GENIE at FNAL

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Fermilab

ν Oscillations

- Flavor and Mass eigenstates are not the same.
- Originally proposed* to solve the "solar neutrino problem."
- Implies non-zero masses for (at least two of the) neutrinos.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \qquad m_1 \neq m_2 \neq m_3$$

*Bruno Pontecorvo: 1957
Z. Maki, M. Nakagawa, S. Sakata: 1962 (Formalism)

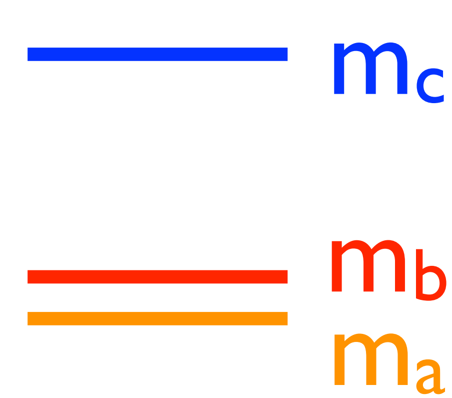
$$\begin{bmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} \begin{bmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{bmatrix}$$

(Greek letters for flavors; Roman letters for masses.)

- MNS/PMNS Matrix
- 3 x 3 Unitary Matrix
  - 3 “Euler Angles”, 1 Complex Phase*

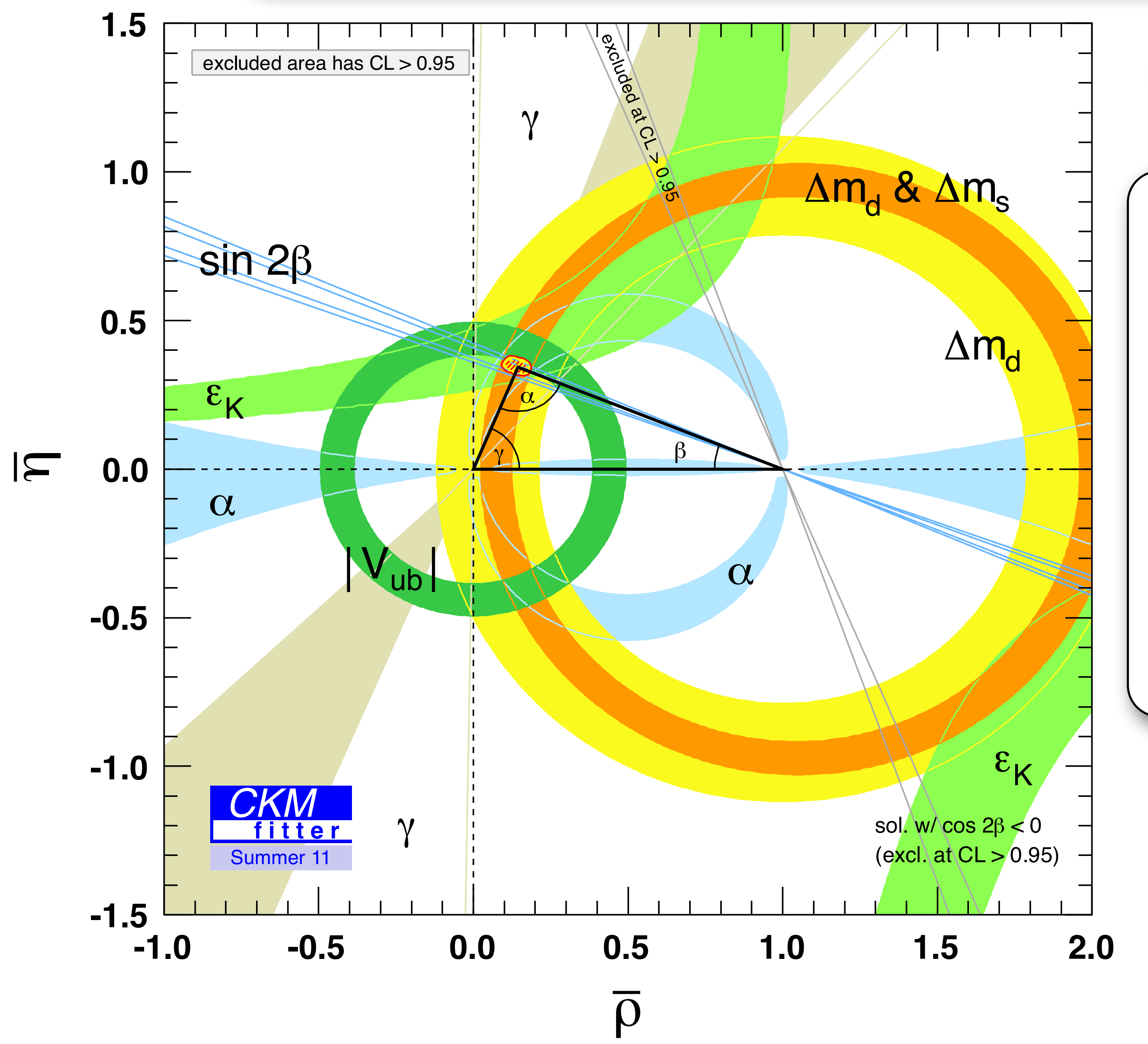
$\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}$

- 3 Masses
  - 2 Independent Splittings

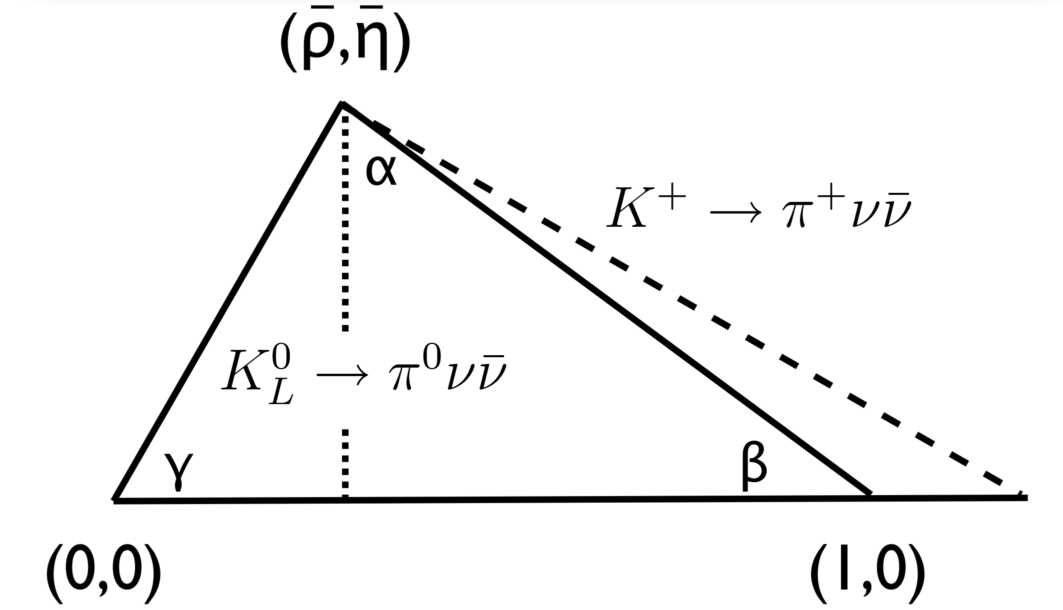


*Set aside Majorana for the moment...

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0.$$



The height of the triangle tells us about CP violation in quarks.

Something sticks out...

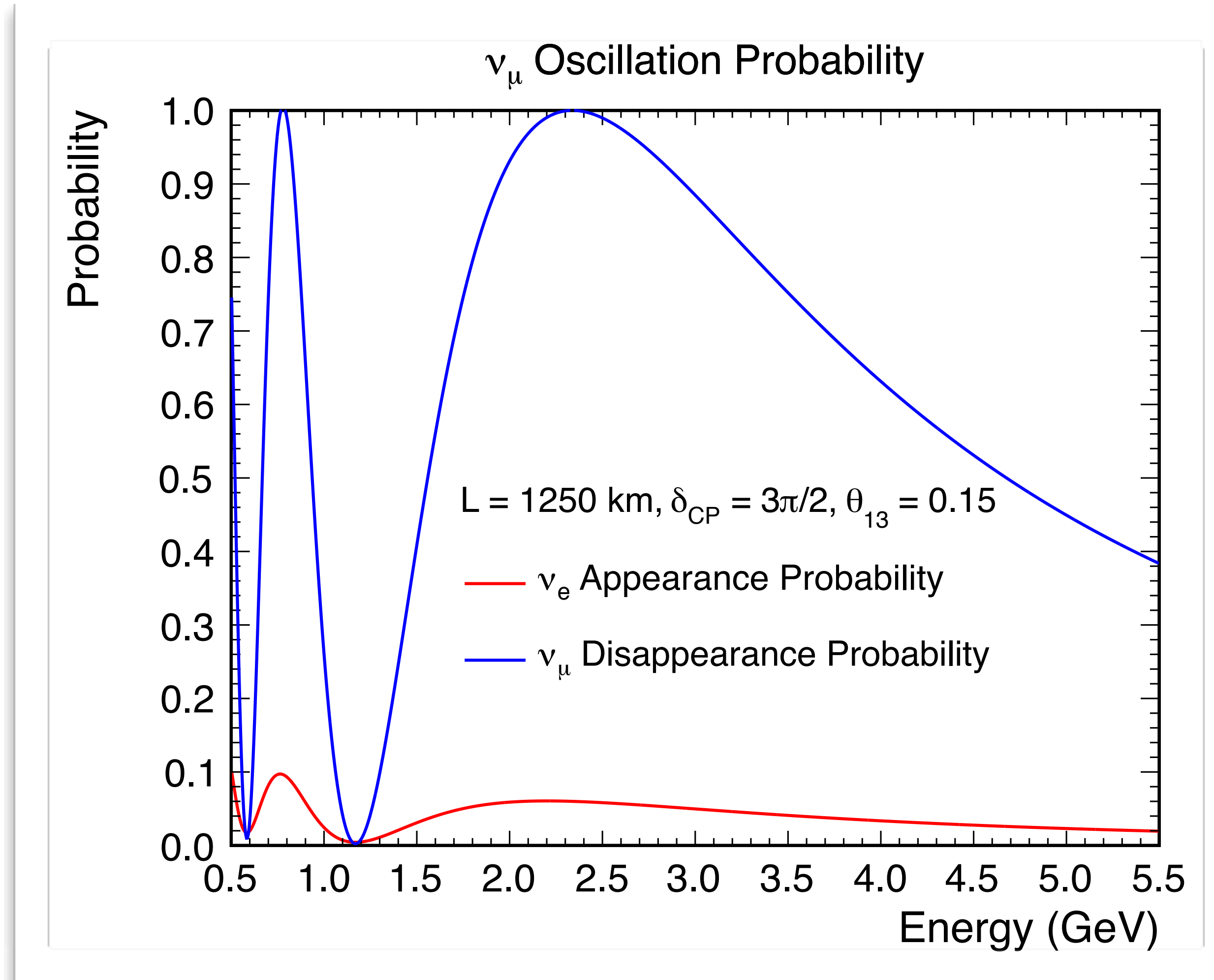
$$|V_{CKM}| \approx \begin{pmatrix} 1 & 0.2 & \epsilon \\ 0.2 & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

