Recent Results in Neutrino Experiments

Dr Ben Still

Queen Mary, University of London

Open Questions…

- Absolute mass scale (kinematic, TOF, $0\nu\beta\beta$ decay, astrophysical limits)
- Dirac vs. Majorana ($0\nu\beta\beta$ decay)
- Majorana phases ($0\nu\beta\beta$ decay)
- Octant of θ_{23} (ν oscillation)
- CP-violation, dirac phase δ_{CP} (ν oscillation)
- Ordering of mass hierarchy sgn(Δm^2_{23}) (ν oscillation)

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Absolute Mass Measurements

- Supernova TOF and energy spectrum
  - <5.8 eV (95% C.L.) hep-ph/1005.3682
- Cosmological: Mass power spectrum
  - $0.2 < \Sigma m_\nu < 2$ eV 95% C.L., model dependent hep-ph/0608060
- Kinematic: Tritium β-decay
  - $m_\nu < 2.2$ eV (95% C.L.) hep-ex/1108.5034v3
- $0\nu\beta\beta$ decay: If ν is Majorana
  - $\langle m_{ee} \rangle = (120\text{-}250)$ meV 90% C.L. hep-ex/1211.3863v2

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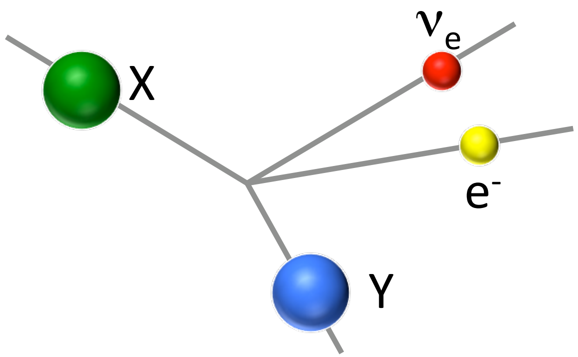
β-Decay Kinematic Mass Measurement



$$K(T) \approx \left[(Q - T)\sqrt{(Q-T)^2 - m_\beta^2} \right]^{1/2}$$

$$Q = M_X - M_Y - m_e$$

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

Effective β mass

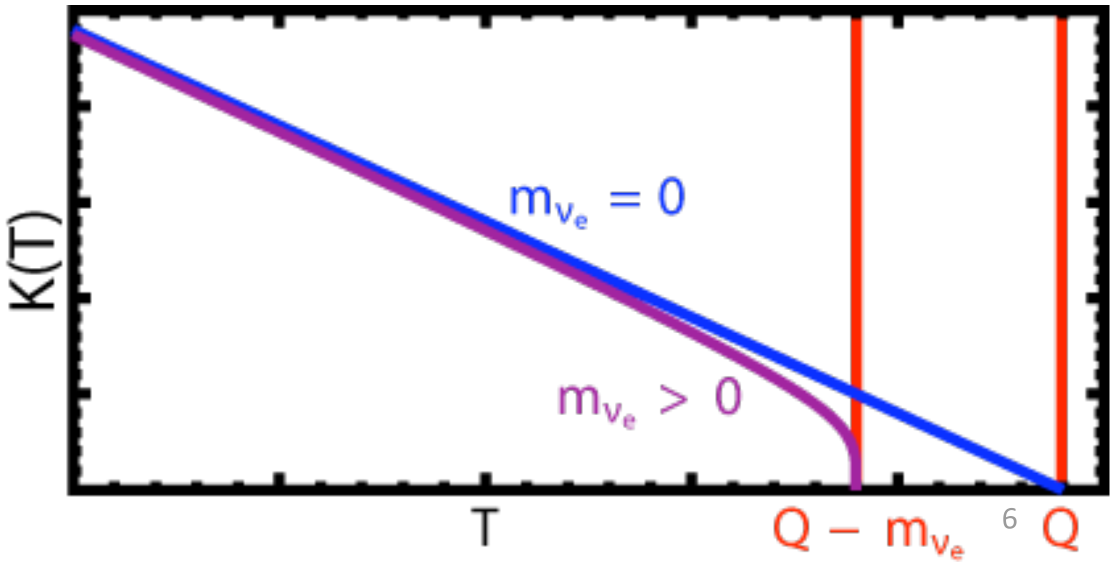
X=^{3}H, Troitsk

$m_\beta < 2.2$ eV/c^2

(95% C.L.)

V. N. Aseev et al

[hep-ex/1108.5034v3](hep-ex/1108.5034v3)



Kinematic Mass Measurement

X=^{3}H, KATRIN

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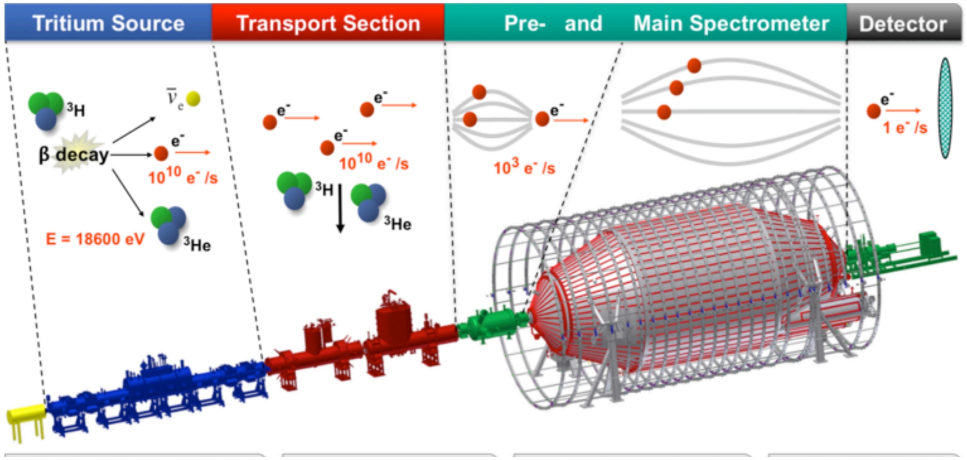

Data Taking - 2015

Sens. at 90% C.L. $m_\nu \approx 0.2$ eV/c^2

5σ Meas. Potential $m_\nu \approx 0.35$ eV/c^2

@ 3 ‘full beam’ years (stats. + sys.)

T. Thümmlera, KATRIN Coll.

hep-ex/1012.2282v1

Kinematic Mass Measurement

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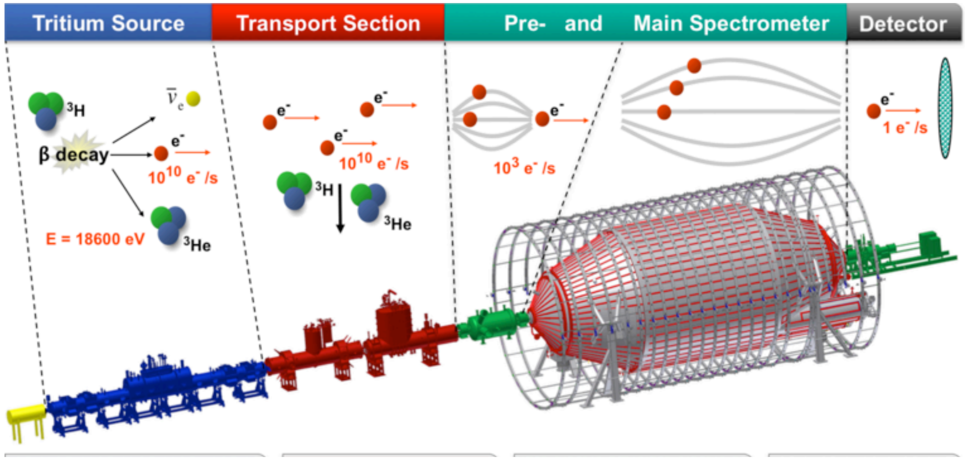

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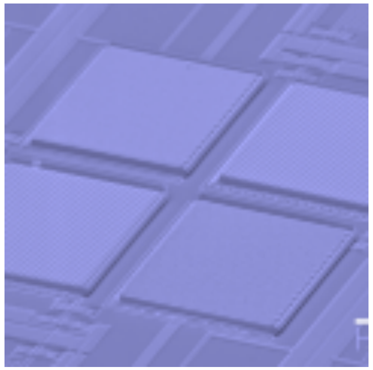
T. Thümmlera, KATRIN Coll.

hep-ex/1012.2282v1

X=^{187}Re,^{163}Ho



MARE/ECHO in R&D Stages

2-3 years

Sens. 0.2eV/c^2 (90% C.L.)

stats only - 10 Yrs 400g ^{187}Re

A. Nucciottia, MARE Coll.

hep-ex/1012.2290v1

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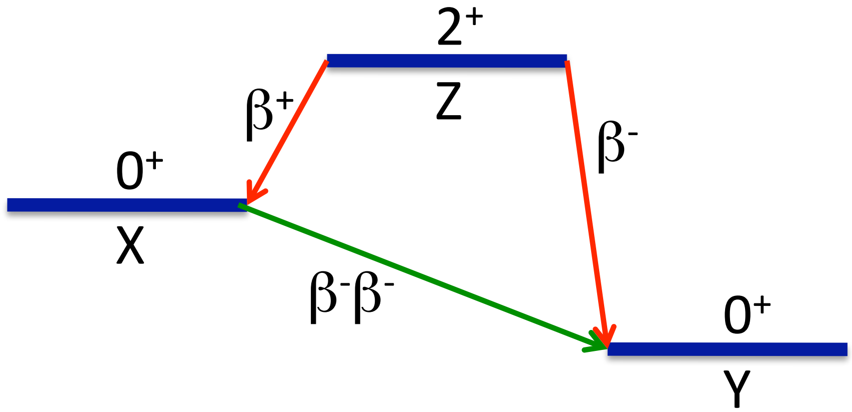
Used in current
and future exp.

0νββ Decay

ββ Decay isotopes

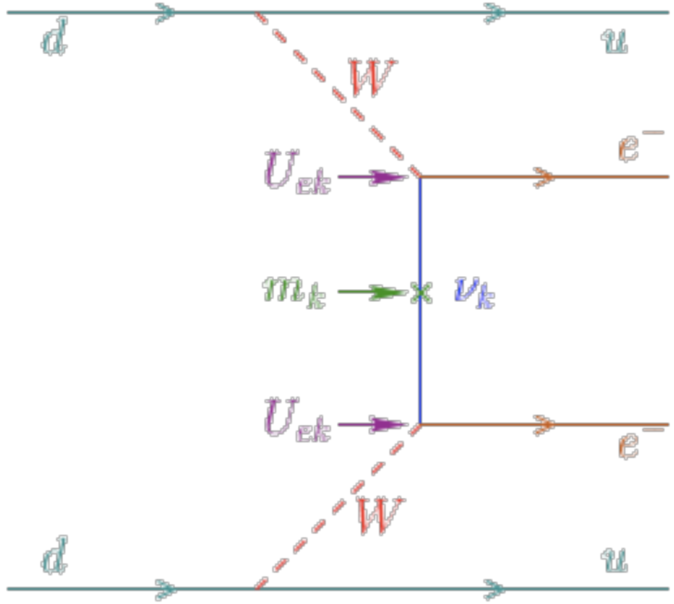
^{76}Ge	^{48}Ca	^{116}Cd
^{136}Xe	^{82}Se	^{128}Te
^{150}Nd	^{96}Zr	^{238}U
^{130}Te	^{100}Mo	



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|m_{\beta\beta}\right|^2$$

$$\left|m_{\beta\beta}\right| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

Effective Majorana Mass



0νββ Decay Results

EXO ^{136}Xe hep-ex/1205.5608	$T_{1/2}^{0\nu}$ > 1.6 x 10^{25} y	$\lvert m_{\beta\beta} \rvert \leq$ 0.14-0.38 eV
KamLAND-Zen ^{136}Xe hep-ex/1211.3863v2	$T_{1/2}^{0\nu}$ > 1.9 x 10^{25} y	
KLZ + EXO ^{136}Xe hep-ex/1211.3863v2	$T_{1/2}^{0\nu}$ > 3.4 x 10^{25} y	$\lvert m_{\beta\beta} \rvert \leq$ 0.12-0.25 eV
CUORICINO ^{130}Te hep-ex/1012.3266	$T_{1/2}^{0\nu}$ > 2.8 x 10^{24} y	$\lvert m_{\beta\beta} \rvert \leq$ 0.3-0.7 eV
Heidel-Moscow ^{76}Ge hep-ph/0103062	$T_{1/2}^{0\nu}$ > 1.9 x 10^{25} y	$\lvert m_{\beta\beta} \rvert \leq$ 0.32-1.0 eV
IGEX ^{76}Ge hep-ex/0202026	$T_{1/2}^{0\nu}$ > 1.57 x 10^{25} y	$\lvert m_{\beta\beta} \rvert \leq$ 0.33-1.35 eV

