e-NuMI

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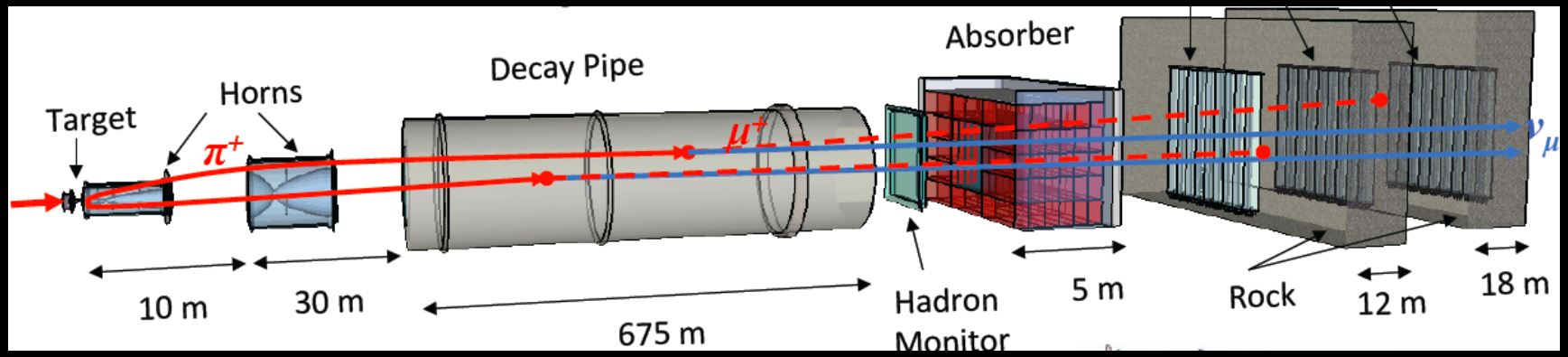
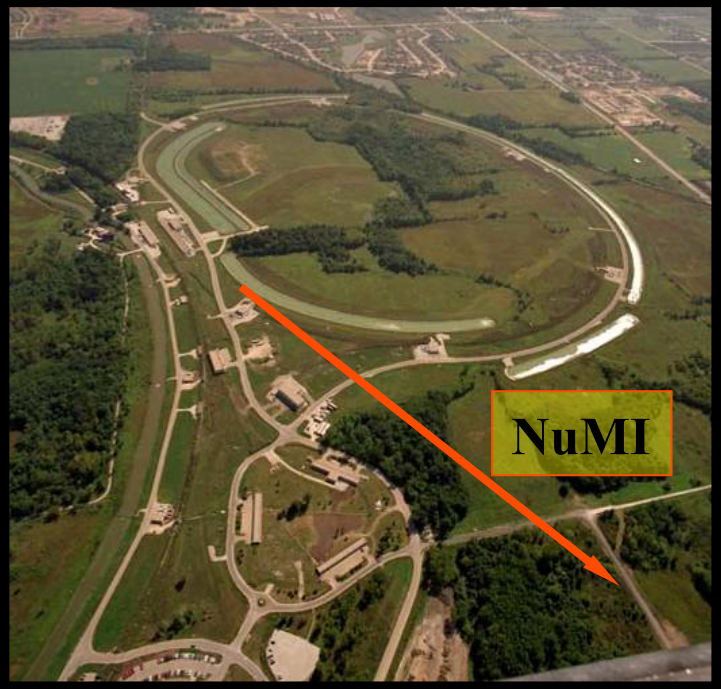
Outline

1. The premise: NuMI
2. Exploiting NuMI
   - More NOvA
   - RADAR
   - CHIPS
3. More on NuMI land
4. Summary & outlook

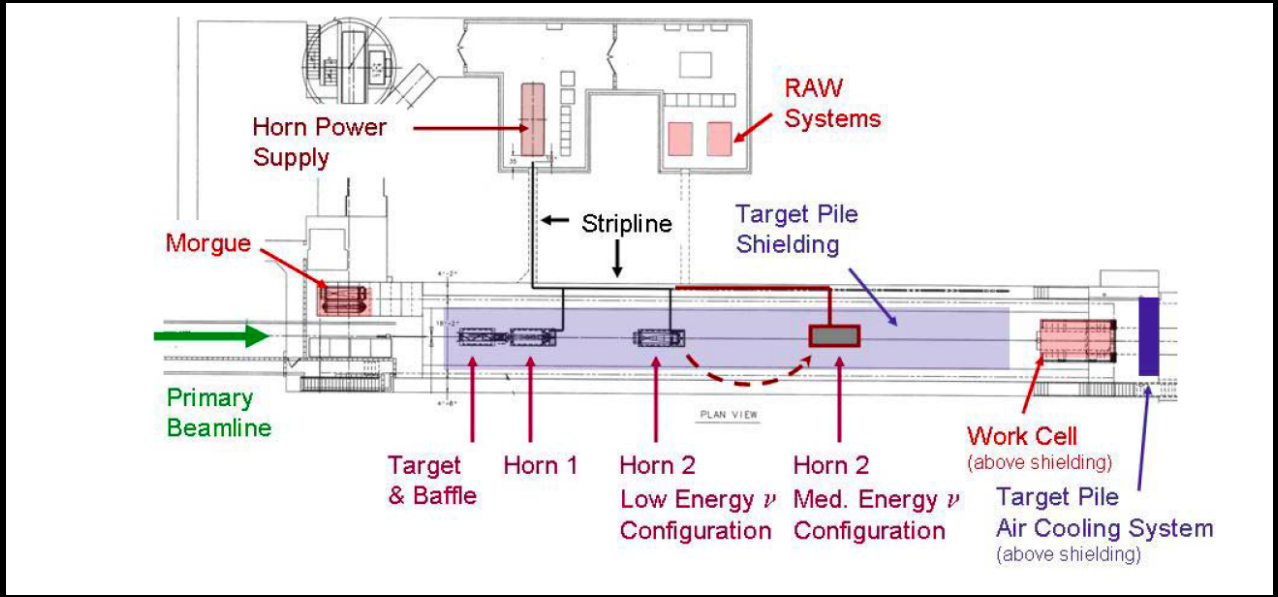
The premise: NuMI (Neutrinos at the Main Injector)

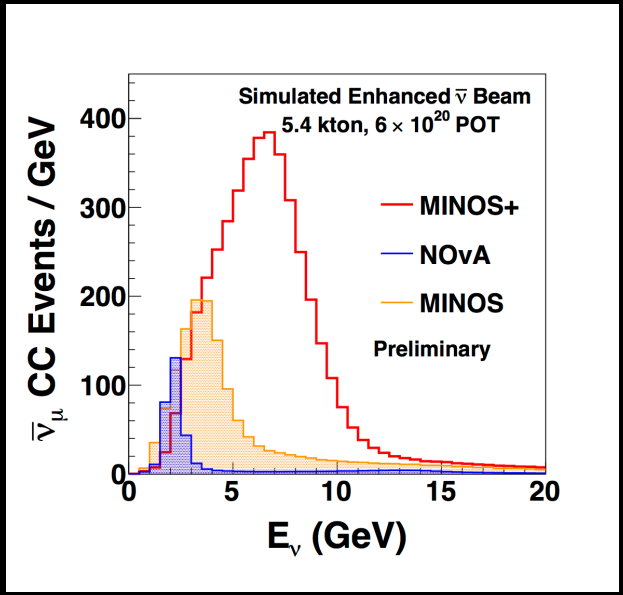


- ✓ Commissioned in 2005 for MINOS
- ✓ Supported the flagship ν program at Fermilab
  - MINOS, MINOS+, MINERvA, ArgoNeuT, PEANUT,…
- ✓ Delivered 1.55e21 POT in 7 years
  - 3.7e13 / 2.2 sec @120 GeV = 323 kW
- ✓ Undergoing an upgrade for NOvA (ANU + PIP)
  - Slip-stacking in Recycler (12 batches)
  - Faster MI ramp time (1.3 sec)
  - Booster RF upgrade
  - … (and much more)
- ✓ → 700 kW → 6e20 POT/y most powerful accelerator neutrino beam for years to come



Medium Energy (ME) NuMI for NOvA

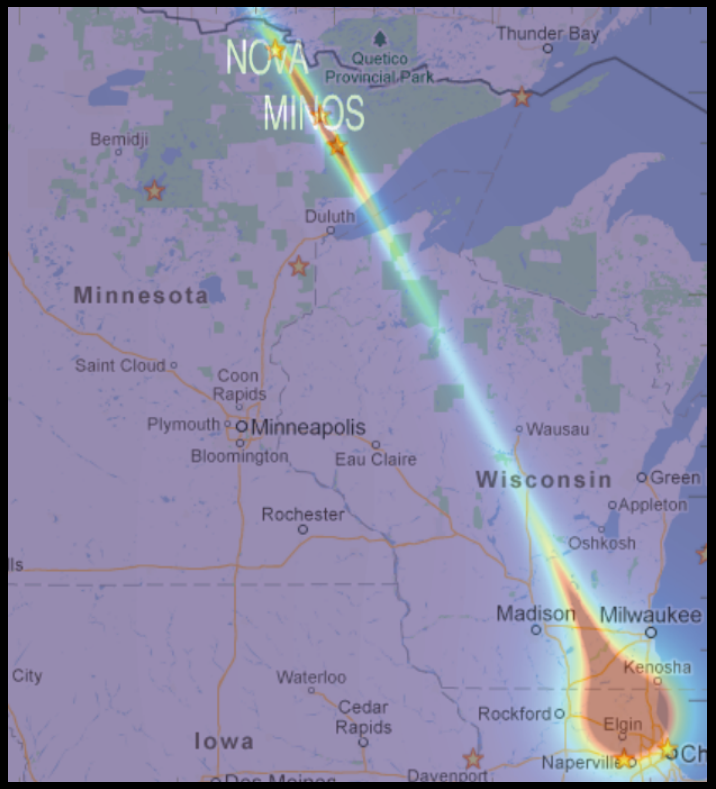




New improved-design target

What is e-NuMI ?

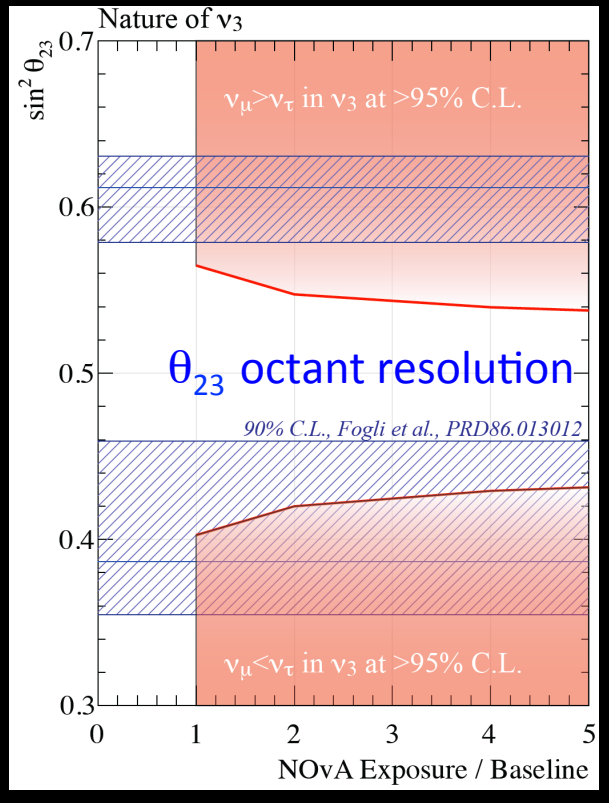
- NuMI = a powerful neutrino beam @ Fermilab for years and until the LBNE beam turns on (circa 2023)
- Seems natural to maximize its use to advance the neutrino oscillations physics program
- e =
  - ✓ exploiting
  - ✓ extending
  - ✓ expanding
    - → currently envisioned Fermilab program
      - → θ_{23} octant
      - → mass hierarchy
      - → CPV
- Grass-roots initiatives
  - ✓ More NOvA
  - ✓ Liquid argon TPC (RADAR)
    - arXiv:1307.6507 [physics.ins-det]
  - ✓ Water Cherenkov detectors (CHIPS)
    - arXiv:1307.5918 [physics.ins-det]



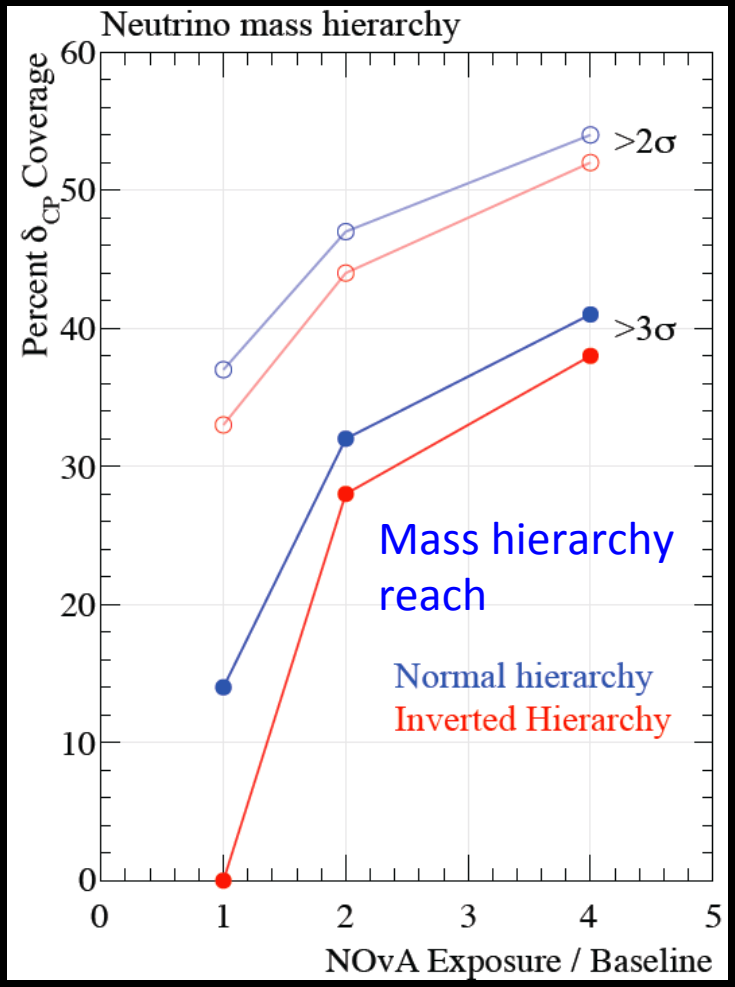
More NOvA

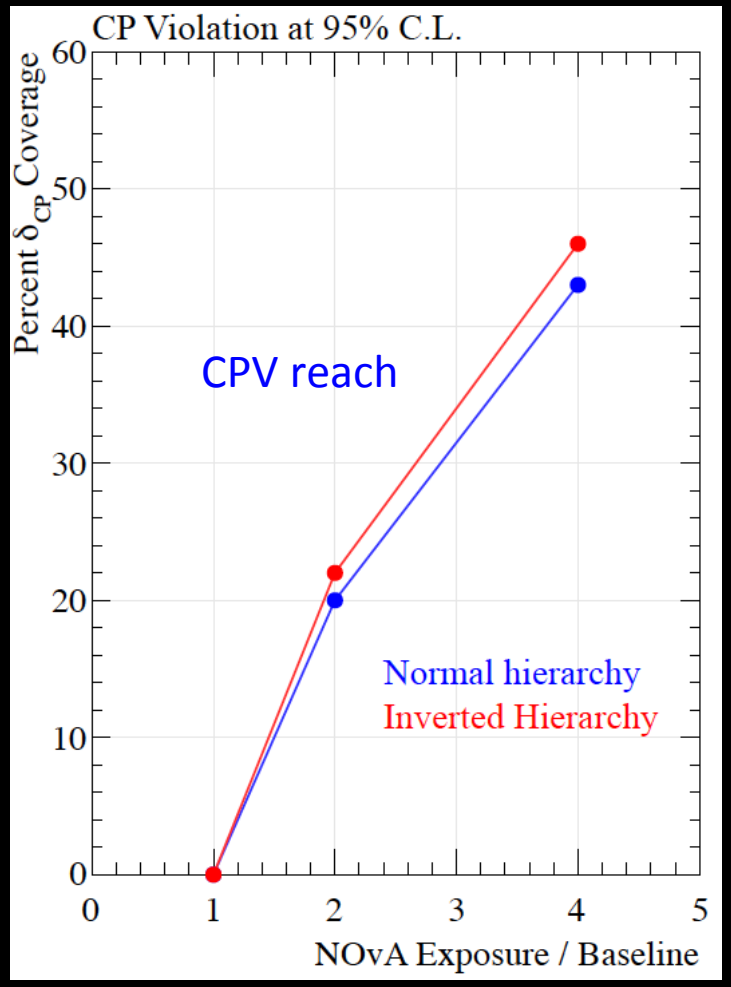
- The most obvious and straightforward extension
- Baseline exposuer: 14 kt*y @ 700 kW in ME NuMI (6e20/y POT)
- This can be doubled by
  - ✓ Adding 4kt more detector mass
  - ✓ And running for 10 years

