The anomalous baryon current and neutrino-photon interactions in the Standard Model

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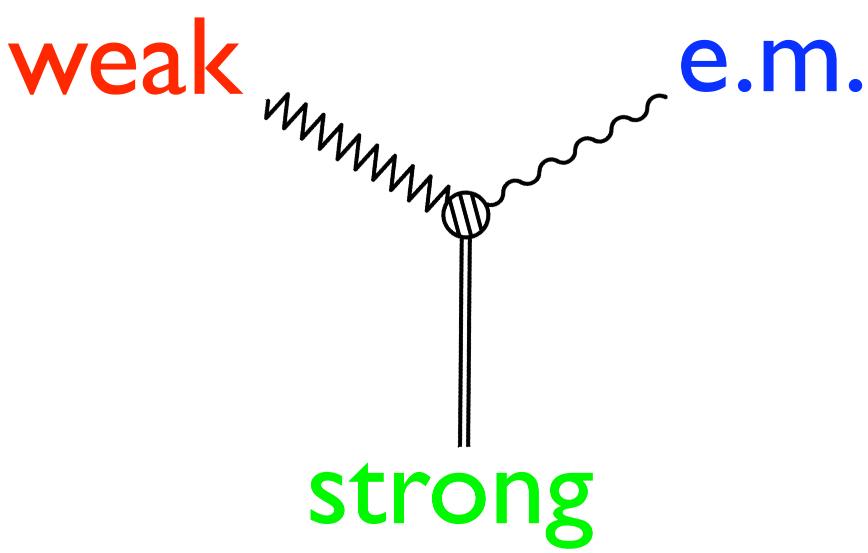
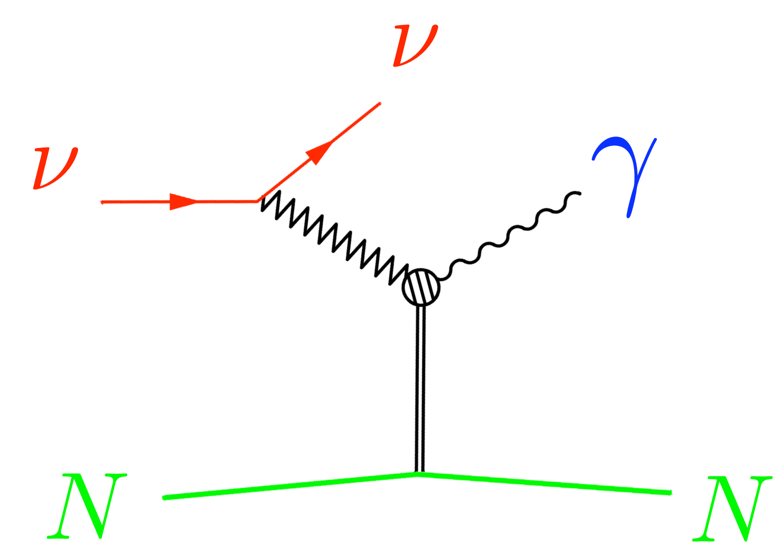
based on:
arXiv:0708.1281, PRL,
arXiv:0712.1230, PRD, with J.A. Harvey and C.T.Hill

Fermilab, 29 February, 2008

A new class of standard model interactions

What if we had a handle like:

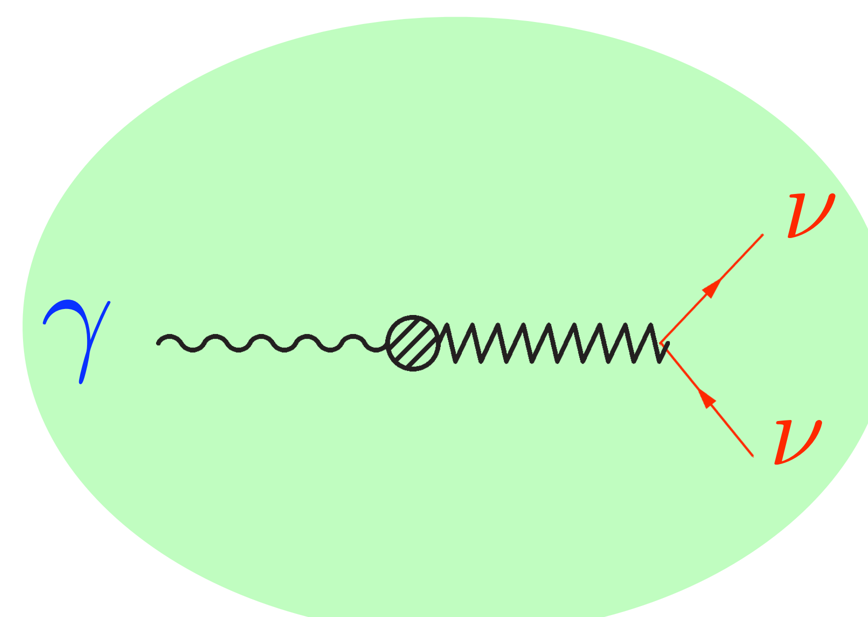




laboratory neutrino detection

- The low-energy Standard Model *does* have such interactions

- Leads to baryon-catalyzed neutrino-photon interactions



neutron star / supernova cooling

Outline

- The (anomalous) baryon current in the Standard Model
- Laboratory probes
- Astrophysical implications

The anomalous baryon current

Fundamental fact about fermions and gauge fields

In the absence of interactions, all fermions are identical

$$\mathcal{L} = \bar{\Psi}\, i\partial\!\!\!/\, \Psi$$

A large number of symmetries

$$\Psi \to e^{i\epsilon}\Psi$$

$$\implies \mathcal{L} \to \bar{\Psi} e^{-i\epsilon} i\partial\!\!\!/ e^{i\epsilon}\Psi = \mathcal{L}$$

$$\Psi = \begin{pmatrix} u_L \\ u_L \\ u_L \\ d_L \\ d_L \\ d_L \\ u_R \\ u_R \\ u_R \\ d_R \\ d_R \\ d_R \\ \nu_L \\ e_L \\ \nu_R \\ e_R \end{pmatrix}$$

But we can't couple gauge fields to too many of the symmetries. If we try, then we find "anomalies"

Naively, can promote the global symmetry

$$\Psi \to e^{i\epsilon}\Psi$$

to a local symmetry

$$\Psi \to e^{i\epsilon(x)}\Psi$$

by adding a gauge field

$$A_\mu \to e^{-i\epsilon}(A_\mu + i\partial_\mu)e^{i\epsilon}$$

Then classically the action is invariant

$$\mathcal{L} = \bar{\Psi}(i\not{\partial} + \not{A})\Psi \to \mathcal{L}$$

Bardeen 1969
Adler 1969
Bell, Jackiw 1969

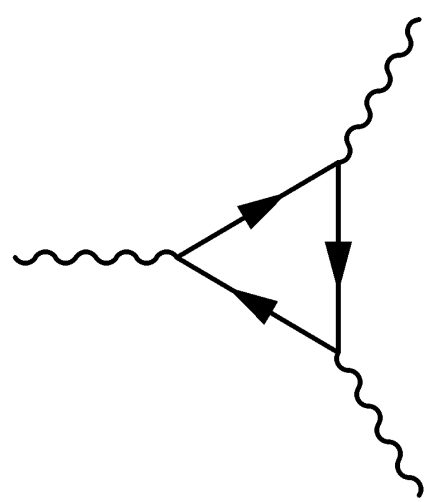
But in the full quantum theory, this is not true generally:

$$\delta(\mathrm{Action}) = \frac{1}{48\pi^2}\int \mathrm{d}^4\mathrm{x}\,\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left[\partial_\mu\epsilon\left(\mathrm{A}_\nu\partial_\rho\mathrm{A}_\sigma - \frac{\mathrm{i}}{2}\mathrm{A}_\nu\mathrm{A}_\rho\mathrm{A}_\sigma\right)\right]$$

Implications of anomalies

First, if we *do* try to couple physical gauge fields to certain symmetries, need to choose non-anomalous ones

Fortunately, the Standard Model makes such a choice



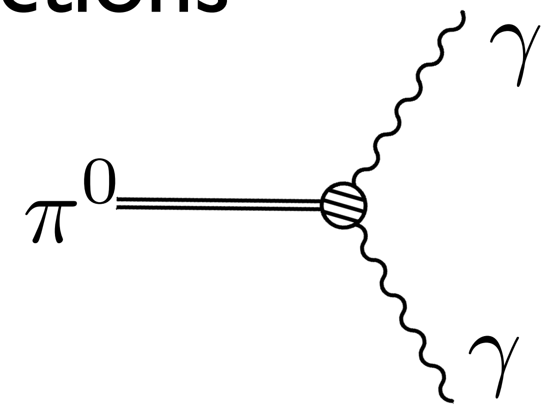
	T^3	Y	$Q = T^3 + Y$
u_L	$1/2$	$1/6$	$2/3$
d_L	$-1/2$	$1/6$	$-1/3$
u_R	0	$2/3$	$2/3$
d_R	0	$-1/3$	$-1/3$
ν_{eL}	$1/2$	$-1/2$	0
e_L	$-1/2$	$-1/2$	-1
ν_{eR}	0	0	0
e_R	0	-1	-1

SU(2) x U(1) $\rightarrow$ U(1)

$$3\left[2\left(\frac{1}{6}\right)^3 - \left(\frac{2}{3}\right)^3 - \left(-\frac{1}{3}\right)^3\right] + 2\left(-\frac{1}{2}\right)^3 - (-1)^3 = 0$$

Implications of anomalies

Second, 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 *did* try an ill-advised gauge transformation on the axial symmetries, have to get the expected anomaly

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

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

Low energy QCD

The QCD lagrangian for massless (u,d,s) quarks is invariant under unitary $SU(3)_L$ x $SU(3)_R$ flavor transformations:

$$Q_L = \begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix}$$

$$\mathcal{L} \sim \bar{Q}\, i\partial\!\!\!/\, Q = \bar{Q}_L\, i\partial\!\!\!/\, Q_L + \bar{Q}_R\, i\partial\!\!\!/\, Q_R$$

$$Q_R = \begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix}$$

But a condensate forms in the QCD vacuum:

$$\langle \bar{Q}_R Q_L \rangle \neq 0$$

For each broken generator, a massless "Nambu Goldstone boson"

Low energy QCD described by unitary matrix of "pions"

$$U(x) = \exp\left[i \begin{pmatrix} \pi^0 + \eta/\sqrt{3} & \sqrt{2}\pi^+ & K^0 \\ \sqrt{2}\pi^- & -\pi^0 + \eta/\sqrt{3} & K^+ \\ \overline{K^0} & K^- & -2\eta/\sqrt{3} \end{pmatrix} \right]$$

Why are these interactions special ?

There are two pieces of the chiral lagrangian that describes low-energy QCD

$$\mathcal{L}_{\mathrm{regular}} = \mathrm{Tr}(D_\mu U D^\mu U^\dagger)$$

$$\mathcal{L}_{\mathrm{anomalous}} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi(\partial_\mu\pi)(\partial_\nu\pi)(\partial_\rho\pi)(\partial_\sigma\pi)] + \ldots$$

These interactions are contained in the anomalous part

- Violate naive selection rules

$$\pi \to -\pi$$

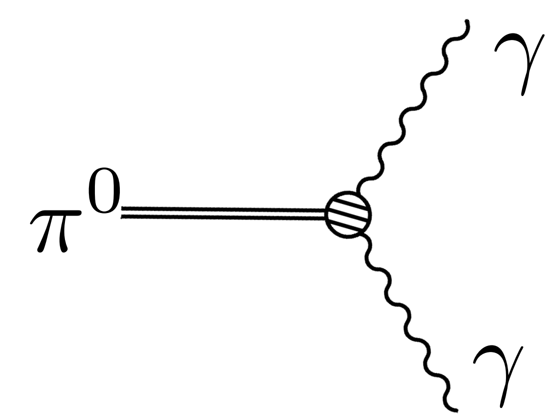
$$\mathcal{L}_{\mathrm{regular}} \to +\mathcal{L}_{\mathrm{regular}}$$

$$\mathcal{L}_{\mathrm{anomalous}} \to -\mathcal{L}_{\mathrm{anomalous}}$$

- Directly related to underlying fermions

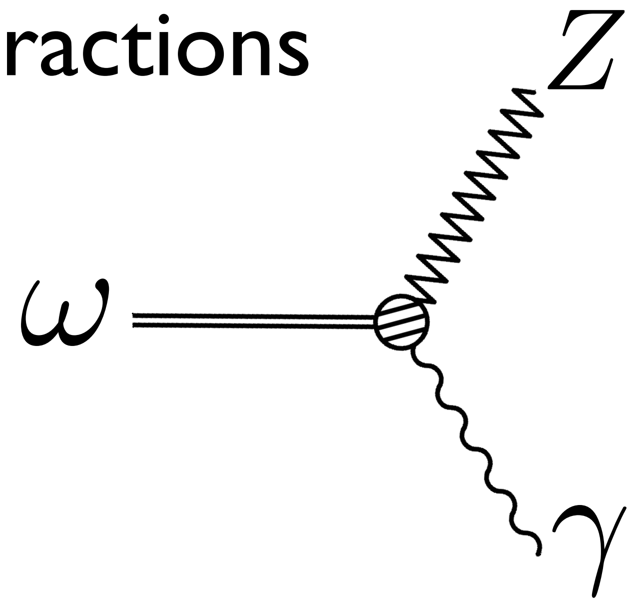
$$\Gamma_{\mathrm{theory}} = \left(\frac{N_c}{3}\right)^2 \frac{\alpha^2 m_\pi^2}{64\pi^3 f_\pi^2} = \left(\frac{N_c}{3}\right)^2 \times 7.6\,\mathrm{eV}$$

$$\Gamma_{\mathrm{expt}} = 7.8(6)\,\mathrm{eV}$$



The anomalous baryon current

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



Baryon number is anomalous in the Standard Model

$$\partial_\mu J^\mu_{\text{baryon}} \propto \epsilon^{\mu\nu\rho\sigma} F^{\text{vector}}_{\mu\nu} F^{\text{axial}}_{\rho\sigma}$$

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

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

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

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

Why this is surprising

Using the intuition
"vector currents are conserved, axial-vector currents are anomalous", there is a unique counterterm that must be added to the chiral lagrangian:

Bardeen 1969

$$\Gamma(U, A, B) \rightarrow \Gamma(U, A, B) - \Gamma(1, A, B)$$

gauge *background*

This subtracts any interaction involving just vector fields (no pions)

But the Standard Model SU(2)xU(1) is not vector-like gauging ! A different counterterm is required

A definitive answer to this question, and explicit connection with baryon anomaly

