Accelerator-based neutrinos
Lecture 3

Kendall Mahn

MICHIGAN STATE
UNIVERSITY

Outline

Last lecture:

- The first neutrino beam
- Conventional neutrino beams
- Experimental challenges of neutrino experiments

This lecture:

- Future neutrino beam proposals for search for δ_{CP} and sterile neutrinos
  - Superbeams: DUNE+LBNO, Hyper-Kamiokande and associated challenges
  - Neutrino factories
  - Isotope based (beta) beams

What is needed to measure δ_{CP}?

Compare ν_e appearance to $\overline{\nu}_e$ appearance to determine an asymmetry:

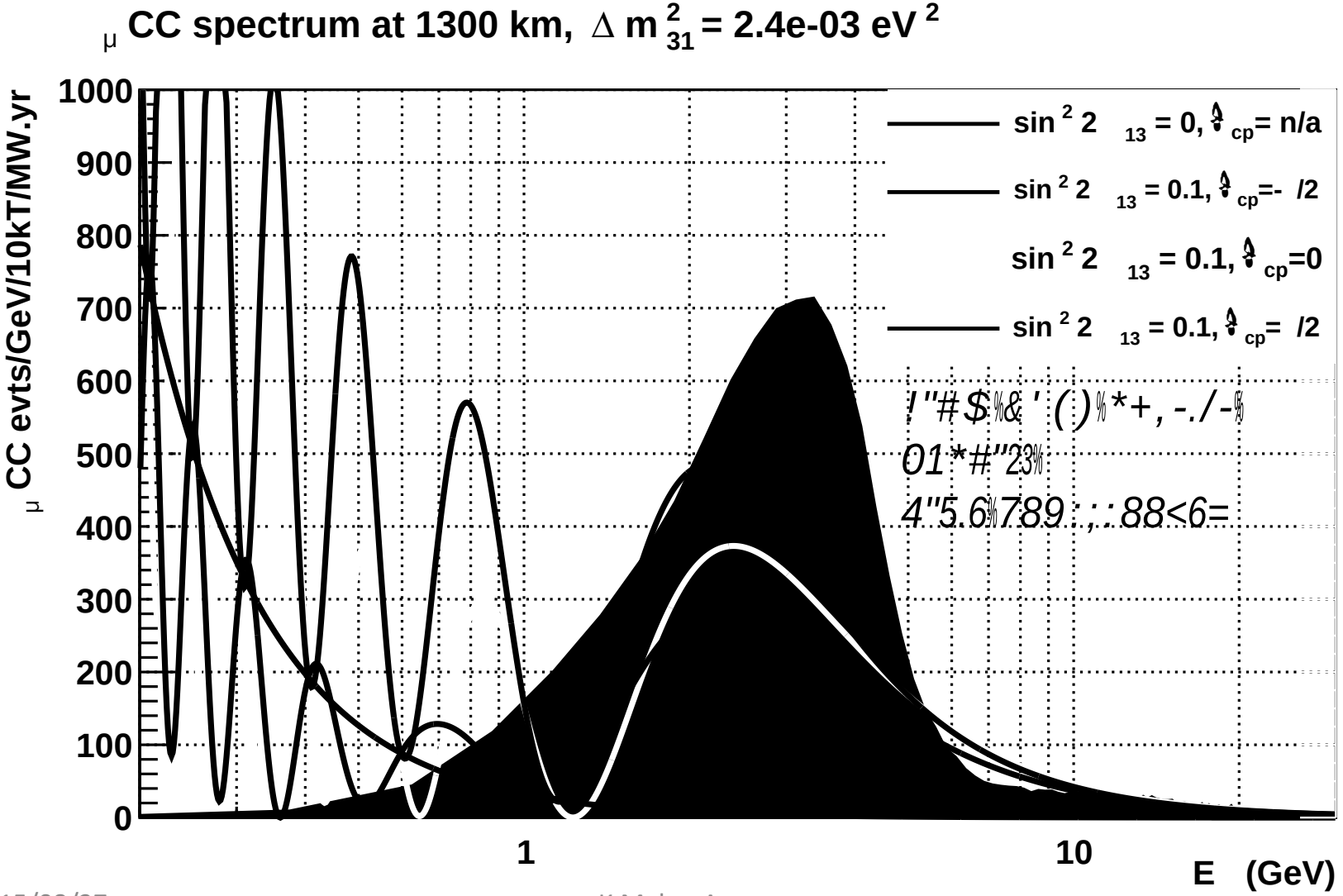
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

With θ_{13} "large", then A_{CP} is small (~20-30%), so a measurement of δ_{CP} will need systematic uncertainties of <5% or better

- T2K's current statistics: 28 events (ν_e appearance probability)
- Need more raw event rate, with a larger detector and/or intense beam

Deep Underground Neutrino Experiment (DUNE)

- Wide band (on-axis) beam can be used to see energy dependence of oscillation
- 1300km distance (Fermilab to South Dakota) for mass hierarchy, δ_{CP} physics
- LAr far detector technology
- Goal: 1% signal uncertainties / 5% background uncertainties



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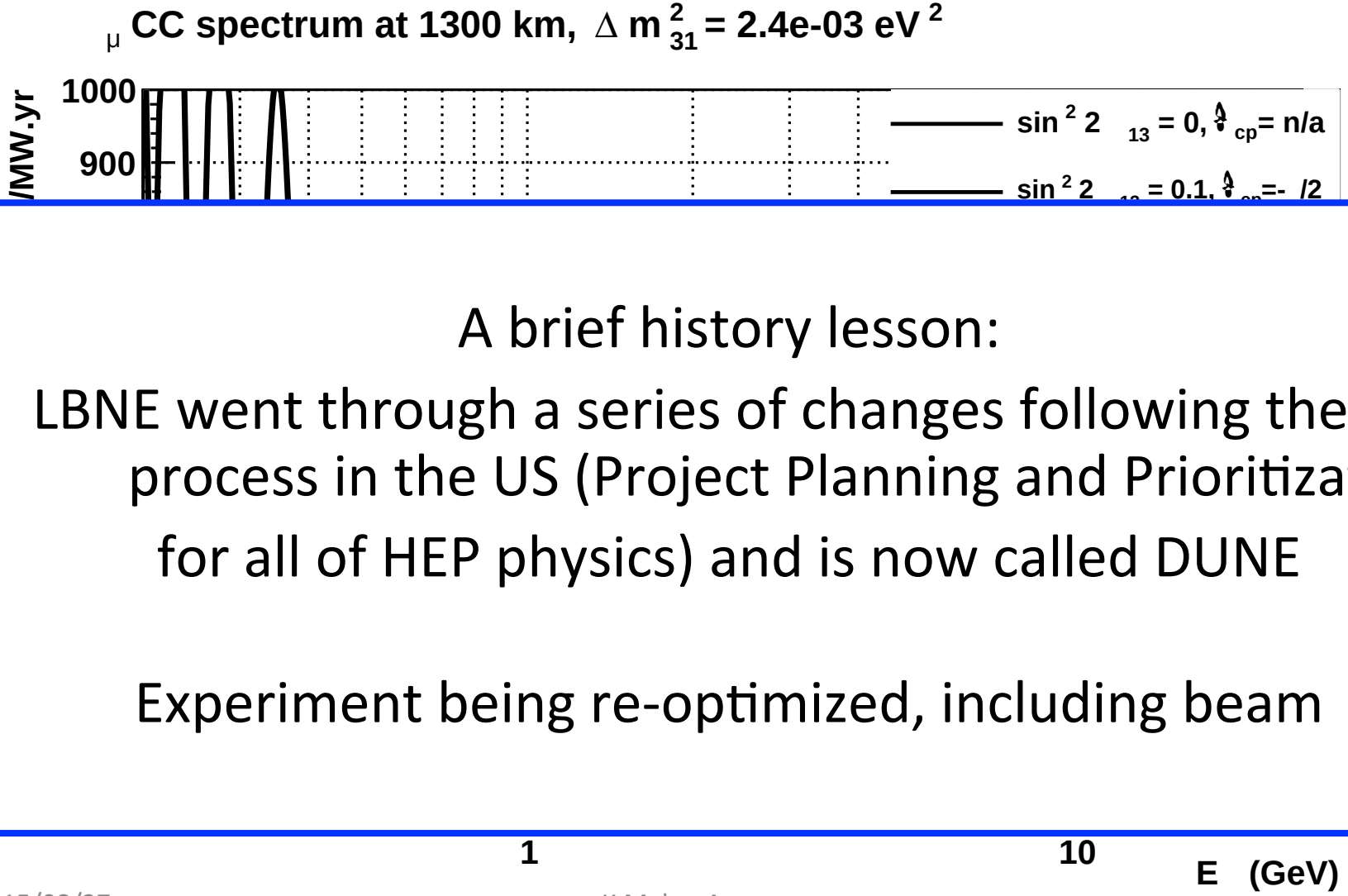


A brief history lesson:

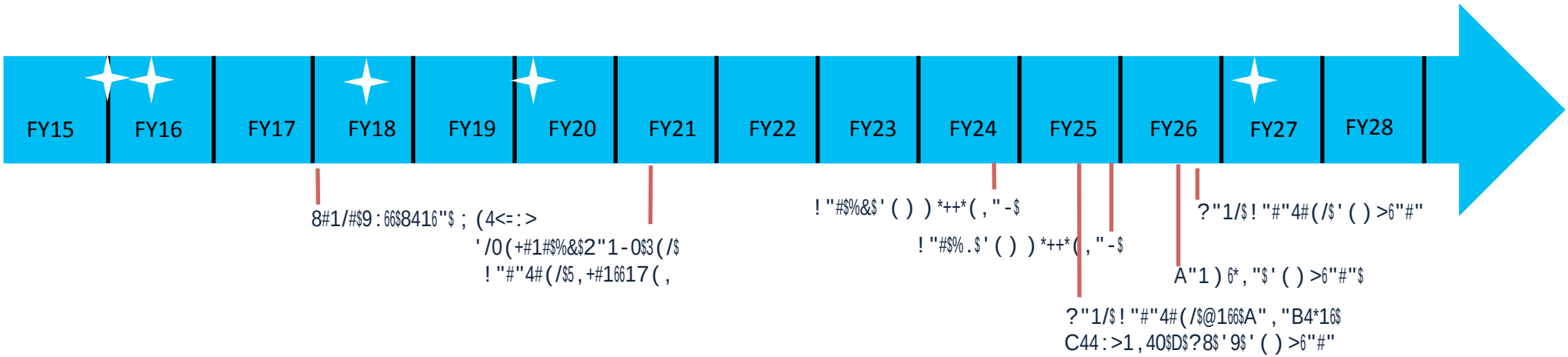
LBNE went through a series of changes following the P5 process in the US (Project Planning and Prioritization for all of HEP physics) and is now called DUNE

Experiment being re-optimized, including beam

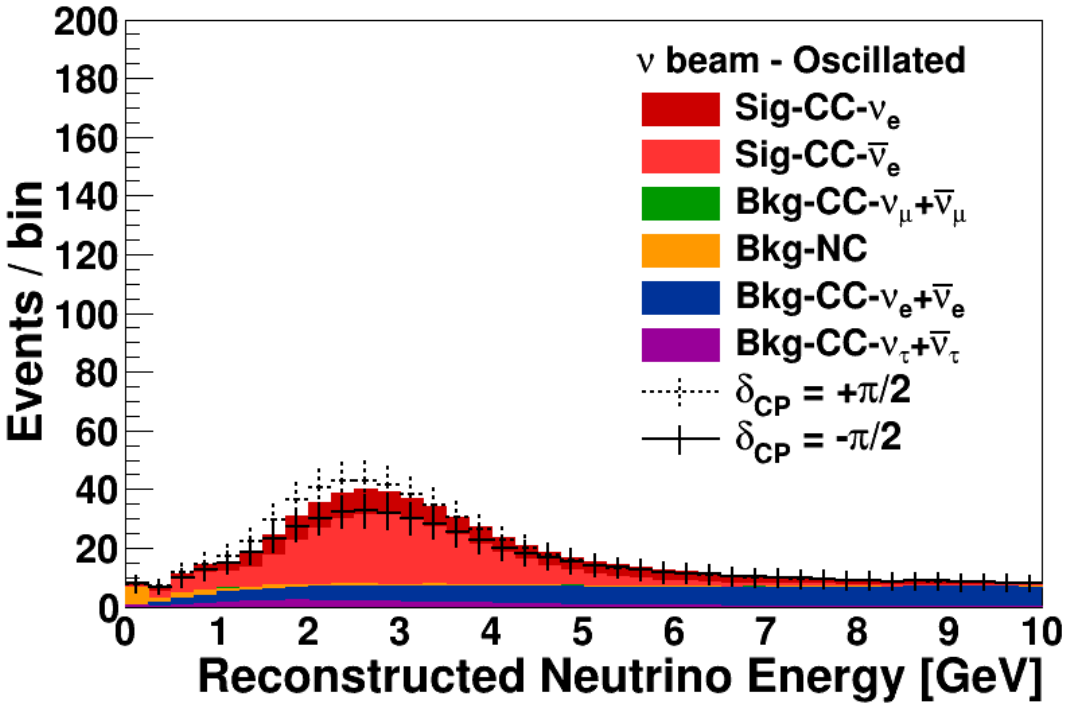
DUNE timeline

Far detector planned as 4 modules (statistics, statistics, statistics…)

- Beamline, near detectors completed in 2026
- 60 – 70 kt.MW.year reach 3σ CPV sensitivity (best case)
- 20 – 30 kt.MW.year reach 5σ MH sensitivity (best case)



DUNE event rates

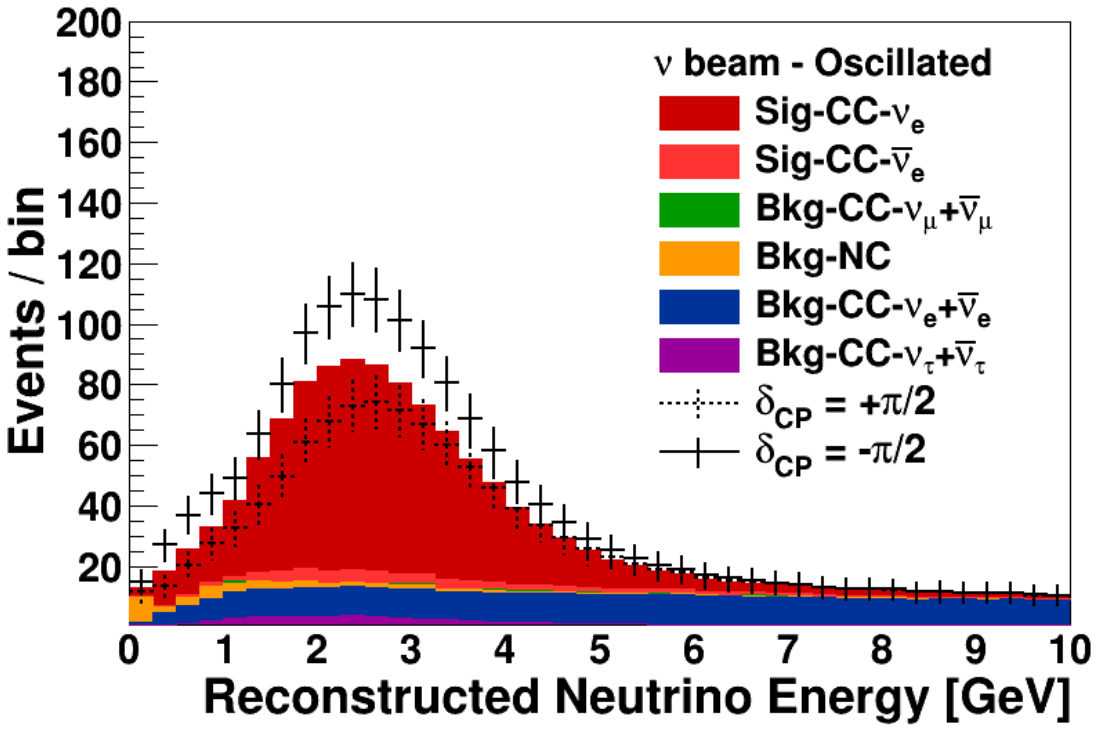


Top plot: neutrino beam operation, selected CC ν_e candidates after oscillation

Bottom plot: antineutrino beam operation, selected CC $\bar{\nu}_e$ candidates

Note the opposite effect of δ_{CP} on the two samples

DUNE event rates



Top plot: neutrino beam operation, selected CC ν_e candidates after oscillation, normal hierarchy

Bottom plot: neutrino beam operation, selected CC ν_e candidates after oscillation, inverted hierarchy

Significant effect of hierarchy%

DUNE sensitivities!

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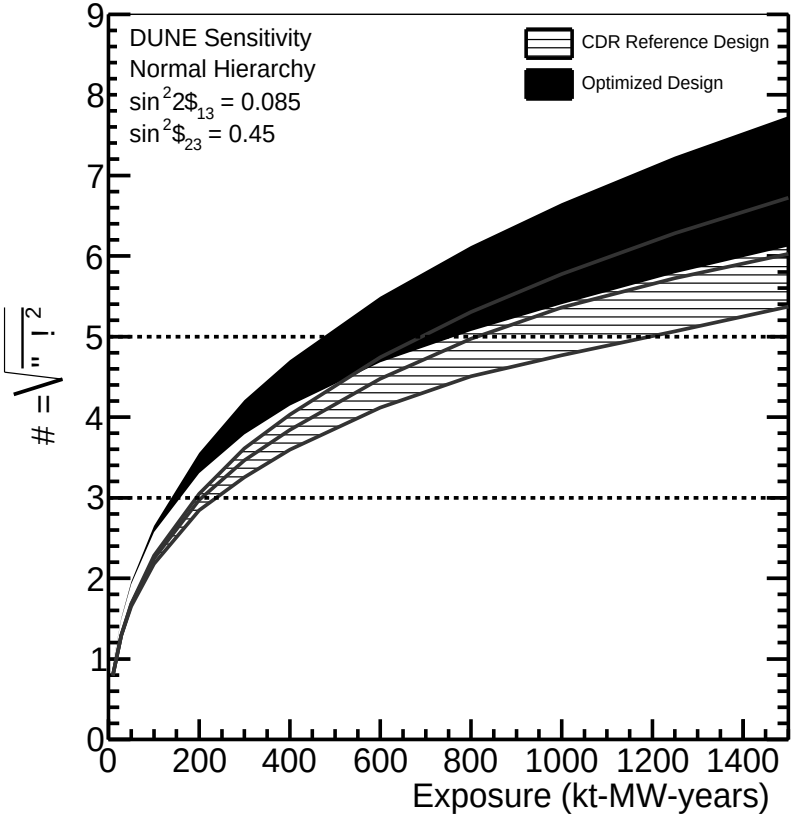

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4!`! C1!`!!!!!!!!

4!`! C0!`!!!!!!!!

