Single photons in neutrino-nucleus scattering: overview and some theory considerations

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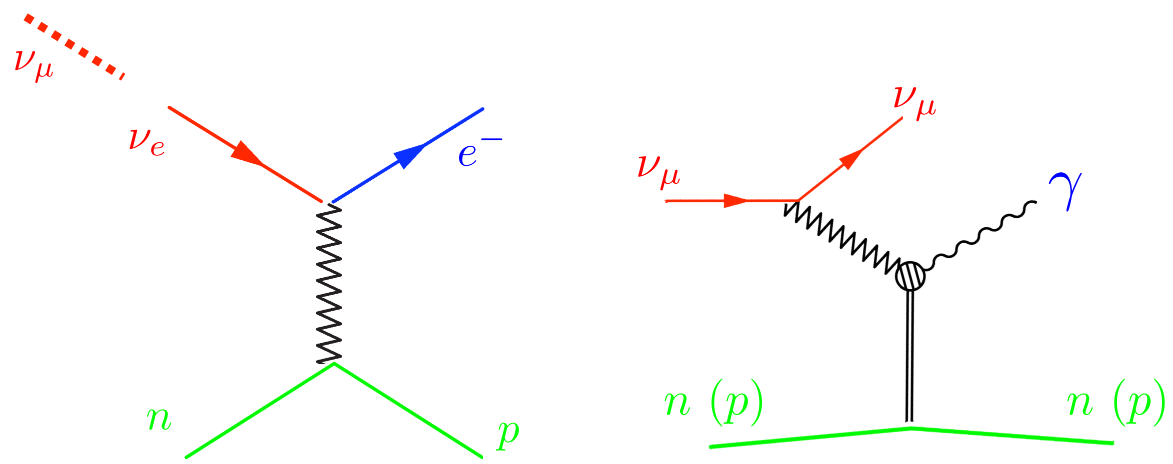
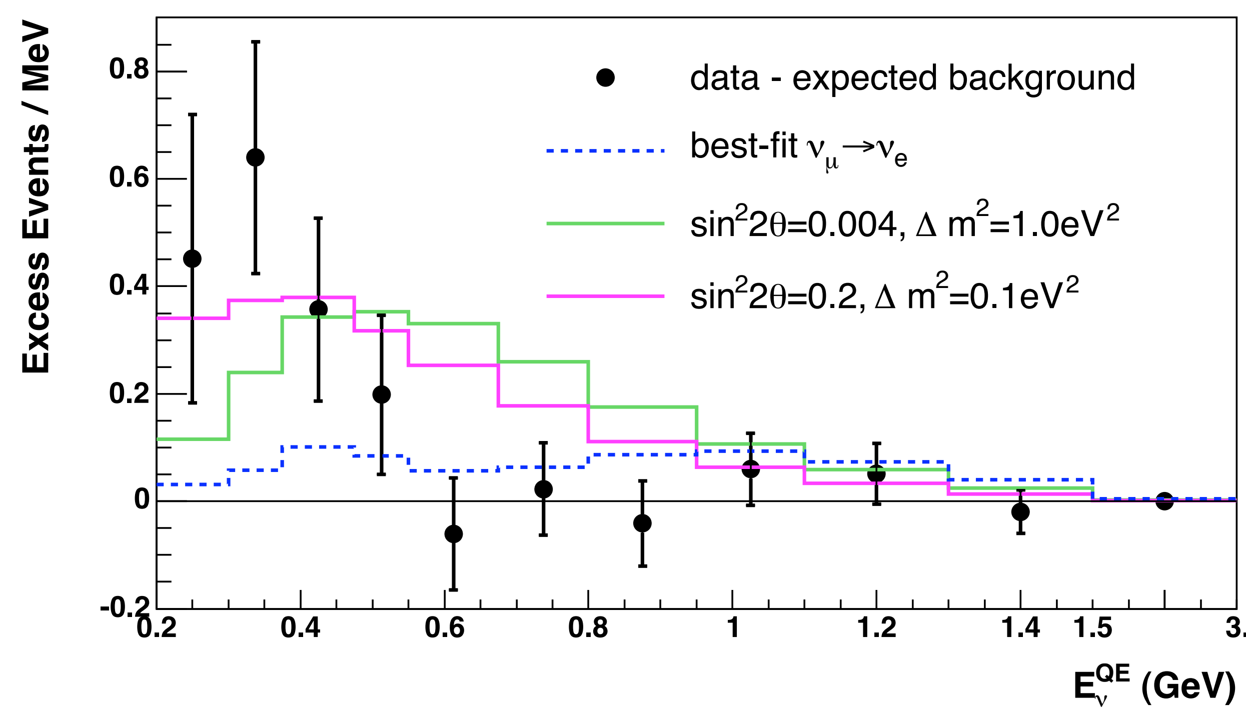
Outline