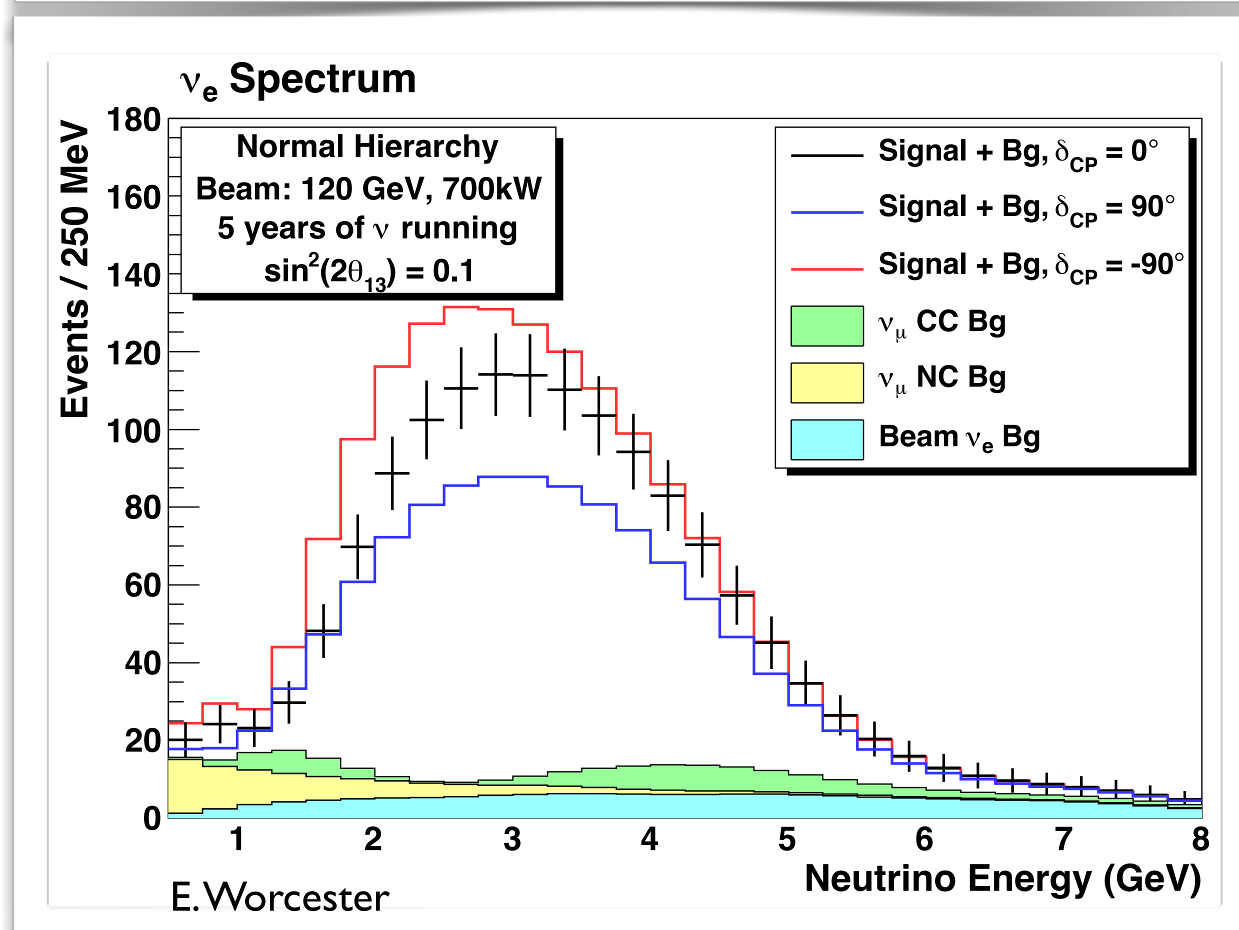
$$|U_{MNS}| \approx \begin{pmatrix} 0.8 & 0.6 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

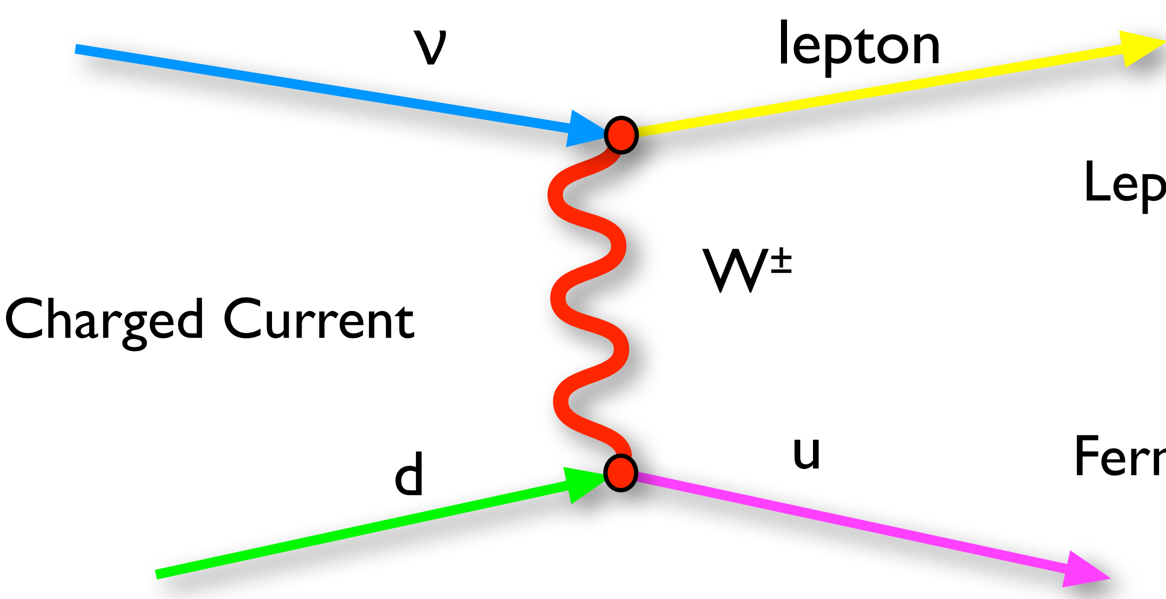
Why?

Challenges

- Statistics!
  - Heavy targets.
  - ... But complicated interaction physics!
- Small effect, even with a many kiloton detector.
- Background systematics are not well known.

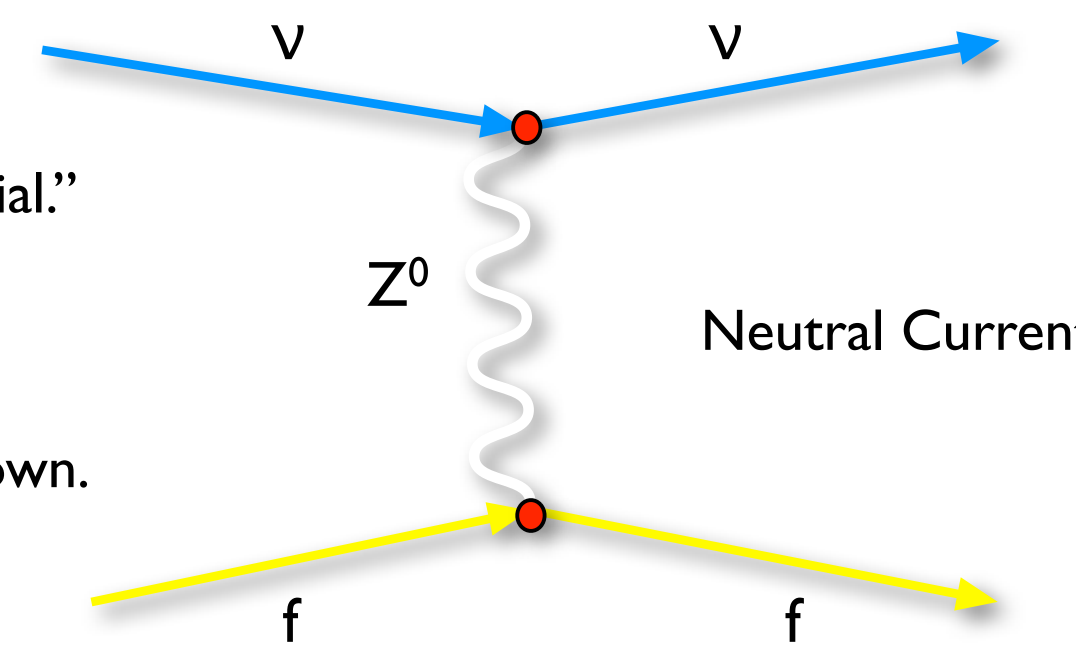




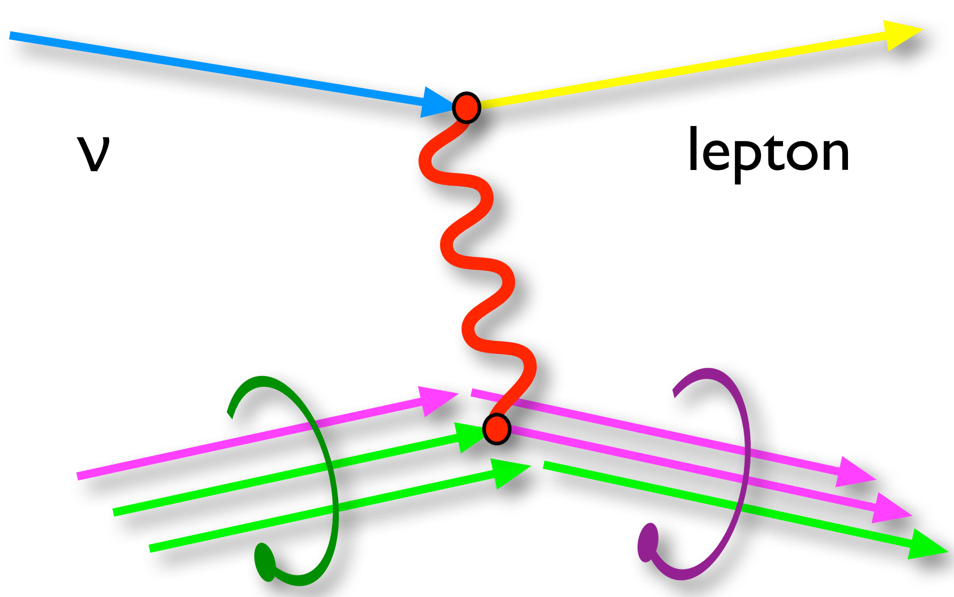


Lepton: "Trivial."

