Some theory inputs and outputs for neutrino measurements

Richard Hill

University of Chicago

Mexican workshop 12 November 2009

OUTLINE

- Standard lore
- Our effective theory of particle physics, circa 2009
- Sampling of lessons from history and current questions
  - neutrinos as dark matter
  - constraints on a 4th generation
  - GUT model building
  - signals and backgrounds to ν_e appearance and extra sterile neutrinos
- Summary

NEUTRINO MASS

In old SM, without RH ν's, neutrino masses not allowed:

For electrons,

$$\mathcal{L} = \lambda_e \bar{E}_L H e_R = m_e(1 + h(x)/v)\bar{e}_L e_R + \dots$$

But for neutrinos, no renormalizable mass term is consistent with gauge invariance

$$\Delta\mathcal{L} \sim m_\nu \bar{\nu}_L^c \nu_L$$

$$E_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

Having observed oscillations, we need to add something - e.g. a "sterile neutrino", i.e., a right-handed neutrino with no gauge couplings

$$\Delta\mathcal{L} = \lambda_\nu \bar{E}_L (i\sigma_2 H^*)\nu_R$$

Just like a mass term for up-type quarks. ν_R isn't charged under any gauge group, so no problem with anomaly consistency

$$\Delta\mathcal{L} = \lambda H \bar{\nu}_R \nu_L$$

This is just one of many possible "portals" from our world to the "other" , "dark", stuff of our universe

$$\Delta\mathcal{L} = \epsilon F^B_{\mu\nu} F'^{\mu\nu}$$

Standard model hypercharge

"Dark" gauge field

recent popularity in inelastic DM models: Weiner, Tucker-Smith; Finkbeiner et.al.; Arkani-Hamed et.al.

$$\Delta\mathcal{L} = c H^\dagger H S^2$$

Standard model Higgs

"Dark" scalar

Neutrinos are (at present) a unique look beyond the SM: should exploit this to the fullest

The properties of this dark stuff have been studied with increasing precision over the past decade

What goes on, on the dark side?

Once we have **ν**$_R$ we can write this interaction:

$$\Delta\mathcal{L} = \lambda_\nu \bar{E}_L (i\sigma_2 H^*)\nu_R$$ *(Dirac mass)*

At renormalizable level, can also write this one:

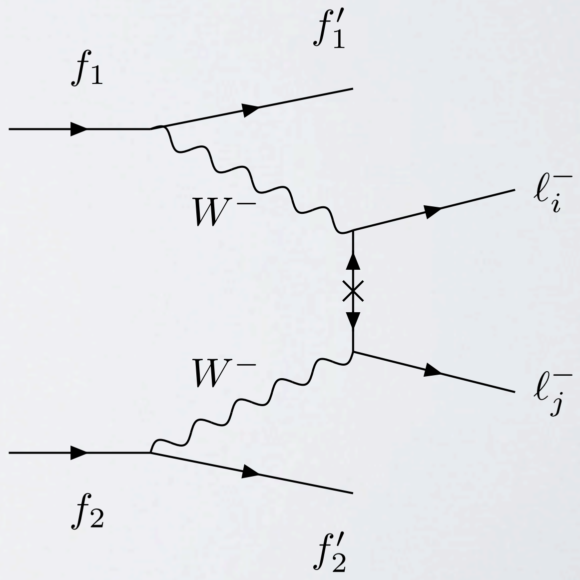
$$\Delta\mathcal{L} = m_R \bar{\nu}_R^c \nu_R$$ *(Majorana mass)*

Everything that's not forbidden is mandatory - the interaction is not forbidden by existing symmetries/principles

This interaction violates lepton-number conservation

- distinct experimental signatures
- possible role in leptogenesis origin of cosmological matter-antimatter asymmetry

$$\not{L} + (B-L) \to \not{B}$$



See-saw ?

If we diagonalize mass matrix, eigenstates are Majorana fermions

$$\Delta\mathcal{L} \sim m_R \bar{\nu}_R^c \nu_R + m_D \bar{\nu}_L \nu_R + h.c. = \frac{1}{2} (\bar{\nu_L}\ \bar{\nu}_R^c) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

$$m_\nu \sim m_R/2 \pm \sqrt{(m_R/2)^2 + m_D^2} \sim m_R, m_D^2/m_R$$

heavy light

Perhaps a coincidence, but if we take m_D of the electroweak scale, observed light neutrino masses require m_R of order the GUT scale, ~10^{15} GeV (*SU(3)xSU(2)xU(1) unification scale*)

$$m_\nu \sim m_{EW}^2/m_{GUT}$$

⇒ *The dark stuff could be GUT remnants*

OUR EFFECTIVE THEORY, CIRCA 2009

Following our nose, we're led to introduce a ν_R. If m_R is large, can "integrate out" ν_R, leaving an effective, nonrenormalizable interaction,

$$\Delta\mathcal{L} \sim \frac{\lambda_\nu^2}{m_R} H E_L H E_L$$

At low energies, effects of heavy RH neutrino indistinguishable from this operator - can remain agnostic about origin of such lepton-flavor violating interactions

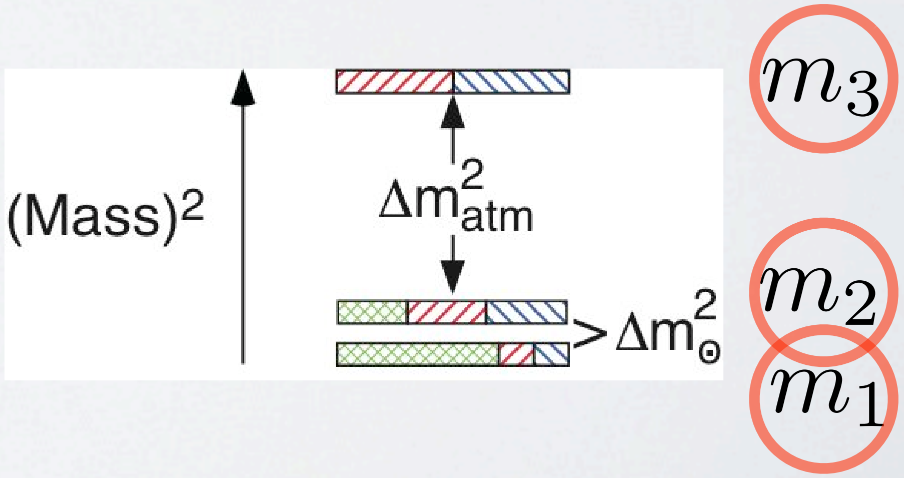
This is the holy grail for low-energy experiments: to uncover new physics by its impact on the low-energy theory. It's our first correction to the Standard Model

Interactions of neutrinos are determined by their gauge interactions, and the masses and mixing due to couplings to the Higgs field:

$$\nu_1 = U_{e1}\nu_e + U_{\mu 1}\nu_\mu + U_{\tau 1}\nu_\tau \, , \quad \text{etc.}$$

$$U = \begin{matrix} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \\ \left[\begin{matrix} c_{12}c_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} \end{matrix} \right. & \begin{matrix} s_{12}c_{13} \\ c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} \\ -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} \end{matrix} & \left. \begin{matrix} s_{13}e^{-i\delta} \\ s_{23}c_{13} \\ c_{23}c_{13} \end{matrix} \right] \end{matrix}$$

$$\times \, \mathrm{diag}(e^{i\alpha_1/2}, \;\; e^{i\,\alpha_2/2}, \;\; 1) \;\; .$$



[plot from B. Kayser]

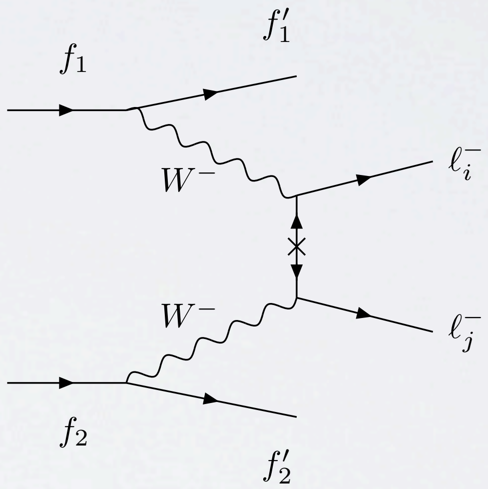
Can divide experiments into two parts:

1) Find out what new fields we should put in the lagrangian

2) Measure the parameters for the interactions between these fields

Several experimental handles:

lepton flavor violation:



neutrino oscillations:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2[1.27\Delta m^2(L/E)]$$

⇒ see experimental review talk by M. Shaevitz

In this talk, a few examples of things we have learned, and can learn, from neutrino experiments. Far from exhaustive.

THE GENERATION PARADIGM

Our experience with quarks has enforced the generation paradigm:

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \quad \lambda \sim \sin\theta_C \sim 0.2$$

But the neutrino mixing confuses the point

$$V_{PMNS} \sim \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \lesssim 0.2 \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

Why should (e, ν_e) "go" with (u,d) ?

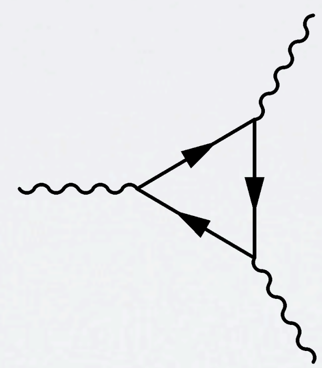
Maybe this paradigm is basically correct, and neutrinos just happen to have larger mixing and less hierarchical masses than charged fermions

Or maybe we're confused - e.g., third generation "special"

$$SU(2)_L \times U(1)_Y \to SU(3)_L \times U(1)_X$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_{y=1/6} \to \begin{pmatrix} u \\ d \\ u' \end{pmatrix}_{x=0} \qquad \begin{pmatrix} t \\ b \end{pmatrix}_{y=1/6} \to \begin{pmatrix} t \\ b \\ t' \end{pmatrix}_{x=1/3}$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_{y=1/6} \to \begin{pmatrix} c \\ s \\ c' \end{pmatrix}_{x=0}$$

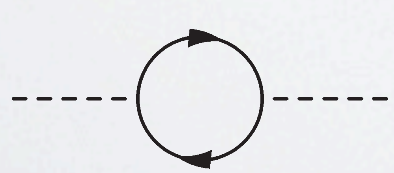
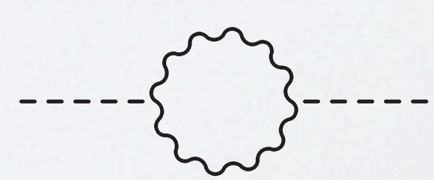


For anomaly cancellation, can have only two "light" generations

Frampton, PRL,69:2889-2891 (1992).

Arkani-Hamed et.al. (2003); Schmaltz, hep-ph/0407143

[*Top quark and new partner may play role in "fine-tuning" a low Higgs mass (little Higgs idea)*

$\delta m_H^2 \sim$  +  + ...]

Or maybe there are more generations..

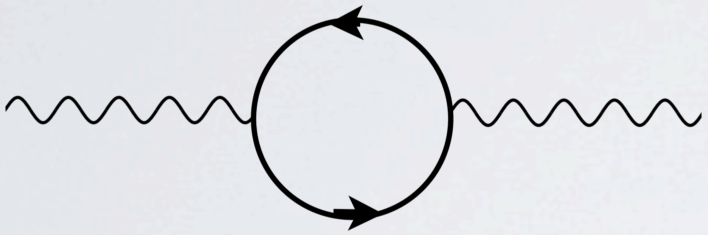
> An extra generation of ordinary fermions is excluded at the 99.999% CL on the basis of the S parameter alone, corresponding to $N_F = 2.81 \pm 0.24$ for the number of families. This result assumes that there are no new contributions to T or U and therefore that any new families are degenerate. In principle this restriction can be relaxed by allowing
>
> July 14, 2006 10:37
>
> *10. Electroweak model and constraints on new physics* **37**
>
> T to vary as well, since $T > 0$ is expected from a non-degenerate extra family. However, the data currently favor $T < 0$, thus strengthening the exclusion limits. A more detailed analysis is required if the extra neutrino (or the extra down-type quark) is close to its direct mass limit [208]. This can drive S to small or even negative values but at the expense of too-large contributions to T. These results are in agreement with a fit to the number of light neutrinos, $N_\nu = 2.986 \pm 0.007$ (which favors a larger value for $\alpha_s(M_Z) = 0.1231 \pm 0.0020$ mainly from R_ℓ and τ_τ). However, the S parameter fits are valid even for a very heavy fourth family neutrino.

Rumors of the death of the 4th generation are exaggerated..

"extra generation ... excluded at the 99.999% CL on the basis of S parameter alone ..."

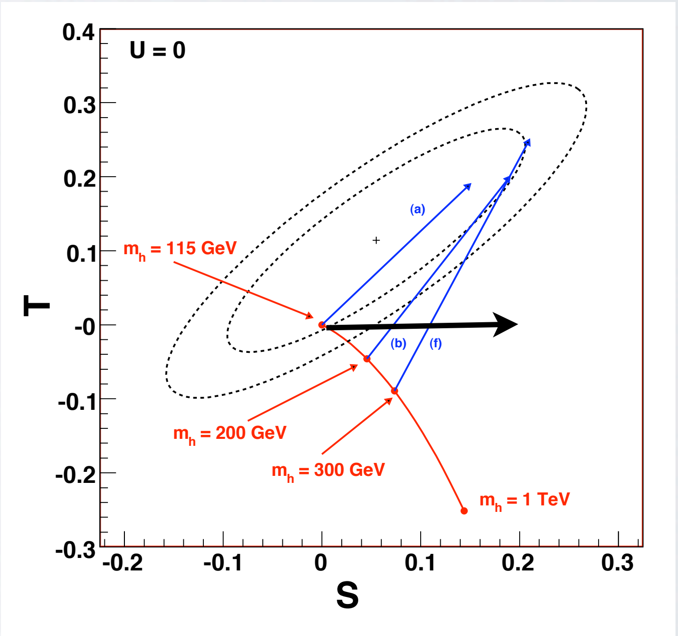
J. Erler hep-ph/0604035; PDG06

Corrections to precision electroweak observables:

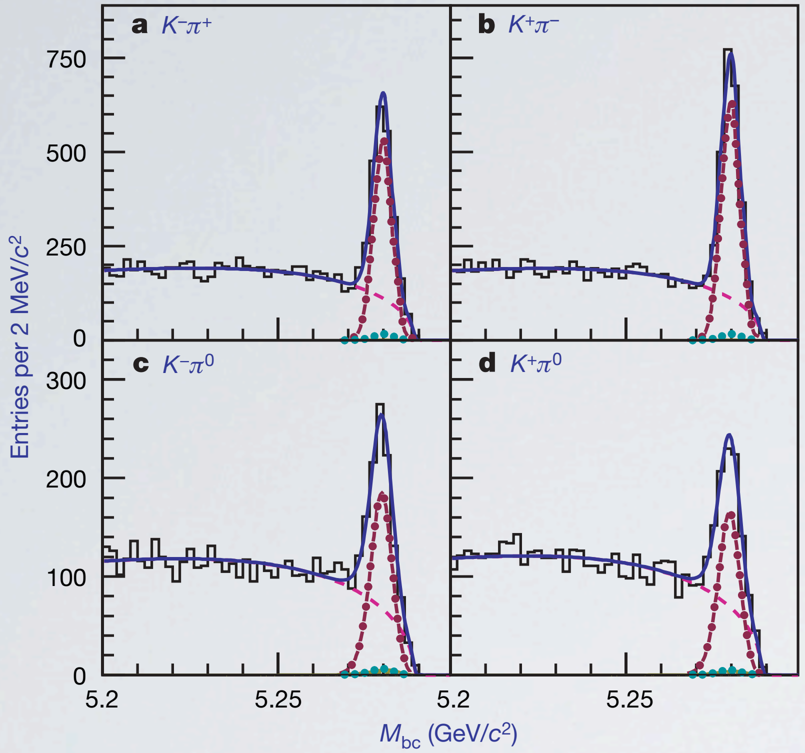


$$\Delta S = \frac{N_c}{6\pi}\left(1 - 2y \log \frac{m_{t'}^2}{m_{b'}^2}\right)$$

