Mauro Mezzetto,
Istituto Nazionale Fisica Nucleare, Padova

The future of neutrino physics (at accelerators)

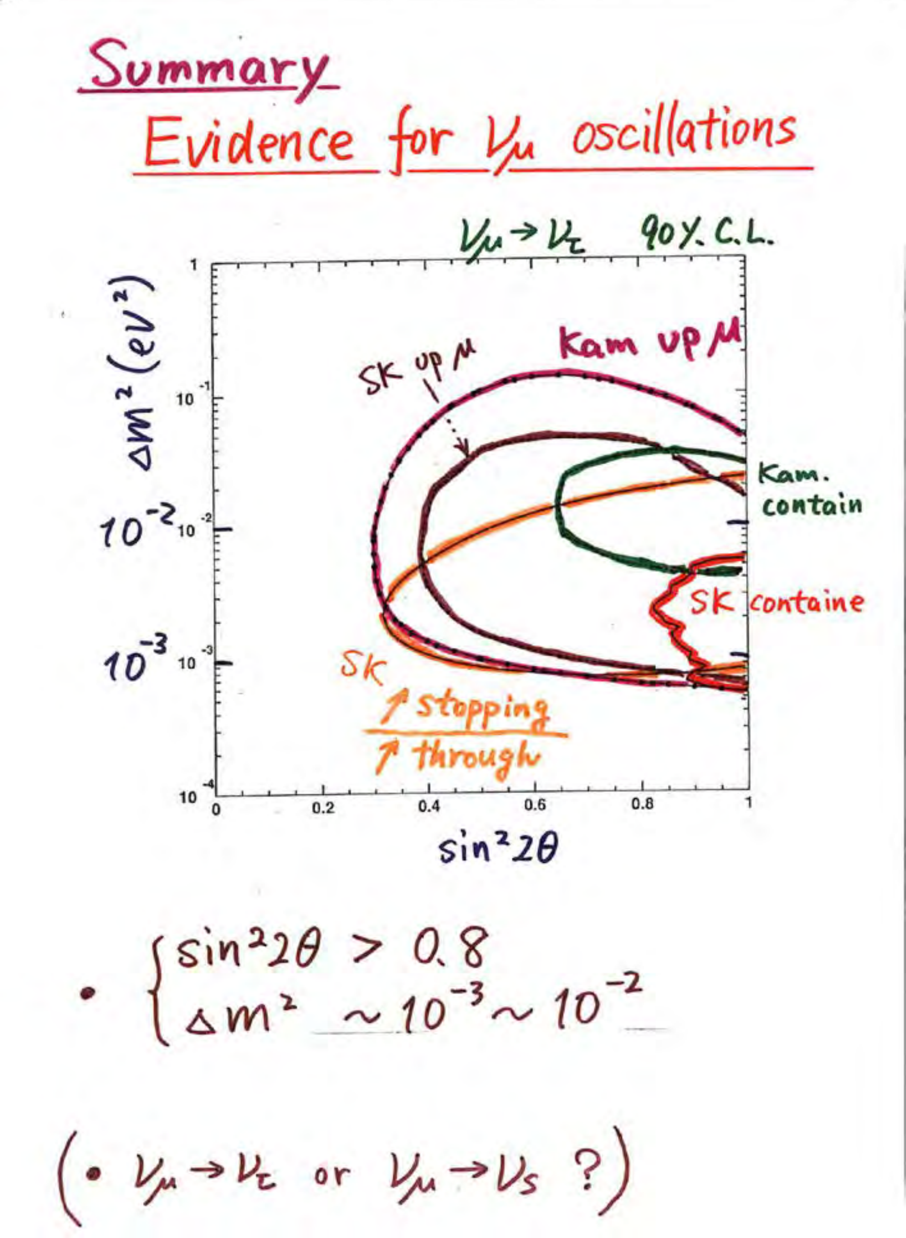
- Present Status
- Concepts, strategies, challenges
- The two players: Dune and Hyper-Kamiokande
- Conclusions

The history began in 1998

The discovery of neutrino oscillations had been made by Super-Kamiokande In 1998 by measuring atmospheric neutrinos.

Long baseline: 1 GeV neutrinos have max of oscillations at about 500 Km.

Very much reduced fluxes: need of gigantic detectors deep underground: ideal detector SK (it's approaching 20 years of leading edge operations).



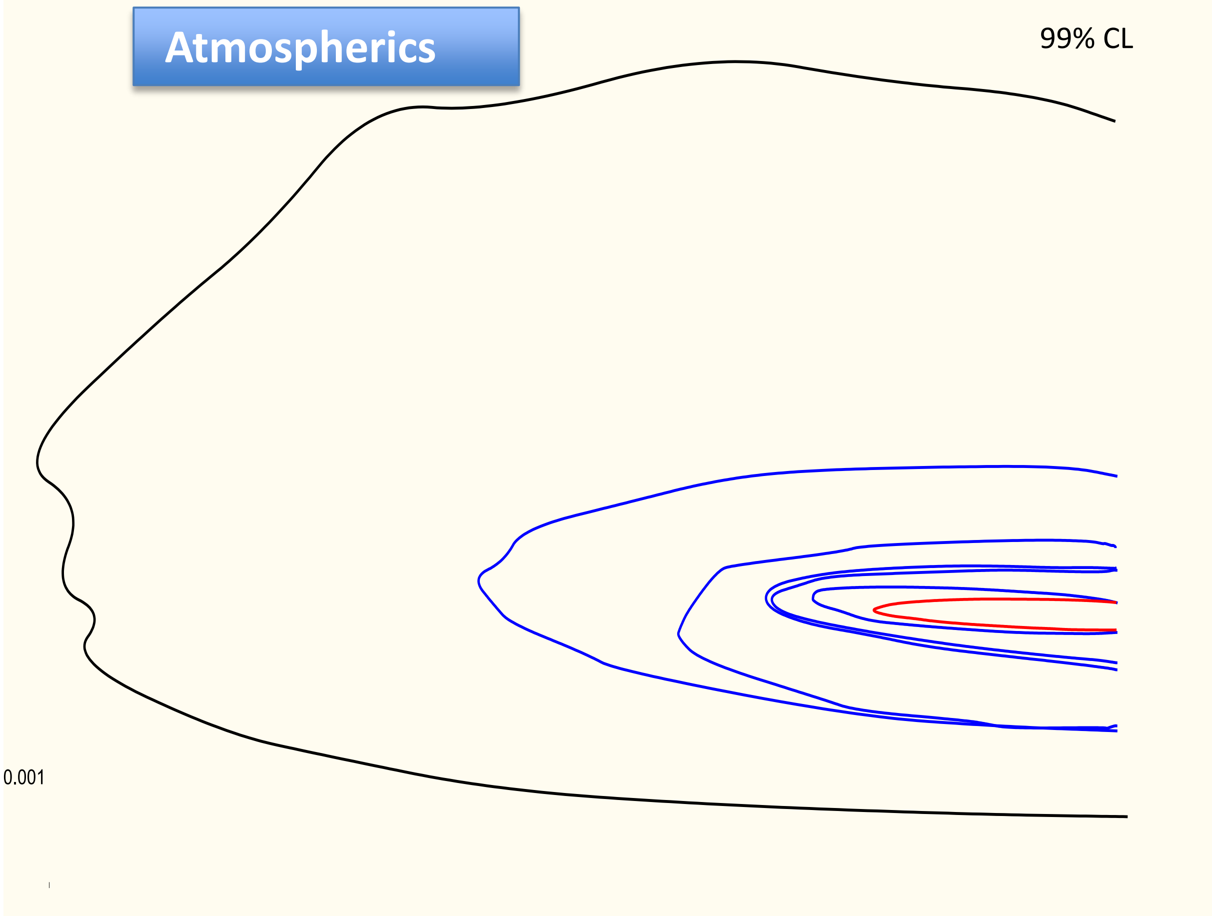
Summary

Evidence for ν_μ oscillations

- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

The progress on atmospheric parameters

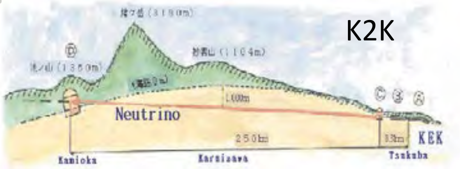


1999

SuperK

MACRO at GRAN SASSO
Monopole, Astrophysics and Cosmic Ray Observatory

2002



2005

2008

MINOS

2010

2012

2014

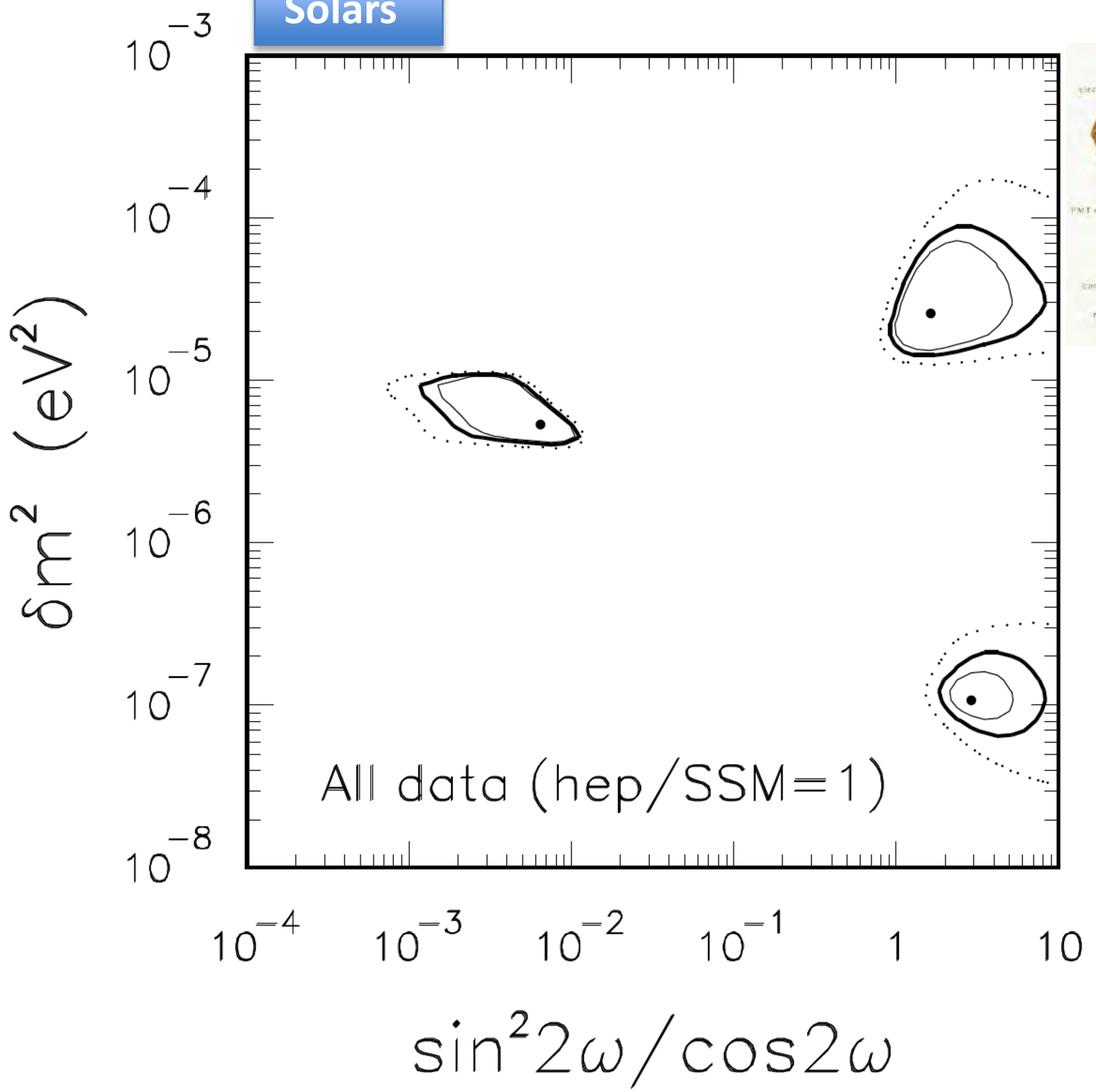
T2K

Along time changed variables, fitting methods, conventions, assumptions ….

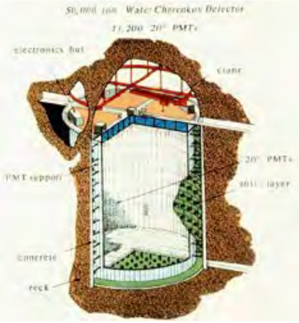
Results also from Opera, Antares, IceCube ….

