Accelerator Neutrino Programme in the USA:

Stephen Parke

Krakow

Jan 6, 2010

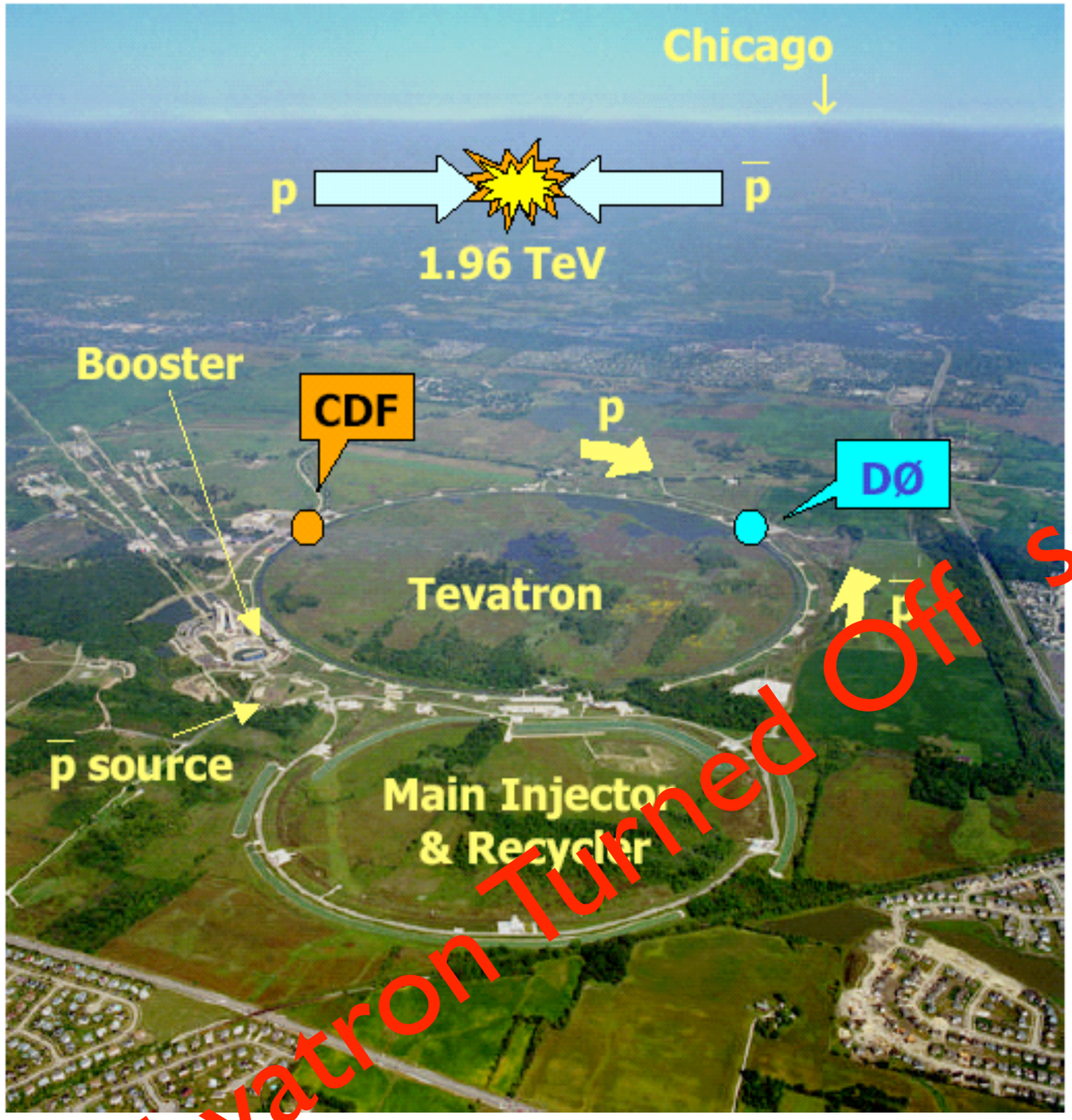
Accelerator Neutrino Program in the Fermilab:

Stephen Parke

Krakow

Jan 6, 2010

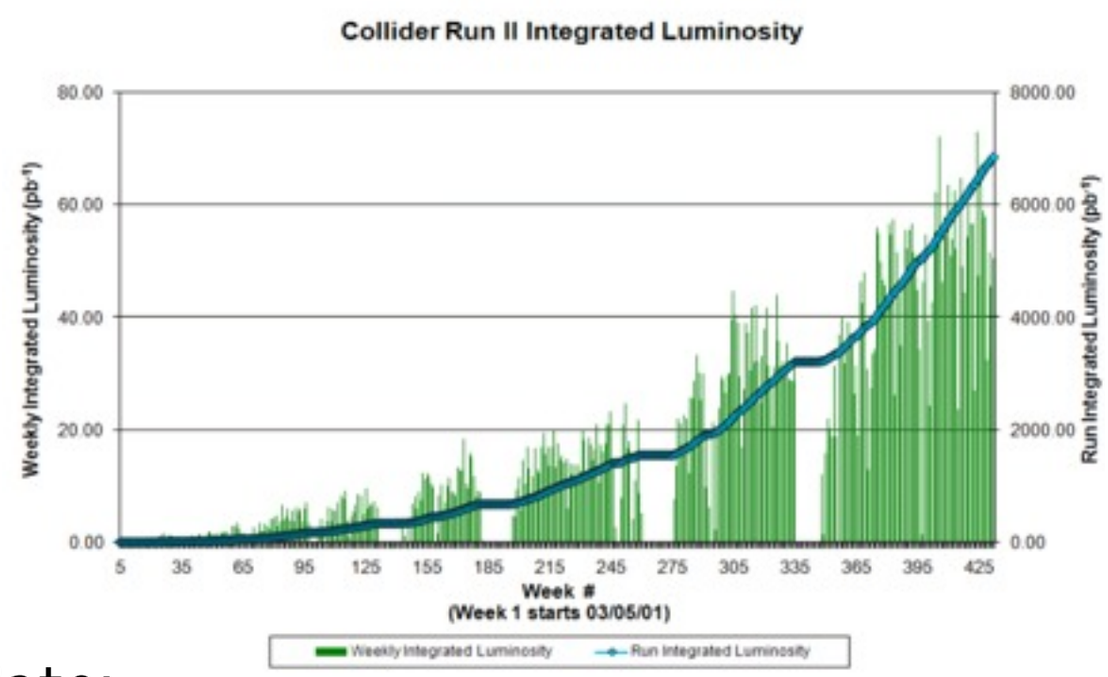
Tevatron: CDF & D0



- 36x36 bunches
- bunch crossing 396 ns
- Run II started in March 2001
- Peak Luminosity:3.5E32 cm^{-2} sec^{-1}
- Run II delivered: ~7 fb^{-1}

Peak Intergrated Luminosity:

$$3.5 \times 10^{32}\ cm^{-2} sec^{-1} \times 3 \times 10^{7} sec \approx 10 fb^{-1}/yr$$



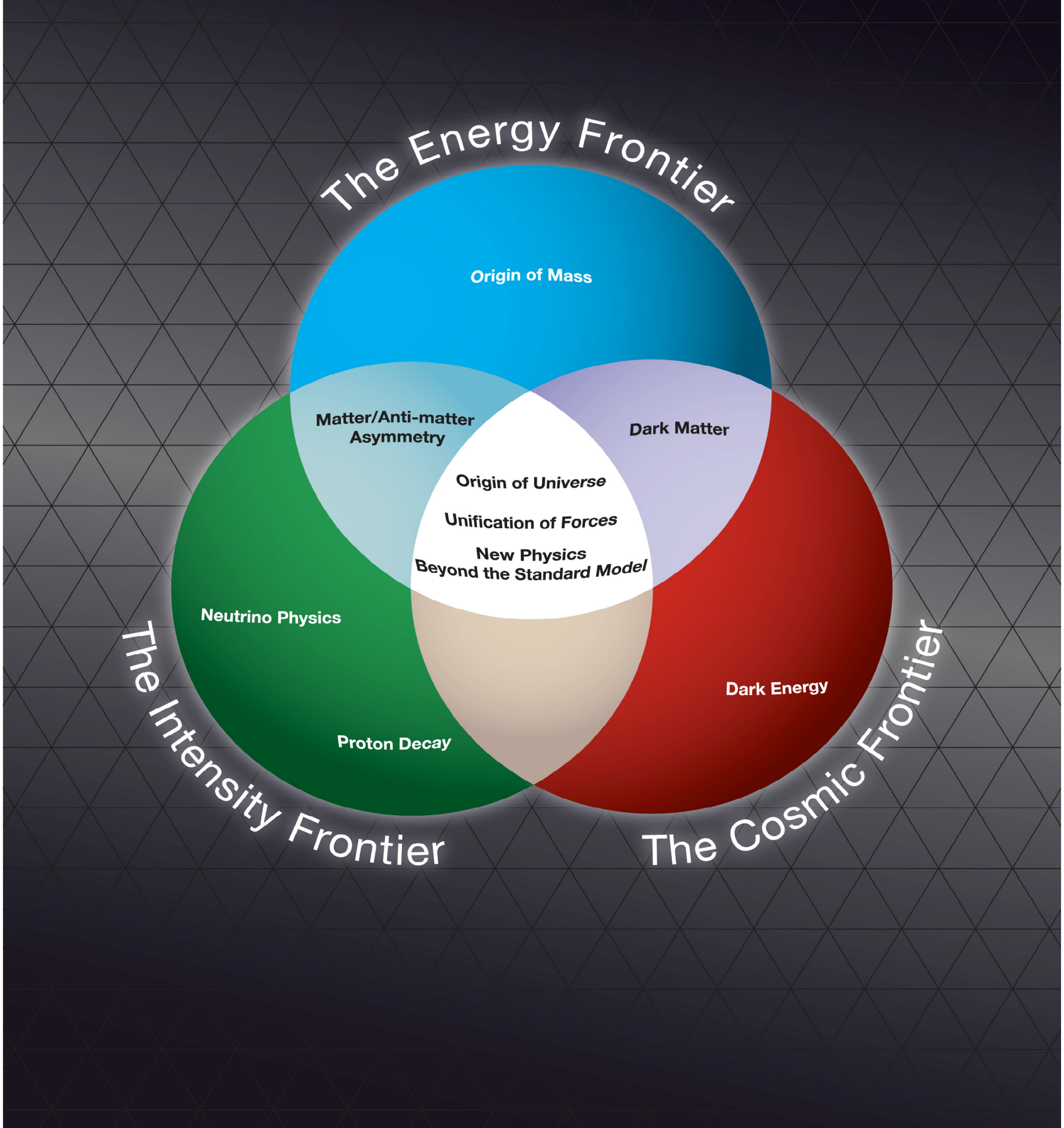
Tevatron Turned Off sometime in 2011

Peak $\bar{p}$ Collection Rate:

$$7 \times 10^{7}/sec$$

Peak $\bar{p}$ Burn Rate:

$$2 \times 3.5 \times 10^{32}\ cm^{-2} sec^{-1} \times 100\ mb = 7 \times 10^{7}/sec$$


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 Copyright © 1998 The New York Times FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

1. Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .
2. . . . and collide with other particles . . .
3. . . . producing a cone-shaped flash of light.
4. The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Last December, Mr. Nichols was convicted of conspiring with Timothy J. McVeigh to use a weapon of mass destruction in the April 19, 1995, bombing of the Alfred P. Murrah Federal Building, but was acquitted of Federal murder charges in the deaths of eight Federal agents who died. Mr. Nichols was found guilty of involuntary manslaughter in those deaths and today was given the maximum sentence of six years in prison for each, to run concurrently with his life sentence. He was also acquitted of actually committing the bombing.

While the conspiracy charge carried a possible death sentence, the jurors need to vote unanimously for such punishment, and they could not do so. The sentencing then fell to Judge Matsch.

Mr. McVeigh was convicted on all

Bajram Curri, in nc
Yugoslavia in three

Refugees
A Bitte

PADESH, Albania,
dent Slobodan Milose
via has unleashed ti
tary operation in the
the end of the war in
thousands of ethnic
the border area wi
reducing their village

At least 10,000
streamed through
passes and thousands

Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ 500km/GeV

Atmos. L/E $\mu \leftrightarrow e$

Solar L/E $e \to \mu, \tau$ 15km/MeV

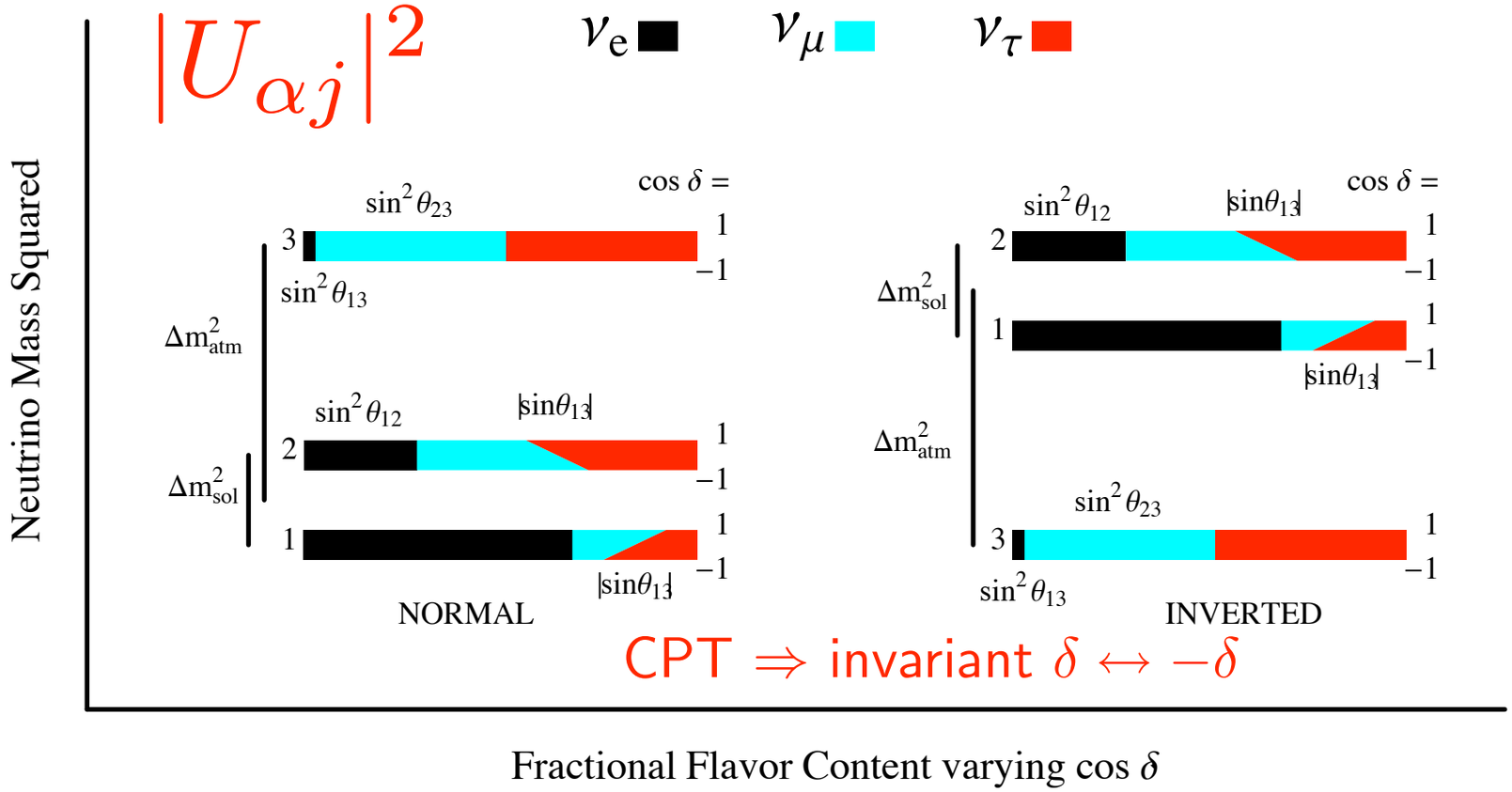
$0\nu\beta\beta$ decay

solar/KamLAND

Reactor/LBL

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Atmospheric Nus



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

$$\sin^2\theta_{12} \sim 1/3$$

$$\sin^2\theta_{23} \sim 1/2$$

$$\sin^2\theta_{13} < 3\%$$

$$0 \leq \delta < 2\pi$$

One Global Fit:

Dominated by

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

KamLAND
MINOS
SNO
SuperK
Chooz

arXiv:0808.2016

At 2σ we have the following limits:

$$\begin{aligned} \sin^2\theta_{13} &< 0.04 \\ |\sin^2\theta_{12} - \frac{1}{3}| &< 0.04 \\ |\sin^2\theta_{23} - \frac{1}{2}| &< 0.12 \end{aligned}$$

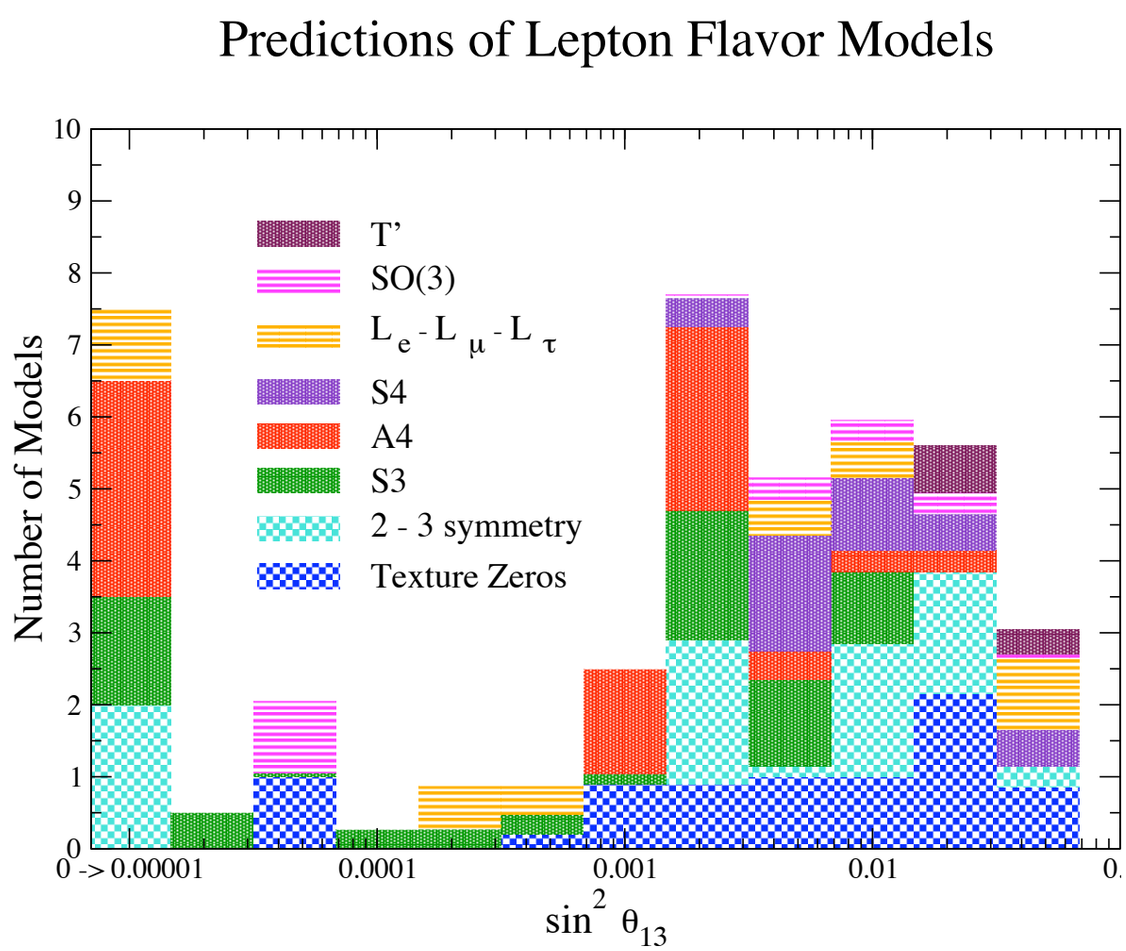
Close to Tri-Bi-Maximal: accident or symmetry ?

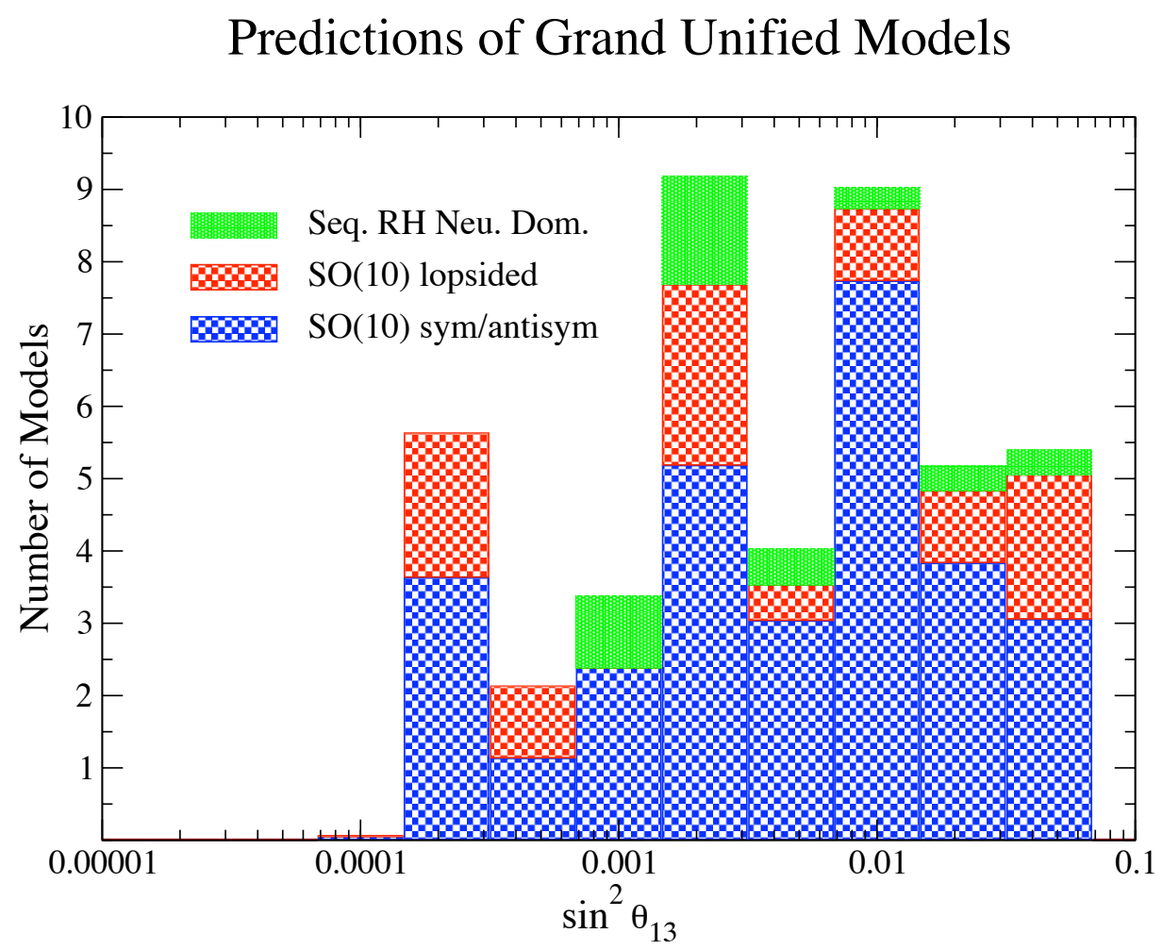
In numerous models:

$$\sin^2\theta_{13},\ |\sin^2\theta_{12} - \tfrac{1}{3}|,\ |\sin^2\theta_{23} - \tfrac{1}{2}| \ \sim\ \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^n$$

Experiment has probed down to n $\approx$ 1/2 to 1 !!!

MODELS:


Predictions of Lepton Flavor Models
Number of Models
T'
SO(3)
L e - L μ - L τ
S4
A4
S3
2 - 3 symmetry
Texture Zeros
0 -> 0.00001
0.0001
0.001
0.01
0.
sin 2 θ13


Predictions of Grand Unified Models
Number of Models
Seq. RH Neu. Dom.
SO(10) lopsided
SO(10) sym/antisym
0.00001
0.0001
0.001
0.01
0.1
sin 2 θ13

Neutrino Questions:

Mass Spectrum:

- Quasi-Degenerate ?
- Hierarchical ?
- Normal or Inverted ?

