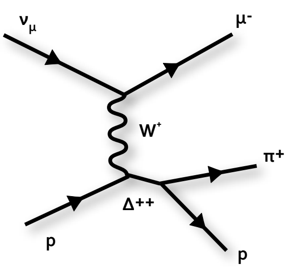
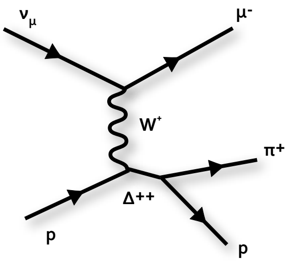


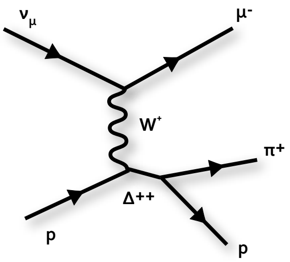
Neutrino-Nucleus Interactions

Gabriel N. Perdue
Fermilab



The Goal of this Lecture

- Explain why neutrino-nucleus interactions are important.
- Explain why neutrino-nucleus interactions are hard to understand.
- Explain what we are doing about it…
    - The focus will be holistic: how do you talk to your colleagues about these problems?… and how do you understand seminars at the lab? (MINERvA, MicroBooNE, ArgoNeut, etc.)

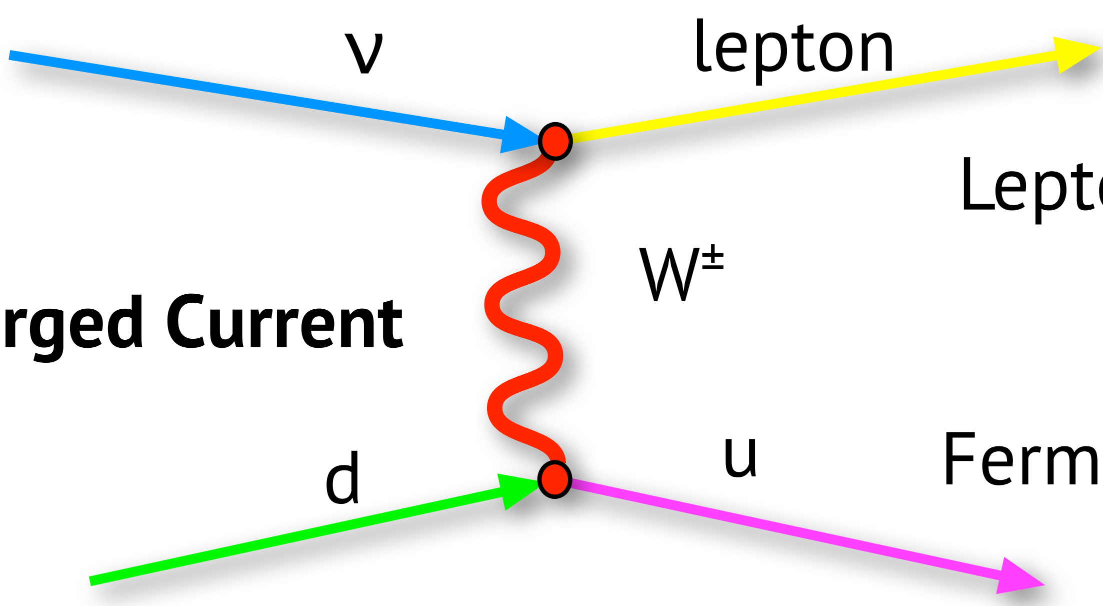


Who is your lecturer?

- I am an associate scientist at Fermilab, working mostly on the MINERvA experiment, LBNE, and the GENIE neutrino event generator.
  - My graduate work was a fixed-target Kaon rare-decay search.
- Given my training and background, I will focus on accelerator-based neutrino scattering experiments in the ~half to ~few GeV region.
- This is not to say other regimes are not interesting, but I will stay in my comfort zone.
  - In particular, for a "complete" understanding, it is useful to study high energy neutrino cross-section experiments (e.g. CCFR, NuTeV) and electron scattering experiments at a variety of energies.

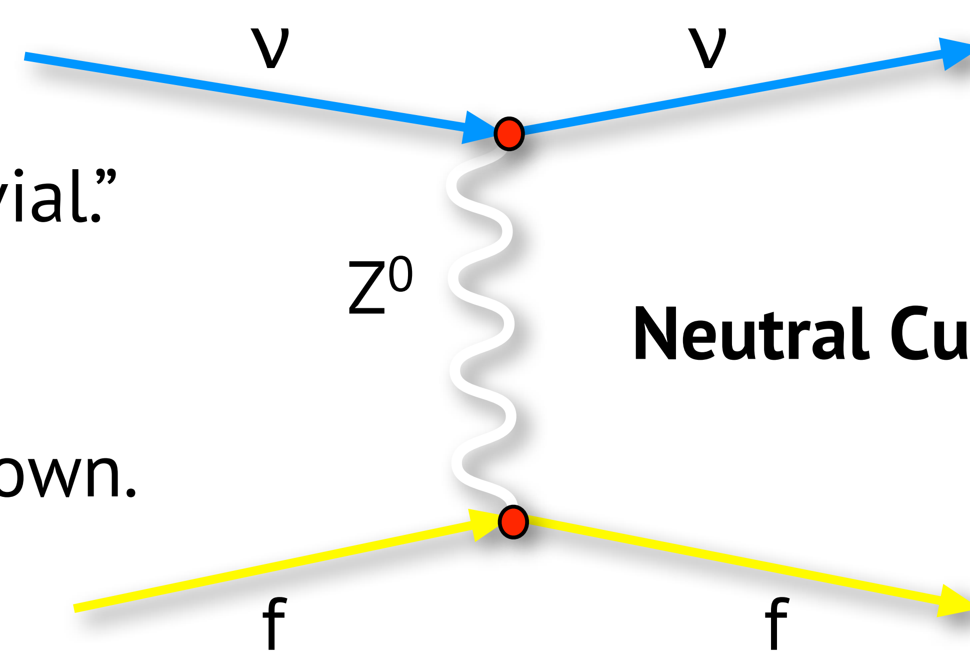
Neutrino Interactions - Weak Force Only!

Charged Current



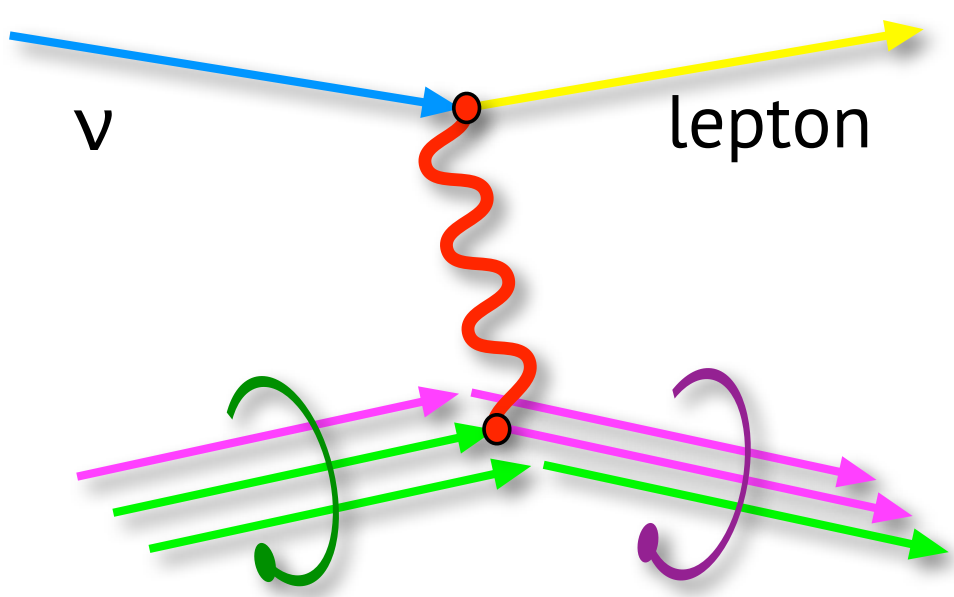
Lepton: “Trivial.”

Fermion: Known.

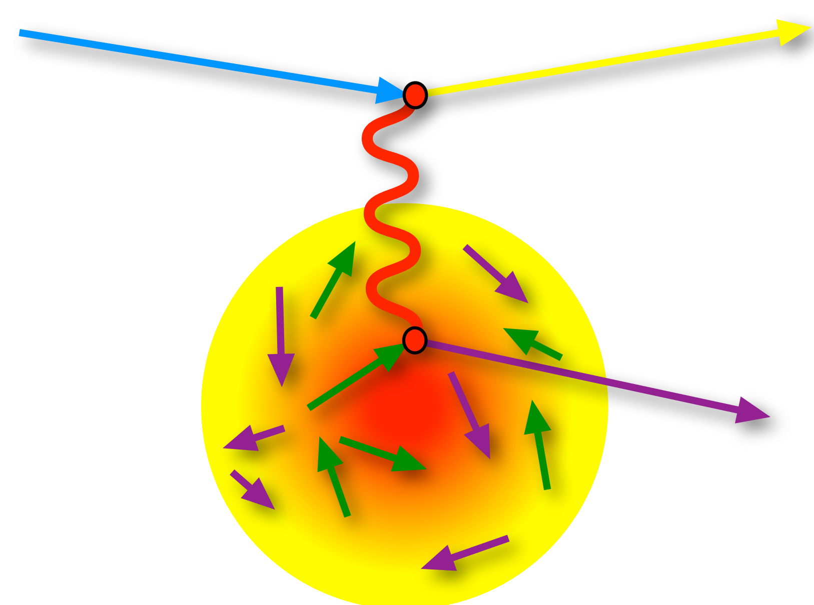


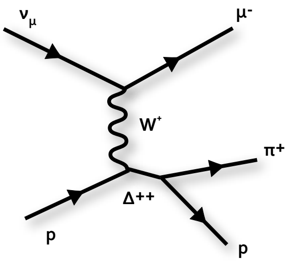
Neutral Current

Free Nucleon:
Parameterize
w/ Form Factors.



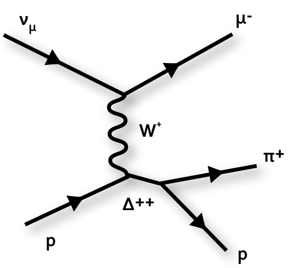
Nucleus:
What is the initial state?
What escapes the nucleus?
?



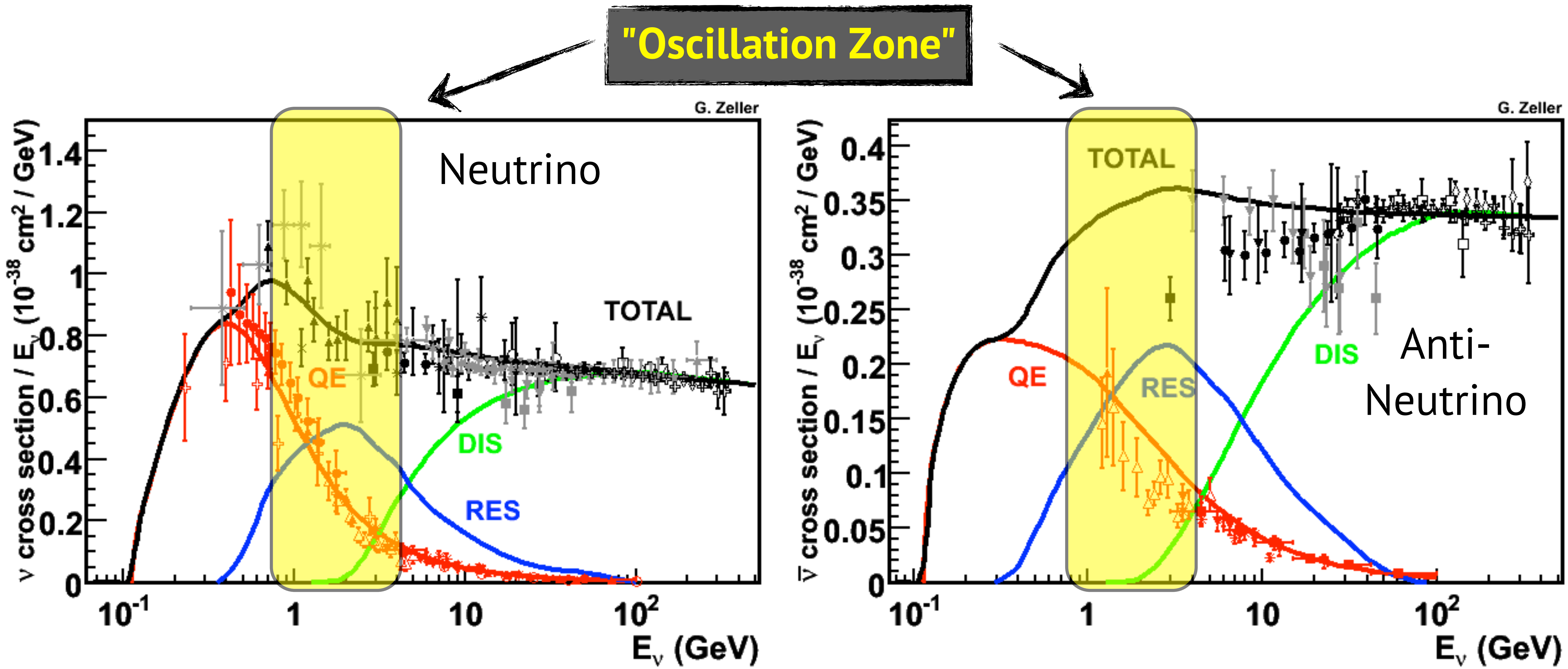


Embedded Assumptions

- There are a few facts that are often buried in the details of discussions of neutrino interactions:
  - Your knowledge of the flux is typically only good to 10-20% and you have no information event-by-event.
  - Kinematic distributions are flux-integrated for a specific flux.
  - Measurements are always convolutions of flux, cross section, nuclear effects, and detector efficiencies.



Reaction Channels

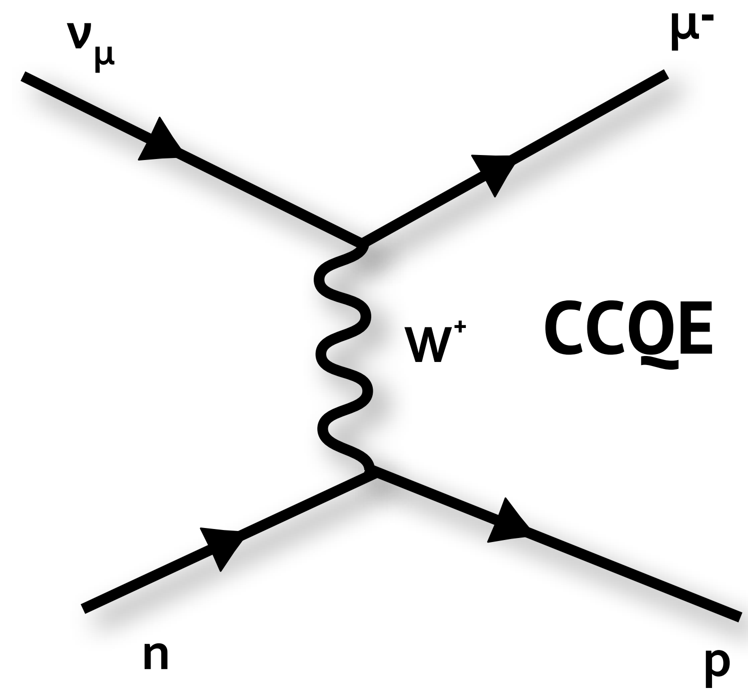


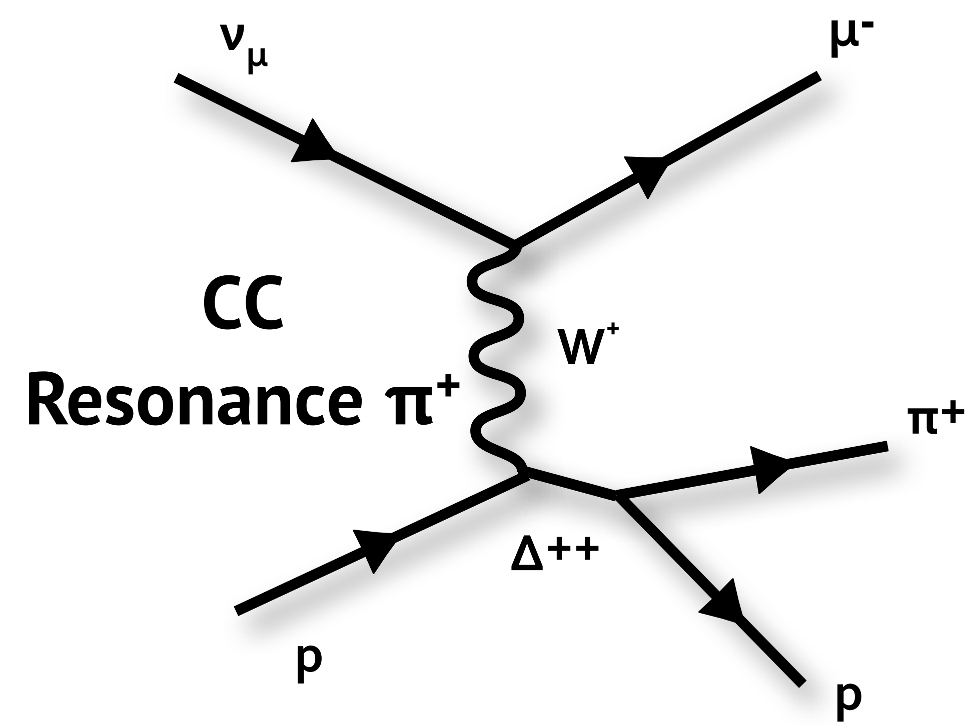
J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", Rev. Mod. Phys. 84, 1307-1341, 2012

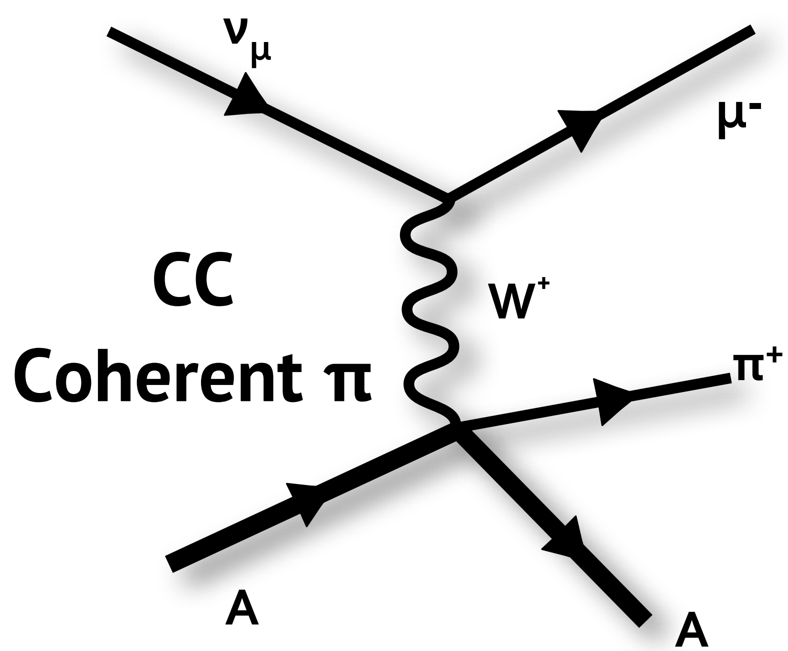
The region of interest is plagued by messy nuclear physics!

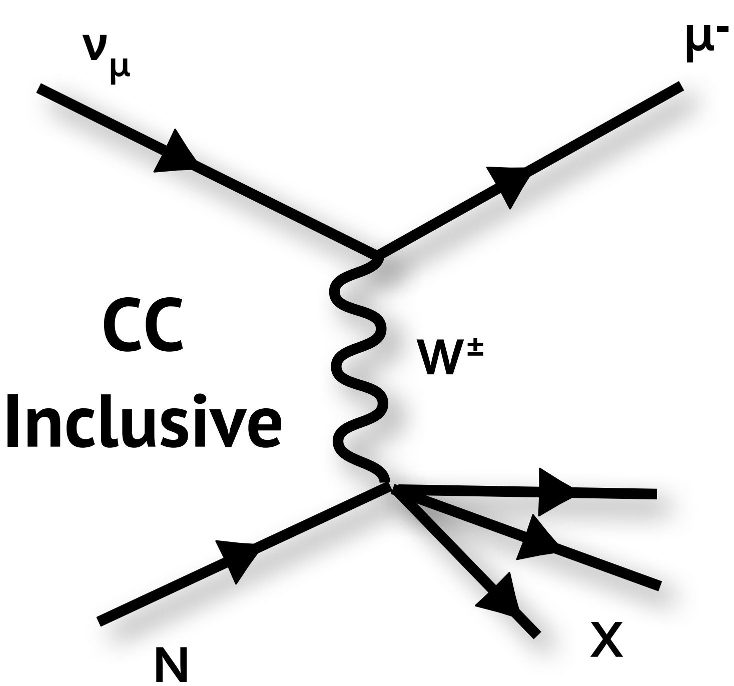
Reaction Channel Menagerie

- Charged-Current: Exchange a W boson.
    - CCQE : Charged-Current Quasi-Elastic
    - CC $\pi^{\pm}$, π^{0}
        - Coherent (no break-up) & Resonance Production
        - Background (Signal?) for the next-generation oscillation experiments.
    - DIS / Inelastic



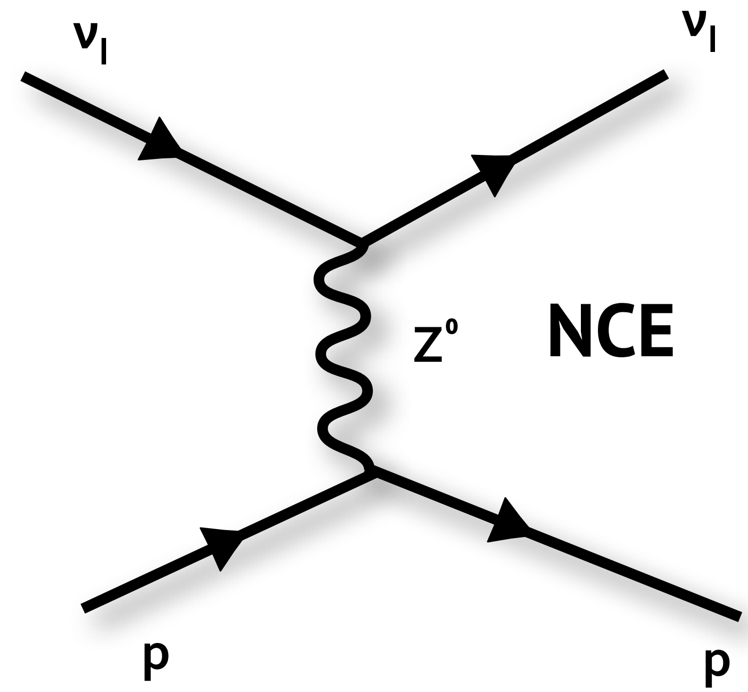




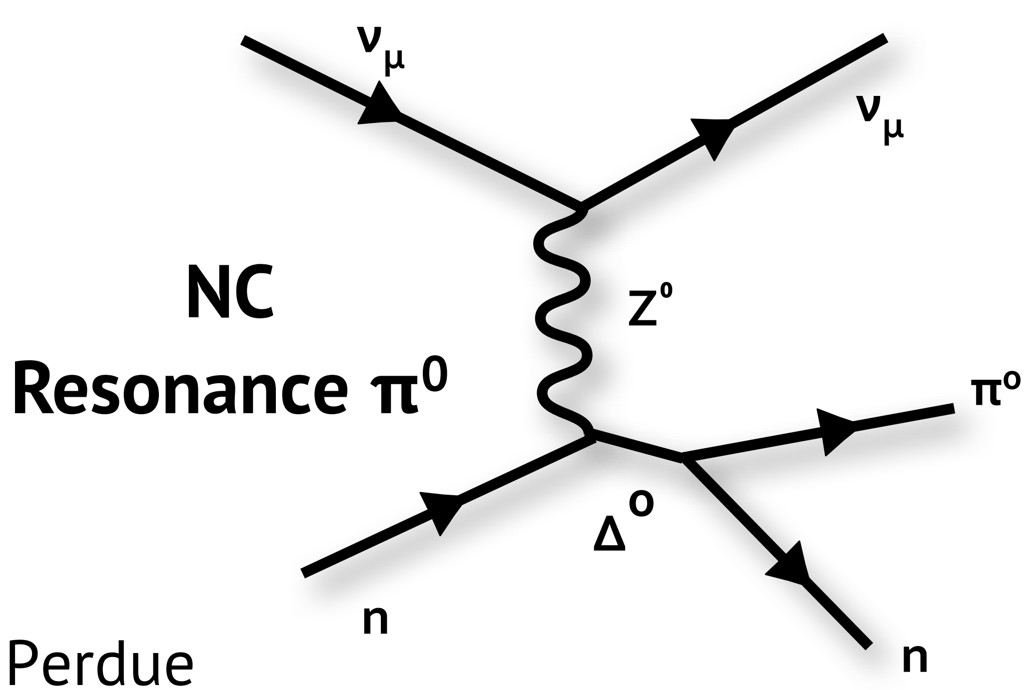


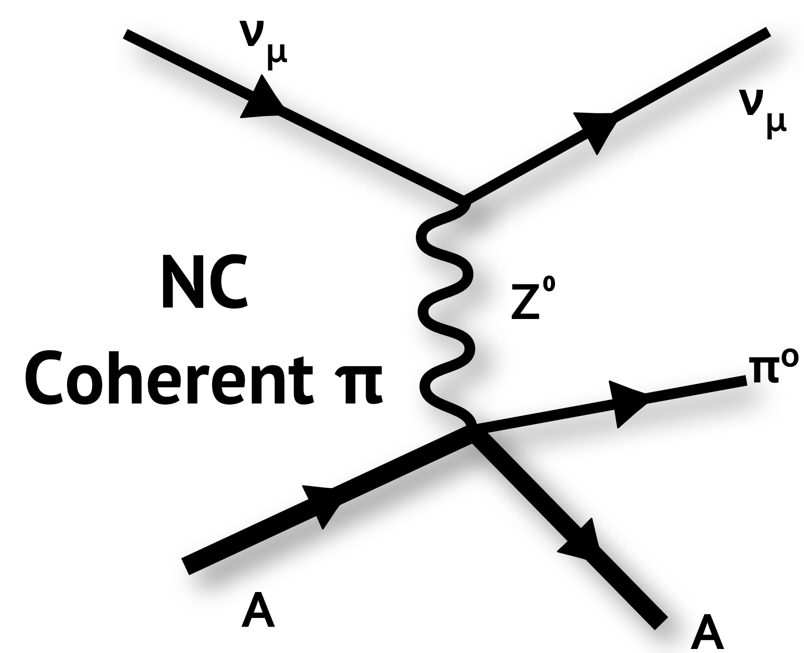
Reaction Channel Menagerie

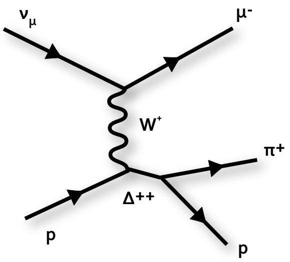
Key Difference: Don't know neutrino flavor!



- Neutral Current: Exchange a Z boson.
- NC Elastic
  - Predicted from CCQE except for NC contribution to the axial form-factor (via strange quarks).
- NC π^0
  - Important δ_{CP} & Mass Hierarchy background.
- Also have DIS.



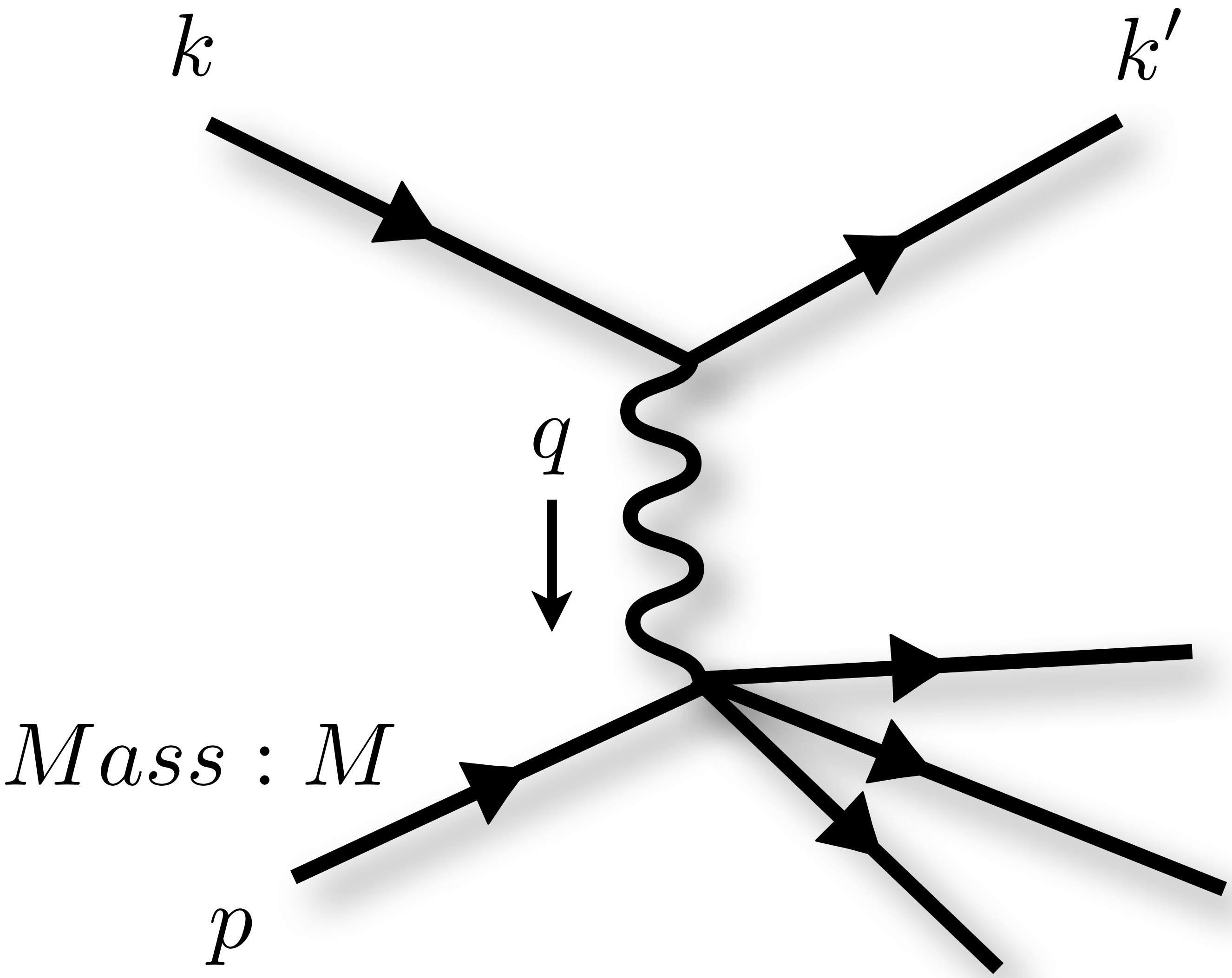




Reaction Channels

- The breakdown on the previous slides was a bit artificial.
    - We may only really be precise in channel definition when scattering from free nucleons.
    - Point of confusion: when people say "CCQE," what do they mean? It can mean something very strict when considering free nucleons, or just "any final state with no pions" when considering nuclear targets.
- In some senses, and especially for nuclear targets, the better way to think about final states is:
    - by current,
    - by number and type of baryon in the final state,
    - by number and type of meson in the final state.
- This is all we may observe.

Neutrino Interaction Jargon : Technical



$$q^2 \equiv (p' - p)^2 = -Q^2$$

(Momentum Transfer)²

Energy transfer.

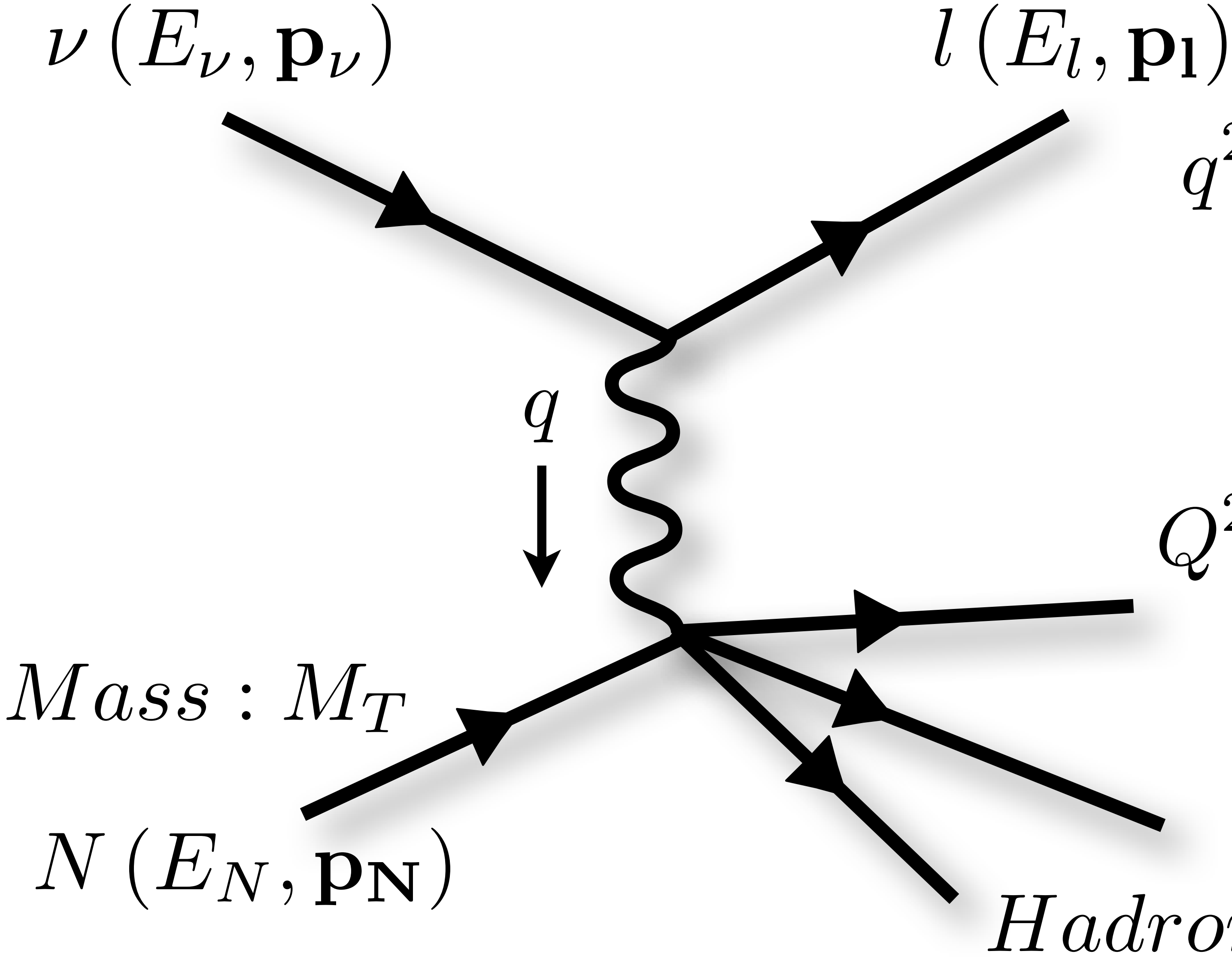
$$\nu \equiv \frac{p \cdot q}{M}$$

$$W^2 \equiv (p + q)^2 = E_H^2 - \mathbf{p_H}^2$$ **(Hadronic Invariant Mass)²**

$$y = \frac{p \cdot q}{p \cdot k}$$ **Inelasticity**

$$x = \frac{-q^2}{2p \cdot q} = \frac{-q^2}{2M\nu}$$ **Parton Momentum Fraction**

Neutrino Interaction Jargon : Practical



$$q^2 \equiv (E_l - E_\nu)^2 - (\mathbf{p_l} - \mathbf{p}_\nu)^2$$
$$= -Q^2$$
$$= t$$ **(Momentum Transfer)²**

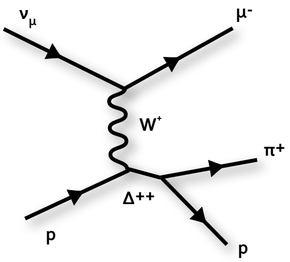
$$Q^2 = 4E_\nu E_\mu \sin^2(\theta/2)$$

$$\nu = E_\nu - E_l$$
Energy transfer.

$$W^2 = M_T^2 + 2M_T E_H - Q^2$$ **(Hadronic Invariant Mass)²**

$$y = 1 - \frac{E_l}{E_\nu}$$ **Inelasticity**

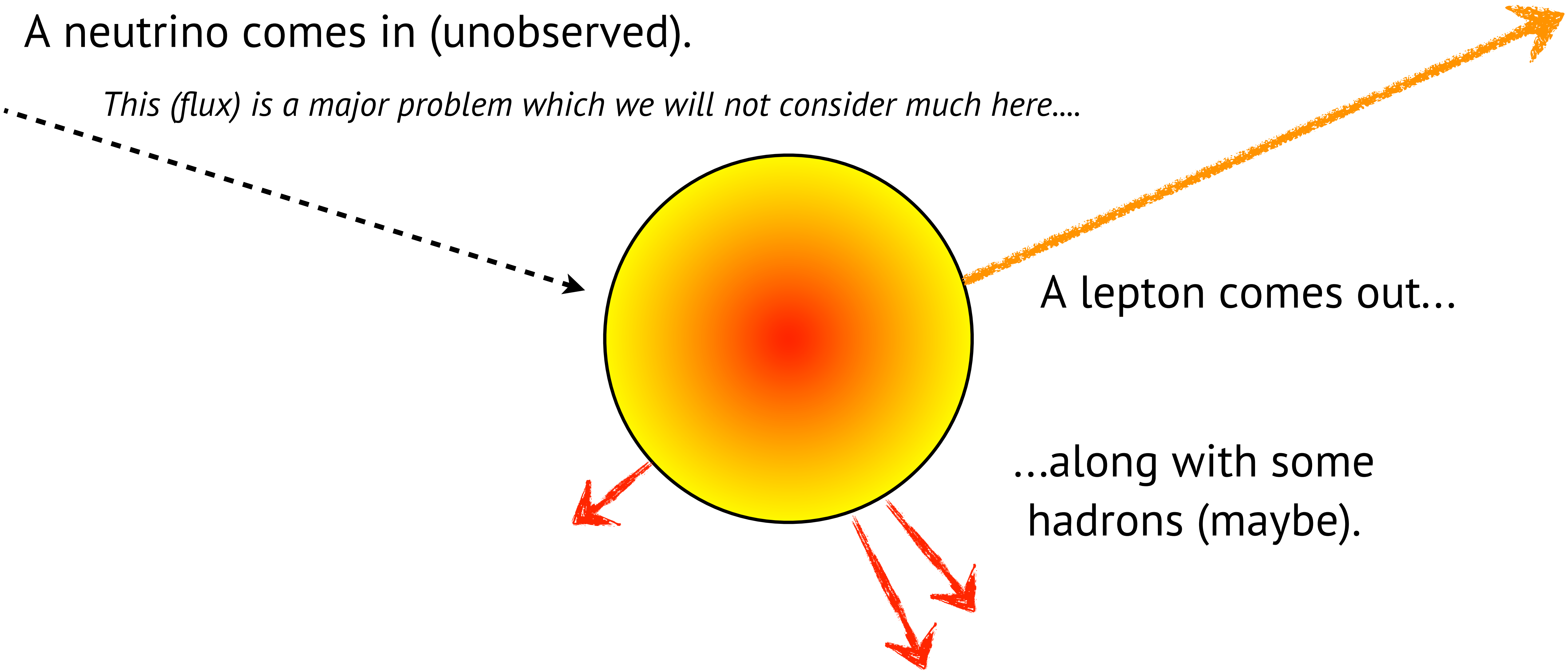
$$x_{Bj} = \frac{Q^2}{2M_T\nu}$$ **Parton Momentum Fraction**



The Basic Problem

A neutrino comes in (unobserved).

This (flux) is a major problem which we will not consider much here....

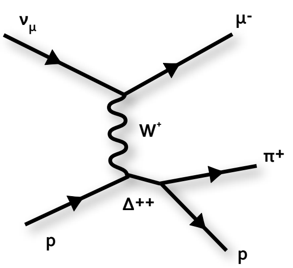


A lepton comes out...

...along with some hadrons (maybe).

What was the neutrino's energy?

We really want flavor too...



Why do we need the energy?

ν_α = Flavor Eigenstates

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

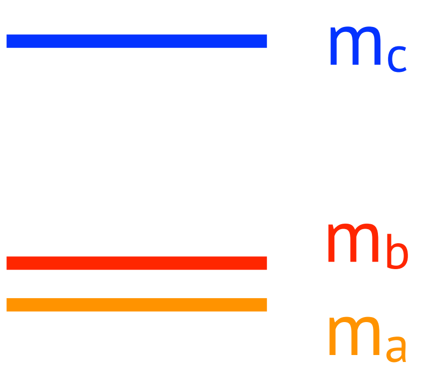
ν_i = Mass Eigenstates

PMNS matrix...

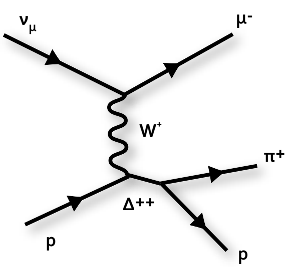
- 3 x 3 Unitary Matrix
  - 3 "Euler Angles", 1 Complex Phase*

$\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}$

- 3 Masses
  - 2 Independent Splittings

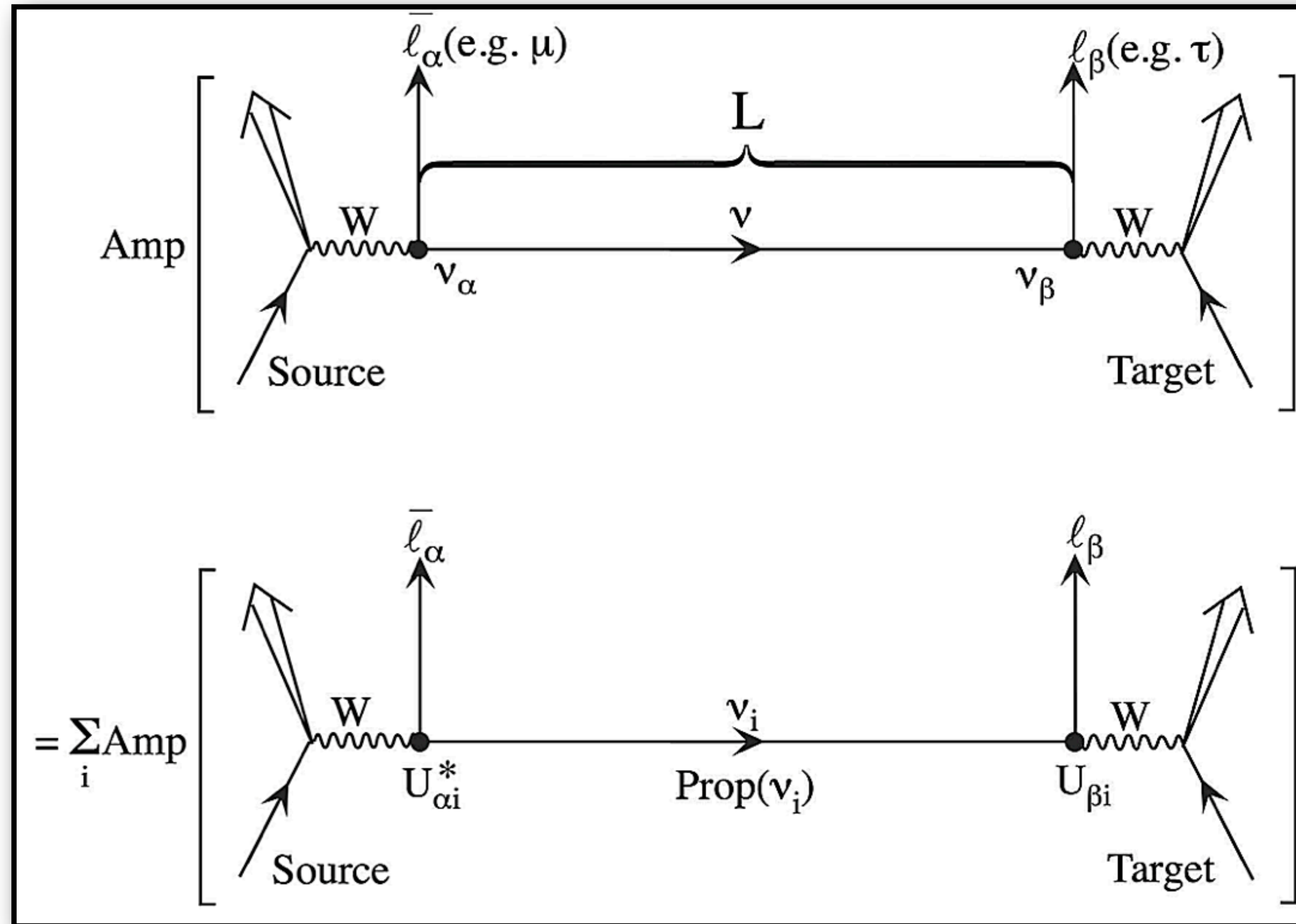


*Plus two Majorana phases - Insanely important!



$$\mathrm{Prop}\left(\nu_j\right) \sim e^{(-i m_j \tau_j)}$$

$$m_1 \neq m_2 \neq m_3$$

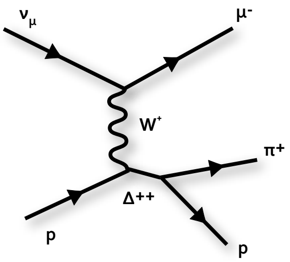


B. Kayser, arXiv 0804.1121

- Flavor eigenstates interact. Flavor states are superpositions of mass states.
  - Different masses ⇒ Different propagators.

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \left|\langle \nu_\beta | \nu\left(L\right)\rangle\right|^2 = \left|\sum_j U^*_{\alpha j} e^{-i m_j^2 \frac{L}{2E}} U_{\beta j}\right|^2$$

  - ⇒ Flavor composition evolves with time.

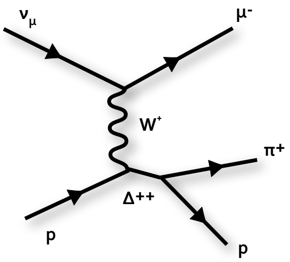


How do we measure PMNS?

$$
\begin{aligned}
P\left(\nu_\mu \to \nu_e\right) &= \left| U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} \right|^2 \\
&= \left| 2 U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2 U^*_{\mu 2} U_{e2} \sin \Delta_{21} \right|^2 \\
&\simeq \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2
\end{aligned}
$$

- We beat these probabilities against each other.
- $\delta \to -\delta$ for antineutrinos.
- Compare neutrinos to antineutrinos to measure CP violation and the mass hierarchy.

$$\Delta_{ij} = 1.27 \Delta m^2_{ij} L/E$$



Probabilities

In MATTER:

$$P_{atm} \sim \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta_{31} - aL)\left(\frac{\Delta_{31}}{\Delta_{31} - aL}\right)^2$$

$$P_{sol} \sim \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(aL)\left(\frac{\Delta_{21}}{aL}\right)$$

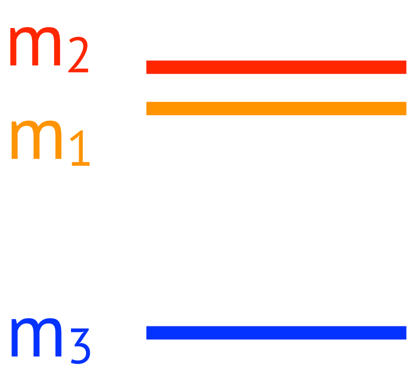
$$a = \pm G_F N_e/\sqrt{2} \sim (4000\ \mathrm{km})^{-1}$$

- The probabilities are a function of the matrix parameters, the mass splittings, and the *neutrino energy!*

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

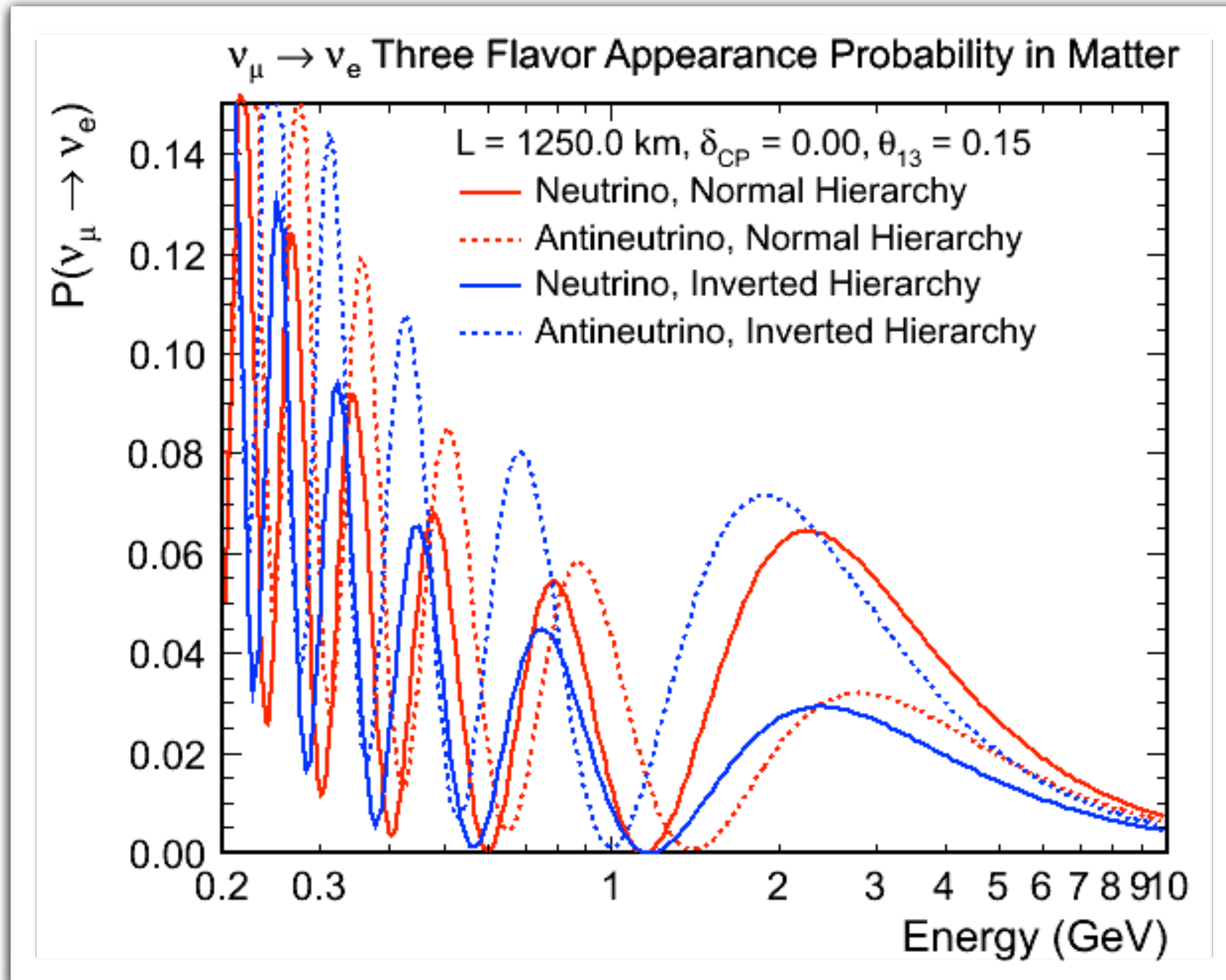
$$P \sim 2\sqrt{P'_{atm}}\sqrt{P'_{sol}}\cos\Delta_{32}\cos\delta_{CP} \mp 2\sqrt{P'_{atm}}\sqrt{P'_{sol}}\sin\Delta_{32}\sin\delta_{CP}$$

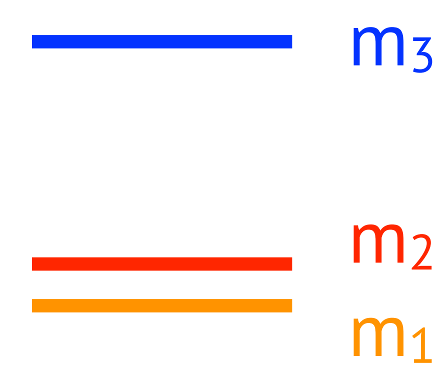
$$\delta_{CP} : 0 \rightarrow 2\pi$$



Inverted

Antineutrino: -δ





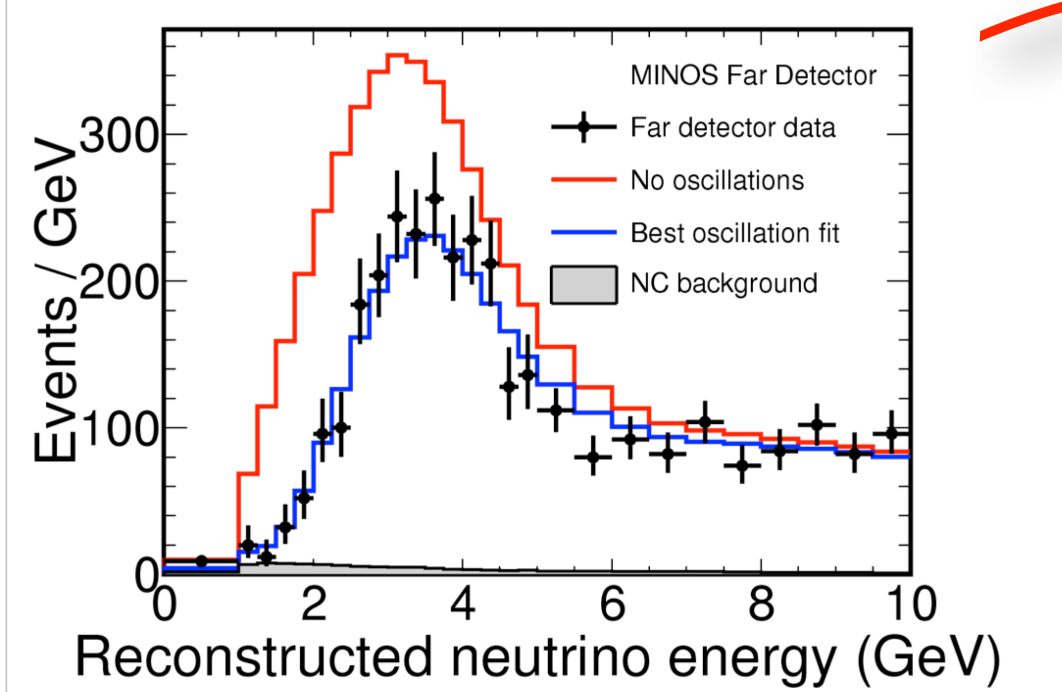
Normal

Neutrino: δ

How do we measure these probabilities?

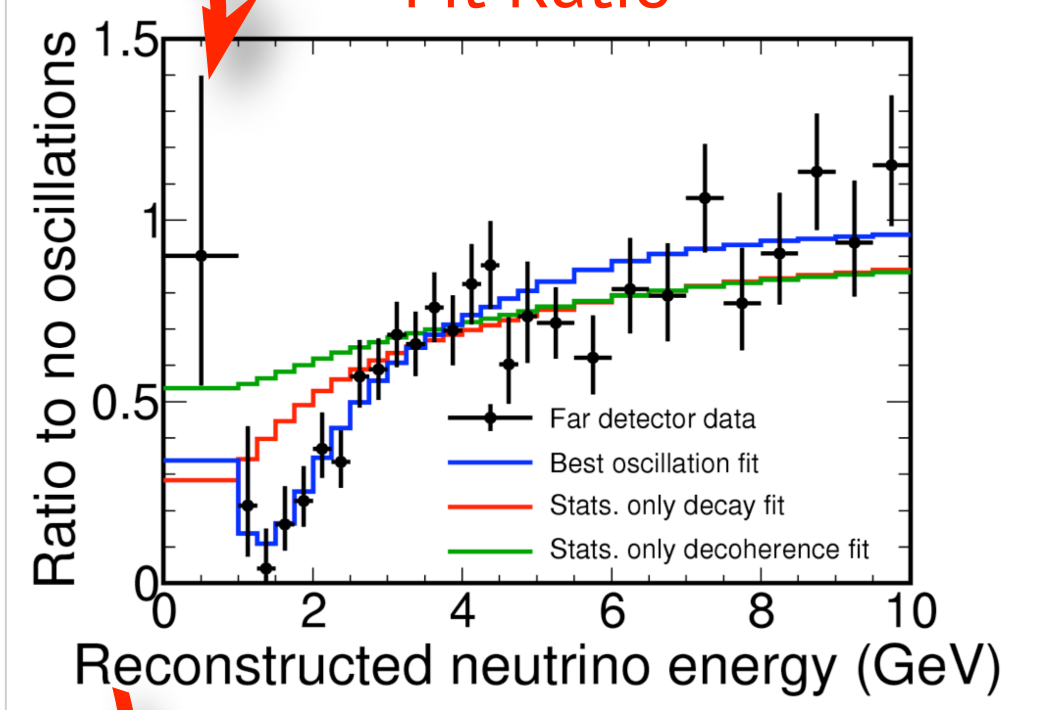
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2 \left[1.27\Delta m^2_{32} (L/E)\right]$$

Measure "Near"/Far

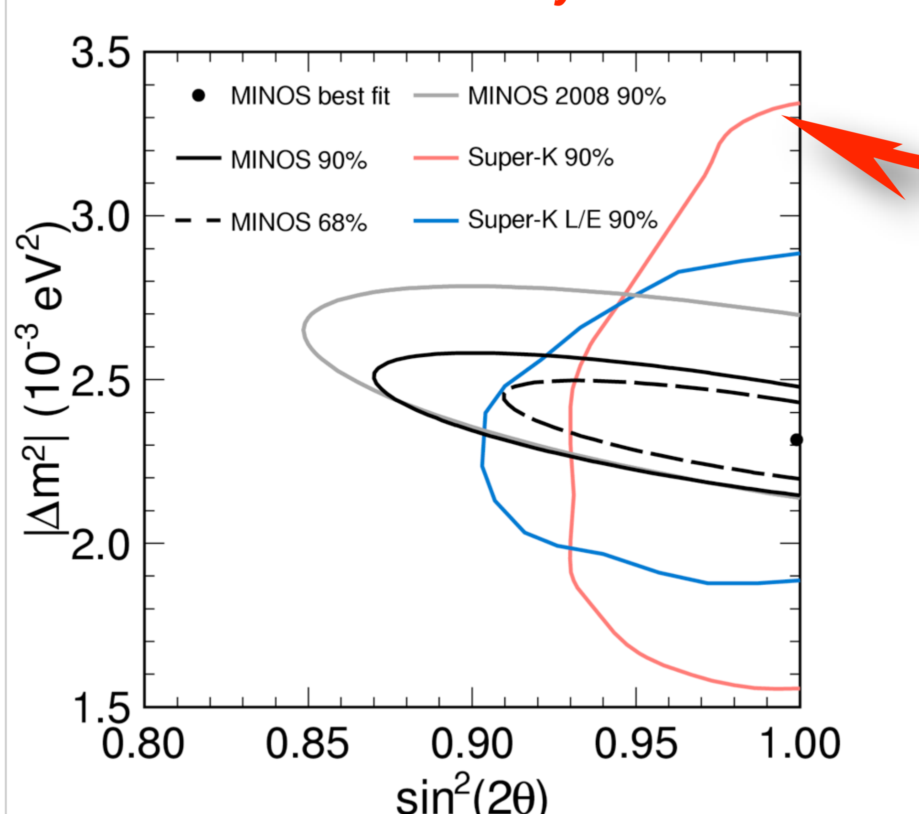


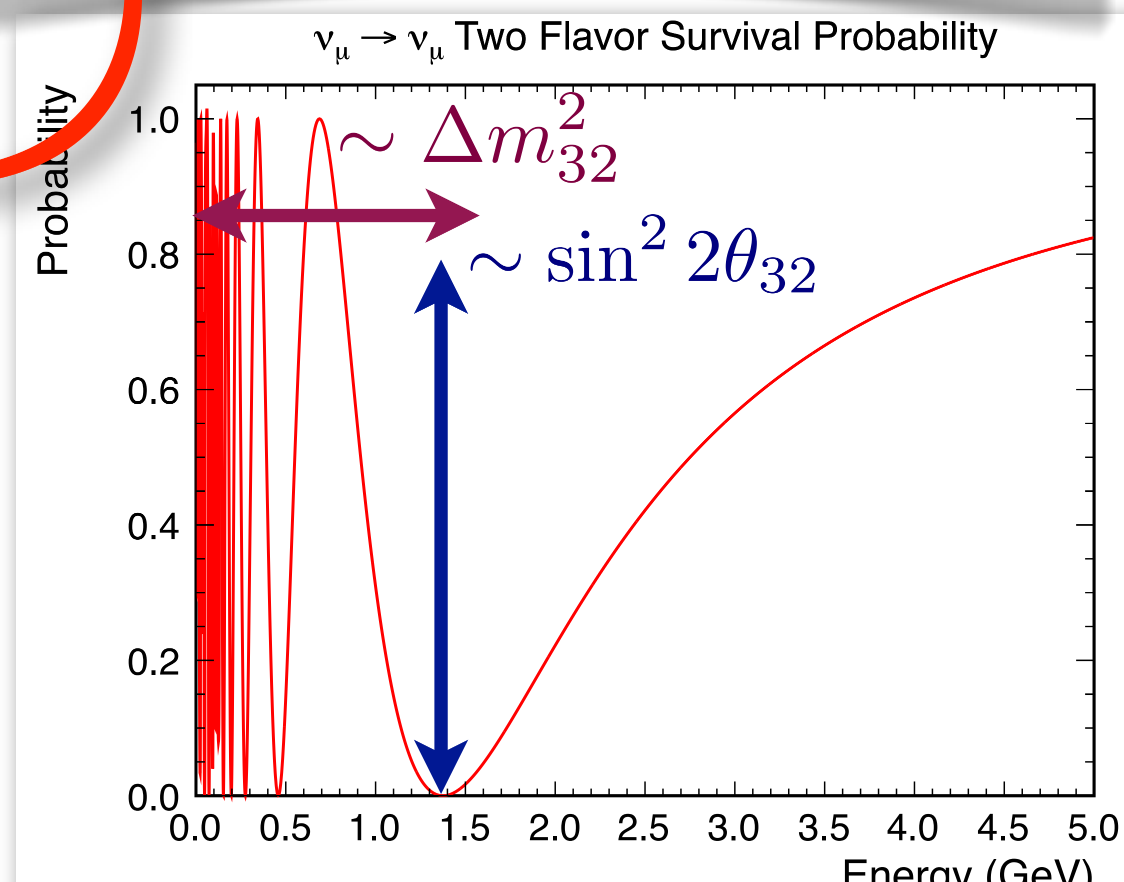
http://www-numi.fnal.gov/PublicInfo/forscientists.html

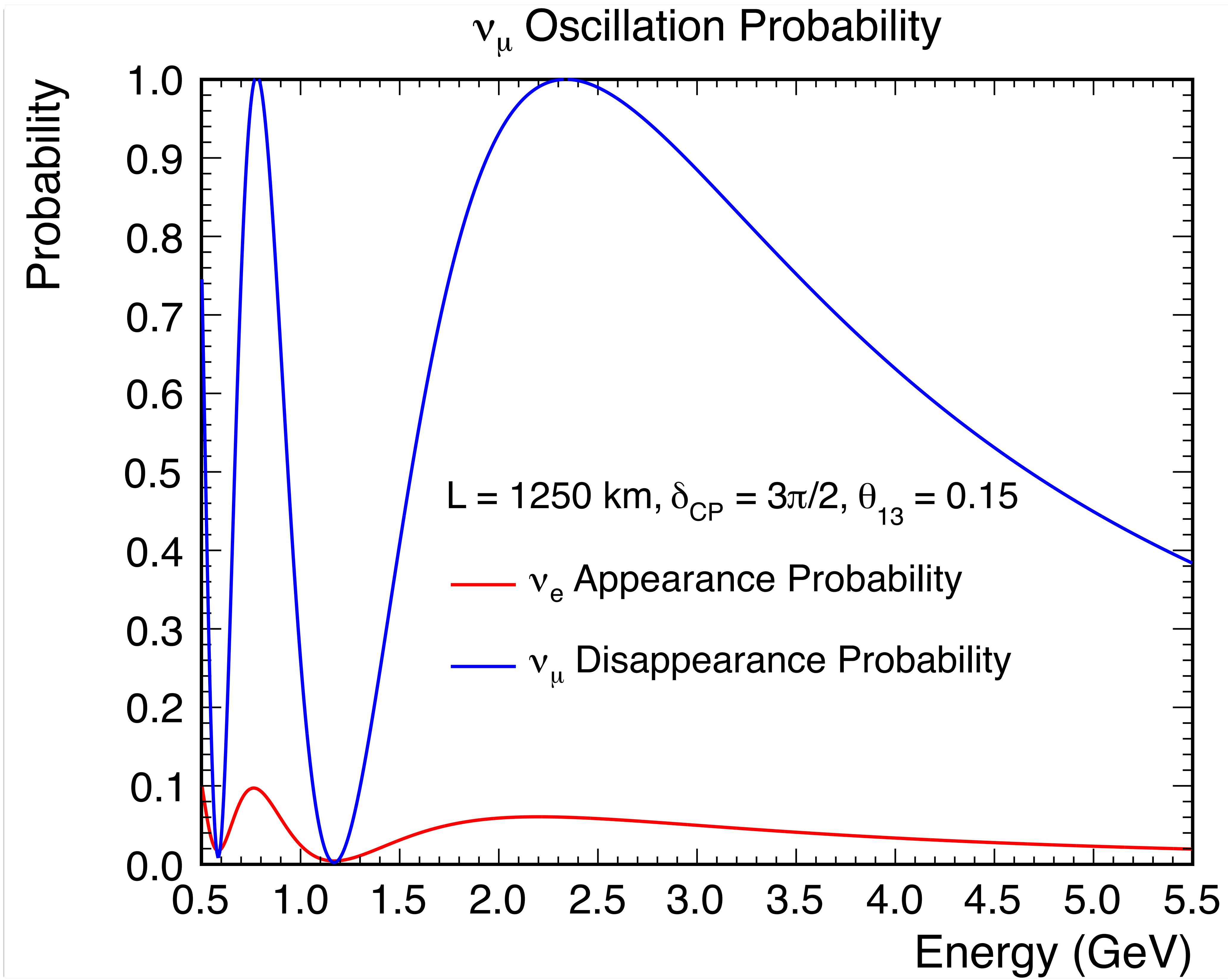
Fit Ratio



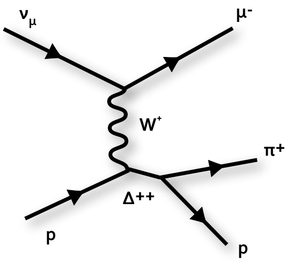
Extract Physics!





