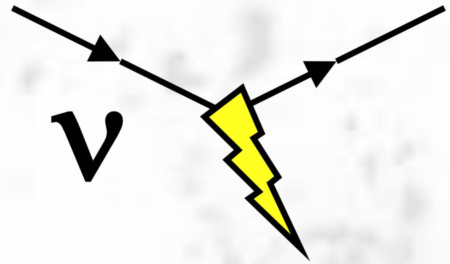
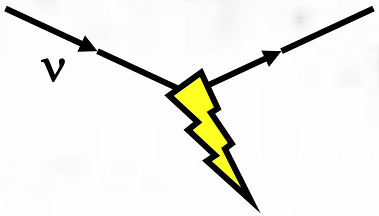
Predicting GeV Electron Neutrino Interactions from Muon Neutrino Interactions



Kevin McFarland
University of Rochester

INT-18-02a

28 June 2018

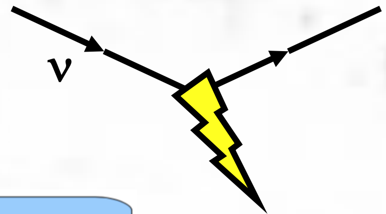


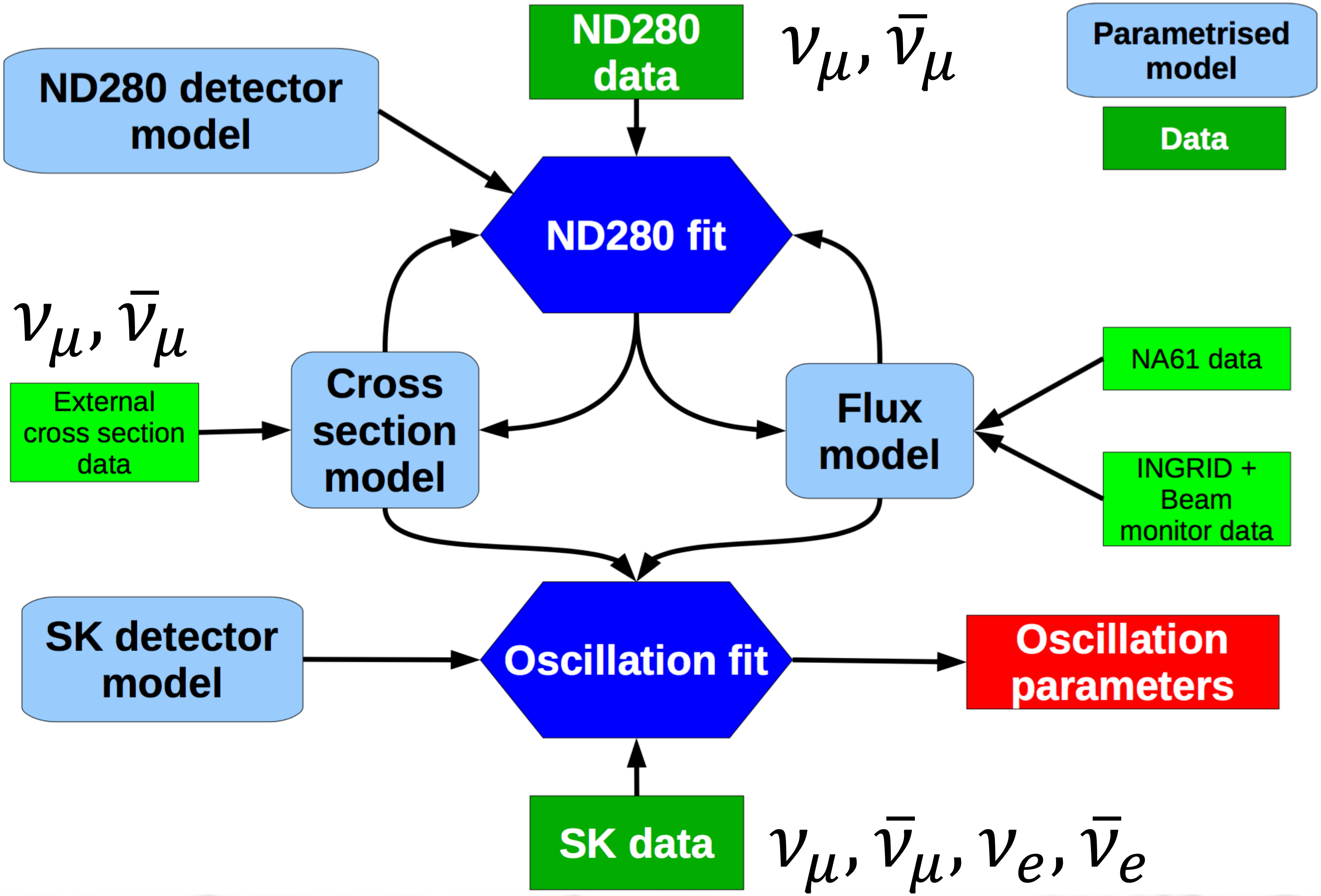
Outline

1. Why are Electron and Muon Neutrino Interactions Different?
2. Effects in CC Elastic on Nucleons
3. Nuclear Effects
4. Effects of Radiative Corrections
5. Will Data Rescue Us?

Spoiler: We must work harder.

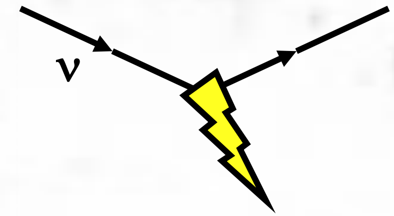
Example: T2K Analysis & flavor





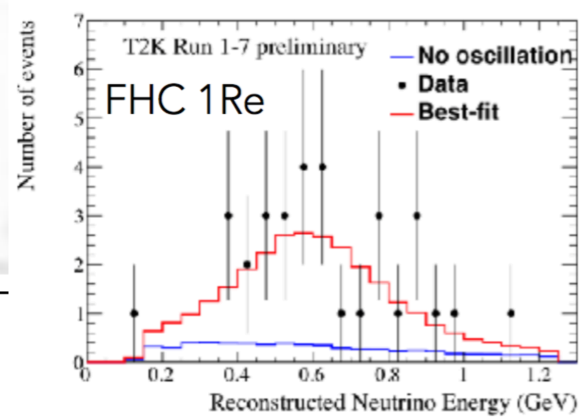
Graphic by Mark Scott

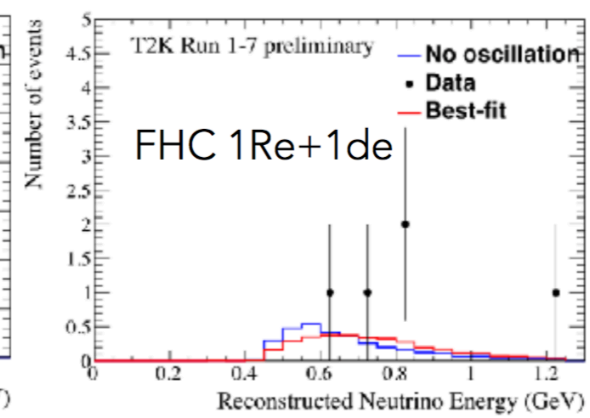
When is precision critical?

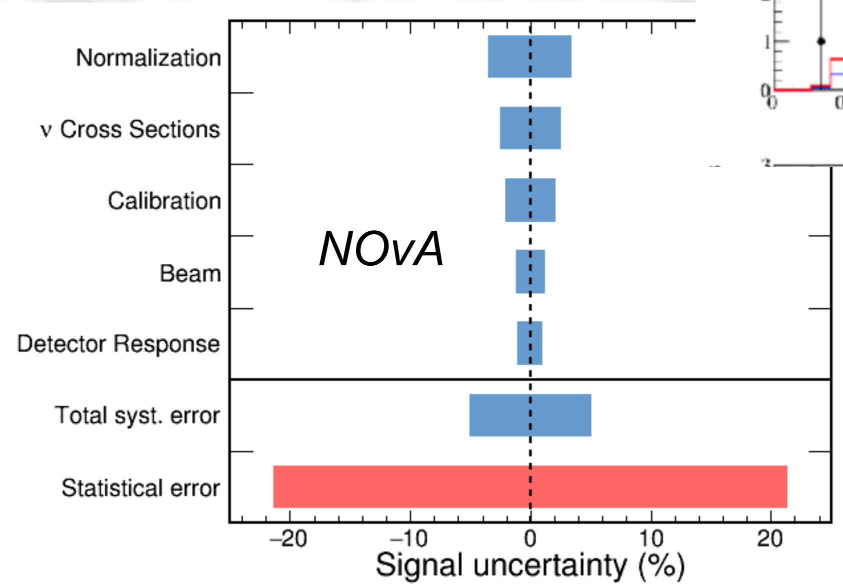


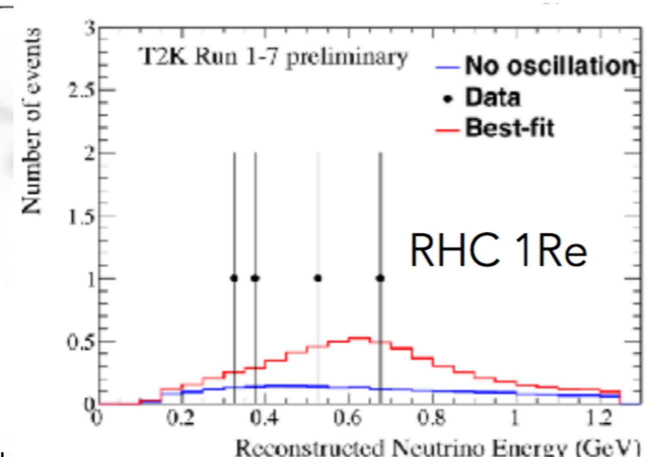
- Luckily,
  not in today's published results.
  'Cause statistics.

