Title: Higher-order corrections for neutrino experiments

Date: Jun 13, 2017 09:00 AM

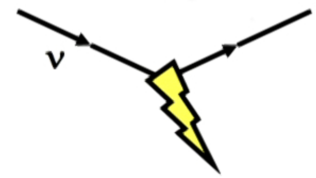
URL: http://pirsa.org/17060007

Abstract:


ν Interactions: When is tree level not enough?
Welcome To
ν
ONTARIO
More to discover
METRIC CONVERSION
MAXIMUM
50
km/h
= 30 mph
Speed Measuring Warning Devices Prohibited
Kevin McFarland
University of Rochester
Perimeter Institute, 12 June 2017

$$50\,\frac{km}{h} = 30\,mph \times \left(1 + \frac{15\alpha_{EM}}{\pi} + \cdots\right)$$

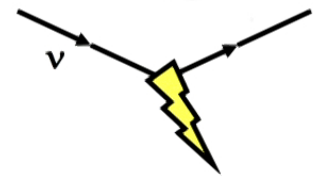
Outline



1. Motivation for Precision Neutrino Measurements
2. Needed Higher Order Calculations
   - Neutrino NC/CC in Deep Inelastic Scattering
   - Neutrino-Electron Elastic Scattering
   - Real Photons in Neutrino Processes
   - Lepton Mass Effects in Low Energy Cross Sections

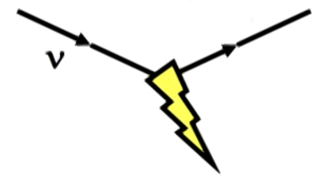
The bulk of this talk borrows heavily from
R. Hill, KSM, manuscript in progress

Neutrino Oscillation Goals



- Now that we have the wonderful tool of neutrino oscillation available to us…
- Of course we want to understand more!
- Is there CP violation in the neutrino sector? And is it consistent with leptogenesis?
- Is there a symmetry to the pattern of masses or mixings?
- Answers to both of these probems require us to make precise measurements of neutrino oscillations

Measurements for CP Violation

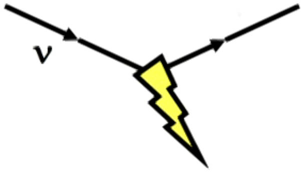


- We often describe CP violation measurements as very simple

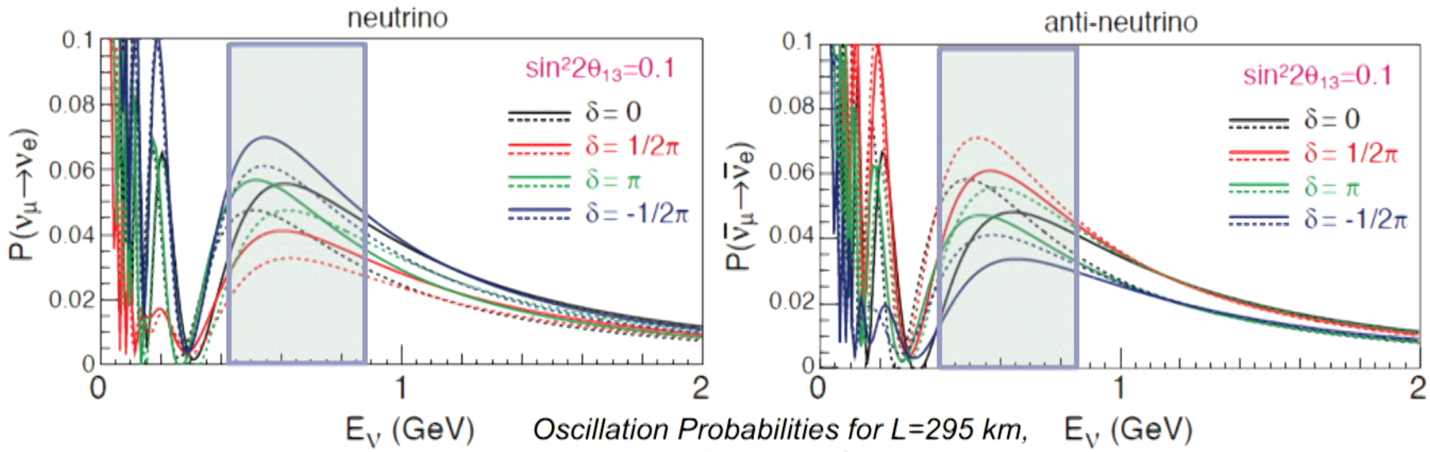
$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

- The real situation is much more complex
  - The oscillation probability differs because of matter effect which depends on mass ordering
  - θ_{13} from reactor experiments is an important input, but requires knowing θ_{23} from $P(\nu_\mu \to \nu_\mu)$ precisely to use it

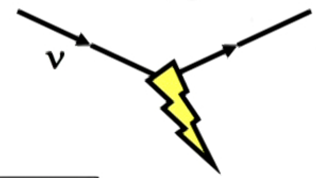
Oscillations: Needs
(J-PARC to Hyper K)



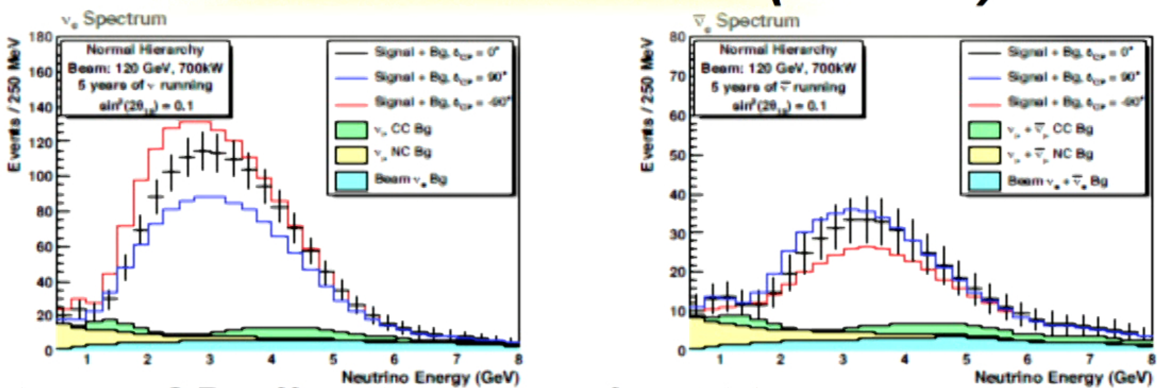
- Discovery of CP violation in neutrino oscillations requires seeing distortions of $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino and anti-neutrino energy



