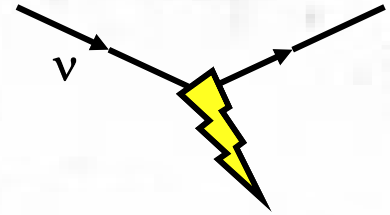
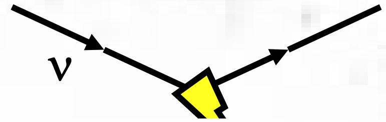
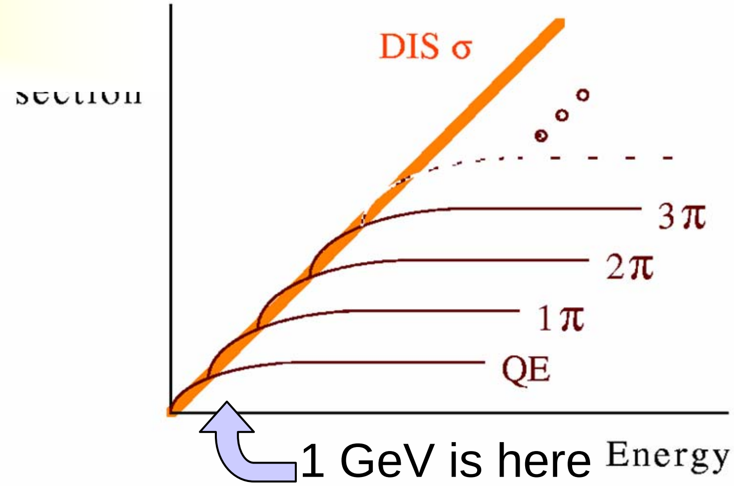


GeV Cross-Sections

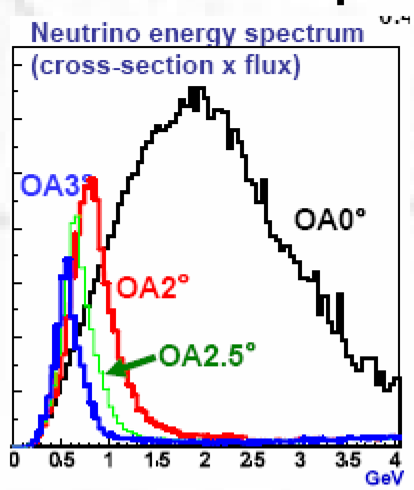
What's special about it? Why do we care?



- Remember this picture?
  - 1-few GeV is exactly where these additional processes are turning on



  - It's not DIS yet! Final states & threshold effects matter
- Why is it important? Example: T2K

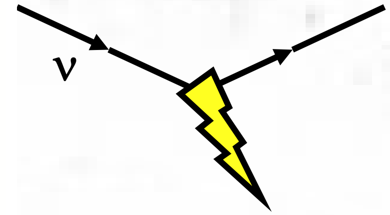


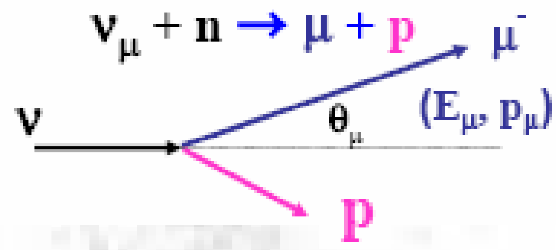
Goals:

1. $\nu_\mu \rightarrow \nu_e$
2. ν_μ disappearance

E_ν is 0.4-2.0 GeV

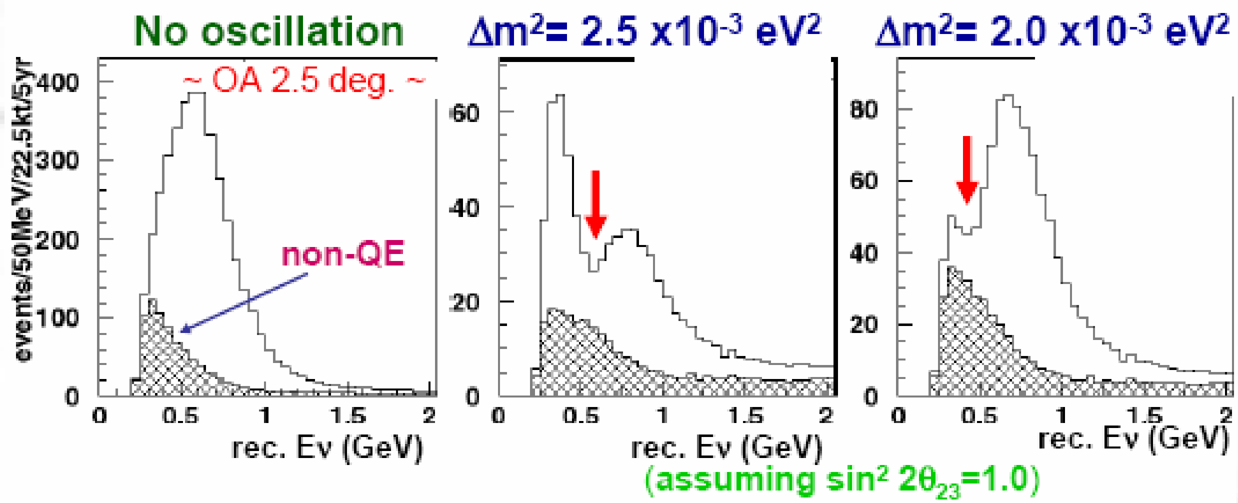
How do cross-sections effect oscillation analysis?



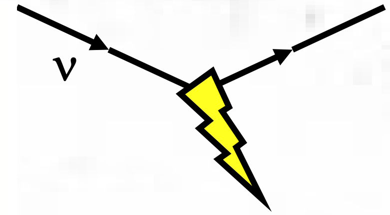


- ν_μ disappearance
  - at Super-K reconstruct these events by muon angle and momentum (proton below Cerenkov threshold in H_2O)
  - other final states with more particles below threshold ("non-QE") will disrupt this reconstruction
- T2K must know these events at few % level to do disappearance analysis to measure Δm^2_{23}, θ_{23}

(fig. courtesy Y. Hayato)

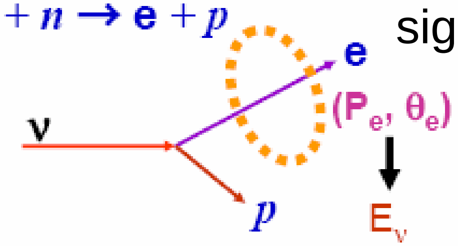


How do cross-sections effect oscillation analysis?

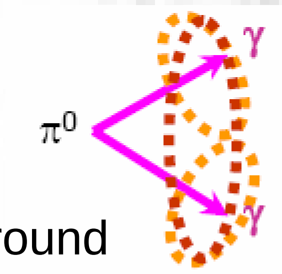


- ν_e appearance
  - different problem: signal rate is very low so even rare backgrounds contribute!

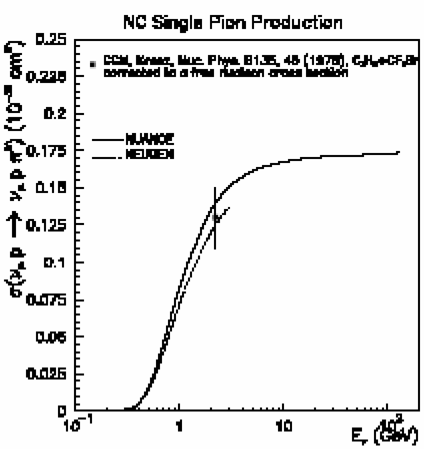
$\nu_e + n \rightarrow e + p$



signal



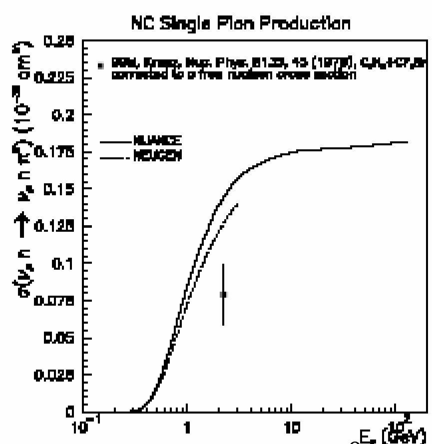
π^0 background from E_ν>peak



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

the world's data on this background

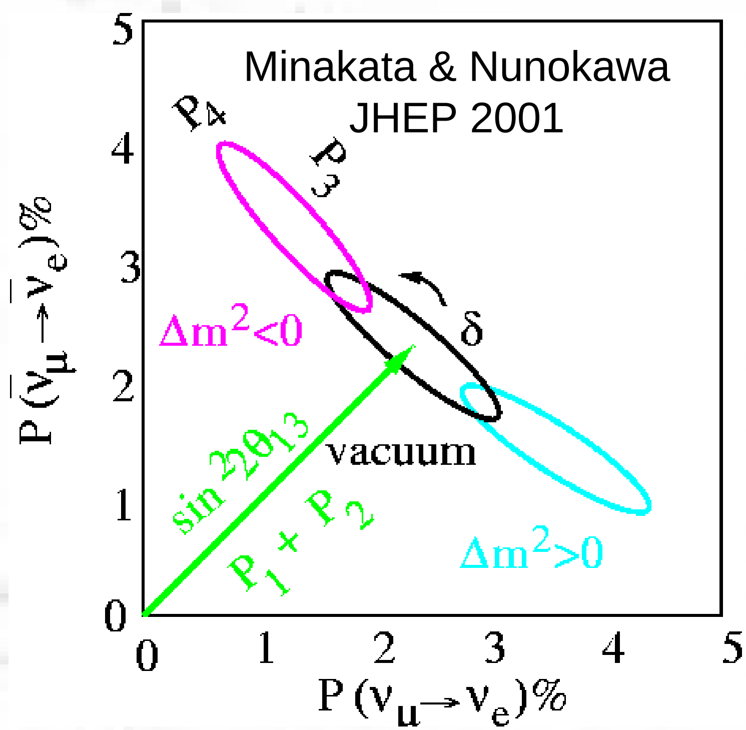
(compiled by G. Zeller, hep-ex/0312061)



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

This should Frighten You

- Remember the end goal of electron neutrino appearance experiments (Boris, Debbie)
- Want to compare two signals with two different sets of backgrounds and signal reactions
  - with sub-percent precision



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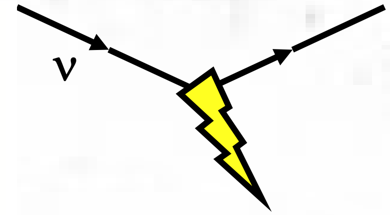
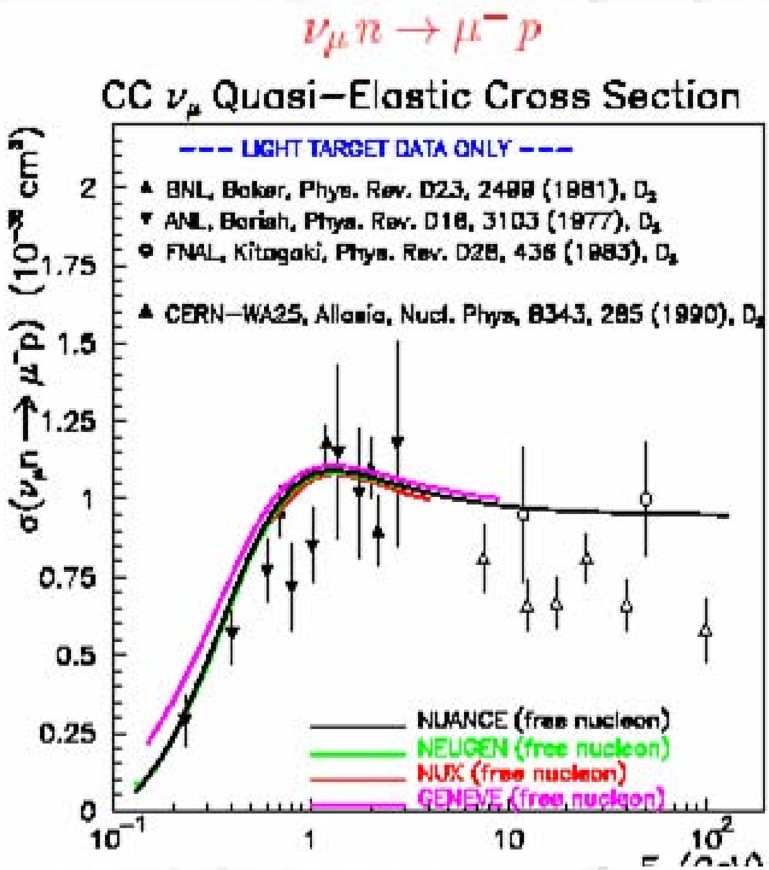
(Quasi-)Elastic Scattering



