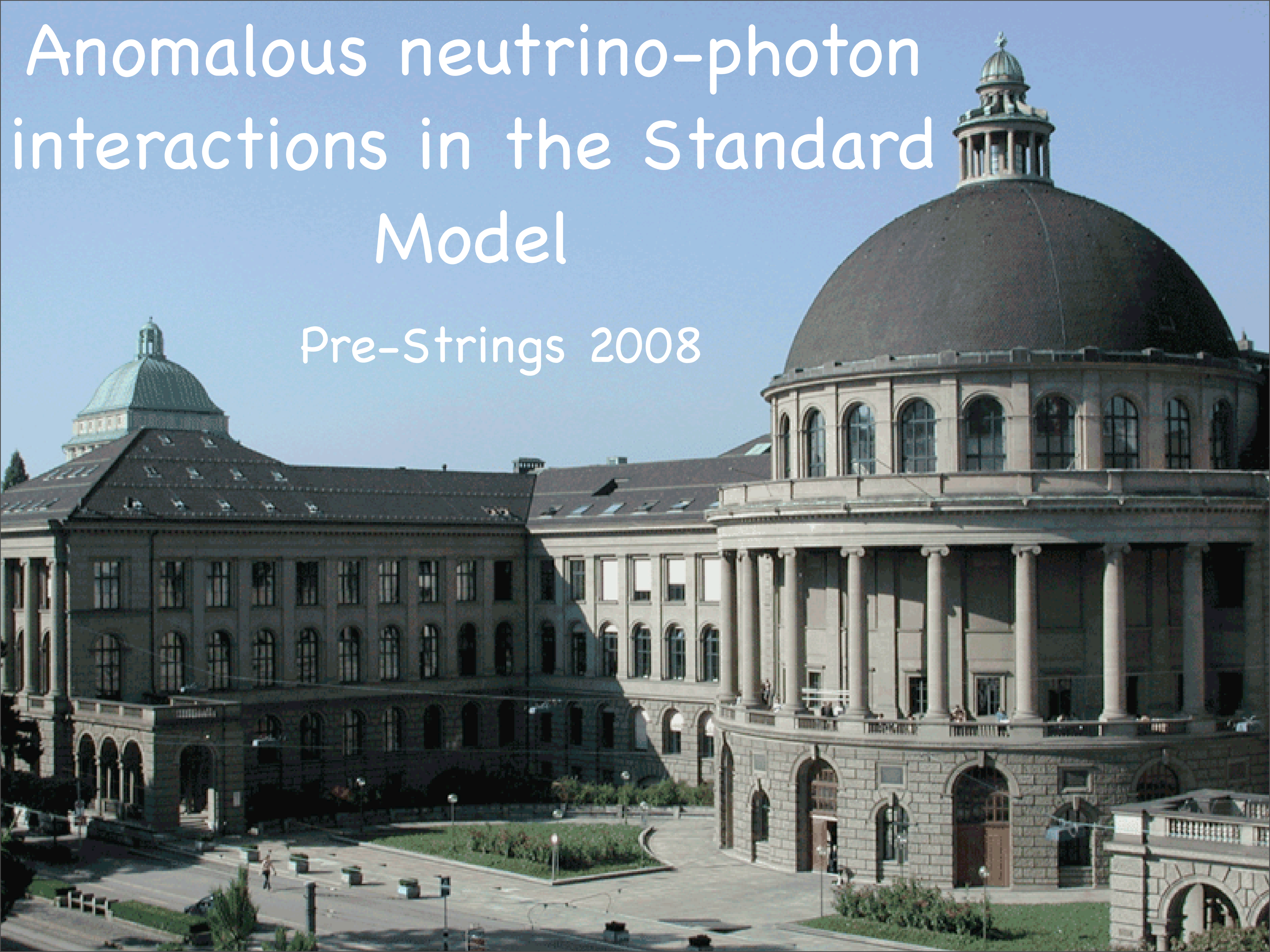

Anomalous neutrino-photon interactions in the Standard Model
Pre-Strings 2008

Based on

- Baryon-Number-Induced Chern-Simons Couplings of Vector and Axial-Vector Mesons in Holographic QCD, PRL 99,14 (2007); arXiv:0704.1604 w/ Sophia Domokos
- Anomaly mediated neutrino-photon interactions at finite baryon density; arXiv:0708.1281 w/ Chris Hill and Richard Hill.
- Standard Model Gauging of the Wess-Zumino-Witten term: Anomalies, Global Currents and pseudo-Chern-Simons Interactions; arXiv:0712.1230 w/ Chris Hill and Richard Hill
- Work in progress w/ Chris Hill and Richard Hill

Outline

yesterday
- Low-Energy QCD, anomalies and WZW term
- pCS terms in a toy model

- pCS terms in the Standard Model

today
- $f_1 \to \rho + \gamma$ as a check of the formalism
- Anomalous neutrino-photon interactions and neutrino-nucleon scattering
- Comparison to the MiniBoone excess

- Other possible applications

Yesterday we discussed some aspects of the WZW term in QCD

$$\Gamma_{WZW} = -\frac{iN_c}{240\pi^2}\int_{M_5} \mathrm{Tr}[(dUU^\dagger)^5]$$

and its generalization to the gauged WZW term: $\Gamma_{WZW}(U, A_L, A_R)$

There is an anomalous gauge variation which matches that of the quarks and tells us that without other fields we cannot gauge the full $U(N_f)_L \times U(N_f)_R$.

For an anomaly free subgroup e.g. $U(1)_{EM}$ the coupling of photons to the pion gives the correct rate for the anomaly-driven decay $\pi^0 \to \gamma + \gamma$.

In the real world there are additional effects which should be included into this description:

- There are charged and neutral current weak interactions. We must gauge $SU(2)_L \times U(1)_Y$ and the anomalies cancel between quarks and leptons.

- There are environments with background baryon and isospin densities which lead to background values of the vector mesons of QCD. These backgrounds must not destroy anomaly cancellation.

We start with $\Gamma_{WZW}(U, A_L, A_R)$ with A_L, A_R gauging $SU(2)_L \times U(1)_Y$ and then add a background of QCD vector and axial-vector mesons ρ, ω, a_1, f_1 .

This gives us $\Gamma_{WZW}(U, A_L, B_L, A_R, B_R)$ where for two flavors,

$$B_L + B_R = \begin{pmatrix} \rho^0 + \omega & \sqrt{2}\rho^+ \\ \sqrt{2}\rho^- & -\rho^0 + \omega \end{pmatrix}$$

$$B_L - B_R = \begin{pmatrix} a_1^0 + f_1 & \sqrt{2}a_1^+ \\ \sqrt{2}a_1^- & -a_1^0 + f_1 \end{pmatrix}$$

As in the toy model, we must add a counterterm to ensure that anomalies cancel between quarks and leptons in the presence of these background fields. This leads to a variety of pCS terms which involve the Standard Model gauge fields and QCD vector and axial-vector mesons, generalizing those found in the toy model.

