New Physics and the LSND, MiniBooNE and ATOMKI anomalies

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CETUP 2024
The Institute for Underground Science at SURF, Lead, South Dakota
July 08, 2024

Short Baseline Anomalies and Sterile Neutrinos

In the absence of any new physics signals at the Large Hadron Collider (LHC), anomalous results at low energy experiments have become the subject of increased attention and scrutiny.

Over the past couple of decades, a number of anomalous results have been observed in experiments which involve the production and detection of neutrinos over short baselines (< 1 km).

Sterile neutrinos of $(\text{mass})^2 = \text{eV}^2$ and consequent active-sterile oscillations have been invoked to explain them.

This hypothesis has come under increasing pressure from recent experimental data (IceCube, MicroBooNE), joint oscillation analyses, cosmology and the requirement of mutual consistency.

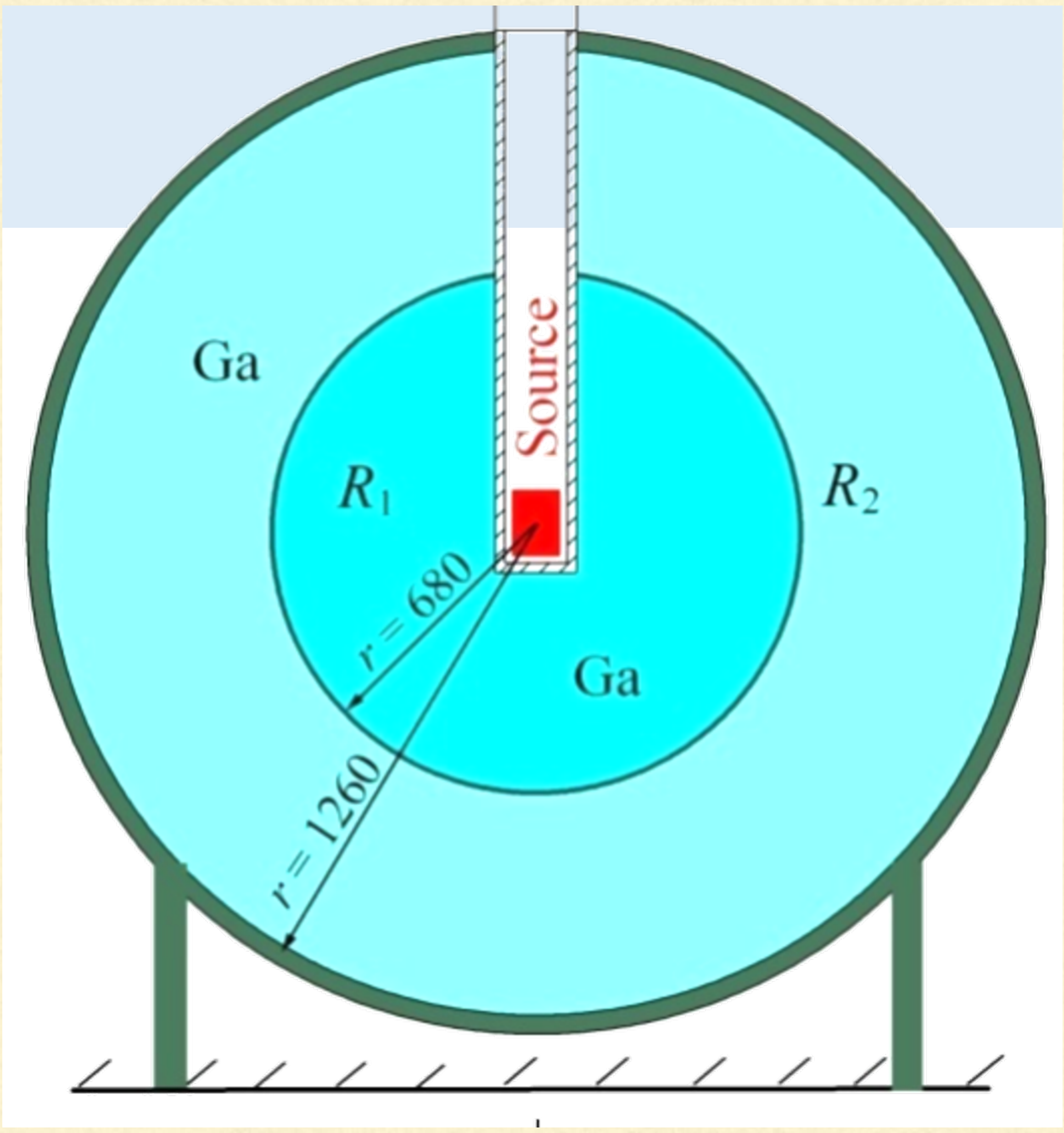
Is other new physics responsible for these anomalies?

Anomalies at Short Baselines.......1) The Gallium source Anomaly

Intense radioactive sources (e.g. Cr, Ar) with well-determined neutrino spectra are used. These neutrinos are captured by Ga via

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

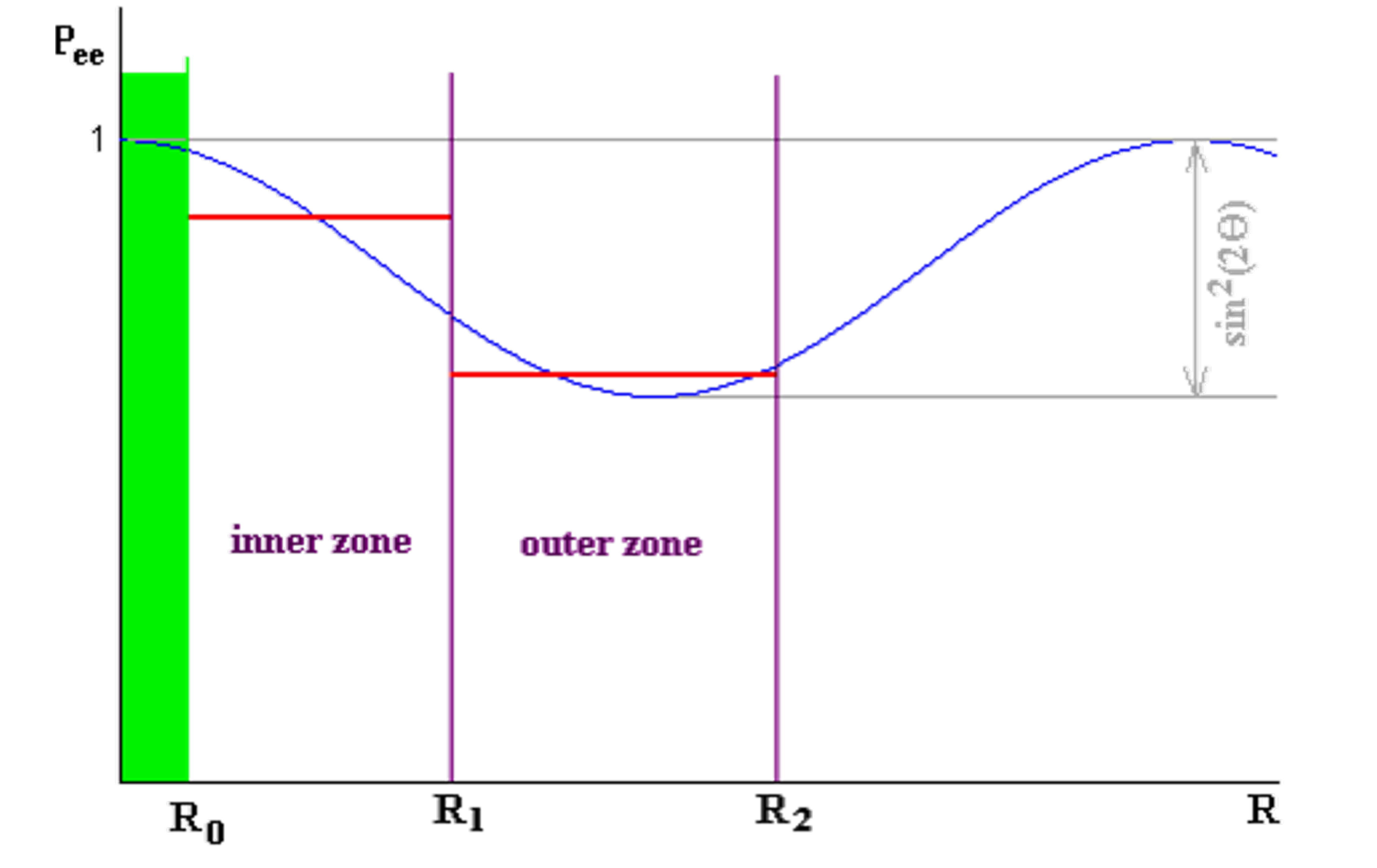
Baselines over which the decay neutrinos propagate are very short, ~ 1 m. However, in the latest experiment (BEST) 2 target zones are created, to see evidence of oscillations.

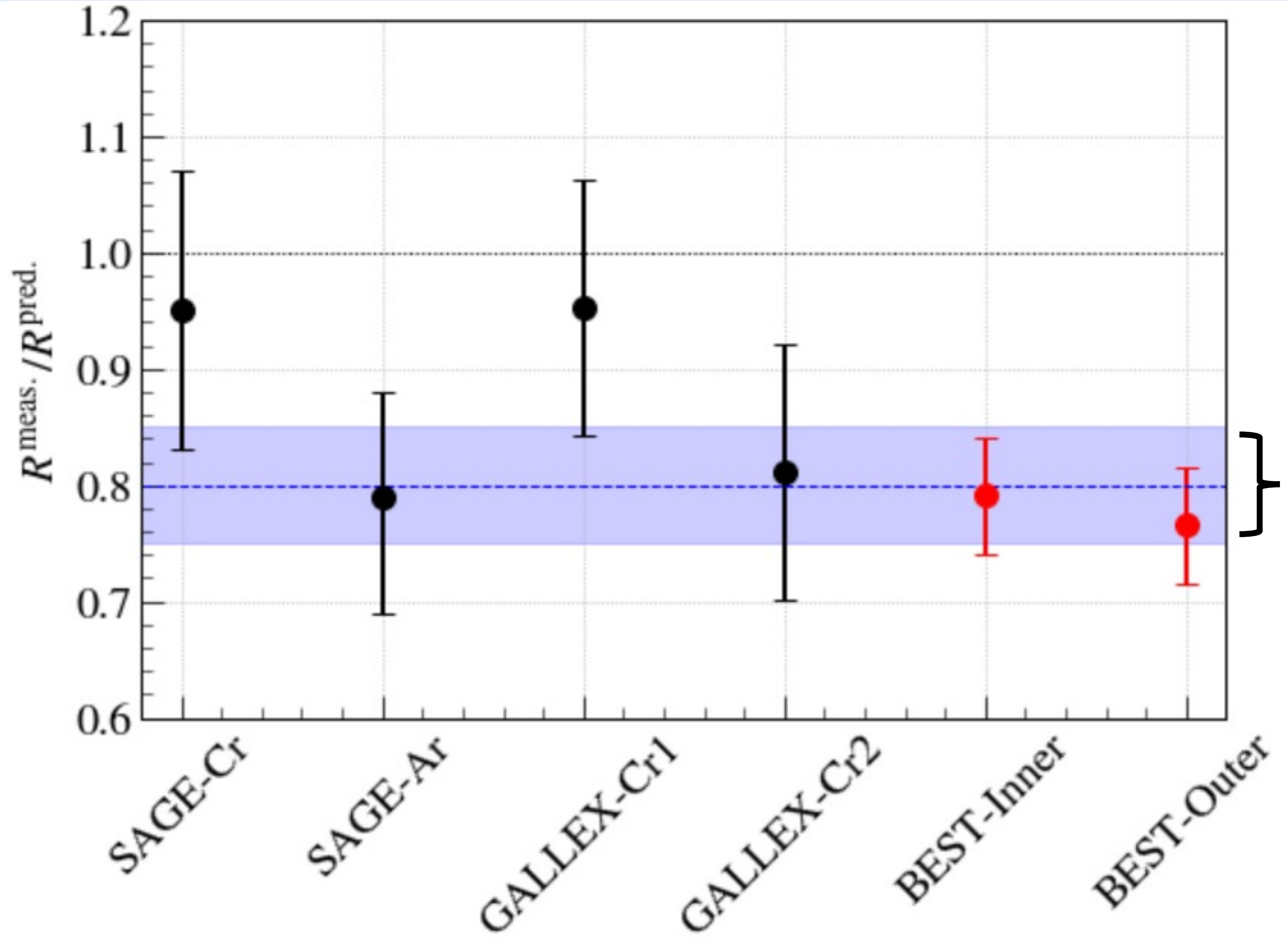


- Radio chemistry for extraction and counting of the ^{71}Ge was developed in SAGE solar measurements. and is well understood

Anomalies at Short Baselines…….1) The Gallium source Anomaly

If one were to understand the SAGE and Gallex results in terms of sterile neutrino oscillations, one would expect these results (shown adjacent) in BEST





Combined result:
$R_0 = 0.80 \pm 0.05$

BEST confirms (with higher statistical precision) (4σ) a deficit in overall flux consistent with earlier SAGE/GALLEX results.

Barinov et al, arXiv:2109.11482, PRL arXiv:2201.07364, PRC 105, (2022) no. 6, 060552

Anomalies at Short Baselines…….1) The Gallium source Anomaly

However, while results can be accommodated in the sterile/active oscillation space, BEST did not observe any variation with distance.

Note that large mixing is required for the oscillation interpretation.

Smoking gun for oscillations is missing

This conflicts with:

——Reactor $\bar{\nu}_e$ which requires much smaller θ_{ee}

(slides below) →

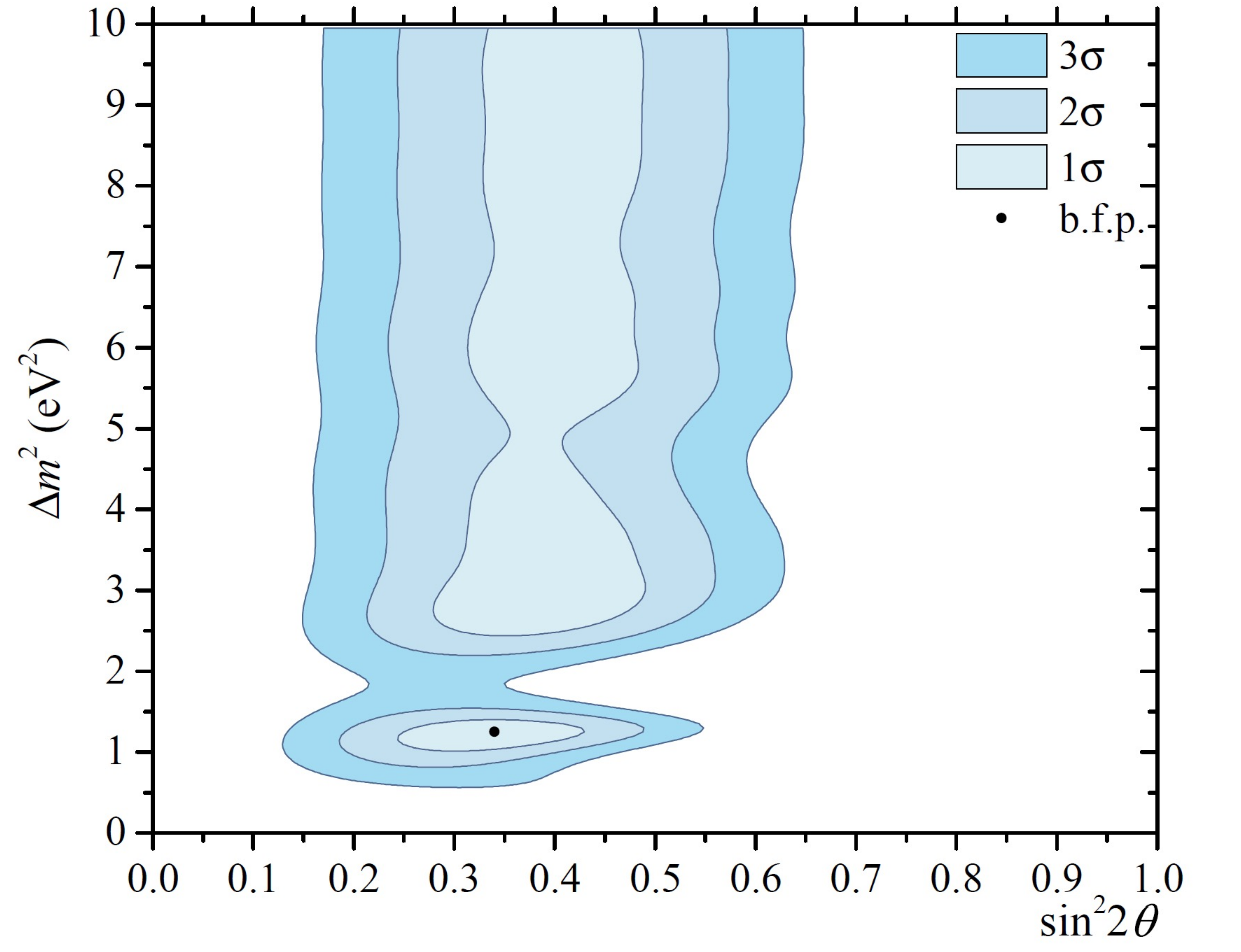


FIG. 8. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta$=0.33, Δm^2 = 1.25 eV^2 and is indicated by a point.

——Solar data, which do not tolerate high θ_{ee}

Possible non-oscillation reasons for the observed deficit could be inaccuracies in 1) xsecs, 2) source strength, 3) counting efficiency 4) extraction efficiency.

No clear answer at present.

Anomalies at Short Baselines…….Reactor Antineutrino Anomaly (RAA)

Reactor antineutrinos are produced from beta decays of neutron-rich fission fragments generated by the heavy isotopes 235U, 238U, 239Pu, and 241Pu

The most important antineutrino fluxes are those produced by the fissions of 235U and 239Pu.

The flux measurement from various reactors, was, until recently, on the average, about 3.5% ($\sim 3\sigma$) lower than predicted from careful calculations done by several groups.

Mueller et al. 1101.2663, Huber 1106.0687, Giunti et al. 2110.06820

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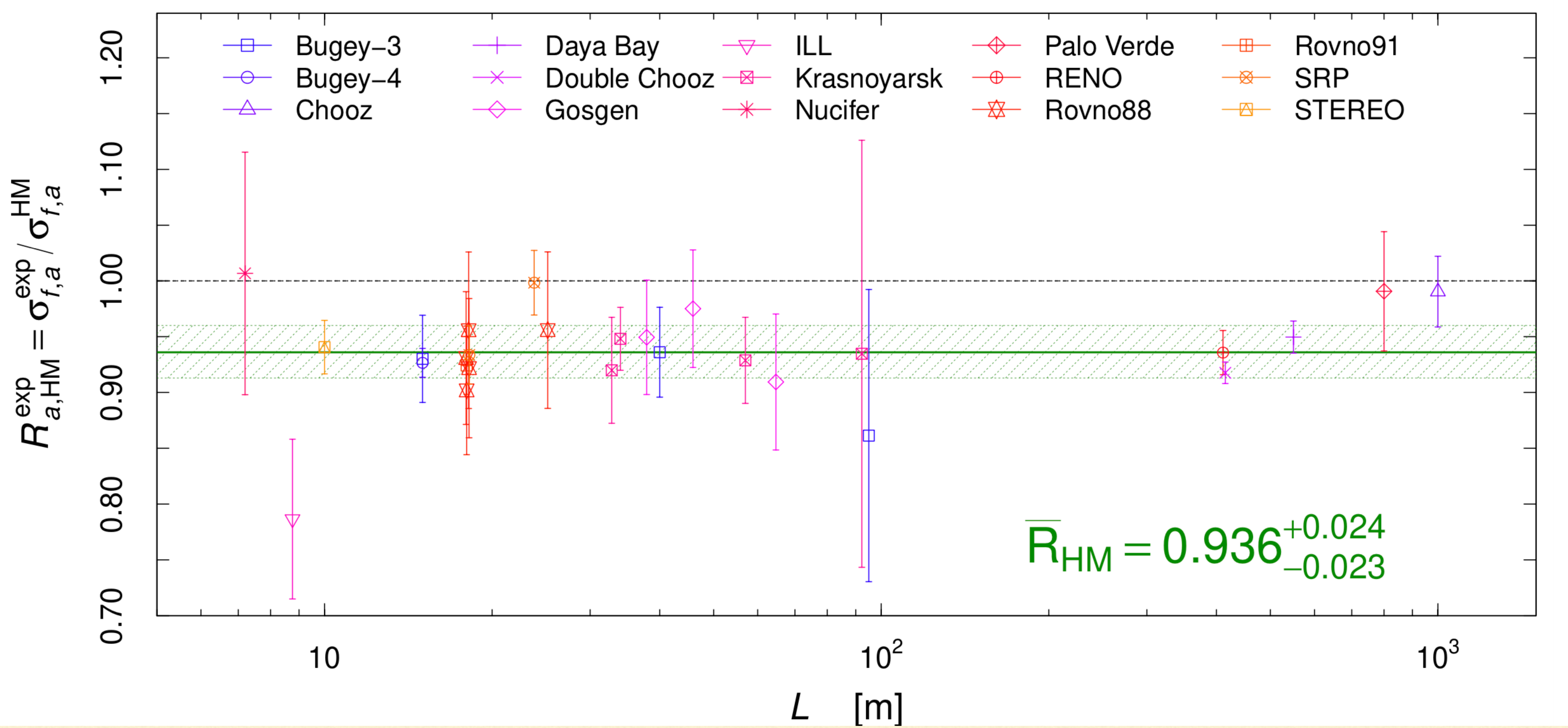
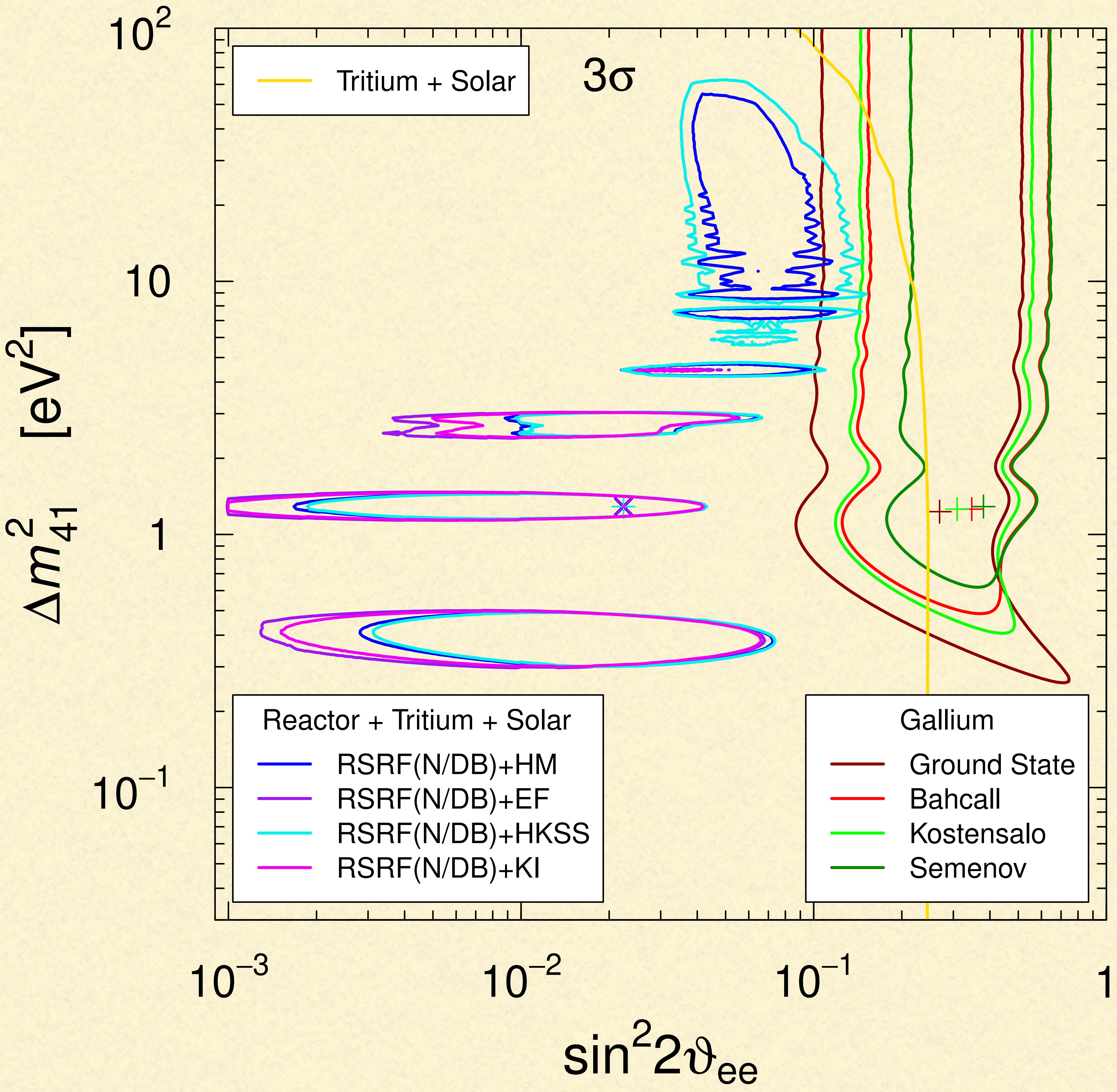
Anomalies at Short Baselines…….Reactor Antineutrino Anomaly (RAA)



Mueller et al. 1101.2663, Huber 1106.0687, Giunti et al. 2110.06820

This raised the possibility that the deficit was due to active-sterile oscillations .



Allowed oscillation regions for RAA in strong tension with oscillation parameters required to explain the Ga anomaly.

