# Low Energy Analysis of $\nu N \to \nu N \gamma$

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# Outline

- theoretical significance of neutrino-photon-baryon interactions
- chiral lagrangian and extrapolation
- some fits to MiniBooNE data

*RJH: arXiv: 0905.0291*

*Harvey, Hill & Hill Phys.Rev.Lett..99, 261601 (2007); Phys.Rev. D77, 085017 (2008)*

# Single photon emission in neutrino-nucleus collisions probe interesting physics

*baryon anomaly.* anomaly in baryon current in presence of $SU(2)_L \times U(1)_Y \Rightarrow$ interactions like

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

*Harvey, Hill & Hill 2007*

( like anomaly in axial current in the presence of $U(1)_{EM} \Rightarrow \pi_0 \rightarrow \gamma\gamma$ )

*skyrmion excitations.* proximity of Δ resonance leads to interesting effects: coherent-resonant phenomena, nuclear superradiance,...

*Important background to* $\nu_e$ *appearance experiments.*

*Applications beyond laboratory neutrino experiments*

- parity violation (anapole moment at finite baryon density)
- astrophysics (neutron star cooling, supernova dynamics)
- axion interactions

## Disentangling multiple effects requires systematic description

⇒ chiral lagrangian at low energy

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

## Some unfinished business in the baryon chiral lagrangian

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

*Gasser, Sainio and Svarc, 1988*

## Need full $SU(2)_L x U(1)_Y$ in $SU(2)_L x SU(2)_R x U(1)_V$

$$\psi_L \rightarrow e^{i\epsilon_L}\psi_L \qquad U(x) = \xi(x)^2 \quad \xi \rightarrow e^{i\epsilon_L}\xi e^{-i\epsilon'} = e^{i\epsilon'}\xi e^{-i\epsilon_R}$$

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

Represent nucleons as isodoublet spinor field, must have peculiar transformation under full $SU(2)_L x SU(2)_R x U(1)_V$

$$\mathrm{N} = \begin{pmatrix} p \\ n \end{pmatrix} \qquad N \rightarrow e^{i\epsilon'_{\mathrm{isovector}} + 3i\epsilon'_{\mathrm{isoscalar}}} N$$

# Working order by order:

5

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

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mass

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

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$$+ c_4^{(3)} \gamma^\nu \gamma_5 [[iD_\mu \, , iD_\nu] \, , A^\mu] + c_5^{(3)} \gamma^\nu \gamma_5 \big\{[[iD_\mu \, , iD_\nu] \, , A_\rho], \{D^\mu \, , D^\rho\}\big\} + \ldots \big] N$$

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(vanishes for neutral fields)

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vector form factor correction: $m_V^2$

axial-vector form factor correction: $m_A^2$

(vanishes for neutral fields)

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vector form factor correction: $m_V^2$

(vanishes for neutral fields)

axial-vector form factor correction: $m_A^2$

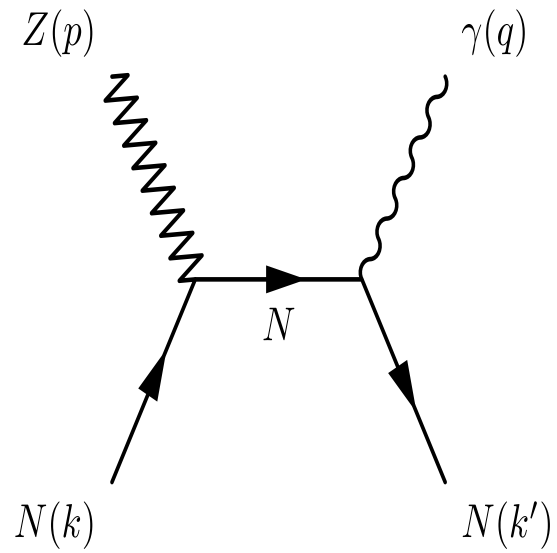
interesting !

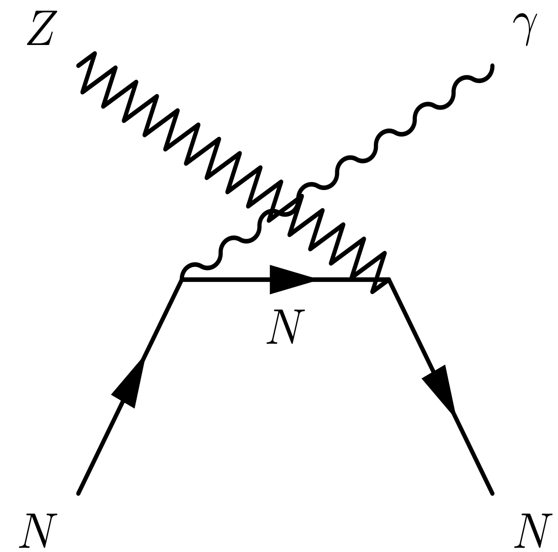
(coherent coupling of baryon, photon, axial weak)

# Phenomenology

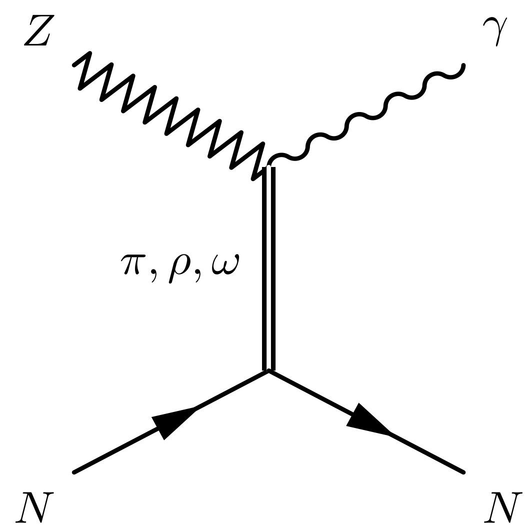
- unfortunately, convergence of the chiral lagrangian is poor for energies above a few hundred MeV
- $E_\nu \sim$ GeV not a great regime for precise calculation, but can perform phenomenological extrapolation to moderate energy
- include dominant resonances in each channel
- nuclear effects: Fermi motion, Pauli blocking - not dominant effects, but should be systematically included; in-medium modifications - can compare to e.g. Compton scattering (won't discuss here)
- have to get our hands dirty to say something useful ...