This leads to a large number of pCS terms:

$$\Gamma_{pCS} = \mathcal{C}\int dZZ\left[\frac{s_W^2}{c_W^2}\rho^0 + \left(\frac{3}{2c_W^2} - 3\right)\omega - \frac{1}{2c_W^2}f\right] + dAZ\left[-\frac{s_W}{c_W}\rho^0 - \frac{3s_W}{c_W}\omega\right] + dZ\left[W^-\rho^+ + W^+\rho^-\right]\frac{s_W^2}{c_W}$$

$$+dA\left[W^-\rho^+ + W^+\rho^-\right](-s_W) + (DW^+W^- + DW^-W^+)\left[-\frac{3}{2}\omega - \frac{1}{2}f\right],$$

$$+\mathcal{C}\int Z\Big\{d\rho^0\left[-\frac{3}{2c_W}\omega - \frac{s_W^2}{c_W}a^0 + \left(-\frac{3}{2c_W} + 3c_W\right)f\right] + d\omega\left[-\frac{3}{2c_W}\rho^0 + \left(-\frac{3}{2c_W} + 3c_W\right)a^0 - \frac{s_W^2}{c_W}f\right]$$

$$+da^0\left[\frac{s_W^2}{c_W}\rho^0 + \left(\frac{3}{2c_W} - 3c_W\right)\omega - \frac{1}{2c_W}f\right] + df\left[\left(\frac{3}{2c_W} - 3c_W\right)\rho^0 + \frac{s_W^2}{c_W}\omega - \frac{1}{2c_W}a^0\right]\Big\}$$

$$+dA\Big\{s_W\rho^0a^0 + 3s_W\rho^0f + 3s_W\omega a^0 + s_W\omega f\Big\} + dZ\Big\{-\frac{s_W^2}{c_W}(\rho^+a^- + \rho^-a^+)\Big\}$$

$$+dA\Big\{s_W(\rho^+a^- + \rho^-a^+)\Big\}$$

$$+\frac{3}{2}\left[W^+D\rho^- + W^-D\rho^+\right](-\omega + f) + \frac{3}{2}\left[W^+(-\rho^- + a^-) + W^-(-\rho^+ + a^+)\right]d\omega$$

$$+\frac{1}{2}\left[W^+Da^- + W^-Da^+\right](-3\omega - f) + \frac{1}{2}\left[W^+(-3\rho^- - a^-) + W^-(-3\rho^+ - a^+)\right]df,$$

$$+\mathcal{C}\int 2\Big[(\rho^-f + \omega a^-)D\rho^+ + (\omega a^+ + \rho^+f)D\rho^- + (\omega a^0 + \rho^0f)D\rho^0 + (\rho^+a^- + \rho^-a^+ + \omega f + \rho^0a^0)d$$

$$+\mathcal{C}\int i\Big\{W^+W^-\Big[3c_WZ\Big]\omega + W^+W^-\Big[\left(c_W + \frac{1}{2c_W}\right)Z\Big]f\Big\},$$

$$+\mathcal{C}\int i\Big\{W^+W^-\left[\frac{3}{2}(\rho^0 + a^0)\omega - \frac{1}{2}(\rho^0 - a^0)f\right]$$

$$+W^+Z\left[\frac{3c_W}{2}\rho^-f - \frac{3c_W}{2}\rho^-\omega - \frac{c_W}{2}a^-f + \frac{3c_W}{2}\omega a^- - \frac{1}{c_W}\rho^-f\right]$$

$$+W^-Z\left[-\frac{3c_W}{2}\rho^+f + \frac{3c_W}{2}\rho^+\omega + \frac{c_W}{2}a^+f - \frac{3c_W}{2}\omega a^+ + \frac{1}{c_W}\rho^+f\right]\Big\},$$

MiniBoone Excess

$f_1 \to \rho + \gamma$

What do we do with such couplings?

- Integrate out the massive $W^{\pm}, Z$ to get couplings for light fields (e.g. $\gamma, \nu, \bar{\nu}$) in the presence of background fields (e.g. baryon number)

- Treat the QCD mesons as fundamental fields in the spirit of Vector Meson Dominance.

The first is more clearly justified, the second involves an approximation which is not under good control, but often works reasonably well, and receives some justification from AdS/QCD.

The decay $f_1 \to \rho + \gamma$ provides a useful sanity check of this analysis. It is observed with a 5% branching ratio $\Gamma(f_1 \to \rho + \gamma) = 1.32 \mathrm{MeV}$

Our coupling leads to

$$\Gamma = \frac{3\alpha}{256\pi^4} \frac{E_\gamma^2}{m_\rho^2} g_\rho^2 g_f^2 \left(1 + \frac{m_\rho^2}{m_f^2}\right)$$

where $E_\gamma = (m_f^2 - m_\rho^2)/2m_f$ is the photon energy in the f_1 rest frame. Agreement with the measured rate requires $g_\rho g_f \sim 50$, a not unreasonable value.

The helicity structure of the amplitude provides additional information. Computing the ratio of decays in which the ρ, in its rest frame, is longitudinally or transversely polarized gives

$$\frac{\Gamma(long)}{\Gamma(trans)} = \frac{m_f^2}{m_\rho^2} \sim 2.8$$

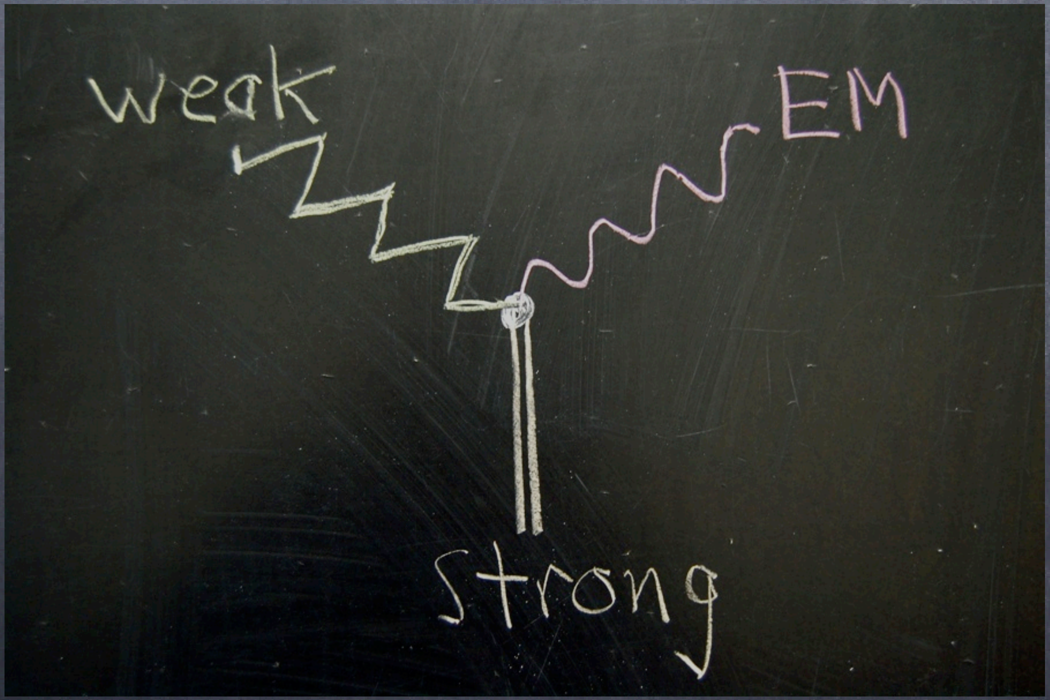
This disagrees with an earlier quark model calculation of Babcock&Rosner. The experimental situation is a bit confused. The primary PDG reference (Coffman et. al.) has conflicting statements. A 1995 experiment by Amelin et.al. gives $\Gamma(long)/\Gamma(trans) = 3.9 \pm 0.9(\mathrm{stat}) \pm 1.0(\mathrm{syst})$

In any event, the analysis using pCS terms is in better agreement with data than previous calculations, and makes further predictions for other decays which may be detected in the near future ($f_1 \to \omega + \gamma, \;\; a_1 \to \omega + \gamma$).