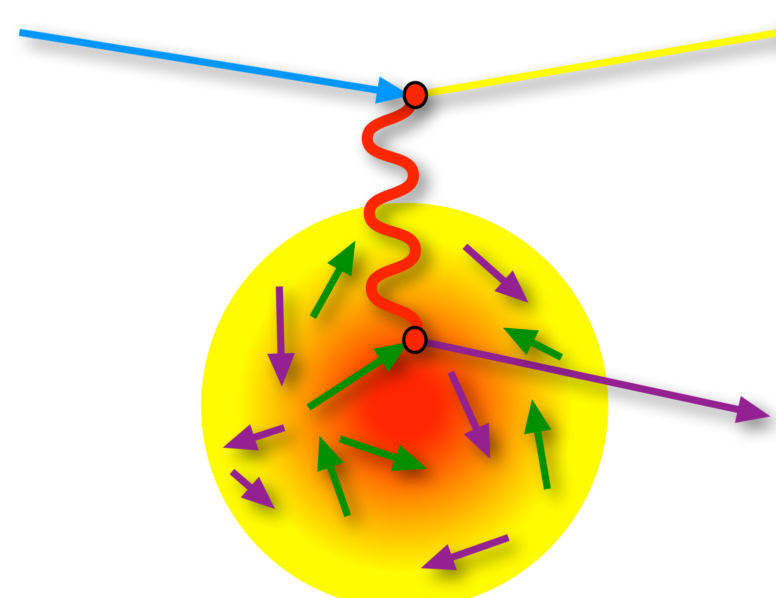
Fermion: Known.

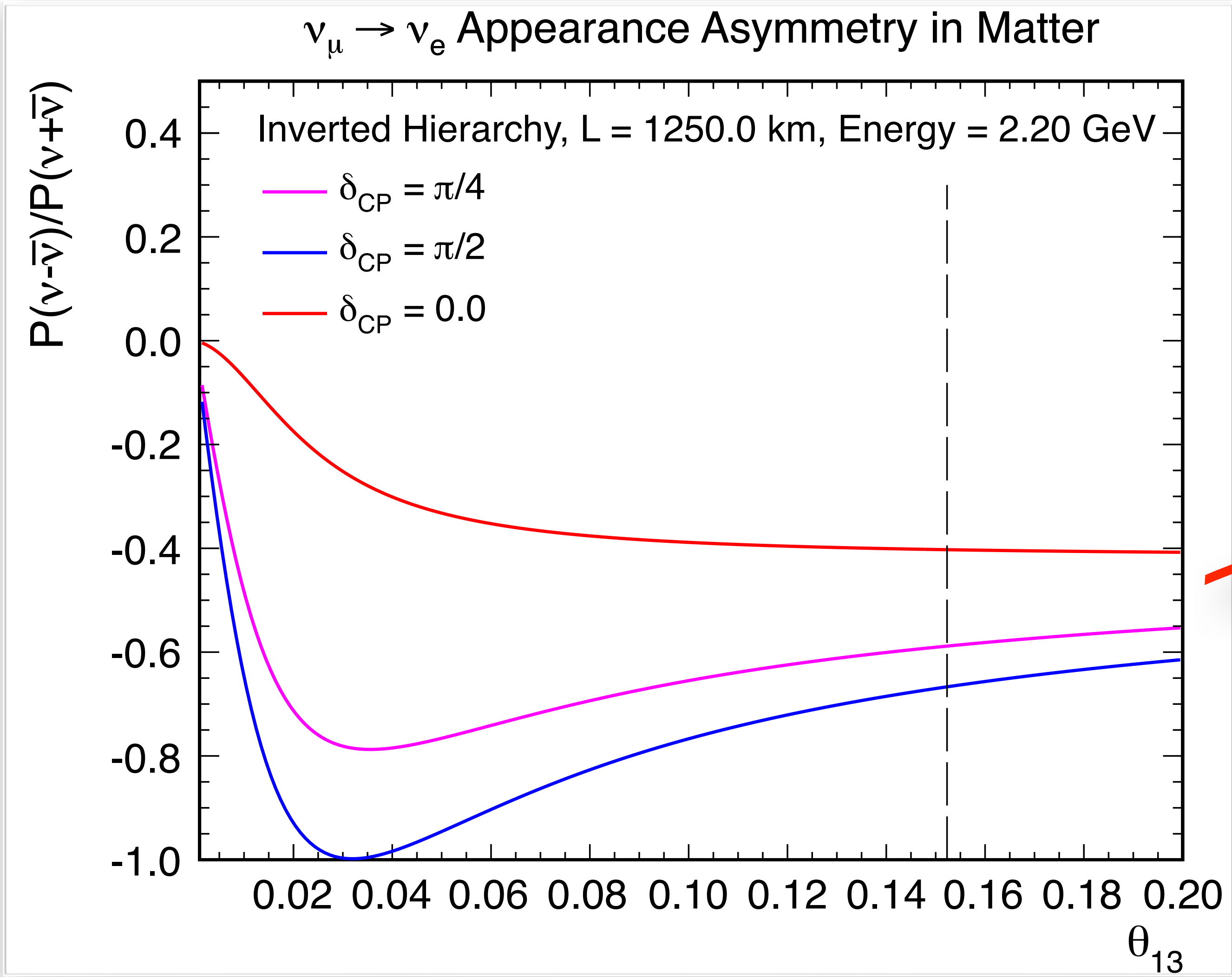


Nucleon: Parameterize
w/ Form Factors.



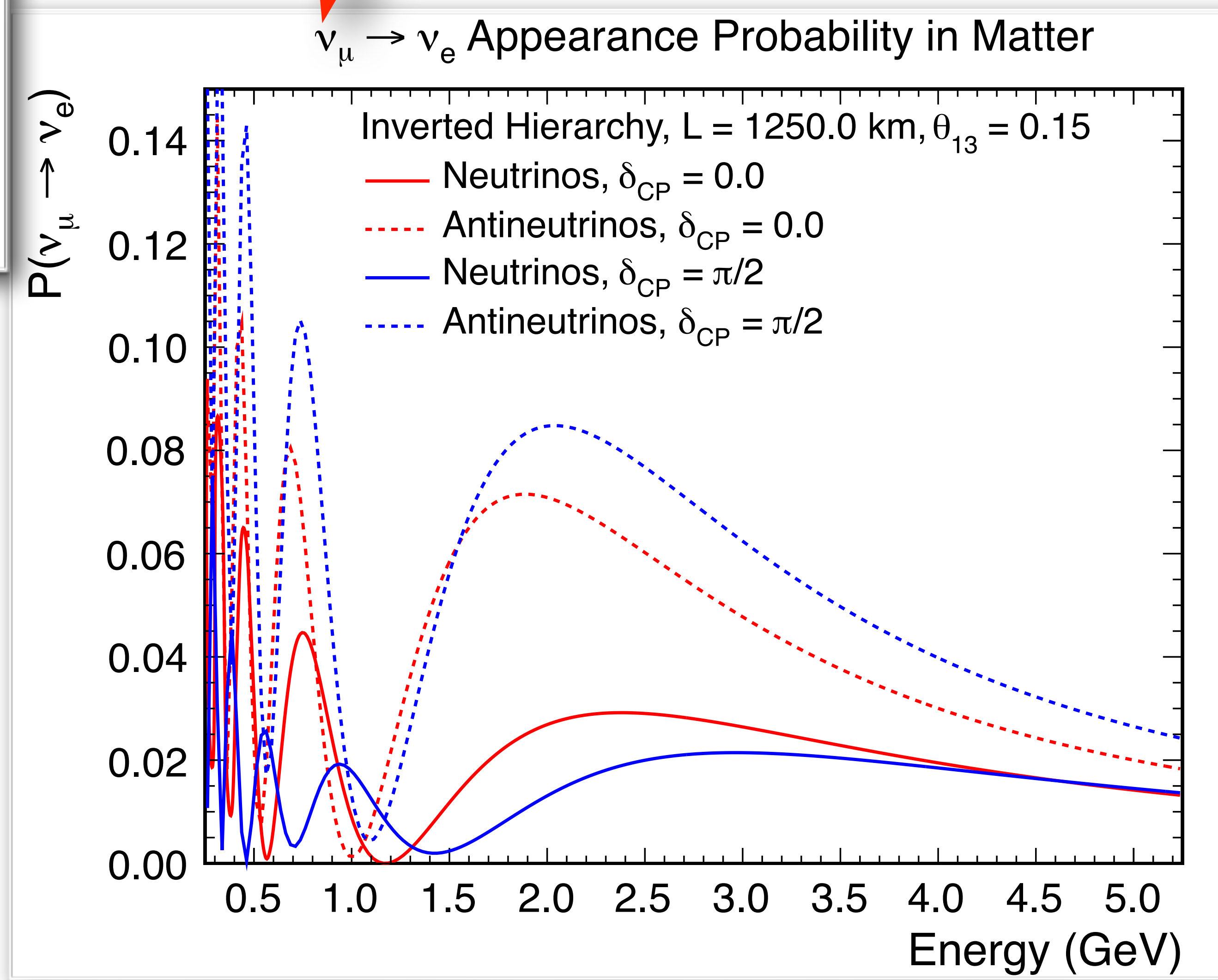
Nucleus: Hard!
Very complex nuclear physics.
But this is where we want σ.





It may look "easy"...

But it isn't.