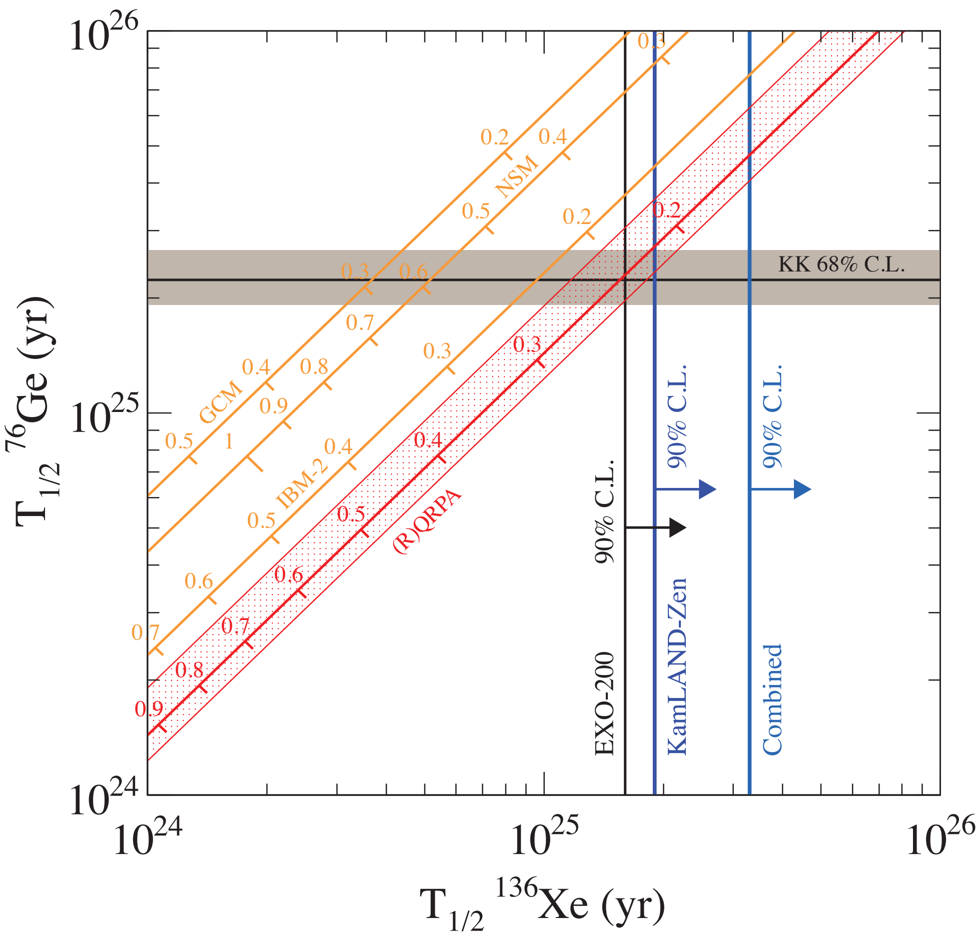
All results stated at 90% C.L.

$0\nu\beta\beta$ Decay Results

Has $0\nu\beta\beta$ been seen by Heidelberg-Moscow?

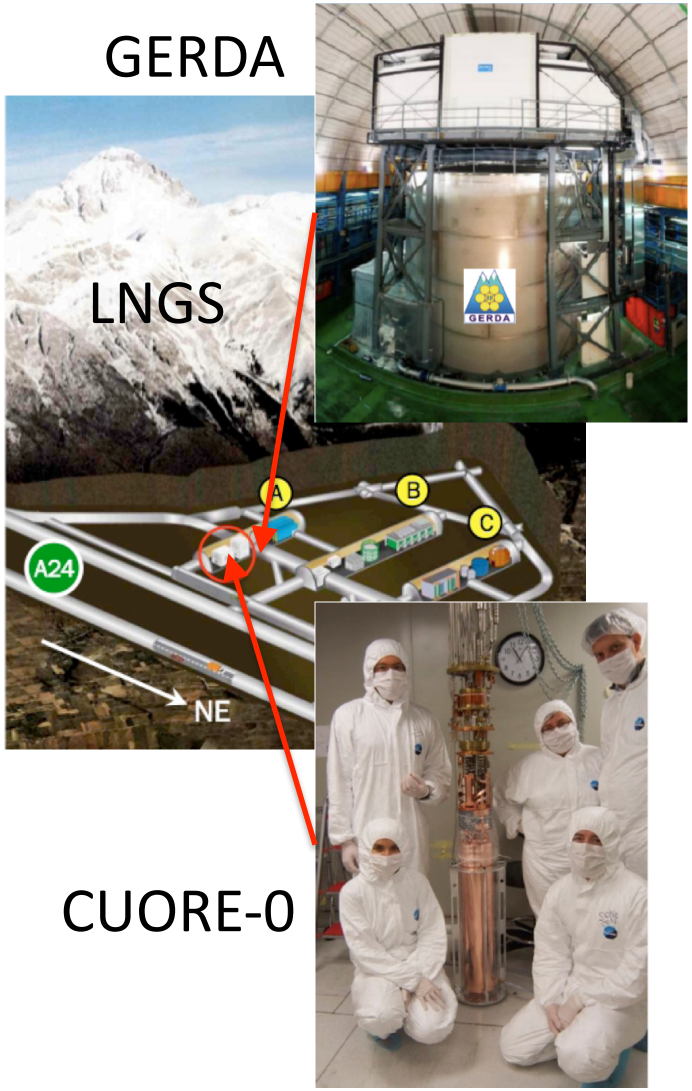
KamLAND-Zen & EXO-200 combination excludes H-M claim at 97.5%

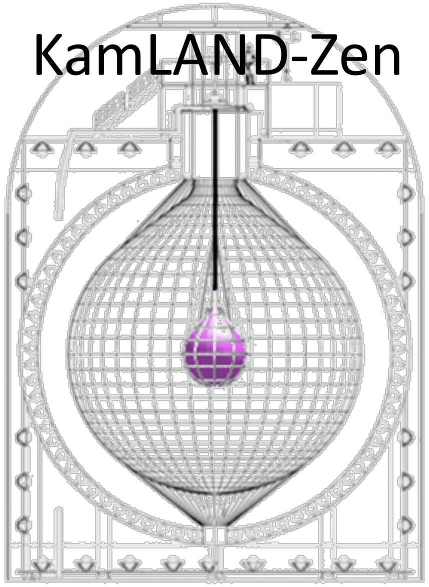
Next Generation of experiments will test H-M claim at 5σ level.

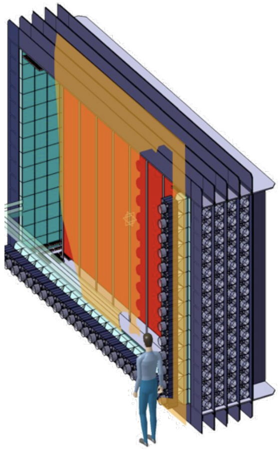


hep-ex/1211.3863v2

0νββ Decay Future



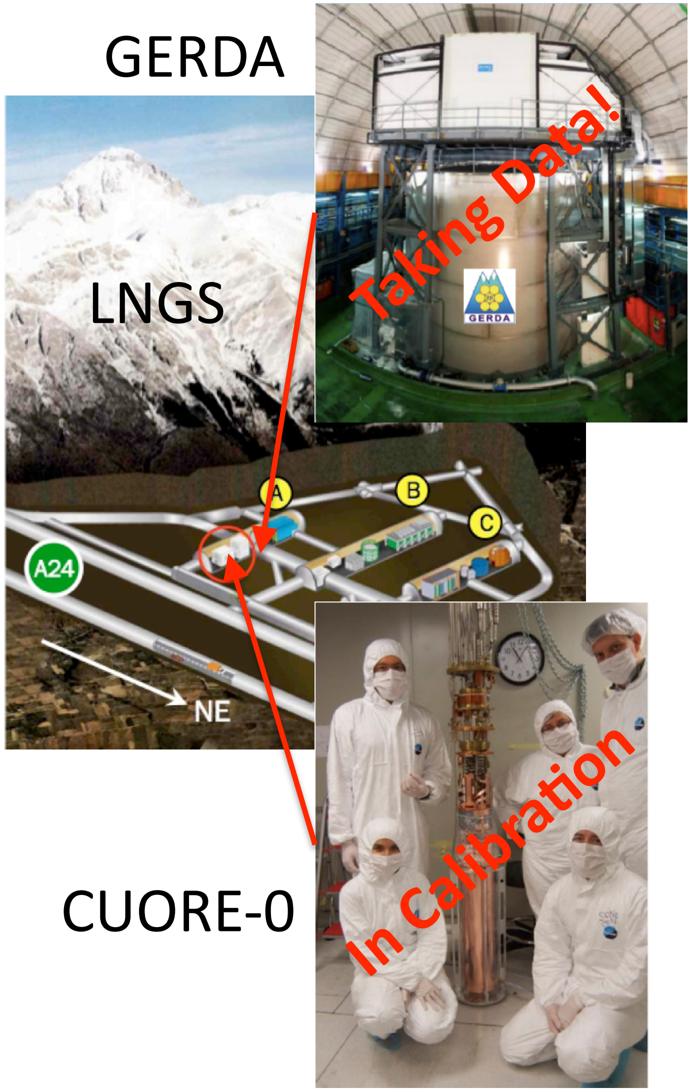



Super NEMO

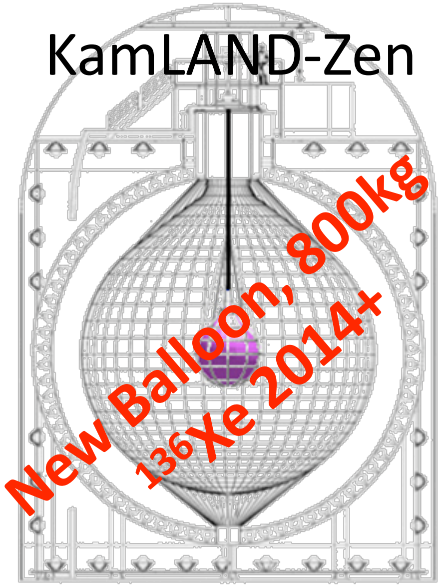
Majorana
NEXT
nEXO

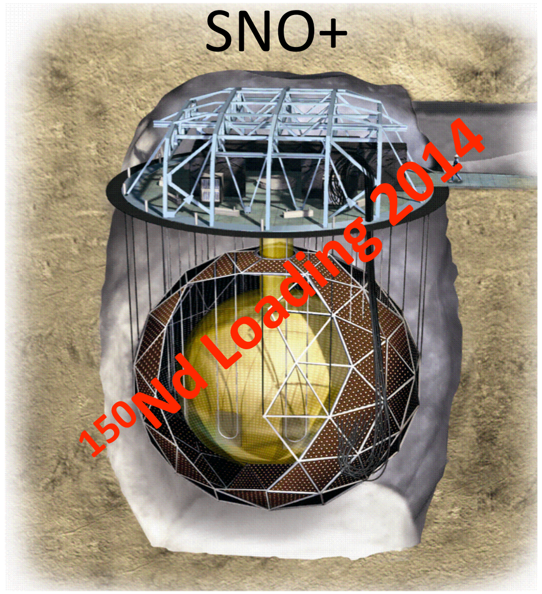
0νββ Decay Future

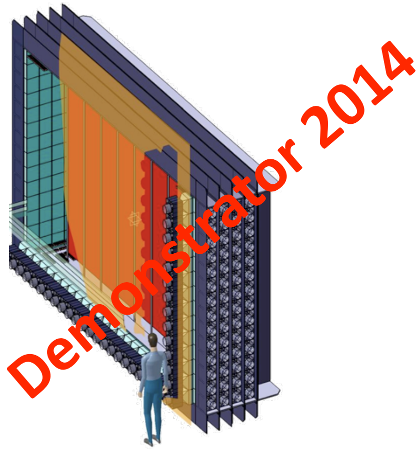
GERDA



CUORE-0







Super NEMO

Majorana
NEXT
nEXO

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Neutrino Oscillation

If neutrinos have mass then... $|\nu_l\rangle = \sum_i U_{li} |\nu_i\rangle$ ... where ...

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Interference Solar

Oscillation probability depends also on mass difference squared Δm^2_{ij}, energy of the neutrino, E, and distance it travels, L.

