Anomaly mediated neutrino photon interactions

New physics in the standard model

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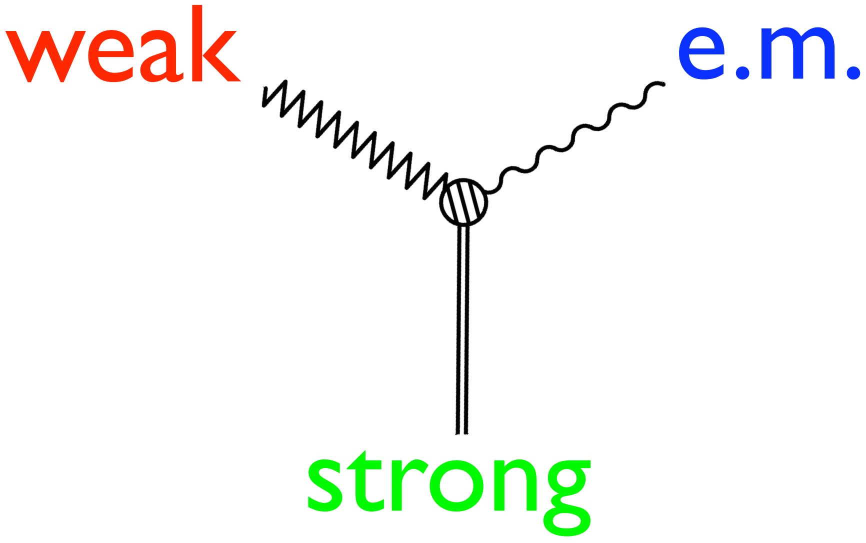
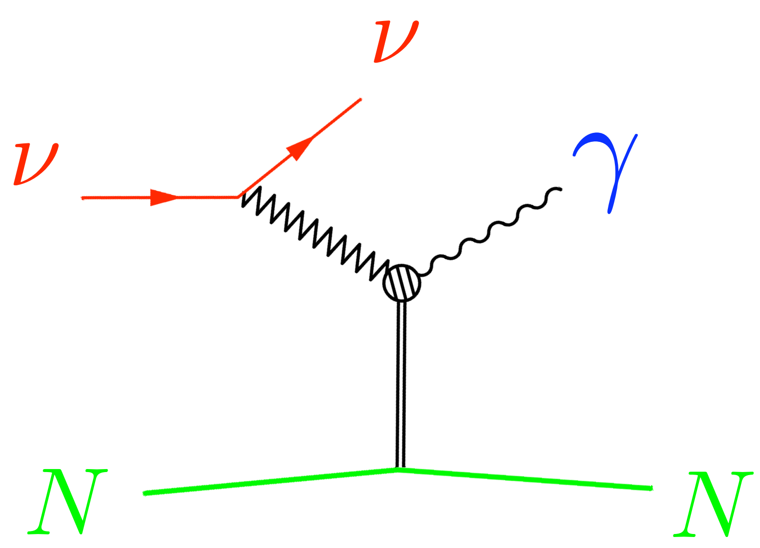
based on:
arXiv:0708.1281, PRL, arXiv:0712.1230, PRD,
with J.A. Harvey and C.T.Hill

La Thuile, 6 March, 2008

A new class of standard model interactions

What if we had a handle like:

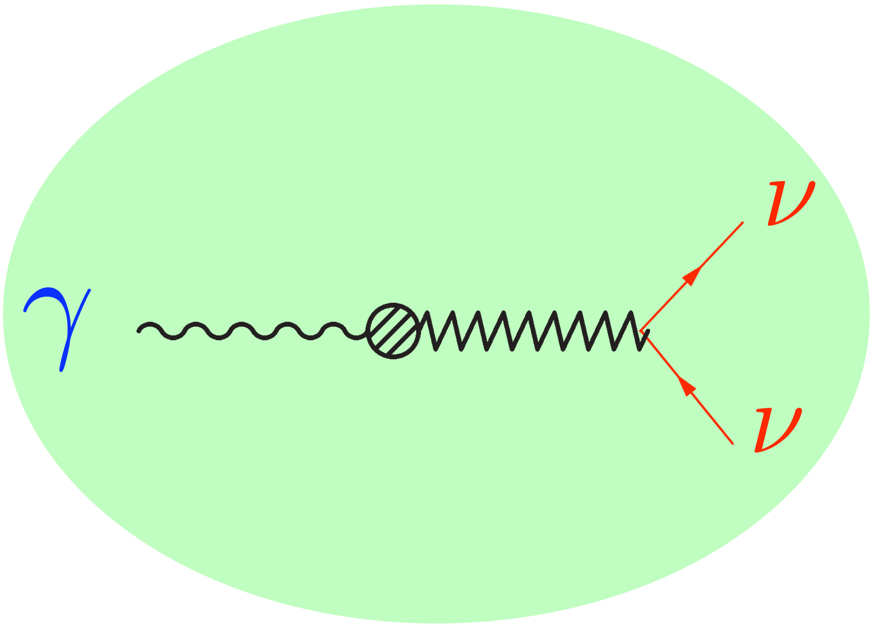




laboratory neutrino detection

- 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

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

$$\Longrightarrow \; \mathcal{L} \rightarrow \bar{\Psi}e^{-i\epsilon}i\partial\!\!\!/ e^{i\epsilon}\Psi = \mathcal{L}$$

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

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

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

to a local symmetry

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

by adding a gauge field

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

Then classically the action is invariant

$$\mathcal{L} = \bar{\Psi}(i\partial\!\!\!/ + A\!\!\!/)\Psi \rightarrow \mathcal{L}$$

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

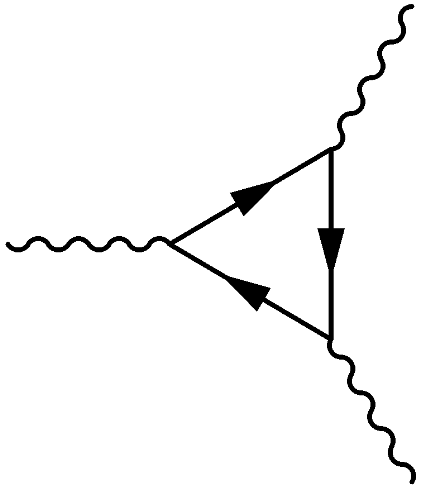
$$\delta(\mathrm{Action}) = \frac{1}{48\pi^2}\int \mathrm{d}^4\mathrm{x}\,\epsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\left[\partial_\mu\epsilon\left(\mathrm{A}_\nu\partial_\rho\mathrm{A}_\sigma - \frac{\mathrm{i}}{2}\mathrm{A}_\nu\mathrm{A}_\rho\mathrm{A}_\sigma\right)\right]$$

Adler 1969
Bell, Jackiw 1969
Bardeen 1969

Implications of anomalies

First, if we *do* 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

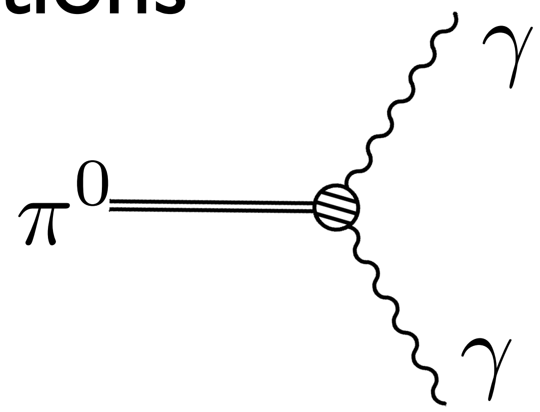
SU(2) x U(1) → U(1)

E.g.

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

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:

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

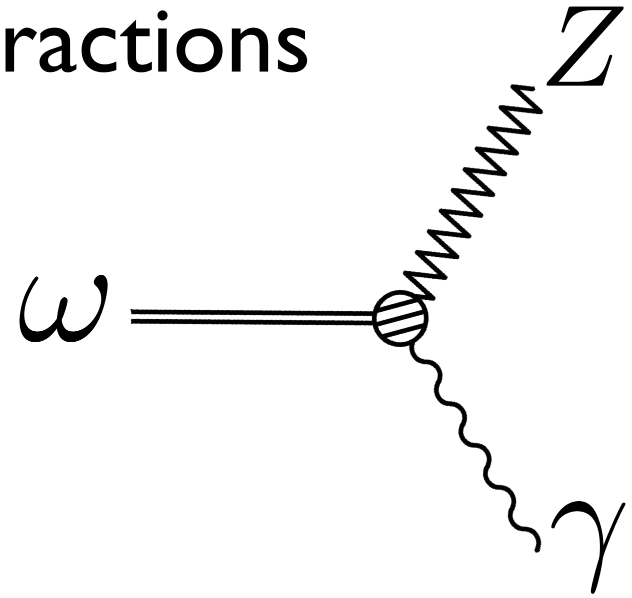
If we *did* try an ill-advised gauge transformation on the axial symmetries, have to get the expected anomaly

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

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

The anomalous baryon current

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



Baryon number is anomalous in the Standard Model

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

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

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

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

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

Why this is surprising

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

$$\Gamma(U, \underset{\nearrow\ \text{gauge}}{A}, \underset{\nwarrow\ \text{background}}{B}) \to \Gamma(U, A, B) - \Gamma(1, A, B)$$

Bardeen 1969

Wess and Zumino 1971

The "Bardeen counterterm" or "Wess-Zumino boundary condition" maintains vector current conservation in the presence of arbitrary backgrounds

This subtracts any interaction involving just vector fields (no pions) !
⇒ "proof" that: "pseudo Chern Simons terms do not exist" !

But the Standard Model SU(2)xU(1) is not vector-like gauging ! Need to revisit the counterterm question

A new counterterm, new interactions, and connection to the baryon number anomaly

Harvey, Hill, Hill 2007

Many ill-advised transformations we could make, and many new interactions that must be present

$$
\begin{aligned}
\Gamma_{AAB} &= \mathcal{C}\int dZZ\left[\frac{s_W^2}{c_W^2}\rho^0+\left(\frac{3}{2c_W^2}-3\right)\omega-\frac{1}{2c_W^2}f\right]+dAZ\left[-\frac{s_W}{c_W}\rho^0-\frac{3s_W}{c_W}\omega\right]+dZ\left[W^-\rho^++W^+\rho^-\right]\frac{s_W^2}{c_W}\\
&\quad +dA\left[W^-\rho^++W^+\rho^-\right](-s_W)+(DW^+W^-+DW^-W^+)\left[-\frac{3}{2}\omega-\frac{1}{2}f\right],
\end{aligned}
$$

$\nu \longrightarrow \nu + \gamma$

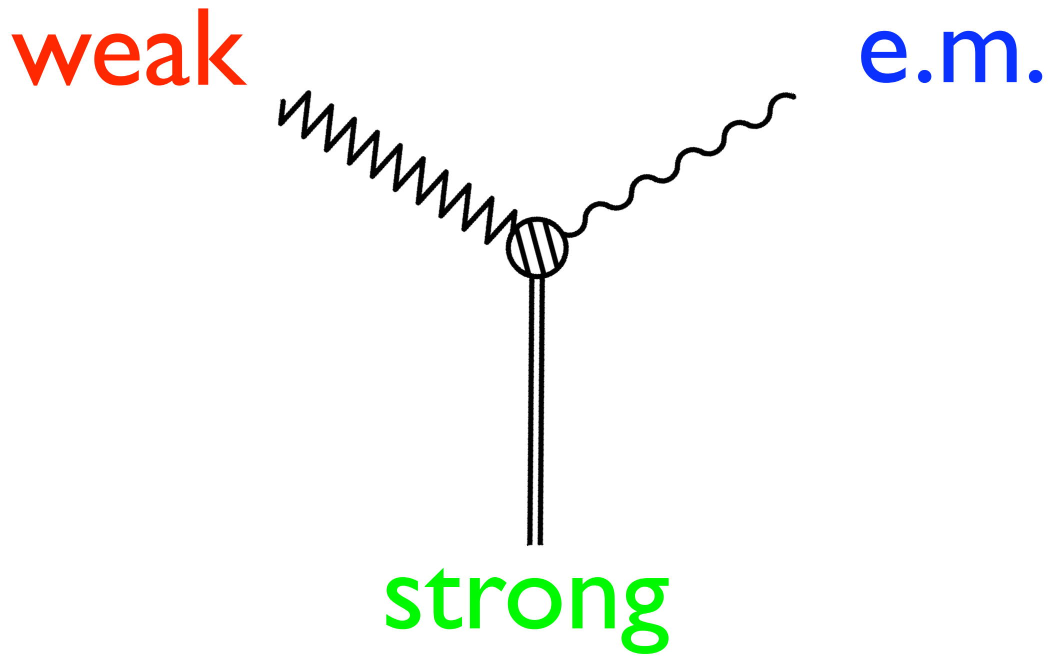
$$
\begin{aligned}
\Gamma_{ABB} &= \mathcal{C}\int Z\Big\{d\rho^0\Big[-\frac{3}{2c_W}\omega-\frac{s_W^2}{c_W}a^0+\left(-\frac{3}{2c_W}+3c_W\right)f\Big]+d\omega\Big[-\frac{3}{2c_W}\rho^0+\left(-\frac{3}{2c_W}+3c_W\right)a^0-\frac{s_W^2}{c_W}f\Big]\\
&\quad +da^0\left[\frac{s_W^2}{c_W}\rho^0+\left(\frac{3}{2c_W}-3c_W\right)\omega-\frac{1}{2c_W}f\right]+df\Big[\left(\frac{3}{2c_W}-3c_W\right)\rho^0+\frac{s_W^2}{c_W}\omega-\frac{1}{2c_W}a^0\Big]\Big\}\\
&\quad +dA\Big\{s_W\rho^0a^0+3s_W\rho^0f+3s_W\omega a^0+s_W\omega f\Big\}+dZ\Big\{-\frac{s_W^2}{c_W}\left(\rho^+a^-+\rho^-a^+\right)\Big\}\\
&\quad +dA\Big\{s_W\left(\rho^+a^-+\rho^-a^+\right)\Big\}
\end{aligned}
$$