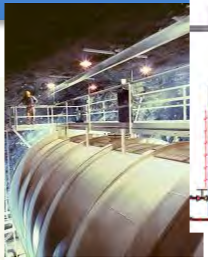
Solar parameters in 1998

Solars



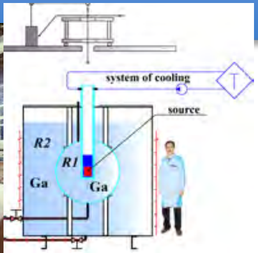
1998

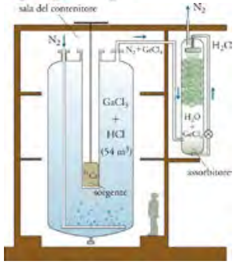




Homestake

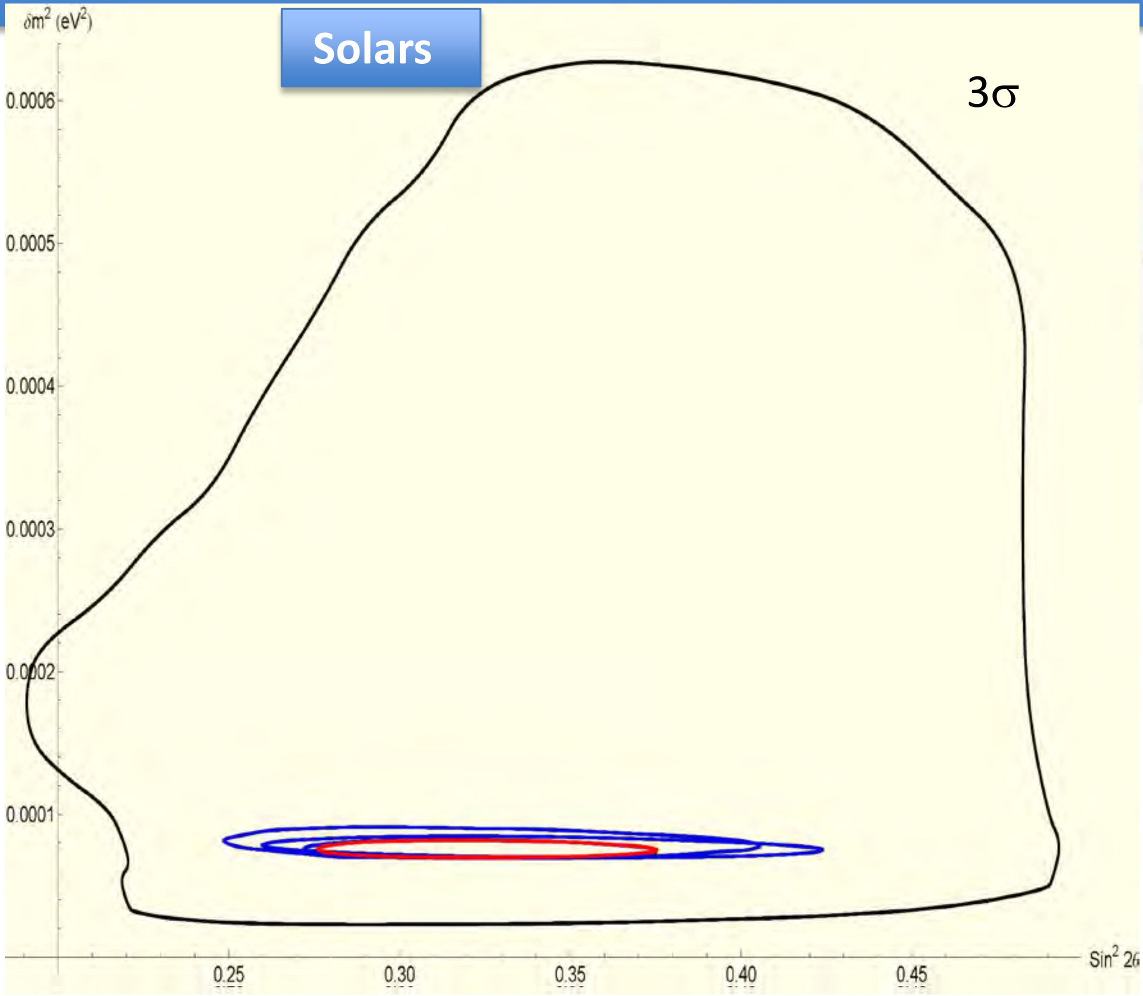
SAGE



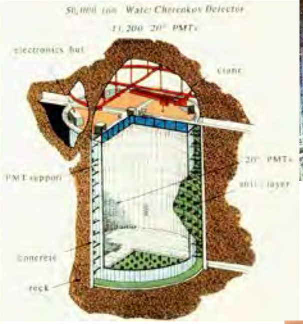


Gallex/GNO

The progress on Solar parameters

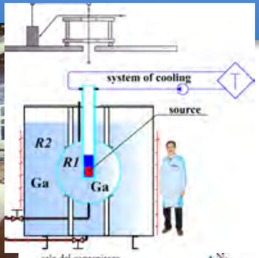


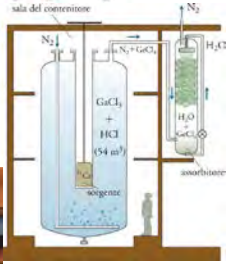
1999



Homestake

SAGE





Gallex/GNO

2002

SNO

2005

2008

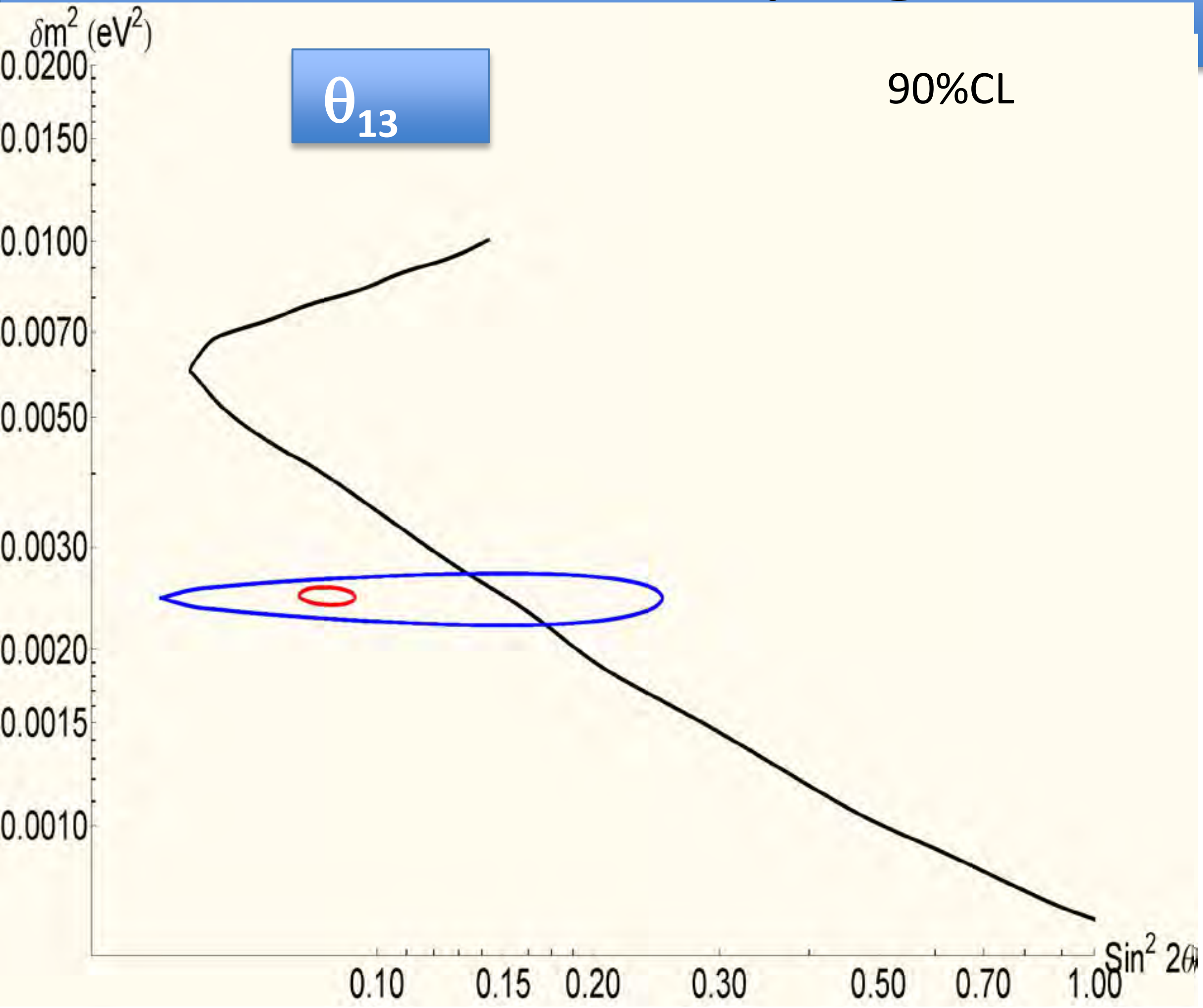
2010

2012

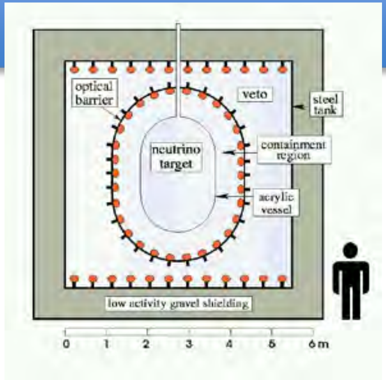
2014

Along time changed variables, fitting methods, conventions, assumptions …. And also some important cross section both at the source and the detector, not to mention the new evaluation of reactor antineutrino rates.

The progress on θ_{13}



1999



2002

2005

2008

2010 At Neutel 2010 Fogli et al.
Start claiming that global fits
Favour $\sin^2 2\theta_{13}=0.1$ at 1.5σ

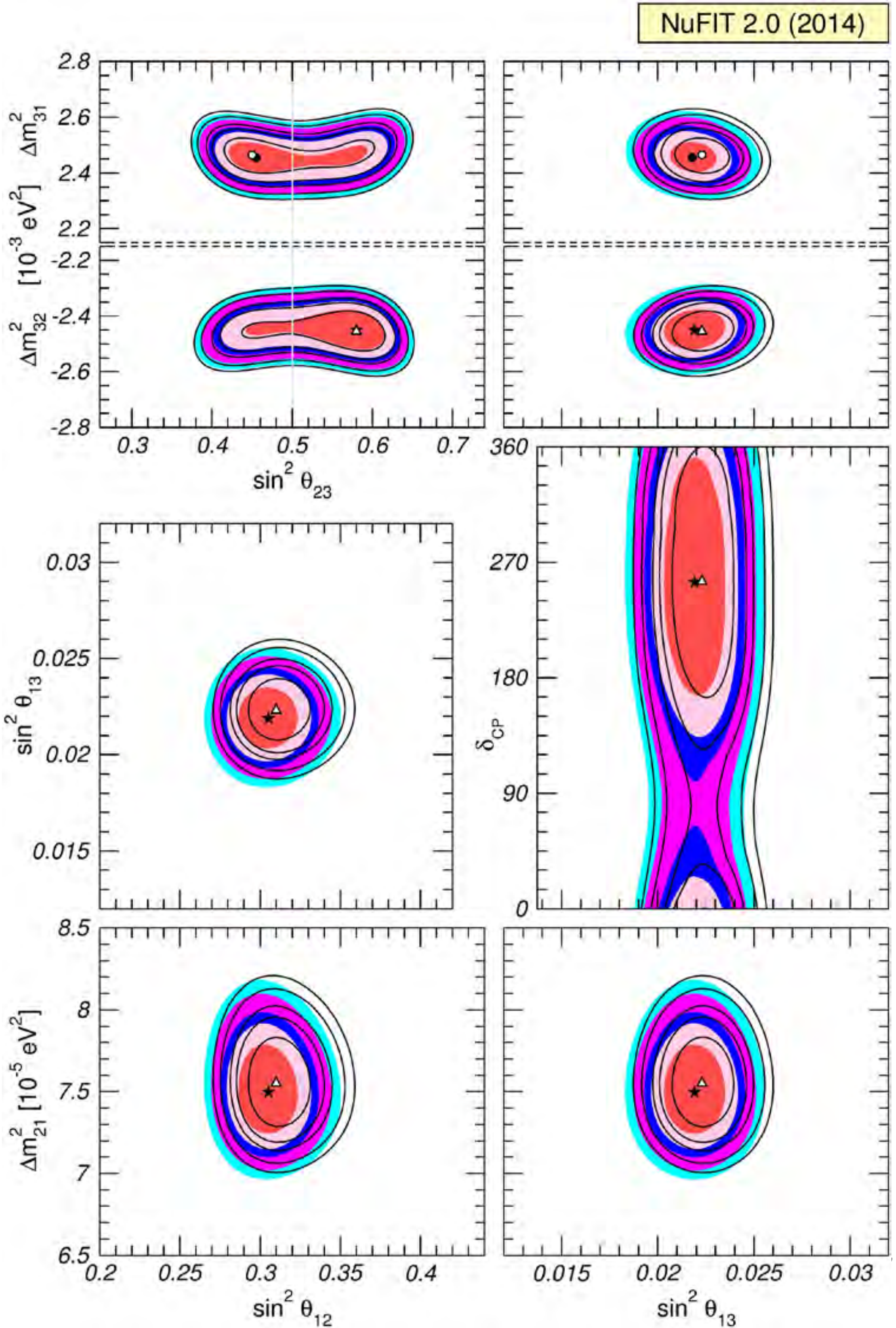
2011

2012

12 years to improve Chooz and θ_{13} was just behind the corner ...

Present situation

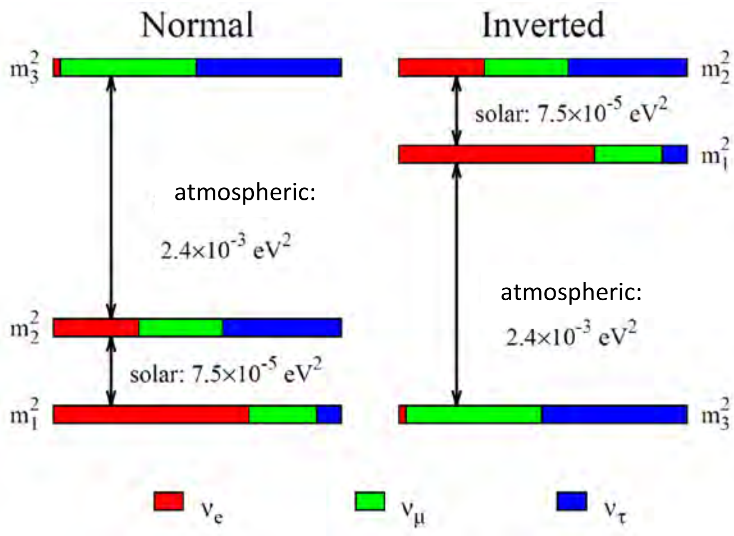
- Precision era started
- Can precision constrain new physics?
- What about unitarity ? (It's assumed in all these plots)



What’s missing

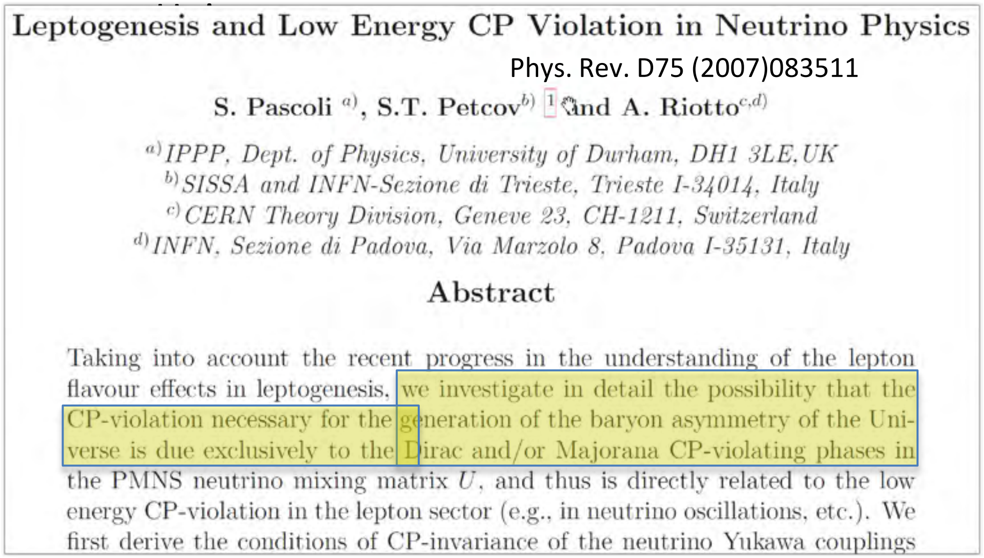
Neutrino mass ordering

- ν_e can be the heaviest or the lightest of neutrinos
- Impacts on prospects of double beta decay detection



Leptonic CP violation

- The last parameter of the Standard Model to be measured
- Intringuing correlations with matter/antimatter asymmetry in the



Leptogenesis and Low Energy CP Violation in Neutrino Physics

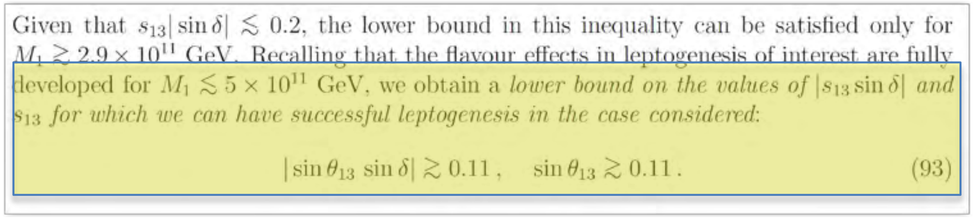
Phys. Rev. D75 (2007)083511

S. Pascoli [a], S.T. Petcov [b] [1] and A. Riotto [c,d]

[a] *IPPP, Dept. of Physics, University of Durham, DH1 3LE,UK*
[b] *SISSA and INFN-Sezione di Trieste, Trieste I-34014, Italy*
[c] *CERN Theory Division, Geneve 23, CH-1211, Switzerland*
[d] *INFN, Sezione di Padova, Via Marzolo 8, Padova I-35131, Italy*

Abstract

Taking into account the recent progress in the understanding of the lepton flavour effects in leptogenesis, we investigate in detail the possibility that the CP-violation necessary for the generation of the baryon asymmetry of the Universe is due exclusively to the Dirac and/or Majorana CP-violating phases in the PMNS neutrino mixing matrix U, and thus is directly related to the low energy CP-violation in the lepton sector (e.g., in neutrino oscillations, etc.). We first derive the conditions of CP-invariance of the neutrino Yukawa couplings



Given that $s_{13}|\sin\delta| \lesssim 0.2$, the lower bound in this inequality can be satisfied only for $M_1 \gtrsim 2.9\times10^{11}$ GeV. Recalling that the flavour effects in leptogenesis of interest are fully developed for $M_1 \lesssim 5\times10^{11}$ GeV, we obtain a *lower bound on the values of* $|s_{13}\sin\delta|$ *and* s_{13} *for which we can have successful leptogenesis in the case considered:*

$$|\sin\theta_{13}\,\sin\delta| \gtrsim 0.11\,, \quad \sin\theta_{13} \gtrsim 0.11\,. \qquad (93)$$

Not covered in this talk

- Absolute masses of neutrinos
- Dirac vs. Majorana

Short term: sterile neutrinos

The 3 ν model is matched by 4 anomalies conspiring to the same oscillation parameters

LSND: a 3.5 σ excess of $\bar{\nu}_e$ events in a neutrino beam created by pion decays at rest. First paper on 1995, the experiment has never been repeated.

MiniBoone: a 10 years effort at Fermilab to check the LSND result at different energies (but same L/E), the final result had been inconclusive.

Reactor anomaly: recent recalculation of neutrino fluxes at reactors showed an enhancement of about 3.5% of absolute fluxes with respect to previous calculations: all the reactor experiments at very short baselines could be reinterpreted as evidence of $\bar{\nu}_e$ disappearance (about 2.5 σ). Recent results on reactor experiments seriously match the reliability of these recent calculations.

Source calibration of Gallex and SAGE: the source calibration of these experiments showed a 15% deficit of ν_e events. To be noted that the calibration had been designed and funded to check the efficiency of the detectors, while the sterile evidence is there assuming 100% efficiency of the detectors.

