ν_e Cross Sections and νSTORM

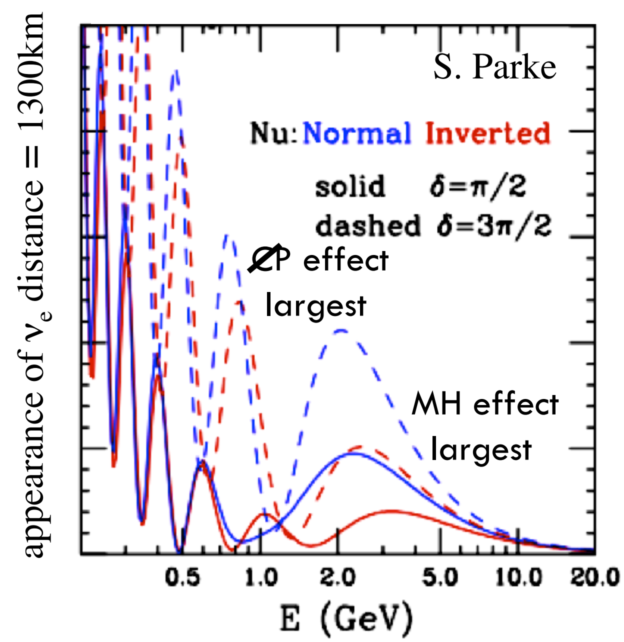
M. Day - K. McFarland: Phys.Rev. D86 (2012) 053003
M.Day: https://www.jlab.org/indicøcontributionDisplay.py?contribId=231&confId=0
S. Zeller: https://indico.fnal.gov/conferenceDisplay.py?confId=5824

NuInt12 – Rio de Janeiro, Brazil
October 2012

Jorge G. Morfín
Fermilab

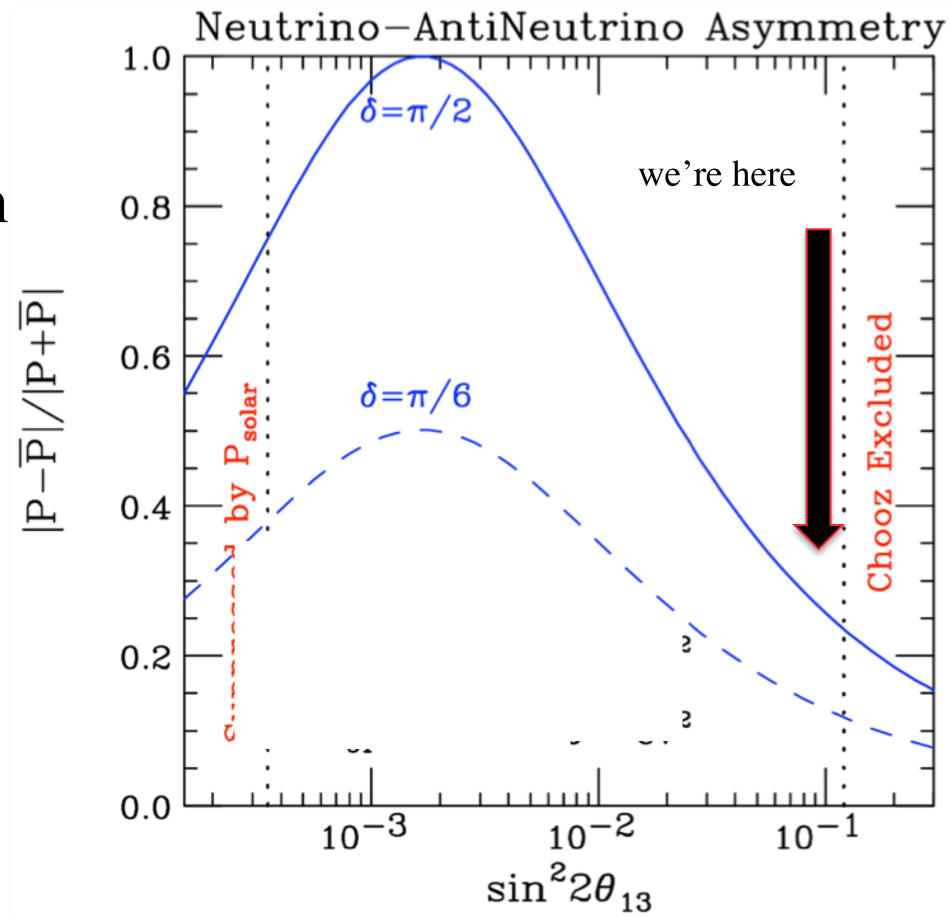
Why are ν_e Cross Sections Important?

- ν_e A – scattering results are interesting on their own.
- Recent determination of large θ_{13} has opened up possibilities of
  - Determining ν mass ordering.
  - Searching for CP-violation in the ν sector.
- To be sensitive to these effects, current/near-future long-baseline experiments will be looking for ν_μ to ν_e and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations over a range of energies.
- These will no longer be only "counting" experiments but rather will depend on observing distortions in the far detectors neutrino energy spectrum in **both neutrino and anti-neutrino samples**.



Why are ν_e and $\bar{\nu}_e$ Cross Sections Important?

- Large θ_{13} means we could have reasonable statistics.
- However, as the now-well-known plot at right suggests, the asymmetry between ν and $\bar{\nu}$ will be small and the goal of constraining the range of δ will demand minimal systematic errors.
- One of these systematics will be our knowledge of ν_e and $\bar{\nu}_e$ cross sections in the relevant energy range.



(not including matter effects & backgrounds)

(S. Parke)

What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:
  $Y(E) \alpha \ \phi(E) \otimes \sigma(E) \otimes Nuc(E' \geq E)$

What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:

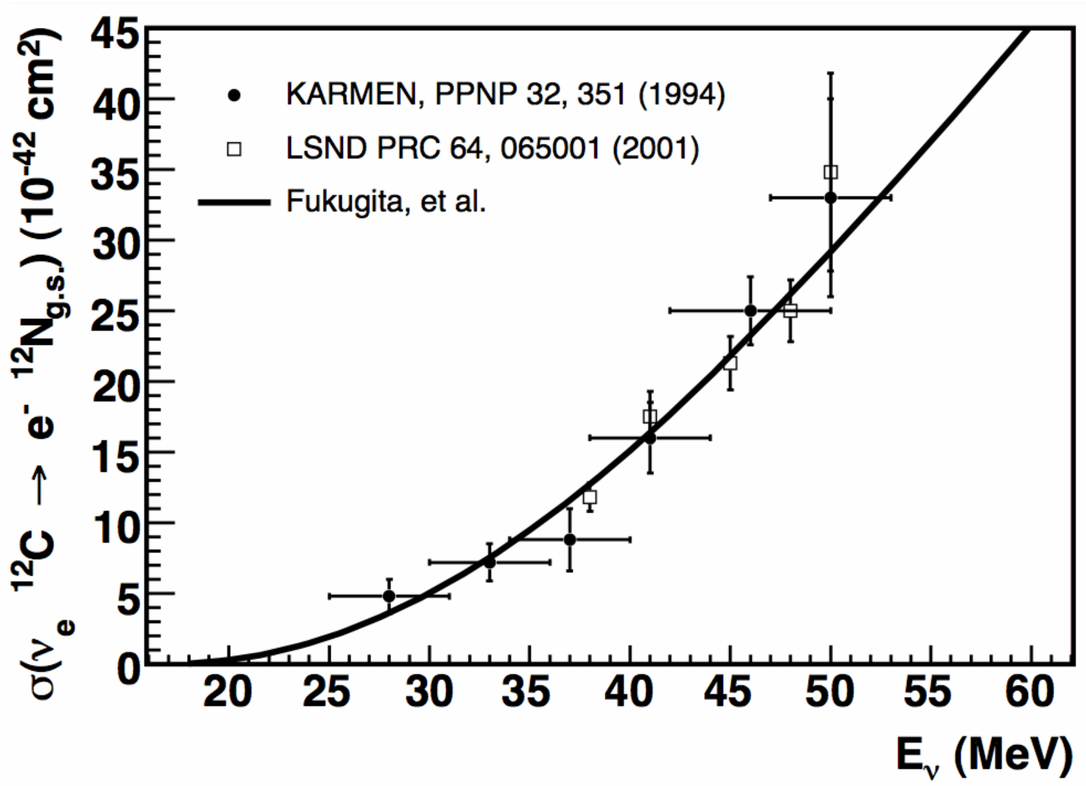
  $Y(E) \propto \phi(E) \otimes \sigma(E) \otimes Nuc(E' \geq E)$ ← effective $\sigma^A(E)$

- When the last two terms are for ν_μ then we have experiments currently measuring these cross sections on relevant nuclear targets but with limited knowledge of the incoming flux for absolute cross sections.
- When the last two terms terms are for ν_e then we have **no** higher energy experimental measurements of these cross sections. We infer them from $\sigma_{\nu\mu}(E)$ results. The validity of this inference directly impacts the uncertainty of the measurements.
- What do we know about $\sigma_{\nu e}(E)$? Mostly very low energy results.
  - Reactor neutrinos studying Inverse Beta Decay
  - Solar neutrino off deuterium (SNO)
  - Stopping π/μ decay neutrinos off higher A targets
  - See Formaggio and Zeller **Rev. Mod. Phys. 84, 1307–1341 (2012).**

Example of Existing Data: Carbon

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

- One of few measurements of spectral shape of σ reflects the upper limit of most existing measurements, E ≤ 50 MeV.