- history/introduction/motivation
- neutrino oscillation implications (sterile neutrino?)
- other new physics implications (proton decay?)
- astrophysical implications (pulsar kicks?)
- nucleon-level knowledge
- nuclear issues

Motivations

phenomenological:



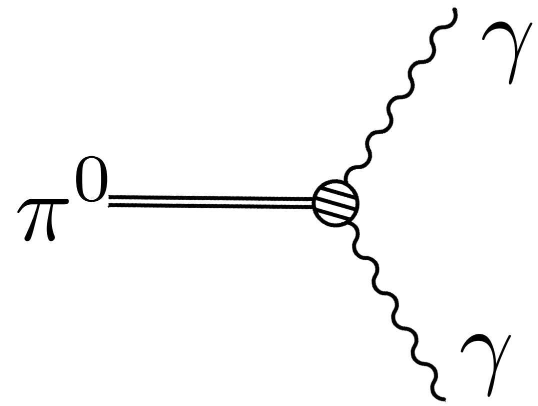


[MiniBooNE, PRL 102, 211801 (2009)]

~ irreducible background for ν_e appearance

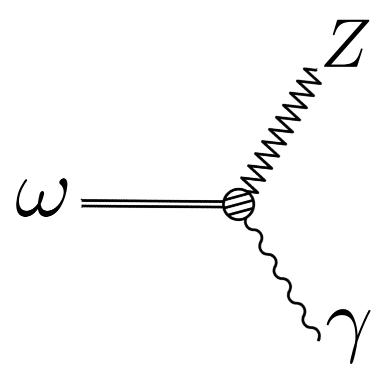
MiniBooNE(other) experiments are(will be) sensitive to this cross section *theoretical:*

Any fields coupling to anomalous symmetries must have peculiar interactions



$$\partial_\mu J_5^\mu \propto \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} \qquad \Rightarrow \qquad \mathcal{L} \sim \epsilon^{\mu\nu\rho\sigma} \pi F_{\mu\nu} F_{\rho\sigma}$$

Similarly, for any field coupled to baryon number

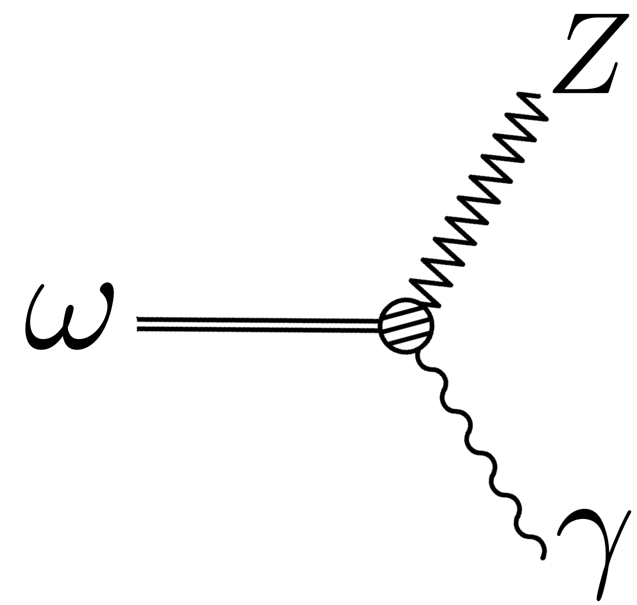


$$\partial_\mu J^\mu_{\text{baryon}} \propto \epsilon^{\mu\nu\rho\sigma} \partial_\mu Z_\nu F_{\rho\sigma} + \ldots \qquad \Rightarrow \qquad \mathcal{L} \sim \epsilon^{\mu\nu\rho\sigma} \omega_\mu Z_\nu F_{\rho\sigma}$$

