Challenges and Opportunities in Understanding Neutrino Properties with Accelerator-based Experiments

Xin Qian

BNL

Outline

- Motivation
- Opportunities of future generations of experiments
- Challenges and Solutions
  - Neutrino Flux
  - Neutrino Detection
- Summary

Neutrino Mass and Mixing: the only well-established new physics been added to the Standard Model

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}\underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}\underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}\underbrace{\begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{0\nu\beta\beta}$$

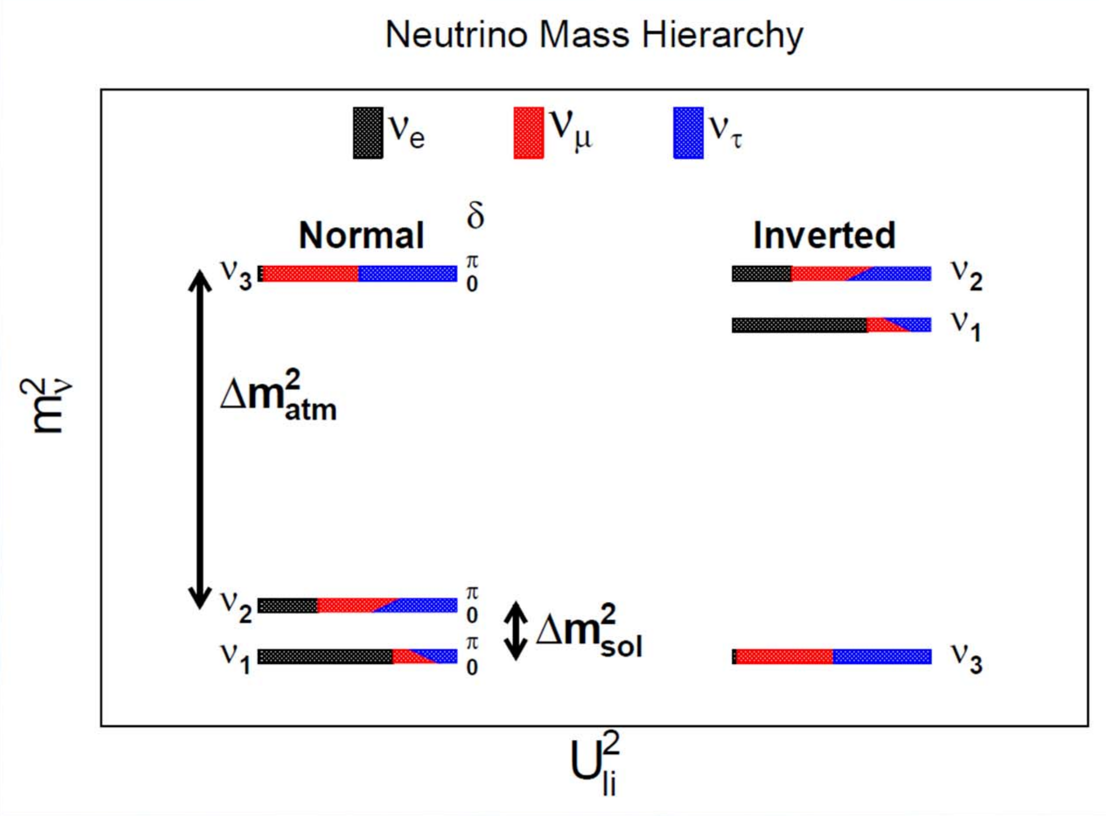
$\Delta m^2_{32} \sim 2.4\times10^{-3}eV^2$	$\Delta m^2_{31} \sim 2.4\times10^{-3}eV^2$	$\Delta m^2_{21} \sim 7.5\times10^{-5}eV^2$
$\theta_{23} \sim 45°$	**θ_{13} ~ 9°** δ = ???	$\theta_{12} \sim 34°$

Accelerator experiments provide crucial inputs:

- Discovery of muon and tau neutrinos
- Confirm atmospheric ν oscillation, the most precise $|\Delta m^2_{32}|$
- First observation of appearance, confirm “large” θ_{13}
- Initial hints of leptonic CP violation together with reactor ν

Some Remaining Questions

- CP violation in the neutrino sector?
- Normal or Inverted Mass Hierarchy?
- Octant: ν_μ >? | =? | <? ν_τ in ν_3
- Dirac or Majorana Neutrinos?
- What is the absolute neutrino mass?



- Is PMNS matrix unitary?
- Any pattern in PMNS matrix?

Search for new CP violation

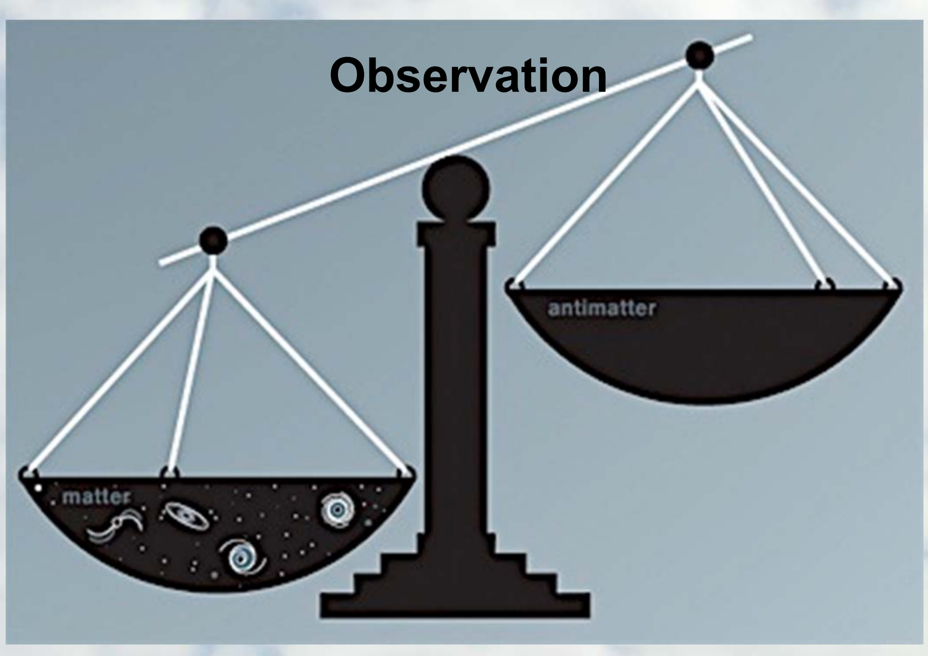
- Charge-Parity (CP) Violation in neutrino sector
  - Crucial for leptogenesis models to explain the large matter-anti-matter asymmetry in the universe
  - J_{CP} is expected to be sizable, as δ_{CP} naturally links to the CP phase of very heavy “see-saw” partner

Model calculation (See-saw type I)

$$|\sin\theta_{13}\sin\delta| > 0.11$$

Pascoli, Petcov, Riotto
PRD75, NPB774, (2007)

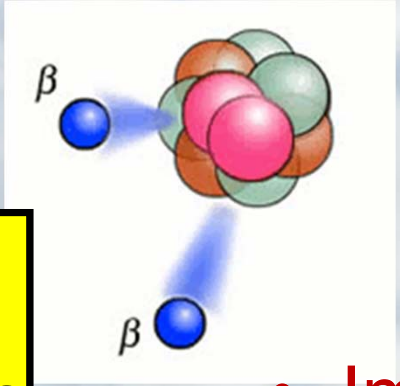
$$\sin\theta_{13}|_{\exp} \approx 0.15$$

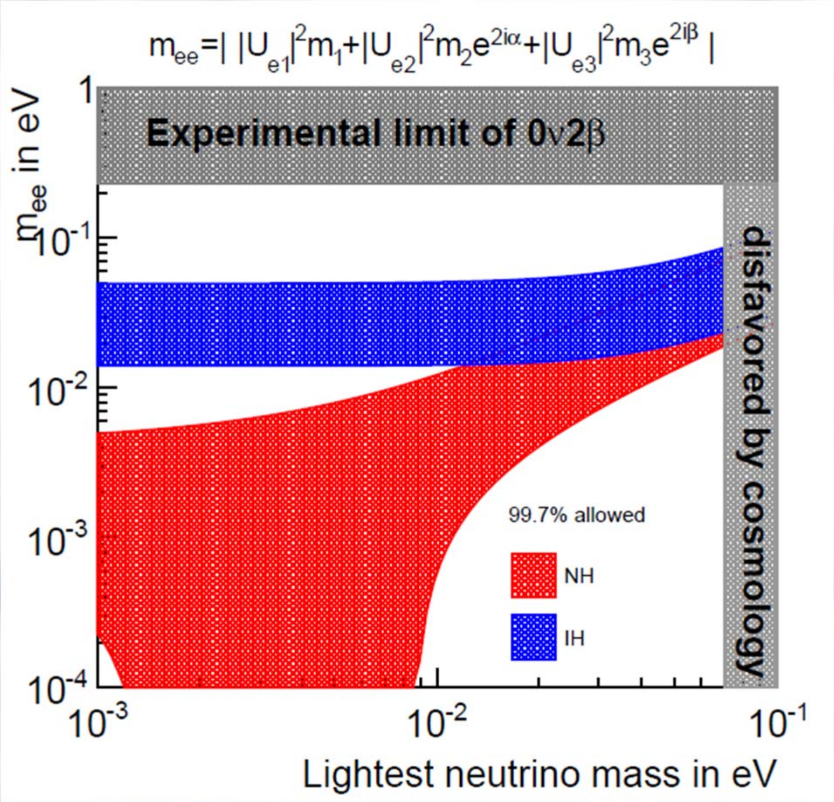


$O(10^{10})$ matter galaxies

Mass Hierarchy

- If inverted hierarchy, planning next-generation discovery-level neutrino-less double beta decay (0vDBD) becomes clear





$$\theta_{23}=45^o+\sqrt{2}\theta_{13}\cos\delta$$

$$\theta_{23}=45^o-\frac{1}{\sqrt{2}}\theta_{13}\cos\delta$$

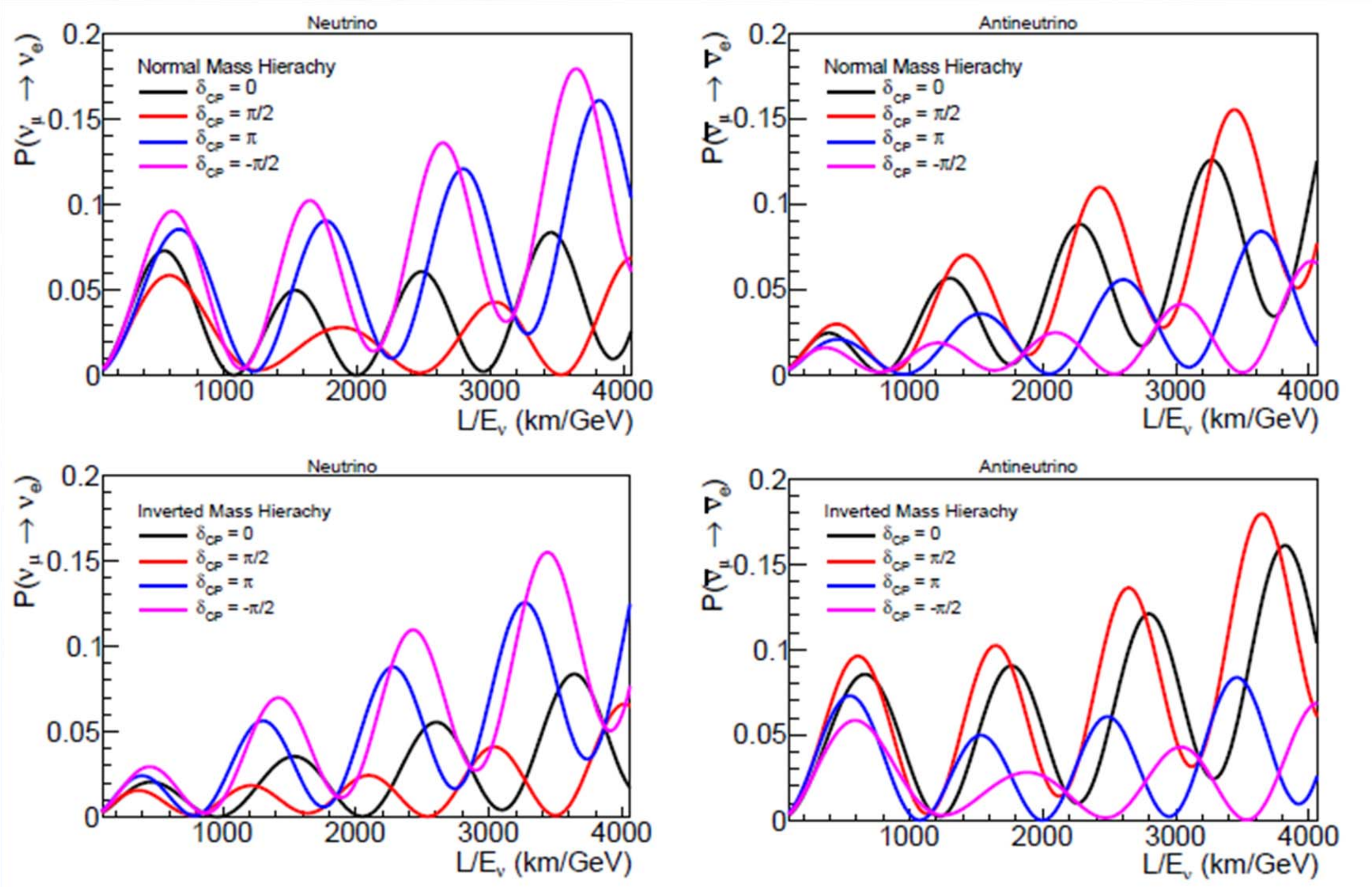
$$\theta_{12}=35^o+\theta_{13}\cos\delta$$

$$\theta_{12}=32^o+\theta_{13}\cos\delta$$

$$\theta_{12}=45^o+\theta_{13}\cos\delta$$

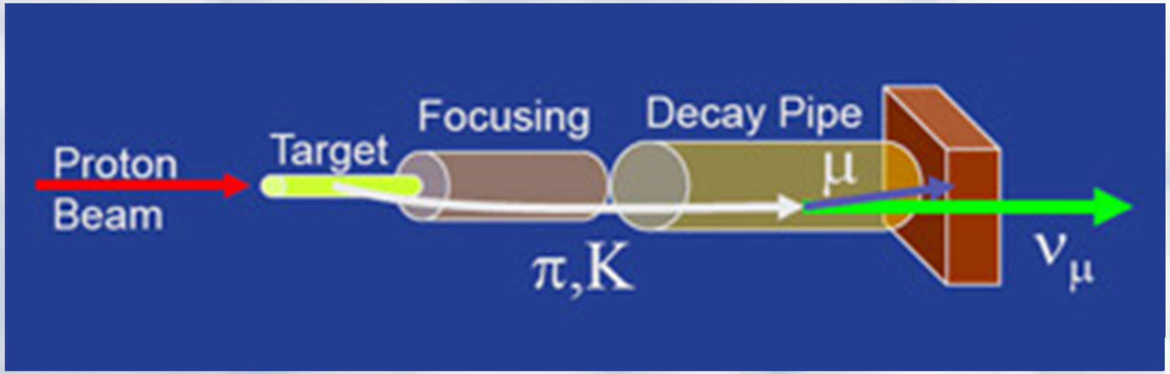
- Important input for model building to explain neutrino mass and mixing (also precision measurements of neutrino mixing)

Accelerator ν_e Appearance



- Oscillation pattern are very sensitive to the value of δ_{CP}, the mass hierarchy, θ_{13}, θ_{23} (Octant), and Δm^2_{32} (5/7)
- Unique opportunity to search for CP violation