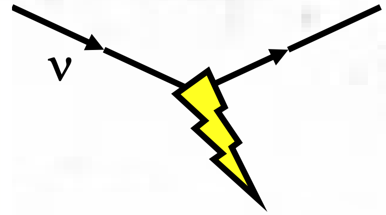
- Elastic scattering leaves a single nucleon in the final state
  - CC “quasi-elastic” easier to observe

$$\nu n \to l^- p$$
$$\bar{\nu} p \to l^+ n$$
$$\overset{(-)}{\nu} N \to \overset{(-)}{\nu} N$$



- State of data is marginal
  - No free neutrons implies nuclear corrections
  - Low energy statistics poor
- Cross-section is calculable
  - But depends on incalculable form-factors
- Theoretically and experimentally constant at high energy
  - 1 GeV^2 is scale of Q^2 limit

Hmmm… What was that last cryptic remark?



- Theoretically and experimentally constant at high energy
  - 1 GeV^2 is scale of Q^2 limit

- Inverse μ–decay:

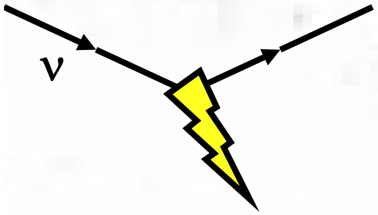
$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

$$\sigma_{TOT} \propto \int_0^{Q^2_{\max}} dQ^2 \frac{1}{(Q^2 + M_W{}^2)^2}$$

$$\approx \frac{Q^2_{\max}}{M_W{}^4}$$

a maximum Q^2 independent of beam energy $\Rightarrow$ constant σ_{TOT}

Elastic Scattering (cont'd)



- How does nucleon structure impact elastic scattering?

$$\nu n \to l^- p$$
$$\bar{\nu} p \to l^+ n$$
$$\overset{(-)}{\nu} N \to \overset{(-)}{\nu} N$$

C.H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972)

$$< N'|J_\mu|N > \; = \; \overline{u}(N')\left[\gamma_\mu F_V^{\prime}(q^2) + \frac{i\sigma_{\mu\nu}q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5\gamma_\mu F_A(q^2)\right] u(N)$$

$$F_V(q^2) \sim \frac{1}{(1-q^2/M_V^2)^2} \qquad F_A(q^2) = \frac{F_A(0)}{(1-q^2/M_A^2)^2}$$

← "dipole approximation"

$\hookrightarrow \mathbf{M_A = 1.032}$ GeV

$\hookrightarrow \mathbf{M_V = 0.84}$ GeV

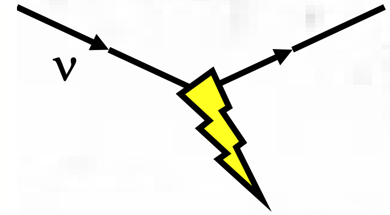
$\hookrightarrow \mathbf{F_A(q^2) = \frac{F_A(0)}{(1-q^2/M_A^2)^2}; \; F_A(0) = -1.25}$

} parameters determined from data

n.b.: we've seen $F_V(0)$ and $F_A(0)$ before in IBD discussion (g_V and g_A)

- "Form factors" modify vanilla V-A prediction of point-like scattering in Fermi theory
  - vector part can be measured in electron elastic scattering

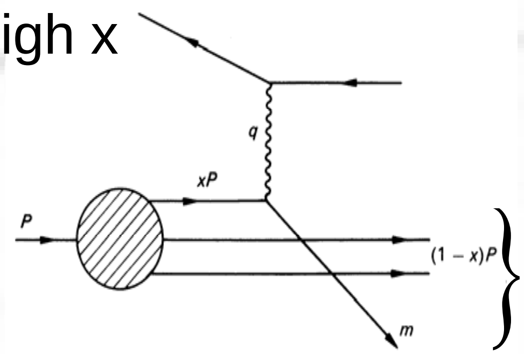
Low W, the Resonance Region



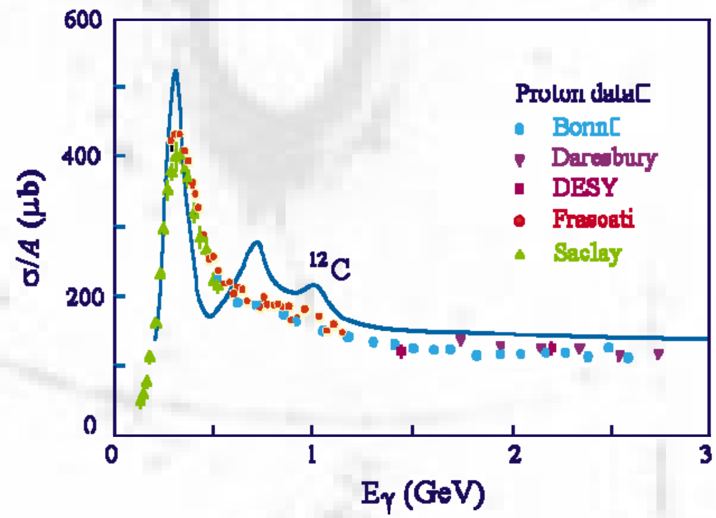
- Intermediate to elastic and DIS regions is a region of resonance production
  - Recall mass[2] of hadronic final state is given by

$$W^2 = M_T^2 + 2M_T\nu - Q^2 = M_T^2 + 2M_T\nu(1-x)$$

  - At low energy, nucleon-pion states dominated by N* and Δ resonances
- Leads to cross-section dominated by discrete (but smeared) W^2
  - Low ν, high x

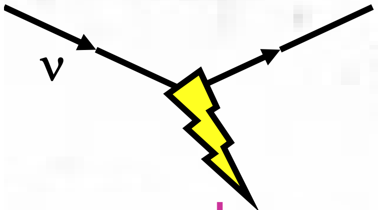


$$W^2$$



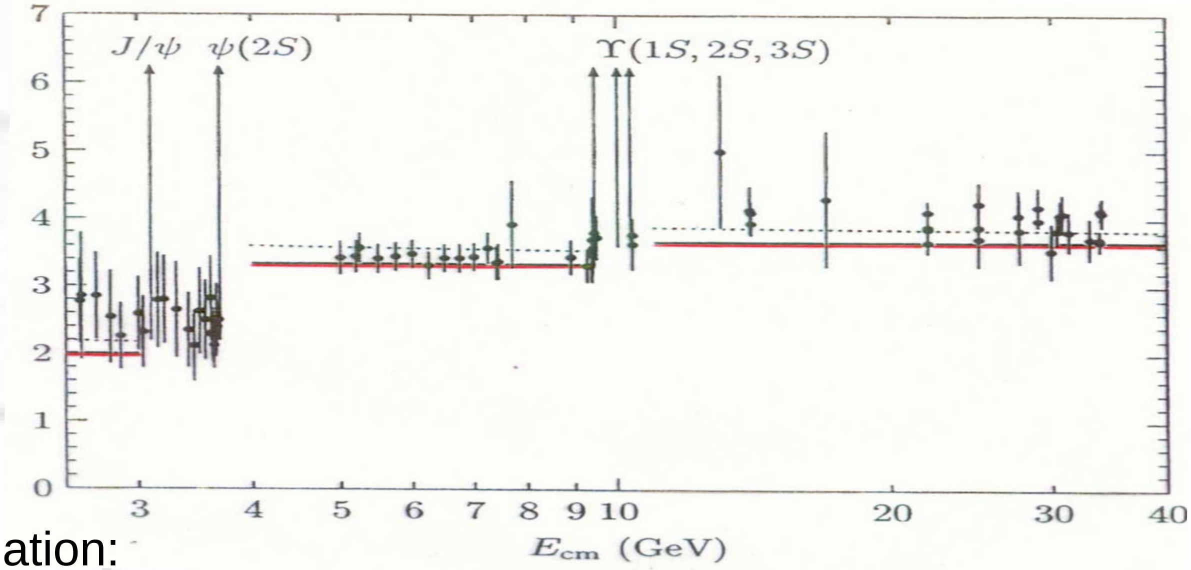
photoabsorption vs E_γ. Line shows protons. More later…

Quark-Hadron Duality



- Bloom-Gilman Duality is the relationship between quark and hadron descriptions of reactions. It reflects:
  - link between *confinement* and *asymptotic freedom*
  - transition from *non-perturbative* to *perturbative* QCD

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

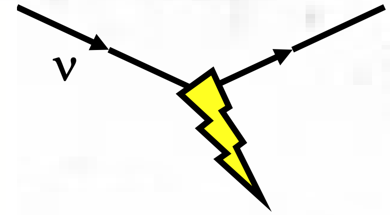


quark-parton model calculation:

$$R = N_C \sum_{q \ni' s > m_q^2} \left(Q_q^{EM}\right)^2 + O(\alpha_{EM} + \alpha_S)$$