I now want to focus on the term

$$\frac{N_c}{48\pi^2}\frac{eg_\omega g_2}{\cos\theta_W}\epsilon_{\mu\nu\rho\sigma}\omega^\mu Z^\nu F^{\rho\sigma}$$

which gives rise to the "321 widget" which links the strong, weak, and EM interactions:

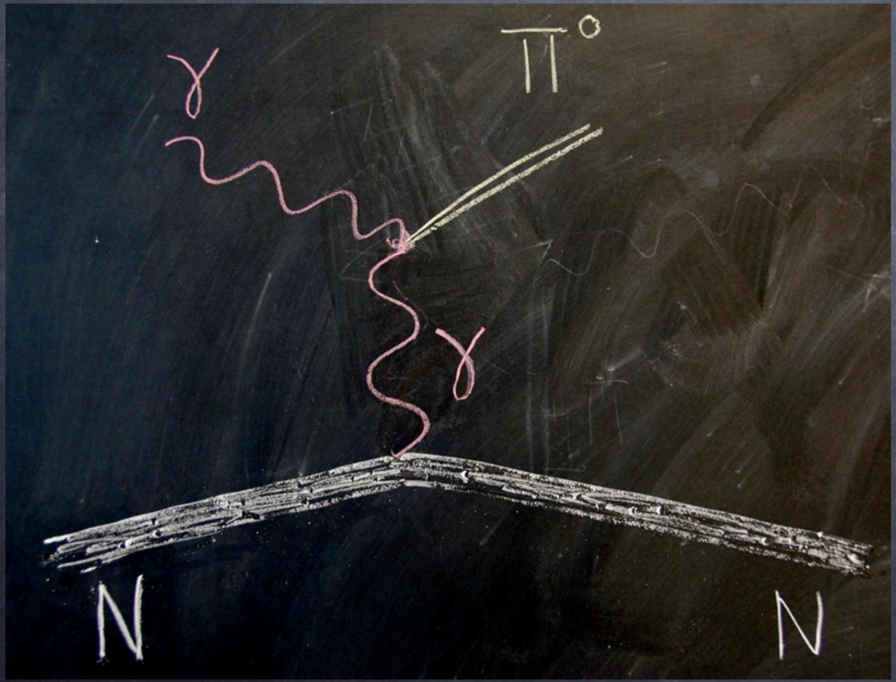


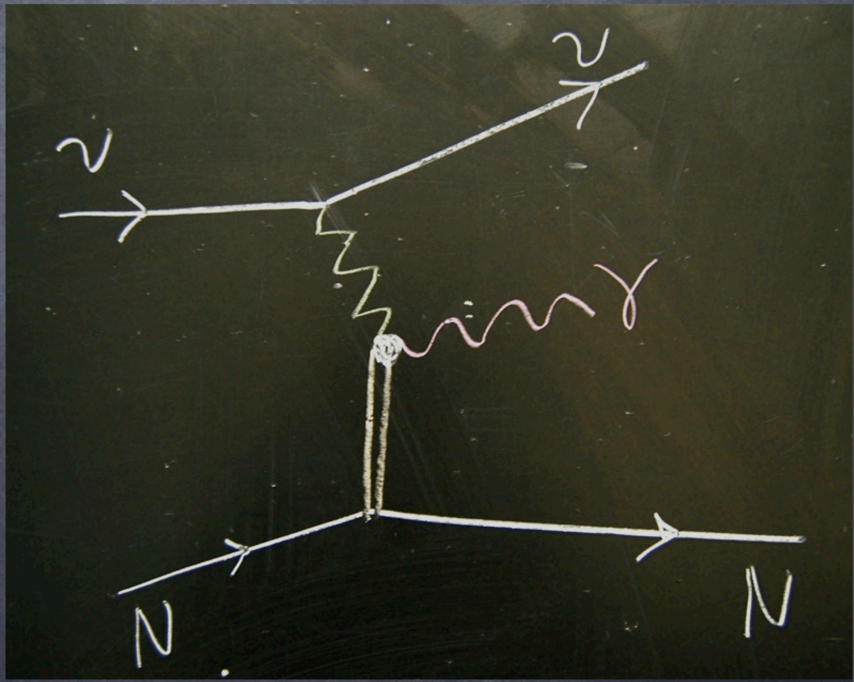
Note that this in not invariant under the "baryon gauge transformation" $\delta\omega = d\epsilon_B$, just as we found in the toy model.

This is a reflection of the fact that the baryon current is anomalous in the Standard Model, a result which has played an important role in scenarios for weak scale baryogenesis. Here we are using the baryon anomaly not to violate baryon number, but rather to drive the mixing between the Z and photon in the presence of non-zero baryon number.

How can we test this anomalous interaction? We need a context where other interactions (e.g. E&M) do not swamp the effect. To treat it as a term in the low-energy effective action we should replace the Z by the low-energy part of the currents it couples to. This suggests we look at processes involving neutrinos. We also need a source that couples to the ω , that is, an object with baryon number. Thus we might expect to see the effects of this interaction in the scattering of neutrinos off of nuclei.

This is quite analogous to the Primakoff effect which probes the anomalous $\gamma - \gamma - \pi^0$ interaction by using nuclei as a source of electric charge. We now use the nucleus as a source of baryon charge, and look for a photon in the final state:

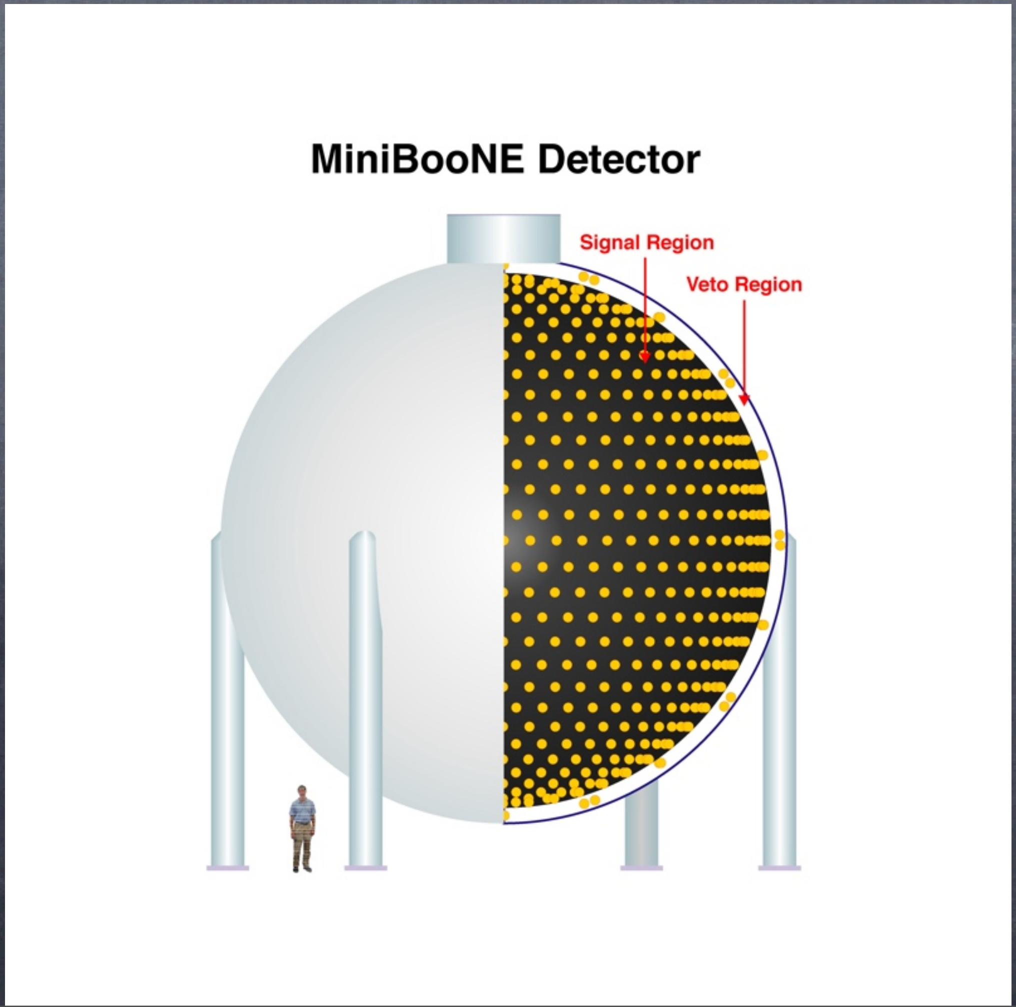




Since this process involves Z^0 exchange, the rate will be very small at low-energies. The approximations used to derive this interaction break down at an energy scale of $4\pi f_\pi \sim 1\ \mathrm{GeV}$ and above this energy the rate will be reduced by form-factor effects. Thus we might hope to see this effect in scattering of neutrinos off nuclei with $100\ \mathrm{Mev} \leq E_\nu \leq 1000\ \mathrm{MeV}$

Luckily there are both current (MiniBoone) and future (T2K) experiments that may be sensitive to this effect that operate in this energy regime.

The MiniBooNE experiment looks for $\nu_\mu \rightarrow \nu_e$ oscillations followed by charged current scattering to produce final state electrons which are detected through their Cerenkov radiation.



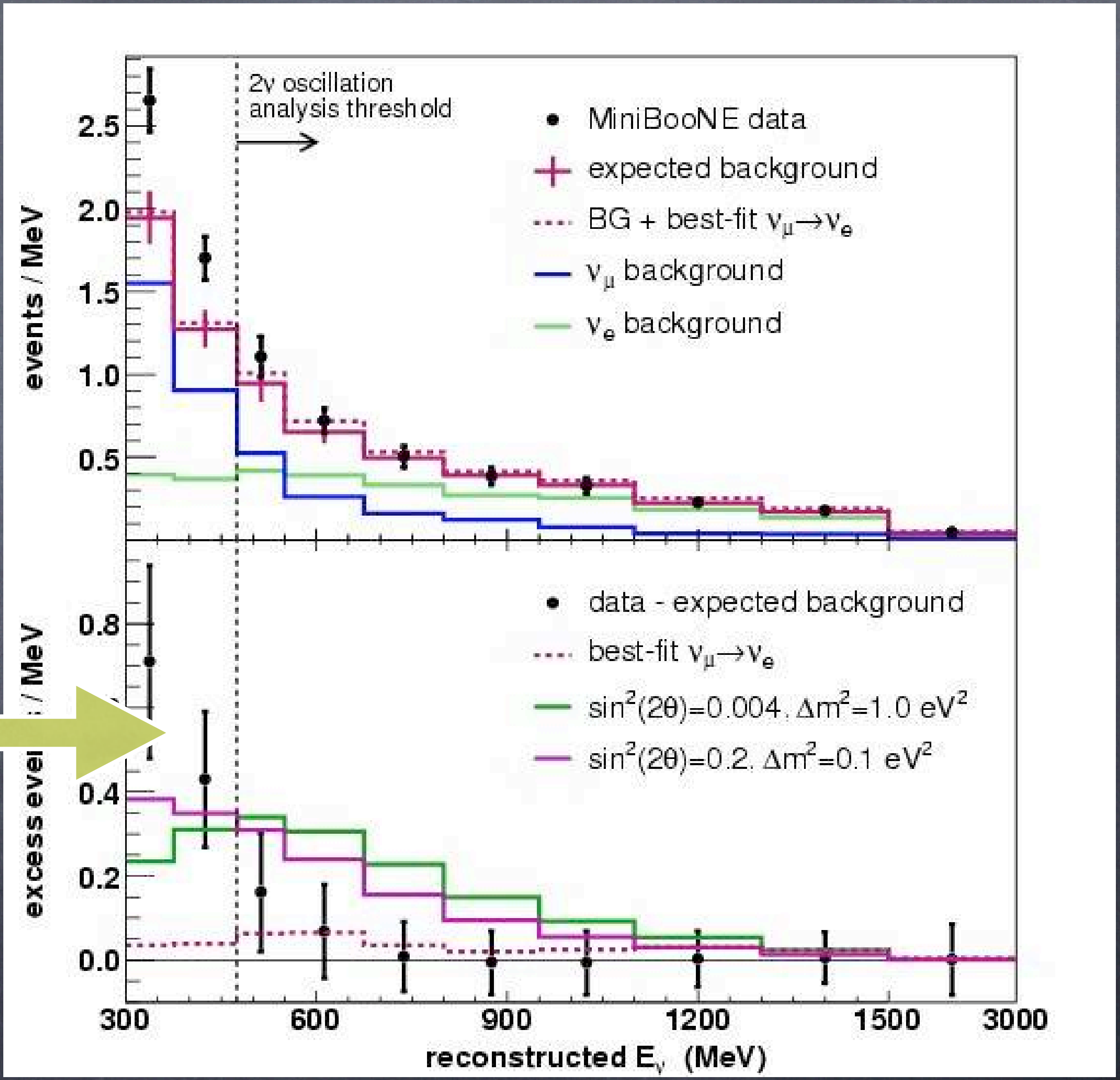
MiniBoone sees an excess at low energies:

$300 < E_\nu < 475\text{MeV}$

$96 \pm 17 \pm 20\text{events}$

excess 3.7σ

(MiniBoone presentation at Lepton-Photon '07)