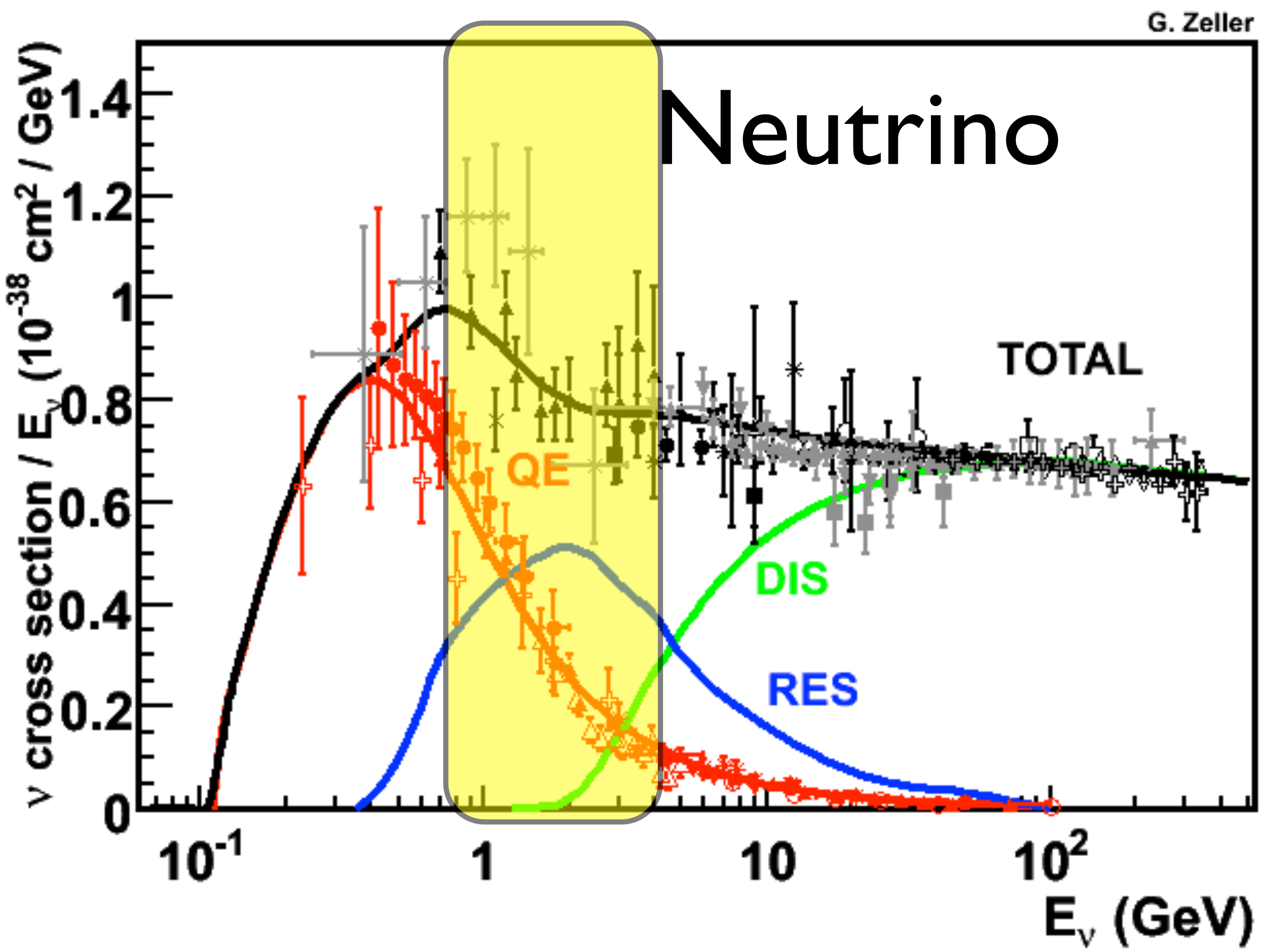


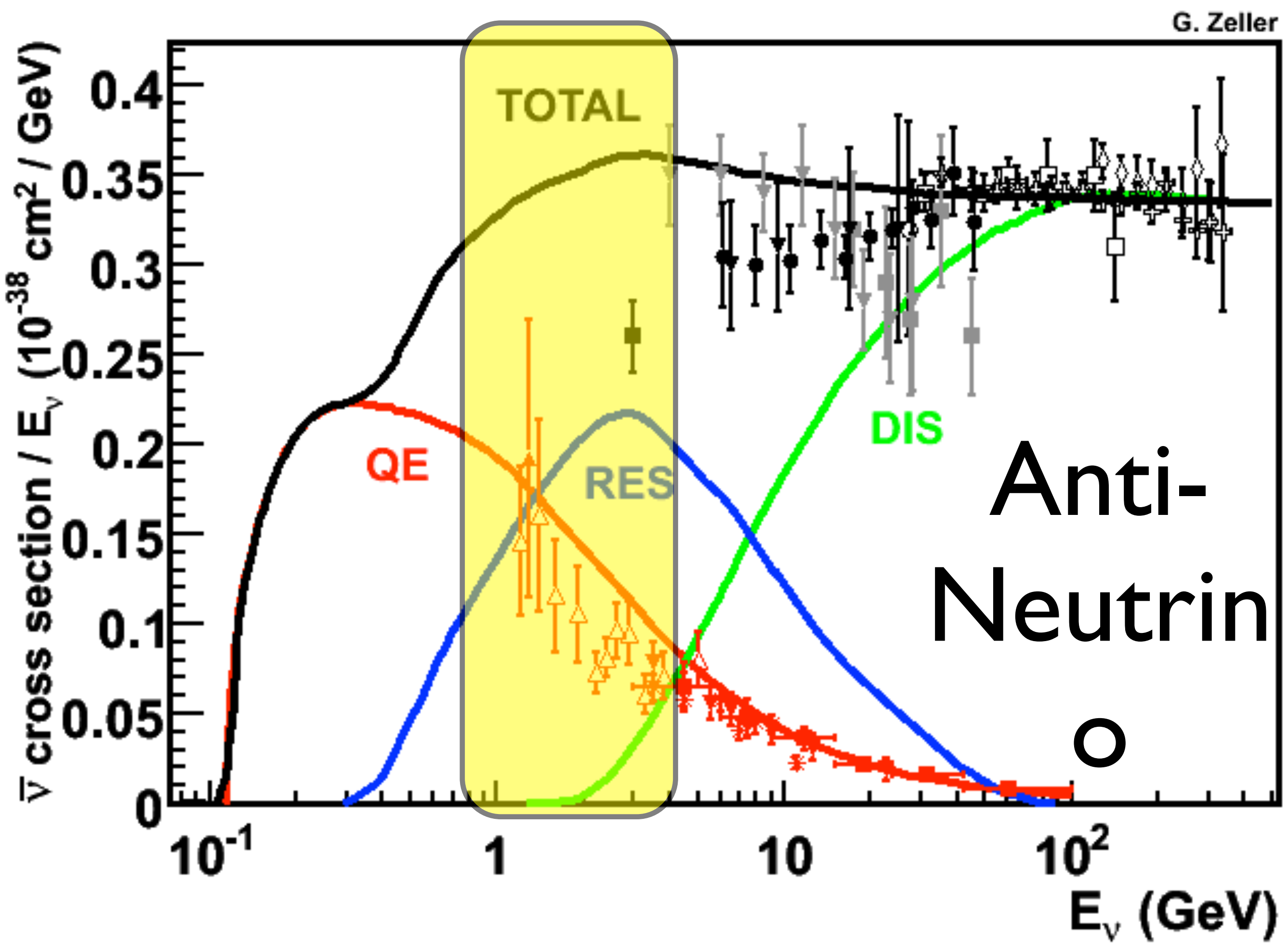
We need a better than 1% level measurement of the neutrino oscillation probability.

Then we have to do it *again* for antineutrinos.

Need Cross-Sections to Extract Probabilities

Known Unknowns





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!

Remember, we need %-level measurements in neutrinos and antineutrinos independently!

GENIE

- Generates Events for Neutrino Interaction Experiments.
- Well-engineered C++ software framework built on sound, classic OO-principles and design patterns.
- Propagates a flux of neutrinos (specified by an ntuple) through a (GEANT-compatible) geometry and simulates the initial interaction and propagation of initial state particles through the nuclear medium (particles exiting the nucleus are handed off to GEANT).
- ROOT provides many core utilities. Also heavily leverages other HEP & FOSS software - LHAPDF, Pythia, GSL, etc.

Andreopoulos, C. and Bell, A. and Bhattacharya, D. and Cavanna, F. and Dobson, J. and others. "The GENIE Neutrino Monte Carlo Generator". Nucl.Instrum.Meth. A614. 87-104. 2010.

```
> ./cloc-1.60.pl R-2_8_0/
    3285 text files.
    3200 unique files.
    7197 files ignored.

http://cloc.sourceforge.net v 1.60  T=113.14 s (11.3 files/s, 4119.1 lines/s)
-------------------------------------------------------------------------------
Language                     files          blank        comment           code
-------------------------------------------------------------------------------
C++                            525          30478          37587         176349
XML                            125          21895           2144         147176
C/C++ Header                   504           9052           8118          22282
Perl                            28            456           1469           3620
make                            47            514            485           1651
Bourne Shell                    34            157            334           1059
Bourne Again Shell               2            145            127            727
SQL                             12             37              0            117
ASP.Net                          1              0              0             39
-------------------------------------------------------------------------------
SUM:                          1278          62734          50264         353020
-------------------------------------------------------------------------------
```

(ASP.Net?)

GENIE

- Created to be the "universal event generator" (covering MeV reactor experiments all the way through PeV+ cosmic experiments) requested during the NuInt conference series.

- It is the most widely-adopted neutrino event generator. Competitors are brittle FORTRAN projects or lack comprehensive features like a flux driver, highly flexible configuration, re-weighting machinery, geometry drivers, charged lepton and hadron interaction drivers, etc.

- Good separation of different levels of abstraction - event handling is decoupled from physics routines, physics routines use visitor and chain of responsibility patterns to allow for fairly arbitrary algorithm stacks.

- Cross-sections are pre-computed and stored in configuration XML (ROOT and XML are both heavily used to store computation results, physics output, and configuration options).

Challenges

- GENIE's framework is good, but the physics models implemented lag the state of the art.
- GENIE has a physics validation framework, but it requires some significant maintenance and further development.
- Very limited manpower (1.5 FTE of active labor as of Summer 2013) has meant slow release schedules and new feature implementation.

A Physics Improvement Projects: The Master List

This list was compiled originally by H. Gallagher [9]. It is not prioritized.

A.1 Fundamental Scattering Processes

- Updated nucleon form factors (BBBA07)
- Adding $\Delta S = 1$ hyperon production
- Adding $\Delta S = 1$ resonance production
- Adding $\Delta S = 1$ DIS production
- Adding $\Delta C = 1$ resonance production
- VHE DIS model (NLO cross section construction?)
- Updated Bodek-Yang (shallow DIS)
- Better ways of combining resonance/shallow-DIS?
- GiBUU resonance model
- Sato-Lee resonance model
- Coherent: PCAC-based (Berger-Sehgal)
- Coherent: PCAC-based (Paschos-Schalla)
- Coherent: Microscopic (Alvarez-Ruso)
- Coherent: Microscopic (Other??)
- Coherent: ρ, a_1 production
- Diffractive production
- Axial-anomaly mediated processes

A.2 Hadronization Models

- AGKY model improvements (F/B asymmetry problems)
- AGKY model improvements (eta production)
- Resonance decay angular distribution fixes
- $\Delta \rightarrow N\gamma$ below $W = M + m_\pi$ threshold

A.3 Nuclear Physics

- Switching from Bodek-Ritchie/neugen3 treatment of off-shell kinematics to PWIA
- Full spectral function implementation
- Multi-nucleon scattering mechanisms (MEC et al.)
- Short-range correlations
- RPA effects
- Full hN intranuclear cascade
- De-excitation photons for all (or select) nuclei
- Nuclear breakup model
- Superscaling models

A.4 Other

- Tau polarization in cross section calculations
- Interfaces to proper tau decay routines (tauola?)
- VLE extension
- New formation zone parameterizations
- Color transparency
- Modifications to DIS structure functions in nuclei (e.g. Butkevich)
- Radiative corrections for ~ 1 GeV processes

9. Gallagher, H.. Future GENIE Development and Possible Roles for FNAL CD. `http://www.pitt.edu/~dytman/NeutrinoGenerator/`; 2013.

Our Goals

- Play a leading role in developing and implementing new physics models and in the development of the framework.
- Support the experiments at Fermilab that use GENIE - configuration, installation, development, and proper use.
    - We should emphasize development specific to the energy regimes that are most critical to lab projects.
- Help develop and maintain the validation tools and infrastructure.
- Serve as a coordination hub for experiments interested in development at the lab (and in the US more broadly - may choose to partner with VA Tech, which is the only (?) university currently interested in making significant new investments in GENIE).

Our Team

- R. Hatcher - Flux and Geometry drivers.
- S. Mrenna - Validation, phenomenological contributions, Pythia integration.
- G. Perdue - FNAL site organizer, developer (physics models and eventually core framework development).
- J. Yarba - Validation.

Our Plan

- Over the next six months:
  - Implement one or two new physics models and produce a developer's manual aimed at enabling new developers to make contributions quickly.
  - Begin to implement the foundation for long-term user support and physics validation.
- At the end of the six-month period there will be an invite-only GENIE workshop at FNAL for ~one dozen physicists focused on model development and implementation.
- Also at that point we will evaluate the initial success of our collaboration and decide on the appropriate level of resources to invest in the project moving forward.