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

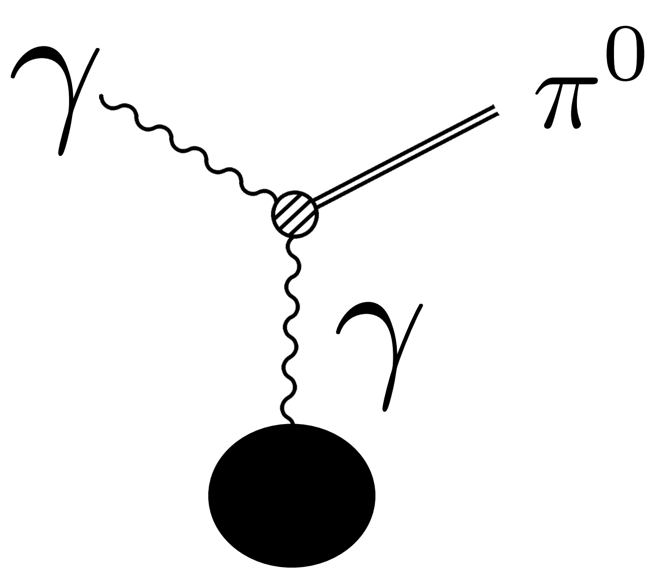
If Z was much lighter, would see e.g. $\omega \to Z\gamma$ directly.

$$\mathrm{Br}(\omega \to \gamma\nu\bar{\nu}) \sim \left(\frac{g_{\mathrm{weak}}^2}{m_W^2}\right)^2 \frac{f_\pi^6}{m_\omega^2} \sim \frac{G_F^2 f_\pi^6}{m_\omega^2} \sim \mathrm{tiny}$$

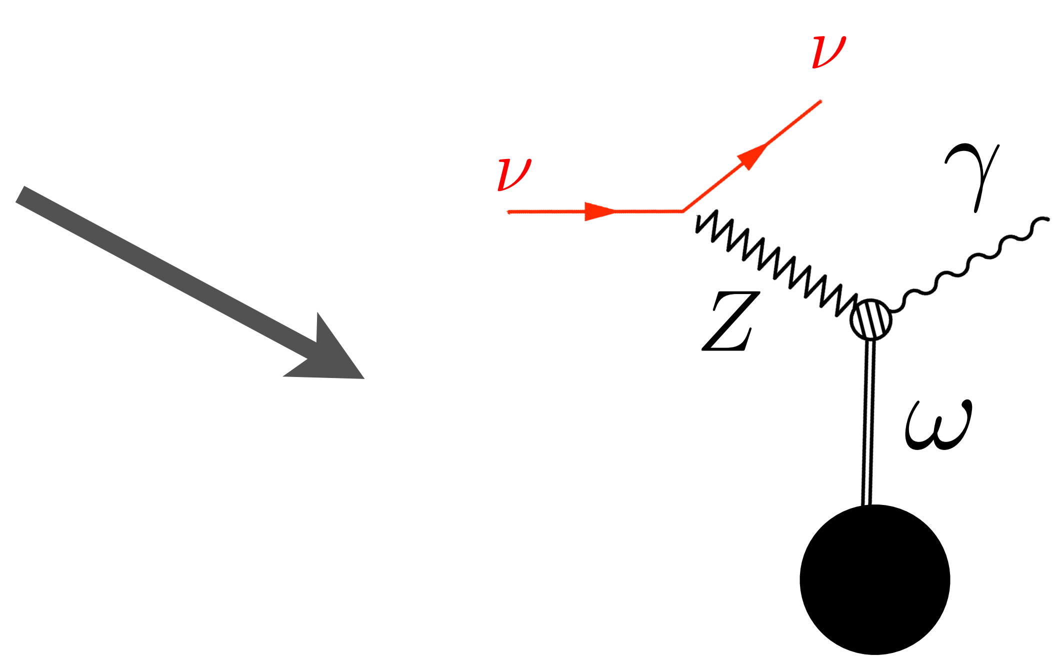


But in practice, Z is heavy (weak interactions are weak !)

