LSND, MiniBooNE and T2K excess events as a signal from heavy neutrino decays

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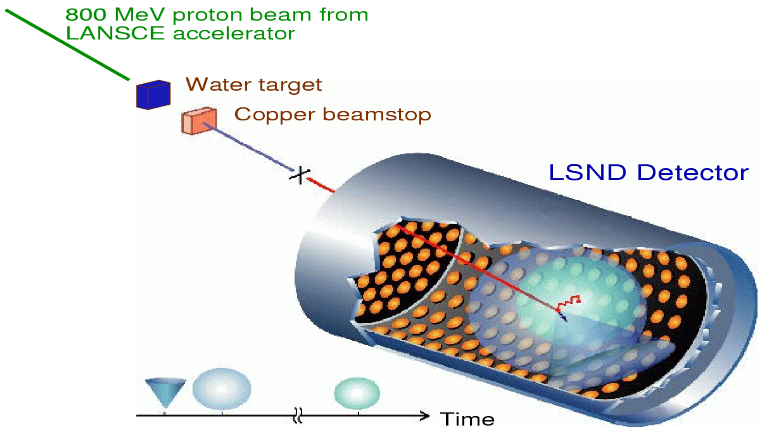
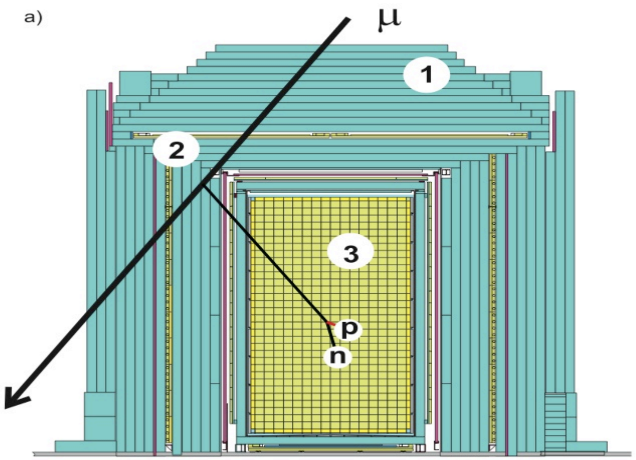
Plan:

- LSND/ KARMEN $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results and ν_h decays.
- MiniBooNE $\nu_\mu / \bar{\nu}_\mu$ excess events as a signal from ν_h decays
- ν_h decays as a possible origin of T2K excess events
- Constraints on ν_h
- Searches for ν_h with existing data and in future experiments
- Summary

S.G., arXive:1009.5536; 1101.4004, 1107.0279

LSND and KARMEN $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results





- LSND experiment (1993-98)
  - 1.8 E23 POT, 167 t LSc
  - L = 30m, 20 < E_ν < 53 MeV
- pion decays at rest:

  $\pi^+ \rightarrow \mu^+ \nu_\mu$

  $\rightarrow \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

DIF ν_μ : DAR $\bar{\nu}_\mu \approx$ 0.03 : 0.97

- e-like event excess

  87.9 ± 22.4 ± 6.0 ev's, 3.8 σ
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations osc.prob.

  (2.64 ± 0.67 ± 0.45) x 10^{-3}

- KARMEN (1997-2001)
  - 5.9 E22 POT, 56 t LSc
  - L = 17 m and 16 < E_ν < 50 MeV
- observed excess of ν_e :

  10 ± 32 events.
- oscillation probability of

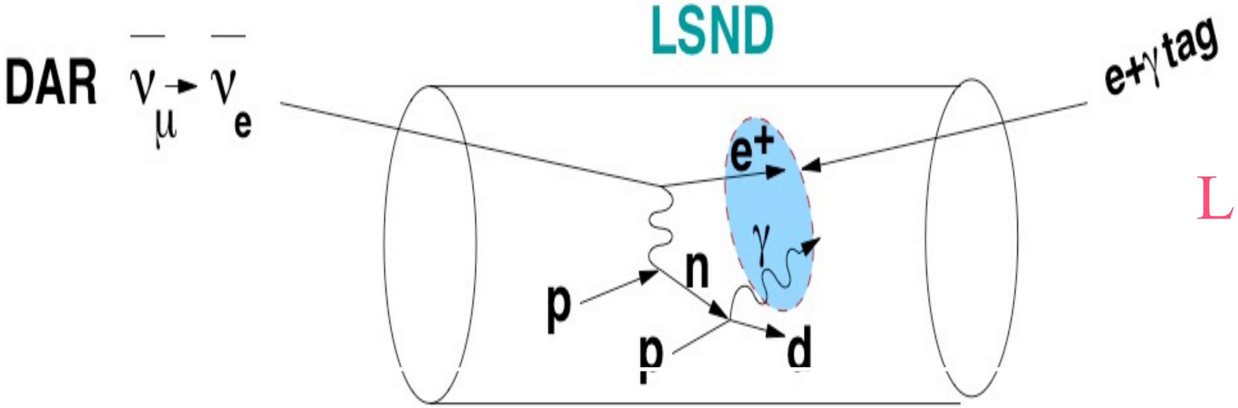
  < 8.5 x10^{-4} 90% CL

no evidence for oscillation.

Signature of the LSND excess: e^+ + delayed γ(2.2MeV)

$n+p \to d+\gamma$

DAR $\bar{\nu}_\mu \to \bar{\nu}_e + p \to e^+ + n$



LSND interpretation:

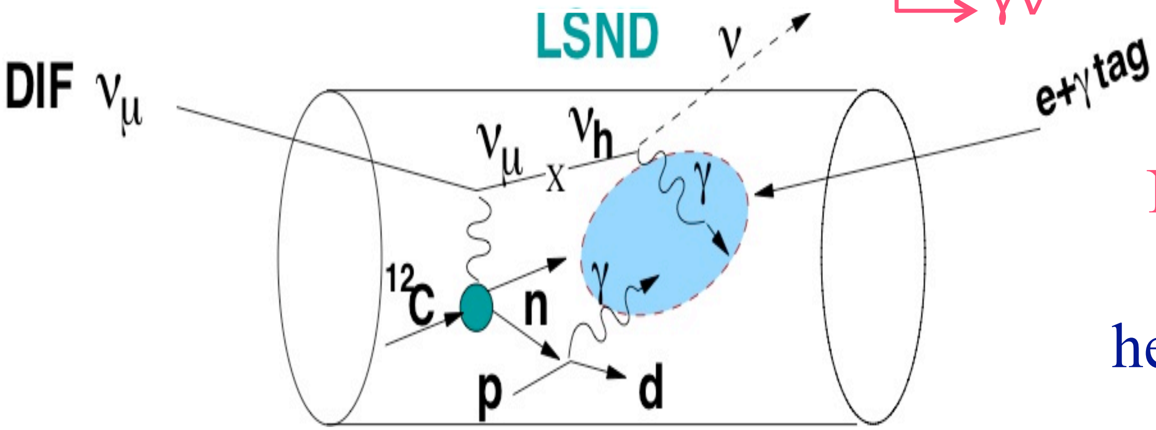
$\bar{\nu}_\mu \to \bar{\nu}_e$ neutrino oscillations

DIF $\pi \to \mu\nu_\mu$

$n+p \to d+\gamma$

$\to \nu_\mu + {}^{12}C \to n + X + \nu_h$

$\nu_h \to \gamma\nu$



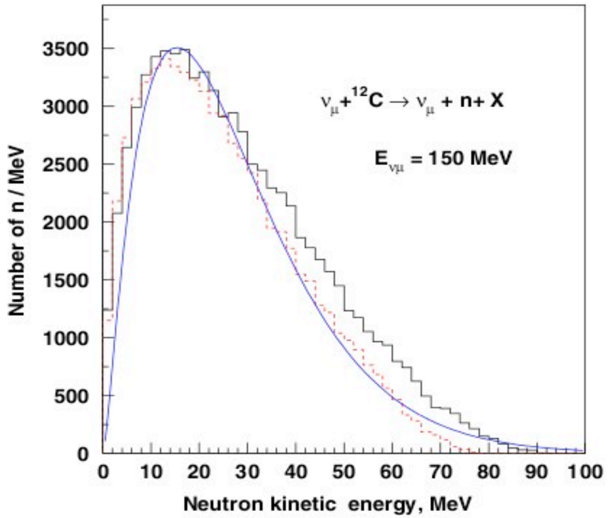
LSND/KARMEN do not discriminate between e and γ

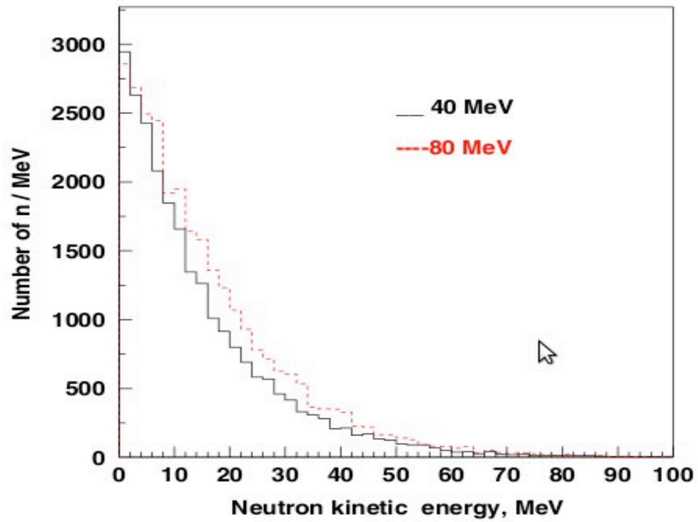
New interpretation: radiative decay of heavy neutrino $\nu_h \to \gamma\nu$

Neutrons from $\nu_\mu + {}^{12}C \rightarrow n + X + \nu_h$

Cross section: $\sigma(\nu_\mu {}^{12}C \rightarrow \nu_h n X) \sim \sigma(\nu_\mu {}^{12}C \rightarrow \nu_\mu n X) x |U_{\mu h}|^2 x F_{ph.s}$

C.J. Horovitz et al. PRC 48,3078(1993); M.C. Martinez et al. PRC 73,024607(2006); G.Garvey et al, PRC 48,1919(1993); E. Kolbe et al., PRC 52, 3437 (1995).