T2K Statistics, Summer 2016	FHC (Neutrino)	RHC (Anti-nu)
1Re & 1Re+1de	37	4





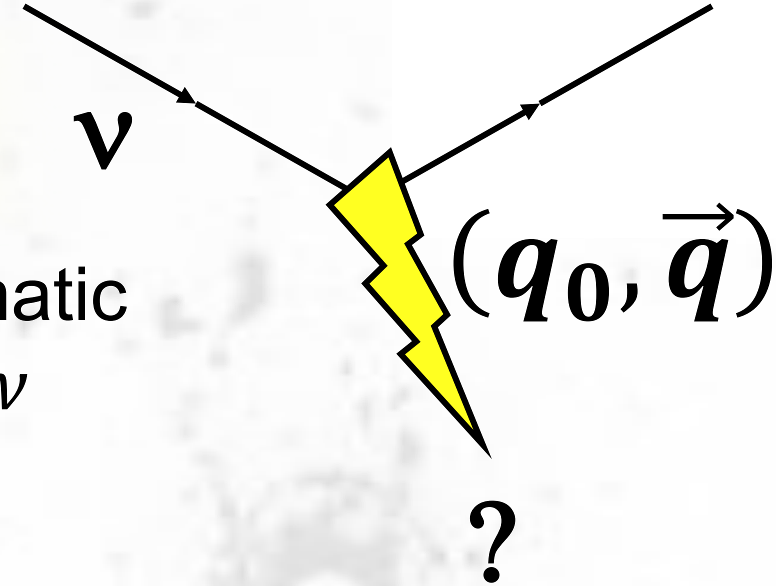


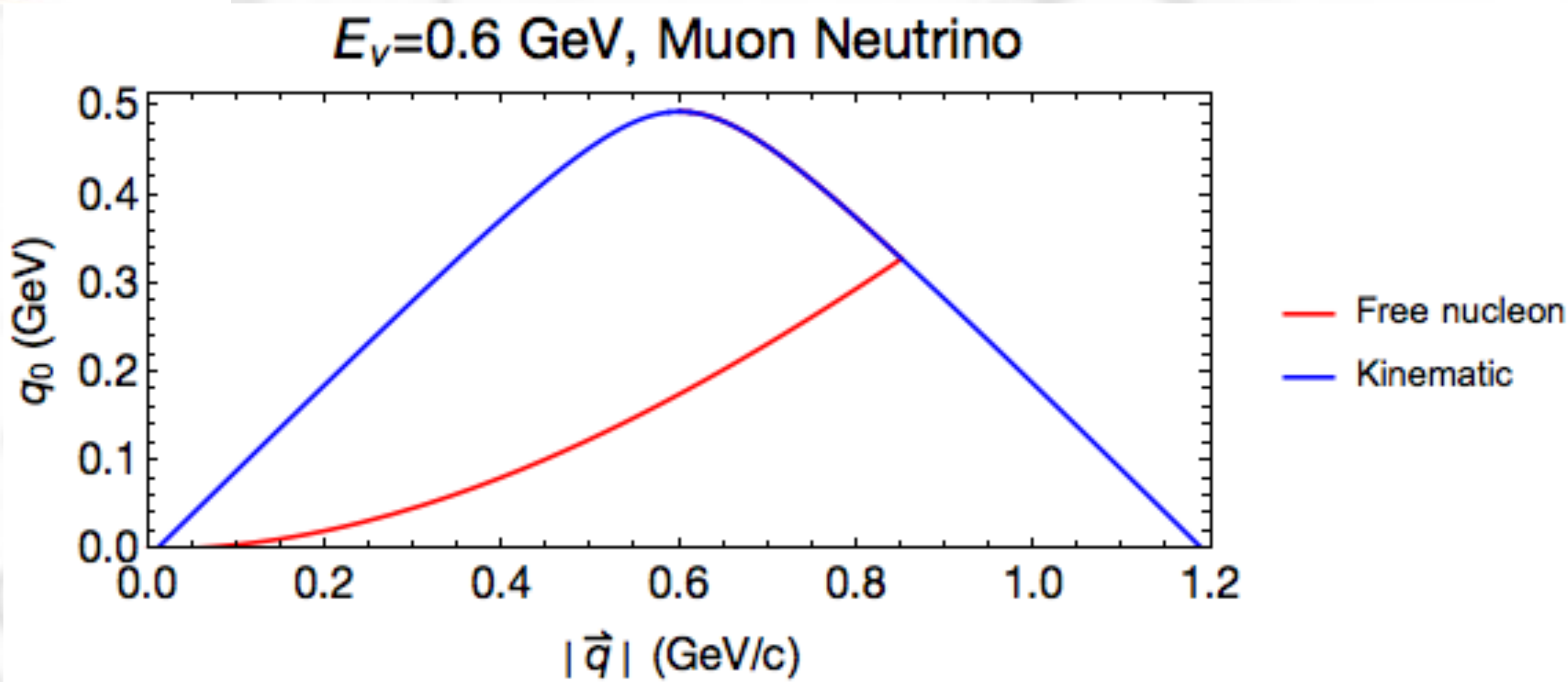


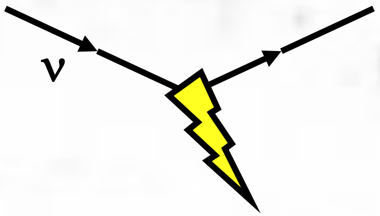
Flavor, Phase Space and Helicity

Flavor Matters

- Consider kinematic boundaries for ν scattering

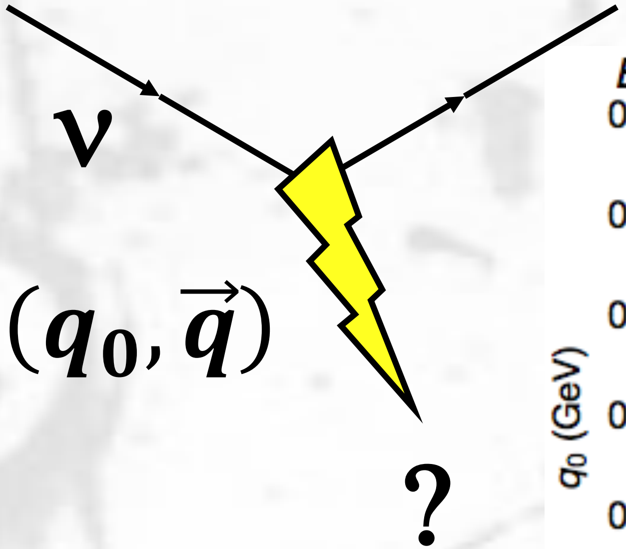


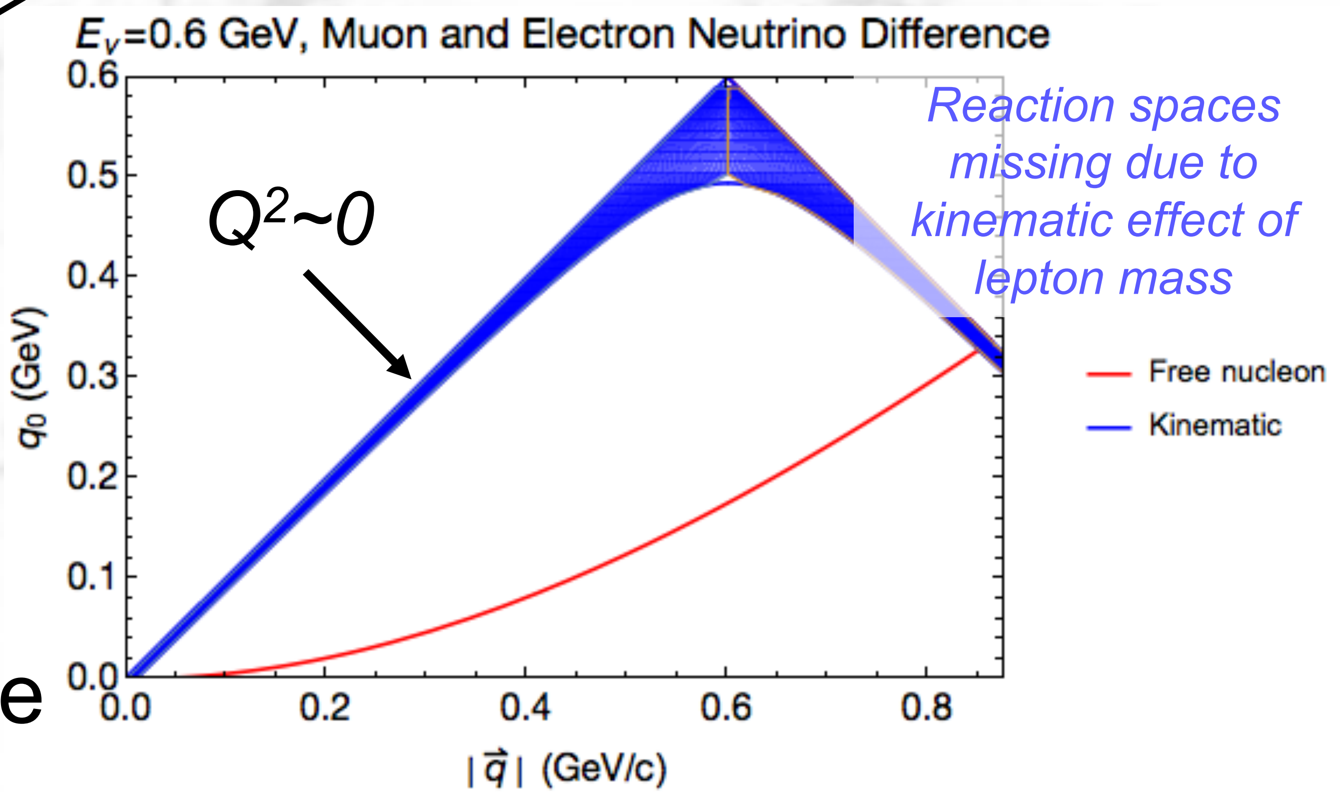




Flavor Matters (cont'd)

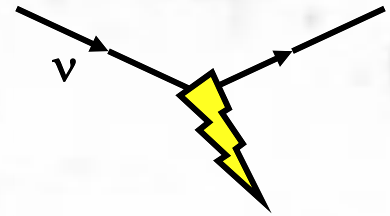
- In CC scattering, mass of lepton affects available energy and momentum transfer





- Must model missing phase space

Flavor Matters (cont'd)



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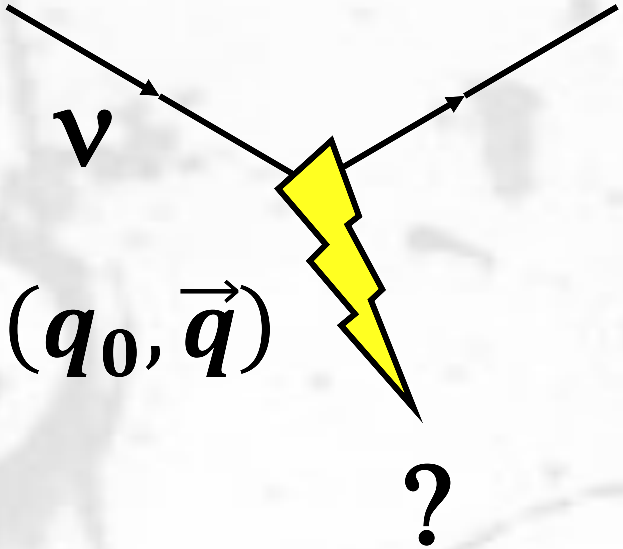
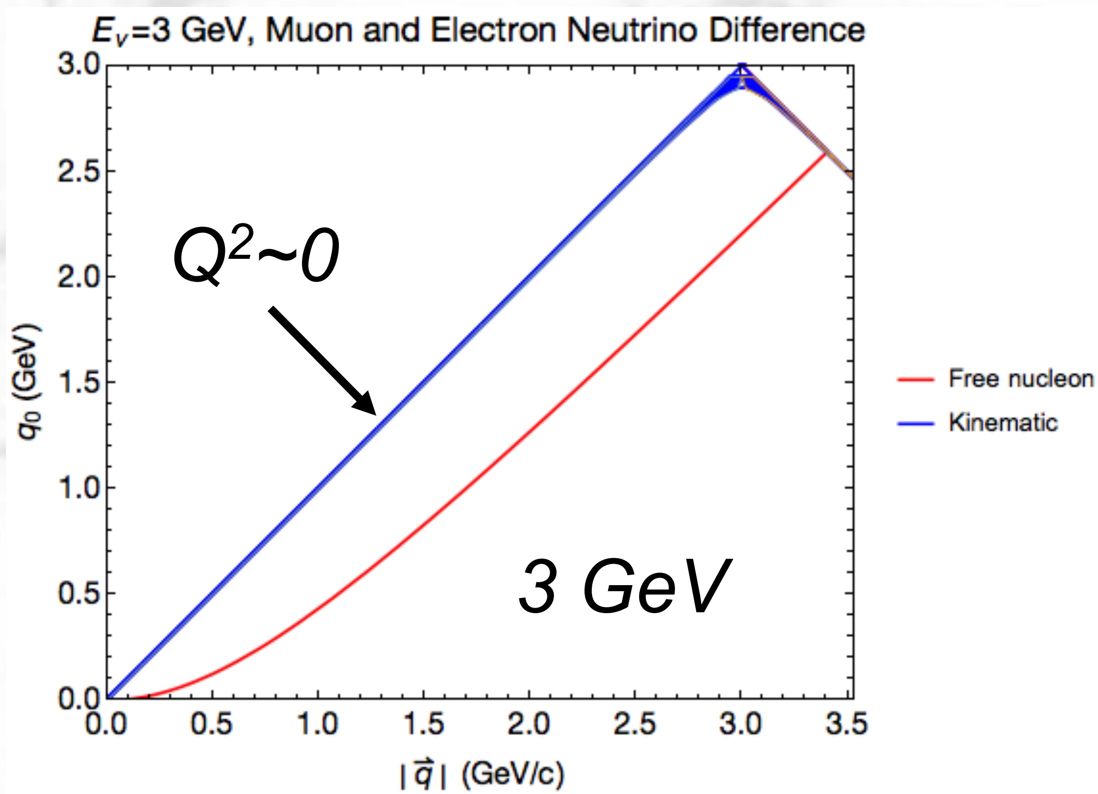
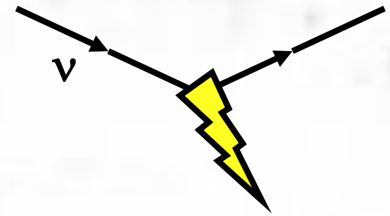