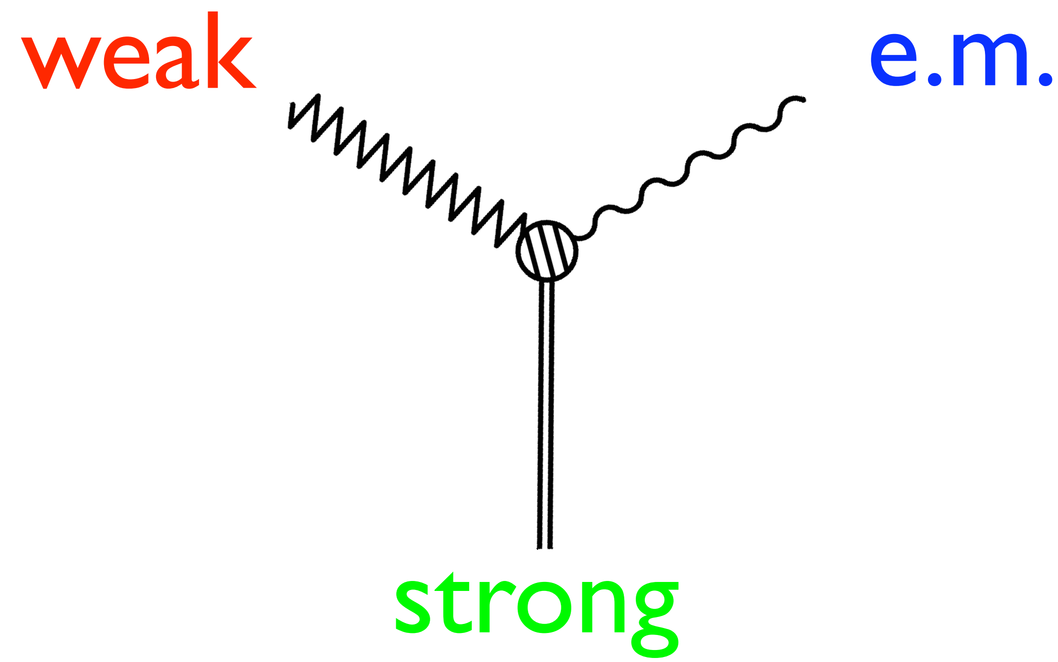
Harvey, Hill, Hill 2007

Many ill-advised transformations we could make, and many interactions

$$
\begin{aligned}
\Gamma_{AAB} &= \mathcal{C}\int dZZ\left[\frac{s_W^2}{c_W^2}\rho^0+\left(\frac{3}{2c_W^2}-3\right)\omega-\frac{1}{2c_W^2}f\right]+dAZ\left[-\frac{s_W}{c_W}\rho^0-\frac{3s_W}{c_W}\omega\right]+dZ\left[W^-\rho^++W^+\rho^-\right]\frac{s_W^2}{c_W}\\
&\quad +dA\left[W^-\rho^++W^+\rho^-\right](-s_W)+(DW^+W^-+DW^-W^+)\left[-\frac{3}{2}\omega-\frac{1}{2}f\right],\\
\Gamma_{ABB} &= \mathcal{C}\int Z\Big\{d\rho^0\Big[-\frac{3}{2c_W}\omega-\frac{s_W^2}{c_W}a^0+\left(-\frac{3}{2c_W}+3c_W\right)f\Big]+d\omega\Big[-\frac{3}{2c_W}\rho^0+\left(-\frac{3}{2c_W}+3c_W\right)a^0-\frac{s_W^2}{c_W}f\Big]\\
&\quad +da^0\left[\frac{s_W^2}{c_W}\rho^0+\left(\frac{3}{2c_W}-3c_W\right)\omega-\frac{1}{2c_W}f\right]+df\Big[\left(\frac{3}{2c_W}-3c_W\right)\rho^0+\frac{s_W^2}{c_W}\omega-\frac{1}{2c_W}a^0\Big]\Big\}\\
&\quad +dA\Big\{s_W\rho^0a^0+3s_W\rho^0f+3s_W\omega a^0+s_W\omega f\Big\}+dZ\Big\{-\frac{s_W^2}{c_W}\left(\rho^+a^-+\rho^-a^+\right)\Big\}\\
&\quad +dA\Big\{s_W\left(\rho^+a^-+\rho^-a^+\right)\Big\}\\
&\quad +\frac{3}{2}\left[W^+D\rho^-+W^-D\rho^+\right](-\omega+f)+\frac{3}{2}\left[W^+(-\rho^-+a^-)+W^-(-\rho^++a^+)\right]d\omega\\
&\quad +\frac{1}{2}\left[W^+Da^-+W^-Da^+\right](-3\omega-f)+\frac{1}{2}\left[W^+(-3\rho^--a^-)+W^-(-3\rho^+-a^+)\right]df\,,\\
\Gamma_{BBB} &= \mathcal{C}\int 2\Big[\left(\rho^-f+\omega a^-\right)D\rho^++\left(\omega a^++\rho^+f\right)D\rho^-+\left(\omega a^0+\rho^0f\right)d\rho^0+\left(\rho^+a^-+\rho^-a^++\omega f+\rho^0a^0\right)d\omega\Big]\\
\Gamma_{AAAB} &= \mathcal{C}\int i\Big\{W^+W^-\Big[3c_WZ\Big]\omega+W^+W^-\Big[\left(c_W+\frac{1}{2c_W}\right)Z\Big]f\Big\},\\
\Gamma_{AABB} &= \mathcal{C}\int i\Big\{W^+W^-\left[\frac{3}{2}(\rho^0+a^0)\omega-\frac{1}{2}(\rho^0-a^0)f\right]\\
&\quad +W^+Z\left[\frac{3c_W}{2}\rho^-f-\frac{3c_W}{2}\rho^-\omega-\frac{c_W}{2}a^-f+\frac{3c_W}{2}\omega a^--\frac{1}{c_W}\rho^-f\right]\\
&\quad +W^-Z\Big[-\frac{3c_W}{2}\rho^+f+\frac{3c_W}{2}\rho^+\omega+\frac{c_W}{2}a^+f-\frac{3c_W}{2}\omega a^++\frac{1}{c_W}\rho^+f\Big]\Big\},\\
\Gamma_{ABBB} &= \mathcal{C}\int i\Big\{W^+\Big[\rho^-\rho^0(\omega-2f)-\rho^-\omega a^0+\rho^0\omega a^-+\omega a^-a^0\Big]\\
&\quad +W^-\Big[\rho^+\rho^0(-\omega+2f)+\rho^+\omega a^0-\rho^0\omega a^+-\omega a^+a^0\Big]\\
&\quad +Z\Big[\rho^+\rho^-\left(\frac{1}{c_W}\omega+\left(-4c_W+\frac{2}{c_W}\right)f\right)+\rho^+\omega a^-\left(-2c_W+\frac{1}{c_W}\right)\\
&\quad +\rho^-\omega a^+\left(2c_W-\frac{1}{c_W}\right)+\omega a^+a^-\left(\frac{1}{c_W}\right)\Big]\Big\}.
\end{aligned}
$$

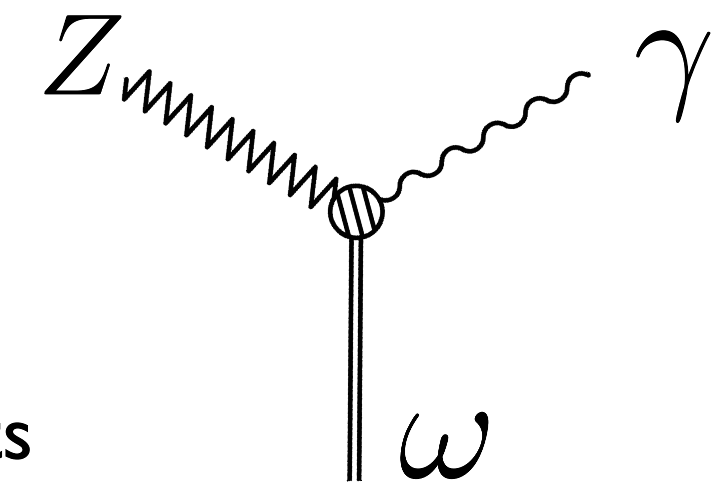
(

We started by asking: what if we had a handle like:



Now we do!

$$\mathcal{L} = \frac{N_c}{48\pi^2}\frac{e g_\omega g_2}{\cos\theta_W}\epsilon^{\mu\nu\rho\sigma}\omega_\mu Z_\nu F_{\rho\sigma}$$



- low energy Standard Model has all of the ingredients to probe the baryon anomaly
  - *take one leg as the isoscalar coupling to nucleons*
  - *take one leg as a photon*
  - *the other is the Z boson*
- most dramatic effects possible in neutrino interactions

A fundamental ingredient in the Standard Model

Could explain baryogenesis at the electroweak phase transition if a large source of CP violation were present:

baryon number

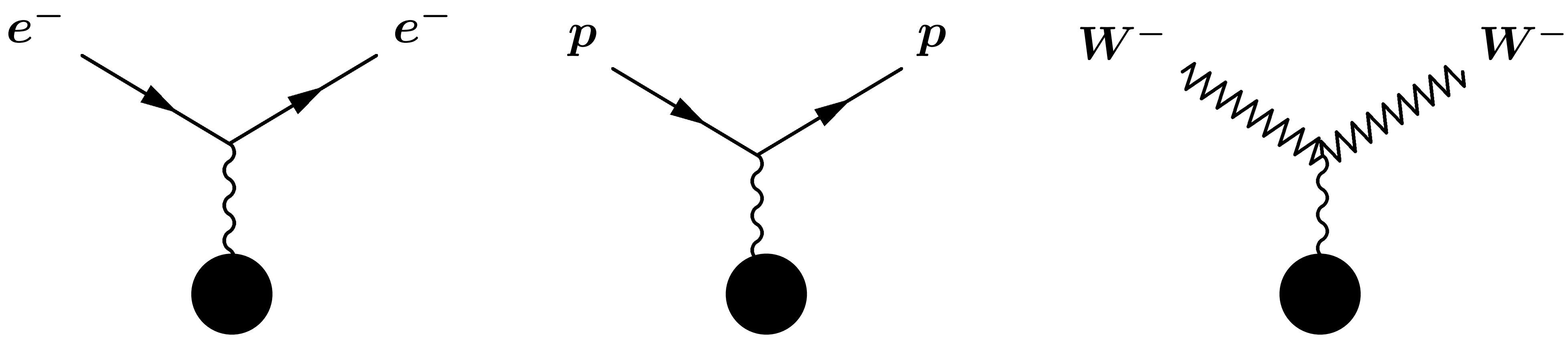
$$\Delta B = \int_{-\infty}^{+\infty} dt\, \frac{\partial B(t)}{\partial t} = \int d^4x\, \partial_\mu J^\mu_{\rm baryon} \propto \int d^4x\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

nonperturbative (“sphaleron”) background of gauge fields

Challenge to experimentalists:
observe this interaction

- probe the baryon anomaly of the Standard Model
- relevant background for neutrino oscillation searches
- interesting astrophysical implications

Given a source of electric charge, can scatter all parts of the electromagnetic current



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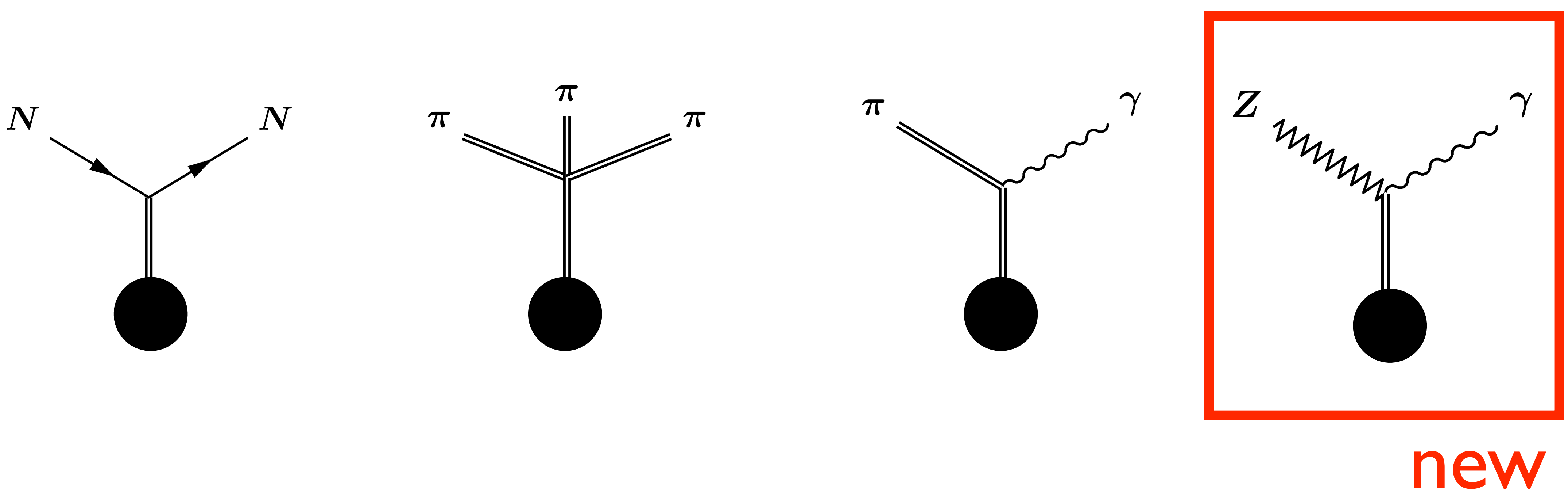
Similarly, given a source of baryon charge, can scatter all parts of the baryon current



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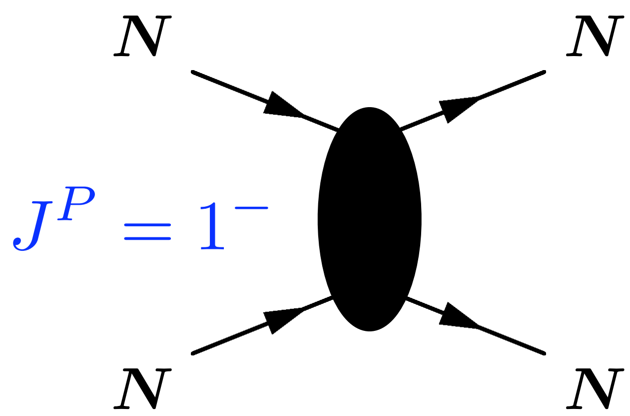
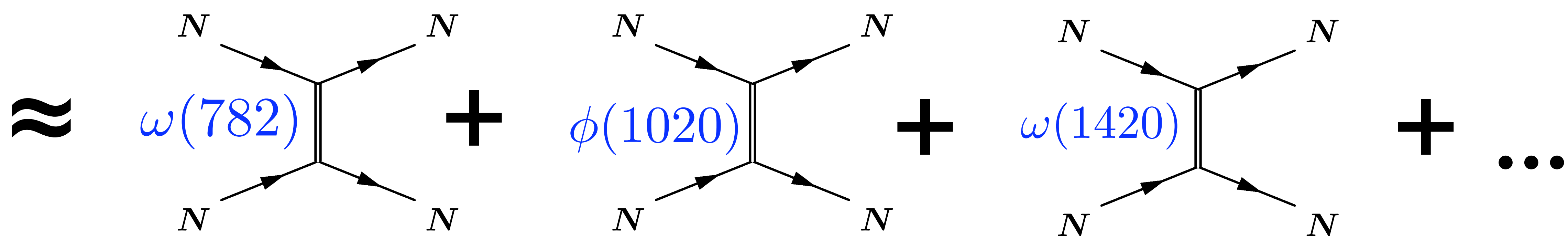
Meson exchange

Nucleon scattering can be described by exchanging mesons in the corresponding channel





- in practice, keep the lowest resonances in each channel, and fit to effective masses and couplings

$$\frac{g_{\omega_1}^2}{m_{\omega_1}^2} + \frac{g_{\omega_2}^2}{m_{\omega_2}^2} + \cdots \rightarrow \frac{g_{\omega}^2}{m_{\omega}^2}$$

The coupling of ω to the baryon current can be probed in meson decays:

$$\underline{\omega \rightarrow 3\pi} : \qquad g = 8.3$$

$$\underline{\omega \rightarrow \pi\gamma} : \qquad g = 8.7$$

- tree-level calculations, errors "10-20% or so"

Similarly, can consider the coupling of ρ to the isospin current:

$$\underline{\rho \rightarrow 2\pi} : \qquad g = 9.0$$

$$\underline{\rho \rightarrow \pi\gamma} : \qquad g = 9.2$$

There are interesting existential questions that can be asked about vector mesons

Does ω couple to baryon number ? Does ρ couple to isospin ?

What *is* ω ?

Main point is that gauge invariance ties together different parts of the baryon current. Vector meson exchange a useful description of baryon interactions

Anomalies are tiny effects, right ?

Depends on the question !