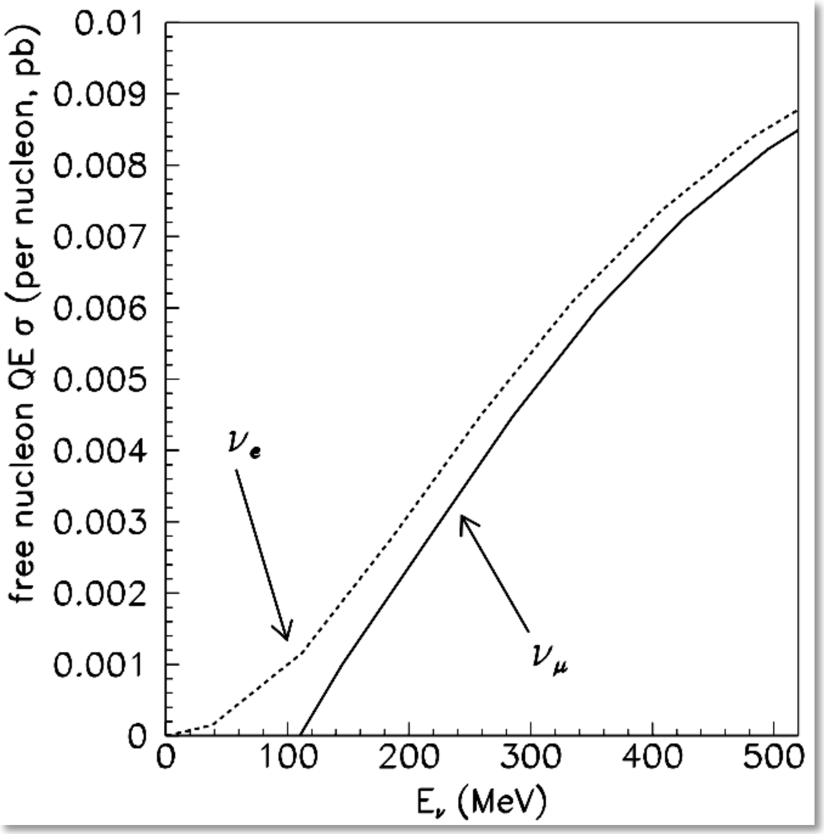


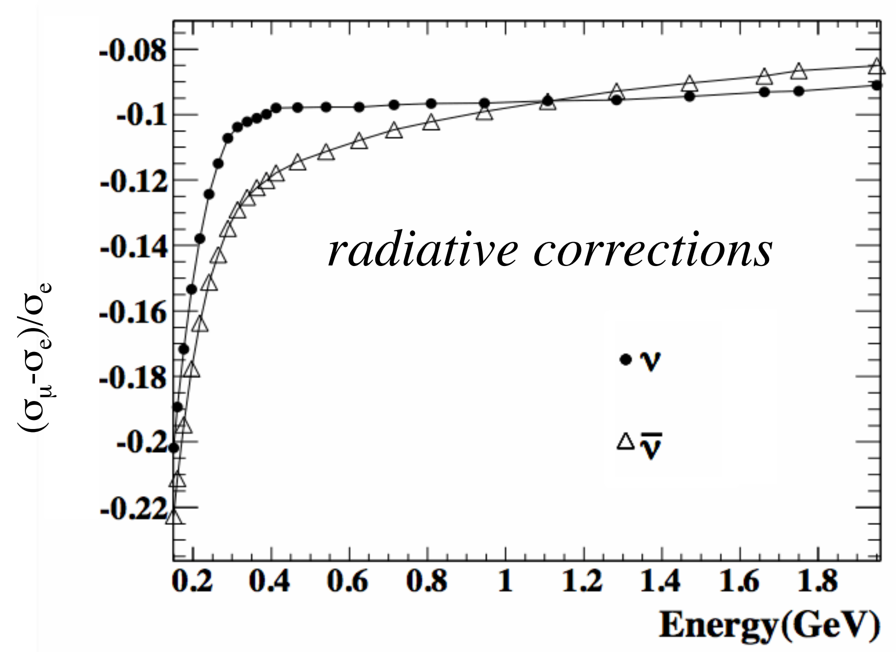
(Formaggio & Zeller, Rev. Mod. Phys. 2012)

What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$?
Quasi-elastic Scattering

Day-McFarland study: Phys.Rev. D86 (2012) 053003

- QE scattering dominates at low energies (2nd oscillation maxima)
- Sources of possible differences and uncertainties - obvious:
  - Kinematic limits from μ / e mass difference.
  - Radiative Corrections. This may be an overestimate. Need full calculation.



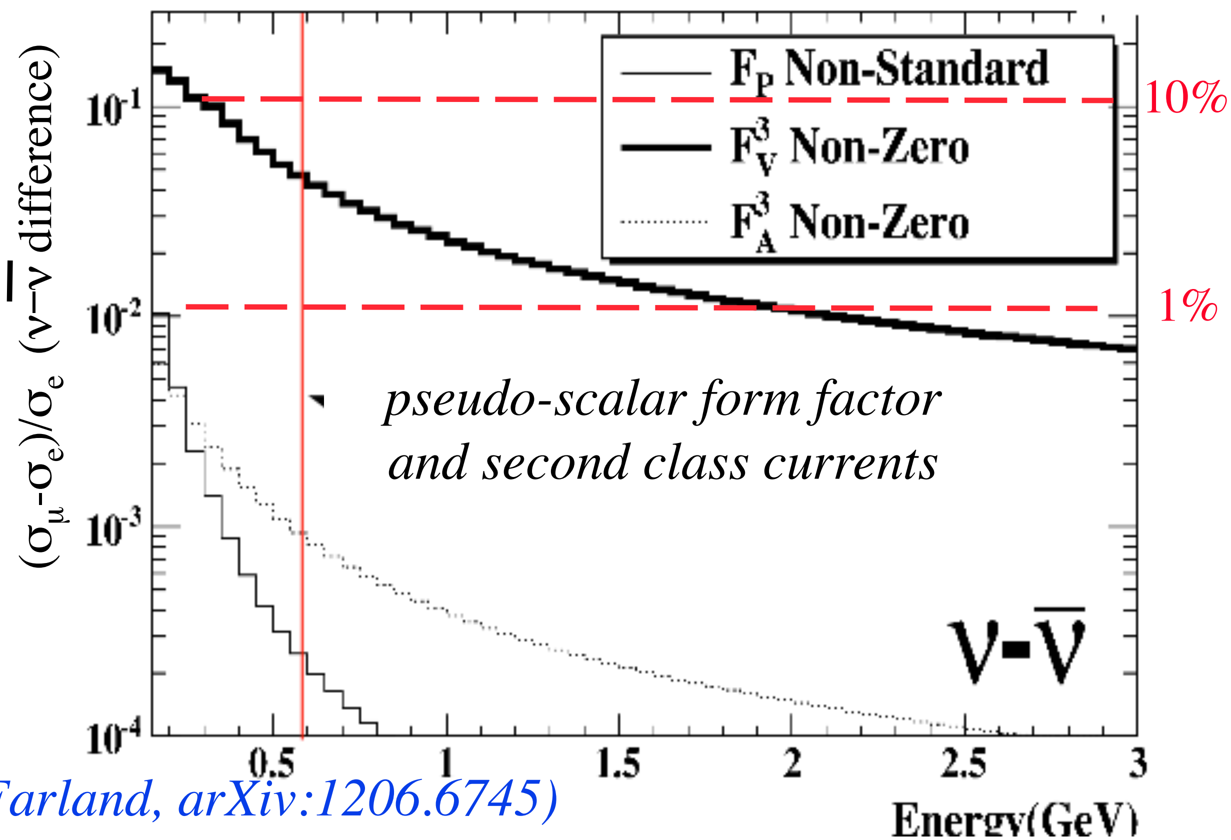


(M. Day, K. McFarland, arXiv:1206.6745)

What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$? Quasi-elastic Scattering

Day-McFarland study: Phys.Rev. D86 (2012) 053003

- Sources of possible differences: form factor uncertainties entering through lepton mass alterations - much more subtle:
  - Form factor contributions – both Axial and Pseudoscalar
  - Second class current contributions to vector and axial-vector form factors
- Possible contribution to CP uncertainties: effect on the FF could be different for ν and $\bar{\nu}$



