Status of Sterile Neutrinos

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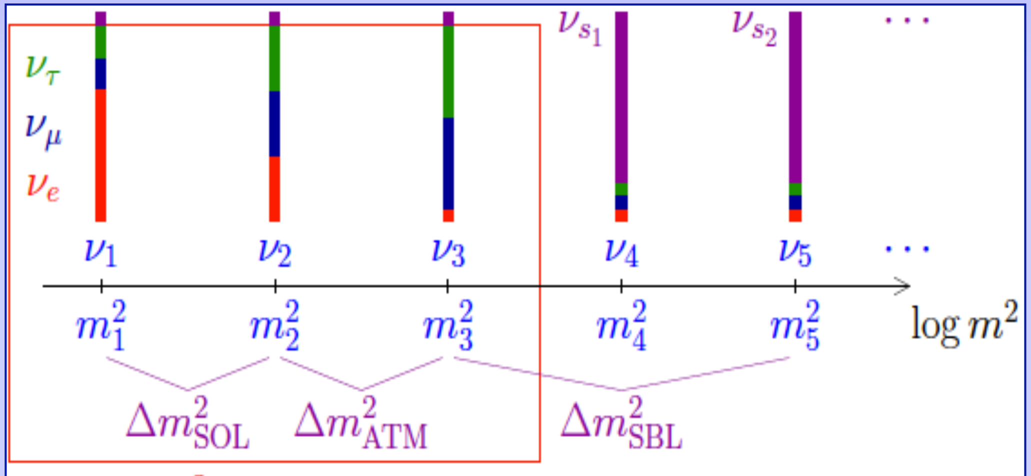
Short Baseline Oscillation & Sterile Neutrinos

Recent Results from short baseline neutrino experiments hint towards high $\Delta m^2 \approx 0.1 - 10$ eV^2 oscillation

Require additional neutrinos with masses at eV scale



Courtesy C. Giunti

- ν_s : Sterile States (no weak interactions)
- Can feel gravity
- Can affect oscillations through mixing
- Well postulated in see-saw models

Introduce ν_R in the SM: Dirac mass $m_D \overline{\nu_R} \nu_L$ + Majorana mass $m_M \overline{\nu_R^c} \nu_R$

6 massive Majorana neutrinos : $(\nu_{eL}, \nu_{\mu L}, \nu_{\tau L})$ + $(\nu_{eR}, \nu_{\mu R}, \nu_{\tau R})$

Light anti-ν_R = Light left-handed ν_s $\nu_R^c \rightarrow \nu_{sL}$

Definition of Short Baseline

Short-baseline means : $L/E \sim 1$ (m/MeV or km/GeV)

It covers a wide range of experiments

- Radioactive $\nu_e/\bar{\nu}_e$ Source experiments
  ($L/E \sim 1$ m/1 MeV)
- Reactor $\bar{\nu}_e$ experiments
  ($L/E \sim 5$ m/5 MeV)
- Accelerator produced ν experiments
  ($L/E \sim 1$ km/1 GeV)
- Atmospheric Neutrinos in IceCube
  ($L/E \sim 1000$ km/1 TeV)

Short Baseline Experiments

$\bar{\nu}_e$ disappearance search (reactor experiments)

- Spectral data: Bugey-3 (at 15, 40 & 95 m)
- Rate only: Bugey-4 (at 15 m), ROVNO, Gösgen, Krasnoyarsk, ILL
- Chooz and Palo Verde at L ≈ 1 km

ν_e disappearance search

- KARMEN & LSND ν_e- carbon cross section estimates
- GALLEX & SAGE radioactive source calibration experiments

Appearance searches ($\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

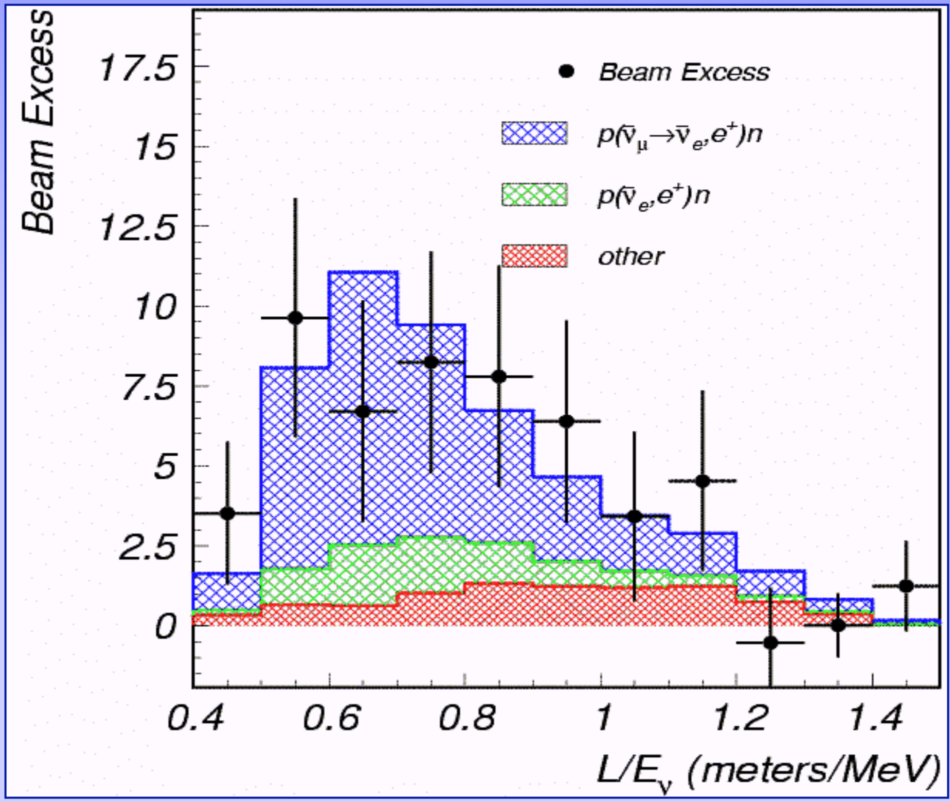
- LSND, MiniBooNE, KARMEN, NOMAD

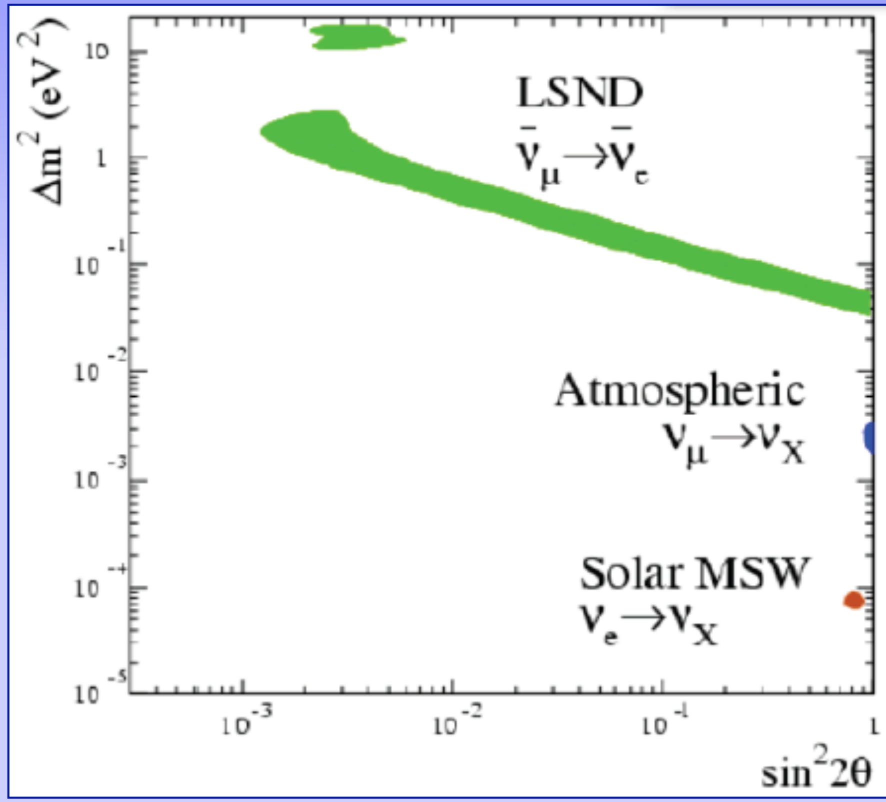
ν_μ disappearance limits

- CCFR, CDHS, MiniBooNE, Atmospheric neutrinos
- Neutral current measurement of MINOS

LSND Result

LSND : L = 30 m, $< E_{\nu_{\bar{\mu}}} > = 40$ MeV





Saw an excess of 87.9 ± 22.4 ± 6.0 events

$3.8\,\sigma$ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$

PRD 64, 112007 (2001)

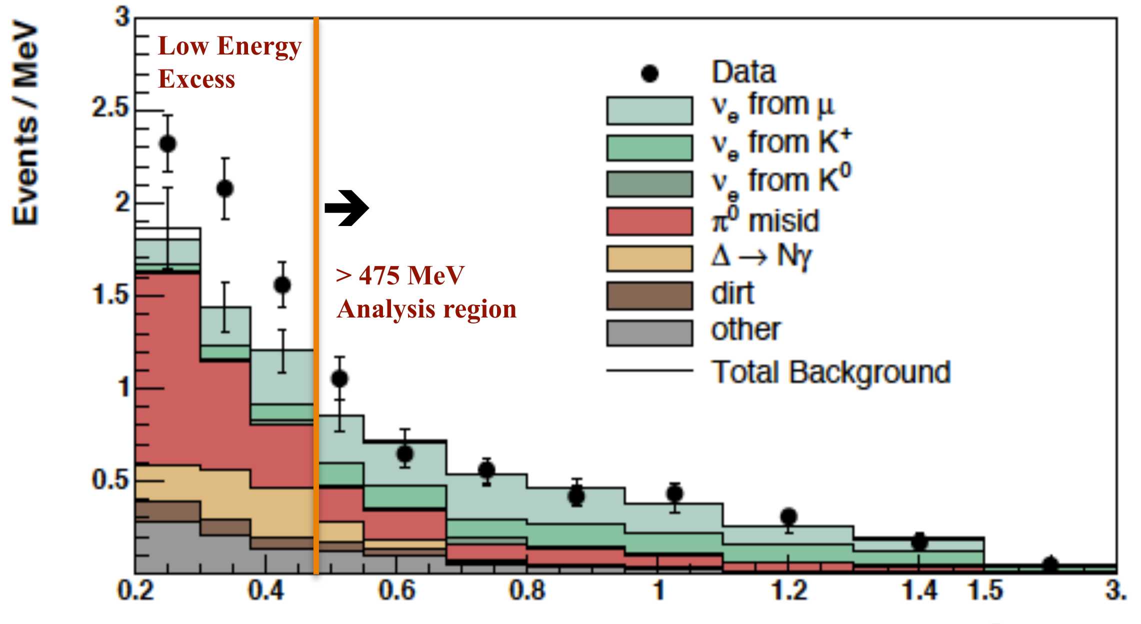
$P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$

Δm^2 ~0.1-10 eV^2, small mixing

Large ($\sin^2 2\theta$, Δm^2) degeneracy

HARP @ CERN can test LSND $\bar{\nu}_e$ background estimate

MiniBooNE Neutrino Results



PRL 98, 231801 (2007), PRL 102, 1101802 (2009)