- Binding energy ~18 MeV
- Fermi momentum ~200 MeV/c
- No nuclear effects (n-rescatt., nucl. levels,..)

n cooling:

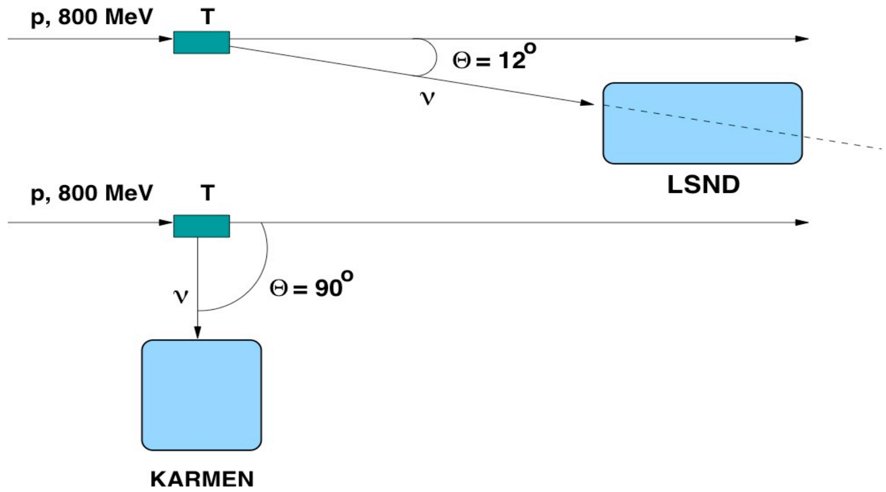
- E_n< 5 MeV at ~25 cm
- Time << n cupture time
- Fraction of high energy secondary n (> 20 MeV) < 2%

Discriminate between n's from $\nu_\mu {}^{12}C \rightarrow nX\nu_h$ and $\overline{\nu}_e\, p \rightarrow e^+ n$ is not simple in LSND: the e+γ tags are identical for both reactions

Why no excess in KARMEN?

- ν_h is produced by DIF, not by DAR ν_μ

$$\pi \rightarrow \mu \nu_\mu$$
$$\quad \hookrightarrow \nu_\mu + {}^{12}C \rightarrow n + X + \nu_h$$
$$\qquad \hookrightarrow \gamma\nu$$



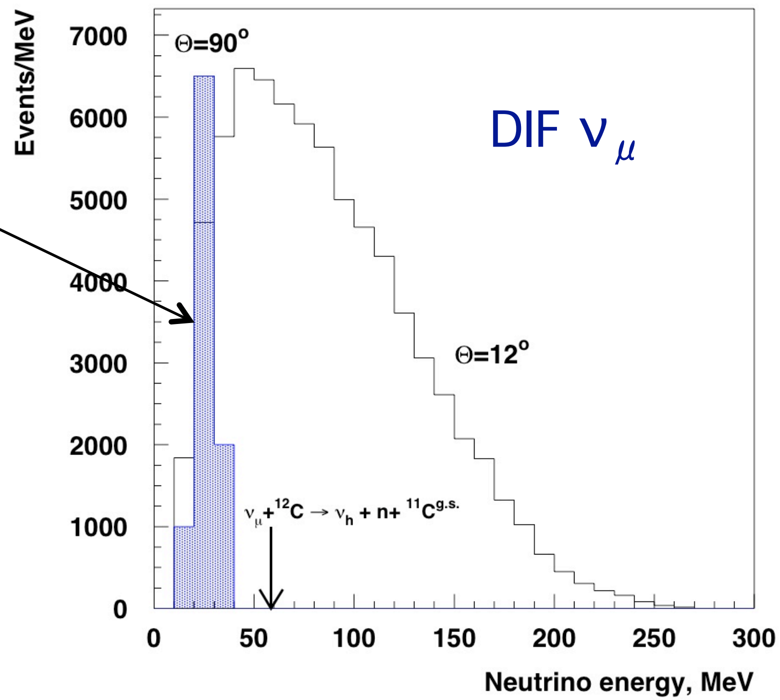
- KARMEN:

  if ν_h > ~40 MeV, it cannot be produced neither by DIF nor DAR ν_μ's due to high energy threshold > ~58 MeV

- LSND:

  if ν_h > ~ 80 MeV, it cannot be effectively produced by DIF ν's due to high mass

$$\sim 40 \text{ MeV} < m_h < \sim 80 \text{ MeV}$$



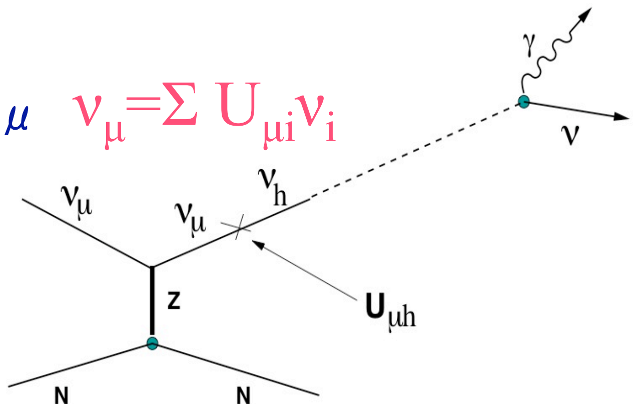
New weakly interacting fermion ν_h :

Properties:

- produced in ν_μ NC interactions
- low mass ν_h > ~40 MeV – too heavy for KARMEN
- high mass ν_h < ~80 MeV - too heavy for LSND
- lifetime < ~ 10^{-8} s - to decay mostly in LSND fiducial volume
- decays dominantly $\nu_h \rightarrow \gamma\nu$

Usefull assumption: ν_h is a component of ν_μ $\nu_\mu = \Sigma\, U_{\mu i}\nu_i$

- muonic coupling $|U_{\mu h}|^2$
- could be produced in ν_μ CC int.
- could be seen in μ, K, D,..decays



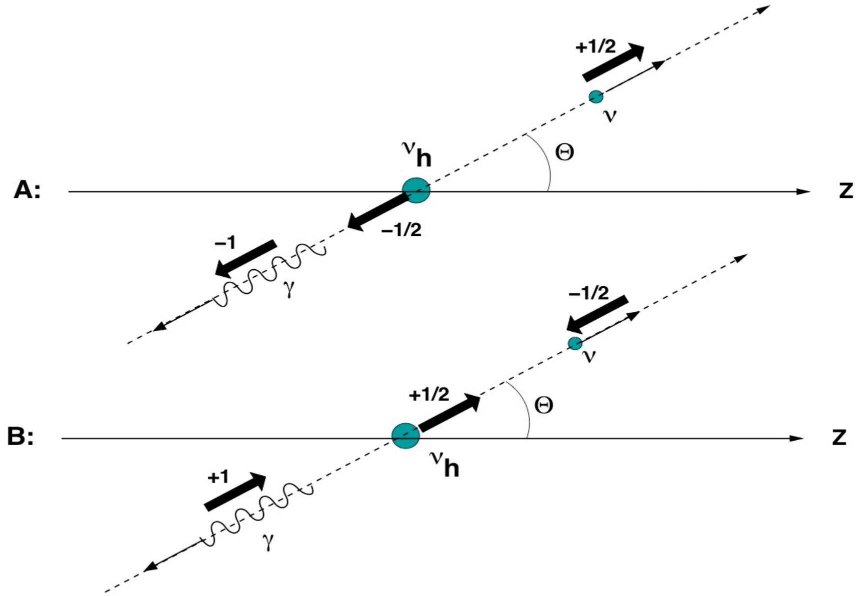
Note: ν_h might also be a new exotic fermion, which is produced preferably in ν_μ NC, e.g. due to $Z\nu_\mu\nu_h$ coupling, as in some E(6) models.

Hewett, Rizzo , Rhys. Rep. 183 (1989) 193.