Current Work

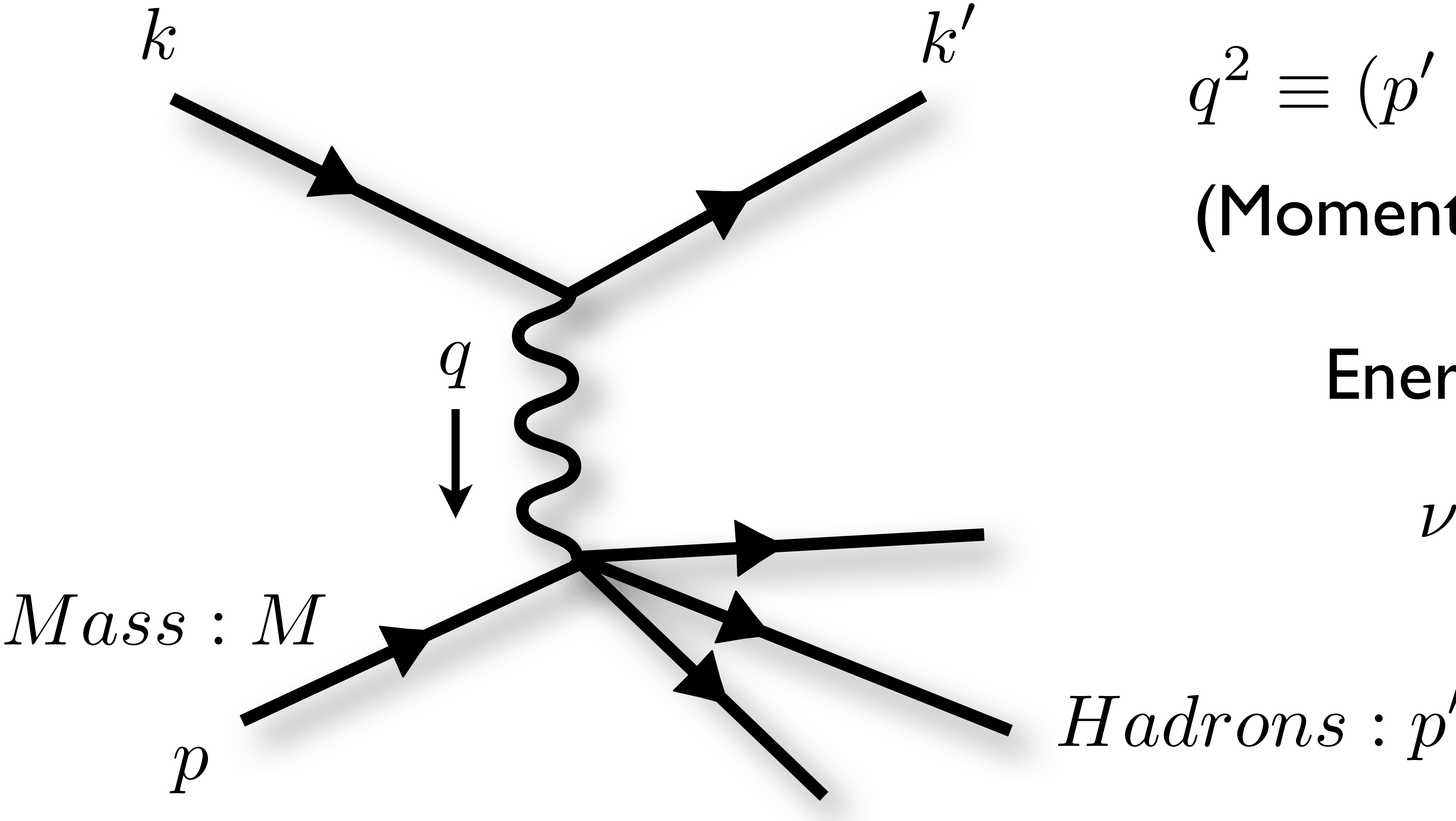
- New coherent scattering model.
- User & support and physics validation.

New Coherent Scattering Model

- We will begin with a relatively simple model with heavy emphasis on achievability.
- The plan is to implement the model and document the process carefully as the first step in writing in the developer's manual.

http://home.fnal.gov/~perdue/DeveloperManual_v0.1.html

Neutrino Interaction Jargon : Technical



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

(Momentum Transfer)^2

Energy transfer.

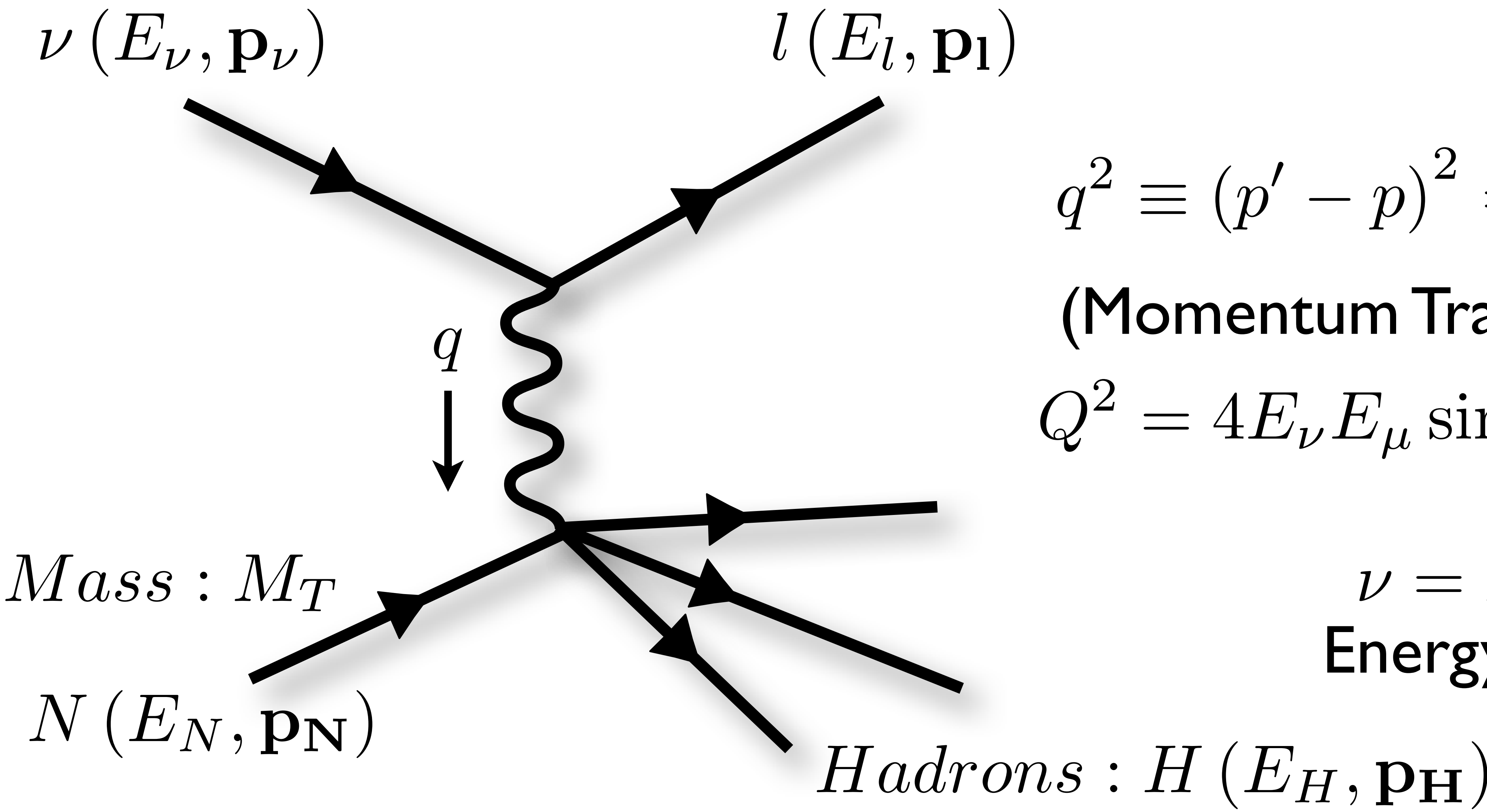
$$\nu \equiv \frac{p \cdot q}{M}$$

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



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

(Momentum Transfer)^2

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

$$\nu = E_\nu - E_l$$

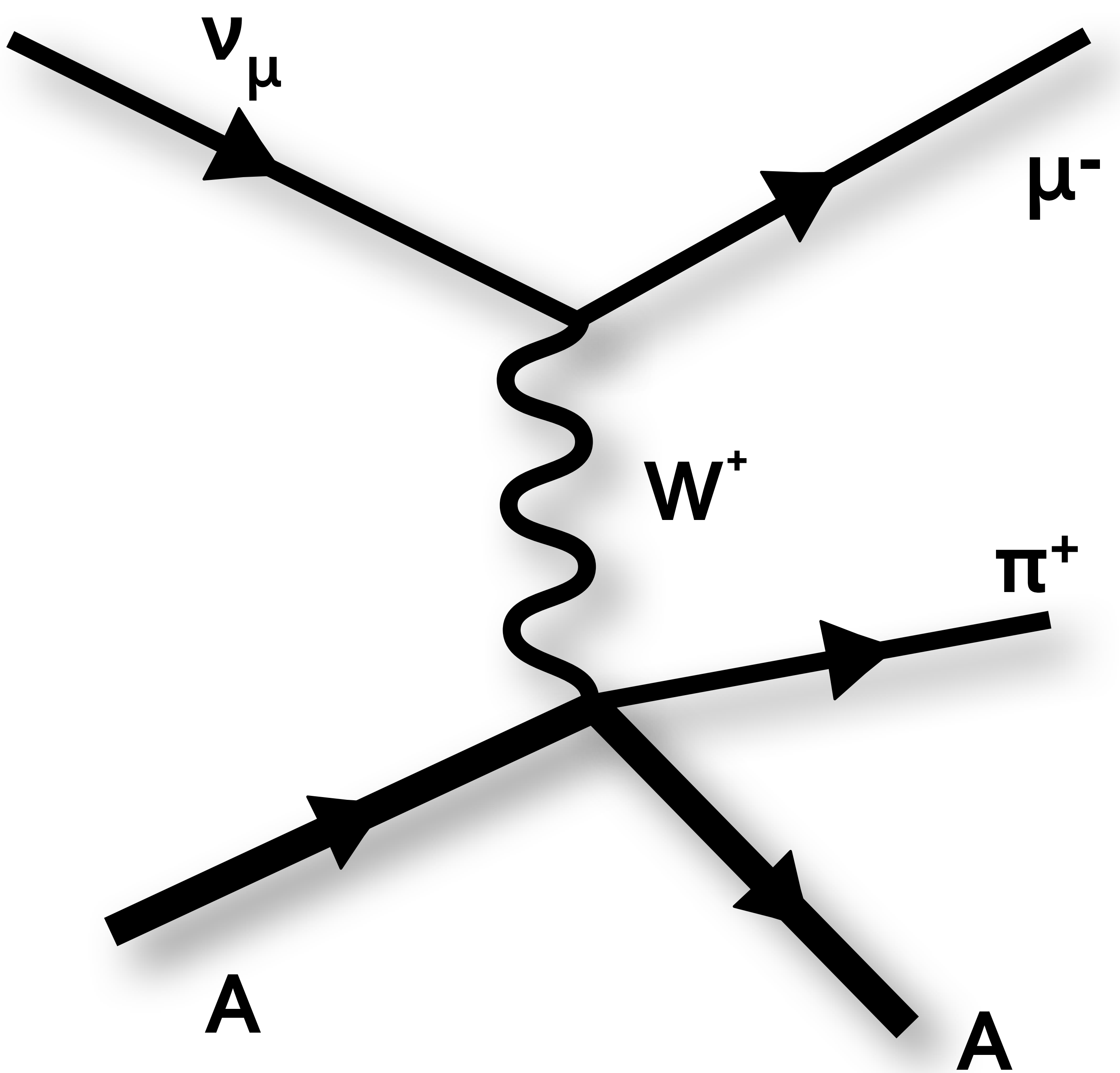
Energy transfer.