For example, some particles are forced to decay through the anomaly

$$\Gamma(\rho) \approx \Gamma(\rho \to 2\pi) = 150\,\mathrm{MeV} \qquad \Gamma(\omega) \approx \Gamma(\omega \to 3\pi) = 8\,\mathrm{MeV}$$

$$\boxed{\mathcal{L}_{\mathrm{regular}} = \mathrm{Tr}(D_\mu U D^\mu U^\dagger)} \qquad \boxed{\mathcal{L}_{\mathrm{anomalous}}}$$

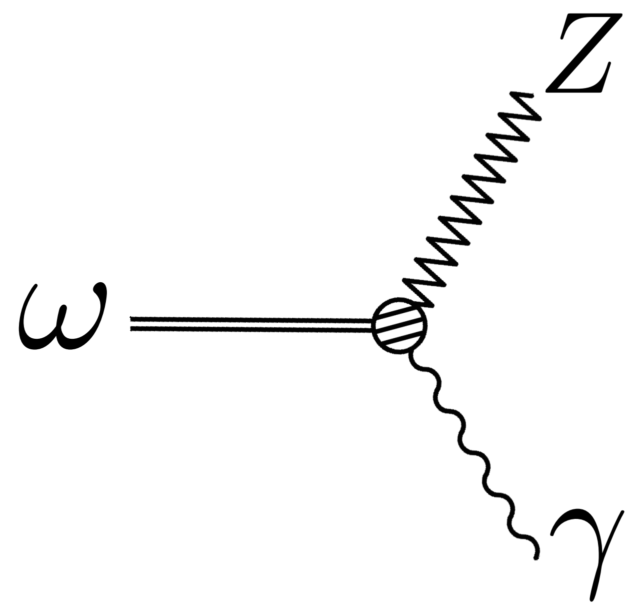
$$D_\mu \Sigma = \partial_\mu \Sigma - ig[\rho^a \tau^a, \Sigma] - ig\cancelto{0}{[\omega, \Sigma]}$$

Baryons enter the chiral lagrangian *only* through the "anomalous" term

So anything having to do with baryon number is necessarily tied up with anomalies

Laboratory probes

Why these effects haven't been observed

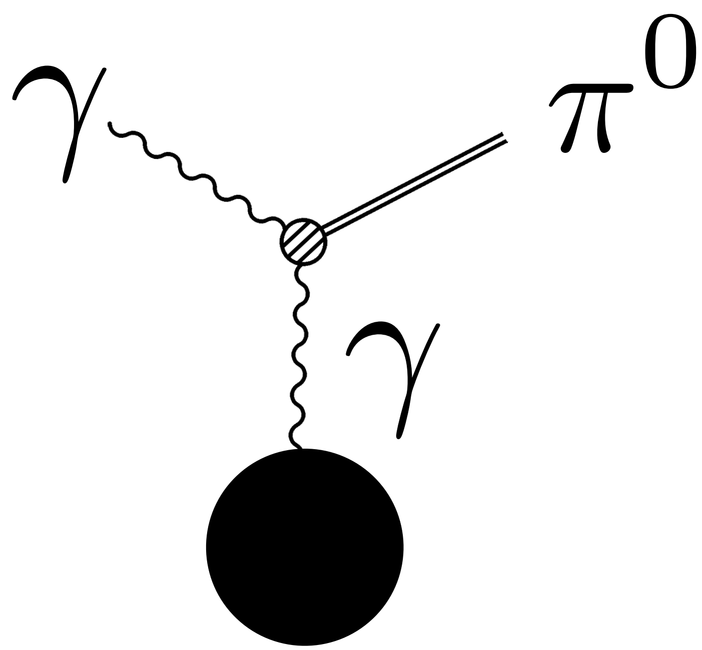


If Z was much lighter, would see e.g. $\omega \to Z\gamma$ directly. But in practice, Z is heavy (weak interactions are weak !)

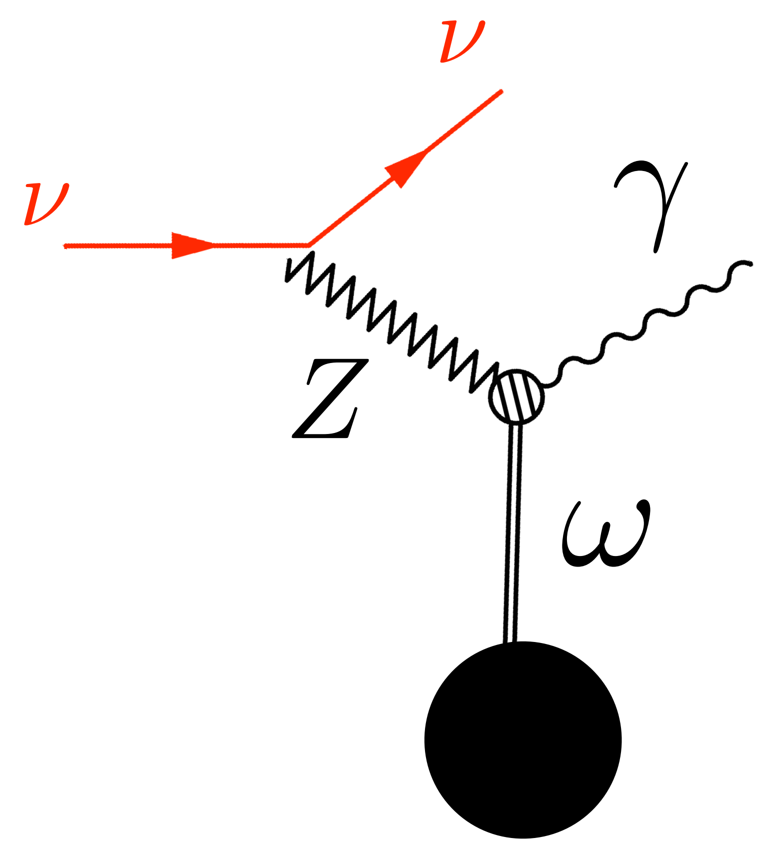
$$\mathrm{Br}(\omega \to \gamma\nu\bar{\nu}) \sim \left(\frac{g^2_{\mathrm{weak}}}{m^2_W}\right)^2 \frac{f^6_\pi}{m^2_\omega} \sim \frac{G^2_F f^6_\pi}{m^2_\omega} \sim 10^{-16}$$

Where to look for it

Compare Primakoff effect:



nucleus=source of
electric charge

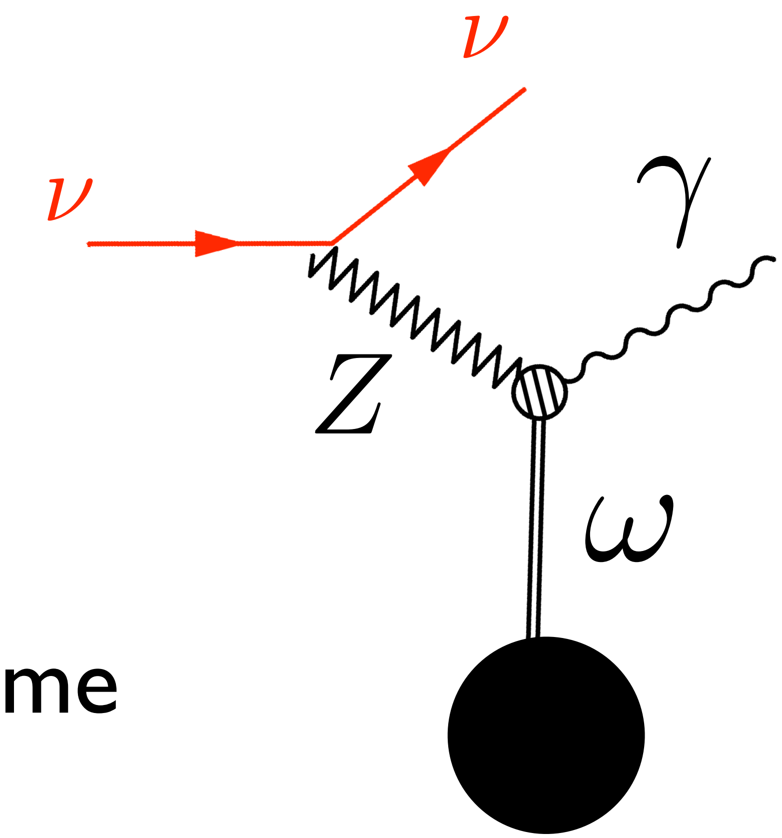


nucleus=source of
baryon number

Just as γ couples to electric charge, ω couples to baryon charge

So interactions involving neutrinos and baryons are especially interesting

Basic detector element is a nucleon



Backgrounds to this interaction come from several sources:

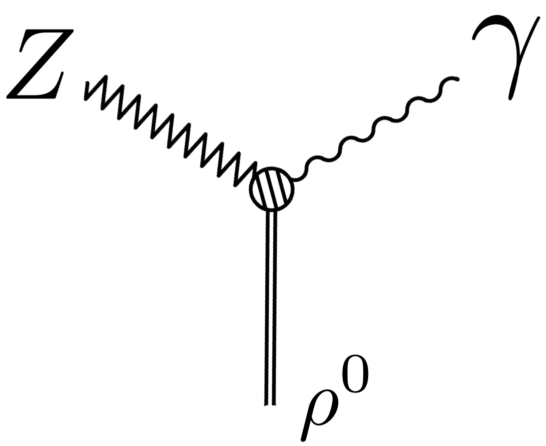
- bremstrahlung and other effects of nuclear structure
- resonant production of photons
- electron scattering (if can't tell photon shower from electron shower)

Reason that this can be prominent: it's not easy to get photons from scattering neutrinos on heavy nucleons !

competing processes

<u>Other vector-current exchanges:</u>

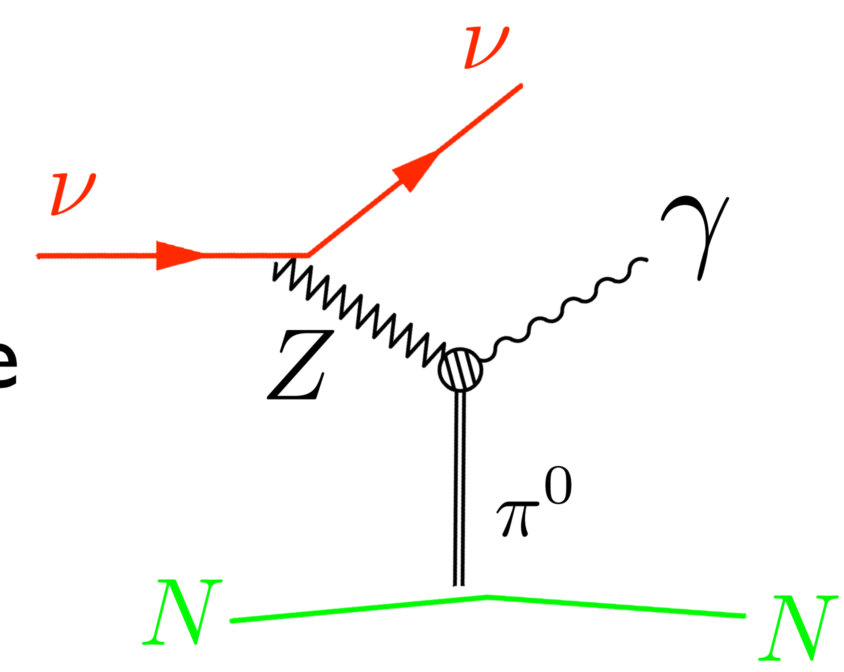
$$\frac{g_{\rho NN}}{g_{\omega NN}} \sim \frac{1+1-1}{1+1+1} = \frac{1}{3}$$



"coherence over the nucleus"

$\Rightarrow$ in amplitude, ρ exchange suppressed by ~(1/3)^2

competing processes

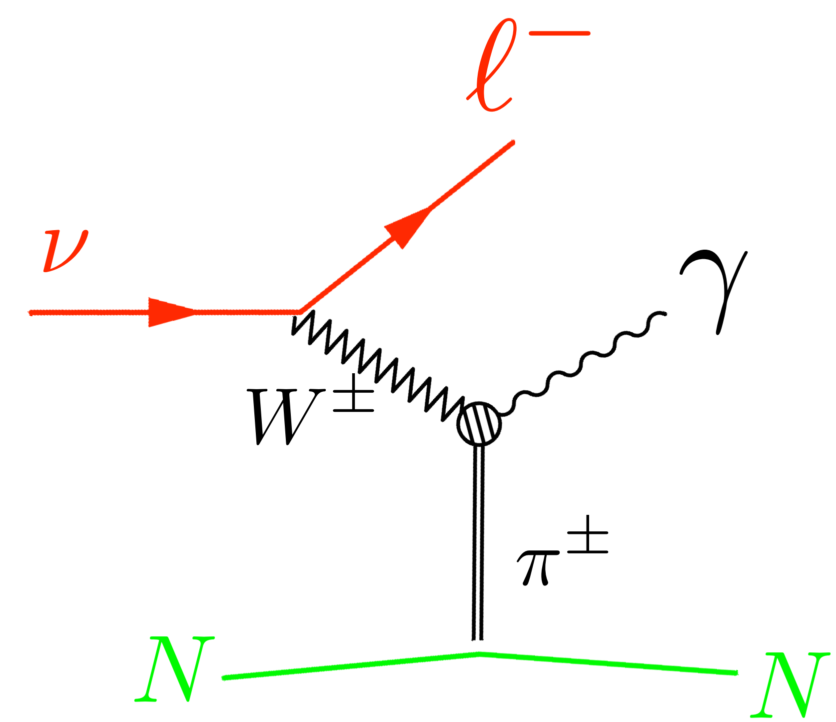


<u>Axial-currents:</u>
pion exchange potentially significant, due to small mass

$$\frac{1}{f_\pi^4} \lesssim \frac{g_\omega^4}{m_\omega^4}$$

but a cancellation makes it small

$$1 - 4\sin^2\theta_W \ll 1$$

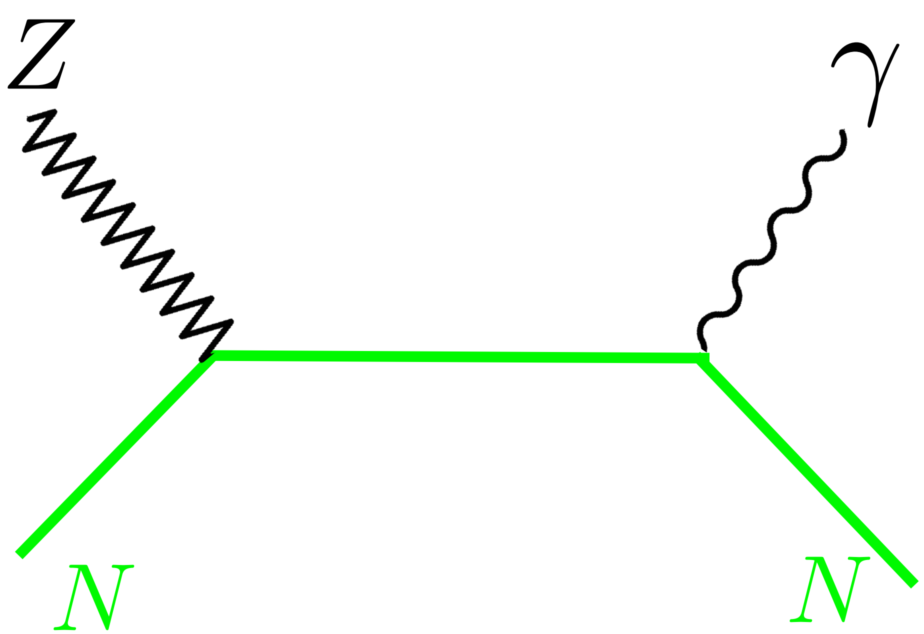


- not coherent over adjacent nucleons
- could in principle be probed in relatd charged-current process

competing processes

<u>Bremstrahlung and related contact interactions</u>

- formally suppressed by nucleon mass

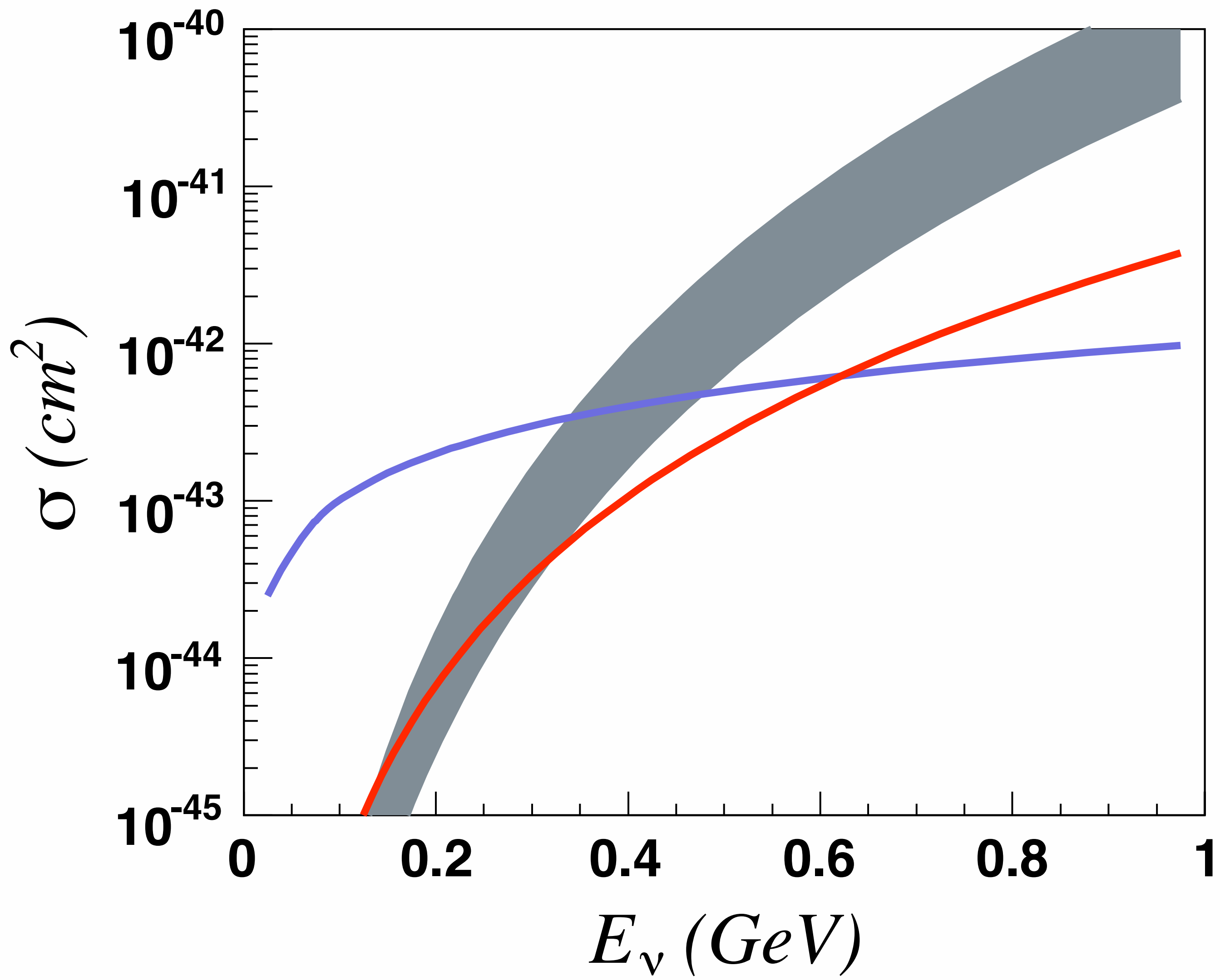


+ ....