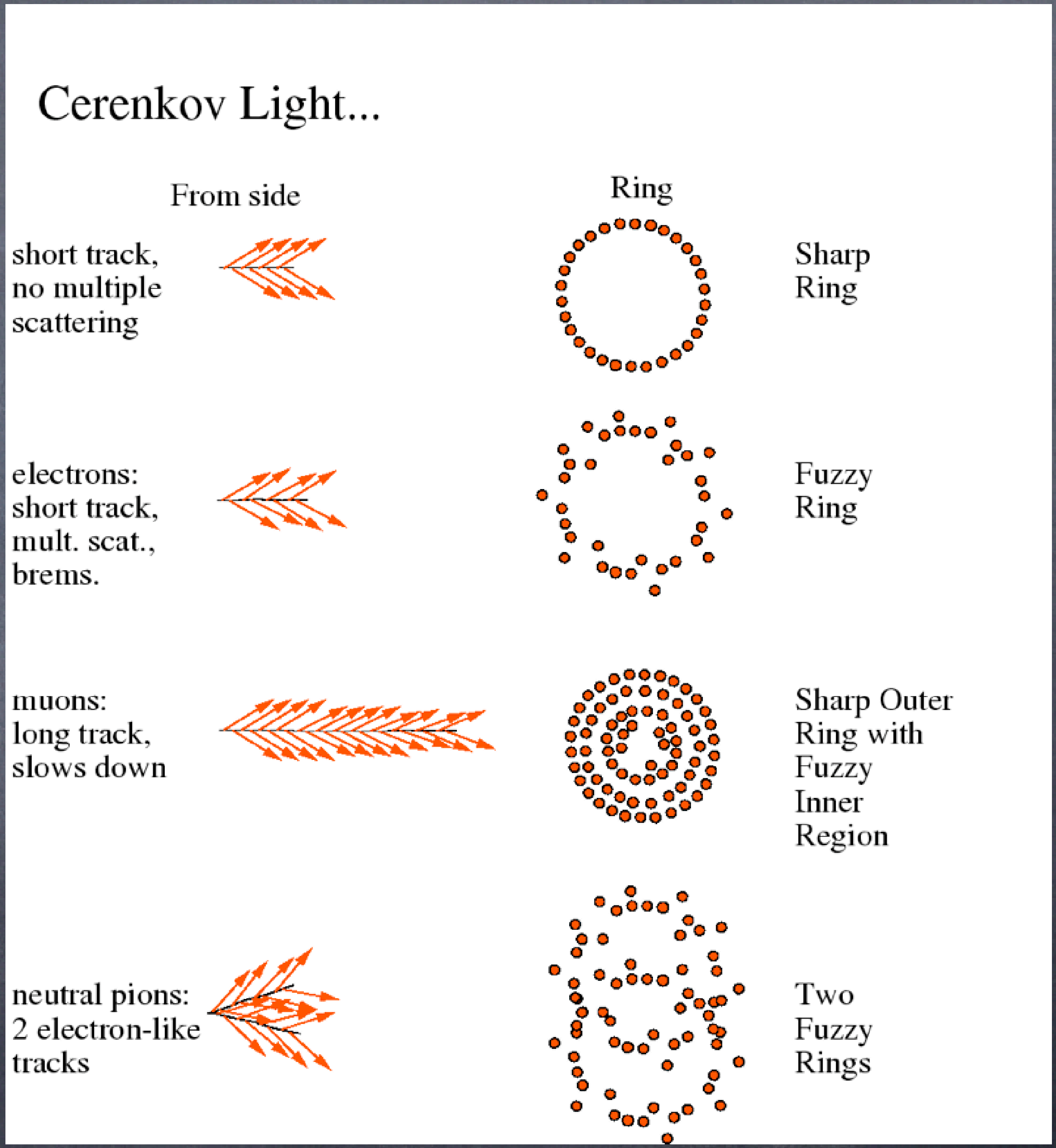


MiniBooNE distinguishes electrons from muons, but cannot discriminate between final state photons and electrons:

Electron

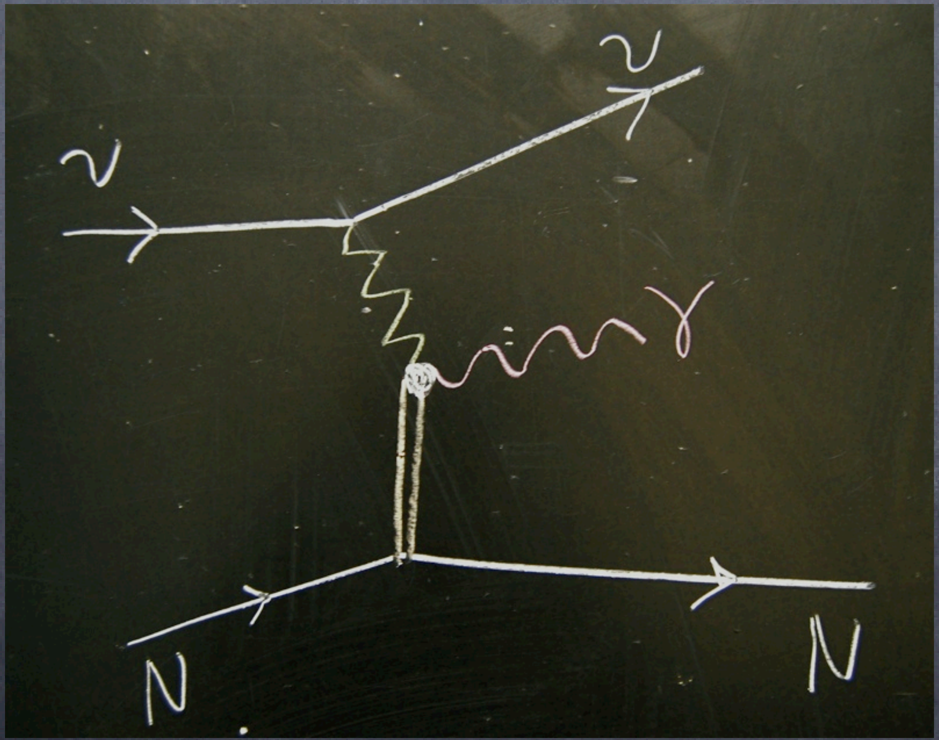
Muon

Two Photons

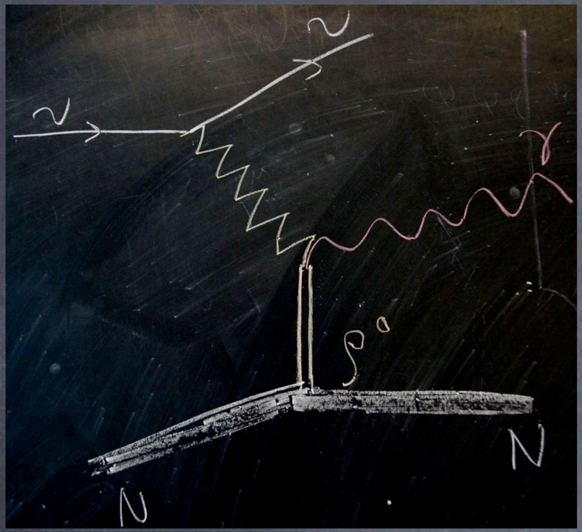


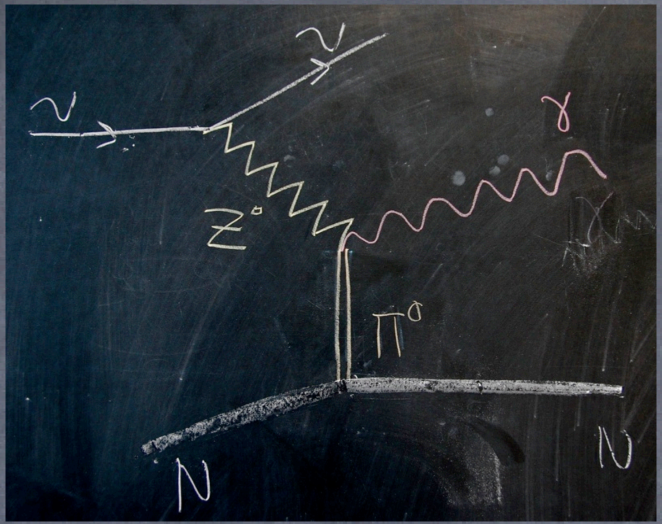
Thanks to Fermilab for graphics.