- The Ash River building planned for 18 kt
- NOvA's budget sufficient for 14 kt
- Keeping supplies and module factories running would require $6M/kt ($9M/kt if re-starting but keeping all the infrastructure intact)
- This opportunity is fast closing as NOvA will finish production of modules in March 2013

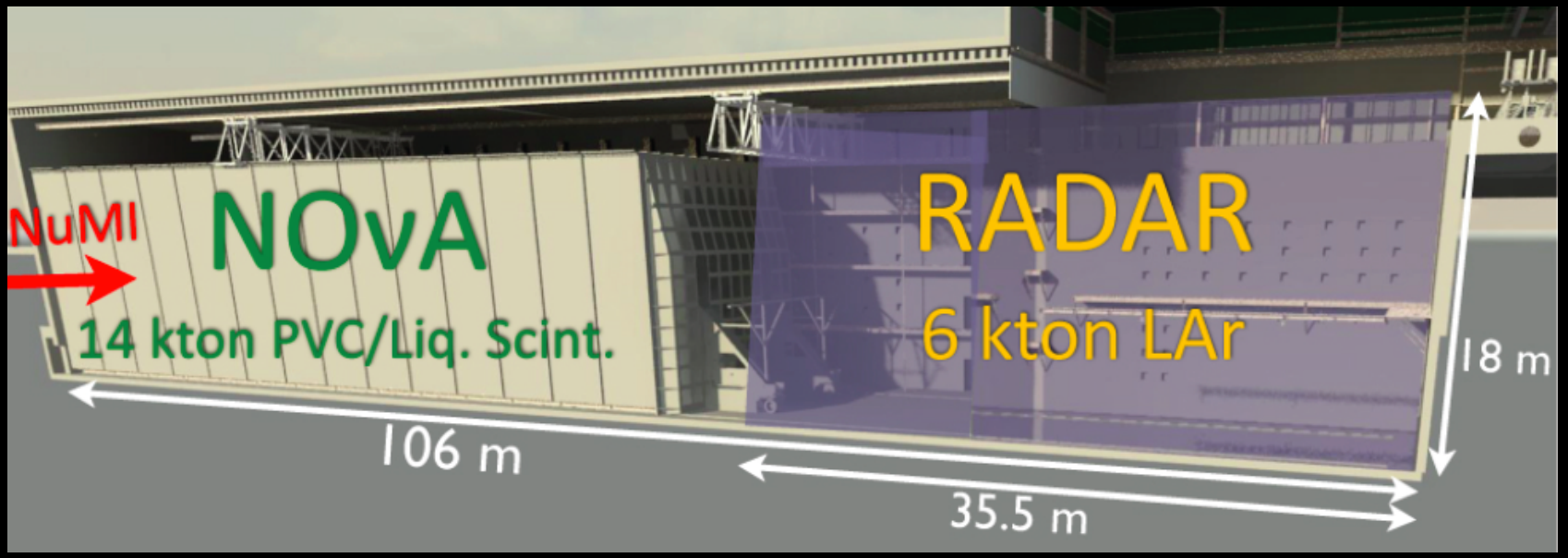


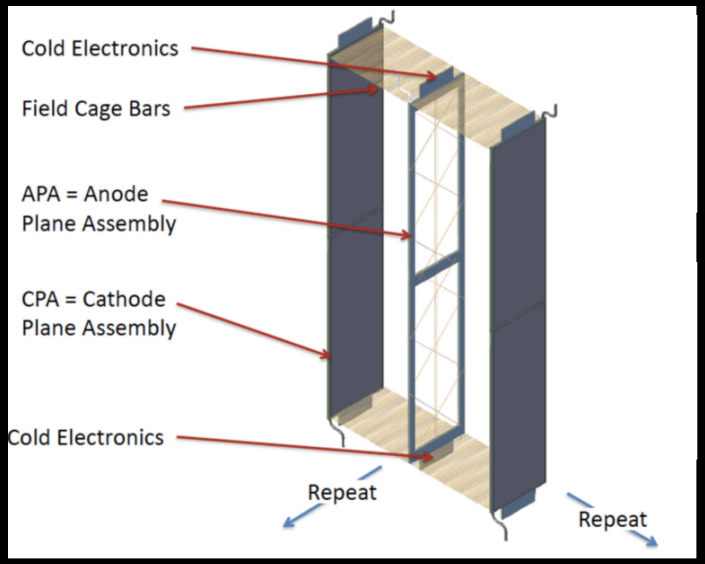
More NOvA


Neutrino mass hierarchy
Percent δ_{CP} Coverage
NOvA Exposure / Baseline
>2σ
>3σ
Mass hierarchy reach
Normal hierarchy
Inverted Hierarchy


CP Violation at 95% C.L.
Percent δ_{CP} Coverage
NOvA Exposure / Baseline
CPV reach
Normal hierarchy
Inverted Hierarchy

RADAR – R&D Argon Detector at Ash River

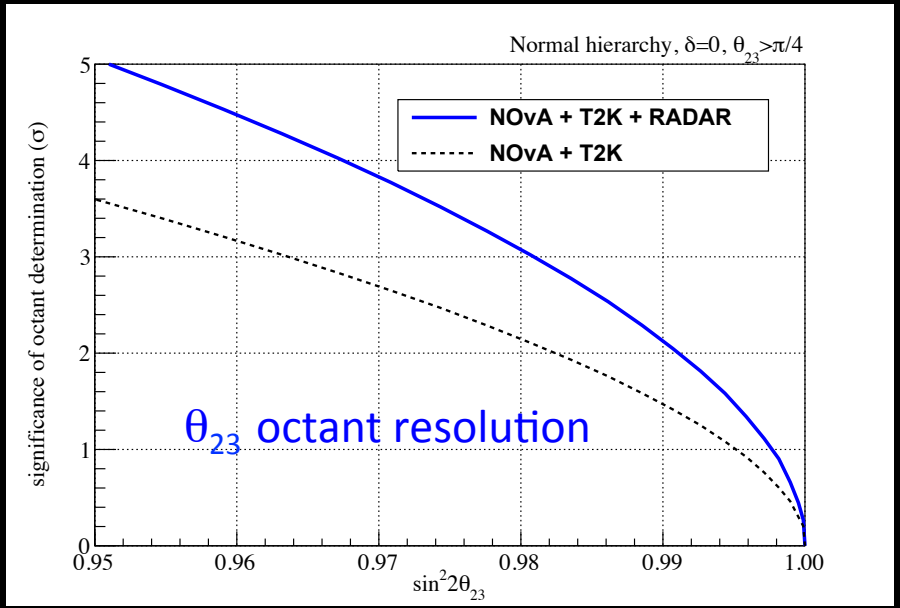




- 6 kt LAr modular TPC
- A step (R&D) towards LBNE
- Enhances NOvA reach
- 5 years construction
- 5 years of running 2018-2023
- Total cost $159M with $58M recoverable for LBNE

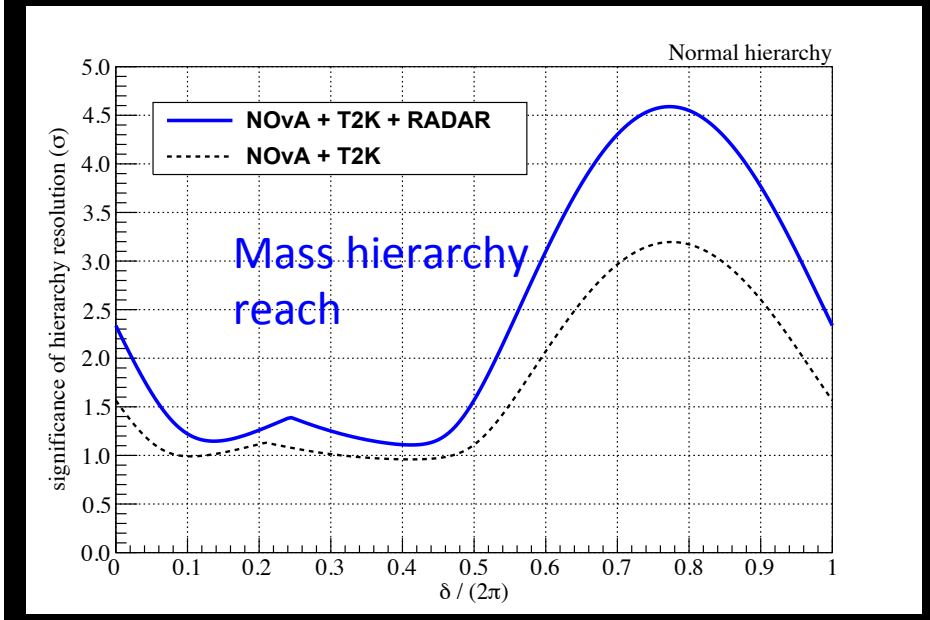
RADAR vs LBNE and θ_{23} octant resolution

- Advance design on the mid-size scale
- Use for cost and technology optimization of LBNE (may pay for itself for a fraction of cost-savings of LBNE)
- Train personnel with expertise essential for LBNE
- Engage international partners

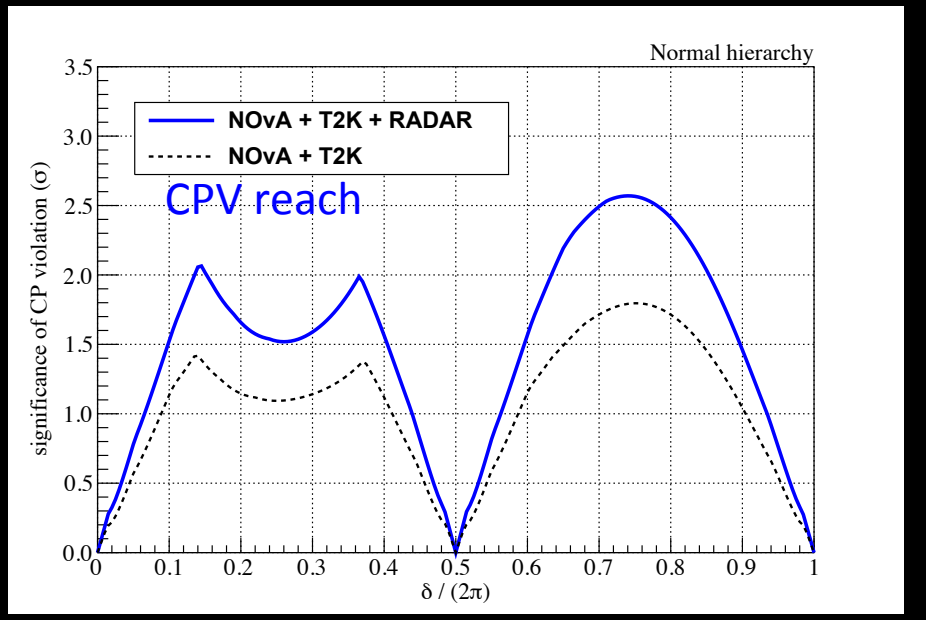


Studies based on scaling NOvA reach

RADAR - more physics benefits



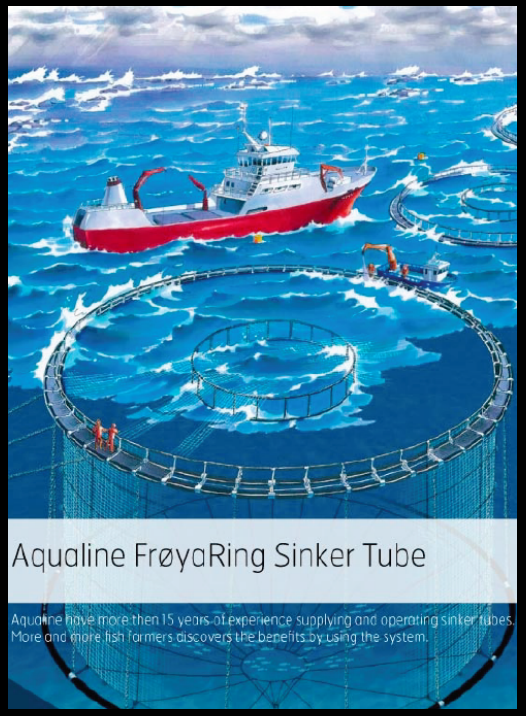
Studies based on scaling NOvA reach

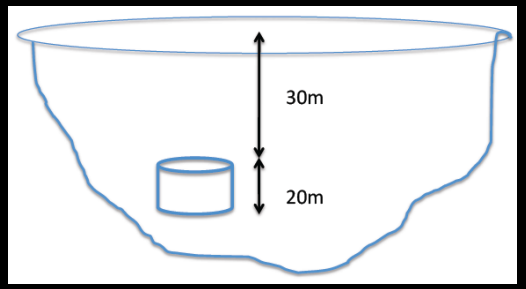


Studies based on scaling NOvA reach

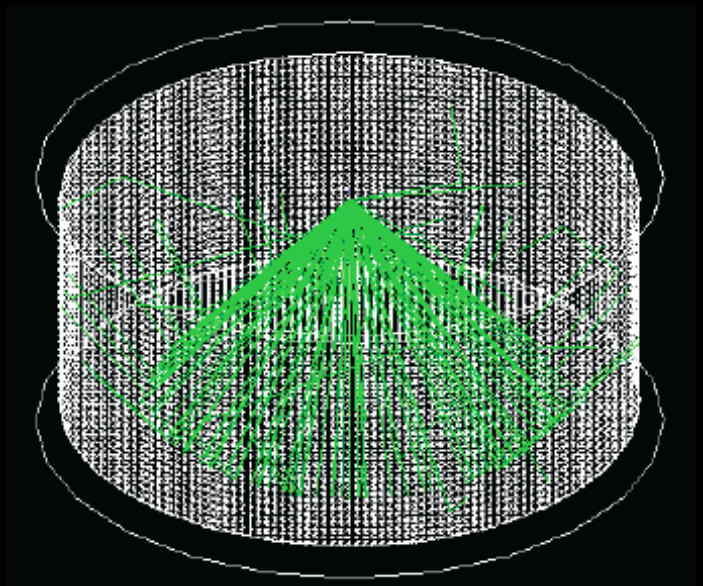
CHIPS - Water Cherenkov in Mine Pits

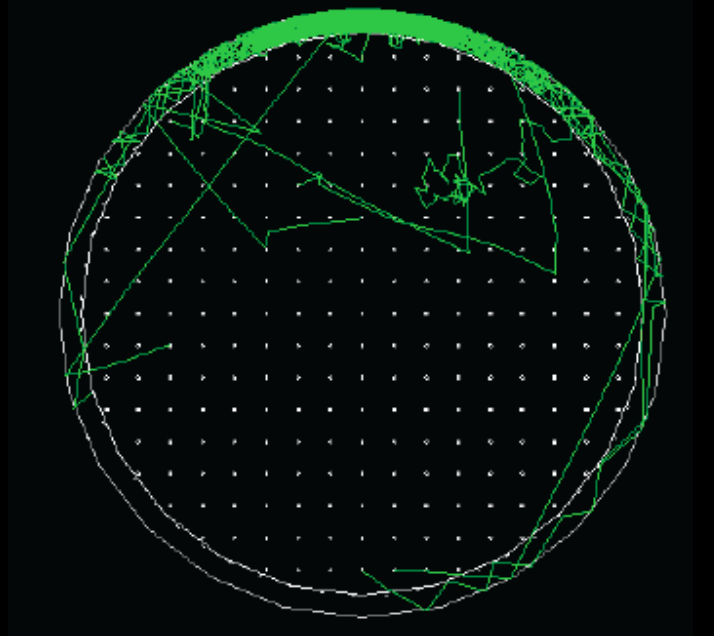
- Explore large mass with a cost-saving construction approach to reduce the WC costs to ~$1M/kt (100kt = $100M)
- Concept (advanced in earlier studies for LBNE) to use industrial fisheries floating platforms and adopt IceCube PMT (DOM) deployment
- Benefits from much earlier studies for GRANDE detector
- Minimize cost of civil construction
- Requires 30-40m water overburden for CR shielding