Six oscillation parameters to measure:

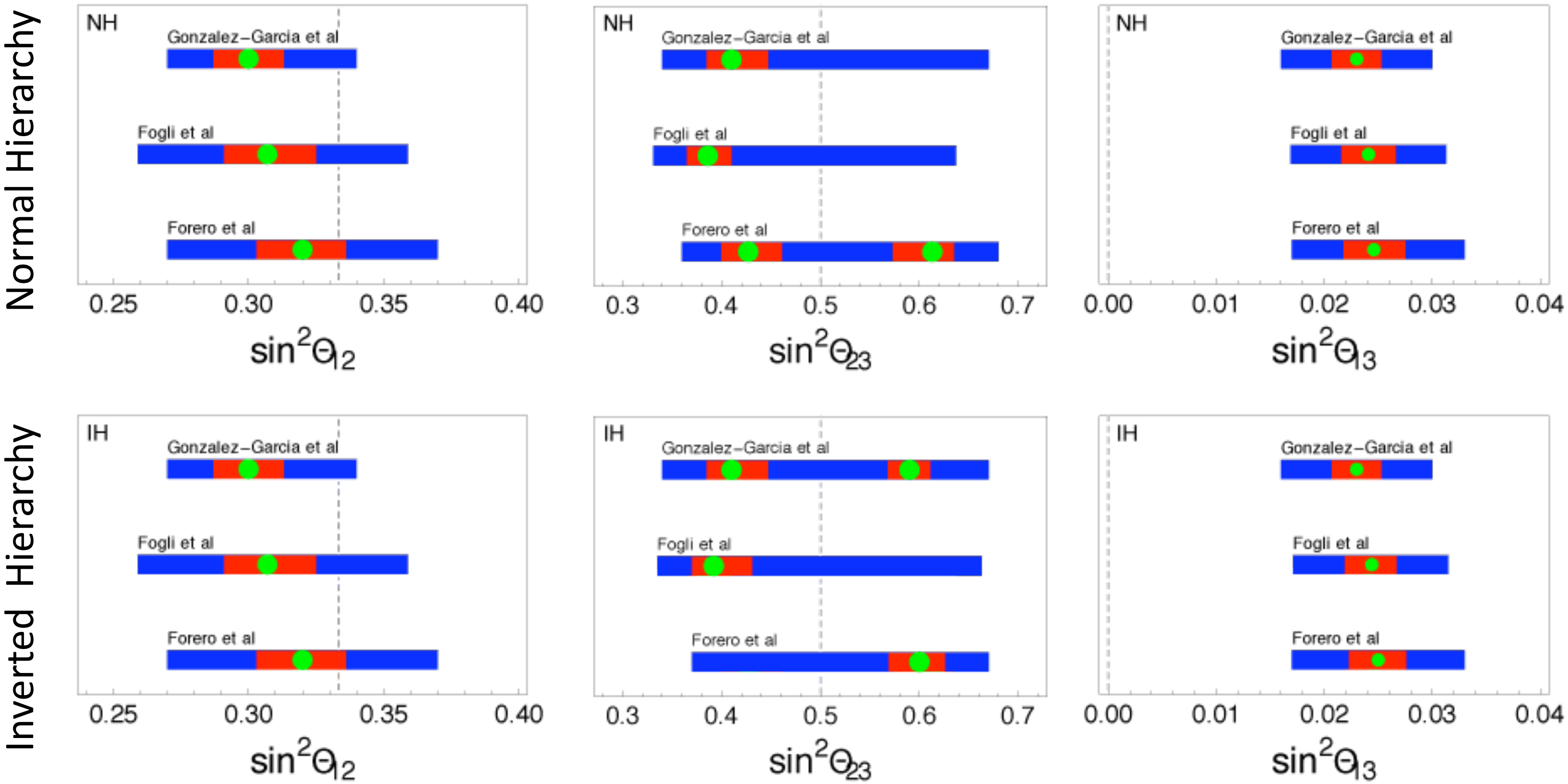
- 3 Mixing angles θ_{23}, θ_{13} and θ_{12}
- 2 Mass squared difference Δm^2_{23} and Δm^2_{12}
- 1 dirac CP-violating phase δ_{CP}

Global Fits After Neutrino 2012

parameter	Forero et al	Fogli et al	Gonzalez-Garcia et al
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	7.62 ± 0.19	$7.54^{+0.26}_{-0.22}$	7.50 ± 0.185
$\Delta m^2_{31}[10^{-3}\text{eV}^2]$	$2.55^{+0.06}_{-0.09}$ $-2.43^{+0.06}_{-0.07}$	$2.43^{+0.06}_{-0.10}$ $-2.42^{+0.11}_{-0.07}$	$2.47^{+0.069}_{-0.067}$ $-2.43^{+0.042}_{-0.065}$
$\sin^2\theta_{12}$	$0.320^{+0.016}_{-0.017}$	$0.307^{+0.018}_{-0.016}$	0.30 ± 0.013
$\sin^2\theta_{23}$	$0.427^{+0.034}_{-0.027}$ & $0.613^{+0.022}_{-0.040}$ $0.600^{+0.026}_{-0.031}$	$0.386^{+0.024}_{-0.021}$ $0.392^{+0.039}_{-0.022}$	$0.41^{+0.037}_{-0.025}$ $0.41^{+0.037}_{-0.025}$ & $0.59^{+0.021}_{-0.022}$
$\sin^2\theta_{13}$	$0.0246^{+0.0029}_{-0.0028}$ $0.0250^{+0.0026}_{-0.0027}$	0.0241 ± 0.0025 $0.0244^{+0.0023}_{-0.0025}$	0.023 ± 0.0023
δ	$(0.80 \pm 1)\pi$ $-(0.03 \pm 1)\pi$	$(1.08^{+0.28}_{-0.31})\pi$ $(1.09^{+0.38}_{-0.26})\pi$	$(1.67^{+0.37}_{-0.77})\pi$

hep-ph/1205.4018 hep-ph/1205.5254 hep-ph/1209.3023

Global Fits After Neutrino 2012



Best Fit

1σ

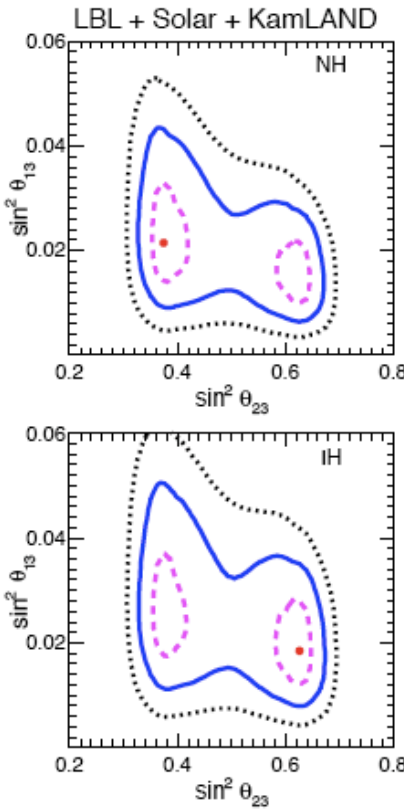
hep-ph/1301.1304

2σ

Global Fits After Neutrino 2012

Normal Hierarchy

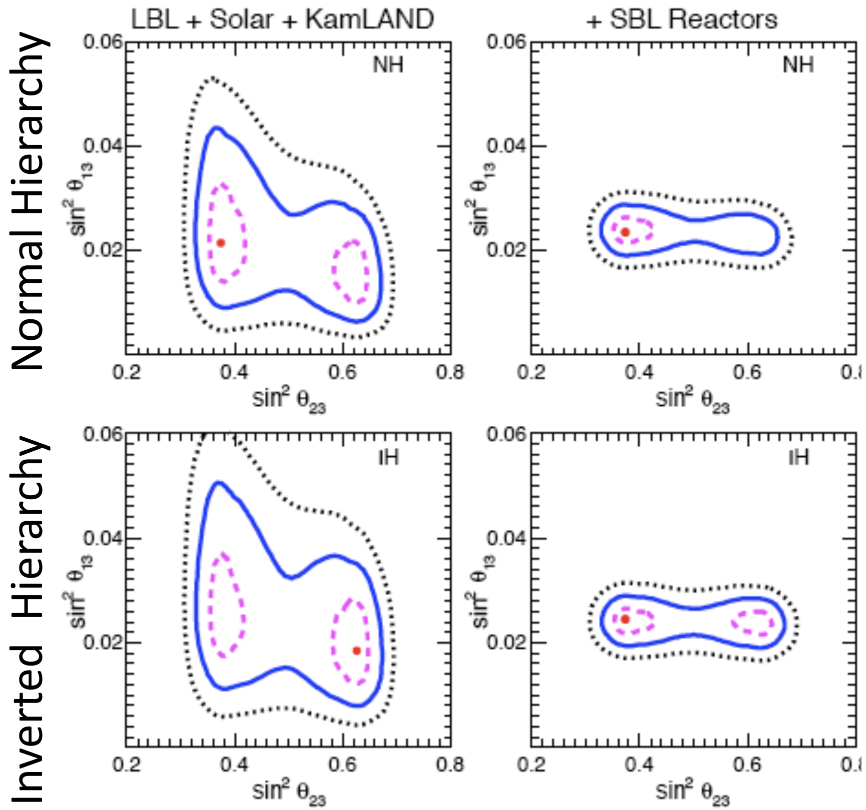
Inverted Hierarchy



LBL experiments anti-correlate θ_{23}-θ_{13}

From Fogli et al. [hep-ph/1205.5254](hep-ph/1205.5254)

Global Fits After Neutrino 2012



LBL experiments anti-correlate θ_{23} -θ_{13}

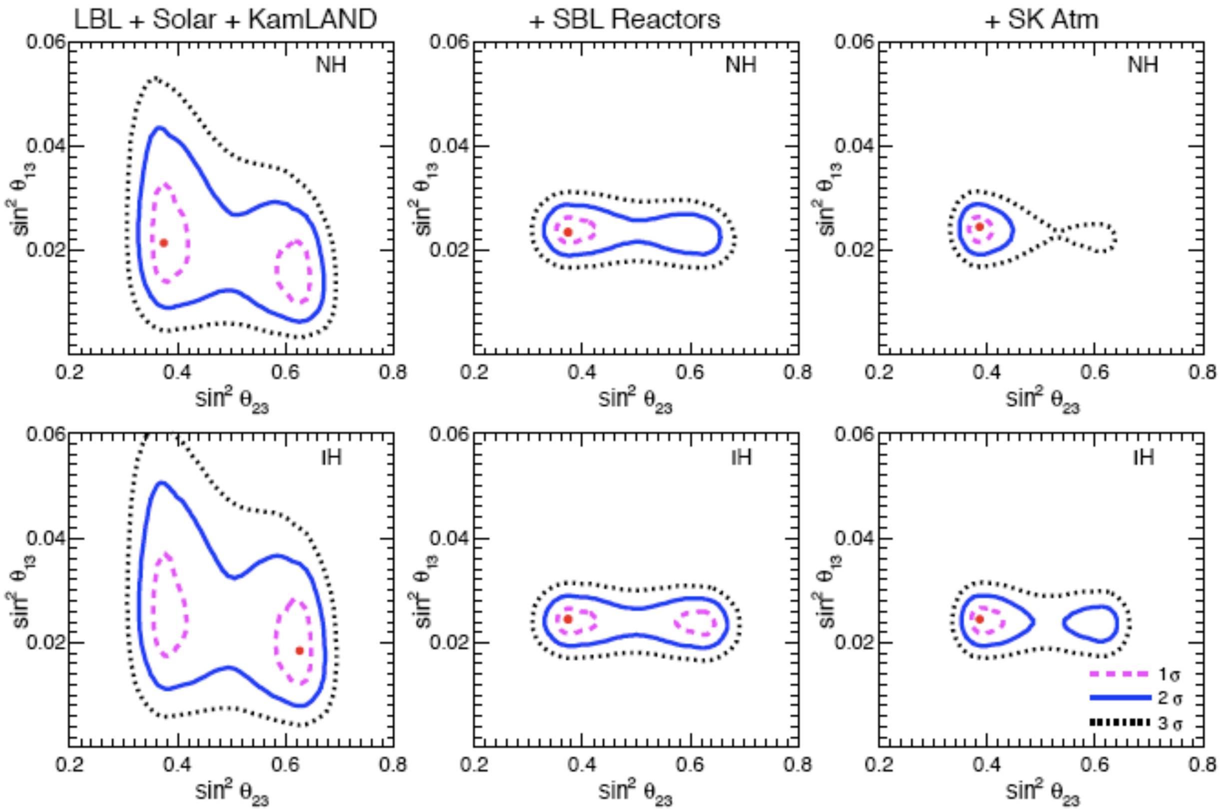
Reactor experiments symmetric in θ_{23} -θ_{13}