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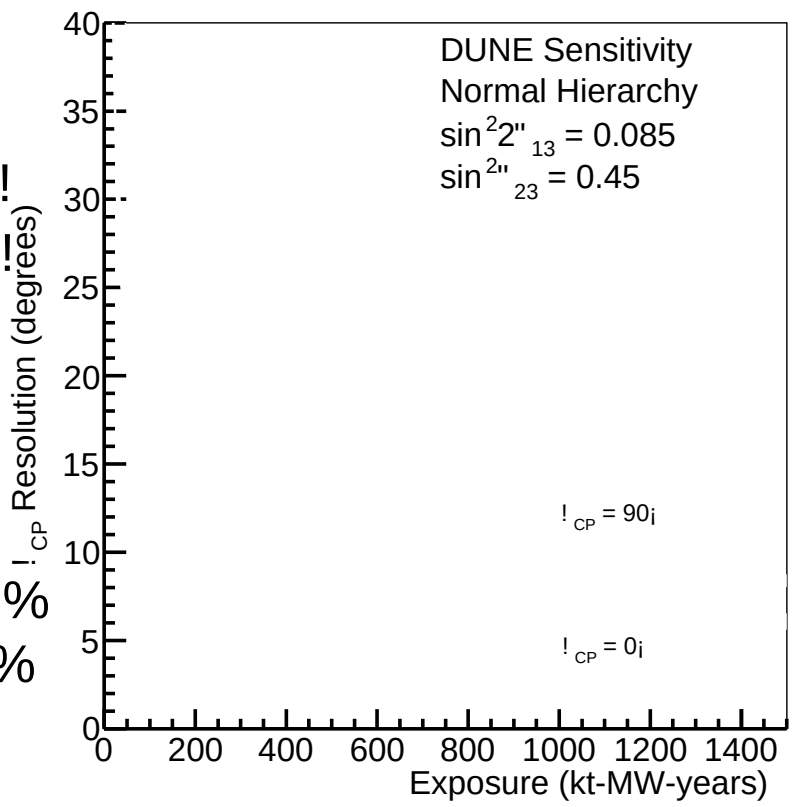

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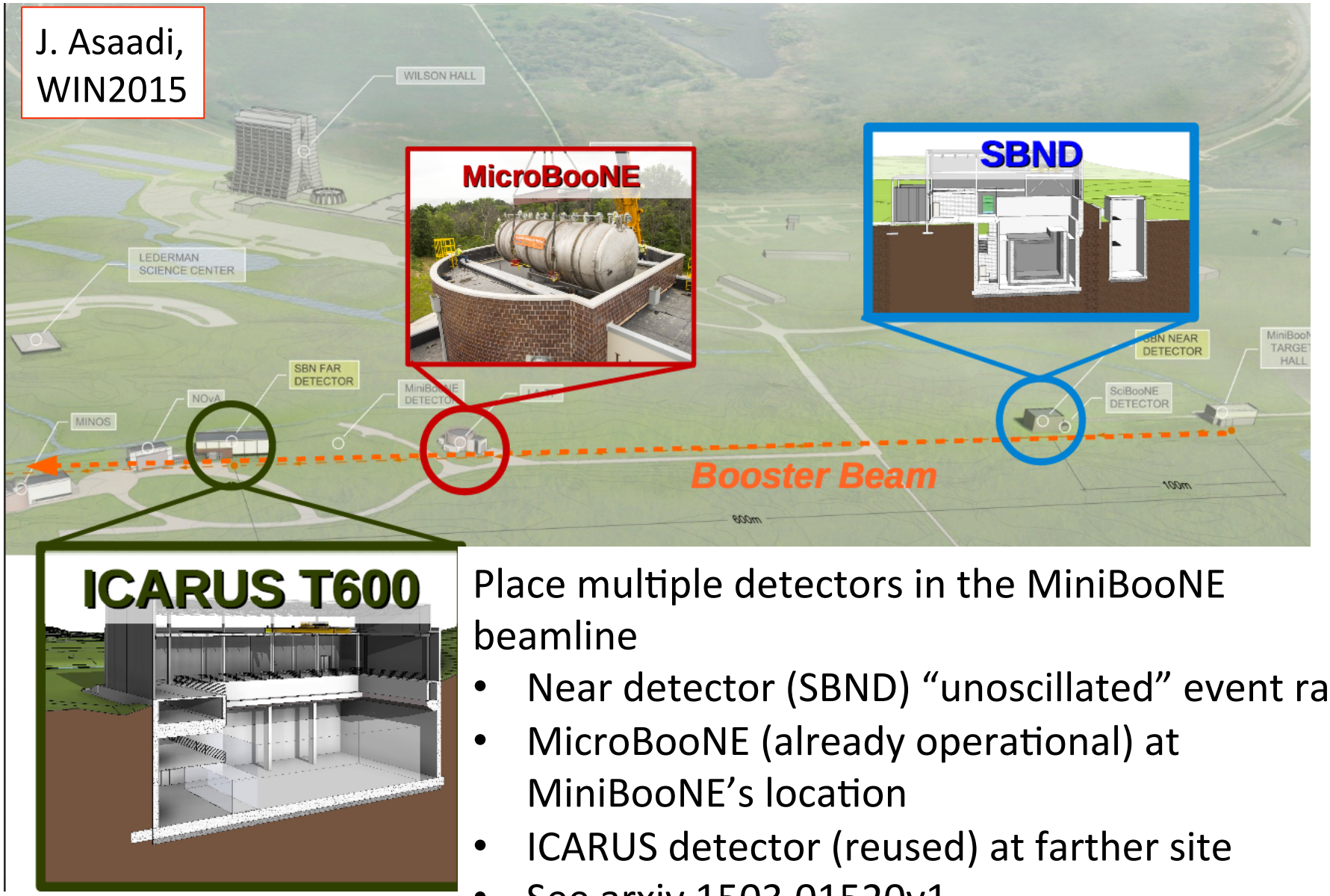
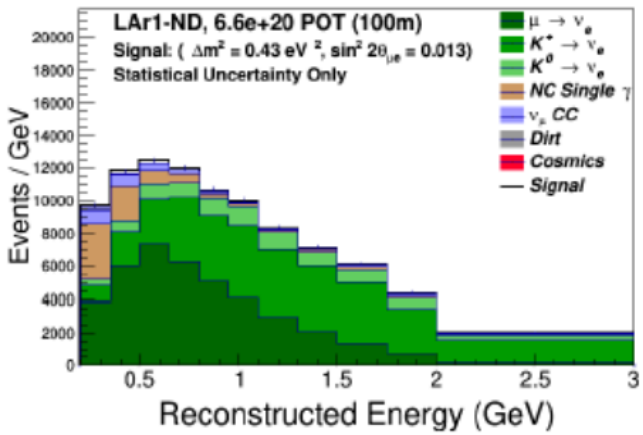
Short baseline neutrino program (SBN)

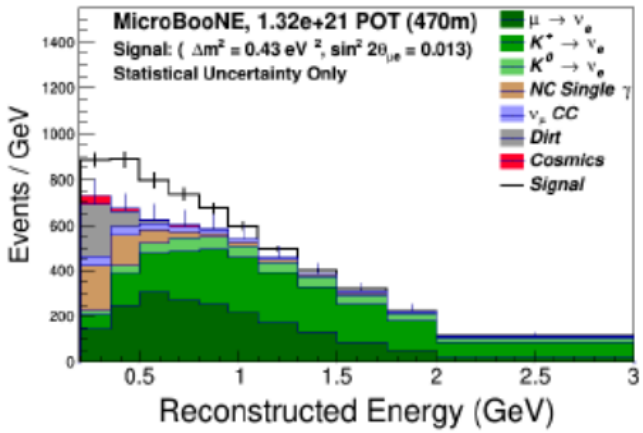


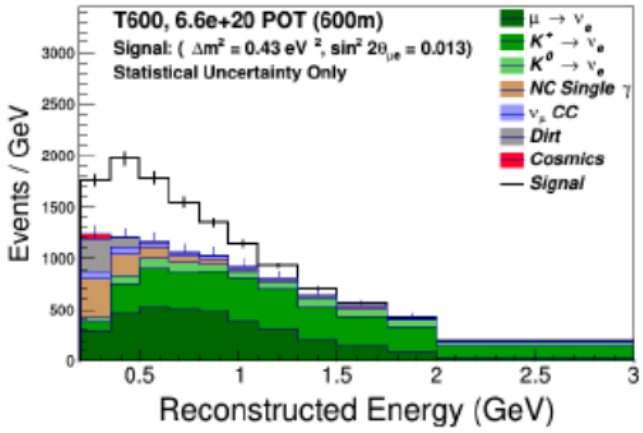
Place multiple detectors in the MiniBooNE beamline

- Near detector (SBND) “unoscillated” event rates
- MicroBooNE (already operational) at MiniBooNE’s location
- ICARUS detector (reused) at farther site
- See arxiv 1503.01520v1

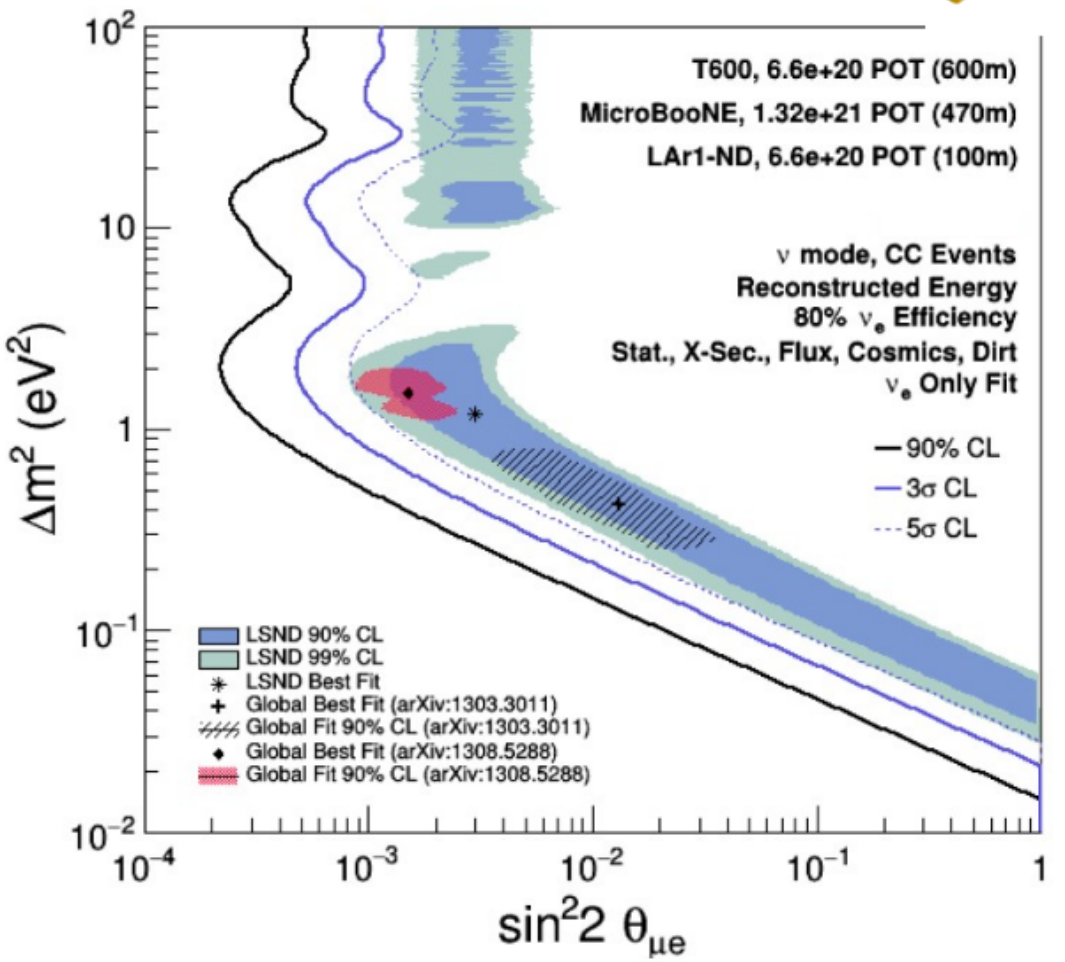
Short baseline neutrino program (SBN)







J. Asaadi, WIN2015



Aim resolve the MiniBooNE/LSND anomaly

Also make competitive disappearance measurement

Challenges:

- External backgrounds at each site
- Single photon contributions are also important

Future LBL experiment: Europe

A +:>"/$J"1) $is the same concept as a conventional neutrino beam, but with a “proton driver” (~MW accelerator)

Possible projects were
FGH I ?G or FA?C$

T. Nakadaira, Neutrino 2012

Future LBL experiment: Europe

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More history (actually ongoing)

DUNE has been merging efforts with the LBNO effort which also proposed LAr technology

Challenge: how do we build ~MW neutrino/antineutrino sources?

Possib

FGH I

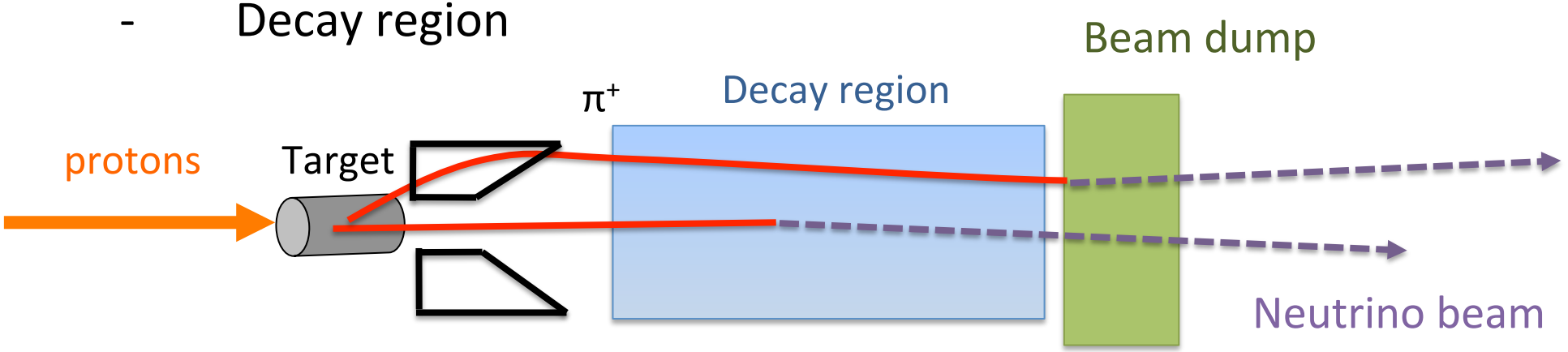
T. Nakadaira, Neutrino 2012

Challenges for superbeams

Achieving ~MW neutrino sources will be a challenge

Complex system mean many points of potential failure:

- Accelerator
- Targets
- Horns
- Decay region



Considerations:

- Direct or indirect contact with high intensity proton beam?
- What materials are used and how long will they last?
- How can components be replaced or disposed of?

NuMI target

NuMI target is water cooled, sits in an enclosure to allow the target to change positions to tune the energy of the beam

Problems:

1) Water cooling system leaked *A-1B%C1%D#E%2#%*"161F2%E421"%G"#$%H14I.FJ%*
2) Motor drive shaft to move the target failed *C4B%2#%"1*H4/1%24"J12%%%*
3) Longitudinal drive failure *A-1B%"1$#21%+4FBH.FJ%/1HH%G#"%"1*4."-K%"1.F-24HH1B%%*

Railing

Concrete wall

Lead-glass window

Horn

Remote lifting table

E. Gschwendtner, NuFact08

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Railing

Concrete wall

Moral: Always have a backup and a backup plan

Prepare for high radiation environment

Lead-g
window

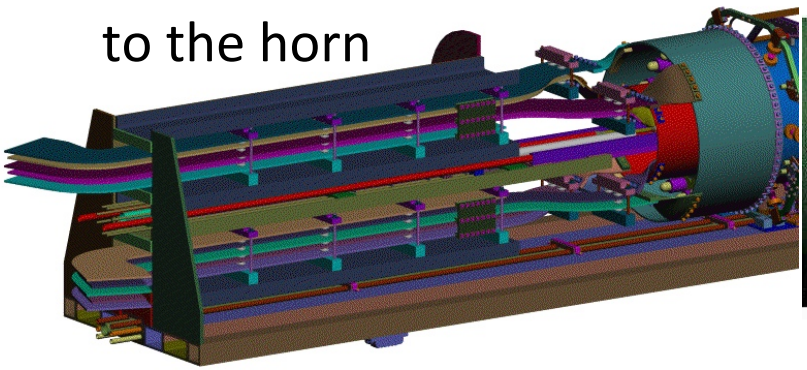
Horn

Remote
lifting table

E. Gschwendtner, NuFact08

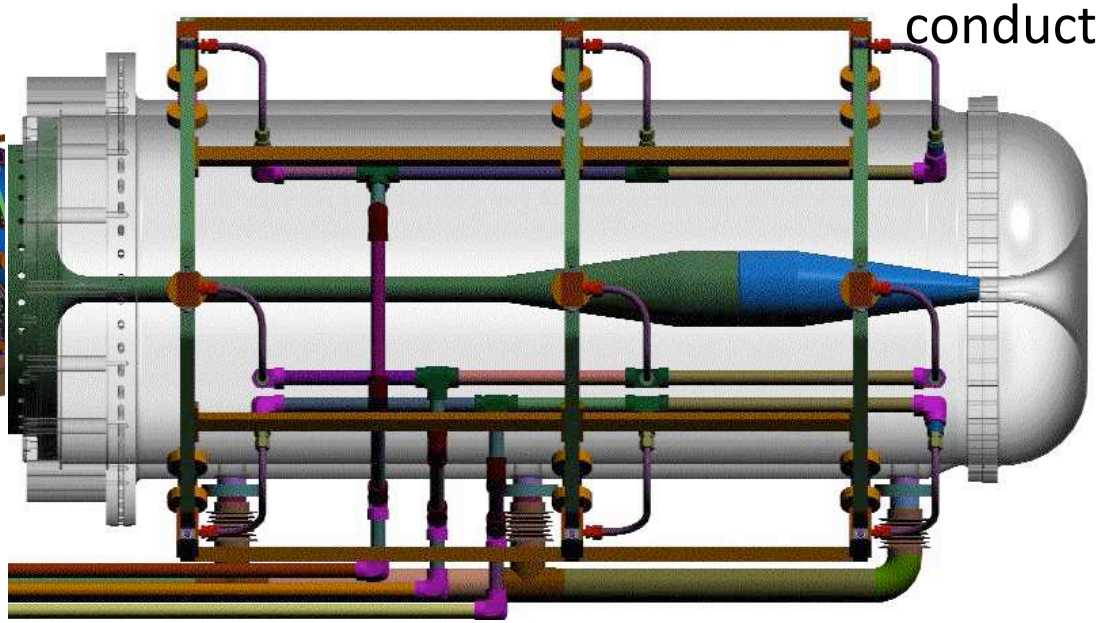
Components of horns

Power supply and striplines which connect to the horn



Cooling system

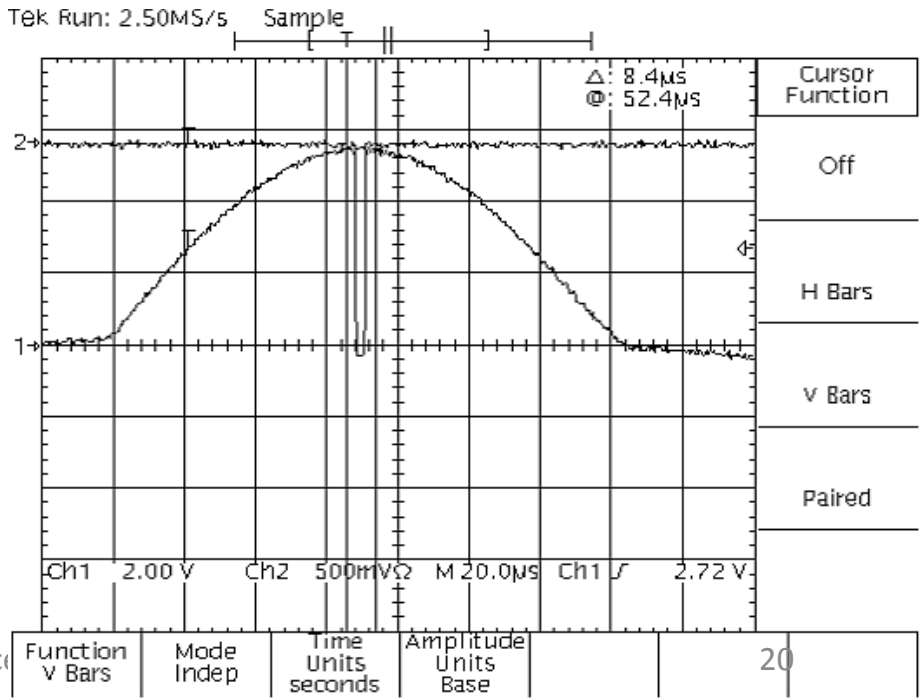
Inner and outer conductors



MiniBooNE horn design drawings (Bartoszek Engineering)

"Pulsed": maximum current goes across conductor for small period of beam

Example: MiniBooNE 170kA at 5Hz



Horns

K2K: *O1*H4/1%+#"F-%L1G#"1%2##%"4B.#4/M61%*

- Final (4th) horn inner conductor failed close to end-of-run, too radioactive

MiniBooNE: *N"1*4"1B%B1B./421B%"1$#21%"1$#64H%-, -21$%*

- First horn failed due to water corroding the stripline from cooling system
- Second horn cooling system bellows modified, never failed

NuMI: *N"1*4"1B%B1B./421B%"1$#21%"1$#64H%-, -21$%4FB%"1$#21%+4FBH.FJ%/1HH%*

- Multiple issues: ground fault, material in water cooling system (resin), water system ceramic seal leaks
- Initially problems were repairable, but later had to replace the first horn

T2K: *N"1*4"1B%B1B./421B%"1$#21%"1$#64H%-, -21$%4FB%"1$#21%+4FBH.FJ%/1HH%*

- Neutrino beamline recovered from severe earthquake
- Power supply component failed, reused older power supply