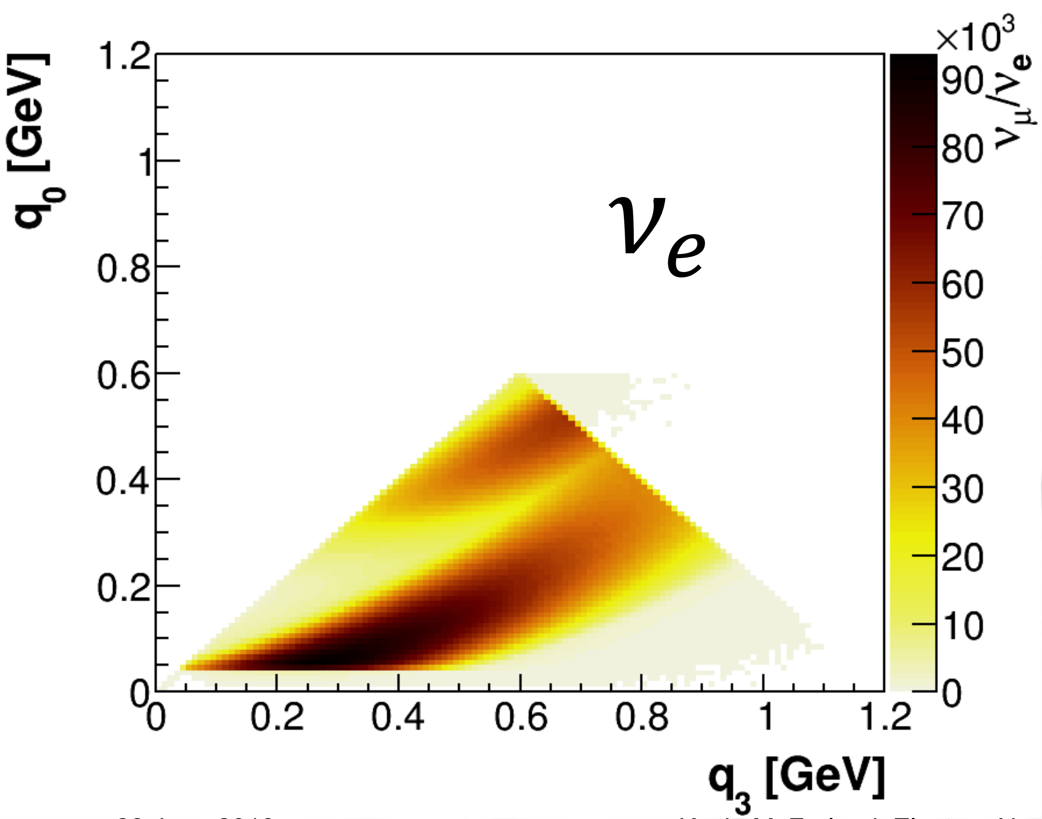


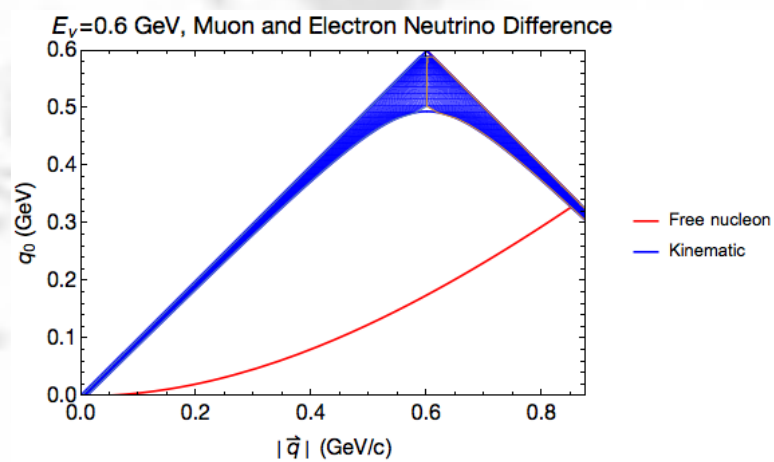
- Must model missing phase space

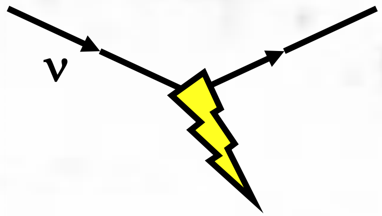


What does GENIE say?

- Nuclear effects smear out the "free nucleon" line, as expected.
- Can see the kinematic boundary. Uh… mostly… ??

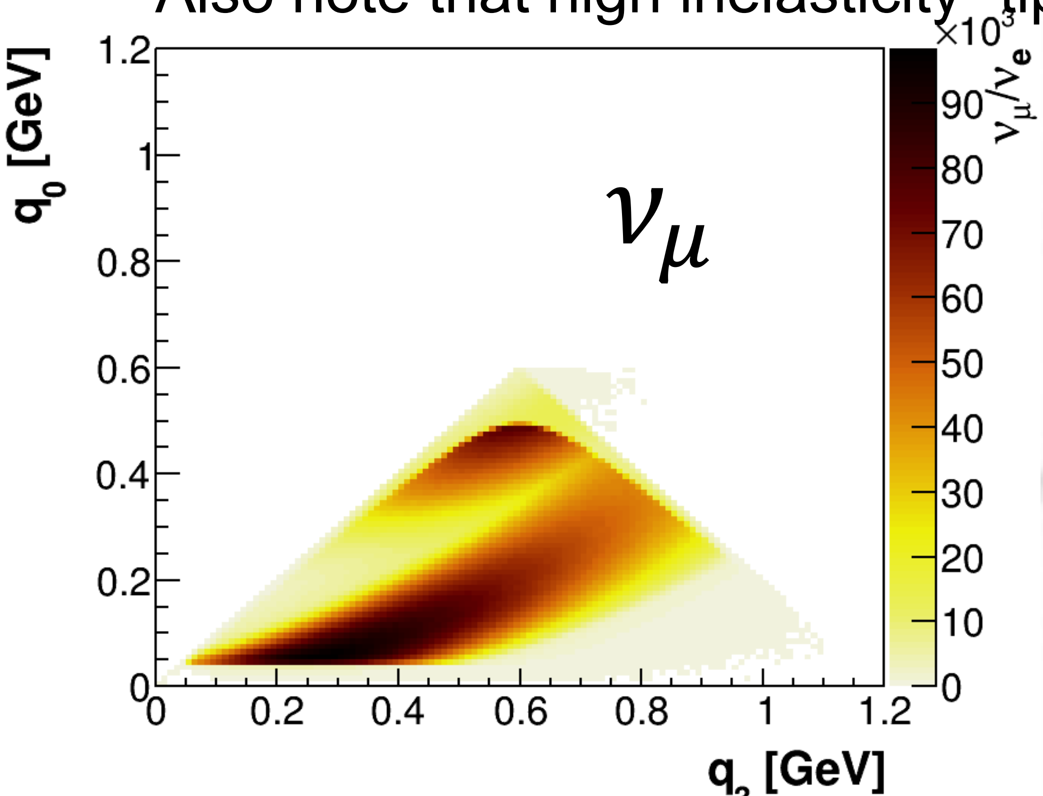


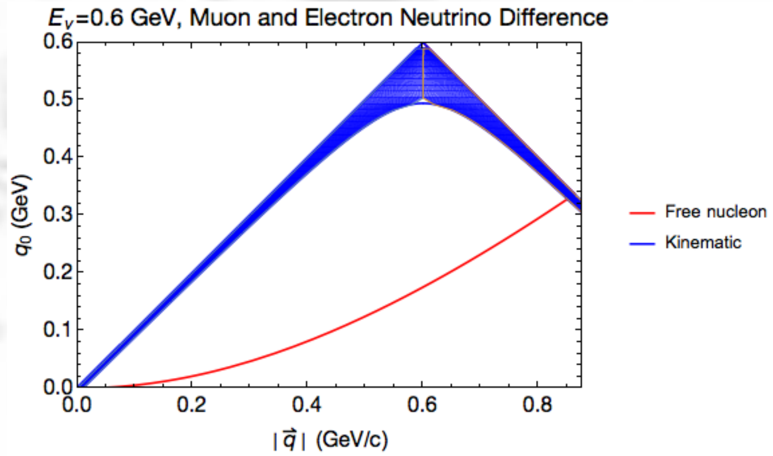




What does GENIE say?

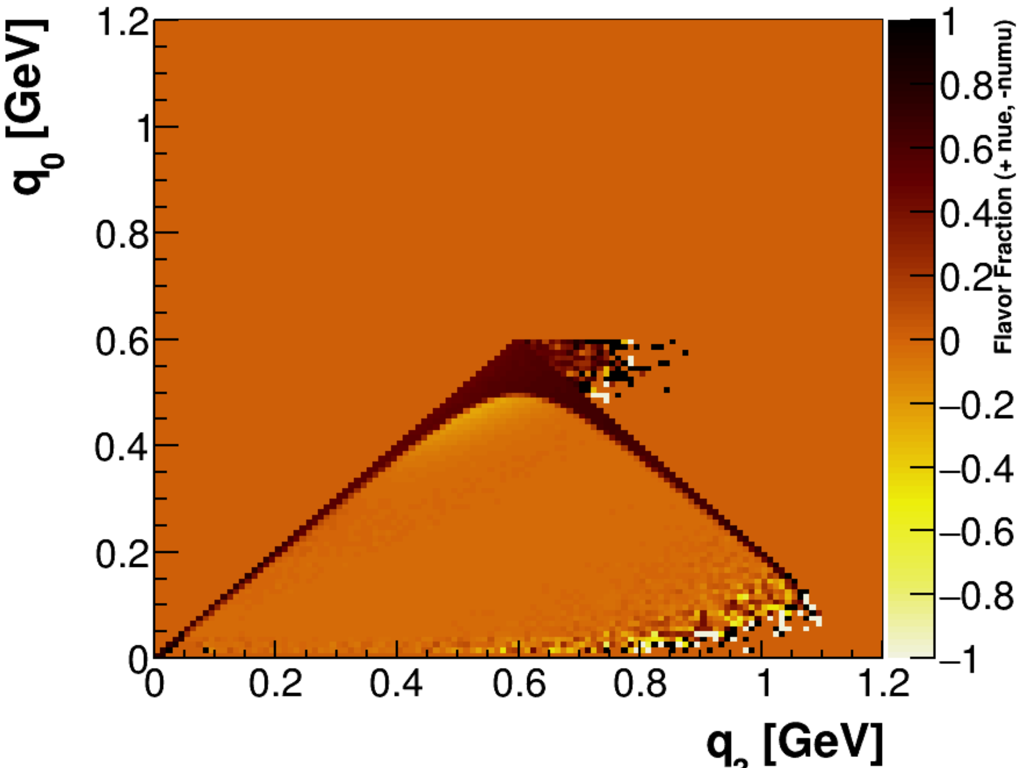
- The flavor dependence for the leading parts of the cross-section is clear.
- But not for all parts of the cross-section interestingly…
- Also note that high inelasticity "tip" increases for muons!