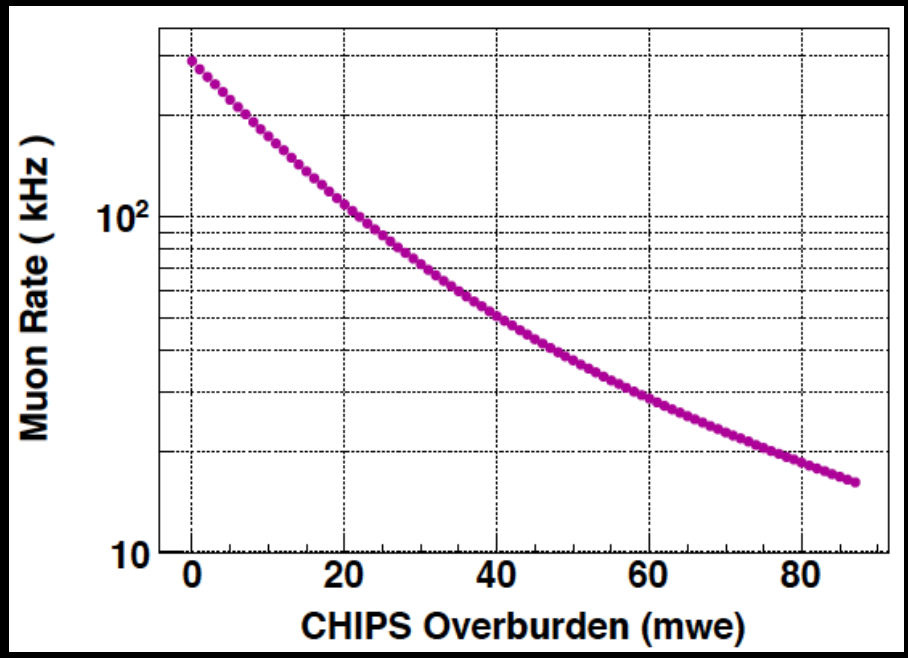


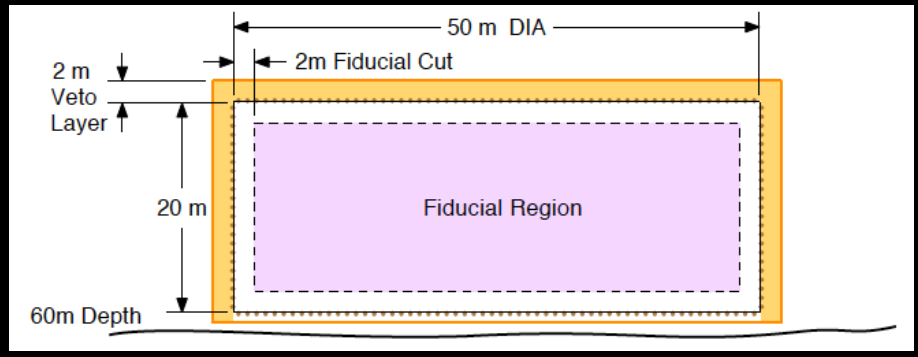


CHIPS Inner and Veto detectors

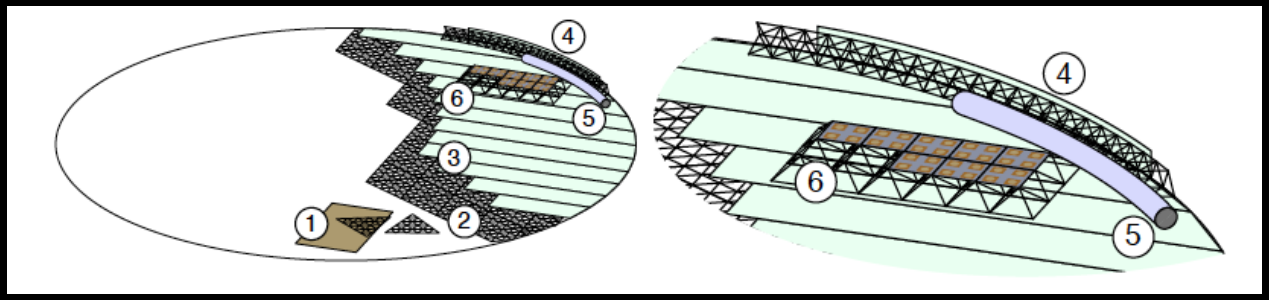




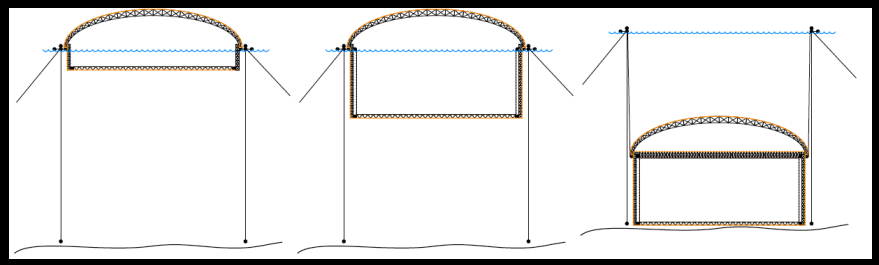


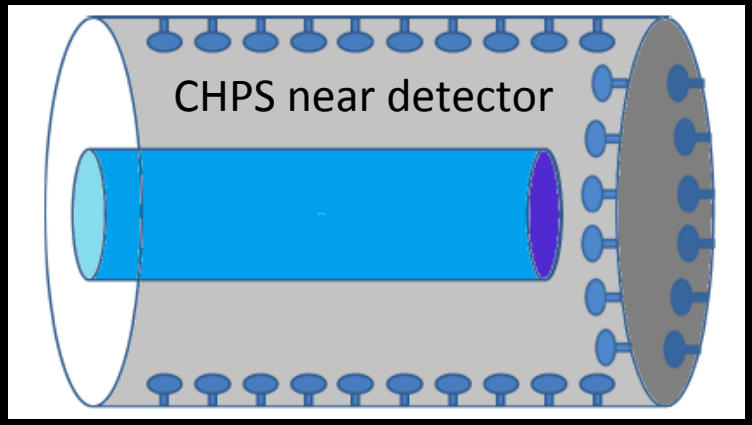


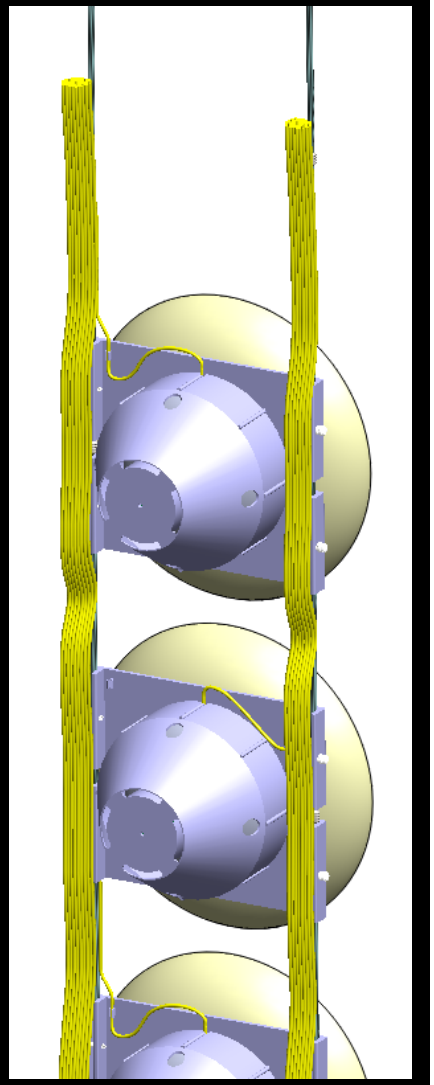
CHIPS components



- Light structure
- Industrial liners separating ID and VD
- Water filtration
- Daq
- 40kt detector
  - ✓ 50(D) x 20 (H) m^2
  - ✓ 10% PK coverage
  - ✓ 14,000 + 600 PMTs (10'' diameter)
- Near detector
- Cost driver: PMTs (60-70%)

