

The CERN to Pyhasalmi long baseline experiment (LBNO): expression of interest

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Saclay, 27 juin 2012

Slides from A. Rubbia, A. Blondel, P. Huber ...

Expression of Interest

for a very long baseline neutrino oscillation experiment (LBNO)

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**230 signataires
(51 labos), dont
34 français dans 6
labos**

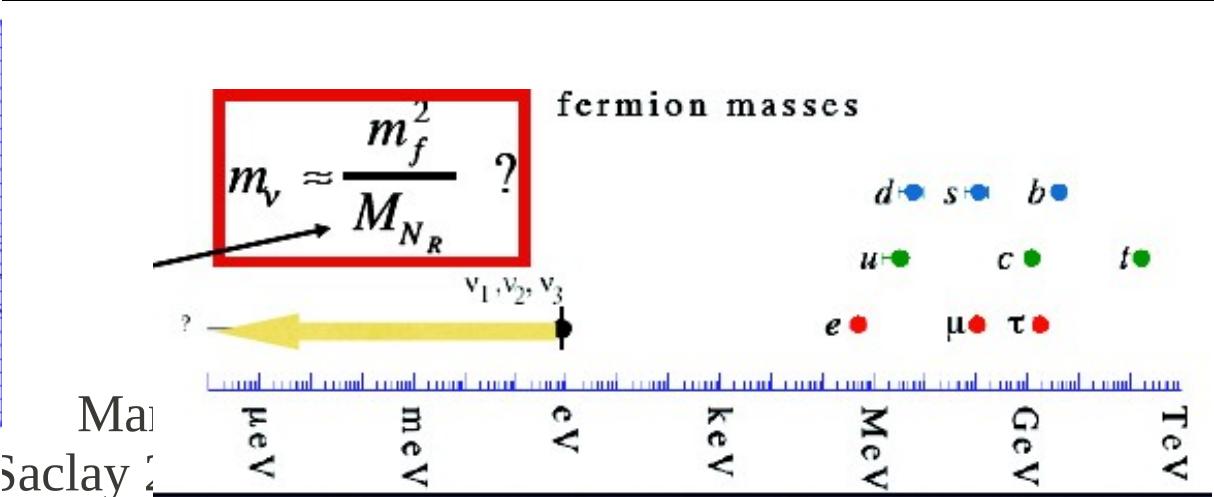
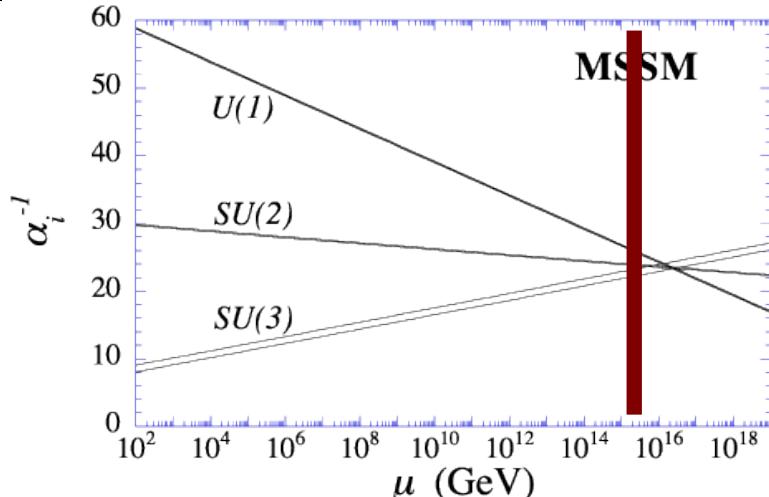
Beyond the Standard Model with neutrinos

- Standard Model = Gauge symmetry group+Lorentz+renormalizability
- Give up the renormalizability
- Effects of physics beyond the SM as effective operators
- Can be classified systematically (Weinberg)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

Lowest order effect of physics at short distances !

$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_\nu \nu \nu$$



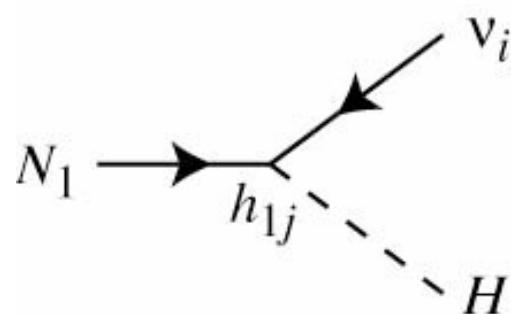
Neutrino and the origin of matter

The universe today contains very little antibaryons ($N_{\text{Bar}} \gg N_{\bar{\text{Bar}}}$) while the initial state is supposed to be symmetric ($N_{\text{Bar}} = N_{\bar{\text{Bar}}}$).

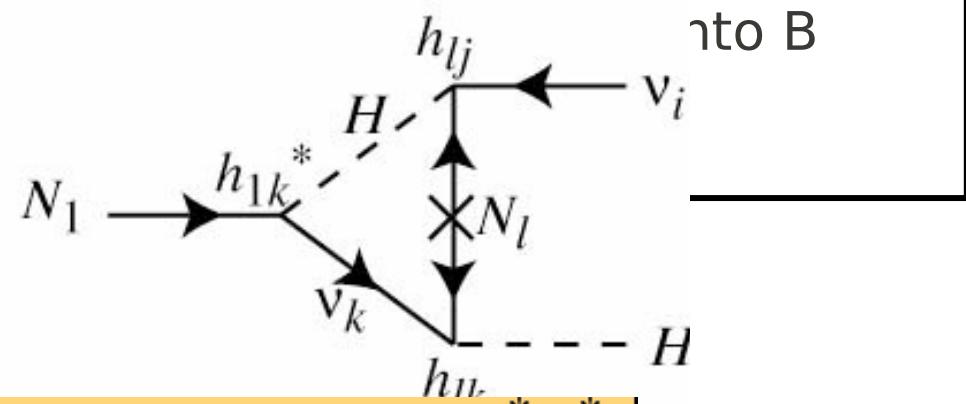
- How can we explain dynamically the observed baryon number B ?
- Sakharov conditions (1967):

- Processes out of thermal equilibrium
- **Violation of C and CP :**
- B violating process

- Decay out of equilibrium of superheavy neutrino ($m \sim \text{GUT scale}$)
- CP violating decays of N to leptons
- Processes violating $B+L$ convert to B



$$\Gamma(N_1 \rightarrow v_i H) - \Gamma(N_1 \rightarrow \bar{v}_i H) \propto \text{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$



Current status of neutrino mass and mixings

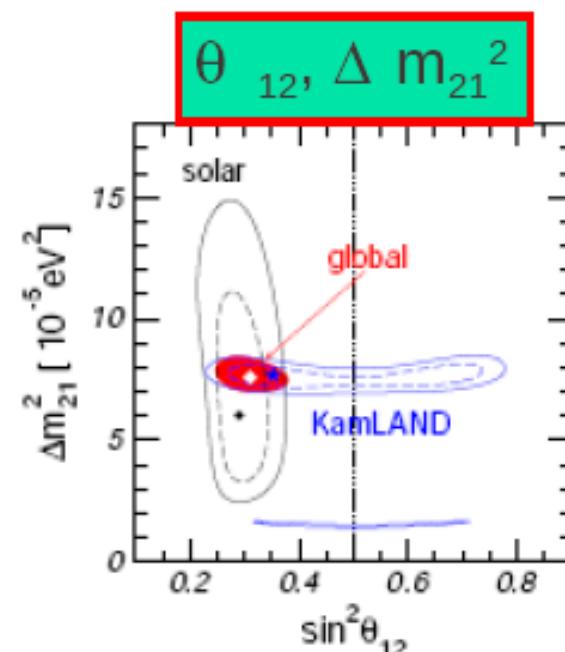
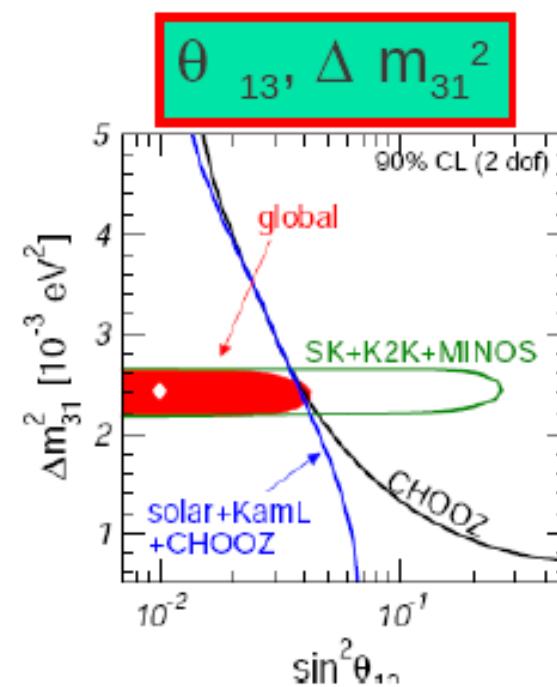
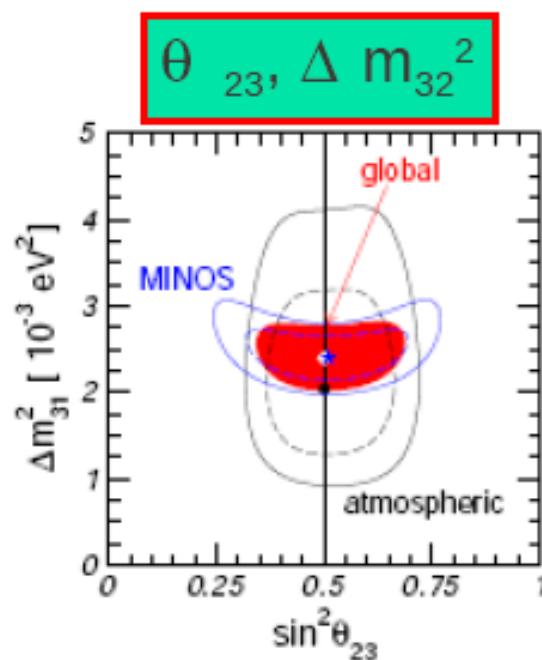
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta}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

3 mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$)

1 CPV phase (δ)

2 (indep.) mass differences ($\Delta m^2_i = m_i^2 - m_j^2$)

Additional phases if Majorana neutrinos



A decade after CHOOZ: the θ_{13} revolution

- T2K (Jun 2011):
 $\sin^2 2\theta_{13} = 0.03 - 0.34$ (90% CL).

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

See talk by GL Fogli

- MINOS (July 2011):
 $\sin^2 2\theta_{13} \neq 0$ at 89% CL.

