Low energy analysis of $\nu N \to \nu N \gamma$
pseudo-Chern Simons terms and Skyrmion tickles

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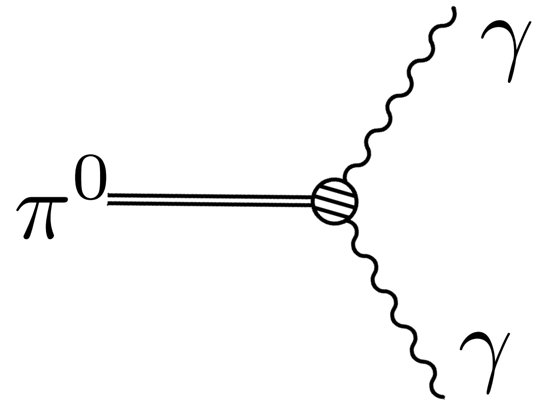
Outline

- vector mesons, WZW and pCS terms
- embedding in chiral lagrangian
- coherent single photon production in neutrino-baryon scattering
- Skyrmion tickles and super-radiance
- some cross sections

based on HHH work (Harvey Hill and Hill)
and work in progress

The 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:

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

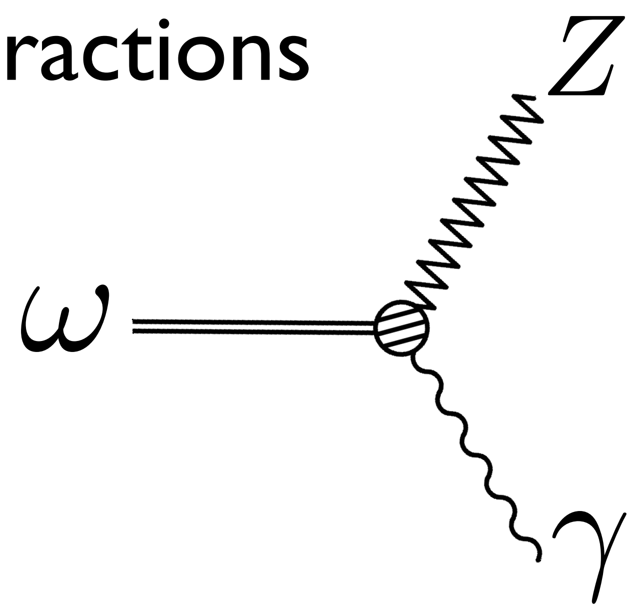
If we *did* try an ill-advised gauge transformation on the axial symmetries, have to get the expected anomaly

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

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

The baryon anomaly

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



Baryon number is anomalous in the Standard Model

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

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

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

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

$$\Rightarrow \quad \delta\mathcal{L} \equiv \epsilon\partial_\mu J_5^\mu \sim \partial_\mu\epsilon[\epsilon^{\mu\nu\rho\sigma} Z_\nu F_{\rho\sigma}] \sim -\epsilon[\epsilon^{\mu\nu\rho\sigma}\partial_\mu Z_\nu F_{\rho\sigma}]$$

Anomalous chiral lagrangian with vector mesons

Conventional (?) wisdom:

"As it turns out that there is no anomalous term in the Ward identities for $<0|T(VVV)|0>$ and that there are anomalous terms for $<0|T(AAA)|0>$, it is logical to associate the anomaly with the axial-vector current."

Cheng and Li textbook, 1984

I.e., "vector currents are conserved, axial-vector currents are anomalous"

But this would predict the absence of pseudo-Chern Simons terms !

Using that:

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

$$\Gamma(U, A, B) \to \Gamma(U, A, B) - \Gamma(1, A, B) \quad \text{[wrong]}$$

gauge *background*

Equivalently:
integrating the anomaly with the "Wess-Zumino boundary condition" maintains vector current conservation in the presence of arbitrary backgrounds

$$\Gamma(U = 1) = 0 \qquad \text{[wrong]}$$

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

$\Rightarrow$ "proof" that: "pseudo Chern Simons terms do not exist" !

The Standard Model SU(2)xU(1) is not vector-like gauging !
New counterterm $\Rightarrow$ fixes new interactions

Counterterm freedom is fixed by requiring that the anomaly of the meson theory match the anomaly of the quark theory

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

$\nu \to \nu + \gamma$

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

$f_1 \to \rho\gamma$

$$
\Gamma_{BBB} = \mathcal{C}\int 2\Big[\left(\rho^-f + \omega a^-\right)D\rho^+ + \left(\omega a^+ + \rho^+ f\right)D\rho^- + \left(\omega a^0 + \rho^0 f\right)d\rho^0 + \left(\rho^+a^- + \rho^-a^+ + \omega f + \rho^0 a^0\right)d\omega\Big]
$$

connections to AdS/CFT models

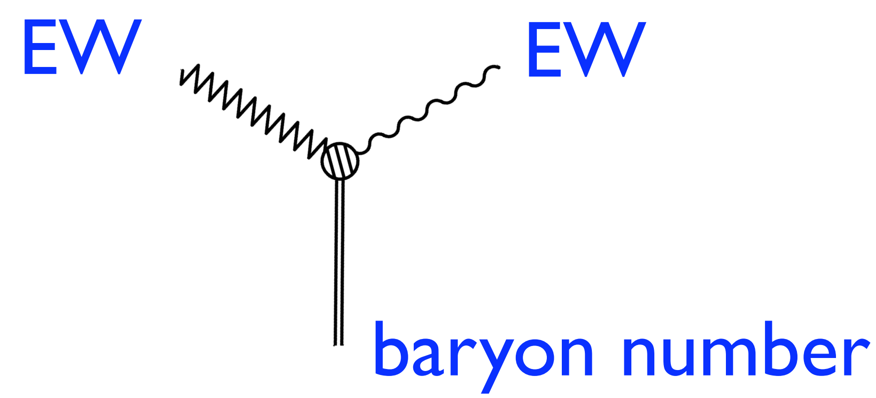
$$
\Gamma_{AAAB} = \mathcal{C}\int i\Big\{W^+W^-\Big[3c_W Z\Big]\omega + W^+W^-\Big[\left(c_W + \frac{1}{2c_W}\right)Z\Big]f\Big\},
$$

$$
\begin{aligned}
\Gamma_{AABB} &= \mathcal{C}\int i\Big\{W^+W^-\left[\frac{3}{2}(\rho^0 + a^0)\omega - \frac{1}{2}(\rho^0 - a^0)f\right] \\
&\quad + W^+Z\left[\frac{3c_W}{2}\rho^-f - \frac{3c_W}{2}\rho^-\omega - \frac{c_W}{2}a^-f + \frac{3c_W}{2}\omega a^- - \frac{1}{c_W}\rho^-f\right] \\
&\quad + W^-Z\Big[-\frac{3c_W}{2}\rho^+f + \frac{3c_W}{2}\rho^+\omega + \frac{c_W}{2}a^+f - \frac{3c_W}{2}\omega a^+ + \frac{1}{c_W}\rho^+f\Big]\Big\},
\end{aligned}
$$

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

etc.

