Neutrino Interactions in the few-GeV region and the MiniBooNE anomaly

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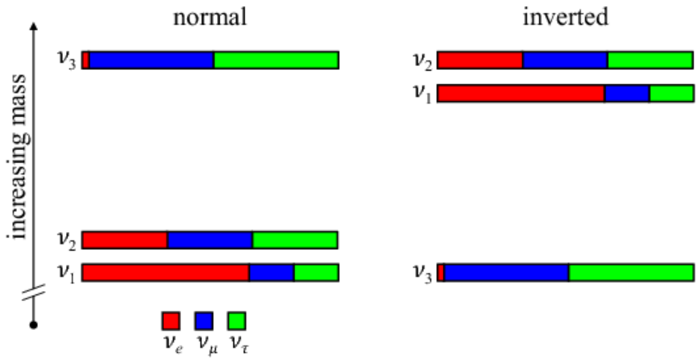
ν oscillation paradigm

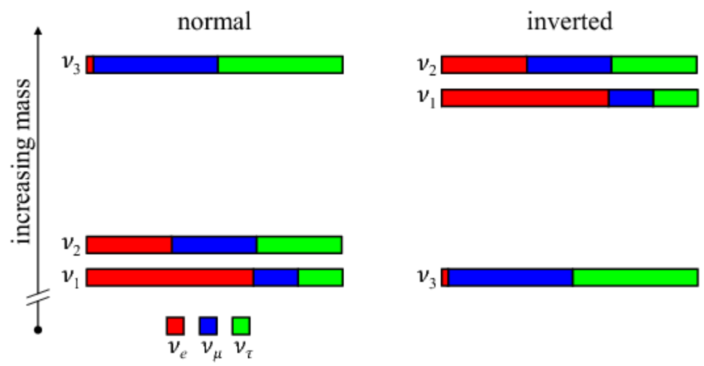
- 3 mixing flavors of mass eigenstates



- supported by solar, atmospheric, reactor and accelerator experiments

ν oscillation paradigm + anomalies

- 3 mixing flavors of mass eigenstates

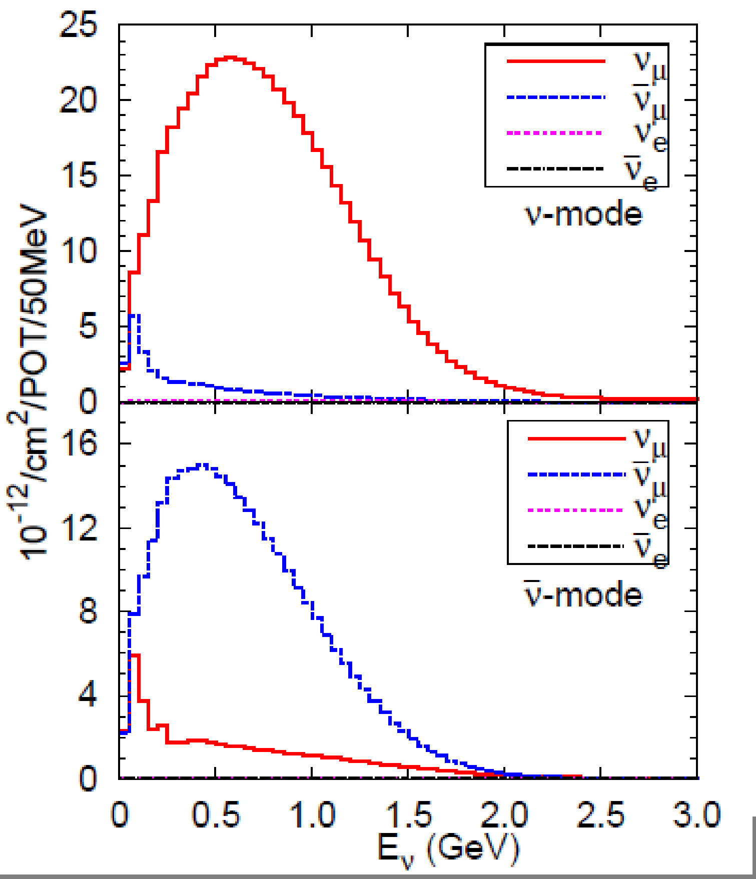


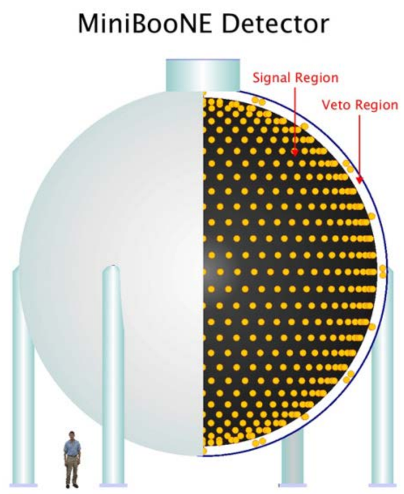
- supported by solar, atmospheric, reactor and accelerator experiments

- Anomalies
  - reactor
  - Gallium radioactive source
  - LSND
  - MiniBooNE

MiniBooNE experiment

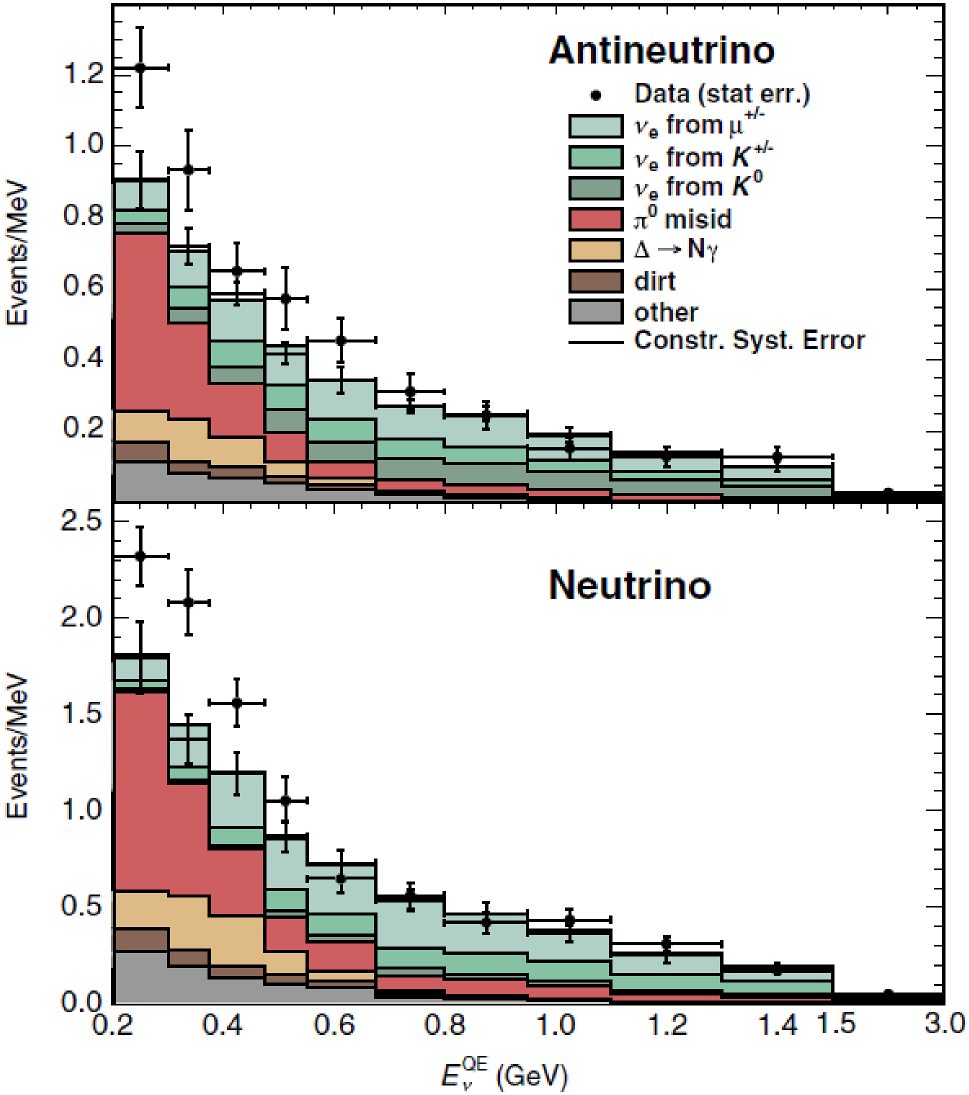
- Target: CH_2 — Aguilar-Arevalo et al, PRL 110 (2013)
- Mass: 806 tons
- Radius: 611 cm
- POT: 6.46 x 10^{20} (ν mode), 11.27 x 10^{20} ($\bar{\nu}$ mode)
- Fluxes: Aguilar-Arevalo et al, PRD 79 (2009)





MiniBooNE anomaly

- e-like events in the MiniBooNE $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search:



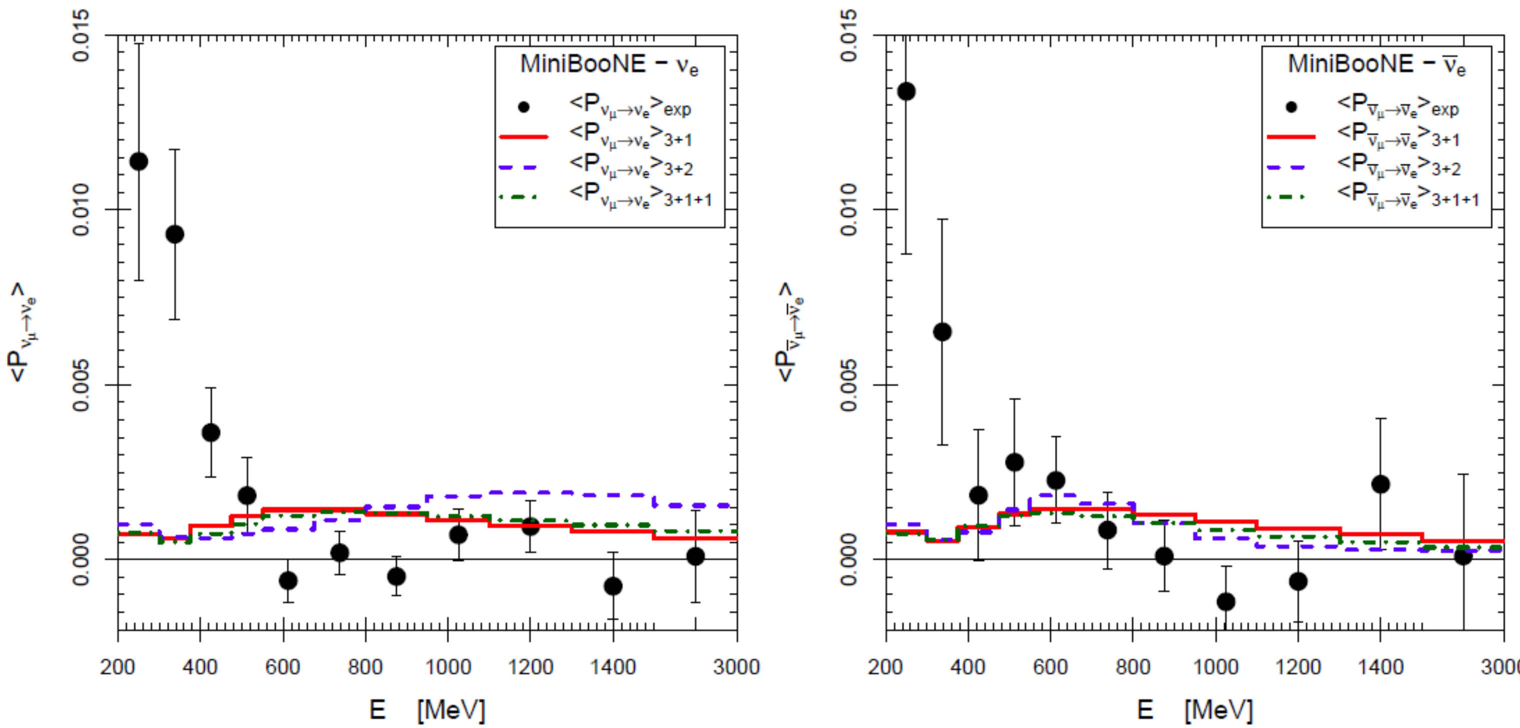
reconstructed ν energy

$$E_\nu^{QE} = \frac{2m_n E_e - m_e^2 - m_n^2 + m_p^2}{2(m_n - E_e + p_e \cos\theta_e)}$$

Aguilar-Arevalo et al., PRL110 (2013) 161801

MiniBooNE anomaly

- Origin of e-like event excess @ MiniBooNE
  - Oscillations: not explained by 1, 2, 3 families of sterile neutrinos
    J. Conrad et al., Adv. High Energy Phys. 2013, C. Giunti et al., PRD88 (2013)
    - Even after taking into account multi-nucleon interactions in E_ν reconstruction Ericson et al., Phys.Rev. D93 (2016)

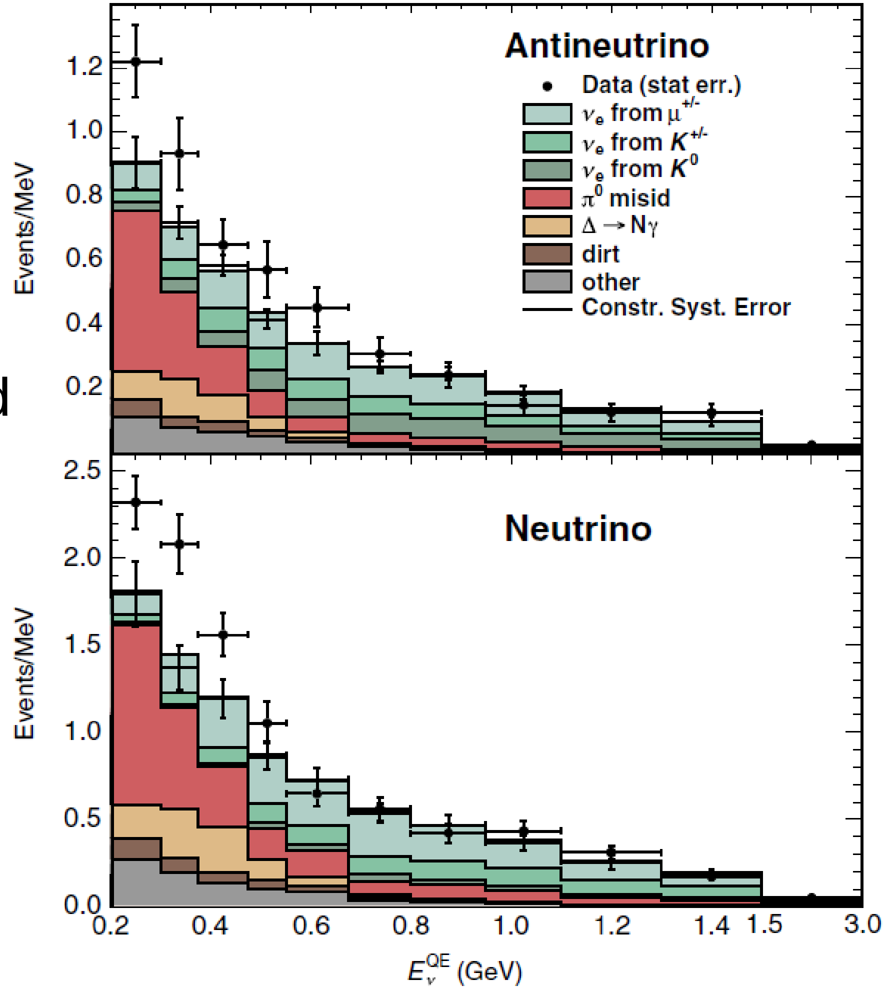


The MiniBooNE low-energy anomaly is incompatible with neutrino oscillations

C. Giunti et al., PRD88 (2013)

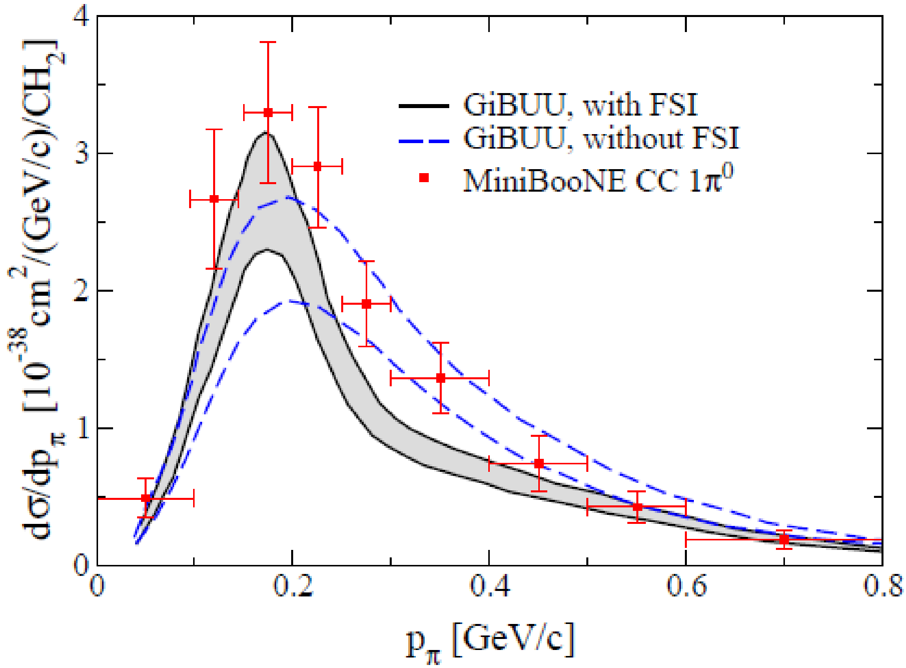
MiniBooNE anomaly

- e-like backgrounds @ MiniBooNE are (in principle) constrained in situ
- NC π^0
  - largest background
  - measured @ MiniBooNE
  - Rein-Sehgal resonance production model + non-resonant background
  - π Final State Interactions

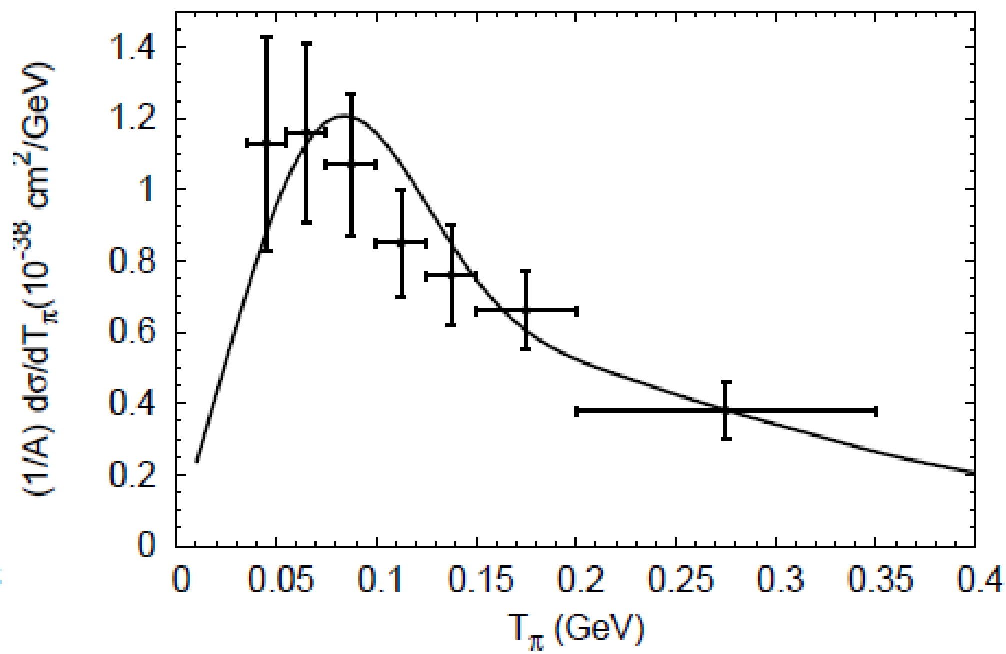


π production on ^{12}C

Comparison to MiniBooNE:
Lalakulich, Mosel, PRC87 (2013)
$CC\pi^0$ data: Aguilar-Arevalo, PRD83 (2011)