Accelerator Neutrino Experiment



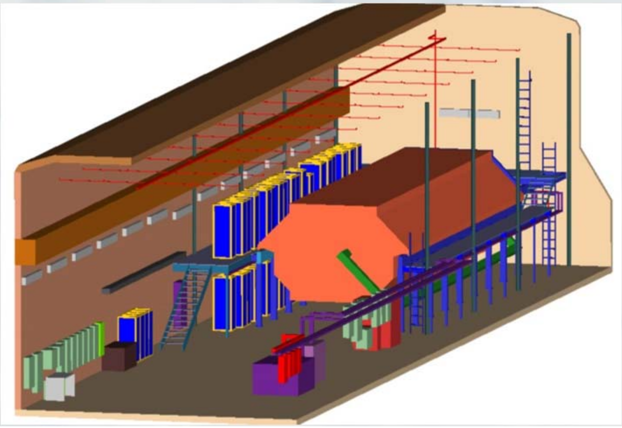
$$\pi^+ \rightarrow \mu^+ + \nu_\mu (\sim 100\%)$$

$$K^+ \rightarrow \mu^+ + \nu_\mu (\sim 63\%)$$

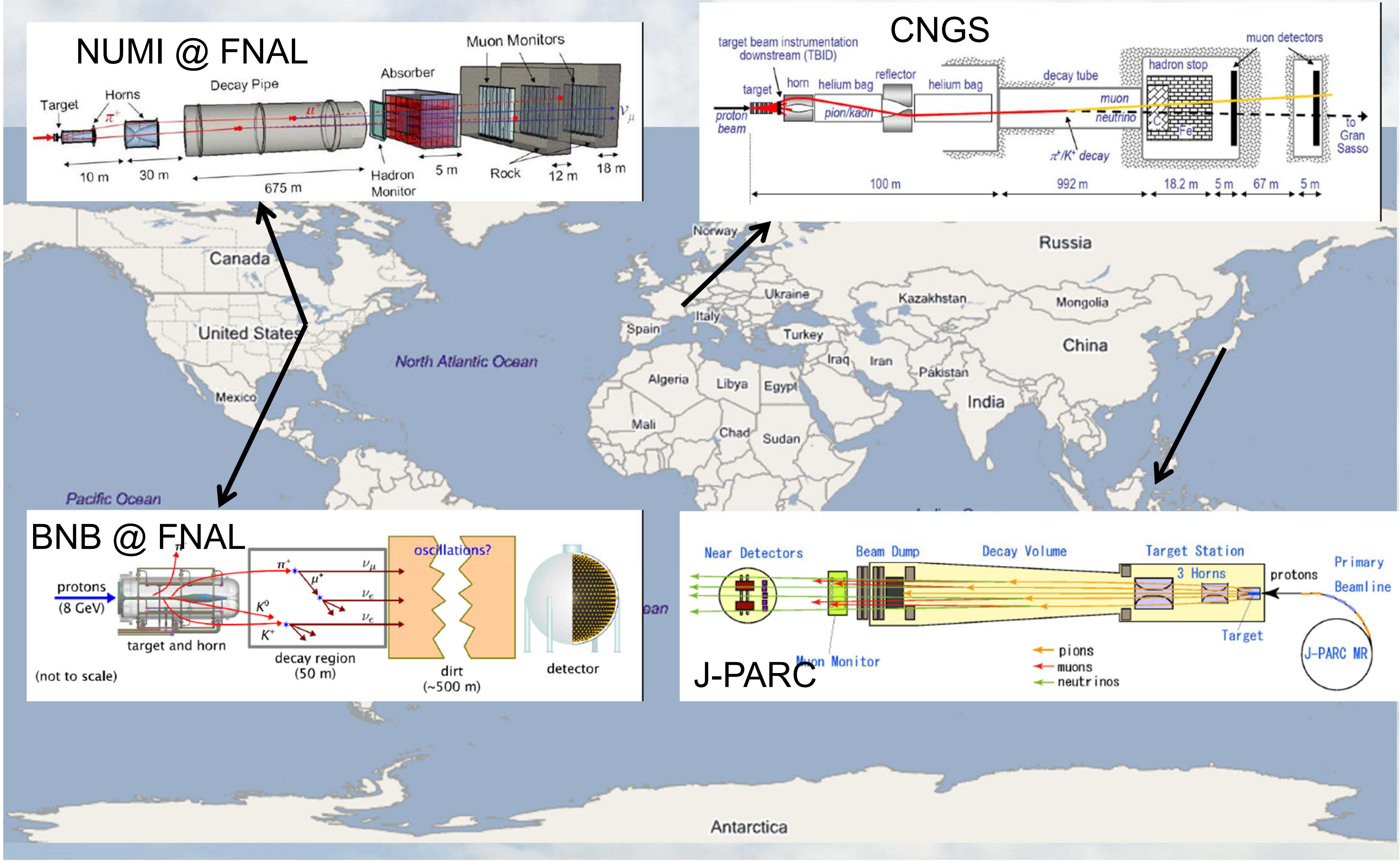
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu (\sim 100\%)$$

$$K^+ \rightarrow \pi^0 e^+ \nu_e (\sim 5\%)$$

- Accelerator Neutrino Beam
- Far Detector to measure Neutrino Oscillation
- Near Detector to categorize Neutrino beam



Recent Accelerator Neutrino Beams



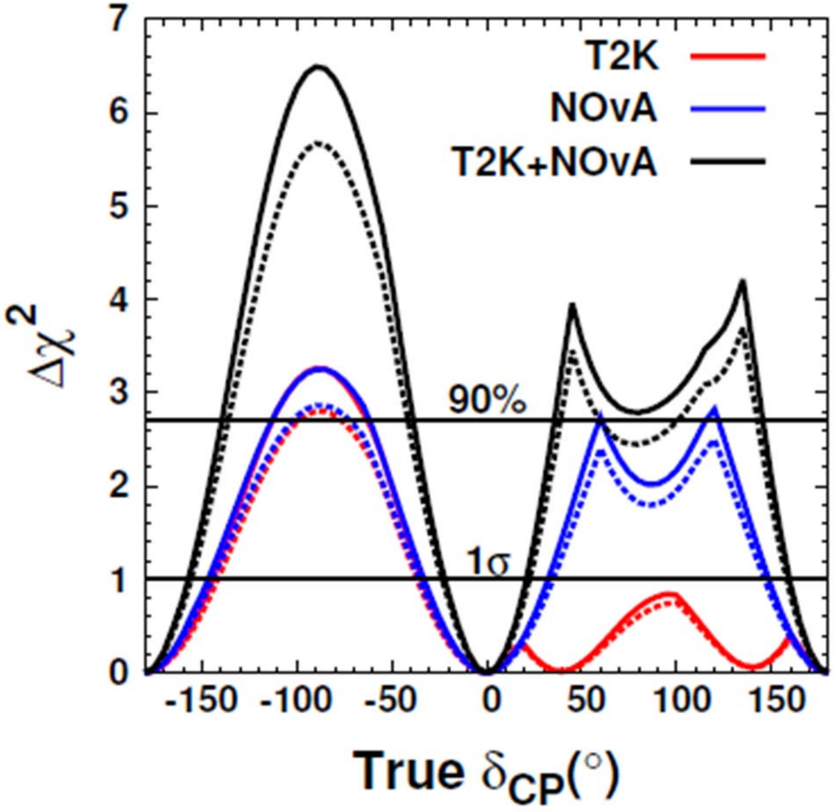
Recent Experiments

Exp.	Beam	Neutrino Energy (GeV)	Proton Power (MW)	Detector Technology	Detector Weight (kt)	Baseline (km)
K2K	**KEK-PS**	**0.3-2.7**	**0.01-0.02**	**Water**	**50**	**250**
MINOS	**NUMI**	**1.0-12**	**0.4**	**Steel Scintillator**	**5.4**	**735**
OPERA	CNGS	5-30	0.5	Lead Emulsion	1.8	732
ICARUS	CNGS	5-30	0.5	Lar-TPC	0.6	732
MiniBooNE	BNB	< 2	0.04	Mineral Oil	0.8	0.54
T2K	**J-PARC**	**0.3-1.5**	**0.75**	**Water**	**50**	**295**
NOVA	**NUMI**	**1.0-3.0**	**0.7**	**Liquid Scintillator**	**15**	**810**
MicroBooNE	BNB	< 2	0.04	Lar-TPC	0.08	0.47

First and Second Generation Oscillation Experiments since 98’

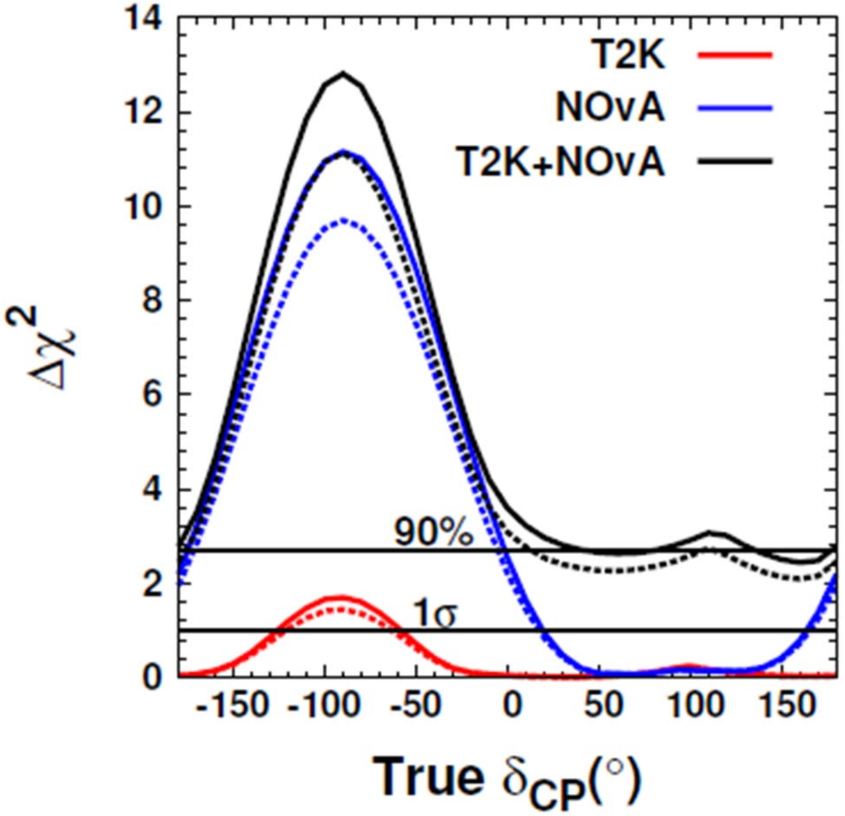
Long-Baseline Experiments

Expected Reach of T2K/Nova



CP Violation

(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



MH sensitivity

(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

- arXiv:1409.7469

Future Experiments

Exp.	Beam	Energy (GeV)	Power (MW)	Detector Technology	Detector Weight (kt)	Baseline (km)
Hyper-K	J-PARC	0.3-1.5	>0.75	Water	1000	295

Hyper-Kamiokande with J-PARC neutrino beam

Hyper-Kamiokande

(Total volume ~ 1M ton)

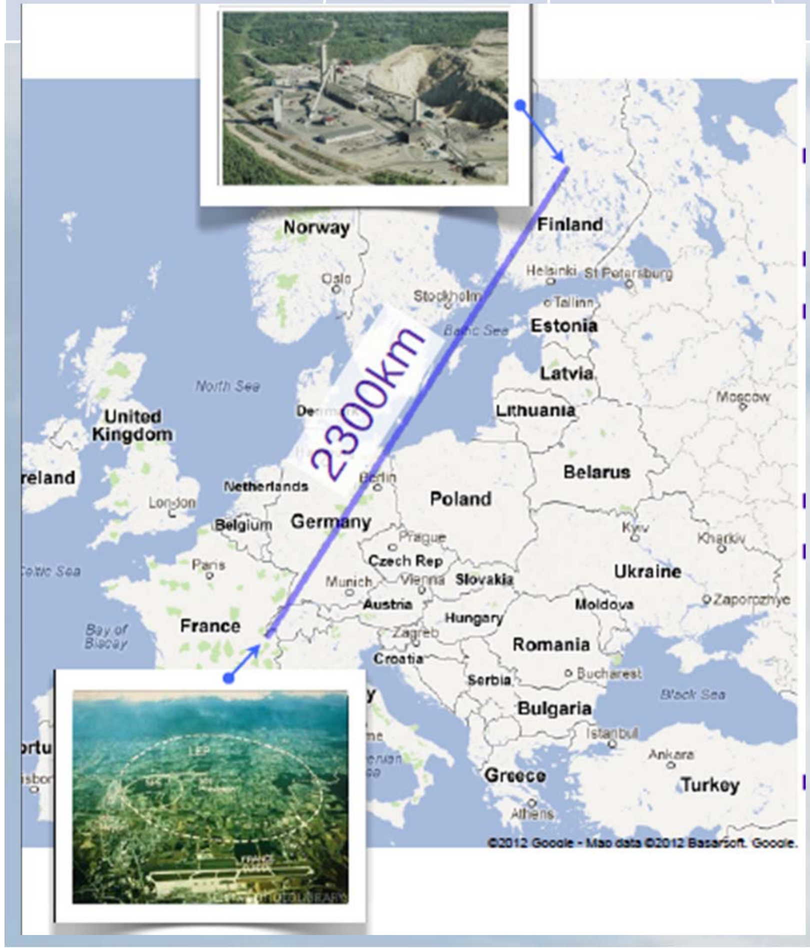
J-PARC Main Ring Neutrino beamline

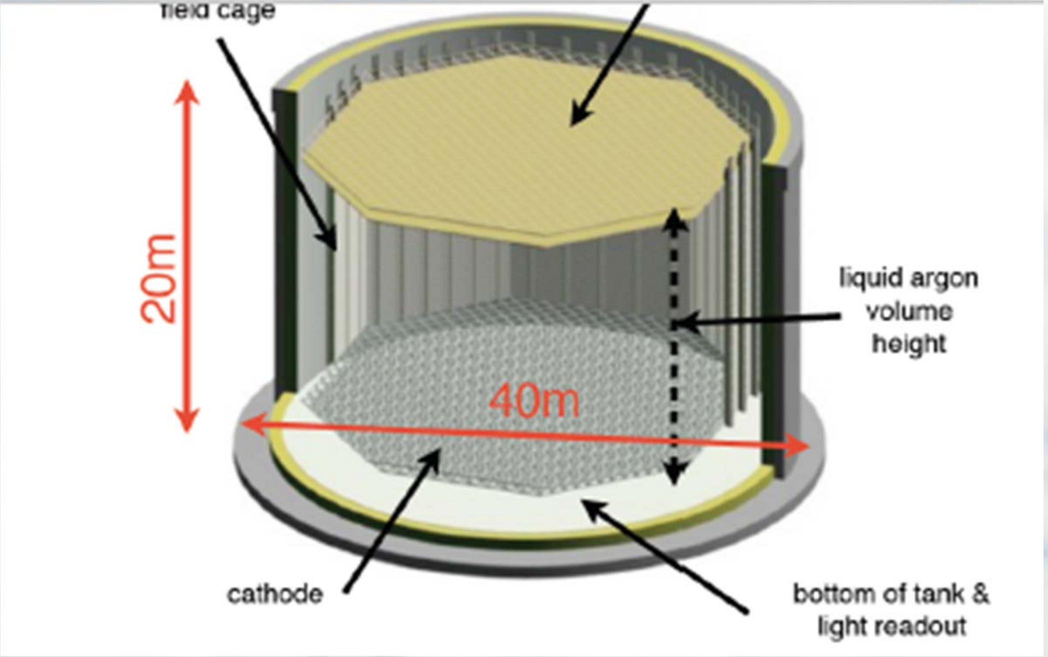
(KEK – JAEA)