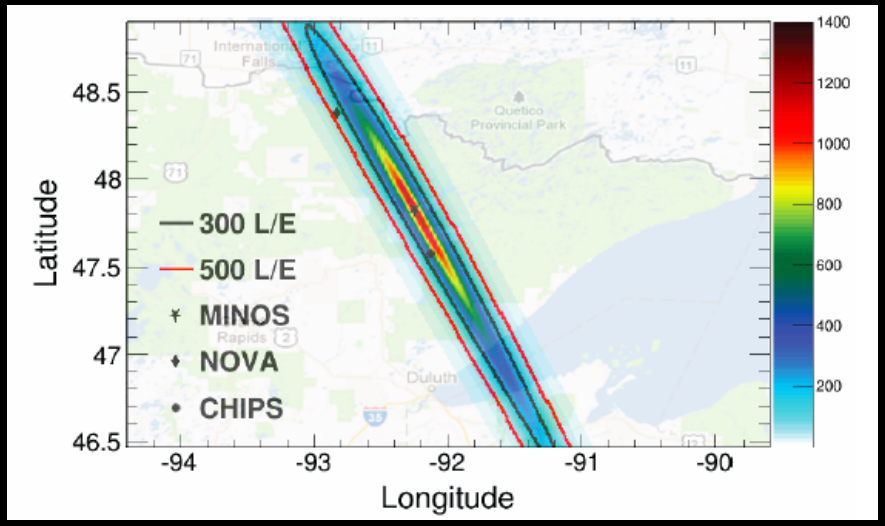


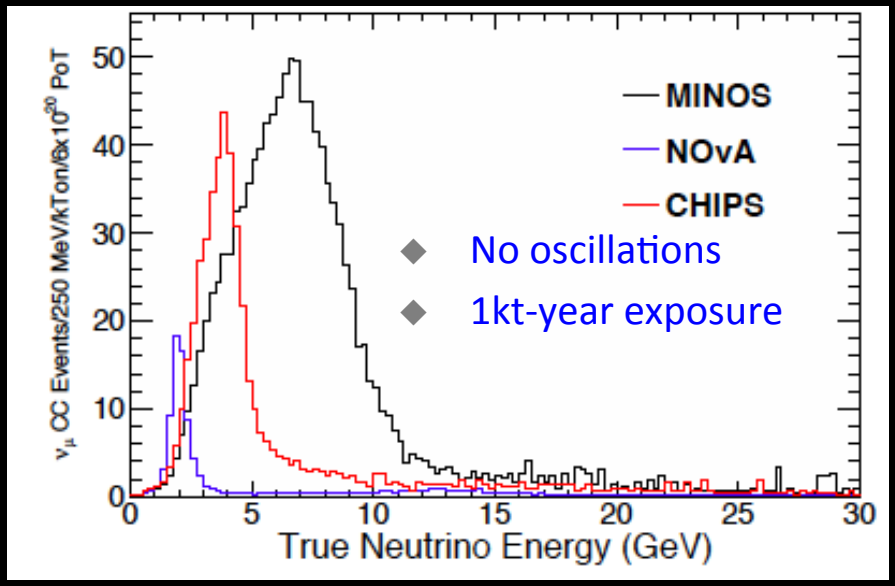




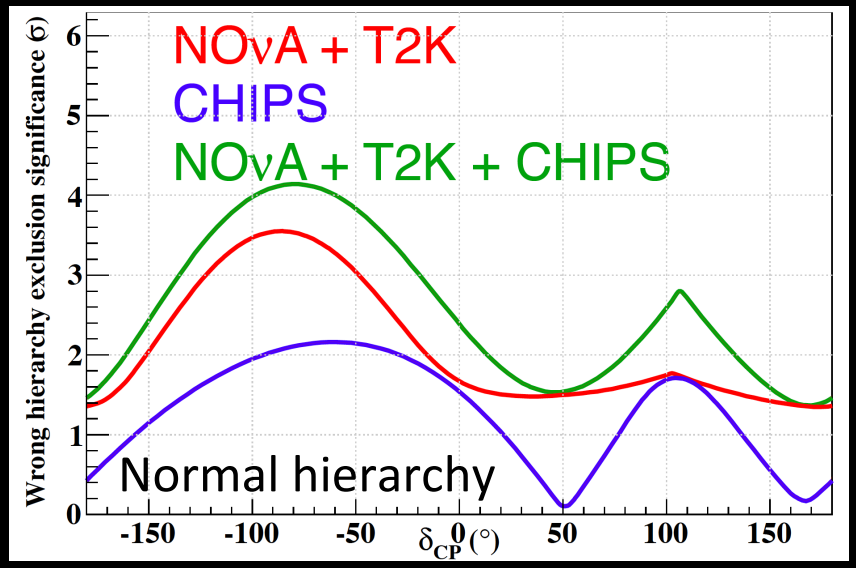
Wentworth Mine Pit 2W

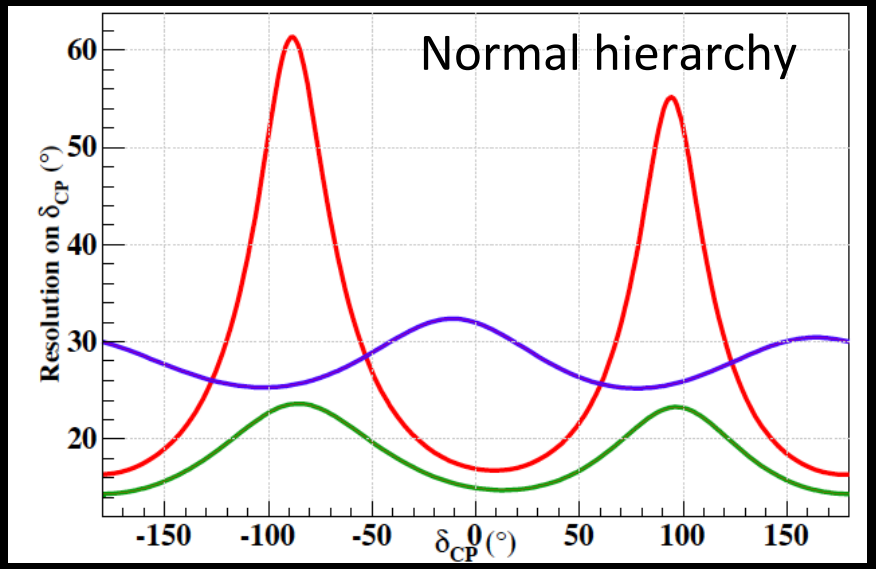
site of Cliffs Natural Resources

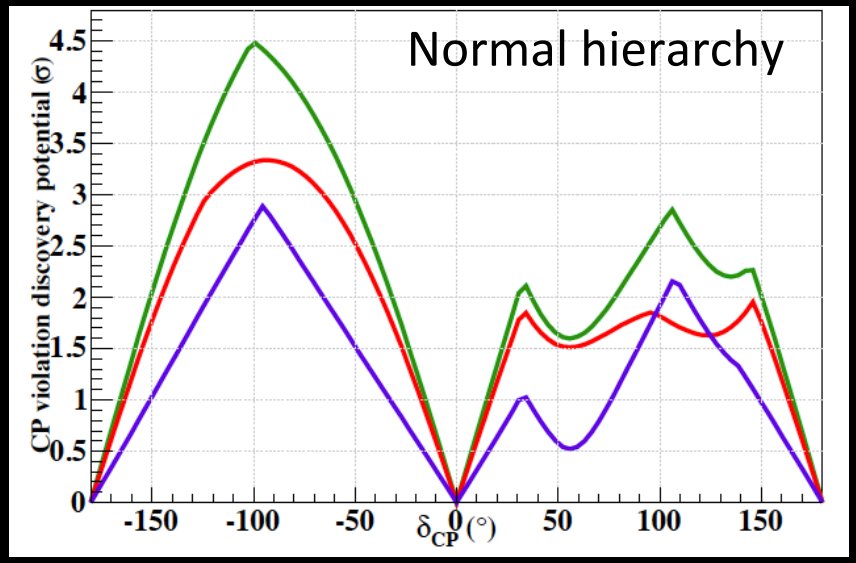




CHIPS 100kt – hierarchy exclusion



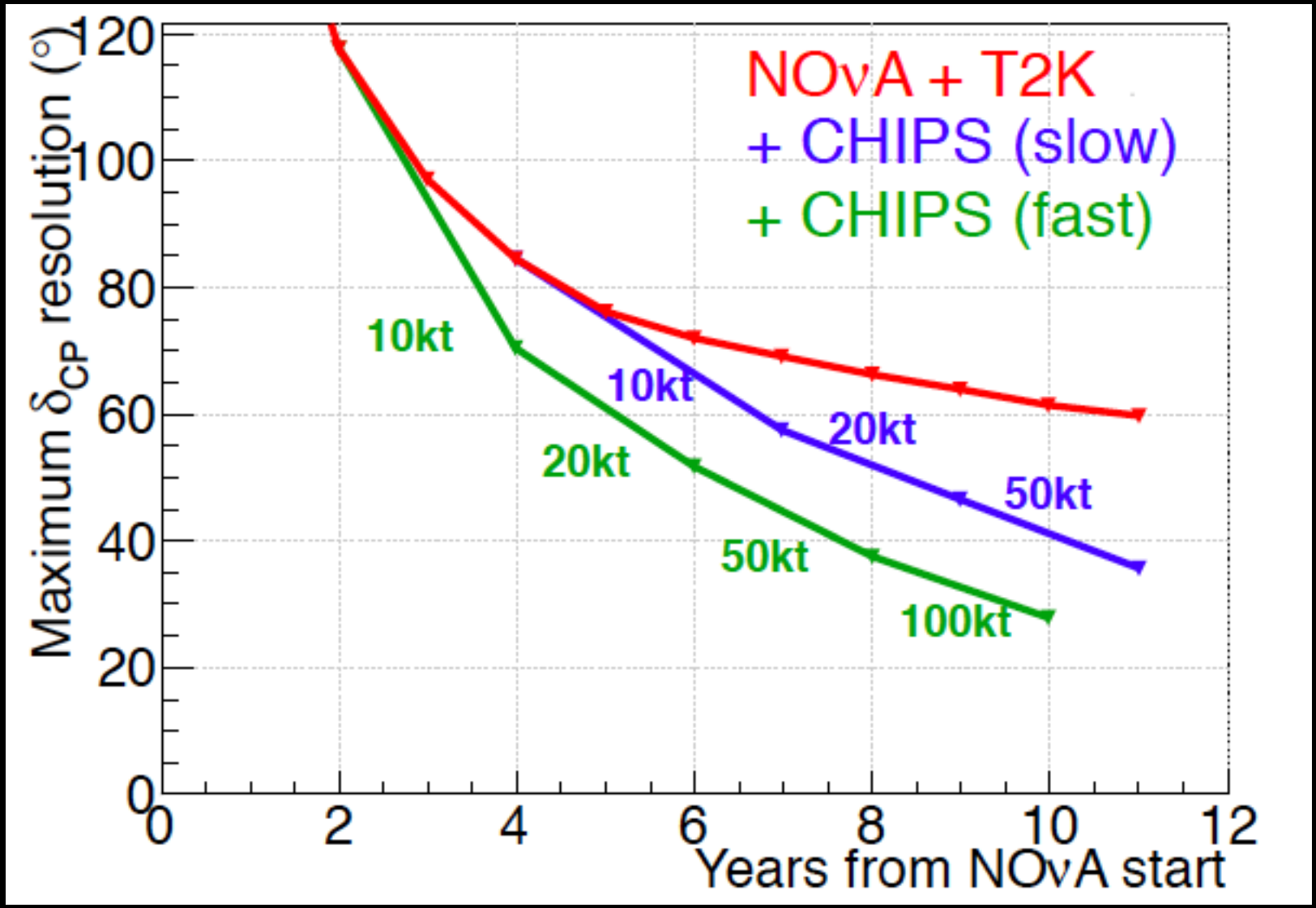




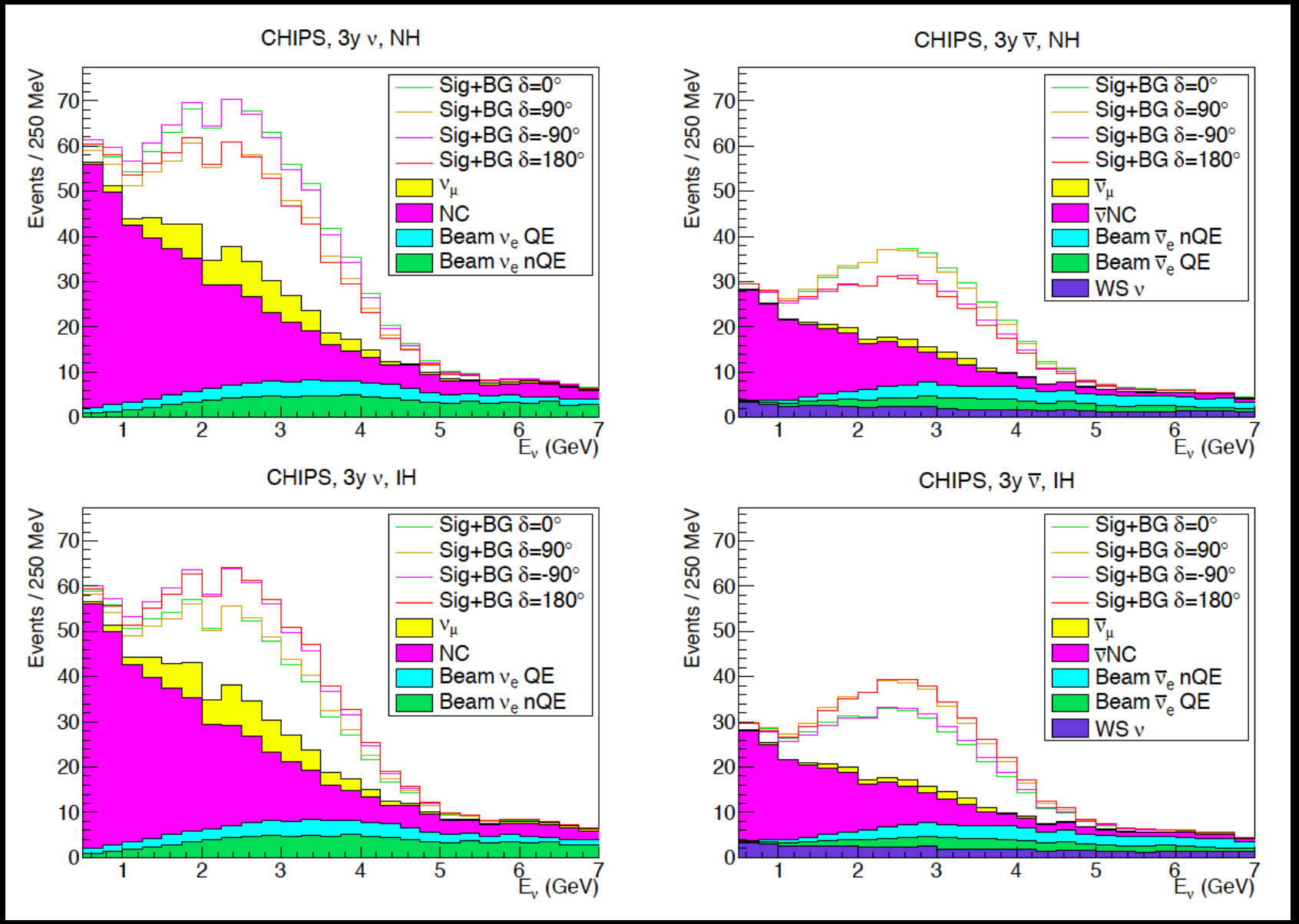
Using GLoBES for now …

NOvA (5y+5y) + T2K (8.8e21POT) + CHIPS (3y + 3y)
NOvA (5y+5y) + T2K (8.8e21POT)
CHIPS (3y + 3y)

CHIPS – more realistic



CHIPS: 3y of neutrinos and antineutrinos

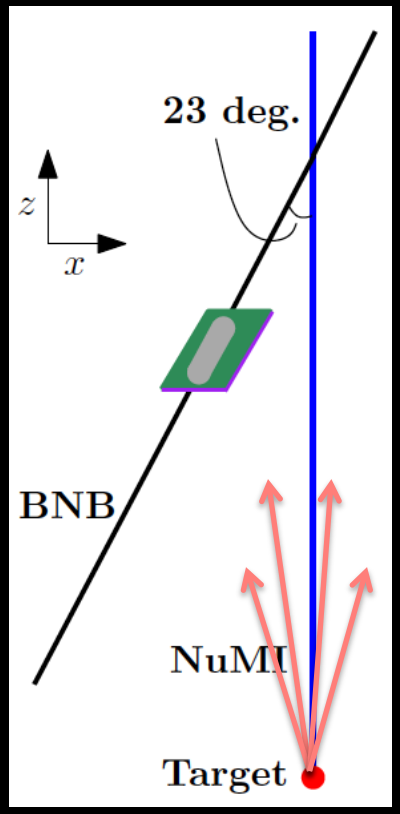


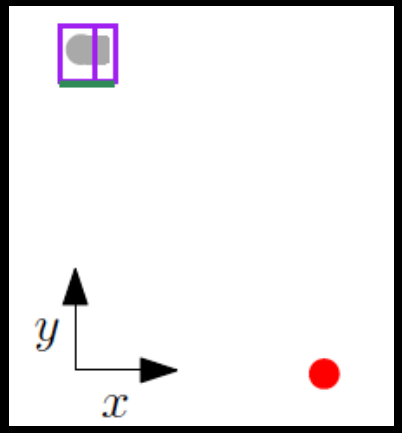
CHIPS in the LBNE beam

- Artificial lakes near LBNE axis in South Dakota

A phase or augmentation of the LBNE program.

NuMI land: MicroBooNE





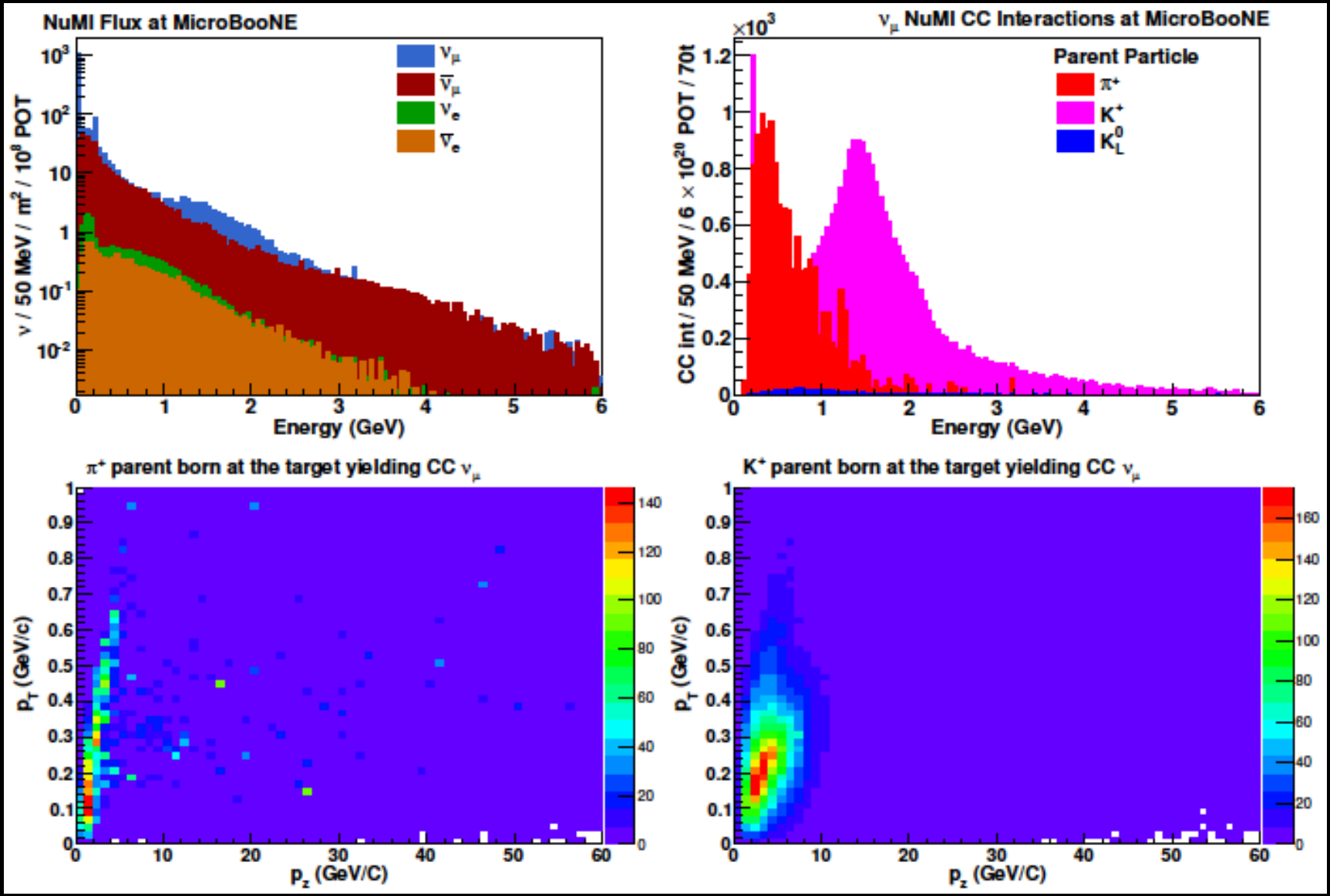
- MicroBooNE sees NuMI neutrinos at about 110 mrad
- This synergy was recognized earlier by MiniBooNE and MINOS: Phys. Rev. Lett. 102, 211801 (2009): *First Measurement of ν_μ and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam*
- High intensity NuMI will allow to collect competitive statistics

Events	BNB	NuMI
Total	145k	60k
ν_μ CCQE	68k	25k
NC π^0	8k	3k
ν_e CCQE	0.4k	1.2k

Both normalized to 6e20 POT

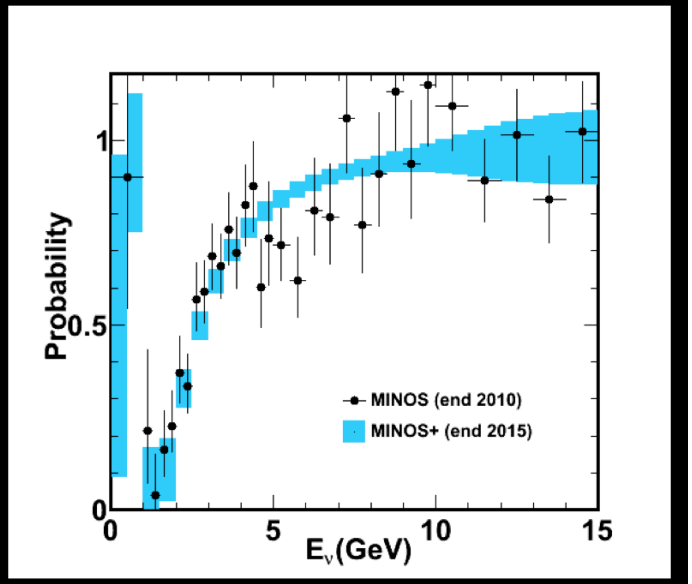
- A powerful tool for additional physics, control and check of systematics, flux constraints …
- Work is started on this recently

NuMI neutrinos in MicroBooNE



NuMI land: NuMI-X

- Facts:
  - ✓ 5 detectors (on- , off- , and off-off- axis) in one beam line
  - ✓ Better knowledge and improved simulations of flux is essential for future 'precision' neutrino experiments
  - ✓ Flux modeling undermanned in all NuMI experiments



- "NuMI-X is a consortium comprising Fermilab neutrino experiments collaborating on the modeling of NuMI beam. Its goal is to develop and maintain the best knowledge about NuMI neutrino fluxes relevant to all NuMI experiments. "
- The consortium includes
  - ✓ **MINOS, MINOS+, MINERvA, ArgoNeuT**
  - ✓ **NOvA,, MicroBooNE**.
- "Collaborating experiments agree to unlimited use of data, code, notes, and documents released to NuMI-X and essential for its mission. "
- Improved hadron production data, including exposures of NuMI target replicas, is anticipated through the US NA61 effort
- Tools and methods developed by NuMI-X will not only improve the NuMI program but will be directly applicable to LBNE and other beams