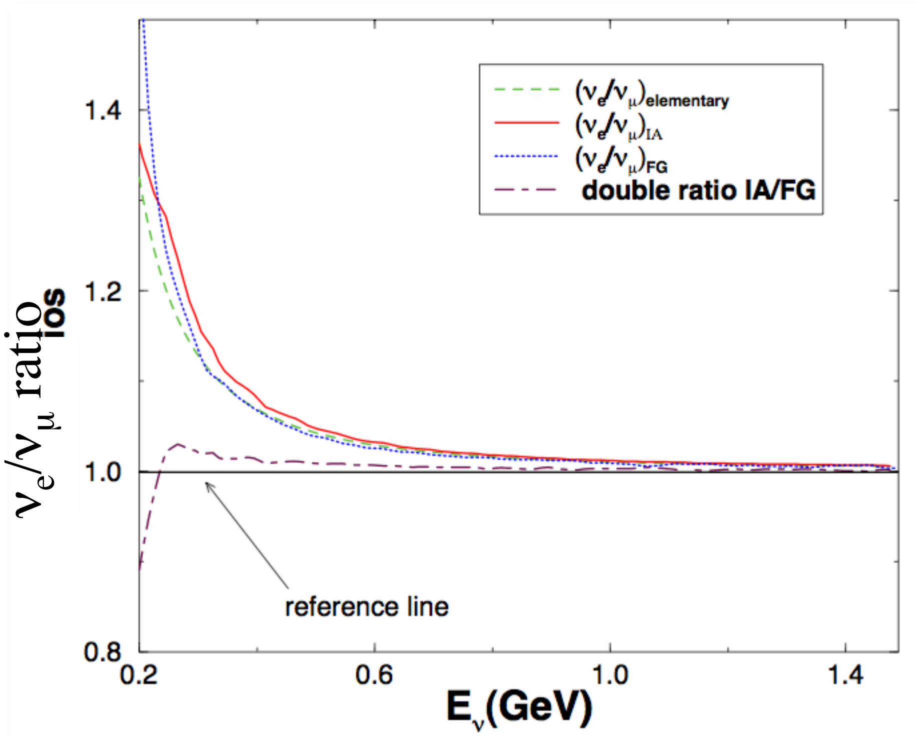
(M. Day, K. McFarland, arXiv:1206.6745)

What are the Differences? Mainly QE Scattering

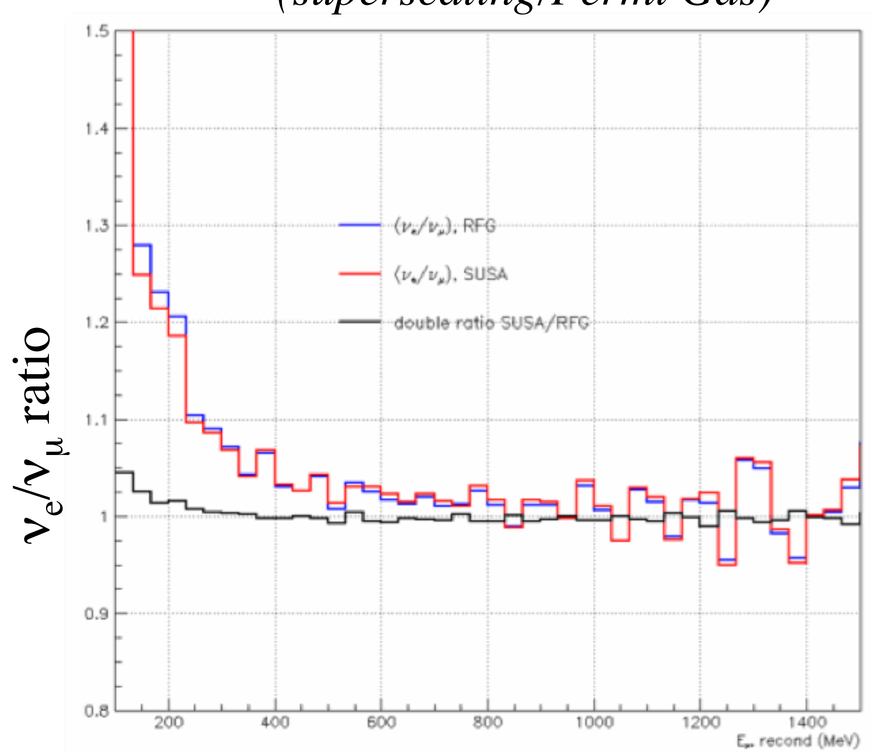
Due to Nuclear Effects

- For standard models, ≤ 5% differences on ν_e/ν_μ ratio E < 200 MeV

(spectral function/Fermi Gas)

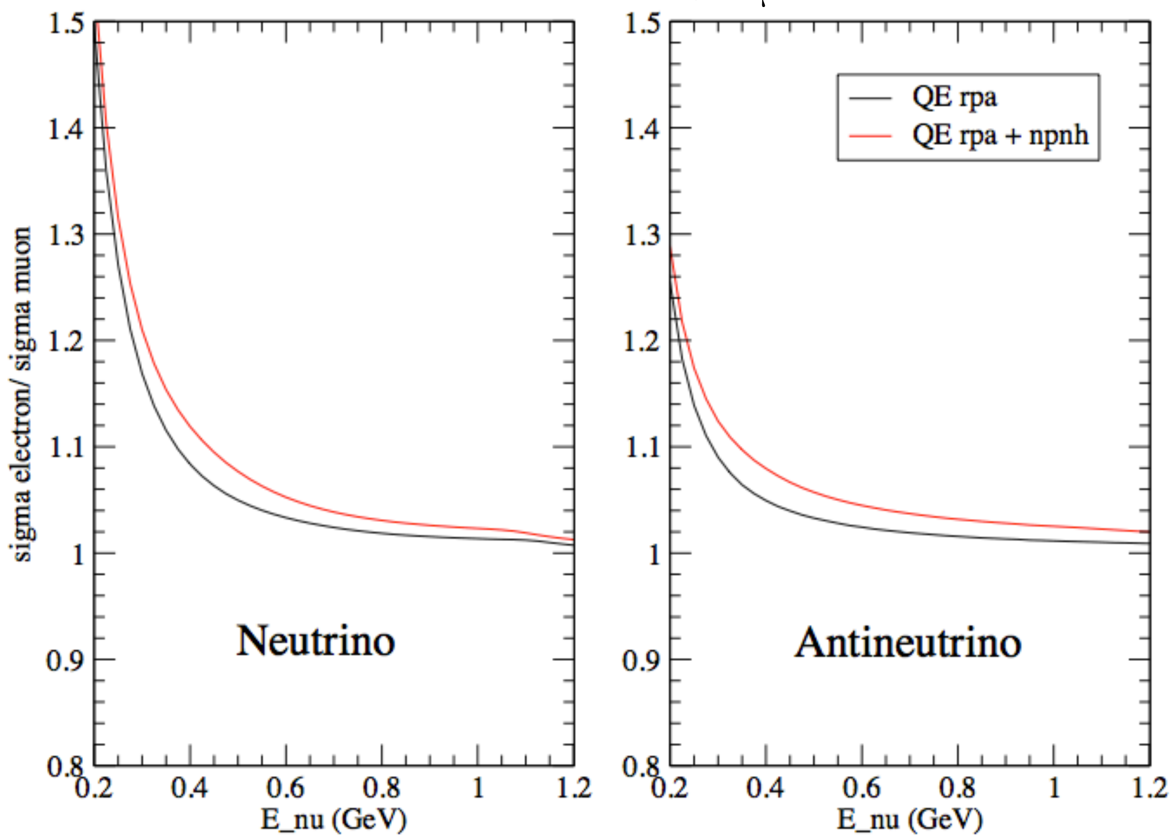


(superscaling/Fermi Gas)



What are the Differences? Mainly QE Scattering
Meson-exchange Current Contributions – Marco Martini via S. Zeller

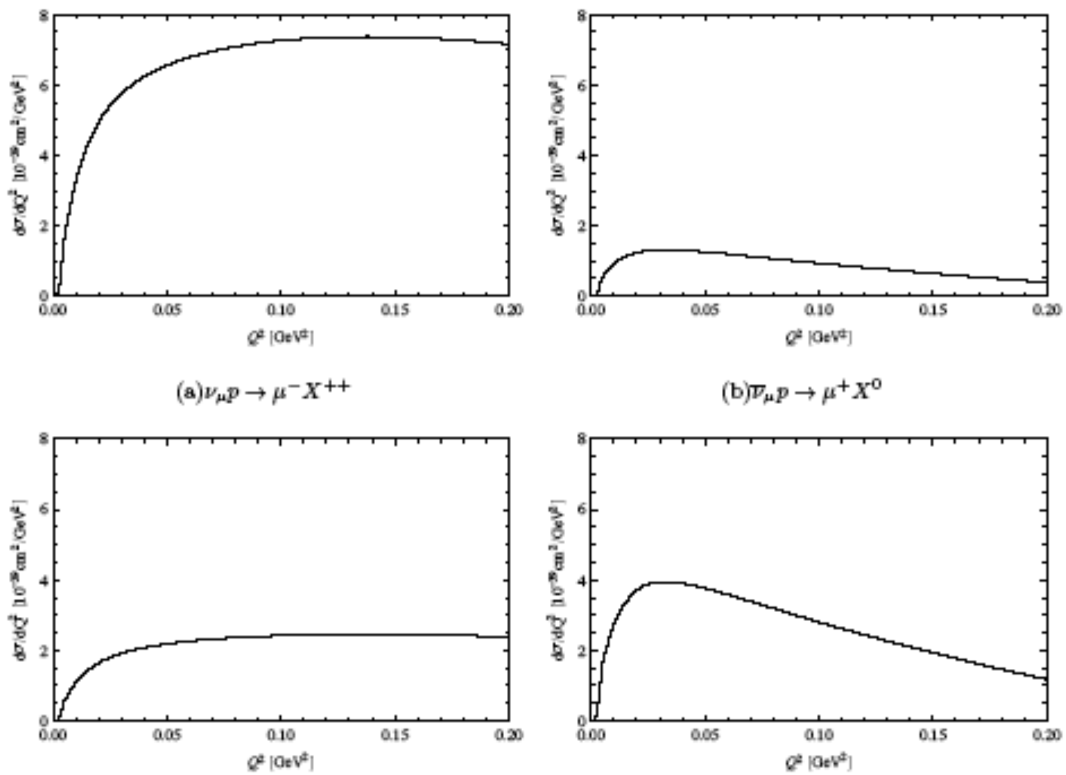
- Hadronic part (nuclear response functions) is the same for ν_e or ν_μ cross section.
- However, the lepton tensor changes → the relative weight of the nuclear responses in the several channels may change.
- The double ratio suggests the effect on the ν_e/ν_μ cross section ratio is ≤ 5% (S. Zeller)