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

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

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

Coherent Pion Production



- In coherent pion production induced by neutrinos, the key signature is that the nucleus remains in the ground state.
- In the limit of an infinitely heavy nucleus (we will have to correct for this eventually) we have relations below.
- Inconsistent definition of t in the literature - some use t, others use t^2.

$$\nu = q_0 = E_\nu - E_\mu = E_\pi$$

$$t^2 = (q - p_\pi)^2 = q^2 - 2\left(E_\pi^2 + E_\nu p_\pi \cos\theta_\pi - P_\mu p_\pi \cos\theta_{\mu\pi}\right) + m_\pi^2$$

Energy transfer to the nucleus (expected to be very small).

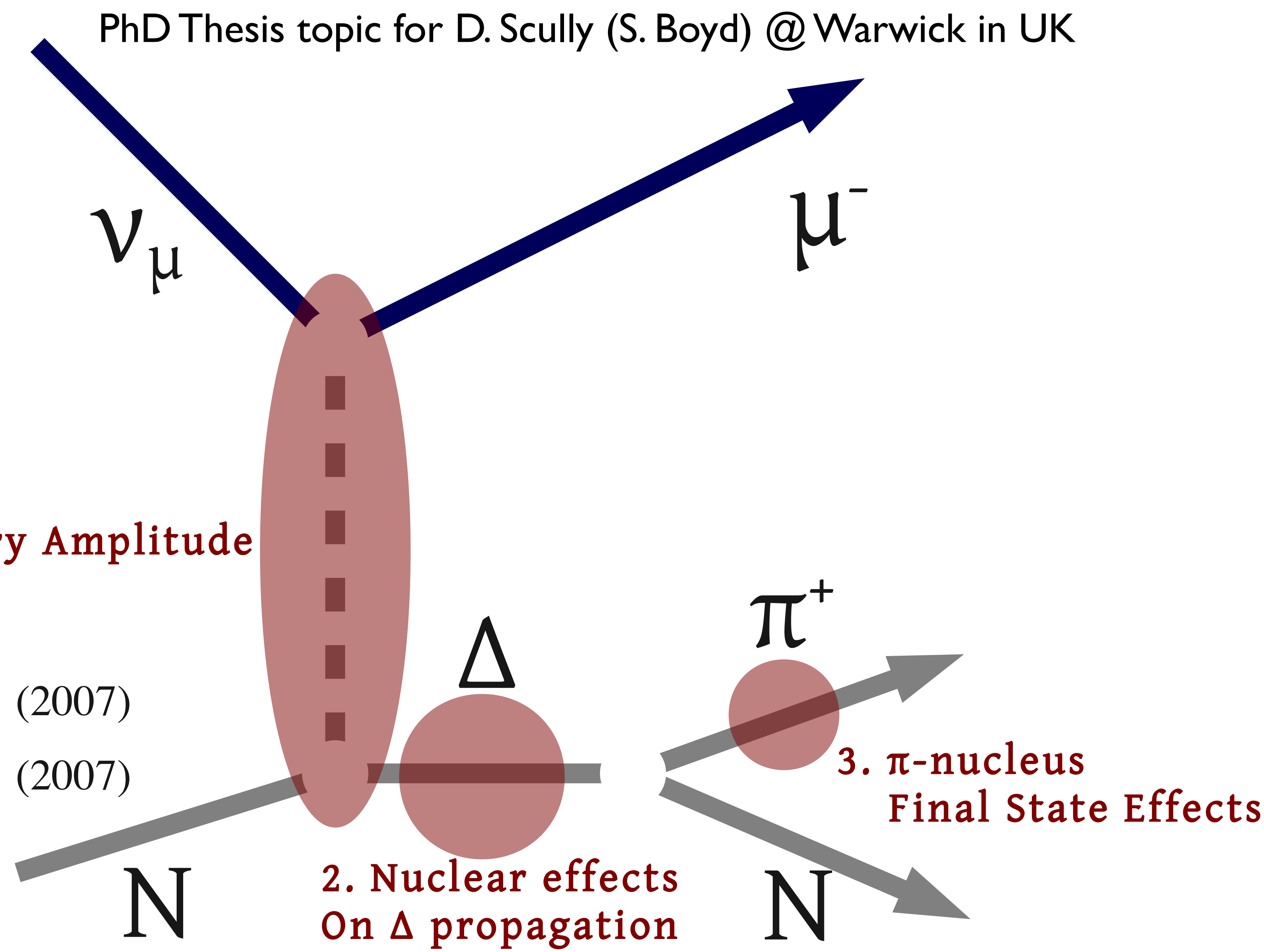
PCAC

- Partially Conserved Axial Current
- Best description of the meaning comes from Adler himself [hep-ph/0505177]:
  - "the axial-vector current is partially conserved, in the sense that the divergence of the axial-vector current behaves at small squared momentum transfer as a good approximation to the pion field, or equivalently, is pion pole dominated."
- Essentially, the PCAC hypothesis relates coherent scattering by neutrinos to pion elastic scattering.
- Proposed in the late 1950's and early 1960's over a series of papers (Adler gets the most credit, Phys. Rev. 135 B963 (1964), but Feynman, Gell-Mann, Goldberger, Treiman, and Nambu were all in the mix).
- Not proven! There are competitors (for coherent scattering, Microscopic Models).

PCAC

- "Dominant Paradigm"
  - Rein-Sehgal, Nucl. Phys. B223 (1983) - Current model in GENIE and many other generators.
    - There is a strong effort across the field to move away from RS because it is known to predict too large of an angle between the final state muon and pion and people suspect it over-predicts the cross-section, especially at low energies. At high energies (over a few GeV) the RS model is very successful.
  - Rein-Sehgal, hep-ph/0606185 - Update for non-zero muon mass (this correction is present in GENIE).
  - Berger-Sehgal, PRD 79, 053003 (2009)
  - Paschos-Schalla
- The main difference between the models is in how they treat the pion-nucleus scattering cross section.

Microscopic Models



L. Alvarez-Ruso et al,

Phys. Rev. C 75 055501 (2007)

Phys. Rev. C 76 068501 (2007)

Also, Hernandez et al. (Not considered here.)

Microscopic Models

- Valid at low (less than 1 GeV) energy.
- The interaction is modeled as the coherent sum of all neutrino-nucleon interactions that produce the final state of interest.
- The L.A.R. et al models were recently added to GENIE by a graduate student at Warwick (UK) as part of a thesis topic.

Rein-Sehgal

Takeaway: Neutrino x-sec ~ kinematics x pion-nucleus x-sec

$$\left(\frac{d\sigma}{dx\ dy\ d|t|}\right)_{Q^2=0} = \frac{G^2 M E}{\pi^2}\frac{1}{2}f_\pi^2\left(1-y\right)\frac{d\sigma\left(\pi^0\mathcal{N}\to\pi^0\mathcal{N}\right)}{d|t|}$$

$$x = \frac{Q^2}{2M\nu}$$
$$y = \frac{\nu}{E}$$

Rein-Sehgal

The pion-nucleus differential cross section:

The pion-nucleon differential cross section in the forward direction:

$$\frac{d\sigma\left(\pi^0\mathcal{N}\rightarrow\pi^0\mathcal{N}\right)}{d|t|} = A^2|F_{\mathcal{N}}|^2\frac{d\sigma\left(\pi^0 N\rightarrow\pi^0 N\right)}{d|t|}\Big|_{t=0}$$

A = # of nucleons, F is the nuclear form factor (including absorption effects).

Using the Optical Theorem, we find:

$$\frac{d\sigma\left(\pi^0\mathcal{N}\rightarrow\pi^0\mathcal{N}\right)}{d|t|}\Big|_{t=0} = \frac{1}{16\pi}\left[\sigma_{\mathrm{tot}}^{\pi^0 N}\right]^2\left(1+r^2\right),\;\; r=\frac{\mathrm{Re}f_{\pi N}\left(0\right)}{\mathrm{Im}f_{\pi N}\left(0\right)}$$

$$\sigma_{\mathrm{tot}} = \frac{4\pi}{k}\mathrm{Im}f\left(0\right)$$

Rein-Sehgal

Looks complicated, but for a cross-section formula, this is quite simple:

$$\frac{d\sigma}{dx\ dy\ d|t|} = \frac{G^2 M}{2\pi^2} f_\pi^2 A^2 E\,(1-y)\,\frac{1}{16\pi}\left[\sigma_{\rm tot}^{\pi^0 N}\,(E\ y)\right]^2 (1+r^2)$$

$$\times\ \left(\frac{m_A^2}{m_A^2+Q^2}\right)^2 e^{-b|t|} F_{\rm abs}$$

Look-up Table

Continuation to non-forward directions.

Nuclear Form Factor, with b related to the nuclear radius by: $b = \frac{1}{3}R^2$

(It is possible to be much fancier with Fabs - GENIE & RS(1983) use a very simple assumption.)

Berger-Sehgal

- Several differences from the RS model, largely “evolutionary” improvements:
    - Different MA (0.95 GeV instead of 1.0).
    - Full form of the kinematic term (no longer assume $Q^2 = 0$).
    - Same (simple) nuclear pion absorption, but cross sections are now estimated via linear interpolation of pion-carbon scattering data.
    - No longer assume an infinitely heavy nucleus when integrating over $|t|$.

Berger-Sehgal

- They rewrite RS as:

$$\frac{d\sigma^{NC}}{dQ^2\ dy\ dt} = \frac{G_F^2 f_\pi^2}{4\pi^2} \frac{1-y}{y} G_A^2 \frac{d\sigma\left(\pi^0 N \to \pi^0 N\right)}{dt}$$

- Differential cross section now in Q^2.
- The extension away from $Q^2 = 0$ produces (see PRD 79, 053003 (2009) - essentially keeping the $Q^2 \neq 0$ terms from the beginning of the derivation rather than tacking them back on in a propagator):

$$\frac{d\sigma^{NC}}{dQ^2\ dy\ dt} = \frac{G_F^2 f_\pi^2}{4\pi^2} \frac{E}{|\mathbf{q}|} u\ v\ G_A^2 \frac{d\sigma\left(\pi^0 N \to \pi^0 N\right)}{dt}$$

$$u, v = \left(E + E_{\text{lepton}} \pm |\mathbf{q}|\right)/2E \qquad G_A = m_A^2 / \left(Q^2 + m_A^2\right)$$

Berger-Sehgal

- For CC processes we may include a lepton mass term (basically just an ugly thing we have to plug in):

$$\left[\left(G_A - \frac{1}{2}\frac{Q^2_{\rm min}}{Q^2 + m_\pi^2}\right)^2 + \frac{y}{4}\left(Q^2 - Q^2_{\rm min}\right)\frac{Q^2_{\rm min}}{\left(Q^2 + m_\pi^2\right)^2}\right]$$

$$Q^2_{\rm min} = m_l^2 \frac{y}{1-y}$$

"Adler Screening Factor"

Berger-Sehgal To-Do

- Code the triple-differential cross section. (Easy, modulo we must do step 3 (particle 4-vectors in harder kinematic case) first to complete this step.)