Summary and outlook

- NuMI (soon) at 700 kW will be the most powerful accelerator neutrino beam until the new LBNE beam is built circa 2023
- To maximize its physics reach beyond NOvA, new ideas are put forth for further exploiting, extending, expanding of the NuMI program
- Two main thrusts, besides building more NOvA, are
  - ✓ Liquid Argon TPC (RADAR)
  - ✓ Water Cherenkov Detector (CHIPS)
- These would "fill the gap" and be a natural canvas to advance
  - ✓ Physics
  - ✓ Technology (potential for substantial savings for LBNE)
  - ✓ Training and expertise buildup of younger generation
  - ✓ Engage international partners
- Seems like a win-win-win-win situation

BACKUP SLIDES

LOI's

CHerenkov detectors In mine PitS (CHIPS)
Letter of Intent to FNAL

P. Adamson[3], S. V. Cao[12], J. A. B. Coelho[13], G. S. Davies[4], J. J. Evans[6], P. Guzowski[6], A. Habig[8], J. Hartnell[11], A. Holin[5], J. Huang[12], A. Kreymer[3], M. Kordosky[14], K. Lang[12], M. L. Marshak[7], R. Mehdiyev[12], J. Meier[7], W. Miller[7], D. Naples[9], J. K. Nelson[14], R. J. Nichol[5], R. B. Patterson[1], G. Pawloski[7], A. Perch[5], M. Pfützner[5], M. Proga[12], A. Radovic[5], M. C. Sanchez[4], S. Schreiner[7], S. Söldner-Rembold[6], A. Sousa[2], J. Thomas[5], P. Vahle[14], C. Wendt[15], L. H. Whitehead[5], and S. Wojcicki[10]

- arXiv:1307.5918 [physics.ins-det]

RADAR - R&D Argon Detector at Ash River
- Letter of Intent -

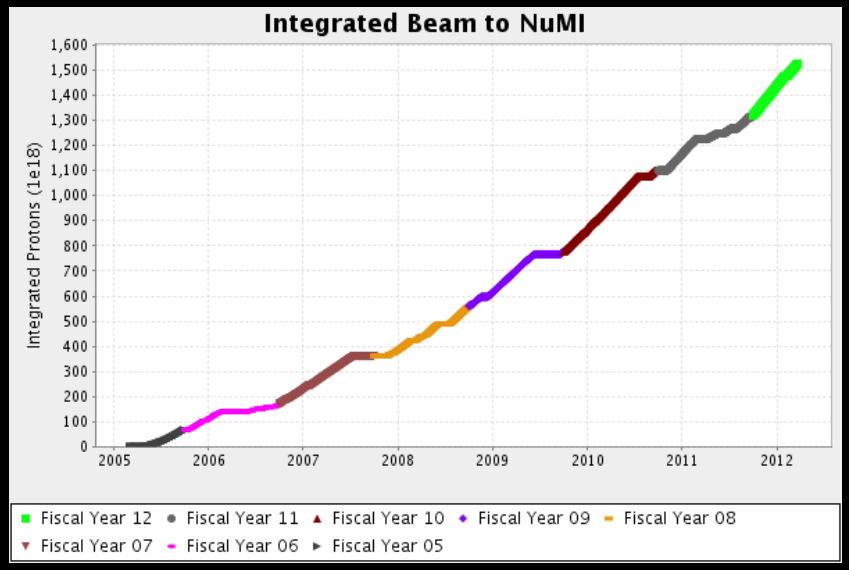
P. Adamson[1], J.J. Evans[2], P. Guzowski[2], A. Habig[3], A. Holin[4], J. Huang[5], M. Kordosky[6], A. E. Kreymer[1], K. Lang[5], M. Marshak[7], R. Mehdiyev[5], W. H. Miller[7], D. Naples[8], R.J. Nichol[4], R. B. Patterson[9], A. Sousa[10], J. Thomas[4], L. H. Whitehead[4]

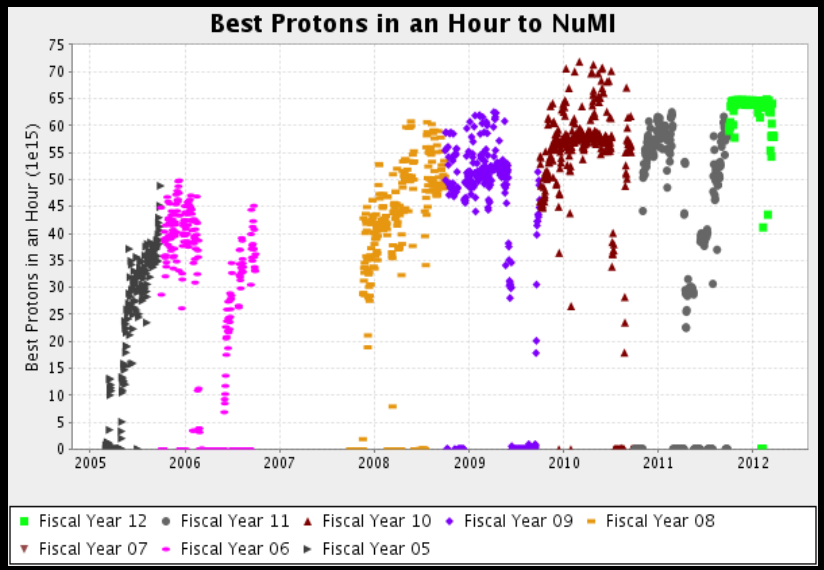
- arXiv:1307.6507 [physics.ins-det]

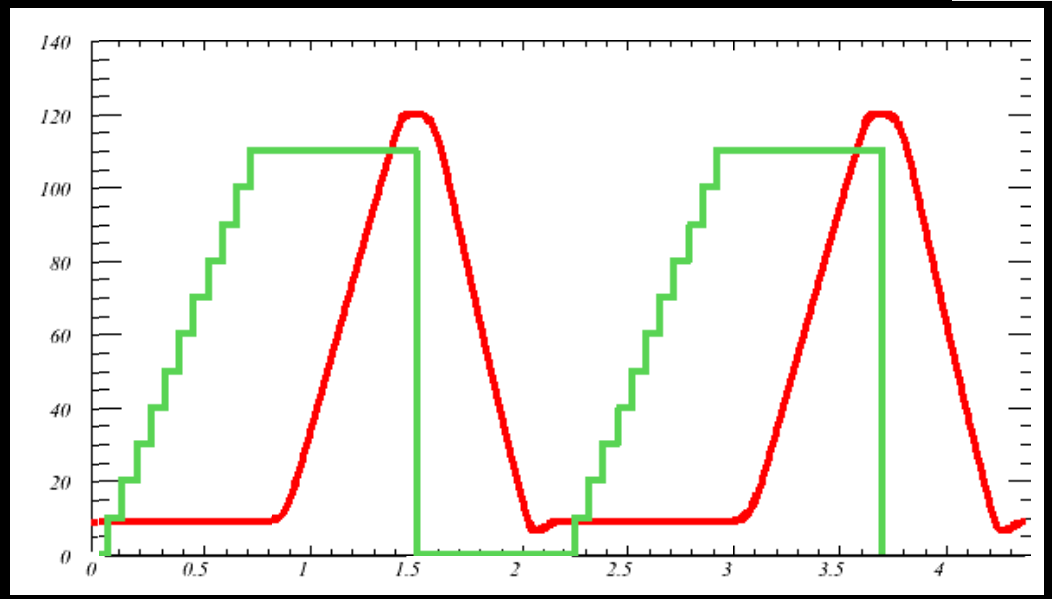
NuMI

	Present Operating Conditions (May 2007)	Proton Plan Multi-batch Slip-stacking in MI	NOνA Multi-batch Slip-stacking in Recycler	Conceptual SNuMI Accumulator Momentum Stacking	Conceptual Project X linear accelerator
8 GeV Intensity (p/Batch)	4.3 - 4.5x10^{12}	4.3x10^{12}	**4.3x10^{12}**	4.5x10^{12}	5.6x10^{13}
Number of 8 GeV Batches to NuMI	7	11	**12**	18	3
MI Cycle Time (sec)	2.4	2.2	**1.3**	1.3	1.4
MI Intensity (protons per pulse or ppp)	3.3x10^{13}	4.5x10^{13}	**4.9x10^{13}**	8.3x10^{13}	1.6x10^{14}
MI to NuMI (ppp)	2.45x10^{13}	3.7x10^{13}	**4.9x10^{13}**	8.3x10^{13}	1.6x10^{14}
NuMI Beam Power (kW)	192	320	**700**	1169	2314
Protons/year to NuMI	2x10^{20}	3x10^{20}	**6x10^{20}**	10x10^{20}	20x10^{20}
MI Protons/hour	4.95x10^{16}	7.3x10^{16}	**1.3x10^{17}**	2.2x10^{17}	1.0x10^{18}

NuMI







Move slip-stacking to recycler

✓ 11 batch -> 12 batch

Increase Main Injector ramp rate

✓ (204 GeV/s -> 240 GeV/s)

330 (380) -> 700kW with only ~10% increase in per-pulse intensity

CHIPS statistics

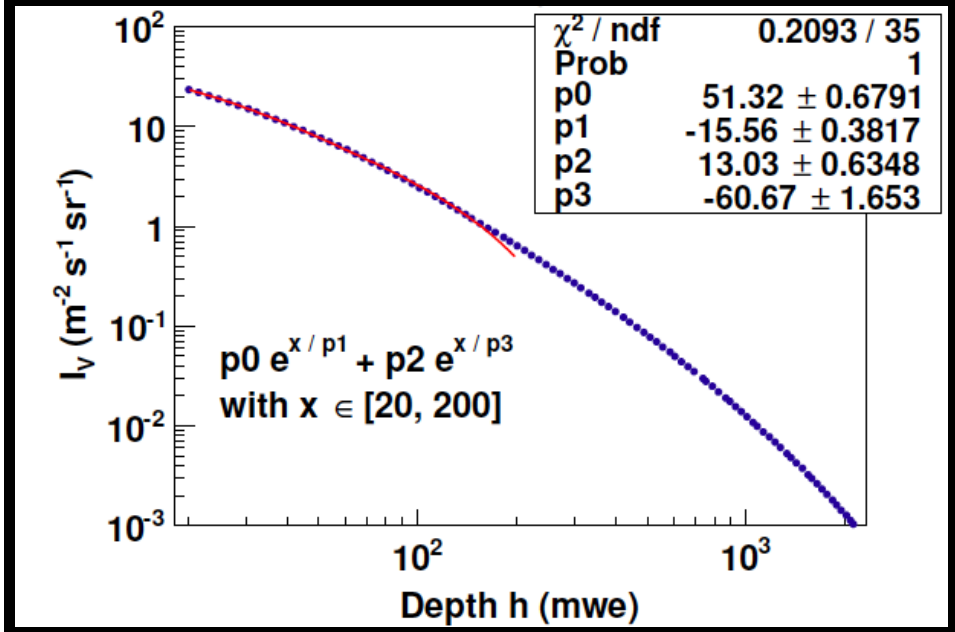
Event Type	ν Mode		$\overline{\nu}$ Mode	
	NH	IH	NH	IH
Appeared ν_e	341	186	199	154
ν_μ-CC	72	74	13	13
NC	401	401	175	175
Beam ν_e	162	163	100	99
Wrong Sign ν			54	54

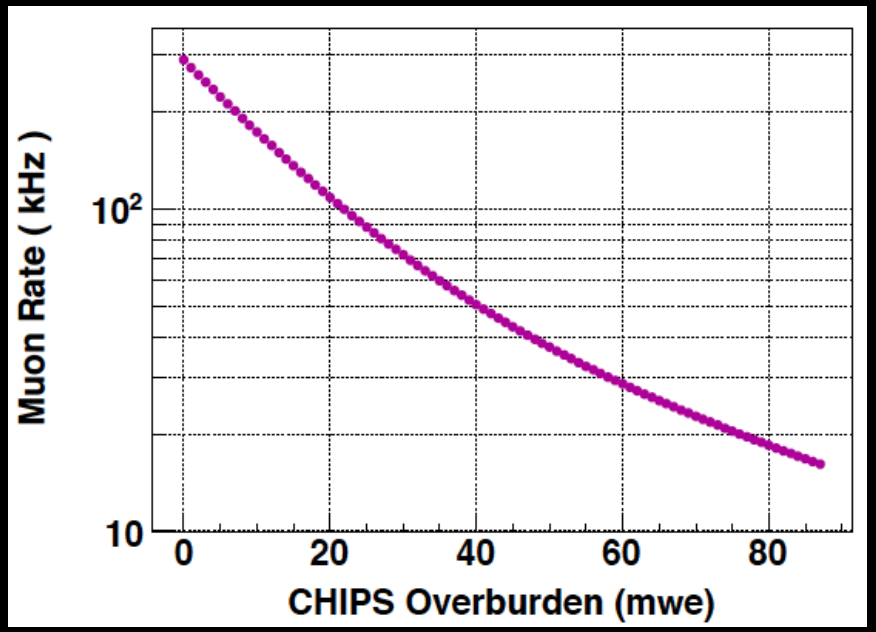
Number of selected events in 100 kton fiducial mass
CHIPS detector after 3 years in each mode,
for both the normal hierarchy (NH) and the inverted hierarchy (IH).

Parameter values used in simulations

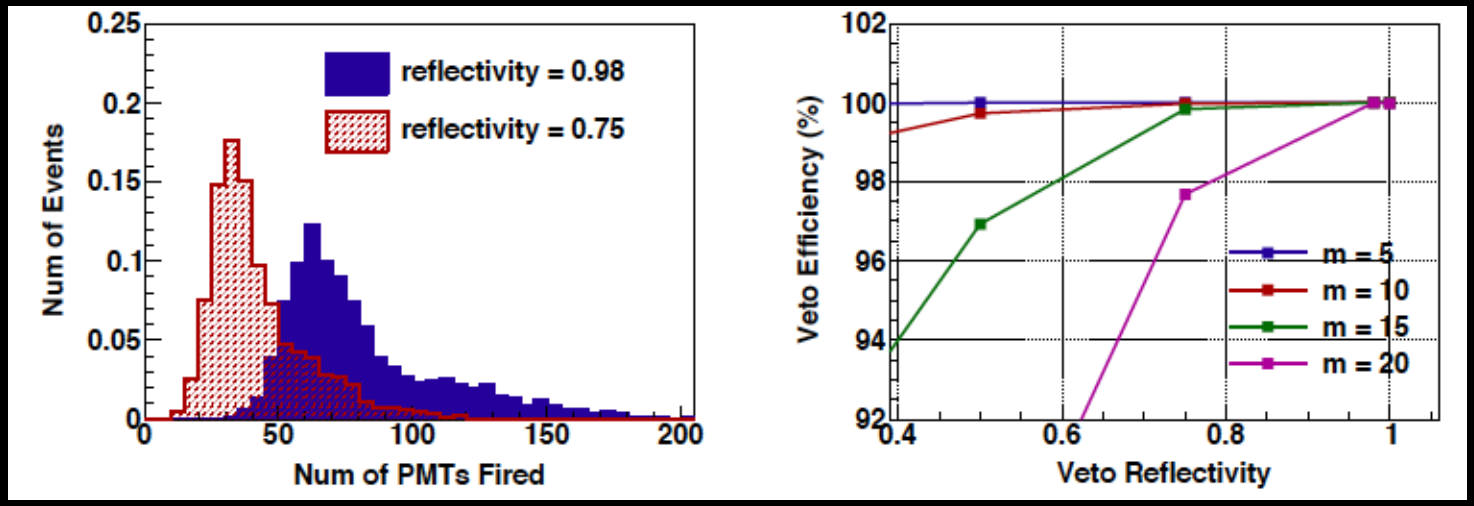
Parameter	Value
$\sin^2\theta_{12}$	0.312
$\sin^2 2\theta_{13}$	0.096
$\sin^2\theta_{23}$	0.39
θ_{23} octant	$\theta_{23} < \pi/4$
Δm^2_{21}	7.6×10^{-5} eV^2
Δm^2_{31} (NH)	2.45×10^{-3} eV^2
Δm^2_{31} (IH)	-2.31×10^{-3} eV^2