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Morals: Learn from previous experiments

Watch for single points of failure

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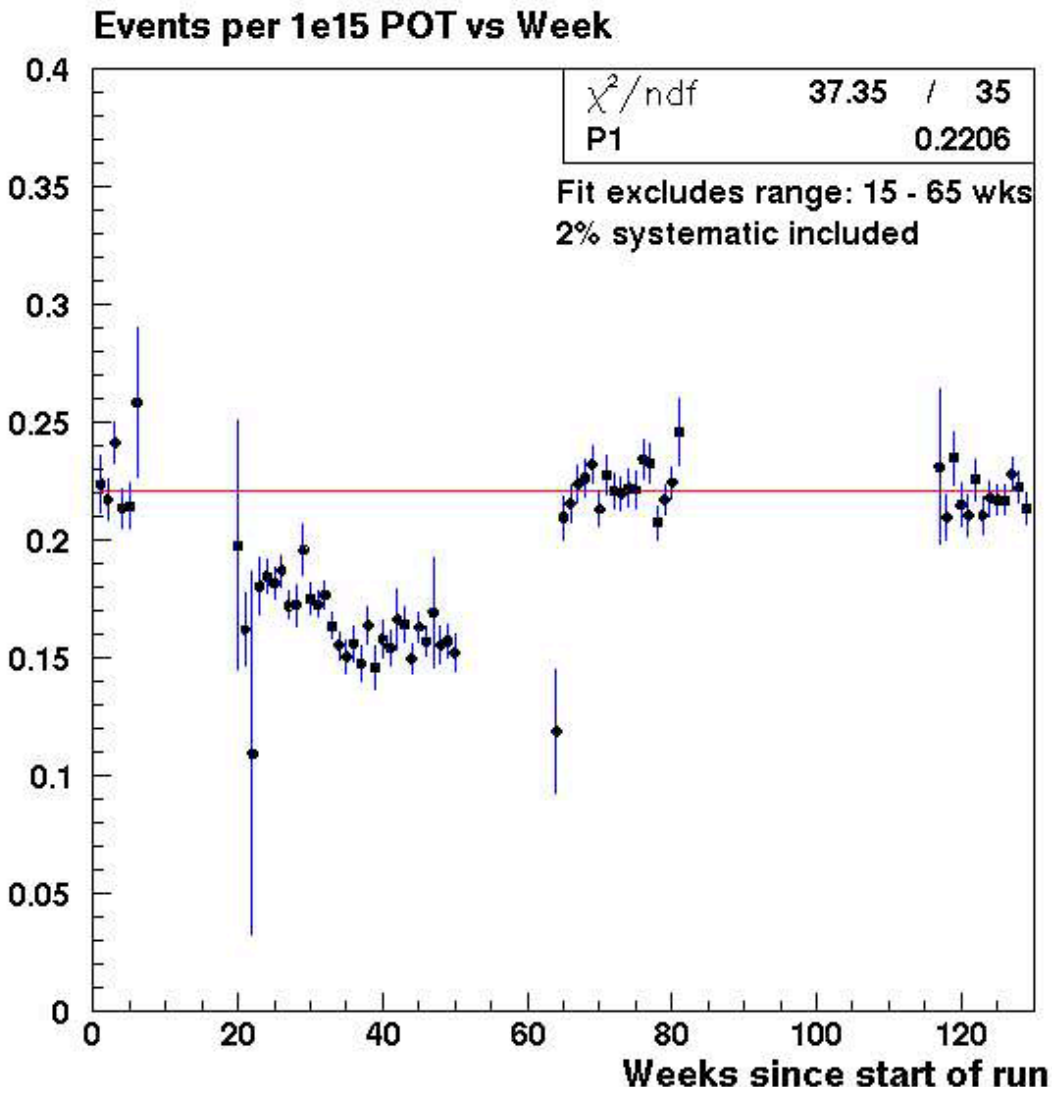
MiniBooNE absorber plates

MiniBooNE's 50m decay region was designed with extra absorbers at 25m which could be placed into the beam

- Shortens decay region, alters beam ν_e composition

In 2006, two of the 10 absorber plates fell into the beamline, and were later removed

E. Gschwendtner, NuFact08



The hardened steel supports for the suspended plates had weakened in the high radiation environment

- Softer steel was used to suspend the plates
- Many experiments now fill decay region with He

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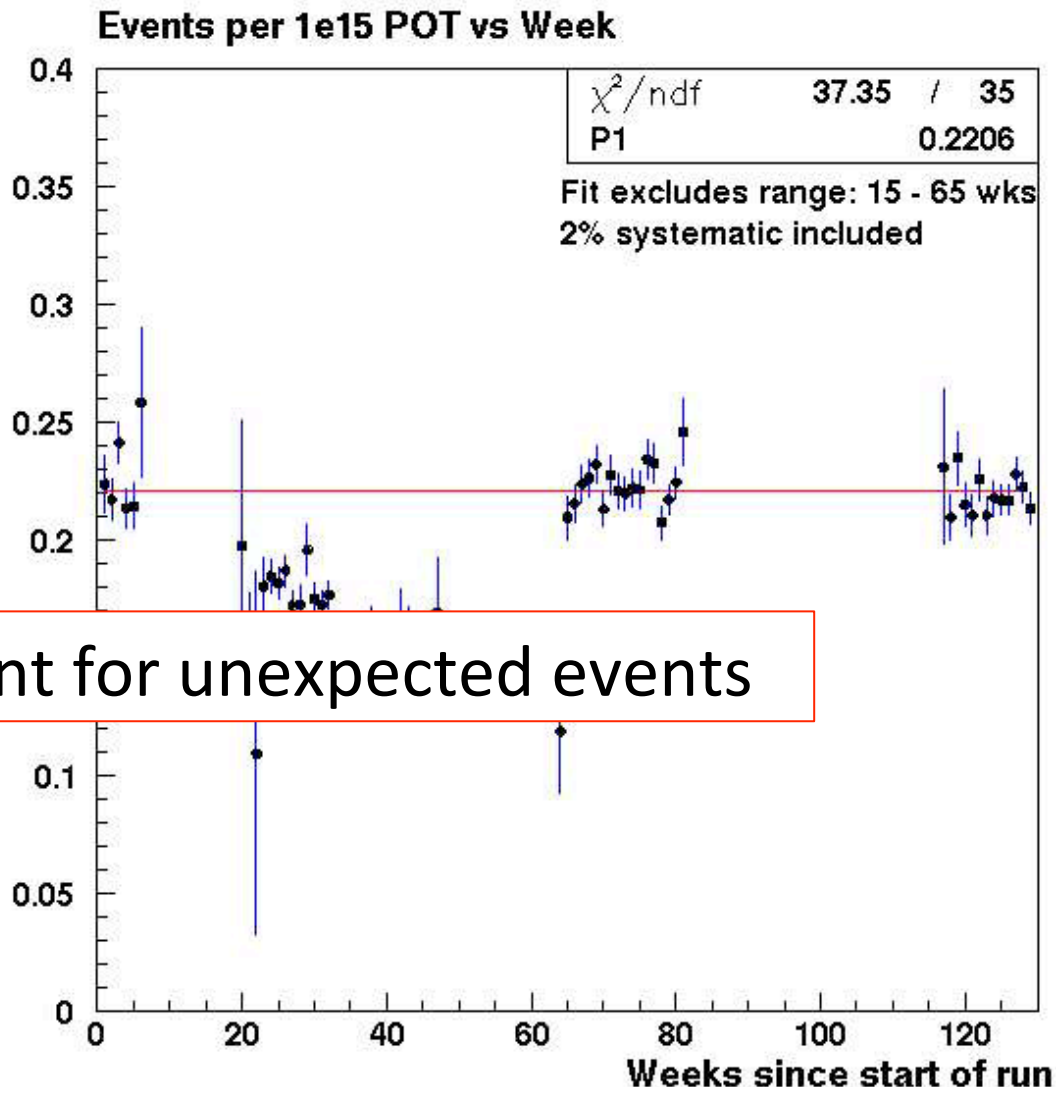


Moral: Be vigilant for unexpected events

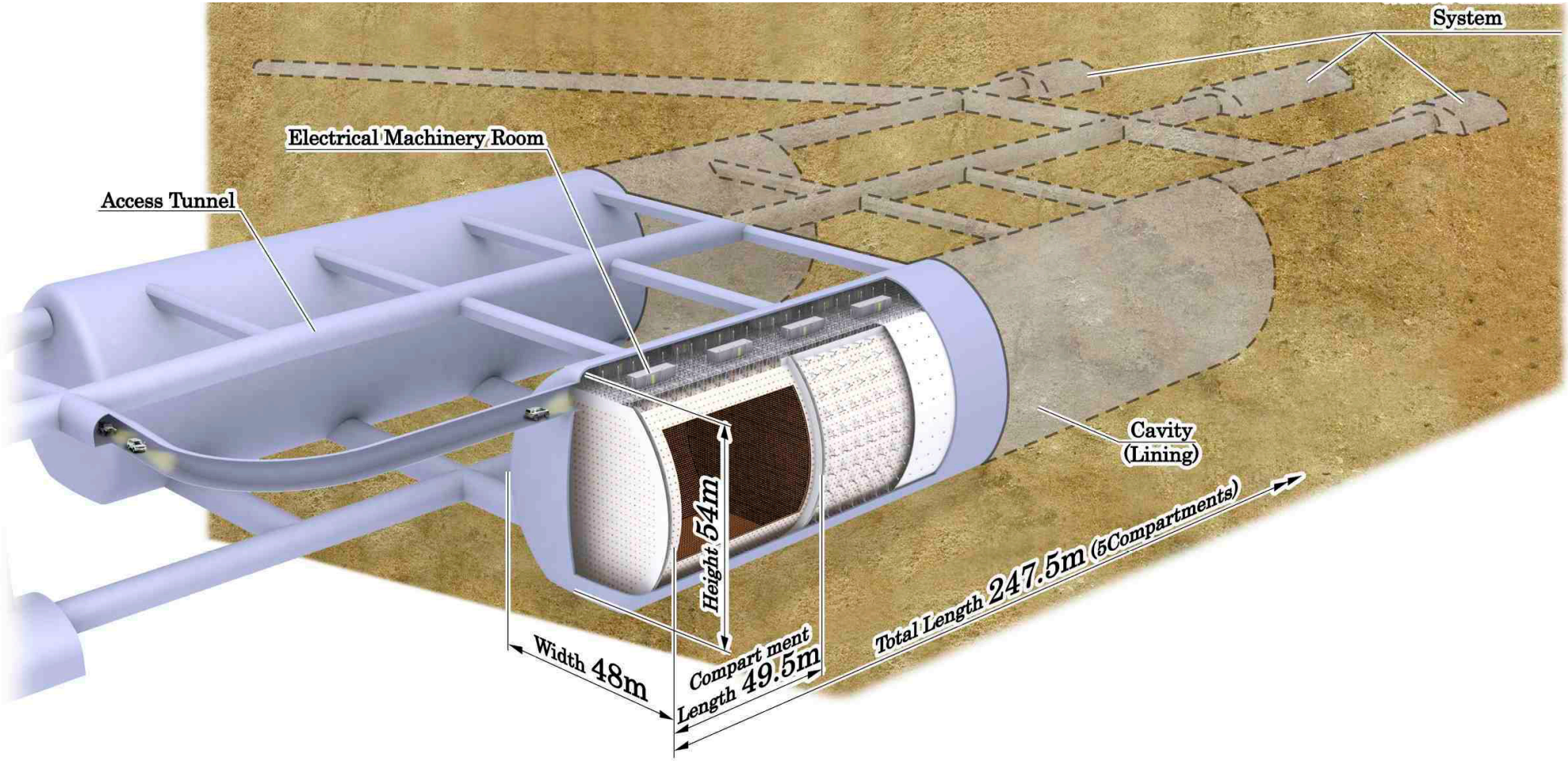
The hardened steel supports for the suspended plates had weakened in the high radiation environment

- Softer steel was used to suspend the plates
- Many experiments now fill decay region with He

Future LBL experiment: Hyper-Kamiokande

~1Mton detector, approximately 25x Super-Kamiokande

- 99,000 inner PMTs, 25,000 veto region PMTs (10 compartments)
- Same neutrino beamline as T2K, different cavern
- Operation 2015 onward



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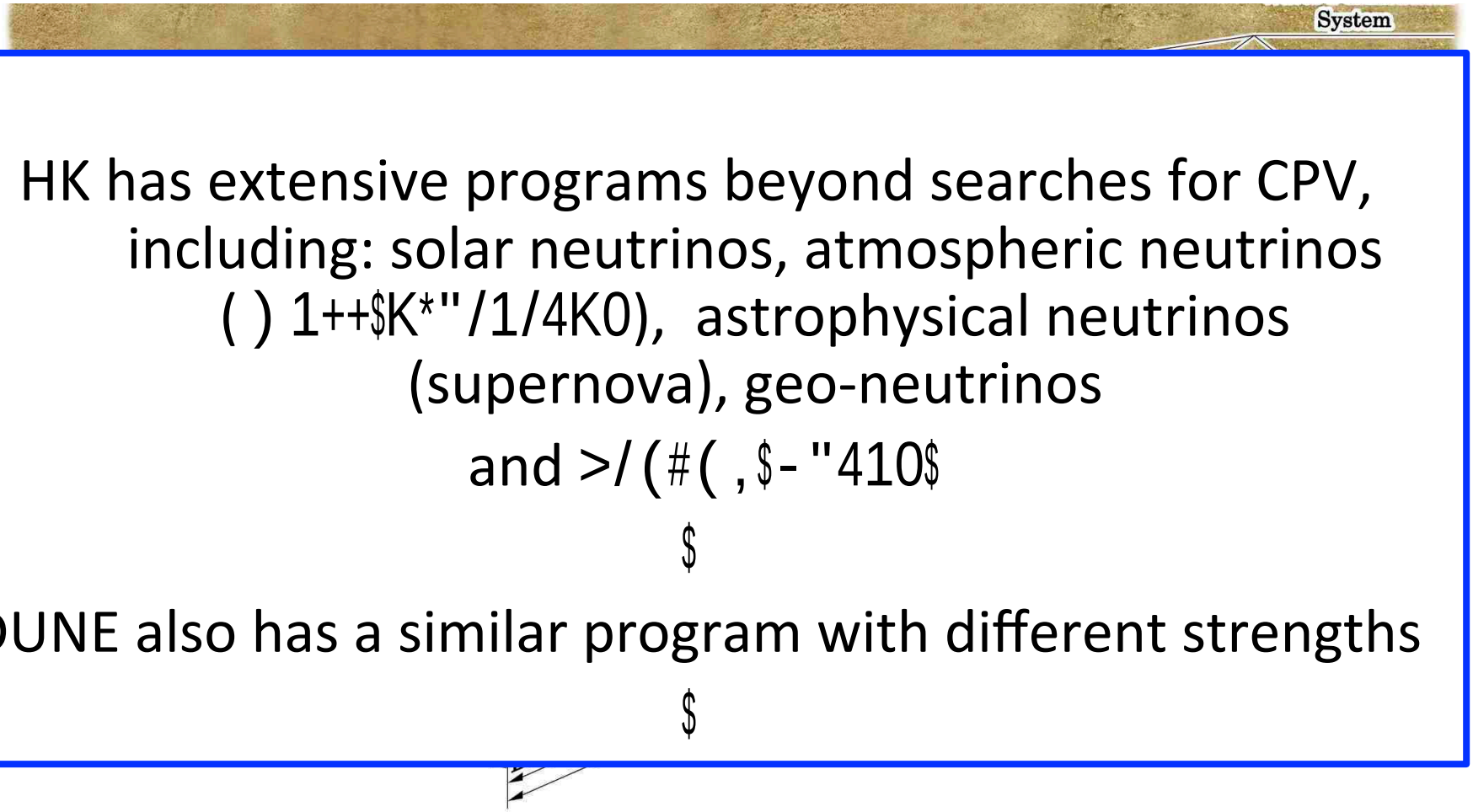


HK has extensive programs beyond searches for CPV, including: solar neutrinos, atmospheric neutrinos ( ) 1++$K*"/1/4K0), astrophysical neutrinos (supernova), geo-neutrinos and >/(#(,$-"410$

$

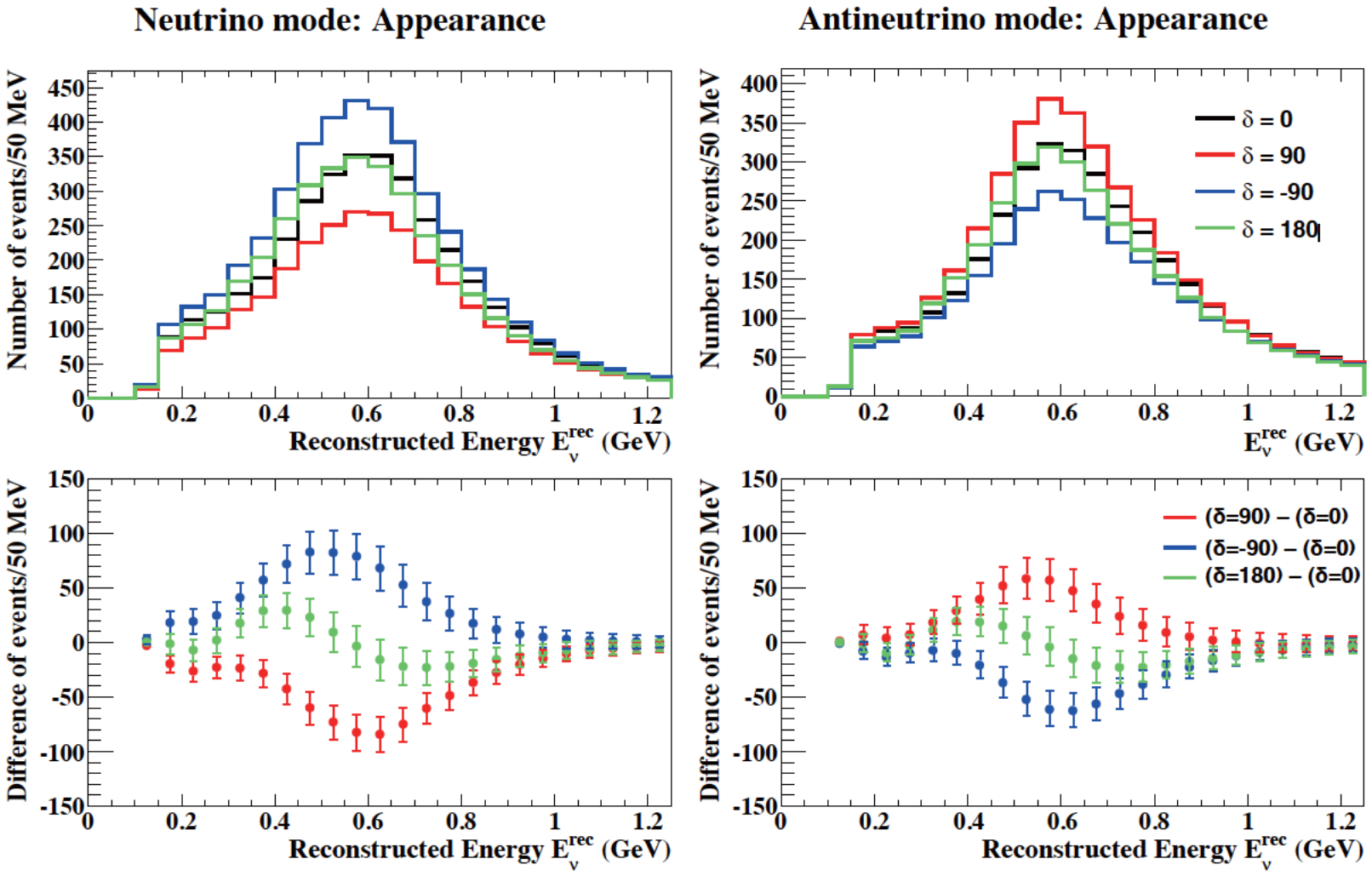
DUNE also has a similar program with different strengths

$

Hyper-Kamiokande sensitivity

Neutrino and antineutrino samples are ~3000, ~2000 events respectively

- Spectrum, rate provides information on δ_{CP}
- Requires hierarchy to be known (determined with atm. dataset if not known before)