Radiative decay of heavy neutrino $\nu_h \to \gamma\nu$

- γ-angular distribution in ν_h rest frame is not generally isotropic: $1+a\cos(\Theta_\gamma)$
- CP conserved, Majorana ν's: $a=0$;
  Dirac ν's: $-1 < a < 1$.
- $\nu_h \to \gamma\nu$ decays is dominant due to, e.g. large enough transition magnetic moment (not exotic at all)

Two helicity amplitudes



γ-energy : $E_\gamma^0 = m_h/2\,(1-m_\nu^2/m_h^2) \approx m_h/2$ for $m_\nu << m_h$

$\nu_h \to \gamma\nu$ decay rate: $\Gamma_{\gamma\nu} = \mu^2_{tr}/8\pi\, m_h^3 (1-m_\nu^2/m_h^2)^3$

M.A.B. Beg, W.J. Marciano, M. Ruderman, PRD 17, 1395 (1978);
L.F. Li and F. Wilczek, PRD 25, 143 (1982);
P.B. Pal and L. Wolfenstein, PRD 25, 766(1982);
R.E. Shrock, Nucl. Phys. B206, 359 (1982);

LSND parameter space

Expected number of $\nu_h \to \gamma\nu$ events in LSND:

$$\Delta N_{\nu_h \to \gamma\nu} \simeq A \int \Phi_{\nu_\mu} \sigma_{\nu_\mu} |U_{\mu h}|^2 f_\gamma f_n f_{phs} P_{dec} P_{abs} \epsilon_\gamma dE$$

Cross check with LSND oscillation signal

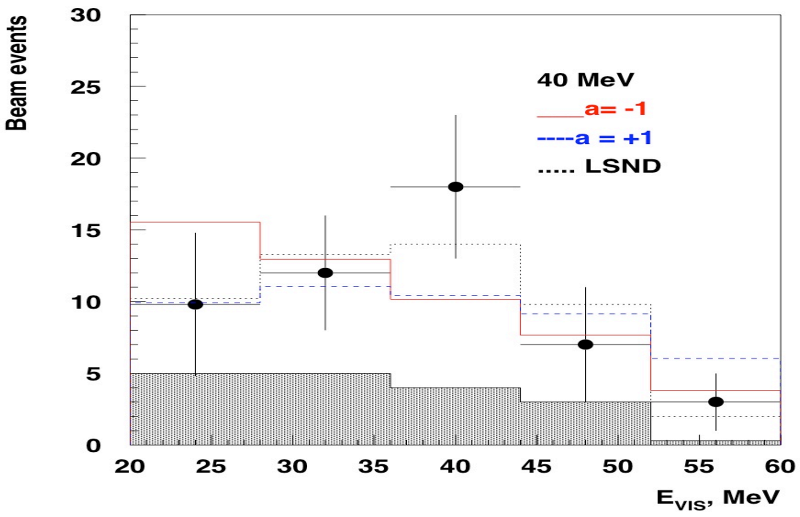
- $A = 7.4 \times 10^{30}$
- $\Phi = 1.26 \times 10^{14}\ \nu/cm^2$
- $\sigma = 0.95 \times 10^{-40}\ cm^2$
- $f_e = 0.9$, $\varepsilon = 0.42$
- $\Delta N_{osc} = 70$ events $P_{osc} \sim 2.64 \times 10^{-3}$ for to be compared

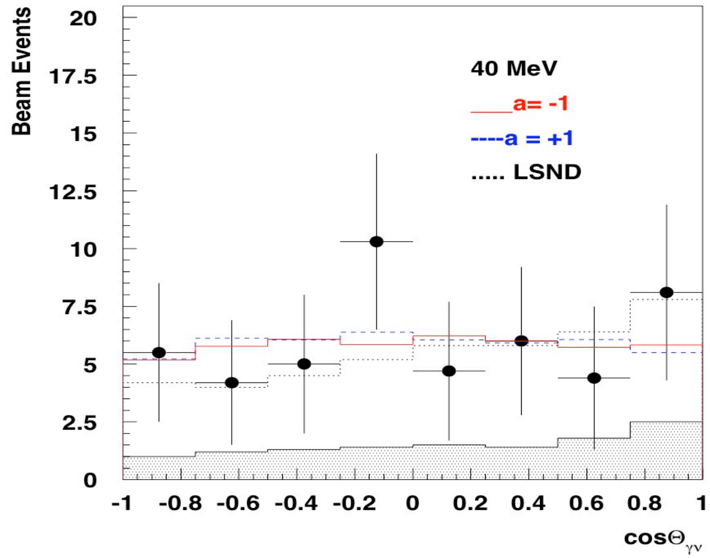
with observed excess $87.9 \pm 22.4 \pm 6.0$ events

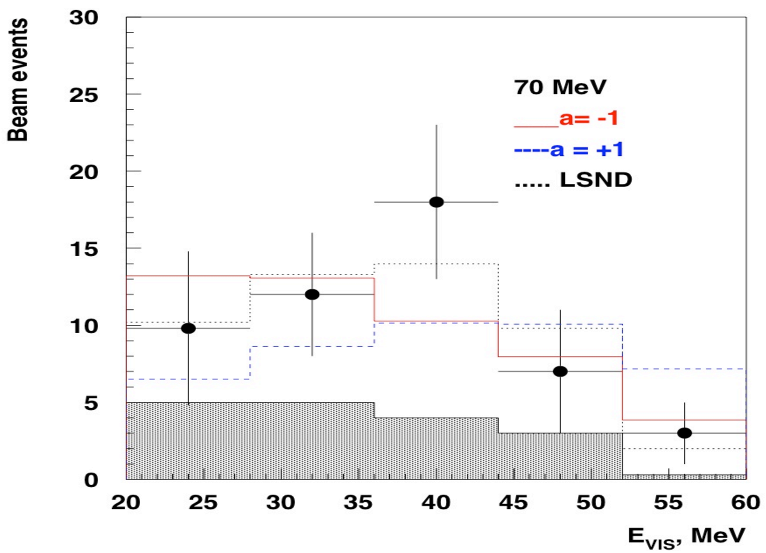
$$\sim 40\ MeV \leq m_h \leq 80\ MeV$$
$$\sim 10^{-3} \leq |U_{\mu h}|^2 \leq 10^{-2}$$
$$\tau \leq \sim 10^{-8}\ s$$

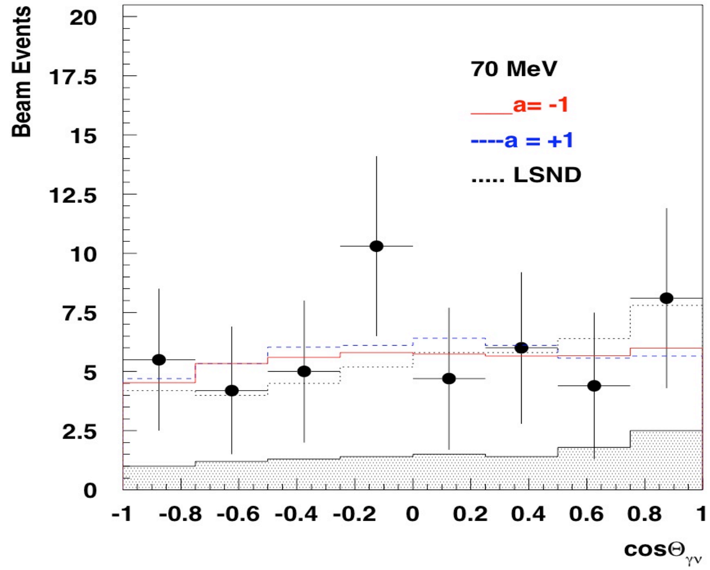
LSND ν_μ excess vs E_{vis} and $\cos\Theta_{\gamma\nu}$