Overall fit: the 4 anomalies can accommodated in the same oscillation model by adding a 4th, sterile, neutrino, with a mass of about 1 eV, nevertheless tensions exist in the global fit

Cosmology: severely constraints total number of neutrinos to 3 and their mass below 1 eV

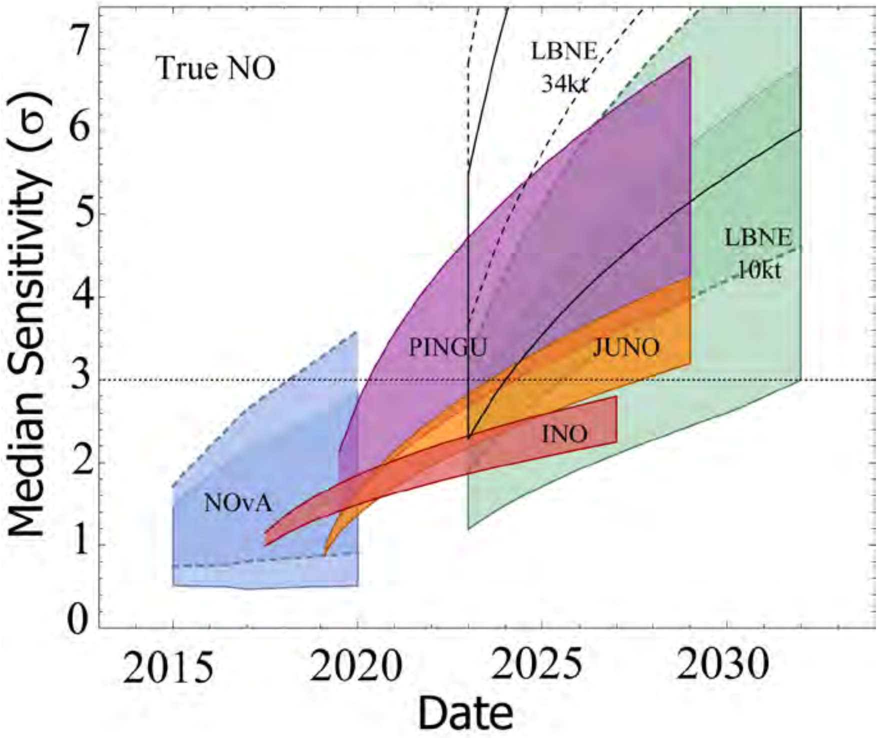
Most economical way to falsify steriles: a convincing null result from the source experiments at Borex (SOX) would falsify the sterile n interpretation of anomalies

Most complete way to explore the phenomenology if steriles exist: the new short baseline project at Fermilab, with 3 liquid argon detectors, has the potential of fully exploit the several manifestations of sterile neutrinos.

Medium term: ν mass ordering

- Pure oscillation effects in ν_e disappearance: **Juno**
- Matter effects in ν_μ disappearance: **INO**, Pingu, Orca, HyperKamiokande
- Matter effects in ν_e appearance: **NOνA**, Dune, T2HK

Blennow et al., JHEP 1403 (2014)028



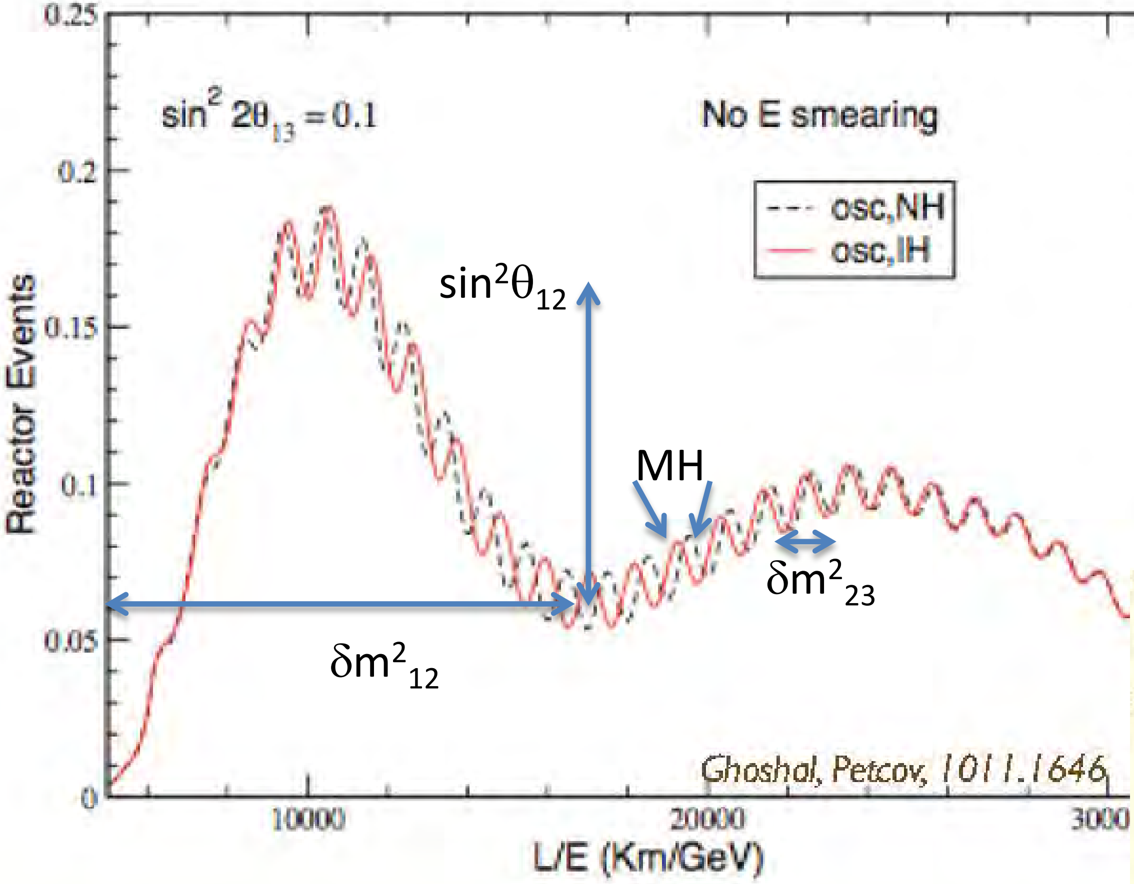
(Very) long baseline ν experiments have the best potential for this measurement ...
... but are also the most expensive and probably the last to come into play

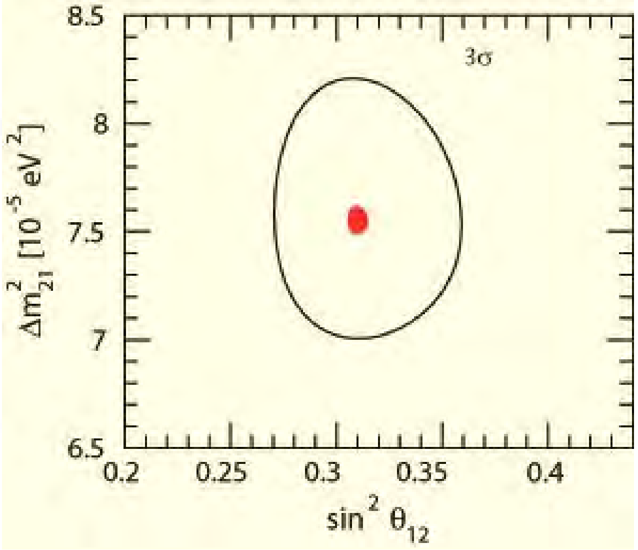
No needs of precision, the experiment has just to decide between +1 and -1.

JUNO

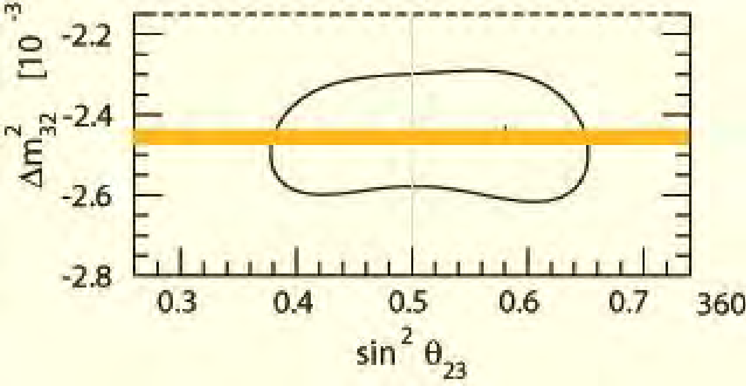
A 20 kton liquid scintillator detector at 50 km from several nuclear reactor plans in China

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \left(c_{12}^2 \cos 2\Delta_{31} + s_{12}^2 \cos 2\Delta_{32}\right)\right] - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2 \Delta_{21}$$





Factor 10 better precision in 3 oscillation parameters

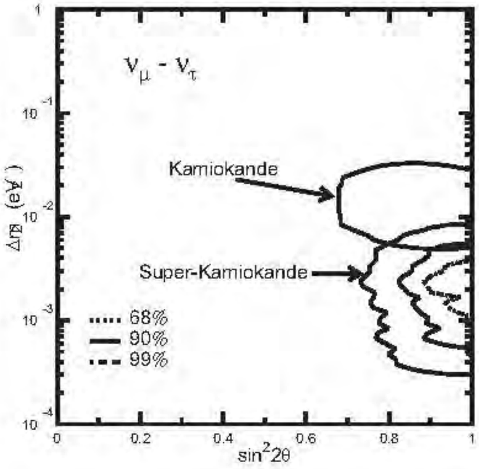


The values of oscillation parameters conspire to make CP violation detectable

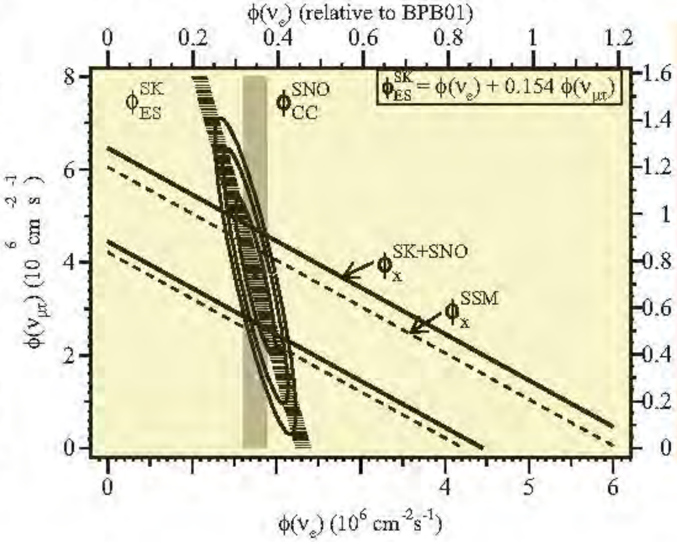
The CP odd term in oscillation formulas is

$$\propto \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin\delta \sin \frac{\Delta m^2_{13} L}{4E}$$

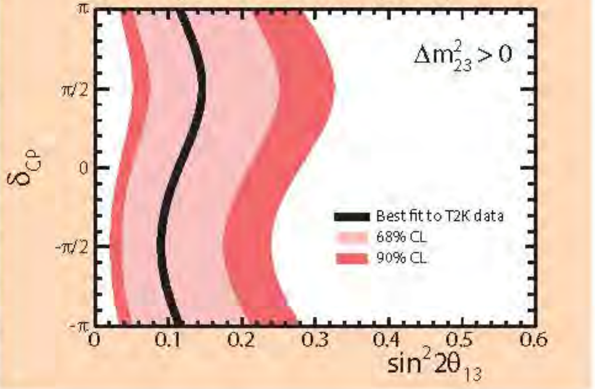
SuperKamiokande PRL 81(1998) 1562



SNO + SK, Phys.Rev.Lett. 87 (2001) 071301



T2K, Phys.Rev.Lett. 107 (2011) 041801

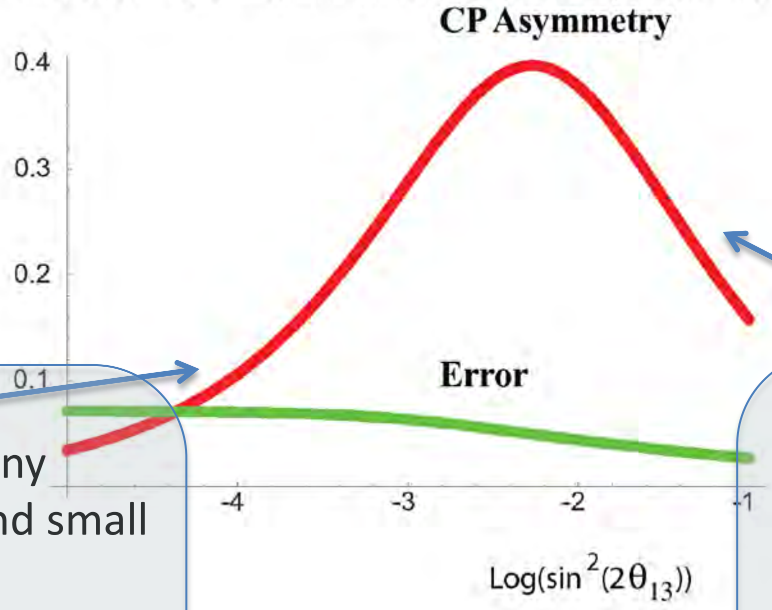


The value of θ_{13} decides the strategy

$$A_{CP} = \frac{P(\nu_\mu\to\nu_e)-P(\overline{\nu}_\mu\to\overline{\nu}_e)}{P(\nu_\mu\to\nu_e)+P(\overline{\nu}_\mu\to\overline{\nu}_e)} \propto \frac{1}{\sin\theta_{13}}$$

Signal statistics is maximum BUT $\nu - \overline{\nu}$ asymmetry is minimum
In other terms systematic errors dominate

Blondel, Cervera, Donini, Huber, MM, Strolin, Acta Phys. Polon. B **37** (2006) 2077



SMALL VALUES:
$\nu_\mu - \nu_e$ transitions are tiny
Need large statistics and small background rates
Transition asymmetry is large
Little effect of systematic errors

Conventional neutrino beams are not enough

LARGE VALUES:
$\nu_\mu - \nu_e$ transitions are large
Relaxed constraints on statistics and background rates
Transition asymmetry is small
Large effects of systematic errors

Conventional neutrino beams maybe enough

The value of θ_{13} decides the strategy

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \propto \frac{1}{\sin\theta_{13}}$$

Signal statistics is maximum BUT $\nu - \overline{\nu}$ asymmetry is minimum
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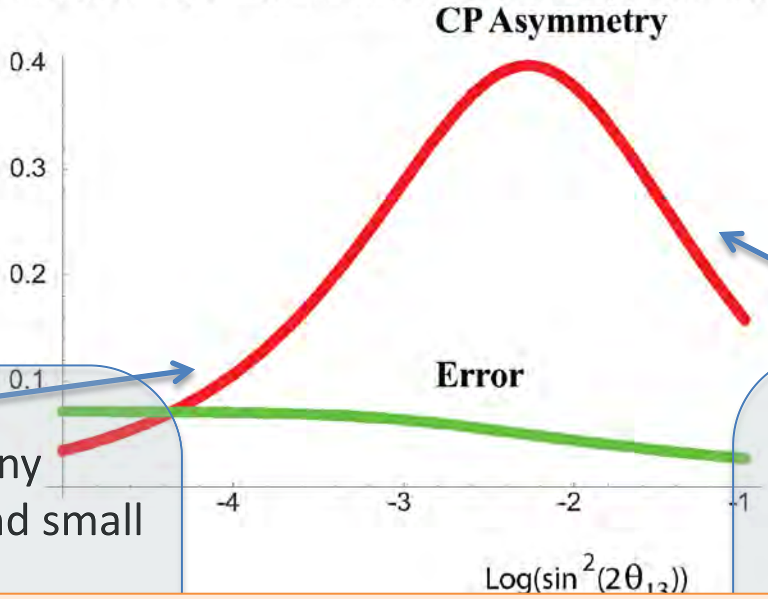
Blondel, Cervera, Donini, Huber, MM, Strolin, Acta Phys. Polon. B **37** (2006) 2077



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$\nu_\mu - \nu_e$ transitions are tiny
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Conventional neutrino
are not enough

LARGE VALUES:
$\nu_\mu - \nu_e$ transitions are large
Relaxed constraints on statistics and background rates
ion asymmetry is small
ffects of systematic errors