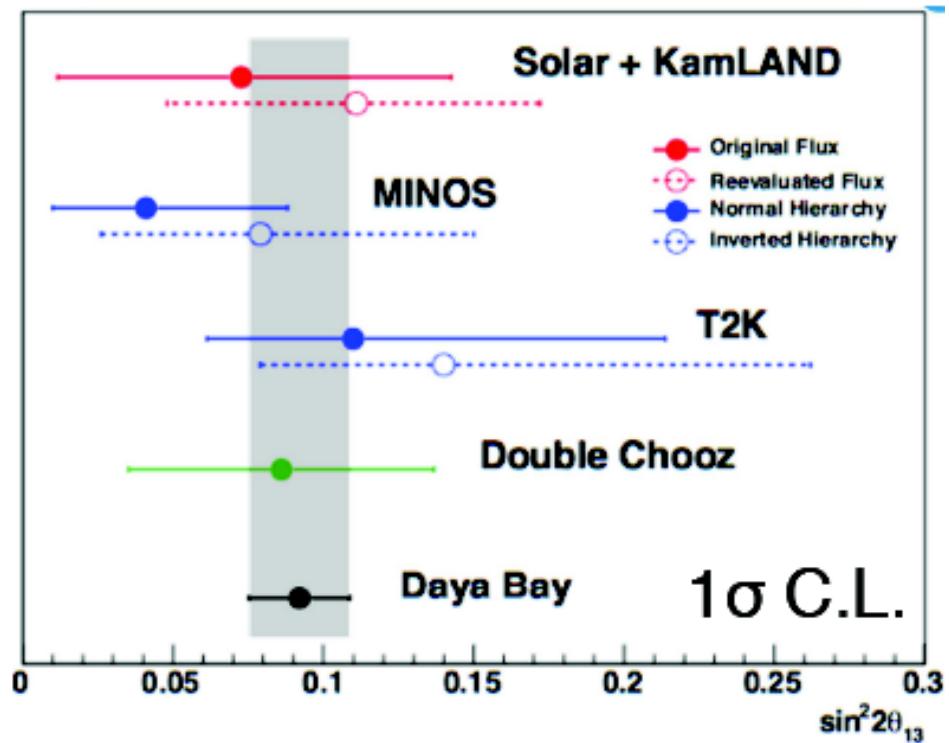
MINOS Collaboration, Phys.Rev.Lett. 107 (2011) 181802

- Double CHOOZ (Dec 2011):
 $\sin^2 2\theta_{13} = 0.017 - 0.16$ (90% CL).

Double CHOOZ Collaboration, arXiv: 1112.6353 [hep-ex].

- Daya Bay (Mar 2012):
 $\sin^2 2\theta_{13} \neq 0$ at 5.2σ (!),
best-fit = 0.092.

Daya Bay Collaboration, arXiv: 1203.1669 [hep-ex].



$$\sin^2 (2\theta_{13}) = 0.092 \pm 0.016(stat) \pm 0.005(syst)$$

- Reno (April 2012):
exclude no oscillations at 4.9σ \longrightarrow $\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$

The knowns and unknowns...

$$\sin^2 \theta_{12} = 0.312^{+0.017}_{-0.015}$$

$$\Delta m_{12}^2 = (7.59^{+0.20}_{-0.18}) \times 10^{-5} \text{ eV}^2$$

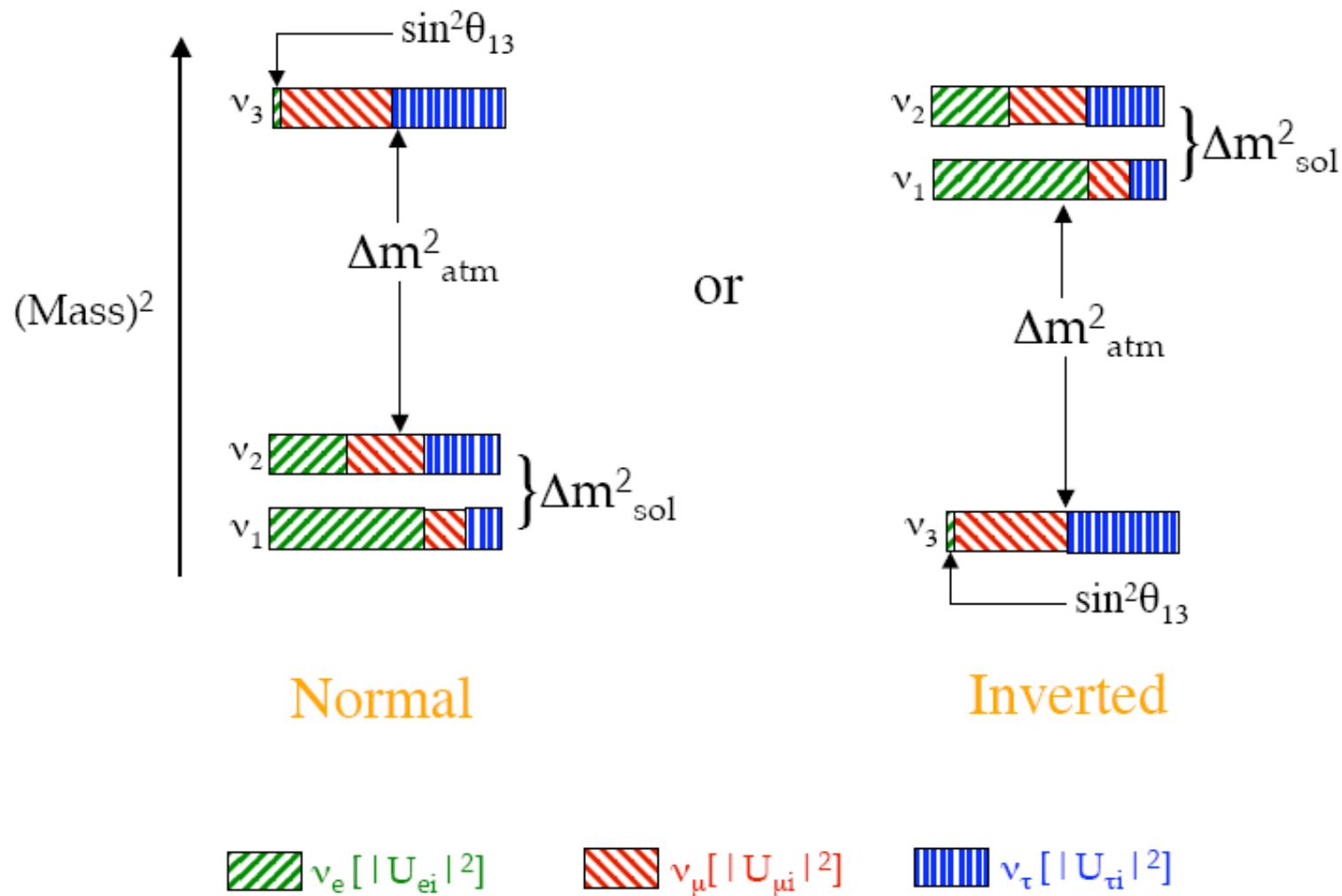
$$\sin^2 \theta_{23} = \begin{cases} 0.51 \pm 0.06 \\ 0.52 \pm 0.06 \end{cases}$$

$$\Delta m_{31}^2 = \begin{cases} 2.45 \pm 0.09 \\ -(2.34^{+0.10}_{-0.09}) \end{cases} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta_{13}) \simeq 0.09 \pm 0.02$$

$\delta_{CP} = [0, 2\pi]$ → *Complex phase is unknown. Because of similarities with CKM matrix, it is natural to expect a CP violation in the lepton sector. But what is the size of the effect ??*

The spectrum, showing its approximate flavor content, is



Next steps

- Theta13 observation opens an exciting possibility in the study of the mixing matrix PMNS
- CP violation phase delta, mass hierarchy, theta23 can be explored at a long baseline neutrino experiment
- The CP violation phase delta could help explaining the matter-antimatter asymmetry (and mystery)
- In the end, we would like to explore PMNS to the same level of accuracy as CKM (eg. Unitarity, cf new physics potential of $Bs \rightarrow \mu\mu$)

What we want to learn

In the context of long baseline neutrino experiments

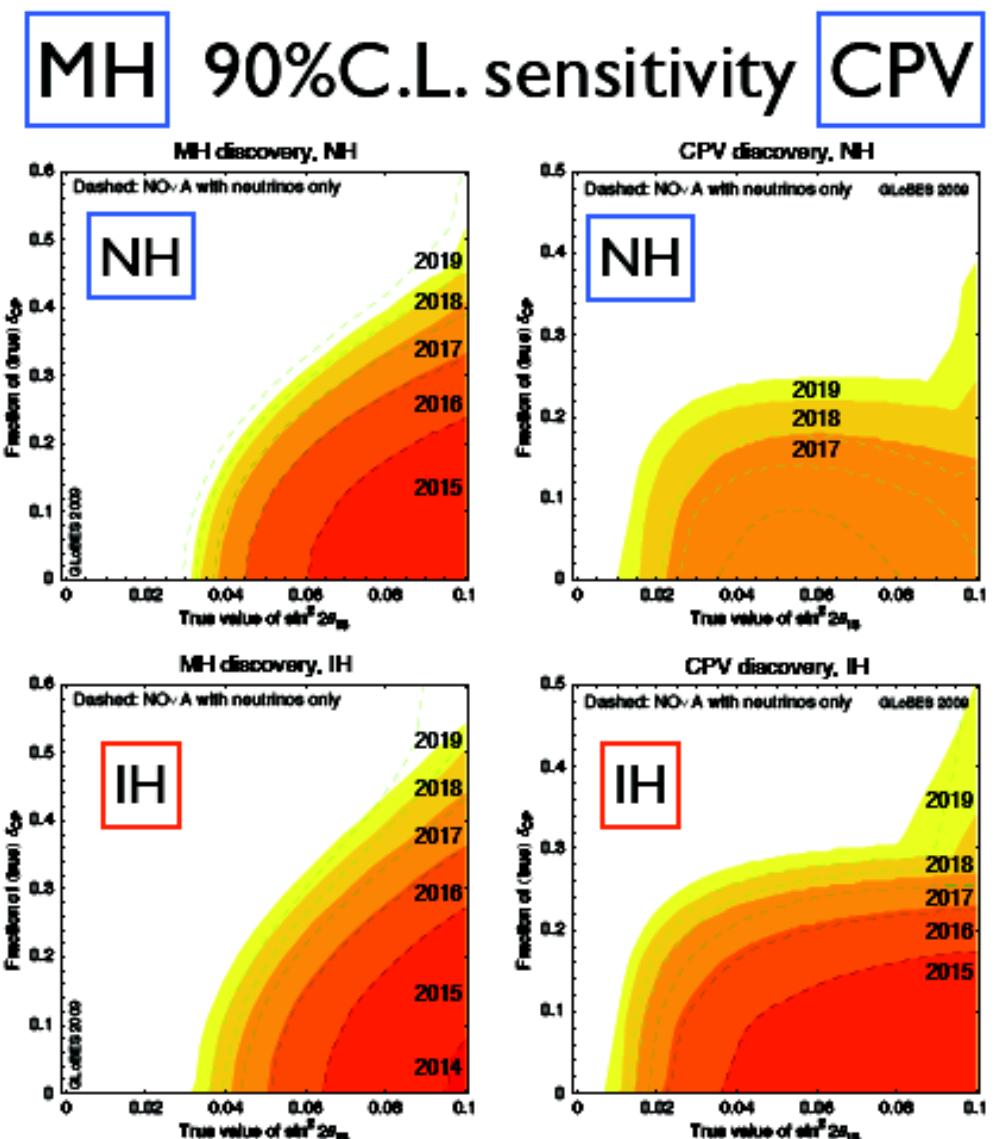
- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- New physics?

It is very difficult to rank those measurements in their relative importance

Given the current state of the theory of neutrinos we can not say with confidence that any one quantity is more fundamental than any other.

