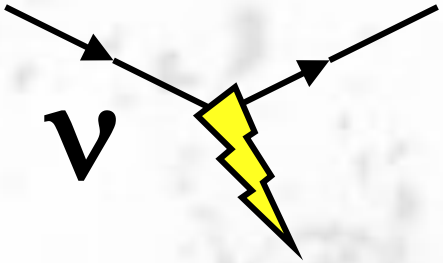
Electron Neutrino Interactions in a Muon Neutrino World



Kevin McFarland
University of Rochester

NuINT17 @ Univ. of Toronto
25 June 2017

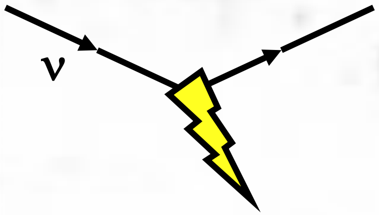
Outline

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

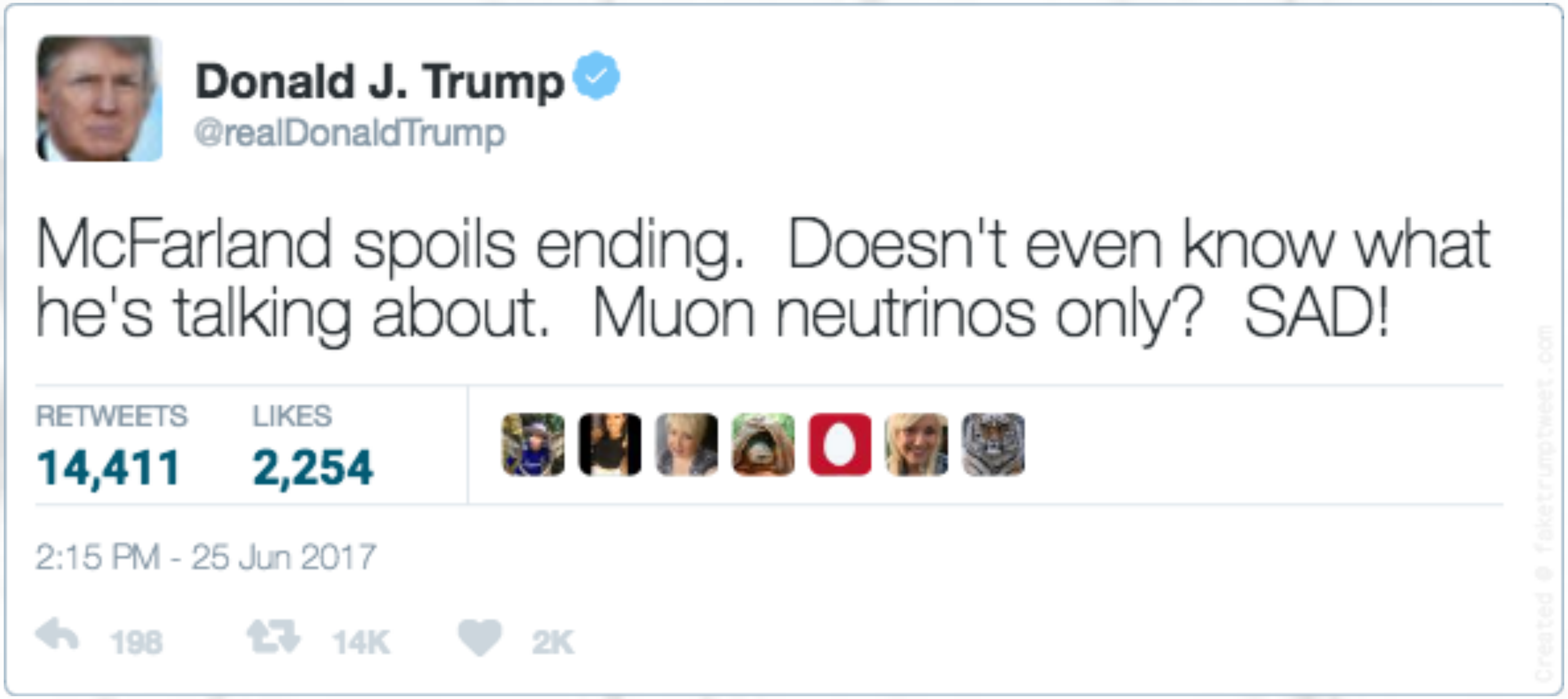
Spoiler: Not enough work has been done.

∴ ***My summary will be sadly incomplete.***

Outline



1. Why are Electron and Muon Neutrino Interactions Different?



Donald J. Trump
@realDonaldTrump

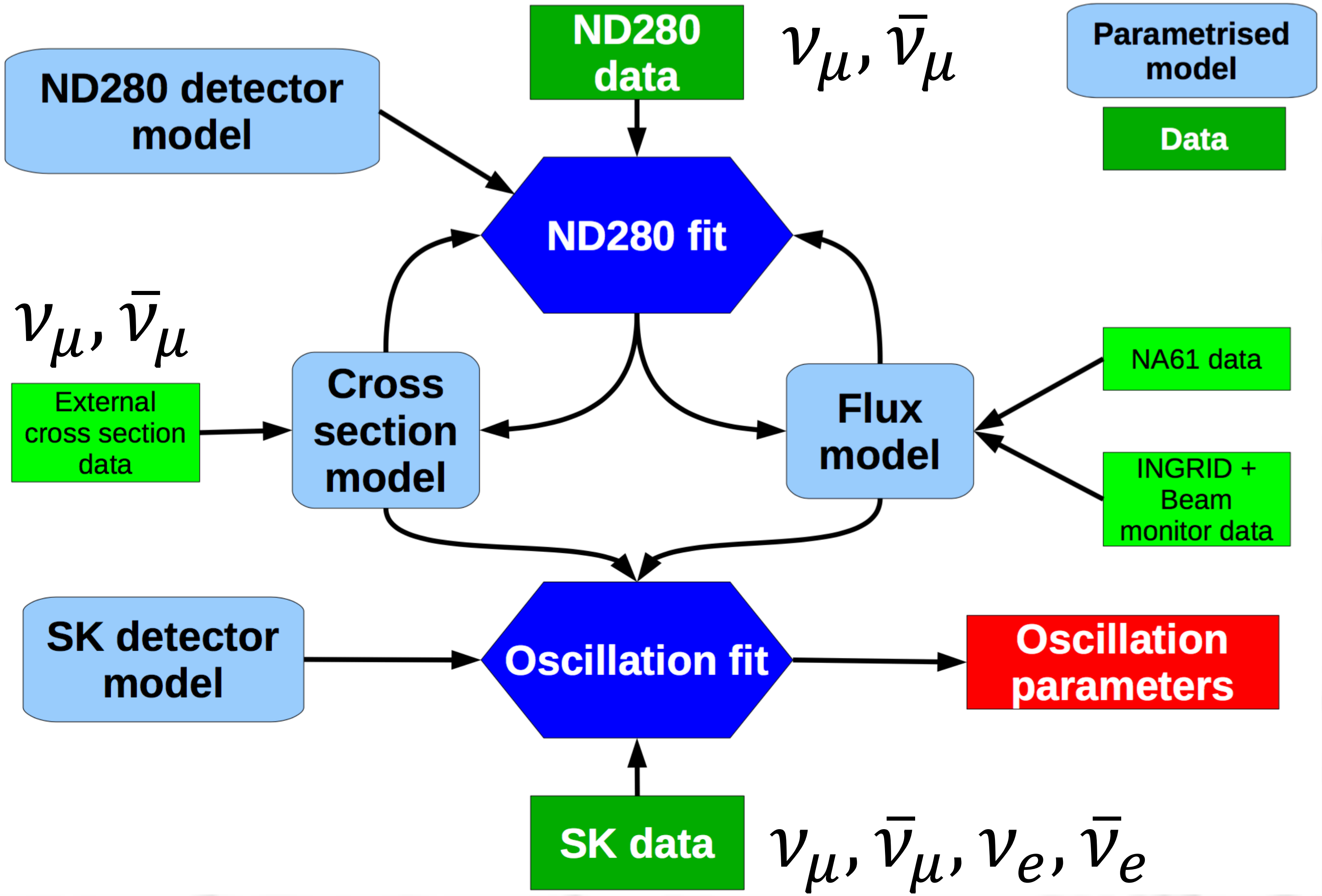
McFarland spoils ending. Doesn't even know what he's talking about. Muon neutrinos only? SAD!

RETWEETS 14,411 LIKES 2,254

2:15 PM - 25 Jun 2017

198 14K 2K

Flavors of the T2K Analysis



ND280 data

$\nu_\mu, \bar{\nu}_\mu$

Parametrised model

Data

ND280 detector model

ND280 fit

$\nu_\mu, \bar{\nu}_\mu$

External cross section data

Cross section model

Flux model

NA61 data

INGRID + Beam monitor data

SK detector model

Oscillation fit

Oscillation parameters

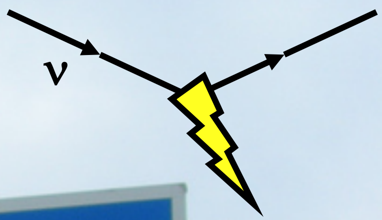
SK data

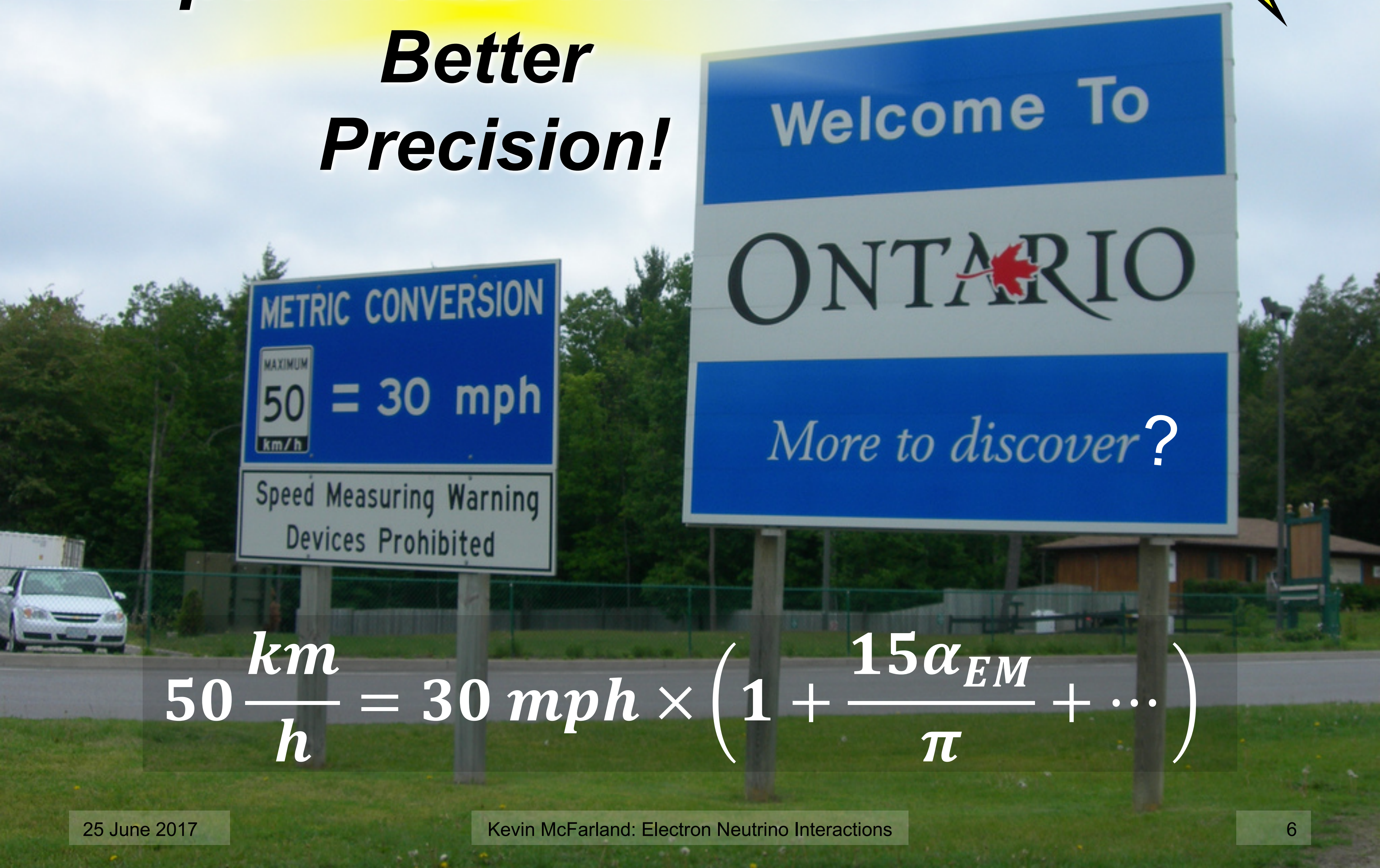
$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

Graphic by Mark Scott

What's Wrong with this Picture?