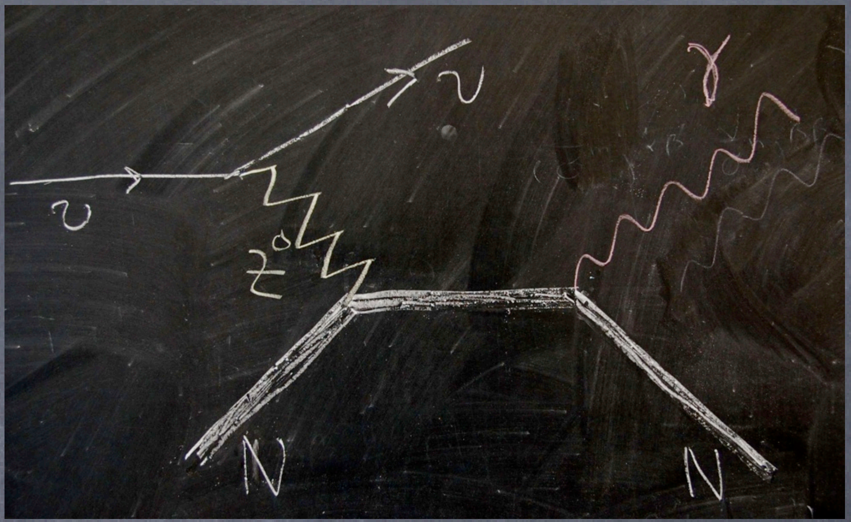
Thus the $Z - \omega - \gamma$ vertex gives a background to the charged current events ($\nu_e + N \to e^- + N'$) MiniBooNE is looking for:



Competing Processes:







Rho exchange suppressed by

$g_\rho / g_\omega \sim 1/3$

Pion exchange suppressed by

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

Brehmstrahlung suppressed by

$1/M_N$

The most naive estimate ignores recoil, form factors, nuclear physics effects (Fermi motion, Pauli blocking), and replaces the neutrino beam by a mono-energetic beam at the peak energy of 700 MeV. This gives

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

Which for every 2x10^5 CCQE events gives

$$\sim 140 \, (\frac{g_\omega}{10})^4$$

events from the anomaly-induced neutrino-photon interaction.

We are working on a more detailed comparison. Including some of the simpler effects leads to reasonable fits to data. Including nuclear recoil and a simple choice of form factor, but using a mono-energetic beam and scattering off of nucleons rather than nuclei gives, up to normalization.

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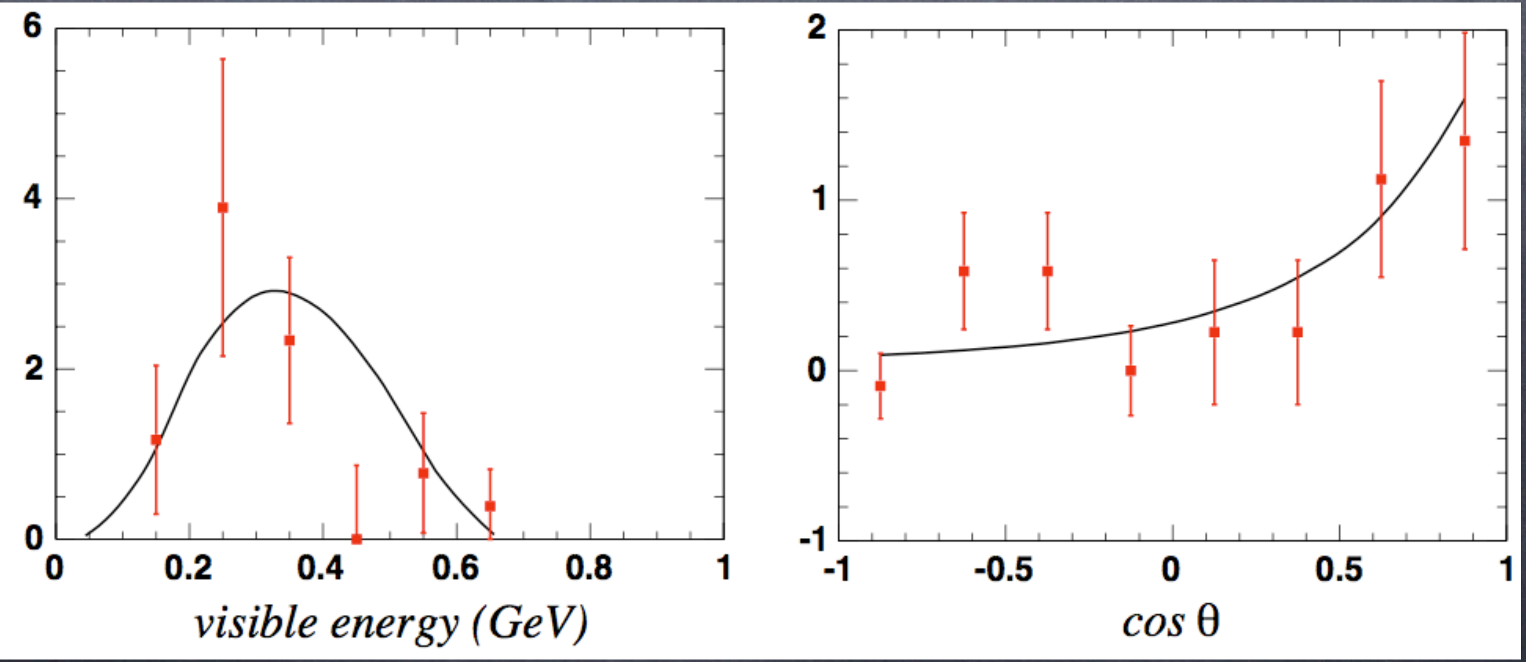
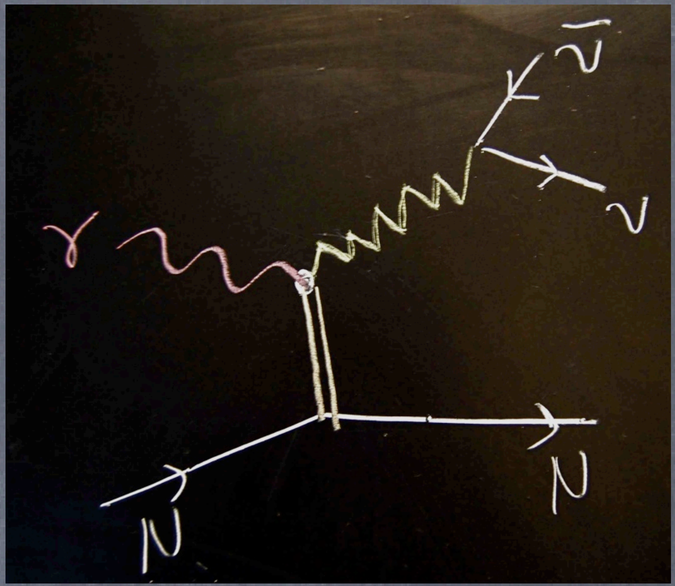


Note that MiniBoone plots the number of events vs. the reconstructed neutrino energy, assuming a two body final state (electron + nucleon).

The previous graphs plots the number of events vs. the (visible) photon energy, which is shared roughly equally with the final state neutrino in a three body final state (neutrino + nucleon + photon). A neutrino beam with a distribution of neutrino energies peaked at 700 MeV is shifted to a distribution of events with final state photons with the photon energy peaked at ~ 350 MeV.

Other Applications:



Neutron Star Cooling,
Supernova dynamics?

Detection of coherent neutrino scattering off of nuclei.