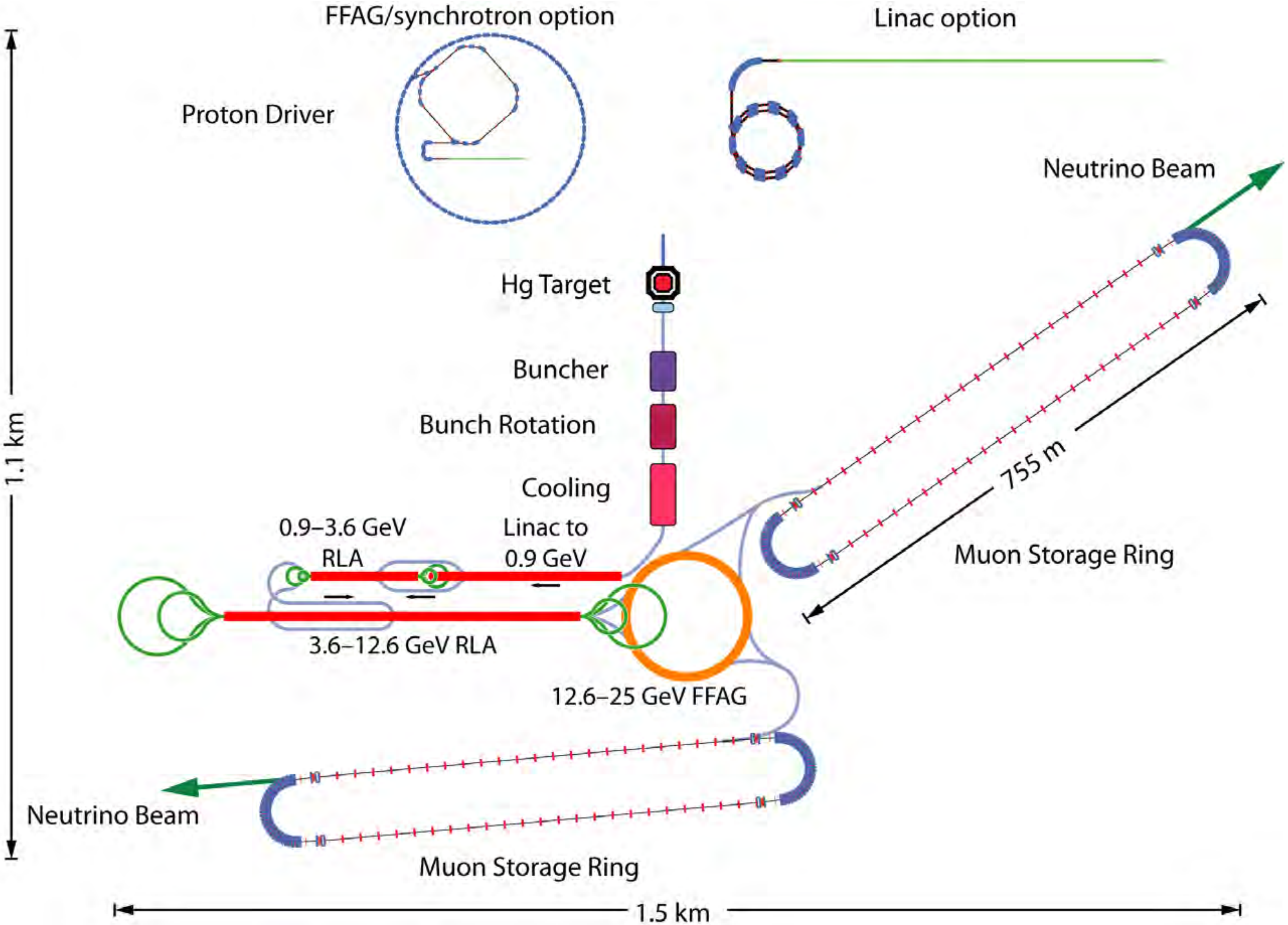
ntional neutrino beams
enough

New concepts for neutrino beams, for the moment, have been abandoned
CP violation searches are designed to use «brute force» upgrades on conventional neutrino beams

New concepts: Neutrino Factories

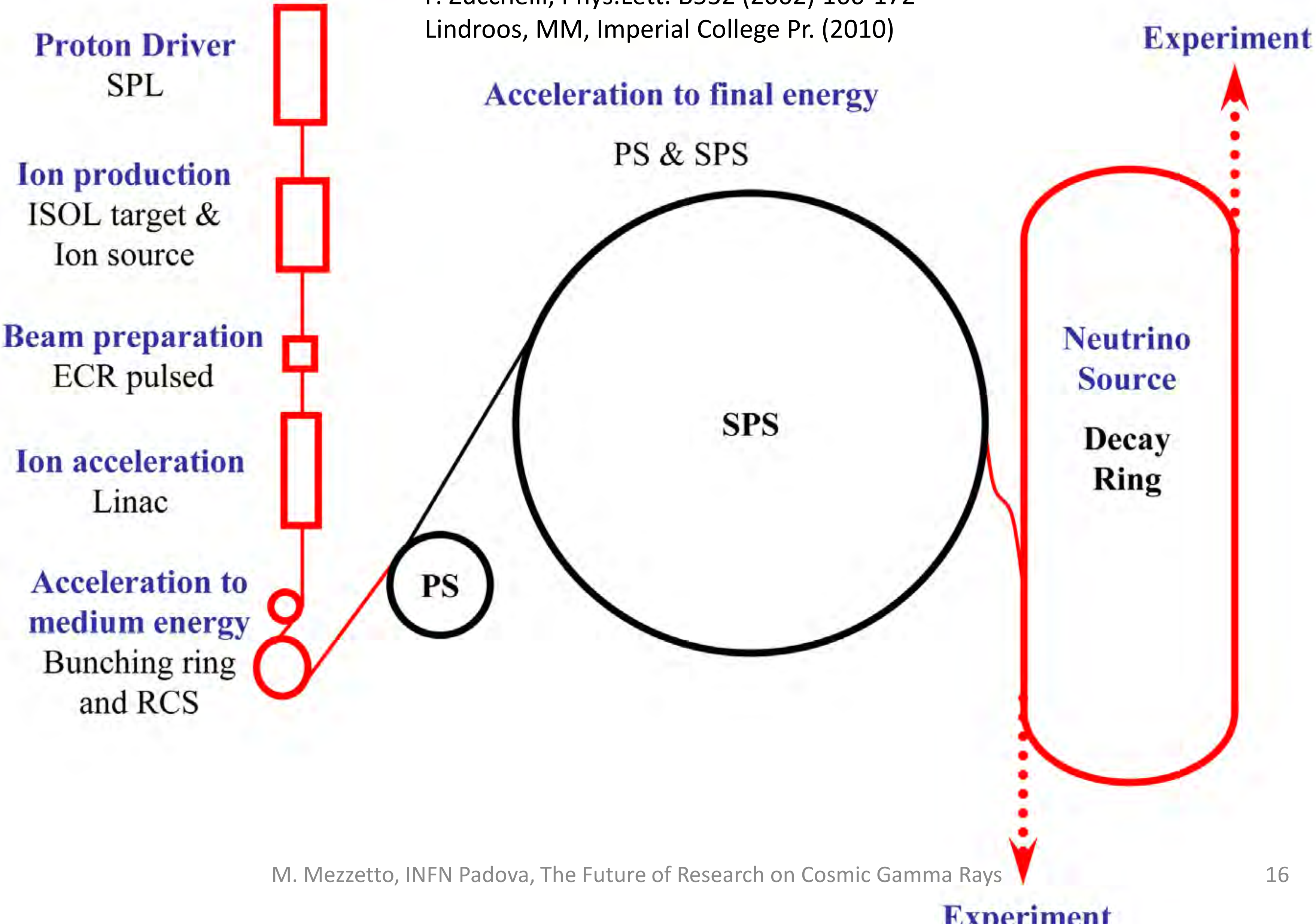
S. Geer, Phys. Rev. D57 (1998) 6989–6997

IDS-NF, arXiv:1112.2853

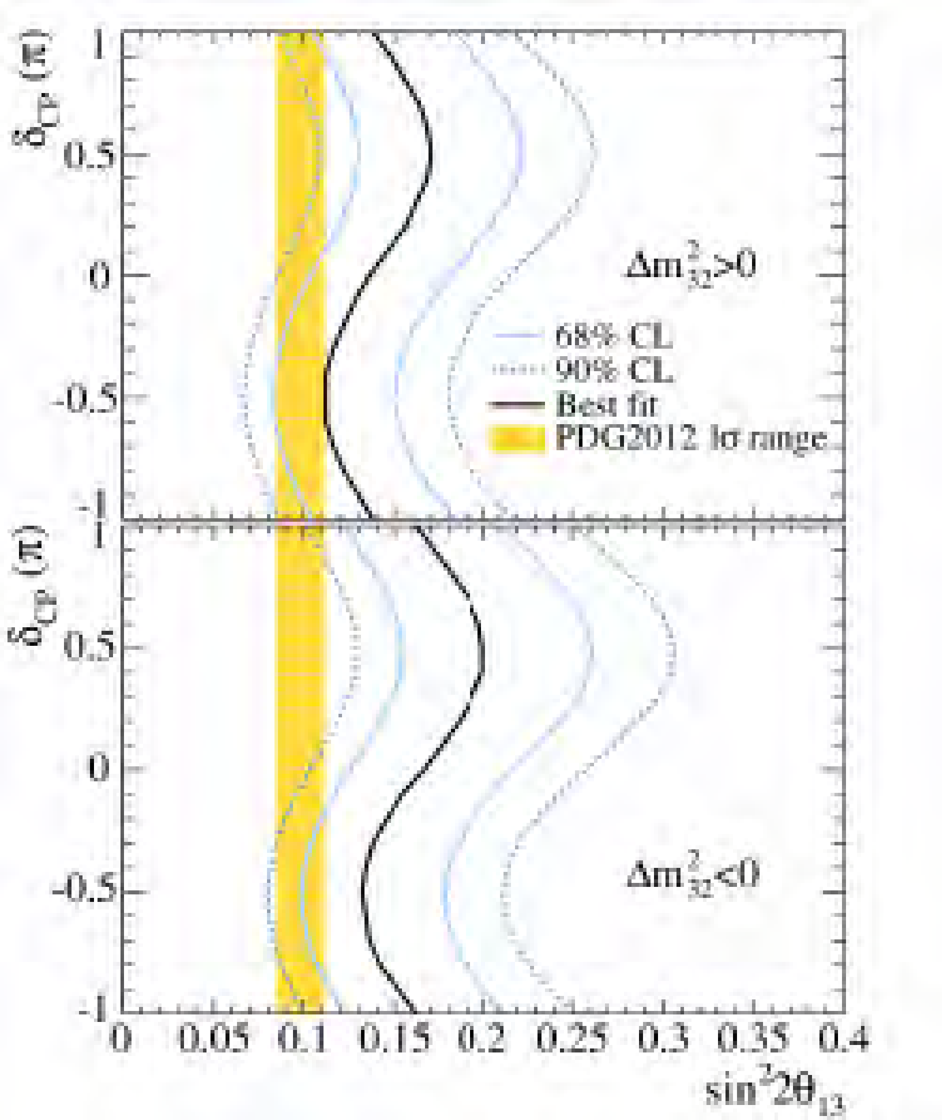


New concepts: Beta Beams

P. Zucchelli, Phys.Lett. B532 (2002) 166-172
Lindroos, MM, Imperial College Pr. (2010)



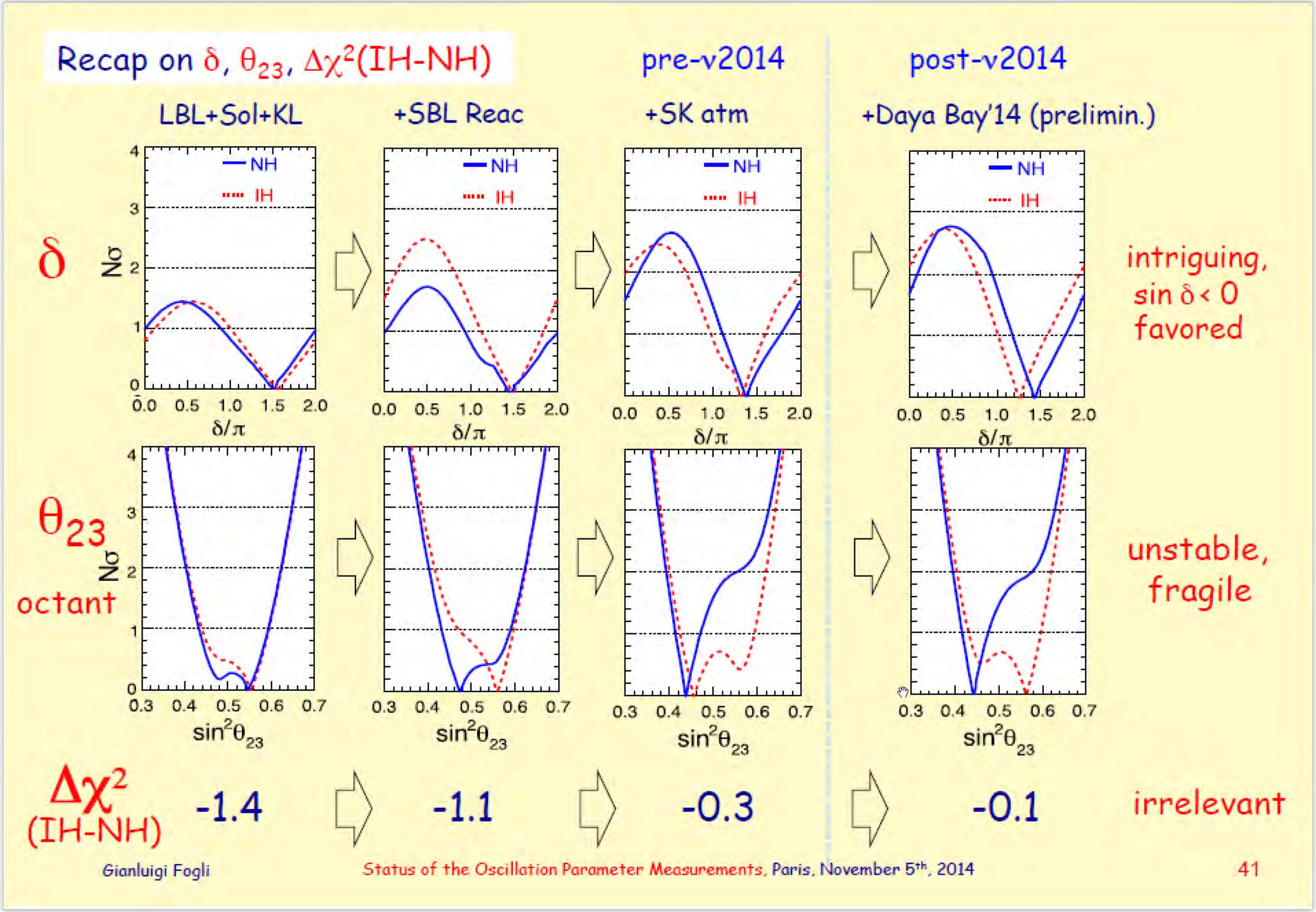
What we know today about δ_{CP}



T2K measures a combination of θ_{13} and δ_{CP} while reactors measure pure θ_{13} effects.

Their combination favour δ_{CP} =-π/2

Hint of CP violation?



Recap on δ, θ_{23}, $\Delta\chi^2$(IH-NH)

pre-ν2014

post-ν2014

δ

intriguing,
$\sin\delta < 0$
favored

θ_{23}
octant

unstable,
fragile

$\Delta\chi^2$
(IH-NH)

-1.4 → -1.1 → -0.3 → -0.1

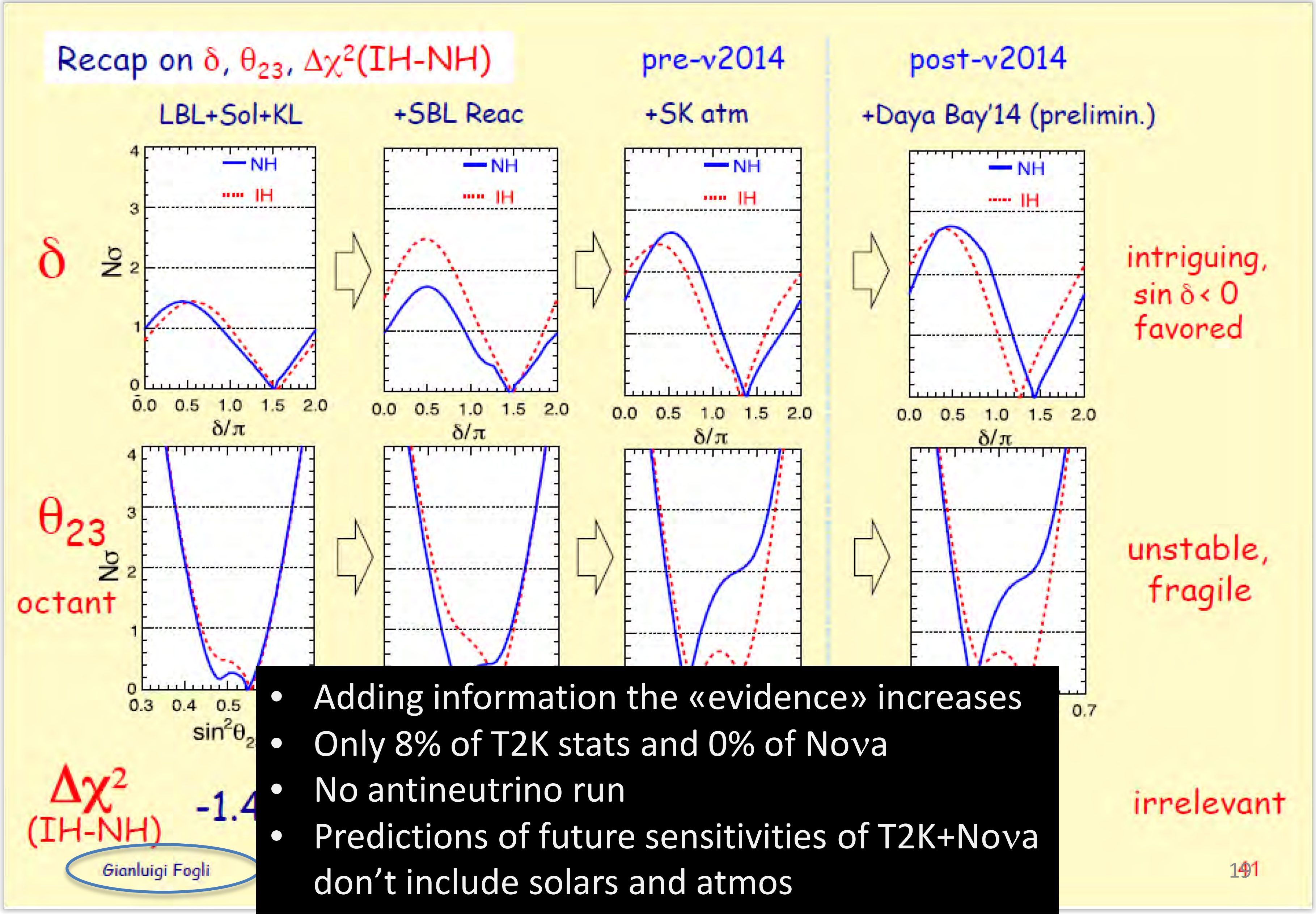
irrelevant

Gianluigi Fogli

Status of the Oscillation Parameter Measurements, Paris, November 5th, 2014

41

Hint of CP violation?