MiniBooNE : L = 541 m, $< E_{\nu_\mu,\bar{\nu}_\mu} >$ = 700 MeV

Aim to establish/refute the LSND claim: Similar L/E as LSND

6.5×10^{20} POT in neutrino mode

E > 475 MeV

- ***Data matches quite well with background prediction***
- ***Ruled out simple 2ν oscillations as LSND explanation at 90% C.L.***

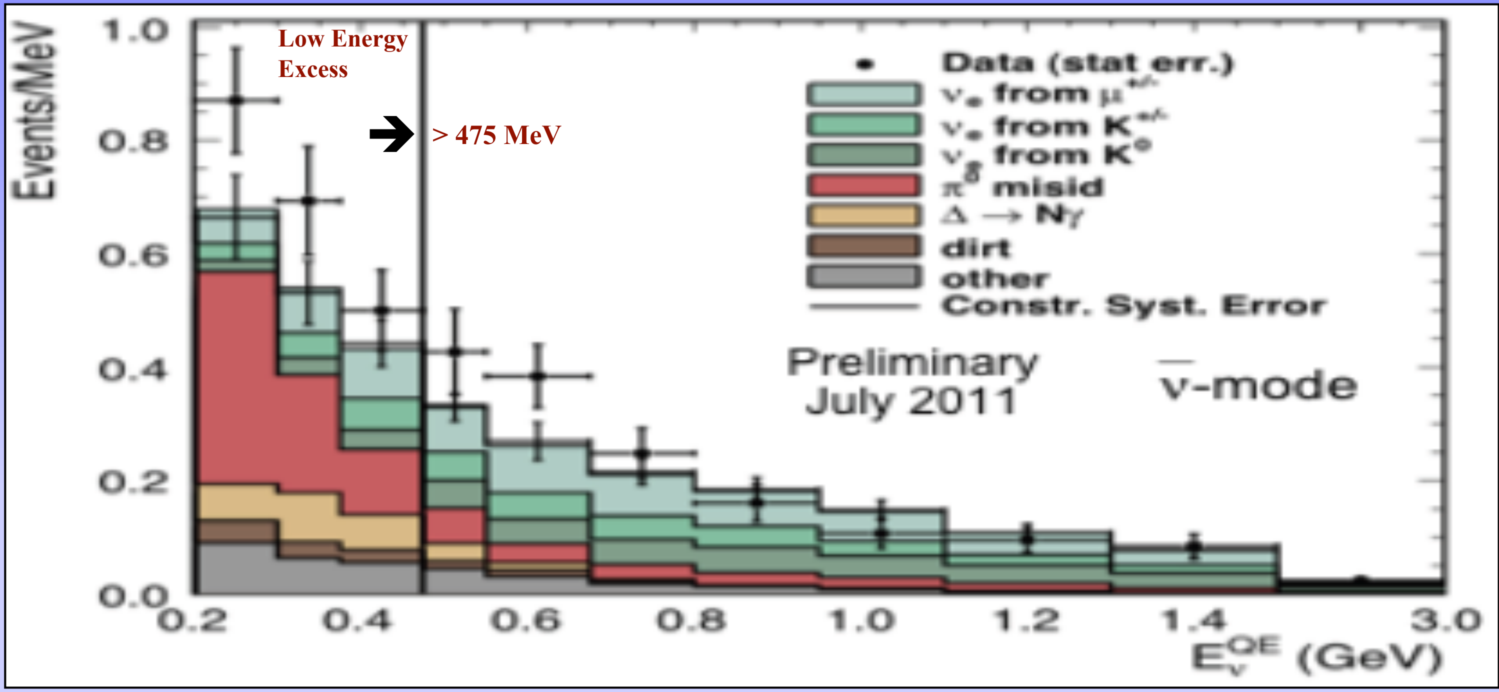
E < 475 MeV

- ***Excess of e^-/γ-like events: $128.8 \pm 20.4 \pm 38.3$ (3σ)***
- ***Shape not consistent with simple 2ν oscillations***
- ***Magnitude consistent with LSND***

Low-Energy Anomaly!

Who ordered this?

MiniBooNE Anti-neutrino (2009-2010)



M. Shaevitz, LowNu2011, Seol, Korea

Excess events: 38.6 ± 18.5 (200-475 MeV), 16.3 ± 19.4 (475-1250 MeV)

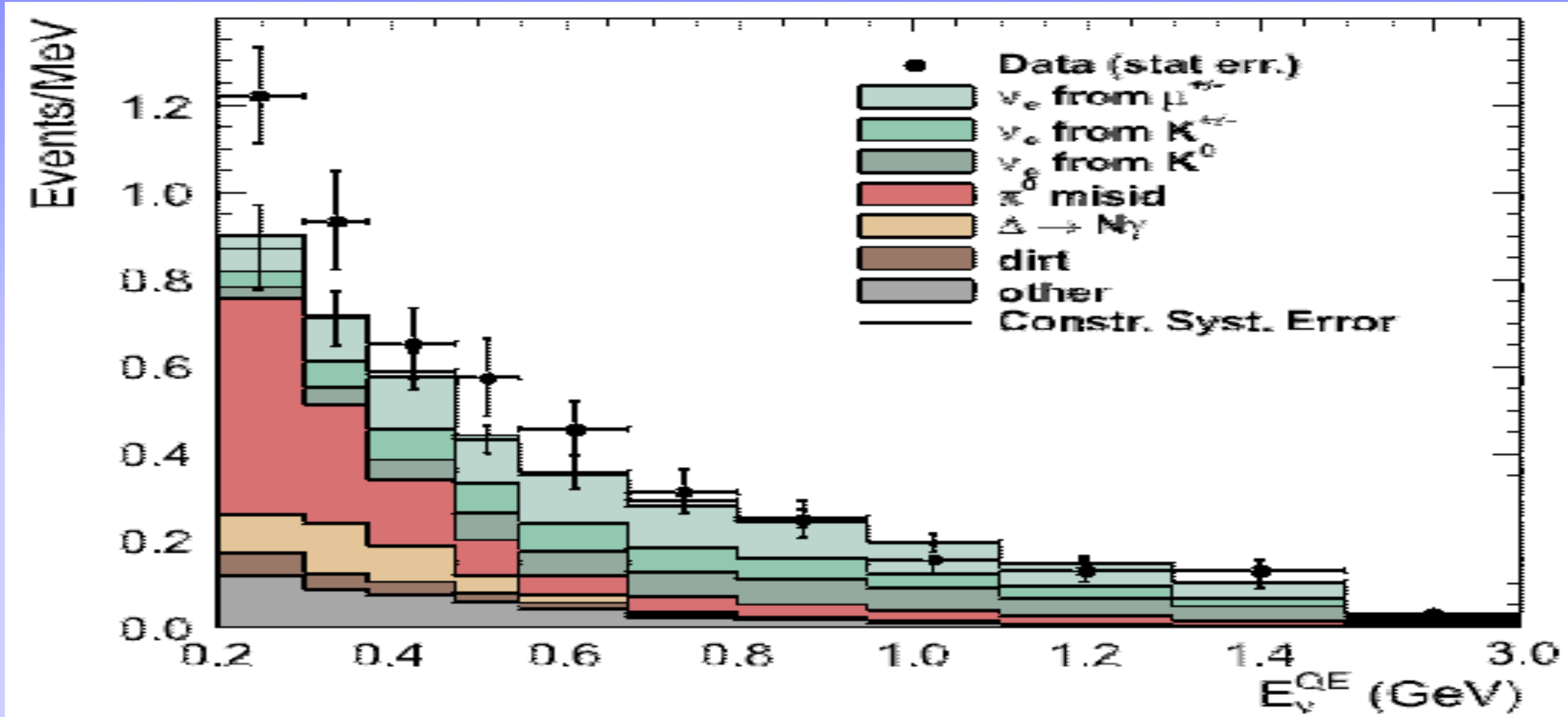
E > 475 MeV (200 MeV)

Excess consistent with a LSND-like 2ν oscillation over background only (null) hypothesis at 91.1% C.L. (97.6% C.L.) [hard to interpret as pure oscillation]

E < 475 MeV

Excess of e^+/γ-like events: 38.6 ± 18.5 [ν & ν̄ results were looking more similar]

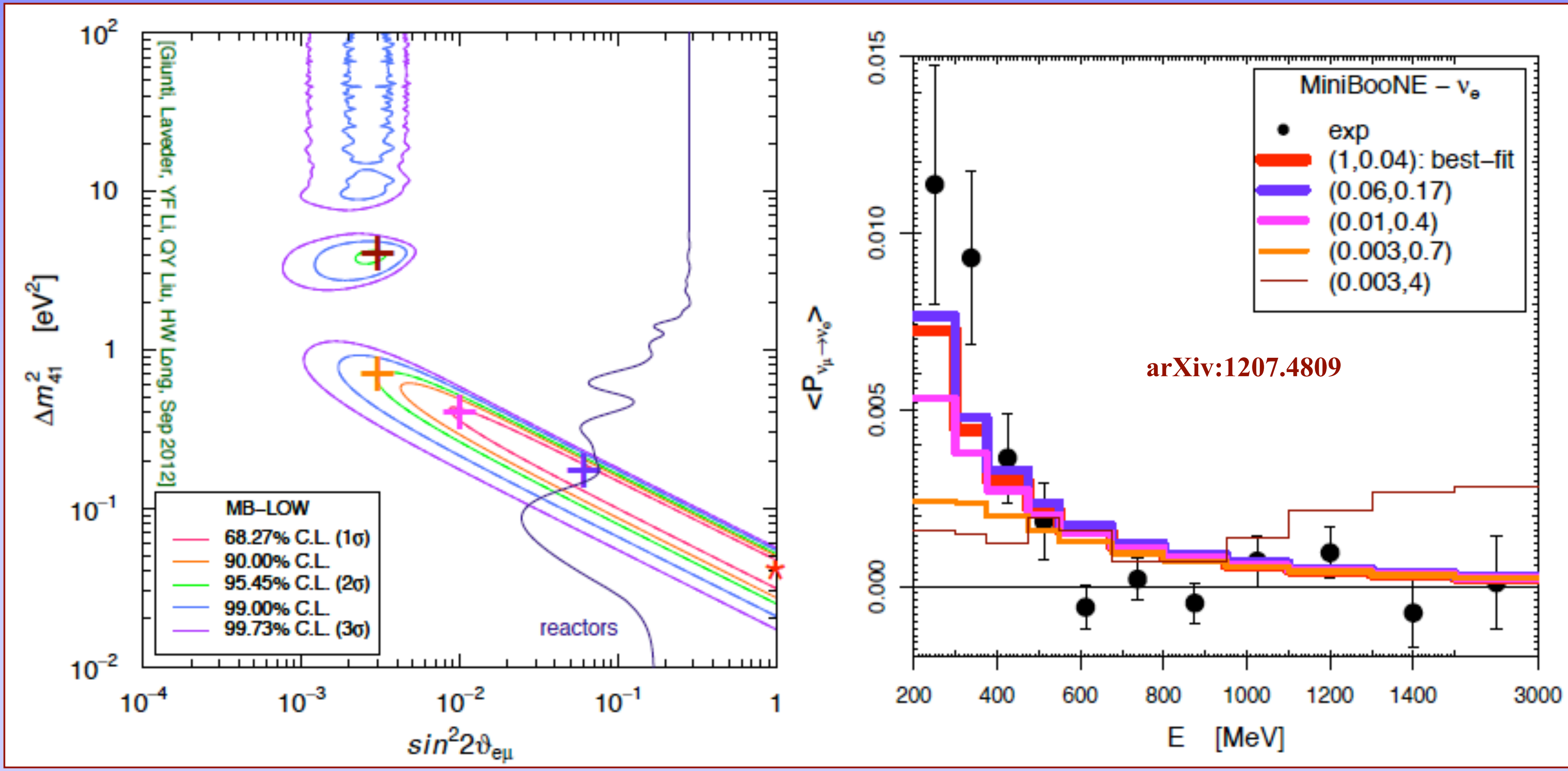
MiniBooNE Anti-neutrino (Neutrino 2012)



		1st half			2nd half	
	data	mc	excess	data	mc	excess
200-475	119	100.5±14.3	18.5 (1.3s)	138	100.0±14.1	38 (2.7s)
475-1250	120	99.1±14.0	20.9 (1.5s)	101	103.1±14.4	-2.2 (-0.2s)

Agreement with LSND is no more there!

