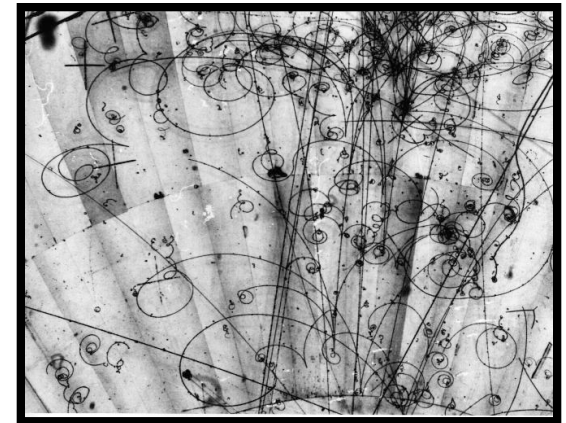
Neutrino Interaction Cross Sections



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

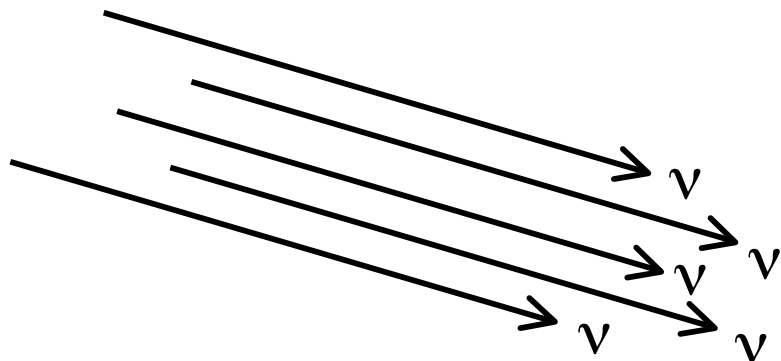
- describe the **important physical processes** necessary to understand ν interactions across a broad energy range
 - we will survey σ_ν 's **from MeV to TeV**
- give a sense of **how well we know** the ν interaction cross sections at each of these energies
- highlight ways in which these cross sections 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 ...

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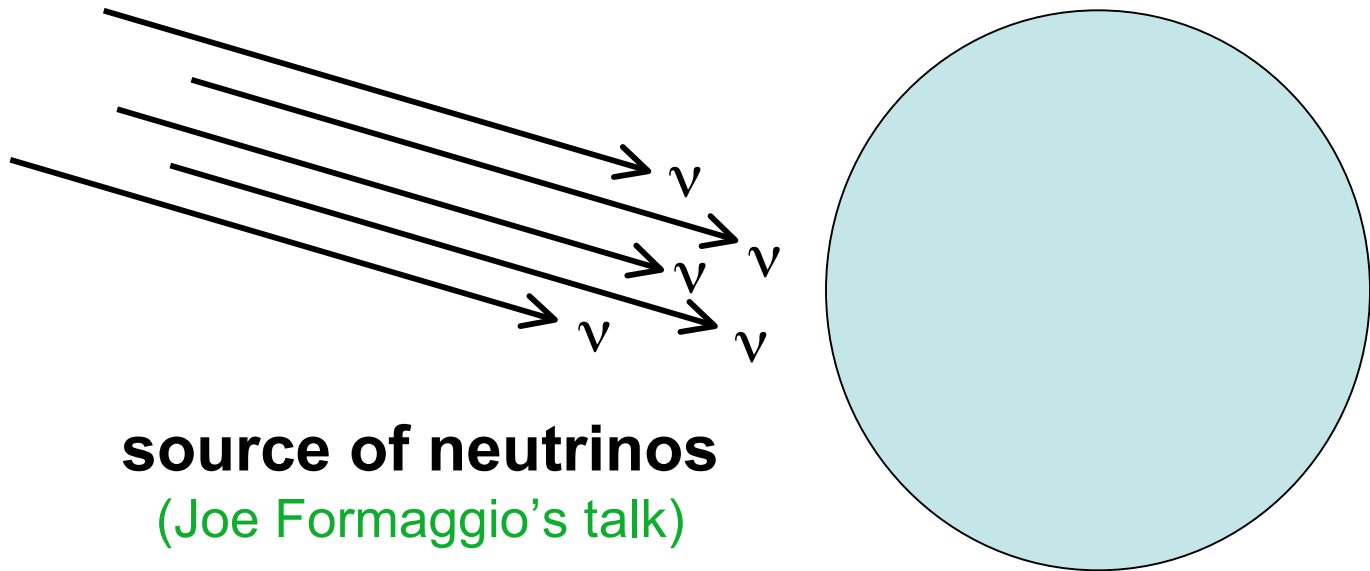
source of neutrinos

(Joe Formaggio's talk)

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

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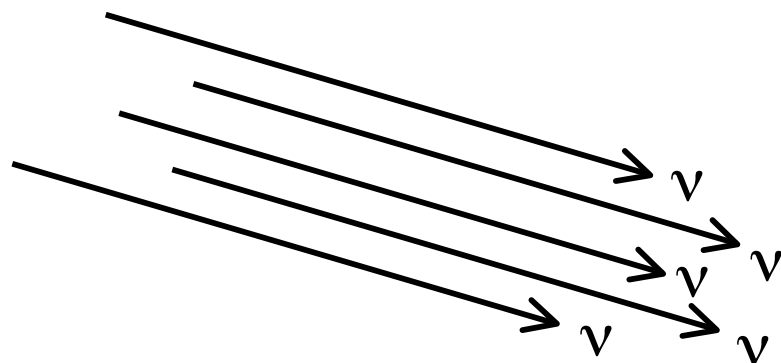
reactor, particle accelerator,
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neutrino detector

(Mark Messier's talk)

Starting Point

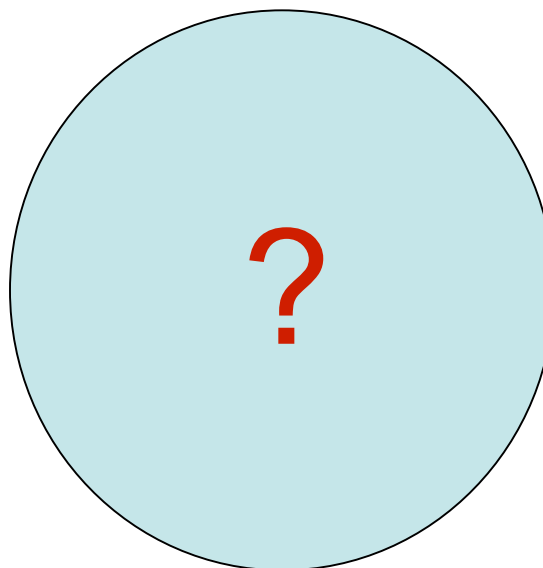
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source of neutrinos

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reactor, particle accelerator,
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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

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

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 ν flux

(# neutrinos)

depends on your ν source

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ν flux

(# neutrinos)

depends on your ν source

ν cross section

tells you probability for ν to interact

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

ν cross section

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

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

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

Number of ν Events

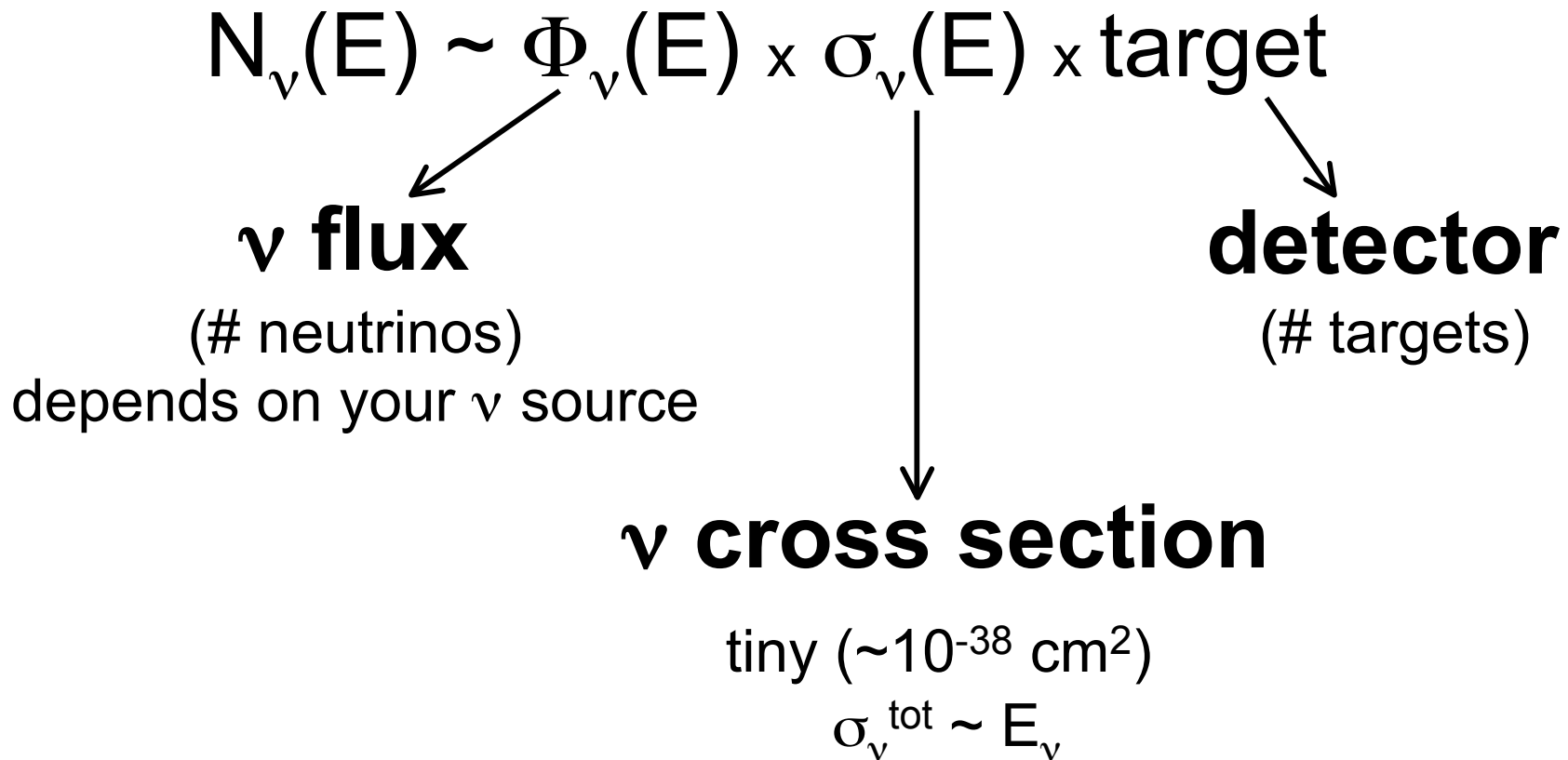
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$$N_{\nu}(E) \sim \Phi_{\nu}(E) \times \sigma_{\nu}(E) \times \text{target}$$

ν flux
(# neutrinos)
depends on your ν source

detector
(# targets)

ν cross section
tiny ($\sim 10^{-38} \text{ cm}^2$)
 $\sigma_{\nu}^{\text{tot}} \sim E_{\nu}$



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

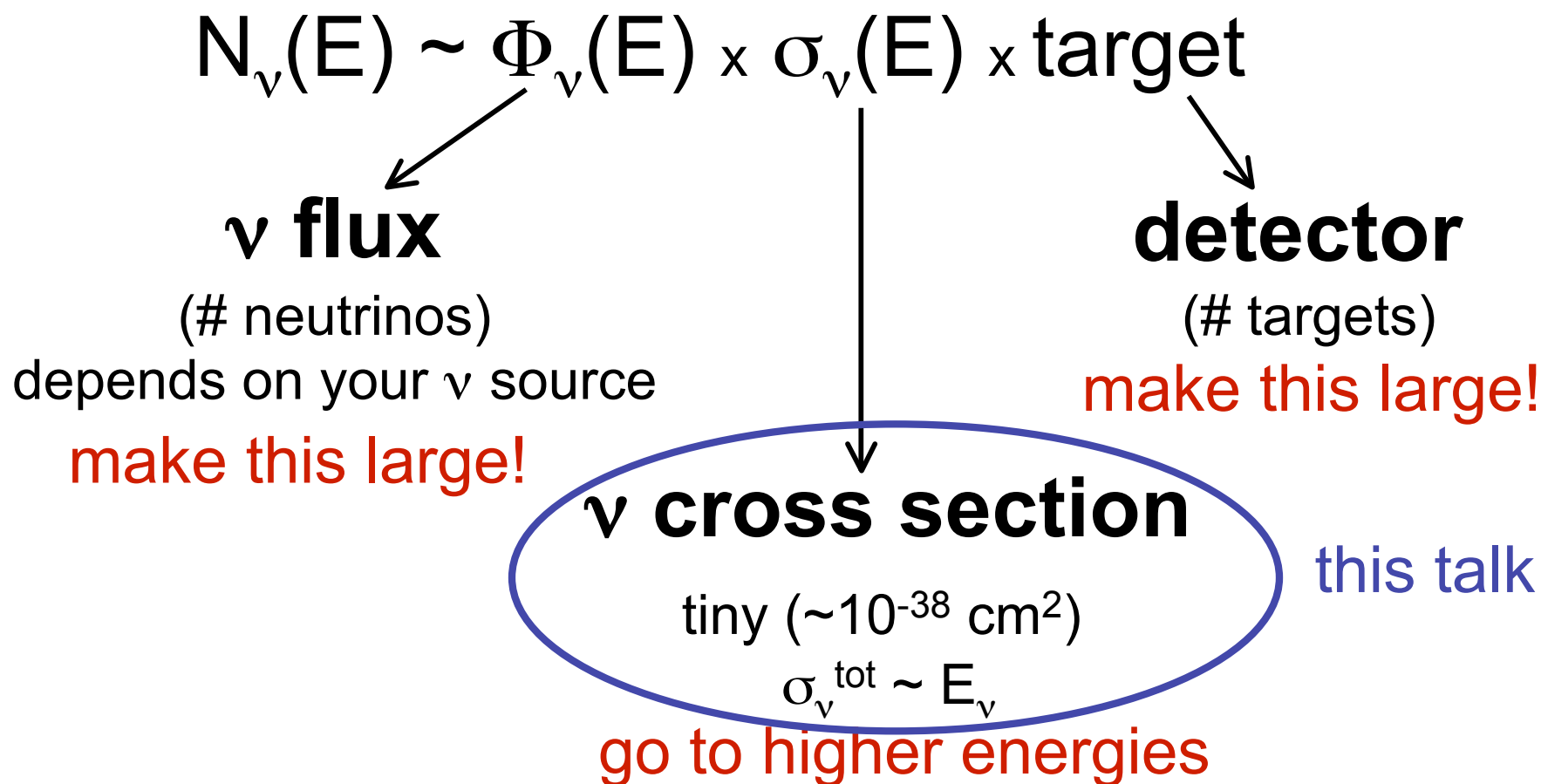
tiny ($\sim 10^{-38} \text{ cm}^2$)

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

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



Measuring σ_v

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

$$\sigma_v(E) \sim \frac{N_v(E)}{\Phi_v(E) \times \text{target}}$$

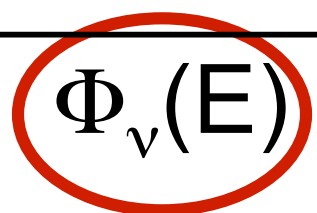
count events

Measuring σ_ν

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

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

count events 



- 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)

Importance of σ_ν

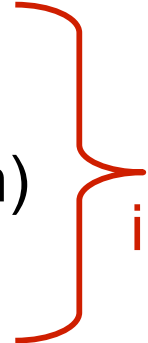
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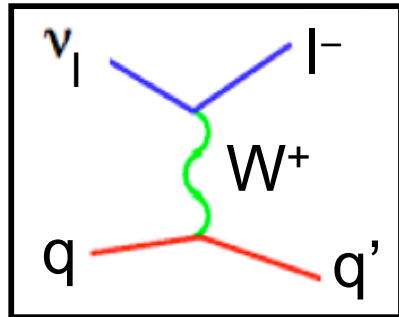
will depend on:

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



next
in this talk

Two Types of Interactions



Charged Current (CC)

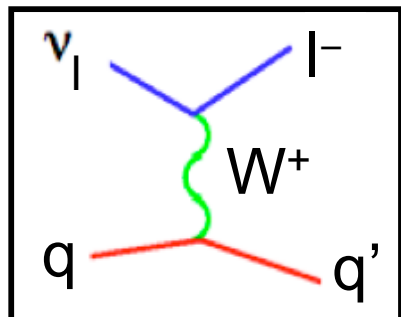
- neutrino in
- charged lepton out

this is how we
detected neutrinos
in the first place

$\nu_e \rightarrow e^-$	$\bar{\nu}_e \rightarrow e^+$	} - flavor of outgoing lepton “tags” flavor of incoming neutrino
$\nu_\mu \rightarrow \mu^-$	$\bar{\nu}_\mu \rightarrow \mu^+$	
$\nu_\tau \rightarrow \tau^-$	$\bar{\nu}_\tau \rightarrow \tau^+$	

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

Two Types of Interactions

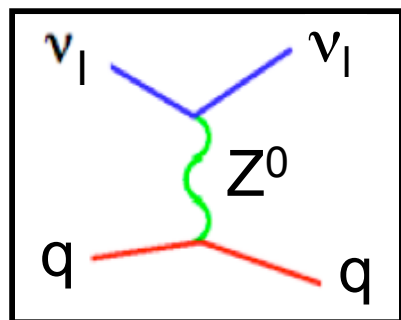


Charged Current (CC)

- neutrino in
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$$\begin{array}{ll}
 \nu_e \rightarrow e^- & \bar{\nu}_e \rightarrow e^+ \\
 \nu_\mu \rightarrow \mu^- & \bar{\nu}_\mu \rightarrow \mu^+ \\
 \nu_\tau \rightarrow \tau^- & \bar{\nu}_\tau \rightarrow \tau^+
 \end{array}
 \left. \vphantom{\begin{array}{l} \nu_e \rightarrow e^- \\ \nu_\mu \rightarrow \mu^- \\ \nu_\tau \rightarrow \tau^- \end{array}} \right\}
 \begin{array}{l}
 \text{- flavor of outgoing lepton "tags"} \\
 \text{flavor of incoming neutrino} \\
 \text{- charge of outgoing lepton} \\
 \text{determines whether } \nu \text{ or anti-}\nu
 \end{array}$$



Neutral Current (NC)

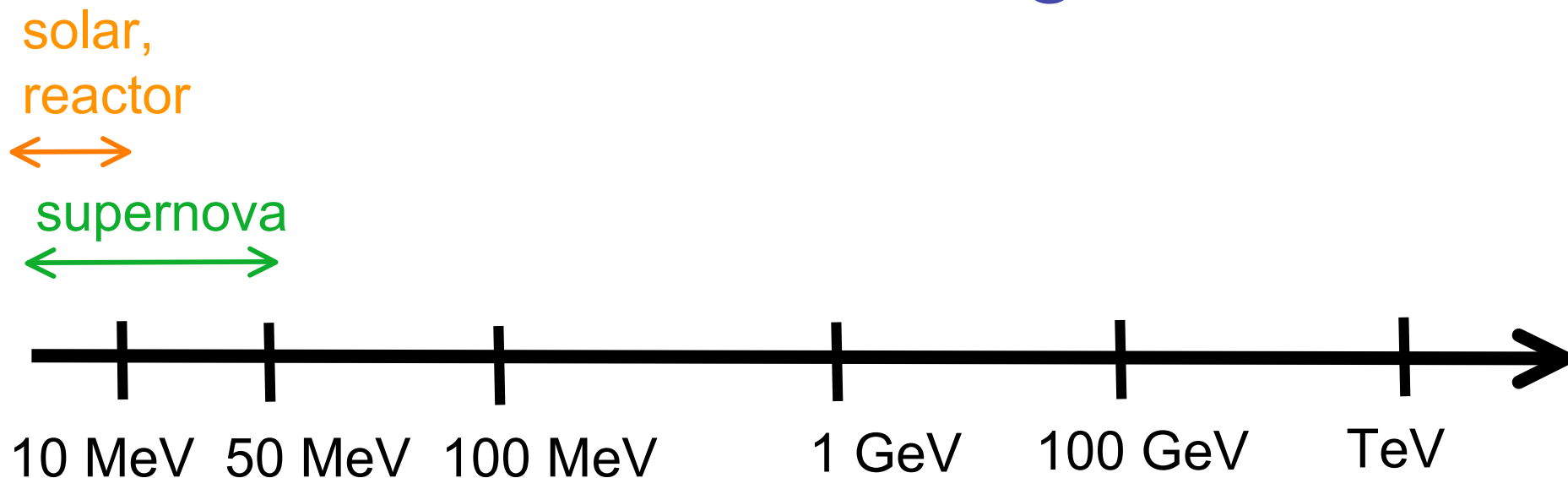
- neutrino in
- neutrino out

1st observed in 1972

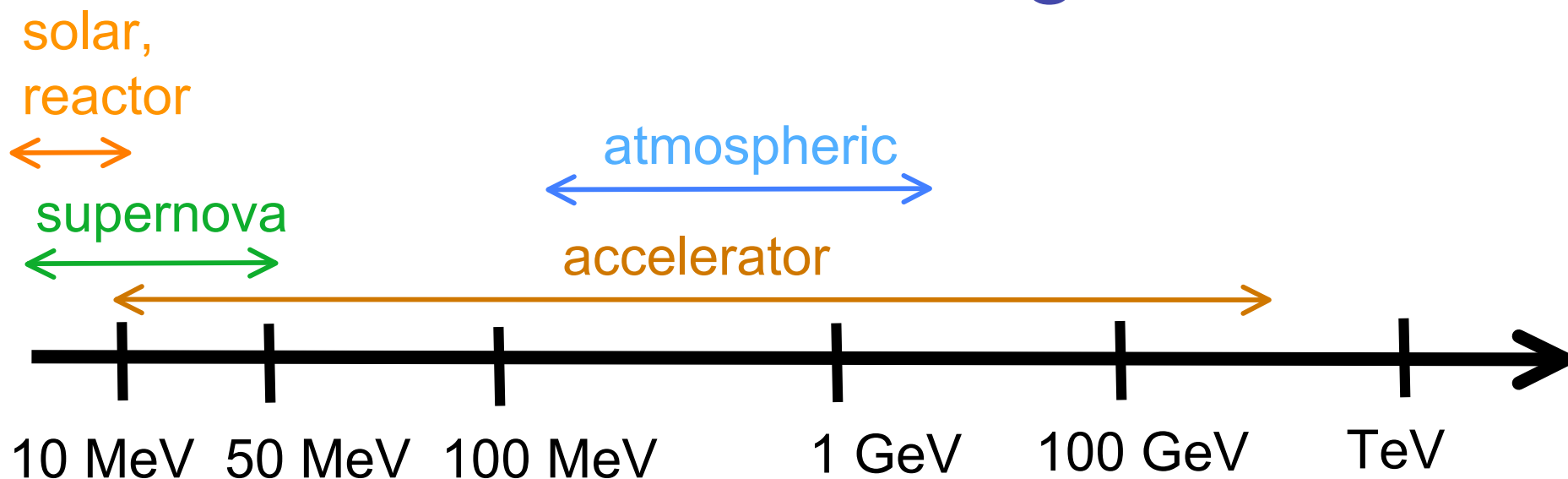


$$\nu_\mu e^- \rightarrow \nu_\mu e^-$$

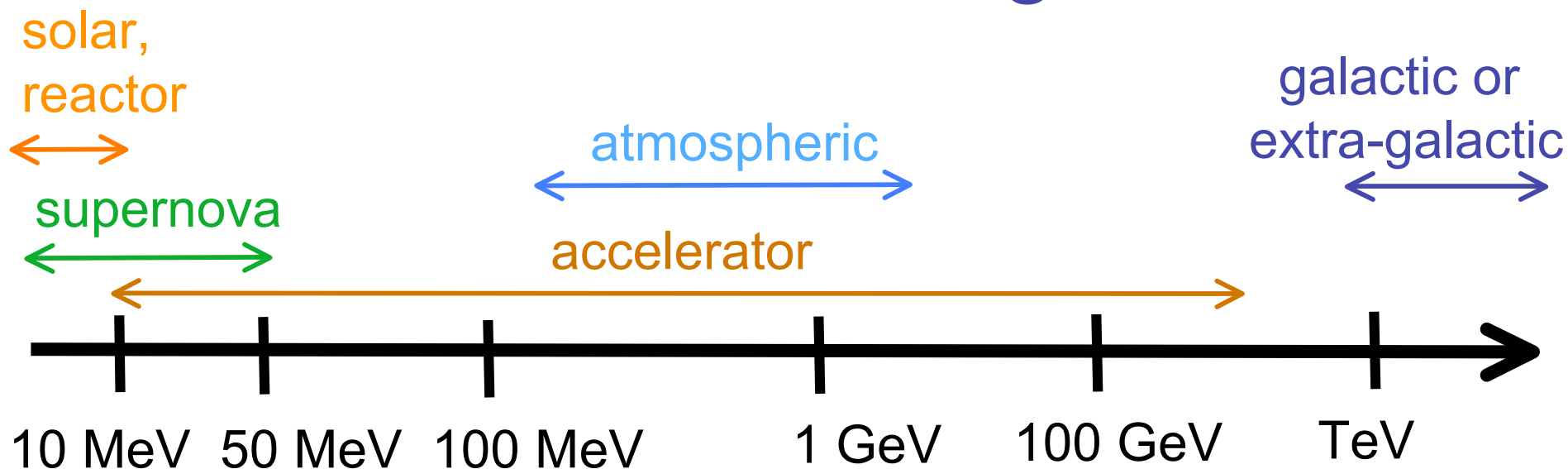
Neutrino Energies



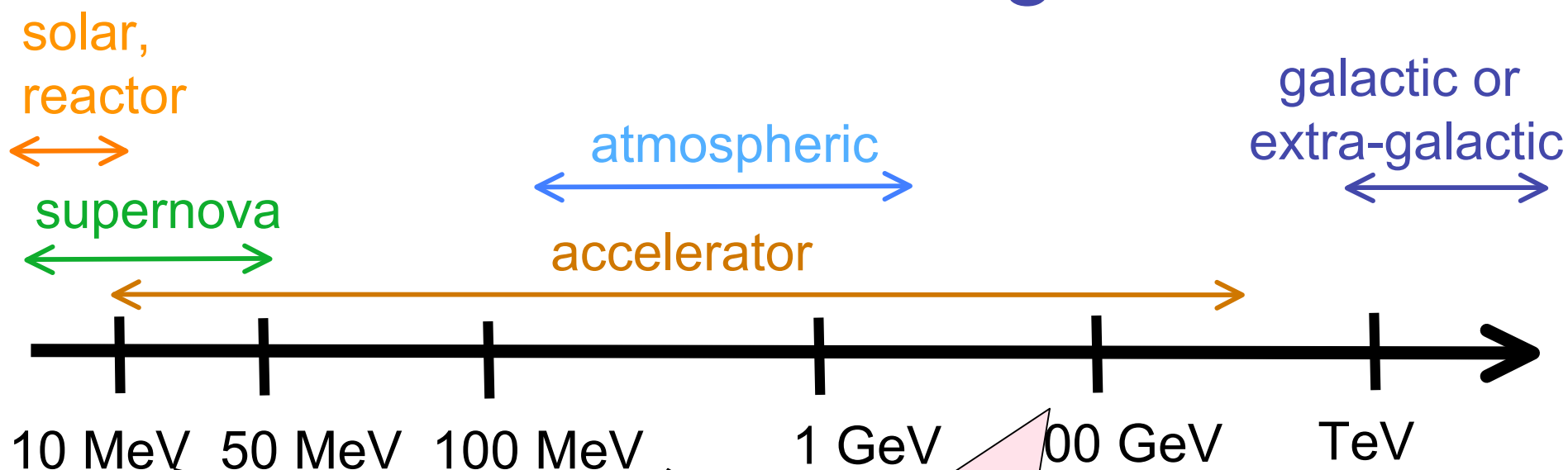
Neutrino Energies



Neutrino Energies

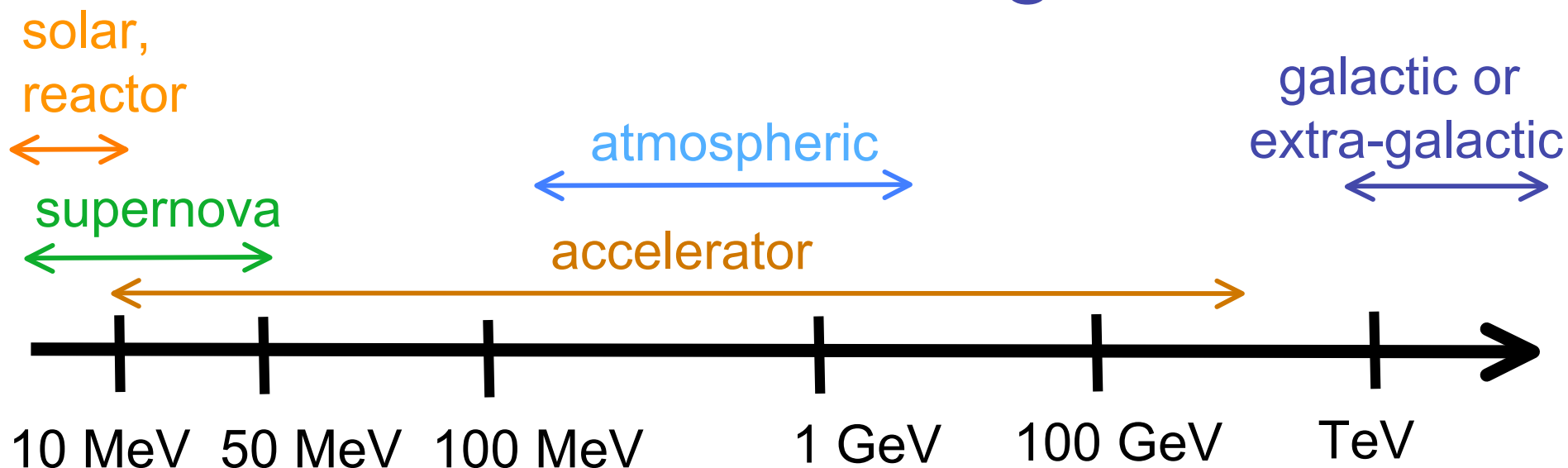


Neutrino Energies



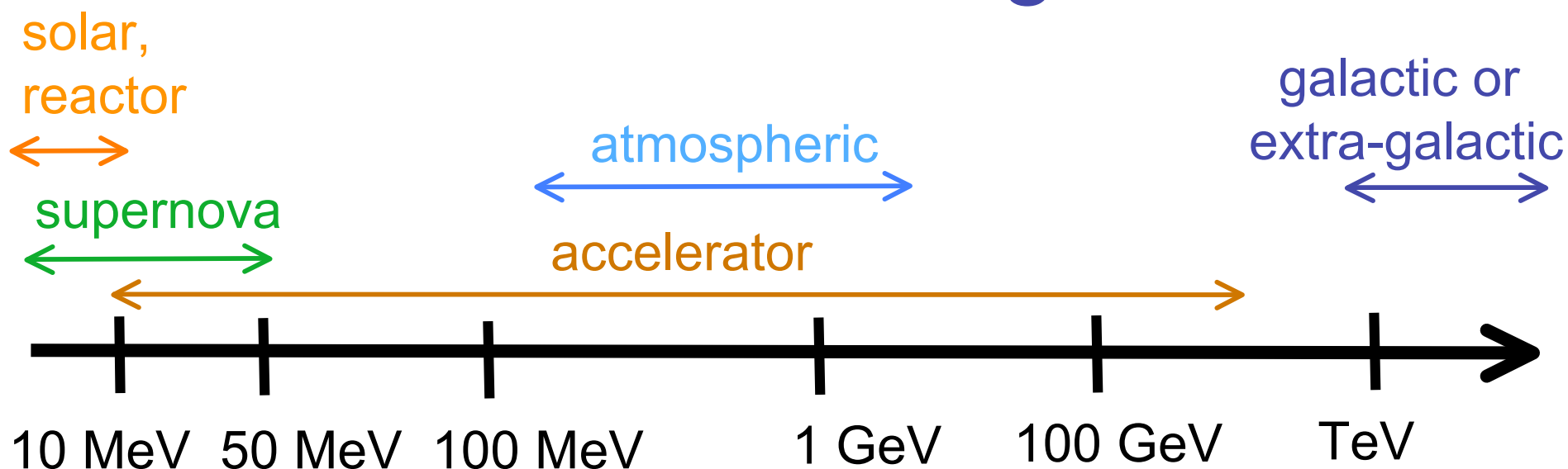
need to predict ν cross sections
over a broad energy range

