LSND/MiniBooNE excess events and heavy neutrino decays

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Plan:

- LSND/ KARMEN $\bar{\nu}_\mu \to \bar{\nu}_e$ results vs radiative decay of heavy neutrino $\nu_h \to \gamma\nu$
- MiniBooNE $\bar{\nu}_\mu$ excess events and $\nu_h \to \gamma\nu$ decays
- MiniBooNE ν_μ excess events and $\nu_h \to \gamma\nu$ decays
- Constraints on ν_h
- Searches for ν_h with future experiments
- Summary

S.G., arXiv:1009.5536; 1101.4004.

LSND excess events

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

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

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

  $\rightarrow \bar{\nu}_e$

- oscillation signature:

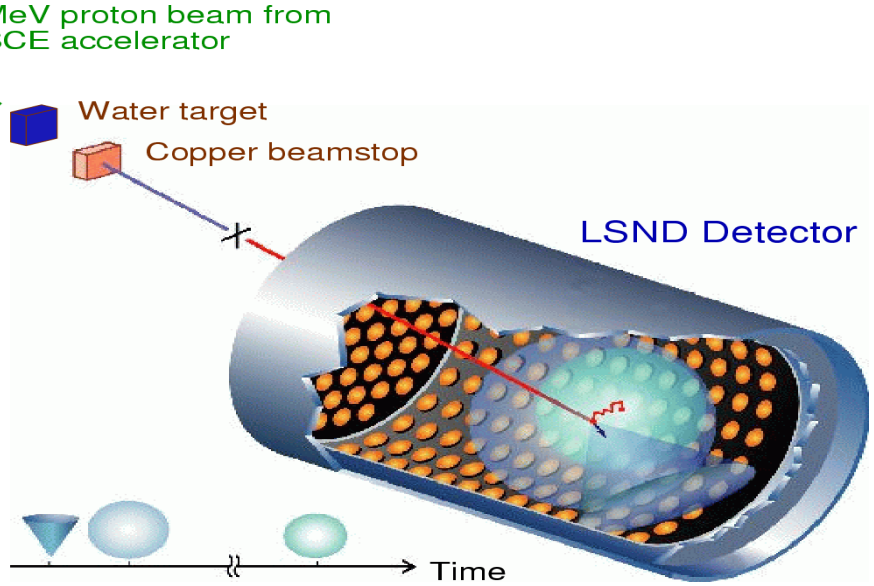
  e^+ - delayed γ pair

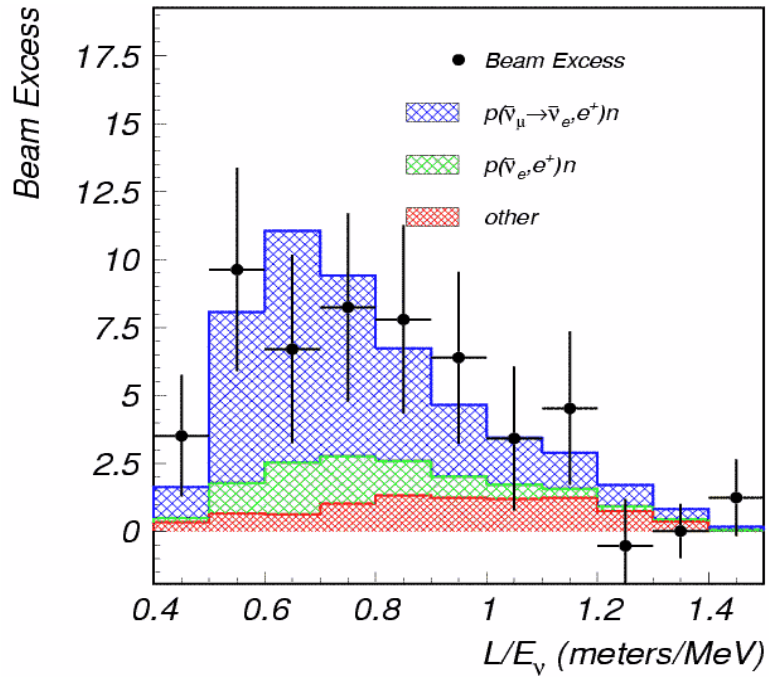
  $\bar{\nu}_e p \rightarrow e^+ n$

  $\rightarrow n\ p \rightarrow d\ \gamma(2.2\text{MeV})$

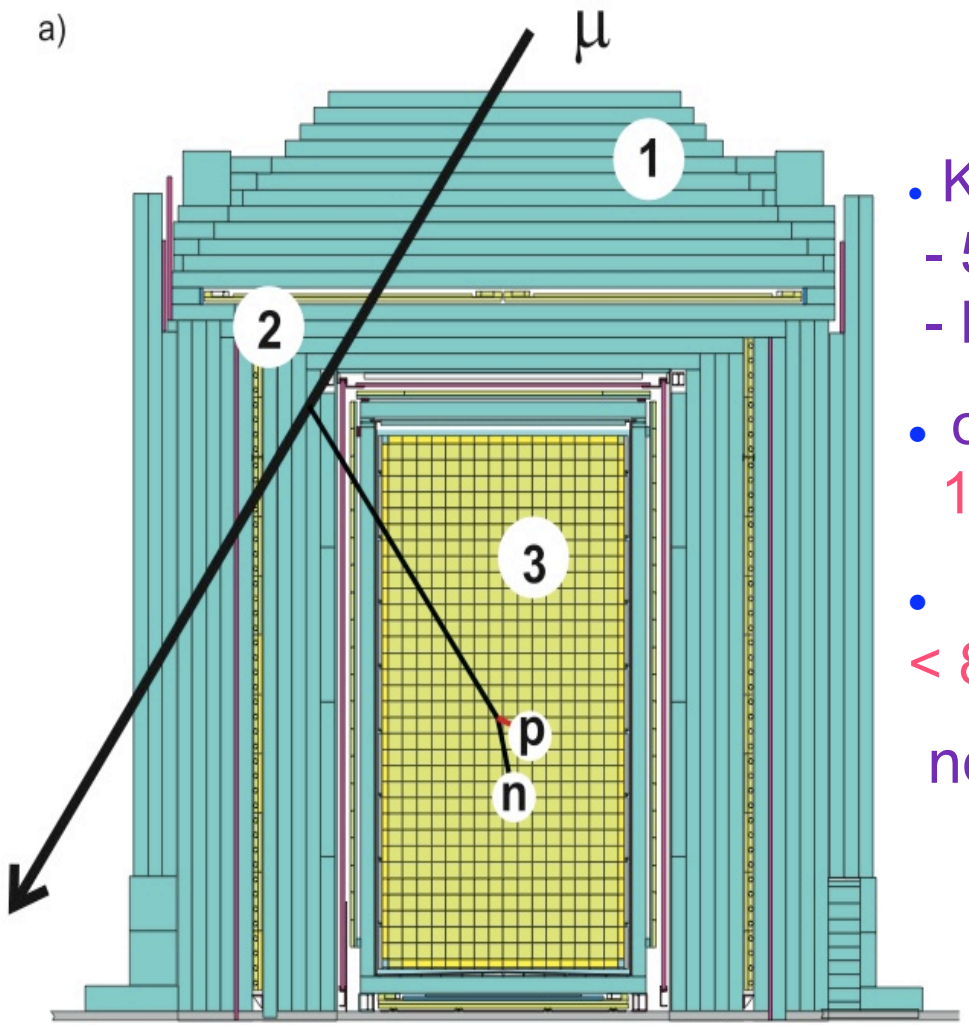
excess 87.9 ± 22.4 ± 6.0 ev's, 3.8 σ

osc.prob. (2.64 ± 0.67 ± 0.45) x 10^{-3}





KARMEN : no evidence for excess



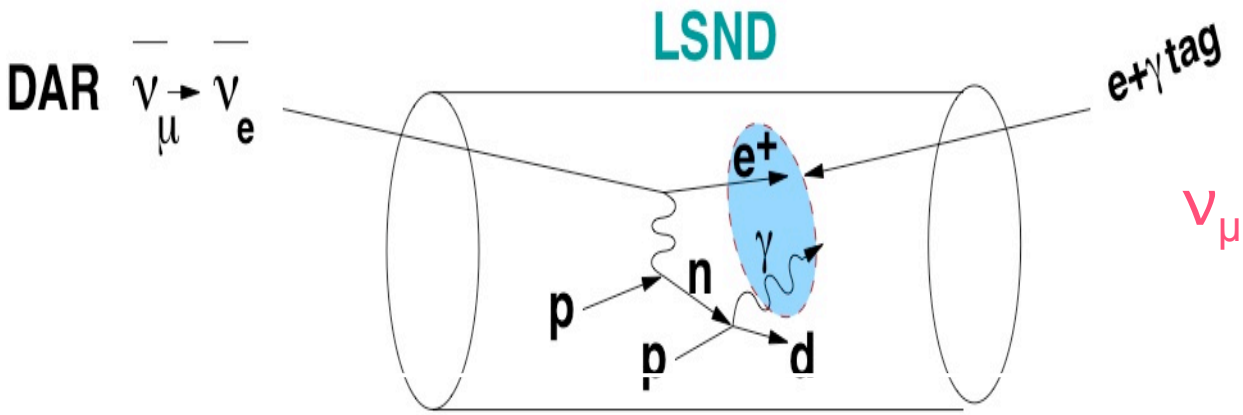
- KARMEN (1997-2001)
  - 5.9 E22 POT, 56 t LSc
  - L = 17 m and 16 < E_ν < 50 MeV
- observed excess of $\overline{\nu}_e$:
  10 ± 32 events.
- oscillation probability of
  < 8.5 x10^{-4} 90% CL

no evidence for oscillation.

Origin of LSND excess

DAR $\nu_\mu \rightarrow \nu_e + p \rightarrow e^+ + n$

Old



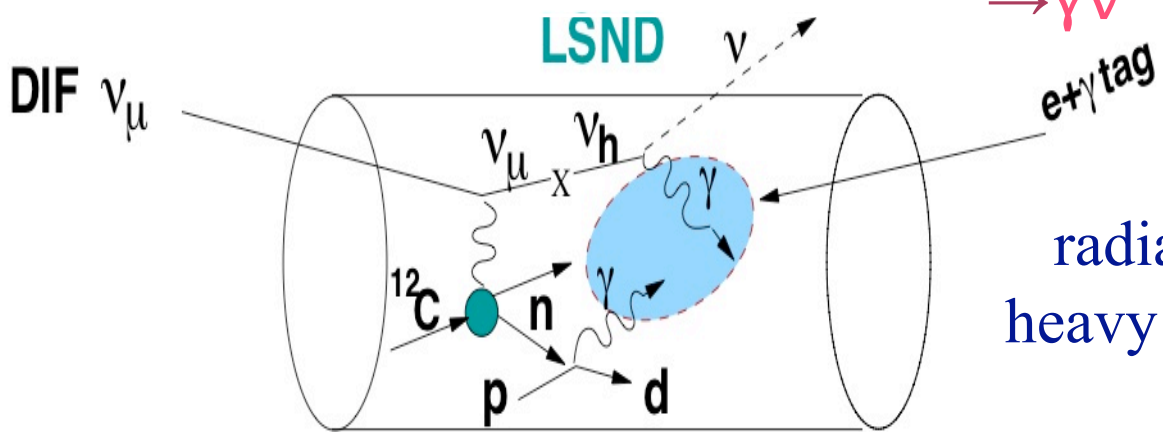
$\nu_\mu \rightarrow \nu_e$ neutrino oscillations

DIF $\pi \rightarrow \mu\nu_\mu$

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

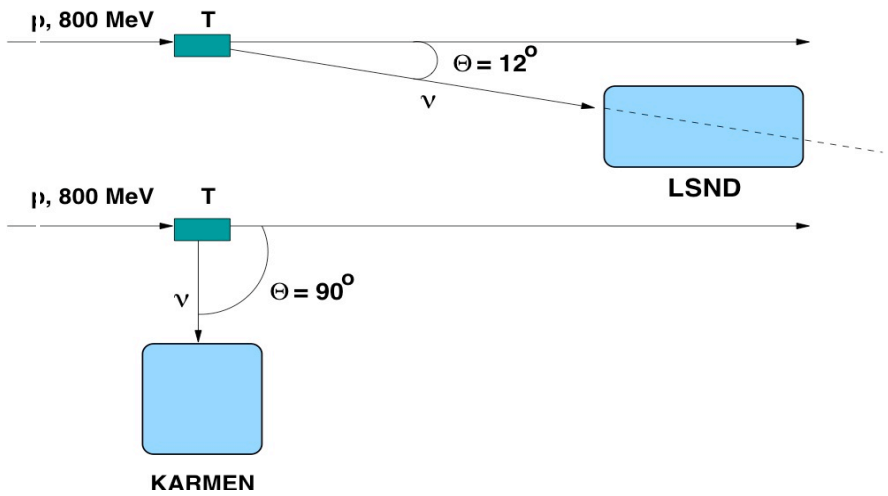
$\rightarrow \gamma\nu$

New



radiative decay of heavy neutrino $\nu_h \rightarrow \gamma\nu$

Why no excess in KARMEN?