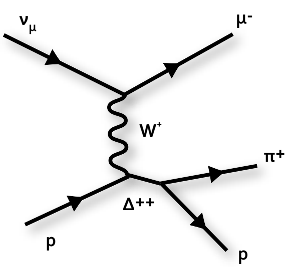


And remember, we need to do it all over again for antineutrinos!



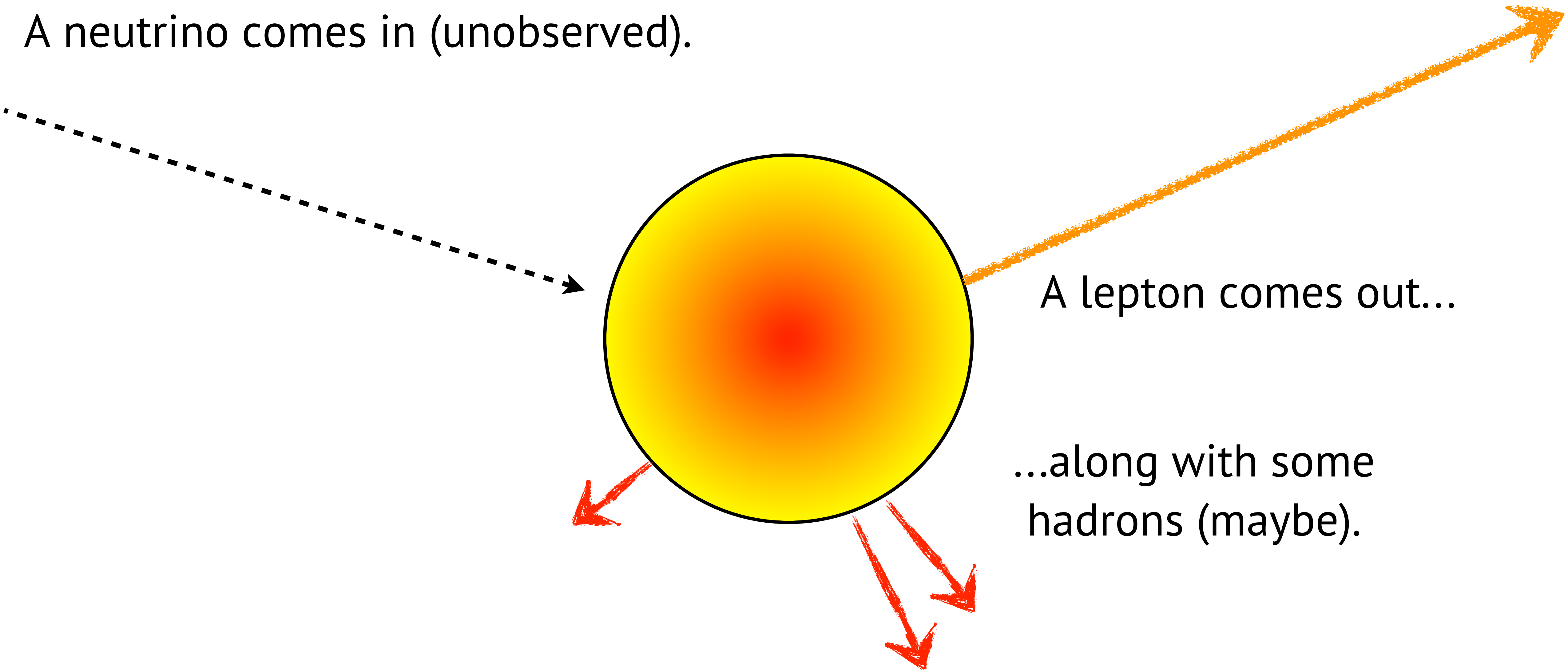
Review

- We need neutrino energy to high precision in our far detector.
- We need neutrino energy in our near detector.
  - These may feature different detector technologies. They *definitely* see different neutrino fluxes.
- We need to understand neutrinos and antineutrinos.
- We're looking for a tiny effect, so "large" systematic uncertainties will destroy the measurement.



Back to our Problem...

A neutrino comes in (unobserved).



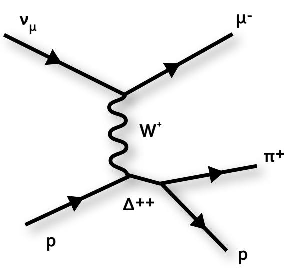
A lepton comes out...

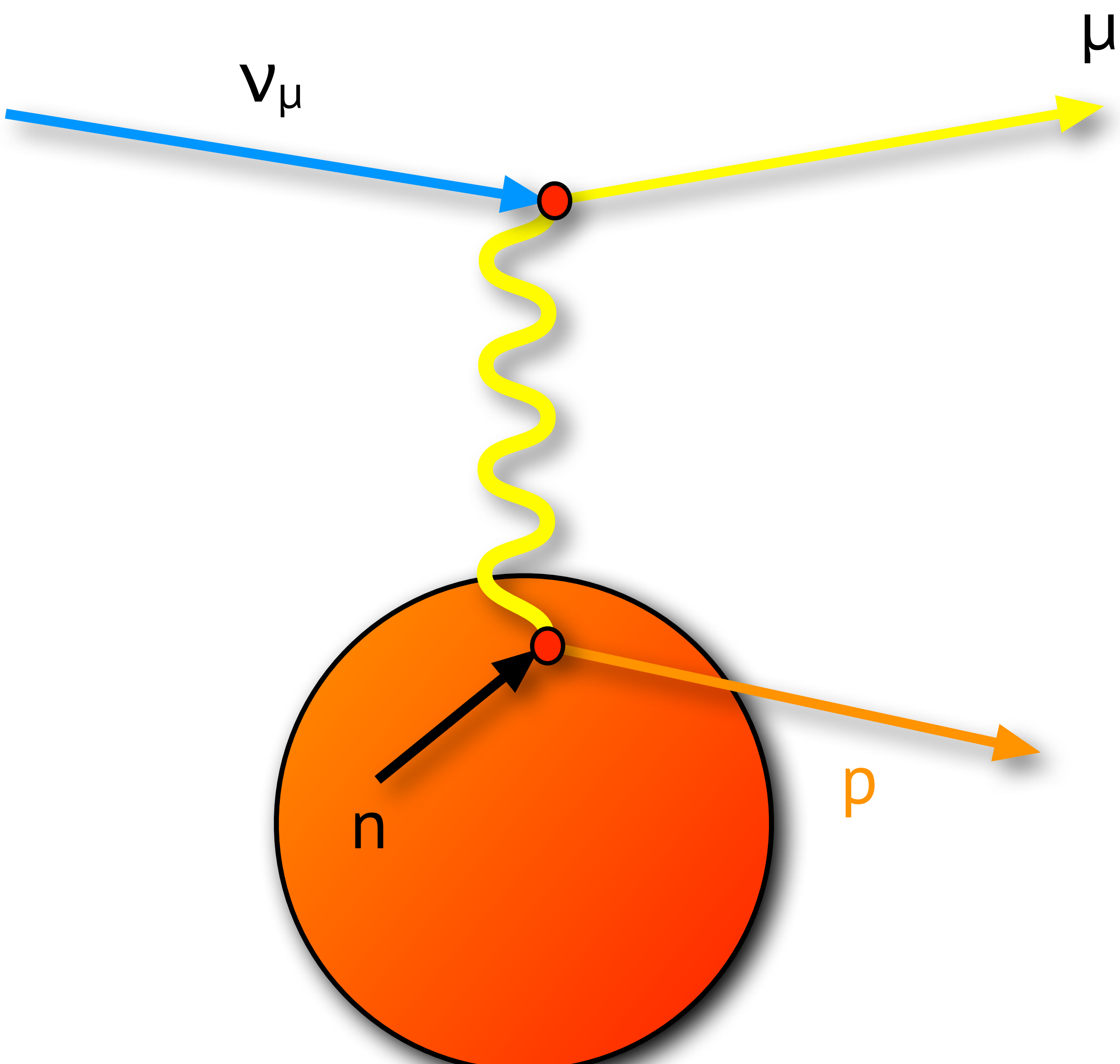
...along with some hadrons (maybe).

What was the neutrino's energy?

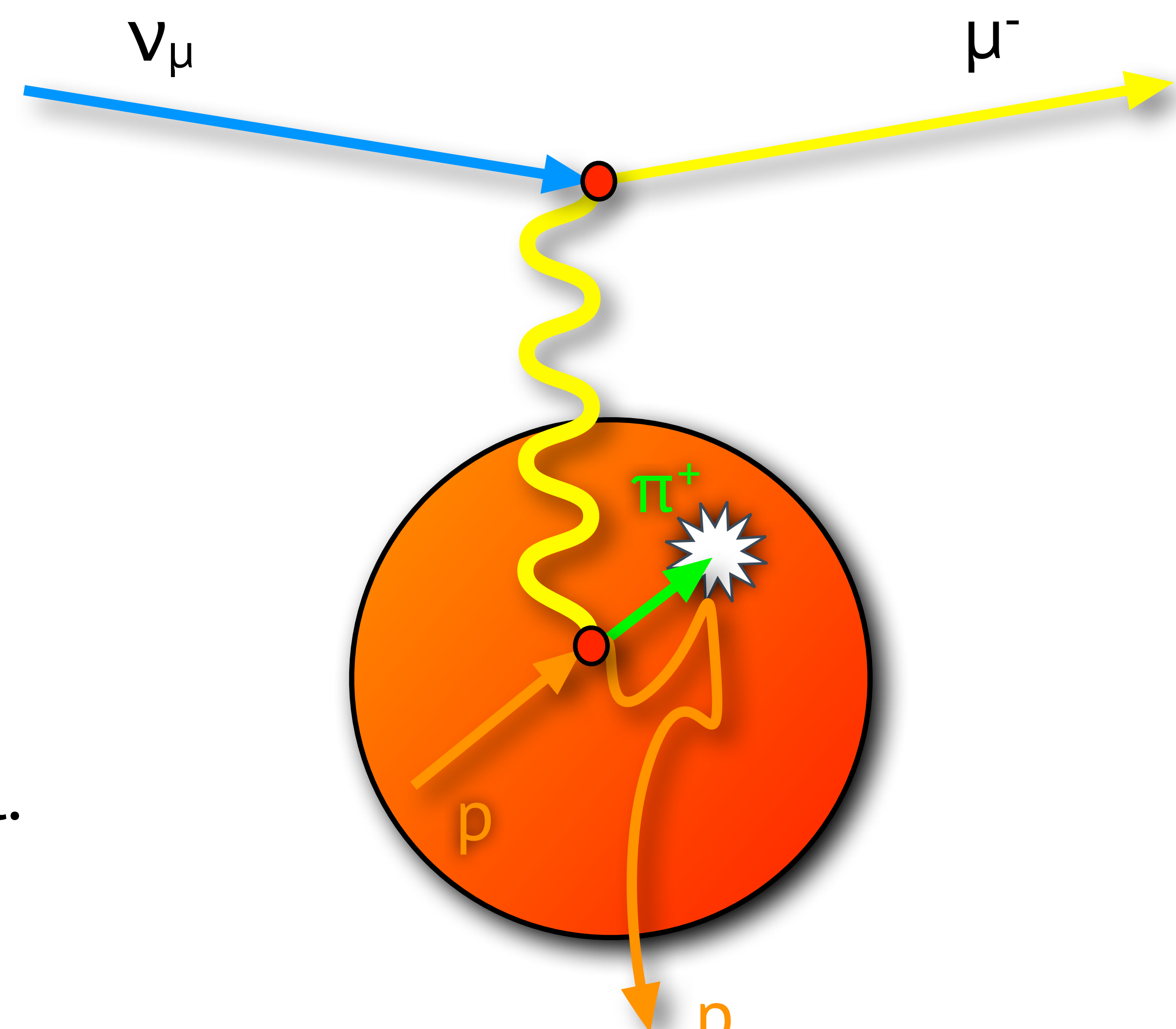
Why not just sum up the energies of all final state particles?

There is a catch...





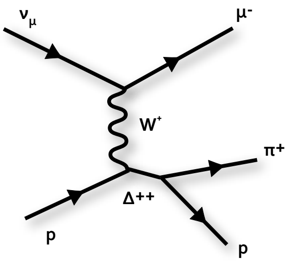
Interactions take place in dense nuclear matter. (Otherwise, your experiment takes 100 years.)



Final State Interactions (FSI) are critical.

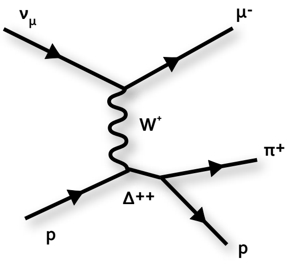
$E_{visible} \neq E_{\nu}$

Not a calibration problem! You need to know, "what are the physics?"



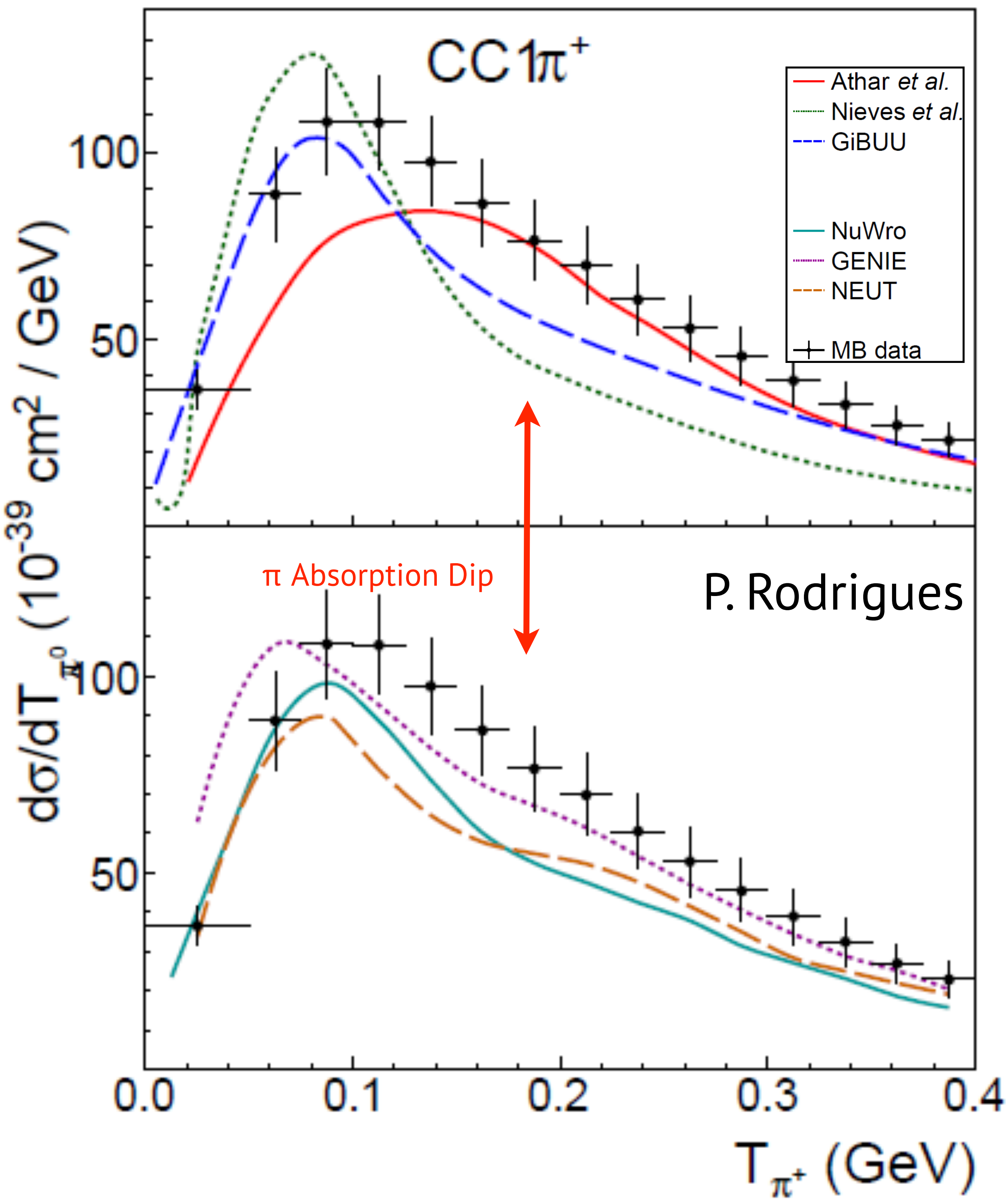
A Note on Jargon

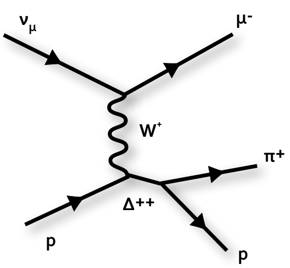
- To some people, "final state interactions" mean interactions with the target that affect the final state (e.g., target structure can change the final state lepton momentum).
- To other people, "final state interactions" mean subsequent interactions of the particles produced at the hard scattering vertex with the nuclear medium, and they are usually referring to hadrons only (leptons are less effected on the way out).
    - Some people are very fired up about using one or the other.
- This situation is confusing and we need to fix it. In this talk I mean the *latter* - interactions in the nuclear medium by particles produced at the vertex after the neutrino interaction.



Final State Interactions (FSI)

- MiniBooNE recently published cross sections for charged current pion production: PRD 83.052007, 2011.
- Event generators and calculations cannot reproduce the pion kinetic energy differential cross section.
- FSI models are responsible for the dip at ~150 MeV.

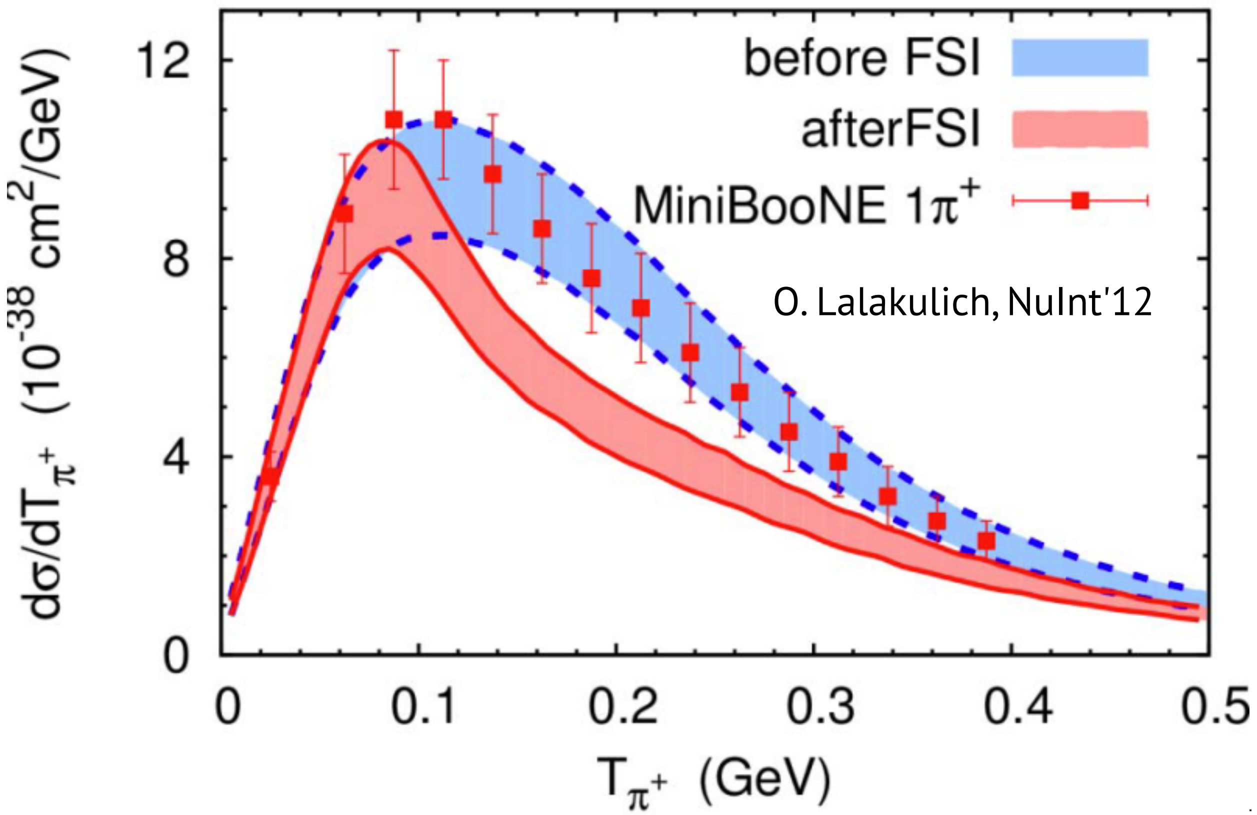


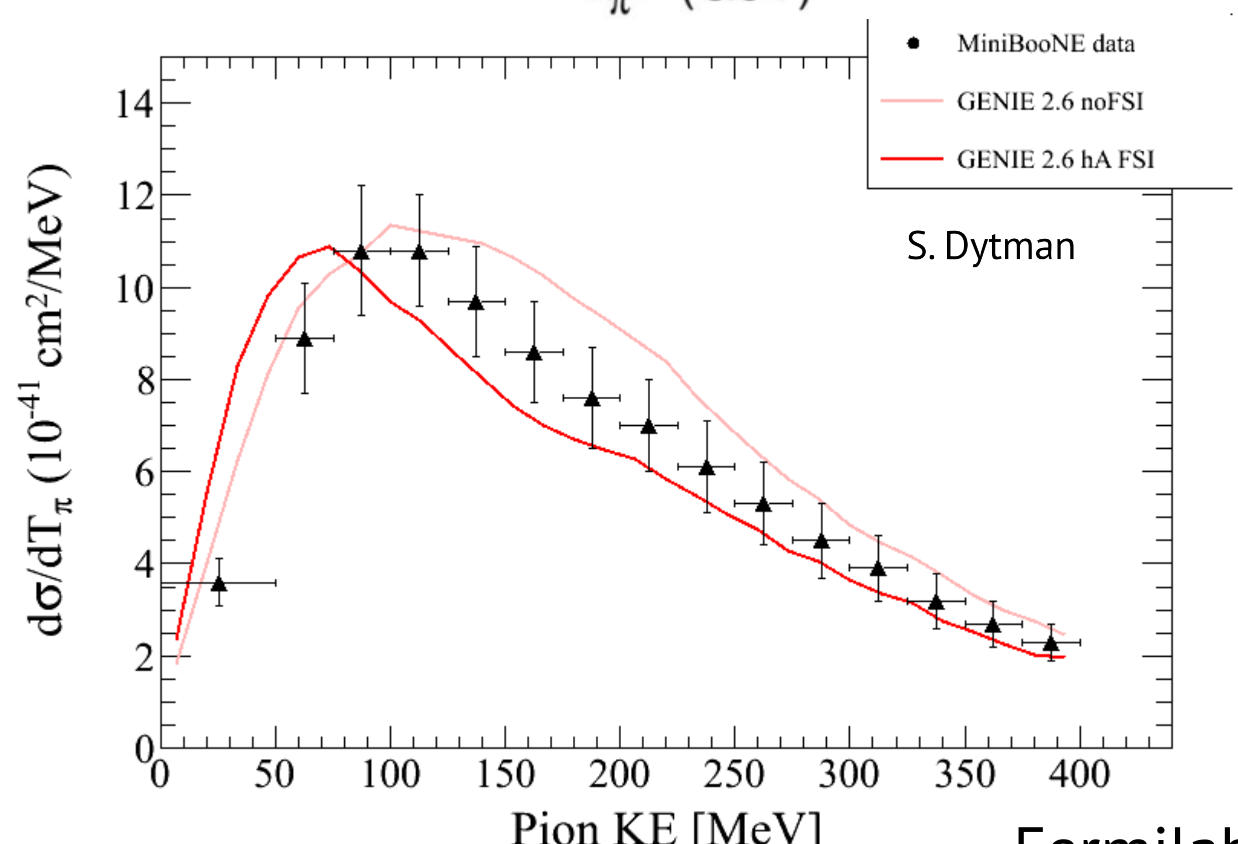


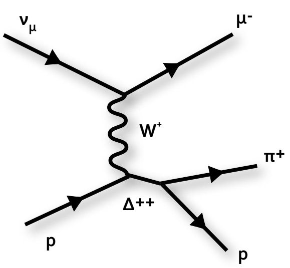
Final State Interactions (FSI)

$$\nu_\mu \mathrm{CH}_2 \to \mu^- \pi^+ \mathrm{X}$$

- Encapsulate our knowledge in "event generator" simulations.
  - MC event generators are critical tools in understanding neutrino interactions with nuclear targets!
- Top (GiBUU model): strong FSI dip. MiniBooNE is consistent with no FSI.
- Bottom (GENIE): weak FSI dip. MiniBooNE is somewhere between no FSI and GENIE's model.
- Conclusion: *Not* that MiniBooNE is "missing" FSI. Rather, *we don't know how to model FSI in our event generators!*





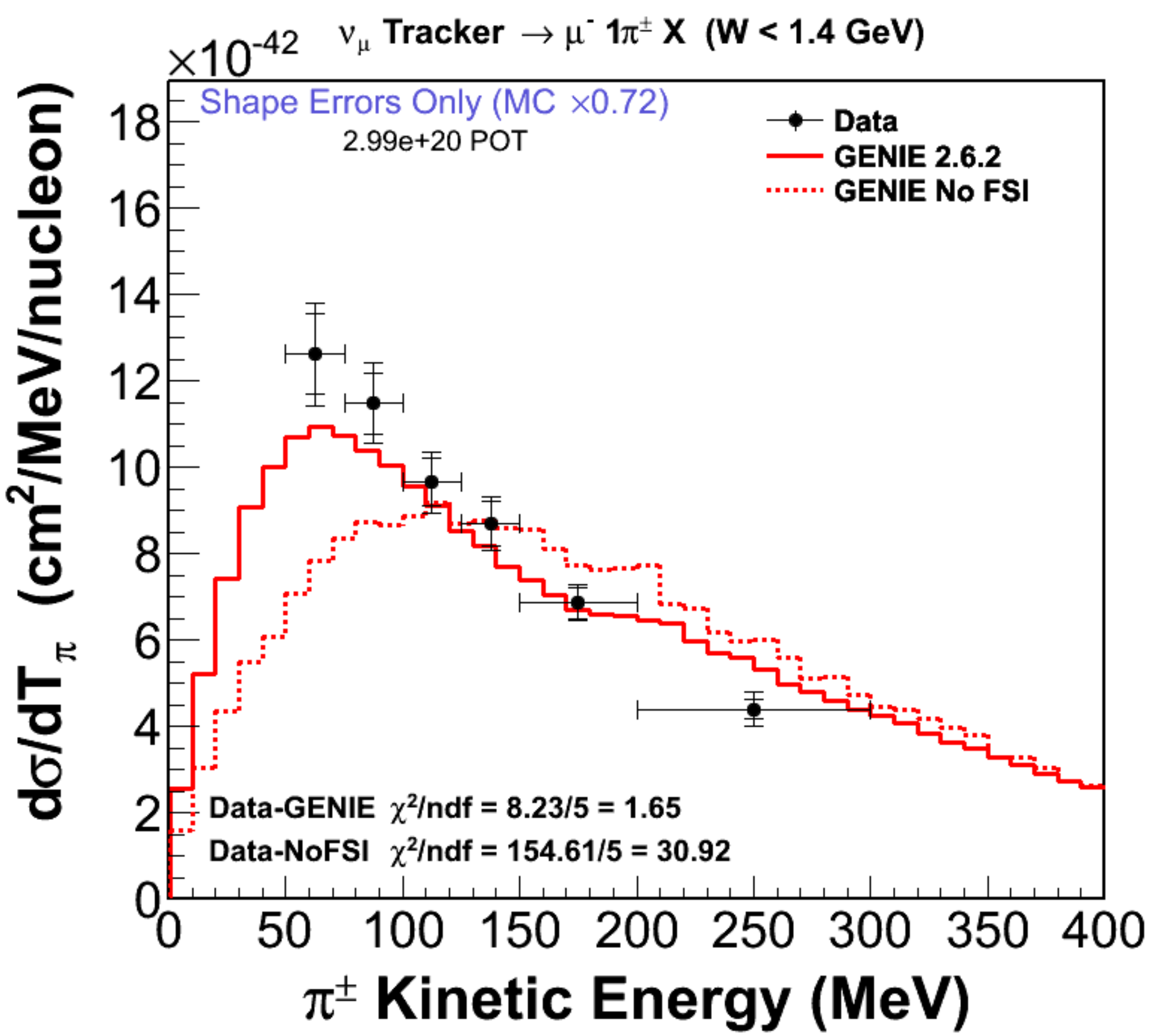


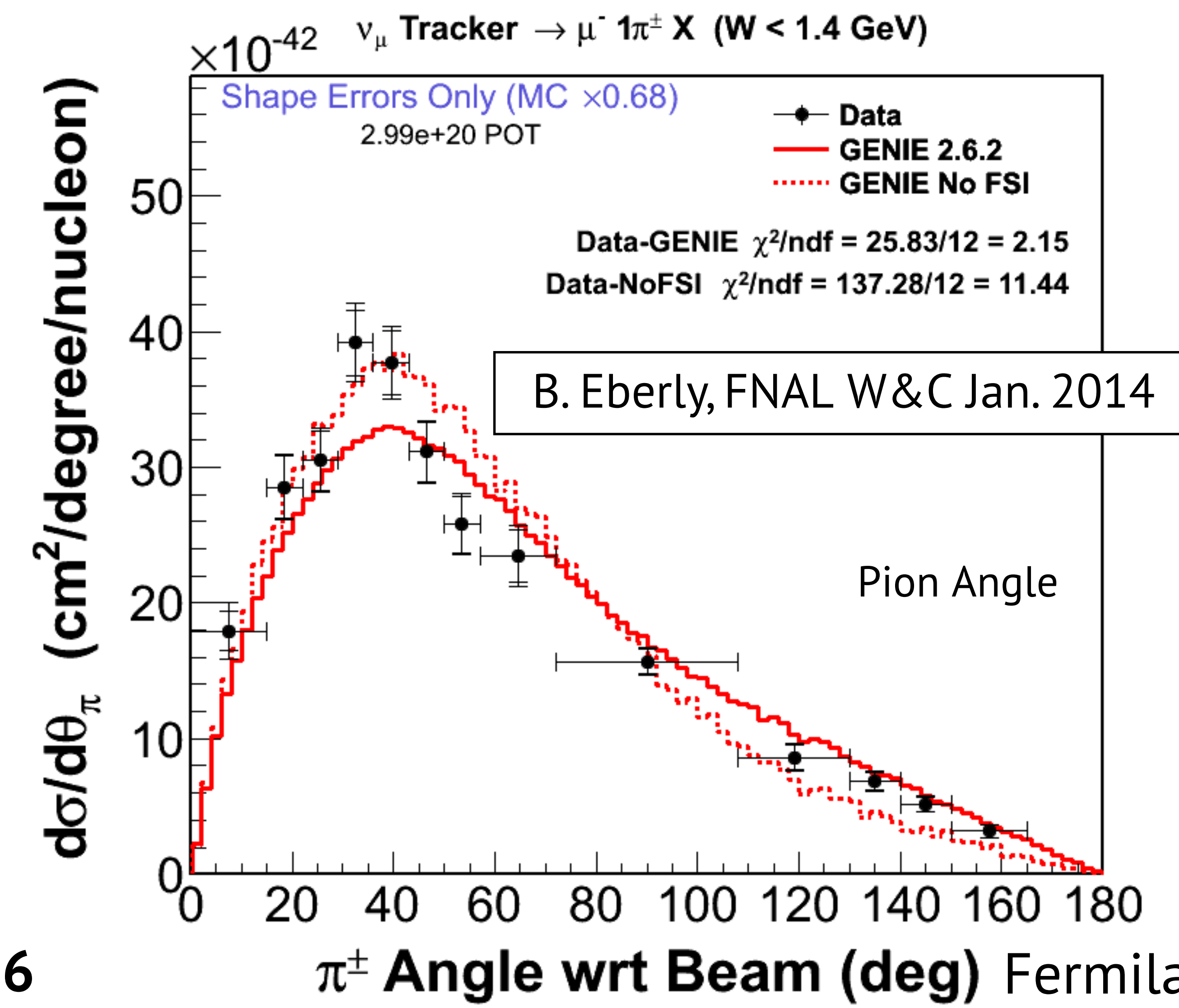
Final State Interactions (FSI)

- Recent MINERvA data prefer (one model of) FSI, but agree with MiniBooNE about the lack of a pion absorption dip.

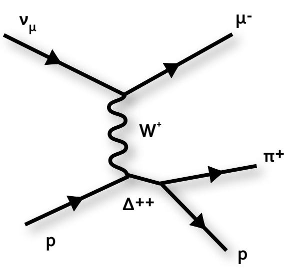
$$\nu_\mu \mathrm{CH} \rightarrow \mu^- \pi^+ \mathrm{X}$$

$$\nu_\mu \mathrm{A} \rightarrow \mu^- \pi^+ \mathrm{A}$$





B. Eberly, FNAL W&C Jan. 2014

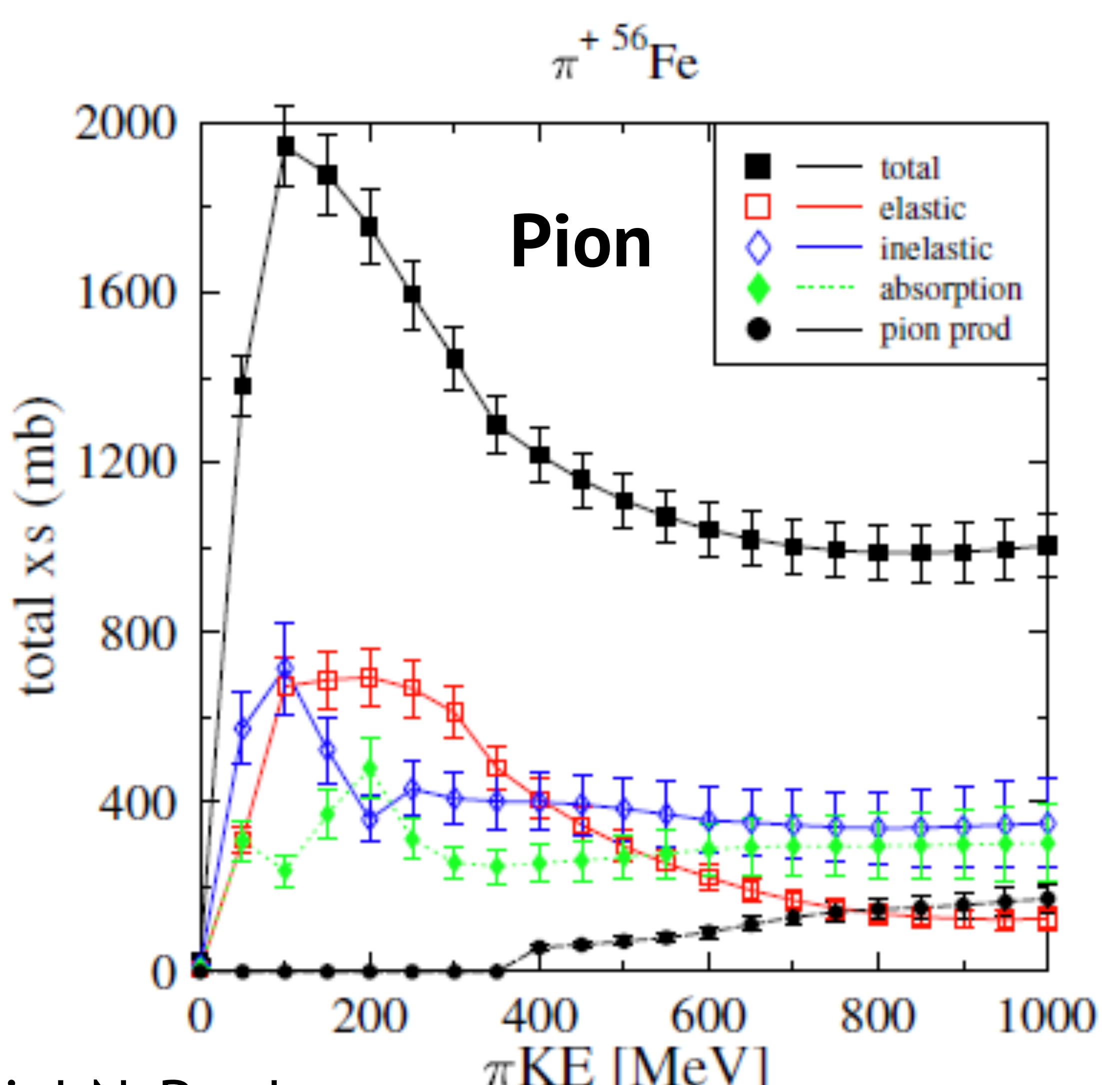


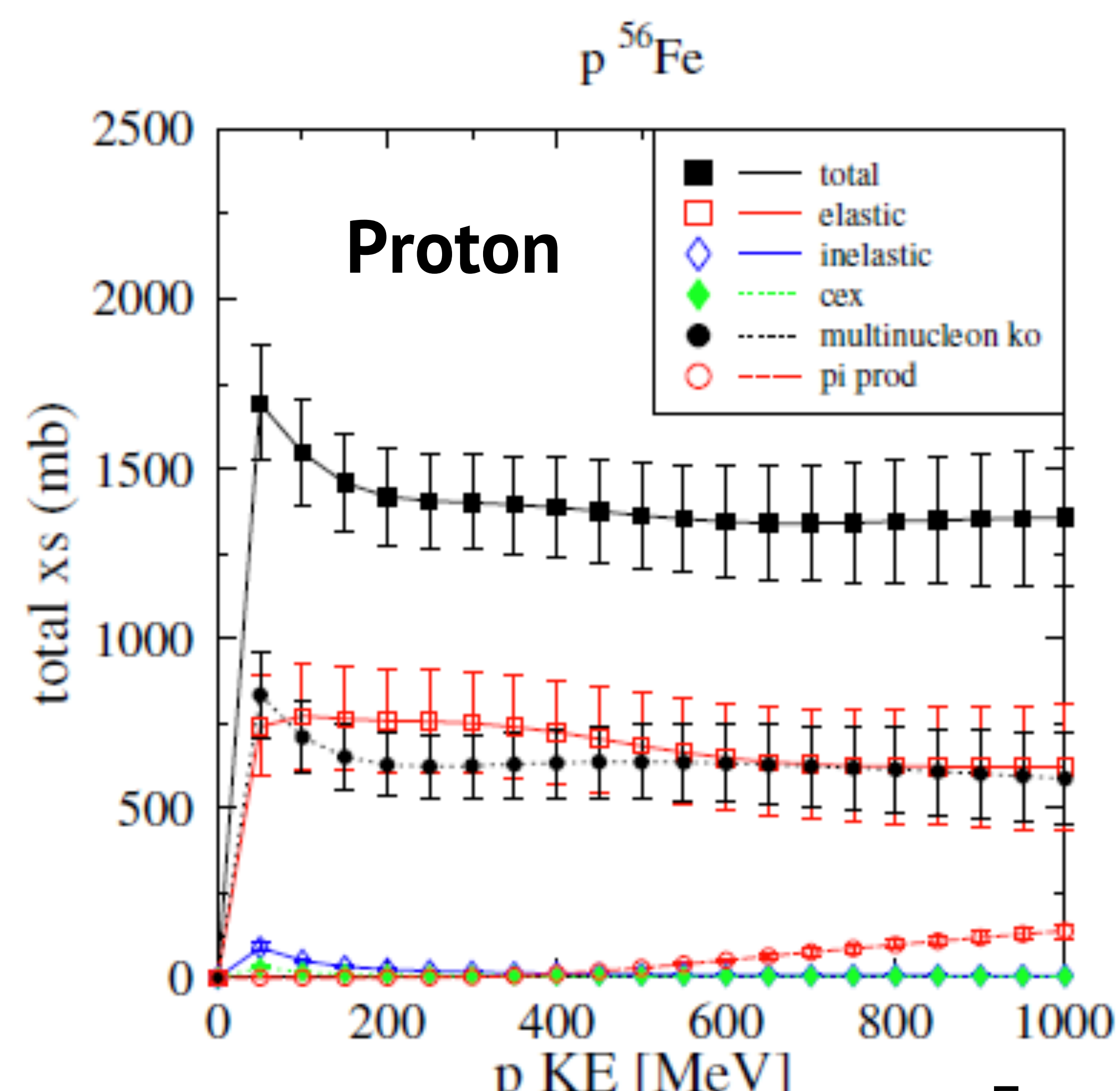
FSI Models

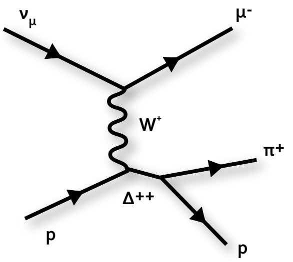
("Experimentalisty" Way)

- GENIE: "hA" (default) - use iron reaction cross section data, isospin symmetry, and $A^{2/3}$ scaling to predict the FSI reaction rates.

- Individual particle energies and angles use data templates or sample from the allowed phase space.



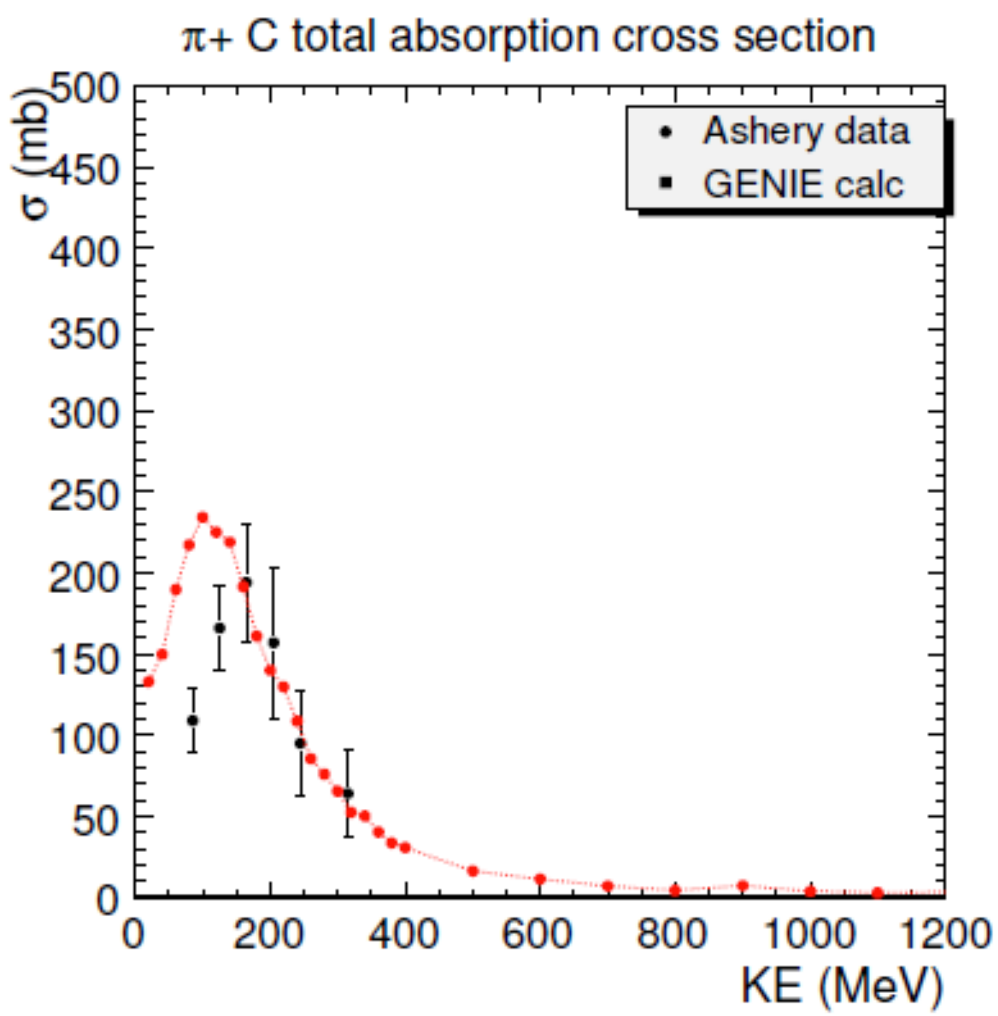




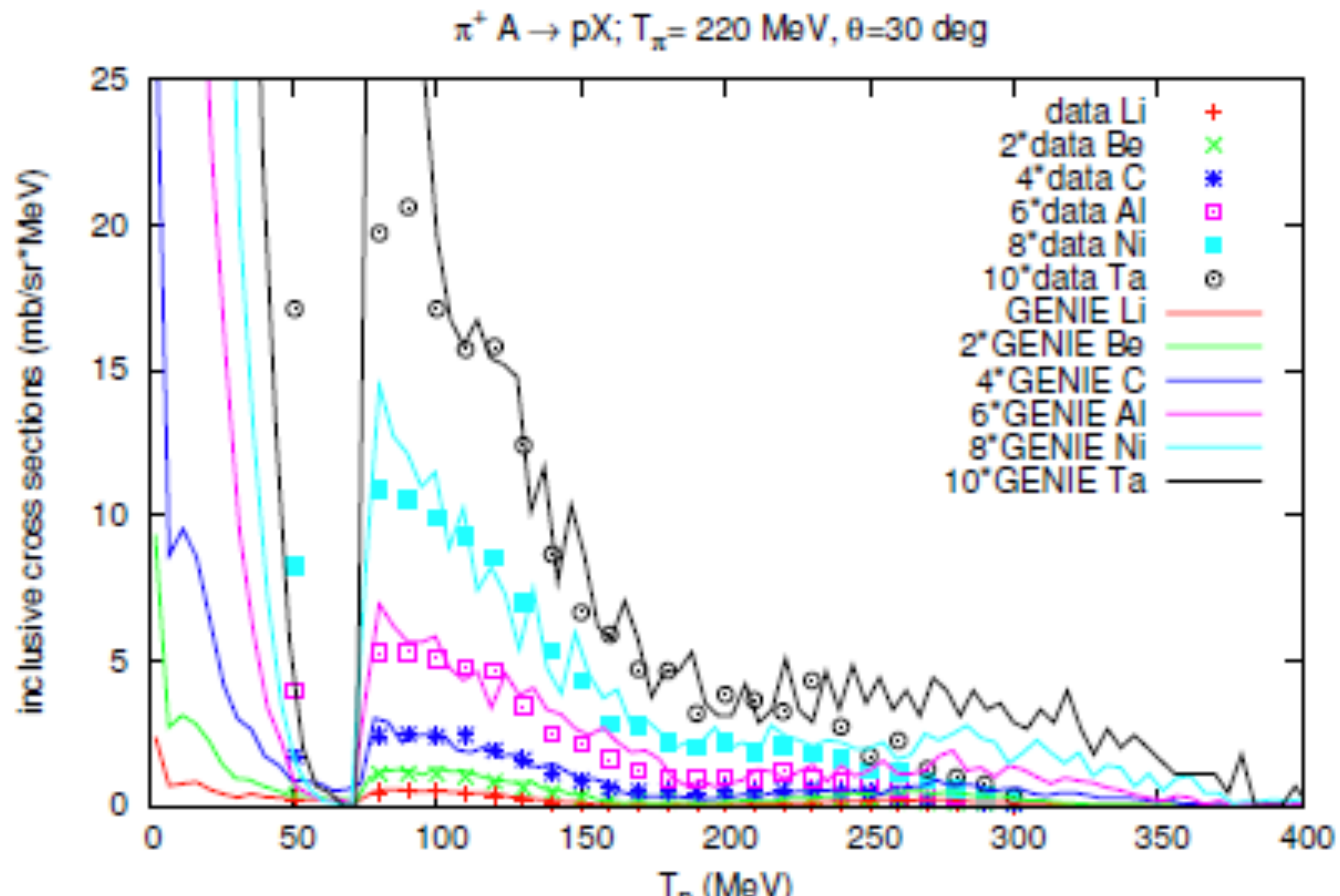
FSI Models

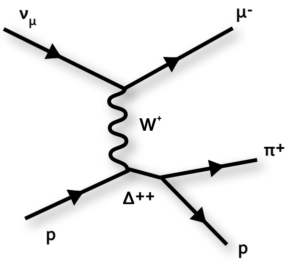
("Experimentalisty" Way)

- GENIE: "hN" - step the final state particles through the nucleus and simulate a cascade using angular distributions as a function of energy.



Pion + A to proton + X for a pion energy & angle



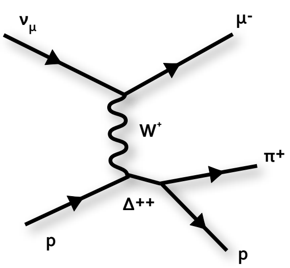


FSI Models

("Theoristy" Way)

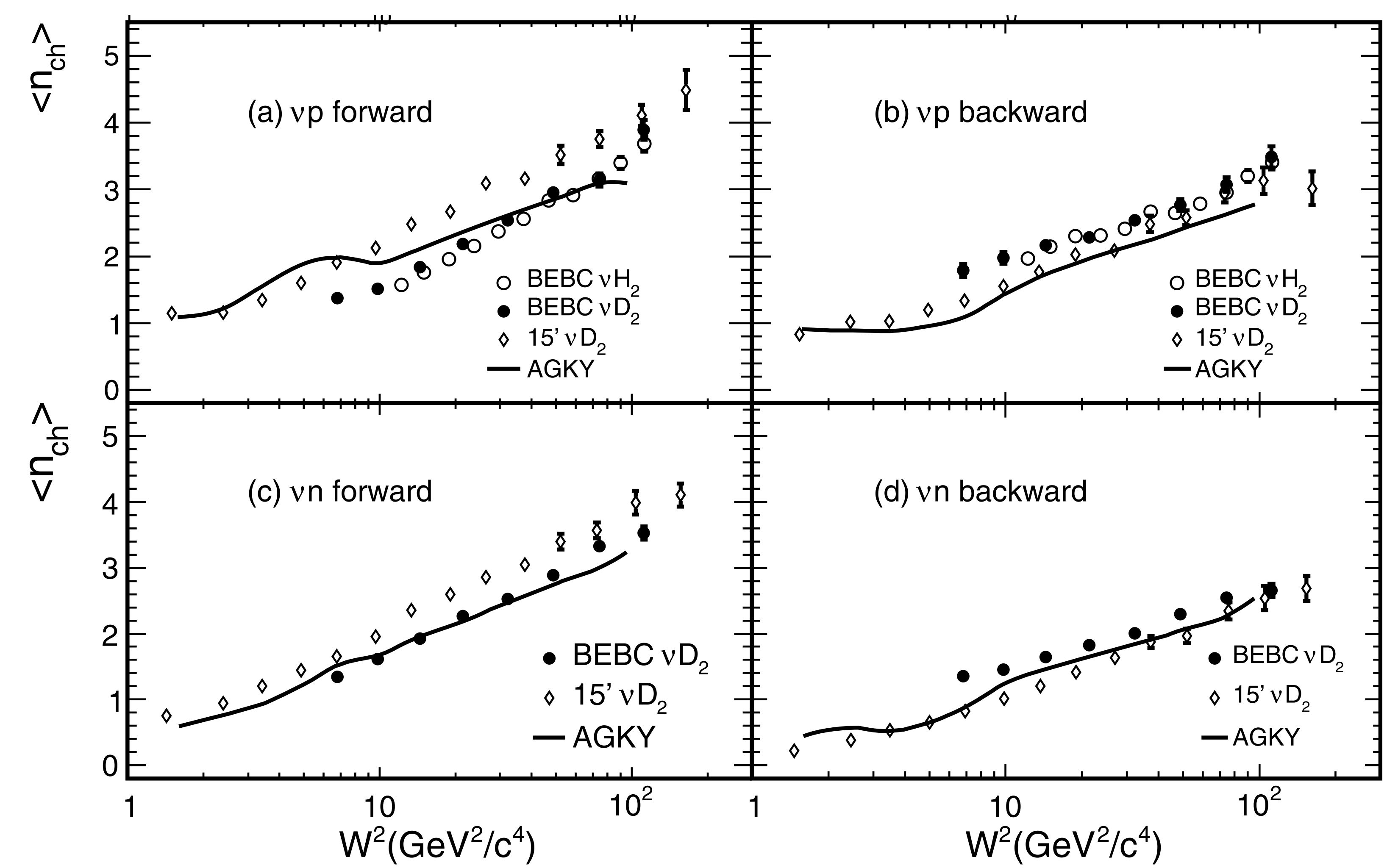
- GiBUU (Giessen Boltzman-Urling-Uhlenbeck)
- General tool for numerical simulations of nuclear reactions. A purely hadronic model (no partonic phase and no lepton transport).
- Based on the BUU equation: propagation and collisions (decays and scattering) of particles in a relativistic mean field.
    - Semiclassical system of coupled equations describing the space-time evolution of the phase-space density. Simulation is a numerical solution to the equation.
- Fundamentally different approach than cascade models.

https://gibuu.hepforge.org/



Modeling Nuclear Effects

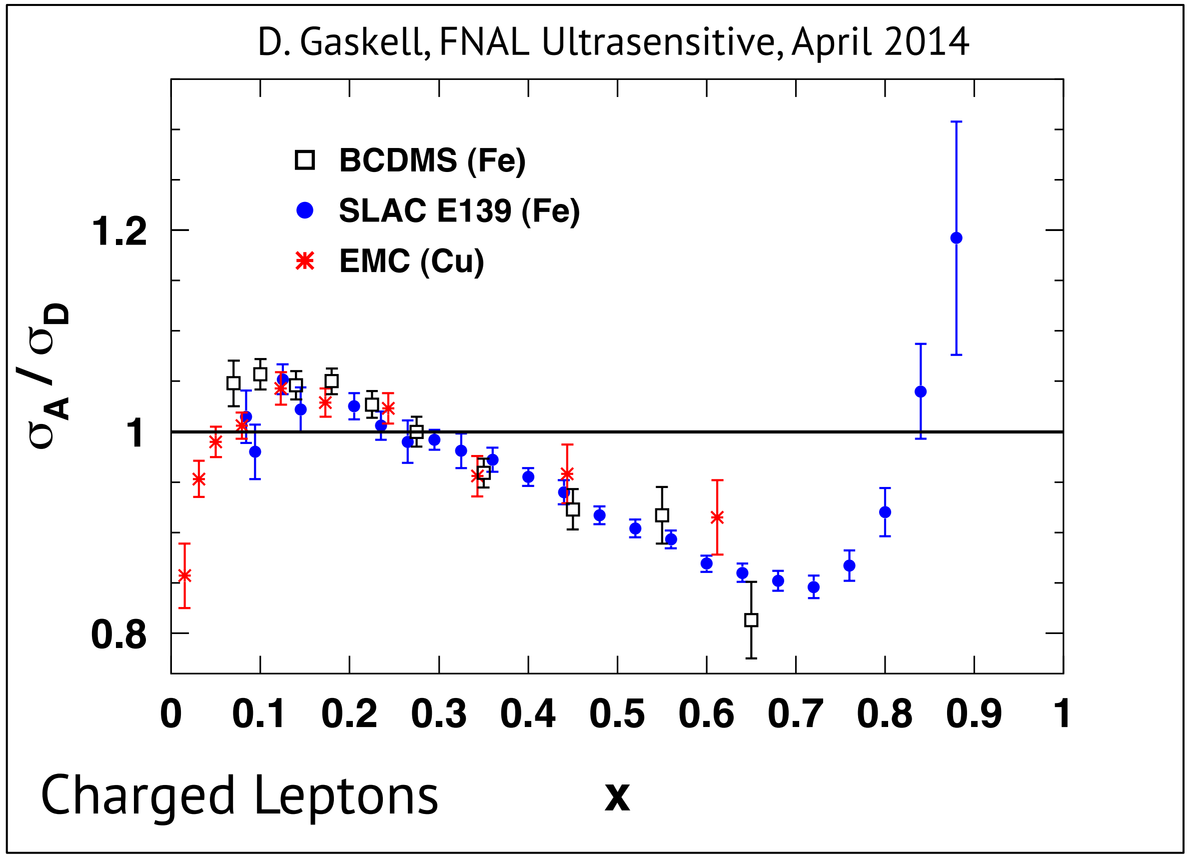
- What about hadronization in the nuclear medium? (What about hadronization anywhere? Especially at low energy!)
- GENIE (for example) does reasonably well, but the validation uses deuterium or hydrogen - little influence from nuclear effects.



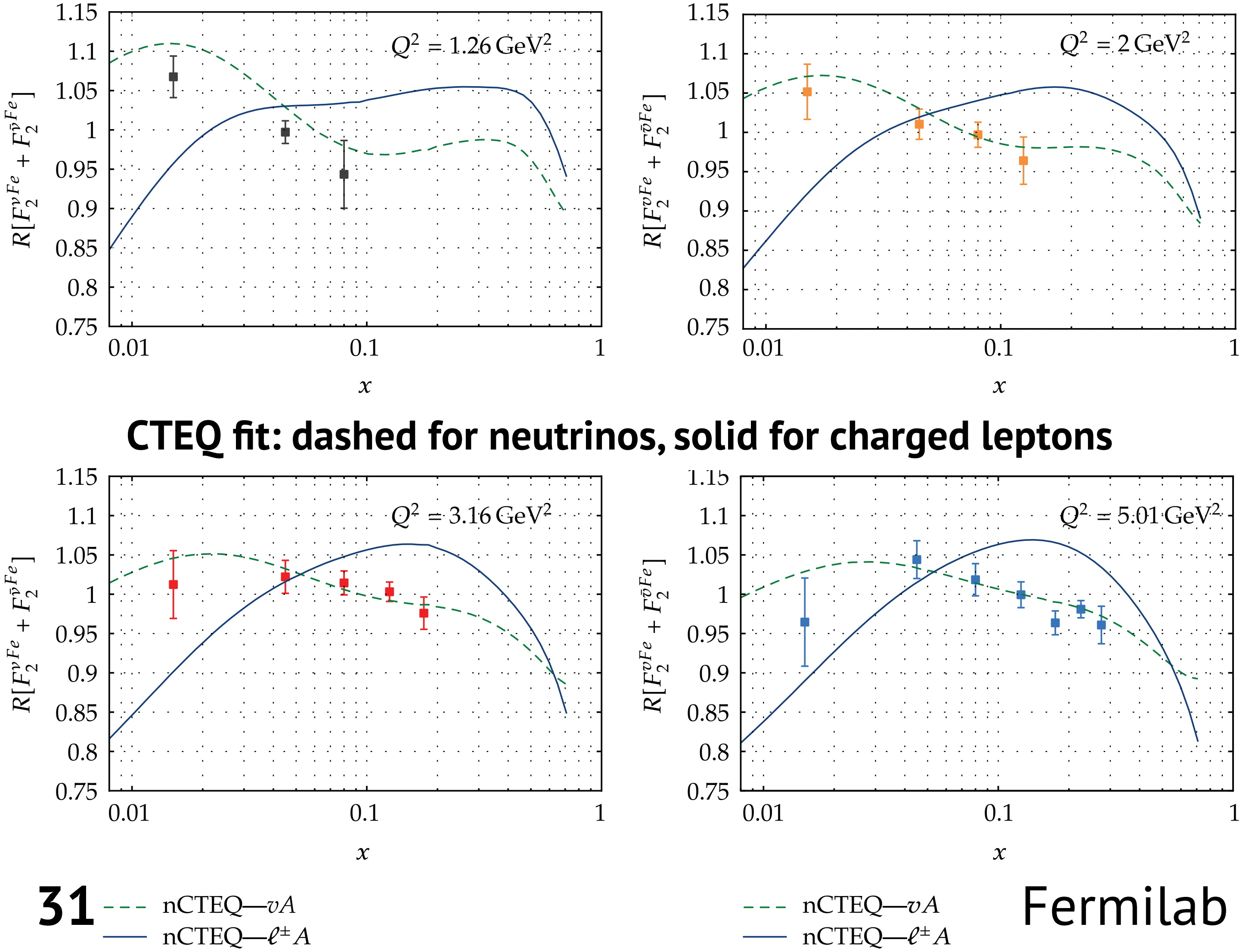
T. Yang et al, Eur. Phys. J C (2009) 63:1-10

Nuclear Effects in Neutrino Scattering

- Quark distributions are modified in nuclei. (See D. Gaskell from this lecture series, last week.)
- Analogous data is lacking for neutrinos (the neutrino ratios use data on iron, but must calculate the denominator).
- Neutrinos see an additional structure function in the nucleus and so provide an important probe of nuclear physics.

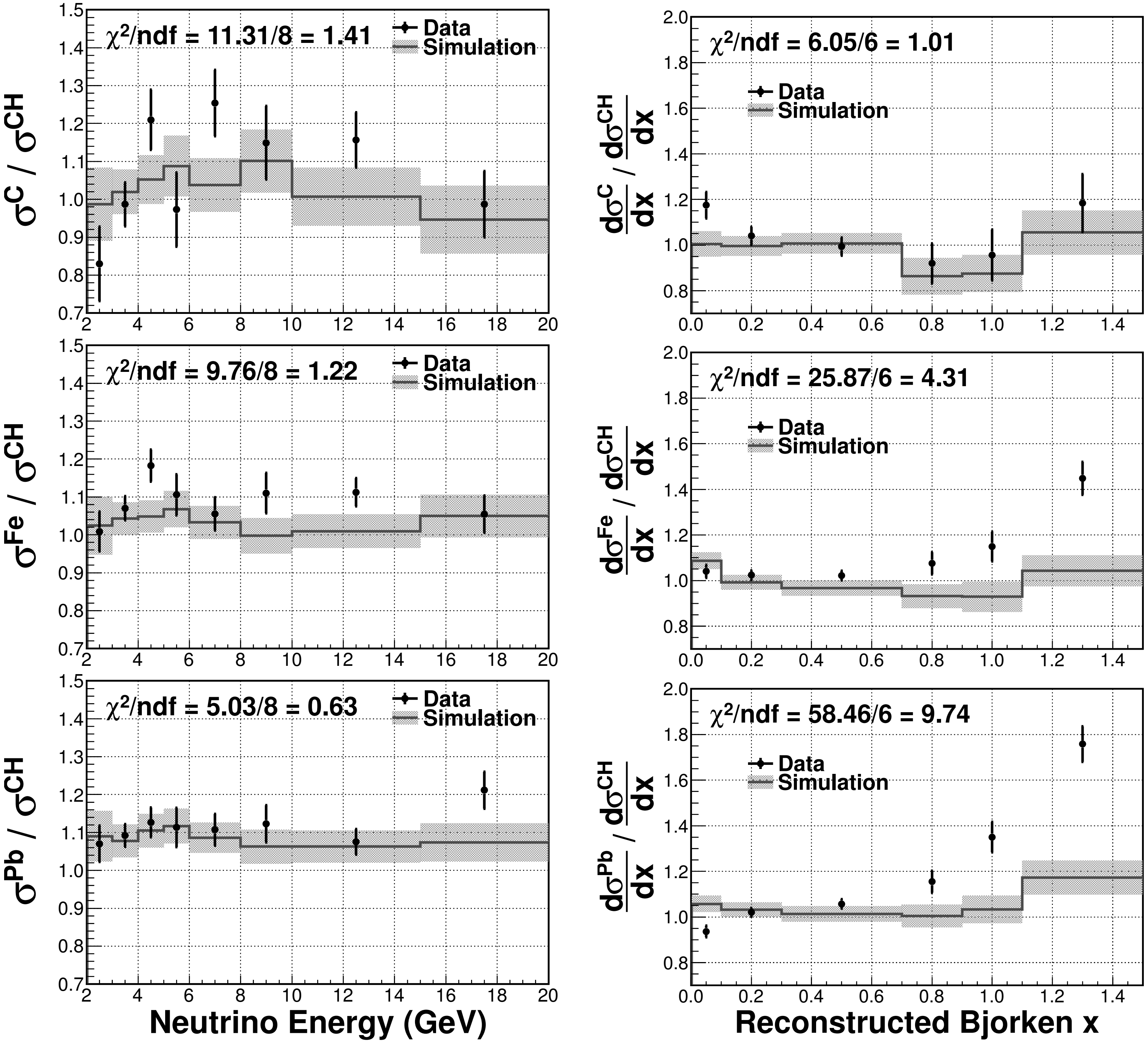


Morfin et al, Adv. in High Energy Phys. 2012, 934597



Nuclear Effects in Neutrino Scattering

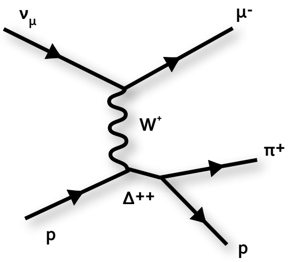
http://arxiv.org/abs/1403.2103



(Bjorken x is reconstructed, not "unfolded.")