$f_1 \longrightarrow \rho\gamma$

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

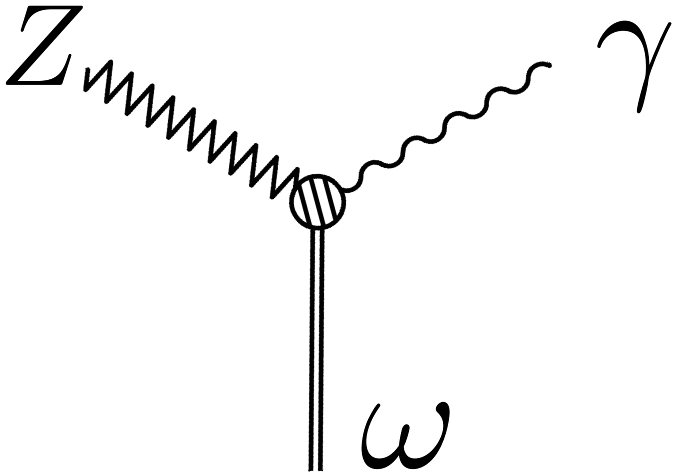
connections to AdS/CFT models

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

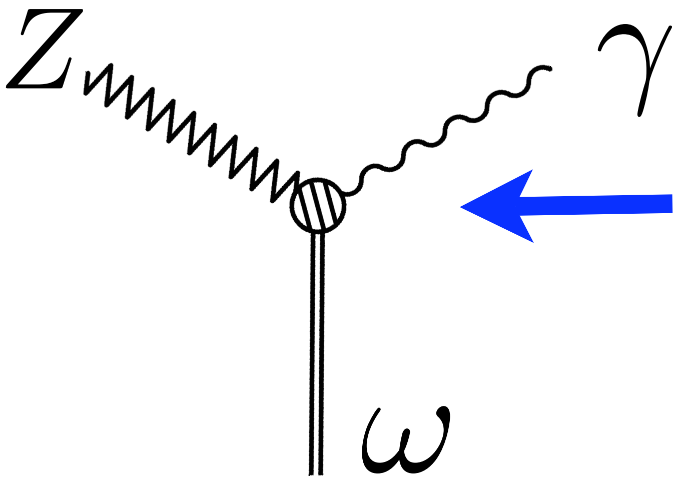
A fundamental ingredient in the Standard Model

E.g. could explain baryogenesis at the electroweak phase transition if a large source of CP violation were present:

baryon number

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

nonperturbative ("sphaleron") configuration of gauge fields



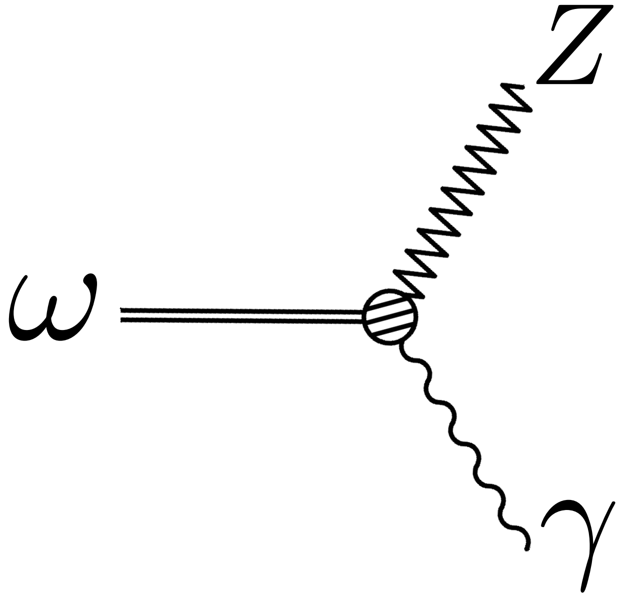
perturbative (in EW fields) manifestation of same physics

Challenge to experimentalists: observe this interaction

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

Laboratory probes

Why these effects haven't been observed

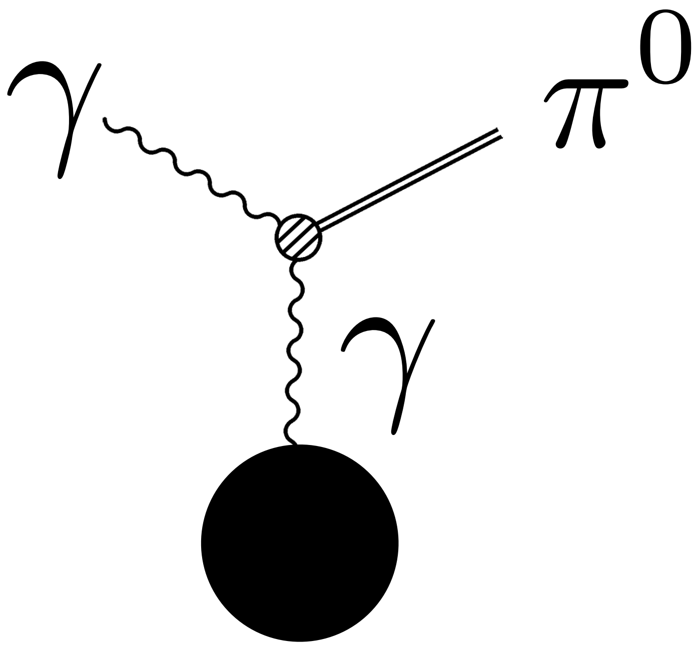


If Z was much lighter, would see e.g. ω→Zγ directly. But in practice, Z is heavy (weak interactions are weak !)

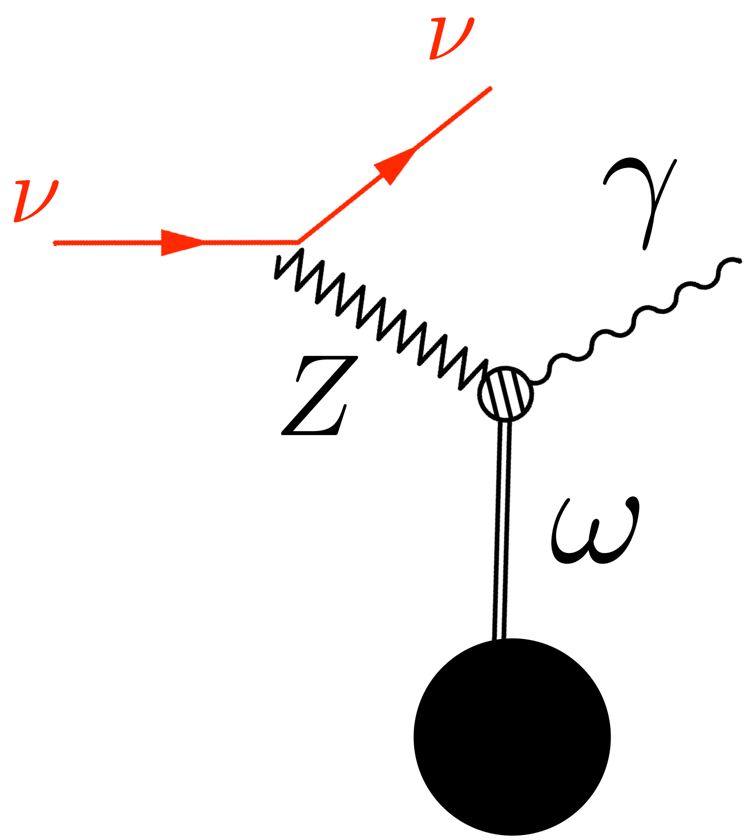
$$\mathrm{Br}(\omega \to \gamma\nu\bar{\nu}) \sim \left(\frac{g^2_{\mathrm{weak}}}{m_W^2}\right)^2 \frac{f_\pi^6}{m_\omega^2} \sim \frac{G_F^2 f_\pi^6}{m_\omega^2} \sim 10^{-16}$$

Where to look for it

Compare Primakoff effect:



nucleus=source of
electric charge

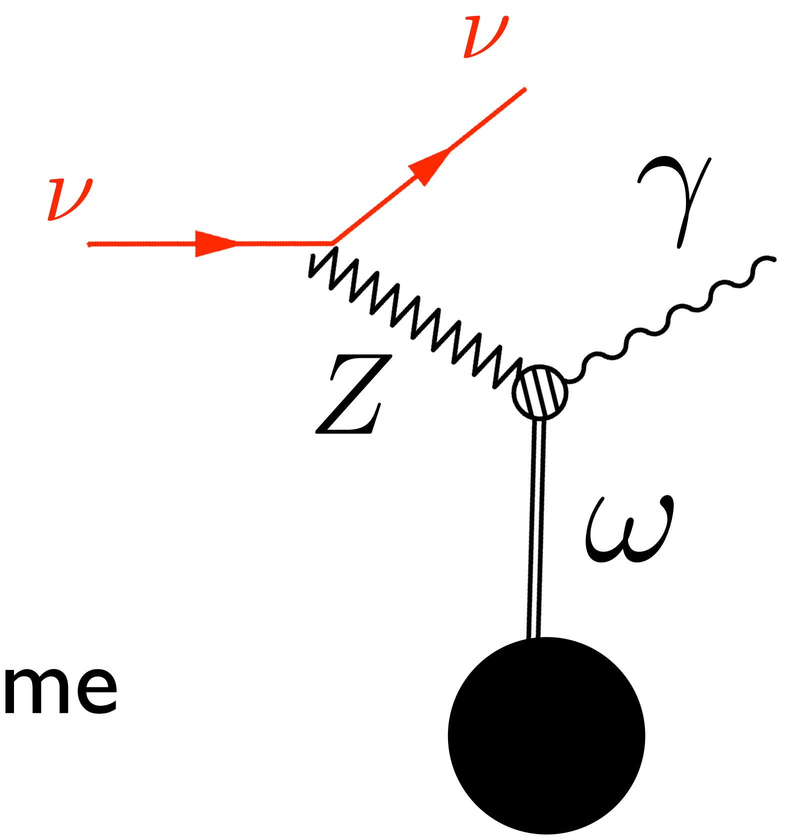


nucleus=source of
baryon number

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



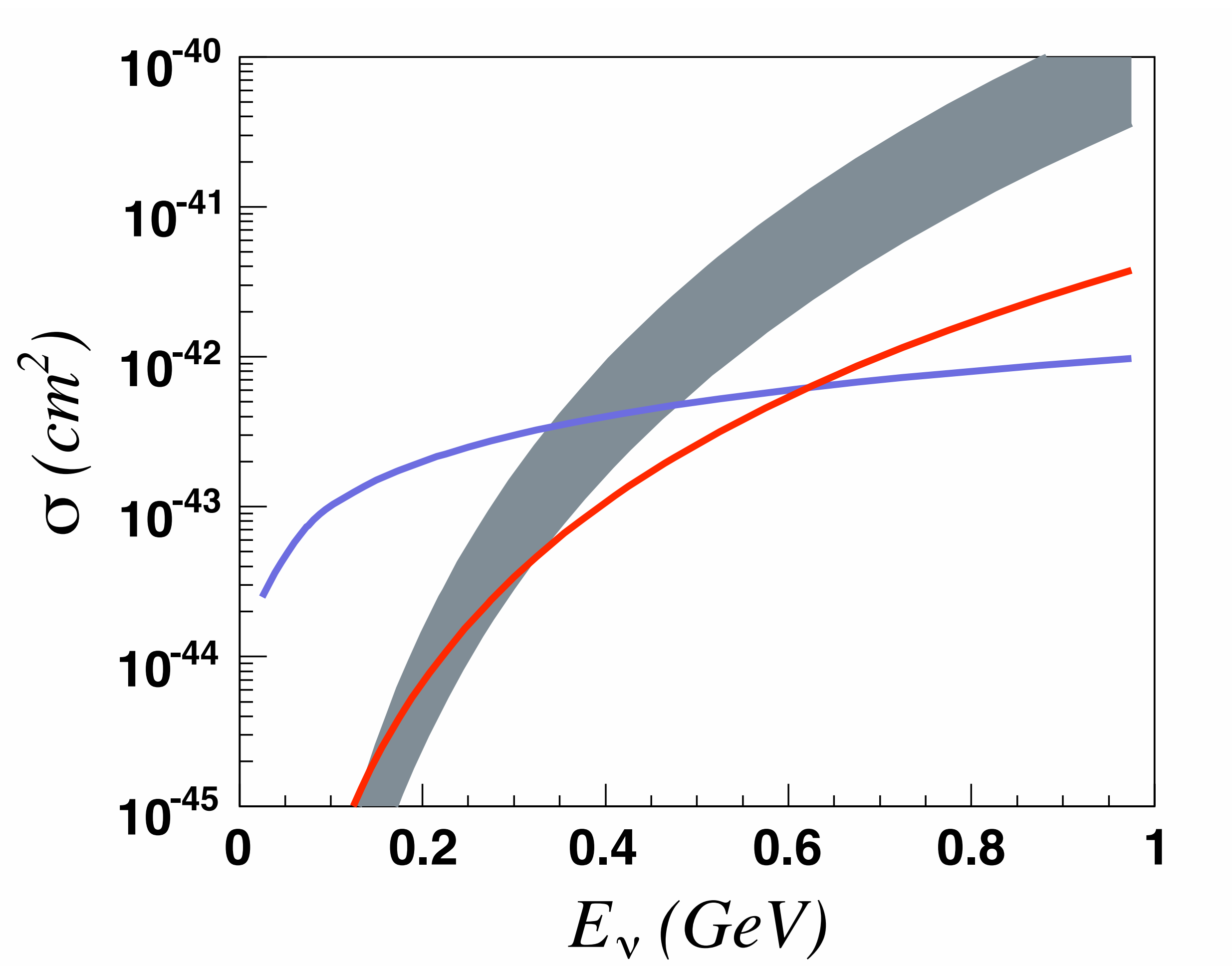
Backgrounds to this interaction come
from several sources:

- 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 !