From Fogli et al. [hep-ph/1205.5254](hep-ph/1205.5254)

Global Fits After Neutrino 2012

Normal Hierarchy

Inverted Hierarchy



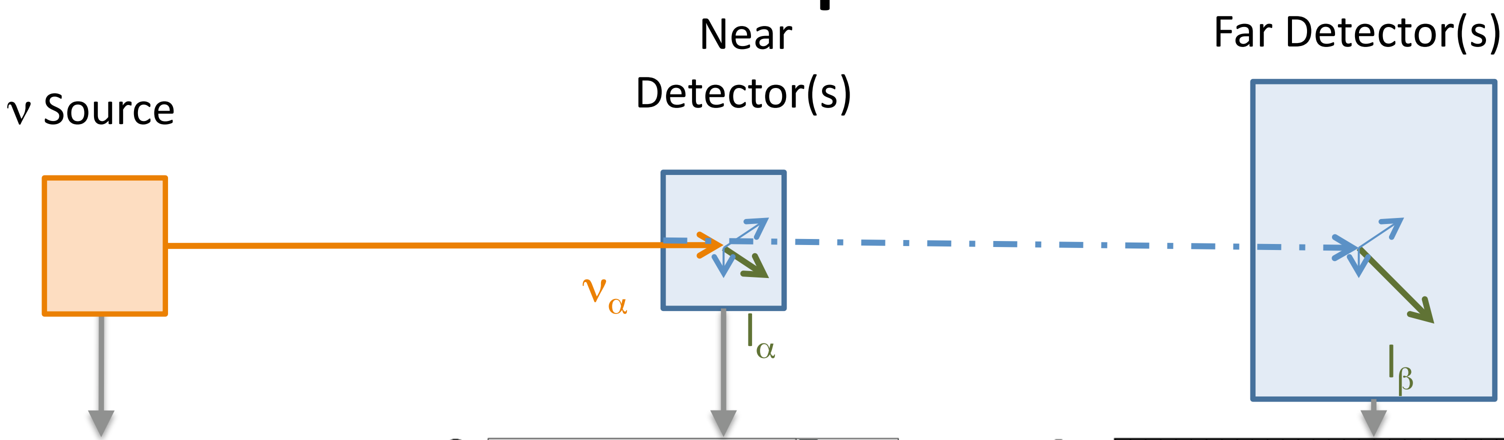
Normal Hierarchy
≤3σ preference

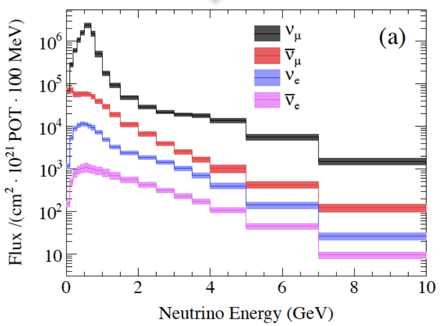
Inverted Hierarchy
≤2σ preference

LBL experiments anti-correlate θ_{23} -θ_{13}	Reactor experiments symmetric in θ_{23} -θ_{13}	Combination yields a hint of preference of first θ_{23} octant

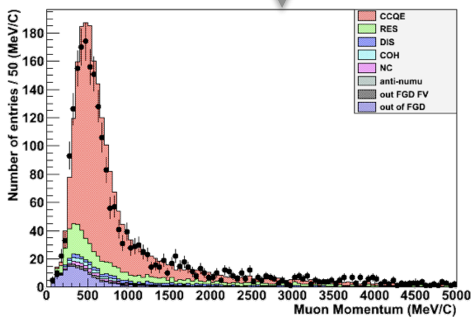
From Fogli et al.
hep-ph/1205.5254

ν Oscillation Experiments

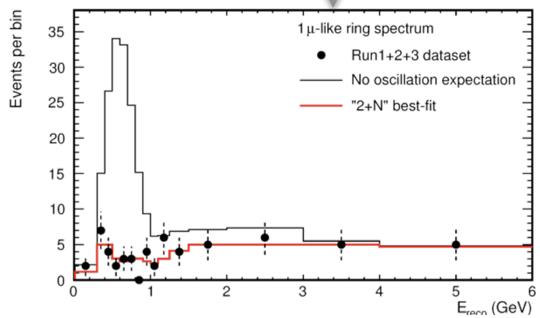




Flux Prediction



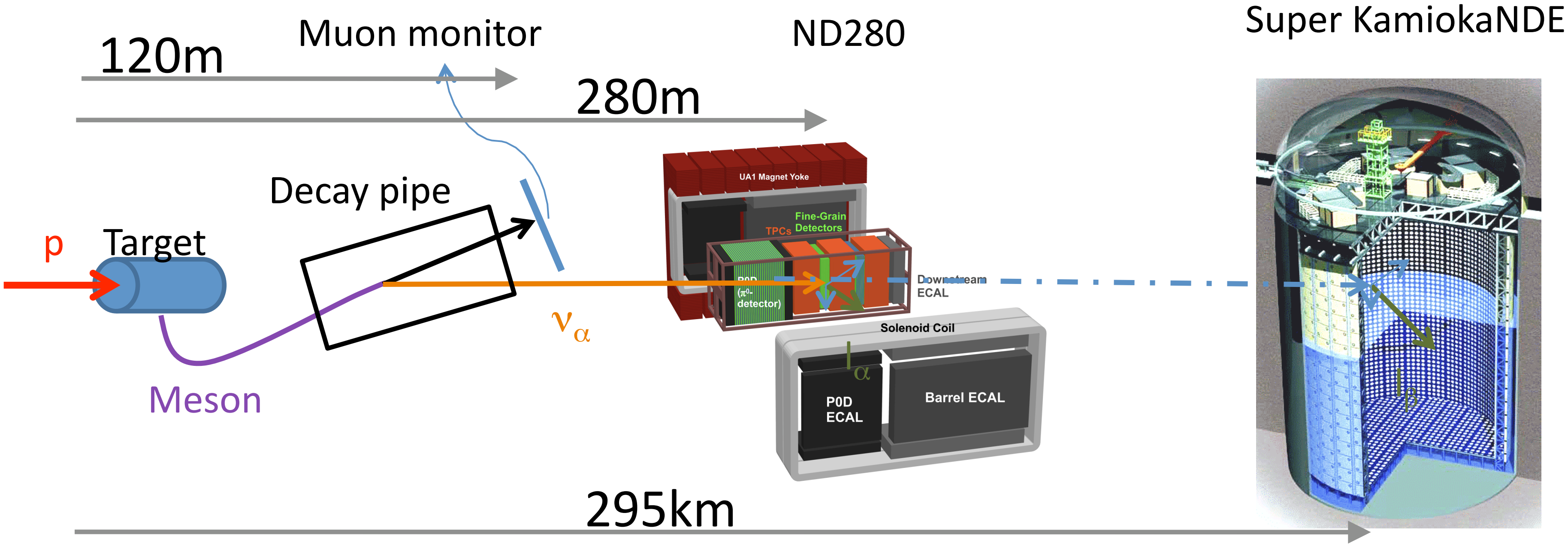
Composition Before Oscillation



Composition After Oscillation

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha i}U^*_{\beta i}\right)\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right)$$
$$+2\sum_{i>j}\Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha i}U^*_{\beta i}\right)\sin\left(\frac{1.27\Delta m^2_{ij}L}{E}\right)$$

T2K; A Long Baseline (LBL) Experiment

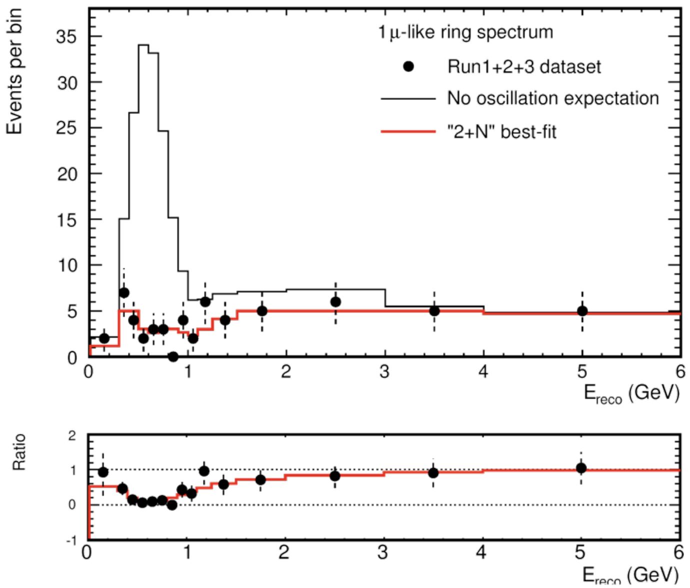


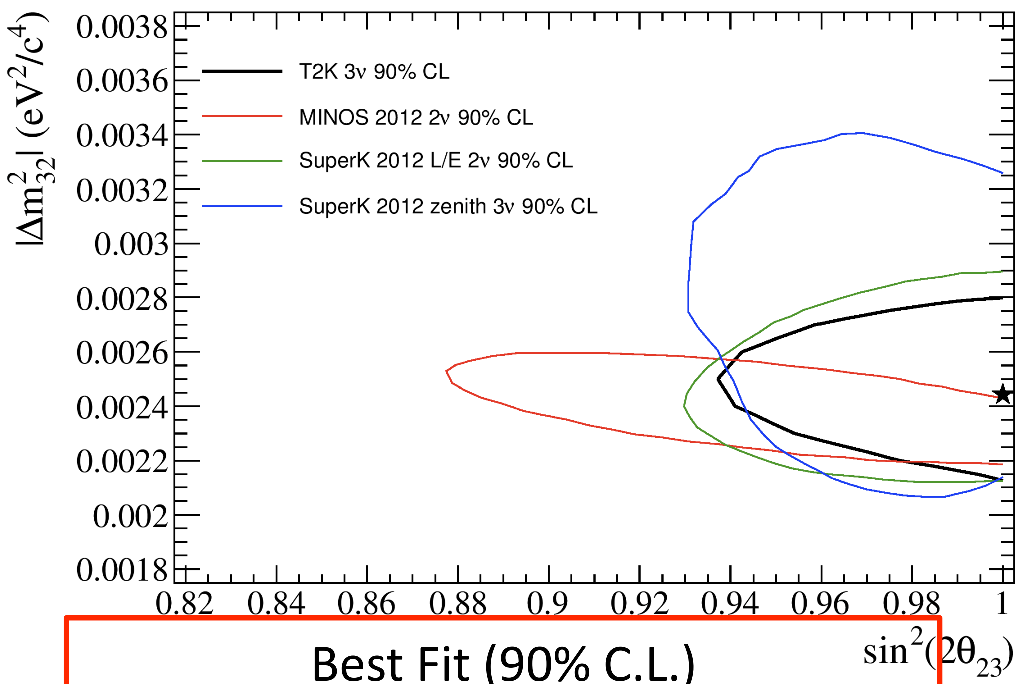
Disappearance: $$P_{\mu\rightarrow\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

Appearance: $$P_{\mu\rightarrow e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

T2K; θ_{23} and Δm^2_{23}

$$P_{\mu\rightarrow\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$





58 Observed Events

205 Expected, No Oscillation

hep-ex/1302.4908

Best Fit (90% C.L.)