What can we do with the coupling of baryon number to electroweak gauge fields?



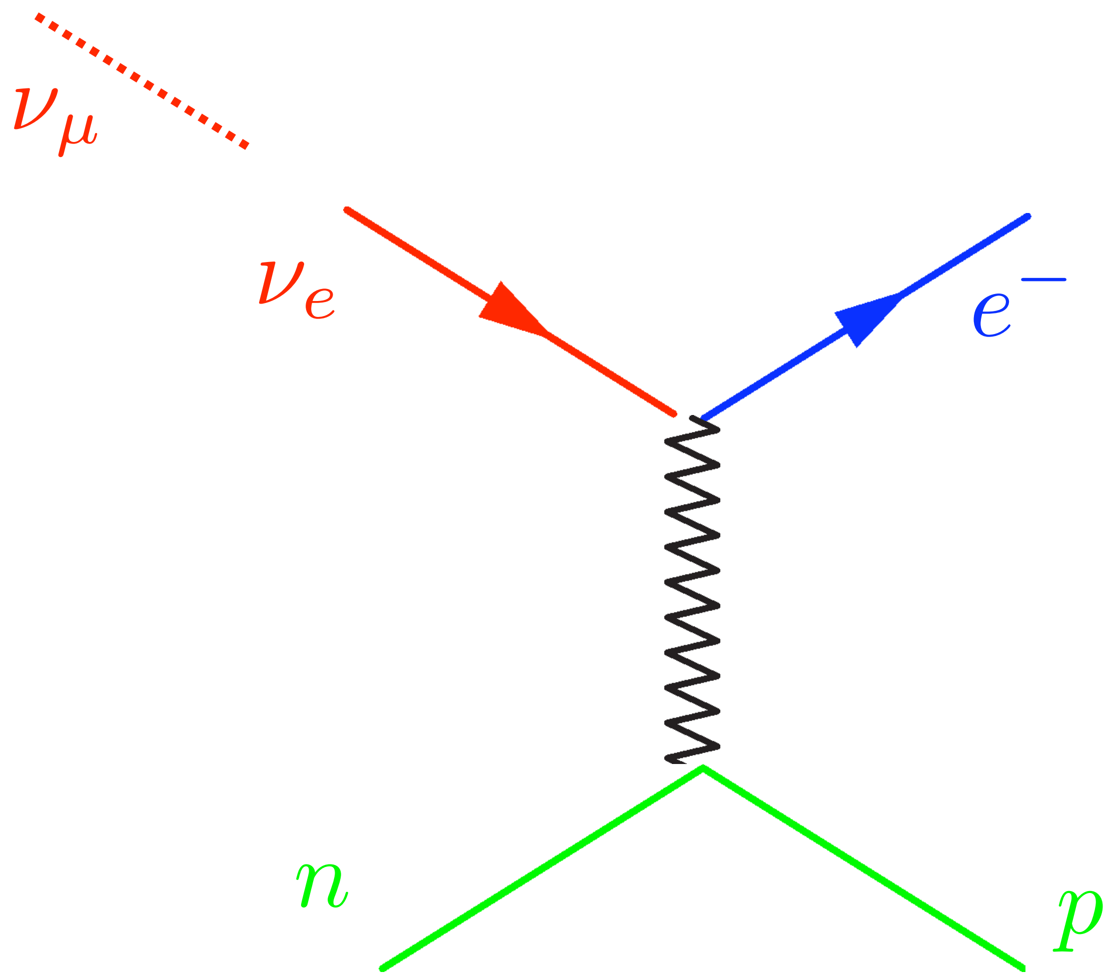
- first, to avoid doubly weak suppression, should take one electroweak field as photon

- this implies the other is the Z boson

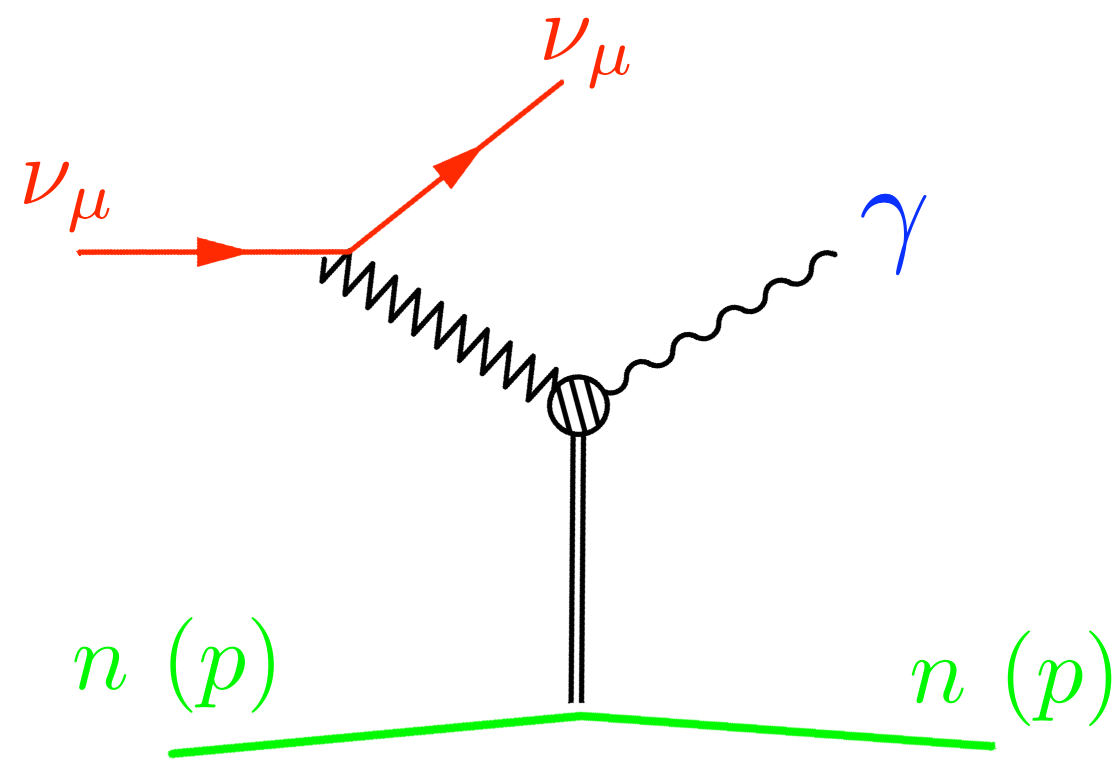
- Z is useful for:

- neutrinos
- parity violation

Baryon catalyzed neutrino-photon interactions



$\nu_e \rightarrow e$ "signal"



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

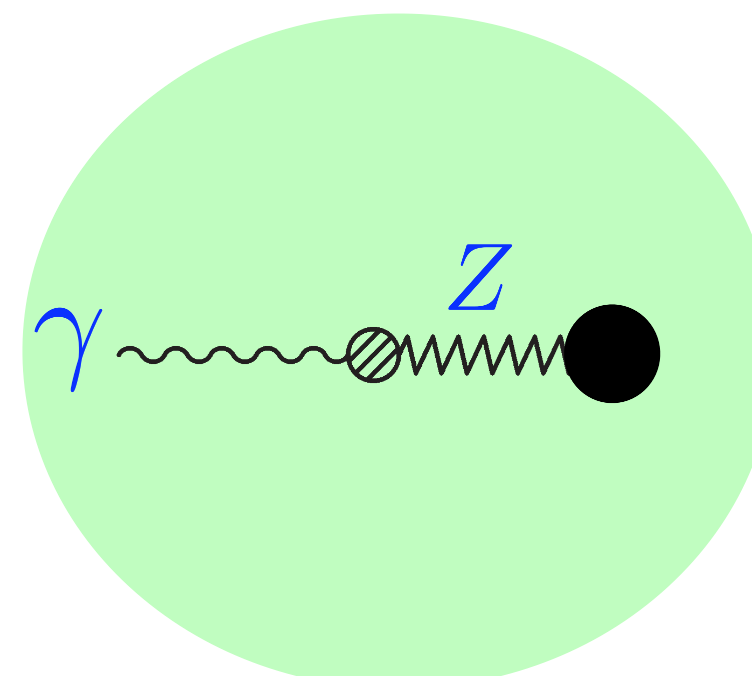
GeV cross sections relevant to MiniBooNE, T2K (lower energy: LSND; higher energy: Nomad, Minos, Minerva, Nova, ...)

Baryon catalyzed parity violation

Can also use the Z for parity violation

E.g., for spin-1/2 particle, can phrase in terms of anapole moment:

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



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

particle's weak coupling

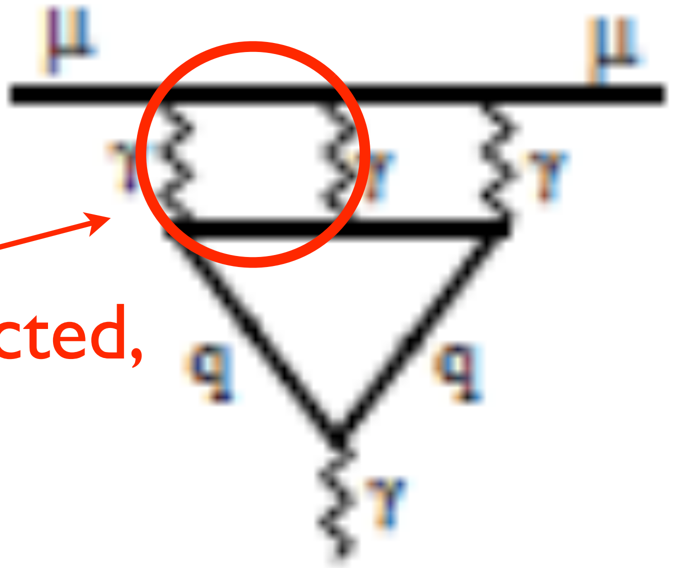
baryon density

Potentially relevant in various low-energy parity-violating observables, e.g. spin-dependent atomic parity violation

Other applications of vector meson action

- radiative decays, e.g. $f_1 \to \rho\gamma$

- modeling hadronic corrections to light-by-light contribution in muon g-2



two vector currents contracted,
AVV triangle

tidying up the baryon chiral lagrangian

Anomalous chiral lagrangian with baryons

Problem: Including U(1) factors with baryons

"In order to avoid complications due to anomalies we disregard the isoscalar vector, axialvector and pseudoscalar currents."

Gasser, Sainio and Svarc, 1988

But we need $SU(2)_L \times U(1)_Y$ for the standard model !
(contains an isoscalar vector piece)

How to baryons transform ?

Recall for pions in the chiral lagrangian, we collected them into a matrix

$$U(x) = \exp\left[i\pi(x)/f_\pi\right]$$

When the quarks transform as

$$\psi_L \rightarrow e^{i\epsilon_L}\psi_L$$
$$\psi_R \rightarrow e^{i\epsilon_R}\psi_R$$

U transforms as

$$U \rightarrow e^{i\epsilon_L} U e^{-i\epsilon_R}$$

The form of the chiral lagrangian is fixed by requiring invariance under this transformation (and an anomaly that matches the quarks)

For baryons, need a transformation law that involves both the left-handed (ε_L) and right-handed (ε_R) rotations, but reduces to the correct isospin transformation law when $\varepsilon_L = \varepsilon_R$

There's an (essentially) unique way to do this

Coleman et.al. 1969
Georgi

Define a new pion field

$$U(x) = \xi(x)^2$$

And for any chiral transformation define a new ε' by demanding

$$\xi \to e^{i\epsilon_L} \xi e^{-i\epsilon'} = e^{i\epsilon'} \xi e^{-i\epsilon_R}$$

$\Rightarrow$ Define nucleon spinor field to transform as:

$$\boxed{N \to e^{i\epsilon'} N}$$

About the "essential" in the essentially unique:

The isoscalar and isovector pieces have different proportionality factors:

$$\cancel{N \to e^{i\epsilon'} N}$$

$$N \to e^{i\epsilon'_{\text{isovector}} + 3i\epsilon'_{\text{isoscalar}}} N$$

3 quarks in the nucleon

Again, having fixed the transformation laws of all fields - including baryons - can proceed to write down most general effective lagrangian