DIF $\pi \rightarrow \mu \nu_\mu$

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

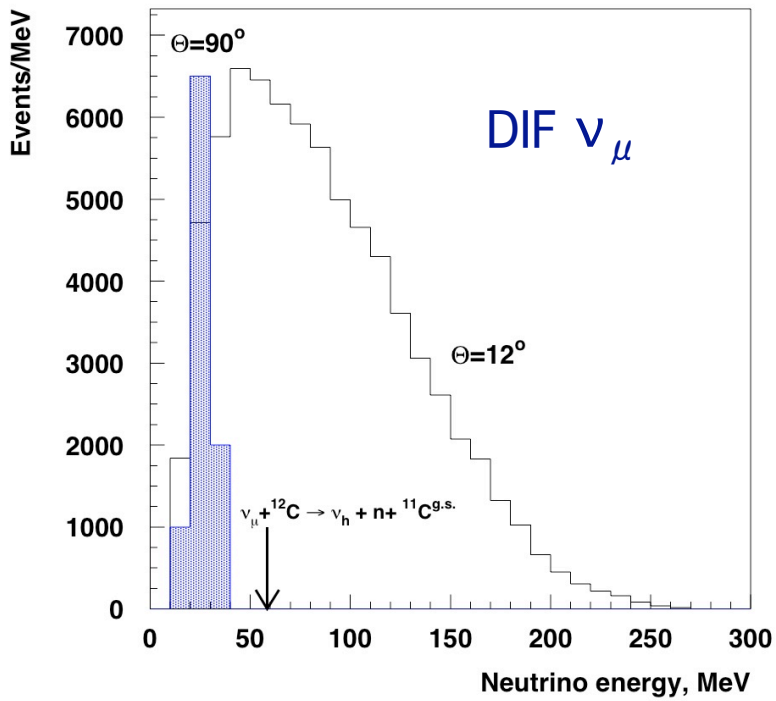
$\rightarrow \gamma\nu$

- Fraction of decays in flight ν's ~3-4%

- LSND/KARMEN/MB do not discriminate between e and γ

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

- LSND: signature (tag n + e-like) event if ν_h <~ 80 MeV, it cannot be effectively produced by DIF ν's due to high mass

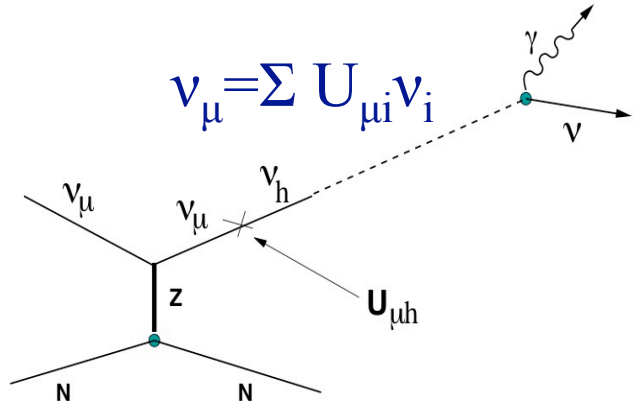


New weakly interacting particle ν_h :

- 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 ns - to decay mostly in LSND fiducial volume
- decays dominantly $\nu_h \rightarrow \gamma\nu$

Usefull assumption: ν_h is a component of ν_μ

$\nu_\mu = \Sigma\, U_{\mu i}\nu_i$

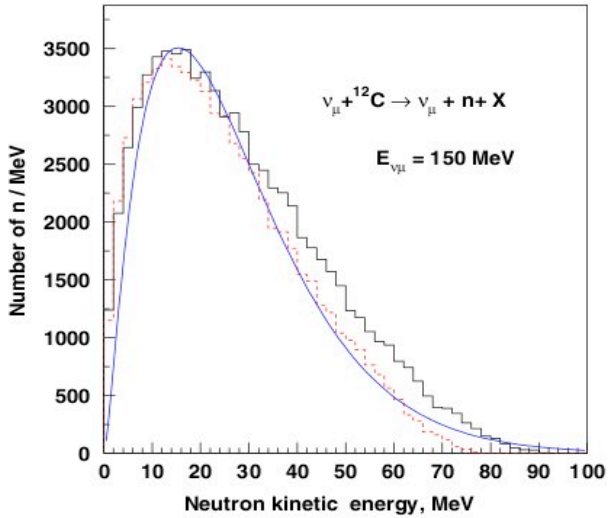


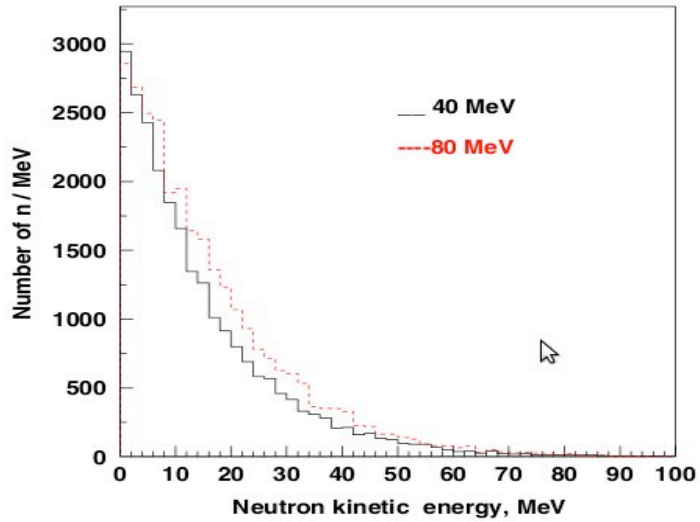
- ➔ muonic mixing $|U_{\mu h}|^2$
- ➔ could be produced in ν_μ CC int.
- ➔ could be seen in μ, K, D,..decays
- ➔ decay rapidly due to, e.g. transition magnetic moment (not exotic at all)
- ➔ γ-angular distribution in ν_h rest frame: $1+a\cos(\Theta_\gamma)$
- ➔ Majorana ν: a=0; Dirac ν: -1< a < 1.

Monte Carlo spectra of neutron kinetic energy in $\nu_\mu + {}^{12}C \rightarrow n + X + \nu_h$

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

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:

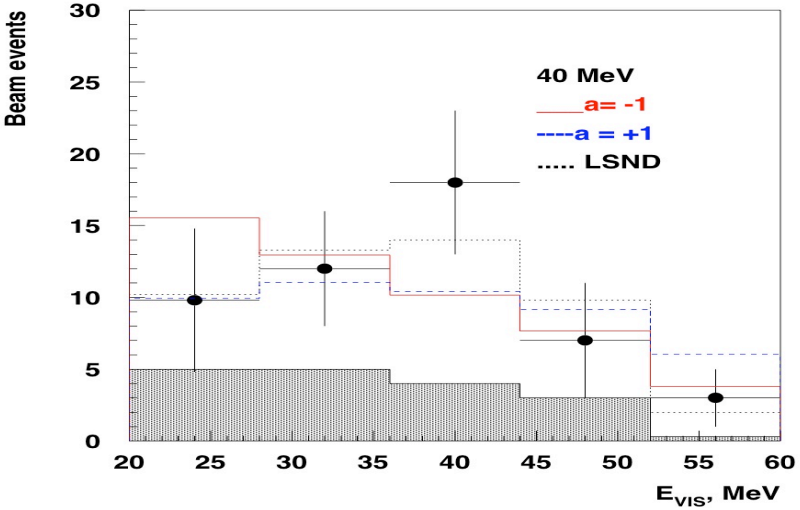
- E_n< 5 MeV at ~25 cm
- Time << n cupture time
- Fraction of high energy secondary n (> 20 MeV) < 2%

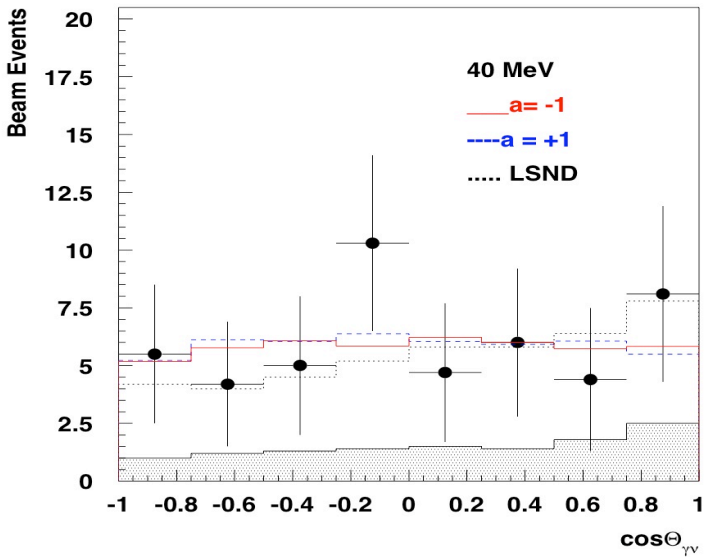
Discriminate between n's from $\nu_\mu\, {}^{12}C \rightarrow n X \nu_h$ and $\bar{\nu}_e p \rightarrow e^+ n$ is not simple in LSND:

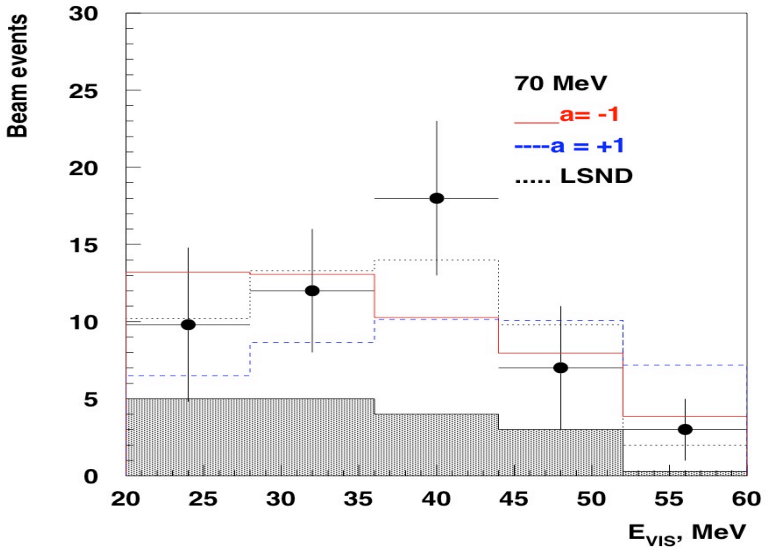
the e+γ tags are identical for both reactions

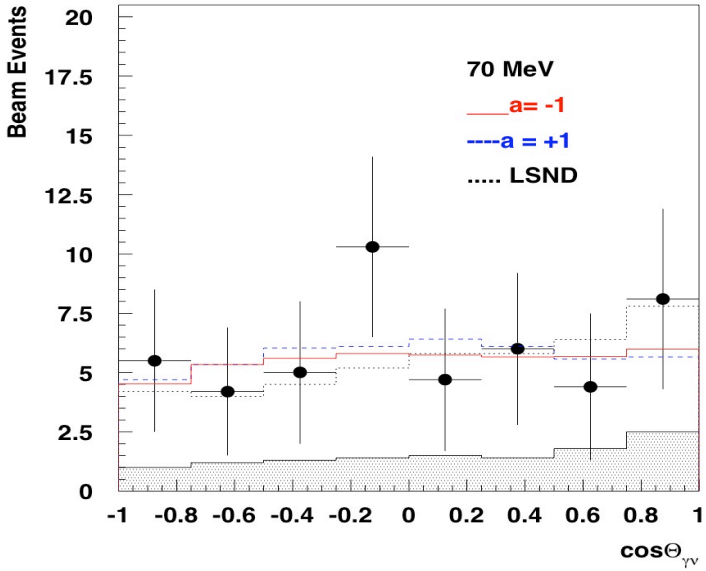
LSND ν_μ excess vs E_{vis} and $\cos\Theta_{\gamma\nu}$