Neutrino Energies



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

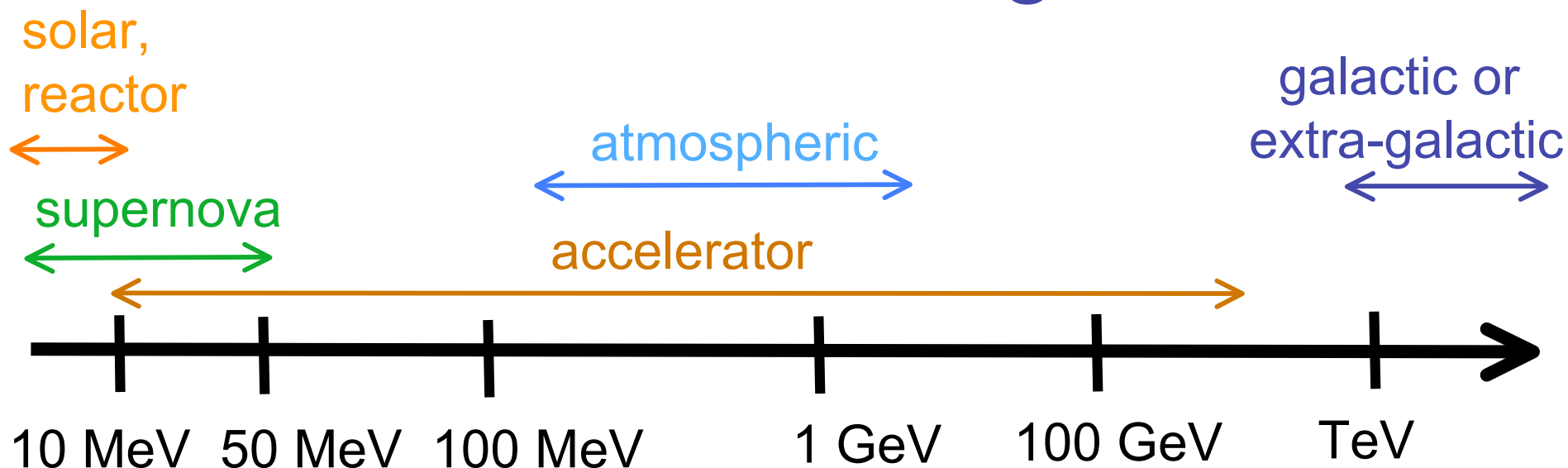
Neutrino Energies



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

ν-nucleon elastic scattering (nucleon form factors)	>	ν-quark inelastic scattering (parton density functions)
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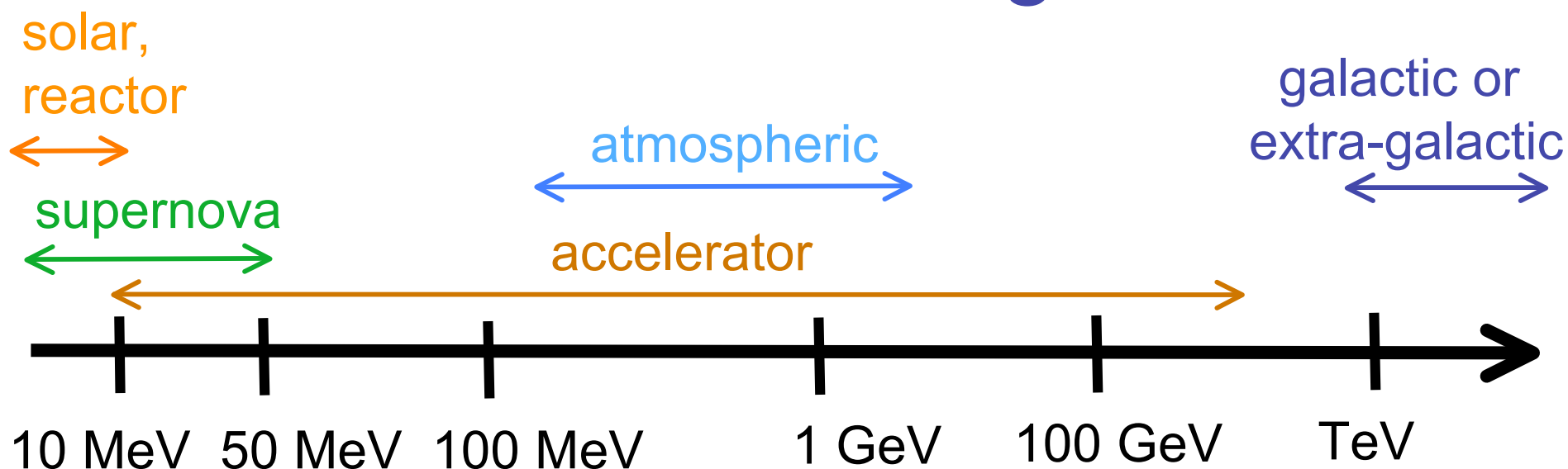
Neutrino Energies



- **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)

Neutrino Energies

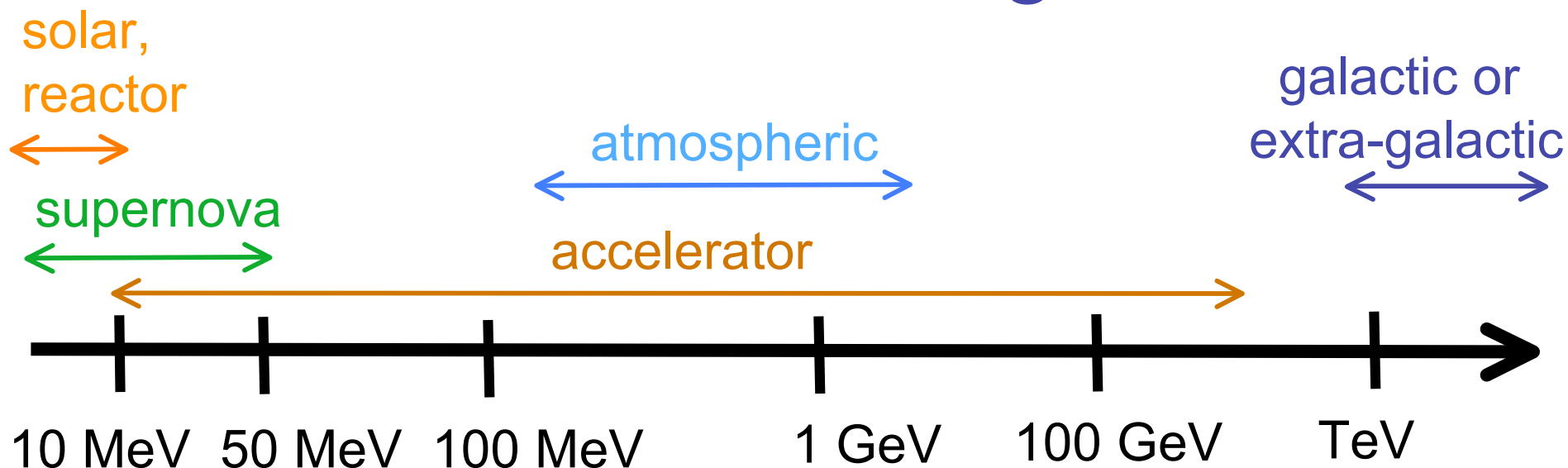


- **target description** is different depending on the ν energy

ν-nucleon elastic scattering (nucleon form factors)	➤	ν-quark inelastic scattering (parton density functions)
---	---------------	---

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

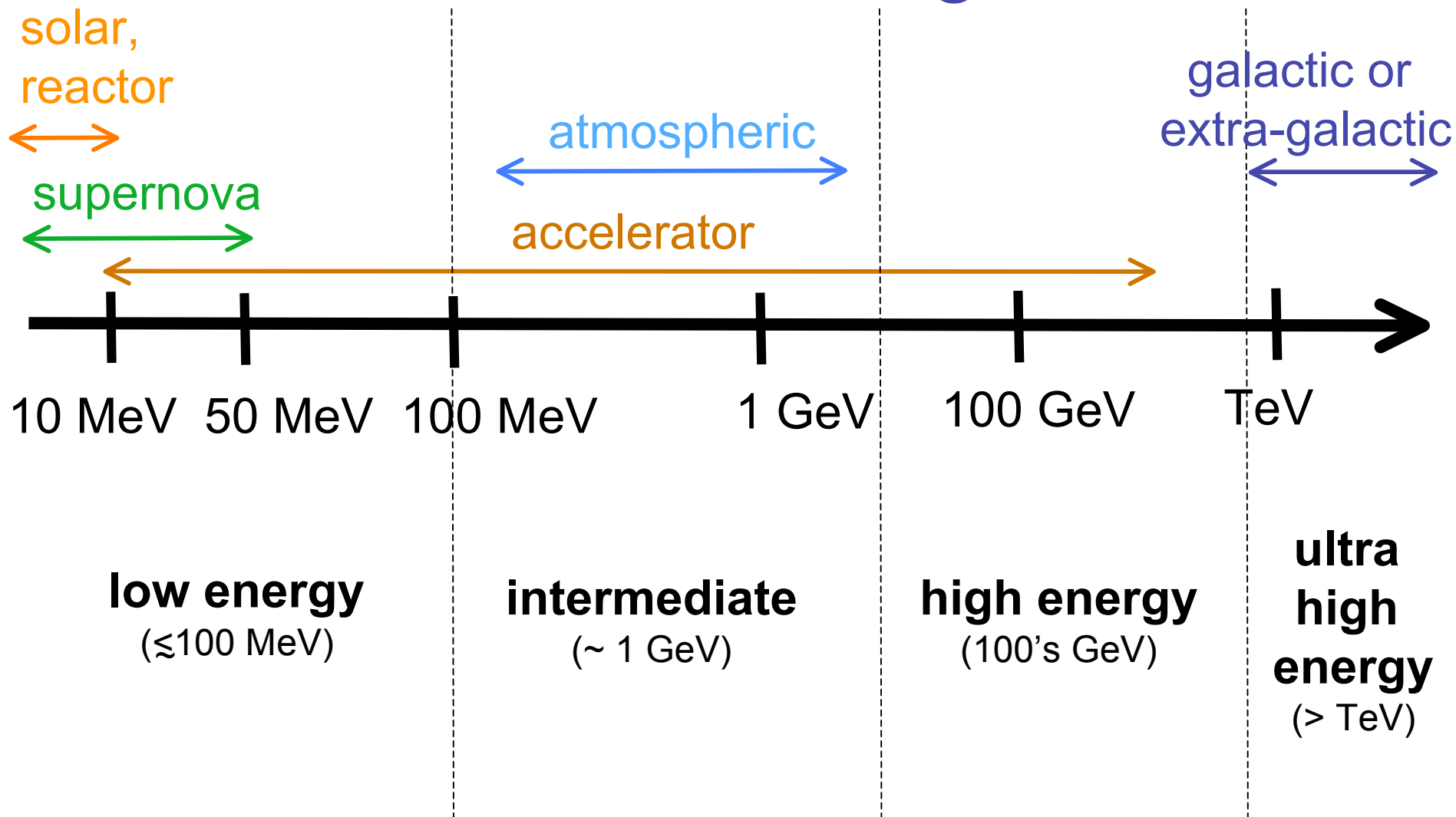
Neutrino Energies



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

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

Neutrino Energies



Structure of Rest of Talk

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

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

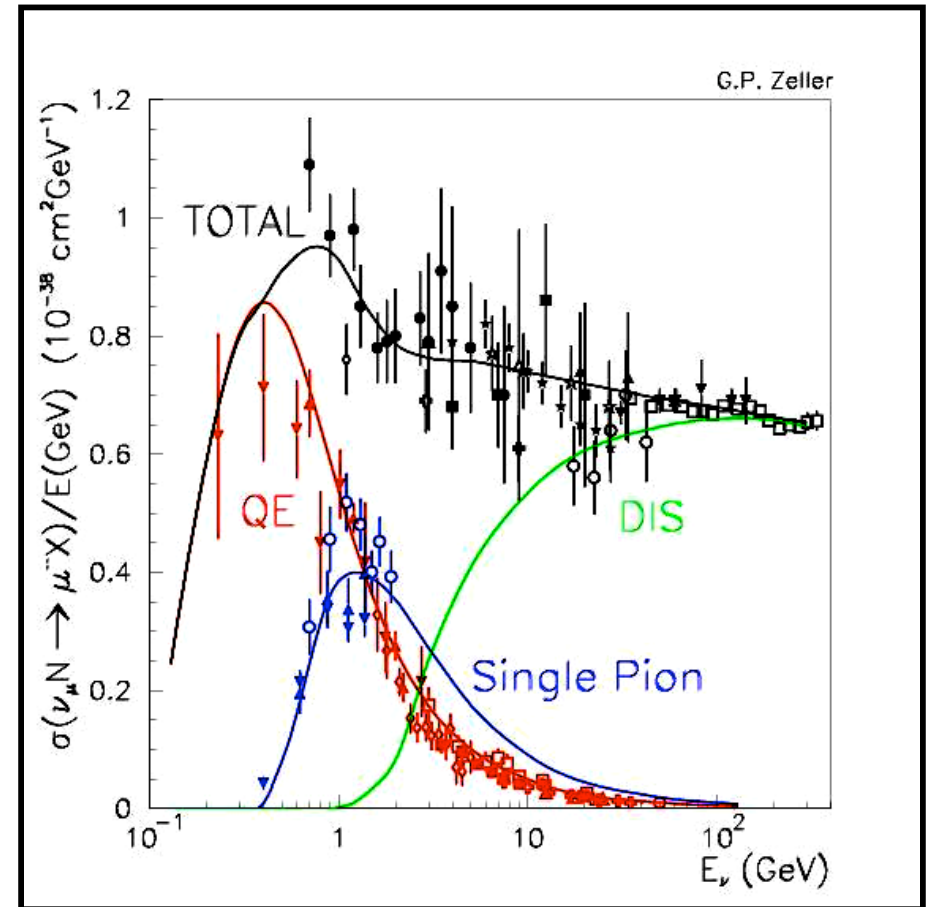
(3) **high energy**
(100's GeV)

(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?

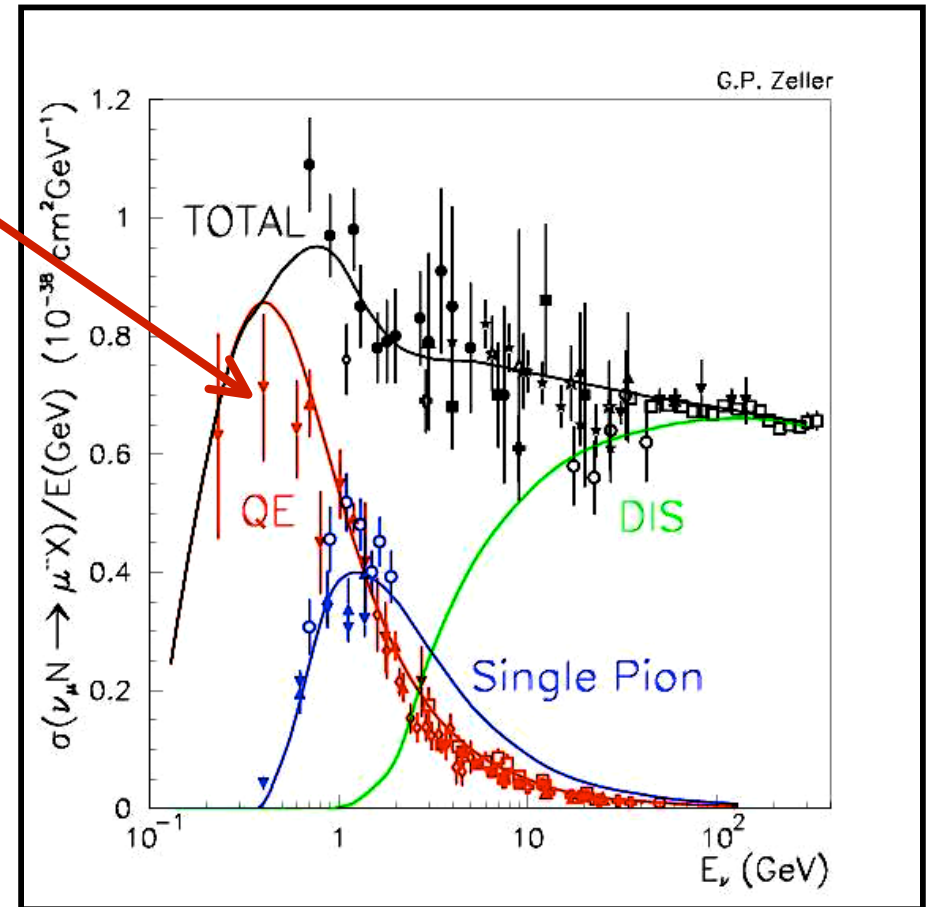
Neutrino Cross Sections

- this will be our template



Neutrino Cross Sections

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

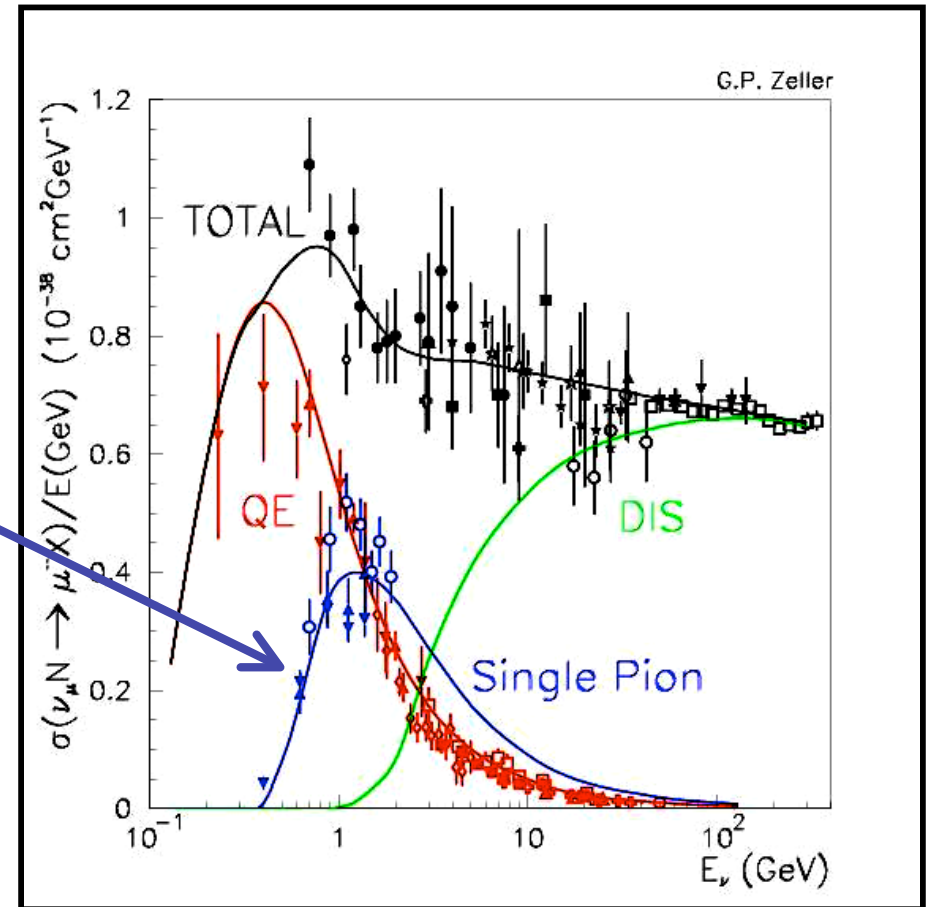


Neutrino Cross Sections

- quasi-elastic scattering

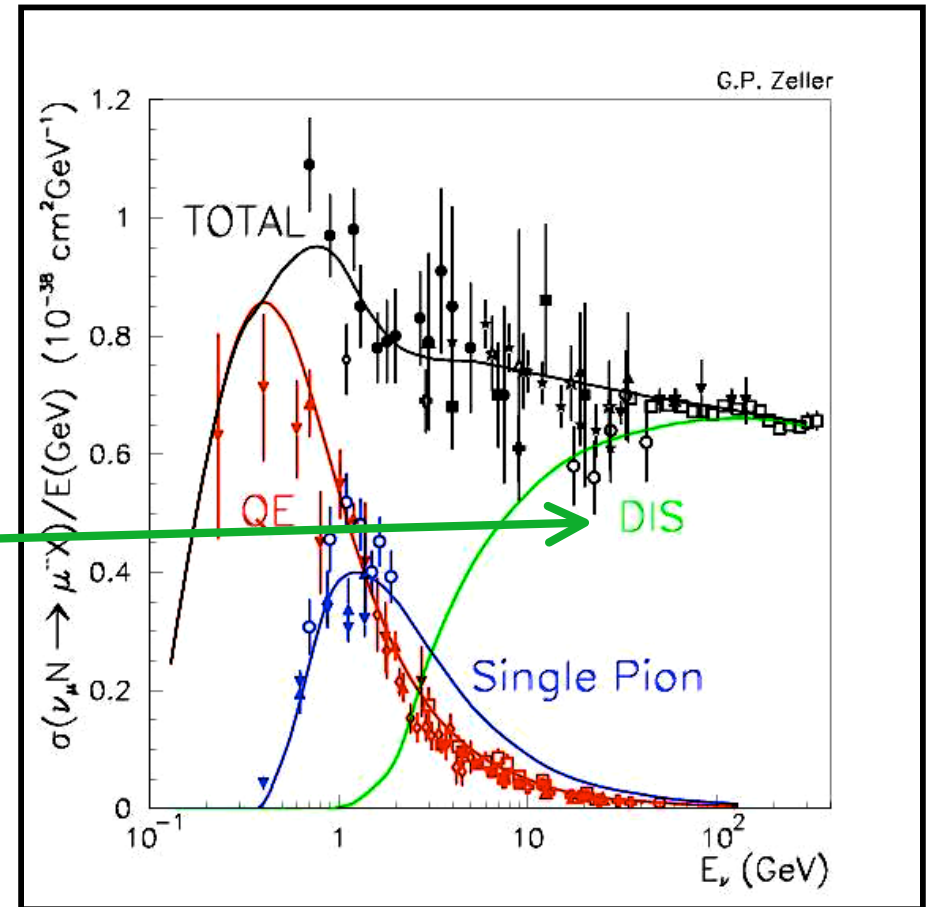


- single π production



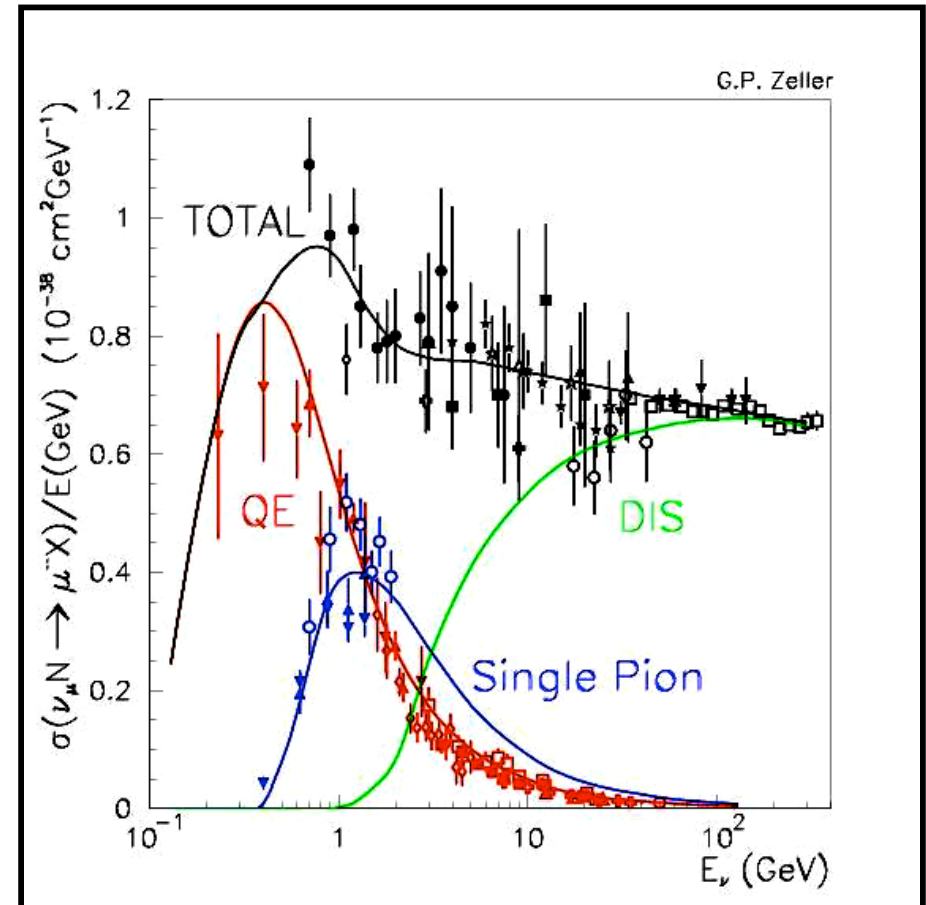
Neutrino Cross Sections

- quasi-elastic scattering
 $\nu_{\mu} n \rightarrow \mu p$
- single π production
 $\nu_{\mu} N \rightarrow \mu N' \pi$
- deep inelastic scattering (DIS)
 $\nu_{\mu} N \rightarrow \mu X$



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)

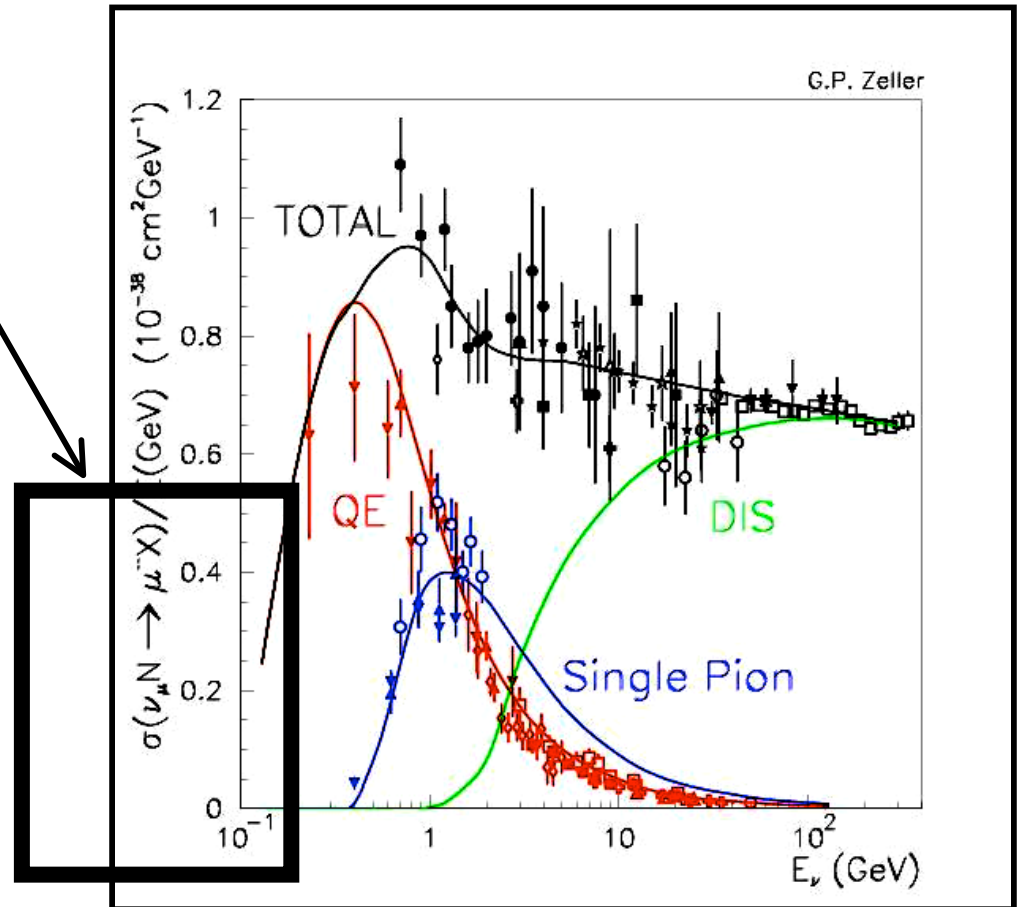


- we'll talk about each of these in the region in which they are relevant

low E
(< 100 MeV)

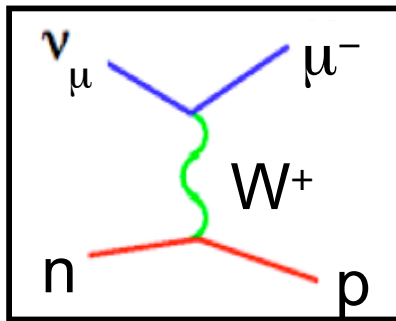
Low Energy

- 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

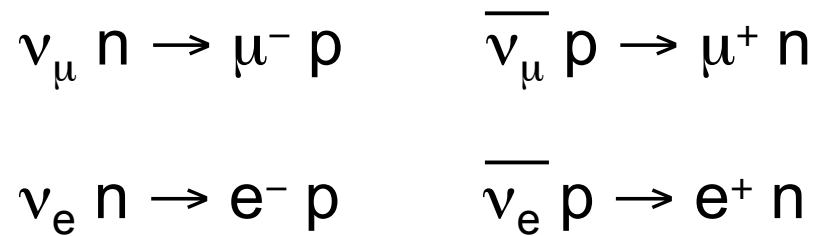


solar, reactor (< 10 MeV) $\longleftrightarrow$ (off the plot)
supernova ($\lesssim 50$ MeV) $\longleftrightarrow$

Quasi-Elastic Scattering



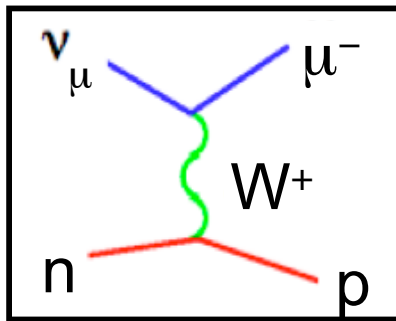
- **simple 2-body interaction**



elastic
(nucleon
stays
Intact)

in CC case, called “quasi-elastic” ... target changes but does not break up

Quasi-Elastic Scattering



- **simple 2-body interaction**

$$\begin{array}{ll} \nu_{\mu} n \rightarrow \mu^{-} p & \bar{\nu}_{\mu} p \rightarrow \mu^{+} n \\ \nu_e n \rightarrow e^{-} p & \bar{\nu}_e p \rightarrow e^{+} n \end{array}$$

elastic
(nucleon
stays
Intact)

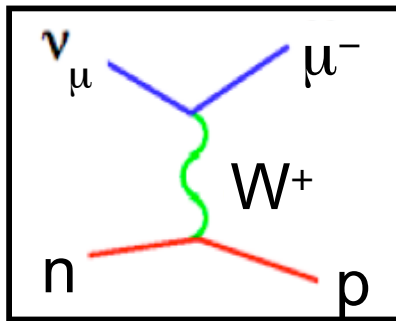
- appealing signal channel for ν oscillation exps because:
 - charged lepton tags flavor of ν ($\mu \Rightarrow \nu_{\mu}$, $e \Rightarrow \nu_e$)
 - can reconstruct E_{ν} from outgoing lepton kinematics
 - straightforward to calculate (especially if ν scattering off free nucleons)

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

low E
(< 100 MeV)

At Low Energy

- simple 2-body interaction



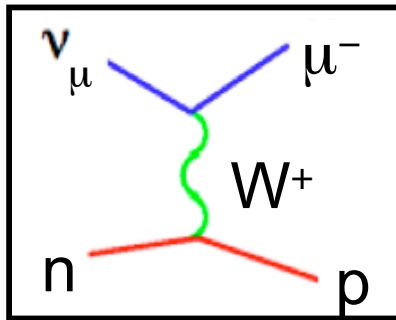
$$\nu_\mu n \rightarrow \mu^- p \quad \bar{\nu}_\mu p \rightarrow \mu^+ n$$

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

low E
(< 100 MeV)