$|U_{\mu h}|^2 = 3\times10^{-3}$, $\tau = 10^{-9}$ s

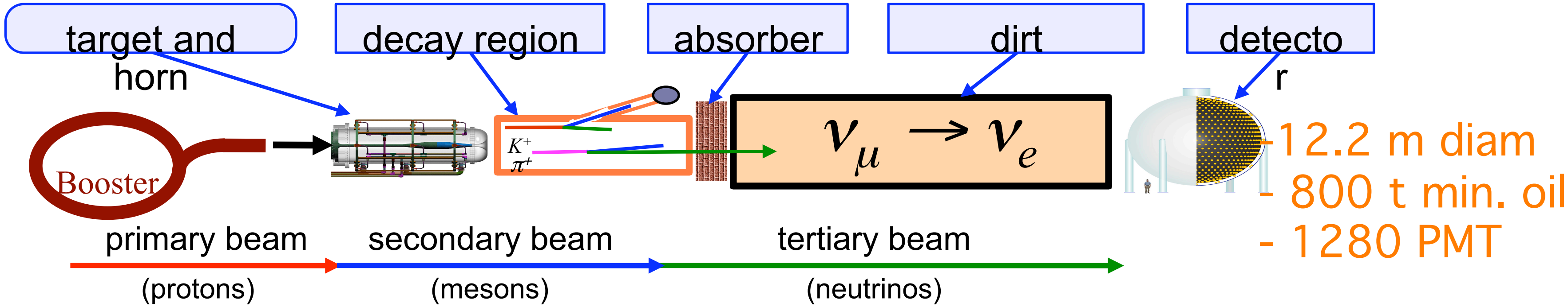




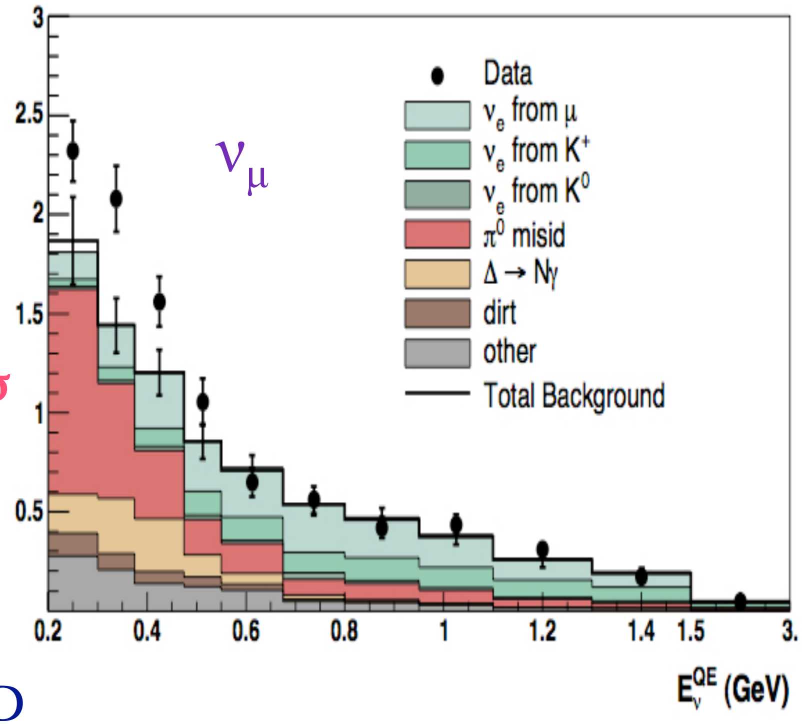




MiniBooNE low-energy excess events (6.5E20 POT)



- designed to test LSND
- E~500 MeV, L~500 m, L/E~ 1
- Search for $\nu_\mu \rightarrow \nu_e$ appearance
- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance



- > 475 MeV good agreement with background
- < 475 MeV **Excess ΔN=129.0±43.0 ,≈3 σ**

➔ 1track events : either e's, or $\gamma \rightarrow$ e+e- pairs

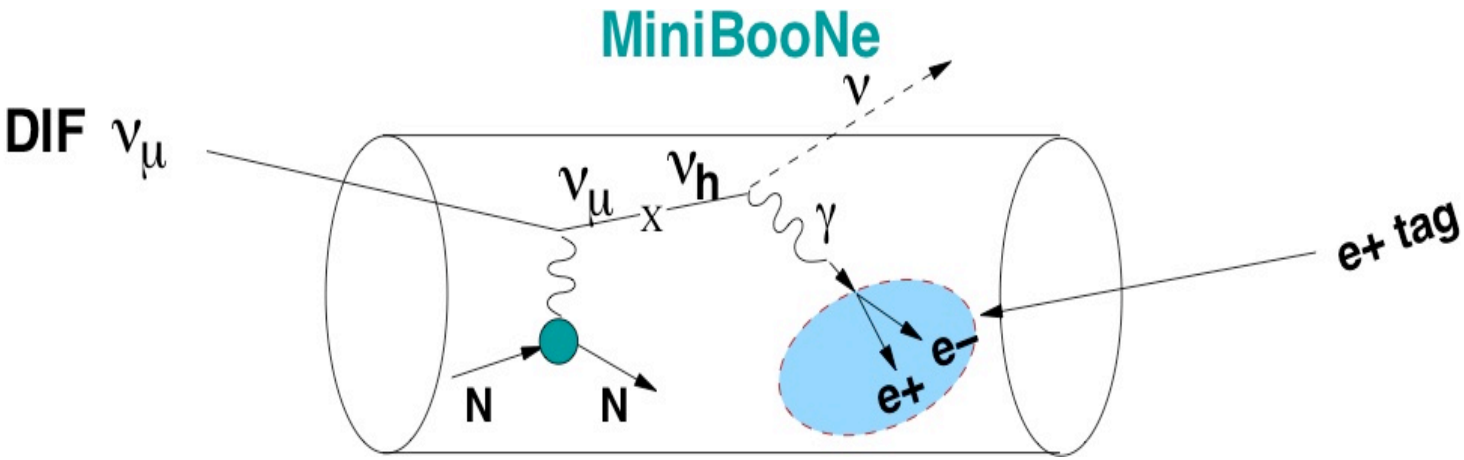
➔ reconstructed ν_μ energy $200 < E^{QE} < 475$ MeV

➔ visible energy $200 < E_{vis} < 400$ MeV

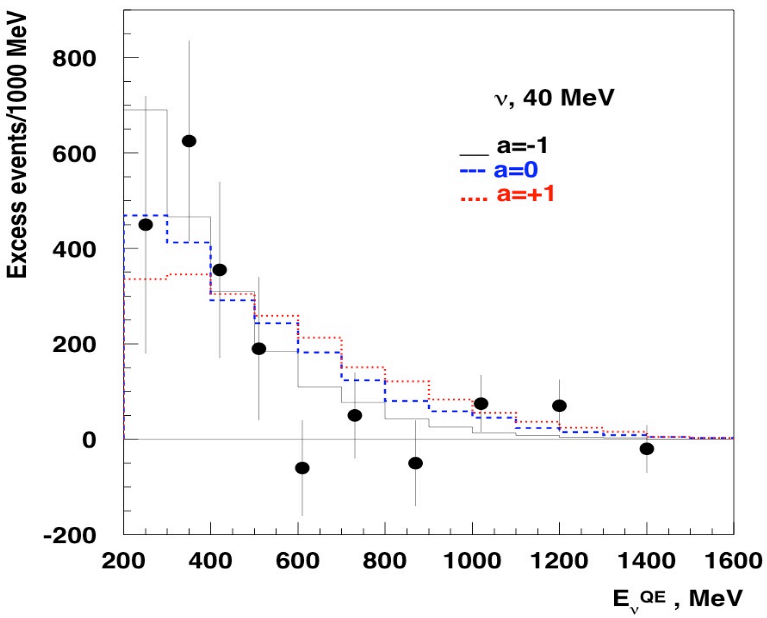
➔ angular distr. is wide, consistent with ν_eQE

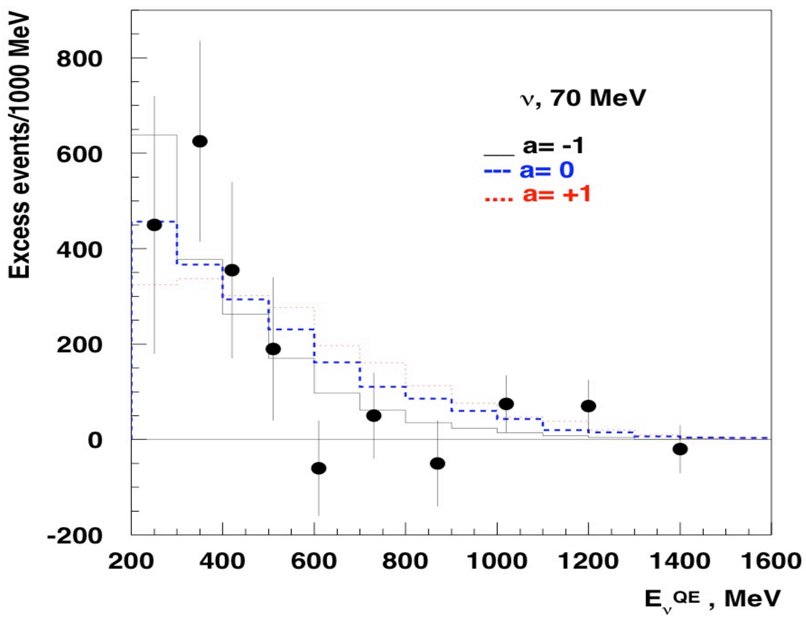
➔ shape inconsistent with 2ν osc. interprt. of LSND