but of course, final state is really sums over discrete hadronic systems

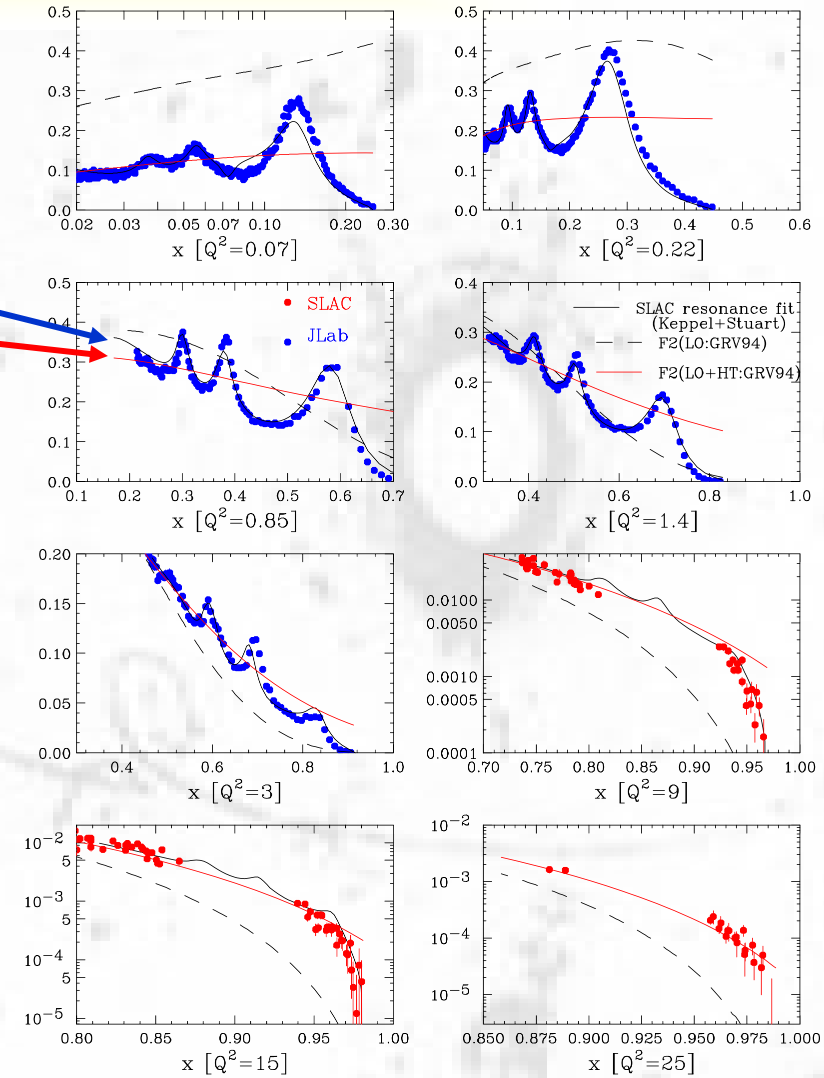
Duality and ν



$$W^2 = M_T^2 + Q^2\left(\frac{1}{x} - 1\right)$$

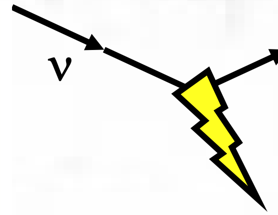
Low Q^2 data

DIS-Style PDF prediction

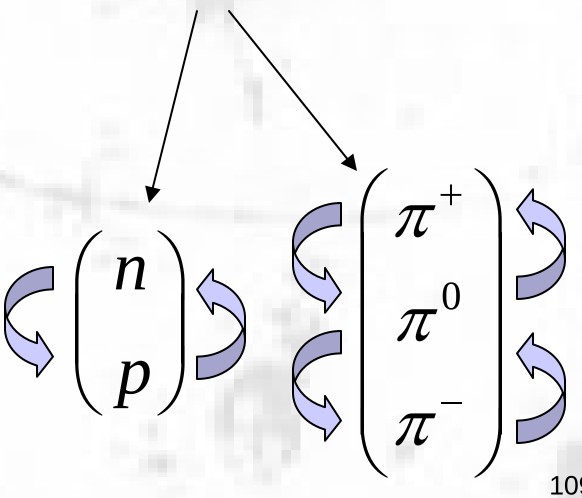


- Governs transition between resonance and DIS region
- Sums of discrete resonances approaches DIS cross-section
- Bodek-Yang: *Observe in electron scattering data; apply to ν cross-sections*

Touchstone Question #7: Duality meets Reality

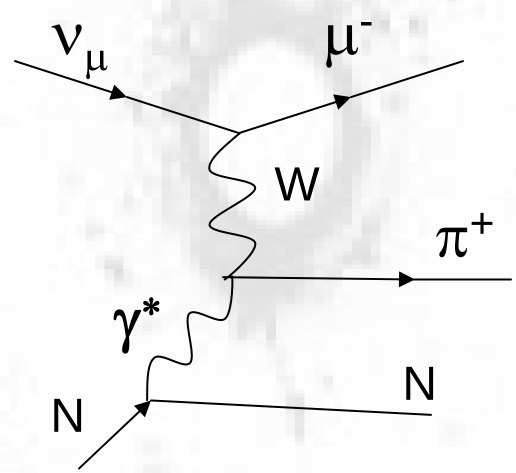


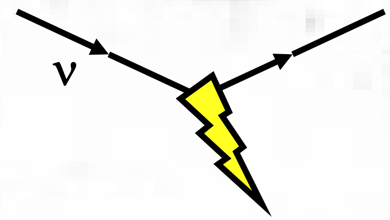
- **A difficulty in relating cross-sections of electron scattering (photon exchange) to charged-current neutrino scattering ($W^{\pm}$ exchange) is that some e-scatting reactions have imperfect ν-scattering analogues.**
- **Write all possible ν_μ CC reactions involving the same target particle and isospin rotations of the final state for each of the following…**
  - **(a)** $e^- n \to e^- n$
  - **(b)** $e^- p \to e^- p$
  - **(c)** $e^- p \to e^- n \pi^+$
  - **(d)** $e^- n \to e^- p \pi^-$



Coherent Inelastic Scattering

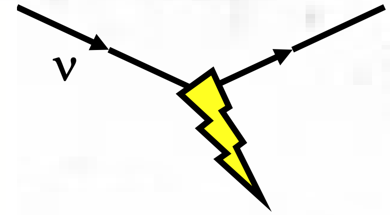
- An inelastic charged-current or neutral-current reaction, at low Q^2, with EM field of the nucleus!
- Not shockingly, this is difficult to calculate
- A dependence essentially unknown.
  - Probably increases with increasing A…
- Low energy dependence controversial

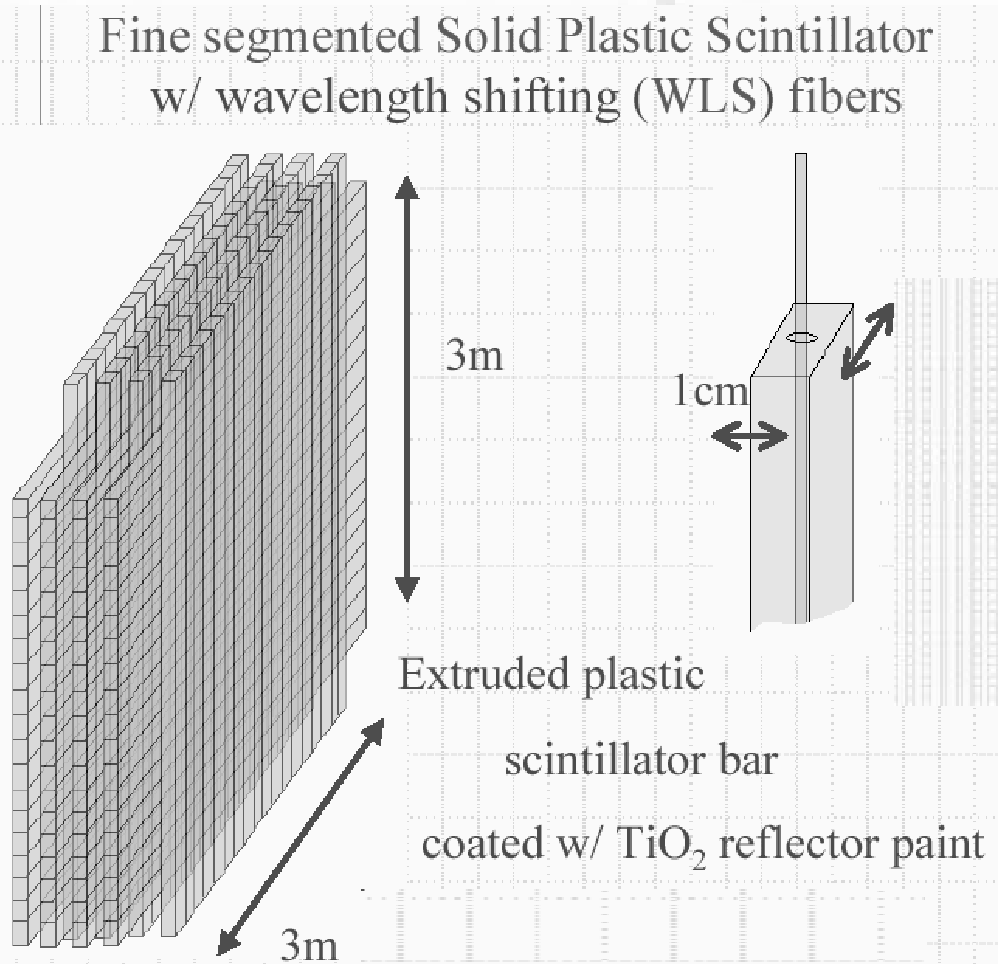




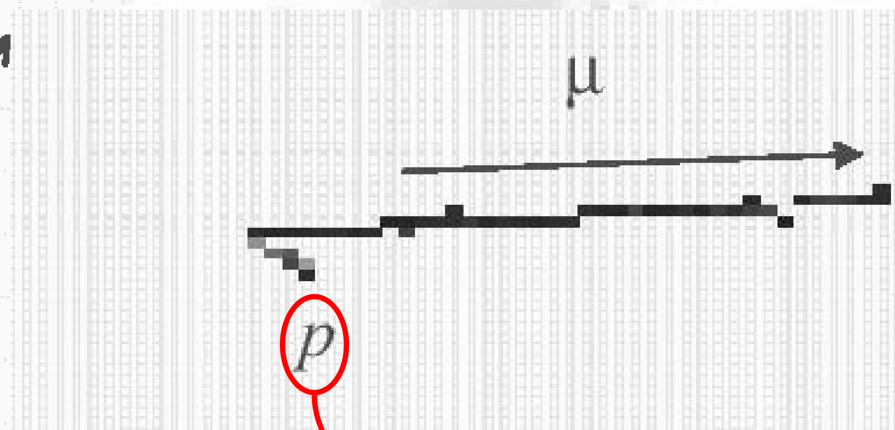
Measuring GeV Cross-Sections

Quasi-Elastic Events



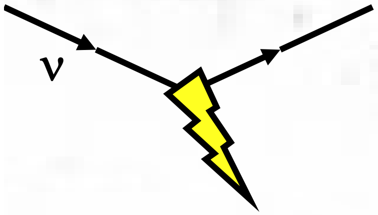


Simulation of K2K "SciBar" detector

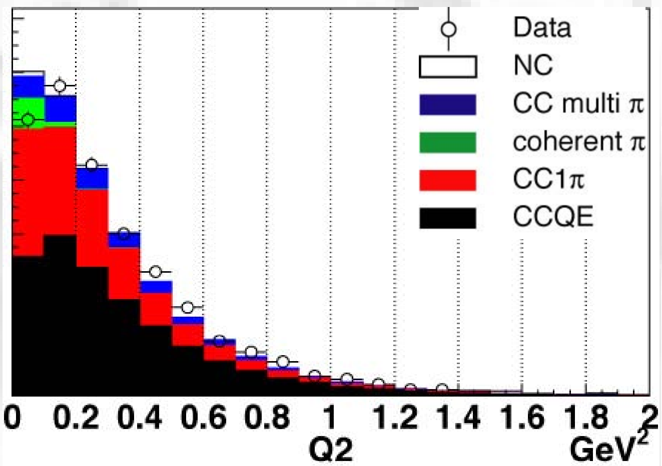


proton is NOT ultra-relativistic!