At Low Energy

- simple 2-body interaction



$$\cancel{\nu_\mu n \rightarrow \mu^- p}$$

$$\cancel{\bar{\nu}_\mu p \rightarrow \mu^+ n}$$

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

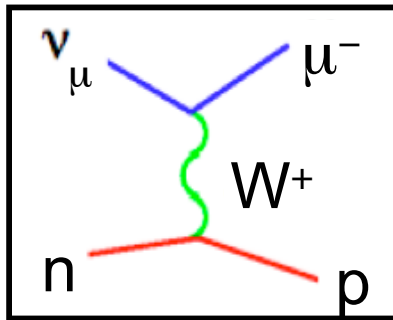
$$\bar{\nu}_e p \rightarrow e^+ n$$

threshold
 > 100 MeV

low E
(< 100 MeV)

At Low Energy

- simple 2-body interaction



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

~~$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$~~

~~$\nu_e + n \rightarrow e^- + p$~~

~~$\bar{\nu}_e + p \rightarrow e^+ + n$~~

threshold
 > 100 MeV

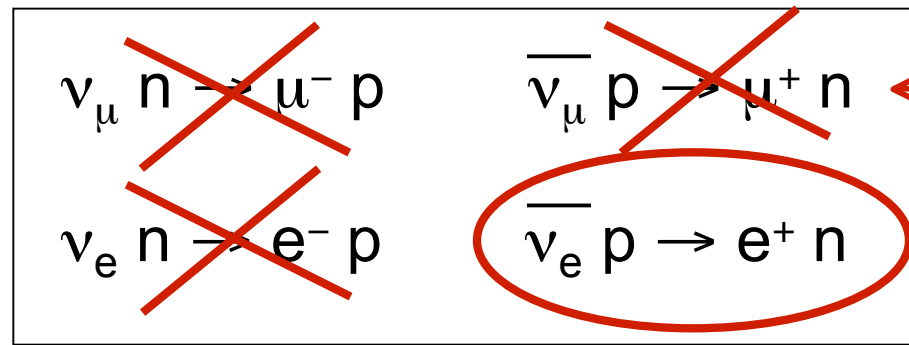
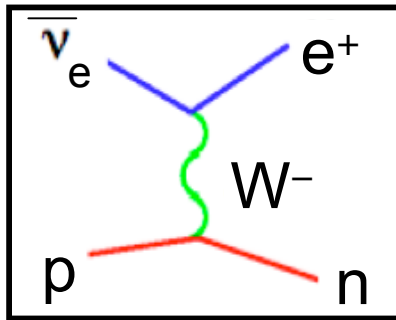
no free neutrons

(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



no free neutrons

threshold
 > 100 MeV

old workhorse
of ν physics
(IBD)

Reines-Cowan
discovery signal



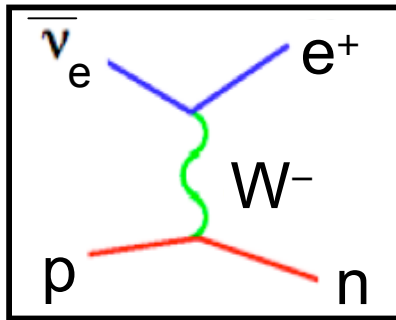
called “inverse beta decay”

remember this is historically the
1st reaction we observed with ν 's

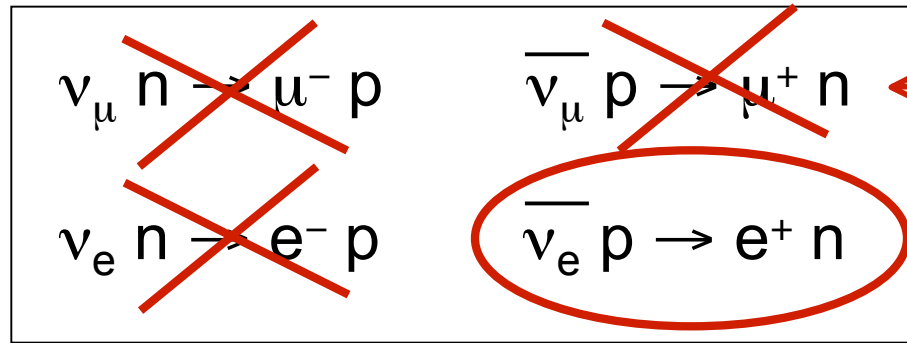
it is still important today!

low E
(< 100 MeV)

At Low Energy



- simple 2-body interaction



no free neutrons

threshold
 > 100 MeV

old workhorse
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Reines-Cowan
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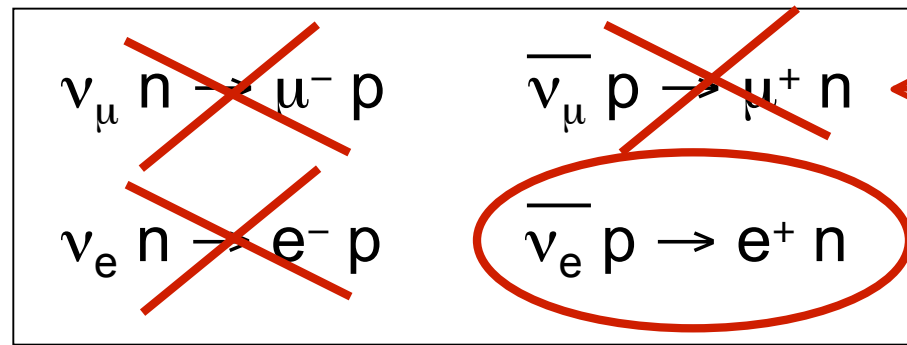
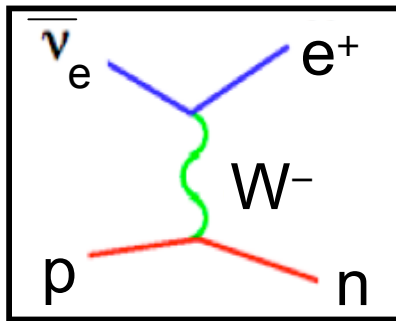
- reaction of choice for detection of reactor & SN ν 's

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

low E
(< 100 MeV)

At Low Energy

• simple 2-body interaction



no free neutrons

threshold
 > 100 MeV

old workhorse
of ν physics
(IBD)

Reines-Cowan
discovery signal

• reaction of choice for detection of reactor & SN ν 's

- dominant σ at these energies
- low threshold $\sim (m_n - m_p) + m_e = 1.8$ 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)

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

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you should
recognize some
familiar quantities

Fermi constant

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

(responsible for small σ)

Cabibbo angle

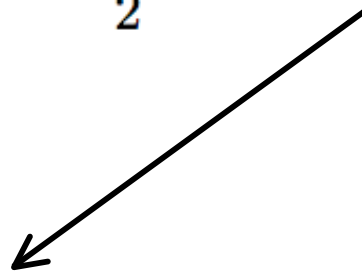
$$\cos \theta_c \sim 0.97$$

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

leptonic tensor



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

easy to calculate, well-known

Quasi-Elastic Scattering

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hadronic tensor

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

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hadronic tensor

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

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

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)

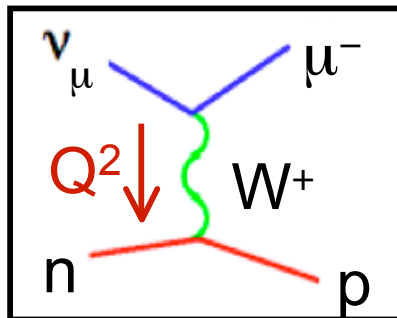
$$d\sigma = \frac{G_F^2 \cos^2 \vartheta_c}{2} 2\pi L^{\mu\nu} W_{\mu\nu} \frac{d^3k}{(2\pi)^3}$$

hadronic tensor

$$W^{\mu\nu}(\omega, q) = \sum_f \langle \Psi_f | J^\mu(q) | \Psi_0 \rangle$$

$$\times \langle \Psi_0 | J^{\nu\dagger}(q) | \Psi_f \rangle \delta(E_0 + \omega - E_f)$$

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form factors
contains all of
the information
on the target

- form factors are functions of Q^2/M^2 ($M \sim 1$ 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:

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

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

low E
(< 100 MeV)

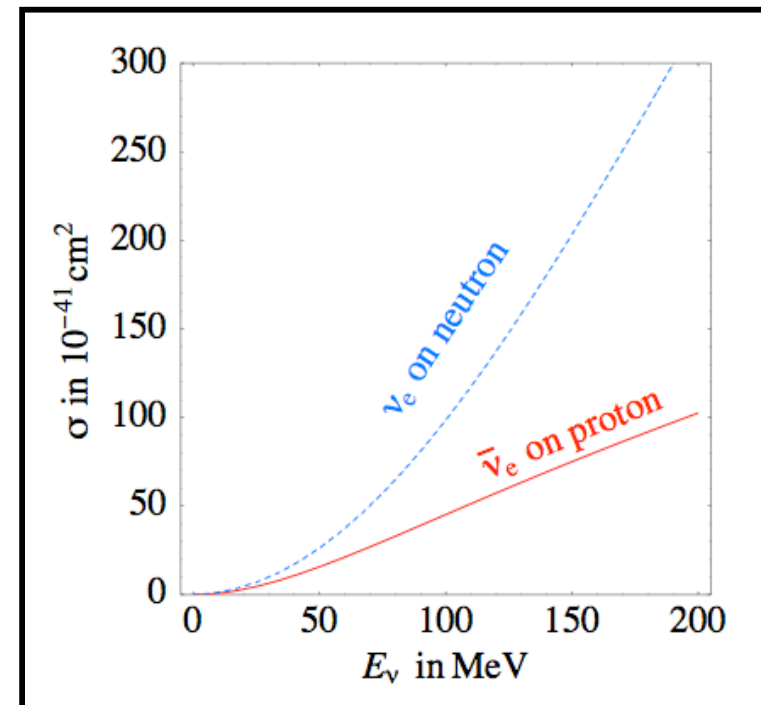
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($F_A \sim 1.267$, $F_V \sim 1.0$) $\nearrow$

- 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)

low E
(< 100 MeV)

Inverse Beta Decay

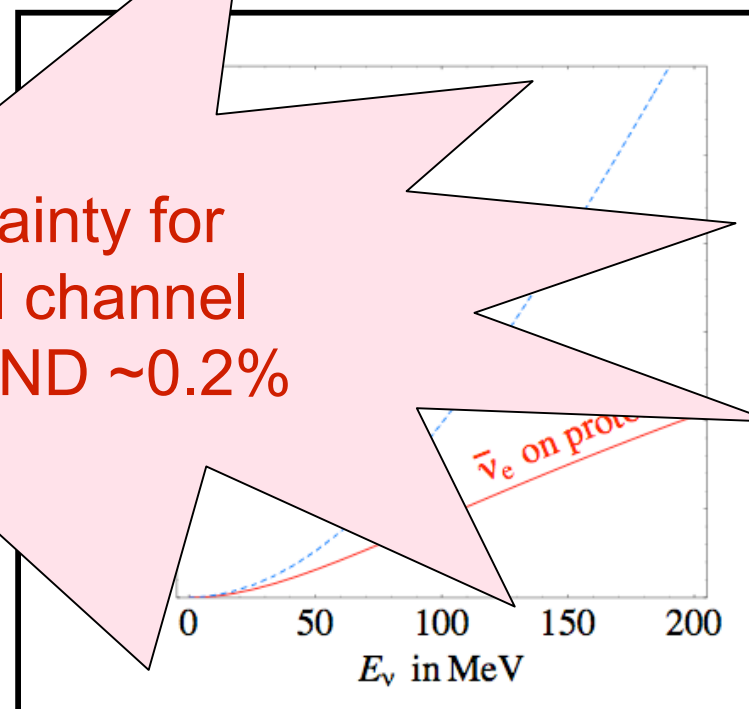
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- parameters well constrained by neutron lifetime
- radiative & final state interactions (are small, calculate)
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uncertainty $< 0.5\%$ at low energies
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σ_ν uncertainty for
IBD signal channel
for KAMLAND $\sim 0.2\%$

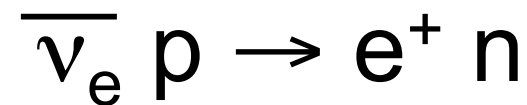


Strumia, Vissani, PLB **564**, 42 (2003)

low E
(< 100 MeV)

Has This Been Measured?

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



- measurements at few-% level, consistent with prediction

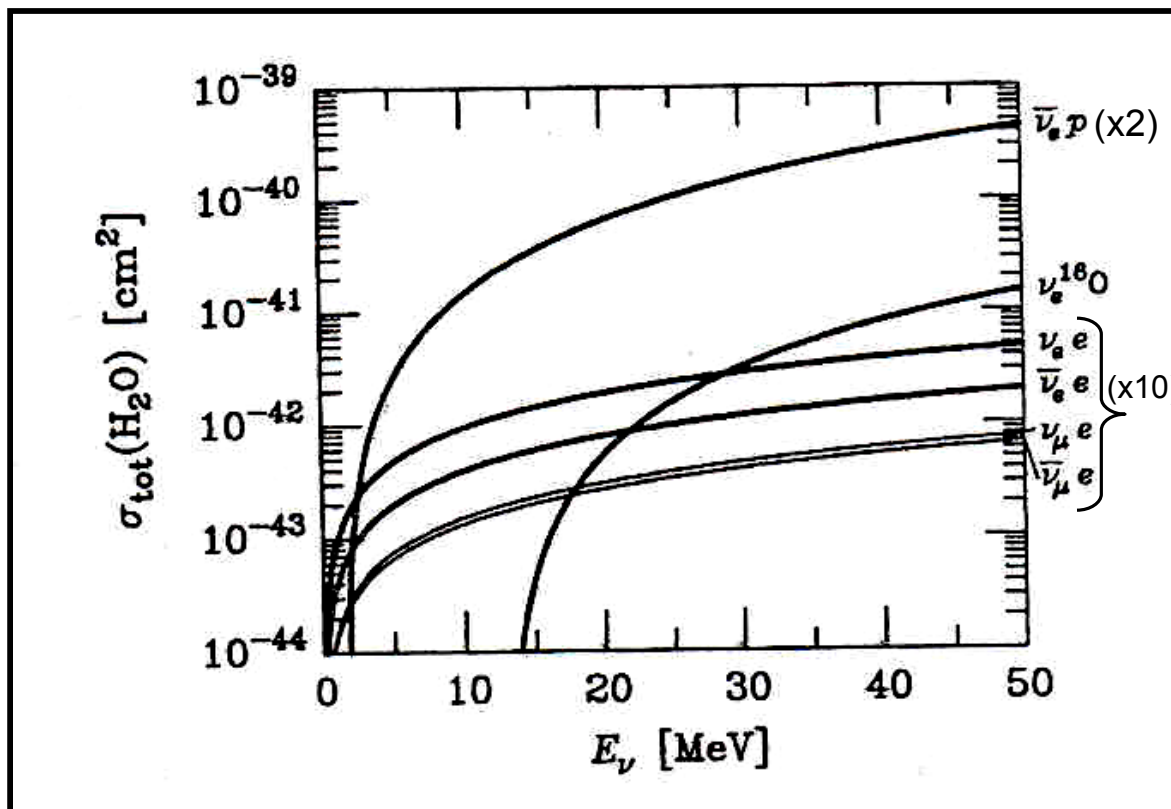
	Goesgen PRD 34 , 2621 (1986)	Krasnoyarsk JETP Lett 54 , 2225 (1991)	Bugey PLB 338 , 383 (1994)
σ_{exp}	3.0%	2.8%	1.4%

- theory is ahead here, σ_{ν} measurements limited by how well we 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)?

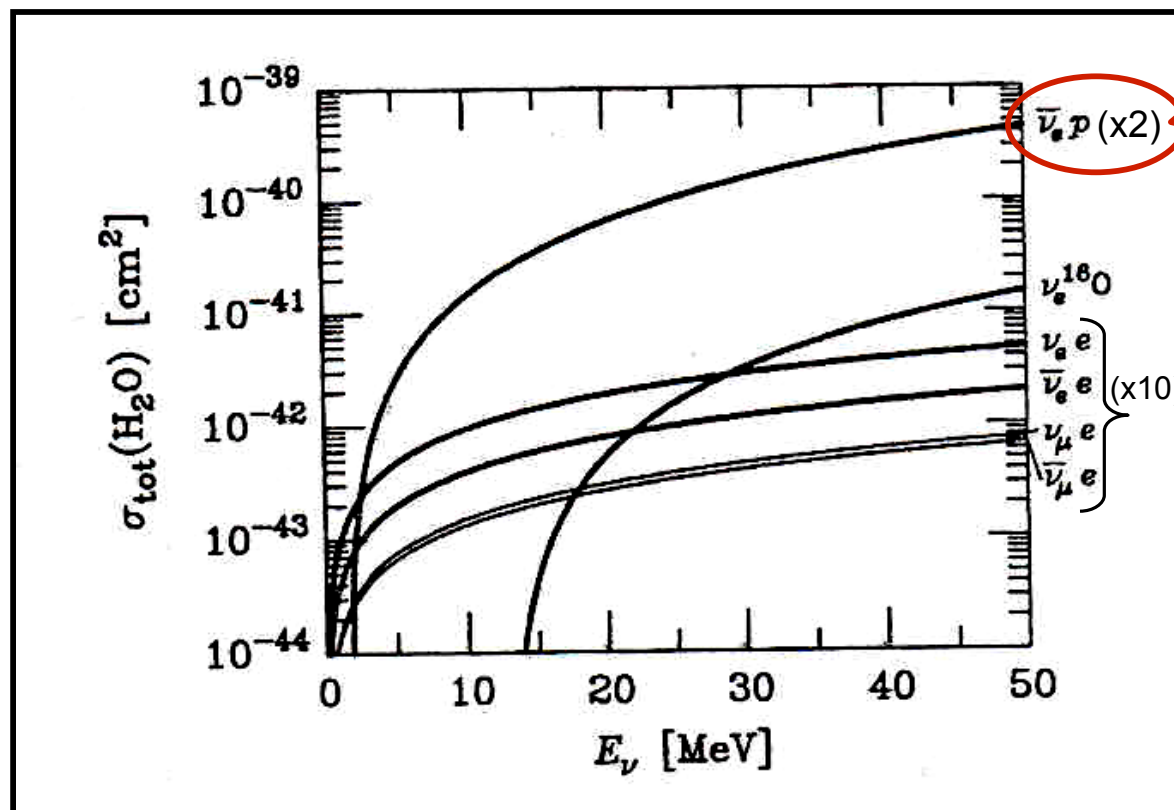


K. Zuber, Neutrino Physics, IOP, 2004

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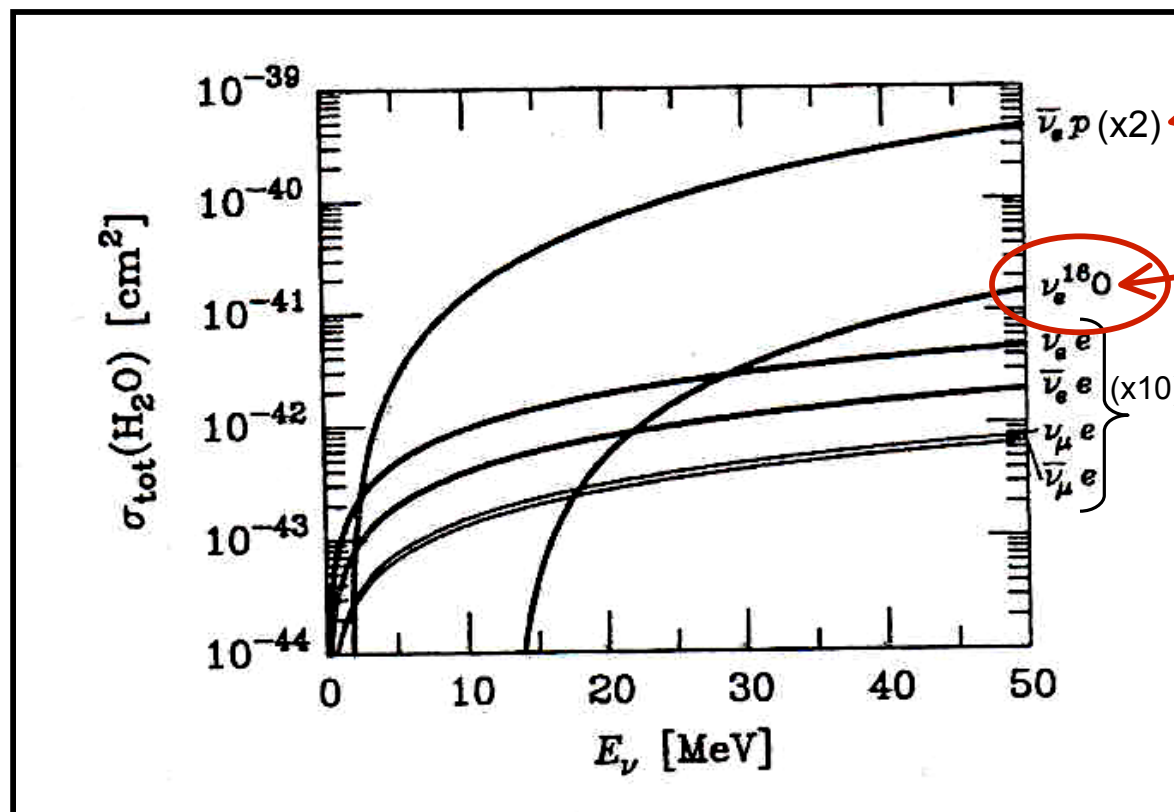


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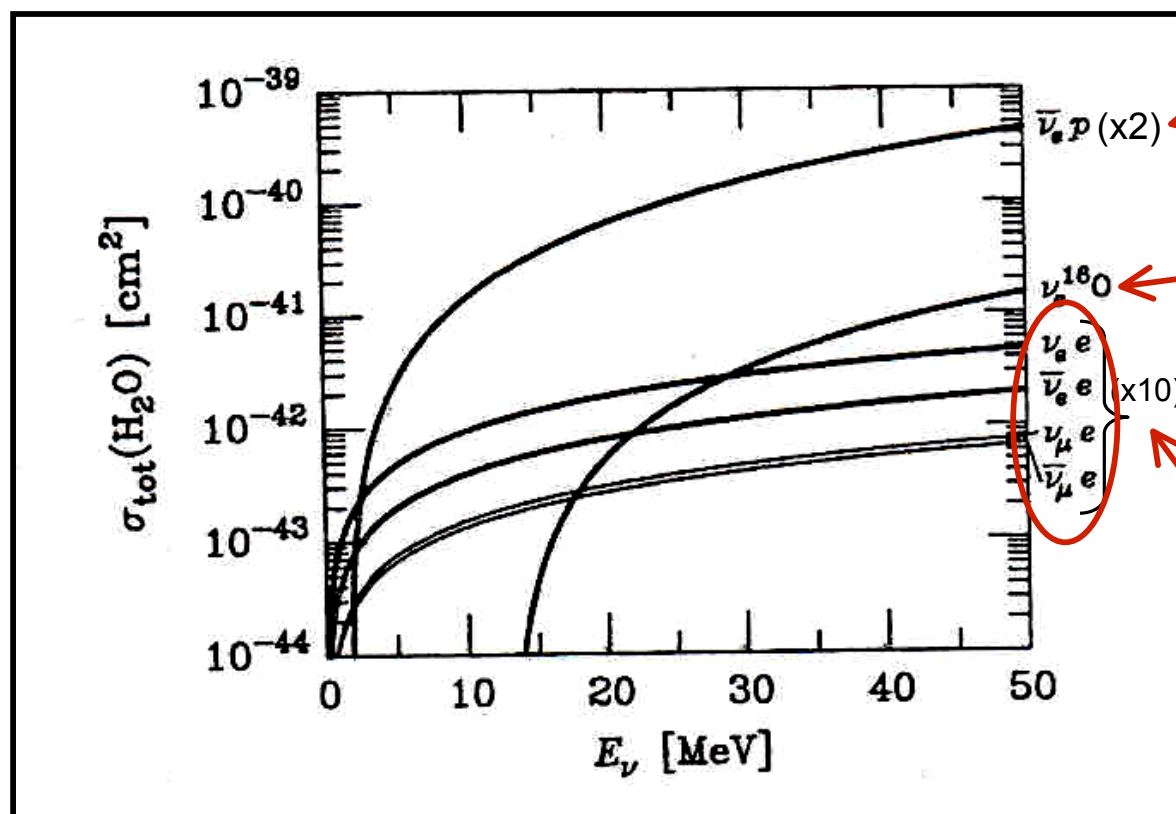


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low E
(< 100 MeV)

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

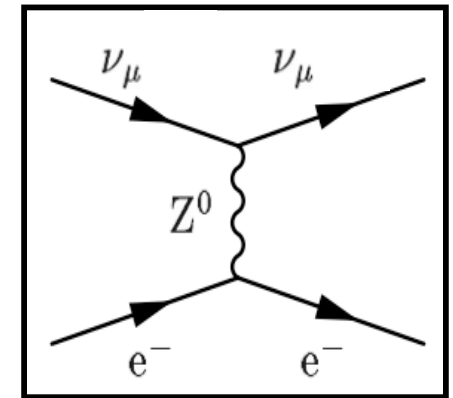
ν 's can also
transfer a lot of
energy to a nucleus
(higher threshold than IBD,
 ~ 10 - 15 MeV)

ν 's can scatter off
electrons in the target

K. Zuber, Neutrino Physics, IOP, 2004

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

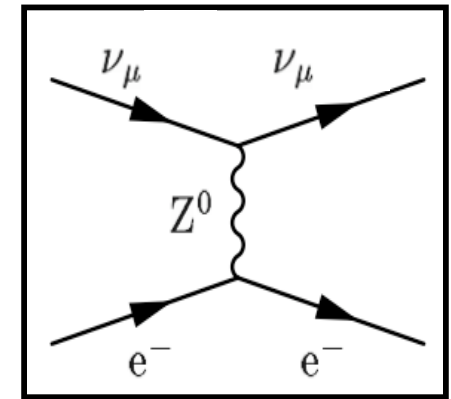
- process in which we 1st discovered NC's!
- purely-leptonic process, so σ calculation is very straightforward (no form factors!)



$$\sigma = \frac{2G_F^2 m_e}{\pi} \left[\left(g_L^2 + \frac{g_R^2}{3} \right) E_\nu - g_L g_R \frac{m_e}{2} \right] \quad \begin{aligned} g_L &= \sin^2 \theta_W \frac{\pm}{\mu, \tau} \frac{1}{2} \\ g_R &= \sin^2 \theta_W \end{aligned}$$

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- some facts
- σ is $\sim$ 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:

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

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)



you will get a very
forward electron

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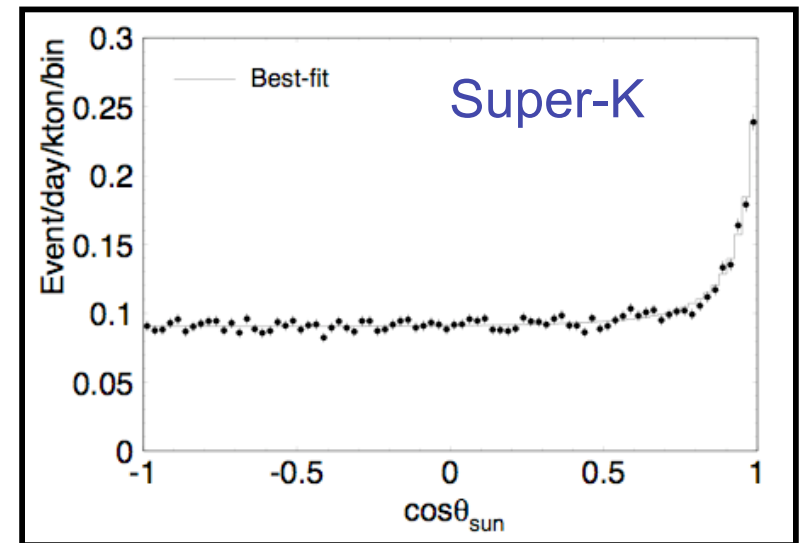
$$E_e \theta_e^2 < 2 m_e$$

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)

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

things to remember here ...

disadvantage

σ is small (small rates)

advantages

directional (very forward emitted e^-)

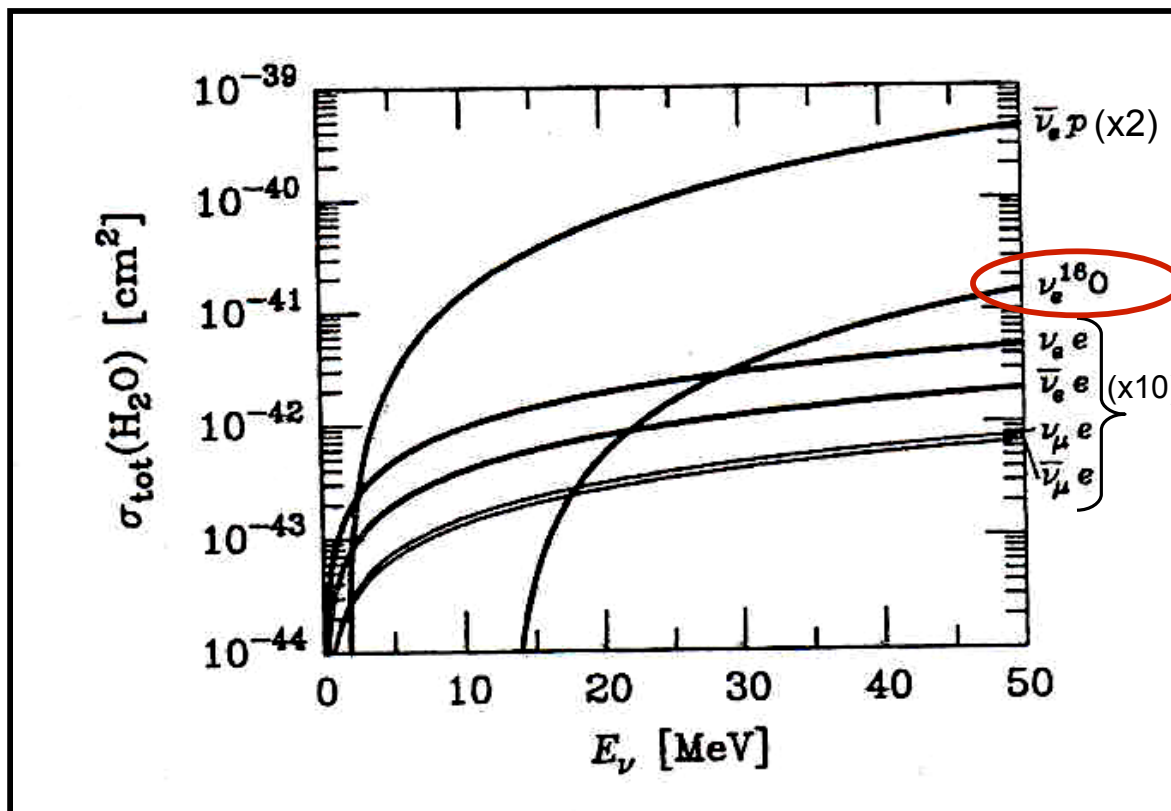
σ extremely well known

(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

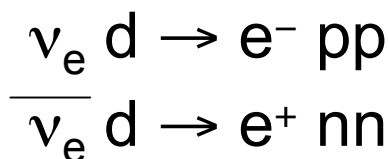
- nature of observables depends on the nuclear physics of the specific nucleus (add'l ejected nucleons or nuclear de-excitation γ 's)

low E
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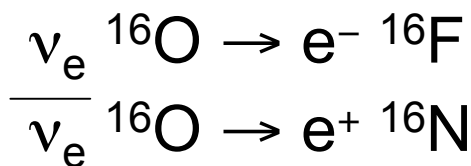
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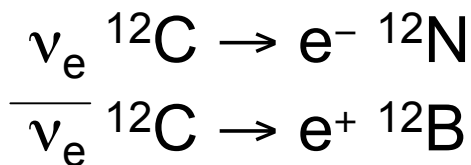
examples
of CC
interactions



deuteron breakup
in heavy water (SNO)



interactions with
 ${}^{16}\text{O}$ in water



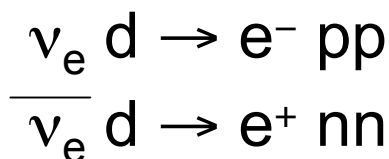
interactions with
 ${}^{12}\text{C}$ in oil, scintillator

low E
(< 100 MeV)