MiniBooNE Neutrino & Anti-neutrino

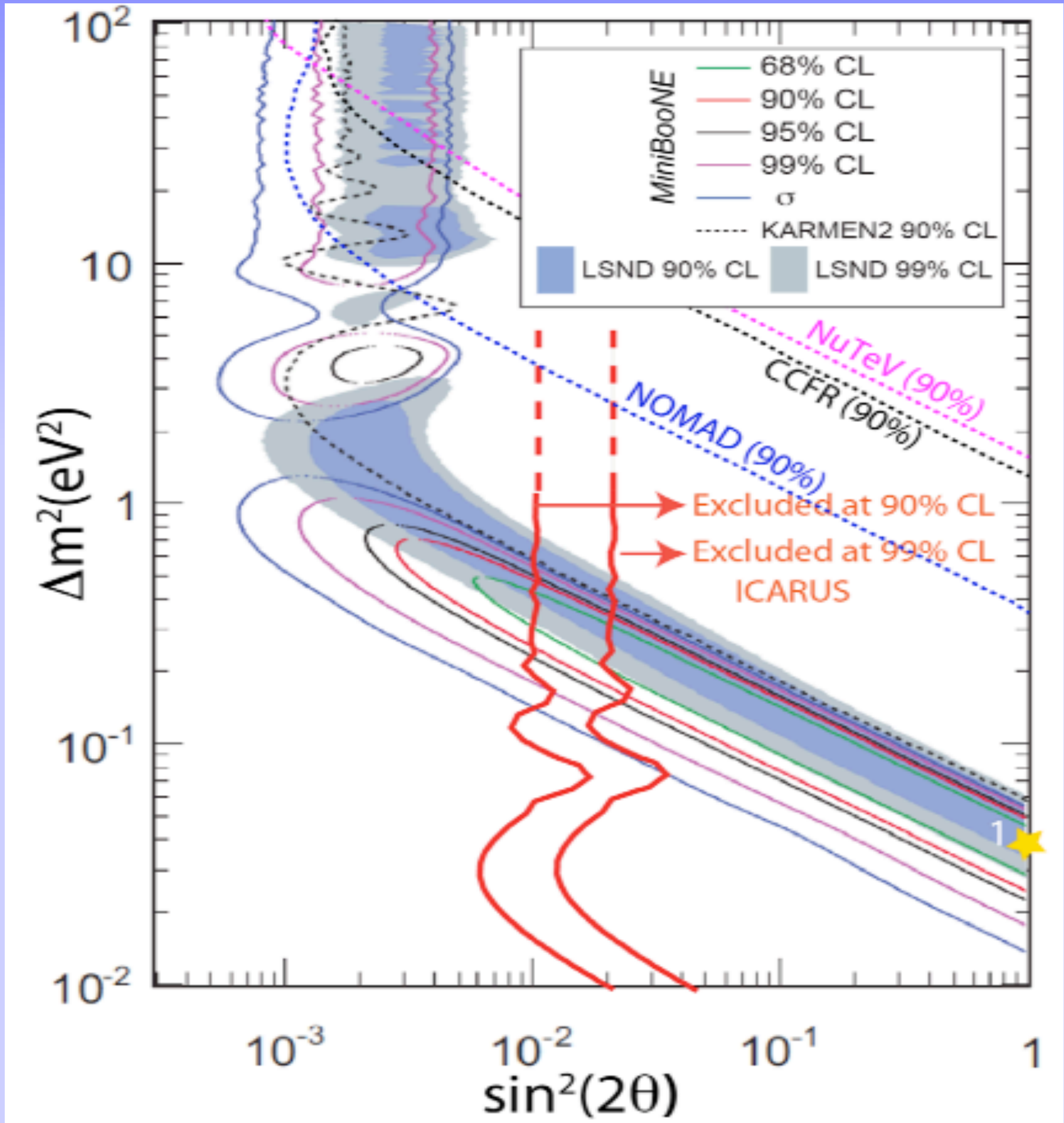


Fit of low-energy excess is marginal and it requires a mass splitting of $\Delta m^2_{41} \lesssim 0.4\text{eV}^2$

Nice idea! There might be some problem in Neutrino energy reconstruction

Martini, Ericson, Chanfray, arXiv:1202.4745

New Results from ICARUS



arXiv:1209.0122

Electron neutrino appearance

Baseline = 730 km (CNGS)

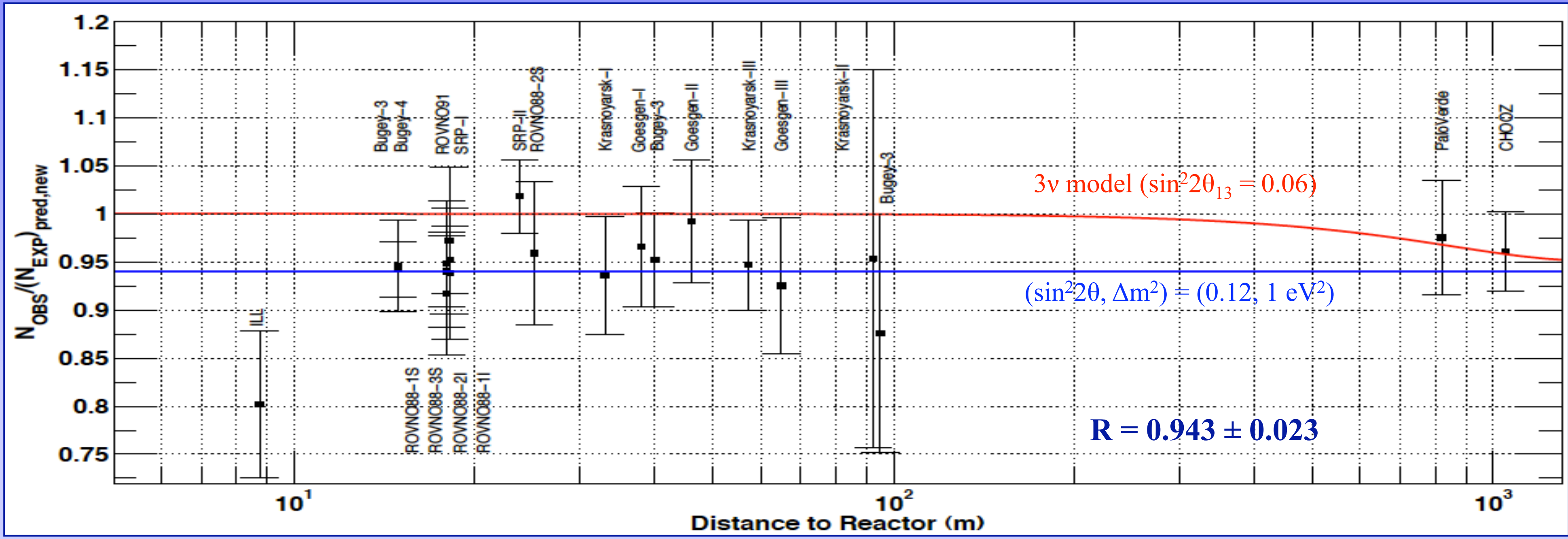
Energy range: 10 to 30 GeV

$$3 \times 10^{-3} < \frac{E}{L} < 9 \times 10^{-3}\ \mathrm{eV}^2$$

2 observed electron neutrino events!

3.7 background electron neutrino events!

Reactor Anti-neutrino Anomaly



Mention et al., arXiv:1101.2755 [hep-ex]

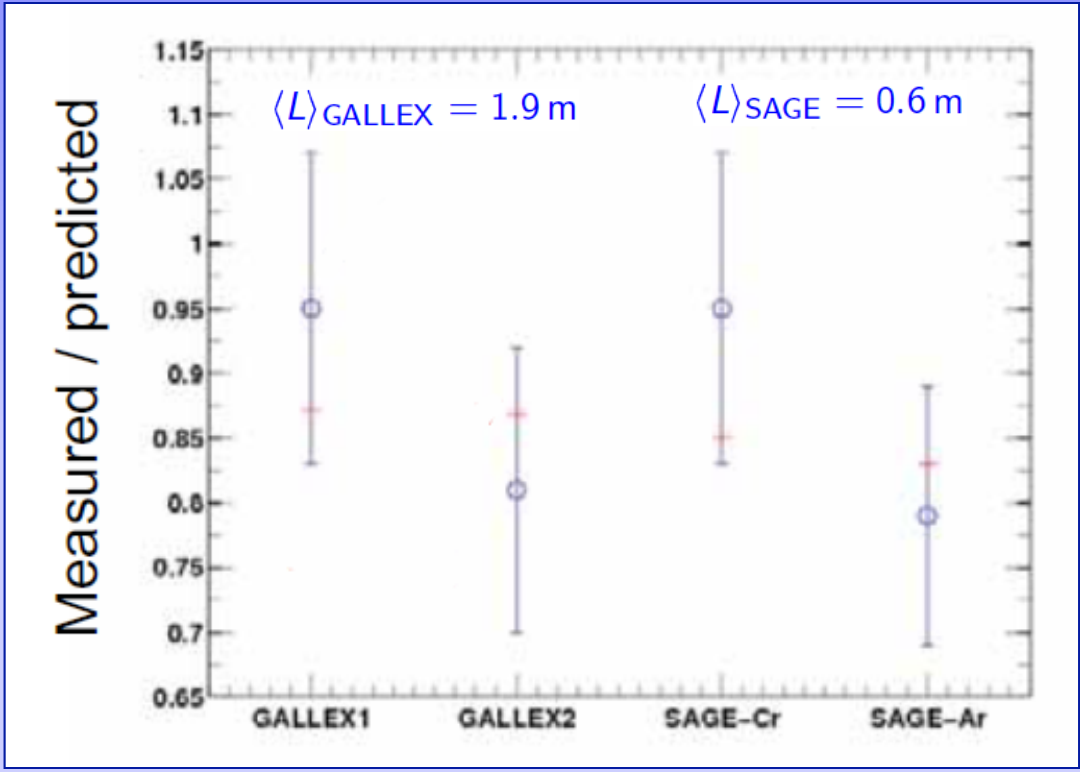
Recent reanalysis of reactor fluxes shows ~ 3.5% upward shift in flux

Mueller et al., arXiv:1101.2663, confirmed by P. Huber, arXiv:1106.0687

Overall reduction in predicted flux compared to existing data can be interpreted as $\bar{\nu}_e$ disappearance with $\Delta m^2 \sim 1 eV^2$ and L = 10 – 100 m

Does source and detector size wash out oscillations?