T2K and NOvA: in the future

- Preliminary estimation of sensitivity of T2K and NOvA *See talk by Schwetz*
- Nominal beam power scenarios (750kW). Need to check beam power assumptions.
- For $\sin^2 2\theta_{13} = 0.1$, approximately (at 90% C.L.):
 - MH: $\approx 50\%$ coverage
 - CPV: $\approx 30\text{-}40\%$ coverage (robustness vs MH ?)
- Is 90% C.L. enough ? at 3σ C.L. sensitivity is highly reduced even with largely increased statistics.
- Atmospherics to the rescue ?
- Official curves to be produced by experiments with revised projections.



Huber et al., JHEP 0911:044,2009

Beyond T2K&NOvA: LBNO ?

- LBNO is a next generation long baseline experiment which aims at a significantly better sensitivity than what is achievable with the combined T2K, NOvA and reactors experiments.
- **LBNO will explicitly observe MH induced matter effects and CP-violation, which is different from simply extracting the hierarchy or δ_{CP} value from global fits of all available data:**
 - ★ Large detectors and intense beam for a significant increase in statistics
 - ★ Measure all active transition (e / mu / tau CC) and active-sterile (NC) at long baseline
 - ★ A precise investigation of the oscillation probabilities as a function of energy (L/E) and a direct comparison of neutrino and antineutrino behaviors to verify the expectations from 3-generations neutrino mixing.
 - ★ A very long baseline to have an excellent separation of the asymmetry due to the matter effects (i.e. the mass hierarchy measurement) and the CP asymmetry due to the δ_{CP} complex phase, and thus to break the parameter degeneracies.
 - ★ To really observe direct and different for neutrinos and antineutrinos MH induced matter and CP-phase induced effects in oscillation probabilities !
- Extend nucleon decay searches, a unique probe for BSM up to the Grand Unification Scale
- Perform very compelling and complementary astrophysics measurements become accessible if the detector is deep underground.

⇒ **A new massive deep underground neutrino observatory for long baseline neutrino studies, capable of proton decay searches, atmospheric and astrophysical neutrino detection**

Oscillation phenomenology

Approximate formula (M. Freund)

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A} - 1)^2} \sin^2((\hat{A} - 1)\Delta) + \alpha \frac{8J_{CP}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) + \alpha \frac{8I_{CP}}{\hat{A}(1 - \hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) + \alpha^2 \frac{\cos^2 \theta_{23} \sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

CPV term CPV term

approximate dependence approximate dependence

$\sim L/E$

quadratic dep. on θ_{13}
matter effect $\sim E$

~ 7500 km
magic bln

~ 2540 kr
magic blr

solar

linear dep. on θ_{13}

$$J_{CP} = 1/8 \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2, \quad \Delta = \Delta m_{31}^2 L / 4E$$

$$\hat{A} = 2VE / \Delta m_{31}^2 \approx (E_\nu / \text{GeV}) / 11 \quad \text{For Earth's crust.}$$

CP asymmetry grows as
 θ_{13} becomes smaller !

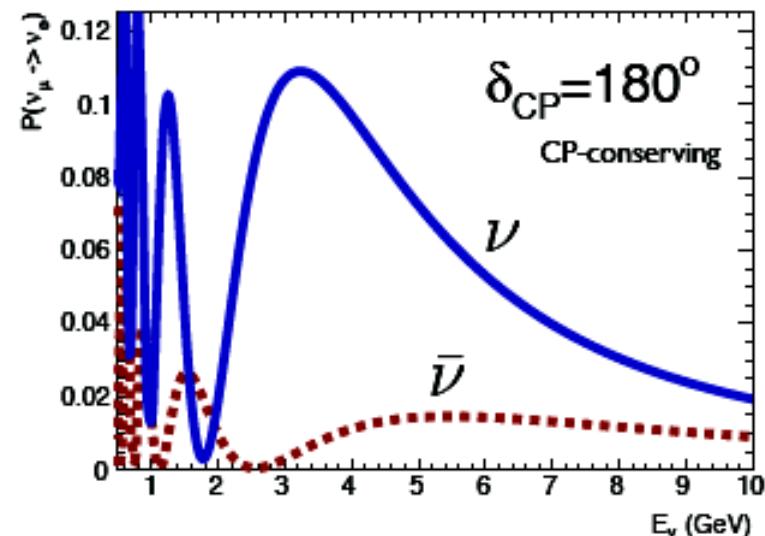
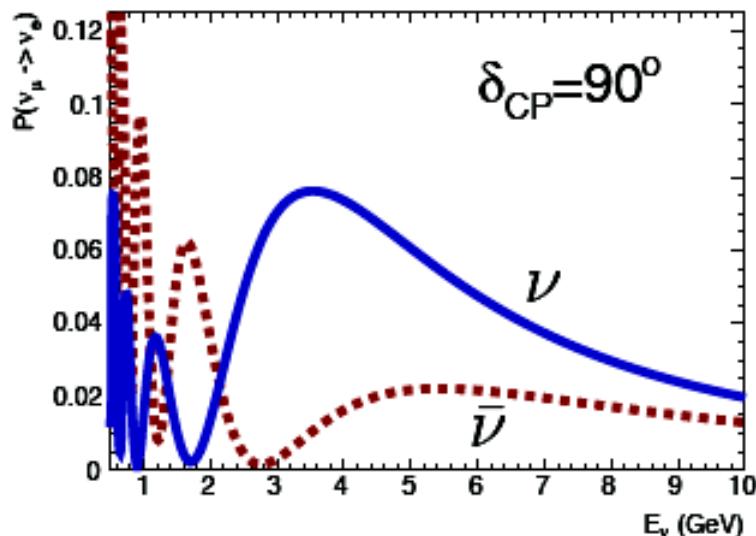
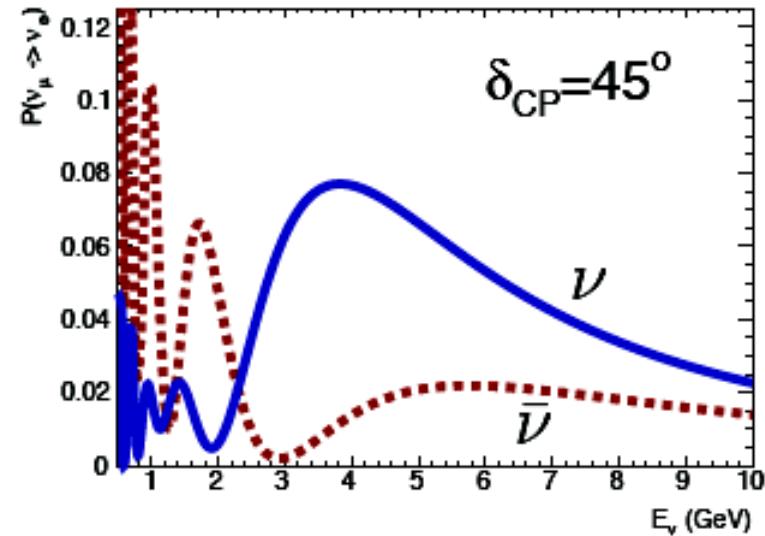
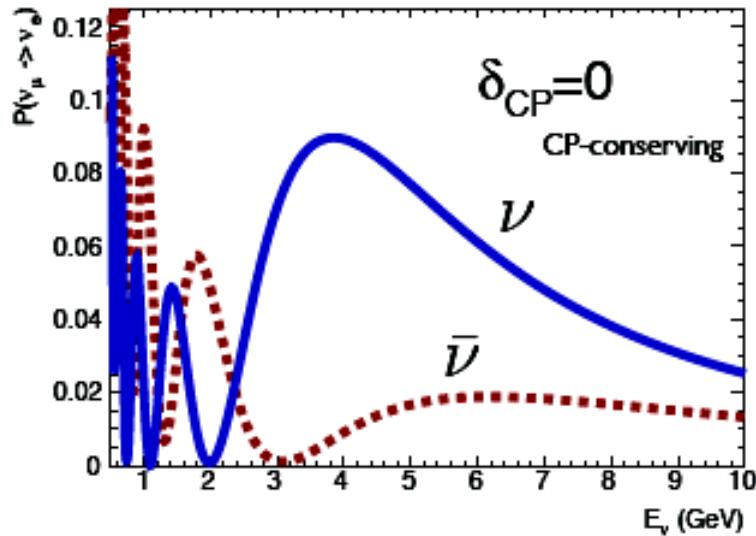
Correlations !

CERN-Pyhäsalmi: oscillations

★ Normal mass hierarchy

L=2300 km

$$\sin^2(2\theta_{13}) = 0.09$$

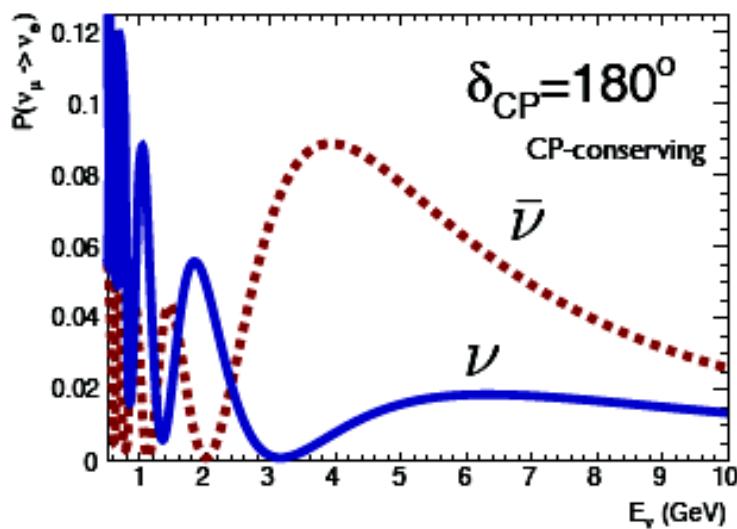
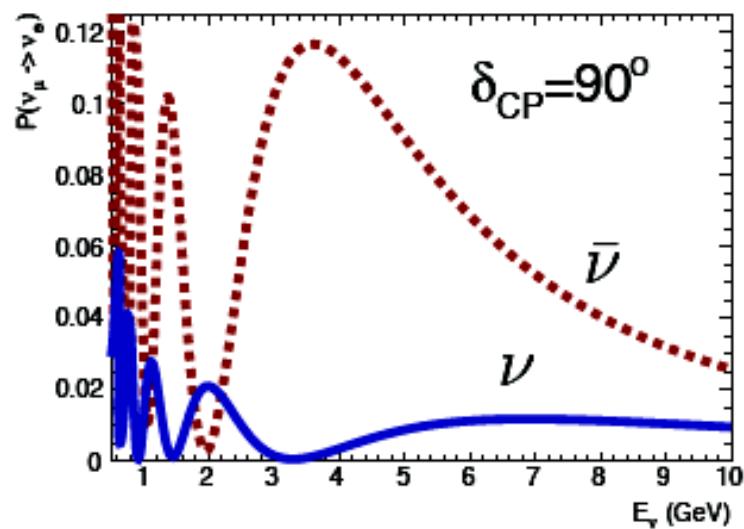
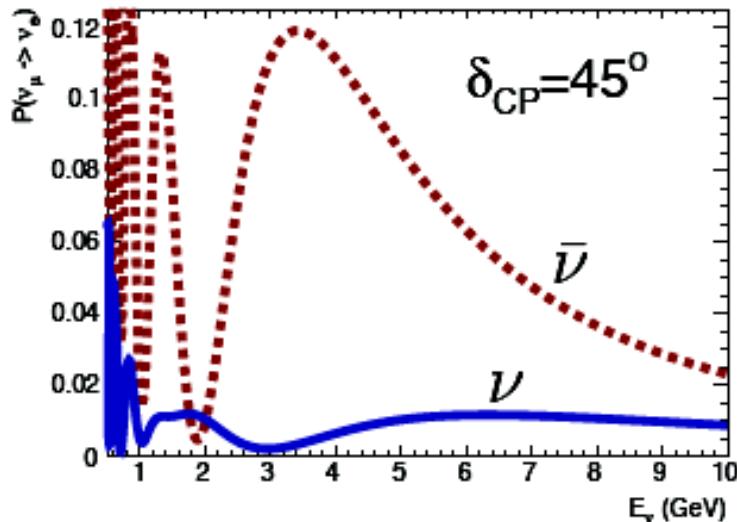
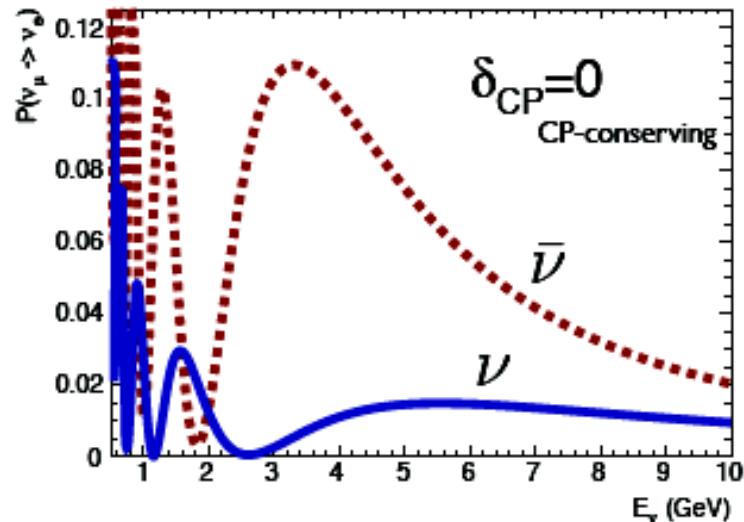