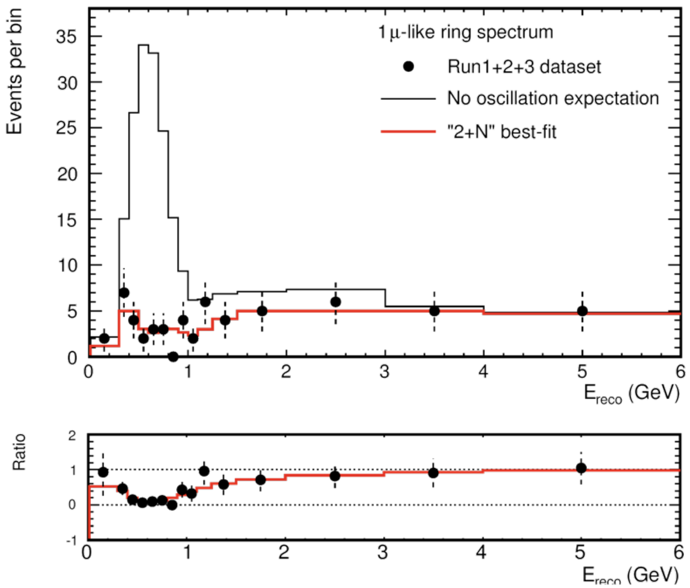
$\sin^2 2\theta_{23} = 1.0\ (\pm\ 0.068)$

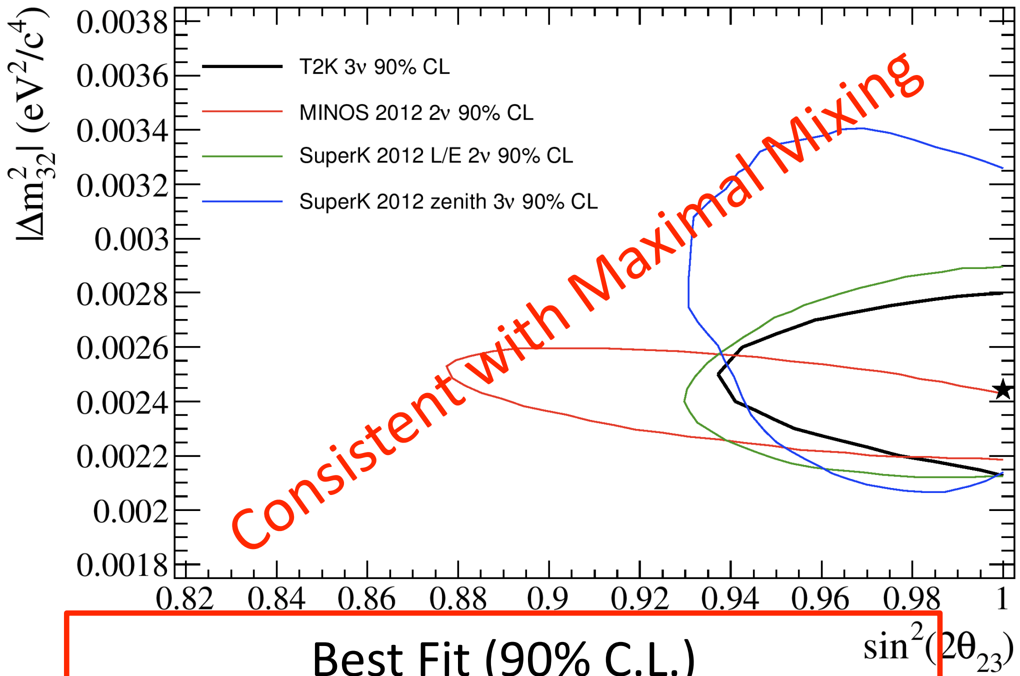
$\Delta m^2_{23} = 2.45\ (\pm\ 0.30)\times 10^{-3}\ eV^2$

T2K; θ_{23} and Δm^2_{23}

NEW

$$P_{\mu\rightarrow\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$





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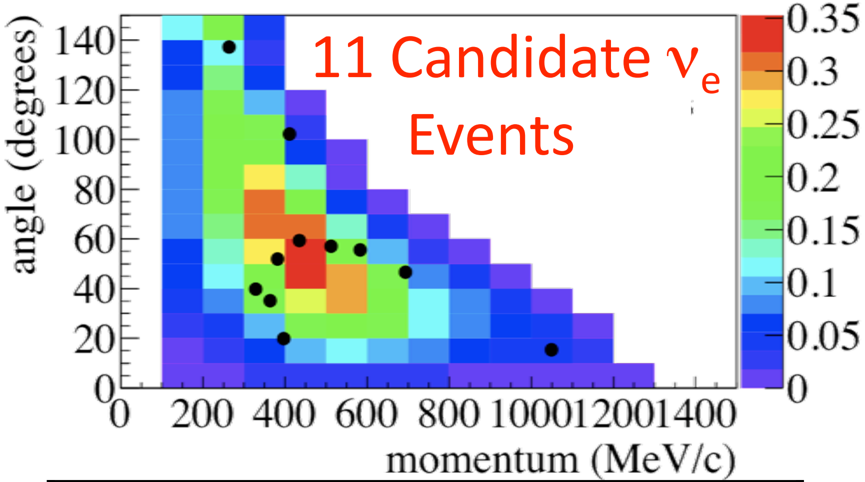
$\sin^2 2\theta_{23}$=1.0 (± 0.068)

Δm^2_{23} = 2.45 (± 0.30)×10^{-3} eV^2

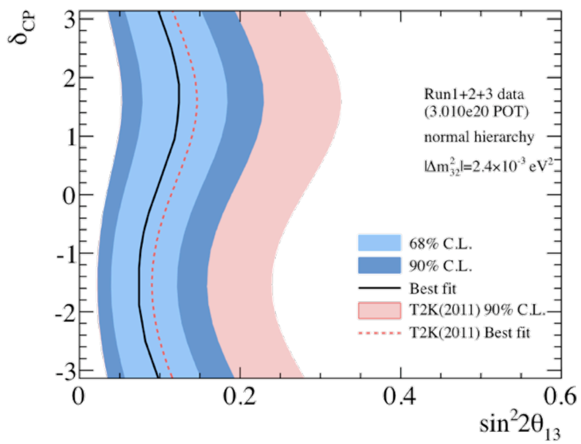
T2K; θ_{13}

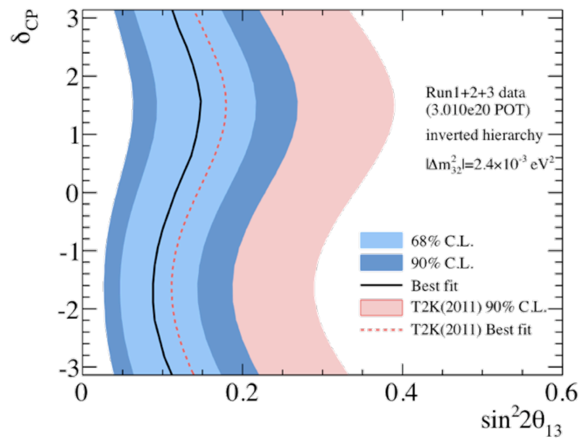
$$P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$



Best Fit w. 1σ Uncertainties	
Normal Hierarchy	0.094 $^{+0.053}_{-0.040}$
Inverted Hierarchy	0.116 $^{+0.063}_{-0.049}$

Update of hep-ex/1106.2822





Daya Bay, RENO, Double Chooz

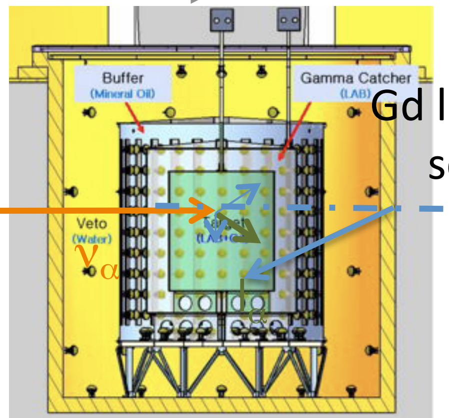
$$P_{e \to e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

Reactor Cores

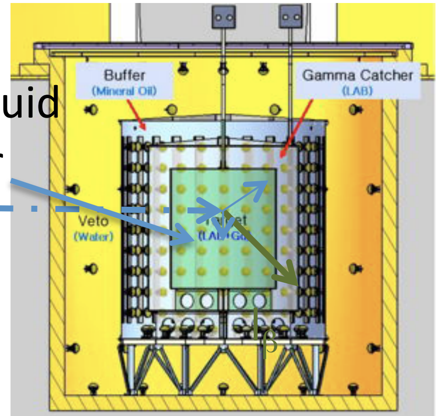
~100m

Near Detector(s)

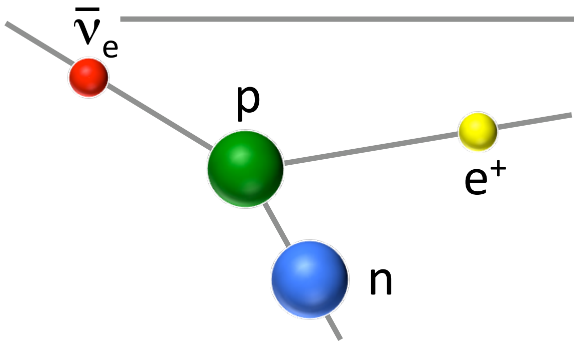
Far Detector(s)



Gd loaded liquid scintillator



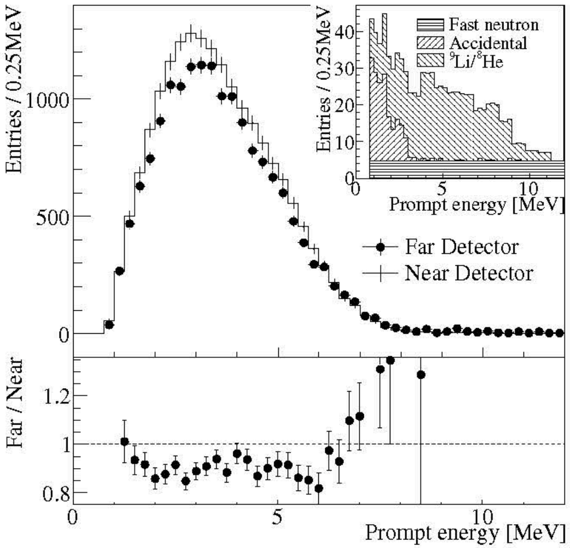
~1km



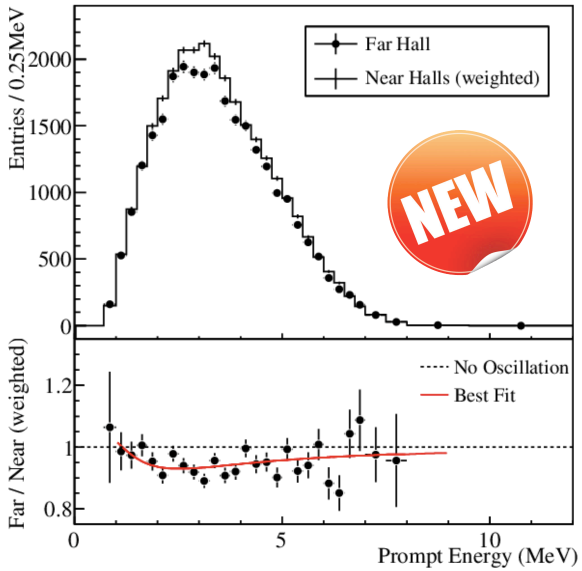
Coincidence signal:

Prompt e+ annihilation E = E_ν – 0.8MeV followed by neutron capture - Gd 28μs, 8MeV /H 180μs, 2.22eV

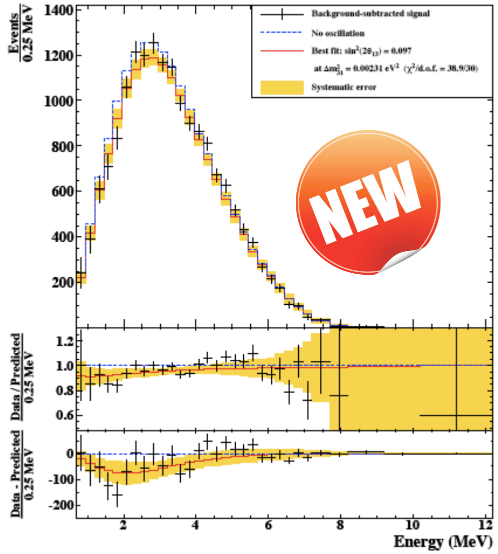
Daya Bay, RENO, Double Chooz



RENO



Daya Bay



Double Chooz

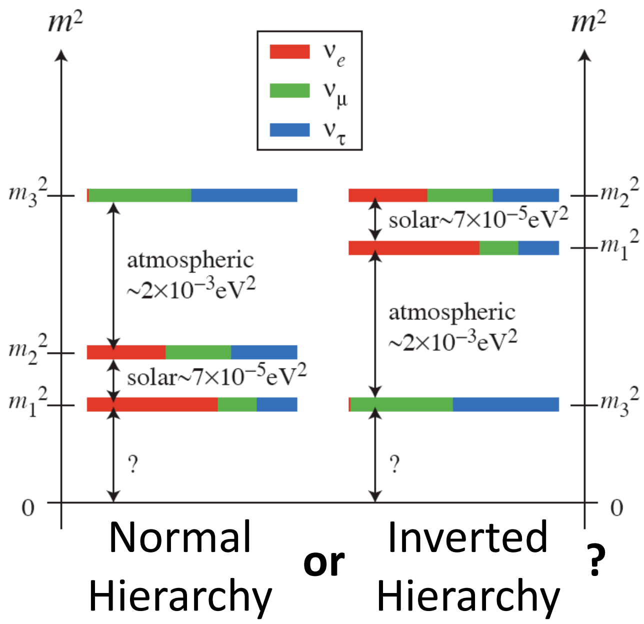
Experiment	$\sin^2 2\theta_{13}$	*stat.*	*syst.*
RENO	0.113	± 0.013	± 0.019
Daya Bay	0.089	± 0.010	± 0.005
Dbl Chooz H	0.097	± 0.034	± 0.034
Dbl Chooz Gd	0.109	± 0.030	± 0.025

