JINR neutrino programme. Daya Bay and JUNO: precision measurements with reactor neutrinos

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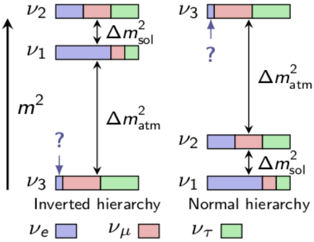
January 16, 2017

1 Neutrino physics and DLNP neutrino programme

2 Daya Bay

3 JUNO

Neutrino mixing



Weak and mass eigenstates differ:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}|\nu_i\rangle$$

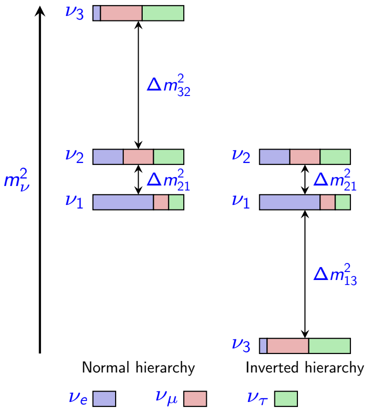
α – flavor states

i – mass states

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

- $\theta_{23} \approx 45^\circ$ established through atmospheric and accelerator experiments: possibly maximal.
- $\theta_{12} \approx 12^\circ$ established through solar experiments and KamLAND: large but not maximal.
- $\theta_{13} \approx 8^\circ$ established by reactor and accelerator experiments: **Daya Bay**, RENO, Double CHOOZ, T2K and MINOS.

Neutrino mass



Mixing parametrized by three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$.

Neutrino mass

- Neutrinos are massive
- Neutrino mass has not been measured
- $\sum m_\nu \lesssim 1\,\text{eV}$ (cosmology)
- $m_e < 2.2\,\text{eV}$ (direct)
- $\langle m_{\beta\beta} \rangle < 0.25\,\text{eV}$ ($0\nu\beta\beta$)

Mass splitting

From oscillation experiments:

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\,\text{eV}^2$
- $\left|\Delta m^2_{32}\right| = (2.42 \pm 0.06) \times 10^{-3}\,\text{eV}^2$
- $\left|\Delta m^2_{32}\right| / \Delta m^2_{21} \sim 32$

Mass hierarchy

Which neutrino is the lightest one: ν_1 or ν_3?

Open neutrino questions

- Lightest neutrino mass.
- Neutrino mass hierarchy (MH)?
- Is there CP-violation? δ_{CP} value? $\hookrightarrow$ probably maximal, $\delta_{CP} \sim 3\pi/4$.
- θ_{23} octant? $\hookrightarrow$ probably, non-maximal.
- Dirac or Majorana? $0\nu\beta\beta$?
- Unitarity of neutrino mixing matrix? Sterile neutrinos?
- Non-standard interactions (NSI)? Lorentz violation?
- Origin of UHE neutrinos.
- Relic neutrinos.
- Diffuse Supernova neutrinos.
- Solar CNO neutrinos.
- Others...

DLNP neutrino program.

$0\nu\beta\beta$: Dirac or Majorana?

- SuperNEMO
- GERDA

Astrophysical, atmospheric, solar and geo- neutrinos

- BAIKAL GVD: Astrophysical and atmospheric neutrino. θ_{23}, Δm^2_{32}. Rich potential.
- BOREXINO: Solar, geo-neutrino, matter effects, θ_{12}, Δm^2_{21}, rare processes.

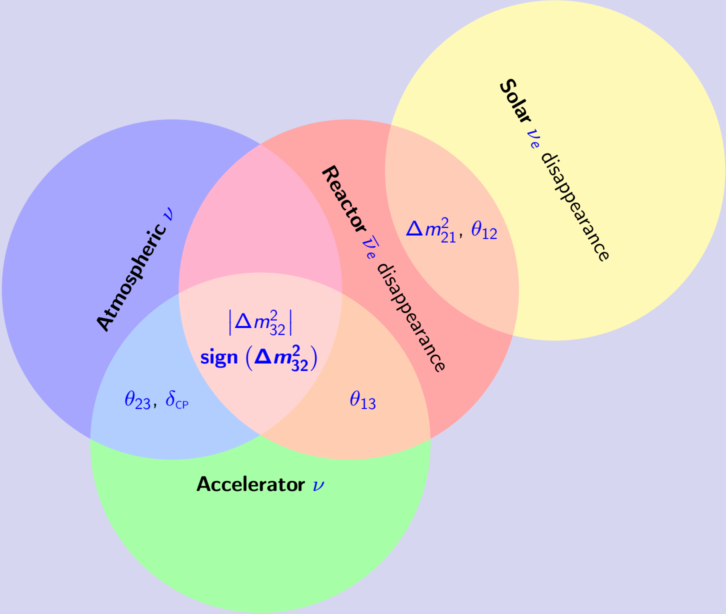
Accelerator (anti)neutrinos

- NOνA: Neutrino mass hierarchy. Δm^2_{32}, θ_{23}.
- OPERA: ν_τ appearance. θ_{23}, Δm^2_{32}.

Reactor and β-decay antineutrinos

- DANSS: Sterile neutrino, reactor antineutrino spectrum, reactor monitoring.
- GEMMA-2: μ_ν anomalous neutrino magnetic moment.
- νGEN: Coherent Neutrino Germanium Nucleus Elastic Scattering.
- SOX (post BOREXINO): Radioactive source. Sterile neutrino search.
- **Daya Bay**: θ_{13}, Δm^2_{32}, sterile neutrino, reactor flux measurement.
- **JUNO**: Mass hierarchy, precise θ_{12}, Δm^2_{21}, Δm^2_{32}; SN neutrinos, geo-neutrinos.

Neutrino oscillations experiments complementarity



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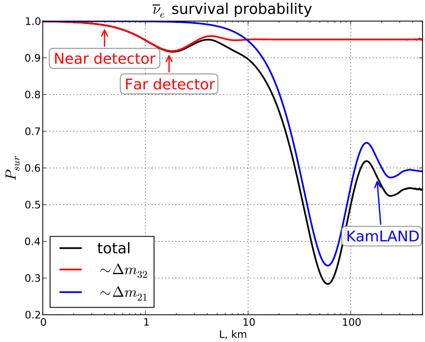
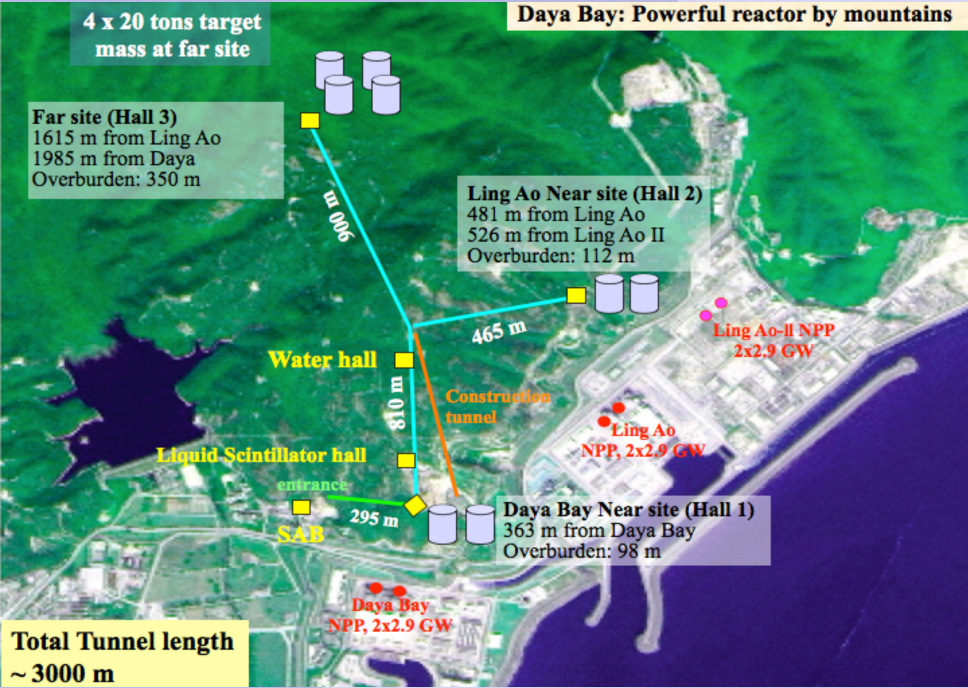
Reactor electron anti-neutrino disappearance



$$1 - P_{\nu_e \to \nu_e} \approx \underline{\sin^2 2\theta_{13}} \sin^2 \Delta_{32} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