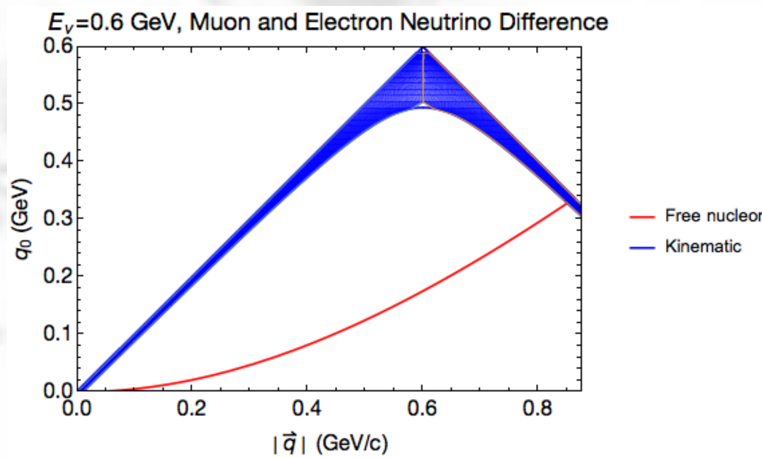




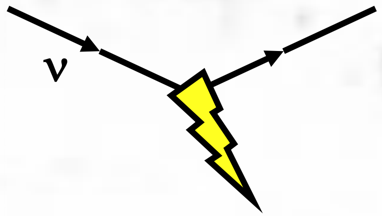
What does GENIE say?

- Flavor difference shows the expected features
  - Interpret lower right as stochastic variation of cross-section tail
  - Low Q^2 high q_0 enhancements for muons is interesting





Mass Terms in Lepton Current



- The lepton current itself also has lepton mass terms in it…

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{d|q^2|d\nu} = \frac{G^2}{32\pi M E^2}\,\overline{\sum}\sum m_{\mu\nu}\,\overline{\sum}\sum W^{\mu\nu}$$

$$= \frac{G^2}{8M^2\pi E^2}\left[2(m^2-q^2)W_1^{\nu,\bar{\nu}} + (4EE'+q^2-m^2)W_2^{\nu,\bar{\nu}} - \frac{m^2(q^2-m^2)}{M^2}W_4^{\nu,\bar{\nu}} - \frac{2Em^2}{M^2}W_5^{\nu,\bar{\nu}} \pm \frac{W_3^{\nu,\bar{\nu}}}{M^2}\left(E(q^2+m^2)+E'(q^2-m^2)\right)\right]$$

Ch. Llewellyn-Smith, Phys Rept. 3C, 261–379 (1972).

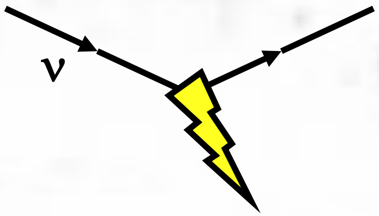
… so this will similarly result in a difference

- Often difficult to probe these directly
  - Most straightforward would be comparison of polarized and unpolarized scattering or ν_μ, ν_e cross-sections. Oops.

Form Factors and Charged Current Elastic Scattering on Nucleons

M. Day and KSM,
Phys.Rev. D86 (2012) 053003

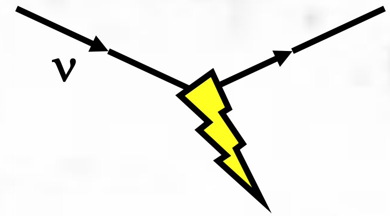
CC Elastic Scattering



Ch. Llewellyn-Smith, Phys Rept. 3C, 261–379 (1972).

- Straightforward to write framework for quasi-elastic scattering on nucleon
- Uncertainties in form factors of nucleon lead to uncertainties in the differences of muon and electron neutrino reaction rates.
- Six allowed form factors of the nucleon that enter:
  - Two "ordinary" vector and one axial form factor
    - Vector form factors measured in electron scattering. Axial form factor from pion leptoproduction, neutrino CCQE on D_2.
  - One pseudoscalar form factor
    - Predicted by PCAC and Goldberger-Treiman to be small.
  - One vector and one axial "second class" current
    - Usually assumed zero because they violate charge symmetry (not a perfect symmetry, e.g., $m_n \neq m_p$) in nucleon system.

CC Elastic Scattering (cont'd)



- Sqeamish?
  Then avert your gaze…

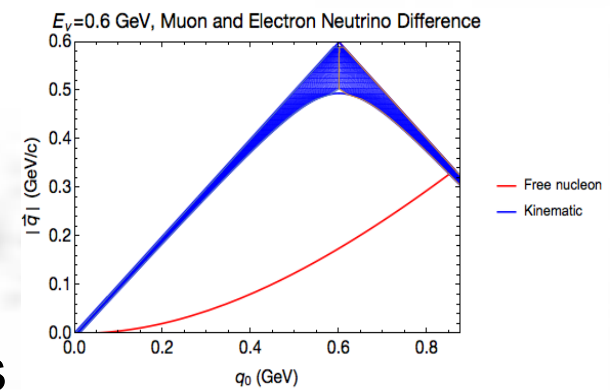
$$\frac{d\sigma}{dQ^2}\left({}^{\nu n\to l^- p}_{\overline{\nu} p\to l^+ n}\right) = \left[A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right] \times \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}$$

Ch. Llewellyn-Smith, Phys Rept. 3C, 261–379 (1972).

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

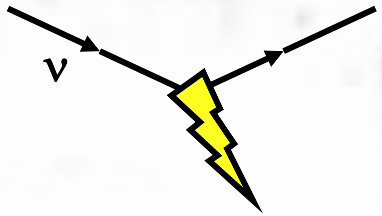
$$B(Q^2) = \frac{Q^2}{M^2} Re F_A^*\left(F_V^1+\xi F_V^2\right) - \frac{m^2}{M^2} Re\left[\left(F_V^1 - \frac{Q^2}{4M^2}\xi F_V^2\right)^* F_V^3 - \left(F_A - \frac{Q^2 F_P}{2M^2}\right)^* F_A^3\right] \text{ and}$$

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



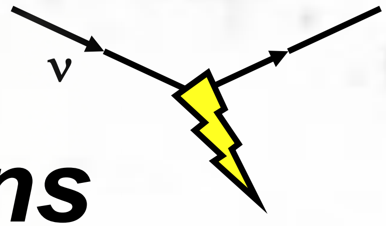
  - Phase space
  - Two terms, including those with F_P, and F^3_V, enter with a factor of m^2/M^2. These are relevant for muon neutrinos at low energies but not for electron neutrinos.

Know Nothing Approach

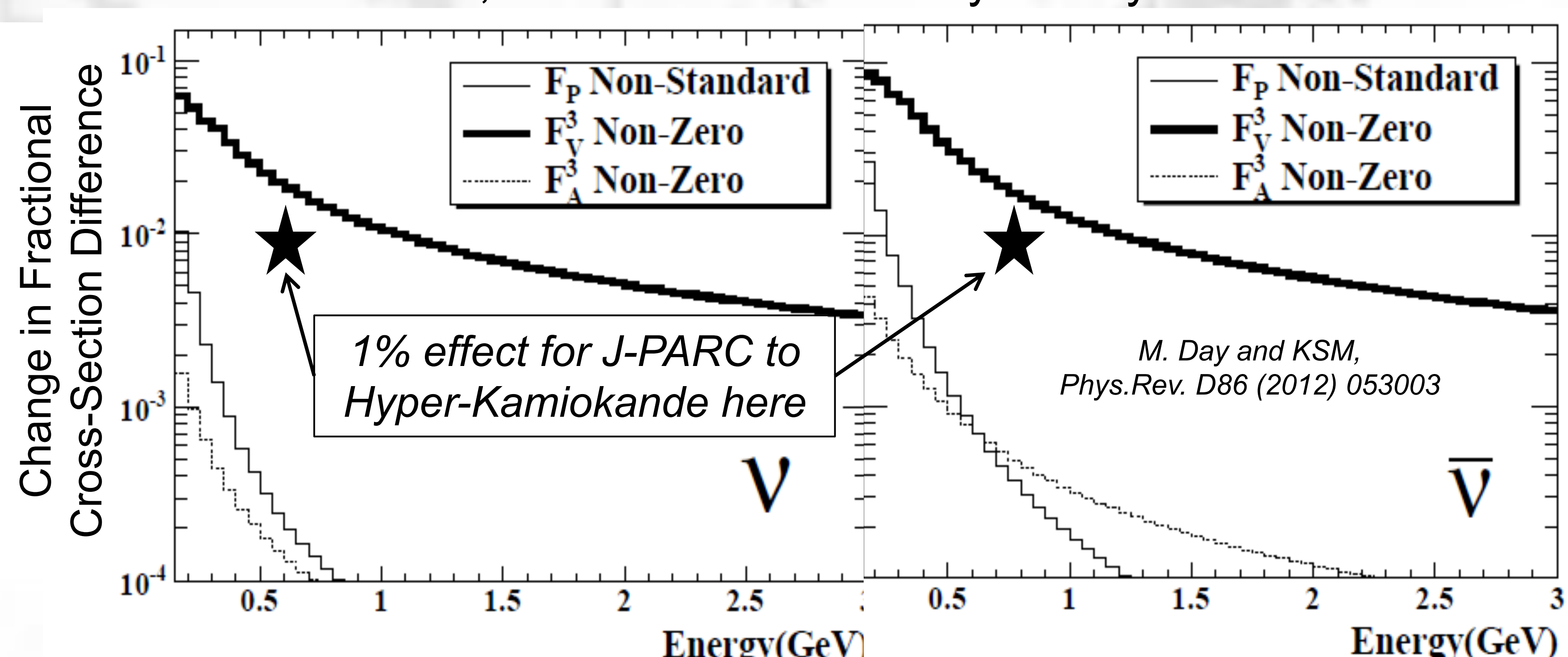


- Look at how large the possible effects of non-standard or unconstrained form factors could be, independent of theoretical prejudice.
  - Constraints on second class currents primarily from beta decay and muon capture on nuclei.
  - Pseudoscalar form factors and axial form factor measured in pion electroproduction.
  - Vector form factors from electron-nucleon elastic scattering.

