# Neutrino oscillations: recent discoveries and future challenges

Marco Zito
IRFU/SPP CEA Saclay

LAL
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# Outline

1) Neutrino masses, mixing and the PMNS paradigm

2) Results from the T2K experiment

3) Next generation long baseline facilities: DUNE and the Neutrino Platform program at CERN including WA105

# Neutrino oscillations

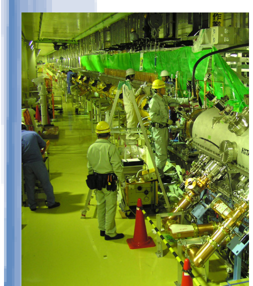
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

$\nu_\mu = -\sin\theta\ \nu_1 + \cos\theta\ \nu_2$

Propagation

Source



W

$\nu_\mu$

μ

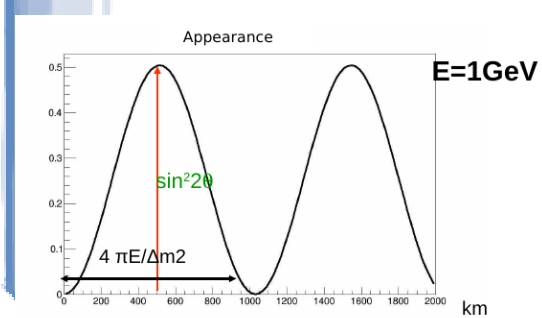
$$\nu_1 \to \exp(-ip_1 x)\,\nu_1$$
$$\nu_2 \to \exp(-ip_2 x)\,\nu_2$$
$$\Delta\varphi = \Delta m^2 L/(4E)$$

$\nu_e$

e

Detector

**L**




$$\boxed{\mathrm{Prob}(\nu_\mu \to \nu_e) = \sin^2(2\theta)\,\sin^2(\Delta m^2 L/4E)}$$

This is a simplified two neutrino scenario

# The neutrino mass term: beyond SM

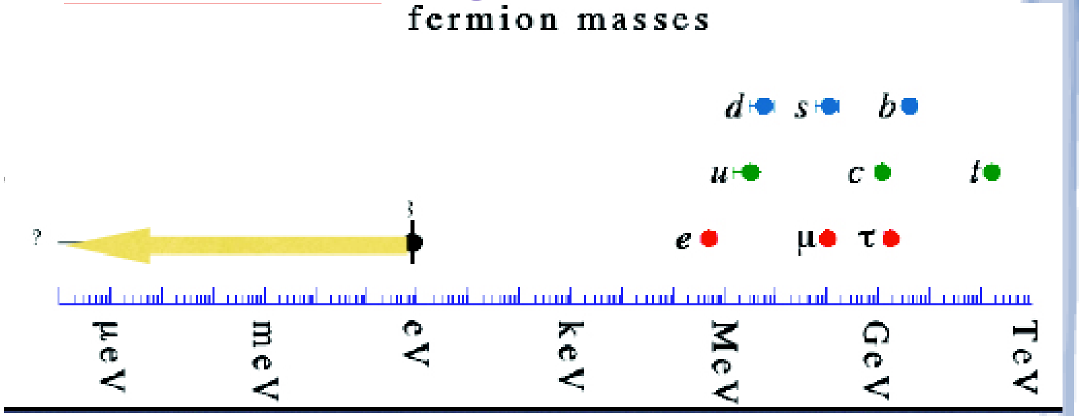
- The Standard Model (only left handed neutrinos) is unable to provide a mass term for neutrinos
- The simplest addition to the lagrangian is

$$M_{Dij}\,\overline{\nu}_{si}\,\nu_{Lj} + M_{Nij}\,\overline{\nu}_{si}\,\nu^{c}_{sj}$$

- If $M_N$=0 Dirac neutrinos
- If $M_N$>>$M_D$ seesaw mechanism (naturally explains light neutrino masses with $M_N$ ~ GUT scale)
- A Majorana mass term emerges also naturally at the lowest order considering the SM as an effective low energy theory

# Neutrino physics: surprising results

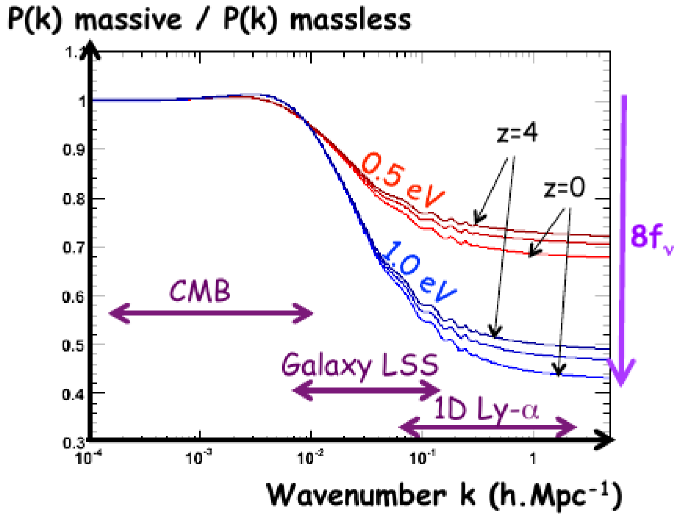
- The extreme lightness of neutrino masses begs a compelling explanation




- The neutrino mixing angles are large, at variance with the quark mixing angles: large CP violation effects are allowed

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Neutrinos play an important role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?

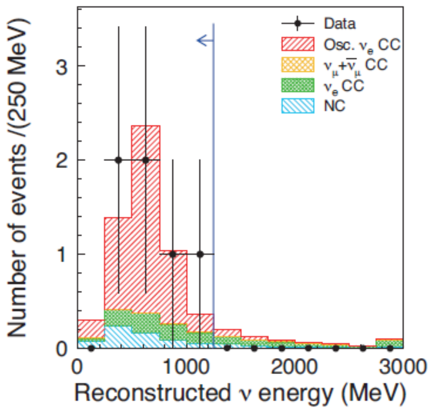


# Baryon asymmetry in the Universe and leptonic CP violation

- To explain the Baryon Asymmetry in the Universe (BAU) (i) C and CP violation, (ii) B violation and (iii) processes out of thermal equilibrium are needed (Sakharov 1967)
- The observed CP violation in the quark sector is many order of magnitudes below what is needed to explain BAU
- The decay of heavy neutral leptons with CP violation may produce a lepton asymmetry first, later converted into a baryon asymmetry: leptogenesis model (Fukugita Yanagida 1986)
- Observing CP violation in the neutrino sector would be a supporting piece of evidence for leptogenesis (NB not a proof!)

# The measurement of the last mixing angle $\theta_{13}$

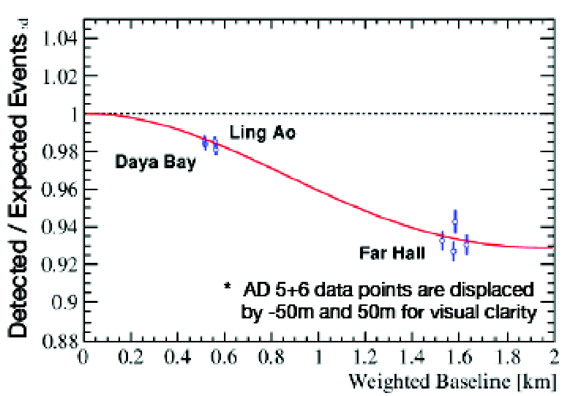
- 2011: early indication by T2K (appearance mode, 2.5 σ)
- 2011-2014 Precise measurement by the Daya Bay experiment (and Reno, Double Chooz)
- Over $10^6$ antineutrinos detected
- Shape distortion agrees with the oscillation prediction

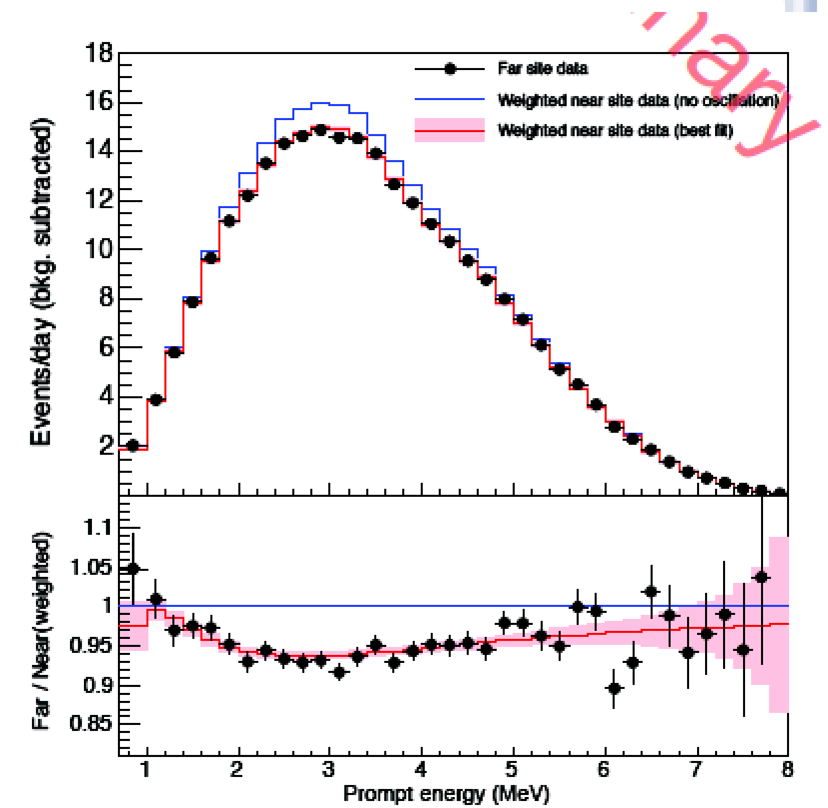



$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$



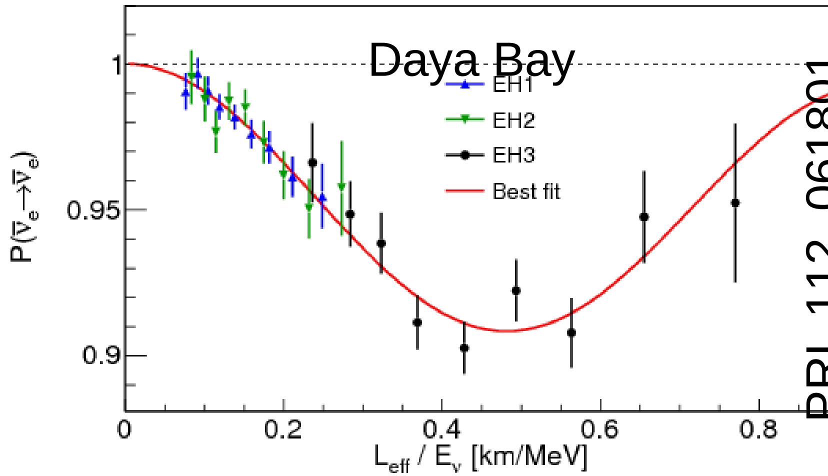



# The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

$s_{ij}=\sin\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been convincingly observed using solar, atmospheric (Nobel prize 2015), reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently unveiling three-neutrino subleading effects




PRL 112, 061801

$$\nu_\mu \to \nu_\tau,\ \nu_\mu,\ \nu_e \quad +\text{CP conj.} \qquad \bar\nu_e \to \bar\nu_e$$

| Parameter | Value | Precision (%) |
|---|---|---|
| $\Delta m^2_{21}$ | $7.5\ 10^{-5}$ eV$^2$ | 2.6 |
| $\theta_{12}$ | 34° | 5.4 |
| $\Delta m^2_{32}$ | $2.4\ 10^{-3}$ eV$^2$ | 2.6 |
| $\theta_{23}$ | 42° | ~10 |
| $\theta_{13}$ | 9° | 6 (Daya Bay 2014) |

Capozzi et al.
ArXiv:1312.2878
Talk by M. Tortola

# Next steps in neutrino physics

1) Is $\theta_{23}$ =45°? which octant ?

2) Determine the mass ordering

3) Measure the CP violation parameter $\delta$

4) Precision tests of the PMNS paradigm (ideally at the % level, as for the CKM matrix)

5) Are there any new neutrino states ?

6) Dirac or Majorana ?

1) Is there a symmetry between $\nu_\mu$ and $\nu_\tau$ ?

2) Help model builders. Impact on cosmology.

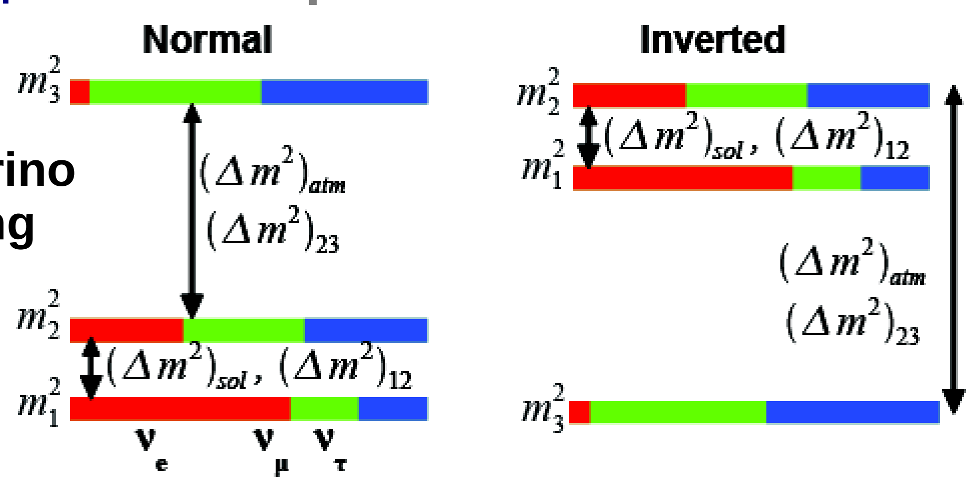
3) Link with leptogenesis. Are we born out of (heavy) neutrinos ?

4) How different are neutrinos ?

5) New states are expected btw 1eV and 10**16 GeV

6) Majorana mass term: major discovery

**Normal neutrino mass ordering**




**Inverted neutrino mass ordering**

# The road towards CP violation: $\nu_\mu \to \nu_e$ : beyond the leading term

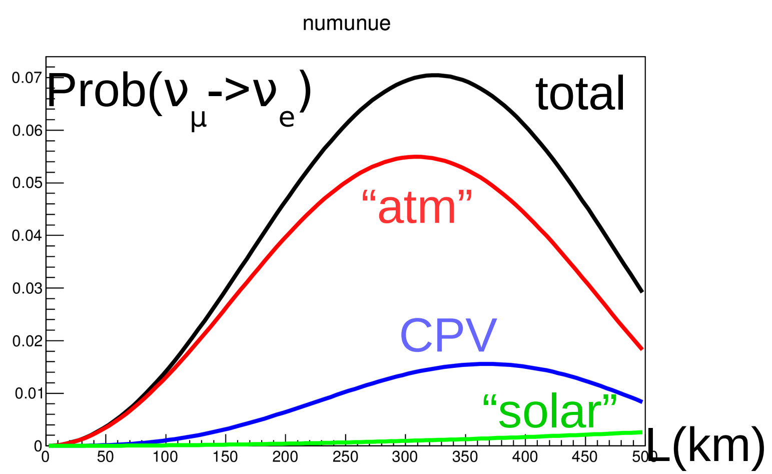
$$P(\nu_\mu \to \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

$$\mp 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

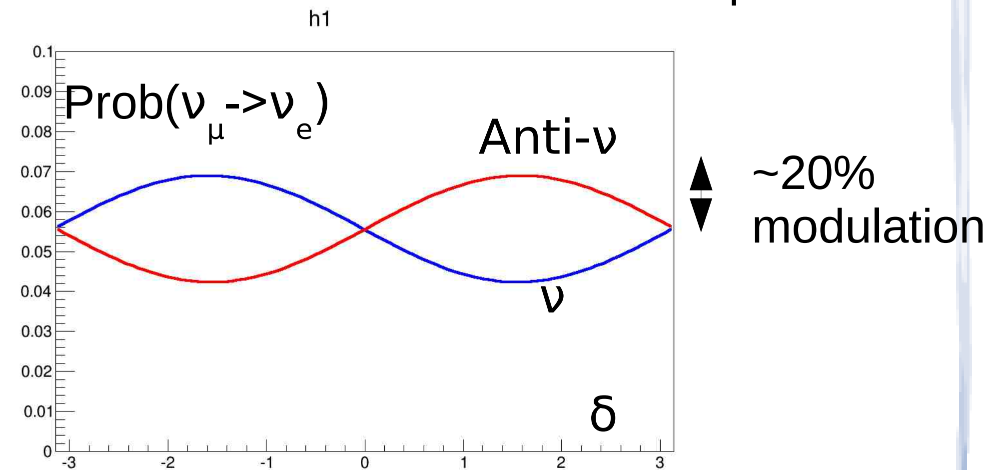
$$+4 S^2_{12} C^2_{13} \left( C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta \right) \sin^2 \Phi_{21}$$ "Solar" term

$$C_{ij} = \cos(\theta_{ij})$$
$$\Phi_{ij} = \Delta m^2_{ij} L / 4E$$

Change sign from ν to anti-ν! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced




E=0.6 GeV




Caution: indicative plots !!