Compare Primakoff effect:



scattering off electric charge

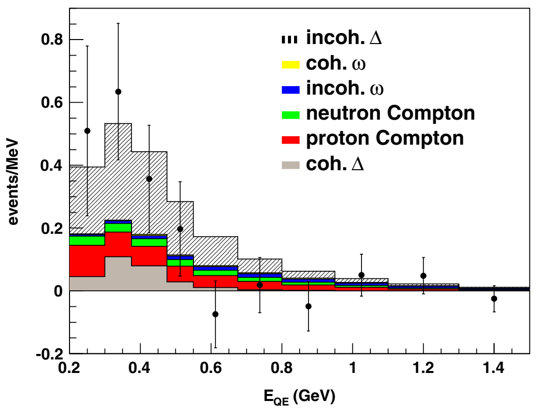


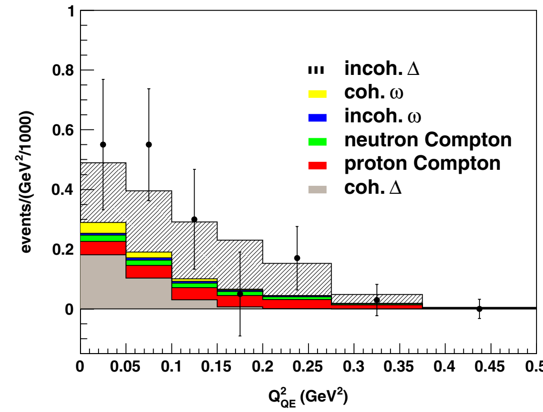
scattering off baryon number

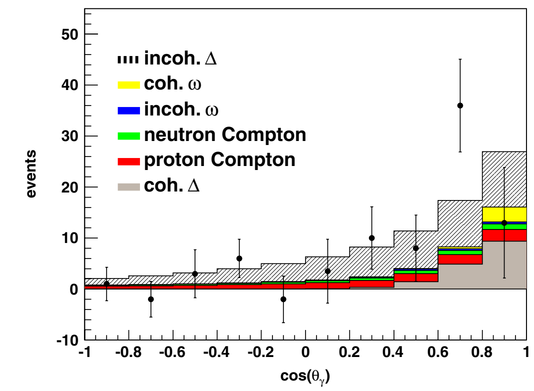
Oscillation implications

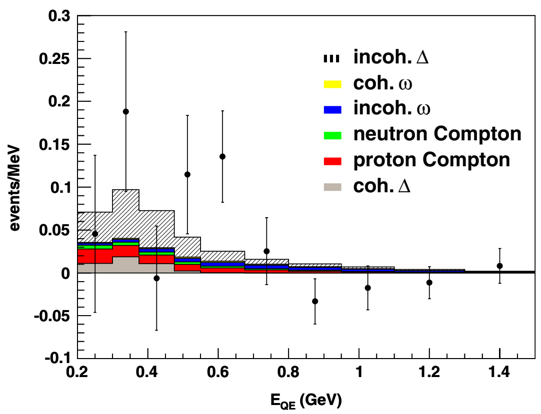
simple model for single photon production:

[RJH PRD 84, 017501 (2011)]









[MiniBooNE, PRL 102, 211801 (2009)]

[MiniBooNE, PRL 105, 181801 (2010)]

Within nucleon/nuclear/flux/reconstruction/.. uncertainties that can and should be debated:

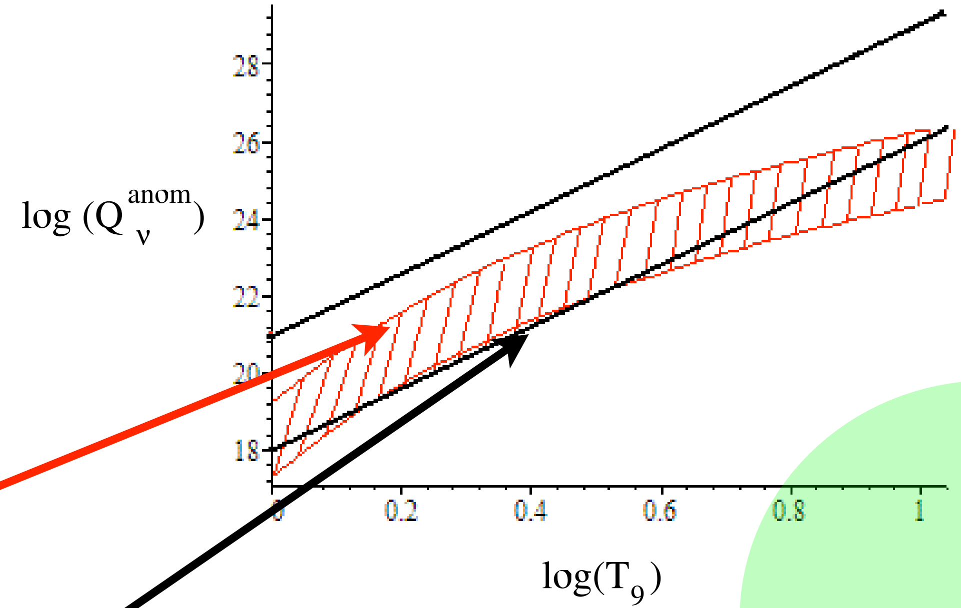
- an unmeasured background with approximate size and kinematic distribution of MiniBooNE's excess