# Include ground state and leading resonances in each channel



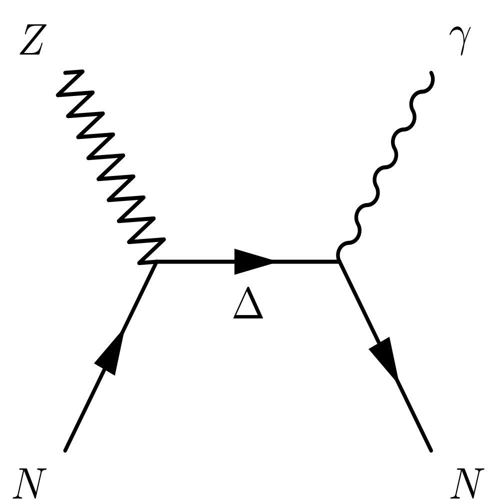

at low E, match onto same (interesting) operator

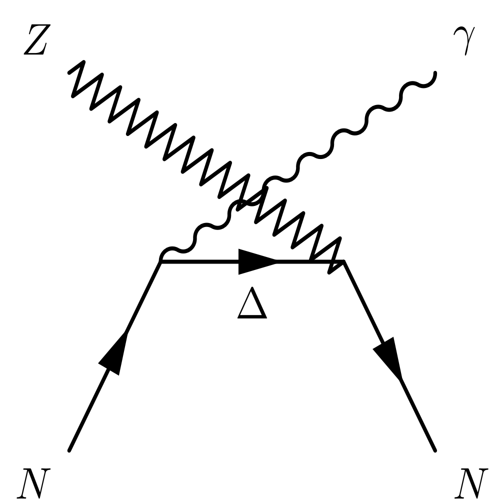



$$\rho : \; 1/N_c^2 \sim 1/9$$

$$\pi : \; (1 - 2s_W^2) - 2s_W^2 \ll 1$$

*Goldman and J. Jenkins 0906.0984*

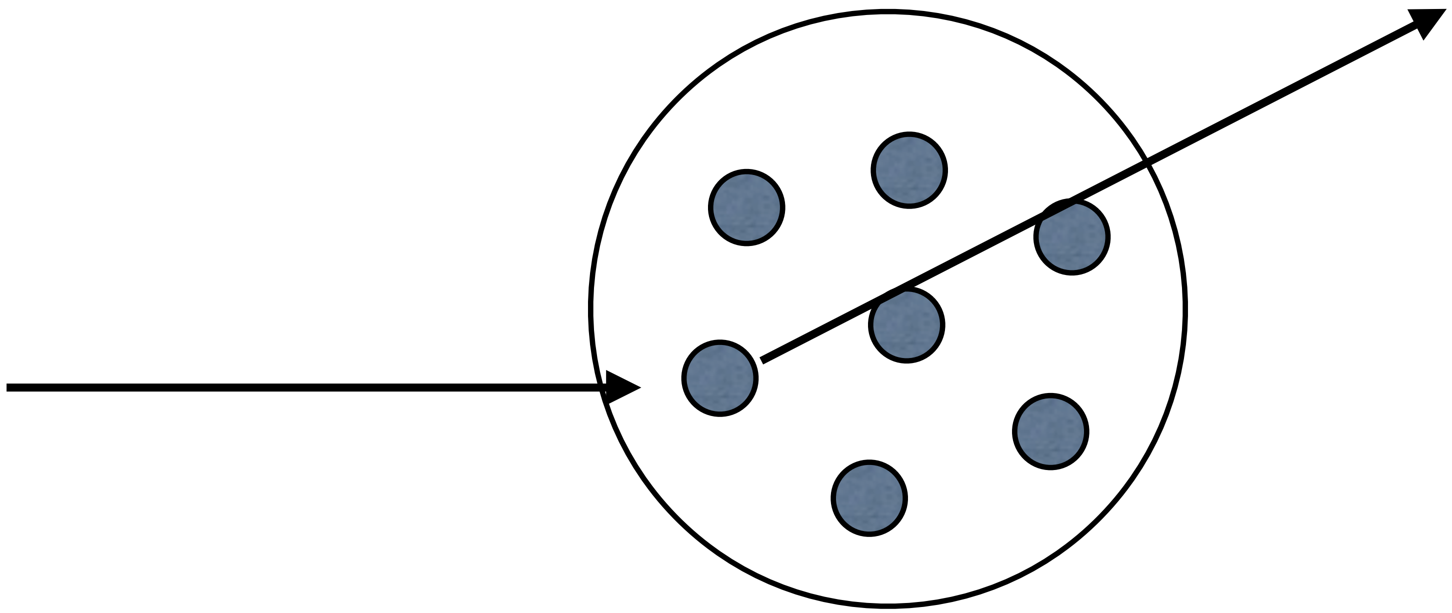



$$\mathrm{m}_\Delta - m_N \sim 1/N_c$$

Scattering on nucleus, can have both incoherent process (ejected nucleon) and coherent process (intact nucleus)

$$Q^2 \lesssim 1/\langle r^2 \rangle \sim A^{-2/3}$$



At small momentum transfer, amplitudes add, $d\sigma \sim A^2$

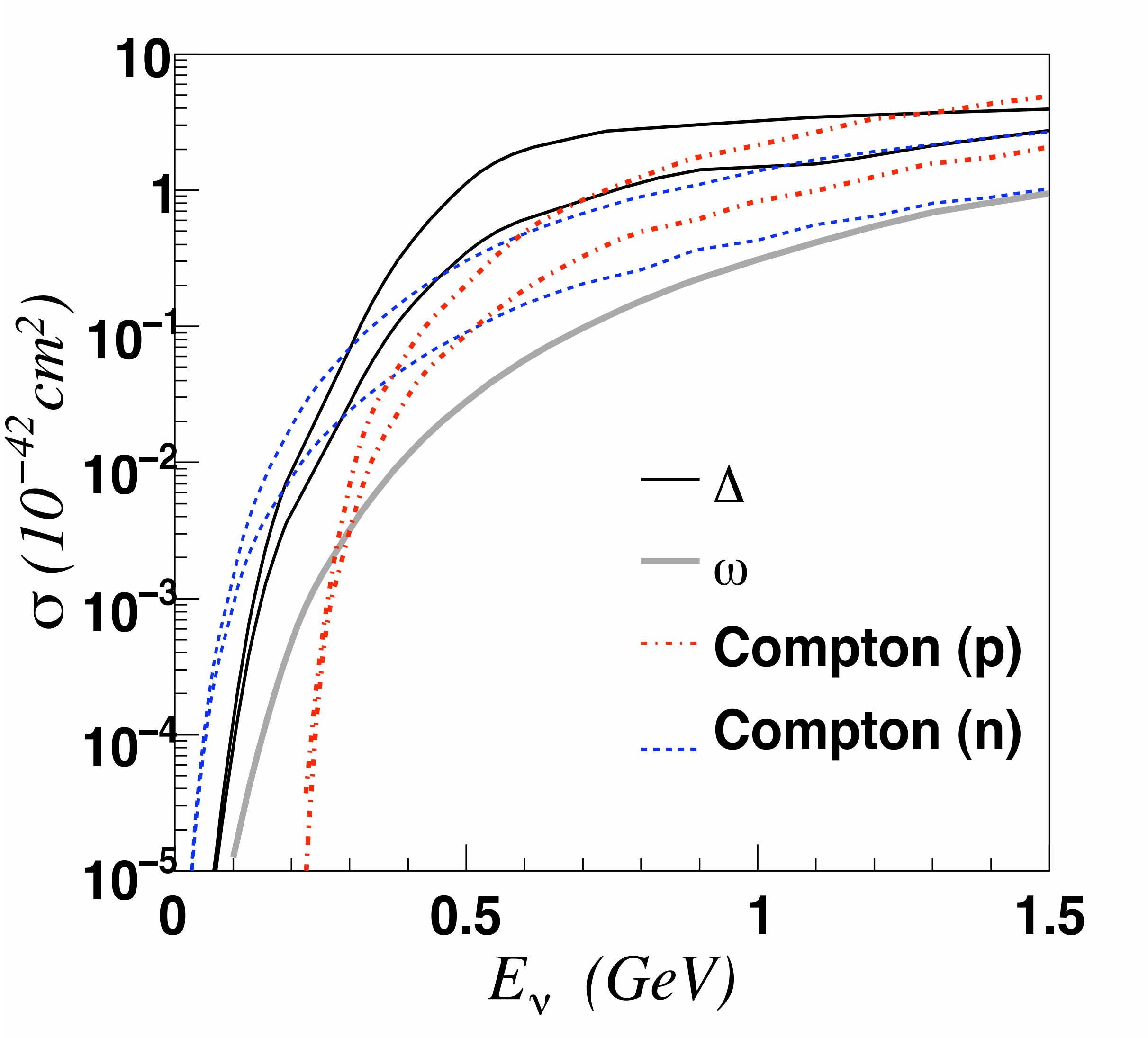
Nontrivial constraints on phase space, can analyze in limit of large nucleus: $A^{1/3}E \to \infty$