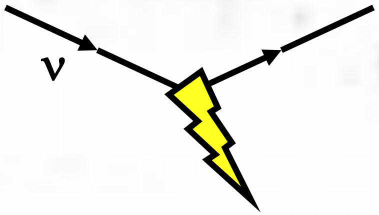
Neutrino Oscillation Experiments Will Need Better Precision!





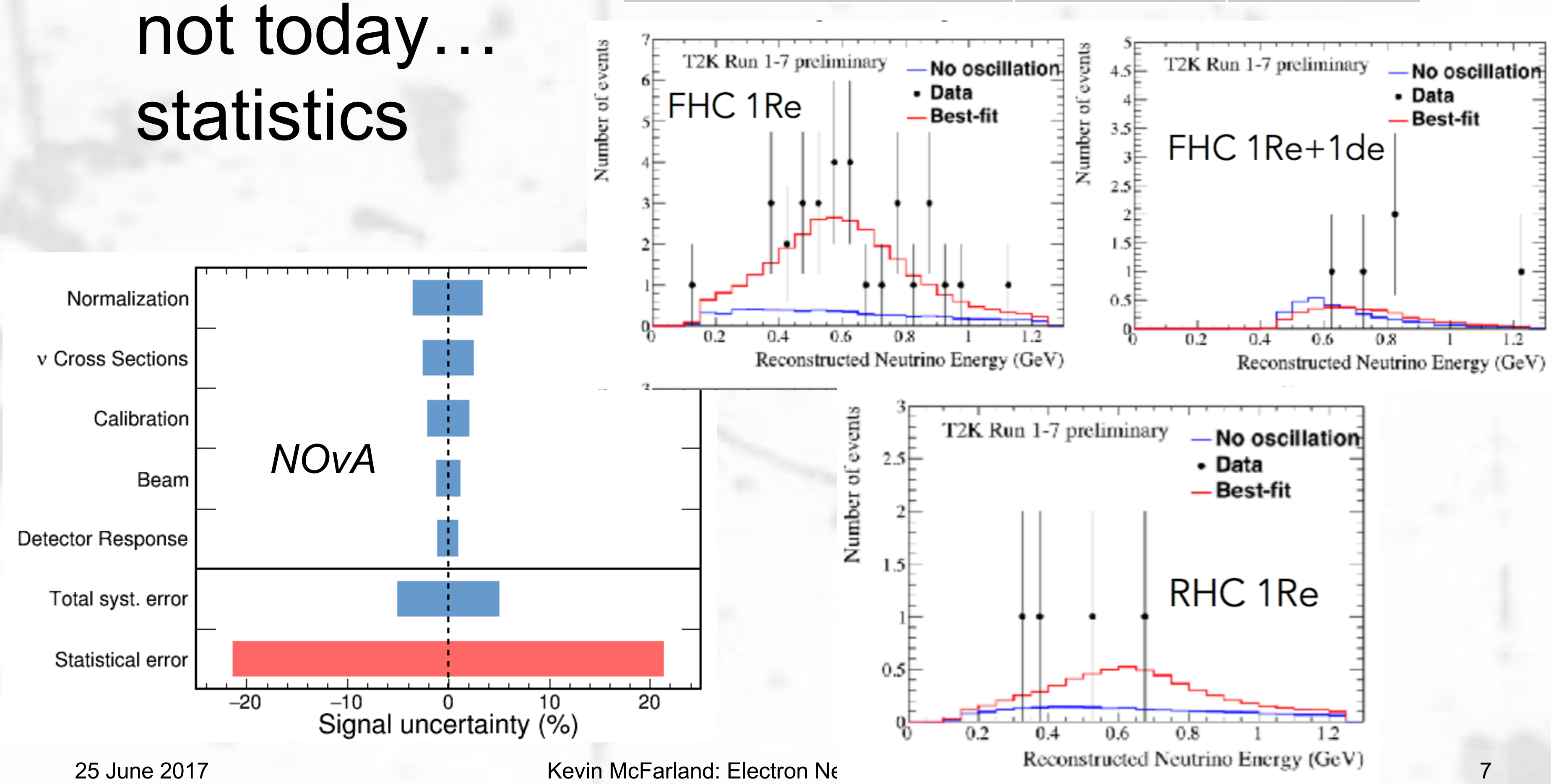
$$\mathbf{50}\,\frac{\boldsymbol{km}}{\boldsymbol{h}} = \mathbf{30}\,\boldsymbol{mph} \times \left(\mathbf{1} + \frac{\mathbf{15}\boldsymbol{\alpha}_{\boldsymbol{EM}}}{\boldsymbol{\pi}} + \cdots\right)$$

When is precision critical?



- Luckily, not today… statistics

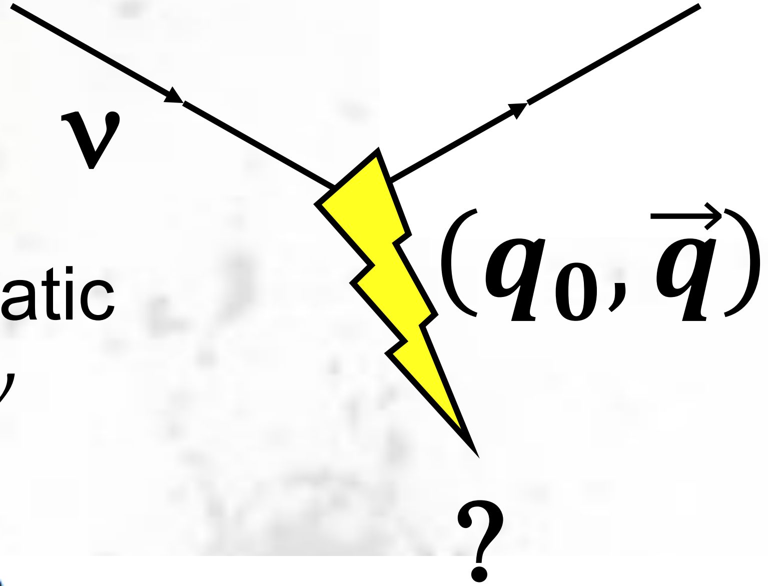
T2K Statistics, Summer 2016	FHC (Neutrino)	RHC (Anti-nu)
1Re & 1Re+1de	37	4