Y. Hayato
Neutrino 2014

Future Experiments

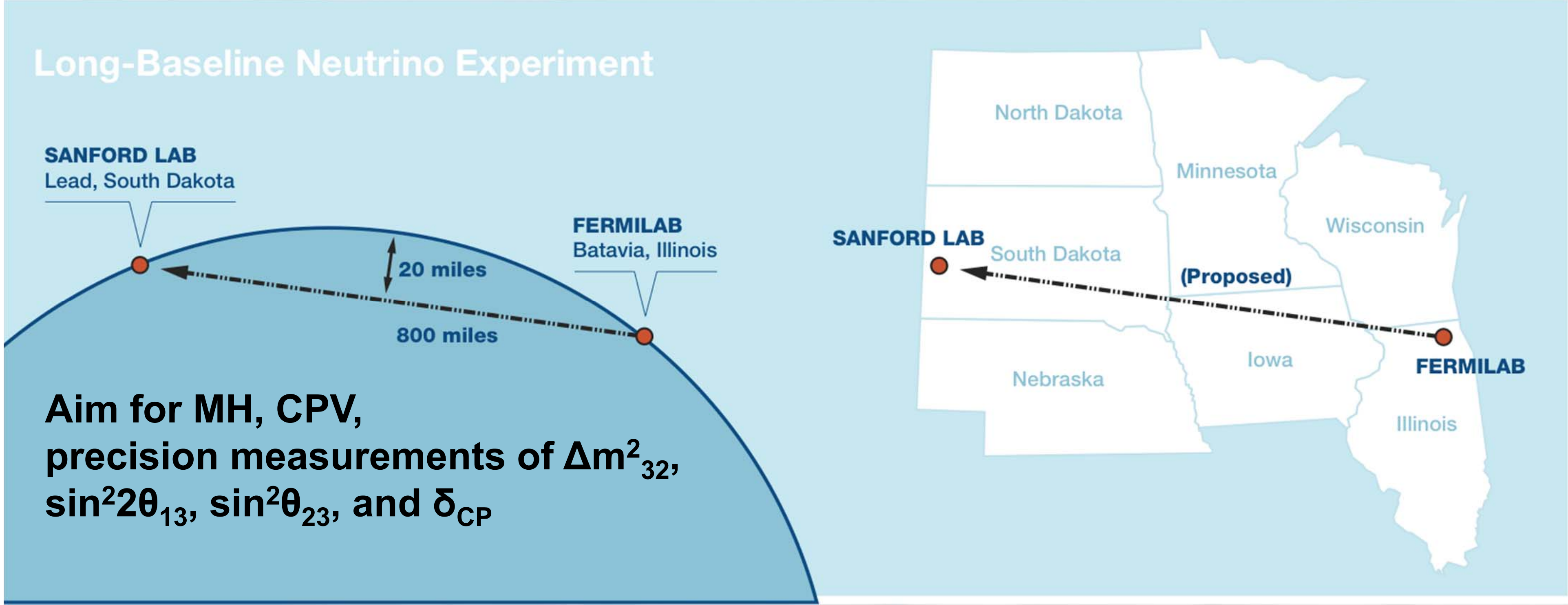
Exp.	Beam	Energy (GeV)	Power (MW)	Detector Technology	Detector Weight (kt)	Baseline (km)
LBNO	CERN	0.5-8.0	0.75	Double-Phase LAr-TPC + MIND	24-70	2300





Future Experiments

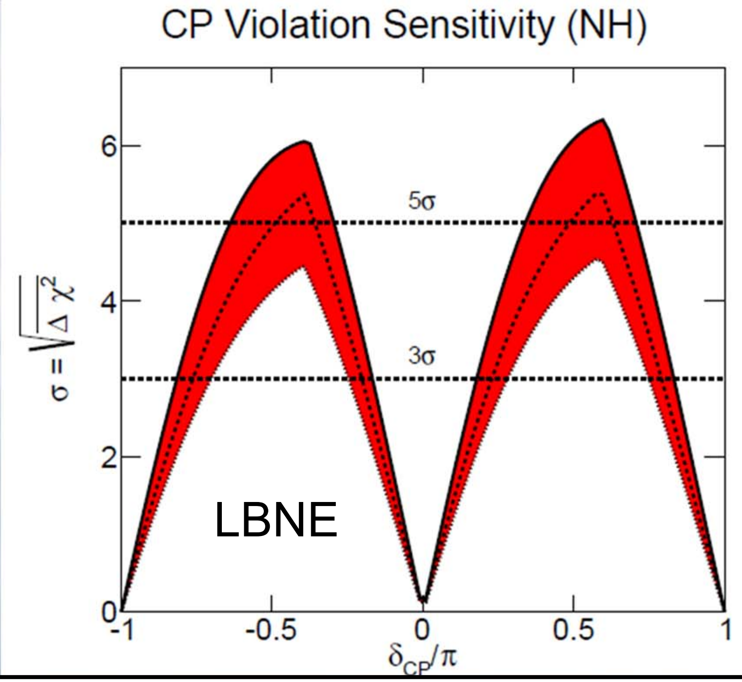
Exp.	Beam	Energy (GeV)	Power (MW)	Detector Technology	Detector Weight (kt)	Baseline (km)
LBNE	FNAL	0.5-5.0	1.2-2.3	Single Phase LAr-TPC	35-70	1300



Aim for MH, CPV, precision measurements of Δm^2_{32}, $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$, and δ_{CP}

FNAL Short Baseline Neutrino Program:
(MicroBooNE) + LAr1-ND, ICARUS-T600 → Continuous LArTPC R&D

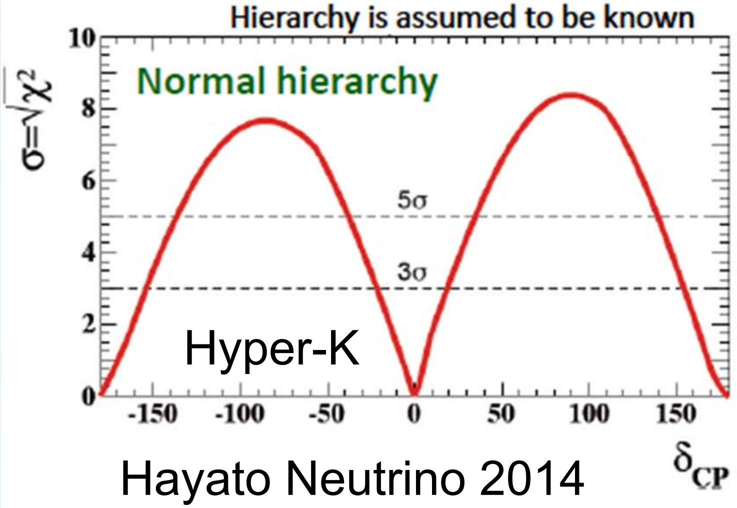
CPV and MH



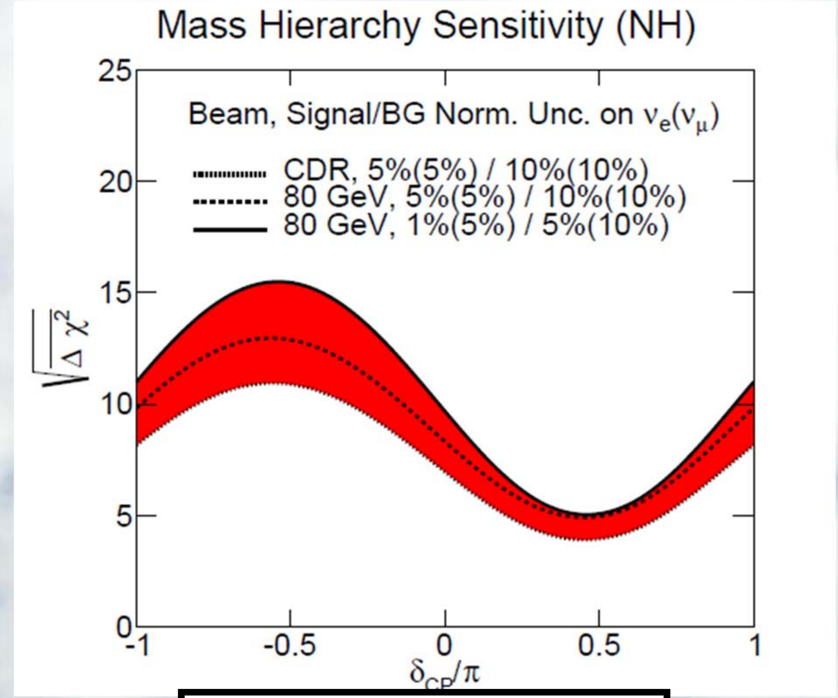
$$\Delta\chi^2 = \min(\chi^2_{\delta=0}, \chi^2_{\delta=\pi}) - \chi^2_{\min}$$

Sensitivity ~ Exclusion of sinδ = 0

(7.5 x 10^7 MW·sec)



Hayato Neutrino 2014

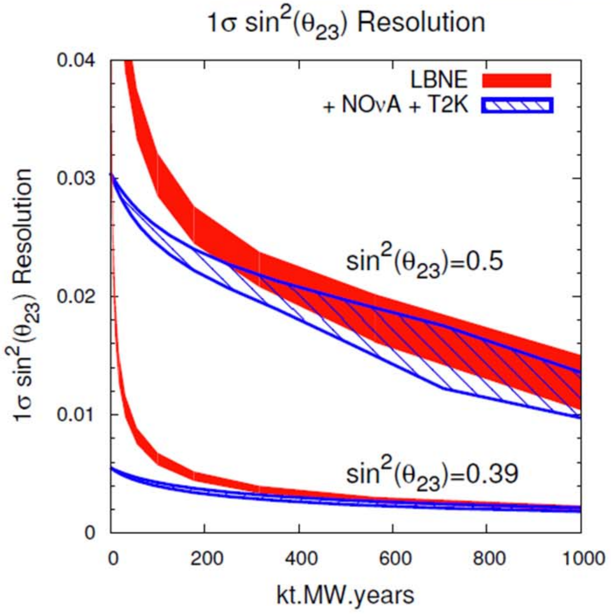


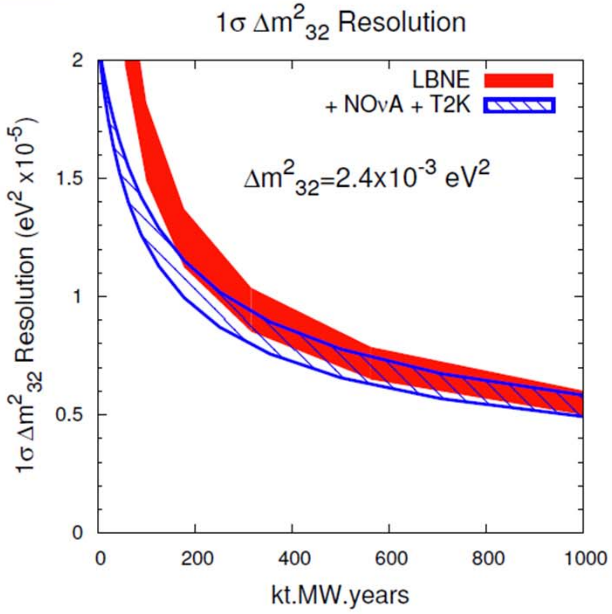
$$\Delta\chi^2 = \chi^2_{IH} - \chi^2_{NH}$$

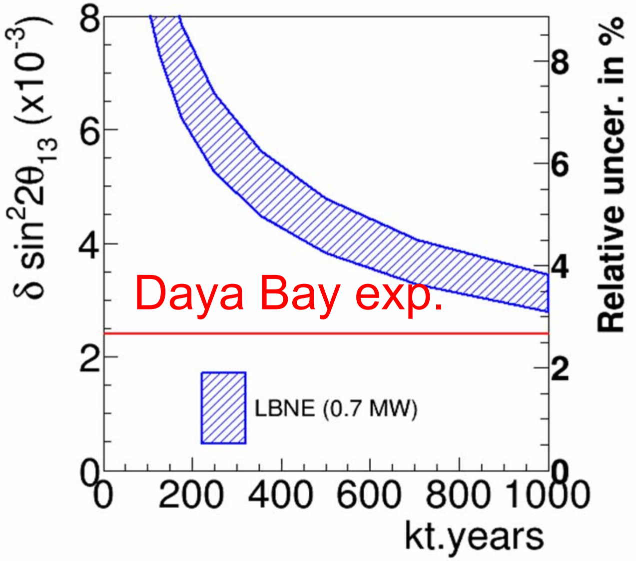
LBNE sensitivity: 1.2 MW x 6 years
1 year ~ 1.65e7 sec

- Unique opportunity to search for CPV
- Unambiguous determination of MH at high significance

Sensitivity of Precision Measurements







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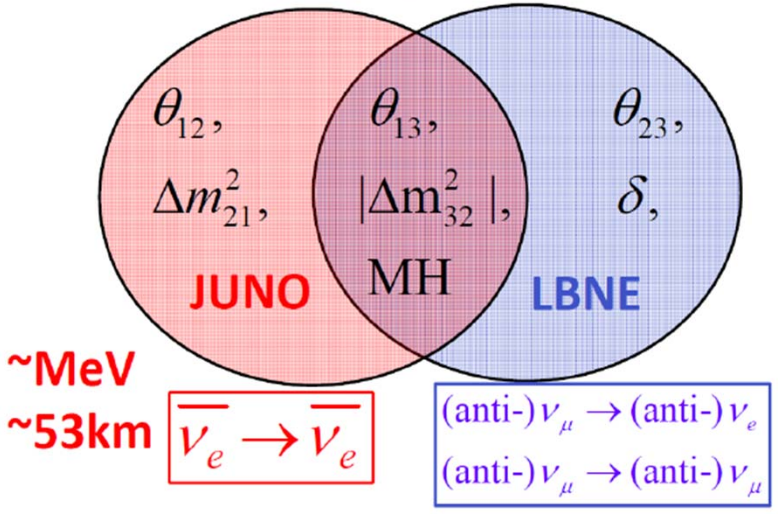

θ_{12}, Δm^2_{21},

JUNO

θ_{13}, $|\Delta m^2_{32}|$, MH

θ_{23}, δ,

LBNE

~MeV

~53km $\overline{\nu_e} \to \overline{\nu_e}$

(anti-)$\nu_\mu \to$ (anti-)ν_e

(anti-)$\nu_\mu \to$ (anti-)ν_μ

~GeV

1300km

Also
Hyper-K
/LBNO

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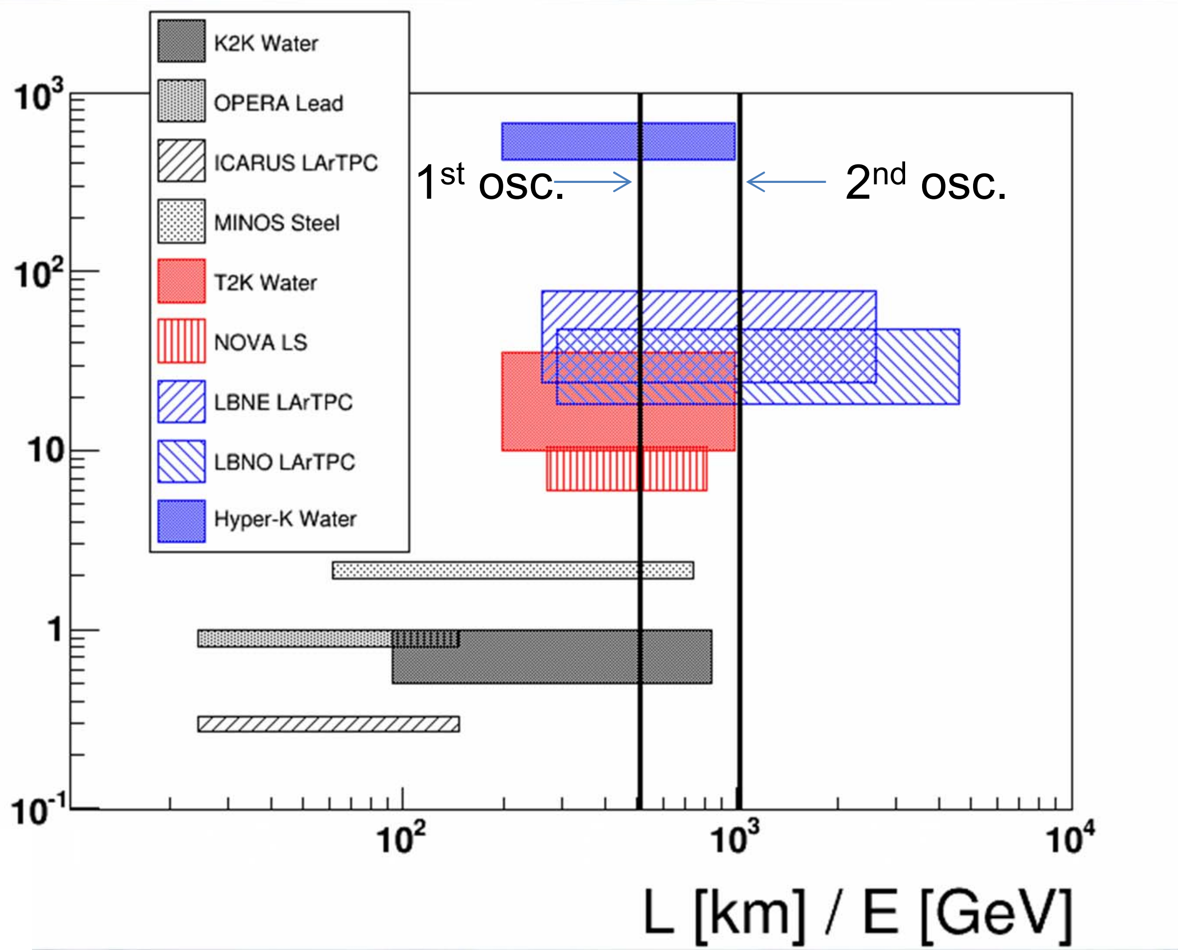
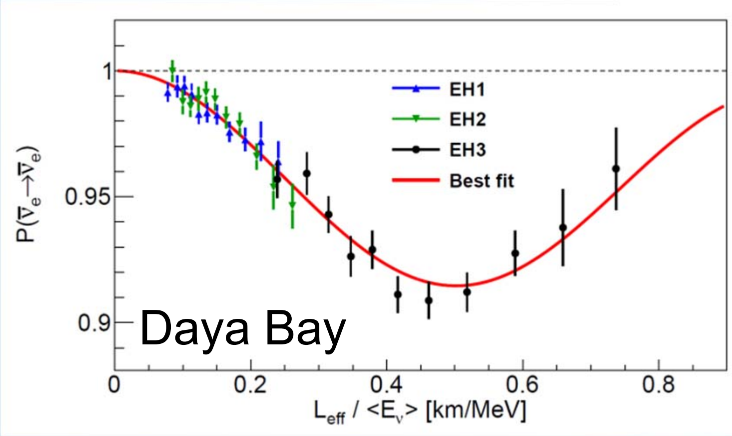
Challenge I: Experiment Scale