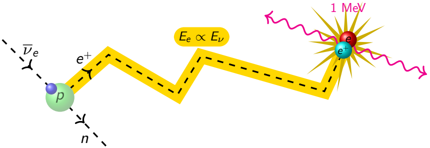
$$\Delta_{jk} = 1267 \cdot \frac{\Delta m^2_{jk}}{\text{eV}^2} \frac{L}{E} \left[\frac{\text{MeV}}{\text{km}}\right]$$

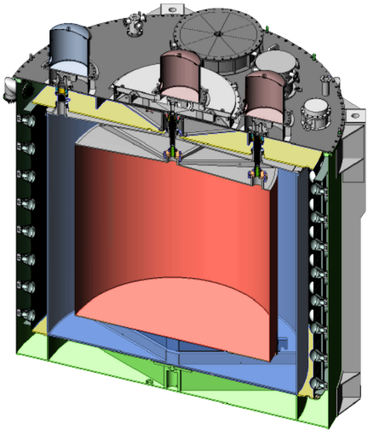
Daya Bay: Powerful reactor by mountains



Antineutrino detection

3-zone antineutrino detector (AD):		
Inner zone	20 t	Gd-doped LS
Middle zone	20 t	LS
Outer zone	40 t	Mineral oil





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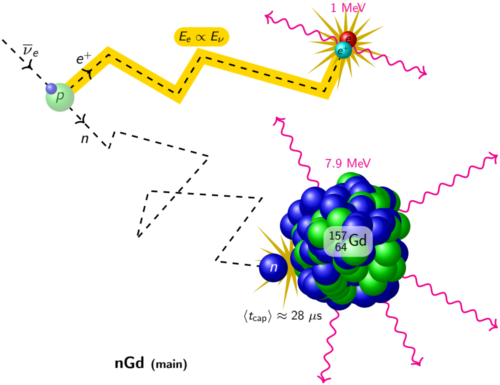
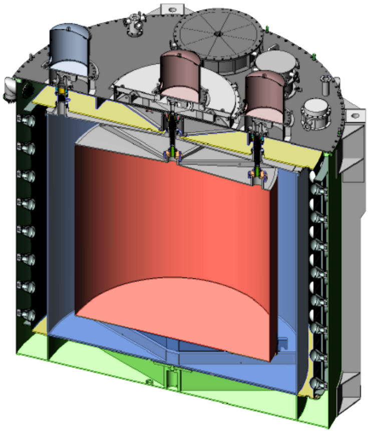


nGd (main)



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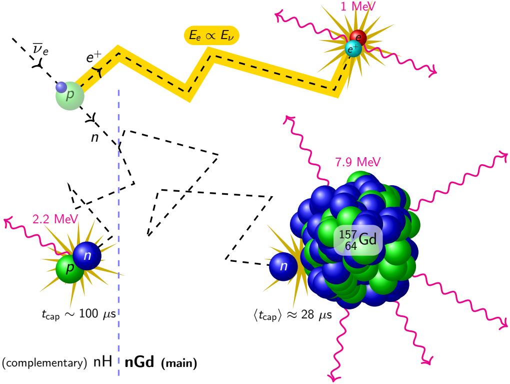
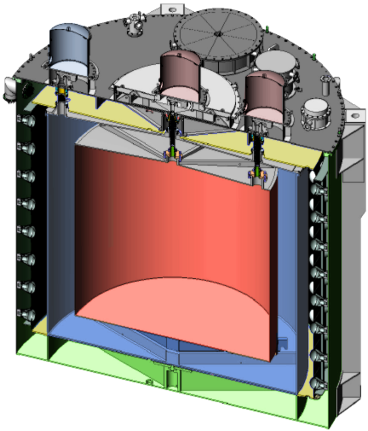


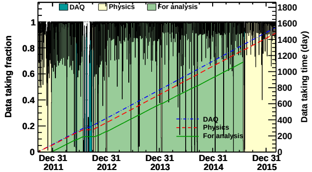


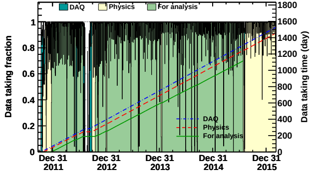
Data periods and publications

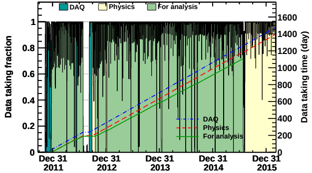
Days	Events (nGd)	nGd	nH
90			
50	~90k	PRL[1203.1669]	
126	>200k	CPC[1210.6327]	
217	>300k	PRL[1310.6732]	PRD[1406.6468]
621	>1M	PRL[1505.03456]	*PRD[1603.03549]
1230	>2.5M	*PRD[1610.04802]	

Days	Sterile	Reactor	Wave packets
217	PRL[1407.7259]	PRL[1508.04233]	
621	PRL[1607.01174] PRL[1607.01177]	*CPC[1607.05378]	*PLB[1608.01661]

- 2AD comparison NIM[1202.6181]
- Muon system NIM[1407.0275]
- Detector NIM[1508.03943]

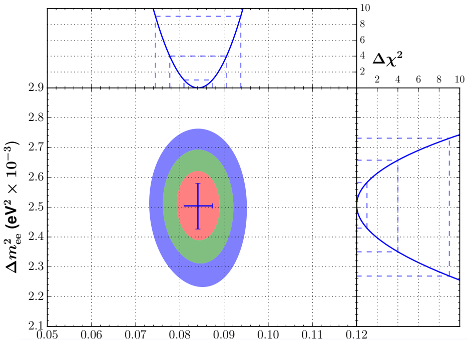


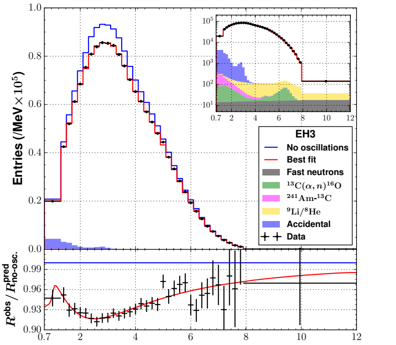




Daya Bay oscillation result

1230 days, arXiv:1610.04802, PRD





$$\sin^2 2\theta_{13} = 8.41 \pm 0.27 \text{ (stat)} \pm 0.19 \text{ (syst)} \qquad \times 10^{-2}$$

$$|\Delta m^2_{ee}| = 2.50 \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (syst)} \qquad \times 10^{-3} \text{ eV}^2$$

$$\chi^2/\text{NDF} = 234.7/263$$

Assuming specific mass hierarchy $|\Delta m^2_{ee}|$ is translated to:

Normal: $|\Delta m^2_{32}| = 2.45 \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (syst)} \qquad \times 10^{-3} \text{ eV}^2$

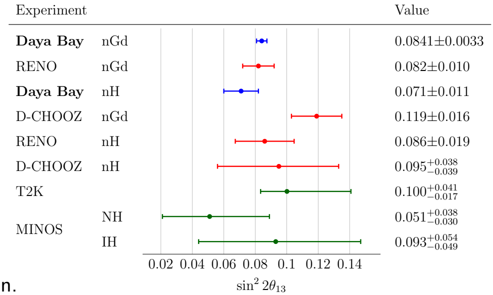
Inverted: $|\Delta m^2_{32}| = 2.56 \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (syst)} \qquad \times 10^{-3} \text{ eV}^2$

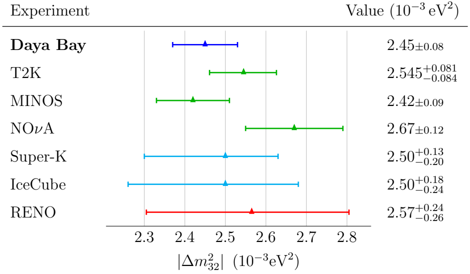
Daya Bay oscillation result

nH, 621 days, arXiv:1603.03549, PRD

nGd, 1230 days, arXiv:1610.04802, PRD

- Most precise $\sin^2 2\theta_{13}$ measurement.
- The non-zero value is excluded at $> 25\sigma$.
- nH $\sin^2 2\theta_{13}$ measurement is world's third in precision.
- Most precise measurement of $\Delta m^2_{ee}/\Delta m^2_{32}$.
- Negligible correlation between $\sin^2 2\theta_{13}$ and Δm^2_{ee}.





Summary

- ✓ Absolute reactor antineutrino flux measurement: $\sim 5\%$ deficit.
- ✓ Reactor antineutrino spectrum shape measurement:
  significant spectral distortion around $5 - 6$ MeV.
- ✓ Stringent limits for sterile neutrinos for $2 \cdot 10^{-4}\ \mathrm{eV}^2 < \Delta m^2_{41} \lesssim 2\ \mathrm{eV}^2$.
- ✓ First experimental constraint on neutrino wave-packet size:
  $\sigma_x > 10^{-11}$ cm at 95% C.L.