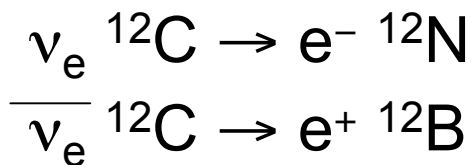
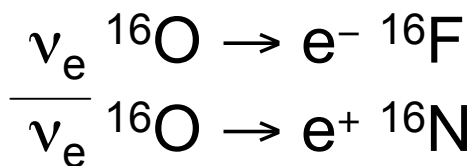
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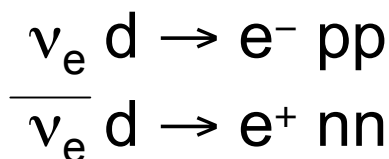
higher thresholds
(10's MeV)
and theoretically
less clean

low E
(< 100 MeV)

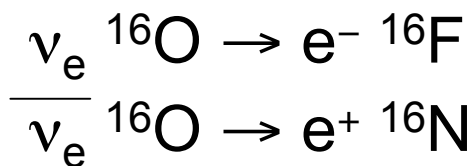
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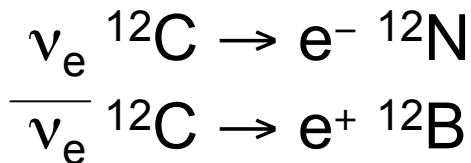
examples
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deuteron breakup
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higher thresholds
(10's MeV)
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- $\nu_e {}^{37}\text{Cl} \rightarrow e^- {}^{37}\text{Ar}$ was 1st reaction used to detect 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

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

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

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

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

cascade of 5-10 MeV
excitation γ 's

15.11 MeV de-excitation γ

low E
(< 100 MeV)

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cascade of 5-10 MeV
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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

$$\text{CC} \left\{ \begin{array}{ll} \nu_e d \rightarrow e^- pp & (\text{threshold} \sim m_p + m_e - m_n + E_B = 1.4 \text{ MeV}) \\ \bar{\nu}_e d \rightarrow e^+ nn & (\text{threshold} \sim m_n + m_e - m_p + E_B = 4.0 \text{ MeV}) \end{array} \right.$$

$$\text{NC} \left\{ \begin{array}{ll} \nu d \rightarrow \nu pn & (\text{threshold} \sim E_B = 2.2 \text{ MeV}) \\ \bar{\nu} d \rightarrow \bar{\nu} pn \end{array} \right.$$

low E
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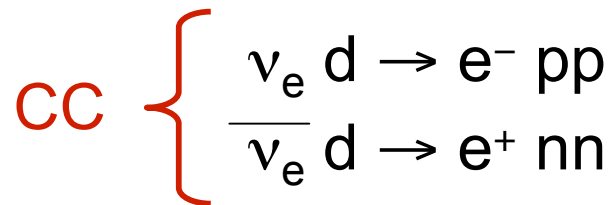
$$\text{NC (flavor blind)} \left\{ \begin{array}{l} \nu d \rightarrow \nu pn \\ \bar{\nu} d \rightarrow \bar{\nu} pn \end{array} \right.$$

measures total flux of active ν 's
independent of oscillations

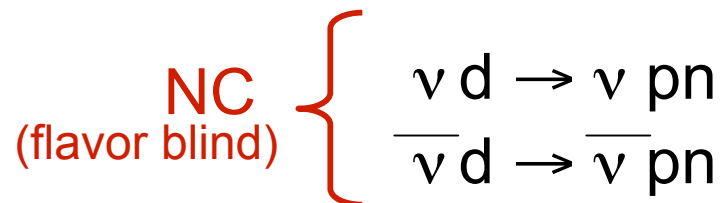
low E
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sensitive to ν oscillations

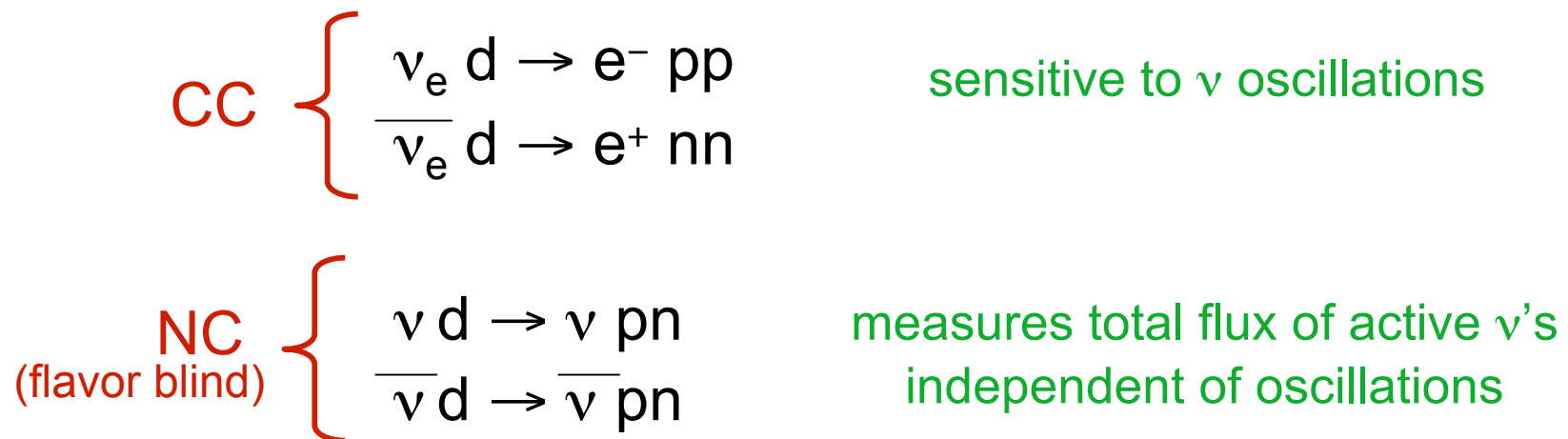


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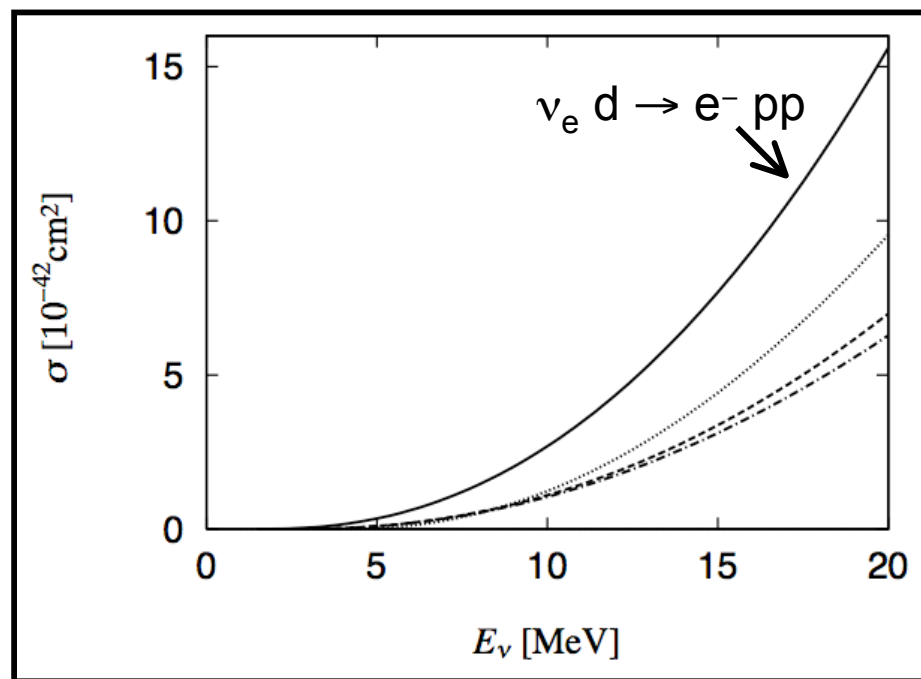


- number of groups have very carefully computed these σ 's

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 $\gamma+d$

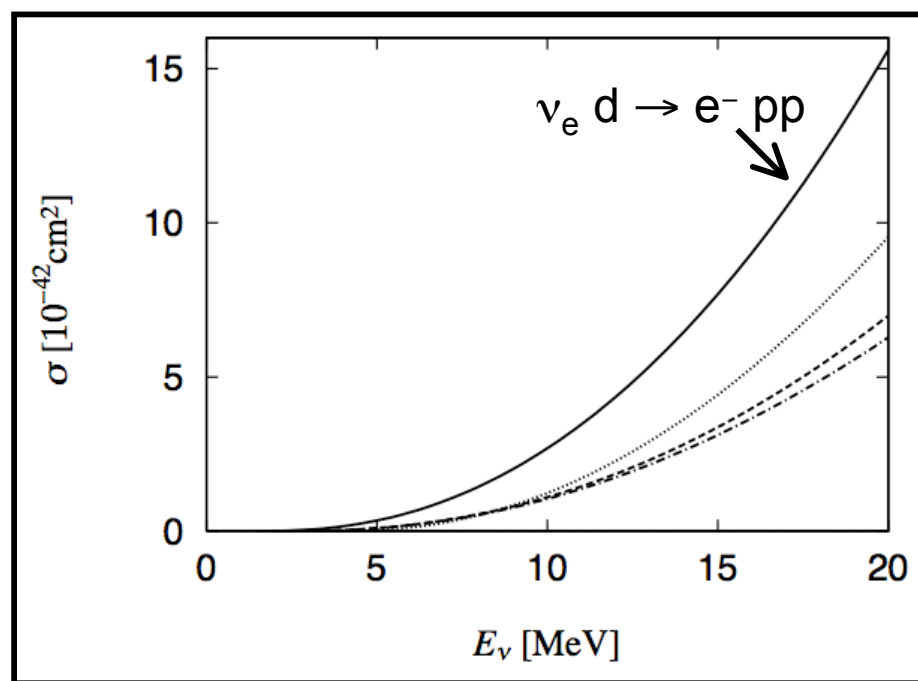


Nakamura *et al.*, PRC **63**, 034617 (2001)

low E
(< 100 MeV)

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 - nucleon is almost free
 - deuteron is stable
 - know neutron lifetime
 - constraints from $\gamma+d$
- σ rather well determined, **theoretical uncertainty is $\sim 1\%$ 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

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

35%
measurement

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

Savannah River [1] $\sigma[10^{-45} \text{ cm}^2/\nu_e]$ (1979)	$\sigma^{ncd} = 3.8 \pm 0.9$	$\sigma_{\text{exp}}^{ncd}/\sigma_{\text{theor}}^{ncd} = 0.8 \pm 0.2$
	$\sigma^{ccd} = 1.5 \pm 0.4$	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{theor}}^{ccd} = 0.7 \pm 0.2$
	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{exp}}^{ncd} = 0.40 \pm 0.14$	$\sigma_{\text{theor}}^{ccd}/\sigma_{\text{theor}}^{ncd} = 0.353$
Krasnoyarsk [2] $\sigma[10^{-44} \text{ cm}^2/\text{fis. } ^{235}\text{U}]$ (1990)	$\sigma^{ncd} = 3.0 \pm 1.0$	$\sigma_{\text{exp}}^{ncd}/\sigma_{\text{theor}}^{ncd} = 0.95 \pm 0.33$
	$\sigma^{ccd} = 1.1 \pm 0.2$	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{theor}}^{ccd} = 0.98 \pm 0.18$
	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{exp}}^{ncd} = 0.37 \pm 0.14$	$\sigma_{\text{theor}}^{ccd}/\sigma_{\text{theor}}^{ncd} = 0.353$
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	$\sigma^{ccd} = 1.17 \pm 0.14 \pm 0.07$	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{theor}}^{ccd} = 1.08 \pm 0.19$
	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{exp}}^{ncd} = 0.43 \pm 0.10$	$\sigma_{\text{theor}}^{ccd}/\sigma_{\text{theor}}^{ncd} = 0.37 \pm 0.08$
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	$\sigma^{ccd} = 1.10 \pm 0.23$	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{theor}}^{ccd} = 0.97 \pm 0.20$
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20-30%
measurements

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

low E
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Bugey [4] $\sigma[10^{-44} \text{ cm}^2/\text{fis.}]$ (1999)	$\sigma^{ncd} = 3.29 \pm 0.42$	$\sigma_{\text{exp}}^{ncd}/\sigma_{\text{theor}}^{ncd} = 1.01 \pm 0.13$
	$\sigma^{ccd} = 1.10 \pm 0.23$	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{theor}}^{ccd} = 0.97 \pm 0.20$
	$\sigma_{\text{exp}}^{ccd}/\sigma_{\text{exp}}^{ncd} = 0.33 \pm 0.08$	$\sigma_{\text{theor}}^{ccd}/\sigma_{\text{theor}}^{ncd} = 0.348 \pm 0.04$

20-30%
measurements

not at all
competitive
with theory

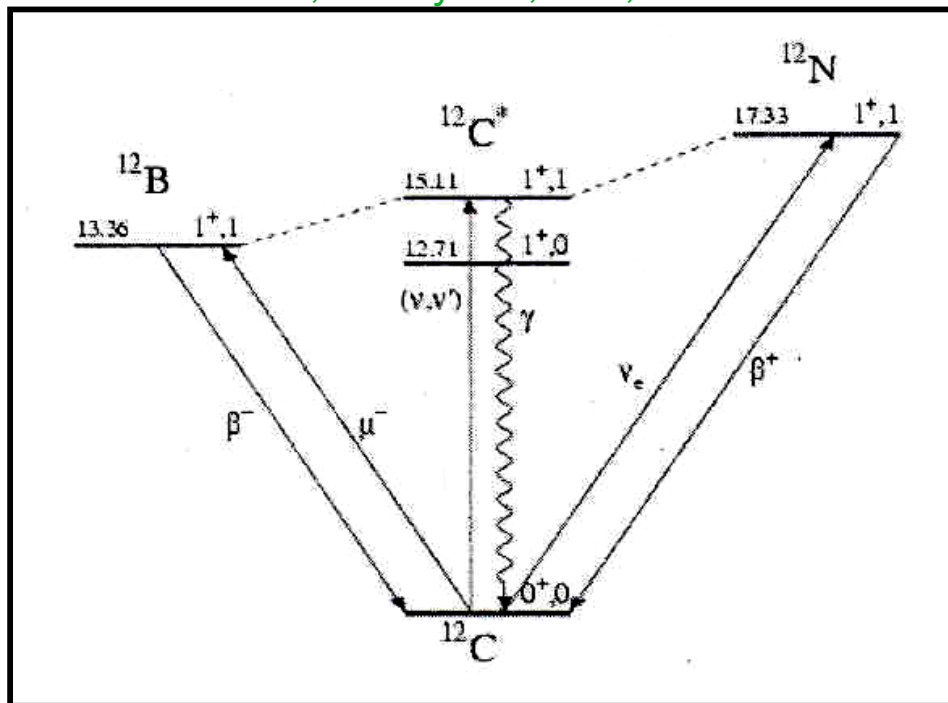
Kozlov *et al.*, Phys. Atom. Nucl. **63**, 1016 (2000)

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

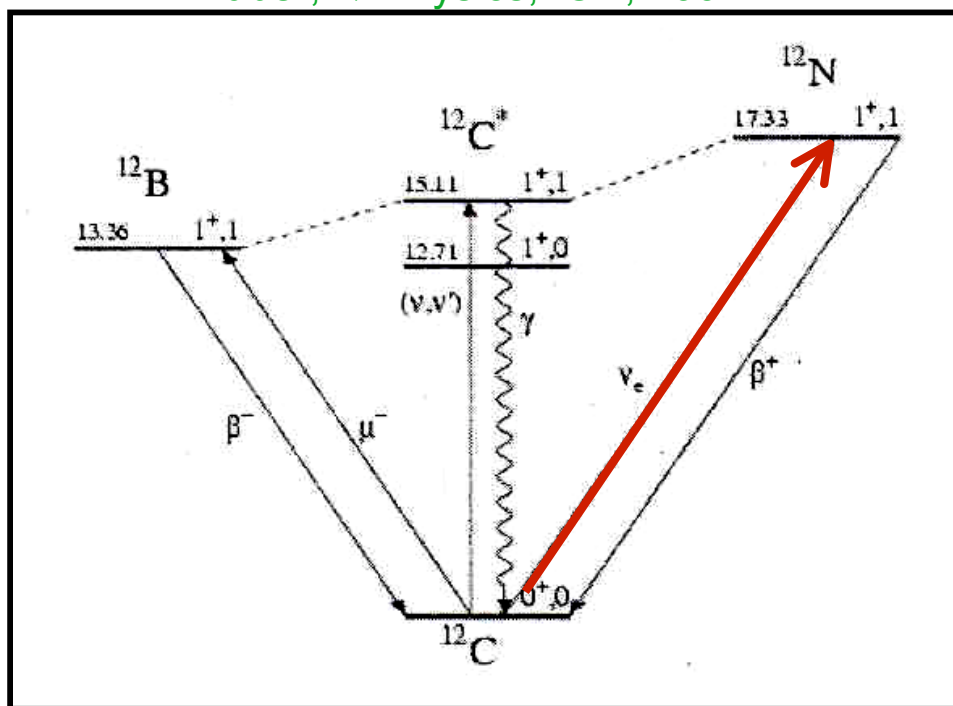


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CC interactions

$$\nu_\mu \, ^{12}\text{C} \rightarrow \mu^- \, ^{12}\text{N}_{\text{gs}}$$

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

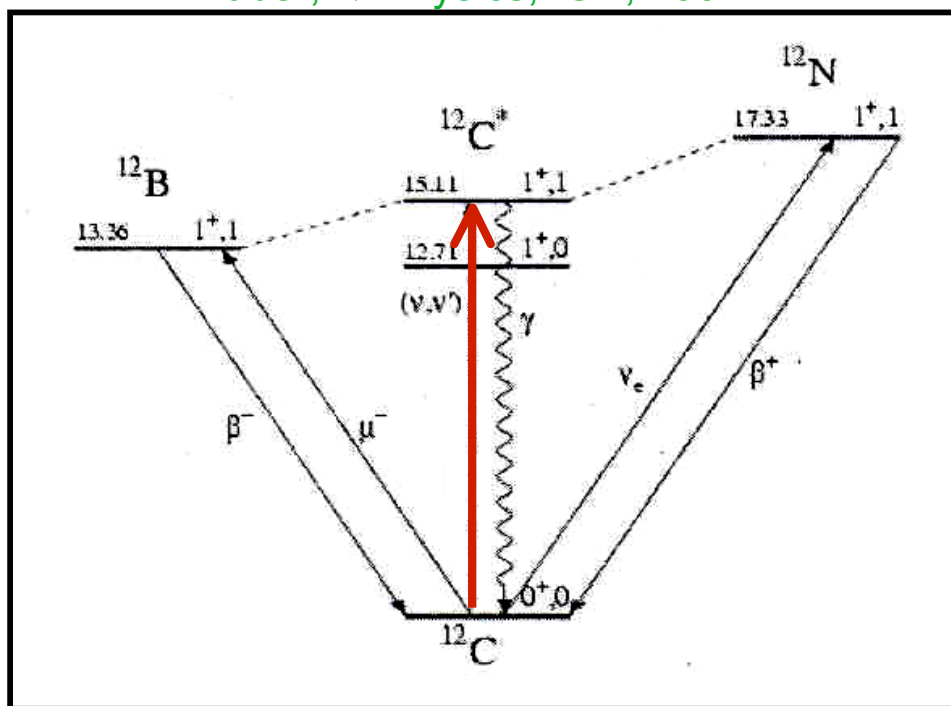
(note: also written as $^{12}\text{C}(\nu_\mu, \mu^-)^{12}\text{N}_{\text{gs}}$ and $^{12}\text{C}(\nu_e, e^-)^{12}\text{N}_{\text{gs}}$)

low E
(< 100 MeV)

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K. Zuber, ν Physics, IOP, 2004



NC interactions

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

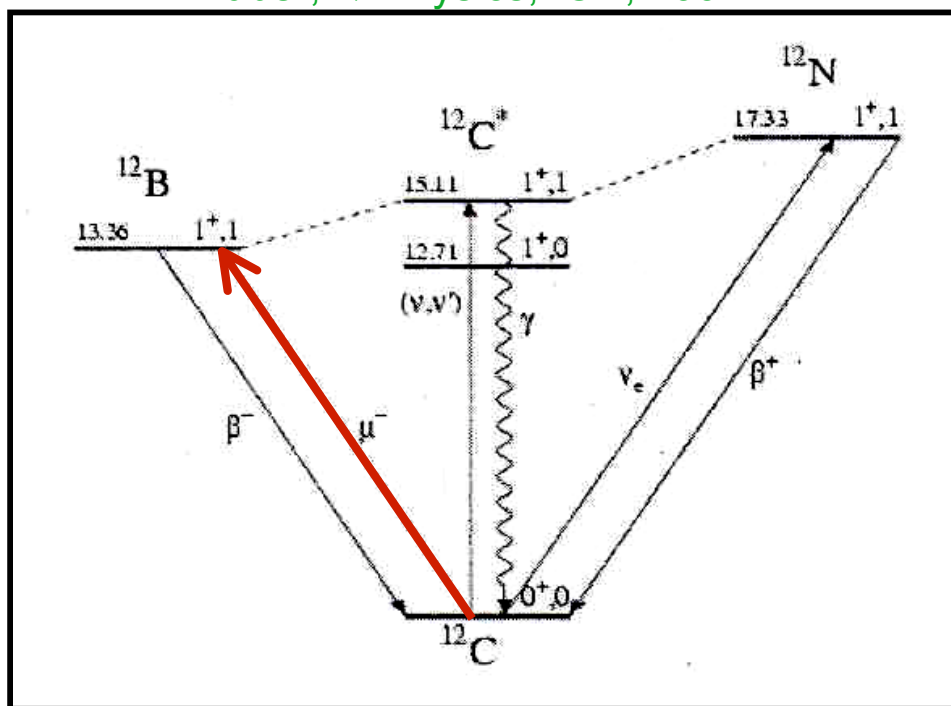
(note: also written as $^{12}\text{C}(\nu, \nu)^{12}\text{C}^*$)

low E
(< 100 MeV)

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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	$^{12}\text{C}(\nu_e, e^-)^{12}\text{N}_{gs}$ decay at rest	$^{12}\text{C}(\nu_\mu, \mu^-)^{12}\text{N}_{gs}$ decay in flight	$^{12}\text{C}(\nu, \nu')^{12}\text{C}(15.11)$ decay at rest
KARMEN	$9.1 \pm 0.5 \pm 0.8$	-	$10.4 \pm 1.0 \pm 0.9$
LSND	$8.9 \pm 0.3 \pm 0.9$	$66 \pm 10 \pm 10$	-
E225	$10.5 \pm 1.0 \pm 1.0$	-	-
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

CC

NC

low E
(< 100 MeV)

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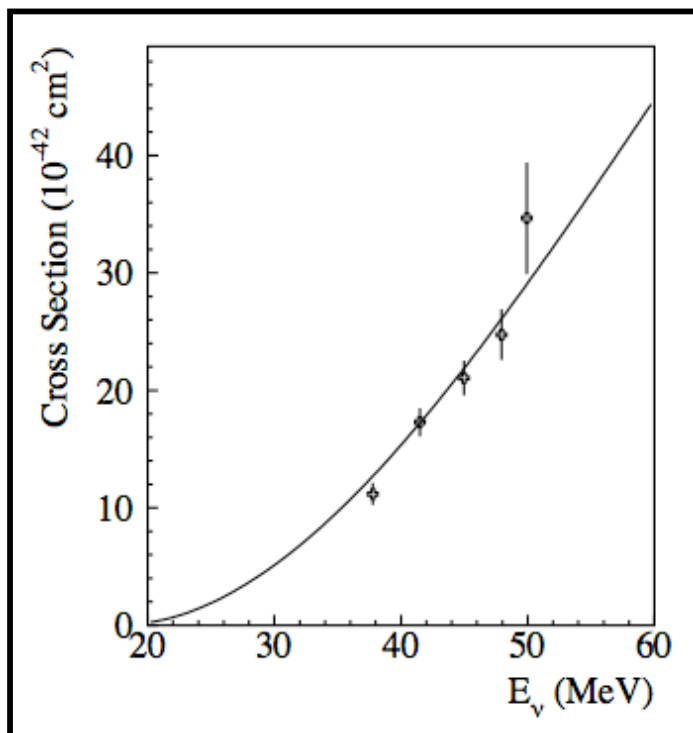
- predictions agree with experimental measurements
- σ for $^{12}\text{N}_{g.s.}$ can be predicted with accuracy of $\sim 5\%$
(have to rely on nuclear theory but can take advantage of a # of constraints from related processes like β decay transitions of various isotopes, μ^- capture, etc.)

low E
(< 100 MeV)

^{12}C

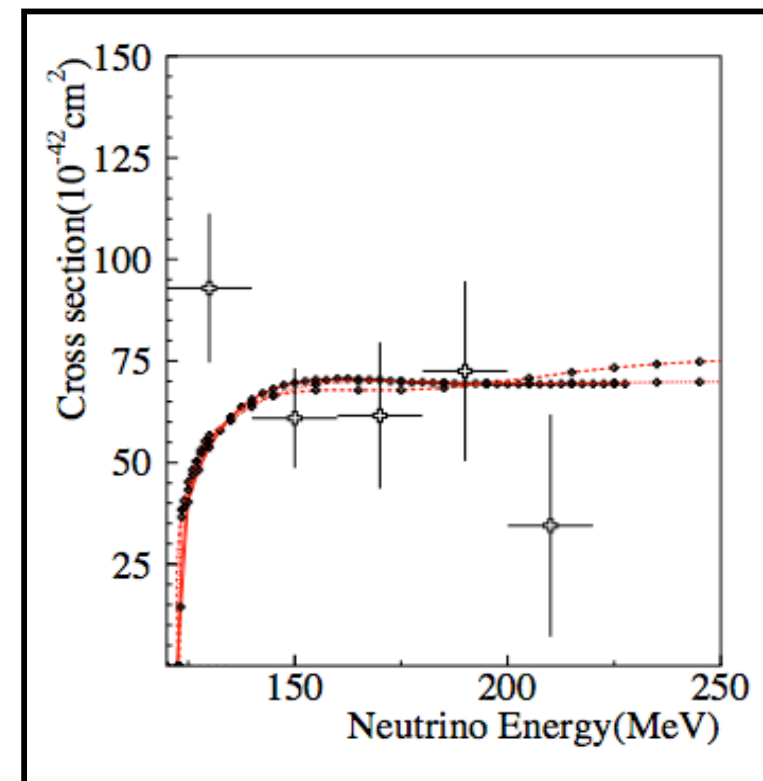
- also measured energy dependence of the cross sections

$$\nu_e \ ^{12}\text{C} \rightarrow e^- \ ^{12}\text{N}_{\text{g.s.}}$$



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

$$\nu_\mu \ ^{12}\text{C} \rightarrow \mu^- \ ^{12}\text{N}_{\text{g.s.}}$$



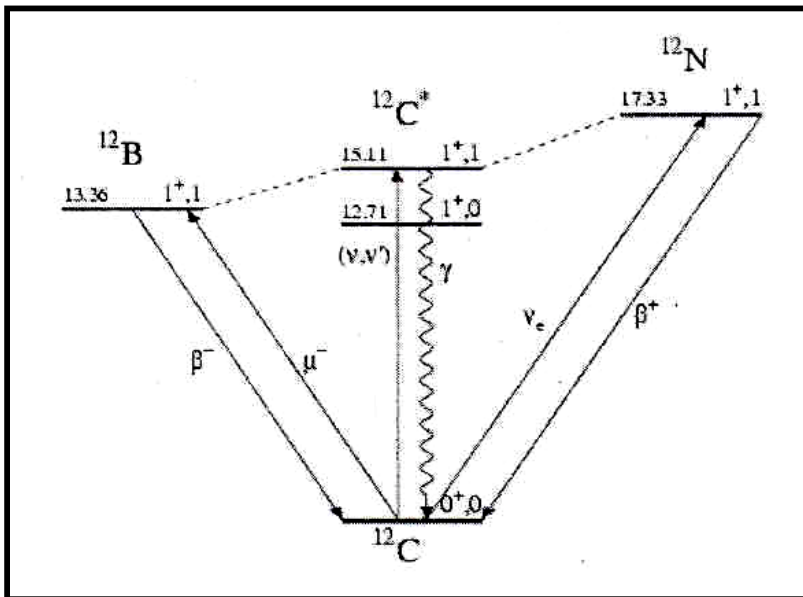
Auerbach *et al.*, PRC **66**, 015501 (2002)
LSND, π^+ DIF

low E
(< 100 MeV)

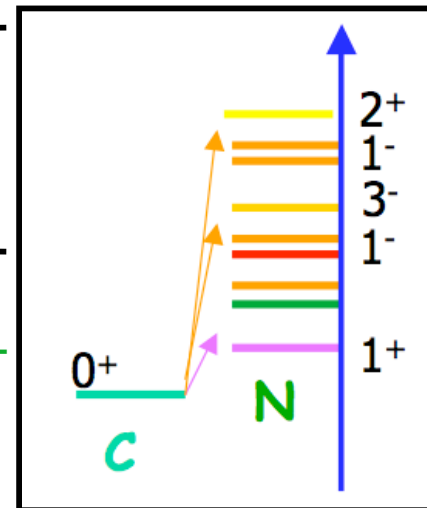
^{12}C

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

K. Zuber, ν Physics, IOP, 2004



C. Volpe



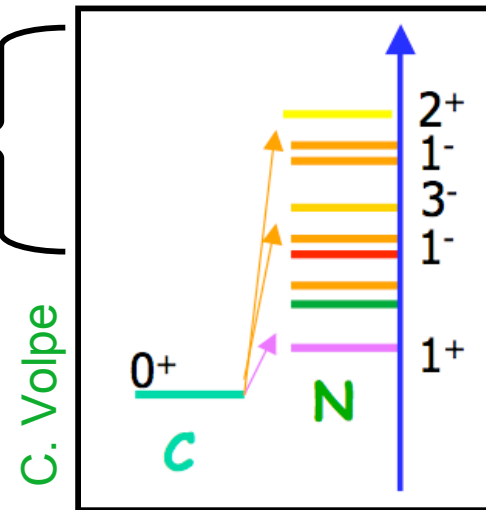
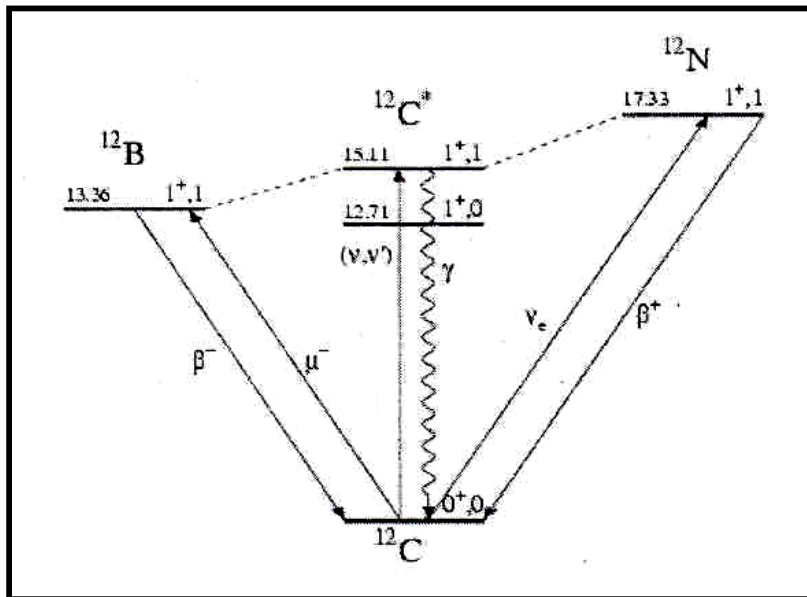
$\nu_{\mu} ^{12}\text{C} \rightarrow \mu^- ^{12}\text{N}^*$
(final state includes all E levels)

low E
(< 100 MeV)

^{12}C

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K. Zuber, ν Physics, IOP, 2004



$\nu_{\mu} ^{12}\text{C} \rightarrow \mu^{-} ^{12}\text{N}^*$
(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 $^{12}\text{N}_{\text{g.s.}}$

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

low E
(< 100 MeV)