Comparison to MINERvA:
Mosel, Gallmeister, PRC96 (2017)
$CC\pi^{\pm}$ data: Eberly et al., PRD 92 (2015)



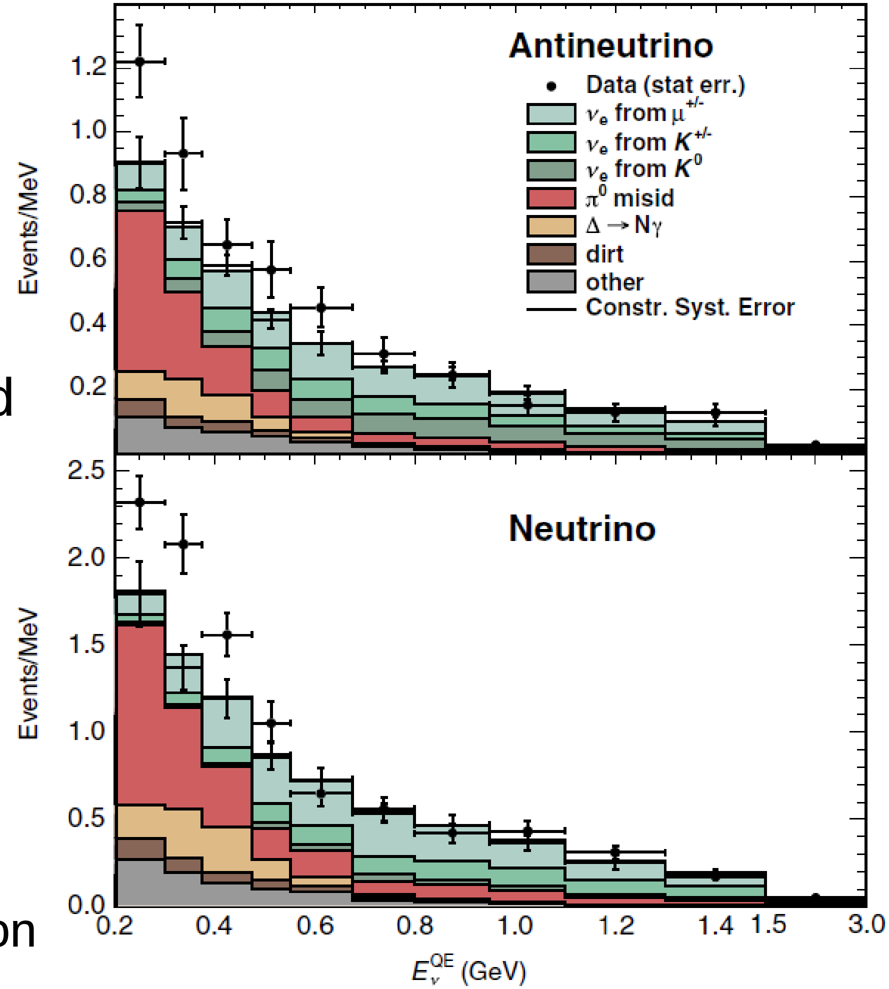
- In spite of flux difference, MiniBooNE and MINERvA data probe the same dynamics and should be strongly correlated Sobczyk, Zmuda, PRC 91 (2015)
- This tension is unlikely to resolve the MiniBooNE anomaly

MiniBooNE anomaly

- e-like backgrounds @ MiniBooNE are (in principle) constrained in situ

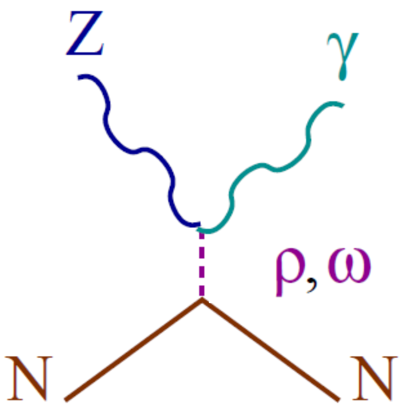
- NC π^0
  - largest background
  - measured @ MiniBooNE
  - Rein-Sehgal resonance production model + non-resonant background
  - π Final State Interactions

- NC $\Delta \to N \gamma$
  - 2nd largest background
  - not directly measured
  - determined from measured NCπ^0
    - MC tuning for resonance production
    - PDG $R \to N \gamma$ branching ratios
  - Unaccounted photon backgrounds?



NCγ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
  - Unaccounted photon backgrounds?



- Harvey et al., PRL 99 (2007)
- ω favored: large (uncertain) isoscalar ωNN coupling

NCγ events at MiniBooNE

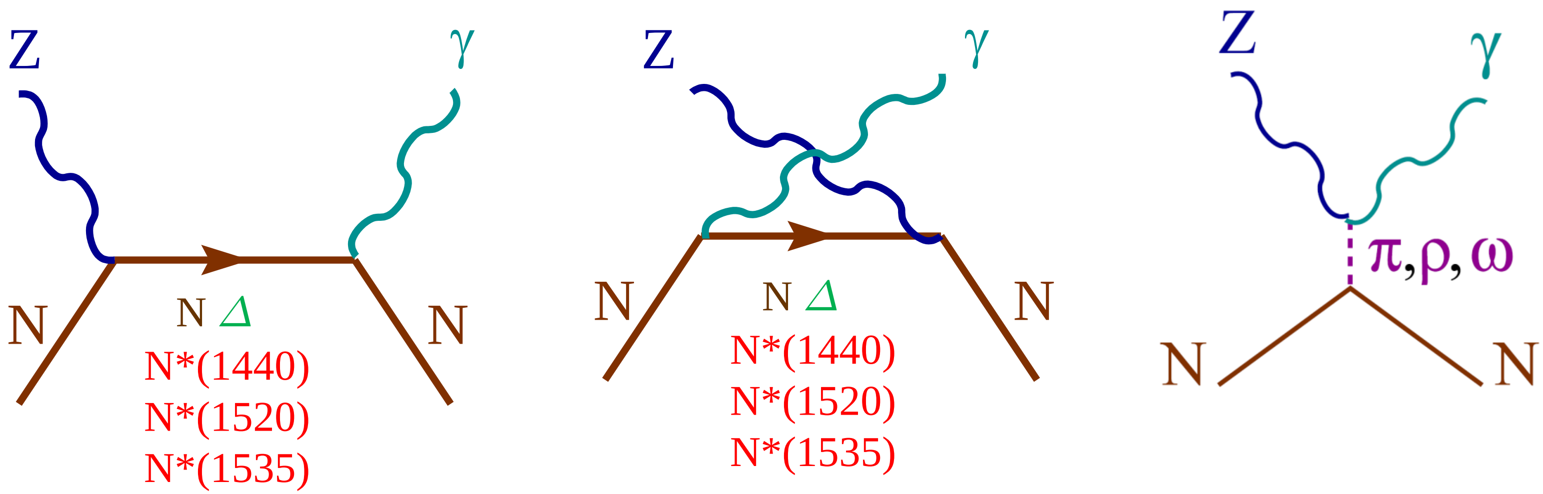
R. Hill, PRD 81 (2010)
Zhang & Serot, PRC 86 (2012)
Wang, LAR, Nieves, PRC 89 (2014)

- Photon emission in NC interactions:
  - on nucleons $\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$
  - on nuclei $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$ ← incoherent

    $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$ ← coherent

Photon emission in NC interactions

- on nucleons $\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$



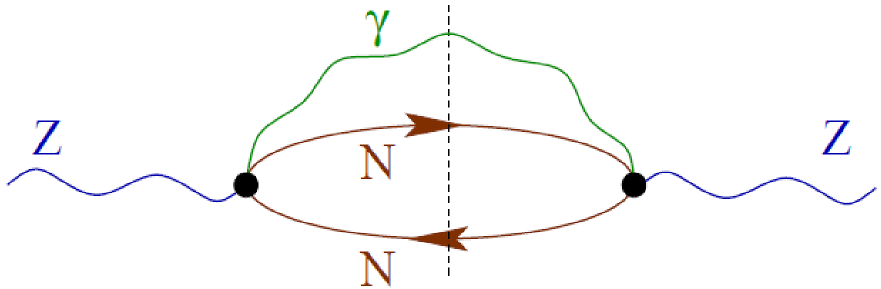
- Weak vector and EM N, N-Δ and N-N* form factors extracted from electron scattering experiments
- Weak axial N, N-Δ and N-N* form factors:
  - (off-)diagonal Goldeberger-Treiman relations for leading couplings
    - e.g. for N-Δ(1232) :

$$C_5^A(0) = \sqrt{\frac{2}{3}} g_{\Delta N \pi} \qquad g_{\Delta N\pi} \Leftrightarrow \Gamma(\Delta \to N\pi) \Leftarrow N\pi \to N\pi$$

  - q^2 dependence consistent with $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$ ANL, BNL data

Photon emission in NC interactions

- on nuclei $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$ $\leftarrow$ incoherent
  - 1p1h1γ excitations in nuclear matter Wang, LAR, Nieves, PRC89 (2014)



  - finite nuclei: Local Density approximation: $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$
  - In-medium modification (broadening) of the $\Delta(1232)$ resonance
- on nuclei $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$ $\leftarrow$ coherent
  - same microscopic input as for the incoherent process
  - Coherent sum over all nucleons:

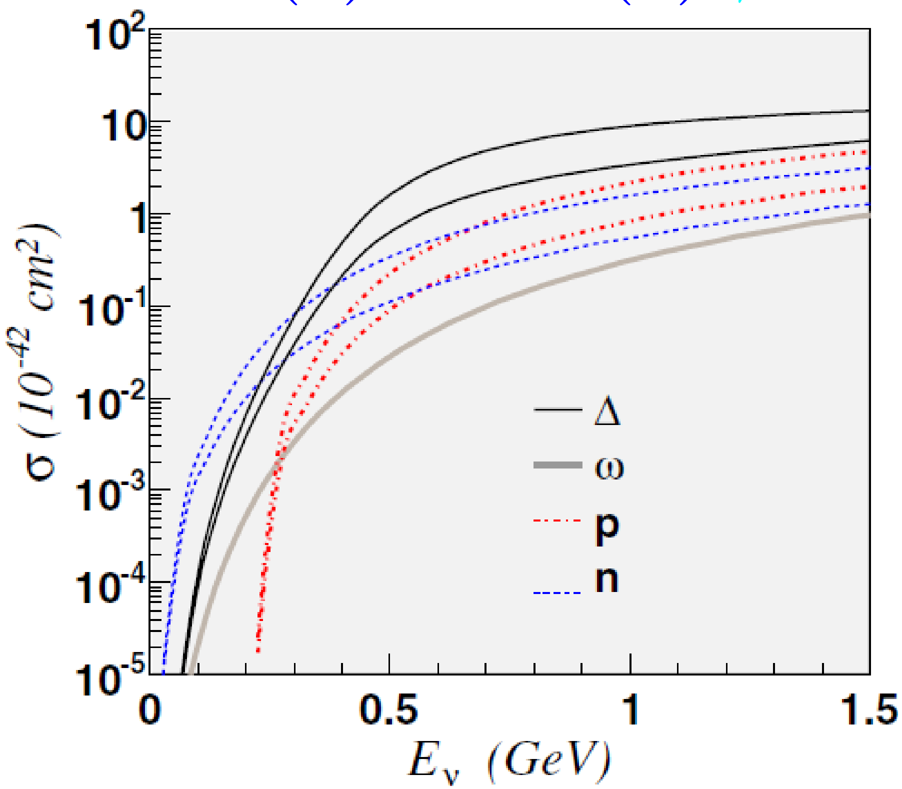
$$\mathcal{M}_r = \frac{G_F\, e}{\sqrt{2}}\, \epsilon^{*(r)}_{\mu} \mathcal{A}^{\mu\alpha} l_\alpha$$

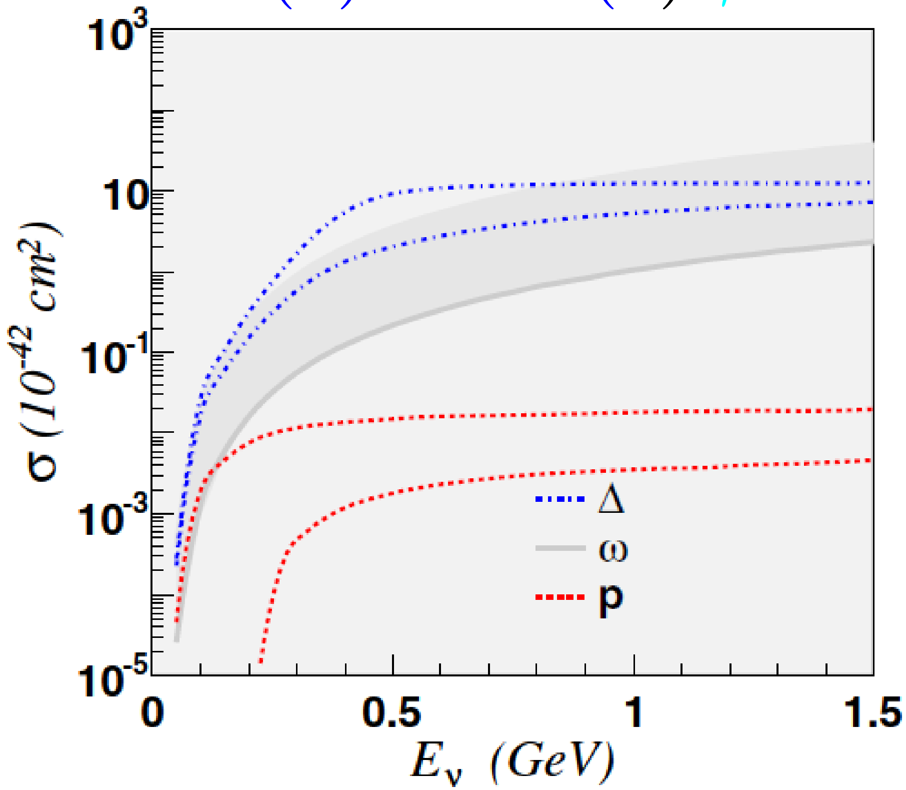
$$\mathcal{A}^{\mu\alpha} = \sum_{r=p,n} \int d\vec{r}\, e^{i(\vec{q}-\vec{q}_\gamma)\cdot\vec{r}} \rho_r(r) \hat{\Gamma}^{\mu\alpha}_r \qquad \hat{\Gamma}^{\mu\alpha}_r = \frac{1}{2} \sum_{i=\mathrm{mech.}} \mathrm{Tr}\left[\bar{u}\, \Gamma^{\mu}_{i(r)}\, u\right]$$

NCγ events at MiniBooNE

- R. Hill, PRD 81 (2010)

$$\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N \qquad \nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$$

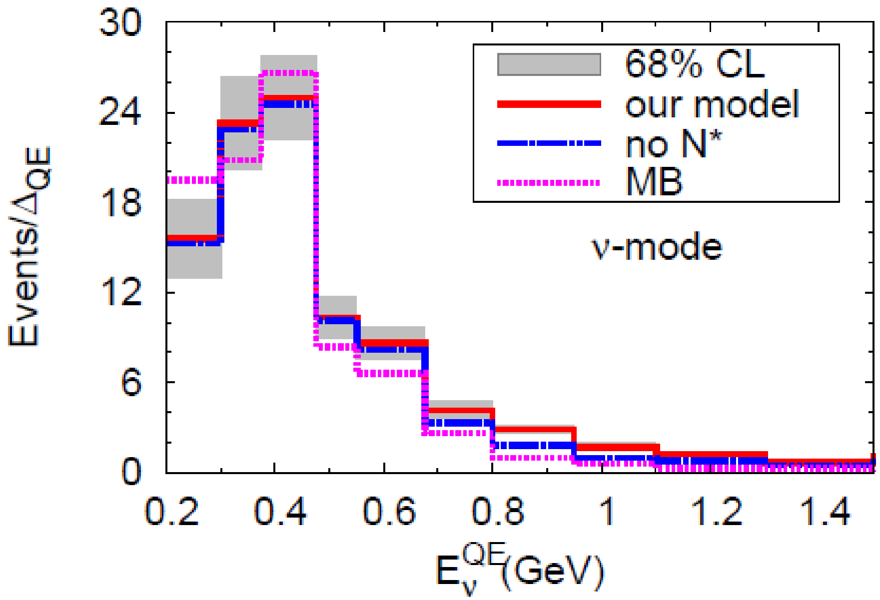


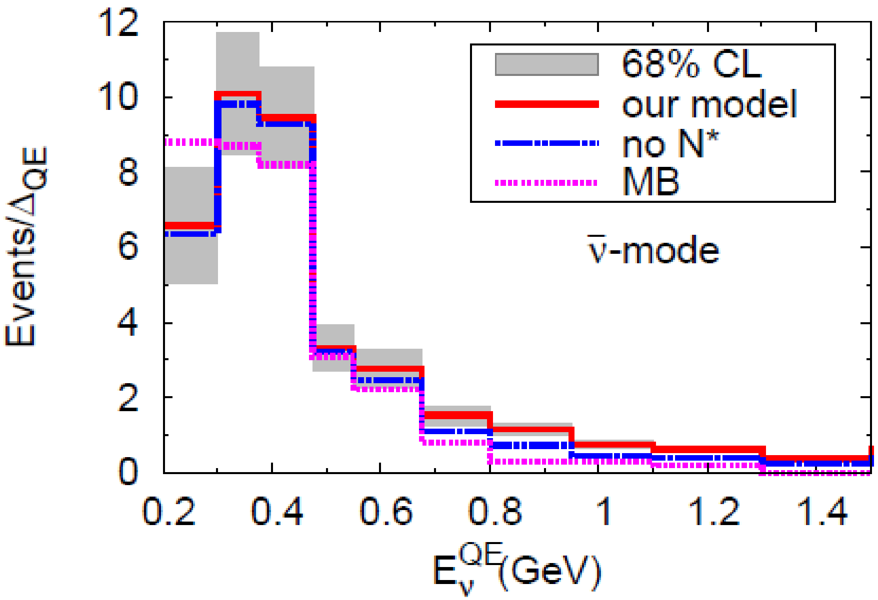


- The ω exchange contribution is very small
- J. Rosner, PRD 91 (2015) ⇒ ¼ smaller
  - Z-ω- γ vertex calibrated by $\tau \to \nu_\tau$ a_1 and $f_1 \to \rho\,\gamma$ decays

NCγ events at MiniBooNE

- Comparison to the MiniBooNE estimate
  - Resonance model (R&S) tuned to π production data
  - Only R $\to$ N γ





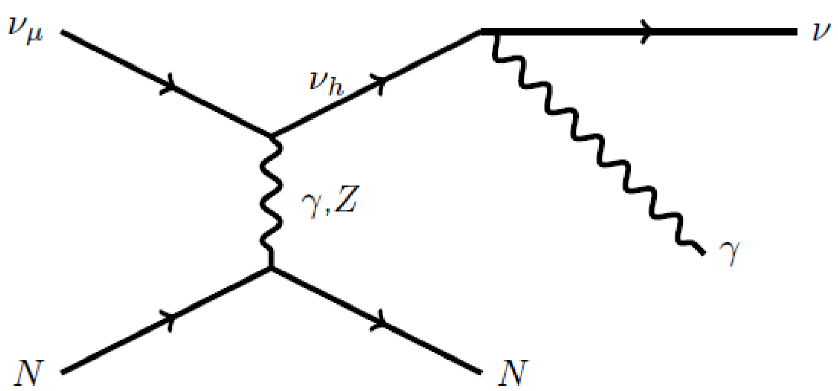
E. Wang, LAR, J. Nieves, PLB 740 (2015)

- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- Same conclusion as Zhang, Serot, PLB 719 (2013)

NCγ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
  - Unaccounted photon backgrounds?
  - Heavy ($\sim$ 50 MeV) ν produced weakly or EM, followed by $\nu_h \to \nu\,\gamma$