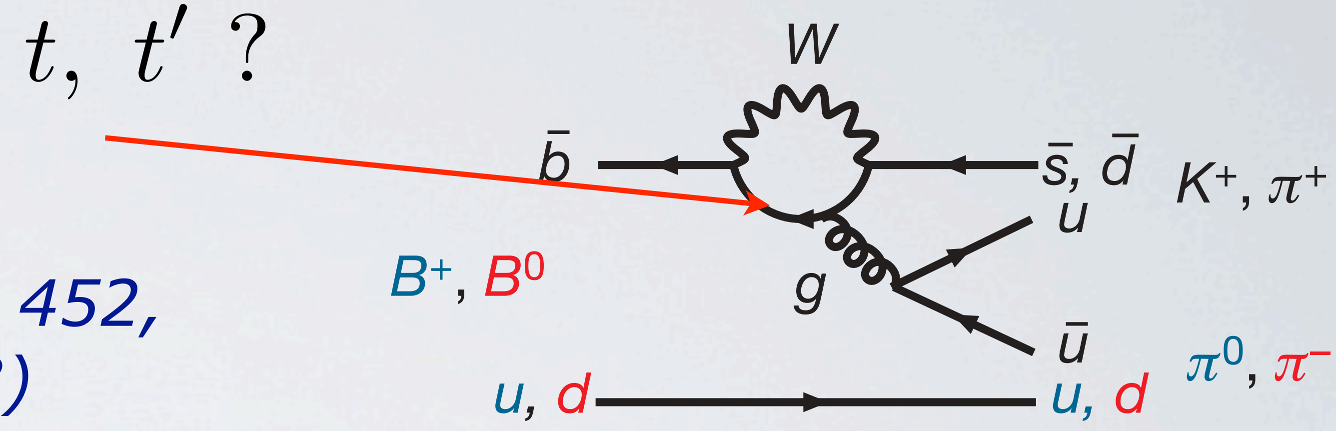
strictly positive for degenerate masses, but compensated by logs, and contributions to T



Kribs et.al., 0706.3718



There may also be hints from B decays, although nonperturbative QCD effects not easy to control



BELLE, Nature 452, 332 (2008)

$$\mathcal{A}_{K^\pm\pi^0} - \mathcal{A}_{K^\pm\pi^\mp} = 0.164 \pm 0.037$$

4th generation not obviously favored or disfavored. But neutrino physics encourages us to think more about the whole generation paradigm.

MORE SURPRISES?

Let's consider a few examples of plausible new-physics scenarios that have been, or can be, constrained by laboratory neutrino measurements
(a very selective collection of historical/current examples)

- heavy neutrino as "the" dark matter
- electroweak see-saw and fourth generation
- tri-bi mixing and GUT indicators..
- other sterile neutrino indications (more portals..)

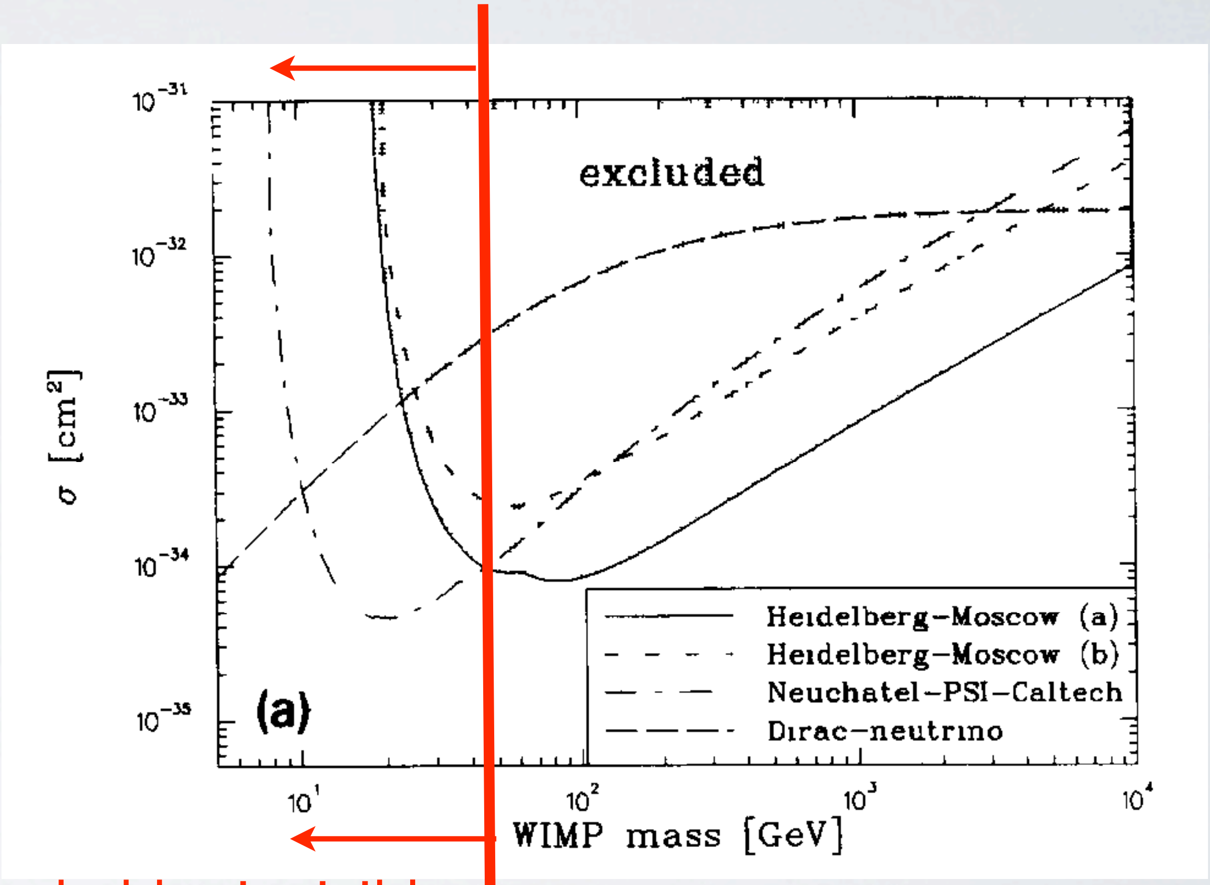
EXAMPLE: STERILE NEUTRINO DARK MATTER

A heavy neutrino was the original WIMP

Nice, because it's a definite model (can't keep tuning the cross section lower as the results come in..)

For Dirac neutrinos, ruled out by Z decay and direct (non-)detection constraints

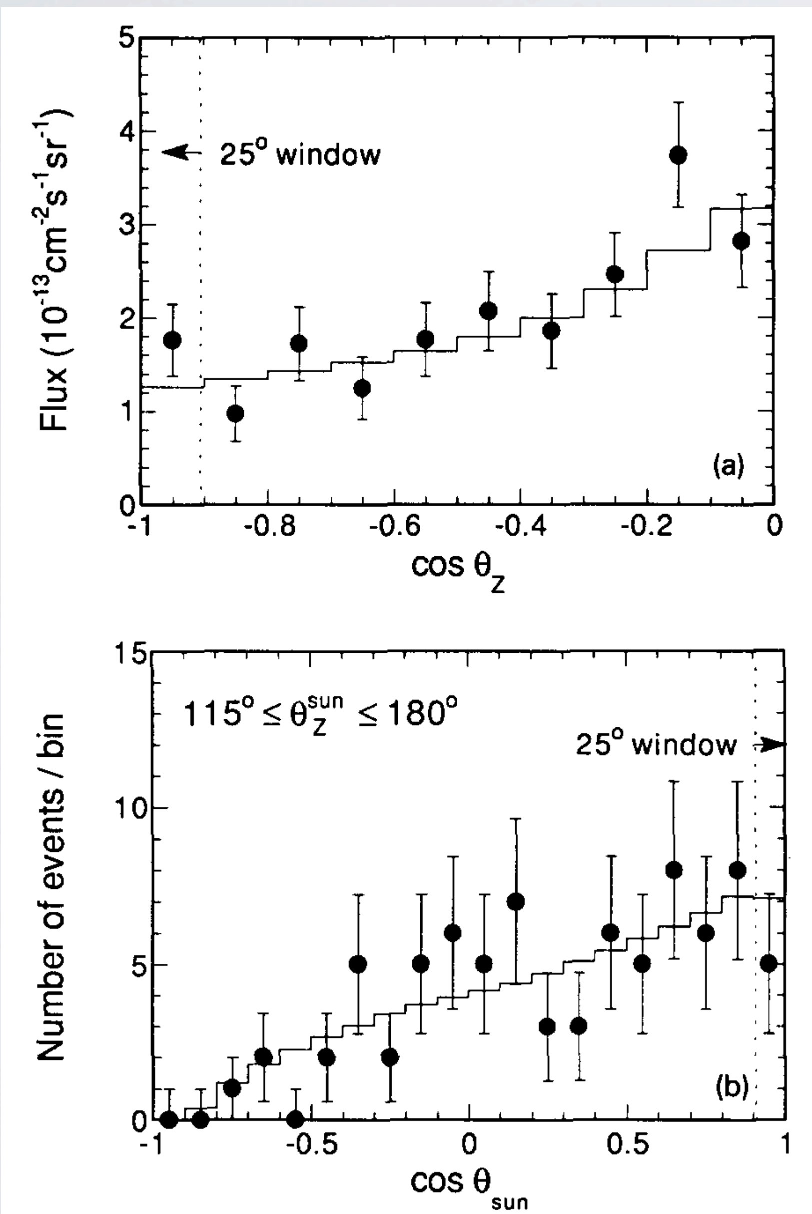
Beck et.al., Phys Lett B336, 141 (1994)



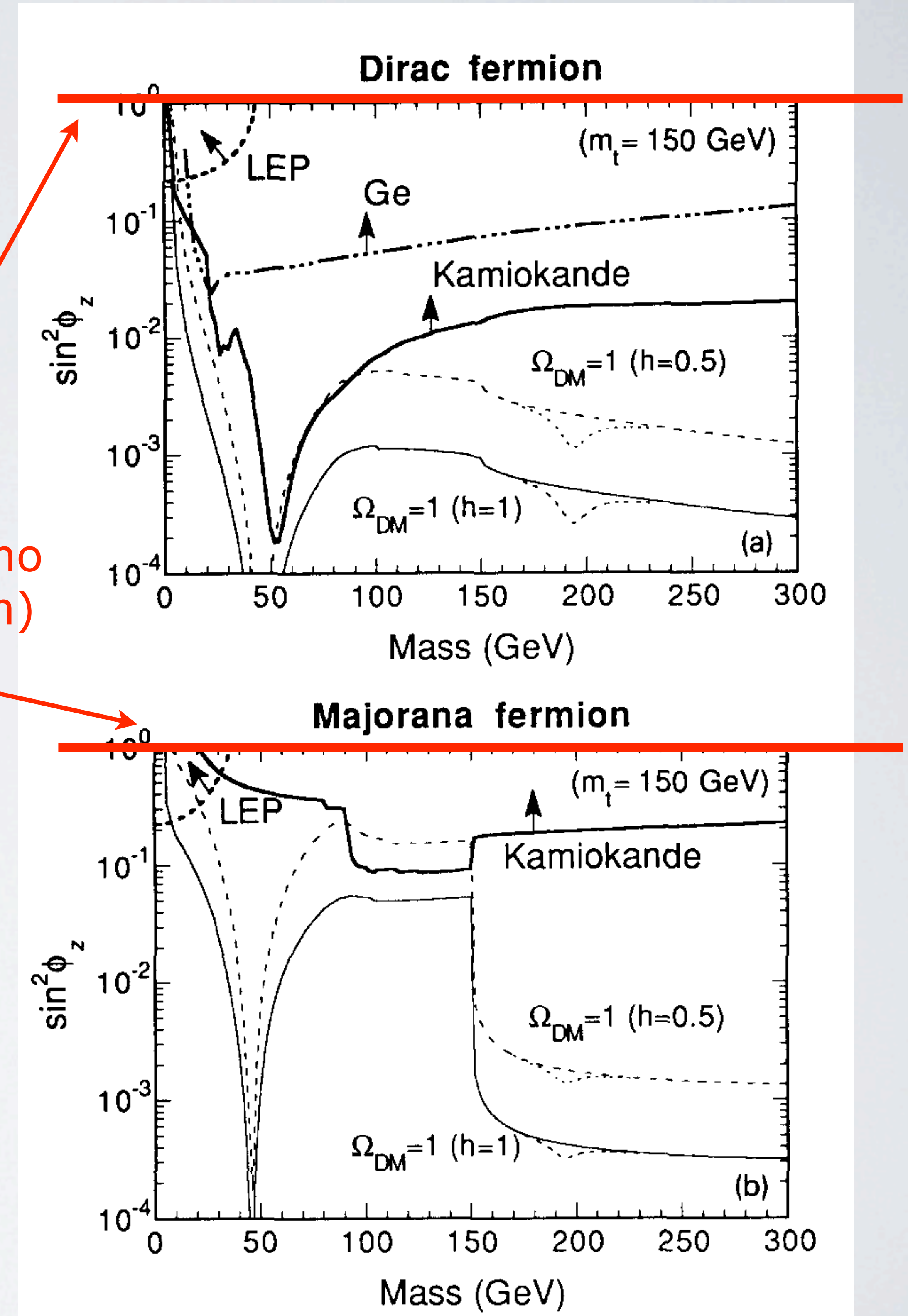
excluded by invisible Z decay

(current exclusions)

Heavy Majorana neutrino was long ago disfavored as primary component of DM, by indirect (non-)detection of upward-going muons at neutrino detector



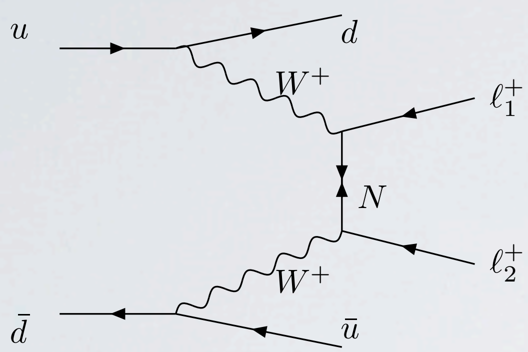
“real” neutrino
(full strength)