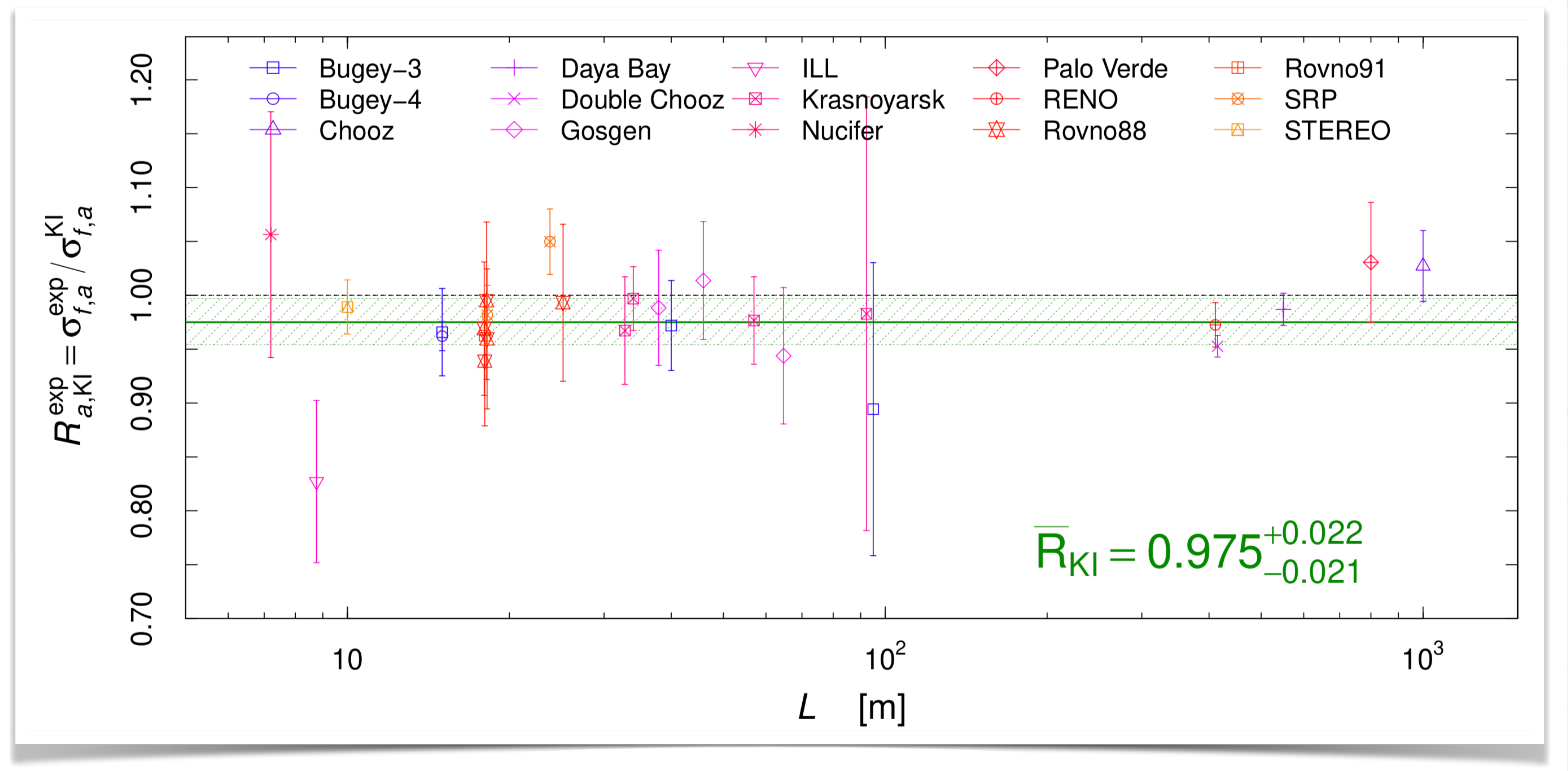
Anomalies at Short Baselines.......Reactor Antineutrino Anomaly (RAA)

Nuclear databases have been improved in recent years, especially through the application of the Total Absorption Gamma-ray Spectroscopy (TAGS) technique for a better identification of the β decay branches.

This new information was used by Fallot et al [18] (EF model) (1904.09358), and Silaeva et al, 2012.09917 to obtain a 235U reactor antineutrino flux that is smaller than that of the earlier models.

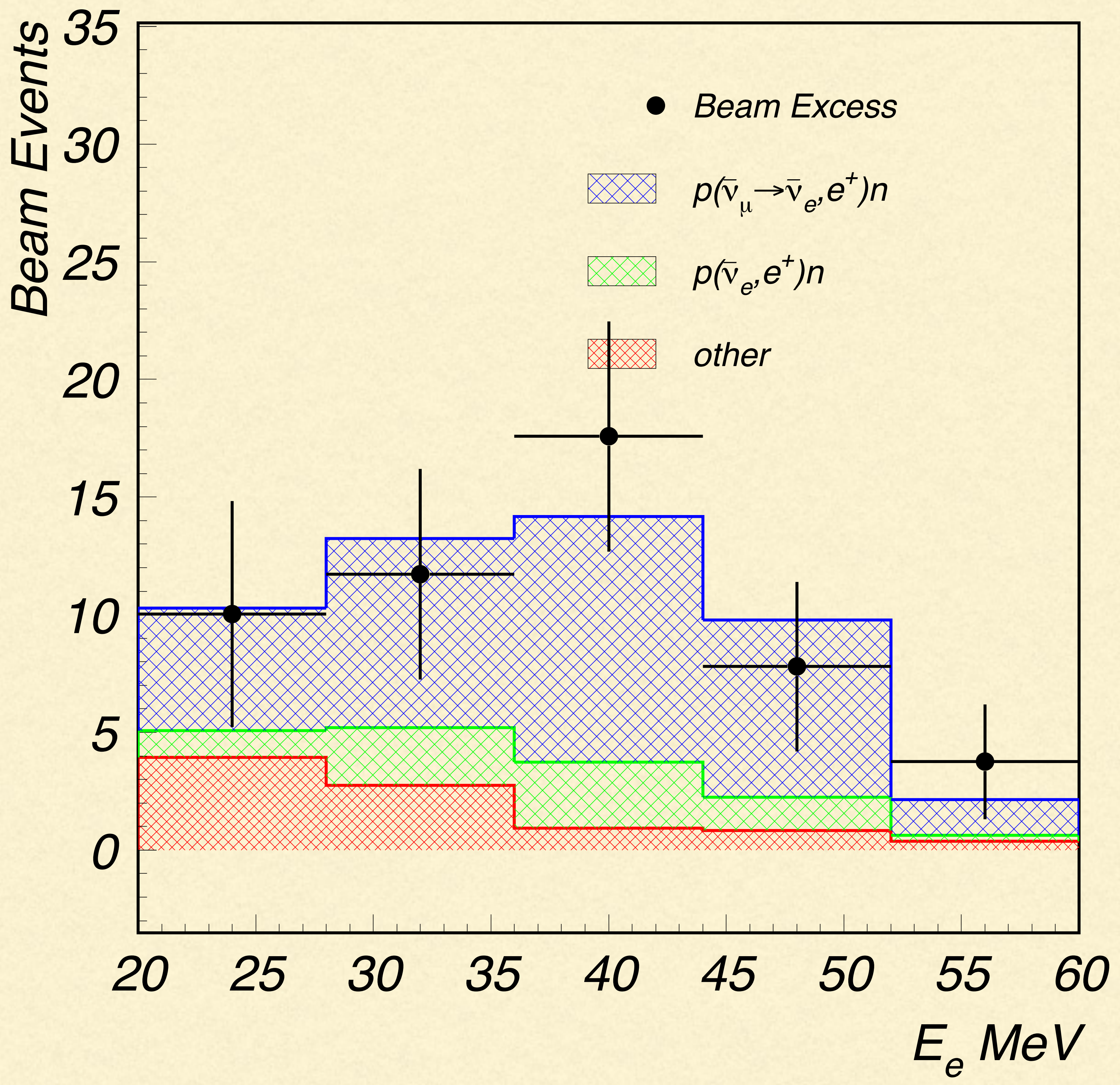
This has led to improved agreement with measured fluxes, and there is now a belief in the community that the RAA has been understood to be a flux calculation/data issue (as opposed to a neutrino deficit issue) .

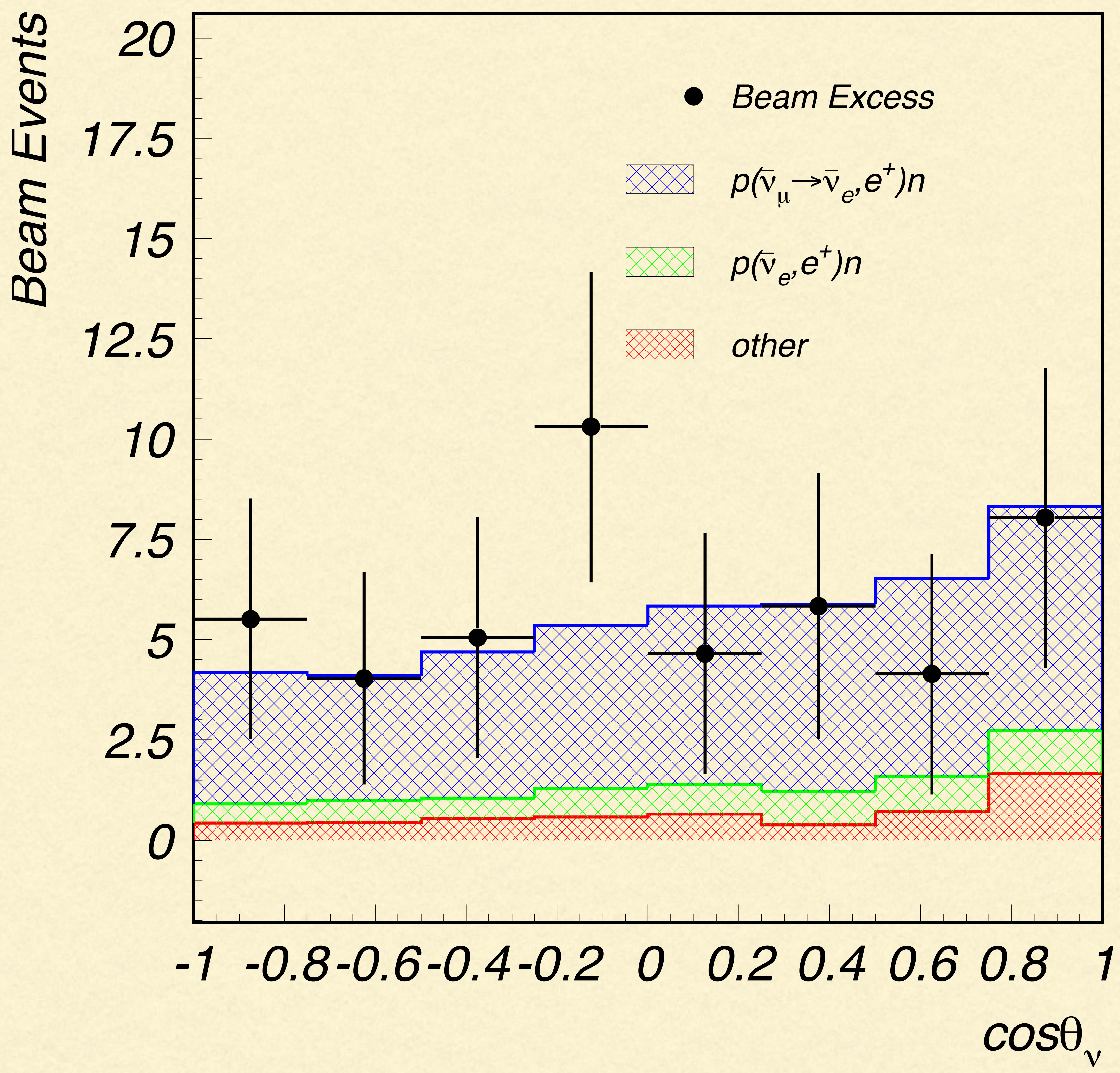
Anomalies at Short Baselines…….Reactor Antineutrino Anomaly (RAA)



Kopeikin et al 2103.01684, Berryman et al 2005.01756, Giunti et al 2110.06820

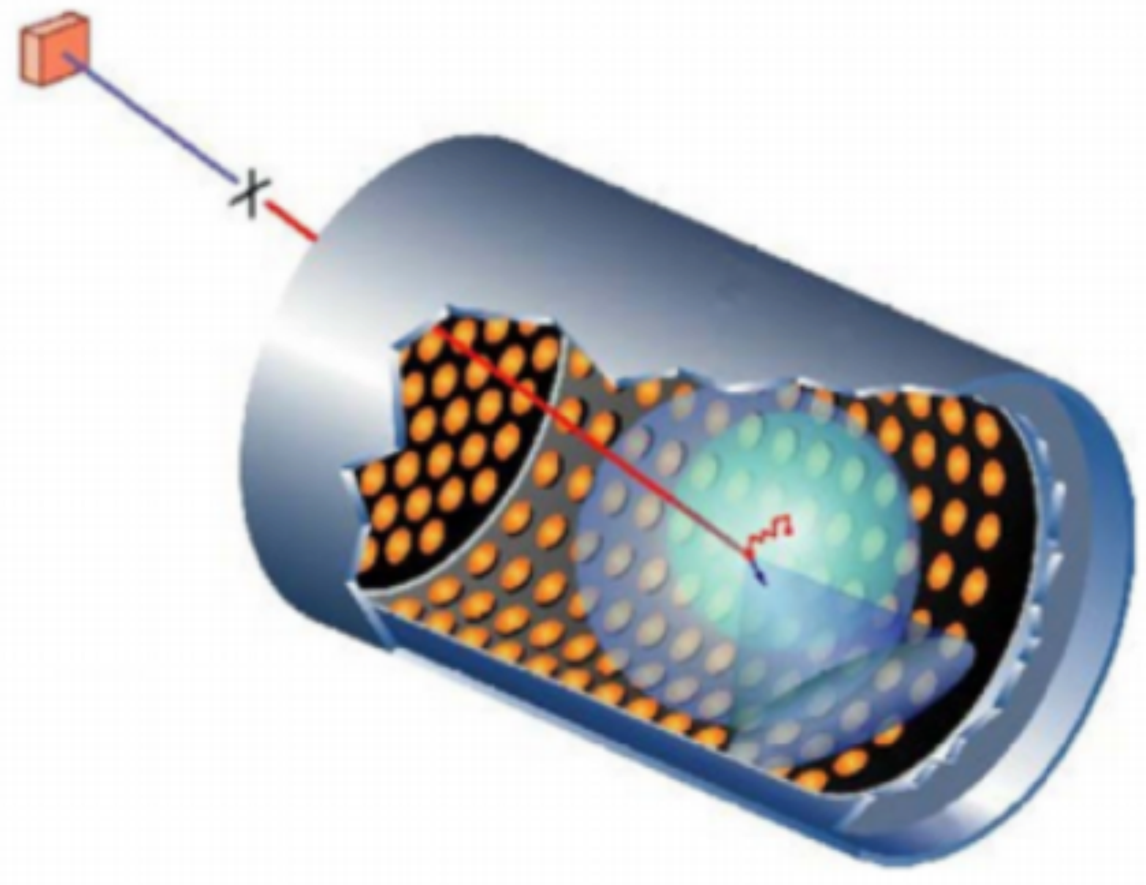
Anomalies at Short Baselines.......LSND (1993-1998)





LSND (3.8σ!)

Mineral oil scintillator detector



- Observation of unexplained electron-like excesses in the LSND at a level of 3.8σ above SM backgrounds.

Blue hatched region is oscillation fit.

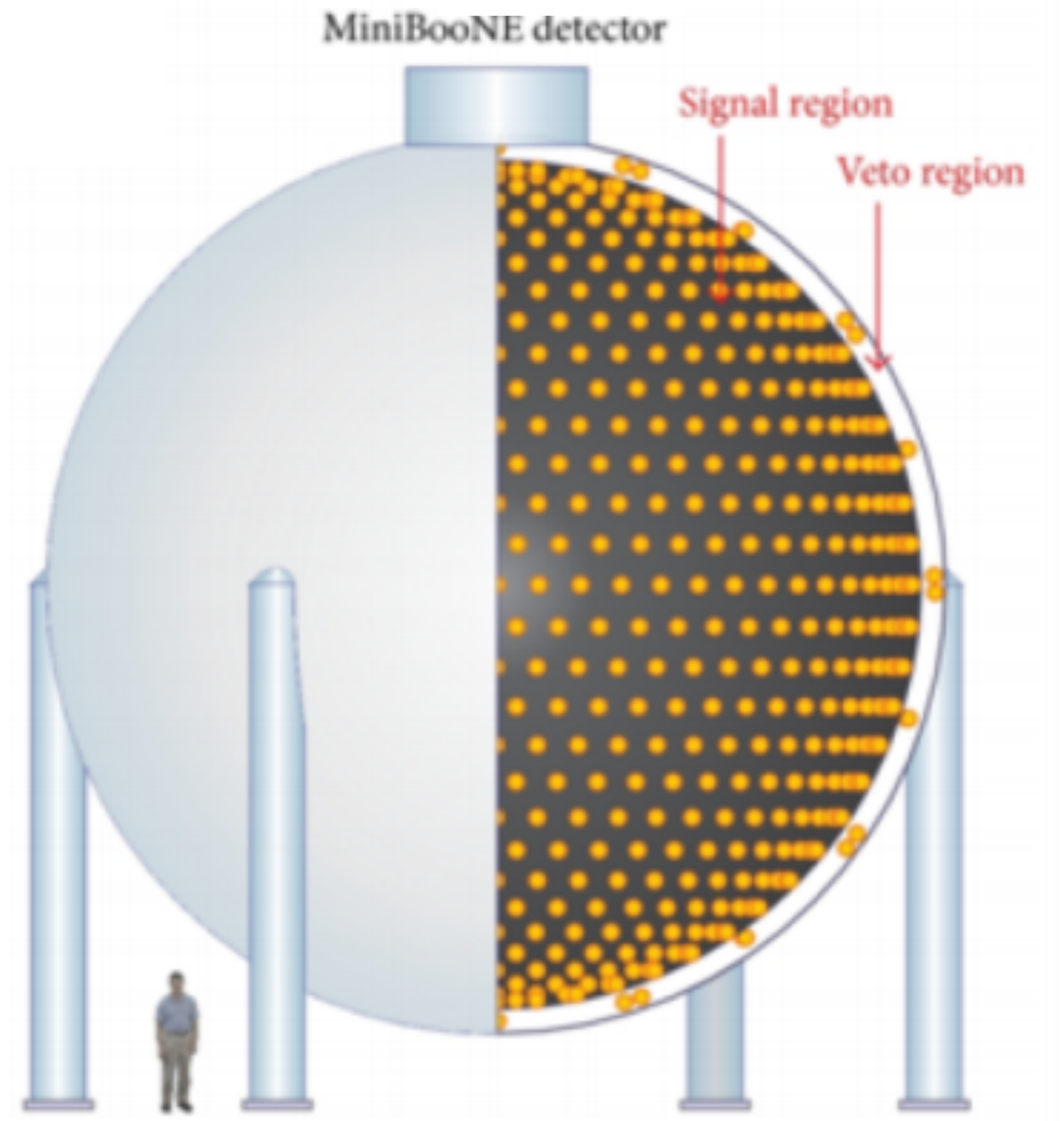
- Note that unlike MB, both energy and angular distributions are relatively flat

$\bar{\nu}_\mu$ From decay at rest (DAR) ν_μ From decay in flight (DIF)

Anomalies at Short Baselines…….MiniBooNE (2002-2017)

MiniBooNE

(4.8σ!)

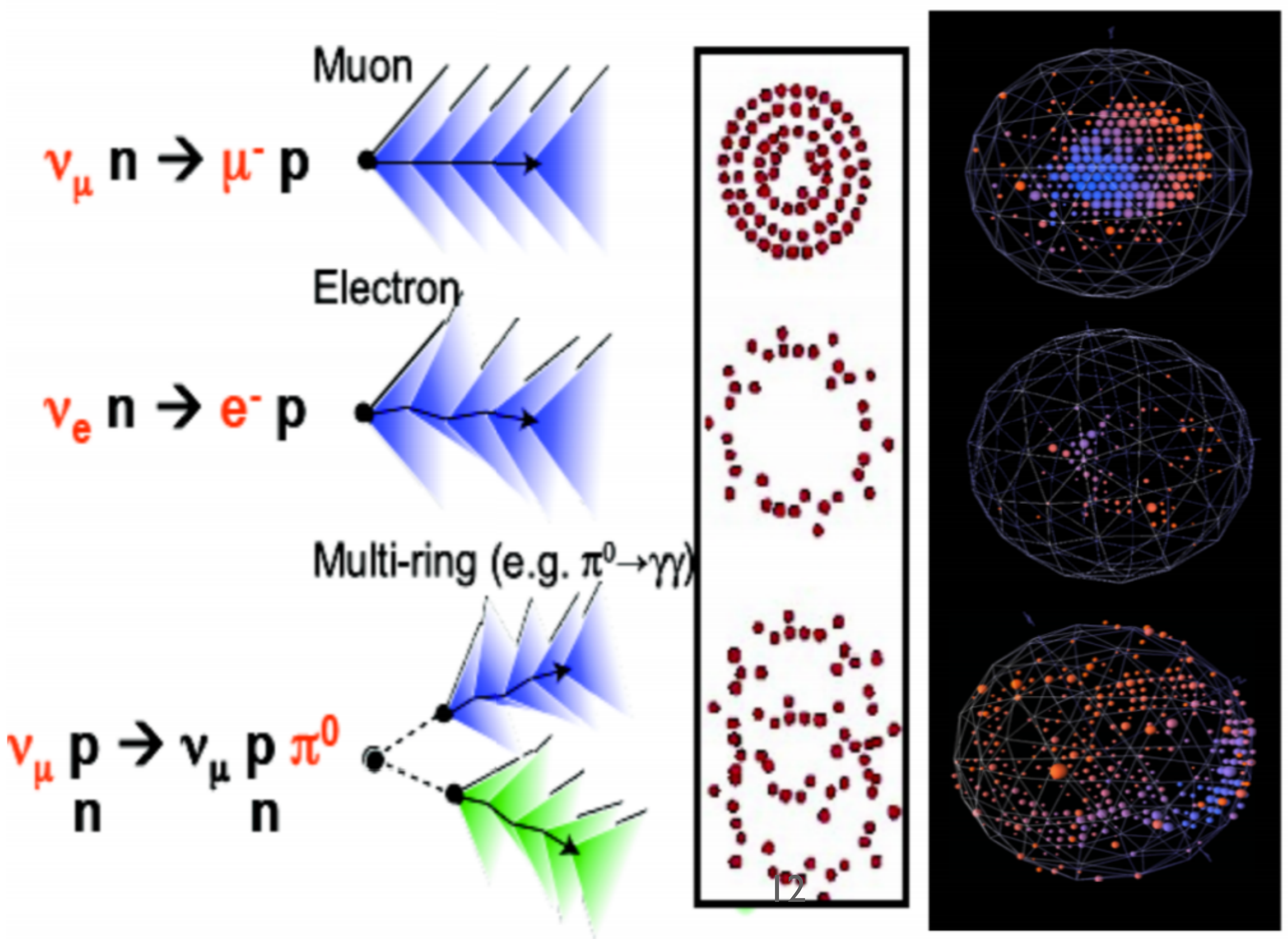


Mineral oil detector, 541 m baseline, 600 MeV (ν_μ) and 400 MeV ($\bar{\nu}_\mu$) peak fluxes.

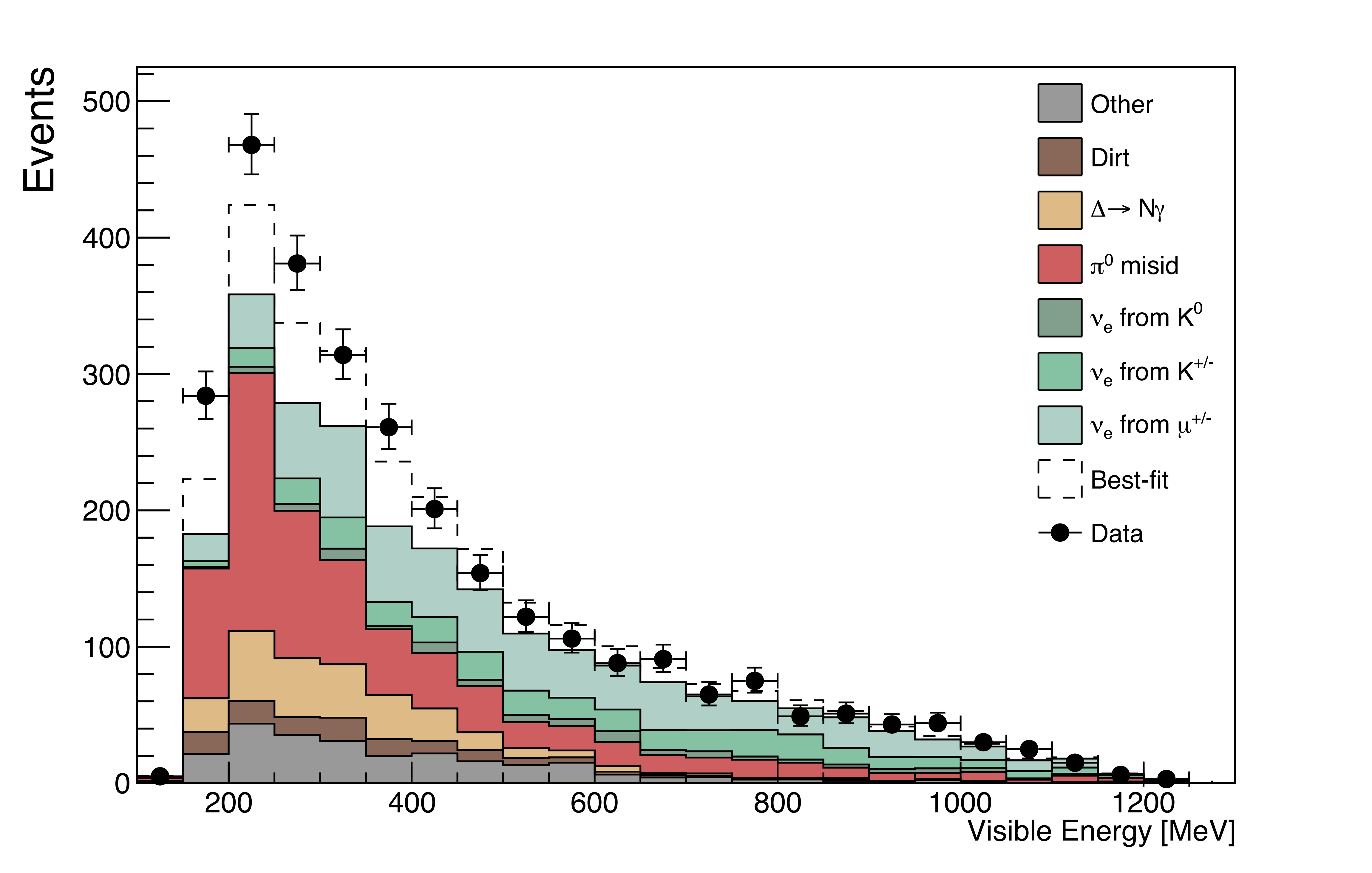
Was specifically built to test the LSND anomaly. Larger L, larger E, same L/E.