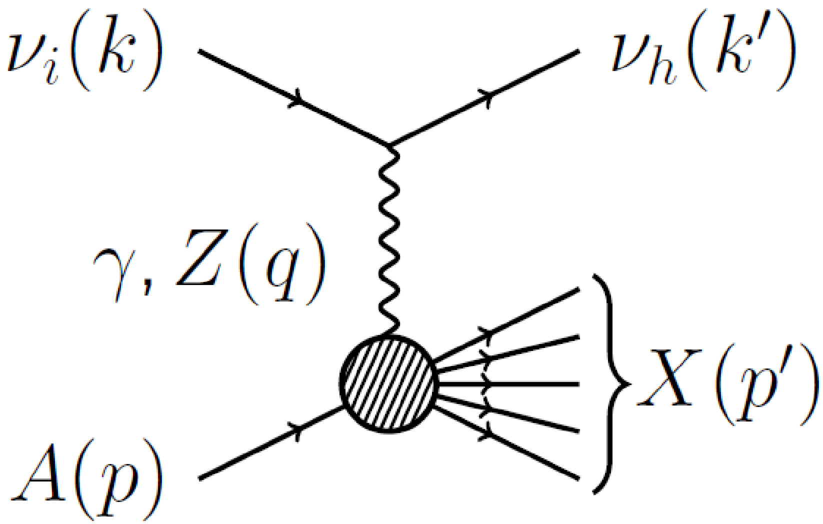
    S. Gninenko, PRL 103 (2009), M. Masip et al, JHEP 1301 (2013)

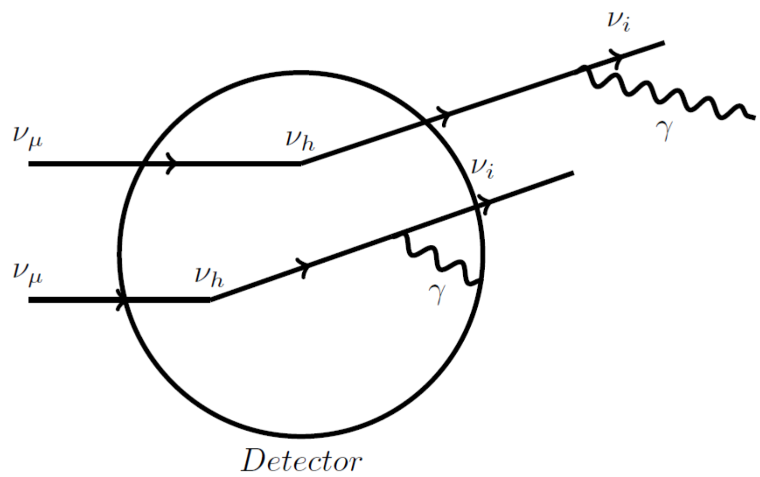


$$\mathcal{L}_{eff} = \frac{1}{2}\mu^i_{tr}\left[\overline{\nu}_h\sigma_{\mu\nu}\left(1-\gamma_5\right)\nu_i + \overline{\nu}_i\sigma_{\mu\nu}\left(1+\gamma_5\right)\nu_h\right]\partial^\mu A^\nu$$

$$\frac{d\Gamma_{\nu_h\to\nu_i\gamma}}{d\cos\theta_\gamma} = \frac{(\mu^i_{tr})^2}{32\pi}m_h^3(1-\cos\theta_\gamma)$$

ν_h production





- on nucleons $\nu_\mu(\bar{\nu}_\mu)\, N \to \nu_h(\bar{\nu}_h)\, N$
- on nuclei $\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, A$ $\leftarrow$ coherent

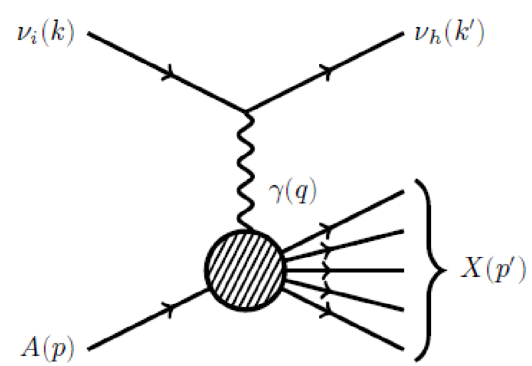
  $\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, X$ $\leftarrow$ incoherent

- ν_h= Dirac ν with m $\approx$ 50 MeV, slightly mixed with ν_μ
- A =^{12}C (MiniBooNE, CH_2)

LAR, E. Saúl Sala, in preparation, arXiv:1705.00353

ν_h production by EM interactions

$$\mathcal{L}_{eff} = \frac{1}{2}\mu_{tr}^{i}\left[\overline{\nu}_h\sigma_{\mu\nu}\left(1-\gamma_5\right)\nu_i + \overline{\nu}_i\sigma_{\mu\nu}\left(1+\gamma_5\right)\nu_h\right]\partial^\mu A^\nu$$



- General expression for the inclusive cross section

$$\nu_\mu(k) + A(p) \to \nu_h(k') + X(p')$$

$$\frac{d\sigma}{dk_0'\,d\Omega'} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{\alpha\left(\mu_{tr}^{\mu}\right)^2}{4\,\pi\,q^4}L_{\mu\nu}W_{EM}^{\mu\nu} \qquad \alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$$

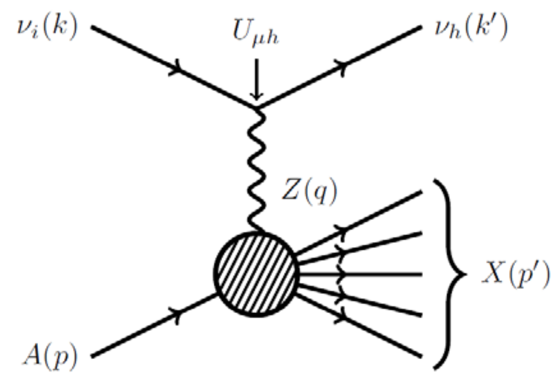
$$\begin{aligned} L_{\mu\nu} &= \frac{1}{4}Tr\left[(\not{k}' + m_h)\sigma_{\mu\alpha}(1-\gamma_5)\not{k}(1+\gamma_5)\sigma_{\nu\beta}\right]q^\alpha q^\beta \\ &= 2(k\cdot k')(k+k')_\mu(k+k')_\nu - 2m_h^2[2k_\mu k_\nu + g_{\mu\nu}(k\cdot k')] + 2m_h^2 i\epsilon_{\mu\nu\alpha\beta}k^\alpha k'^\beta \end{aligned}$$

$$W_{EM}^{\mu\nu} = W_1\left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu}\right) + \frac{W_2}{M^2}\left(p^\mu - \frac{p\cdot q}{q^2}q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2}q^\nu\right)$$

- Structure functions $W_{1,2}$ are
  - process specific
  - probed in electron elastic and QE scattering

ν_h production by NC interactions

$$\nu_\mu = U_{\mu 1}\nu_1 + U_{\mu 2}\nu_2 + U_{\mu 3}\nu_3 + U_{\mu h}\nu_h + \cdots$$



- General expression for the inclusive cross section

$$\nu_\mu(k) + A(p) \to \nu_h(k') + X(p')$$

$$\frac{d\sigma}{dk'_0\, d\Omega'} = \frac{|\vec{k'}|}{|\vec{k}|} \frac{|U_{\mu h}|^2 G_F^2}{(2\pi)^2} L_{\mu\nu} W^{\mu\nu}$$

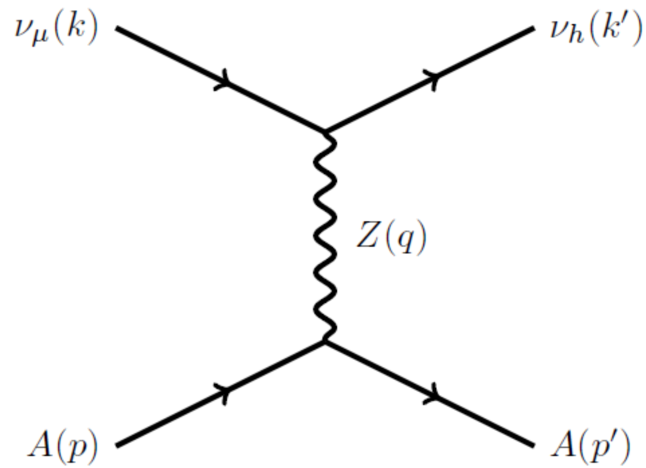
$$\begin{aligned} L_{\mu\nu} &= Tr\left[(\not{k}' + m_h)\gamma_\mu(1-\gamma_5)\not{k}\gamma_\nu(1-\gamma_5)\right] \\ &= 8(k'_\mu k_\nu + k'_\nu k_\mu - g_{\mu\nu}(k\cdot k') + i\epsilon_{\mu\nu\alpha\beta}k'^\alpha k^\beta) \end{aligned}$$

$$\begin{aligned} W^{\mu\nu}_{NC} &= -W_1 g^{\mu\nu} + W_2\frac{p^\mu p^\nu}{M^2} + W_4\frac{q^\mu q^\nu}{M^2} + W_5\frac{p^\mu q^\nu + q^\mu p^\nu}{M^2} \\ &\quad + W_3 i\epsilon^{\mu\nu\alpha\beta}\frac{p_\alpha q_\beta}{2M^2} + W_6\frac{p^\mu q^\nu - q^\mu p^\nu}{M^2} \end{aligned}$$

- Structure functions $W_{1,2}$ are
  - process specific
  - probed in electron and neutrino elastic and QE scattering