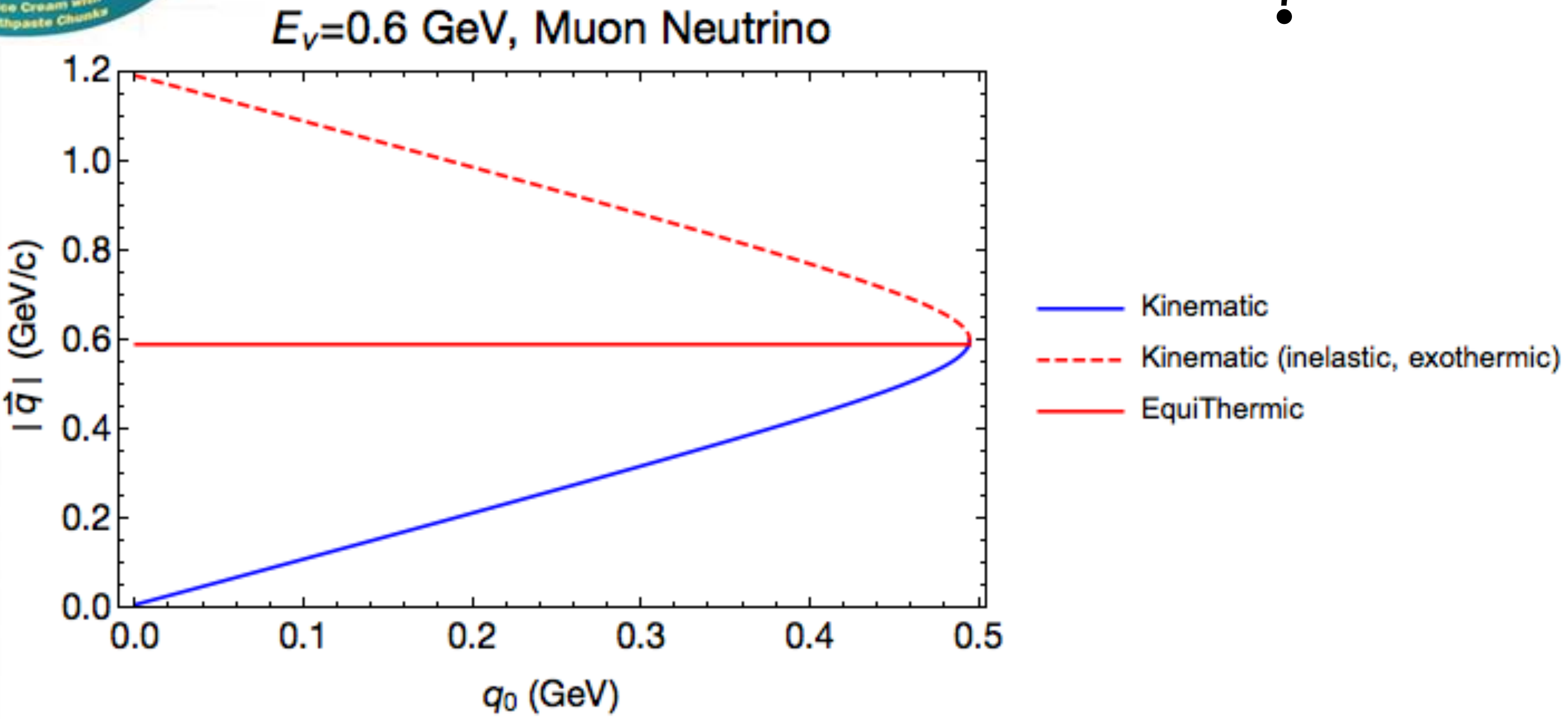


Flavor, Phase Space and Helicity

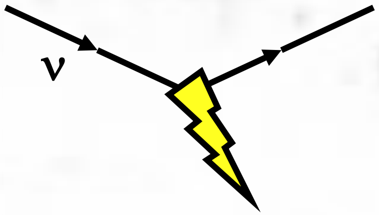
Flavor Matters

- Consider kinematic boundaries for ν scattering

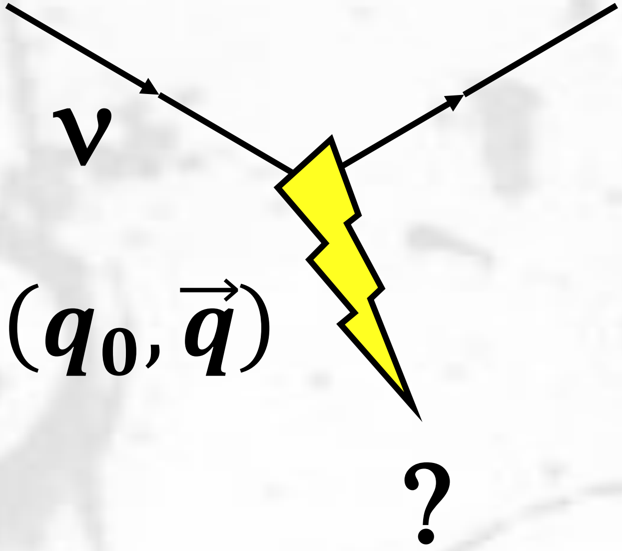




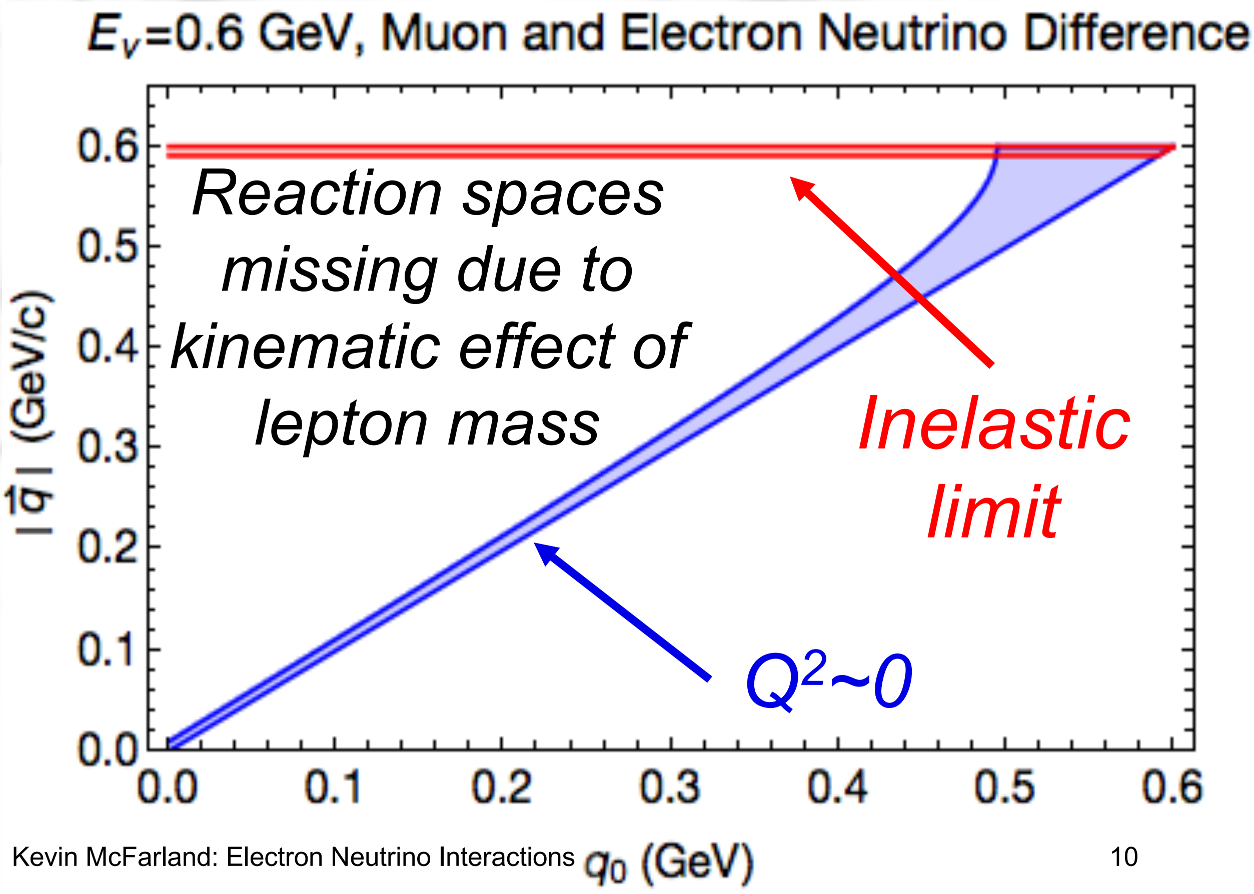
Flavor Matters ***(cont'd)***



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



- Must model missing phase space

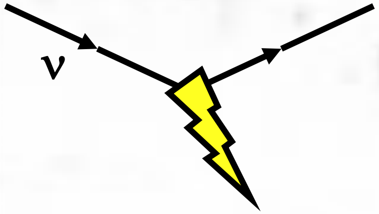

E_ν=0.6 GeV, Muon and Electron Neutrino Difference

Reaction spaces missing due to kinematic effect of lepton mass

Inelastic limit

Q^2~0

Mass Terms in Lepton Current



- And of course the lepton current itself also has lepton mass terms in it…

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

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

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

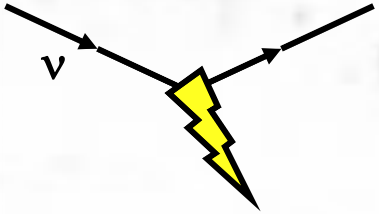
… so this will similarly result in a difference

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

Example: Form Factors and Charged Current Elastic Scattering on Nucleons

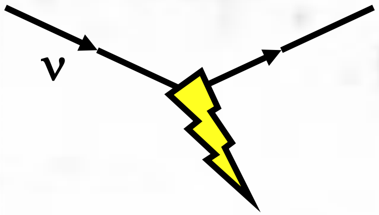
M. Day and KSM,
Phys.Rev. D86 (2012) 053003

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…

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

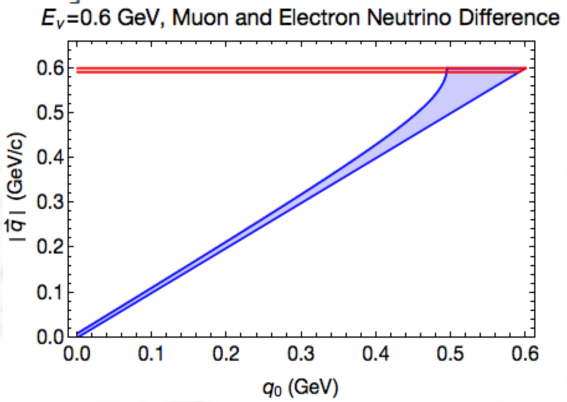
Ch. Llewellyn-Smith, Phys Rept. 3C, 261–379 (1972).

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

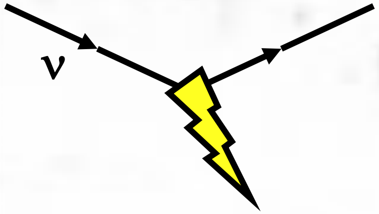
$$B(Q^2) = \frac{Q^2}{M^2}ReF_A^*\left(F_V^1+\xi F_V^2\right) - \frac{m^2}{M^2}Re\left[\left(F_V^1 - \frac{Q^2}{4M^2}\xi F_V^2\right)^* F_V^3 - \left(F_A - \frac{Q^2 F_P}{2M^2}\right)^* F_A^3\right] \text{ and}$$

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

  - 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.

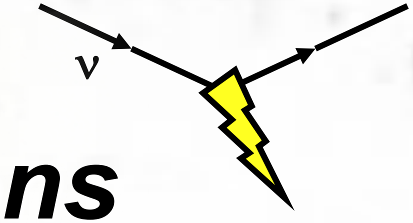


Know Nothing Approach

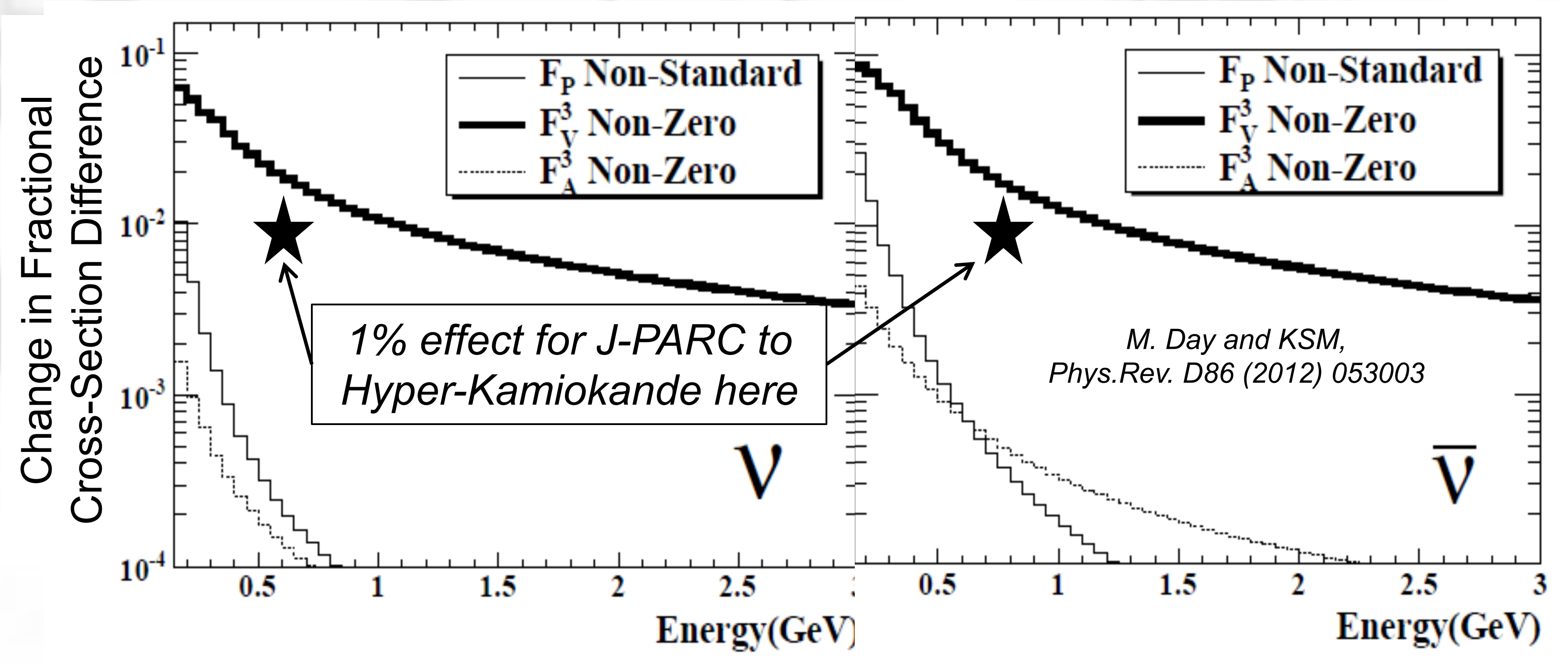


- Can look at how large the possible effects of non-standard or unconstrained form factors could be, independent of theoretical prejudice.
    - Constraints on second class currents primarily from beta decay and muon capture on nuclei.
    - Pseudoscalar form factors and axial form factor measured in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

Results for Neutrino Cross-Section Differences on Nucleons



- Our conclusion: 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.