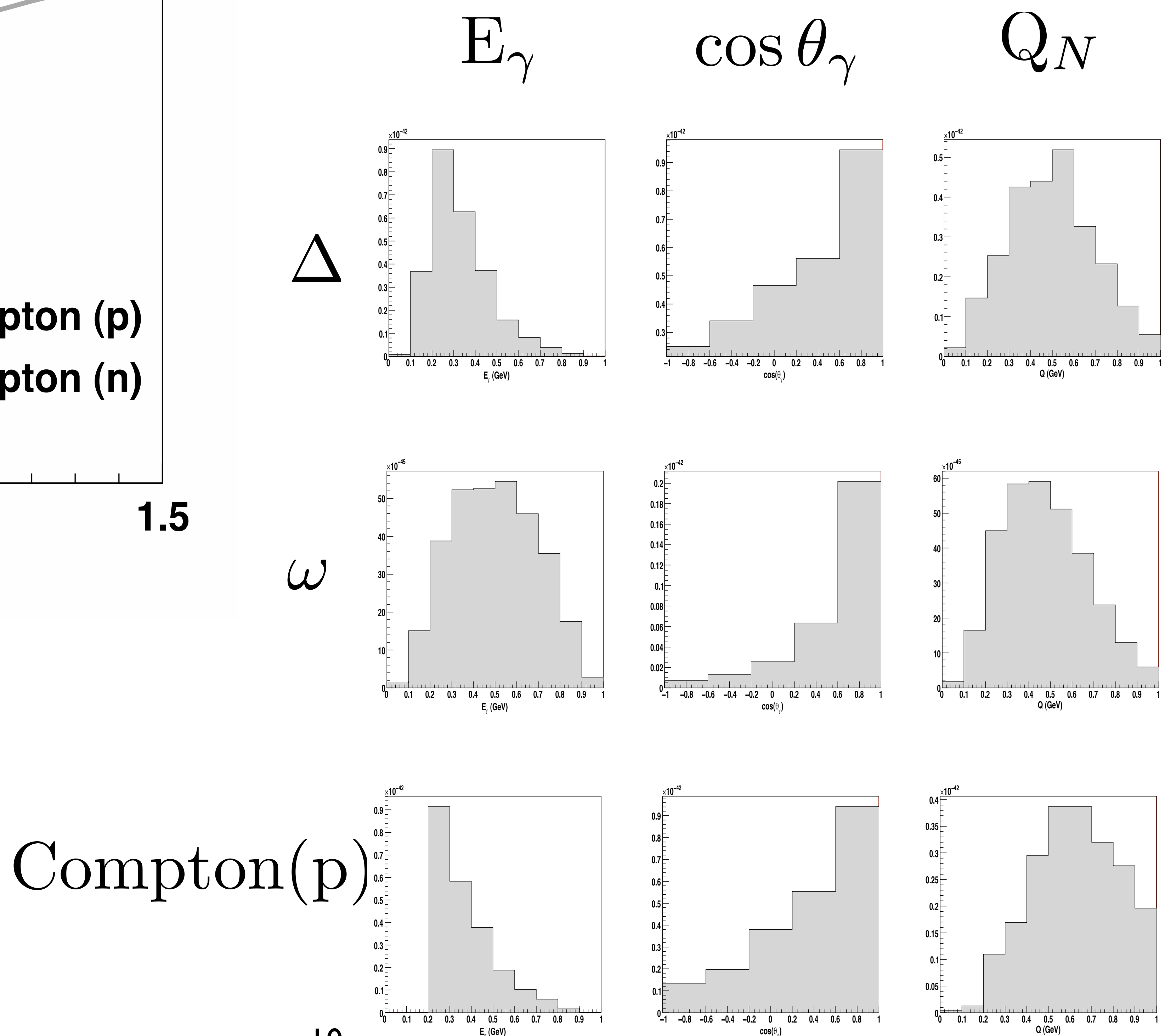
$$d\sigma_\Delta / d\cos\theta \sim A^{4/3}(1-\cos^2\theta)$$
$$d\sigma_\omega / d\cos\theta \sim A^{2/3}E^2\delta(\cos\theta)$$
$$d\sigma_{\text{Compton}} / d\cos\theta \sim A^{4/3}E^2\log(E/E_{\text{min}})$$

# Why is it so #?! hard to calculate?

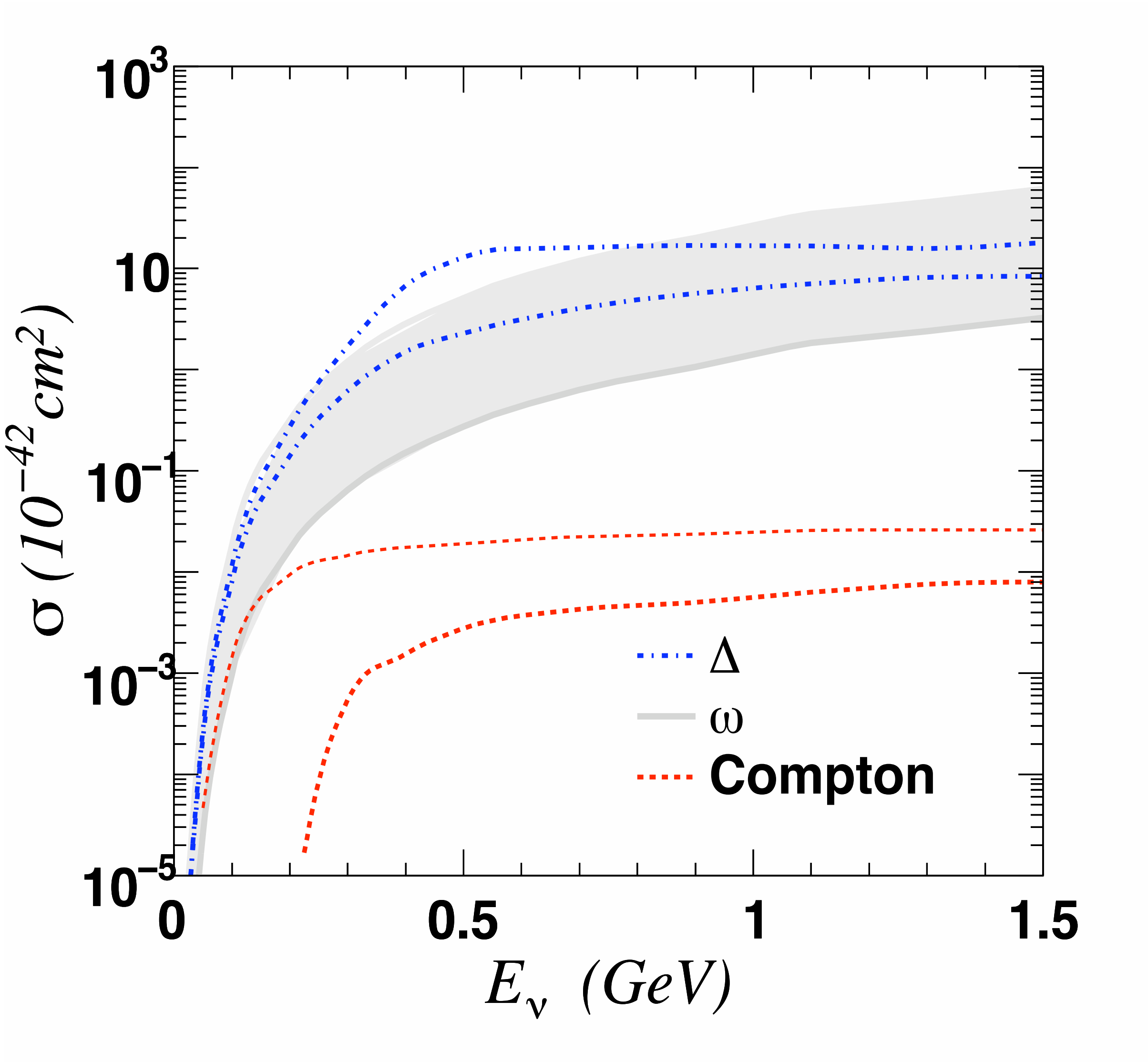
- what are the errors ? $\approx$ what is the expansion ?
- need to get creative: $1/N_c$, z(dispersive), 1/A(nucleus), ...
- without support from data, errors to tree-level meson exchange are "$1/N_c$" ~ 30% if all relevant states are considered ( large energy $\Rightarrow$ need more states)
- model independent approach: decompose into helicity amplitudes. but 12 of them, depending on multiple kinematic invariants - need dynamical model/small parameter expansion