# Matter effect on neutrino oscillations

- Neutrino interactions with matter produce an additional dephasing btw mass eigenstates, similar to the optical refraction index

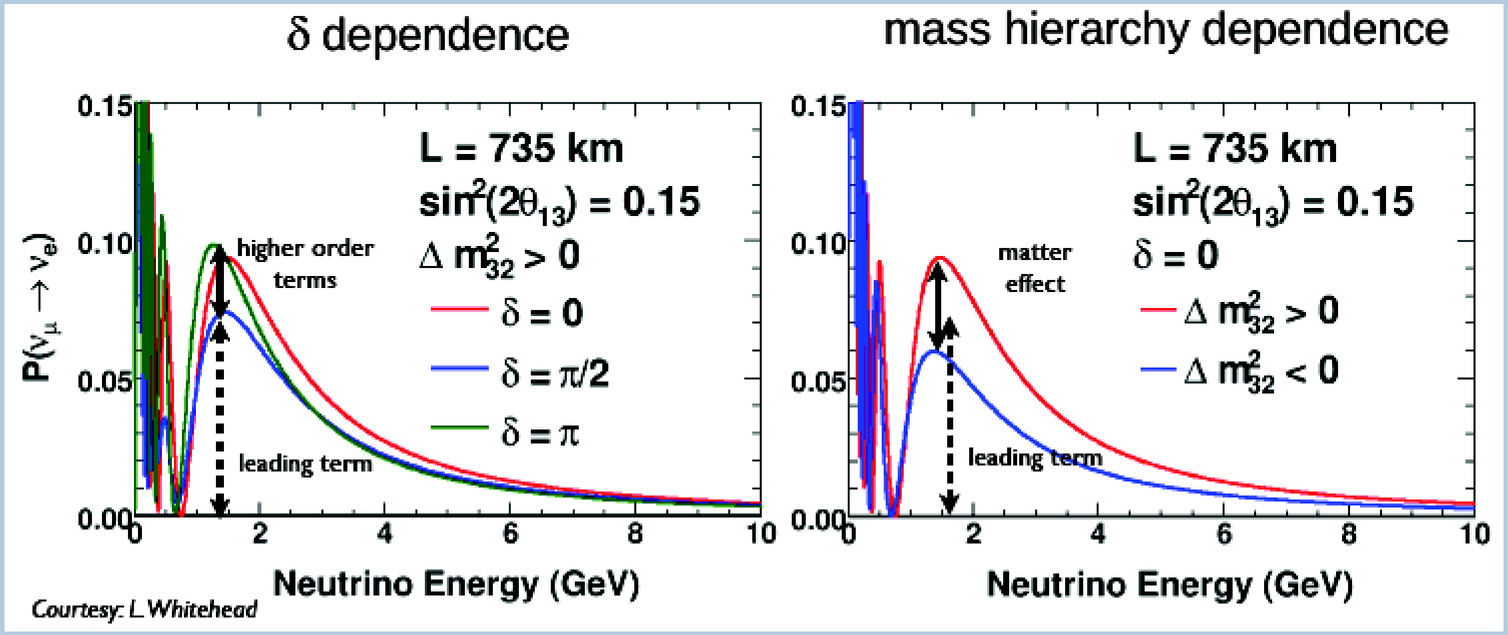
$$\sin^2 2\theta_m = \frac{\sin^2(2\theta)(\Delta m^2/2E)^2}{\sqrt{(\cos(2\theta)(\Delta m^2/2E) - \sqrt{2}G_F n_e)^2 + \sin^2(2\theta)(\Delta m^2/2E)^2}}$$

Maximum mixing even with a tiny mixing angle

$$E_{res} = 7\,GeV\left(\frac{4.5\,g/cm^3}{\rho}\right)\left(\frac{\Delta m^2}{2.4\,10^{-3}\,eV^2}\right)\cos(2\theta_{13})$$

The resonance appears either for neutrinos or antineutrinos, depending on the sign of $\Delta m^2$ (MH)

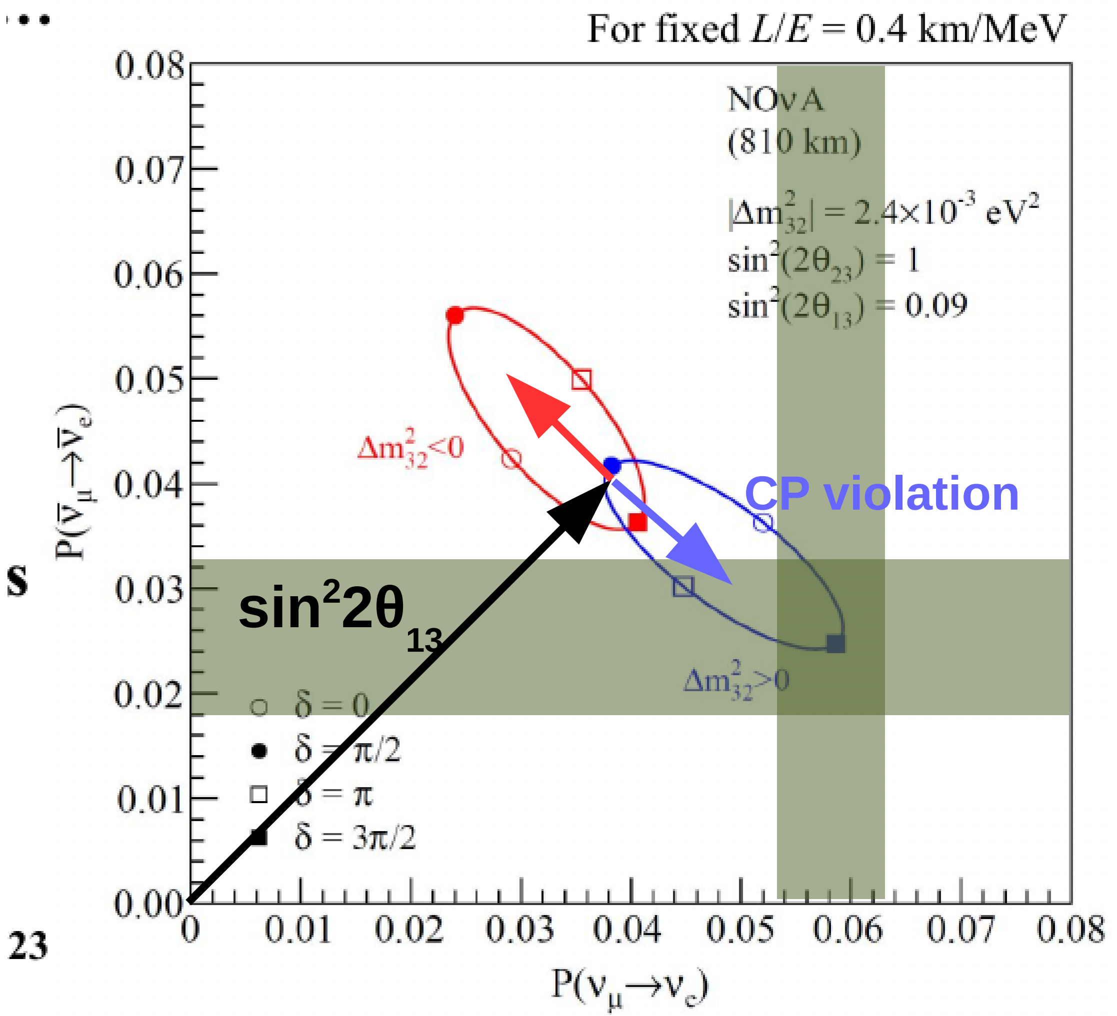
# Interplay of CP and Matter Effects




- The simple study of the CP asymmetry is obscured (or enriched) by matter effects (interaction of ν with e in the traversed matter) that mimic a CP effect
- This complication can be seen as a challenge or an opportunity : clean measurement of mass hierarchy

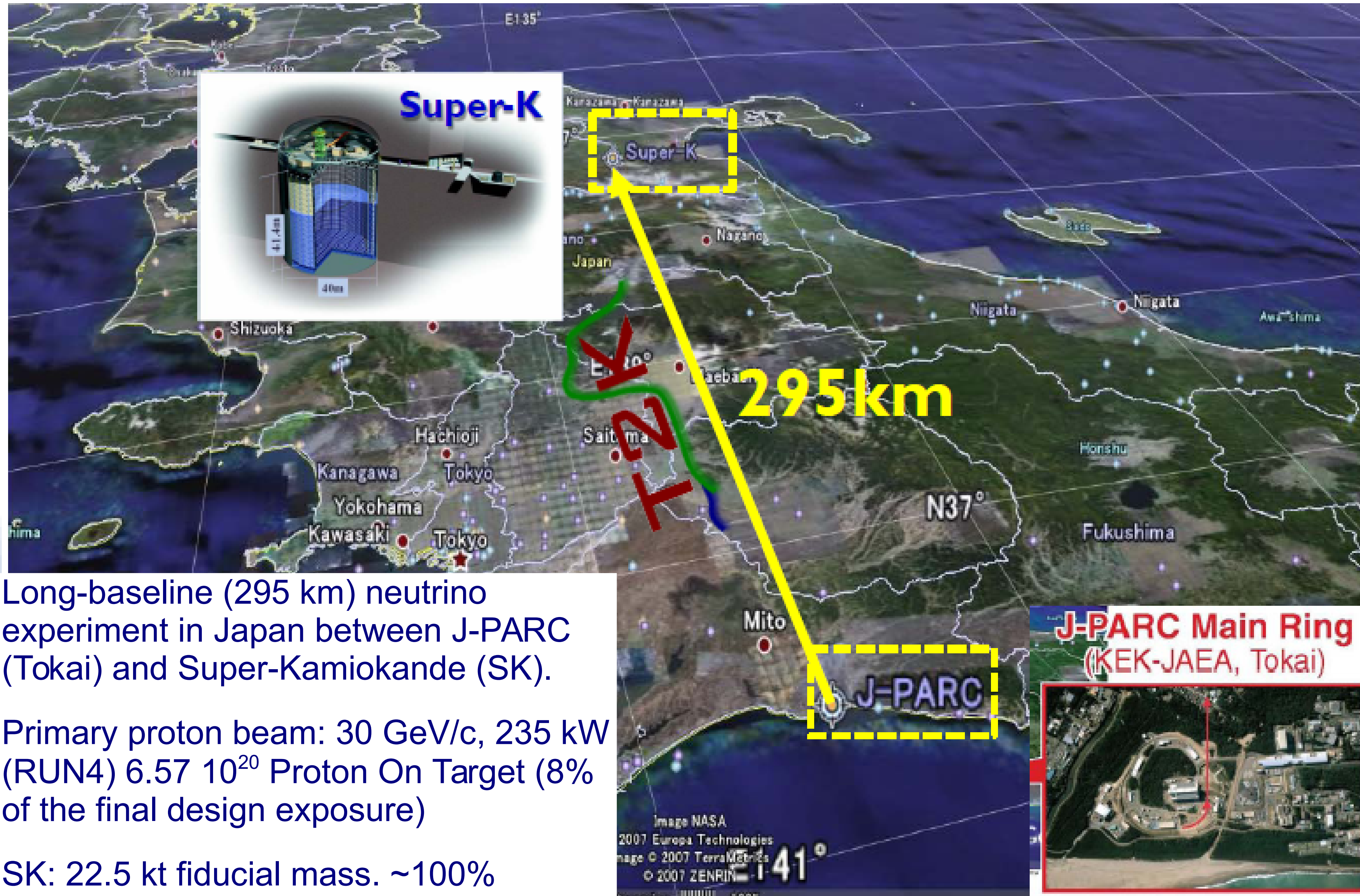
# Interplay of CP and matter effects

Courtesy NOVA collaboration



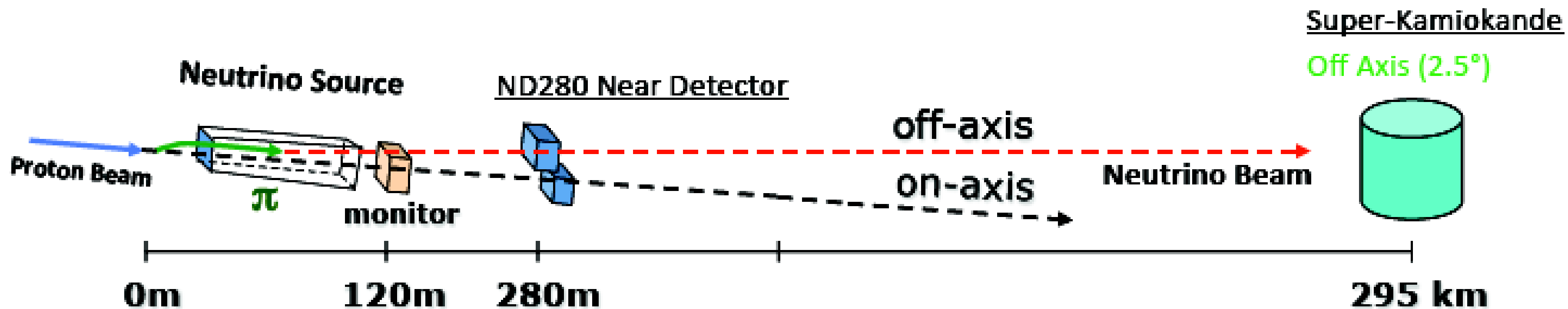

Effect of **inverse** or **direct** mass ordering

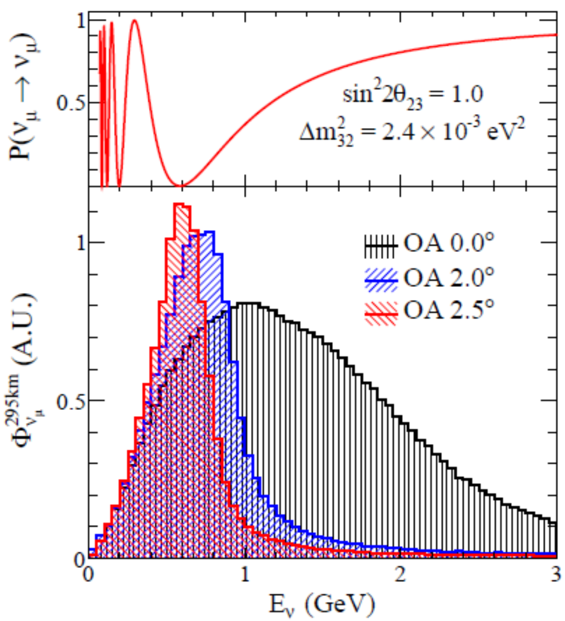
# The Tokai to Kamioka (T2K) experiment



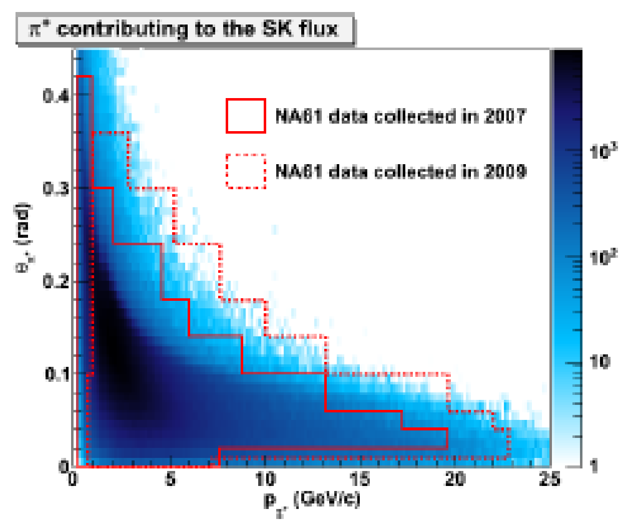

- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, 235 kW (RUN4) 6.57 $10^{20}$ Proton On Target (8% of the final design exposure)
- SK: 22.5 kt fiducial mass. ~100% livetime