Mixings:

- Deviations from $U_{Tri-Bi-Max}$

  $\sin^2\theta_{13}$, $(\sin^2\theta_{23} - 1/2)$, $(\sin^2\theta_{12} - 1/3)$
- Relationship between these deviations and

  $V_{CKM} - 1$

  if any ?
- Magnitude and sign of CPV:

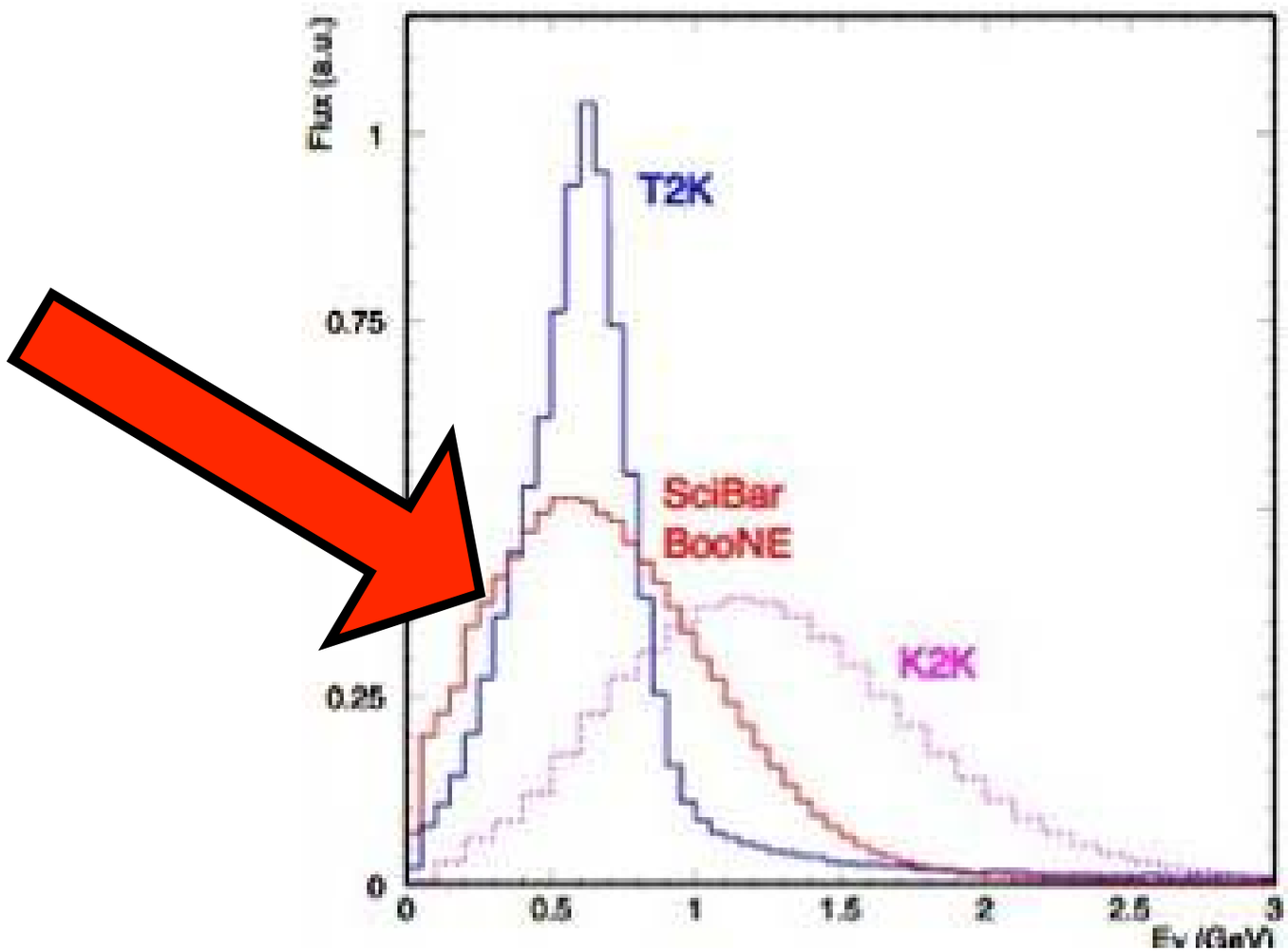
  $\propto \sin\theta_{13}\sin\delta$

Surprises!!!

Neutrino Beams @ Fermilab

- Booster Neutrinos (8 GeV protons)
  - » miniBooNE, SciBooNE, microBooNE
- Neutrinos at Main Injector (NuMI)
  - –(120 GeV protons)
    - » MINOS (near+far), ArgoNut, MINERVA, NOvA
- New Beamline to DUSEL
  - –(60 -120 GeV protons)
    - » LBNE

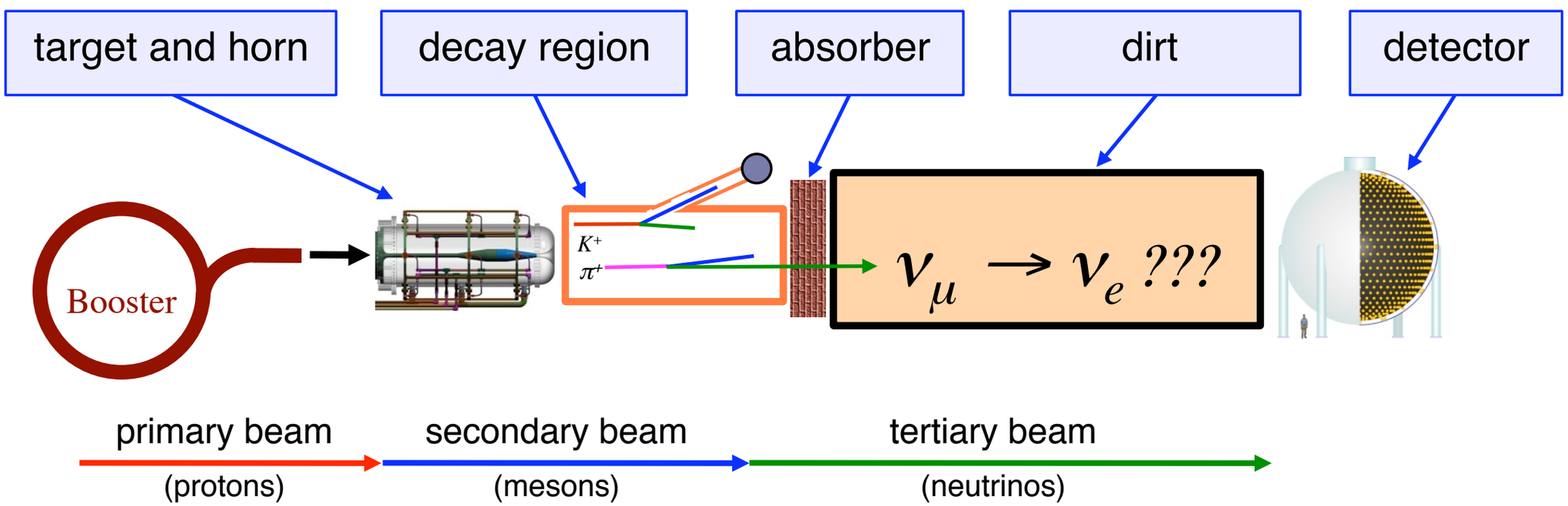
- Booster Neutrinos (8 GeV protons)
  - » miniBooNE, SciBooNE, microBooNE



MiniBooNE's Design Strategy

Keep L/E same as LSND
while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$



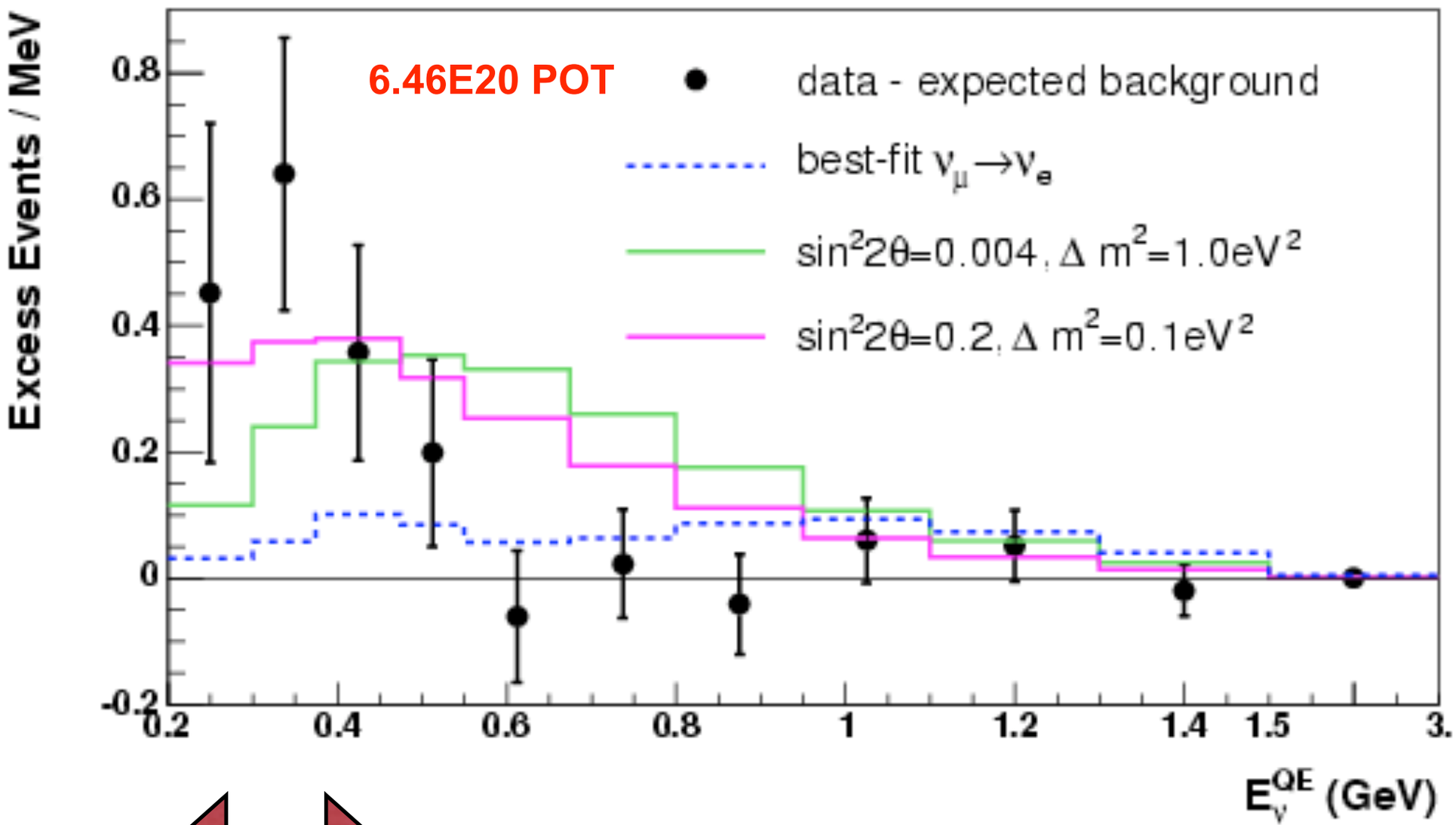
Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

MiniBooNE ν_e appearance data show a low-energy excess

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

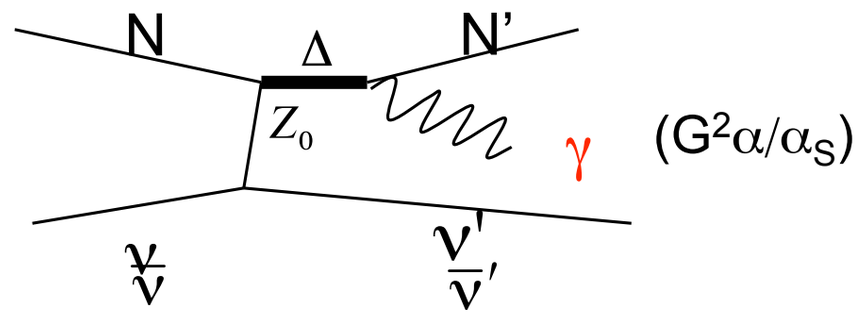
Excess from 200-475 MeV = 128.8+-20.4+-38.3 events



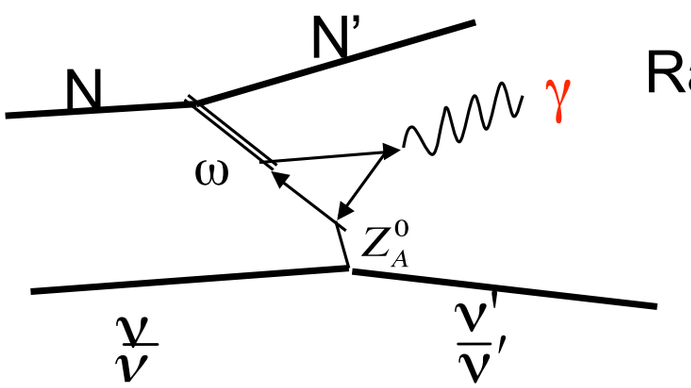
Excess

Backgrounds: Order ($G^2\alpha\alpha_s$) , single photon FS

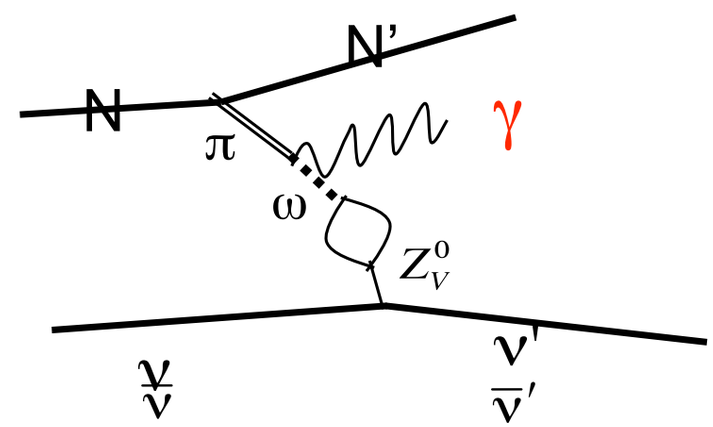
Dominant process accounted for in MC!



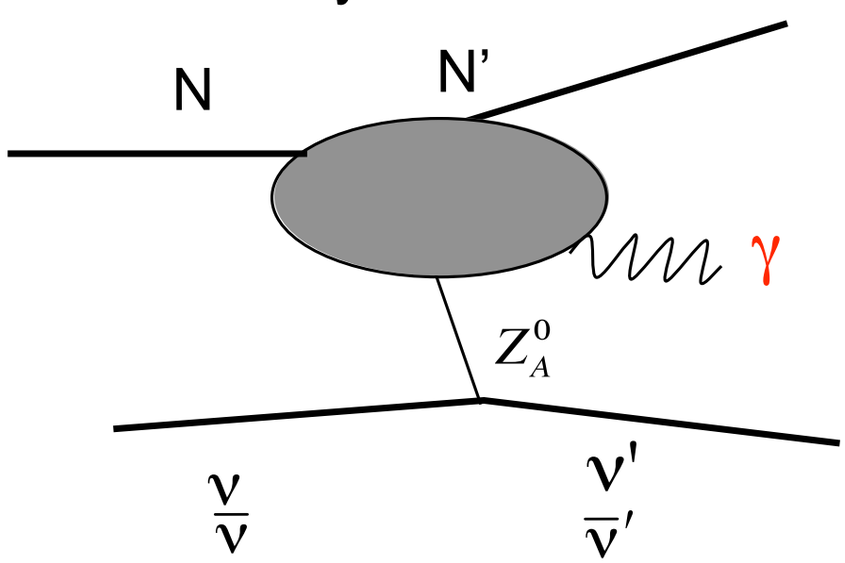
Radiative Delta Decay



Axial Anomaly



Other PCAC



So far no one has found a NC process to account for the $\nu,\bar{\nu}$ difference & the ν low-energy excess. Work is in progress:

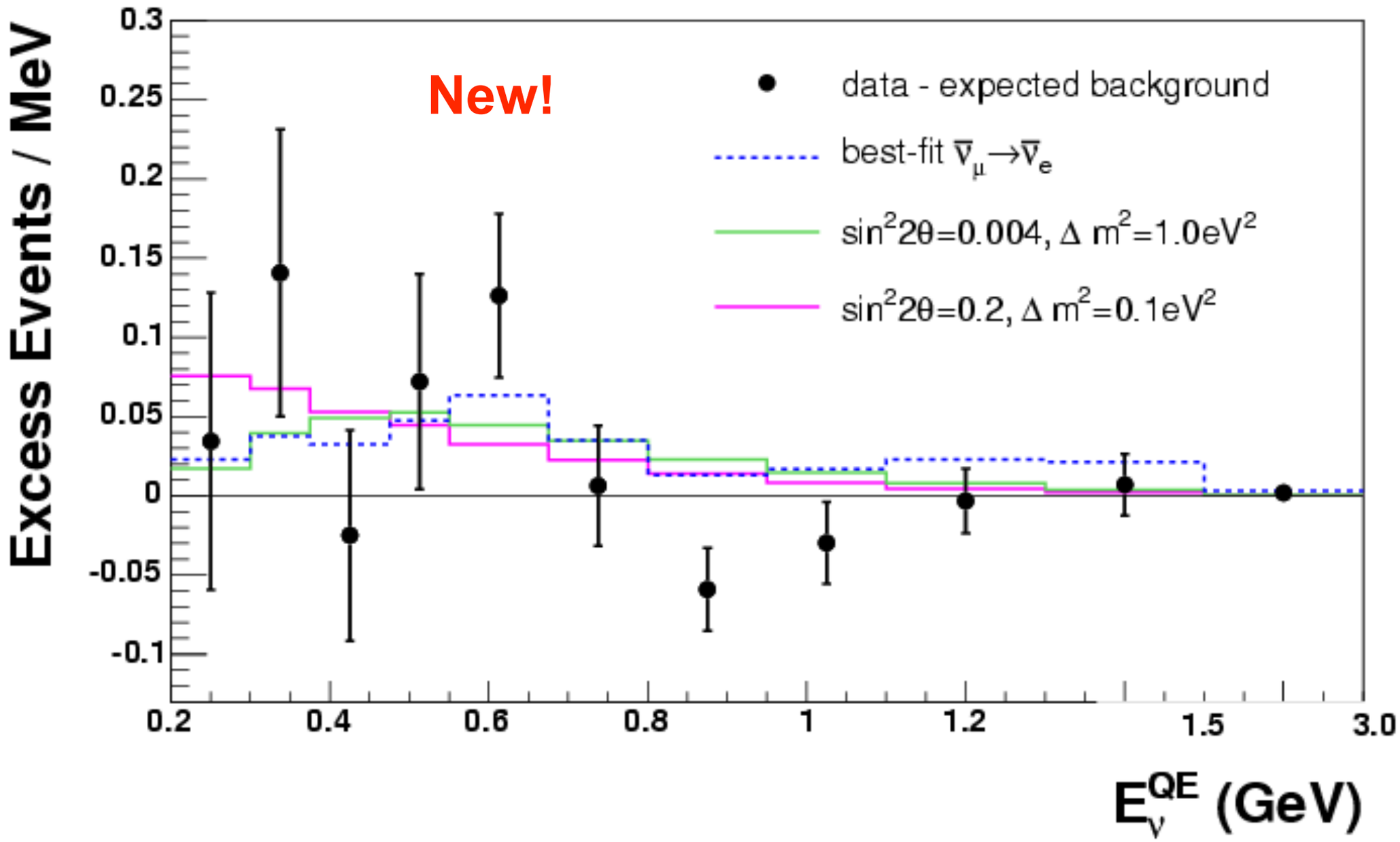
R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

MiniBooNE $\bar{\nu}_e$ appearance data are inconclusive at present but are consistent so far with LSND

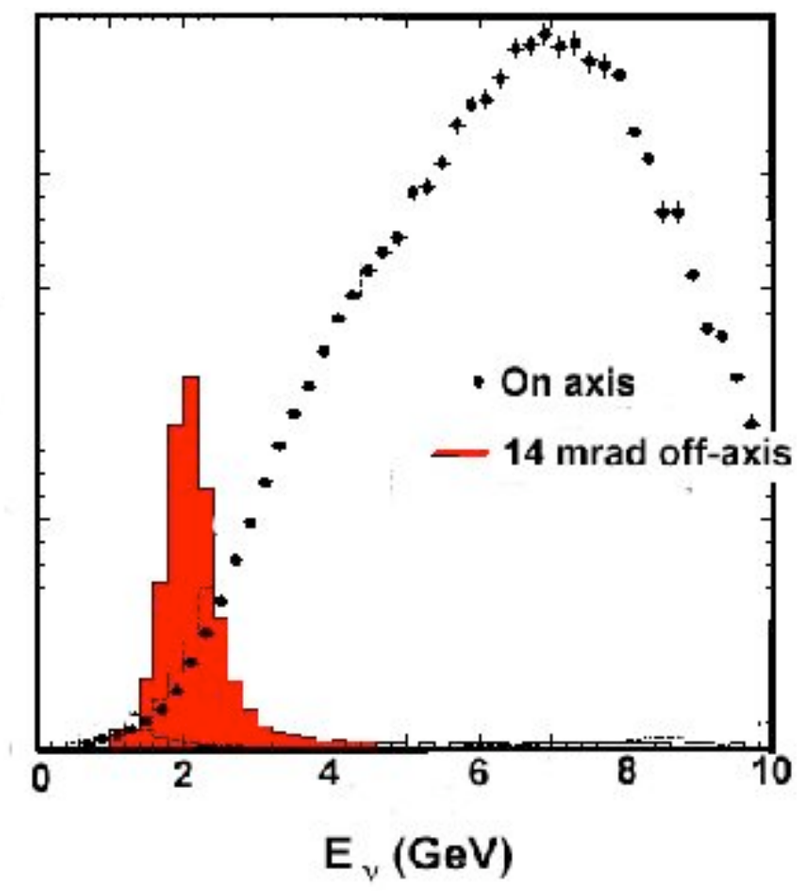
Excess from 200-475 MeV = 11.4 ± 9.4 ± 11.2 events

Preliminary for 4.863E20 POT (~50% increase in POT!)



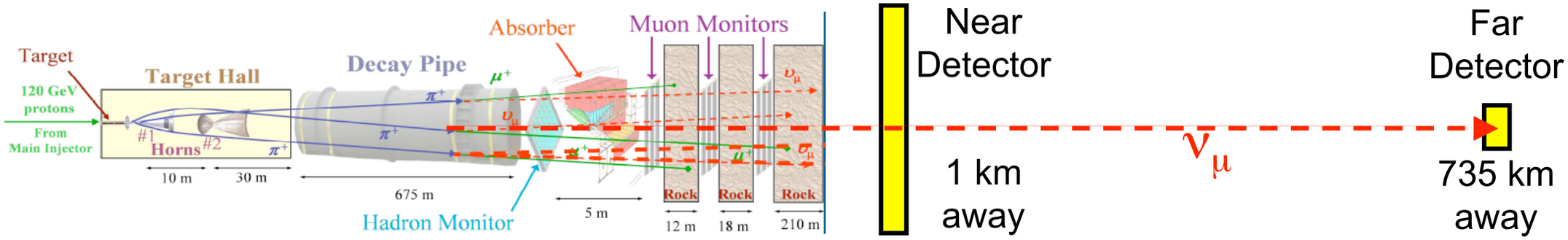
Proposal to move miniBooNE from 541 to 200 m

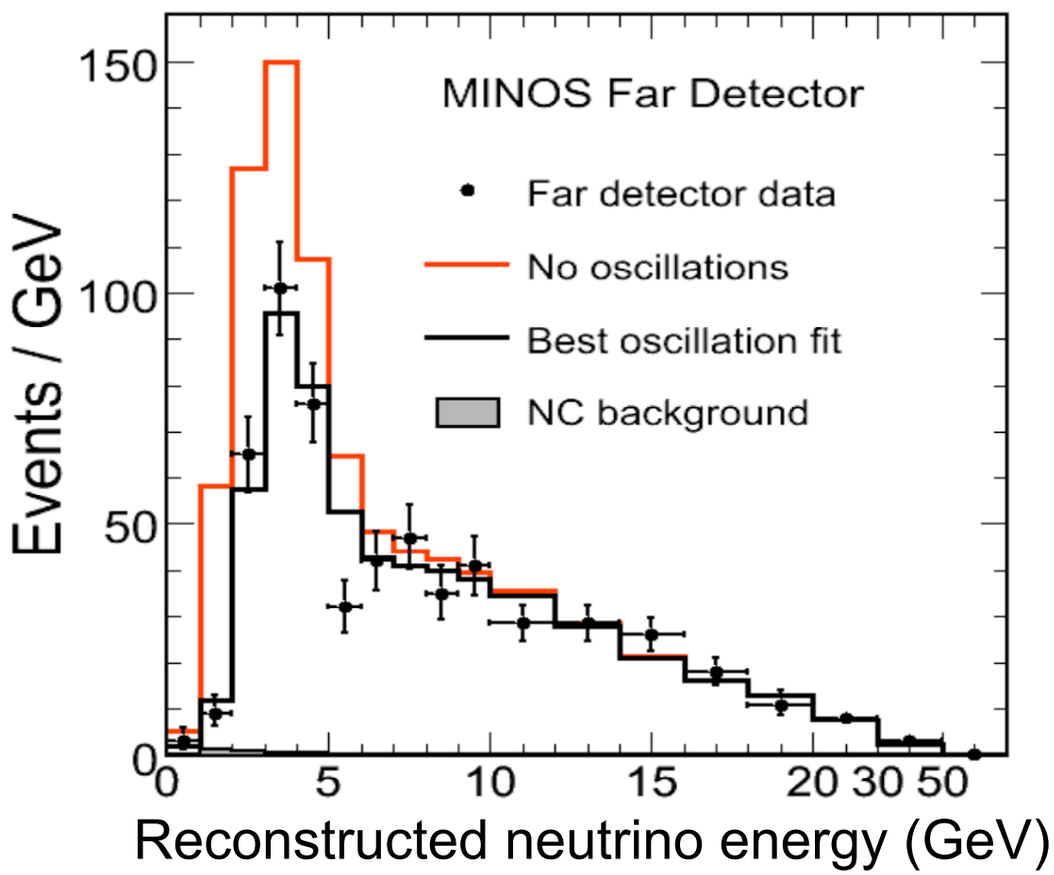
- Neutrinos at Main Injector (NuMI)
  - (120 GeV protons)
    - » MINOS (near+far), ArgoNut, MINERVA, NOvA