Recap on δ, θ_{23}, $\Delta\chi^2$(IH-NH)

pre-ν2014

post-ν2014

intriguing, sin δ < 0 favored

unstable, fragile

irrelevant

Gianluigi Fogli

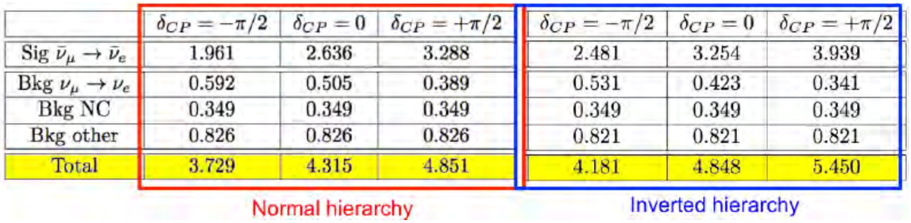
41

- Adding information the «evidence» increases
- Only 8% of T2K stats and 0% of Nova
- No antineutrino run
- Predictions of future sensitivities of T2K+Nova don't include solars and atmos

Two very recent results

Antineutrinos at T2K (EPS 2015)

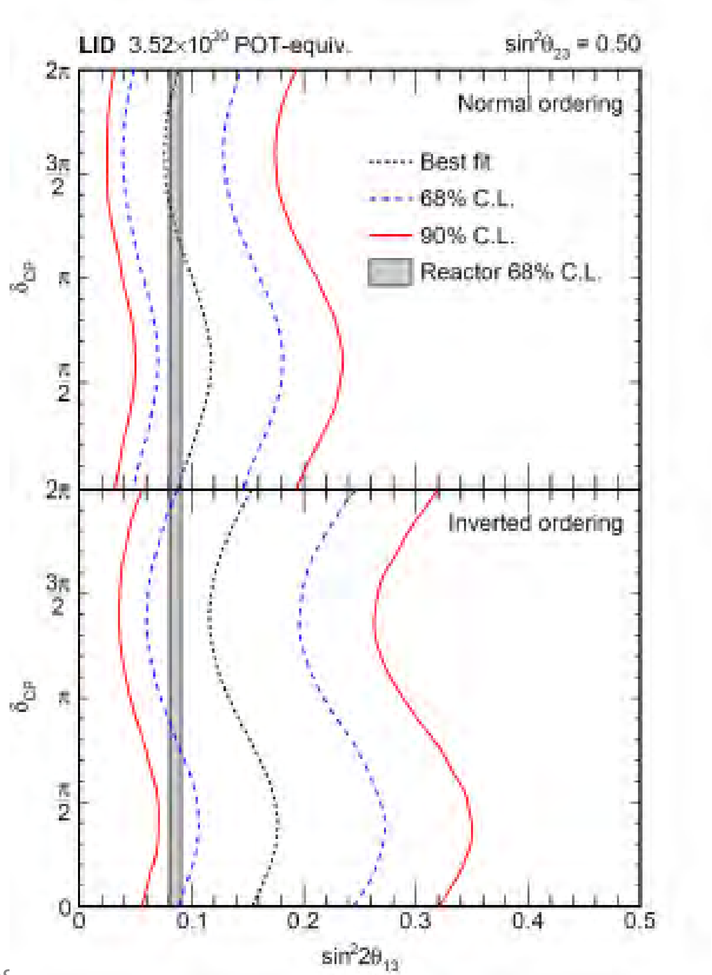
Exposure: 4 10^{20} pot
3 events detected
Excludes that ν_e excess is due to unknown backgrounds
3 times more statistics next year



	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288	2.481	3.254	3.939
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389	0.531	0.423	0.341
Bkg NC	0.349	0.349	0.349	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826	0.821	0.821	0.821
Total	3.729	4.315	4.851	4.181	4.848	5.450

Normal hierarchy
Inverted hierarchy

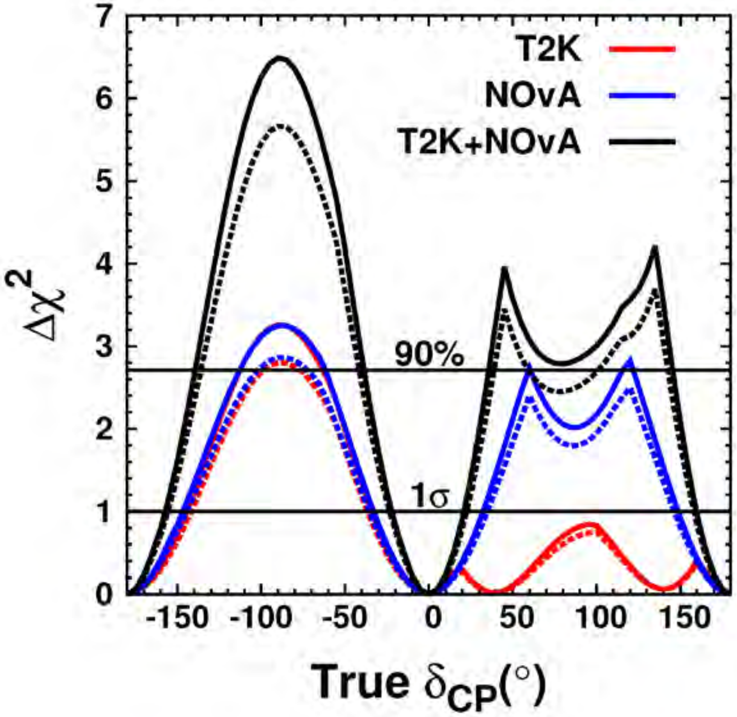
Nova, 7.6% of full statistics (LP2015)



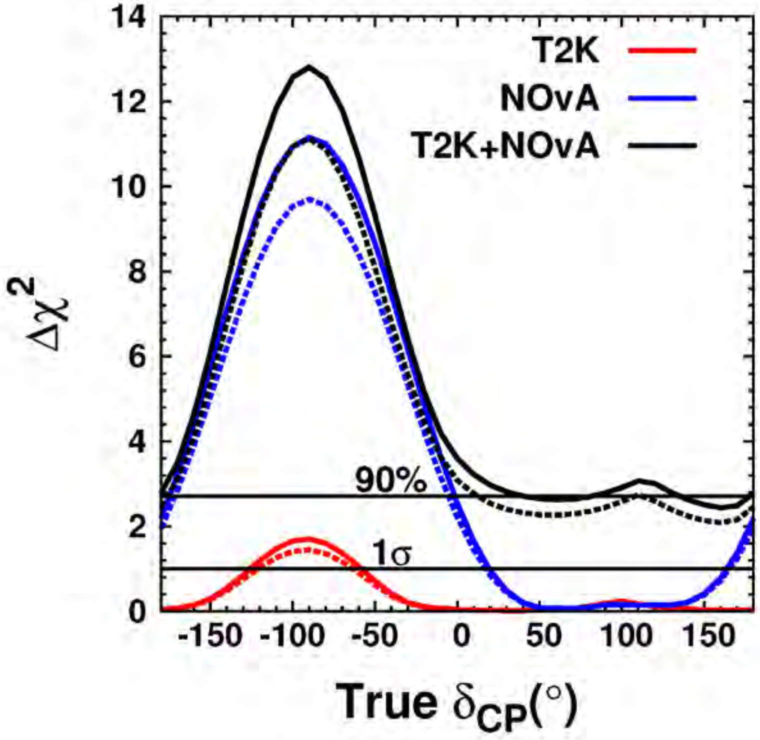
Projection of T2K+Novα at full statistics

From T2K collaboration: **PTEP 2015 (2015) 4, 043C01**

CP

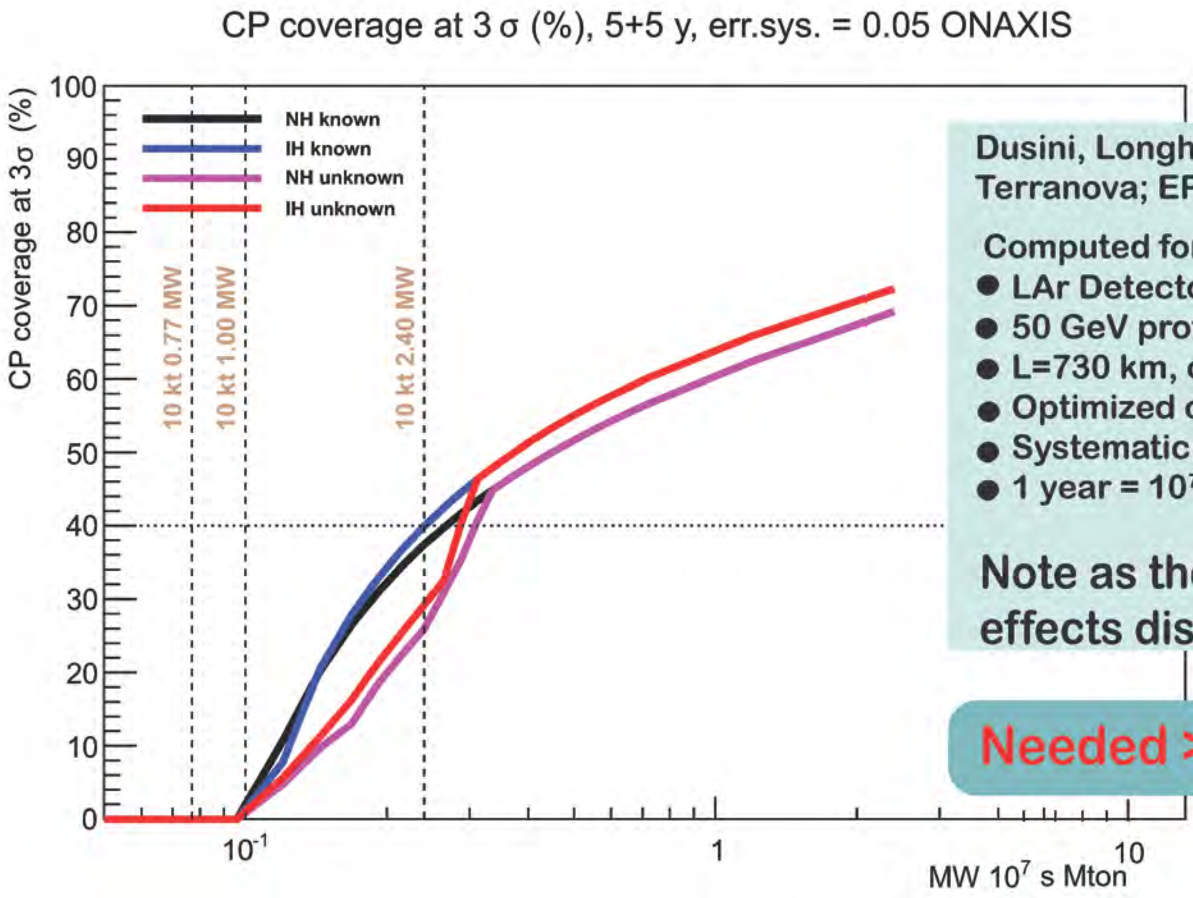


MH



Full statistics of the running experiments: T2K and Novα, equal ν and $\bar{\nu}$ runs, dashed lines: including systematics

Good CP coverage requires order of 1 Mton *x* Mwatt *x* year



Dusini, Longhin, MM, Patrizii, Sioli, Sirri, Terranova; EPJ C73 (2013) 2392

Computed for:

- **LAr Detector**
- **50 GeV proton beam**
- **L=730 km, on-axis**
- **Optimized optics**
- **Systematic errors: 5%**
- **1 year = 10^7 s**

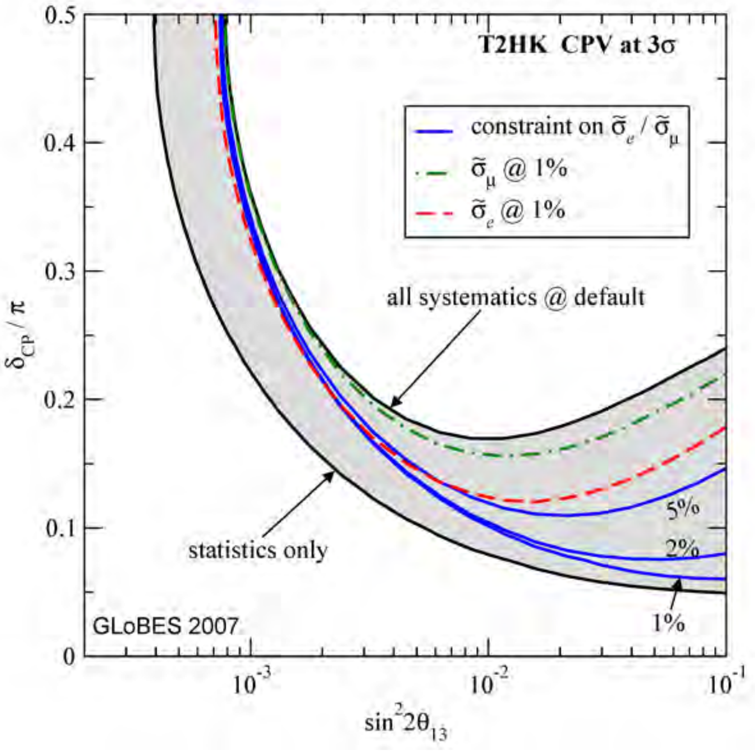
Note as the MH degeneracy effects disappear with exposure

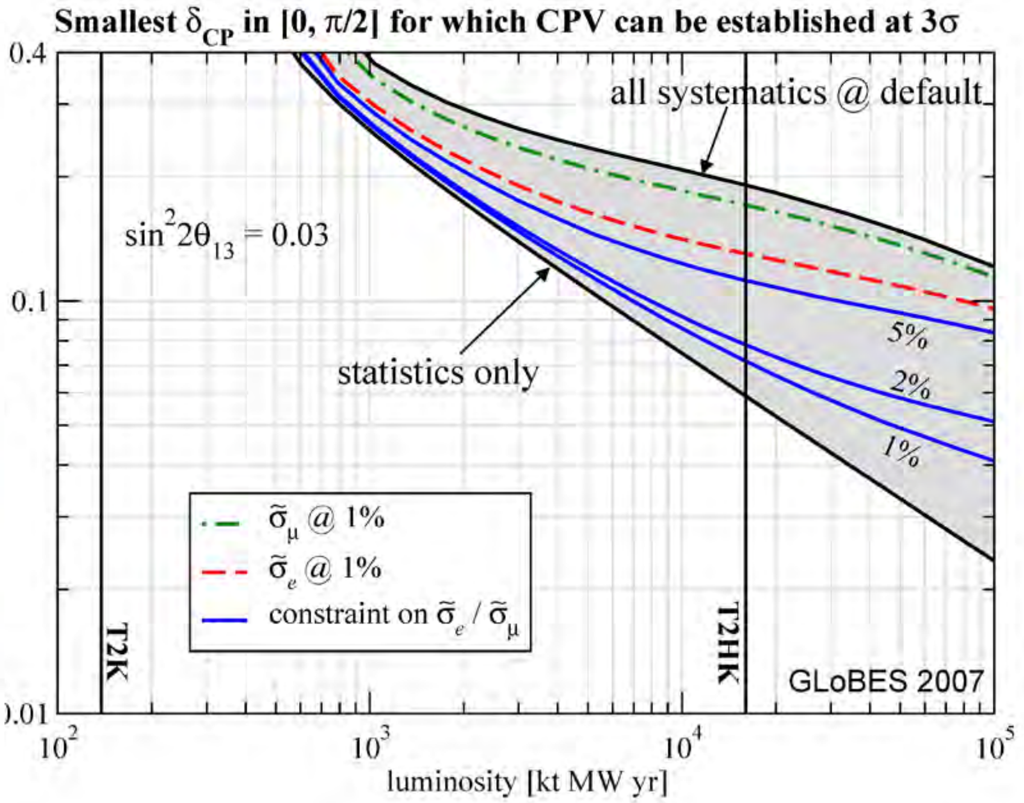
Needed >1 Mton x MW x year

Effects of systematic errors on CP sensitivity

Since a long time they are known to be the real bottleneck (or in positive the only convincing way of enhancing the experiment sensitivity)