As a very rough guide neglect:

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



anomaly mediated $\nu \to \nu\gamma$

(coupling uncertainty only)

"bremstrahlung"

electron scattering

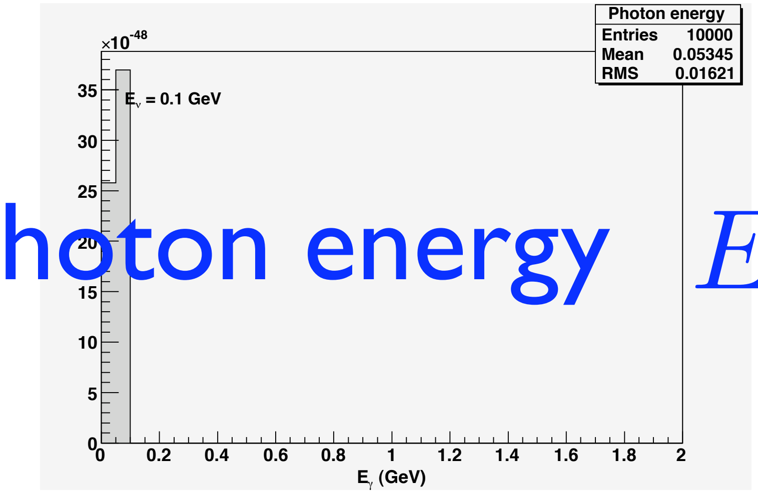
On small nuclei, energies of order several 100 MeV a promising place to look

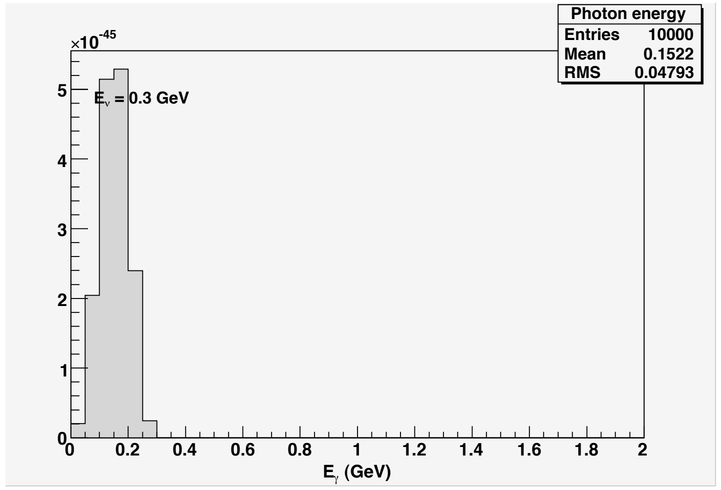
- at small energy, nuclear enhancements significant
- at large energy, chiral lagrangian description breaks down

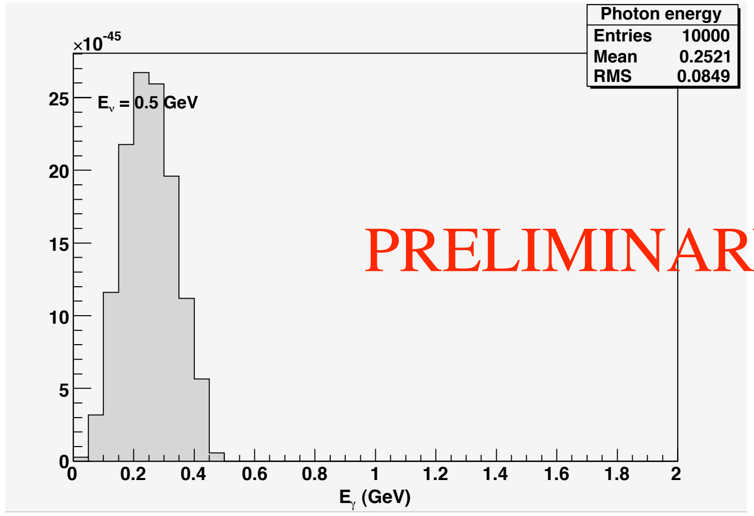
Assume typical values of nuclear parameters *[Machleidt et.al. Phys Rep (1987)]*
What does the cross section look like?

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

photon energy E_γ

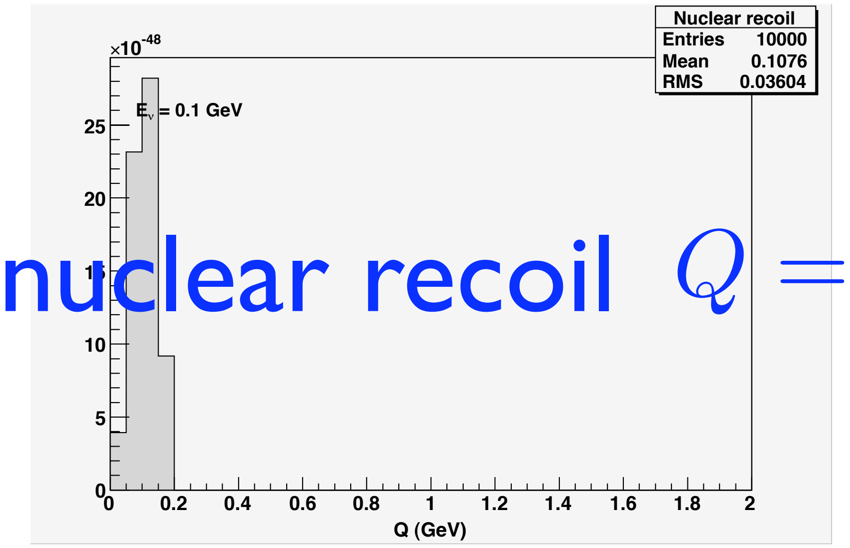


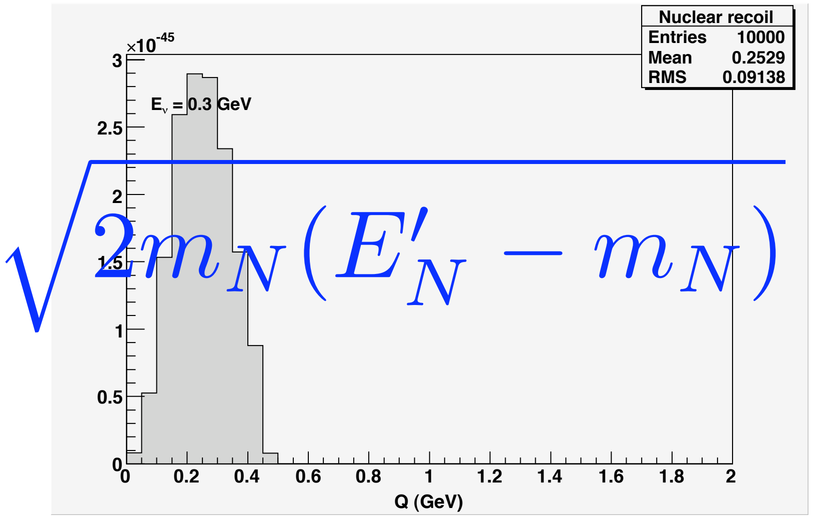


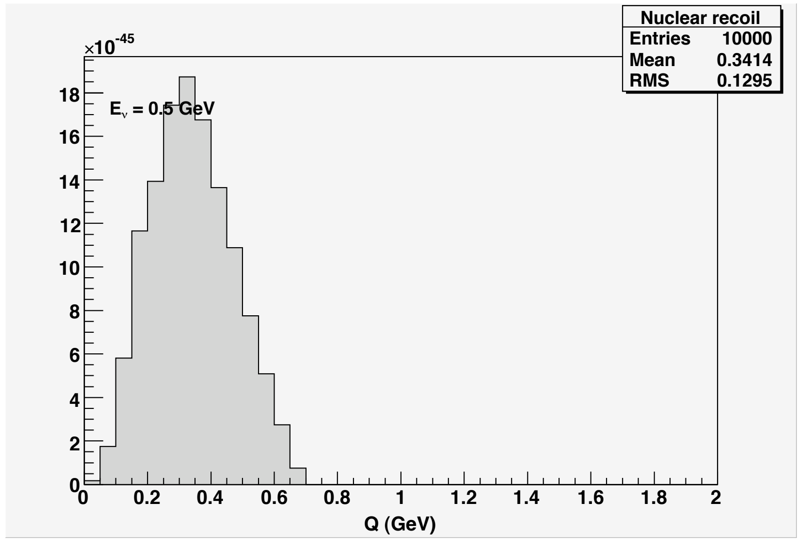


PRELIMINARY

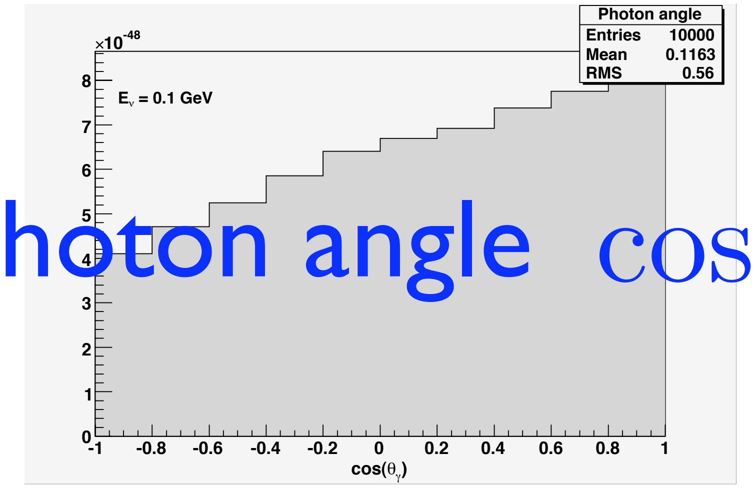
nuclear recoil $Q = \sqrt{2m_N(E'_N - m_N)}$