Oscillation Probabilities for L=295 km, Hyper-K LOI

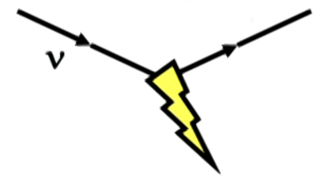


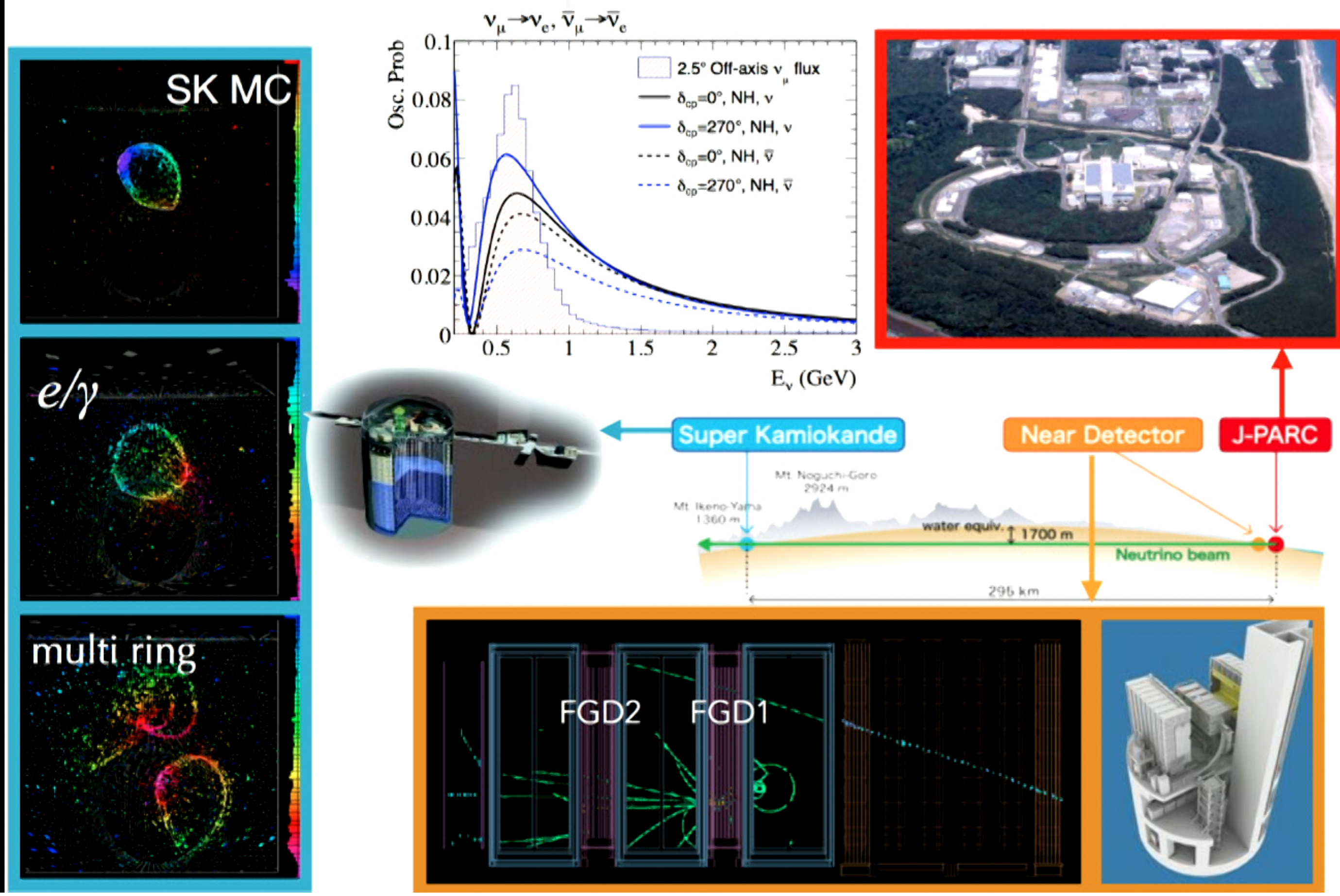
Oscillations: Needs (DUNE)



- Maximum CP effect is range of red-blue curve
- Backgrounds are significant, vary with energy and are different between neutrino and anti-neutrino beams
  - Pileup of backgrounds at lower energy makes 2nd maximum only marginally useful, even in an optimized design
- Spectral information plays a role
  - CP effect may show up primarily as a rate decrease in one beam and a spectral shift in the other

Example: T2K



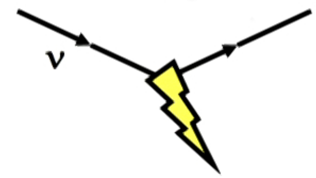


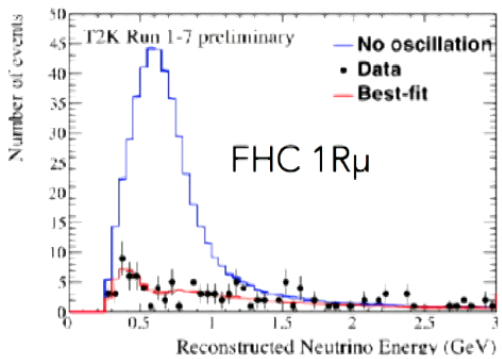
Graphic by Hiro Tanaka

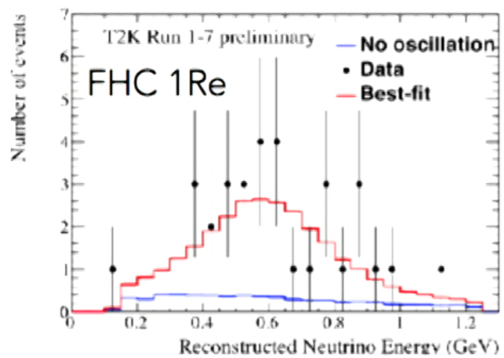
13 June 2017

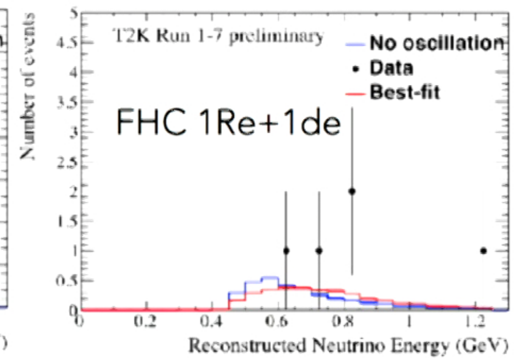
Kevin McFarland: Neutrinos and Higher Orders