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









LSND parameter space

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

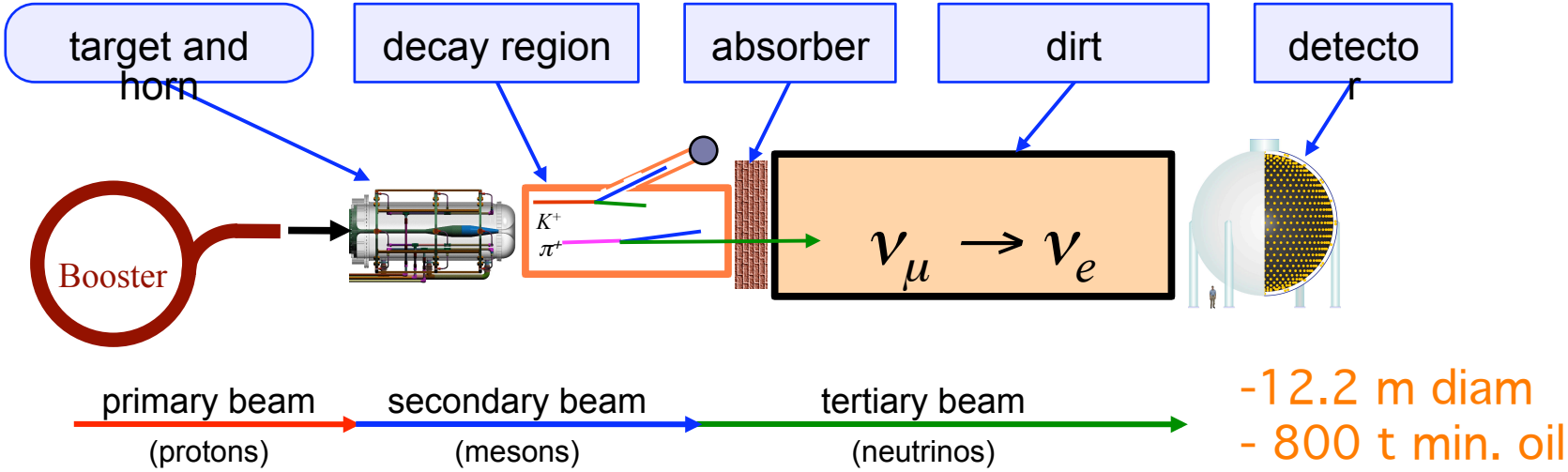
$$\Delta N_{\nu_h \rightarrow \gamma\nu} \simeq A \int \Phi_{\nu_\mu} \sigma_{\nu_\mu} |U_{\mu h}|^2 f_\gamma f_n f_{phs} P_{dec} P_{abs} \epsilon_\gamma dE$$

- ~ 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

Cross check with LSND oscillation signal

- $A = 7.4 \times 10^{30}$
- $\Phi = 1.26 \times 10^{14}\ \nu/cm^2$
- $\sigma = .95 \times 10^{-40}\ cm^2$
- $f_e = 0.9$, $\varepsilon = 0.42$
- $\Delta N_{osc} = 70$ 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

MiniBooNE



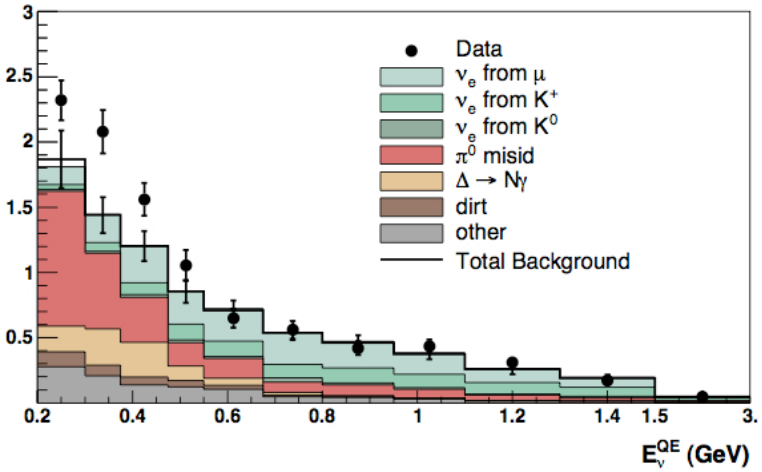
-12.2 m diam
- 800 t min. oil
- 1280 PMT

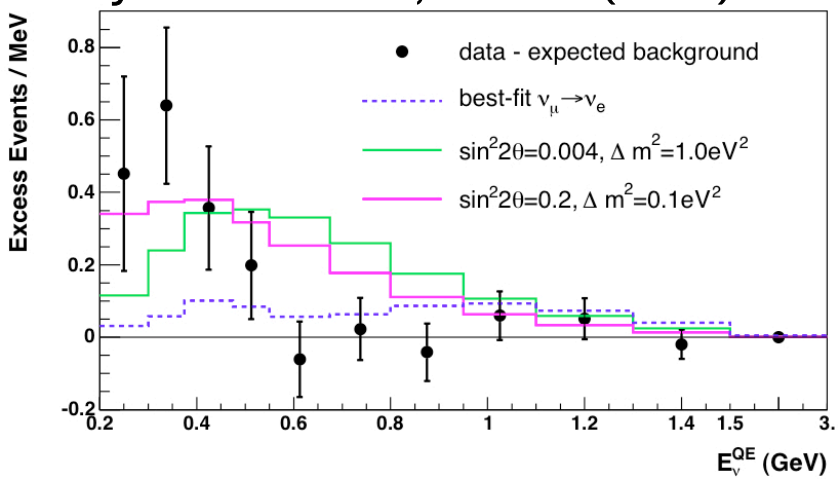
- designed to test LSND
- L/E same as LSND, different systematics, energy, event signature
- LSND E~30 MeV, L~30 m, L/E~ 1

  MiniBooNE E~500 MeV, L~500 m, L/E~ 1
- Search for ν_μ -> ν_e appearance
- Search for $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ appearance

MiniBooNE neutrino excess events (6.5E20 POT)

Phys. Rev. Lett. 98, 231801 (2007)



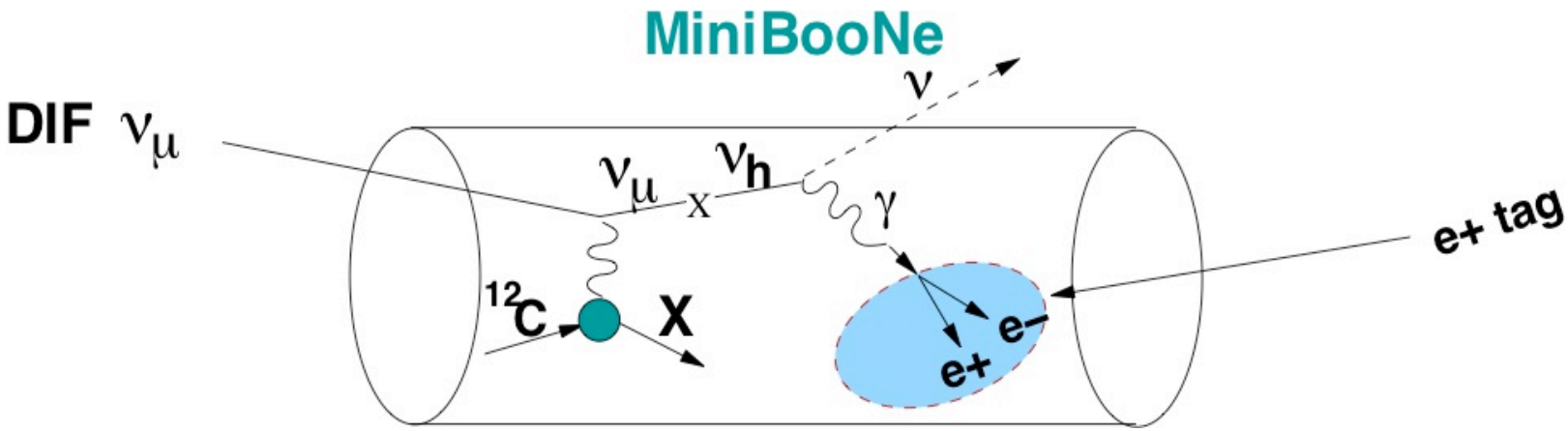


- > 475 MeV good agreement with background
  408 events vs 386 ± 20(stat) ±30(syst) expected
- < 475 MeV 544 events vs 415 ± 20(stat) ±39(syst) expected

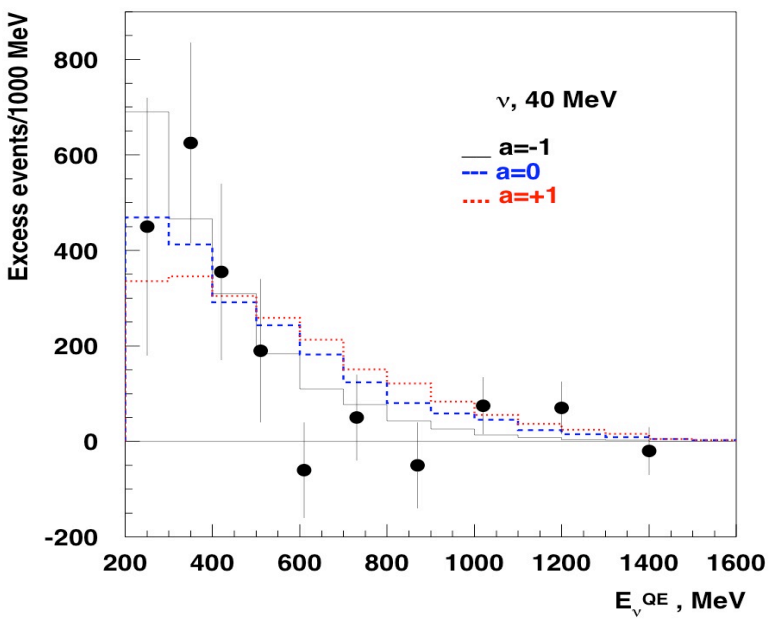
Excess ΔN=129.0±43.0 ≈3 σ

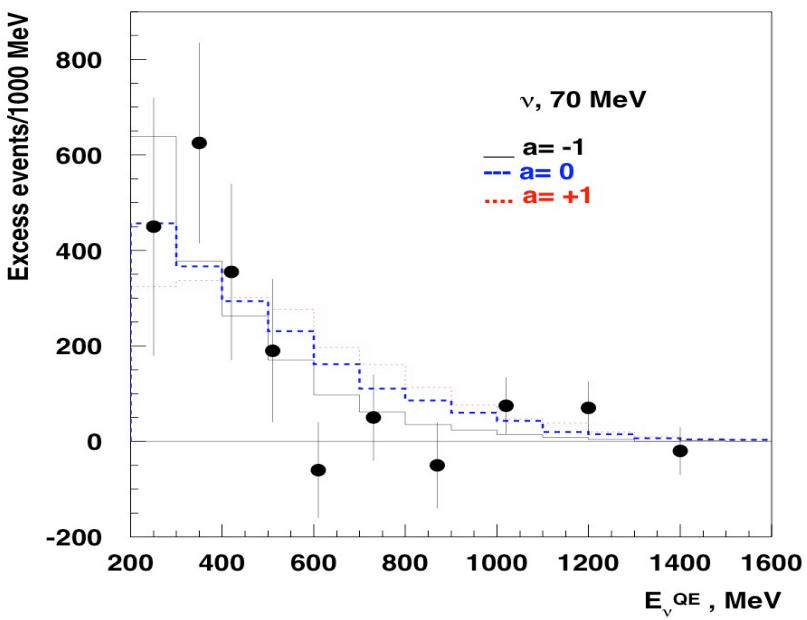
- ➔ track events : either electrons, or $\gamma \rightarrow e^+e^-$ pairs
- ➔ reconstructed ν_μ energy $200 < E^{QE} < 475$ MeV
- ➔ reconstructed visible energy $200 < E_{vis} < 400$ MeV
- ➔ angular distrubution is wide, consistent with ν_eQE
- ➔ shape inconsistent with 2ν oscillation interpretation of LSND