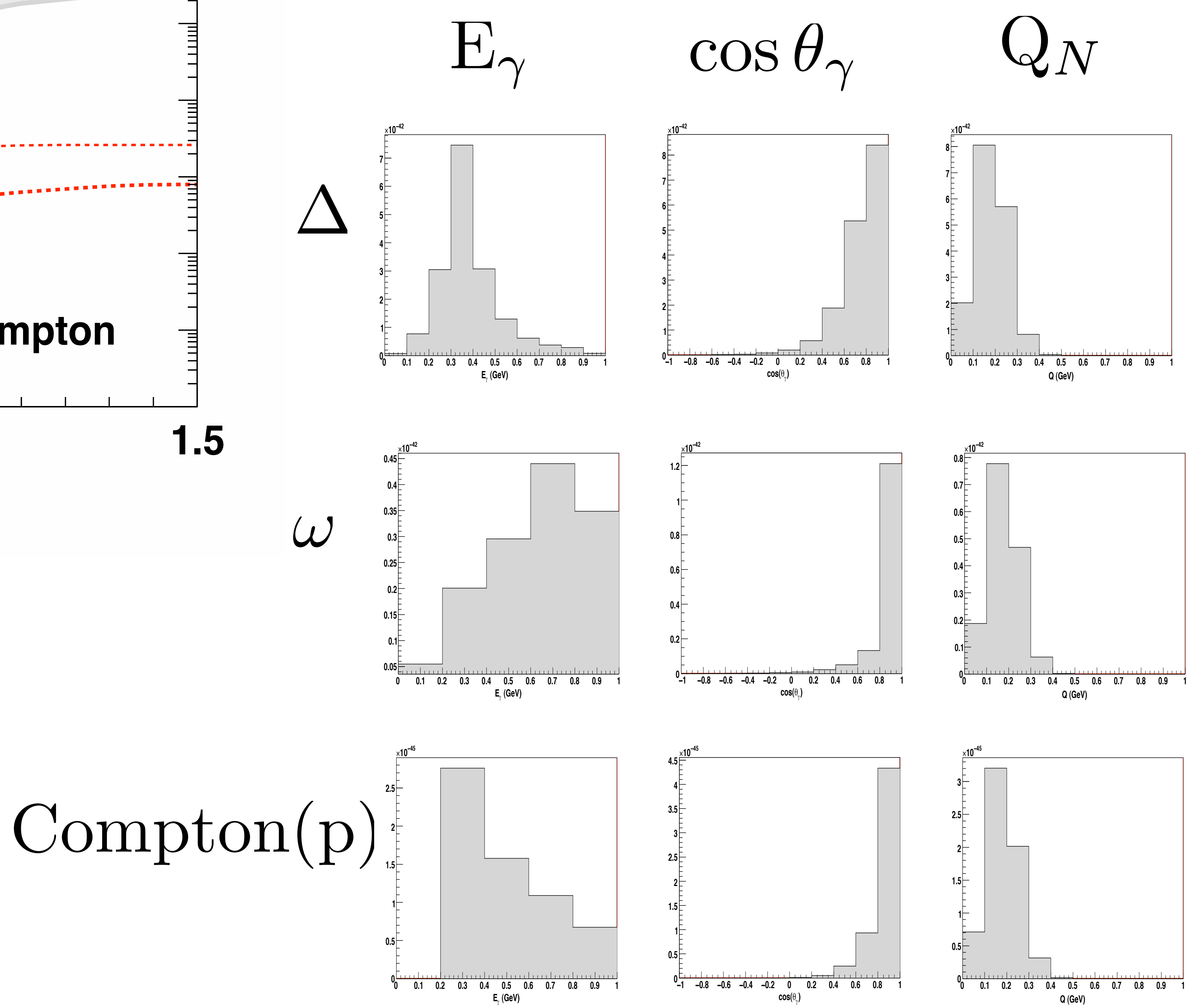
# Single nucleon (incoherent) cross sections