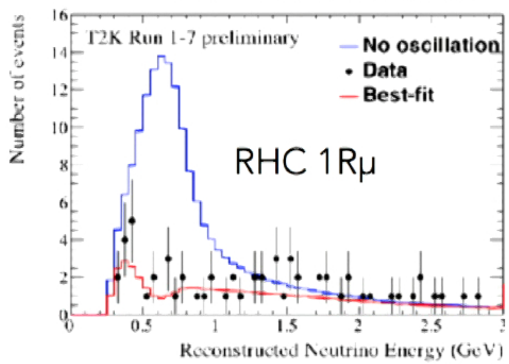
Events at Far Detector

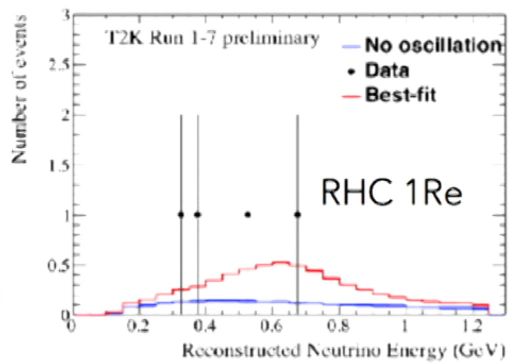












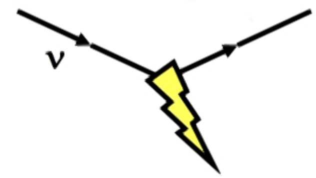
Events: No Osc→Obs

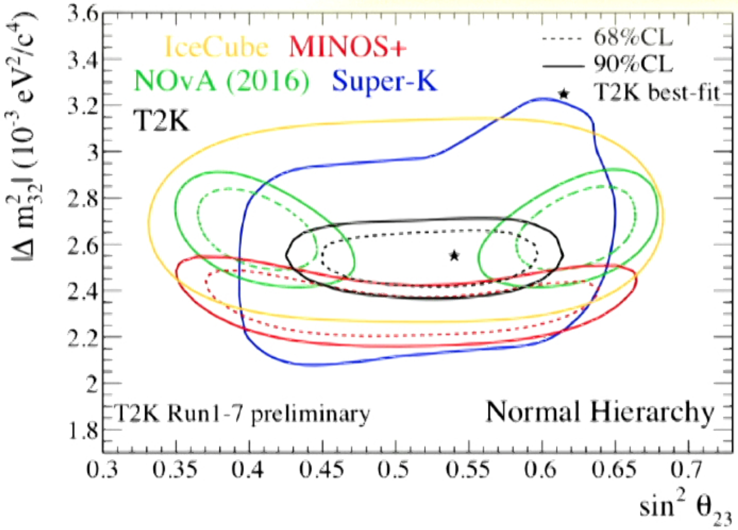
	FHC	RHC
1Re	6→32	2.4→4
1Re+de	0.8→5	n/a
1Rμ	481→ 135	177→ 66

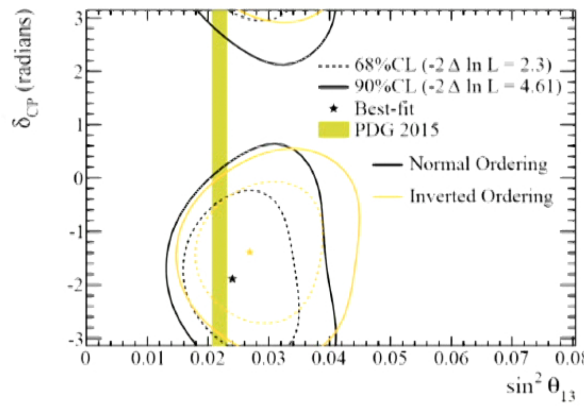
New sample: CC1π^+ (1Re+1de)

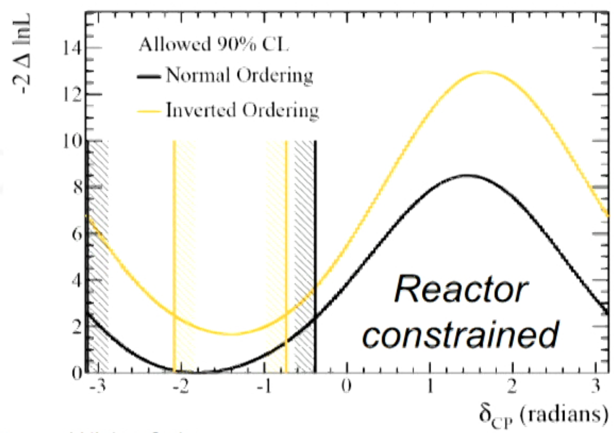
Decay electron from $\pi \rightarrow \mu \rightarrow e$