radiative decay of heavy neutrino $\nu_h \rightarrow \gamma\nu$



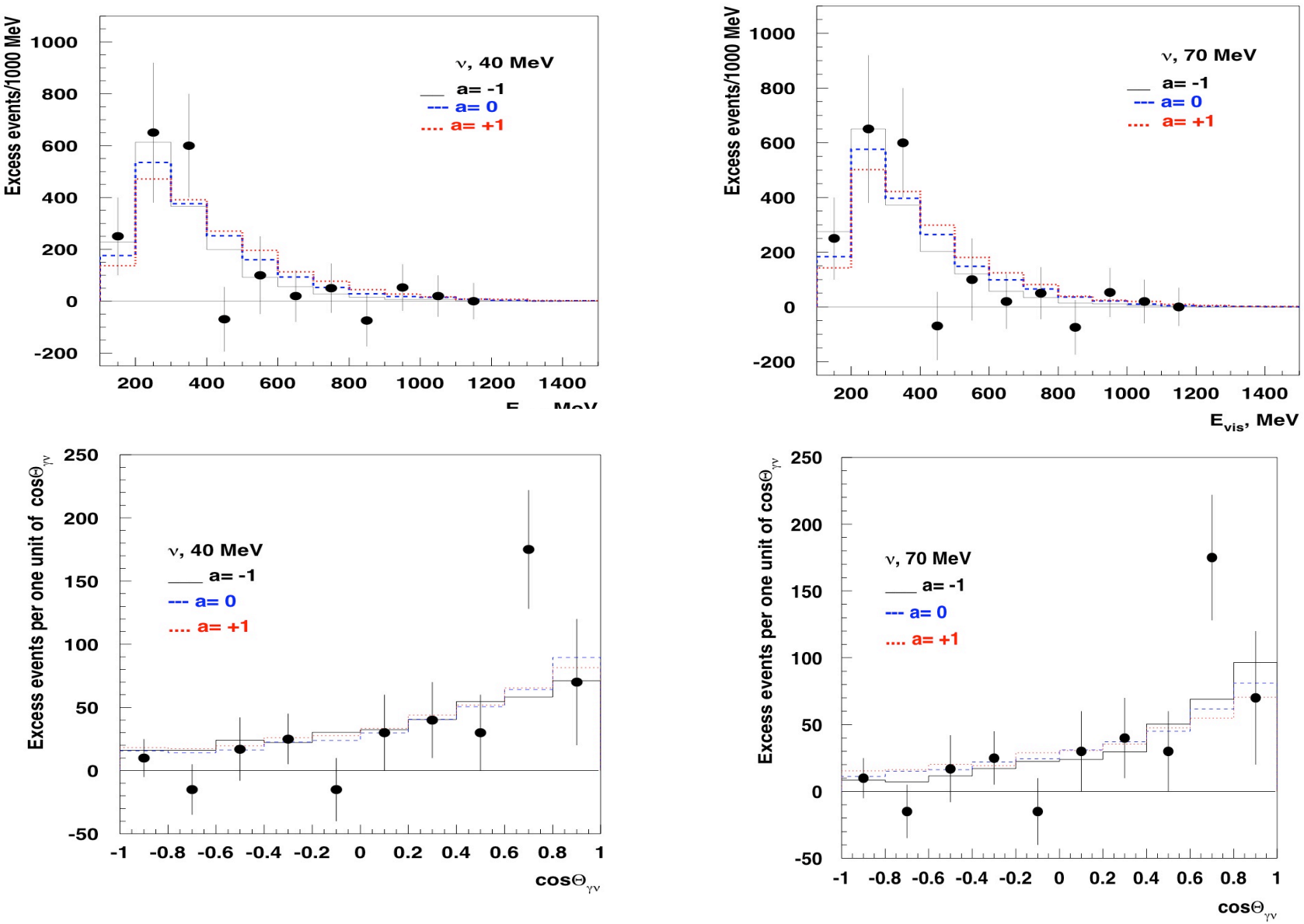
ν_h interpretation of ν_μ excess vs E_{QE} $|U_{\mu h}|^2=3\times10^{-3}$, $\tau=10^{-9}$ s



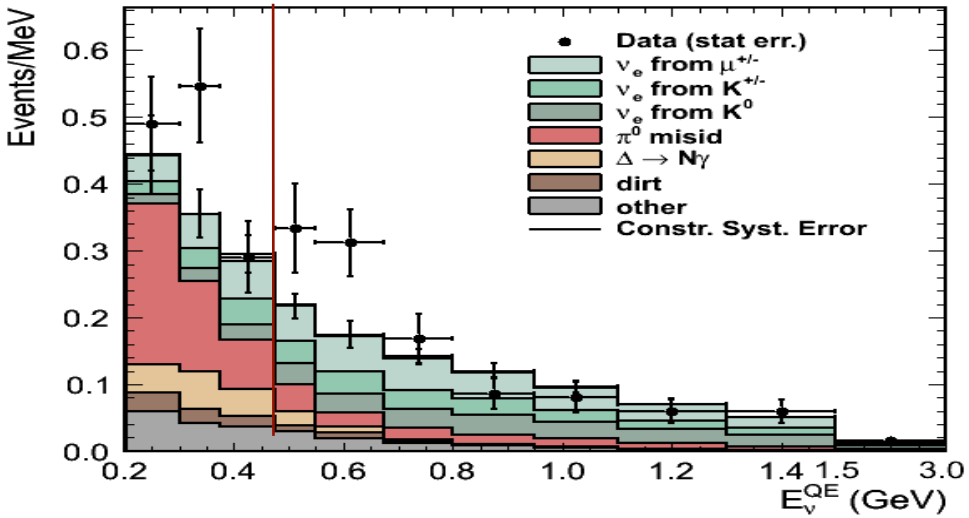


ν_h interpretation of ν_μ excess vs E_{vis} and $\cos\Theta_{\gamma\nu}$

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



MiniBooNE antineutrino excess events (5.66E20 POT)



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

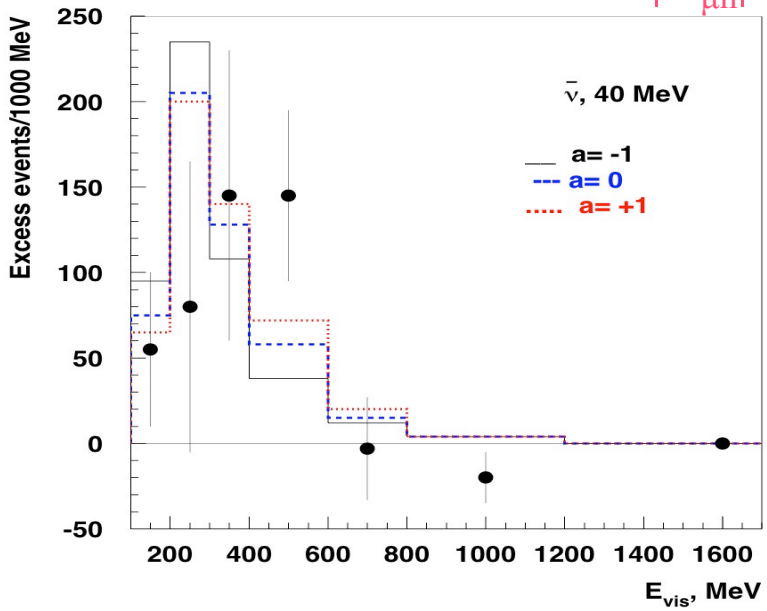
- > 475 MeV, 120 events vs 99 ± 10(stat) ±10(syst) expected: 20.9±14 ev
- < 475 MeV, 119 events vs 100 ± 10(stat) ±10(syst) expected:18.5±14 ev

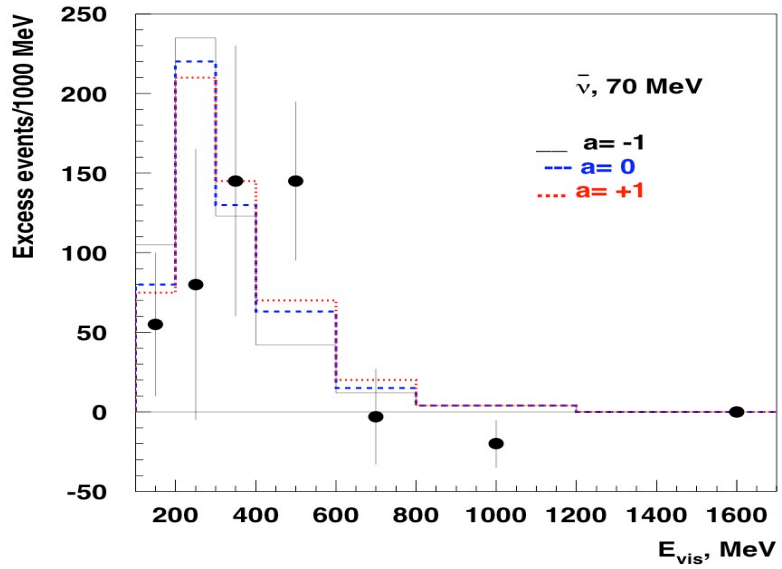
Excess ΔN=43.2±22.5 ≈2 σ

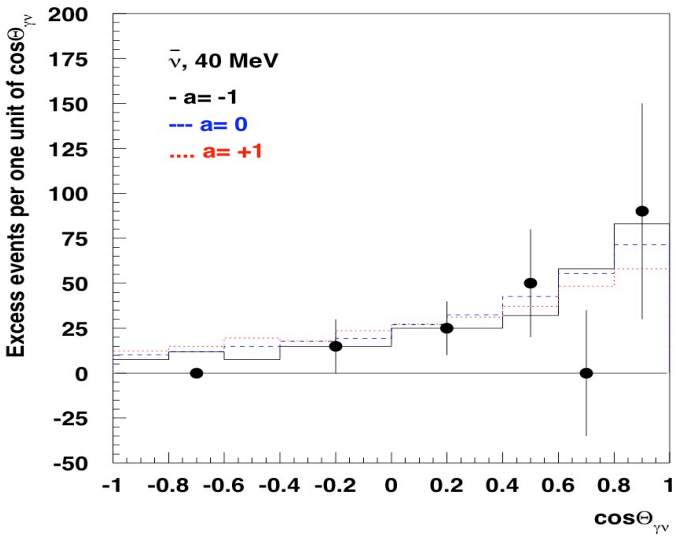
- ➔ track events : either electrons, or $\gamma \rightarrow$ e+e- pairs
- ➔ reconstructed ν_μ energy 200< E^{QE}< 800 MeV
- ➔ reconstructed visible energy 200< E_{vis}< 700 MeV
- ➔ angular distrubution is wide, consistent with ν_eQE
- ➔ shape >475 MeV consistent with 2ν oscillation interpretation of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

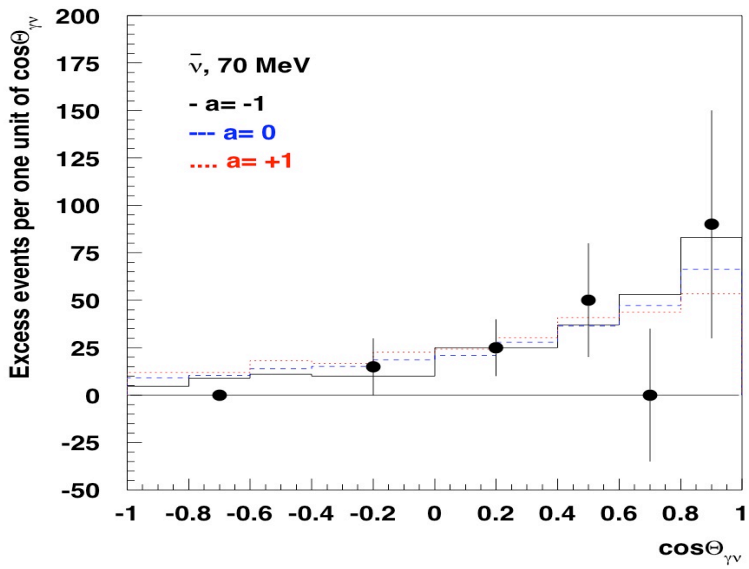
ν_h interpretation of $\bar{\nu}_\mu$ excess vs E_{vis} and $\cos\Theta_{\gamma\nu}$