New contributions to atomic parity violating effects (e.g. nuclear anapole moments).

Conclusions

There are a set of SM couplings which involve both the SM gauge fields and the vector fields of QCD which are distinguished by their violation of "natural parity" and their relation to anomalies.

The couplings give a reasonable prediction for certain vector meson decays and may account for the MiniBoone excess at low-energies.

These couplings should have a variety of other applications in astrophysics and nuclear physics/ QCD.

pCS terms in AdS/QCD

5D AdS with IR cutoff: $$ds^2 = \frac{1}{z^2}\left(-dz^2 + dx^\mu dx_\mu\right)$$

$$0 < z \leq z_m$$

UV (at $z = 0$) — IR scale (at z_m)

Fields:

$$A_L^{a,\mu} \sim j_L^{a,\mu} = \bar{q}_L t^a \gamma^\mu q_L$$
$$A_R^{a,\mu} \sim j_R^{a,\mu} = \bar{q}_R t^a \gamma^\mu q_R$$
$$X^{\alpha,\beta} \sim \bar{q}^\alpha q^\beta$$

We will gauge $U(N_f)_L \times U(N_f)_R$ and focus on $N_f = 2$

$$S = \int d^4x dz \sqrt{|g|} Tr \left[|DX|^2 + 3|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2) \right]$$

with $g_5^2 = 12\pi^2/N_c$

One finds the pi, rho, a1 etc. by expanding around the tachyon solution

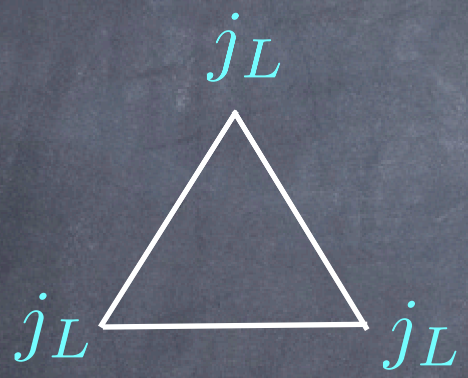
$$X_0(z) = \frac{1}{2} m_q \mathbf{1} z + \frac{1}{2} \sigma \mathbf{1} z^3$$

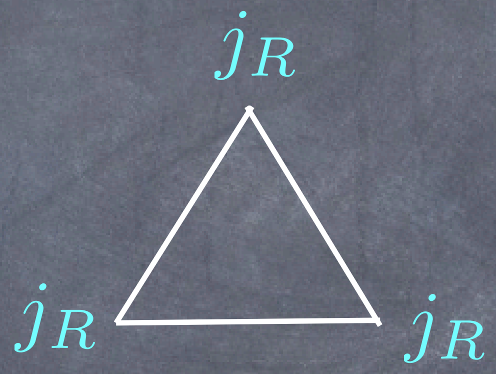
Coeff. of $\bar{q}q$ in S_{QCD} — Exp. value $\langle \bar{q}q \rangle$

The model is defined by three parameters: z_m, m_q, σ

Add Chern-Simons terms

In QCD there are anomalies:





The AdS dual involves terms which are gauge invariant in bulk, but vary on the bndy in the same way that QCD would if coupled to fictitious flavor gauge fields.

$$S_{CS} = \frac{N_c}{24\pi^2}\int \omega_5(A_L) - \omega_5(A_R)$$

with
$$\begin{aligned} d\omega_5 &= TrF^3 \\ \delta\omega_5 &= d\omega_4^1 \end{aligned}$$

This can also be understood in the S-S model where such couplings arise from a term on the D8-branes

$$S_{anom} = \int_{\Sigma_p} C \wedge ch(F) = \int_{\Sigma_9} C_3 \wedge TrF^3 + \cdots$$

which in the D4-background with $\int_{S^4} G_4 = 2\pi N_c$ gives the same couplings

Restrict to lightest isoscalar modes:

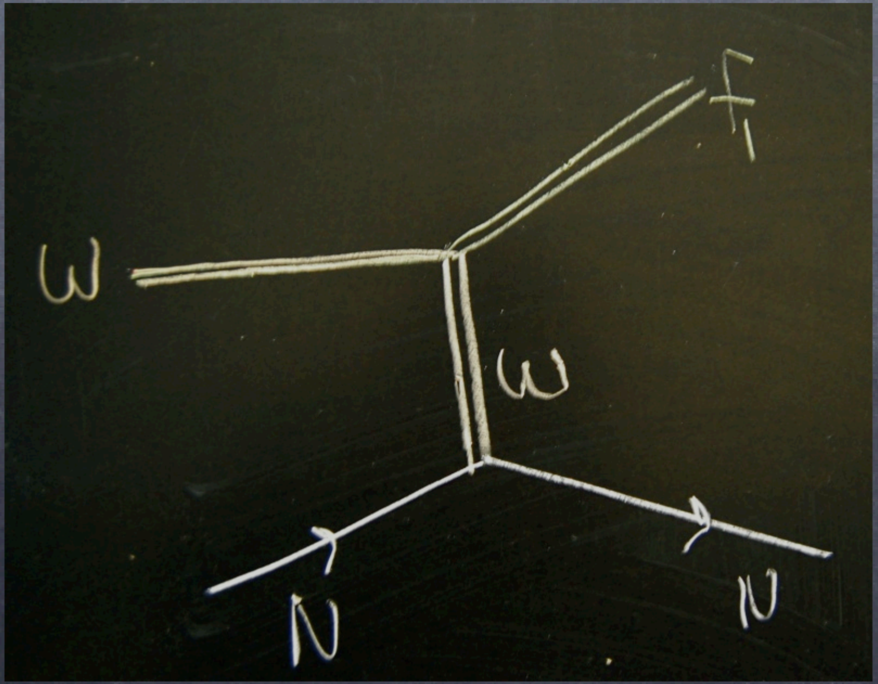
$$\begin{aligned}\pi^a(x,z) &= \pi^a(x)\psi_\pi(z)\\ V_\mu(x,z) &= g_5\,\omega_\mu(x)\psi_\omega(z)\\ A_\mu(x,z) &= g_5\,f_\mu(x)\psi_f(z)\end{aligned}$$

one finds a pCS term (among others)

$$S_{f\omega\omega} \sim g_{f\omega\omega}\int d^4x\epsilon^{\mu\nu\lambda\rho} f_\mu\omega_\nu\partial_\lambda\omega_\rho$$

with $g_{f\omega\omega}$ determined in terms of integrals over z and the parameters of the model, leading to $g_{f\omega\omega} \sim 9$.

This might be visible in polarized photon-proton scattering experiments planned for Hall D at JLab $\gamma + p \to f_1 + p$ with $\gamma \to \omega$ using VMD and measurement of the f_1 polarization used to distinguish omega exchange from other effects.