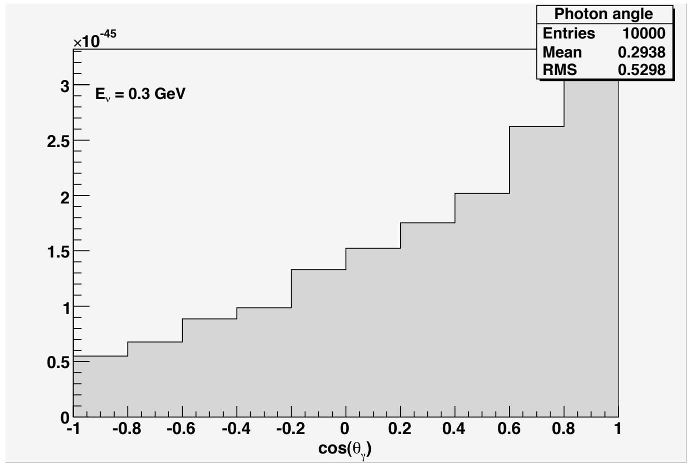


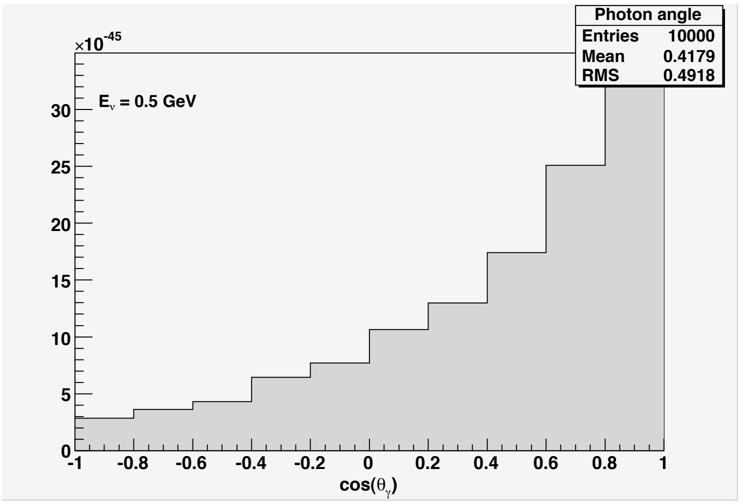




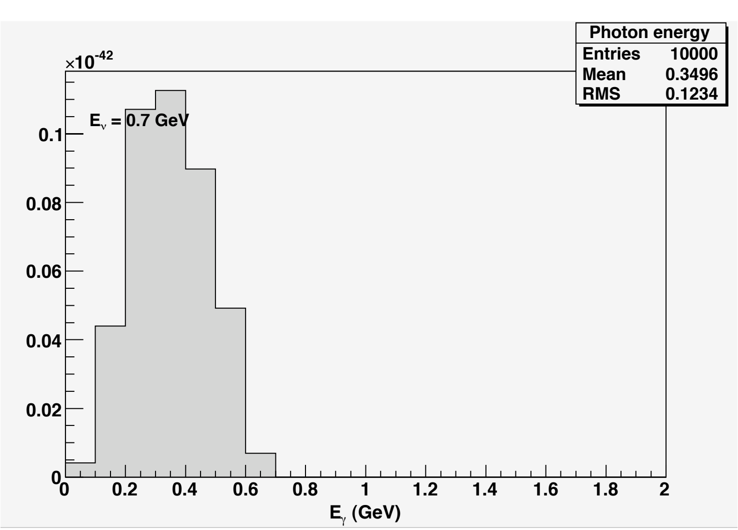
photon angle $\cos\theta_\gamma$

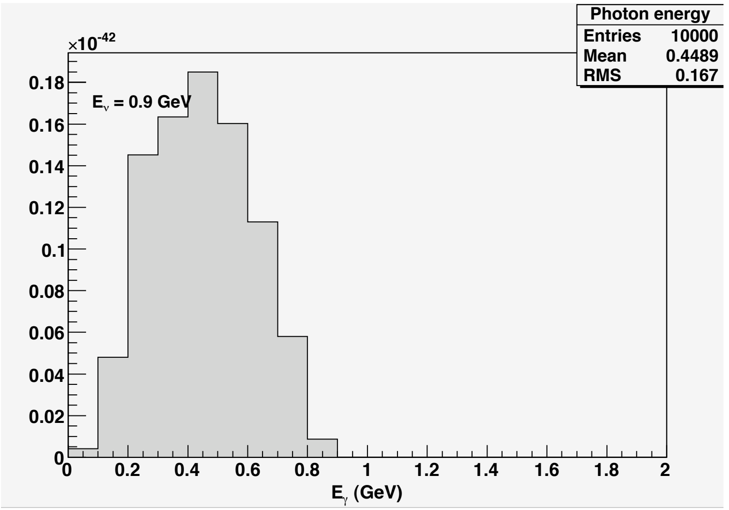


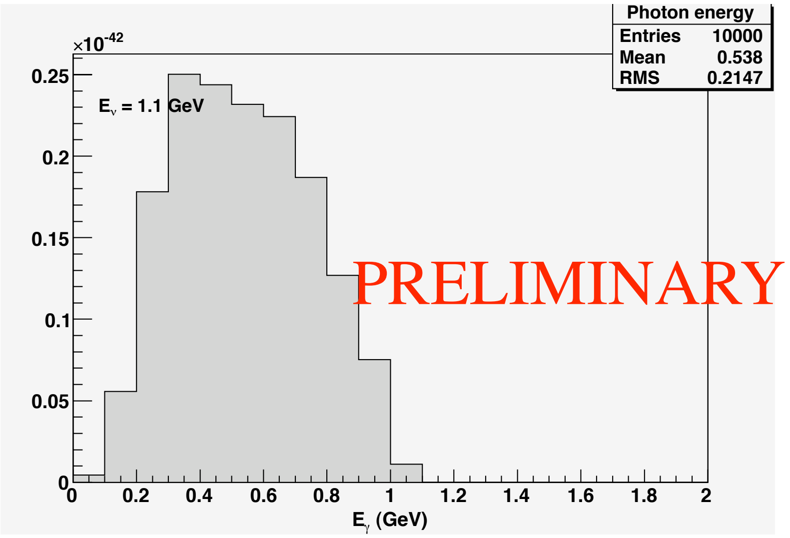


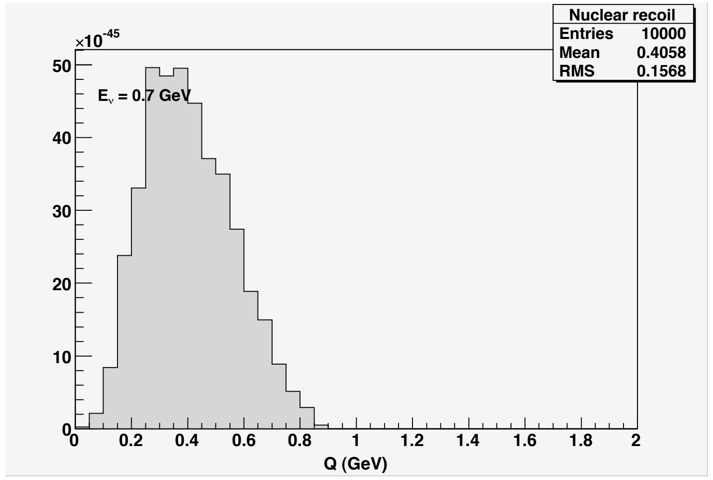


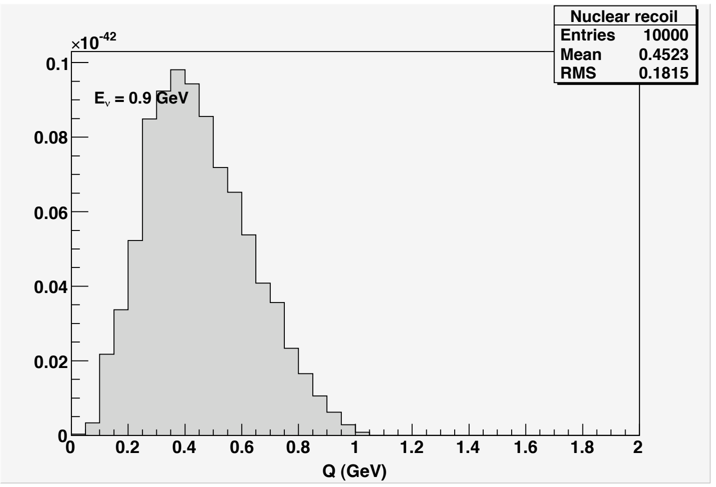
$E_\nu = 700\,\mathrm{MeV}$ $E_\nu = 900\,\mathrm{MeV}$ $E_\nu = 1100\,\mathrm{MeV}$

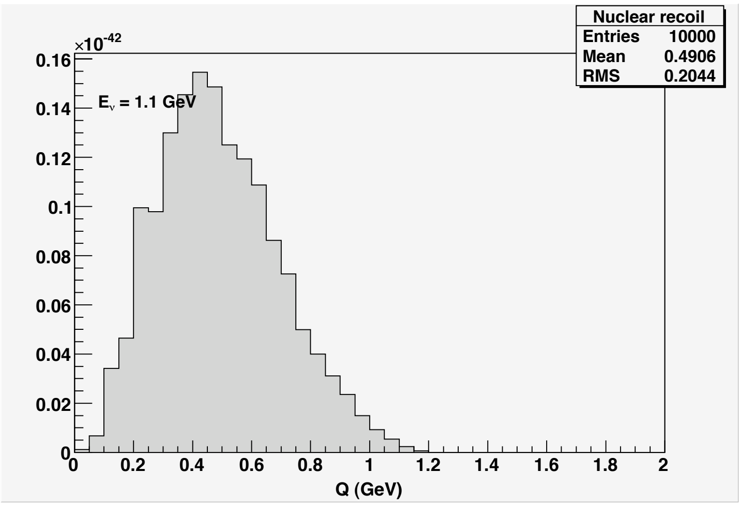


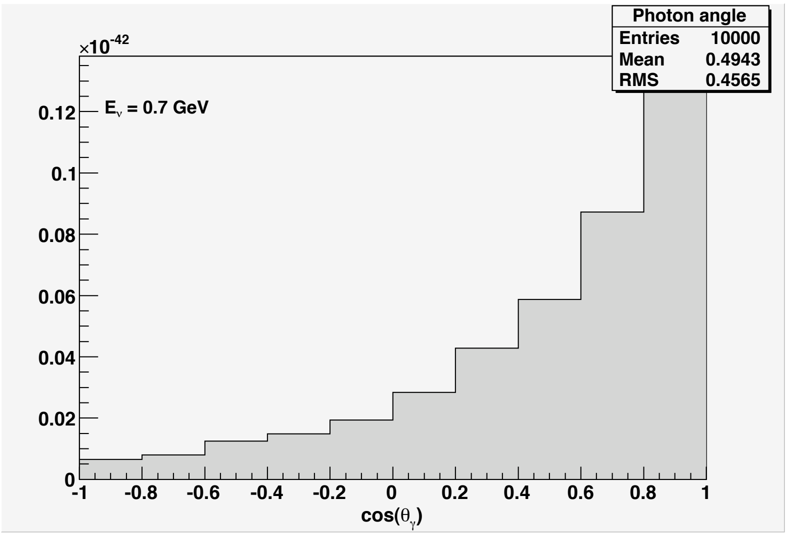


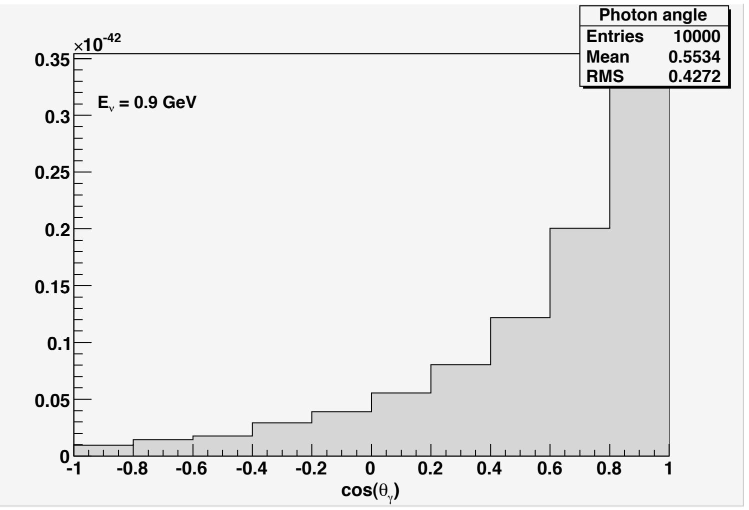


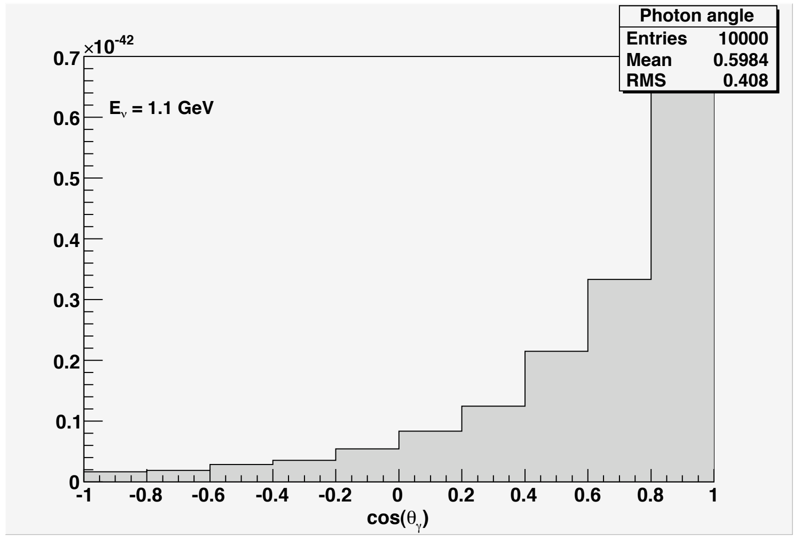












Scattering on isolated nucleons

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
- Final state: Pauli blocking
- Coherence

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

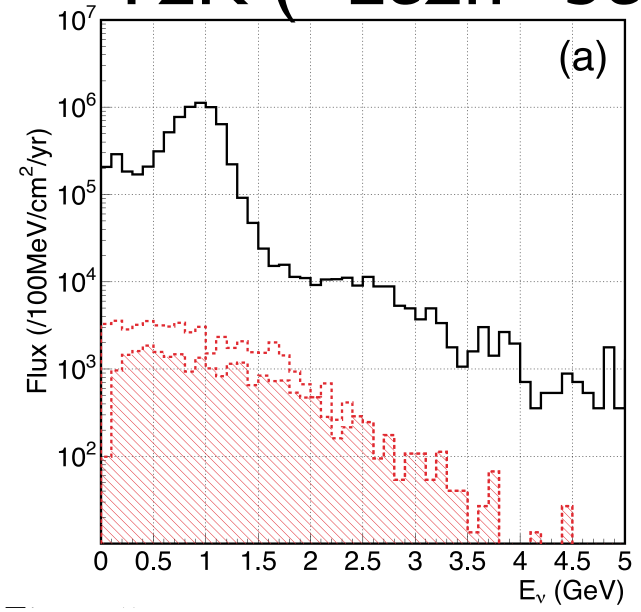
A good place to look:

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

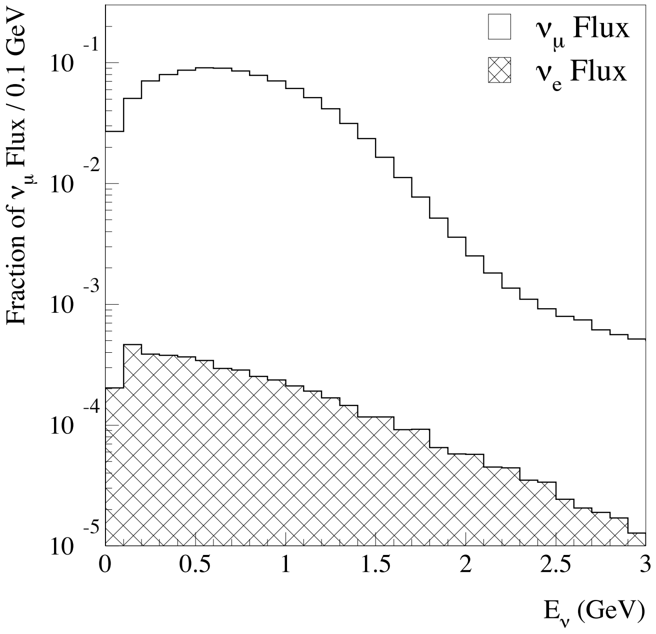
- pure beam of ν_μ, unless we can distinguish final state electron from final state photon (otherwise a $\nu_e \to e$ background)

⇒ overlap with experiments looking for ν_μ oscillations !

T2K (“Le2π” beam)