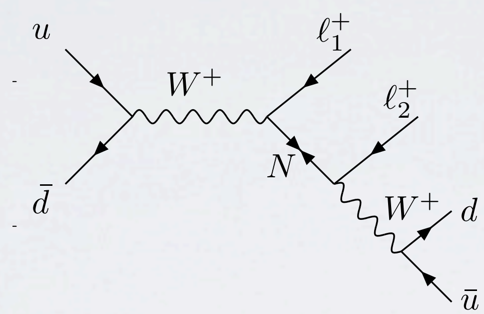


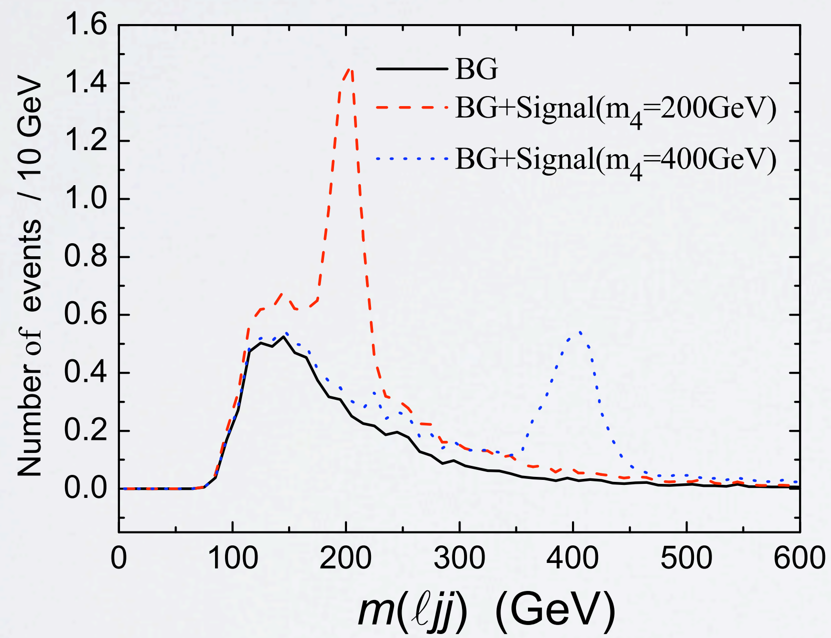
Mori et.al. (Kamiokande), PLB 289, 463 (1992)

NU'S AT THE LHC

They may not be *the* dark matter, but if high-mass states are out there, could see them at LHC

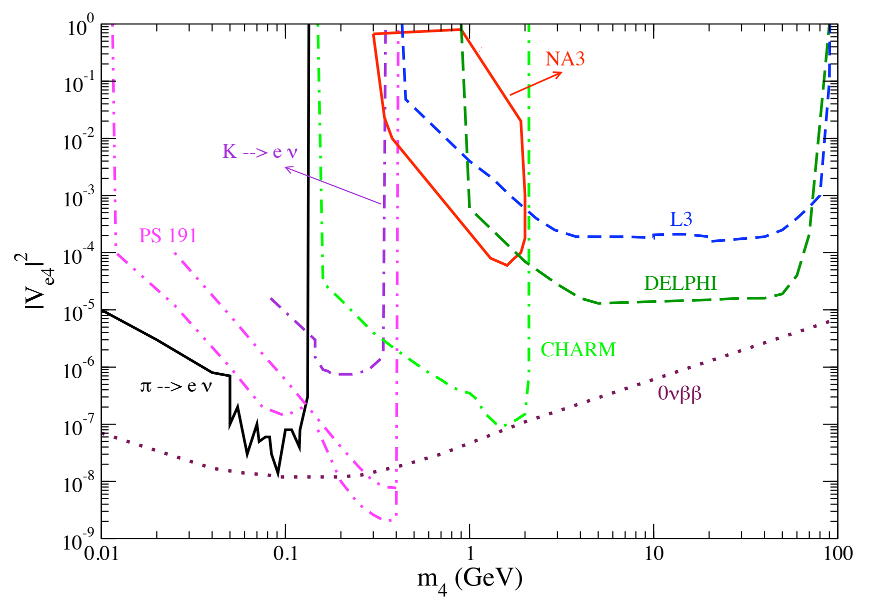




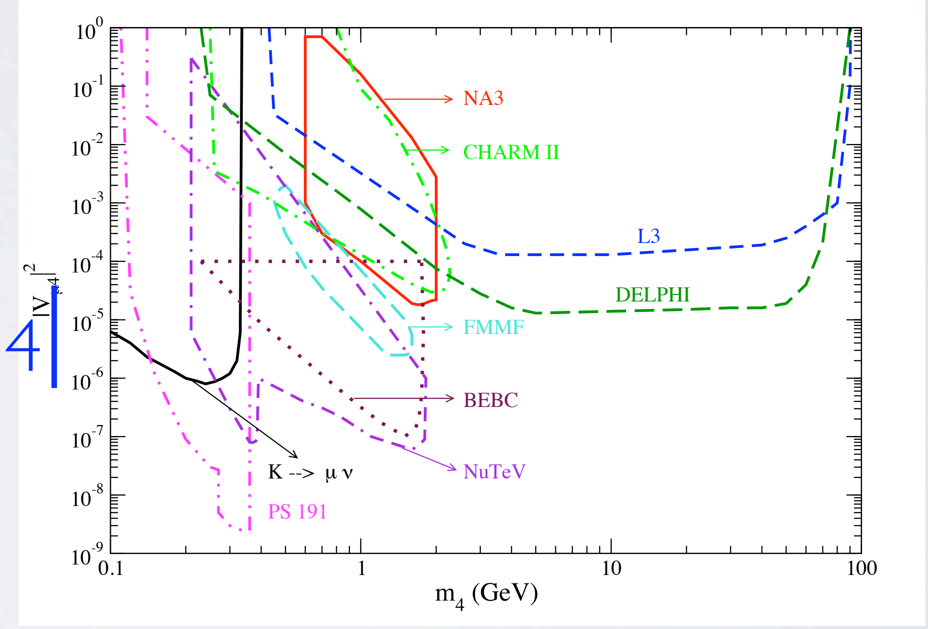


e.g. Atre, Han, Pascoli, Zhang, arXiv:0901.3589

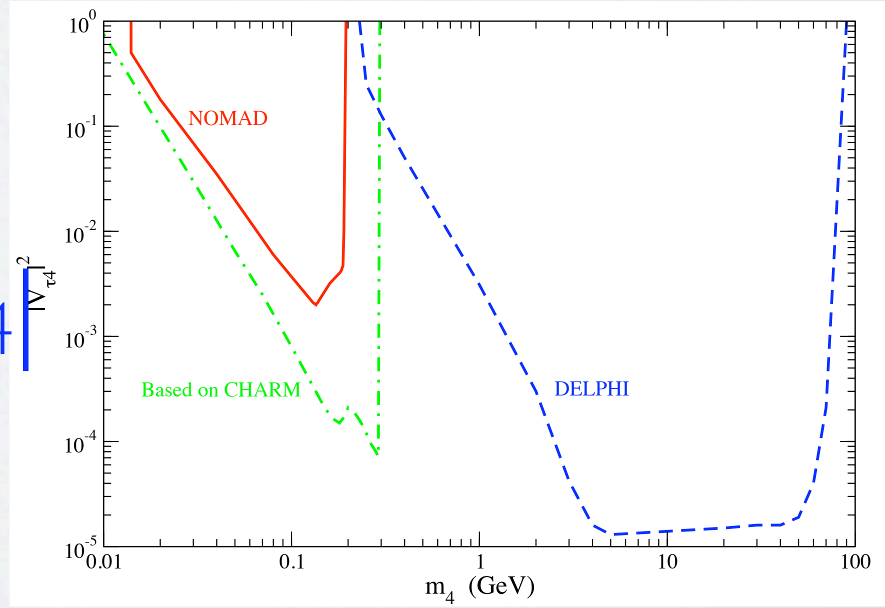
$|U_{e4}|$



$|U_{\mu 4}|$



$|U_{\tau 4}|$



EXAMPLE: 4TH GENERATION AND ELECTROWEAK SEESAW

An obvious objection to the naturalness of a 4th generation is the absence of a 4th light neutrino: $m_{\nu 4} > m_Z/2 \sim 45$ GeV

m_e	m_μ	m_τ	$m_{\ell 4}$
0.0005 GeV	0.106	1.8	?

But recall the see-saw mechanism that may be at work: $M \sim \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$

$$m_\nu \sim m_R/2 \pm \sqrt{(m_R/2)^2 + m_D^2} \sim m_R,\ m_D^2/m_R$$

If we take the Dirac mass of order the charged lepton mass, and the Majorana masses all of order the weak scale, then we would naturally explain the heaviness of the 4th "light" neutrino

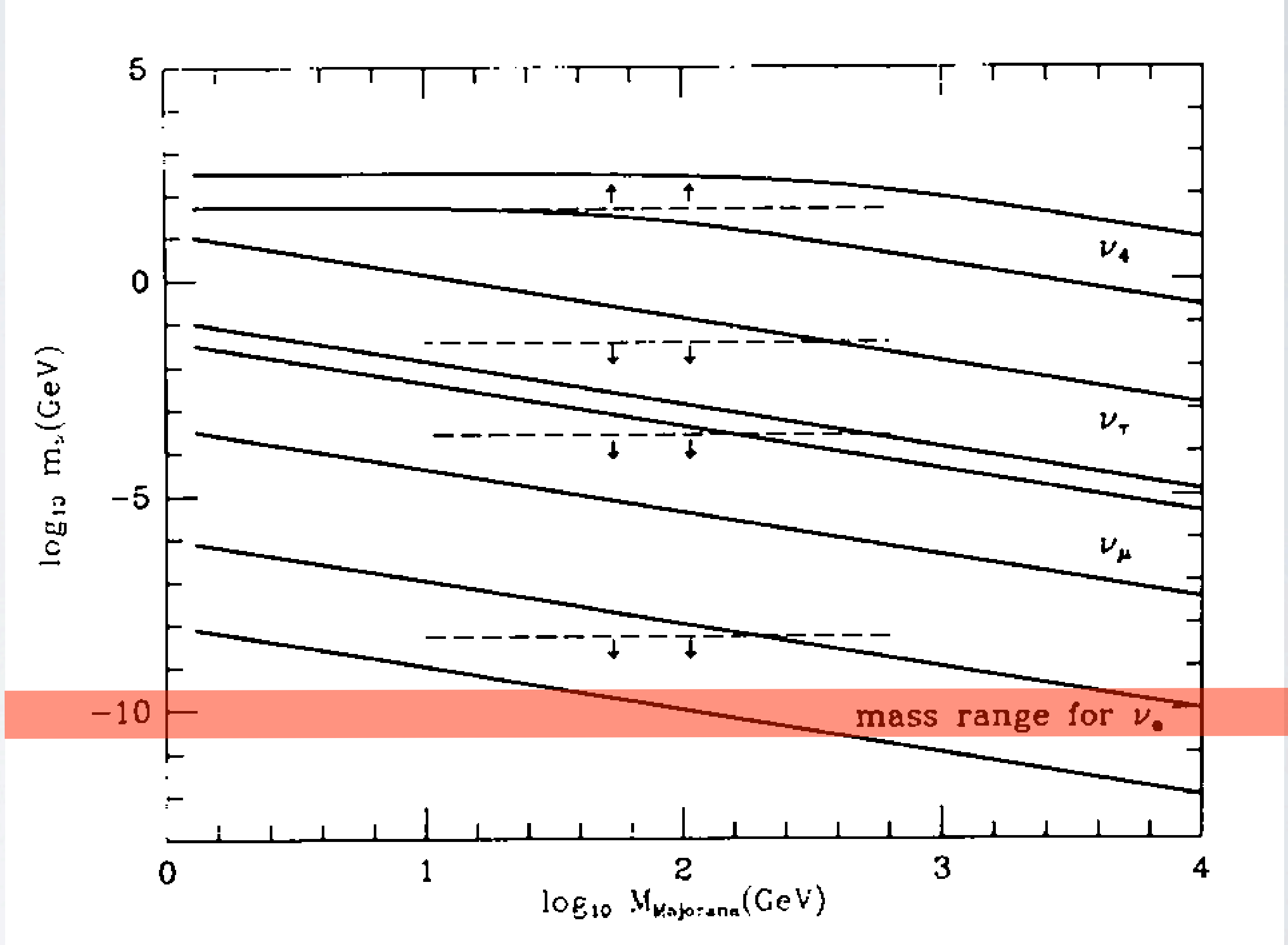
e.g. C.T.Hill & Paschos 1990

predictions:

m_R bounded below: light neutrinos must be light

m_R bounded above: 4th generation neutrino not below $m_Z/2$

abundant data has intervened: the average neutrino mass scale is too low to allow a universal weak-scale m_R



can still tune parameters, but not as natural (several constraints need to be satisfied for low scale ν_R also)

EXAMPLE: CLUES TO GUTS ?

Besides the seeming coincidence of the neutrino mass scale with a seesaw'ed GUT scale (10^{19}GeV), perhaps there are indications of GUT physics in the pattern of neutrino mixing:

E.g., it's interesting that the measured mixing angles are consistent with the "tri-bi" mixing

$$U_{\mathrm{TBM}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Harrison et.al. PLB 530, 167 (2002)

Such a scheme could arise from a discrete permuation symmetry on the fermion generations, although ideas from where that would come from are sparse

Can cook up schemes motivated by GUTs, e.g. merge SU(5) GUT with tetrahedral (T') permutation symmetry, and some symmetry breaking scalar fields

	T_3	T_a	$\overline{F}$	H_5	$H'_{\overline{5}}$	Δ_{45}	ϕ	ϕ'	ψ	ψ'	ζ	N	ξ	η
SU(5)	10	10	$\overline{5}$	5	$\overline{5}$	45	1	1	1	1	1	1	1	1
T'	1	2	3	1	1	$1'$	3	3	$2'$	2	$1''$	$1'$	3	1
Z_{12}	ω^5	ω^2	ω^5	ω^2	ω^2	ω^5	ω^3	ω^2	ω^6	ω^9	ω^9	ω^3	ω^{10}	ω^{10}
Z'_{12}	ω	ω^4	ω^8	ω^{10}	ω^{10}	ω^3	ω^3	ω^6	ω^7	ω^8	ω^2	ω^{11}	1	1

Chen and Mahanthappa, 0910.5467

$|U_{e3}| = 0.0583$?

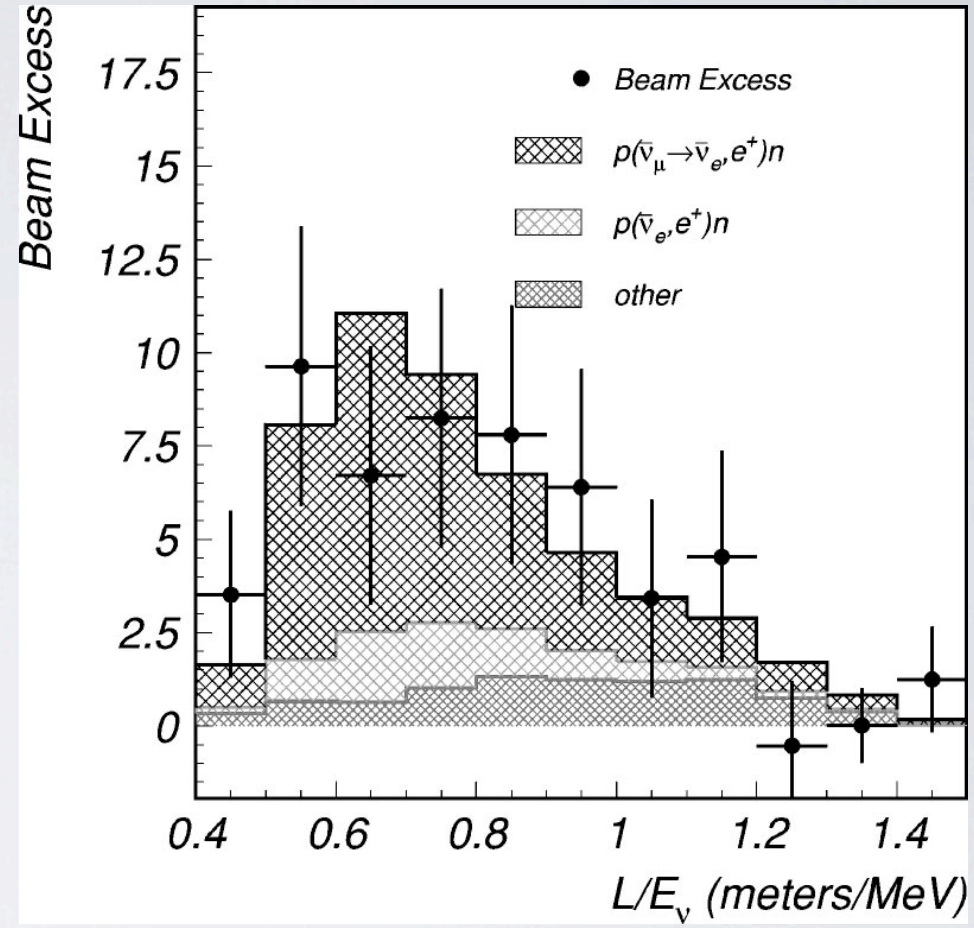
By imposing sufficiently many constraints/symmetries on the interactions, find that not all parameters are independent. But need a guiding principle for embedding tri-bi into fundamental theory.