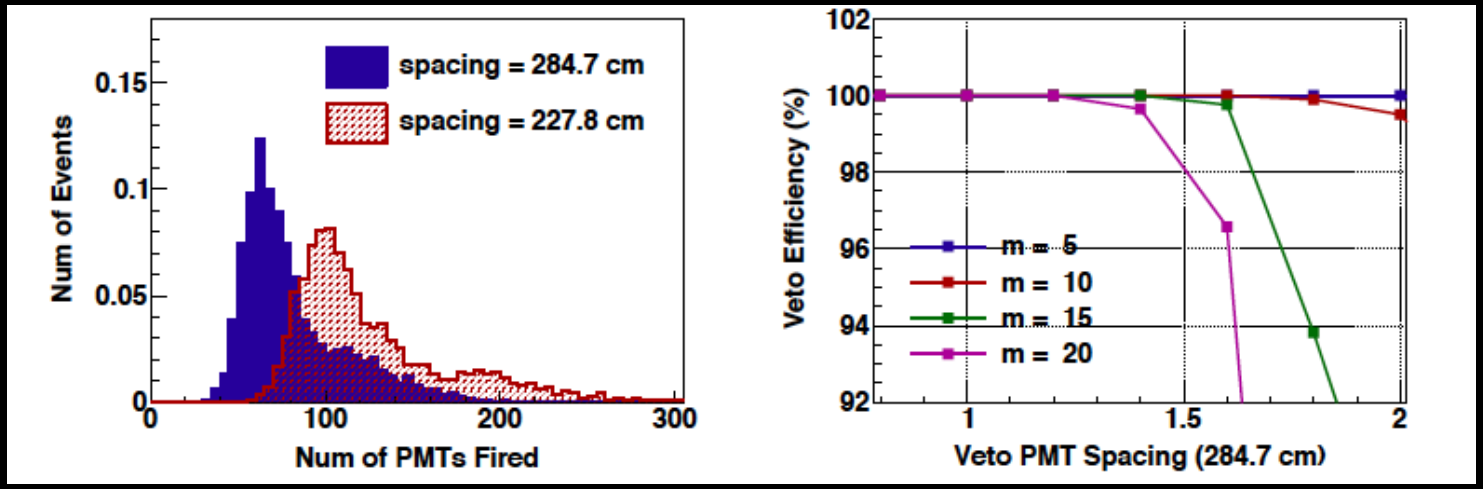
CR in shallow overburdens



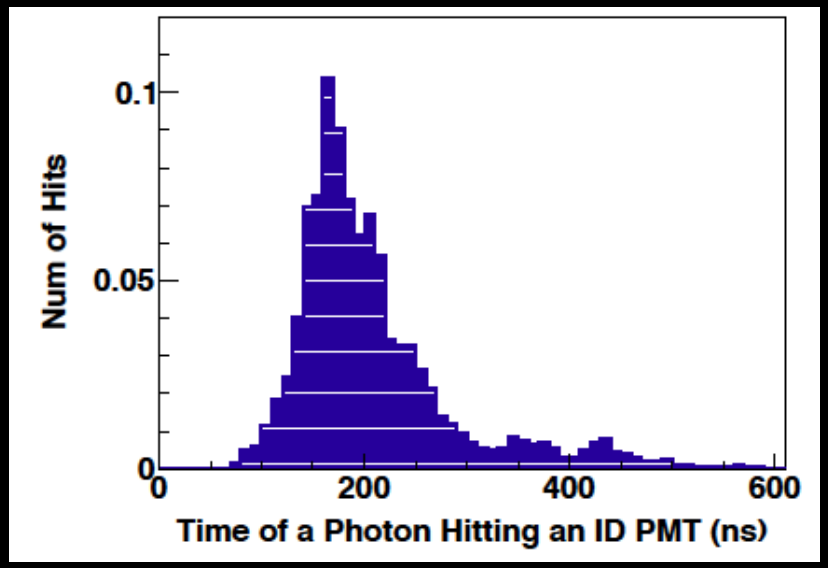


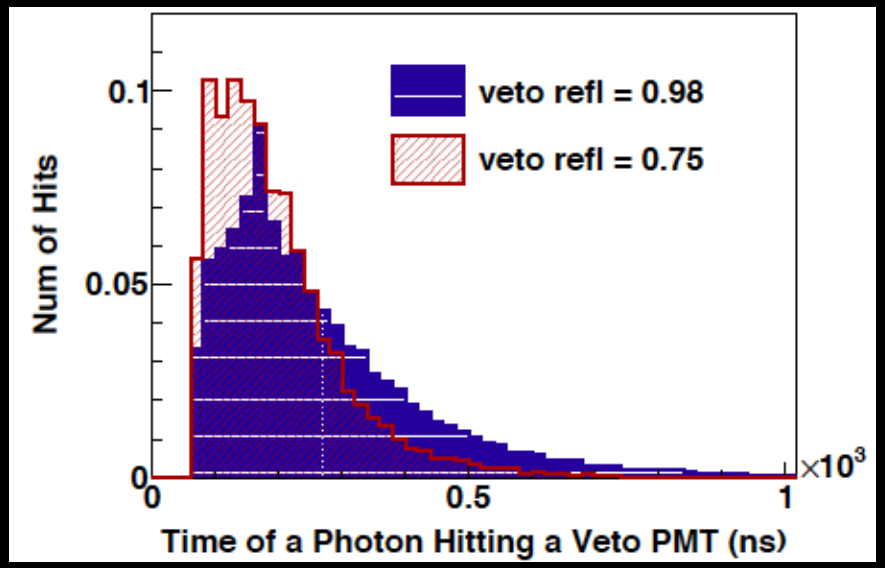
Veto for CHIPS



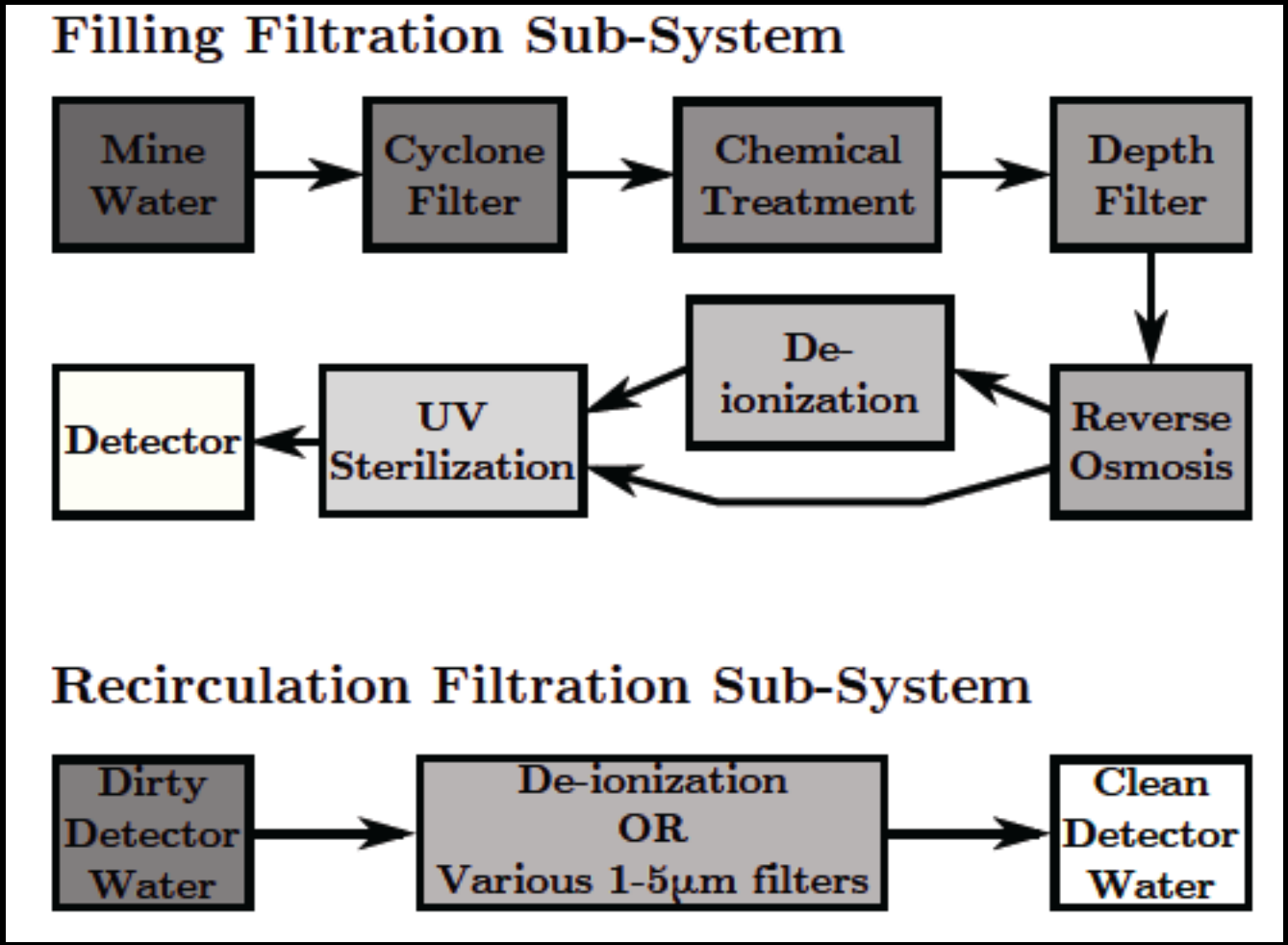


CHIPS event span

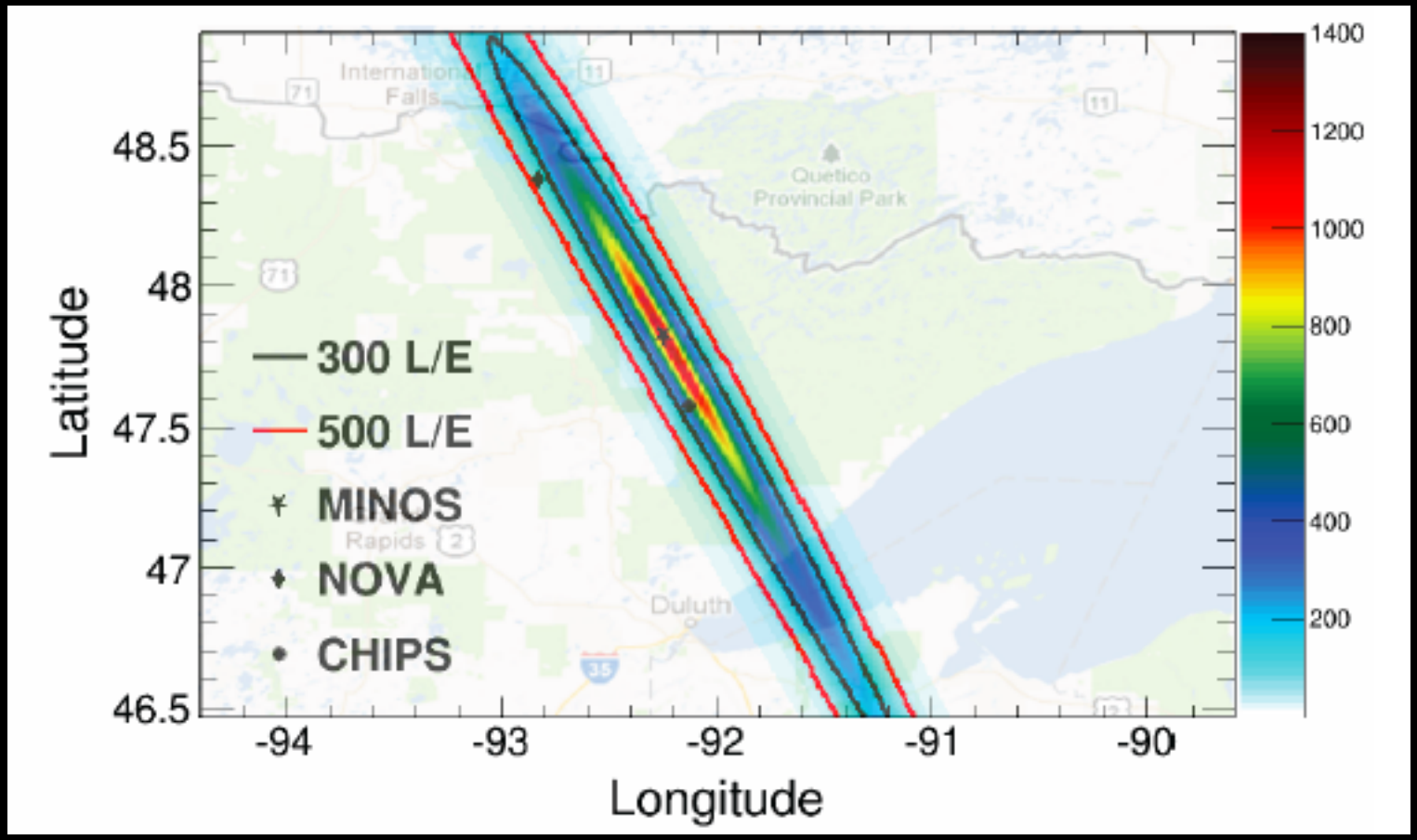




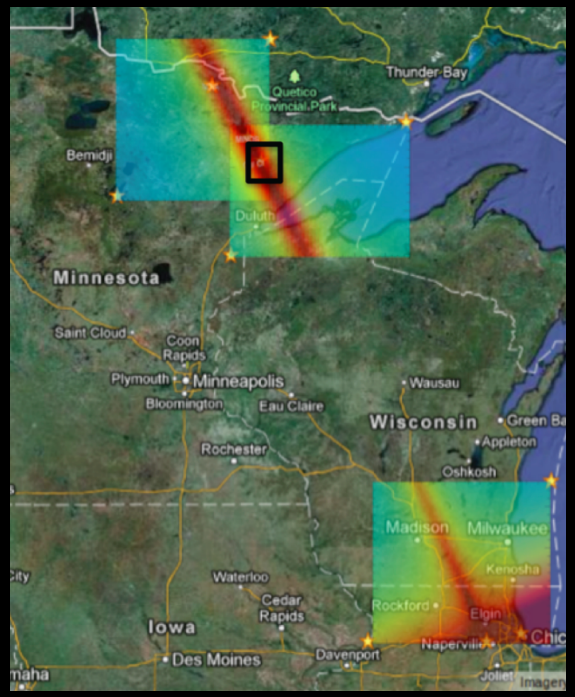
Water filtration

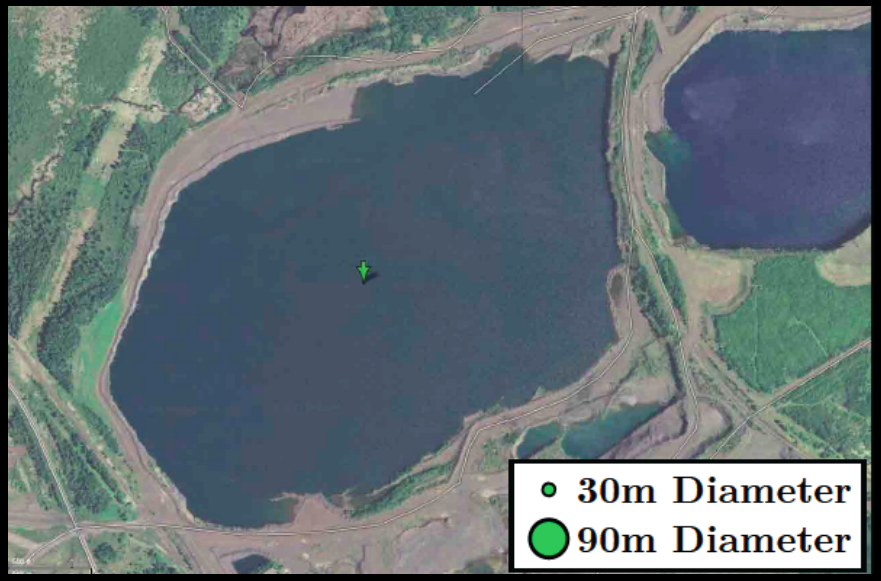


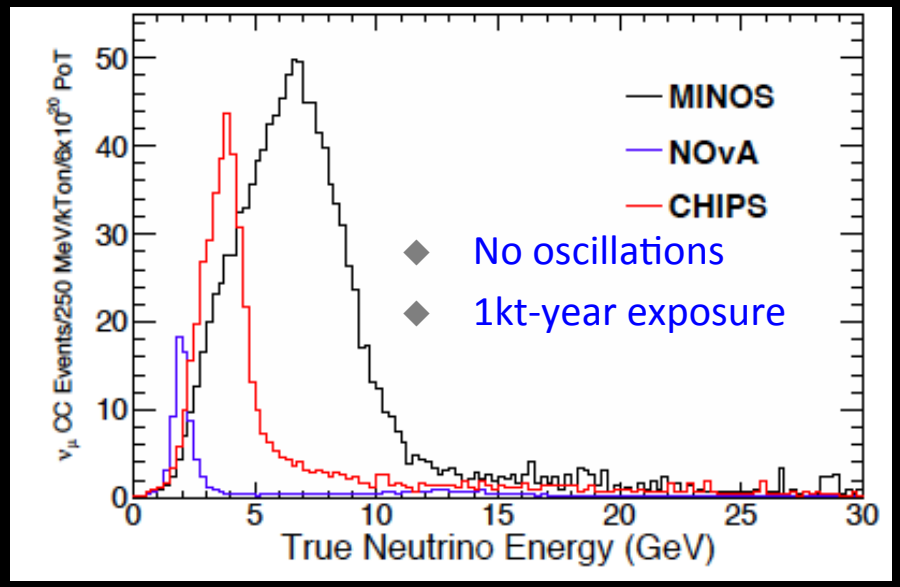
NuMI in Northern Minnesota



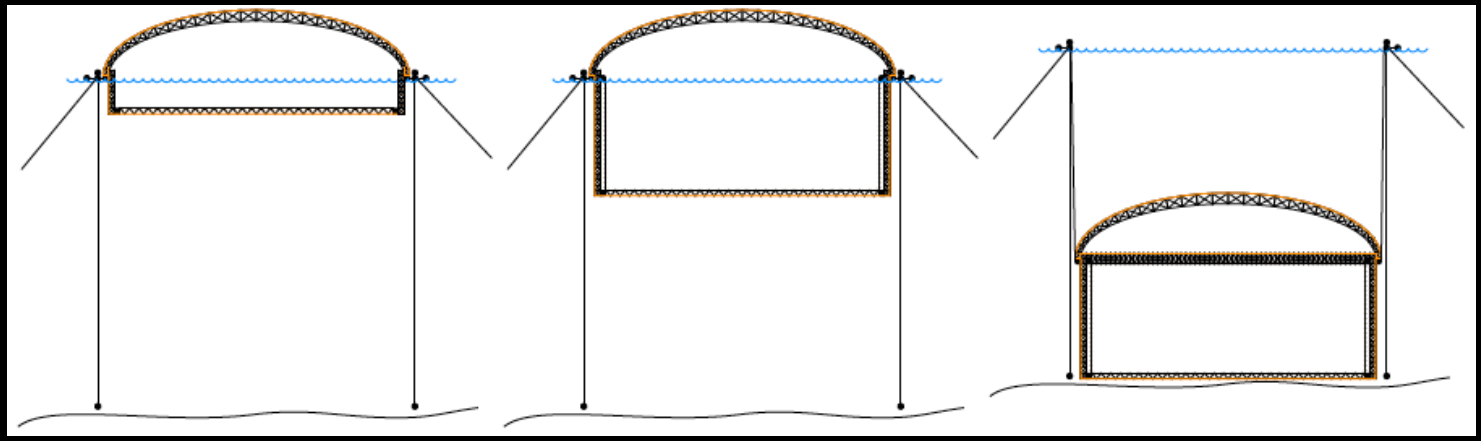
Wentworth Pit



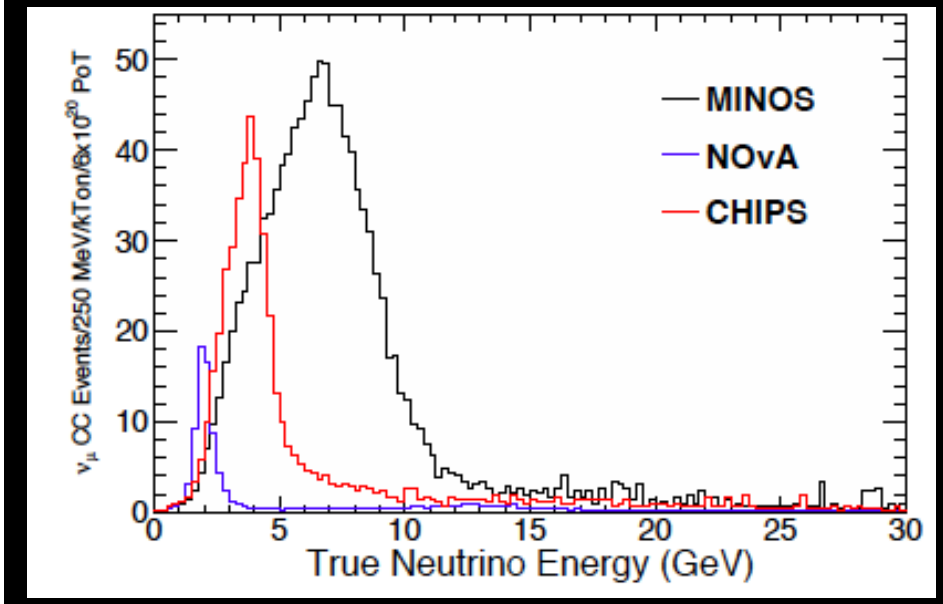