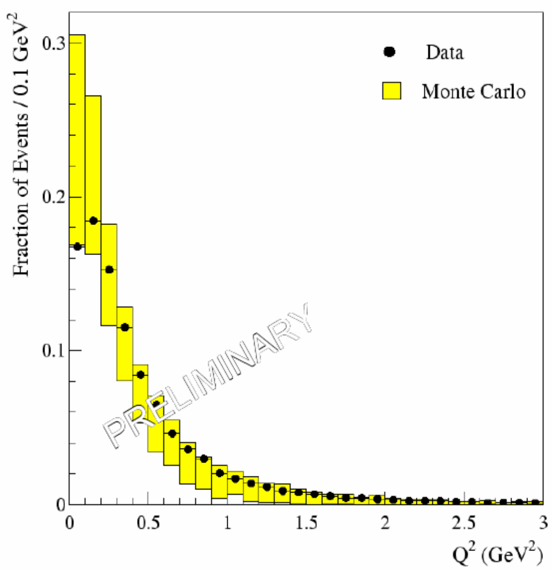
Quasi-Elastic Region (Low Q^2) on ^{12}C



- First glimpses at quasi-elastic rich low Q^2 region on C nuclei…

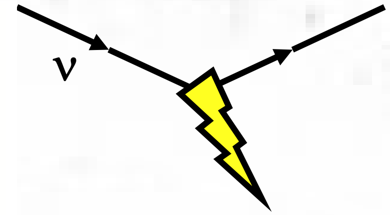


Q2 distribution for K2K SciBar detector

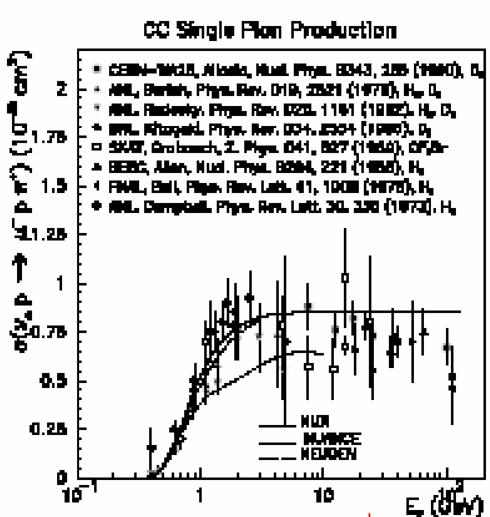


Q2 distribution for MiniBooNE

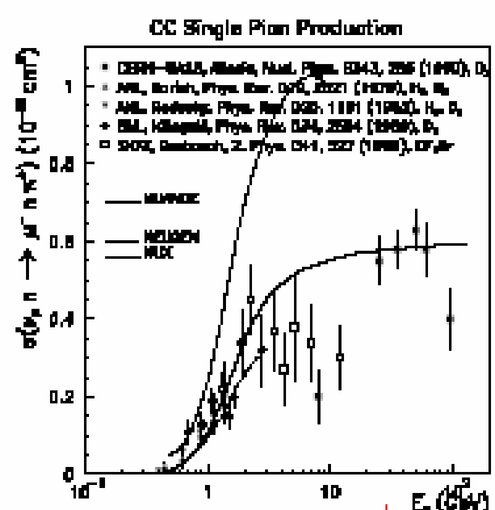
Resonance Region Data



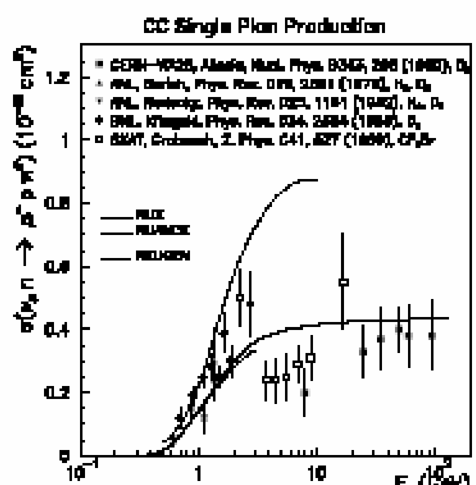
- Data here, again, is impressively imprecise
  - This will be a problem if details of cross-sections are needed where resonance production is dominant. *Need differential distributions*!
    - o ~1-2 GeV important for T2K (background), NOvA (signal)



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

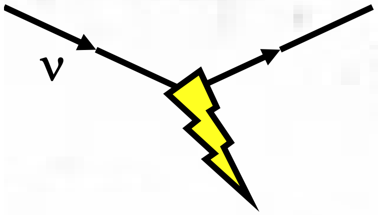


$\nu_\mu n \rightarrow \mu^- n \pi^+$

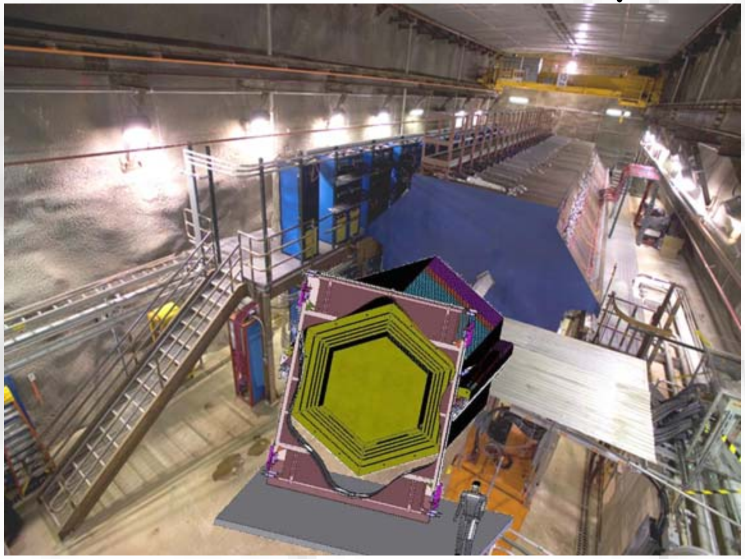


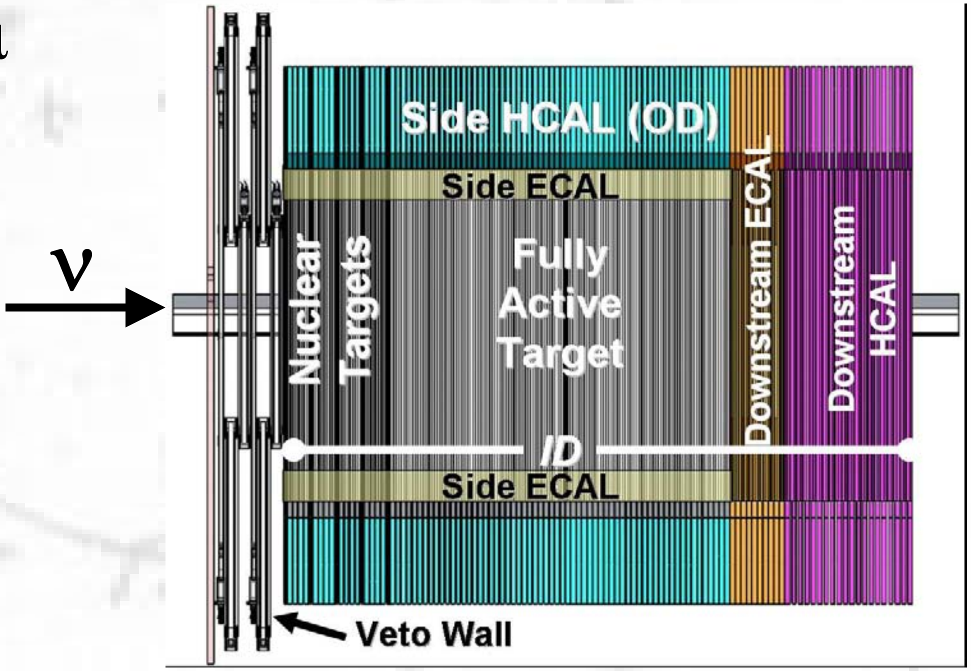
$\nu_\mu n \rightarrow \mu^- p \pi^0$

How to measure resonance region cross-sections?



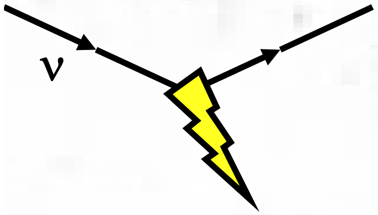
- Need a high granularity detector (like SciBar) but in a higher energy beam and with improved containment of γ, $\pi^{\pm}$, μ



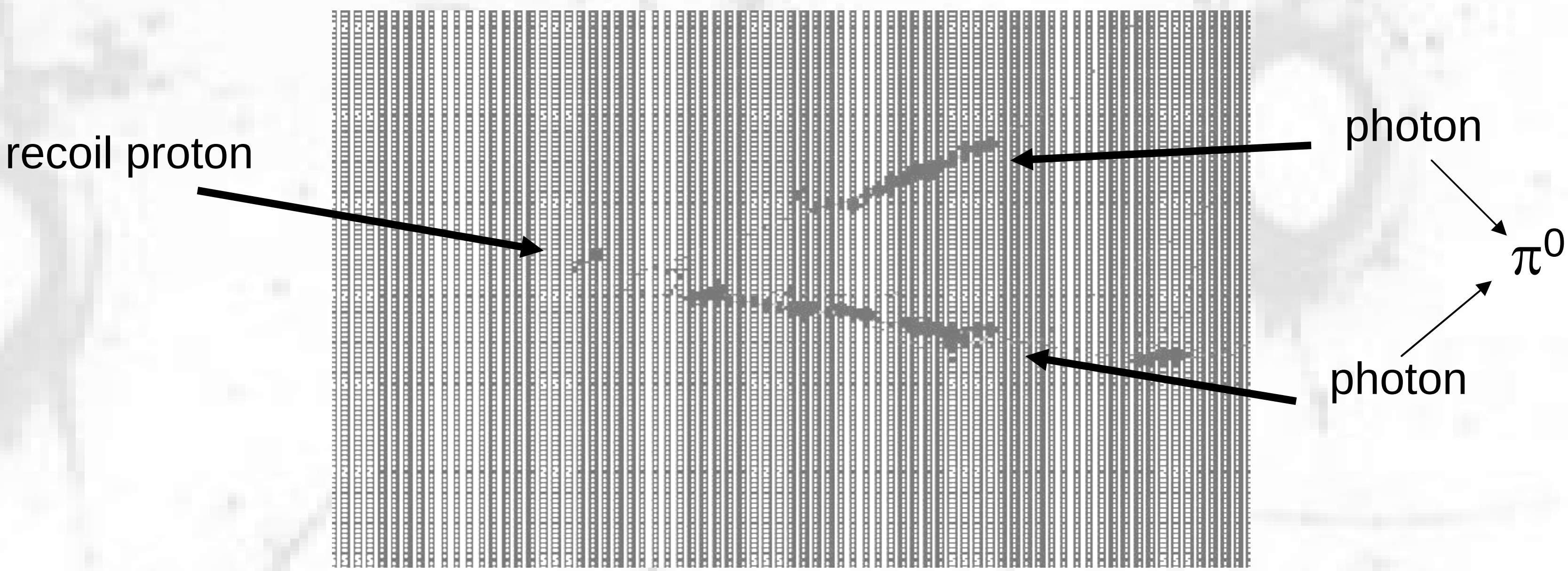


- MINERνA at NuMI
  - "chewy center" (active target)
  - with a crunchy shell of muon, hadron and EM absorbers

What can MINERνA see?