- Next generation accelerator-based experiments aim at **1-2 order** increase in the overall exposure underground (Water + LArTPC)
- **500-1000 people ~ 1 B$ scale**

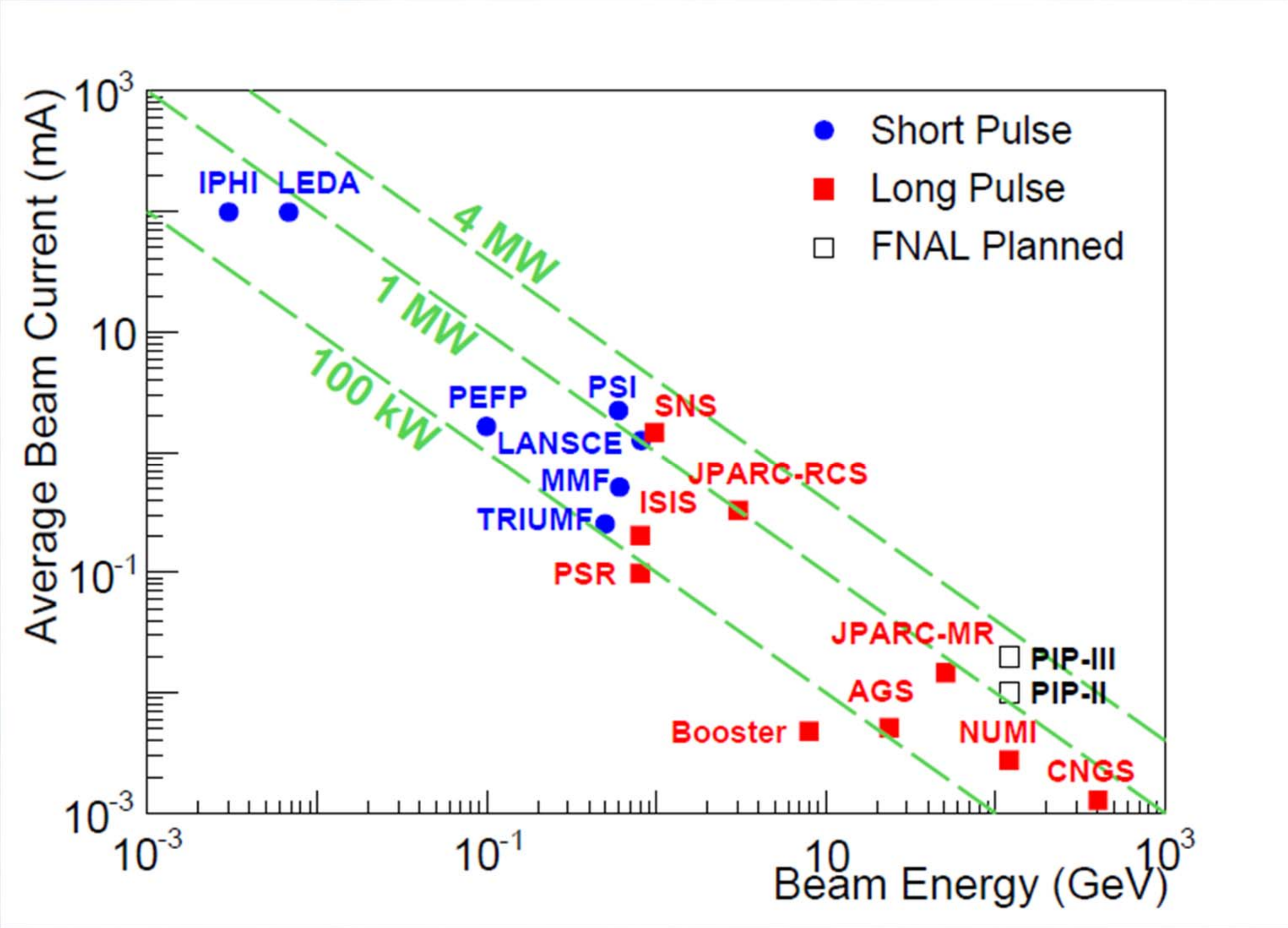




We are lucky that the MH/Octant CPV (if maximal) are within reach given the large θ_{13}!

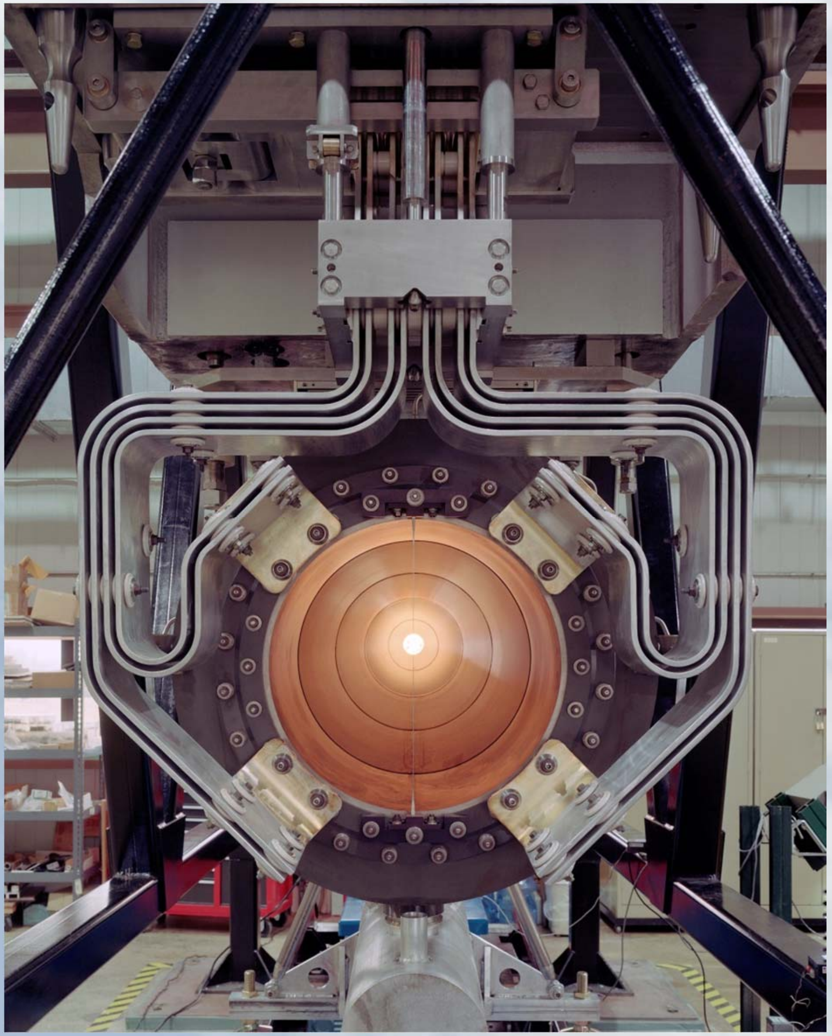
Challenge II: MW-power Beam

- High-quality beam to injector
- Accelerating high current beam to high energy
- Low beam loss during transportation



- MW-power is crucial to reach required statistics for long-baseline accelerator experiments

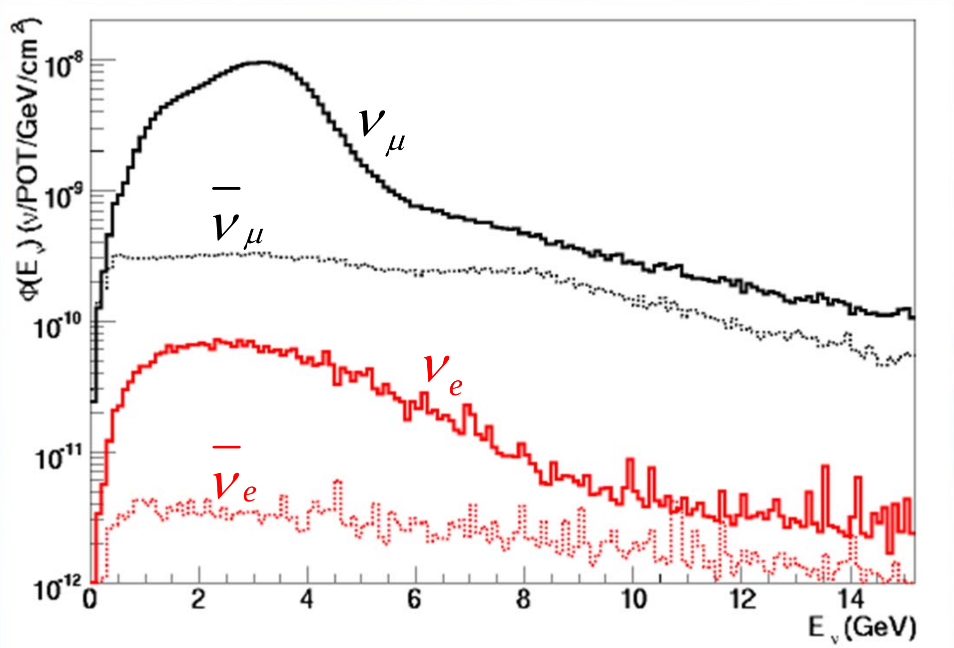
Challenge II: MW-power Beam

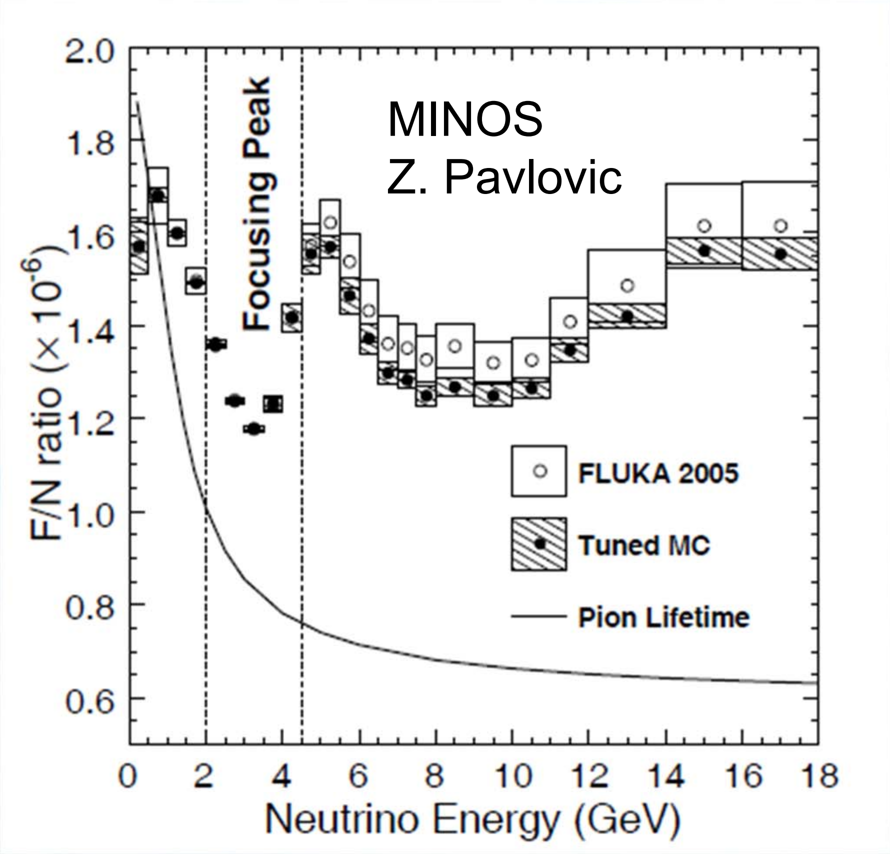


- Challenges:
  - Thermal shock
  - Remote handling
  - Cooling
  - Radiation protection
  - Design of beam window, target, horn
  - Radiation damage

- Robust target and horn system for extreme power densities and extreme radiation

Challenge III: Categorization of Neutrino Beam




MINOS
Z. Pavlovic

v_μ flux is crucial to signal, v_e flux is irreducible background
It is crucial to categorize neutrino fluxes with near detector(s)

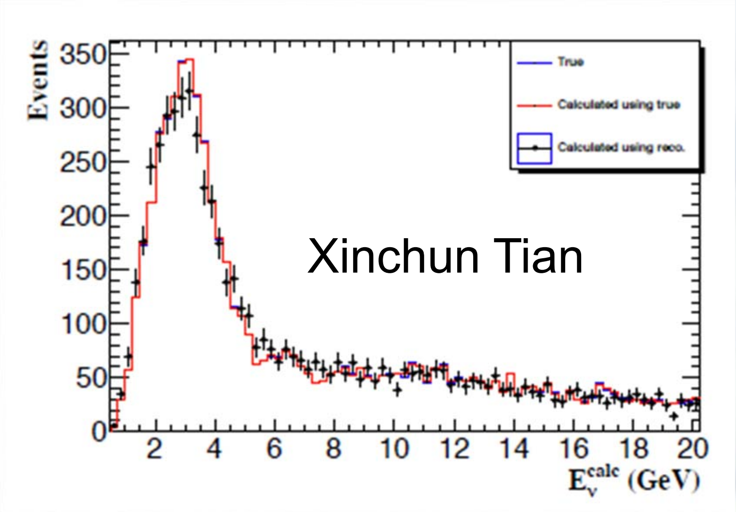
Absolute and Relative Flux Determination

- ν-e NC elastic scattering

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

Also $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$



Xinchun Tian

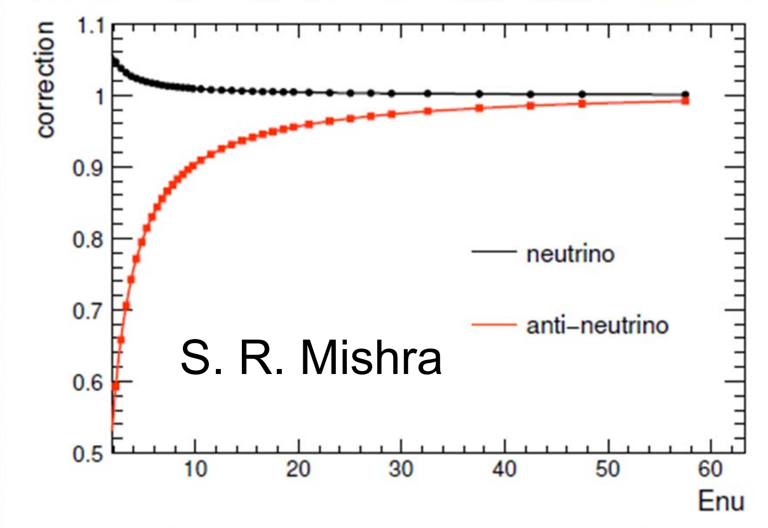
Aim ~2% determination of absolute flux

$$N(\nu < \nu_0) = C \cdot \Phi(E_\nu) \cdot \nu_0 \cdot \left[1 + O\left(\frac{\nu_0}{E_\nu}\right)\right]$$