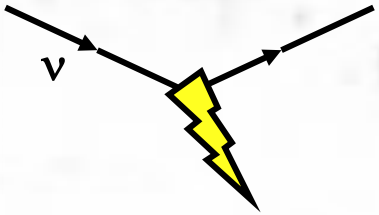
1% effect for J-PARC to Hyper-Kamiokande here

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

How might one reduce this uncertainty?

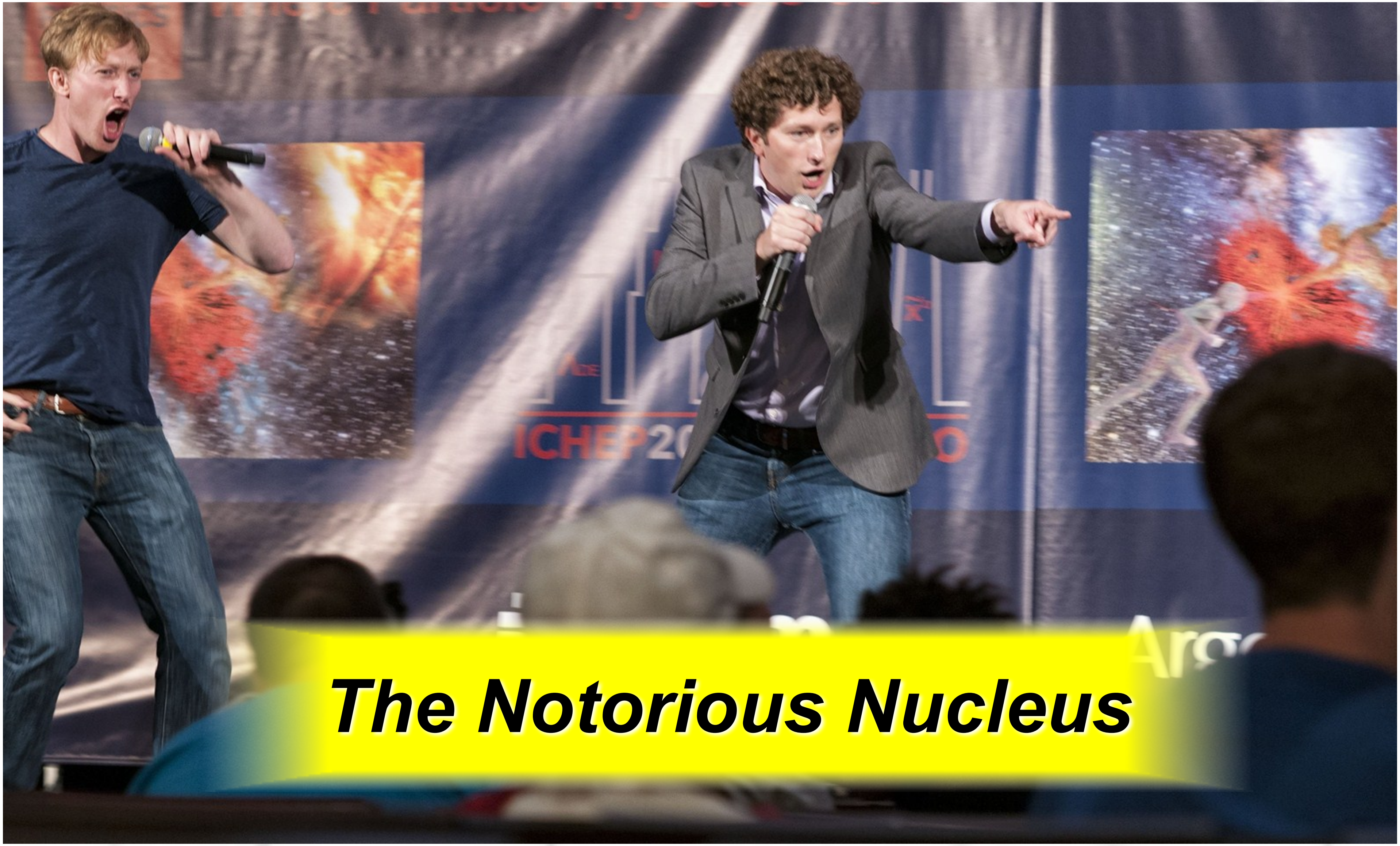
- High statistics neutrino and anti-neutrino muon neutrino CCQE on nuclei has potential to constrain second-class currents
  - Effect is distinctive in Q^2 and energy.
  - Only seen in muon neutrinos.
  - MINERvA, T2K, NOvA should have useful data.
  - But nuclear uncertainties will complicate this ☹
- Could study muon and electron neutrinos together with a muon decay source, e.g., NuStorm.
- Lots of expensive ideas for solving this directly, but it may be that none will rescue us.

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 constrain second class currents
- But there are other reactions to consider with different form factor uncertainties
  - Someone should analyze these! Especially for NOvA…
- And then there is the effect of the nucleus…

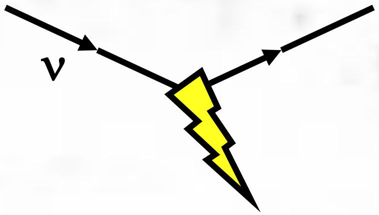
Some work on this alredy!
Paschos, E.A. et al.
arXiv:1209.4219;
Rafi Alam, M. et al. Phys.Rev. D88 (2013) 077301

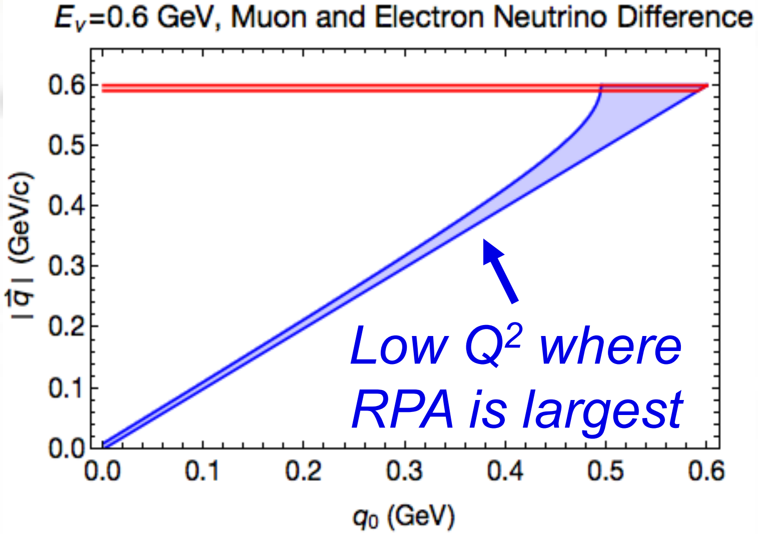


The Notorious Nucleus

Rapper MC Truth and unnamed hype man expressing their anger at nuclei. (Photo courtesy Chicago Tribune)

What will change in the nucleus?



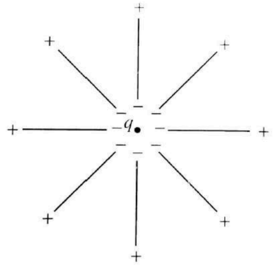

E_ν=0.6 GeV, Muon and Electron Neutrino Difference

Low Q^2 where RPA is largest

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

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

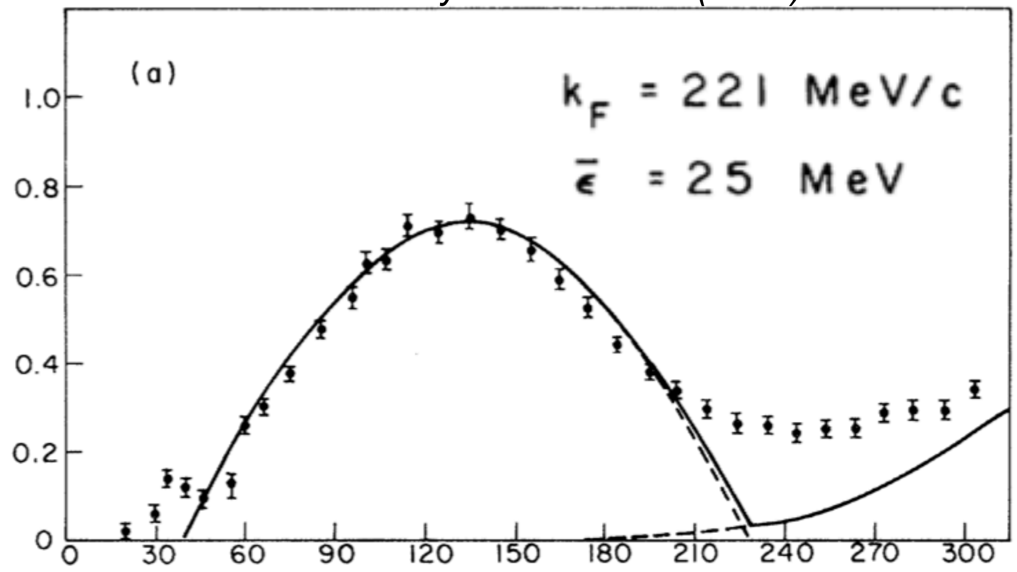


- Kinematic boundaries will shift due to nuclear effects (binding, Fermi motion)
  - To get this right, must treat these effects carefully
  - Probably insufficiently careful in generators today.

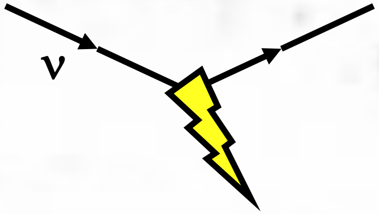
Binding and Fermi Motion

- Arie Bodek and Tejin Cai at Rochester are doing some work on this
- Arie didn't get a talk, and it's relevant for the topic
- So I offered to yield some of my time to the gentleman from Rochester…
- Short summary:
  - 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

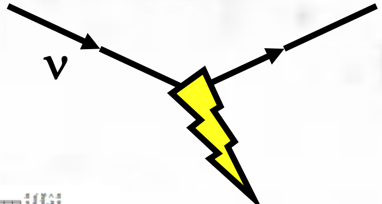


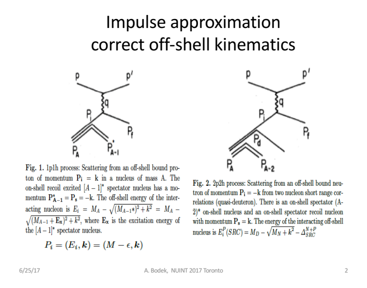
So I asked Arie to Prepare "a Slide or Two"



- After 23 years of working with Arie, you'd think I would have known what I'd get…

So I asked Arie to Prepare “a Slide or Two”





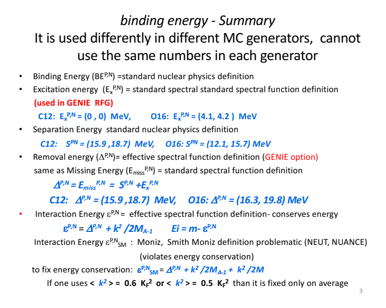
Impulse approximation correct off-shell kinematics

Fig. 1. 1p1h process: Scattering from an off-shell bound proton of momentum $P_i = k$ in a nucleus of mass A. The on-shell recoil excited $[A-1]^*$ spectator nucleus has a momentum $P^*_{A-1} = P_s = -k$. The off-shell energy of the interacting nucleon is $E_i = M_A - \sqrt{(M_{A-1}*)^2 + k^2} = M_A - \sqrt{(M_{A-1} + E_x)^2 + k^2}$, where E_x is the excitation energy of the $[A-1]^*$ spectator nucleus.