# T2K: Main Experimental Features

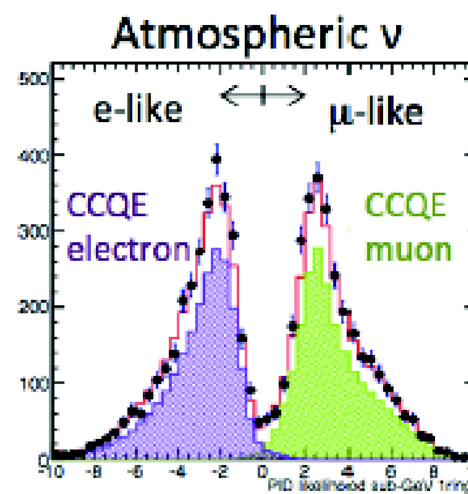



Off-axis beam.
Flux has a narrow peak tuned for the first oscillation maximum



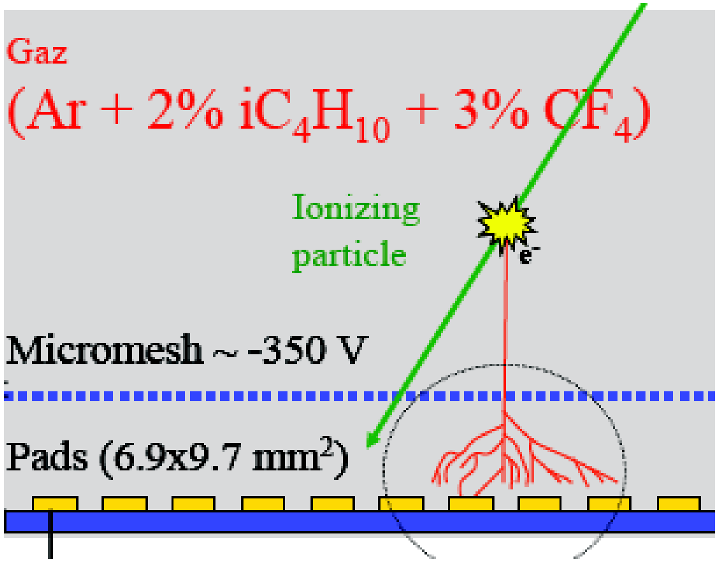

Pion and kaon production measured by the NA61 exp. at CERN



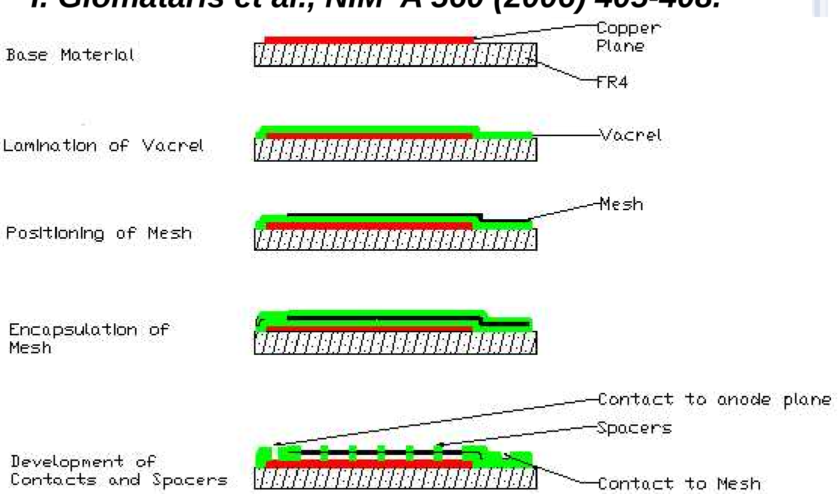

Excellent particle identification capabilities in SK (misid <1%)

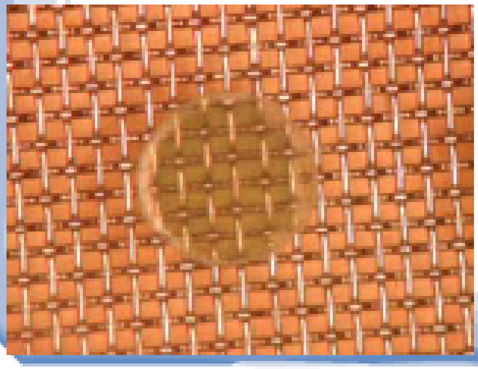
# Micropattern gas detectors

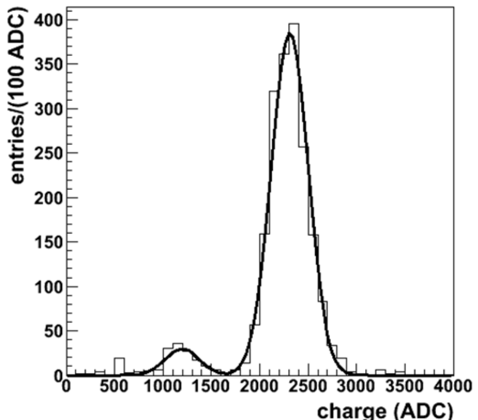
- Modern gas detectors with thin gaps and without wires: most popular are Micromegas and GEM
- Built with standard methods of PCB industry
- Fast, cheap, versatile, possibility to industrialize the process
- Compass, T2K first large scale applications
- Atlas New Small Wheel, ILC TPC, Double Phase Liquid Argon TPC WA105->DUNE



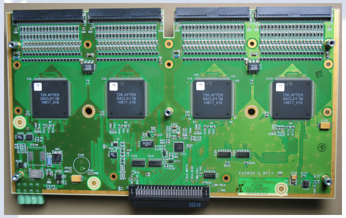

*I. Giomataris et al., NIM A 560 (2006) 405-408.*



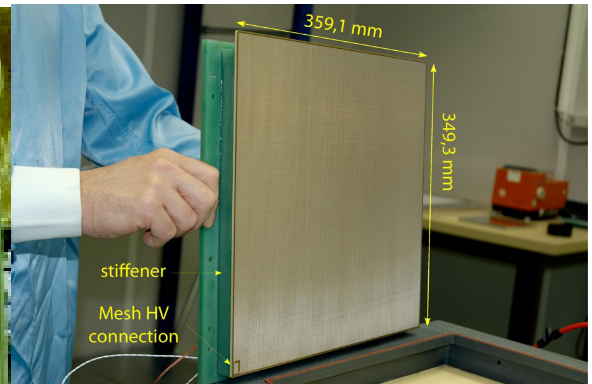



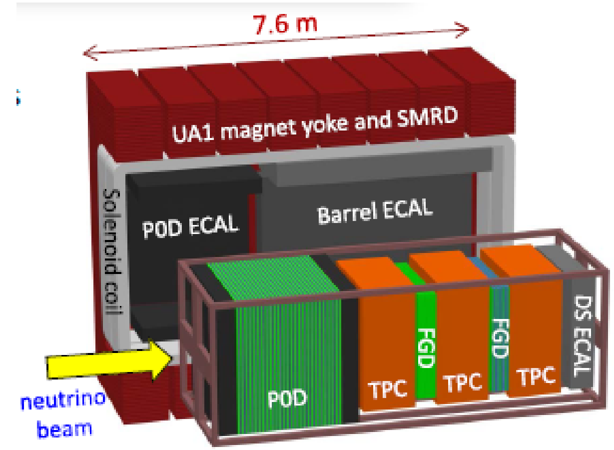


NIM A 637 2011 25

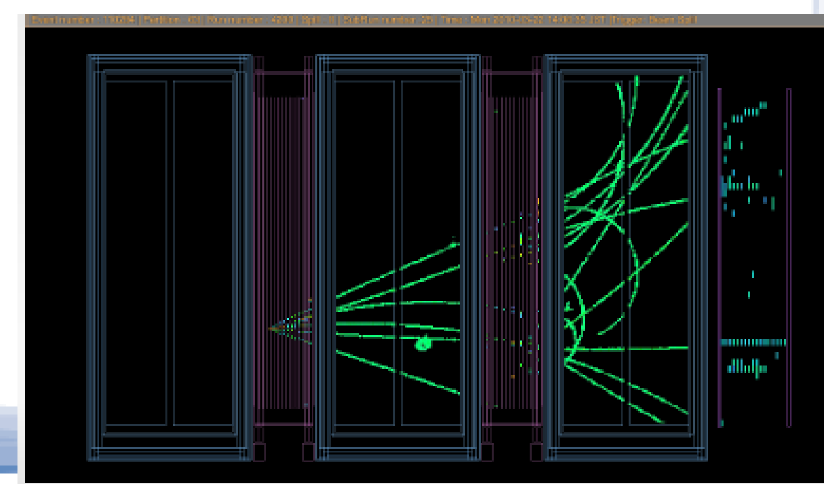


# The T2K near detector TPC

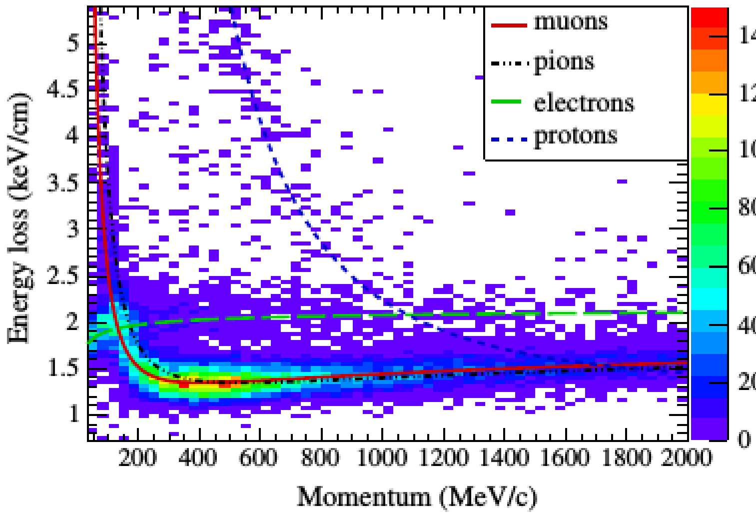

- Three large TPC for the T2K near detector
- The first large TPC using MPGD
- ~9 m**2 equipped with bulk Micromegas detectors
- Playing a key role in the study of the neutrino flux and interactions (charge, momentum and dE/dx PID)
- Space resolution : 0.6 mm
- Momentum res. 9% at 1 GeV
- dE/dx: 7.8 % (MIP)

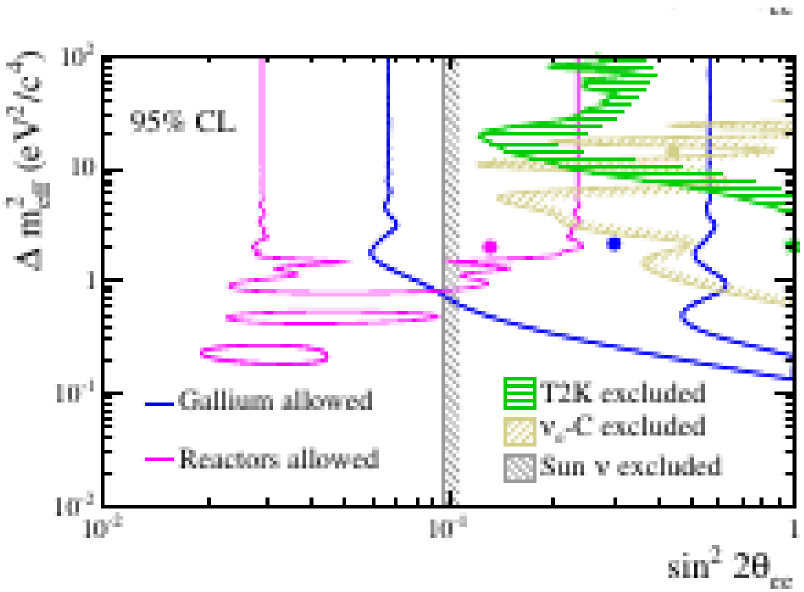


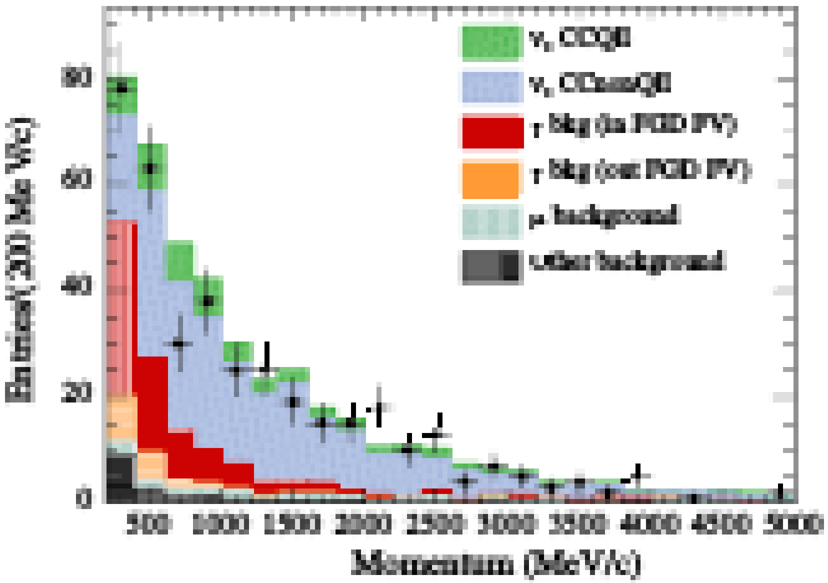
72 Micromegas and 120k channels functioning flawlessly since 2009 (dead channels 144/124272)

# Physics with the T2K TPC

- Neutrino interactions in the near detector : flux and cross-section constraint
- Nu_e flux (meas/pred= 1.01±0.10) and cross-sections (here 1/10 of T2K full sample)
- Sterile neutrino studies

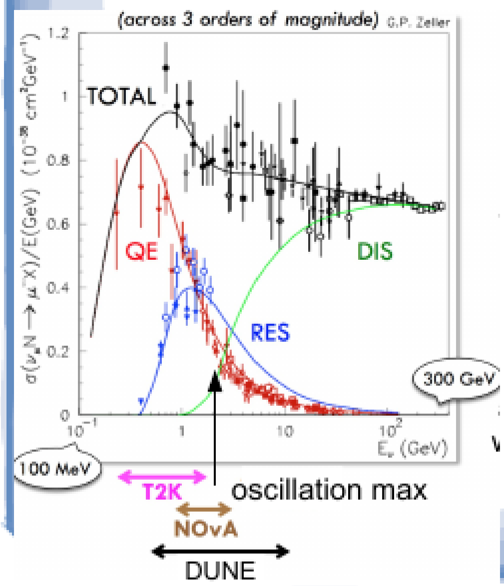


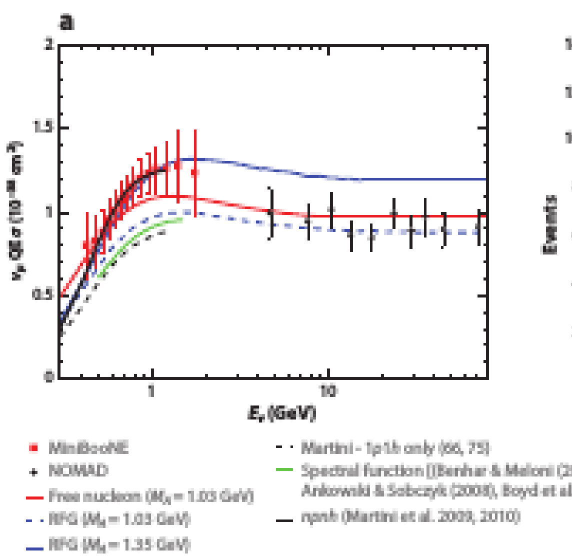



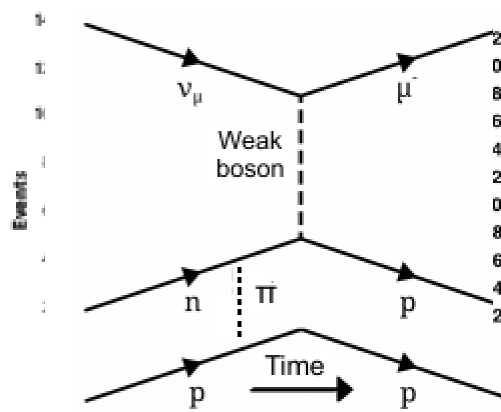



# The problem with neutrino cross-sections

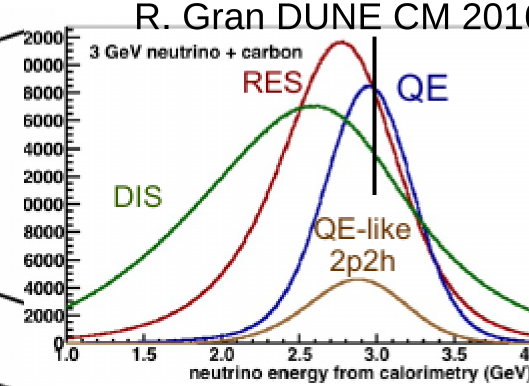
- Neutrino cross-section : incomplete knowledge and inconsistencies. No comprehensive, precise and established model.
- Up to 40% of the cross-section was unaccounted until recent work (~2000), still poorly known
- Other channels plagued by inconsistencies between experiments
- Problem compounded by the fact that no neutrino beam is monochromatic, the flux is known with 10% accuracy at most
- And all experiments infer the neutrino energy from either the lepton kinematics or the hadronic energy (resolution and bias depend on channel, and nu/antinu effects)