Oscillation Parameters



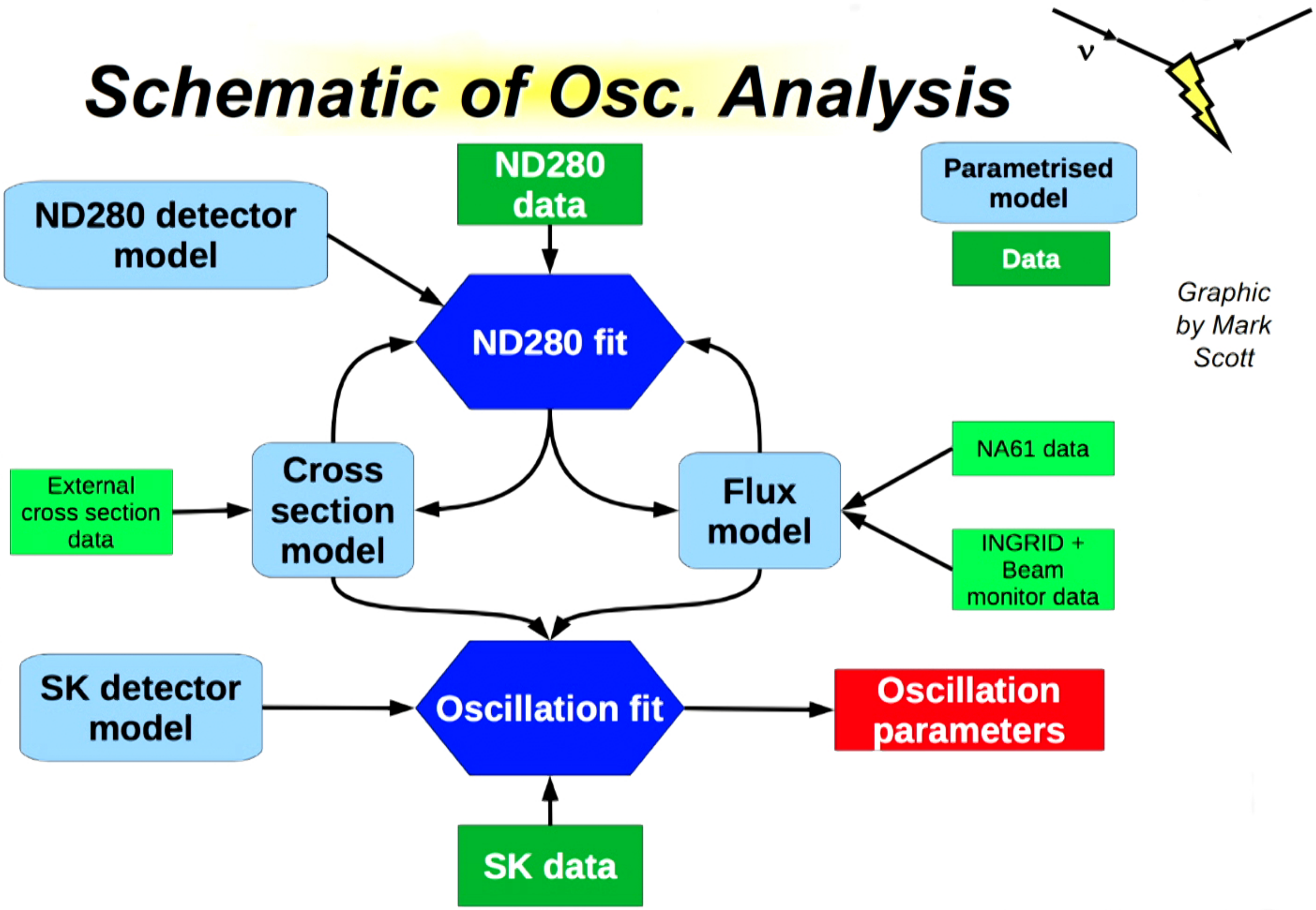






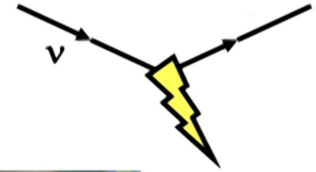
- Large ν_μ disappearance suggests maximal mixing
- Large ν_e appearance suggests normal ordering, 2nd octant and $\delta_{CP} \sim {}^{-\pi}/_2$

Schematic of Osc. Analysis

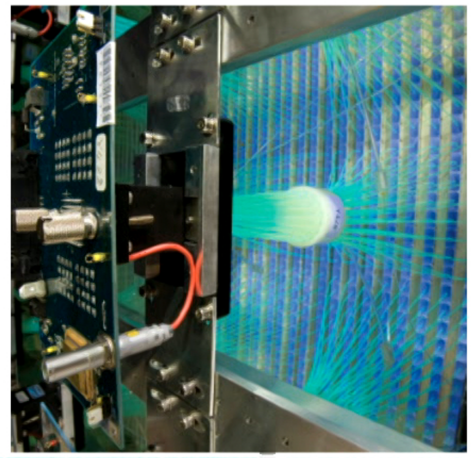


Graphic by Mark Scott

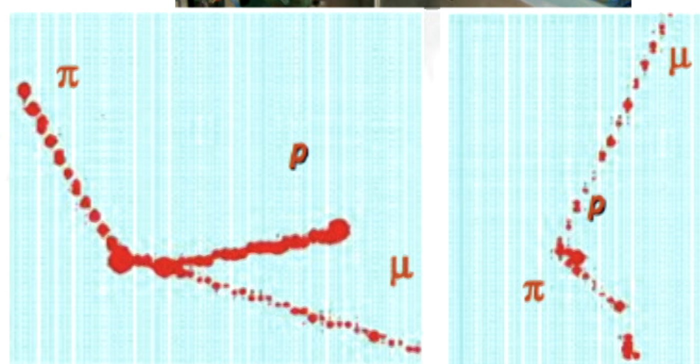
Segmented Scintillator, e.g., NOvA



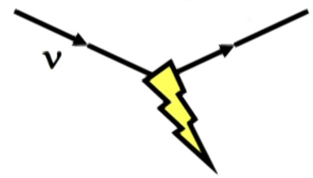
- Lower thresholds, particle ID by dE/dx, calorimetric energy reconstruction
  - i.e., vertex activity
- Segmentation is typically cm
  - Overlapping tracks
- But like water, photon and electron interactions are slow to develop
- Reconstruction not uniform in angle



This is not NOvA!

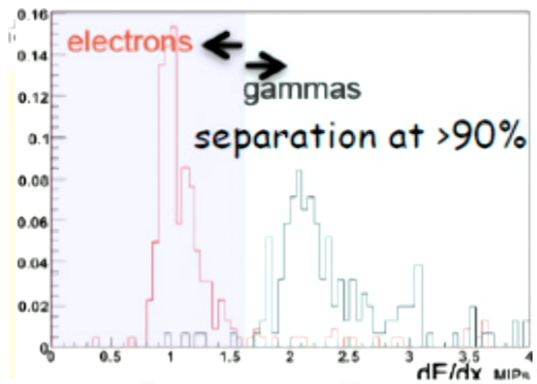


Figures from M. Wascko

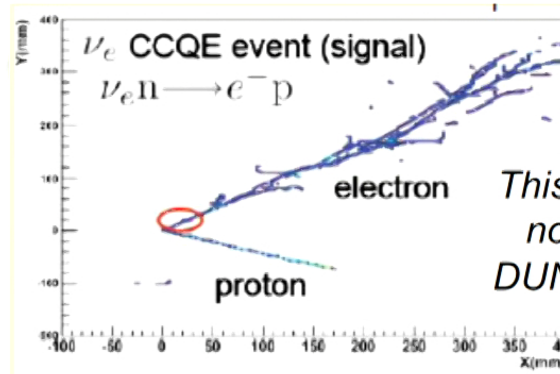


Liquid Argon, e.g., DUNE

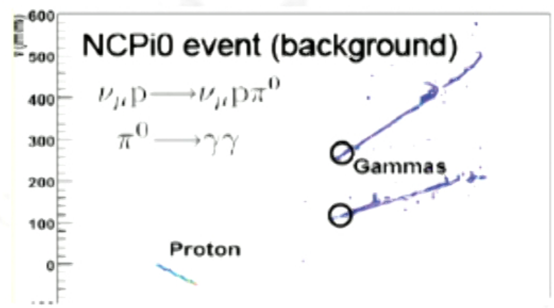
- Low threshold, great particle ID
- But Z is high, so rapid electromagnetic showers



- Reconstruction is not always so straightforward with this level of detail available
  - E.g., inelastic hadron interactions

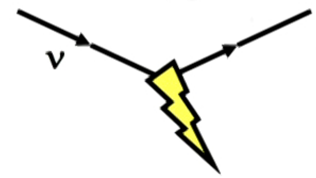


This is not DUNE!