Results for Neutrino Cross-Section Differences on Nucleons



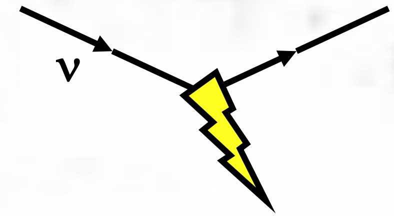
- We concluded most form factor uncertainties are small
- Possible effect from F^3_V of few % at J-PARC to T2K/HK
  - Neutrino and anti-neutrino effects are opposite in sign for second class currents, so could fake a CP asymmetry.



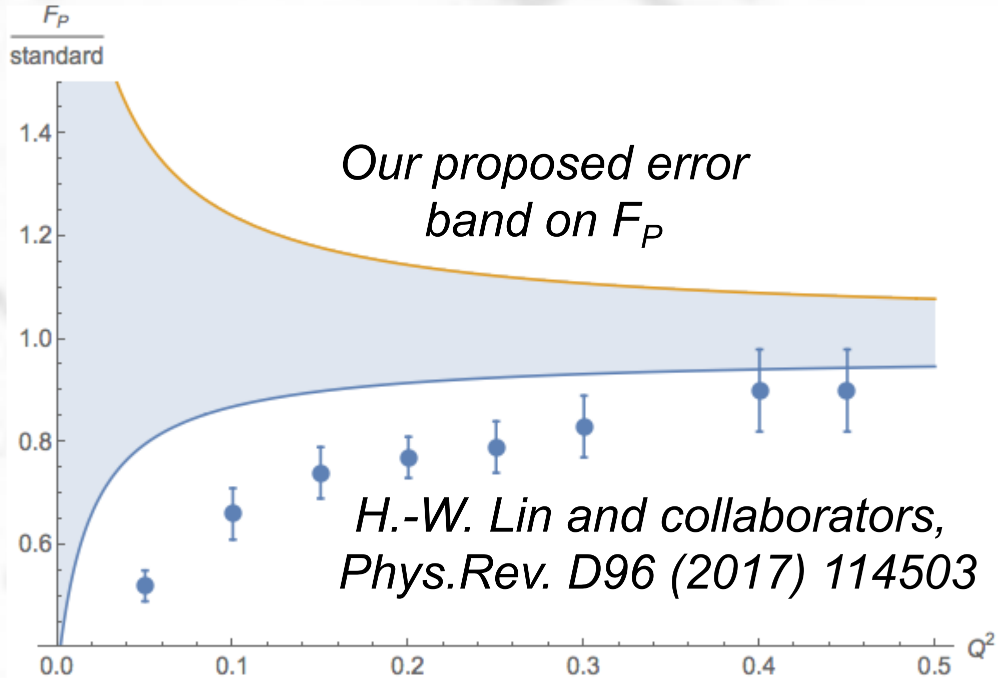
How to reduce second class current uncertainty?

- High statistics neutrino and anti-neutrino muon neutrino CCQE on nuclei has potential to constrain second-class currents
  - Effect is distinctive in Q^2 and energy.
  - Only seen in muon neutrinos.
  - MINERvA, T2K, NOvA should have useful data.
  - But nuclear uncertainties complicate this ☹
- Could study muon and electron neutrinos together and compare cross sections.
- Can it be shown not to be large on the lattice? Nucleon level probably. Nuclei?

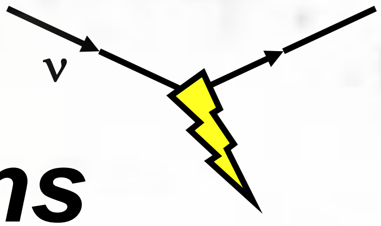
This week's update: Revisiting F_P



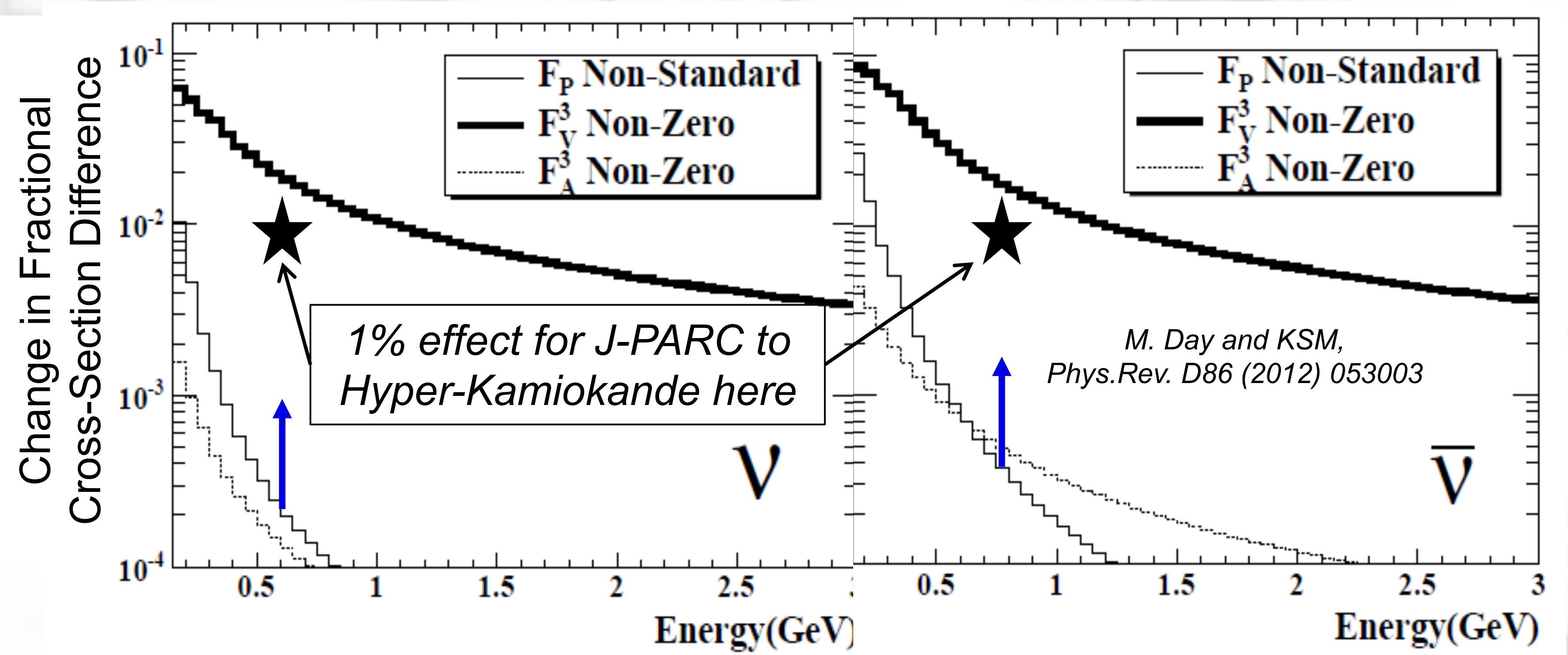
- I learned at this meeting that there were recent, reliable lattice calculations of F_P!
- It turns out that these don't agree with our conclusions from the 2012 analysis.



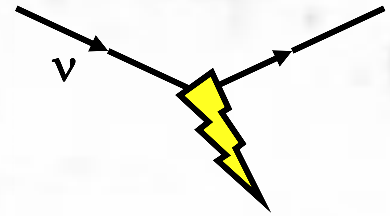
Revisiting Neutrino Cross-Section Differences on Nucleons



- Lattice result suggests that the F_P effect could be larger by a factor of ”several”.
- Still probably not a leading concern.



Speaking of working harder…



- I went through one example of nucleon level uncertainties for charged current elastic process.
- To briefly summarize, the physics in generators should (mostly) leave small uncertainties for cross section differences.
  - With work to be done to experimentally or theoretically constrain second class currents.
- But there are other processes to consider with different form factor uncertainties
  - Someone should analyze these! Especially for NOvA, DUNE…

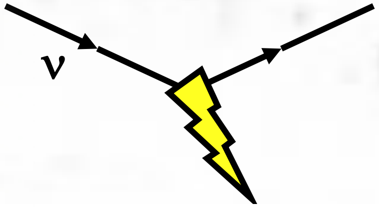
Some work on this alredy!
Paschos, E.A. et al. arXiv:1209.4219;
Rafi Alam, M. et al. Phys.Rev. D88 (2013) 077301

- And then there is the effect of the nucleus…

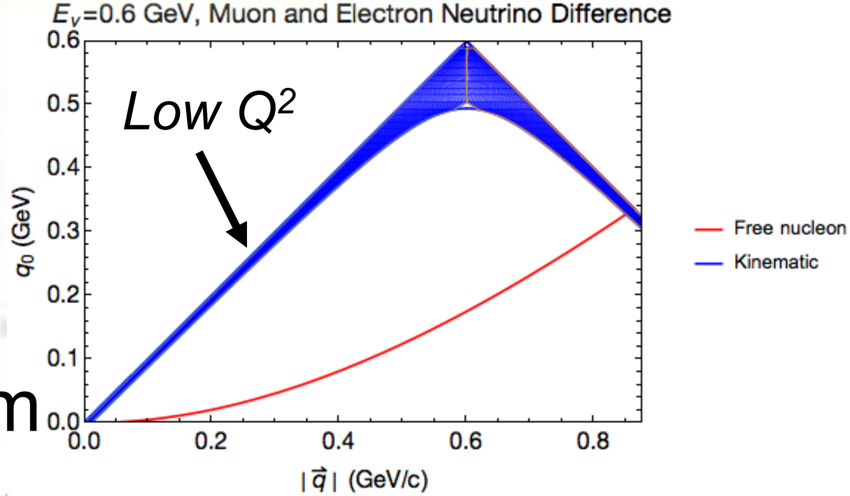
Nuclear Effects and Neutrino Flavor Differences

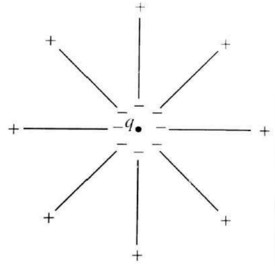
Work in progress from DUNE interaction “reweight” group:
Kendall Mahn, Luke Pickering, Dan Ruterbories, KSM,
Clarence Wret, Kirk Bays, Dan Cherdack
Michigan State, Rochester, CalTech, Houston

What will change in the nucleus?