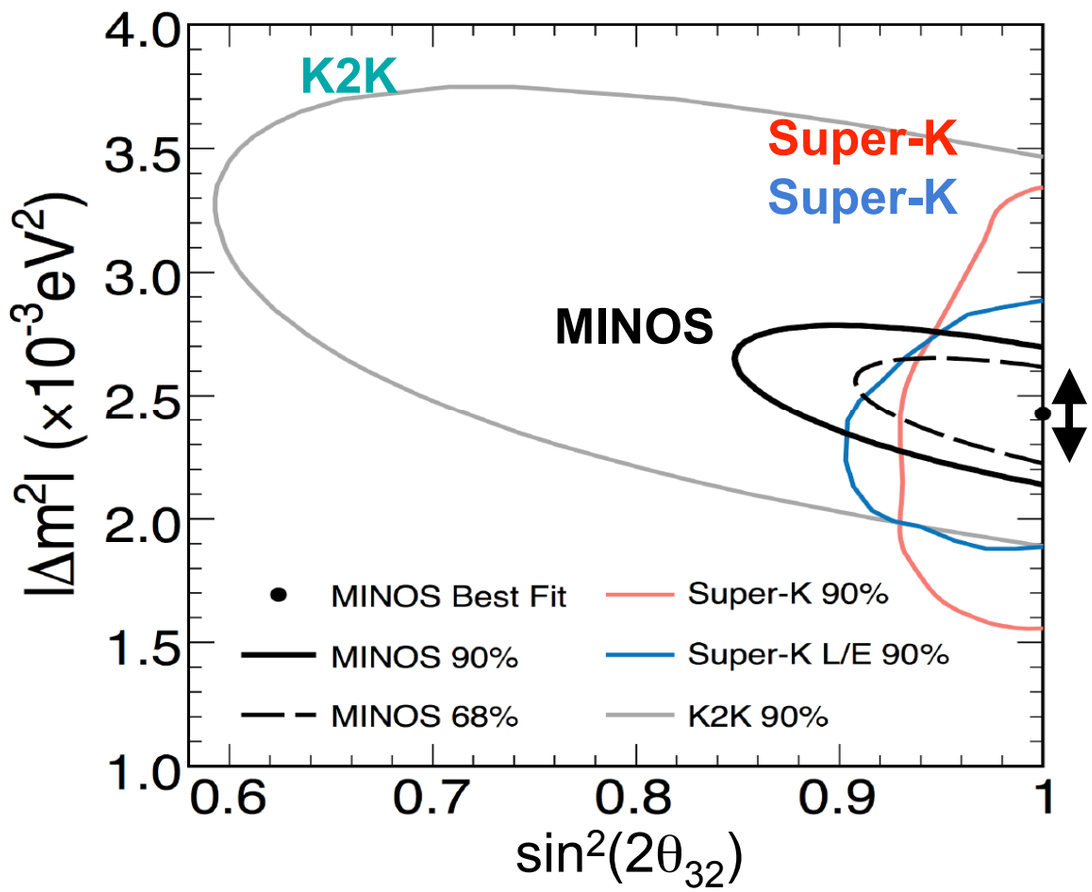


N
Ontario
NOvA
(off-axis)
MINOS (on-axis)
Dakota
Minnesota
735 km
Wisconsin
Michigan
1300 km
Milwaukee
tector
Iowa
MiniBooNE
SciBooNE
MINERvA
Chicago

MINOS: $\nu_\mu \rightarrow \nu_X$ (Best Δm^2_{32} measurement)





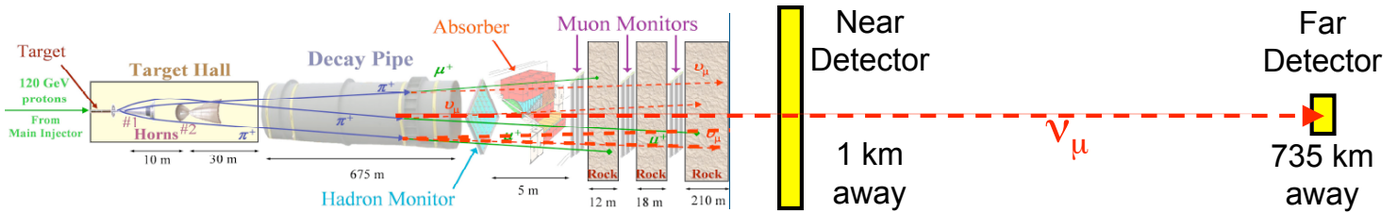


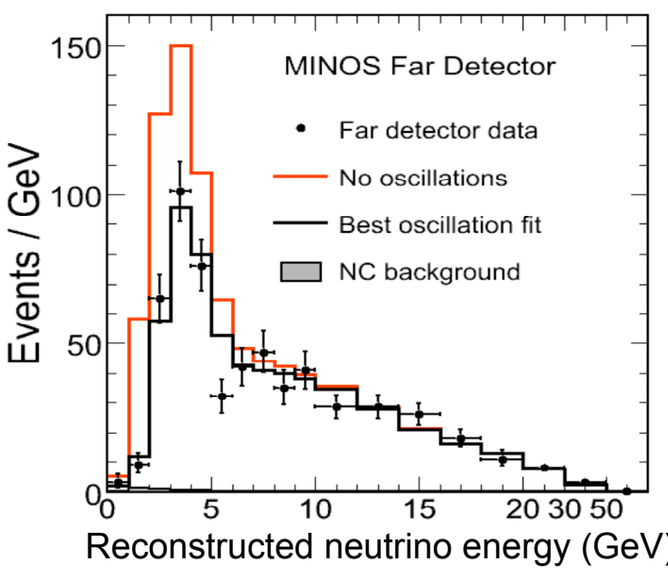
$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2

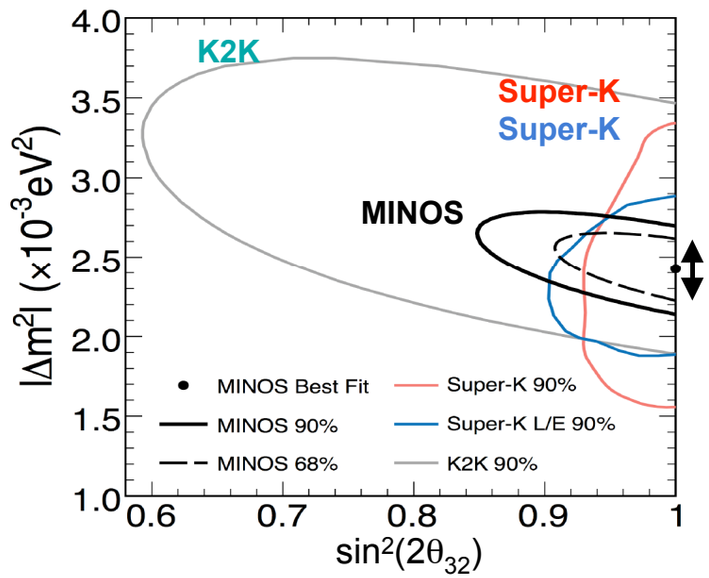
5%

at 68% C.L.

MINOS: $\nu_\mu \rightarrow \nu_X$ (Best Δm^2_{32} measurement)







$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2

at 68% C.L.

5%

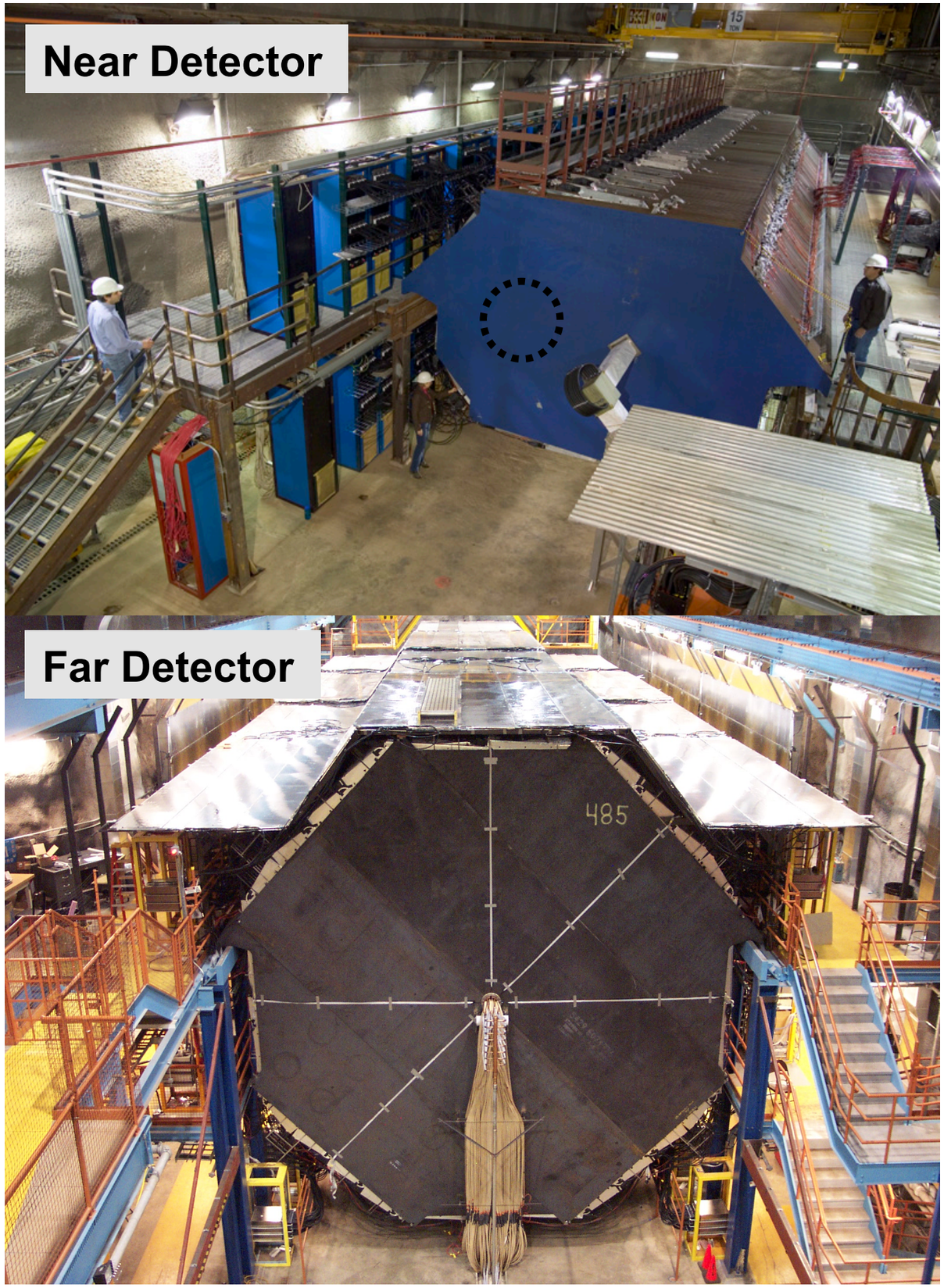
Which δm^2 does MINOS measure?

ν_μ weighted average of $|\delta m^2_{32}|$ and $|\delta m^2_{31}|$

$$\delta m^2_{\mu\mu} \approx \cos^2\theta_{12}|\delta m^2_{32}| + \sin^2\theta_{12}|\delta m^2_{31}|$$
$$= |\delta m^2_{32}| \pm \sin^2\theta_{12}\,|\delta m^2_{21}|$$

$\sim$ 1% shift to $|\delta m^2_{32}|$

sign depends on hierarchy!!!

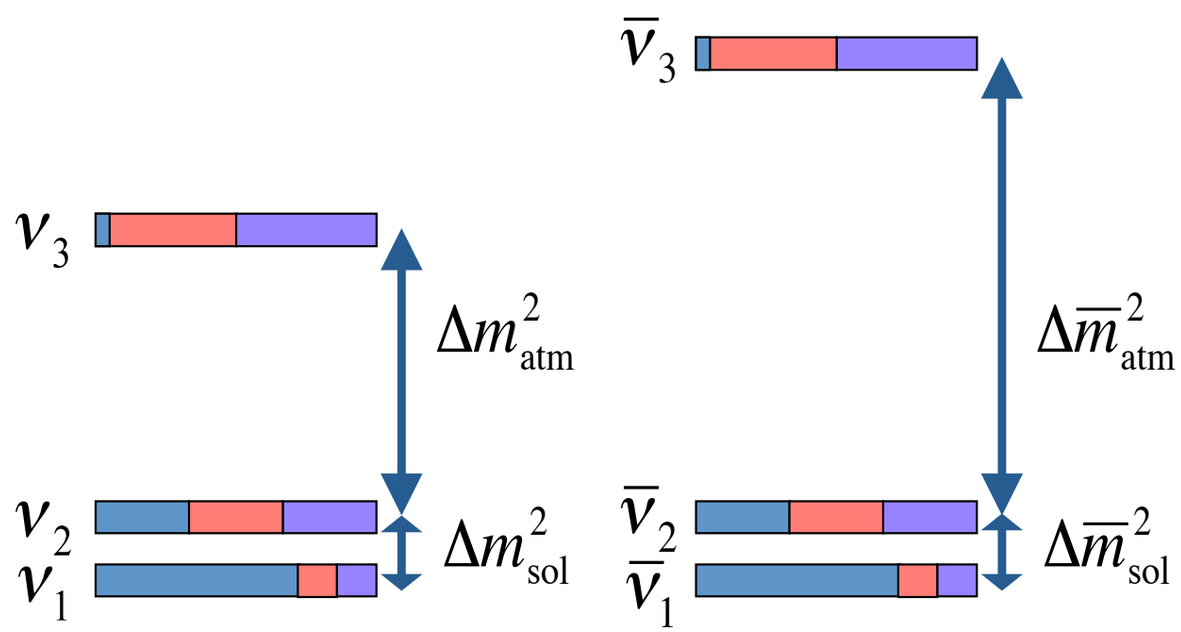


MINOS Detectors

- Massive
  - 1 kt Near detector
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

$\bar{\nu}_\mu$ Disappearance

- Do ν_μ and $\bar{\nu}_\mu$ oscillate in the same way?



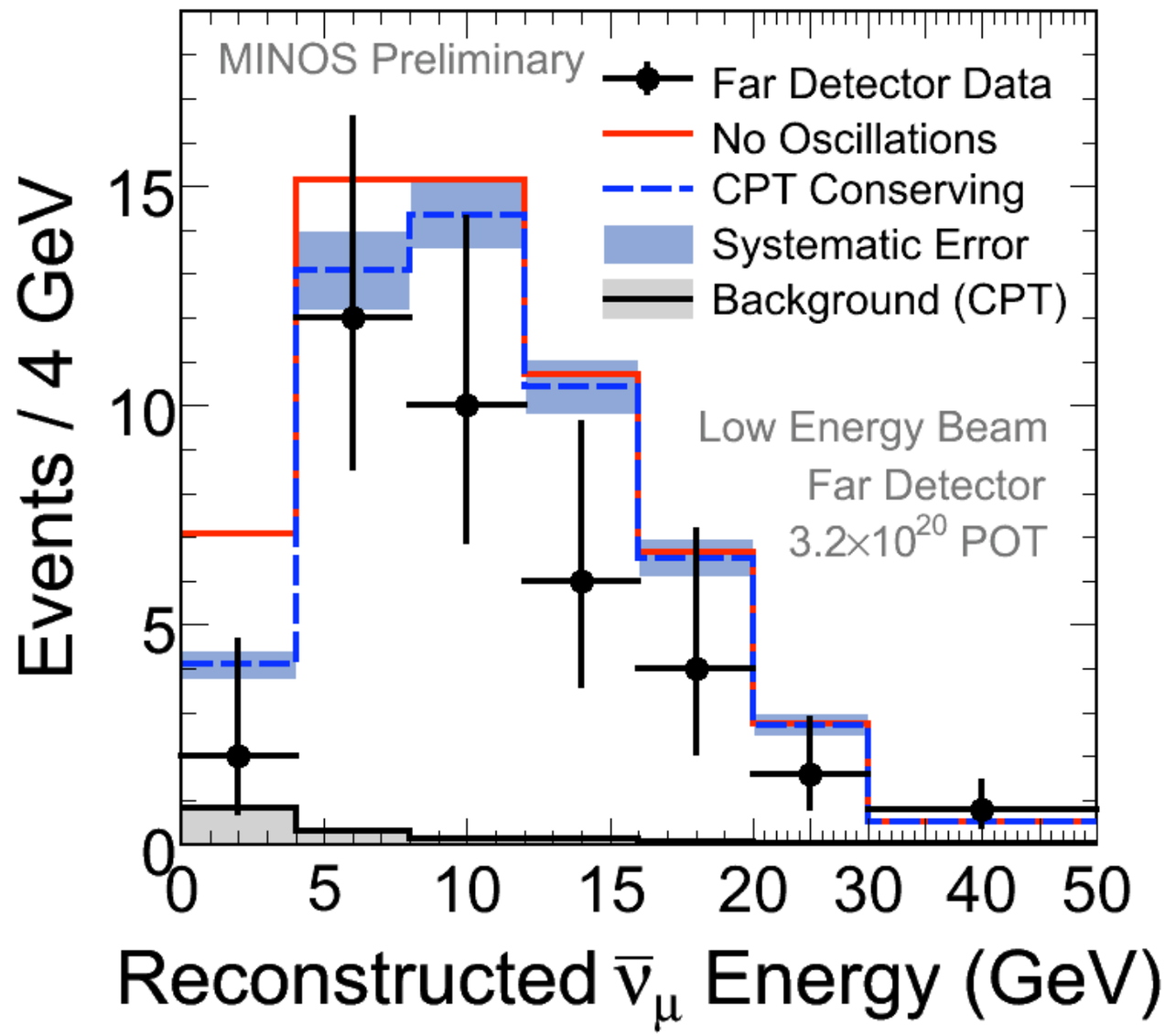
- If not, then could be evidence for CPT violation or non-standard interactions

2 sigma hint of CPT violation → Anti-Neutrino running in fall 2009

Far Detector Spectrum

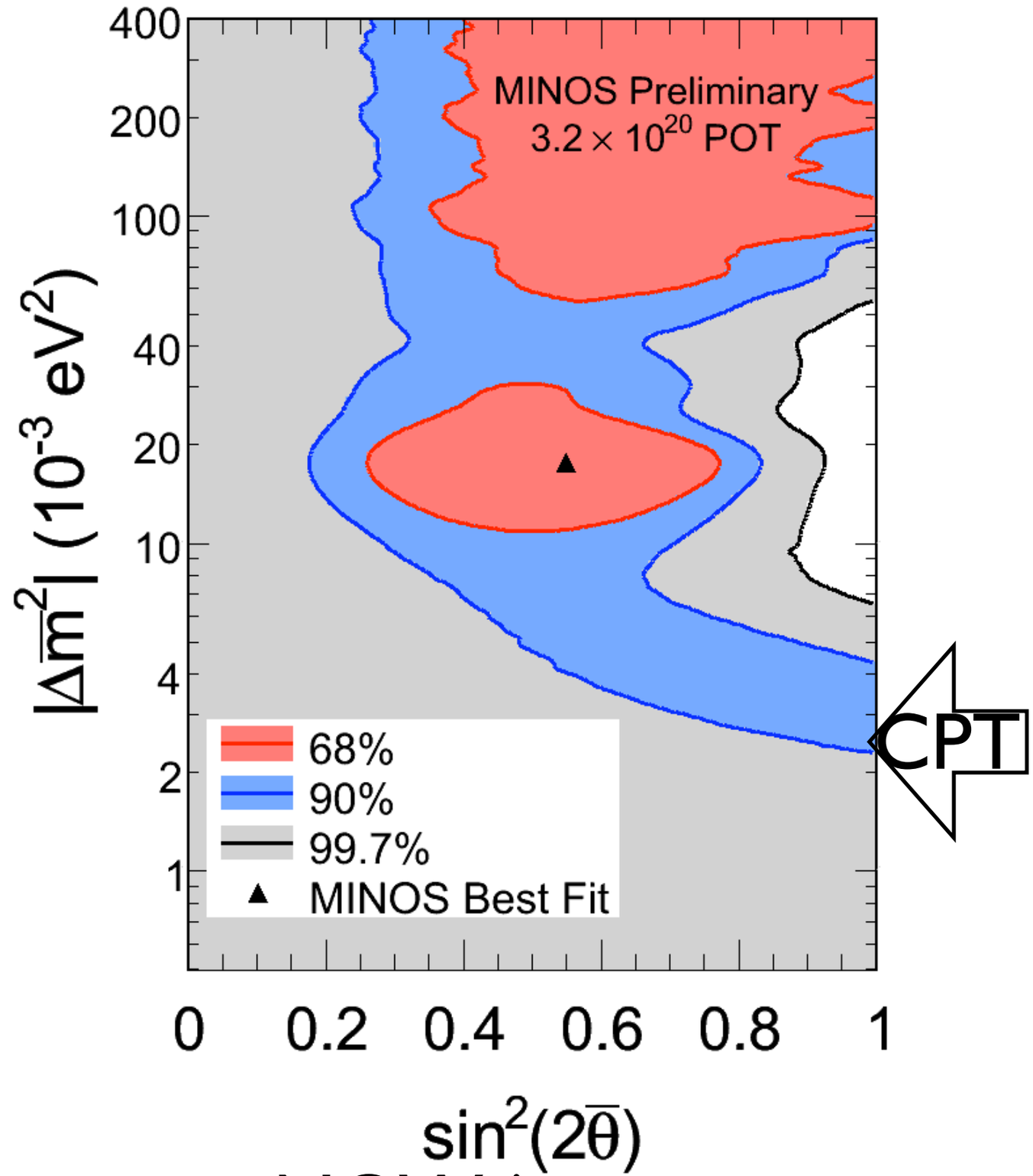
- Observe **42 events** in the Far detector
- First direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment

- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)



Allowed Region

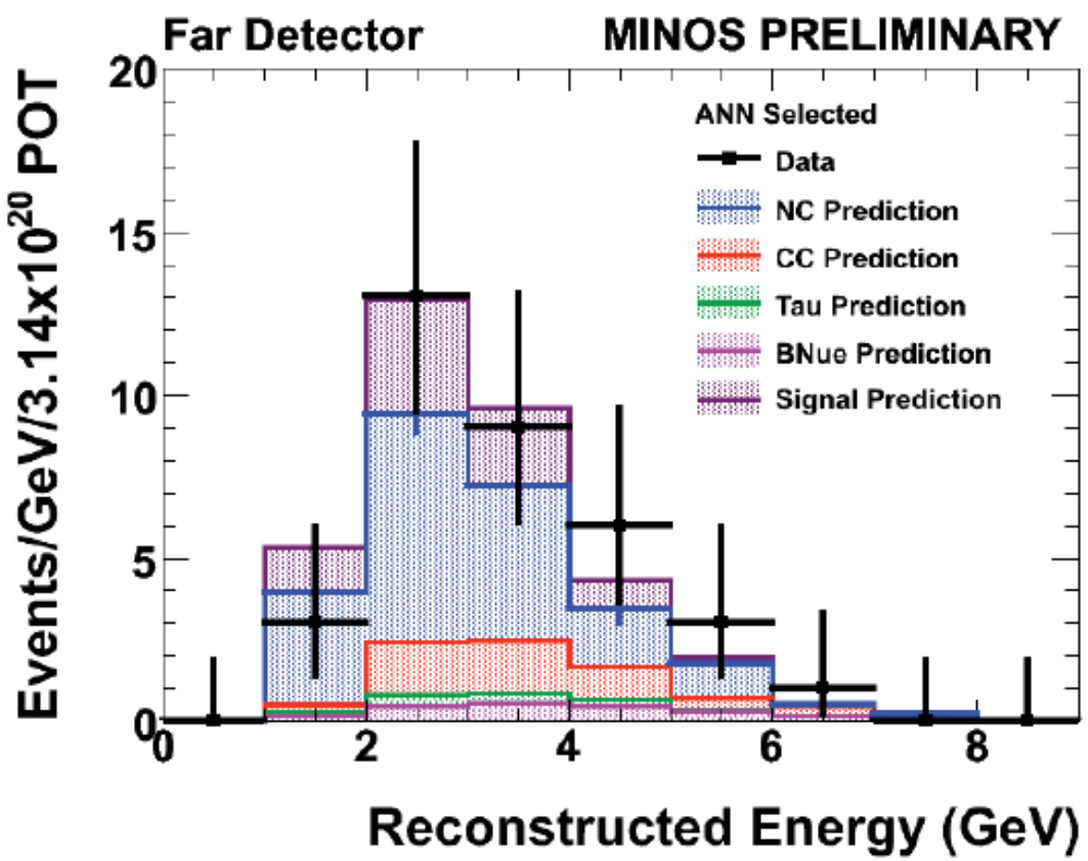
- Contours obtained using Feldman-Cousins technique, including systematics
- Null oscillation hypothesis excluded at 99%
- CPT conserving point from the MINOS neutrino analysis is within 90% contour
- $\bar{\nu}_\mu$ best fit is at high value, due to deficit at high energy
- Unshaded region around maximal mixing is excluded at 99.7% C.L.