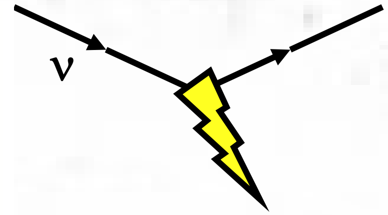


- With high granularity, can reconstruct a broad variety of exclusive final states

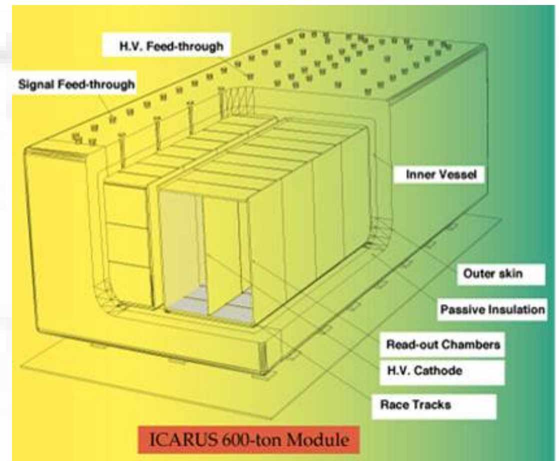


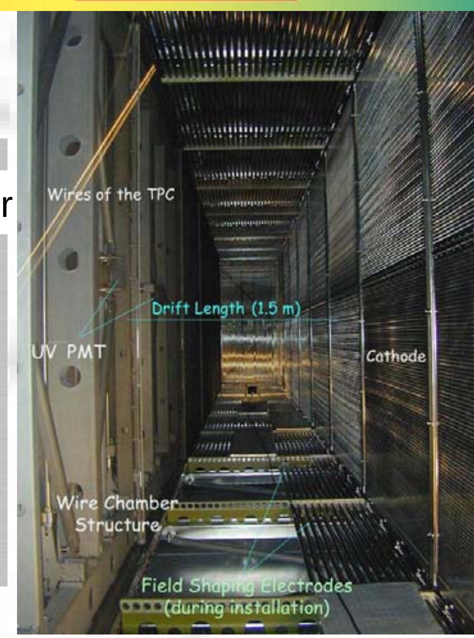
$$\nu_\mu p \rightarrow \nu_\mu p \pi^0,\ \pi^0 \rightarrow \gamma\gamma$$

More Precise Tracking…

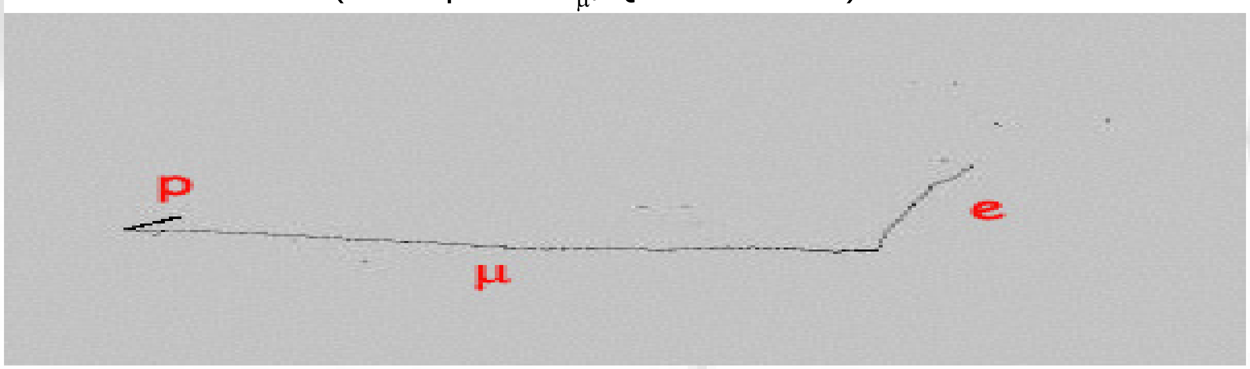


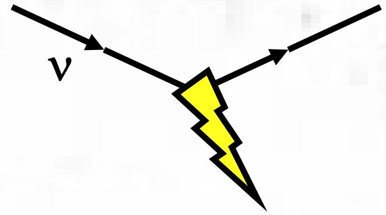
- A Liquid Ar TPC offers near bubble chamber precision in tracking
  - can be in magnetic field (momentum precision limited by dense medium)
- Not simple or inexpensive
- Not easy to incorporate other nuclei





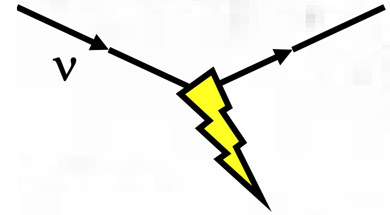
MonteCarlo Event (atmospheric ν_μ, QE interaction) in an ideal LAr detector





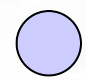
Cross-Sections on Nucleons in a Nucleus

Nuclear Effects in Elastic Scattering

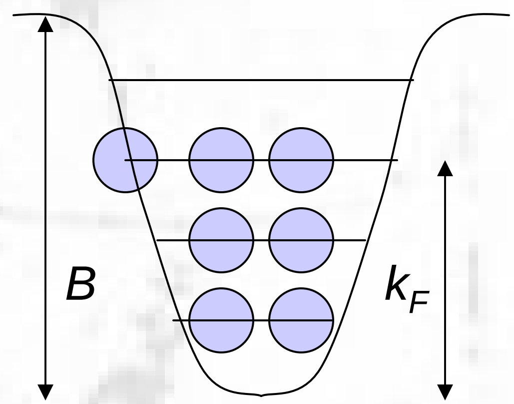


- Two effects
  - In a nucleus, target nucleon has some initial momentum which modifies the observed scattering
    - o Often handled in a "Fermi Gas" model of nucleons filling available states up to some initial state Fermi momentum, k_F

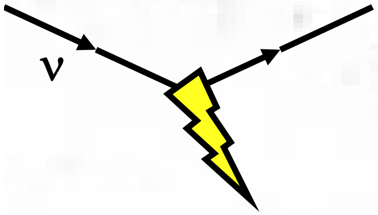
ν



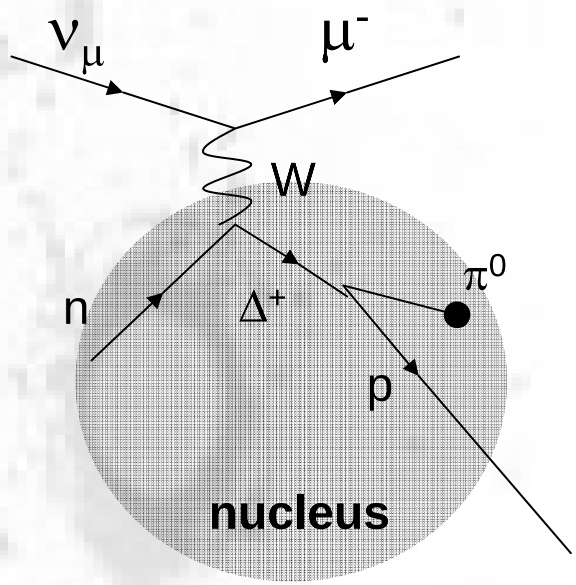
  - Outgoing nucleon can interact with the target
    - o Usually treated as a simple binding energy
    - o Also, Pauli blocking for nucleons not escaping nucleus… states are already filled with identical nucleon



Nuclear Effects in Elastic Scattering (cont'd)

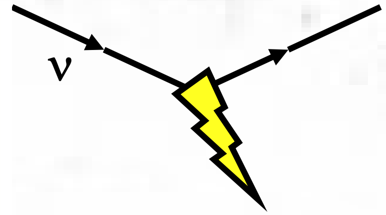


- Also other final states can contribute to apparent "quasi-elastic" scattering through absorption in the nucleus…
  - kinematics may or may not distinguish the reaction from elastic

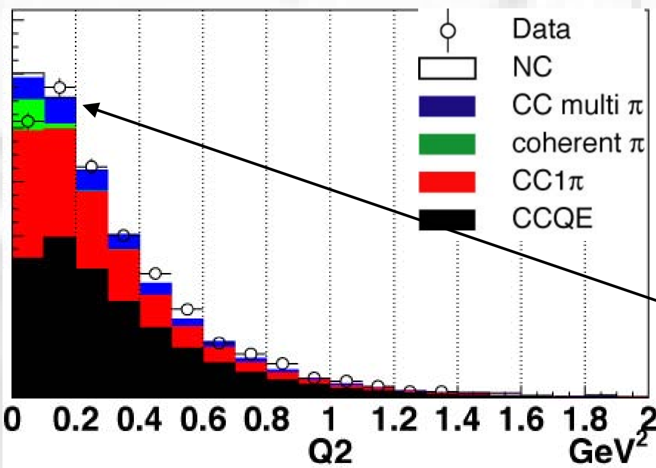


- Theoretical uncertainties are large
  - At least at the 10% level
  - If precise knowledge is needed for target (e.g., water, liquid argon, hydrocarbons), dedicated measurements will be needed
    - o Most relevant for low energy experiments, i.e., T2K

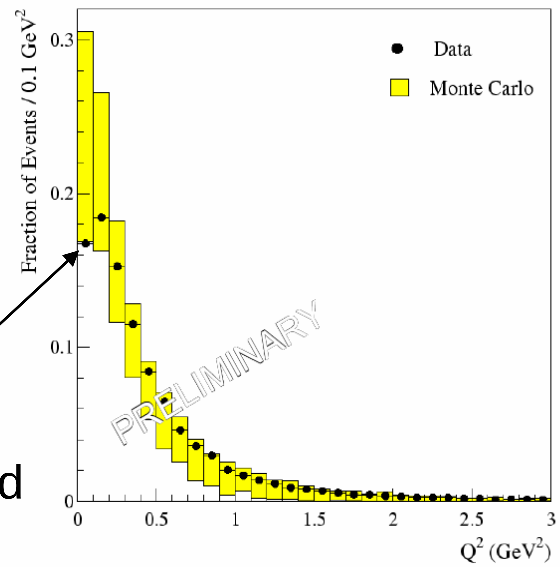
Low Q^2 Data on ^{12}C



- Glimpses at quasi-elastic rich low Q^2 region on ^{12}C…



Larger than expected rollover at low Q^2



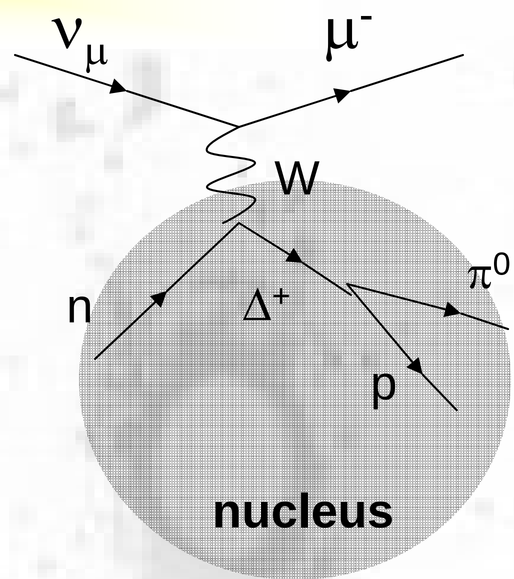
Q2 distribution for K2K SciBar detector

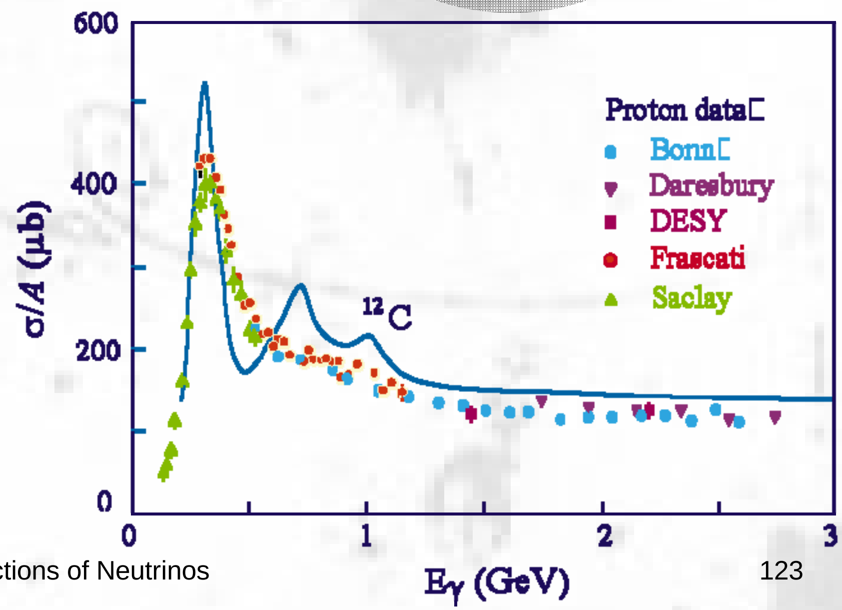
Q2 distribution for MiniBooNE

- Data suggests nuclear effects are not well modeled
  - K2K working on program of determining which of the many contributions has the deficit
  - K2K has indications it is coherent contribution. Ongoing story…