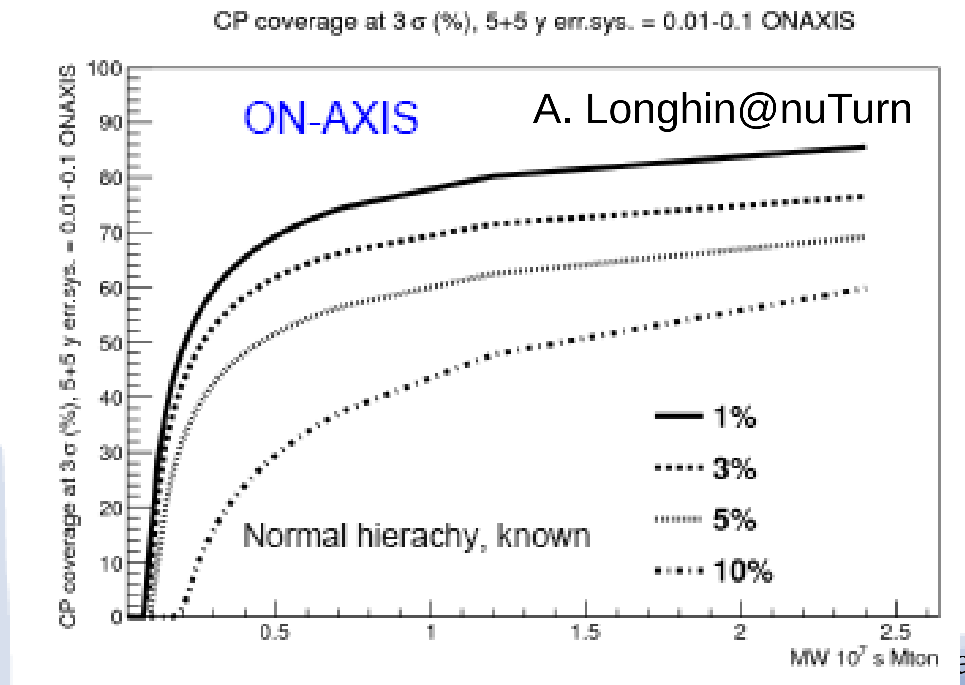



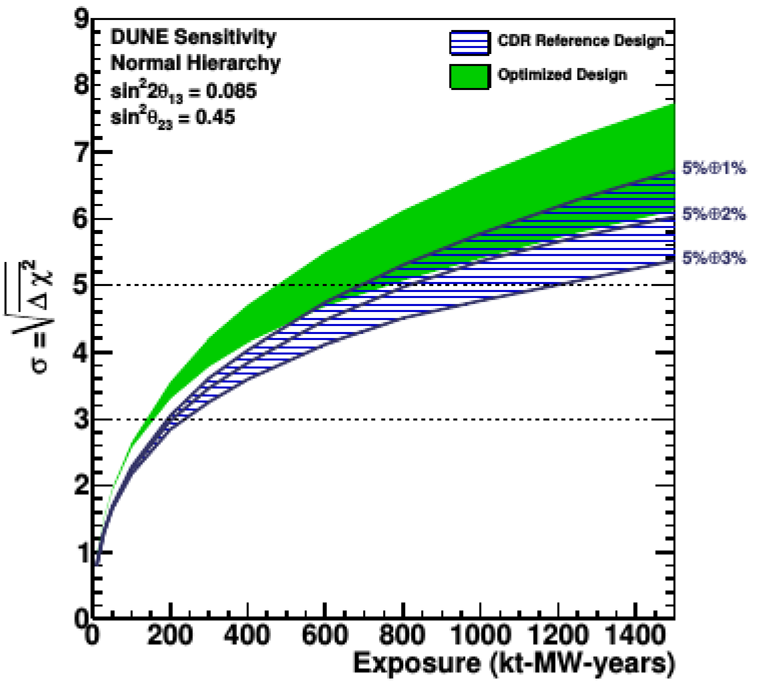

R. Gran DUNE CM 2016



# Cross-section and long-baseline efforts

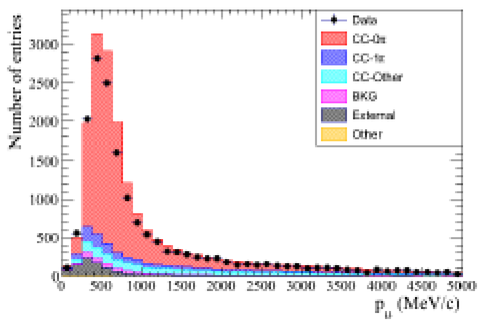
- Improving systematic uncertainty from 5 to 3% is equivalent to doubling the far detector mass (0.5 Mt in this example)
- Generically true both for DUNE and HK

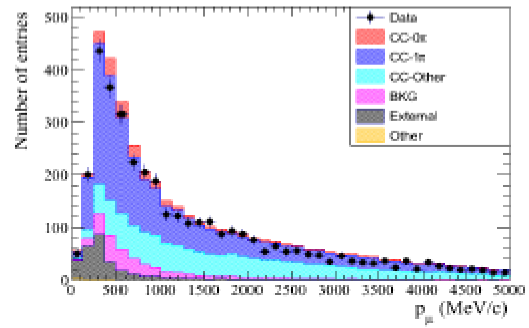


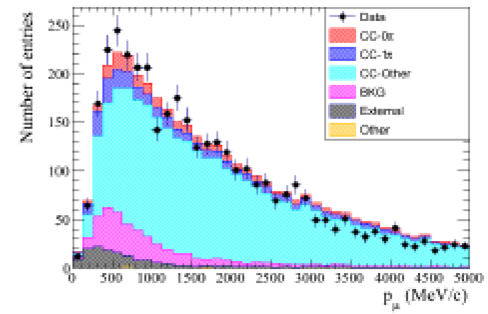




arco

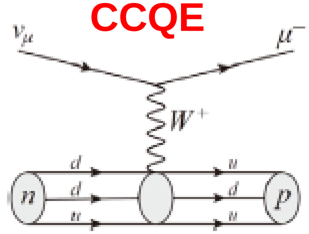
# T2K Near detector constraint



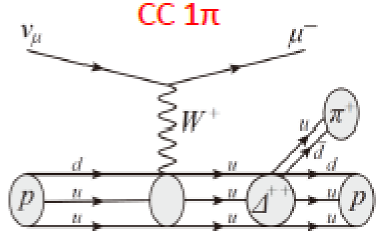



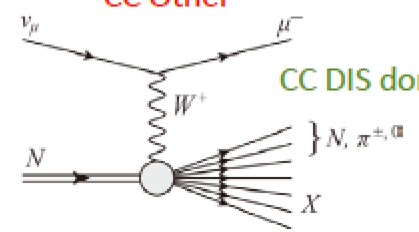

**CCQE**




CC 1π

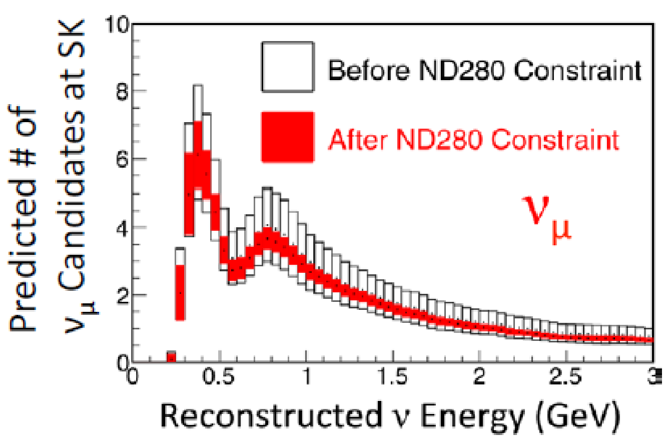


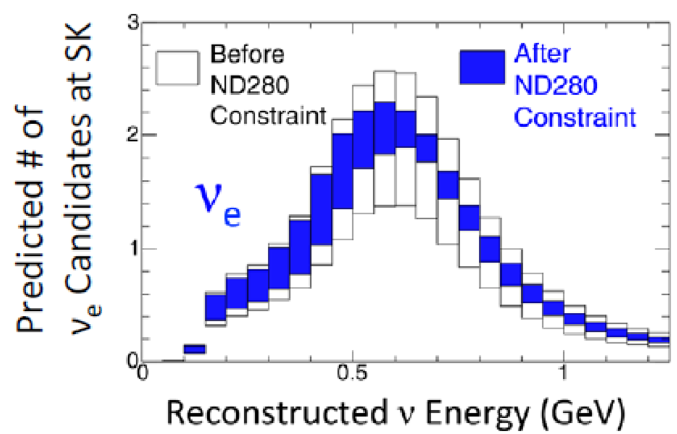

CC Other




CC DIS dominated

Flux and cross-section systematic uncertainty on $N_{SK}$ significantly reduced to ~7%

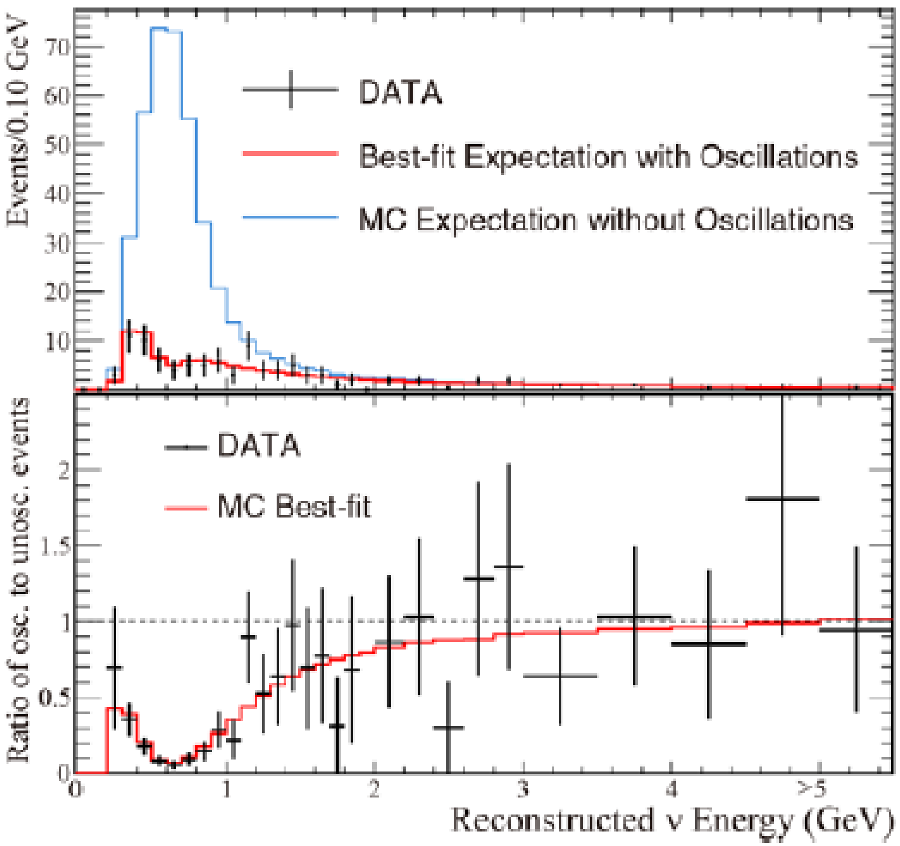


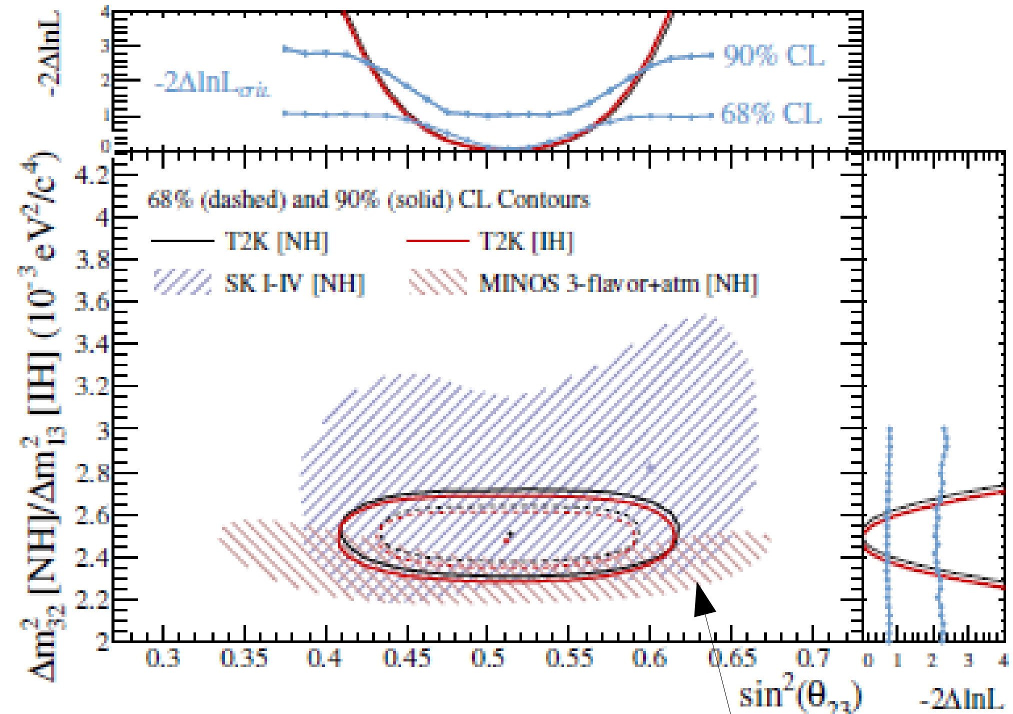
$\nu_\mu \rightarrow \nu_\mu$

Phys. Rev. Lett. 112, 181801 (2014)

# T2K $\nu_\mu$ disappearance measurement




Talk by A. Himmel




Notice recent MINOS 3-flavor result

| Oscillation parameters | | Best-fit value |
|---|---|---|
| NH | $\sin^2(\theta_{23})$ | $0.514^{+0.055}_{-0.056}$ |
| | $\Delta m^2_{32}$ ($10^{-3}$ eV$^2$) | $2.51 \pm 0.10$ |
| IH | $\sin^2(\theta_{23})$ | $0.511 \pm 0.055$ |
| | $\Delta m^2_{13}$ ($10^{-3}$ eV$^2$) | $2.48 \pm 0.10$ |

$N_{obs} = 120$

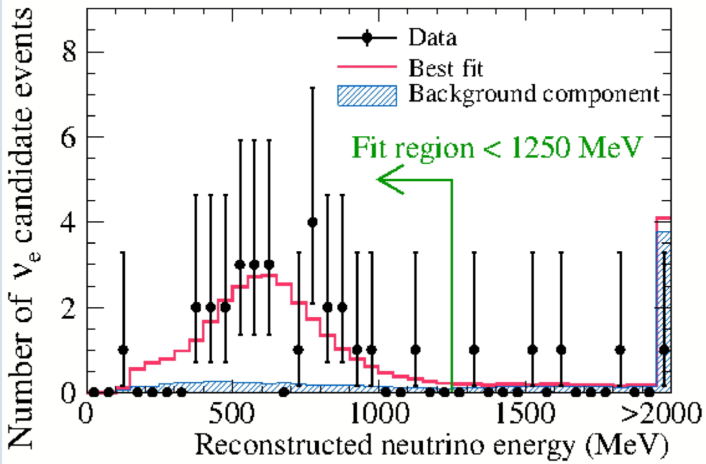
$N_{exp}$ (no osc) = 446±23(syst.)

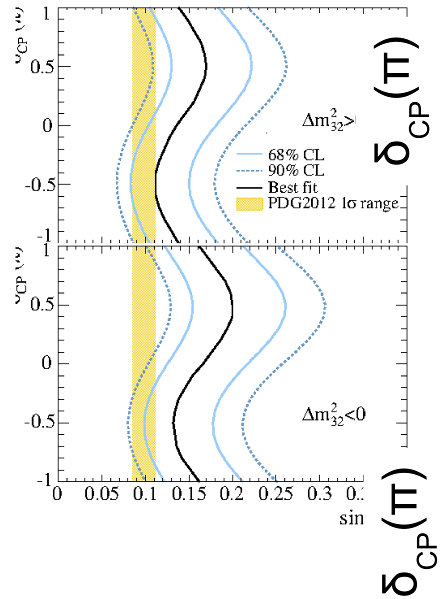
Data favor maximum disappearance.