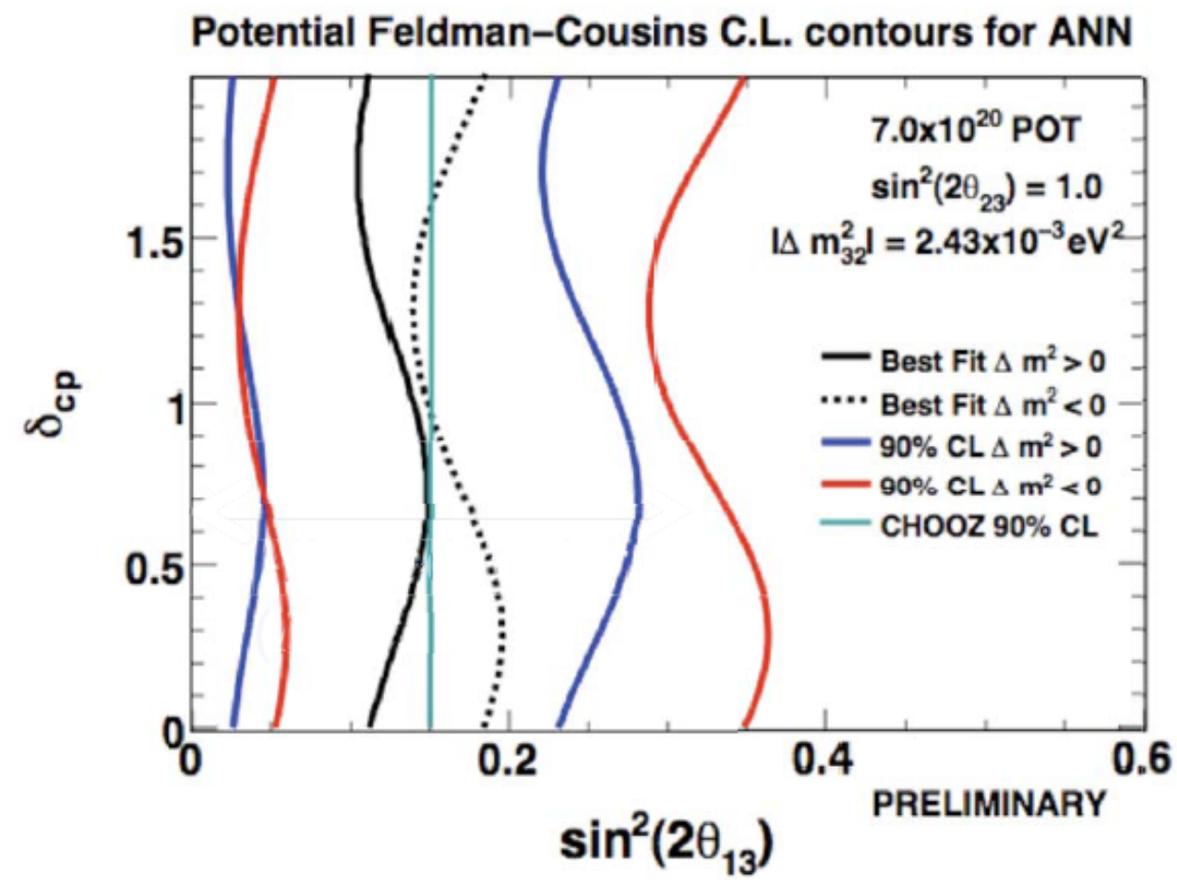


- more Anti-neutrino running NOW !

MINOS Electron Neutrino Appearance Search

- First results: consistent with no oscillations
  - 35 events measured, 25±2 predicted w/o oscillations
- Very challenging analysis, Neutral Current background levels high, multiple data-driven cross-checks needed
- Over twice this data set already taken, results pending…

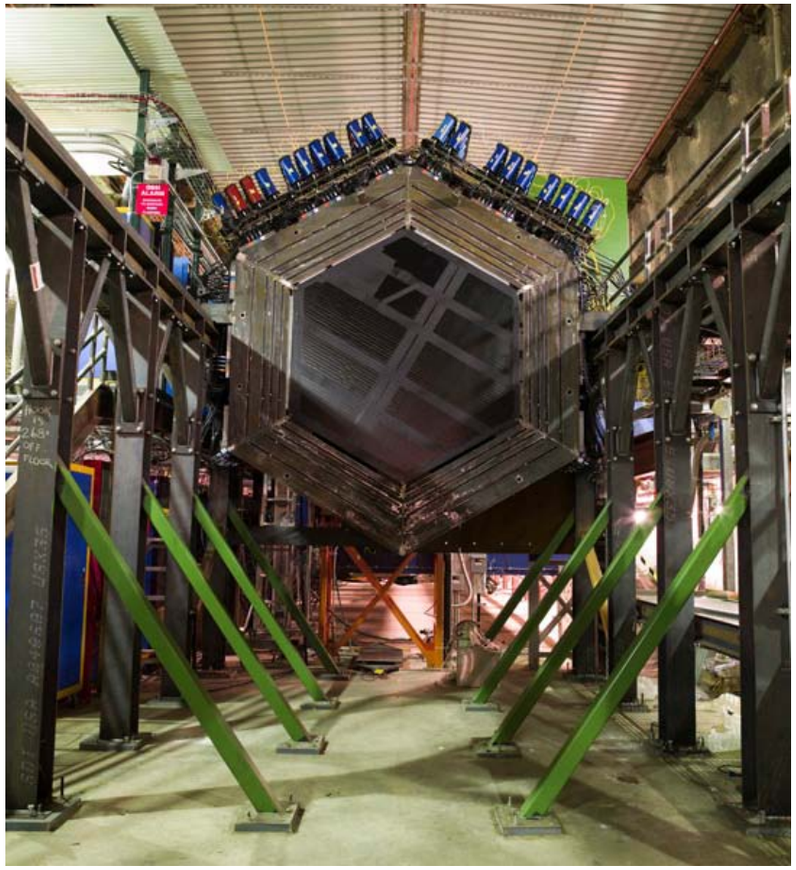


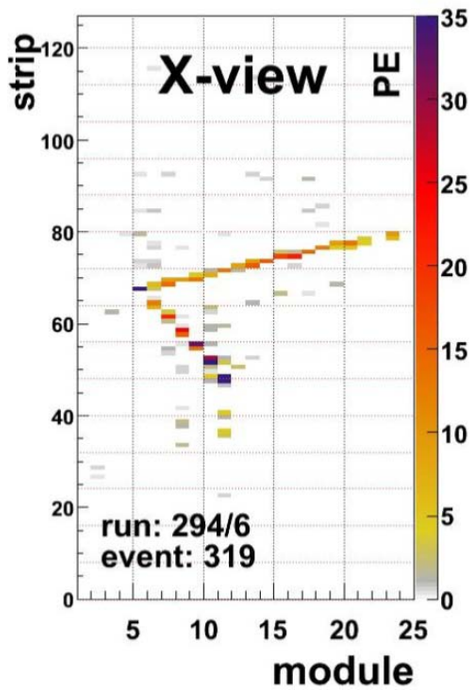


Ref: MINOS, arXiv:0909.4996 [hep-ex]

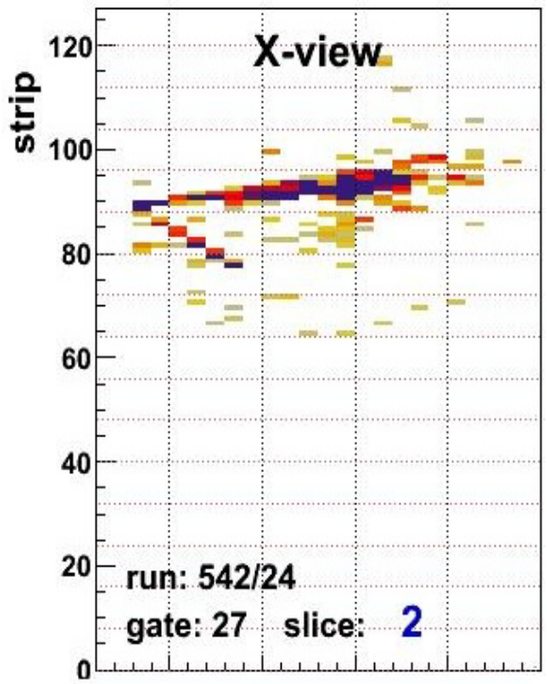
MINERνA

- Compact, fully active neutrino detector designed to study ν-N interactions
- Detector with several different nuclear targets allows 1st study of neutrino nuclear effects:
  - He, C, Fe, Pb (and maybe water!)
  - Data below, candidate reaction given

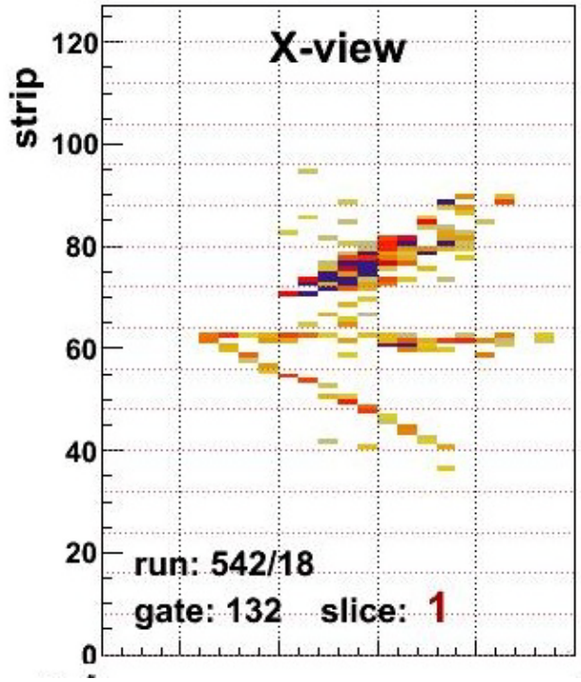




$\nu_\mu + n \rightarrow \mu^- + p$

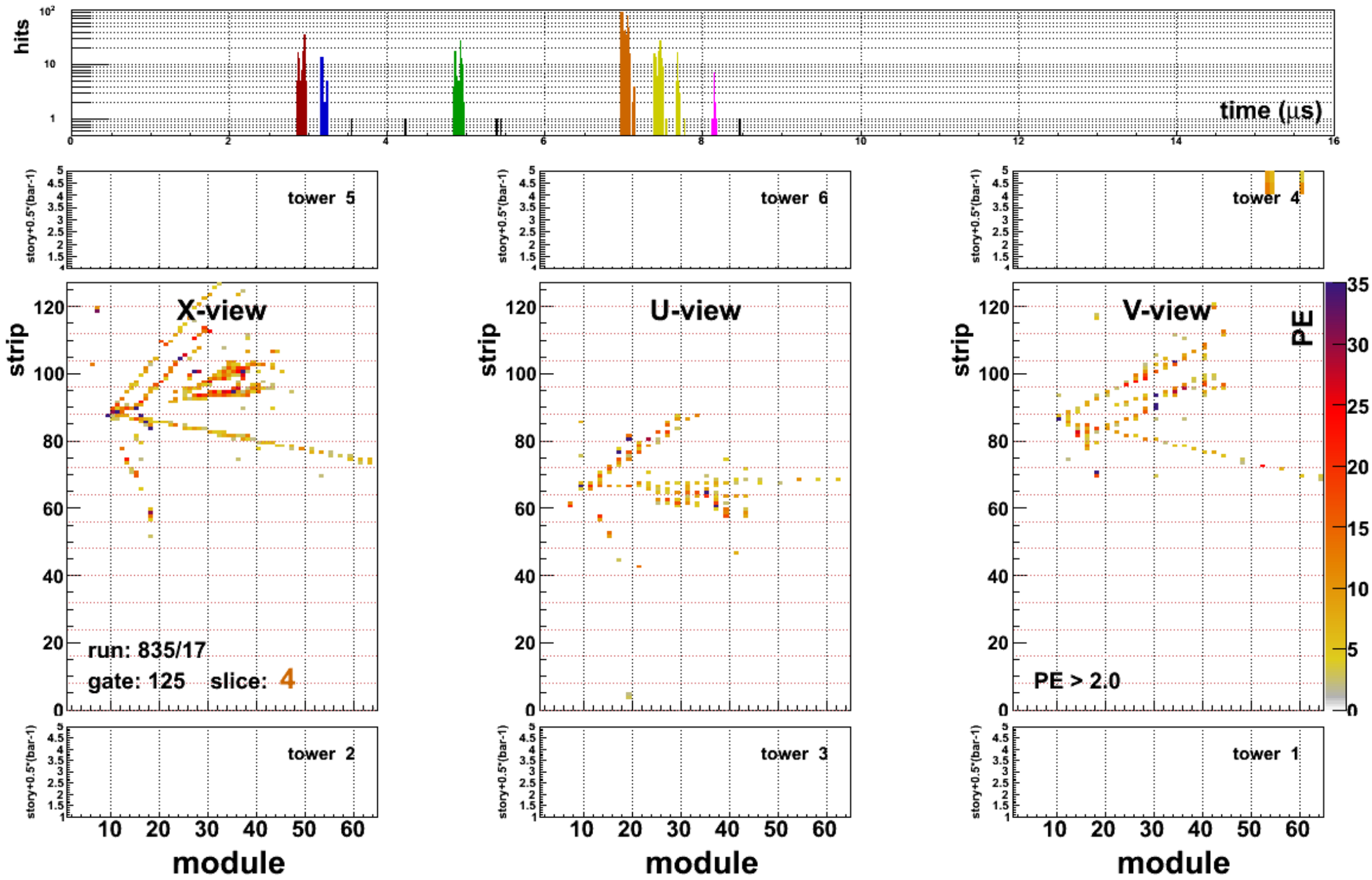


$\nu_e + n \rightarrow e^- + p$



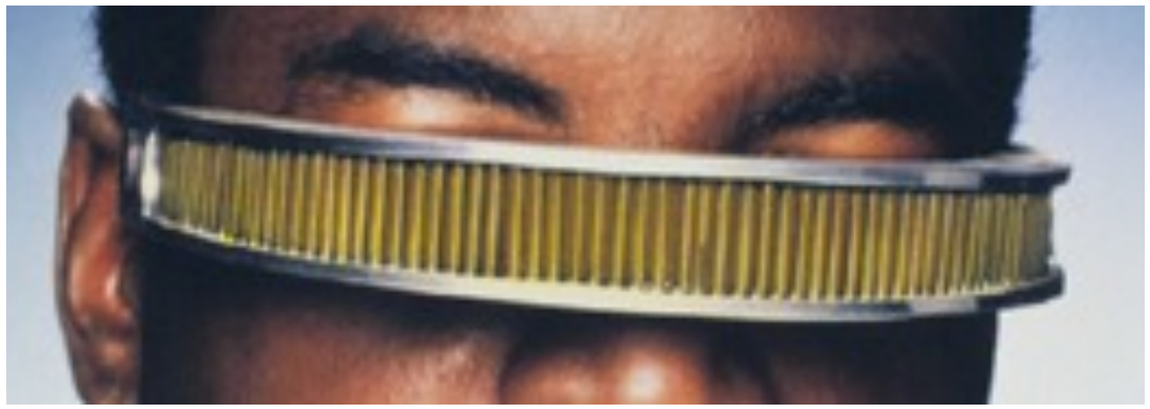
$\nu_\mu + n \rightarrow \mu^- + \pi^0 + X$

MINERvA's First (Anti-Neutrino) Light!



Taking data with 55% of full detector + Pb, Fe, CH targets

Star Trek: The Next Generation



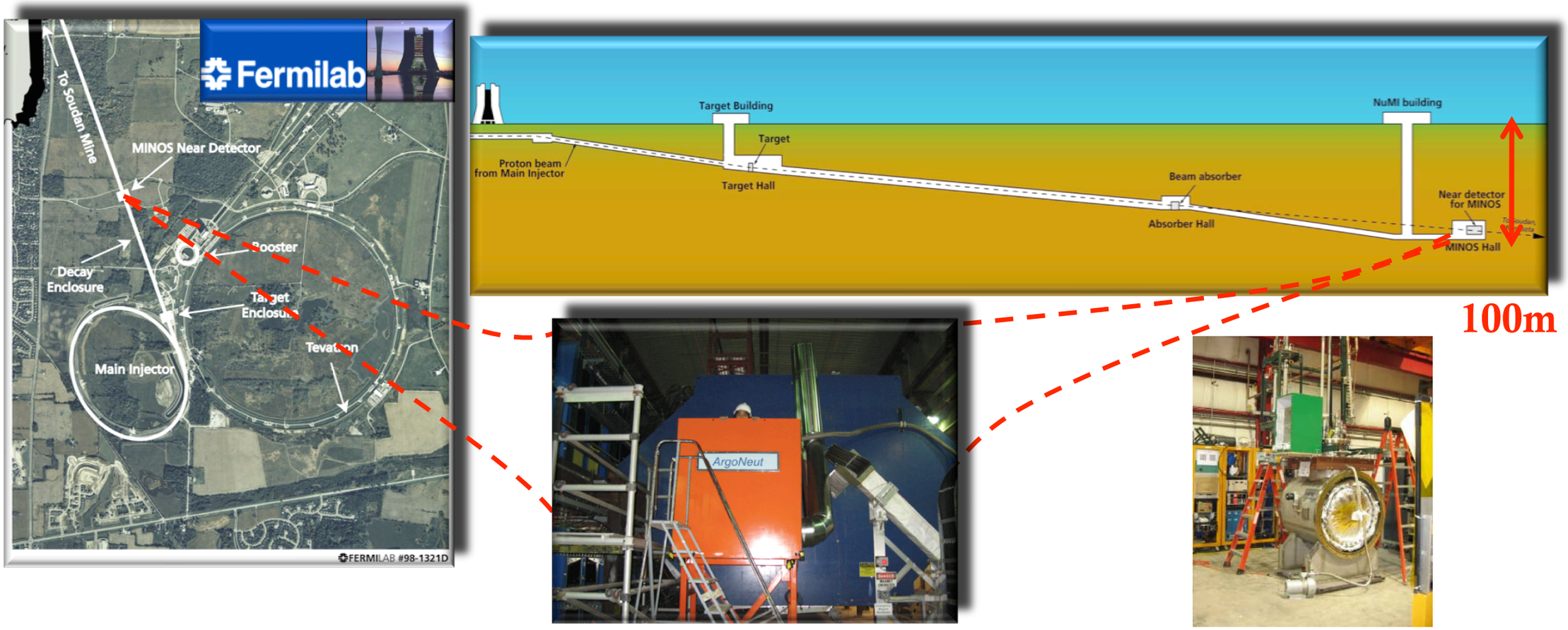
The visor "sees" Neutrinos!!!

Geordi La Forge: in "The Enemy"

The ArgoNeuT Experiment

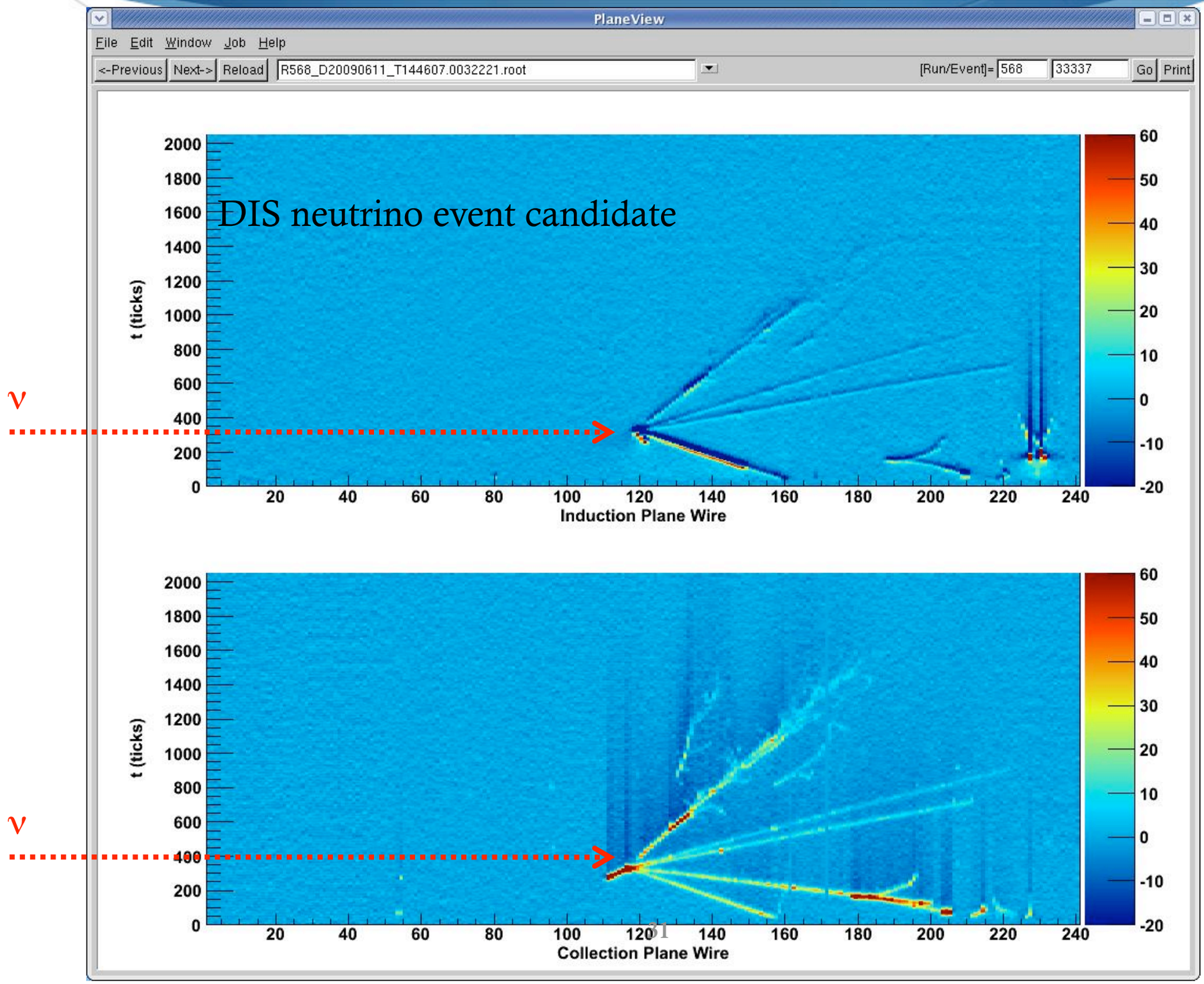
- ArgoNeuT is a joint NSF/DOE R&D project at Fermilab (USA) to expose a small Liquid Argon TPC to the NuMI low energy neutrino beam.

- ArgoNeuT detector is presently located between MINERνA and the MINOS near detector at NuMI Tunnel – 100m underground. Muons escaping the TPC are reconstructed in MINOS ND.

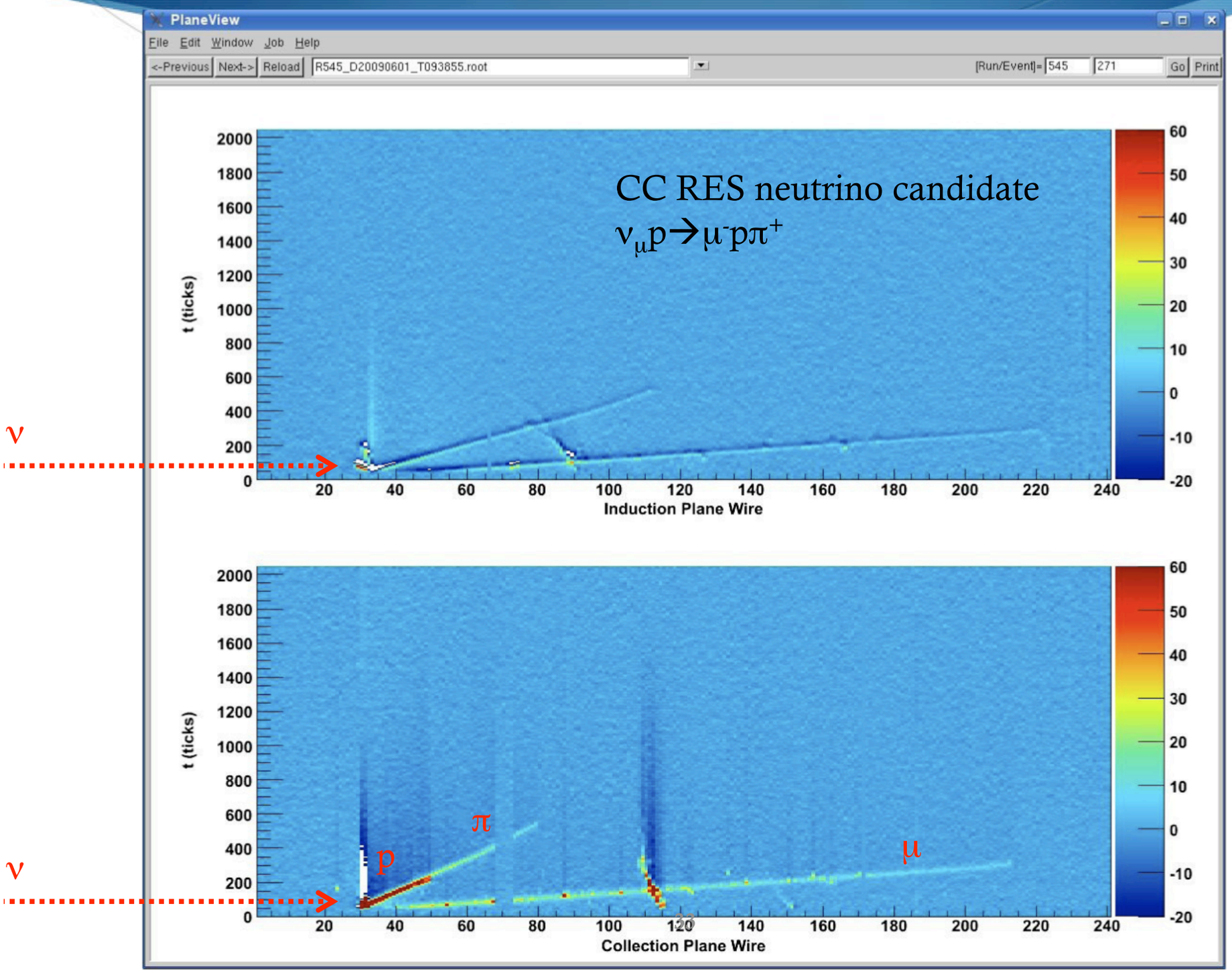


- Collecting events in the 0.1 to 10 GeV range, ArgoNeuT is producing the first ever data for low energy neutrino interactions within a LArTPC.