Unfortunately, without an understanding of the possible origin of such a permutation symmetry, difficult to conjecture the size of corrections

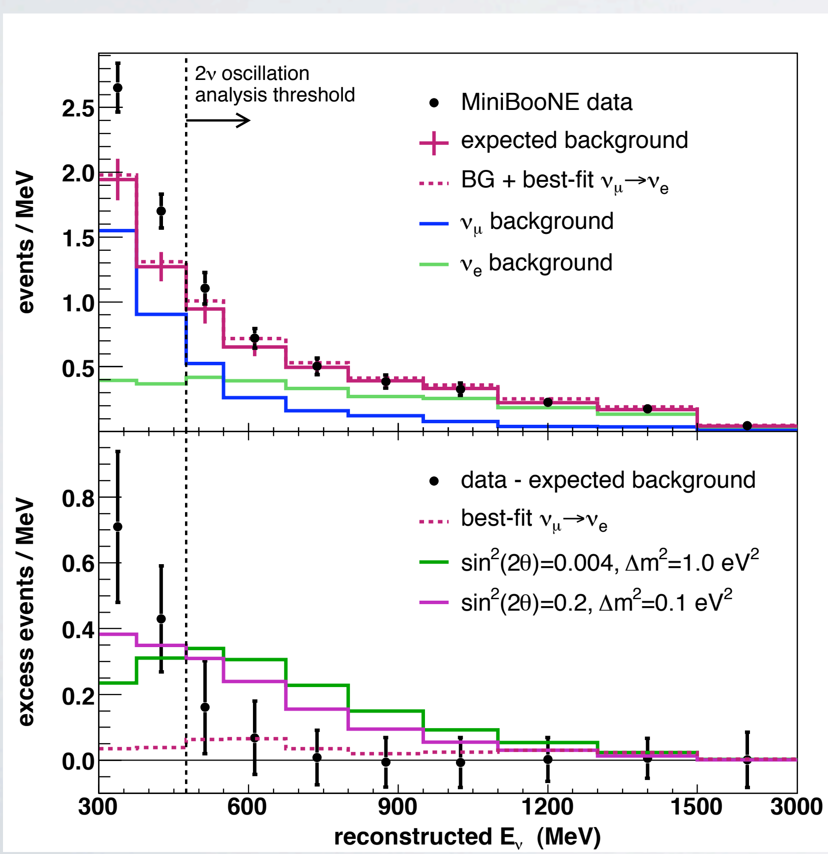
EXAMPLE: OTHER STERILE NU'S?

Not obvious a priori that there are exactly three light sterile neutrinos

LSND - signal for high **Δ***m*^{2} *oscillation ?*



LSND, PRD 64, 12007 (2001)

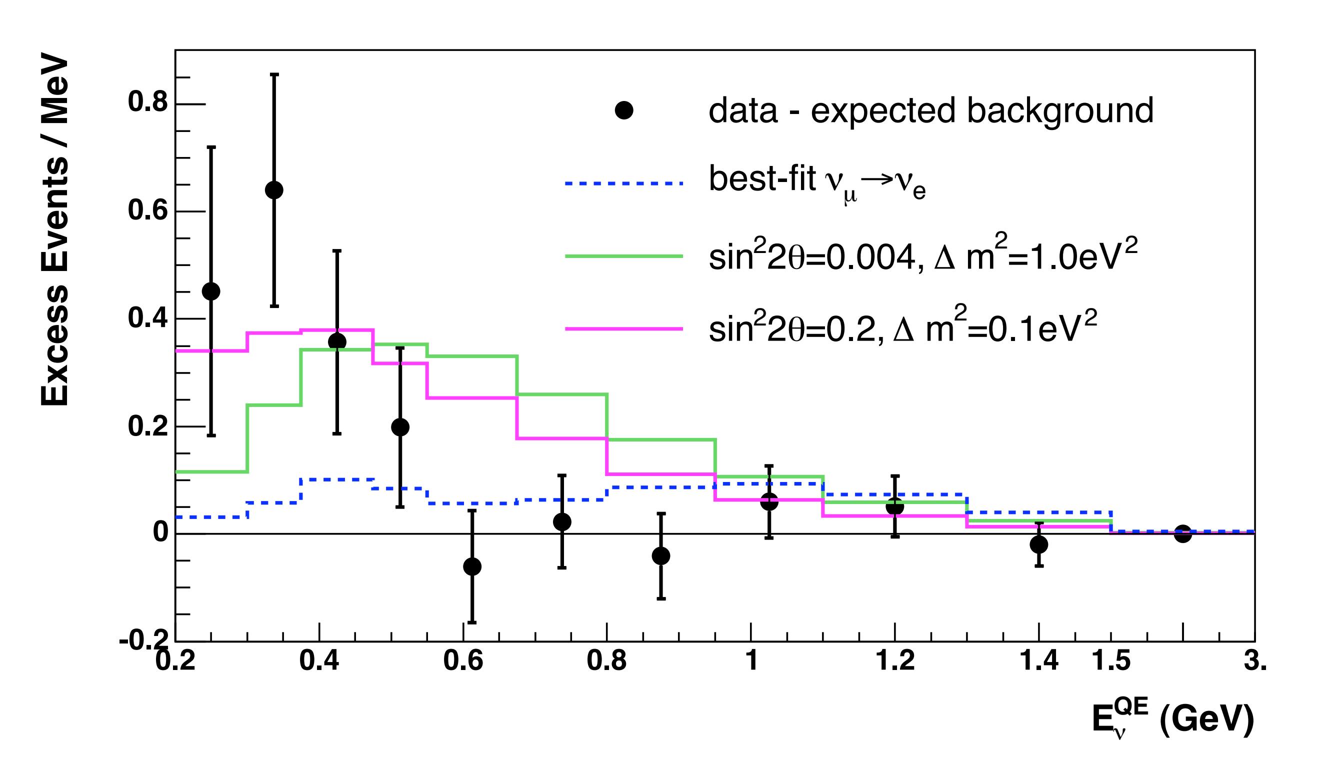


the 2-neutrino oscillation interpretation has since been refuted

MiniBooNE PRL 98, 231801 (2007)

But another mystery ?

- low energy excess of electron-like events in muon neutrino beam



[MiniBooNE, PRL 102, 211801 (2009)]

Some proposed explanations:

- resonance from large extra dimensions

Pas, Pakvasa & Weiler, hep-ph/0504096

- gauged B-L model with 3 sterile neutrinos

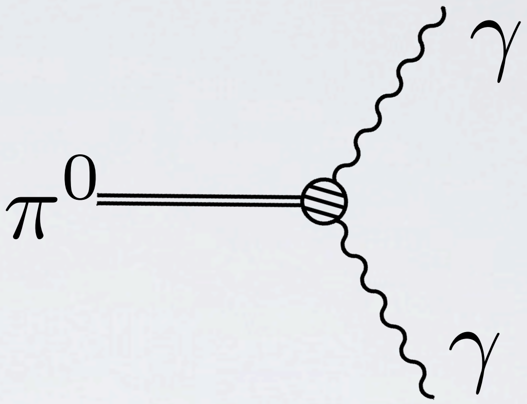
Nelson & Walsh, 0711.1364

- some overlooked standard model physics: (coherent) single photon production

Harvey, Hill & Hill, PRL 99, 261601 (2007)

Axial anomaly

Any fields coupling to anomalous symmetries must have peculiar interactions



E.g., the pion is generated by the axial-vector current, which is anomalous:

$$\partial_\mu J_5^\mu \propto \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

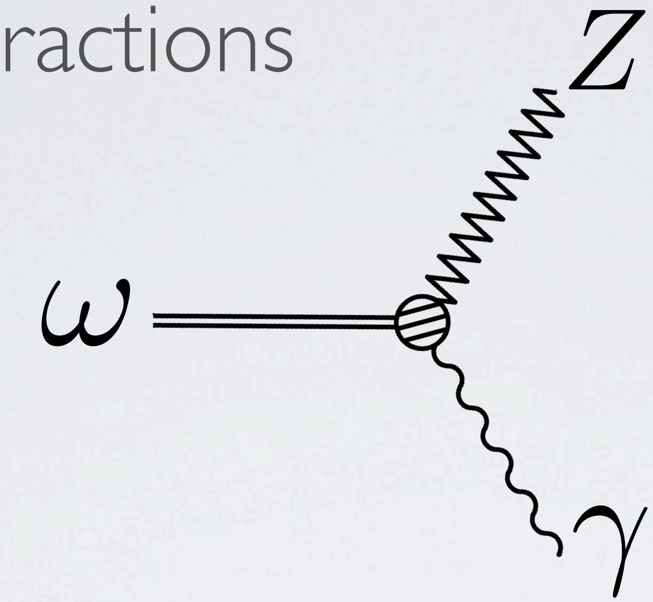
If we try an ill-advised gauge transformation on the axial symmetries, have to get the expected anomaly

$$\mathcal{L} \sim \epsilon^{\mu\nu\rho\sigma} \pi F_{\mu\nu} F_{\rho\sigma}$$

$$\pi \rightarrow \pi + \epsilon \qquad \Rightarrow \qquad \delta\mathcal{L} \equiv \epsilon \partial_\mu J_5^\mu \sim \epsilon[\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}]$$

Baryon anomaly

Again, any fields coupling to anomalous symmetries must have peculiar interactions



Baryon number is anomalous in the Standard Model

$$\partial_\mu J^\mu_{\rm baryon} \propto \epsilon^{\mu\nu\rho\sigma}\partial_\mu Z_\nu F_{\rho\sigma} + \ldots$$

If we make an ill-advised gauge transformation, have to find an anomaly

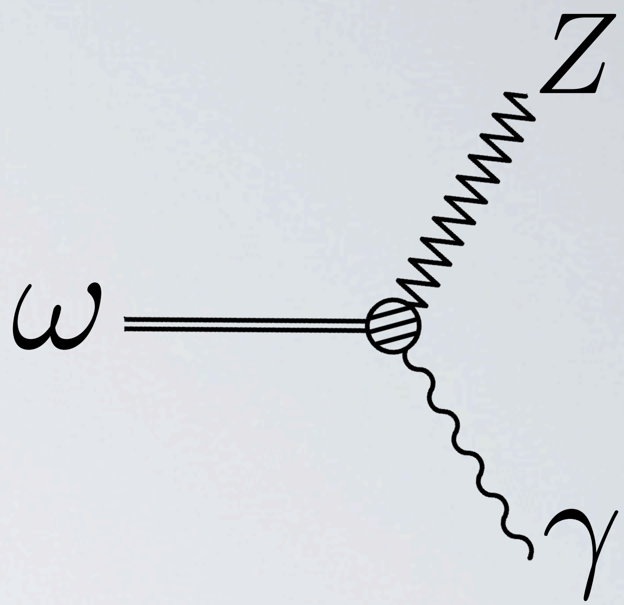
$$\mathcal{L} \sim \epsilon^{\mu\nu\rho\sigma}\omega_\mu Z_\nu F_{\rho\sigma}$$

$$\delta\omega_\mu = \partial_\mu \epsilon$$

$$\Rightarrow \quad \delta\mathcal{L} \equiv \epsilon\partial_\mu J^\mu_5 \sim \partial_\mu\epsilon[\epsilon^{\mu\nu\rho\sigma} Z_\nu F_{\rho\sigma}] \sim -\epsilon[\epsilon^{\mu\nu\rho\sigma}\partial_\mu Z_\nu F_{\rho\sigma}]$$

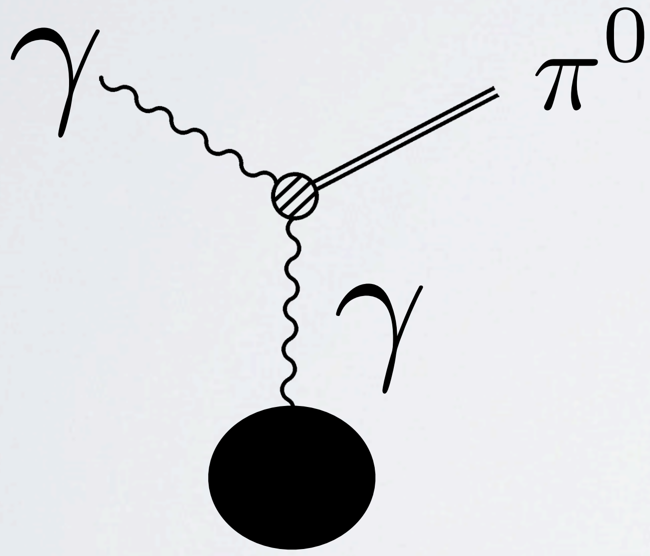
If Z was much lighter, would see e.g. **ω→Zγ** *directly.*

$$\mathrm{Br}(\omega \to \gamma\nu\bar{\nu}) \sim \left(\frac{g^2_{\mathrm{weak}}}{m^2_W}\right)^2 \frac{f^6_\pi}{m^2_\omega} \sim \frac{G^2_F f^6_\pi}{m^2_\omega} \sim \mathrm{tiny}$$

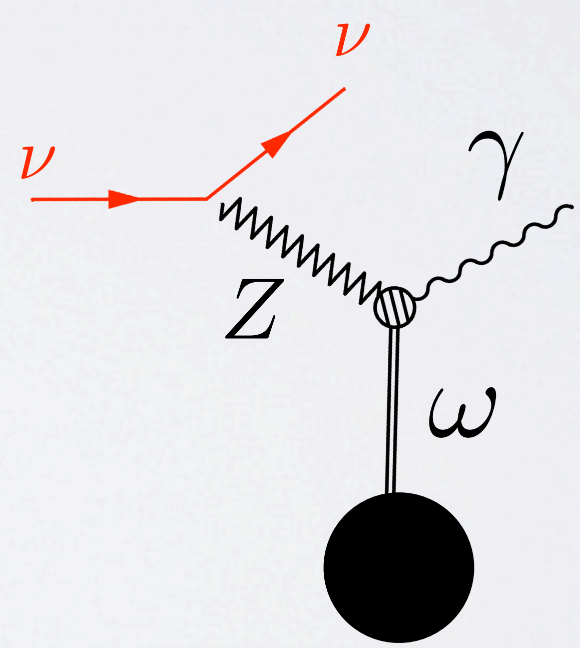


But in practice, Z is heavy (weak interactions are weak !)