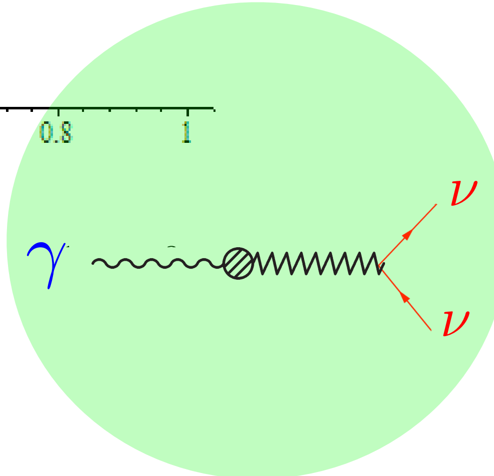
- approximate agreement between neutrino and antineutrino modes for required enhancement relative to MC

Astrophysical implications?

An enhanced coherent single-photon cross section has interesting implications

Astrophysics: mechanism for neutron star cooling





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

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

similar dynamics may play a role in pulsar kicks - large velocities of supernova remnants, generated by asymmetric neutrino emission

$$j_{pv}/j_0 \sim \alpha\beta B$$

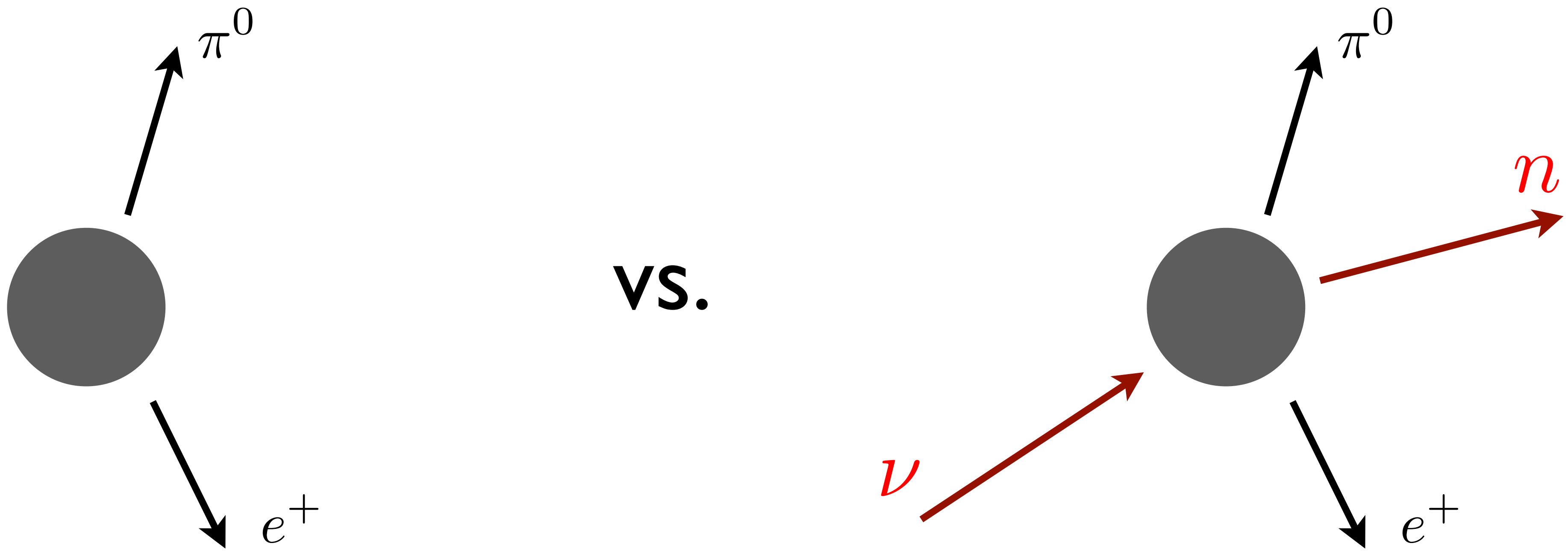
[Vilenkin ApJ 451, 700 (1995), ...]