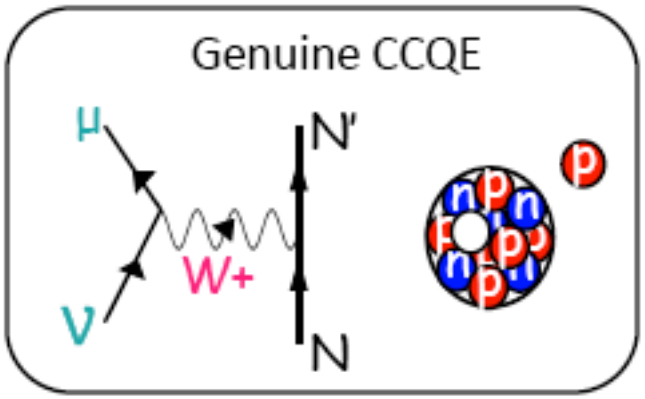
Challenge: sources of systematics

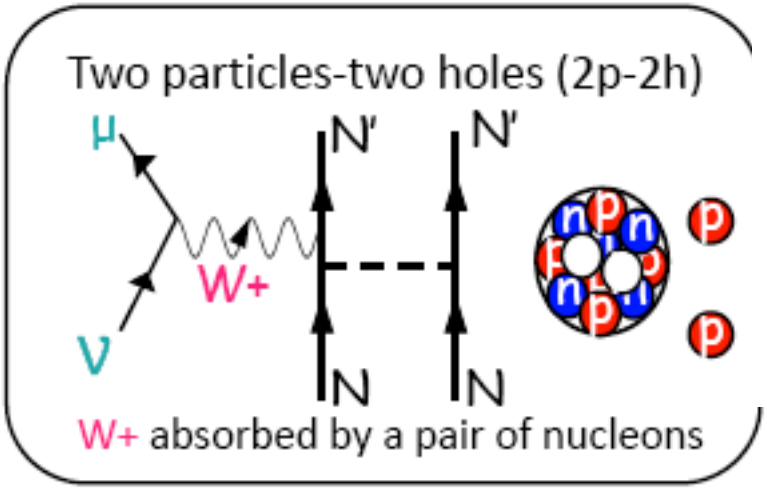
: ,4"/#1*,7"+$	L$M$$ -*+1>N$	L$"$1>>$
ν flux+xsec (before) after ND constraint	(21.7%) ±2.7%	(26.0%) ±3.2%
ν unconstrained xsec	±5.0%	±4.7%
Far detector	±4.0%	±2.7%
Total	(23.5%) ±7.7%	(26.8%) ±6.8%

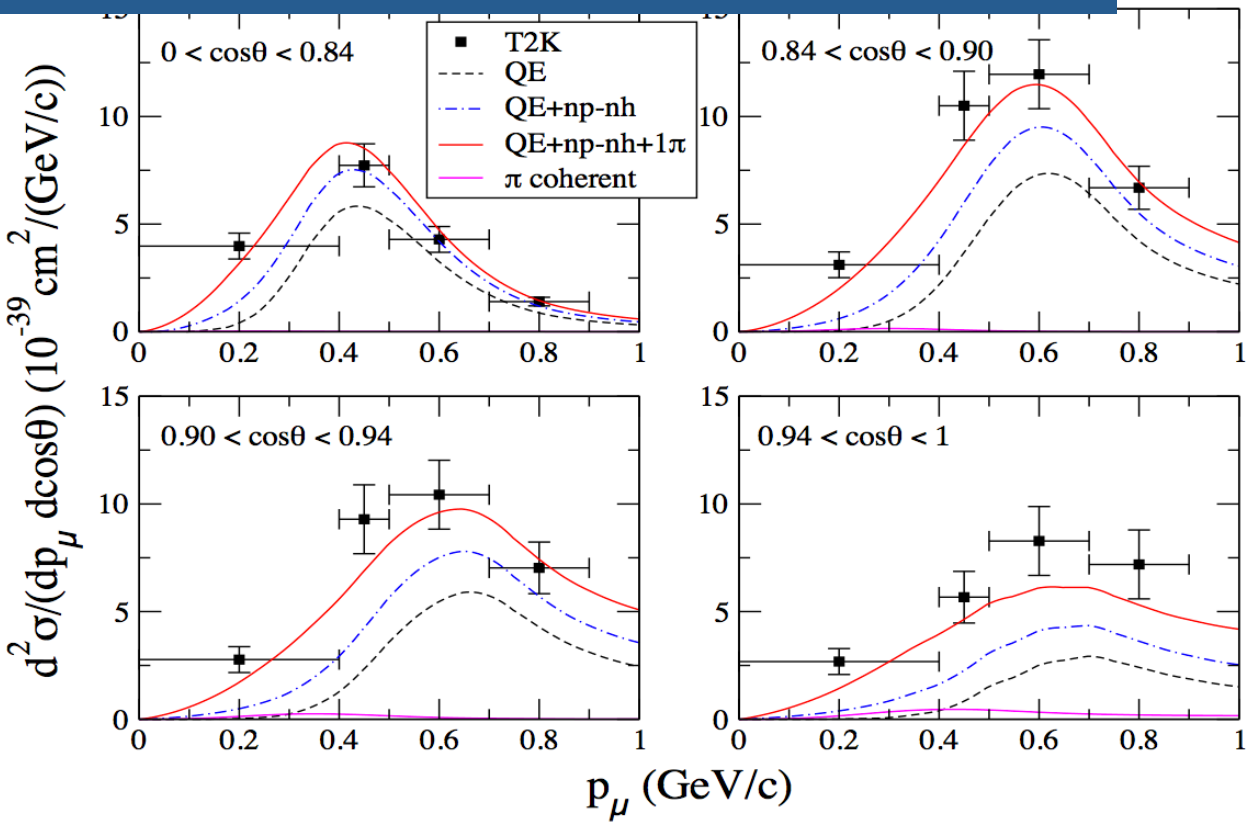
Significant systematic uncertainties in T2K oscillation analyses are from uncertainties on the CCQE, CC1π neutrino interaction models

- Disagreements between models and existing neutrino experiment data (e.g. MiniBooNE, SciBooNE, MINERvA, T2K and NOMAD)
- Differences between new theoretical models and those currently used by T2K

Are we measuring CCQE?







Martini and Ericson, Phys.Rev. C90 (2014) 2, 025501

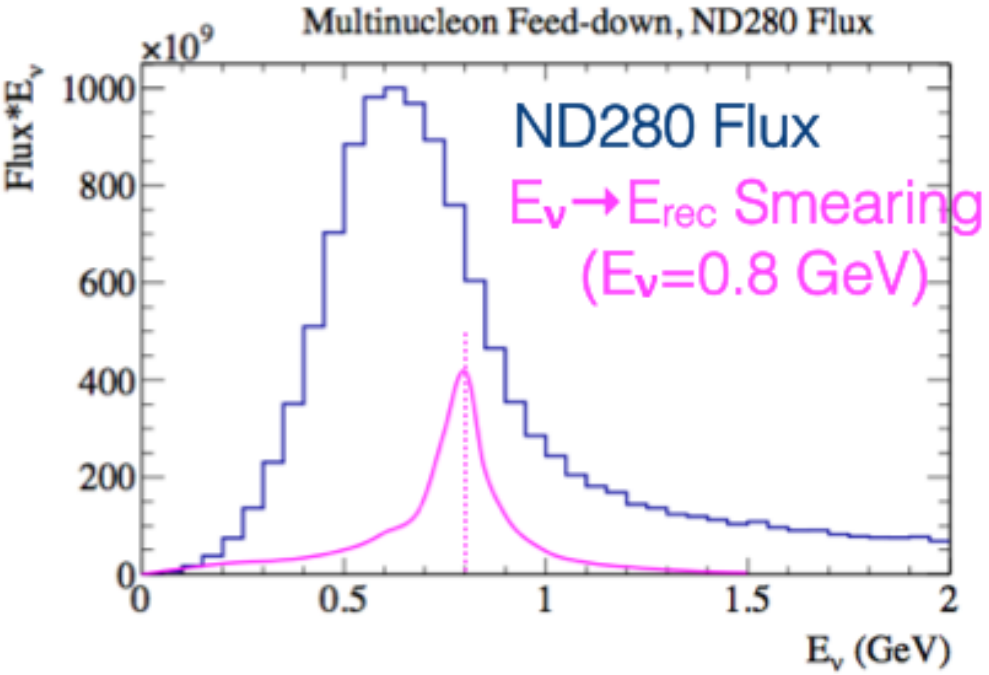
T2K inclusive data: Phys.Rev. D87 (2013) 9, 092003

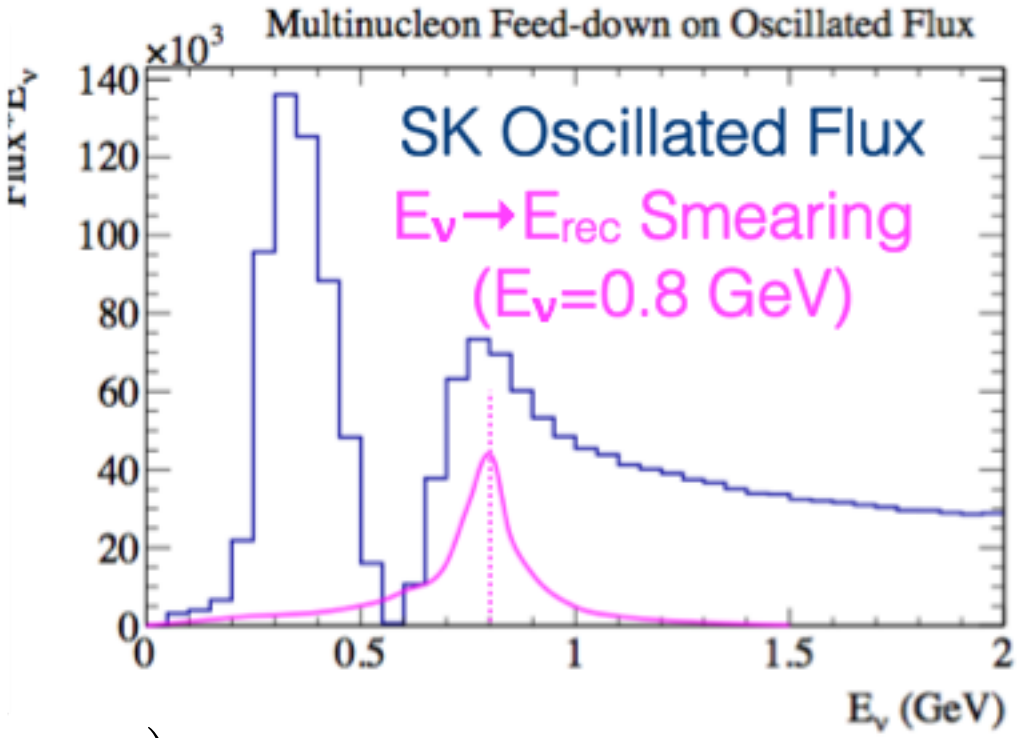
"Multinucleon" processes may explain the enhanced CCQE cross section observed by MiniBooNE, SciBooNE experiments

- CCQE interaction simulated as interaction on a single nucleon (1p1h)
- Two models:
- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)

Why the cross section model matters

Cross section model couples through the different fluxes measured by ND and FD





$$FD(\nu_e) = \Phi \times \sigma \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$

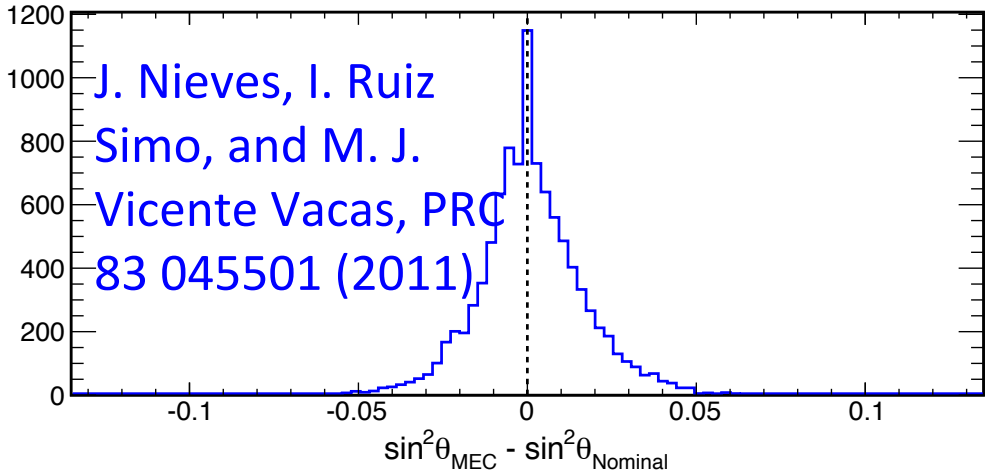
$$ND(\nu_\mu) = \Phi \times \sigma \times \epsilon_{ND}$$

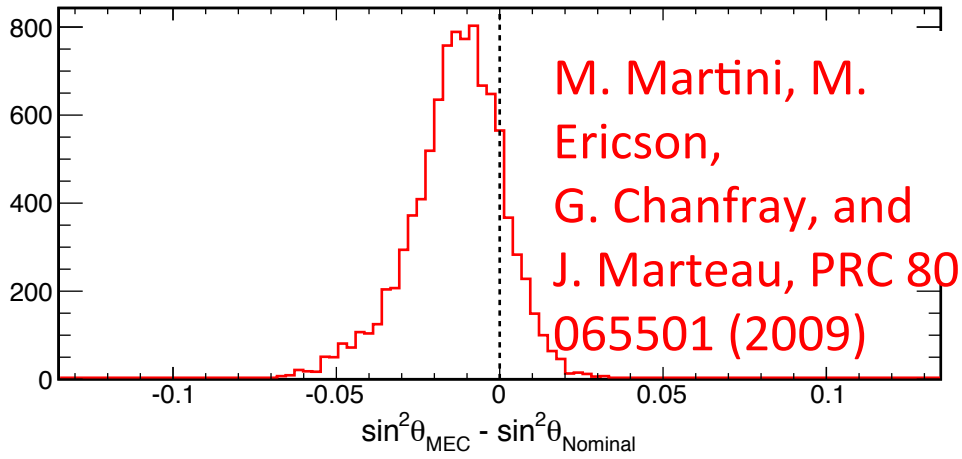
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n}{2(m'_n - \quad)}$$

Overall increase to cross section cancels in extrapolation, but any shifts between true to reconstructed E feed down into oscillation dip and are ~degenerate with θ_{23} measurement

- Multinucleon interactions occur at a higher average energy, but reconstruct at a lower energy
- Similar issue for CC1π+ backgrounds where pion is not tagged (absorbed in nucleus or detector)

Effect on oscillation analysis from multinucleon processes





Tested possible bias on T2K disappearance measurement

- Generate fake data under flux, detector, cross section variations, and perform full oscillation analysis including ND constraint
- For each fake data set, compare fitted θ_{23} with and without a 2p2h model present

Nieves et al model: 0.3% mean, 3.2% RMS

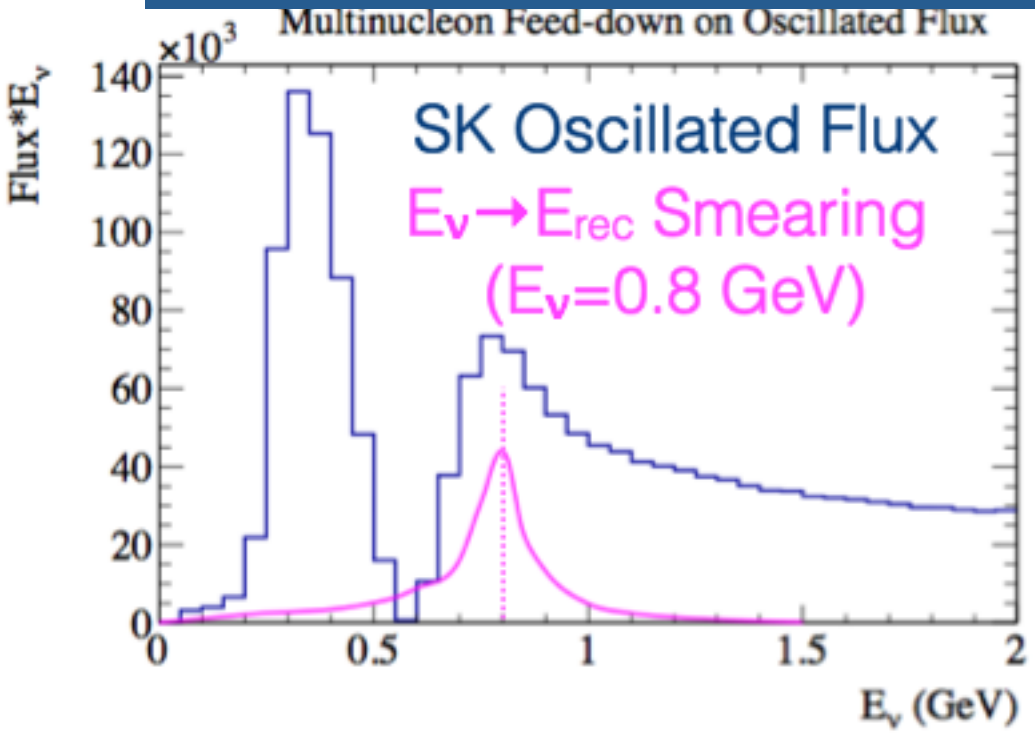
"increased Nieves" = Martini model: -2.9% mean, 3.2% RMS

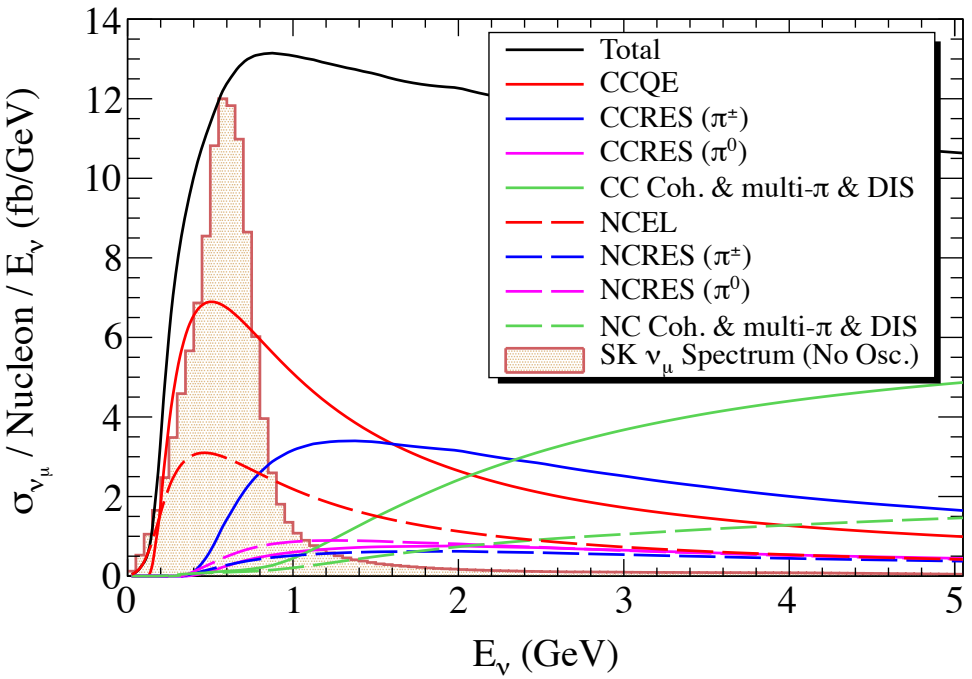
%?.JF.O/4F2%"1H4M61%2#%/@""1F2%-, -21$4M/%@F/1"24.F2, %#F%F1@2".F#P$#B1%%
B.-4**14"4F/1%4F4H, -.-%%Q6-;%<;9R%F#FP/4F/1HH.FJ%/"#--%-1/M#F%@F/1"24.F2, K%:;:R%2#24H%S%
T4, %/"1421%F1@2".F#U4FMF1@2".F#%4-, $$12".1-%