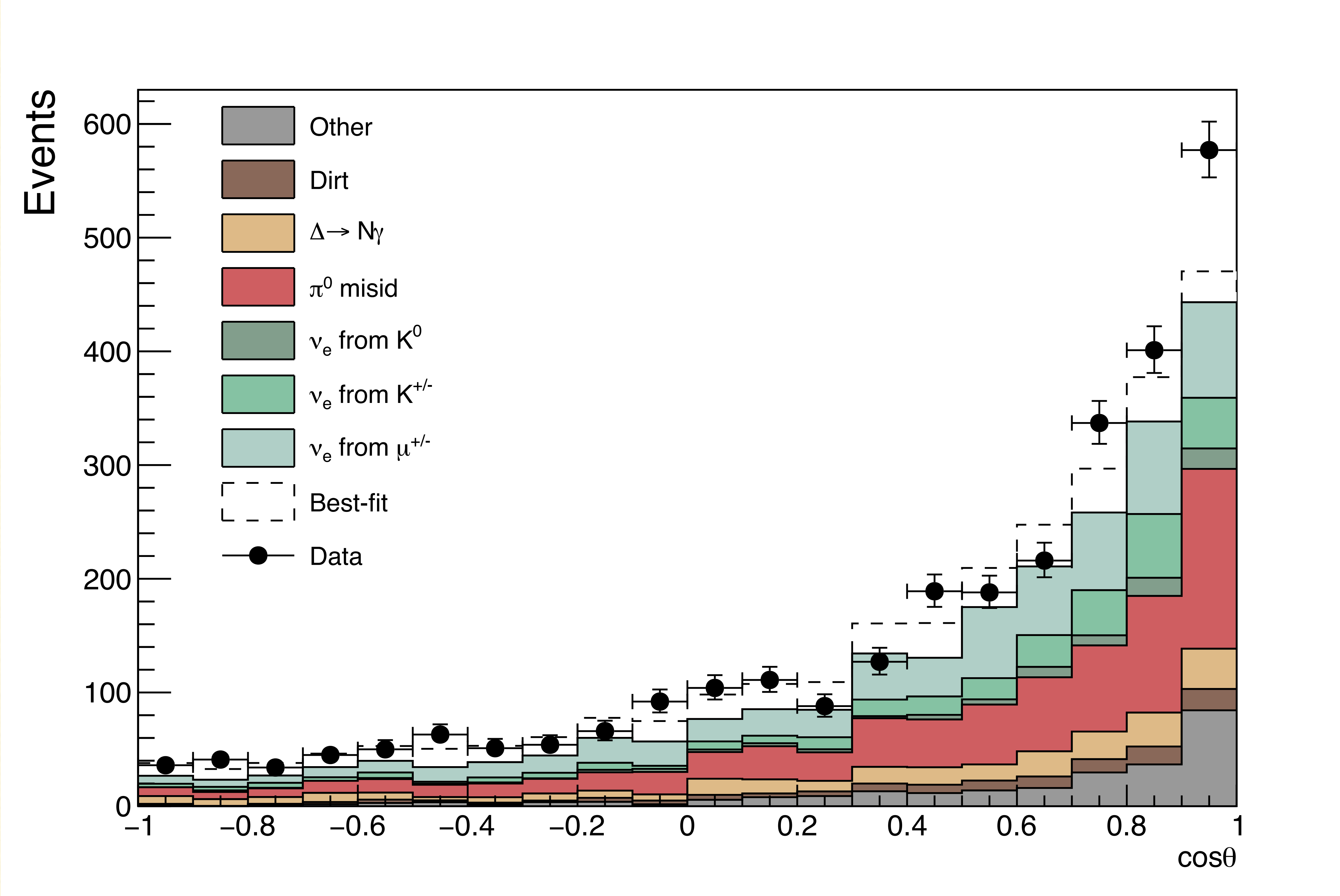
Three typical event signatures:

- Muon-neutrino CCQE produces sharp photon ring on PMTS,
- Electron-neutrino CCQE events produces fuzzy ring,
- Muon-neutrino NC can produce π_0: two gammas -> two fuzzy rings.



Anomalies at Short Baselines.......MiniBooNE





- A 4.8σ excess in electron-like events for neutrino and antineutrino modes in the MiniBooNE (MB) detector is observed

- SM: 2309 events
  Data: 2870
  Excess: 560

Excess is not small. Note it is at level of important SM backgrounds

Distinctive energy and angular distribution

Dashed line is oscillation fit. Not a good fit at low energies or forward angles where most events present

MiniBooNE status……..

Possible systematics like :

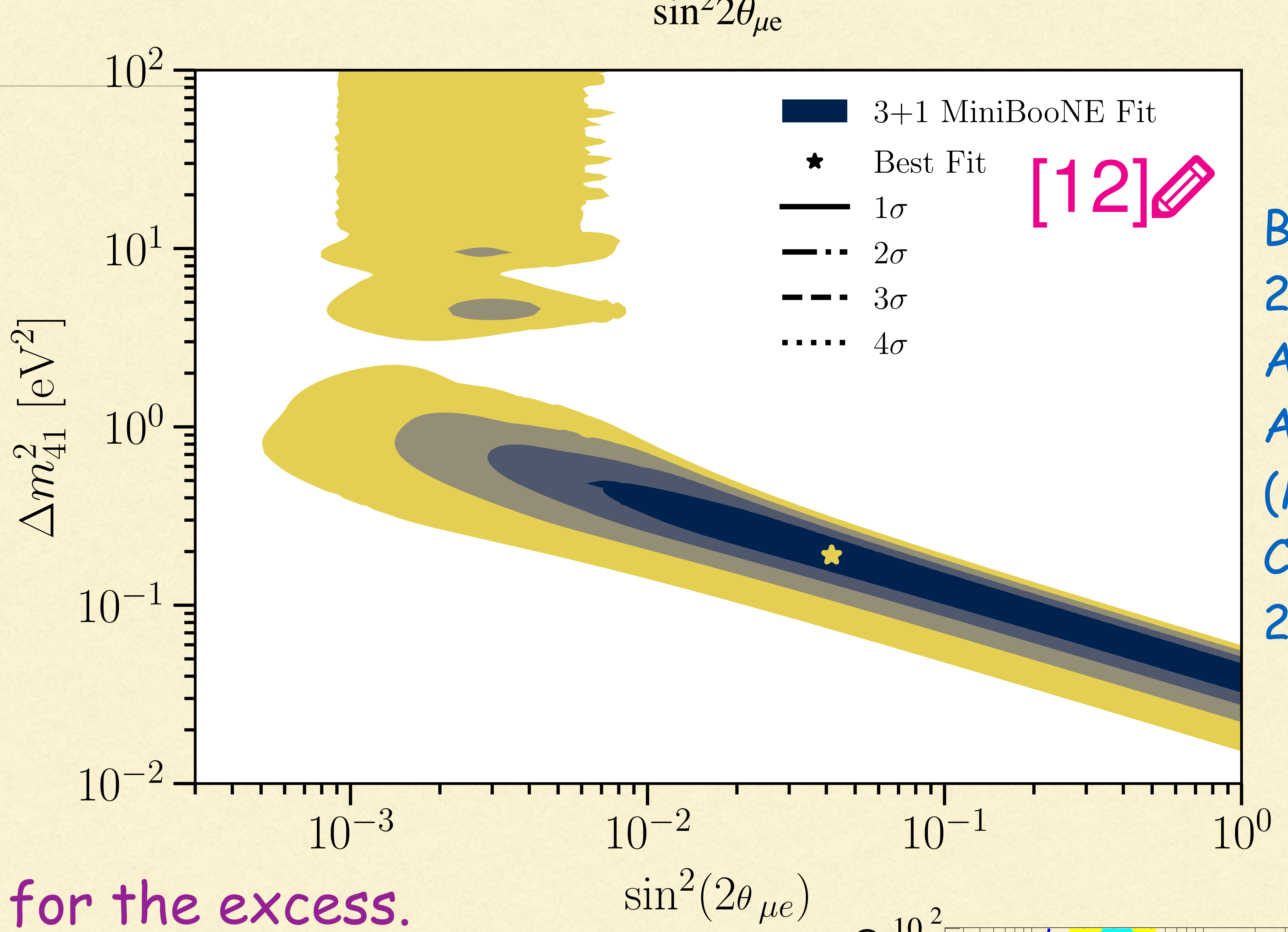
—Single photon from NC misidentified as e^- from ν_e

—π^0 Coming from NC identified as e

— incorrect reconstruction of neutrino energy

Have been extensively tested for .

At present, no combination of these can account for the excess.

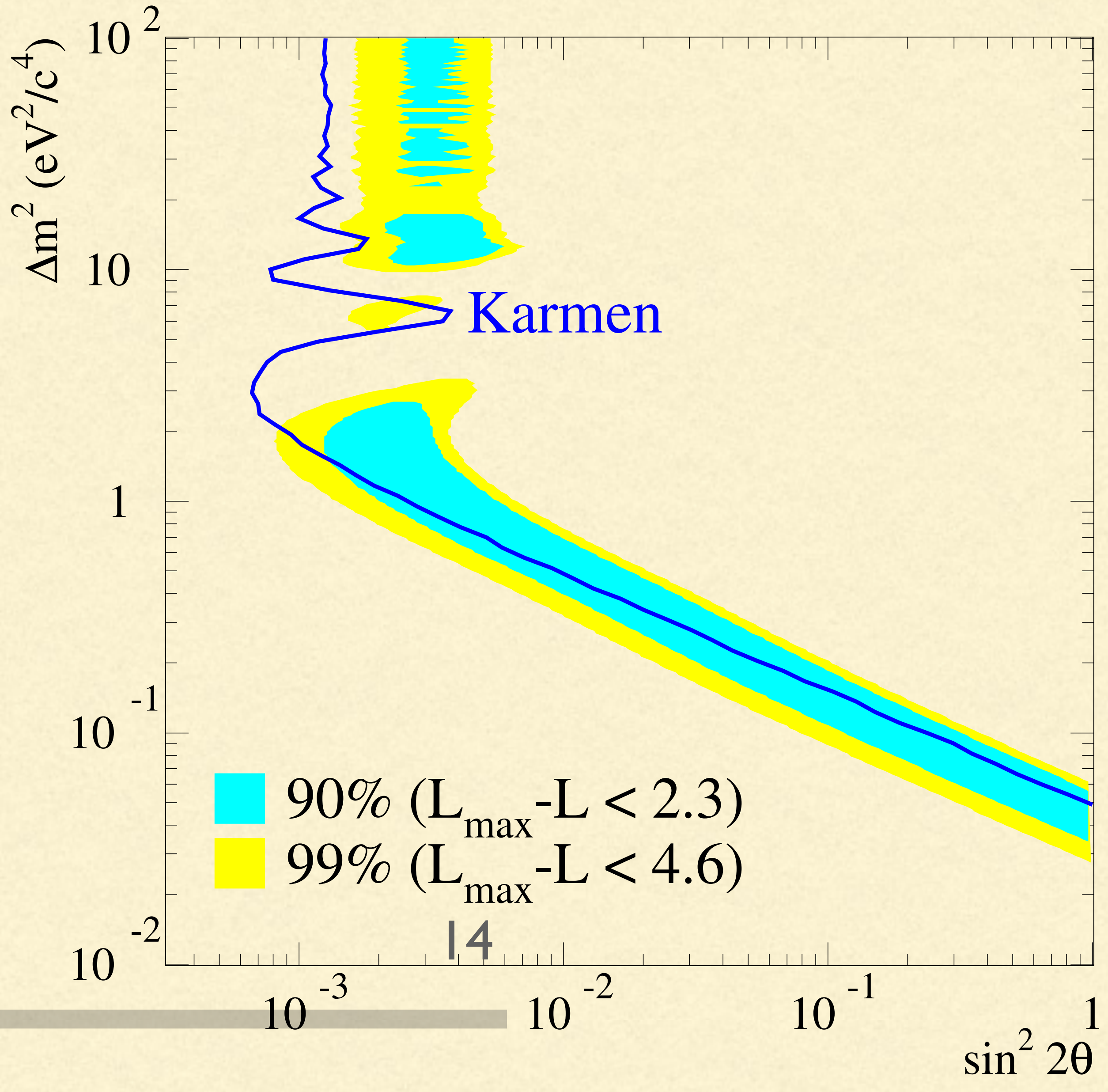


Brdar and Kopp, 2109.08157, A.A.Aguilar-Arevalo et al (MiniBooNE Collaboration) 2201.01724

Earlier oscillation allowed region for MB has been revised after

accounting for $\bar{\nu}_e$ beam contamination and $\bar{\nu}_\mu$ calibration.

Note overlap with allowed LSND region



Maltoni, Nu 2024 talk

Tension between appearance and disappearance for active-sterile oscillations

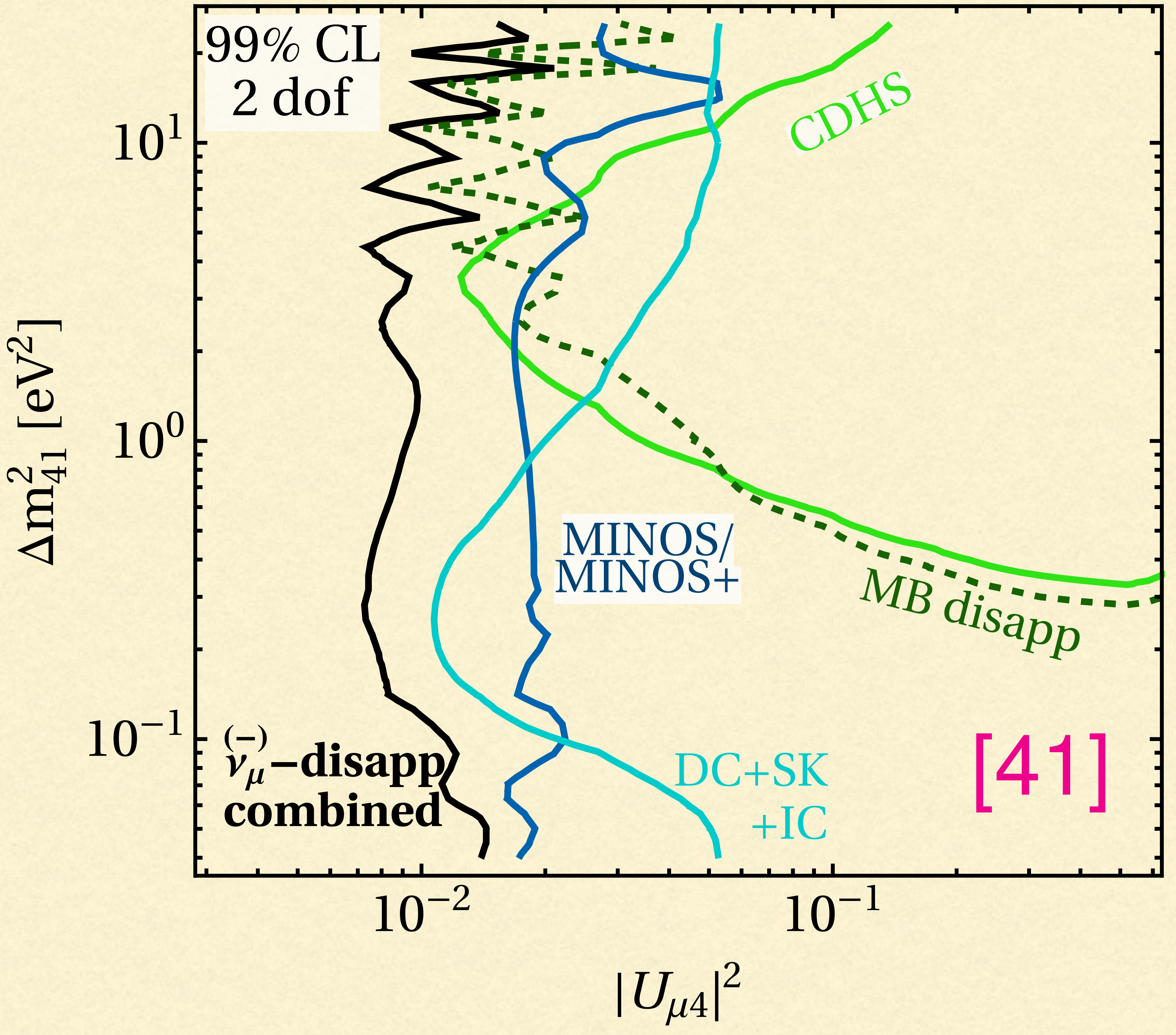
We note that non-zero nu_mu-nu_ e appearance requires both nu_e and nu_mu disappearance

Many experiments have looked for ν_μ disappearance :

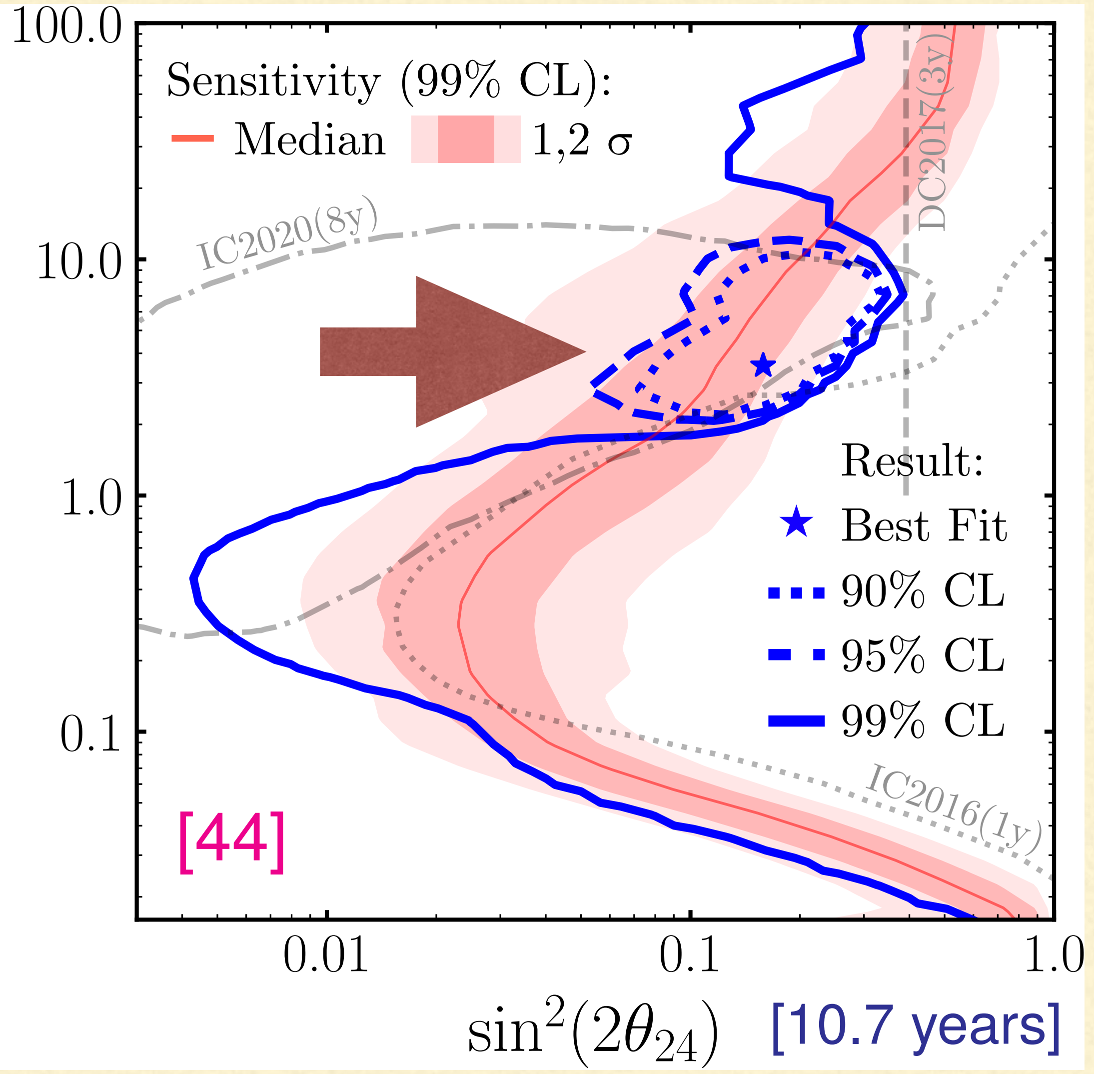
- CDHS (ν) – MiniBooNE ($\nu, \bar{\nu}$) – SciBooNE ($\nu, \bar{\nu}$)

- MINOS (ν) – NOνA (ν) – SK atmos ($\nu, \bar{\nu}$)

- no hint of ν_μ disappearance has been observed;



Small island earlier allowed by IceCube is now disfavoured by their latest results, which require $|U_{\mu4}|^2 < 0.0534$ at 90% CL under the assumption that $\Delta m^2_{41} \geq 1 eV^2$.

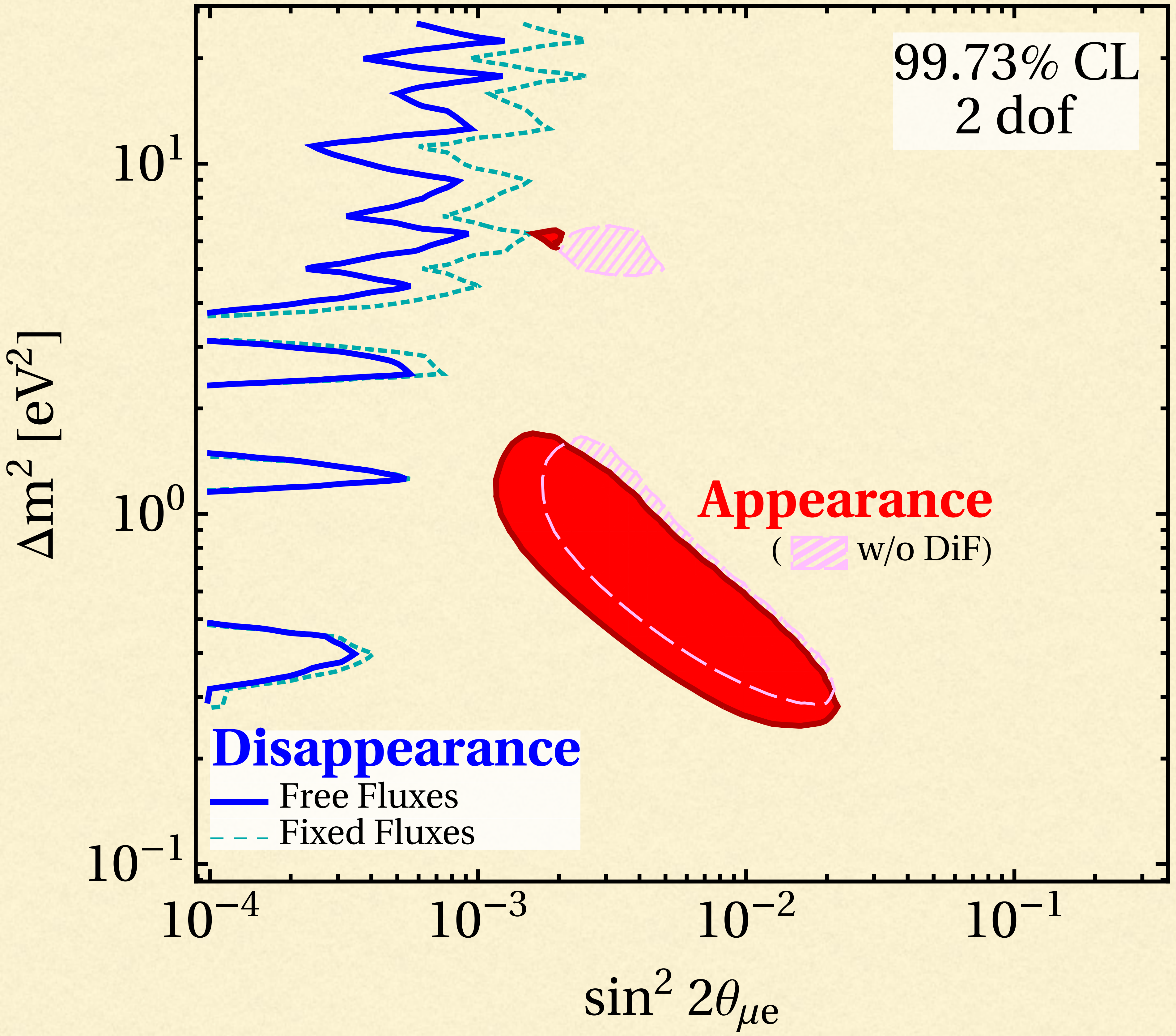


R. Abbasi et al, (IceCube Collab.) 2407.01314

Dentler et al, 1803.10661

Tension between appearance and disappearance for active-sterile oscillations

- Combined analyses to test the active-sterile hypothesis for short baseline anomalies by various groups all reveal a common underlying problem: **Strong tension between appearance and disappearance data**



Dentler et al 1803.10661

Additionally, eV scale sterile neutrinos are constrained by Cosmology…….