effective electron magnetic moment (large)

contribution of electron to inverse mean free path (small)

Interaction that has both significant parity violation *and* significant contribution to scattering required to generate observed kick

Implications for proton decay



Experimental reach limited by atmospheric backgrounds

These backgrounds differ in the hadronic final state, in particular neutron content

Significant overlap with neutrino cross section problem: energy range, need to understand final state interactions

Could imagine a situation where a few signal-like events are detected, but proton decay interpretation relies on O(1) factors in predicted neutron fraction of neutrino backgrounds

Any new experimental handles are useful

Nucleon level knowledge

Why is it so #?! hard to calculate?

- what are the errors ? $\approx$ what is the expansion ?
- need to get creative: $1/N_c$, z(dispersive), 1/A(nucleus), ...
- model independent approach: decompose into helicity amplitudes. but 12 of them, depending on multiple kinematic invariants - need dynamical model/small parameter expansion

Caution is warranted. E.g., in the case of axial-vector form factor entering CCQE. Only *one* poorly constrained invariant amplitude F_A a function of only *one* kinematic variable Q^2, yet significant (~40%) cross section uncertainty

Systematic expansion at low energy:

$$\mathcal{L}^{(0)} = -c^{(0)}\bar{N}N, \qquad \mathcal{L}^{(1)} = \bar{N}[c_1^{(1)} i\not{D} - c_2^{(1)} \not{A}\gamma_5]N,$$

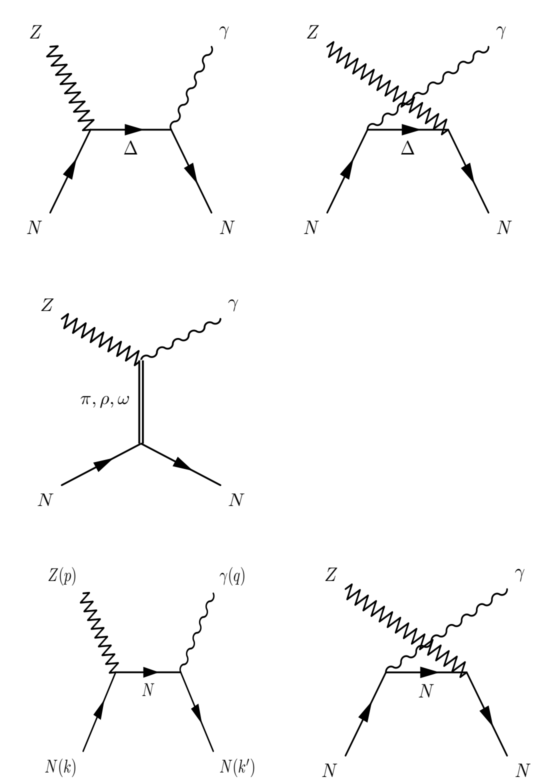
$$\mathcal{L}^{(2)} = \bar{N}\Big[-c_1^{(2)}\frac{i}{2}\sigma^{\mu\nu}\,\mathrm{Tr}([iD_\mu, iD_\nu]) - c_2^{(2)}\frac{i}{2}\sigma^{\mu\nu}\tau^a\,\mathrm{Tr}(\tau^a[iD_\mu, iD_\nu]) + \cdots\Big]N,$$