Gallium Neutrino Anomaly



Calibration measurements for the GALLEX & SAGE solar neutrino detectors using intense radioactive ν_e fluxes from ^{51}Cr & ^{37}Ar

^{51}Cr : 747 KeV (82%)
^{37}Ar: 811 KeV (90%)

Detection process:

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

Measurements consistently lower than expectation

Suggests possible ν_e disappearance at 2.7σ due to active – sterile oscillation

Giunti and Laveder, arXiv:1006.3244

How well do we know the efficiencies of the radiochemical detection processes?

Severe constraints for short baseline oscillations

- Limit on ν_e disappearance from LSND & KARMEN using ν_e - C scattering data

  Conrad & Shaevitz, arXiv:1106.5552 ; Giunti & Laveder, arXiv:1111.1069

- Strong limit on ν_μ disappearance from CDHS & CCFR experiments

  CDHS: PLB 134 (1984) 281 ; CCFR: PRD 59 (1999) 031101

- New SciBooNE/MiniBooNE ν_μ disappearance limit even stronger than earlier

  K.B.M. Mahn et al., arXiv:1106.5685

- Less stringent limits for $\bar{\nu}_\mu$ disappearance from MiniBooNE

  A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

- No hint of steriles in atmospheric & solar ν data in the required parameter range

  Maltoni & Schwetz, arXiv:0705.0107

- MINOS near and far detector NC data set limits on ν_μ disappearance

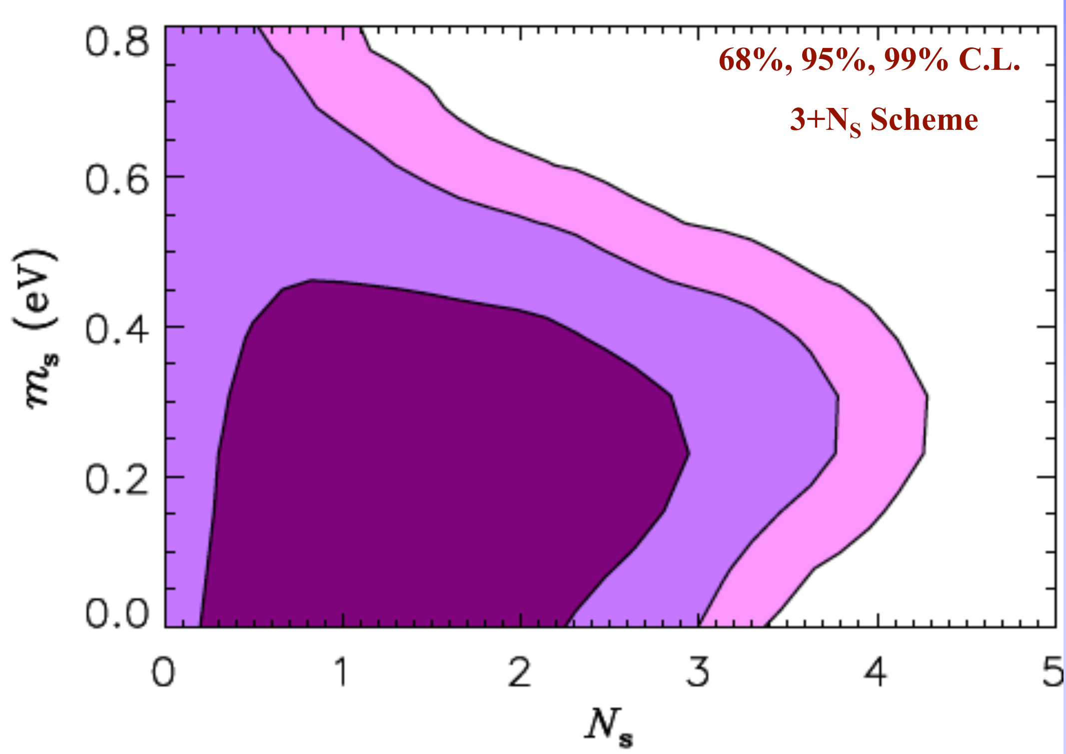
  P. Adamson et al., PRL 107, 011802 (2011) ; Giunti & Laveder, arXiv: 1109.4033

- KARMEN limits $\bar{\nu}_e$ appearance, NOMAD limits ν_e appearance

  KARMEN: PRD 65, 112002 (2002) ; NOMAD: PLB 570, 19 (2003)

Cosmological Constraints

N_S = # of thermalized sterile ν states



Hamann et al., arXiv:1006.5276

Precision cosmology & BBN mildly favor extra radiation in the universe beyond photons and ordinary neutrinos:

Supporting the existence of low mass sterile neutrinos

CMB & LSS in ΛCDM model: $N_S = 1.3 \pm 0.9$ with $m_s < 0.66$ eV @ 95% C.L.

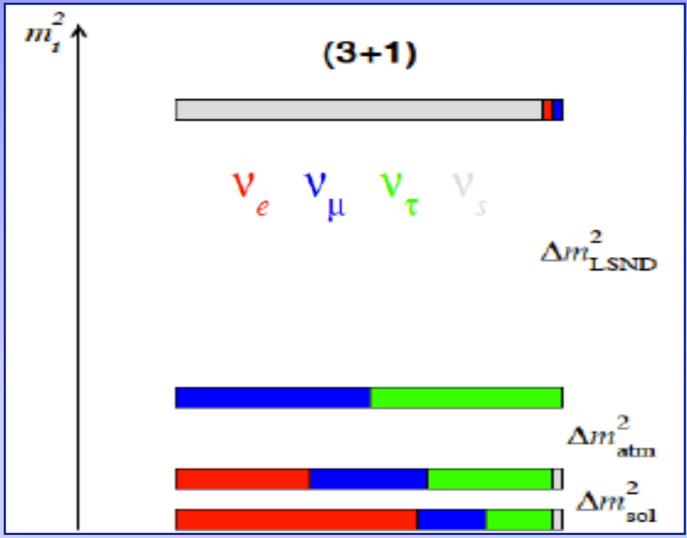
CMB+LSS+BBN: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

Hamann et al., arXiv:1108.4136

! New CMB data from Planck spacecraft will shed more light on this issue !

3+1 short baseline oscillations

Perturbation of 3ν mixing



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

↑ SBL

Add one sterile ν with three active ones at the eV scale

SBL approximation : $\Delta m^2_{21} \approx \Delta m^2_{31} \approx 0$ (2-flavor case)

Appearance

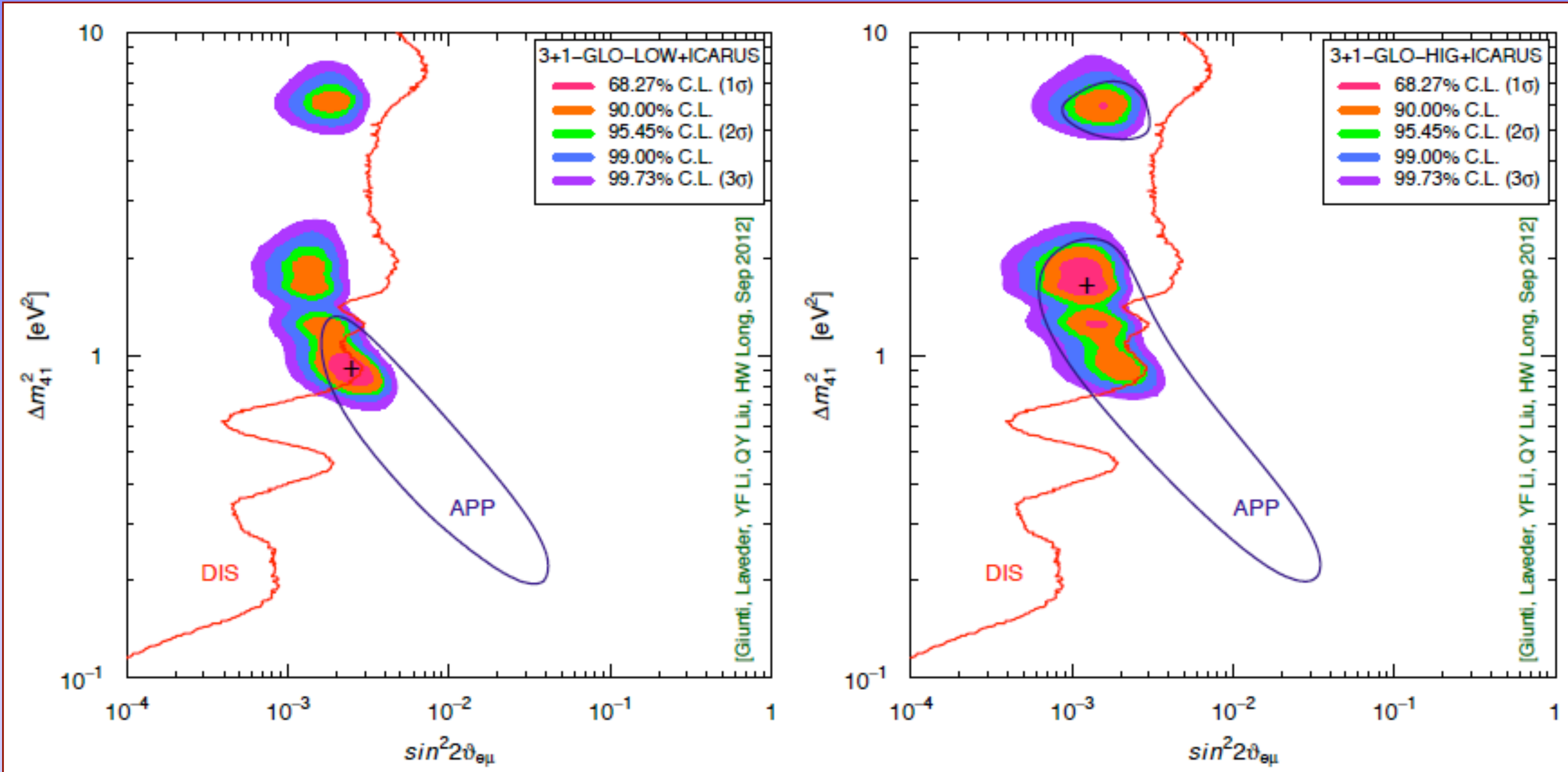
$$P_{\mu e} = \sin^2 2\theta_{\rm app} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm app} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

Disappearance

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\rm dis} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm dis} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

Constrain U_{e4} ($U_{\mu 4}$) from ν_e (ν_μ) disappearance experiments which put bound on appearance amplitude $|U_{e4} U_{\mu 4}|$