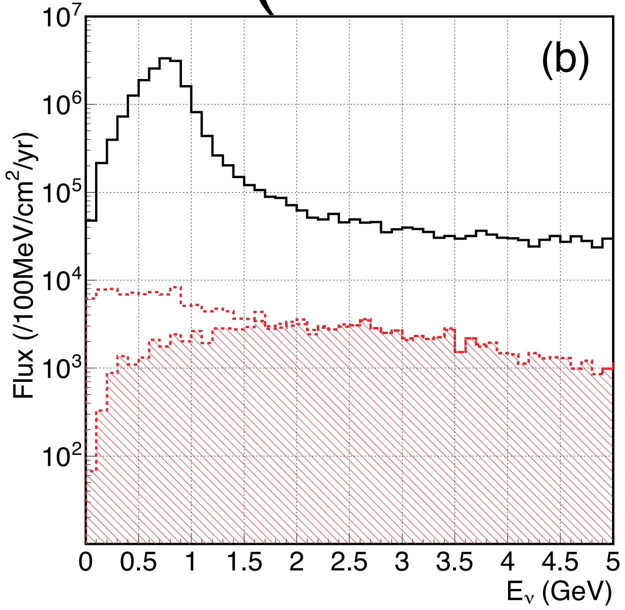


MiniBooNE



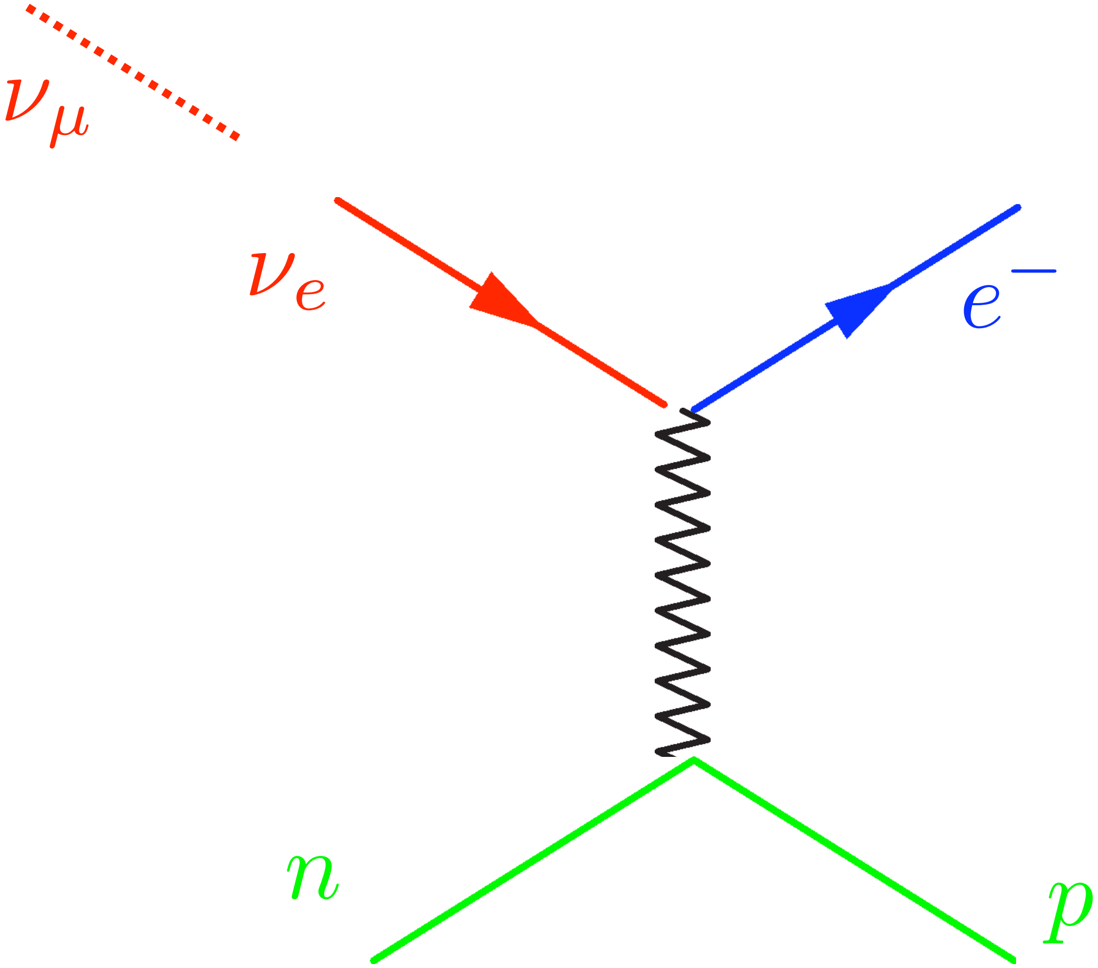
[J. Monroe, MiniBooNE, hep-ex/0408019]

T2K (“OA2” beam)

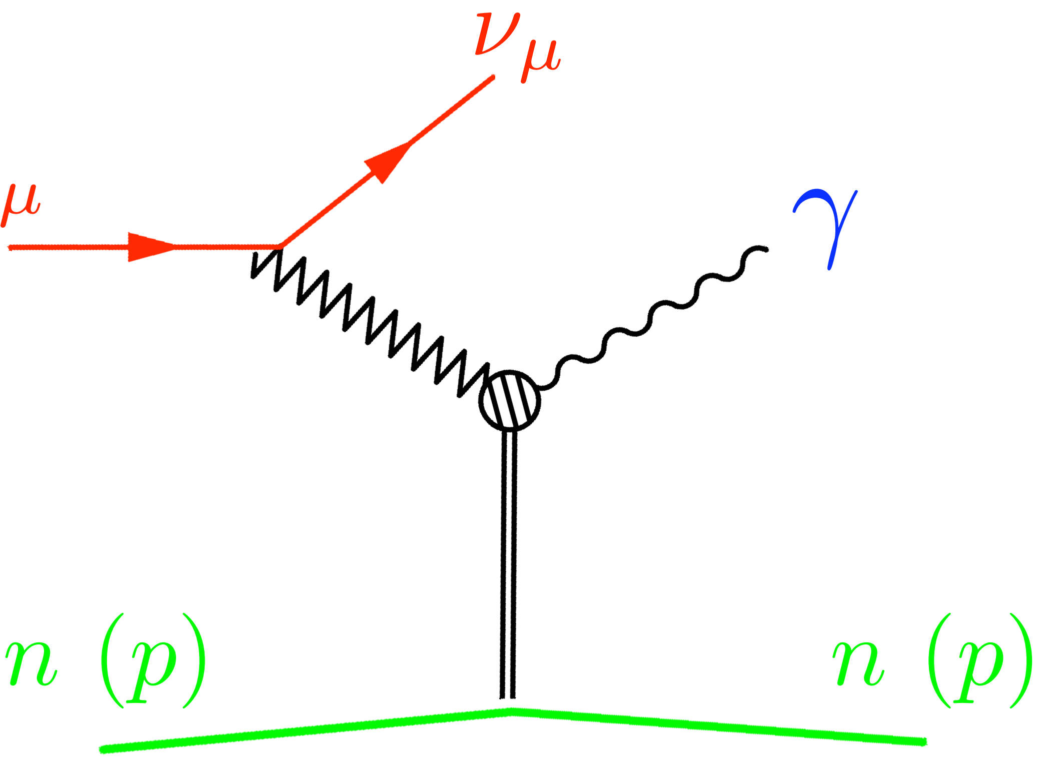


[Itow et. al., T2K, hep-ex/0106019]

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 on order of:

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

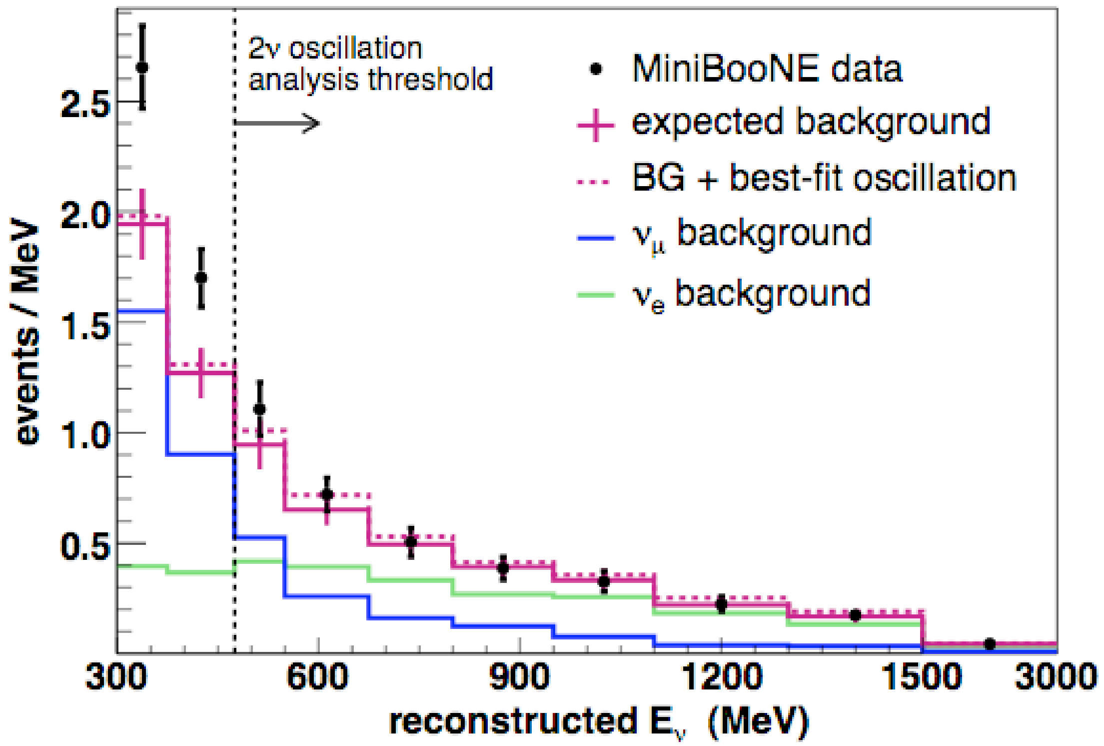
new events.

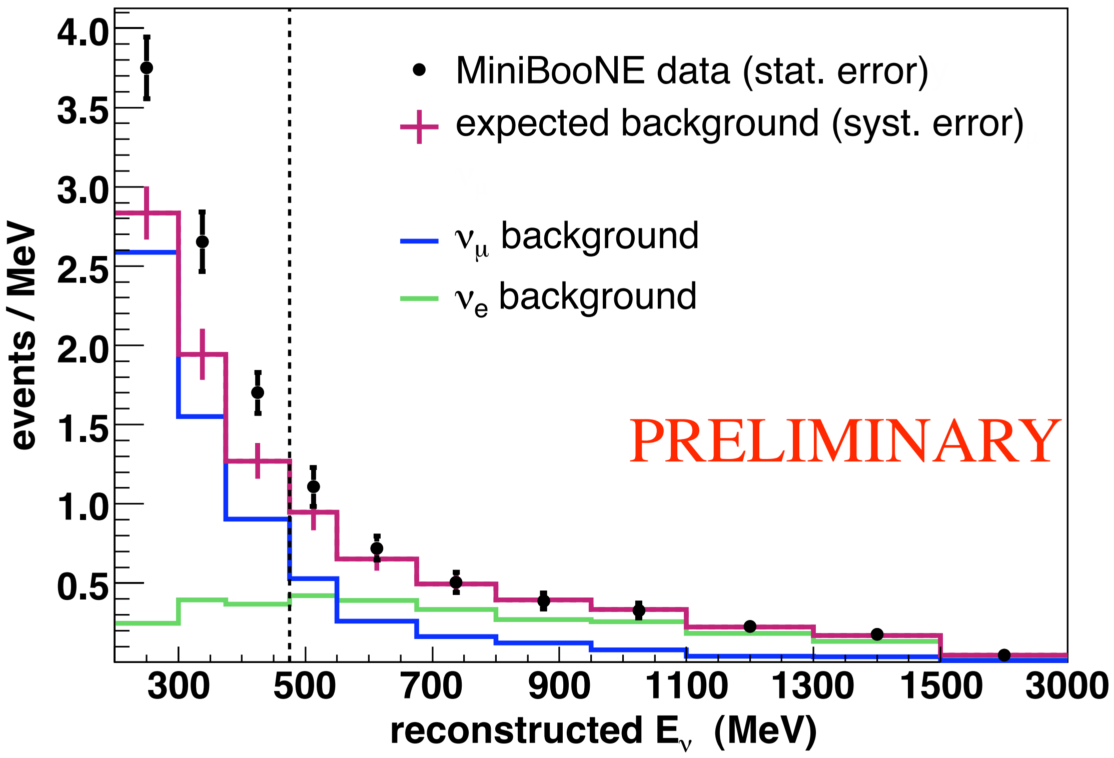
This normalization is very rough, but tens to hundreds of events are expected

More accurate normalization requires complete flux information, acceptance corrections, form factors, 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

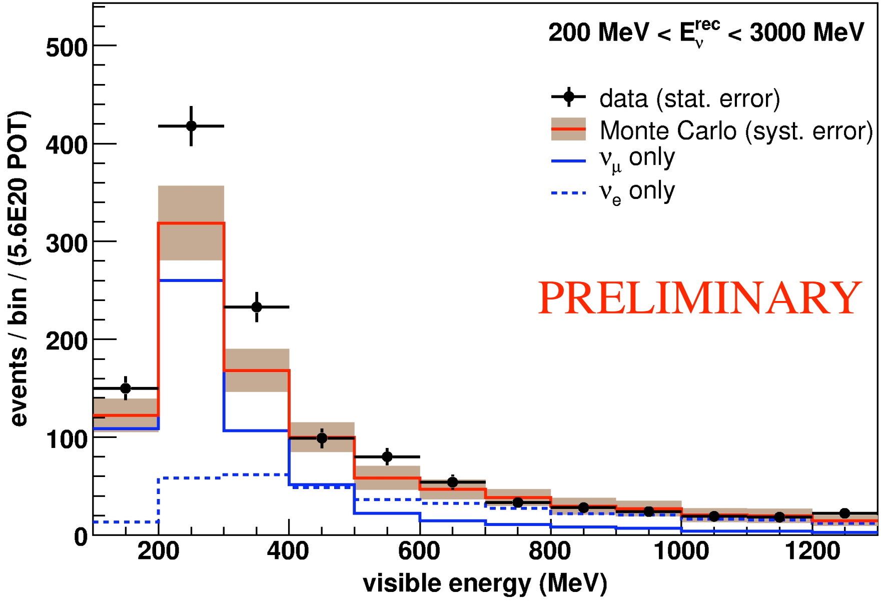
- excess of events at low energy appears to be growing ! Is it real ? Is anything else left out ?