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ν -deuteron	$\sim 1\%$ (< 10 MeV) less certain higher E	25-30% one ν_e , several $\bar{\nu}_e$	solar ν's (SNO) reactor ν's (Bugey)

low E
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ν - ^{12}C	$\sim 5\%$ ($^{12}\text{N}_{\text{gs}}$) less certain $^{12}\text{N}^*$	10-20% KARMEN, LSND	SN + atmospheric ν's (threshold too high for solar or reactor, unless pick diff nucleus)

low E
(< 100 MeV)

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- σ 's are well known because can tie them to other processes

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low E
(< 100 MeV)

What I Didn't Talk About

solar ν 's
(Homestake, GALLEX, SAGE)

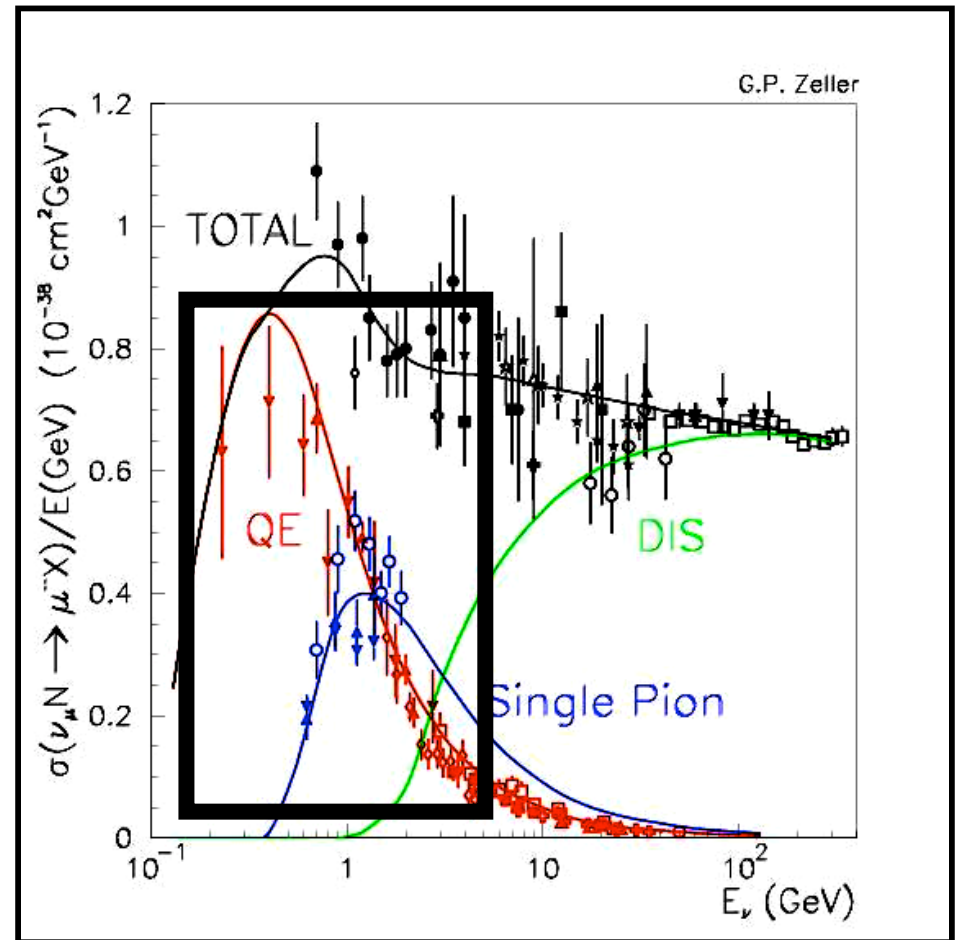
ICARUS

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

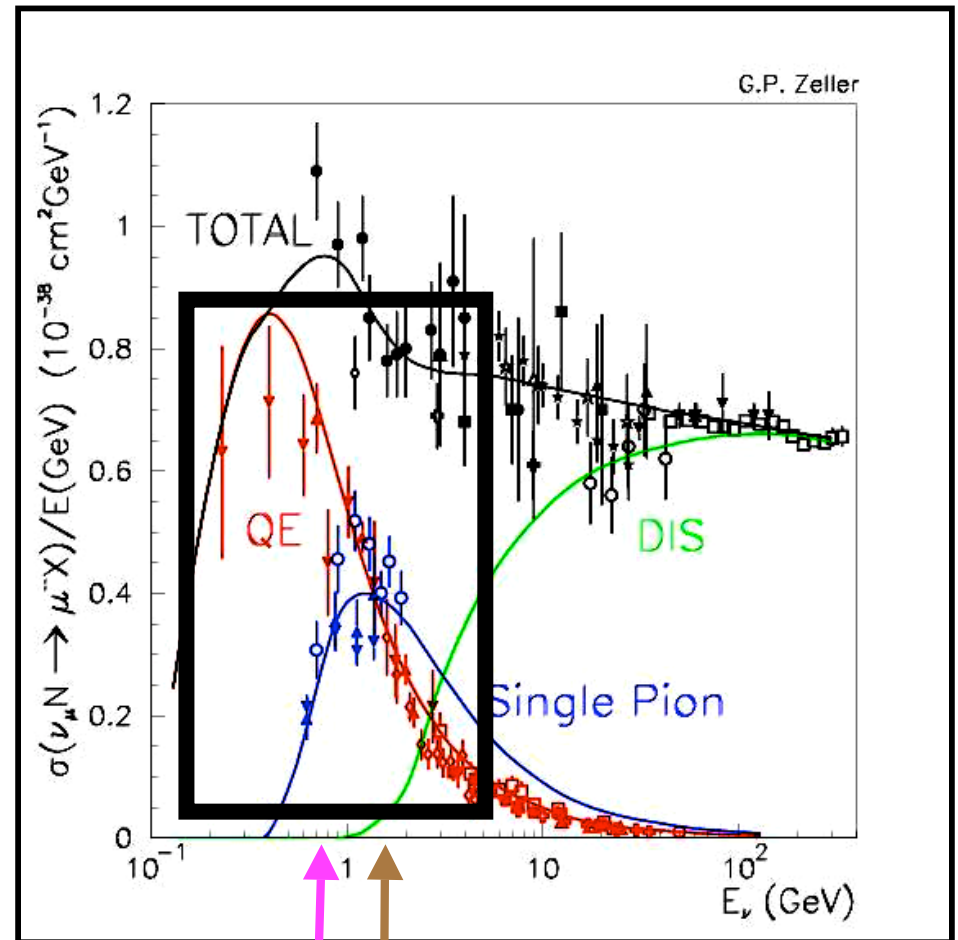


atmospheric $\longleftrightarrow$

intermediate
(~ 1 GeV)

Intermediate Energies

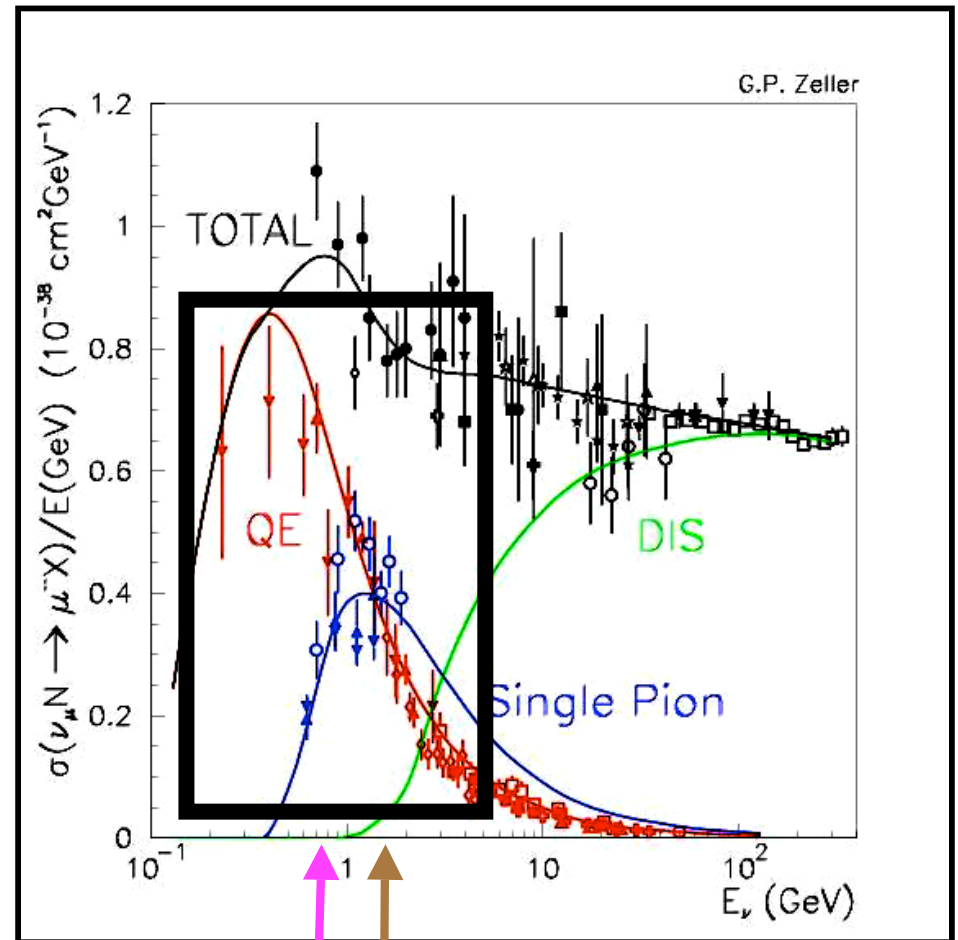
- important for studies of **atmospheric ν 's**
- future **accelerator-based** ν experiments will all be operating in this E range



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)

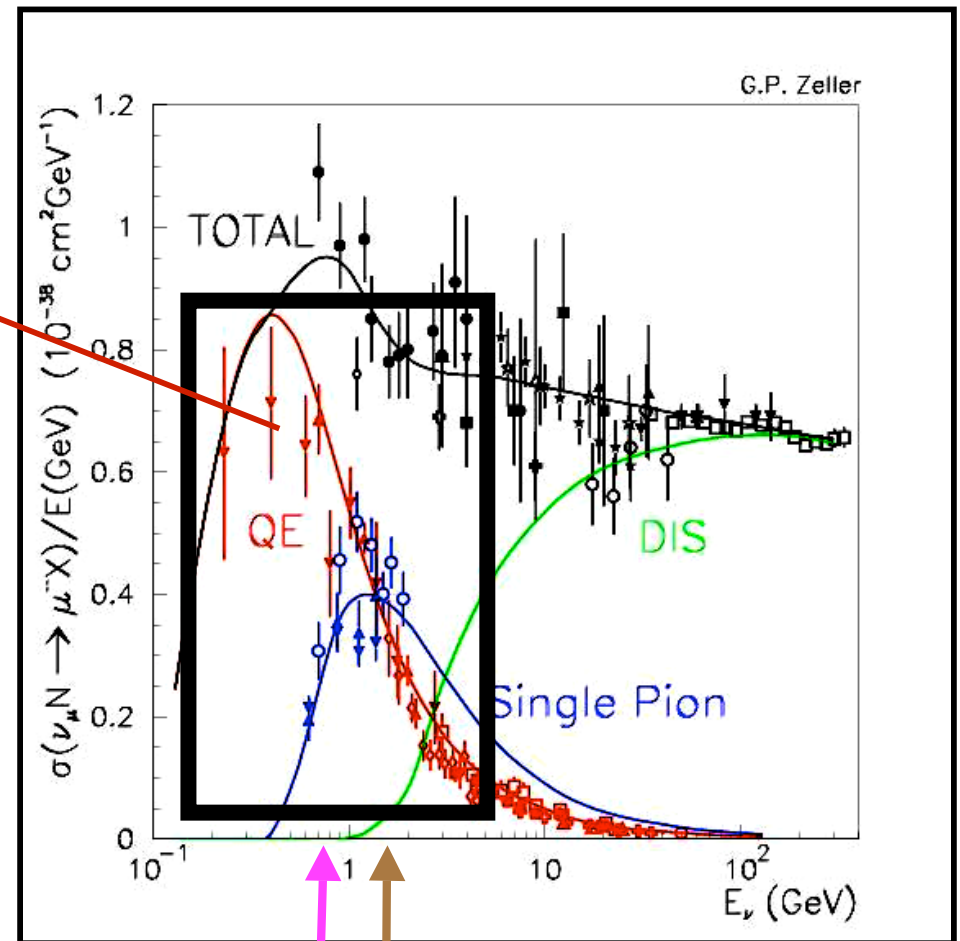
Intermediate Energies

QE scattering

at higher energies
 $E_\nu \sim 1 \text{ GeV}$

$$\begin{pmatrix} \nu_\mu n \rightarrow \mu^- p \\ \nu_e n \rightarrow e^- p \end{pmatrix}$$

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



T2K

NOvA

DUSEL

atmospheric

intermediate
(~ 1 GeV)

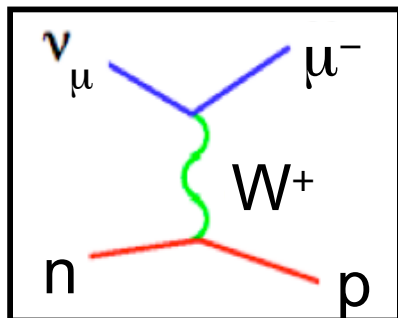
QE Scattering at 1 GeV

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

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

hadronic tensor

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



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

intermediate
(~ 1 GeV)

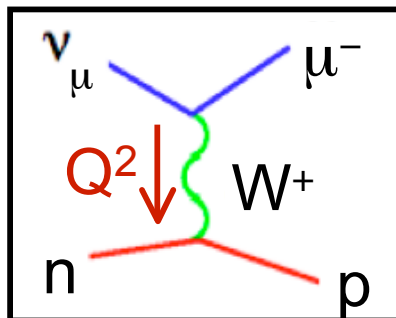
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remember:
form factors
encapsulate
info about the
structure of the
object are
scattering from

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

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

intermediate
(~ 1 GeV)

QE Scattering at 1 GeV

- FFs are not calculable, need to measure experimentally

intermediate
(~ 1 GeV)

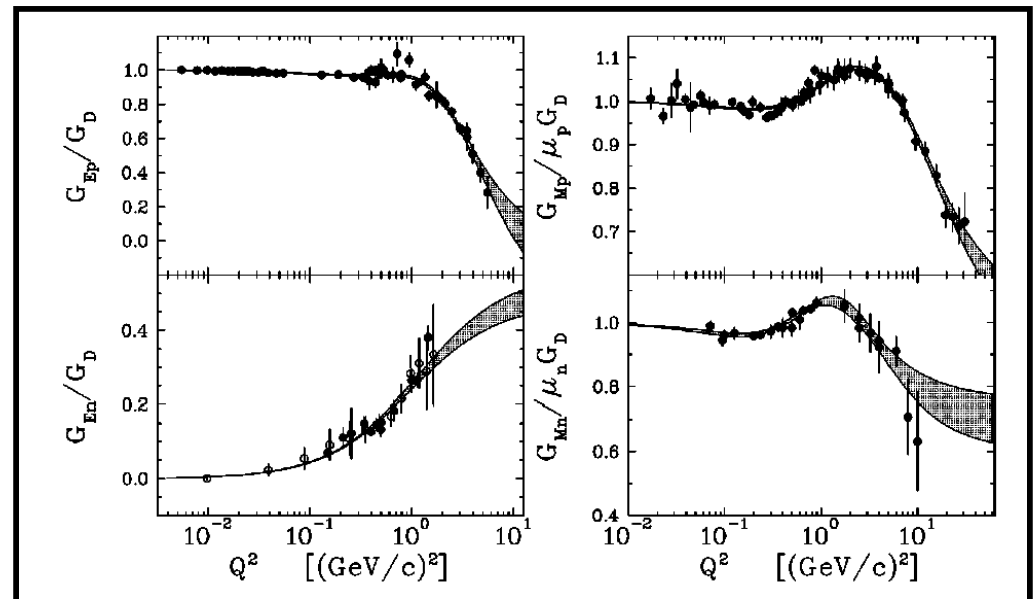
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vector form factors

- 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)

QE Scattering at 1 GeV

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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 ...

intermediate
(~ 1 GeV)

QE Scattering at 1 GeV

- FFs are not calculable, need to measure experimentally

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

axial form factor

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

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

QE Scattering at 1 GeV

- FFs are not calculable, need to measure experimentally

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axial form factor

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

- Q² 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)

QE Scattering at 1 GeV

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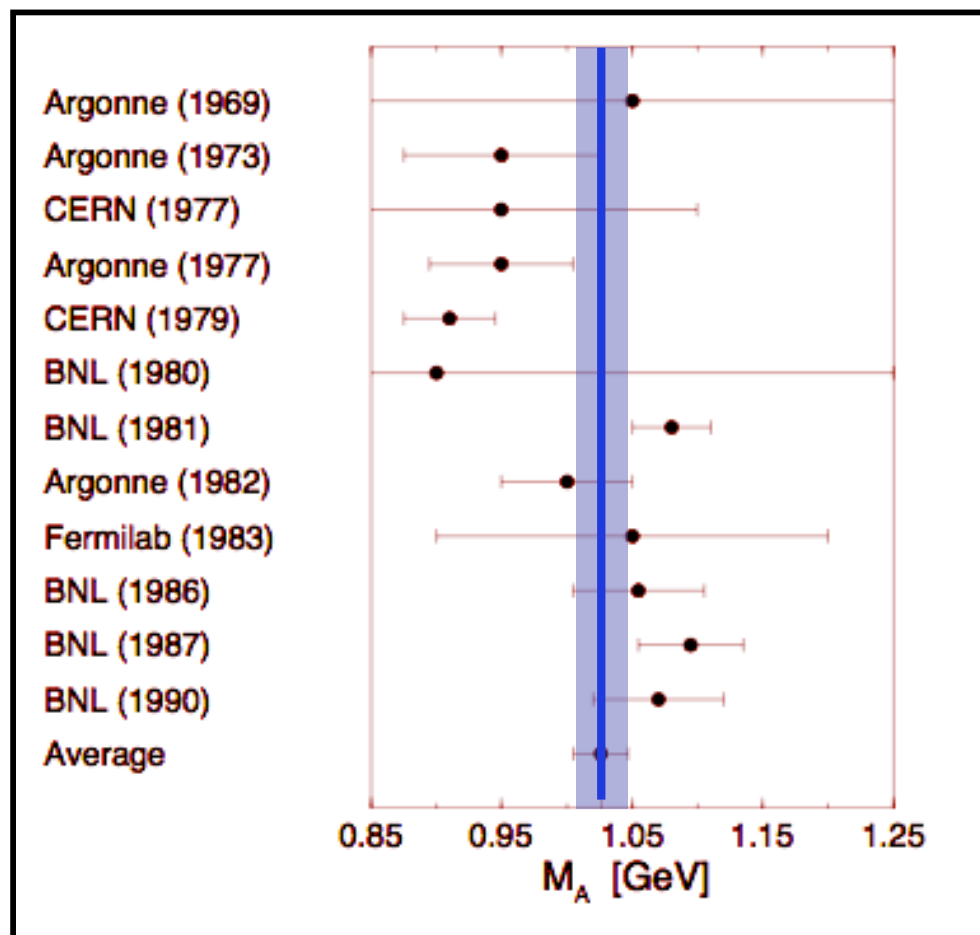
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must be measured experimentally!

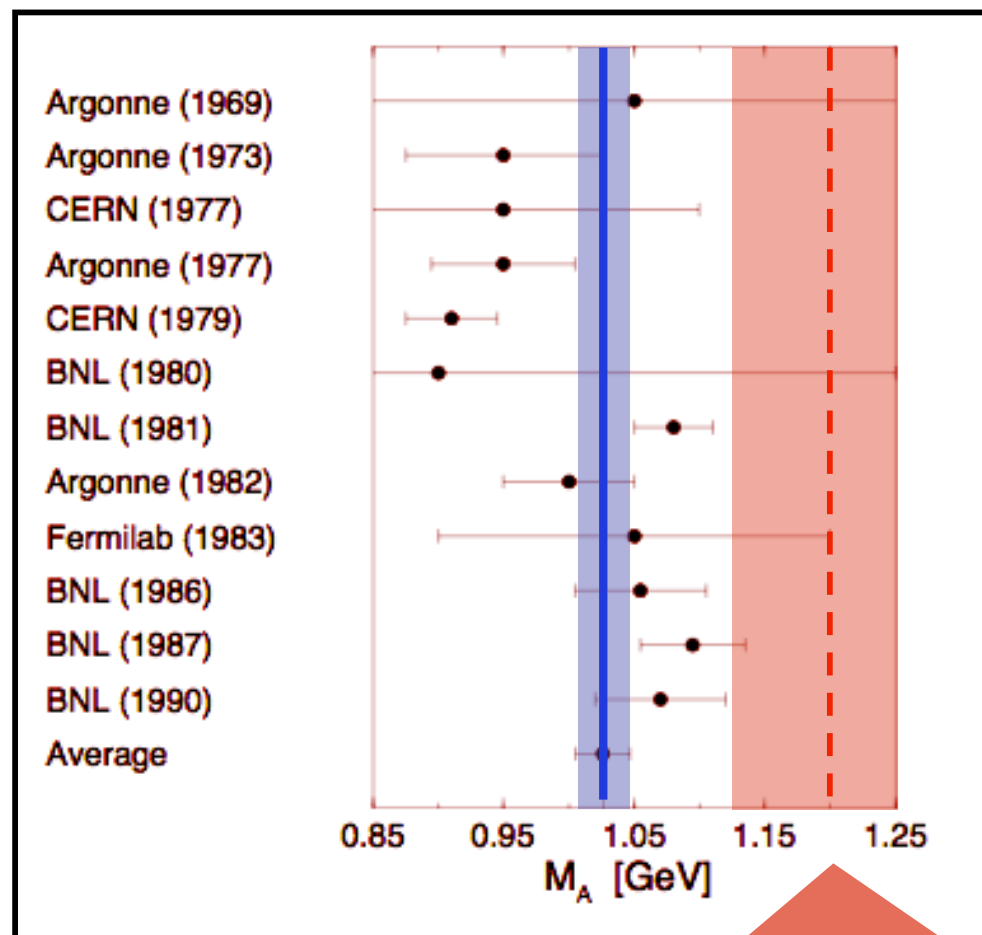
M_A Measurements



past world average:
 $M_A = 1.03 \pm 0.02 \text{ GeV}$

- 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



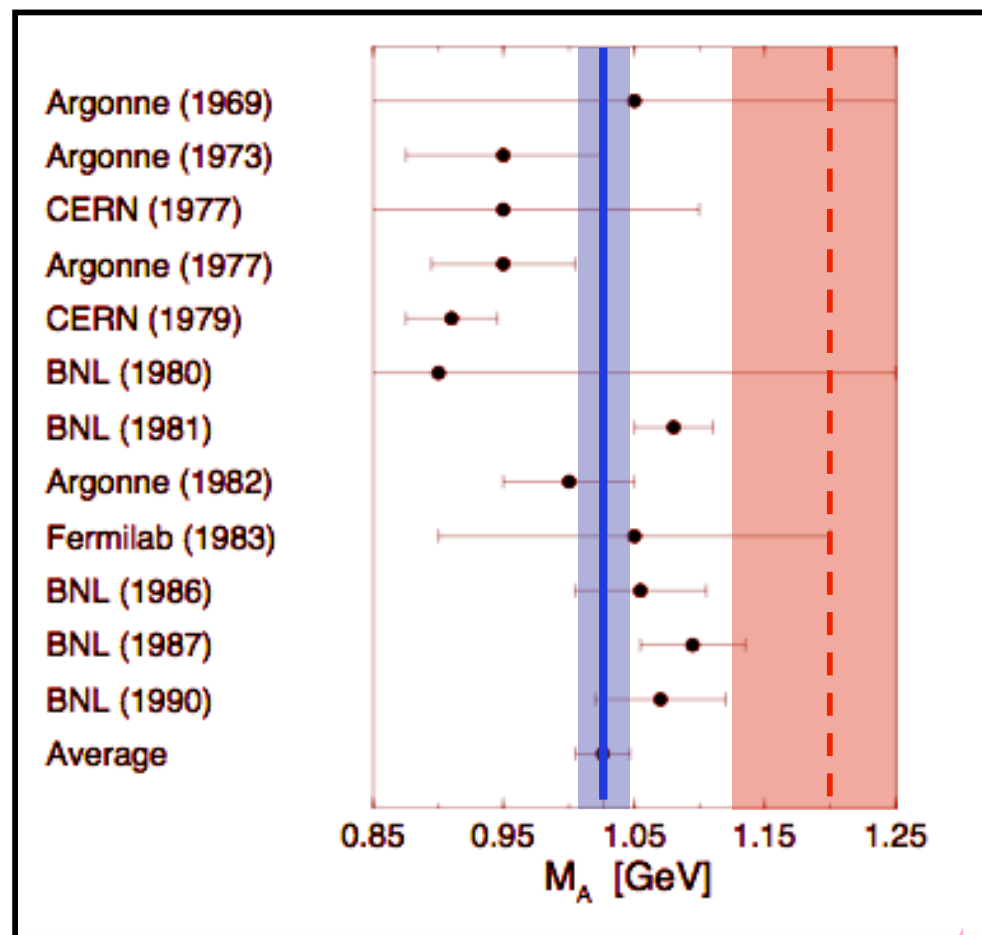
past world average:
 $M_A = 1.03 \pm 0.02$ GeV

- **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

Modern M_A



past world average:
 $M_A = 1.03 \pm 0.02$ GeV



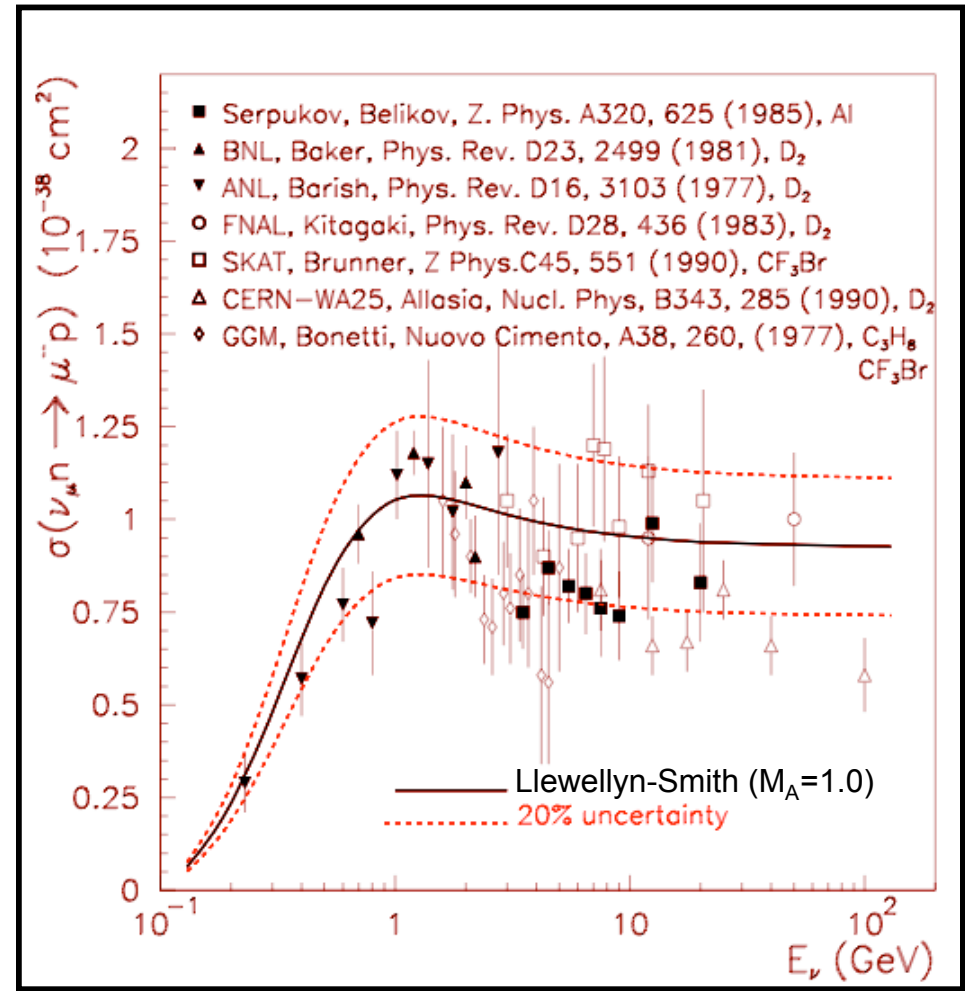
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- **NOMAD** (^{12}C , $Q^2 > 0$)
 arXiv:0812.4543 [hep-ex]
 $M_A = 1.07 \pm 0.07$ GeV

intermediate
(~ 1 GeV)

QE Cross Section

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

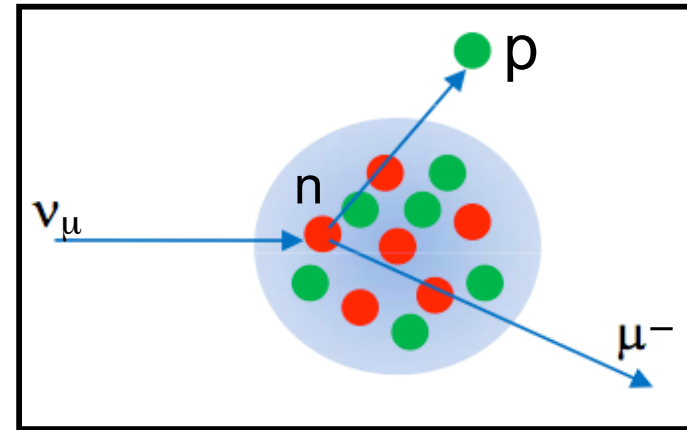
- large span at any given E_{ν}
- typically assign
~20% σ uncertainty
at these energies
(recall: known to <0.5% E_{ν} < 10 MeV)
- most of the data on D_2
- oscillation experiments use
heavier targets!



intermediate
(~ 1 GeV)

Nuclear Effects

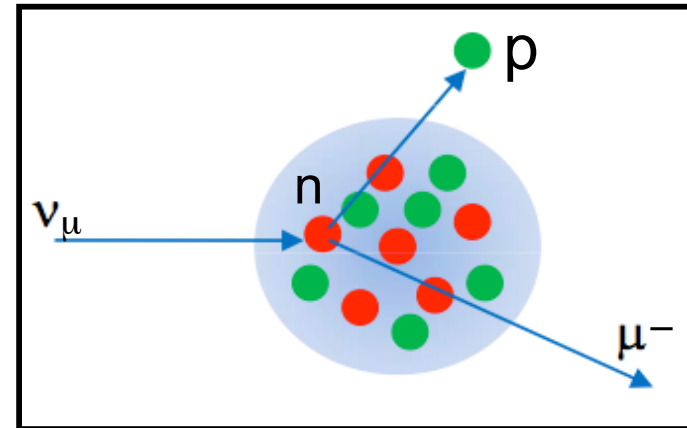
- for ν scattering off heavier targets (^{12}C , ^{16}O , ^{56}Fe , etc.), need to account for fact that nucleons are in fact part of a nucleus



intermediate
(~ 1 GeV)

Nuclear Effects

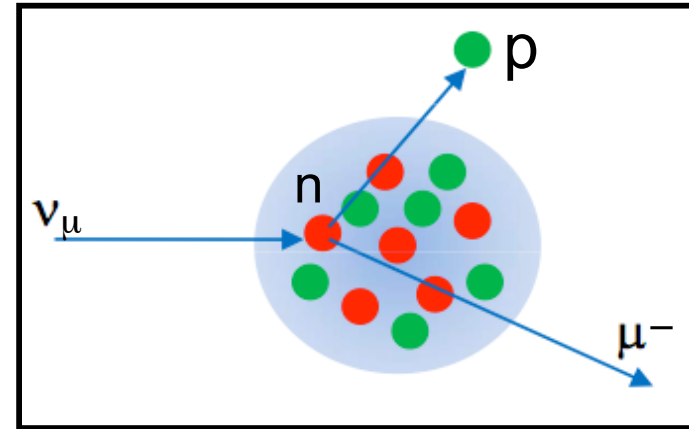
- in a nucleus, target nucleon has some initial momentum which modifies the observed scattering



intermediate
(~ 1 GeV)