3+1 Global Fit



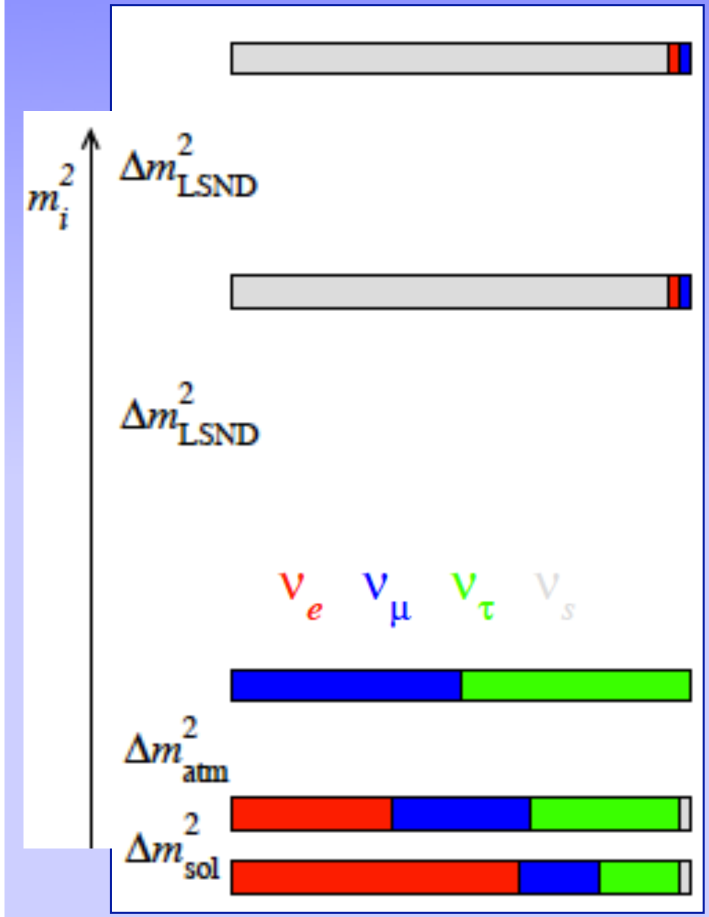
Carlo Giunti, NOW2012

No Osc. GoF = 0.021%
3+1 GoF = 9.9%
PGoF = 0.01%

No Osc. GoF = 0.87%
3+1 GoF = 32%
PGoF = 0.7%

Appearance & disappearance data are marginally compatible!

3+2 short baseline oscillations



Add 2 sterile neutrinos with 3 active ones at the eV scale

SBL approximation : $\Delta m^2_{21} \approx \Delta m^2_{31} \approx 0$ and $x_{ij} \equiv \Delta m^2_{ij} L/4E$

Appearance

$$P_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 x_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 x_{51} + 8|U_{e4}U_{\mu 4}U_{e5}U_{\mu 5}| \sin x_{41} \sin x_{51} \cos(x_{54} - \delta)$$

$\delta \equiv arg(U^*_{e4}U_{\mu 4}U_{e5}U^*_{\mu 5})$ is the CP-phase

Disappearance

$$P_{\alpha\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2 x_{54}$$

CPV (δ): **Can accommodate the possible mismatch between neutrino & anti-neutrino data!**

Constrain $|U_{ei}|$ & $|U_{\mu i}|$ (i=4,5) from disappearance experiments which put bound on appearance amplitude $|U_{ei} U_{\mu i}|$

Do we need 3+2 scenario anymore?

- 3+2 is preferred over 3+1 only if there is CP-violating difference in neutrino and anti-neutrino appearance experiments
- 2010 MiniBooNE anti-neutrino data indicated neutrino-anti-neutrino difference
- Then it was reasonable and useful to consider 3+2
- Neutrino-Anti-neutrino difference almost vanished with new 2012 MiniBooNE anti-neutrino data
- Also, there are severe constraints from cosmology for two extra sterile neutrinos, specially in ΛCDM model

What do we need? Any Future Plans?

- Both positive & negative hints for sterile high Δm^2 oscillation

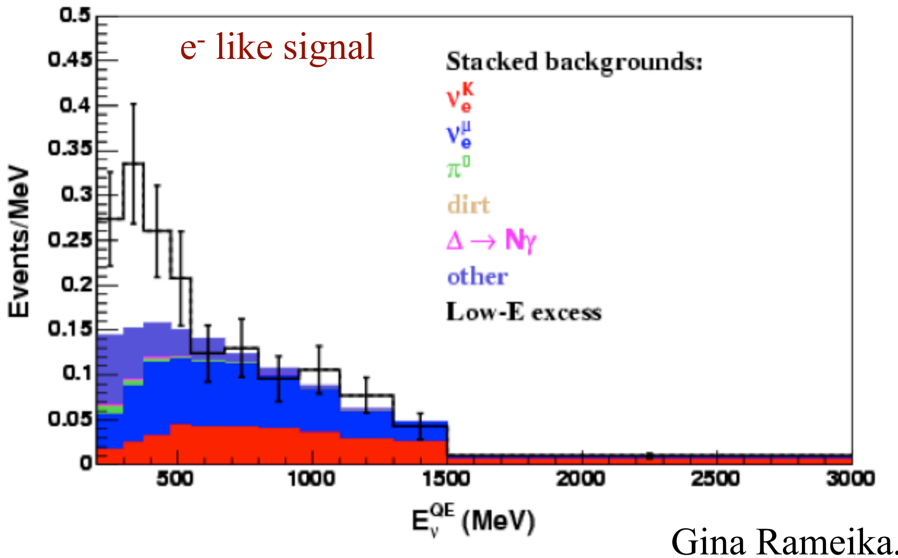
  !! Nothing is conclusive !!

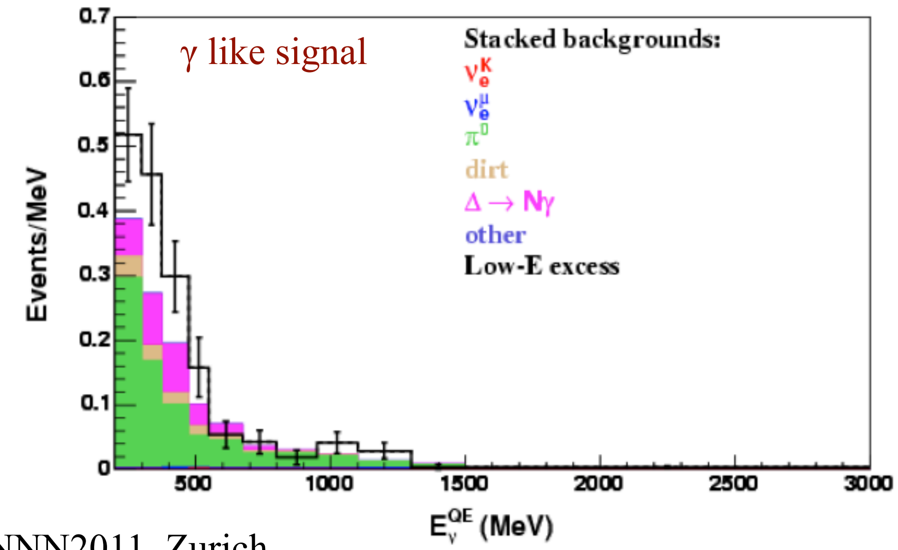
- Need new high precision short baseline experiments to perform appearance and disappearance searches at high significance involving both neutrinos and anti-neutrinos

- There is a diverse set of SBL experiments, spanning a wide range in L and E, have been proposed to validate/refute the 3+N models and to resolve the present anomalies at high significance

MicroBooNE at FNAL (Approved)

- *LArTPC (70 tons fiducial volume), located at 470 m in the Booster Neutrino Beamline*
- *2 times better PID efficiency than MiniBooNE, only 3% mis-ID (Online late 2013)*
- *Unique e^-/γ discrimination: photons give twice the ionization at conversion point*
- *Can predict if low-E excess in MiniBooNE (ν) due to single electron or photon events*





Gina Rameika, NNN2011, Zurich

36.8 excess events, 41.6 background
5.7σ stat. significance for E < 475MeV

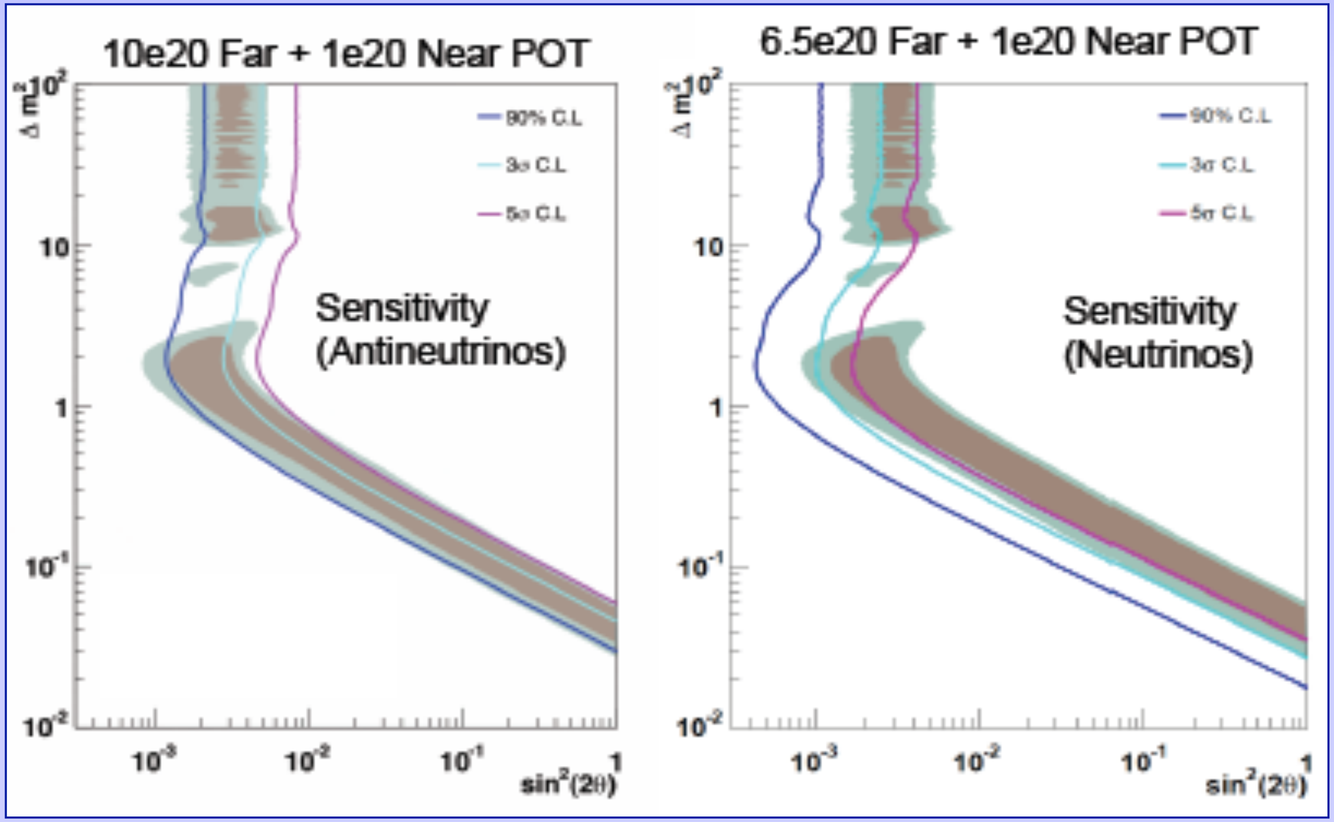
6×10^{20} POT

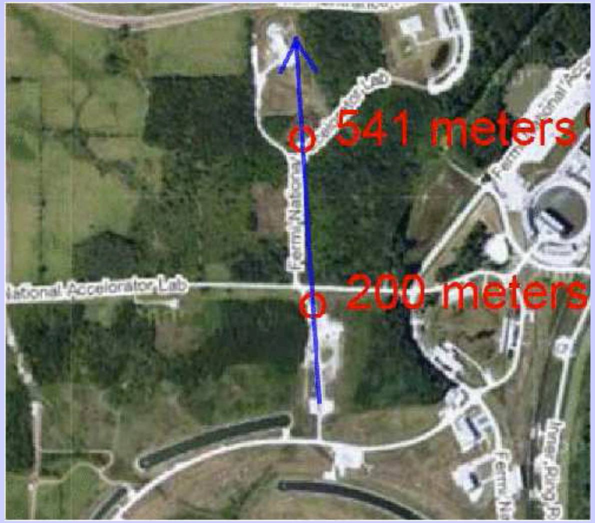
36.8 excess events, 78.9 background
4.1σ stat. significance for E < 475 MeV