- In SuperNova Early Warning System since end of 2014.
- **More physics analyses under preparation:**
  - Lorentz/CPT invariance
  - Muon modulation
  - Neutron yield
  - Combined analysis with RENO and Double-CHOOZ experiments.
  - Others...
- **stay tuned...**

New publications:
1603.03549 PRD
1607.01174 PRL
1607.01177 PRL
1607.05378 CPC
1608.01661 EPJC
1610.04802 PRD

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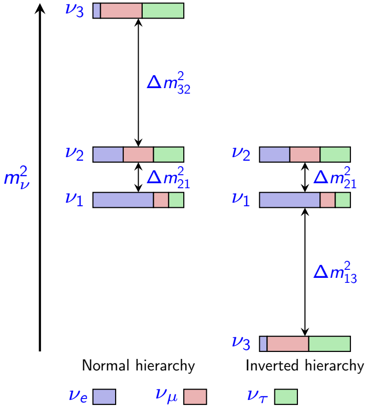
Neutrino mass



Mixing parametrized by three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$.

Neutrino mass

- Neutrinos are massive
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Mass hierarchy

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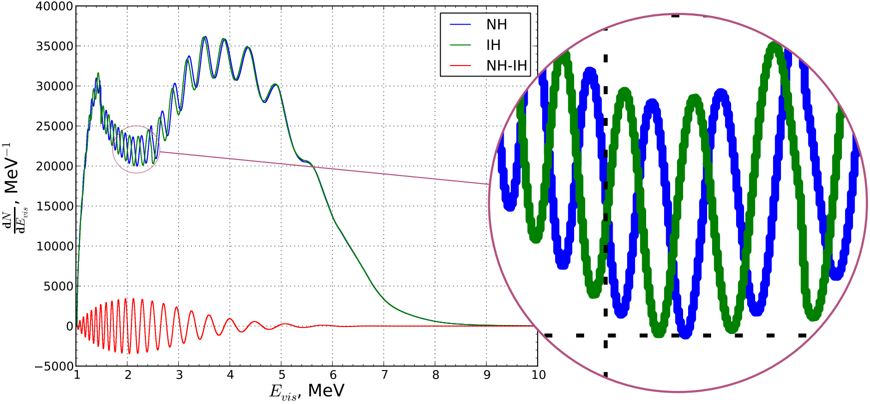
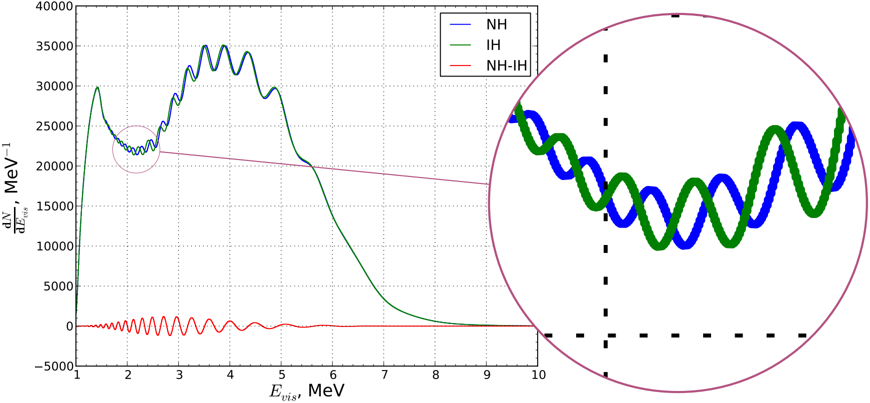
Neutrino mass hierarchy on reactor experiments



- Picture: ideal energy resolution.
- Unique oscillation panorama at 53 km: $\sim$ 20 oscillation cycles.
- $< 1\%$ precision on θ_{12}, Δm^2_{21}, Δm^2_{32}.
- Required energy resolution $\lesssim 3\%$.

Neutrino mass hierarchy on reactor experiments



- Picture: energy resolution 3%.
- Unique oscillation panorama at 53 km: $\sim$ 20 oscillation cycles.
- $< 1\%$ precision on θ_{12}, Δm^2_{21}, Δm^2_{32}.
- Required energy resolution $\lesssim 3\%$.

Detector requirements

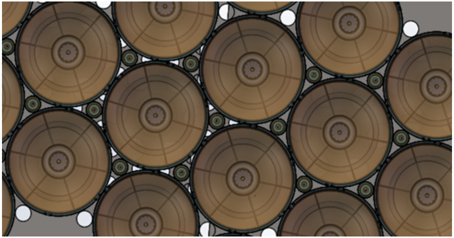
CDR: 1508.07166 Physics: 1507.05613

Energy resolution = photon collection (to some extent).

	KamLAND	JUNO	Factor
Target mass (kt)	1	20	20
Energy resolution ($\%/\sqrt{E}$)	6	$\lesssim 3$	0.5
Light yield (p. e.)	250	1200	$\sim$5
PMT coverage	34 %	75%	$\sim$2.2

Solutions:

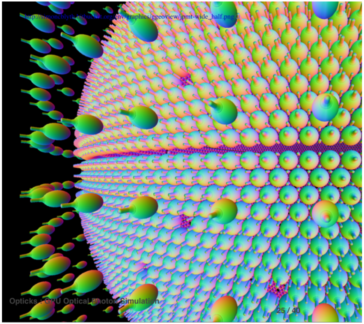
- Use 20″, high QE (35%) PMTs
- Use 3″ PMTs in between
- No Gd in scintillator
- Optimized fluor concentration
- Attenuation length > 20 m

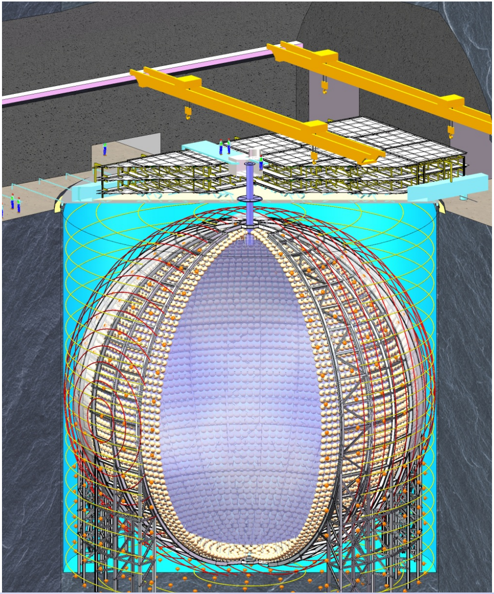


JUNO detector

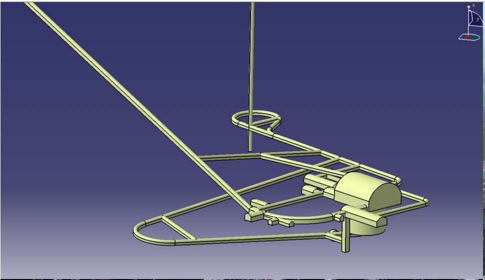
Challenges

- High QE PMT ($\sim$ 35%)
- Highly transparent LS
- Huge detector: 20 kt, $\varnothing$34.5 m
- 20k 20″ PMTs
- 36k 3″ PMTs





Civil construction



Progress: tunnel 1020 m/1340 m, shaft 485 m/611 m. To be completed in 2018.

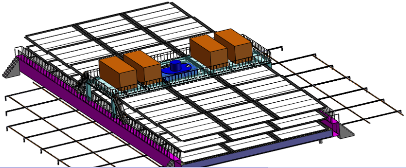
JUNO schedule

- 2013 — Complete conceptual design, complete civil design and bidding
- 2014 — Start civil construction, complete prototyping PMT and detector
- 2015 — PMT production line manufacturing
- 2016 — Start PMT production, start detector production or bidding
- 2017 — Complete civil construction, start detector construction and assembly
- 2018 — Start LS production
- 2019 — Complete detector assembly, installation and filling
- 2020 — **Start of data taking**

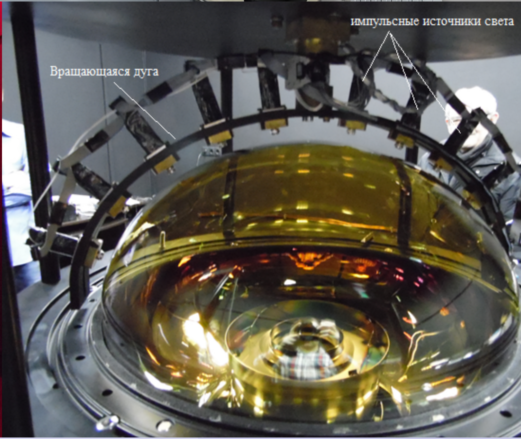
JINR contribution

JINR group of JUNO experiment participates in several key tasks:

- Powering JUNO:
  PMT high voltage R&D
- Muon veto:
  Opera TT $\longrightarrow$ precise μ detector
- Earth Magnetic Field:
  PMT protection R&D
- PMT testing:
  New PMT research lab at DLNP
- Liquid scintillator:
  purification methods and measurements
- Experiment sensitivity estimation
- MC and data analysis:
  - Hierarchy and oscillations
  - Solar and geo- neutrinos
  - Rare processes

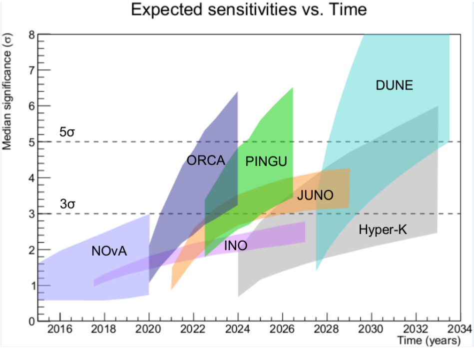


PMT lab



Summary

Sensitivity plot: KM3NeT@NOW2016 | CDR: 1508.07166 | Physics: 1507.05613



- JUNO physics program is competitive and complementary!
- Mass hierarchy determination (independent of δ_{CP} and θ_{23}).
- Probing PMNS matrix unitarity to $\sim$1% level.
- Precise measurement of neutrino mixing parameters:

  Δm^2_{21} : 3% $\rightarrow$ **0.6%** $\quad$ $\sin^2 2\theta_{12}$: 6% $\rightarrow$ **0.7%**

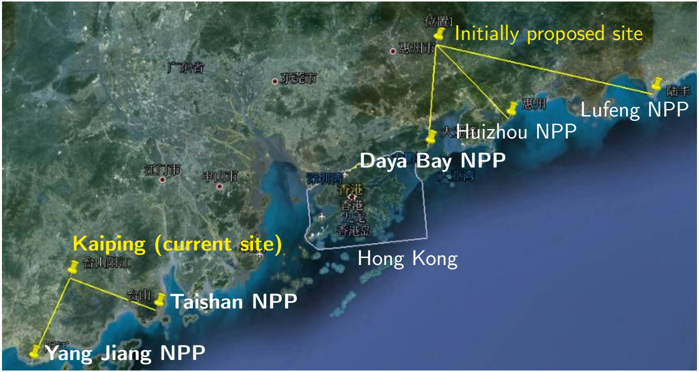
  Δm^2_{32} : 5% $\rightarrow$ **0.6%** $\quad$ $\sin^2 2\theta_{13}$: 15% (DB: 3%)

- Other physics topics:
  - Supernovae neutrino
  - Solar and geo- neutrino
  - Sterile neutrino
  - Atmospheric neutrino
  - Exotic searches
  - Proton decay
  - Others...

Backup slides...

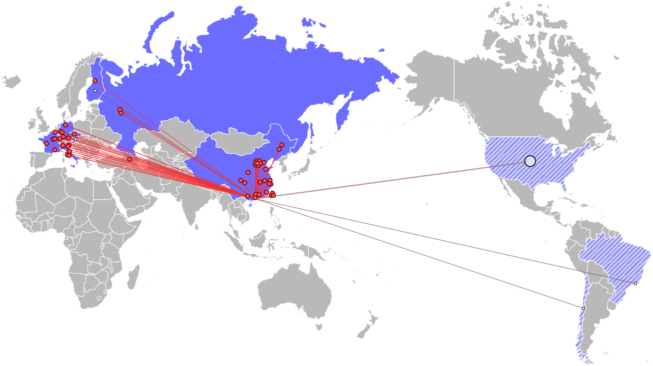
Experiment location

Kaiping country of Jiangmen city



- Nuclear power plants Yang Jiang (17.4 GW_{th}) and Taishan (18.4 GW_{th}) are under construction.

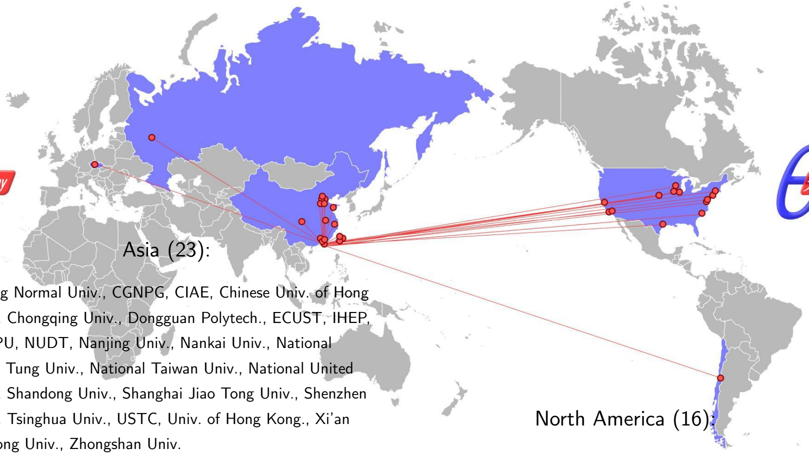
JUNO collaboration



JUNO

- 398 scientists and engineers
- from 57 institutions
- from Asia, Europe and South America
- including 32 from Russia (23 from JINR)

Daya Bay collaboration



Asia (23):

Beijing Normal Univ., CGNPG, CIAE, Chinese Univ. of Hong Kong, Chongqing Univ., Dongguan Polytech., ECUST, IHEP, NCEPU, NUDT, Nanjing Univ., Nankai Univ., National Chiao Tung Univ., National Taiwan Univ., National United Univ., Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Univ. of Hong Kong., Xi'an Jiaotong Univ., Zhongshan Univ.

Europe (2) and Sourth America (1):

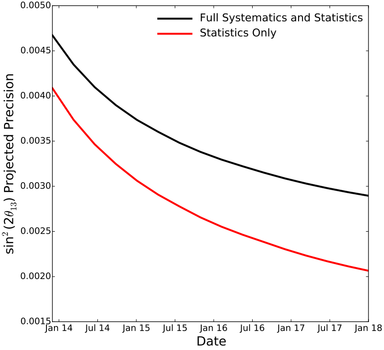
Charles University, **Joint Institute for Nuclear Research**, Catholic Univ. of Chile.

North America (16):

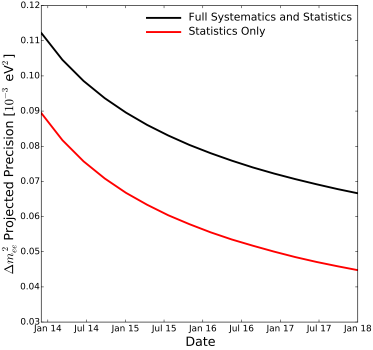
Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytech., Sienna College, Temple Univ., UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. Wisconsin, Virginia Tech, William & Mary, Yale.

Daya Bay sensitivity

$\sin^2 2\theta_{13}$ sensitivity projection:

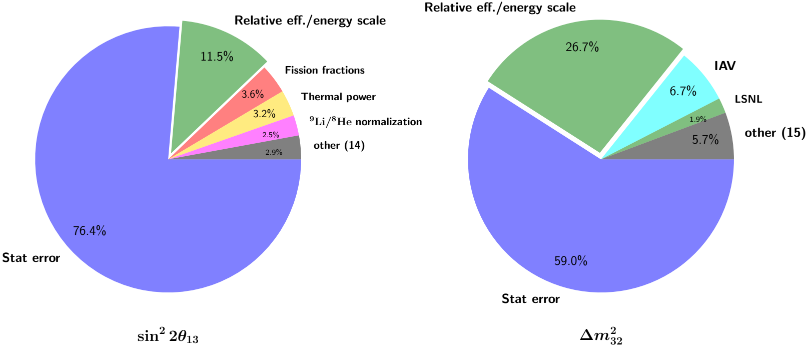


Δm^2_{ee} sensitivity projection:



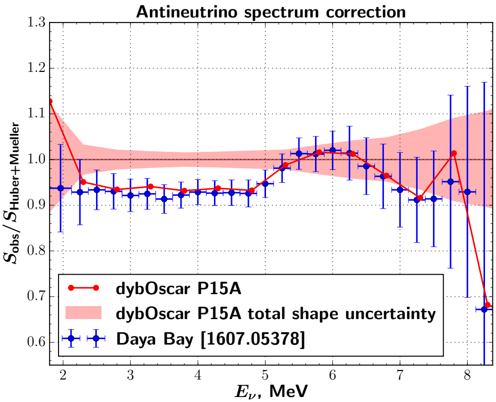
- Expect reaching 3% sensitivity on both parameters after 2017.