%

%V$*#"24F2%G#"%G@2@"1%H#FJ%L4-1H.F1%*"#J"4$%Q7P<R%@F/1"24.FM1-S%

Summary of challenge





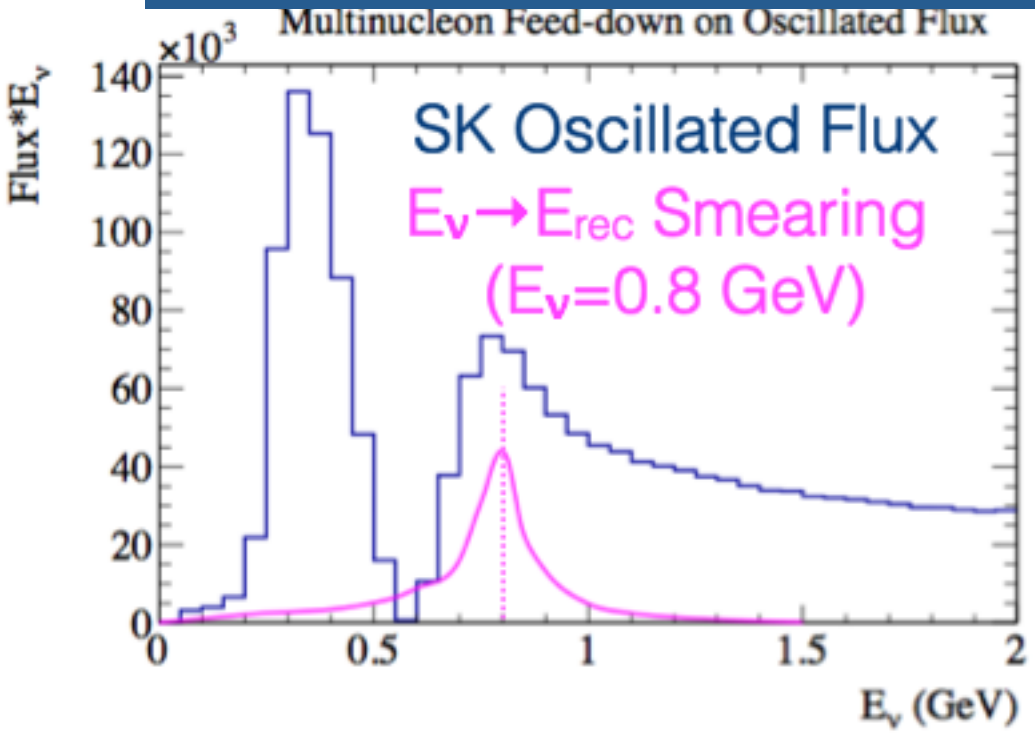
Challenges of neutrino interactions at 1 GeV

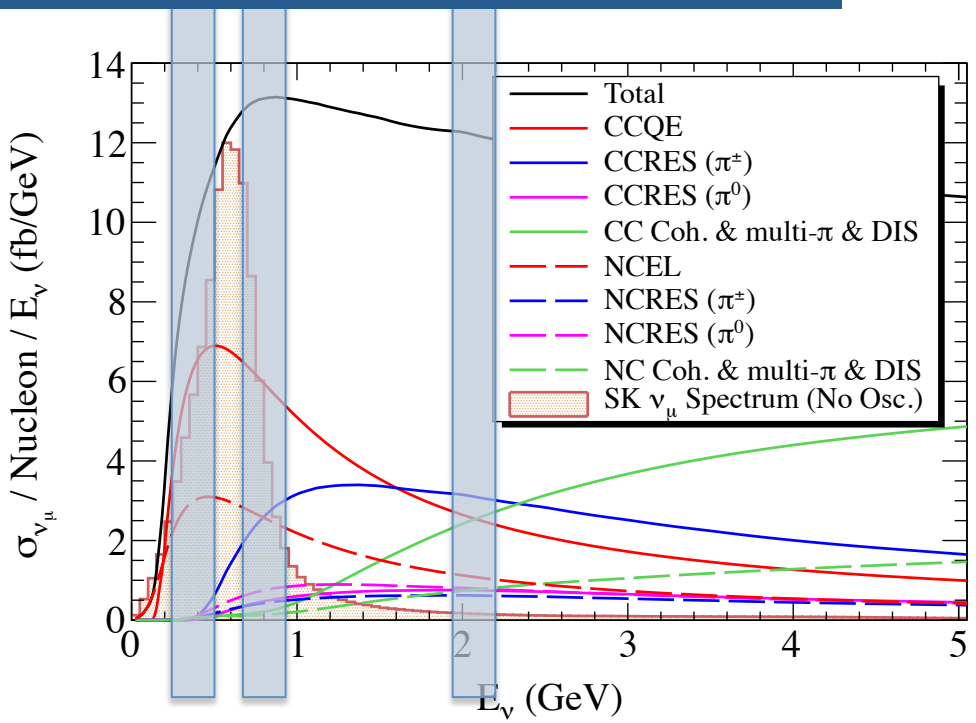
- Are we seeing new multinucleon processes? Issues with CCQE,1π model?

Difficult to isolate a control sample of multinucleon events

- Measure a particular topology (CC with no pions) integrated over the flux, which includes multiple processes
- Flux is not identical at near and far detectors, if only just from oscillation

Summary of challenge





Challenges of neutrino interactions at 1 GeV

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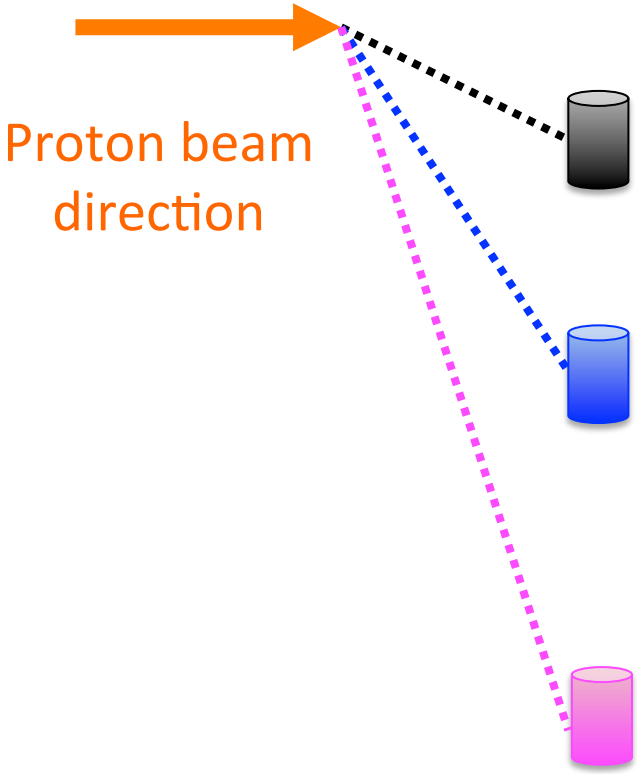
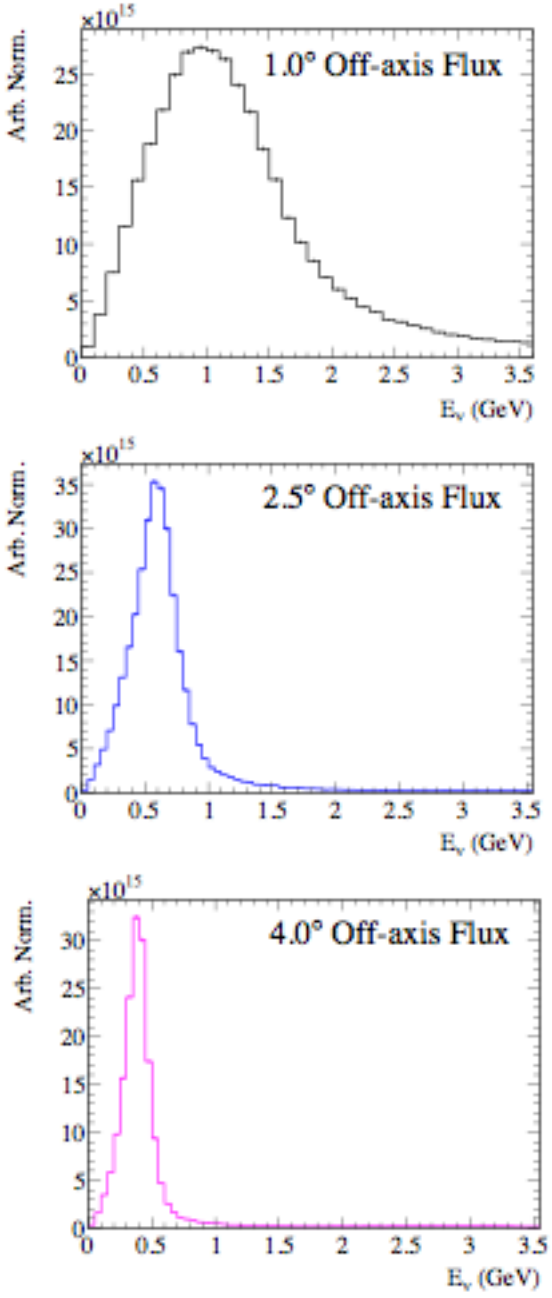
VG%E1%+4B%4%B."1/2%*"#L1W%4%X$#F#1F1"J1M/Y%F1@2".F#%L14$W%%
E1%/#@HB%.-#H421%B.Z1"1F2%*"#/1--1-%.FB1*1FB1F2H,%%

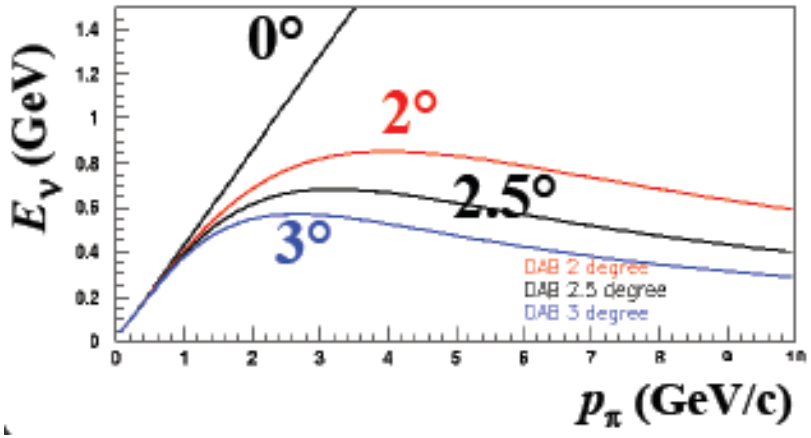
Novel neutrino spectrometer: nuPRISM





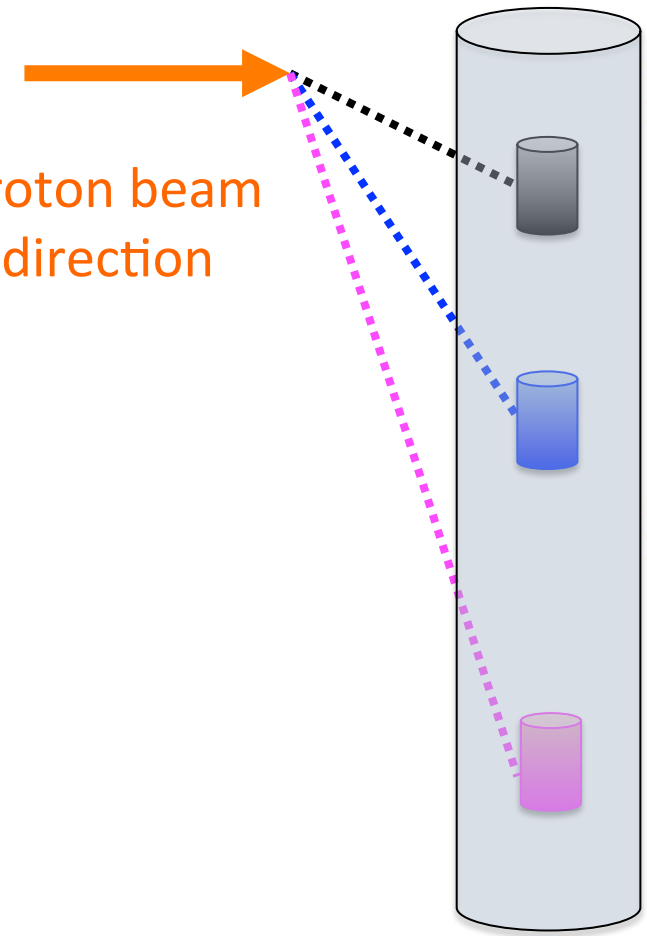
Example using T2K beamline

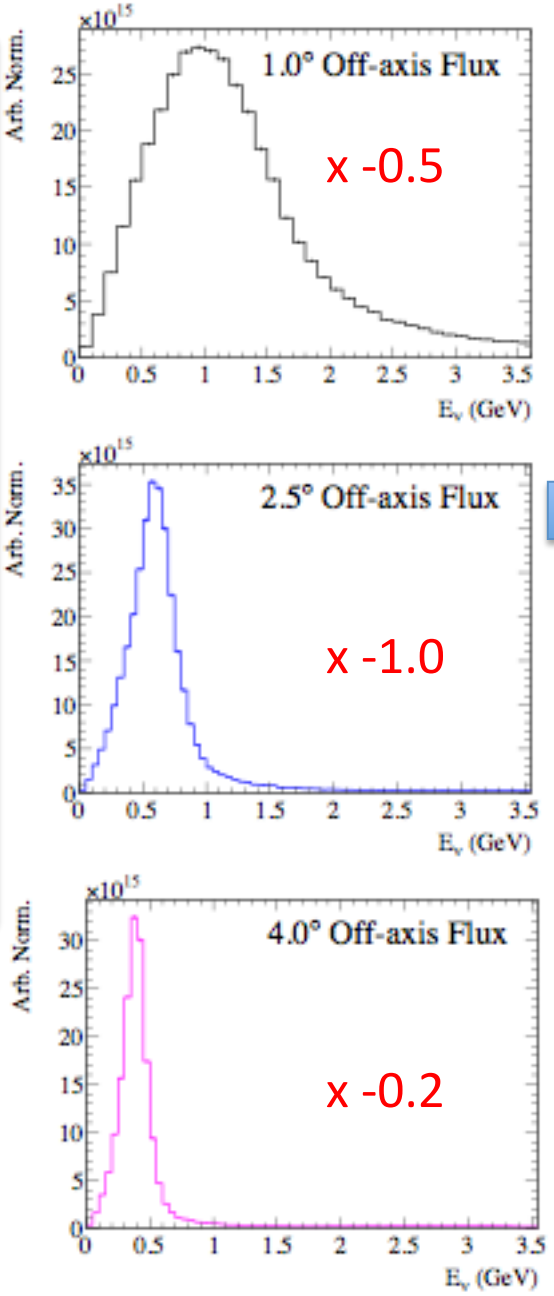
As off-axis angle increases, flux spectrum narrows and peak shifts down, due to the kinematics of pion decay



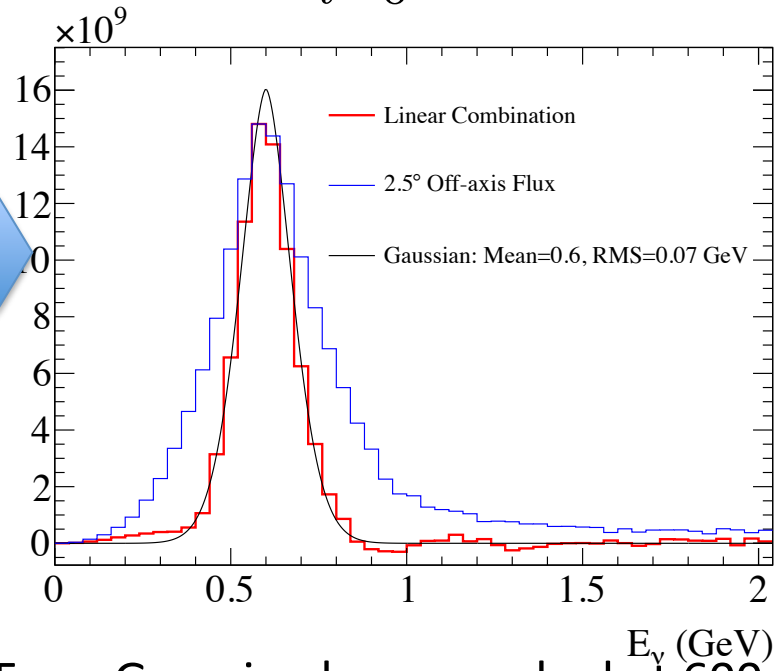
Novel neutrino spectrometer: nuPRISM

Proton beam direction





$$\Phi(E_\nu) = \sum_{i=0°}^{\theta_{max}} C_i \ \phi_i(E_\nu)$$

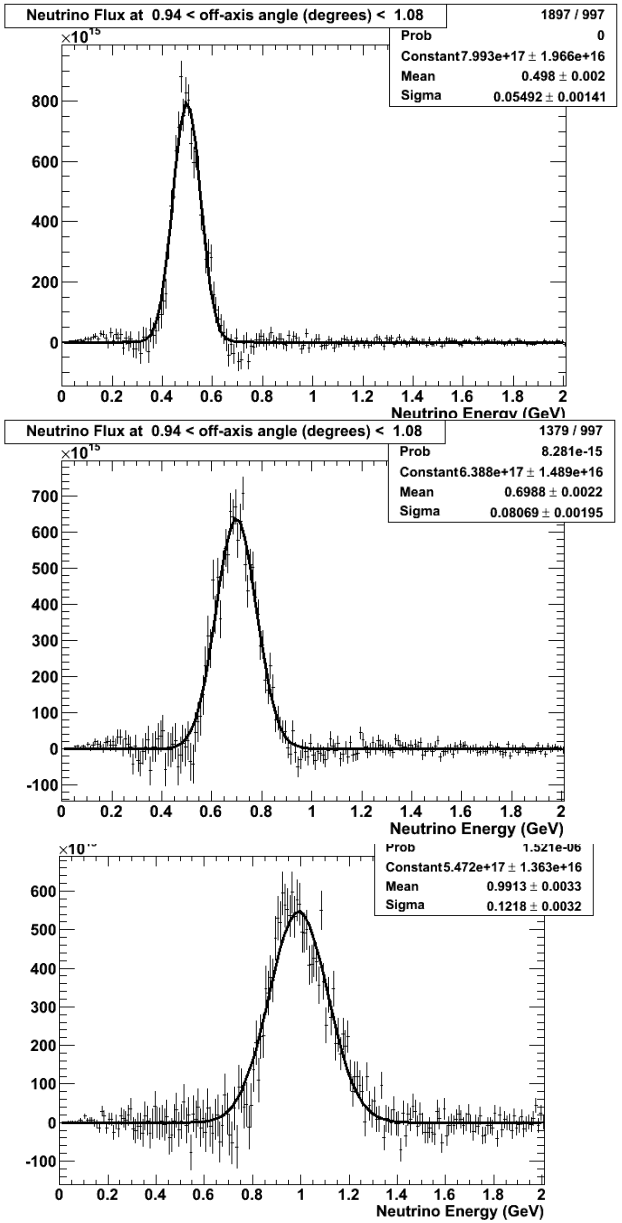


For a Gaussian beam peaked at 600 MeV, use linear combination of 30 offaxis angles:

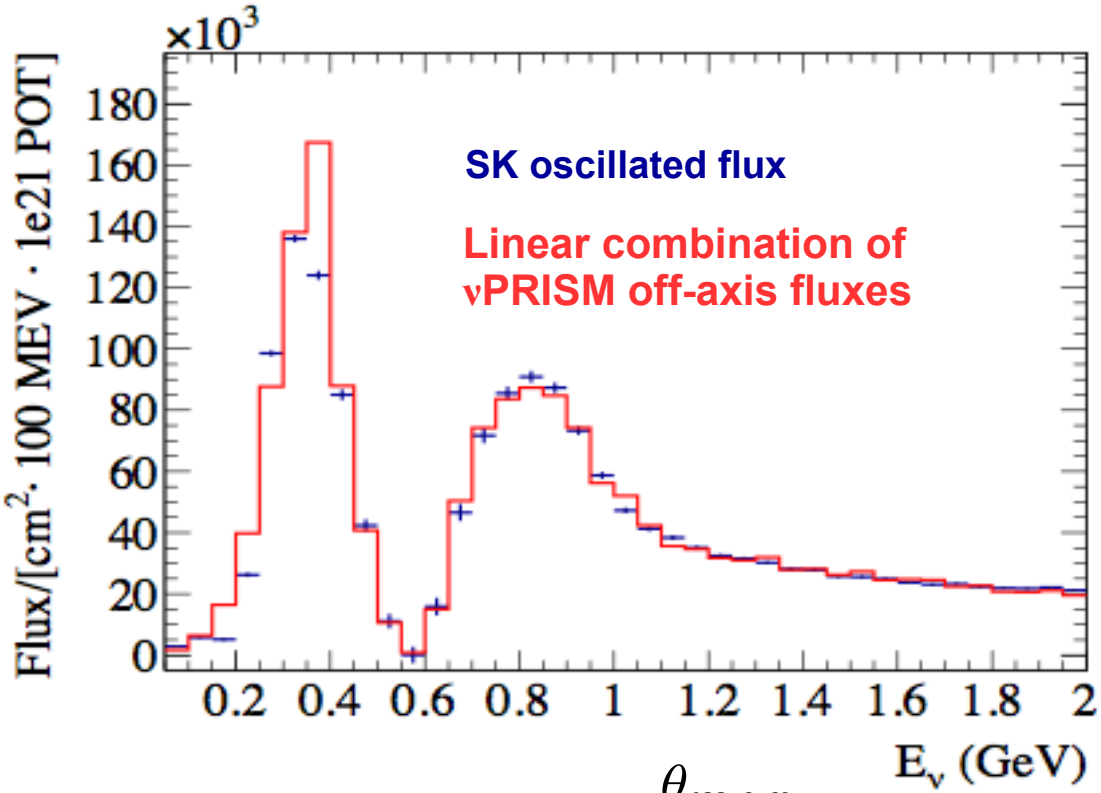
- 0°– 6° corresponds to 1.2 GeV -0.25 GeV
- Cancels HE tail

nuPRISM and an oscillation analysis

Cross section model dependence enters through correction of different fluxes measured by ND and FD