ν_h production by NC interactions

- $\nu_\mu(k) + A(p) \to \nu_h(k') + A(p')$



$$W^{\mu\nu} = \frac{1}{2M}\int \frac{d^3p'}{2E'}\delta^4(k'+p'-k-p)H^{\mu\nu}$$

$$H^{\mu\nu} = J^\mu_{NC}(J^\nu_{NC})^*$$

$$J^\mu_{NC} = 2\left(p^\mu - \frac{p\cdot q}{q^2}q^\mu\right)F_W(q^2)$$ $\leftarrow$ as in CEνNS

$$F_W(q^2) = \frac{1}{2}\left[F_p(q^2)(1-4\sin^2\theta_W) - F_n(q^2)\right] \qquad F_{p,n}(q^2) = \int d^3r e^{i\vec{q}\cdot\vec{r}}\rho_{p,n}(r)$$

$$W_1 = 0$$

$$W_2 = \frac{M_A}{E'}\delta(E'+k'_0-m_N-k_0)F_W(q^2) = 4W_4 = 2W_5$$

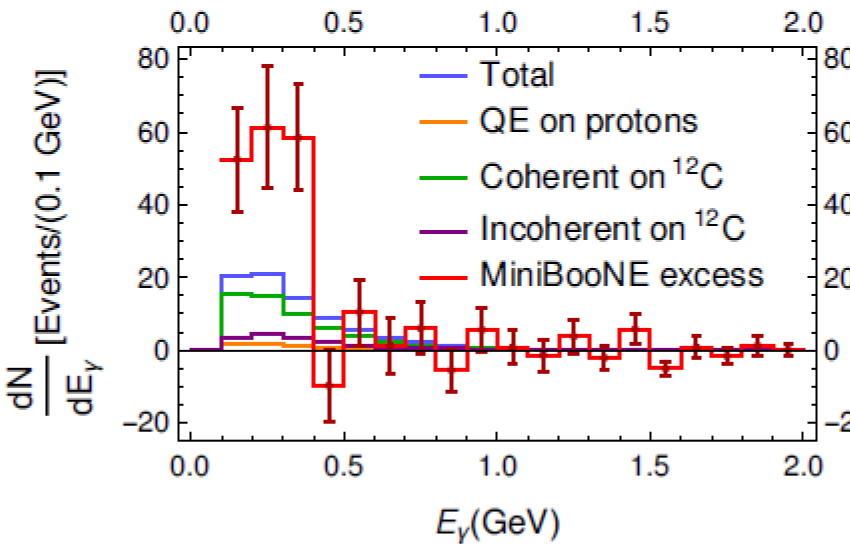
$$\frac{d\sigma}{dt} = \frac{|U_{\mu h}|^2 G_F^2}{8\pi(s-M_A^2)^2}\left[4(s-M_A^2)^2 + 4st - m_h^2\,(4s+t) + m_h^4\right]F_W^2(t)$$

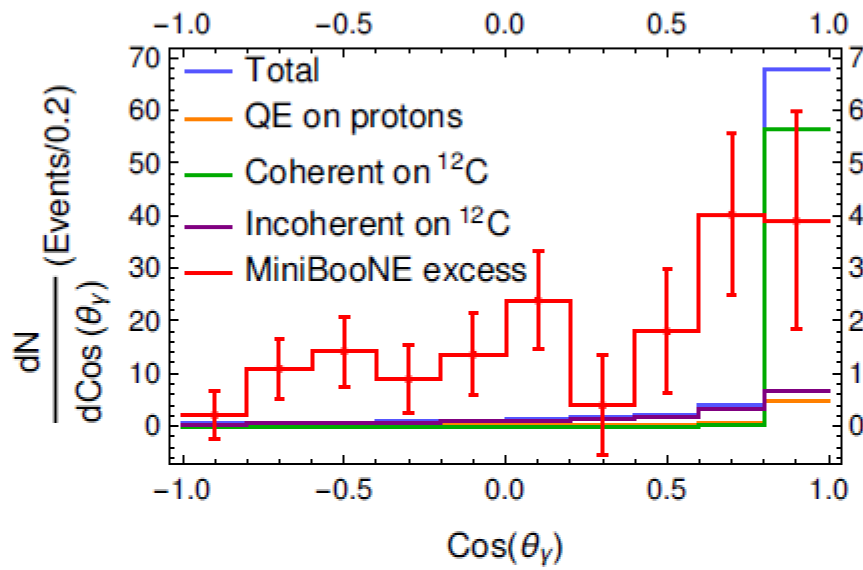
Results

- Choice of parameters from M. Masip et al, JHEP 1301 (2013)
  - m_h= 50 MeV
  - τ_0 = 5×10^{-9} s
  - BR($\nu_h \to \nu_\mu \gamma$)= 10^{-2}
  - $|U_{\mu h}|^2 = 3 \times 10^{-3}$

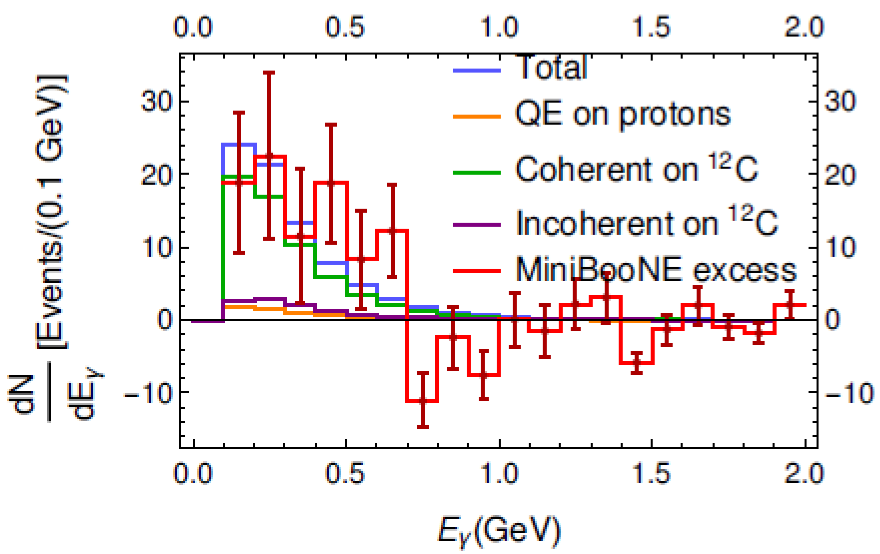
Events @ MiniBooNE

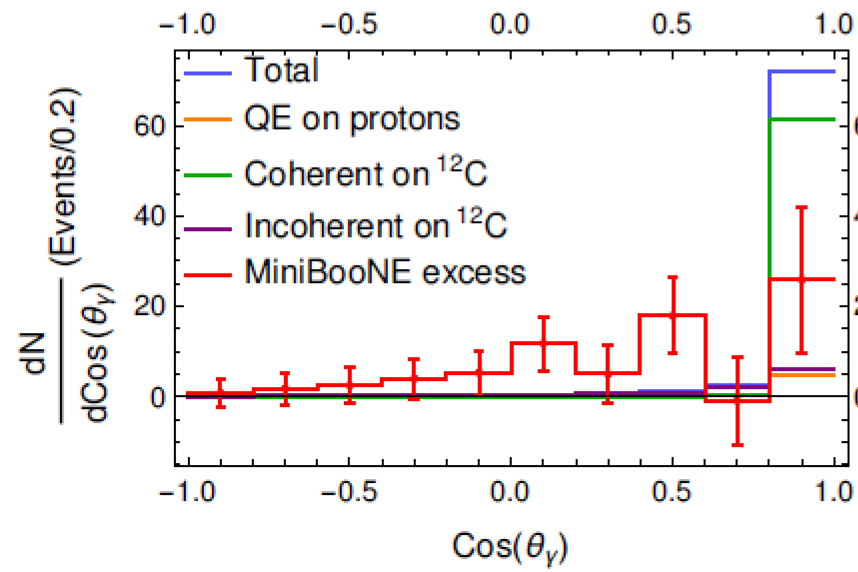
- ν mode





- $\bar{\nu}$ mode





Results

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  - τ_0 = 5×10^{-9} s
  - BR($\nu_h \to \nu_\mu \gamma$)= 10^{-2}
  - $|U_{\mu h}|^2 = 3 \times 10^{-3}$
  - does not explain the MiniBooNE excess of events

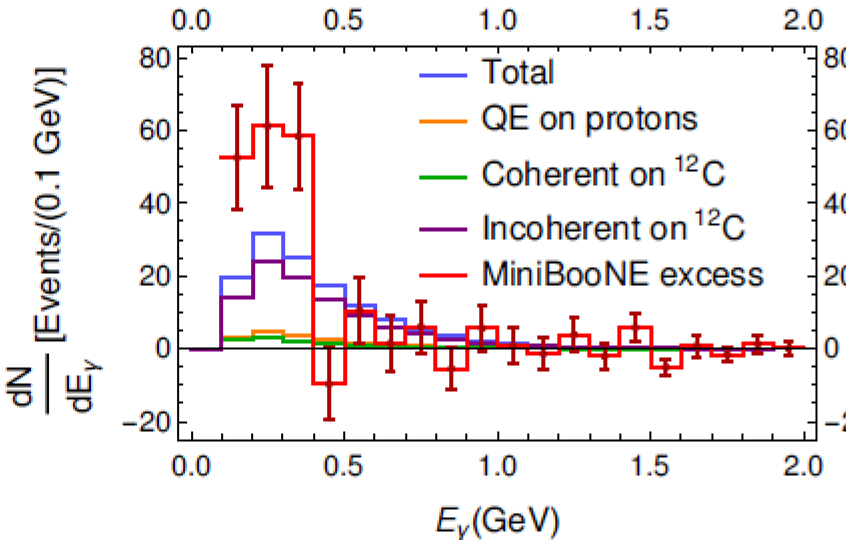
Results

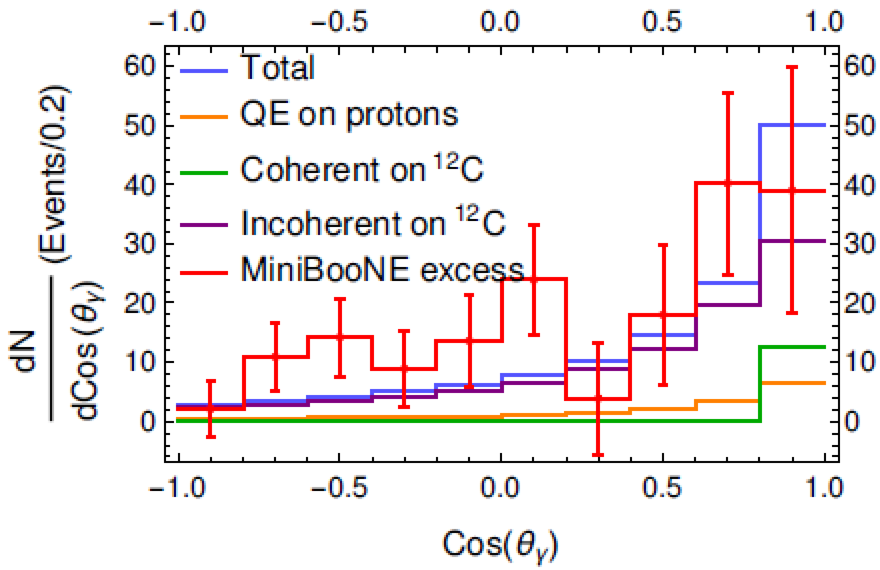
- LSND compatible range by S. Gninenko, PRL 103 (2009)
  - m_h > 40 MeV (KARMEN), m_h < 80 MeV (LSND)
  - $|U_{\mu h}|^2 > 10^{-3}$ (muon lifetime), $|U_{\mu h}|^2 < 10^{-2}$ (LEP)
  - $\tau_0 < 10^{-8}$ s (LSND)