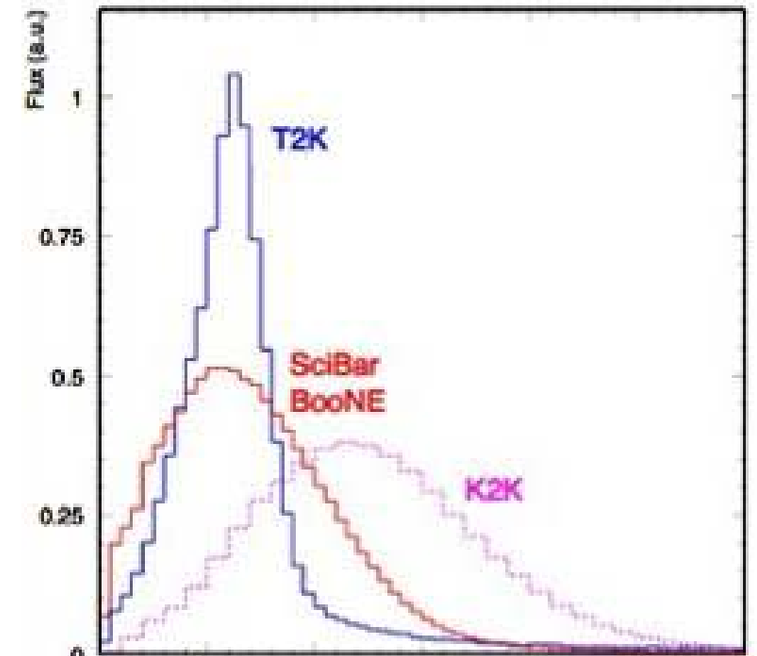
ArgoNeuT Event Display: Raw Data



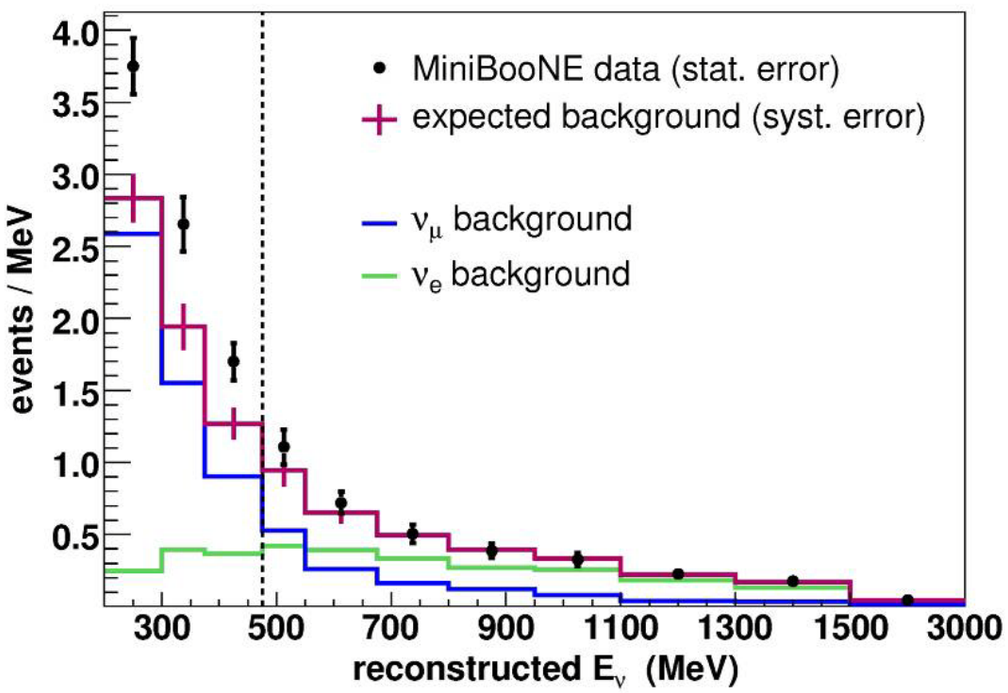
ArgoNeuT Event Display: Raw Data



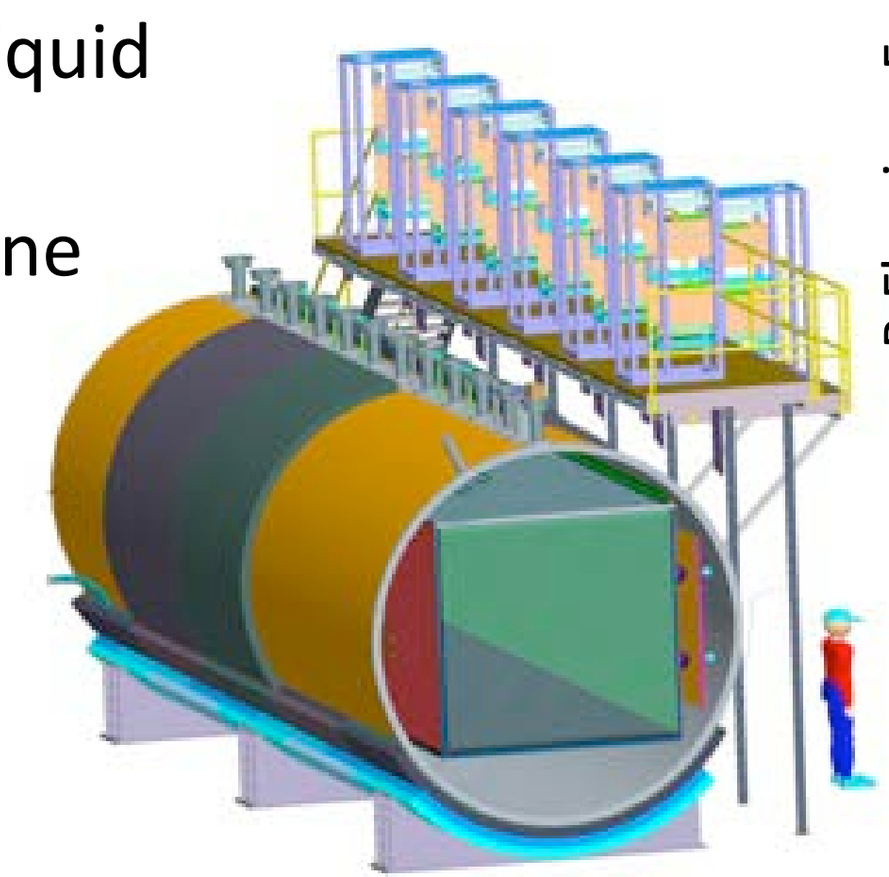
MicroBooNE



- Booster Neutrino Beamline: Energy spectrum overlaps with T2K



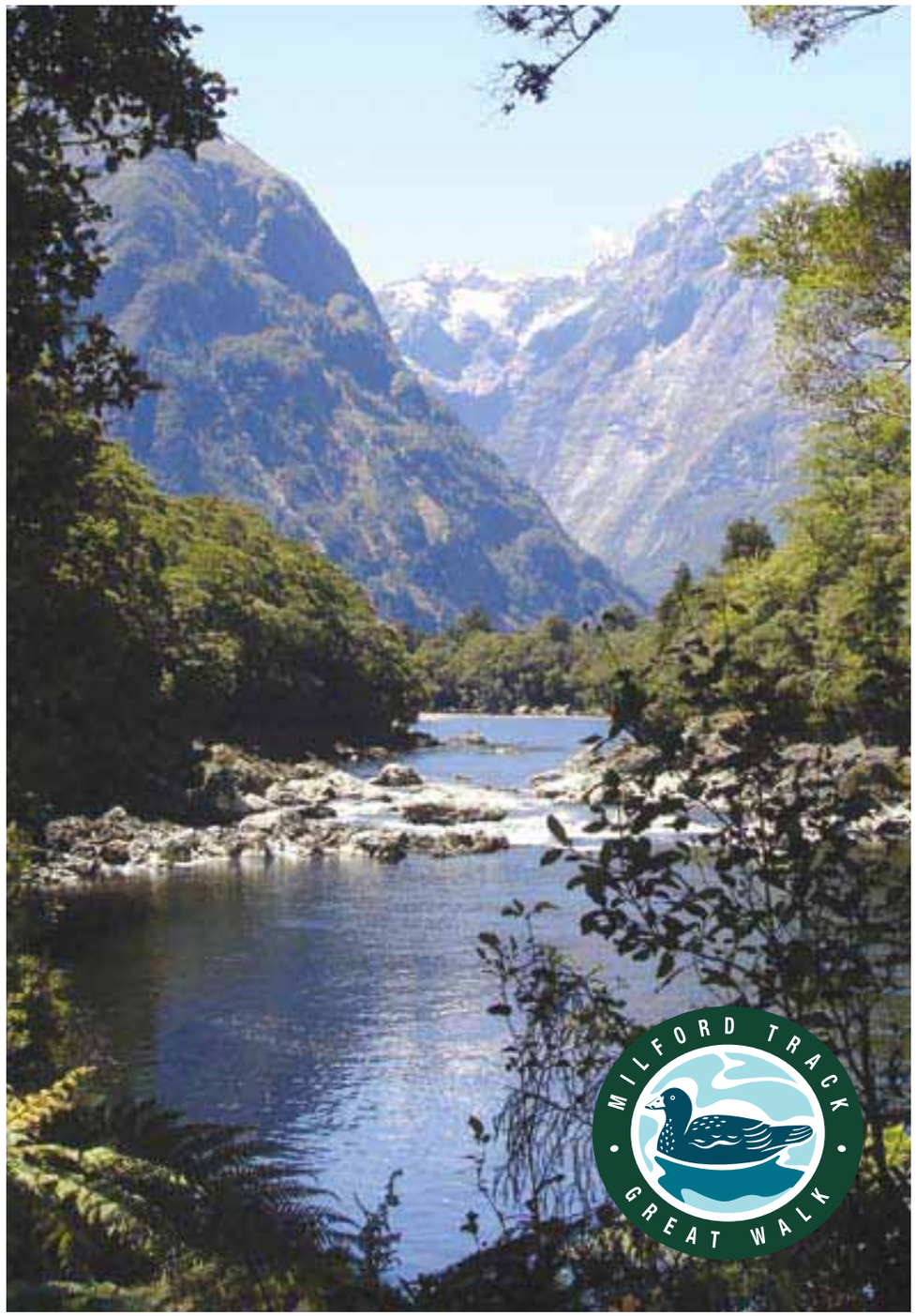
170 tons Liquid Argon,
1km baseline



- Excess of low energy events seen at MiniBooNE:
  what are the implications for T2K?
- Put scalable Liquid Argon detector technology in Booster ν Beamline

http://www-microboone.fnal.gov

R. Fleming, Fermilab PAC 3/2008



Department of Conservation
Te Papa Atawhai

$\sin^2\theta_{13}$ from LBL:

$$\nu_\mu \longrightarrow \nu_e$$

and related processes:

$$
\begin{array}{ccccc}
 & & \text{CP} & & \\
 & \nu_\mu \longrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \\
\text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\
 & \nu_e \longrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \longrightarrow \bar{\nu}_\mu & \\
 & & \text{CP} & &
\end{array}
$$

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \ \sin\Delta_{21}$

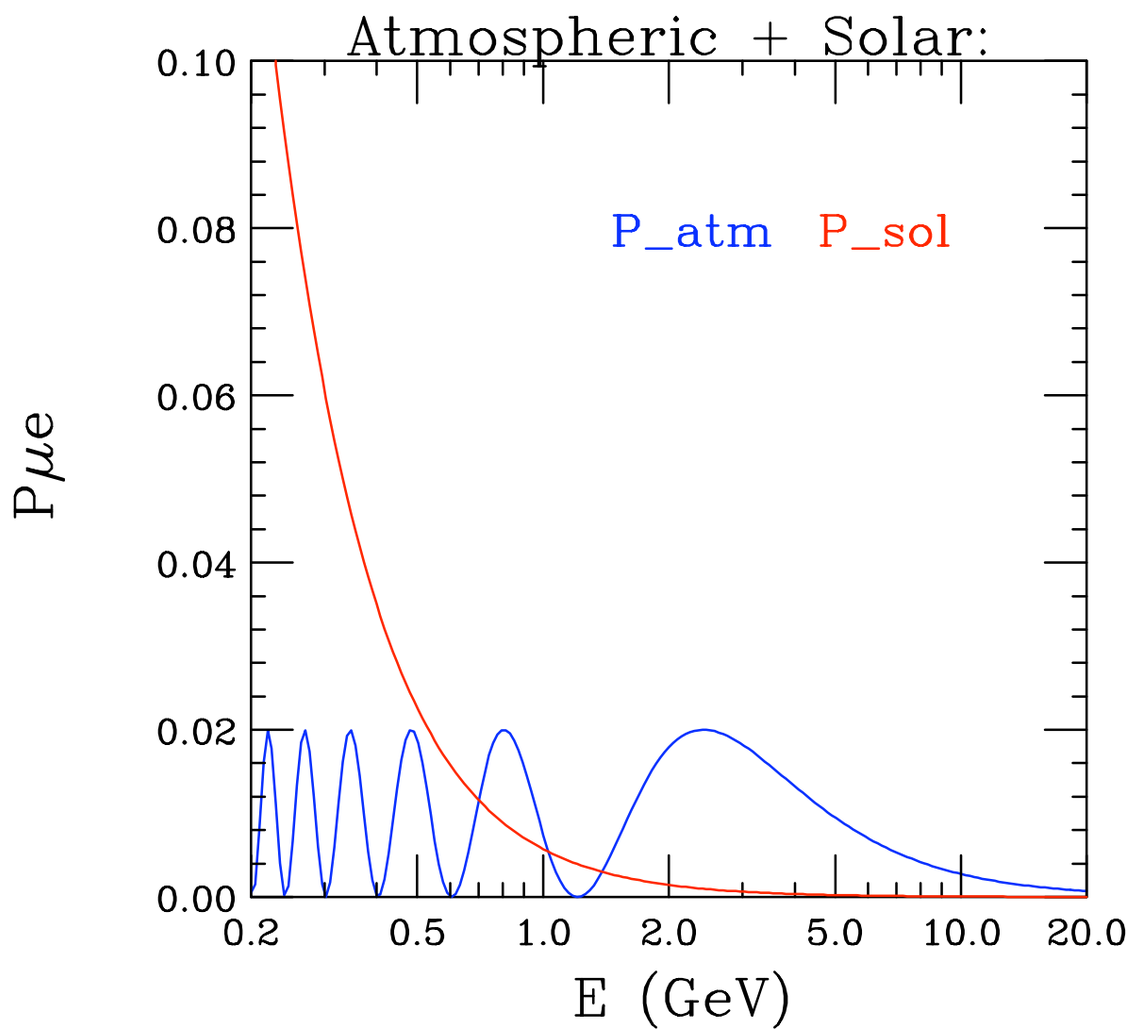
$$\boxed{P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm} P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}}$$

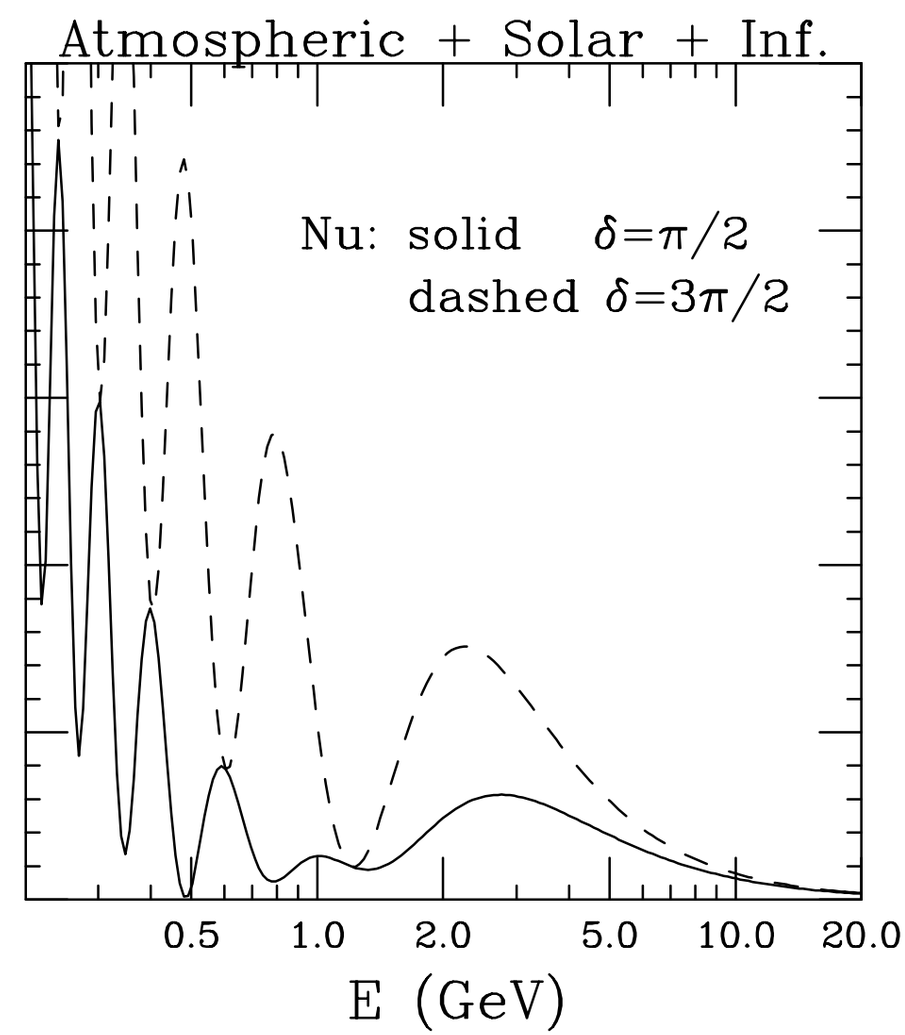
only CPV

$$\cos(\Delta_{32} \pm \delta) = \cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta$$

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$



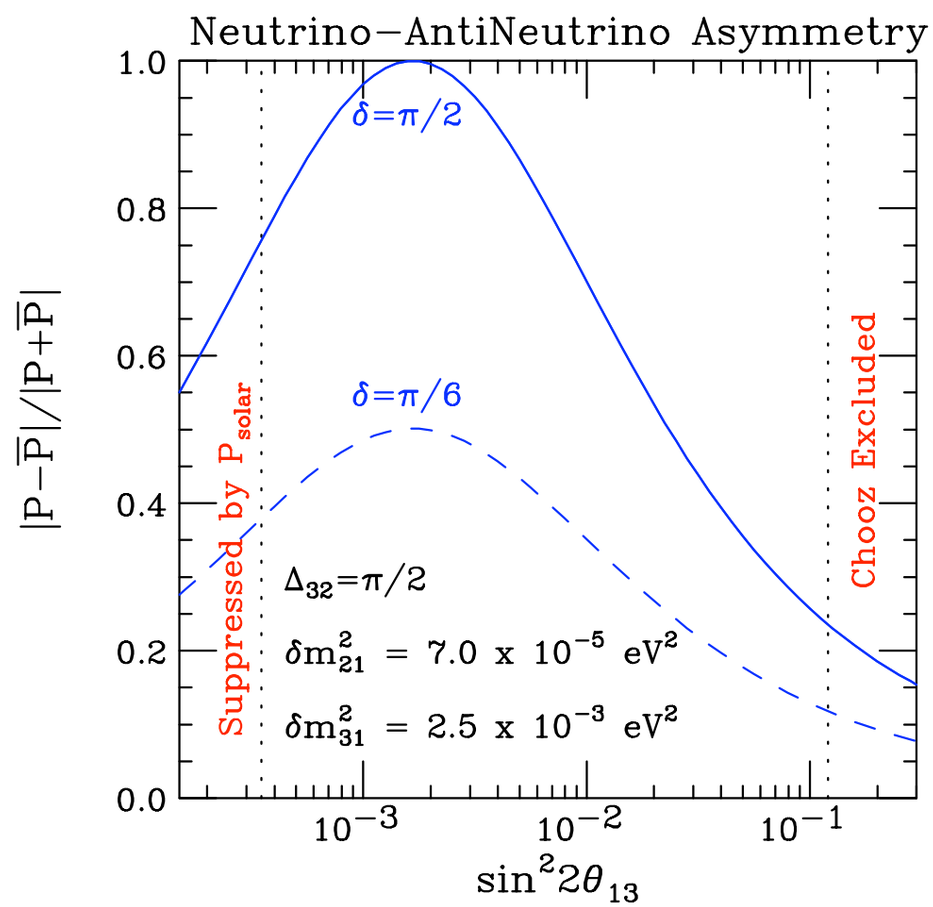


x 3

phase varies

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

Asymmetry Peaks:



at the first peak

$$P_{atm} \leq P_{sol} \quad \text{when} \quad \sin^2 2\theta_{13} \leq \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}} \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 0.001$$

Appearance Probability for 2 Flavor Neutrino Oscillations:

$$P_0 = |\sin 2\theta \sin \Delta|^2$$

where kinematic phase $\Delta = \frac{\delta m^2 L}{4E}$

limit $\hbar \to 0$?

In matter

$$P_N = |\sin 2\theta \, \frac{\sin(\Delta - aL)}{(\Delta - aL)} \Delta|^2$$

where $a = G_F N_e / \sqrt{2} \approx (4000 \ km)^{-1}$

when $L <<< a^{-1}$ then $P_n \to P_0$

In Matter:

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

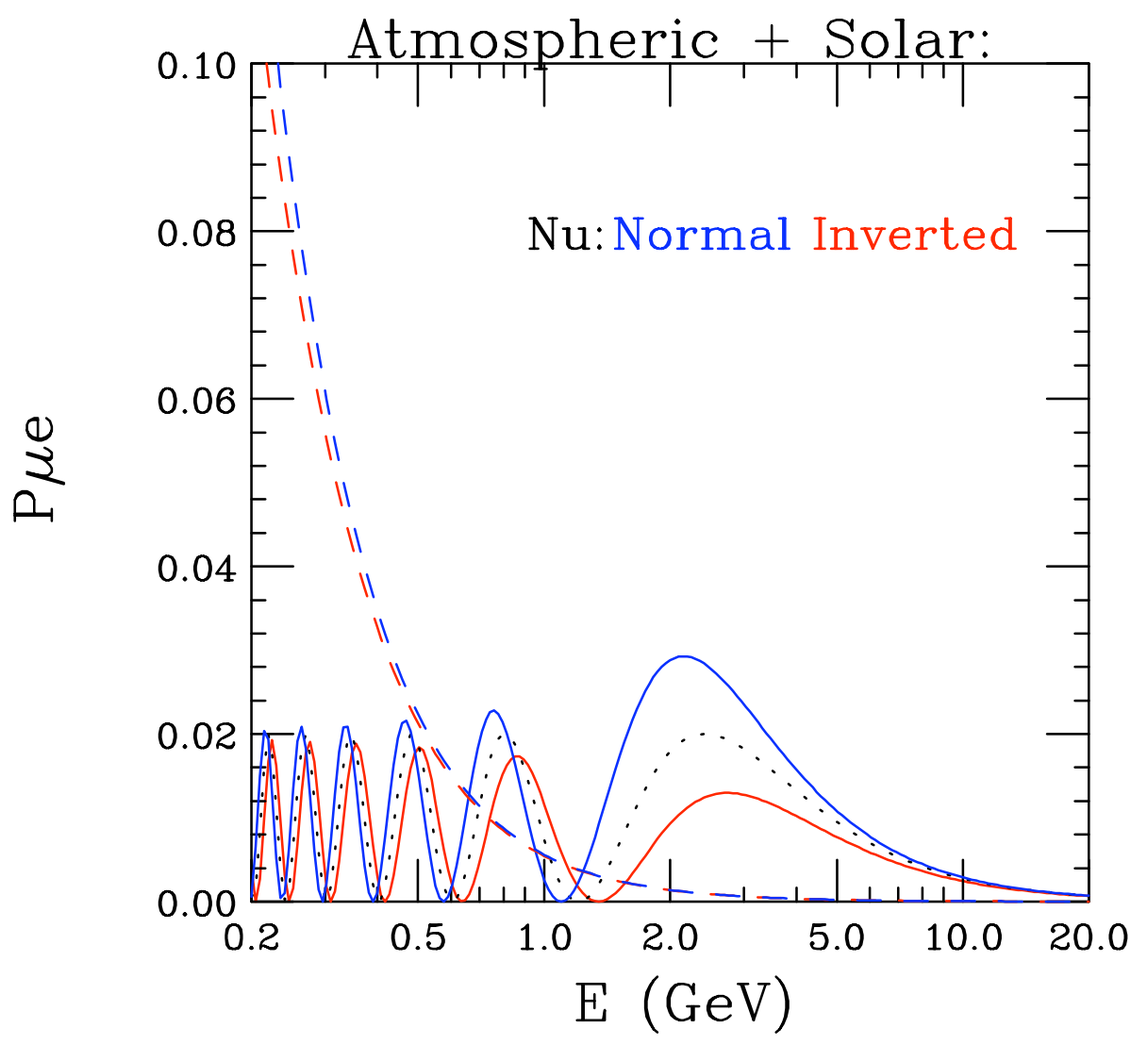
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)} \Delta_{31}$