$$P_i = (E_i, \boldsymbol{k}) = (M - \epsilon, \boldsymbol{k})$$

Fig. 2. 2p2h process: Scattering from an off-shell bound neutron of momentum $P_i = -k$ from two nucleon short range correlations (quasi-deuteron). There is an on-shell spectator (A-2)* on-shell nucleus and an on-shell spectator recoil nucleon with momentum $P_s = k$. The energy of the interacting off-shell nucleus is $E^P_i(SRC) = M_D - \sqrt{M_N + k^2} - \Delta^{N+P}_{SRC}$

6/25/17 A. Bodek, NUINT 2017 Toronto 2



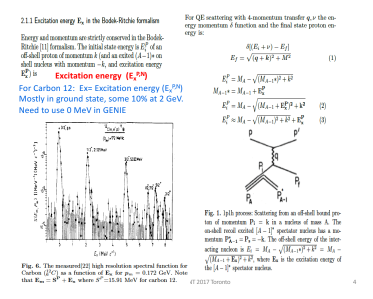
binding energy - Summary It is used differently in different MC generators, cannot use the same numbers in each generator

- Binding Energy ($BE^{P,N}$) =standard nuclear physics definition
- Excitation energy ($E_x^{P,N}$) = standard spectral standard spectral function definition
  (used in GENIE RFG)
  C12: $E_x^{P,N}$ = (0 , 0) MeV, O16: $E_x^{P,N}$ = (4.1, 4.2) MeV
- Separation Energy standard nuclear physics definition
  C12: S^{PN} = (15.9 ,18.7) MeV, O16: S^{PN} = (12.1, 15.7) MeV
- Removal energy ($\Delta^{P,N}$)= effective spectral function definition (GENIE option)
  same as Missing Energy ($E_{miss}^{P,N}$) = standard spectral function definition
  $\Delta^{P,N} = E_{miss}^{P,N} = S^{P,N} + E_x^{P,N}$
  C12: $\Delta^{P,N}$ = (15.9 ,18.7) MeV, O16: $\Delta^{P,N}$ = (16.3, 19.8) MeV
- Interaction Energy $\varepsilon^{P,N}$ = effective spectral function definition- conserves energy
  $\varepsilon^{P,N} = \Delta^{P,N} + k^2/2M_{A-1}$ $E_i = m - \varepsilon^{P,N}$
  Interaction Energy $\varepsilon^{P,N}_{SM}$: Moniz, Smith Moniz definition problematic (NEUT, NUANCE)
  (violates energy conservation)

to fix energy conservation: ***$\varepsilon^{P,N}_{SM} = \Delta^{P,N} + k^2/2M_{A-1} + k^2/2M$***

If one uses **< k^2 > = 0.6 K_F^2 or < k^2 > = 0.5 K_F^2** than it is fixed only on average

3



2.1.1 Excitation energy E_x in the Bodek-Ritchie formalism

Energy and momentum are strictly conserved in the Bodek-Ritchie [11] formalism. The initial state energy is E^P_i of an off-shell proton of momentum k (and an exited $(A-1)*$ on shell nucleus with momentum $-k$, and excitation energy E^P_x) is **Excitation energy ($E_x^{P,N}$)**

For Carbon 12: Ex= Excitation energy ($E_x^{P,N}$)
Mostly in ground state, some 10% at 2 GeV.
Need to use 0 MeV in GENIE

Fig. 6. The measured[22] high resolution spectral function for Carbon ($^{12}_6C$) as a function of E_x for $p_m = 0.172$ GeV. Note that $E_m = S^P + E_x$ where S^P=15.91 MeV for carbon 12.

For QE scattering with 4-momentum transfer q, ν the energy momentum δ function and the final state proton energy is:

$$\delta[(E_i + \nu) - E_f]$$
$$E_f = \sqrt{(q+k)^2 + M^2} \quad (1)$$

$$E^P_i = M_A - \sqrt{(M_{A-1}*)^2 + k^2}$$
$$M_{A-1}* = M_{A-1} + E^P_x$$
$$E^P_i = M_A - \sqrt{(M_{A-1} + E^P_x)^2 + k^2} \quad (2)$$
$$E^P_i \approx M_A - \sqrt{(M_{A-1})^2 + k^2} + E^P_x \quad (3)$$

Fig. 1. 1p1h process: Scattering from an off-shell bound proton of momentum $P_i = k$ in a nucleus of mass A. The on-shell recoil excited $[A-1]^*$ spectator nucleus has a momentum $P^*_{A-1} = P_s = -k$. The off-shell energy of the interacting nucleon is $E_i = M_A - \sqrt{(M_{A-1}*)^2 + k^2} = M_A - \sqrt{(M_{A-1} + E_x)^2 + k^2}$, where E_x is the excitation energy of the $[A-1]^*$ spectator nucleus.

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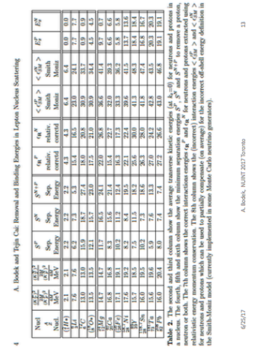

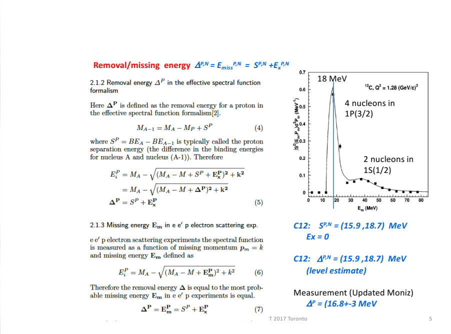

Removal/missing energy ***$\Delta^{P,N} = E_{miss}^{P,N} = S^{P,N} + E_x^{P,N}$***

2.1.2 Removal energy Δ^P in the effective spectral function formalism

Here Δ^P is defined as the removal energy for a proton in the effective spectral function formalism[2].

$$M_{A-1} = M_A - M_P + S^P \quad (4)$$

where $S^P = BE_A - BE_{A-1}$ is typically called the proton separation energy (the difference in the binding energies for nucleus A and nucleus (A-1)). Therefore

$$E^P_i = M_A - \sqrt{(M_A - M + S^P + E^P_x)^2 + k^2}$$
$$= M_A - \sqrt{(M_A - M + \Delta^P)^2 + k^2}$$
$$\Delta^P = S^P + E^P_x \quad (5)$$

2.1.3 Missing energy E_m in e e′ p electron scattering exp.

e e′ p electron scattering experiments the spectral function is measured as a function of missing momentum $p_m = k$ and missing energy E_m defined as

$$E^P_i = M_A - \sqrt{(M_A - M + E^P_m)^2 + k^2} \quad (6)$$

Therefore the removal energy Δ is equal to the most probable missing energy E_m in e e′ p experiments is equal.

$$\Delta^P = E^P_m = S^P + E^P_x \quad (7)$$

C12: $S^{P,N}$ = (15.9 ,18.7) MeV
Ex = 0

C12: $\Delta^{P,N}$ = (15.9 ,18.7) MeV
(level estimate)

Measurement (Updated Moniz)
Δ^P = (16.8+-3 MeV

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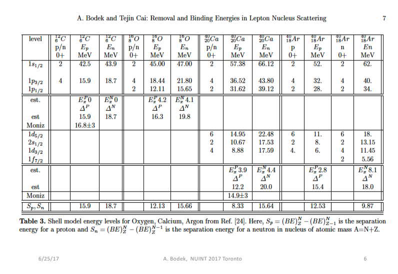

A. Bodek and Tejin Cai: Removal and Binding Energies in Lepton Nucleus Scattering 7

level	$^{12}_6C$ p/n 0+	$^{12}_6C$ E_p MeV	$^{12}_6C$ E_n MeV	$^{16}_8O$ p/n 0+	$^{16}_8O$ E_p MeV	$^{16}_8O$ E_n MeV	$^{40}_{20}Ca$ p/n 0+	$^{40}_{20}Ca$ E_p MeV	$^{40}_{20}Ca$ E_n MeV	$^{40}_{18}Ar$ p 0+	$^{40}_{18}Ar$ E_p MeV	$^{40}_{18}Ar$ n 0+	$^{40}_{18}Ar$ En MeV
$1s_{1/2}$	2	42.5	43.9	2	45.00	47.00	2	57.38	66.12	2	52.	2	62.
$1p_{3/2}$	4	15.9	18.7	4	18.44	21.80	4	36.52	43.80	4	32.	4	40.
$1p_{1/2}$				2	12.11	15.65	2	31.62	39.12	2	28.	2	34.
est.		E^P_x 0	E^N_x 0		E^P_x 4.2	E^N_x 4.1							
		Δ^P	Δ^N		Δ^P	Δ^N							
est		15.9	18.7		16.3	19.8							
Moniz		16.8±3											
$1d_{5/2}$							6	14.95	22.48	6	11.	6	18.
$2s_{1/2}$							2	10.67	17.53	2	8.	2	13.15
$1d_{3/2}$							4	8.88	17.59	4.	6.	4	11.45
$1f_{7/2}$												2	5.56
est.								E^P_x 3.9	E^N_x 4.4		E^P_x 2.8		E^N_x 8.1
								Δ^P	Δ^N		Δ^P		Δ^N
est								12.2	20.0		15.4		18.0
Moniz								14.9±3					
S_p, S_n		15.9	18.7		12.13	15.66		8.33	15.64		12.53		9.87

Table 3. Shell model energy levels for Oxygen, Calcium, Argon from Ref. [24]. Here, $S_p = (BE)^N_Z - (BE)^N_{Z-1}$ is the separation energy for a proton and $S_n = (BE)^N_Z - (BE)^{N-1}_Z$ is the separation energy for a neutron in nucleus of atomic mass A=N+Z.

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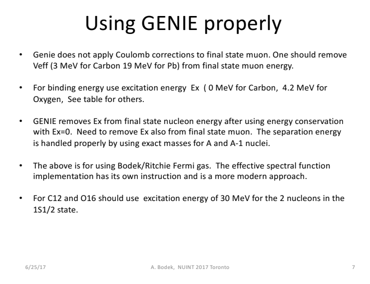

Using GENIE properly

- Genie does not apply Coulomb corrections to final state muon. One should remove Veff (3 MeV for Carbon 19 MeV for Pb) from final state muon energy.
- For binding energy use excitation energy Ex (0 MeV for Carbon, 4.2 MeV for Oxygen, See table for others.
- GENIE removes Ex from final state nucleon energy after using energy conservation with Ex=0. Need to remove Ex also from final state muon. The separation energy is handled properly by using exact masses for A and A-1 nuclei.
- The above is for using Bodek/Ritchie Fermi gas. The effective spectral function implementation has its own instruction and is a more modern approach.
- For C12 and O16 should use excitation energy of 30 MeV for the 2 nucleons in the 1S1/2 state.

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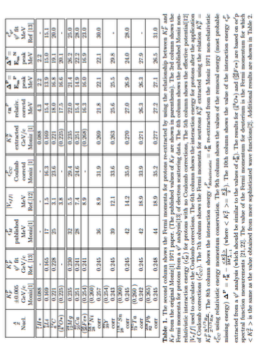

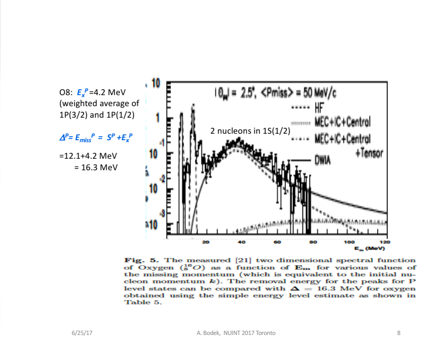

O8: E_x^P=4.2 MeV
(weighted average of 1P(3/2) and 1P(1/2)

$\Delta^P = E_{miss}^P = S^P + E_x^P$

=12.1+4.2 MeV
= 16.3 MeV

Fig. 5. The measured [21] two dimensional spectral function of Oxygen ($^{16}_8O$) as a function of E_m for various values of the missing momentum (which is equivalent to the initial nucleon momentum k). The removal energy for the peaks for P level states can be compared with Δ = 16.3 MeV for oxygen obtained using the simple energy level estimate as shown in Table 5.