- for neutron, dominant effect is magnetic form factor,
- for proton, no other large enhancements

As a very rough guide neglect:

- form factor and recoil suppression (valid for E<<1 GeV)
- coherence and other enhancements



On small nuclei, energies of order several 100 MeV a promising place to look

- at small energy, nuclear enhancements significant: coherence, short-range correlations
- at large energy, chiral lagrangian description breaks down

Higher energy

Focus is on low energy, where chiral lagrangian description is appropriate.

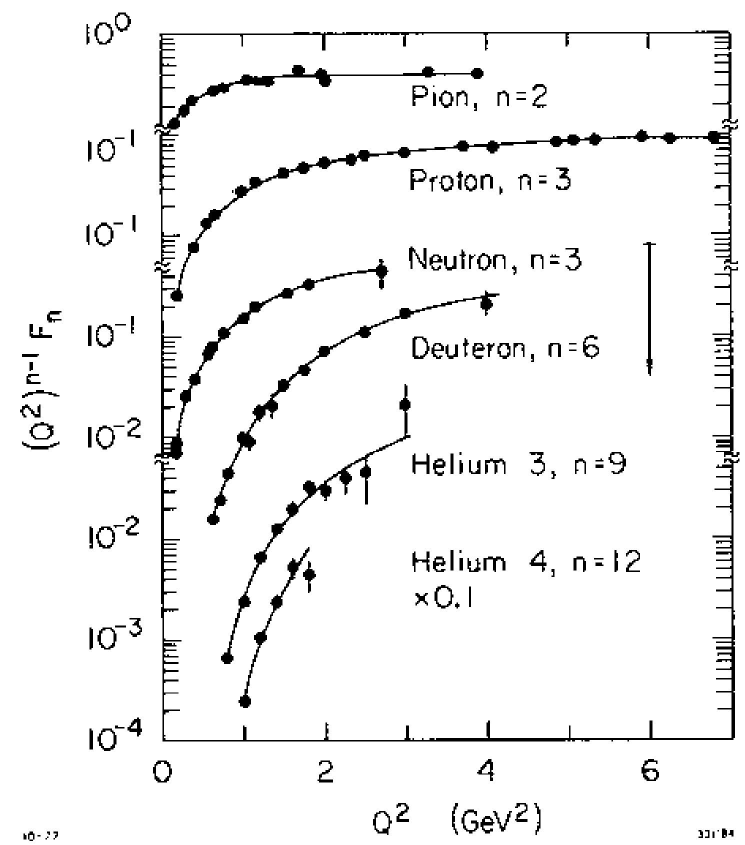
To control extrapolation into higher energy, consider asymptotic limit, where perturbative scaling laws apply

$$\Delta\sigma \sim \frac{1}{s}\int d\Phi\,|\mathcal{M}|^2 \sim s^{1-n_i-2N_f^{\mathrm{baryon}}-N_f^{\mathrm{meson}}}$$

$$\sim s^{m-2} \qquad\qquad \sim \left[s^{2-(n_i+n_f)/2}\right]^2$$

In principle, hard exclusive processes calculable in terms of universal hadron wavefunctions

In practice difficult to constrain normalization, but scaling is satisfied



Brodsky, Lepage 1981

E.g. consider charged-current scattering

$$\nu + n \to e^- + p$$

$$\Delta\sigma \sim \frac{1}{s}\int d\Phi\, |\mathcal{M}|^2 \sim s^{1-n_i-2N_f^{\rm baryon}-N_f^{\rm meson}}$$

$$\sim s^{-1} \cdot 1 \cdot s^{-4}$$

$$\sim |F(s)|^2 \left(\frac{1}{m_Z^2+s}\right)^2 s^2$$

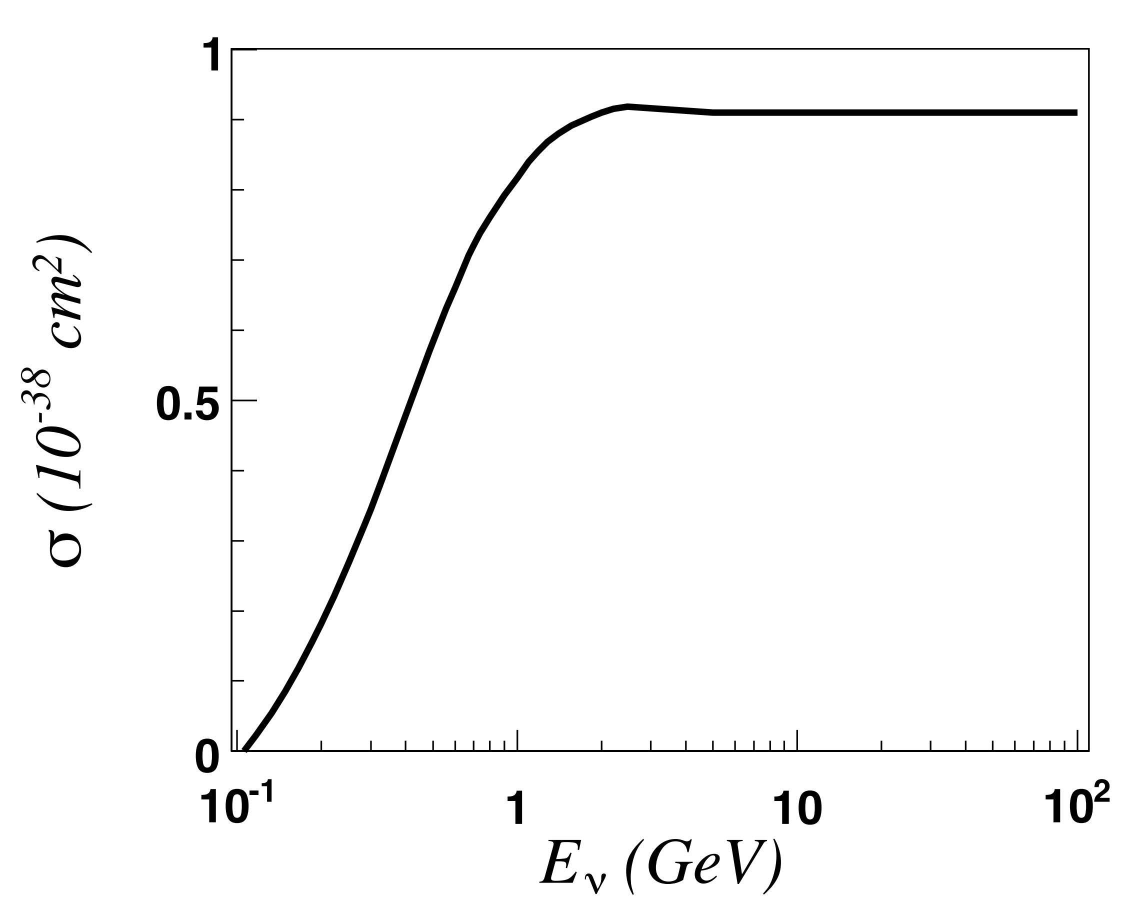
$$\Longrightarrow F(Q^2) \sim \frac{1}{Q^4}$$

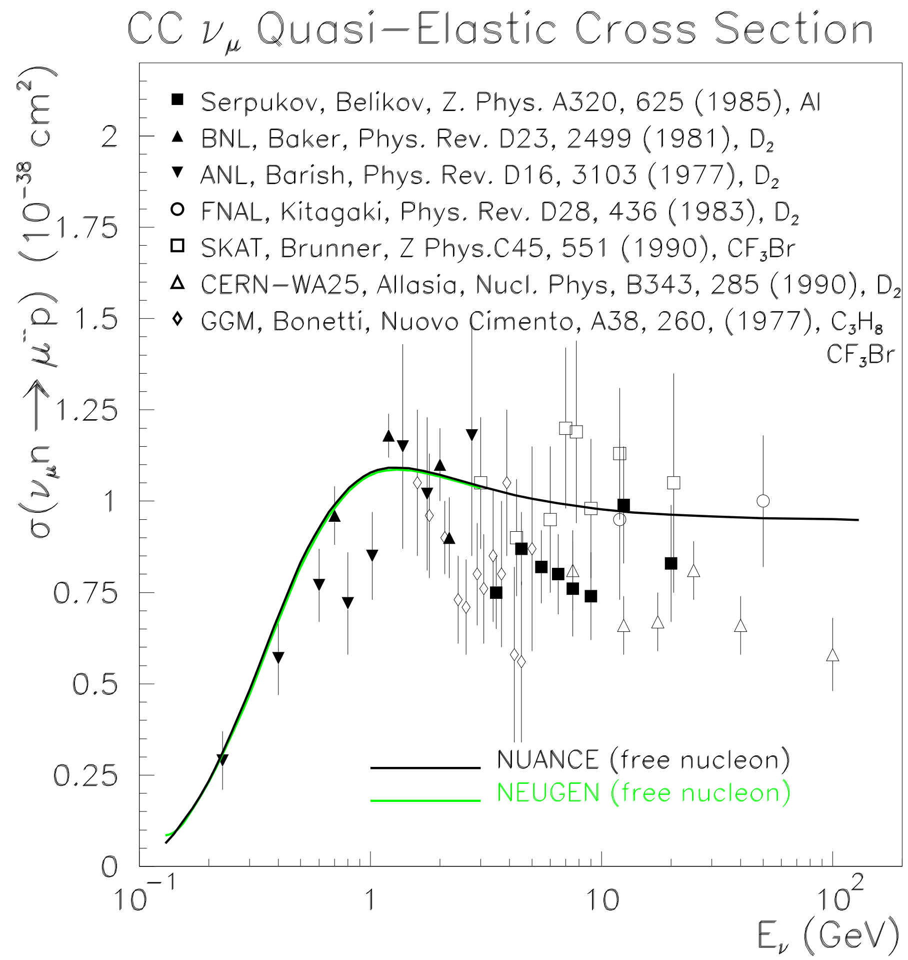
This suggests the simple ansatz $$F(Q^2) = \frac{1}{(1+Q^2/m^2)^2}$$

By analyticity, scale m set by (axial-)vector masses in the crossed channel:

$$\nu + e^+ \to \bar{n} + p$$

Can fit m_A to data, extrapolation gives a reasonable description over the entire energy range





G. Zeller hep-ex/0312061

At low energy,

$$\sigma \sim \frac{G_F^2}{\pi}(C_V^2 + 3C_A^2)E_\nu^2$$

Using scaling laws to extrapolate to higher energy gives reasonable description

In practice, some experimental guidance required:

$$C_V = 1\,, \quad C_A = 1.26$$
$$m_V \sim 1.0\,\mathrm{GeV}\,, \quad m_A \sim 1.2\,\mathrm{GeV}$$

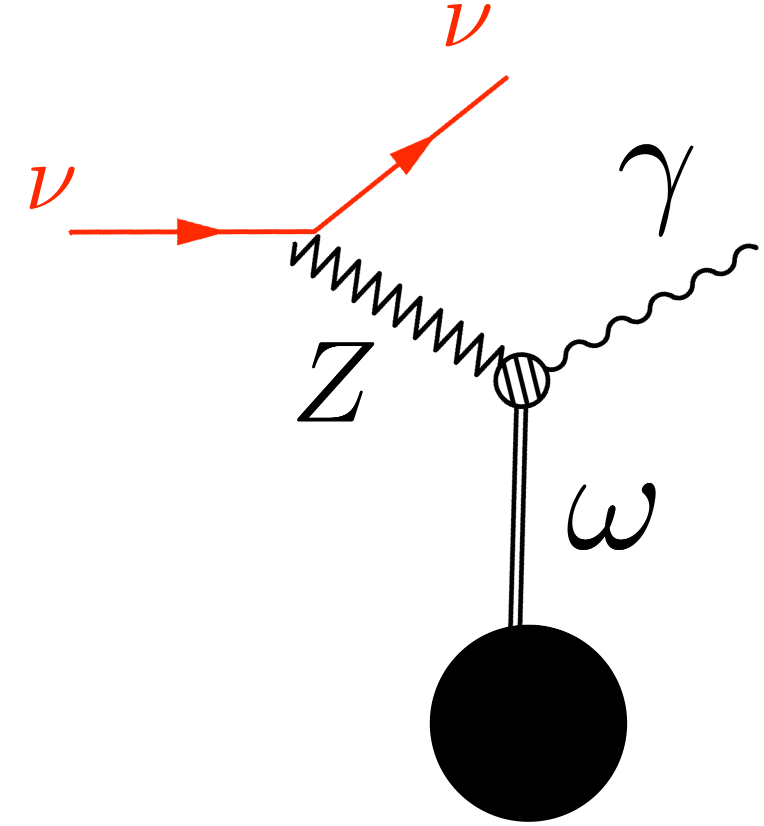
Apply similar arguments to anomaly-mediated process

$$\nu + n \rightarrow \nu + \gamma + n$$

$$\nu + p \rightarrow \nu + \gamma + p$$

At low energy,

$$\sigma \approx \frac{1}{480\pi^6} G_F^2 \alpha \frac{g_\omega^4}{m_\omega^4} E_\nu^6$$



Include factor:

$$F(Q^2) = \frac{1}{(1 + Q^2/m_A^2)^2}$$

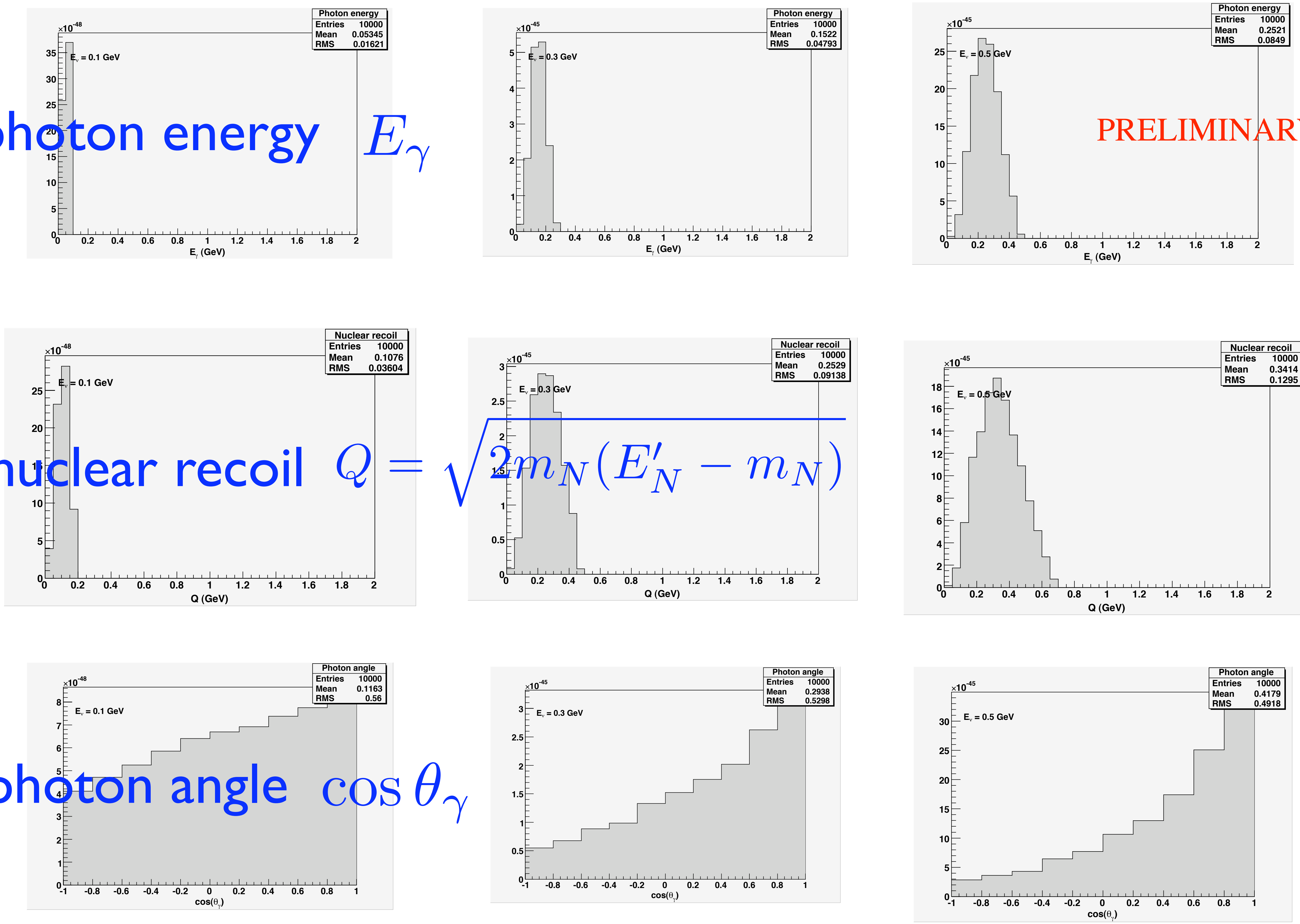
Take m_A at scale of axial-vector mesons