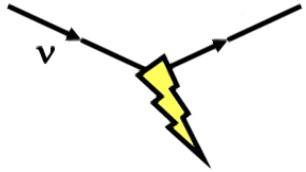


Figures from G. Barker

Neutrino Interactions and Oscillations

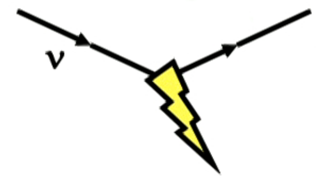


- Uncertainties in neutrino interactions are important, which is why Kendall, Gabe and I are here…
  - Why? Energy reconstruction from final state, identification of electrons and muons in presence of hadrons, differences between ν and $\bar{\nu}$, prediction of ν_e interactions from study of ν_μ
- Targets are hydrocarbons, water, argon
  - Nuclear effects are thought to be ~10% corrections. We are making progress on these.
- EWK radiative corrections are likely ~1%. But…



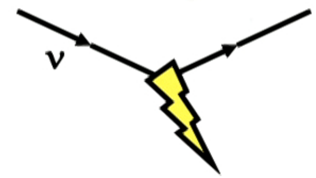
Status of Relevant Calculations of Radiative Corrections in Neutrinos

What has been done?



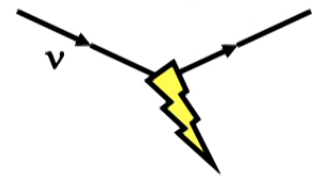
- Deep Inelastic Scattering, i.e., $\nu q \to \nu/\ell q'$
  - Outdated calculations using quark mass regularization
    D.Yu. Bardin, V.A. Dokuchaeva Sov.J.Nucl.Phys. 39 (1984) 563, Yad.Fiz. 39 (1984) 888-894
  - Modern calculations in unrealistic observables
    K.P.O. Diener, S. Dittmaier, W. Hollik, Phys.Rev. D69 (2004) 073005
    A.B. Arbuzov, D.Yu. Bardin, L.V. Kalinovskaya, JHEP 0506 (2005) 078
  - Modern calculations in realistic observables!
    K.-P.O. Diener , S. Dittmaier, W. Hollik, Phys.Rev. D72 (2005) 093002
- Neutrino-Electron Elastic Scattering
  - Modern calculation in unrealistic observable for high energy experiments (done for solar neutrinos)
    S. Sarantakos, A. Sirlin, W.J. Marciano, Nucl.Phys. B217 (1983) 84-116
    John N. Bahcall, Marc Kamionkowski, Alberto Sirlin, Phys.Rev. D51 (1995) 6146-6158

What do we not have?



- Neutrino-electron elastic scattering needs correct observable for high energy flux usage (DUNE)
- Model for real photons and their effects at a few 100 MeV to a few GeV neutrino energies
- Difference from virtual corrections because of lepton mass

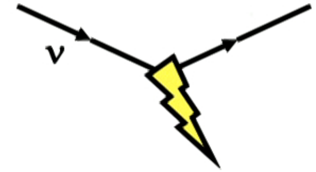
We should be worried!



- In fact, yesterday at President Trump's cabinet "lovefest", this was one of the items highlighted by Energy Secretary Rick Perry that was causing him to rethink his new appreciation for his department

Trump's Cabinet, With a Prod, Extols the 'Blessing' of Serving Him JUNE 12, 2017

We should be worried!



- In fact, yesterday at President Trump's cabinet "lovefest", this was one of the items highlighted by Energy Secretary Rick Perry that was causing him to rethink his new appreciation for his department
- And predictably, a Twitter tantrum followed this morning…

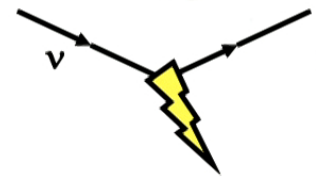
Trump's Cabinet, With a Prod, Extols the 'Blessing' of Serving Him JUNE 12, 2017

Donald J. Trump
@realDonaldTrump

Neutrino radiative corrections totally inadequate for precision frontier! Sad! Demand theorists testify under oath. Waterboarding?

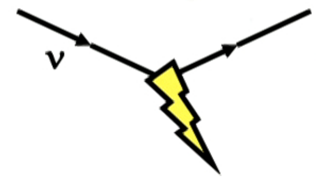
RETWEETS 7,655 LIKES 1,308

6:21 AM - 13 Jun 2017



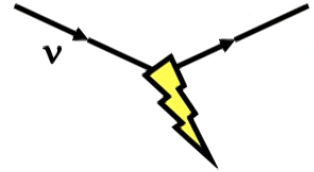
Deep Inelastic Scattering

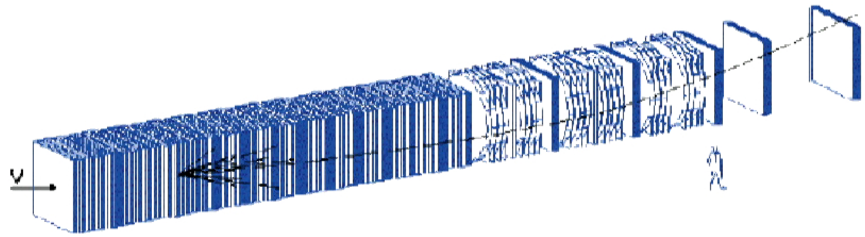
Why Deep Inelastic Scattering?