Compare Primakoff effect:

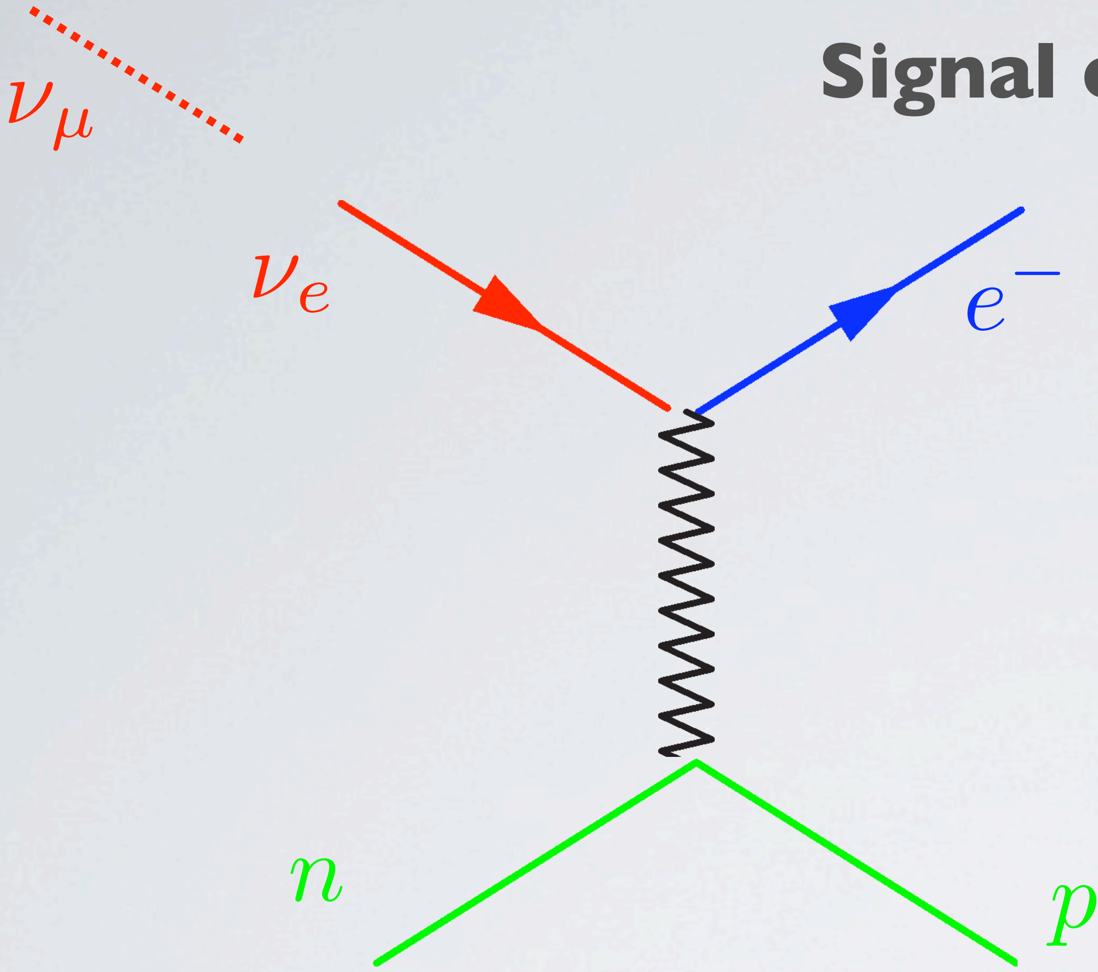


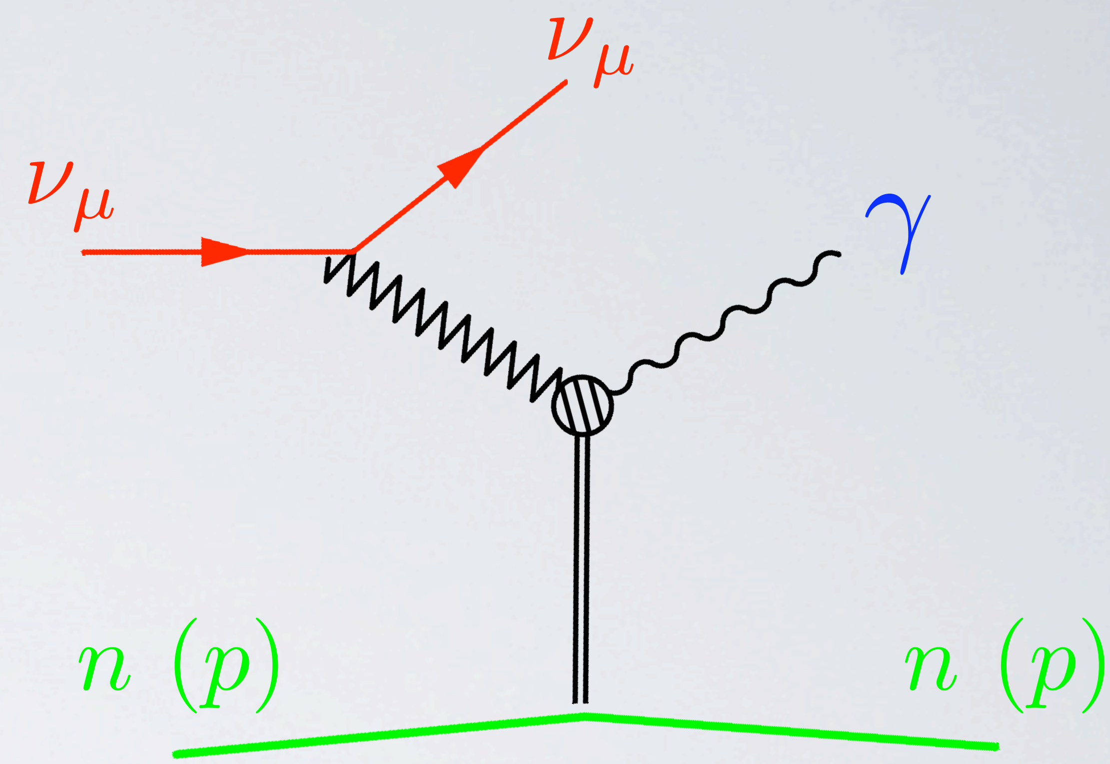
Coherent scattering off electric charge



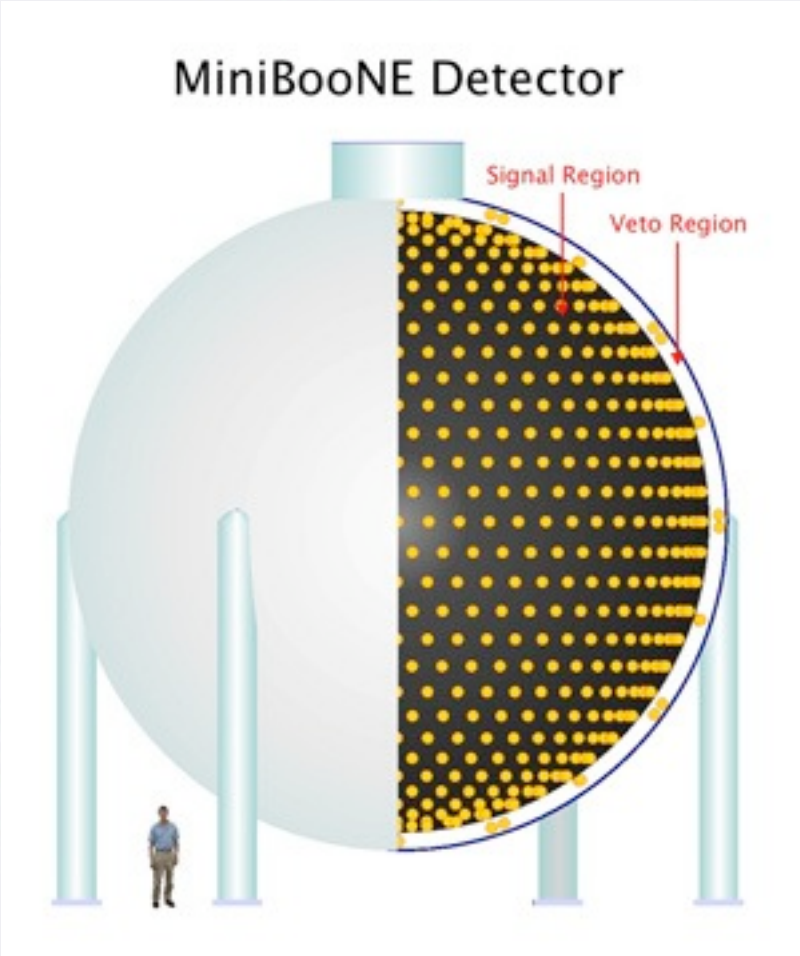
Coherent scattering off baryon number

Signal or background ?





$\nu_e \rightarrow e$ “signal”



$\nu_\mu \rightarrow \gamma$ “background”

At energies of order 1 GeV, an extrapolation of the chiral lagrangian gives a meaningful estimate for various mechanisms of single photon production

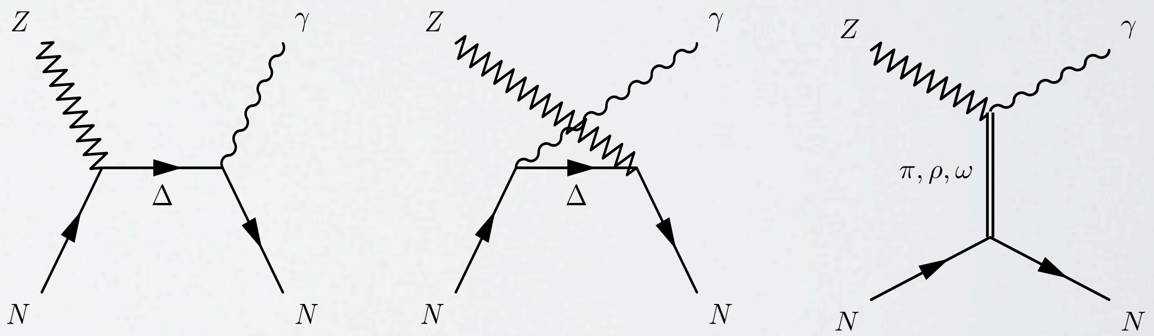
R.J. Hill, 0905.0291

Through three-derivative order, a unique operator couples baryon number to neutral current and electromagnetism

$$\frac{c}{m_N^2} i\epsilon^{\mu\nu\rho\sigma} \bar{N}\gamma_\sigma N \mathrm{Tr}(\{A_\mu, [iD_\nu, iD_\rho]\})$$

Significant pollution/enhancement from the Delta resonance:

$$\begin{aligned} c &\sim c_\Delta + c_\omega + c_\rho \\ &\sim 5.0 + 1.5 + 0.2 \end{aligned}$$

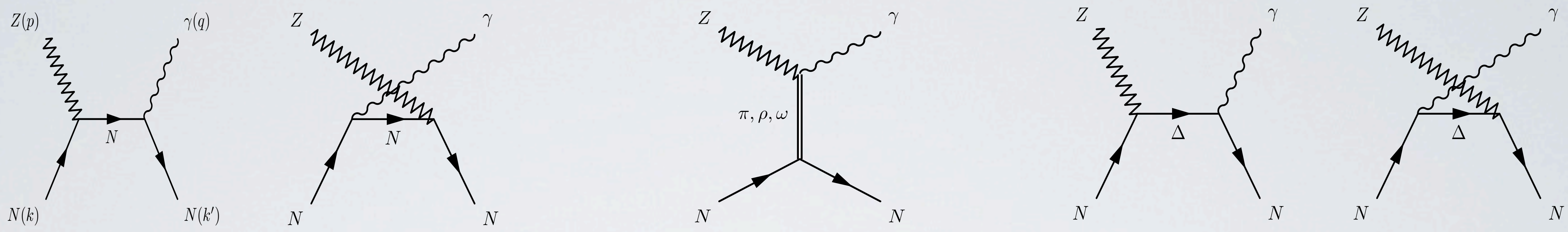


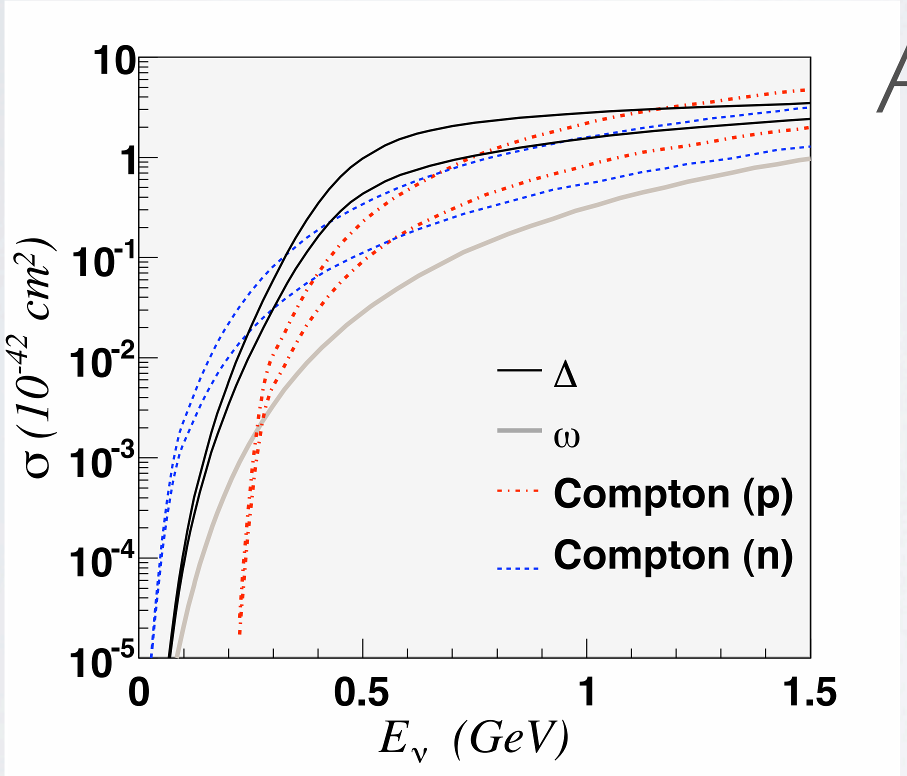
At large energies, these bifurcate into separate s- and t-channel resonance contributions

WHY IS IT SO #?! HARD TO CALCULATE?