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

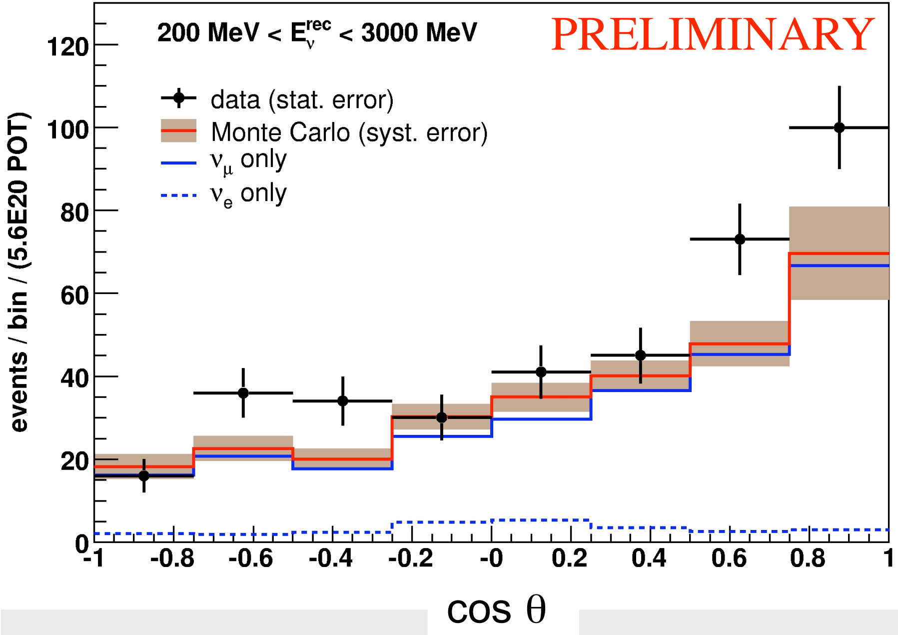
- if it's a 3-body state, E_ν underestimated

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

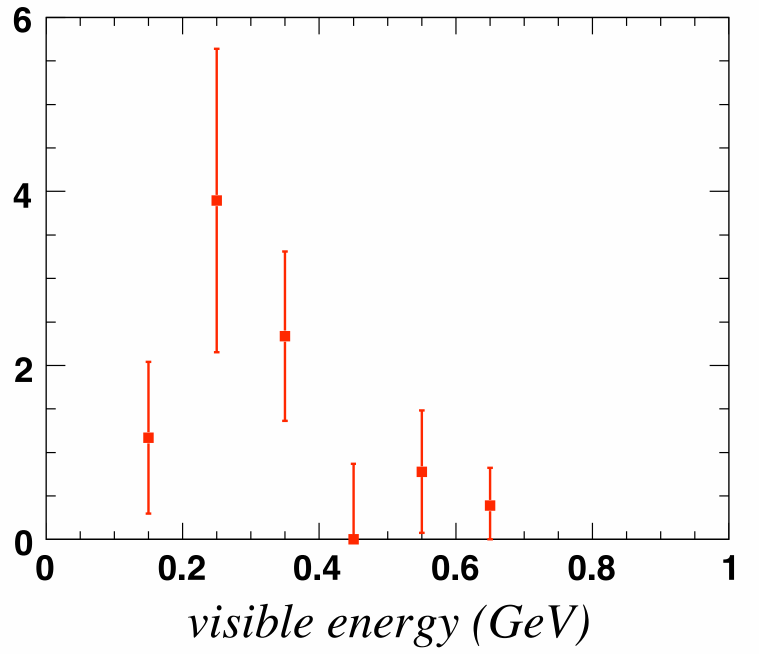
visible energy, $200<E_\nu<3000$ MeV

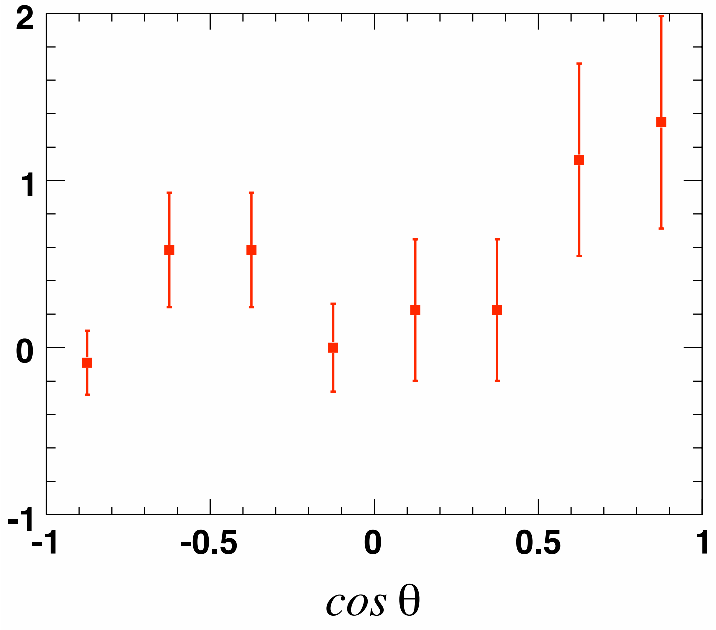


cos θ , $200<E_\nu<3000$ MeV



[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
- MicroBooNE
- ... ?

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:

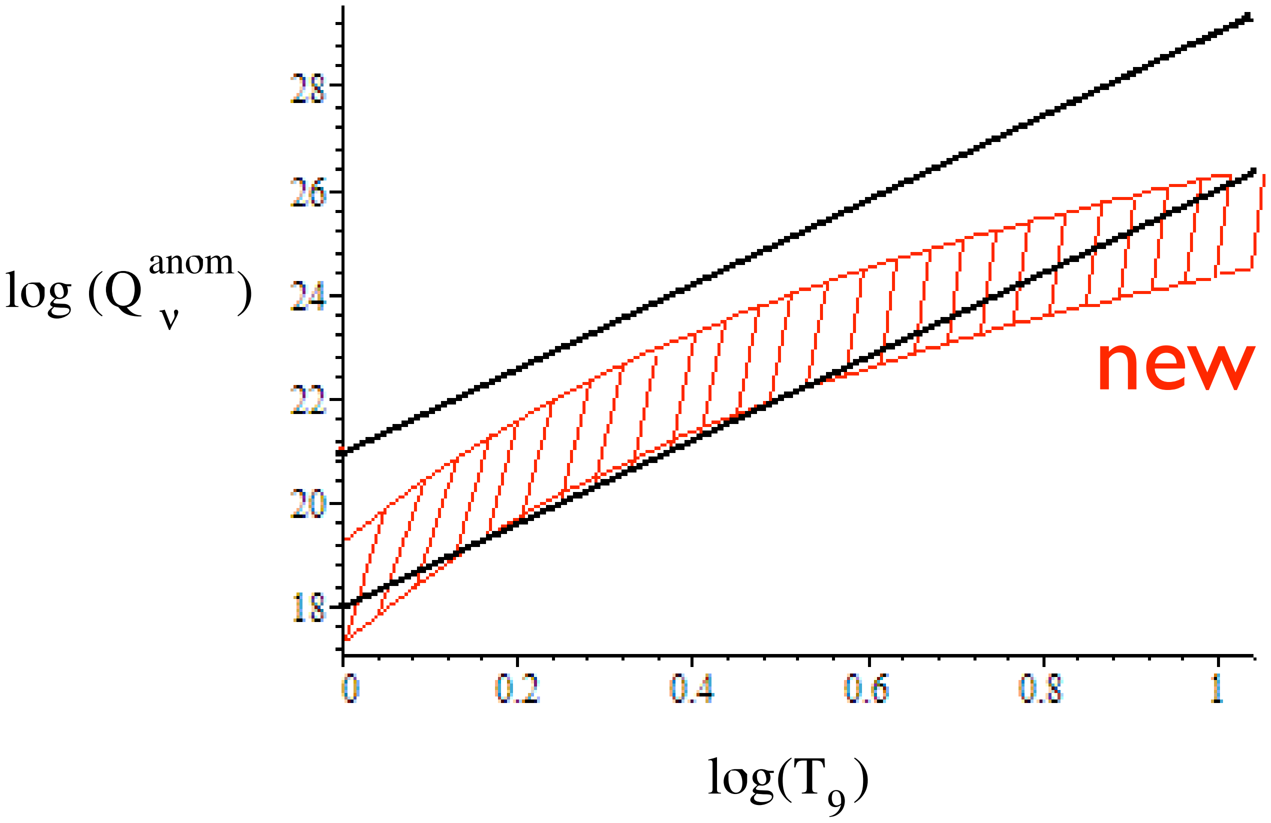
$$Q_\nu^{\mathrm{mUrca}} = (10^{18} - 10^{21}) \times \left(\frac{T}{10^9\, K} \right)^8 \mathrm{erg\, s^{-1}\, cm^{-3}}$$

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

New interaction, massive photon to neutrinos:

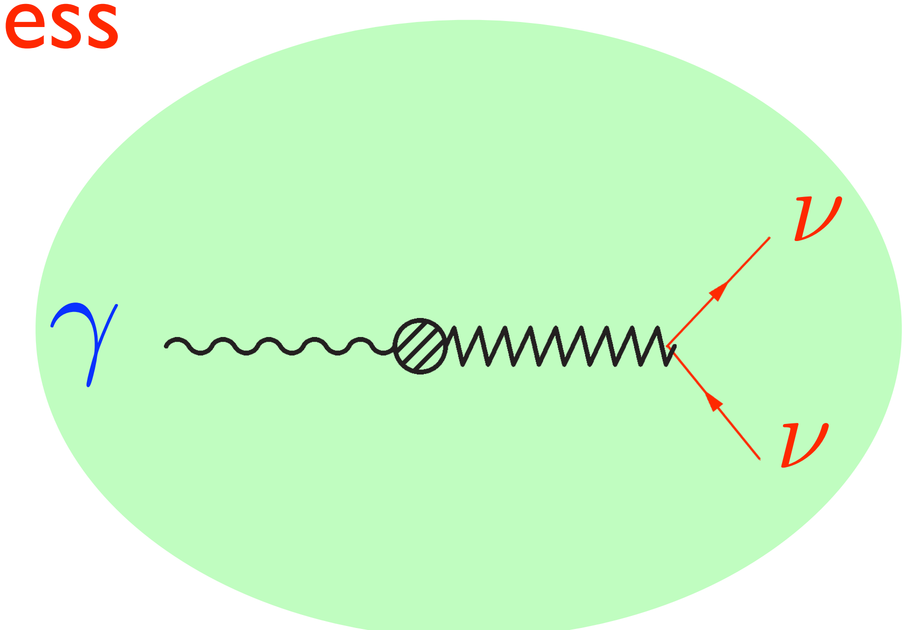
$T_9 = T/10^9\,\mathrm{K}$

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



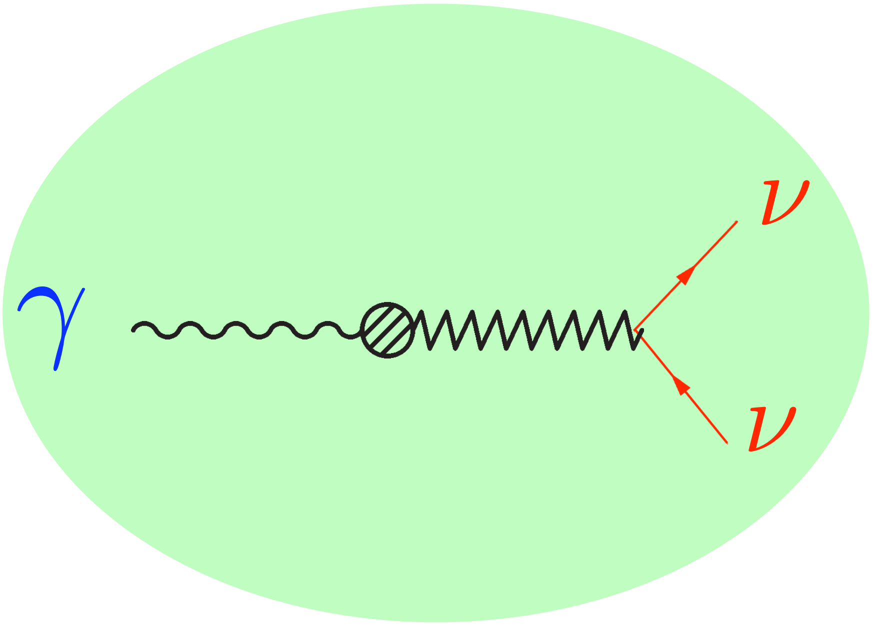
estimated range of other processes

new process

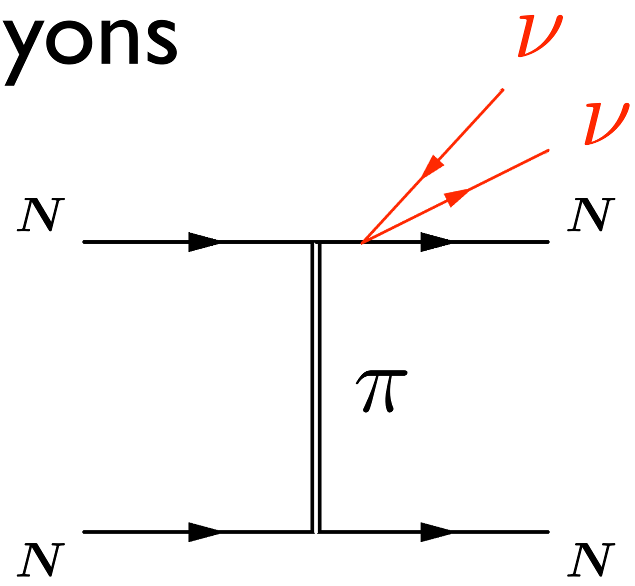


Neutrino pair production in supernova

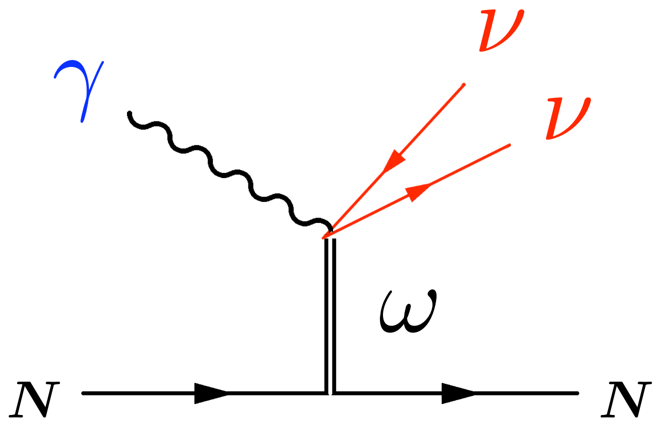
Perhaps even more relevant is the pair production of neutrinos in a supernova core



Lots of thermal photons, lots of baryons



vs.



- 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

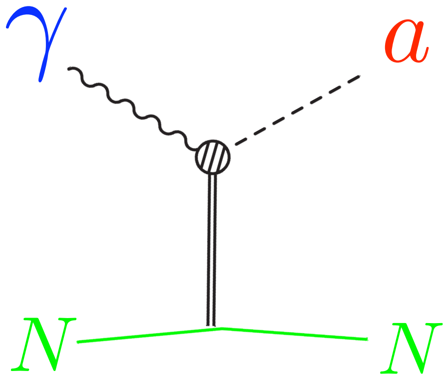
Supernova cooling from photon-axion-baryon coupling:

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

Bound from observed duration of SN1987A:

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

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



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

Other directions

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 !

Why are these interactions special ?