Error budget



- $\sin^2 2\theta_{13}$ uncertainty is dominated mostly by statistics and relative efficiency uncertainty.
- Δm^2_{32} uncertainty is dominated by statistics and relative energy scale uncertainty.
- Statistics and systematics has almost equal impact on Δm^2_{32} uncertainty.

Best fit antineutrino spectrum

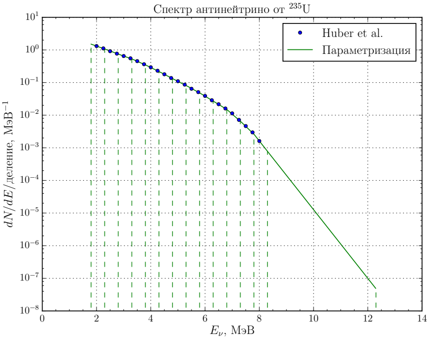


- Continuous best fit antineutrino spectrum obtained simultaneously with oscillation parameters is in good agreement with official result.
- The correlation between oscillations and spectral parameters is negligible.

Параметризация спектра антинейтрино

Спектр $\overline{\nu}_e$ от каждого изотопа параметризуется кусочно-гладкой функцией:

$$S_{ij]}\left(E^{\nu}\right) = n_j k_{ij} e^{-b_{ij}\left(E^{\nu} - E^{\nu}_j\right)},$$
$$E_{\nu} \in \left(E^{\nu}_j, E^{\nu}_{j+1}\right).$$



- k_{ij} — модельный спектр от изотопа i в E^{ν}_j.
- n_j — коррелированная поправка для интервала j.
- b_j — отношение наблюдаемого среднего спектра антинейтрино к ожидаемому:

$$n(E) = \frac{\langle S(E)\rangle_{\text{obs}}}{\langle S(E)\rangle_{\text{Huber+Mueller}}}.$$

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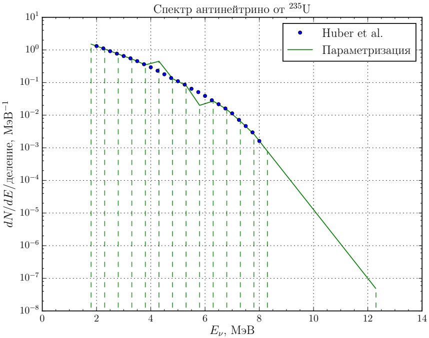
$$S_{ij]}\left(E^{\nu}\right) = n_j k_{ij} e^{-b_{ij}\left(E^{\nu} - E^{\nu}_j\right)},$$

$$E_{\nu} \in \left(E^{\nu}_j, E^{\nu}_{j+1}\right).$$



- k_{ij} — модельный спектр от изотопа i в E^{ν}_j.
- n_j — коррелированная поправка для интервала j.
- b_j — отношение наблюдаемого среднего спектра антинейтрино к ожидаемому:

$$n(E) = \frac{\langle S(E)\rangle_{\text{obs}}}{\langle S(E)\rangle_{\text{Huber+Mueller}}}.$$

Uncertainties summary

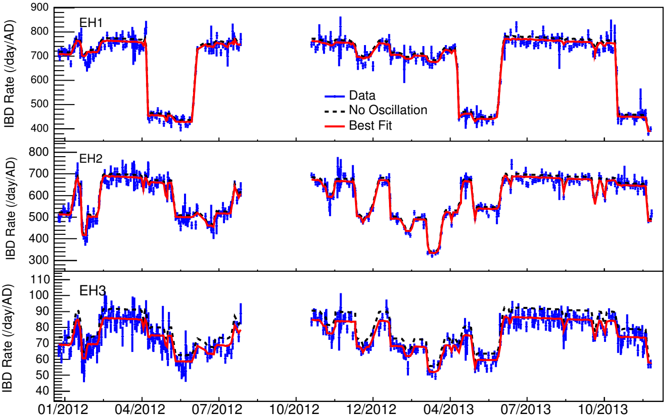
Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.92%	**0.03%**
Flasher cut	99.98%	0.01%	**0.01%**
Prompt energy cut	99.8%	0.10%	**0.01%**
Delayed energy cut	92.7%	0.97%	**0.08%**
Capture time cut	98.7%	0.12%	**0.01%**
Multiplicity cut		0.02%	**0.01%**
Gd capture fraction	84.2%	0.95%	**0.10%**
Spill-in	104.9%	1.00%	**0.02%**
Livetime	100.0%	0.002%	**0.01%**
Combined	**80.6%**	1.93%	**0.13%**

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	**0.8**%

- Only uncorrelated uncertainties are relevant for Near/Far oscillation analysis.
- Largest systematics smaller than Far site statistics (∼1%).

- Influence of uncorrelated reactor systematics is reduced by far/near measurement.

Antineutrino rates (621 days)



- More than 1M neutrino interactions
- Detected rate correlates with reactor flux expectations.
- Normalization is determined by data fit.

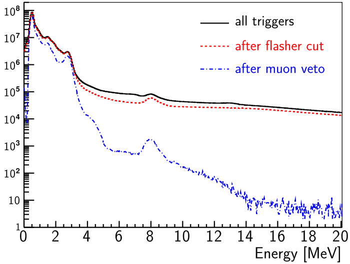
IBD selection criteria

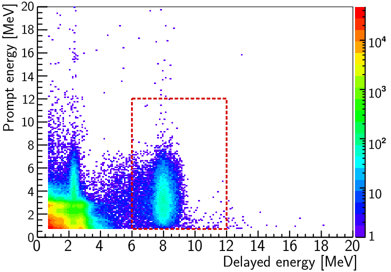
Inverse beta decay:

- $\overline{\nu}_e + p \longrightarrow e^+ + n$
- $\sim 28~\mu s:~~ n + Gd \longrightarrow Gd^* \longrightarrow$
  $\longrightarrow Gd + \sum \gamma$ (8 MeV)

Selection:

1. Reject spontaneous PMT light emission (99.98%).
2. Prompt energy (positron):
   0.7 MeV $< E_p <$ 12 MeV (99.88%).
3. Delayed energy (neutron capture):
   6 MeV $< E_p <$ 12 MeV (90.9%).
4. Neutron capture time:
   $1~\mu s < \Delta t < 200~\mu s$ (98.6%).
5. Reject muons:
   - Water pool muons Nhits>12: 0.6 ms
   - AD muons with E>12 MeV: 1 ms
   - AD shower muon E>2.5 GeV: 1 s
6. Multiplicity: no other signal with $E > 0.7$ MeV in $\pm 200~\mu s$ of IBD

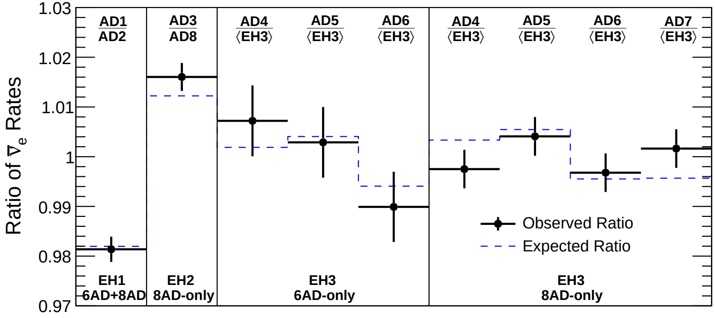




Side-by-side Comparison

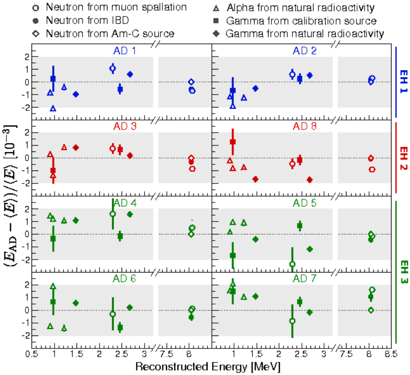
1230 days, arXiv:1610.04802→PRD

- One of the most significant improvements was the reduction of the relative detection efficiency uncertainty from 0.2 % to 0.13 %.
- Side-by-side rates are consistent with expectations:

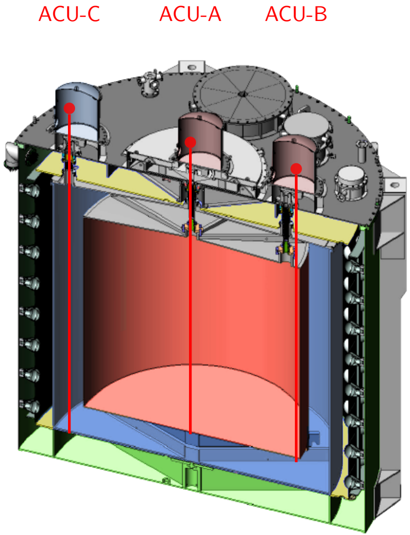


- $\sin^2 2\theta_{13}$ uncertainty is dominated by statistics and relative detection efficiency uncertainty.