Rate Only (RENO, Daya Bay)

Rate + Shape (Dbl Chooz H, Dbl Chooz Gd)

Future LBL - Mass Hierarchy & δ_{CP}

Longer baseline experiments utilise matter effects (Â) to determine MH



$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\hat{\Delta}_{31})$$
$$- \alpha\frac{J_{CP}\sin\delta_{CP}}{\hat{A}(1-\hat{A})}\sin(\hat{\Delta}_{31})\sin(\hat{A}\hat{\Delta}_{31})\sin((1-\hat{A})\hat{\Delta}_{31})$$
$$+ \alpha\frac{J_{CP}\cos\delta_{CP}}{\hat{A}(1-\hat{A})}\cos(\hat{\Delta}_{31})\sin(\hat{A}\hat{\Delta}_{31})\sin((1-\hat{A})\hat{\Delta}_{31})$$
$$+ \alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\hat{\Delta}_{31})$$

$$\hat{\Delta}_{31} = \left(\delta m^2_{31}\right)\frac{L}{4E_\nu} \qquad \hat{A} = \frac{2VE_\nu}{\left(\delta m^2_{31}\right)}$$

Degeneracy between sgn(Δm^2_{23}) and δ_{CP} broken in comparison of

$P\left(\nu_\mu \to \nu_e\right)$ and $P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$

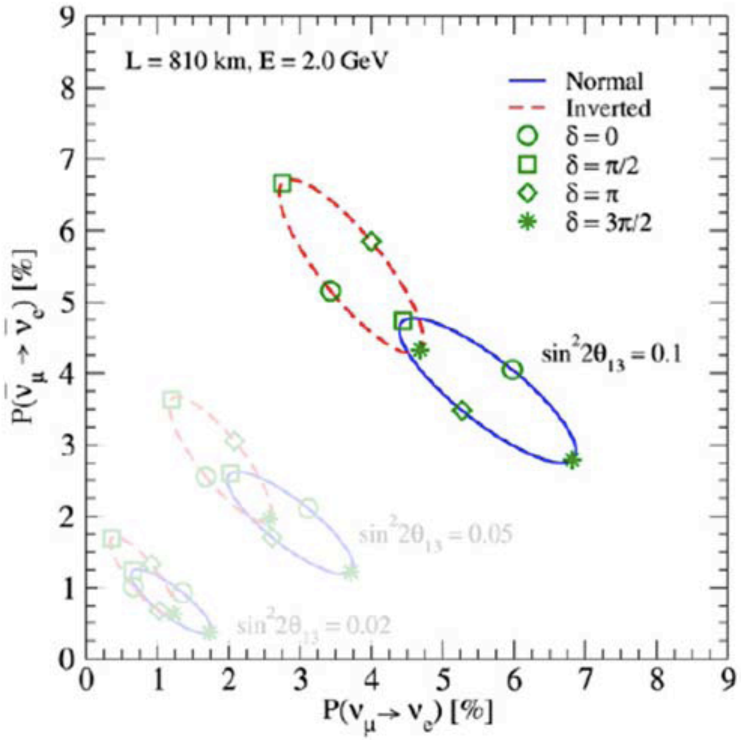
Near Future LBL; NOνA

Baseline, L = 810km

$<E_\nu>$ = 2GeV

Near (Far) Detector

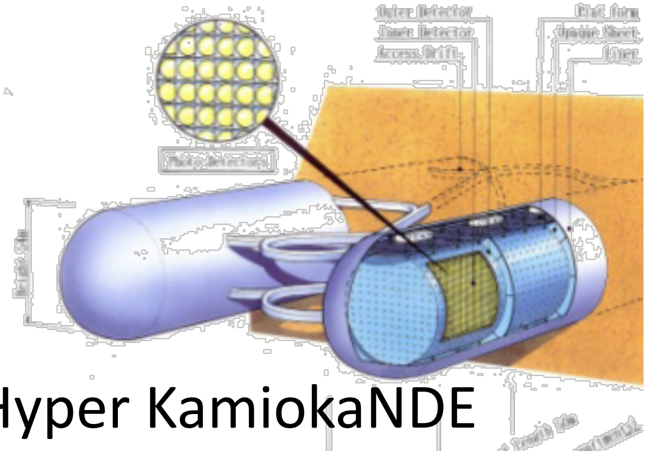
0.3 (14) kT Liquid Scint.



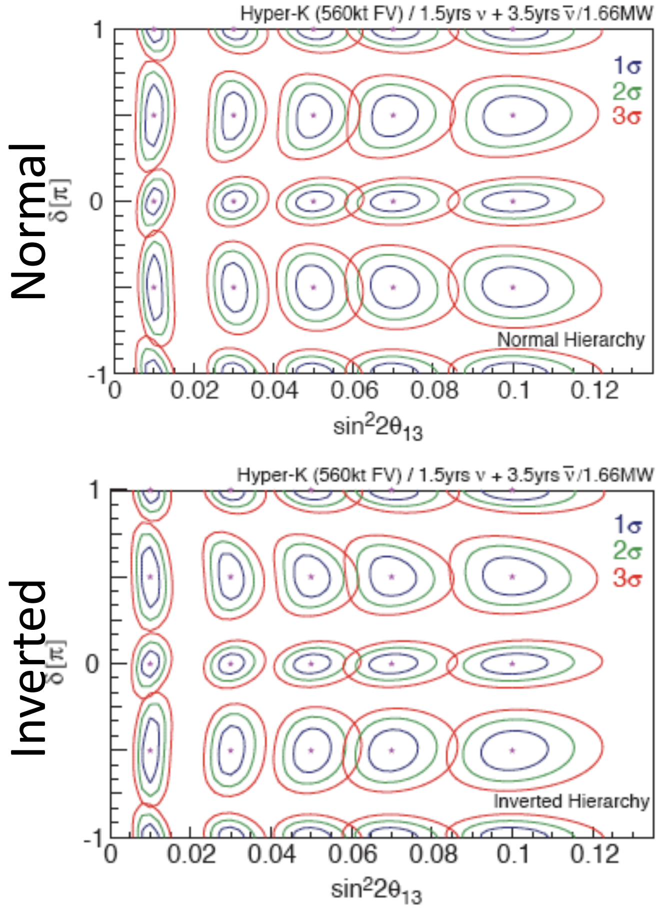
- Detectors in construction
- NUMI beam re-starts May 2013 @ 700 kW (6 months ramp-up)

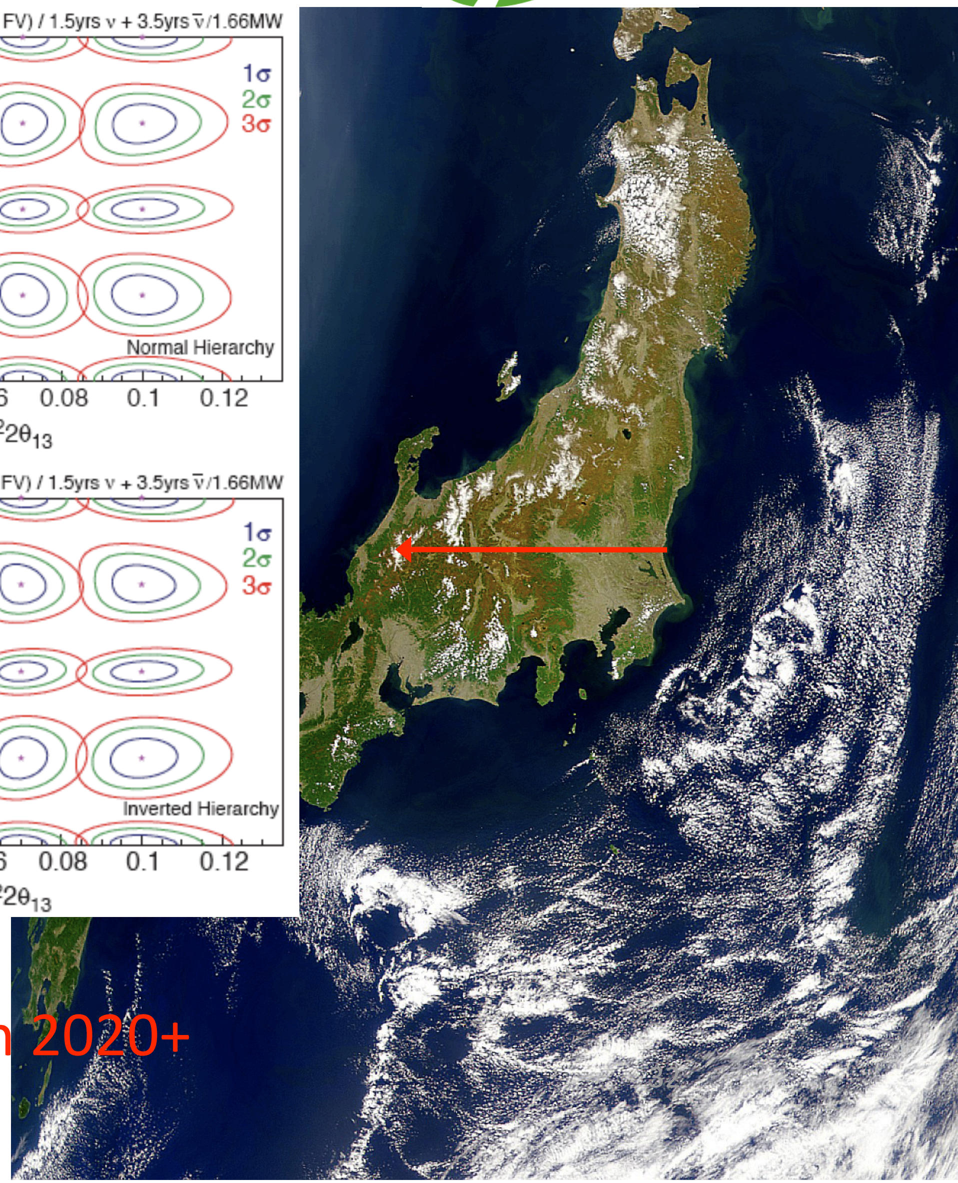
Future LBL; J-PARC

Upgrade of T2K
Baseline, L = 295 km
<E_ν> = 0.5 GeV
Far Detector
990 kT Water.