- Include pion cross section tables / parametrization. (Done)

    - Discovered later that GENIE has a parameterization of the BS pion-nucleon cross-sections. Prefer this to a Spline from the tables? Probably - re-reading the paper indicates BS parameterized the x-sec tables.

- Construct particle 4-vectors given (Q^2,y,t). (There are some un-evaluated complications for Rein-Sehgal, do the same carry over?) (Subtle? No calculation in the literature with finite mass nucleus (usual assumption is M = \infty).)

- Determine total cross section (choose bounds of integration). (Subtle)

- Clean-up code (e.g., in the class COHKinematicsGenerator, there are two (soon to be three) methods like `CalculateKin_ReinSeghal(GHepRecord *) const` (and _AlvarezRuso, _BergerSehgal) that have a lot of repeated (copy-pasted) code - rewrite these to stay DRY).

BS Ref:

http://pdg.lbl.gov/2008/hadronic-xsections/hadron.html
http://pdg.lbl.gov/2008/hadronic-xsections/pimp_total.dat
http://pdg.lbl.gov/2008/hadronic-xsections/pipp_total.dat
http://pdg.lbl.gov/2008/hadronic-xsections/pimdeut_total.dat
http://pdg.lbl.gov/2008/hadronic-xsections/pipdeut_total.dat

Any reason not to use (use 08 to verify BS plots):
http://pdg.lbl.gov/2013/hadronic-xsections/hadron.html

Validation: High Level

- A large amount of work has been already invested in the GENIE validation suite
  - Validation applications are available for eA, nu-A, hA.
  - Available as part of GENIE distribution, /src/validation hierarchy.
  - Implemented in a form of C++ code with the use of Root machinery (as opposed to Root scripts).
  - There's a good collection of datasets used for validation/benchmarking: eA, ... Datasets stored in a form of root and/or txt files, stored under /data/validation hierarchy.
  - There's also a collection of production-type Perl scripts; at a glance, they are means for parallel processing of multiple validation jobs, for example various "beams" on various nuclei. The production scripts are said to be tested on the RAL Tier2 PBS farm. Apparently, the RAL computing bases has been GENIE's principal validation resources.
- We'd like to:
  - Adapt and reuse as much of the invested work as possible.
  - Expand the validation suite with regards to physics aspects of our interest.
    - But for this, we'll need to evaluate if the current implementation is scalable, etc.

Validation: Current Experience

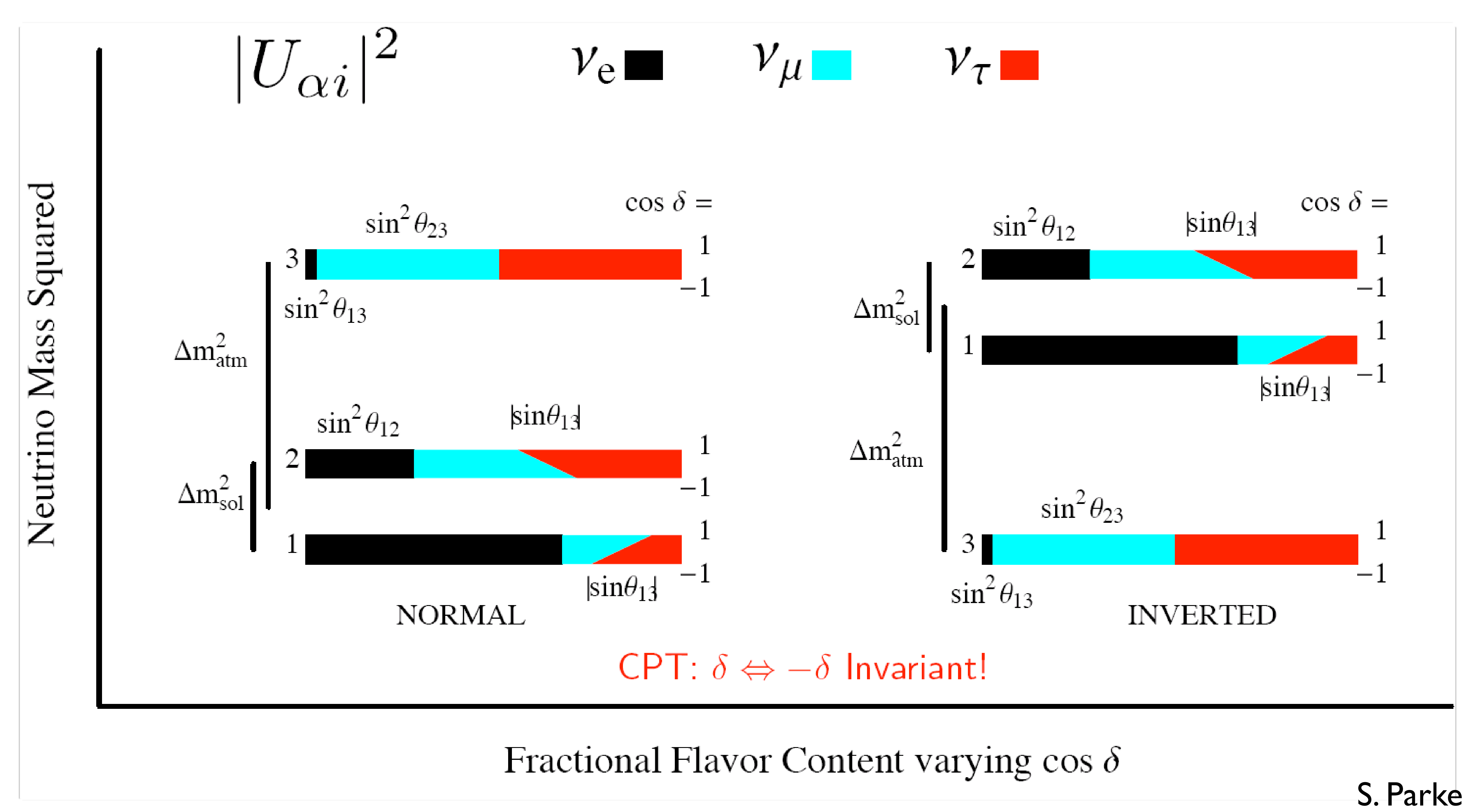
- A sample code (eA) builds and runs fine.
- Interactive run only; no tries of batch-like runs.
- No problem finding/accessing validation dataset at run time - hardcoded default location.
- Output in a form of Root file containing TCanvas (not histograms); additional PS file output.
- BIG QUESTION: WHAT IS THE POLICY REGARDING INPUT SAMPLES ?
  - Default: if no input sample is specified , only data points are displayed.
  - NO explicit documentation about input sample location and/or generation.
  - There's a reasonable amount of information on event generation in the GENIE Phys.Ref.Manual but there needs to be direct instructions regarding specific validation samples.
    - Given this, no estimate of the needs of CPU (or perhaps other resources).
- Question-2: It's not obvious if regression testing is included, but there might be special configuration options at the level of submission scripts - need to learn more.

Validation: General Questions

- How often/regular does the GENIE validation suite gets executed ? As a whole ? Or partially ?
- What resources are available/used for the GENIE validation round(s) ? Only RAL ? Or others ?
- How to access the resources (authentication, etc.) ?
- How are the tests deployed (manually, automated,...) ?
- How is the output staged back ?
- How are relevant experts are alerted ?
- What were there the issues in the latest validation round ?

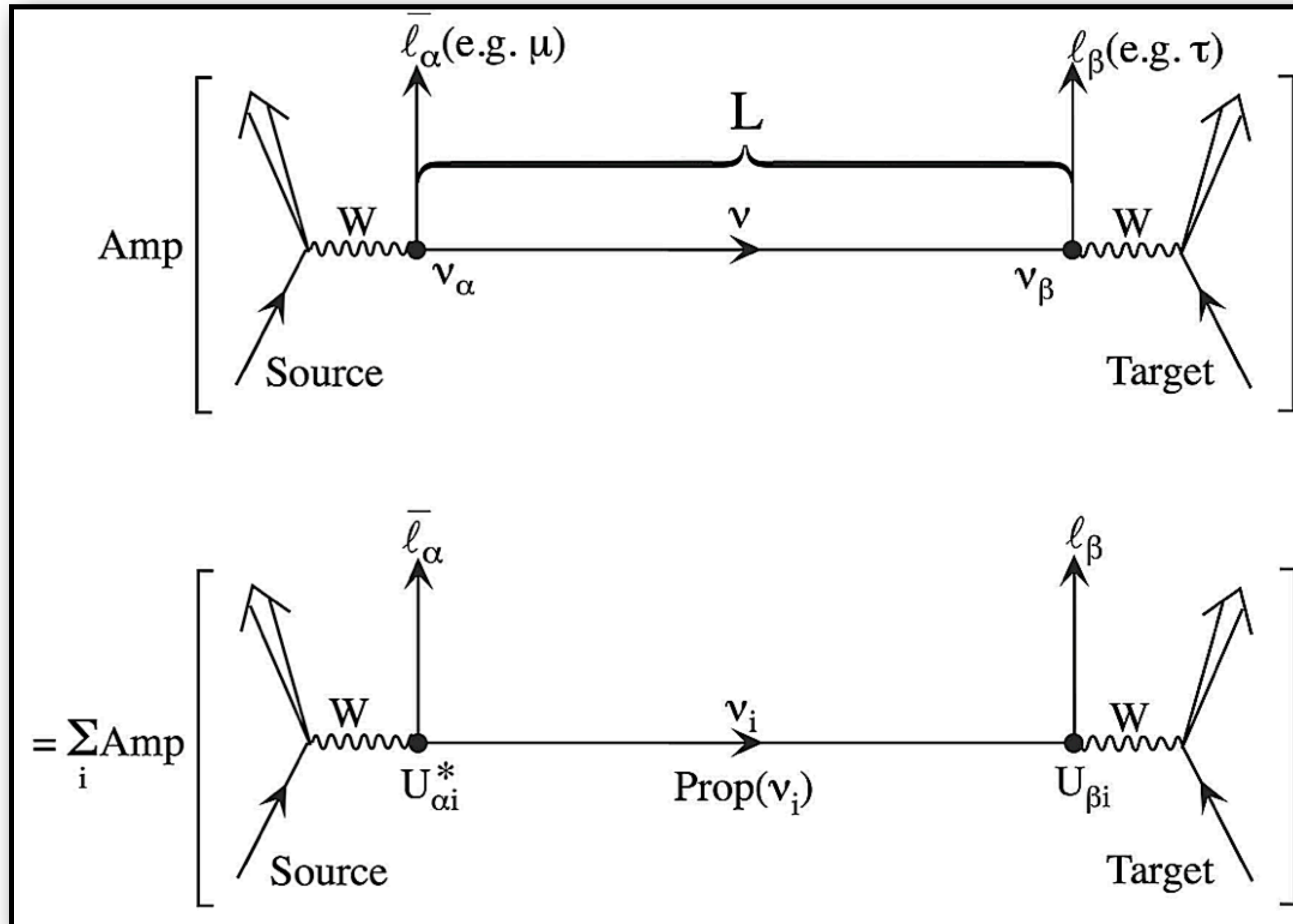
Backup

(Long Baseline) Neutrino Oscillation:
We want to measure the HIERARCHY and δ_{CP}.



$$\mathrm{Prop}\,(\nu_j) \sim e^{(-im_j\tau_j)}$$

$$m_1 \neq m_2 \neq m_3$$



B. Kayser, arXiv 0804.1121

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

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

- ⇒ Flavor composition evolves with time.