More precise extrapolation requires experimental guidance

For typical values of parameters, what does the cross section look like?

g_ω, nucleon form factors: Machleidt et.al. 1987

$E_\nu = 100\,\mathrm{MeV}$ $E_\nu = 300\,\mathrm{MeV}$ $E_\nu = 500\,\mathrm{MeV}$



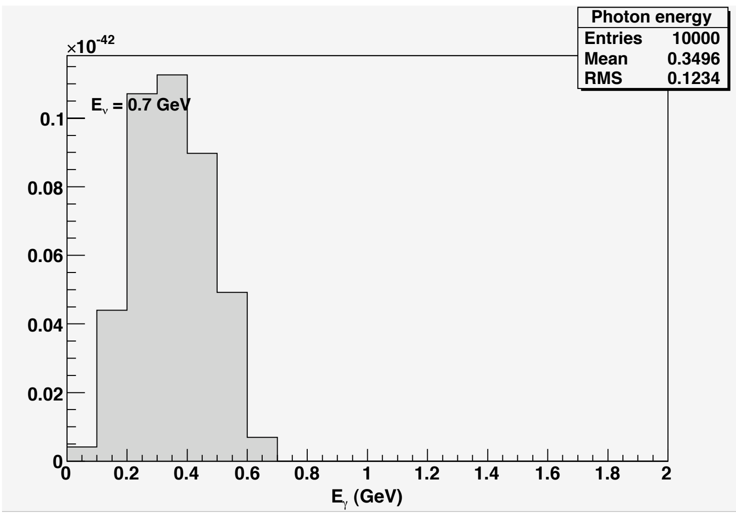
photon energy E_γ

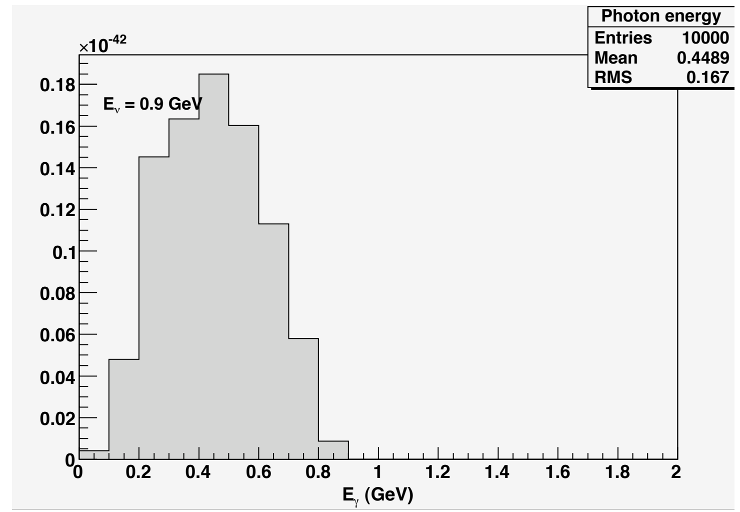
PRELIMINARY

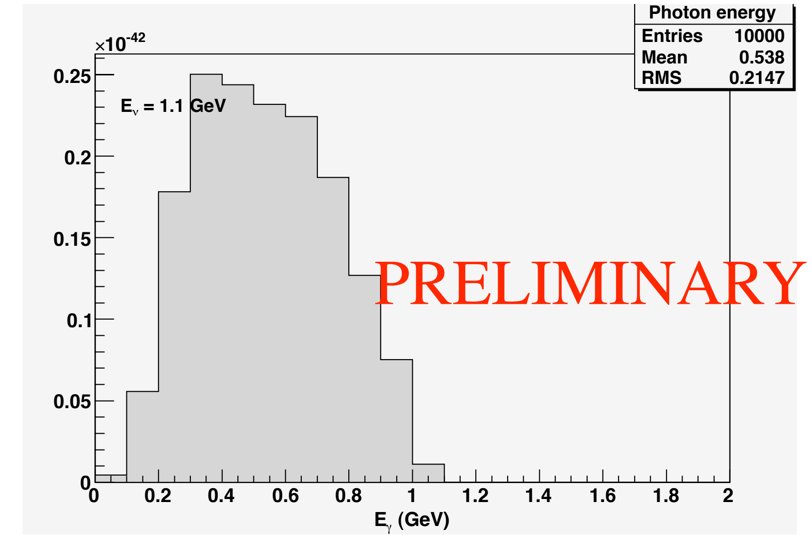
nuclear recoil $Q = \sqrt{2m_N(E'_N - m_N)}$

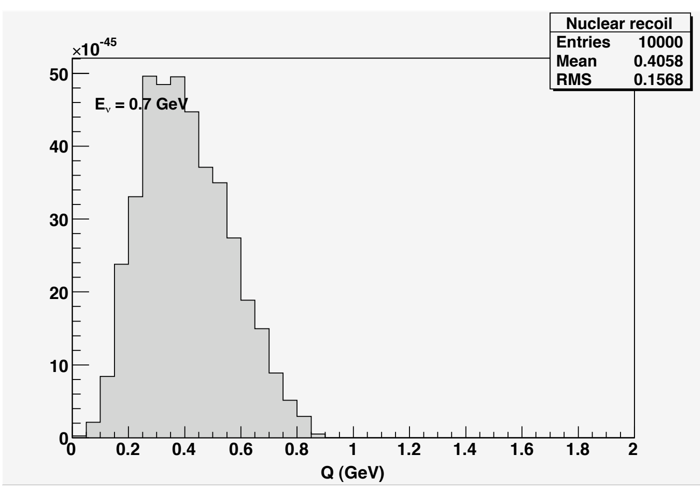
photon angle $\cos\theta_\gamma$

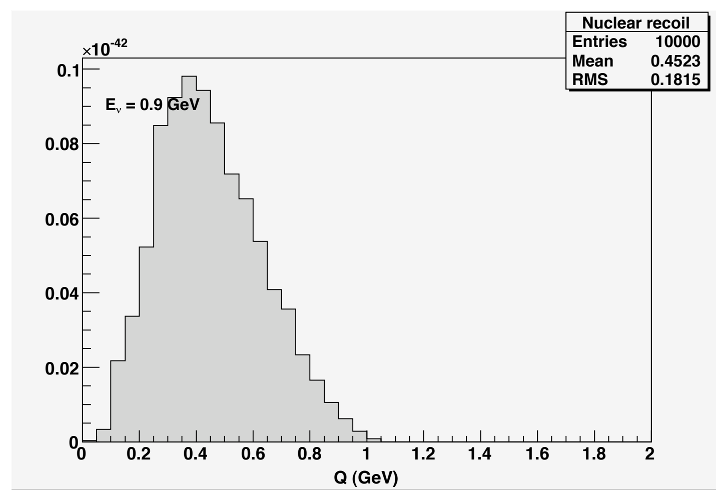
$E_\nu = 700\,\mathrm{MeV}$ | $E_\nu = 900\,\mathrm{MeV}$ | $E_\nu = 1100\,\mathrm{MeV}$

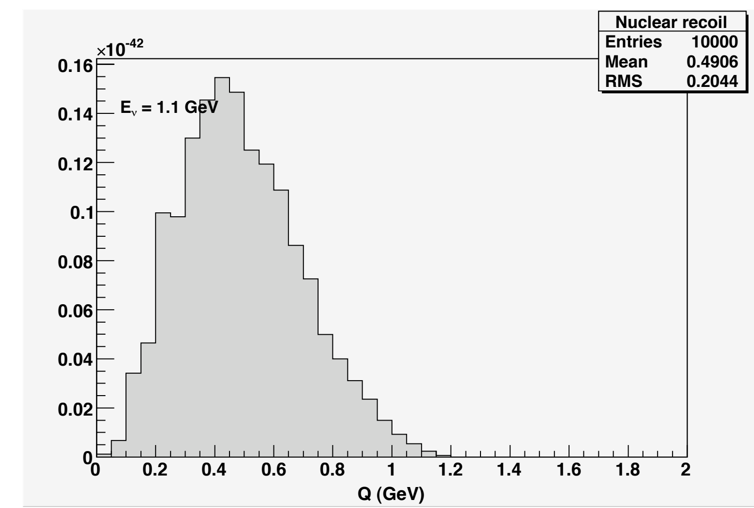


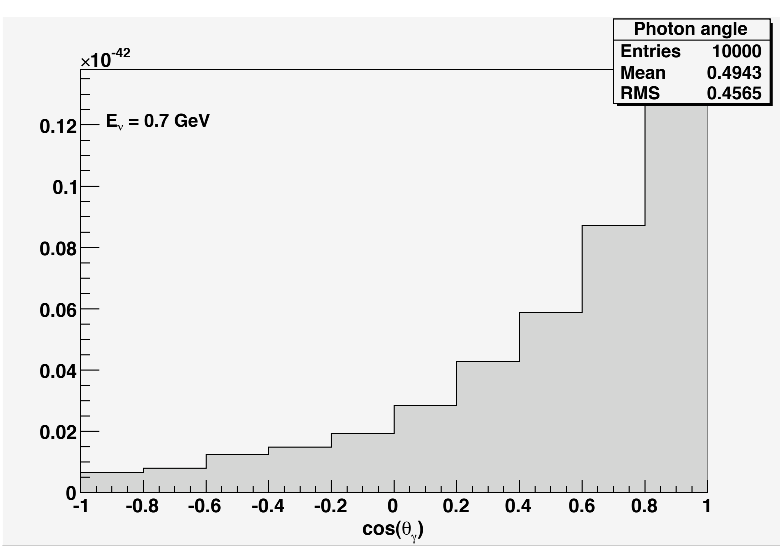


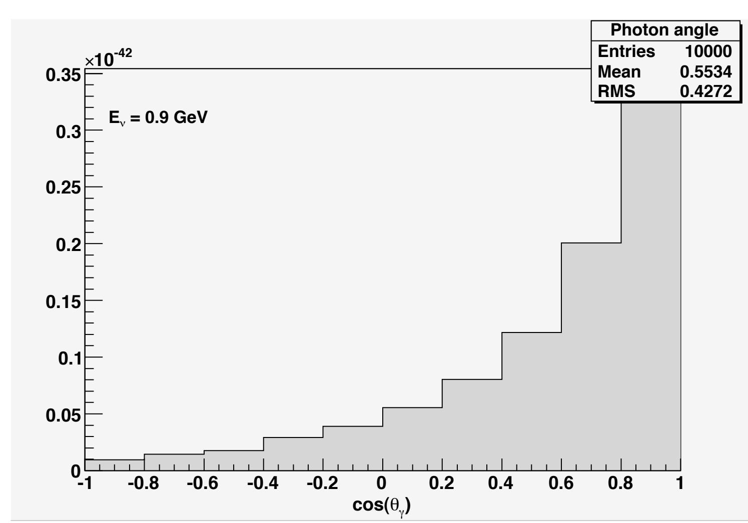


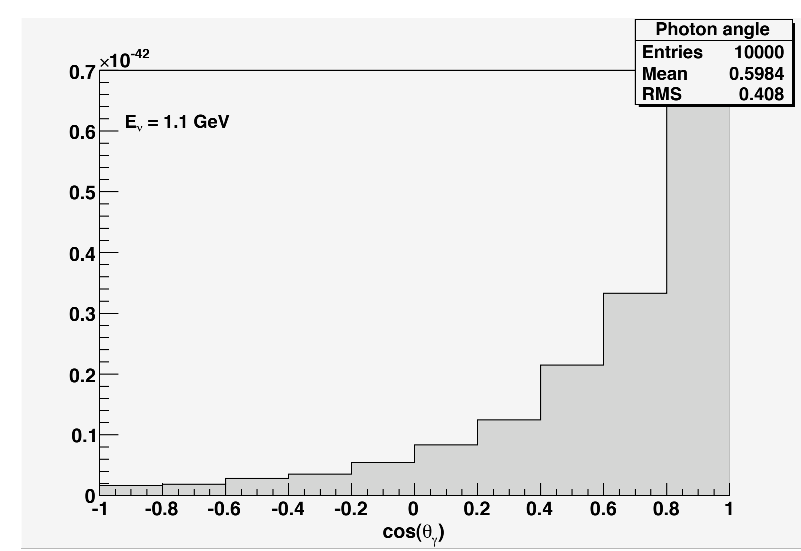












Scattering on isolated nucleons

At low energies:

Characteristic photon energy distribution:

$$\frac{d\sigma}{dE_\gamma} \propto E_\gamma^3 (E - E_\gamma)^2$$

And photon angle distribution:

$$\frac{d\sigma}{d\cos\theta} \propto \text{const.}$$

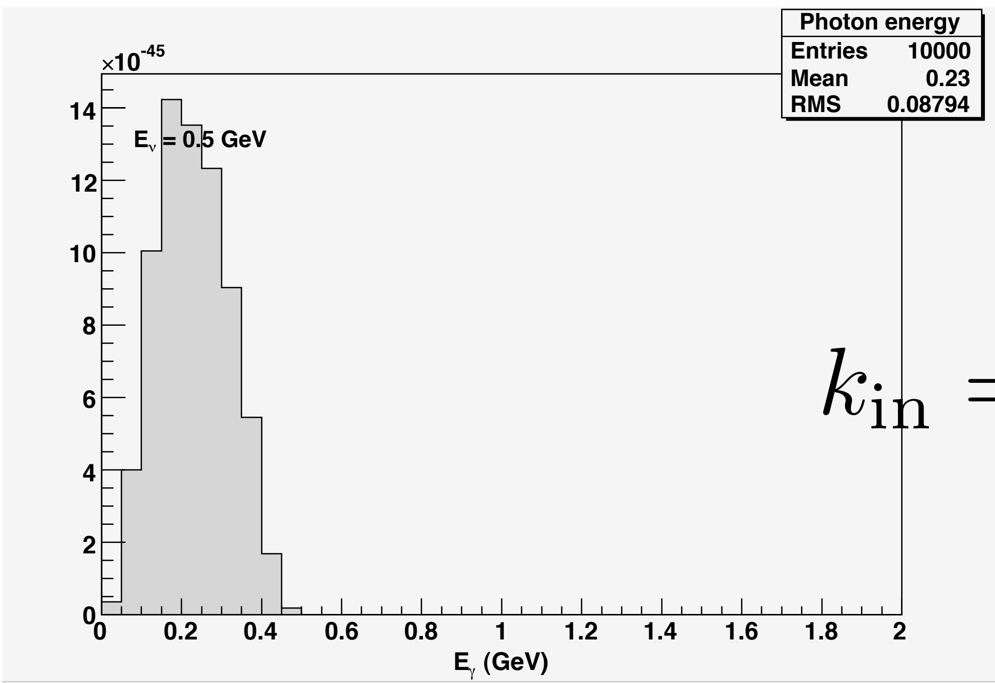
General features:

- photon pulled forward at large energy
- beam energy shared between photon and outgoing neutrino

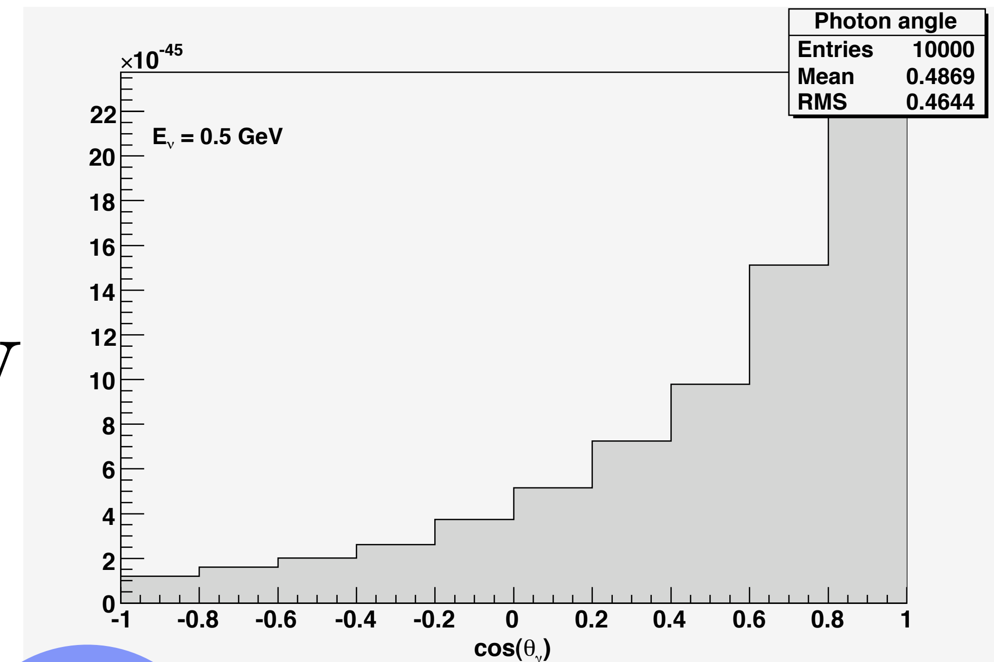
Nuclear effects

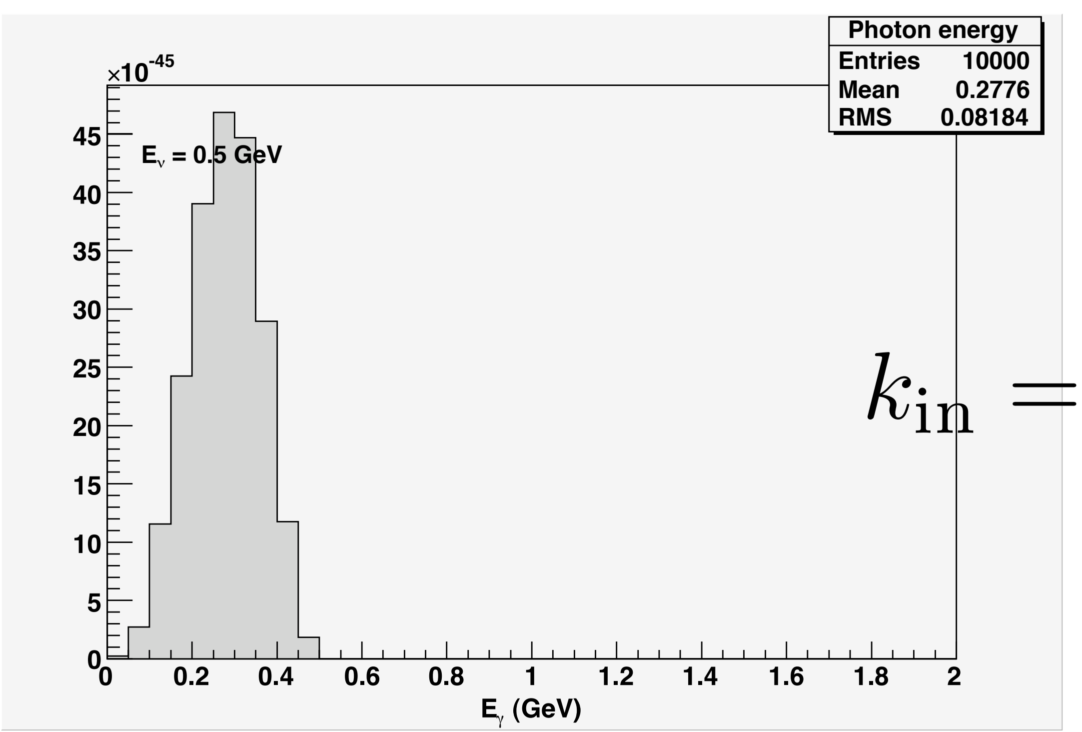
Inside a nucleus, interactions between nucleons

Initial state: Fermi motion

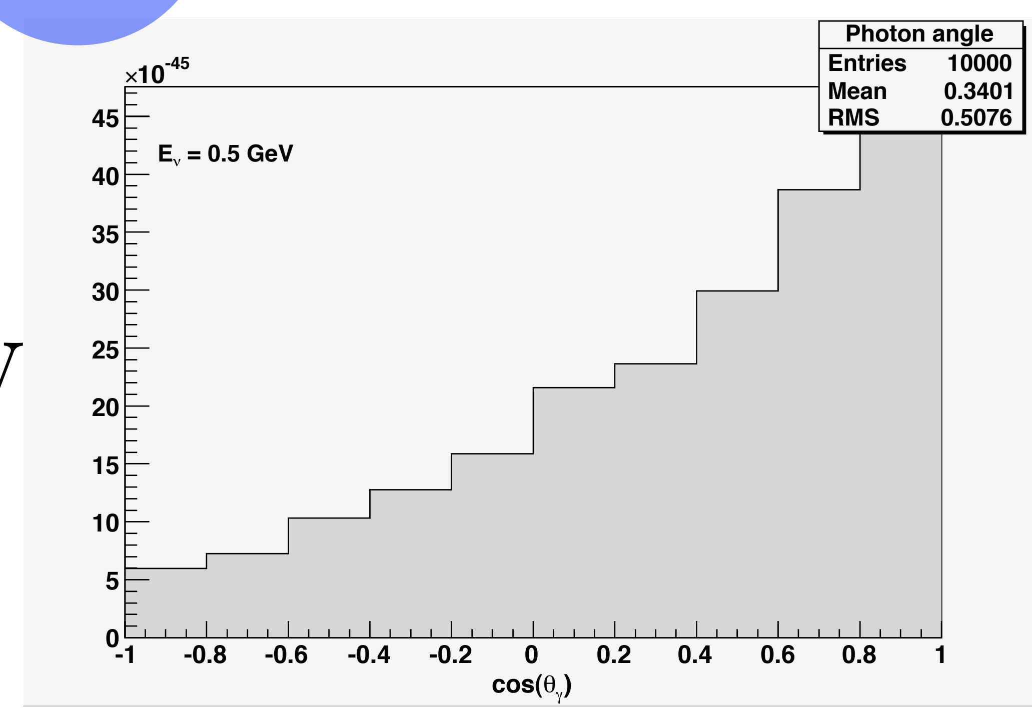


$$k_{\rm in} = +200\,{\rm MeV}$$





$$k_{\rm in} = -200\,{\rm MeV}$$

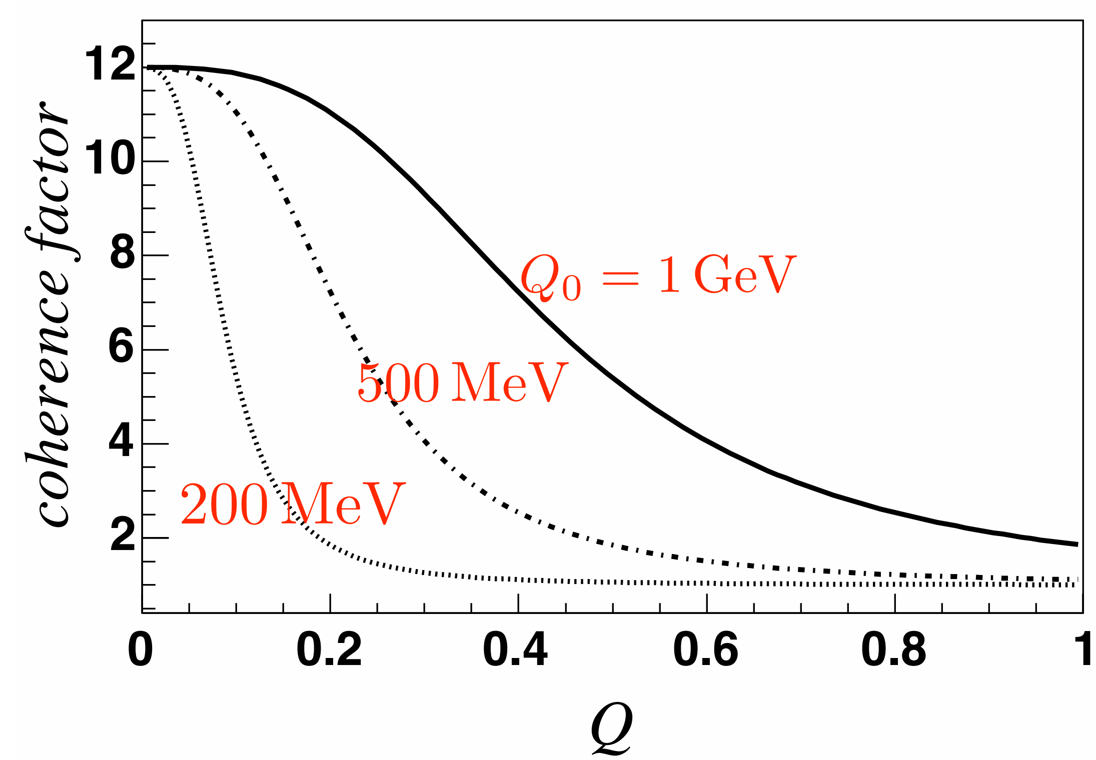


Nuclear effects

Inside a nucleus, interactions between nucleons

- Initial state: Fermi motion
- Final state: Pauli blocking
- Coherence

$$Q^2 = 2m_N\,(E_{N'} - m_N)$$



- At low Q^2, $\sigma \propto A^2$
- At high Q^2, $\sigma \propto A$

Very schematic model:

\# nuclei in a "coherence volume"

\# of coherence volumes

$$A = a \times \left(\frac{A}{a}\right)$$

$$\sigma = (a^2\sigma_0) \times \frac{A}{a} = A\,a\,\sigma_0$$

$$a \sim \frac{V}{V_0} \sim \frac{(4\pi/3)Q^{-3}}{(4\pi/3)r_0^3} \sim \left(\frac{Q_0}{Q}\right)^3 \sim A \times \frac{1+(Q/Q_0)^3}{1+A(Q/Q_0)^3}$$

At large energies, not expected to be a dominant effect

some PCAC arguments focused on small Q^2: Rein and Sehgal 1981

Current and near future neutrino experiments should be sensitive to anomaly mediated interactions

- probe the baryon anomaly of the standard model

- signals and backgrounds for neutrino oscillation searches

- constrain new neutrino interactions for astrophysics

A good place to look:

- $E_\nu \approx$100 MeV to 1000 MeV where process is prominent and theory controlled (coherence can make low energy important too)

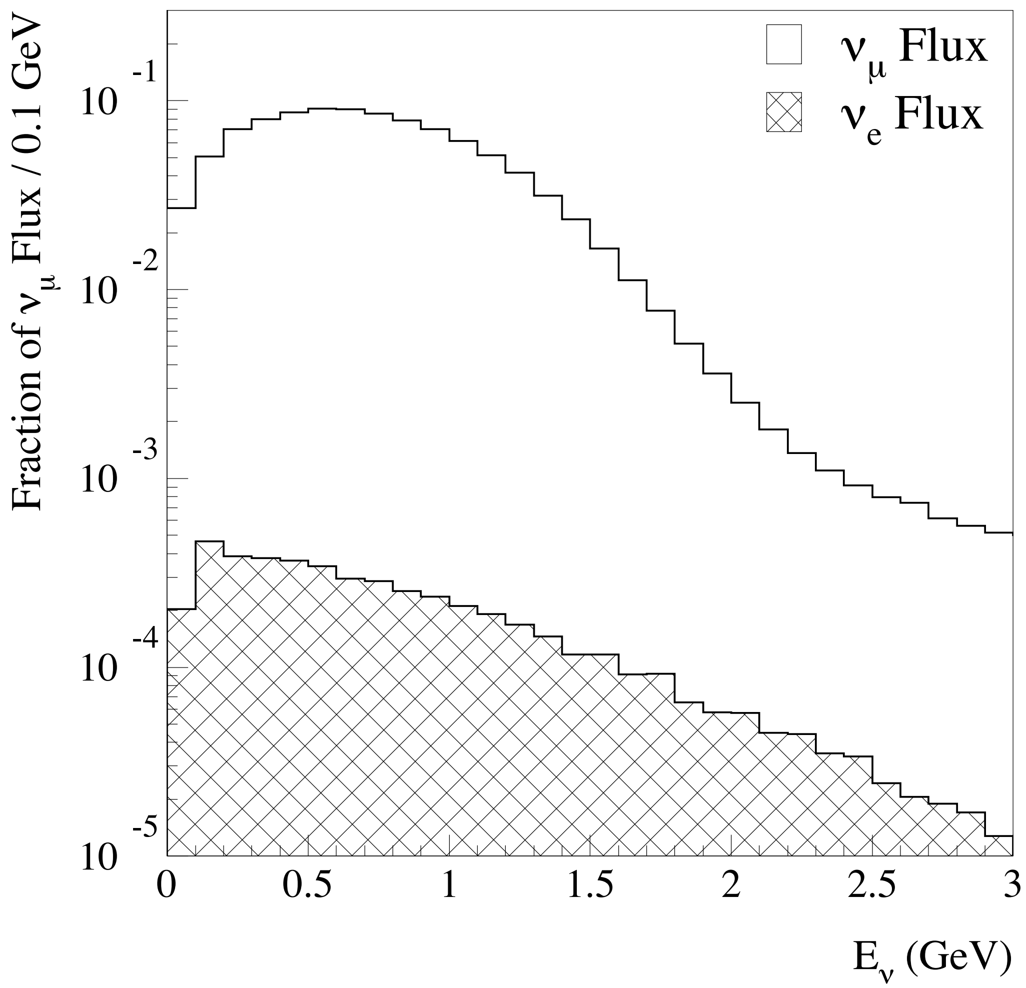
- pure beam of ν_μ, unless we can distinguish final state electron from final state photon (otherwise a $\nu_e \to e$ background)

$\Rightarrow$ overlap with experiments looking for ν_μ oscillations !