Nuclear Effects in Resonance Region

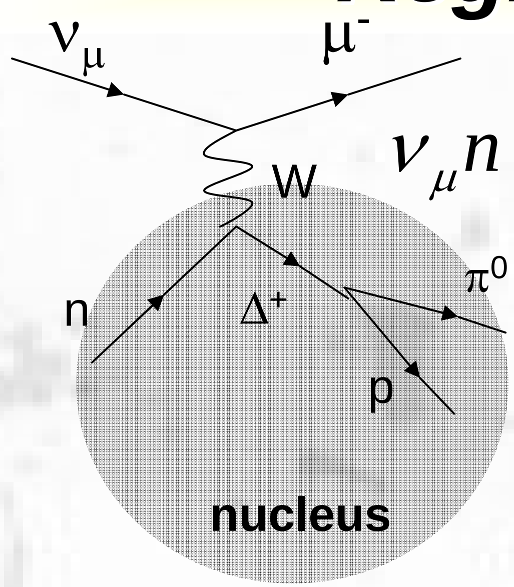
- An important reaction like
  $$\nu_\mu n \to \mu^- p \pi^0$$
  (ν_e background) can be modified in a nucleus
- Production kinematics are modified by nuclear medium
  - at right have photoabsorption showing resonance structure
  - line is proton; data is ^{12}C
  - except for first Δ peak, the structure is washed out
  - interactions of resonance inside nucleus



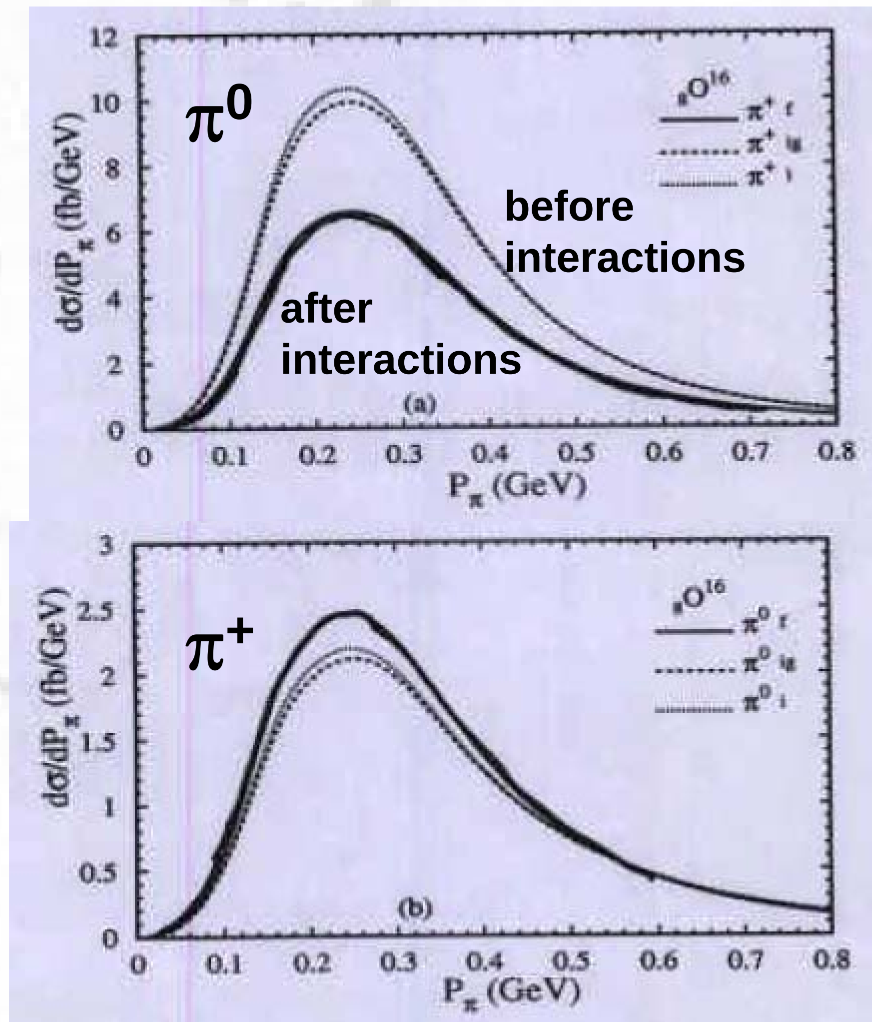


Nuclear Effects in Resonance Region (cont'd)

model of
E. Paschos, NUINT04

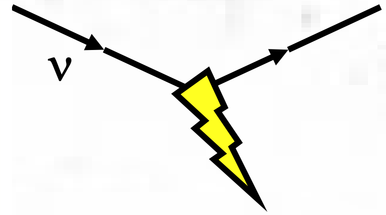


$$\nu_\mu n \rightarrow \mu^- p \pi^0$$



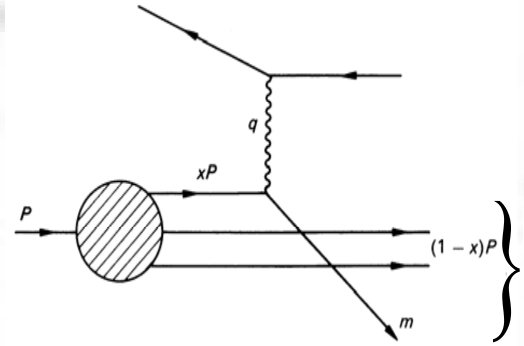
- How does nucleus affect π^0 after production
- Rescattering. Absorption.
- Must measure to predict ν_e backgrounds!

Touchstone Question #8



- **Two questions with (*hint*) related answers…**
  1. **Remember that W^2 is…**

$$W^2 = M_P^2 + 2M_P\nu - Q^2$$
$$= M_P^2 + 2M_P\nu\left(1 - x\right)$$

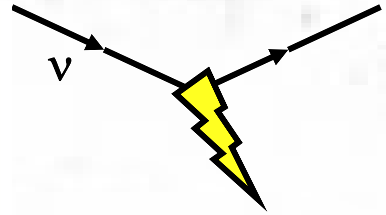


W^2

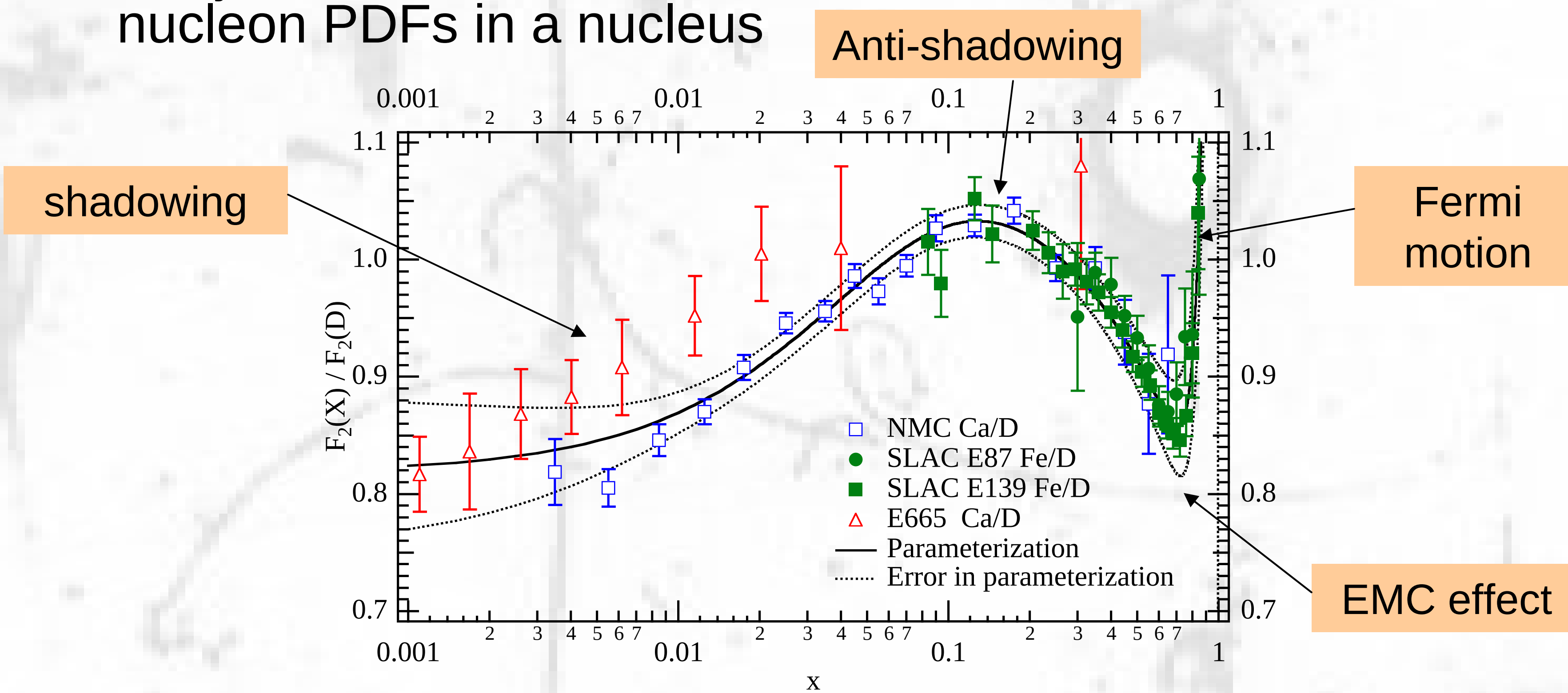
the square of the invariant mass of the hadronic system. ($\nu = E_\nu - E_\mu$; x is the parton fractional momentum)
It can be measured, as you see above with only leptonic quantities (neutrino and muon 4-momentum).
In neutrino scattering on a scintillator target, you observe an event with a recoiling proton and with W reconstructed (perfectly) from leptonic variables <M_p. Explain this event.

  2. **In the same scintillator target, you observe the reaction…** $\nu_\mu\,{}^{12}\mathrm{C} \rightarrow \mu^- p \pi^- + \text{remnant nucleus}$
Why might this be puzzling? Explain the process.