- Our fit: χ^2/DoF = 101/54
  - m_h= 68.6 MeV
  - $\tau_0 = 2.5 \times 10^{-9}$ s
  - BR($\nu_h \to \nu_\mu \gamma$)= 8.4×10^{-4} $\Leftrightarrow$ EM ν_h production strongly suppressed
  - $|U_{\mu h}|^2 = 10^{-2}$

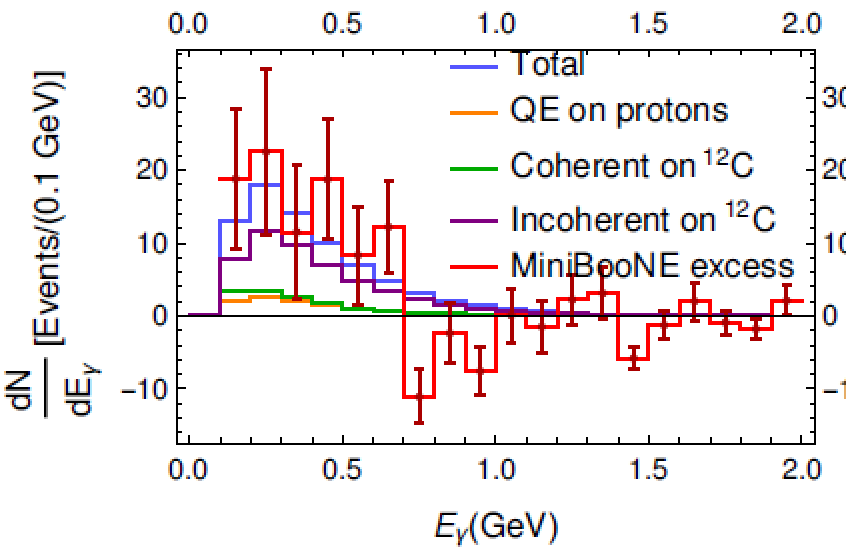
Events @ MiniBooNE

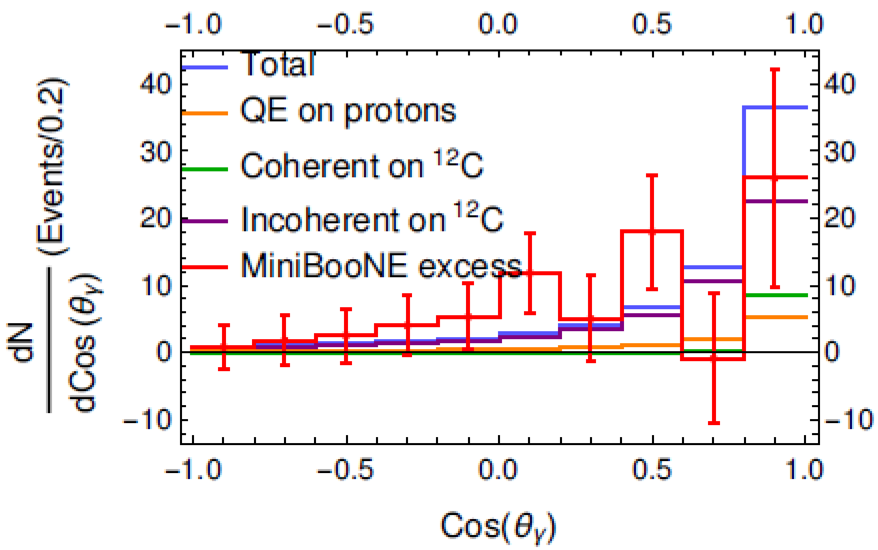
- ν mode



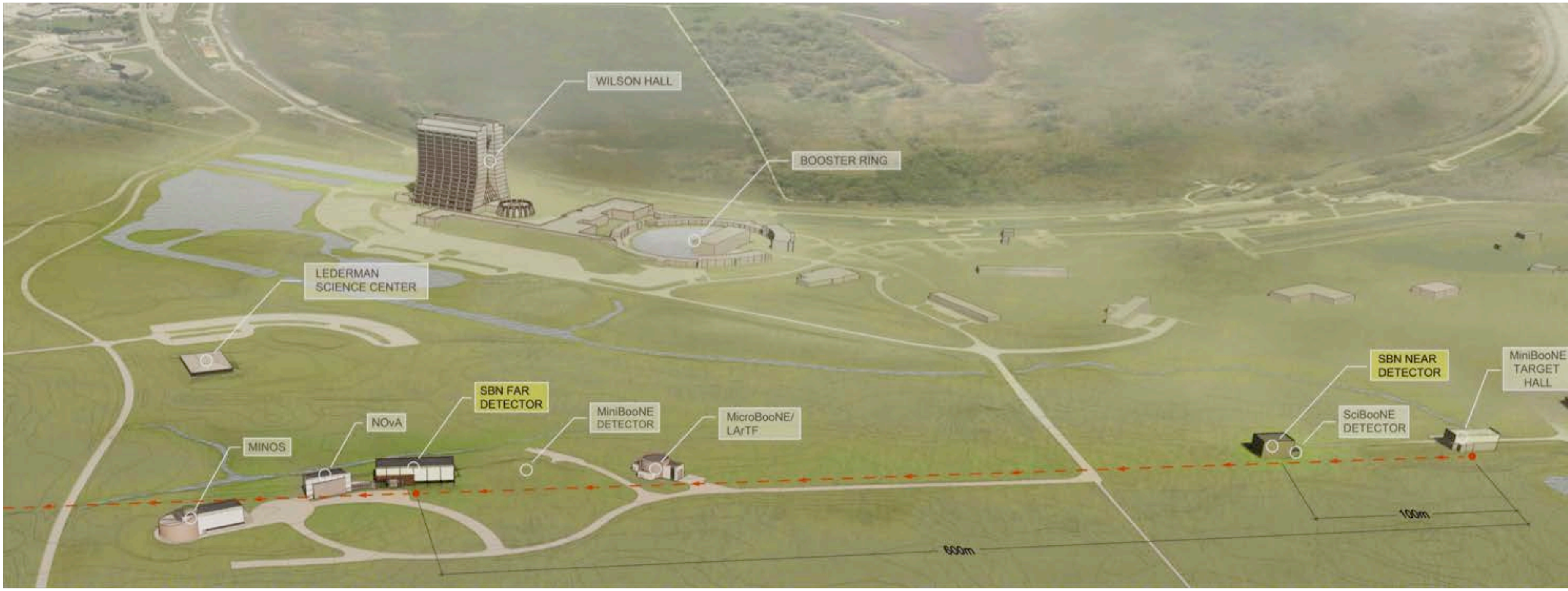


- $\bar{\nu}$ mode



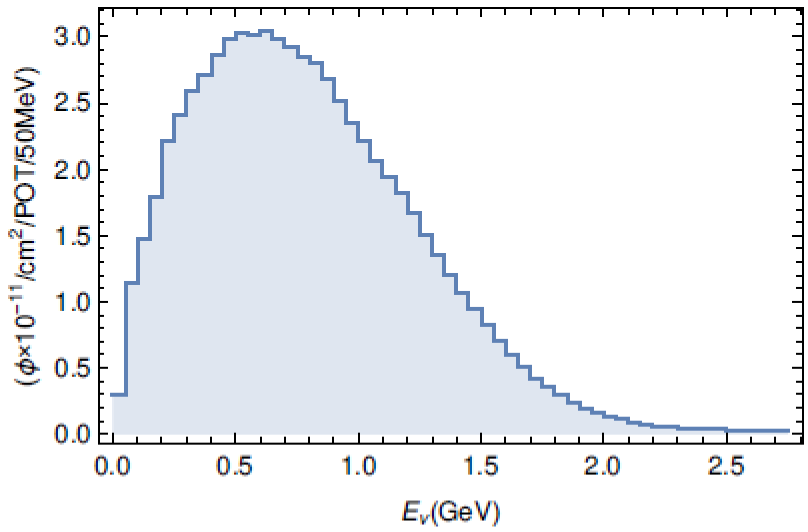


SBN

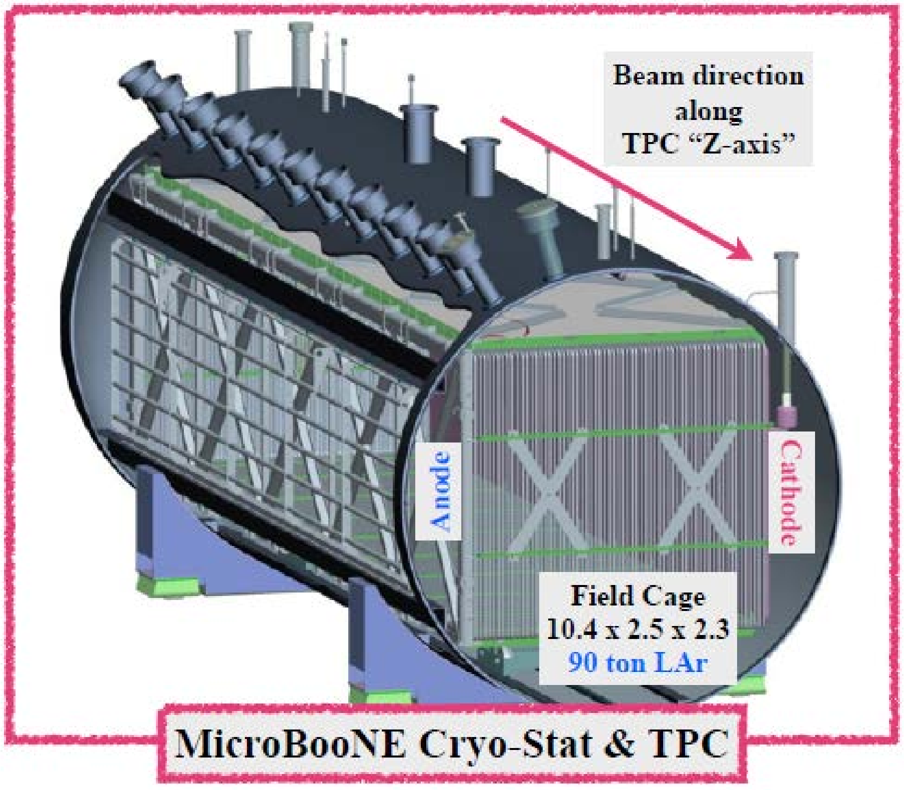

WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
SBN NEAR DETECTOR
MiniBooNE TARGET HALL
SciBooNE DETECTOR
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
NOvA
MINOS
100m
600m