Huber, MM, Schwetz, JHEP 0803 (2008) 021





Systematic errors

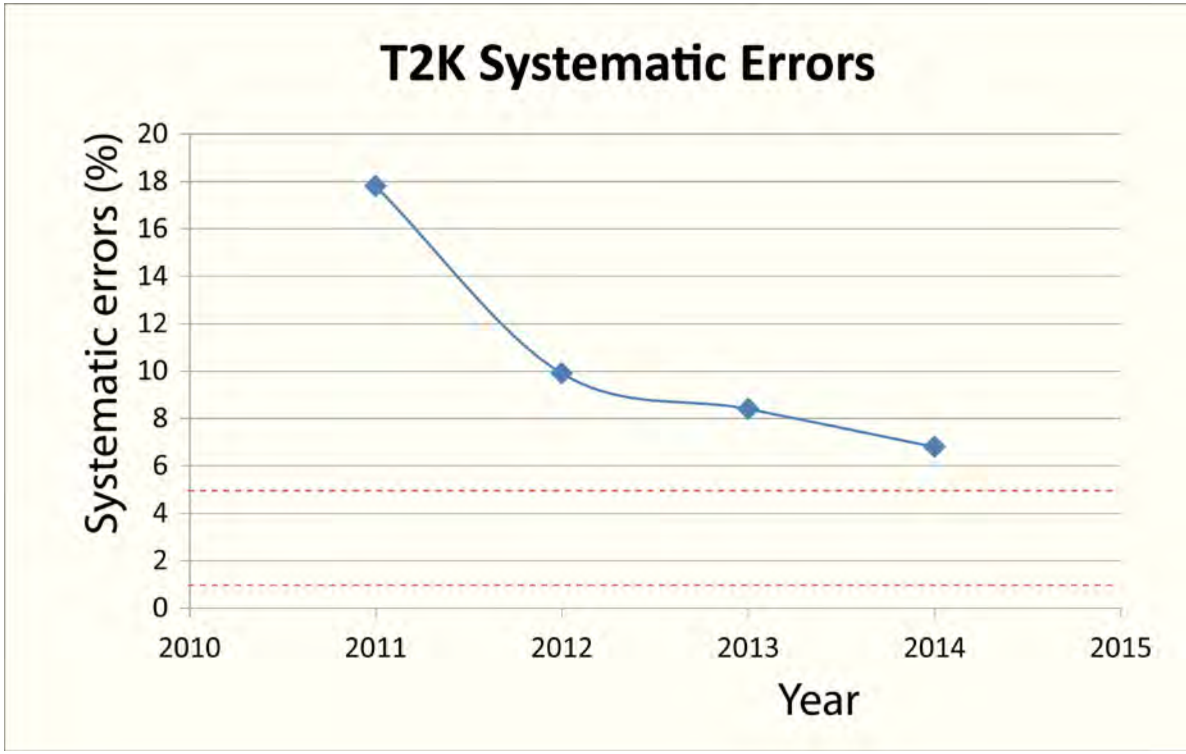
The experience of T2K

A sophisticated close detector station: ND280 + Ingrid

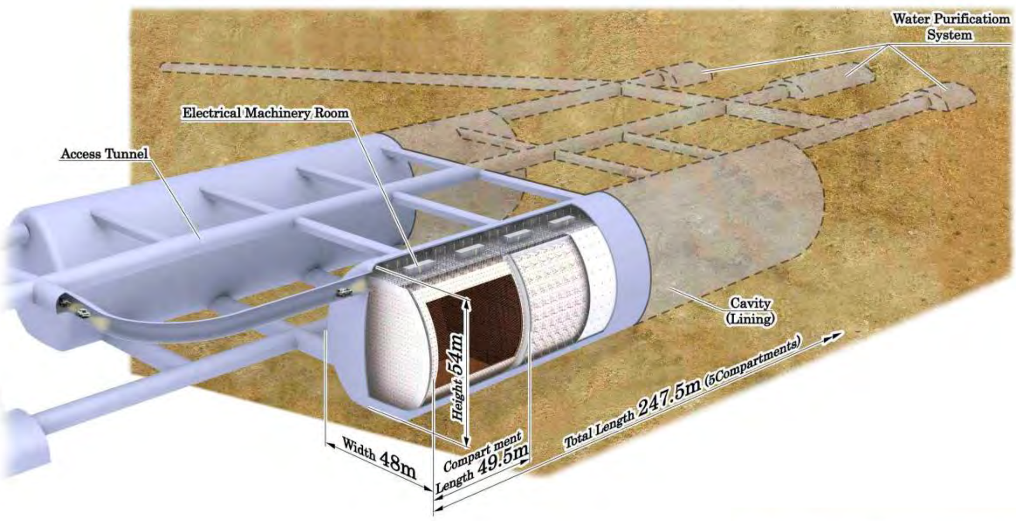
The best quality hadroproduction data ever produced (NA61) already included

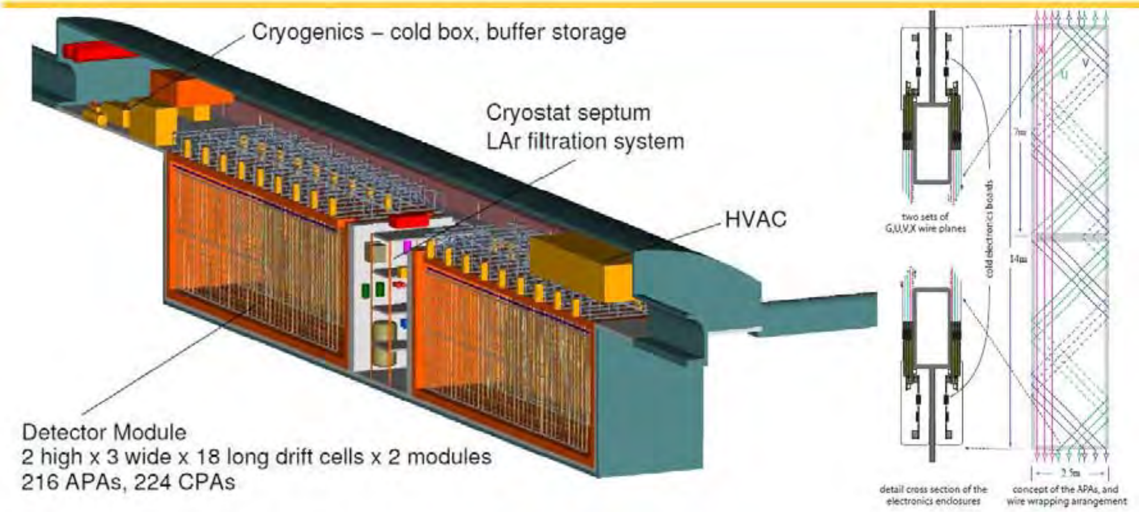
A huge, qualified, effort by the largest collaboration ever seen in neutrino physics

At present limited by statistics



Two players: Dune and HyperKamiokande





Hyper-Kamiokande Detector

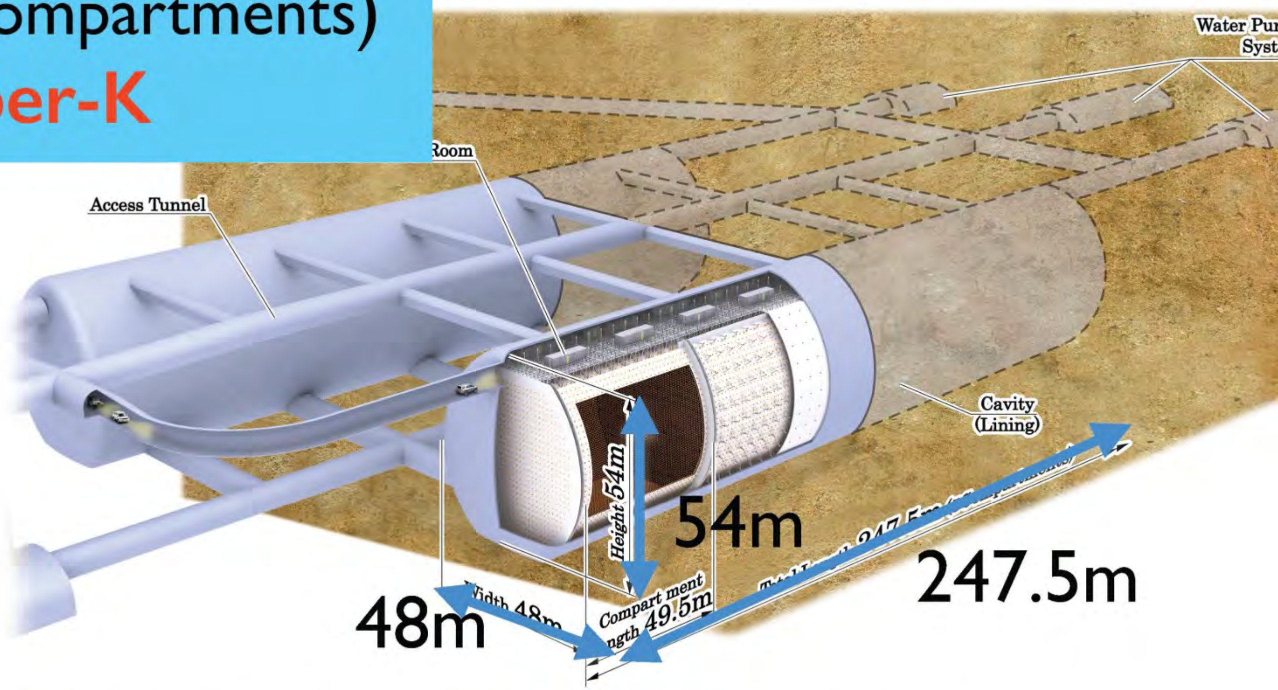
Total volume:	0.99 Mton
Inner volume:	0.74 Mton
Outer volume:	0.2 Mton
Fiducial volume:	0.56 Mton

(0.056Mton × 10 compartments)

x25 of Super-K

Hyper-K WG,
arXiv:1109.3262
arXiv:1309.0184
arXiv:1502.05199
(to appear in PTEP)

- 99,000 20” PMT for inner-det. (20% coverage)
- 25,000 8” PMT for outer-det.



Multi-purpose detector for a wide range of science

M. Thomson, 2nd LNI

LBNF and DUNE

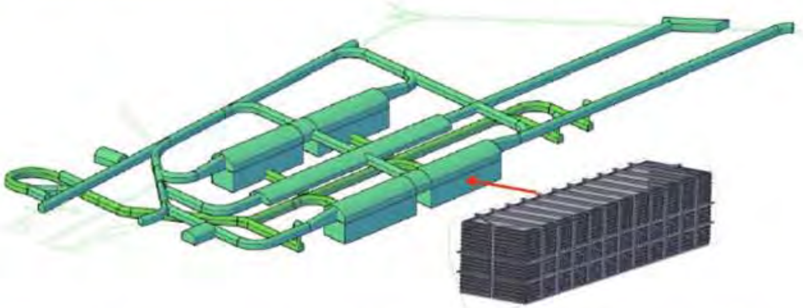
LBNF-DUNE: 1.2 MW beam from FNAL, 40 kt Lar TPC at SURF, 1st 10kt installation in 2021, CD-1 refresh out in June, CD2a-CD3a (cavern) this autumn

★ **Three main pillars**

1) **LBL Neutrino Physics**
   - CPV in the leptonic sector
   - Mass Hierarchy
   - Precision oscillation physics (θ_{23} octant, …)
   - Testing 3-flavour paradigm
2) **Nucleon Decay**
   - Targetting SUSY-favoured modes, e.g. $p \to K^{+}\nu$
3) **Astro-particle Physics**
   - Core collapse super-nova, sensitivity to $\boldsymbol{\nu_e}$

\+ **Precision neutrino physics in the near neutrino detector**

★ **LBNF will provide "homes" for the DUNE FD modules**
- Four caverns + four cryostats for four 10 kt FD LAr-TPCs



★ **Modular design provides flexibility w.r.t. FD design and funding**

CP violation: general considerations

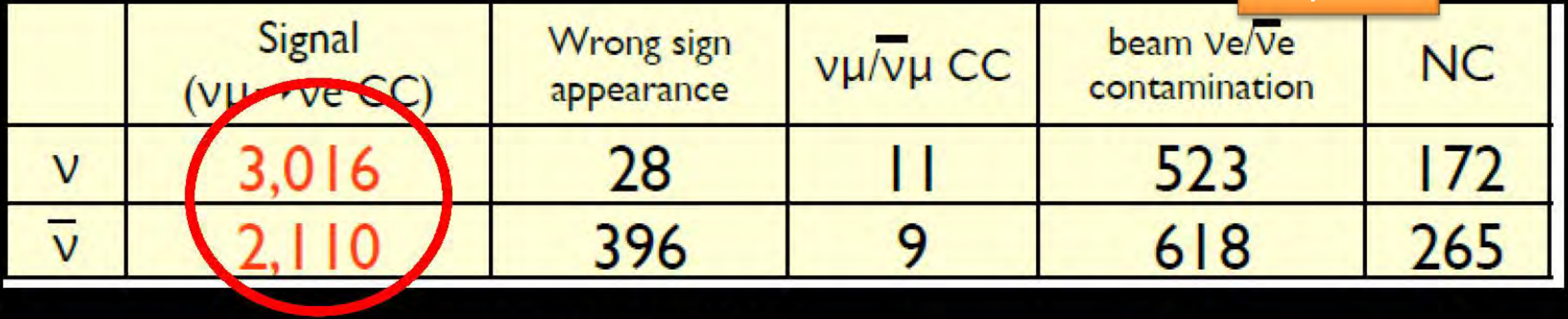
- **HK**:
  - short baseline →no matter effects: pure CP but reduced MH
  - Off axis → reduced intrinsic ν_e contamination, reduced NC backgrounds

- **DUNE**:
  - Long baseline → sensitive to matter effects: excellent performances in MH
  - On axis: second oscillation maximum and sensitive to ν_τ appearance (tiny effects at 1300 km)
  - On axis: Extended lever of arm for measurement of oscillation parameters

CP violation: just event numbers

HYPERK , $\delta_{CP}=0$, and NH

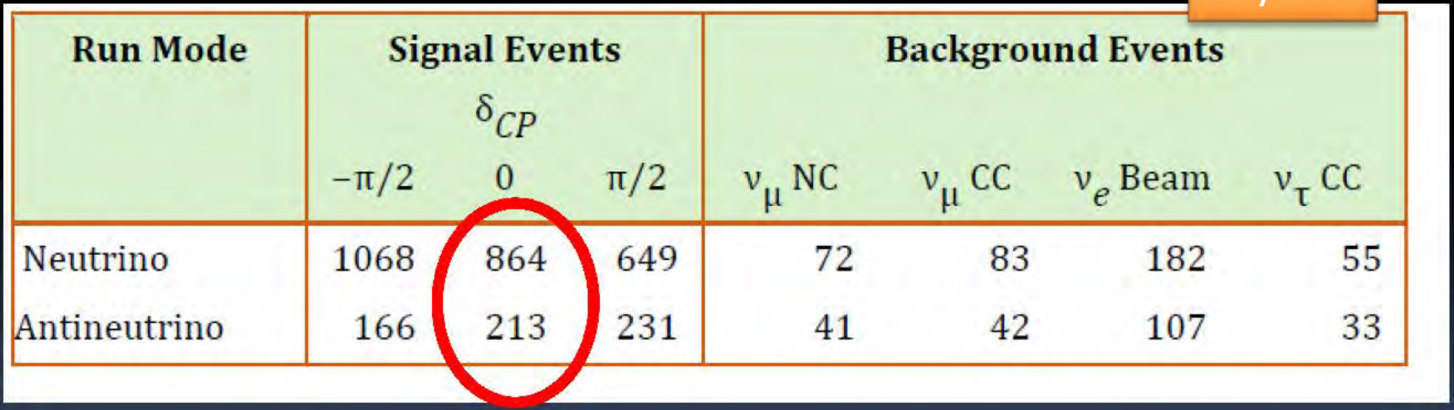
10 years



	Signal ($\nu\mu \to \nu e$ CC)	Wrong sign appearance	$\nu\mu/\bar{\nu}\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