Calibration

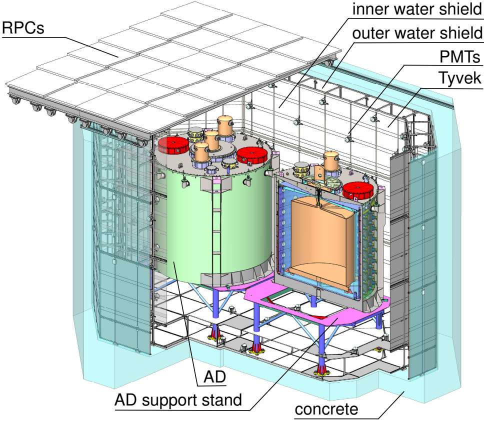


Relative energy scale uncertainty for nGd analysis: 0.2%.

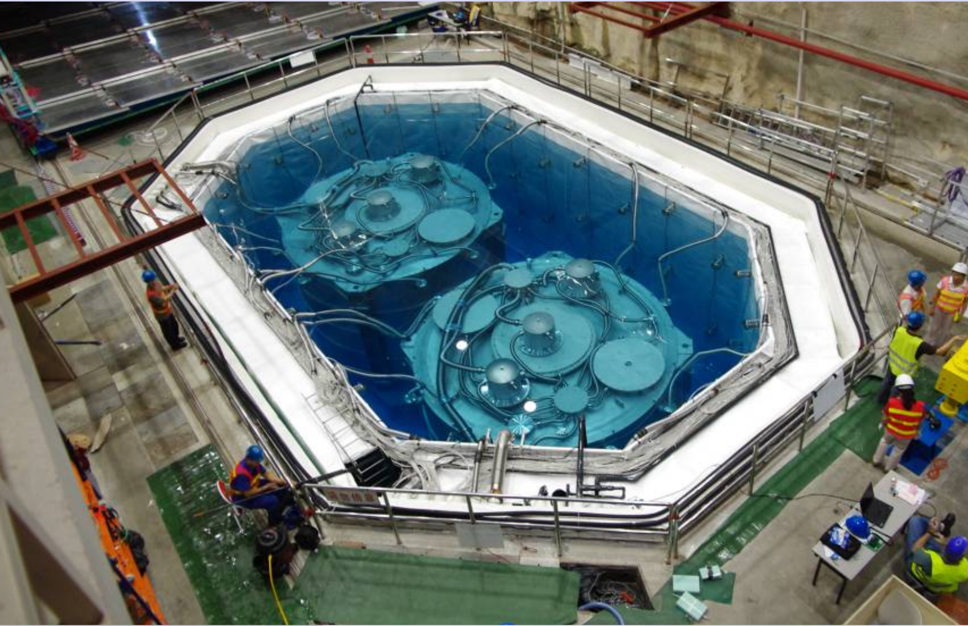


Muon veto system

- Water pool:
  - Shield against the external radioactivity and cosmogenic background.
  - Cherenkov muon tracker.
  - 288 8" PMTs in each Near Hall.
  - 384 8" PMTs in each Far Hall.
  - Outer water shield (1 m).
  - Inner water shield (>2.5 m).
- 4-layer RPC veto:
  - Muon tracker.
  - 54 modules in each Near Hall.
  - 81 modules in the Far Hall.
- Goal efficiency 99.5% with uncertainty $< 0.25\%$.

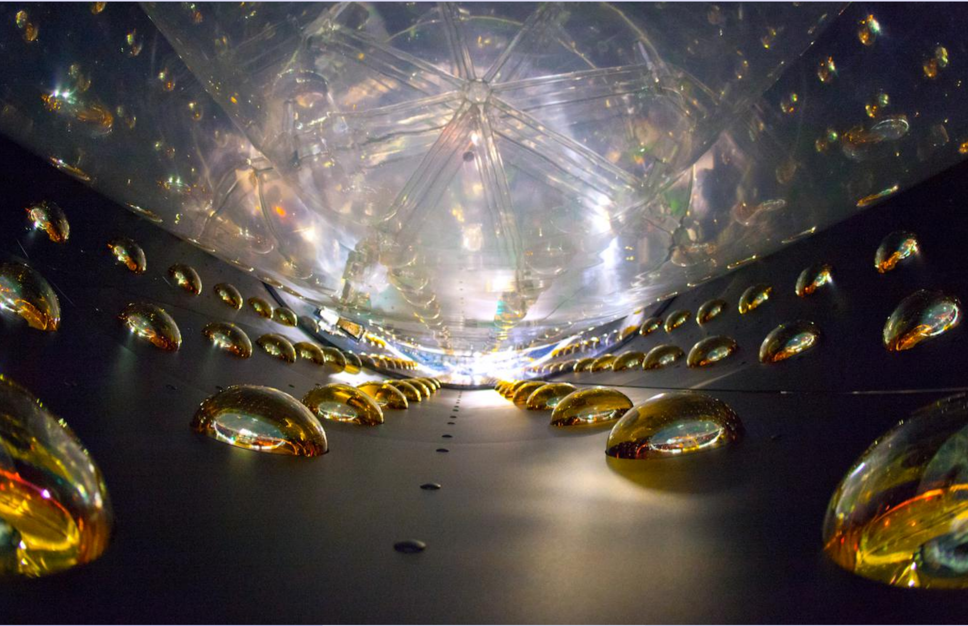


Experimental hall 1



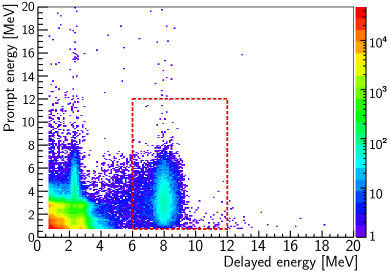
Experimental hall 3

Inside the AD



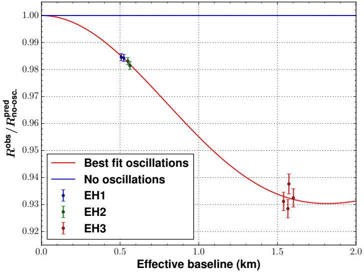
Background summary

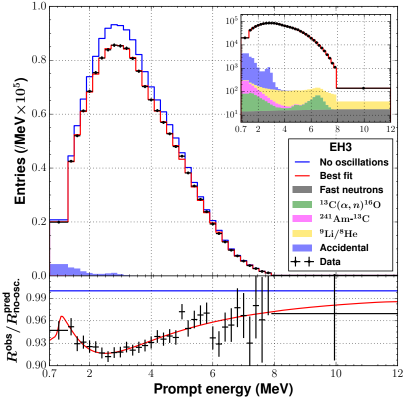
	Near Halls B/S, %	Far Hall B/S, %	Uncertainty	Estimation method
Accidentals	1.4	2.3	$\sim 1\%$	Calculated based on uncorrelated signals
$^{9}Li/^{8}He$	0.4	0.4	50%	Measured with after-muon events
Fast neutrons	0.1	0.1	50%	Measured with tagged muon events
^{241}Am-^{13}C	0.03	0.2	50%	MC, benchmarked with single γ and strong ^{241}Am-^{13}C source
$^{13}C(\alpha, n)^{16}O$	0.01	0.1	50%	Calculated from measured radioactivity



Far vs. near comparison

1230 days, arXiv:1610.04802, PRD





The observed **event rate deficit** and **relative spectrum distortion** are highly consistent with oscillation interpretation.

Independent nH oscillation analysis

621 days, arXiv:1603.03549, PRD

Key points:

- ✓ Additional statistics (+20 ton/AD)
- ✓ Largely independent systematics
- ✗ Lower delayed energy ($\sim$2.2 MeV)
- ✗ More accidentals
- ✗ Loosely defined fiducial volume

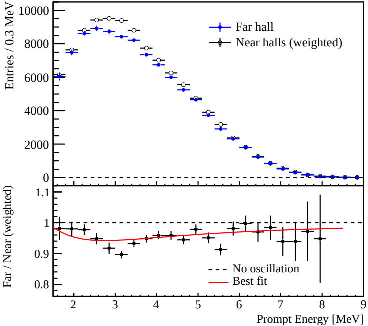
nH

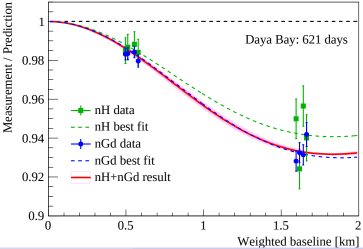
$$\sin^2 2\theta_{13} = \mathbf{0.071 \pm 0.011}$$

nH+nGd

$$\sin^2 2\theta_{13} = \mathbf{0.082 \pm 0.004}$$

- Observed significant rate deficit.
- Spectral distortion consistent with oscillations.
- Third world precise measurement after Daya Bay (nGd) and RENO (nGd).