MicroBooNE

- LArTPC
- Active mass: 86.6 tons
- Dimensions: 10.3 $\times$ 2.3 $\times$ 2.3 m
- Run plan: 6.6 $\times$ 10^{20} POT
- Acciarri et al., arXiv:1503.01520
- Flux prediction:

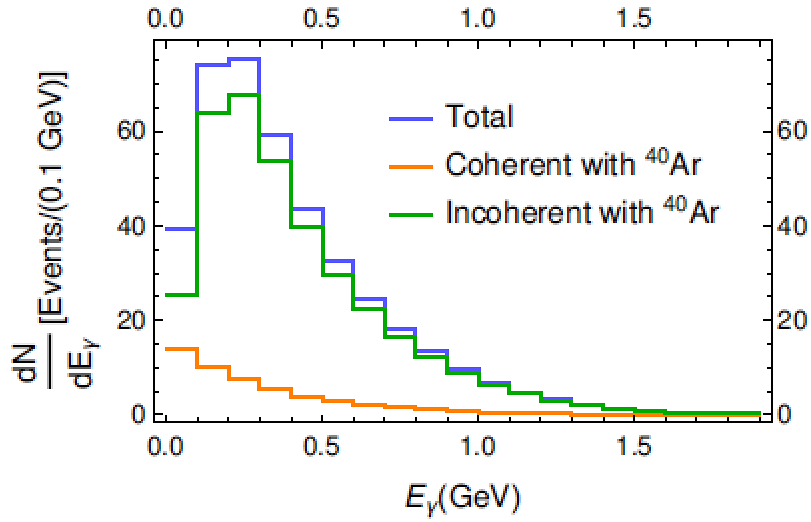


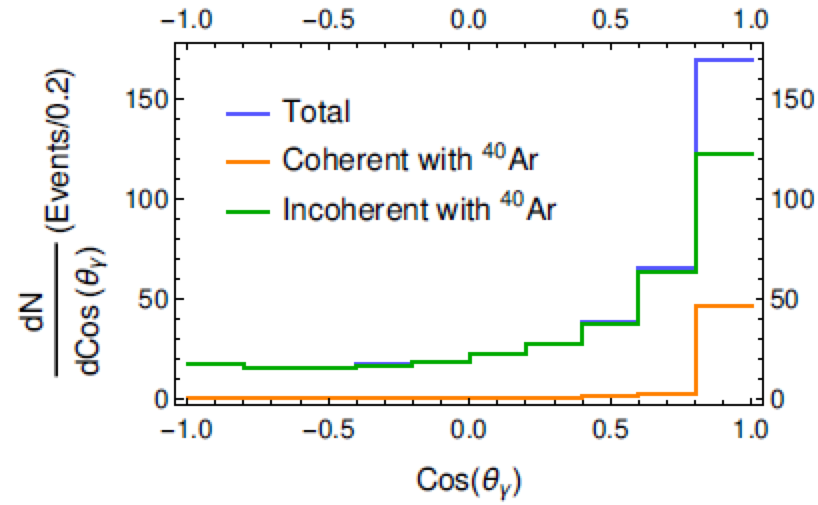
Z. Pavlovic, private comunication



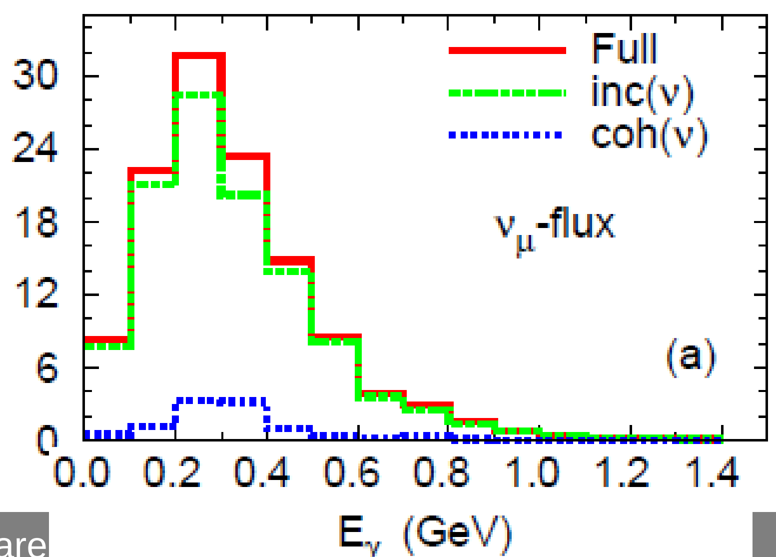
Events @ MicroBooNE

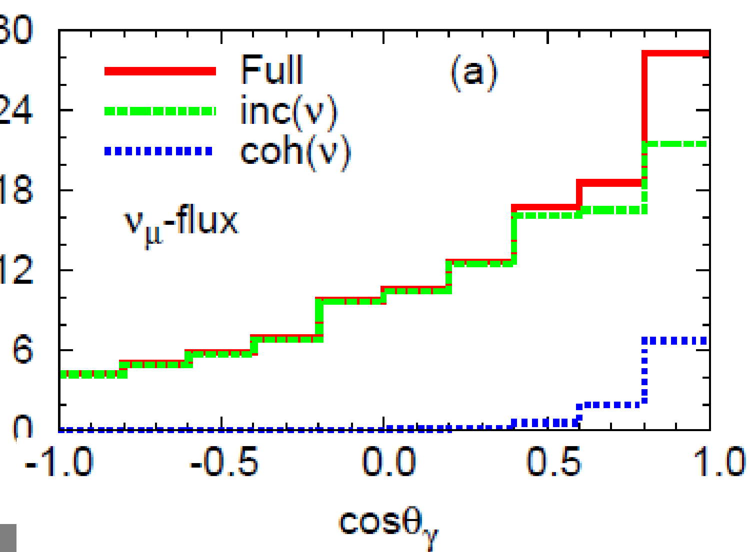
- ν mode





- SM prediction LAR & Wang



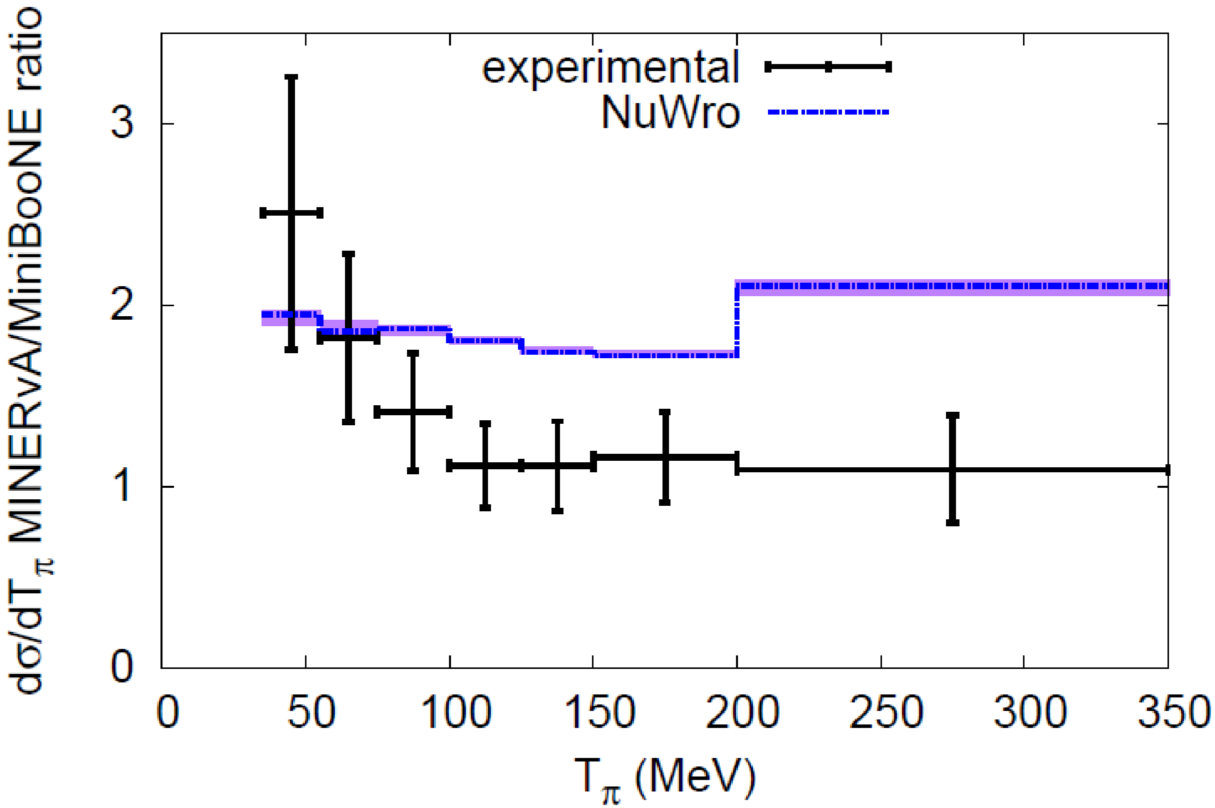


Summary

- The origin of the MiniBooNE anomaly is still not understood.
- Hard to reconcile with global oscillation analyses.
- Poorly understood ν interactions and/or unaccounted backgrounds could be the key
- Standard Model NCγ : insufficient to explain the excess of events
- Production and radiative decay of heavy sterile neutrinos has been proposed as a possible solution
  - not entirely satisfactory but could still be a sizable contribution.
- Further insight from the SBN program at Fermilab.

π production on ^{12}C

- Sobczyk, Zmuda, PRC 91 (2015)



- In spite of flux difference, MiniBooNE and MINERvA data probe the same dynamics and should be strongly correlated