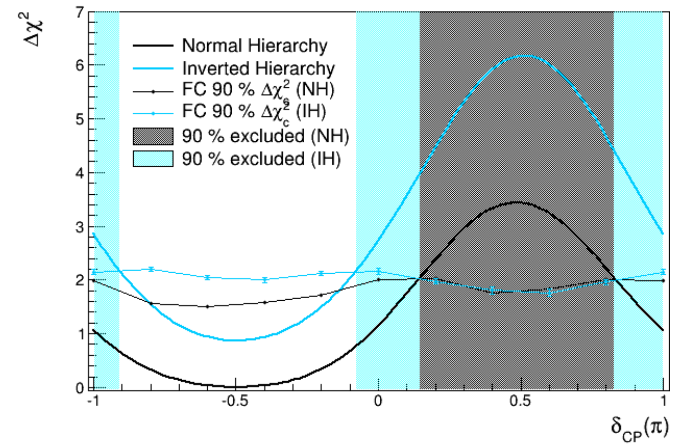
$\nu_\mu \rightarrow \nu_e$

Phys. Rev. D 91, 072010

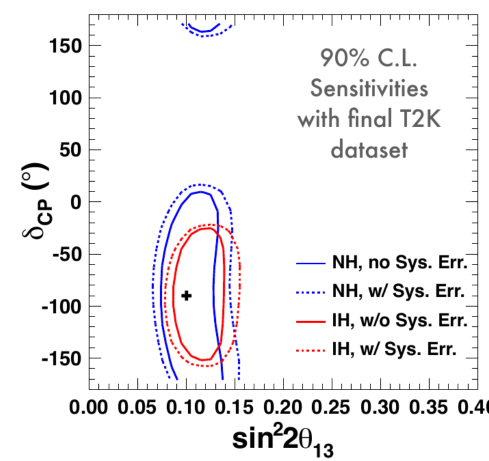
# T2K first limits on CP violation




- Comparing the 28 observed $\nu_e$ events in T2K with $\theta_{13}$ measured at reactor experiments provides first hints of CP violation
- Full T2K data set (today ~10% of total) might provide ~2 σ evidence
- NOvA (data taking started in 2014) provides additional sensitivity at a different L
- <u>However precision determination requires a new facility</u>

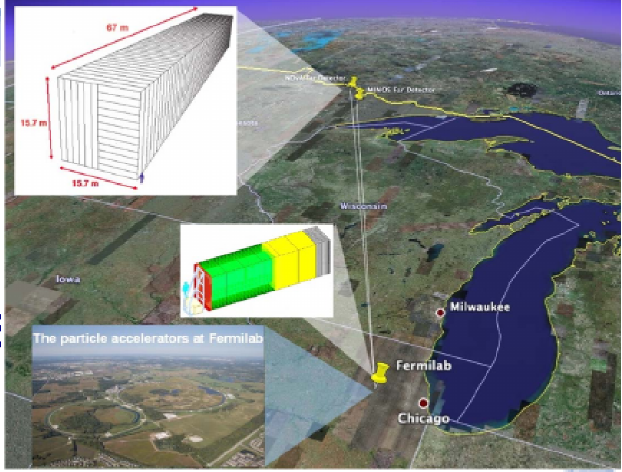



arXiv:1409.7469

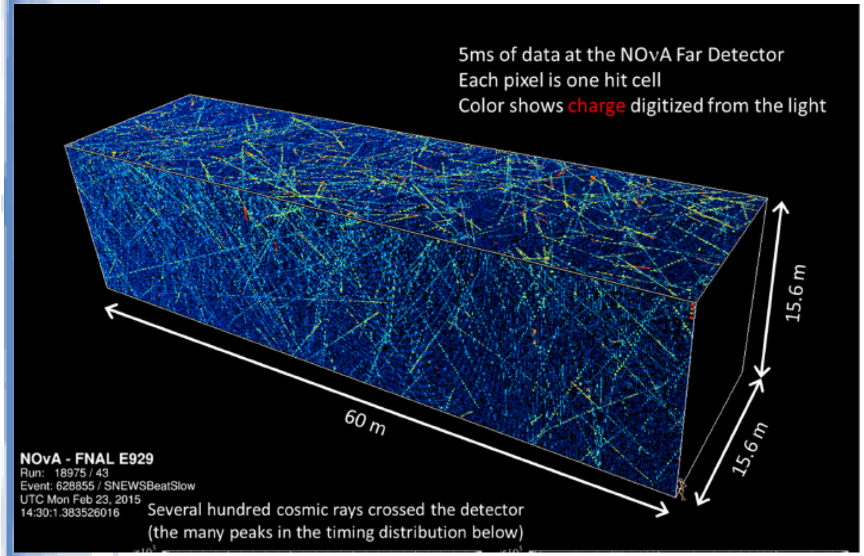
Pascoli Petcov Riotto 2007

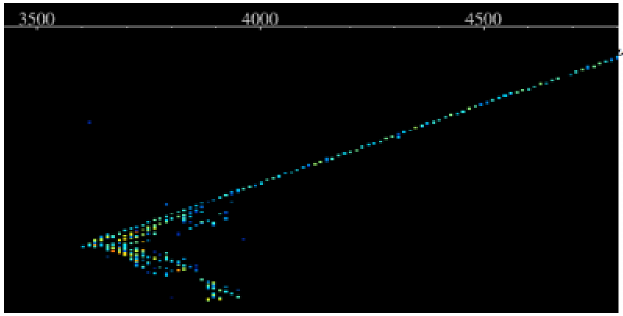
Leptogenesis w/o new sources of CP violation except delta ? OK if $|\sin\theta_{13}\sin\delta| \geq 0.11$

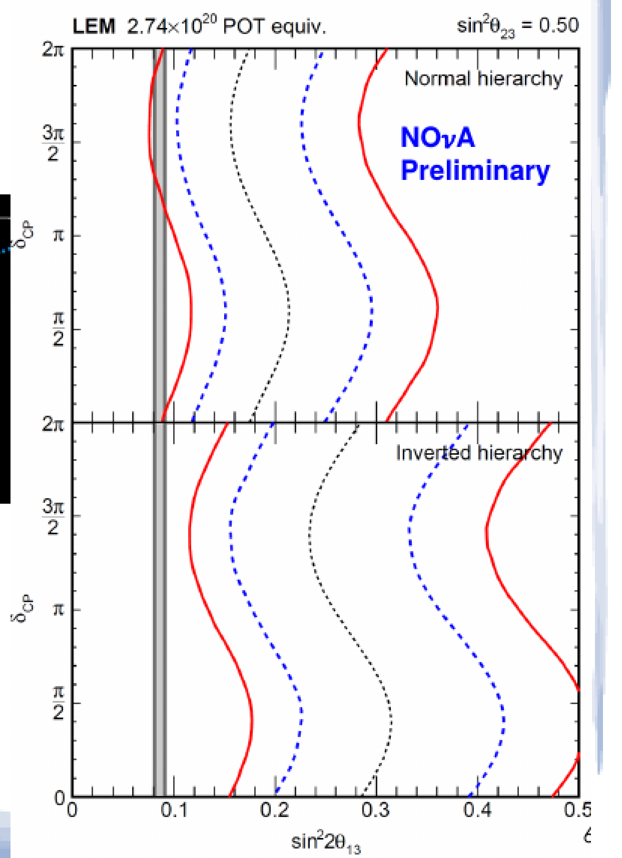
# NOvA




- 810 km baseline from FNAL to Ash River (Minnes
- Off-axis NUMI beam (2 GeV) with 500->700 kW
- 14kt surface liquid scintillator segmented detector
- First prel. results presented at NUFACT2015
- IH disfavored at 2 sigma

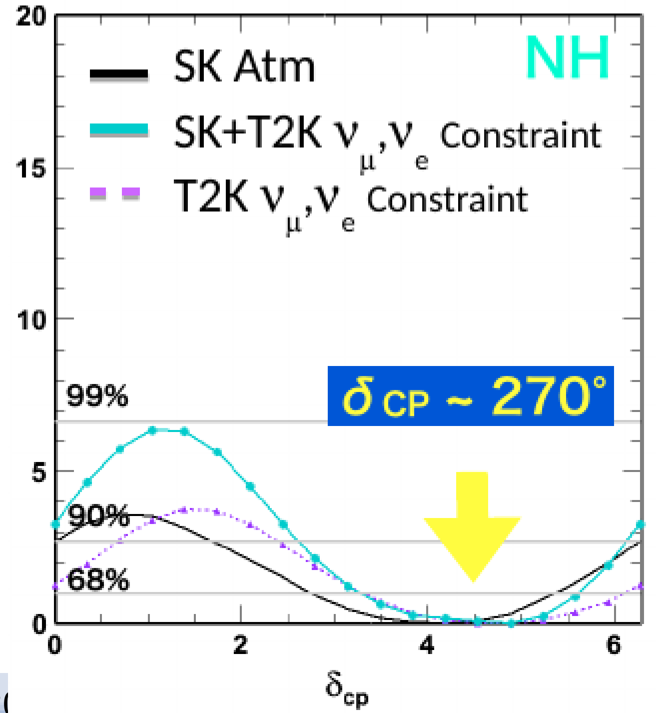


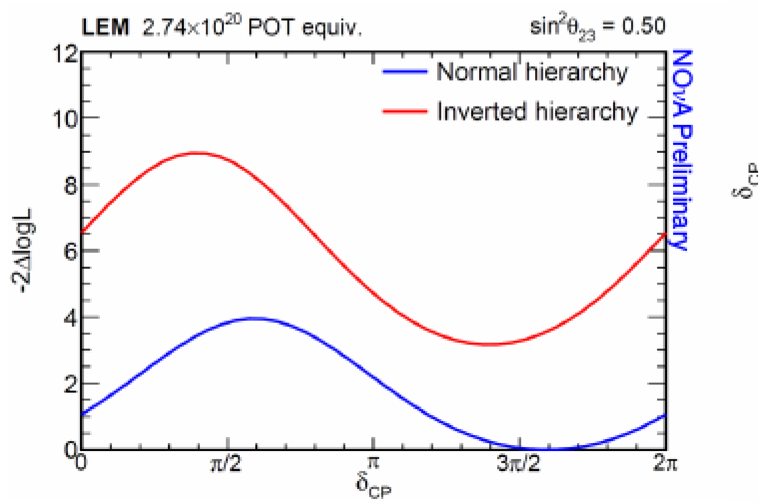



# T2K+SK+NOvA

- T2K: initial hint of delta around 3π/2
- SK (atmospherics) : similar trend
- NOvA: similar trend




NOVA (August 2015)




Ryan Patterson, Caltech

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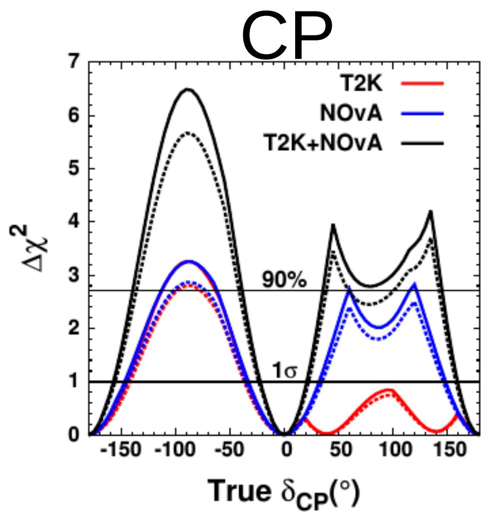
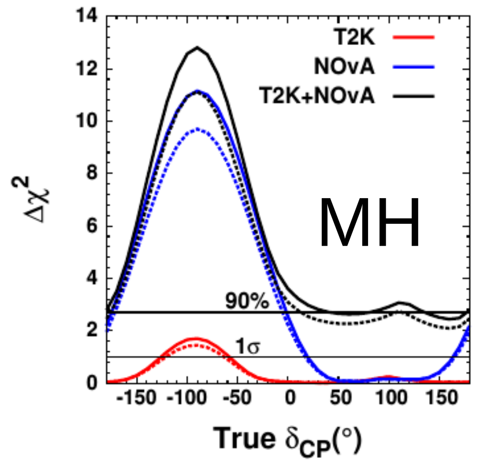
# Final reach of T2K and NovA

- Similar sensitivity to CP for T2K and NOvA
- Better sensitivity to MH for NOvA (larger baseline)
- Best sensitivity for δ=-π/2 and NH
- Each can reach 90% CL or higher
- T2K proposes an extention (T2K-II) up to 2026 to increase by ~3 the effective data set
- Current T2K results based on neutrino only and ~5% of the total data set. Stay tuned for the releaseof neutrino+antineutrino result (July 2016)



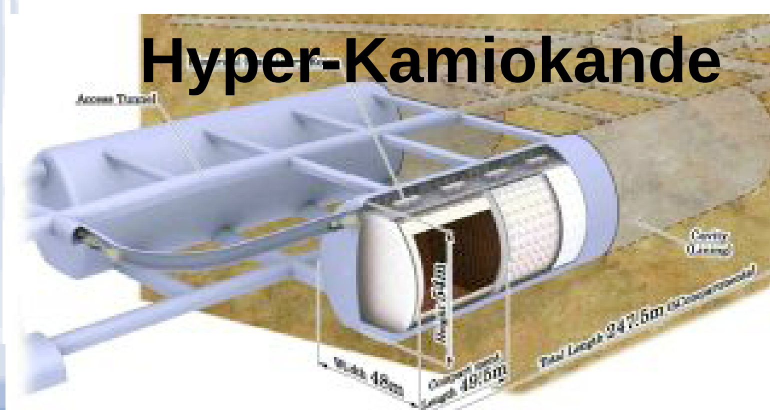

(b) 1:1 T2K, 1:1 NO$\nu$A $\nu$:$\bar{\nu}$, NH

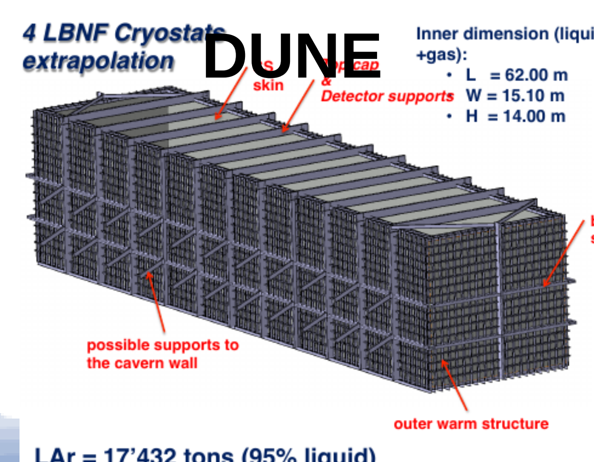



(b) 1:1 T2K, 1:1 NO$\nu$A $\nu$:$\bar{\nu}$, NH

# Strategies for CP

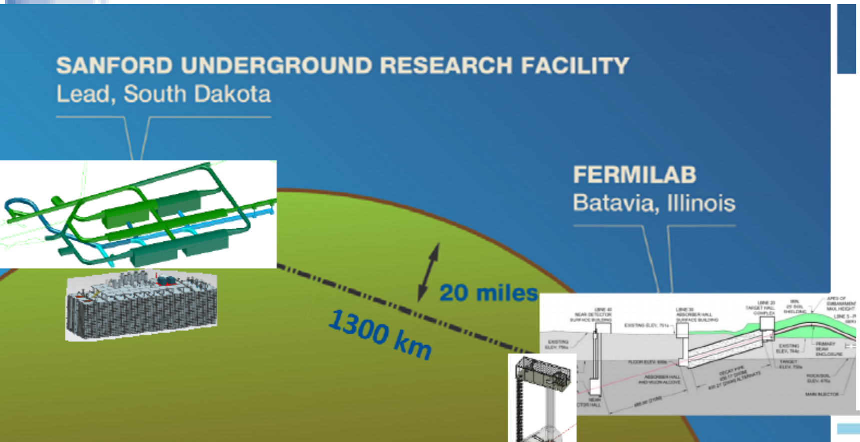
- Short baseline (~100-300 km), lower energy (<1 GeV), narrow beam, large Water Cherenkov (~500 kT). Concentrates on $\nu/\bar{\nu}$ asymmetry around the first oscillation max.
- Longer baseline (>1000 km), higher energy (>1 GeV), wide beam, Liquid Argon TPC. All final states accessible, E/L oscillation pattern and second maximum



# The LBNF/DUNE project

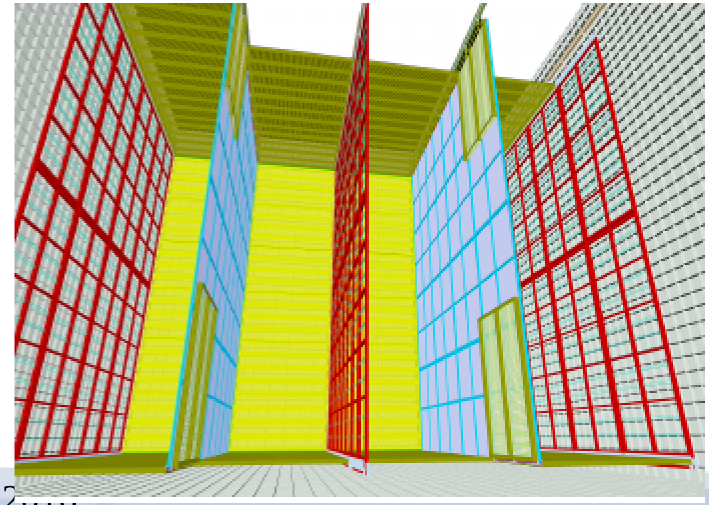

- LBNF DUNE: flagship particle physics project in the US (P5 recommendation)
- 1300 km baseline from FNAL to SURF (South Dakota)
- Based on PIP-II upgrade to FNAL accelerator complex: 1.2 MW at 120 GeV (ultimate beam power 2.4 MW)
- Sophisticated near detector(s) on FNAL site
- SURF: 4 caverns with 4x10 kt fiducial mass far detector

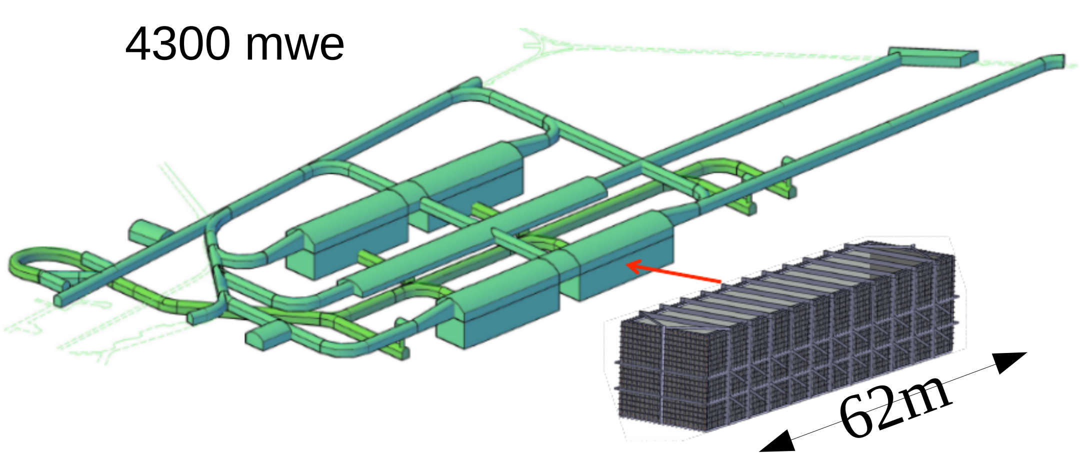



CDR released last July: CD1 passed, CD3-a (excavation) ~OK. CD2 in 2019.
LBNF LOI: deployment of first 10kt module in 2021
Collaboration strengthened (>700) and more international (India, CERN, Laguna-LBNO)