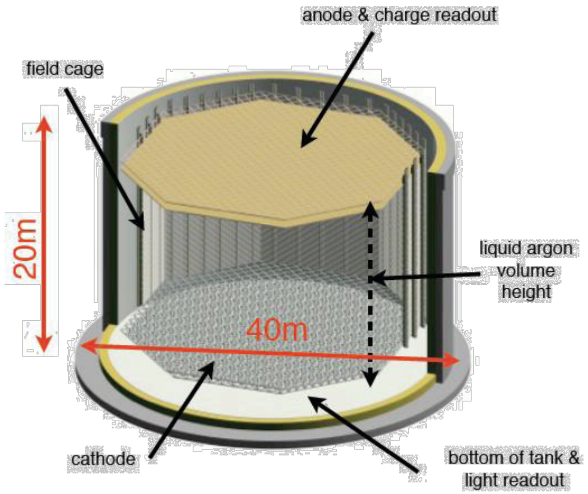
Hyper KamiokaNDE
hep-ex/1109.3262v1



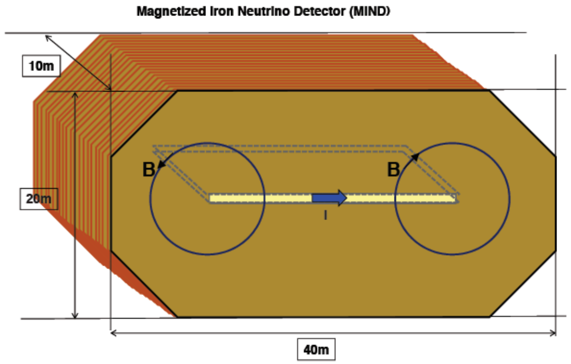


Operation 2020+

Future LBL; LAGUNA-LBNO



20 kt double-phase LAr
LEM TPC (GLACIER)



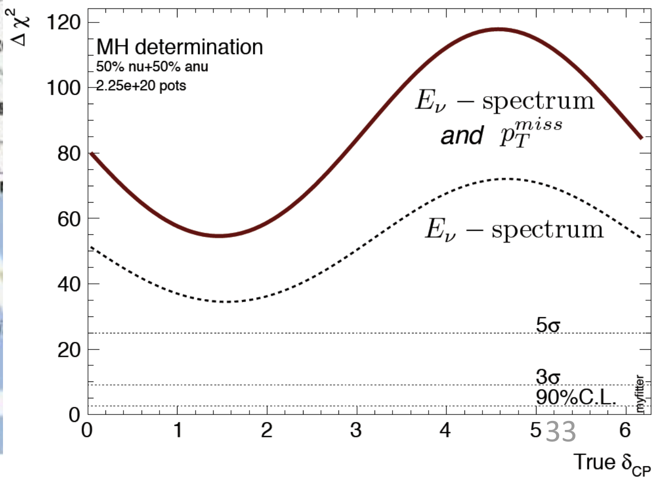
35kt magnetised muon
detector (MIND)

CERN-SPSC-2012-021

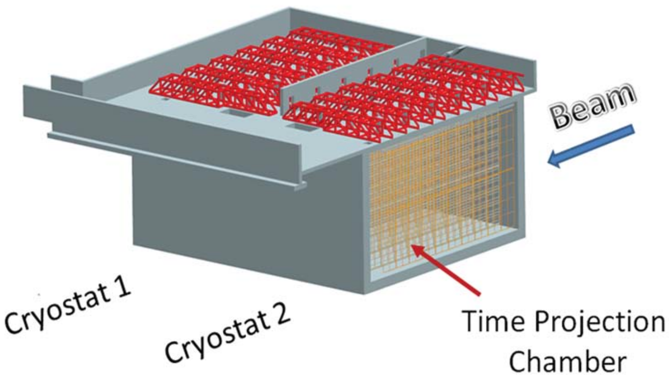
CERN -> Pyhäsalmi
Baseline, L = 2300 km
$\langle E_\nu \rangle$ = 5 GeV

Protvino -> Pyhäsalmi
Baseline, L = 1160 km
$\langle E_\nu \rangle$ = 2.5 GeV

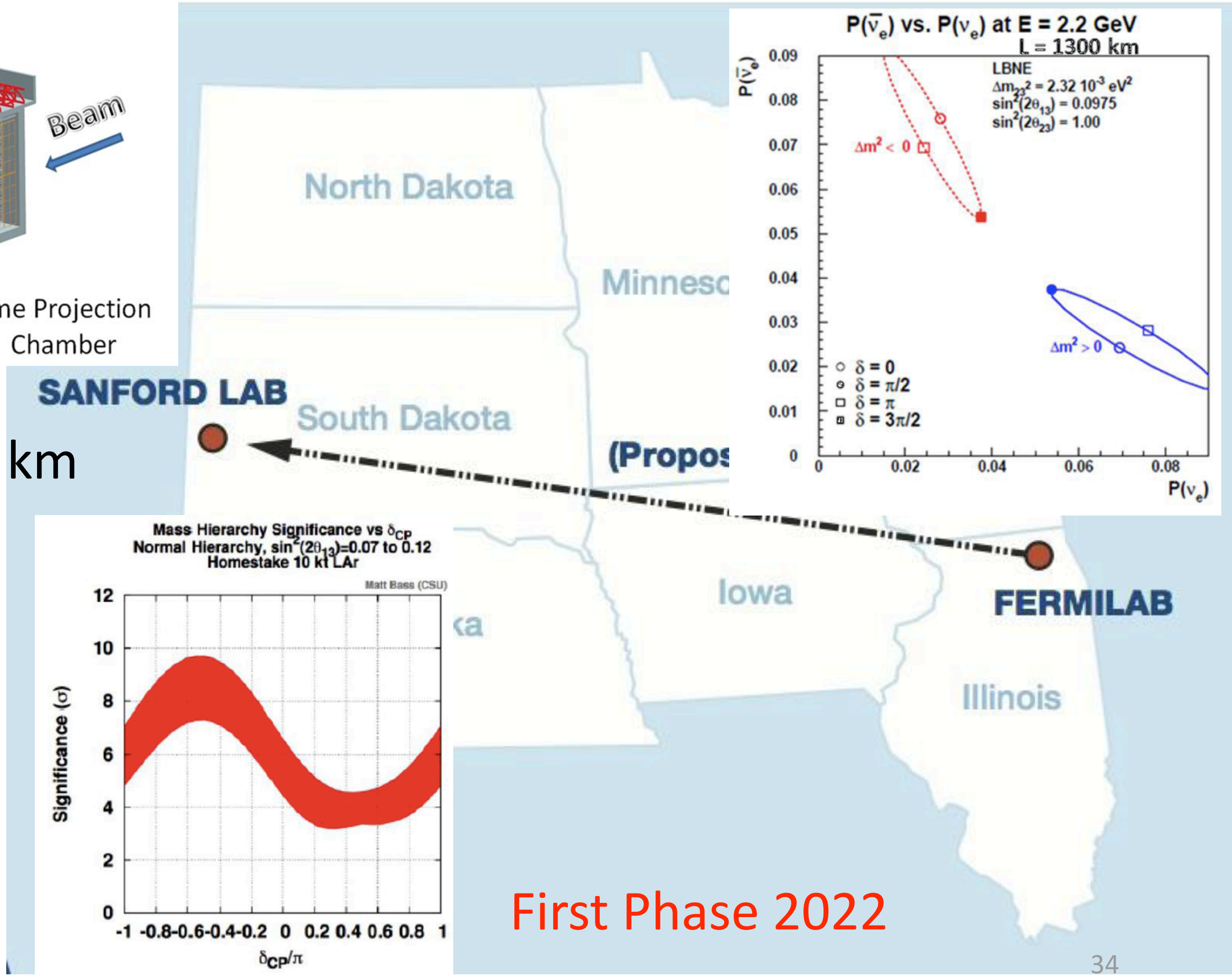
Operation 2023?



Future LBL; LBNE



Baseline, L = 1300 km
$\langle E_\nu \rangle$ = 2.2 GeV
Far Detector
10 kTLAr TPC

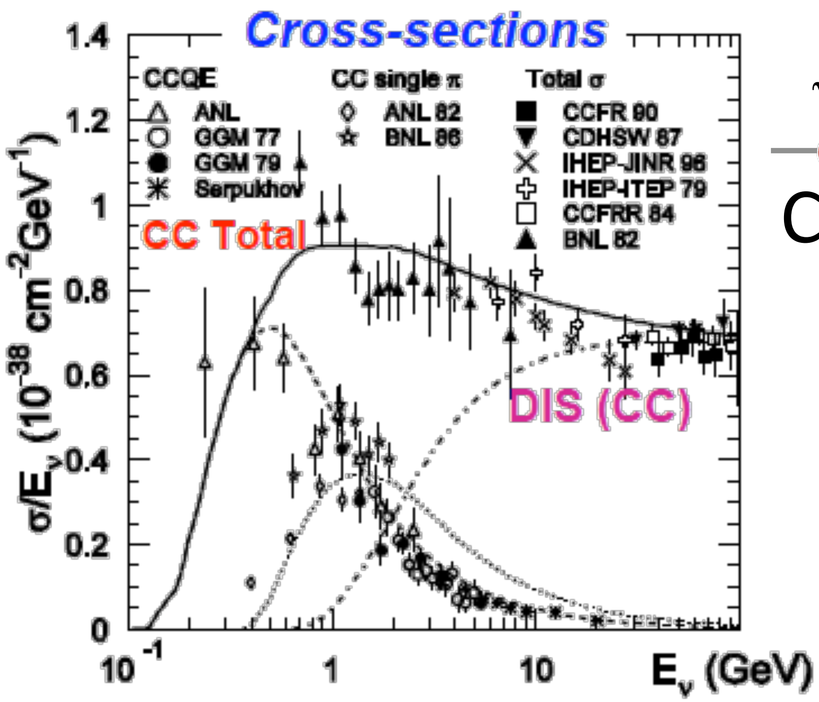


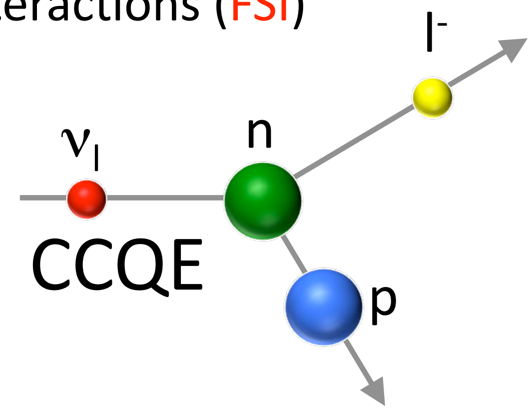
First Phase 2022

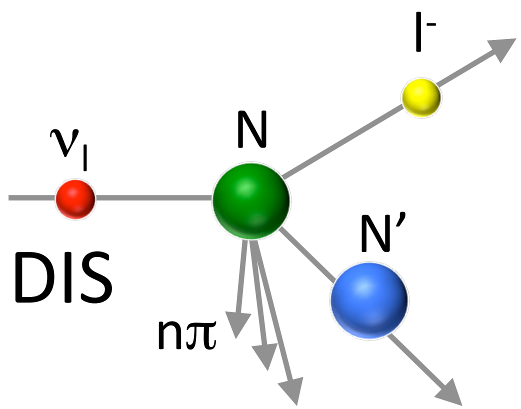
Neutrino-Nucleon Cross Sections

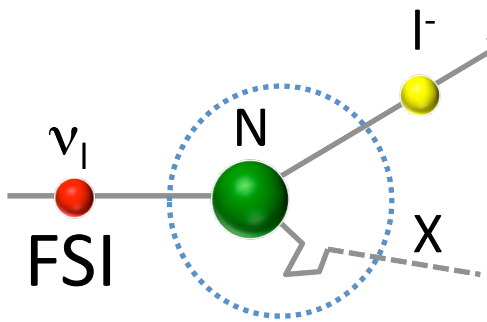
Different detector materials require knowledge of absolute neutrino cross sections.

- High Energy – Deep Inelastic Scattering (DIS) interactions dominate
- Low Energy – Charged Current Quasi Elastic (CCQE) interactions dominate.
- At all Energies – Final State Interactions (FSI)



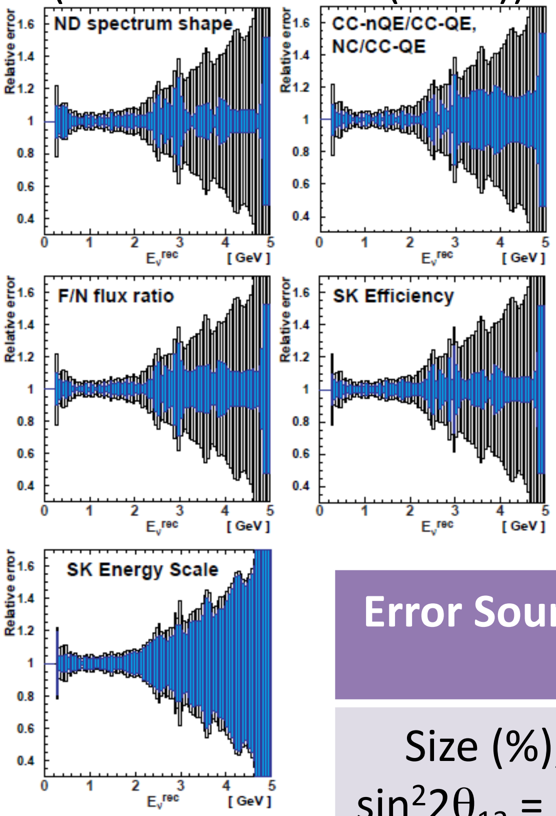






Neutrino-Nucleon Cross Sections Errors

K2K ν_μ disappearance (PRD 74: 072003 (2006))



MINOS (PRL 106:181801 (2011))

Source of systematic uncertainty	$\delta(\Delta m^2)$ $(10^{-3}\,\mathrm{eV}^2)$	$\delta(\sin^2(2\theta))$
(a) Hadronic energy	0.051	< 0.001
(b) μ energy (range 2%, curv. 3%)	0.047	0.001
(c) Relative normalization (1.6%)	0.042	< 0.001
(d) NC contamination (20%)	0.005	0.009
(e) Relative hadronic energy (2.2%)	0.006	0.004
(f) $\sigma_\nu(E_\nu < 10$ GeV)	0.020	0.007
(g) Beam flux	0.011	0.001
(h) Neutrino-antineutrino separation	0.002	0.002
(i) Partially reconstructed events	0.004	0.003
Total systematic uncertainty	0.085	0.013
Expected statistical uncertainty	0.124	0.060