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







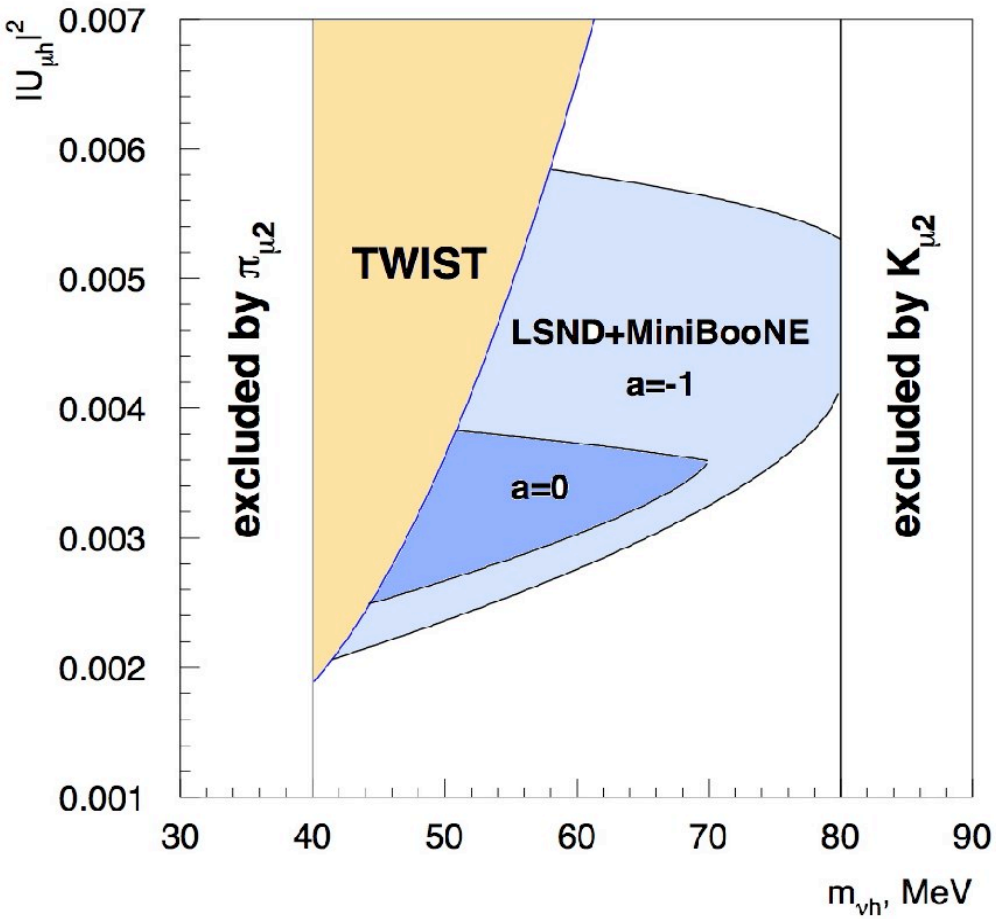


Combined LSND-MiniBooNE parameter window

~ 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, CERN)
- Muon processes: Michel spectrum (TWIST), G_F (MuLan), rad./rare muon decays
- Neutrino experiments $\nu_h \rightarrow e+e-\nu$: CHARM, NOMAD, NuTeV, PS191, BEBC,...
- LEP Z->νν* -> ννγ: ALEPH, DELPHI
- Cosmology, astrophysics

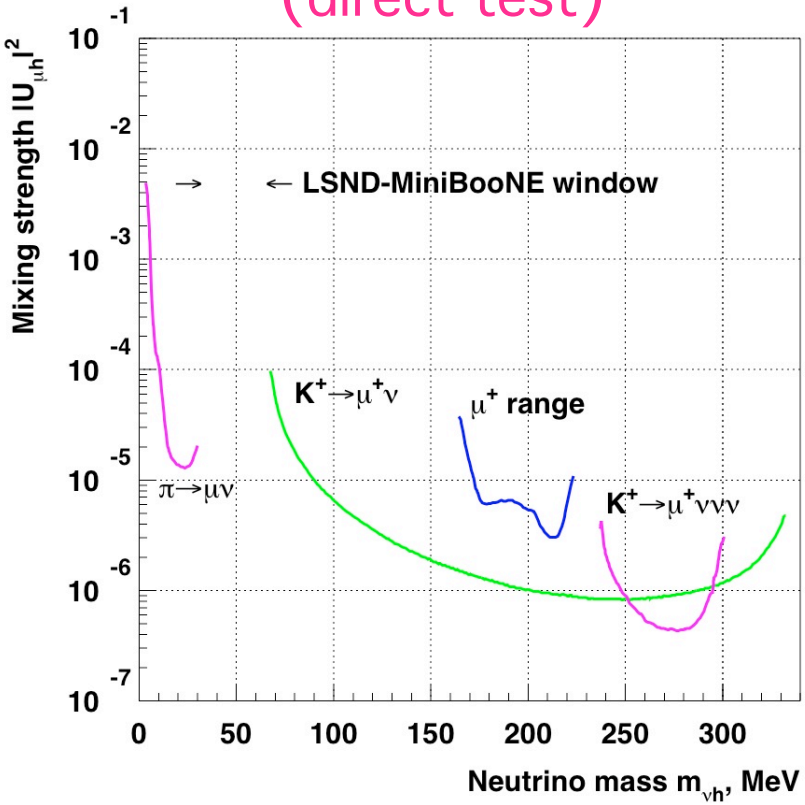
All consistent with LSND-MiniBooNE values

Some tension with radiative muon capture on hydrogen, 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.

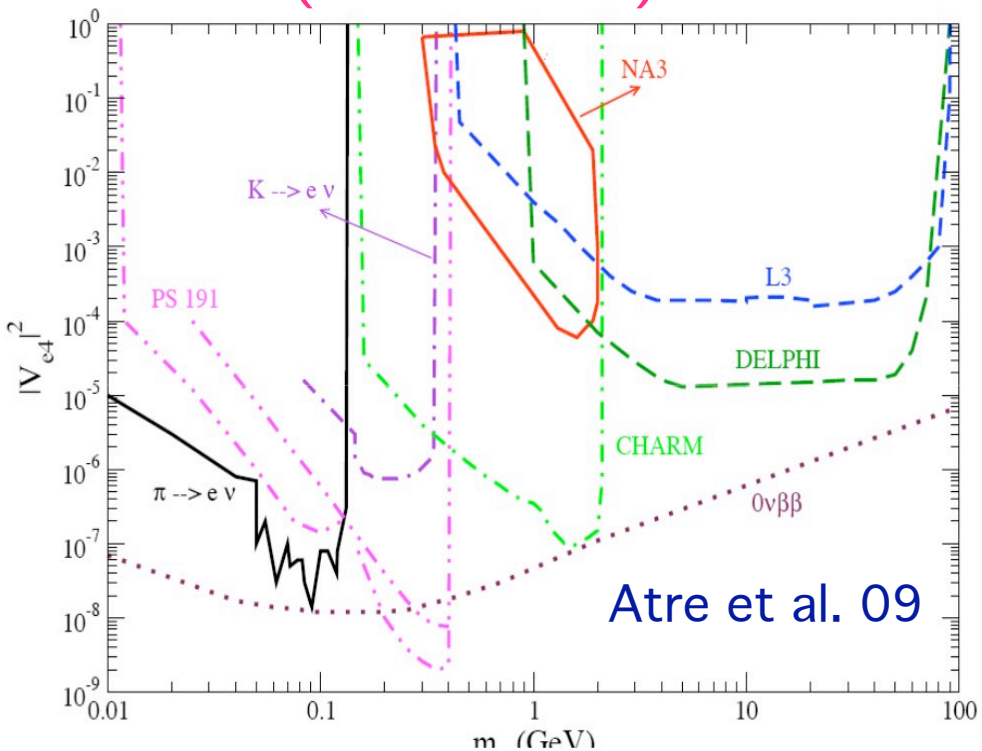
Most sensitive limits on $|U_{\mu h}|^2$ vs ν_h mass

$K \rightarrow \mu\nu_h$ (KeK)
(direct test)



Big Surprise!
for ~40 MeV≤ m_h ≤80 MeV
no constraints on $|U_{\mu h}|^2$

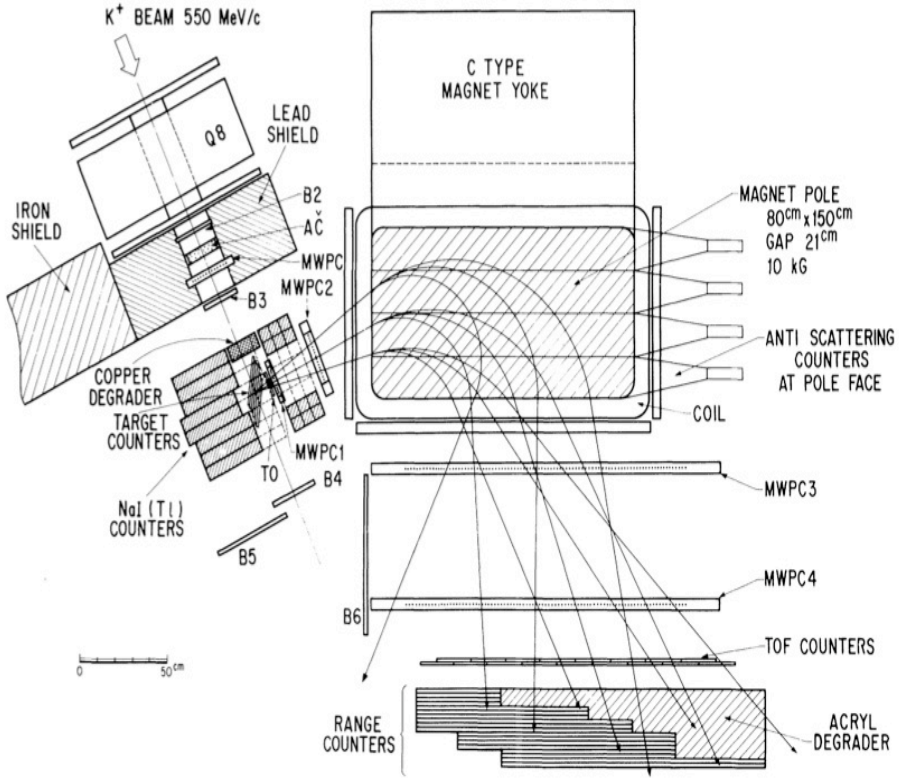
$\nu_h \rightarrow e^+e^-\nu$ (PS191, CERN)
(indirect test)

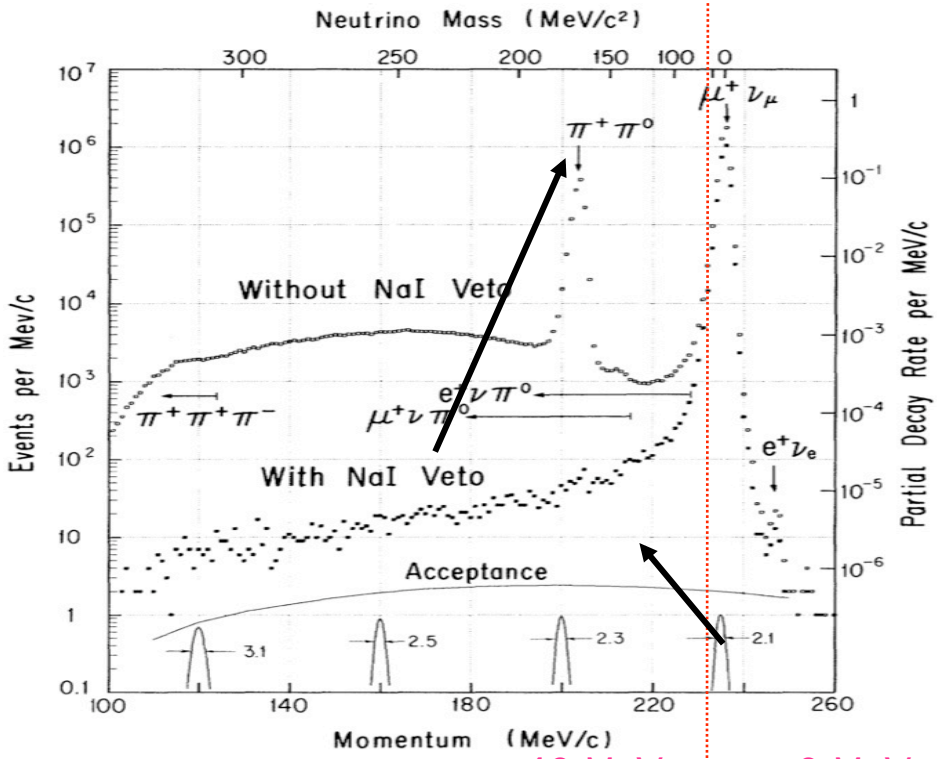


PS191 limits are evaded
for ~40 MeV≤ m_h ≤80 MeV
due to prompt $\nu_h \rightarrow \gamma\nu$ decay and
low mass target