Absolute reactor antineutrino flux

621 days, arXiv:1607.05378→CPC

- Consistent between ADs
- Consistent with world average
- Supports reactor anomaly existence

Huber+Mueller

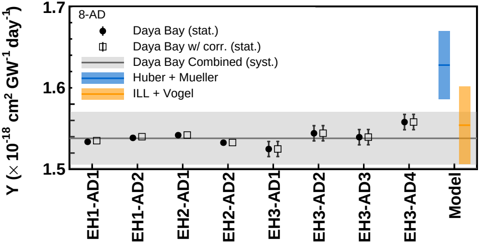
Data/prediction: **0.946** ± **0.020**

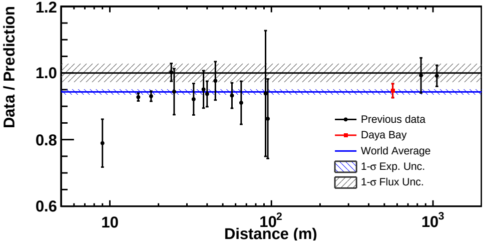
ILL+Vogel

Data/prediction: **0.992** ± **0.021**

Huber+Mueller (global)

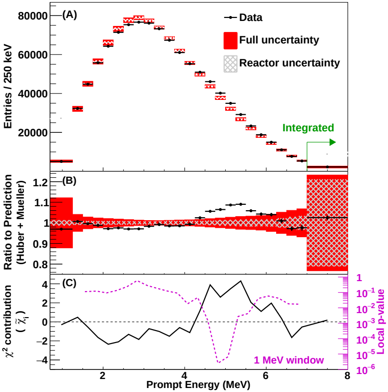
Data/prediction:
0.943 ± **0.008** (exp) ± **0.023** (model)





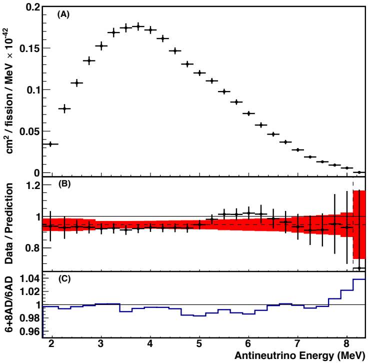
Reactor antineutrino spectrum

Observed positron spectrum



- Bump feature around 5–6 MeV.
- Consistent with other experiments.
- Seen for both Huber+Mueller/ILL+Vogel.

Extracted antineutrino spectrum



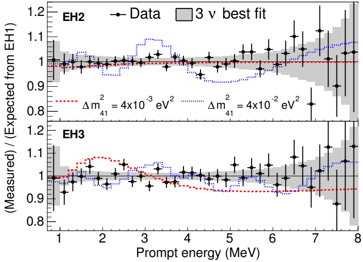
- **Global significance:** **2.9σ.**
- **Local significance:** **4.4σ.**

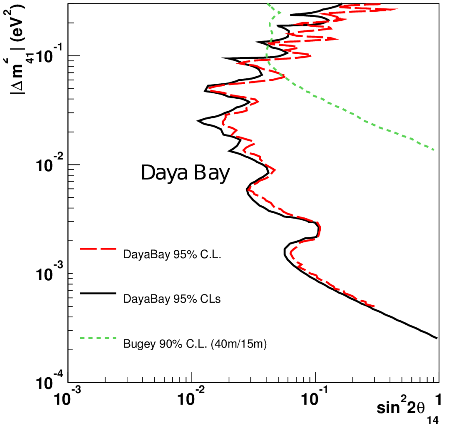
621 days, arXiv:1607.05378→CPC

Light sterile neutrino search

217 days, arXiv:1407.7259, PRL

- Sterile neutrino will cause spectral distortions at the near and far sites.
- Relative measurement independent of reactor related systematics.
- **Result is consistent with 3-flavor oscillations.**

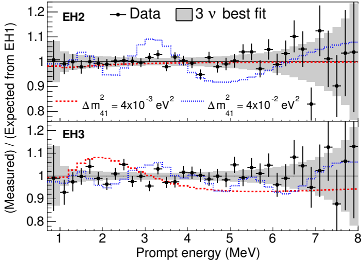


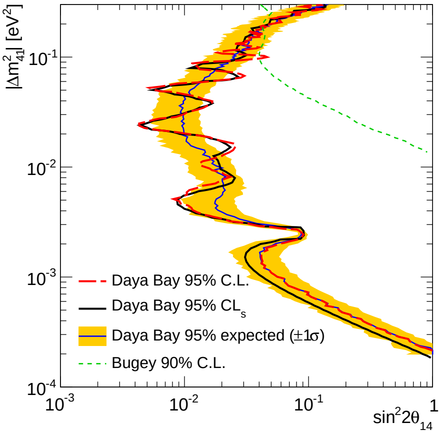


Light sterile neutrino search

621 days, arXiv:1607.01174, PRL

- Sterile neutrino will cause spectral distortions at the near and far sites.
- Relative measurement independent of reactor related systematics.
- **Result is consistent with 3-flavor oscillations.**

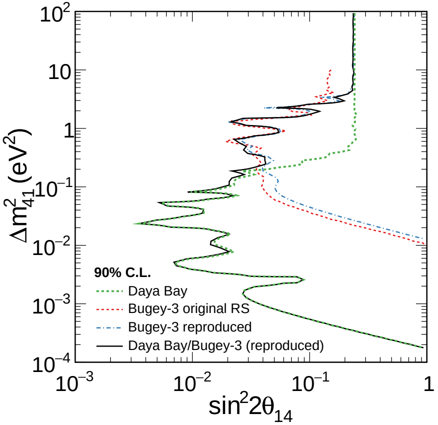




Light sterile neutrino search with Bugey-3 and MINOS

621 days, arXiv:1607.01174, PRL

- Combining Daya Bay and Bugey-3 data strongly constrains Δm^2_{41} and $\sin^2 2\theta_{41}$.
- Combining Daya Bay and Bugey-3 and MINOS data allows to constrain Δm^2_{41} and $\sin^2 2\theta_{41}$ $\sin^2 2\theta_{42}$.
- Joint analysis strongly suggests that LSND results is not due to **sterile neutrino**.

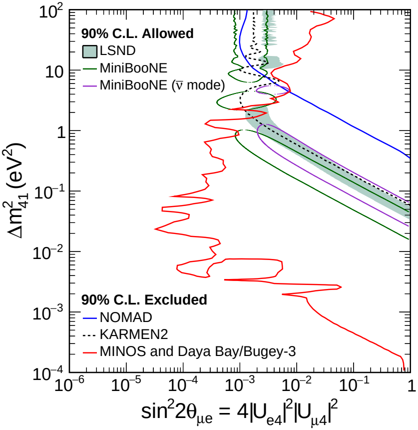


Light sterile neutrino search with Bugey-3 and MINOS

621 days, arXiv:1607.01174, PRL

+MINOS, arXiv:1607.01177, PRL

- Combining Daya Bay and Bugey-3 data strongly constrains Δm^2_{41} and $\sin^2 2\theta_{41}$.
- Combining Daya Bay and Bugey-3 and MINOS data allows to constrain Δm^2_{41} and $\sin^2 2\theta_{41} \sin^2 2\theta_{42}$.
- Joint analysis strongly suggests that LSND results is not due to **sterile neutrino**.



Wave packet effects

621 days, arXiv:1608.01661→EPJC

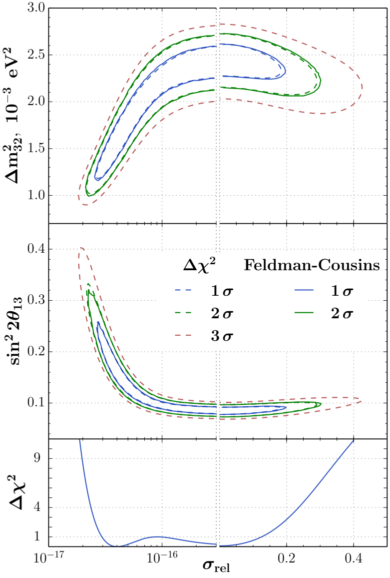
- The obtained limits read

$$2.38 \cdot 10^{-17} < \sigma_{\rm rel} < 0.23,$$

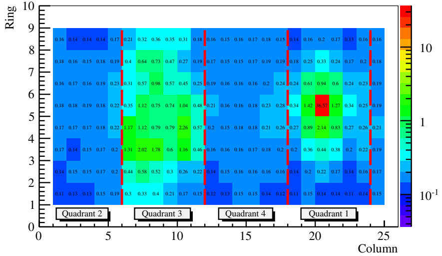
- taking into account the reactor/detector sizes:

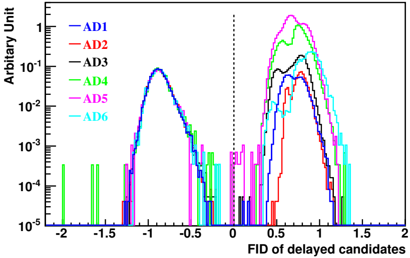
$$\boxed{10^{-11}\ \text{cm} \ \lesssim \sigma_x} \lesssim 2m.$$

- These results ensure unbiased measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32} within the PW model.