T2K ν_e appearance (PRL 107:041801 (2011))

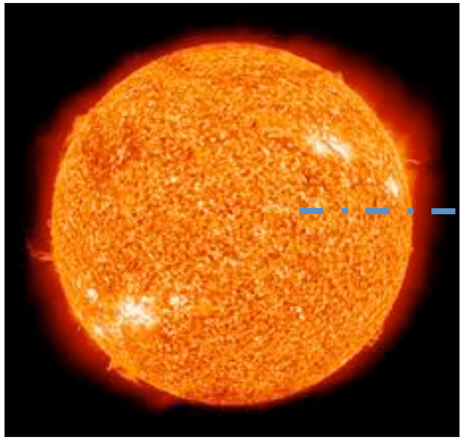
Error Source	Flux	Near Detector	Near Detector Stats.	Xsec	SK	Total
Size (%); $\sin^2 2\theta_{13} = 0.1$	8.5	+5.6/-5.2	2.7	**10.5**	9.4	+17.6/-17.5

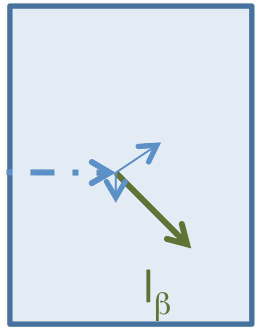
T2K, MINERνA, LBNE, LBNO & νStorm (ν_e) are examples of current and future experiments that will improve understanding of ν cross sections

Summary

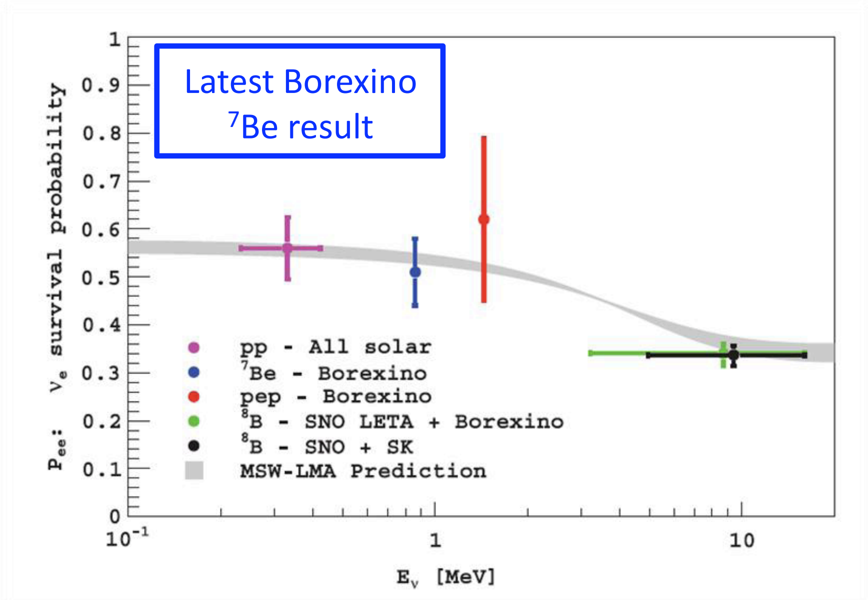
- θ_{13} is large! So measurement of lepton CP-violation might be possible in the near future.
- There are still other open questions.
- Next generation of experiments in combination will answer these questions.
- We need a greater understanding of neutrino cross-sections to achieve these goals.
- Exciting time to be in neutrino physics!

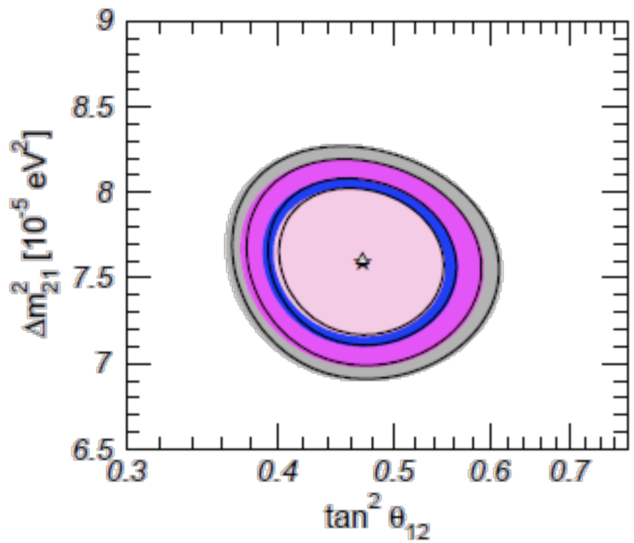
Solar ν's





Best Fit w. 1σ Uncertainties	
Δm^2_{12}=	7.50 ± 0.2 x 10^{-5}eV
$\sin^2 2\theta_{12}$ =	0.86 ± 0.02



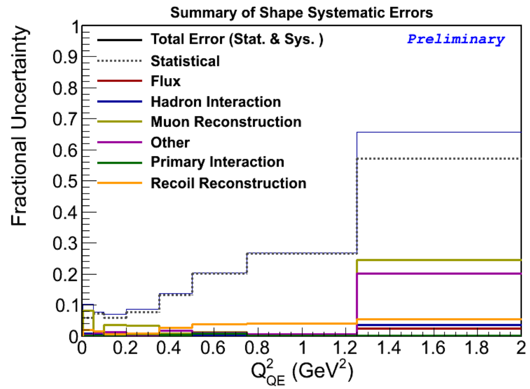


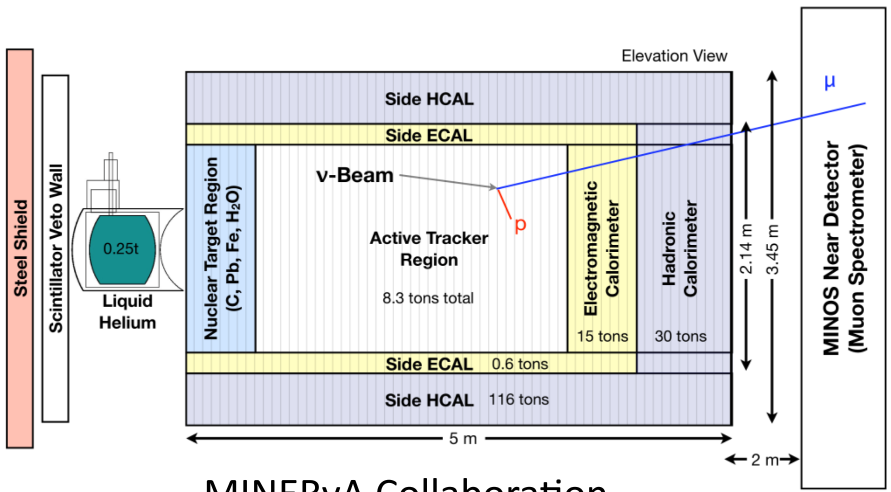
Some Current Cross Section Experiments

Plenty of experiments will help increase our understanding now and in the near future:

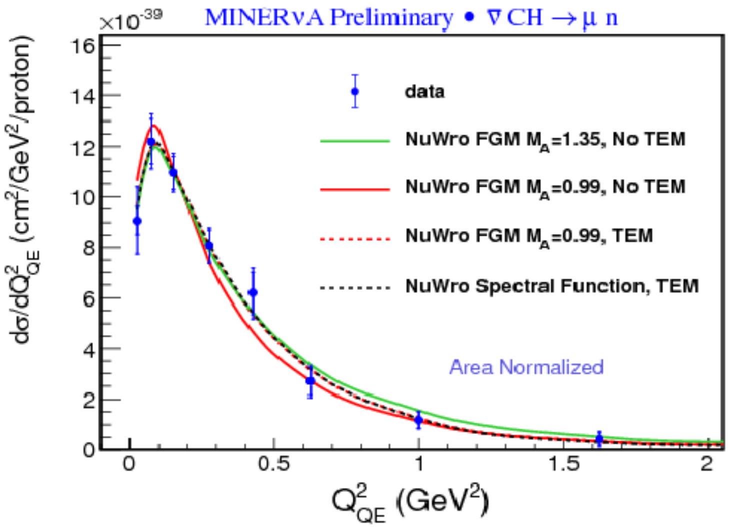
- T2K
- MiniBooNE
- SciBooNE
- ArgoNeuT
- MINERνA*

} Currently taking data





MINERvA Collaboration



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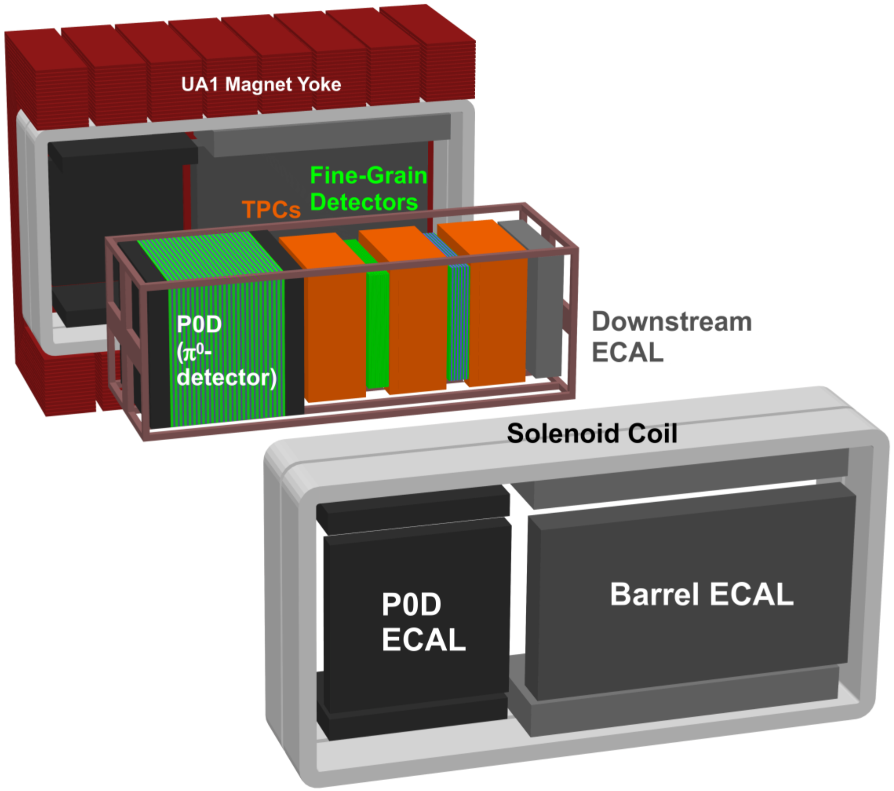

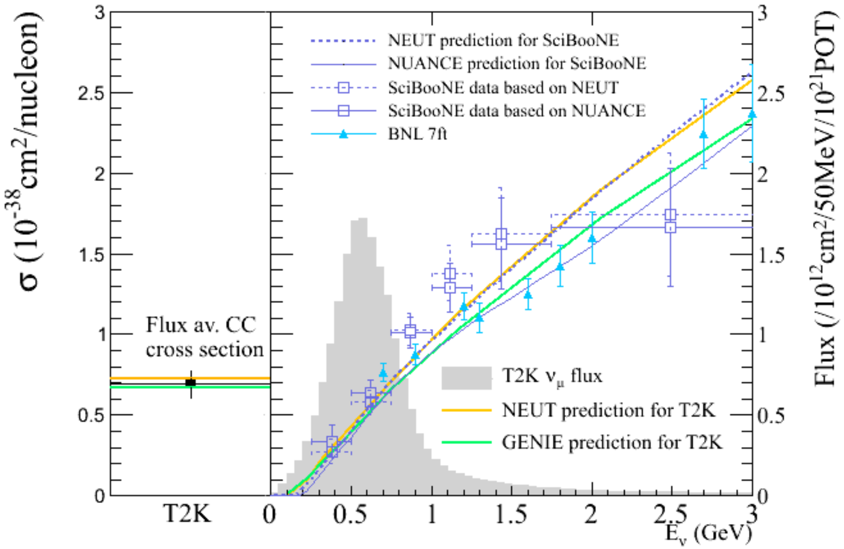

A. Weber, NuInt2012

Status of Oscillation Parameters