What are the Differences? Δ Production

Paschos – Schalla: arXiv:1209.4219

- Manny and his student have investigated ν_μ and $\overline{\nu}_\mu$ differences in Δ production in the low-Q ($Q^2 \approx m_\pi^2$) region where PCAC dominates the axial contribution.
- At E = 1-2 GeV, V part and V/A interference same size → cancel for $\overline{\nu}$
- Use the Adler-Nussinov-Paschos model for nuclear corrections.



(a) $\nu_\mu p \rightarrow \mu^- X^{++}$

(b) $\overline{\nu}_\mu p \rightarrow \mu^+ X^0$

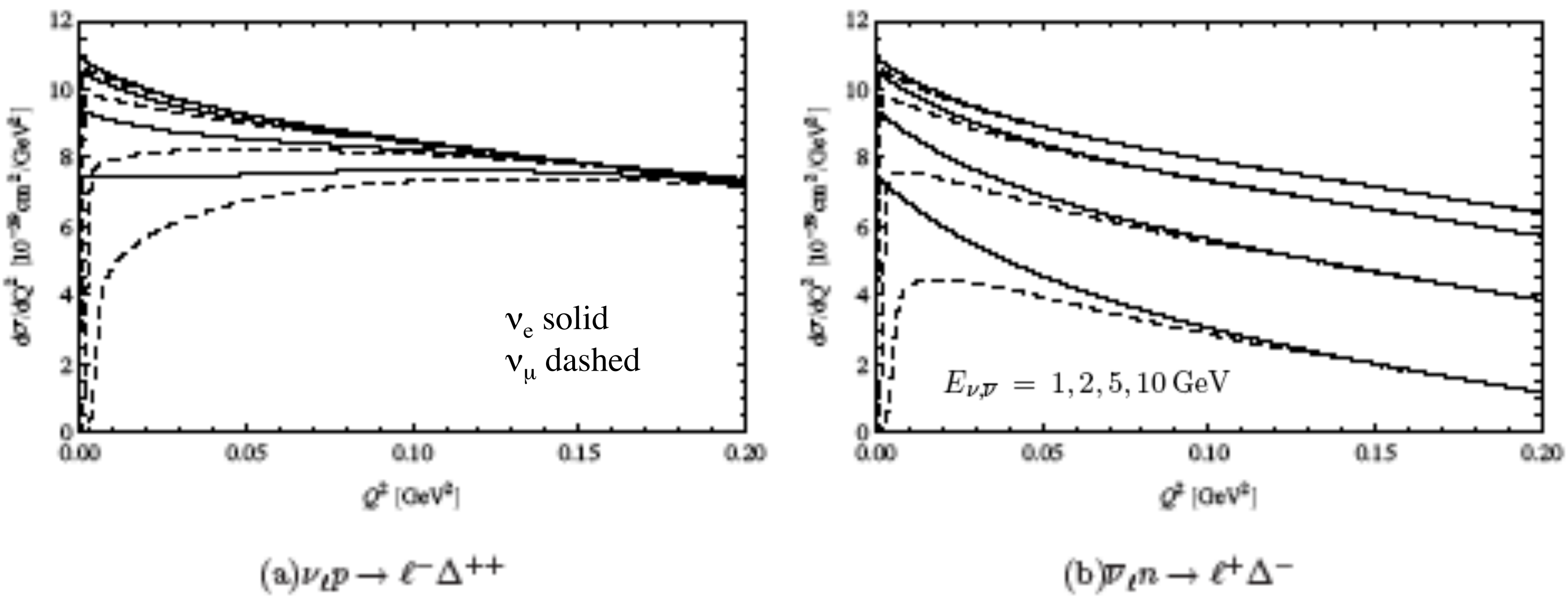
(c) $\nu_\mu n \rightarrow \mu^- X^+$

(d) $\overline{\nu}_\mu n \rightarrow \mu^+ X^-$

What are the Differences? Δ Production

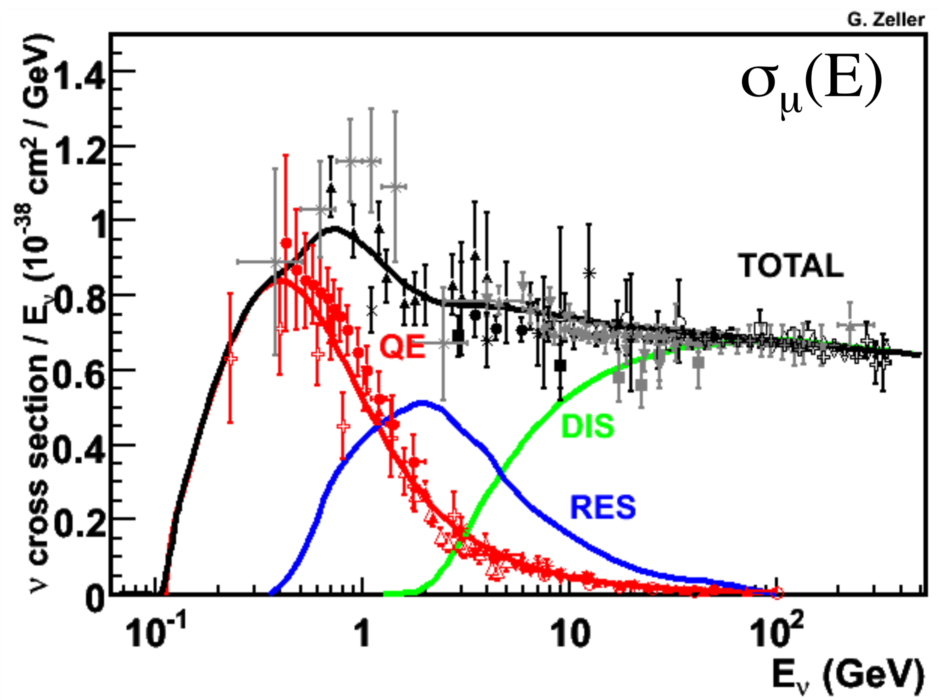
Paschos – Schalla: arXiv:1209.4219

- Paschos-Schalla predicts the following differences in cross sections where only the lepton mass term contributions are shown and any differences in form factors are not yet included.



Can we Actually MEASURE these Differences in the 0.5 – 6 GeV region

- Need to measure the $\sigma_e(E)$ of multiple channels to predict spectrum at the far detector.
  - Want an intense source of ν_e events.
  - Would like to know the flux of ν_e (and ν_μ, by the way) to order 1%.