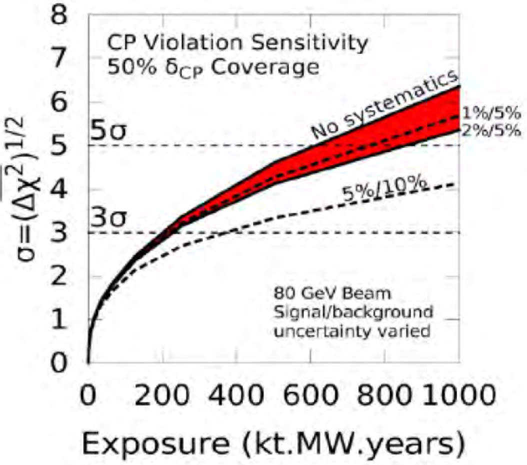
ELBNF 40KT

6 years

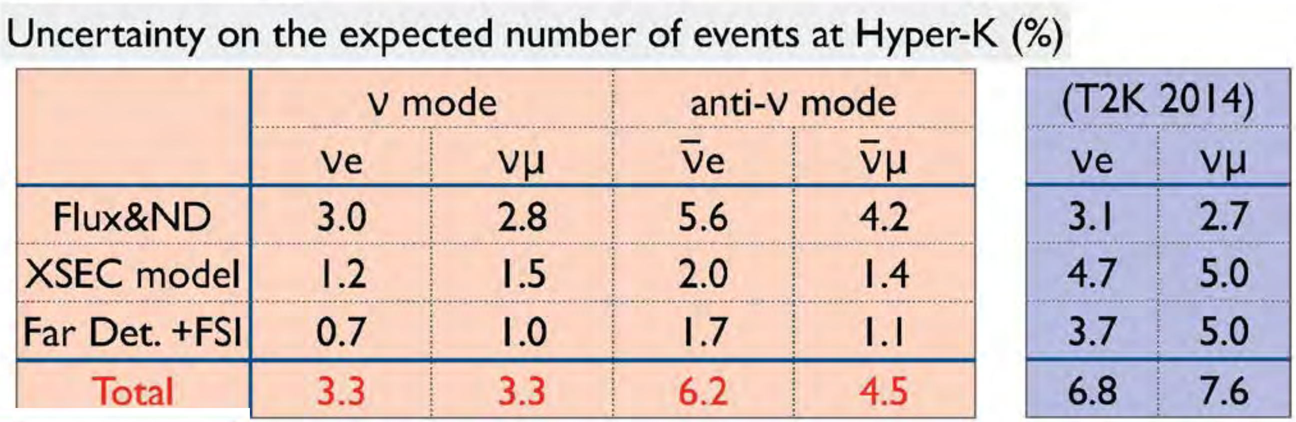


Run Mode	**Signal Events**			**Background Events**			
		δ_{CP}					
	$-\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	1068	864	649	72	83	182	55
Antineutrino	166	213	231	41	42	107	33

CP violation: systematic errors



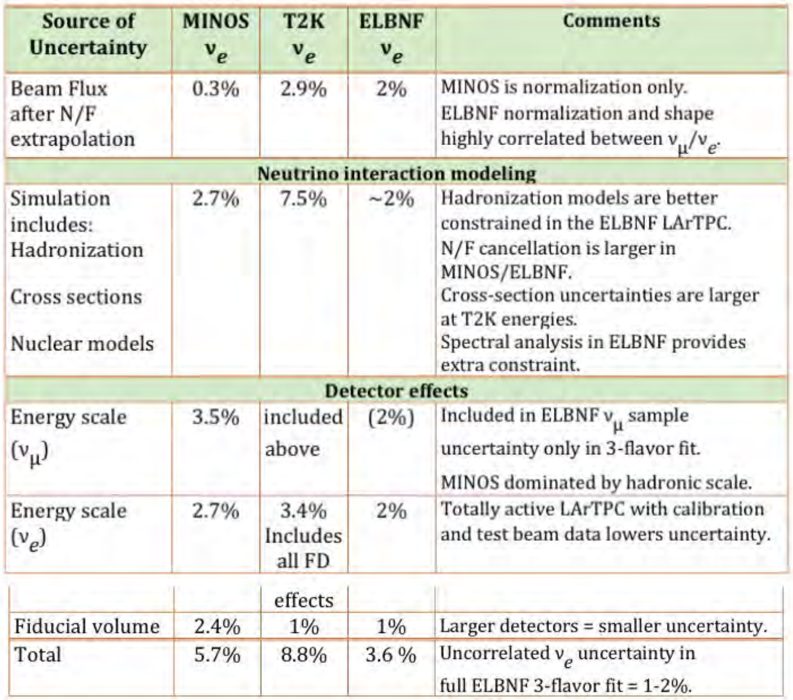
HK estimation assuming identical close detector as T2K



Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode	
	νe	νμ	$\bar{\nu}$e	$\bar{\nu}$μ
Flux&ND	3.0	2.8	5.6	4.2
XSEC model	1.2	1.5	2.0	1.4
Far Det. +FSI	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

(T2K 2014)	
νe	νμ
3.1	2.7
4.7	5.0
3.7	5.0
6.8	7.6



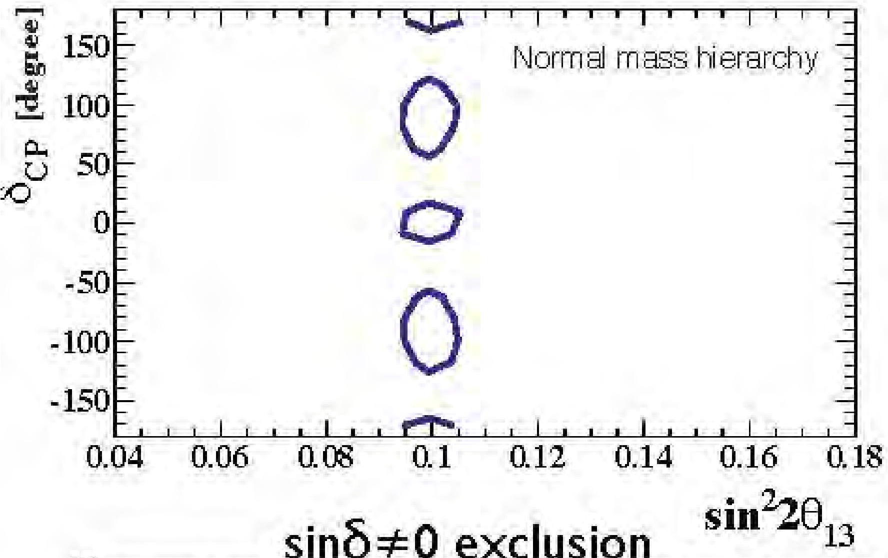
Source of Uncertainty	MINOS ν_e	T2K ν_e	ELBNF ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	2.9%	2%	MINOS is normalization only. ELBNF normalization and shape highly correlated between ν_μ/ν_e.
Neutrino interaction modeling				
Simulation includes: Hadronization Cross sections Nuclear models	2.7%	7.5%	~2%	Hadronization models are better constrained in the ELBNF LArTPC. N/F cancellation is larger in MINOS/ELBNF. Cross-section uncertainties are larger at T2K energies. Spectral analysis in ELBNF provides extra constraint.
Detector effects				
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in ELBNF ν_μ sample uncertainty only in 3-flavor fit. MINOS dominated by hadronic scale.
Energy scale (ν_e)	2.7%	3.4% Includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	8.8%	3.6 %	Uncorrelated ν_e uncertainty in full ELBNF 3-flavor fit = 1-2%.

Dune estimation extrapolating from Minos (no LAr close detector data so far) arXiv:1502.05199 (to appear in PTEP)

Expected sensitivity to CP asymmetry

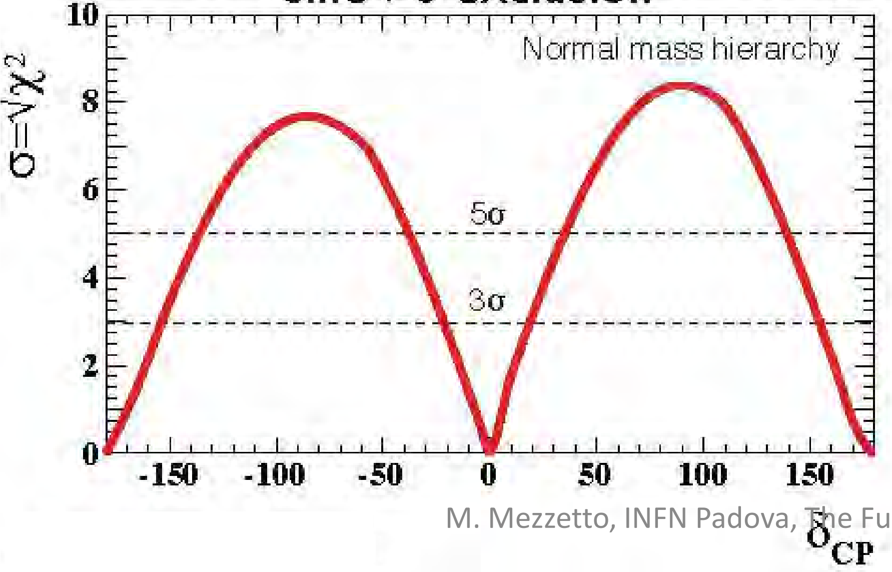
Mass hierarchy assumed to be known

90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)

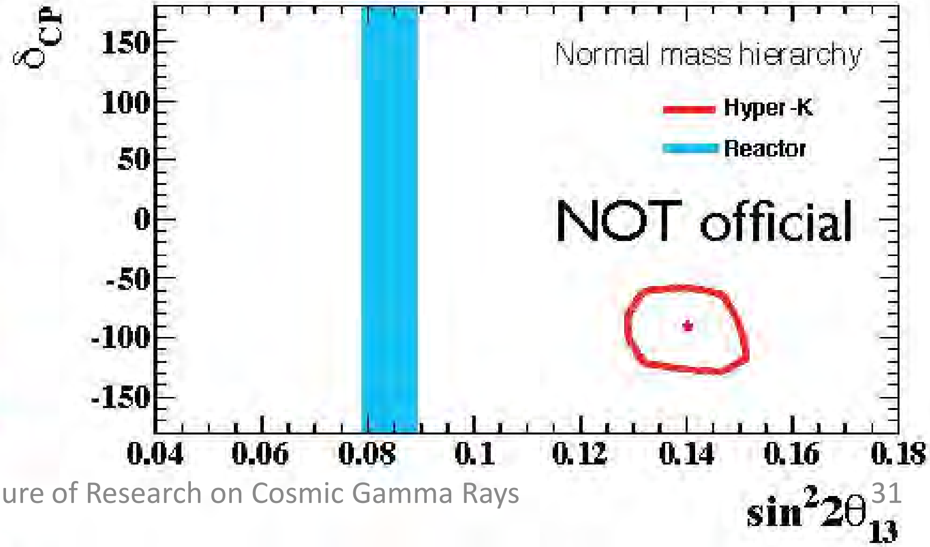


- Exclusion of $\sin\delta=0$
  - $>3\sigma$ for 76% of δ
  - $>5\sigma$ for 58% of δ
- Possible to establish CP violation in the lepton sector!

sinδ≠0 exclusion



Or, we may see some surprise

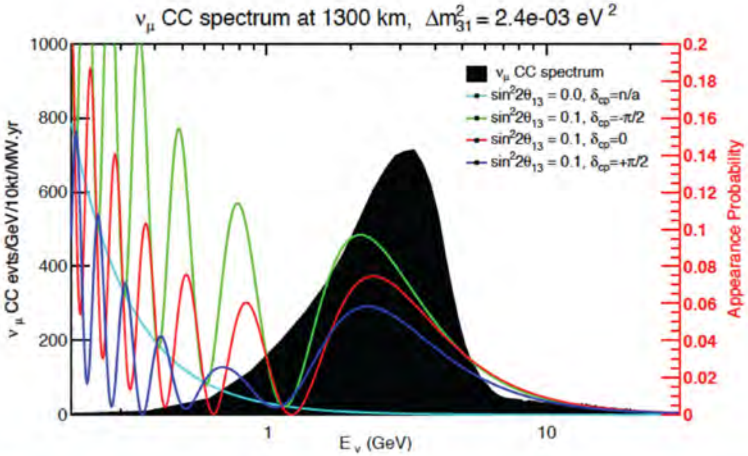


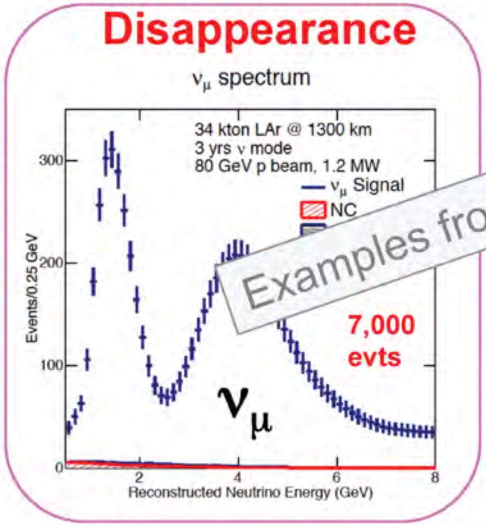
LBL Scientific Strategy

★ **Measure oscillated spectra at 1300 km in a wide-band beam**

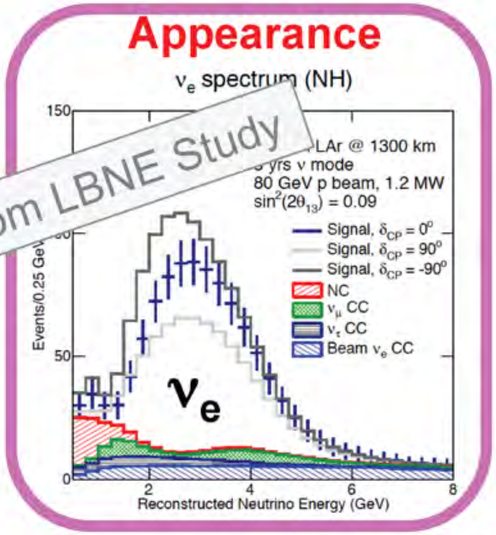
★ **Determine MH and θ_{23} octant, probe CPV and search for ν non-standard-interactions (NSIs) in a single experiment**

- **Long baseline:**
  - Matter effects are large (~40 %)
  - MH and CPV effects are separable: removes ambiguities
- **Wide-band ν_μ beam:**
  - Measure ν_e and ν_μ spectra over wide range of energies





Disappearance

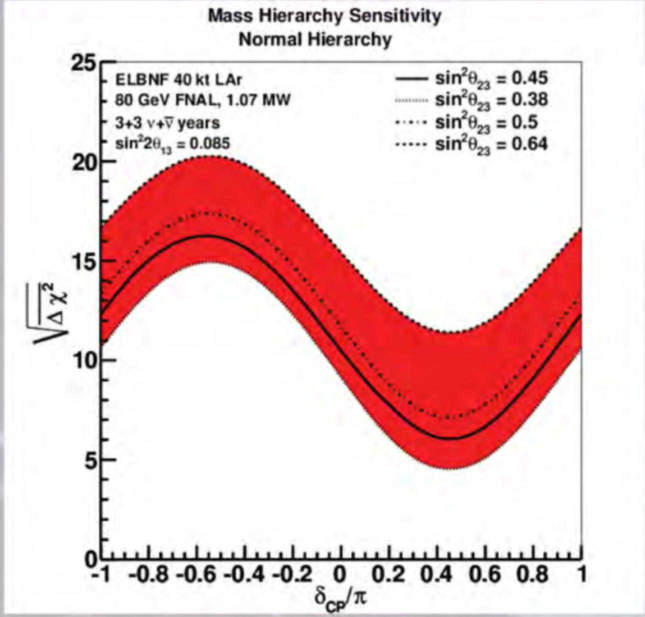


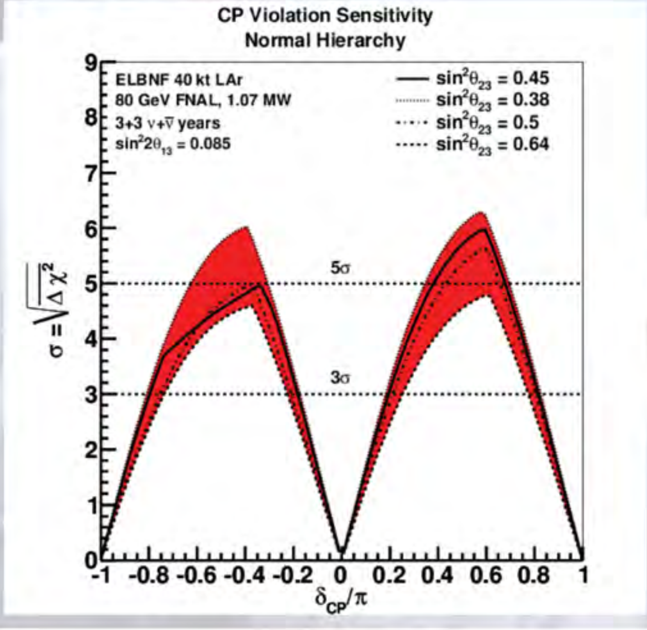
Appearance

Examples from LBNE Study

e.g. CPV & MH

- **Ultimate sensitivity depends:**
  - Beam power – need νs
  - Detector mass – detect the νs
  - Experiment/Facility design – optimize for CPV
  - Beam efficiency
- **Sensitivities (as presented in "ELBNF" LoI)**