Any relativistic neutrino species will contribute to the energy density of the Universe as radiation. Their total contribution may be parametrised by the parameter N_{eff}

Cosmology is sensitive to neutrinos in a way that is complementary to laboratory searches. It is less sensitive to individual masses and mixings, but is more directly affected by the absolute mass scale,

$$\frac{\rho_r - \rho_\gamma}{\rho_\nu^{\mathrm{std}}} = N_{\mathrm{eff}}\,,$$

e ρ_r is the total radiation energy density, ρ_γ is the photon contribution

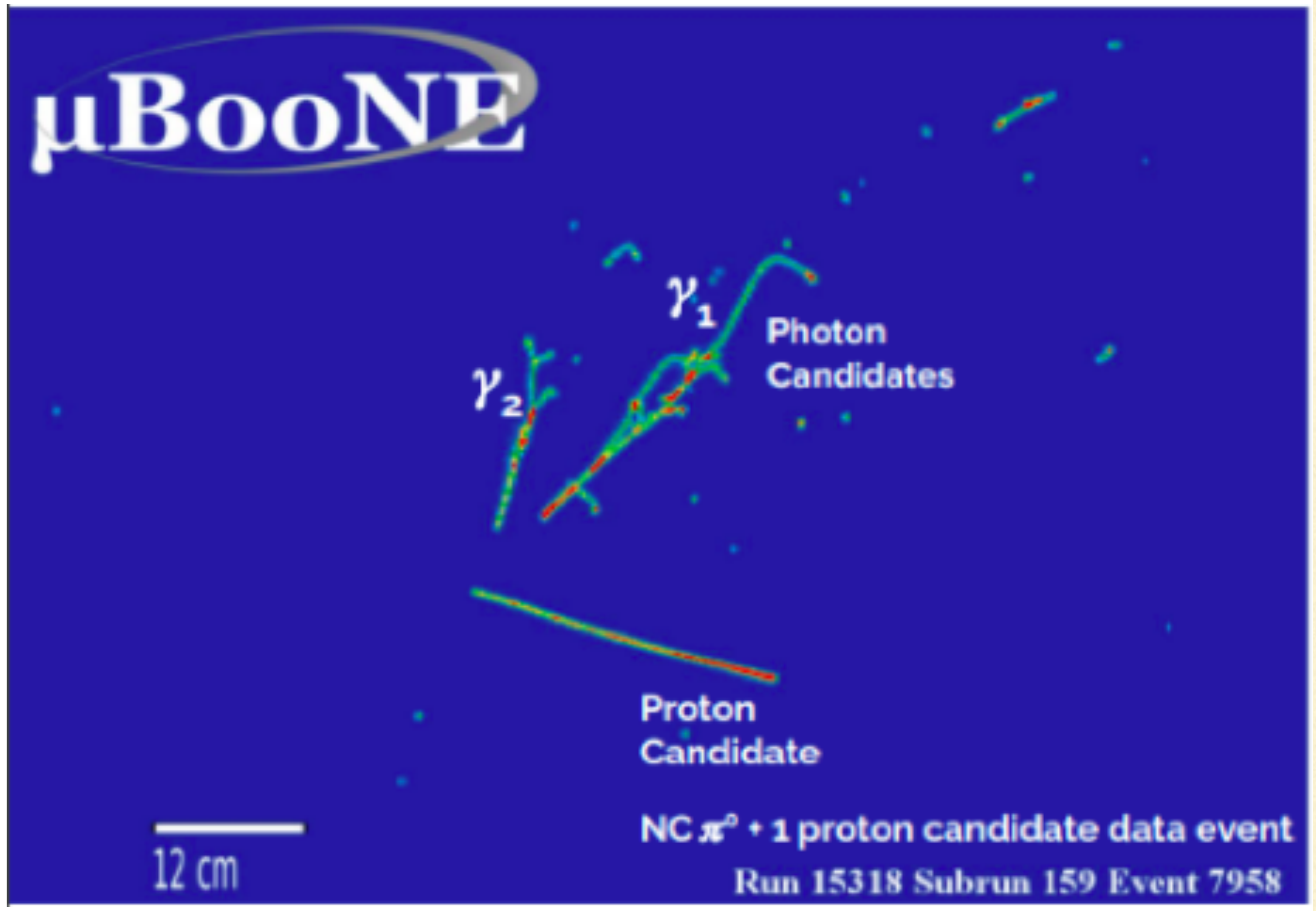
$$\rho_\nu^{\mathrm{std}} = 2 \times \frac{7}{8}\frac{\pi^2}{30}\left(\frac{4}{11}\right)^{4/3} T^4.$$

However, N_{eff} = 3.044 +- 0005 in the SM, leaving no space for an additional sterile relativistic neutrino species

Also, from PLANCK data,

$$\sum m_\nu < 0.26\,\mathrm{eV}\ (95\%\mathrm{CL}).$$

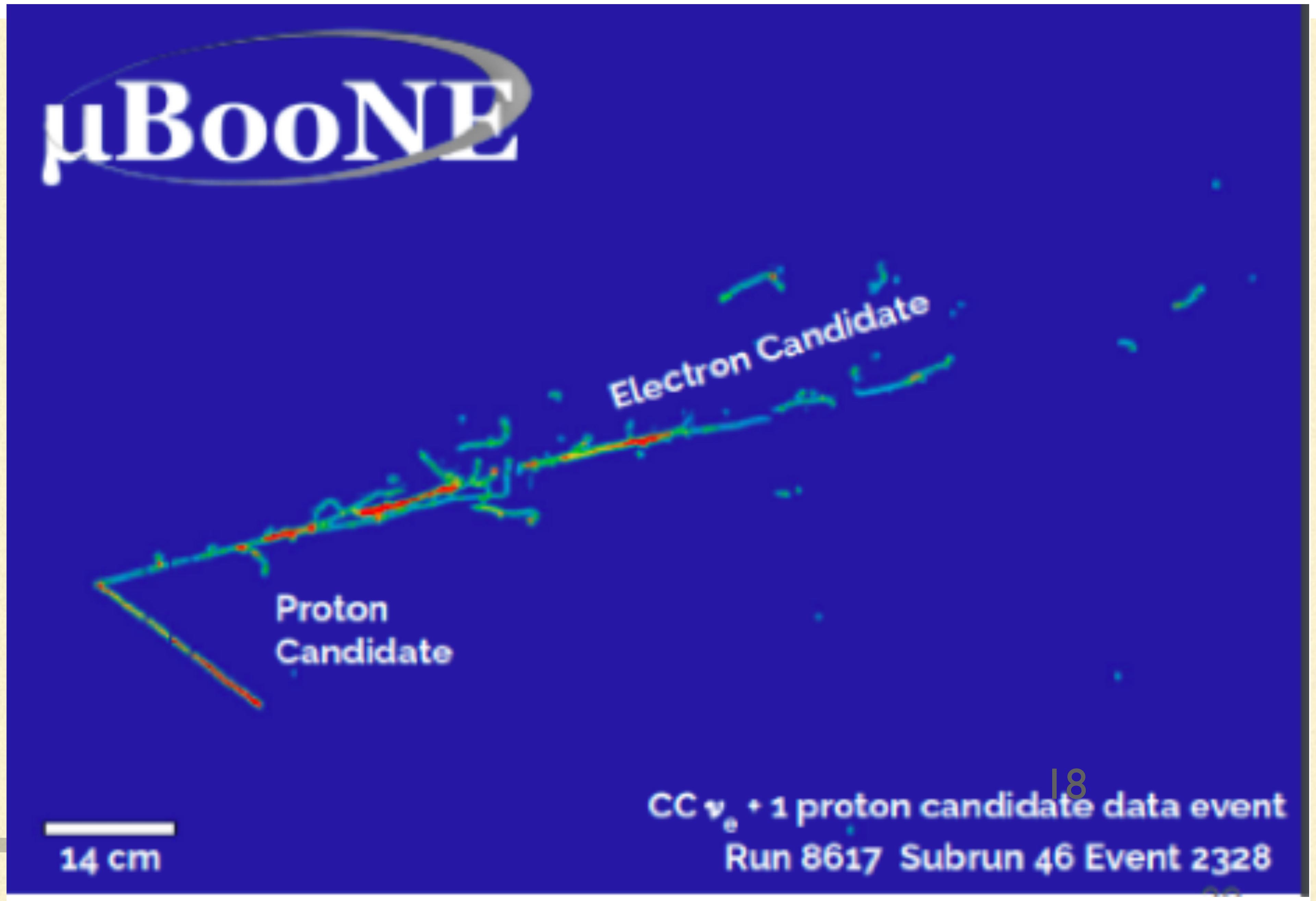
MicroBooNE (to test MB)



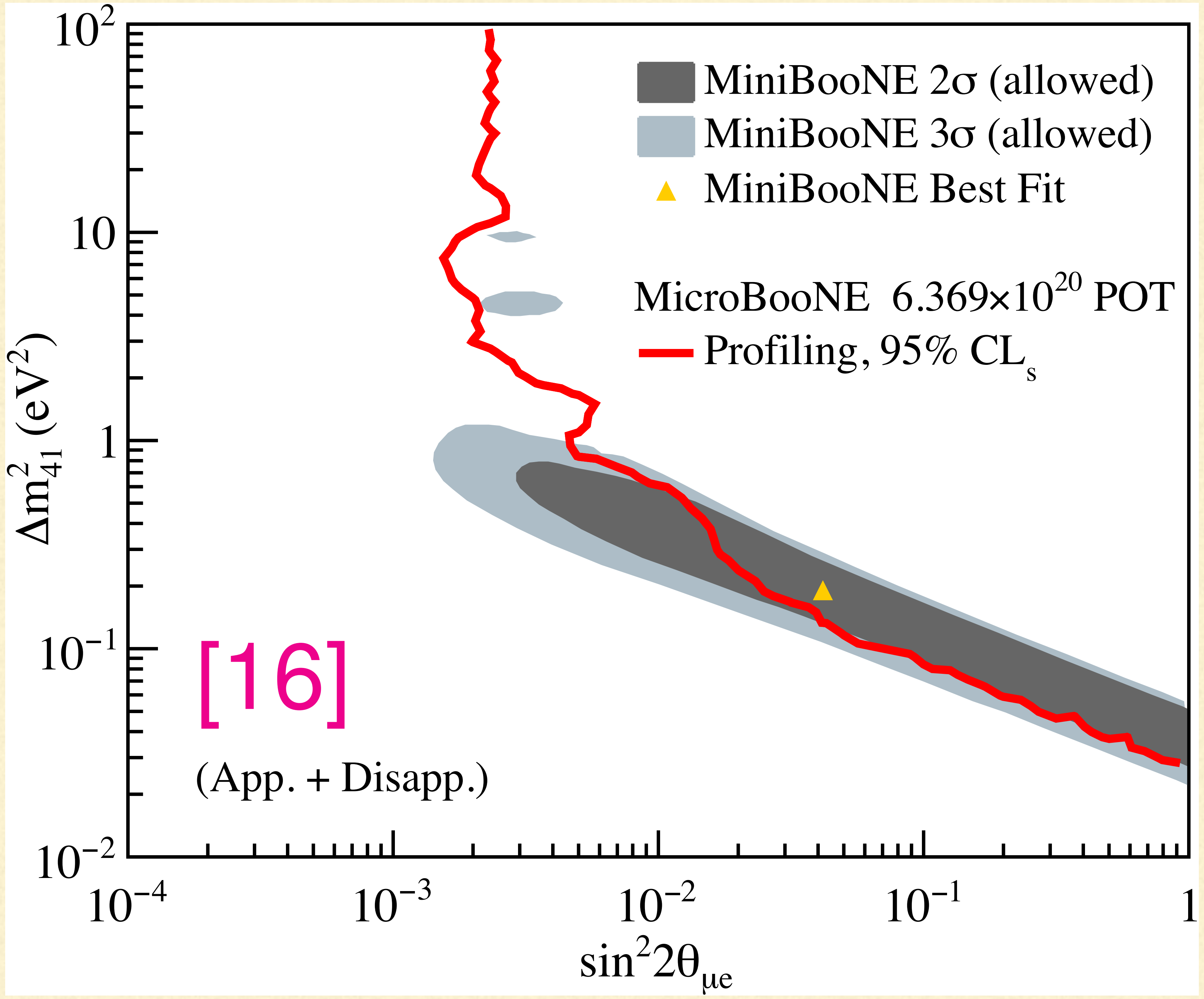
80 ton LAr TPC, L=468.5 m

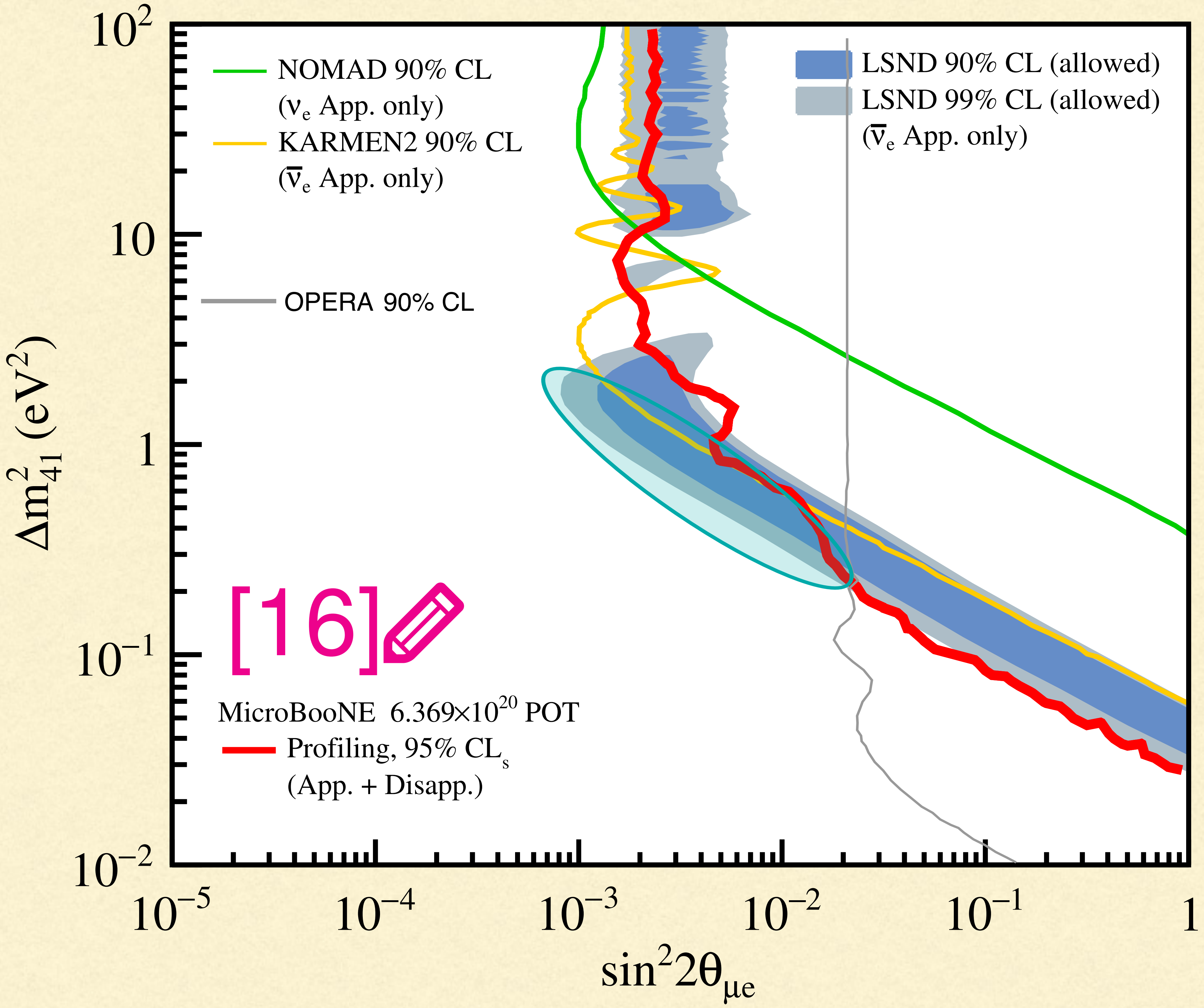
Excellent particle identification capabilities.

Can potentially distinguish electrons , protons and photons



MicroBooNE ……….





MicroB has performed a 4ν analysis that disfavours much of MB/LSND appearance space

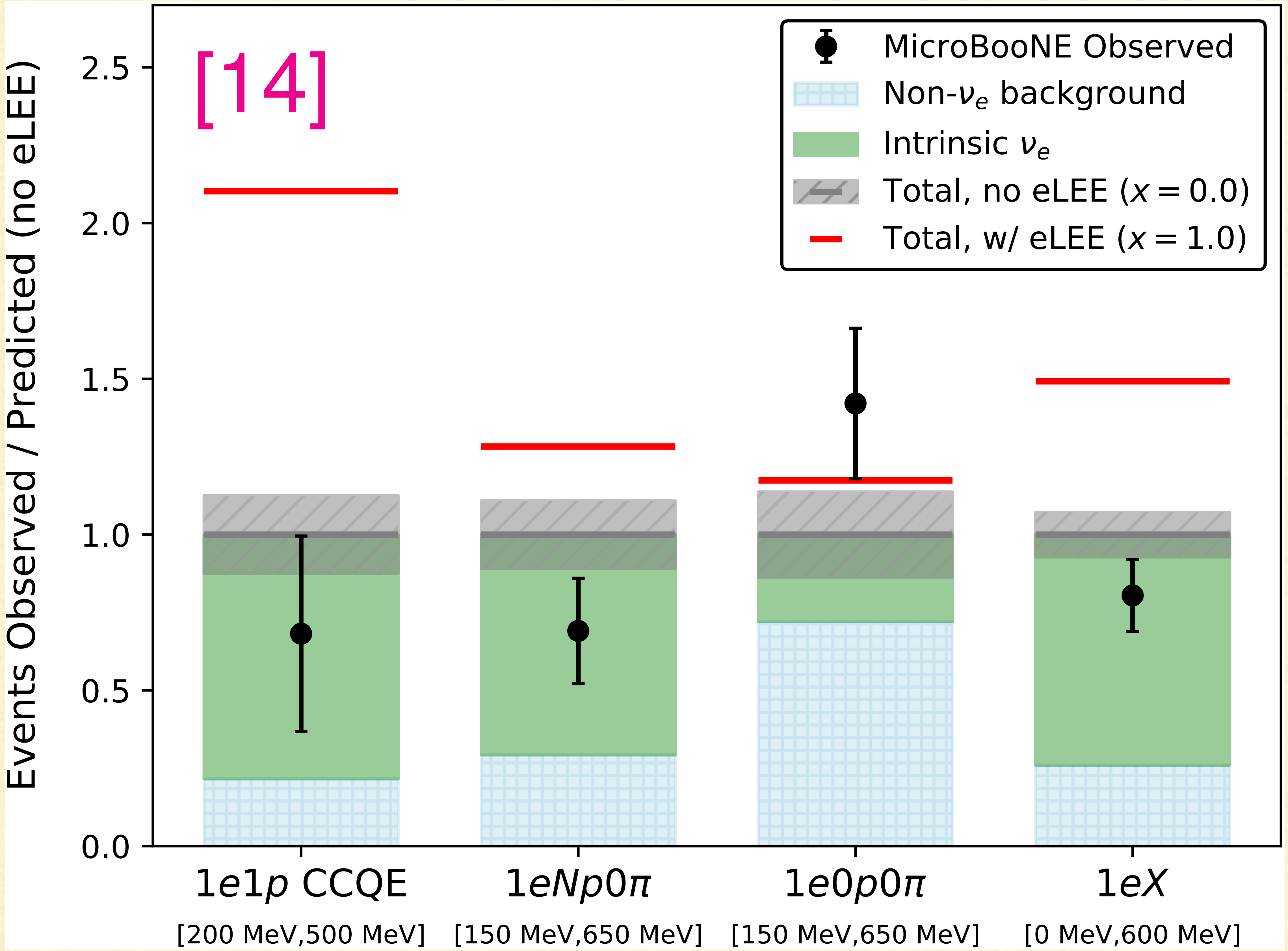
Region now allowed ➡ $0.1 \lesssim \Delta m^2_{41}/\text{eV}^2 \lesssim 1$ and $10^{-3} \lesssim \sin^2\theta_{\mu e} \lesssim \text{few} \times 10^{-2}$

Maltoni, Nu 2024 talk

MicroBooNE ……….

MicroBooNE has found no evidence for any additional π^0 or γ production which may simulate an electron-like signal in MB.

A search for νe induced interactions has also not provided any evidence of an excess.

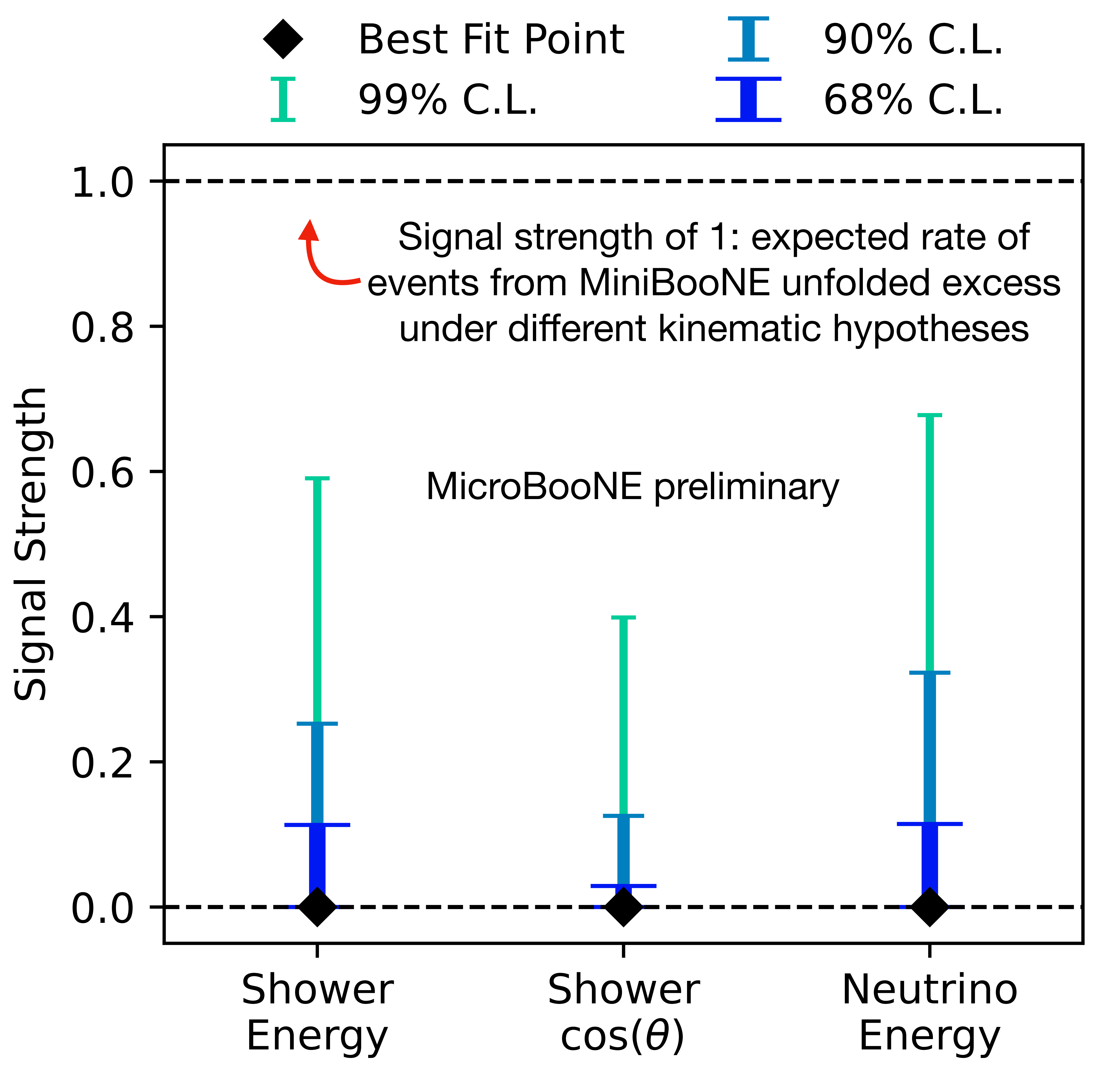


Maltoni, Nu 2024 talk

MicroBooNE ……….latest results

- data compatible with background-only prediction
- **data inconsistent with ν_e-like excess at > 99% CL**
- results consistent across kinematic variables tested.