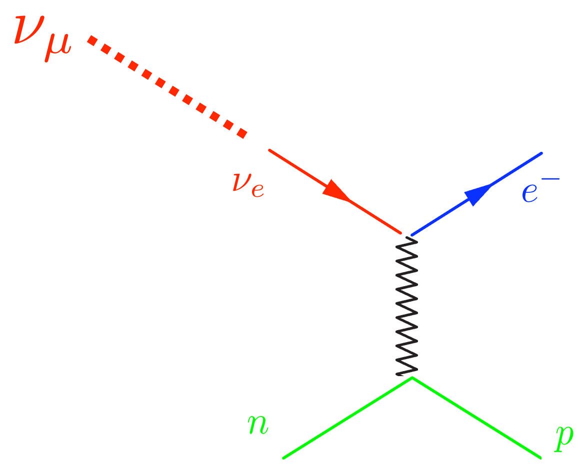


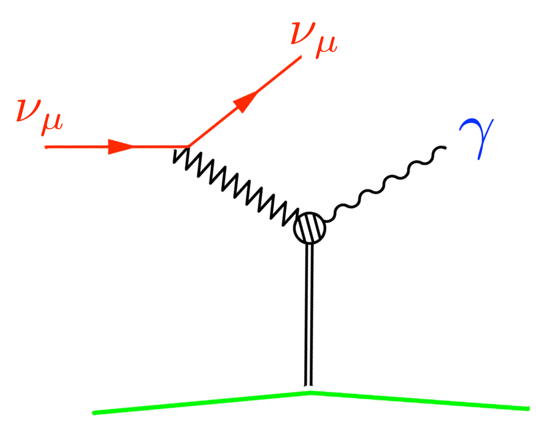



# Coherent cross sections ($^{12}C$)



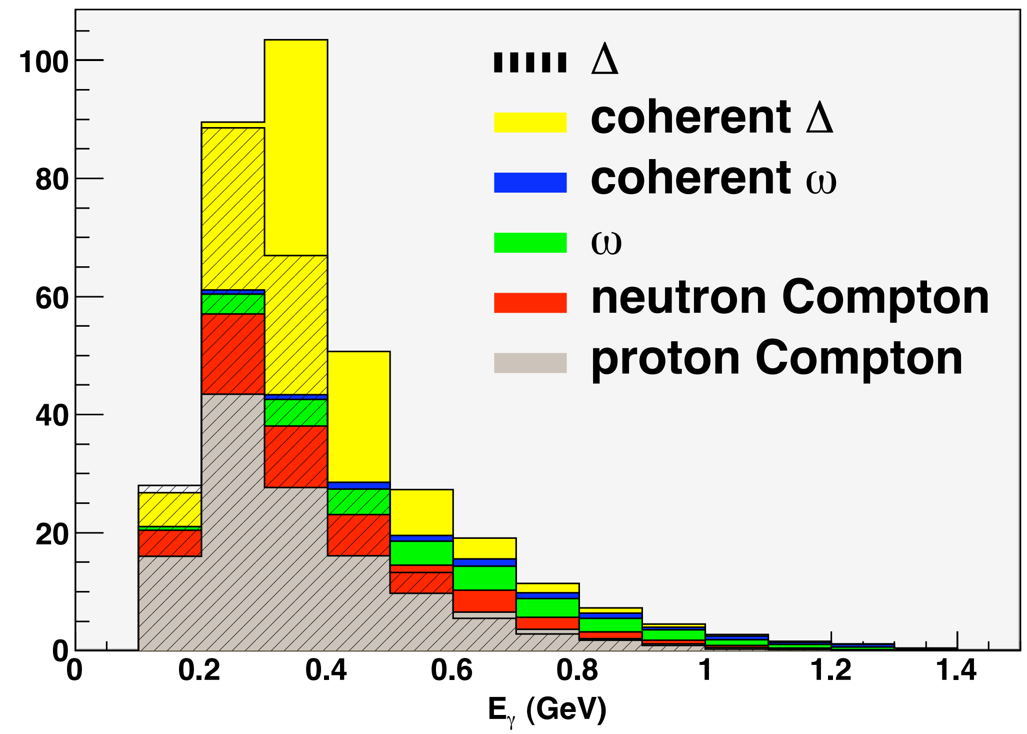


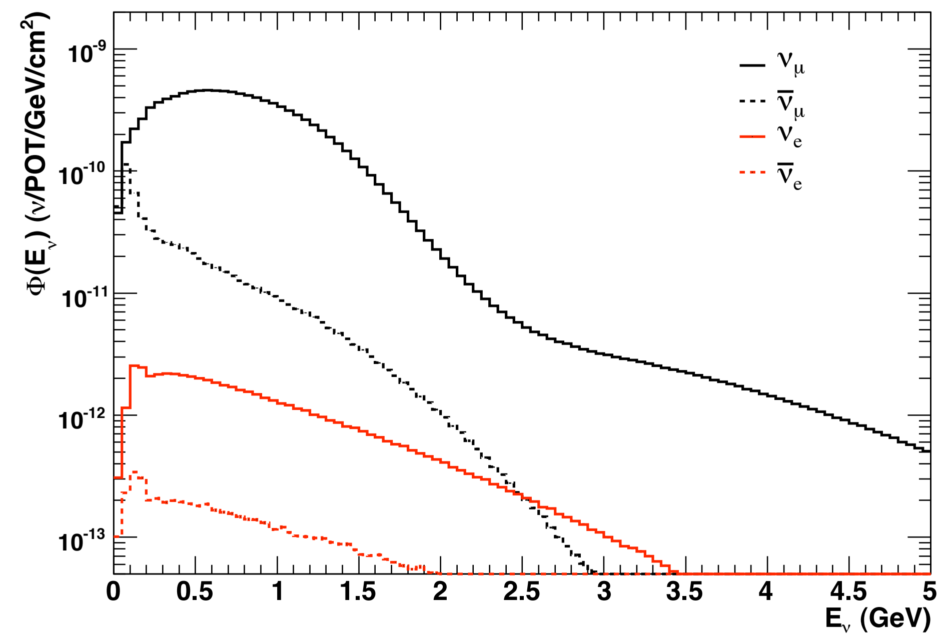

- MiniBooNE has presented a careful analysis of electron-like events in beams of primarily muon neutrinos / antineutrinos
- Interesting to compare this data, and apparent excess at low energy, with predictions of new single-photon events
- Potential background at other $\nu_e$ appearance experiments (higher energy not a focus of this talk - requires further theory)
- Preliminary results:

# flux averaging (MiniBooNE ν mode)

6.46e20 POT

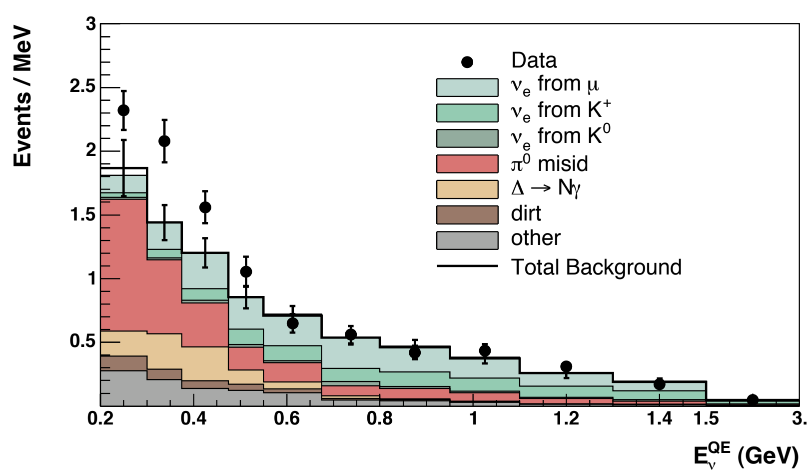



⇐

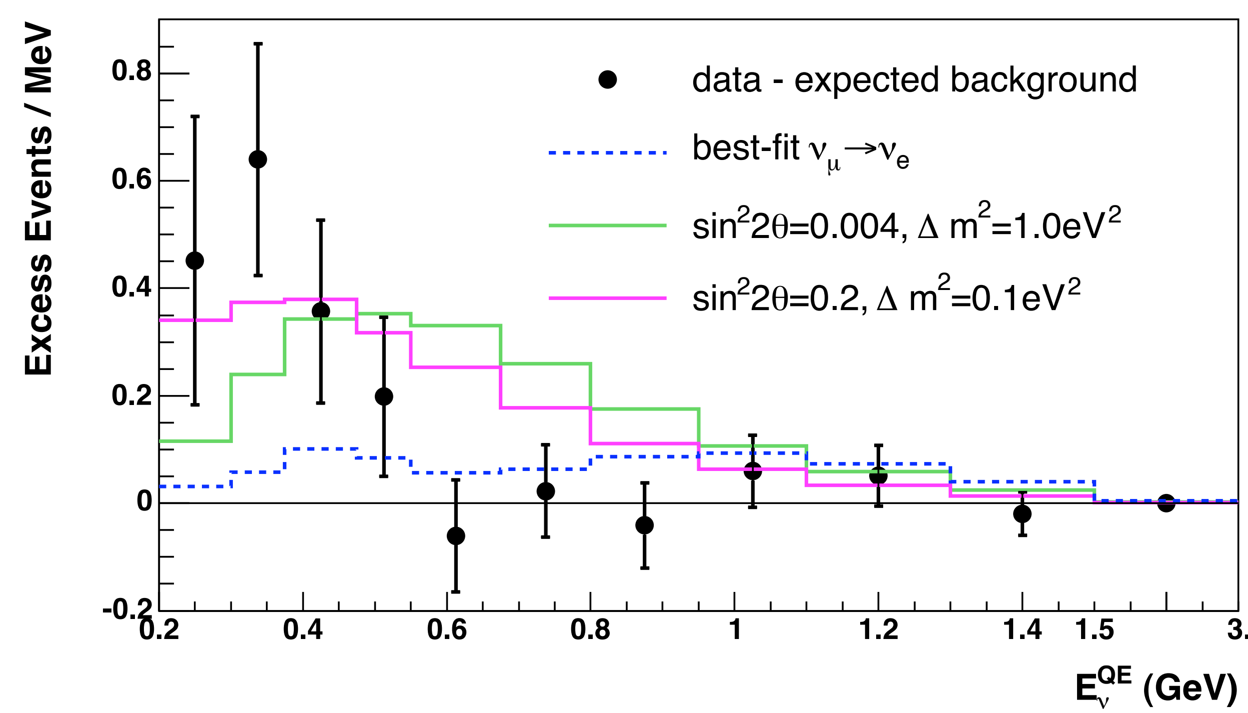



*[MiniBooNE, Phys. Rev. D 79, 072002 (2009)]*

$$E_\nu^{QE} \approx E_{\rm vis}/[1-(E_{\rm vis}/m_N)(1-\cos\theta)]$$




*[MiniBooNE, PRL 102, 211801 (2009)]*

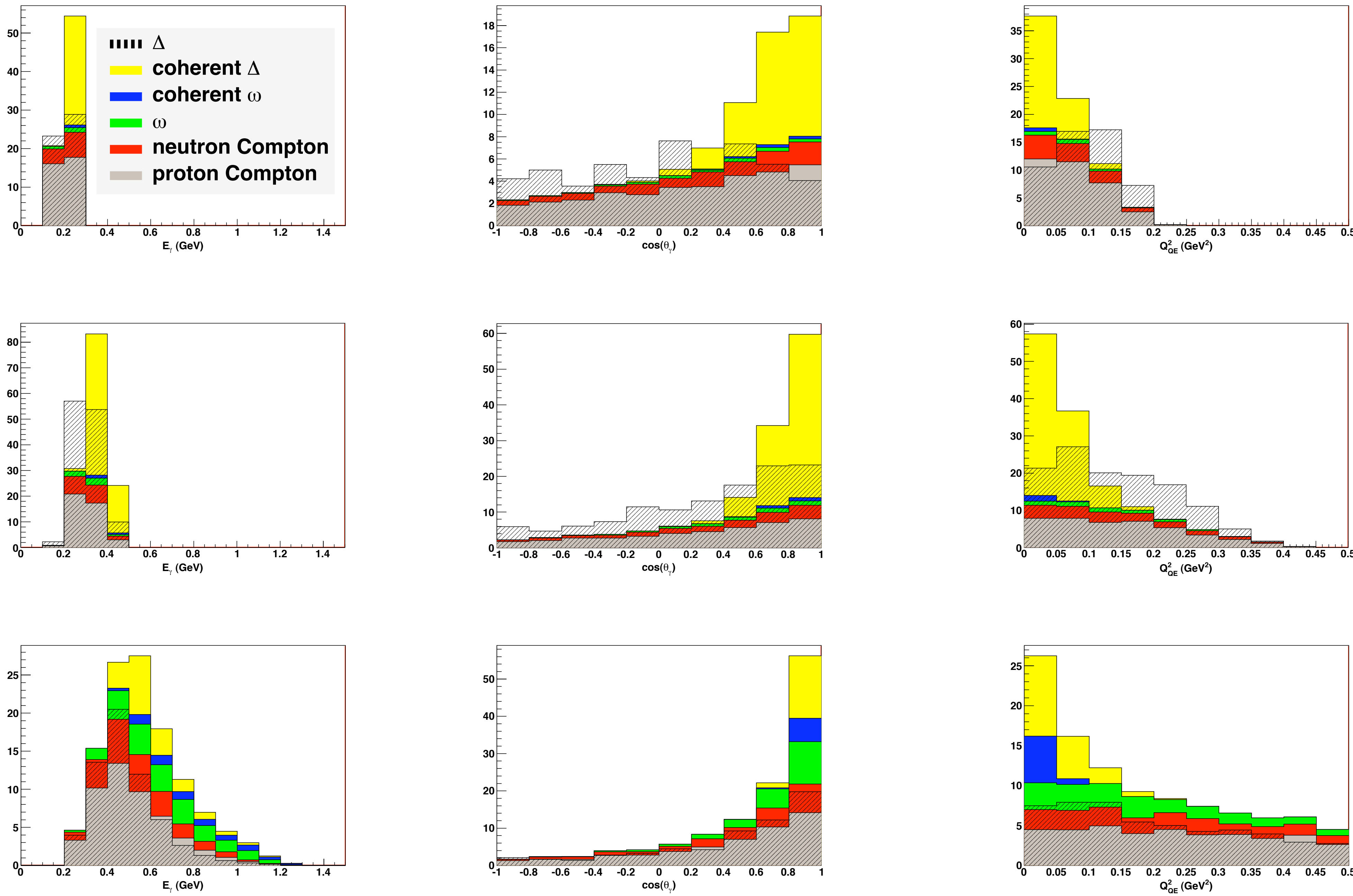


# flux averaged distributions (MiniBooNE ν mode)

200-300 MeV

300-475

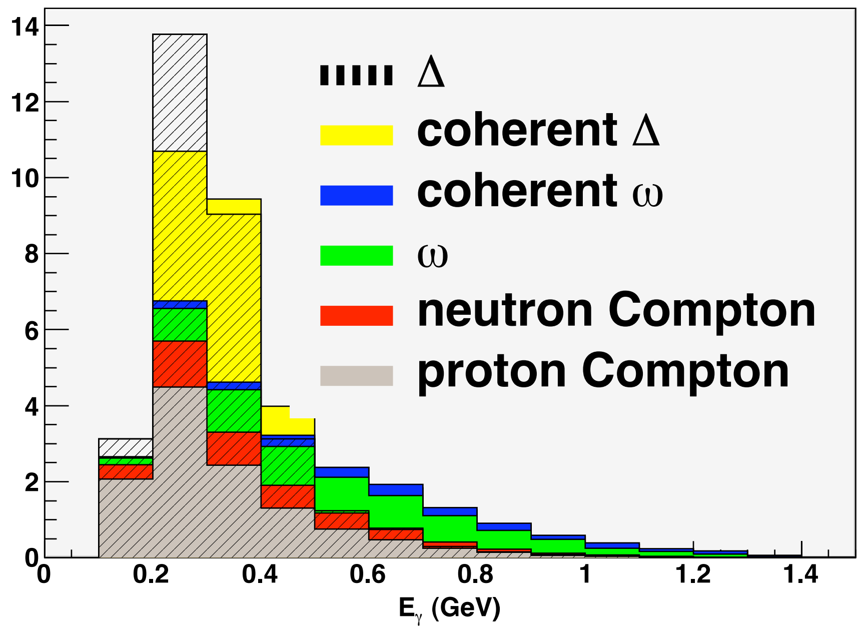
475-1250




$$(\mathrm{Q}^2)^{QE} \approx 2E_\nu^{QE} E_{\mathrm{vis}}(1 - \cos\theta)$$