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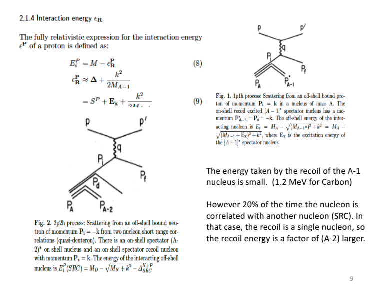

2.1.4 Interaction energy ϵ_R

The fully relativistic expression for the interaction energy ϵ^P of a proton is defined as:

$$E^P_i = M - \epsilon^P_R \quad (8)$$
$$\epsilon^P_R \approx \Delta + \frac{k^2}{2M_{A-1}}$$
$$= S^P + E_x + \frac{k^2}{2M_{A-1}} \quad (9)$$

Fig. 1. 1p1h process: Scattering from an off-shell bound proton of momentum $P_i = k$ in a nucleus of mass A. The on-shell recoil excited $[A-1]^*$ spectator nucleus has a momentum $P^*_{A-1} = P_s = -k$. The off-shell energy of the interacting nucleon is $E_i = M_A - \sqrt{(M_{A-1}*)^2 + k^2} = M_A - \sqrt{(M_{A-1} + E_x)^2 + k^2}$, where E_x is the excitation energy of the $[A-1]^*$ spectator nucleus.

Fig. 2. 2p2h process: Scattering from an off-shell bound neutron of momentum $P_i = -k$ from two nucleon short range correlations (quasi-deuteron). There is an on-shell spectator (A-2)* on-shell nucleus and an on-shell spectator recoil nucleon with momentum $P_s = k$. The energy of the interacting off-shell nucleus is $E^P_i(SRC) = M_D - \sqrt{M_N + k^2} - \Delta^{N+P}_{SRC}$

The energy taken by the recoil of the A-1 nucleus is small. (1.2 MeV for Carbon)

However 20% of the time the nucleon is correlated with another nucleon (SRC). In that case, the recoil is a single nucleon, so the recoil energy is a factor of (A-2) larger.

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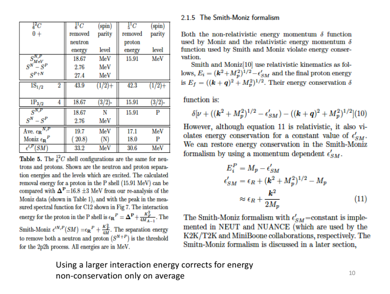


$^{12}_6C$ 0 +	$^{11}_6C$ removed neutron energy	(spin) parity level	$^{11}_5C$ removed proton energy	(spin) parity level
$S^{N,P}_{MeV}$	18.67	MeV	15.91	MeV
$S^N - S^P$	2.76	MeV		
S^{P+N}	27.4	MeV		
$1S_{1/2}$ 2	43.9	(1/2)+	42.3	(1/2)+
$1P_{3/2}$ 4	18.67	(3/2)-	15.91	(3/2)-
$S^{N,P}$	18.67	N	15.91	P
$S^N - S^P$	2.76	MeV		
Ave. $\epsilon_R{}^{N,P}$	19.7	MeV	17.1	MeV
Moniz $\epsilon_R{}^P$	(20.8)	(N)	18.0	P
$\epsilon'^{,P}(SM)$	33.2	MeV	30.6	MeV

Table 5. The $^{12}_6C$ shell configurations are the same for neutrons and protons. Shown are the neutron and proton separation energies and the levels which are excited. The calculated removal energy for a proton in the P shell (15.91 MeV) can be compared with Δ^P=16.8 ±3 MeV from our re-analysis of the Moniz data (shown in Table 1), and with the peak in the measured spectral function for C12 shown in Fig 7. The interaction energy for the proton in the P shell is $\epsilon_R{}^P = \Delta^P + \frac{K_F^2}{4M_{A-1}}$. The Smith-Moniz $\epsilon'^{N,P}(SM) = \epsilon_R{}^P + \frac{K_F^2}{4M}$. The separation energy to remove both a neutron and proton (S^{N+P}) is the threshold for the 2p2h process. All energies are in MeV.

2.1.5 The Smith-Moniz formalism

Both the non-relativistic energy momentum δ function used by Moniz and the relativistic energy momentum δ function used by Smith and Moniz violate energy conservation.

Smith and Moniz[10] use relativistic kinematics as follows, $E_i = (\boldsymbol{k}^2 + M_p^2)^{1/2} - \epsilon'_{SM}$ and the final proton energy is $E_f = ((\boldsymbol{k}+\boldsymbol{q})^2 + M_p^2)^{1/2}$. Their energy conservation δ function is:

$$\delta[\nu + ((\boldsymbol{k}^2 + M_p^2)^{1/2} - \epsilon'_{SM}) - ((\boldsymbol{k}+\boldsymbol{q})^2 + M_p^2)^{1/2}] (10)$$

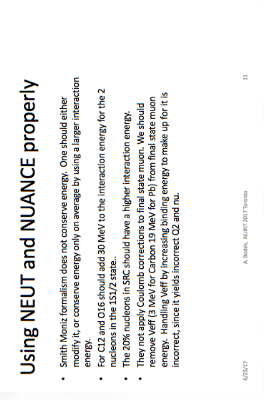
However, although equation 11 is relativistic, it also violates energy conservation for a constant value of ϵ'_{SM}. We can restore energy conservation in the Smith-Moniz formalism by using a momentum dependent ϵ'_{SM}.

$$E^P_i = M_p - \epsilon'_{SM}$$
$$\epsilon'_{SM} = \epsilon_R + (\boldsymbol{k}^2 + M_p^2)^{1/2} - M_p$$
$$\approx \epsilon_R + \frac{\boldsymbol{k}^2}{2M_p} \quad (11)$$

The Smith-Moniz formalism with ϵ'_{SM}=constant is implemented in NEUT and NUANCE (which are used by the K2K/T2K and MiniBoone collaborations, respectively. The Smitn-Moniz formalism is discussed in a later section,

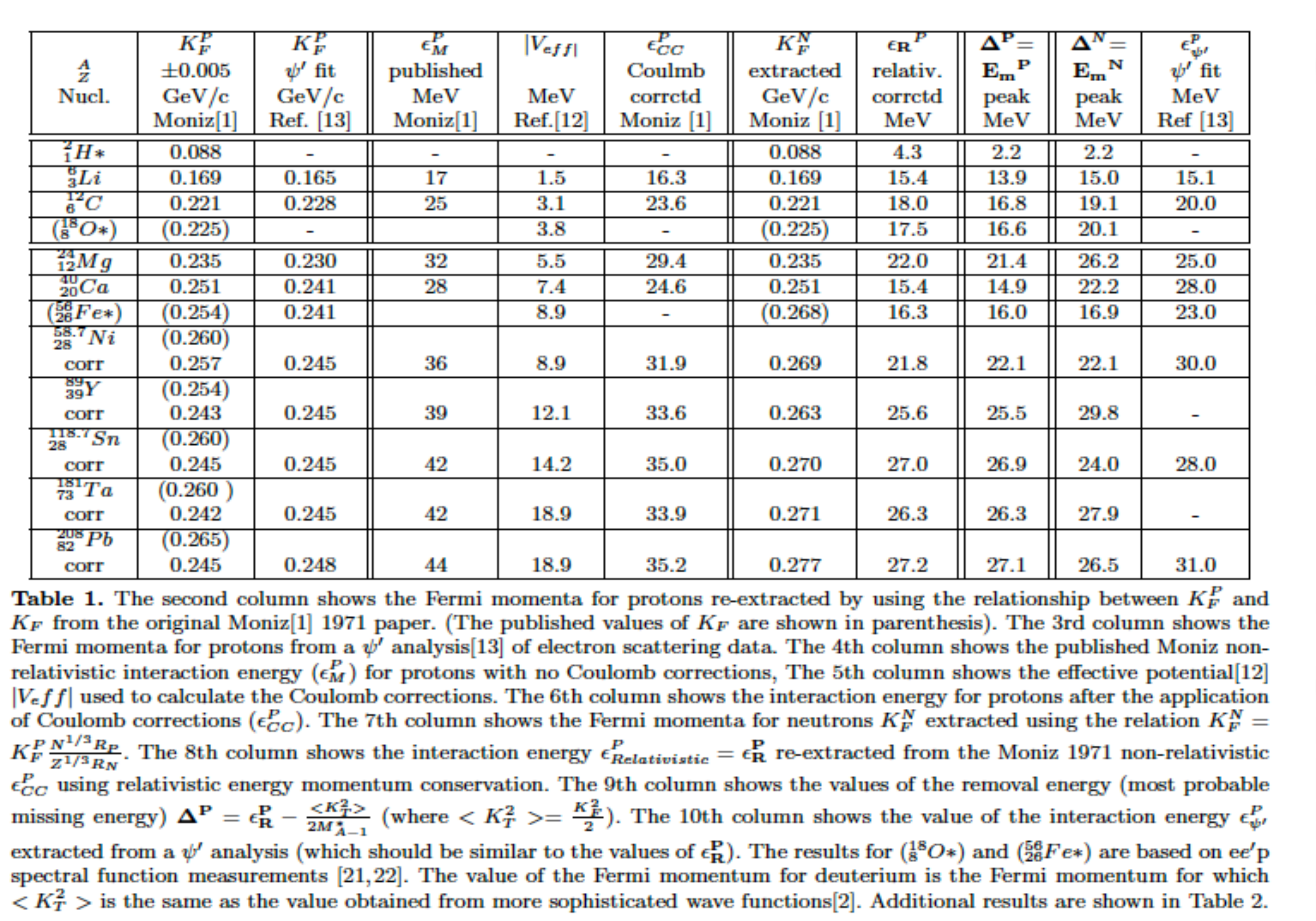
Using a larger interaction energy corrects for energy non-conservation only on average

10



“a Slide or Two”