Working order by order:

$$\mathcal{L}_0 = M c^{(0)} \bar{N} N$$

mass

$$\mathcal{L}_1 = \bar{N}\left[c_1^{(1)} i \not{D} - c_2^{(1)} \not{A} \gamma_5 \right] N$$

vector coupling: C_V

axial-vector coupling: C_A

$$\mathcal{L}_2 = \frac{1}{M} \bar{N}\left[- c_1^{(2)} \frac{i}{2} \sigma^{\mu\nu} \mathrm{Tr}([iD_\mu \,, iD_\nu]) \right] N$$

anomalous magnetic moment: a_N

$$\mathcal{L}_3 = \frac{1}{M^2} \bar{N}\Big[c_1^{(3)} \gamma^\nu [iD_\mu, [iD^\mu, iD_\nu]] + c_2^{(3)} \gamma^\nu \gamma_5 [iD_\mu, [iD^\mu, A_\nu]] + c_3^{(3)} i \epsilon^{\mu\nu\rho\sigma} \gamma_\sigma \{ A_\mu, iD_\nu iD_\rho \}$$
$$+ c_4^{(3)} \gamma^\nu \gamma_5 [\cancel{[iD_\mu, iD_\nu]}, A^\mu] + c_5^{(3)} \gamma^\nu \gamma_5 \{ \cancel{[[iD_\mu \,, iD_\nu], A_\rho]}, \{ D^\mu \,, D^\rho \} \} + \ldots \Big] N$$

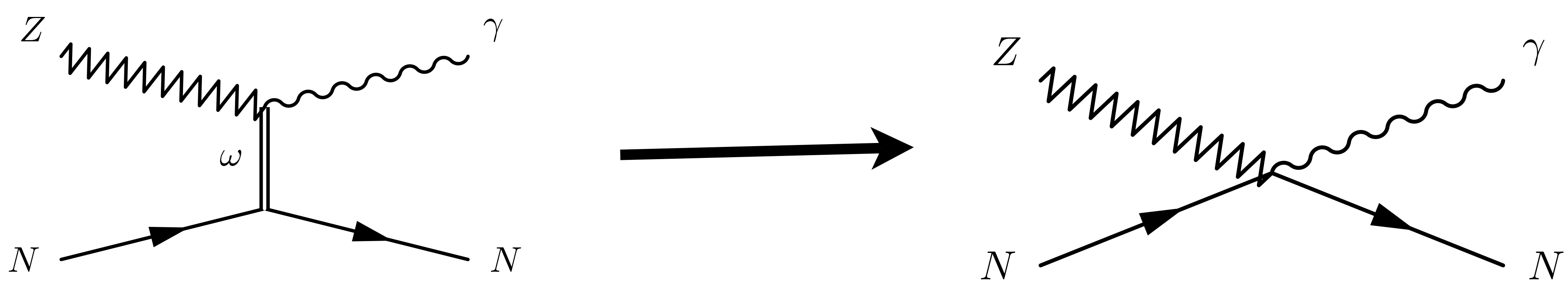
vector form factor correction: m_V^2

axial-vector form factor correction: m_A^2

NEW !

(vanishes for neutral fields)

⇒ the only "new" operator is the low-energy manifestation of pseudo-Chern Simons terms
(through 3-derivative order, at most one axial-vector field)

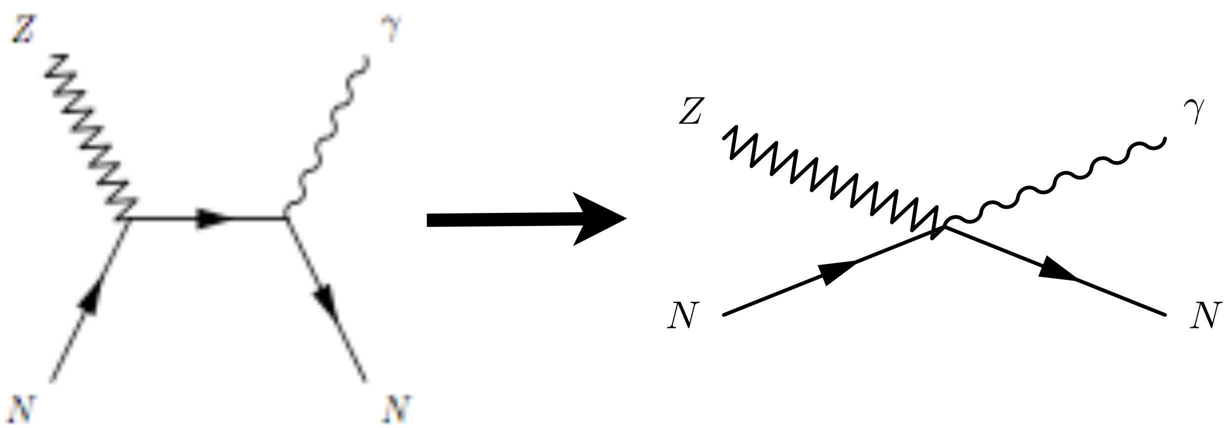


$$\left(g_\omega \bar{N}\gamma^\mu N\right)\frac{1}{m_\omega^2}\left(\frac{e g_2 g_\omega}{16\pi^2\cos\theta_W}\epsilon^{\mu\nu\rho\sigma}Z_\nu F_{\rho\sigma}\right) = \left(\frac{e g_2 g_\omega^2}{16\pi^2\cos\theta_W m_\omega^2}\right)\bar{N}\gamma^\mu N\epsilon^{\mu\nu\rho\sigma}Z_\nu F_{\rho\sigma}$$

determines coefficient of new operator

(also a contribution from Δ excitation)

⇒ This operator has the special property that it involves the axial-vector Z, yet acts coherently on adjacent nucleons