- Low-$\nu_0 = E_\nu - E_\mu$ method

$$(anti-)\nu_\mu + N \rightarrow \mu^\mp + X$$

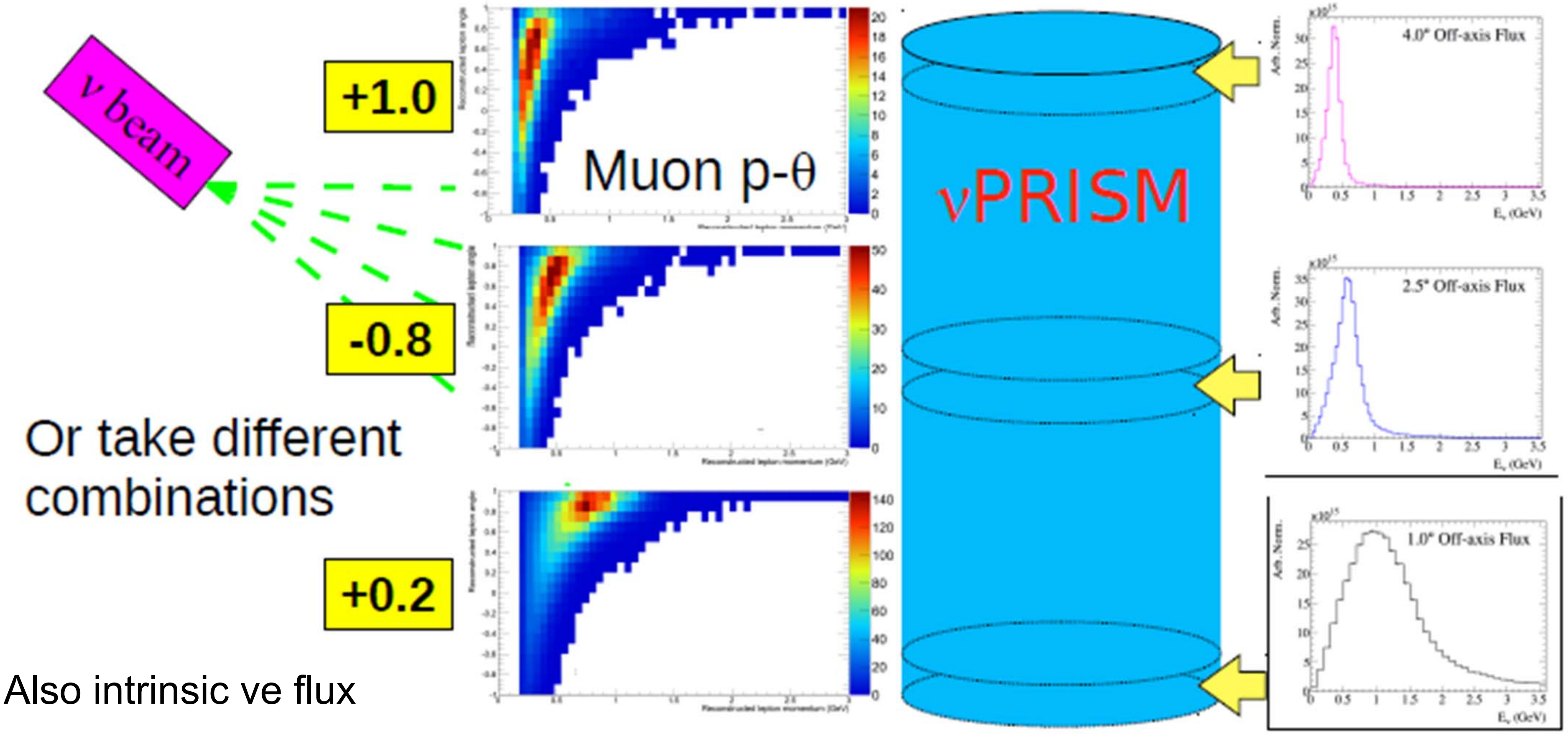
S. R. Mishra Proceeding.
A. Bodek et al., EPJC 72, 1973 (2012)



S. R. Mishra

Aim ~1-2% determination of relative flux

νPRISM detector concept

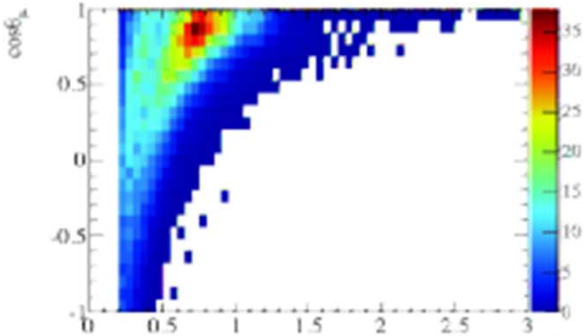


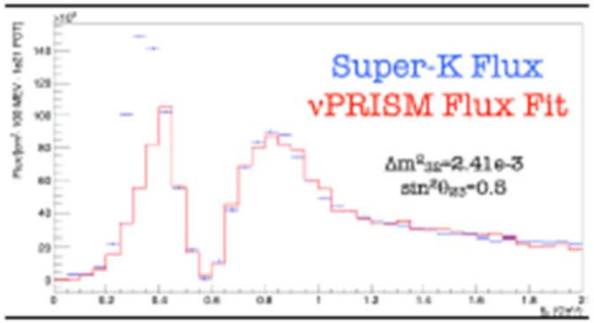
Or take different combinations

Also intrinsic ve flux

Cross section measurements

Mono-energetic neutrino beam …





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    - Water Cerenkov Detector
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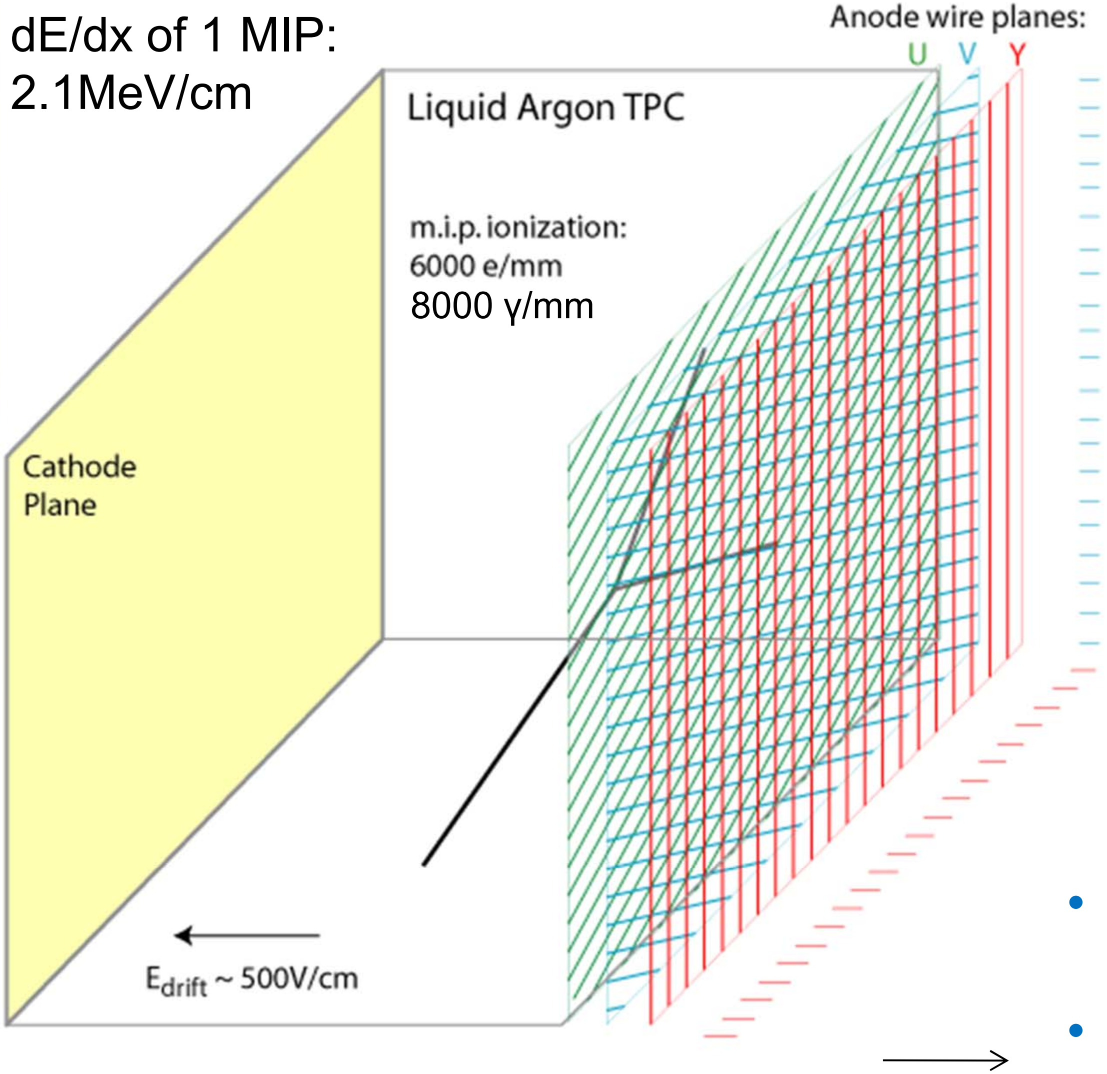
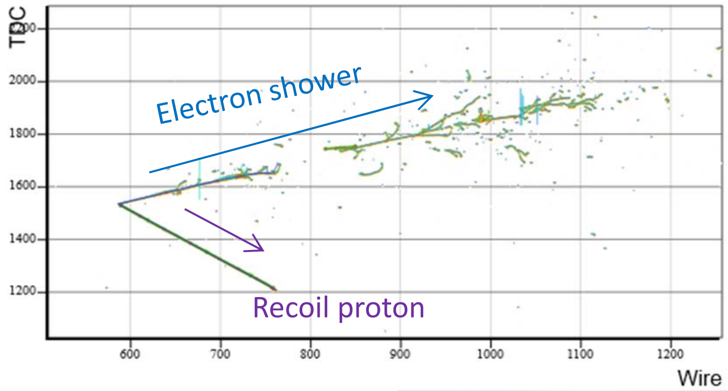
Excellent new opportunity with high res. LArTPC

dE/dx of 1 MIP:
2.1MeV/cm



First proposed by C. Rubbia, **1977** → **ICARUS**;

- Argon: most abundant noble gas (1.3% by weight)
- Electron drift v: 1.6 km/s
- Position resolution ~ mm
- PID: dE/dx through charge collection + event topology

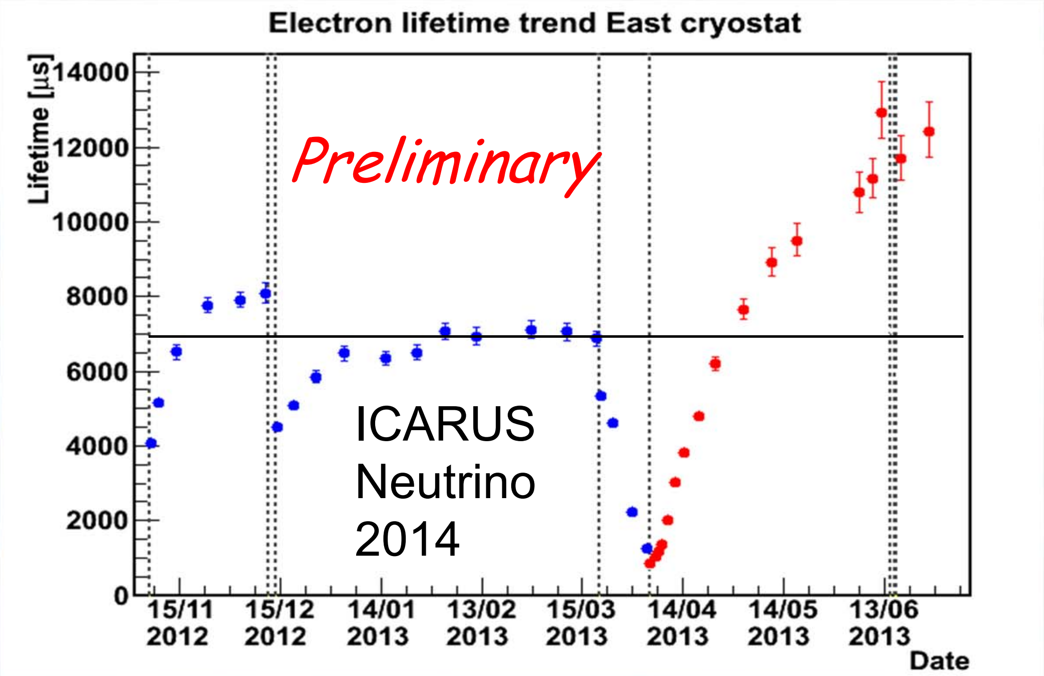


- stopping muon 1% momentum resolution
- 16% with multiple scattering
- 20 MeV resolution for π^0 mass

Challenge: LAr Purity

iii) Electron lifetime: collected charge

- Ionized electron collide 10^{12} times every second
- Within the ~ ms drift time, if electron collides with an impurity and get attached, we lose it



Preliminary

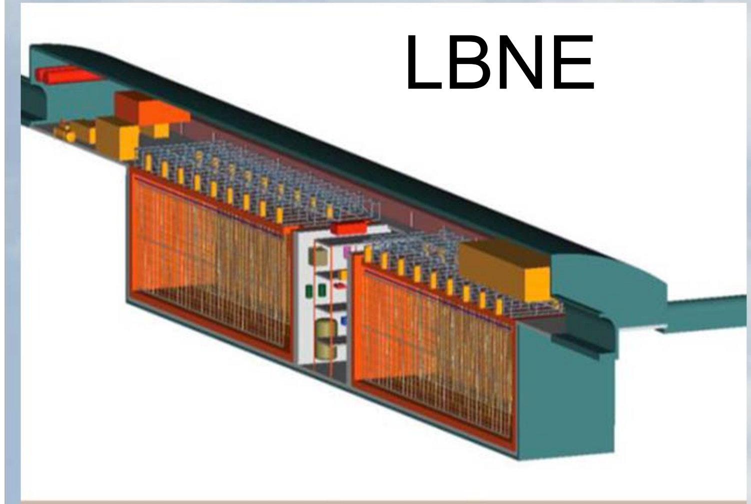
ICARUS
Neutrino
2014

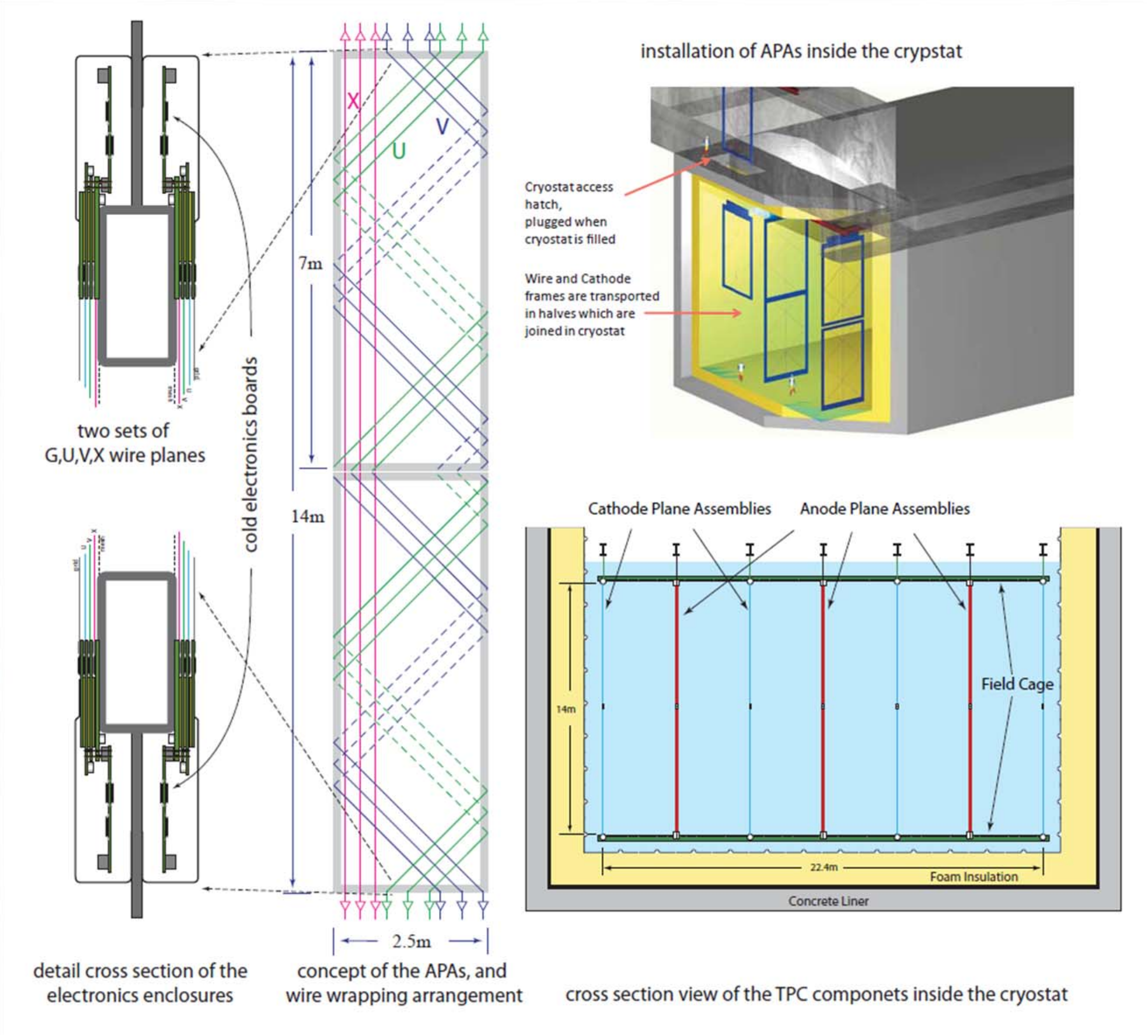
$$Q_{collect} = Q_{drift} \cdot e^{-t_{drift}/T_{lifetime}}$$