CERN-Pyhäsalmi: oscillations

★ Inverted mass hierarchy

L=2300 km

$$\sin^2(2\theta_{13}) = 0.09$$



From magic baseline to an experiment

- We need a Wide Band Beam (1st and 2nd maximum)
- Need good energy resolution also at 2nd maximum to use L/E for CP extraction
- E_osc~ 5 GeV : no water Cherenkov
- A detector with better eff. and background rejection than SK or NOVA but similar mass as first step : 20 kT fine sampling tracking detector
- We consider a Liquid Argon Detector
- Underground : astrophysics and proton decay
- Use of a conventional beam
- Performances can improve in steps : larger mass, beam power

New LAGUNA-LBNO neutrino beam

LAGUNA-LBNO WP4

- **CN2PY horn focused neutrino beam towards Pyhäsalmi/FI**
 - ▶ Starting point is SPS and CNGS operation (achieved 420kW)
 - ▶ Consider protons extraction, transfer & secondary beam lines
 - ▶ Design optimized target and horn focusing systems.
 - ▶ Afford relatively short decay tunnel ≈300m, but 10deg dip angle
 - ▶ Necessity of a near detector station to achieve target systematic errors
 - ▶ Consider dedicated set of hadron-production measurements
- **Benefit from improved performance of SPS+injectors; consider further options to upgrade power of SPS:**
 - ▶ SPS intensity is upgraded to 7×10^{13} ppp at 400 GeV with cycle time = 6 seconds.
 - ▶ Yearly integrated pot = $(0.8\text{--}1.3) \times 10^{20}$ pot / yr
 - ▶ Total integrated (12 years) = $(1\text{--}1.5) \times 10^{21}$ pot
 - ▶ Range corresponds to sharing 60–85%
 - ▶ Studies ongoing within CERN accelerator team in LAGUNA-LBNO WP4
- **Upgrade path: HP-PS accelerator (50 GeV) with significant power improvement compared to SPS complex (→ “MW” beam). Exploit synergies with the NF R&D.**

Pyhäsalmi far site location



- ▶ CUPP : Centre for Underground Physics in Pyhäsalmi (www.cupp.fi)
- ▶ Location: $63^{\circ} 39' 31''\text{N}$ – $26^{\circ} 02' 48''\text{E}$
- ▶ Distances (by roads)
 - ▶ Oulu – 165 km
 - ▶ Jyväskylä – 180 km
 - ▶ Helsinki – 450 km
- ▶ Distance to CERN 2300 km
- ▶ Good traffic connections
 - ▶ the main highway: Helsinki – Jyväskylä – Oulu – ...
 - ▶ the second busiest airport in Oulu
 - ▶ rail yard at the mine
- ▶ Inhabitants: ~6000

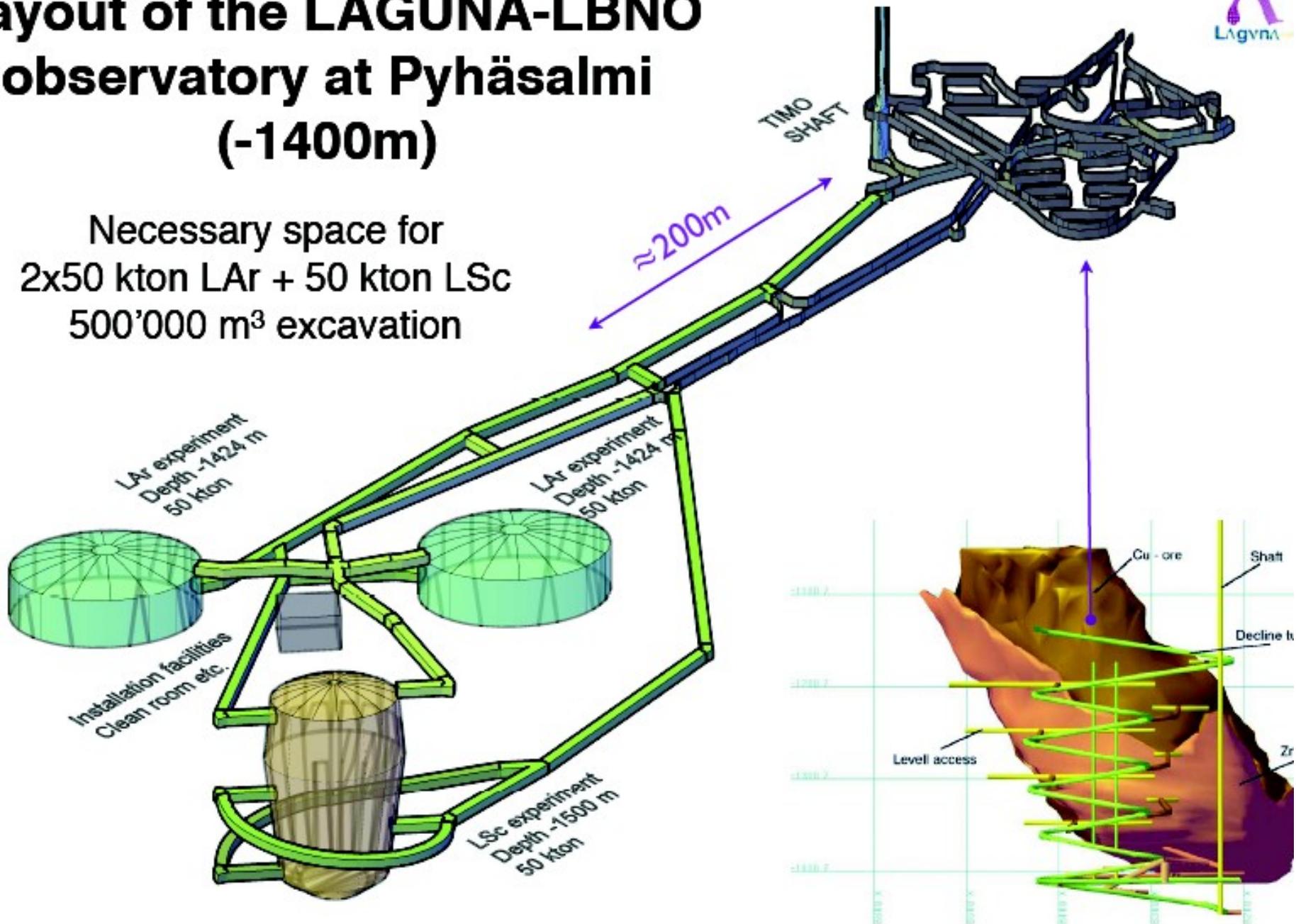
Being extensively investigated
in LAGUNA DS since 2008

2100 km from RAL, 1500 km from
DESY, and 1160 km from Protvino.

Layout of the LAGUNA-LBNO observatory at Pyhäsalmi (-1400m)



Necessary space for
2x50 kton LAr + 50 kton LSc
500'000 m³ excavation



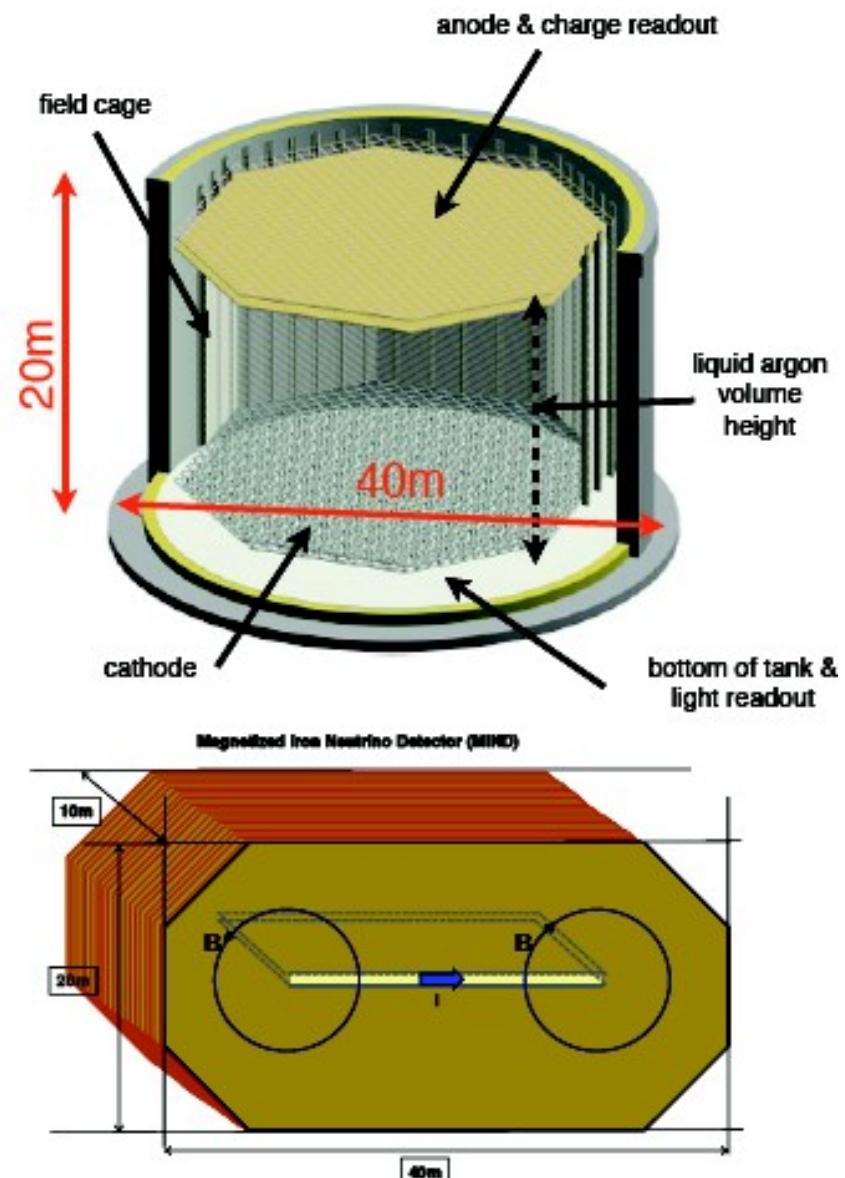
Far underground detectors

- Double phase LAr LEM TPC (GLACIER):
best detector for electron appearance
measurements with excellent energy
resolution and small systematic errors