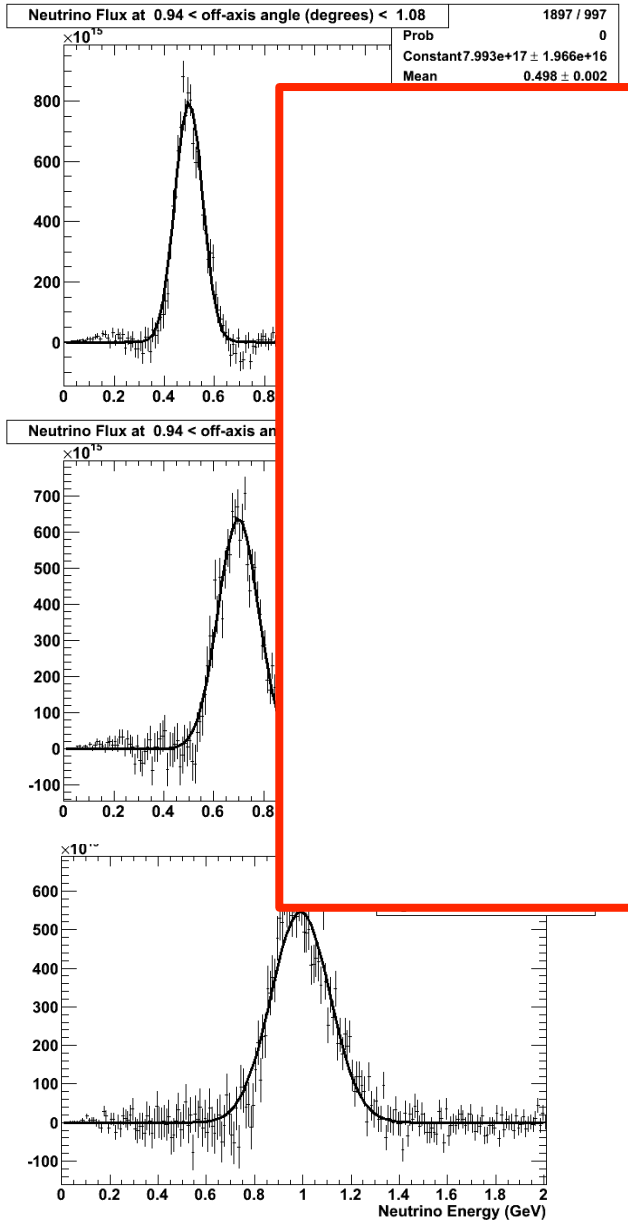
A-1%H.F14"%/#$L.F4M#F%21/+F.[@1%2#%J1F1"421%#-/.HH421B%
*-*1/2"@$%G"#$%B.Z1"1F2%#Z45.-%4FJH1-%*



$$\Phi(\Delta m^2_{32}, \theta_{23}) = \sum_{i=0°}^{\theta_{max}} k_i \ \phi_i(E_\nu)$$

nuPRISM and an oscillation analysis

Cross section model dependence enters through correction of different fluxes measured by ND and FD

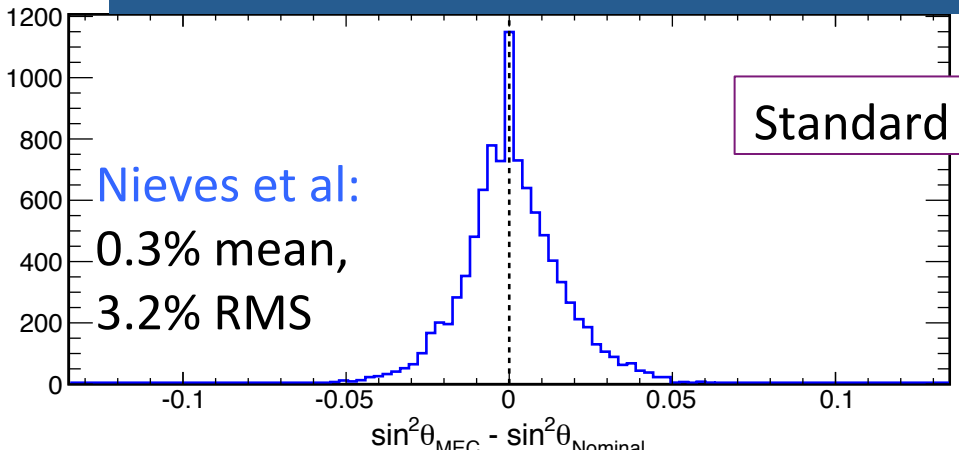


νPRISM:

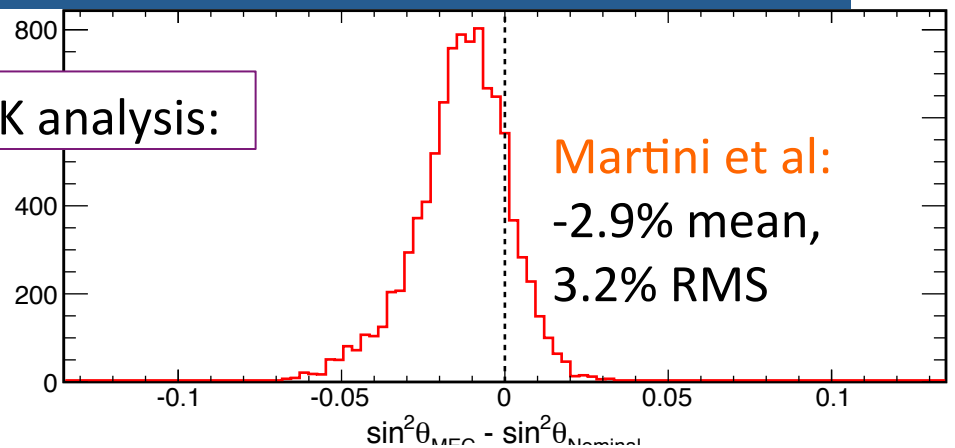
Neutrino
Precision
Reaction
Independent
Spectrum
Measurement

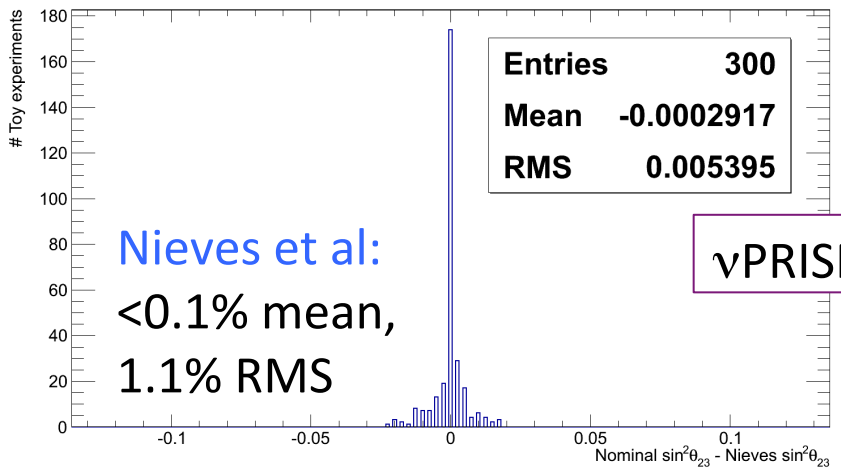
$$\Phi(\Delta m^2_{32}, \theta_{23}) = \sum_{i=0°}^{\theta_{max}} k_i \ \phi_i(E_\nu)$$

nuPRISM and an oscillation analysis

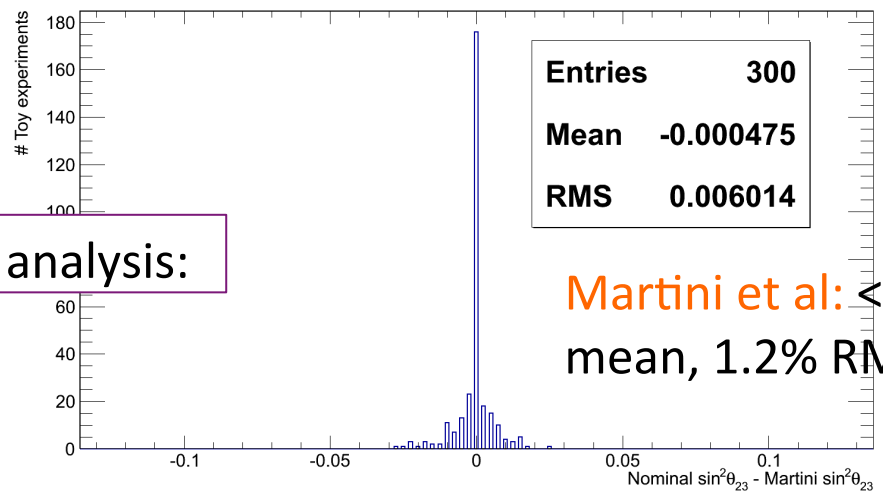


Standard T2K analysis:





νPRISM analysis:



Reminder: tested possible bias on T2K disappearance measurement

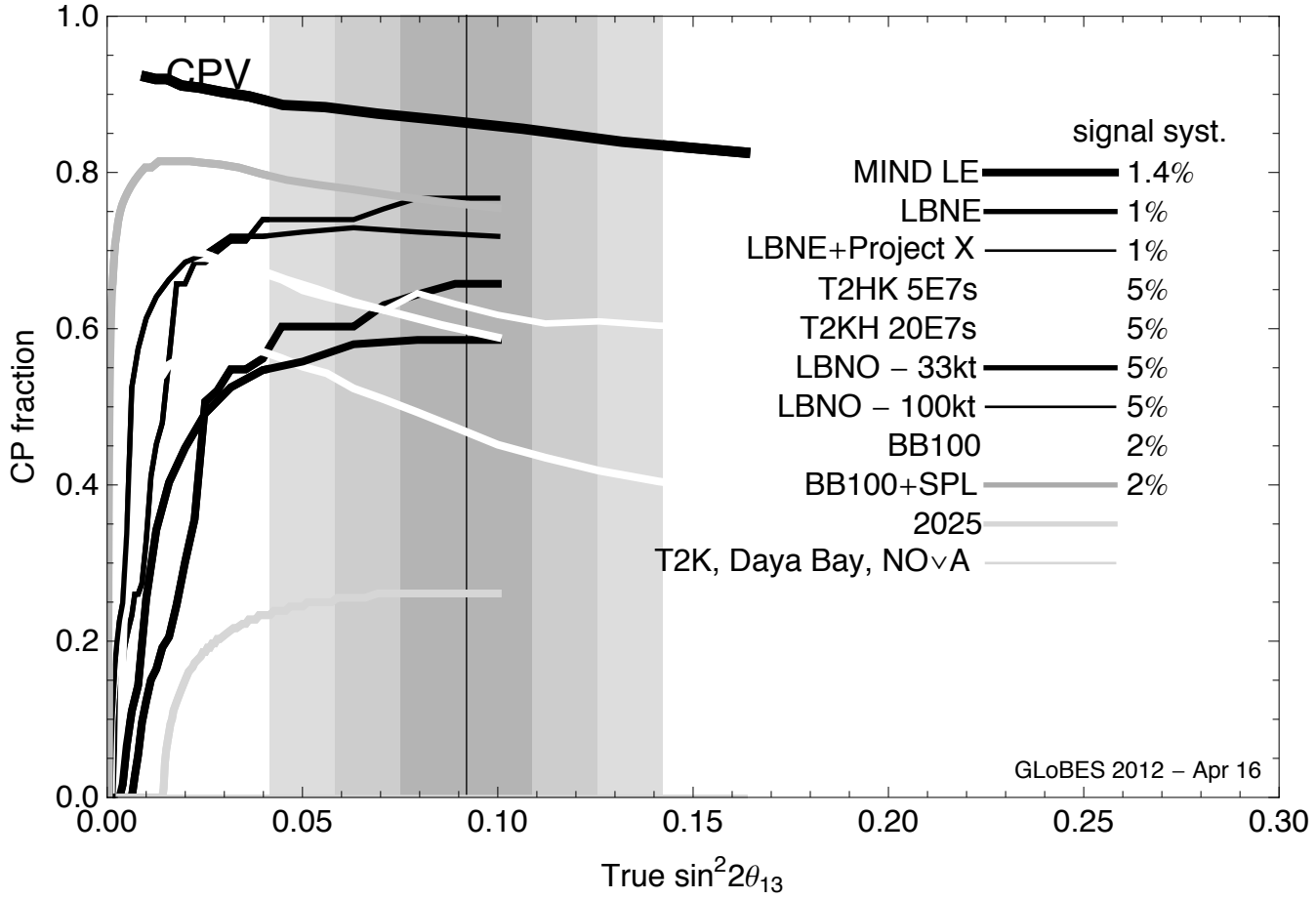
- Generate fake data under flux, detector, cross section variations, and perform full oscillation analysis including ND constraint
- For each fake data set, compare fitted θ_{23} with and without a 2p2h model present

%%%%%%%%

% %'.4-%"1*H4/1B%L,%B424%B".61F%$14-@"1$1F2%

N#--.LH1%(\%G#"%C,*1"P]4$.#I4FB1;%^**"#4/+%$4,%E#"I%G#"%#2+1"%15*1".$1F2-%%

Roadmap



With θ_{13} "large", then ACP is small (~20-30%), so the measurement of δcp needs uncertainties of <5% or better on normalization and shape

Future experiments need rate! Superbeams may be possible but will be challenging. What are some other ideas for neutrino sources?

A muon-based neutrino beam?

Only one neutrino and antineutrino produced in muon decay (pure beam)

$$\mu^- \rightarrow e^+ + \overline{\nu}_e + \nu_\mu$$

Flux is "easy": measure muons rate and kinematics

Sign selects flavor; control of muon polarization affects neutrino/antineutrino flux

S. Geer, hep-ph/9712290v1

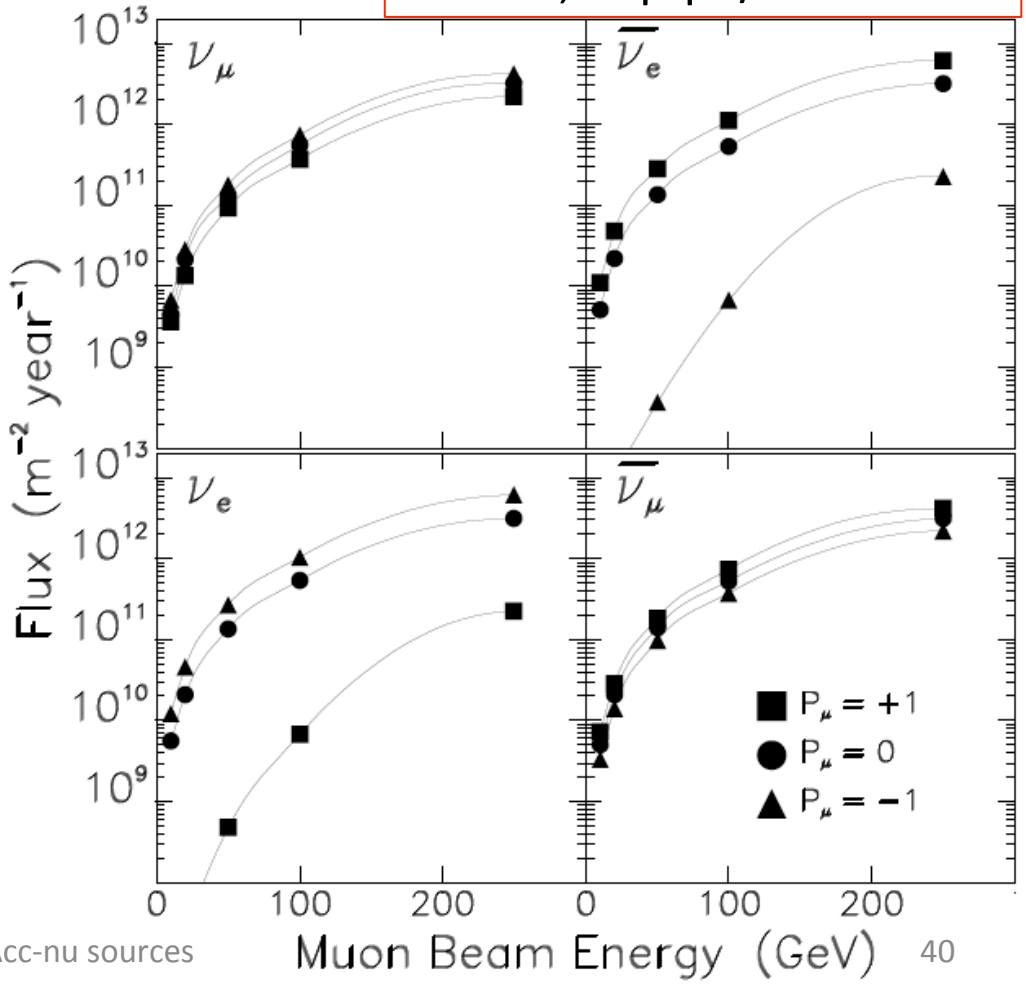
Example CP violation long baseline experiment: ν_e to ν_μ oscillation

Impressive rate even at 9900km (wow!)