- ICARUS reached 12 ms electron lifetime
- Expect longer electron lifetime in MicroBooNE

Challenge: Detector Size

Volume: 15m x 24m x 49m x 2
Total Liquid Argon Mass:
~50,000 tonnes
Fiducial Mass for ν Physics:
~35,000 tonnes





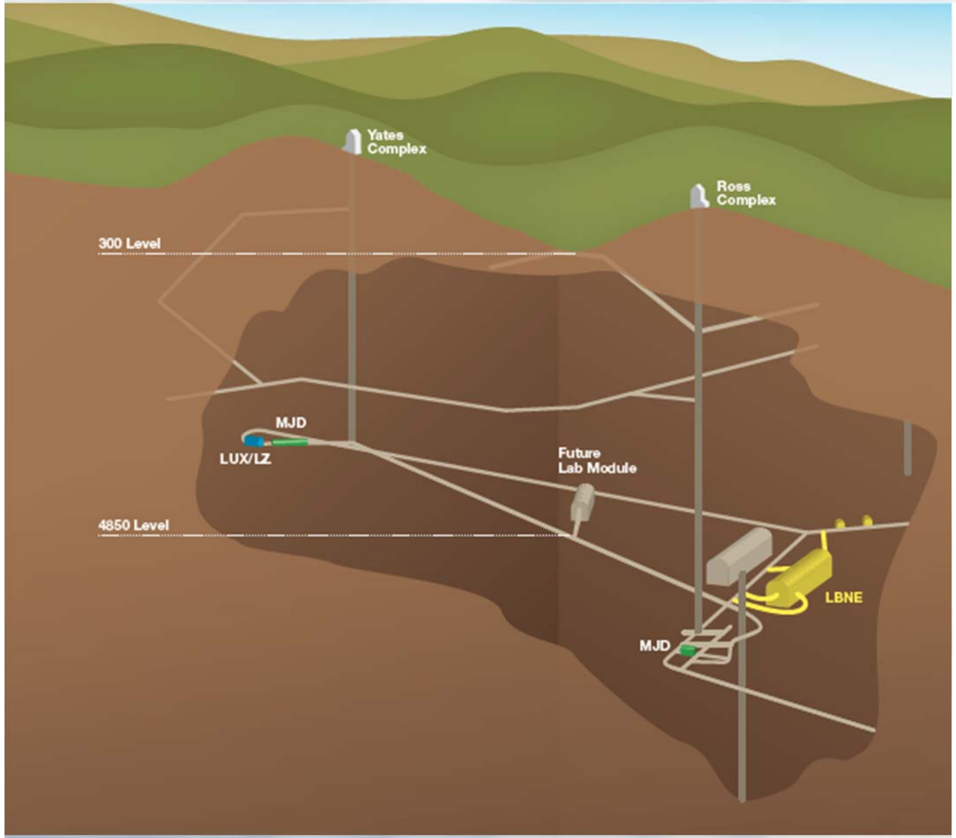
detail cross section of the electronics enclosures

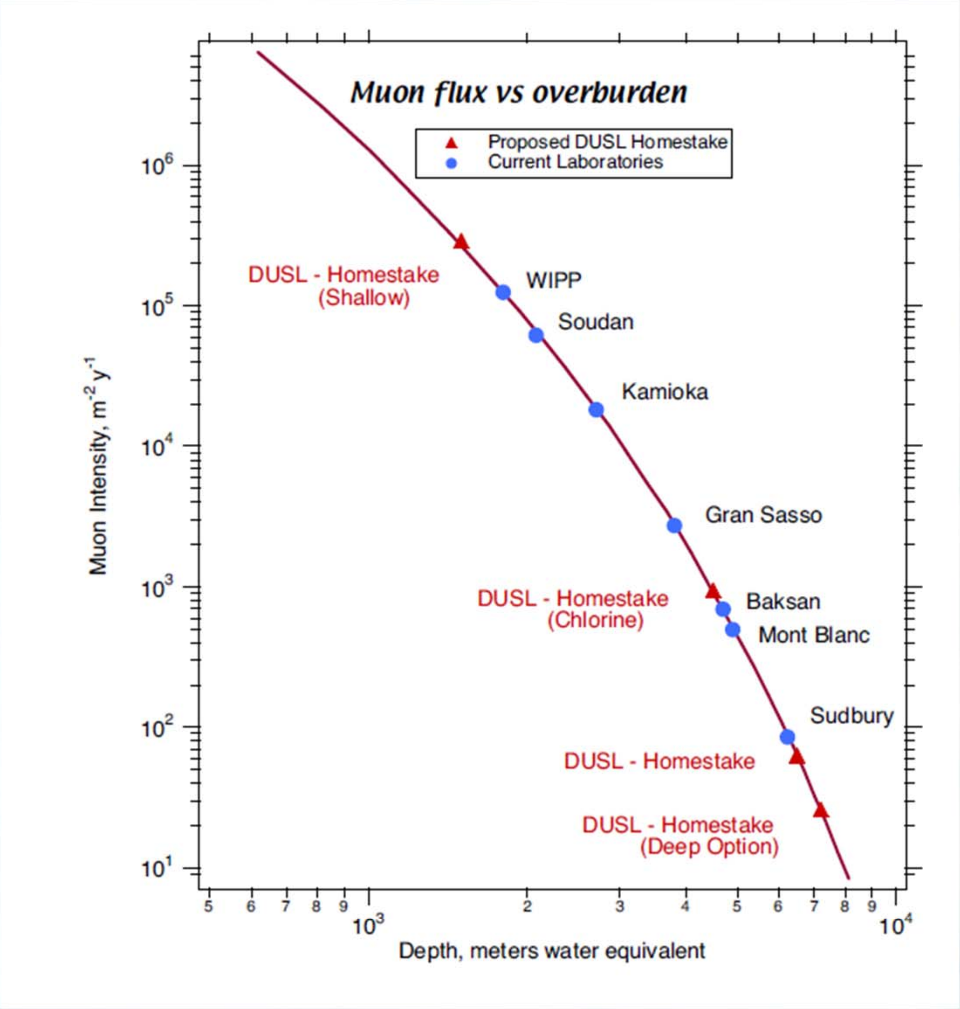
concept of the APAs, and wire wrapping arrangement

cross section view of the TPC componets inside the cryostat

- Modular design is the key!

Importance of going/being Underground



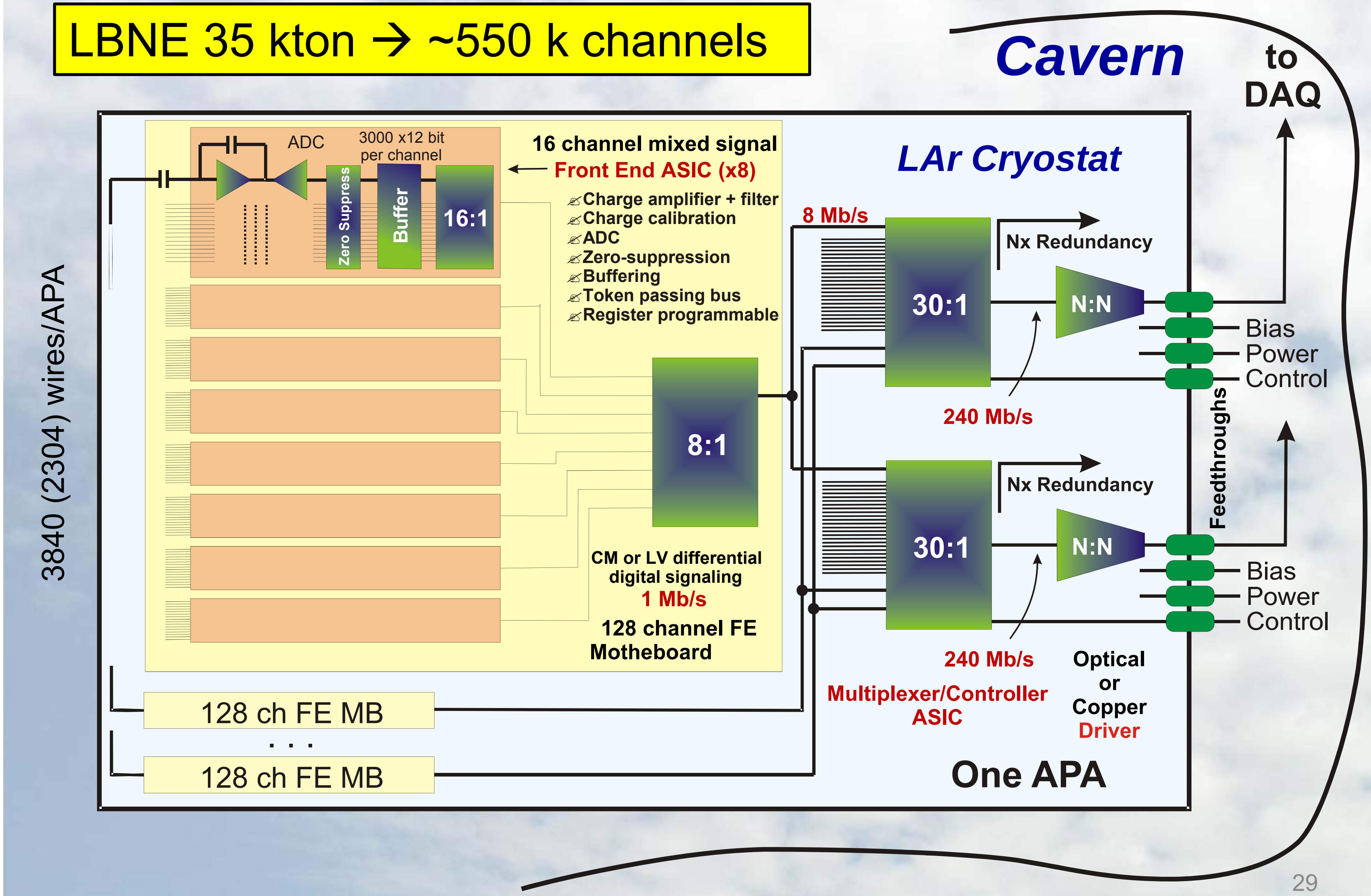


Significant reduction of cosmic-related backgrounds as well as space charge

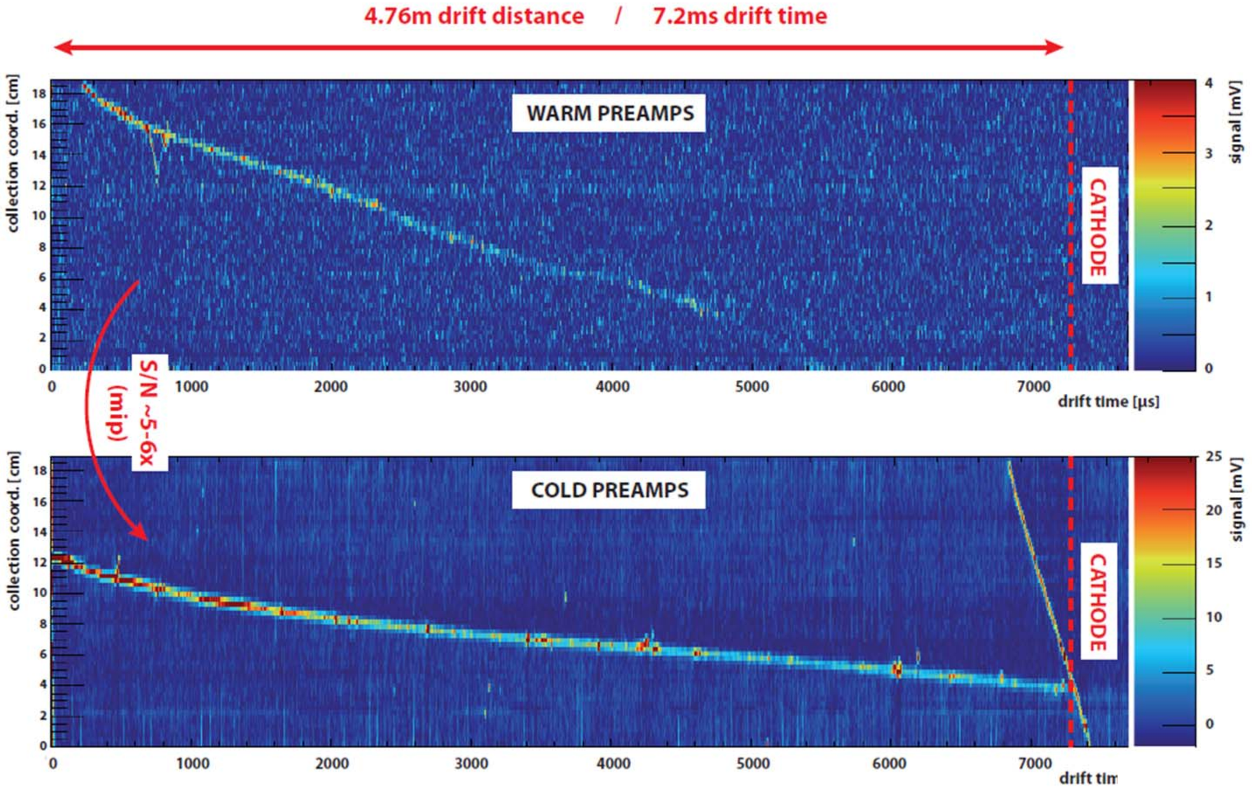
- Enable proton decay, atmospheric neutrino oscillation, supernova ν detection