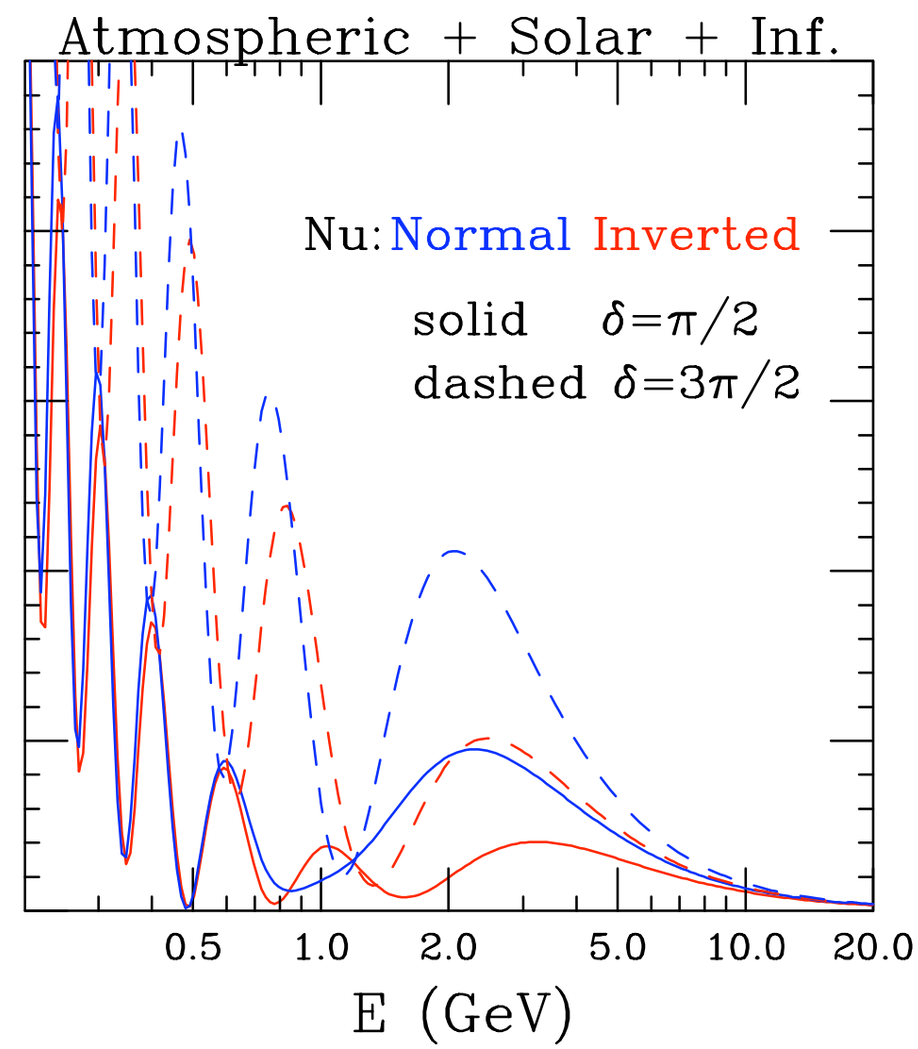
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





$\nu_\mu \longrightarrow \nu_e$

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+2\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}$$

$$*\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

CPV

$$*(\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta)$$

CPC

$$+\cos^4\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$(\Delta_{31}-aL) = \Delta_{31}\left(1-\frac{aL}{\Delta_{31}}\right) = \Delta_{31}\left(1-\frac{2\sqrt{2}G_F N_e E}{\delta m_{31}^2}\right)$$

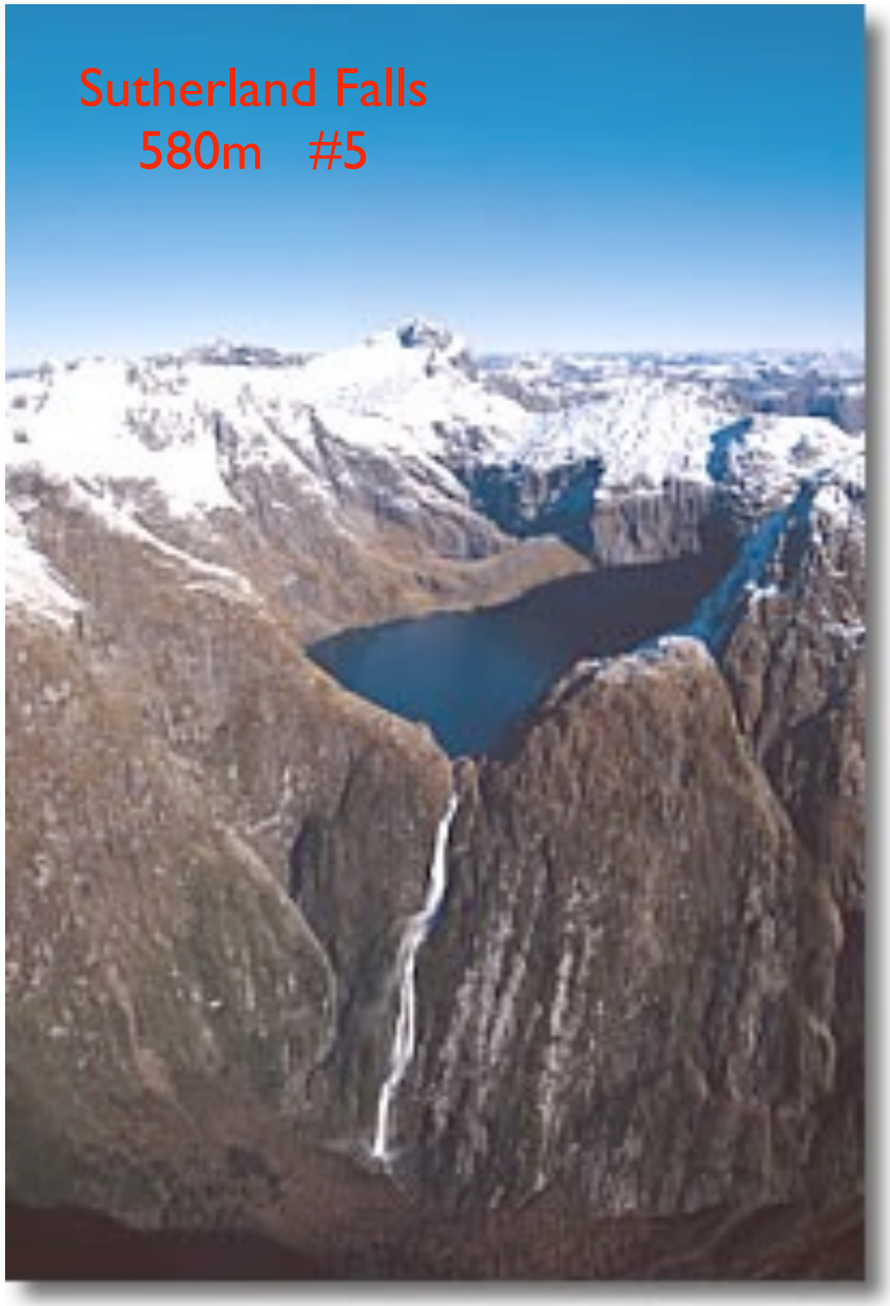
$$\Delta_{32} \approx \Delta_{31}$$

$$J = \sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}\sin\delta$$

$$\nu_\mu \longrightarrow \nu_e$$

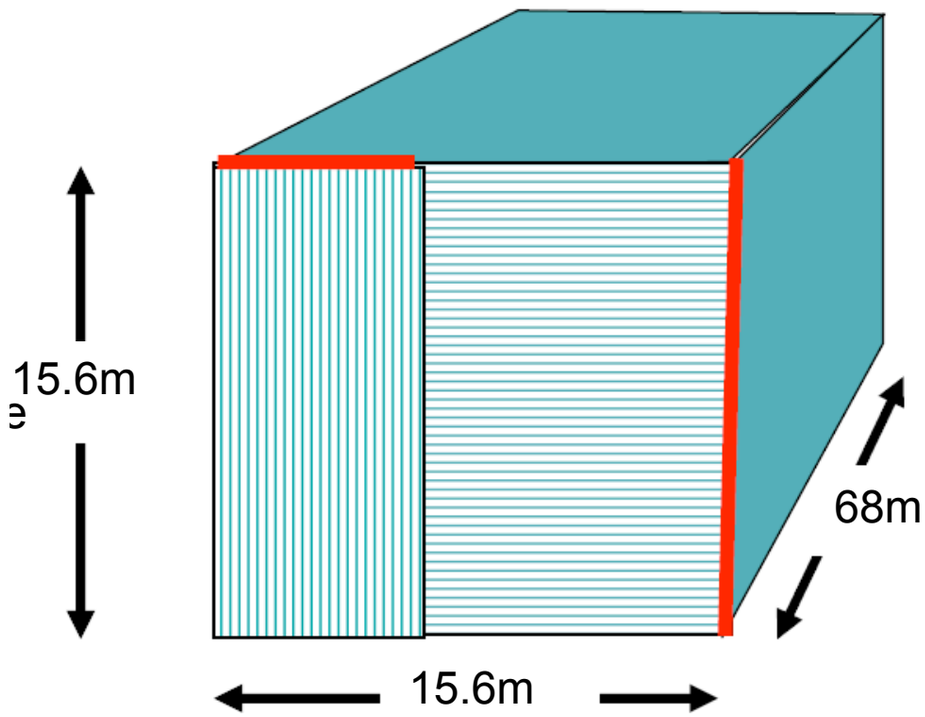
$$P_{\mu\to e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}|^2$$

Sensitivity to CPV and Mass Hierarchy !!!



N
Ontario
NOvA
(off-axis)
MINOS (on-axis)
Dakota
Minnesota
735 km
Wisconsin
Michigan
1300 km
Milwaukee
tector
Iowa
MiniBooNE
SciBooNE
MINERvA
Chicago

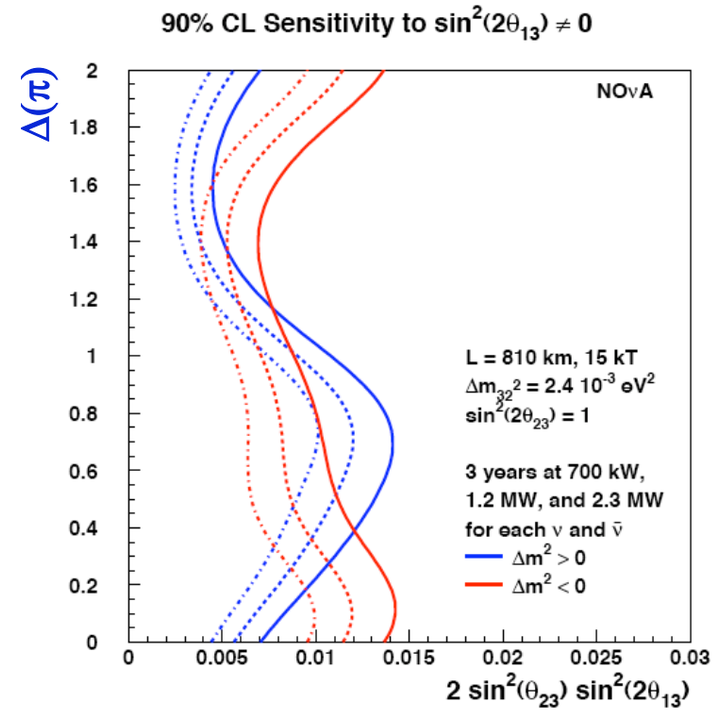
NOvA:



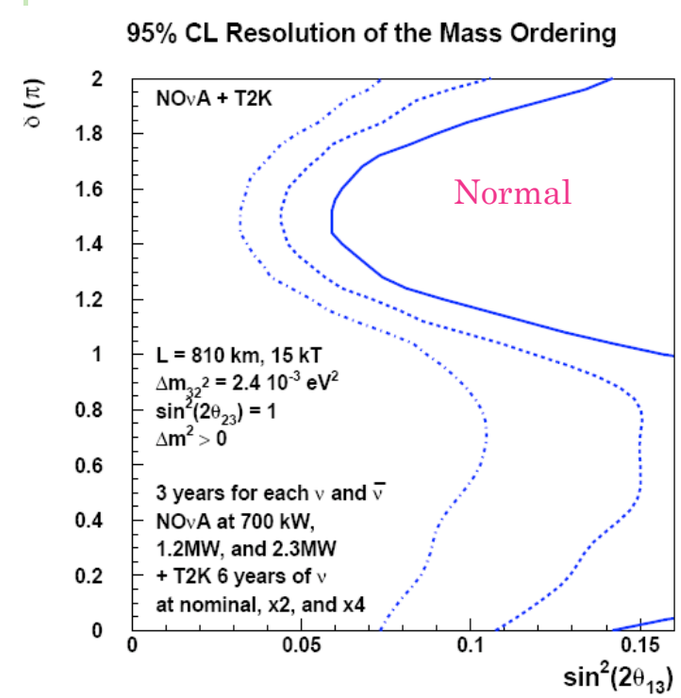
- 15 ktons
- 15.6m x 15.6m x 68m
- 1003 liquid scintillator planes, (~73% active)
- Scintillator cells 3.8 x 6.0 x 1540 cms
- Read out from one side per plane with APDs
- Expected average signal at far end of 30pe

$\langle P(\nu_\mu \to \nu_e)\rangle \sim 0.5 - 1.0\%$ at 90% CL

θ_{13} from ν_e appearance



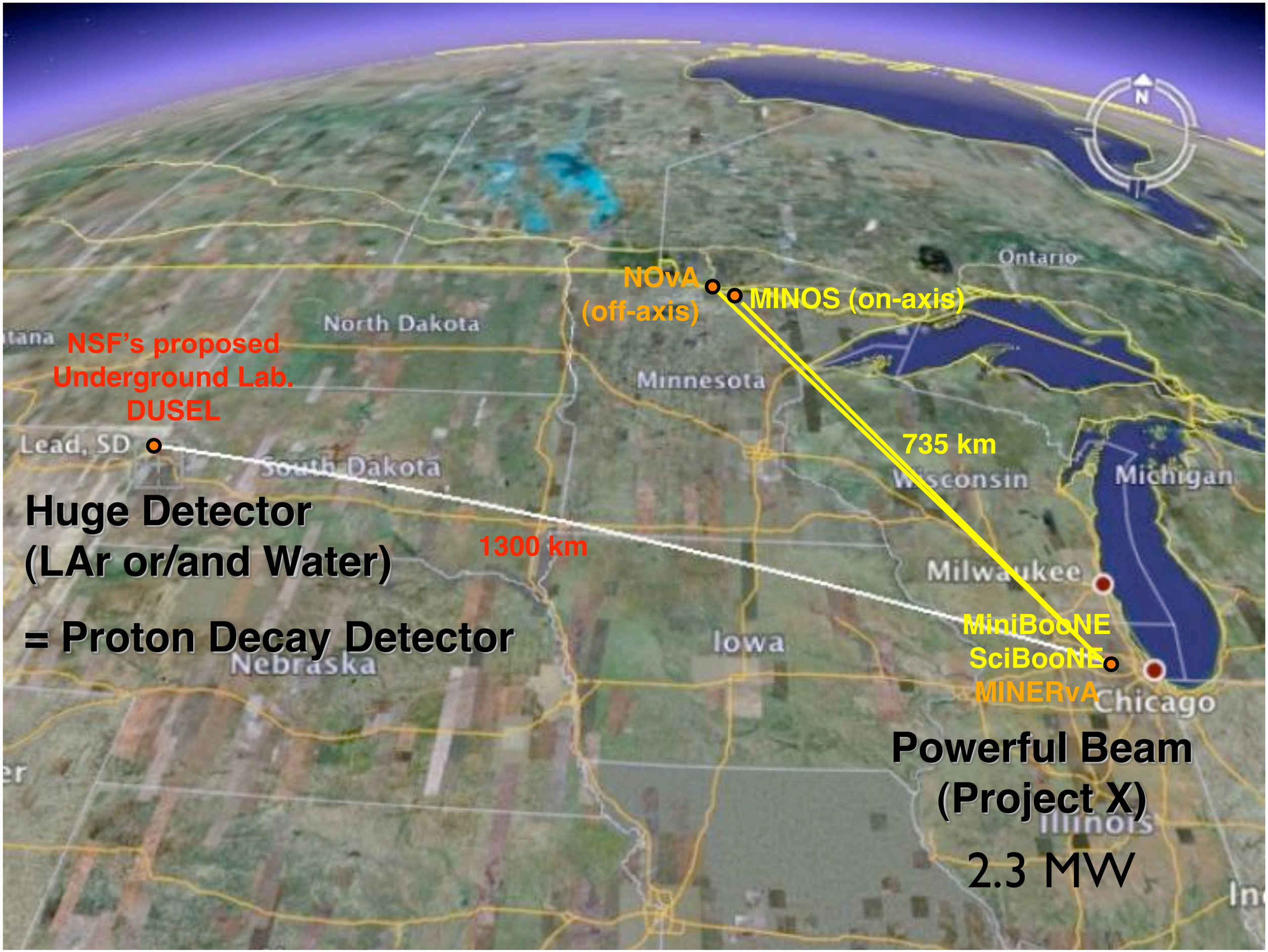
95% CL Sensitivity to the Mass Ordering



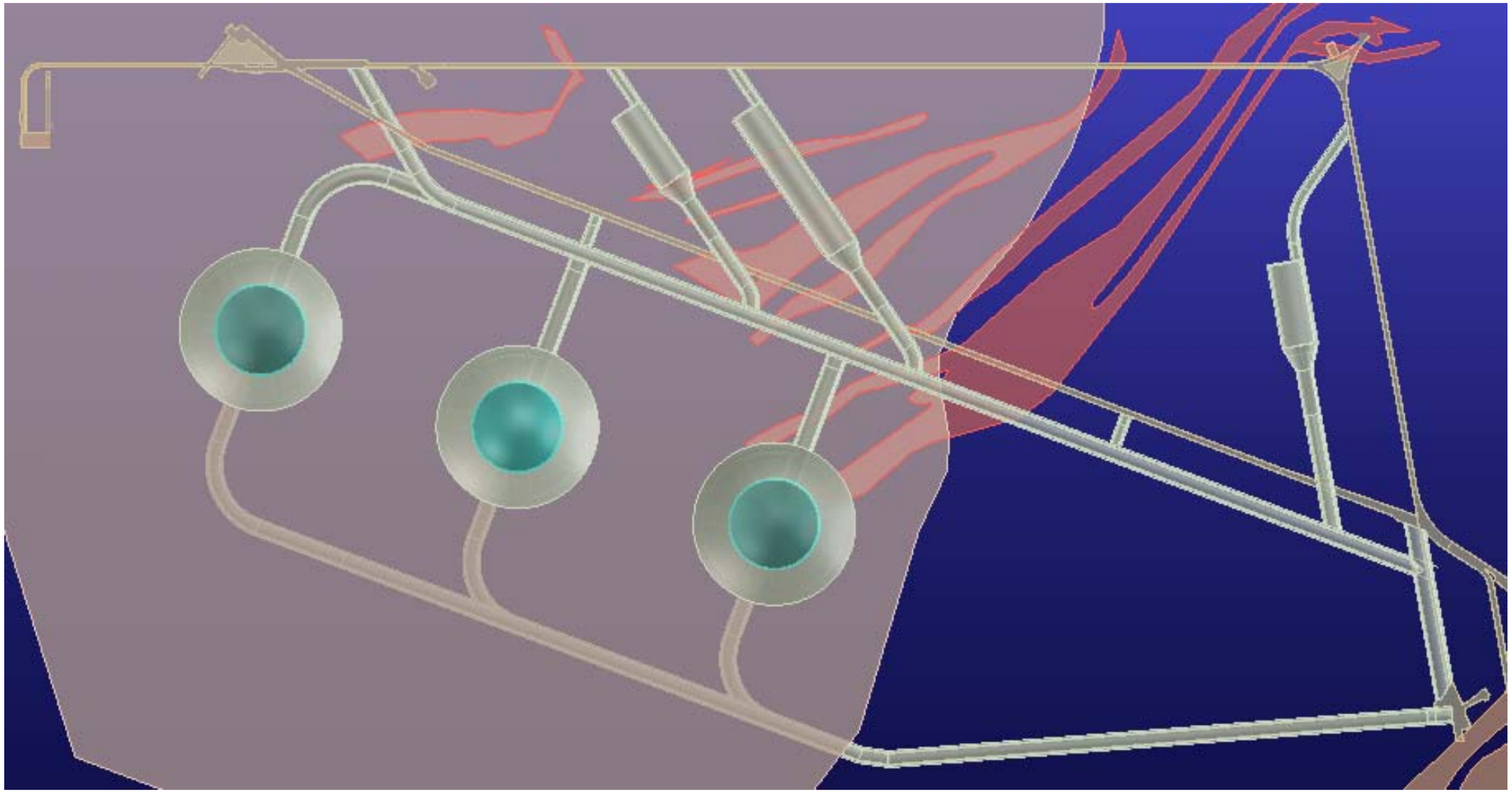
NOvA: Far Detector Building

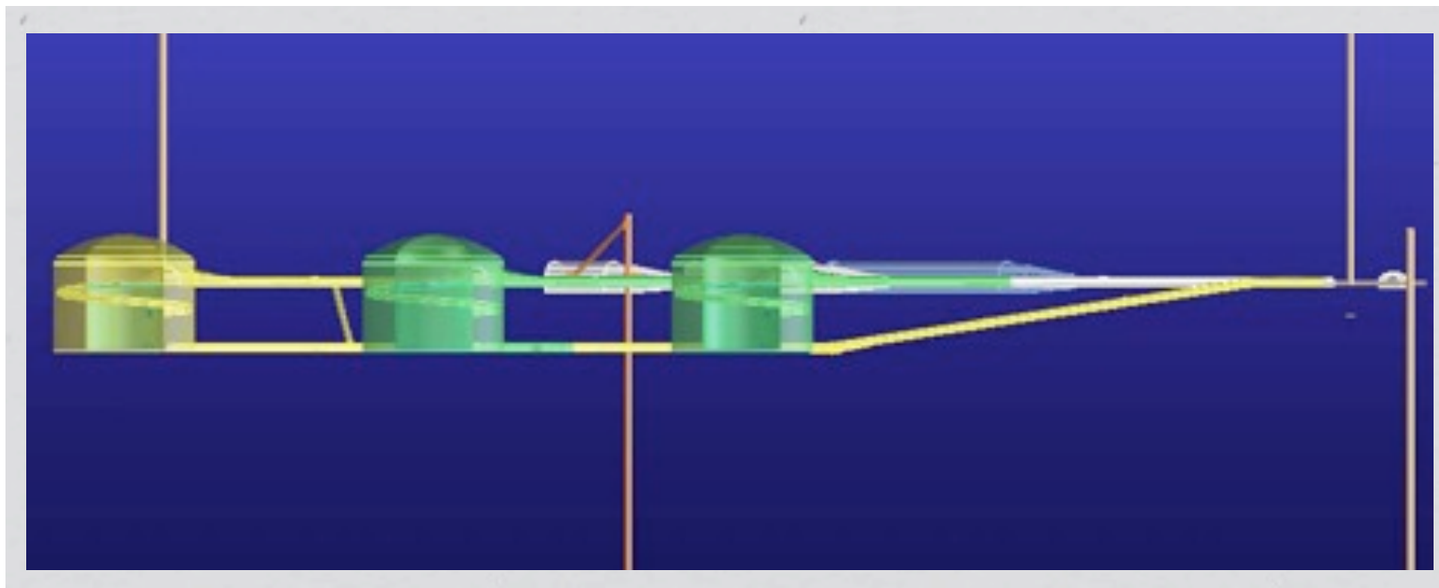
Ref: S. Dixon, FNAL All Experimenter's Meeting 12/7

- New Beamline to DUSEL
  - (60 -120 GeV protons)
    - » LBNE


NOvA
(off-axis)
MINOS (on-axis)
Ontario
North Dakota
NSF's proposed
Underground Lab.
DUSEL
Minnesota
Lead, SD
735 km
South Dakota
Wisconsin
Michigan
Huge Detector
(LAr or/and Water)
1300 km
Milwaukee
= Proton Decay Detector
MiniBooNE
SciBooNE
MINERvA
Iowa
Nebraska
Chicago
Powerful Beam
(Project X)
Illinois
2.3 MW

layout of 4850 level

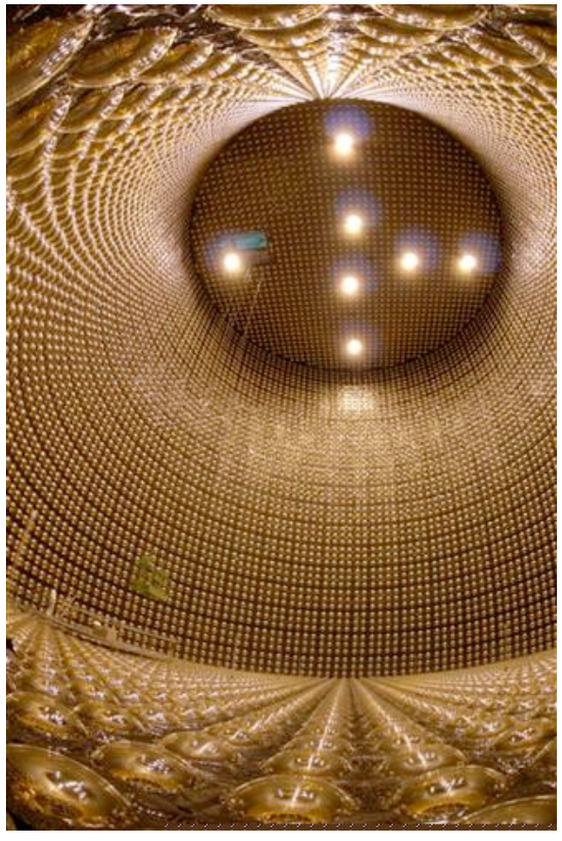




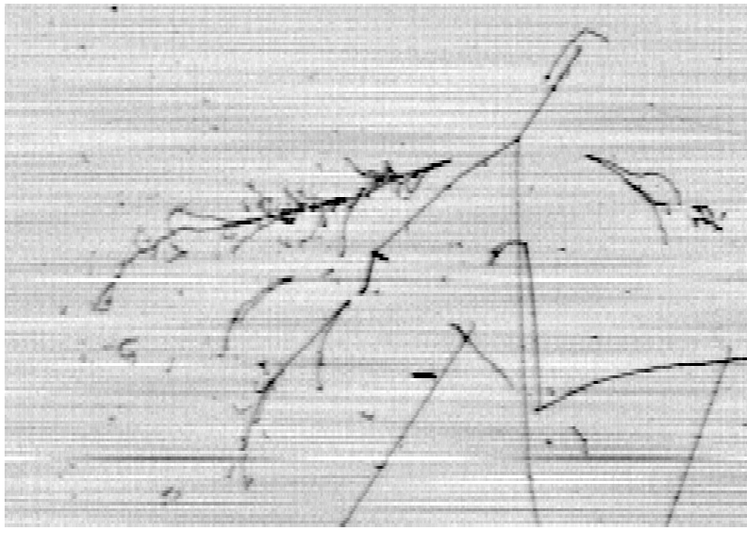
Intensity frontier: detector options

Options under consideration:
~300 kt WC, ~100 kt LAr, or some combination of the two.
Fermilab supports both technologies.