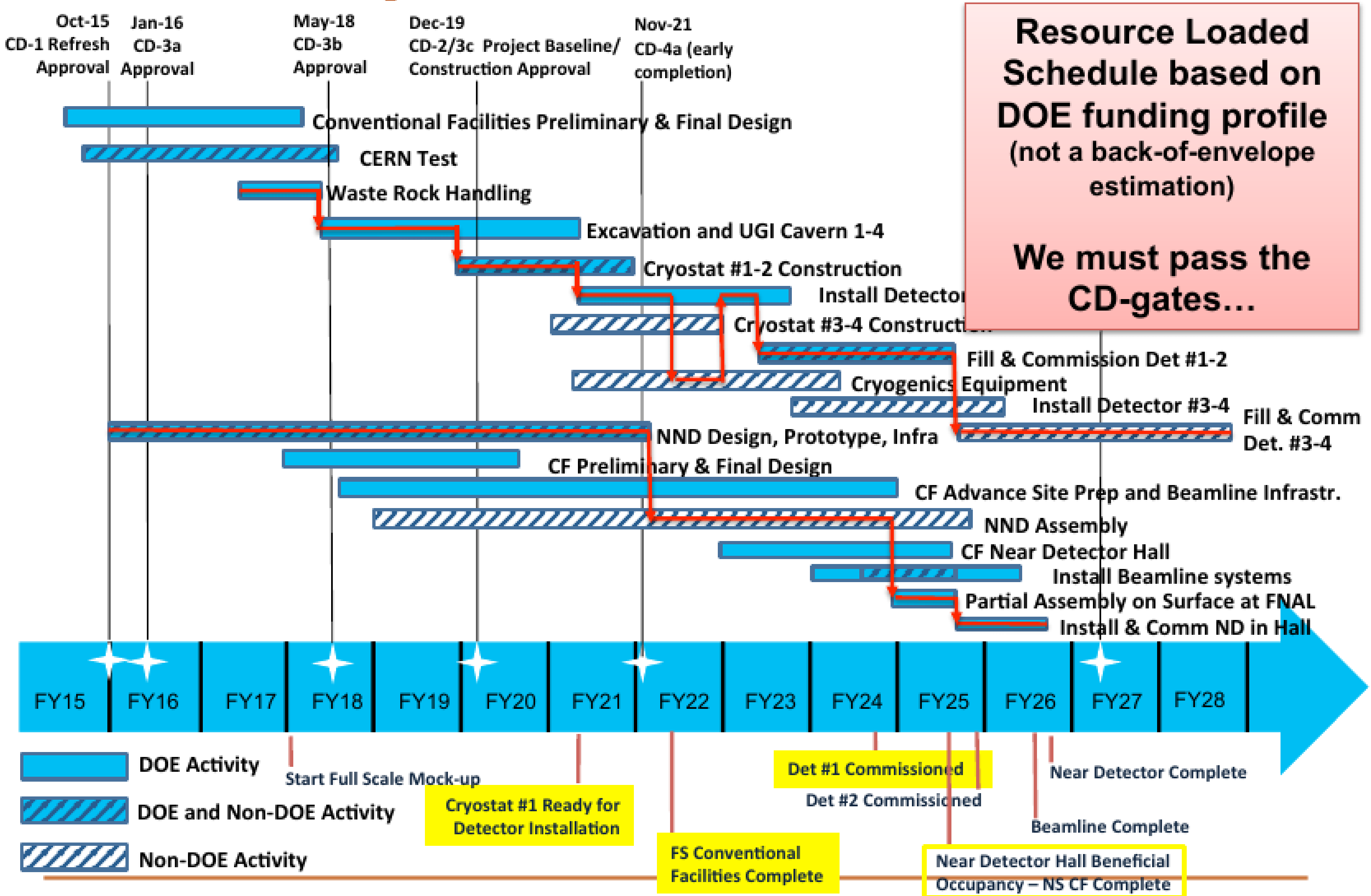
# The Sanford Underground Research Facility (SURF)

- Historical site for neutrino physics: laboratory of the Homestake Ray Davis solar neutrino experiment
- Today hosting dark matter experiments (LUX/LZ)
- Major refurbishing of the facility ongoing
- Underground lab includes four large caverns and other infrastructure
- Reference detector design : Liquid Argon TPC





# Timeline presented at CD1-R




**Resource Loaded Schedule based on DOE funding profile**
(not a back-of-envelope estimation)

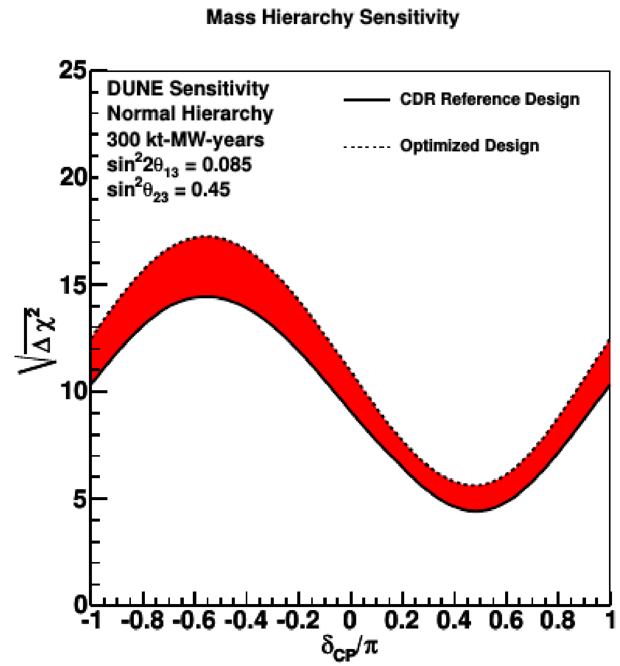
**We must pass the CD-gates…**

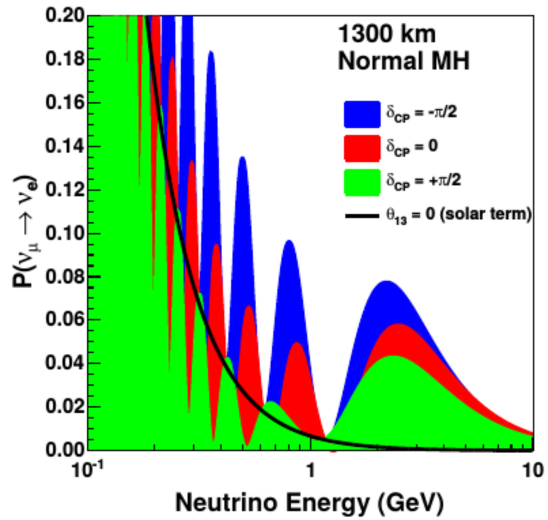
6 09.04.15 André Rubbia I DUNE : Organization and strategy

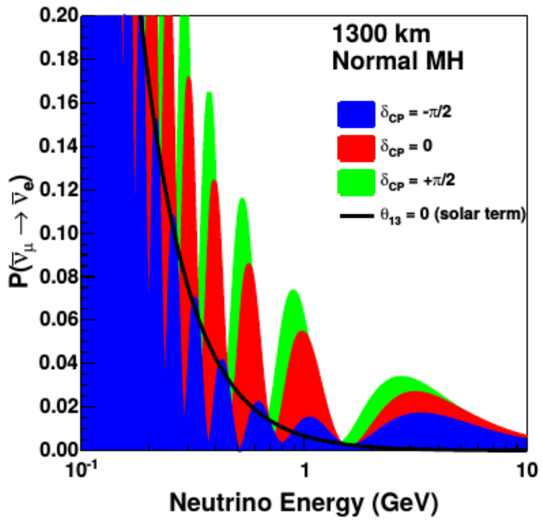
ArXiv:1512.06148

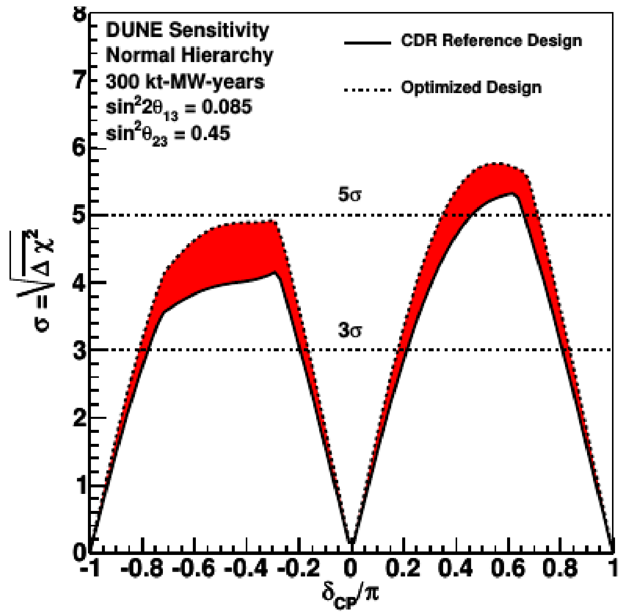
# LBNF/DUNE sensitivity

- >3 σ for CP sensitivity over a large fraction of the phase space
- >5 "σ" for Mass Ordering
- 300 kt-MW-years = 3.5 (nu)+3.5 antinu) with 40kt and 1.07 MW beam (80 GeV)



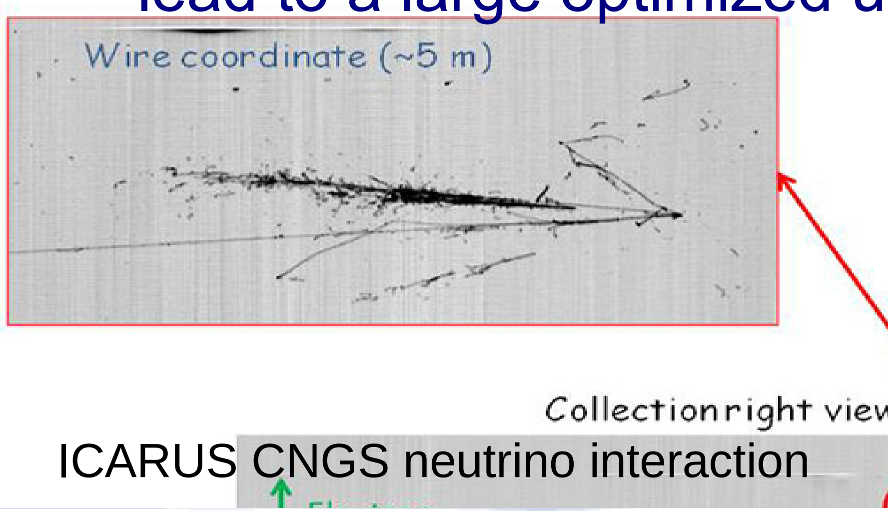



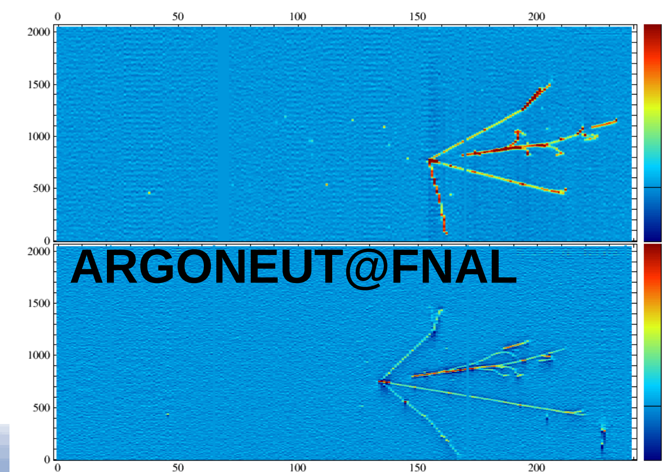



# Why Liquid Argon TPC ?

- Technology pioneered by the ICARUS collaboration
- Fully active high granularity detector (voxel ~$3x3x0.4mm^3$): a modern bubble chamber
- PID (from range and dE/dx) and high resolution calorimetry
- Sensitive to $\nu_\mu$, $\nu_e$ and $\nu_\tau$
- Currently used by the MicroBoone short baseline exp.
- A full program with several prototypes and demonstrators will lead to a large optimized underground detector

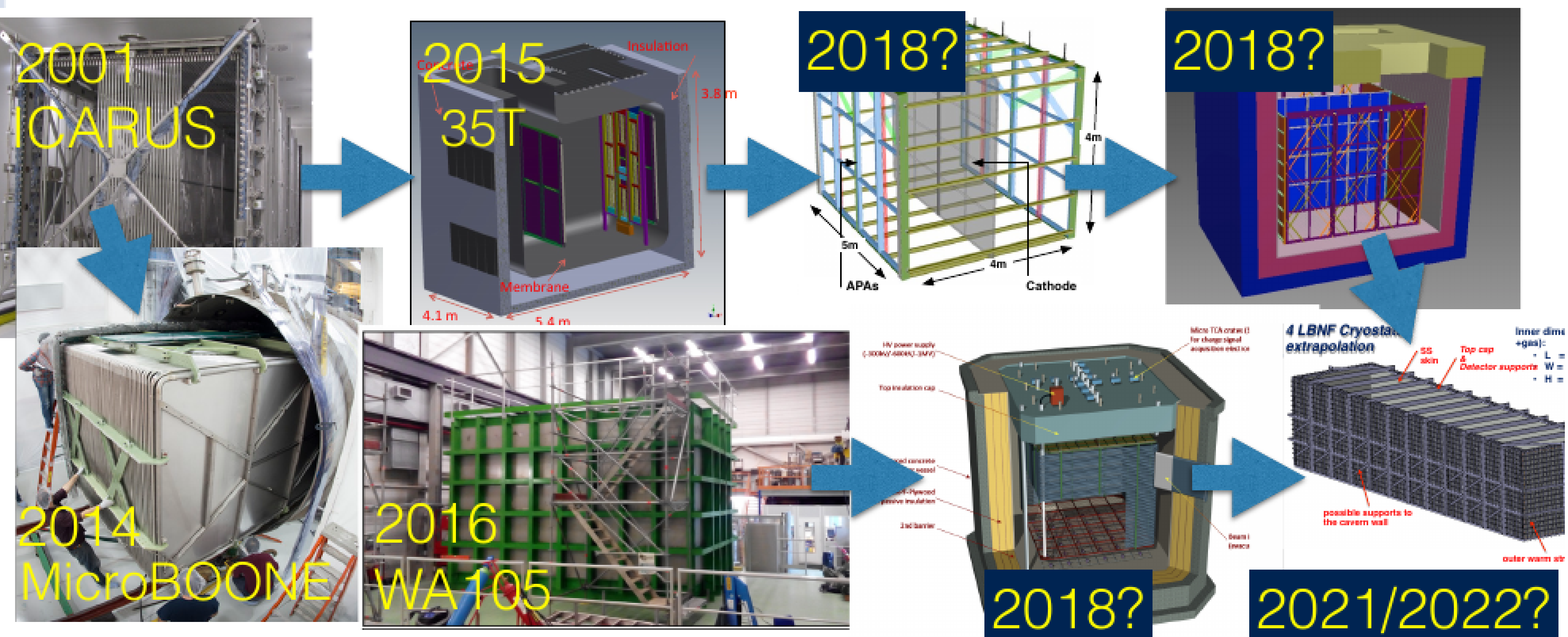



ICARUS CNGS neutrino interaction



# Path towards DUNE Far Detector

Crucial role played by the Fermilab prototypes and SB program and by the CERN Neutrino Platform towards providing the optimal cost-effective design for the Far Detector with proven solutions