$$
\begin{aligned}
T^{00} &= \frac{1}{2}\biggl\{\frac{1}{m}\Bigl[F_1C_V(2\boldsymbol{q}\cdot\boldsymbol{p}) + F_1C_A(-2\boldsymbol{\sigma}\cdot\boldsymbol{q})\Bigr] \\
&\quad + \frac{1}{m^2}\Bigl[F_1C_V\left(2\boldsymbol{q}\cdot\boldsymbol{p}\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'}) - i\boldsymbol{\sigma}\cdot\boldsymbol{q}\times\boldsymbol{p}\right) + F_1C_2\left(-i\boldsymbol{\sigma}\cdot\boldsymbol{q}\times\boldsymbol{p}\right) \\
&\qquad + F_1C_A\left(-\boldsymbol{q}\cdot\boldsymbol{p}\boldsymbol{\sigma}\cdot(\boldsymbol{k}+\boldsymbol{k'}) - \boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})\boldsymbol{\sigma}\cdot\boldsymbol{q}\right) + F_2C_V\left(-i\boldsymbol{\sigma}\cdot\boldsymbol{q}\times\boldsymbol{p}\right)\Bigr]\biggr\}, \\
T^{i0} &= \frac{1}{2}\biggl\{\frac{1}{m}\Bigl[F_1C_V(2p^i) + F_1C_A(-2\sigma^i)\Bigr] \\
&\quad + \frac{1}{m^2}\Bigl[F_1C_V\Bigl(\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})p^i + \boldsymbol{q}\cdot\boldsymbol{p}(k^i+k'^i) - i(\boldsymbol{p}\times\boldsymbol{\sigma})^i + i\boldsymbol{q}\cdot\boldsymbol{p}(\boldsymbol{q}\times\boldsymbol{\sigma})^i\Bigr) \\
&\qquad + F_1C_2\left(-i(\boldsymbol{p}\times\boldsymbol{\sigma})^i\right) + F_1C_A\left(-\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})\sigma^i - p^i\boldsymbol{\sigma}\cdot(\boldsymbol{k}+\boldsymbol{k'})\right) \\
&\qquad + F_2C_V\left(-i(\boldsymbol{p}\times\boldsymbol{\sigma})^i + \boldsymbol{q}\cdot\boldsymbol{p}i(\boldsymbol{q}\times\boldsymbol{\sigma})^i\right) + F_2C_A\Bigl((k^i+k'^i)\boldsymbol{q}\cdot\boldsymbol{\sigma} - \boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})\sigma^i\Bigr)\Bigr]\biggr\} \\
T^{0j} &= \frac{1}{2}\biggl\{\frac{1}{m}\Bigl[F_1C_V(2q^j) + F_1C_A(-2\boldsymbol{q}\cdot\boldsymbol{p}\sigma^j)\Bigr] \\
&\quad + \frac{1}{m^2}\Bigl[F_1C_V\Bigl(\boldsymbol{q}\cdot\boldsymbol{p}(k^j+k'^j) + \boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})q^j + i(\boldsymbol{q}\times\boldsymbol{\sigma})^j - i\boldsymbol{p}\cdot\boldsymbol{q}(\boldsymbol{p}\times\boldsymbol{\sigma})^j\Bigr) \\
&\qquad + F_1C_2\left(-i\boldsymbol{q}\cdot\boldsymbol{p}(\boldsymbol{p}\times\boldsymbol{\sigma})^j + i(\boldsymbol{q}\times\boldsymbol{\sigma})^j\right) \\
&\qquad + F_1C_A\left(-q^j\boldsymbol{\sigma}\cdot(\boldsymbol{k}+\boldsymbol{k'}) + (1-2\boldsymbol{q}\cdot\boldsymbol{p})\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})\sigma^j\right) \\
&\qquad + F_2C_V\left(i(\boldsymbol{q}\times\boldsymbol{\sigma})^j\right) + F_2C_A\Bigl(i(\boldsymbol{q}\times\boldsymbol{p})^j + (k^j+k'^j)\boldsymbol{q}\times\boldsymbol{\sigma} - q^j(\boldsymbol{k}+\boldsymbol{k'})\cdot\boldsymbol{\sigma}\Bigr)\Bigr]\biggr\} \\
T^{ij} &= \frac{1}{2}\biggl\{\frac{1}{m}\Bigl[F_1C_V(2\delta^{ij}) + F_1C_A\left(-2p^i\sigma^j + 2(\delta^{ij}\boldsymbol{q}\cdot\boldsymbol{\sigma} - q^j\sigma^i)\right) + F_2C_A\left(2(\delta^{ij}\boldsymbol{q}\cdot\boldsymbol{\sigma} - q^j\sigma^i)\right)\Bigr] \\
&\quad + \frac{1}{m^2}\Bigl[F_1C_V\bigl(i\epsilon^{ijr}\sigma^r(-1+\boldsymbol{p}\cdot\boldsymbol{q}-\boldsymbol{k}\cdot\boldsymbol{k'}) + k'^ik'^j - k^ik^j + k'^iq^j + q^ik'^j + q^ik^j + k^iq^j \\
&\qquad + i\epsilon^{jrs}\sigma^s(-(k+k')^r(k+k')^i - p^rp^i + q^rq^i) + i\epsilon^{irs}\sigma^s((k+k')^r(k+k')^j - p^rp^j + q^rq^j)\bigr) \\
&\qquad + F_1C_2\bigl(-i\epsilon^{ijr}\sigma^r + i\epsilon^{jrs}p^r(\delta^{is}\boldsymbol{\sigma}\cdot\boldsymbol{q} - p^i\sigma^s - q^s\sigma^i)\bigr) \\
&\qquad + F_1C_A\bigl(-(1-\boldsymbol{p}\cdot\boldsymbol{q})i\epsilon^{ijr}q^r - \delta^{ij}\boldsymbol{\sigma}\cdot(\boldsymbol{k}+\boldsymbol{k'}) + \boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})(q^j\sigma^i - \delta^{ij}\boldsymbol{q}\cdot\boldsymbol{\sigma}) \\
&\qquad\qquad + \sigma^j(-\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{k'})q^i - 2\boldsymbol{q}\cdot\boldsymbol{k'}k'^i + 2\boldsymbol{q}\cdot\boldsymbol{k}k^i)\bigr) \\
&\qquad + F_2C_V\bigl(-i\epsilon^{ijr}\sigma^r + i\epsilon^{irs}q^r(-\delta^{sj}\boldsymbol{\sigma}\cdot\boldsymbol{p} + q^j\sigma^s + p^s\sigma^j)\bigr) \\
&\qquad + F_2C_2\bigl(2i\epsilon^{jrs}p^r(\delta^{is}\boldsymbol{\sigma}\cdot\boldsymbol{q} - q^s\sigma^i)\bigr) \\
&\qquad + F_2C_A\bigl((\boldsymbol{q}\cdot\boldsymbol{p}q^r - p^r)i\epsilon^{ijr} + (k+k')^j\sigma^i - \delta^{ij}(\boldsymbol{k}+\boldsymbol{k'})\cdot\boldsymbol{\sigma}\bigr)\Bigr]\biggr\}.
\end{aligned}
$$

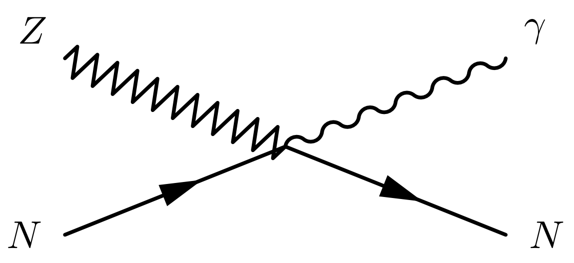
higher-order corrections from Compton scattering all involve nucleon spin or momenta

tickling the skyrmion

interested in cross sections in GeV energy range - Nc the only expansion parameter