Three Flavor Oscillations: $\nu_\mu \rightarrow \nu_e$

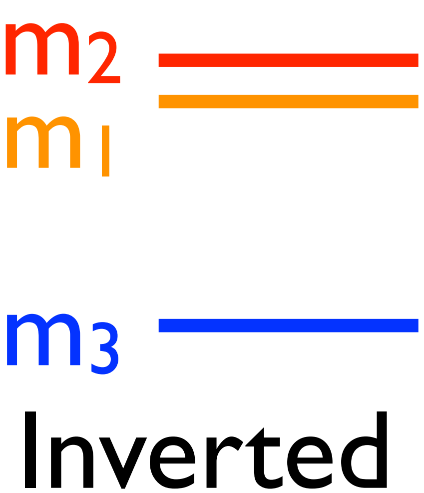
$$
\begin{aligned}
P\left(\nu_\mu \rightarrow \nu_e\right) &= \left| U_{\mu 1}^* e^{-i m_1^2 L/2E} U_{e1} + U_{\mu 2}^* e^{-i m_2^2 L/2E} U_{e2} + U_{\mu 3}^* e^{-i m_3^2 L/2E} U_{e3} \right|^2 \\
&= \left| 2 U_{\mu 3}^* U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2 U_{\mu 2}^* U_{e2} \sin\Delta_{21}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

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

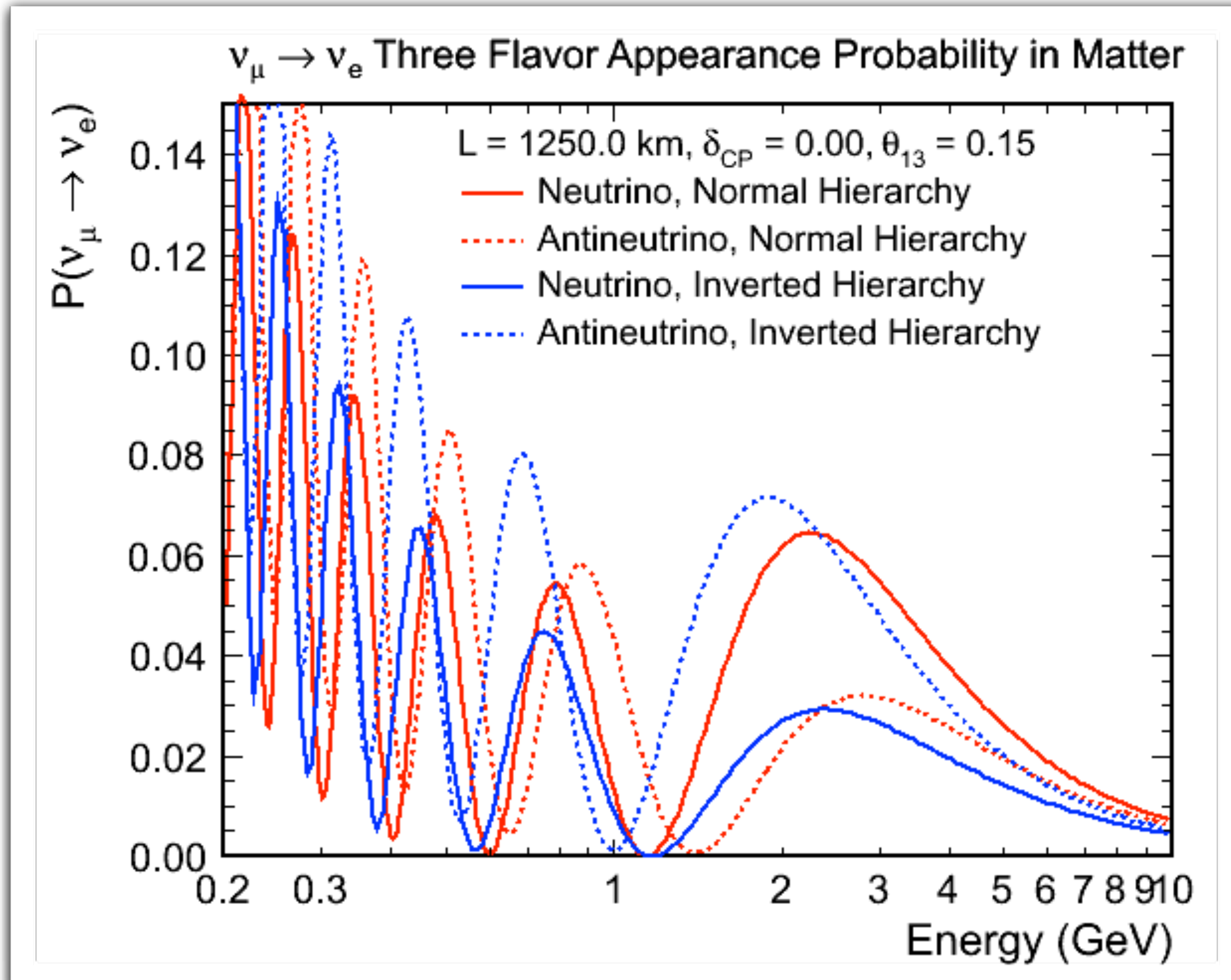
$$\Delta_{ij} \equiv 1.27 \Delta m_{ij}^2 L/E$$

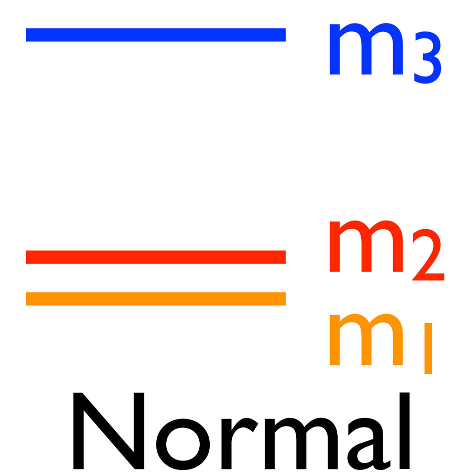
$$P \sim 2\sqrt{P'_{atm}}\sqrt{P'_{sol}}\cos(\Delta_{32})\cos\delta_{CP} \mp 2\sqrt{P'_{atm}}\sqrt{P'_{sol}}\sin(\Delta_{32})\sin\delta_{CP}$$

Need very precise measurement with neutrinos and then again with antineutrinos!
Extract these probabilities by measuring event rates...



Antineutrino: -δ

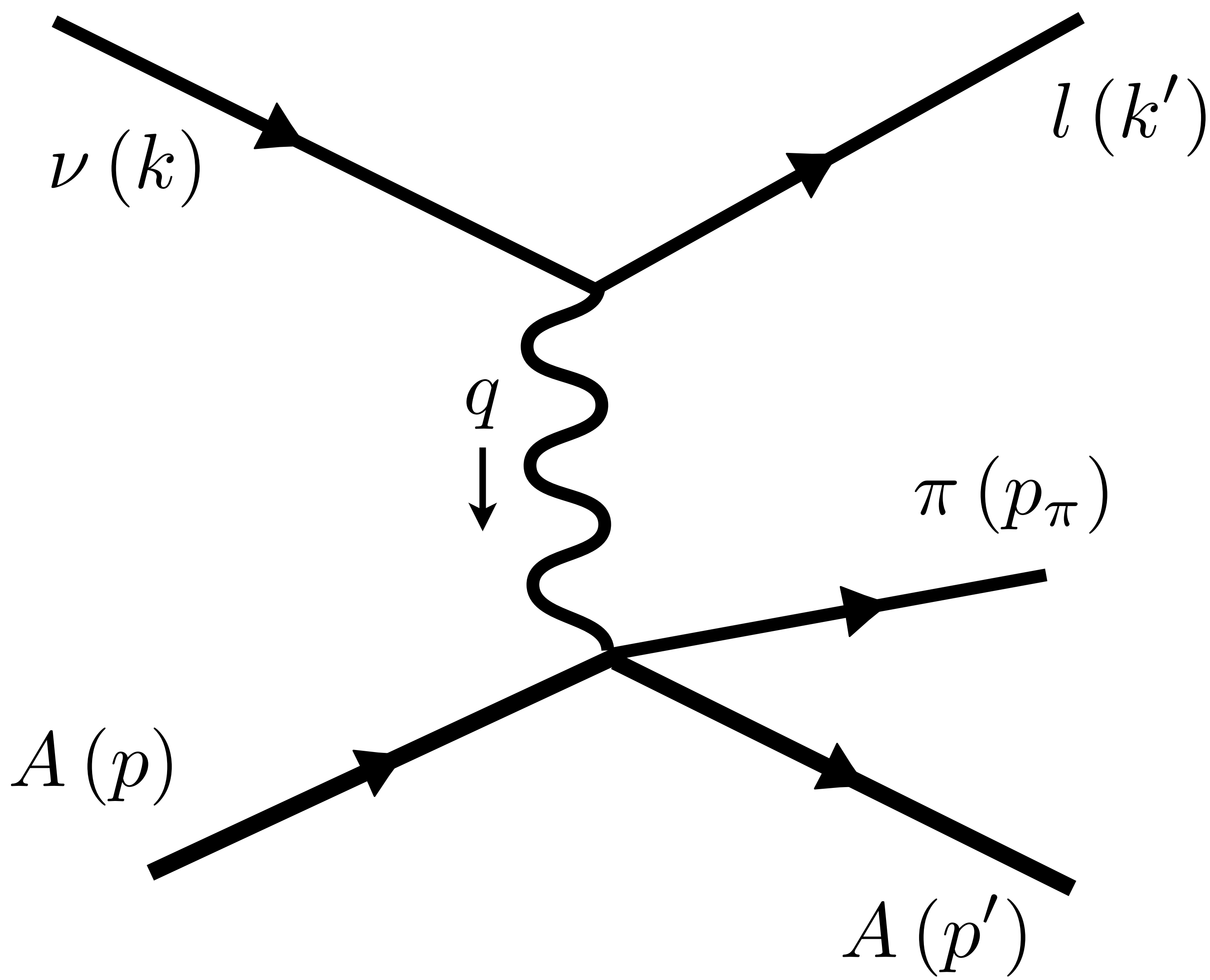




Neutrino: δ

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

Coherent Pion Production



Coherent Pion Production