- Nuclear response changes the scattering in missing phase space
- E.g., nuclear screening from W+ by nuclear polarization (RPA)
  - EM analogy in atoms



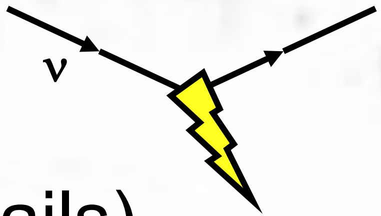


G. D. Megias, J. E. Amaro , M. B. Barbaro, J. A. Caballero T. W. Donnelly, I. Ruiz Simo, Phys.Rev. D94 (2016) no.9, 093004

M. Ericson, M.V. Garzelli, C. Giunti, M. Martini, Phys.Rev. D93 (2016) no.7, 073008

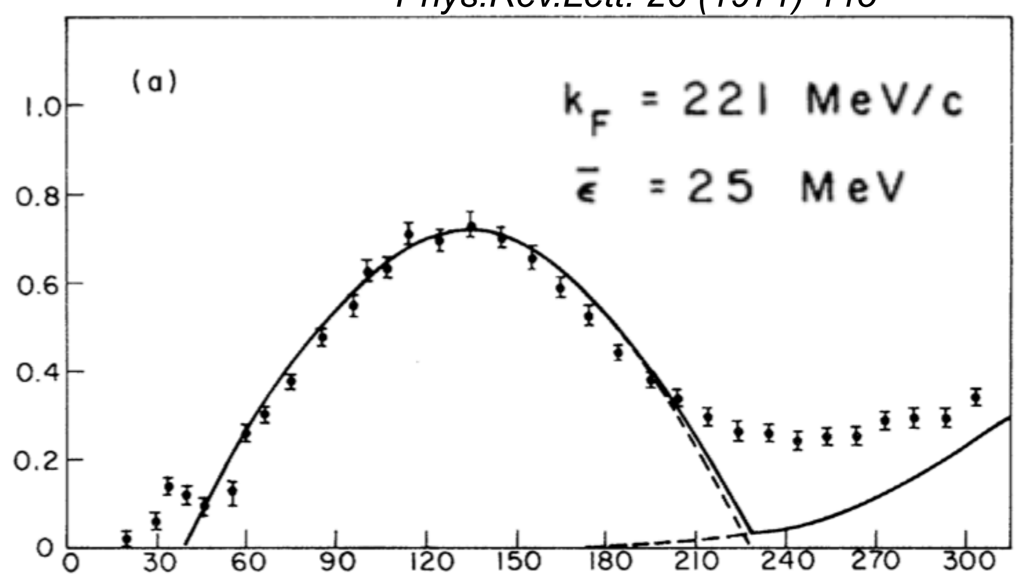
- Kinematic boundaries will shift due to nuclear effects (binding, Fermi motion)
  - To get this right, must treat these effects carefully
  - Probably insufficiently careful in generators today.

Binding and Fermi Motion

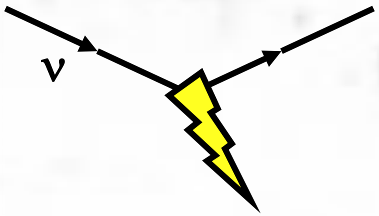


- There are uncertainties in Fermi motion (tails) and removal energy (see e.g., A. Bodek arXiv:1801.079)
- These effects shift population near flavor dependent kinematic boundaries.
- An overly short summary of uncertainties for neutrinos:
  - We use electron data to infer binding and Fermi Motion.
  - It pays to be careful.
  - Otherwise, might as well use R. Perry *et al* data

E.J. Moniz, I. Sick, R.R. Whitney , J.R. Ficenec, Robert D. Kephart, W.P. Trower. Phys.Rev.Lett. 26 (1971) 445

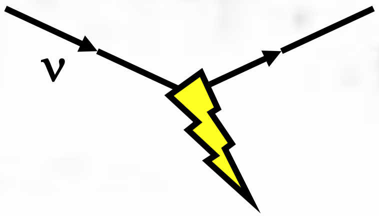


A Brief Summary of arXiv:1801.079

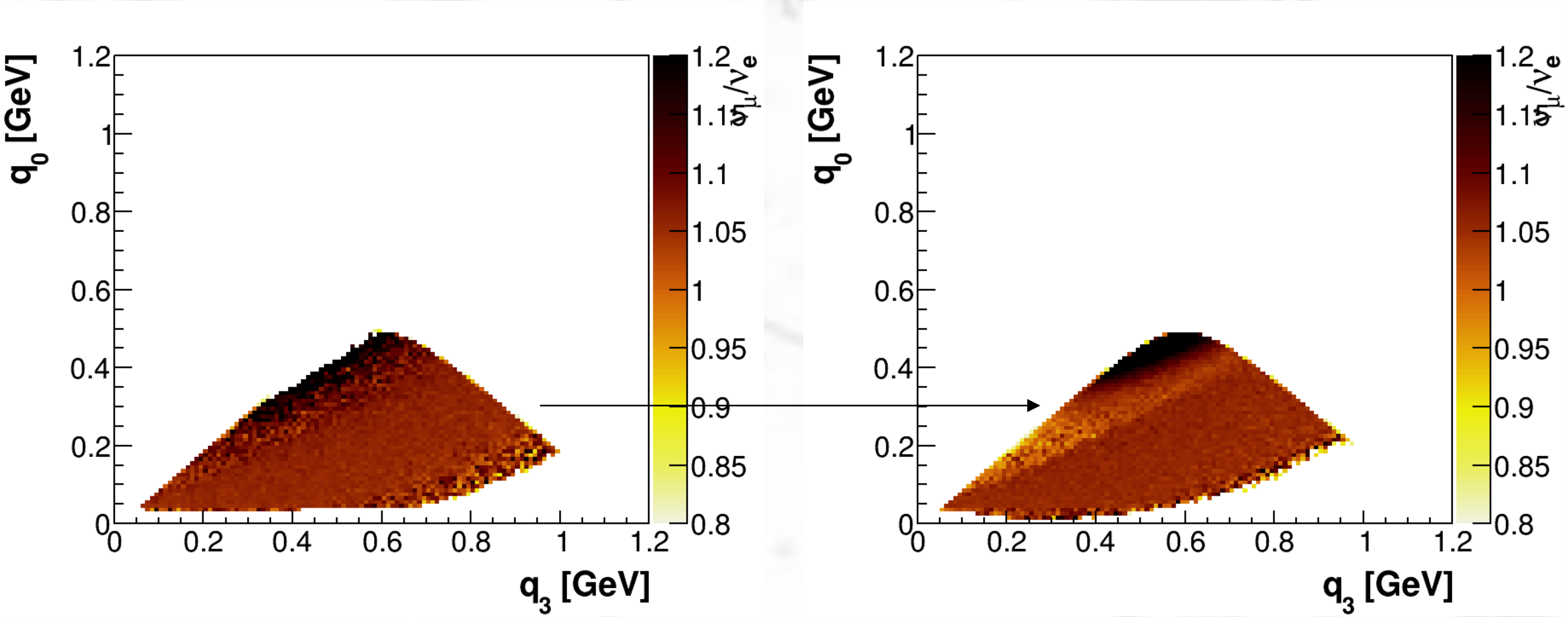


- The original analysis and many subsequent analyses of the Moniz data need corrections
  - Coulomb effects & Relativistic kinematics (averaged)
- If analyzed carefully, find consistency between shell model, (e,e'p) data, and Moniz data. Where all datasets exist, consistent w/in a few MeV
- Implementation in generators have to be careful of double counting effects like final state mass
  - GENIE has an $\mathcal{O}(10)$ MeV mistake due to a double counting of nuclear masses.
- Matters for ν_μ/ν_e. "This is a talk about ν_μ/ν_e." – Arlo Guthrie

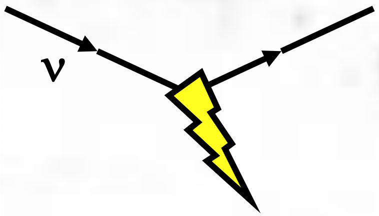
High Fermi momentum tail
(Bodek-Ritchie model in GENIE)



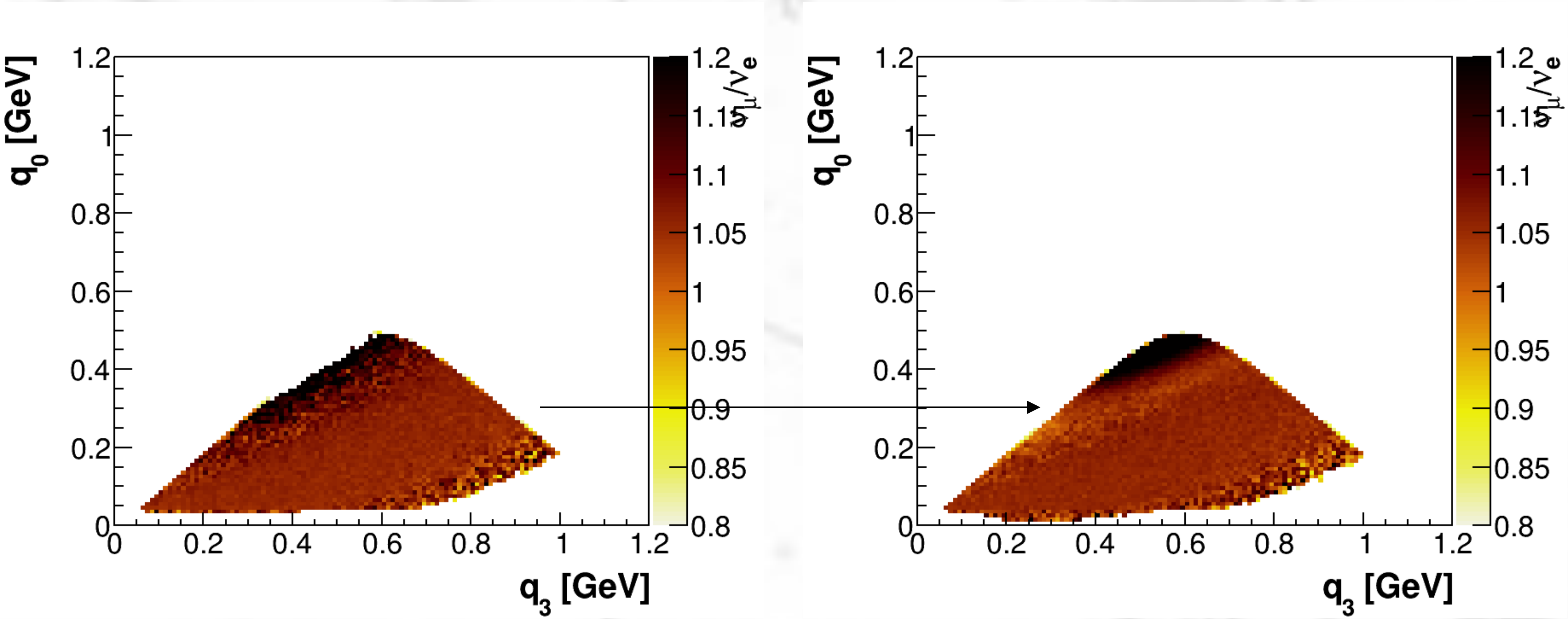
- The effect of a (maybe unrealistic) truncation in the Bodek-Ritchie tail on ν_μ/ν_e.

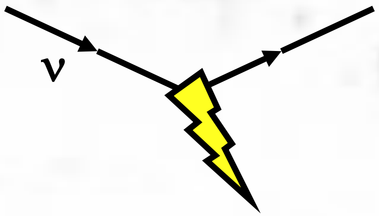


Order ~10 MeV shift in removal energy



- The effect of a (maybe unrealistic) shift in removal energy on ν_μ/ν_e.