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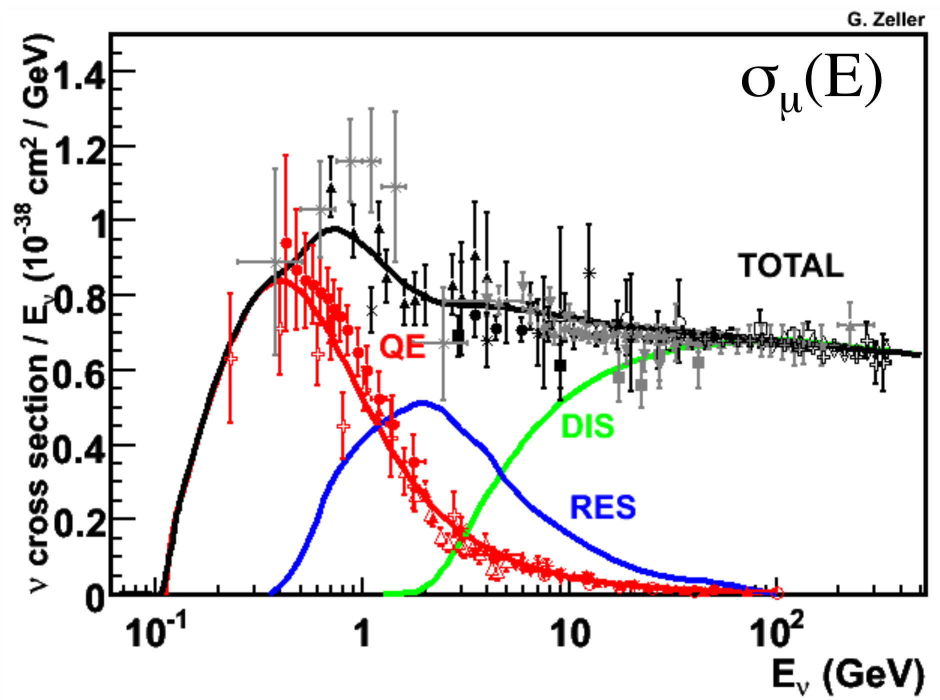
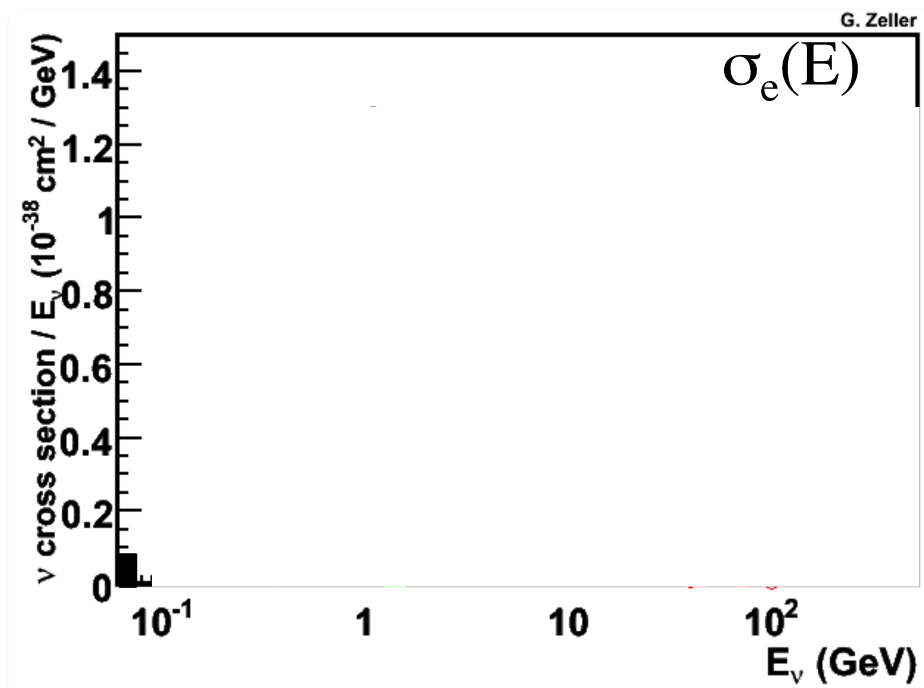
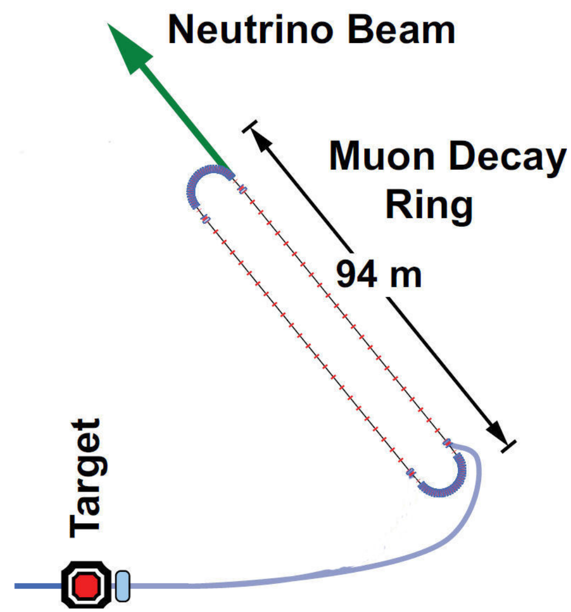




Enter - νSTORM

Neutrinos from Stored Muons – Alan Bross Presentation on Friday

- High-Precision ν interaction physics program.
  - ν_e and $\bar{\nu}_e$ cross-section measurements.
- Address the large Δm^2 oscillation regime, make a major contribution to the study of sterile neutrinos.
  - Either allow for precision study (in many channels), if they exist in this regime.
  - Or greatly expand the dis-allowed region.

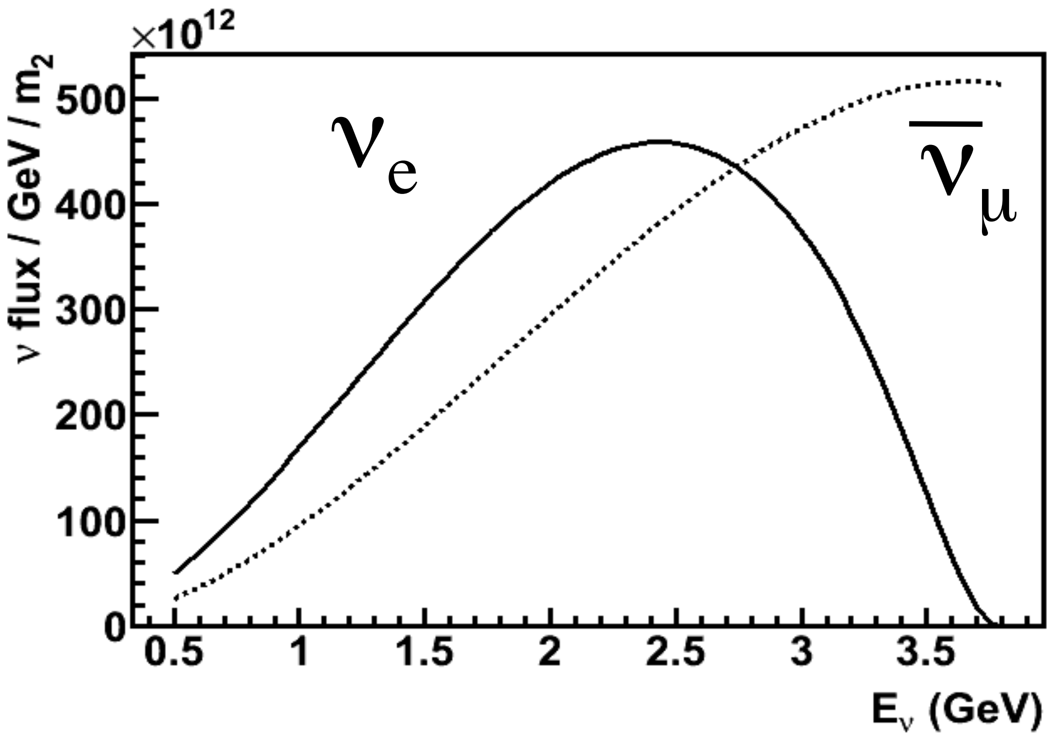


- Provide a technology test demonstration (μ decay ring) and μ beam diagnostics test bed.
- Provide a precisely understood ν beam for detector studies.
- **Change the conception of the neutrino factory.**

The νSTORM Neutrino Beam

$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$ $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$

- The νSTORM beam will provide a very well-known ($\delta\,\phi(E) \approx 1\%$) beam of ν and $\bar{\nu}$.
- A high-intensity source of ν_e events for experiments.



3.8 GeV μ^+ stored, 150m straight, flux at 100m

(thanks to Sam Zeller and Chris Tunnell!)

μ^+

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

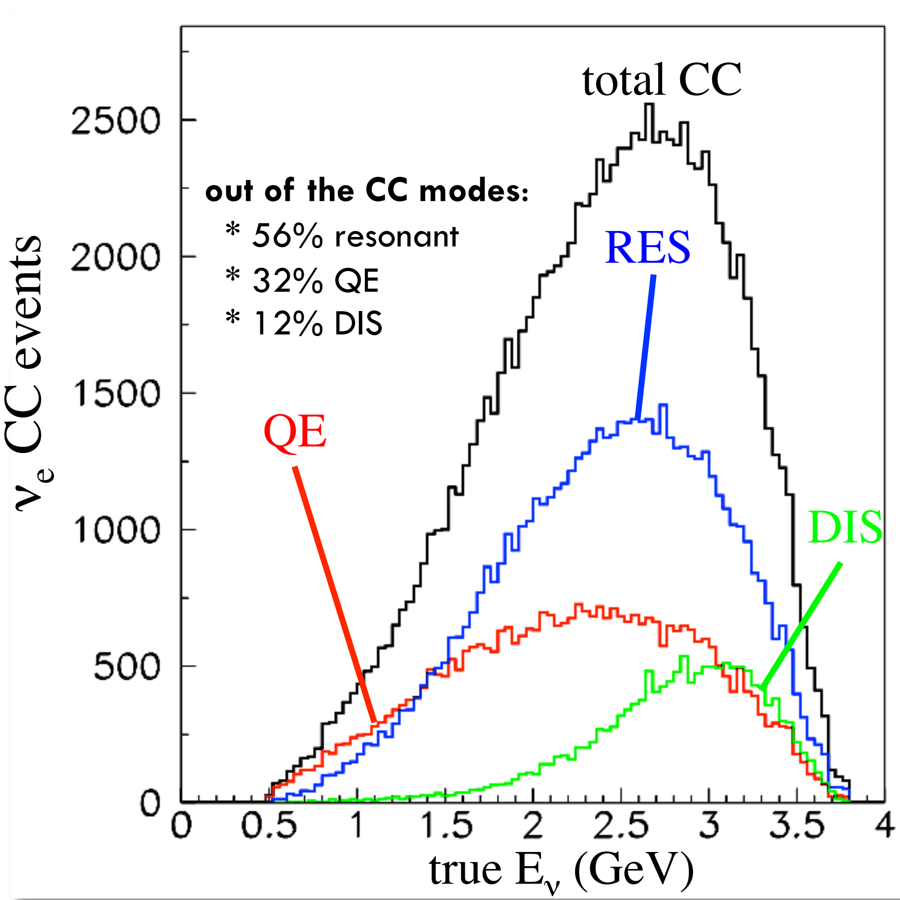
μ^-

Channel	N_{evts}
$\bar{\nu}_e$ NC	709,576
ν_μ NC	1,584,003
$\bar{\nu}_e$ CC	1,784,099
ν_μ CC	4,626,480