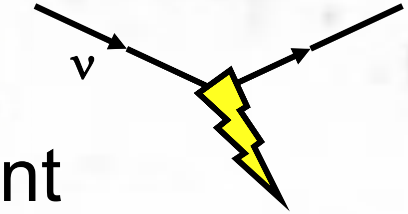
Neutron *Proton* *Neutron* *Proton*



$^{A}_{Z}$ Nucl.	K_F^P ±0.005 GeV/c Moniz[1]	K_F^P ψ' fit GeV/c Ref. [13]	ϵ_M^P published MeV Moniz[1]	$\lvert V_{eff}\rvert$ MeV Ref.[12]	ϵ_{CC}^P Coulmb corrctd Moniz [1]	K_F^N extracted GeV/c Moniz [1]	$\epsilon_{\mathbf{R}}{}^P$ relativ. corrctd MeV	$\mathbf{\Delta^P}=$ $\mathbf{E_m}{}^{\mathbf{P}}$ peak MeV	$\mathbf{\Delta}^N=$ $\mathbf{E_m}{}^{\mathbf{N}}$ peak MeV	$\epsilon_{\psi'}^P$ ψ' fit MeV Ref [13]
$^{2}_{1}H*$	0.088	-	-	-	-	0.088	4.3	2.2	2.2	-
$^{6}_{3}Li$	0.169	0.165	17	1.5	16.3	0.169	15.4	13.9	15.0	15.1
$^{12}_{6}C$	0.221	0.228	25	3.1	23.6	0.221	18.0	16.8	19.1	20.0
$(^{18}_{8}O*)$	(0.225)	-		3.8	-	(0.225)	17.5	16.6	20.1	-
$^{24}_{12}Mg$	0.235	0.230	32	5.5	29.4	0.235	22.0	21.4	26.2	25.0
$^{40}_{20}Ca$	0.251	0.241	28	7.4	24.6	0.251	15.4	14.9	22.2	28.0
$(^{56}_{26}Fe*)$	(0.254)	0.241		8.9	-	(0.268)	16.3	16.0	16.9	23.0
$^{58.7}_{28}Ni$ corr	(0.260) 0.257	0.245	36	8.9	31.9	0.269	21.8	22.1	22.1	30.0
$^{89}_{39}Y$ corr	(0.254) 0.243	0.245	39	12.1	33.6	0.263	25.6	25.5	29.8	-
$^{118.7}_{28}Sn$ corr	(0.260) 0.245	0.245	42	14.2	35.0	0.270	27.0	26.9	24.0	28.0
$^{181}_{73}Ta$ corr	(0.260) 0.242	0.245	42	18.9	33.9	0.271	26.3	26.3	27.9	-
$^{208}_{82}Pb$ corr	(0.265) 0.245	0.248	44	18.9	35.2	0.277	27.2	27.1	26.5	31.0

Table 1. The second column shows the Fermi momenta for protons re-extracted by using the relationship between K_F^P and K_F from the original Moniz[1] 1971 paper. (The published values of K_F are shown in parenthesis). The 3rd column shows the Fermi momenta for protons from a ψ' analysis[13] of electron scattering data. The 4th column shows the published Moniz non-relativistic interaction energy (ϵ_M^P) for protons with no Coulomb corrections, The 5th column shows the effective potential[12] $|V_eff|$ used to calculate the Coulomb corrections. The 6th column shows the interaction energy for protons after the application of Coulomb corrections (ϵ_{CC}^P). The 7th column shows the Fermi momenta for neutrons K_F^N extracted using the relation $K_F^N = K_F^P \frac{N^{1/3}R_P}{Z^{1/3}R_N}$. The 8th column shows the interaction energy $\epsilon_{Relativistic}^P = \epsilon_{\mathbf{R}}^{\mathbf{P}}$ re-extracted from the Moniz 1971 non-relativistic ϵ_{CC}^P using relativistic energy momentum conservation. The 9th column shows the values of the removal energy (most probable missing energy) $\mathbf{\Delta^P} = \epsilon_{\mathbf{R}}^{\mathbf{P}} - \frac{<K_T^2>}{2M_{A-1}^*}$ (where $< K_T^2 >= \frac{K_F^2}{2}$). The 10th column shows the value of the interaction energy $\epsilon_{\psi'}^P$ extracted from a ψ' analysis (which should be similar to the values of $\epsilon_{\mathbf{R}}^{\mathbf{P}}$). The results for $(^{18}_{8}O*)$ and $(^{56}_{26}Fe*)$ are based on ee′p spectral function measurements [21,22]. The value of the Fermi momentum for deuterium is the Fermi momentum for which $< K_T^2 >$ is the same as the value obtained from more sophisticated wave functions[2]. Additional results are shown in Table 2.

Here's a Brief Summary…



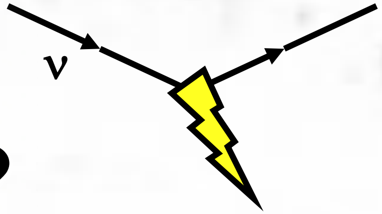
- The original analysis and many subsequent analyses of the Moniz data need corrections
  - Coulomb effects & Relativistic kinematics (averaged)
- If analyzed carefully, find consistency between shell model, (e,e'p) data, and Moniz data. Where all datasets exist, consistent w/in a few MeV
- Implementation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

Radiative Corrections in Neutrino Scattering

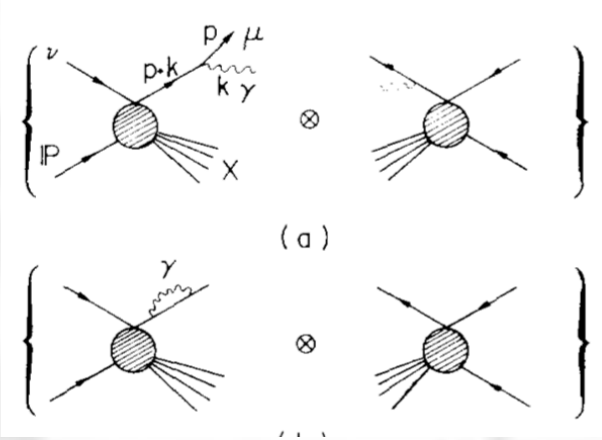
A story in which we find we have the tools...
but not the willpower (yet!) to get results.
Encourage your theory friends to help us!

Informed by work by R. Hill, KSM,
manuscript 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)

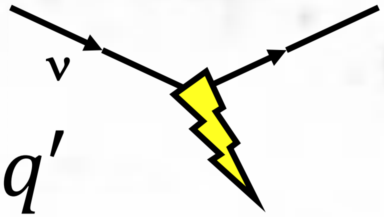
$$\frac{d\sigma_{\mathrm{obs}}}{dE_\mu\, d\Omega} = \frac{d\sigma_{\mathrm{B}}}{dE_\mu\, d\Omega} + \frac{\alpha}{2\pi} \ln \frac{4E^{*2}_\mu}{\mu^2} \int_0^1 dz \frac{1+z^2}{1-z} \times \left\{ \frac{1}{z} \frac{d\sigma_{\mathrm{B}}}{d\tilde{E}_\mu\, d\Omega}\bigg|_{\tilde{E}_\mu = E_\mu / z} \theta(z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

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

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

- 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, $\nu q \to \nu/\ell q'$
    - Outdated calculations using quark mass regularization
    - Modern calculations in unrealistic observables
    - Modern calculations in realistic observables!

D.Yu. Bardin, V.A. Dokuchaeva Sov.J.Nucl.Phys. 39 (1984) 563, Yad.Fiz. 39 (1984) 888-894

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

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.

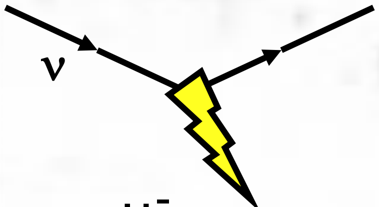
S. Sarantakos, A. Sirlin, W.J. Marciano, Nucl.Phys. B217 (1983) 84-116

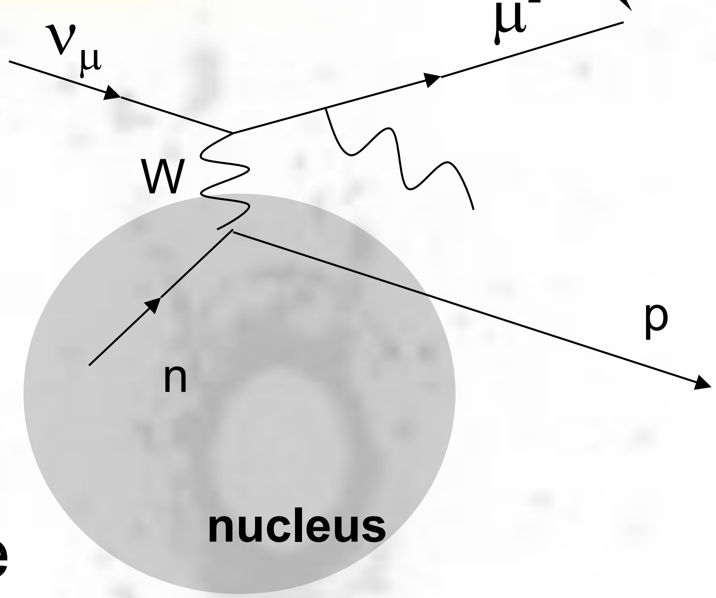
John N. Bahcall, Marc Kamionkowski, Alberto Sirlin, Phys.Rev. D51 (1995) 6146-6158

M. Passera, Phys.Rev. D64 (2001) 113002

- So tools exist for the calculations

What do we need to study?

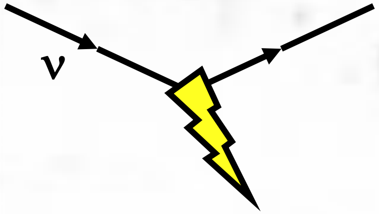




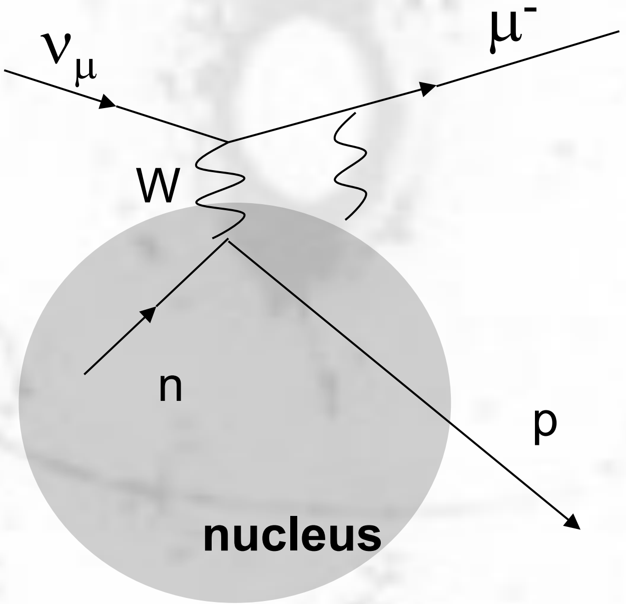
quasielastic scattering

- 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.
- 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.

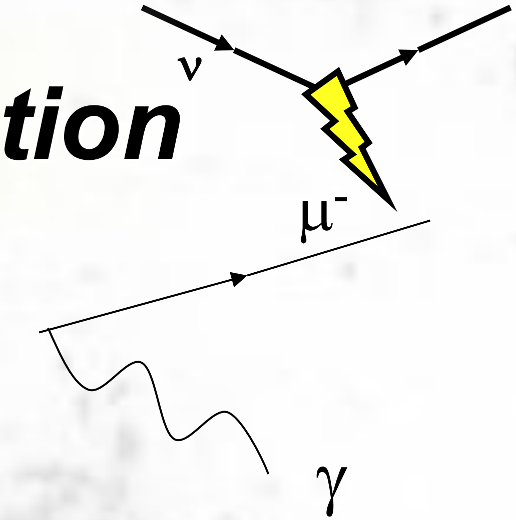
Does Lepton Mass affect an "Inclusive" Cross Section?



- By inclusive cross-sections, I mean the exclusive low energy processes that dominate at T2K, NOvA, 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!