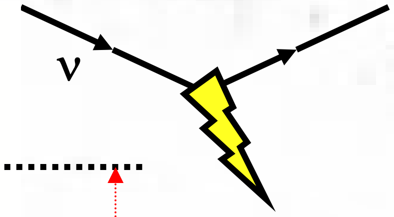
Nuclear Effects in DIS



- Well measured effects in charged-lepton DIS
  - Maybe the same for neutrino DIS; maybe not… all precise neutrino data is on Ca or Fe targets!
  - Conjecture: these can be absorbed into effective nucleon PDFs in a nucleus



Nuclear Effects in IBD, Inverse Electron Capture



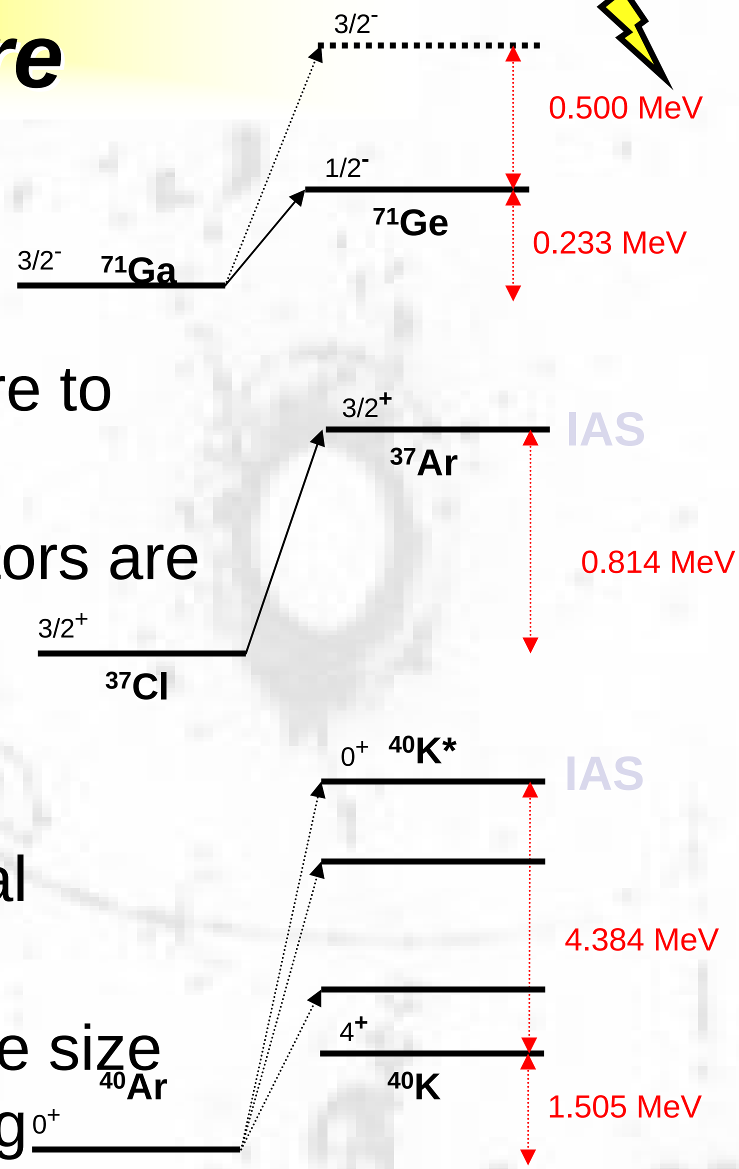
$$\bar{\nu}_e + A_Z \rightarrow e^+ + A_{Z-1}$$

$$\nu_e + A_Z \rightarrow e^- + A_{Z+1}$$

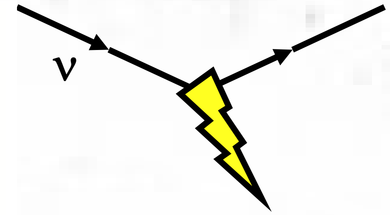
- Complicated nuclear physics phenomenology which I don't care to detail here
- Suffice it to say that the form factors are not as simple to calculate

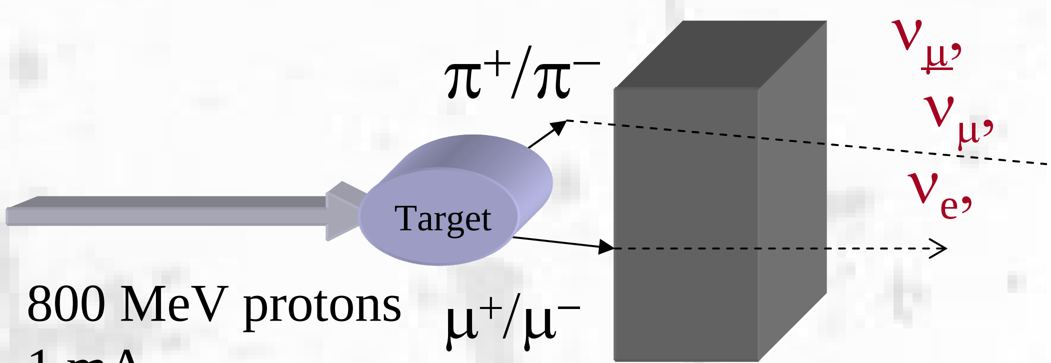
  $\Delta J=0$ (Fermi Trans.),

  $\Delta J=\pm 1$ (Gamow-Teller Trans.)
- Threshold energies are less trivial
  - sometimes multiple states
- Also have corrections due to finite size of nucleus and electron screening



Example: LSND

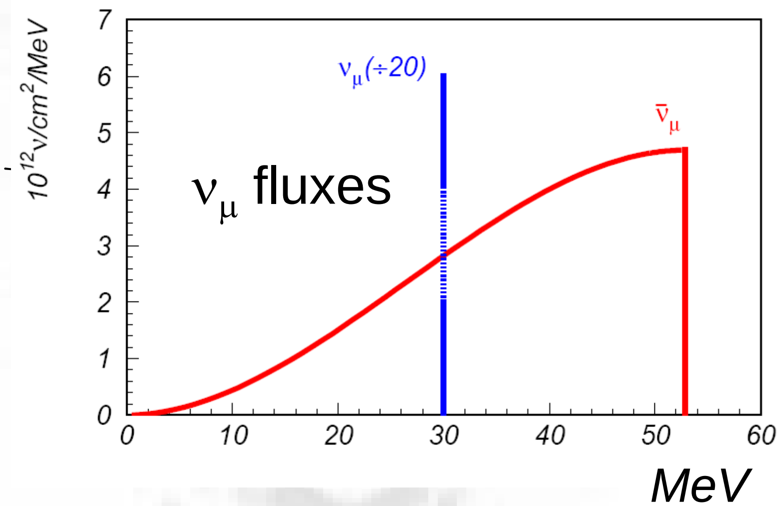




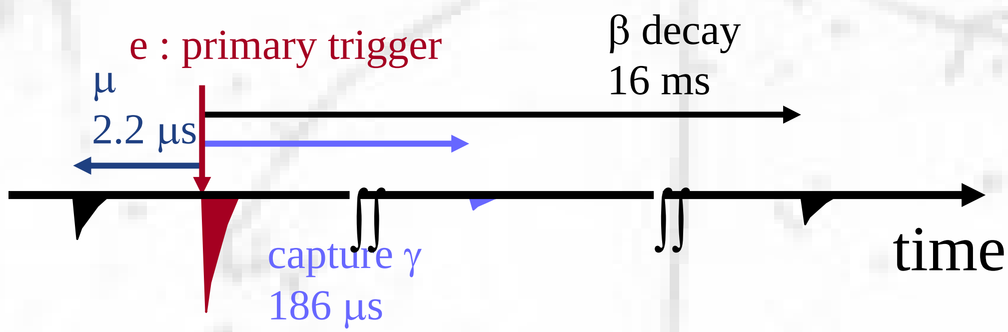
800 MeV protons
1 mA
6% duty ratio

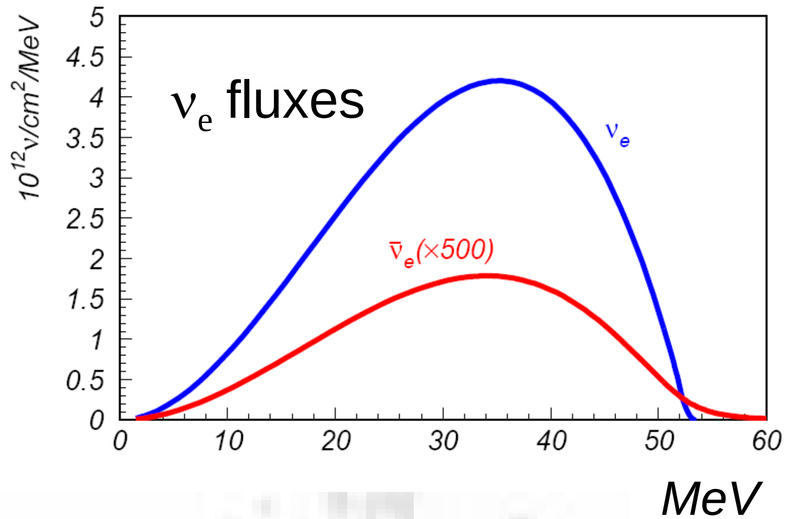
Cu Beam
Dump

L = 30 meters



Decay at Rest Fluxes: from π^+,μ^+ decays, at 800MeV protons, make more π^+ than π^-





Example: LSND Reactions

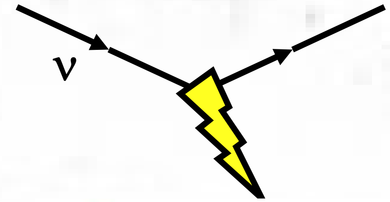
- At 10s of MeV, anti-neutrino charged-current interactions
  - can occur from free protons
  - but no allowed states are present in a potential recoil ^{12}B nucleus
- By contrast, neutrino charged-current interactions
  - produce ^{12}N which has energetically allowed exicted states (and rare transition to ground state)

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

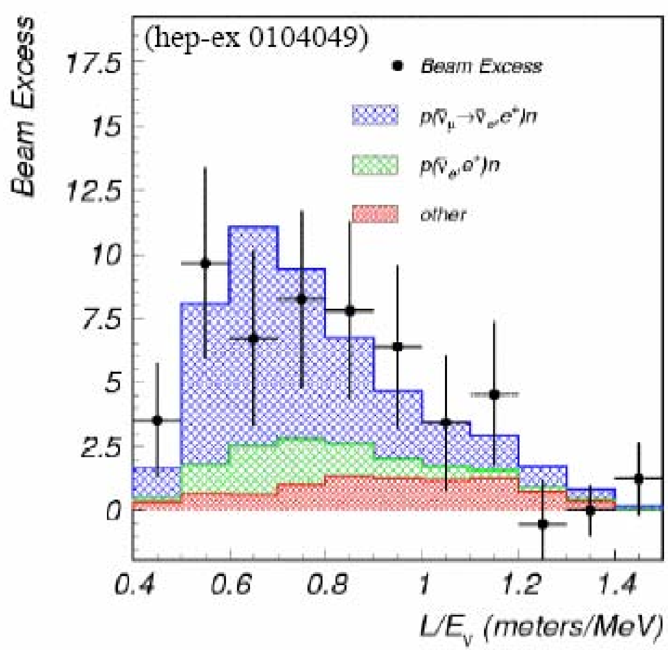
← *oscillation signatures* →

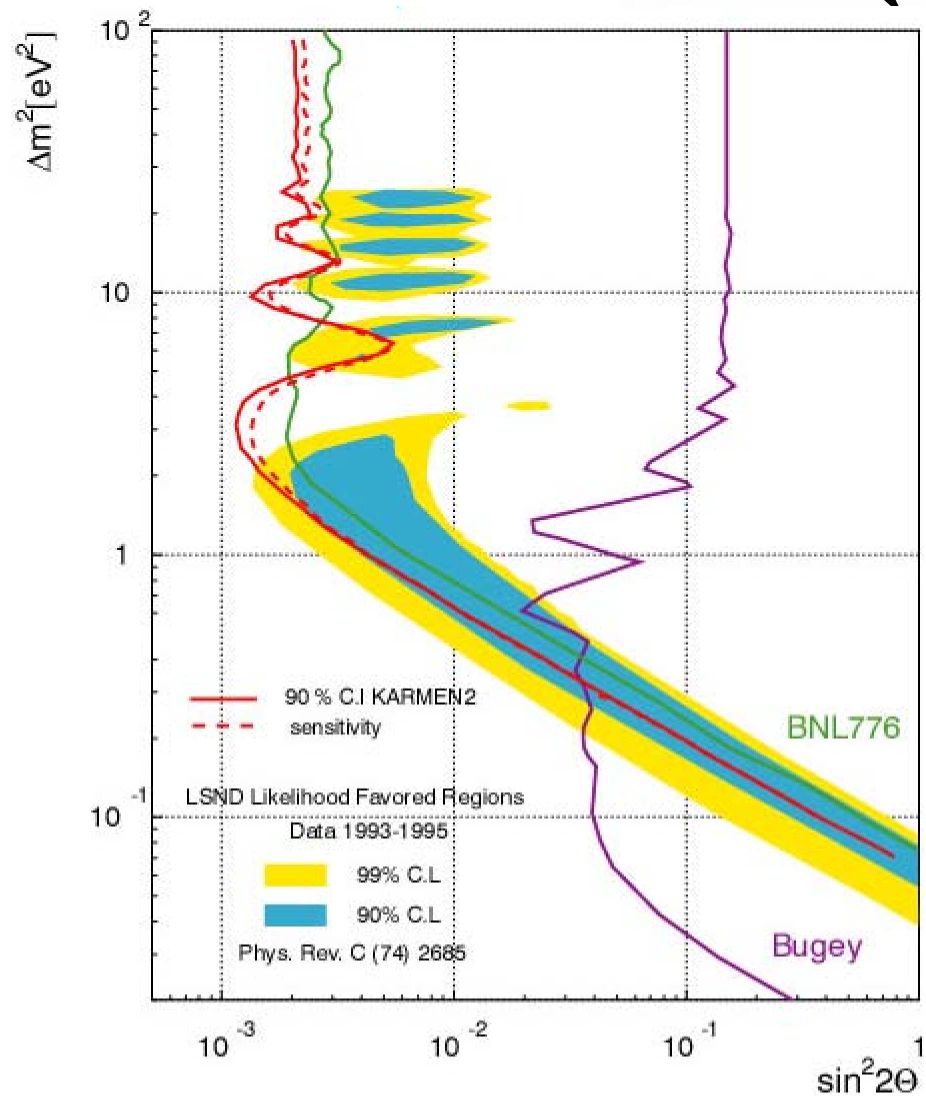
$$\nu_\mu C \rightarrow \mu^-\, N^*$$
$$\nu_e C \rightarrow e^-\, N^*$$
$$\nu_\mu C \rightarrow \mu^-\, N_{GS}$$
$$\nu_e C \rightarrow e^-\, N_{GS}$$