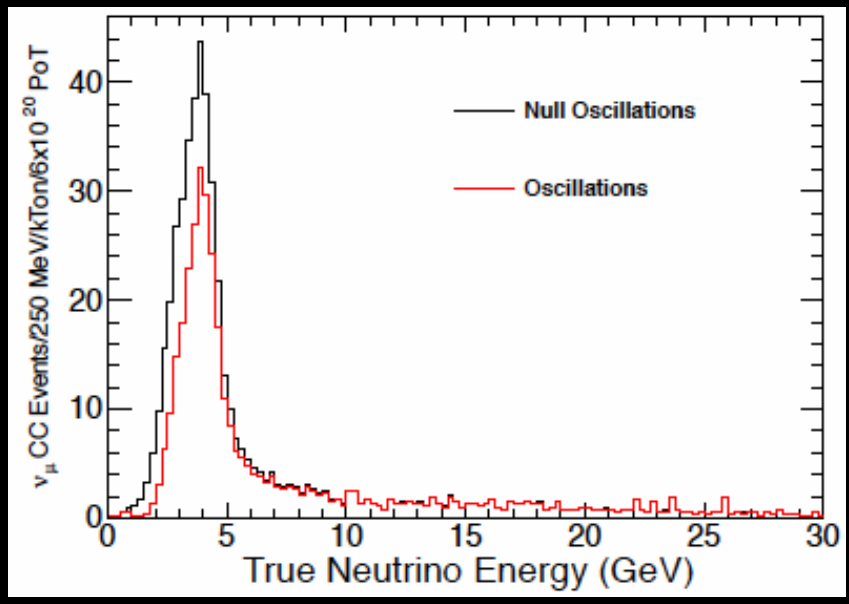


CHIPS concept



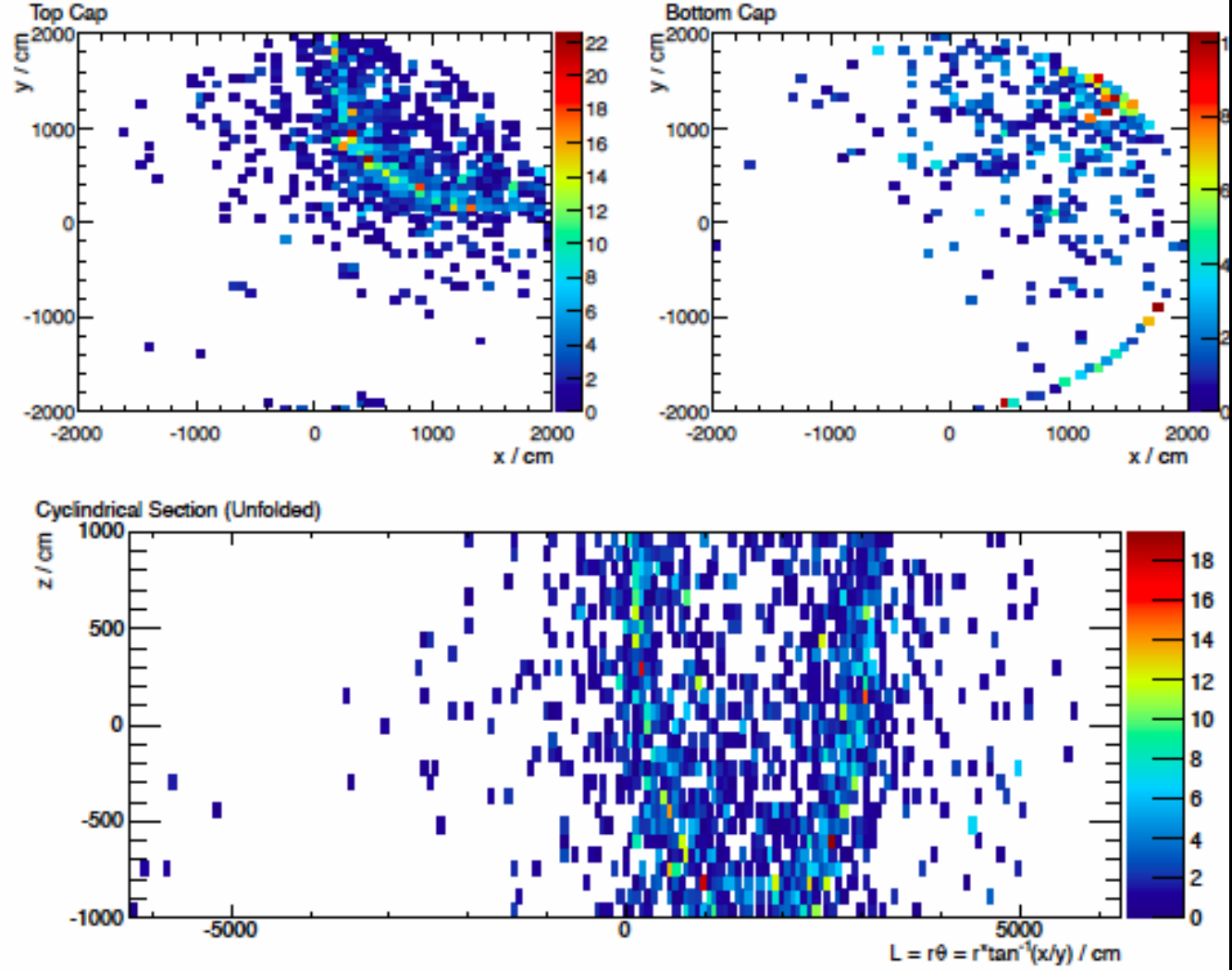
NuMI spectra



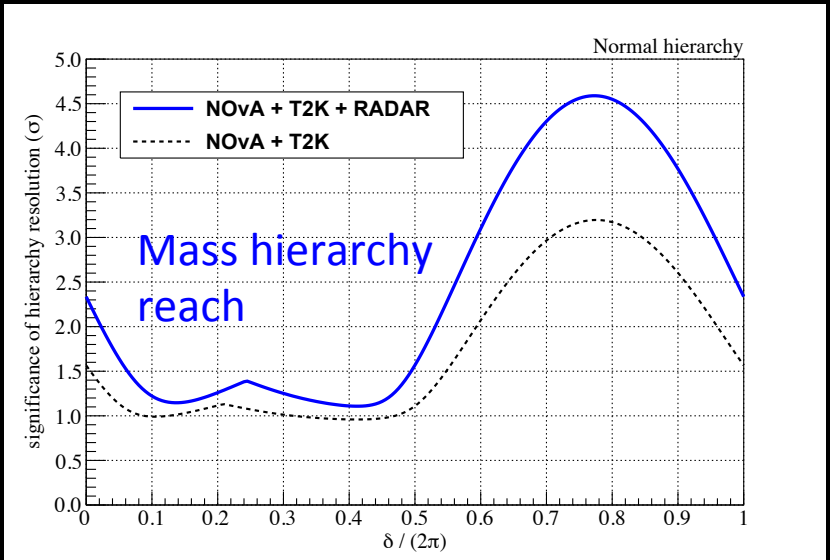


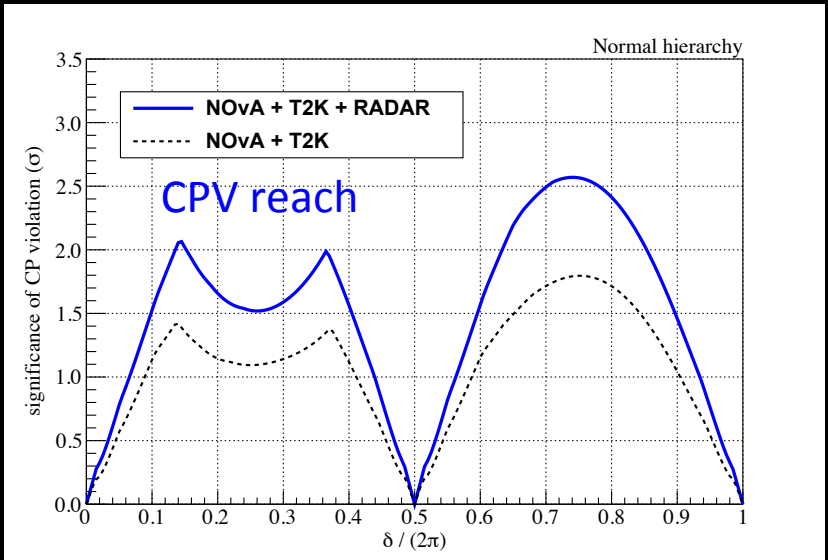
CHIPS event display: 1.6 GeV CC ν_e

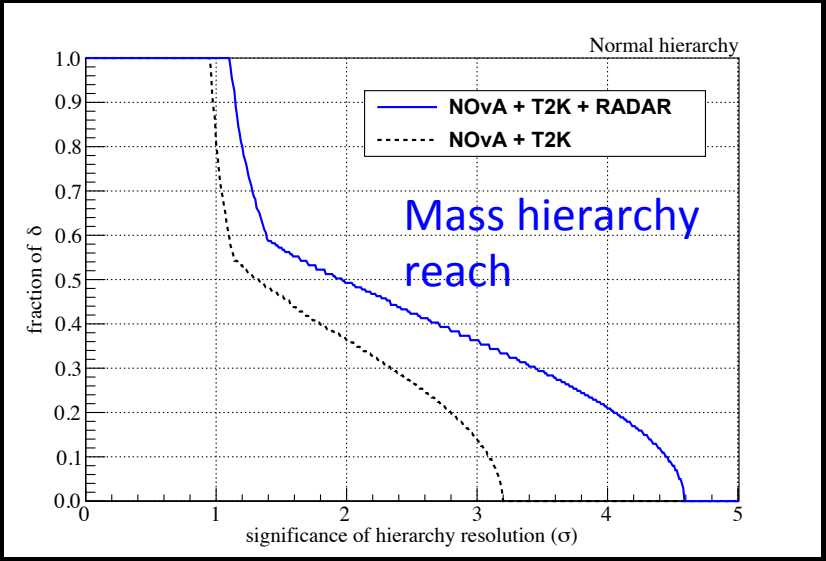
(in the middle of the detector)

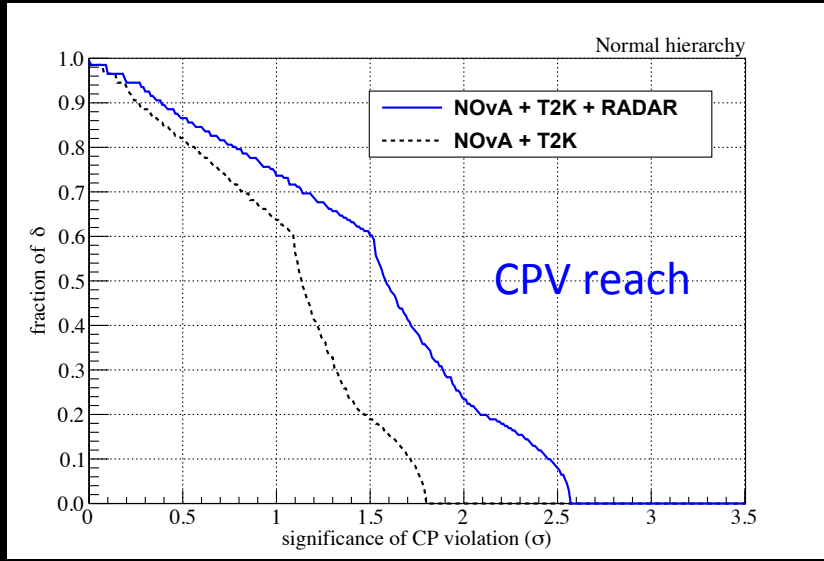


RADAR

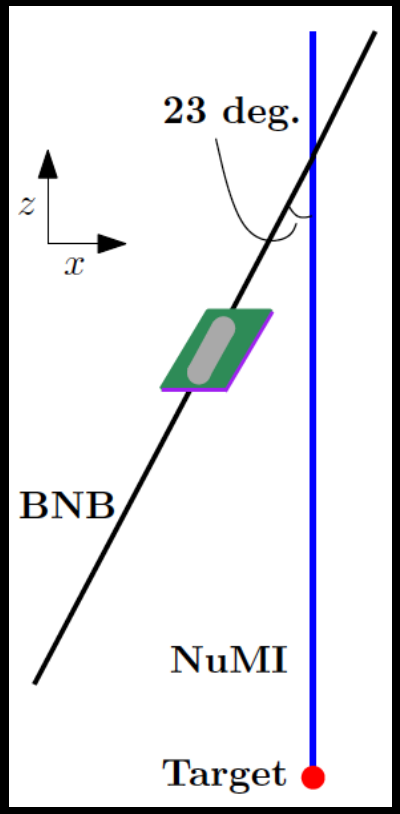

Normal hierarchy
NOvA + T2K + RADAR
NOvA + T2K
Mass hierarchy reach
significance of hierarchy resolution (σ)
δ / (2π)