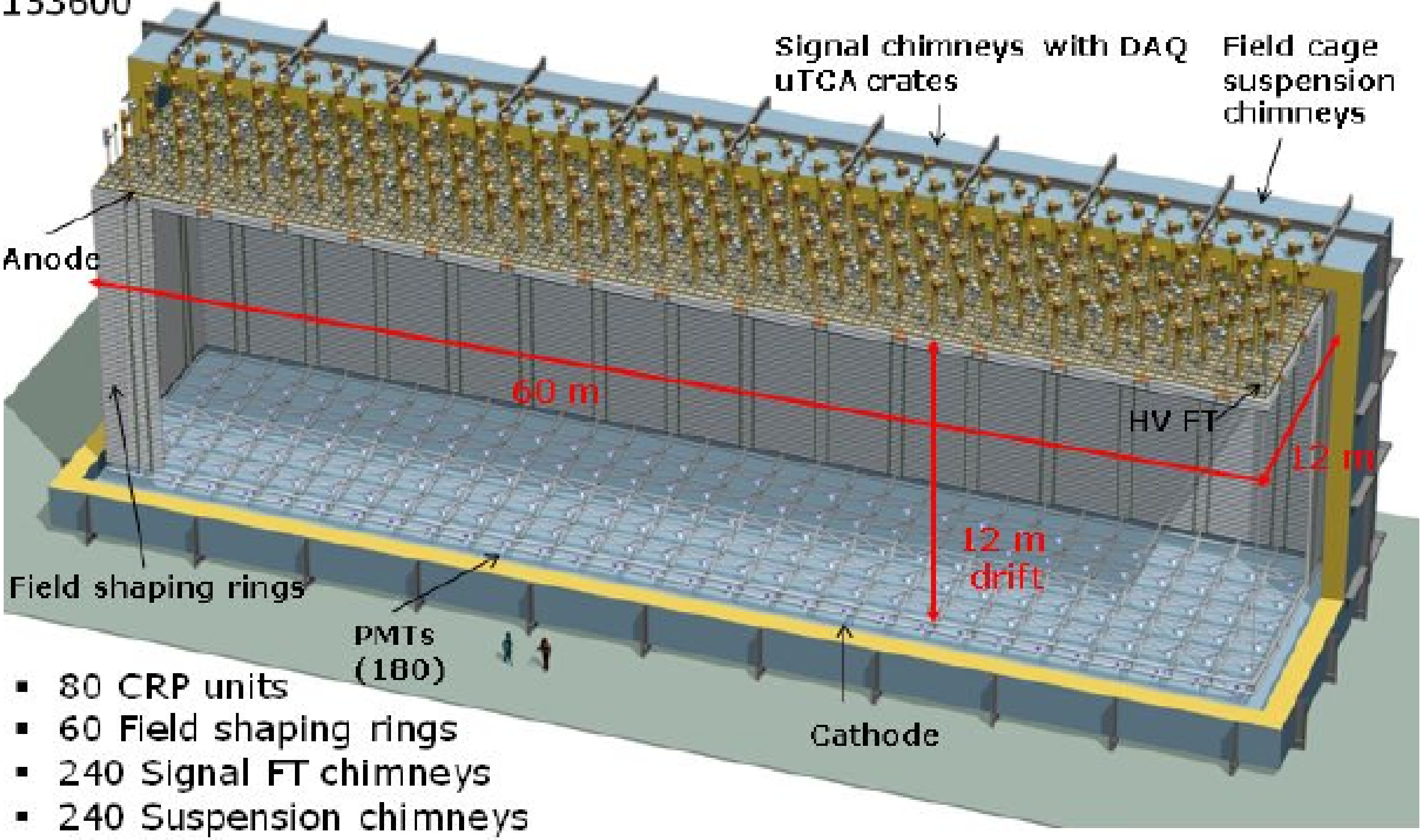



A. Rubbia, 2nd LNIF 2015

# Dual-Phase DUNE FD

**Dual-Phase DUNE FD**: 20 times replication of Dual-Phase ProtoDUNE (drift 6m → 12m)

Active LAr mass: 12.096 kton, fid mass: 10.643 kton, number of channels: 153600




- 80 CRP units
- 60 Field shaping rings
- 240 Signal FT chimneys
- 240 Suspension chimneys
- 180 PMTs

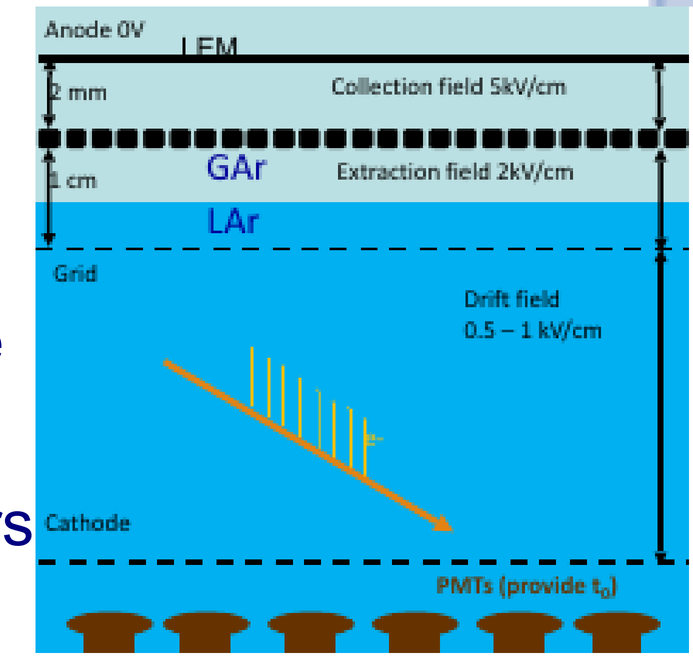
# Advantages of double (dual) – phase Liquid Argon TPC

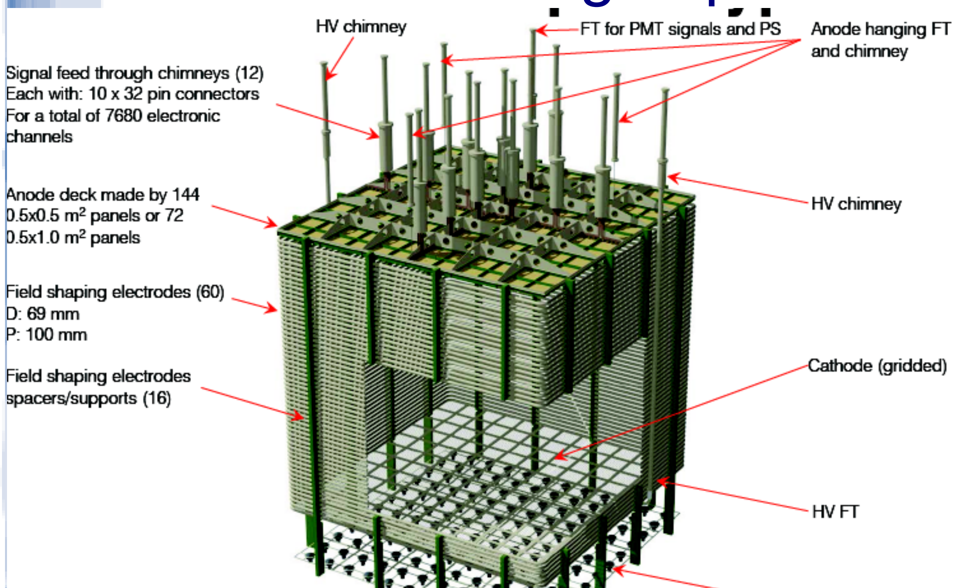
Compared to the single phase design, the dual phase provides:

- Fully active volume without dead material
- Lower number of readout channels
- Finer readout pitch
- More robust S/N with tunable gain
- Lower detection threshold
- Better reconstruction of the events
- Access to preamplifiers (outside of Lar volume)

# The WA105 project at CERN

- A large (300 t, 6x6x6m3) demonstrator of the liquid Argon dual phase TPC
- Crucial feature: gas amplification
- TPC mounted in a membrane cryostat, in the North Area at CERN
- Experiment approved by CERN, ~100 authors
- Test with a charged particle beam in 2018




# Aims of WA105 project

System test of the most critical aspects of a large Lar TPC like

- Membrane cryostat (used in LNG industry)
- HV power supply and feedthrough
- LEM for gas amplification
- Preamplifiers mounted on the FT flanges (outside LAr)
- Lar purity
- In a setup with a size comparable to a 10 kt module (CRP 1/20, drift 1/2)

Detailed calorimetric studies with 3x3 mm**2 granularity, fully active, full containment of hadronic showers with 1-12 GeV charged particle beam

# WA105: neutrino and pion interactions

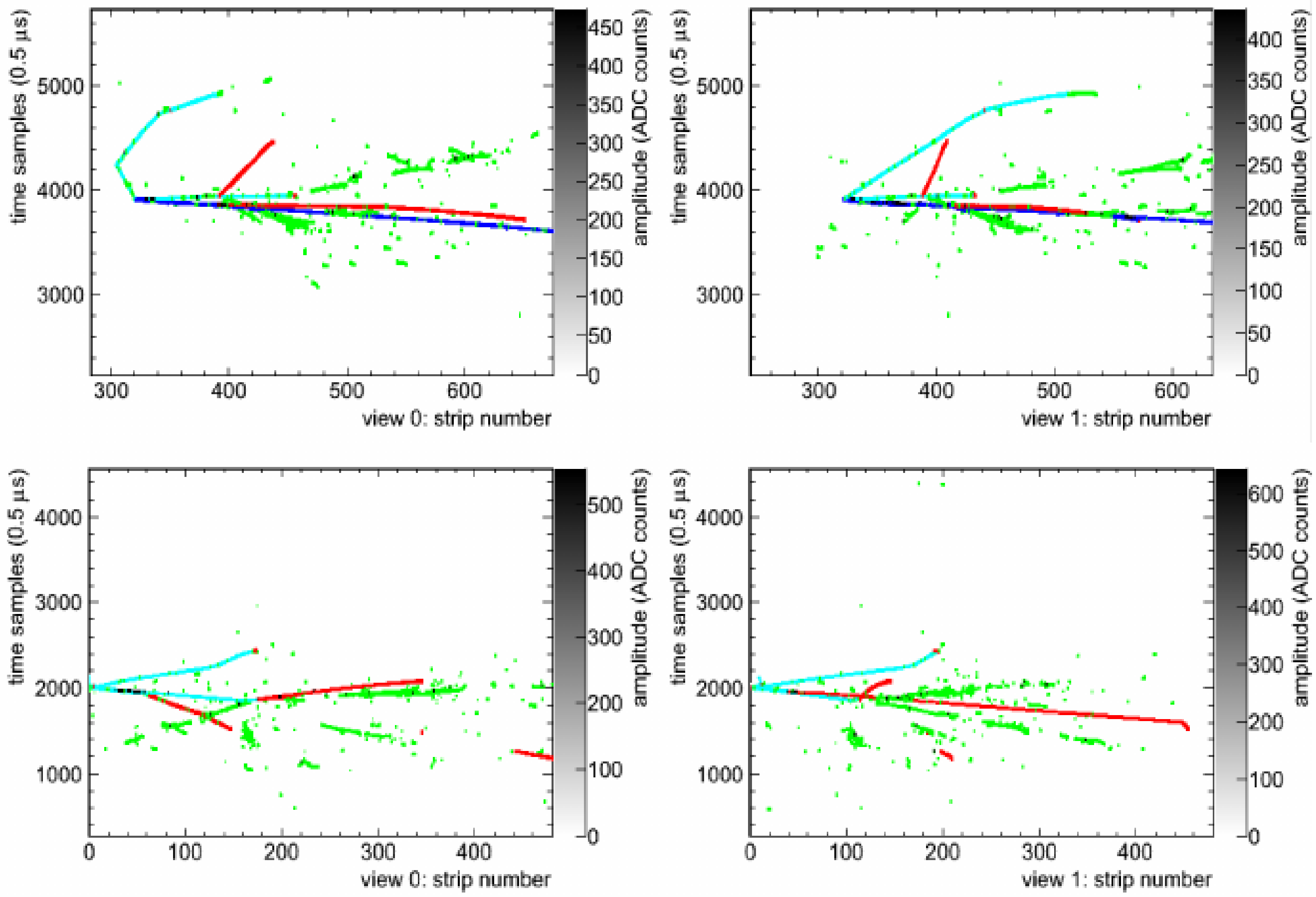
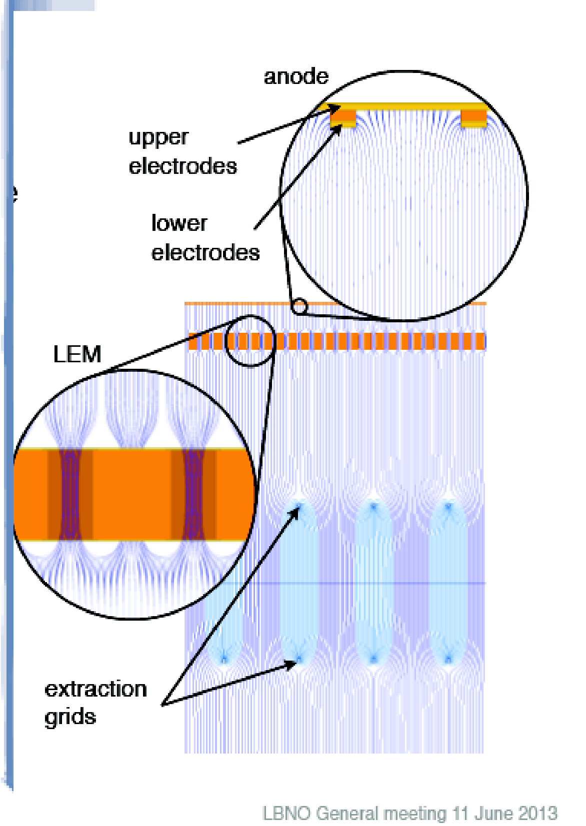
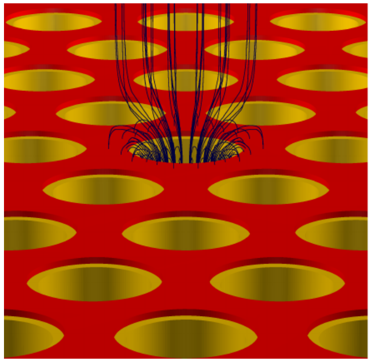


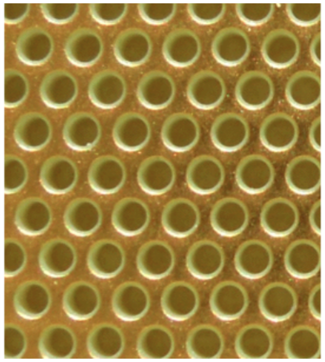

FIG. 8: MC comparison of neutrino and pion interactions: (top) 5 GeV muon neutrino interaction (bottom) 5 GeV pion interaction. The secondary particles produced in the two interactions (blue=muon, green=electron, red=proton, cyan=pion) have very similar characteristics (except for the muon in the case of the neutrino charged current (CC) interactions) and can be used to assess the performance of the detector and test the energy flow reconstruction algorithms. A precise knowledge of the incoming particle energy (not possible in a neutrino beam) is necessary to calibrate and check the linearity of the the response.

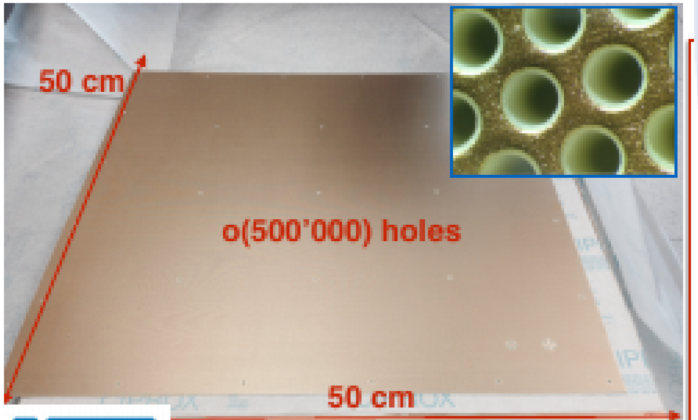
# LEM and WA105

- Gas amplification in ultrapure Argon (no quencher) is challenging
- Large Electron Multiplier (~thick GEM) has proved gain up to ~100
- Need to design, QC, calibrate and mount 36m2 for WA105 (3000 m² for DUNE 10kt)