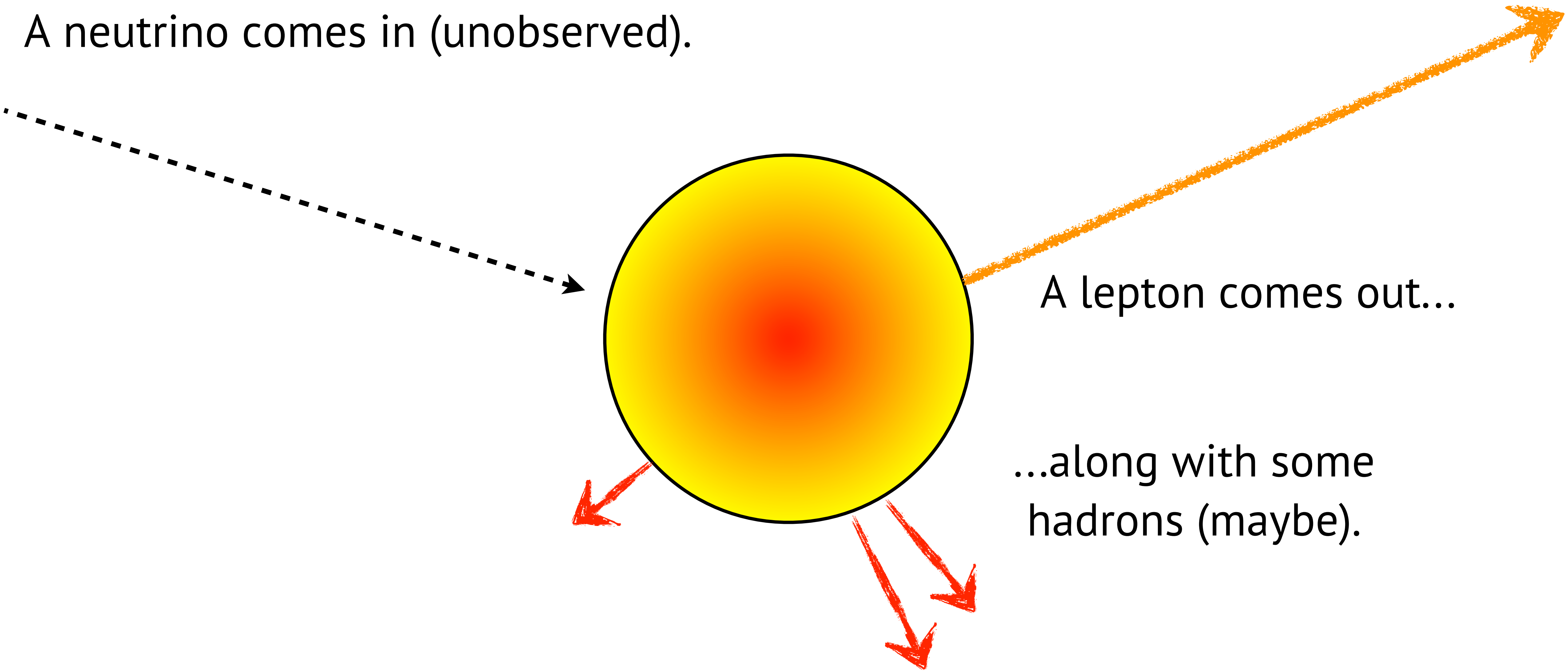
- Recent cross section ratio results from MINERvA, looking at the same detector in the same beam, suggest that nuclear effects are sizable and not well-modeled.
- The total cross section ratios (as a function of neutrino energy) show reasonable agreement with the predictions from MC event generators, but x-dependent effects are not reproduced.
- This is not simply a problem with GENIE - comparisons to other theory models (Kulagin-Petti, Bodek-Yang) show similar discrepancies.

S. A. Kulagin and R. Petti, Nucl. Phys. A 765, 126 (2006)
S. A. Kulagin and R. Petti, Phys. Rev. D 76, 094023 (2007)
A. Bodek, U. K. Yang arXiv:1011.6592 (2013)



Back to our Problem...

A neutrino comes in (unobserved).

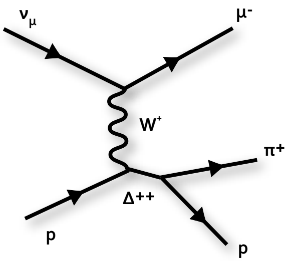


A lepton comes out...

...along with some hadrons (maybe).

What was the neutrino's energy?

Okay, can we instead infer something from the kinematics of the final state?



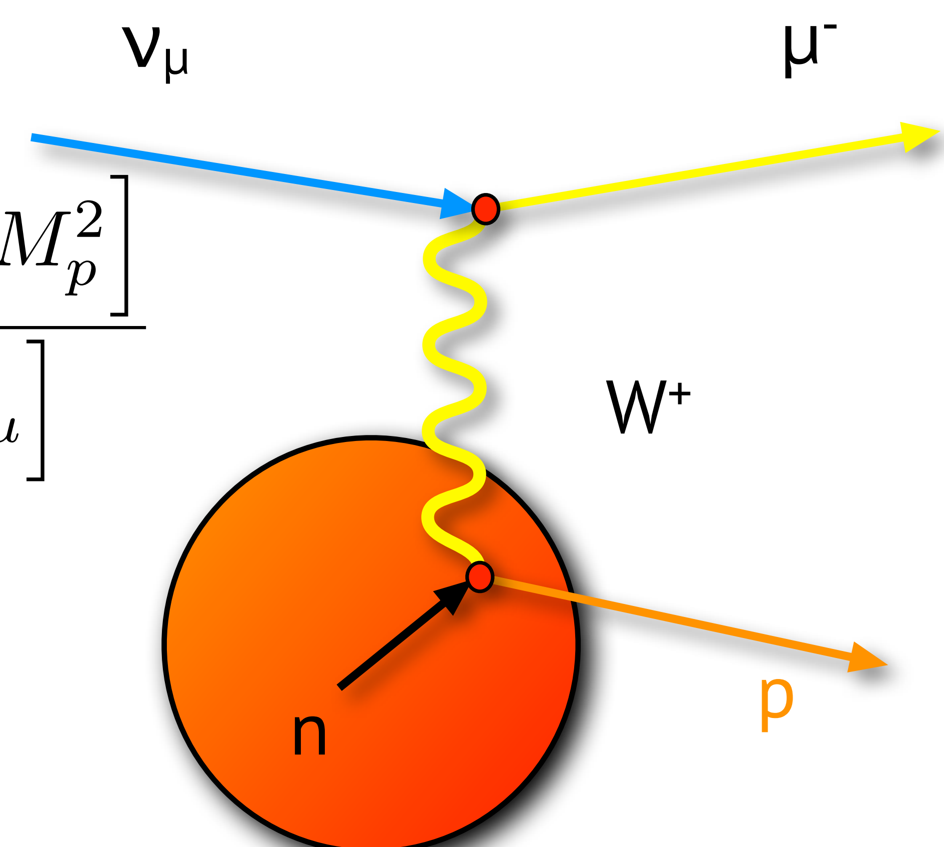
Idea: Use Quasi-Elastics

(Flip nucleons for antineutrino scattering.)

$$E_\nu^{QE} = \frac{2\,(M_n - E_B)\,E_\mu - \left[(M_n - E_B)^2 + m_\mu^2 - M_p^2\right]}{2\left[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right)$$

$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

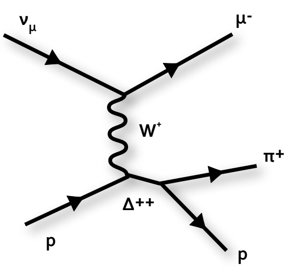


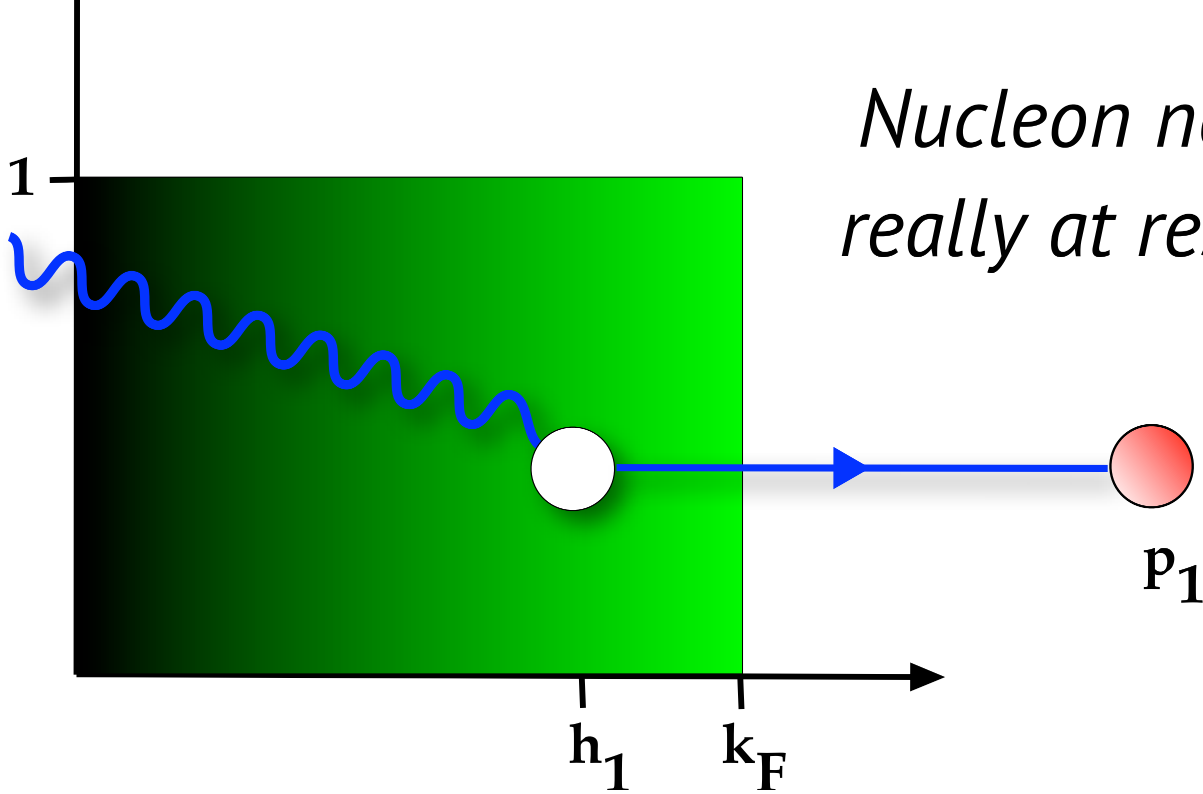
$$\nu_l + n \to l^- + p$$

$$\bar{\nu}_l + p \to l^+ + n$$

Get everything with just the lepton!

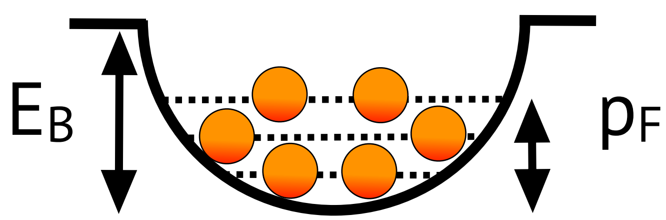
Fermi Gas Model



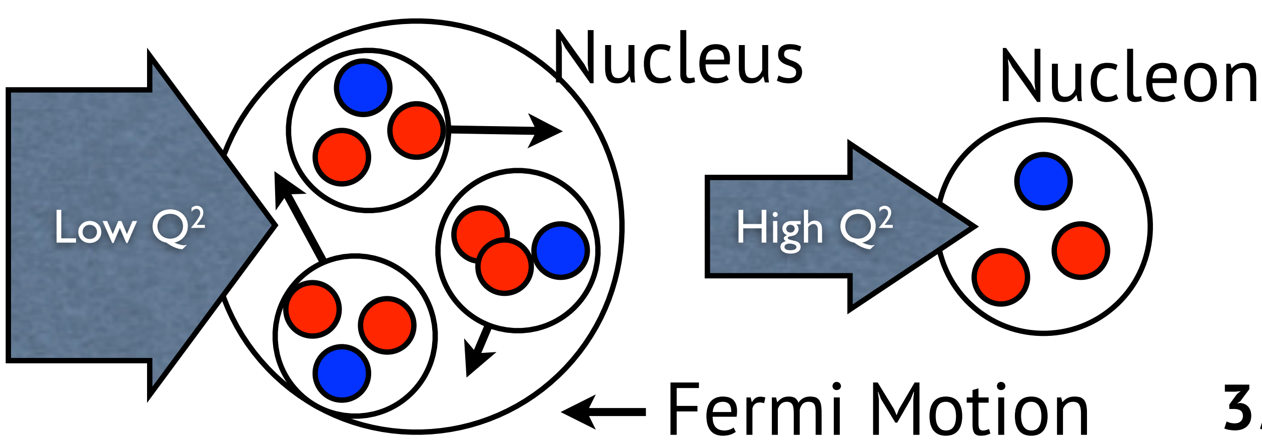


Nucleon not really at rest!

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



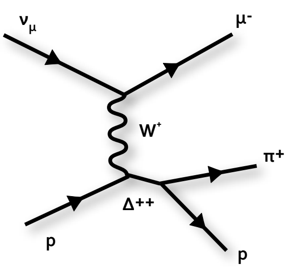
^{12}C	E_B = 25 MeV	p_F = 220 MeV/c



- Impulse approximation: scatter off independent single nucleons summed (incoherently) over the nucleus.
- In the FGM, all the nucleons are non-interacting and all states are filled up to k_F.
- The IA becomes problematic when the momentum transfer is *smaller* than ~300 MeV (think about the de Broglie wavelength and remember 1 fm = 1/200 MeV).

It is nice to see this problem getting high-level attention.

Smith and Moniz, 1972, Nucl. Phys. B43, 605



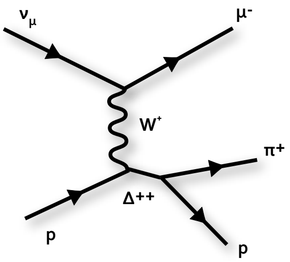
QE Cross Section

ν Cross Section: $$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A\left(Q^2\right) \pm B\left(Q^2\right)\frac{s-u}{M^2} + C\left(Q^2\right)\frac{(s-u)^2}{M^4}\right]$$

- Early formalism by Llewellyn Smith.
- Vector and Axial-Vector Components.
  - Vector piece can be lifted from ("easier") electron scattering data.
  - We have to measure the Axial piece.
- Q^2 is the 4-momentum transfer ($-q^2$).
- s and u are Mandelstam variables.
- The lepton vertex is known; the nucleon structure is parameterized with 2 vector (F_1, F_2) and 1 axial-vector (F_A) form factors.
  - Form factors are $f(Q^2)$ and encoded in A, B, and C.

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

R. Johnson, http://www.physics.uc.edu/~johnson/Boone/cross_sections/free_nucleon/quasielastic.pdf



Form Factors

$$A \simeq \frac{t}{M^2}\left(|f_{1V}|^2 - |f_A|^2\right) + \frac{t^2}{4M^2}\left(|f_{1V}|^2 + \xi^2 |f_{2V}|^2 + |f_A|^2 + 4\xi \mathrm{Re}\left(f_{1V} f_{2V}^*\right)\right)$$
$$+ \frac{t^3 \xi^2}{16 M^6} |f_{2V}|^2$$

$$B \simeq \frac{1}{M^2}\left(\mathrm{Re}\left(f_{1V} f_A^*\right) + \xi \mathrm{Re}\left(f_{2V} f_A^*\right)\right) t$$

$$C = \frac{1}{4}\left(|f_{1V}|^2 + |f_A|^2 - \frac{\xi^2 |f_{2V}|^2}{4M^2} t\right)$$

$$f_A\left(q^2\right) = \frac{f_A(0)}{\left(1 - \frac{q^2}{M_A^2}\right)^2}$$

f_A is the axial-vector form factor. We must *measure* this in ν-scattering. *Typically, we* ***assume*** *a dipole form (**not required!***).*

The ***form factors*** (f) contain parameterized information about the target (general shape of the form factors comes from symmetry arguments).

Not calculable from first principles, instead we measure them experimentally.

 *See e.g. PRD 84, 7, 073006 (2011)

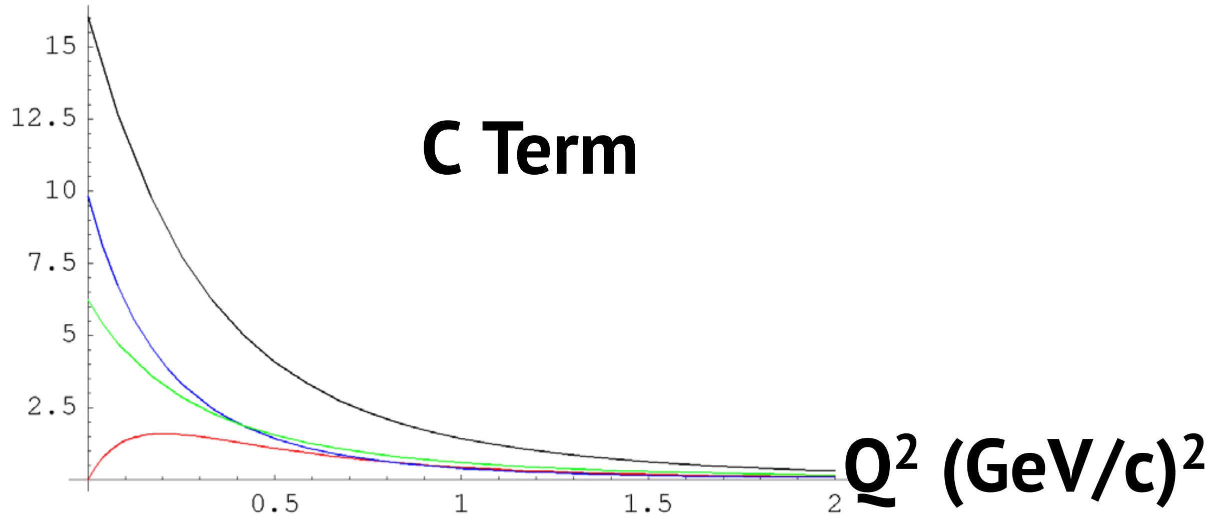


Figure 1. Sum of all terms in C is black. The contribution from the $|f_{1V}|^2$ is in red, the $|f_{2V}|^2$ in blue and the $|f_A|^2$ term is in green.

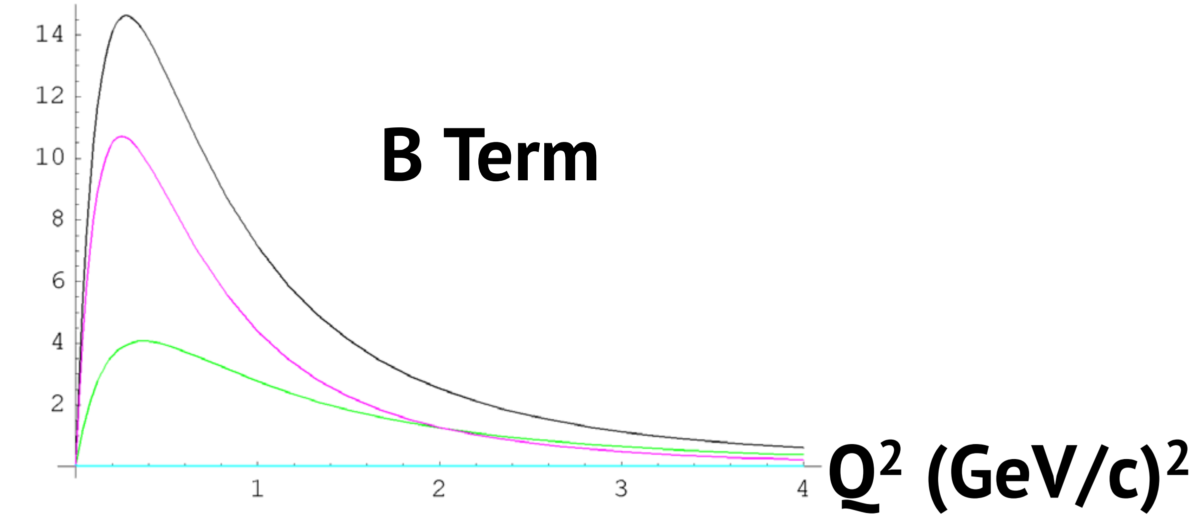


Figure 2. "B" as a function of Q^2. Sum of all terms is black. The $\mathrm{Re}\left(f_{1V} f_A^*\right)$ term is magenta and the $\mathrm{Re}\left(f_{2V} f_A^*\right)$ term is green. All other terms are small and plotted along the *x* axis.

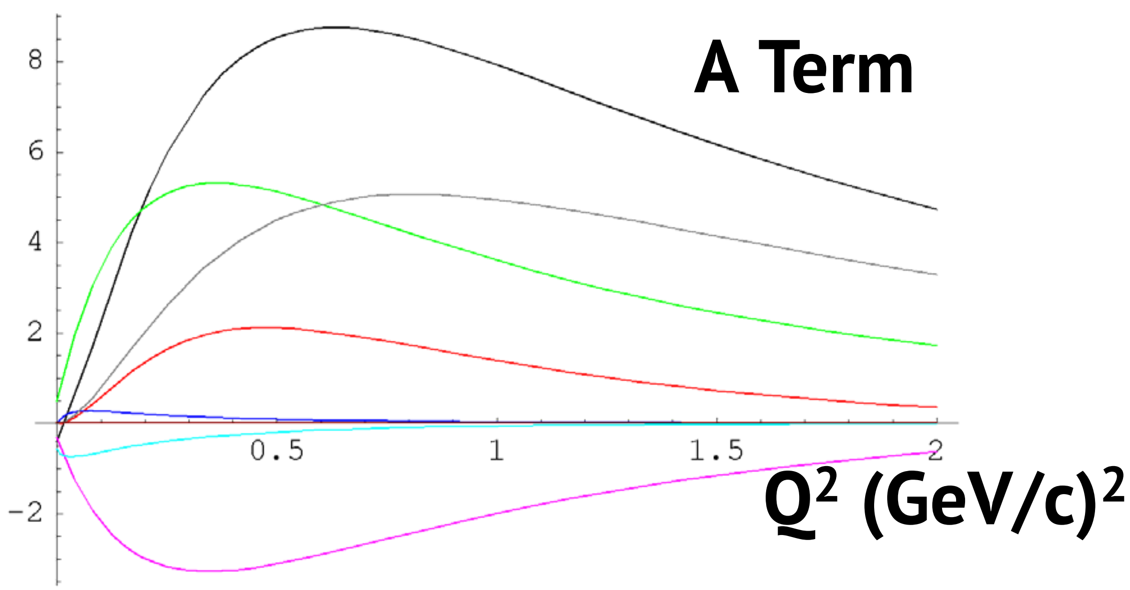


Figure 3. The "A" term. Sum of all terms is black. The term proportional to $|f_{1V}|^2$ is blue, the term with $|f_{2V}|^2$ is red, the term with $|f_A|^2$ is green, the term with $|f_P|^2$ is magenta, the term with $\mathrm{Re}\left(f_{1V} f_{2v}^*\right)$ is light blue, the term with $\mathrm{Re}\left(f_{1V} f_A^*\right)$ is yellow (almost on the *x* axis), the term with $\mathrm{Re}\left(f_{2V} f_A^*\right)$ is gray, and the term with $\mathrm{Re}\left(f_A f_P^*\right)$ is brown (again, almost on the *x* axis).

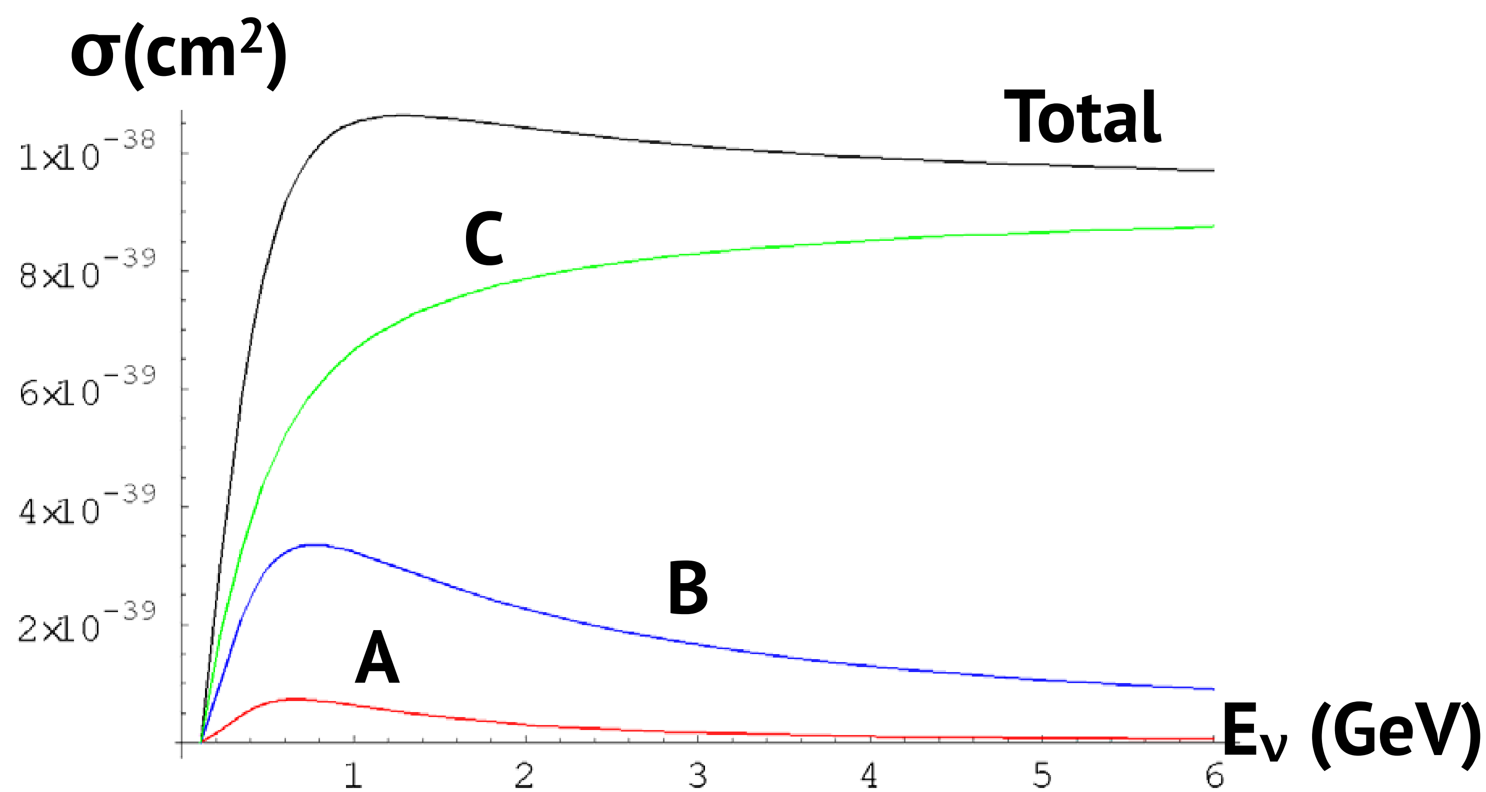
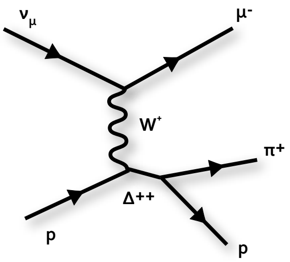


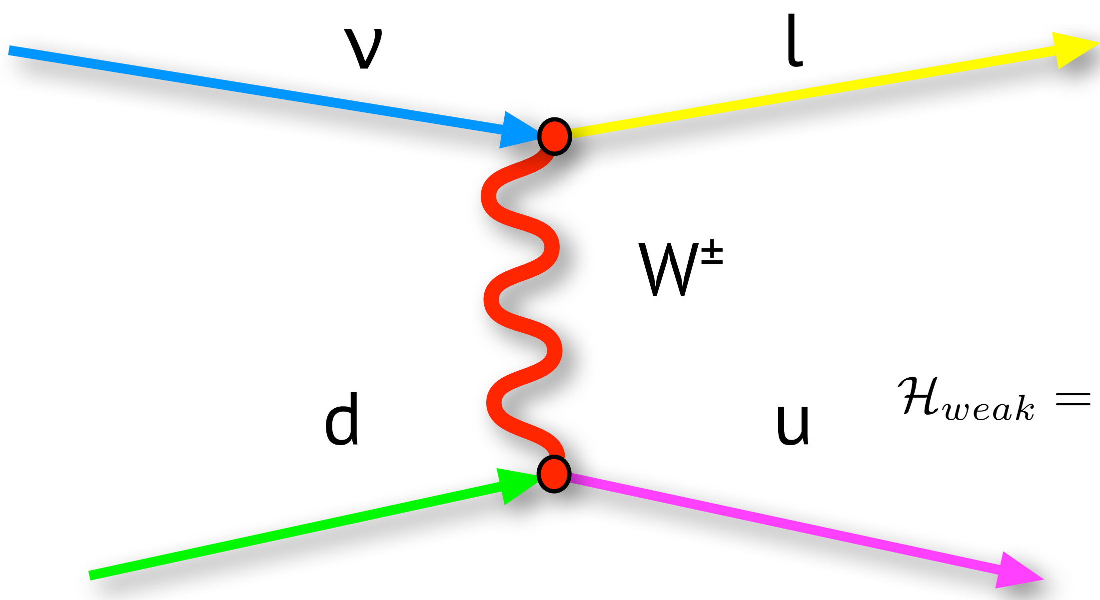
Figure 4. Total neutrino neutron quasielastic cross section (black) and the contributions to the cross section from the "C" term (green), the "B" term (blue) and the "A" term (red).

http://www.physics.uc.edu/~johnson/Boone/cross_sections/free_nucleon/quasielastic.pdf



Form Factors

“Intuition” for the axial form factor & M_A...



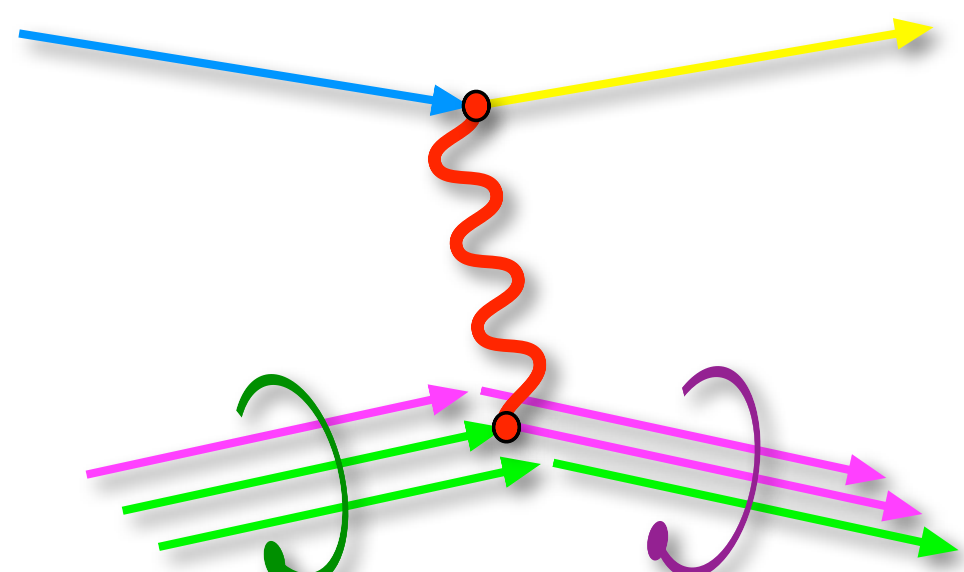
We know how to handle scattering for Dirac particles:

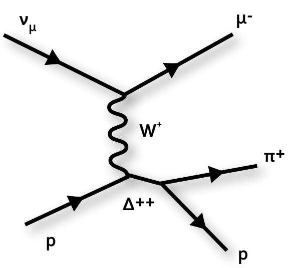
$$\mathcal{H}_{weak} = \frac{4\, G_F}{\sqrt{2}} \left[\bar{l}/\bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2}\nu\right] \left[\bar{f}'\gamma_\mu \left(g_L \frac{1-\gamma_5}{2} + g_R \frac{1+\gamma_5}{2}\right) f\right] + h.c.$$

Real protons are more complicated!

Form Factor : Fourier Transform of the Charge Distribution

$$\rho\left(r\right) = \rho_0 e^{-mr}$$





Form Factor : Fourier Transform of the Charge Distribution

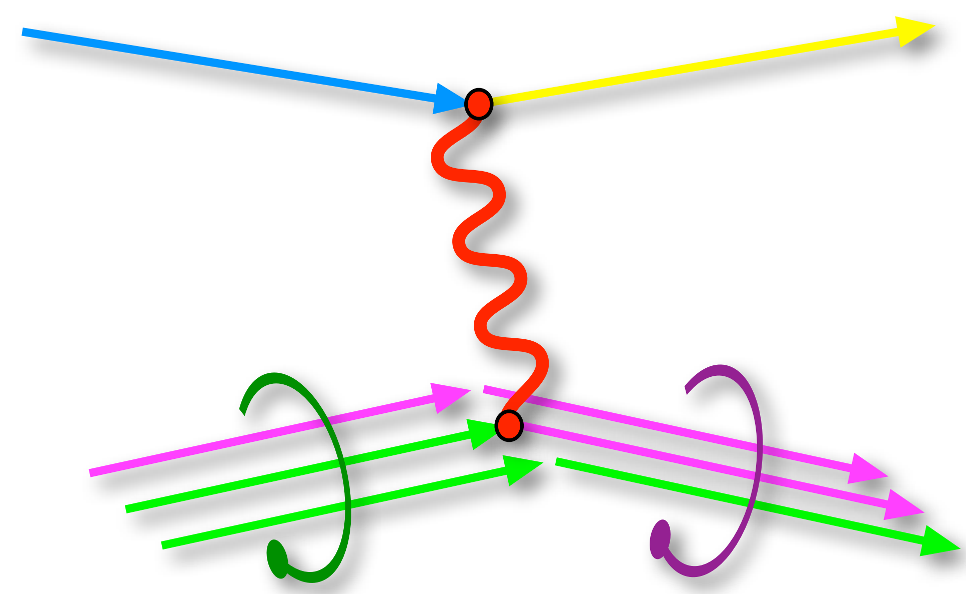
$$\rho\left(r\right) = \rho_0 e^{-mr}$$

$$F\left(|q|^2\right) = N\int e^{-mr} e^{i\vec{q}\cdot\vec{x}} d^3x$$

$$= 2\pi N \int r^2 e^{-mr} e^{i|q|r\cos\theta} dr d\left(\cos\theta\right)$$

$$= \frac{2\pi N}{i|q|}\int_0^\infty r\left[e^{-(m-i|q|)r} - e^{-(m+i|q|)r}\right] dr$$

$$= \frac{8\pi N}{m^3\left(1+\frac{|q|^2}{m^2}\right)^2}$$



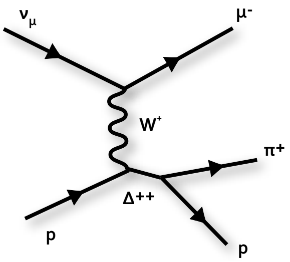
Normalization:

$$N\int e^{-mr} d^3x = 1 \Rightarrow N = m^3/8\pi$$

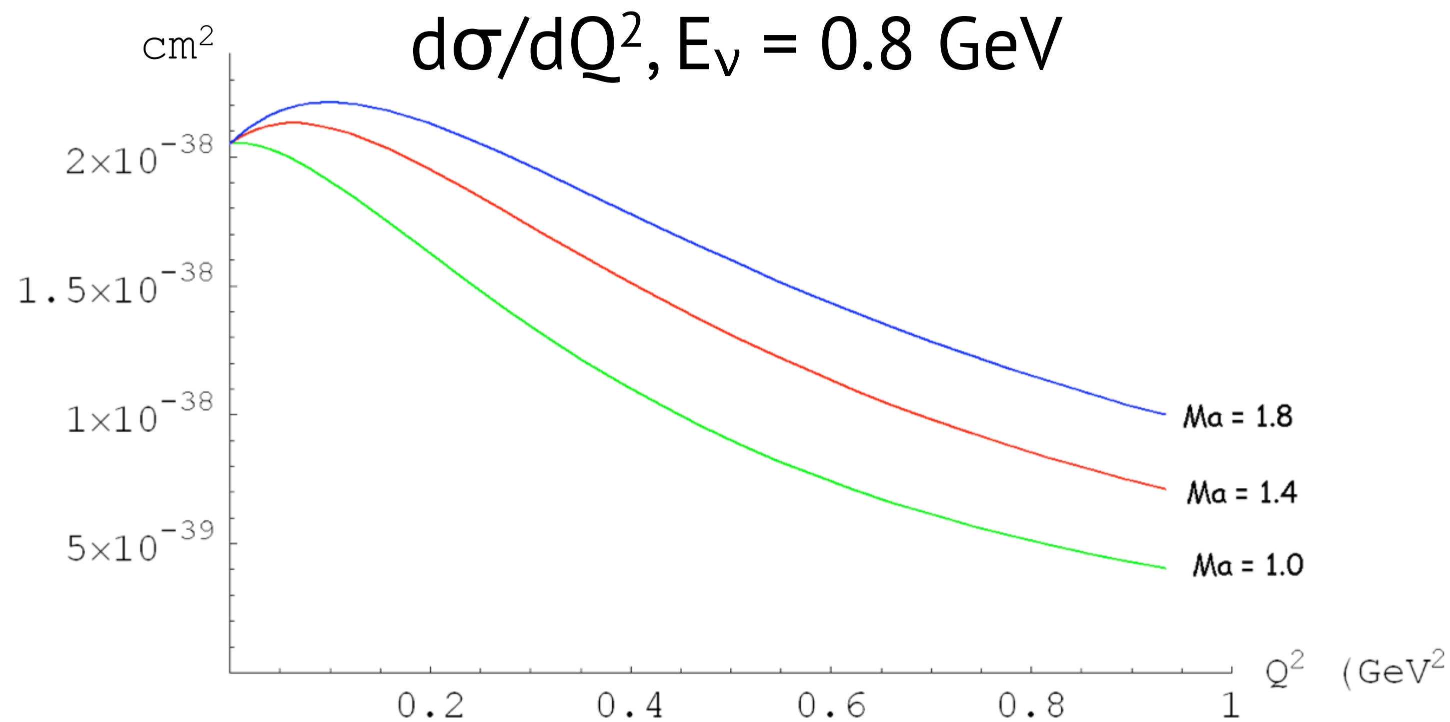
$$\Rightarrow F\left(q^2\right) = \frac{1}{\left(1-\frac{q^2}{m^2}\right)^2}$$

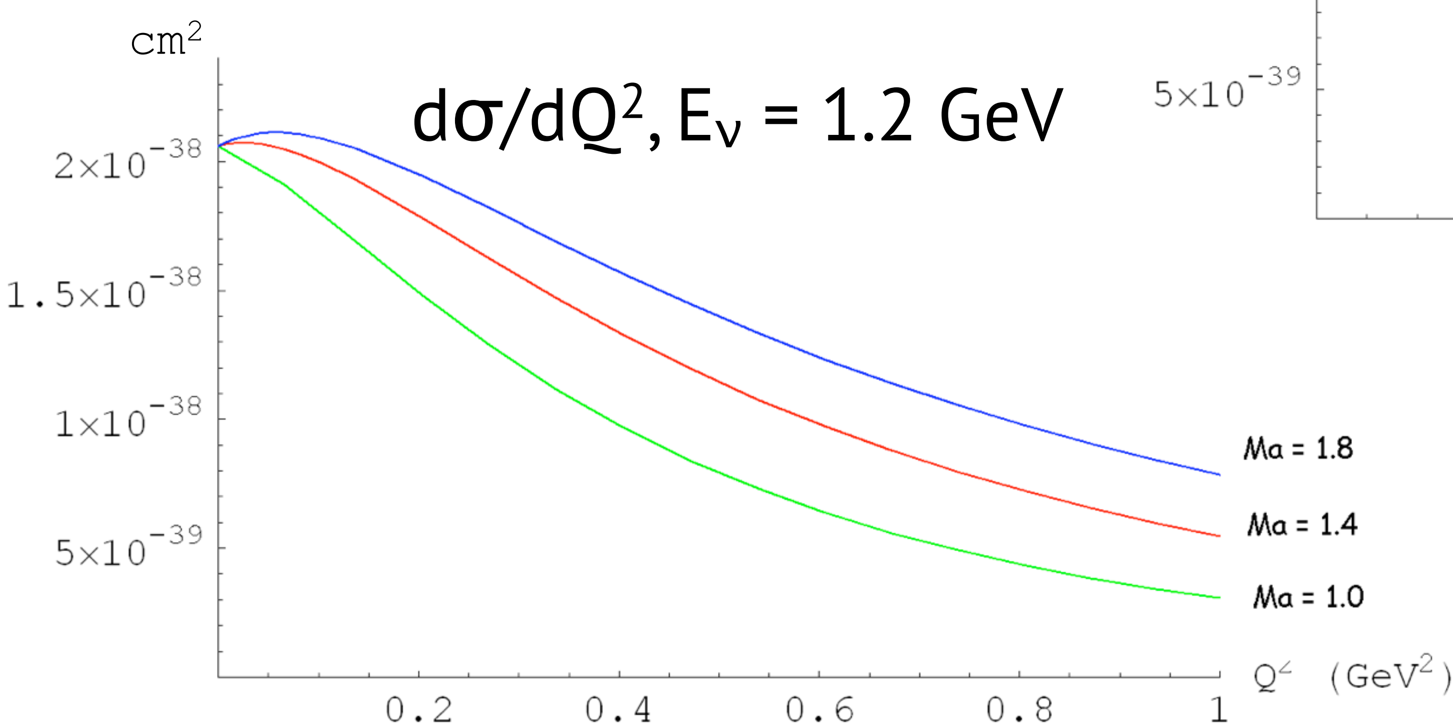
M_A

Q^2 dependence $\Longleftrightarrow$ Finite nucleon size.

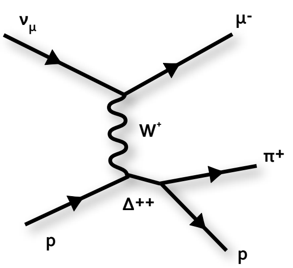


The Effect of M_A



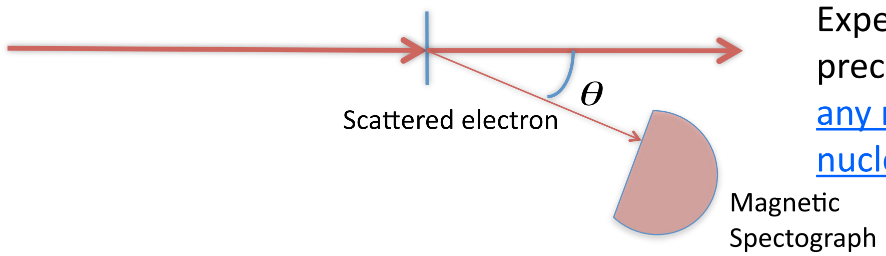


http://www.physics.uc.edu/~johnson/Boone/cross_sections/free_nucleon/Varying_MA_plots.html

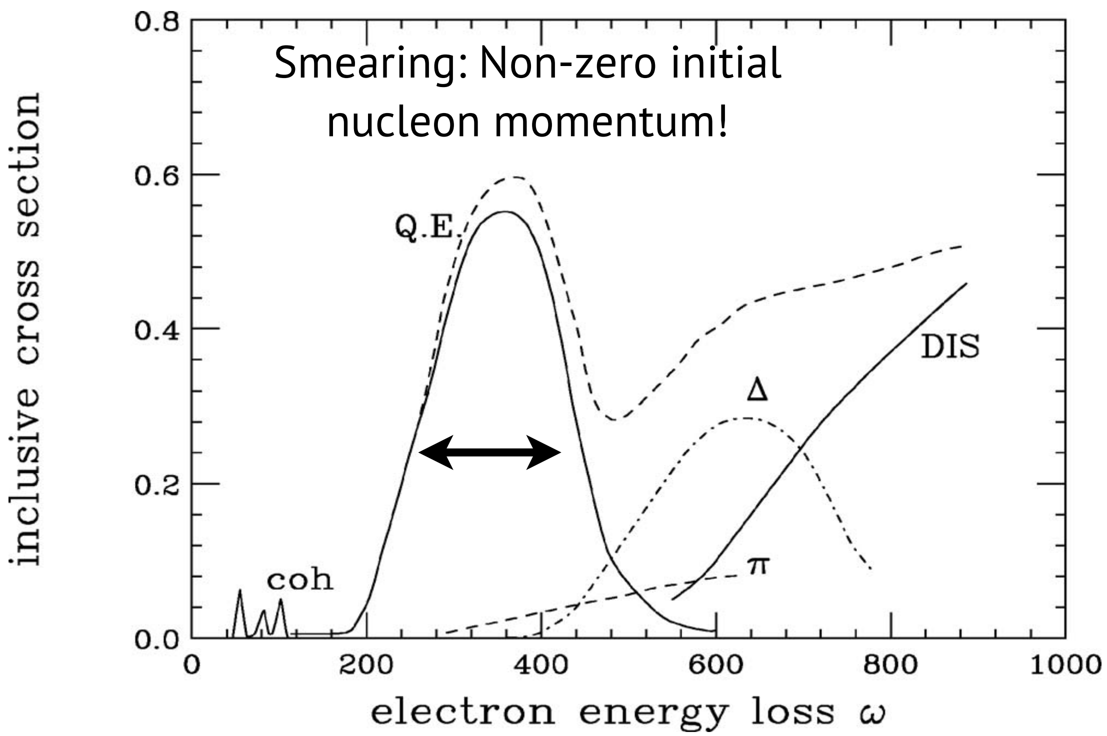


Vector Form Factors

- f_{1V} & f_{2V} come from high precision electron scattering experiments.
- Notice the small error bars…

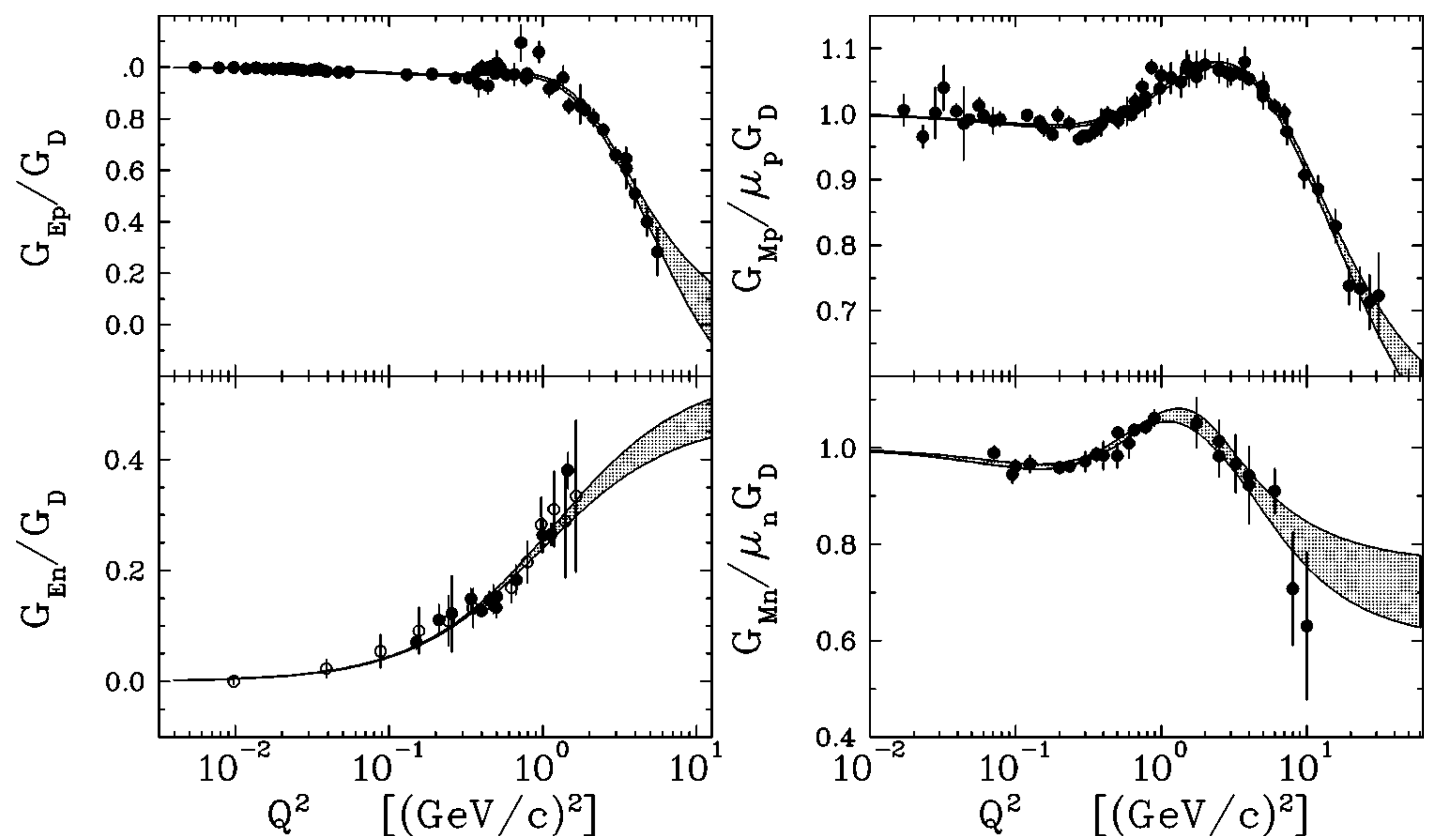


Experimentally, q and ω are precisely known without any reference to the nuclear final state



J. Carlson, FNAL Short-Baseline Neutrino Workshop, 2011

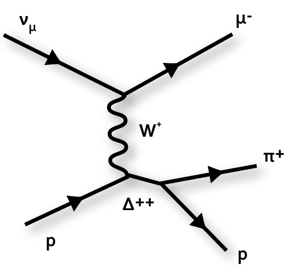
Nucleon Electromagnetic Form Factors
(presented as a ratio to a dipole form factor)



J.J. Kelly, PRC 70, 068202 (2004)

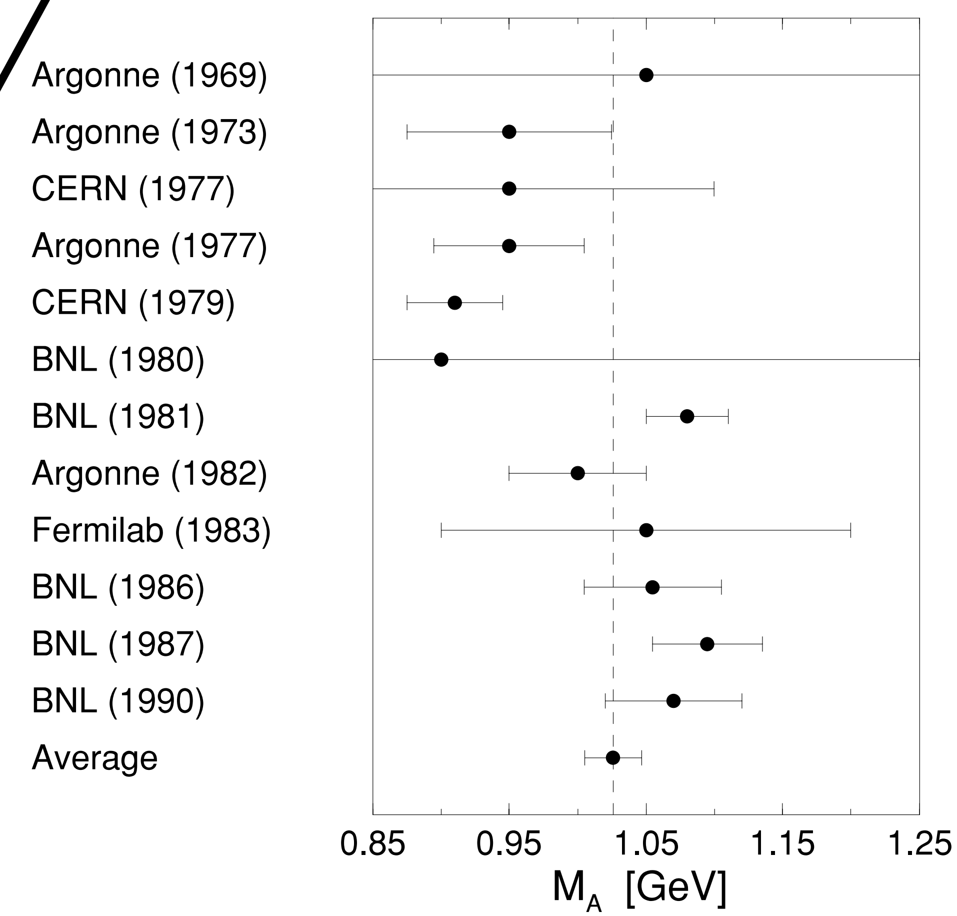
$$G_D = \left(1 + Q^2/\Lambda^2\right)^{-2}$$
$$\Lambda^2 = 0.71\ \ (\mathrm{GeV/c})^2$$

Llewellyn Smith & CCQE Cross Sections



$$F_A\left(Q^2\right) = \frac{-g_A}{\left(1 + Q^2/M_A^2\right)^2}$$

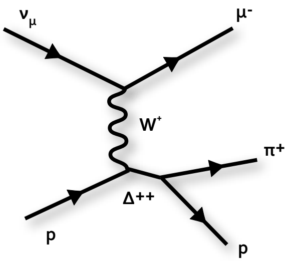
- Standard Application:
  - Assume a Fermi Gas Model with parameters from electron scattering (or a favorite nuclear model).
    - Typically (FGM) assume the Impulse Approximation.
  - Vector form factors from electron scattering.
  - Assume dipole form for Axial-vector form factor. Everything now follows from M_A. Measure the x-section, get M_A.
  - $F_A(0)$ is measured in beta-decay.



Bernard et al 2002 J. Phys. G: Nucl. Part. Phys. 28 R1

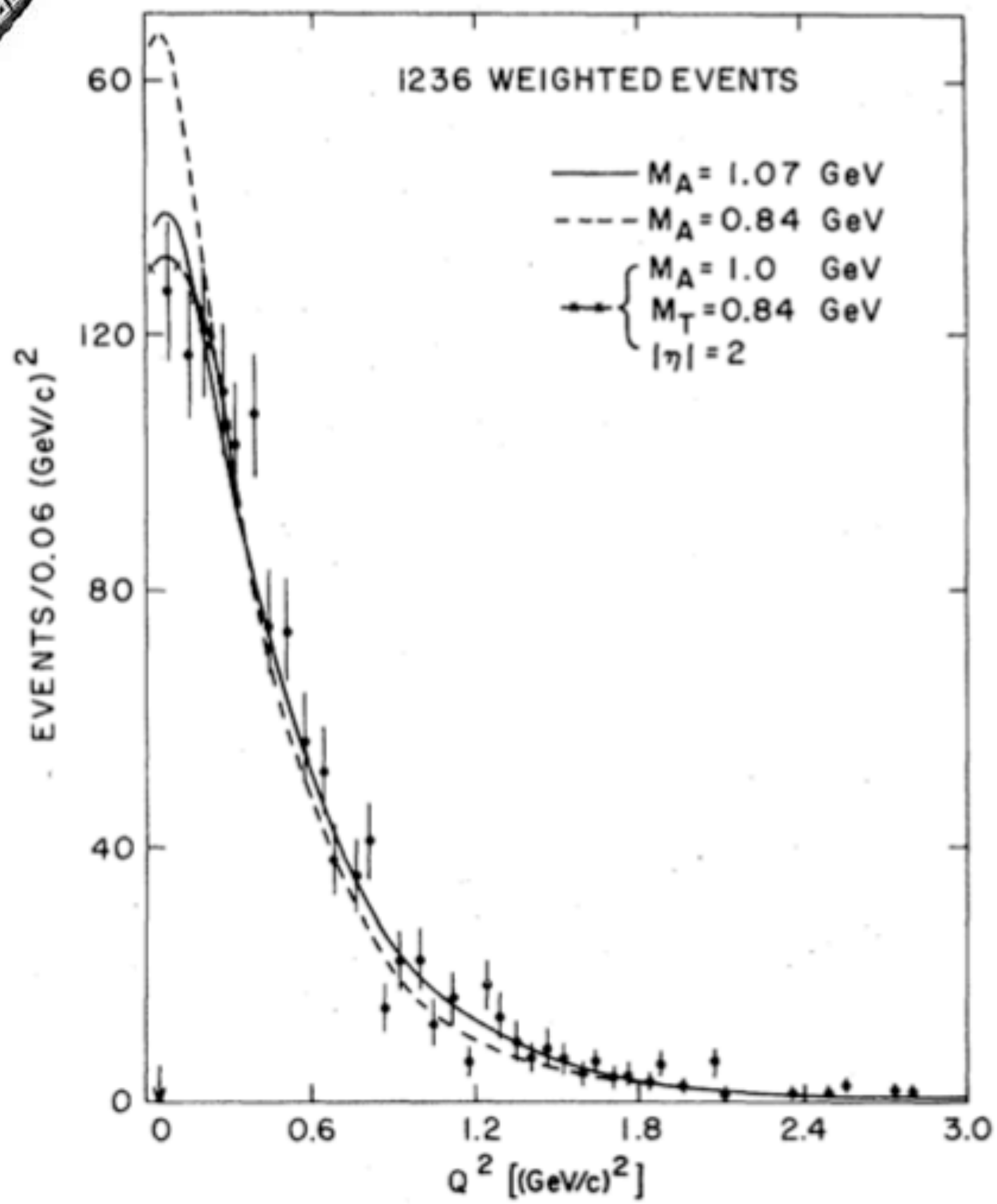
Relativistic Fermi Gas: Smith, Moniz, NPB 43, 605 (1972)

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261.



Flux

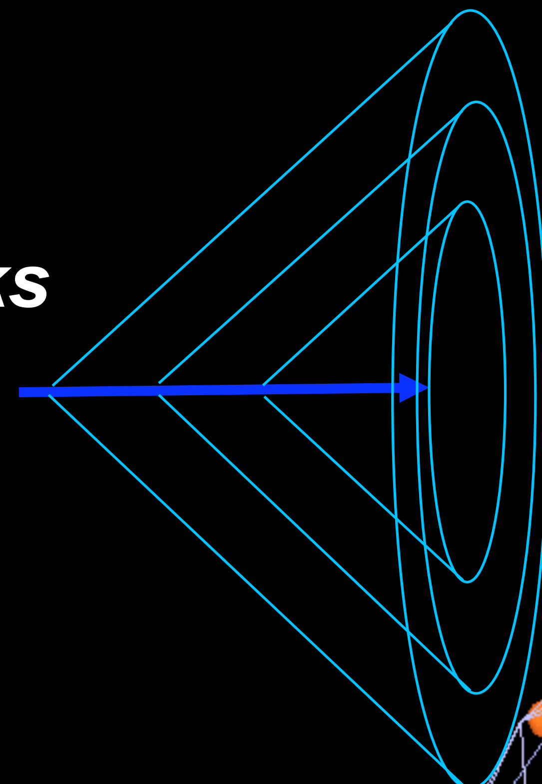
- Aside…
- In the bad old days:
  - Fit CCQE $d\sigma/dQ^2$ for best Axial Mass parameter.
    - You only need the shape, not the level, to get M_A.
  - Use Llewelyn-Smith to calculate the cross section.
  - Use the cross-section to calculate the flux.
  - Use the flux to measure the cross-section!



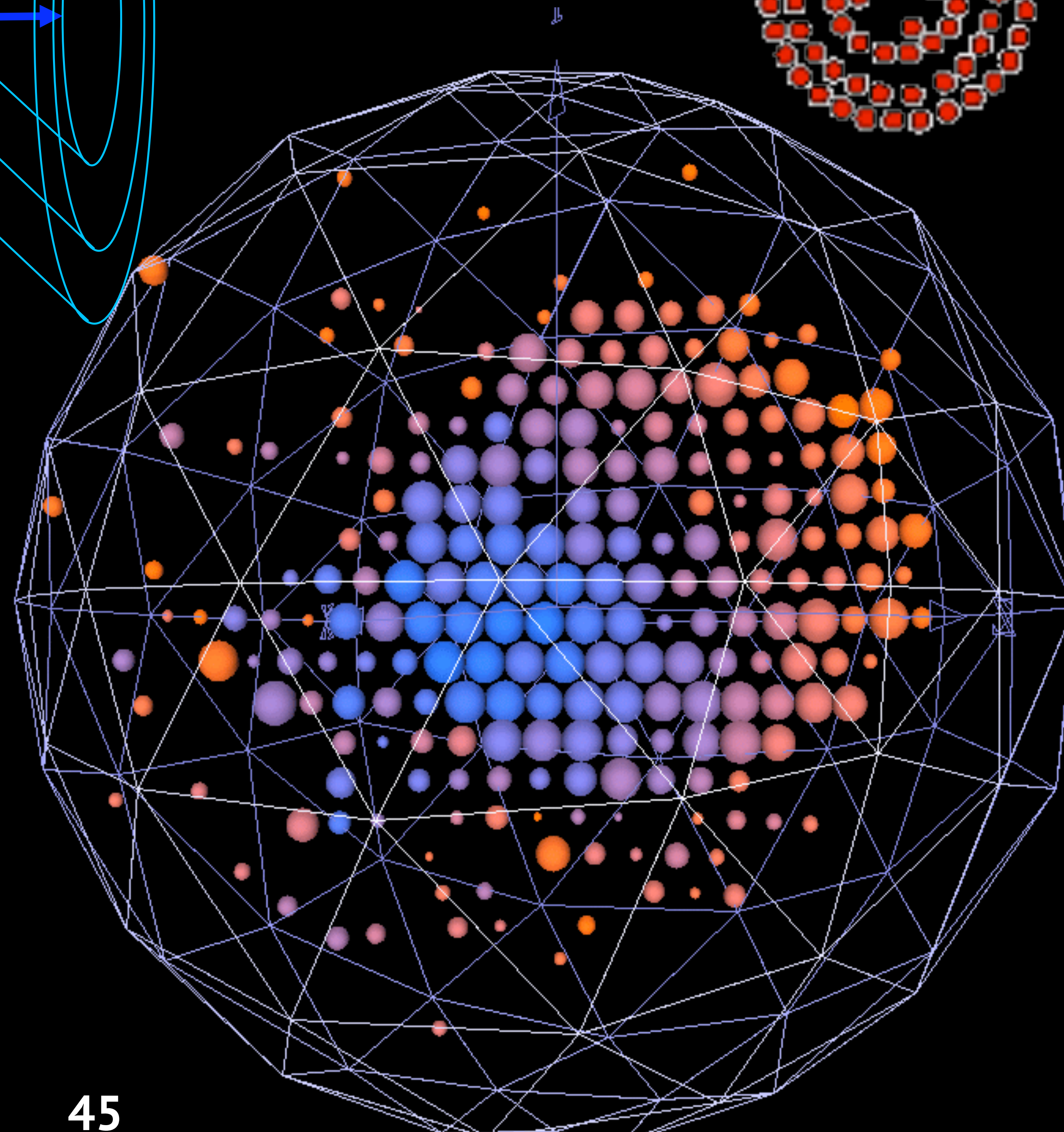
MiniBooNE: Protons Invisible

MiniBooNE collaboration, NIM.A599(2009)28

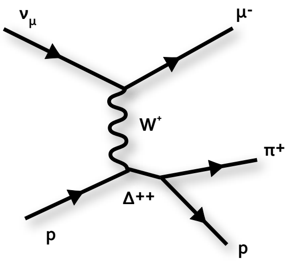
- ***Muons***
  - ***Sharp, clear rings***
    - ***Long, straight tracks***
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons



No problem: Subtract resonant pion background and assume Quasi-Elastic.