Flashers identification





Flashers — PMTs spontaneously emitting light:

- $\sim 5\%$ of PMTs
- $\sim 5\%$ of the events
- Rejected based on the topology

$$d_{max} = Q_{max}/Q_{sum}$$

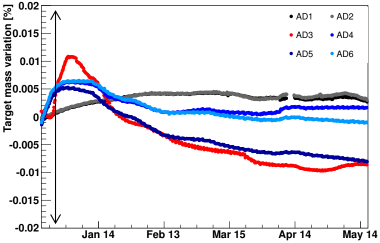
$$d_{quad} = Q_3/(Q_2 + Q_4)$$

$$\mathrm{FID} = \log_{10}\left[\left(\frac{d_{quad}}{1}\right)^2 + \left(\frac{d_{max}}{0.45}\right)^2\right] < 0$$

AD liquids

Target mass:

- Target mass is measured during filling by the load cell with precision of ∼ 3kg, 0.015%.
- Cross-checked by the Coriolis meters with precision of 0.1%.
- $M_{\text{target}} = M_{\text{fill}} - M_{\text{overflow}}$



Liquid scintillator composition:

- LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15mg/L)
- One year 1-ton prototype monitoring on GdLS stability.

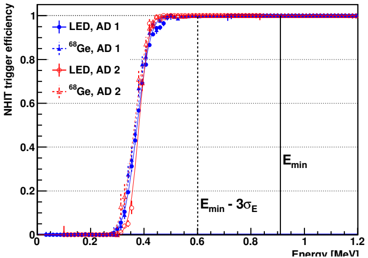
Liquids storage and filling:

- Fill each AD from all 5 storage tanks.
- Fill ADs in pairs.
- Recirculate storage tanks.

Trigger

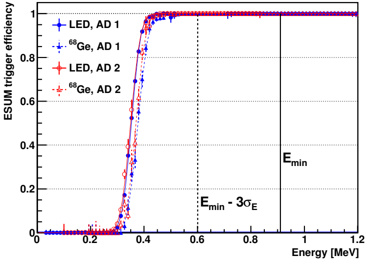
Trigger criteria:

- Signal > 0.25 p. e.:
  - Nhit > 45.
  - Esum > 0.4 MeV.
- Water pool:
  - Nhit > 12.

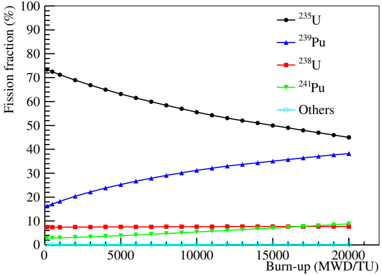


Trigger efficiency:

- Measured from LED light and ^{68}Ge source.
- No measurable inefficiency above 0.7 MeV.
- Minimal $E_p \approx 0.95$ MeV.



Reactor flux expectation



$$S(E) = \frac{W_{\mathrm{th}}}{\sum_k f_k E_k} \sum_i f_i S_i(E)$$

Information provided by the NPP:

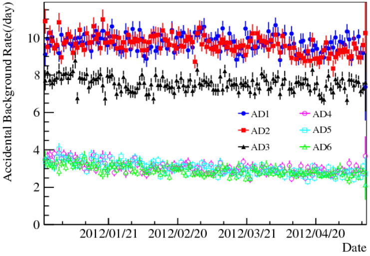
- W_i — thermal power.
- f_i — relative isotope fission fraction.

Neutrino data:

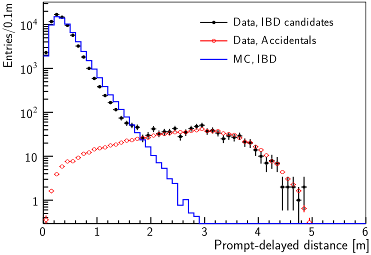
- E_i — energy released per fission:
  - V. Kopeikin, L. Mikaelyan, and V. Sinev, Phys. Atom. Nucl. **67**, 1892 (2004).
- $S_i(E)$ — antineutrino spectra per fission:
  - W. G. K. Schreckenbach, G. Colvin and F. von Feilitzsch, Phys. Lett. **B160**, 325 (1985).
  - A. F. von Feilitzsch and K. Schreckenbach, Phys. Lett. **B118**, 162 (1982).
  - A. A. Hahn *et al.*, Phys. Lett. **B218**, 365 (1989).
  - P. Vogel, G. K. Schenter, F. M. Mann, and R. E. Schenter, Phys. Rev. C**24**, 1543 (1981).
  - T. Mueller *et al.*, Phys. Rev. C**83**, 054615 (2011).
  - P. Huber, Phys. Rev. C**84**, 024617 (2011) [Erratum-ibid. **85**, 029901(E) (2012)].

Backgrounds: accidentals

Accidental event — two independent signals accidentally satisfy event selection criteria.



Figure

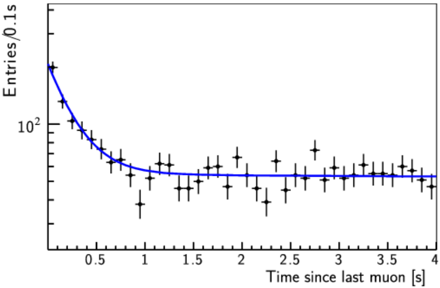


Figure

- Calculated based on prompt and delayed rates.
- Cross-checks:
  - Prompt-delayed distance distribution.
  - Off-window coincidence.

Backgrounds: ^{9}Li/^{8}He

Long-lived cosmogenic isotopes of ^{9}Li/^{8}He decay with both β and neutron emission.

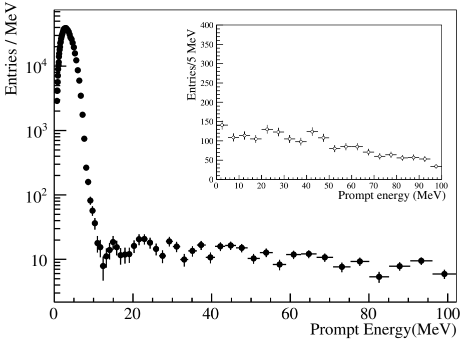


Figure

- Calculated by fitting the time-after-last-muon events distribution. Based on known half-life times:
  - ^{9}Li $\lambda = 178ms$
  - ^{8}He $\lambda = 119ms$
- Cross-checks:
  - Analyze muon samples with and without followed neutrons.

Backgrounds: fast neutrons

Fast neutrons can produce recoil protons, which mimic prompt signal. Neutron capture itself is the delayed signal.



Figure

- Method I:
  - Collect events with $12\ \text{MeV} < E_p < 100\ \text{MeV}$
  - Extrapolate the spectrum to the $E_p < 12\text{MeV}$
- Method II:
  - Use water pool and RPC to determine the number of fast neutrons.

Backgrounds: ^{241}Am-^{13}C and ^{13}C(α, n)^{16}O

Correlated background from ^{241}Am-^{13}C sources (ACU):

- Neutron inelastic scattering on ^{56}Fe + neutron capture on Fe/Cr/Mn/Ni.
- Estimated based on simulation.
- Cross checked with data.

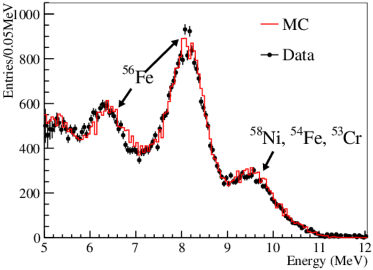


Figure: Energy spectrum of the events near the top of ADs in the Far Hall.

Correlated ^{13}C(α, n)^{16}O background:

- ^{238}U, ^{232}Th, ^{227}Ac and ^{210}Po α rates are measured.
- Neutron yield is calculated with MC.

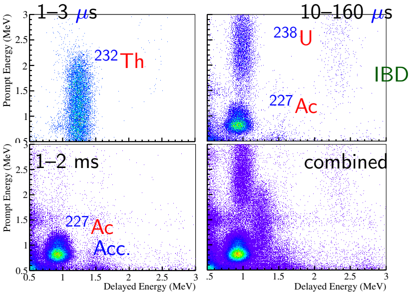


Figure: Correlations of prompt and delayed energy for cascade decay chains.