# flux averaging (MiniBooNE ν-bar mode)

3.39e20 POT

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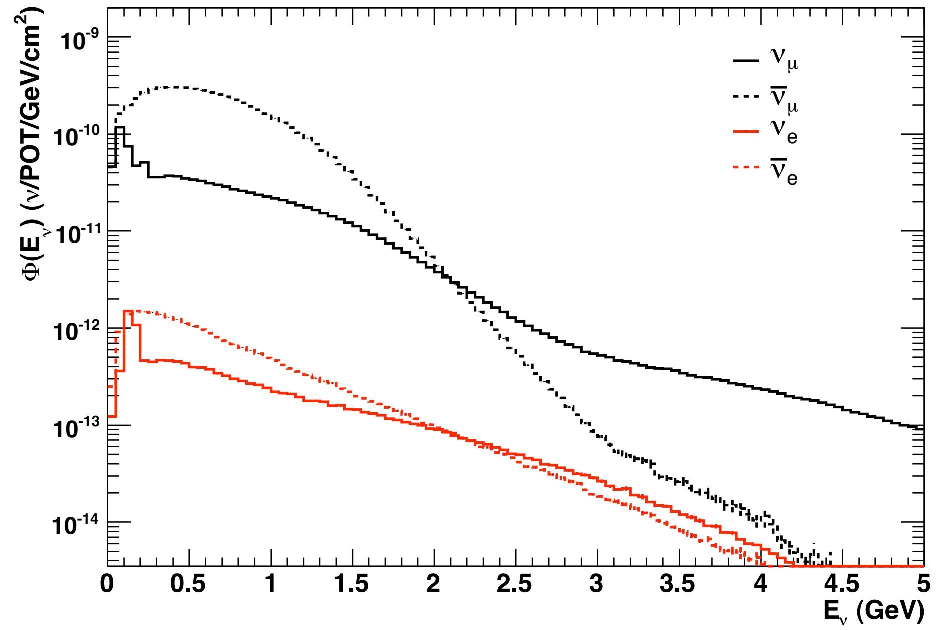
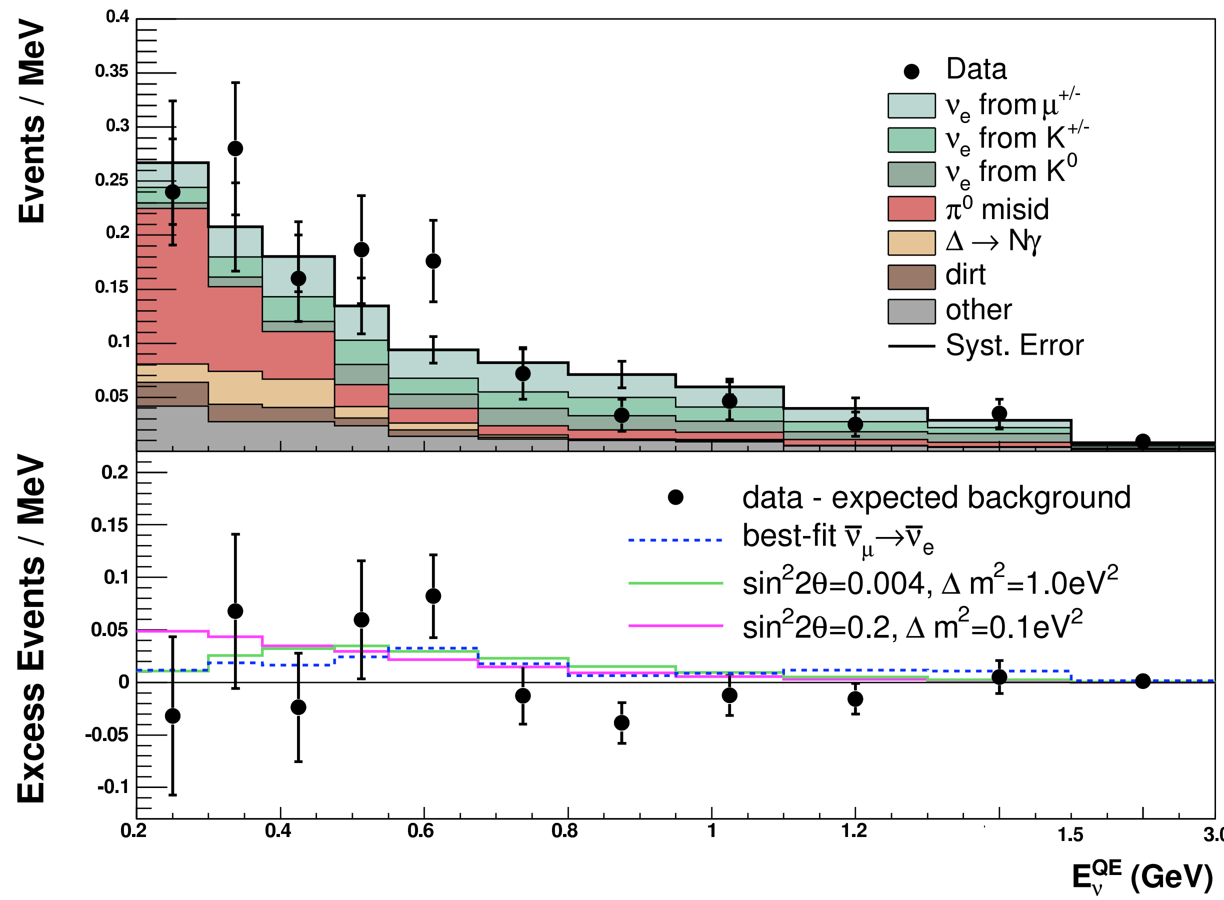



*[MiniBooNE, Phys. Rev. D 79, 072002 (2009)]*




*[MiniBooNE, arXiv:0904.1958]*

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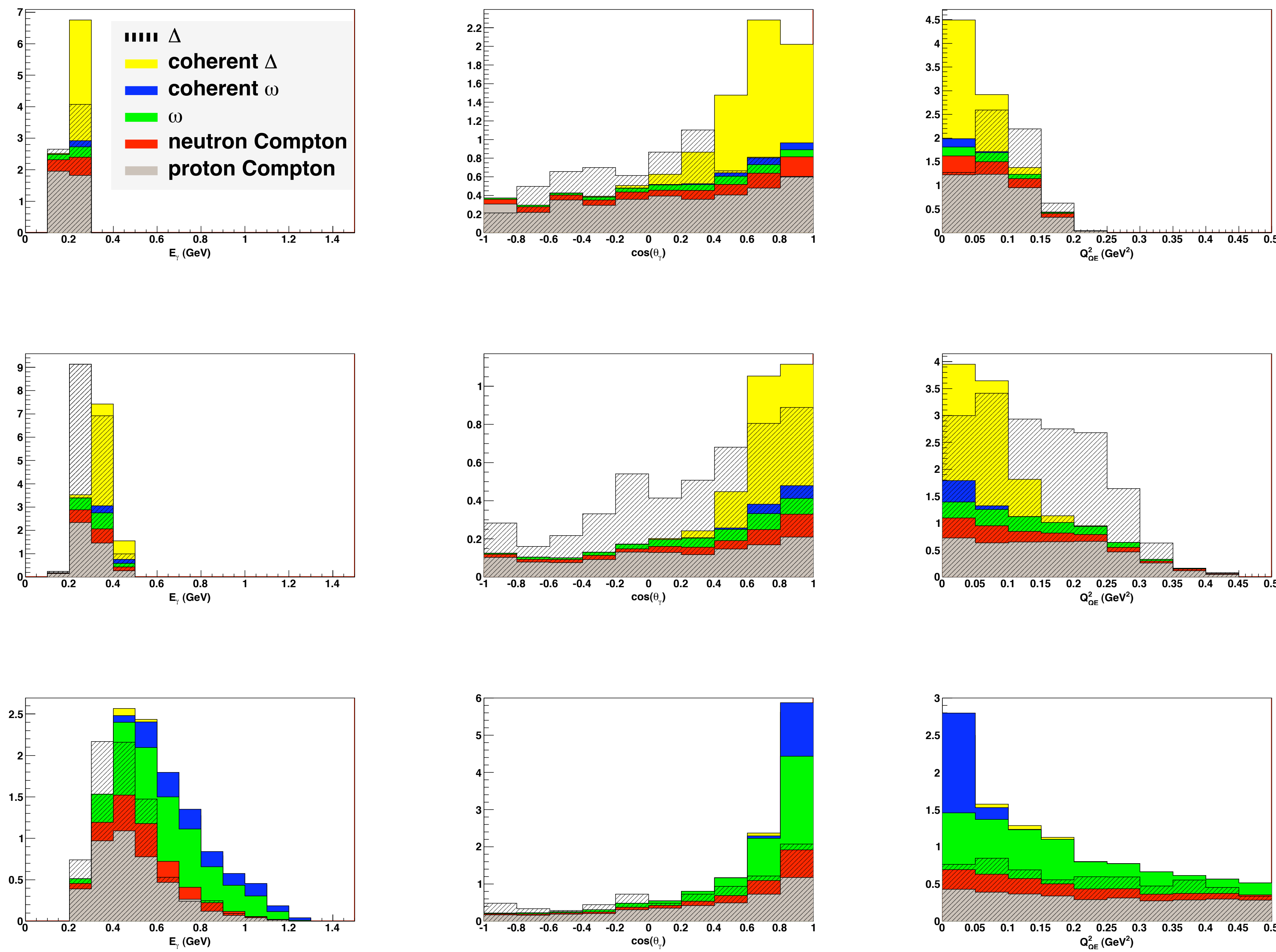


ν

| | new events | excess | Δ-direct | Δ (MB) |
|---|---|---|---|---|
| 200-300 MeV | 75 [23] | 45(26) | 52 [16] | 20 |
| 300-475 | 139 [42] | 84(25) | 123 [37] | 48 |
| 475-1250 | 119 [36] | 22(36) | 61 [18] | 19 |