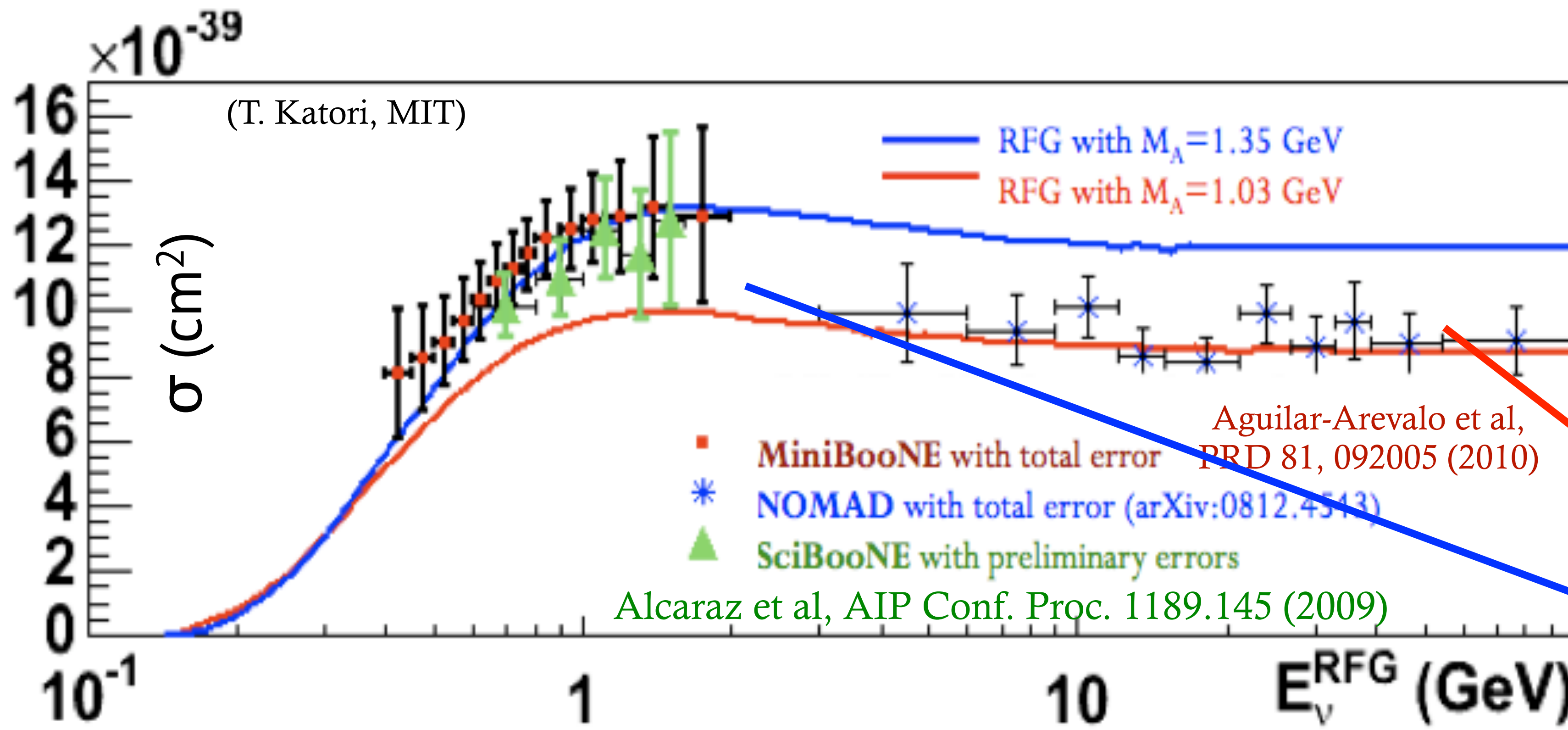


T. Katori, New Trends in High Energy Physics, Alushta, Ukraine, 2011



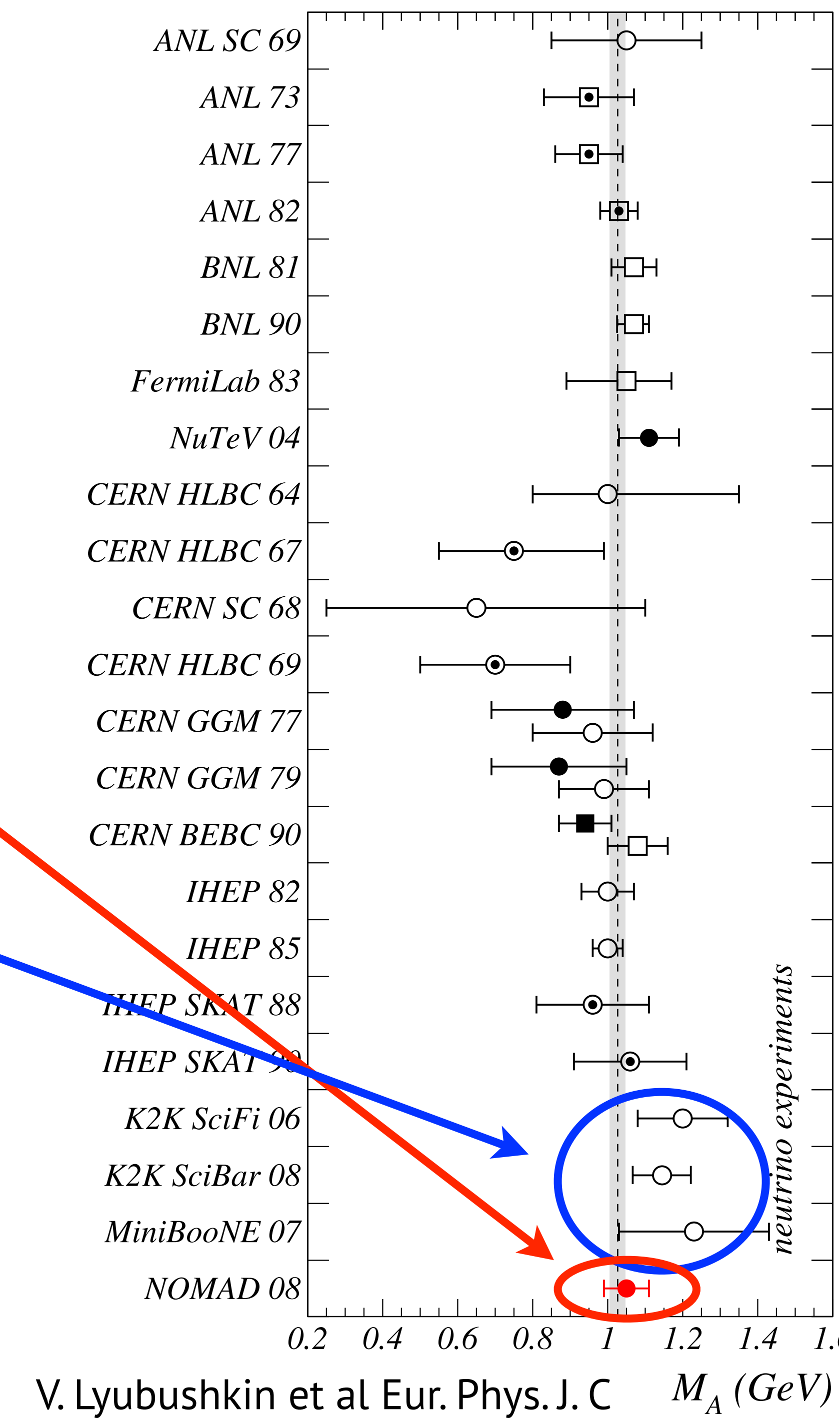
Quasi-Elastic Scattering

We get something unexpected...



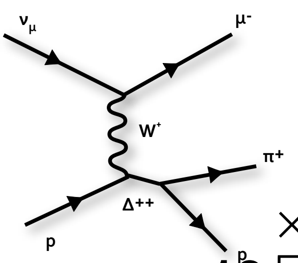
High statistics experiments
using **heavy targets at low E.**

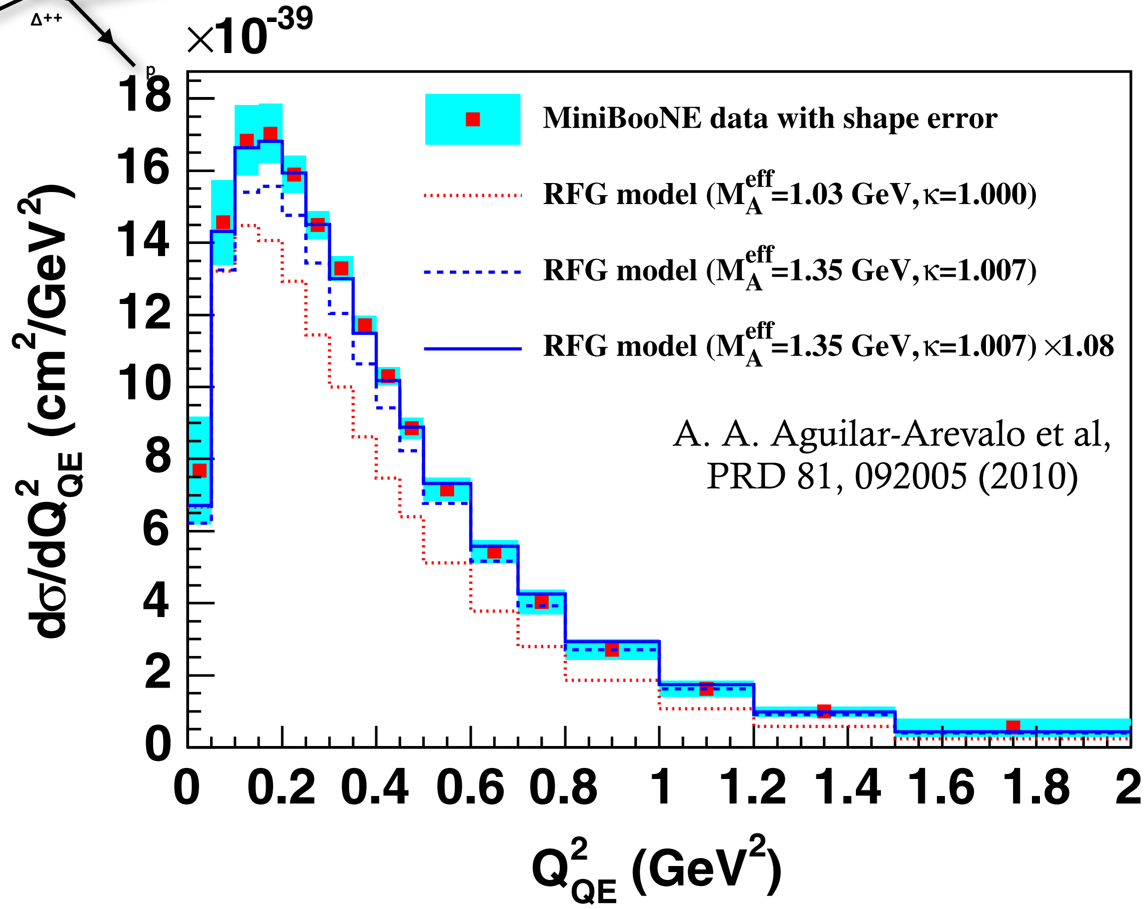
$\langle M_A \rangle = 1.026$

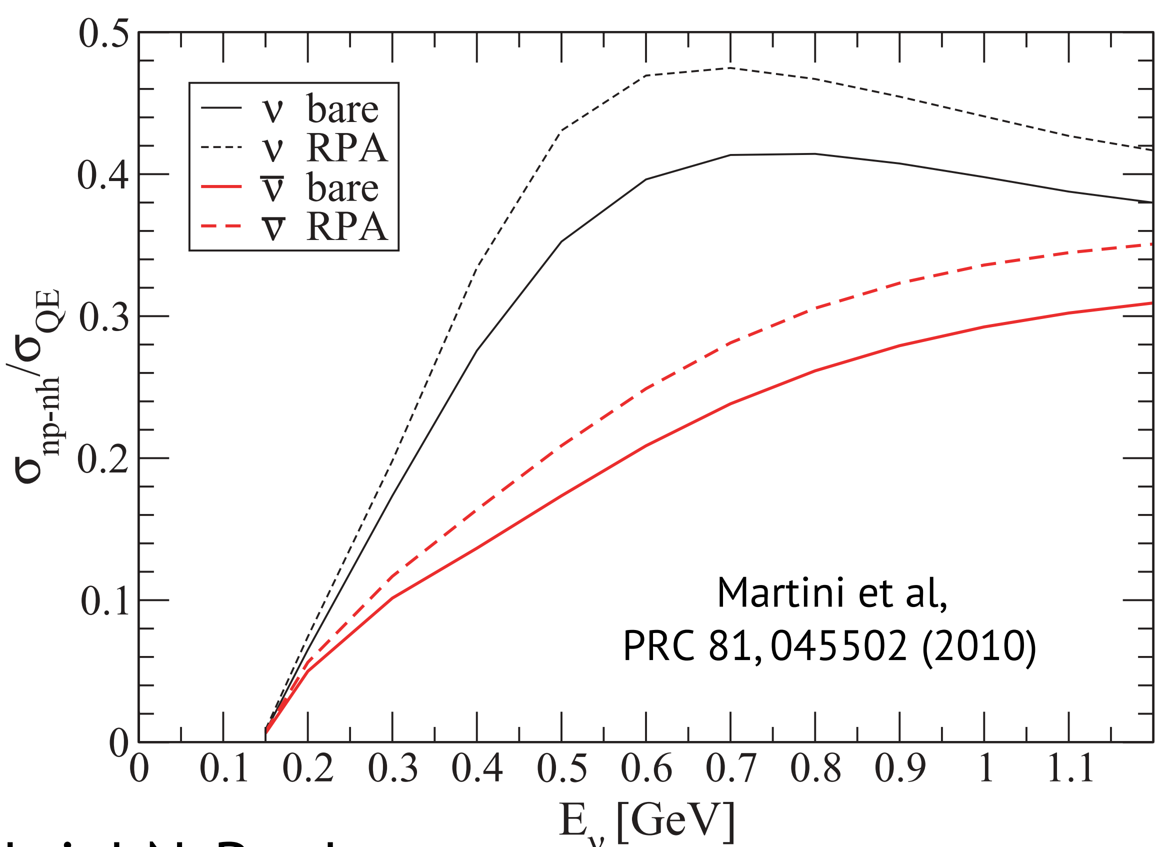


V. Lyubushkin et al Eur. Phys. J. C (2009) 63: 355–381 (NOMAD)

Axial Mass "Anomaly"*





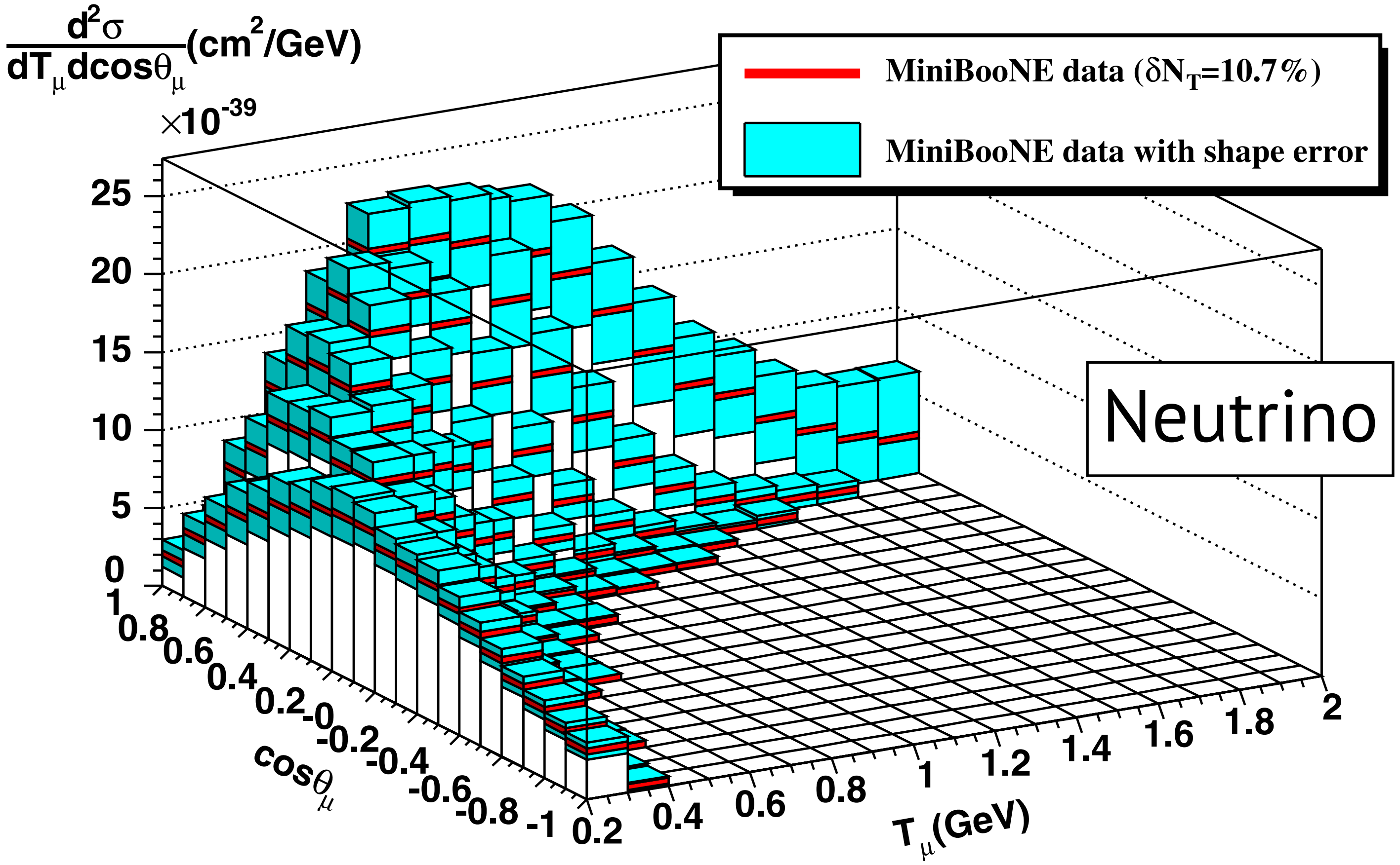


- One way to fit the data and keep the "classical" picture of QE scattering is to raise the value of the axial mass. But does this make sense?
- We are confusing the definitions of CCQE: here we have a *nuclear target*.
- Meson-Exchange-Currents (MEC): Scatter off correlated pairs ("2p2h") of nucleons instead of free nucleons.
- Many interesting models (some very good), but no "universal" agreement on size (even direction for antineutrinos).
- MINERvA, T2K, ArgoNeuT, MicroBooNE, etc. should be able to directly detect this effect.

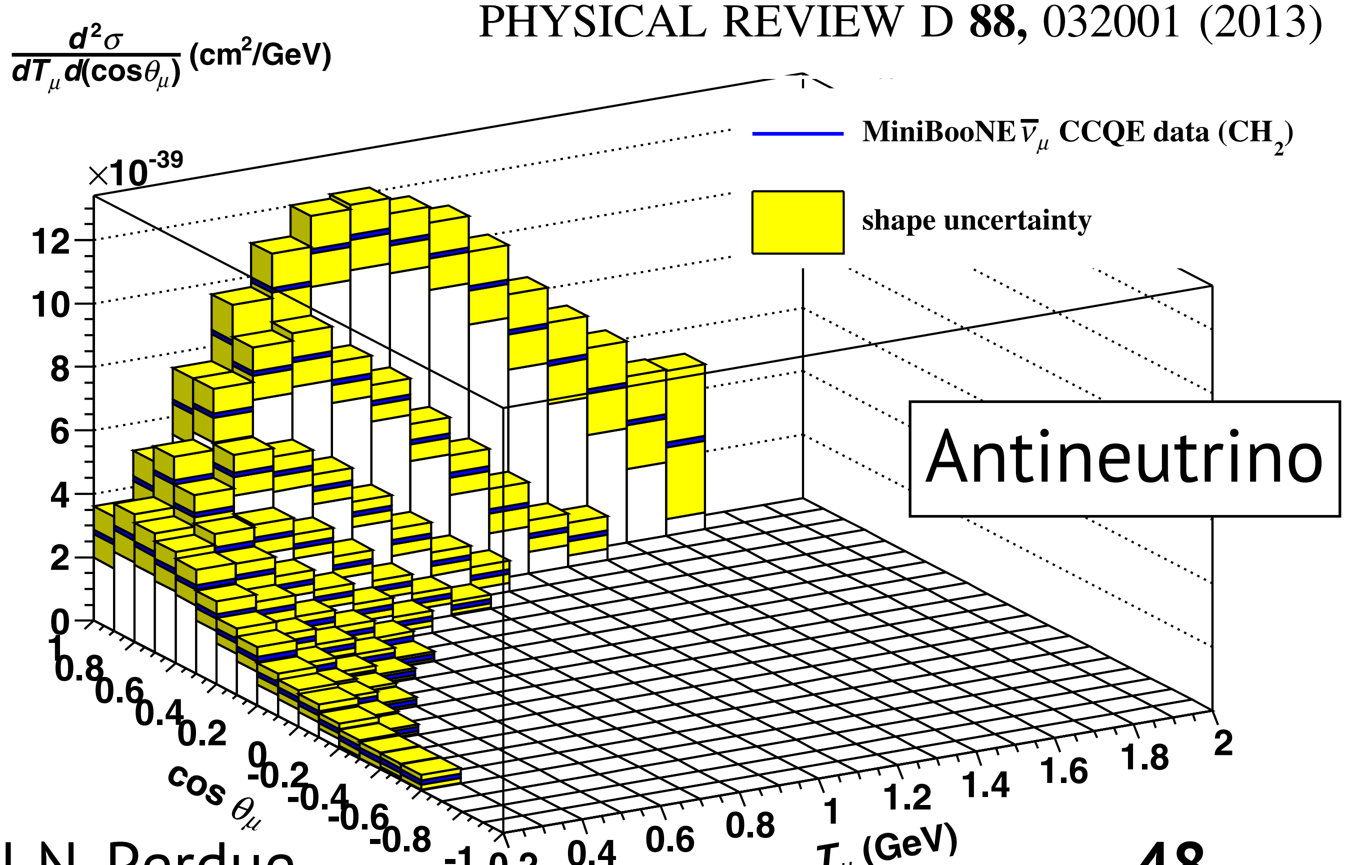
*Nobody really calls it that anymore.

In case you were thinking the discrepancy in the cross section as a function of energy wasn't that significant, MiniBooNE also measured a double-differential cross section. There is just no way to explain this data with a QE model.

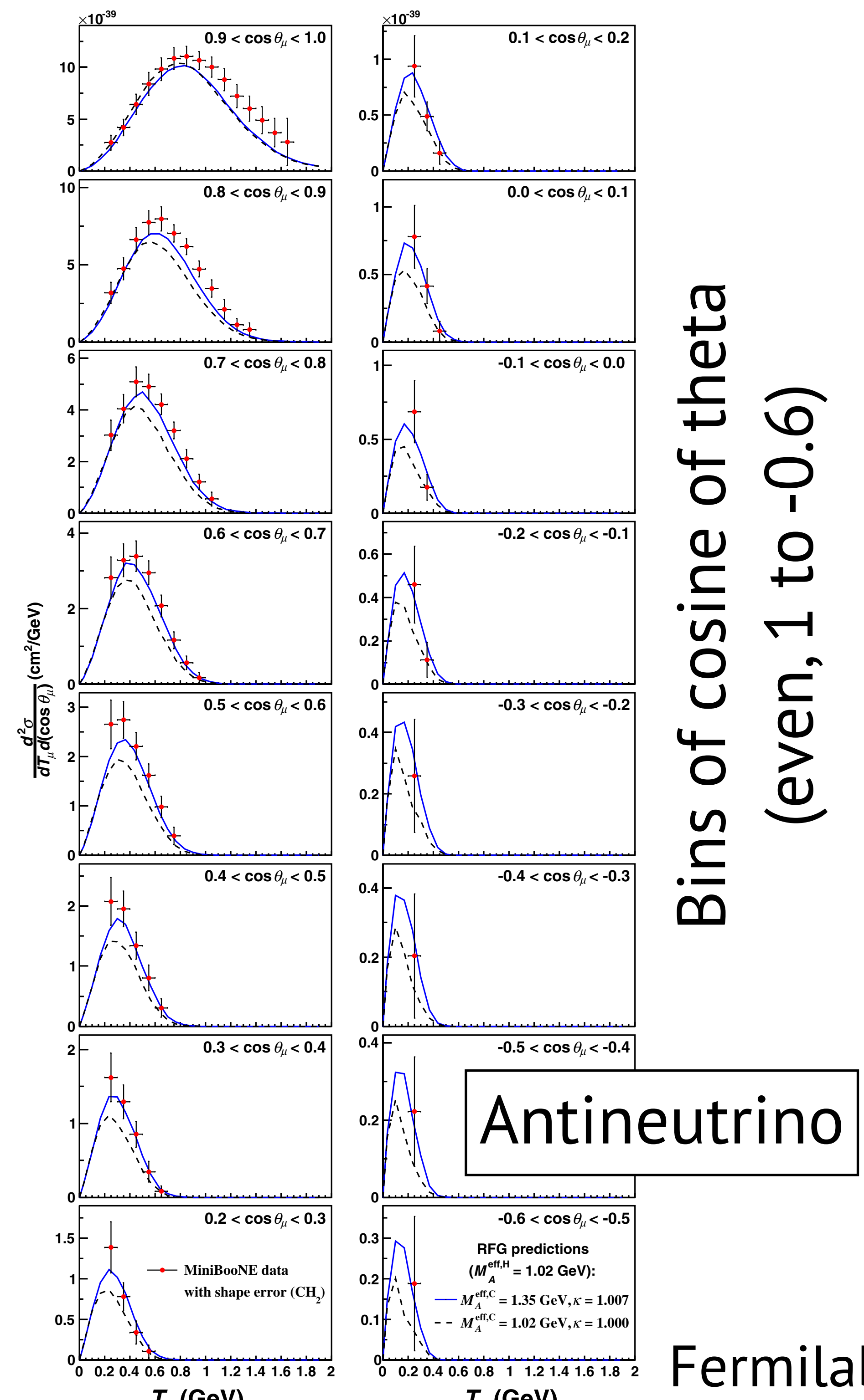
PHYSICAL REVIEW D **81,** 092005 (2010)



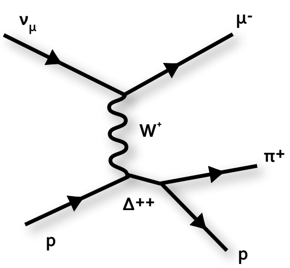
PHYSICAL REVIEW D **88,** 032001 (2013)



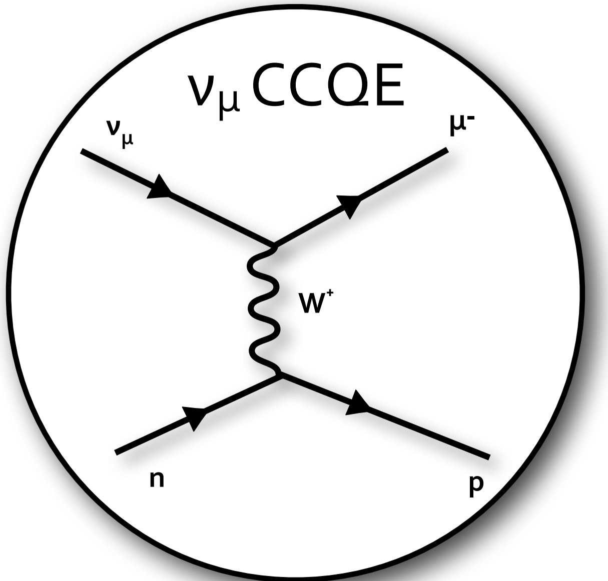
PHYSICAL REVIEW D **88,** 032001 (2013)

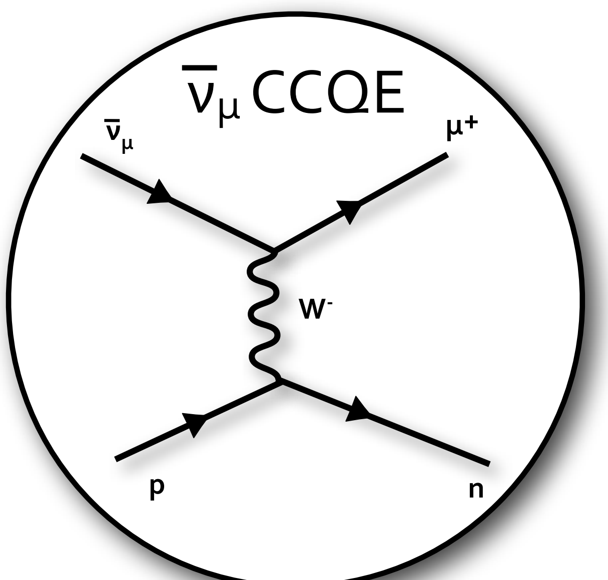


Bins of cosine of theta (even, 1 to -0.6)



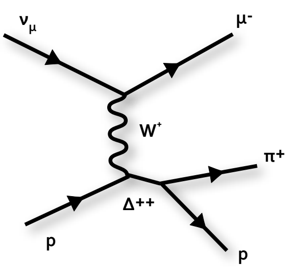
MINERvA CCQE Results



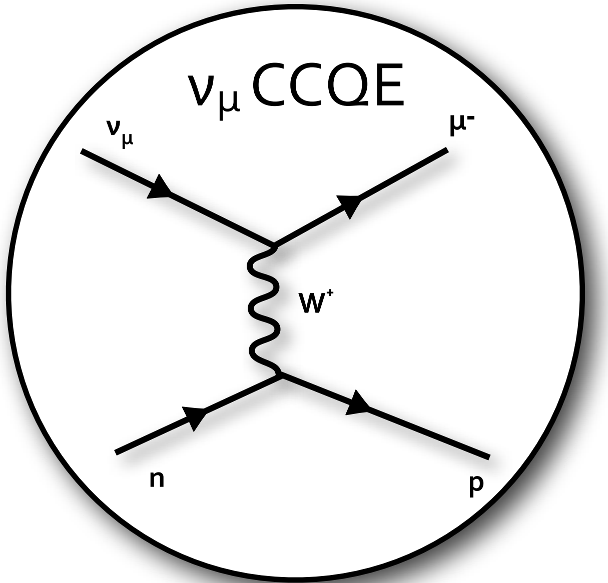


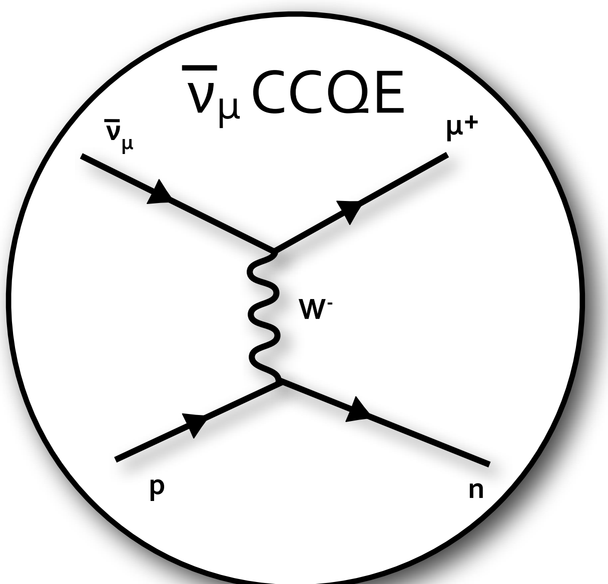
- $d\sigma/dQ^2$ on a (mostly) hydrocarbon target.
- Flux integrated over 1.5 to 10 GeV in the NuMI "Low Energy" Configuration.
- Muons are sign and momentum analyzed in the MINOS Near Detector (puts a lower-bound on momentum).
- See FNAL Wine & Cheese (D. Schmitz) on 10 May 2013 for more details.

$Q^2_{QE} = -m^2_\mu + 2E^{QE}_\nu \left(E_\mu - \sqrt{E^2_\mu - m^2_\mu}\cos\theta_\mu\right)$ = Four momentum transfer



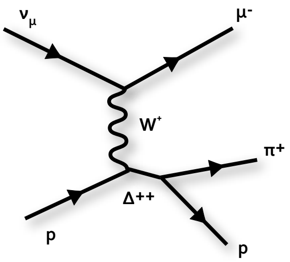
MINERvA CCQE Results





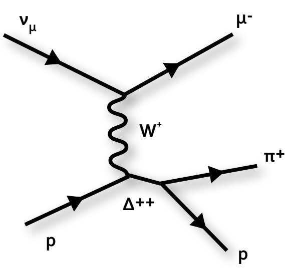
- Important differences from MiniBooNE:
  - Low energy hadrons near the vertex are observable.
  - Higher neutrino energy gives a higher Q^2 reach.
  - Many current multi-nucleon correlation models are non-relativistic. This won't work at MINERvA energies, but the relativistic calculations are orders of magnitude harder.
  - In *this* analysis MINERvA analyzes only forward muons. Due to the beam energy, the boost is strongly forward anyway, but MiniBooNE also looks at backwards-going muons in their analysis. There is reason to think the multi-nucleon contributions may be strongest there.

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right)$$ = Four momentum transfer

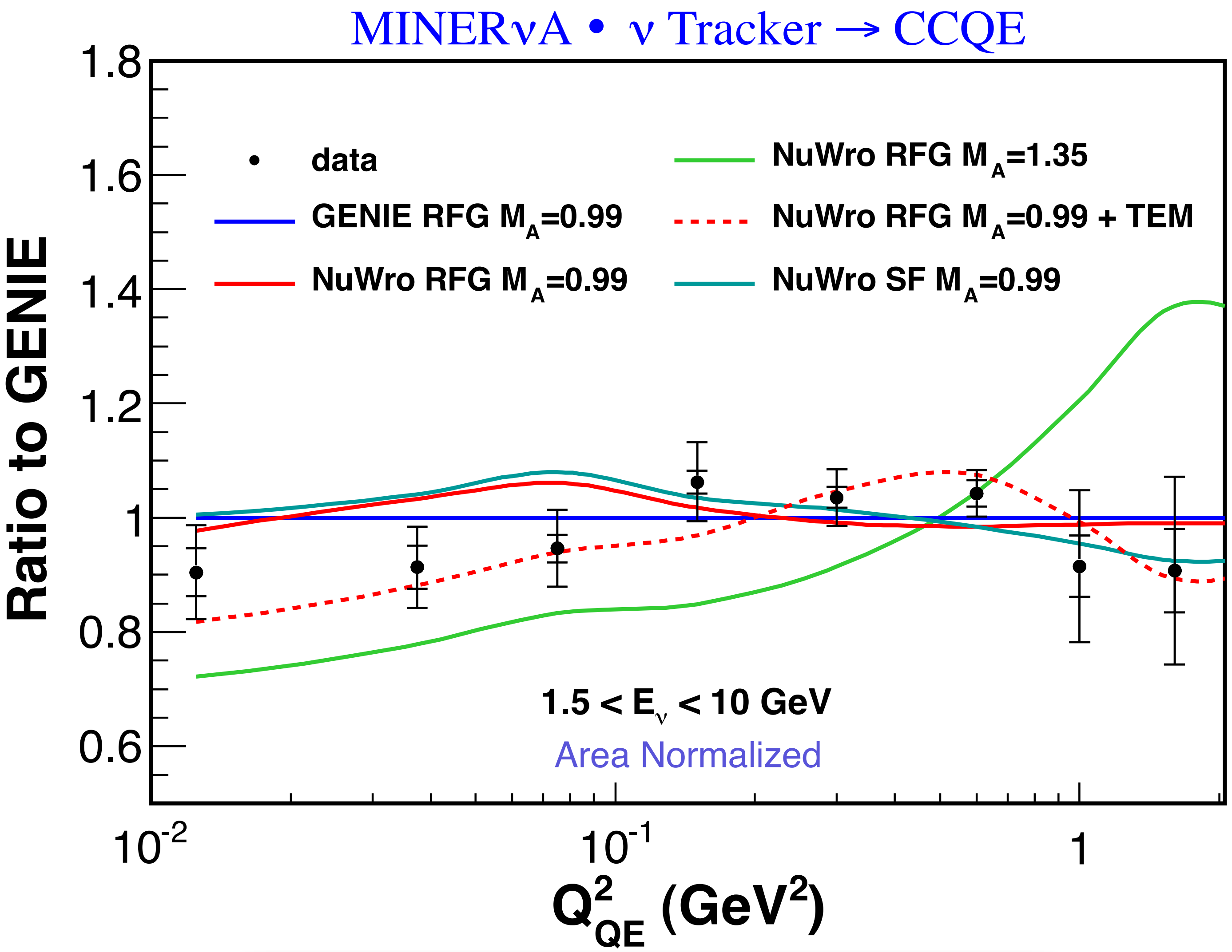


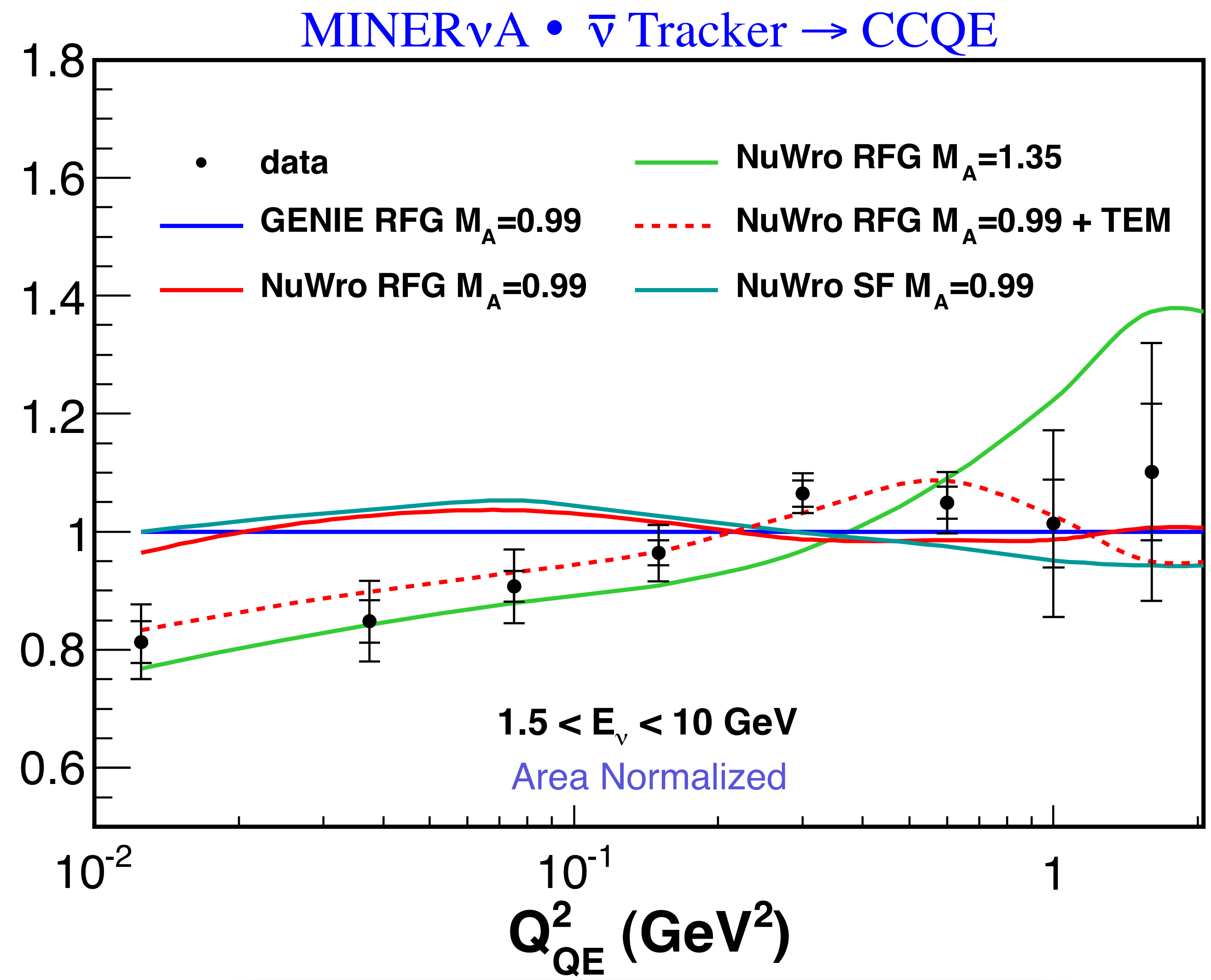
Nuclear Models

- Relativistic Fermi Gas (RFG), M_A = 0.99 GeV/c^2
  - The standard used in essentially all event generators.
- Relativistic Fermi Gas (RFG), M_A = 1.35 GeV/c^2
  - Motivated by recent measurements & successful at low Q^2.
- Nuclear Spectral Function (SF), M_A = 0.99 GeV/c^2
  - A more realistic model of the nucleon momentum distribution.
- Transverse Enhancement Model (TEM), M_A = 0.99 GeV/c^2
  - Empirical model modifying the magnetic form factors of bound nucleons to create the enhancement in the transverse cross-section observed in electron scattering (attributed to correlated pairs of nucleons).
- Vary *one* thing at a time in our comparisons…



Neutrino (Left), Antineutrino (Right)



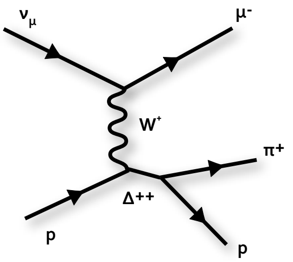


Neutrino

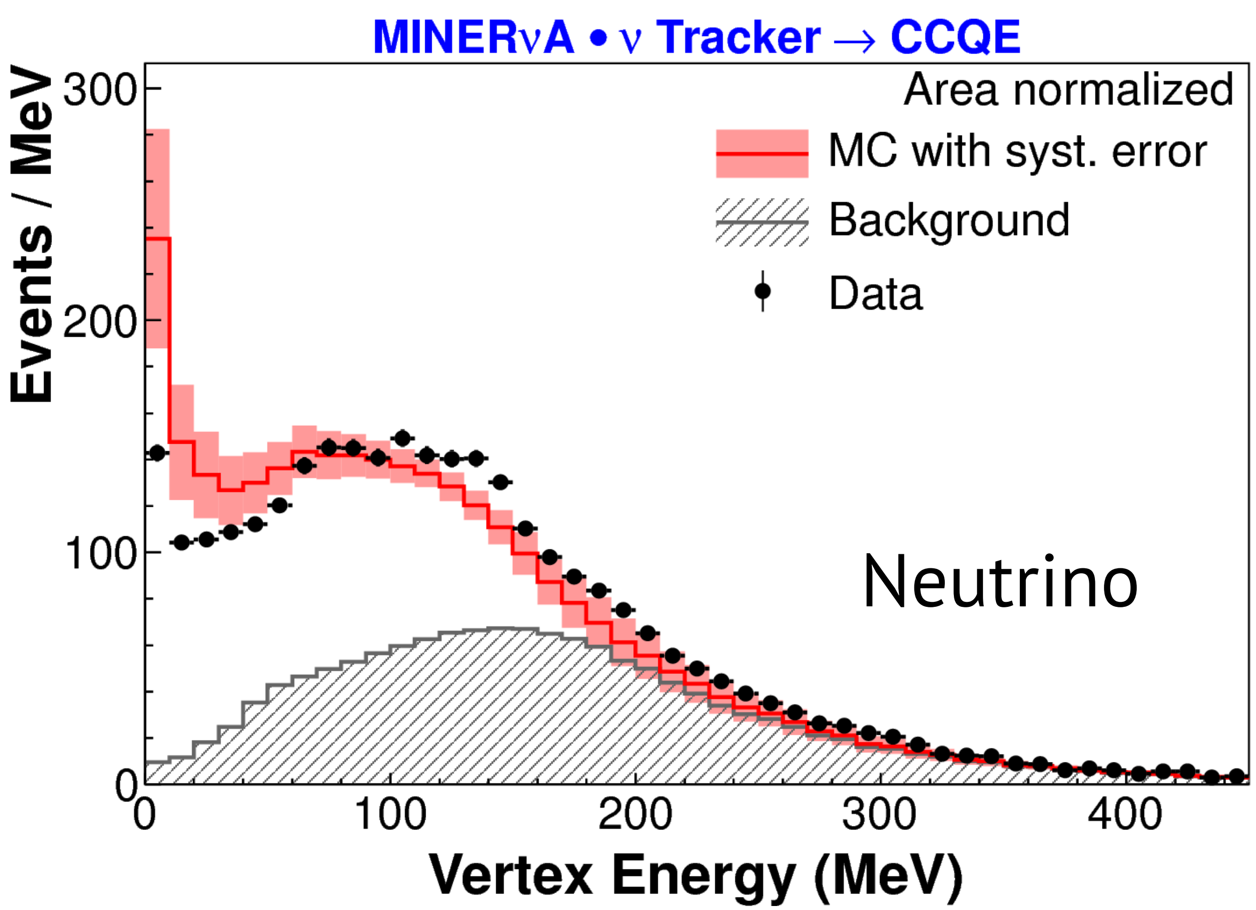
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

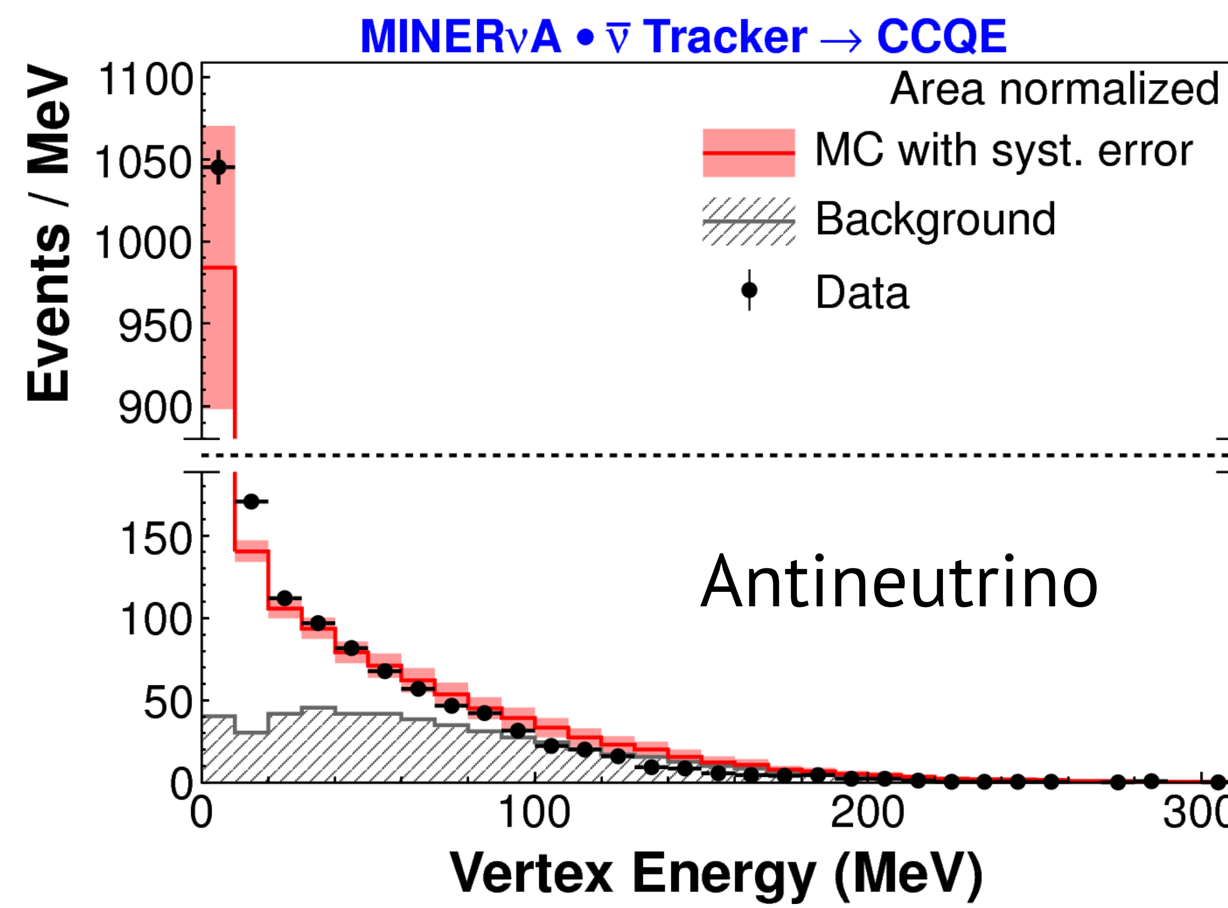
Antineutrino

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99



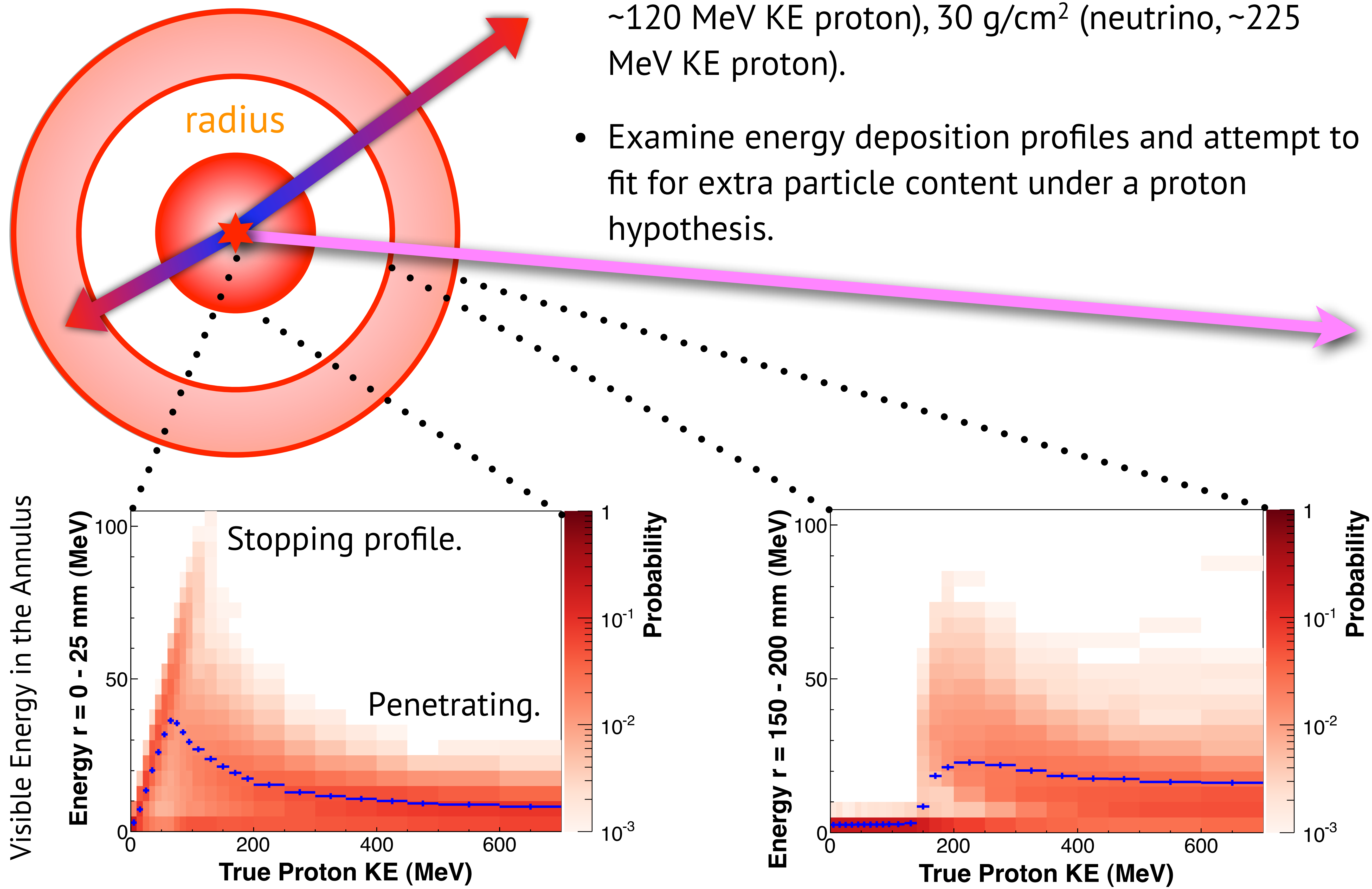
Vertex Energy

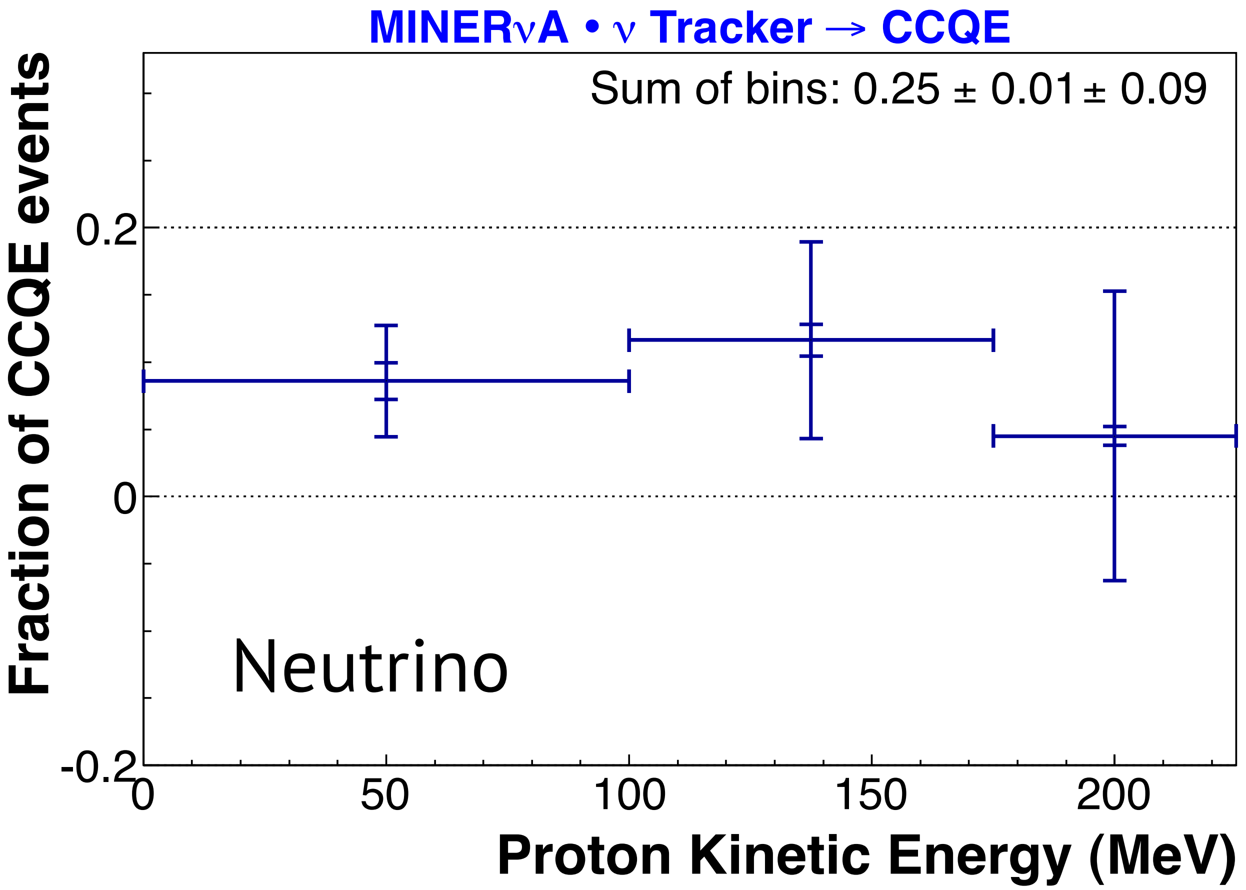


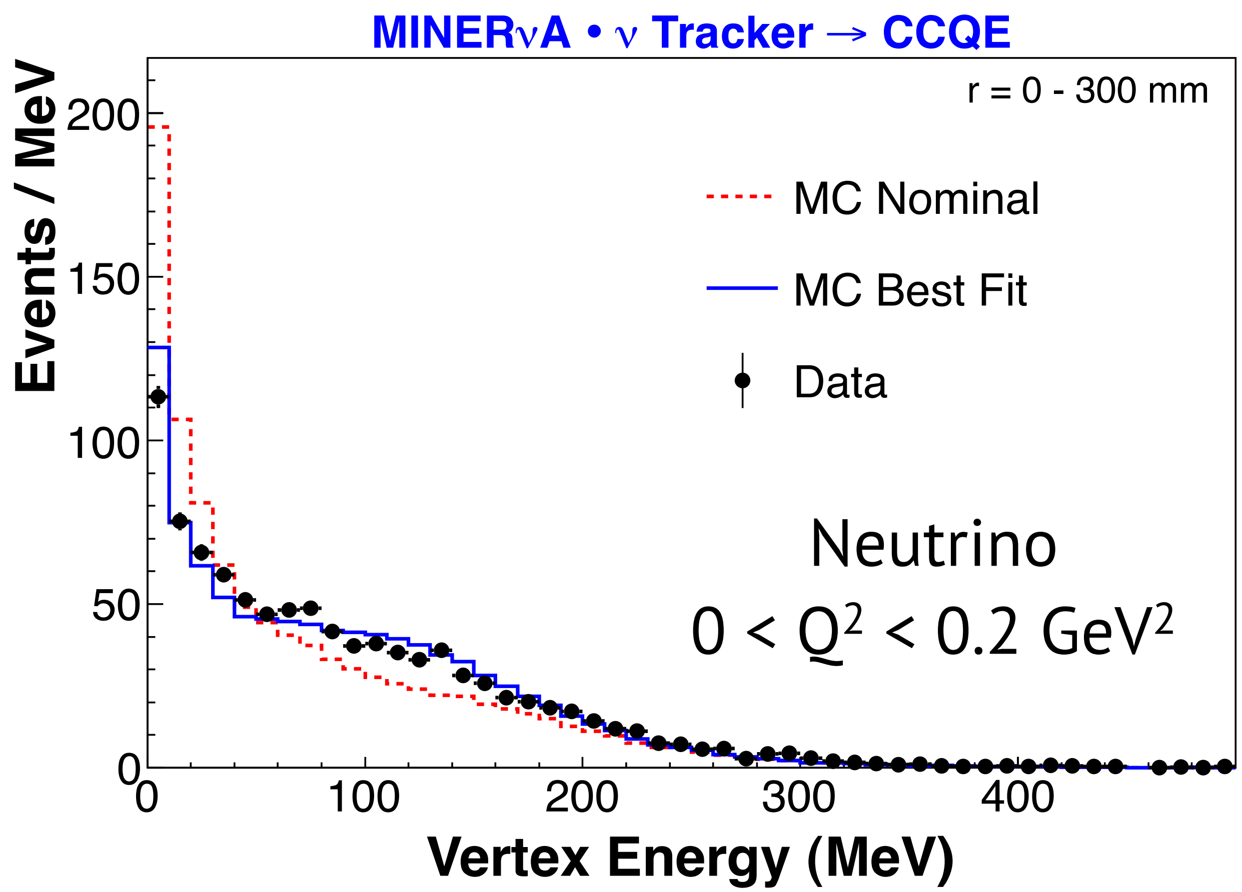


- Energy near the vertex is not used as part of the event selection because we are not confident in our MC to produce a realistic hadron spectrum.
- Indeed, in the data, we see a harder vertex energy distribution for neutrinos, and a slightly softer distribution for antineutrinos.

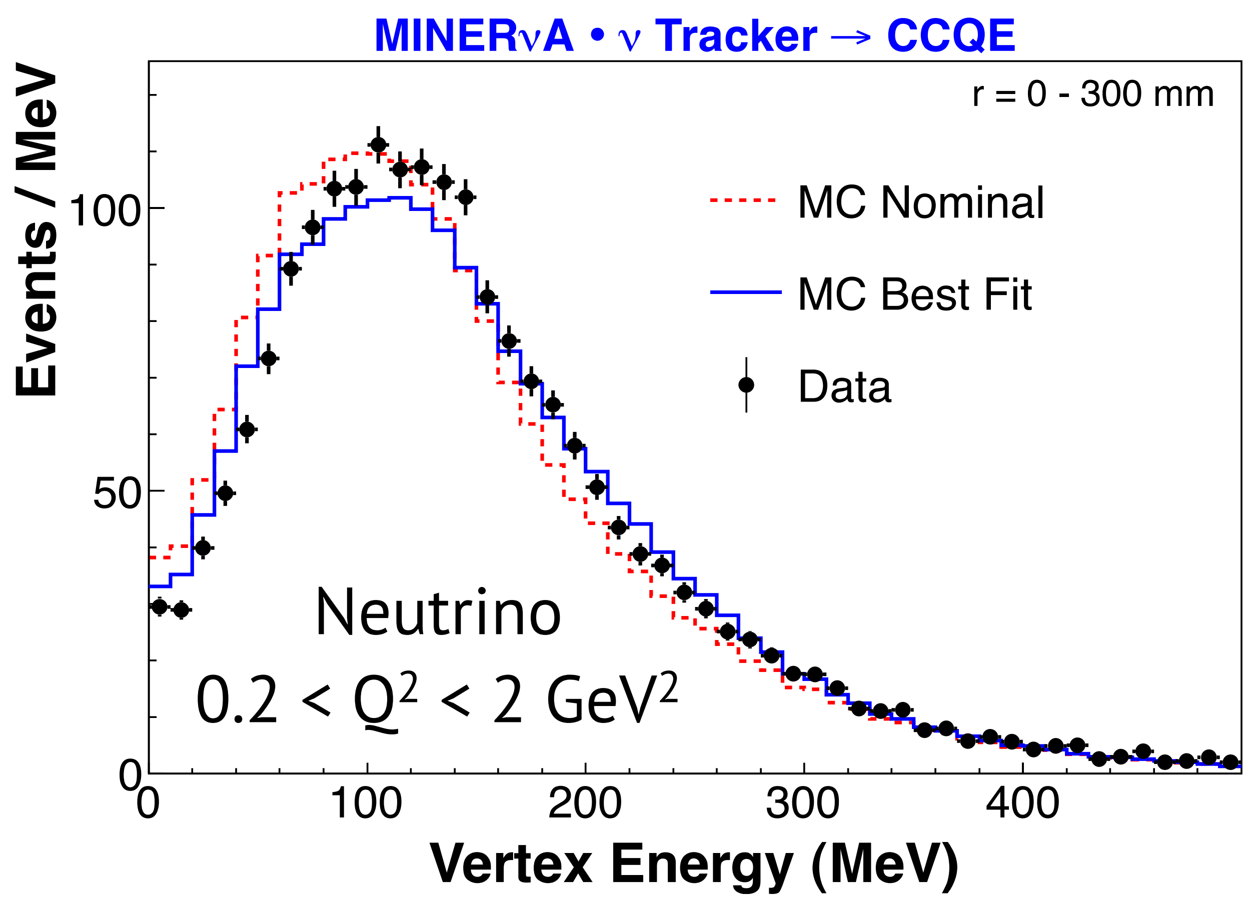
- Study annular rings out to 10 g/cm^2 (antineutrino, ~120 MeV KE proton), 30 g/cm^2 (neutrino, ~225 MeV KE proton).
- Examine energy deposition profiles and attempt to fit for extra particle content under a proton hypothesis.

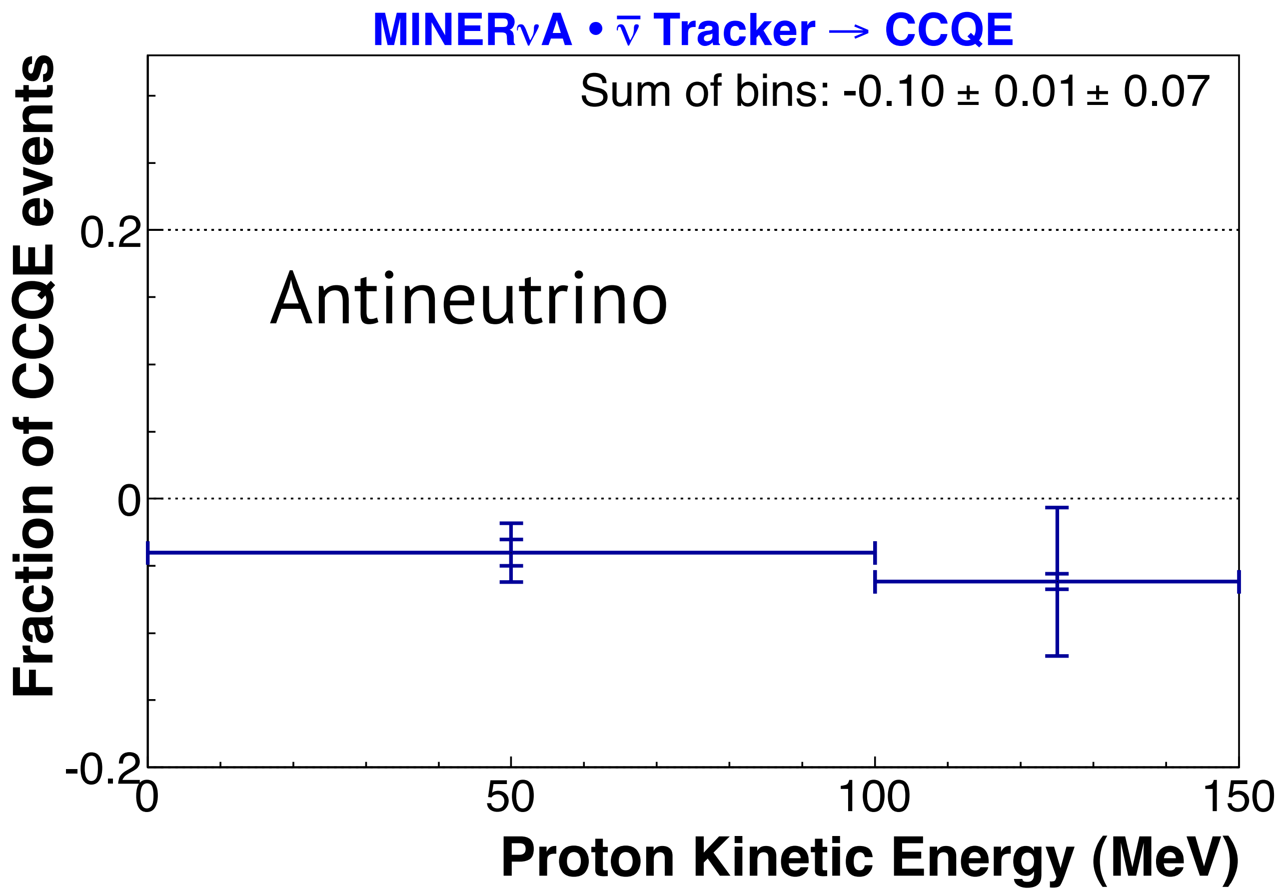


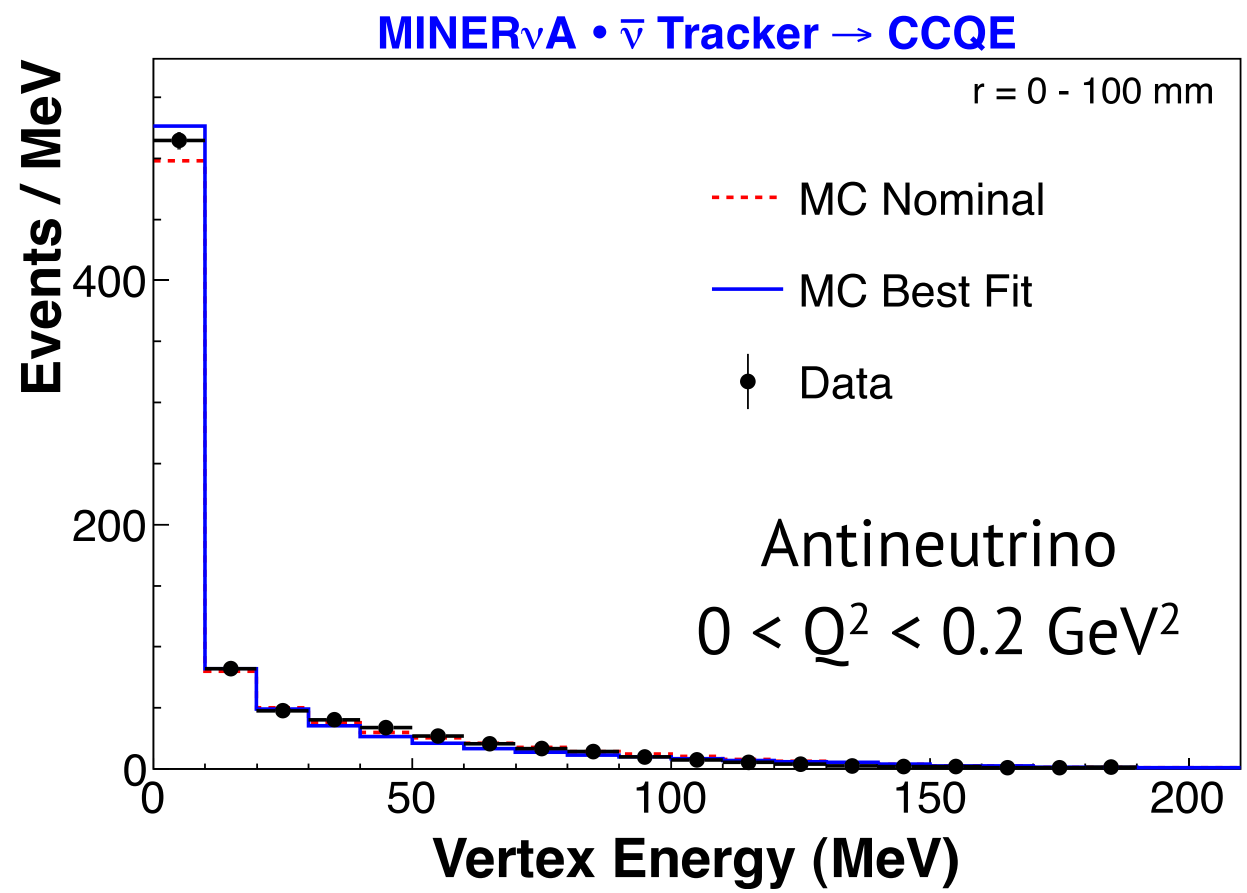




- In our neutrino data, we find that adding an additional low-energy proton (KE < 225 MeV) to (25 ± 9)% of QE events improves agreement.