Nuclear Effects

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



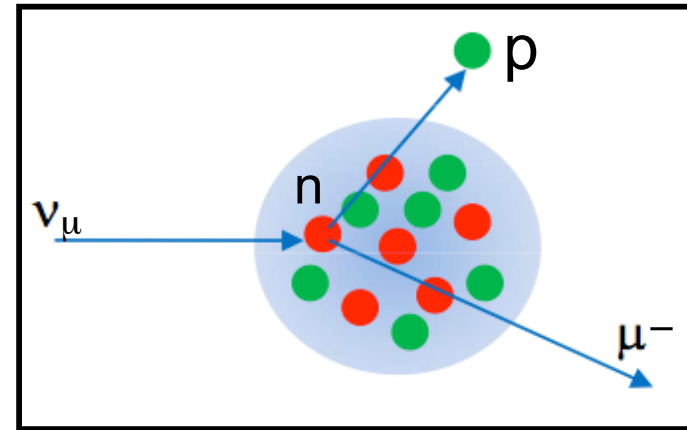
- hadronic tensor now an integral over initial nucleon states

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

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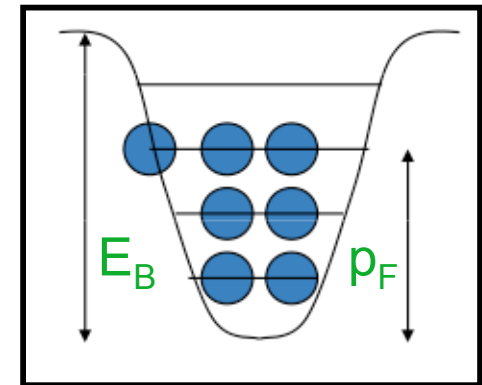
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- simplest: **Fermi Gas model**
(2 free parameters)

$$p_F = 220 \text{ MeV}/c \text{ } (^{12}\text{C})$$

$$E_B = 25 \text{ MeV}$$

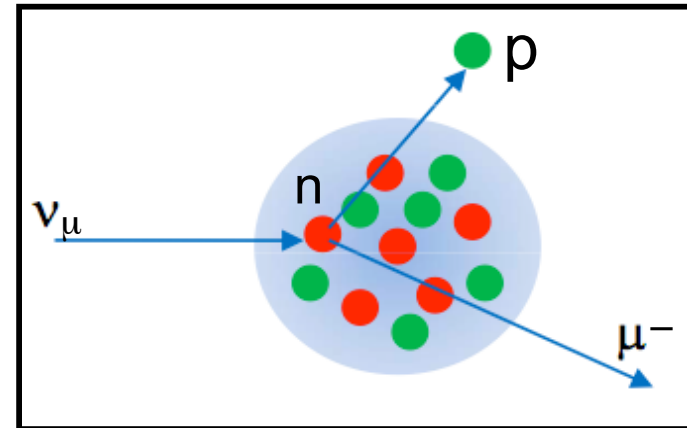


$$P_{RFGM}(\mathbf{p}, E) = \left(\frac{6 \pi^2 A}{p_F^3} \right) \theta(p_F - \mathbf{p}) \delta(E_{\mathbf{p}} - E_B + E)$$

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

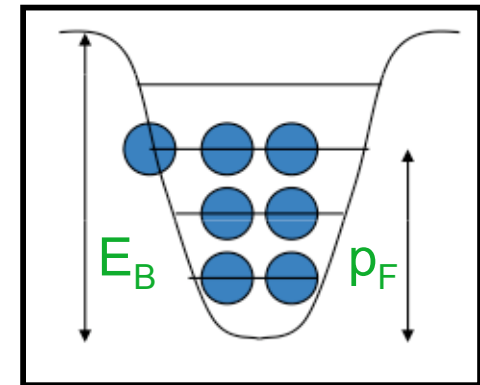
$$W_A^{\mu\nu} = \frac{1}{2} \int d^3p dE P(\mathbf{p}, E) \frac{1}{4 E_{|\mathbf{p}|} E_{|\mathbf{p}+\mathbf{q}|}} W^{\mu\nu}(\tilde{p}, \tilde{q})$$

- simplest: **Fermi Gas model**

(2 free parameters)

$$p_F = 220 \text{ MeV}/c \text{ } (^{12}\text{C})$$

$$E_B = 25 \text{ MeV}$$

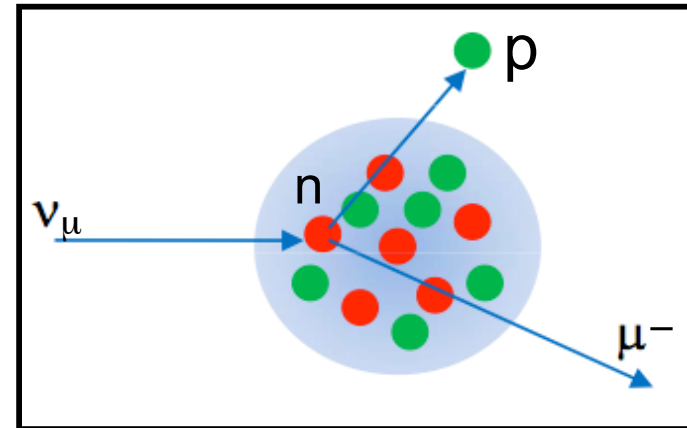


- energy transfer $> E_B$
- final state: $p_p > p_F$ (Pauli blocking)

intermediate
(~ 1 GeV)

Nuclear Effects

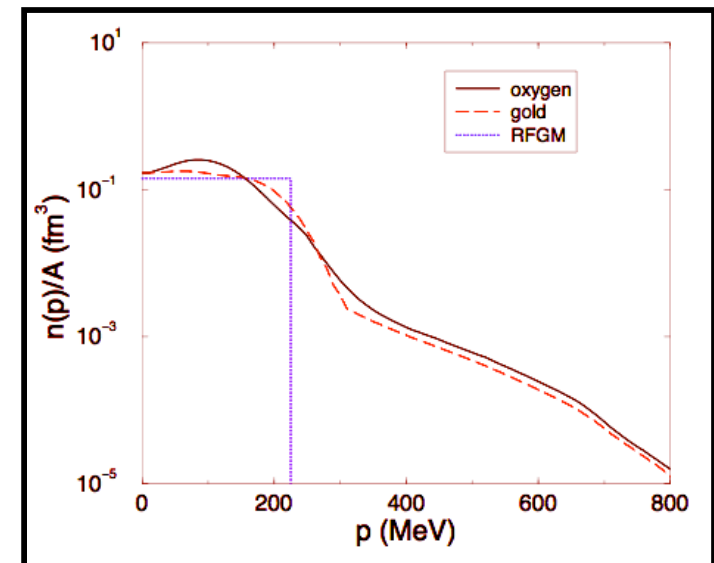
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$$W_A^{\mu\nu} = \frac{1}{2} \int d^3p dE \underbrace{P(\mathbf{p}, E)}_{\text{circled in red}} \frac{1}{4 E_{|\mathbf{p}|} E_{|\mathbf{p}+\mathbf{q}|}} W^{\mu\nu}(\tilde{p}, \tilde{q})$$

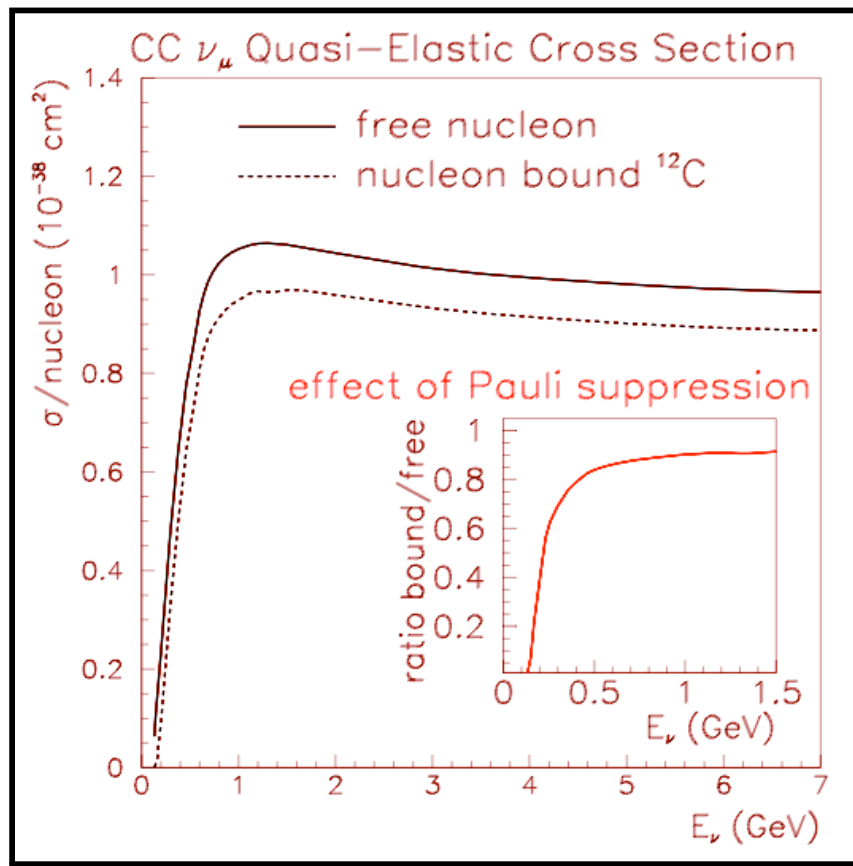
- simplest: **Fermi Gas model**
- more realistic: **spectral functions superscaling**



intermediate
(~ 1 GeV)

Nuclear Effects

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



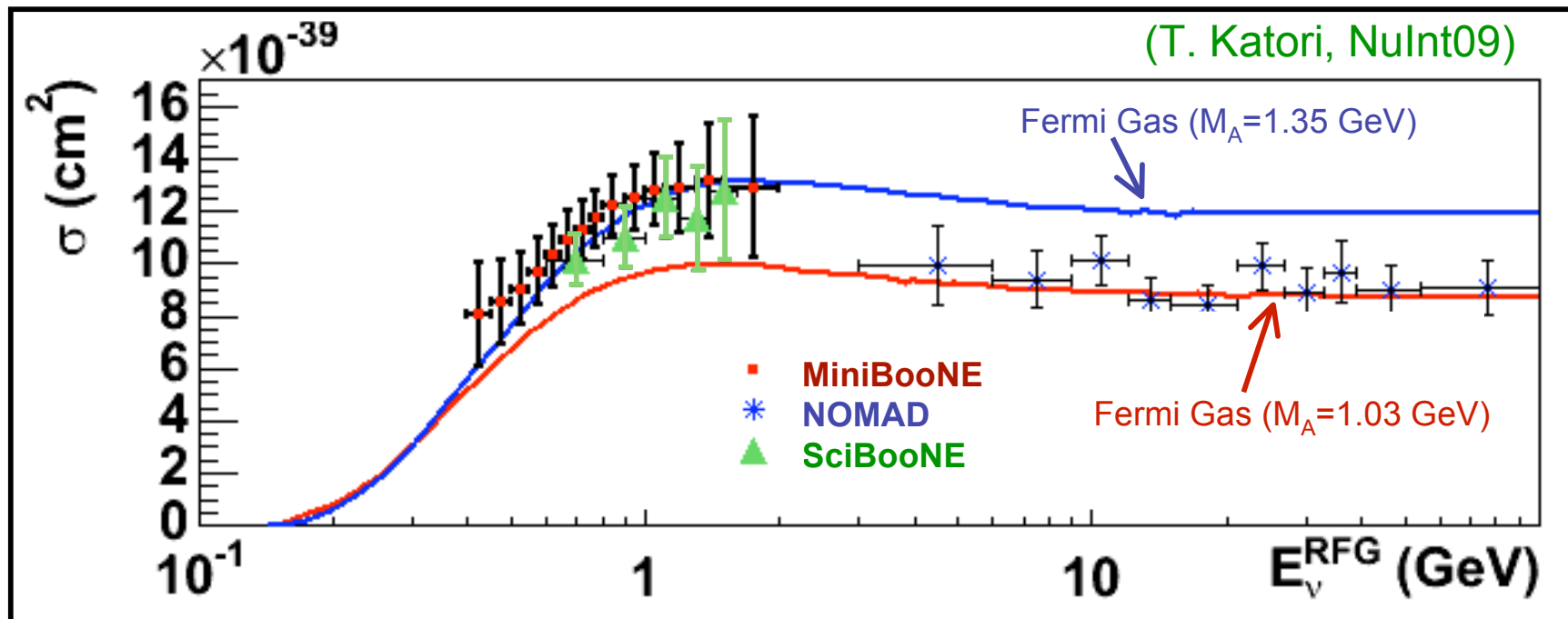
- significant suppression at low E_ν (and low Q^2) if the target is ^{12}C , ^{16}O , etc.



intermediate
(~ 1 GeV)

ν_μ QE Scattering on ^{12}C

- modern measurements of QE σ at these energies

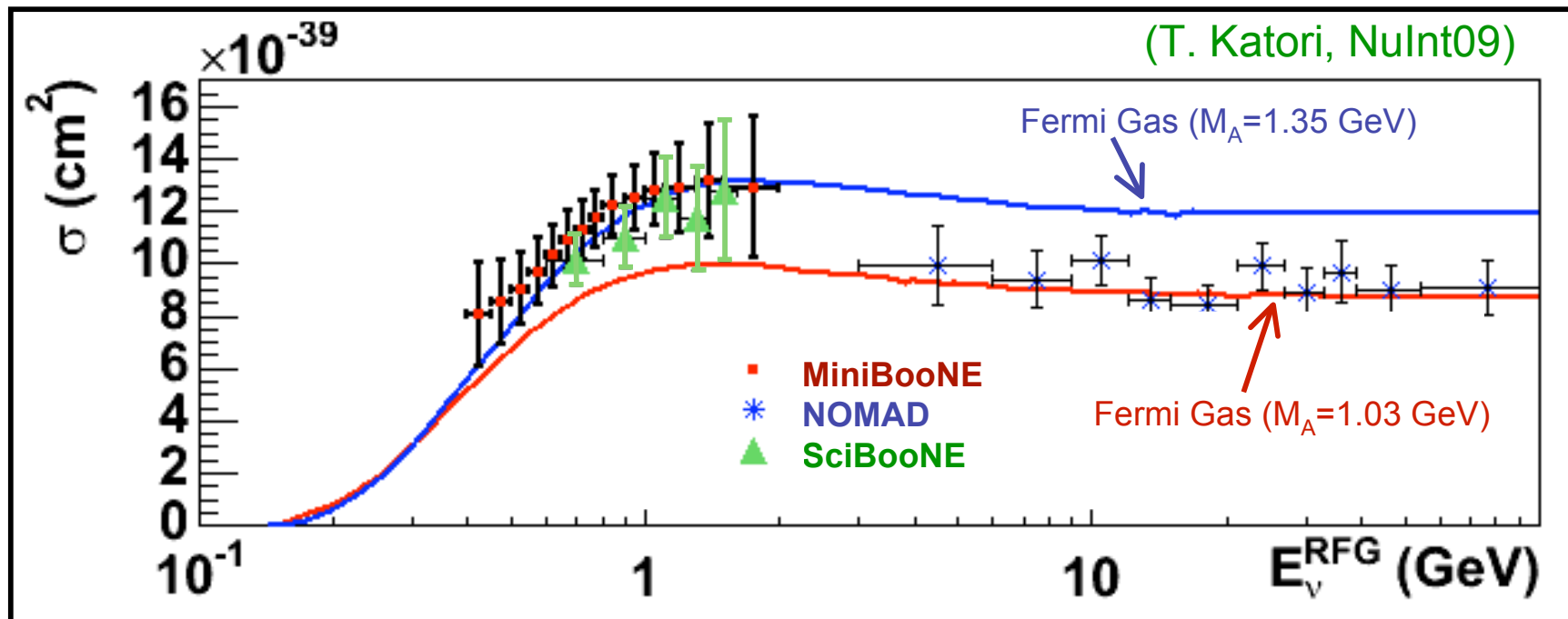


checking this decades later!

intermediate
(~ 1 GeV)

ν_μ QE Scattering on ^{12}C

- modern measurements of QE σ at these energies



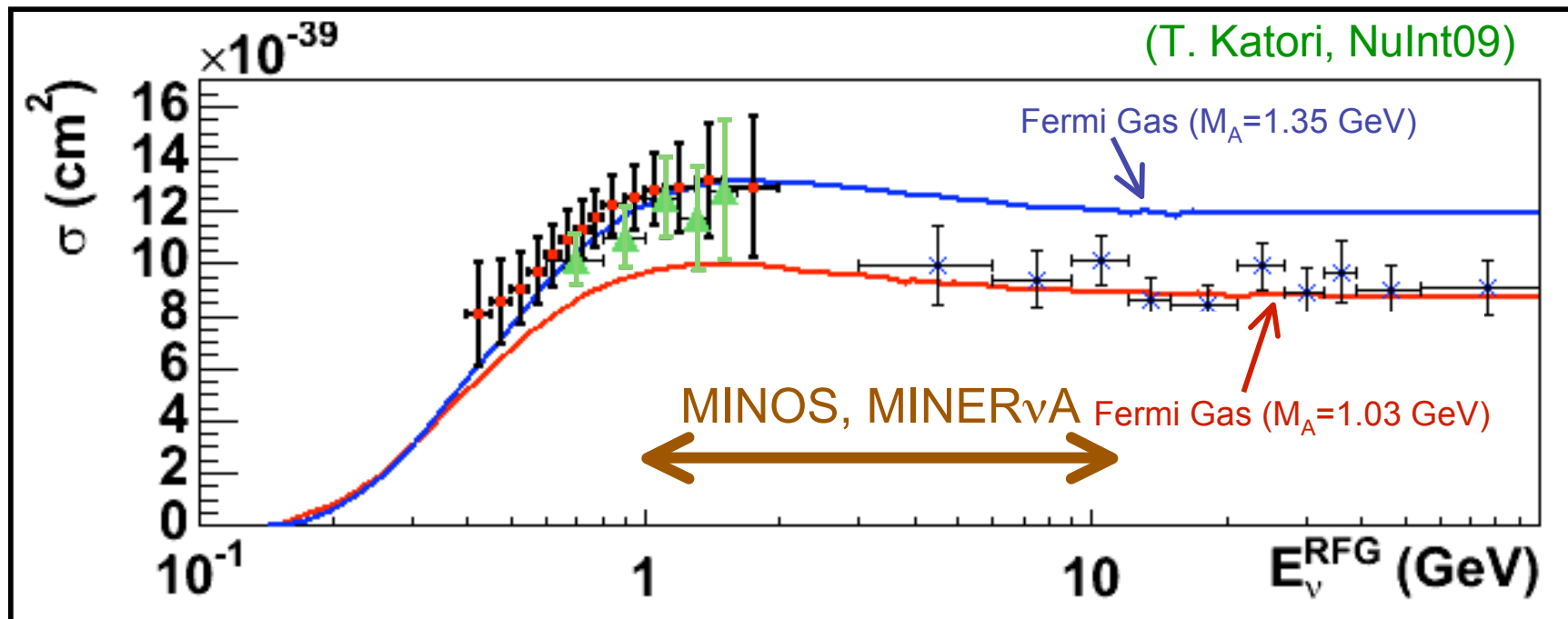
- ~ 30% difference between QE σ measured at low & high E both on ^{12}C ?!



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

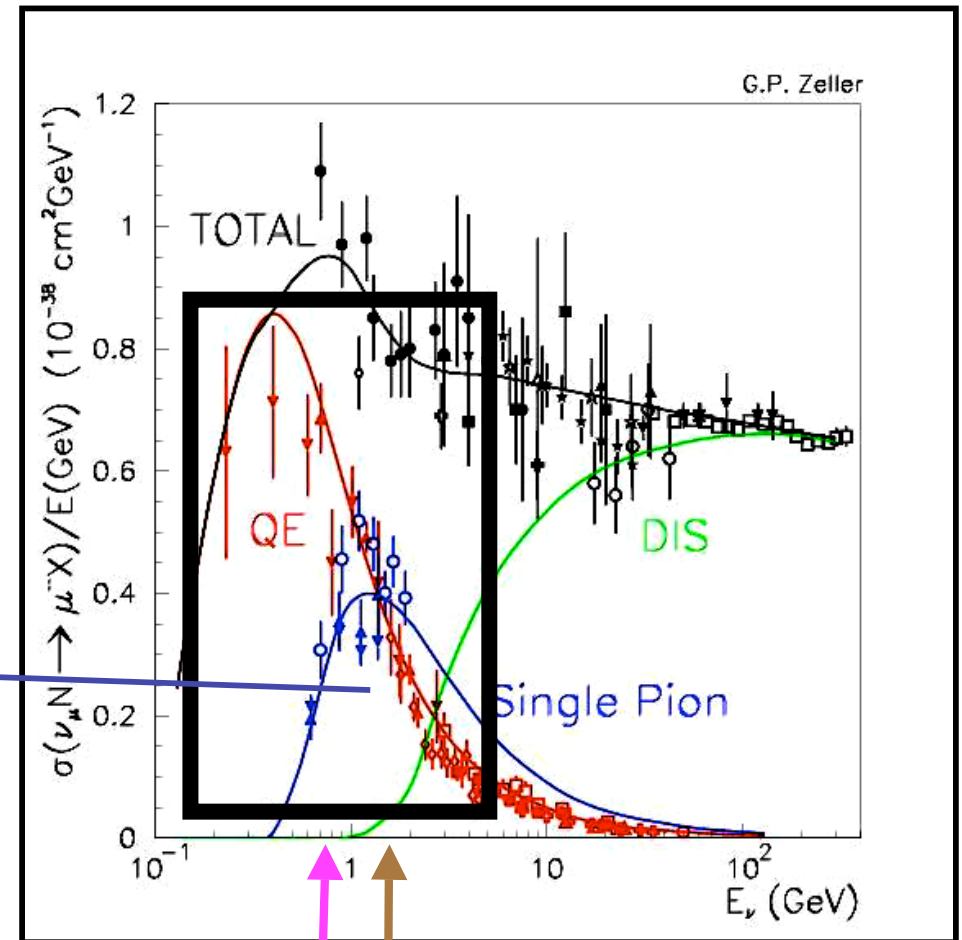
M_A & nuclear effects
important for accurate
prediction of ν QE scattering
at ~1 GeV
(atmospheric, accelerator)

intermediate
(~ 1 GeV)

Intermediate Energies

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

single pion
production



T2K

NOvA

DUSEL

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):

$$\nu_\mu p \rightarrow \mu^- p \pi^+$$

$$\nu_\mu n \rightarrow \mu^- n \pi^+$$

$$\nu_\mu n \rightarrow \mu^- p \pi^0$$

$$\nu_\mu p \rightarrow \nu_\mu n \pi^+$$

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

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

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

nucleon
+ pion(s)
final state

intermediate
(~ 1 GeV)

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

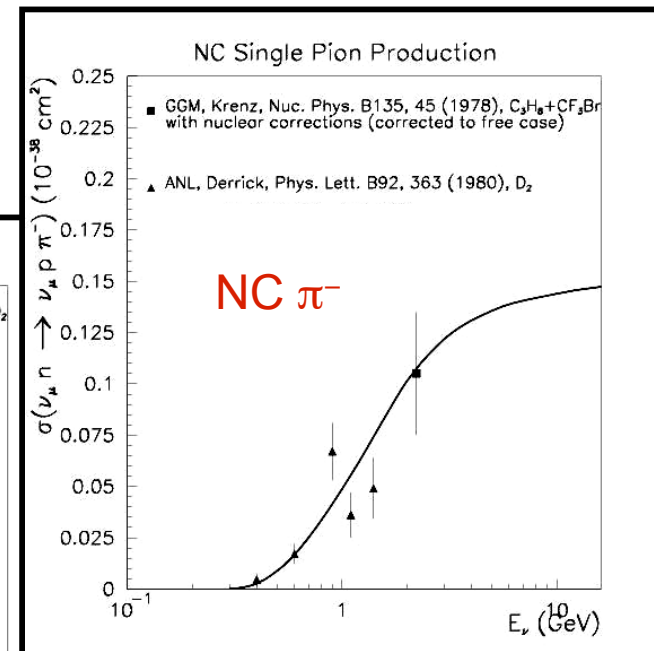
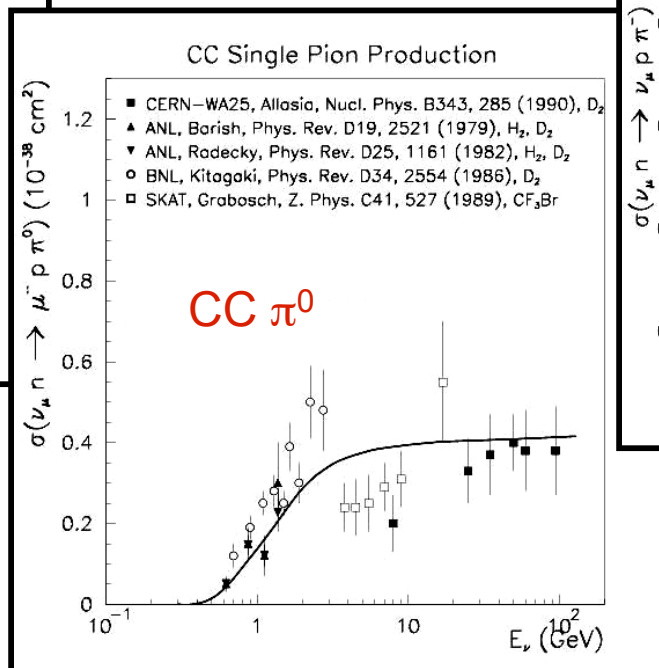
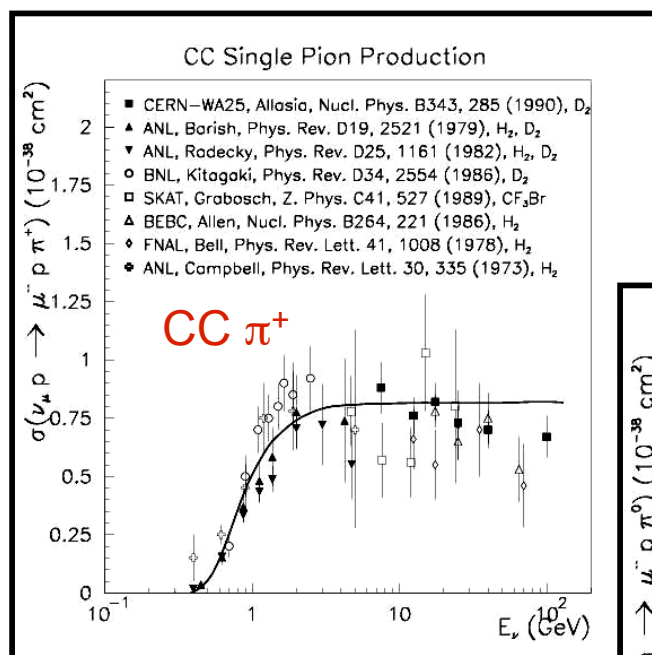
nucleon
+ pion(s)
final state

- main contribution is from $\Delta(1232) \rightarrow N\pi$
- 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 $\Delta \rightarrow N\gamma$!

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 $\nu_{\mu} \rightarrow \nu_e, \theta_{13}$

intermediate
(~ 1 GeV)

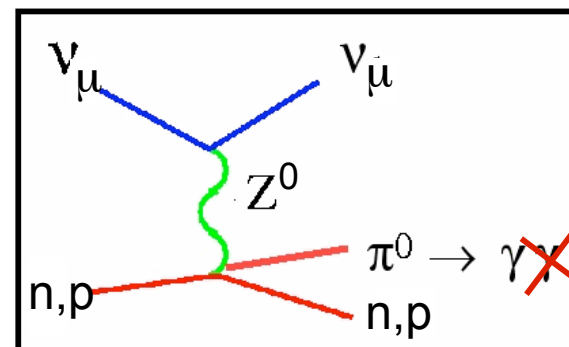
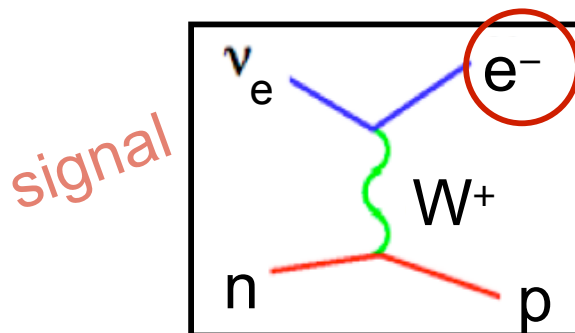
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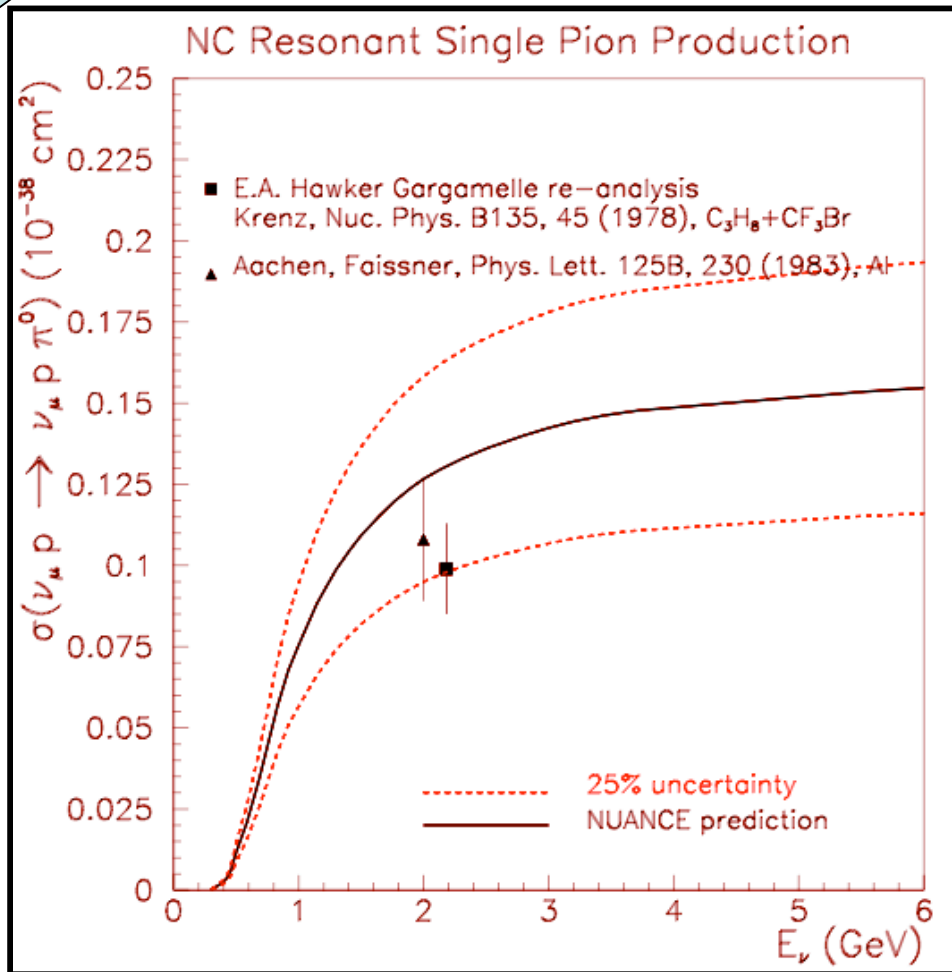
- **important for neutrino oscillation experiments**
 - important background for experiments looking for $\nu_{\mu} \rightarrow \nu_e, \theta_{13}$

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



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

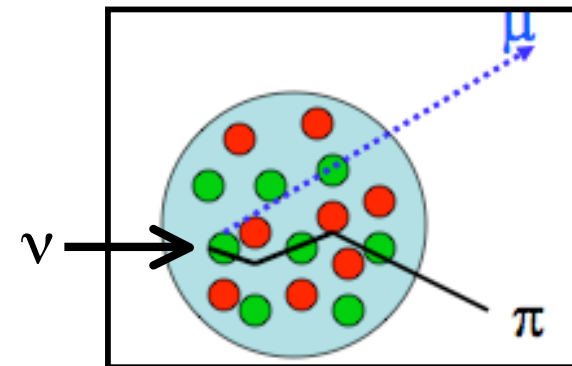
this σ tells you how many π^0 background events should expect to have

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

intermediate
(~ 1 GeV)

Final State Interactions

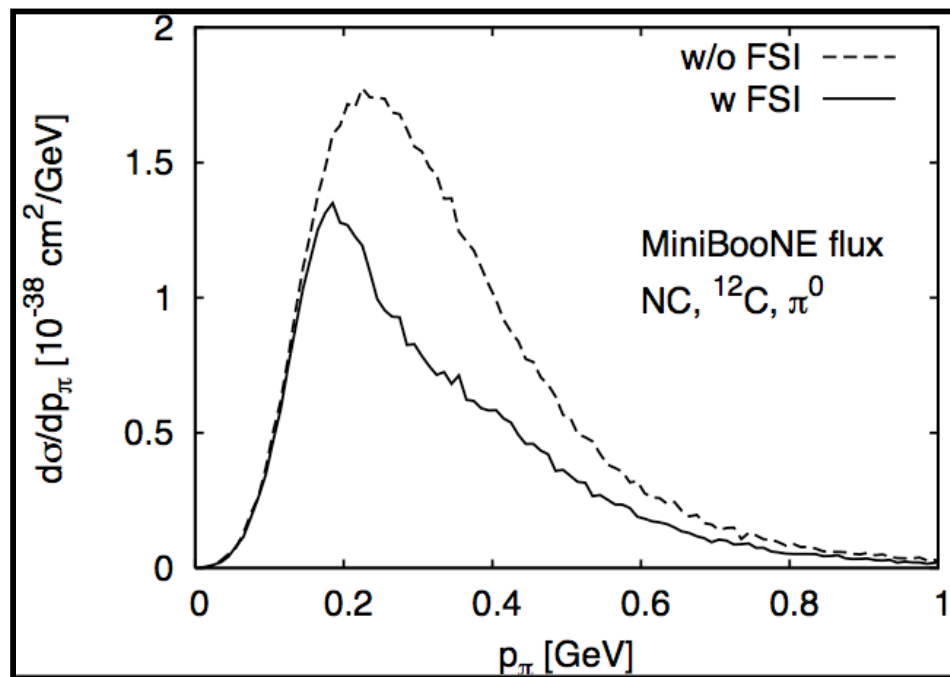
- nuclear effects further complicate this description
(once produce π^0 , has to get out of nucleus, FSI alter π^0 kinematics!)