LSND (and KARMEN) Results:



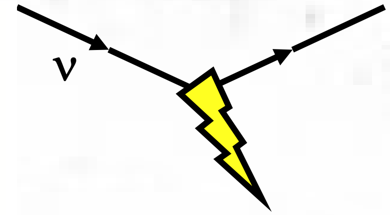
- LSND anti-ν_e excess
  - Detected by coincidence of positron and delayed neutron capture (gammas)
  - 87.9±22.4±6.0 events
  - Not confirmed by KARMEN experiment at ISIS





Connections to Low Energy and Ultra-High Energy Cross-Sections

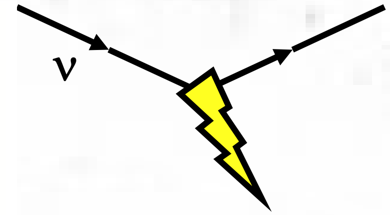
Ultra-High Energies



- At energies relevant for UHE Cosmic Ray studies (e.g., IceCube, ANITA)
  - ν-parton cross-section is dominated by high Q^2, since $d\sigma/dQ^2$ is constant
    - o at high Q^2, scaling violations have made most of nucleon momentum carried by sea quarks
    - o see a rise in σ/E_ν from growth of sea at low x
    - o neutrino & anti-neutrino cross-sections nearly equal
  - *Until* Q^2»M_W^2, then propagator term starts decreasing and cross-section becomes constant

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(q^2 - M^2)^2}$$

Touchstone Question #9: Where does σ Level Off?



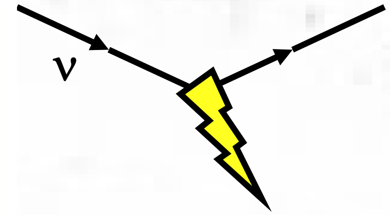
- *Until* $Q^2 \gg M_W^2$, then propagator term starts decreasing and cross-section becomes constant

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(q^2 - M^2)^2}$$

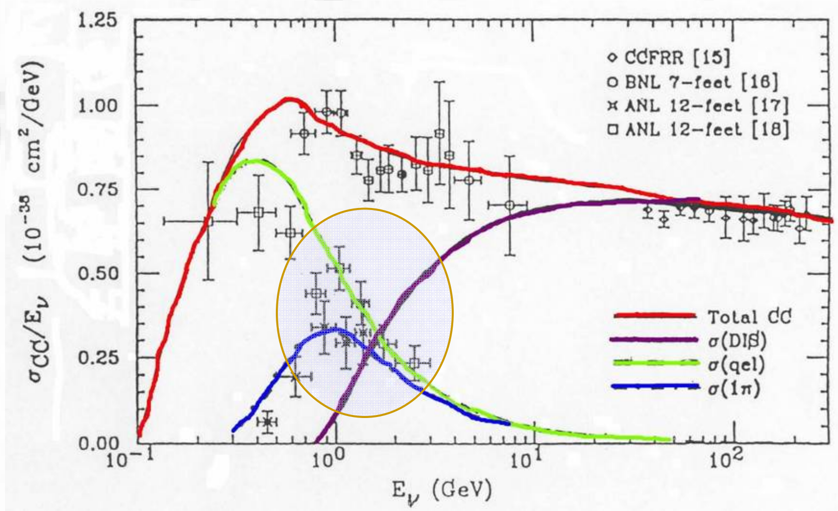
- At what beam energy for a target at rest will this happen?

(a) $E_\nu \sim 10\text{TeV}$ **(b)** $E_\nu \sim 10,000\text{TeV}$ **(c)** $E_\nu \sim 10,000,000\text{TeV}$

Threshold Effects

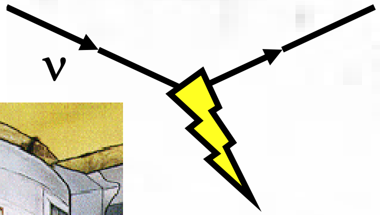


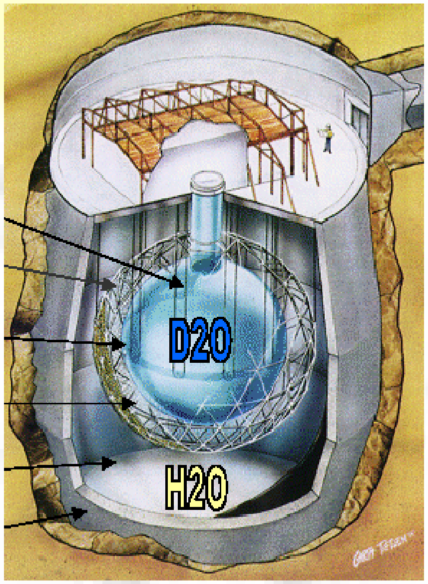
- At 1-few GeV, cross-section makes a transition between DIS-like and resonant/elastic
  - Why? "Binding energy" of target (nucleon) is ~1 GeV, comparable to mean Q^2



- What are other thresholds?
  - Binding energy of nucleus is >>(M_n-M_p)≈1 MeV, typically 1/10ths – 10s of MeV
  - Binding energies of atoms are <~$Z^2 m_e c^2 \alpha_{EM}/2$~10-$10^5$ eV
  - Binding energies of ν, ℓ$^\pm$, quarks (*into hypothetical constituents that we haven't found yet*) are > 10 TeV

Example: SNO





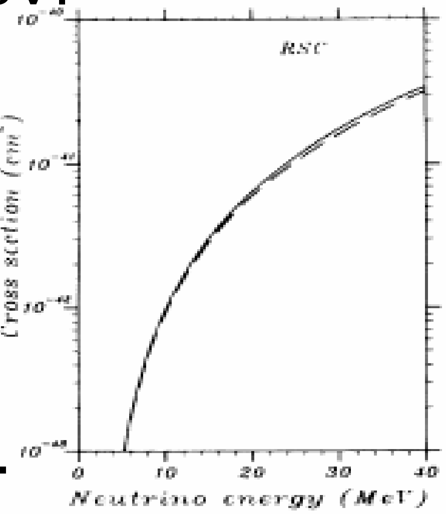
- Three reactions for observing ν from sun (E_ν ~ few MeV

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

  - ^{2}H, ^{16}O binding energies are 13.6eV, ~1 keV.
  - Therefore, e^- are "free". $\sigma \propto E_\nu$

CC $\nu_e + d \Rightarrow p + p + e^-$

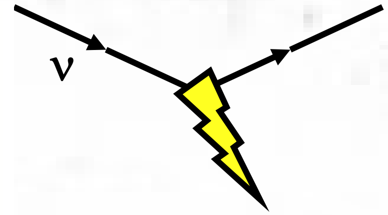
NC $\nu_x + d \Rightarrow p + n + \nu_x$



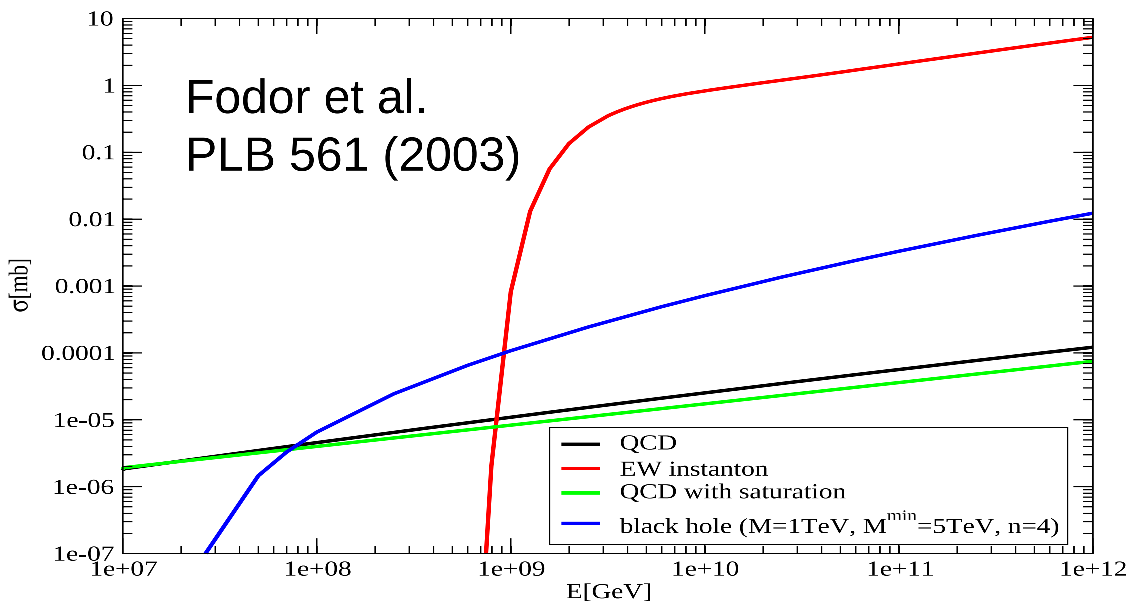
  - But binding energy of deuteron is 2.2 MeV. Energy threshold for NC of a few MeV.

(Bahcall, Kuboeara, Nozawa, PRD38 1030)

Example: Ultra-High Energies

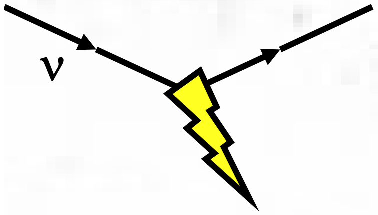


- At UHE, can we reach thresholds of non-SM processes?
  - E.g., structure of quark or leptons, black holes from extra dimensions, etc.
  - Th



Conclusions

What Should I Remember from These Lectures?



- Understanding neutrino interactions *is key* to precision measurements of neutrino oscillations at accelerators
- Weak interactions couple to single chirality of fermions
  - Consequences for scattering on point-like particles
- Neutrino scattering rate proportional to energy
  - Point-like target (electron, quark), below real boson exchange
- Target (proton, nucleus) structure is a significant complication to theoretical prediction of cross-section
  - Particularly problematic near inelastic thresholds
  - We can learn things by analogy with DIS (duality) and electron scattering
  - But improved neutrino cross-section measurements are required by next generation oscillation experiments