- leading amplitudes given by tree-level meson exchange

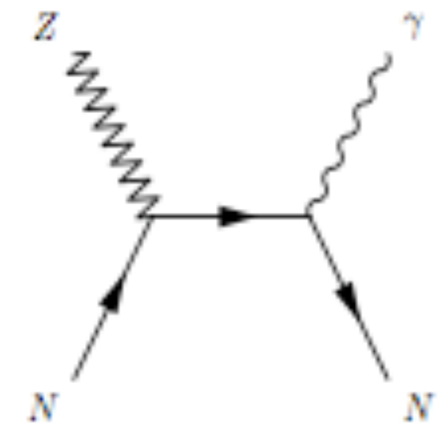
- for matching, dominant contributions in t-channel are ω, ρ



- dominant contributions in s-channel is Δ (and nucleon)

strategy *- normalize and extrapolate chiral lagrangian using leading resonances in each channel (and add phenomenological form factors to represent higher resonances, and match onto perturbative scaling)*

“violations” of N_c counting rules



Consider the propagator:

$$m_\Delta^2 - (m_N v + k)^2 = m_\Delta^2 - m_N^2 - 2Em_N \approx m_\Delta^2 - m_N^2$$

At small energy, enhancement from suppressed mass splitting:

$$\frac{m_N^2}{m_\Delta^2 - m_N^2} = \frac{m_N^2}{(m_\Delta + m_N)(m_\Delta - m_N)} \sim N_c^2$$

Analog in pion-nucleon scattering: low energy amplitude grows with N_c (should be constant). No paradox, since at fixed energy:

$$m_\Delta^2 - (m_N v + k)^2 = m_\Delta^2 - m_N^2 - 2Em_N \approx -2Em_N$$

large contribution to pCS term from Delta:

$$c \sim \frac{g_A}{4}\frac{1+a_p-a_n}{m_\Delta/m_N-1} \sim N_c^5 \sim 5$$

cf. omega:

$$c \sim \frac{9}{32\pi^2}\frac{g'^2 m_N^2}{m_\omega^2} \sim N_c^3 \sim 1.5$$

and rho:

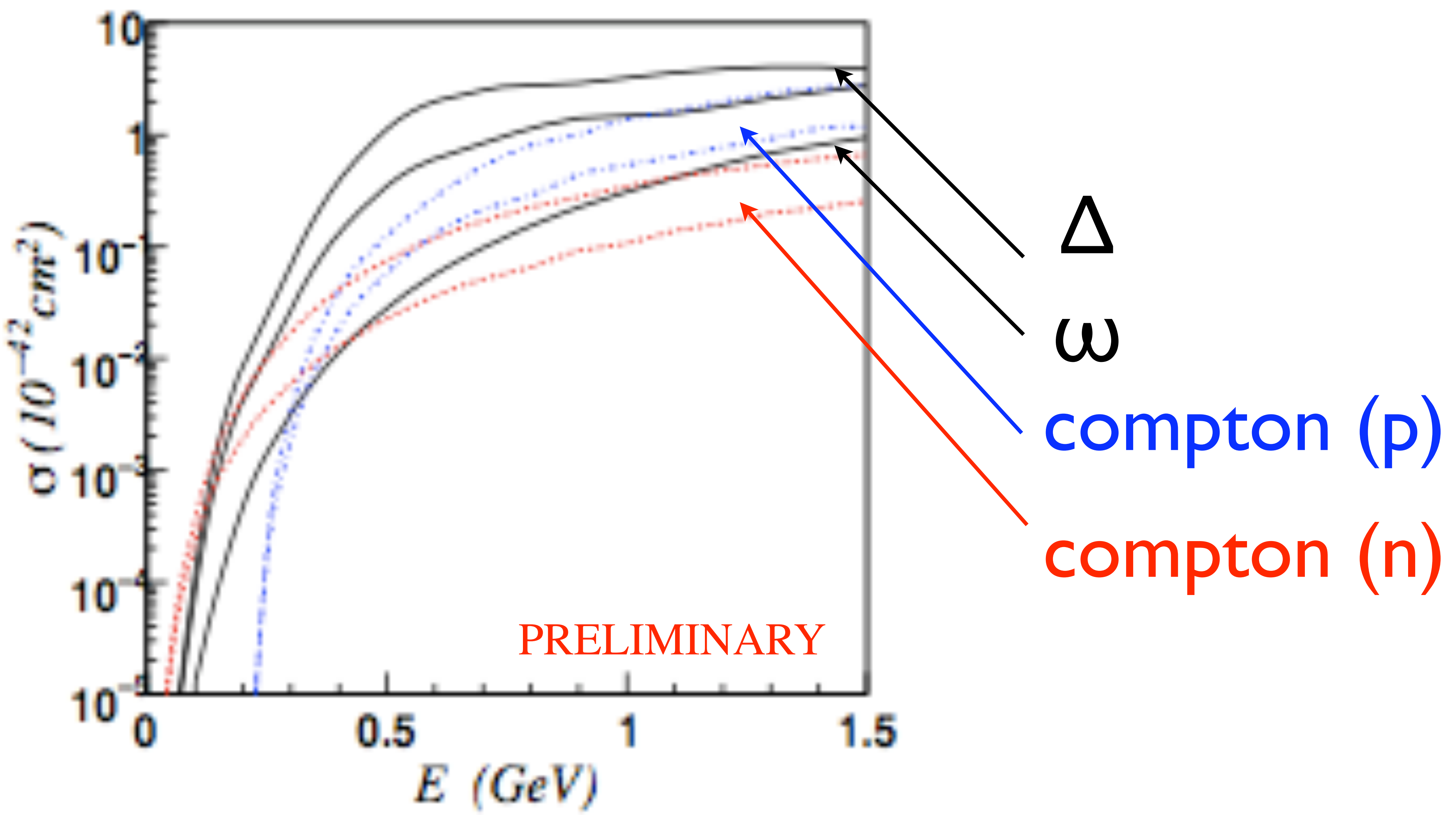
$$c \sim \frac{1}{32\pi^2}\frac{g^2 m_N^2}{m_\omega^2} \sim N_c^3 \sim 0.2$$

- so at very low energy, expect Delta to dominate (barring interesting in-medium effects, etc.)

$$g_A \sim N_c,\; f_\pi \sim \sqrt{N_c},\; m_\Delta - m_N \sim N_c^{-1},\; m_N \sim N_c,$$
$$g, g' \sim N_c^{-1/2},\; g_{\omega NN} \sim N_c g',\; g_{\rho NN} \sim g$$
$$g_{\pi N\Delta} = \tfrac{3}{2} g_{\pi NN},\; \mu_{N\Delta} = (\mu_p - \mu_n)/\sqrt{2}$$