- ▶ Exclusive final states, low energy
threshold on all particles
- ▶ Excellent ν energy resolution and
reconstruction ability from sub GeV
to a few GeV, from single prong to
high multiplicity
 - Suitable for spectrum measurement
with needed wide energy coverage
- ▶ Excellent π^0 /electron discrimination
 - Wide band On-Axis beam is tolerable

- Magnetized Muon Detector (MIND):
conventional and well-proven detector
for muon CC, and NC

- ▶ muon momentum & charge determination,
inclusive total neutrino energy
- ▶ $r\mu/w\mu$ with NF



A multi-purpose neutrino observatory

- Physics case : MH, CPV, Proton decay, Nu astrophysics
- Sensitivity to ν_e , ν_μ , ν_τ
- A multi-purpose detector : fine grained tracker, PID, calorimeter, hadronic energy

Full imaging

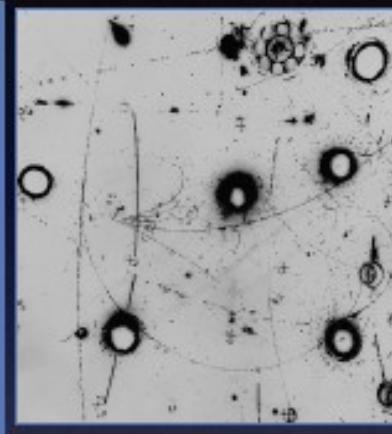
- Fully active, homogeneous, high-resolution device: **high statistics neutrino interaction studies with bubble chamber accuracy.**
- Reconstruction of low momentum hadrons (below Cerenkov threshold), especially recoiling protons: a proton of 1070 MeV/c (Cerenkov threshold in Water) travels 1 metre in LAr.
- Exclusive measurement of vNC events with clean π^0 identification and a very good e/ π^0 discrimination.

Active R/D at FNAL and KEK

Real event in ICARUS

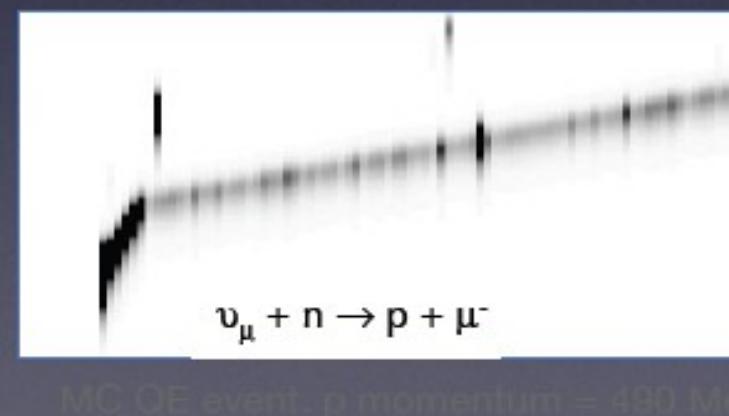
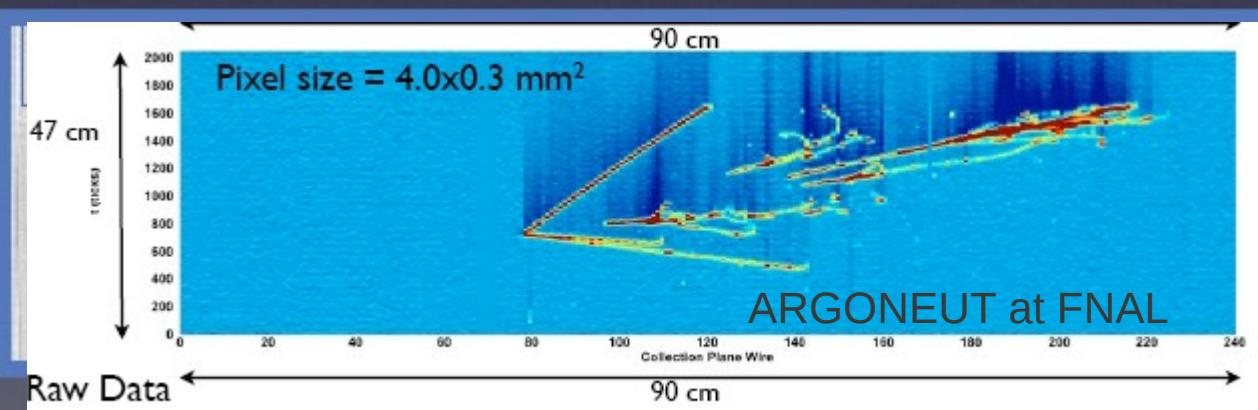


Gargamelle bubble chamber



High granularity: Sampling = $0.02 X_0$
"bubble" size $\approx 3 \times 3 \times 0.4 \text{ mm}^3$

bubble diameter $\approx 3 \text{ mm}$



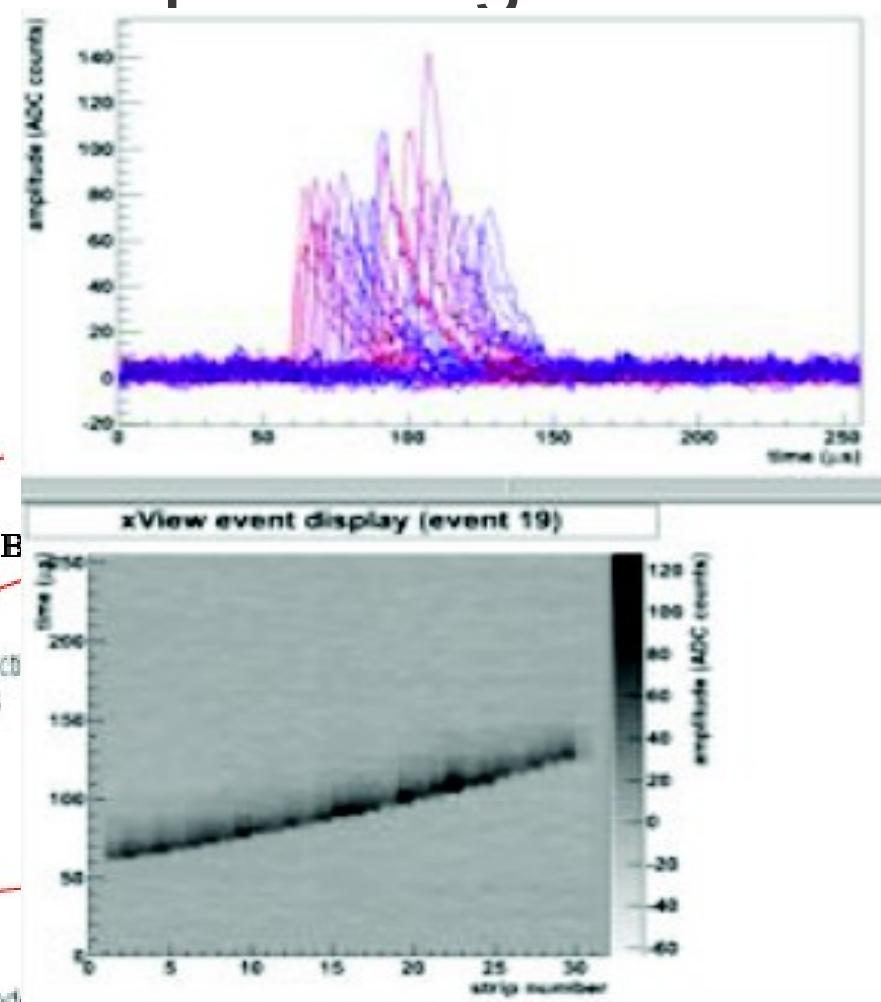
Micromegas R/D with pure Argon

Bulk-micromegas Strip readout

mesh HV



ETHZ Cryostat
at CERN



Stable operation in cryogenic environment
2ppb O₂ in Lar
First cosmics tracks observed
Amplification