BooNE (a near detector for MiniBooNE)

- *Build a new MiniBooNE like detector at 200 m (near detector for MiniBooNE)*
- *Flux, cross-section and optical model errors cancel in 200 m/500 m ratio analysis*

Gain statistics rapidly, already have far detector data

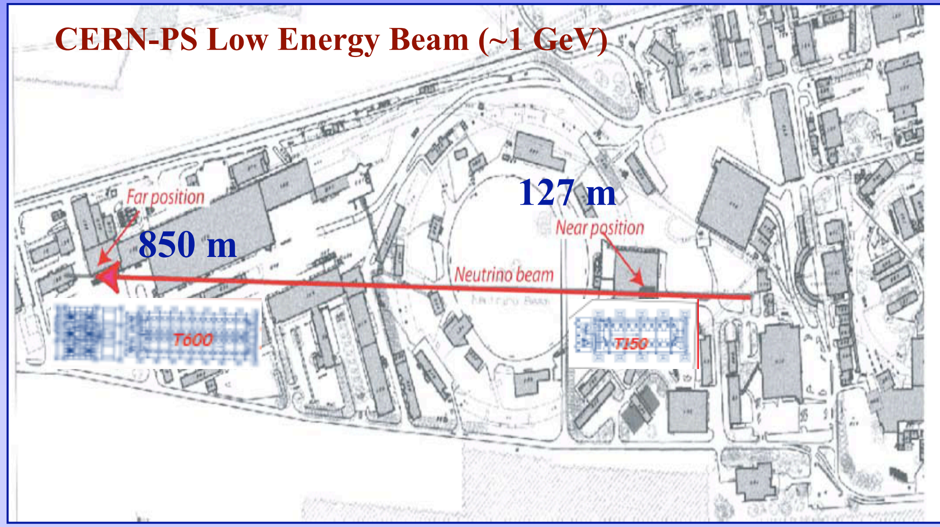




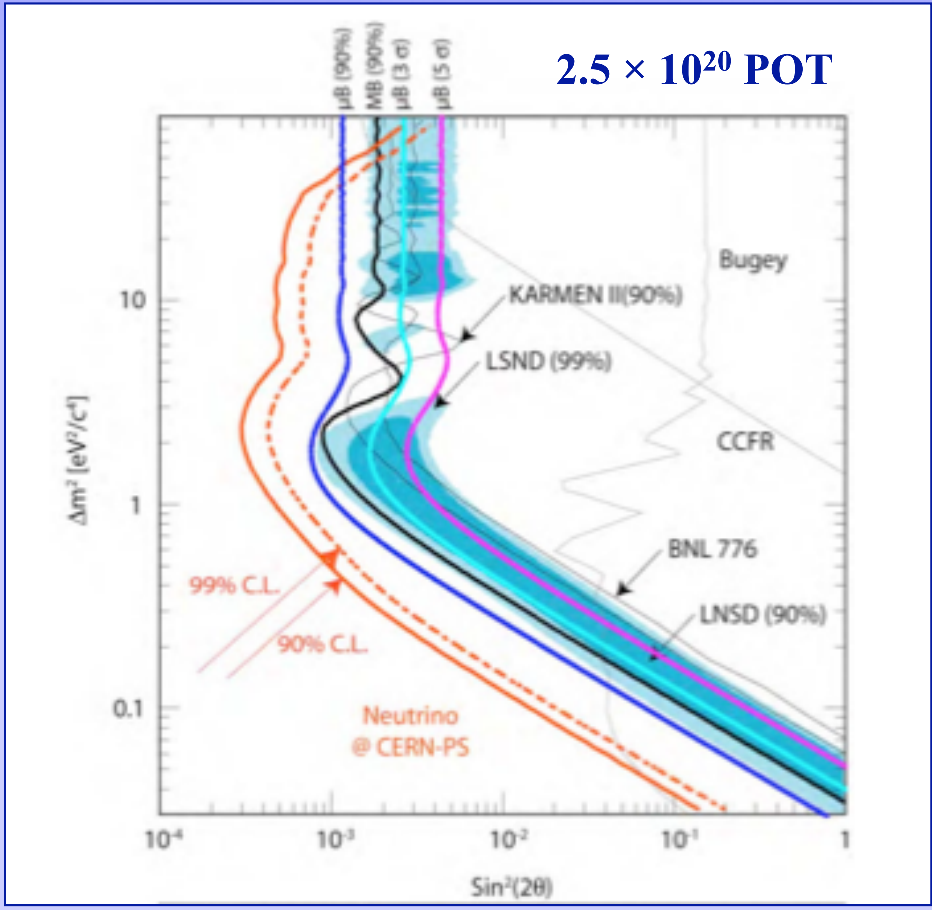
LOI arXiv:0910.2698

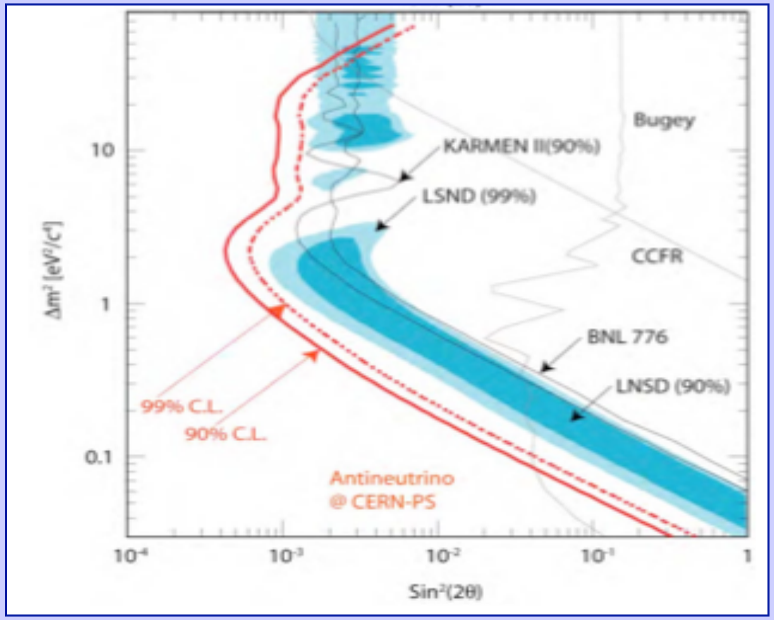
CERN Low Energy Two Detector Experiment

600 tons ICARUS at 850 m and 150 tons LAr at 127 m in the CERN-PS beam line



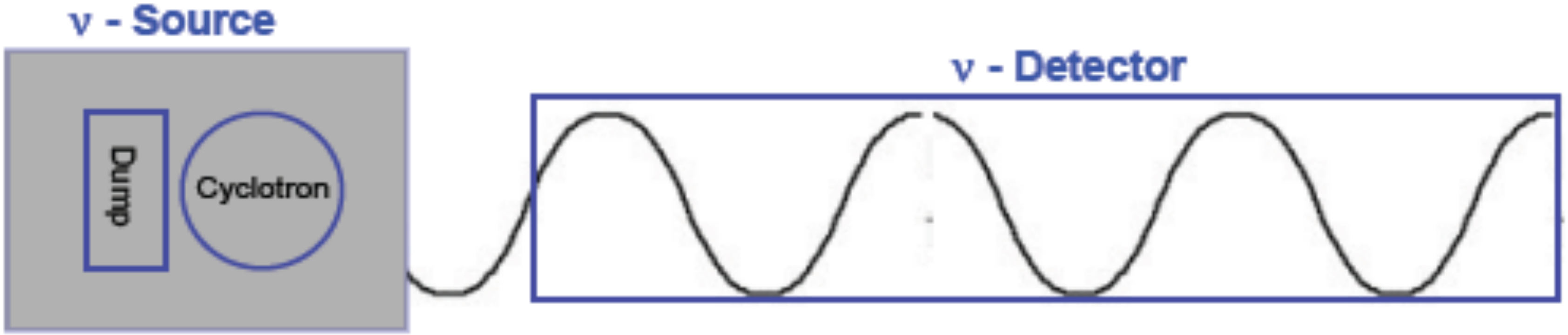
2.5×10^{20} POT





LOI arXiv:0909.0355

Very Short Baseline Oscillation Experiment



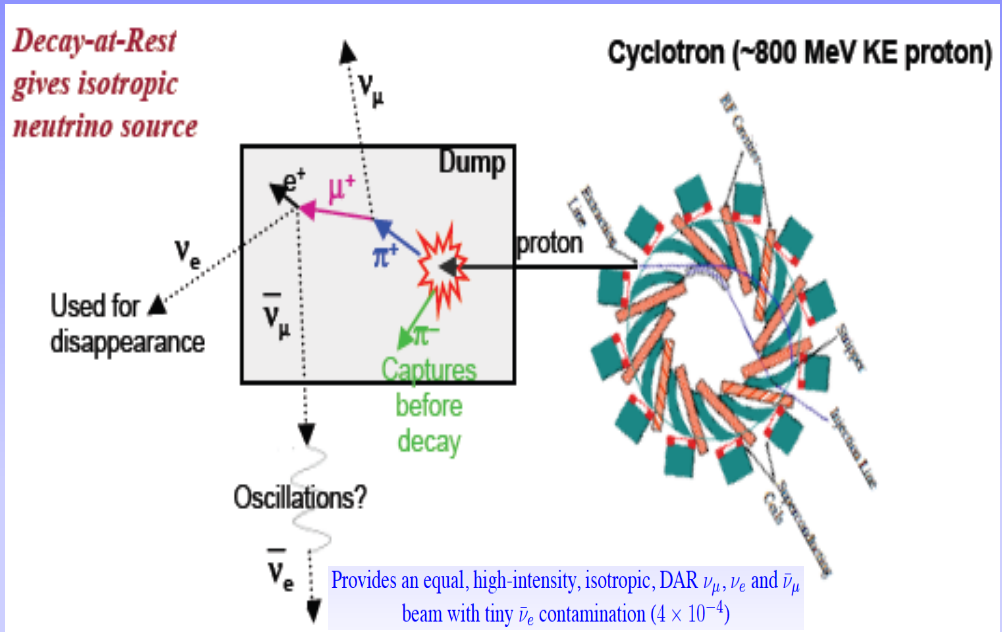
$1/L^2$ flux rate modulated by $\text{Prob}_{osc} = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L / E\right)$