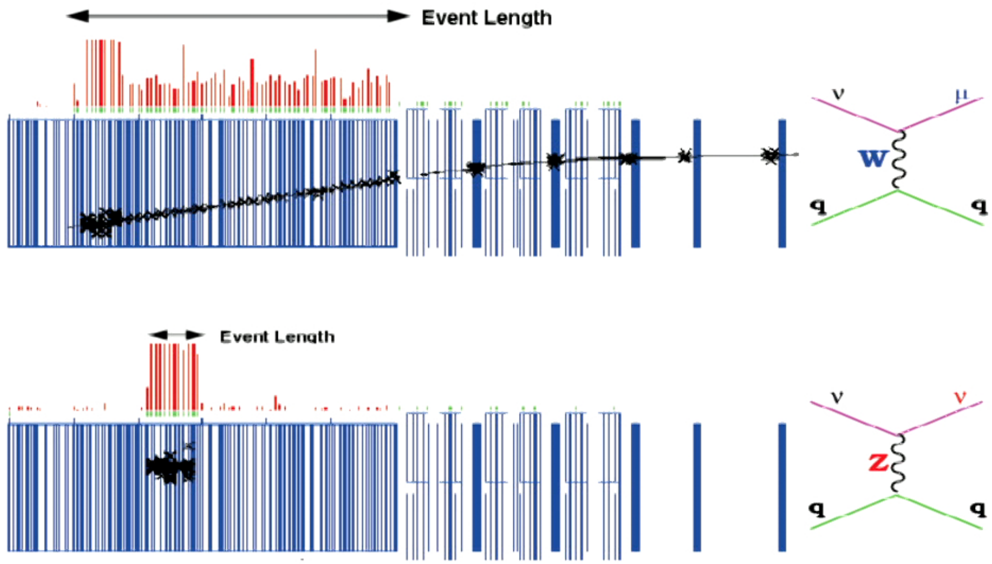


- Precision $\nu q \to \nu / \ell q'$ is not an issue for oscillation experiments, but it is used for
  - Neutrino structure functions (CCFR, NuTeV, MINERvA)
  - Studies of neutrino analog to EMC effect (MINERvA)
  - Studies of NC/CC for electroweak observables and nuclear effects (CDHS, CCFR, NuTeV)
- Radiative corrections cause
  - Differences in NC and CC DIS (final state lepton)
  - Distortion of kinematics in structure function measurements

Example: NuTeV

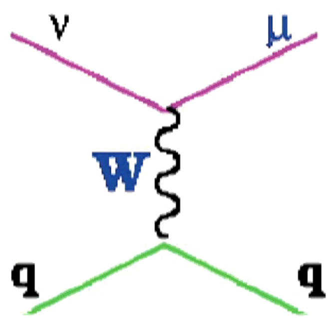




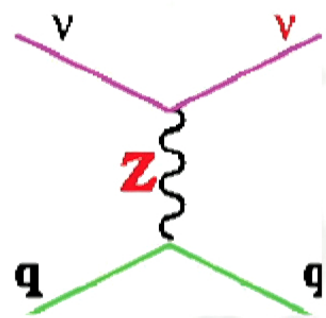


DIS NC/CC Ratio

- Experimentally, it's "simple" to measure ratios of neutral to charged current cross-sections on an isoscalar target to extract NC couplings



W-q coupling is I_3

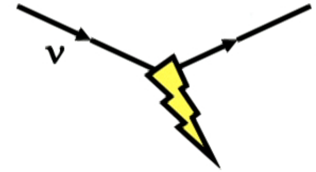


Z-q coupling is $I_3\text{-}Q\sin^2\theta_W$

Llewellyn Smith Formulae

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \left(\left(u_L^2 + d_L^2\right) + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}} \left(u_R^2 + d_R^2\right) \right)$$

- Holds for isoscalar targets of u and d quarks only
  - Heavy quarks, differences between u and d distributions are corrections
- Isospin symmetry causes PDFs to drop out, even outside of naïve quark-parton model



NuTeV Fit to R^{ν} and $R^{\nu bar}$

- NuTeV result:

NuTeV Collaboration (G.P. Zeller et al.). Phys.Rev.Lett. 88 (2002) 091802

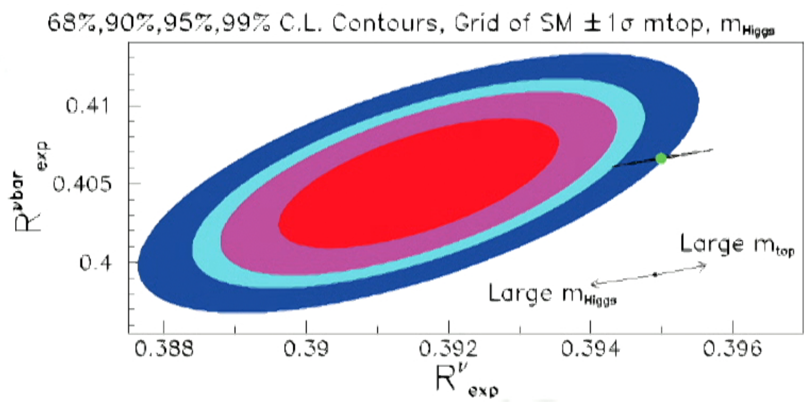
$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$
$$= 0.2277 \pm 0.0016$$

(Previous neutrino measurements gave 0.2277 ± 0.0036)

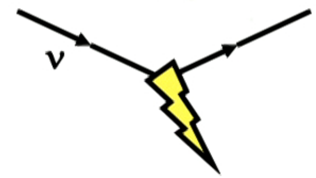
- Standard model fit (LEPEWWG, ca 2001): 0.2227 ± 0.00037

A 3σ discrepancy…

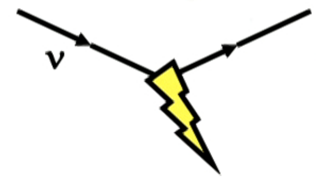
$$R^{\nu}_{\rm exp} = 0.3916 \pm 0.0013$$
$$(SM: 0.3950) \quad \Leftarrow 3\sigma \ difference$$
$$R^{\bar{\nu}}_{\rm exp} = 0.4050 \pm 0.0027$$
$$(SM: 0.4066) \quad \Leftarrow Good\ agreement$$



Here the situation is under control, more or less…

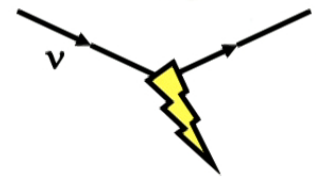


- Deep Inelastic Scattering, i.e., $\nu q \rightarrow \nu/\ell q'$
  - NuTeV used outdated calculations (m_q reg.)
    D.Yu. Bardin, V.A. Dokuchaeva Sov.J.Nucl.Phys. 39 (1984) 563, Yad.Fiz. 39 (1984) 888-894
  - Modern calculations in realistic observables now exist
    K.-P.O. Diener , S. Dittmaier, W. Hollik, Phys.Rev. D72 (2005) 093002
- Impossible to exactly correct NuTeV to the modern calculations, but difference is likely <0.1% in ratios
  - Problem in being more precise is that it is not easy to quantify effect of properly including QED evolution in PDFs after the fact