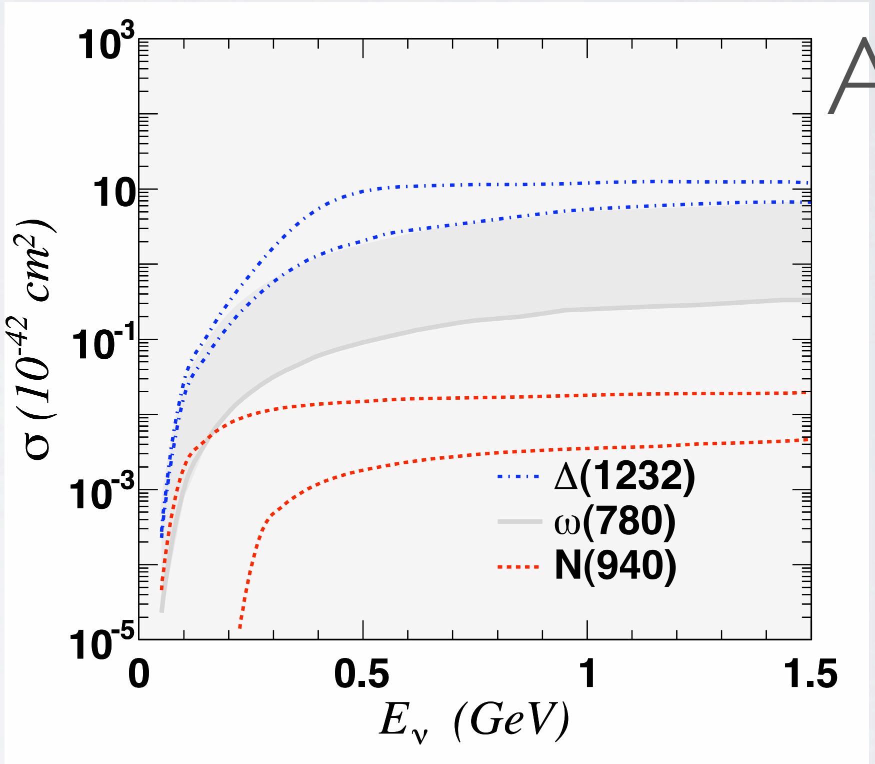
- what are the errors ? ≈ what is the expansion ?
- need to get creative: $1/N_c$, z(dispersive), 1/A(nucleus), ...
- model independent approach: decompose into helicity amplitudes. but 12 of them, depending on multiple kinematic invariants - need dynamical model/small parameter expansion
- without support from data, errors to tree-level meson exchange are "$1/N_c$" ~ 30% if all relevant states are considered (large energy ⇒ need more states)

Tabulate the various contributions, consider both incoherent (nucleon knock-out) and coherent cross sections





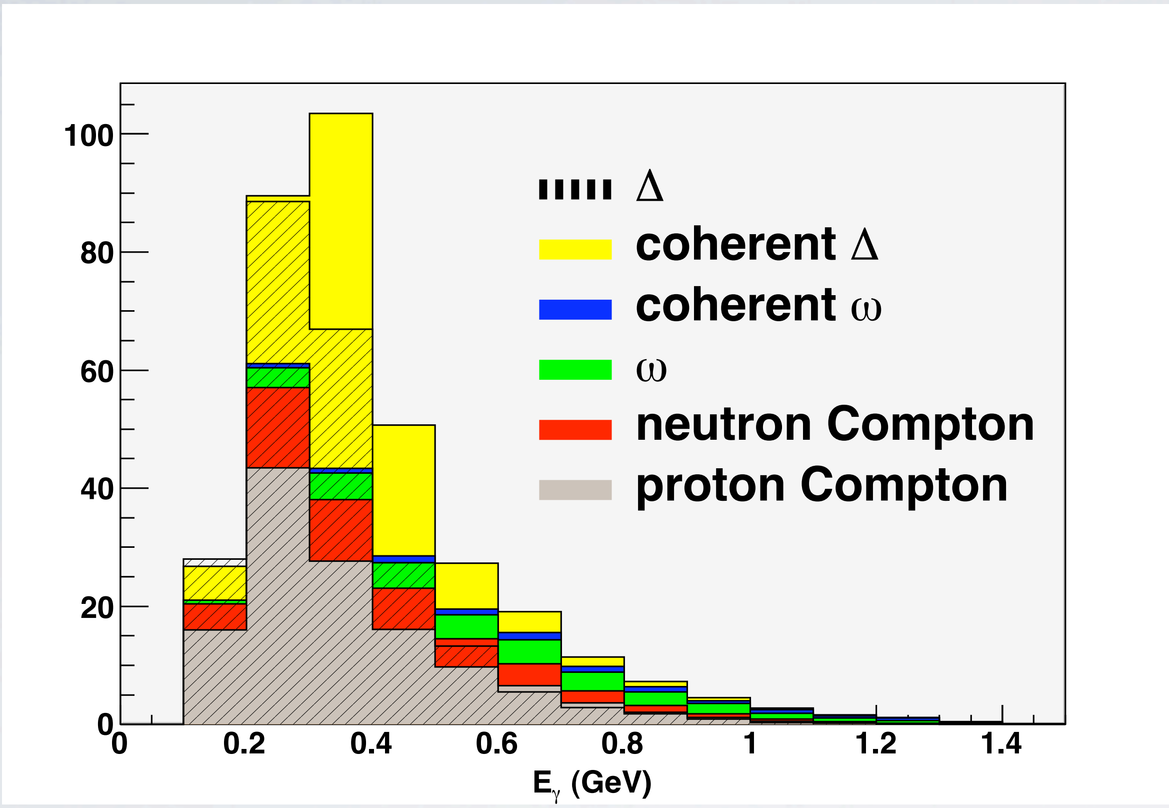
A=1



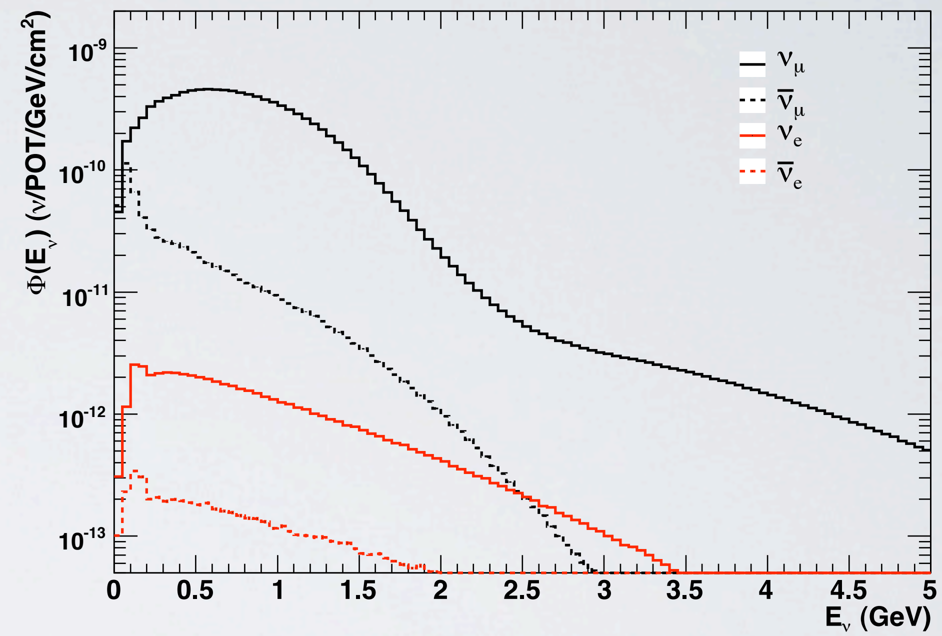
A=12

Include phenomenological form factors, and perform flux averaging to yield predictions for MiniBooNE spectrum

flux averaging (MiniBooNE ν mode 6.46e20 POT)

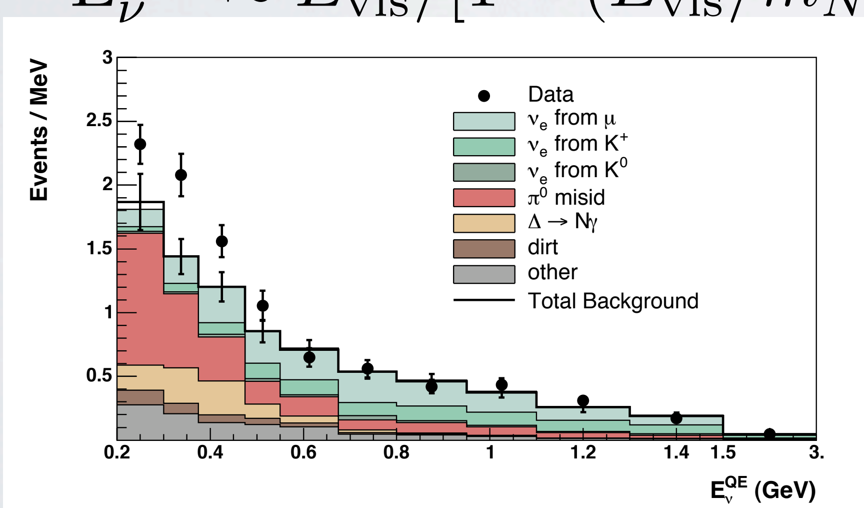


⇐

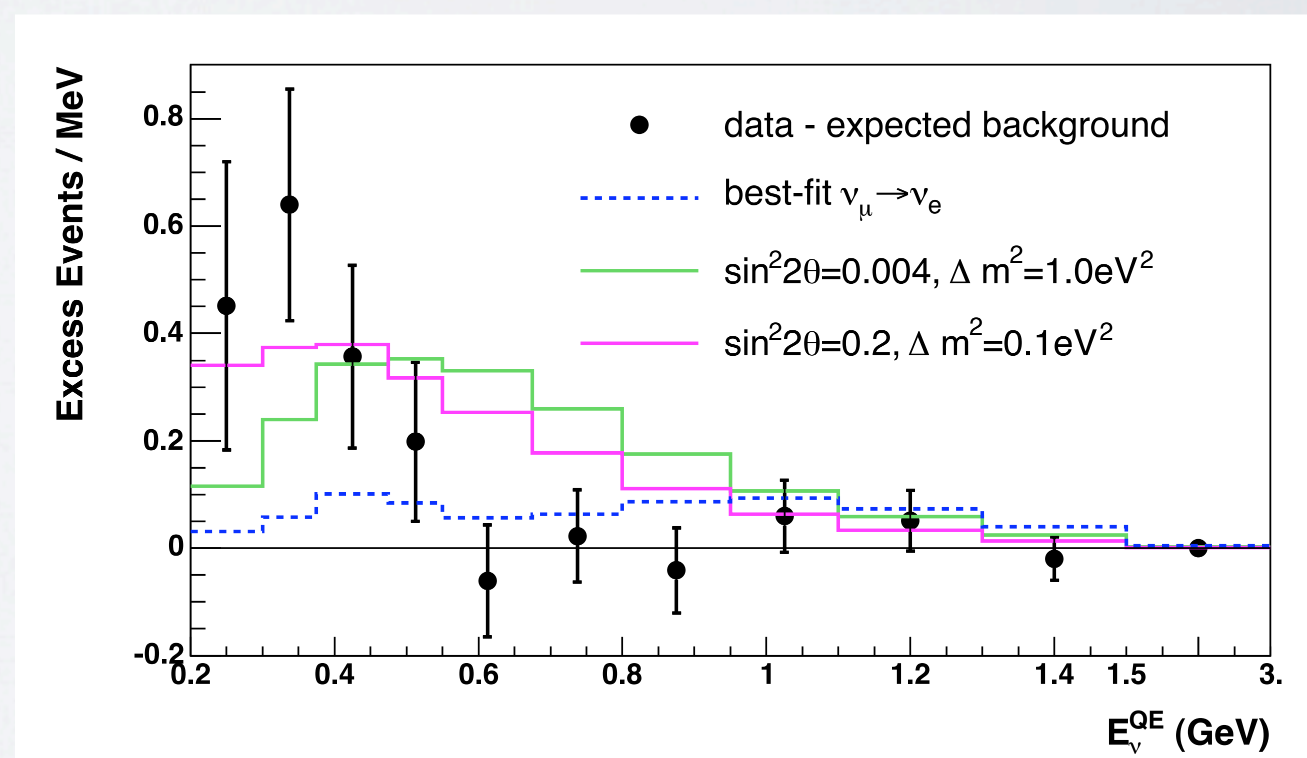


[MiniBooNE, Phys. Rev. D 79, 072002 (2009)]

$$E_\nu^{QE} \approx E_{\rm vis}/[1-(E_{\rm vis}/m_N)(1-\cos\theta)]$$



[MiniBooNE, PRL 102, 211801 (2009)]



An excess of “electrons”

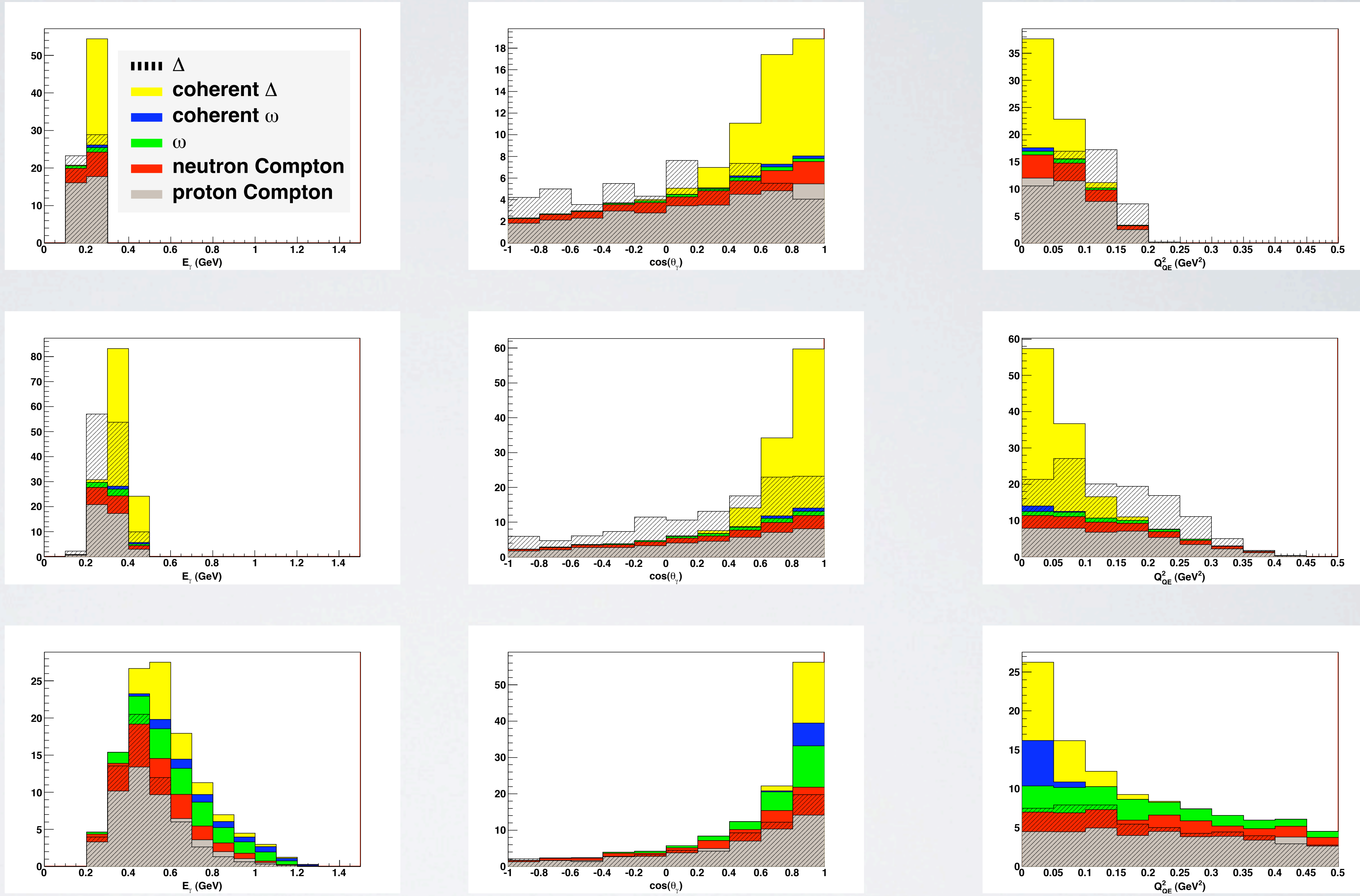
flux averaged distributions (MiniBooNE ν mode)