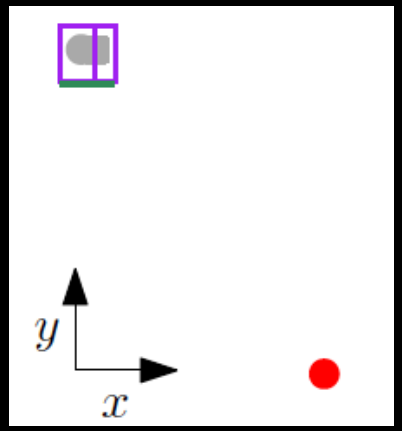

Normal hierarchy
NOvA + T2K + RADAR
NOvA + T2K
CPV reach
significance of CP violation (σ)
δ / (2π)

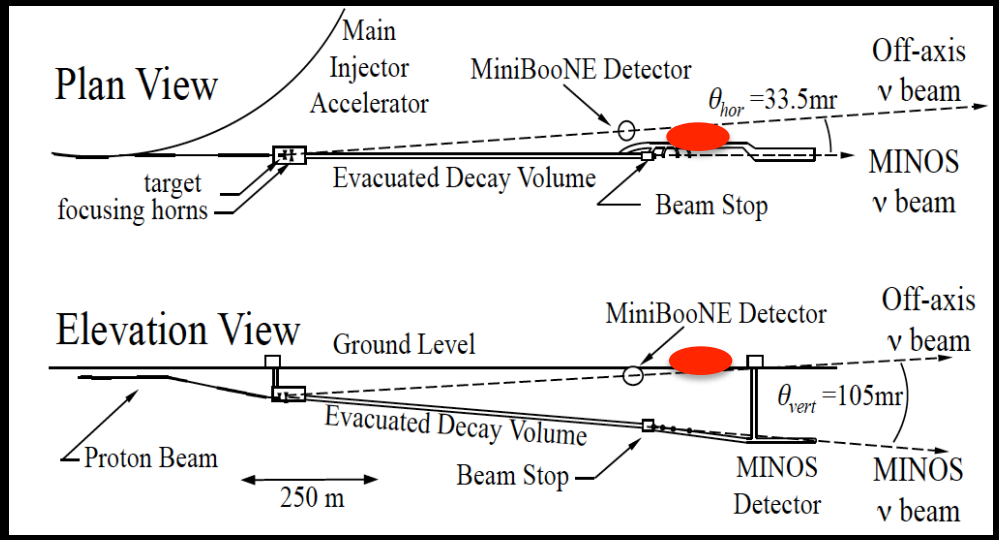

Normal hierarchy
NOvA + T2K + RADAR
NOvA + T2K
Mass hierarchy reach
fraction of δ
significance of hierarchy resolution (σ)


Normal hierarchy
NOvA + T2K + RADAR
NOvA + T2K
CPV reach
fraction of δ
significance of CP violation (σ)

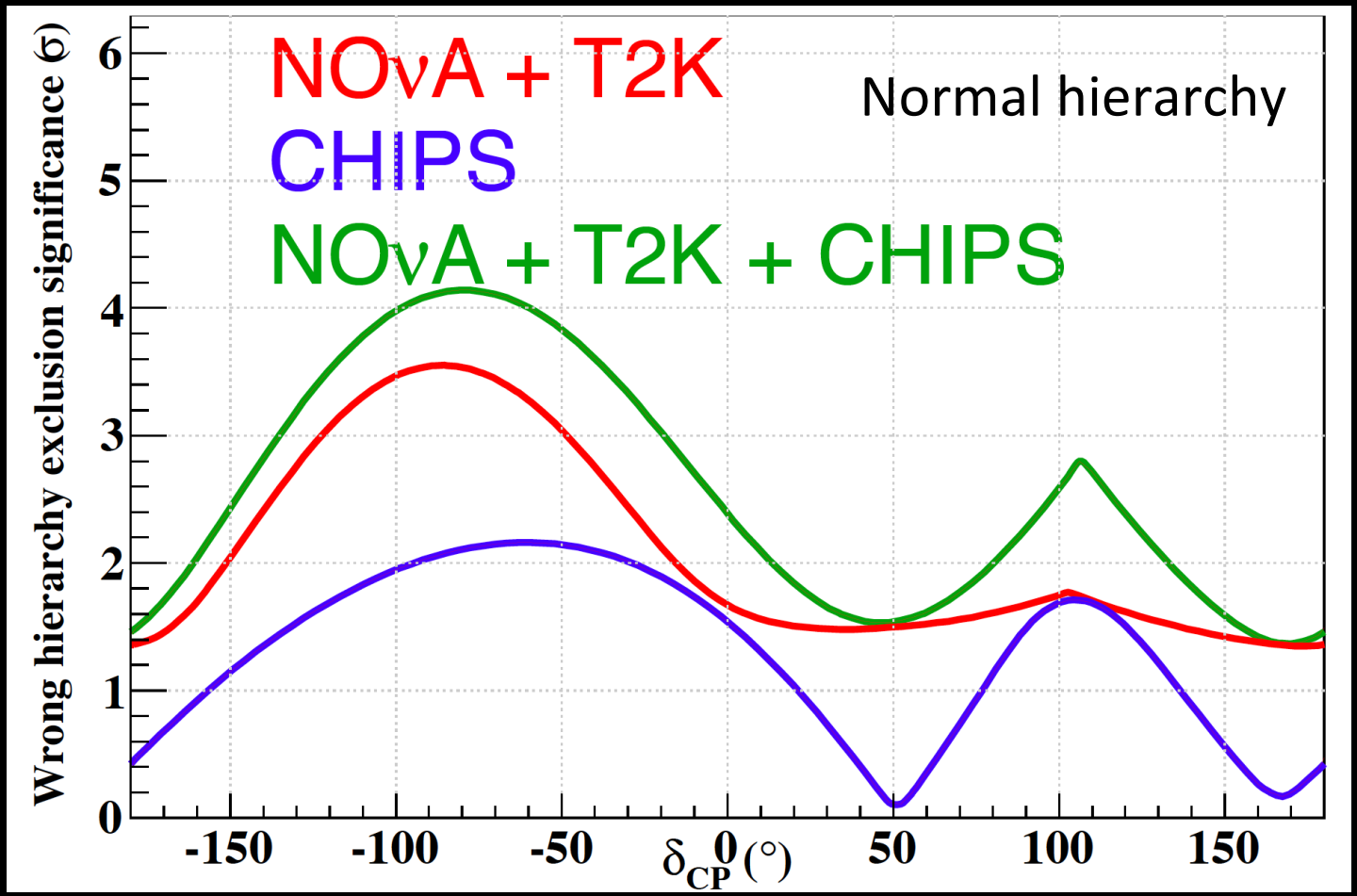
MicroBooNE and NuMI





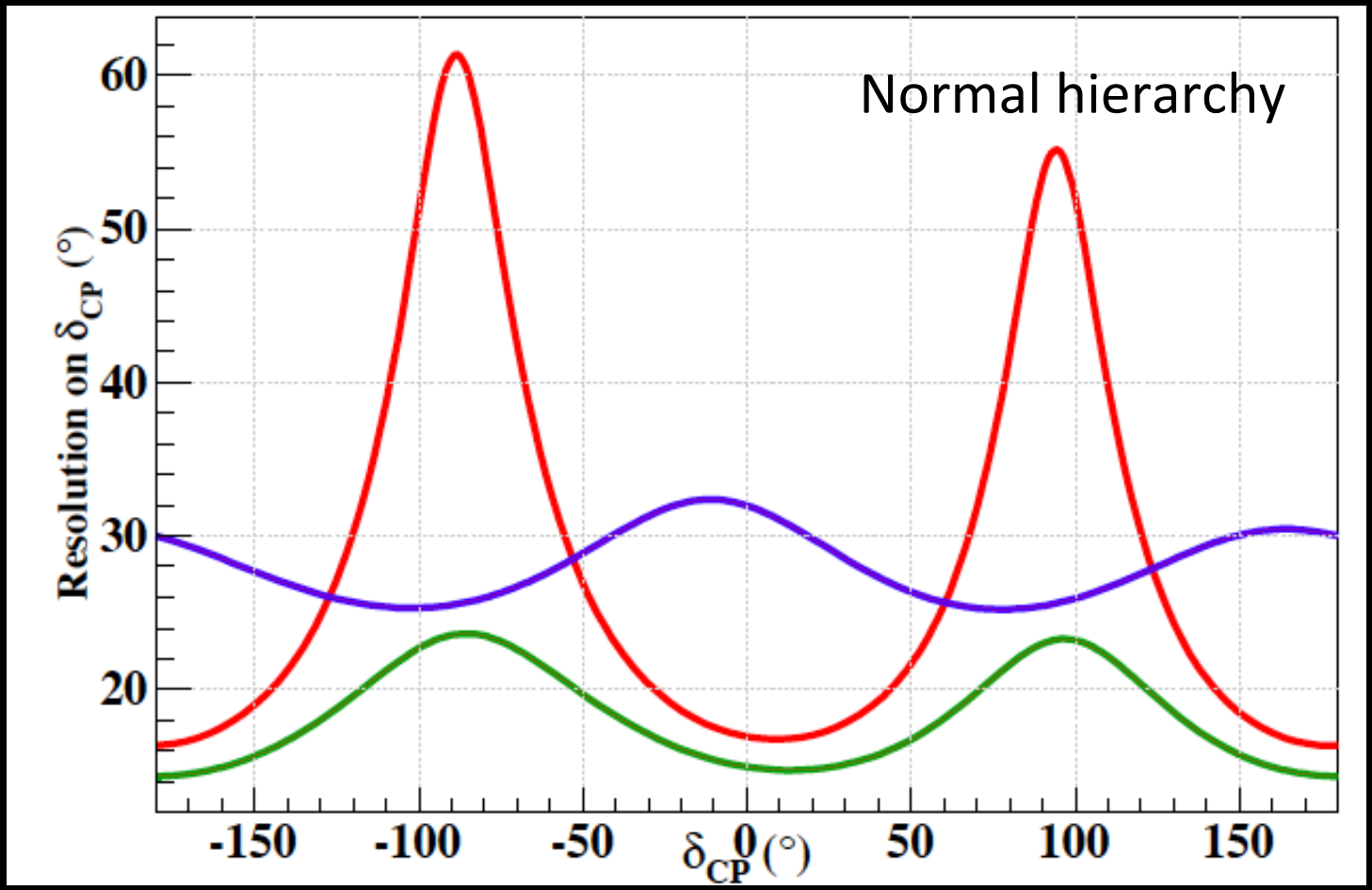


CHIPS 100kt – hierarchy exclusion



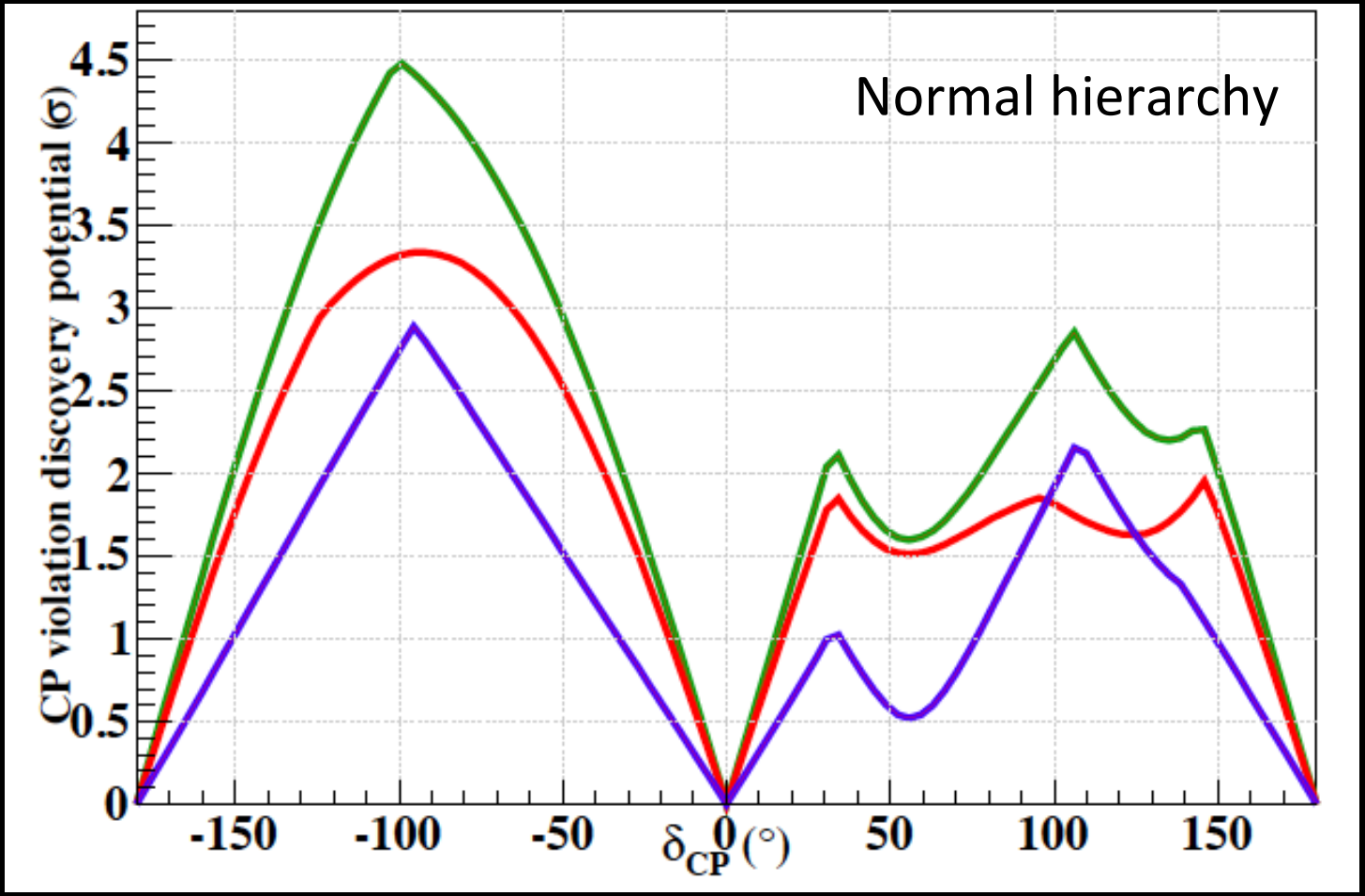
NOvA (5y+5y) + T2K (8.8e21POT) + CHIPS (3y + 3y)
NOvA (5y+5y) + T2K (8.8e21POT)
CHIPS (3y + 3y)

CHIPS 100kt – δ_{CP} resolution



NOvA (5y+5y) + T2K (8.8e21POT) + CHIPS (3y + 3y)
NOvA (5y+5y) + T2K (8.8e21POT)
CHIPS (3y + 3y)

CHIPS 100kt – CP violation discovery potential



NOvA (5y+5y) + T2K (8.8e21POT) + CHIPS (3y + 3y)
NOvA (5y+5y) + T2K (8.8e21POT)
CHIPS (3y + 3y)