Search for μ at far detector

$\overline{\nu}_\mu$ in beam would produce μ^+

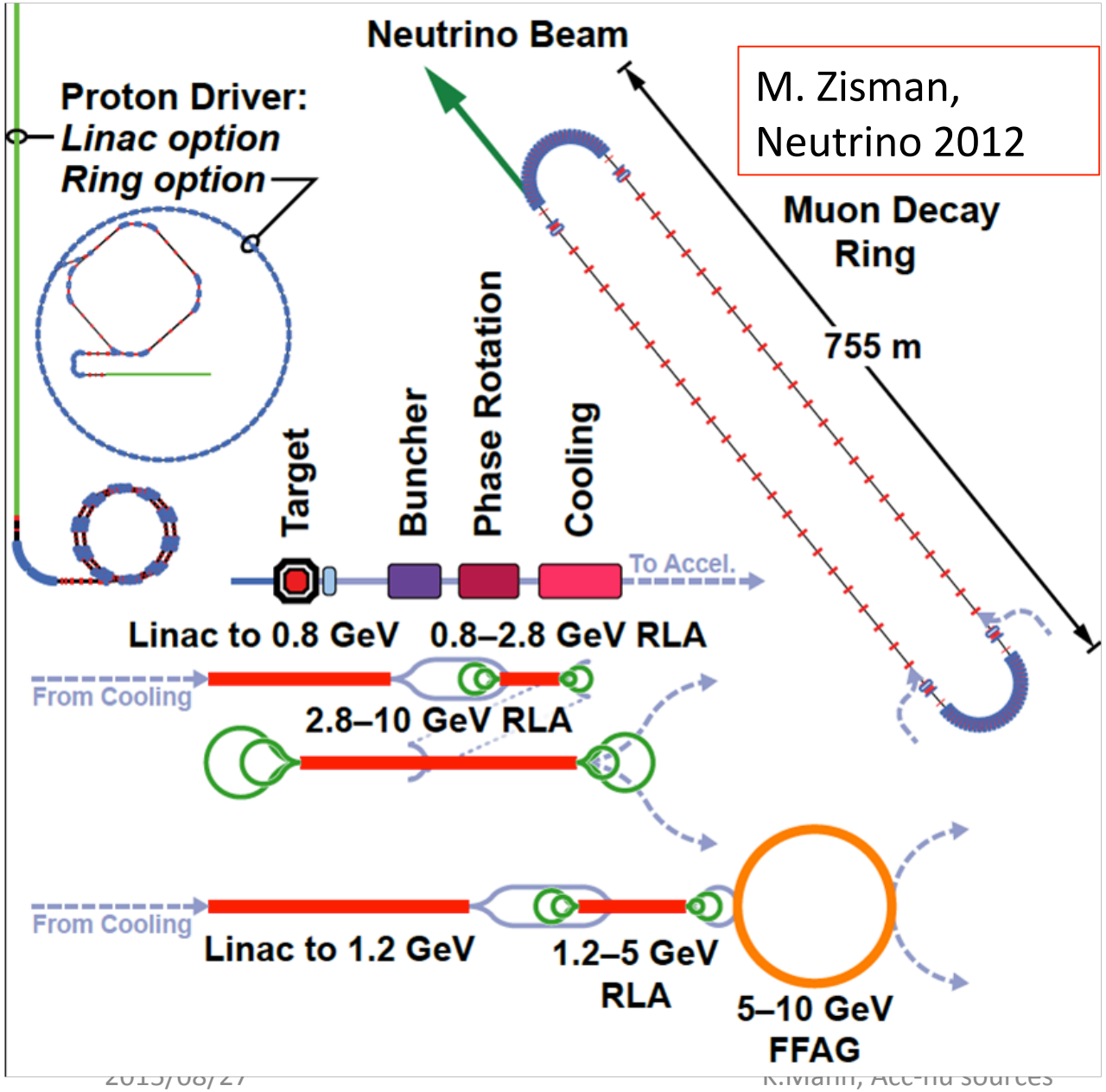
- Other (NC) backgrounds: π decay to μ, π mistaken for μ
- Need a detector with sign selection
- Magnetized Iron Neutrino Detector (MIND)
- Totally Active Scintillator Detector



A neutrino factory

Use a standard neutrino beamline to produce pions and let them decay to muons

Requires a superbeam (HARP) and liquid target (MERIT, mercury)



Bunch and phase rotate them

Cool them (MICE)

Accelerate them (EMMA)

Store them, and let them decay to produce a neutrino beam

Dedicated R&D projects to produce each of the steps:

1) Large energy spread, transverse phase space of the muons
2) Short lifetime before decay requires rapid beam manipulations

A neutrino factory

Use a standard neutrino beamline to produce pions and let them decay to muons

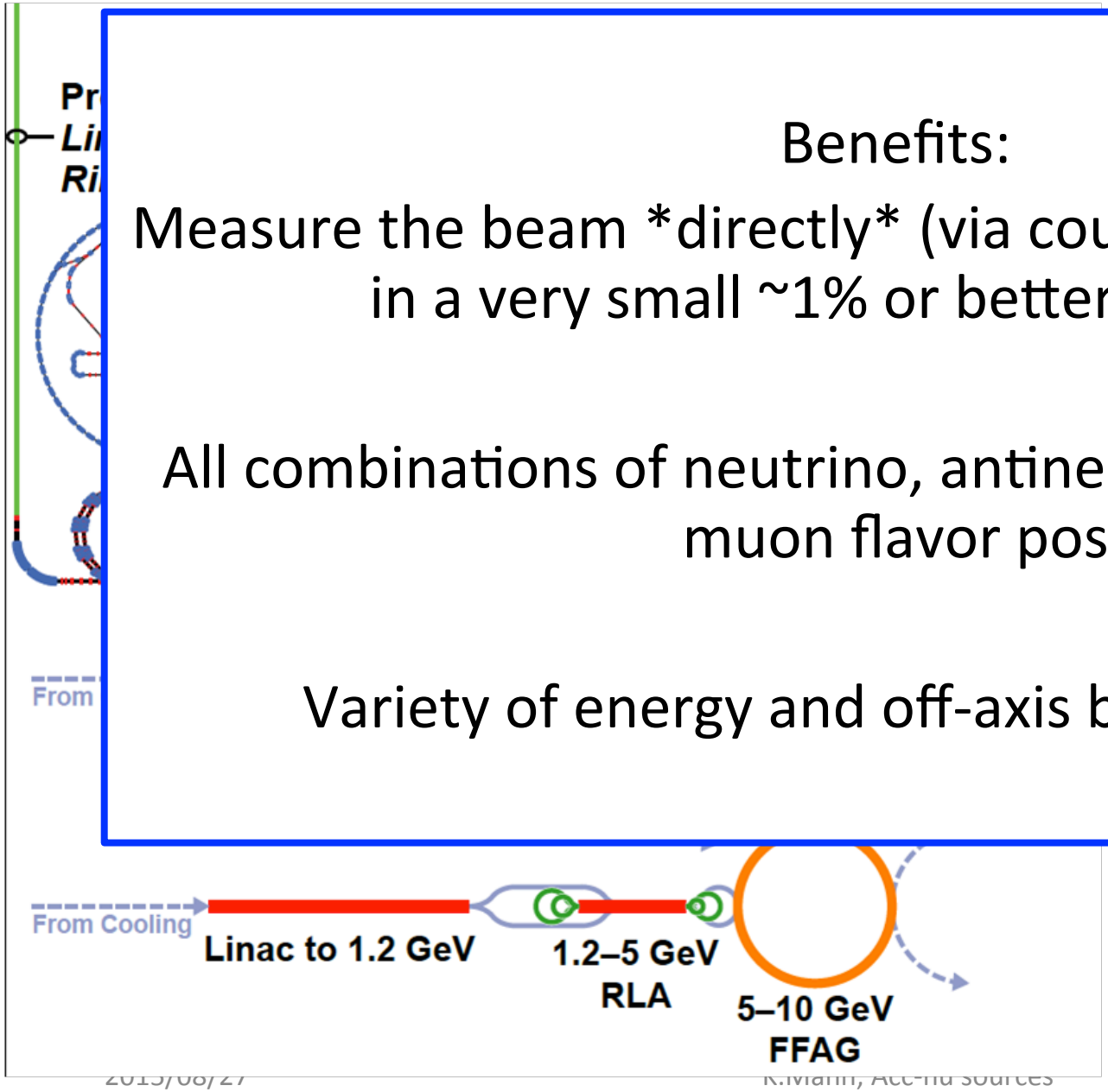
Requires a superbeam (HARP) and liquid target (MERIT, mercury)

Benefits:

Measure the beam *directly* (via counting muons) results in a very small ~1% or better flux uncertainty

All combinations of neutrino, antineutrino and electron, muon flavor possible

Variety of energy and off-axis beams possible

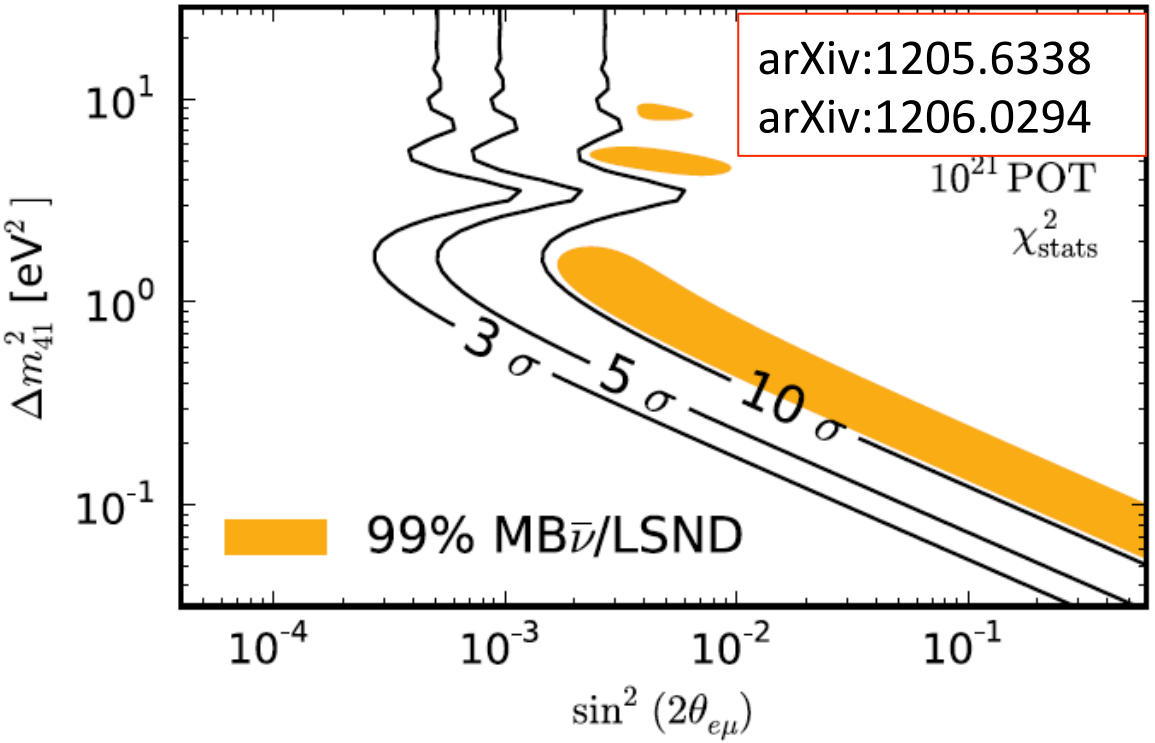


2) Short lifetime before decay requires rapid beam manipulations

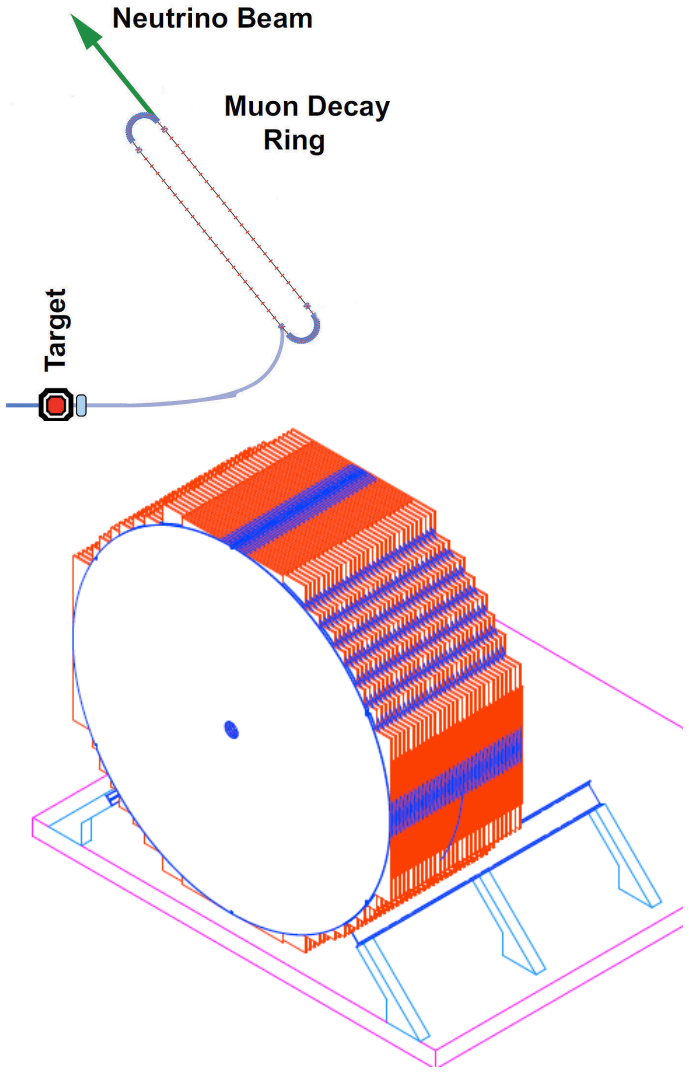
Example use of a neutrino factory: vSTORM

Build a starter facility for a neutrino factory with existing technology (minimal R&D)

- 60 GeV p beam
- Produce and focus π for μ beam
- Build muon decay ring to produce
- Neutrinos from STORed Muons



Physics goals: sterile ν search (ν_e to ν_μ osc)
E~3 GeV, L~2km



Far detector needs sign selection:

- CC ν_μ produces μ^-, and reject μ^+
- MINOS-like detector (iron plates in B field)

What about isotope decay?

- Isotopes (beta emitters) also produce pure ν or $\overline{\nu}$ beams:

$$^{6}_{2}He^{++} \rightarrow ^{6}_{3}Li^{+++} + e^{-} + \overline{\nu}_{e}$$

P. Zucchelli
Phys Lett B 532
(2002) 166–172

CP violation experiment with a beta beam is similar to a neutrino factory

- ν_e to ν_μ oscillation (or antineutrino mode)

Additional advantages:

- No need for a magnetized detector
- Energy spectrum determined from electrons emitted from decay at rest, and boost:
  Assuming γ~100, get E_ν~0.4 GeV

$$E_\nu \leq 2Q\gamma$$

- "Free" focusing of ν beam comes from boost:

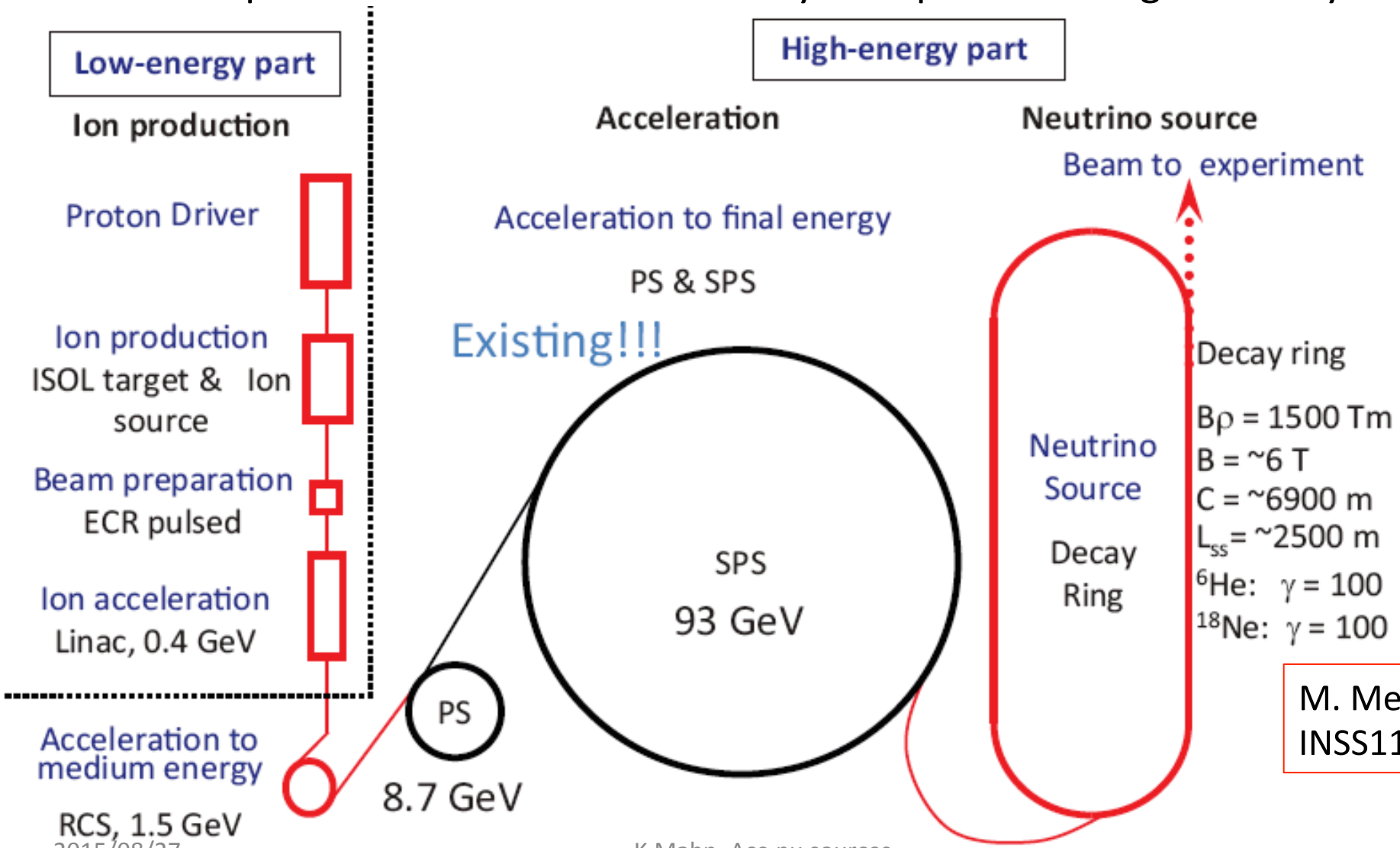
$$\theta \leq \frac{1}{\gamma}$$

A beta beam

Also requires proton driver, like neutrino factory

Work ongoing to prepare sufficient production and acceleration of isotopes

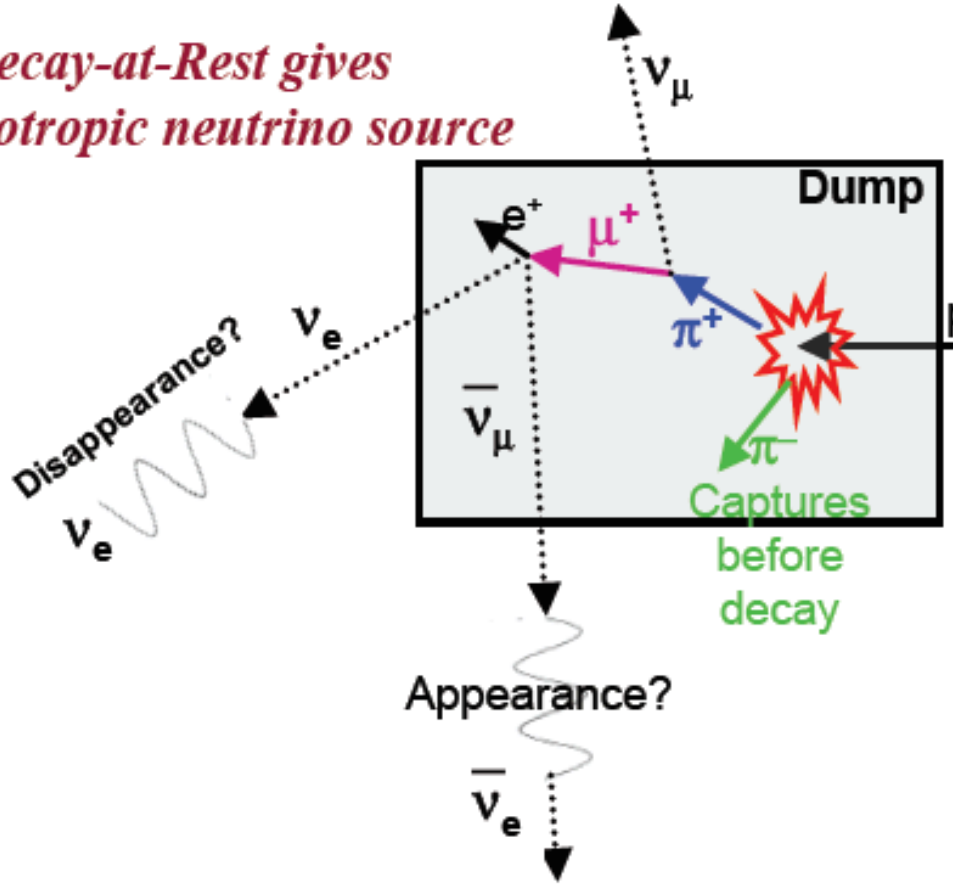
- Long isotope lifetime to avoid decays during acceleration
- Short isotope lifetime otherwise too many isotopes to manage in decay ring



M. Mezzetto, INSS11

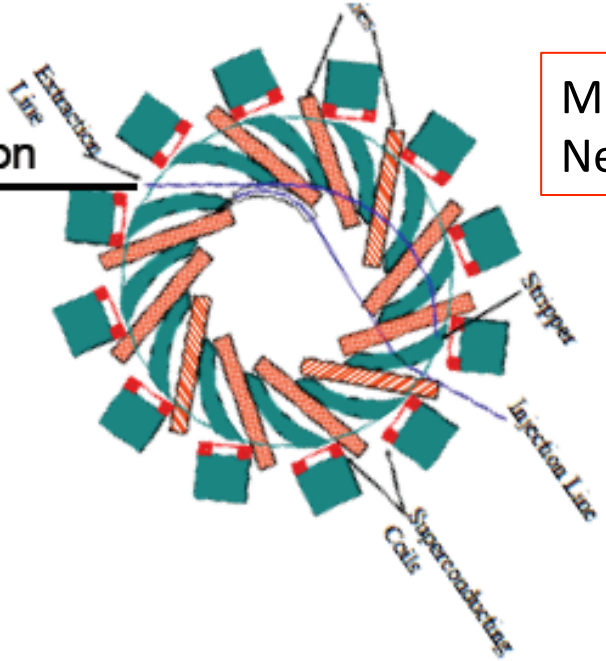
Decay at rest (DAR) or "beam dump" beams