MiniBooNE excess as a signal from $\nu_h \rightarrow \gamma\nu$



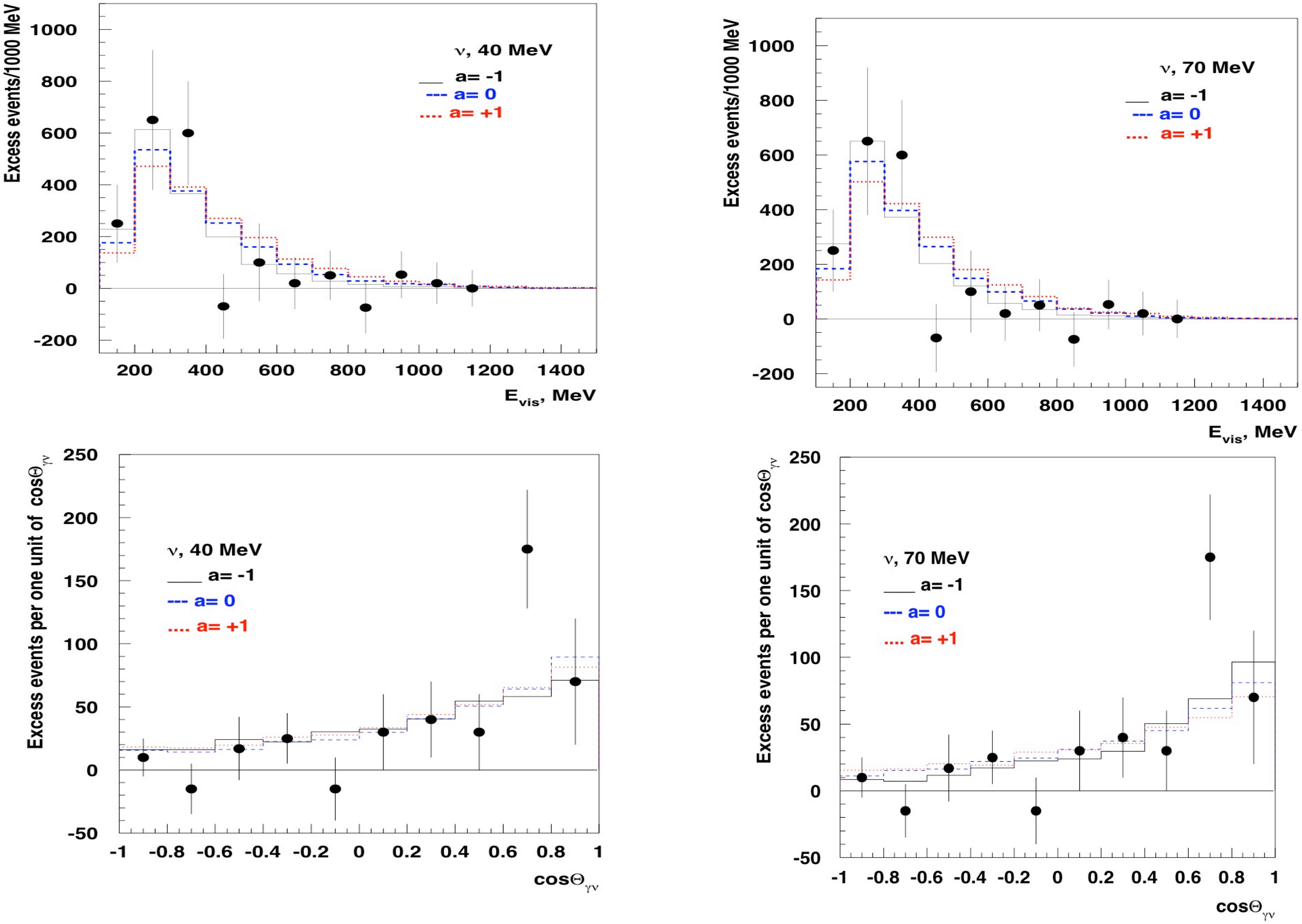
Comparison of E^{QE} distributions, $|U_{\mu h}|^2=3\text{x}10^{-3}$, $\tau=10^{-9}$ s



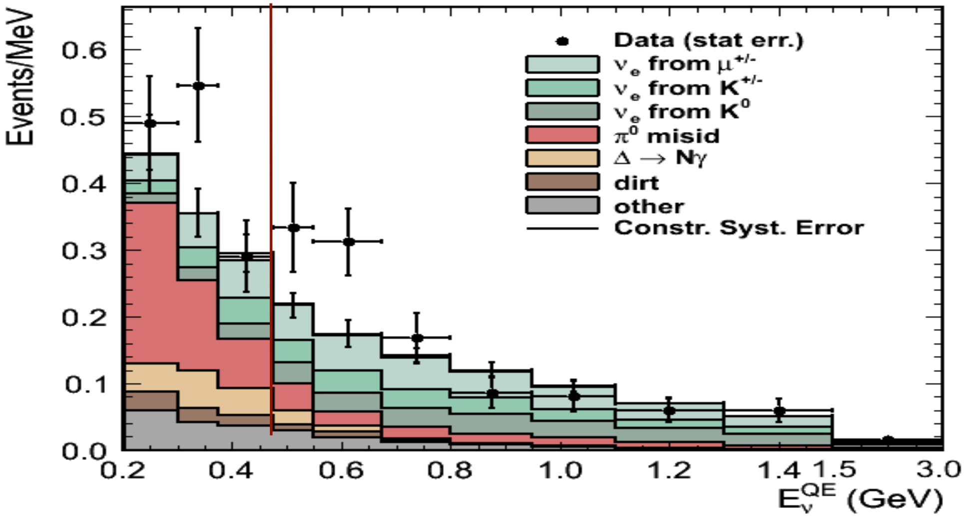


Comparison of E_{vis} and $\cos\Theta_{\gamma\nu}$ distributions

$|U_{\mu h}|^2 = 3\times10^{-3}$, $\tau = 10^{-9}$ s



MiniBooNE antineutrino excess events (5.66E20 POT)



Phys. Rev. Lett.105, 181801 (2010)

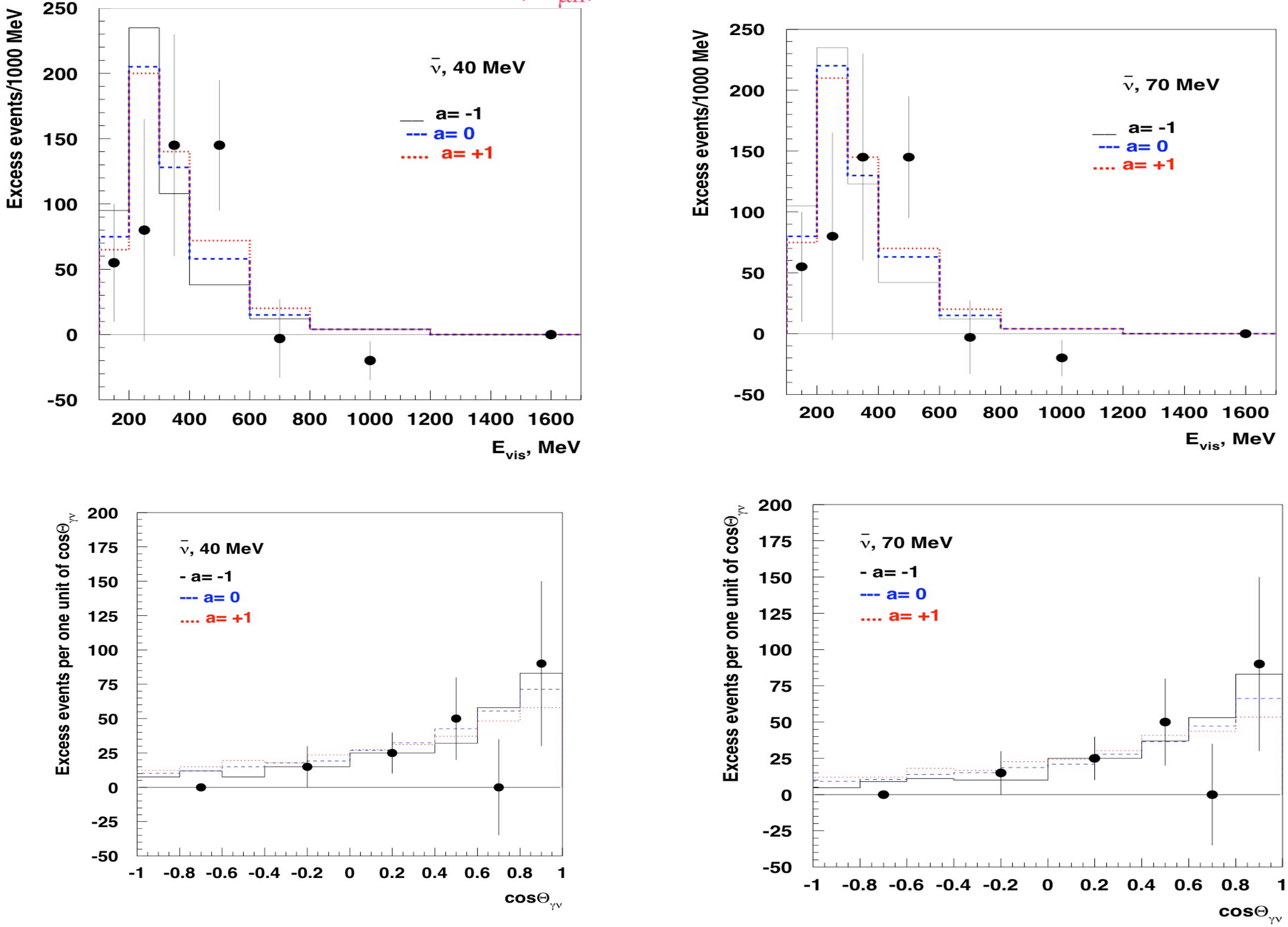
- $>$ 475 MeV, 120 events vs 99 ± 10(stat) ±10(syst) expected
- $<$ 475 MeV, 119 events vs 100 ± 10(stat) ±10(syst) expected

Excess ΔN=43.2±22.5 ≈2 σ

- → track events : either electrons, or $\gamma \rightarrow$ e+e- pairs
- → reconstructed ν_μ energy 200< E^{QE}< 800 MeV
- → reconstructed visible energy 200< E_{vis}< 700 MeV
- → angular distrubution is wide, consistent with ν_eQE
- → shape >475 MeV consistent with 2ν oscillation interpretation of LSND