Caratelli, (MicroBooNE collab) Nu 2024 talk



MicroBooNE results……

"These results disfavor the hypothesis that the MiniBooNE low-energy excess originates solely from an excess of ve interactions. Instead, one or more additional mechanisms [45–52] are required to explain the MiniBooNE observations. "

(MicroBooNE Collab, 2210.10216)

- [45] A.de Gouvˆea,O.L.G.Peres,S.Prakash,andG.V. Stenico, arXiv:1911.01447 [hep-ph].
  (Sterile to active decay)
- [46] S. Vergani, N. W. Kamp, A. Diaz, C. A. Argu¨elles, J. M. Conrad, M. H. Shaevitz, arXiv:2105.06470 [hep-ph].
  (Mix of sterile osc and decay to active)
- [47] J. Asaadi, E. Church, R. Guenette, B. J. P. Jones, and A. M. Szelc, arXiv:1712.08019 [hep-ph].
  (New matter resonance effects)
- [48] D. S. M. Alves, W. C. Louis, and P. G. deNiverville, arXiv:2201.00876 [hep-ph].
  (New matter resonance effects)
- [49] E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, arXiv:1807.09877 [hep-ph].
  (Up-scattering and additional Z')
- [50] P. Ballett, S. Pascoli, and M. Ross-Lonergan, arXiv:1808.02915 [hep- ph].
  (Up-scattering and additional Z')
- [51] W. Abdallah, R. Gandhi, and S. Roy, arXiv:2010.06159 [hep-ph].
  (Up-scattering and additional Z')
- [52] W. Abdallah, R. Gandhi, and S. Roy, arXiv:2006.01948 [hep-ph].
  (Up-scattering and Additional scalars)

Plus

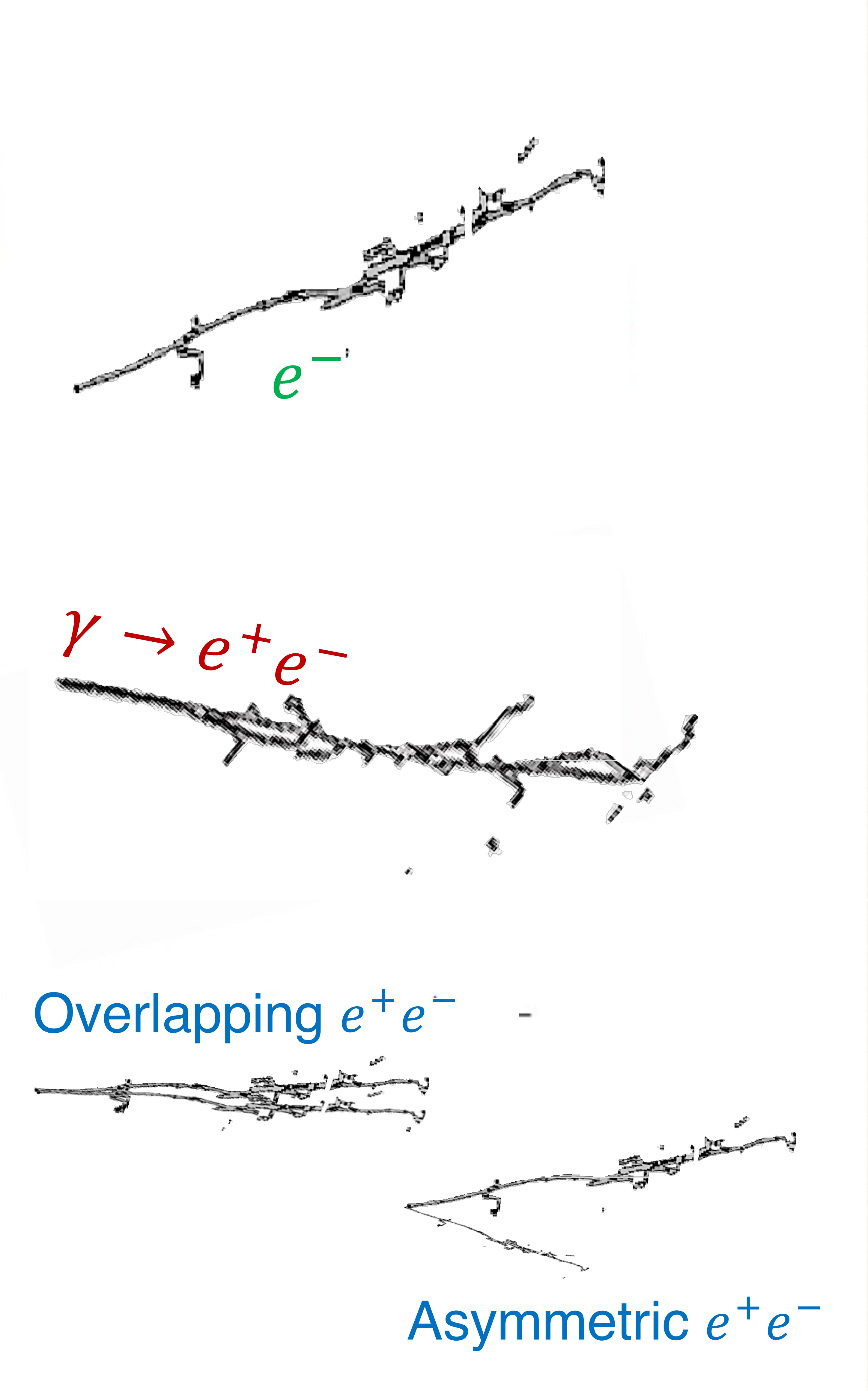
arXiv 2406.07643 ;W. Abdallah, RG, T. Ghosh, N. Khan, Samiran Roy, Subhojit Roy

Some general comments…………

An important point: Both MB and LSND were mineral oil detectors measuring $E_{visible}$, unable to distinguish electrons from photons or e+e- pairs

New physics (NP) proposals rely on this limitation

For a NP interaction giving an electron-like signal due to pair production in the LSND/MB detectors, a new mediator is required.
This can in principle be a vector, axial vector , scalar or pseudo scalar

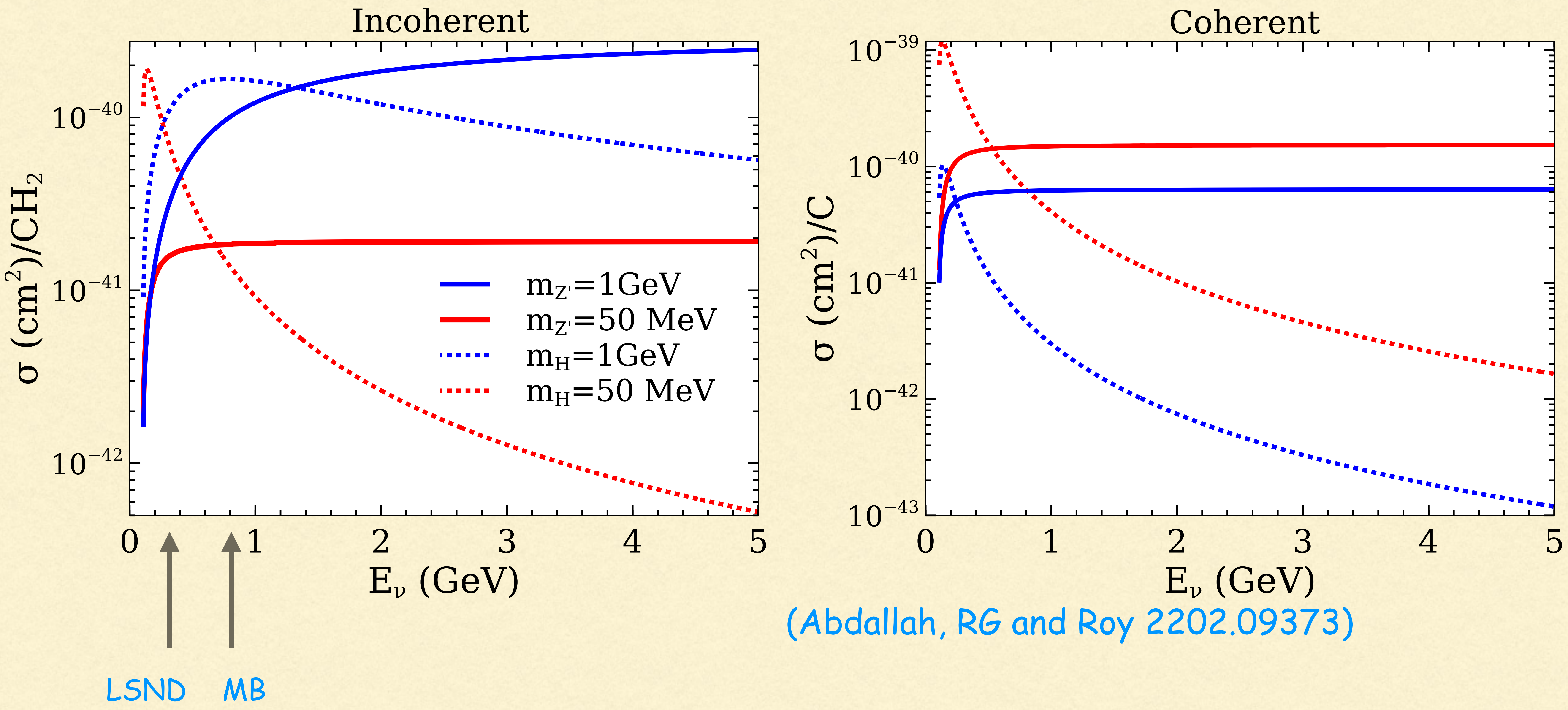


New mediators , LSND and MB, ……

Using an additional Z' and heavier sterile neutrinos, it is possible to get good fits to the MB data

Bertuzzo, Jana, Machado & Funchal, 1807.09877;
Ballet, Pascoli, Ross-Lonergon 1808.02915;
Abdallah, RG and Roy 2006.01948)

However, it is very difficult to explain both LSND and MB simultaneously using these ingredients, because a vector mediator does not give enough events at LSND

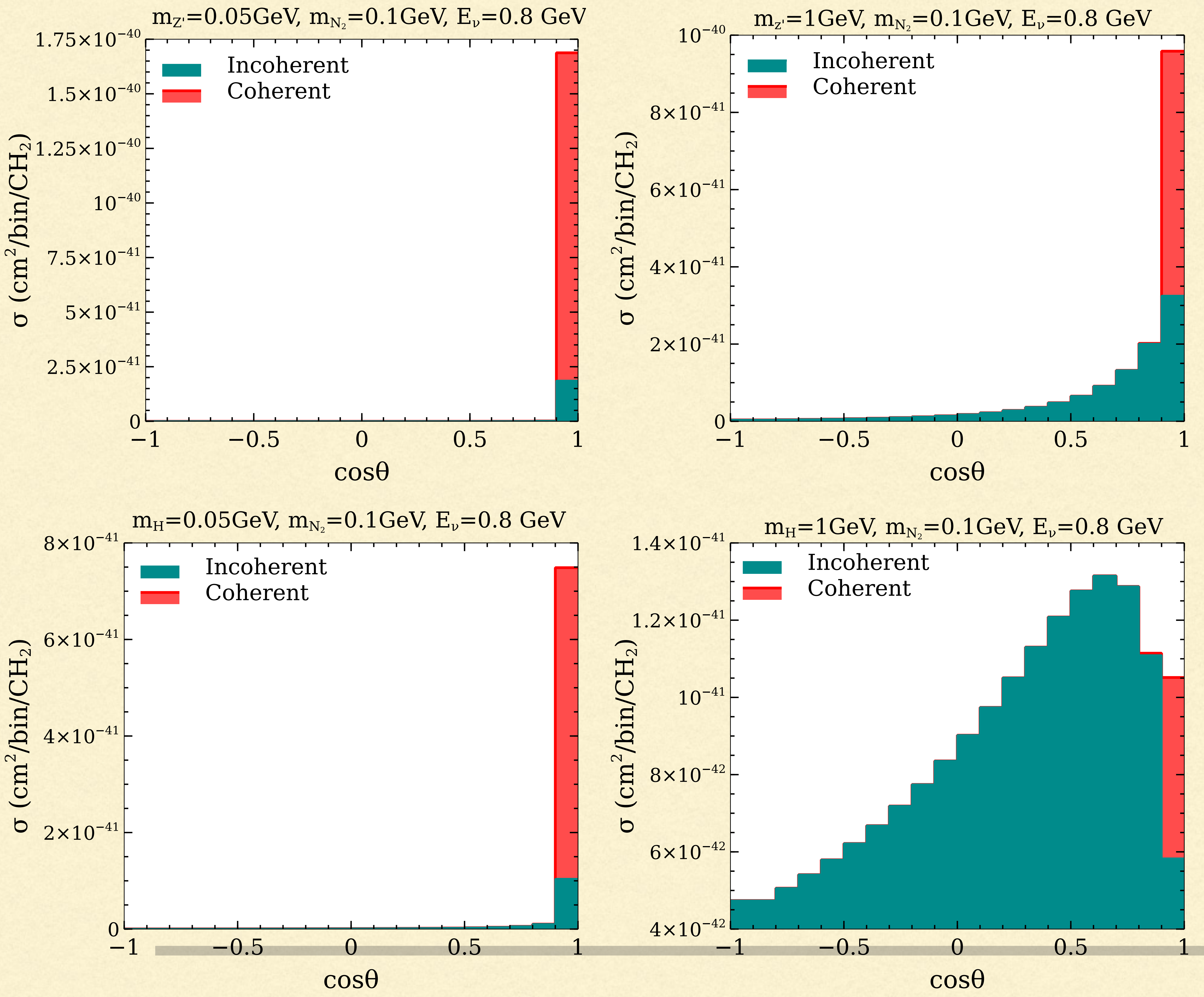


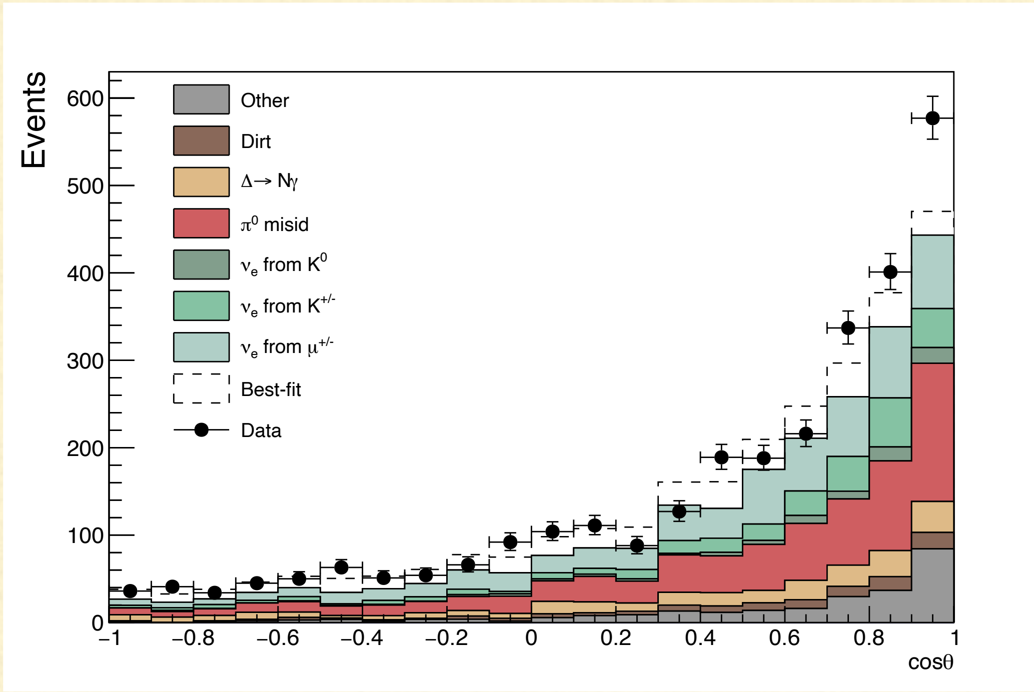
(Abdallah, RG and Roy 2202.09373)

Vector models, given the shape of the xsec, violate constraints by experiments with higher E, e.g. CHARM II (E_nu ~ 20 GeV and MINERvA, E_nu ~ 4-5 GeV)

Scalar mediators not only avoid HE constraints that vector mediators have difficulty avoiding, but also give enough events at LSND once you get the required number at MB.

What does one learn if one demands that the new physics resolve both LSND and MB, as opposed to just MB.



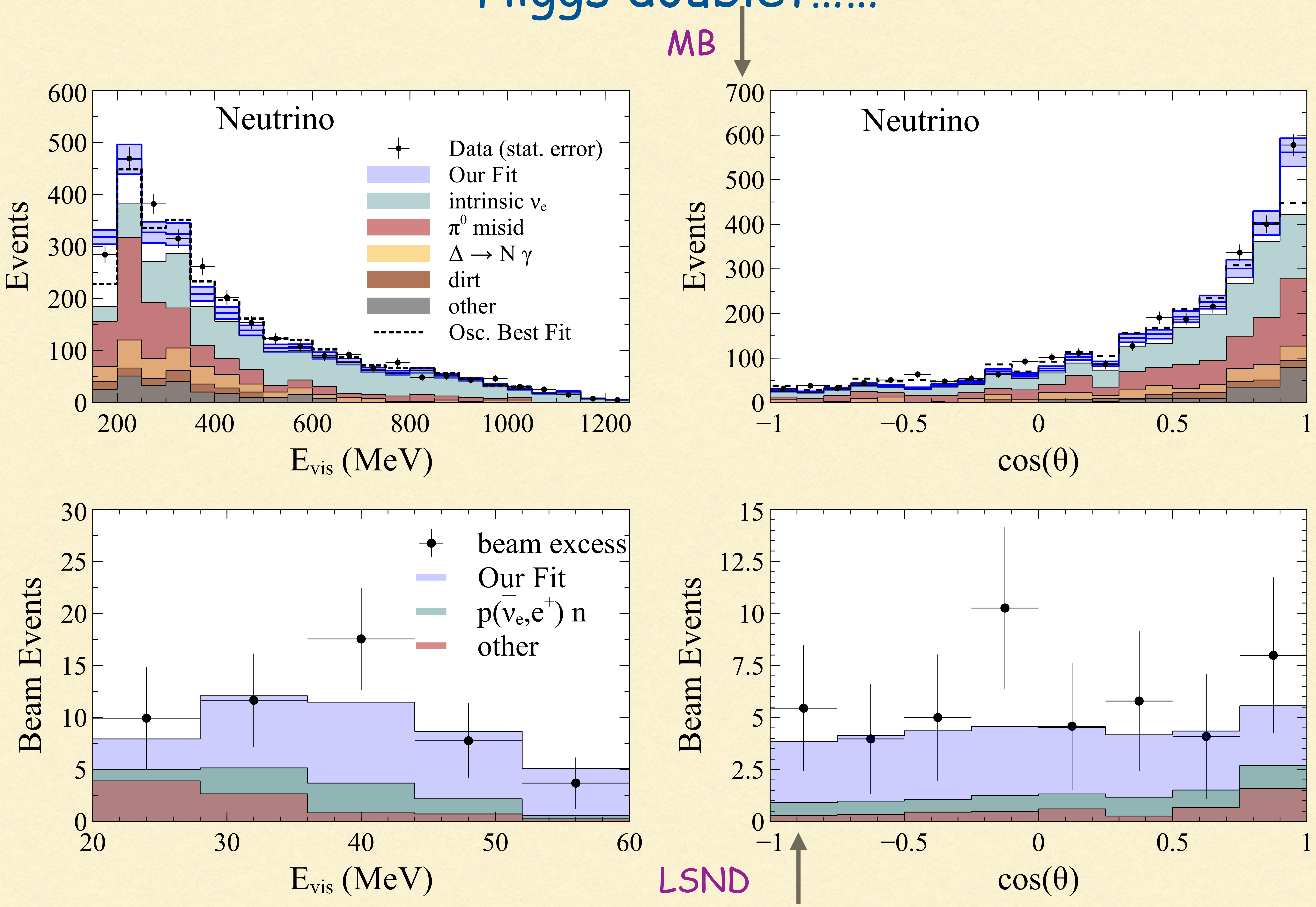


By studying the angular distribution at MB for both light and not so light scalar and vector mediators, one discerns the need for both a light and an intermediate mass mediator

An intermediate mass scalar mediator tends to give event contributions to all angular bins, unlike a vector.

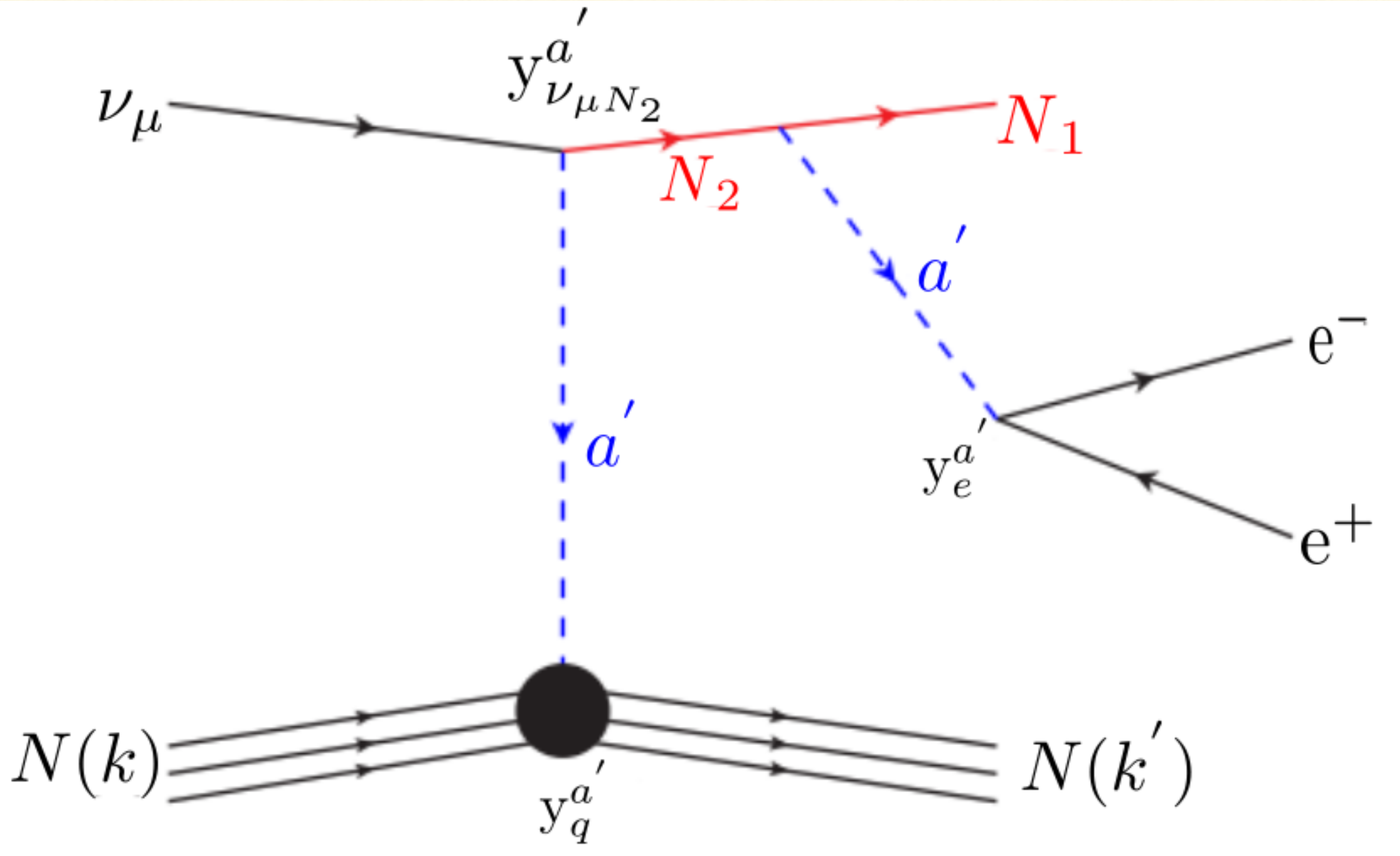
(Abdallah, RG and Roy 2202.09373)

Results with a light real scalar and an intermediate CP even Higgs form a second Higgs doublet……



(Abdallah, RG and Roy 2010.06159)

The interaction and the model……



We extend the scalar sector of the SM by incorporating a second Higgs doublet, and also add a singlet pseudoscalar $\phi_{h'} = i\, A_3^0/\sqrt{2}$. Additionally, three right-handed neutrinos help generate neutrino masses via the seesaw mechanism and participate in the interaction which generates electron-like signals in MB and LSND. We can write the scalar potential V as

$$V = V_{2\mathrm{HDM}} + V_{h'}, \tag{2.1}$$

The interaction and the model……

$$V_{\rm 2HDM} = \mu_1|\phi_h|^2 + \mu_2|\phi_H|^2 + \frac{\lambda_1}{2}|\phi_h|^4 + \frac{\lambda_2}{2}|\phi_H|^4 + \lambda_3|\phi_H|^2|\phi_h|^2 + \lambda_4(\phi_h^\dagger\phi_H)(\phi_H^\dagger\phi_h)$$
$$+\frac{\lambda_5}{2}\{(\phi_h^\dagger\phi_H)^2 + h.c\} + (\lambda_6|\phi_h|^2 + \lambda_7|\phi_H|^2)\,(\phi_h^\dagger\phi_H + \phi_H^\dagger\phi_h),$$

$$V_{h'} = \mu'|\phi_{h'}|^2 + \lambda'_2|\phi_{h'}|^4 + \lambda'_3|\phi_h|^2|\phi_{h'}|^2 + \lambda'_4|\phi_H|^2|\phi_{h'}|^2 + \{(\lambda'_5|\phi_{h'}|^2 - \mu_3)(\phi_h^\dagger\phi_H)$$
$$+(m_1|\phi_h|^2 + m_2|\phi_H|^2 + m_3\phi_h^\dagger\phi_H - m_s\phi_{h'})\phi_{h'} + h.c.\}.$$

$$\phi_h = \begin{pmatrix} G^+ \\ \frac{v+H_1^0+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_H = \begin{pmatrix} H_2^+ \\ \frac{H_2^0+iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_{h'} = i\,A_3^0/\sqrt{2}\,.$$

$$\langle\phi_h\rangle = v(\equiv v_{SM}) \simeq 246\ \text{GeV}$$

While the combination of a light (15-20 MeV) scalar and an intermediate (750 MeV) one provide a very good fit to MB and LSND, a light pseudo scalar of the same mass does better

This is because it only has incoherent scattering with the nucleons of the spin-0 Carbon nucleus hence the event contribution is not just predominantly forward.

The important a' couplings for our purpose are those with quarks and electrons

$$\mathcal{L}_{a'qq} = y_q^{a'}\, a'\bar{q}\, i\gamma_5\, q\,.$$

Effective couplings to nucleons can then be calculated

$$F_N = \frac{m_N}{m_q} \sum_{q=u,d,s} \Delta_q^{(N)} \left(y_q^{a'} - \sum_{q'=u,..,t} y_q^{a'} \frac{\overline{m}}{m_{q'}} \right), \tag{3.2}$$

where $\Delta_q^{(N)}$ are the quark spin components of the nucleon N,

$$\frac{1}{\overline{m}} = \frac{1}{m_u} + \frac{1}{m_d} + \frac{1}{m_s}, \tag{3.3}$$

$\Delta_u^{(p)} = 0.84$, $\Delta_d^{(p)} = -0.44$, $\Delta_s^{(p)} = -0.03$, $\Delta_u^{(n)} = -0.44$, $\Delta_d^{(n)} = 0.84$, $\Delta_s^{(n)} = -0.03$ [88].