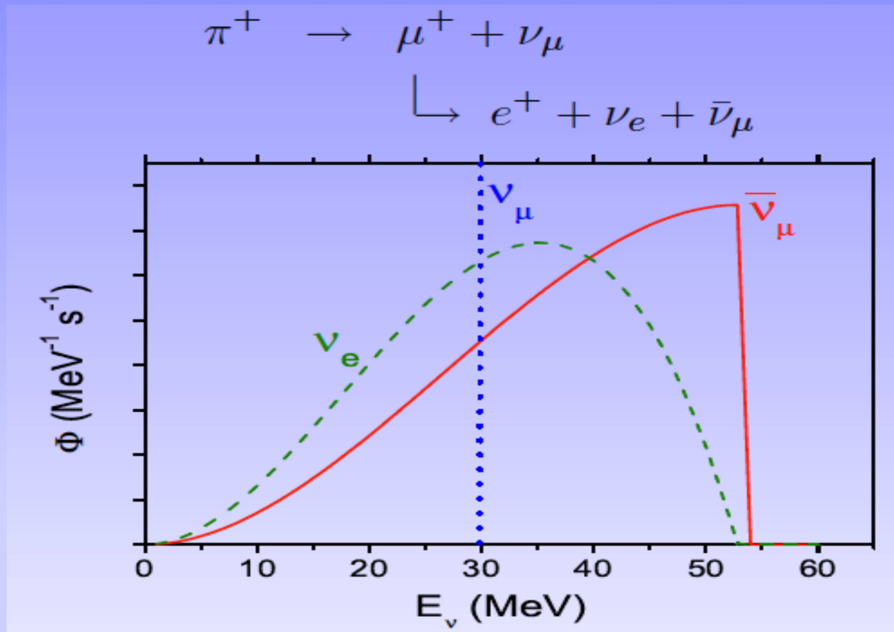
Neutrino Sources

- **Decay-at-rest beam from proton beam dump**
- **Small core reactor source**
- **Very high activity radioactive source**

- **Observe the L/E dependence of the event rates within a long ν detector**
- **Background distribution is either independent of L or goes like $1/L^2$**
- **Powerful verification of the short baseline oscillation/new physics**

Decay-At-Rest (or Beam Dump) Neutrino Source



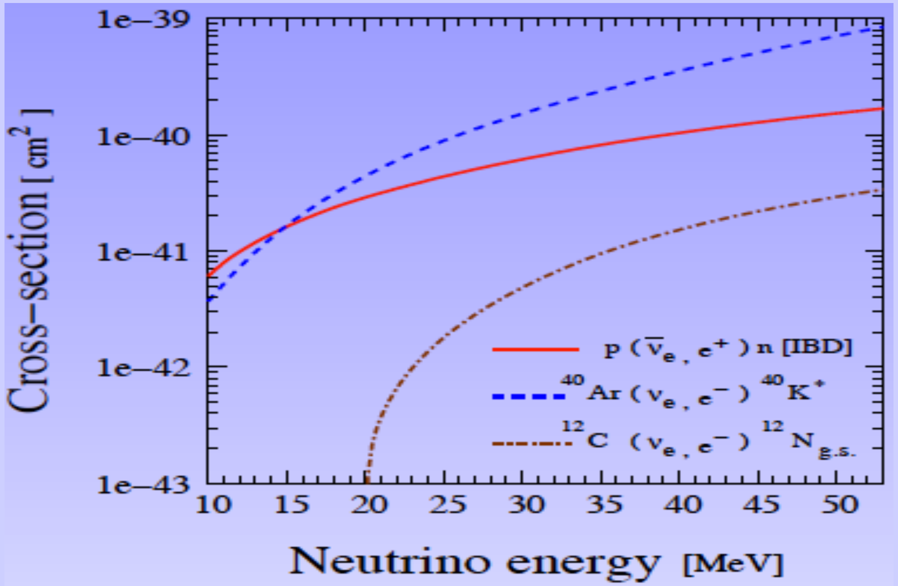


800 MeV protons from cyclotrons interact in a low-A target (C, H_2O) producing π^+ and, at a low level, π^-

$$p + X \rightarrow \pi^{\pm} + X'$$

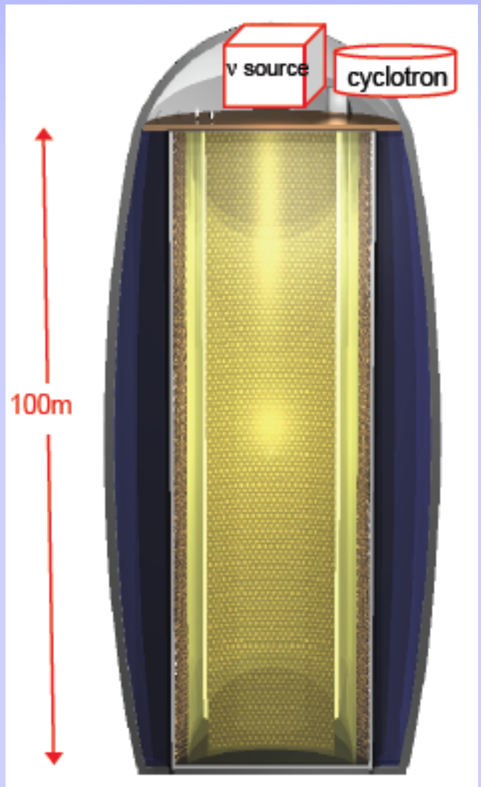
Low-A target is embedded in a high-A, dense material where pions are brought to rest

π^- & daughter μ^- captured before DIF, minimizing $\bar{\nu}_e$

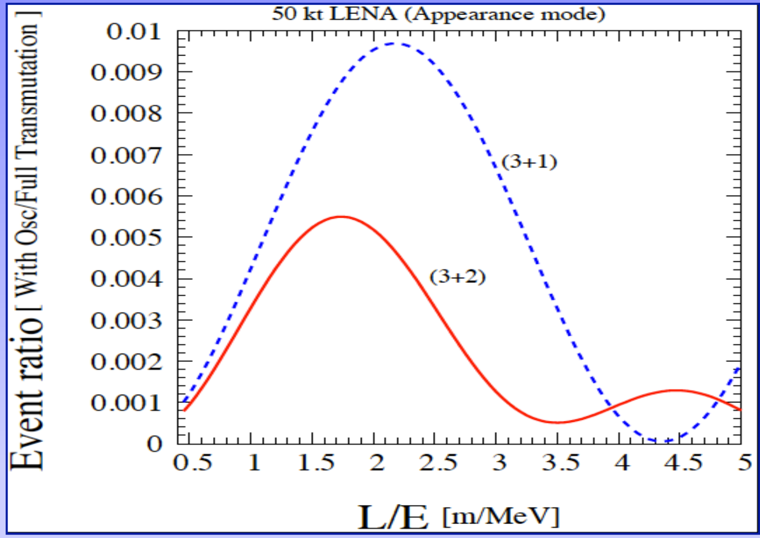


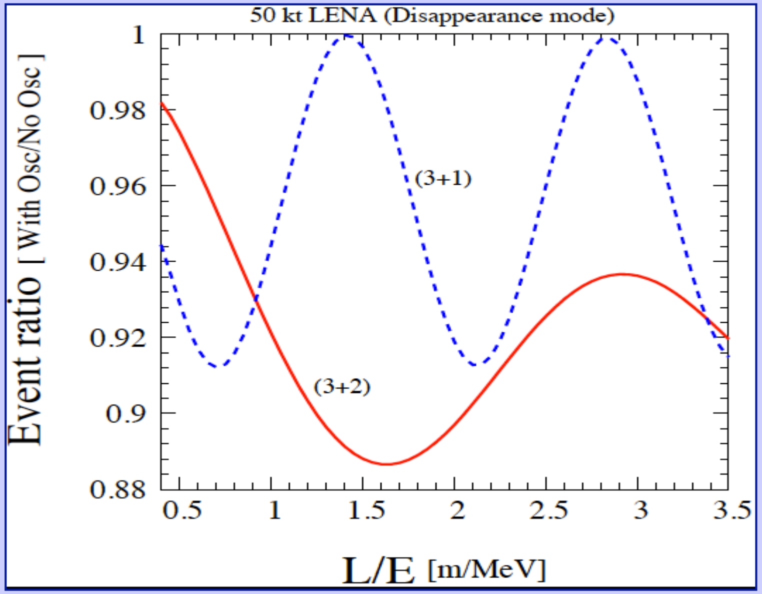
Short Baseline Neutrino Oscillation Waves

- LENA Scintillation Detector
- 50 kt fiducial mass
- Source-to-detector face = 20 m
- Deep location (4000 mwe)
- Negligible cosmic muon background



Similar study with NOνA & Gd doped Super-Kamiokande





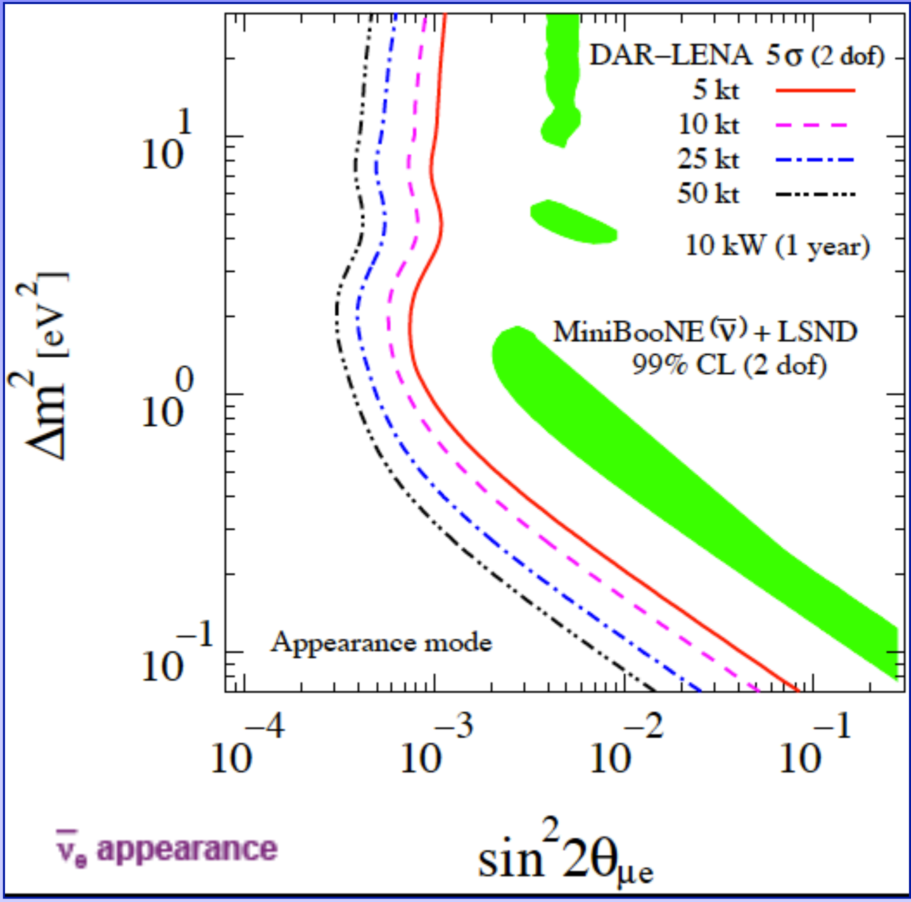
Agarwalla and Huber, arXiv: 1007.3228
Agarwalla, Conrad and Shaevitz, arXiv: 1105.4984