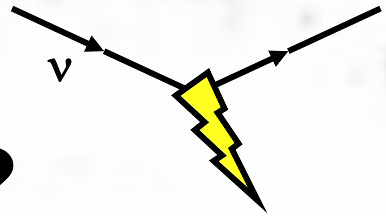




Radiative Corrections in Neutrino Scattering

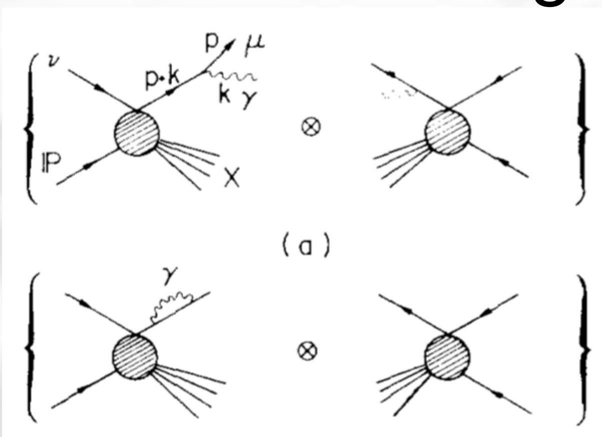
A story in which we find we have the tools...
but not the willpower (yet!) to get results.
Encourage your theory friends to help us!

Informed by work by R. Hill, KSM,
manuscript still in preparation



Why might radiative corrections depend on flavor?

- Consider the leading logs from the lepton leg in neutrino charged current scattering



deRújula, Petronzio, Savoy-Navarro, Nucl. Phys. B154 394 (1979)

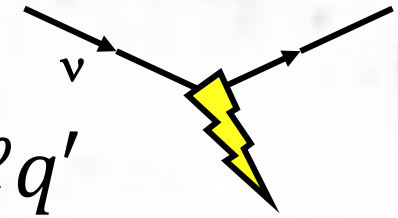
$$\frac{d\sigma_{\mathrm{obs}}}{dE_\mu\, d\Omega} = \frac{d\sigma_{\mathrm{B}}}{dE_\mu\, d\Omega} + \frac{\alpha}{2\pi}\ln\frac{4E_\mu^{*2}}{\mu^2}\int_0^1 dz\, \frac{1+z^2}{1-z} \times \left\{\frac{1}{z}\frac{d\sigma_{\mathrm{B}}}{d\tilde{E}_\mu\, d\Omega}\bigg|_{\tilde{E}_\mu = E_\mu/z} \theta(z - z_{\mathrm{min}}) - \frac{d\sigma_{\mathrm{B}}}{dE_\mu\, d\Omega}\right\} + \mathrm{O}\left(\frac{\alpha}{2\pi}\right),$$

$$4E_\mu^{*2} = 2m_{\mathrm{p}}E_\nu(1 - y + xy) = [Q^2 + 2m_{\mathrm{p}}E_\mu]^2/2m_{\mathrm{p}}E_\nu\,,$$

$$z_{\mathrm{min}} = \frac{E_\mu}{E_\nu}\left(1 + \frac{E_\nu}{m_{\mathrm{p}}}(1 - \cos\theta_{\mathrm{lab}})\right),$$

- Lepton mass in a large log
- So the effects of radiative corrections will certainly depend on neutrino flavor

What has been done?



- Deep Inelastic Scattering, $\nu q \rightarrow \nu/\ell q'$
  - 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!

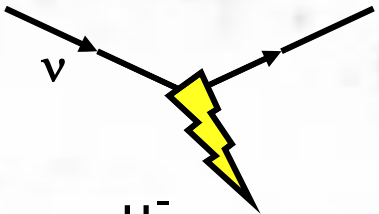
    K.-P.O. Diener , S. Dittmaier, W. Hollik, Phys.Rev. D72 (2005) 093002
- Neutrino-Electron Elastic Scattering
  - Modern calculations for observables for both accelerator and solar energies.

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

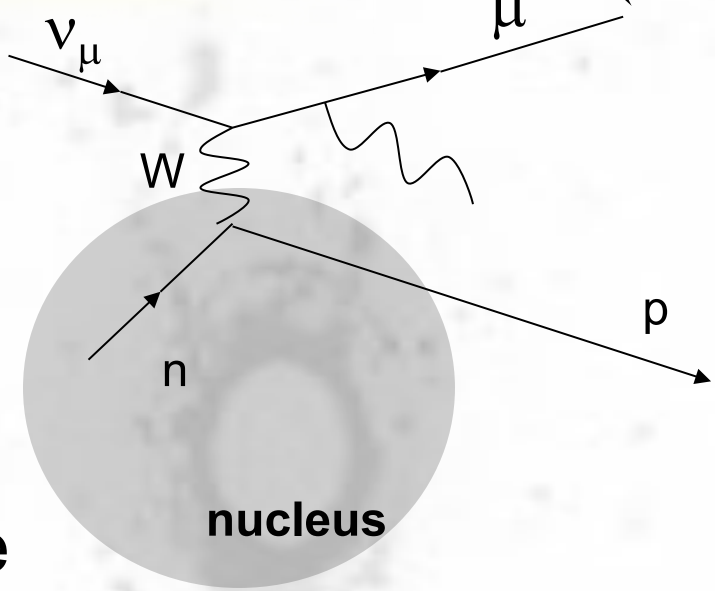
    John N. Bahcall, Marc Kamionkowski, Alberto Sirlin, Phys.Rev. D51 (1995) 6146-6158

    M. Passera, Phys.Rev. D64 (2001) 113002
- So tools exist for the calculations

What do we need to study?



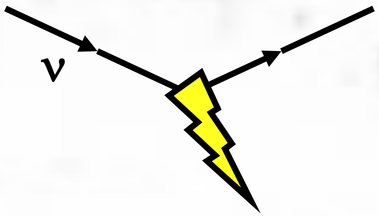
- Inclusive scattering rate?
  - KNL theorem suggests lepton mass effects from lepton leg should be small
  - Box diagrams? T2K guesses effect might be ~2%, but there is no guidance from calculation.



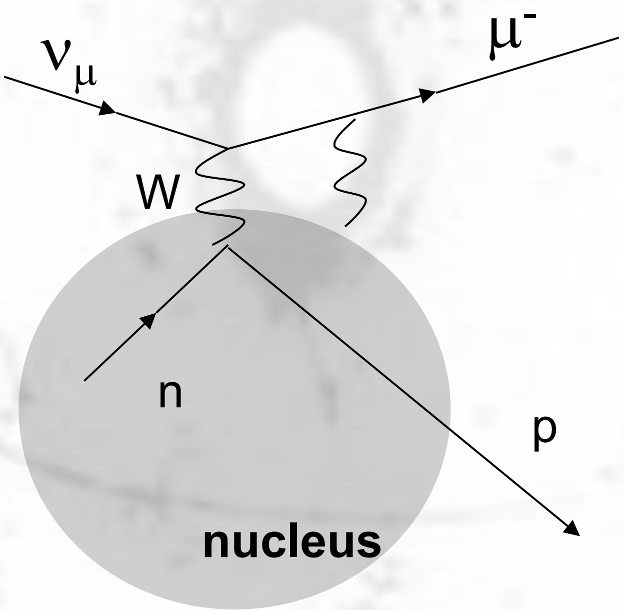
quasielastic scattering

- Radiation of real photons
  - As in the diagram above, effect will be different for muon and electron neutrinos
  - Comments follow about relevance of this process.

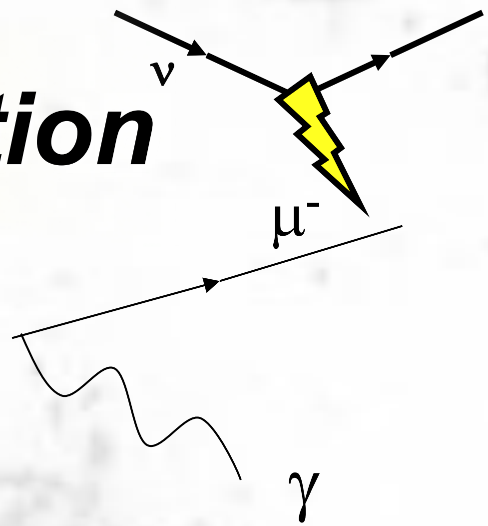
Does Lepton Mass affect an “Inclusive” Cross Section?



- By inclusive cross-sections, I mean the exclusive low energy processes that dominate at T2K, NOvA, low part of DUNE energies
- E.g., quasielastic scattering
- I recognize the horrors implicit in the “Feynman diagram” on the right
  - And pion production is only worse to contemplate.
- But if this is difference at the few % level in ν_μ and ν_e scattering, it really matters!

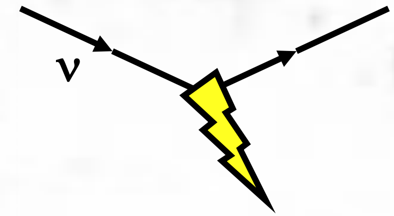


Real Photons & Reconstruction

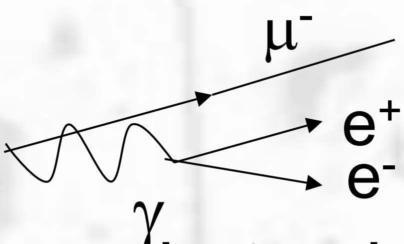


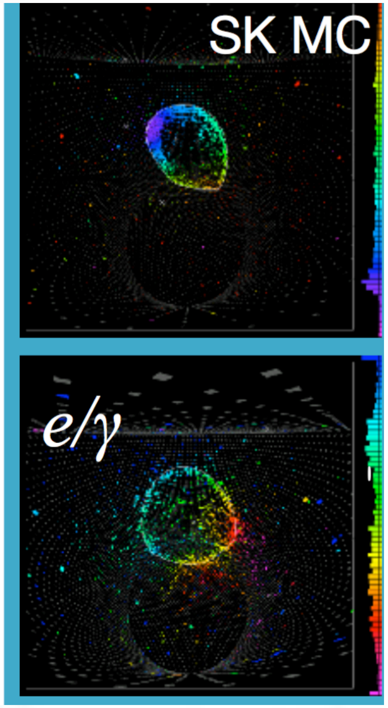
- Consider two cases
  - Collinear(ish) radiation with lepton
  - Other
- If radiation is collinear, what does it do?
  - It can disrupt lepton energy reconstruction
  - Different for electrons (adds to electron energy) and muons (reconstruction by range vs total ionization)
  - Most frighteningly, it 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?