Cold Electronics

LBNE 35 kton → ~550 k channels

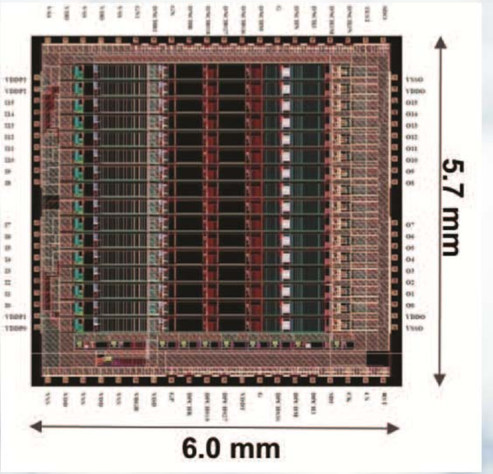


Cold vs. Warm Electronics



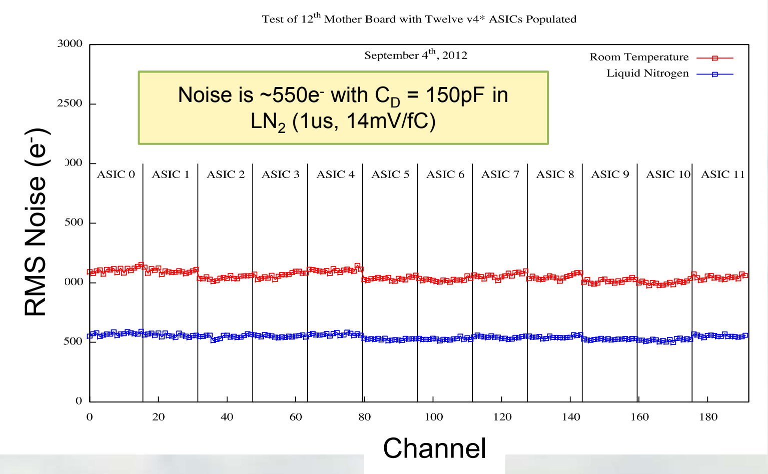
ARGONTUBE results, Univ. Bern

Noise level is about half with cold electronics

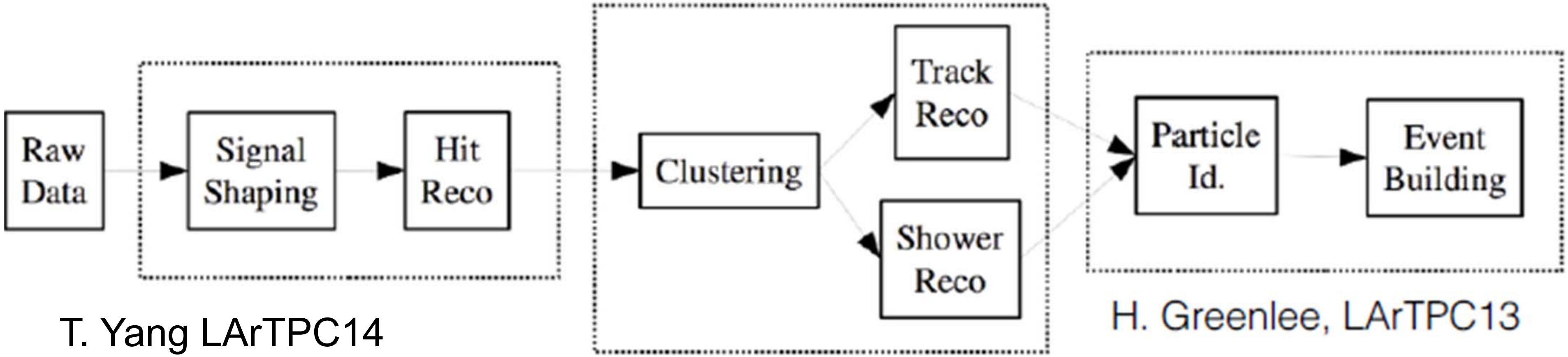


BNL low-noise CMOS ASIC

Performance is constant from RT to 77K, except for noise



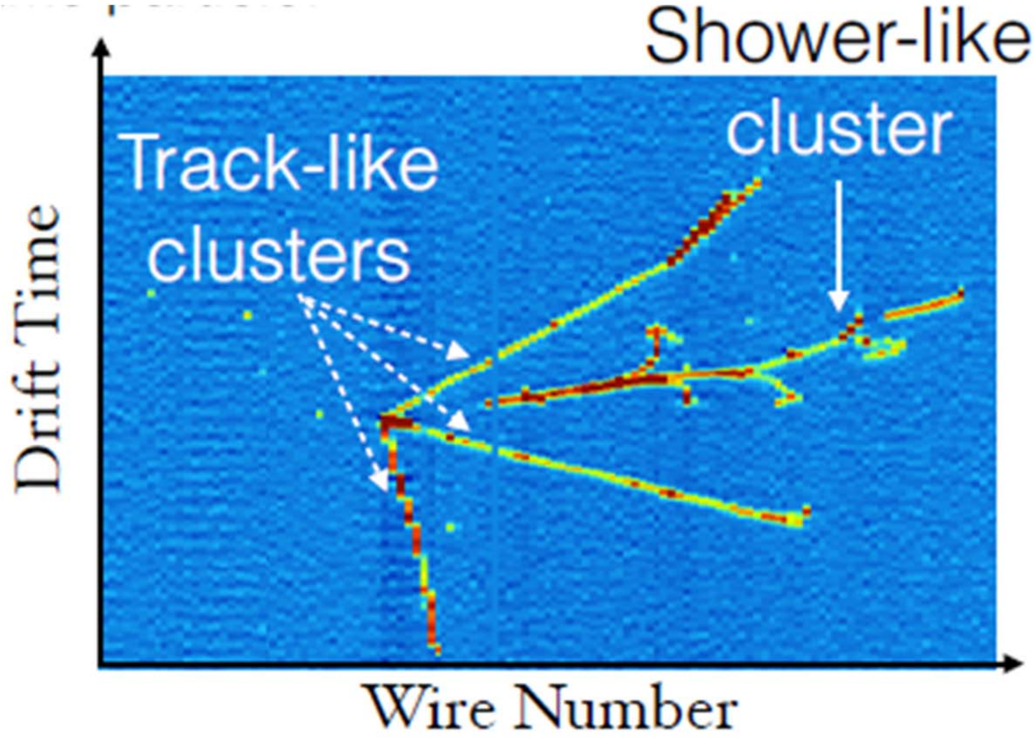
Challenge: Event Reconstruction



Raw Data → Signal Shaping → Hit Reco → Clustering → Track Reco / Shower Reco → Particle Id. → Event Building

T. Yang LArTPC14

H. Greenlee, LArTPC13

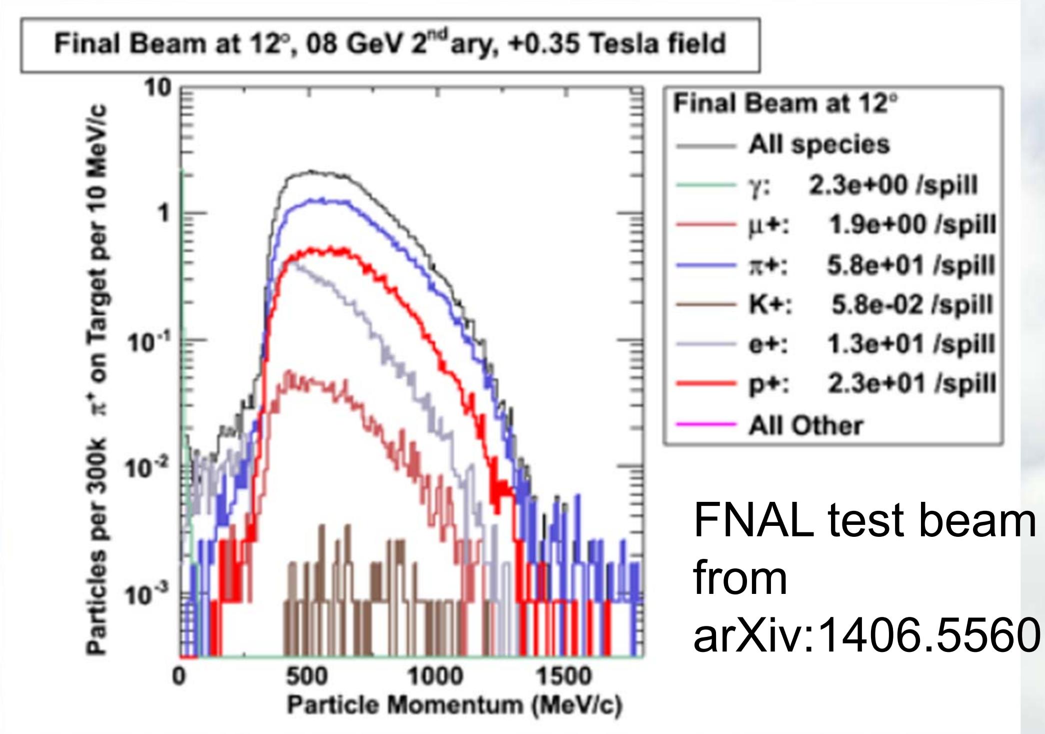


- High-quality automated event reconstruction in LAr is crucial and in developing

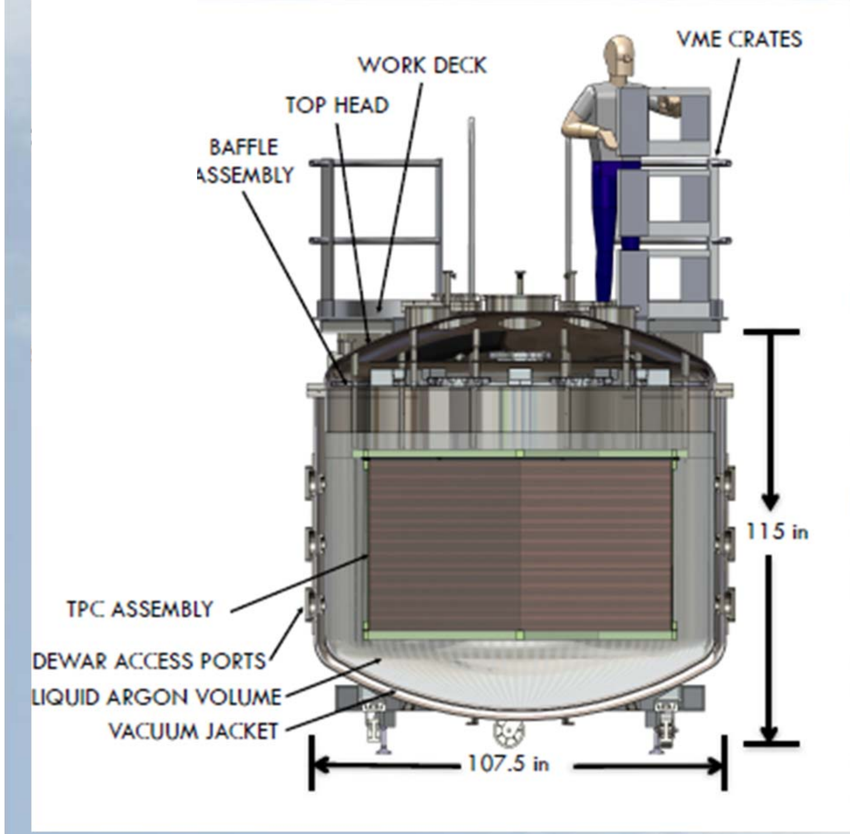
μBooNE

Test Beam Experiments

- Use a well-defined charged particle beam to study LAr TPC
  - Single particle tracks
  - E&M Shower
  - Hadronic Shower



FNAL test beam from arXiv:1406.5560



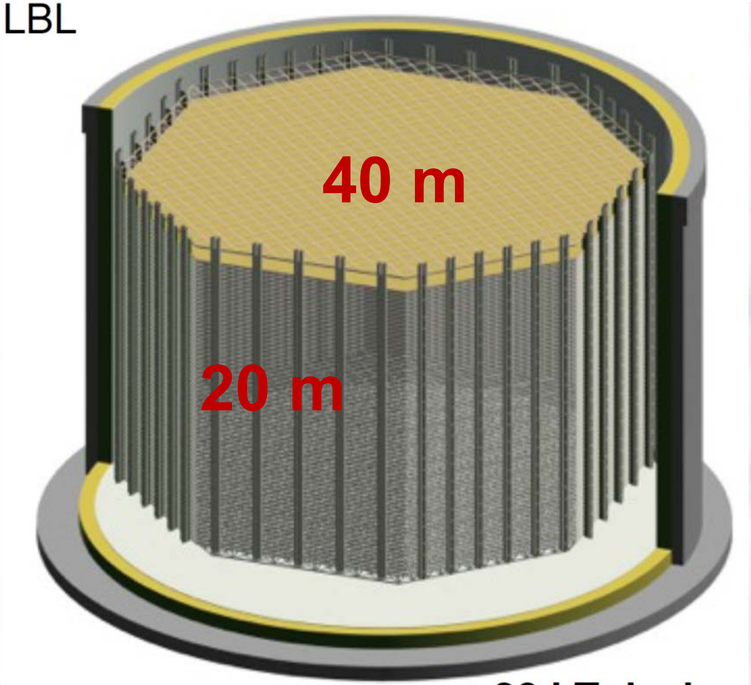
- Lariat (FNAL)
- WA105 (CERN)
- Captain
  Energy response to neutrons

Challenges in Double-Phases LArTPC

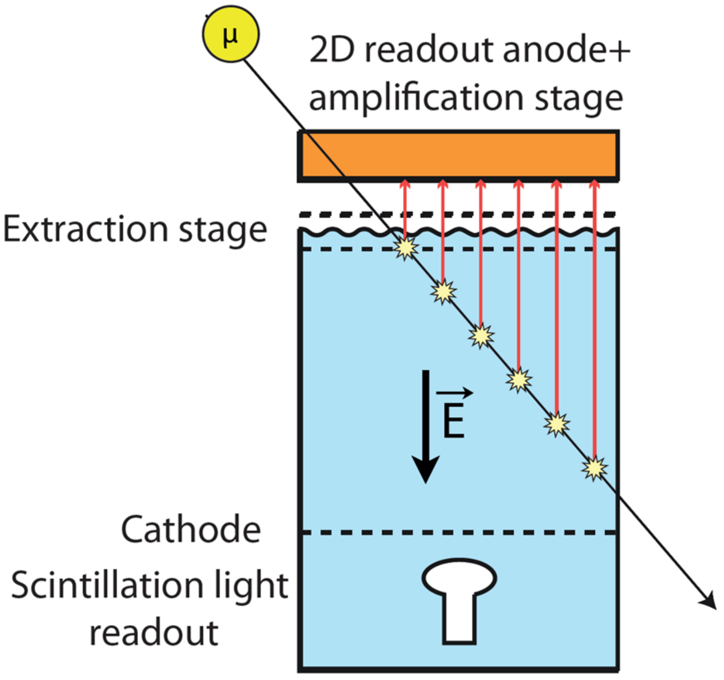
- Higher Gain, larger fiducial mass,
- GEM readout → ultimate 3D imaging

- HV (~10^6 V) and ultra LAr purity is required for 20 m drift distance
- Light collection: short Raleigh scattering length and light detector placement
- GEM gain uniformity