event rates per 1E21 POT - 100 tons at 50m

ν_e Event Fractions in νSTORM

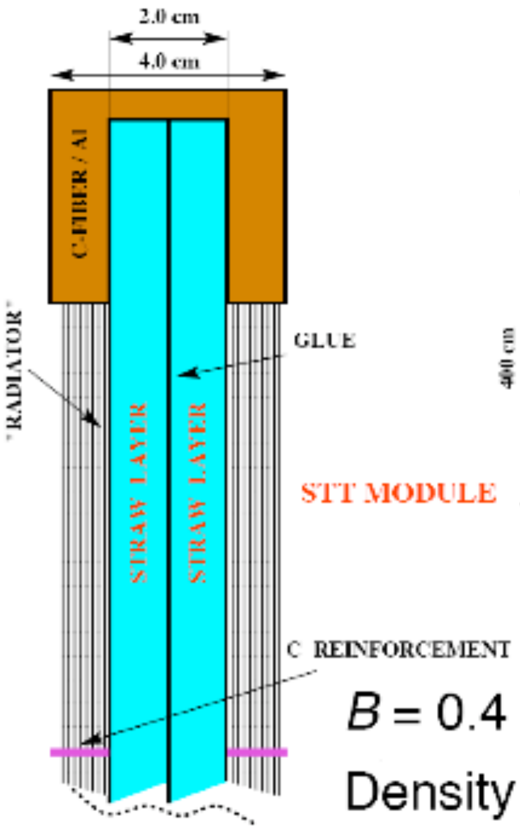
- ν_e produced by 3.8 GeV μ^+ beam.

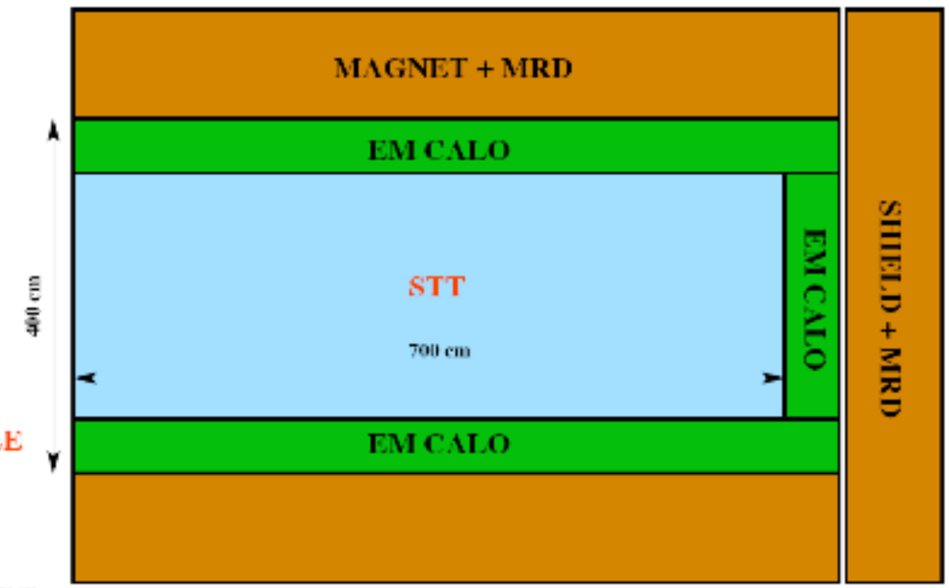


- For $\overline{\nu}_e$ sample, 52% resonant, 40% QE, 8% DIS)

νSTORM Near Detector
High Resolution Straw-tube Magnetized Detector

- HighRes – Mishra/Petti





$B = 0.4$ T.

Density = 0.1 g/cm3, 85% in the radiator foils.

Transition Radiation ⇒ Electron ID ⇒ γ (w. Kinematics)

dE/dx ⇒ Proton, π, K ID

Magnet/Muon Detector ⇒ μ

High Resolution Near Detector

- NOMAD-like resolution in HiRes detector allows to:
  - Measure absolute flux using ν - e elastic scattering –
  - Measure quasi-elastic scattering
  - NC vs CC events (NOMAD with 90% purity)
  - Coherent π^0
  - Comparison $\sin^2\theta_W$ from DIS and $\nu\, e \rightarrow \nu\, e$
  - 77 different physics topics!

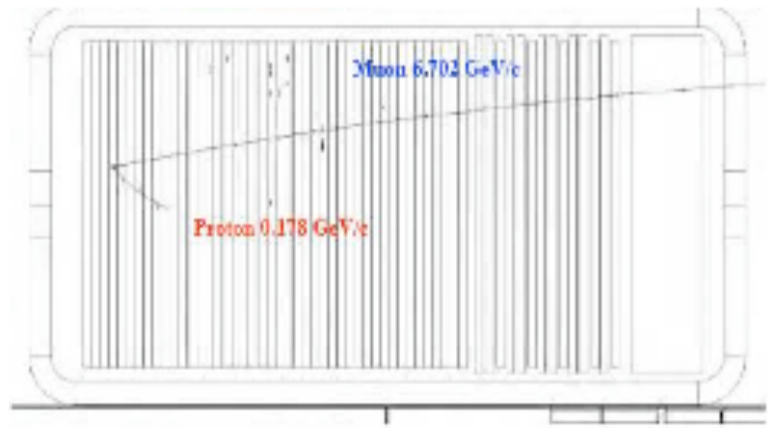
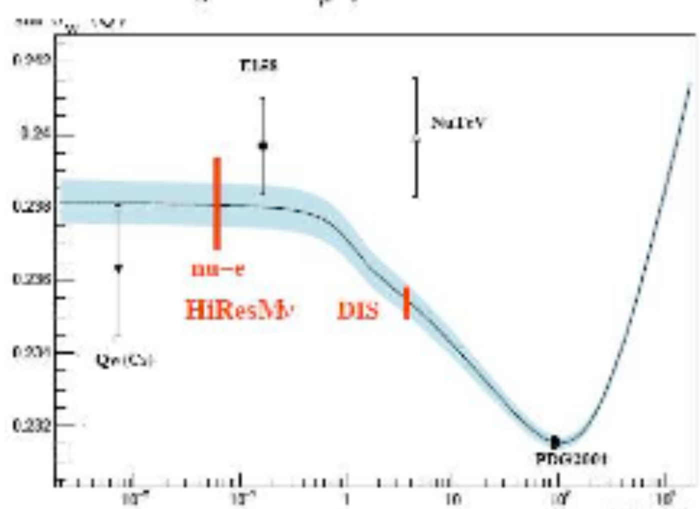