Search for ν_h in $K_{\mu 2}$ decays at KEK

R.S.Hayano et al. PRL 49,1305 (1982)





m= 40 MeV 234 MeV/c | m= 0 MeV, 236 MeV/c

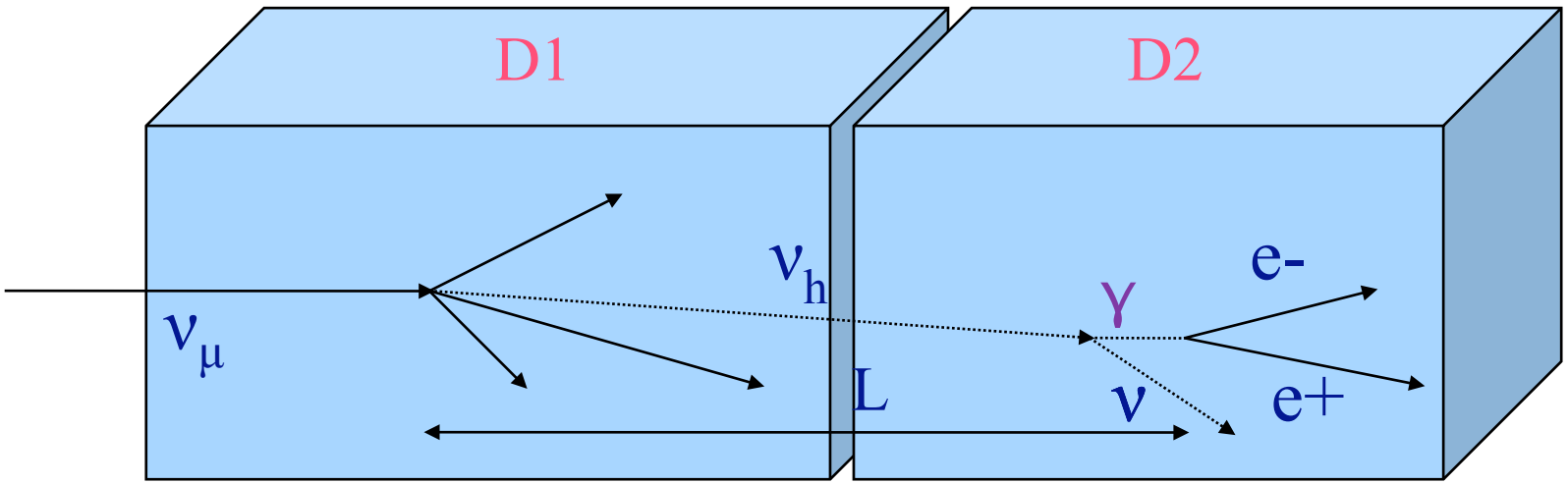
- good muon mom. resolution for peak from K -> $\mu \nu_h$ ~ 1 % (FWHM)
- poor hemiticity: high continues backg. level from K -> $\mu \nu \gamma$ decay
- ECAL self-γ-veto due to prompt ν_h decay

Searches for $\nu_h \to \gamma\nu$ with future experiments

- direct test in ν_μNC interactions: $\nu_\mu + A \to \nu_h(\to \nu\gamma) + X$
-
- muon decay at rest: $\mu \to e\nu + \nu_h \to e\nu + \nu\gamma$

- K decays in flight /at rest: $K \to \mu + \nu_h \to \mu + \nu\gamma$
-
- atmospheric neutrino telescopes, Masip, Masjuan, arXiv:1103.0689

Direct search for ν_h in ν_μ NC: $\nu_\mu + A \rightarrow \nu_h(\rightarrow \nu\gamma) + X \rightarrow \nu e^+e^- + X$



- detector: two D1 and D2 parts
  D1: ν_μ NC shower dump +primary vertex
  D2, e.g. a'la NOMAD: good particle ID, secondary vertex, …
- $\nu_h \rightarrow \nu\gamma$ signature: single e+e- pair, L >> λ_{in}
- advantages to search for short τ :
  ν_h decay length ~ E
  absorption length ~ ln(E)
- disadvant. : 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

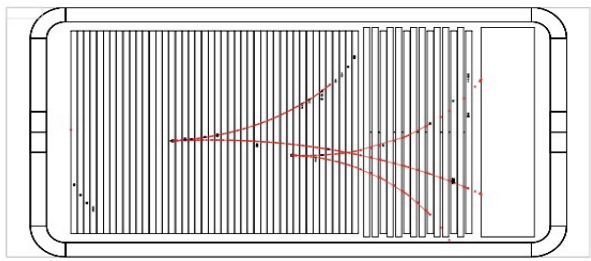
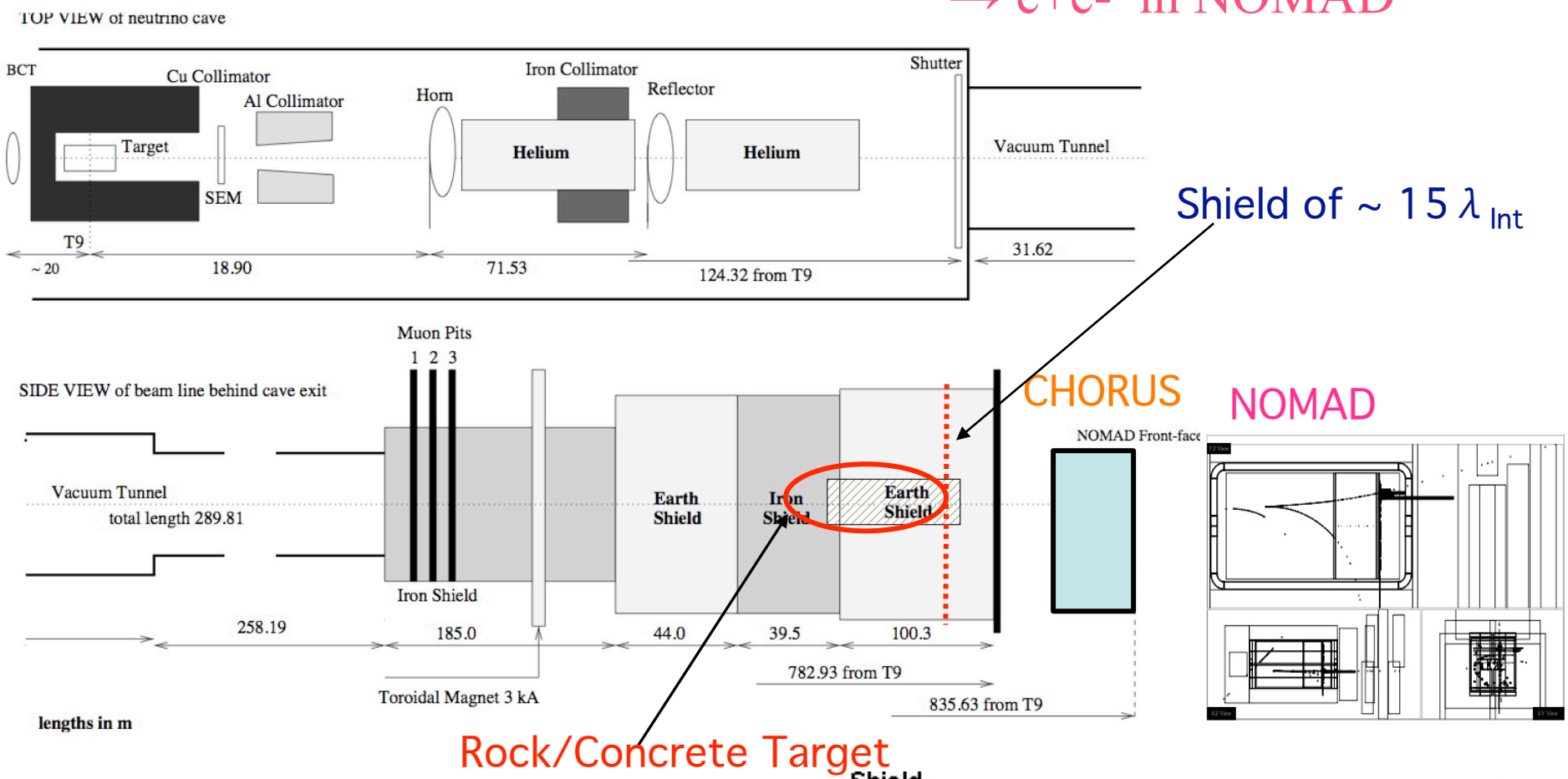
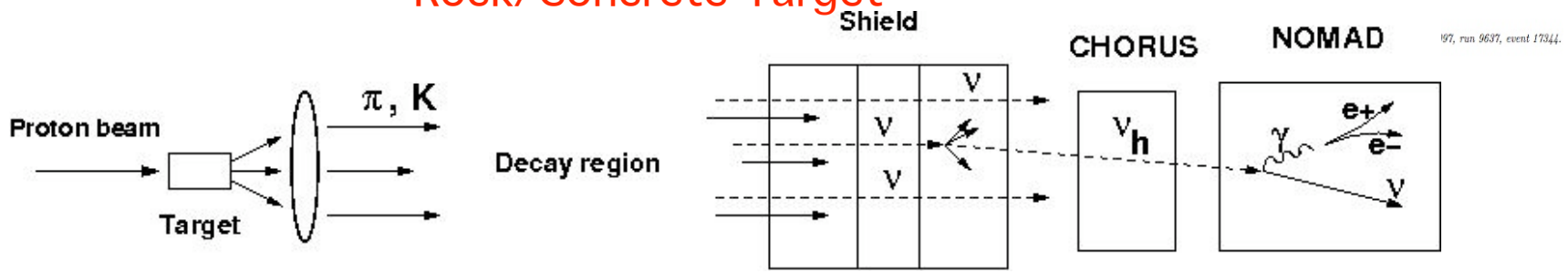


Fig. 2. Schematic of the DC tracker and a coherent π^0 event candidate in NOMAD where both photons from the π^0 decay convert in the DC's. The red crosses represent drift chamber digitizations that are used in the track-reconstruction, whereas the black ones are not. The upstream ($\gamma 1$) and downstream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

Search for e+e- excess from $\nu_\mu A \rightarrow \nu_h(\rightarrow \gamma\nu)\ X$