- large Nc relations compare (too?) well with electroproduction data for N-Delta couplings

incoherent (single nucleon) cross sections



- includes form factors, recoil
- compton-like cross section divergent at small photon energy (bremstrahlung emission) - cut E_γ > 200 MeV

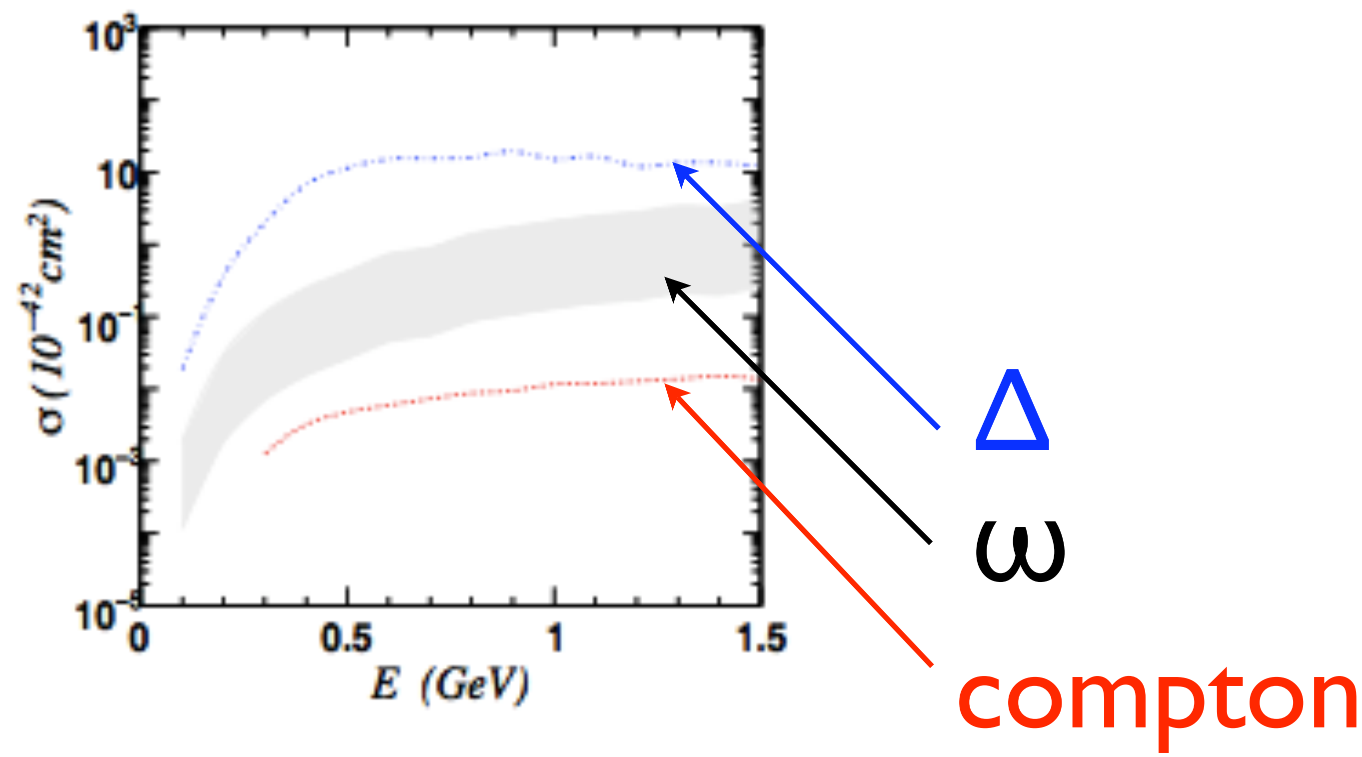
coherent cross sections

three types of contributions:

- Compton-like scattering on weak and e.m. vector charges of nucleus = initial and final-state radiation from (as yet unobserved) coherent neutrino-nucleus scattering

- omega mediated

- Delta mediated



The three contributions to coherent photon production are distinguished by kinematic distributions and scalings in limit of large nucleus/large energy

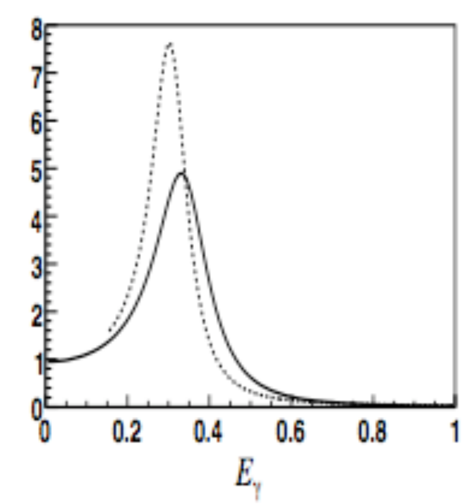
$$F(Q^2) = e^{-bQ^2}$$

Consider the limit of large $bE^2 \sim A^{2/3} E^2$

To avoid exponential suppression, photon must be emitted in either soft or collinear region. scaling of cross section depends on behavior of amplitudes in these regions

- *compton*: soft region, $A^{4/3} E^2 \log(E/Emin)$, flat distribution in photon angle

- *Delta*: soft, $A^{4/3} E^0$; $(1-\cos^2\vartheta_\gamma)$ angular distribution (some relation to Dicke super-radiance for atoms)



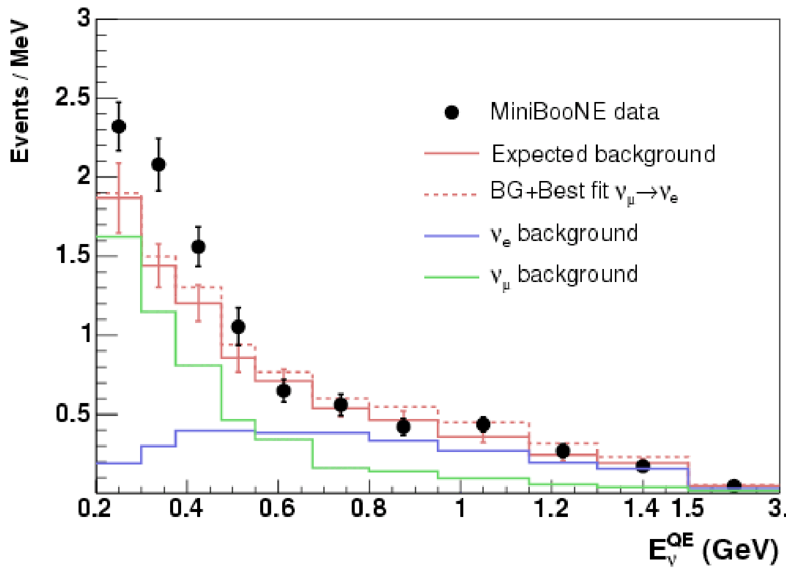
- *omega*: collinear, $A^{2/3} E^2$, forward photon