The total sec is given by

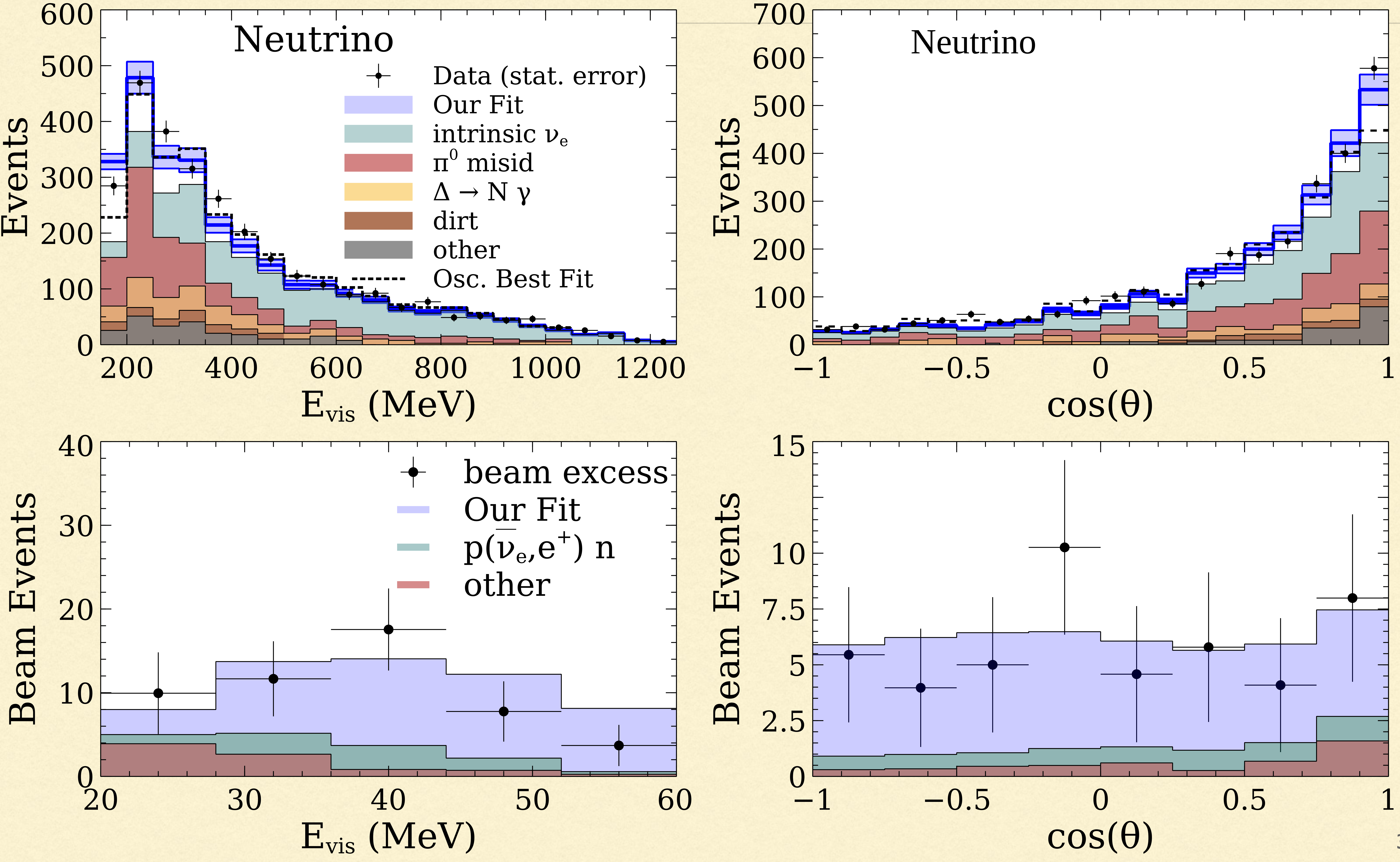
$$\left[\frac{d\sigma}{dE_{N_2}}\right]_{\mathrm{CH}_2} = \Big[\underbrace{(8F_p^2 + 6F_n^2)}_{\text{incoherent}}\Big]\frac{d\sigma}{dE_{N_2}}.$$

Total events

$$\mathrm{N}_{\text{events}} = \eta \int dE_\nu dE_{N_2} \frac{d\Phi^\nu}{dE_\nu}\frac{d\sigma}{dE_{N_2}} \times \mathrm{BR}(N_2 \to N_1 a'),$$

m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{a'} \times 10^6$	$y_e^{a'} \times 10^5$	$y_\mu^{a'} \times 10^5$	$M_{H^\pm}$	$y_c^{a'}$	$y_t^{a'}$
70 MeV	120 MeV	10 GeV	4.34	2.3	1	305 GeV	0	0
$M_{a'}$	M_H	$\sin\xi$	$y_d^{a'} \times 10^6$	$y_{\nu_\mu N_2}^{a'} \times 10^2$	$\lambda_{N_{12}}^{a'}$	M_A	$y_s^{a'}$	$y_b^{a'}$
17 MeV	300 GeV	0.01	4.0	3.15	0.1	400 GeV	0	0

Table 1: Benchmark parameter values used to generate the event spectrum in LSND and MB.

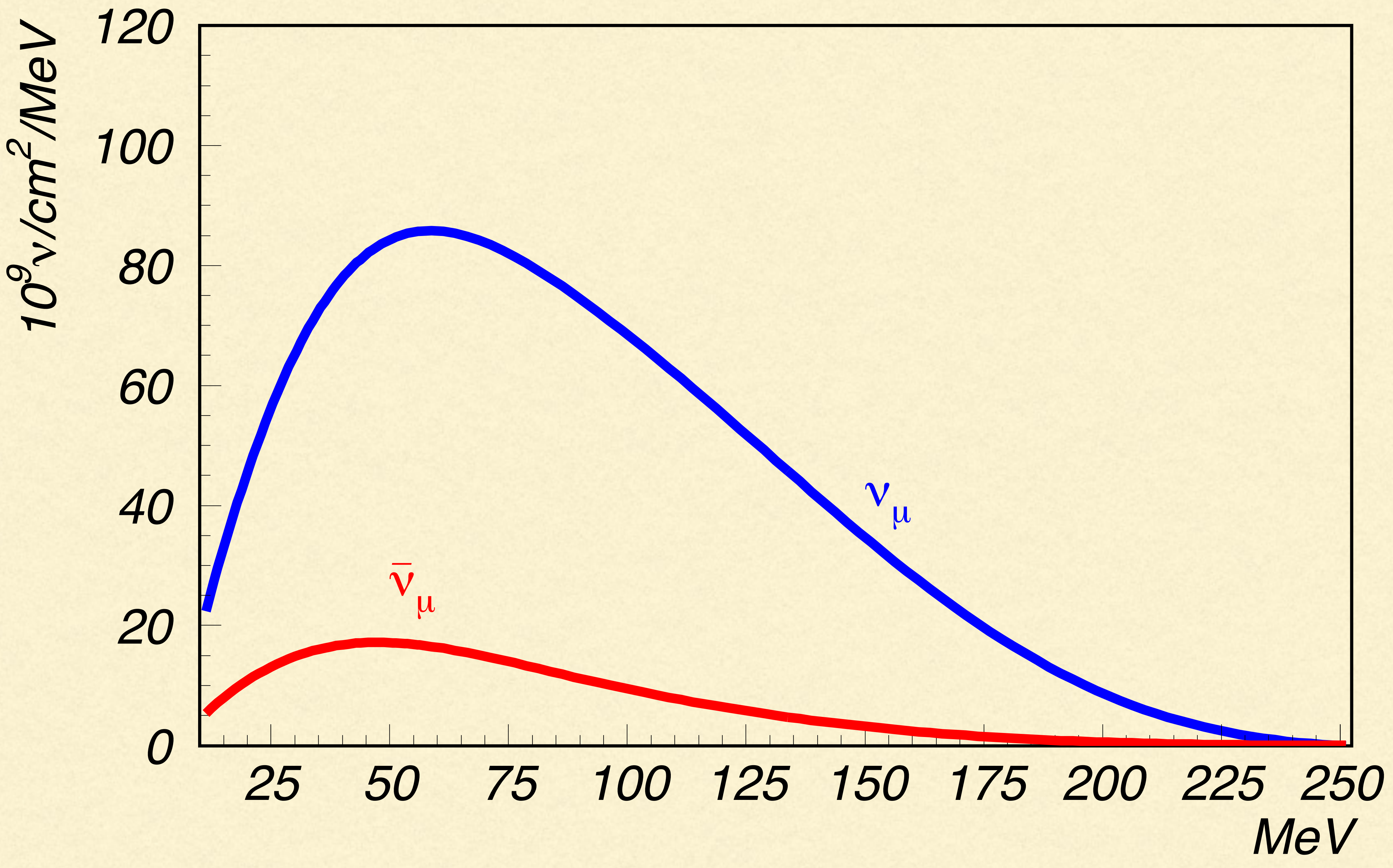


Neutrino
Data (stat. error)
Our Fit
intrinsic ν_e
π^0 misid
$\Delta \to N\gamma$
dirt
other
Osc. Best Fit
Events
E_{vis} (MeV)
Neutrino
Events
$\cos(\theta)$
beam excess
Our Fit
$p(\bar{\nu}_e, e^+)\ n$
other
Beam Events
E_{vis} (MeV)
Beam Events
$\cos(\theta)$

Our model requires the production of a relatively heavy N_2 (120MeV).

$\bar{\nu}_\mu$ Flux from DAR is not energetic enough to produce it, hence all events in our model come from DIF flux

$$\nu_\mu \, \mathrm{CH}_2 \;\rightarrow\; n \, N_2 \, X \;\rightarrow\; n \, N_1 \, h' \, X \;\rightarrow\; N_1 \, \gamma \, e^+ e^- \, X$$



We note that KARMEN had a energy peaked around 30 MeV, hence the process in our model cannot take place, leading to a null signal prediction.

The ATOMKI anomaly….

Seen in the decay of excited states of ^{8}Be, ^{4}He and recently in ^{12}C

- The emission of a virtual photon by the nucleus, which decays to an e^+e^- pair, (Internal Pair Creation (IPC)), i.e.,

$$p + A \to N^* \to N + e^+ + e^- \,. \tag{5.1}$$

The experiment observes unexpected bumps in the invariant mass and angular separation of the pair, as opposed to SM expectation that both the invariant mass and angular distribution would fall monotonically.

Data is consistent with the production of an new particle X with

$$M_X = 16.7 \pm 0.35(\mathrm{stat}) \pm 0.5(\mathrm{sys}) \quad \mathrm{MeV},$$

From parity and angular momentum conservation, X can be a vector, axial vector or pseudo scalar

The BR fraction is

$$\frac{\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, X) \times \mathrm{BR}(X \to e^+e^-)}{\mathrm{BR}(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, \gamma)} = 5.8 \times 10^{-6}\,.$$

The observations correspond to an excess of 6.8 sigma

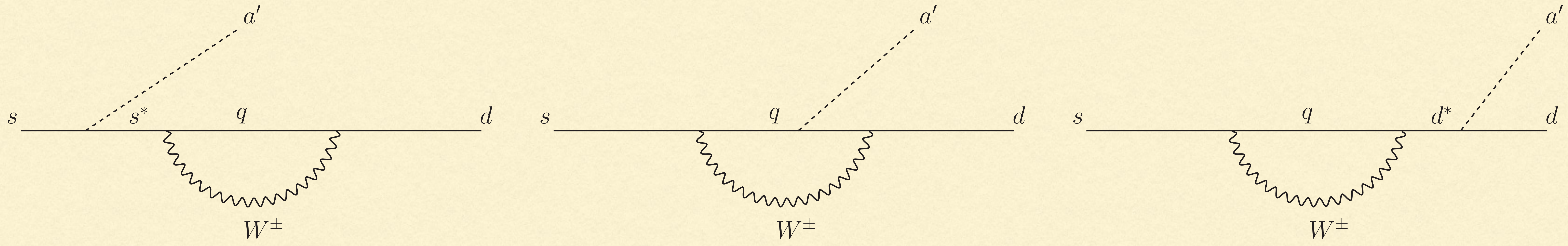
The effective average coupling to nucleons from which one gets couplings to the quarks is, is

$$\bar{h}_N^2 \equiv \frac{(F_p + F_n)^2}{4}\,.$$

m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{a'}\times 10^5$	$y_e^{a'}\times 10^5$	$y_\mu^{a'}\times 10^5$	$M_{H^\pm}$	$y_c^{a'}\times 10^3$	$y_t^{a'}\times 10^5$
70 MeV	120 MeV	10 GeV	-5.043	2.3	1	305 GeV	6.366	-1.3
$M_{a'}$	M_H	$\sin\xi$	$y_d^{a'}\times 10^5$	$y_{\nu_\mu N_2}^{a'}\times 10^4$	$\lambda_{N_{12}}^{a'}$	M_A	$y_s^{a'}\times 10^5$	$y_b^{a'}$
17 MeV	300 GeV	0.01	-1.3	2.84	0.1	400 GeV	-1.3	0

Couplings to quarks are significantly higher than what they were for MB/LSND alone, in order to obtain a fit identical to the one for MB and LSND alone.

This requires a more careful treatment of constraints , specifically flavour violating meson decays e.g.



Other important constraints come from beam dump experiments, electroweak precision experiments, vacuum stability , unitarity.

Abdallah, RG, Roy, 2010.06159 ;
W. Abdallah, RG, T. Ghosh, N. Khan, Samiran Roy, Subhojit Roy , 2406.07643

Conclusions……

- Short baseline anomalies like the Ga source anomaly, the RAA, LSND and MB have reached a stage where a host of complementary experiments and theoretical inputs have helped gradually clarify the situation.
  - Improved data on beta spectra and consequent improved flux calculations point to a disappearance of the RAA.

- The situation with the Ga anomaly is unclear, given that the most recent experiment, BEST, verified the presence of the deficit but could not detect any L variation, which would have signalled active sterile oscillations

- Attempts to understand the anomalies using oscillations with eV scale neutrinos show a very strong tension between appearance and disappearance data and with cosmology, while also exhibiting a lack of inner consistency.

The MB and LSND anomalies persist with a high combined statistical significance of 6.1 sigma

Conclusions……

MicroBooNE has recently made important strides in helping establish that SM backgrounds are unlikely to be responsible for the MB signal, strengthening the case that MB and possibly LSND could be signals for new physics.

It is significant that most new physics proposals invoke heavier neutrinos (HNLs)

We have provided an example of such new physics with a light 17 MeV pseudo scalar mediator combined with a second Higgs doublet and 3 RH neutrinos.

The model provides an excellent fit to MB and LSND alone, and to MB, LSND and ATOMKI, and gives SM neutrino mass squared differences in conformity with global oscillation data.

Confirmation of the ATOMKI anomaly by other independent experiments (MEG II, PADME) is important.

A definitive resolution must await results from the Fermilab Short Baseline Program, with its 3 detectors , MicroBooNE, ICARUS and SBND which will test proposals such as ours.

Thank you for your attention!

Back-up Slides

LSND useful......

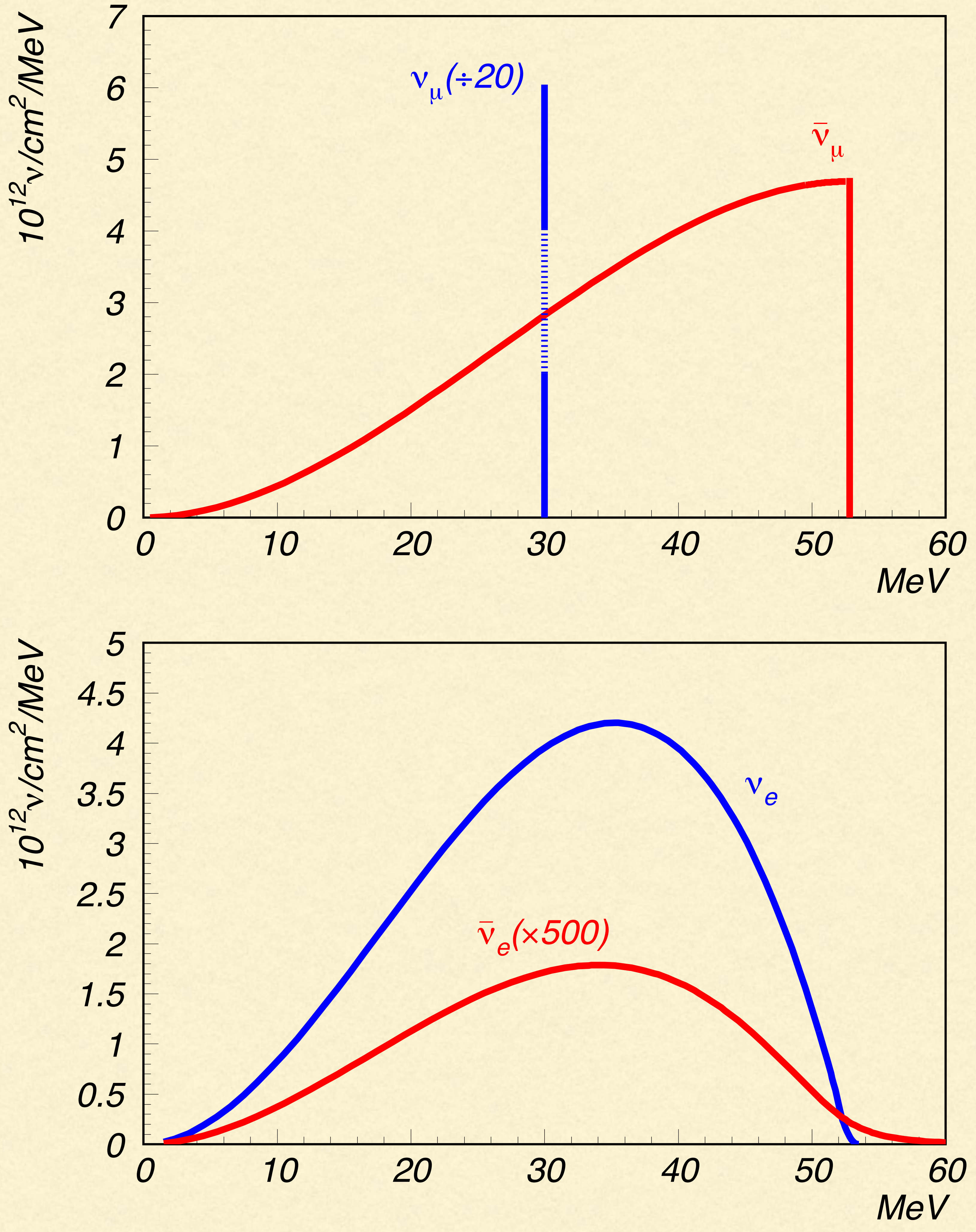


FIG. 3: The decay-at-rest neutrino fluxes averaged over the detector.

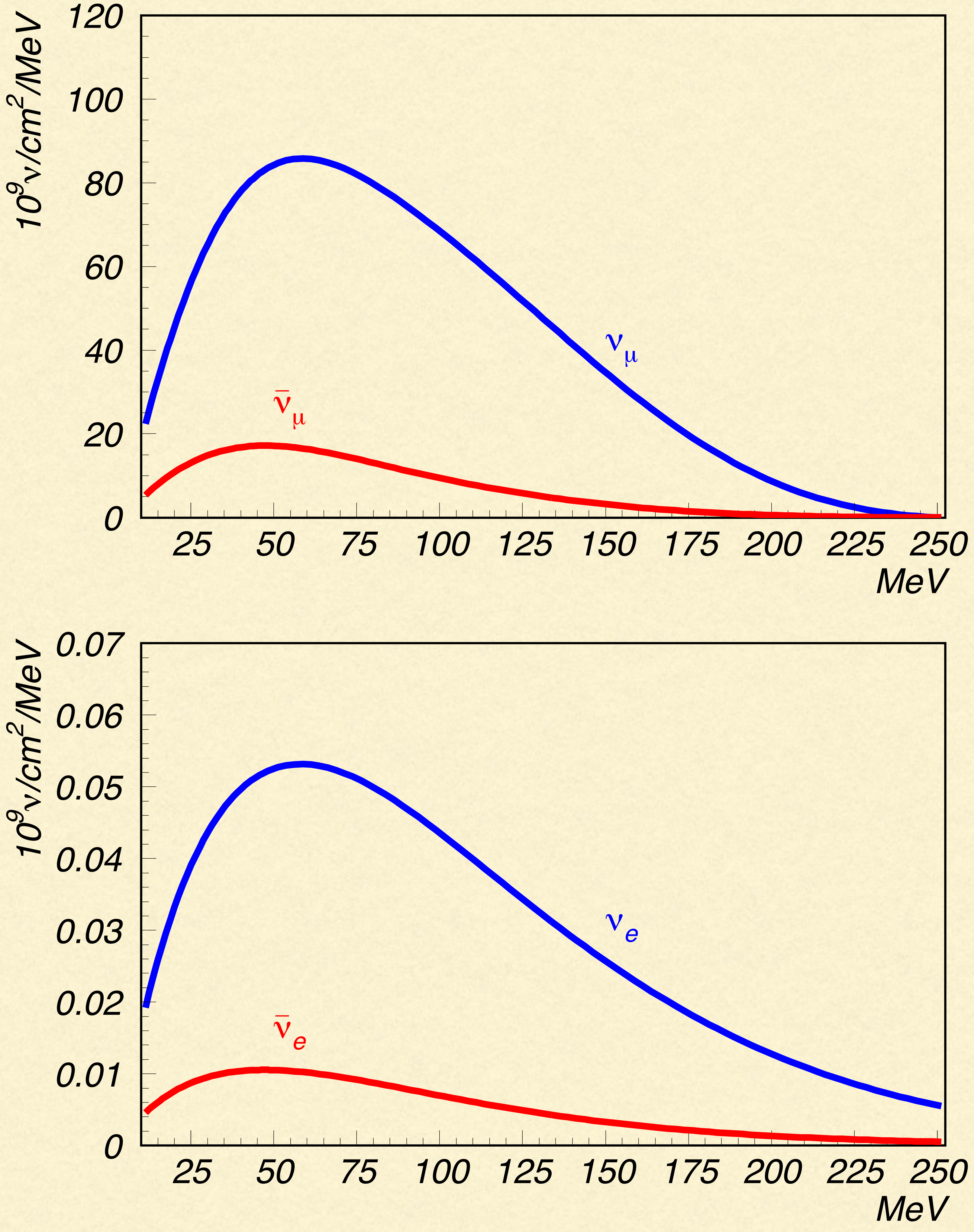
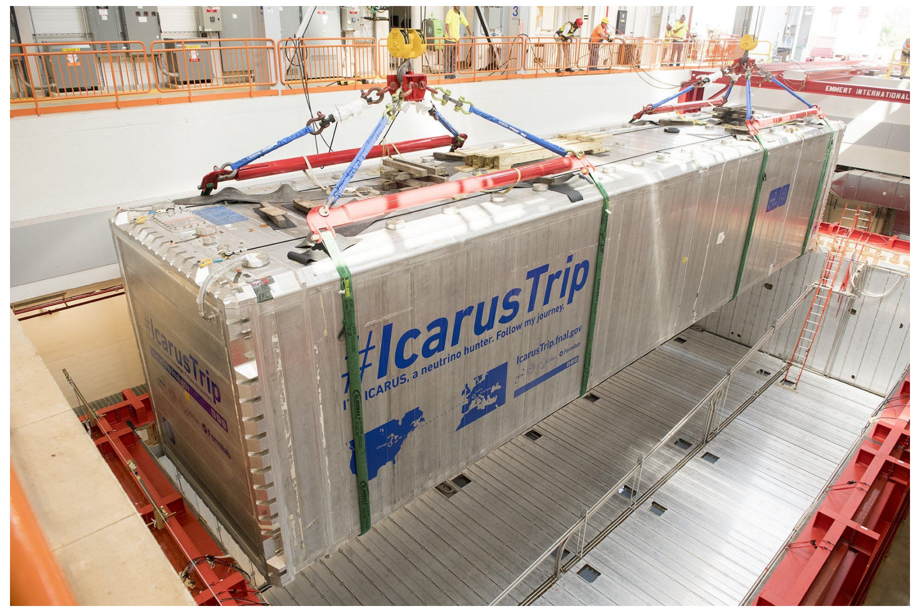


FIG. 4: The decay-in-flight neutrino fluxes averaged over the detector.