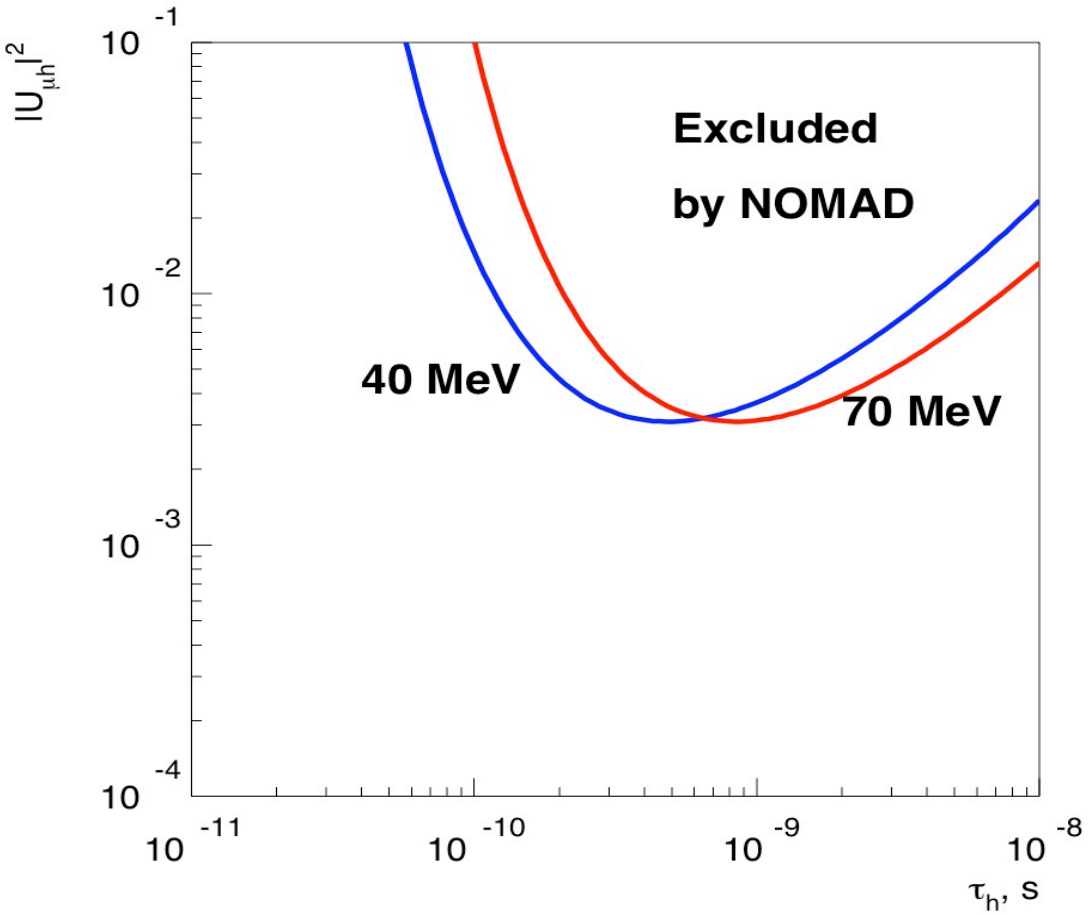
$\rightarrow$ e+e- in NOMAD





No primary vertex ID. Rate of single γ from coherent π^0/γ production?

Very preliminary limits



Work in progress. Analysis of NOMAD data (4.1E19 POT)on search for ν_τ-ν_h mixing, PLB 506 (2001) 27; 527(2002)23

Limit on $K \to \mu + \nu_h \to \mu + \nu\gamma(\to e+e-)$ from NOMAD. Based on result of a search for 33.9 MeV KARMEN particle (4.1E19 POT)

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PHYSICS

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New results on a search for a 33.9 MeV/c^2 neutral particle π^+ decay in the NOMAD experiment

NOMAD Collaboration

Abstract

We report on a direct search in NOMAD for a new 33.9 MeV/c^2 neutral particle (X) produced in pion decay in flight, $\pi \to \mu X$ followed by the decay $X \to \nu e^+ e^-$. Both decays are postulated to occur to explain the time anomaly observed by the KARMEN experiment. From the analysis of the data collected during the 1996–1998 runs with 4.1×10^{19} protons on target, a single candidate event consistent with background expectations was found. The search is sensitive to a pion branching ratio $\mathrm{BR}(\pi \to \mu X) > 3.7 \times 10^{-15}$, significantly smaller than previous experimental limits.

Keywords: Neutrino mixing; Neutrino decay

Search for $K \rightarrow \mu + \nu_h \rightarrow \mu + \gamma\nu \rightarrow e+e-$ in NOMAD

Flux $K/\pi \sim 0.1$

$\langle E_\nu \rangle$ ratio ~73/24.3

Expected limit

$|U_{\mu h}|^2 < \sim A \exp(B/\tau)$

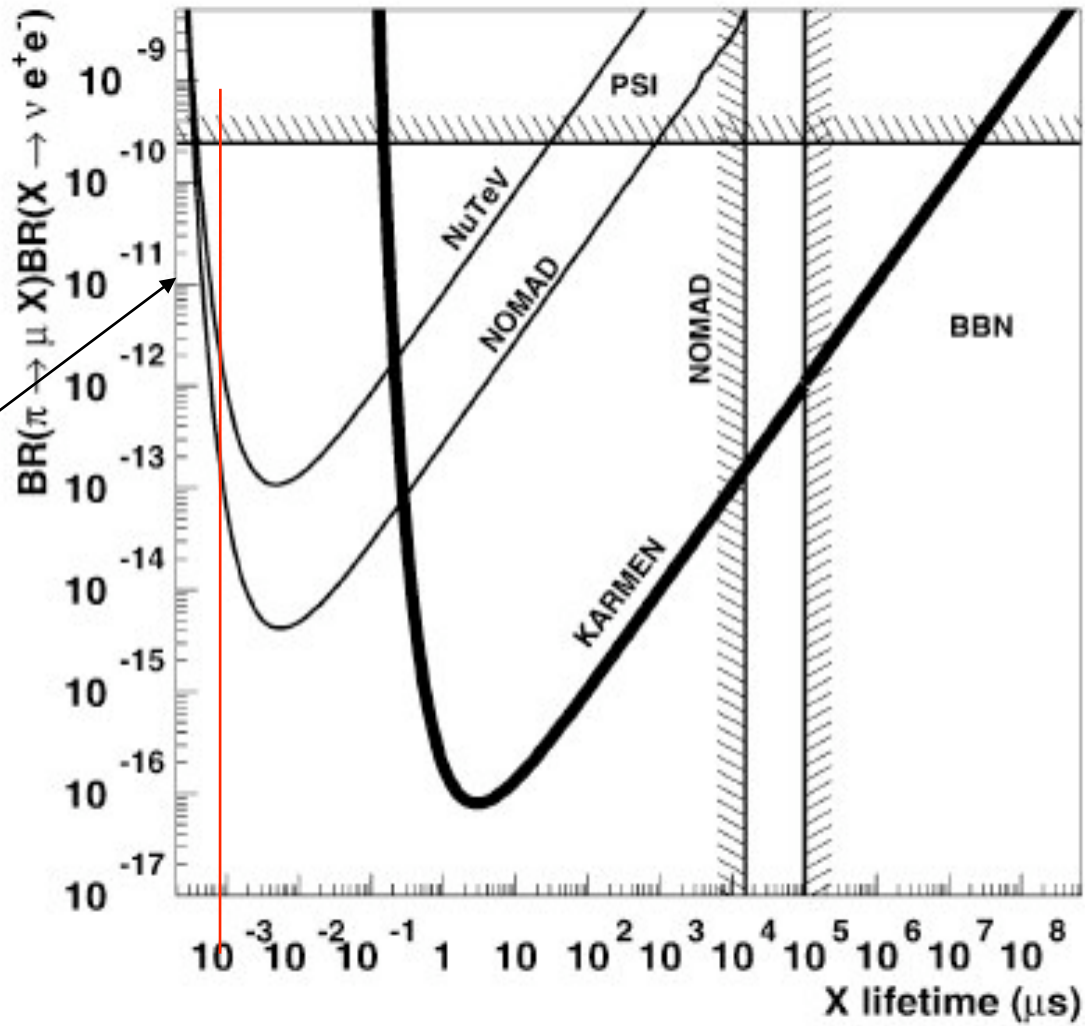
very sensitive to τ

Preliminary

$|U_{\mu h}|^2 > 10^{-3}$, for

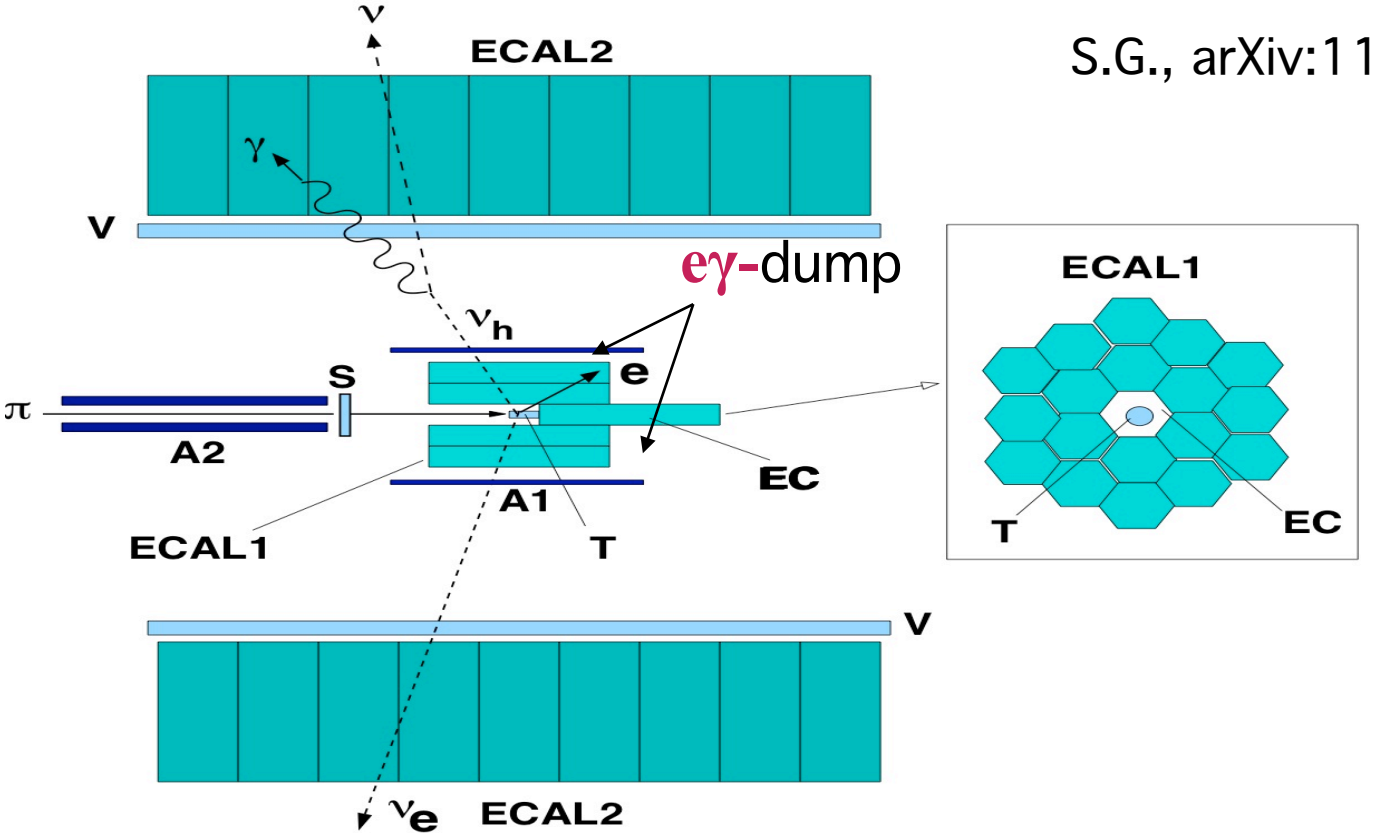
$\sim 0.3 \times 10^{-9} < \tau < \sim 10^{-9}$

could be excluded



Search for $\mu \to e\nu+\nu_h \to e\nu+\nu\gamma$ / $K \to \mu+\nu_h \to \mu+\nu\gamma$ decays at rest

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

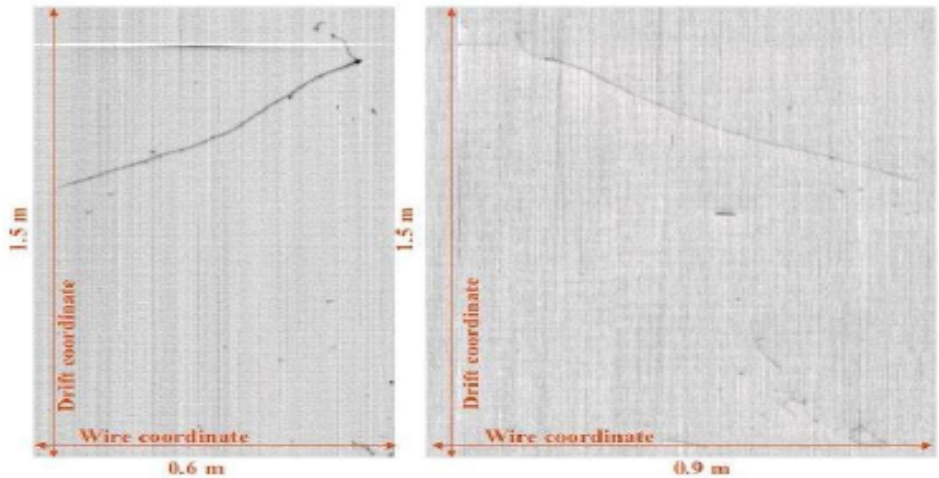


- $\nu_h \to \nu\gamma$ signature: stop $(\pi+\mu)$(or $K+\mu$) x ECAL1 x ECAL2
- expected sensitivity: $|U_{\mu h}|^2 \sim 10^{-8} \exp(0.3/\tau[\mathrm{ns}])$
- muon rate $\sim 3\times10^4$ /s , running time ~1 m
- PIBETA (PSI) excess in $\mu \to e\nu\nu\gamma$ to be checked!