$$\begin{aligned}\mathcal{L}^{(3)} = \bar{N}[&c_1^{(3)}\gamma^\nu[iD_\mu, \mathrm{Tr}([iD^\mu, iD_\nu])] + c_2^{(3)}\gamma^\nu[iD_\mu, \tau^a\,\mathrm{Tr}(\tau^a[iD^\mu, iD_\nu])] + c_3^{(3)}\gamma^\nu\gamma_5[iD_\mu, [iD^\mu, A_\nu]] \\ &+ c_4^{(3)} i\epsilon^{\mu\nu\rho\sigma}\gamma_\sigma\,\mathrm{Tr}(\{A_\mu, [iD_\nu, iD_\rho]\}) + c_5^{(3)} i\epsilon^{\mu\nu\rho\sigma}\gamma_\sigma\tau^a\,\mathrm{Tr}(\tau^a\{A_\mu, [iD_\nu, iD_\rho]\}) + c_6^{(3)}\gamma^\nu\gamma_5[[iD_\mu, iD_\nu], A^\mu] \\ &+ c_7^{(3)}\frac{1}{4m_N^2}\gamma^\nu\gamma_5\{[[iD_\mu, iD_\nu], A_\rho], \{iD^\mu, iD^\rho\}\} + \cdots]N.\end{aligned}$$

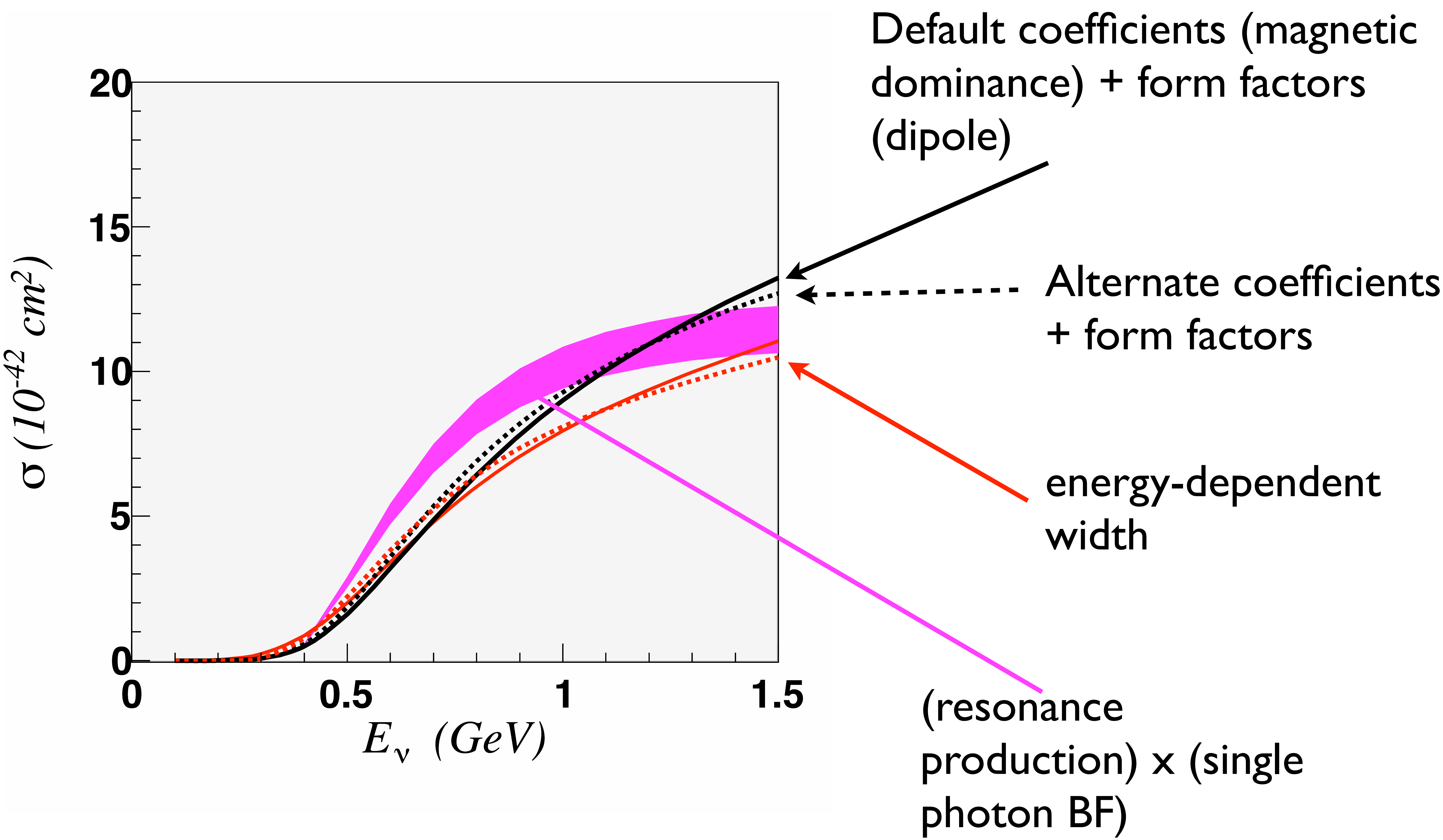
coherent coupling of vector+axial-vector fields to baryons