But this is a bonus - didn't set out to explain existing data

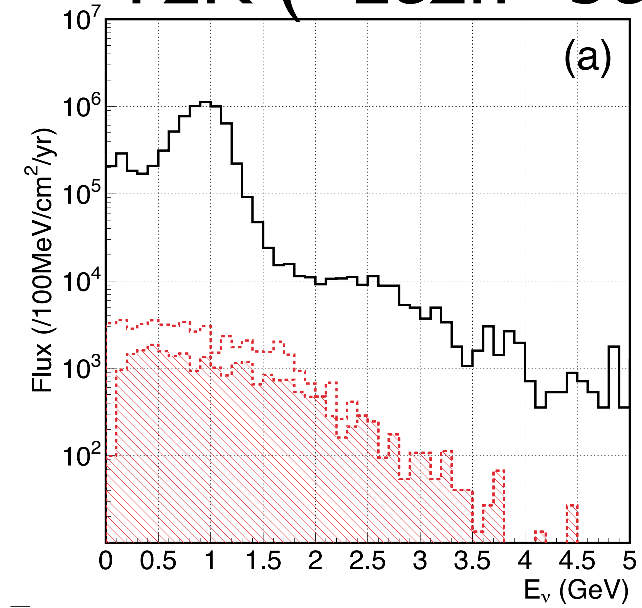
Some examples:

MiniBooNE

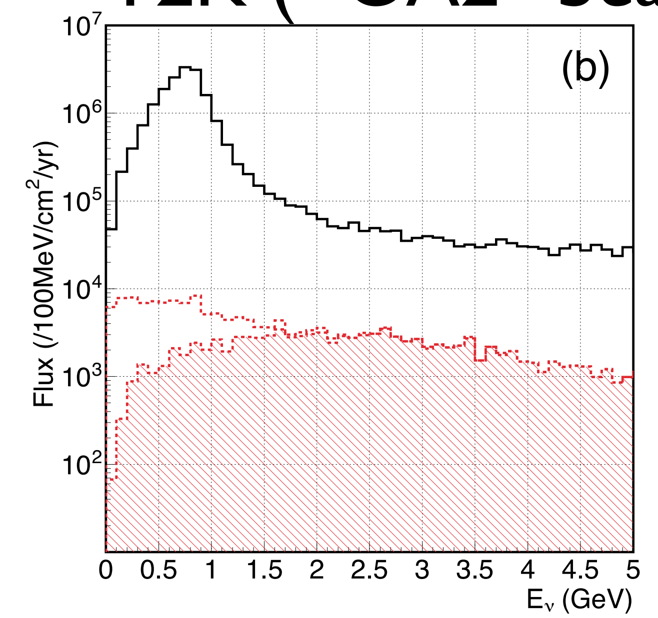


[J. Monroe, MiniBooNE, hep-ex/0408019]

T2K ("Le2π" beam)

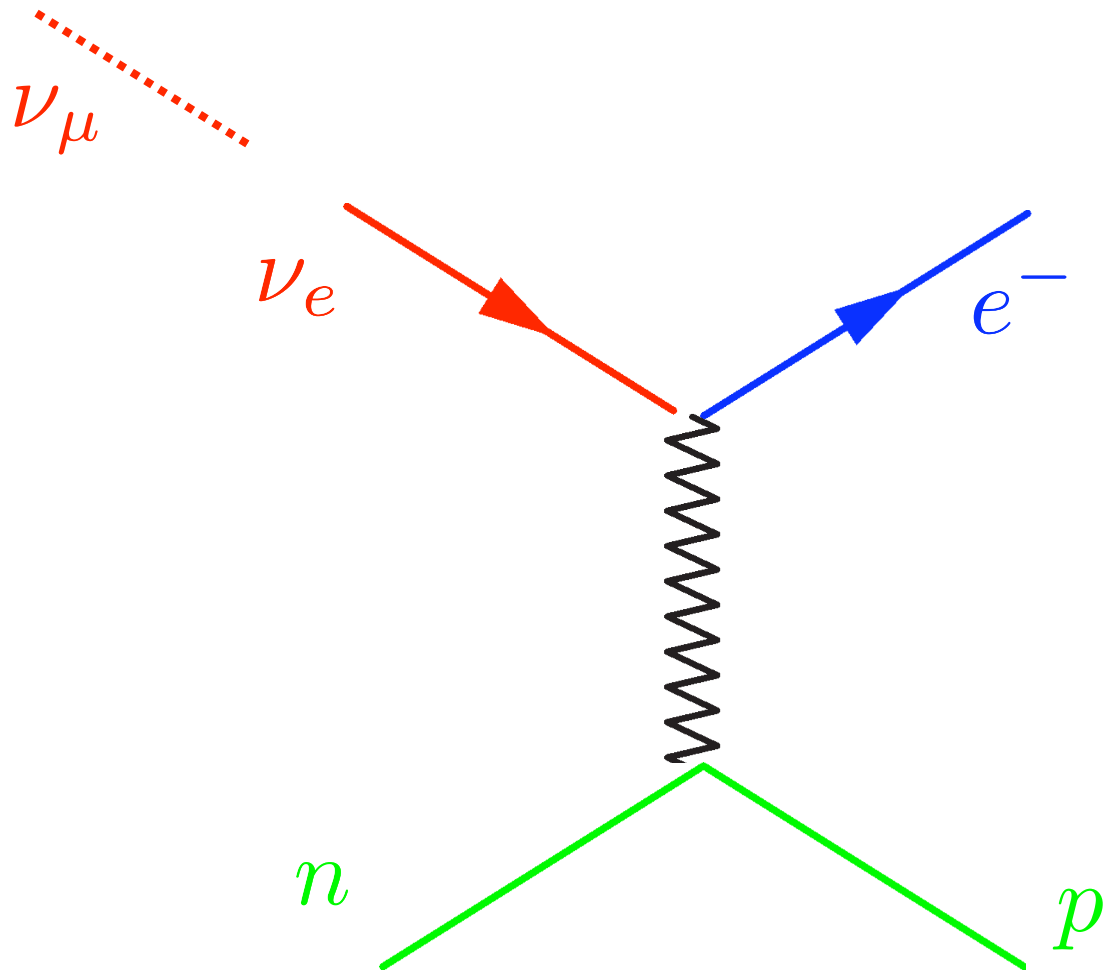


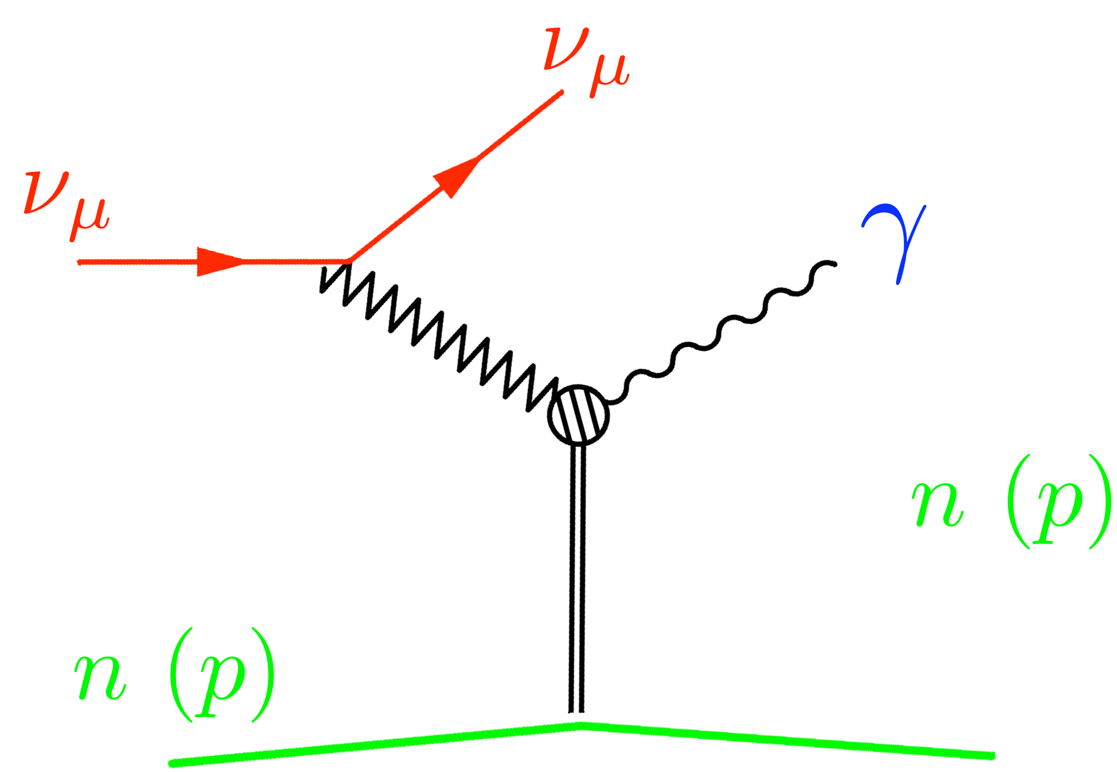
T2K ("OA2" beam)



[Itow et. al., T2K, hep-ex/0106019]

Signal or background ?





$\nu_e \rightarrow e$ "signal"

$\nu_\mu \rightarrow \gamma$ "background"

Is this process observable ?

For a rough estimation, normalize to charged current interactions, neglecting form factor and recoil:

$$\sigma \approx \frac{1}{480\pi^6} G_F^2 \alpha \frac{g_\omega^4}{m_\omega^4} E_\nu^6$$

E.g. at MiniBooNE, for a flux of 700 MeV ν's, for every 2x10^5 CCQE events, expect:

$$\sim 120 \left(\frac{g_\omega}{10}\right)^4$$

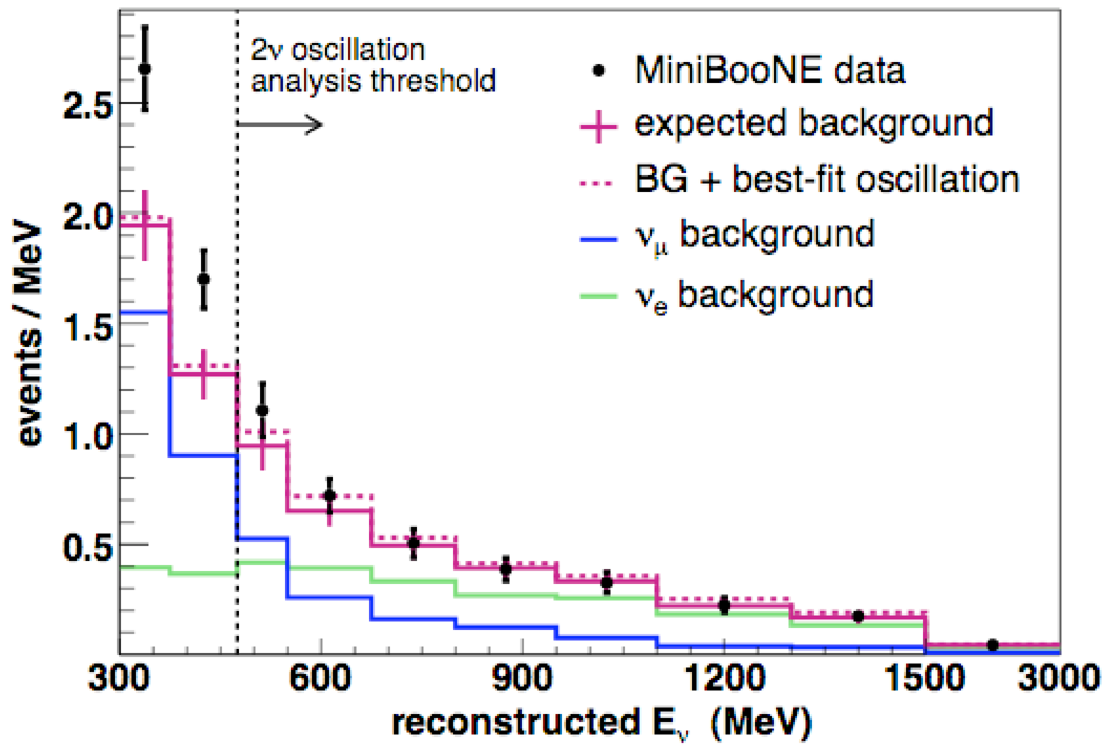
new events.

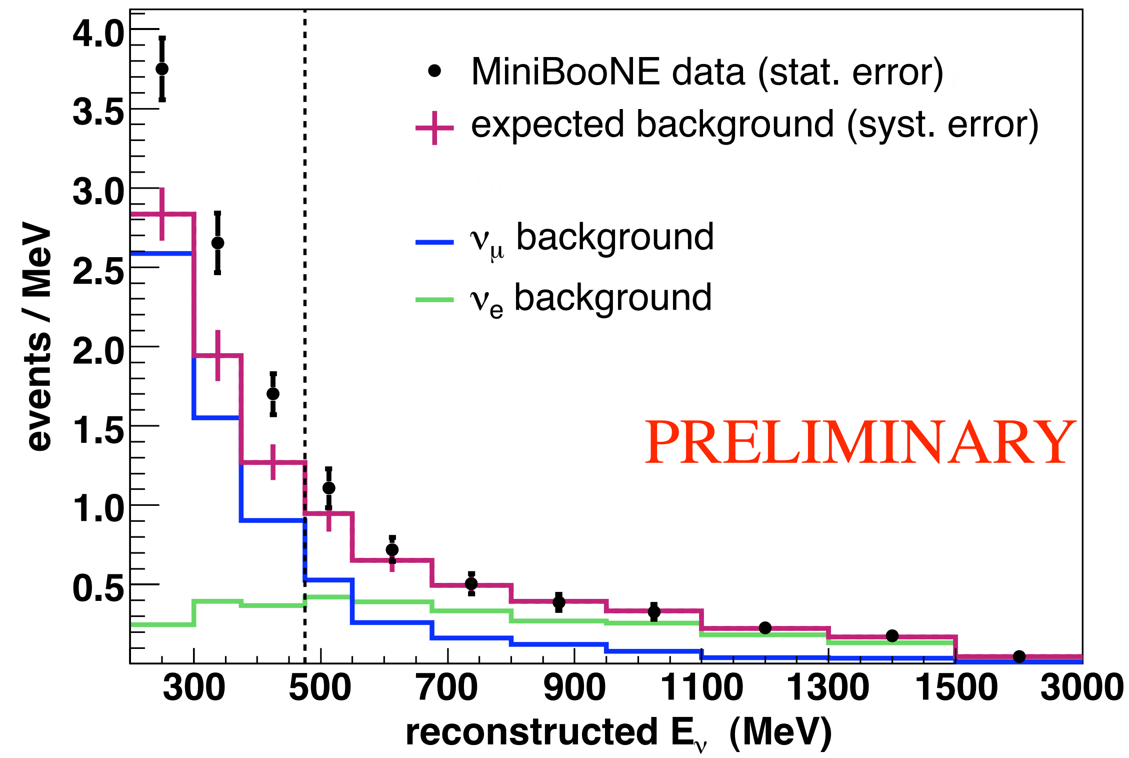
This normalization is very rough, but several tens to several hundreds of events are expected

More accurate normalization requires complete flux information, acceptance corrections, plus nuclear corrections

Has this process been seen at MiniBooNE ?

Events that look like ν_e charged-current scattering





- energy dependence of excess not consistent with 2 neutrino oscillation

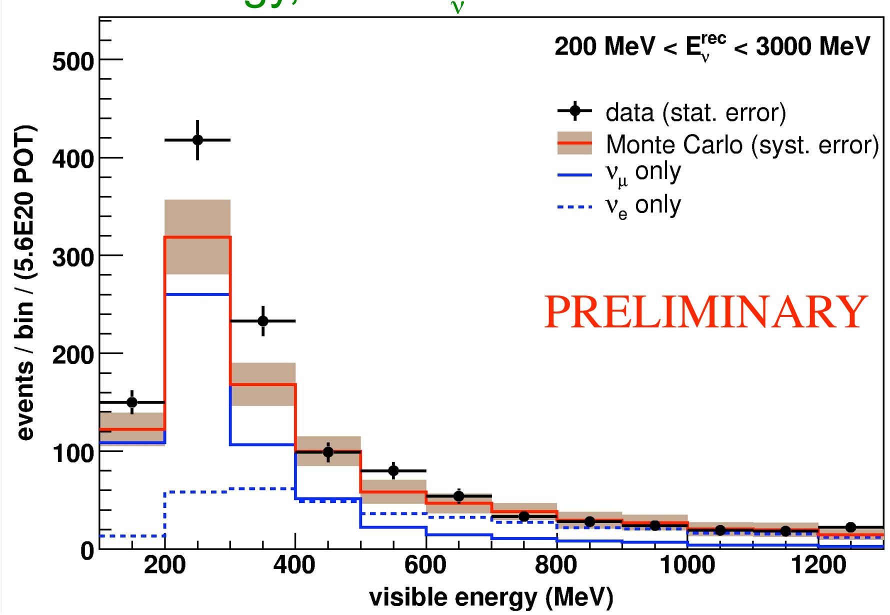
- excess of events at low energy appears to be growing ? Is it real ? Is anything else left out ?

- the "reconstructed E_ν" assumes 2-body kinematics to find initial-state energy from final state "electron" energy and angle

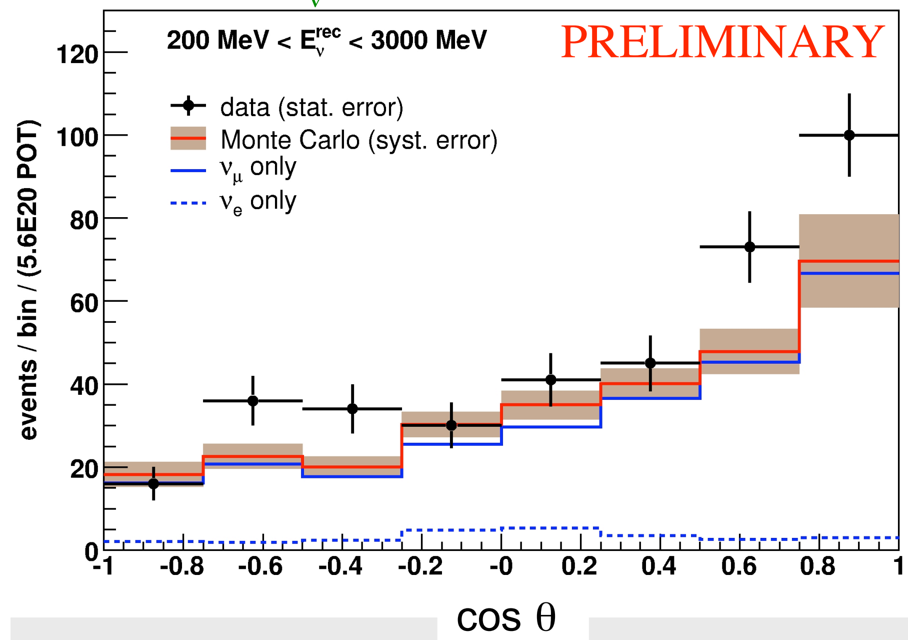
- if it's a 3-body state, E_ν underestimated

- what does the excess look like in terms of visible (electron or photon) energy ?