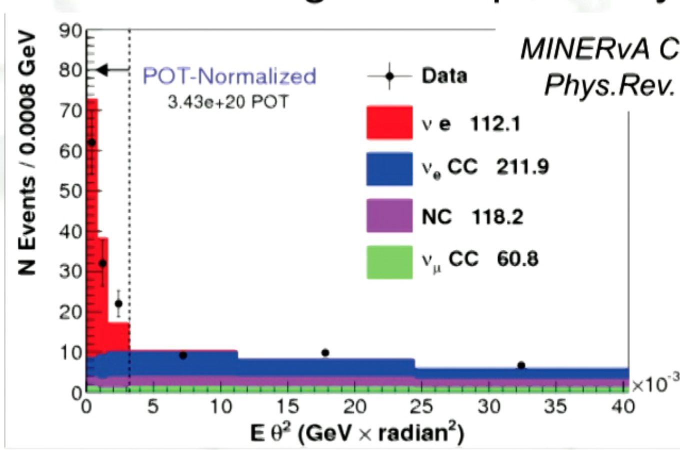


Neutrino Electron Elastic Scattering

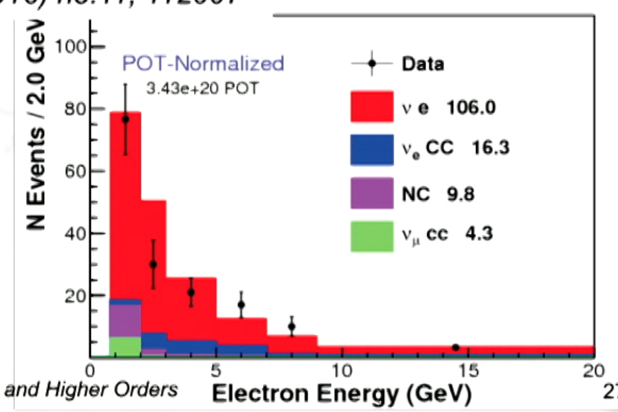
Neutrino-Electron Scattering



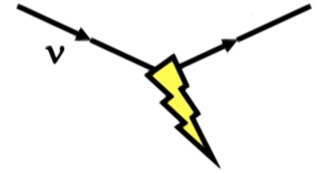
- $\nu e^- \rightarrow \nu e^-$. Rare reaction… parts in 10^4
- Why do we care? Can be used as a “standard candle” to measure neutrino flux.
  - At least at higher energies, DUNE and NOvA
  - Backgrounds probably too high at T2K, Hyper-K



MINERvA Collaboration (J. Park et al.), Phys.Rev. D93 (2016) no.11, 112007



Neutrino-Electron Scattering

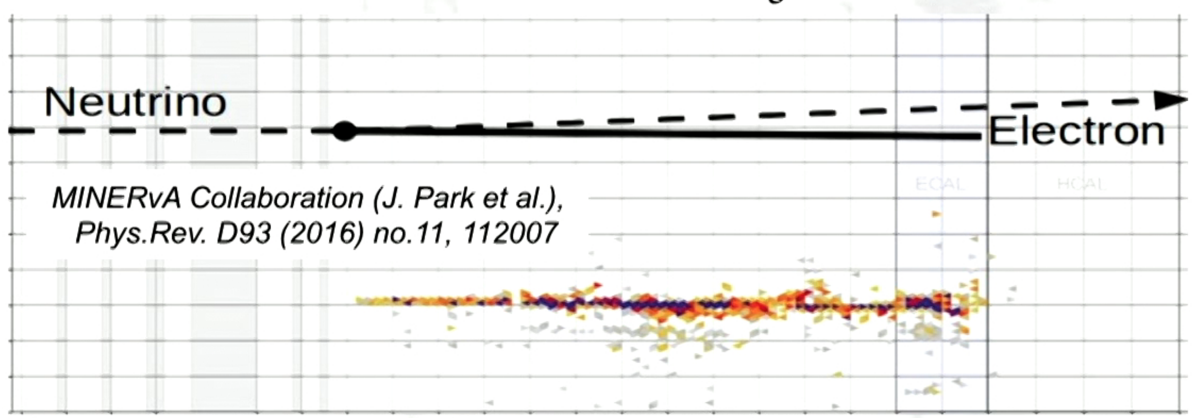


- However, there is a “simple” problem to solve
- In high energy experiments, a real radiated photon is clustered with the electron. Measure $E_{\nu}^{initial} - E_{\nu}^{final}$, not E_e.

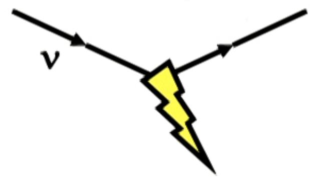
S. Sarantakos, A. Sirlin, W.J. Marciano, Nucl.Phys. B217 (1983) 84-116

- Current calculations predict $\frac{d\sigma}{dE_e}$

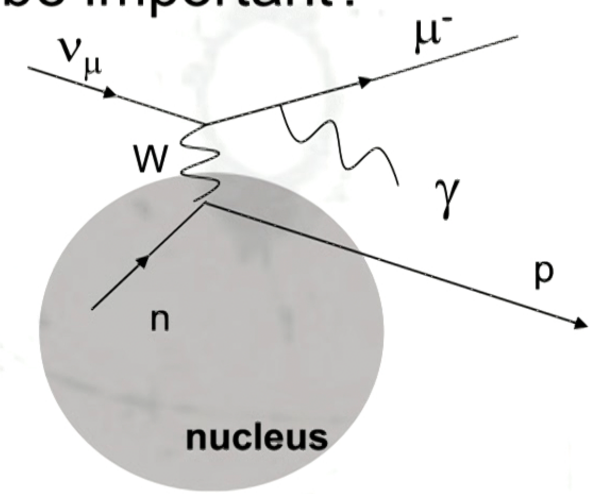
John N. Bahcall, Marc Kamionkowski, Alberto Sirlin, Phys.Rev. D51 (1995) 6146-6158



Real Photons: A Sad Tale of Reconstruction Woes

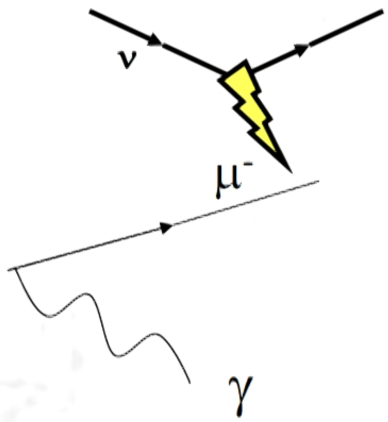


- Neutrino event generators (Gabe will summarize) do not have radiated photons in them
- Could real photon radiation be important?
  - The assumption was no
  - Sadly, it's not clear that this is correct. Possibility to disrupt reconstruction is serious even if probability is low
- So, what do I mean by real photon disruption?