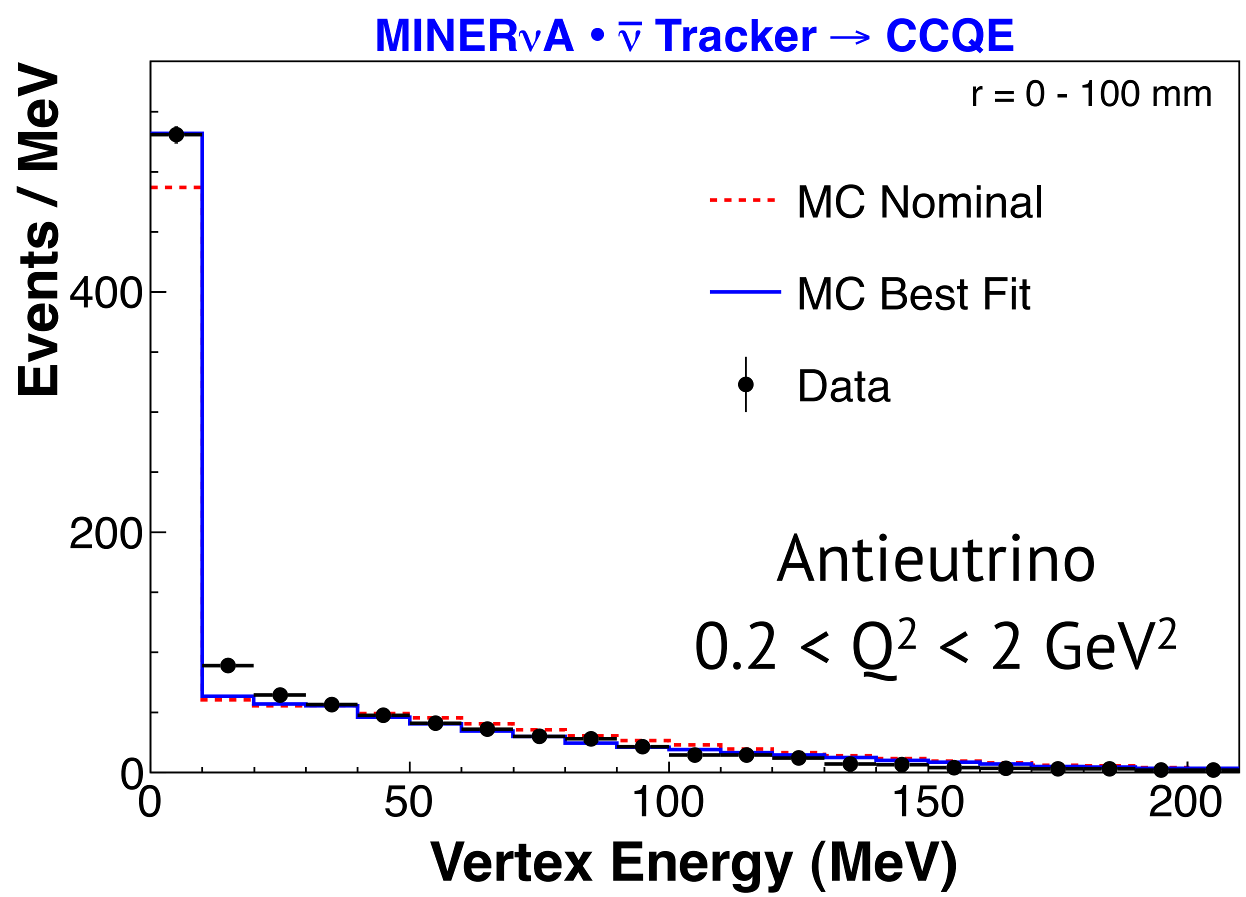






- In our antineutrino data, we find no such evidence.

- Indeed, there is some evidence of an over-prediction in the number of protons with the data preferring (-10 ± 7)% of QE events to have an extra proton.

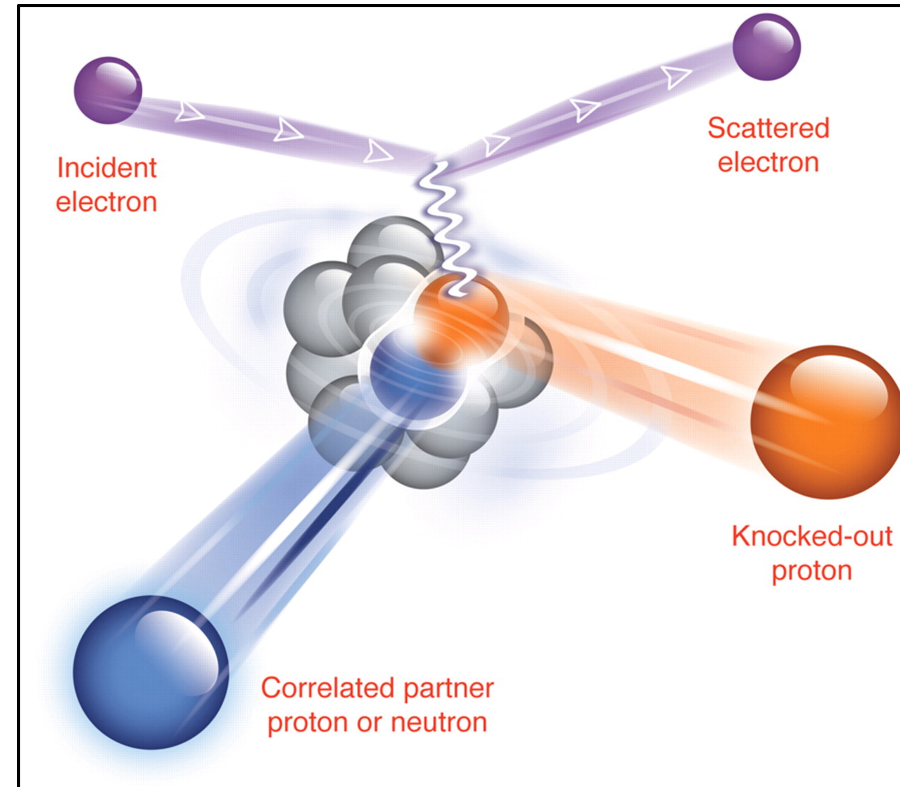


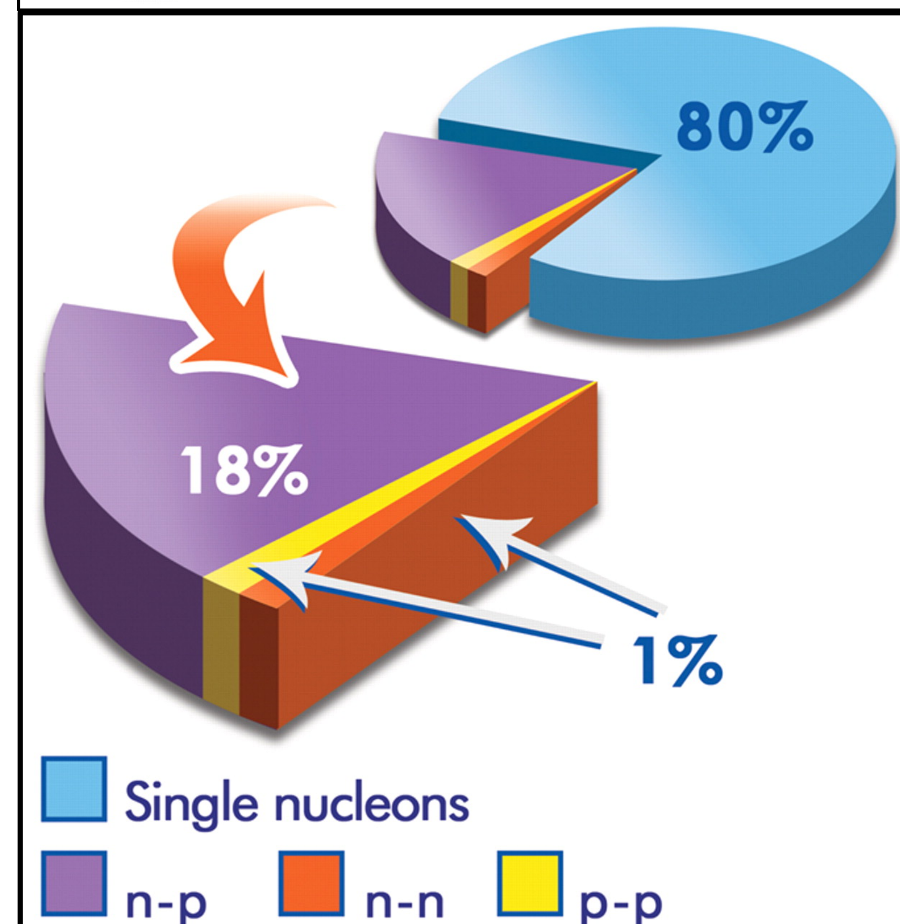
- Multi-nucleon models predict mostly correlated n-p pairs.

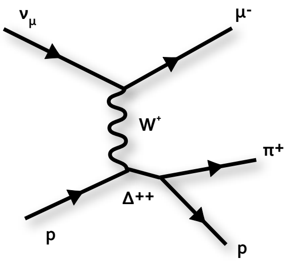
- For CCQE events, this would lead naturally to p-p final states for neutrinos and n-n final states for antineutrinos.

  - Intriguing consistency with our results!

- Final State Interactions (FSI) make this a somewhat murky picture, but the appropriate systematics are considered in the analysis and the trend is hard to explain any other way as simply.

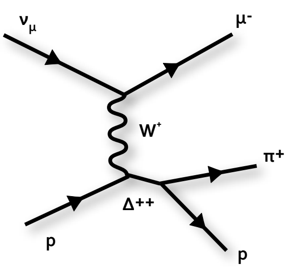






Confusion Reigns

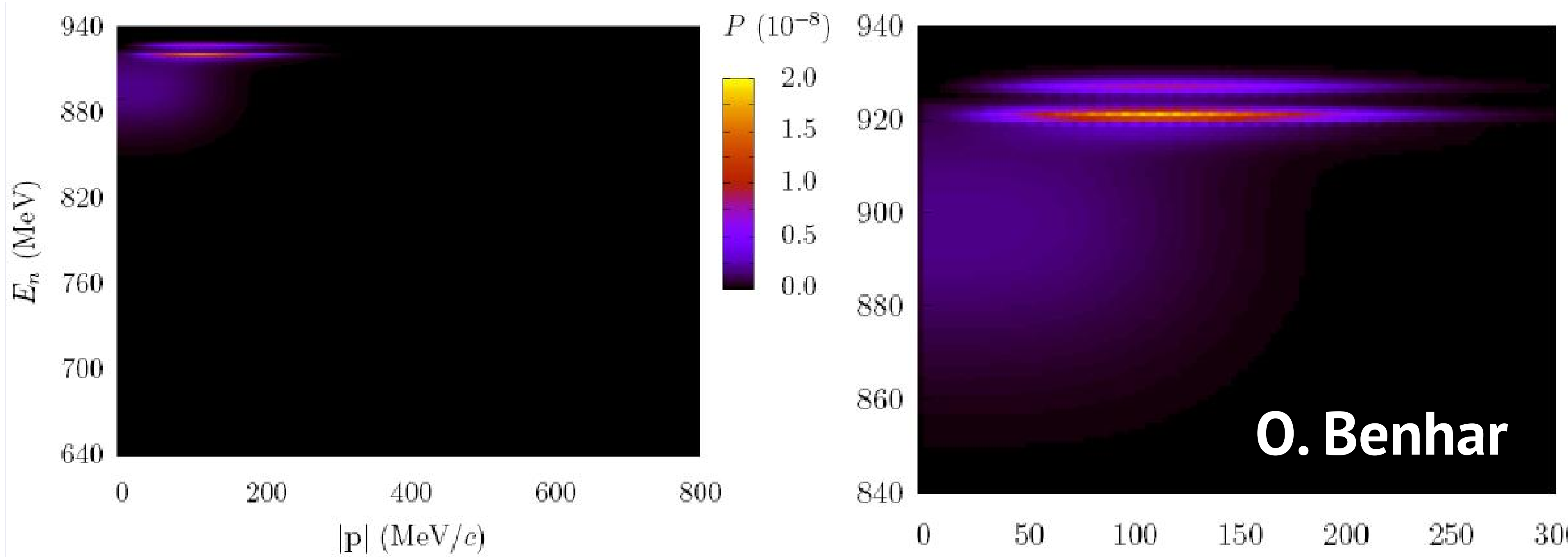
- What are we scattering off of anyway?
  - Single nucleons?
  - Coupled nucleons?
  - Quarks?
  - The entire nucleus?
- We need a good nuclear model for the initial state as well. Nobody is shocked by this, but recall that Llewellyn Smith and the RFG worked well for a long time and work well at "high" energy.
- We run into problems when doing precision physics in the long-baseline (non-reactor) energy regime.



Spectral Functions

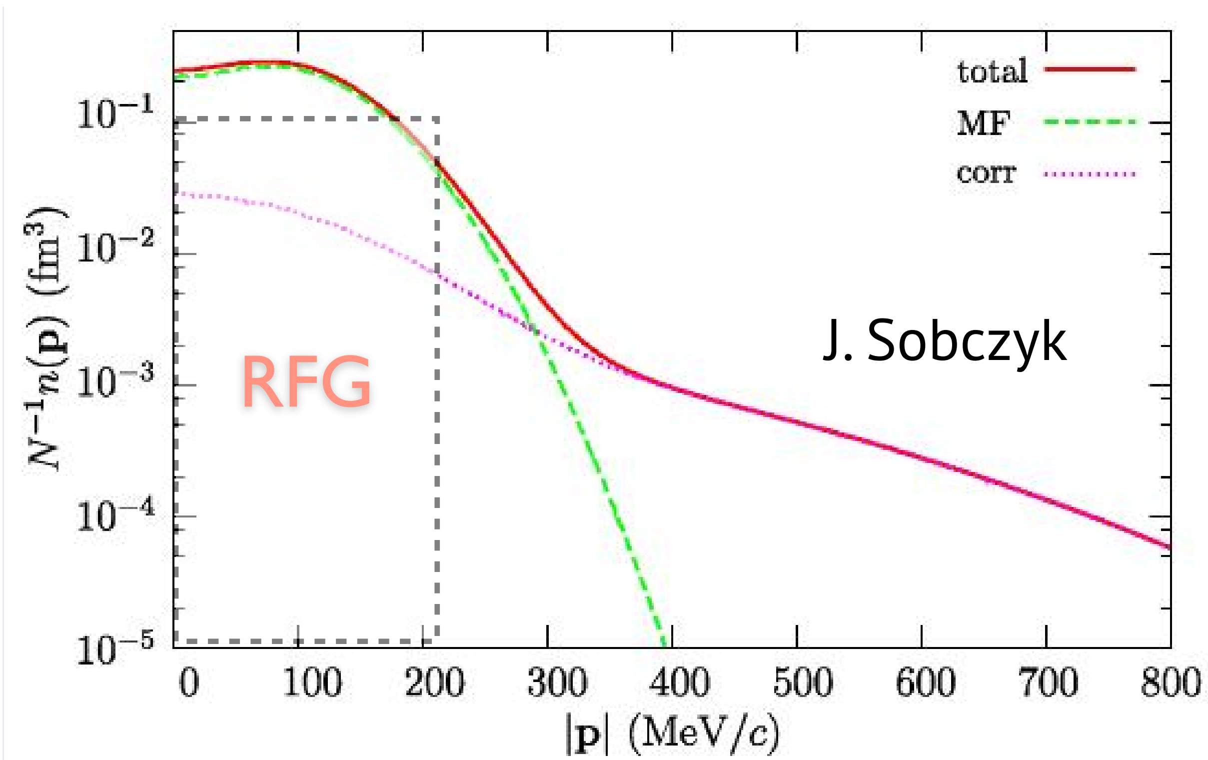
Spectral Function for Oxygen

- Most event generators use the Fermi Gas model.
- But there are better options: *Spectral Functions*.
- Technically FGM is a "spectral function" also - SFs offer momentum distributions and removal energy for nuclei.

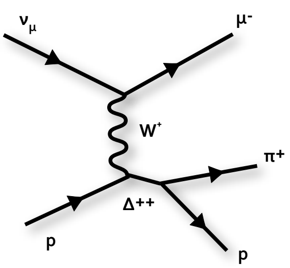


Shell Orbitals are visible:

	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$
E (MeV)	45	18.44	12.11



- The Mean Field (MF) and Short-range Correlations (SRC) contributions are separated here.
- The high momentum tail (absent in the Fermi Gas Model) comes from correlated pairs of nucleons.

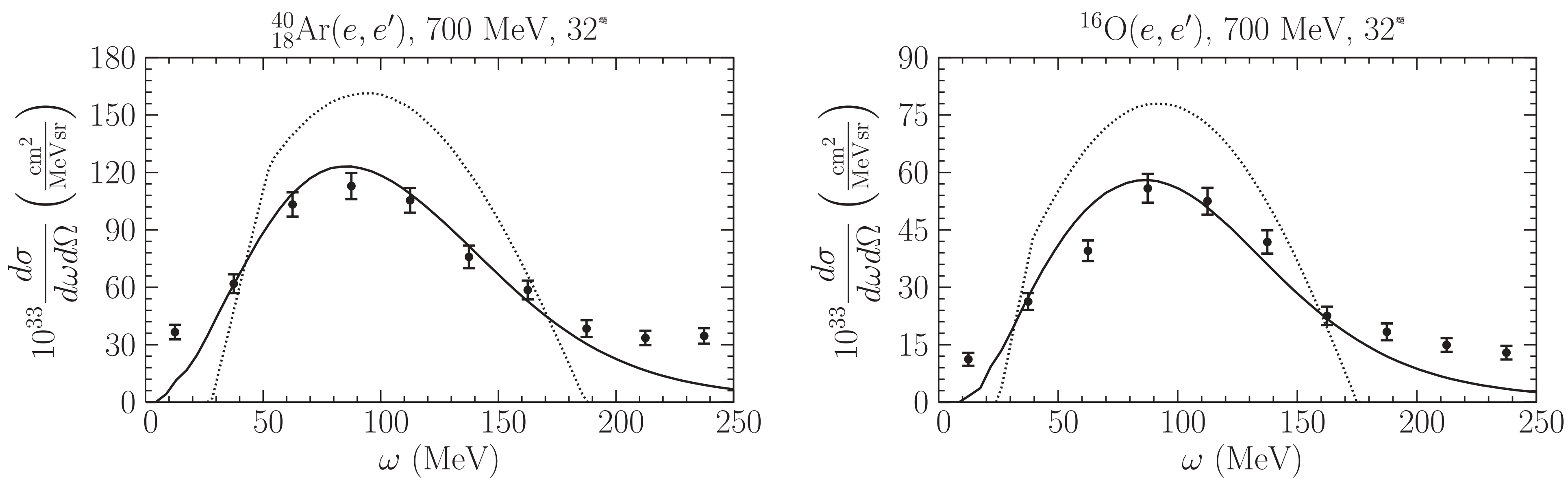


Spectral Functions

Electron Scattering Data

Argon

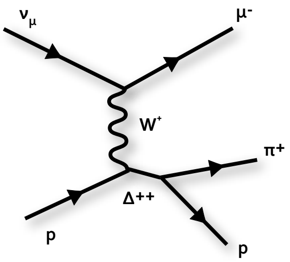
Oxygen



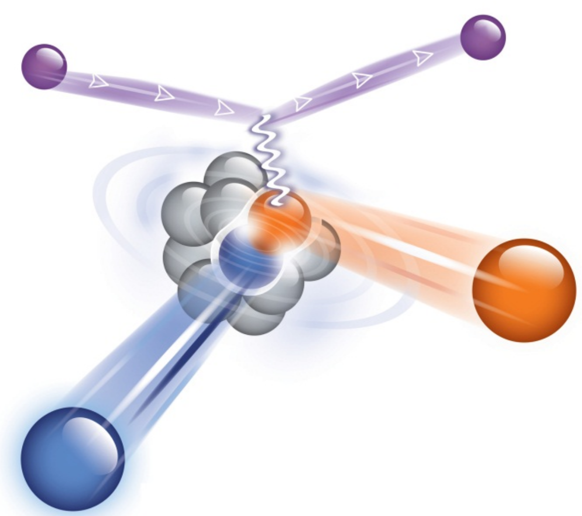
A. Ankowski and J. Sobczyk, PRC 77, 044311

- Typically, spectral functions better reproduce the quasielastic peak.

- Comparison of a Gaussian Spectral Function (GSF, solid) and Fermi Gas Model (FGM, dashed) for Argon (left) and Oxygen (right) in electron scattering data.

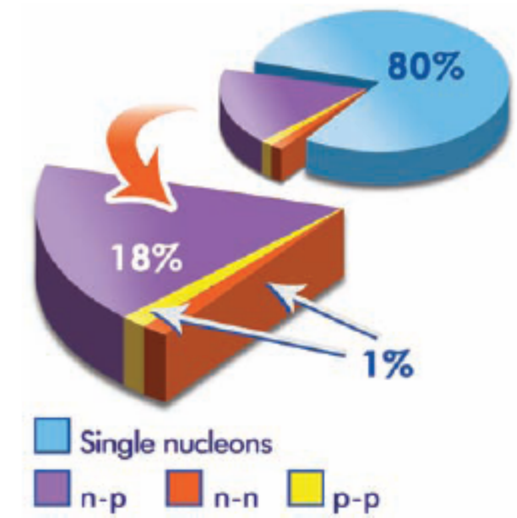


Short-Range Correlations & MEC



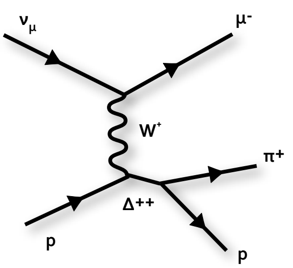
Recent Jlab analyses of ^{12}C quasi-elastic scattering with **electrons** have demonstrated significant probabilities to see multiple nucleons knocked out.

*R. Subedi et al., Science **320**, 1476 (2008)*



- The kinematics may be altered there is a ~20% chance of scattering from a correlated pair of nucleons rather than a single nucleon.
- This is not a new idea in quasielastic scattering, but evidence in charged lepton scattering now strengthens the case.
- See D. Gaskell's talk last week for more on the relationship between the EMC (not MEC!) effect and short range correlations.
  - Neutrinos as probes that see different structure functions may have something important to say about short range correlations. (Flavor-tasting by neutrinos vs antineutrinos?)

Dekker et al., PLB **266**, 249 (1991)
Singh, Oset, NP **A542**, 587 (1992)
Gil et al., NP **A627**, 543 (1997)
J. Marteau, NPPS **112**, 203 (2002)
Nieves et al., PRC **70**, 055503 (2004)
Martini et al., PRC 80, 065001 (2009)



Your favorite nuclear model...

Theorist: It doesn't need to match the data, it just needs to be correct.

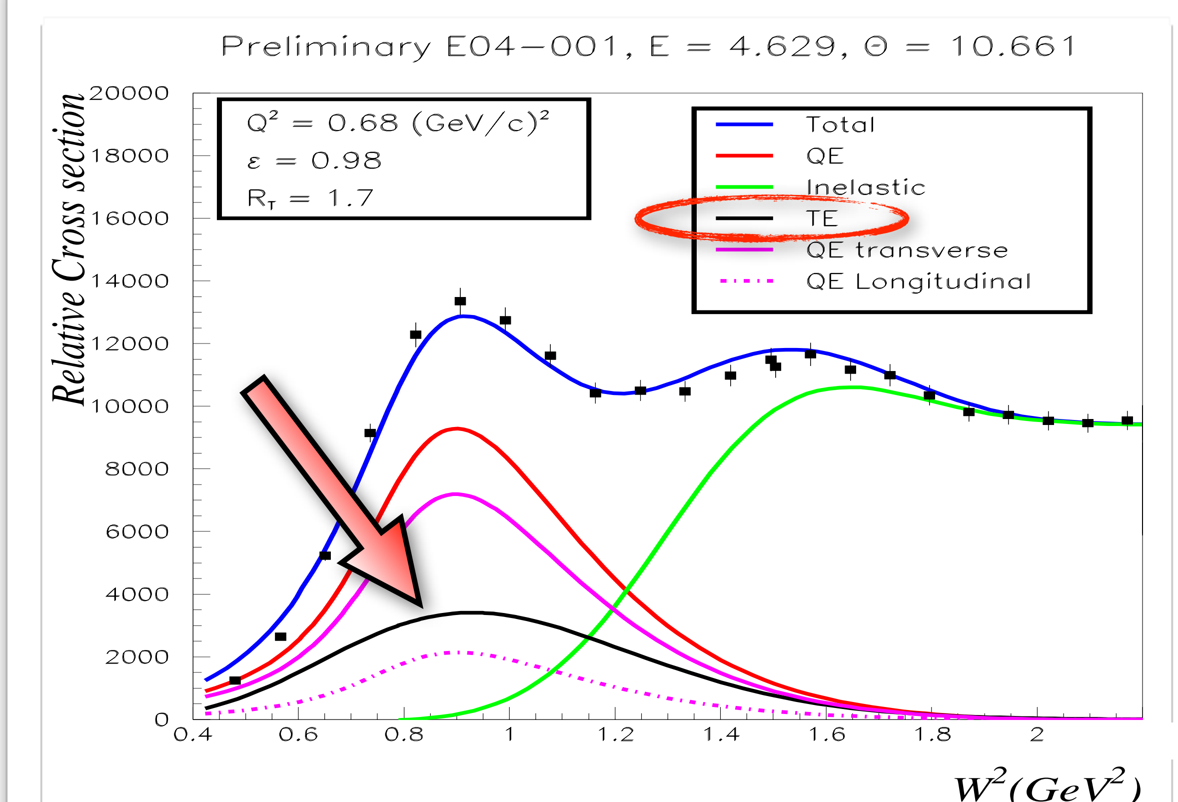
Experimentalist: It doesn't need to be correct, it just needs to match the data.

Transverse Enhancement

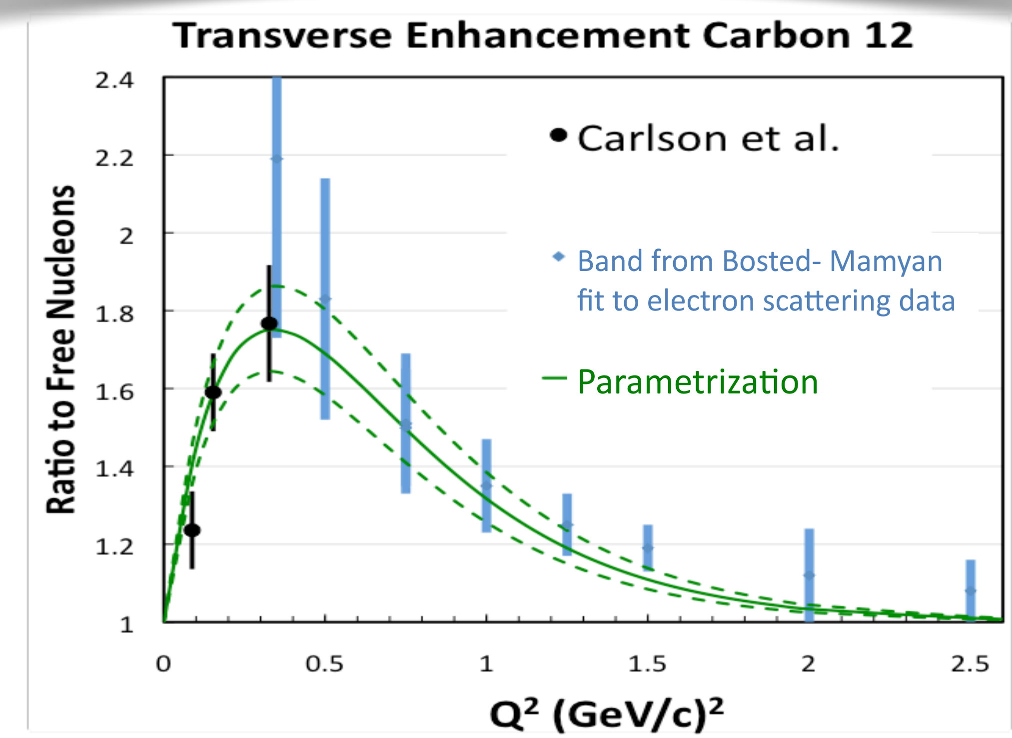
Bodek, Budd, and Christy Eur.Phys.J. C71 (2011) 1726

- The sort of model experimenters love - it may or may not be right, but it matches data (MiniBooNE - NOMAD).
- Separate the cross section into "longitudinal" and "transverse" components (polarization of the virtual photon) in electron scattering.
- Modify only vector magnetic form factors with e$^-$ scattering data - everything else is single free nucleon.
- e$^-$ scattering data suggests only the longitudinal portion of the QE x-section is ~universal free nucleon response function - the transverse component shows an enhancement relative to this approach.

$$\frac{d^2\sigma}{d\Omega d\omega} = \Gamma\left[R_T(q,\omega) + \epsilon \cdot R_L(q,\omega)\right]$$

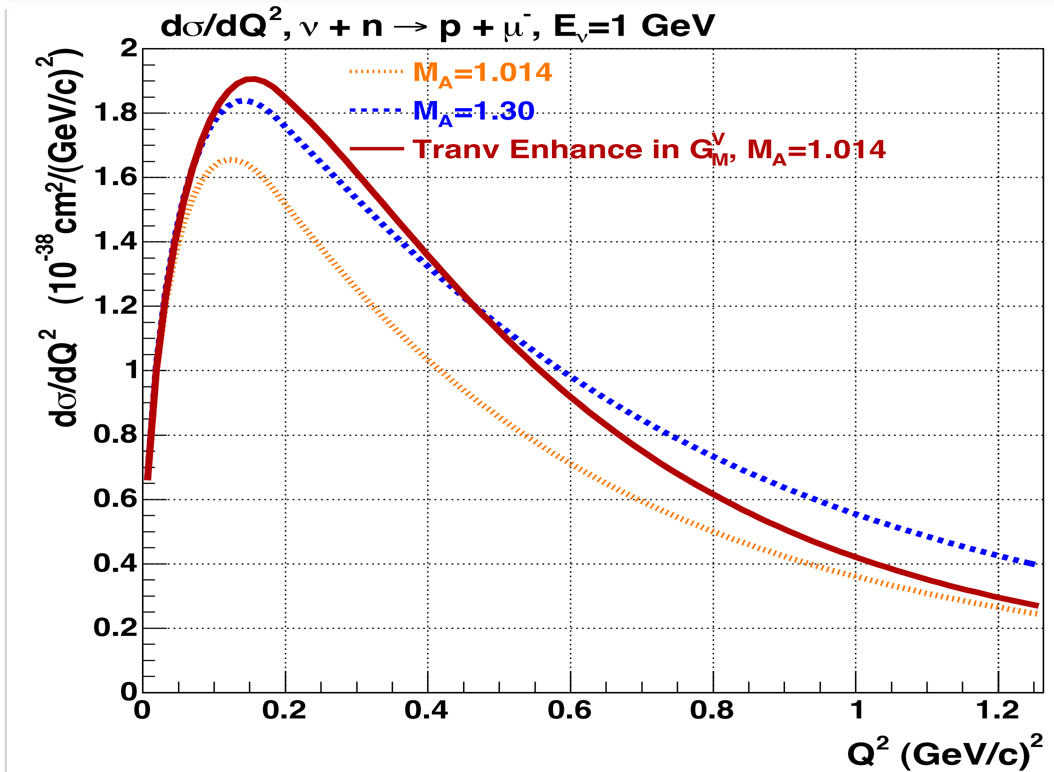


Bodek, Budd, and Christy Eur.Phys.J. C71 (2011) 1726

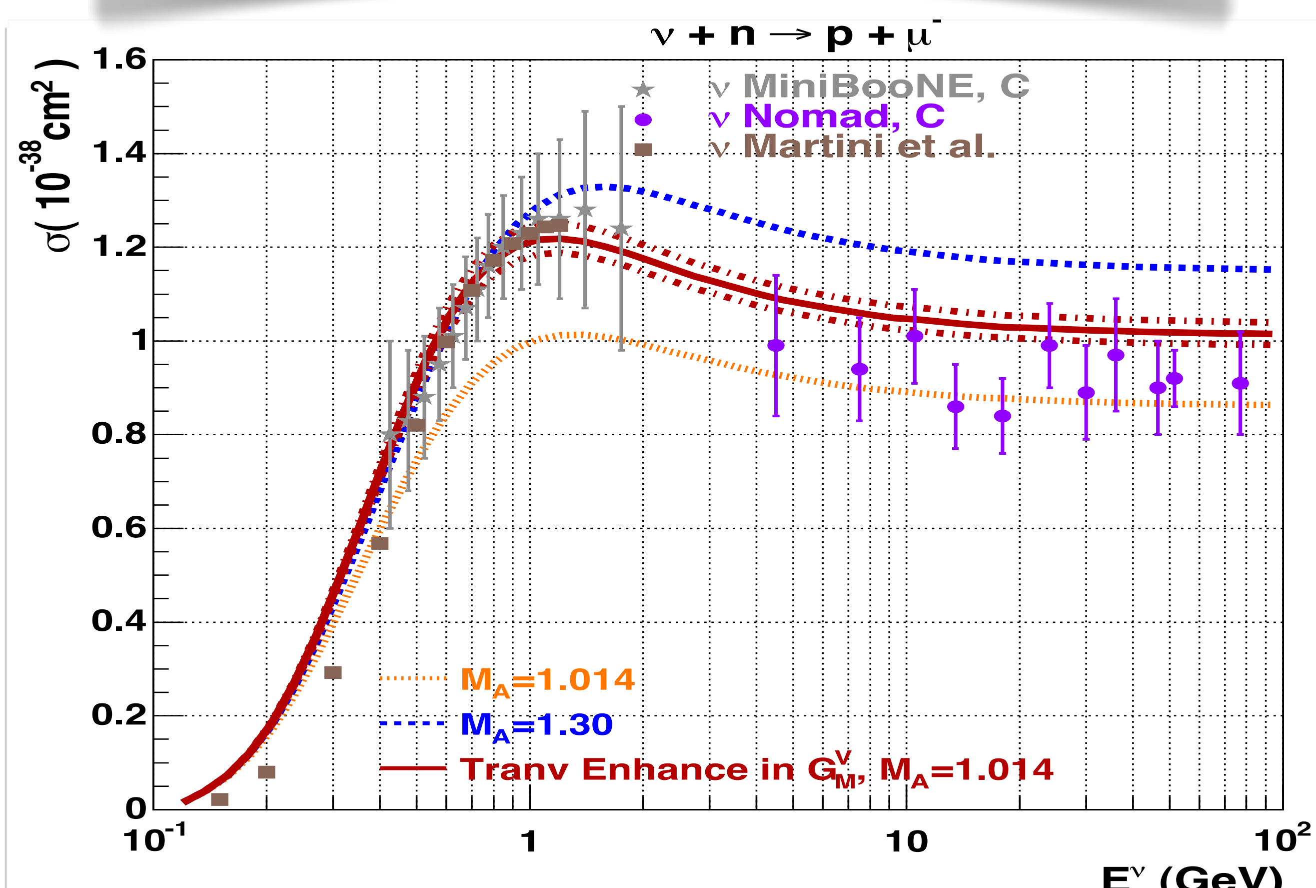


Fit to electron scattering data from JUPITER (JLab E04-001) to extract enhancement as a function of Q^2.

Transverse Enhancement

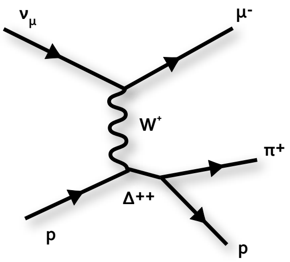


Bodek, Budd, and Christy Eur.Phys.J. C71 (2011) 1726

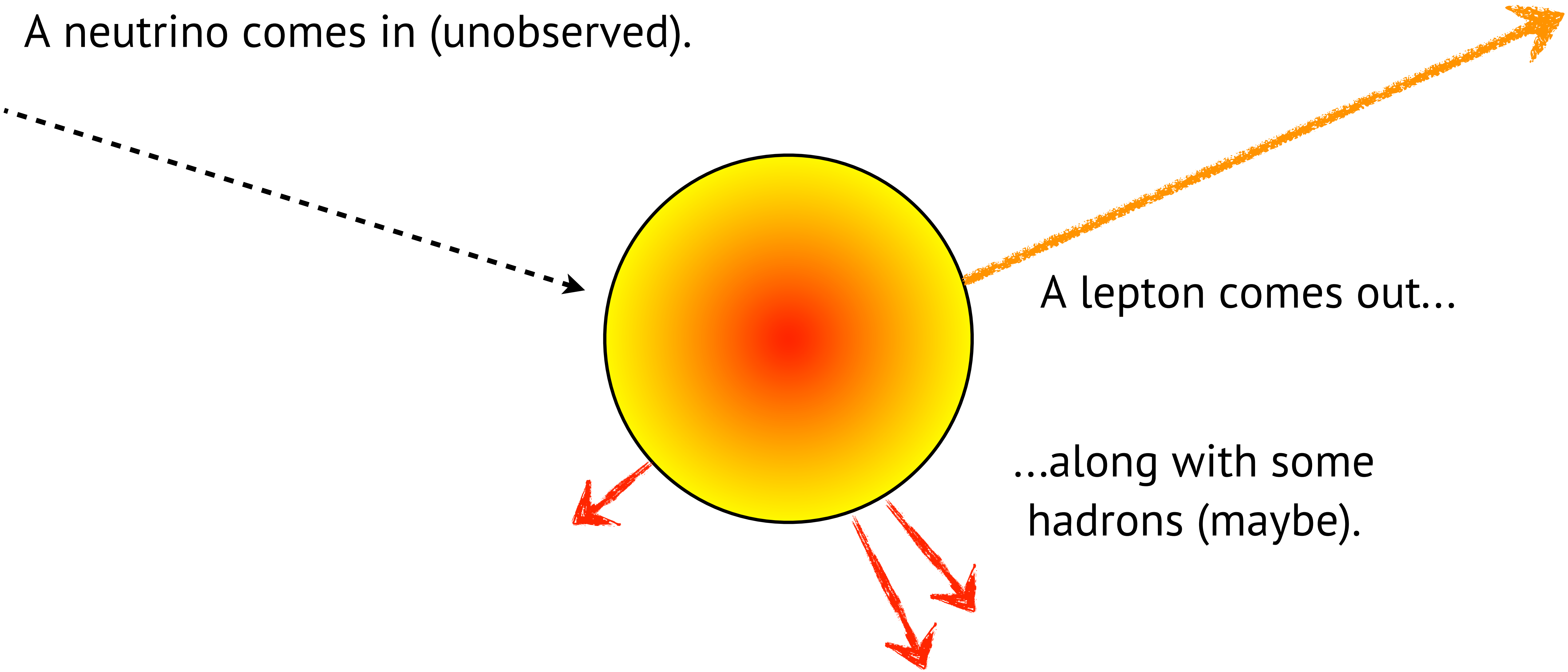


Bodek, Budd, and Christy Eur.Phys.J. C71 (2011) 1726

- $d\sigma/dQ^2$ w/ M_A = 1.014 GeV & TEM is very similar to the result for M_A = 1.3 GeV for Q^2 < 0.6 (GeV/c)^2.
- For high Q^2, the TEM contribution is small.
- Experiments at high energy often remove low Q^2 values from their M_A fits - predict an even lower M_A due to steep slope for $d\sigma/dQ^2$ at M_A = 1.014 GeV.

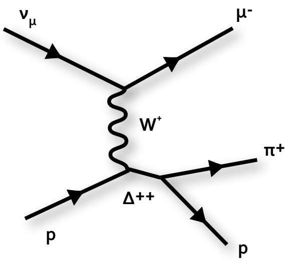


Back to our Problem...



What was the neutrino's energy?

Okay, let's go back to the first idea and try to do a better job.



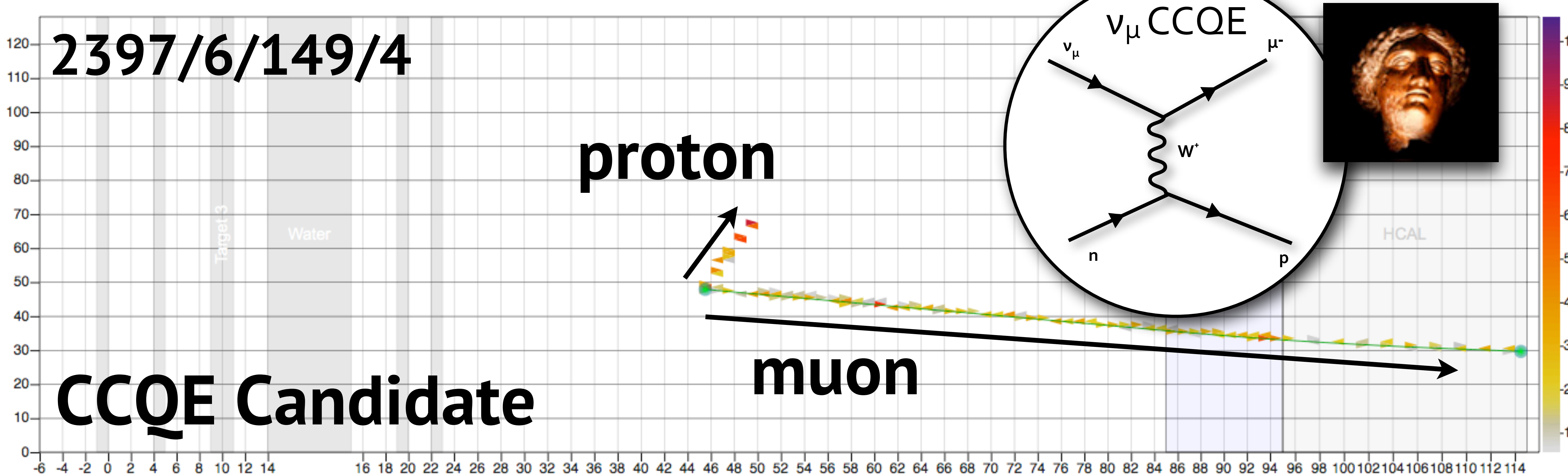
Liquid Argon

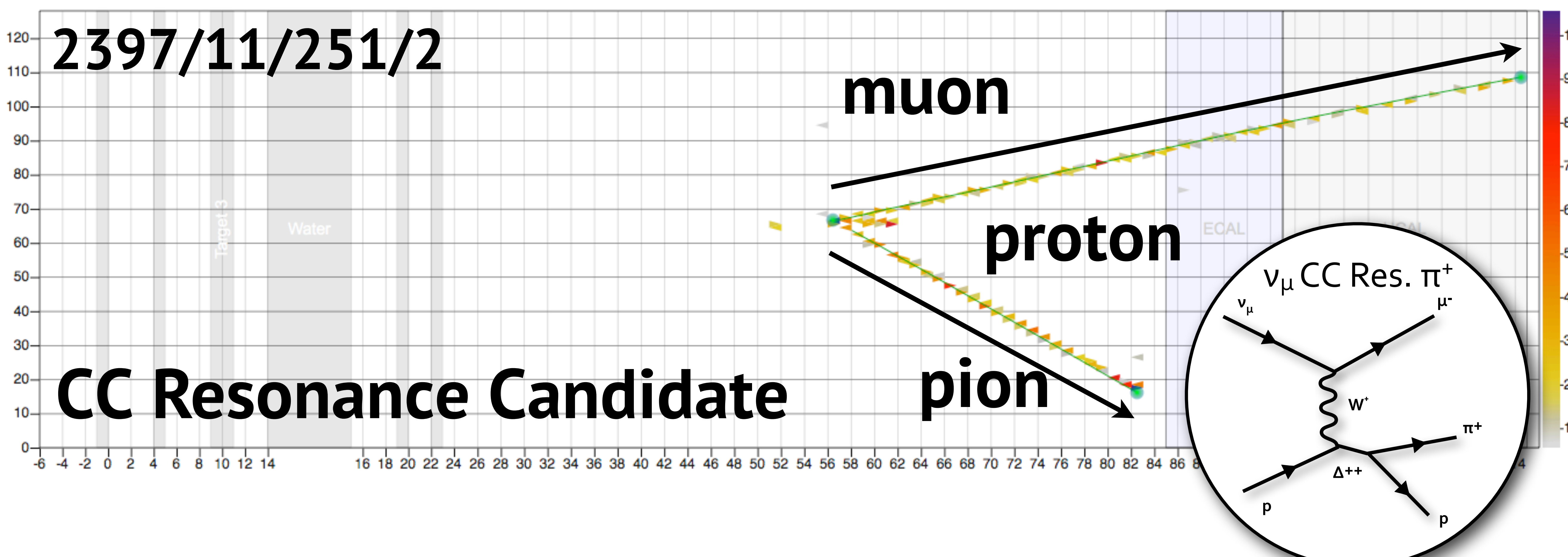
…scintillator too!

- Now that we know some of the problems, let's look at a few images of neutrino interactions (for inspiration).

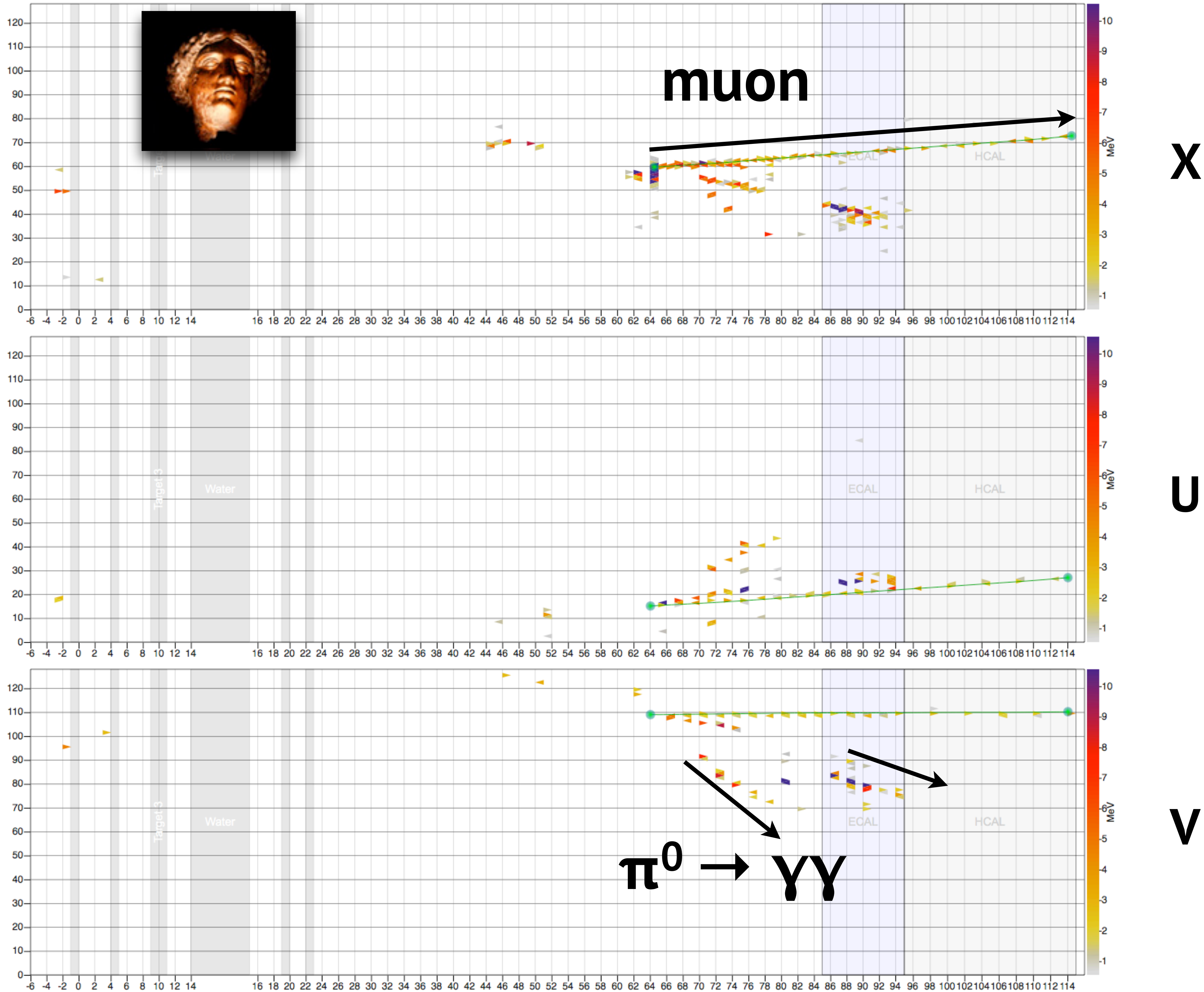
- In order to understand neutrino interactions we need very detailed information on everything in the final state.

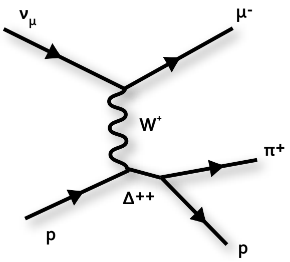
- The classic trade-off in neutrinos is to give up detail for sheer detector mass, but we've realized we need to be more clever…


2397/6/149/4
proton
muon
CCQE Candidate
νμ CCQE
νμ
μ-
W+
n
p
Water
Target 3
HCAL
MeV

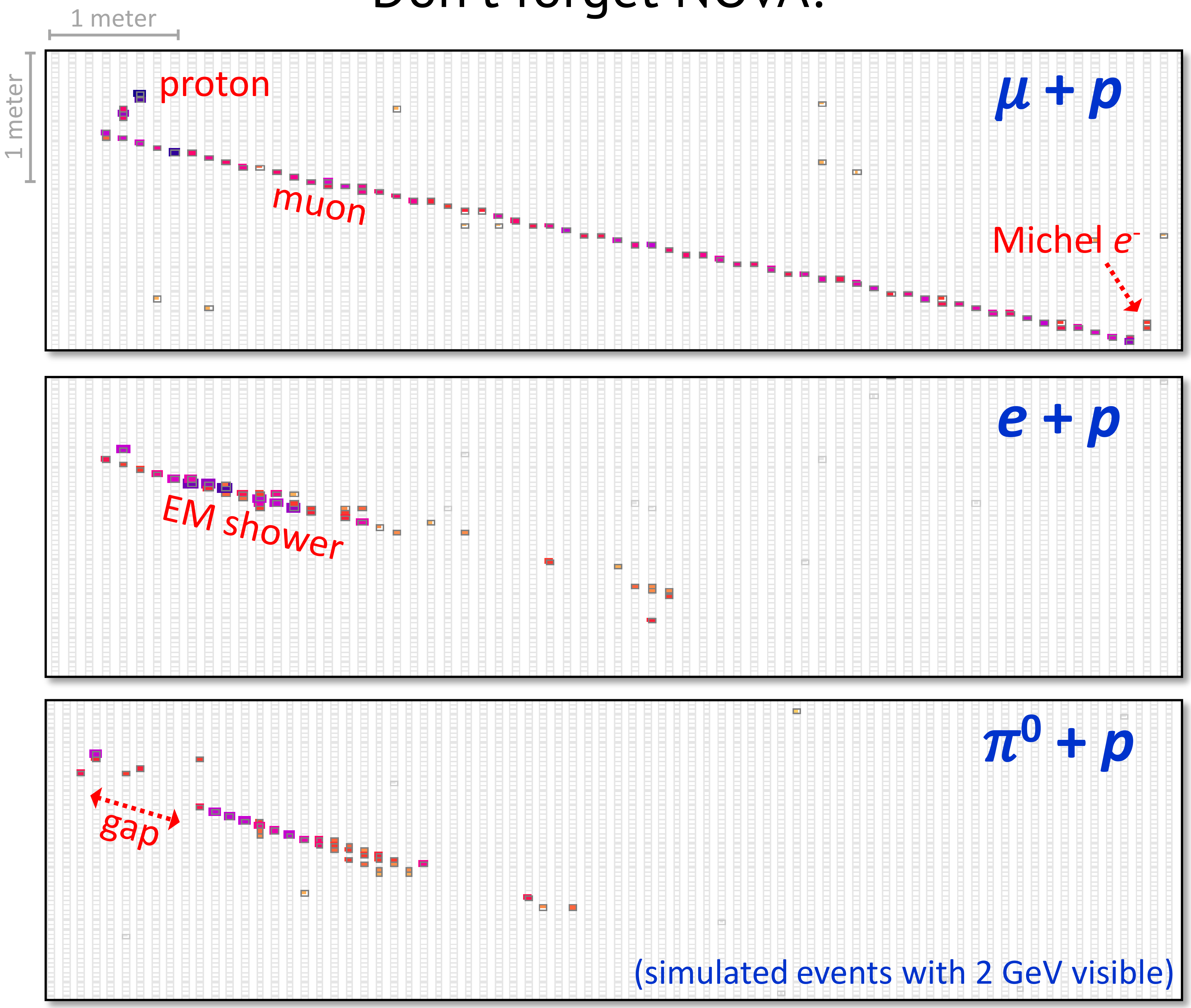

2397/11/251/2
muon
proton
pion
CC Resonance Candidate
νμ CC Res. π+
νμ
μ-
W+
π+
Δ++
p
p
Water
Target 3
ECAL
MeV

Data - 2397/8/1167/2



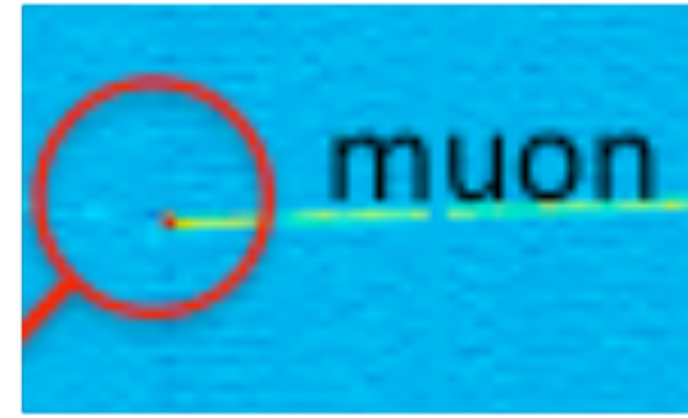


Don't forget NOvA!

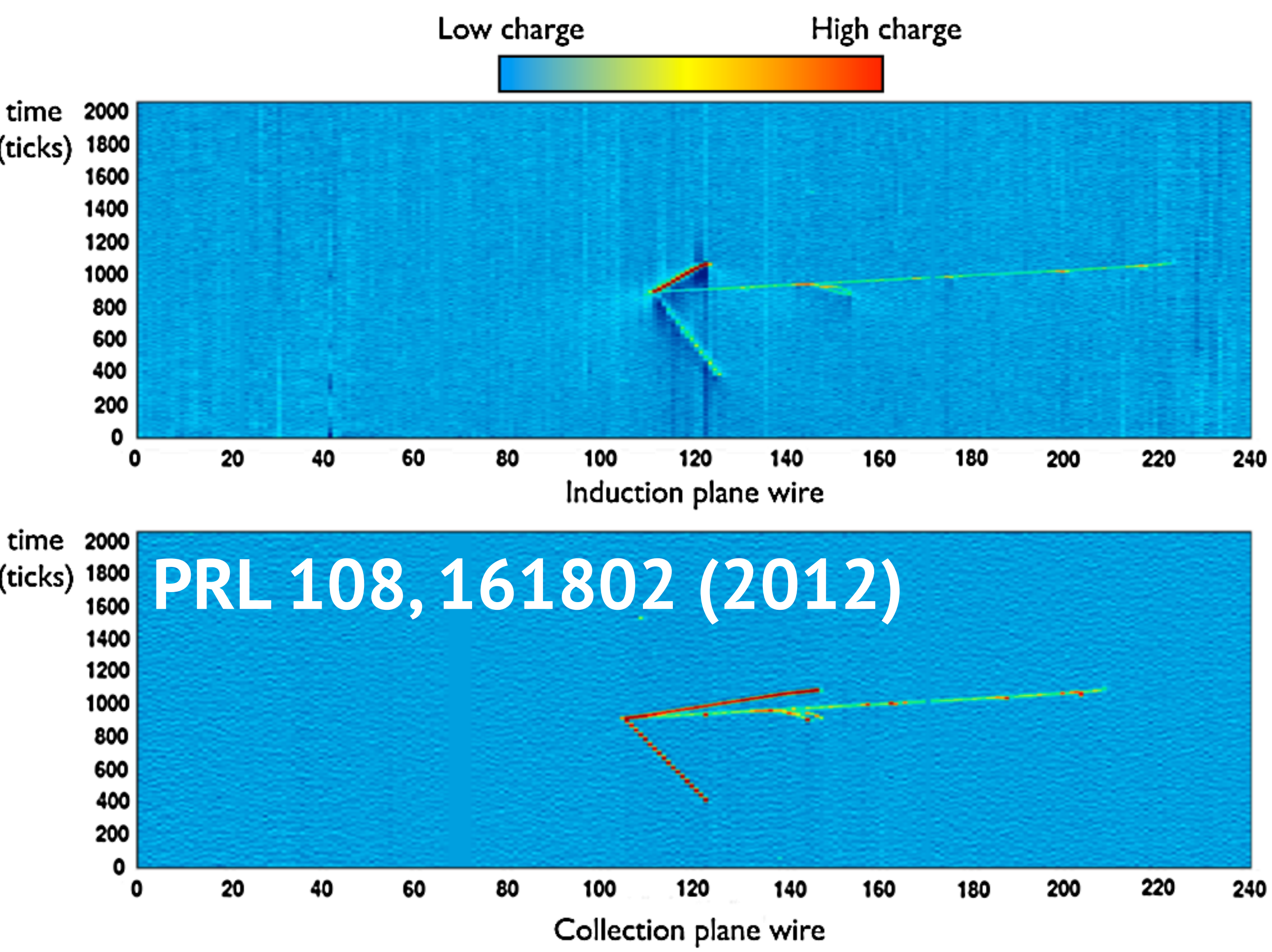


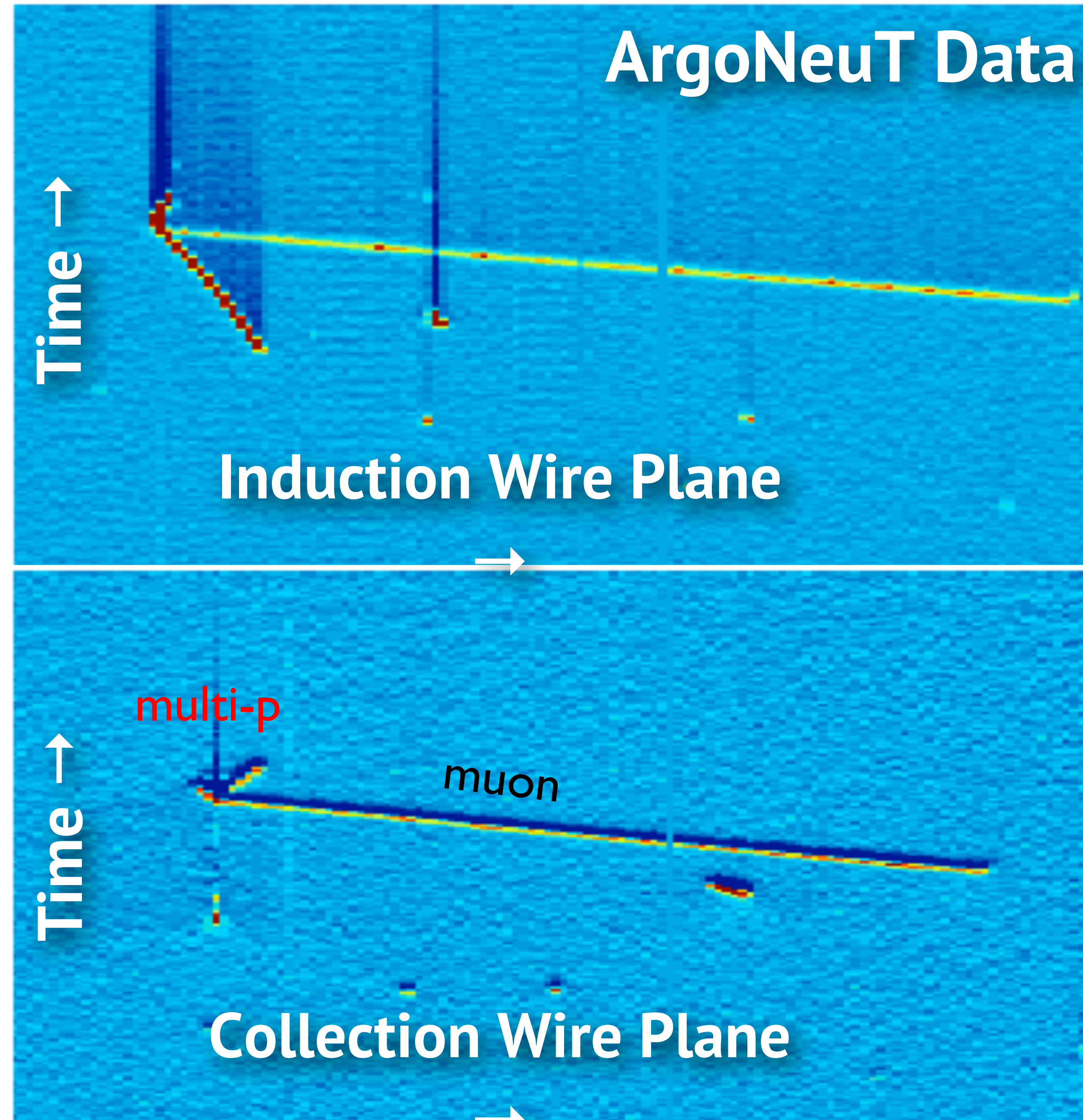
Ryan Patterson, Caltech

Liquid Argon TPCs

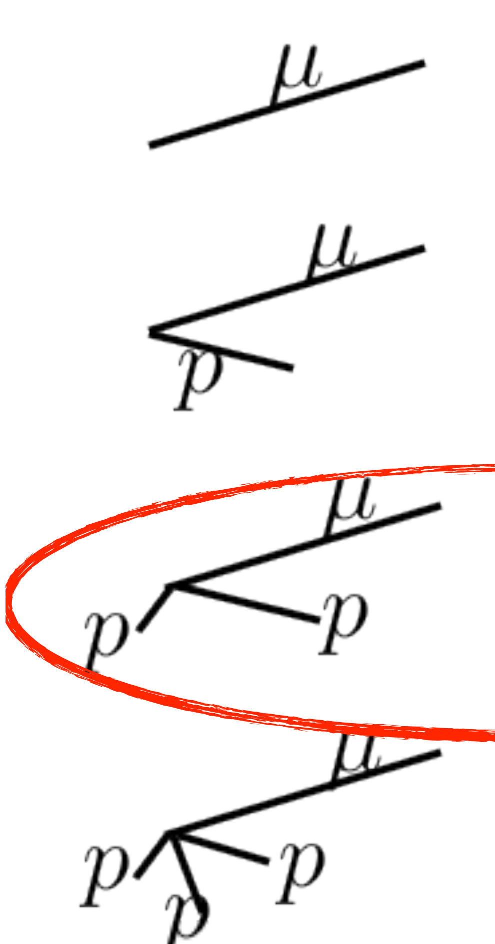


- Try to see EVERYTHING leaving the nucleus....
- See R. Guenette's talk from earlier in this series.