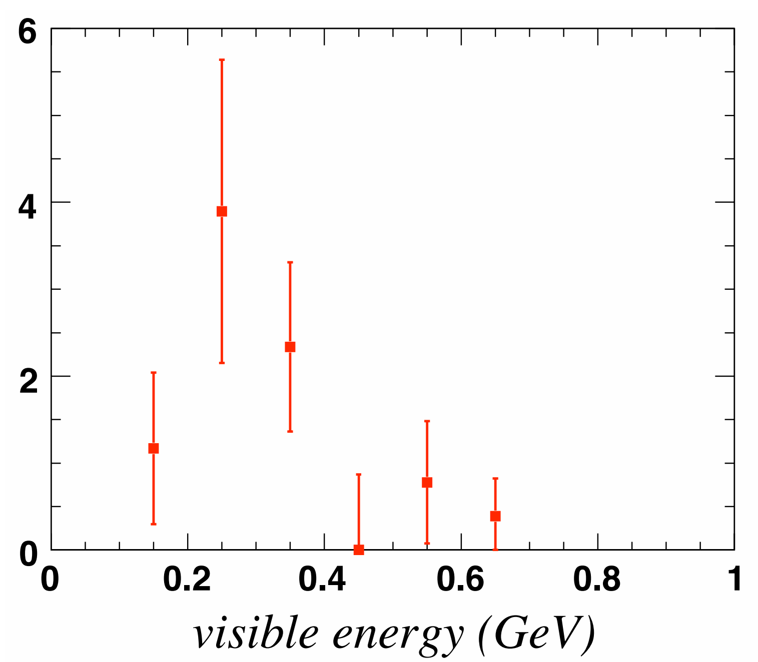
visible energy, $200<E_\nu<3000$ MeV

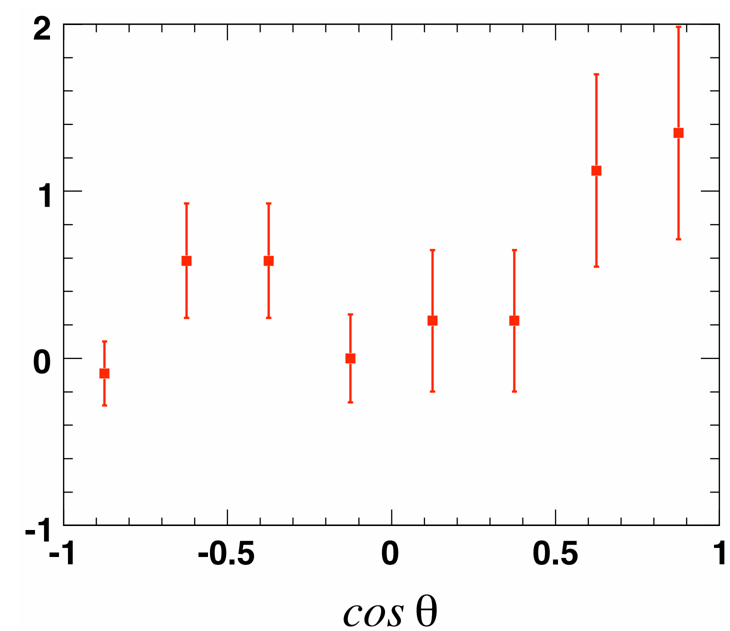


cos θ , $200<E_\nu<3000$ MeV



[R. Tayloe, MiniBooNE, Lepton Photon 07]





- within (large) uncertainties, consistent with anomaly-mediated photon process
- more detailed study in progress
- new experimental handles would be useful

Higher energy

Focus so far has been on energies < 1 GeV, where chiral lagrangian description is appropriate. Important for:

- T2K
- SciBooNE
- *... ?*

Interesting to look at higher energies

- an interesting process for its own sake

- help constrain intermediate energies ≈ 1 GeV

- *NOMAD*
- *MINIBOONE in NUMI beam*
- *MINERVA*
- *NOVA*
- *... ?*

Astrophysical implications

Neutrino cooling of neutron star

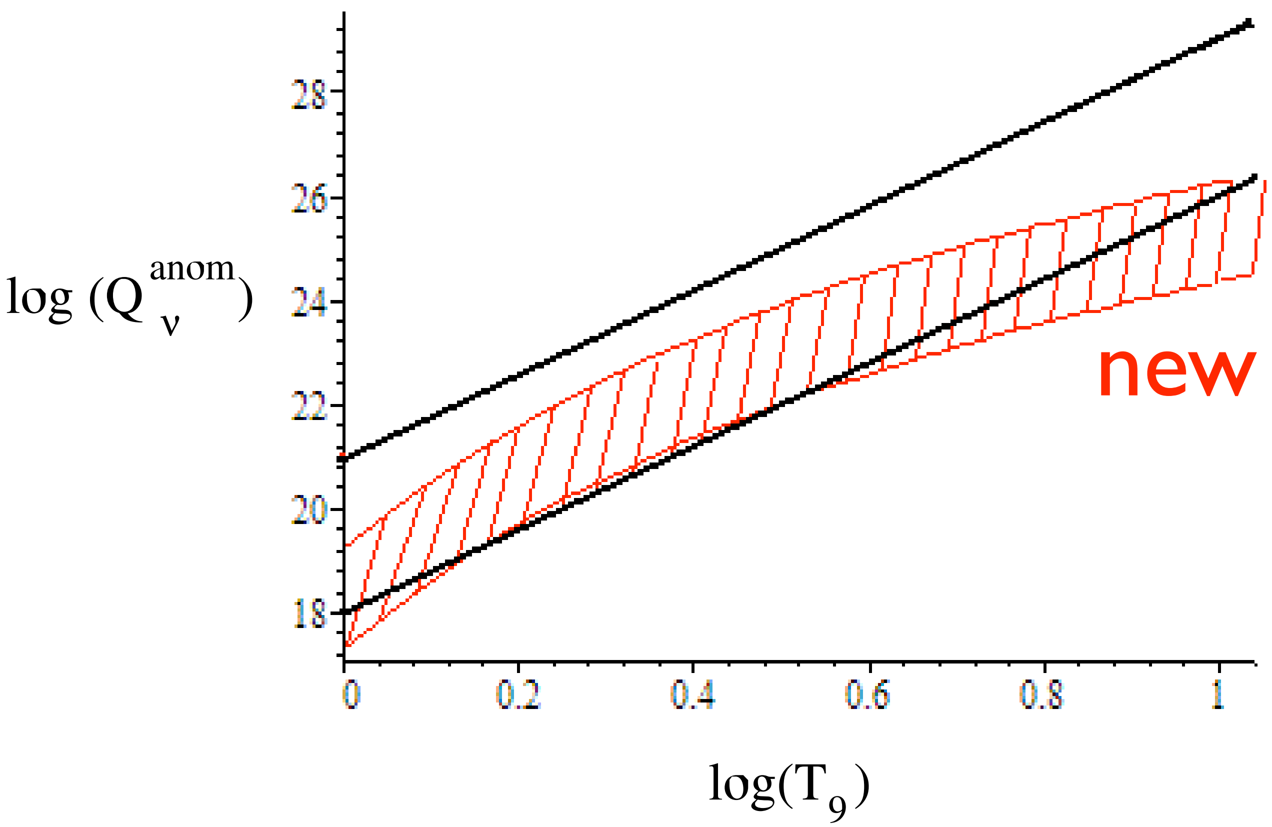
Contribution to young NS cooling from other sources:

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

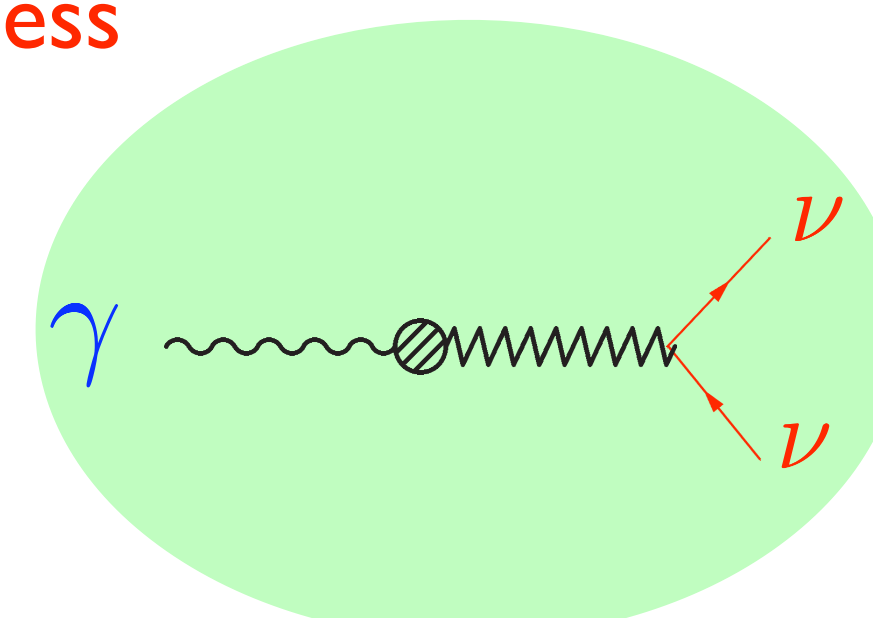
$m = m_\gamma / 1\,\mathrm{MeV}$

New interaction, massive photon to neutrinos: $T_9 = T/10^9\,\mathrm{K}$

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

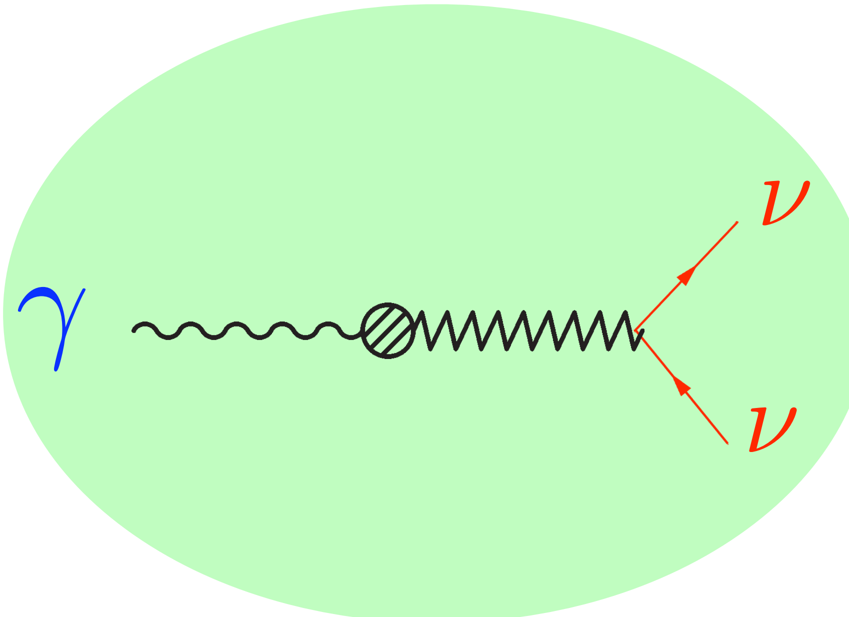


estimated range
of other processes

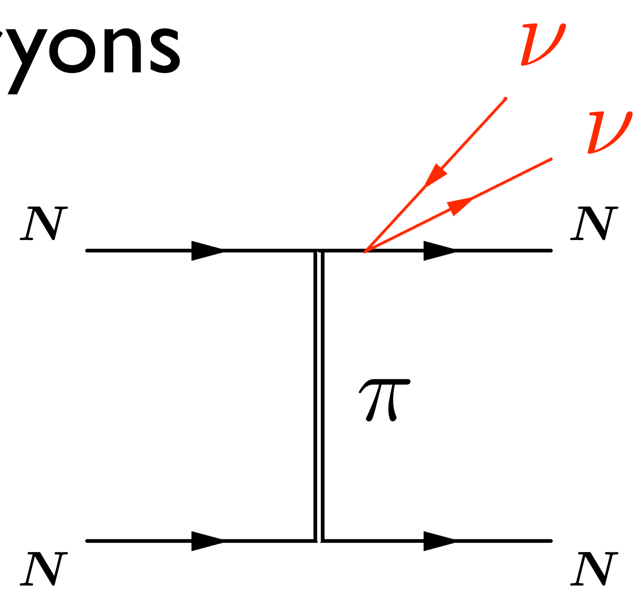


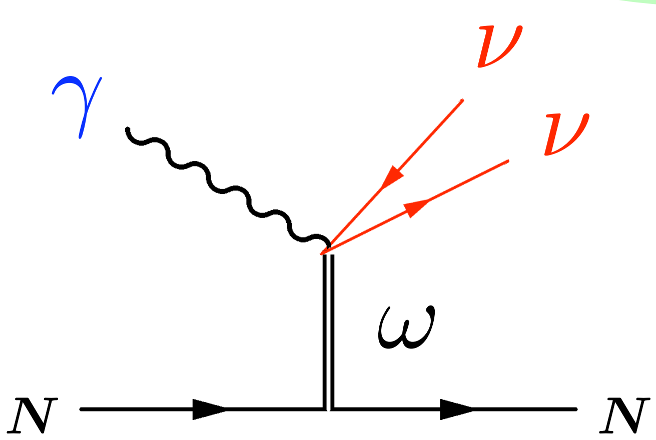
Neutrino pair production in supernova

Perhaps even more relevant is the pair production of neutrinos in a supernova core



Lots of thermal photons, lots of baryons





- Unlike bremstrahlung contribution, anomaly mediated process (via omega) acts coherently on adjacent nucleons

- In a hot SN core, neutrinos don't escape freely, although production of μ and τ neutrinos may play important role

- Can look at axion analog - simpler to interpret for weak coupling

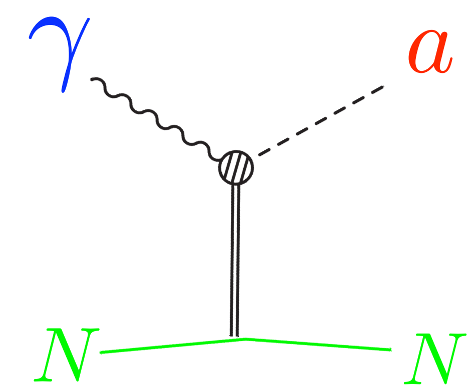
Axion cooling of supernova

Supernova cooling from photon-axion-baryon coupling:

$$Q/\rho \approx 10^{-27}\,\mathrm{GeV}\,\left(\frac{10^8\mathrm{GeV}}{f_a}\right)^2\left(\frac{g_\omega}{10}\right)^4\left(\frac{T}{30\,\mathrm{MeV}}\right)^8$$

Bound from observed duration:

$$Q/\rho < 10^{19}\,\mathrm{erg\,g^{-1}\,s^{-1}} = 7.3\times 10^{-27}\,\mathrm{GeV}$$



$$\Longrightarrow\;\; f_a \gtrsim 10^8\,\mathrm{GeV}$$

- probes a new coupling of the axion
- competitive (at least) to other constraints
- have completely ignored coherence
- have ignored in-medium suppression of m_ω

Other directions

Coherent coupling to photons and baryons

Many astrophysical applications to explore

- *neutron star cooling;*
- *supernova energy transfer?*
- *SN nucleosynthesis?*
- *magnetic field enhancements?*
- *neutron star kicks?*

Summary

- new class of Standard Model interactions emerge at low energy in connection with the baryon anomaly

- effects of these interactions is small, but potentially significant in situations with neutrinos, photons, baryons

- should be observable at present and/or near-future neutrino experiments

- any new experimental handles would be very useful

- these interactions appear to have exciting astrophysical applications: a quarks to the cosmos problem !