Electron pi0 separation

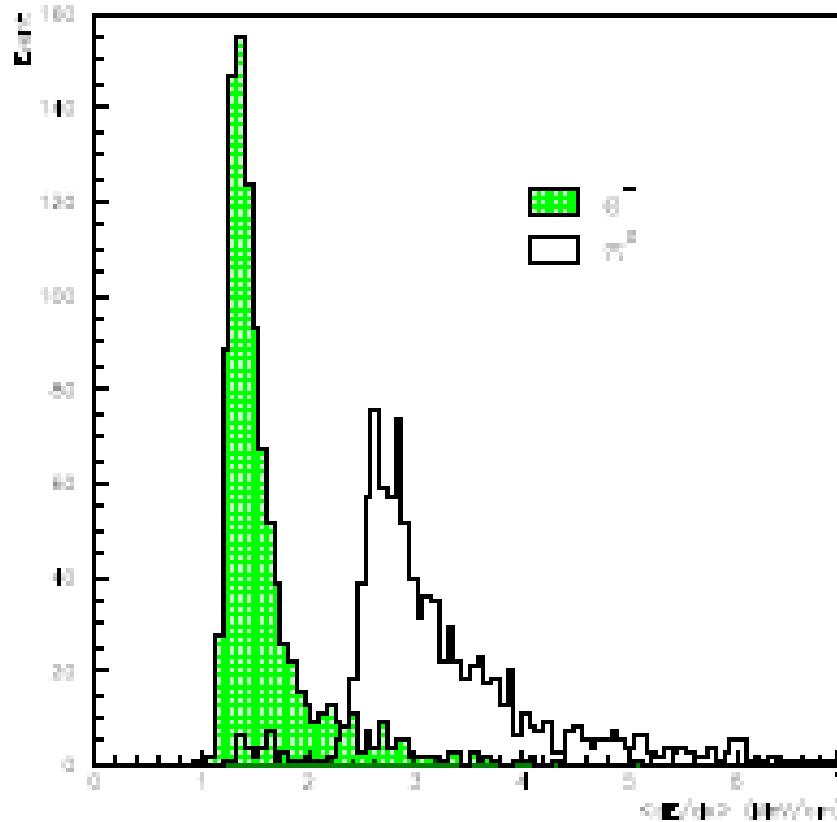
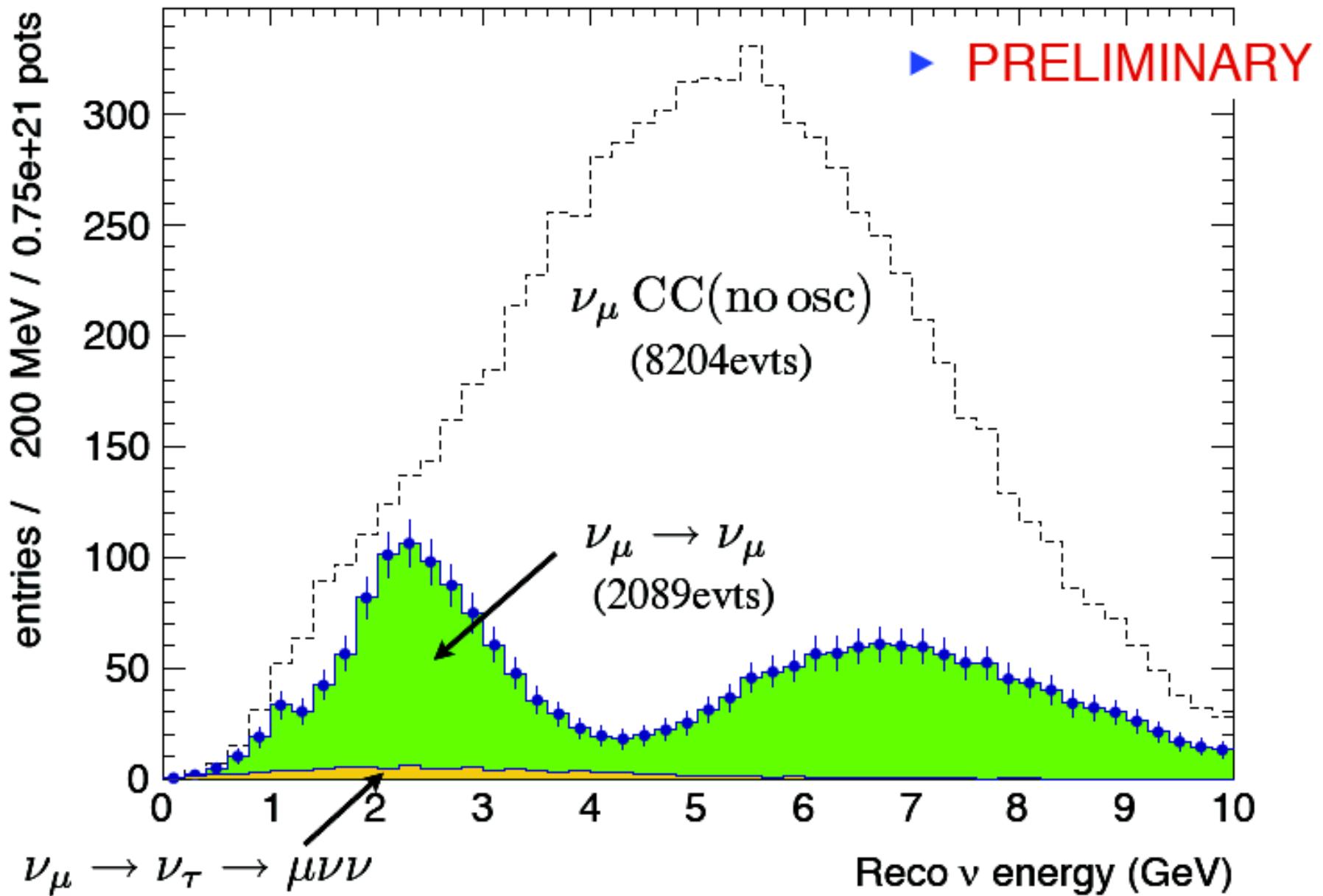


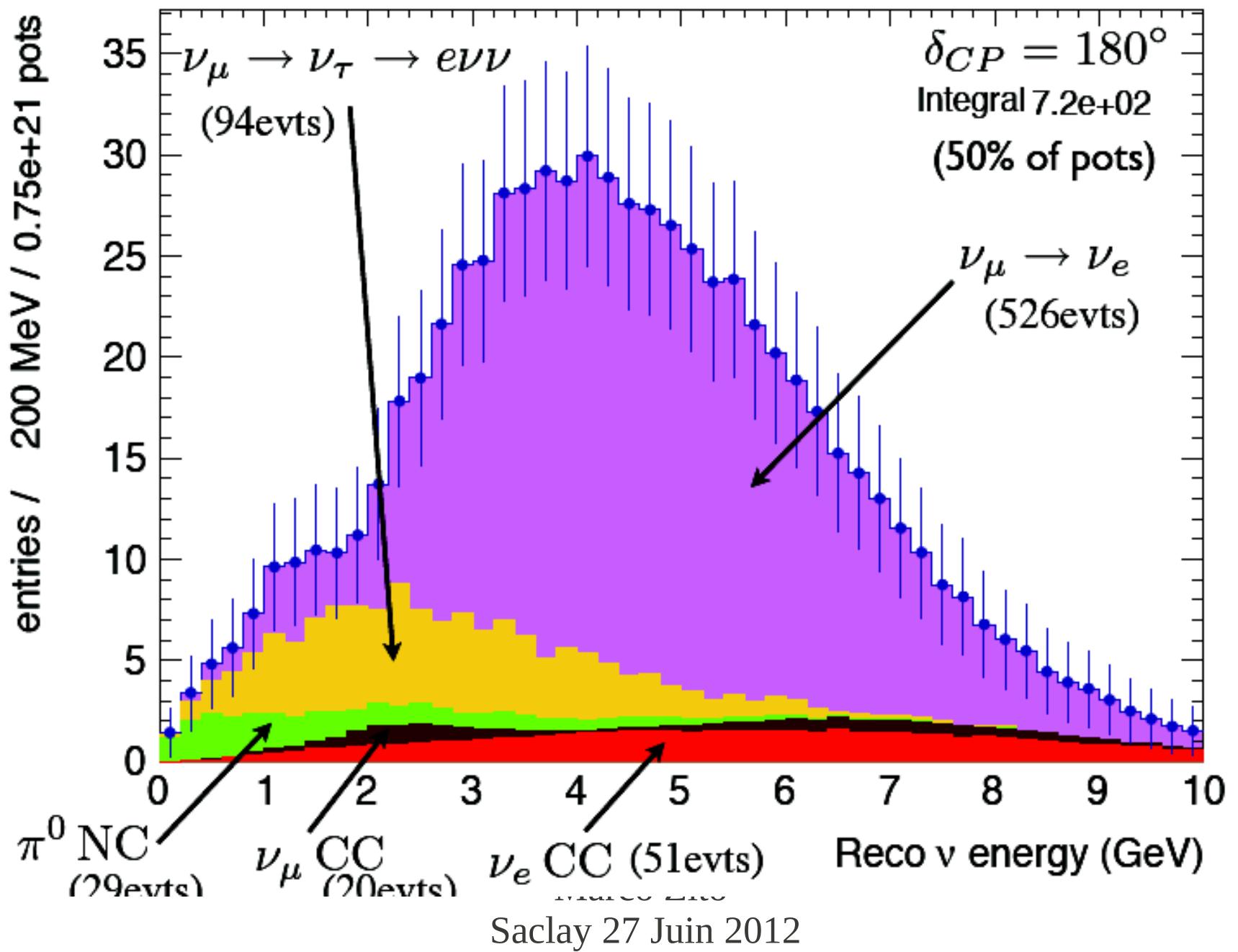
FIG. 29: The e^- (hatched area) and π^0 (blank area) can be separated with 90% e^- identification efficiency and 3.7% of π^0 contamination by a $\langle dE/dx \rangle$ cut at 2.21 MeV/cm. The $\langle dE/dx \rangle$ is the average over the first 8 successive wires.

μ -like sample



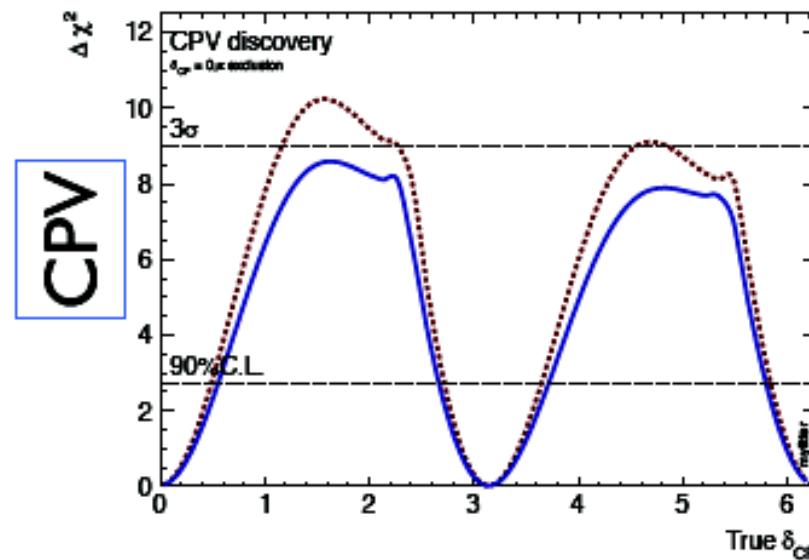
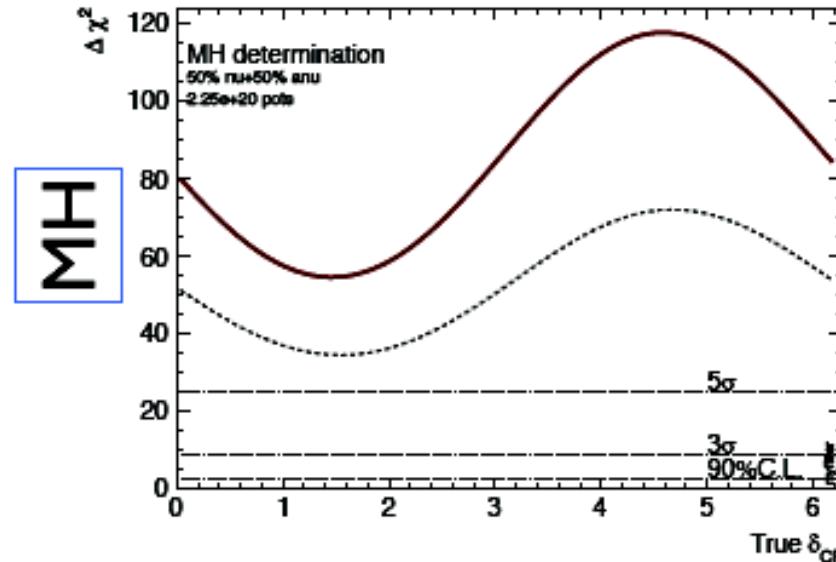
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e-like sample



MH & CPV sensitivities

- Estimation using all systematic errors mentioned previously.
- Nominal beam power scenarios (700kW).
- For $\sin^2 2\theta_{13} = 0.1$, approximately (at 90% C.L.):
 - MH: 100% coverage at $>5\sigma$ in a few years of running
 - CPV: $\approx 60\%$ coverage and evidence for maximal CP ($\pi/2, 3\pi/2$) at 2.9σ in 10 years
- CPV coverage already sensitive to systematic errors.
- With more details studies and a better definition of the near detector, hadron production measurements, and other auxiliary measurements, they might be reduced.
- In case of negative result, the CPV sensitivity can be improved with longer running periods and/or an increase in beam power and far detector mass. For instance, CPV becomes accessible at $>3\sigma$'s C.L. for 75% of the δ_{CP} parameter space with a three-fold increase in exposure, provided that systematic errors can be controlled well below the 5% level.