New paper this weekend: arXiv 1404.4809



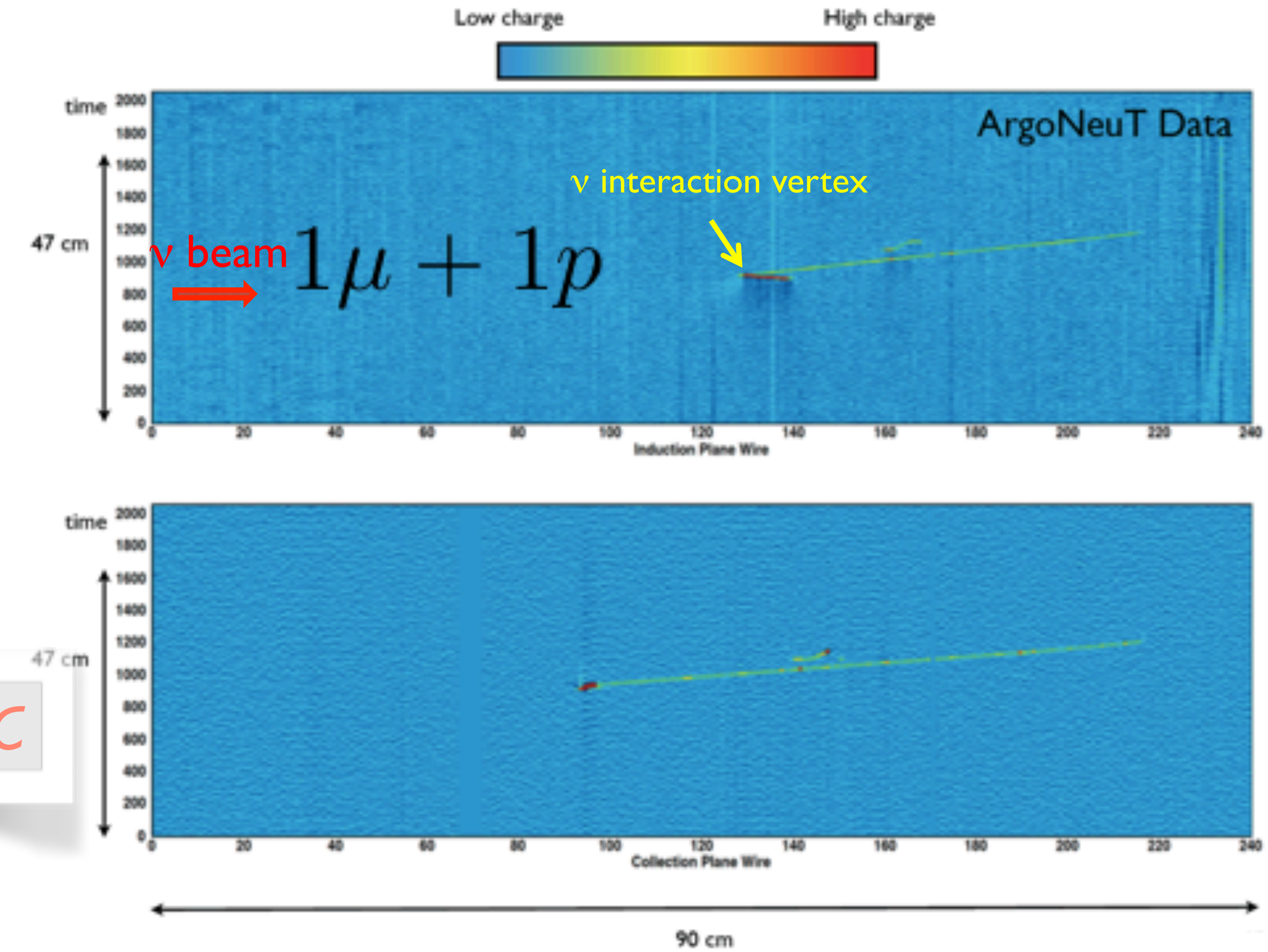
$1\mu + 0p$

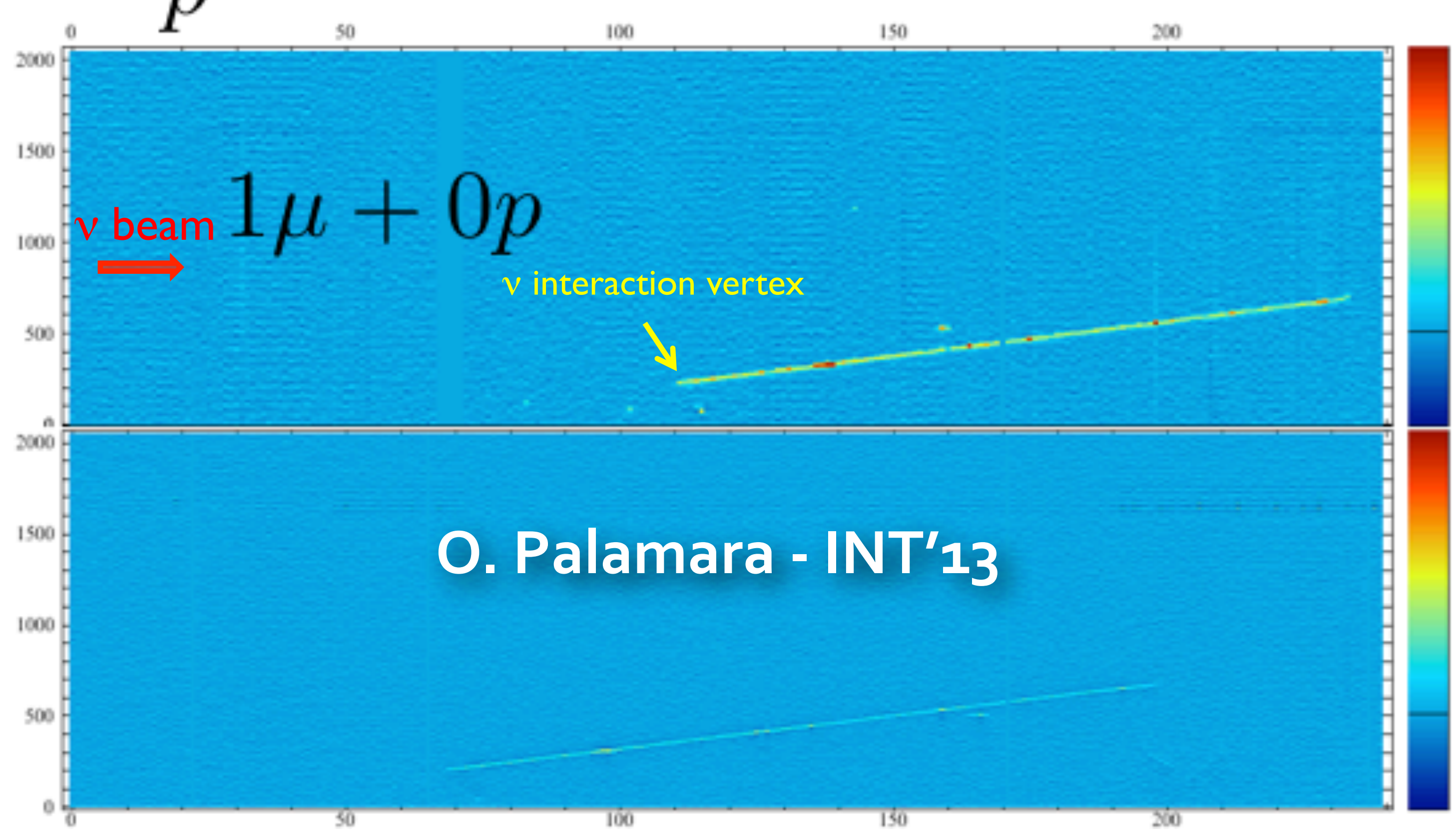
$1\mu + 1p$

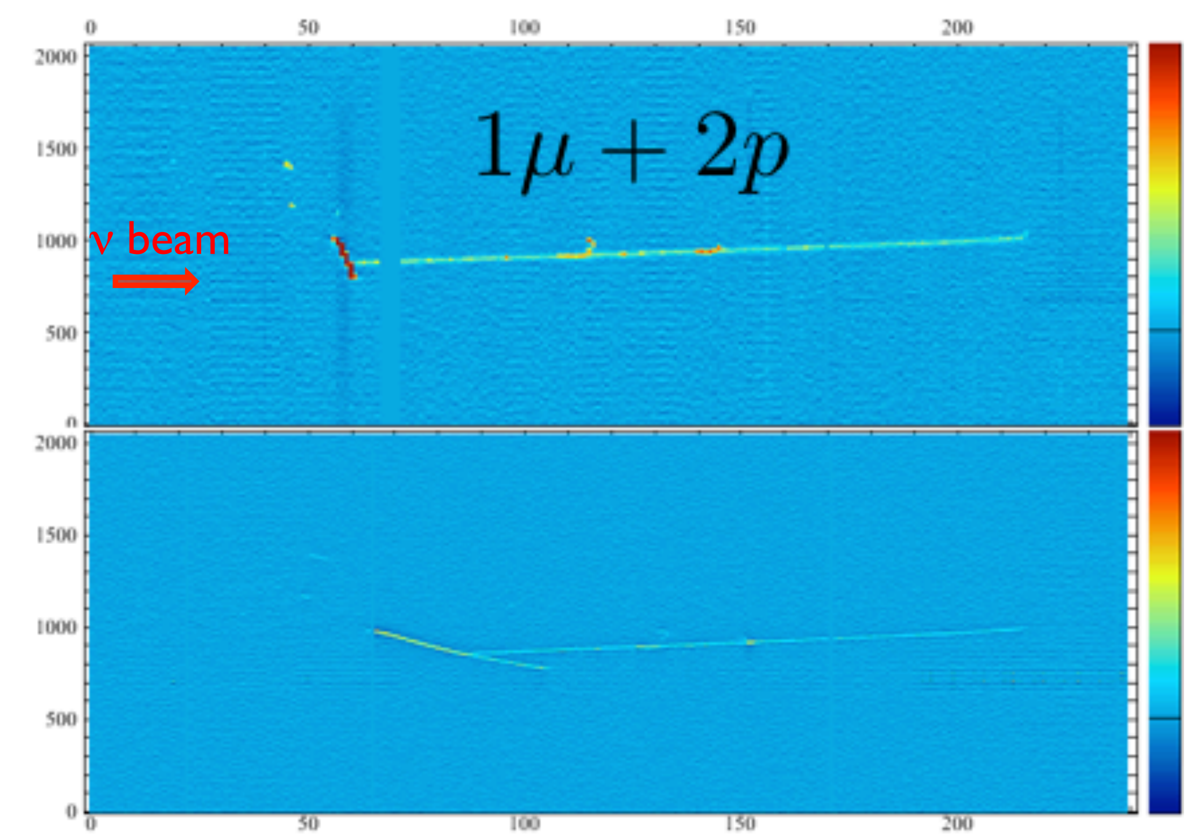
$1\mu + 2p$

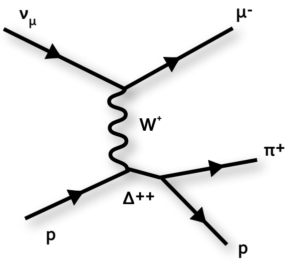
Sensitive to SRC

$1\mu + 3p$



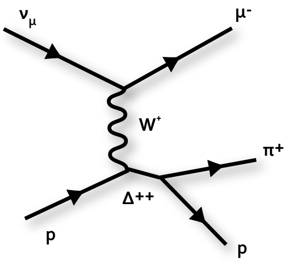






Conclusions

- Neutrino interaction physics is "messy" but an important gatekeeper to really big questions we would like to answer about neutrinos.
  - It looks like we all need to build expertise in nuclear physics and particle physics questions may be able to help drive progress in that field.
- Current and future experiments at Fermilab are directly tackling these problems and there is a great interactive feedback loop running with the theory community and MC generators developers.
- The keys to future success are lots of data at different energies on different targets (and lots of data on the targets we really care about!). We need to factorize the (flux times cross section times nuclear effects) problem!



Back-up

TABLE XVI: Summary of the contributions to the total uncertainty on the predicted number of events, assuming $\sin^2 2\theta_{13}$=0 and $\sin^2 2\theta_{13}$=0.1, separated by sources of systematic uncertainty. Each error is given in units of percent.

Error source	$\sin^2 2\theta_{13}$= 0	0.1
Beam flux & ν int. (ND280 meas.)	8.5	5.0
ν int. (from other exp.)		
$x_{CCother}$	0.2	0.1
x_{SF}	3.3	5.7
p_F	0.3	0.0
x^{CCcoh}	0.2	0.2
x^{NCcoh}	2.0	0.6
$x^{NCother}$	2.6	0.8
x_{ν_e/ν_μ}	1.8	2.6
W_{eff}	1.9	0.8
$x_{\pi-less}$	0.5	3.2
$x_{1\pi E_\nu}$	2.4	2.0
Final state interactions	2.9	2.3
Far detector	6.8	3.0
Total	13.0	9.9

K. Abe et al, arXiv 1304.0841

- Cross-section and interaction uncertainties (especially the nuclear physics model) are a significant part of the total error budget, even with constraints from a Near Detector!

Overview of the T2K experiment, where a high intensity beam of ν_μ is created at Tokai and sent 300 km under ground to the water Cherenkov detector Super-Kamiokande.

CCQE Cross Section	
M_A^{QE}	The mass parameter in the axial dipole form factor for quasi-elastic interactions
x_1^{QE}	The normalization of the quasi-elastic cross section for $E_\nu < 1.5$ GeV
x_2^{QE}	The normalization of the quasi-elastic cross section for $1.5 < E_\nu < 3.5$ GeV
x_3^{QE}	The normalization of the quasi-elastic cross section for $E_\nu > 3.5$ GeV
Nuclear Model for CCQE Interactions (separate parameters for interactions on O and C)	
x_{SF}	Smoothly changes from a relativistic Fermi gas nuclear model to a spectral function model
p_F	The Fermi surface momentum in the relativistic Fermi gas model
Resonant Pion Production Cross Section	
M_A^{RES}	The mass parameter in the axial dipole form factor for resonant pion production interactions
$x_1^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu < 2.5$ GeV
$x_2^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu > 2.5$ GeV
$x^{NC1\pi^0}$	The normalization of the NC1π^0 cross section
$x_{1\pi E_\nu}$	Varies the energy dependence of the 1π cross section for better agreement with MiniBooNE data
W_{eff}	Varies the distribution of $N\pi$ invariant mass in resonant production
$x_{\pi-less}$	Varies the fraction of Δ resonances that decay or are absorbed without producing a pion
Other	
$x^{CCcoh.}$	The normalization of CC coherent pion production
$x^{NCcoh.}$	The normalization of NC coherent pion production
$x^{NCother}$	The normalization of NC interactions other than NC1π^0 production
$x_{CCother}$	Varies the CC multi-π cross section normalization, with a larger effect at lower energy
$\vec{x}_{FSI}$	Parameters that vary the microscopic pion scattering cross sections used in the FSI model
x_{ν_e/ν_μ}	Varies the ratio of the CC ν_e and ν_μ cross sections

Nuclear Effects in *Electron* Scattering

EMC Effect and Quark Distributions in Nuclei

Measurements of F_2^A / F_2^D (EMC, SLAC, BCDMS,…) have shown definitively that quark distributions are modified in nuclei.

Nucleus is not simply an incoherent sum of protons and neutrons

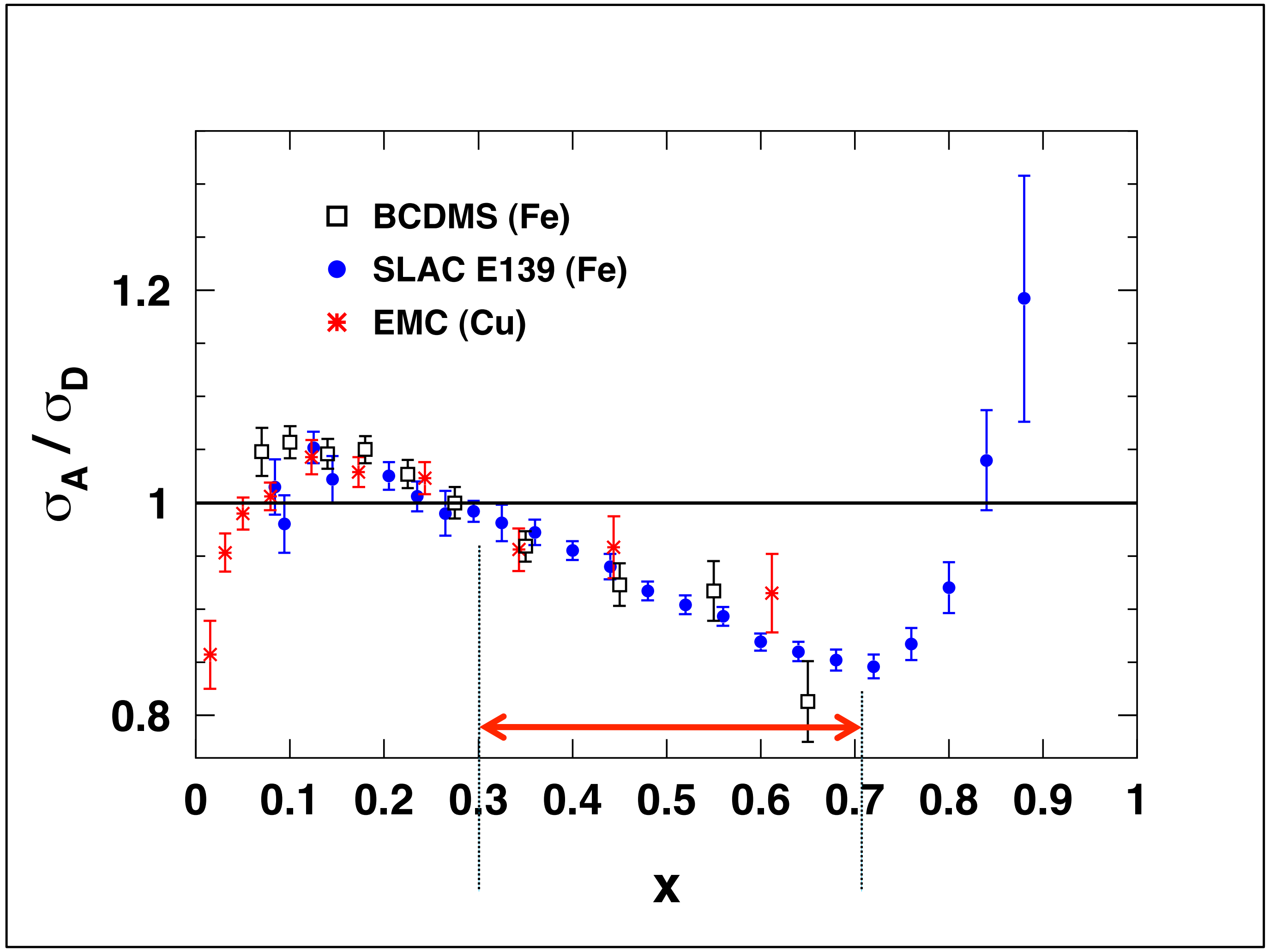
Observed properties:

1. *x*-dependence same for all *A*

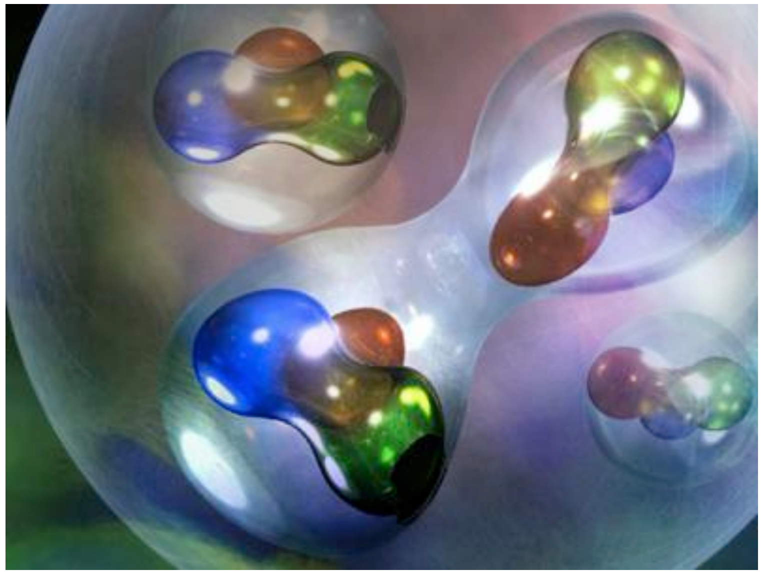
Shadowing:	$x<0.1$
Anti-shadowing:	$0.1<x<0.3$
EMC effect:	$x>0.3$

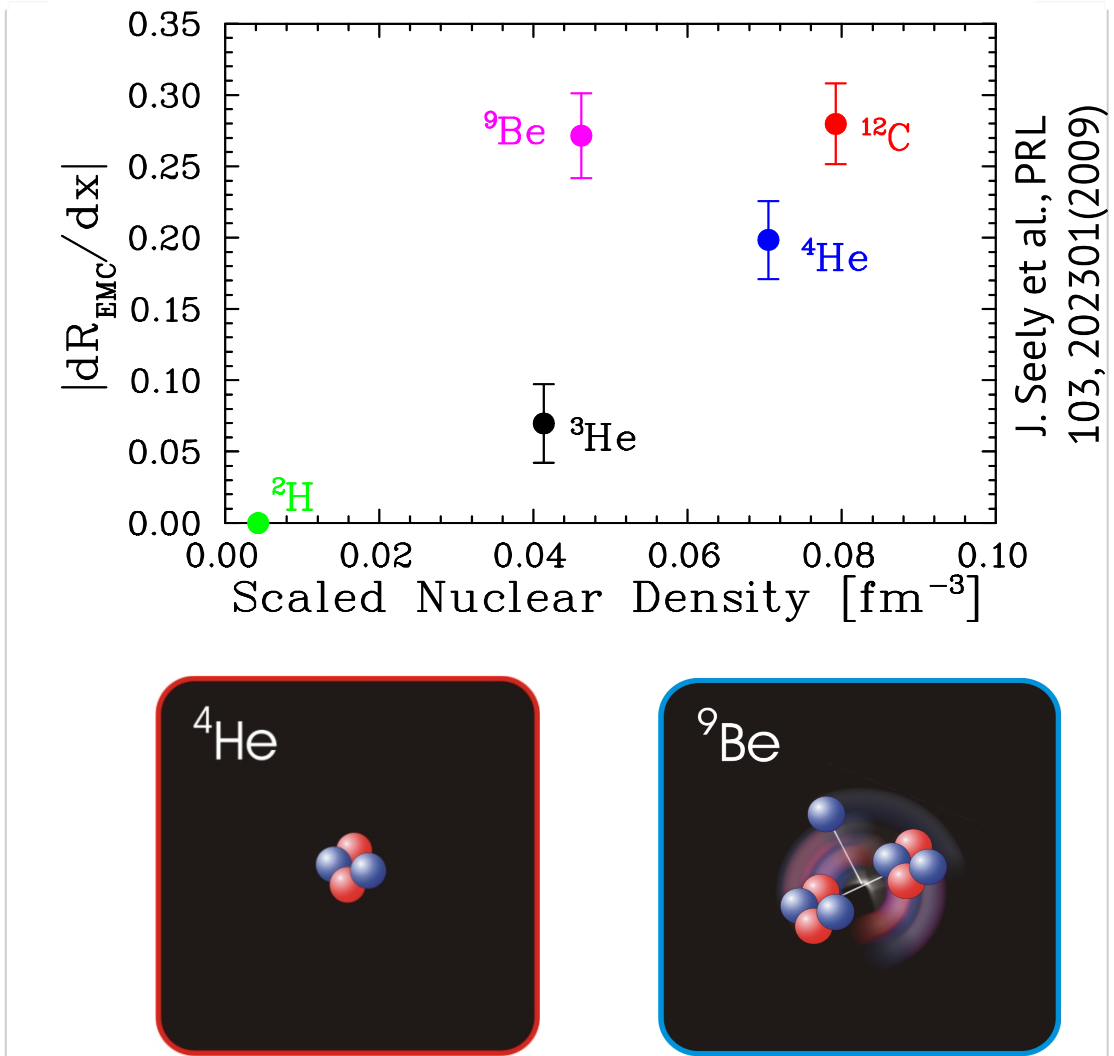
2. Size of EMC effect depends on *A* (i.e. minimum at $x=0.7$

D. Gaskell, ECT 2012, Trento
Hadrons in the Nuclear Medium



Short-Range Correlations and the EMC Effect





D. Gaskell, ECT 2012, Trento
Hadrons in the Nuclear Medium

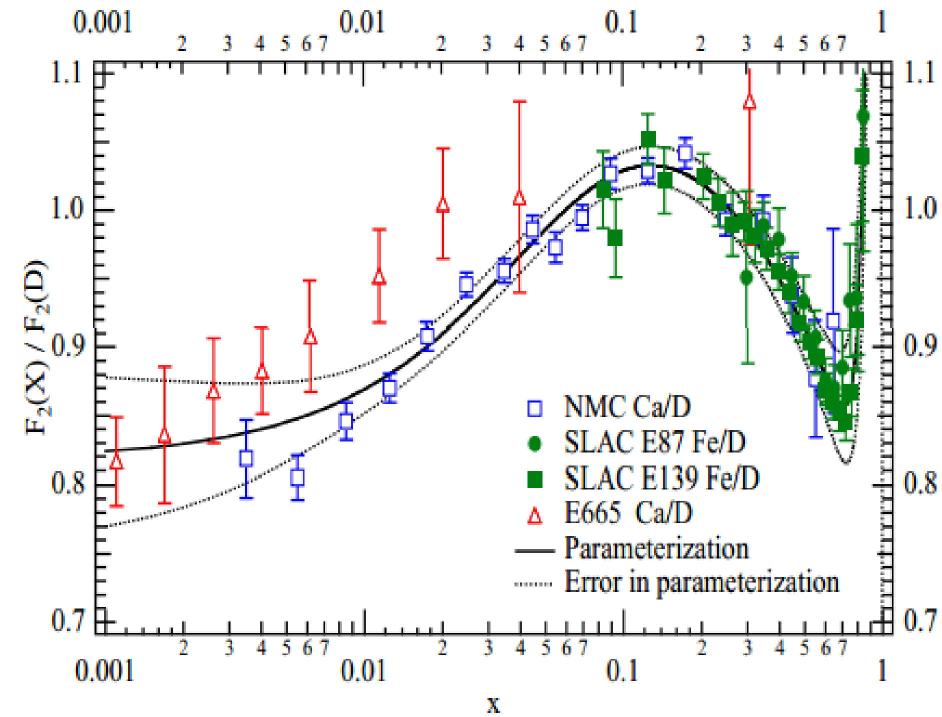
- ^{9}Be has a low average density - structure ~ 2α + n.
- Most nucleons are tightly-grouped (α-like).
- EMC effect modulated by local instead of average density?
- Is there a relation to MEC in neutrino scattering?

Simulations of Nuclear Modification

Our Simulation | GENIE 2.6.2

- Bodek-Yang Model (2003)
- Fit to charged lepton data
- All nuclei have same modification
  - All treated as isoscalar iron

A. Bodek, I. Park, and U.-K. Yang,
Nucl. Phys. Proc. Suppl. 139, 113 (2005)



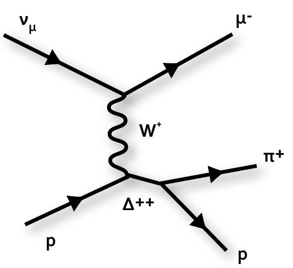
Compare to Other Models

Differ by only < 1%

S. A. Kulagin and R. Petti, Nucl. Phys. A 765, 126 (2006)
S. A. Kulagin and R. Petti, Phys. Rev. D 76, 094023 (2007)
A. Bodek, U. K. Yang arXiv:1011.6592 (2013)

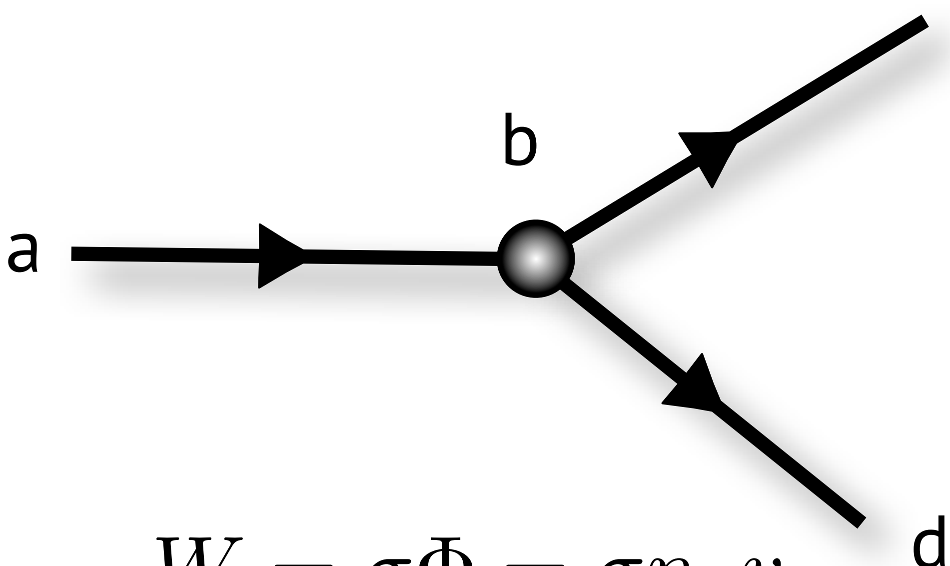
- Kulagin-Petti (KP)
  - Microphysical model
  - Starts with neutrino-nucleon F1, F2, F3
  - Incorporates A-dependent effects
- Bodek-Yang 2013(BY)
  - Similar to GENIE
  - Specific fits for C, Fe, Pb

x	C/CH G	C/CH σ_{st} %	C/CH KP Δ%	C/CH BY Δ%	Fe/CH G	Fe/CH σ_{st} %	Fe/CH KP Δ%	Fe/CH BY Δ%	Pb/CH G	Pb/CH σ_{st} %	Pb/CH KP Δ%	Pb/CH BY Δ%
0.0–0.1	1.050	1.0	0.3	0.0	1.011	0.5	-0.4	1.2	1.037	0.5	-1.5	0.8
0.1–0.3	1.034	0.7	-0.3	0.0	1.017	0.3	-0.7	-0.5	1.071	0.3	-1.0	-0.7
0.3–0.7	1.049	0.8	-0.1	0.0	1.049	0.4	0.0	0.0	1.146	0.4	0.4	0.6
0.7–0.9	1.089	1.8	-0.1	0.0	0.995	0.9	0.4	0.1	1.045	0.9	0.1	0.7
0.9–1.1	1.133	2.3	-0.1	0.0	0.948	1.1	0.2	0.0	0.985	1.1	0.2	0.2
1.1–1.5	1.111	2.2	0.0	0.0	0.952	1.1	0.0	0.0	1.036	1.1	0.1	0.0



Basic Formalism

$$a + b \rightarrow c + d$$

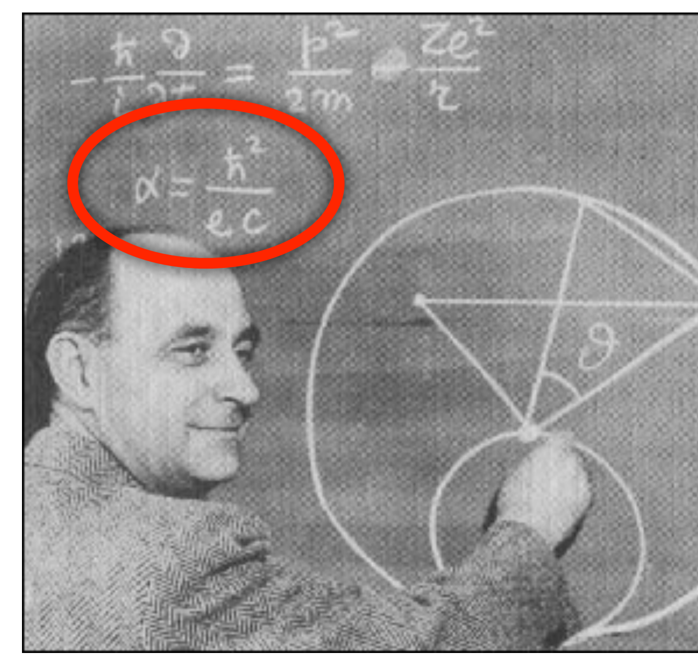


$$W = \sigma \Phi = \sigma n_a v_{ab}$$

Fermi's Second Golden Rule

$$W = \frac{1}{h} \left| M_{if} \right|^2 \rho_f$$

Fermi makes the rules.

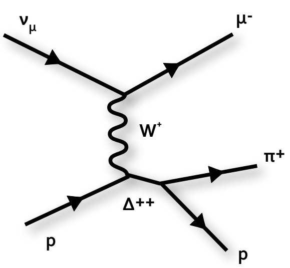


M is the "Matrix Element"

Perturbation Theory: $M_{if} = \int \psi_f^* \mathcal{H} \psi_i d\tau$

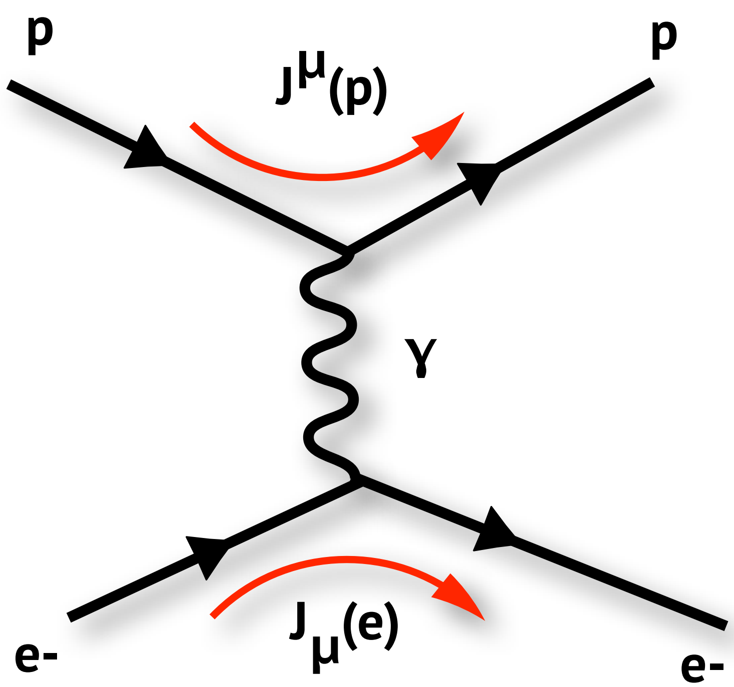
ρ_f is the density of states (phase space factor).

$$\sigma \left(a + b \rightarrow c + d \right) \propto \left| M_{if} \right|^2 \rho_f$$



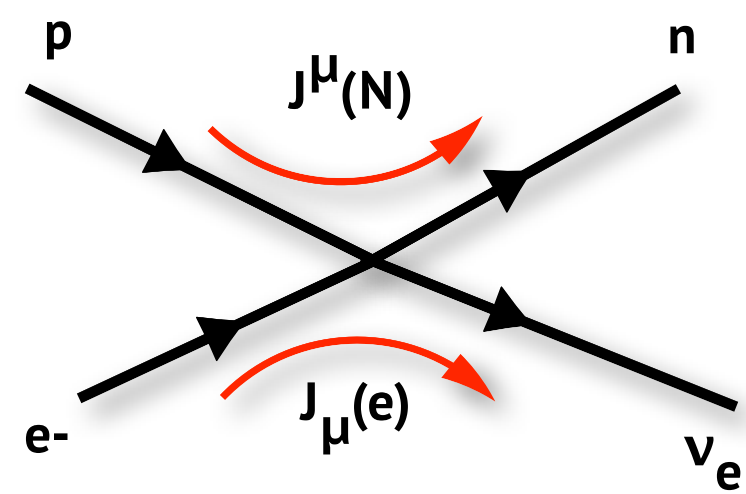
First Attempt: Fermi, 1932

Current-Current description of EM.



$$M_{em} = (e\bar{u}_p\gamma^\mu u_p)\left(\frac{-1}{q^2}\right)(-e\bar{u}_e\gamma^\mu u_e)$$

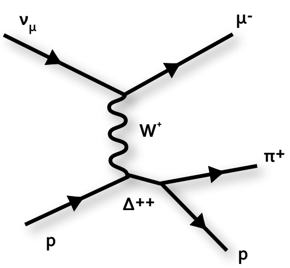
Point interaction of four spin-1/2 fields.



$$M_{weak-CC-Fermi} = G_F\left(\bar{u}_n\gamma^\mu u_p\right)\left(\bar{u}_\nu\gamma_\mu u_e\right)$$

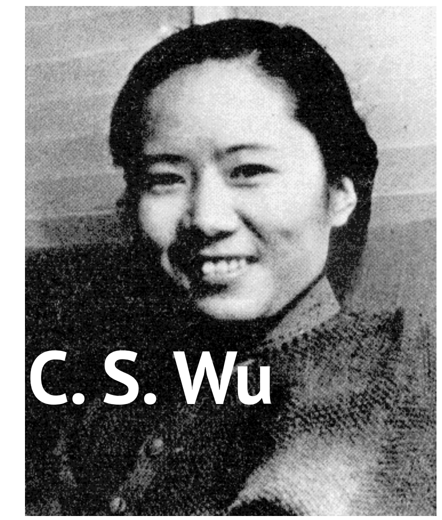
G_F is not dimensionless (GeV^{-2}) : we need to measure it in β & μ decays.

$$\frac{G_F}{(\hbar c)^3} = \sqrt{\frac{\hbar}{\tau_\mu}\frac{192\pi^3}{(m_\mu c)^5}} \simeq 1.166\times 10^{-5}\mathrm{GeV}^{-2}$$

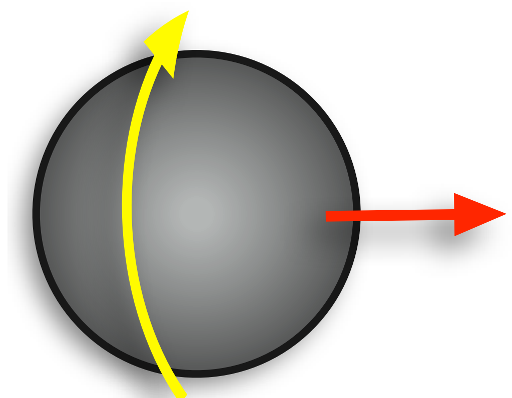


First Attempt: Fermi, 1932

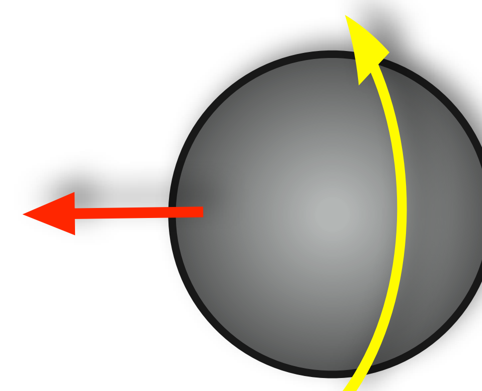
- Actually worked pretty well!
- Bethe-Peierls (1934) used it to compute the cross-section for inverse-beta decay for ~MeV neutrinos.
    - $\sigma \sim 5 \times 10^{-44}$ cm^2 for E ~ 2 MeV
- The calculation is correct to about a factor of two (to account for the then unknown phenomenon of *maximal parity violation* in the weak interaction).



Left Handed



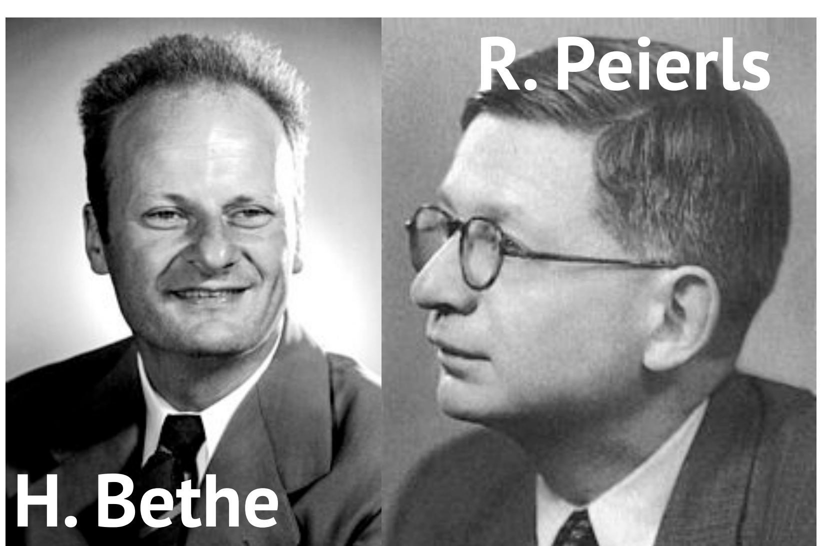
Right Handed

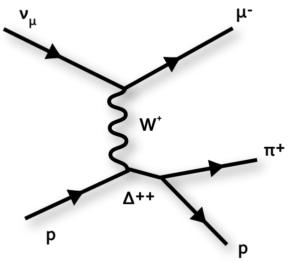


$$n \rightarrow e^- + p + \bar{\nu}_e$$

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

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





Comment...

- It has likely already become clear that neutrinos interact rarely.
  - R. Plunkett: “The neutrinos see a world of ghosts when they are traveling.”*
- What is the mean free path for a neutrino in lead?

$$
\begin{aligned}
MFP_{lead} &\sim \frac{1.66 \times 10^{-27}\,\mathrm{kg}}{(\sigma_{\nu-N}\,\mathrm{m}^2)\,(11400\,\mathrm{kg/m^3})} \\
&\sim 10^{16}\,\mathrm{m}
\end{aligned}
$$

Over a light year!

Accelerator (1-100 GeV): MFP ~ 10^{12} m (~billion miles).

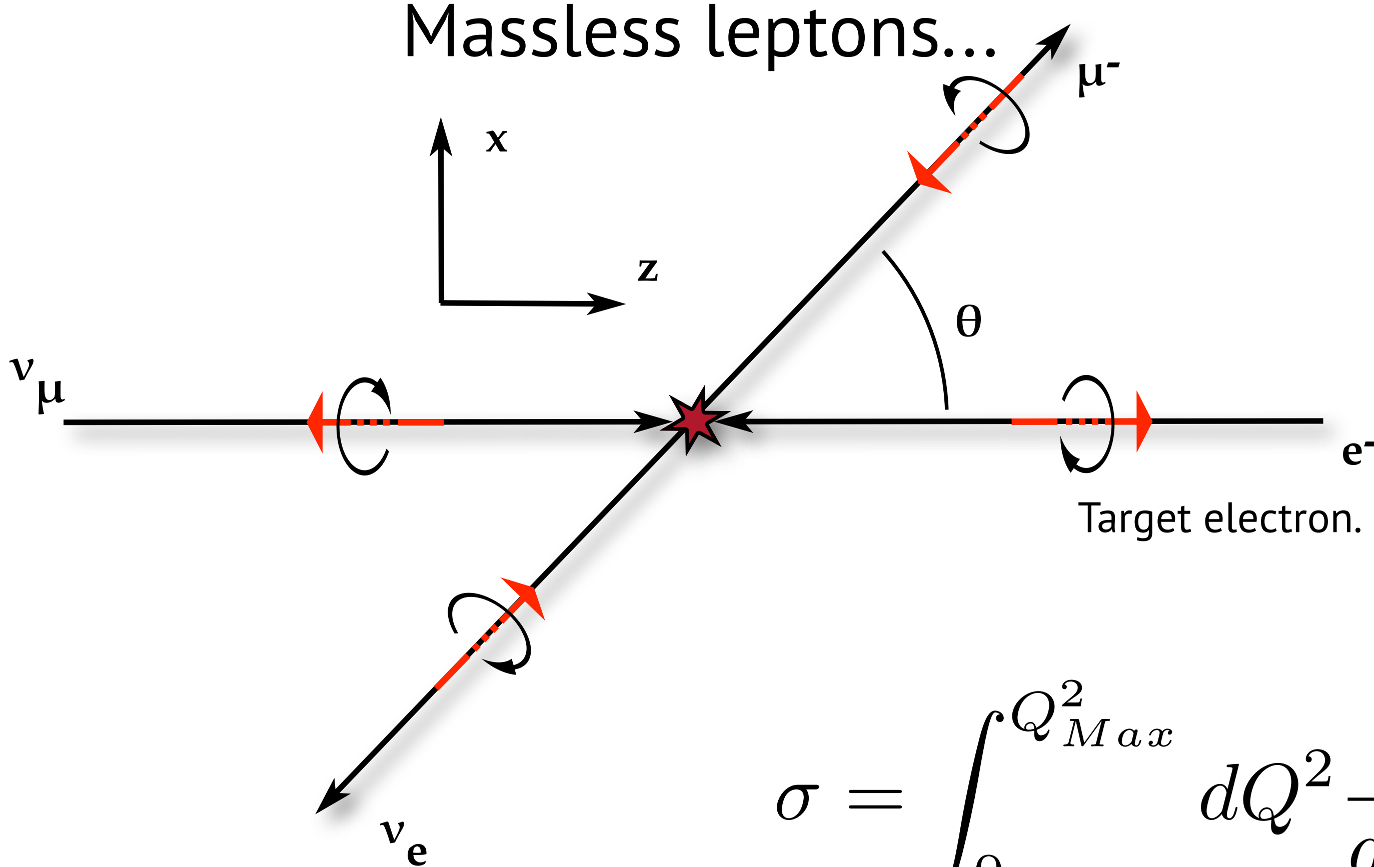
Protons? σ~10^{-25} cm^2; MFP ~ 10 cm

*http://chicagotonight.wttw.com/2011/09/28/faster-light-experiments

- A bit old, but a good example of how to talk to the public about science.

K. McFarland, arXiv 0804.3899

Massless leptons...



Spin zero initial state!

$$\frac{d\sigma}{dq^2} = \frac{|\mathcal{M}|^2}{64\pi p_\nu^2 M_T^2}$$

$$\propto \frac{1}{\left(q^2 - M_W^2\right)^2}$$

$$\sigma = \int_0^{Q^2_{Max}} dQ^2 \frac{d\sigma}{dQ^2} \propto \int_0^{Q^2_{Max}} dQ^2 \frac{1}{\left(Q^2 + M_W^2\right)^2}$$

$$= \frac{Q^2_{Max}}{M_W^4} \text{ for } M_W^2 \gg Q^2$$

Constant of proportionality..

$$\frac{g_W^4}{32\pi} = M_W^4 \times \frac{G_F^2}{\pi}$$

Center of momentum frame...

$$Q^2 = 2E_\nu^{*2}\left(1 - \cos\theta^*\right)$$

Q^2 bounds...

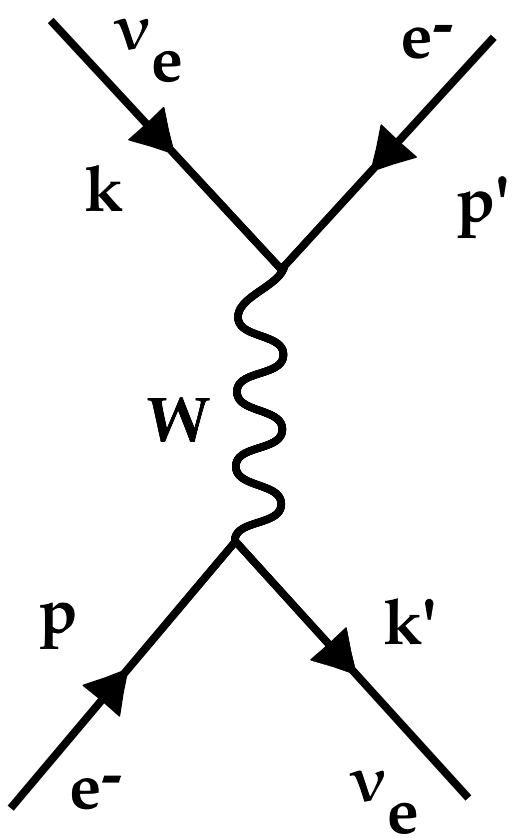
$$0 \leq Q^2 \leq 4E_\nu^{*2} = s$$

$$\sigma\left(\nu_\mu e^- \to \mu^- \nu_e\right) = \frac{G^2}{\pi} s$$

$$s = m_e^2 + 2m_e E_\nu$$

~Zero!

Neutrino-Electron Scattering



Assume: $m_e = 0$ & $s = (k+p)^2 = 2k \cdot p = 2k' \cdot p'$

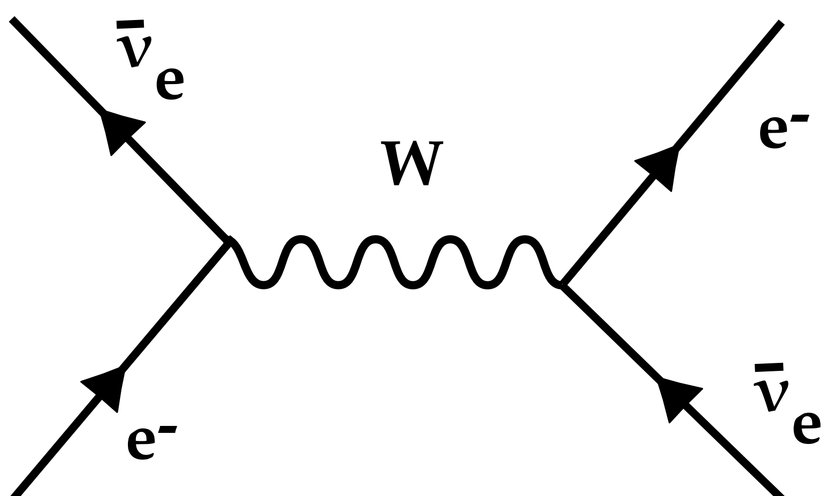
$$\frac{1}{2}\sum_{spins} |\mathcal{M}|^2 = 64 G_F^2 (k \cdot p)(k' \cdot p')$$

$$= 16 G_F^2 s^2$$

Skip a lot of steps! See: *Halzen & Martin* Quarks & Leptons or *Griffiths* Intro. to Elementary Particles.

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\overline{|\mathcal{M}|^2} = \frac{G_F^2 s}{4\pi^2} \implies \sigma = \frac{G_F^2 s}{\pi}$$

Anti-Neutrino-Electron Scattering



By crossing the neutrinos of previous diagram, we have the result for antineutrinos, replacing s with t:

$$\frac{1}{2}\sum_{spins} |\mathcal{M}|^2 = 16 G_F^2 t^2$$

$$= 4 G_F^2 s^2 (1 - \cos\theta)^2$$

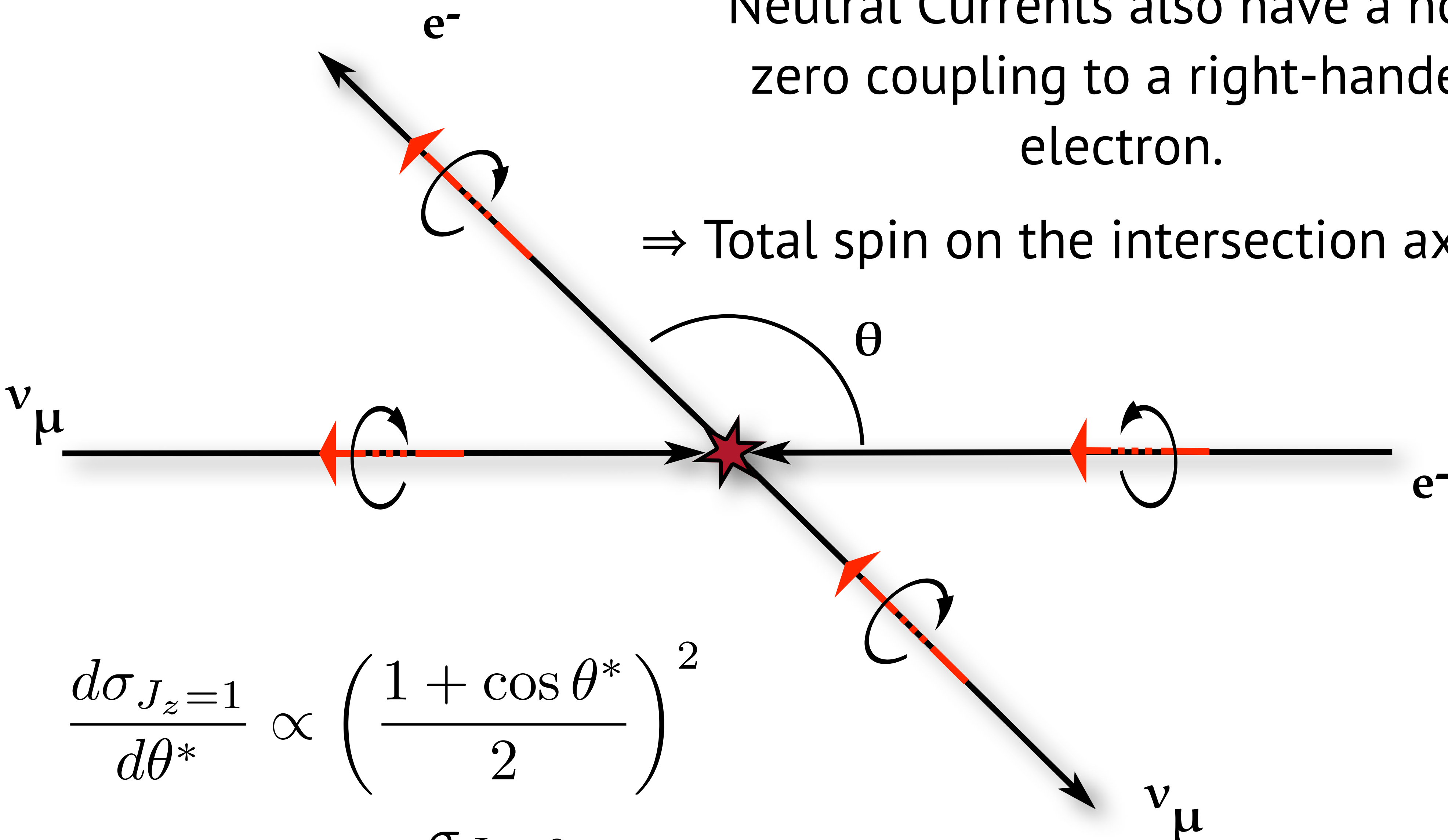
Integrating over angles, we have:

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 s}{16\pi^2}(1-\cos\theta)^2 \implies \sigma = \frac{G_F^2 s}{3\pi}$$

Neutral Current Lepton Scattering

Neutral Currents also have a non-zero coupling to a right-handed electron.

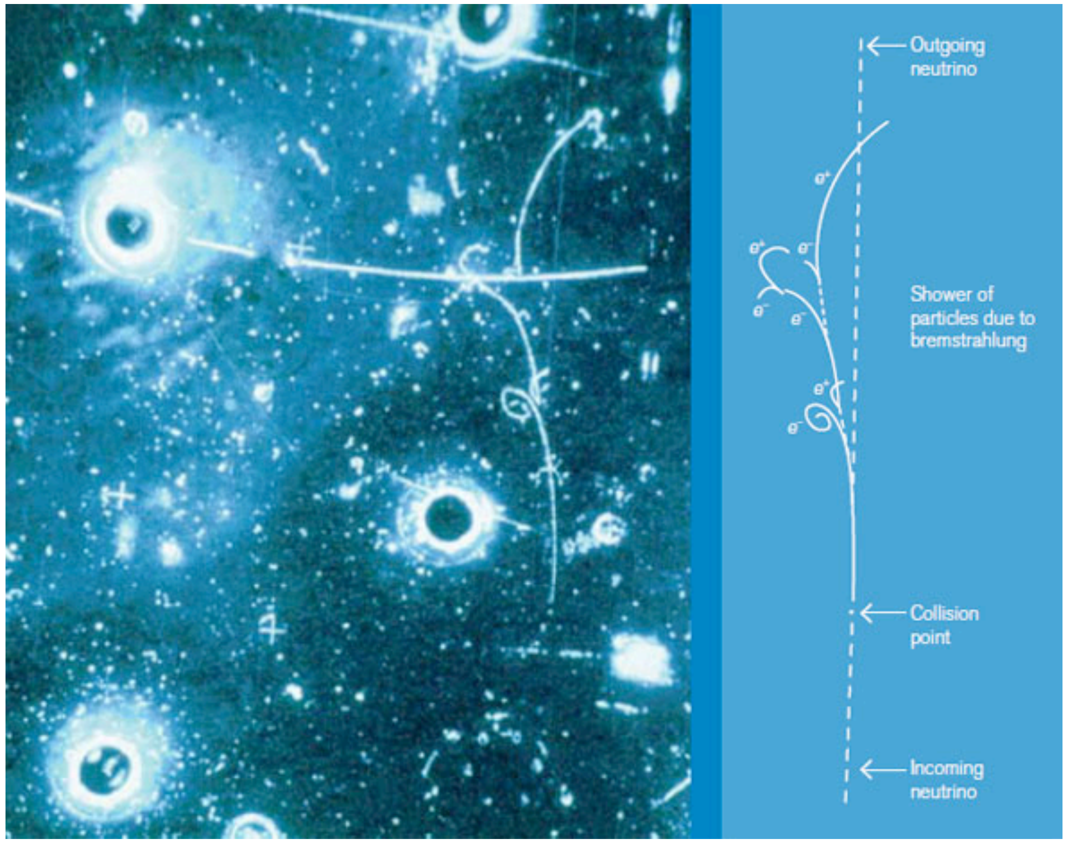
$\Rightarrow$ Total spin on the intersection axis is 1.



$$\frac{d\sigma_{J_z=1}}{d\theta^*} \propto \left(\frac{1+\cos\theta^*}{2}\right)^2$$

$$\sigma_{J_z=1} = \frac{\sigma_{J_z=0}}{3}$$

Non-forward scattering is suppressed.



Neutral Current Couplings

http://www.symmetrymagazine.org/cms/?pid=1000741

	g_L	g_R
e, μ, τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
ν	1/2	0
u, c, t	$1/2 - 2/3 \times \sin^2\theta_W$	$-2/3 \times \sin^2\theta_W$
d, s, b	$-1/2 + 1/3 \times \sin^2\theta_W$	$1/3 \times \sin^2\theta_W$

K. McFarland, arXiv 0804.3899

The couplings are linear terms in the matrix element and are therefore squared in the cross-section:

$$\sigma_{J_z=0} = \frac{G_F^2 s}{\pi}\left(-\frac{1}{2} + \sin^2\theta_W\right)^2$$

$$\sigma_{J_z=1} = \frac{1}{3}\frac{G_F^2 s}{\pi}\left(\sin^2\theta_W\right)^2$$

$$\sigma_{Total}\left(\nu_\mu e^- \to \nu_\mu e^-\right) = \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W\right)$$

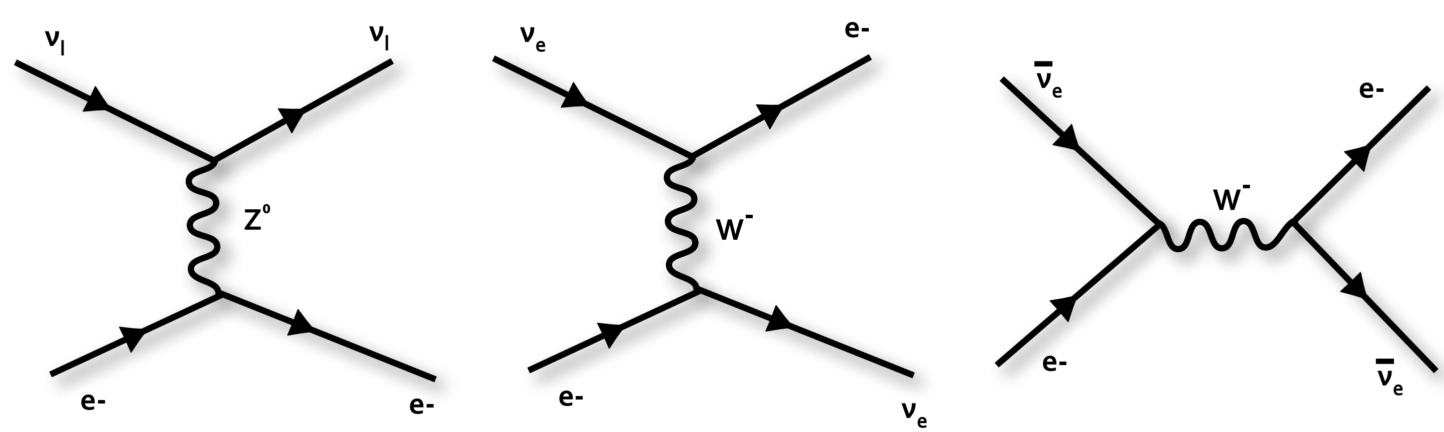
For ν_e, CC interactions are of course available and NC and CC interfere.

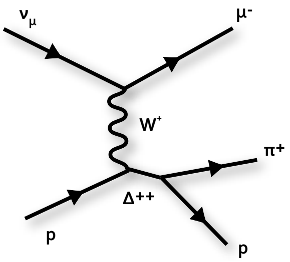
⇒ Add amplitudes, not cross-sections.

This provides an effective coupling:

$$-1/2 + g_L = -1 + \sin^2\theta_W$$

$$\sigma_{Total}\left(\nu_e e^- \to \nu_e e^-\right) = \frac{G_F^2 s}{\pi}\left(1 - 2\sin^2\theta_W + \frac{4}{3}\sin^4\theta_W\right)$$





Strength of the Weak

If $M_W^2 >> q^2$...

$$\frac{G_F}{(\hbar c)^3} = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2} = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W c^2}\right)^2$$

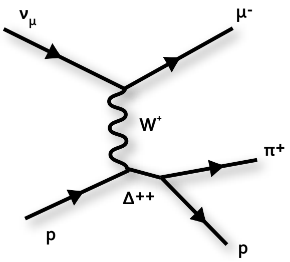
$M_W \sim 80\ \mathrm{GeV}/c^2 \Rightarrow g_W \sim 0.7$

$$\alpha_{EM} = \frac{g_e^2}{4\pi} = \frac{1}{137}$$

$$\alpha_W = \frac{g_W^2}{4\pi} = \frac{1}{29}$$

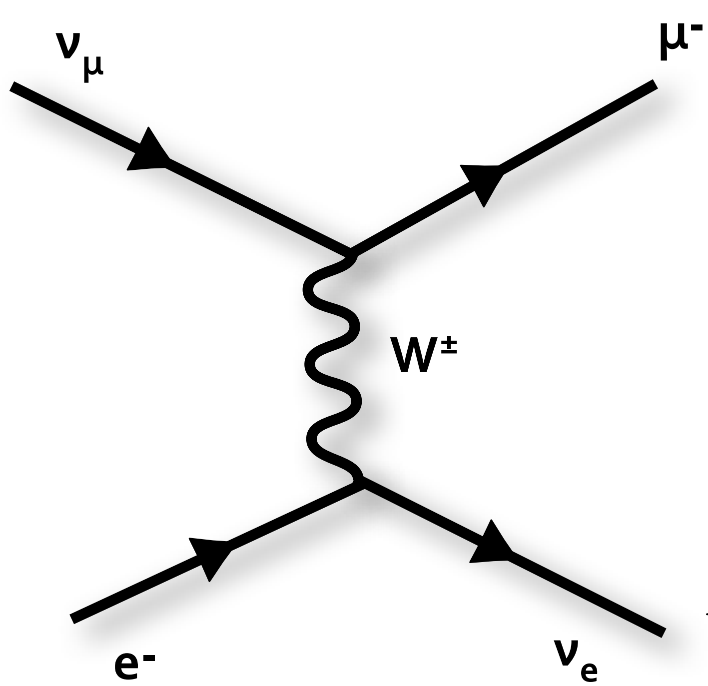
In the limit of 5 ≃ 1 (☺), these couplings are *equal*.
At sufficiently high center-of-mass energy, the interactions are of equal strength.

But what about energies well below M_W? Why is the Weak interaction called weak?



Strength of the Weak

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



$$\begin{aligned} s &\equiv (p_1 + p_2)^2 \\ &= (E_\nu + m_e)^2 - (\mathbf{p}_\nu)^2 \\ &= E_\nu^2 - p_\nu^2 + m_e^2 + 2E_\nu m_e \\ &\simeq 2E_\nu m_e \end{aligned}$$

For a 100 GeV neutrino...

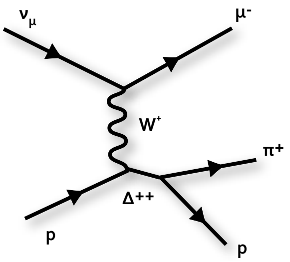
$$E_{CM} = s \simeq 2E_\nu m_e = 2 \times (100 \times 0.000511)\ \mathrm{GeV} = 0.1\ \mathrm{GeV}$$

$\frac{d\sigma}{dq^2} \propto \frac{1}{(M^2 - q^2)^2}$ & $M_W \sim 80\ \mathrm{GeV} \not\Rightarrow$ Must "borrow" energy (not at LIBOR rates)

$$80 \gg 0.1 \implies \Delta E \Delta t \geq \frac{\hbar}{2} \implies t \sim \frac{\hbar}{\Delta E} \sim 8 \times 10^{-27}\ \mathrm{s}$$

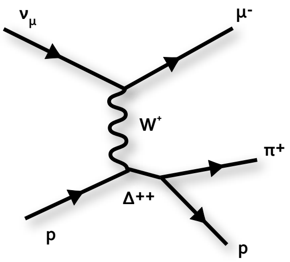
$$d = t \times c \sim 3 \times 10^{-18}\ \mathrm{m}$$

"Range" of the force.



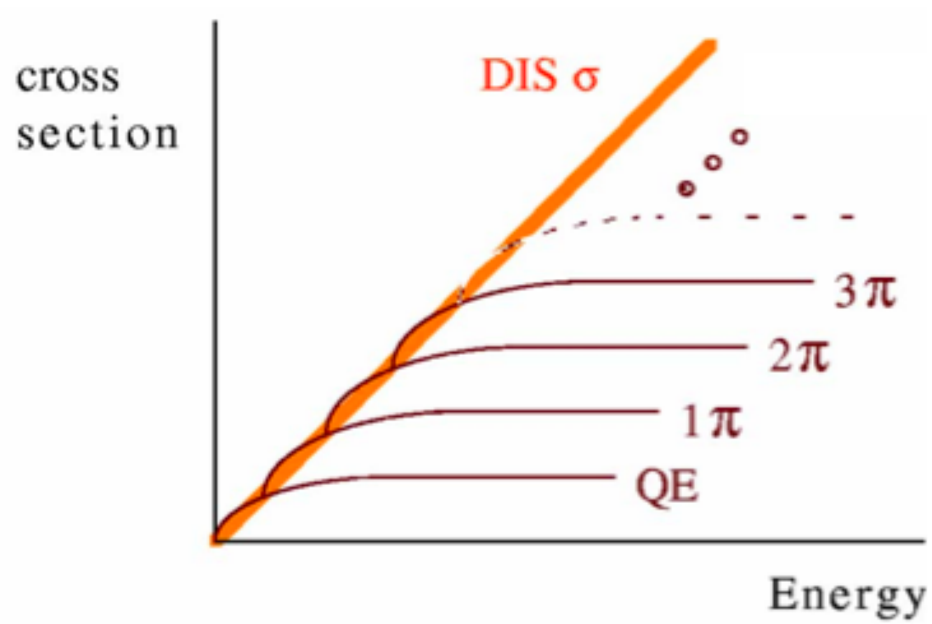
Heavy-Target Scattering

- Inelastic Scattering
  - Produce new particles, probe inner structure of the nucleon.
- (Quasi-)Elastic Scattering
  - Resolve nuclear structure, scatter off of (independent?) nucleons.

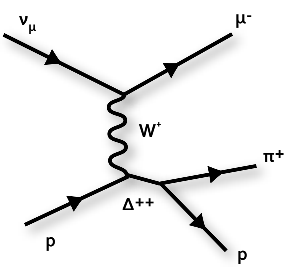


Features

- Cross-sections scale ~linearly with the number of targets.
- Experiments often report cross-sections per:
  - Isoscalar nucleon (sum of protons and neutrons)
  - Atom (e.g. per ^{12}C, etc.)
  - Per proton / neutron (typically for anti-nu / nu)



The total cross-section increases linearly with energy!