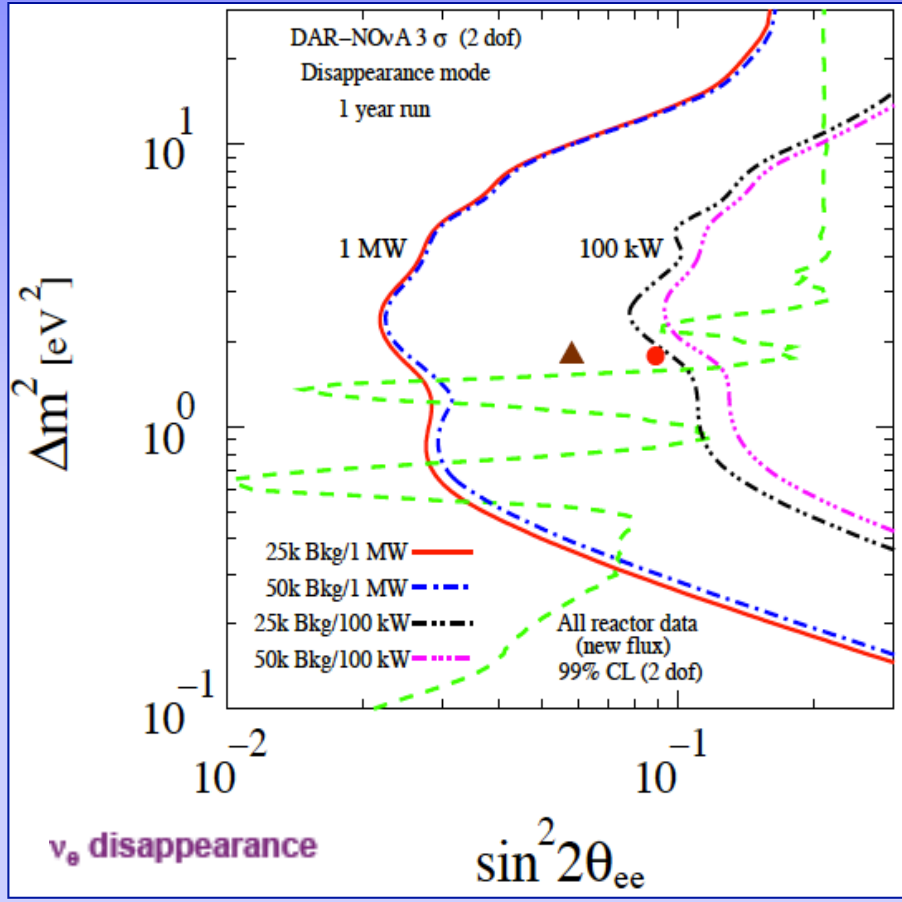
Distinguish between (3+1) & (3+2) models

Rate + Shape measurement

Several L/E bins cancel systematic uncertainties

Sensitivity Limit to Sterile Neutrino Oscillation





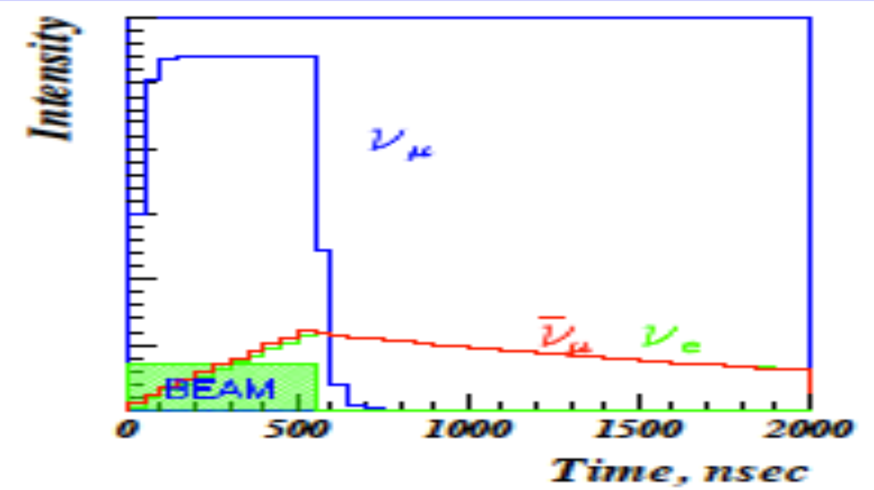
- LENA style detector
- Cover 'LSND' at 5σ with 5 kt LENA & 10 kW cyclotron in 1 year

- NOνA
- Cover 'Reactor Anomaly' at 3σ with 100 to 1000 kW in 1 year

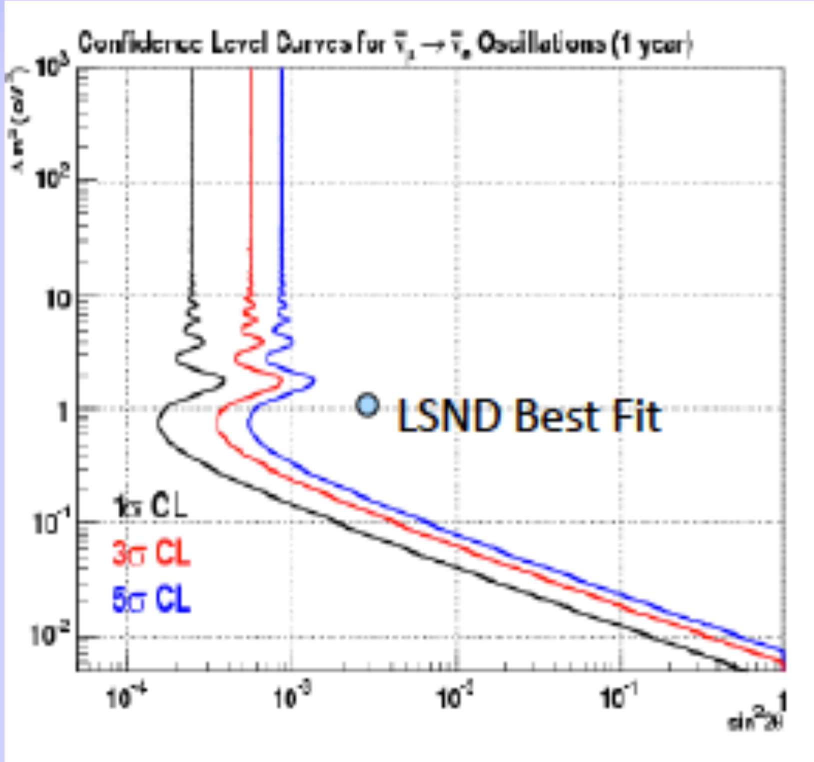
Agarwalla, Conrad and Shaevitz, arXiv: 1105.4984

OscSNS proposal at ORNL@USA

- Spallation Neutron Source @ ORNL
- 1.3 GeV protons on Hg target (1.2 MW)
- Free source of ν (well known spectrum)
- Place 25 tons LS near detector at 18 m
- Place 500 tons LS far detector at 60 m

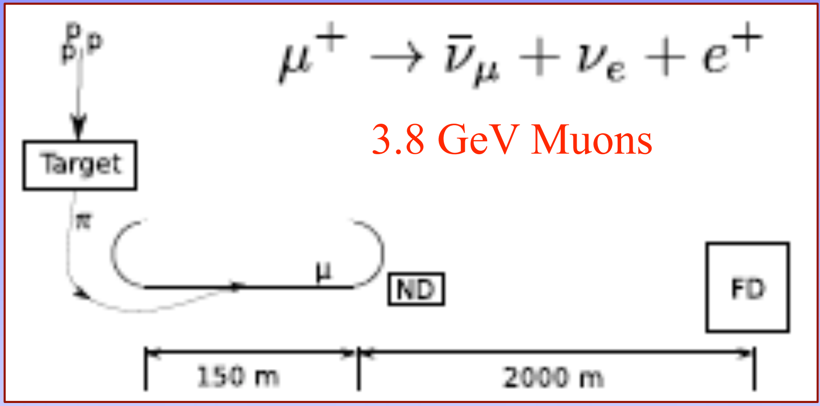


Short duty-factor, beam pulse 695 ns



OscSNS proposal, hep-ph/0501013

νSTROM: Neutrinos from Stored Muons



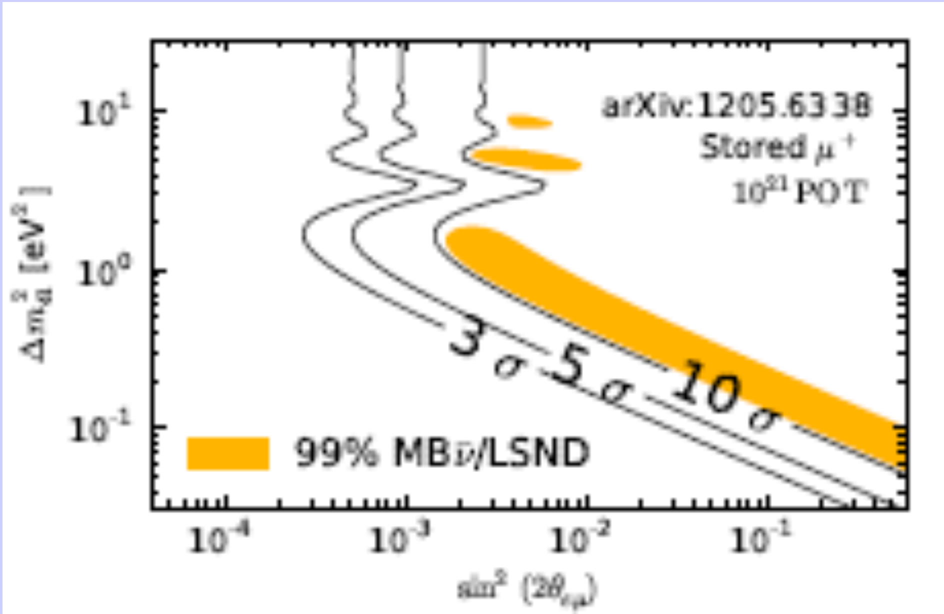
LSND: Muon anti-neutrino -> electron anti-neutrino

νSTORM: electron neutrino -> muon neutrino

CPT(LSND) = νSTORM

Muons are easier to detect than positrons
Flux uncertainties are less in νSTORM

- Simplest implementation of the NF concept
  - 60 GeV protons on solid target (100 kW)
  - Horn capture and π transfer
  - Decay ring



- Performance assumptions
  - 10^{21} 60 GeV/c POT
- Yields ≈ $2X10^{18}$ useful ν
- ≈2000 m baseline
- 1.3 kT Minos-like detector

arXiv: 1205.6338

Concluding Remarks

- Several interesting, but inconclusive hints for sterile neutrinos
- Global fit of world neutrino and anti-neutrino data in 3+1 scheme show considerable tension between various experiments
- Need new powerful experiments to have a conclusive $\geq 5\sigma$ results
- Establishing the existence of sterile neutrinos would open a powerful window on new physics beyond the Standard Model

For More Discussions on Steriles : Take a look at !

http://cnp.phys.vt.edu/white_paper/whitepaper.pdf

Thank You !