LBNO EoI: the physics reach

- Initial setup 20 kton LAr LEM TPC + MIND + CERN SPS 700kW upgrade
- **Ultimate** long baseline oscillations measurements:
 - LBNO can measure all transitions ($e/\mu/\tau$) and determine precisely oscillation parameters. It can achieve a **5 σ C.L. determination of the neutrino mass hierarchy** in a few years. In a 10 years run, it explores a **significant part of the CPV parameter space, namely 60% CPV coverage at 90% C.L.**
 - Both the local situation and the distance make it such that it can evolve into larger detector(s) and a more powerful beams (e.g HP-PS and/or NF) and thus, **offers a long term vision**. For example, with a three-fold increase in exposure, **it reaches 75% CPV coverage at 3 σ C.L.** Competitive with T2HK (even more with JPARC MR at 700kW...) and LBNE.
- **Strongly** extended sensitivity to nucleon decay in several channels.
E.g. some channels with sensitivity similar to HK:
$$Br(p \rightarrow \bar{\nu} K) > 2 \times 10^{34} \text{y}(90\% \text{C.L.}) \quad Br(n \rightarrow e^- K^+) > 2 \times 10^{34} \text{y}(90\% \text{C.L.})$$
- **Interesting** astrophysics: LBNO acts as an nu-observatory in the 10 MeV-100 GeV range.
5600 atmospheric events/yr **relic SN, WIMP annihilation, ...**
>10000's events @ SN explosion@10kpc



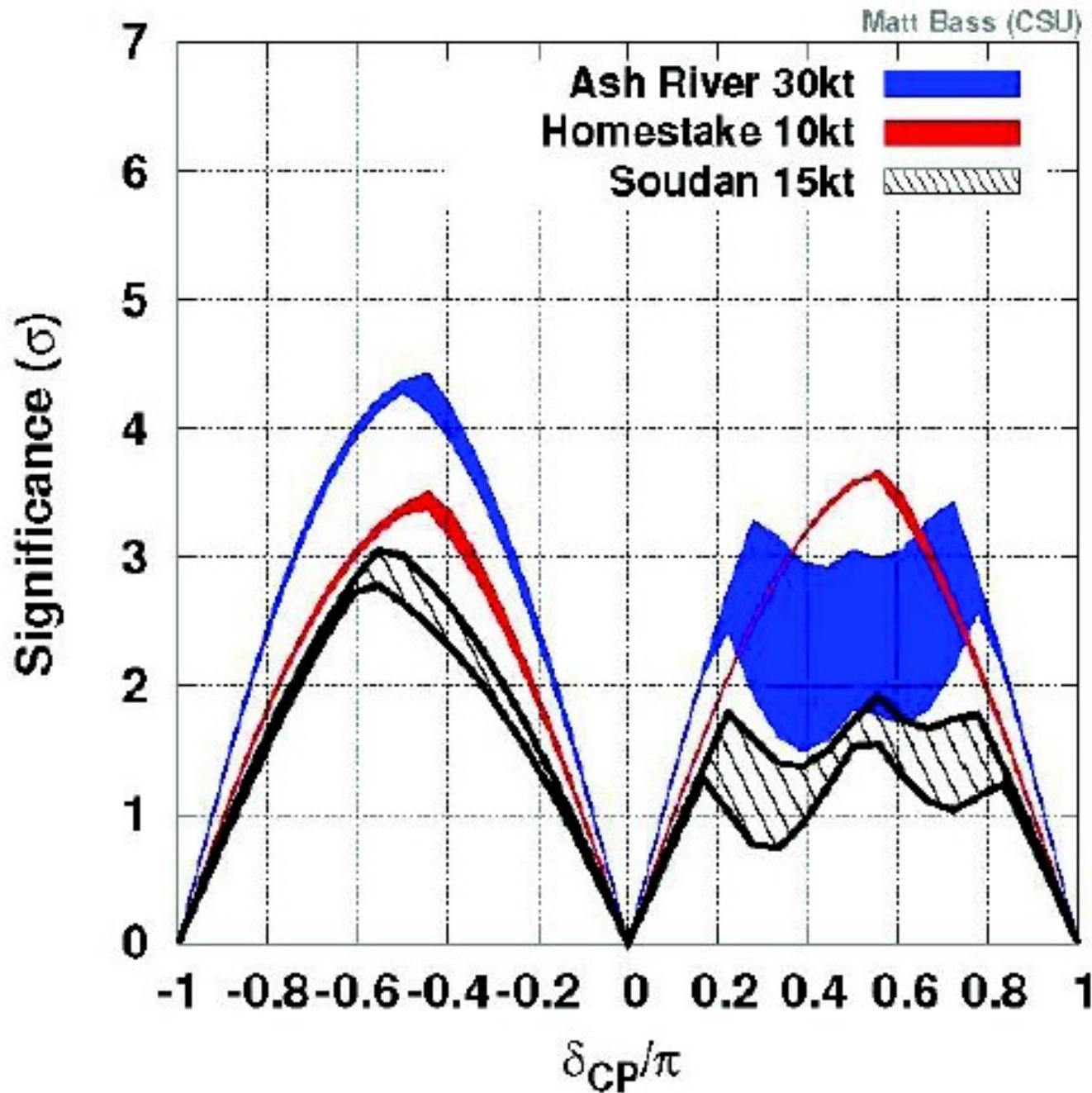
Milestones - Timescale

LAGUNA Design Study funded for site studies:	2008-2011
Categorize the sites and down-select:	Sept. 2010
LAGUNA-LBNO: detector design, costing and LBL beam options	2011-2014
Submission of LBNO EoI to CERN	2012
Critical decision	2015 ?
Excavation-construction (incremental):	2016-2021 ?
Phase 1 LBL physics start:	2023 ?
Phase 2 incremental step implementation:	>2025 ?

Conclusions

- Unique scientific potential of LBNO CERN to Pyhasalmi with a neutrino beam based on SPS
 - Conclusive mass hierarchy determination
 - Significant exploration of CP phase delta
 - X10 sensitivity for nucleon decay and astrophysics program
- LBNO has a clear upgrade path : larger mass and beam energy up to the ultimate facility the Neutrino Factory
- EOI submitted to SPSC and input to the strategy process

CPV Significance vs δ_{CP}
NH(IH considered), $\sin^2(2\theta_{13})=0.07$ to 0.12



Case of Hyper-K

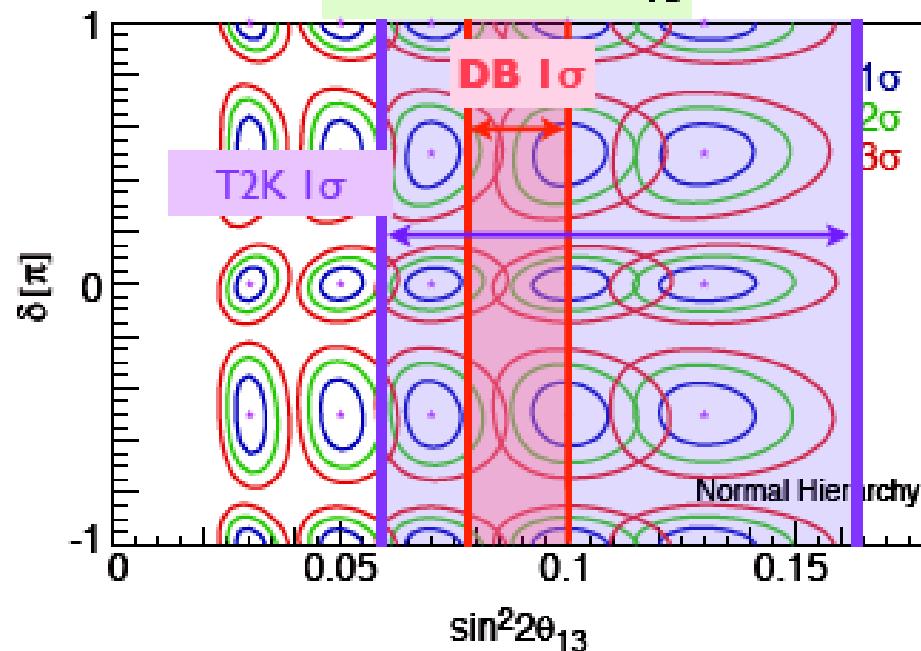
Poster #209

0.75MW×10yrs

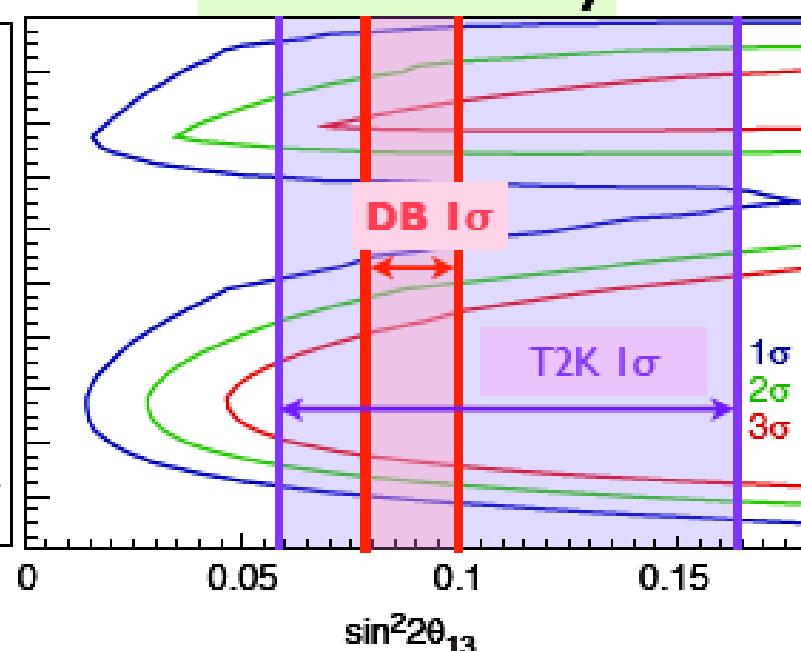
(3yrs ν , 7yrs $\bar{\nu}$)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$