Inelastic Reactions

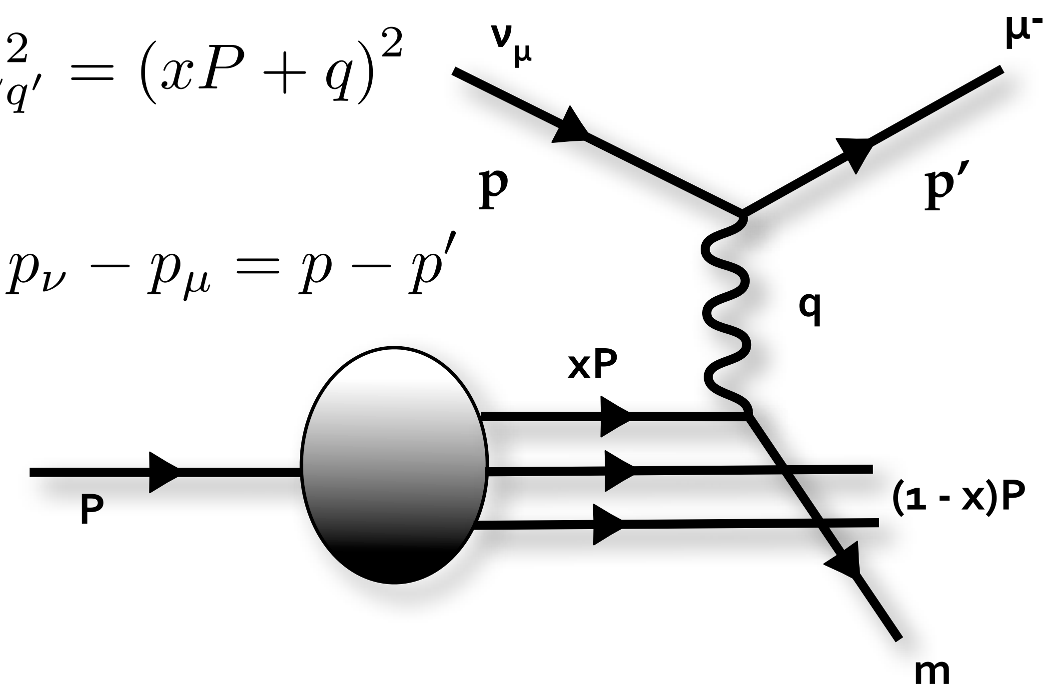
- "Real" scattering involves very complicated targets. Electroweak theory does not provide couplings for composite particles (e.g. nucleons).
- We assume *massless* leptons in the following section...

In DIS, the neutrino scatters against an individual parton, carrying momentum fraction x, inside the nucleon.

$$m_q^2 = x^2 P^2 = x^2 M_T^2$$

$$m_{q'}^2 = (xP + q)^2$$

$$q = p_\nu - p_\mu = p - p'$$



Transition Region - Messy Final States, but not scattering cleanly off partons.

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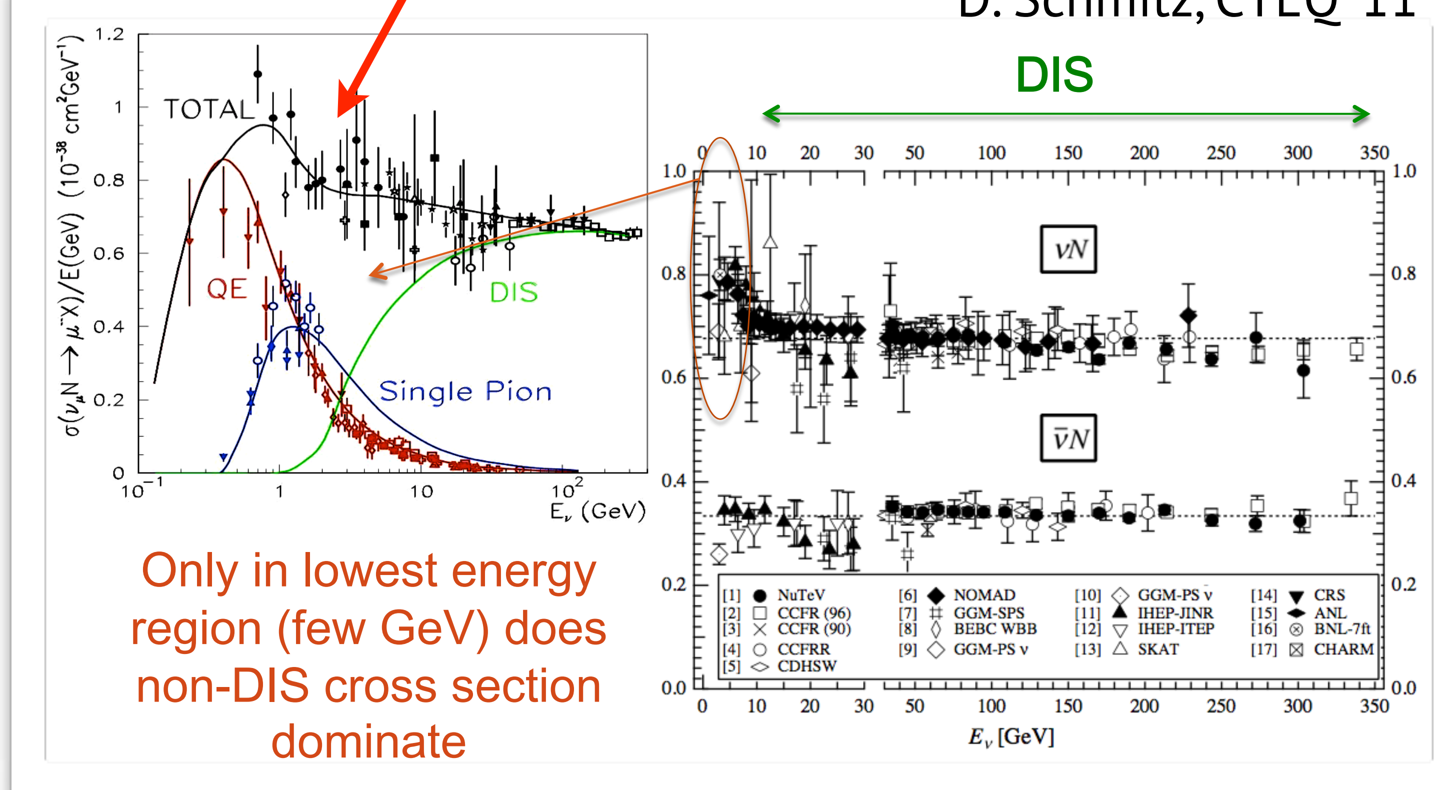
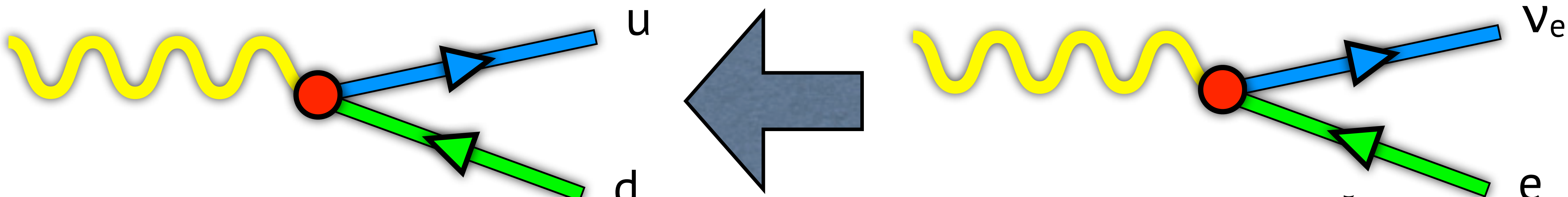


Neutrino-Quark Scattering

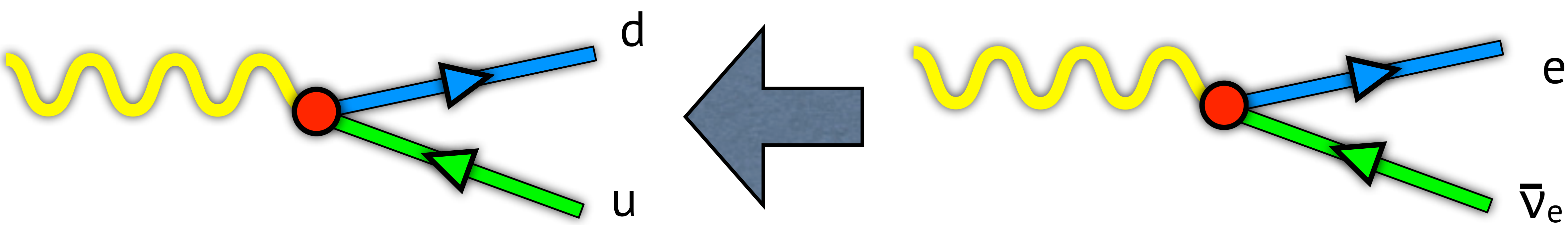
"Charge-raising" quark current

Electron weak current



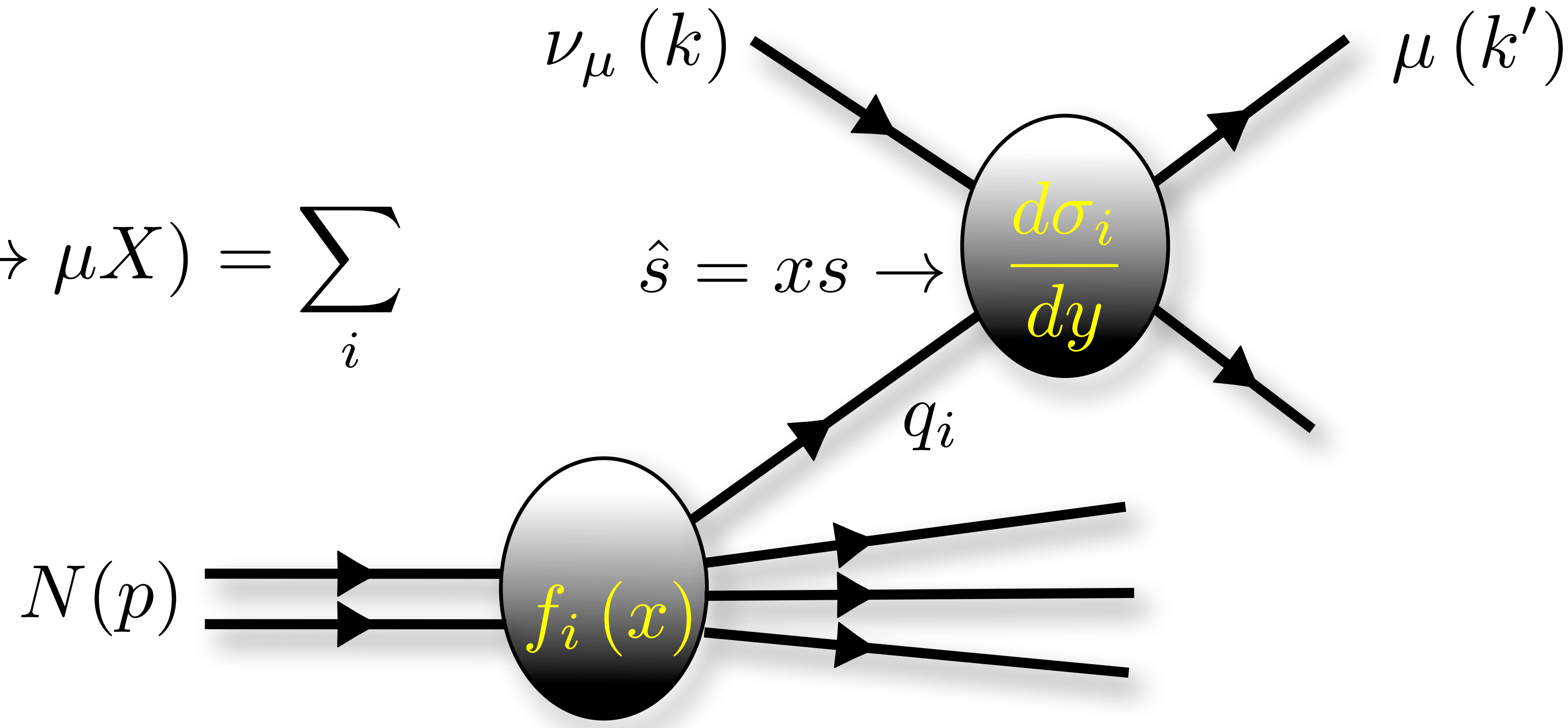
$$J_q^\mu = \bar{u}_u \gamma^\mu \left(\frac{1-\gamma^5}{2} \right) u_d \qquad J_e^\mu = \bar{u}_\nu \gamma^\mu \left(\frac{1-\gamma^5}{2} \right) u_e$$

Hermitian Conjugates give the charge-lowering weak currents...



$$\frac{d\sigma}{d\Omega}\left(\nu_\mu d \to \mu^- u\right) = \frac{G_F^2 s}{4\pi^2} \qquad \frac{d\sigma}{d\Omega}\left(\bar{\nu}_\mu u \to \mu^+ d\right) = \frac{G_F^2 s}{16\pi^2}\left(1+\cos\theta\right)^2$$

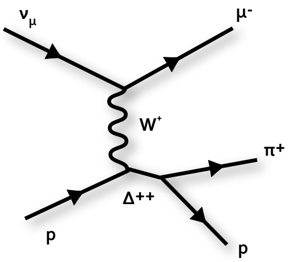
$$\frac{d^2\sigma}{dx\,dy}\left(\nu N \to \mu X\right) = \sum_i$$

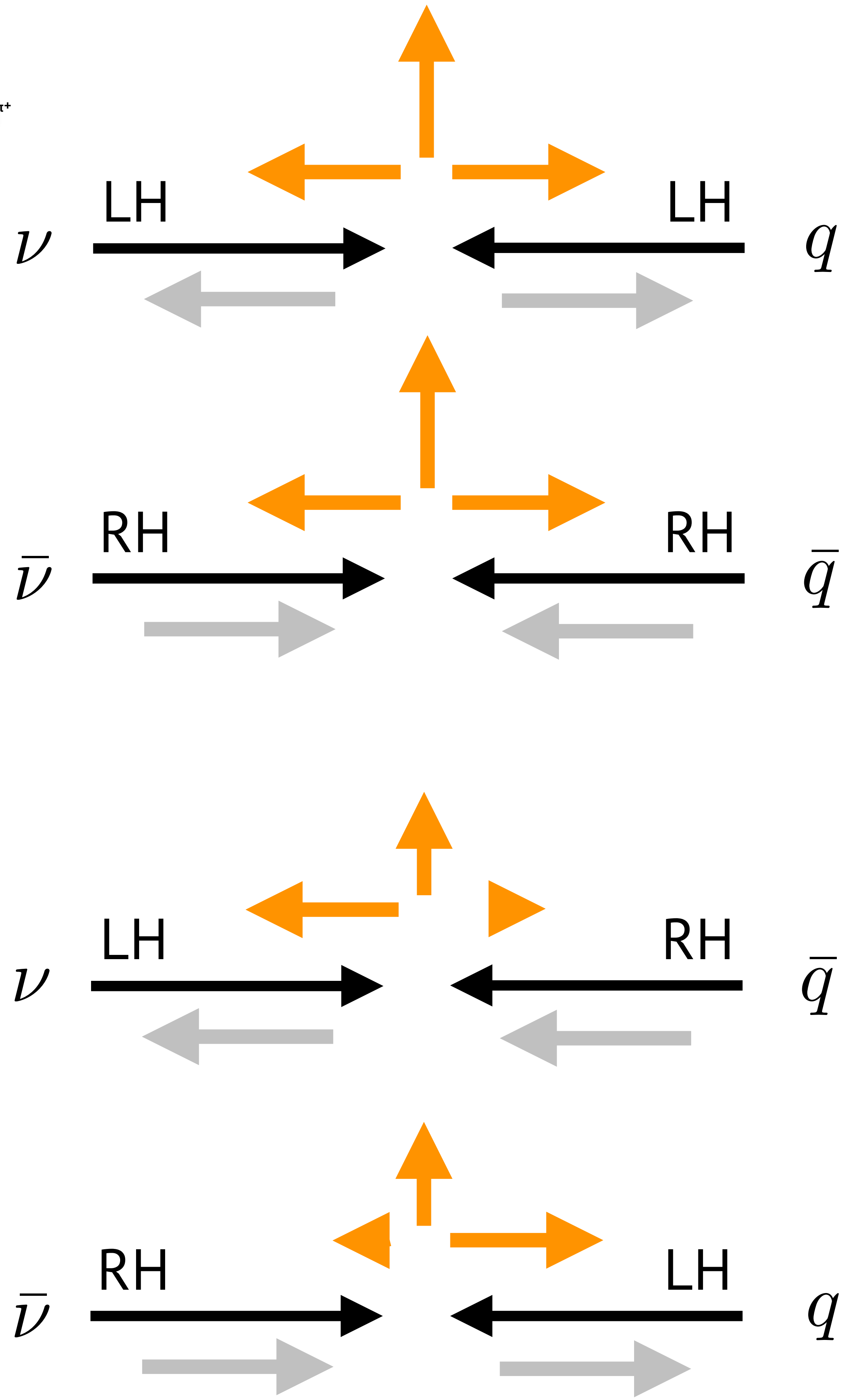


$$= \sum_i f_i\left(x\right)\left(\frac{d\sigma_i}{dy}\right)_{\hat{s}=sx}$$

$$1 - y \equiv \frac{p \cdot k'}{p \cdot k} = \frac{1}{2}\left(1 + \cos\theta\right)$$ & Center-of-Mass Energy = xs

$$\frac{d\sigma}{dy}\left(\nu_\mu d \to \mu^- u\right) = \frac{G_F^2 xs}{\pi} \qquad \frac{d\sigma}{dy}\left(\bar{\nu}_\mu u \to \mu^+ d\right) = \frac{G_F^2 xs}{\pi}\left(1 - y\right)^2$$





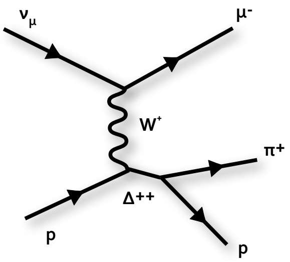
neutrino + quark
anti-neutrino + anti-quark

$$\frac{d\sigma}{dy}(\nu q) = \frac{d\sigma}{dy}(\bar{\nu}\bar{q}) = \frac{G_F^2}{\pi} sx$$

neutrino + anti-quark
anti-neutrino + quark

$$\frac{d\sigma}{dy}(\bar{\nu} q) = \frac{d\sigma}{dy}(\nu\bar{q}) = \frac{G_F^2}{\pi} sx\,(1-y)^2$$

$$1 - y \simeq \frac{1}{2}(1+\cos\theta)$$

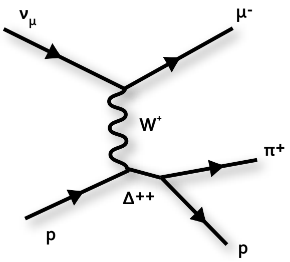


Parton Distribution Functions q(x) : Charge and Helicity

- Neutrinos and anti-neutrinos "taste" different quark flavors!
  - Neutrinos: d, s, u-bar, c-bar *ONLY*
  - Anti-neutrinos: u, c, d-bar, s-bar *ONLY*
- Scattering is *not* from free quarks though! We must use *parton distribution functions!*
  - We cannot calculate these with QCD, but we do know they are universal:

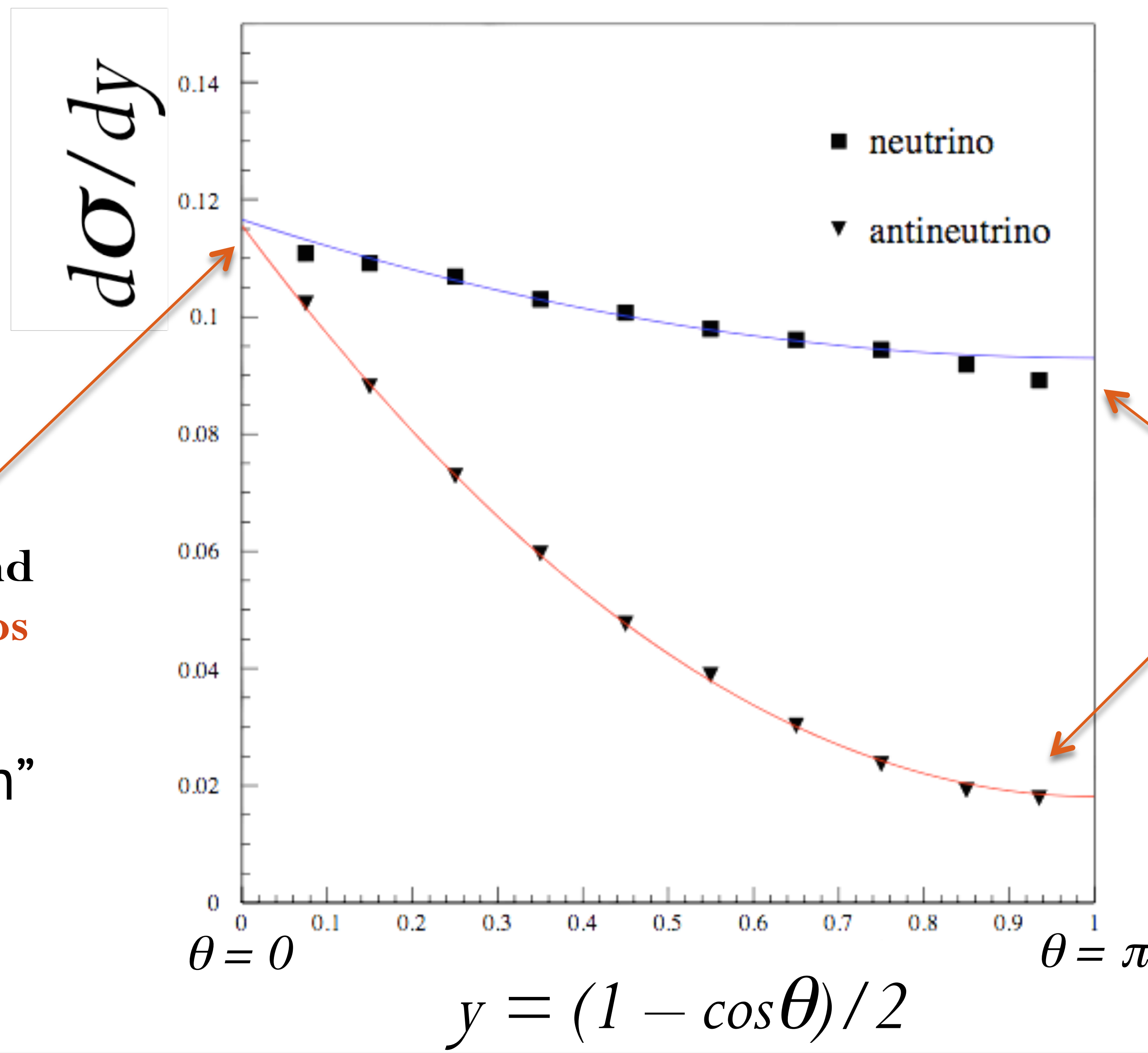
$$\frac{d^2\sigma}{dx\,dy}\left(\nu + \mathrm{proton}\right) = \frac{G_F^2 s}{\pi} x \left[d\left(x\right) + s\left(x\right) + \left[\bar{u}\left(x\right) + \bar{c}\left(x\right)\right]\left(1-y\right)^2\right]$$

$$\frac{d^2\sigma}{dx\,dy}\left(\bar{\nu} + \mathrm{proton}\right) = \frac{G_F^2 s}{\pi} x \left[\bar{d}\left(x\right) + \bar{s}\left(x\right) + \left[u\left(x\right) + c\left(x\right)\right]\left(1-y\right)^2\right]$$



$$y = 1 - \frac{E_l}{E_\nu}$$ **Inelasticity**

Neutrino CC DIS cross section vs. y



y = 0
neutrinos and antineutrinos the same

"All Lepton"

"All Hadron"

y = 1
neutrinos only see quarks
antineutrinos only see antiquarks

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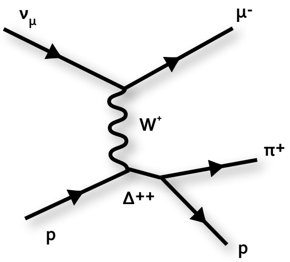


Nucleon Structure Functions

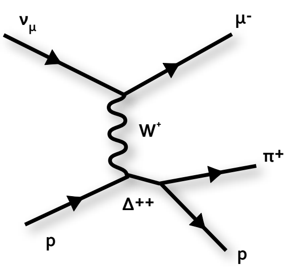
- We may write the ν-N cross-sections in a model-independent way using three nucleon structure functions: F_1, F_2, xF_3:

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dx\,dy} = \frac{G_F^2 M_T E}{\pi}\left[xy^2 F_1\left(x,Q^2\right) + \left(1 - y - \frac{xyM_T}{2E}\right)F_2\left(x,Q^2\right) \pm y\left(1-\frac{1}{2}y\right)xF_3\left(x,Q^2\right)\right]$$

- We may invoke Callan-Gross ($2xF_1 = F_2$) to simplify. *Deviations:*

$$R \equiv \left(1 + \frac{4M_T^2 x^2}{Q^2}\right)\frac{F_2}{2xF_1} - 1$$

- The functions $F_2(x,Q^2)$, $xF_3(x,Q^2)$, and $R\,(x,Q^2)$ may now be experimentally charted from the measured DIS cross-section, $d\sigma/dy$, in bins of x and Q^2.



Nucleon Structure Functions

neutrino… (top)

$$\frac{d^2\sigma^{\nu A}}{dx\,dy} \propto \left[F_2^{\nu A}\left(x,Q^2\right) + xF_3^{\nu A}\left(x,Q^2\right)\right] + (1-y)^2\left[F_2^{\nu A}\left(x,Q^2\right) - xF_3^{\nu A}\left(x,Q^2\right)\right] + f\left(R\right)$$

$$\frac{d^2\sigma^{\bar{\nu} A}}{dx\,dy} \propto \left[F_2^{\bar{\nu} A}\left(x,Q^2\right) - xF_3^{\bar{\nu} A}\left(x,Q^2\right)\right] + (1-y)^2\left[F_2^{\bar{\nu} A}\left(x,Q^2\right) + xF_3^{\bar{\nu} A}\left(x,Q^2\right)\right] + f\left(R\right)$$

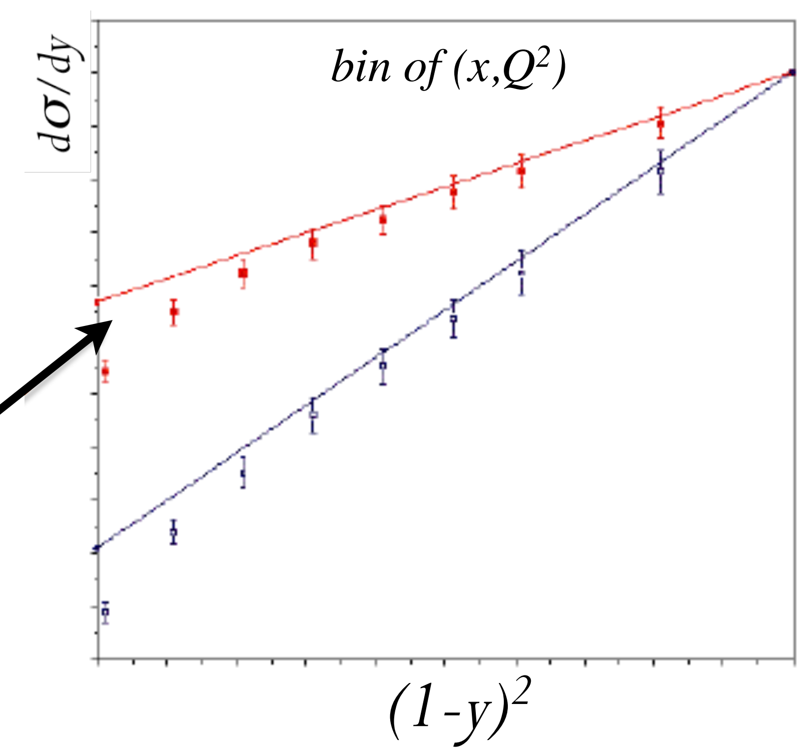
anti-neutrino… (bottom)

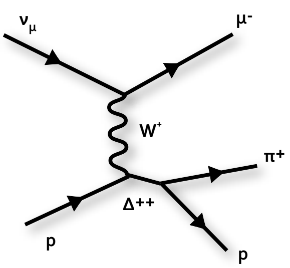
Equations of lines!

$$y \propto m \times x + b$$

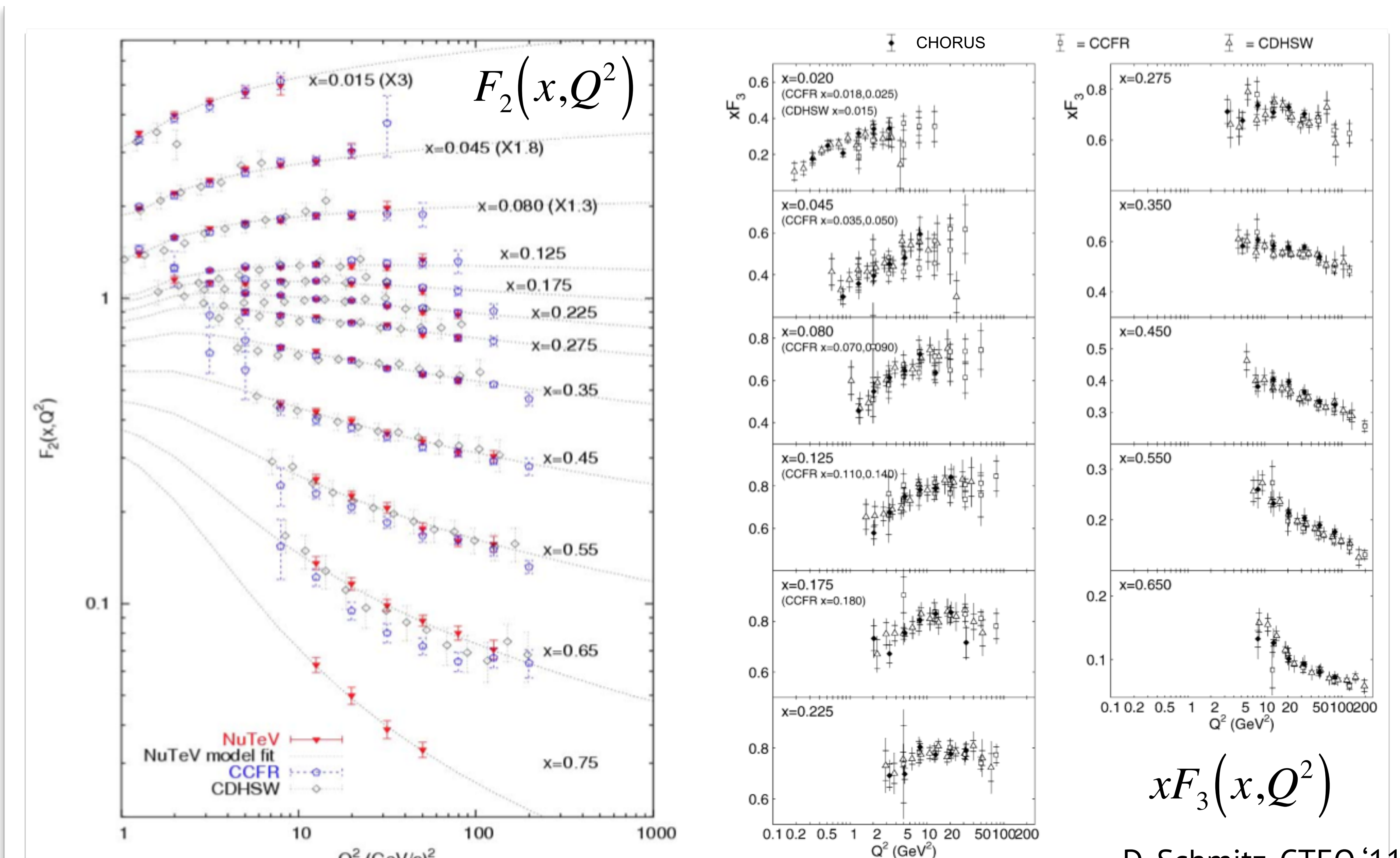
Fit for F_2, xF_3 in bins of (x,Q^2).

C.G. R is related to excursions from a straight-line slope.





Nucleon Structure Functions



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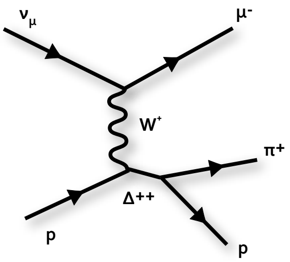


Structure Functions & PDFs (Charged Current)

Leading order expressions to relate SFs to PDFs:

$$F_2^{\nu N}\left(x,Q^2\right) = x\left[u+\bar{u}+d+\bar{d}+2s+2\bar{c}\right]$$
$$F_2^{\bar{\nu} N}\left(x,Q^2\right) = x\left[u+\bar{u}+d+\bar{d}+2\bar{s}+2c\right]$$
$$xF_3^{\nu N}\left(x,Q^2\right) = x\left[u-\bar{u}+d-\bar{d}+2s-2\bar{c}\right]$$
$$xF_3^{\bar{\nu} N}\left(x,Q^2\right) = x\left[u-\bar{u}+d-\bar{d}-2\bar{s}+2c\right]$$

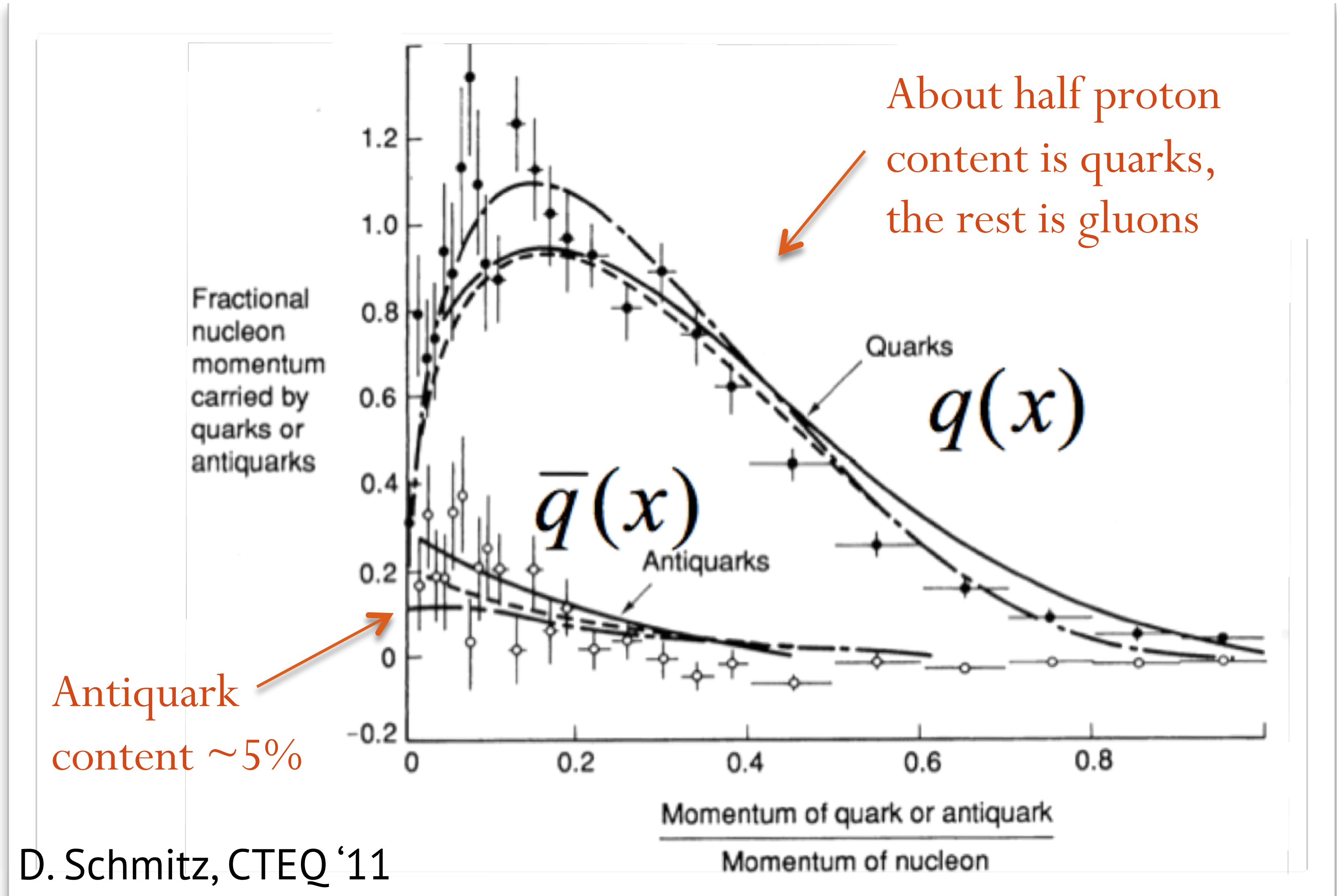
Assuming c = c-bar & s = s-bar:

$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u}+\bar{d}+2\bar{c}\right) = 2U + 4\bar{c}$$
$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u}+\bar{d}+2\bar{s}\right) = 2U + 4\bar{s}$$
$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[(s+\bar{s})-(c+\bar{c})\right] = 4\bar{s} - 4\bar{c}$$

Parton Distribution Functions

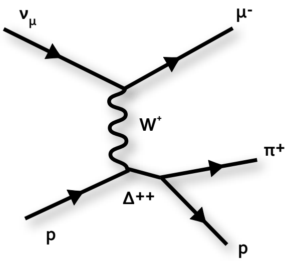
If there were no valence quarks (Q-bar = 0):

$$\frac{\sigma(\bar{\nu})}{\sigma(\nu)} = \frac{\int_0^1 dy\,(1-y)^2}{\int_0^1 dy} = \frac{1}{3}$$

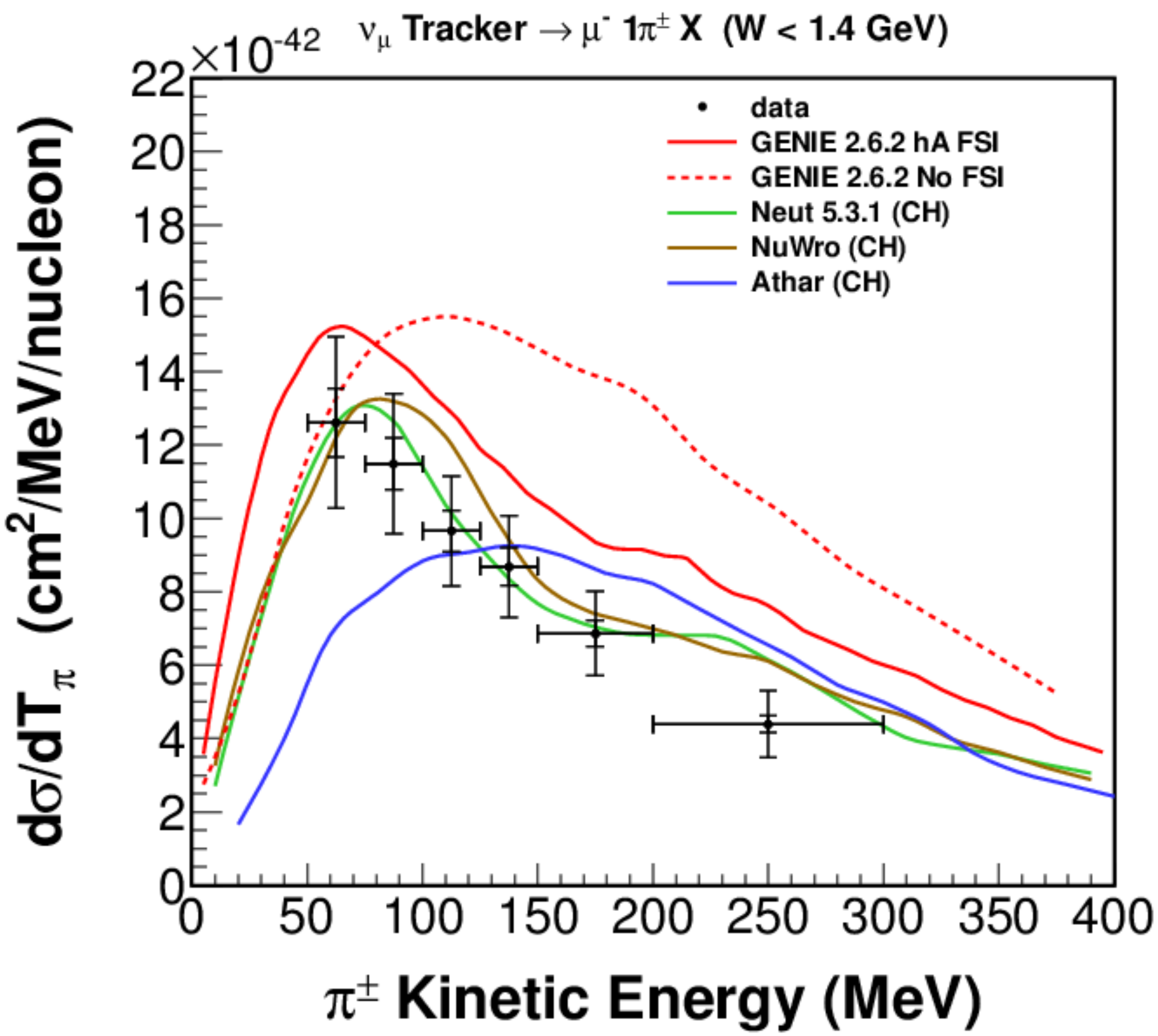


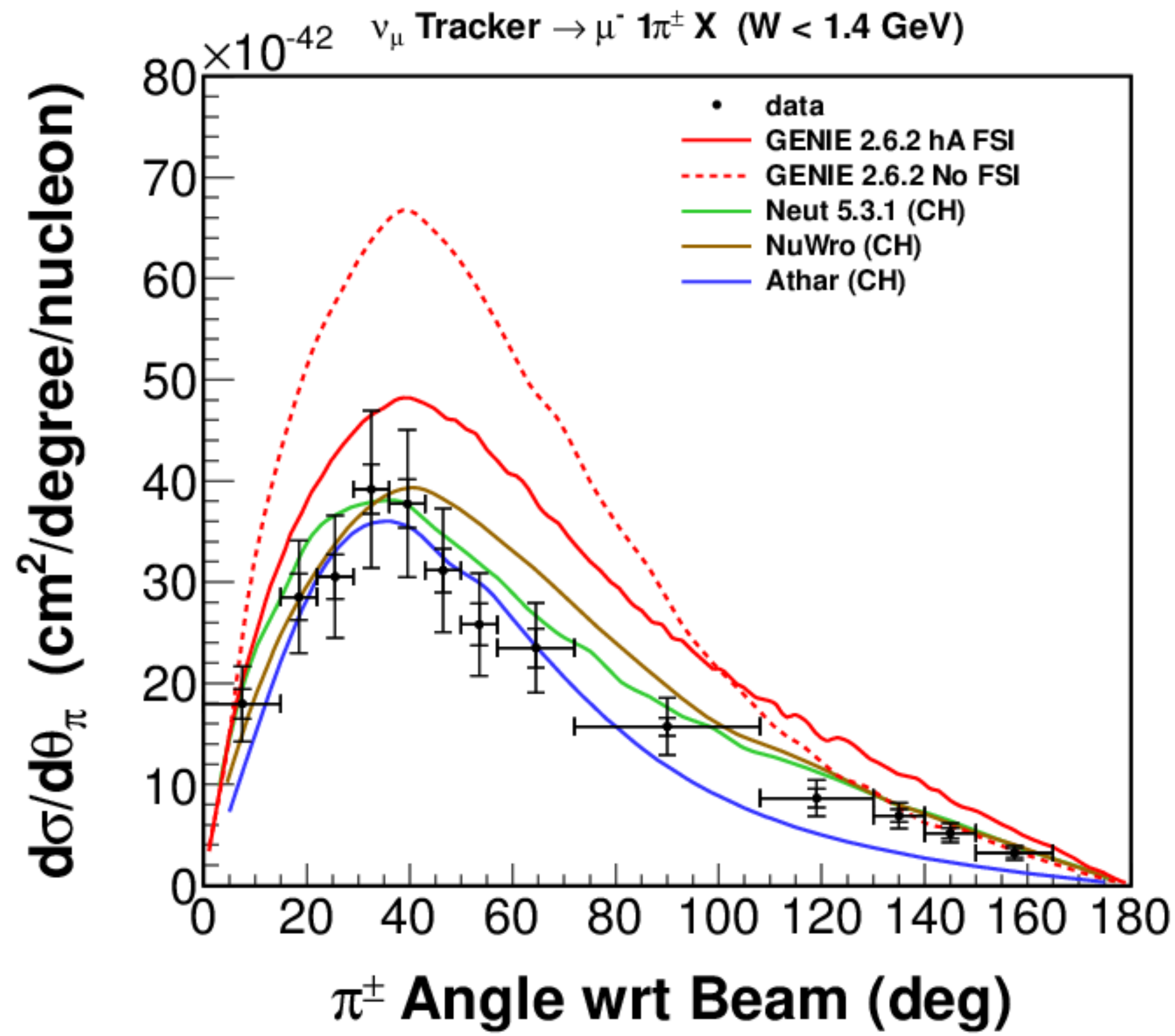
$$\frac{d^2\sigma}{dx\,dy}(\nu+\mathrm{proton}) = \frac{G_F^2 sx}{2\pi}\left[Q(x) + (1-y)^2\bar{Q}(x)\right]$$

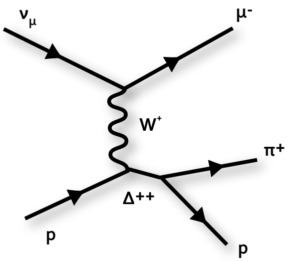
$$\frac{d^2\sigma}{dx\,dy}(\bar{\nu}+\mathrm{proton}) = \frac{G_F^2 sx}{2\pi}\left[\bar{Q}(x) + (1-y)^2 Q(x)\right]$$



Single Pion Production in MINERvA







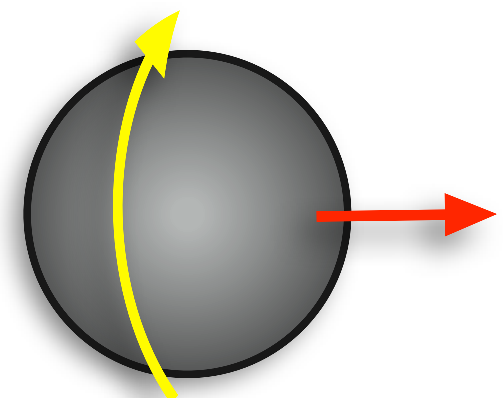
CP?

Spin

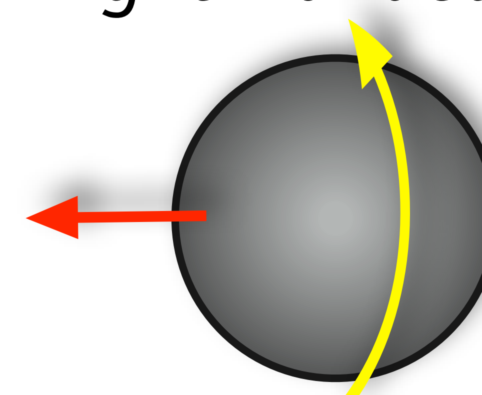
Momentum

- Charge Conjugation Symmetry (C): Flips the sign of all internal quantum numbers (e.g., electric charge, lepton number, etc.). C does not affect mass or chirality (handedness).
- Parity Symmetry (P): Inverts space (sends a vector x to -x). This inverts the handedness of a particle.

Left Handed

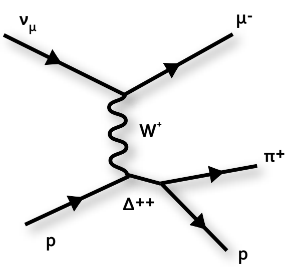


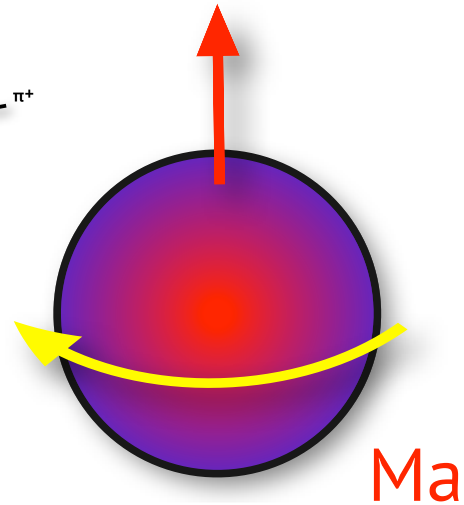
Right Handed



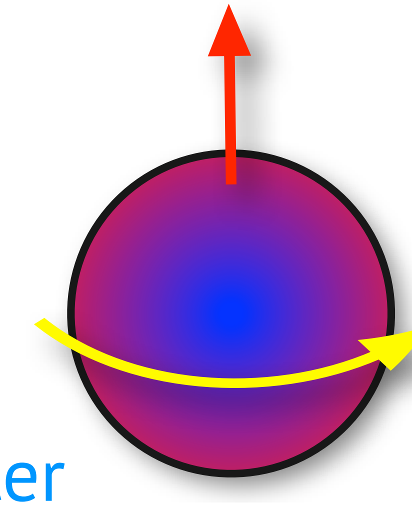
e^+

e^-



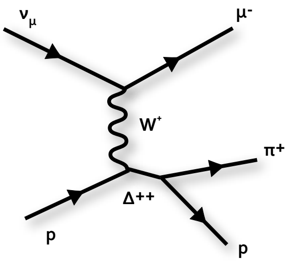


CP Violation



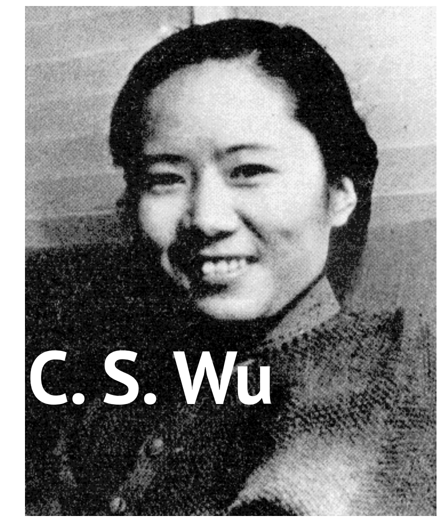
Matter ⟵ CP ⟶ Antimatter

- It is required to explain the baryon asymmetry of the universe - why we have more matter than antimatter.
- CP violation emerges naturally, in a three generation quark model. But it is too small to explain the baryon asymmetry by itself.
- It has not been observed in the lepton sector.



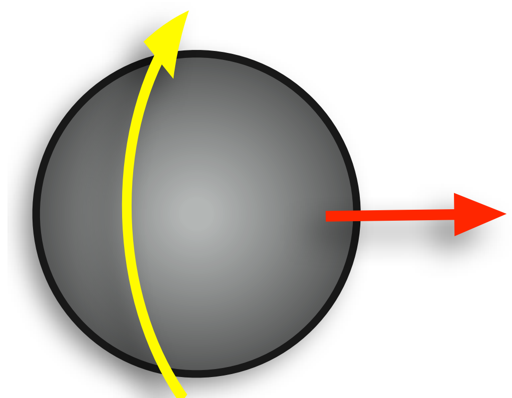
Parity Violation

$$h = \vec{J} \cdot \hat{p}$$



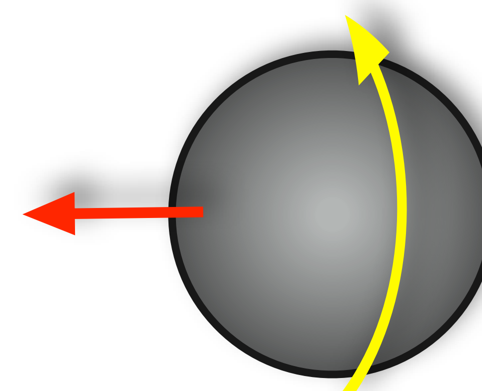
- Handedness? We are typically talking about *helicity*.
- Helicity is the projection of a particle's spin onto the direction of the momentum. If the sign of "h" is negative, the particle is *left handed*, if it is positive, it is *right handed*.

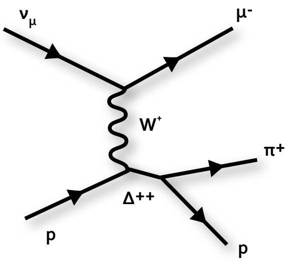
Left Handed



Use the "right" rule at the right time...

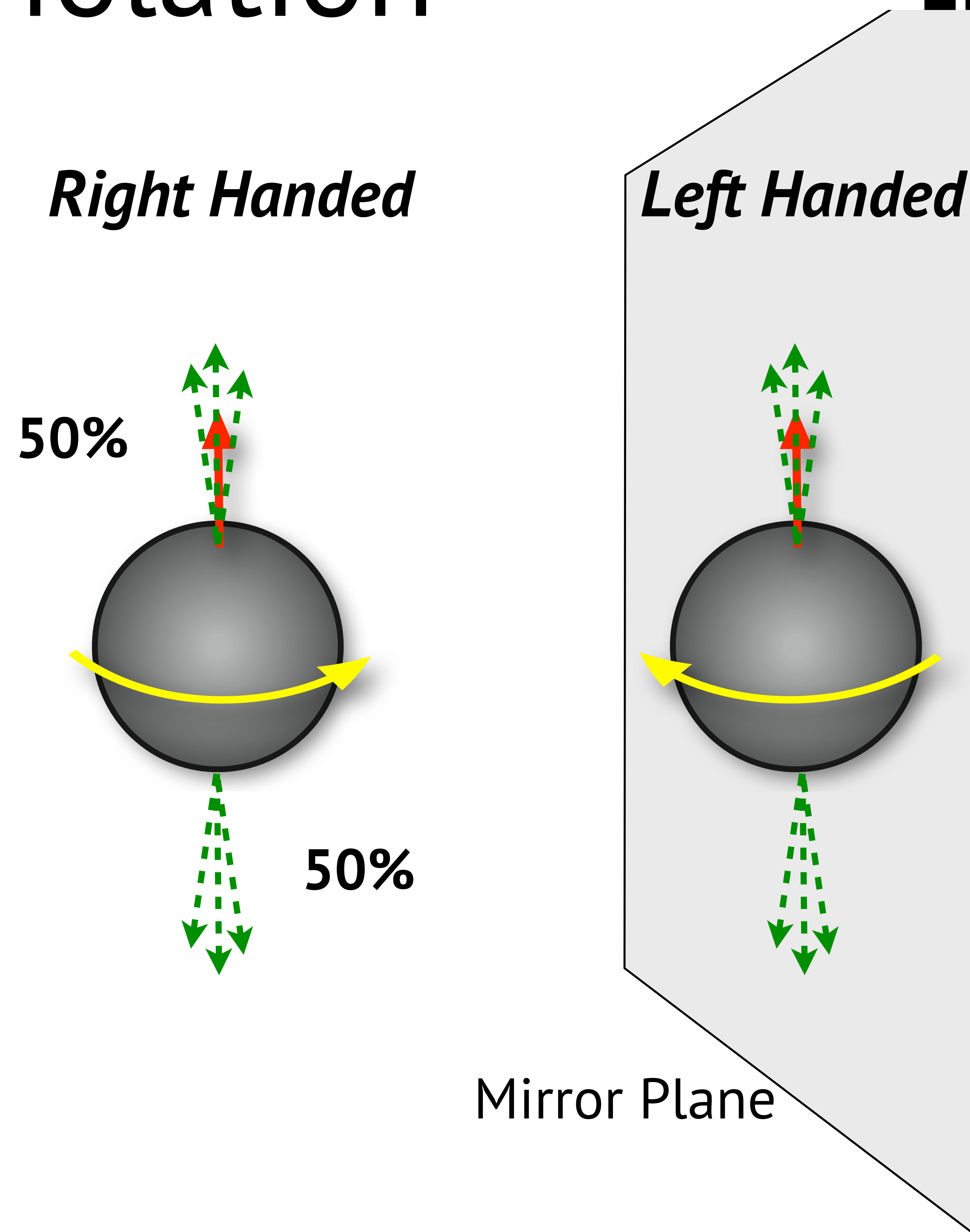
Right Handed

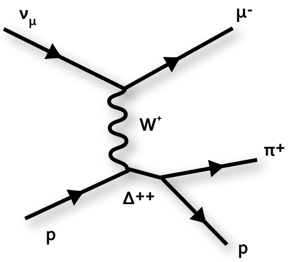




Parity Violation

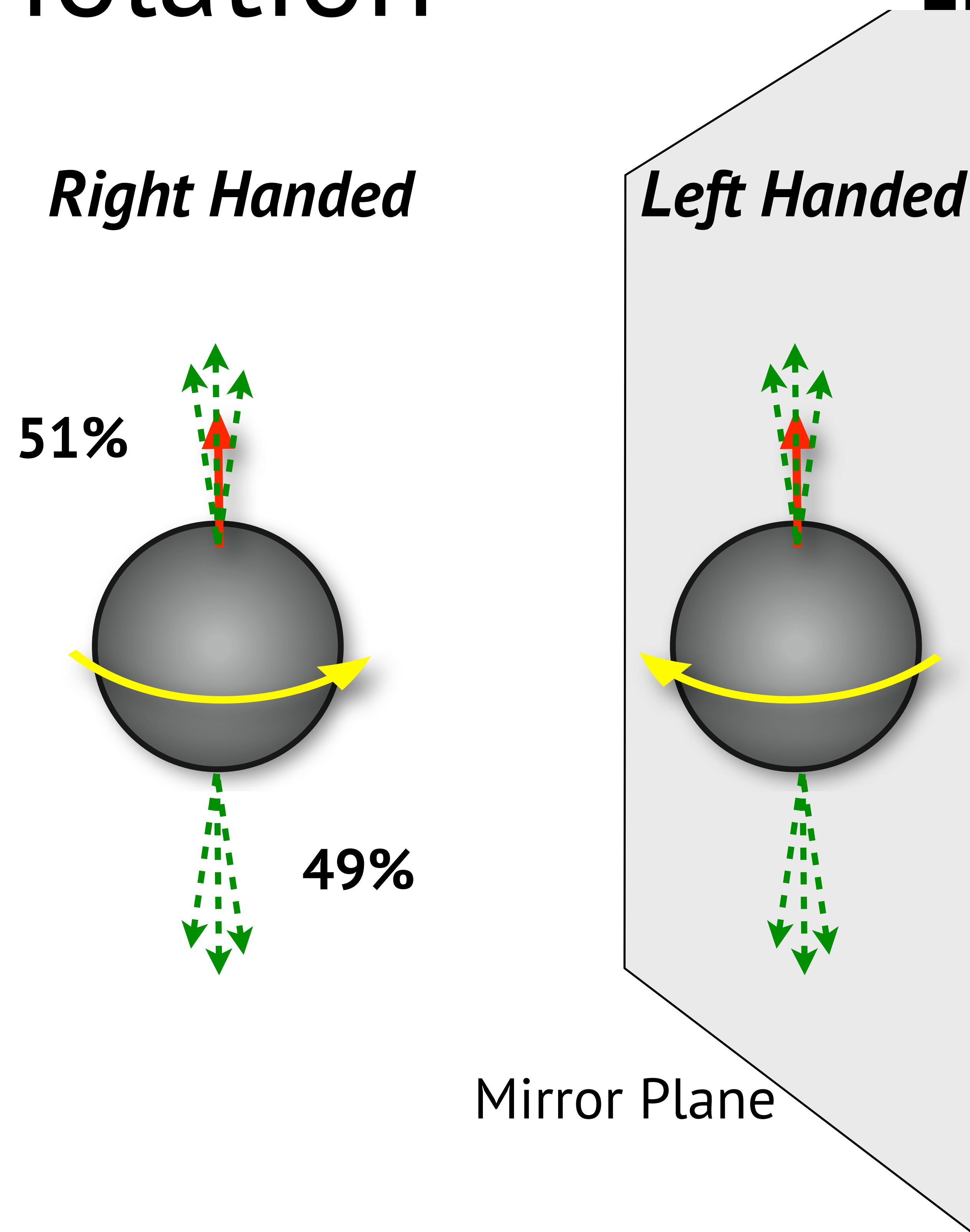
- Suppose we have an atom decaying into a lighter nuclei and emitting a daughter particle.
- If Parity were conserved, we would expect to see this...
- With a 50/50 chance for the direction of the emitted daughter to be aligned/anti-aligned with the parent spin, we can't use a mirror to check the physics...

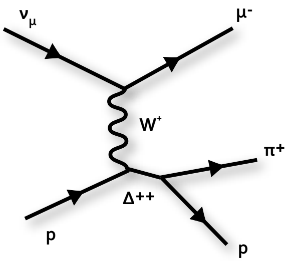




Parity Violation

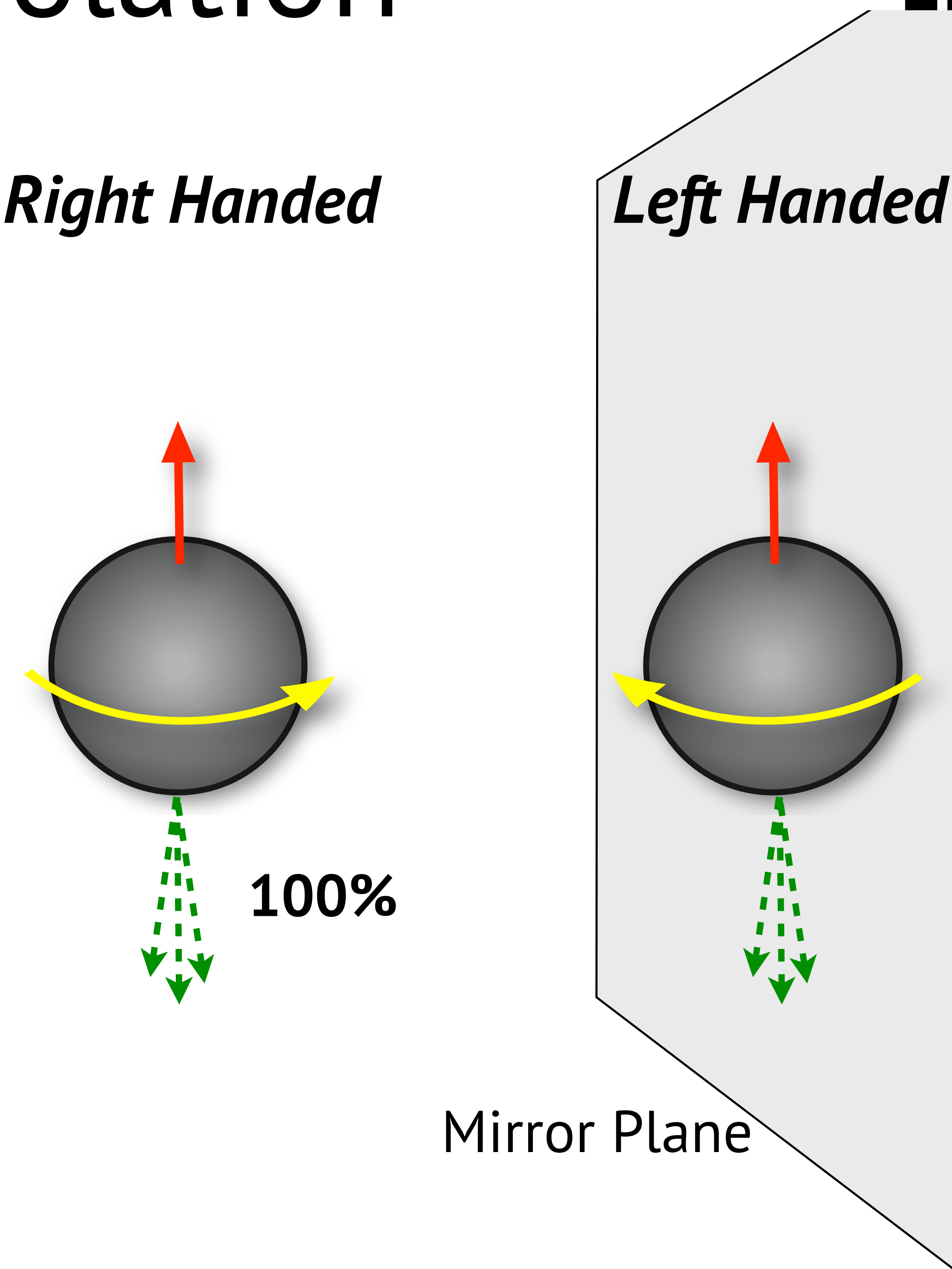
- As soon as we see this though, we know Parity is violated!
- There is a preference for a specific handedness in the decay.

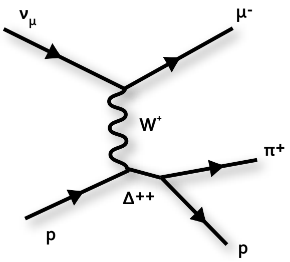




Parity Violation

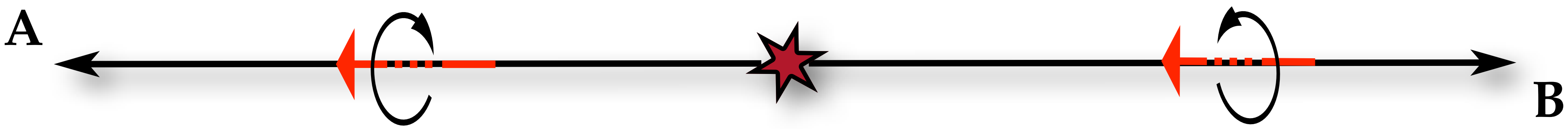
- Interestingly, the Weak force actually works like ***this***...
- (Don't dwell on the specific cartoon drawn - the point is the handedness preference is *maximal*.)





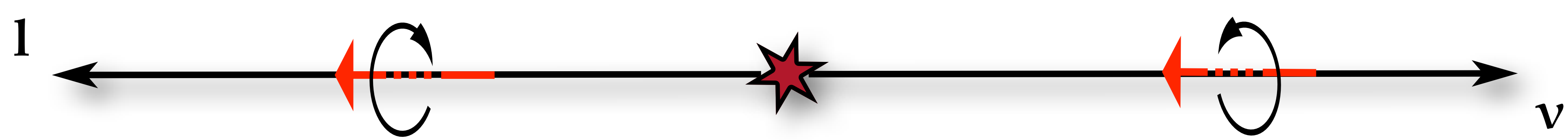
Parity Violation

Suppose the initial spin is 1 and we decay to spin-1/2 fermions A & B...
(Black Arrow is momentum, Red is spin.)

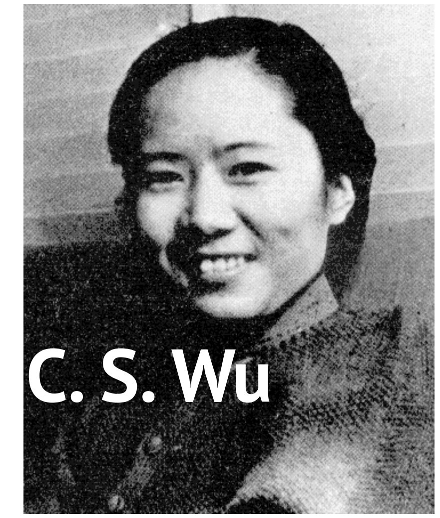


A is right handed, B is left handed.