$\chi^2$ = 1.5/2 d.o.f. (scale = 0.51),

$\chi^2$ = 3.8/3 d.o.f. (scale = 0.3),

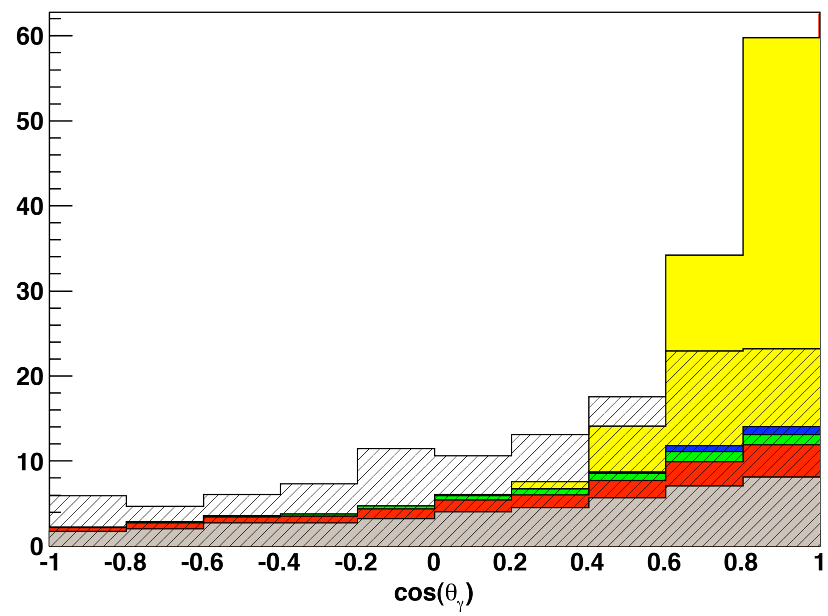
ν-bar

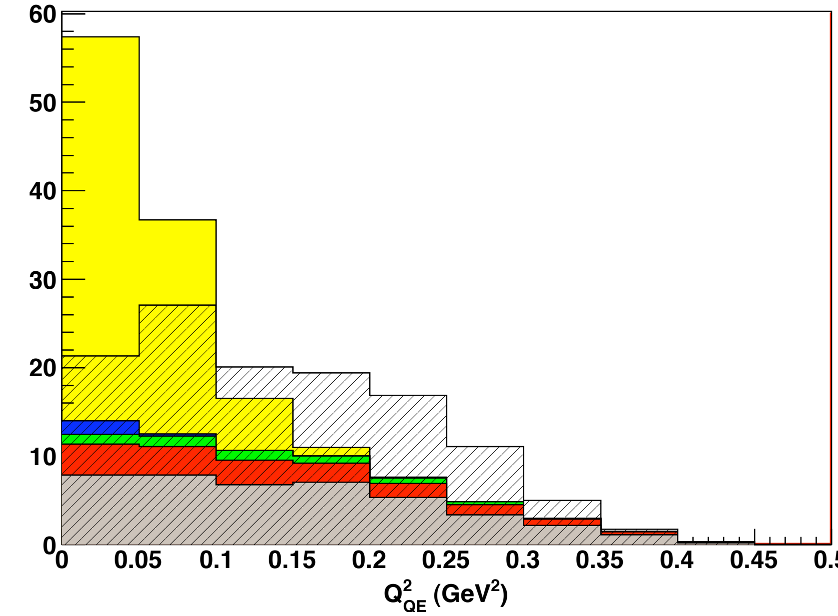
| | | | | |
|---|---|---|---|---|
| 200-300 MeV | 9.3 [2.8] | -0.5(11.7) | 6.7 [2.0] | 1.7 |
| 300-475 | 13 [3.8] | | 17.3 [5.2] | 4.9 |
| 475-1250 | 12 [3.6] | 3.2(10.0) | 7.7 [2.3] | 2.0 |

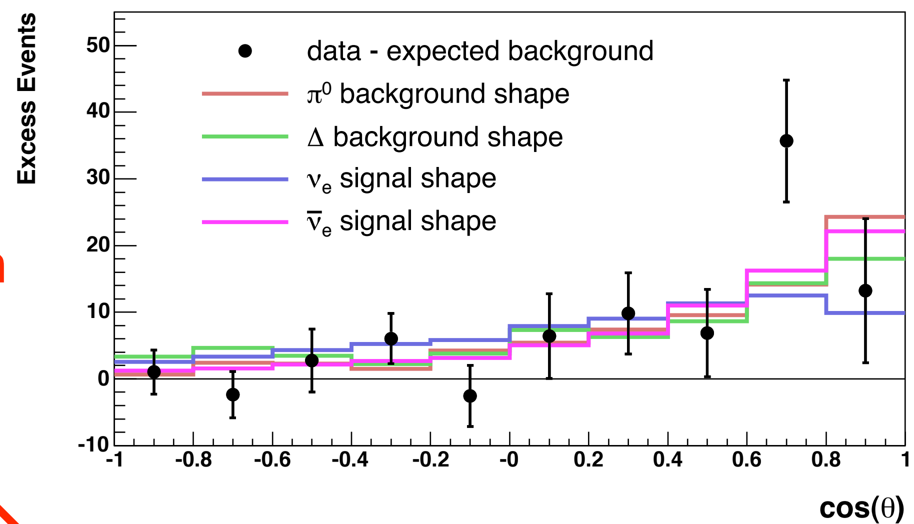
$\chi^2$ = 0.3/2 d.o.f. (scale = 0.3),

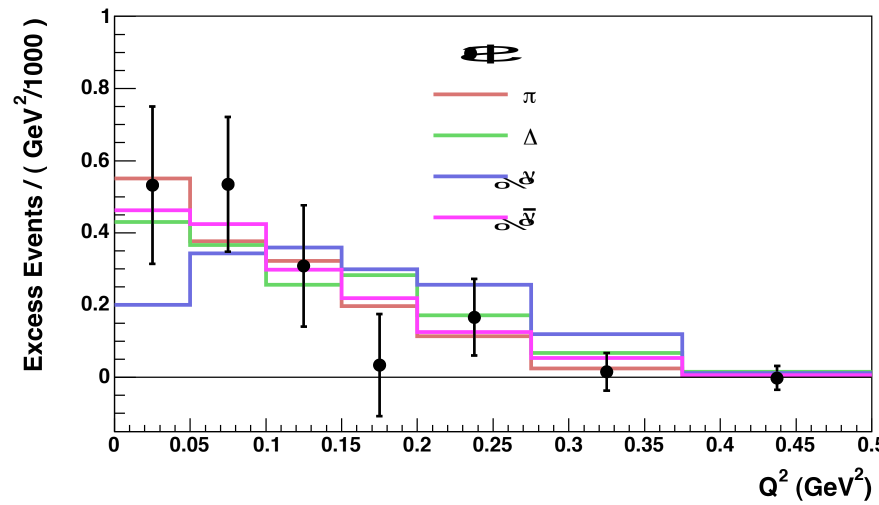
⇒ size consistent with data

- should do more complete efficiency analysis




float normalization

$\chi^2$ = 9.9 / 9 d.o.f. (scale = 0.51)

$\chi^2$ =2.5 / 6 d.o.f. (scale = 0.60)

$\chi^2$ = 12.7 / 10 d.o.f. (scale = 0.30)

$\chi^2$ =8.0 / 7 d.o.f. (scale = 0.30)

30% efficiency

⇒ shape consistent with excess

| Process | $\chi^2(cos\theta)/9$ DF | $\chi^2(Q^2)/6$ DF | Factor Increase |
|---|---|---|---|
| NC $\pi^0$ | 13.46 | 2.18 | 2.0 |
| $\Delta \to N\gamma$ | 16.85 | 4.46 | 2.7 |
| $\nu_e C \to e^- X$ | 14.58 | 8.72 | 2.4 |
| $\bar{\nu}_e C \to e^+ X$ | 10.11 | 2.44 | 65.4 |

*[MiniBooNE, PRL 102, 211801 (2009)]*

# Summary

- single photon events in neutrino-baryon scattering probe interesting (standard model) physics
- several mechanisms present, relevance varies with energy
- adding these events gives plausible explanation of MiniBooNE low-E excess
- potentially relevant background at T2K: mimics signal, varies with target material