Figure 14: A ν_μ-QE candidate in NOMAD



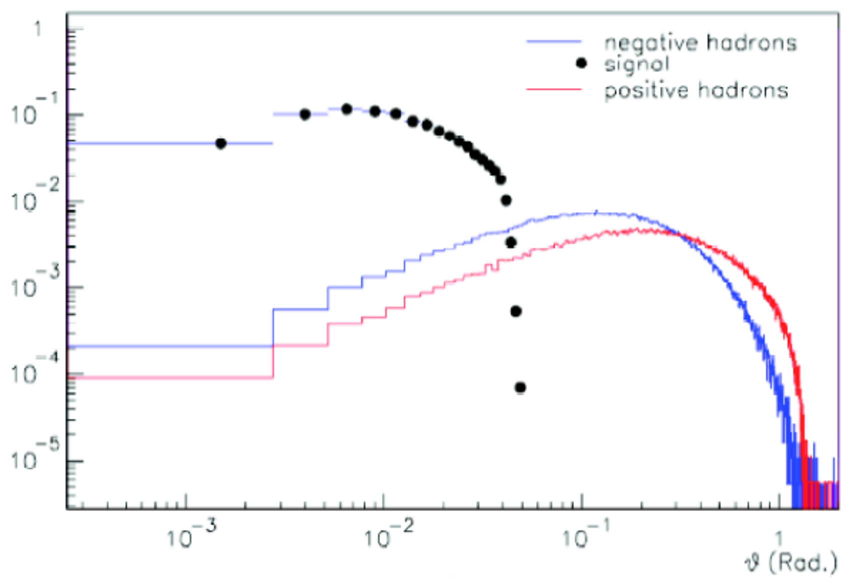
ν-e NC elastic scattering

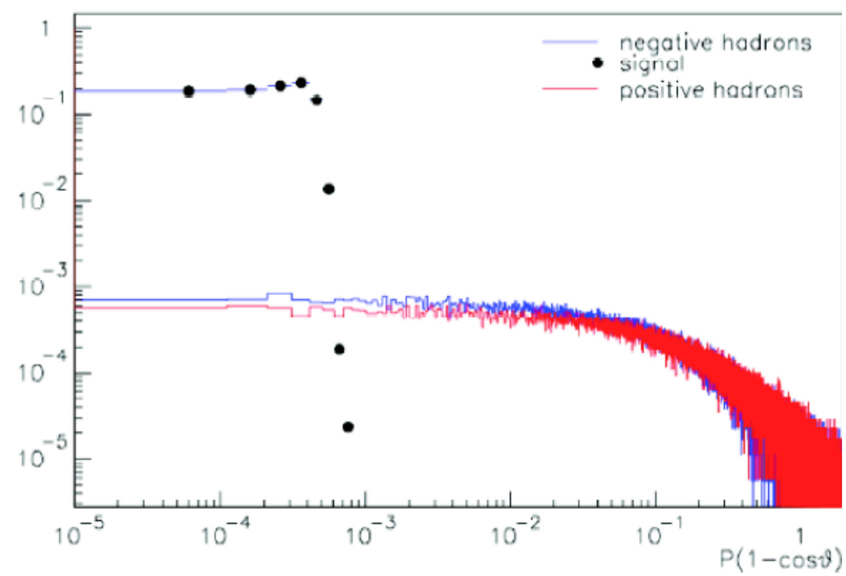
Mishra

$$\sigma(\nu_l e \to \nu_l e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}\left[1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W\right]$$

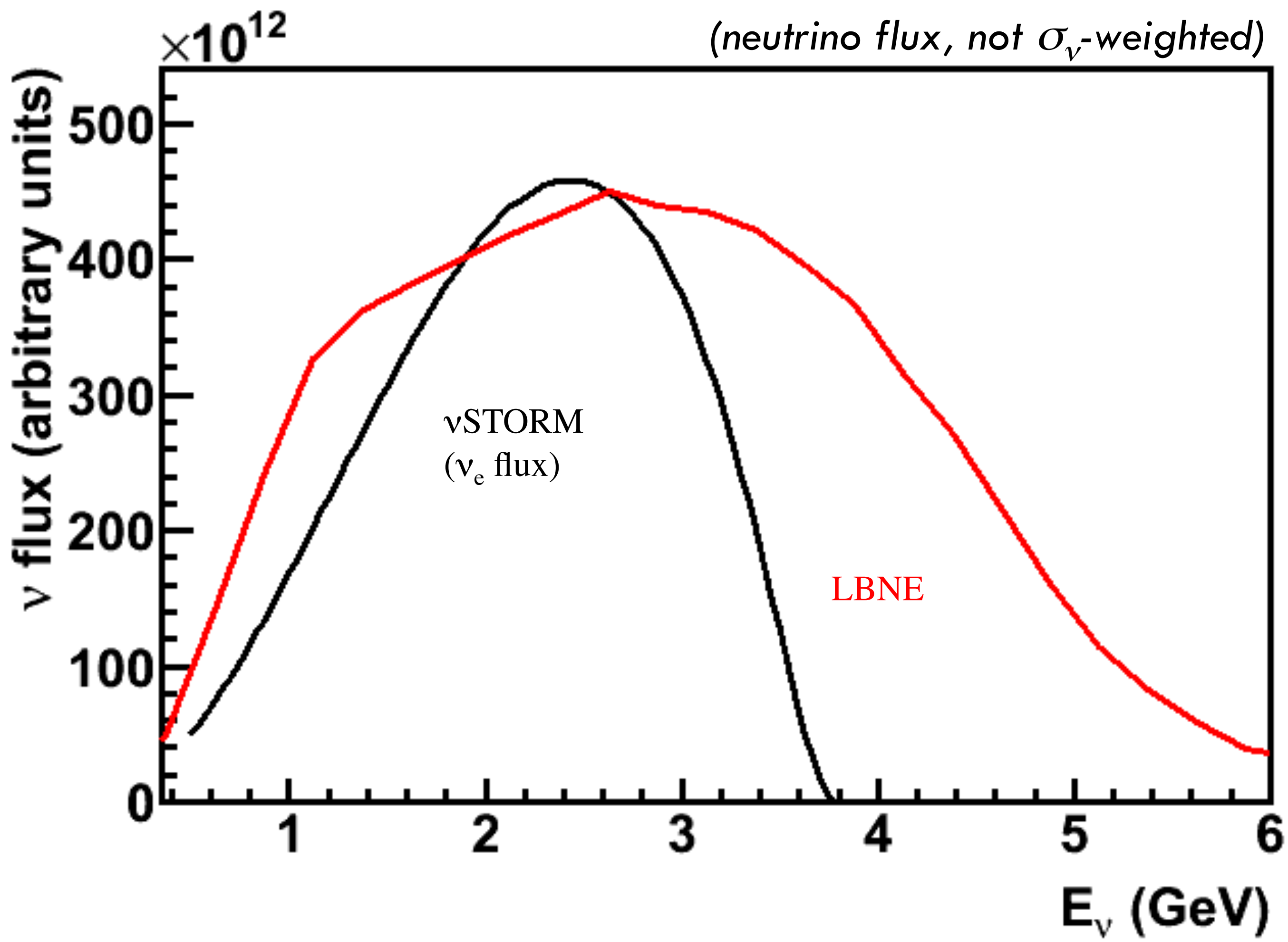
$$\sigma(\bar{\nu}_l e \to \bar{\nu}_l e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}\left[\frac{1}{3} - \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W\right]$$

$$\sim 10^{-42}(E_\nu/\,\mathrm{GeV})\; cm^2$$





Practicality of νSTORM Neutrino Spectrum



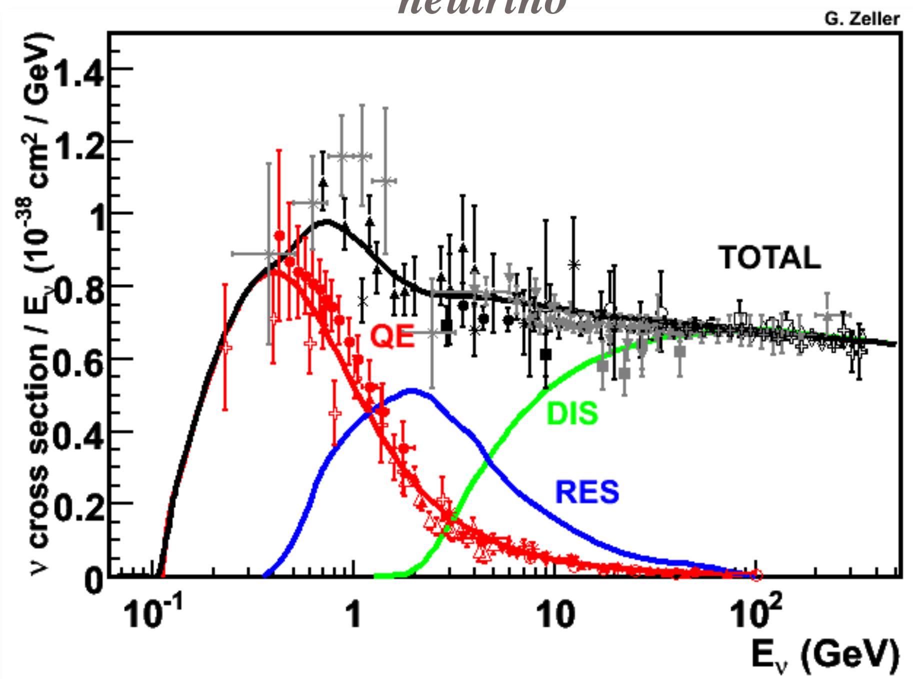
Conclusions

- An important systematic error in measurement of CP-violations could be our knowledge of ν_e cross sections.
  - Simply assuming we can infer ν_e cross sections from ν_μ cross sections is unjustified.
  - Simply correcting cross section for the difference in lepton mass is not necessarily sufficient.
- There is then a need to actually measure ν_e cross sections to minimize the systematic error from this source.
- νSTORM, based on the decay of a circulating beam of muons, could provide an intense beam of well-know flux (order 1%) of ν_e (and $\bar{\nu}_\mu$) for ν_e and $\bar{\nu}_\mu$ cross section measurements in a single experiment.
- Stay-tuned for the presentation of Alan Bross on Friday afternoon for details of the νSTORM facility and agenda.