Comparison of E_{vis} and $\cos\Theta_{\gamma\nu}$ distributions

$|U_{\mu h}|^2 = 3\times10^{-3}$, $\tau = 10^{-9}$ s

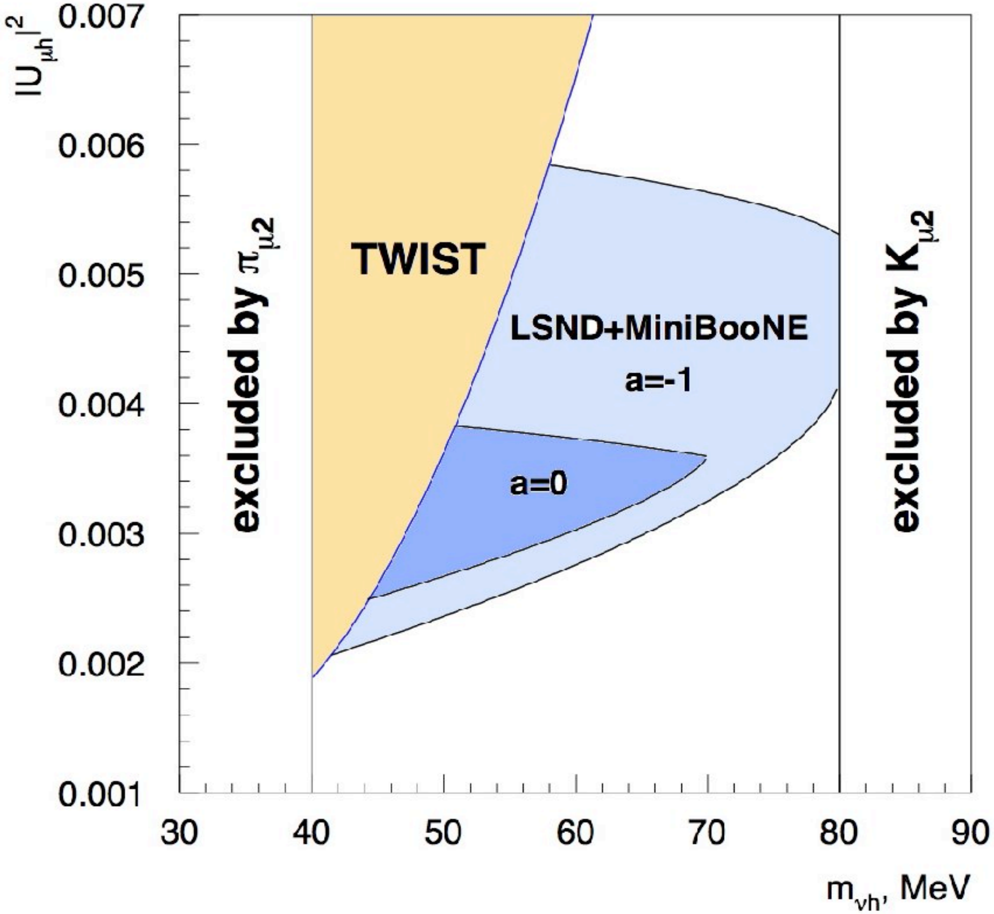


Combined LSND-MiniBooNE parameter window

$\sim$40 MeV $\leq m_h \leq$ 80 MeV

$\sim 10^{-3} \leq |U_{\mu h}|^2 \leq 10^{-2}$

$\tau \leq \sim 10^{-9}$ s



Are these values consistent with
the results of previous measurements ?

Experimental constraints on $|U_{\mu h}|^2$

- Two-body decays of pions and kaons, e- μ universality tests.... — PSI, KEK, NA-62, CERN
- Muon processes:
  - Michel spectrum — TWIST
  - G_F — MuLan
  - $\mu \to e\nu\nu\gamma$ — PIBETA
  - $\mu \to e\gamma$ — MEGA
  - Some tension, radiative μ capture on H — TRIUMPH

  but can be relaxed e.g. for a bit longer lifetime, or with other suggestions.

McKeen, Pospelov PRD 82, 113018 (2010); S.G.,arXive:1011.5560

- Neutrino experiments
  - $\nu_h \to e{+}e{-}\nu$: — PS191, CHARM, NOMAD, NuTeV, BEBC,...
- LEP Z->νν* -> ννγ: — ALEPH, DELPHI
- Cosmology, astrophysics — SN1987A, ..

All consistent with LSND-MiniBooNE values

Most sensitive limits on $|U_{\mu h}|^2$ vs ν_h mass

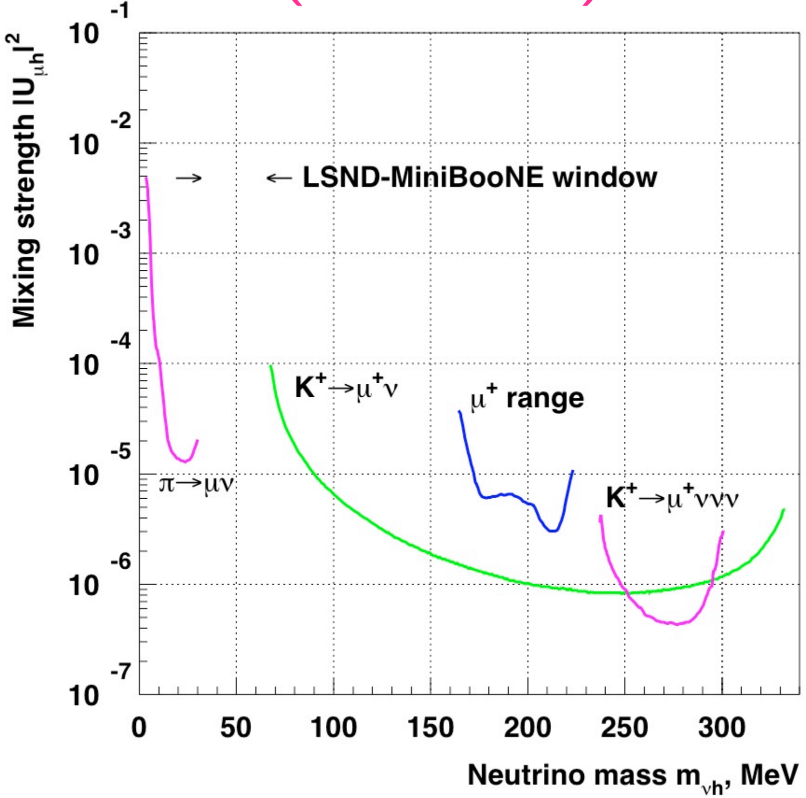
$K\rightarrow\mu\nu_h\rightarrow\mu+\nu\gamma\rightarrow e+e-$ excess

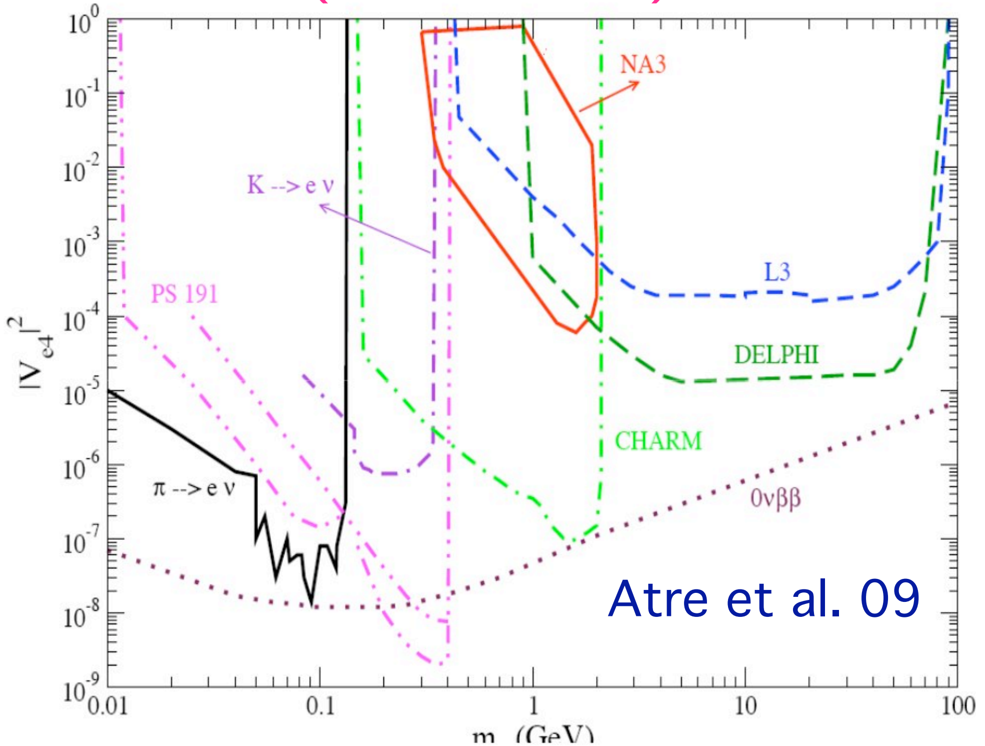
(PS191,CERN)