Decay-at-Rest gives isotropic neutrino source



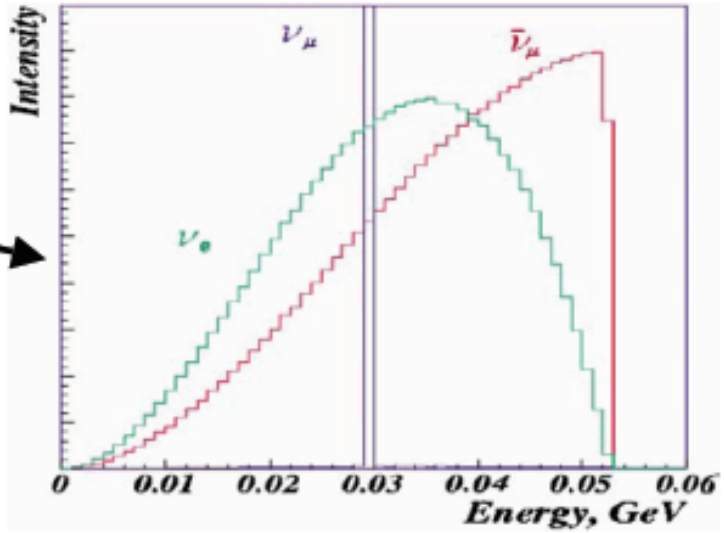
Cyclotron or Other Proton Source

(>800 MeV proton for π production)



M. Shaevitz, Neutrino 2012

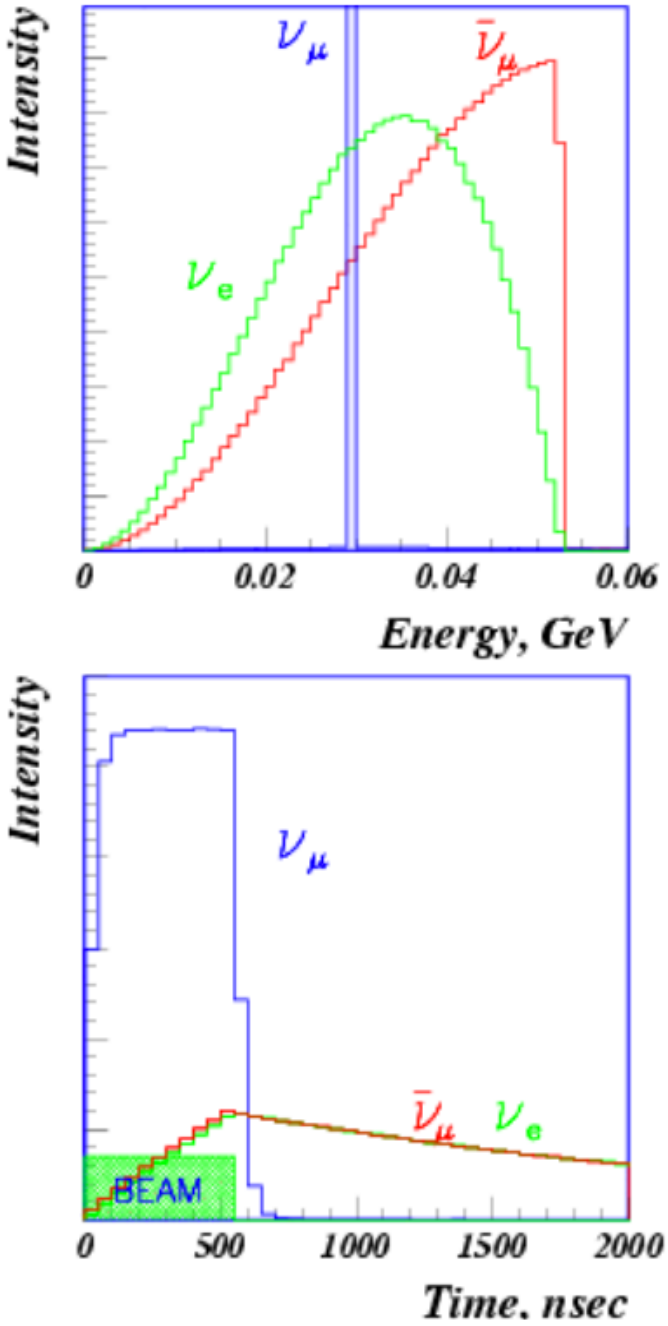
Each π^+ decay gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ with known energy spectrum



~1 ma of 800 MeV protons (like LSND)

$\Rightarrow$ 0.17 π^+/proton $\Rightarrow$ 2.3×10^{24} ν/yr

Decay at rest (DAR) source, detection



Features:

- $\bar{\nu}_\mu$ oscillates to $\bar{\nu}_e$
- no intrinsic beam background
- Information from timing

Detection: Inverse beta decay coincidence signal:

- $\bar{\nu}_e$ interacts, produces electron (prompt)
- Neutron captures, releasing ~8MeV photons (delayed)
- Well known cross section
- Flux controlled by nue + ^{12}C -> e- + ^{12}N

OscSNS: arXiv:1307.7097

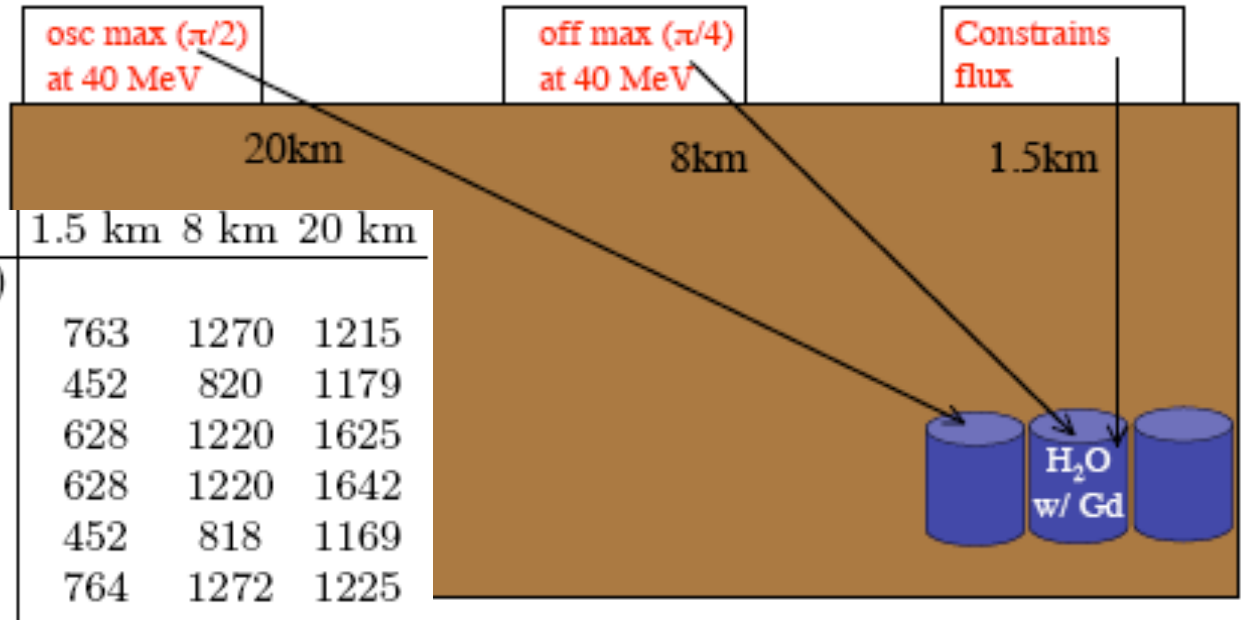
CP violation with DAR beam

Daedalus:

- Instead of a fixed baseline and multiple detectors, use multiple beamlines and one detector; short distances mean matter effects can be neglected
- Requires compact, intense cyclotrons and a large H_2O detector such as Hyper-Kamiokande:
- $\overline{\nu}_\mu$ to $\overline{\nu}_e$ oscillation:
  - Identify $\overline{\nu}_e$ with inverse beta decay (signal)
  - Use different beam on periods to associate events with each baseline
  - Relative normalization between sources done with ν+e and ν_e+O interactions

PRL 104 (2010) 141802

Event Type	1.5 km	8 km	20 km
IBD Oscillation Events ($E_\nu > 20$ MeV)			
$\delta_{CP} = 0^0$, Normal Hierarchy	763	1270	1215
" , Inverted Hierarchy	452	820	1179
$\delta_{CP} = 90^0$, Normal Hierarchy	628	1220	1625
" , Inverted Hierarchy	628	1220	1642
$\delta_{CP} = 180^0$, Normal Hierarchy	452	818	1169
" , Inverted Hierarchy	764	1272	1225

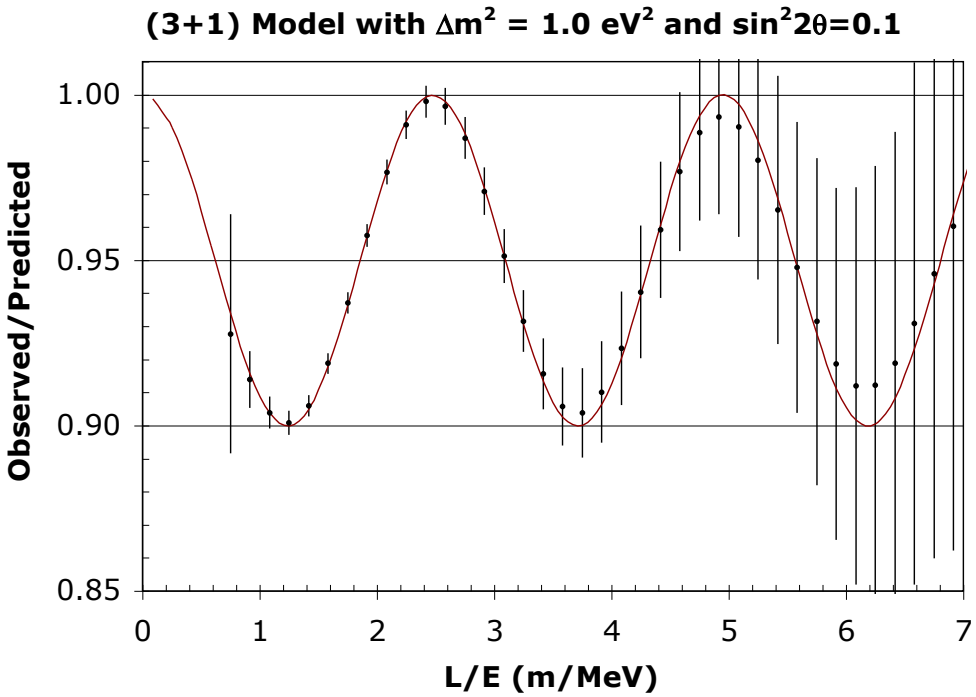


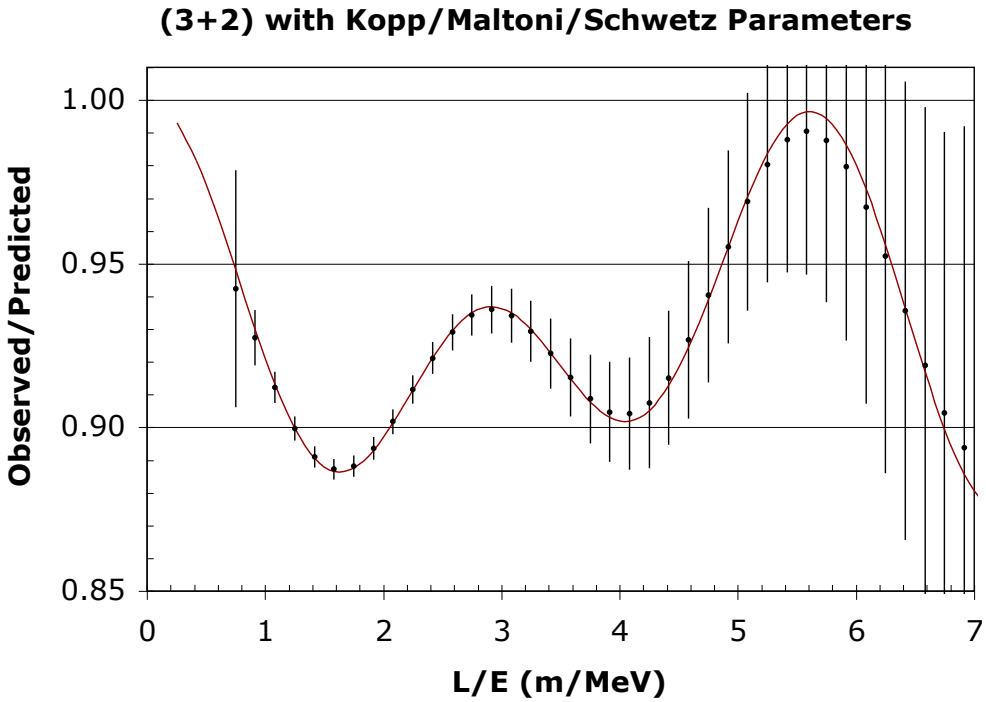
Sterile neutrinos with DAR beams

IsoDAR: Isotope decay at rest

- Intense neutrino source produced from activating ^{7}Li, decays to produce ν_e beam
- Requires compact, intense cyclotrons and a liquid scintillator detector (KamLAND)
- $\overline{\nu}_e$ disappearance:
  - Identify $\overline{\nu}_e$ with inverse beta decay (signal)
  - Oscillation probability changes with *L* over short distances, further details of nature of sterile (or other) anomaly

PRL 109 (2012) 141802



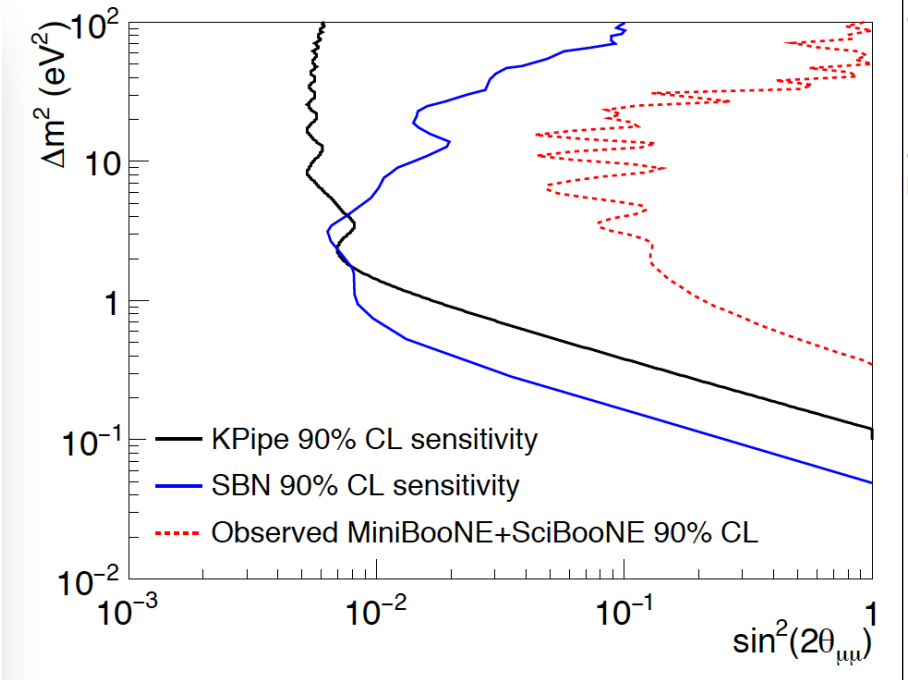


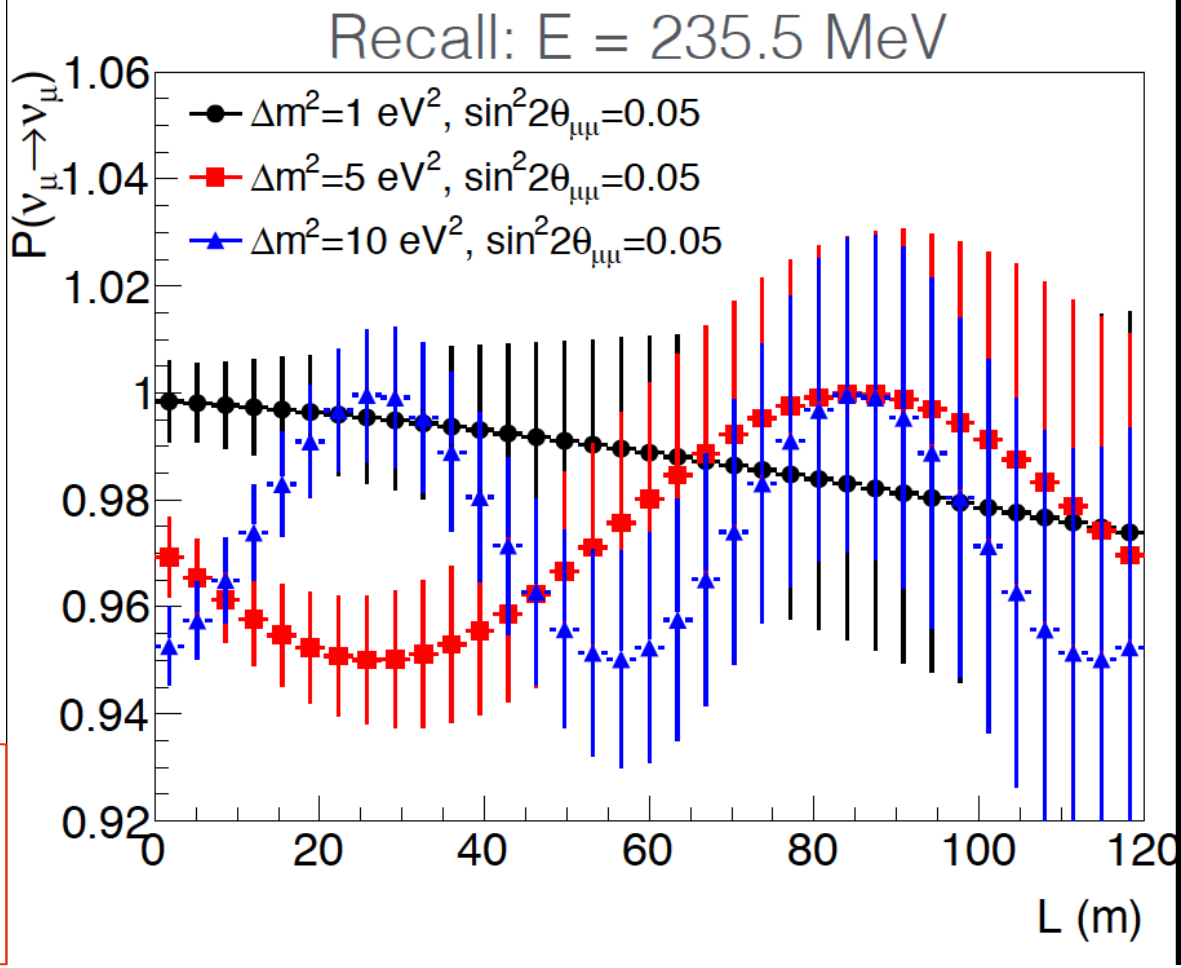
Sterile neutrinos with DAR beams

Kpipe: Isotope decay at rest

- Beam dump at J-PARC produces kaons which decay at rest, monoenergetic flux
  - Uses neutron source. Direct checks of LSND (OscSNS, JSNS) use such beams
- Large, cylindrical tank of liquid scintillator
- ν_μ disappearance: tag with CCQE interaction

arXiv:1506.05811,
S. Axani, DPF2015





More details:
OscSNS: arXiv:1307.7097
JSNS: arXiv:1310.1437,arXiv1502.02255

Summary

Accelerator based neutrino beams are a cornerstone of neutrino physics

- Discovery of the muon neutrino type
- Study of neutrino mixing
- Searches for non standard interactions, like sterile neutrinos

Future experiments will continue to use neutrino beams

- Building and improving on what we've learned about accelerator based neutrino beams thus far
- Or employing new kinds of beamlines to approach the physics differently
- Beta beams? Neutrino factories? Your idea here!

Backup slides