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

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

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

These interactions are contained in the anomalous part

- Violate naive selection rules

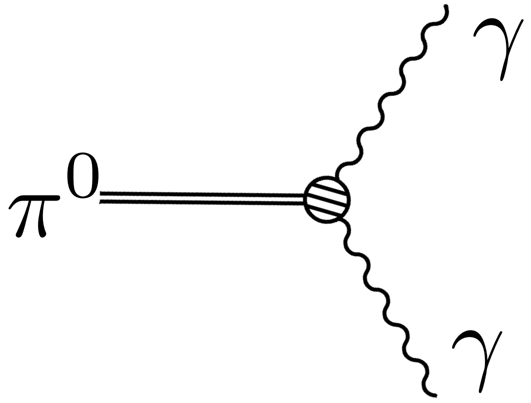
$$\pi \longrightarrow -\pi$$

$$\mathcal{L}_{\text{regular}} \longrightarrow +\mathcal{L}_{\text{regular}}$$

$$\mathcal{L}_{\text{anomalous}} \longrightarrow -\mathcal{L}_{\text{anomalous}}$$

- Directly related to underlying fermions

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

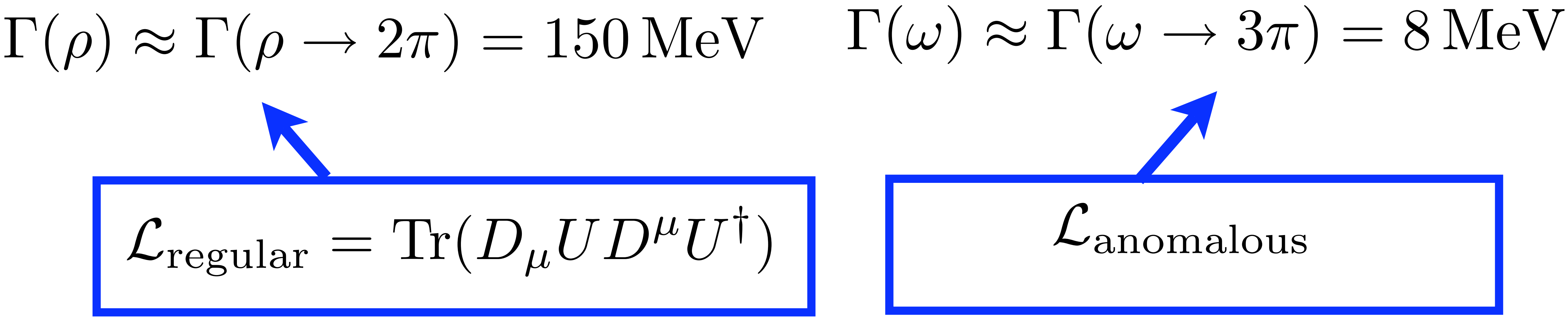


$$\Gamma_{\text{expt}} = 7.8(6)\,\text{eV}$$

Anomalies are tiny effects, right ?

Depends on the question !

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



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

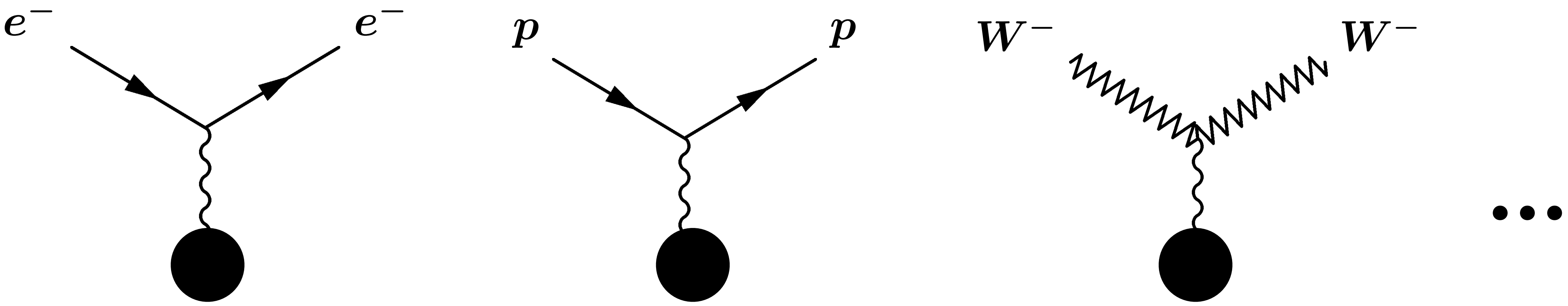
$$\boxed{\mathcal{L}_{\text{regular}} = \mathrm{Tr}(D_\mu U D^\mu U^\dagger)} \qquad \boxed{\mathcal{L}_{\text{anomalous}}}$$

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

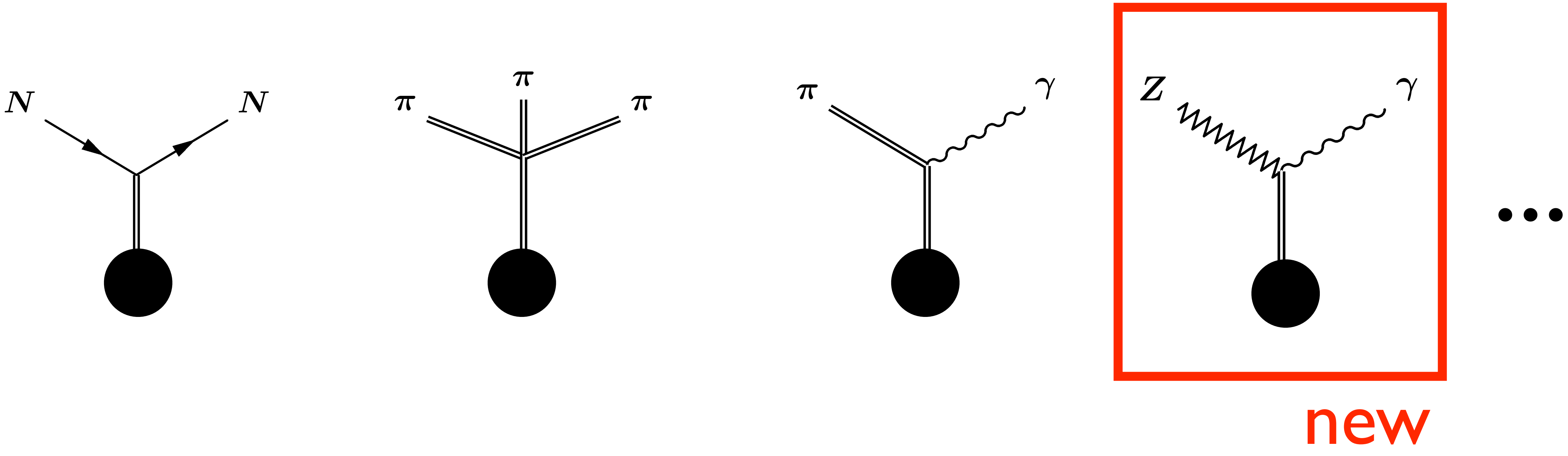
Baryons enter the chiral lagrangian *only* through the "anomalous" term

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

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

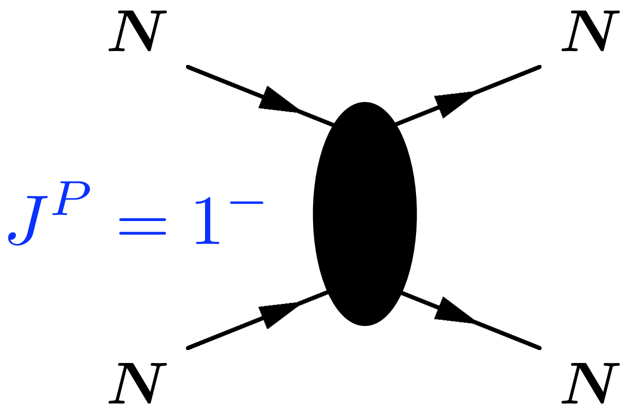


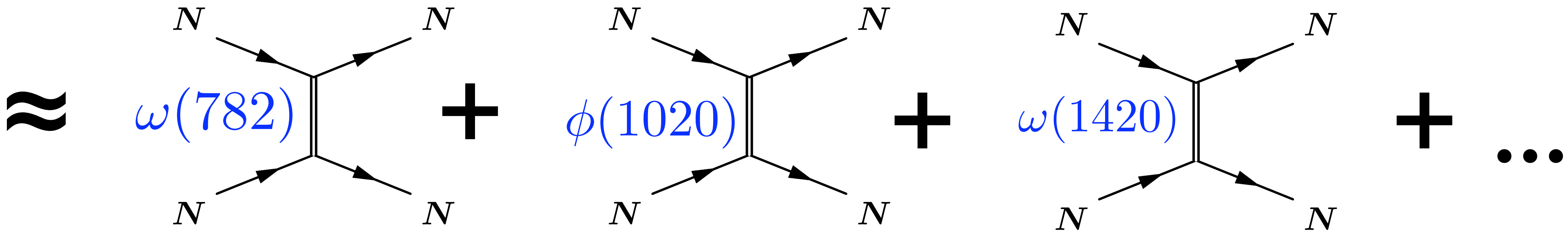
Similarly, given a source of baryon charge, can scatter all parts of the baryon current



Meson exchange

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





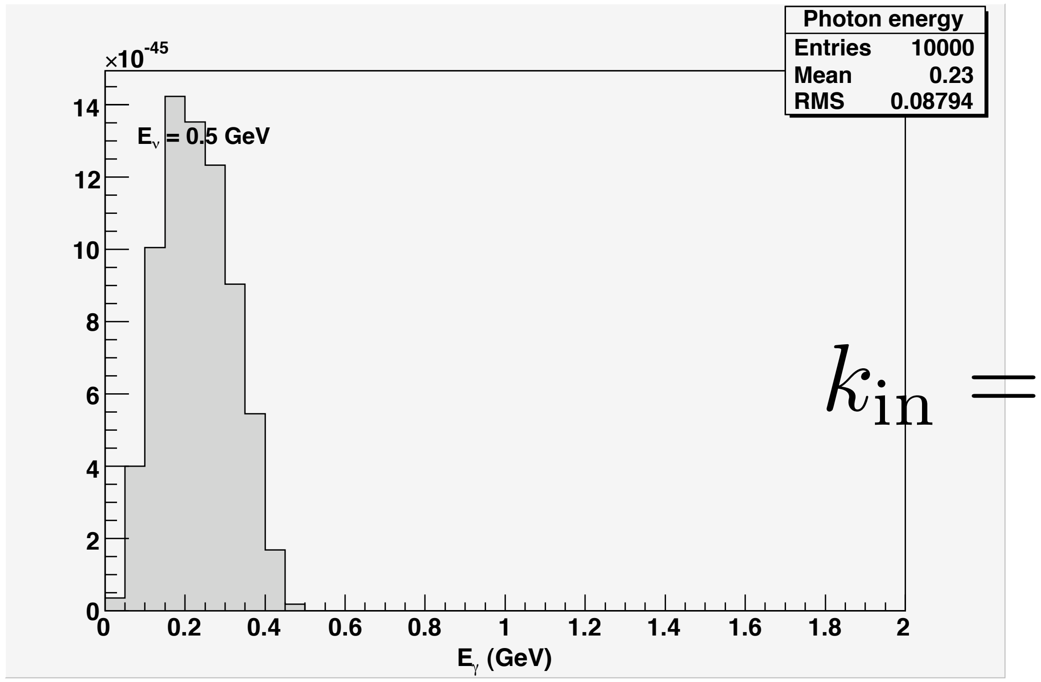
- in practice, keep the lowest resonances in each channel, and fit to effective masses and couplings

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

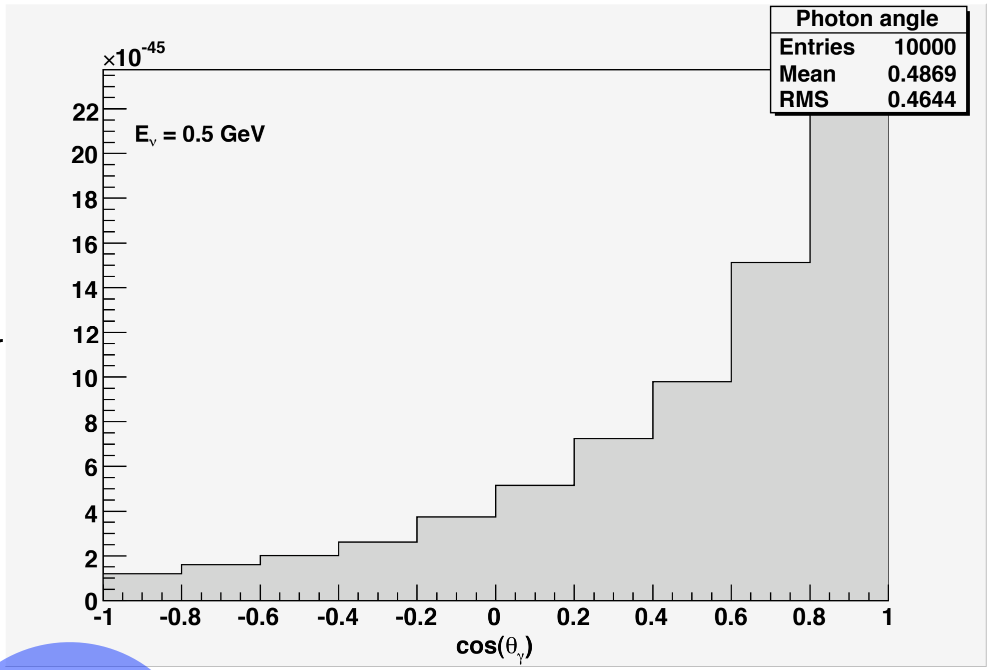
Nuclear effects

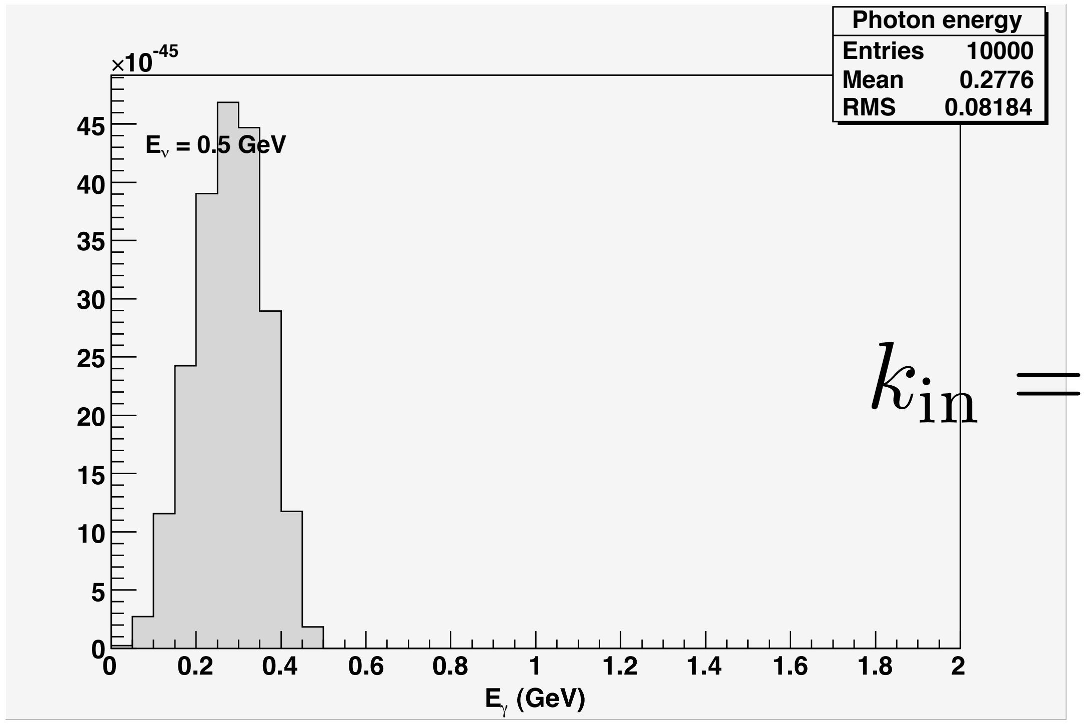
Inside a nucleus, interactions between nucleons