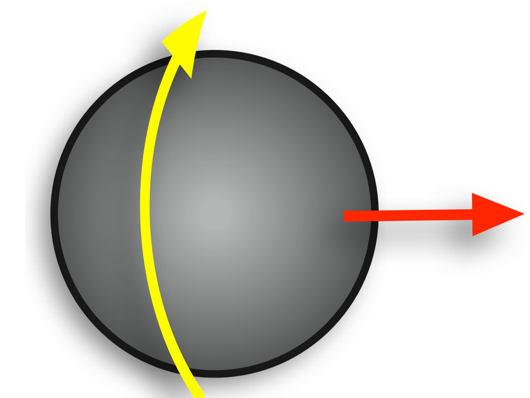
A is left handed, B is right handed. Parity is not violated...



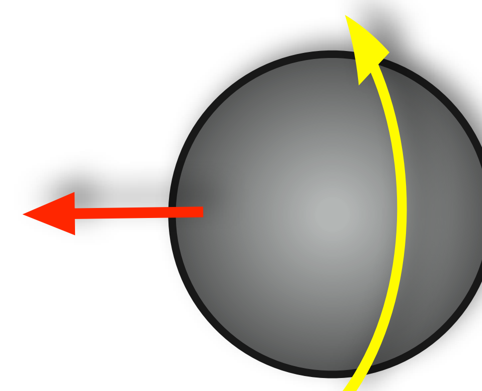
The neutrino is ALWAYS left handed!

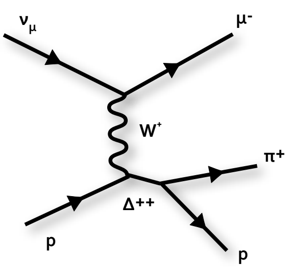


Left Handed



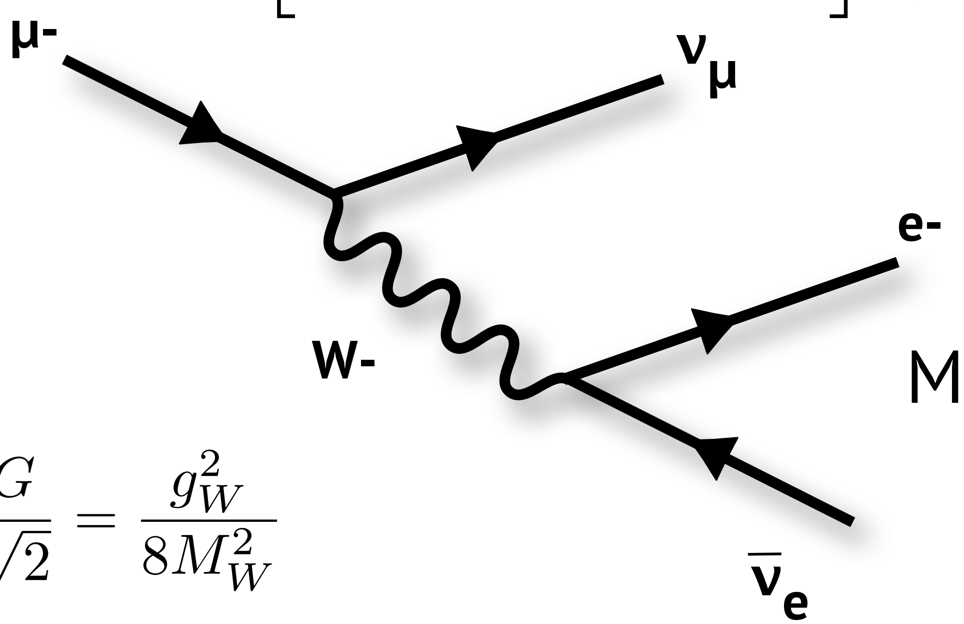
Right Handed





Weak Interactions in the Standard Model

$$M_{\mu-decay} = \left[\frac{g_W}{\sqrt{2}}\bar{u}_\nu \gamma^\sigma \frac{(1-\gamma^5)}{2} u_\mu\right]\left(\frac{1}{M_W^2 - q^2}\right)\left[\frac{g_W}{\sqrt{2}}\bar{u}_e \gamma^\sigma \frac{(1-\gamma^5)}{2} u_{\bar{\nu}_e}\right]$$

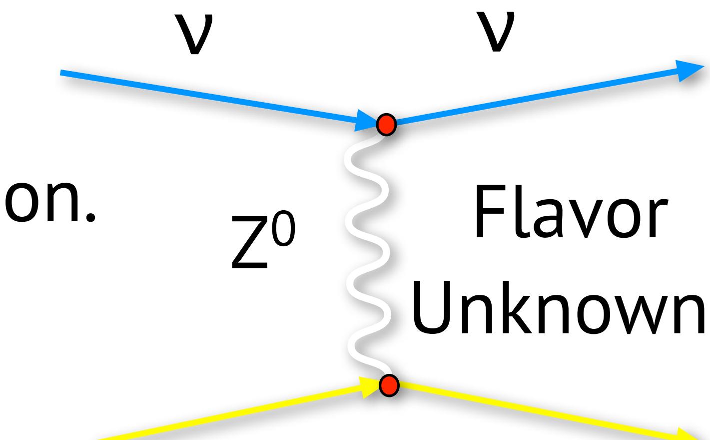


Massive Propagator!

Parity Violation.

$$\frac{G}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$

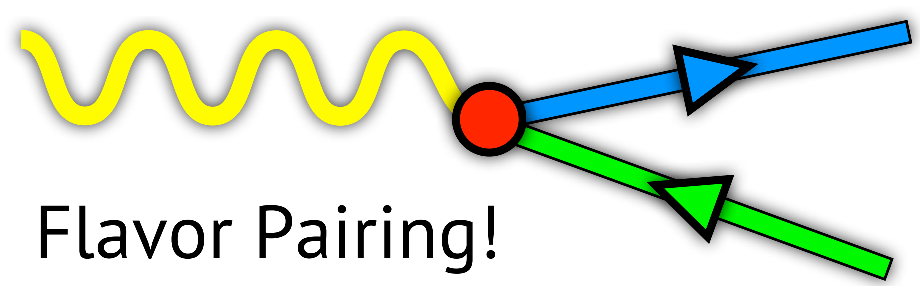
Neutral Current (NC)



Lepton Number Conservation*

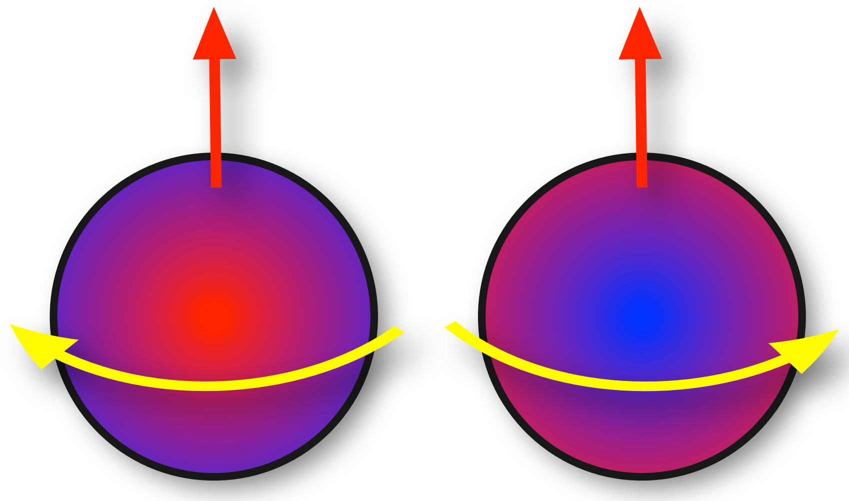
Parti	e^-	e^+	ν_e	anti-
l_e	+1	-1	+1	-1

Charged Current (CC) $W^\pm$



*Actually, “hiding” behind Parity violation. Hmmm...

Helicity, Chirality, & Parody, oops, Parity!



Left-Helicity Right-Helicity

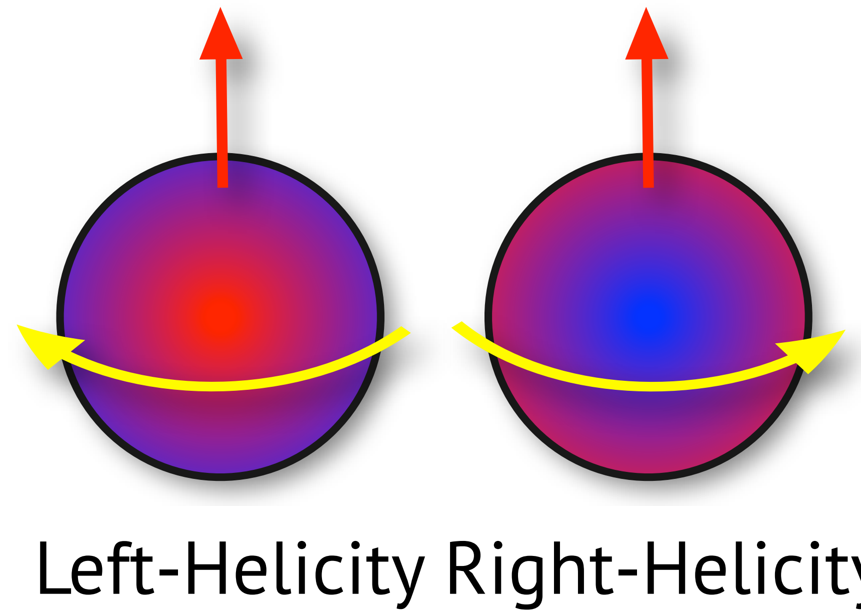
- ***The Weak force is left-handed.***
  - ($1-\gamma^5$) projects onto **left-handed states for massless fermions** and **right-handed states for massless anti-fermions**.

$$\frac{1}{2}\left(1-\gamma^5\right)\psi = \psi_L$$

- **Helicity**
  - Projection of spin along a particle's momentum vector.
  - **Frame-dependent for massive particles.**

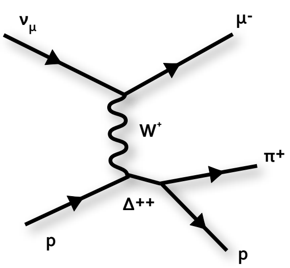
- **Chirality**
  - Lorentz invariant version of helicity (= helicity for massless particles).
  - It is determined by whether the particle transforms in a right or left-handed representation of the Poincaré group. Some representations (e.g. Dirac spinors) have right and left-handed components. We define projection operators that project out either the right or left hand components.

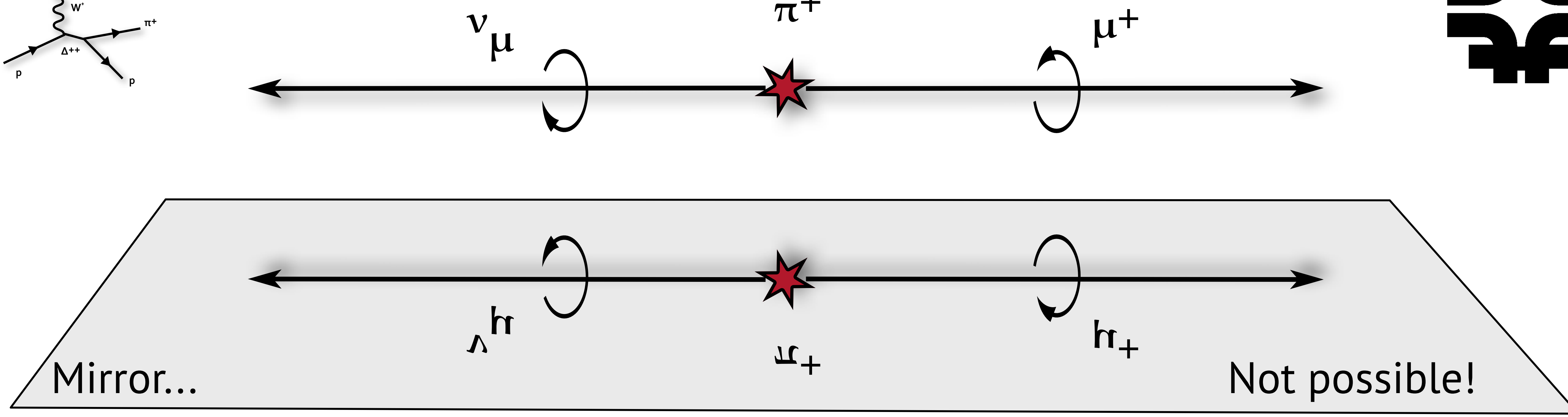
Helicity, Chirality, & Parody, oops, Parity!



- ***The Weak force is left-handed.***
  - More simply, the Weak force couples to *left-handed stuff* and *right-handed anti-stuff*.
  - Handedness is frame dependent for massive particles.
  - To the extent neutrinos are massless, the Weak force couples to left-handed neutrinos and right-handed anti-neutrinos only.

$$\frac{1}{2}\left(1-\gamma^{5}\right)\psi=\psi_{L}$$





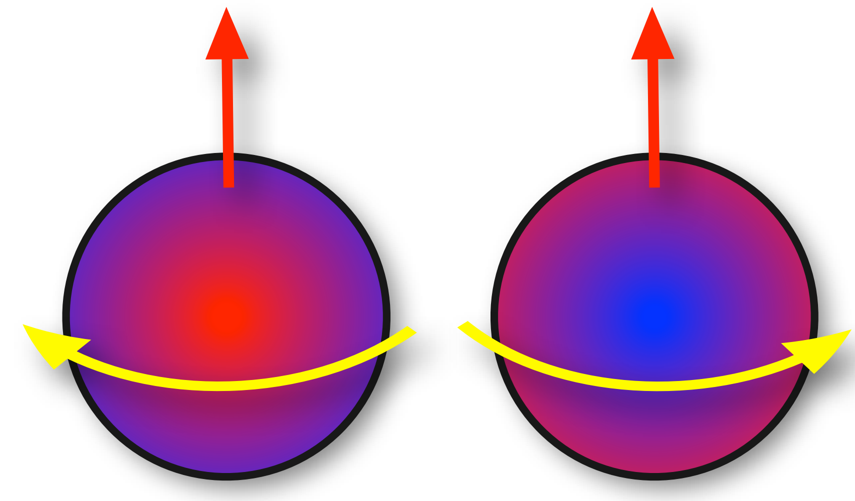
- The pion is spin zero, so daughters must have opposite spins (equal helicities).

- The neutrino is always left-handed, so anti-lepton must also be left-handed. But if the anti-lepton were truly massless, it would only exist as a right-handed particle and the decay would be impossible!

$$R_\pi = \frac{\Gamma\left(\pi^+ \to e^+\nu_e\right)}{\Gamma\left(\pi^+ \to \mu^+\nu_\mu\right)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 1.23 \times 10^{-4}$$

To the extent the electron is "massless," pion decay to electrons is highly suppressed.

Helicity, Chirality, & Parody, oops, Parity!



Left-Helicity Right-Helicity

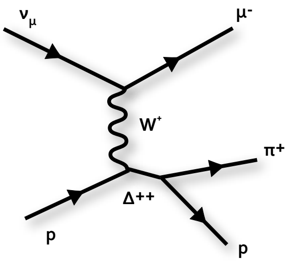
$$\Sigma_{4x4} = \begin{pmatrix} \sigma_{2x2} & 0 \\ 0 & \sigma_{2x2} \end{pmatrix}$$

- ***The Weak force is left-handed.***

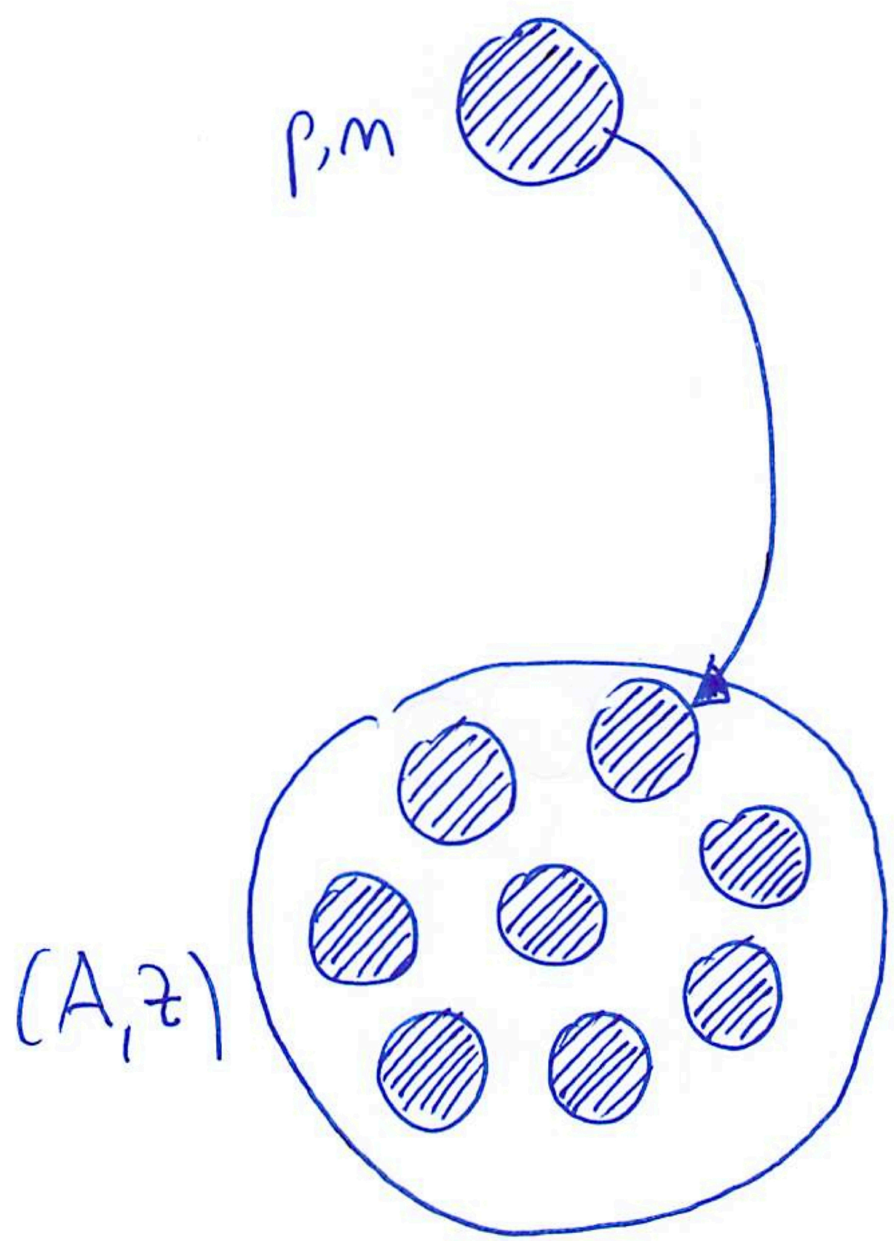
$$\frac{1}{2}\left(1-\gamma^5\right)\psi =\simeq \left(\Sigma \cdot p\right)\psi$$

$$\frac{1}{2}\left(1-\gamma^5\right)\psi = \psi_L = \alpha\phi_L + \beta\phi_R$$

$$\frac{1}{2}\left(1-\gamma^5\right)\psi = \psi_L$$



DESCRIPTION OF NUCLEON



STRUCTURE FUNCTIONS

$F_1(x,Q^2), F_2(x,Q^2), xF_3(x,Q^2),$ .....

$\boxed{\delta f(x)}$

DESCRIPTION OF NUCLEUS

SPECTRAL FUNCTION

$\mathcal{P}(\varepsilon, \mathbf{p})$

R. Petti, ECT Trento, 2012

QMC methods

J. Carlson, INT13,
http://www.int.washington.edu/PROGRAMS/13-54w/

Basic Idea: project specific low-lying states from initial guess (or source)

$$\Psi_0 = \exp\left[-H\tau\right] \Psi_T$$

Use Feynman path integrals to compute propagator

$$\exp\left[-H\tau\right] = \prod \exp[-H\delta\tau]$$

$$\exp[-H\delta\tau] \approx \exp[-T\delta\tau] \exp[-V\delta\tau]$$

diffusion branching

Applications: condensed matter (Helium, electronic systems, ...
nuclear physics (light nuclei, neutron matter, SMMC...)
atomic physics (cold atoms,...)

Various formulations: DMC/GFMC, AFMC, AFDMC, Lattice

GFMC Algorithm:

Branching random walk in 3A (36 for ^{12}C) dimensions

Asynchronous Dynamic Load Balancing (ADLB) Library

Each step moves A particles and updates

$2^A \times \binom{A}{Z}$ complex amplitudes (2 GB for ^{12}C gs)

significant linear algebra for each step

tuned by physicists and math/CS staff at ANL

Similar branching random walks with linear algebra used in condensed matter physics (lattice calculations)

up to ~2M threads

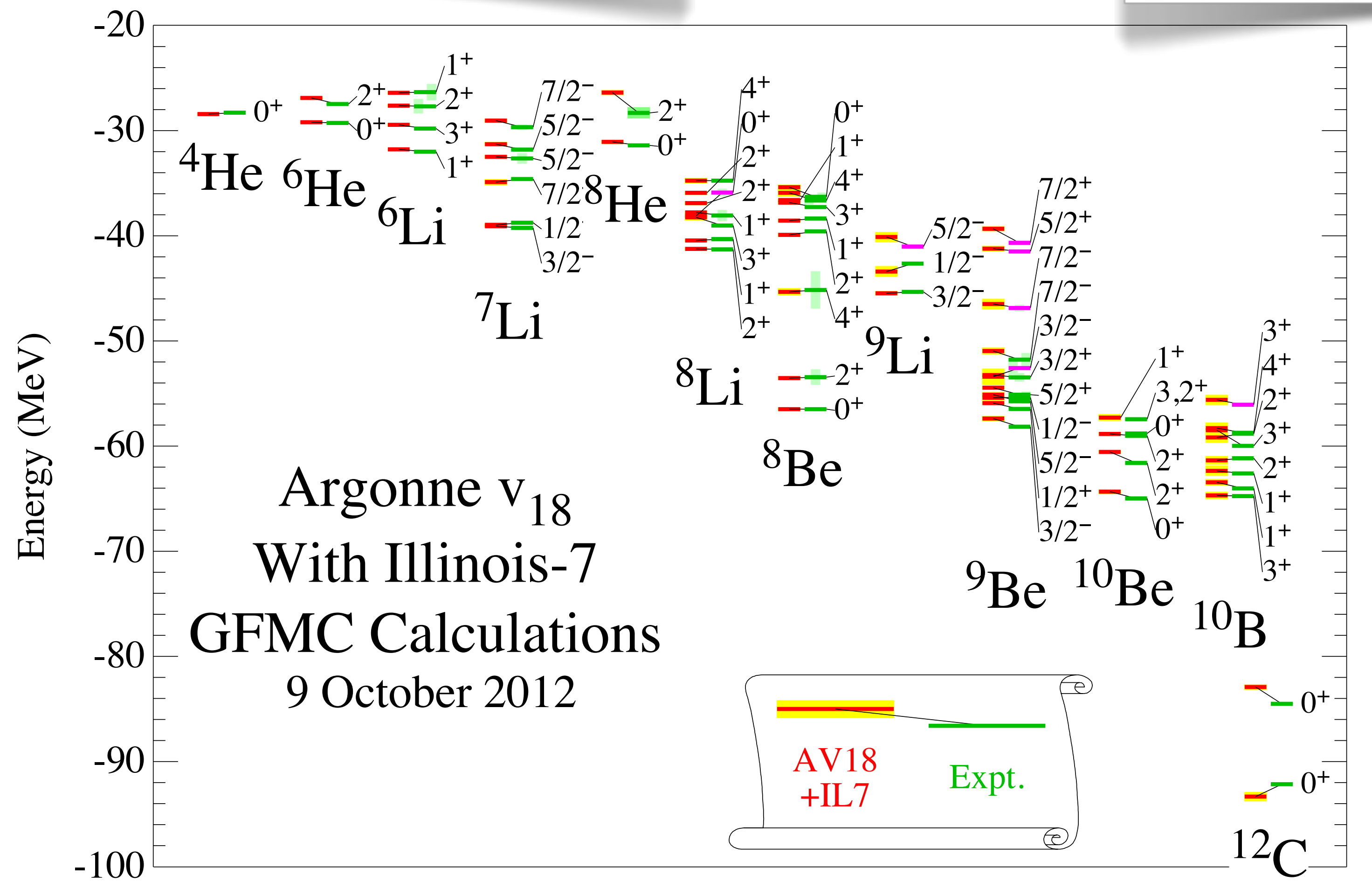
Other methods: NCSM, Coupled Cluster, ...

J. Carlson, INT13

Spectra of Light Nuclei

J. Carlson, INT13,
http://www.int.washington.edu/PROGRAMS/13-54w/

Any chance we can get Argon?
Just asking for a friend...

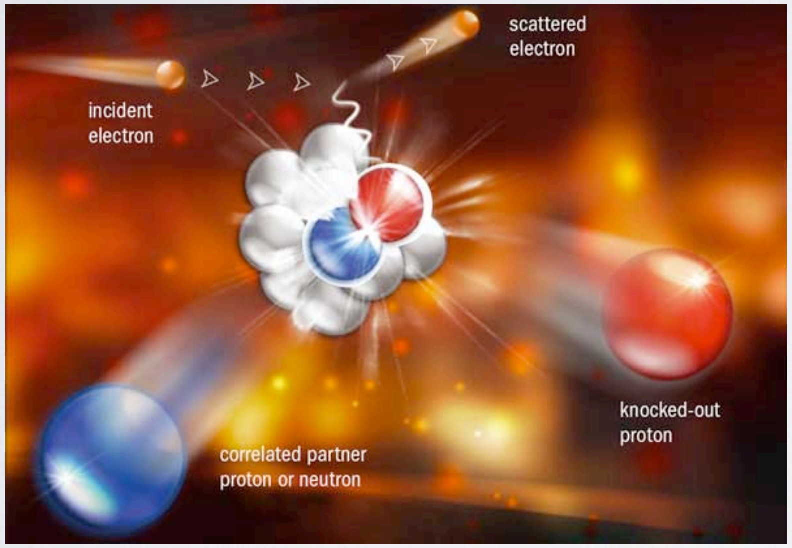


Spectra must be correct to describe low-energy transitions, reactions, etc.

Back-to-back pairs: pn vs pp,nn in ^{12}C

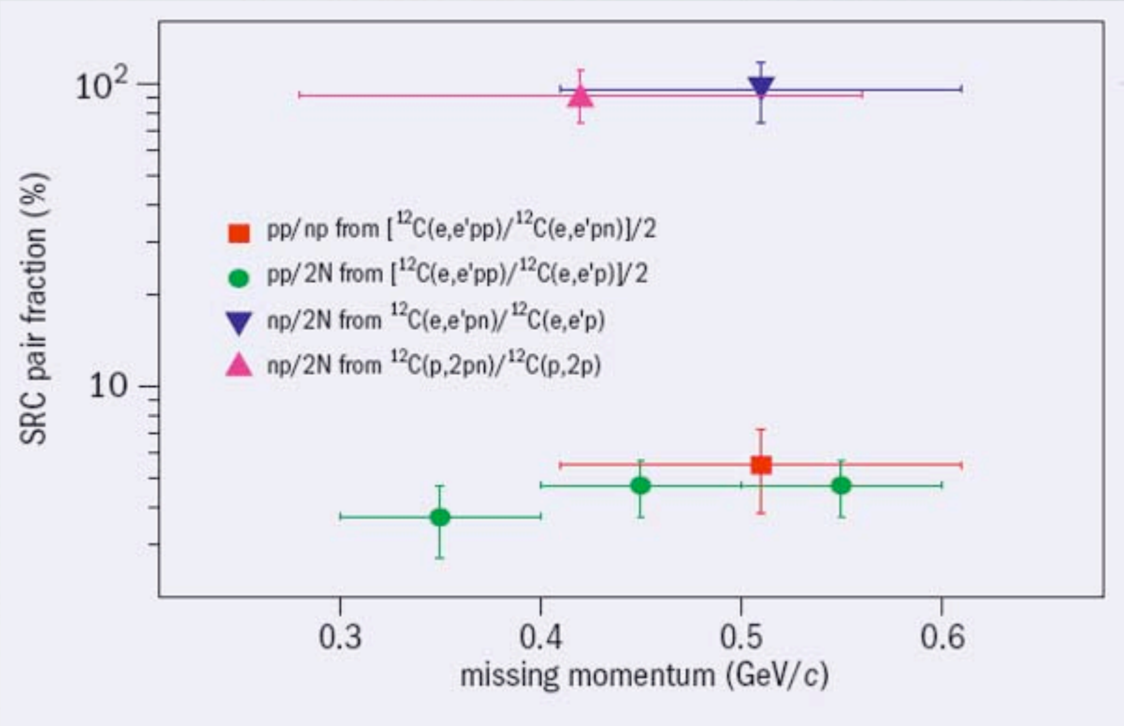
J. Carlson, INT13,
http://www.int.washington.edu/PROGRAMS/13-54w/

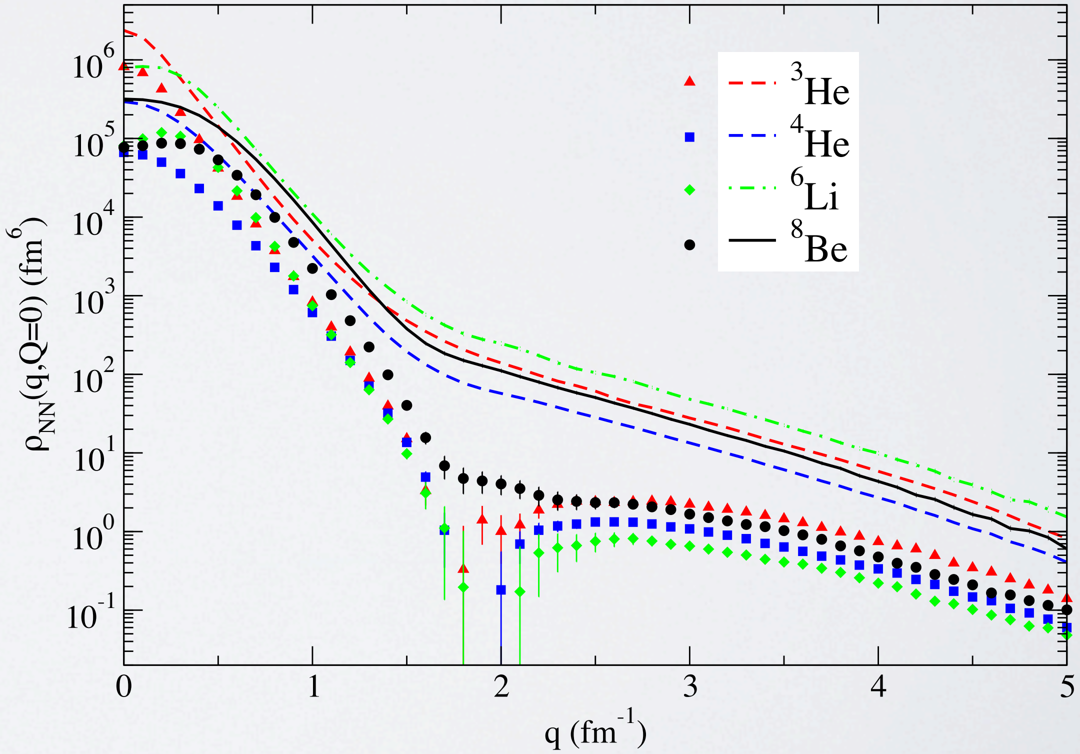
JLAB, BNL
back-to-back pairs in ^{12}C



np pairs dominate over nn and pp

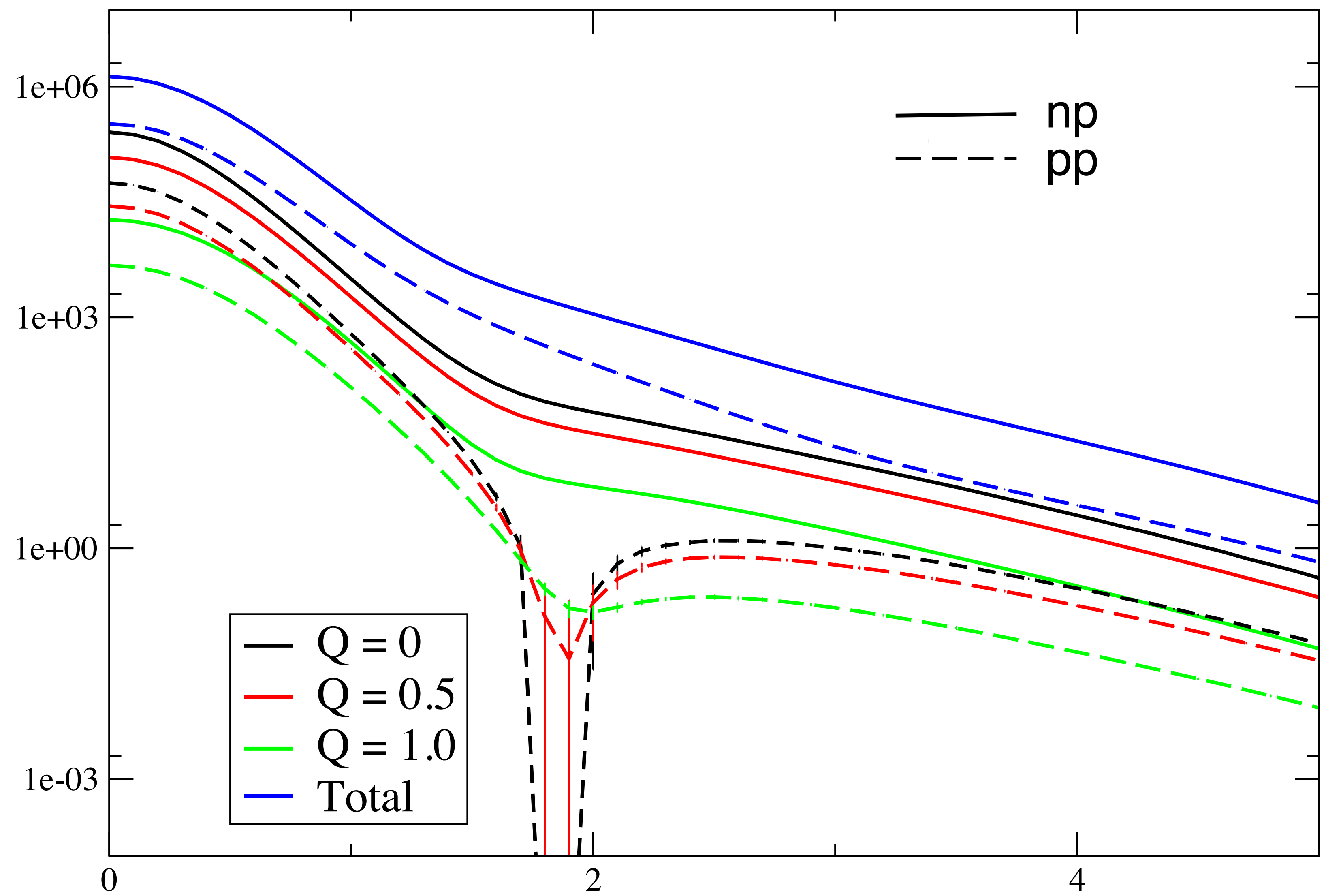
E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.
M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.
R Subedi *et al.* 2008 **Science 320** 1475.





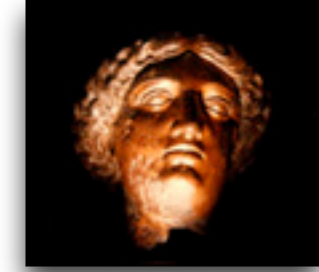
http://www.phy.anl.gov/theory/research/momenta2/

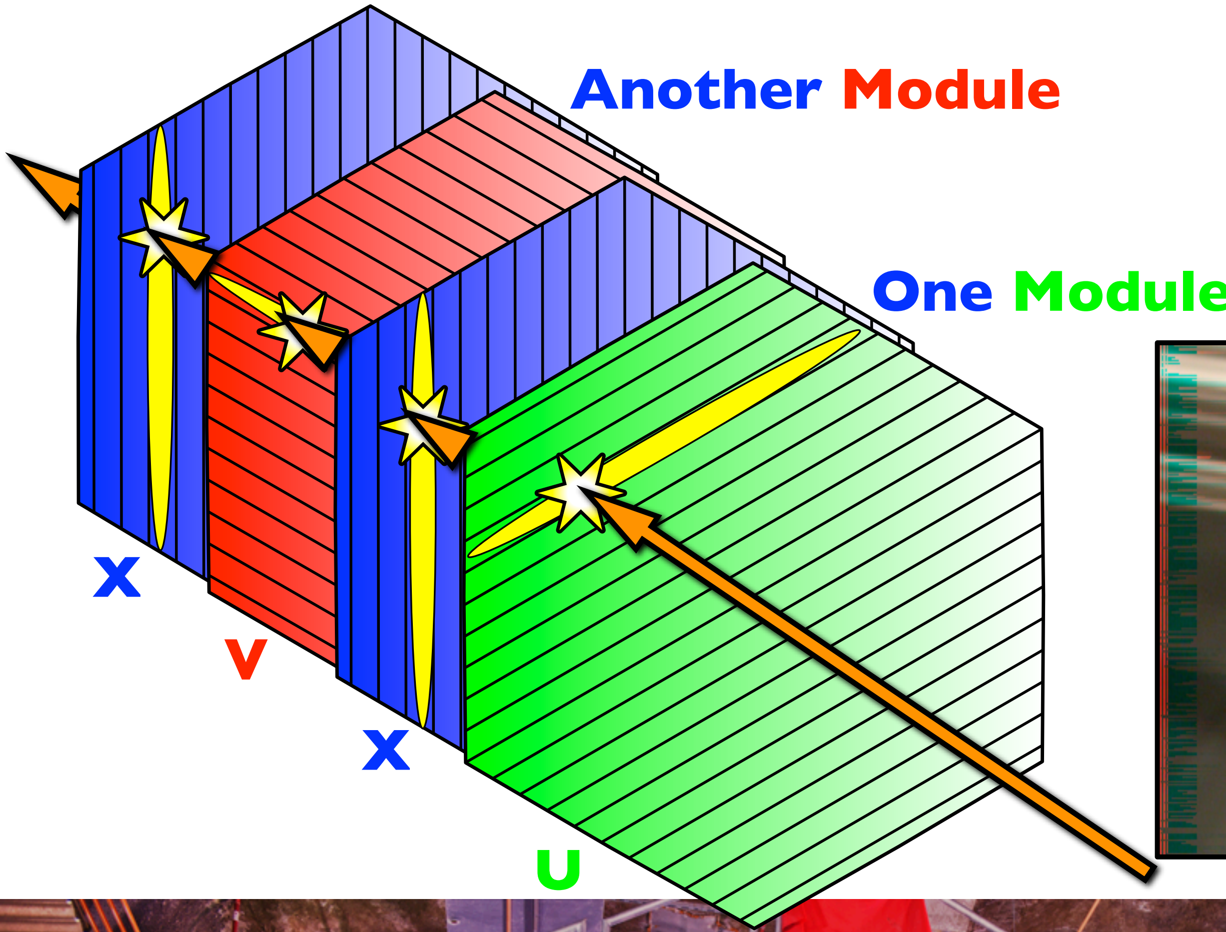
pair momenta vs Q: pn vs pp,nn in ^{4}He

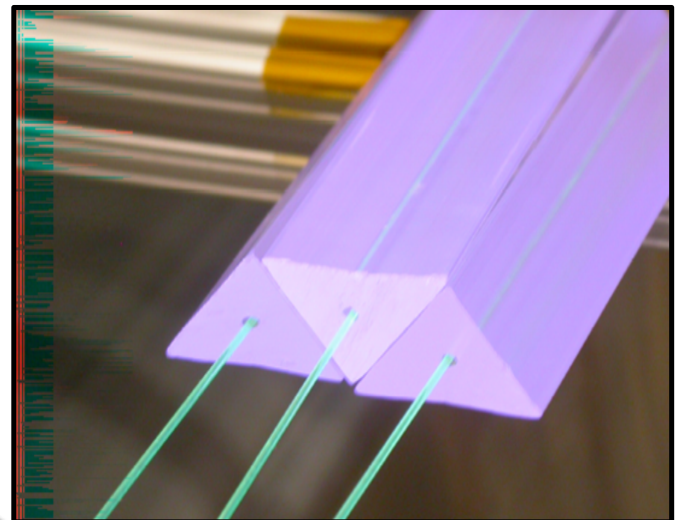


J. Carlson, INT13,
http://www.int.washington.edu/PROGRAMS/13-54w/

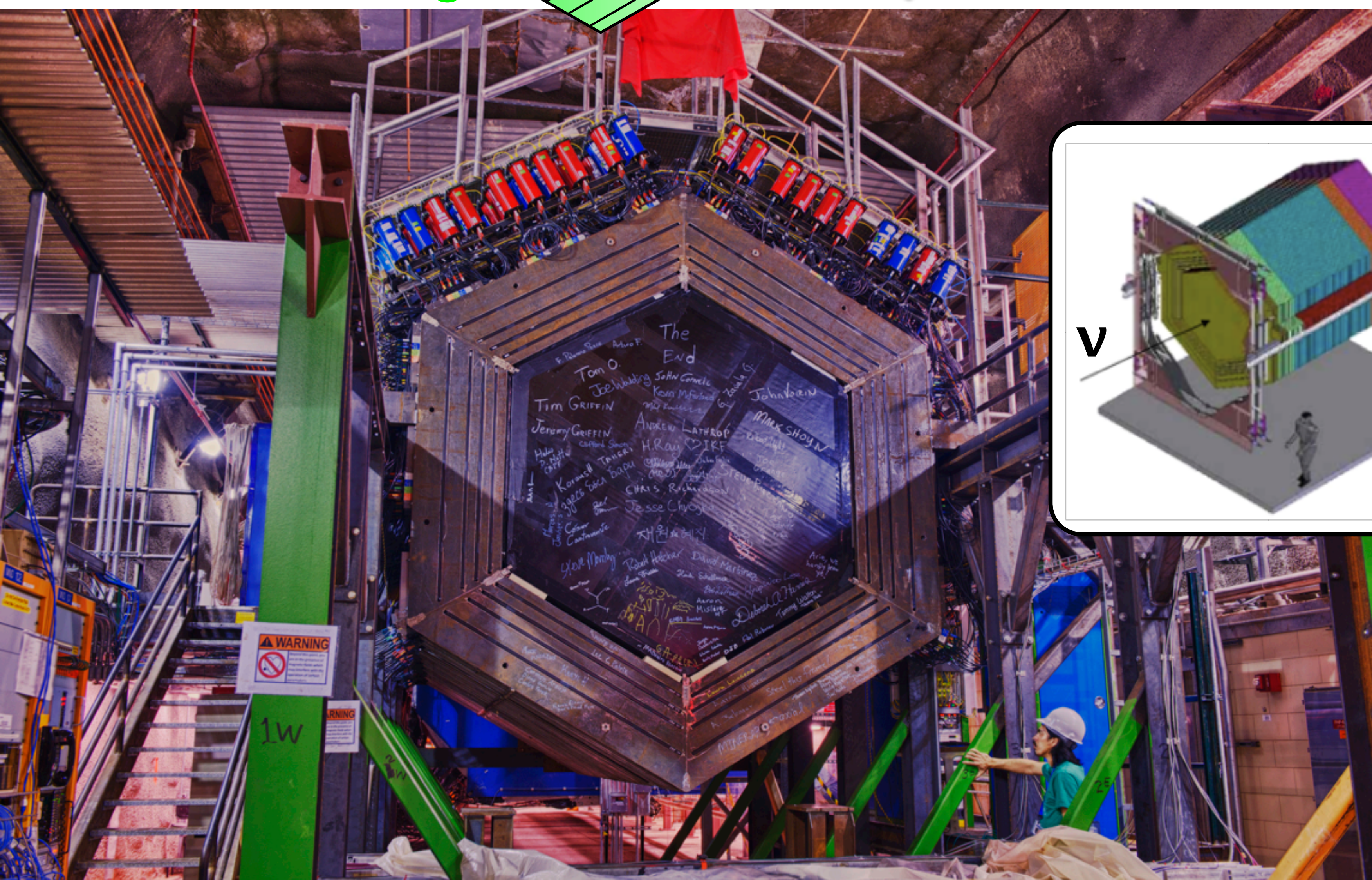
MINERνA



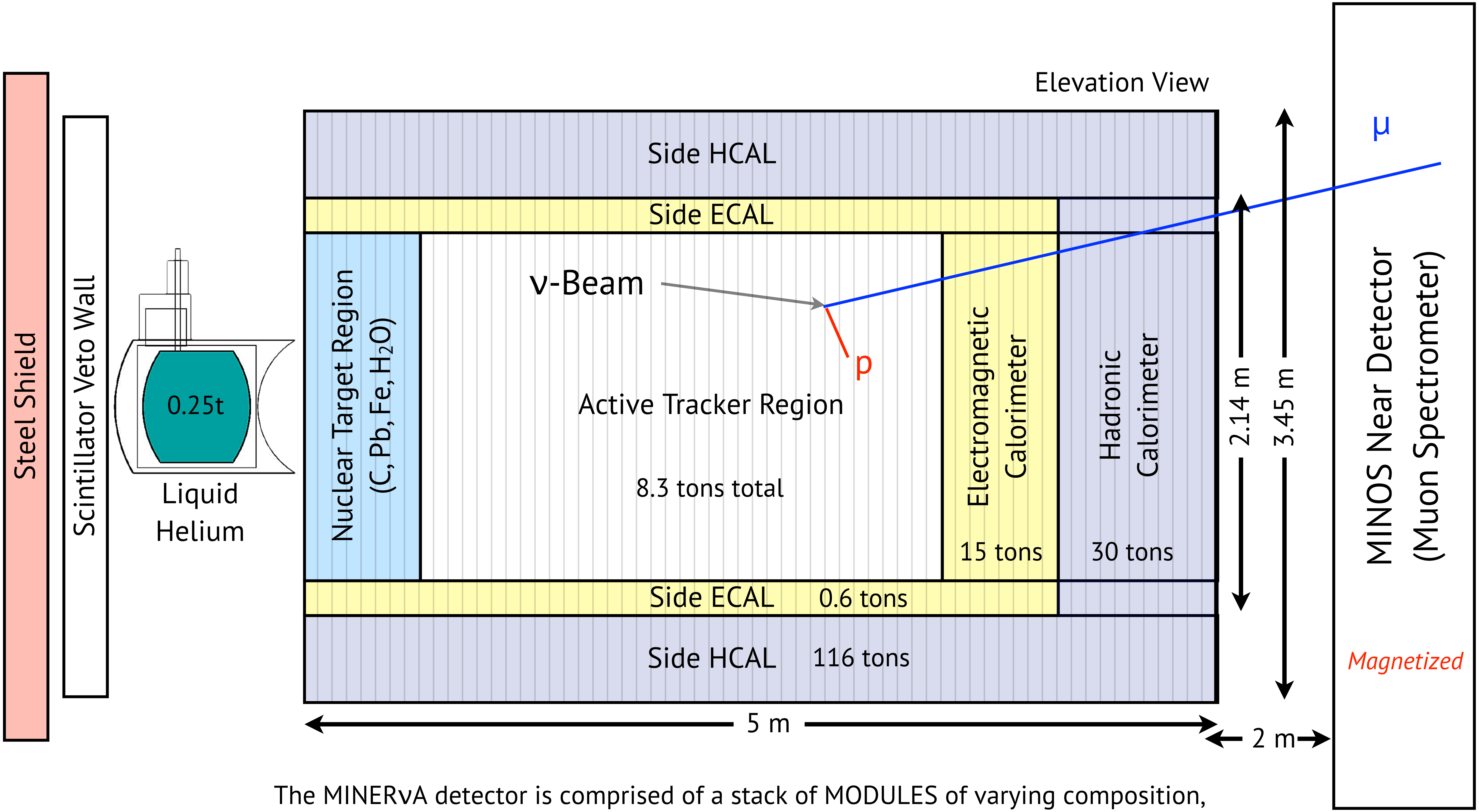




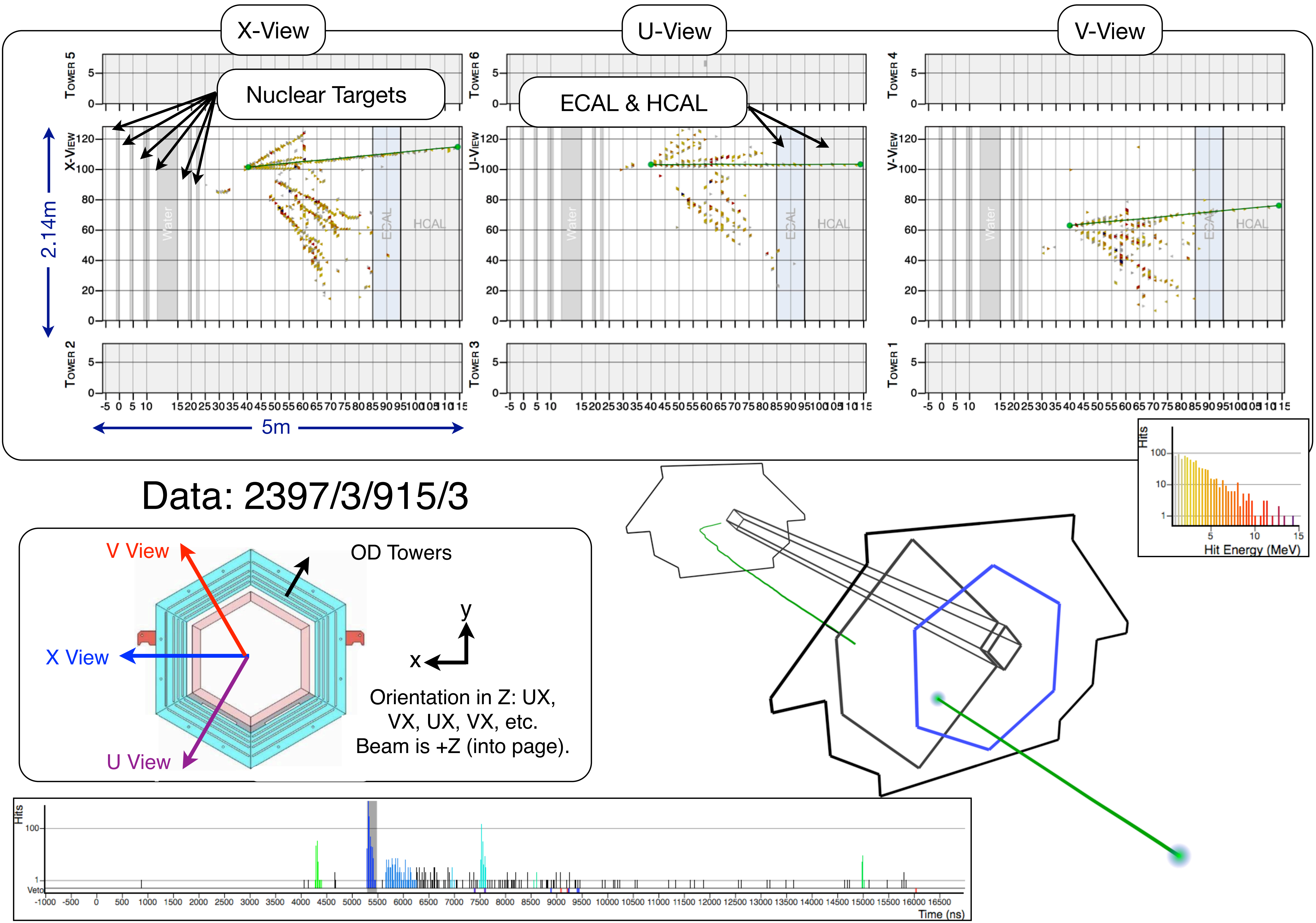
- Fine-grained resolution for excellent kinematic measurements.
- Low-energy cross-section program well-suited to next-generation oscillation experiments.
- Nuclear effects with a variety of target materials ranging from Helium to Lead. Especially important for ME run.



The Best Thing Since Sliced Bread...

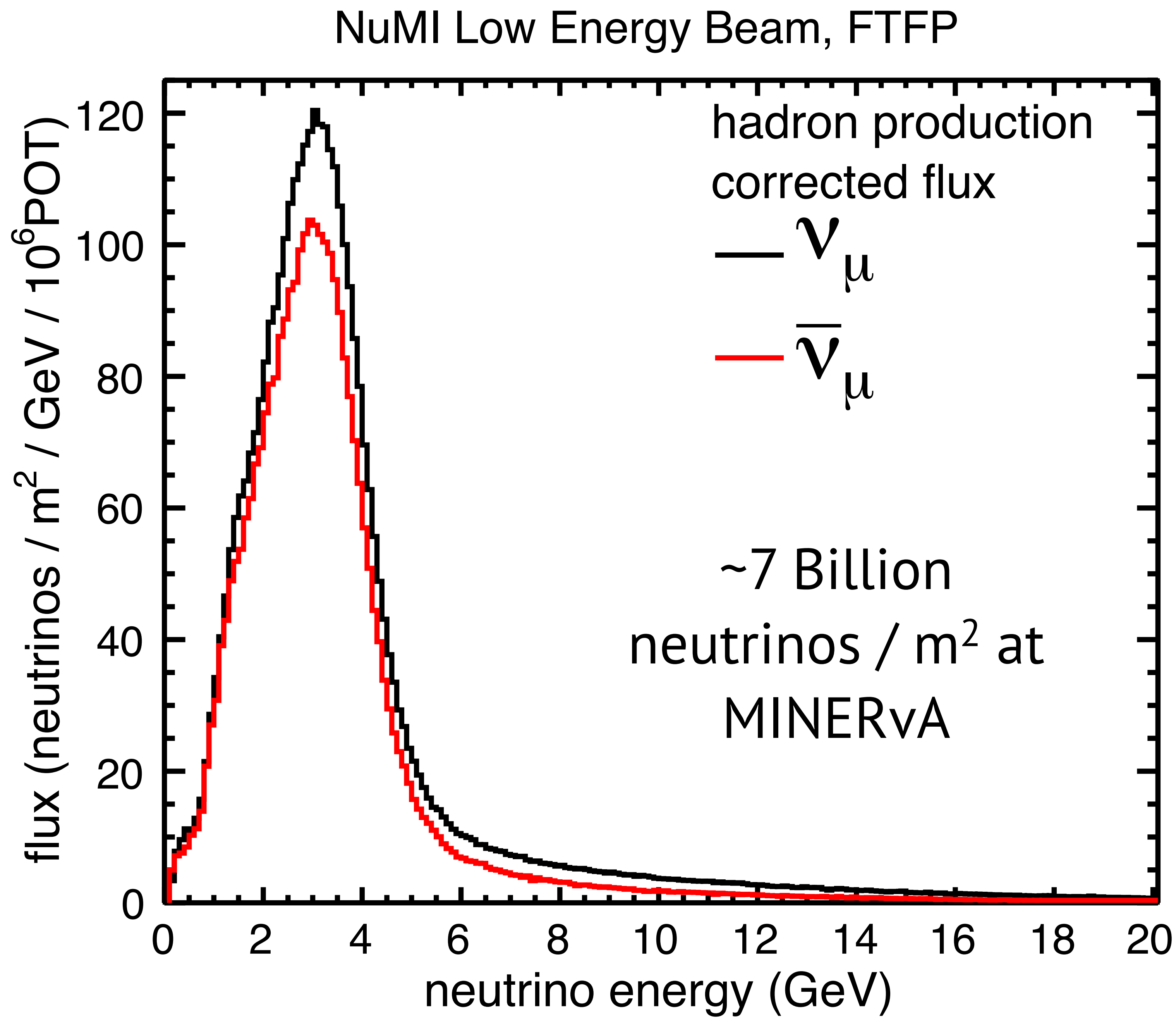


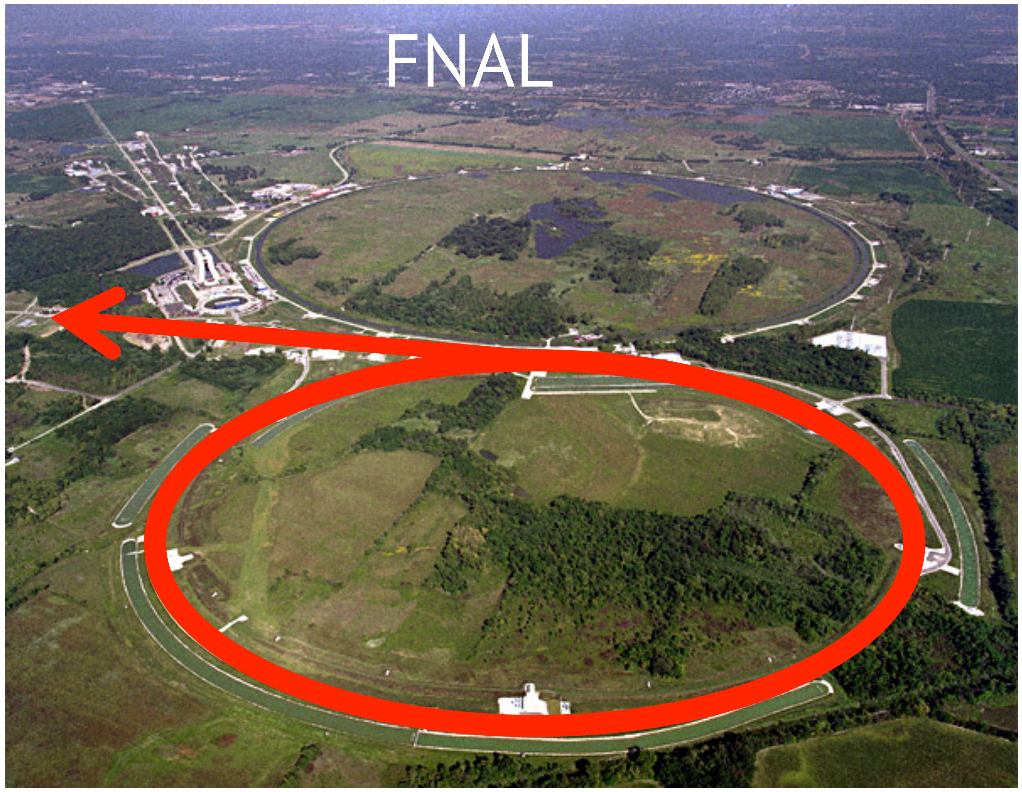
The MINERνA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H_2O).



X-View
U-View
V-View
Nuclear Targets
ECAL & HCAL
Tower 5
Tower 6
Tower 4
Tower 2
Tower 3
Tower 1
X-View
U-View
V-View
Water
ECAL
HCAL
2.14m
5m
Data: 2397/3/915/3
V View
X View
U View
OD Towers
y
x
Orientation in Z: UX, VX, UX, VX, etc.
Beam is +Z (into page).
Hits
Hit Energy (MeV)
Veto
Time (ns)

Neutrino Beam





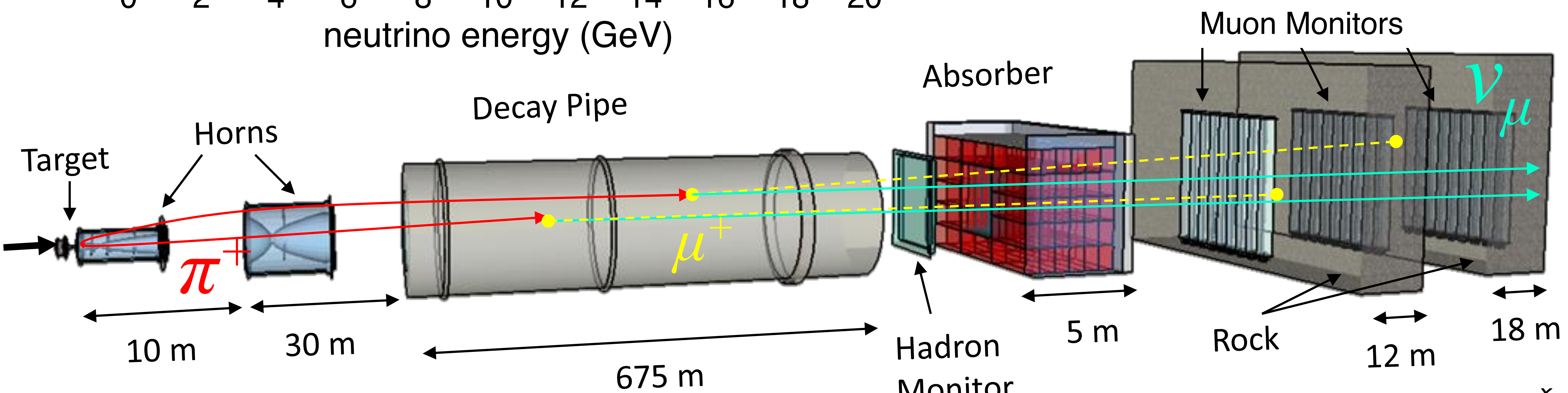
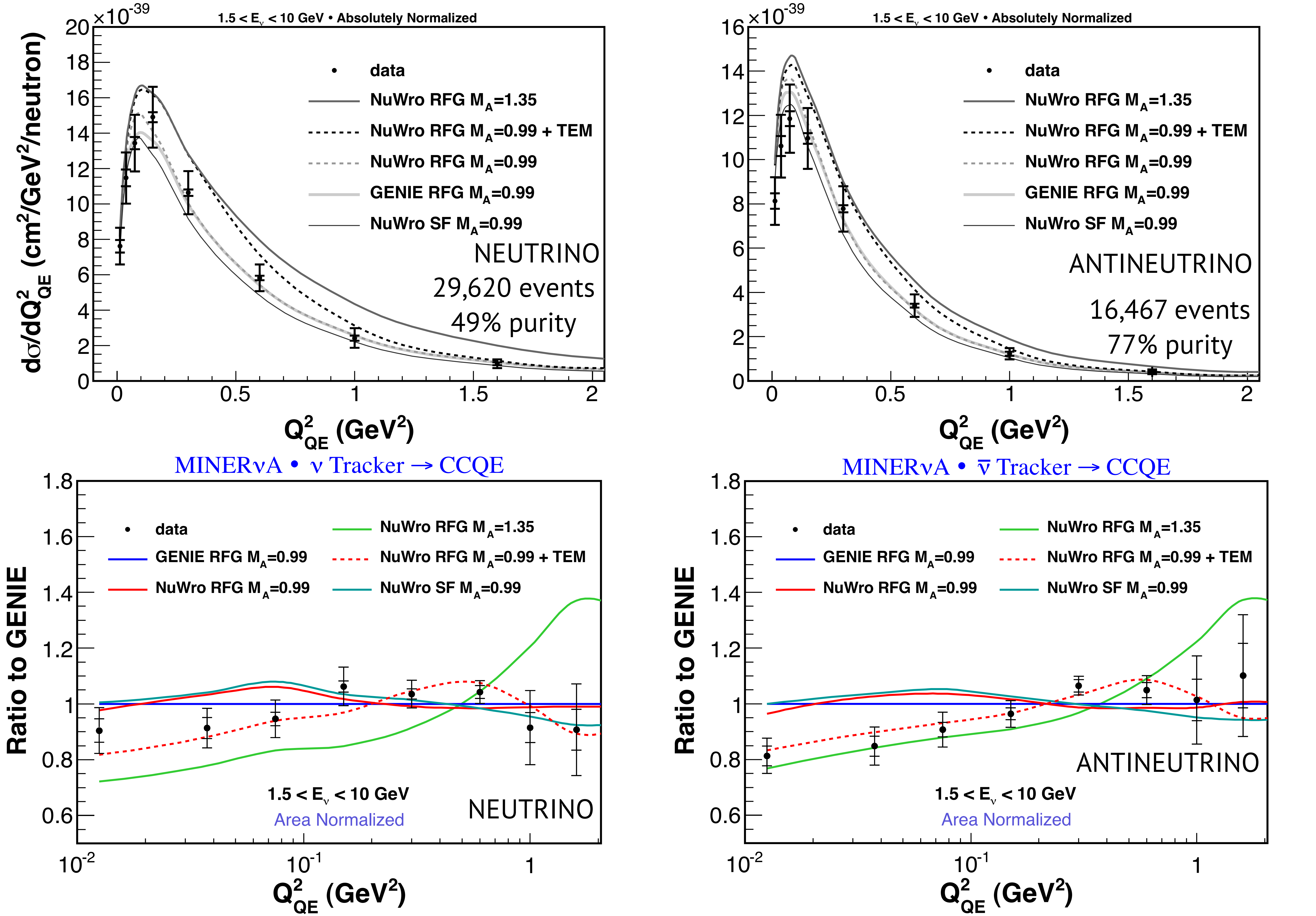


figure courtesy Ž. Pavlović


1.5 < Eν < 10 GeV • Absolutely Normalized
dσ/dQ²QE (cm²/GeV²/neutron)
×10⁻³⁹
data
NuWro RFG MA=1.35
NuWro RFG MA=0.99 + TEM
NuWro RFG MA=0.99
GENIE RFG MA=0.99
NuWro SF MA=0.99
NEUTRINO
29,620 events
49% purity
Q²QE (GeV²)
1.5 < Eν < 10 GeV • Absolutely Normalized
ANTINEUTRINO
16,467 events
77% purity
Q²QE (GeV²)
MINERνA • ν Tracker → CCQE
Ratio to GENIE
1.5 < Eν < 10 GeV
Area Normalized
NEUTRINO
Q²QE (GeV²)
MINERνA • ν̄ Tracker → CCQE
Ratio to GENIE
ANTINEUTRINO
1.5 < Eν < 10 GeV
Area Normalized
Q²QE (GeV²)

ArgoNeuT

- 175L Liquid Argon Time Projection Chamber (TPC).
- First step in the US liquid argon program (MicroBooNE, LBNE) & first LArTPC in a low-energy neutrino beam.
- Physics run in the NuMI Beam June '09 ⊕ Sept. '09 - Feb. '10.
  - Located between MINOS ND and MINERvA & utilized MINOS for muon momentum and charge sign.

TPC / Cryostat Volume	175 / 500 L
# of Electronics Channels*	480
Wire Pitch	4 mm
Max Drift Length	0.5 m (330 μs)
Electric Field	500 V/cm

*Two readout planes: Induction & Collection
Each Channel: 2048 Samples / 400 μs