Search for $\mu \to e\nu + \nu_h \to e\nu + \nu\gamma$ with stop cosmic muons.

ICARUS

suggested by a PRD referee of arxiVe:1101.4004

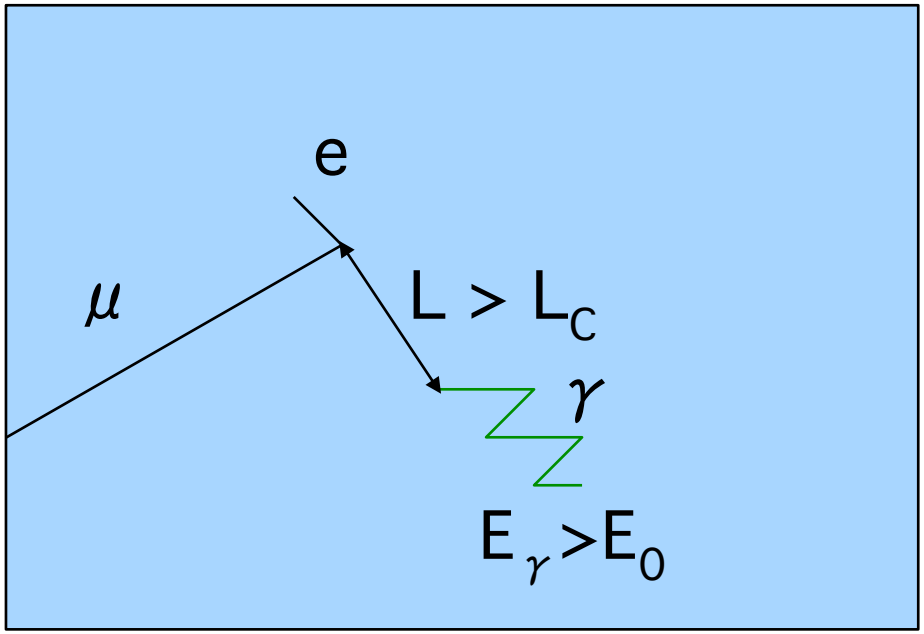


Radiative μ-decay:

- small angle $\theta_{e\gamma}$,
- energy spectrum $N_\gamma \sim 1/E_\gamma$

Signature of (e-γ) excess from $\mu \to e\nu + \nu_h \to e\nu + \nu\gamma$

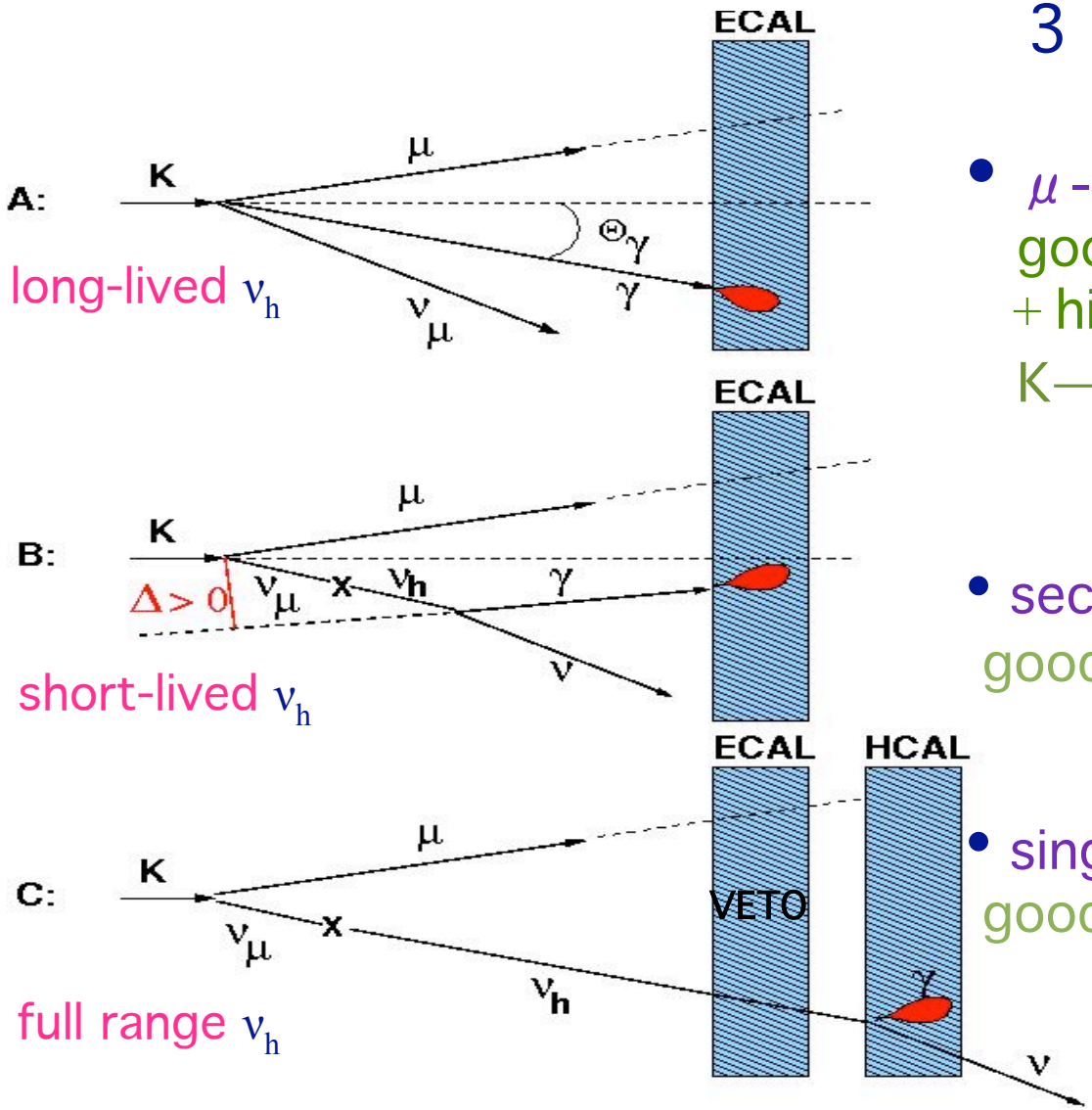
- large angle $\theta_{e\gamma}$,
- $L > L_C$
- $E_\gamma > E_0$



Search for $\mu \to e\nu + \nu \to e\nu + \nu\gamma$

with stop cosmic μ in MiniB.?

Search for ν_h in K decays in flight at NA62 at CERN



3 possible signatures

- μ-peak from K -> $\mu\,\nu_h$
  good muon mom. resolution
  + high eff. gamma veto for
  $K \to \mu\nu\gamma$; $\mu\pi^0\gamma$ … decays.

- secondary vertex from $\nu_h \to \nu\gamma$
  good photon directionallity

- single μ x ECAL=0 x HCAL >0
  good hermiticity required.

The best sensitivity is a subject of further study

SUMMARY

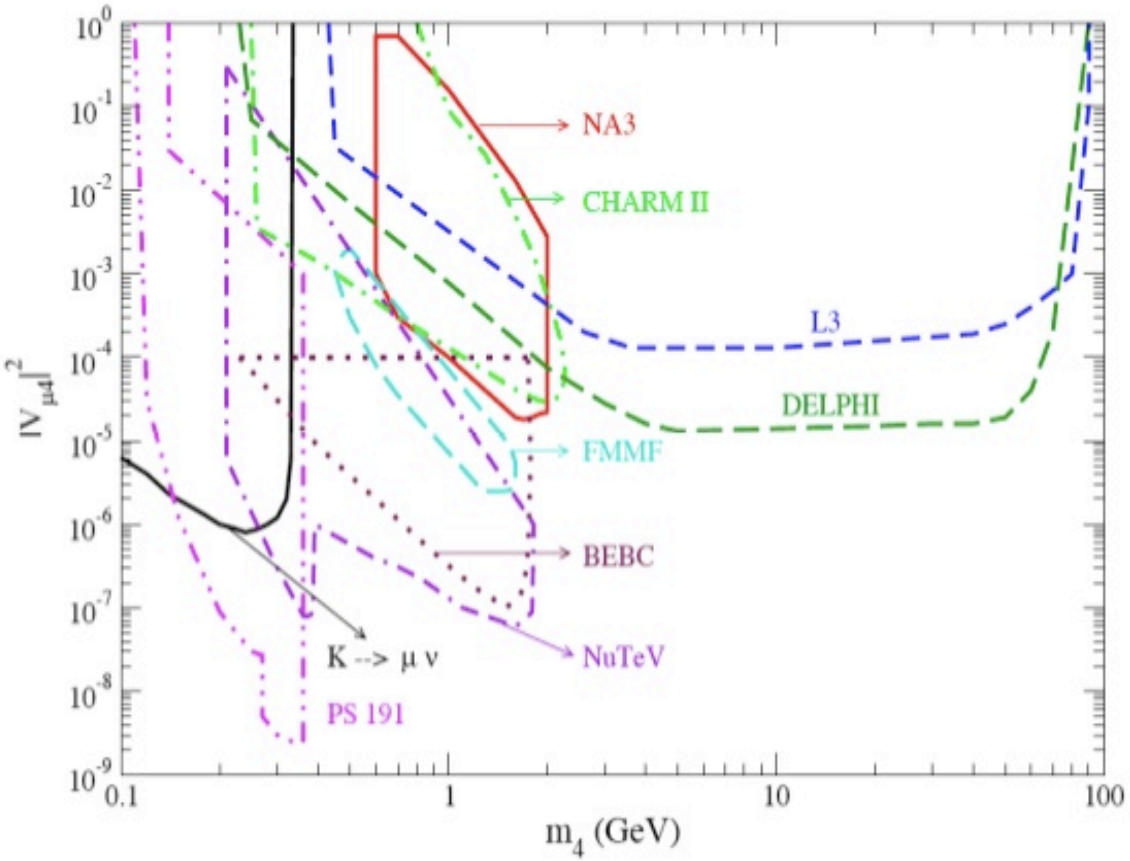
- heavy sterile ν_h's: ~40 MeV $\leq m_h \leq$ 80 MeV,
  ~$10^{-3} \leq |U_{\mu h}|^2 \leq 10^{-2}$,
  ~$10^{-11} \leq \tau \leq 10^{-9}$ s

  could reconcile LSND, KARMEN and MiniBooNe puzzling results.
  - explain excess events in LSND,
  – no excess in KARMEN,
  – excess events in ν_μ / $\bar{\nu}_\mu$ MiniBooNE,
  – provide distributions consistent with observations.

- existing constraints on ν_h are consistent with LSND-MiniB. values.
  - ν_h is too heavy for π decays, too light for K decays
  -escapes in ν experiments due to dominant $\nu_h \rightarrow \gamma\nu$ 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

Backup Slides


NA3
CHARM II
L3
DELPHI
FMMF
BEBC
NuTeV
K --> μ ν
PS 191
$|V_{\mu 4}|^2$
m_4 (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.1
1
10
100

LSND,KARMEN, MiniBooNE

Experiment	Event excess	Energy range, MeV	Background
LSND, ν_μ 1.8E23 POT	87.9±22.4±6.0 3.8 σ	20–60	53.8
KARMEN, ν_μ 5.9E22 POT	10±32 No excess	16–50	15.8±0.5
MiniBooNE, ν_μ 6.64E20 POT	129.0±43.0,≈3 σ 22.1 ± 35.7	200–475 475–1250	415.2±43 386.0±35.7
MiniBooNE, ν_μ 5.66E20 POT	43.2±22.5 , ≈2 σ 18.5±14.3, 1.3 σ 20.9±13.9, 1.5 σ	200–1250 200–475 475–1250	233.8±22.5 105±14.3 99.1±13.9