Extra Slides/Toy Model

A Toy Model with pCS

		B_L	B_R	L_L	L_R
"quarks"	q_L	1	0	0	0
	q_R	0	1	0	0
"leptons"	ℓ_L	0	0	1	0
	ℓ_R	0	0	0	1

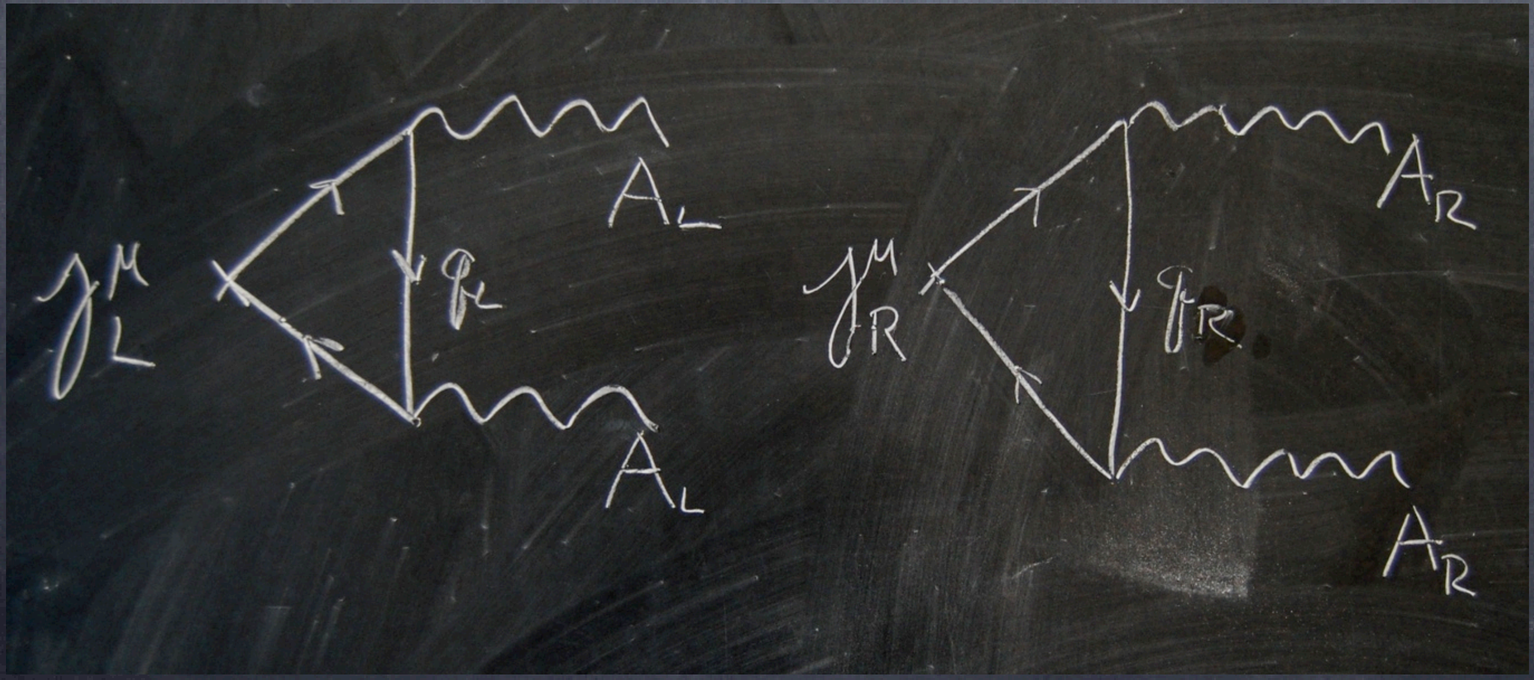
We gauge $U(1)_L \times U(1)_R$ with generators

$$\begin{aligned} Q_L &= B_L - L_L \\ Q_R &= B_R - L_R \end{aligned}$$

The action is

$$S = \int d^4x\, \bar{q}_L(i\partial\!\!\!/ + A\!\!\!/_L)q_L + \bar{q}_R(i\partial\!\!\!/ + A\!\!\!/_R)q_R$$
$$+\bar{\ell}_L(i\partial\!\!\!/ - A\!\!\!/_L)\ell_L + \bar{\ell}_R(i\partial\!\!\!/ - A\!\!\!/_R)\ell_R$$
$$-\tfrac{1}{4}(F_L)^2 - \tfrac{1}{4}(F_R)^2$$

The quark sector by itself has triangle anomalies



$$\delta S_q^{eff} = \frac{1}{24\pi^2}\int\left[-\epsilon_L dA_L dA_L + \epsilon_R dA_R dA_R\right]$$

But this anomaly is cancelled by the leptons so that we can consistently gauge $U(1)_L \times U(1)_R$

We now generalize this model in two ways:

- We add a quark mass term and integrate out the quarks.
- We add in a background field coupling to the (anomalous) vector baryon current.

To add a mass term consistent with gauge invariance we add a Higgs field with a non-zero vev $\Phi = ve^{i\phi/f}$ coupled to the quarks leading to

$$m_q e^{i\phi/f} \bar{q}_L q_R + h.c. \qquad \phi/f \sim \pi^0/f_\pi \text{ in QCD}$$

The $U(1)_L \times U(1)_R$ acts as

$$\delta_L q_L = i\epsilon_L q_L, \; \delta_L A_L = d\epsilon_L, \; \delta_L \phi/f = \epsilon_L$$

$$\delta_R q_R = i\epsilon_R q_R, \; \delta_R A_R = d\epsilon_R, \; \delta_R \phi/f = -\epsilon_R$$

Now consider the low-energy theory after integrating out the massive quarks. This is a function of ϕ, A_L, A_R and since the anomalies must still cancel, it must have an anomalous variation equal to that of S_q^{eff} (D'Hoker and Farhi). This "WZW" contribution is

$$\begin{aligned}\Gamma_{WZW} = & - \frac{1}{24\pi^2}\int\Big(A_L A_R dA_L + A_L A_R dA_R \\ & + \frac{\phi}{f}\left[dA_L dA_L + dA_R dA_R + dA_L dA_R\right]\Big)\end{aligned}$$

We now add a new ingredient: a background field coupled to the baryon current (like the omega meson in QCD).

$$S_q \to \int d^4x \; \bar{q}_L(i\partial\!\!\!/ - A\!\!\!/_L - \omega\!\!\!/)q_L + \bar{q}_R(i\partial\!\!\!/ - A\!\!\!/_R - \omega\!\!\!/)q_R$$

This leads to new terms in the variation of the WZW term proportional to omega:

$$\delta\Gamma_{WZW} = -\frac{1}{24\pi^2}\int \begin{array}{l} \epsilon_L\big(2dA_L d\omega + d\omega d\omega\big) \\ -\epsilon_R\big(2dA_R d\omega + d\omega d\omega\big) \end{array}$$

Since omega doesn't couple to leptons, the anomaly no longer cancels. But, as one might expect, this can be fixed by adding a local counterterm whose variation cancels the omega dependent terms in $\delta\Gamma_{WZW}$:

$$\Gamma_c = \frac{1}{24\pi^2}\int \big(2\omega A_R dA_R - \omega A_R d\omega - (R \leftrightarrow L)\big)$$

The effective action then has the anomaly related terms

$$\begin{aligned}\Gamma_{eff} &= \Gamma_{WZW}(\phi, A_L + \omega, A_R + \omega) + \Gamma_c \\ &= \underbrace{\Gamma_{WZW}(\phi, A_L, A_R)} + \Gamma_{pCS}\end{aligned}$$

Variation cancelled by leptons

where in terms of $A_L = Z + A, \quad A_R = A$

$$\Gamma_{pCS} = \frac{1}{8\pi^2} \int \big(\underbrace{\omega [2dA + dZ]}_{\text{gauge invariant massless field strength}} + \omega d\omega \big) \underbrace{(Z - d\phi / f)}_{\text{gauge invariant massive vector}}$$

This term correctly generates the anomaly in the baryon current by varying $\delta \omega = d\epsilon_B$