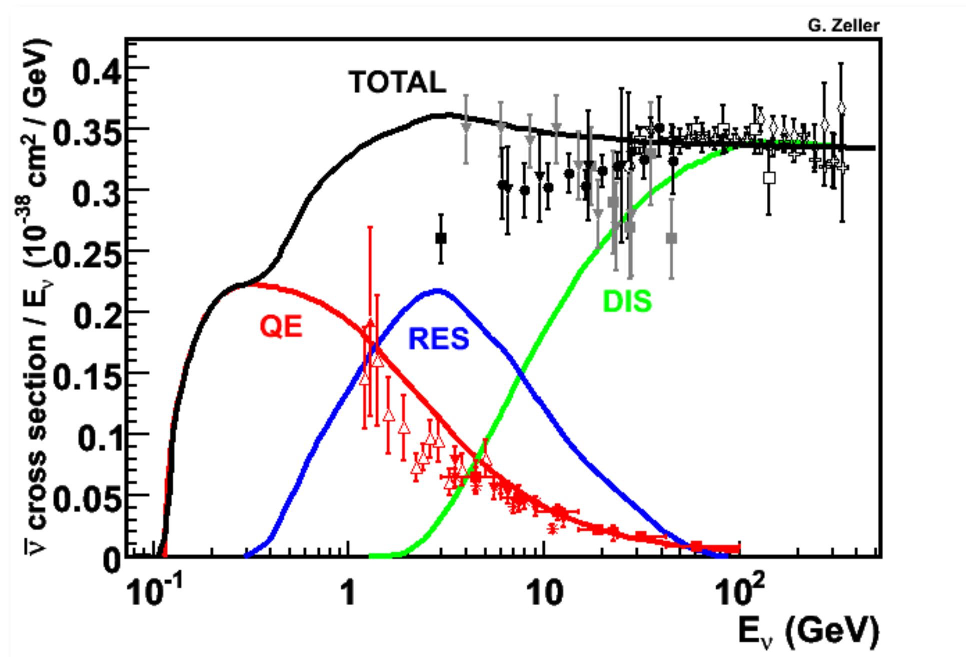
Extra Details

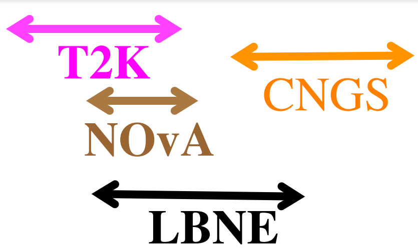
Current Knowledge

neutrino



antineutrino





ν_e Event Fractions in νSTORM

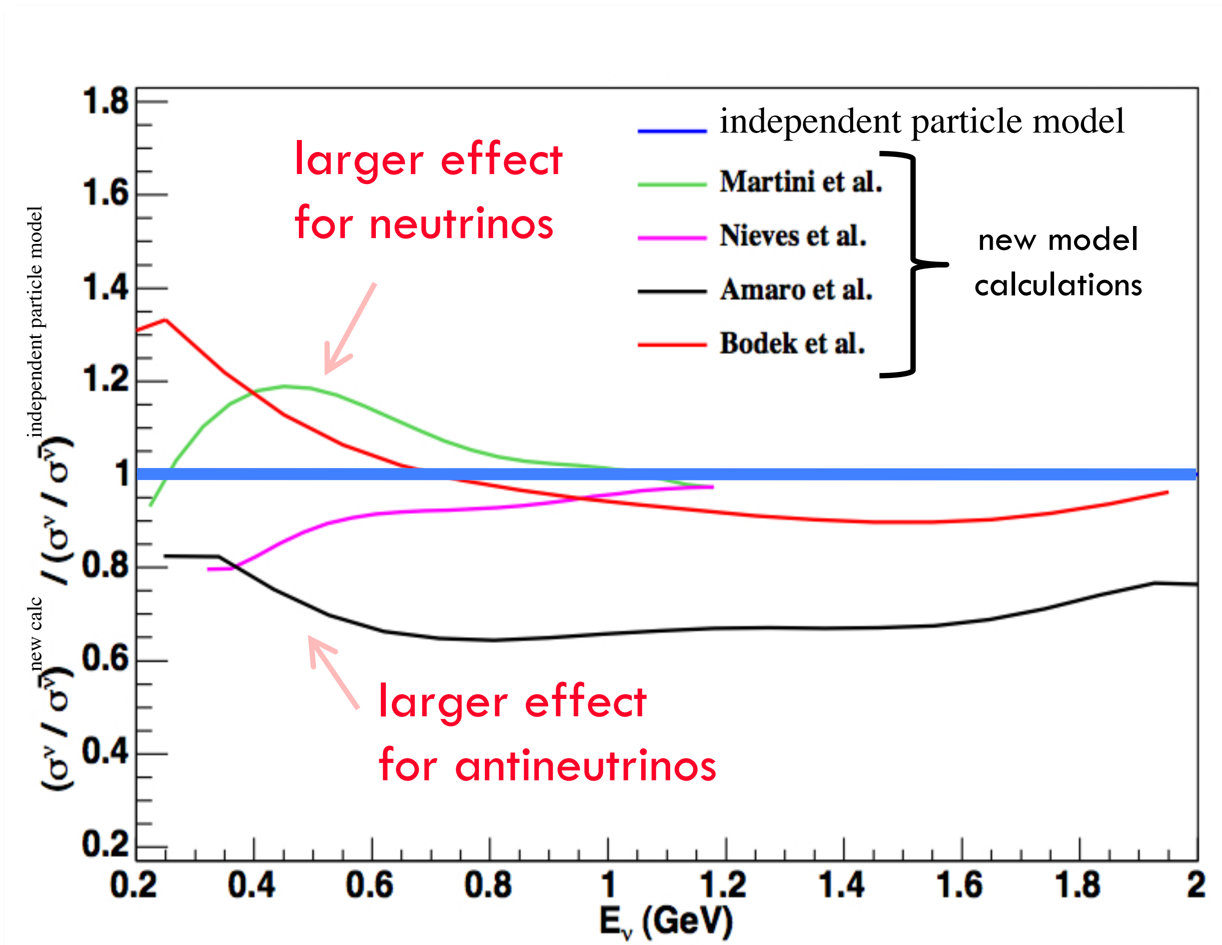
sources of ν_e events produced by νSTORM 3.8 GeV μ^+ beam

production mode	# fraction of total (%)
QE ($\nu_e\, n \rightarrow e^-\, p$)	23.3
NC elastic ($\nu_e\, N \rightarrow \nu_e\, N$)	10.0
CC resonant π^+ ($\nu_e\, N \rightarrow e^-\, N\, \pi^+$)	25.5
CC resonant π^0 ($\nu_e\, n \rightarrow e^-\, p\, \pi^0$)	5.6
NC resonant π^0 ($\nu_e\, N \rightarrow \nu_e\, N\, \pi^0$)	6.4
NC resonant $\pi^\pm$ ($\nu_e\, N \rightarrow \nu_e\, N\, \pi^\pm$)	4.5
CC DIS ($\nu_e\, N \rightarrow e^-\, X$, $W > 2$)	8.3
NC DIS ($\nu_e\, N \rightarrow e^-\, X$, $W > 2$)	2.7
other CC	9.9
other NC	3.8
total CC	72.7
total NC	27.3

Table 1: NUANCE-predicted ν_e event rate fractions for a 3.8 GeV μ^+ beam, 100m from the source. Processes are defined at the initial neutrino interaction vertex and do not include final state effects. These estimates have been integrated over the νSTORM flux spectrum and do no include detector efficiency or acceptance corrections.

$\nu_\mu/\bar{\nu}_\mu$ QE Ratio

- current models give different predictions for $\nu_\mu/\bar{\nu}_\mu$ QE scattering



Full Cross Section Expression

$$\frac{d\sigma}{dQ^2}\left({\nu n \to l^- p \atop \bar{\nu} p \to l^+ n}\right) = \left[A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right] \times \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}$$

$$|F_A|^2 - \left(4 - \frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\xi|F_V^2|^2\left(1 - \frac{Q^2}{4M^2}\right) + \frac{4Q^2 Re F_V^{1*}\xi F_V^2}{M^2}$$

$$-\frac{Q^2}{M^2}\left(4 + \frac{Q^2}{M^2}\right)|F_A^3|^2 - \frac{m^2}{M^2}\left(|F_V^1 + \xi F_V^2|^2 + |F_A + 2F_P|^2 - \left(4 + \frac{Q^2}{M^2}\right)\left(|F_V^3|^2 + |F_P|^2\right)\right)\Bigg]$$

$$B(Q^2) = \frac{Q^2}{M^2} Re F_A^*\left(F_V^1 + \xi F_V^2\right) - \frac{m^2}{M^2} Re\left[\left(F_V^1 - \frac{Q^2}{4M^2}\xi F_V^2\right)^* F_V^3 - \left(F_A - \frac{Q^2 F_P}{2M^2}\right)^* F_A^3\right]$$

$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 + \frac{Q^2}{M^2}|F_A^3|^2\right)$$

- F_p, $F^3{}_A$ and $F^3{}_V$ terms are less well studied