- Initial state: Fermi motion

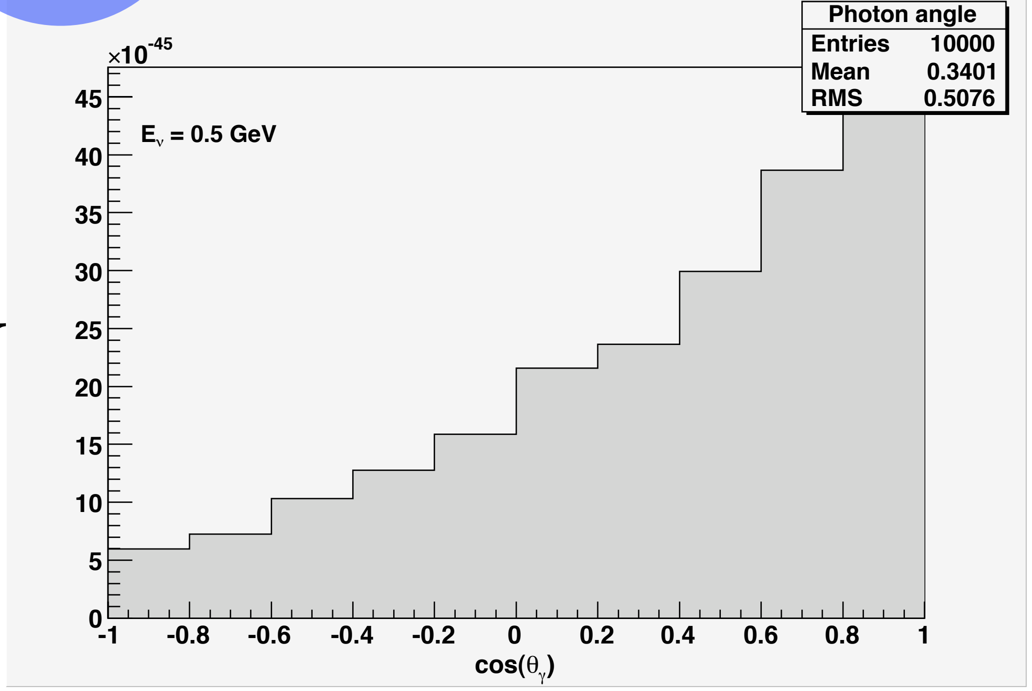


$$k_{\rm in} = +200\,{\rm MeV}$$





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



Nuclear effects

Inside a nucleus, interactions between nucleons

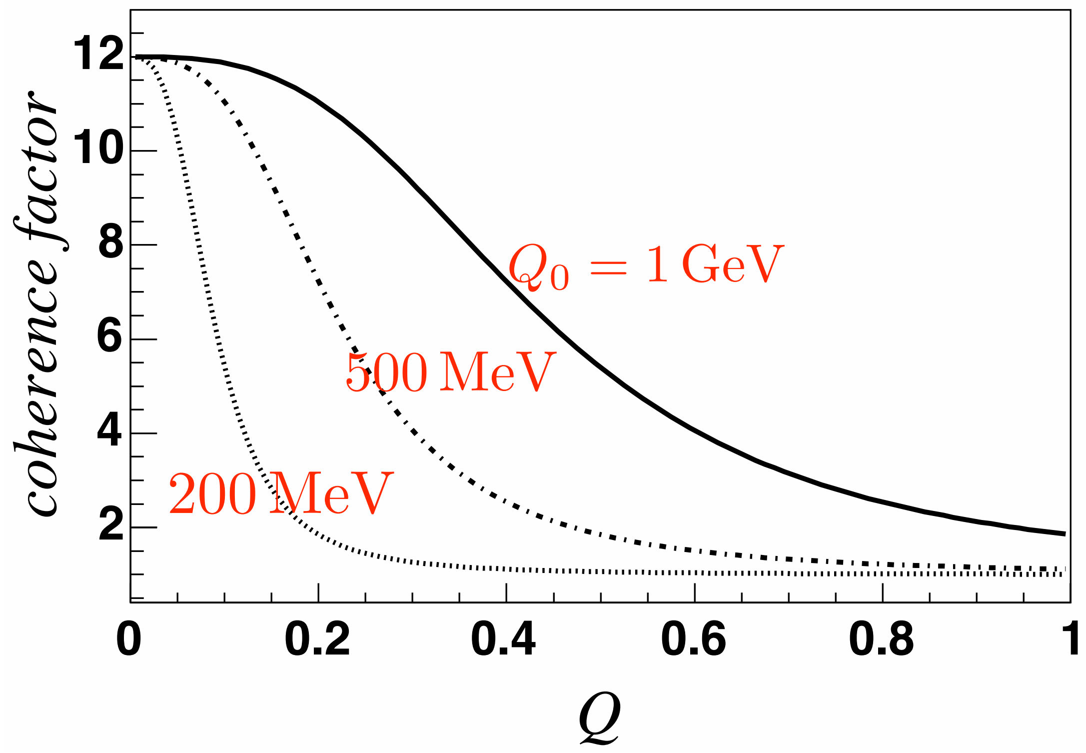
- Initial state: Fermi motion
- Final state: Pauli blocking
- Coherence

- At low Q², $\sigma \propto A^2$

- At high Q², $\sigma \propto A$

Very schematic model:

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



nuclei in a "coherence volume"

of coherence volumes

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

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

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

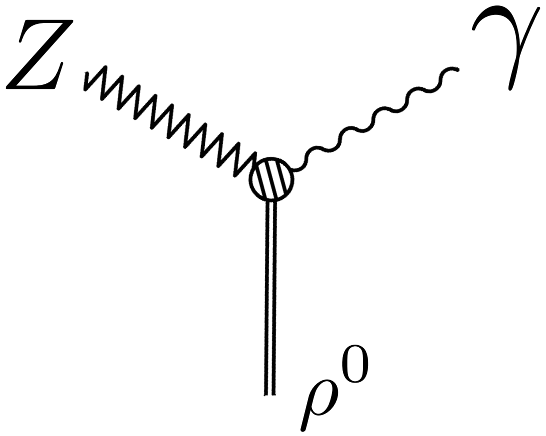
At large energies, not expected to be a dominant effect

some PCAC arguments focused on small Q²: Rein and Sehgal 1981

competing processes

Other vector-current exchanges:

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

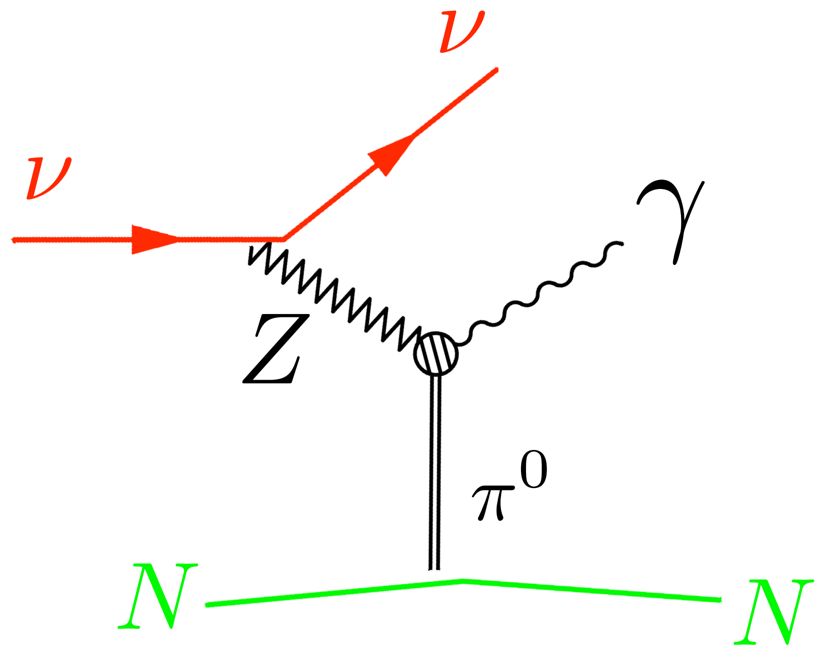


"coherence over the nucleus"

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

competing processes

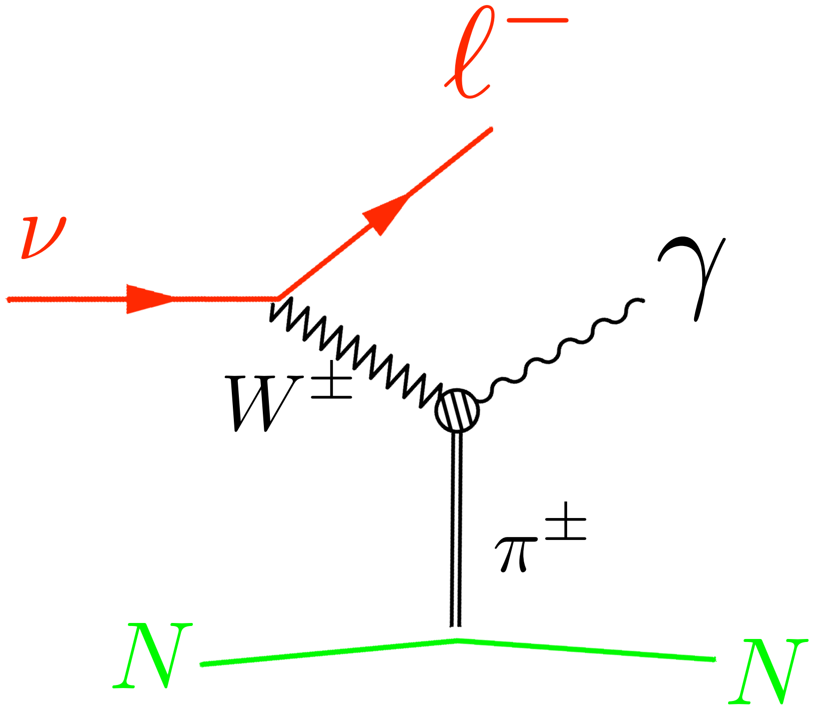
<u>Axial-currents:</u>
pion exchange potentially significant, due to small mass



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

but a cancellation makes it small

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

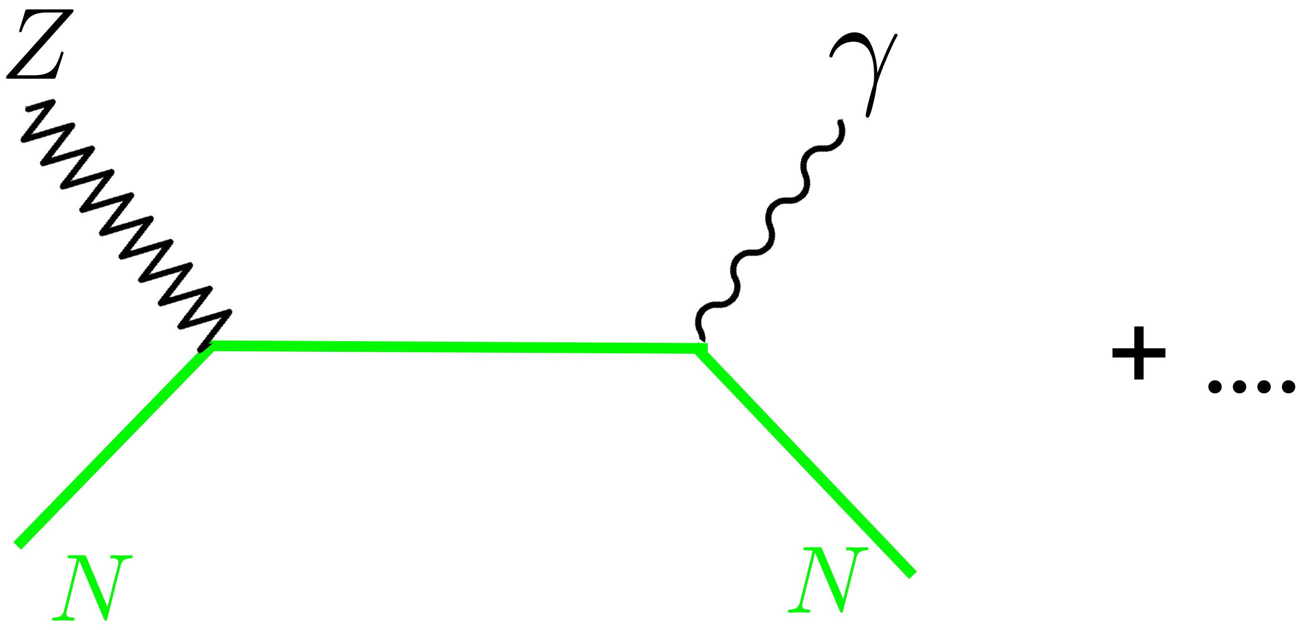


- not coherent over adjacent nucleons
- could in principle be probed in relatd charged-current process

competing processes

Bremstrahlung and related contact interactions

- formally suppressed by nucleon mass



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