Short Baseline Neutrino Program at Fermilab

Anne Schukraft talk at Neutrino 2022

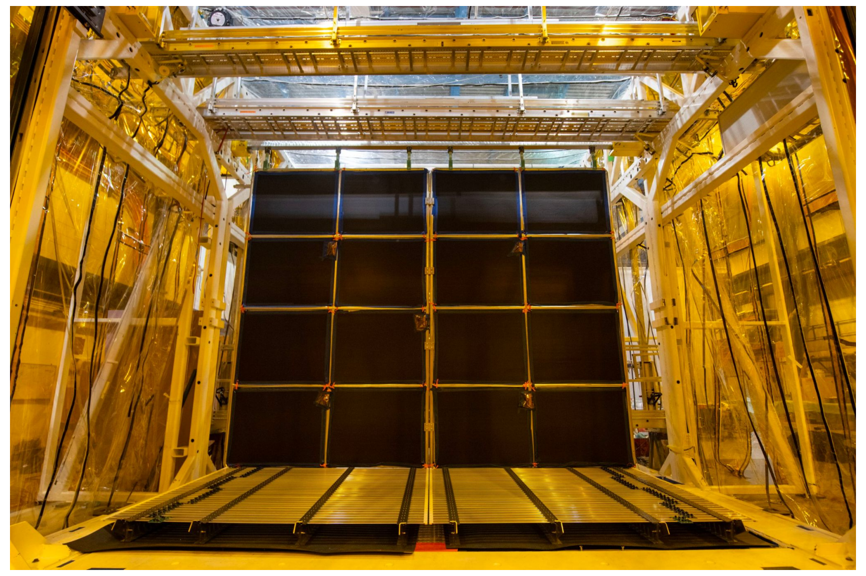


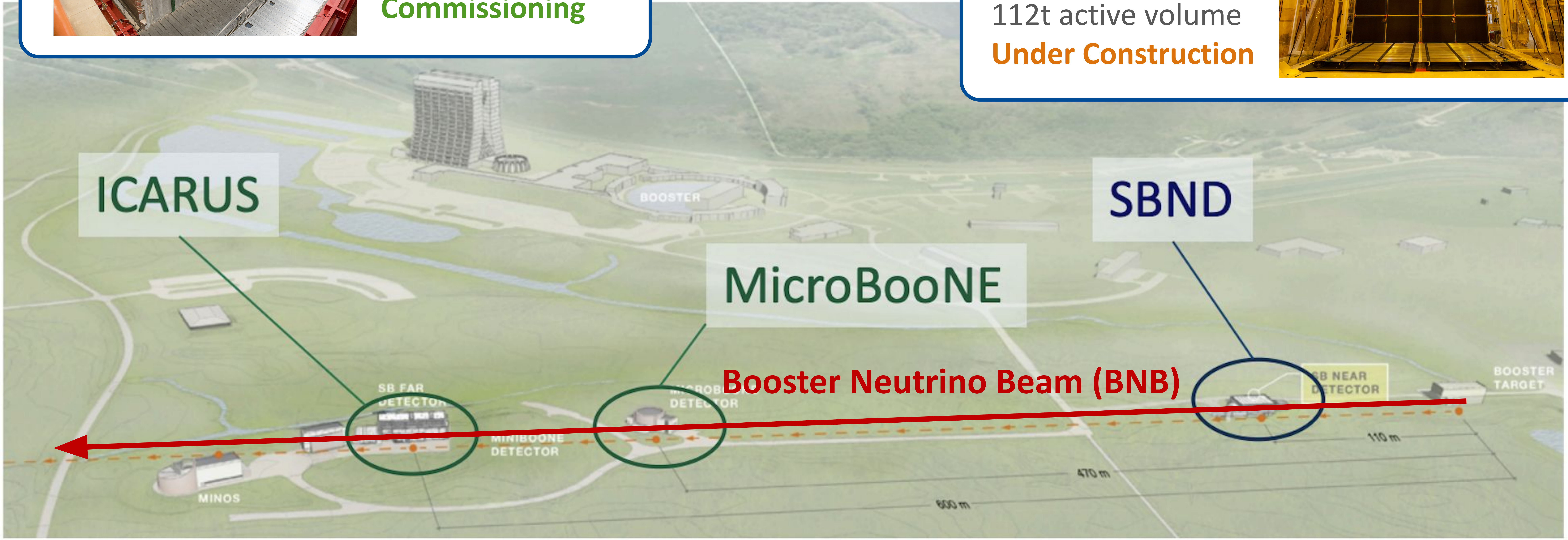
ICARUS

600m baseline
470t active volume
Commissioning

SBND

110m baseline
112t active volume
Under Construction



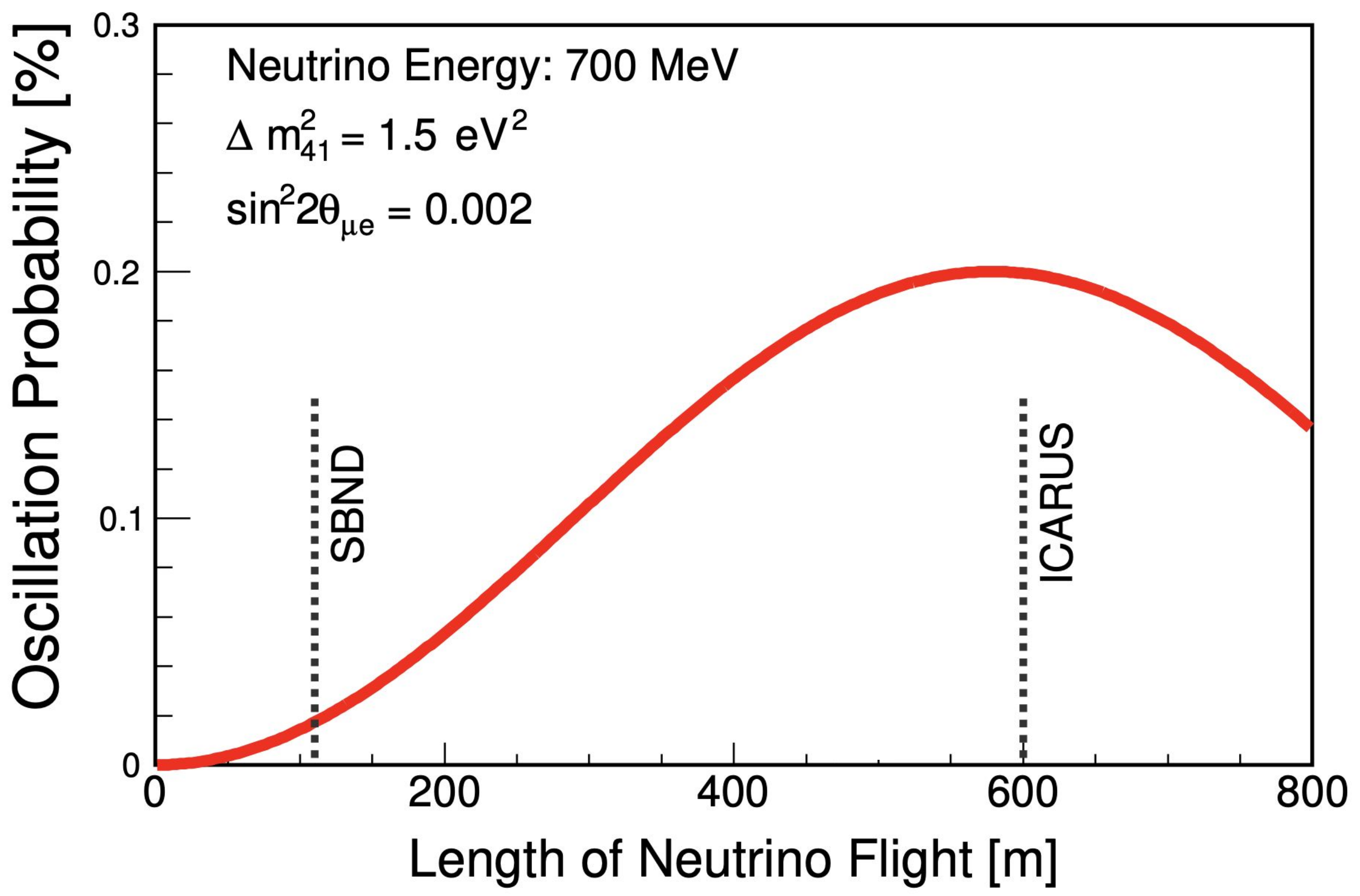


- Three detectors sampling the *same neutrino beam* at different distances

SBN Oscillation Sensitivity

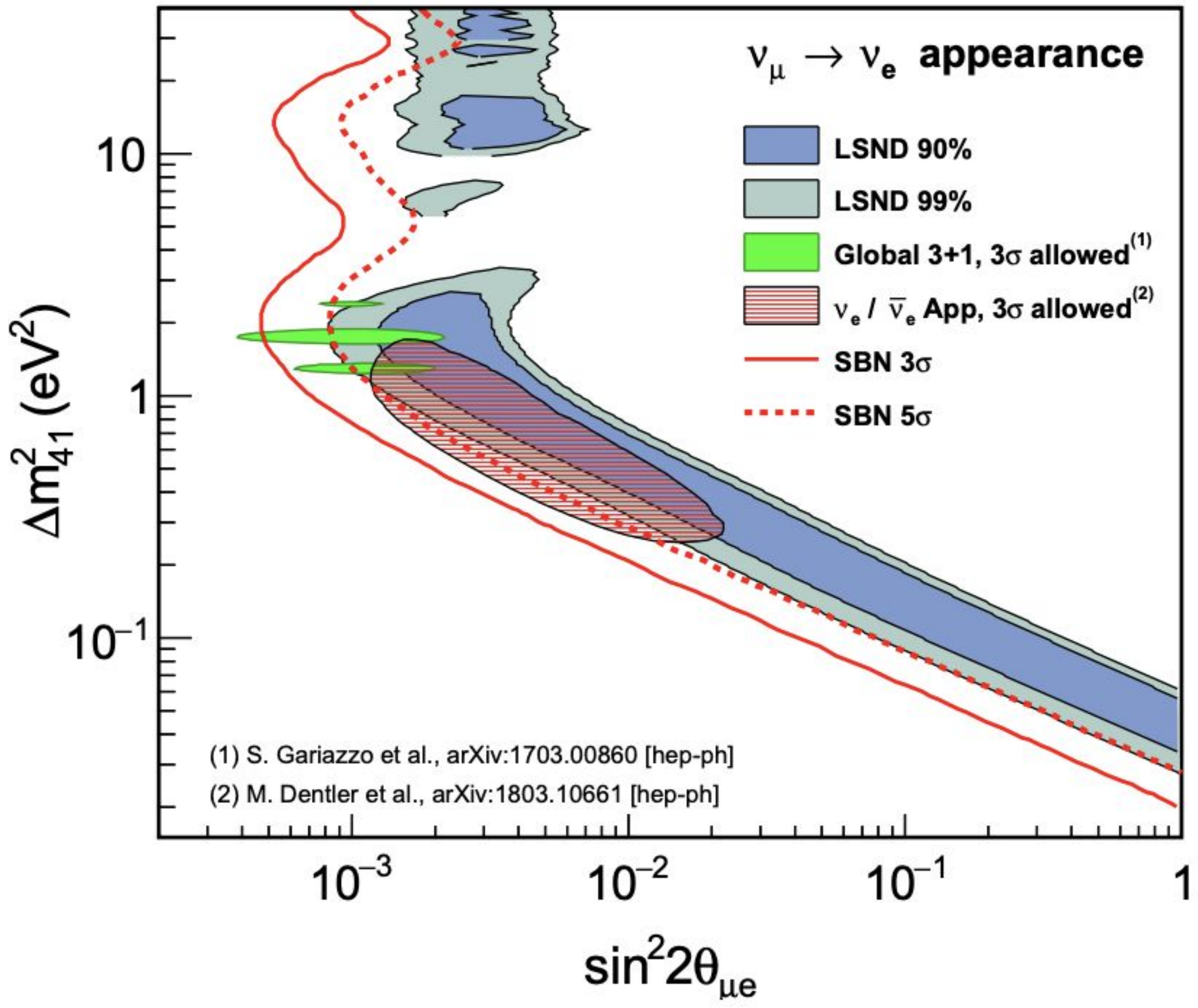
Anne Schukraft talk at Neutrino 2022

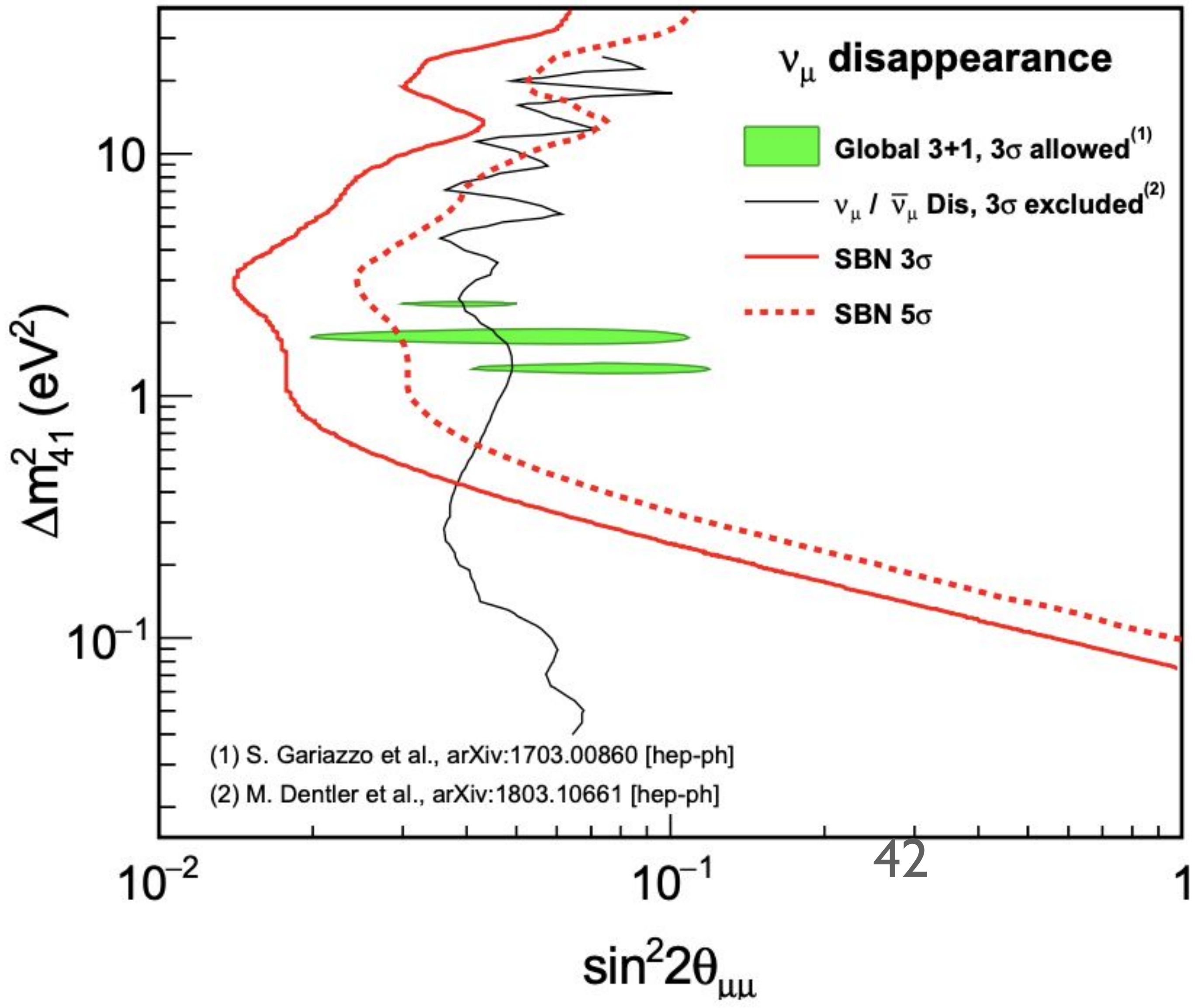
- SBND + ICARUS will test the sterile neutrino hypothesis
  - can cover the parameter space favored by past anomalies with 5σ significance
- Observing neutrino flux at different distances from the beam target
- Effective systematics constraint through near detector (SBND) and same detector technology in near and far detector
- **Search for appearance of ν_e and disappearance of ν_μ within the same experiment**
  - current results show a 4.7σ tension between ν_e appearance and ν_μ disappearance channels



P. Machado et al, arXiv:1903.04608V11

(SBN sensitivities for 6.6 x 10^{20} protons on the BNB target)





Standard Neutrino oscillations……..in the vacuum

$$P(\nu_e \to \nu_\mu; L) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right),$$

$$P(\nu_e \to \nu_e) = 1 - P(\nu_e \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e) = P(\nu_\mu \to \nu_\mu),$$

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+ 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

$\alpha, \beta = e, \mu, \tau$.

Standard Neutrino oscillations…….in the vacuum

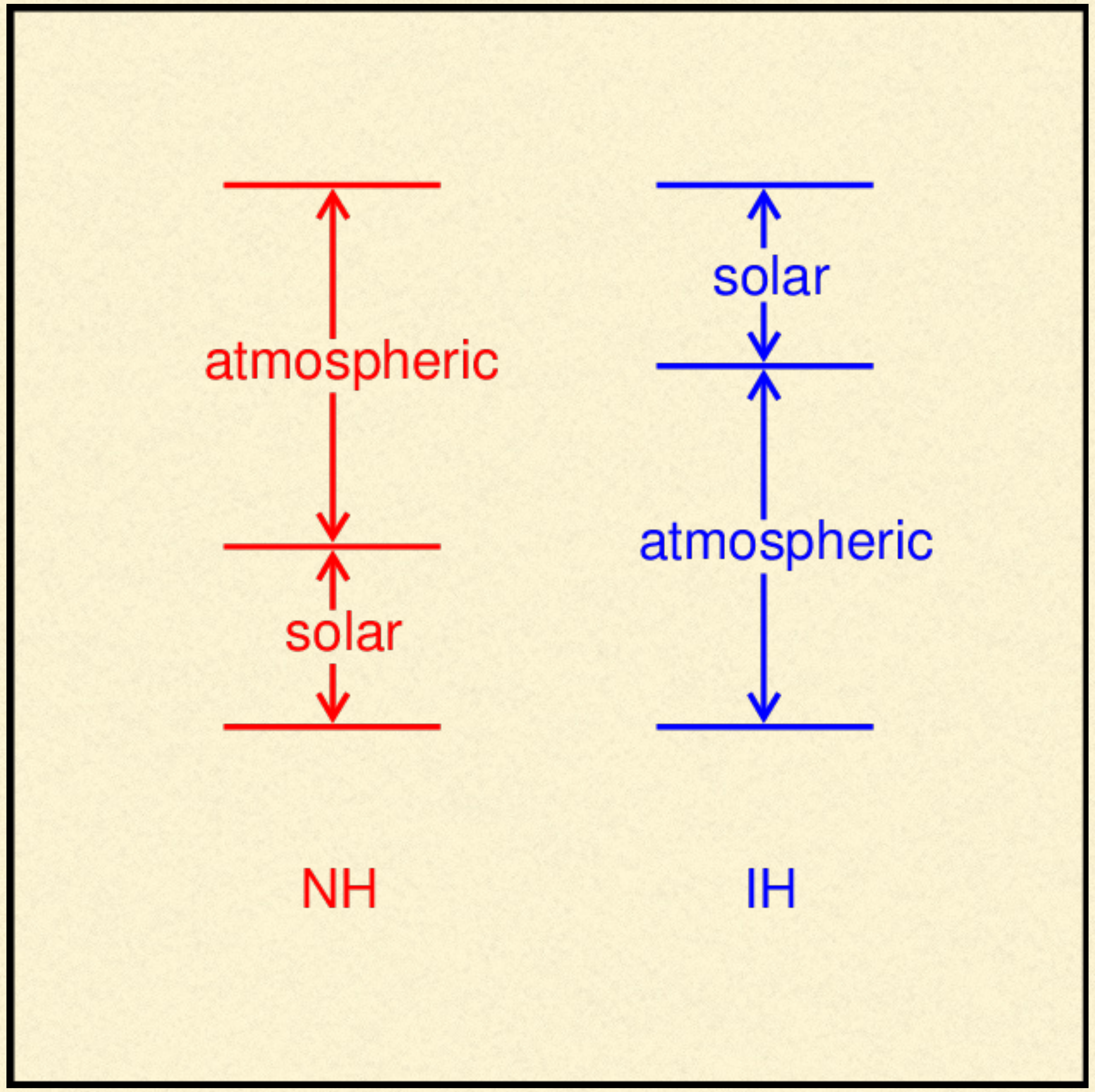
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix},$$

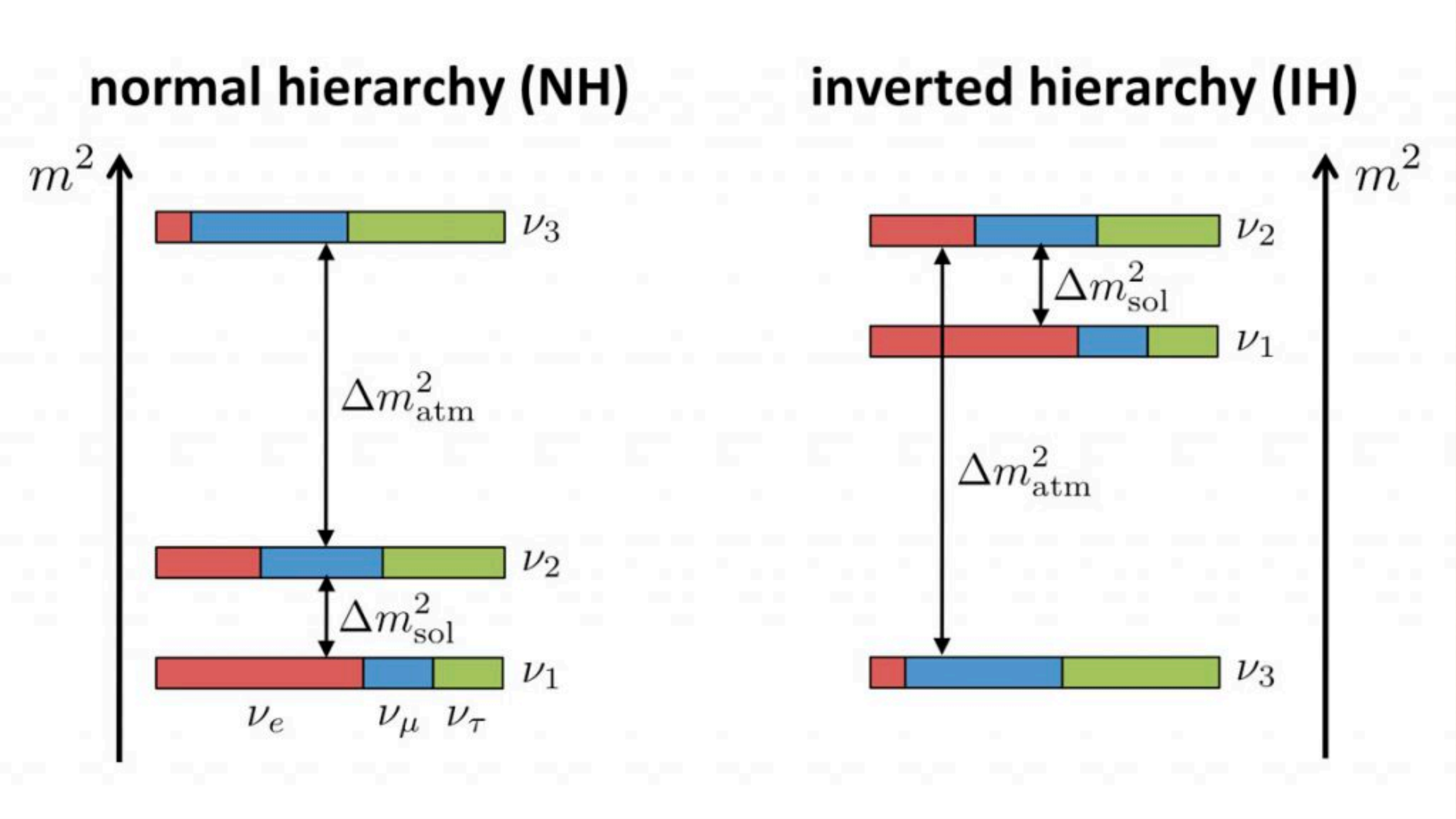
U relates the weak interaction eigenstates and the mass eigenstates through the leptonic mixing parameters θ_{12}, θ_{13}, θ_{23}, δ (the Dirac CP-violating phase), as well as ρ and σ (the Majorana CP-violating phases).

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} \equiv \cos(\theta_{ij})$ and $s_{ij} \equiv \sin(\theta_{ij})$.

Mass hierarchy of neutrinos





Useful SBL formulae

$$P_{\alpha\beta} = \sum_{j,k=1}^{4} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \exp\left[- i \frac{\Delta m_{jk}^2 L}{2E} \right] .$$

General, for all baselines

$$U \equiv R_{34}(\theta_{34})\, R_{24}(\theta_{24}, \delta_{24})\, R_{14}(\theta_{14})\, R_{23}(\theta_{23})\, R_{13}(\theta_{13}, \delta_{13})\, R_{12}(\theta_{12}, \delta_{12})\,, \qquad (2)$$

where $R_{ij}(\theta_{ij})$ denotes a real rotation matrix in the (ij)-plane with rotation angle θ_{ij}, and $R_{ij}(\theta_{ij}, \delta_{ij})$ includes in addition a complex phase δ_{ij}. In most cases, however, we will present

For the following discussion the so-called short-baseline limit of eq. (1) will be useful. This limit refers to the situation where $\Delta m_{21}^2 L/4E \ll 1$, $\Delta m_{31}^2 L/4E \ll 1$, so that standard three-flavor oscillations have not had time to develop yet. In this case, eq. (1) generically simplifies to

$$P_{\alpha\alpha}^{\rm SBL} = 1 - 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)\, \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right), \qquad (3)$$

$$P_{\alpha\beta}^{\rm SBL} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2\, \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right). \qquad (\alpha \neq \beta) \qquad (4)$$

$$\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}|^2 |U_{\mu 4}|^2 .$$

Useful SBL formulae

The high-energy IceCube analysis from ref. [52] exploits the fact that active-to-sterile neutrino oscillations in matter are resonantly enhanced by the MSW effect [55, 56] at an energy of

$$E_{\rm res} = 5.3\ \text{TeV} \times \left(\frac{5\ \text{g/cm}^3}{\rho_\oplus}\right)\left(\frac{\Delta m^2_{41}}{1\ \text{eV}^2}\right). \quad (8)$$

The effective mixing angles $\theta_{\alpha\beta}$ for short-baseline oscillations are defines below

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \sin^2 2\theta_{\alpha\beta} \cdot \sin^2\left(1.267 \frac{\Delta m^2_{41} L}{E}\right)$$

ν_e disappearance: $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

ν_μ disappearance: $\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}\left(1 - \cos^2\theta_{14}\sin^2\theta_{24}\right)$

ν_e appearance: $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$

- non-zero ν_e appearance requires both ν_e and ν_μ disappearances

$$P_{ee} \simeq 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right).$$

Useful SBL formulae. (2210.10216)

$$|U_{e4}|^2 = \sin^2\theta_{14},$$
$$|U_{\mu 4}|^2 = \cos^2\theta_{14}\ \sin^2\theta_{24},$$
$$|U_{s4}|^2 = \cos^2\theta_{14}\ \cos^2\theta_{24}\ \cos^2\theta_{34},$$

$$\Delta_{41} \equiv \frac{\Delta m_{41}^2 L}{4E} = 1.267\left(\frac{\Delta m_{41}^2}{\mathrm{eV}^2}\right)\left(\frac{\mathrm{MeV}}{E}\right)\left(\frac{L}{\mathrm{m}}\right)$$

$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2|\delta_{\alpha\beta} - |U_{\beta 4}|^2|.$$

$$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14},$$
$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\ \sin^2\theta_{24},$$
$$\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}(1 - \cos^2\theta_{14}\sin^2\theta_{24}),$$
$$\sin^2 2\theta_{es} = \sin^2 2\theta_{14}\ \cos^2\theta_{24}\ \cos^2\theta_{34},$$
$$\sin^2 2\theta_{\mu s} = \cos^4\theta_{14}\ \sin^2 2\theta_{24}\ \cos^2\theta_{34}.$$

Notes on excess in 1e0p0pi channel in MicroB

Each selection shows a strong preference for the absence of an electron-like MiniBooNE signal, with the exception of the 1e0p0π se- lection, driven by a data excess in the lowest energy bins, which also contain the highest contributions from non-νe backgrounds.