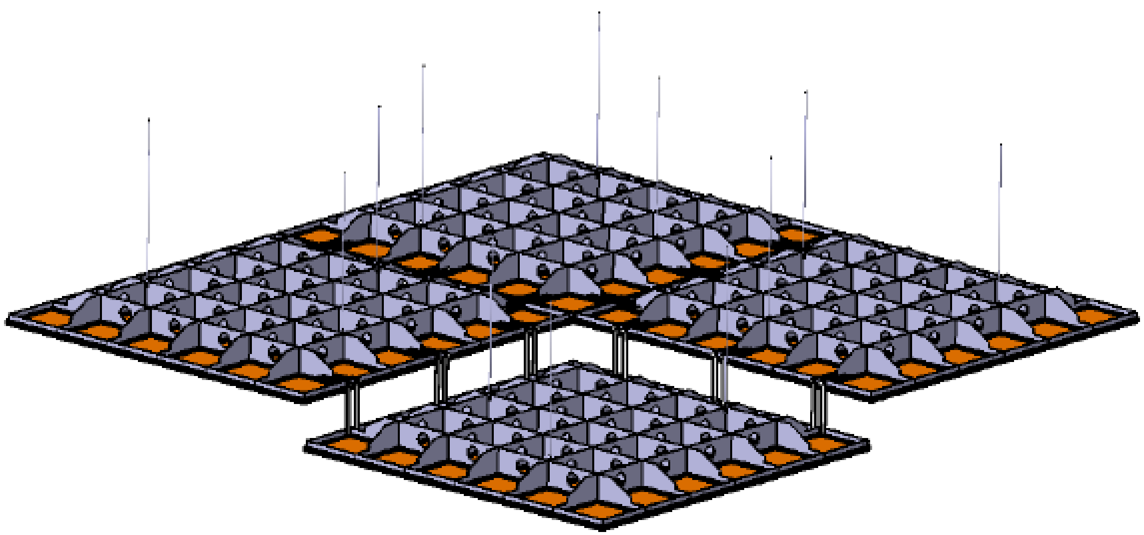



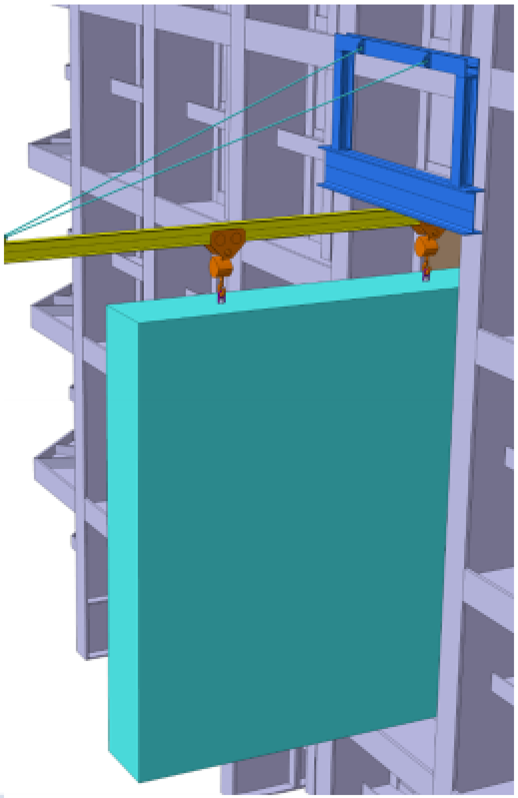




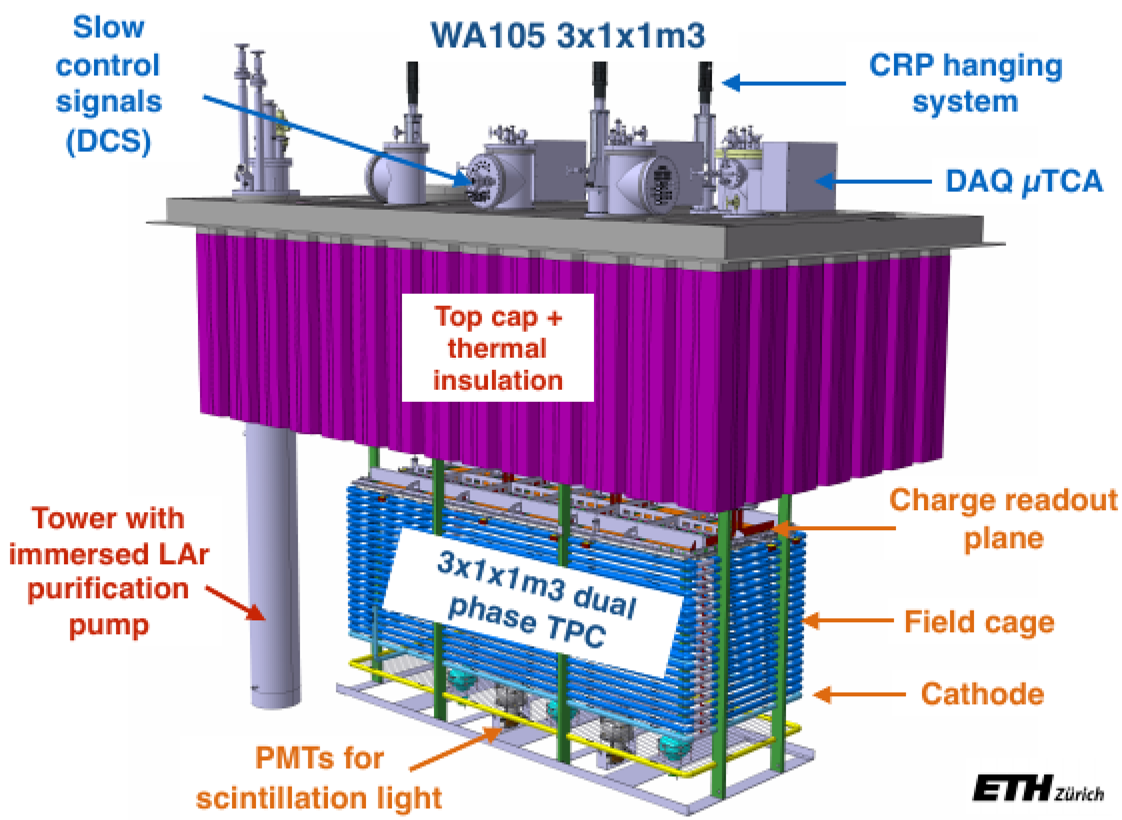

# The Charge Readout Plane

- Units of 3x3 m**2 – 36 LEM each
- Suspension system (3 points) adjust for height and planarity





# Top Cap of Lar-Proto



# Status of Lar-Proto

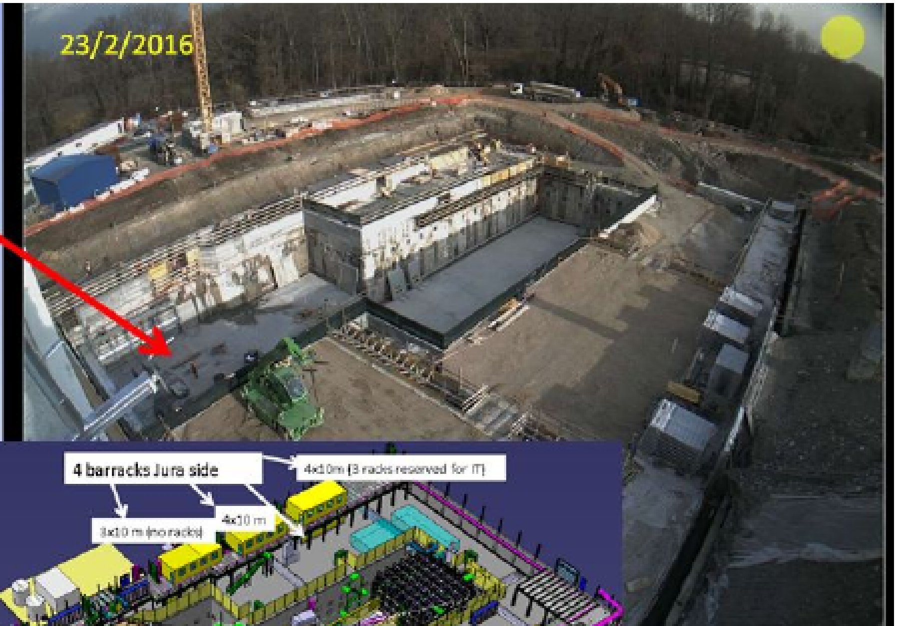
# WA105 detector and physics program

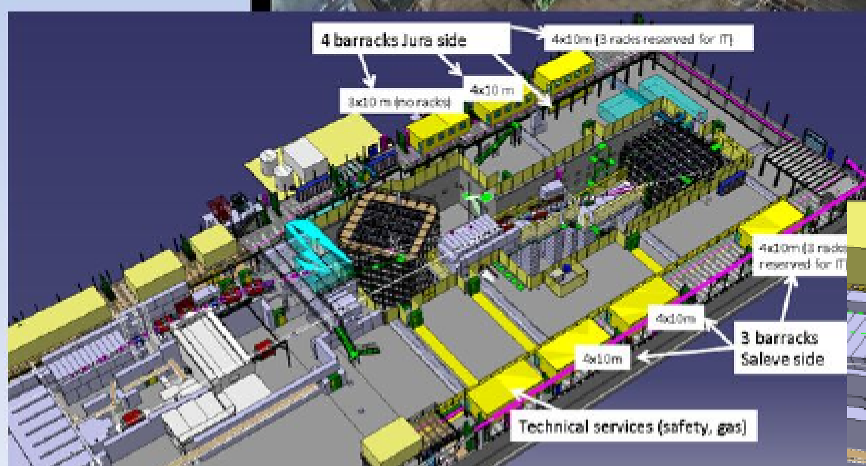
- 2016: WA105 will operate the 25 t Lar Proto → valuable experience with the system component
- 2017: procurement/integration/commissioning for the 300 t Lar-Demo
- 2018: WA105 will take data with a pion and electron beam enabling high precision studies of the detector and its performance, a beam test for DUNE
- This physics program includes: automated reconstruction, pion and proton cross-sections, calorimetry studies

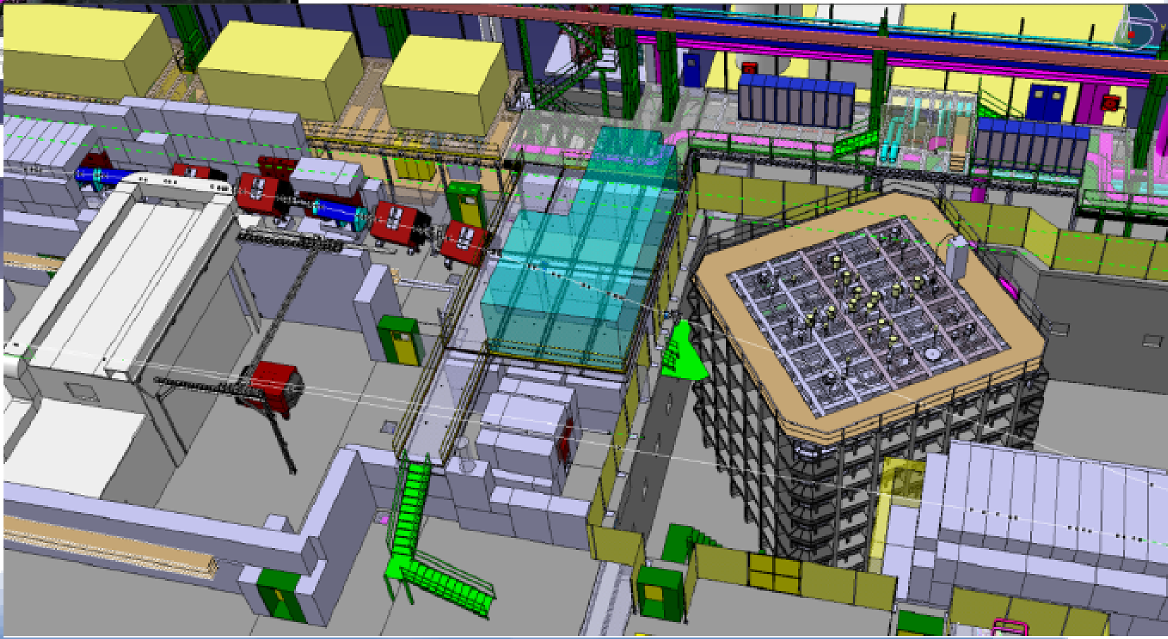
# Status of EHN1 Hall

EHN1:

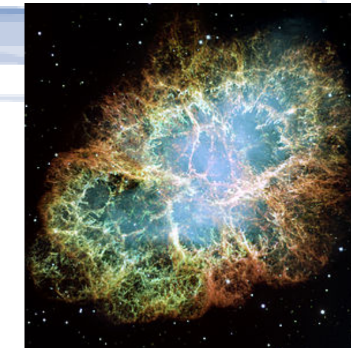
6x6x6 will be here



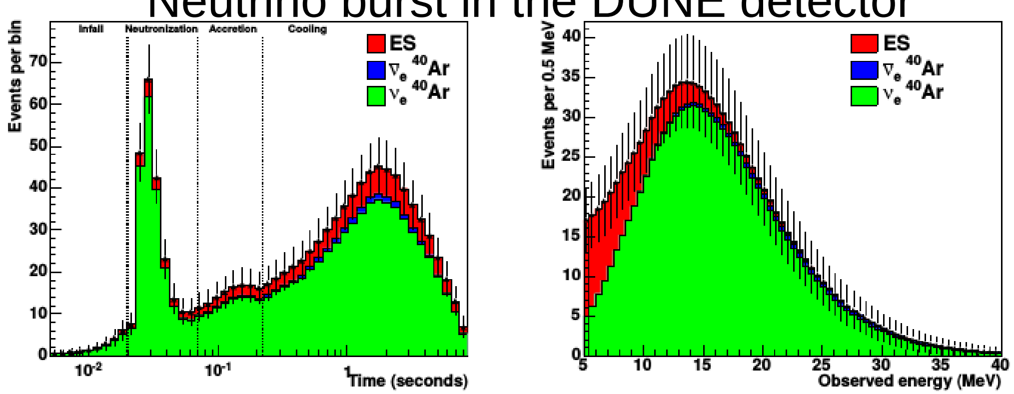



# Proton decay studies and neutrinos from the universe



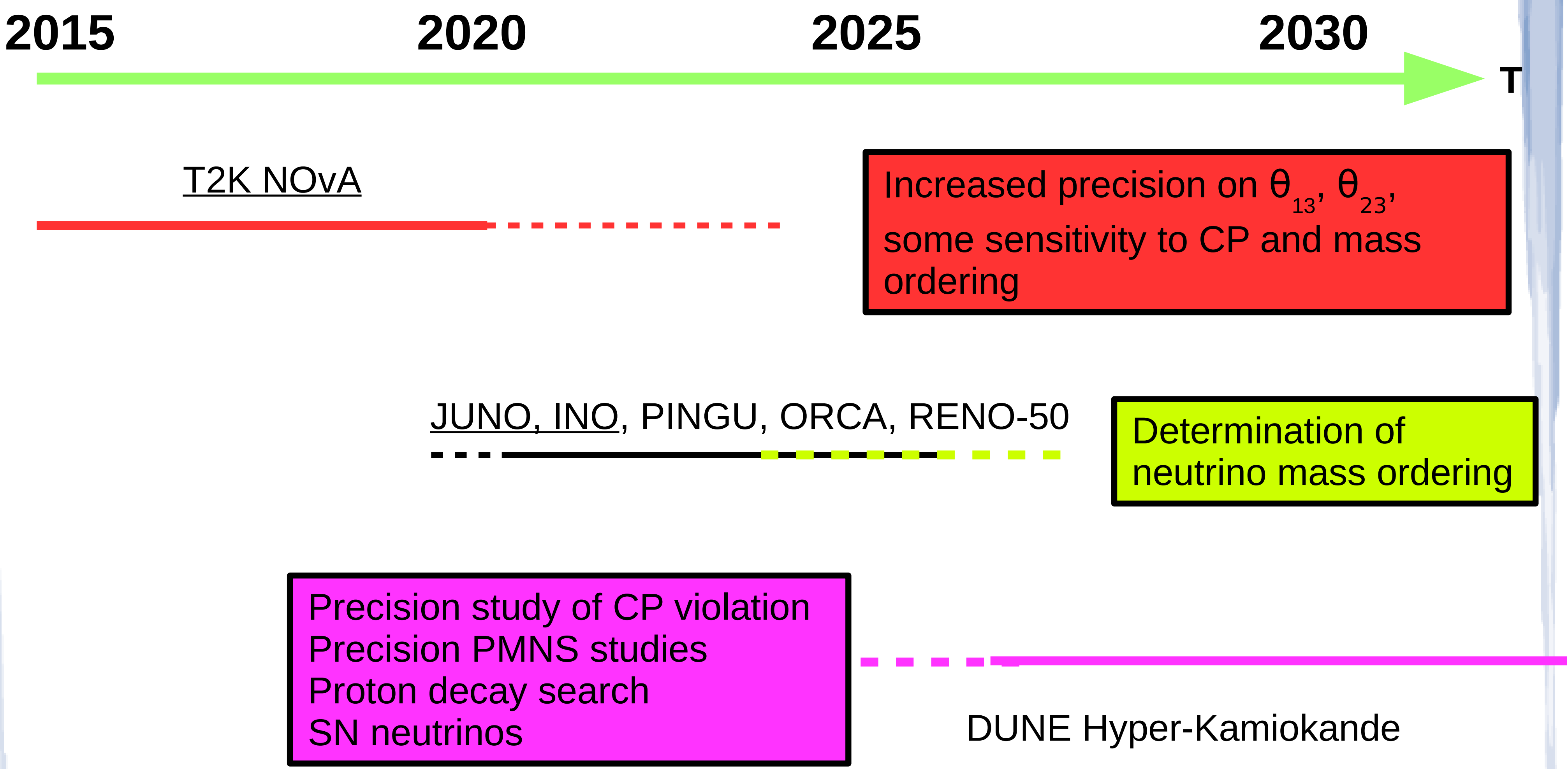
- Large underground detectors like JUNO, DUNE and Hyper-Kamiokande are excellent observatories for a variety of non-accelerator physics studies
- Search for proton decay can attain limit of $10^{35}$ years
- Neutrinos from Supernova explosions : up to several $10^{5}$ (to be compared to 24 for SN1987A). Liquid argon: tag $\nu_e$ with $\nu_e\ ^{40}Ar \rightarrow e^-\ ^{40}K^*$
- 200 solar $\nu$/day at HK
- Study of atmospheric neutrinos: mass ordering
- Large complementarity between different detection techniques

Neutrino burst in the DUNE detector




LBNF LOI

# Neutrino oscillation physics from today to ~2030




+ studies of possible new eV mass neutrinos : (reactor, sources, beam) 2015-2020

# Conclusions

- The study of neutrino oscillations has provided many surprising discoveries in the last 15 years, establishing the three neutrino mixing paradigm, implying physics beyond the SM
- The field is approaching the few % precision era due to dedicated experimental efforts. This requires a matching precision in the control of the beam flux, composition and neutrino cross-sections
- The experiments start to be sensitive to CP violation. T2K and NovA will provide improved precision in the next 5 (10) years, at 2 sigma level (depending on $\delta$)
- The WA105 (CERN) project will demonstrate the advantages of the double phase Liquid Argon TPC
- In the next decade DUNE will explore a large parameter space with unprecedented precision