Proton Decay

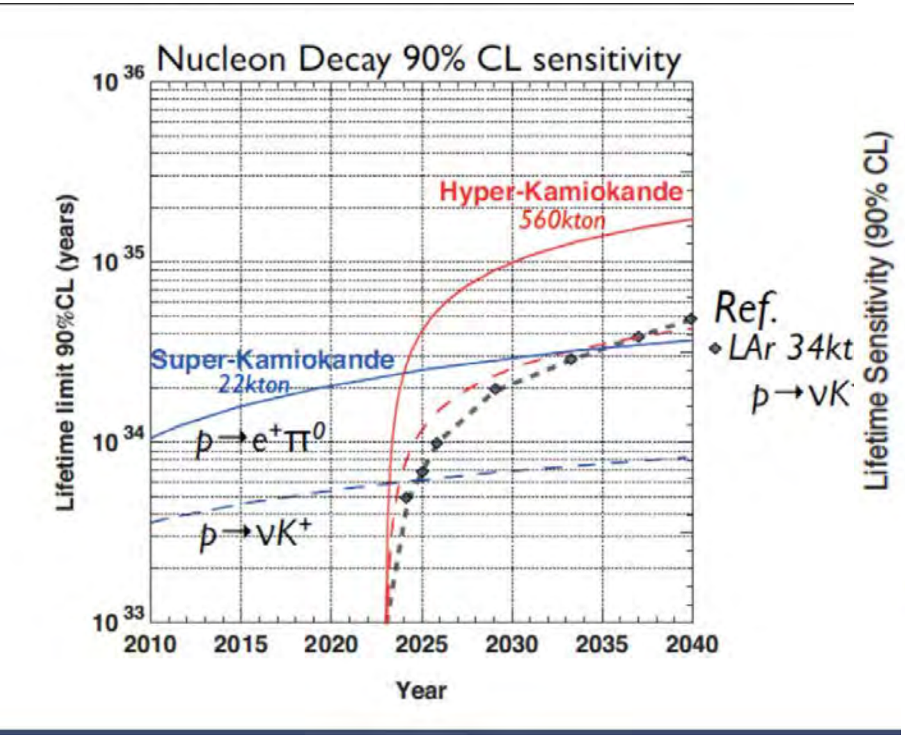
HK

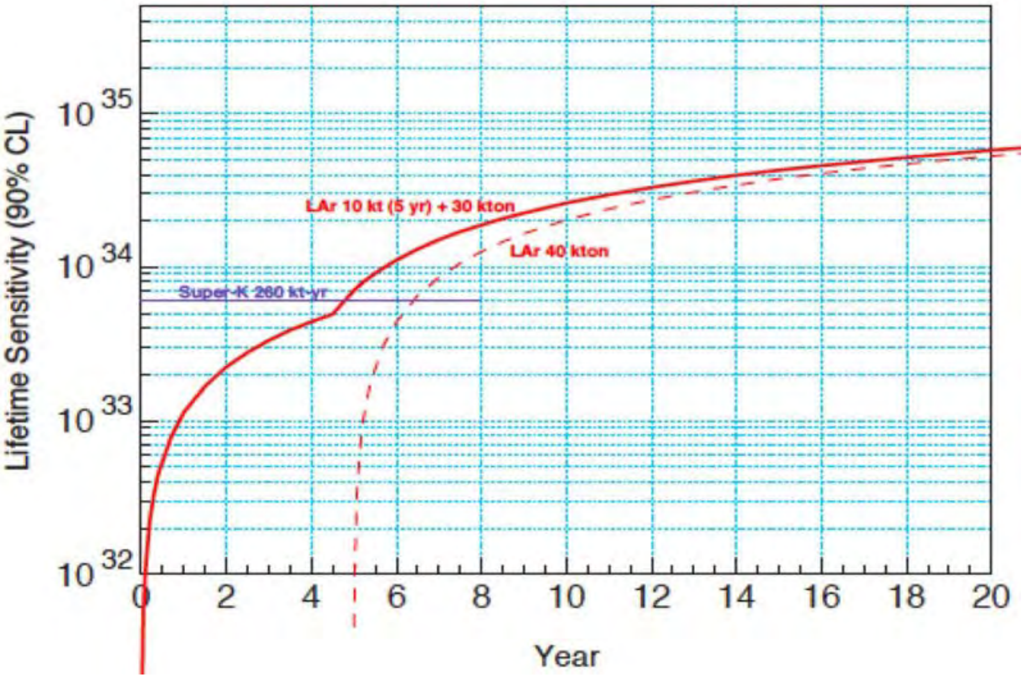
– $p \to e^+ + \pi^0$ 1.3×10^{35} yrs (90% CL UL)
5.7×10^{34} yrs (3σ discovery)

– $p \to \bar{\nu} + K^+$ 3.2×10^{34} yrs (90% CL UL)
1.2×10^{34} yrs (3σ discovery)

DUNE

- Will improve Super-Kamiokande limits in very few channels, notably in the $p \to K^+ \nu$ channel





Supernova Neutrinos

HK

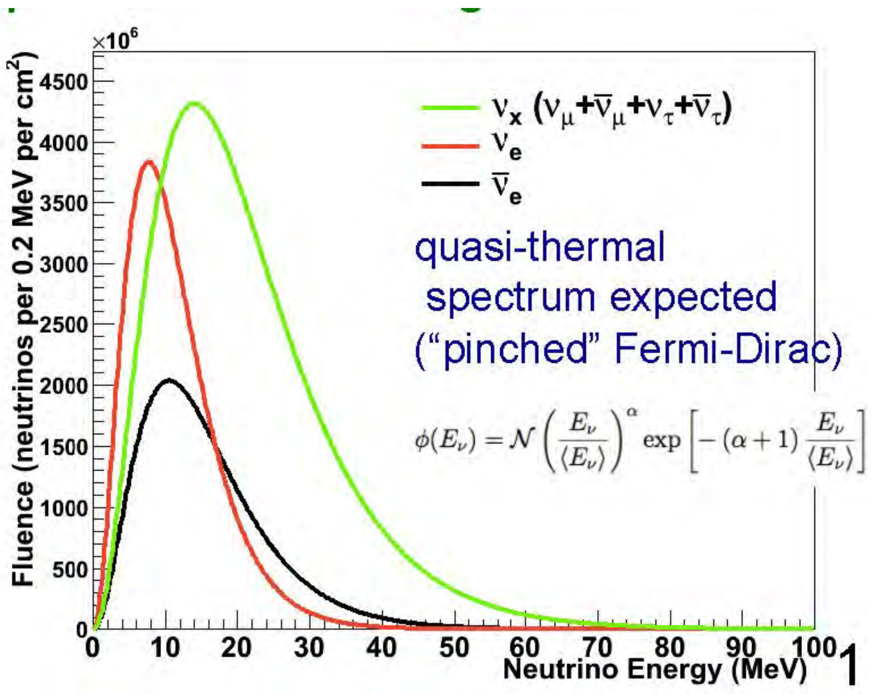
Mainly $\overline{\nu}_e$ from $\overline{\nu}_e\, p \rightarrow e^+\, p$

- Burst from galactic center (10 kpc)
  170,000 – 260,000 ν's
- Burst from Andromeda Galaxy
  30 – 50 ν's
- Supernova relic ν
  200 in 10 years

DUNE

Mainly ne from $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

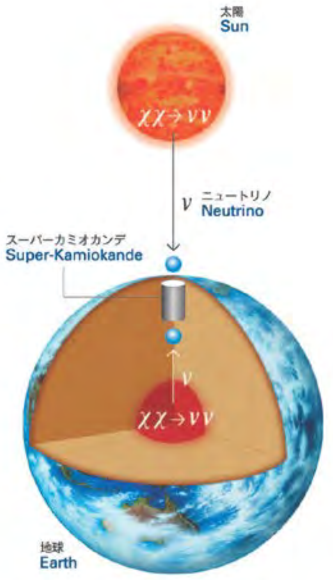
- Burst from galactic center (10 kpc)
  ~ 900 ν's in 10 kton detector



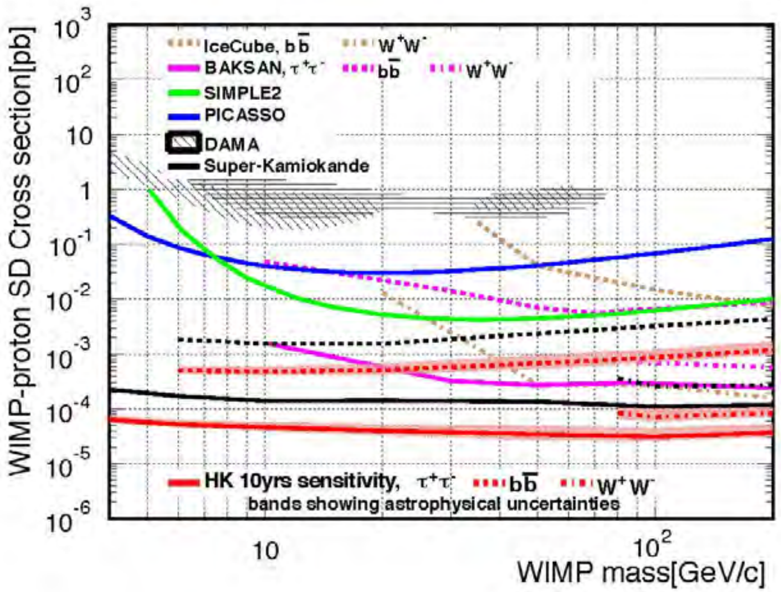
quasi-thermal spectrum expected ("pinched" Fermi-Dirac)

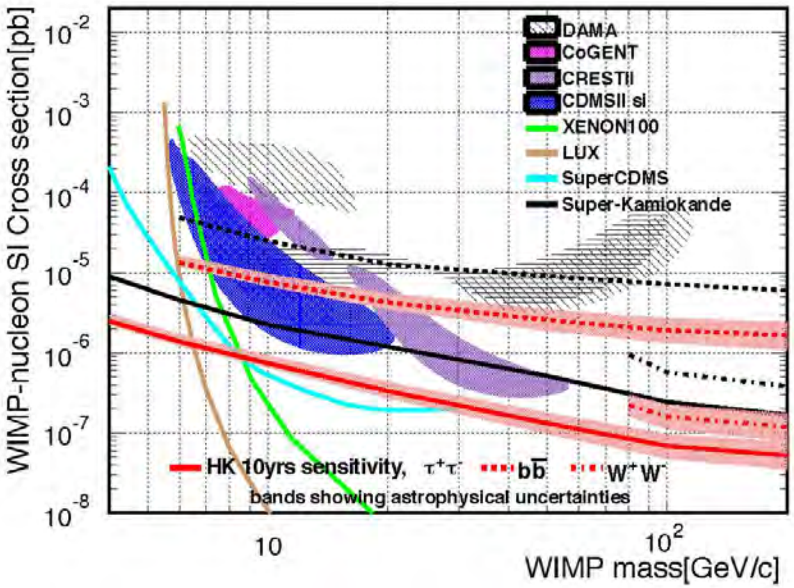
$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

WIMP annihilation at Sun

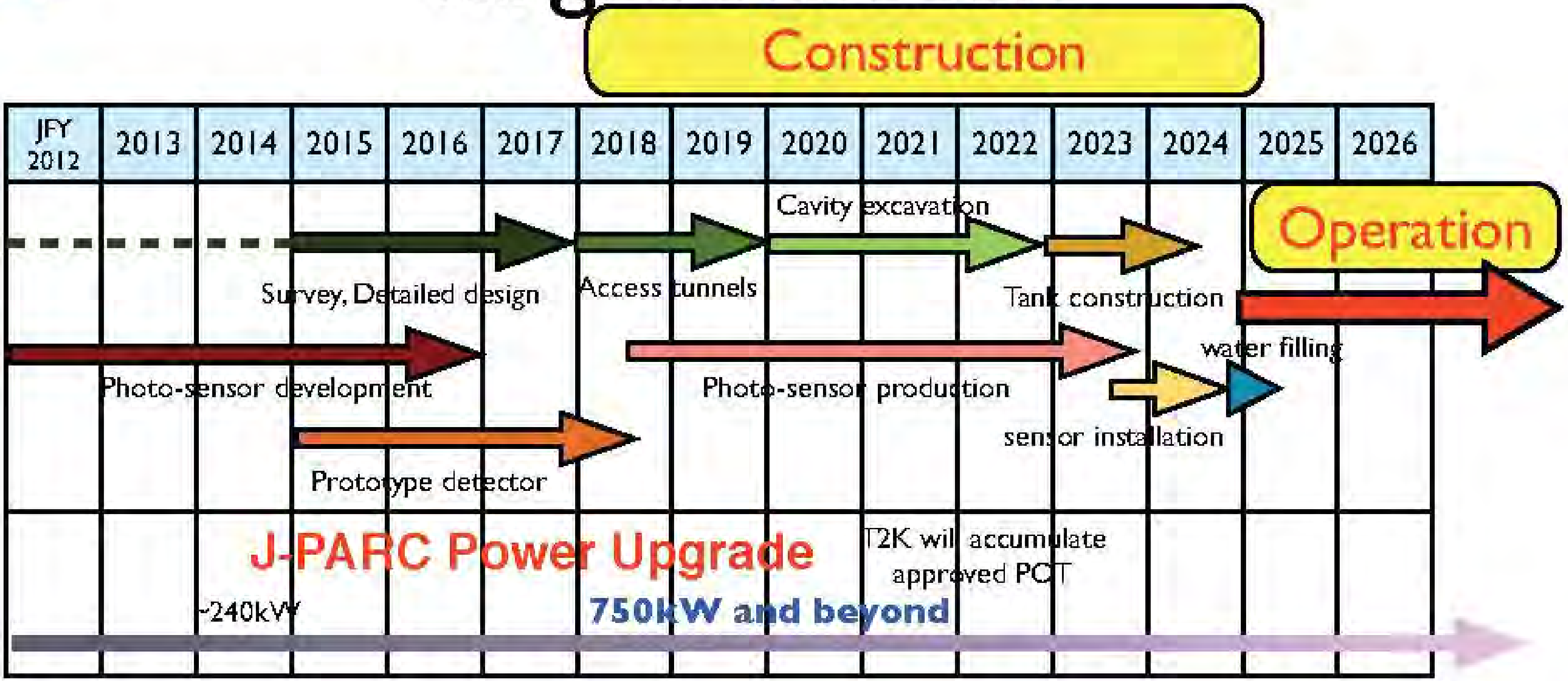


SK updated results recently presented by Nakahata-san at Neutel 2015
HK sensitivity by far the best Spin Dependent (SD) and very competitive in the SI low WIMP mass region





Target schedule



-2018 Construction starts

-2025 Data taking start

-2028 Discovery of Neutrino CP violation ?

-2030 Discovery of Proton Decay ?

-20xx Detection of supernova neutrinos

-20xx Discovery of new phenomena

Towards Construction

- ★ **DUNE-LBNF design builds on strength**
  - i.e. the in-depth work from LBNE, LBNO and others
  - Design at or beyond “conceptual design level”
  - Realistic resource-loaded schedule being assembled
  - DOE CD-1-Refresh in July 2015
    - “CDR level” review – defining cost range

- ★ **Things are progressing very rapidly**
  - DOE CD-2a/CD-3a for **Far Site CF** in Nov 2015
    - Would allow early start to far site excavation
    - **A major milestone**
- ★ **Aiming (realistically) for**
  - Far site excavation starting ~2018
  - Far detector installation starting **2021/2022**

Conclusions

- Bright future for accelerator neutrino physics, unfortunately not in Europe.
- Main goal: CP violation in the leptonic sector
- But also unitarity tests of the 3ν mixing matrix
- The gigantic far detectors have an excellent non-accelerator physics program in their own
- The sophisticated close detectors will have their hard job in measuring neutrino cross sections in all their tricky manifestations