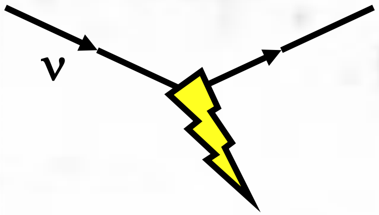


Real Photons & Reconstruction

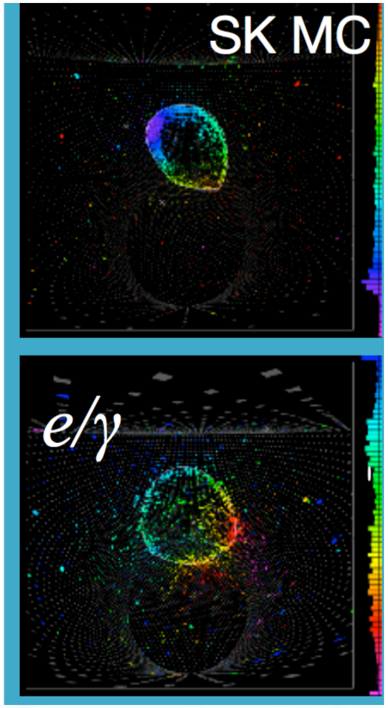


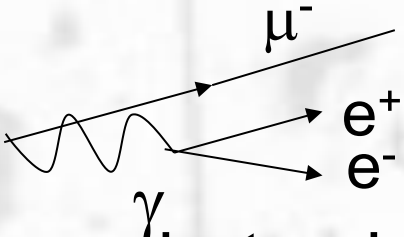
- Consider two cases
  - Collinear(ish) radiation with lepton
  - Other
- If radiation is collinear, what does it do?
  - It can disrupt lepton energy reconstruction
  - Different for electrons (adds to electron energy) and muons (reconstruction by range vs total ionization)
  - Most frighteningly, it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

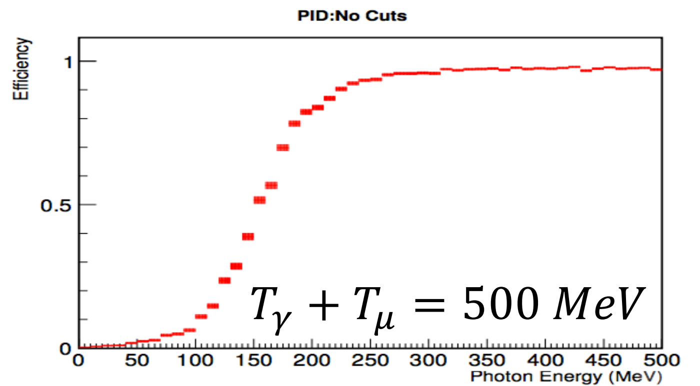


- Increased fuzziness of electron ring at bottom compared to muon at top

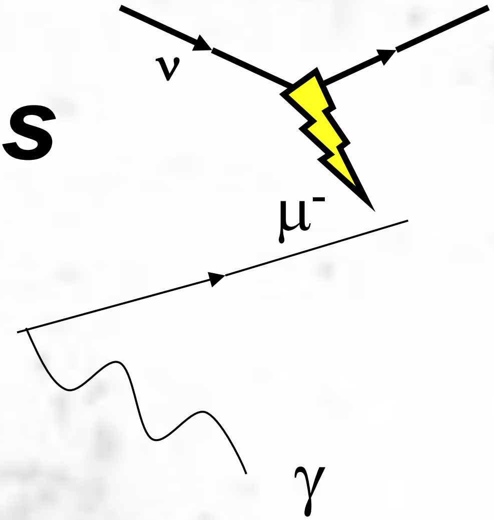




- If the collinear photon has a signfiicant fraction of the muon energy, it will appear as an electron
  - Roughly requires photon energy to be 40% of muon energy for a significant probability in Super-K
  - Rare, very bad, event

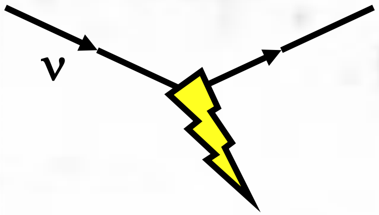


More Reconstruction Woes



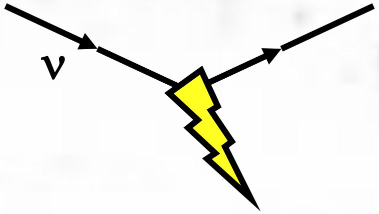
- Consider two cases
  - Collinear(ish) radiation with lepton
  - Other
- If radiation is not collinear, what does it do?
  - If detector is just summing final state energy (DUNE, NOvA) it probably of little consequence
  - But at T2K and Hyper-K, it is very bad
    - Reconstruction will often infer 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.

Radiative Corrections Summary



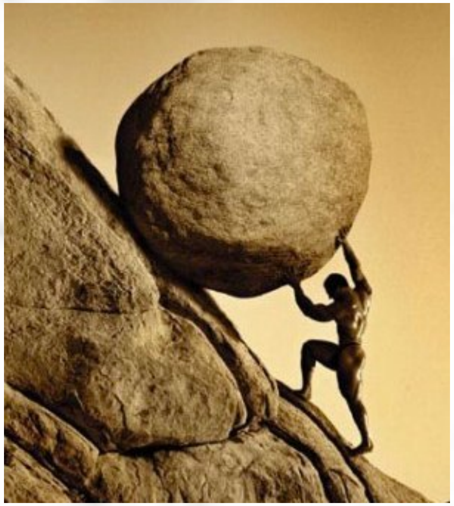
- Virtual corrections to the total cross-sections are a real concern. Not known. Guess is “small”
- We also need calculations of differential cross-sections for reactions with photons
  - In particular, total energy in energetic photons that are collinear, and energy and angles of energetic non-collinear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

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

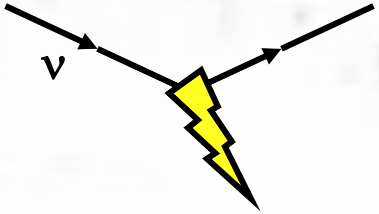


Measurements of Electron Neutrino Interactions

Sisyphus never had it so hard…

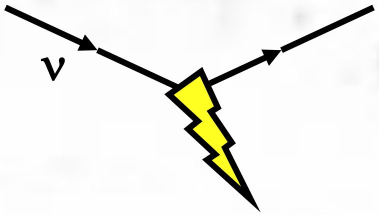


Another tough way to make a living…

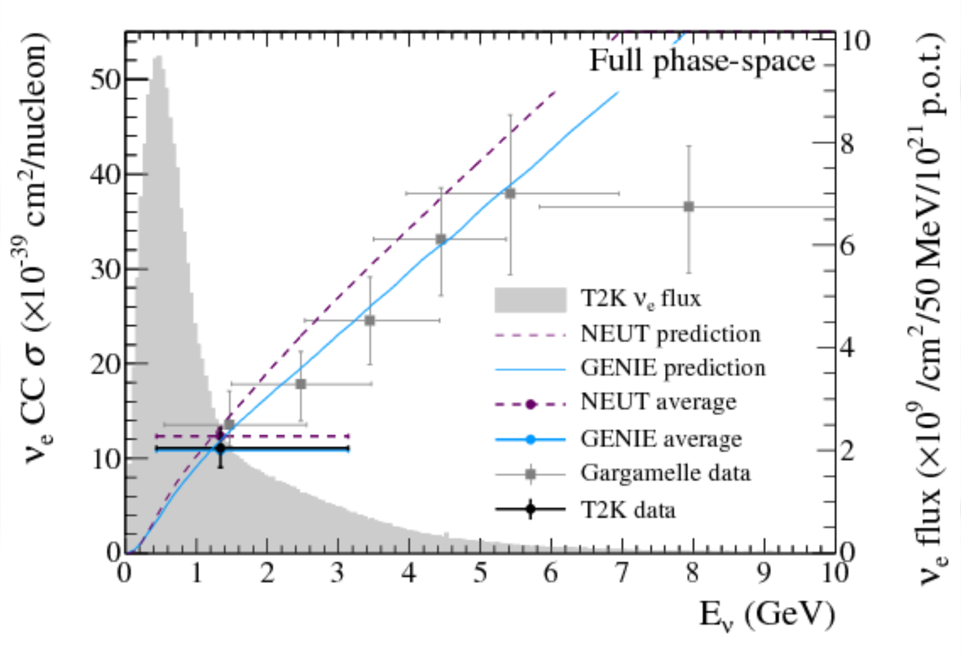


- Accelerator experiments can try to measure ν_e scattering directly
    - But large backgrounds from the factor of ~100 more ν_μ in the beam, and different electron reconstruction systematics than μ
- All the modern experiments are trying this
- Editorial thought: NOvA has the combination of statistics, detector, that *may* be most favorable
- But we are currently *far* from required precision

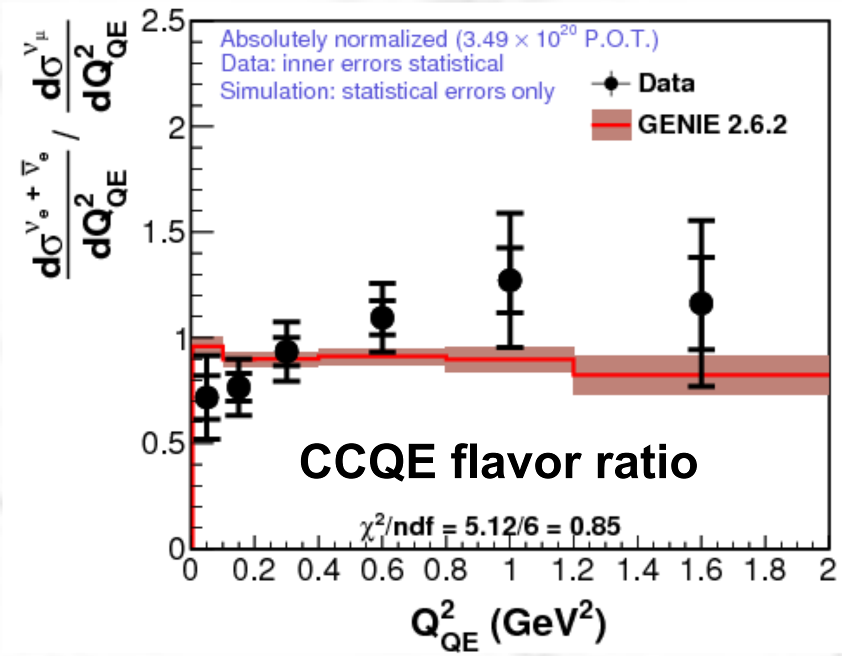
Recent Results



- Recent 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

See also presentations by S. King, J, Paley for updates from T2K and NOvA

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!
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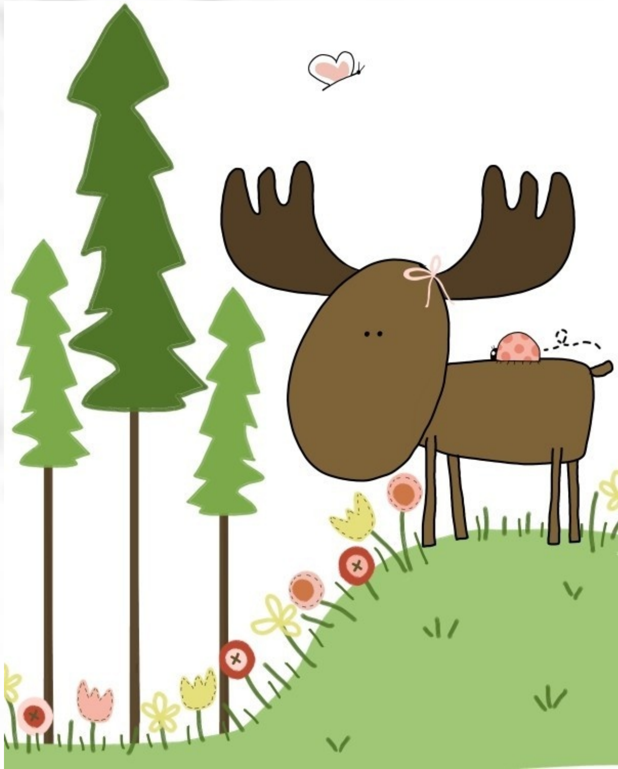

- *I know of now definitive show stoppers, but we are not out of the woods yet.*