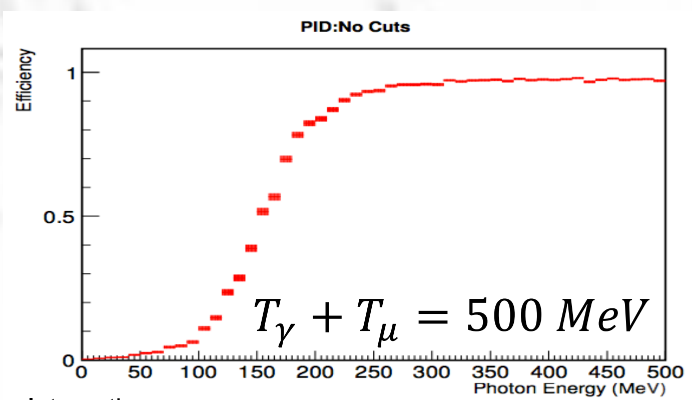


- Increased fuzziness of electron ring at bottom compared to muon at top

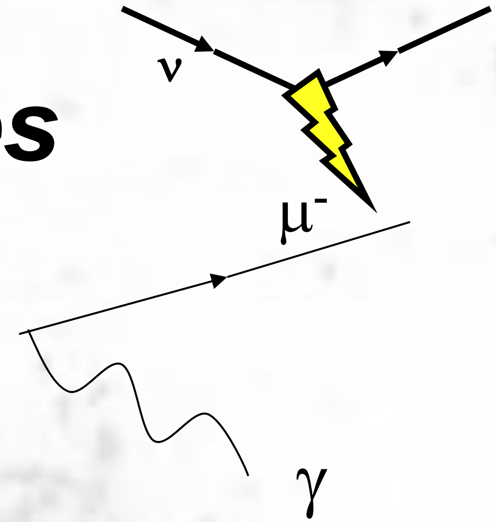




- If the collinear photon has a signficant fraction of the muon energy, it will appear as an electron
  - Roughly requires photon energy to be 40% of muon energy for a significant probability in Super-K
  - Rare, very bad, event

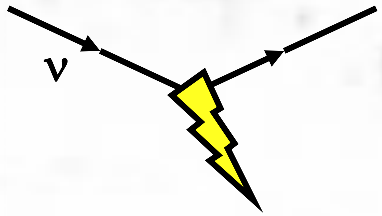


More Reconstruction Woes



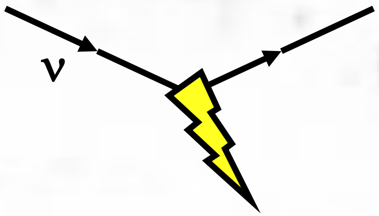
- Consider two cases
  - Collinear(ish) radiation with lepton
  - Other
- If radiation is not collinear, what does it do?
  - If detector is just summing final state energy (DUNE, NOvA) it probably of little consequence
  - But at T2K and Hyper-K, it is very bad
    - o Reconstruction will often infer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

Radiative Corrections Summary



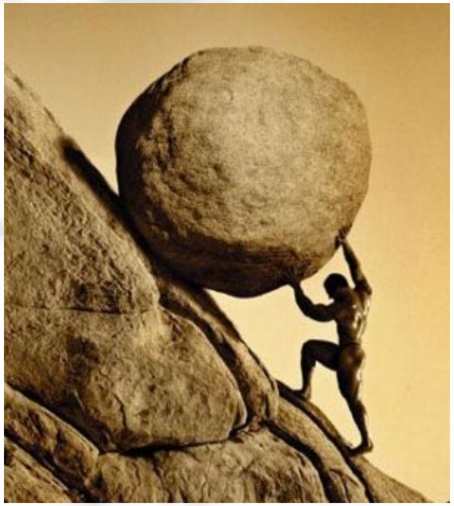
- Virtual corrections to the total cross-sections are a real concern. Not known. Guess is “small”
- We also need calculations of differential cross-sections for reactions with photons
  - In particular, total energy in energetic photons that are collinear, and energy and angles of energetic non-collinear photons
- Energetic? Collinear? Depends on detector

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

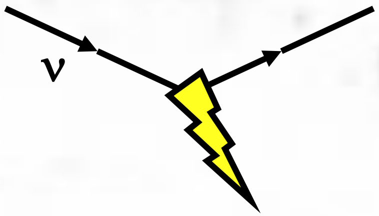


Measurements of Electron Neutrino Interactions

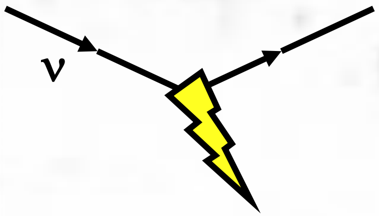
Sisyphus never had it so hard…



Another tough way to make a living…



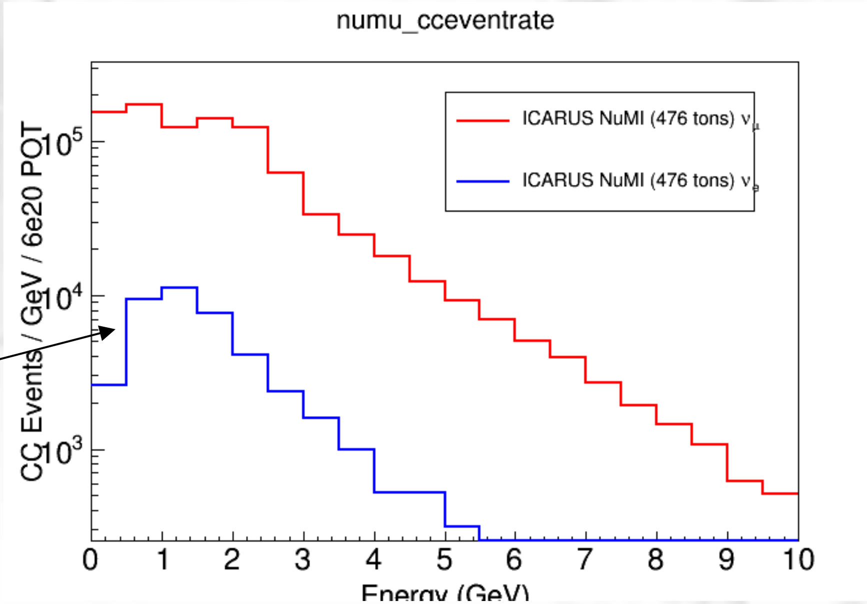
- Accelerator experiments can try to measure ν_e scattering directly
  - But large backgrounds from the factor of ~100 more ν_μ in the beam, and different electron reconstruction systematics than μ
- All the modern experiments are trying this.
- NOvA and ICARUS have combinations of statistics, detector, that *may* be most favorable.



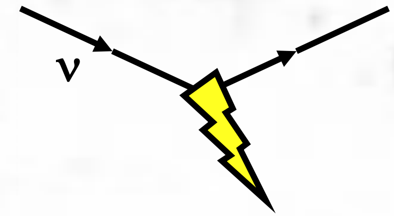
NOvA and ICARUS

- NOvA is a huge detector with a lot of statistics.
- ICARUS sits far off axis for NuMI beam, so 1% electron neutrinos becomes ~10% for ~1 GeV.
  - Many effects should be biggest at low energies.

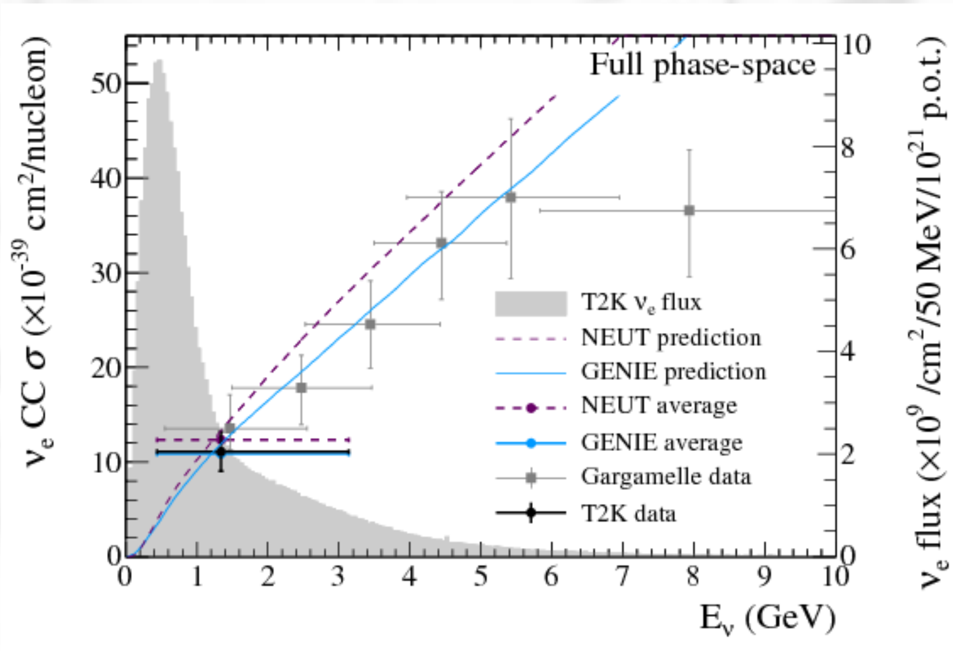
Few 10000s of events at ~1 GeV



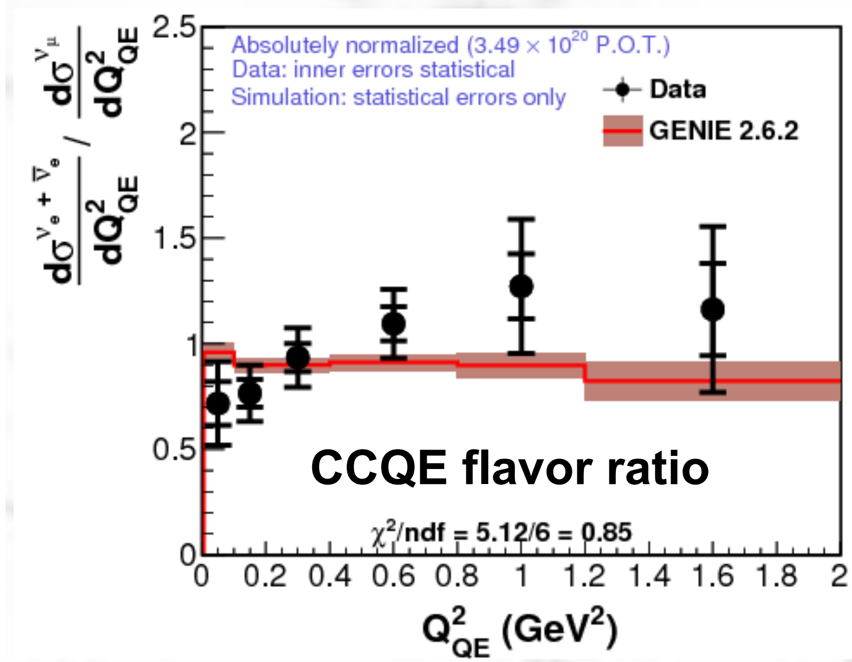
Recent Results



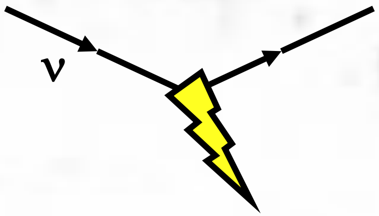
- Published measurements of inclusive ν_e scattering (T2K) and ν_e CCQE (MINERvA)
  - Data is not sensitive to smaller than ~20% differences



T2K Collaboration, Phys.Rev.Lett. 113 (2014) 241803 and Phys.Rev. D91 (2015) 112010



MINERvA Collaboration (Wolcott, J. et al.) Phys.Rev.Lett. 116 (2016), 081802



Summary and Conclusions

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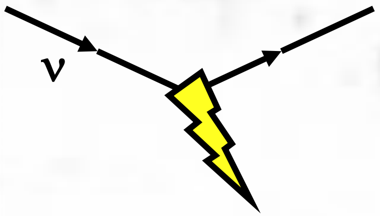
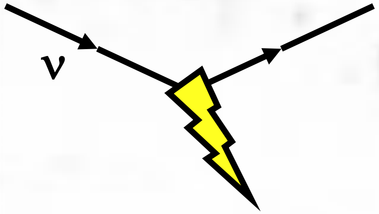


- Today, differences between ν_μ and ν_e are either controlled, or small enough that we are "safe"
- This happy accident of imprecise data will not persist forever. We hope not, anyway!
- Need work (now!) on
  inelastic processes,
  nuclear models
  and radiative corrections

Summary and Conclusions



- Today, differences between ν_μ and ν_e are either controlled, or small enough that we are "safe"
- This happy accident of imprecise data will not persist forever. We hope not, anyway!
- Need work (now!) on inelastic processes, nuclear models and radiative corrections
- *And maybe we'll just get lucky?*