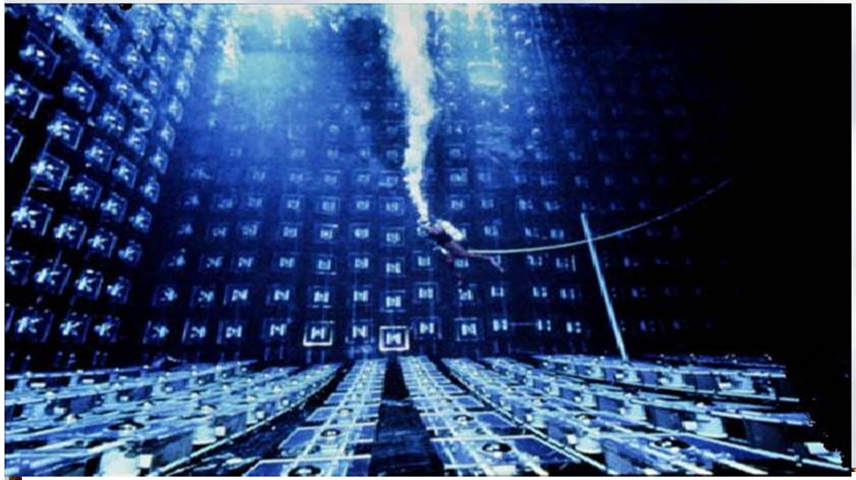
- Active R&D ongoing



20 kT design



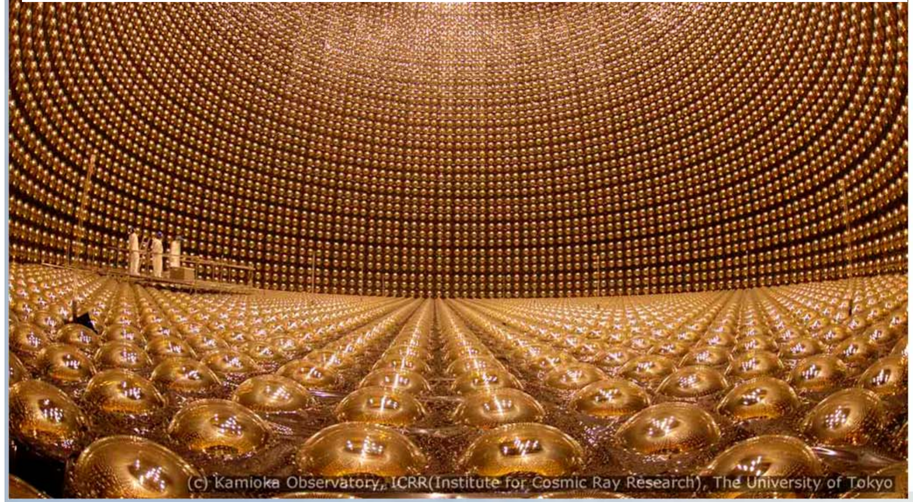
Water Cerenkov Detector



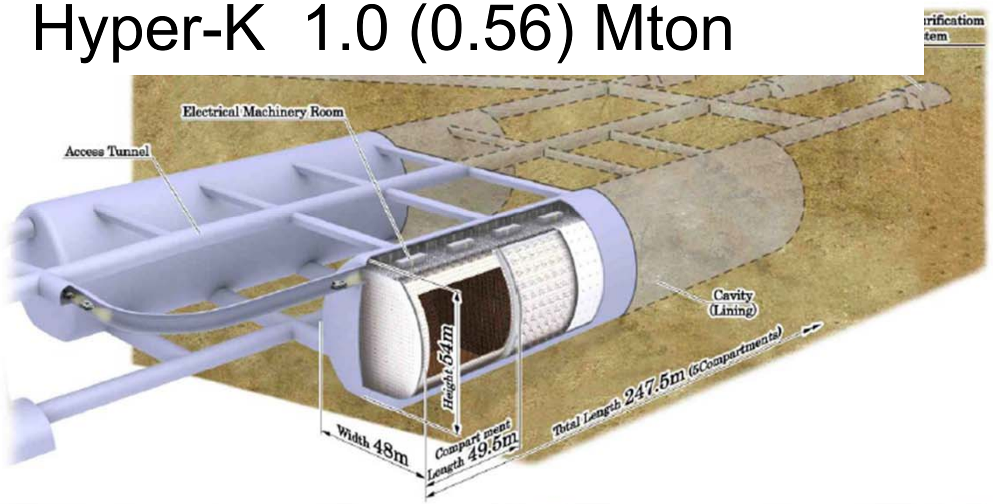
IMB 6.8 kton

Kamiokande 3 kton

Super-K 50 (22.5) kton


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

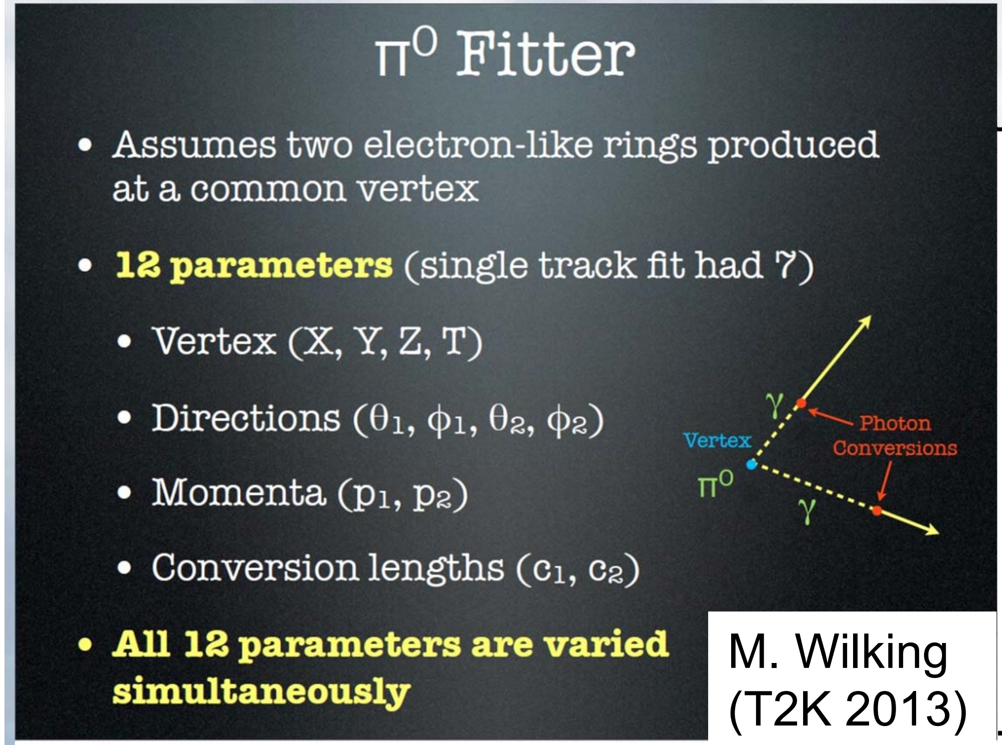
Hyper-K 1.0 (0.56) Mton



Cost effective for large mass, cheaper than LAr

Focusing on lepton detect., lower efficiency than LAr at high E_v

π^0 background

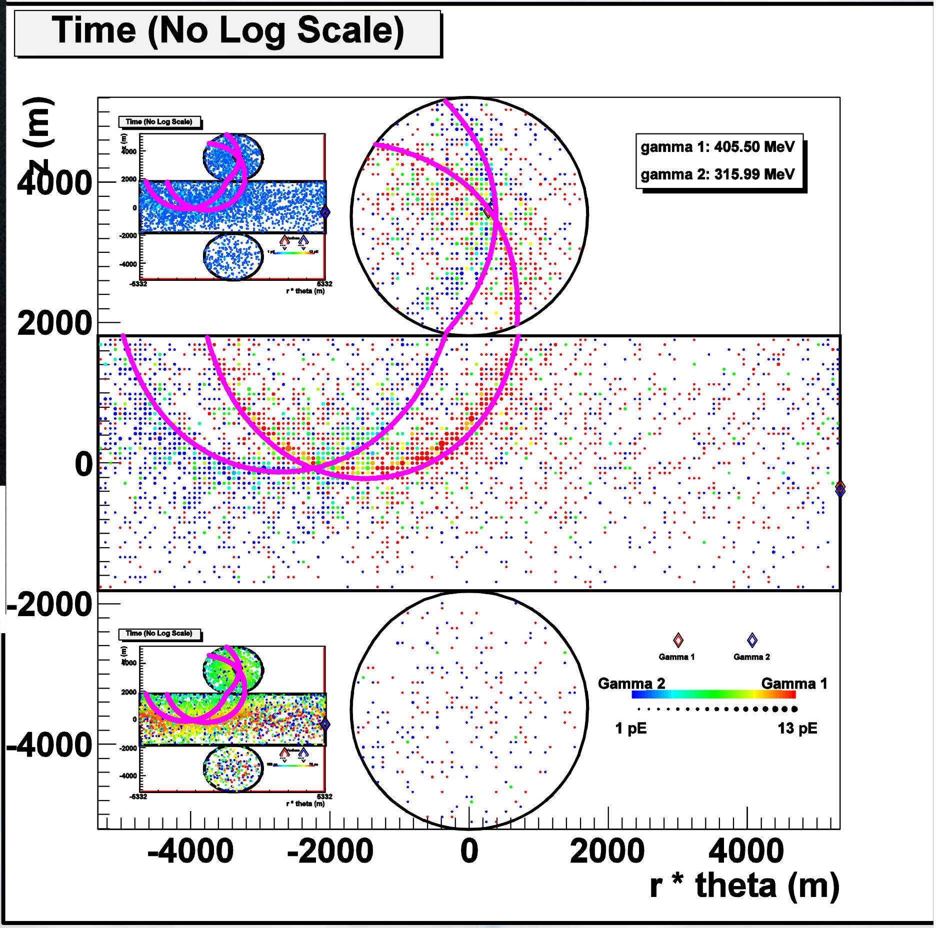


π^0 Fitter

- Assumes two electron-like rings produced at a common vertex
- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, ϕ_1, θ_2, ϕ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)
- ***All 12 parameters are varied simultaneously***

M. Wilking (T2K 2013)

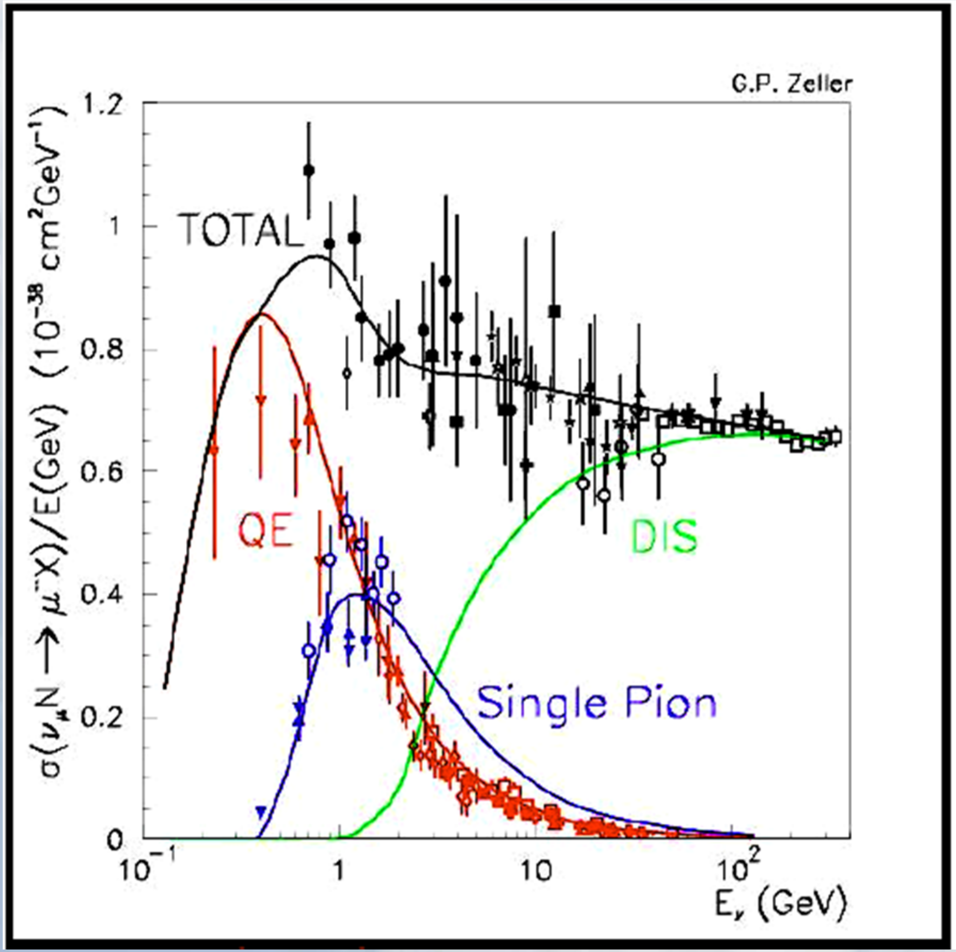
$$\nu+N\rightarrow\nu+N+\pi^0$$

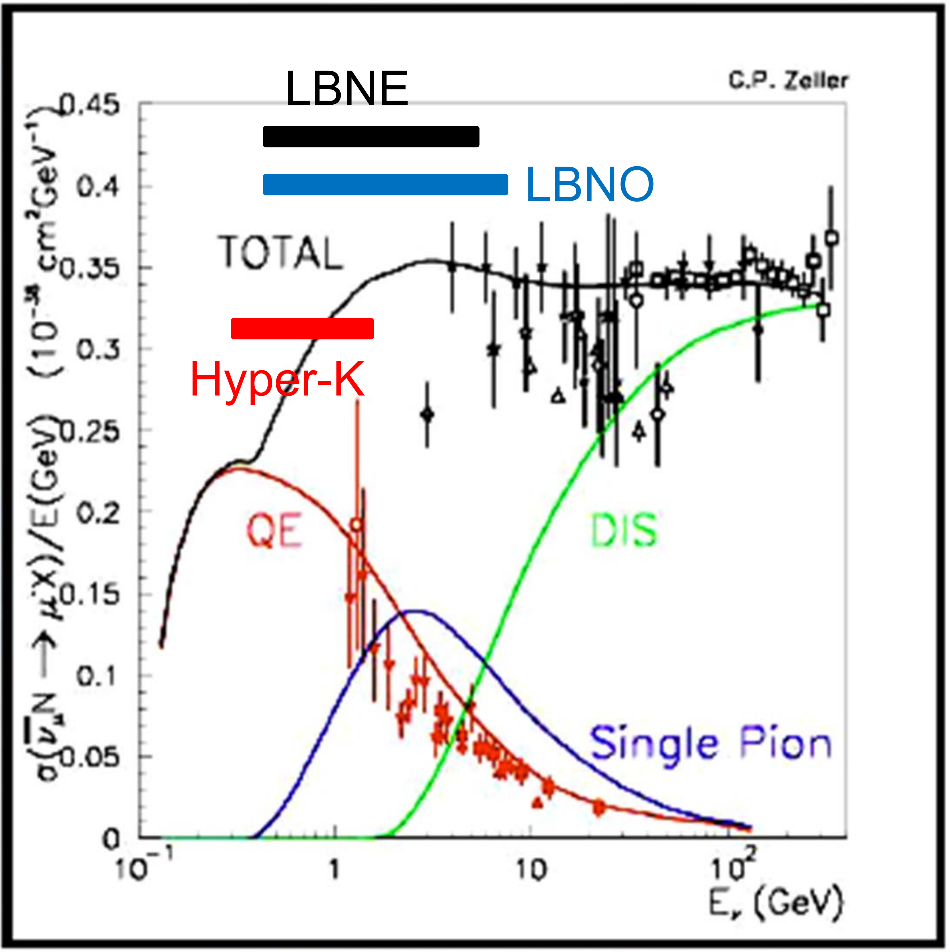


- 1.26 NC π^0 backgrounds
  70% removed with new alg.
- Observed 28 events

Good role model for the LArTPC reconstruction development

ν-A Cross Section

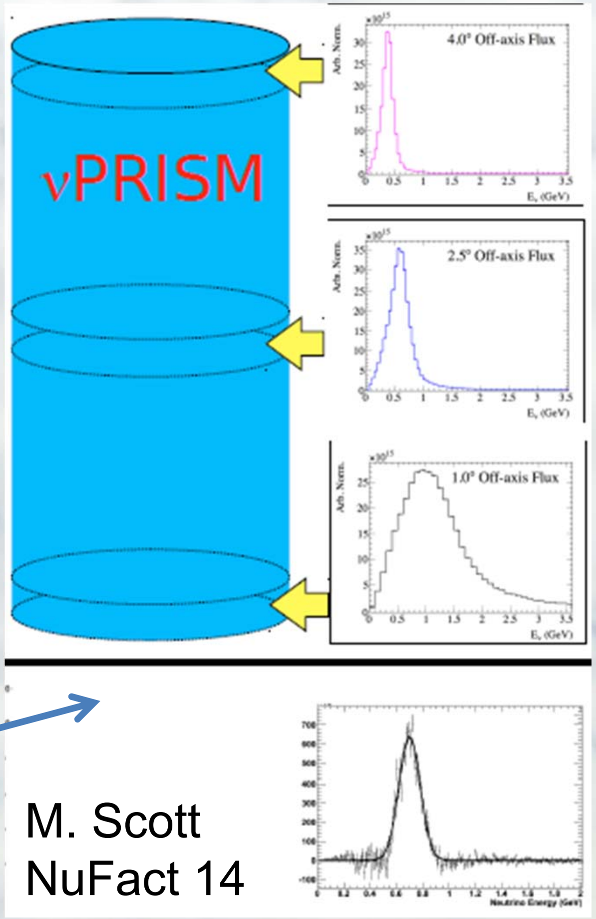




- Understanding Neutrino Interaction (nuclear effect) is crucial for the oscillation experiments
  - Neutrino energy reconstruction + normalization

Rapid Progresses

- Experiments:
  - – Bubble chamber exp. (ANL/BNL) → MiniBooNE, Argoneut, Minerva, T2K-ND, MicroBooNE …
- Event Generator:
  - – GENIE, NEUT, GIBUU, NuWro …
  - – Validation with electron scattering data from (SLAC, MIT-Bates, JLab …)
- Future measurements:
  - – Low-nu method + Fine Grain Tracker (LBNE)
  - – nuPRISM Concept



M. Scott
NuFact 14

Summary

- Accelerator-based neutrino experiments will continue to deliver high-quality physics results
  - Determination of the MH will aid planning neutrinoless double beta decay experiments
  - Establishment of lepton CPV will be revolutionary: possible explanation of matter dominance in universe
  - Excellent opportunities in FNAL, JPARC …
- Scale of next-generation experiment is well-known, broad acceptance in the world, and within reach
  - There are various technical issues relating to the scale, but no show stopper
  - Issues on how to analyze data: increase signal efficiency, reduce backgrounds, keep systematics low is working out by the entire community