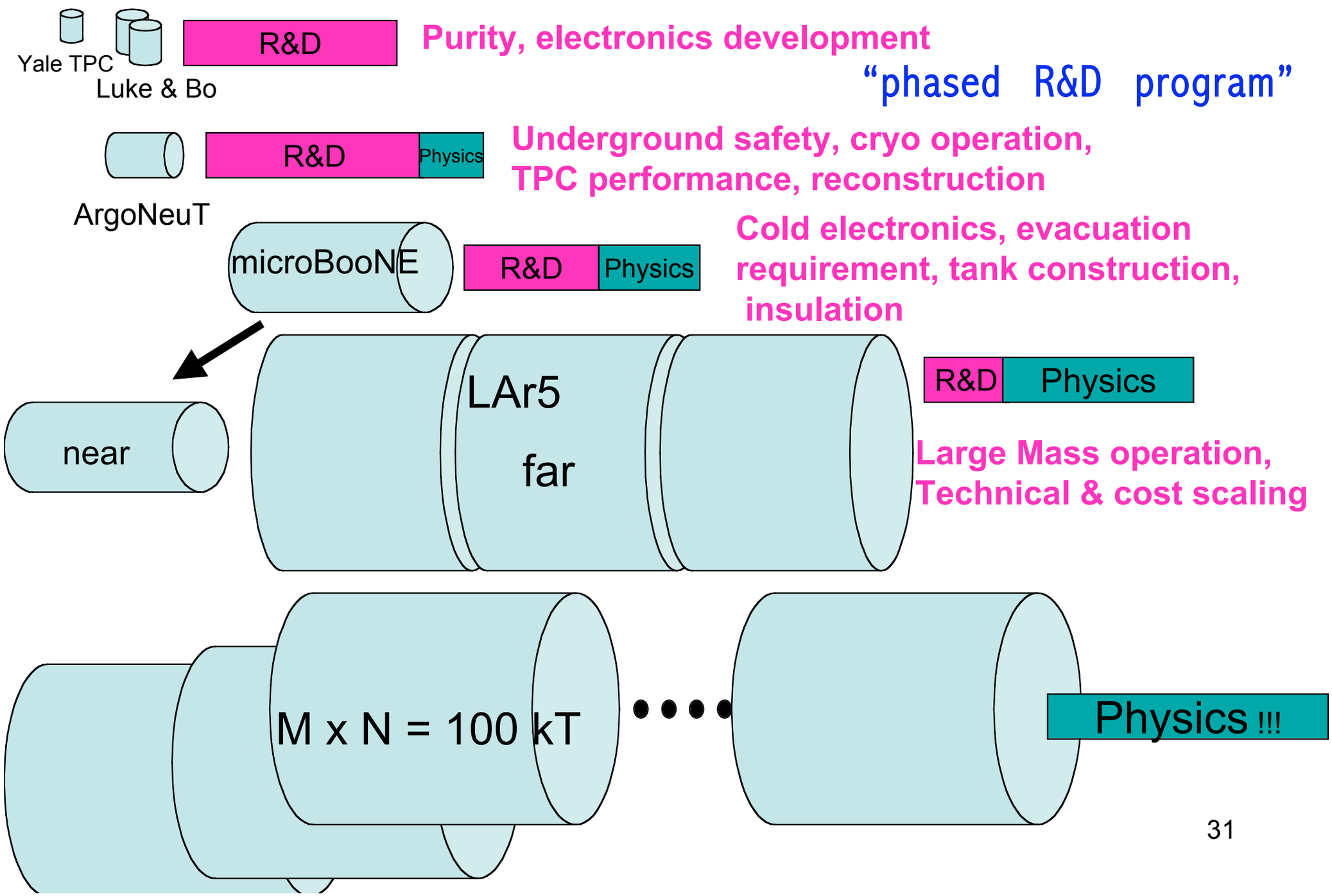
- Water Cerenkov
  - Known technology



- Liquid Argon TPCs
  - Great promise (x 3-4)

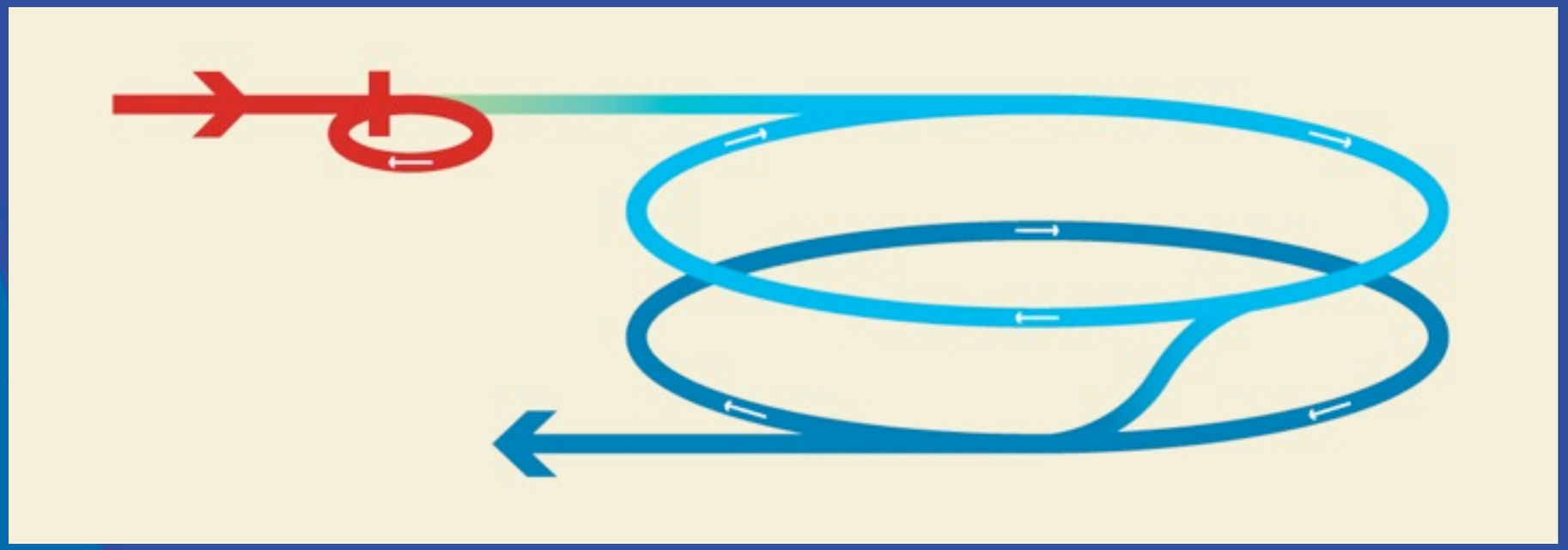


Evolution of the Liquid Argon Physics Program



Project X and LBNE to Homestake

- 5% of the time line, the 2 GeV linac feeds a simple Rapid Cycling Synchrotron (RCS), 500m circumference, to strip, accumulate and boost the energy to 8 GeV
- Six pulses of the SAB are transferred to the recycler, filling the existing recycler, and every 1.4 sec transferred to the Main Injector for acceleration to high energies (60 GeV to 120 GeV)

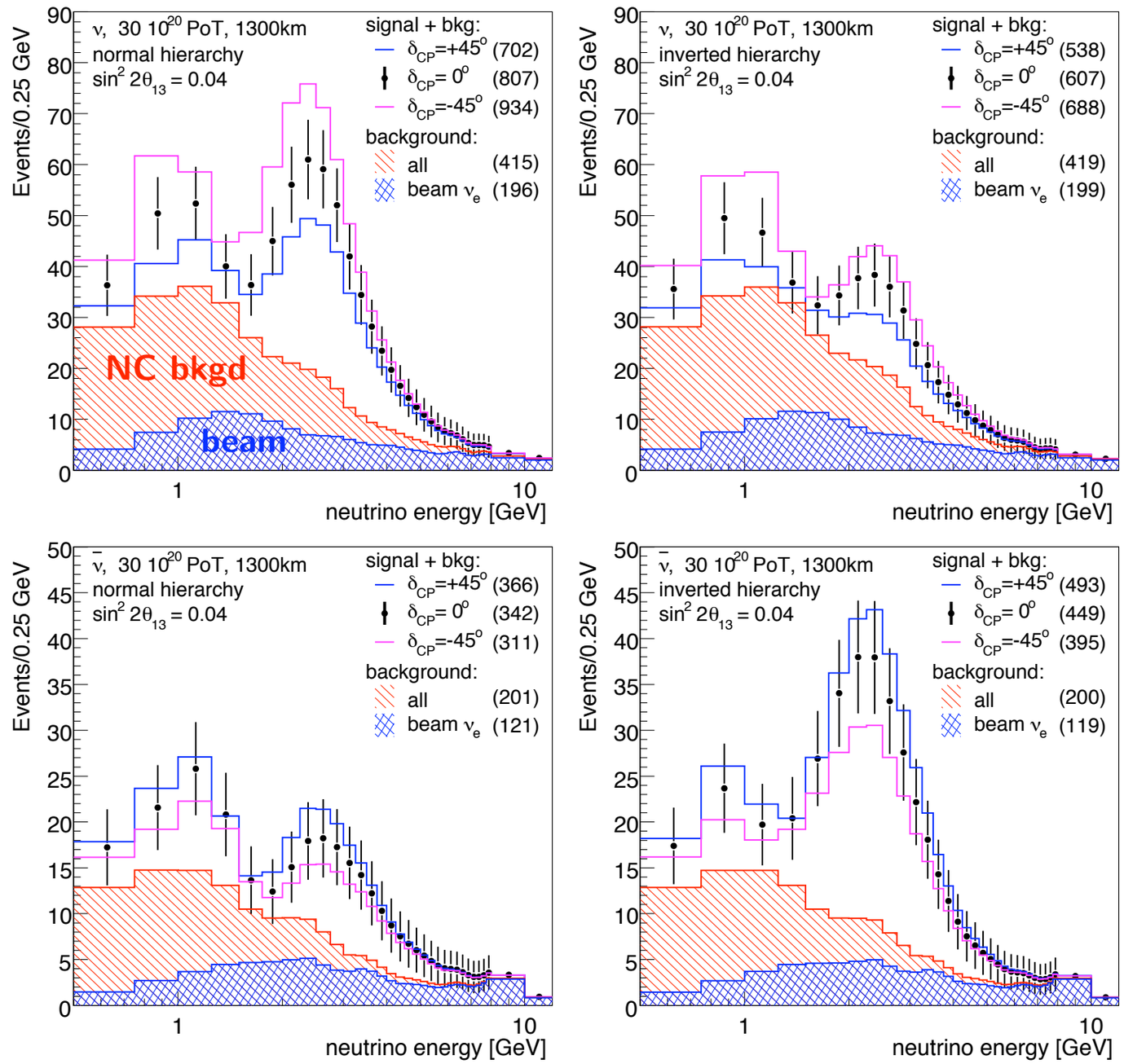


WATER CERENKOV: 300 KT

Normal Inverted

ν

$\bar{\nu}$



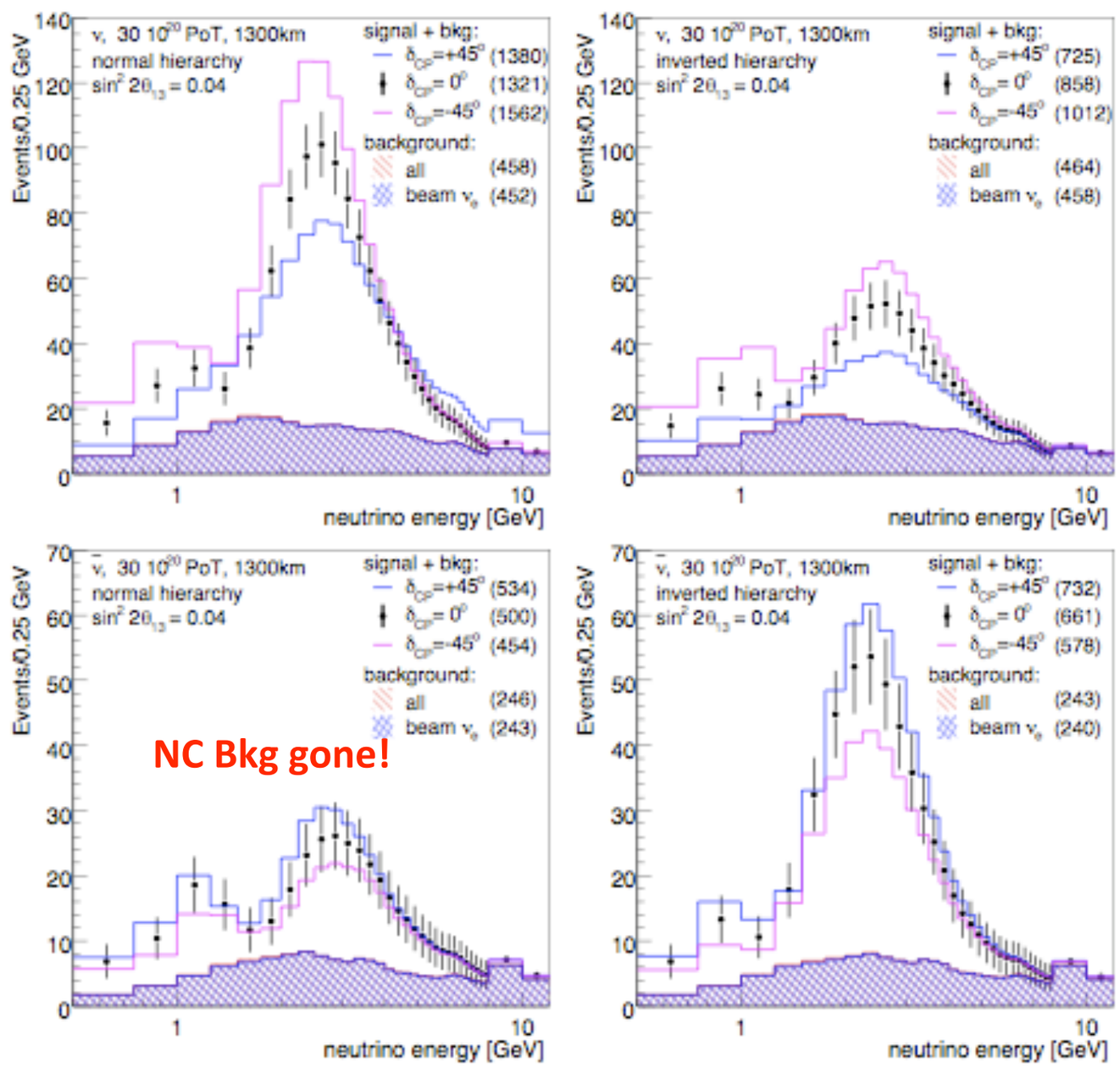
arXiv:0705.4396

LIQUID ARGON: 100KT

Normal Inverted

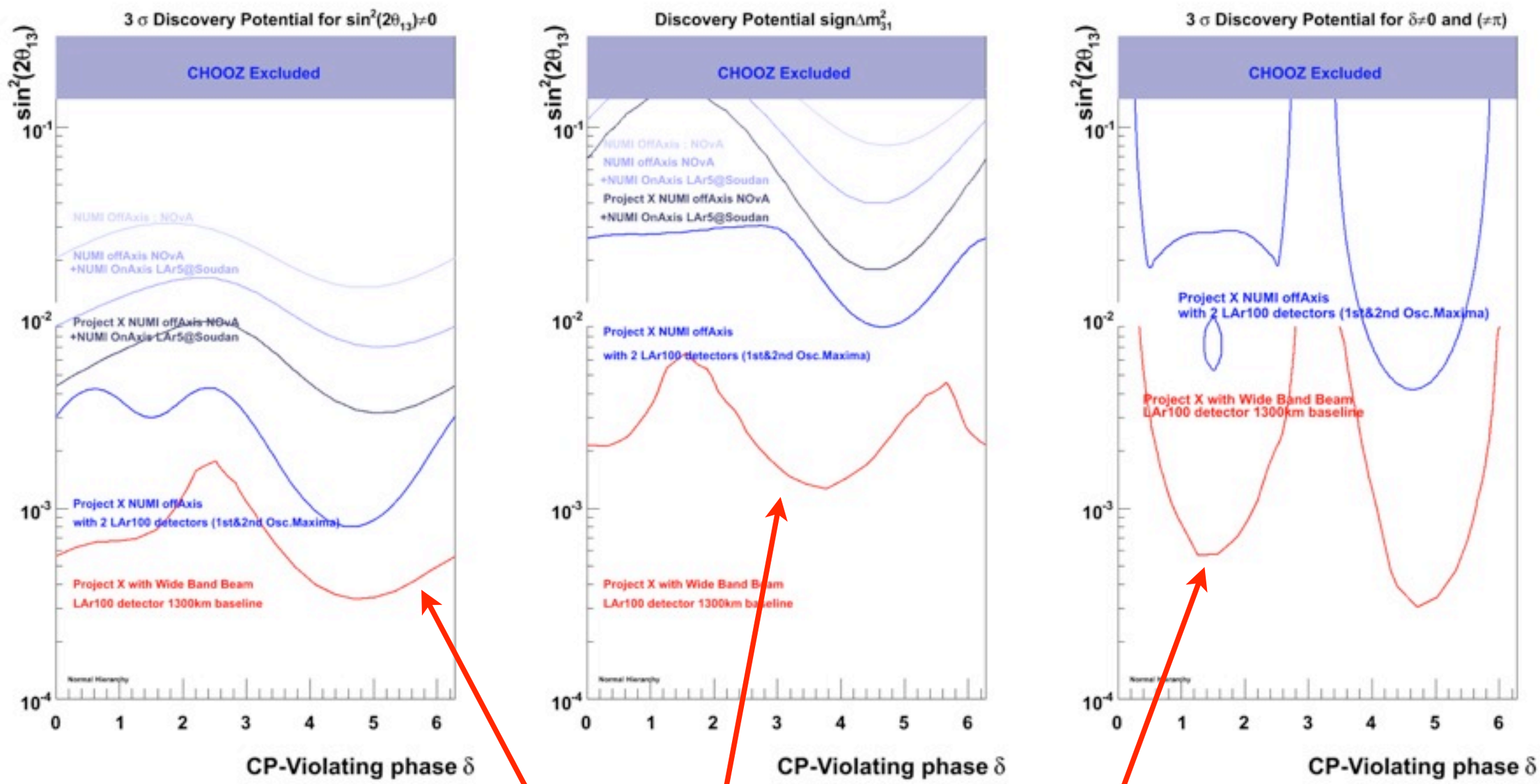
ν

$\bar{\nu}$



Studies suggest 100 kt LAR = 300kt WC

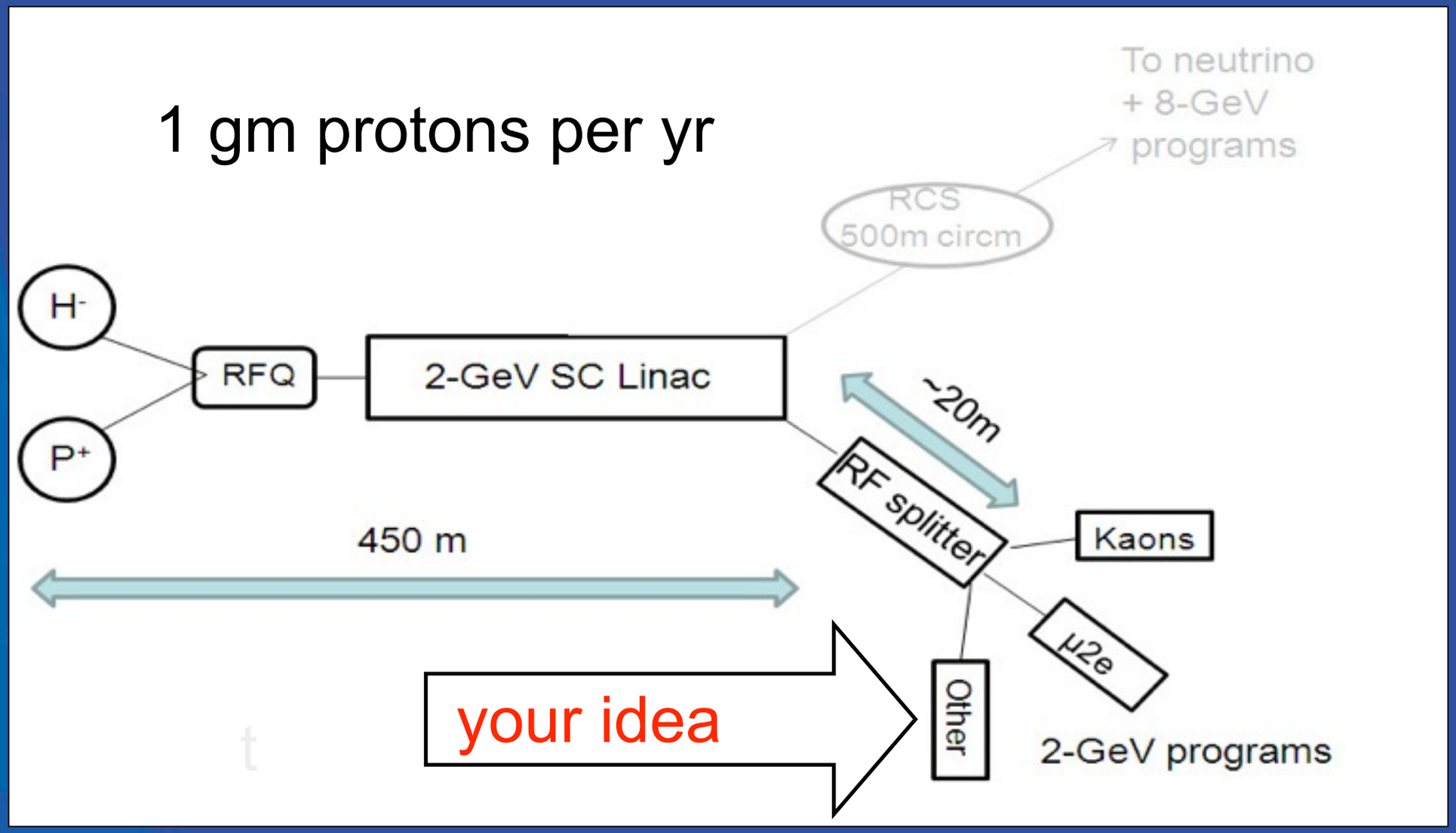
Sensitivity:



LAr 100kt 3+3 yrs 20e20 POT/yr

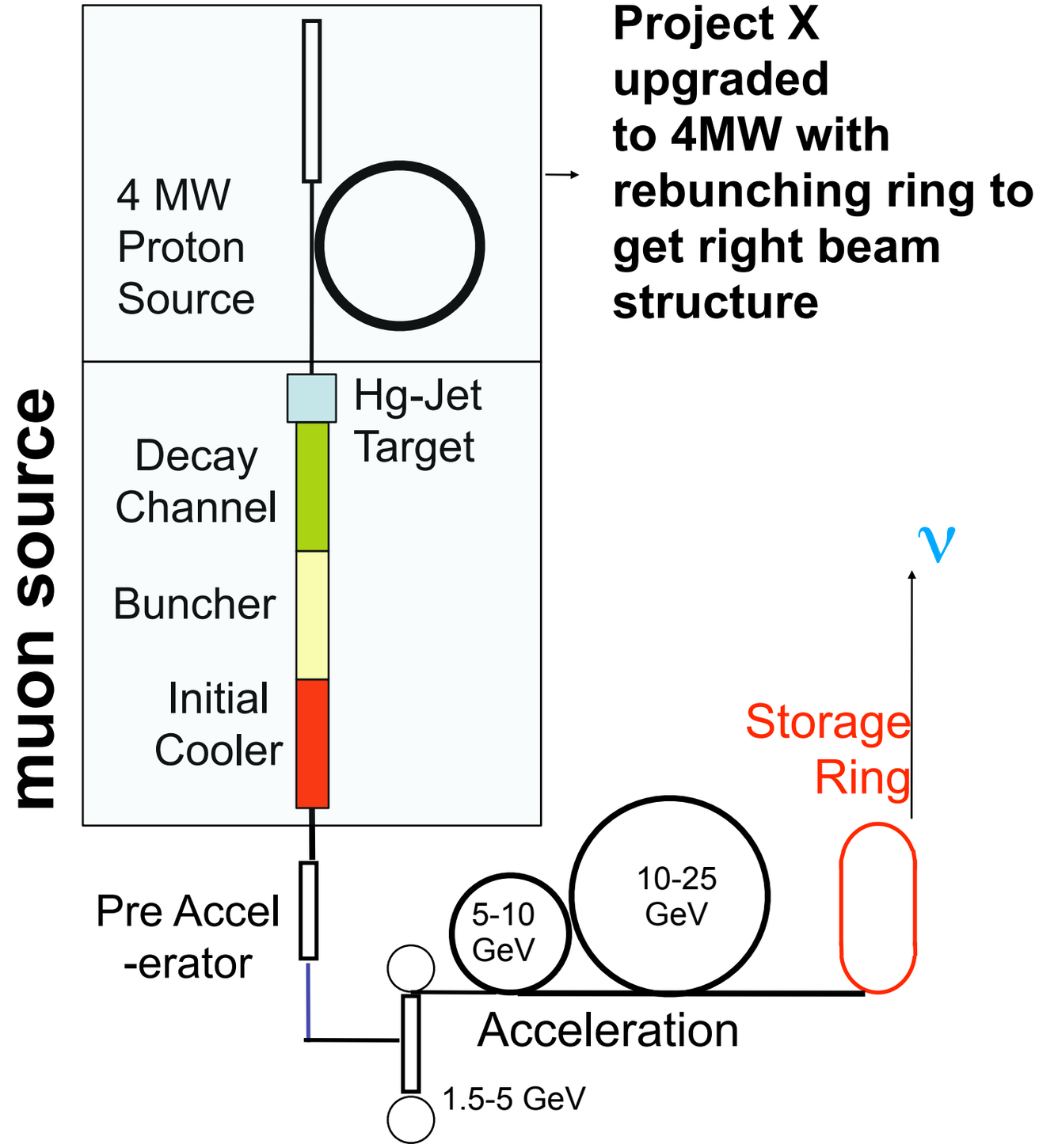
Project X and 2-3 GeV beams

- The greatest potential for rare processes comes from 2 MW continuous beam. Intensity experiments need continuous beam: pile up is the main limitation in pulsed beams