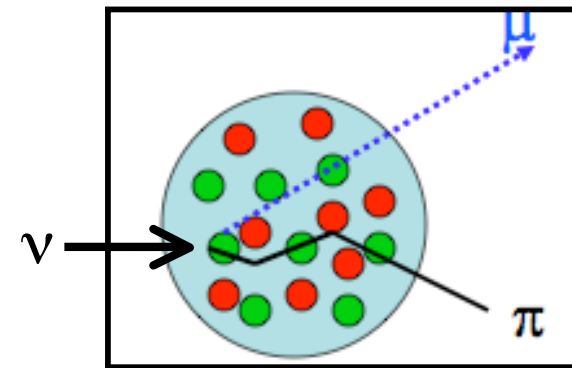
intermediate
(~ 1 GeV)

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(T. Leitner, E_ν beam ~ 1 GeV)



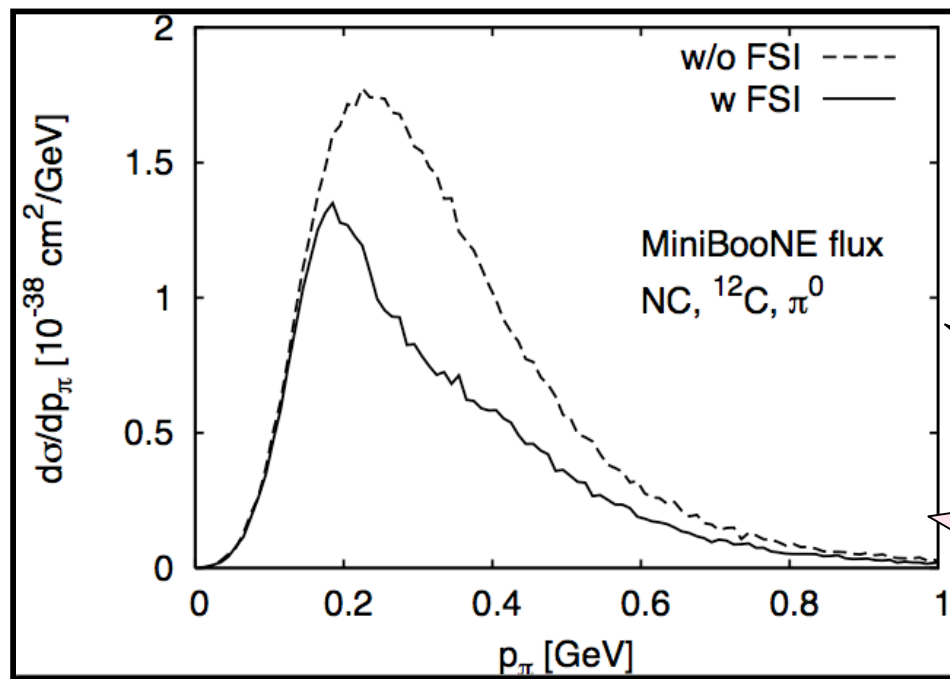
- example, at $E_\nu = 1$ GeV
~20% of π^0 get absorbed
~10% charge exchange ($\pi^0 \rightarrow \pi^{+,-}$)

- need to predict initial interaction σ and final state effects

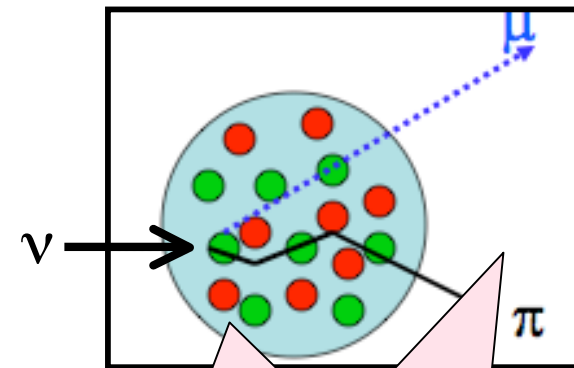
intermediate
(~ 1 GeV)

Final State Interactions

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(T. Leitner, E_ν beam ~ 1 GeV)



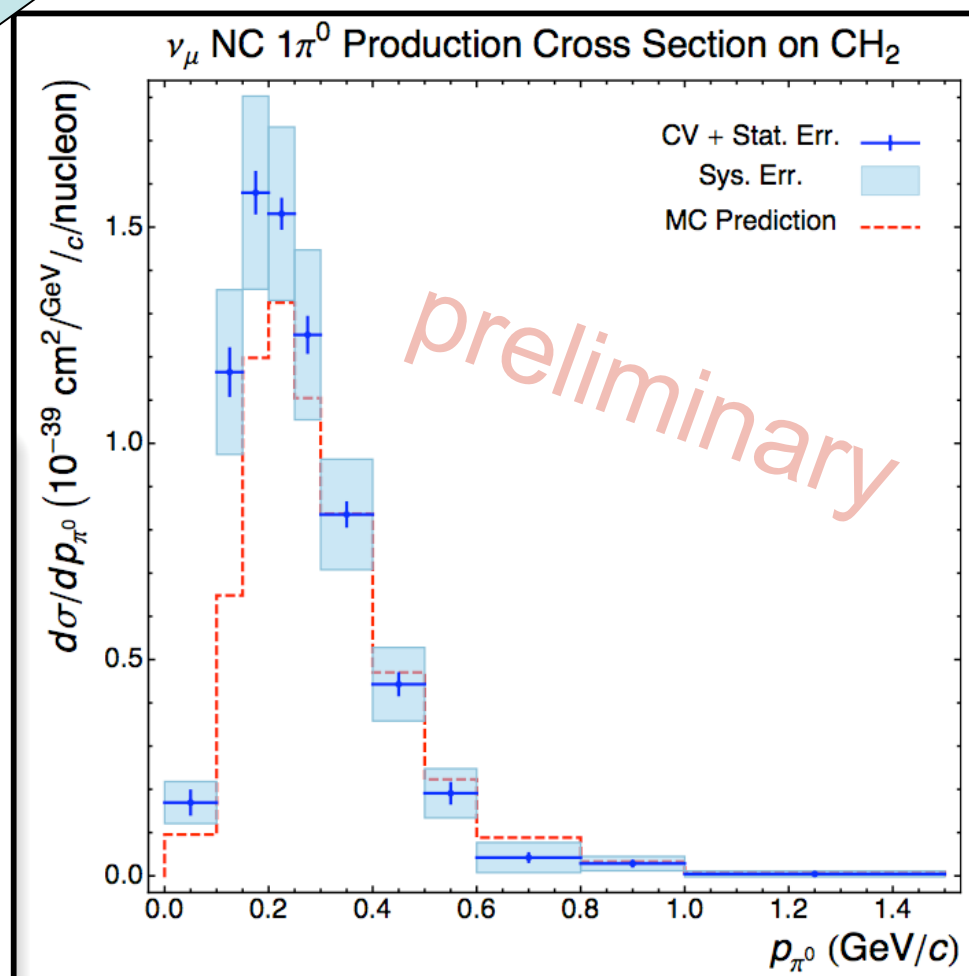
• ex2

must measure to predict
 ν_e backgrounds!

- need to predict initial interaction σ and final 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)

Intermediate Energy Scorecard

process	σ uncertainty	importance
QE	~20-30% (M_A ? nuclear effects?)	signal channel for atmospheric & accelerator-based ν osc exps

intermediate
(~ 1 GeV)

Intermediate Energy Scorecard

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π production	~25-40% + FSI uncertainties	background channels for atmos & accelerator-based ν osc exps

intermediate
(~ 1 GeV)

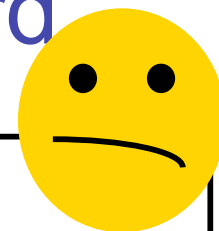
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- σ 's about an order of magnitude less well known than what we saw at low energy ... complex region
- nuclear effects & FFs create added complications & uncertainty

intermediate
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Intermediate Energy Scorecard



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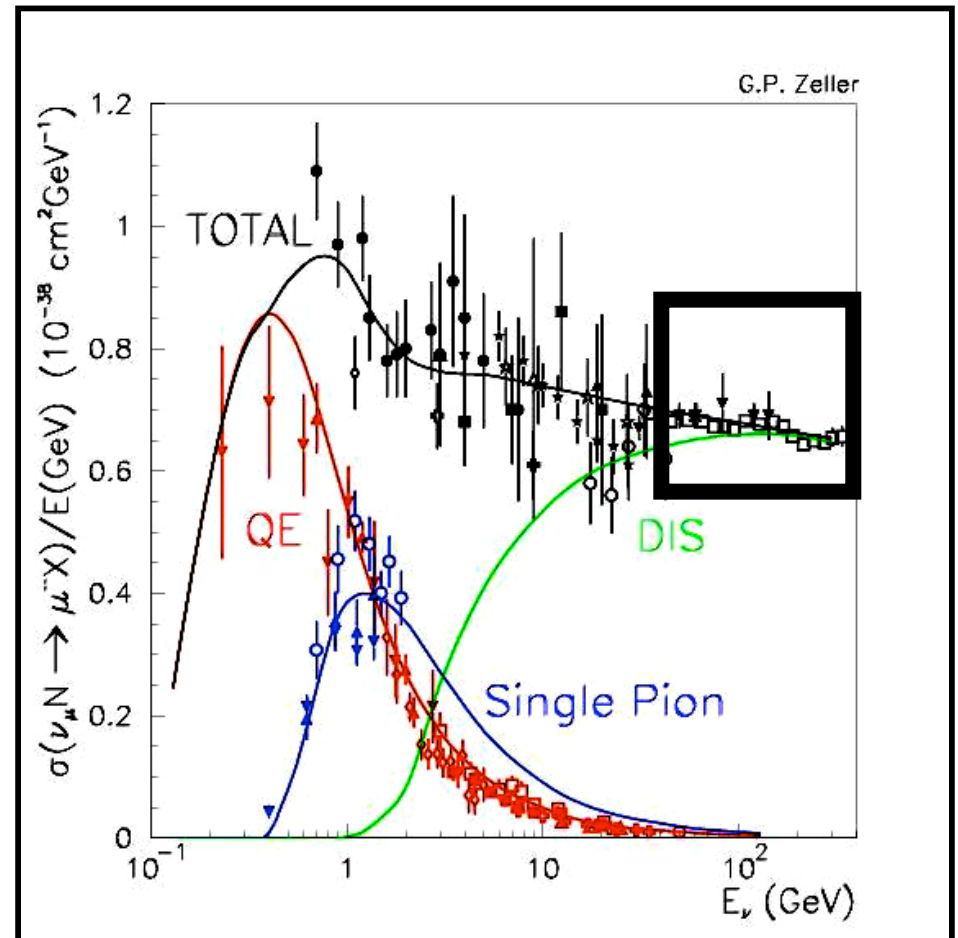
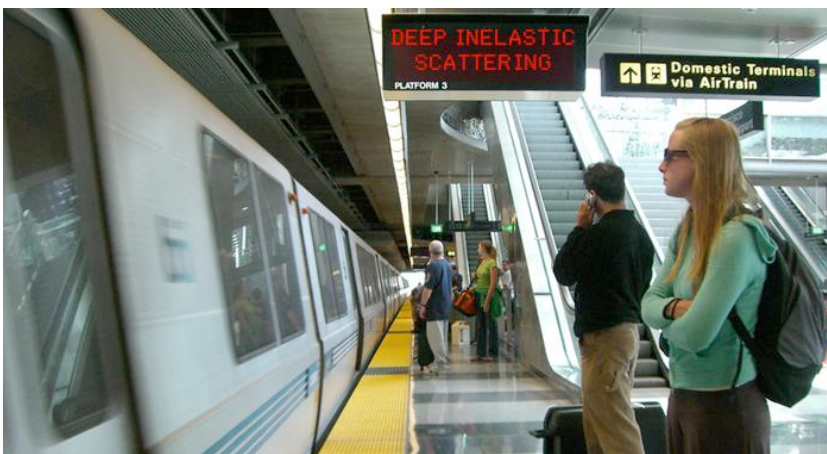
What I Didn't Talk About

- **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

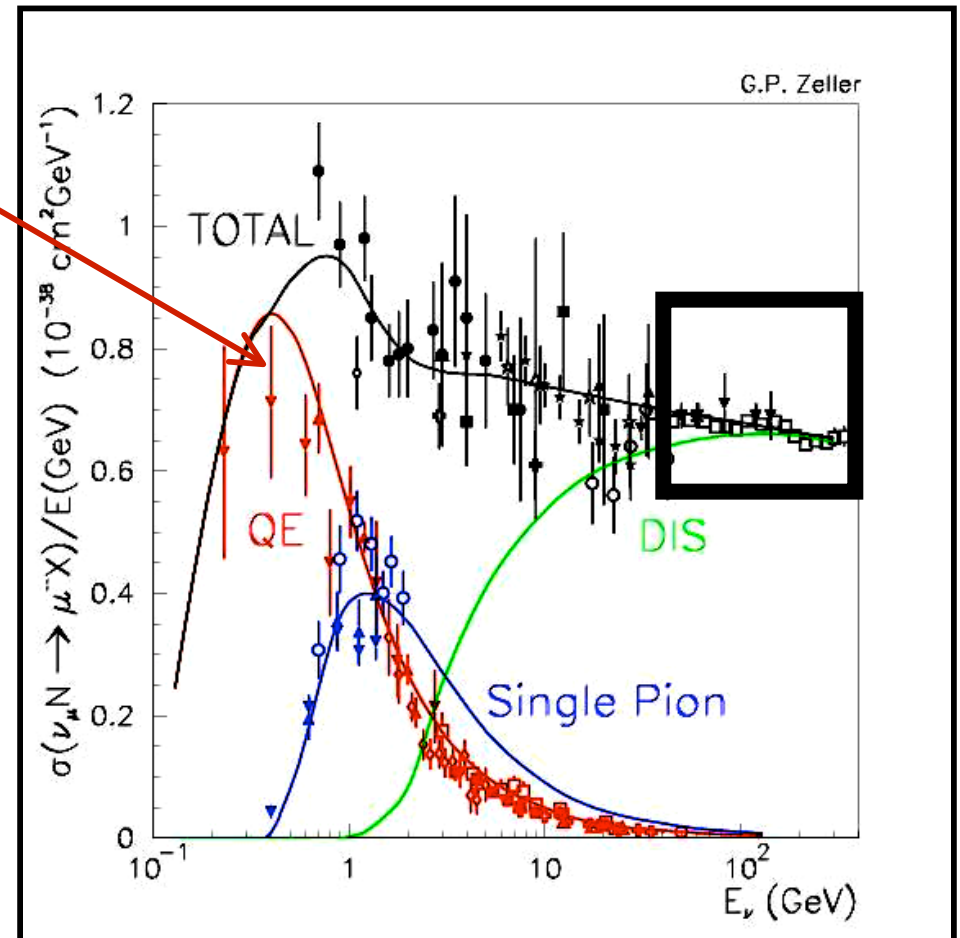
- let's move up to an energy range where safely in deep inelastic scattering (DIS) regime
- dominant process at these energies



high E
(100's GeV)

ν DIS Cross Sections

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

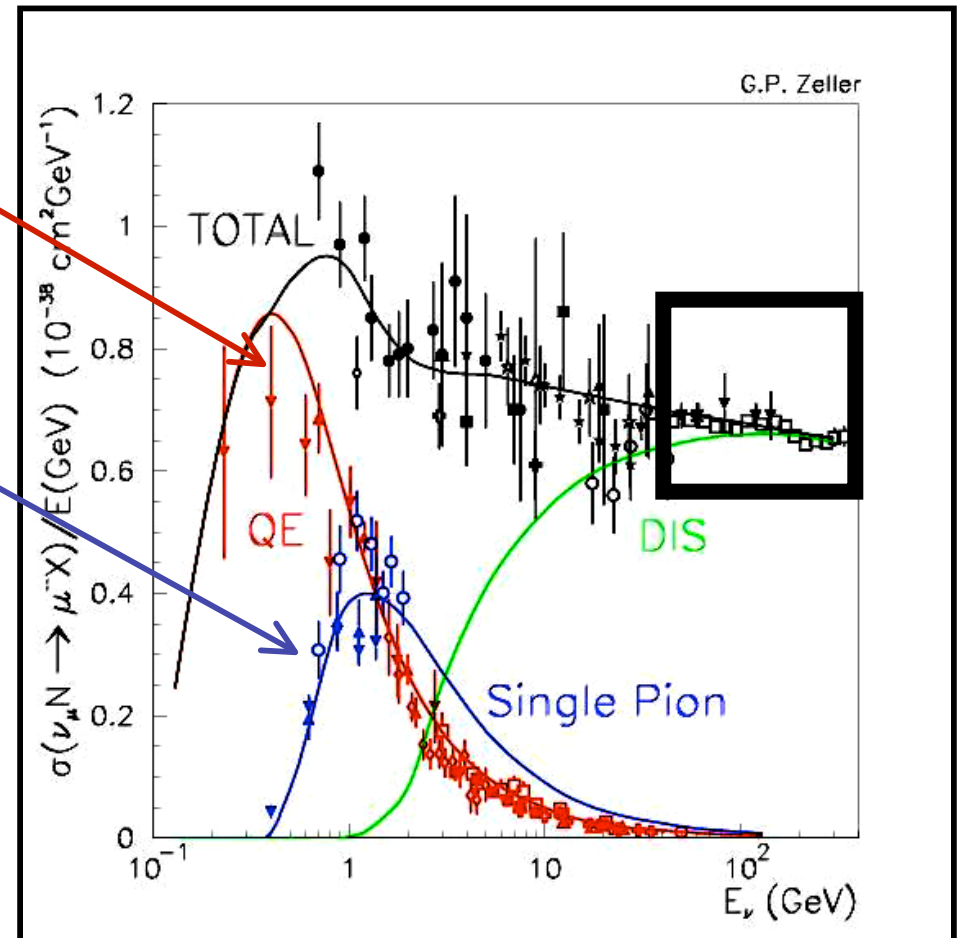


high E
(100's GeV)

ν DIS Cross Sections

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nucleon goes
to excited state
(Δ or $N^* \rightarrow N \pi$)



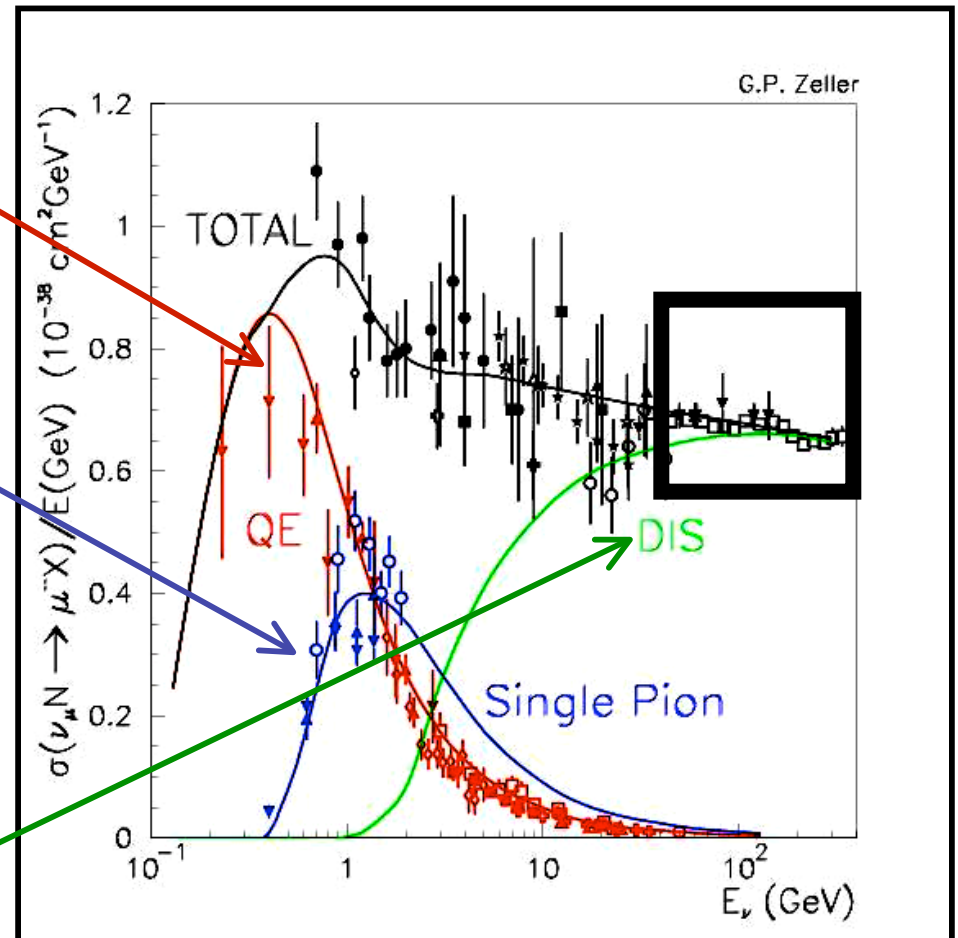
high E
(100's GeV)

ν DIS Cross Sections

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



high E
(100's GeV)

ν DIS Cross Sections

nucleons



pions

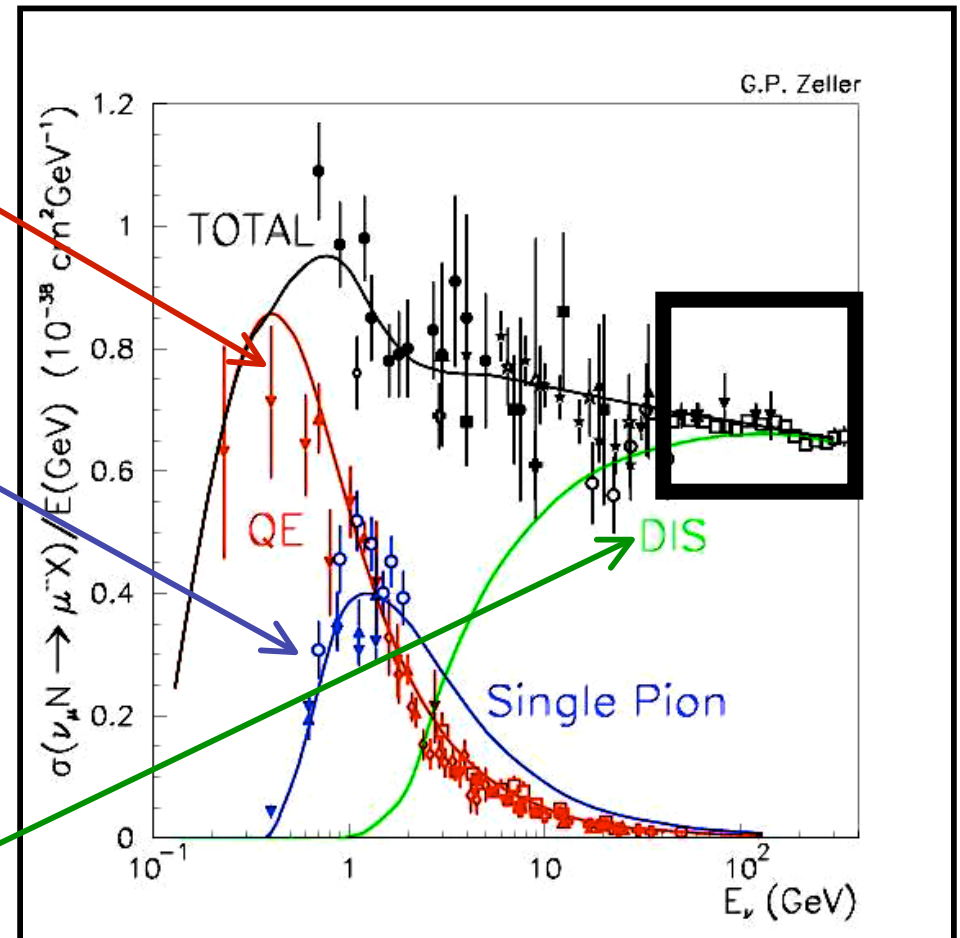


hadronic
shower

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

nucleon goes
to excited state
(Δ or $N^* \rightarrow N \pi$)

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

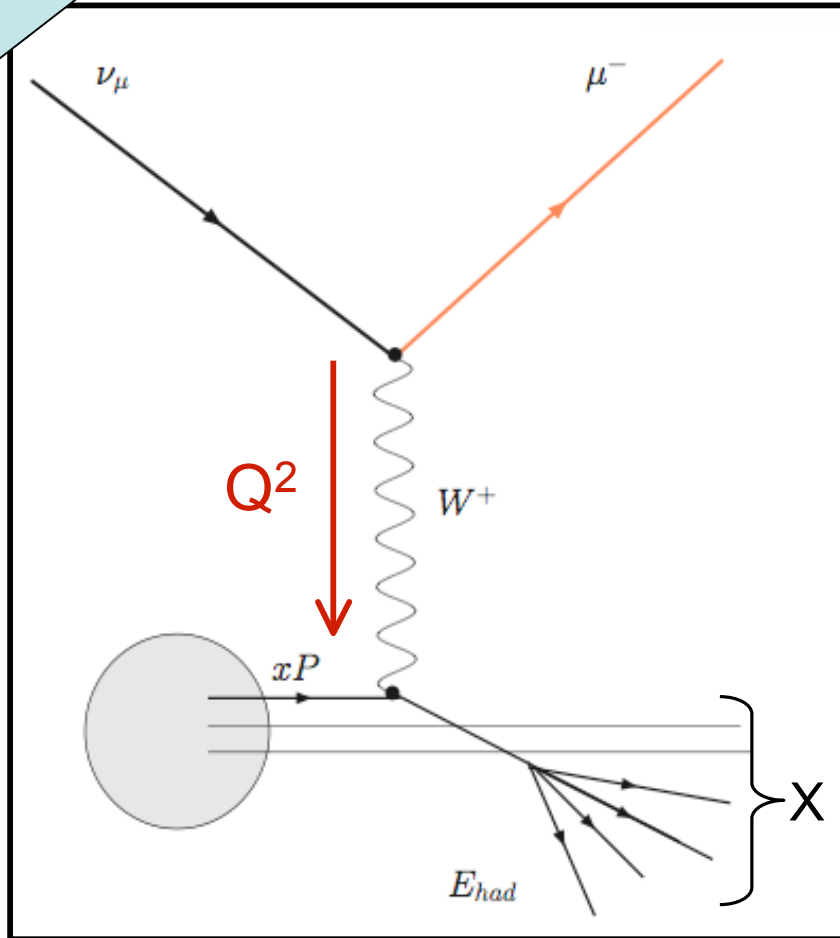


high E
(100's GeV)

Deep Inelastic Scattering

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

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



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

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

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

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

high E
(100's GeV)

ν DIS Cross Section

- written in its simplest form ...