δ vs. $\sin^2 2\theta_{13}$

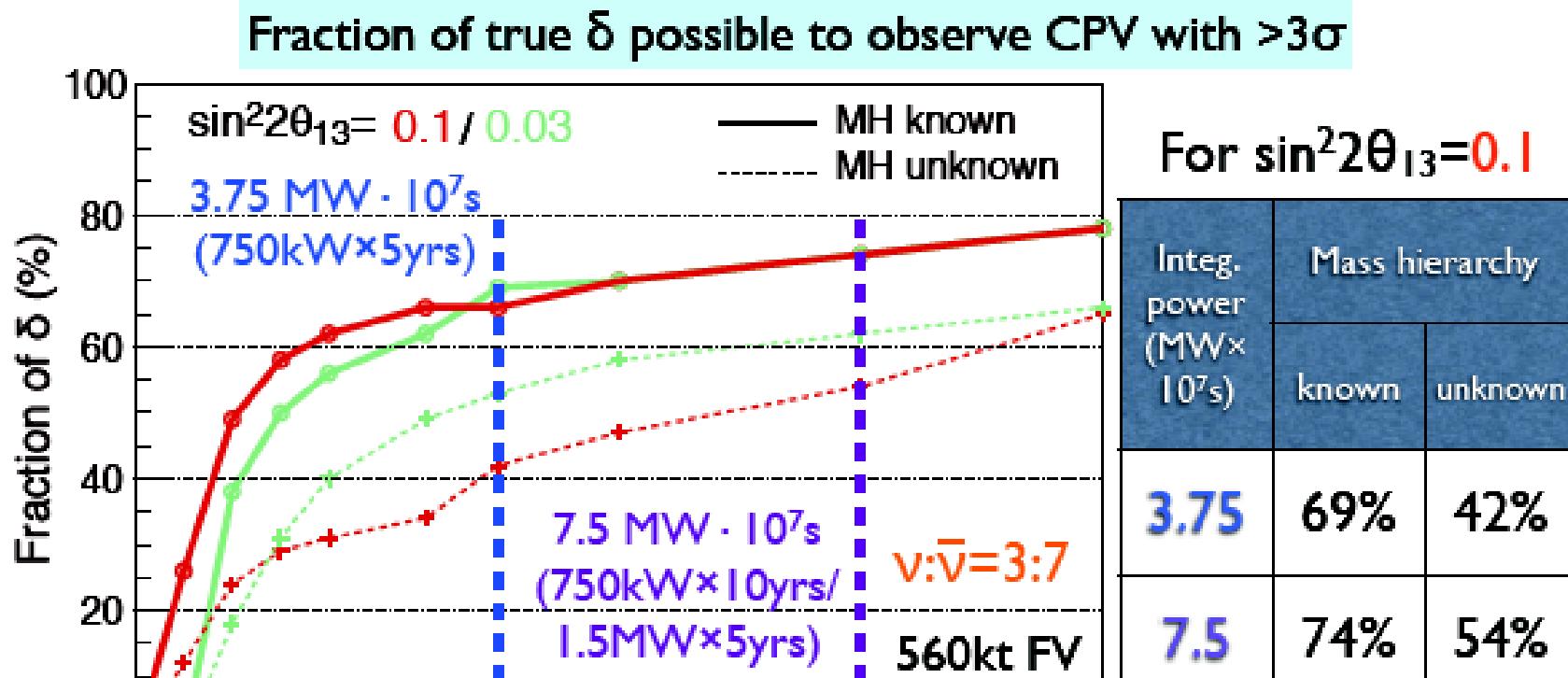


Mass hierarchy



Good sensitivity for CPV and MH over currently suggested parameter region

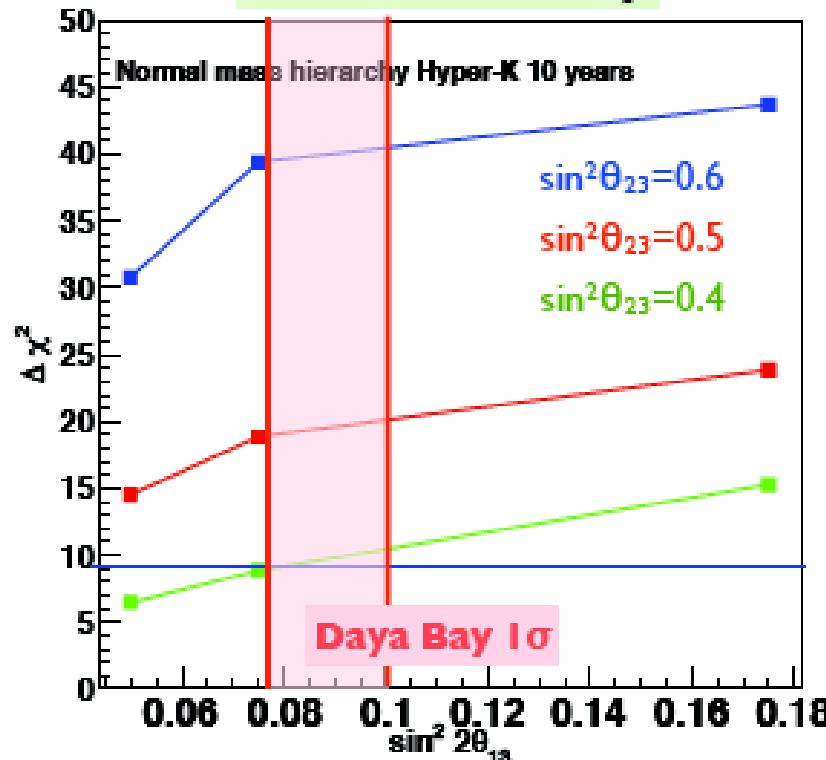
Sensitivity to CP violation (HK)



- With known mass hierarchy (atm v, other expt's), CP violation can be observed (3σ) for $\sim 70\%$ of δ

Atmospheric ν (Hyper-K)

Mass hierarchy



>3 σ with 5-10 years

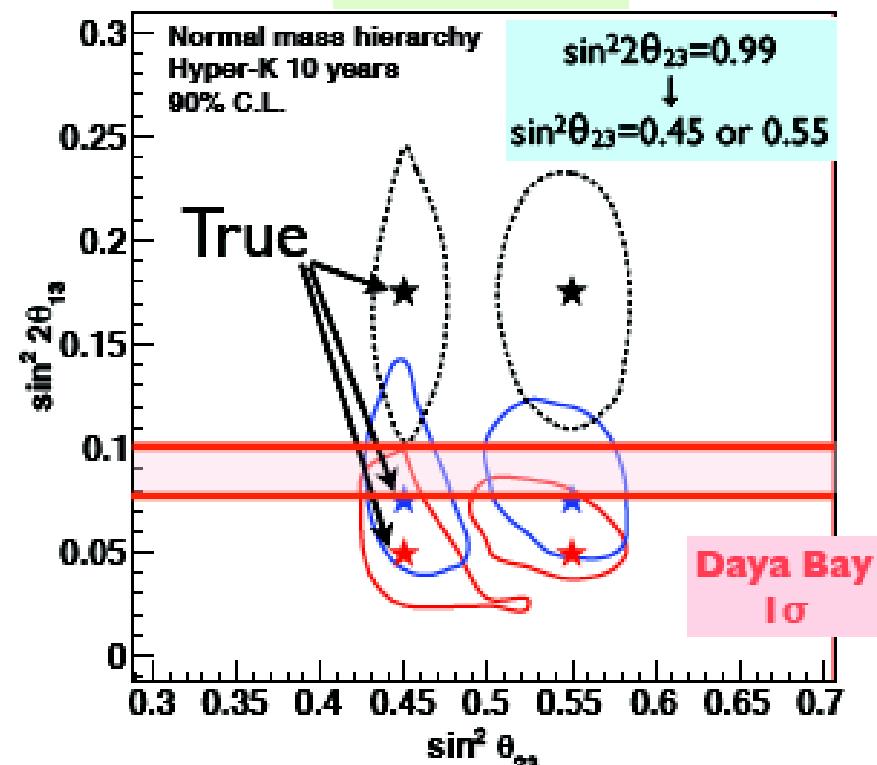
resonance term in ν_e

$$\propto \sin^2 \theta_{13} m$$

Complementary to acc. ν

Better sensitivity with larger $\theta_{13} \rightarrow$ encouraging

θ_{23} octant



Resolved if $\sin^2 2\theta_{23} < 0.99$

Masashi Yokoyama (U.Tokyo)

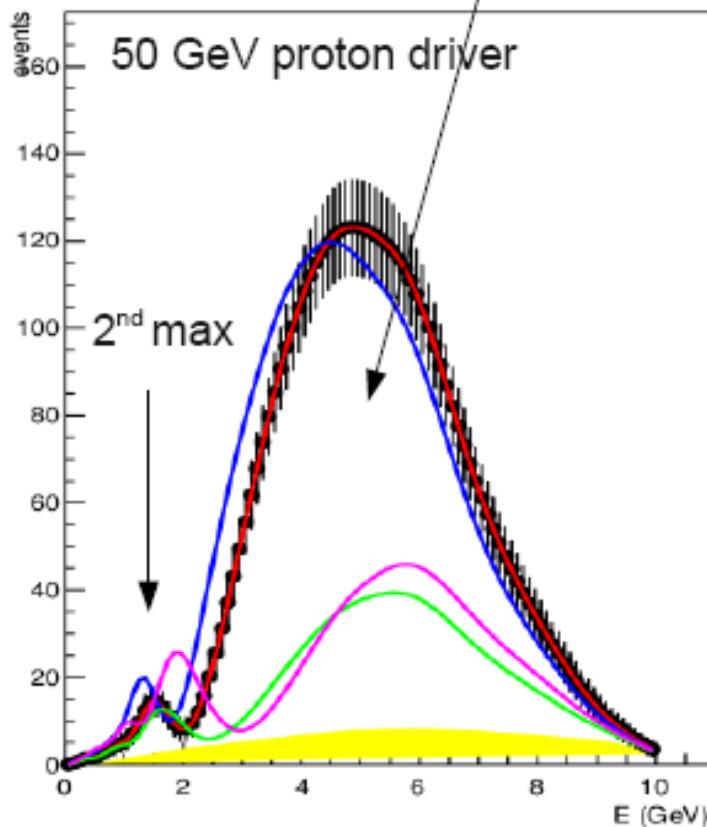
Future water Cherenkov detectors

10

2290 \leftrightarrow 730 km

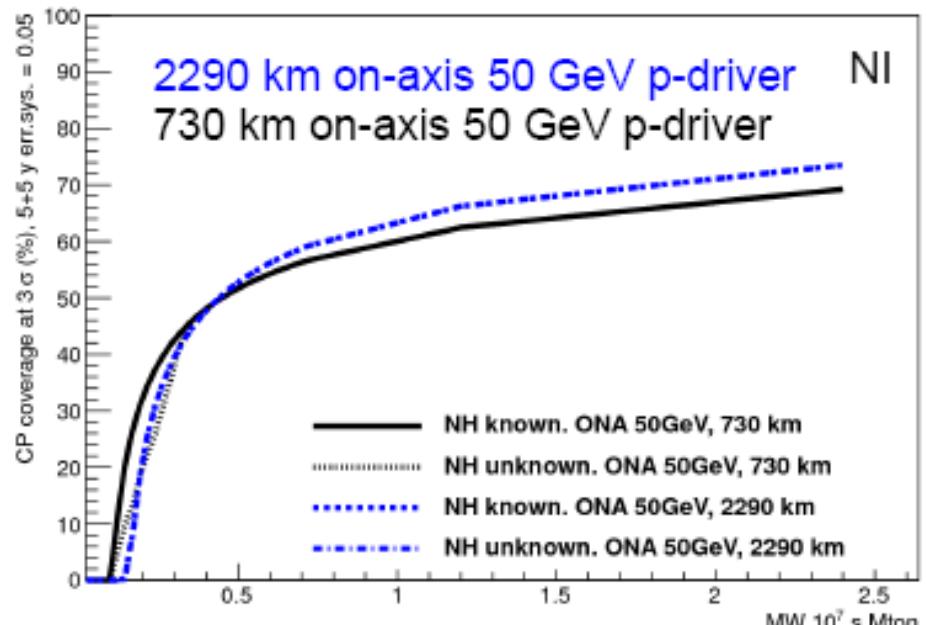
- MH: 2290 km is superior (large matter effects), no ambiguities from MH knowledge

$$\nu_e \text{ 5 y } 100 \text{ kt } \delta = 0.0 \text{ rad. N.H.}$$



- CP violation: not a huge difference
- Higher coverage at 2290 at high exposures (where 2nd max starts to play a role)

CP coverage at 3σ (%), 5+5 y err.sys. = 0.05



CP coverage at 3σ (%), 5+5 y err.sys. = 0.05