E_ν^{QE}

200-300 MeV

300-475

475-1250



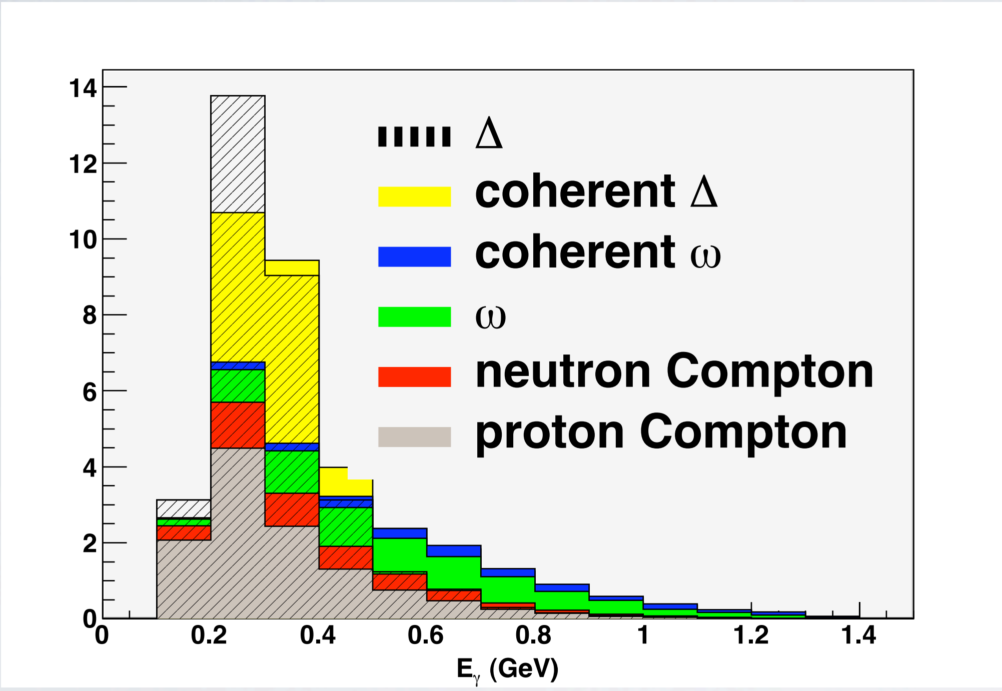
E

cosθ

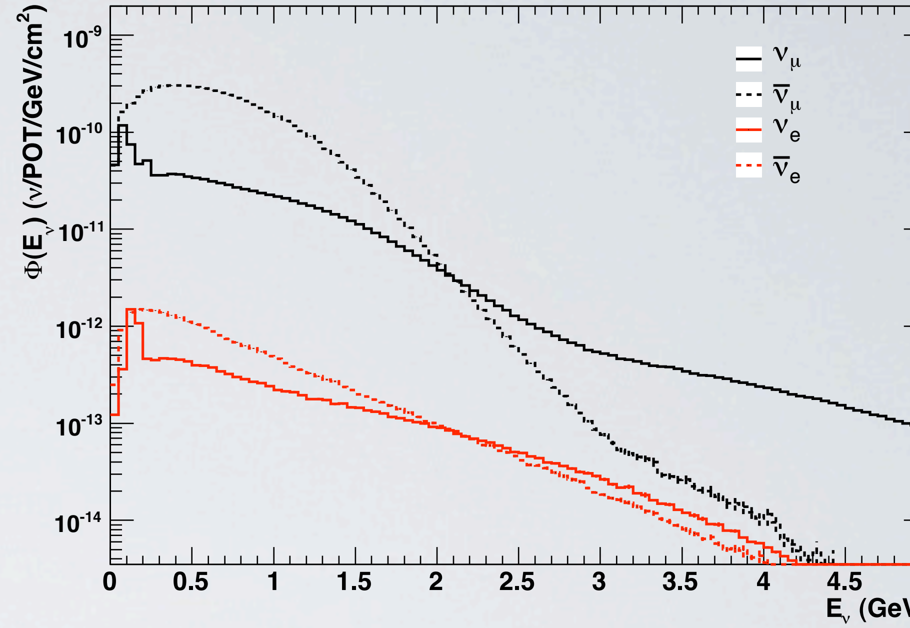
Q²

$$(\mathrm{Q}^2)^{QE} \approx 2E_\nu^{QE} E_{\mathrm{vis}}(1-\cos\theta)$$

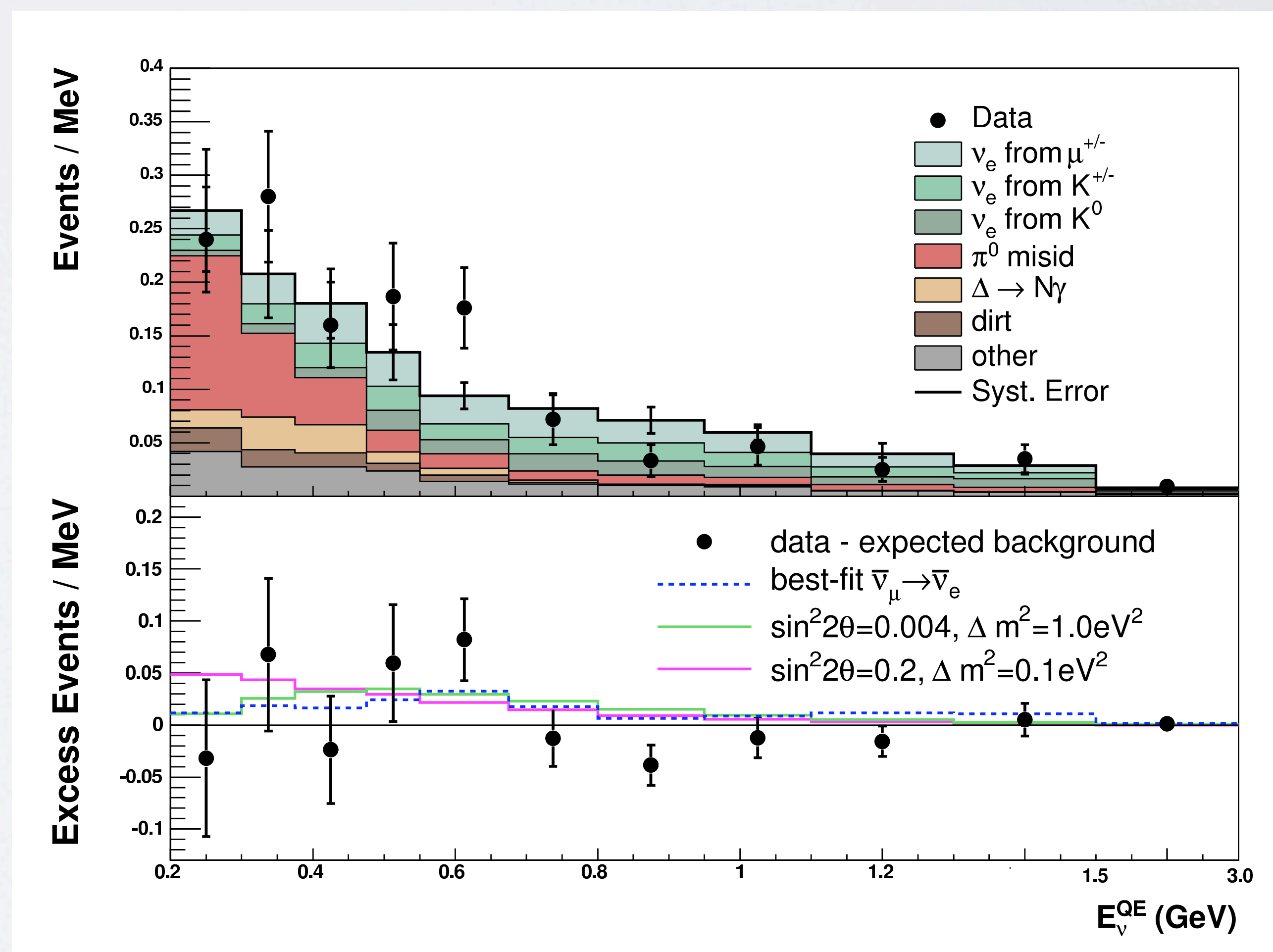
flux averaging (MiniBooNE ν-bar mode 3.39e20 POT)



$\Leftarrow$



[MiniBooNE, Phys. Rev. D 79, 072002 (2009)]



[MiniBooNE, arXiv:0904.1958]

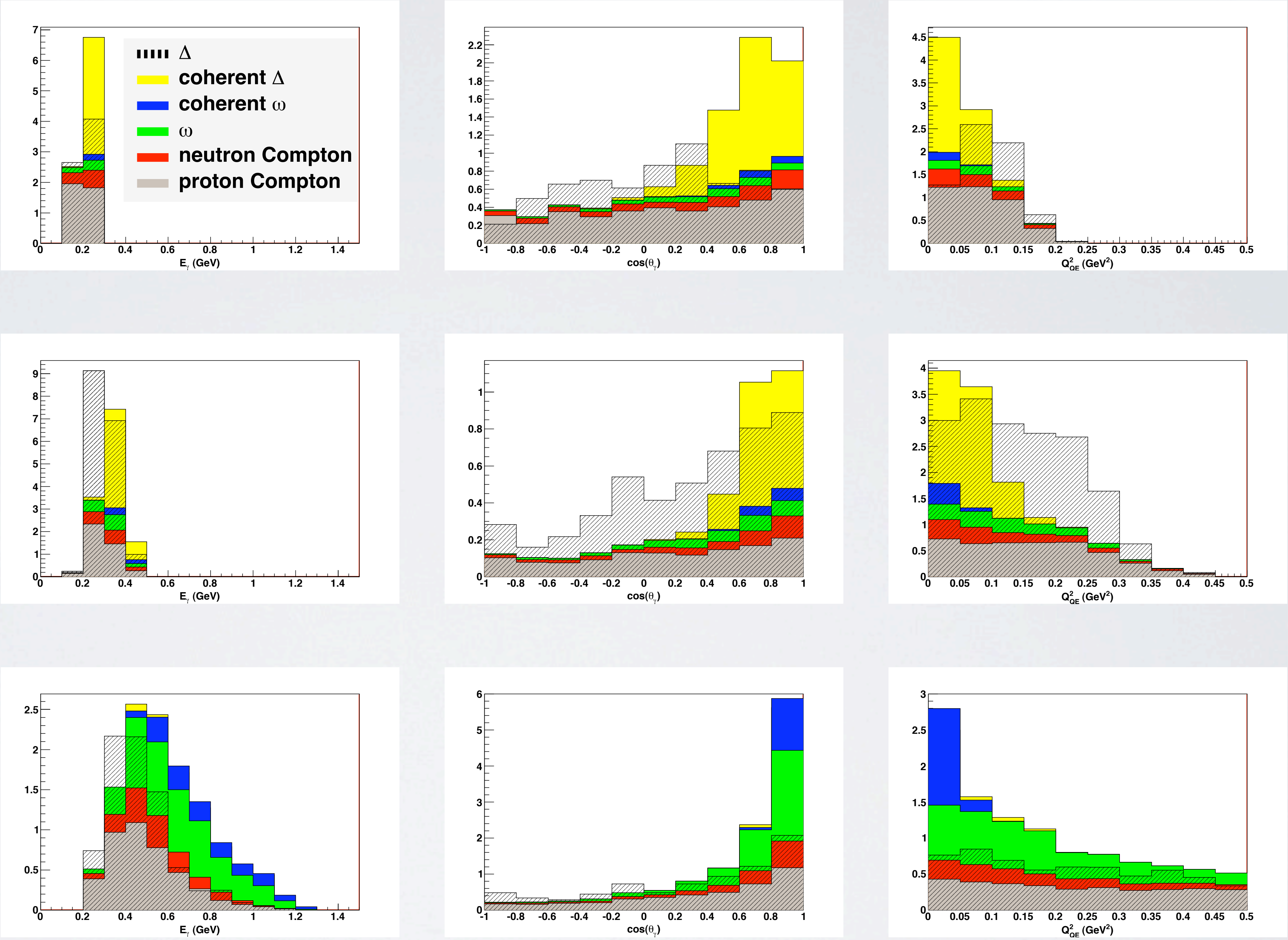
flux averaged distributions (MiniBooNE ν-bar mode)

E_ν^{QE}

200-300 MeV

300-475

475-1250



<u>ν</u>

	new events	excess	Δ-direct	Δ (MB)
200-300 MeV	75 [23]	45(26)	52 [16]	20
300-475	139 [42]	84(25)	123 [37]	48
475-1250	119 [36]	22(36)	61 [18]	19

apply 30% acceptance

$\chi^2 = 1.5/2$ d.o.f. (scale = 0.51),

$\chi^2 = 3.8/3$ d.o.f. (scale = 0.3),

estimate of incoherent events

included in MiniBooNE bkgd.