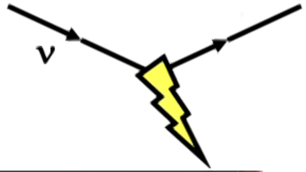
quasielastic scattering

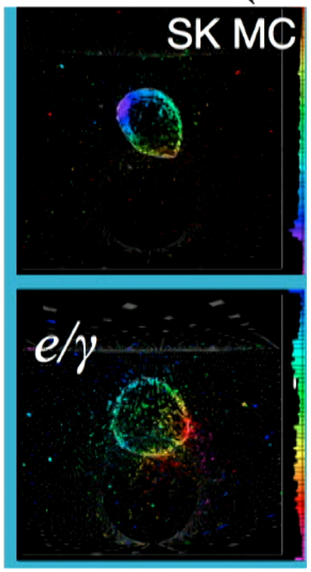
Reconstruction Woes



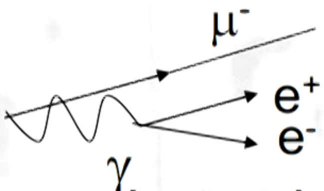
- Consider two cases
  - Collinear(ish) radiation with lepton
  - Other
- If radiation is collinear, what does it do?
  - It can disrupt lepton energy reconstruction
  - Different for electrons (adds to electron energy) and muons (reconstruction by range vs total ionization)
  - Most frighteningly, it can make muons look like they are electrons (electromagnetic shower of photon)
    - Remember that muons are common and electrons are rare in these experiments!

Muon+photon fakes Electron?

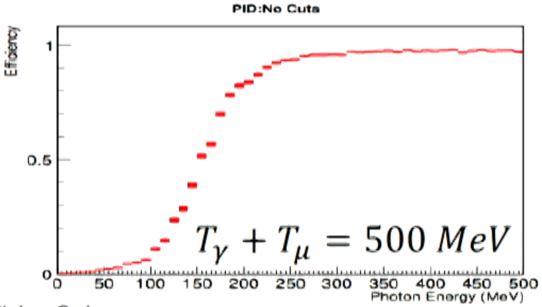




- Increased fuzziness of electron ring at bottom compared to muon at top



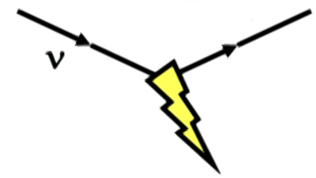
- If the collinear photon has a signfiicant fraction of the muon energy, it will appear as an electron
  - Roughly requires photon energy to be 40% of muon energy for a significant probability in Super-K
  - Rare, very bad, event



More Reconstruction Woes

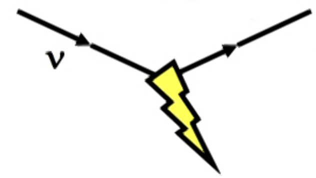
- Consider two cases
  - Collinear(ish) radiation with lepton
  - Other
- If radiation is not collinear, what does it do?
  - If detector is just summing final state energy (DUNE, NOvA) it probably of little consequence
  - But at T2K and Hyper-K, it is very bad
    - o Reconstruction will often infer the presence of a $\pi^0 \to \gamma\gamma$ with a missed photon, and it will remove the event from the quasielastic (oscillation) sample
- Oh and we can't measure this. $\pi^0 \to \gamma\gamma$ bkgnd.

Real Photons: Summary



- I've shown some ways that real photons can disrupt reconstruction in $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu \rightarrow \nu_\mu)$ at near term accelerator experiments
- We need calculations of differential cross-sections for reactions with photons
  - In particular, total energy in energetic photons that are collinear, and energy and angles of energetic non-collinear photons
- Energetic? Collinear? Depends on detector

	Scintillator (NOvA)	Water (T2K)	Largon (DUNE)
Collinear with lepton?	<7°	<12°	<15°
Photon energy threshold (MeV)	30 (100 for PID)	25	10 (100+ for PID)



Virtual Corrections to Cross Sections and Lepton Mass Effects

From a recent T2K talk I gave…

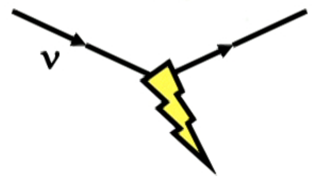
Elastic Processes on Nucleons (cont'd)

- Several additional poorly constrained uncertainties

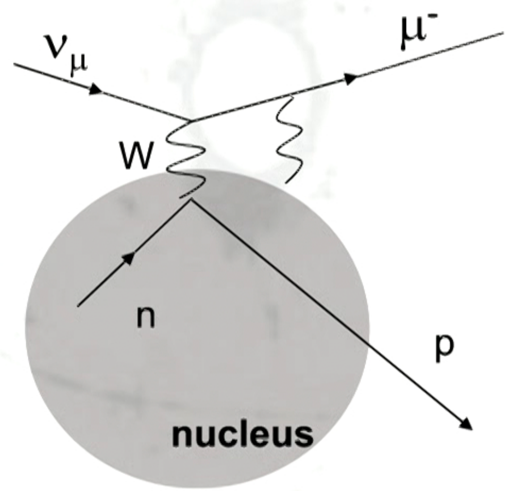
M. Day and K. S. McFarland. Phys. Rev. D 86, 053003 (2012)

  – Possibility of nuclear induced second class current effective form factors
    - At T2K energies, ~2% difference in ν_e and ν_μ CC elastic cross sections possible. Less at high energy
  – At all energies, EWK vertex corrections differences for ν_e and ν_μ thought to be "small" (KNL theorem), but there is no calculation
    - T2K puts in an additional 2% systematic
  – Lumped together as a ν_e/ν_μ uncertainty

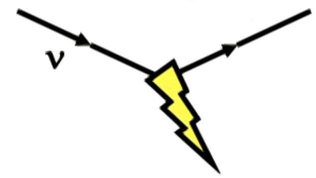
Can Lepton Mass affect an "Inclusive" Cross Section?



- By inclusive cross-sections, I mean the exclusive low energy processes that dominate at T2K, NOvA, DUNE energies
- E.g., quasielastic scattering
- I recognize the horrors implicit in the "Feynman diagram" on the right
  - And there are more… pion production
- But if this is difference at the few % level in ν_μ and ν_e scattering, it really matters!

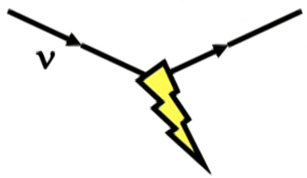


Have I done my job here?



- I've made the point that precision neutrino measurements are necessary to learn what we want to know from oscillations
- There are several places where calculations or better estimations of effects of radiative corrections are important for this program
  - Some are probably "easy" with standard methods, e.g., improvements to neutrino-electron scattering
  - Some, those involving nuclear response, need some serious consideration and new methods
- I can assure you of one thing, however.

Have I done my job here?



- I've made the point that precision neutrino measurements are necessary to learn what we want to know from oscillations
- There are several places where calculations or better estimations of effects of radiative corrections are important for this program
  - Some are probably "easy" with standard methods, e.g., improvements to neutrino-electron scattering
  - Some, those involving nuclear response, need some serious consideration and new methods
- I can assure you of one thing, however. Your solution to this problem will be highly cited!