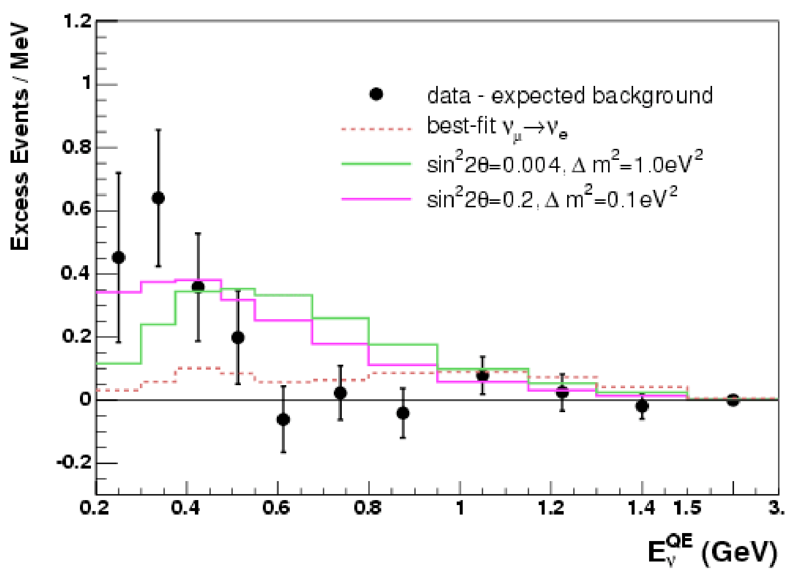
1GeV is midway between small and large bE^2 limits

Summary

- single photon events in neutrino-nucleon scattering involve several mechanisms
- theory - tidying up the chiral lagrangian coupled to baryons and arbitrary electroweak currents; large Nc surprises, simplifications
- phenomenology - important as background to neutrino experiments (more to come)

Final Results: Extend 2ν fit to low E

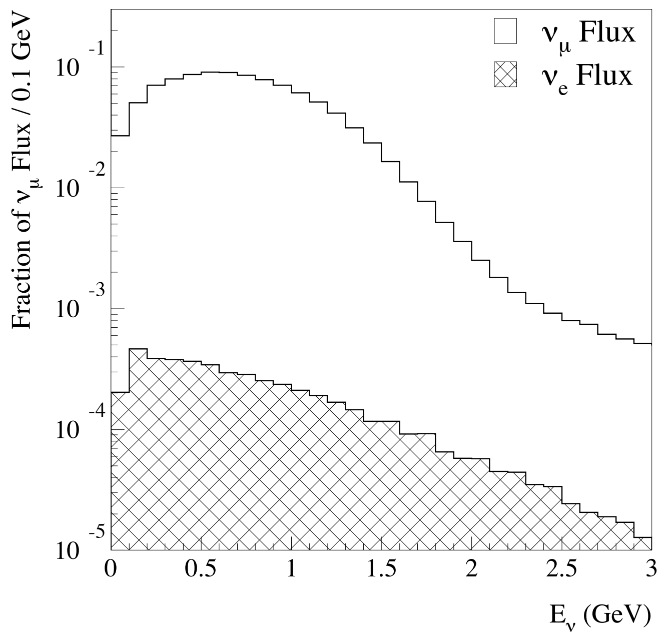




	E_ν>475 MeV	E_ν>200 MeV
Null fit χ^2 (prob.):	9.1(91%)	22.0(28%)
Best fit χ^2 (prob.):	7.2(93%)	18.3(37%)

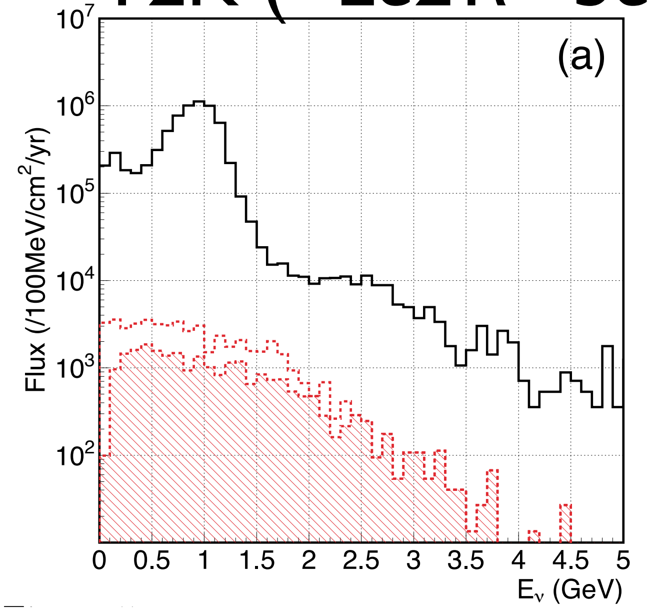
- Adding 3 bins to fit causes chi^2 to increase by 11 (expected 3)
- Can see the problem...the best 2ν fit that can be found does not describe the low E excess.

MiniBooNE

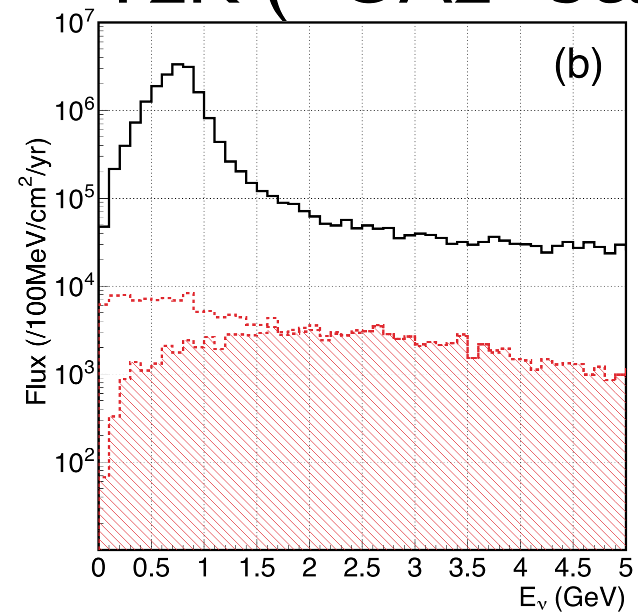


[J. Monroe, MiniBooNE, hep-ex/0408019]

T2K ("Le2π" beam)



T2K ("OA2" beam)



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