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

vector boson propagator

just like
in QE case

high E
(100's GeV)

ν DIS Cross Section

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leptonic tensor

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

high E
(100's GeV)

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leptonic tensor

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

hadronic tensor

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

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

$$F_1(x, Q^2) = W_1(x, Q^2)$$

$$F_2(x, Q^2) = \frac{\nu}{M} W_2(x, Q^2)$$

$$F_3(x, Q^2) = \frac{\nu}{M} W_3(x, Q^2)$$

$$F_4(x, Q^2) = \frac{\nu}{M} W_4(x, Q^2)$$

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high E
(100's GeV)

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$$F_5(x, Q^2) = W_5(x, Q^2)$$

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

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

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

high E
(100's GeV)

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

high E
(100's GeV)

ν DIS Cross Section

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

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

measures density
distribution of all quarks
& antiquarks in the nucleon

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

measures the valence
distribution

high E
(100's GeV)

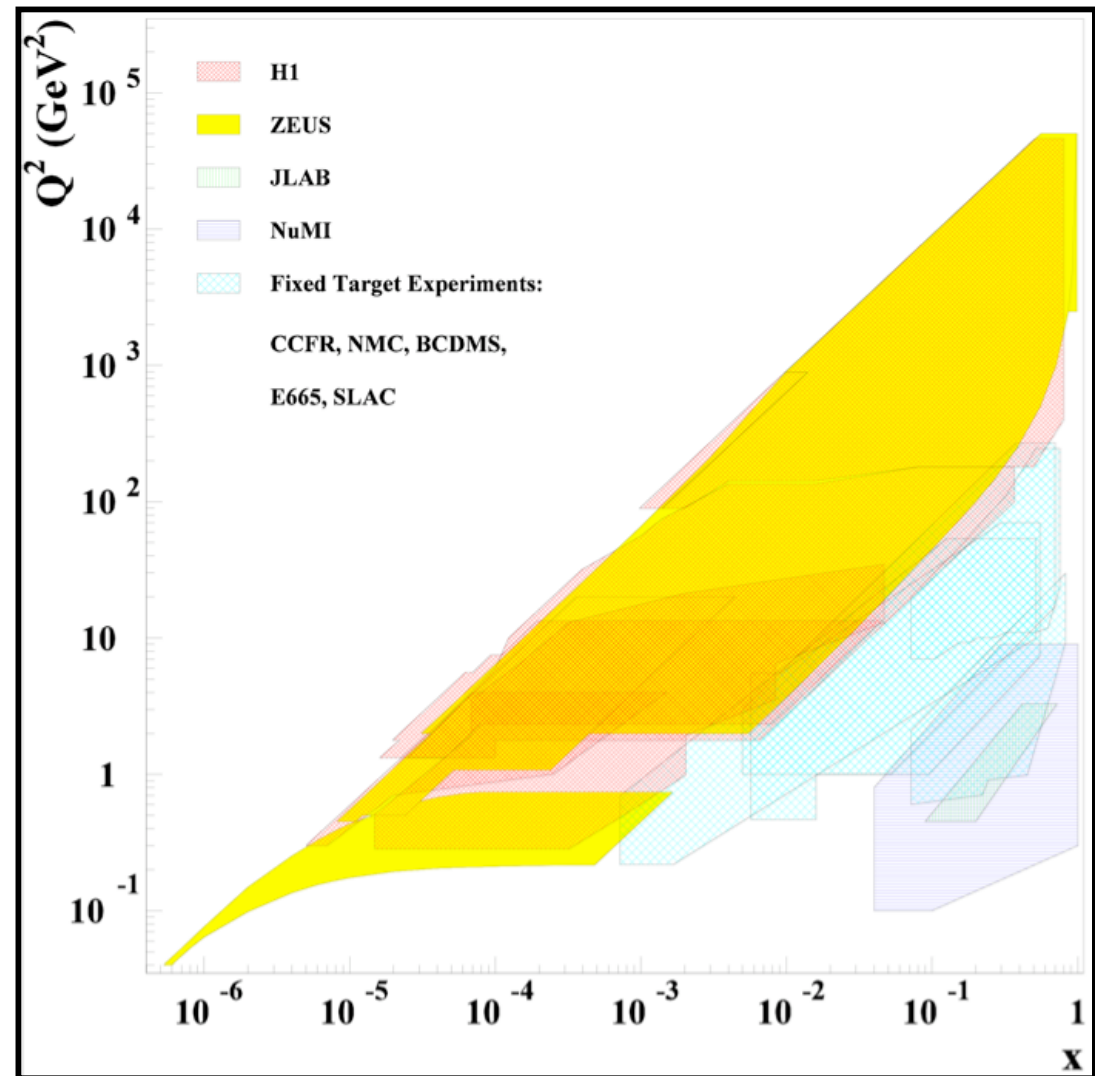
Experimental Coverage

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

$$0.1 < Q^2 < 10^4 \text{ GeV}^2$$

$$10^{-6} < x < 1$$

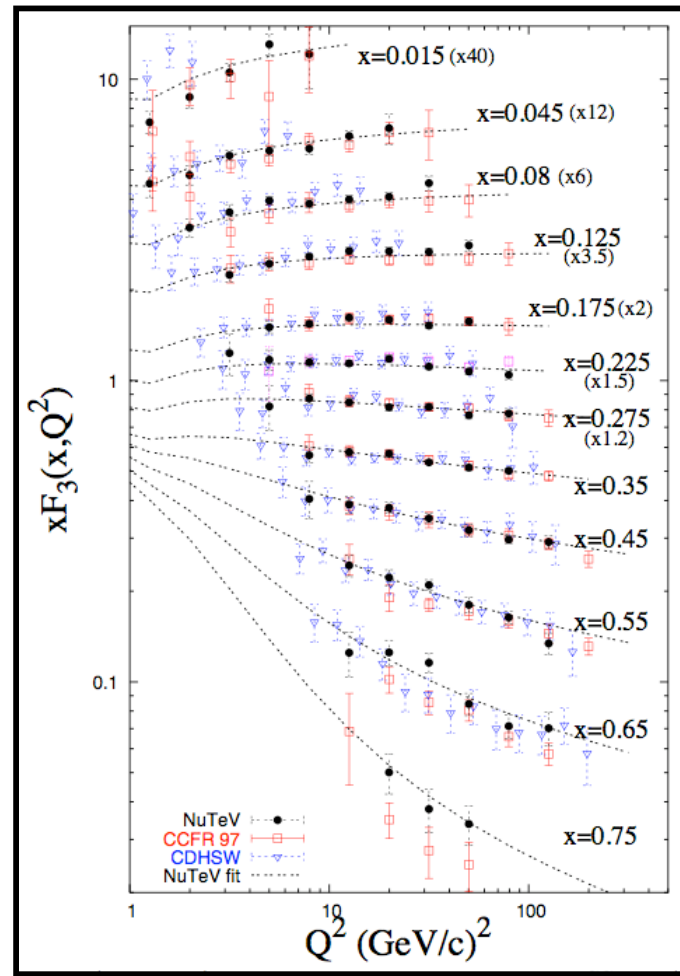
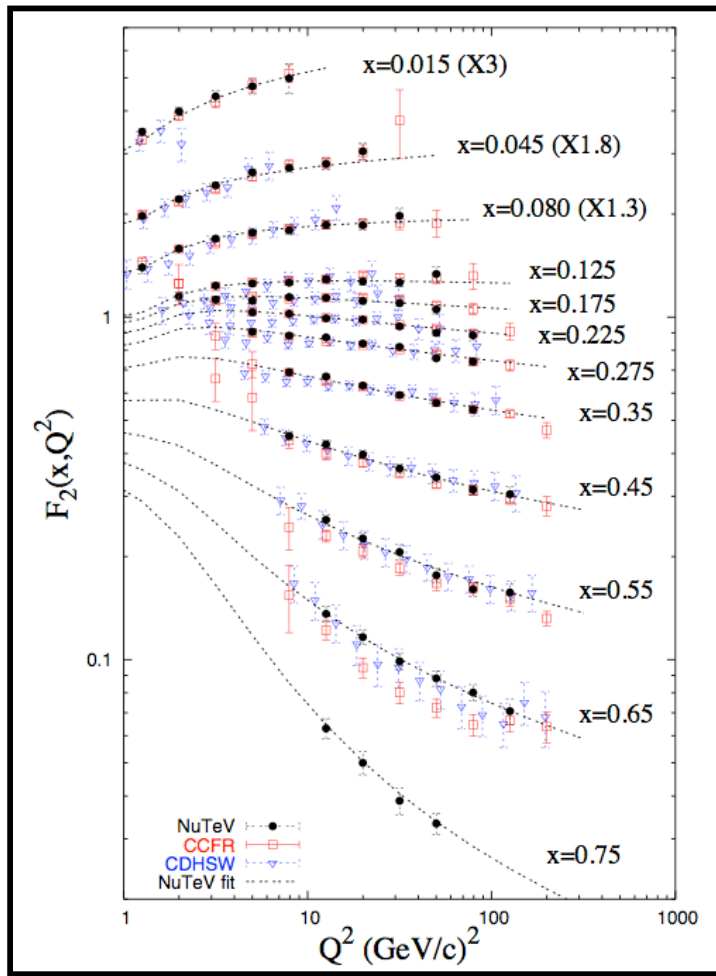
- measurements at HERA (H1, ZEUS) have extended reach to low x , high Q^2



high E
(100's GeV)

Structure Functions

- example from ν DIS experiments

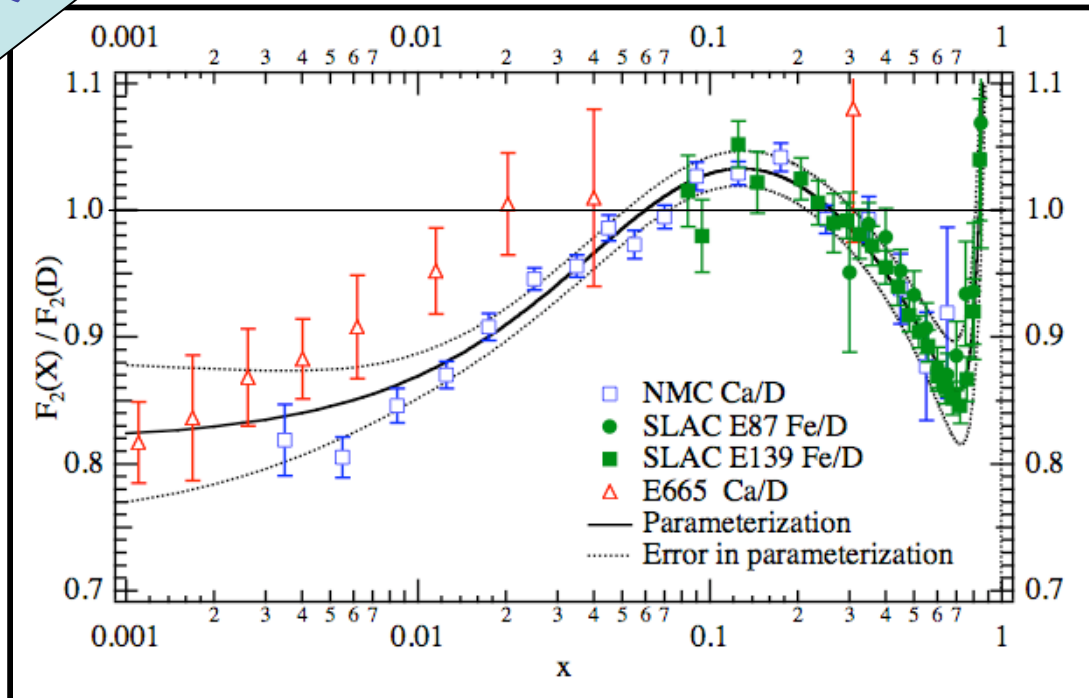


- quark model and pQCD make definite predictions for ν DIS scattering which are beautifully confirmed by experiment

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

high E
(100's GeV)

Nuclear Effects



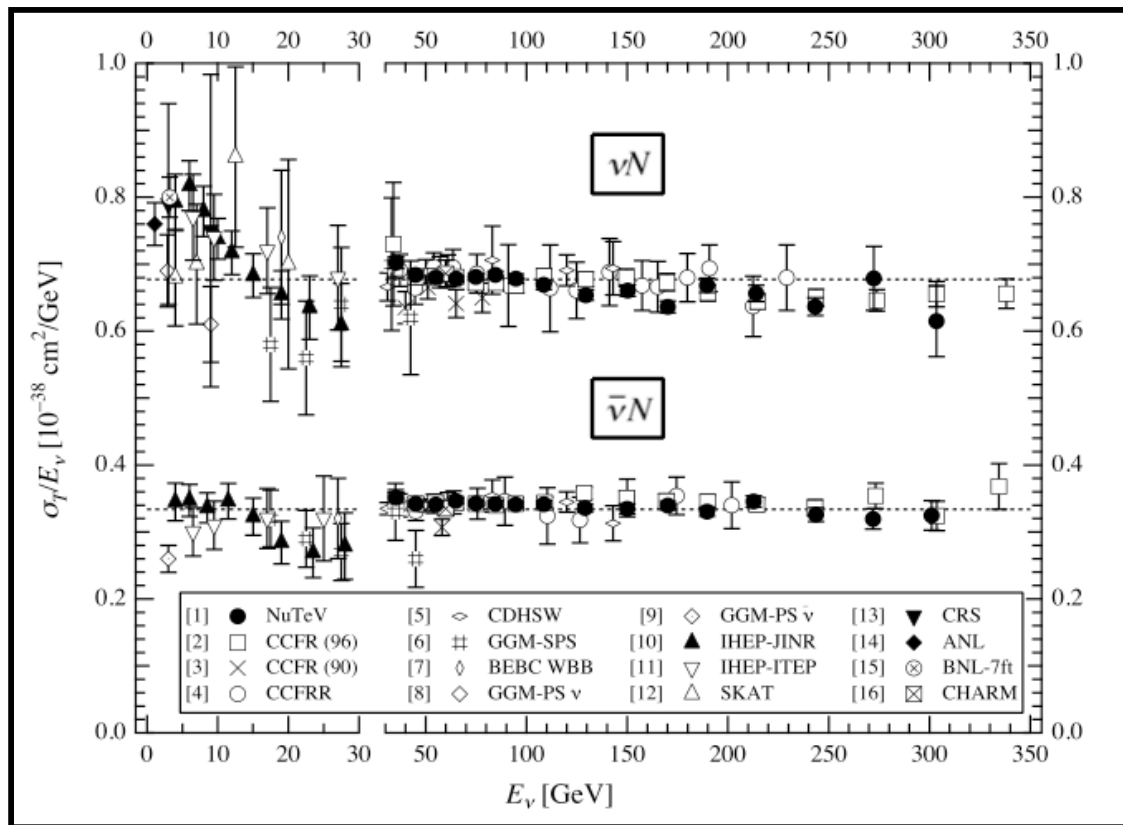
- in charged lepton scattering, observe that the SFs measured on heavy nuclei differ from those on D
- differences observed over entire x region

- 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



What I Didn't Talk About

- **ν_τ cross sections**

- need to include add'l SFs that we neglected, $\propto (m_l)^2$
- OPERA ($\nu_\mu \rightarrow \nu_\tau$ in CNGS beam)

- **heavy charm production** ($\nu_\mu N \rightarrow \mu^- c X$)

- σ is suppressed at low E_ν ("slow rescaling", $x \rightarrow \xi$)
- used to measure s and $\bar{s}$ quarks ($s \rightarrow c$)

- **NC DIS** ($\nu_\mu N \rightarrow \nu_\mu X$)

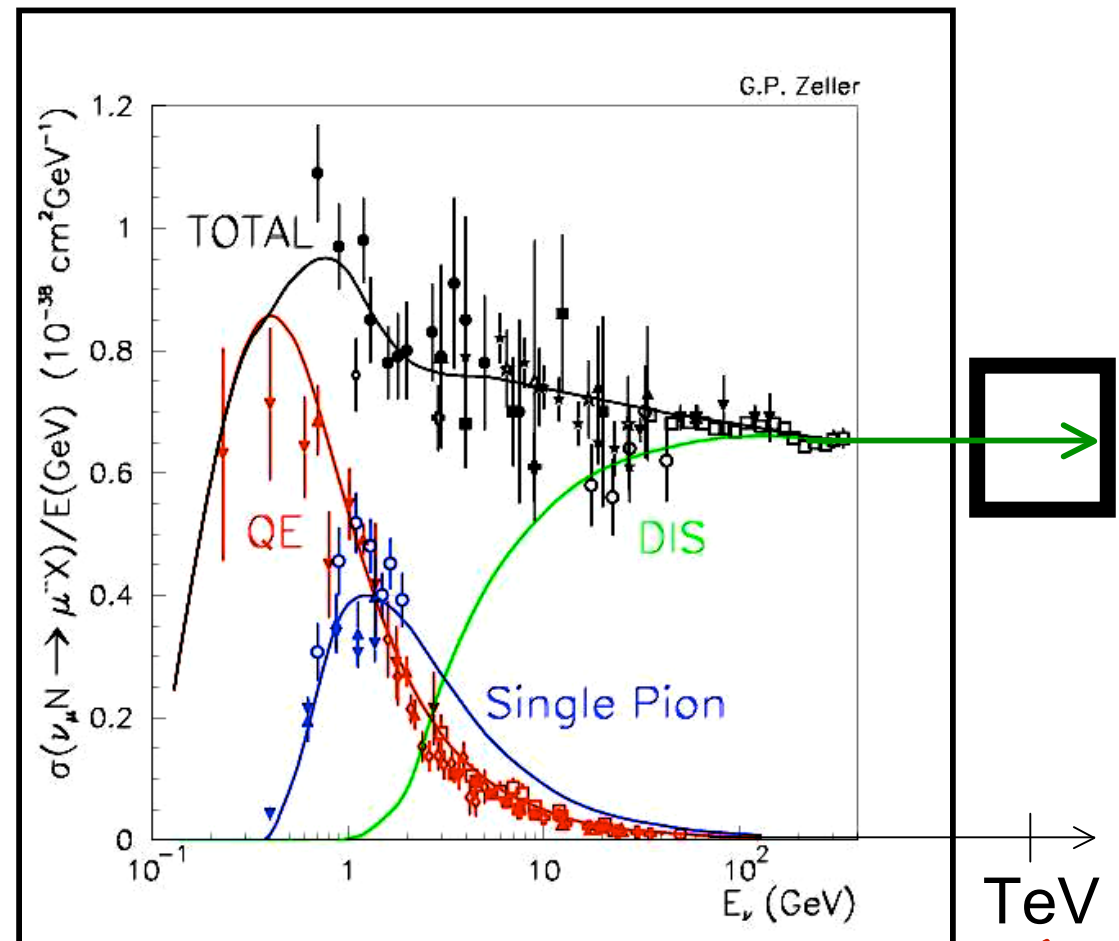
- formalism is the same ($m_l \rightarrow 0$, add'l couplings $\sim \sin^2\theta_w$)

- **added effects**

- target mass effects, radiative corrections, NLO (gluons, R_L)

Ultra High Energy

- ν 's with $E_\nu > \text{TeV}$
- observation of UHE cosmic rays ($> 10^{10} \text{ GeV}$) gives hope for a flux of UHE neutrinos (Jenni Adam's talk)
- use DIS $\nu_\mu N \rightarrow \mu^- X$ to detect UHE ν 's



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

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

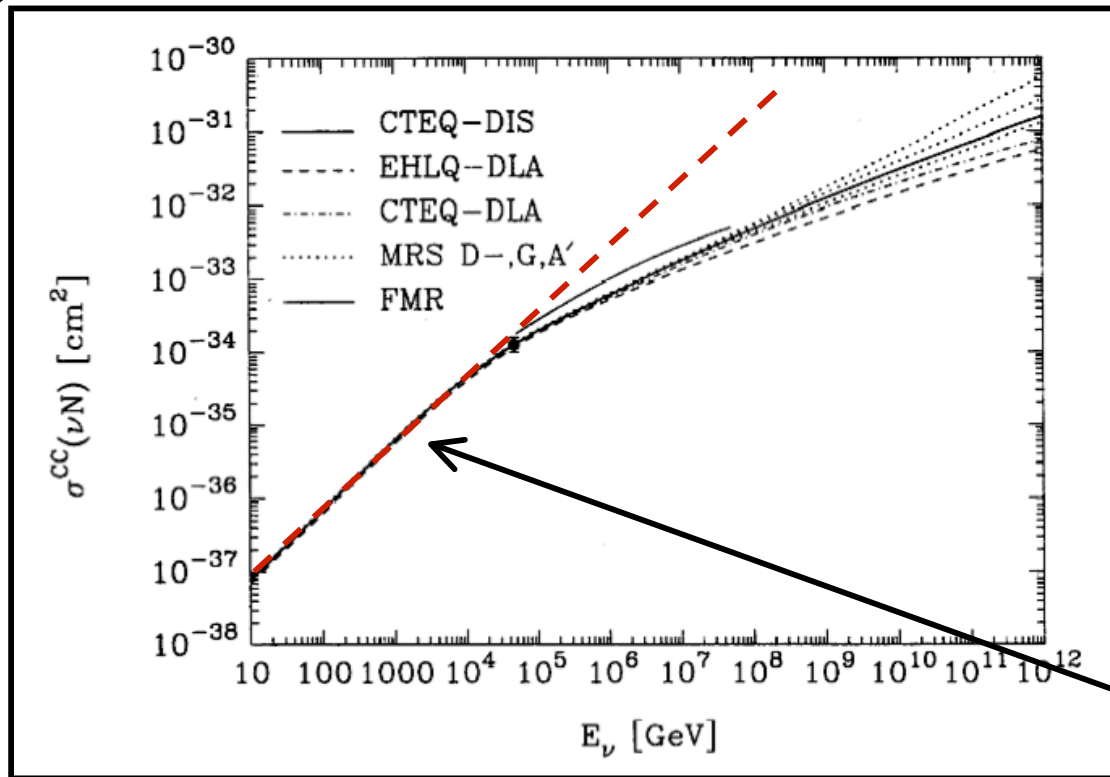
$$\left. \begin{array}{l} Q^2 \sim M_W^2 \\ x \sim \frac{M_W^2}{2ME_\nu} \end{array} \right\} \begin{array}{l} \text{due to presence of propagator term} \\ \frac{1}{(1 + Q^2/M_{W,Z}^2)^2} \end{array}$$

- extrapolation of PDFs to **small x** is crucial at highest energies
(ex., $E_\nu < 10^{12}$ GeV means $Q^2 \sim 10^4$ GeV², $x \sim 10^{-8}$... large extrapolation!)

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($> \text{TeV}$)

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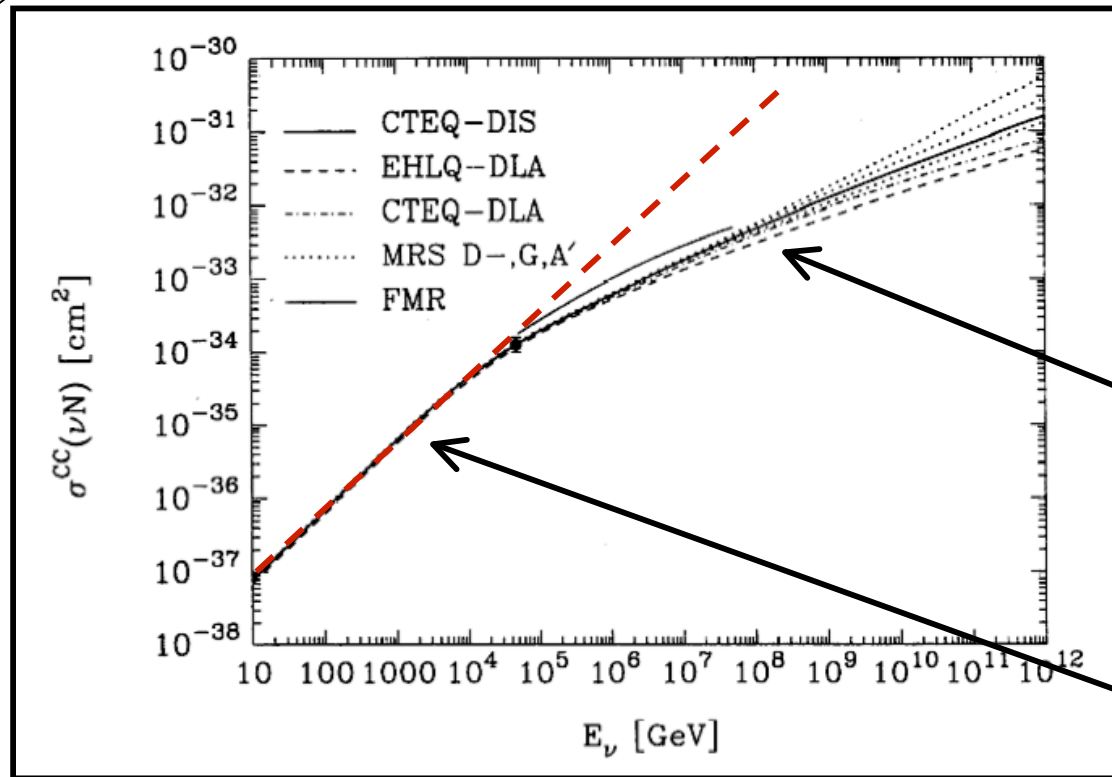
Gandhi *et al.*, *Astropart Phys* **5**, 81 (1996)

linear rise up to
 $\sim 10^4 \text{ GeV} \sim M_W^2$

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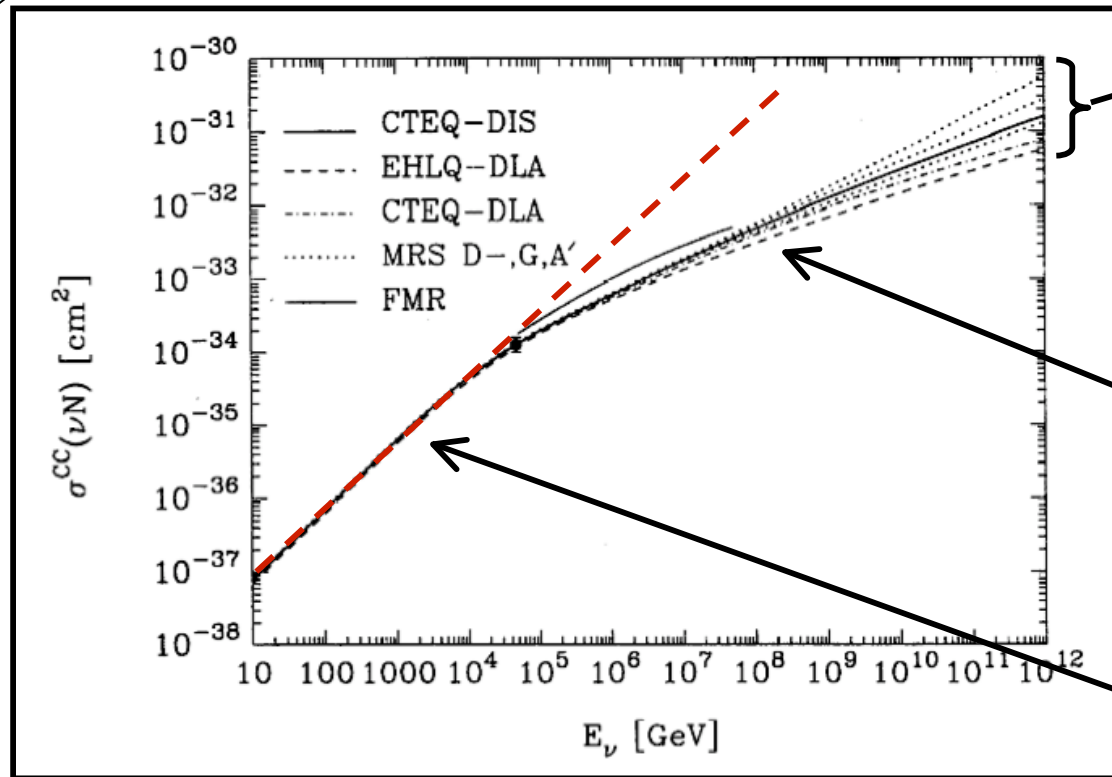
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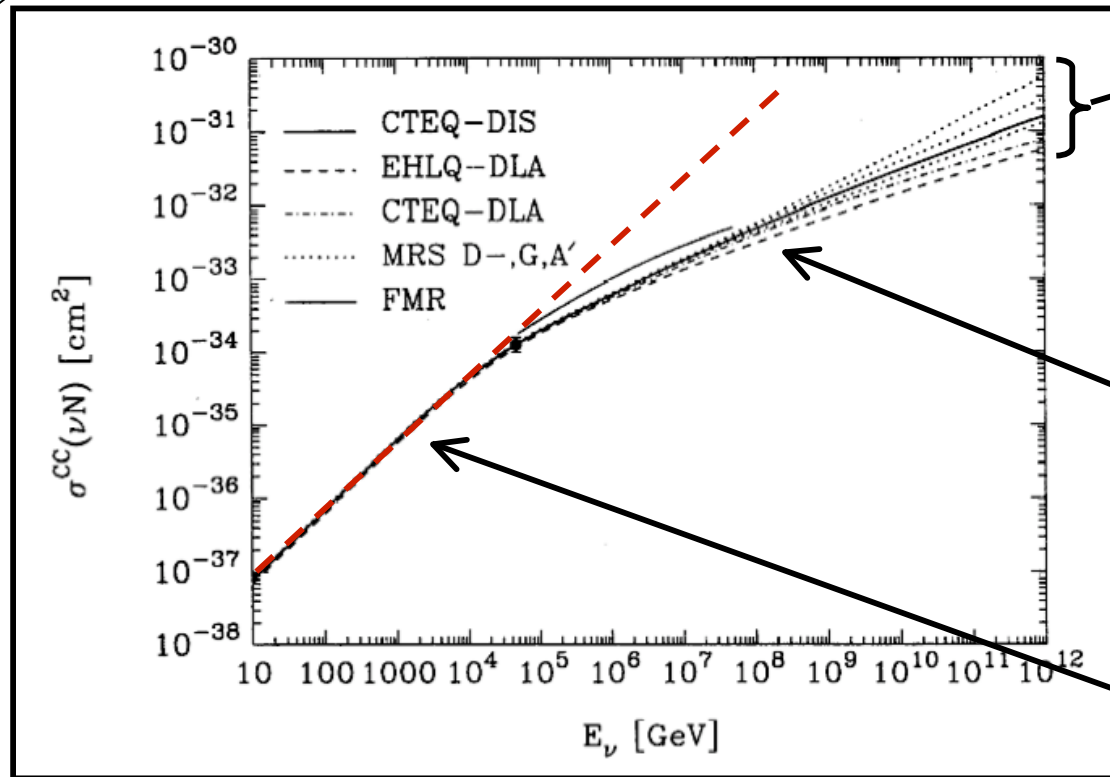
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- impressive that can predict across 11 orders of magnitude in E_{ν} !

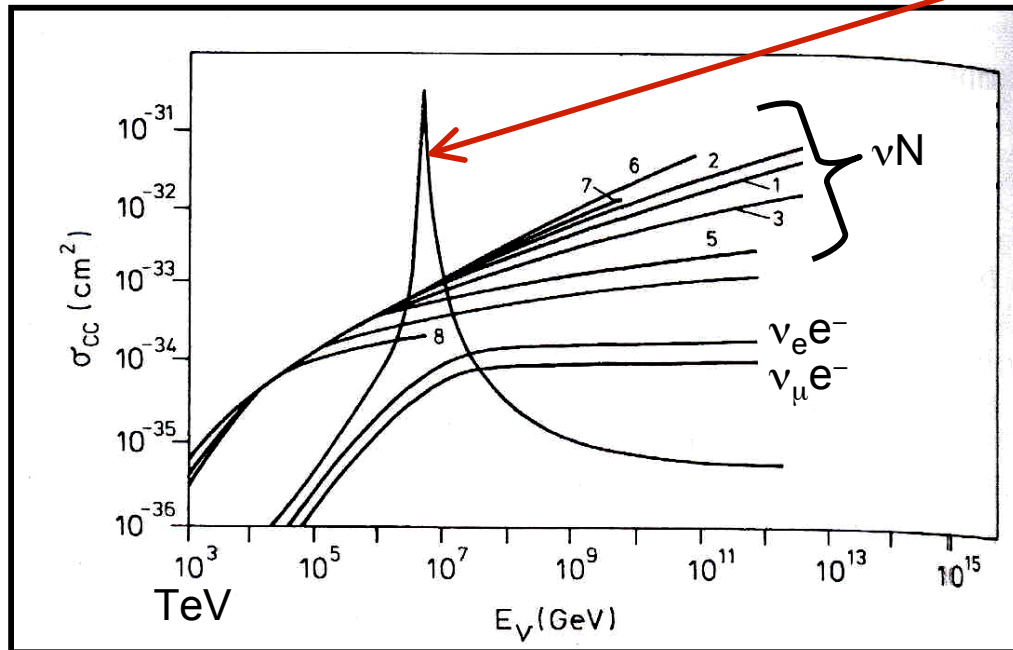
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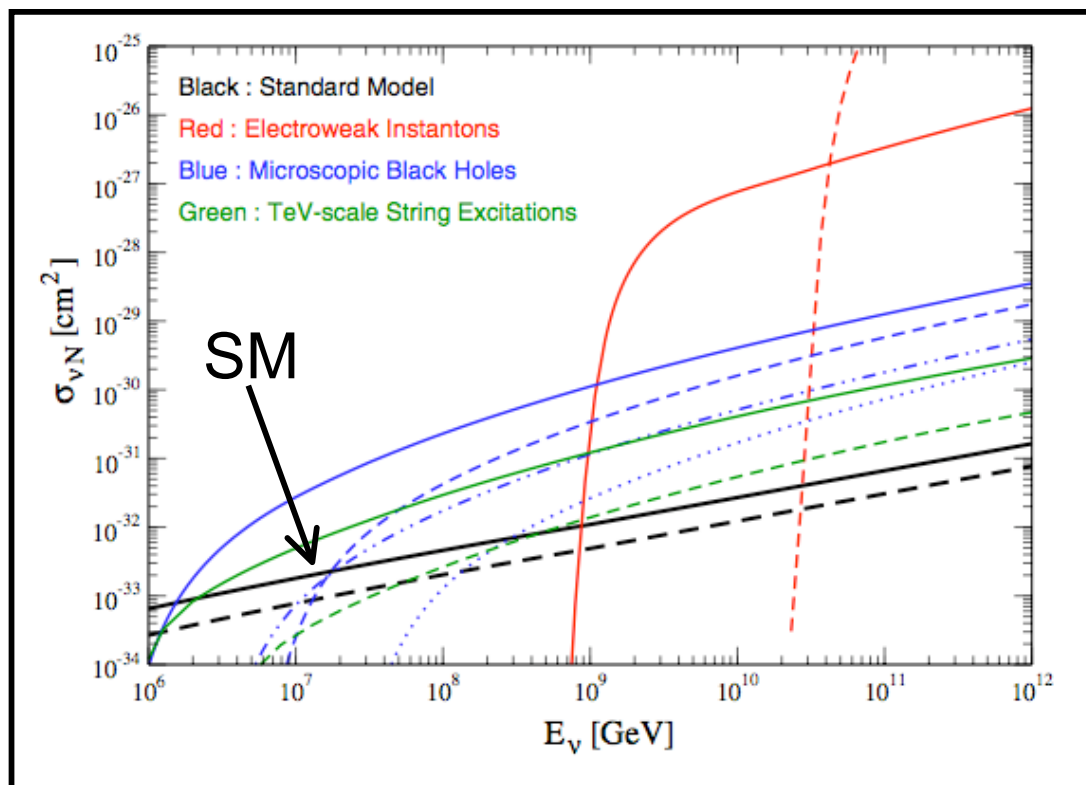
- resonance at E_ν of $M_W^2/2m_e \sim 6 \times 10^6 \text{ GeV}$
- same process first suggested by Glashow (1960) as a means to directly detect W boson

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

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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 $\sim 14 \text{ TeV}$
 - UHE $\nu > 100 \text{ TeV}$

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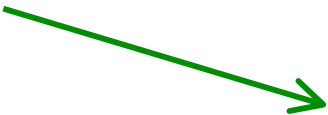
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• MiniBooNE
• SciBooNE
• MINOS ND
• MINER ν A!

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- 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)