(indirect test)

Extra peak in $K\rightarrow\mu\nu_h$ (KeK)

(direct test)





Big Surprise!

for ~40 MeV≤ m_h ≤80 MeV

no constraints on $|U_{\mu h}|^2$

PS191 searched for $K\rightarrow\mu\nu_h\rightarrow\mu+\nu e+e-$

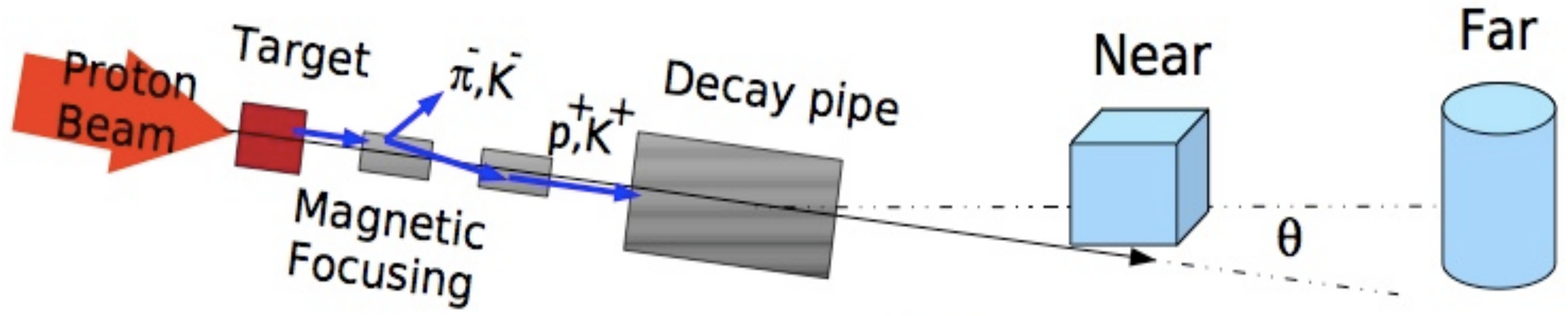
limits on $|U_{eh}|^2$ are evaded

for ~40 MeV≤ m_h ≤80 MeV

due to prompt $\nu_h\rightarrow\gamma\nu$ decay and very light target

T2K excess of e-like events

Abe et al., arXiv:1106.2822[hep-ex]



- LBL search for ν_μ -> ν_e appearance
- off-axis ν_μ , <E> ~600 MeV, L~280 km
- Near detectors: prediction of rate at Far from SM interactions
- Far detector is the SuperK

Excess ΔN= 4.5 events (6 observed, 1.5±0.3 expected) / 1.43e20 pot

(excess signature is similar to MiniB.)

→ track events : either electrons, or $\gamma \longrightarrow$ e+e- pairs

→ reconstructed ν_μ energy $200 < E^{QE} < \sim 1500$ MeV

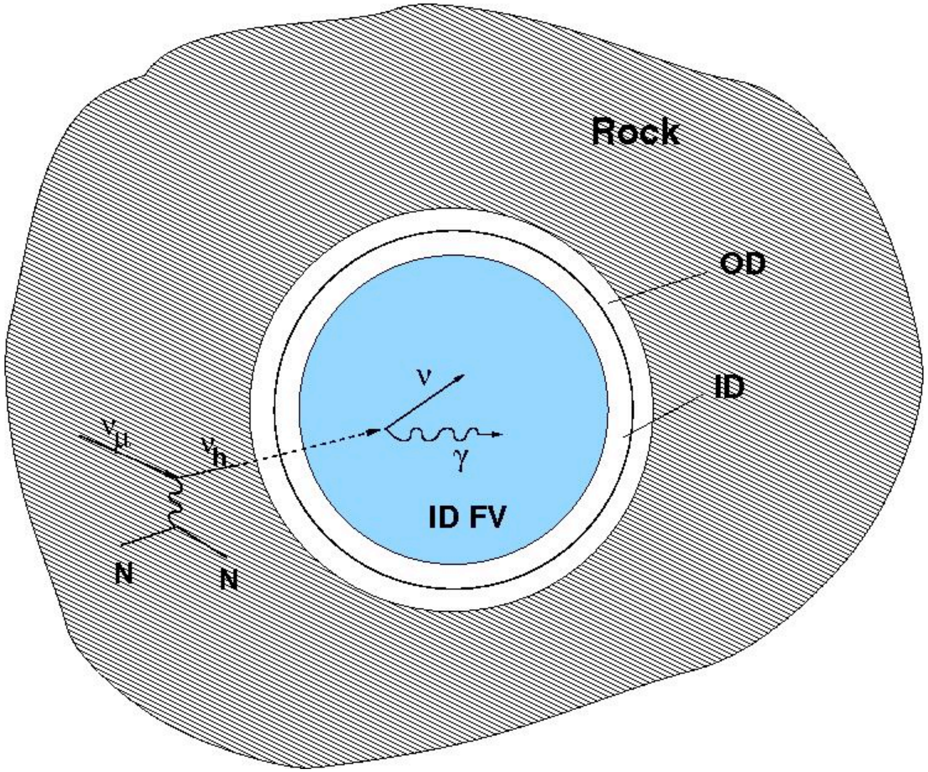
→ reconstructed visible energy $E_{vis} > \sim 100$ MeV

→ angular distrubution consistent with ν_eQE

→ shape consistent with ν oscillations interpretation with $\Theta_{13} \neq 0$

$\nu_h \rightarrow \gamma\nu$ event rate at SuperK

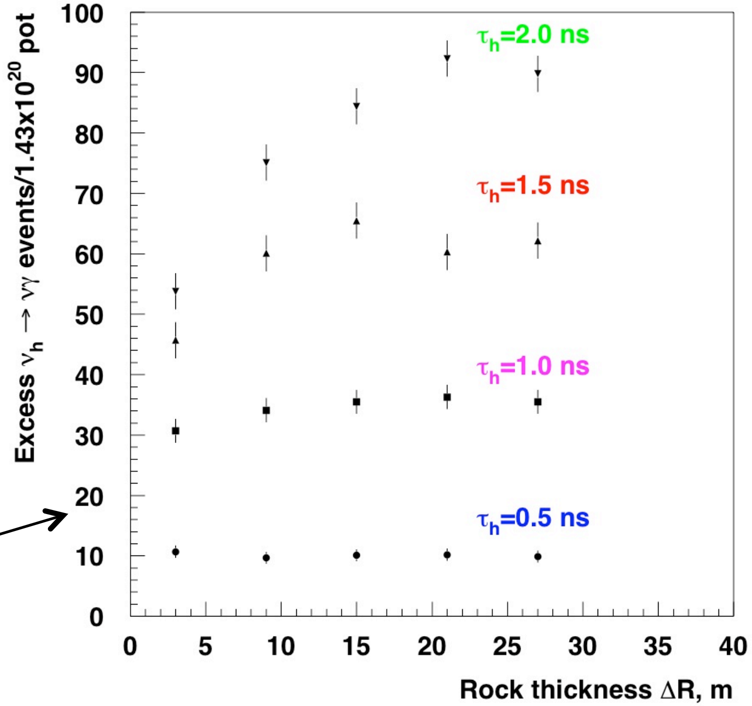
SuperK top view



S.G., arXiv:1107.0279 [hep-ph]

- ID+OD, 50 kt, water
- ID FV, 22.5 kt

$|U_{\mu h}|^2 = 1$, $m_h = 50$ MeV

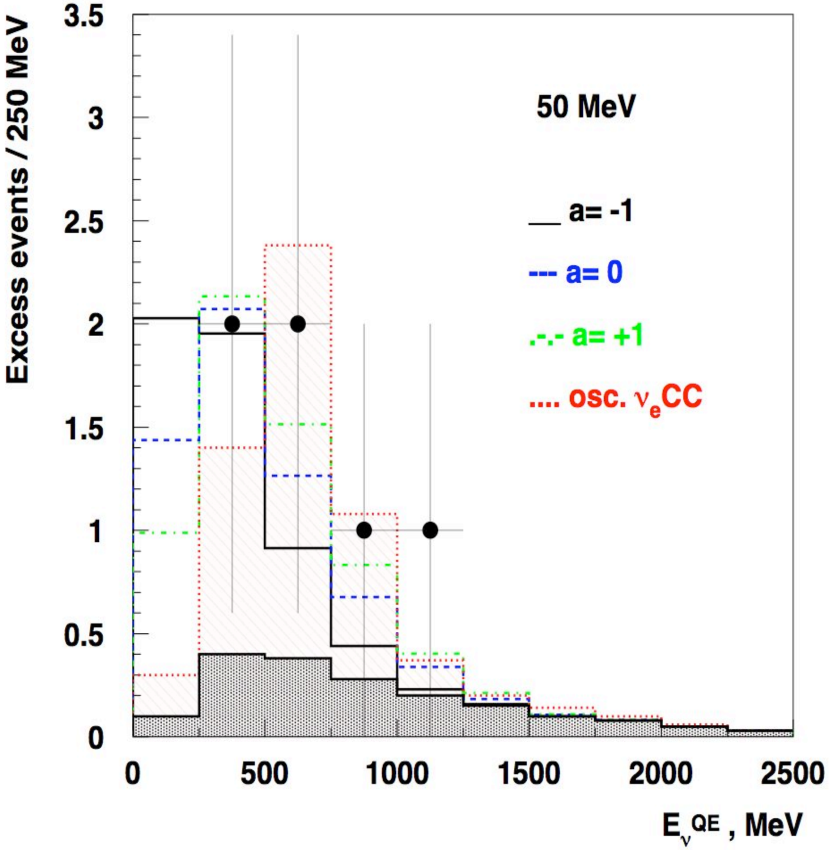


Contributions from ν_μ NC interactions $|U_{\mu h}|^2 = 1$, $\tau = 1.5\text{x}10^{-9}$ s:

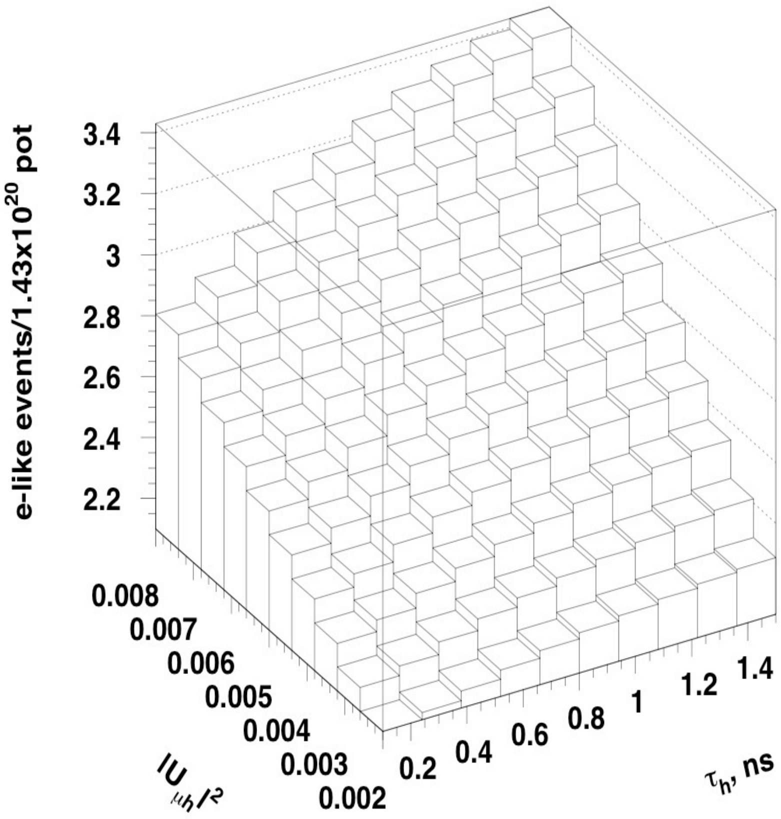
- FV – 38 %
- outside FV – 21 %
- Rock – 41 %
- roughly, FV rate $\sim|U_{\mu h}|^2$, rock rate$\sim|U_{\mu h}|^2$ x τ

Comparison of E^{QE} distributions

$\tau = 10^{-9}$ s



$m_h = 50$ MeV



Distributions combined with background, shape consistent with data, χ^2 test p-values > 0.7

Prob(n_{exc} > 5 events) > 25 %

T2K excess of e-like events could originate from ν_h decays

Searches for $\nu_h \to \gamma\nu$ with existing data and in future experiments

- direct test in ν_μNC interactions:

  $\nu_\mu + A \to \nu_h(\to \nu\gamma) + X$

  S.G., arXiv:1009.5536 [hep-ph]
  NOMAD Coll., in progress

- muon decay at rest:

  $\mu \to e\nu + \nu_h \to e\nu + \nu\gamma$

  S.G., arXiv:1101.4004 [hep-ex]

- K decays in flight /at rest:

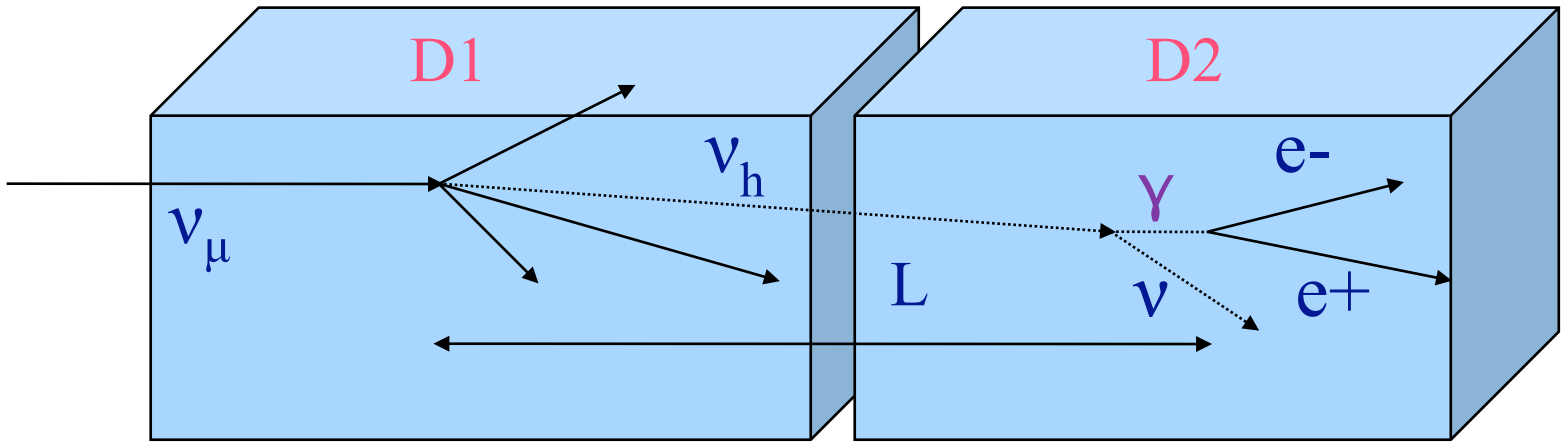
  $K \to \mu + \nu_h \to \mu + \nu\gamma$

  S.G., arXiv:1101.4004 [hep-ex]
  NA-62, in progress
  ISTRA+ , in progress
  C. Dib et al., arXiv:1105.4664 [hep-ph]

- atmospheric neutrino telescopes, Masip, Masjuan, arXiv:1103.0689

Search for displaced converted photons in ν_μ NC:

$\nu_\mu + A \to \nu_h (\to \nu\gamma) + X \to \nu e^+e^- + X$



- Detector of two parts: dence D1 and light D2

  D1: high rate, primary vertex, ν_μ NC shower dump to minimize background leak to D2;

  D2, e.g. a'la NOMAD: good particle ID and measur., secondary vertex.
- $\nu_h \to \nu\gamma$ signature: single e+e- pair displaced at $L >> \lambda_{int}$
- advantages to search for short τ :

  ν_h decay length ~ E

  absorption length ~ ln(E)
- disadvantage: e+e- efficency drops with E

Background for single γ events

- π^0 decays
- K0 decays in flight
- neutron reactions
- coherent π^0/γ production

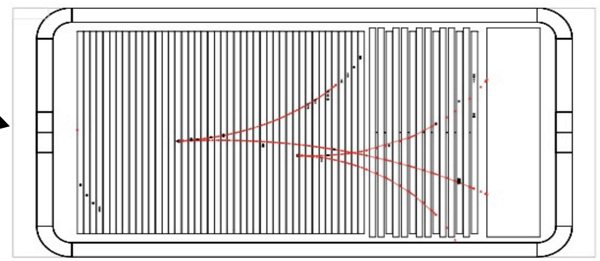


Fig. 2. Schematic of the DC tracker and a coherent π^0 event candidate in NOMAD where both photons from the π^0 decay convert in the DC's. The red crosses represent drift chamber digitizations that are used in the track-reconstruction, whereas the black ones are not. The upstream ($\gamma 1$) and downstream ($\gamma 2$) momentum vectors when extrapolated upstream intersect within the fiducial volume.

SUMMARY

- ν_h's: ~40 MeV ≤ m_h ≤ 80 MeV,
  ~10^{-3} ≤ $|U_{\mu h}|^2$ ≤ 10^{-2},
  ~10^{-11} ≤ τ ≤ 10^{-9} s

  could reconcile LSND, KARMEN and MiniBooNe results.
  - explain size of the excess events in LSND and in ν_μ / $\bar{\nu}_\mu$ MiniBooNE,
  - no excess in KARMEN,
  - provide distributions consistent with observations.
- could explain the size and shape of e-like excess in T2K
- experimental constraints on ν_h are consistent with LSND-MiniB. values:
  - ν_h is too heavy for π decays, too light for K decays
  - escape in ν experiments due to dominant prompt $\nu_h \to \gamma\nu$ decay
- searches for ν_h in ν_μNC, μ, and K experiments are complementary to current efforts to clarify LSND/MiniB anomalies.
  - (dis)prove ν_h interpretation of LSND/MiniBooNE excess
  - close the $|U_{\mu h}|^2$ gap for m_h ~40 – 80 MeV
- if ν_h is preferably produced in ν_μNC, then
  results of CC searches should be interpreted carefully.