Expansion breaks down at energies of order f_π ~ 100 MeV

⇒ model by resonance insertions ("sticking in form factors") or dispersive analysis to relate invariant amplitudes to observables



illustrative variations for Delta resonance modeling



Nuclear issues

Why is it so #?! hard to calculate?

- nuclear cross sections at 1 GeV (#?!)
- must translate nucleon-level amplitudes to nuclear cross sections
- final state interactions: O(1) factors relating nucleon-level ratio of pi0/gamma to nuclear-level
- experimental handles in electron scattering?

Dipping a toe into the nuclear realm...

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

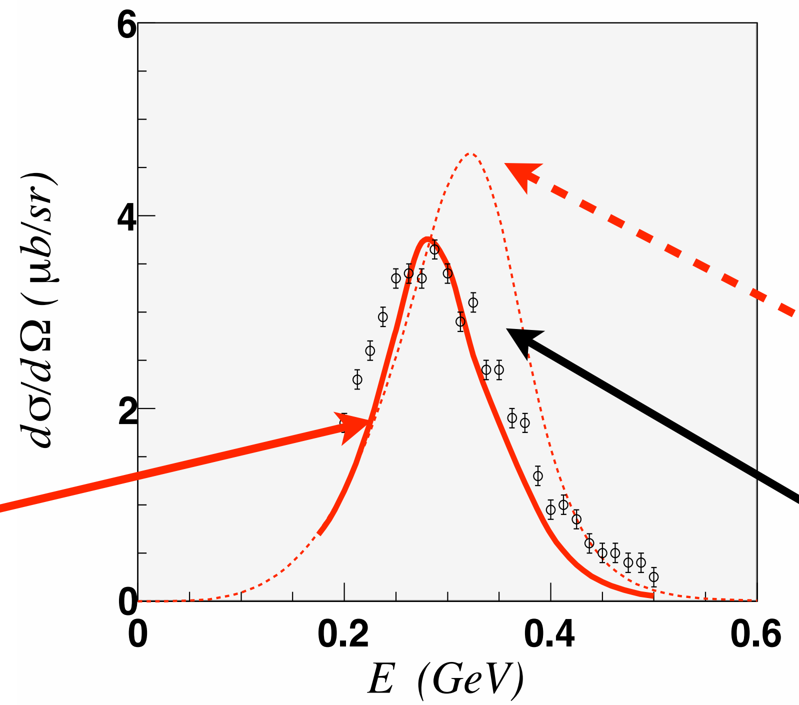
$$\Gamma_\Delta \sim \Gamma_0 (p_\Delta / p_0)^3$$

$$m_\Delta \rightarrow m_\Delta + \delta\Sigma$$

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

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

Drechsel et.al. NPA, 660, 423.



energy-dependent width & model for in-medium effects

energy-independent width (simplest model)

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

Peak height somewhat reduced, position shifted.

Gross features unchanged.

Single photon production in ν-N overview

- ~irreducible background to ν_e appearance searches: must be directly measured (cf. Katori's talk)
- other motivations to measure and constrain neutron content in neutrino nucleus scattering: e.g., important background for proton decay
- potentially interesting astrophysical implications of an enhanced neutral current interaction in presence of e.m. fields and baryons
- difficulties at both nucleon and nuclear levels
- nucleon level: invariant amplitude decomposition and hadronic modeling (cf. talks of Zhang, Nieves and Ruso)
- nuclear level: final state interactions significantly affect pi0/gamma ratio emerging from nucleon-level interactions

- the stakes are large: important backgrounds for sterile neutrinos, proton decay, potential astrophysical implications within SM
- requires dedicated efforts at particle, nucleon, nuclear, detector levels