<u>ν-bar</u>

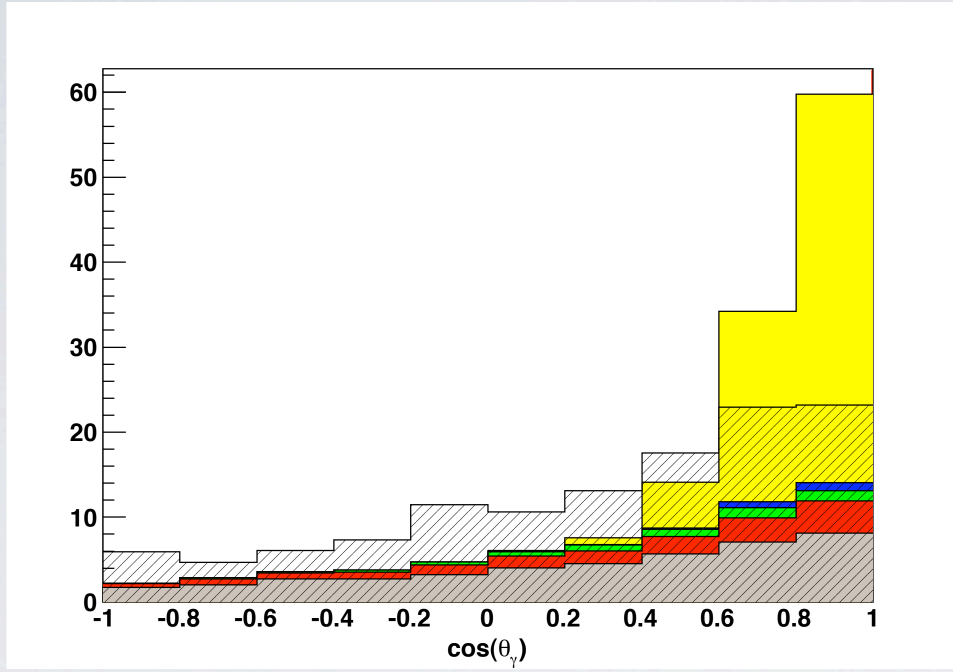
200-300 MeV	9.3 [2.8]	-0.5(11.7)	6.7 [2.0]	1.7
300-475	13 [3.8]		17.3 [5.2]	4.9
475-1250	12 [3.6]	3.2(10.0)	7.7 [2.3]	2.0

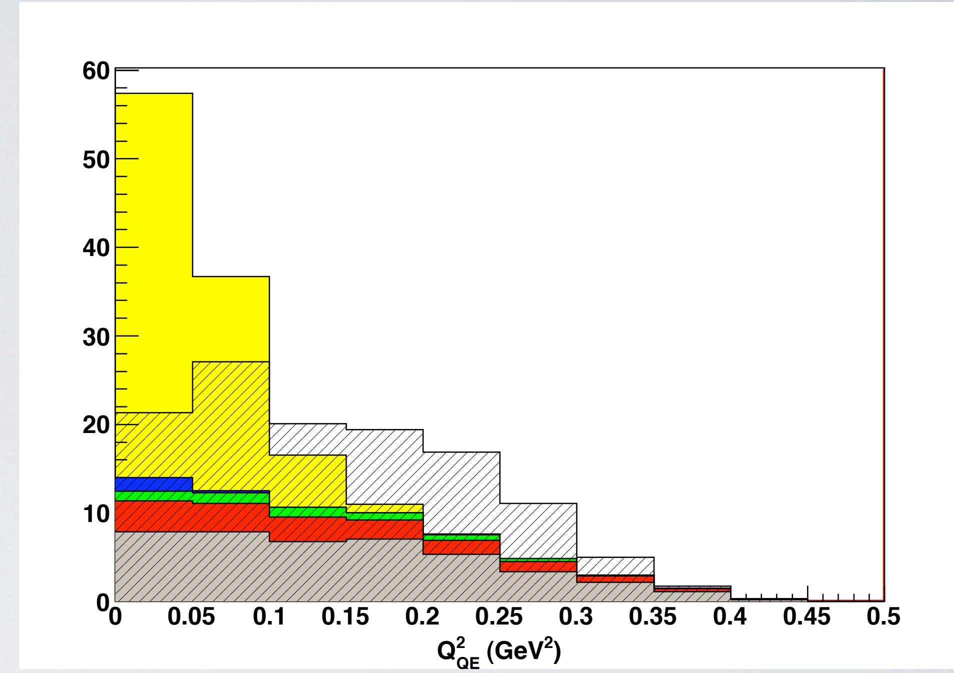
$\chi^2 = 0.3/2$ d.o.f. (scale = 0.3),

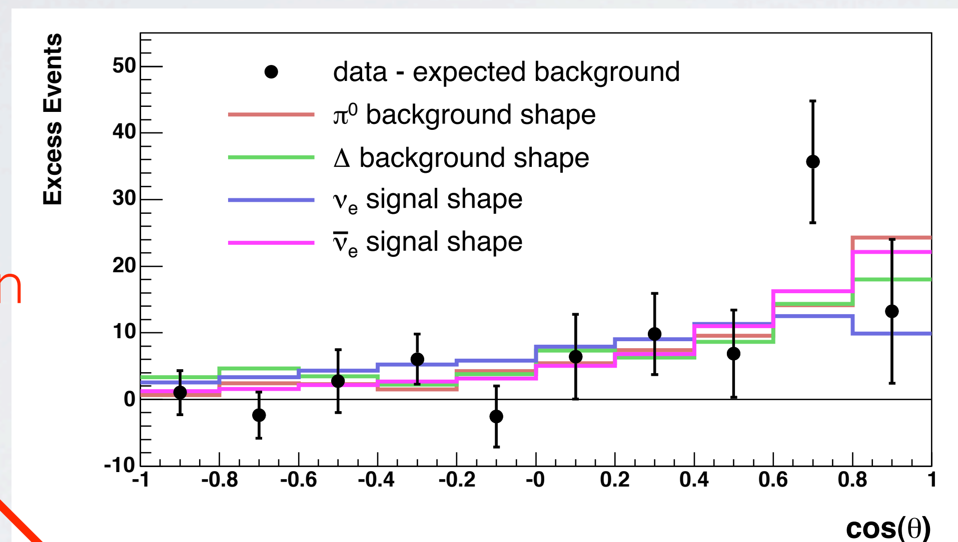
⇒ size appears consistent with data

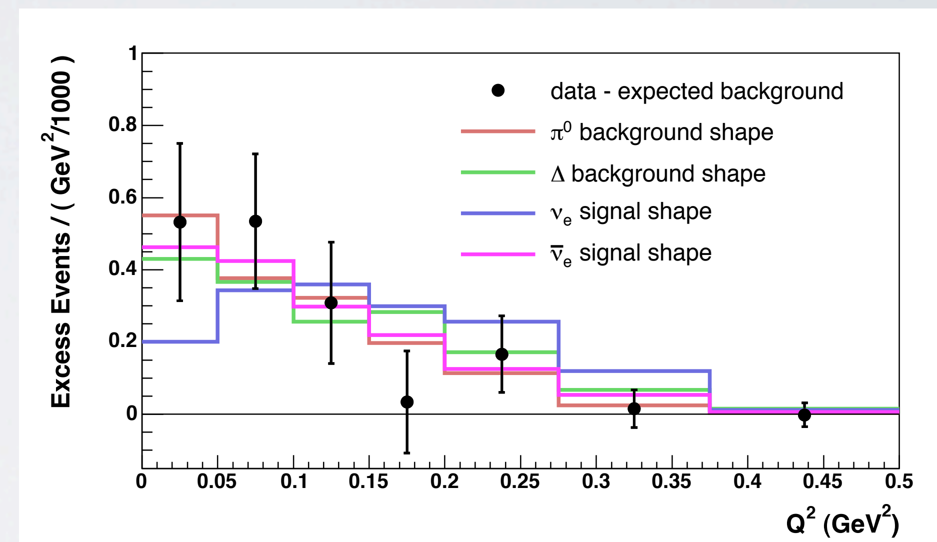
- should do more complete efficiency analysis, incorporate nuclear effects

shape comparison









float normalization

$\chi^2 = 9.9 / 9$ d.o.f. (scale = 0.51)

$\chi^2 = 2.5 / 6$ d.o.f. (scale = 0.60)

30% efficiency

$\chi^2 = 12.7 / 10$ d.o.f. (scale = 0.30)

$\chi^2 = 8.0 / 7$ d.o.f. (scale = 0.30)

$\Rightarrow$ shape appears consistent with excess

Process	$\chi^2(cos\theta)/9$ DF	$\chi^2(Q^2)/6$ DF	Factor Increase
NC π^0	13.46	2.18	2.0
$\Delta \to N\gamma$	16.85	4.46	2.7
$\nu_e C \to e^- X$	14.58	8.72	2.4
$\bar{\nu}_e C \to e^+ X$	10.11	2.44	65.4

[MiniBooNE, PRL 102, 211801 (2009)]

Dipping a toe into the nuclear realm...

$$\frac{1}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta}$$

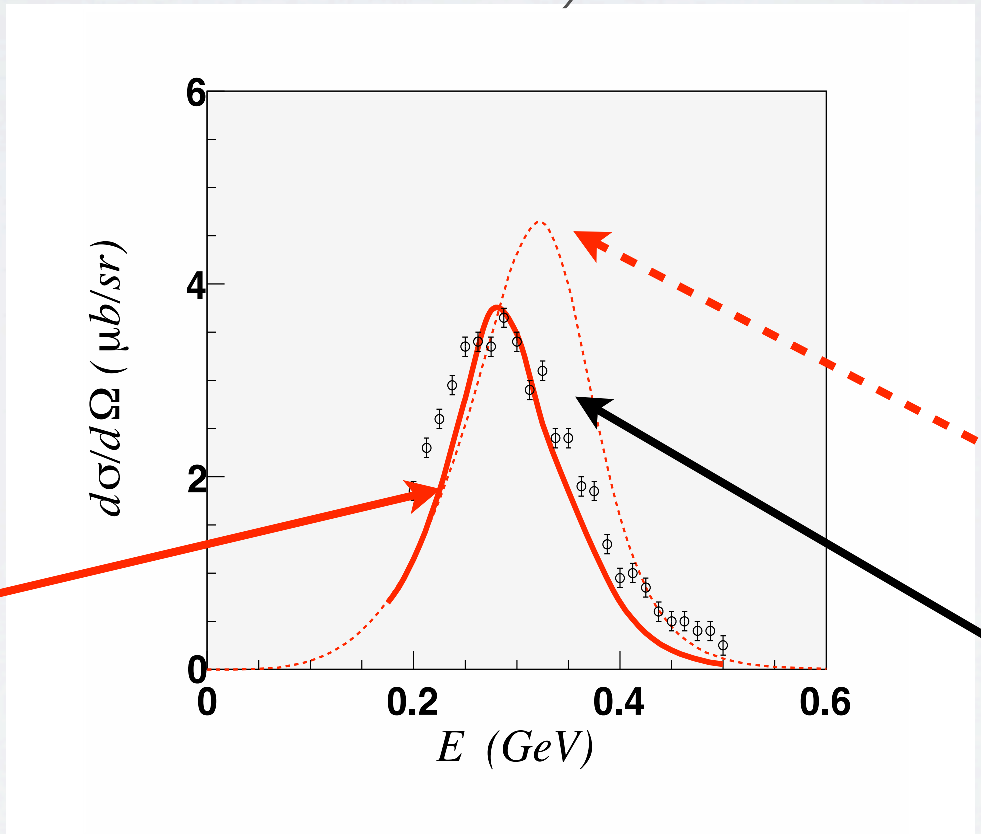
$$\Gamma_\Delta \sim \Gamma_0 (p_\Delta / p_0)^3$$

$$m_\Delta \to m_\Delta + \delta\Sigma$$

Model self-energy by phenomenological model (calibrated from pion photoproduction on helium, carbon)

$$\delta\Sigma = V(E_\gamma) F(q^2)$$

Drechsel et.al. NPA, 660, 423.



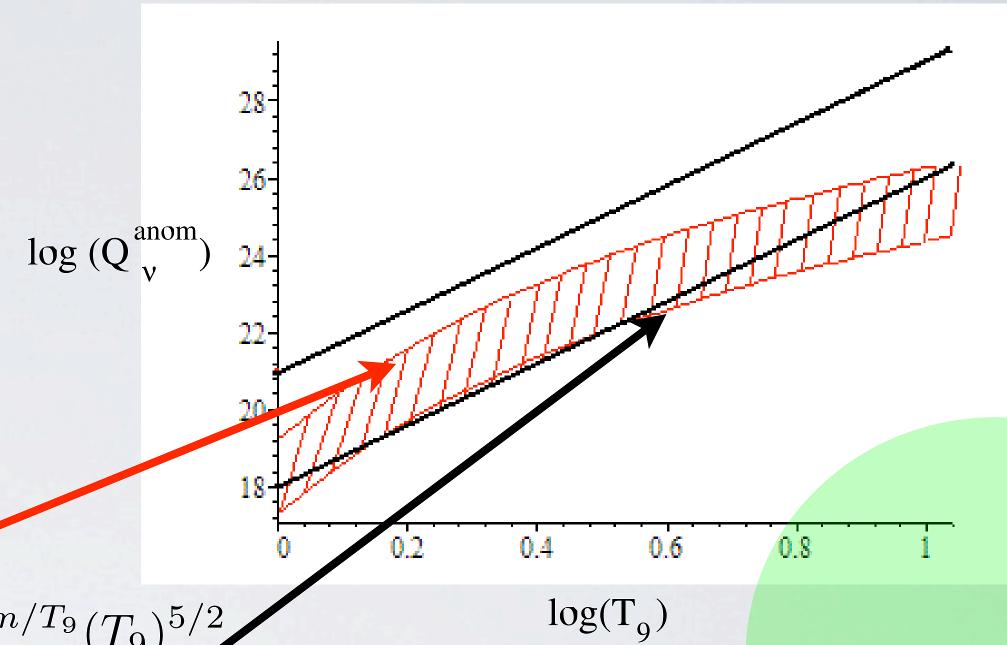
energy-dependent width & model for in-medium effects

energy-independent width (simplest model)

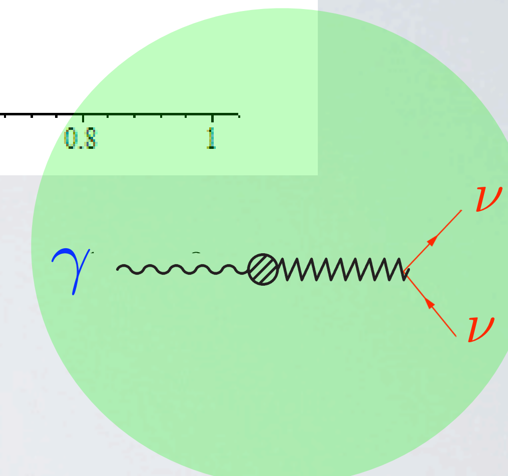
Data from Wissmann et al, PLB 335, 119 (1994).

Peak height somewhat reduced, position shifted. Gross features unchanged.

An enhanced coherent single-photon cross section has interesting implications



Astrophysics: mechanism for neutron star cooling



$$Q_\nu^{\mathrm{anom}} \approx 2\times 10^{22}\,\mathrm{erg\,s^{-1}\,cm^{-3}} m^{9/2}\left(\frac{g_\omega}{10}\right)^4 e^{-12m/T_9}(T_9)^{5/2}$$

$$Q_\nu^{\mathrm{mUrca}} = (10^{18}-10^{21})\times\left(\frac{T}{10^9\,K}\right)^8 \mathrm{erg\,s^{-1}\,cm^{-3}}$$

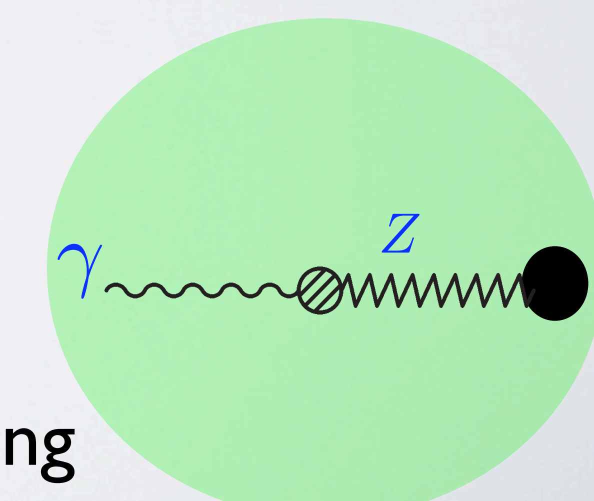
Parity violation: particles with weak charge acquire an anapole moment in nuclear medium, e.g. shell nucleon in heavy nucleus:

$$\langle k'|J_\mu^{e.m.}|k\rangle \sim \frac{a(q^2)}{m^2}\bar{u}(k')(\not{q}q_\mu - q^2\gamma_\mu)\gamma_5 u(k)$$

$$a(0) = \frac{e}{4\pi^2}\frac{G_F}{\sqrt{2}}\frac{g_\omega^2}{m_\omega^2} m n_B C_V$$

baryon density

particle's weak coupling



SUMMARY

- ν's provide a first look beyond the SM, and have changed our comfortable view of flavors and generations
- besides "new" new physics, ν's tell us interesting things about QCD, astrophysics, cosmology
- there are discrete questions that should be answered in the next decade(s): *is there lepton flavor violation? is θ_{13} nonzero? do neutrino interactions violate CP? are there more neutrinos/more generations?*
- An interesting time..