With the exception of the 1e0p0π selection which is the least sensitive to a simple model of the MiniBooNE low-energy excess, MicroBooNE rejects the hypothesis that νe CC interactions are fully responsible for that ex- cess (x = 1) at >97% CL for both exclusive (1e1p CCQE, 1eNp0π) and inclusive (1eX) event classes.

Useful SBL formulae. (Caratelli talk, MicroB, Nu 2024)

3+1 parametrization

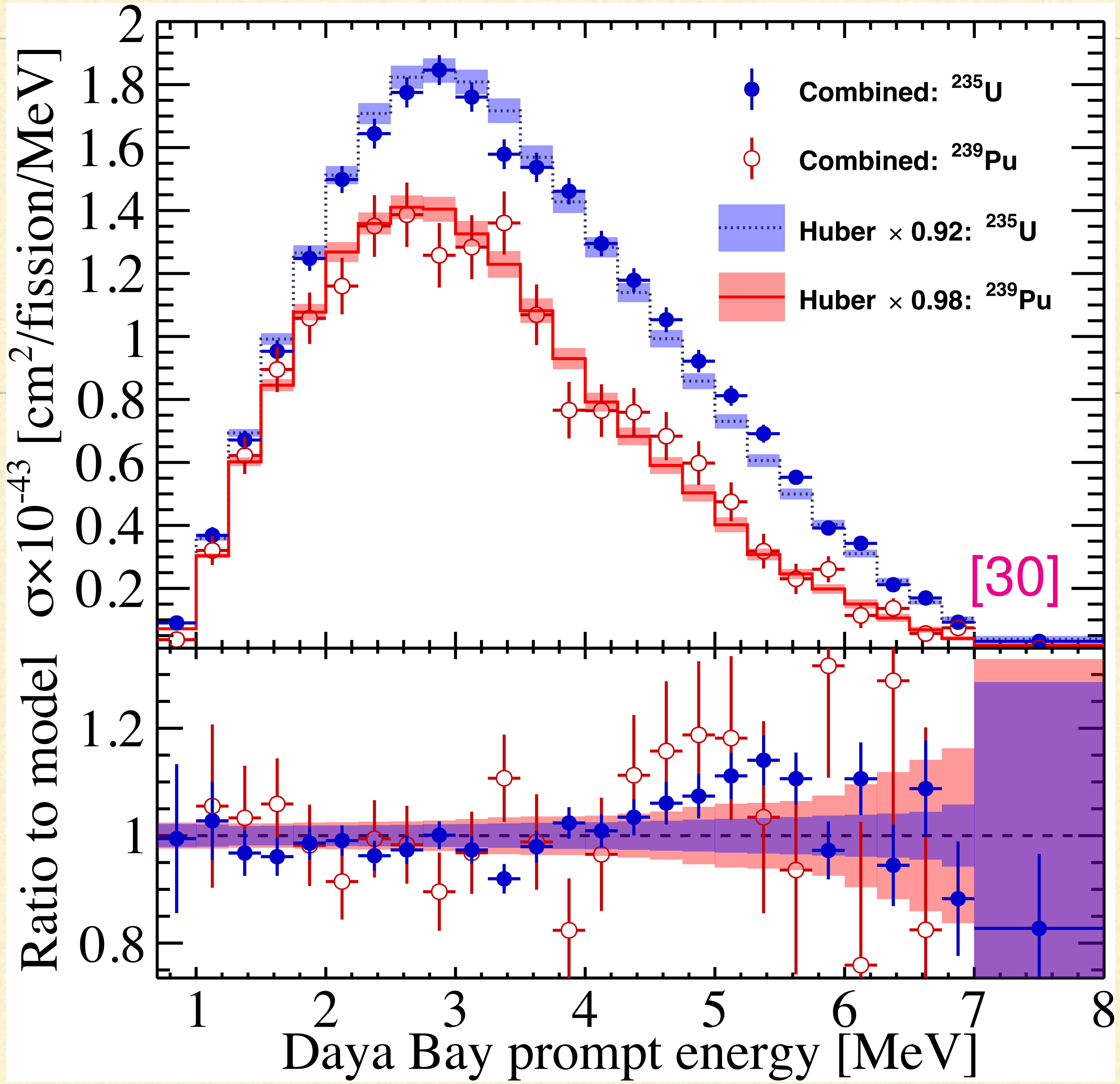
Full 3+1 search ⟶

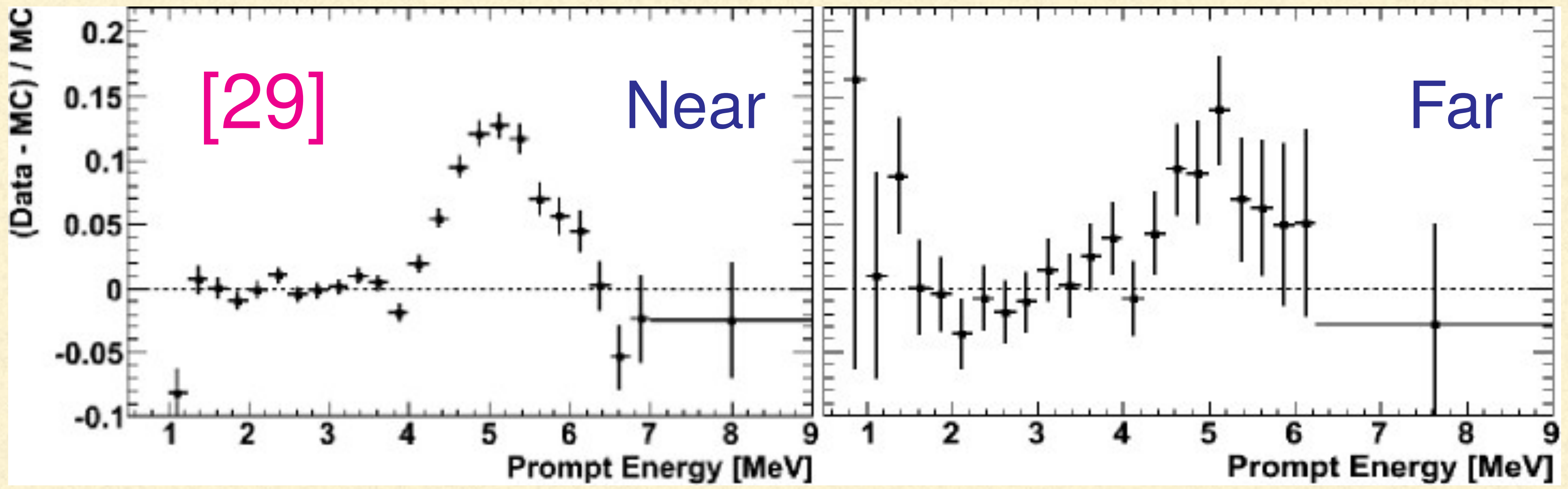
$$P_{\nu_e \to \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2\Delta_{41},$$
$$P_{\nu_\mu \to \nu_\mu} = 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2\Delta_{41},$$
$$P_{\nu_\mu \to \nu_e} = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2\Delta_{41}.$$

$\sin^2 2\theta_{ee}$	$= \sin^2 2\theta_{14}$	$= 4(1 - \lvert U_{e4}\rvert^2)\lvert U_{e4}\rvert^2$
$\sin^2 2\theta_{\mu\mu}$	$= 4\cos^2\theta_{14}\sin^2\theta_{24}\left(1 - \cos^2\theta_{14}\sin^2\theta_{24}\right)$	$= 4(1 - \lvert U_{\mu 4}\rvert^2)\lvert U_{\mu 4}\rvert^2$
$\sin^2 2\theta_{\mu e}$	$= \sin^2 2\theta_{14}\sin^2\theta_{24}$	$= 4\lvert U_{\mu 4}\rvert^2\lvert U_{e4}\rvert^2$
$\sin^2 2\theta_{es}$	$= \sin^2 2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}$	$= 4\lvert U_{e4}\rvert^2\lvert U_{s4}\rvert^2$
$\sin^2 2\theta_{\mu s}$	$= \cos^4\theta_{14}\sin^2 2\theta_{24}\cos^2\theta_{34}$	$= 4\lvert U_{\mu 4}\rvert^2\lvert U_{s4}\rvert^2$

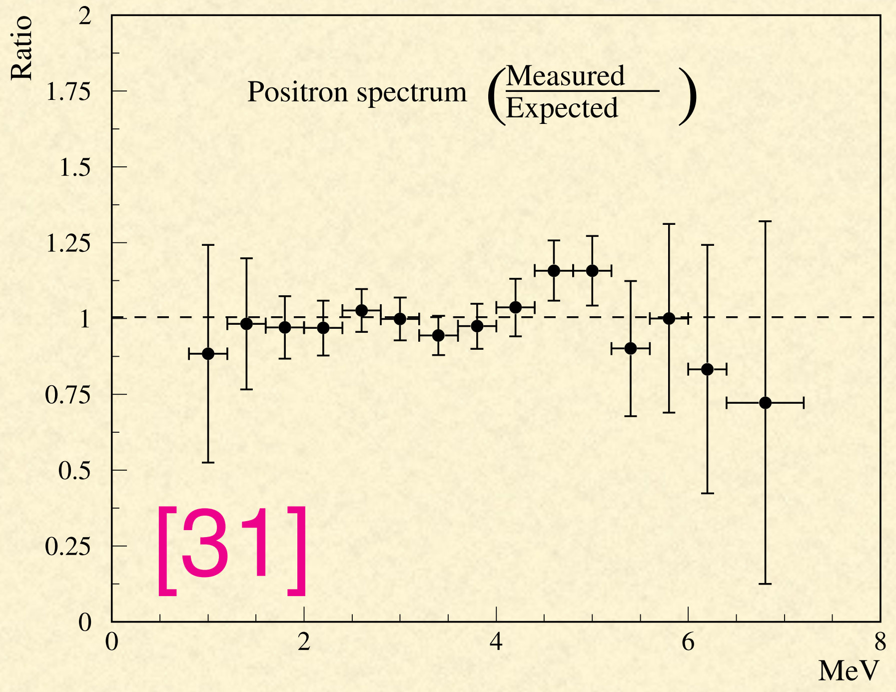
$\bar{\nu}_e$ disapp: 5 MeV excess

- Neutrino 2014: RENO [29] reported an excess of events around 5 MeV;
- seen by most reactors (also old Chooz [31]);
- DB+Prospect [30]: affect both $^{235}\mathrm{U}$ & $^{239}\mathrm{Pu}$;
- excess (not deficit) & independent of $L \Rightarrow$ **flux feature**, not ~~**sterile oscillations**~~;
- accounted by HKSS, but not by EF and KI $\Rightarrow$ reactor fluxes require further scrutiny.





⇝ [Sonzogni]



[29] S.H Seo [RENO], talk at Neutrino 2014, Boston, USA, June 2-7, 2014

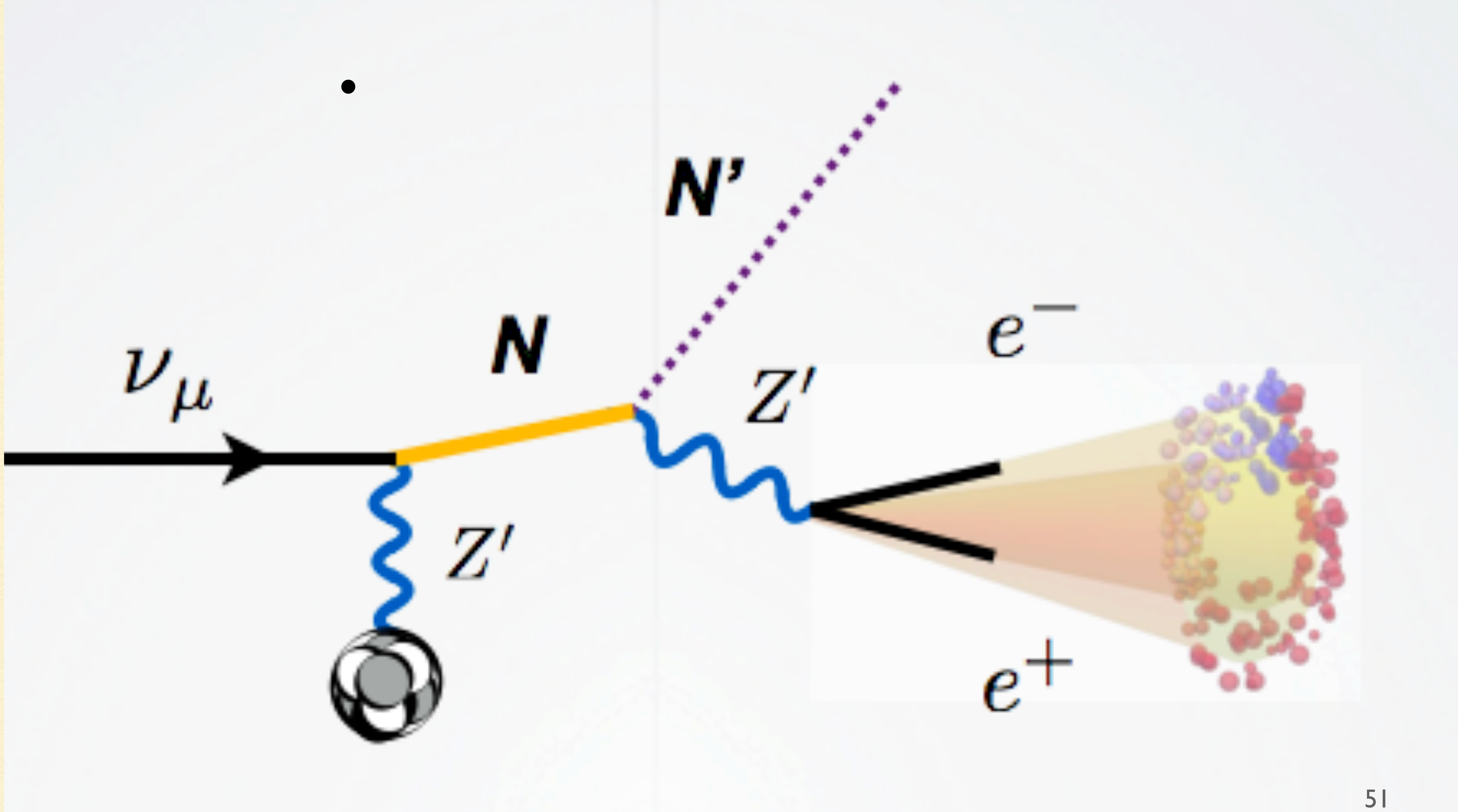
[30] F.P. An *et al.* [DB+Prospect], PRL **128** (2022) 081801 [arXiv:2106.12251]

[31] M. Apollonio *et al.* [Chooz], PLB **466** (1999) 415 [hep-ex/9907037]

New Physics solutions to MB and LSND

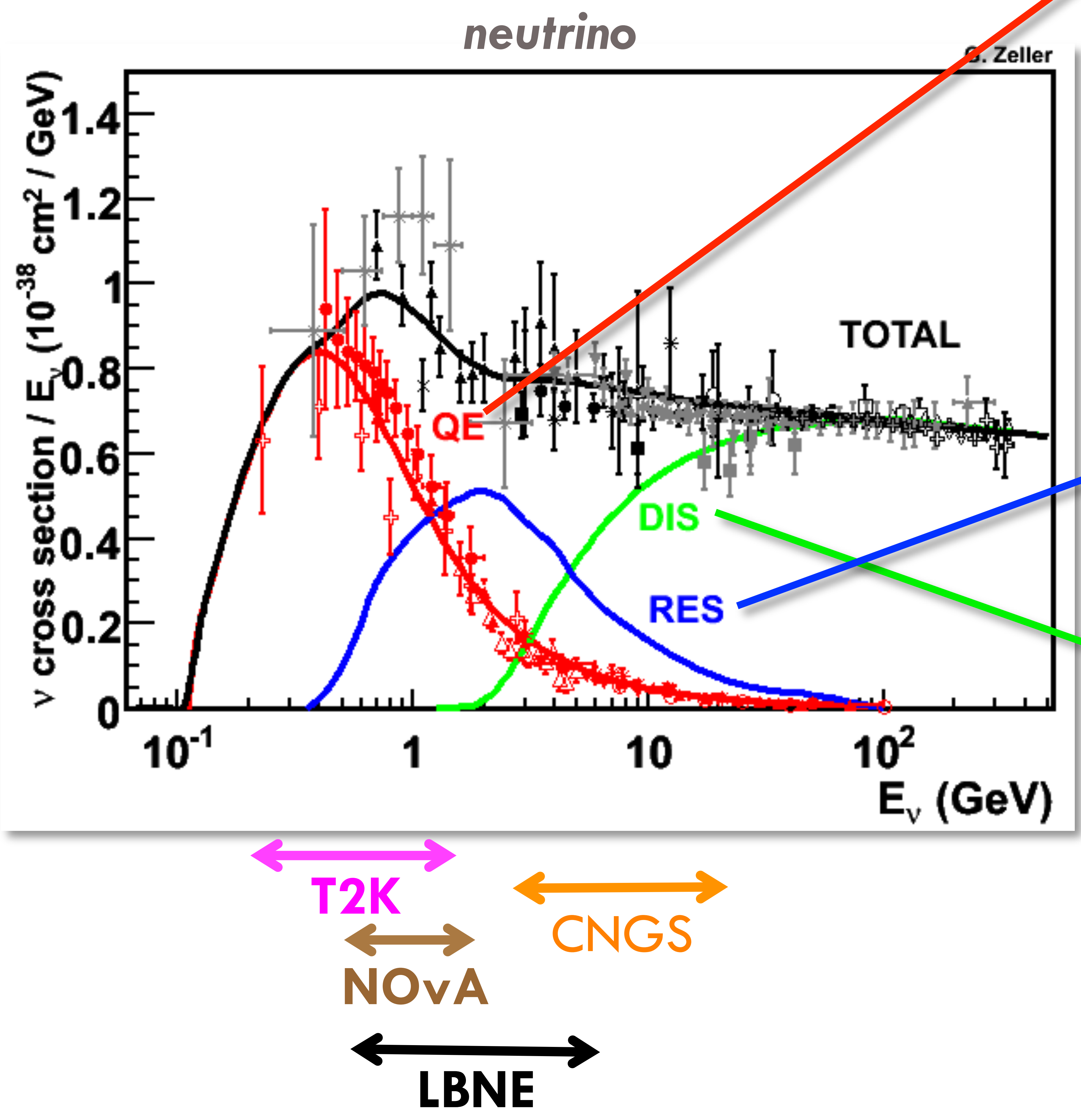
- Generic new physics process
-

NSI, but at low energies



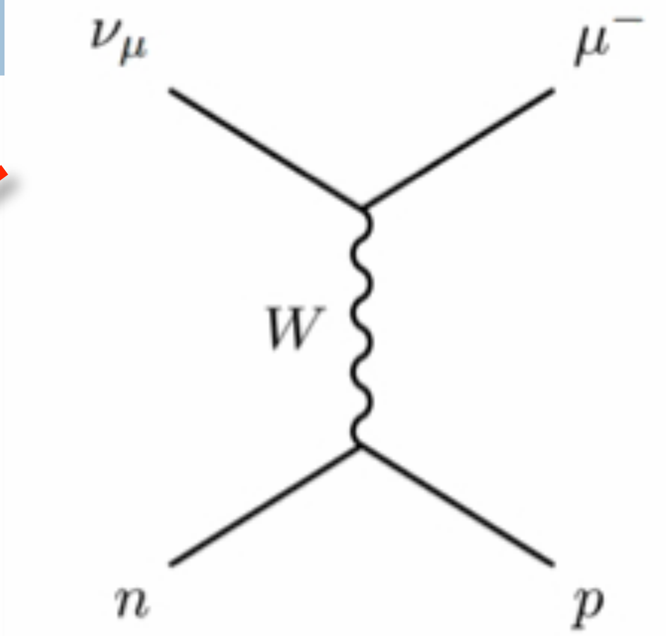
Complicated Region

(our accelerator-based ν event samples contain contributions from multiple reaction mechanisms)



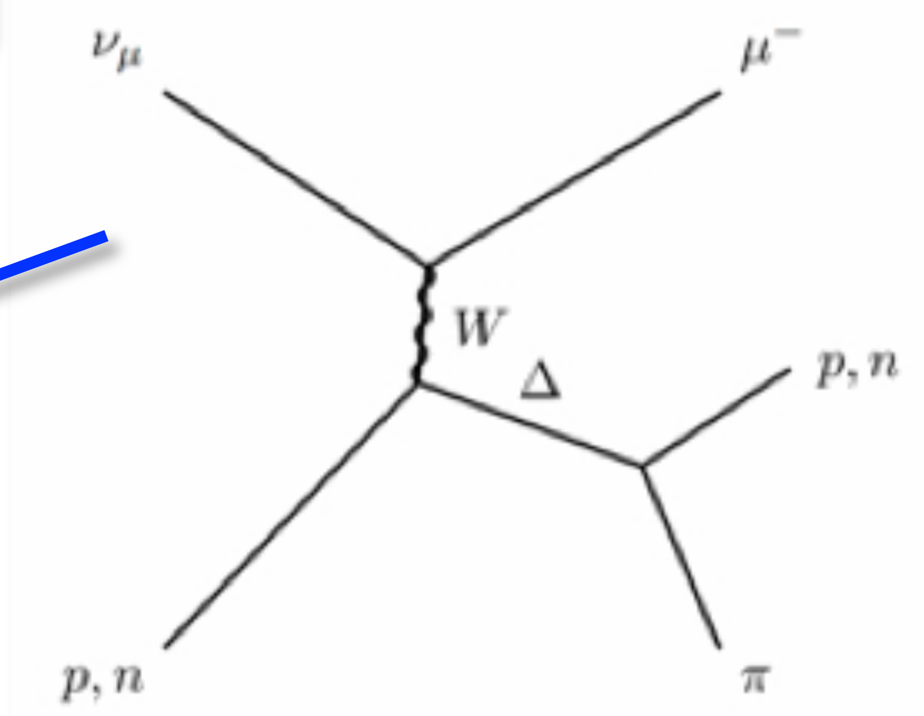
CC Quasi-elastic

nucleon changes, but doesn't break up



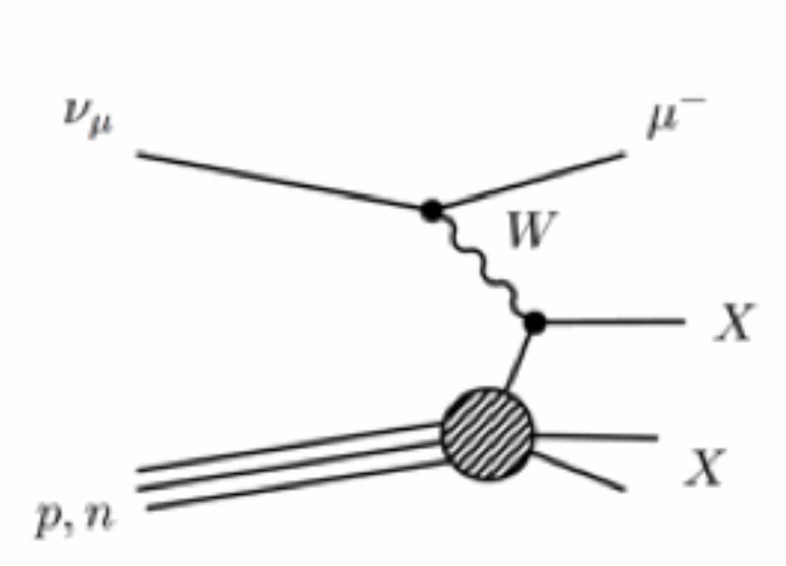
CC Single pion

nucleon excites to resonance state



CC Deep Inelastic

nucleon breaks up



let's start with QE …

sis. We note that X^k_{ij} and $\bar{X}^k_{ij}$ are independent Yukawa matrices. The fermion masses receive contributions only from X^k_{ij}, since in the Higgs basis only ϕ_h acquires a non-zero VEV while $\langle\phi_H\rangle = 0 = \langle\phi_{h'}\rangle$, leading to $X^k = \mathcal{M}_k/v$, where $\mathcal{M}_k$ are the fermion mass matrices. In this basis, $\bar{X}^k_{ij}$ are free parameters and non-diagonal matrices. Hereafter, we work in a basis in which the fermion (leptons and quarks) mass matrices are real and diagonal, where $U_k\mathcal{M}_kV_k^\dagger = m_k^{\rm diag}$ are their bi-unitary transformations.

After rotation, one finds the following coupling strengths of the scalars h, h' and H with fermions (leptons and quarks), respectively:

$$y^h_f = \frac{m_f}{v}, \; y^{h'}_f = y^f Z^{\mathcal{H}}_{32} = y^f\, s_\delta, \; y^H_f = y^f Z^{\mathcal{H}}_{22} = y^f\, c_\delta, \quad (15)$$