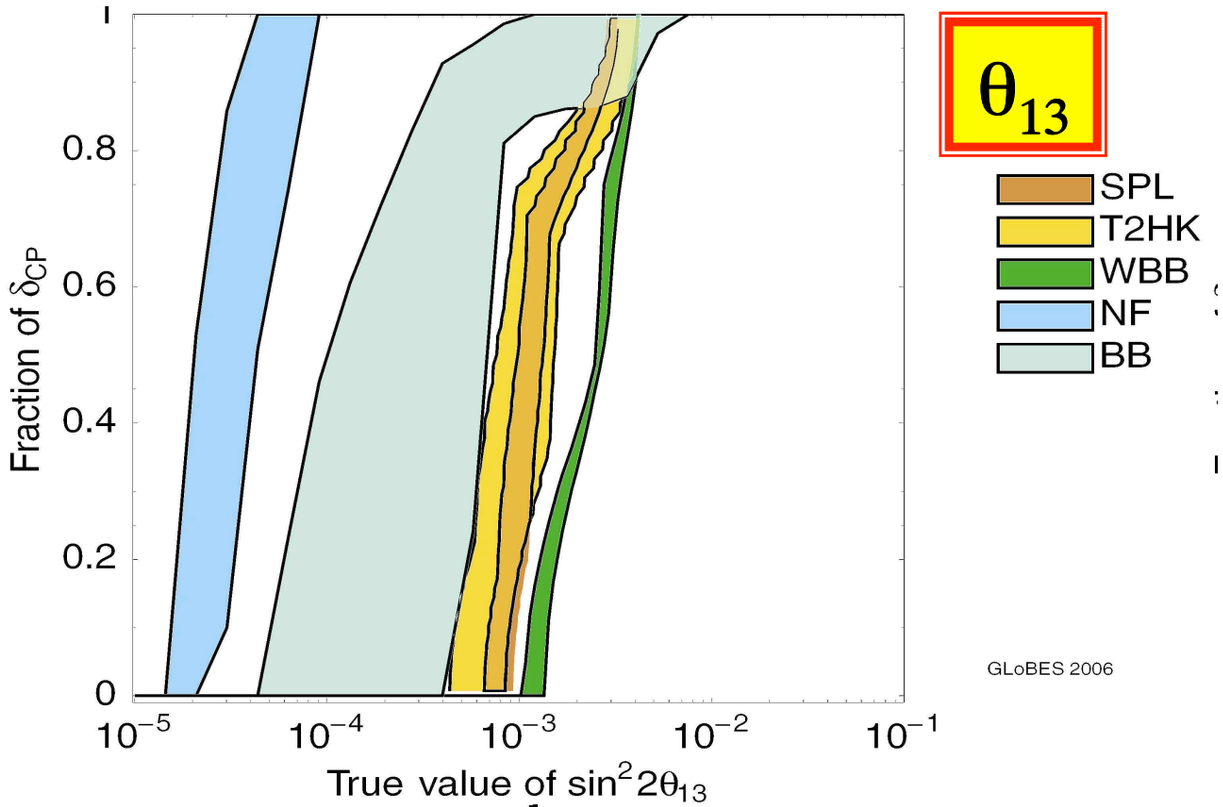


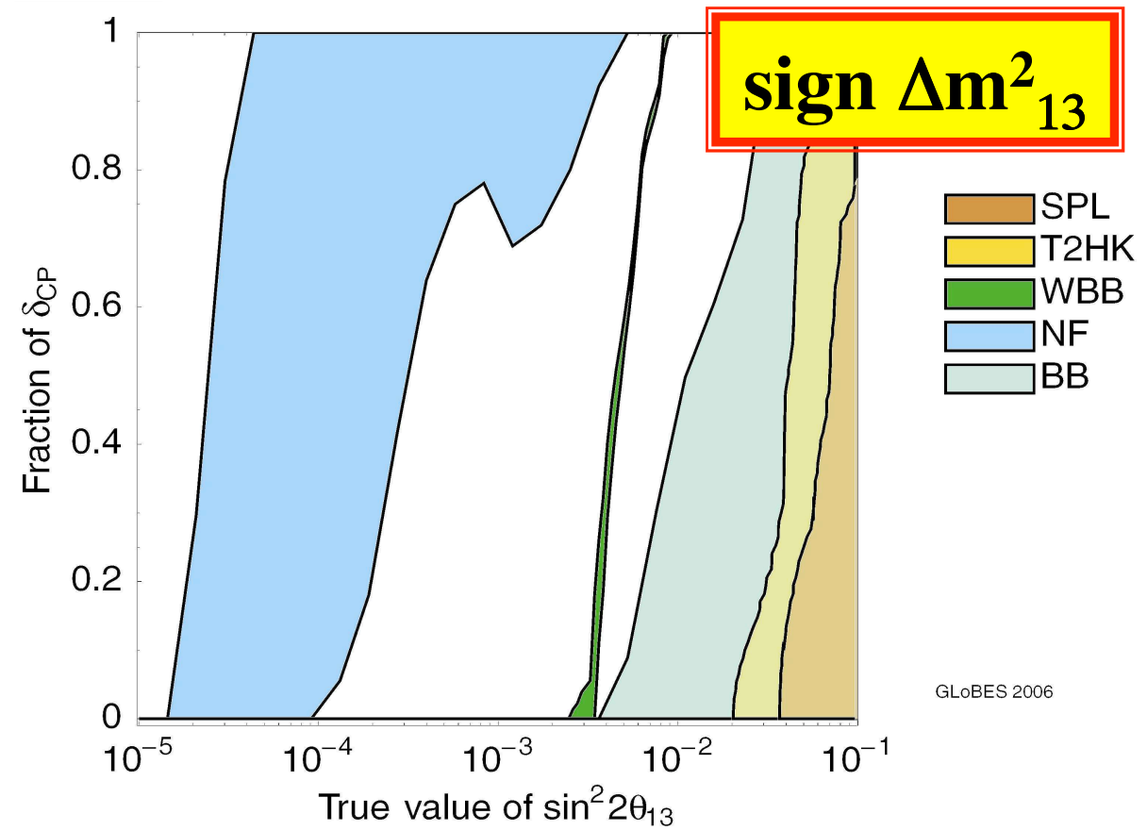
Neutrino Factory Schematic

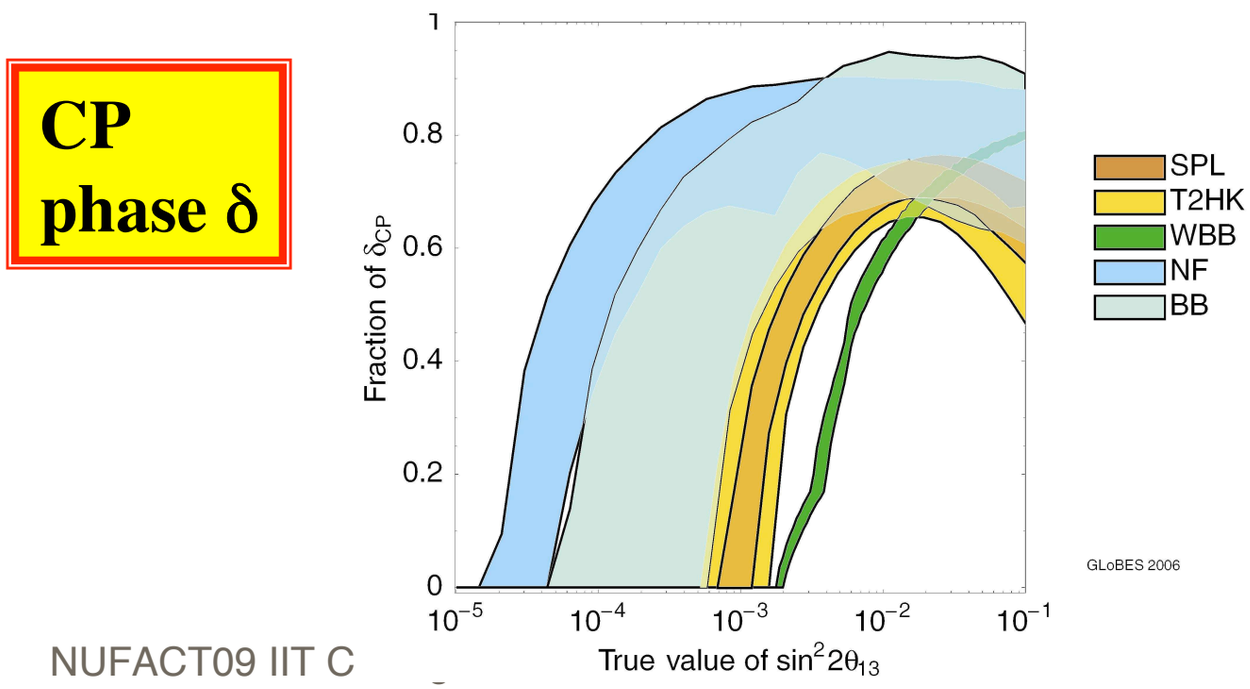
- Proton Source
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce transverse emittance
- Acceleration
  - 130 MeV $\rightarrow E_{NF}$
- Storage Ring
  - store for 500 turns; long straight section



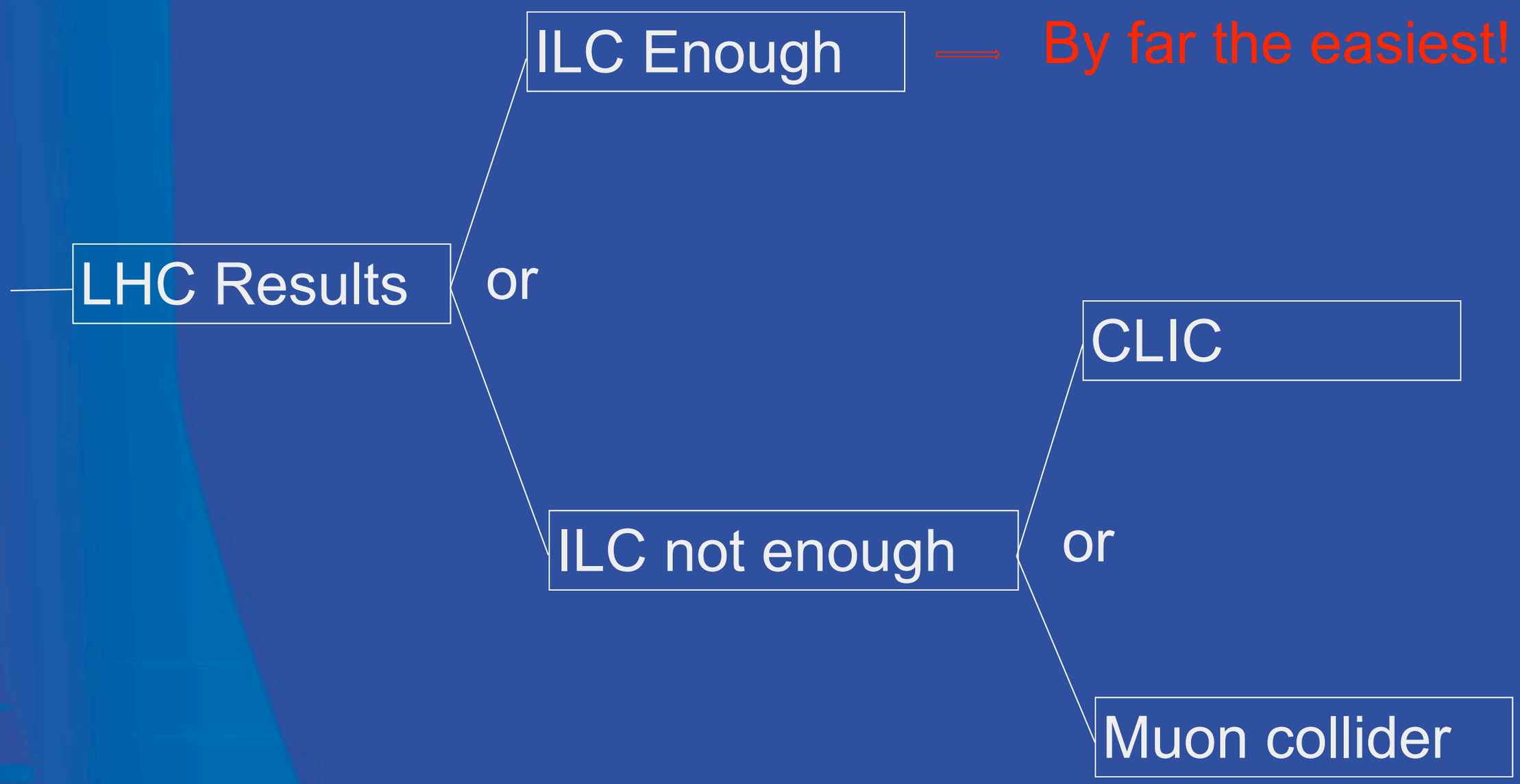
Physics Sensitivity:



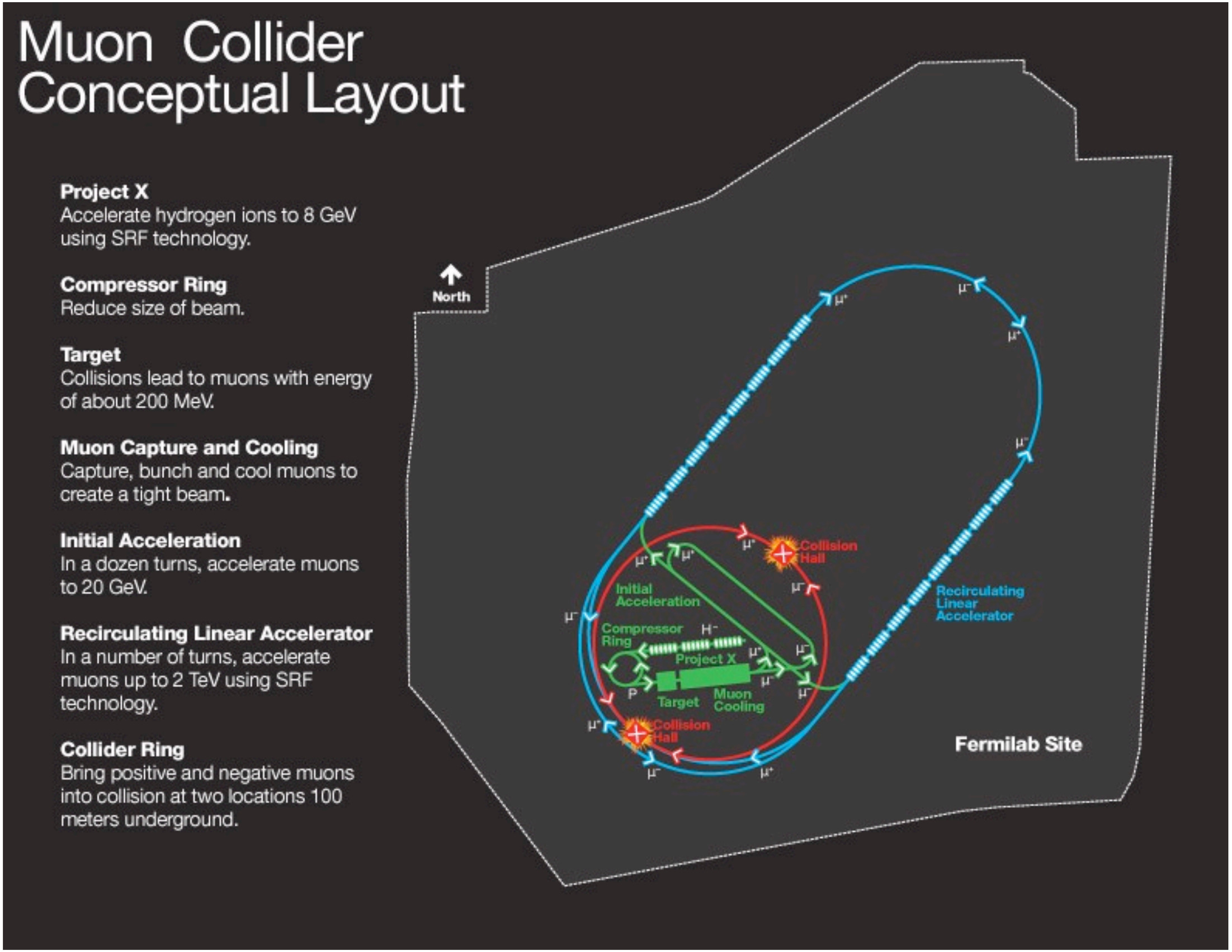




Lepton colliders beyond LHC

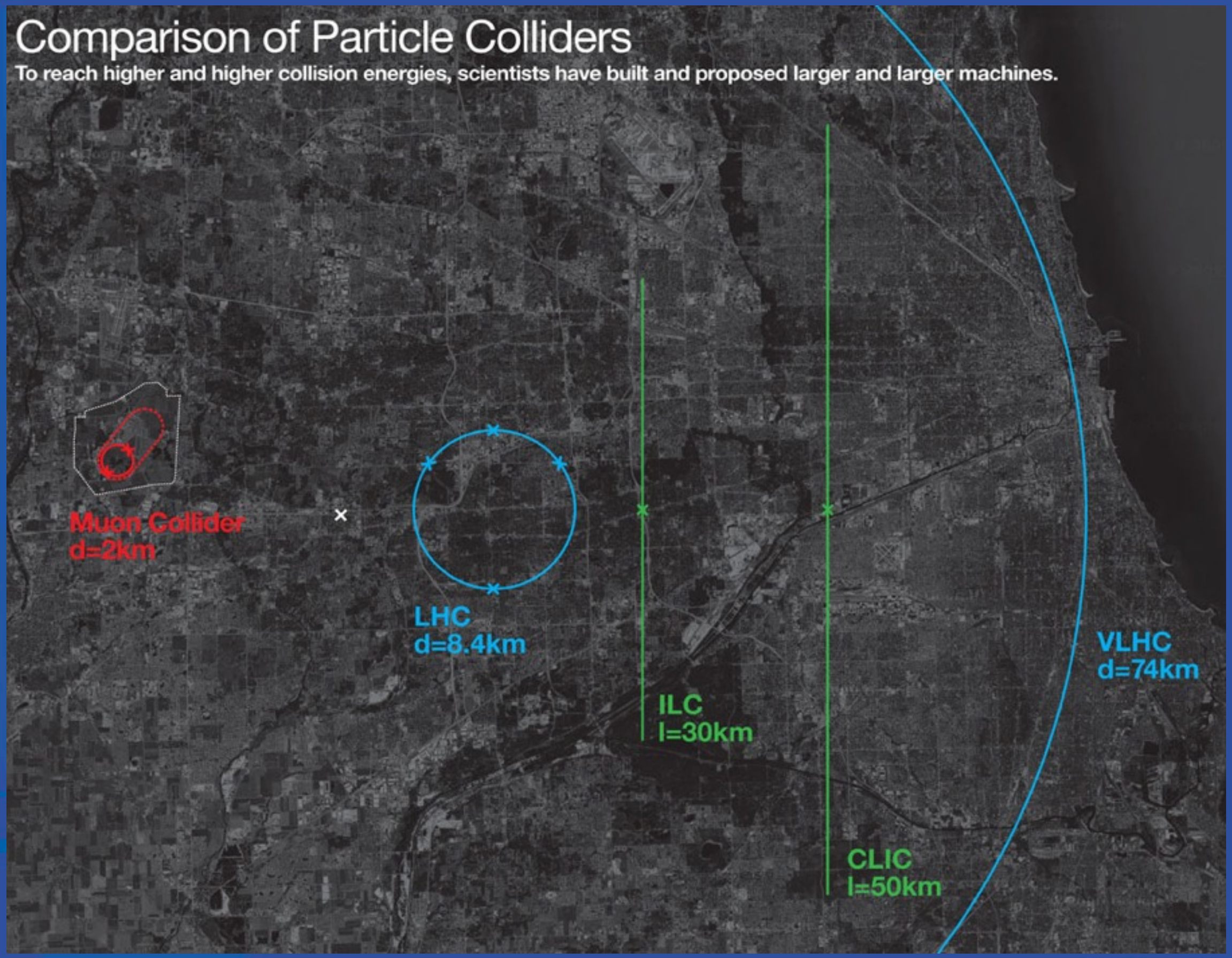


4 TeV


Muon Collider
Conceptual Layout
Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.
Compressor Ring
Reduce size of beam.
Target
Collisions lead to muons with energy of about 200 MeV.
Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.
Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.
Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.
Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.
North
Collision Hall
Initial Acceleration
Compressor Ring
Project X
Target
Muon Cooling
Recirculating Linear Accelerator
Fermilab Site

Comparison of Particle Colliders

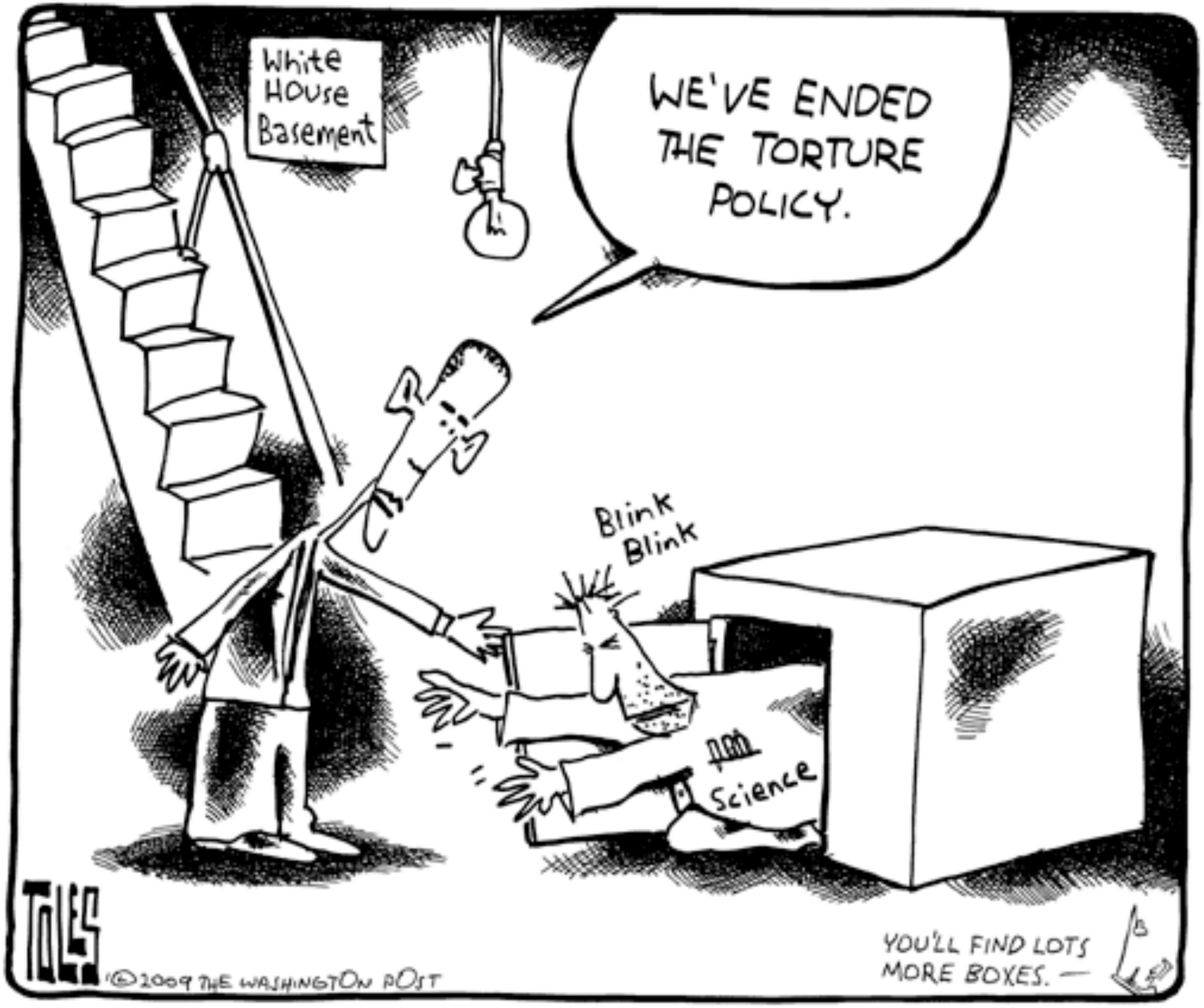
To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



Neutrinos at Fermilab

- Near Term:
  - Suit of New Neutrino Experiments
    - NOvA, mircoBooNE, MINERVA
    - maybe kaons, anti-protons
- Mid-Term: Project X (2 MW @ 120 GeV + 2 MW at 2 GeV)
  - LBNE (300 kton H20 / 100kton LAr)
  - Rare Kaon Exp. and Mu2e, g-2, Your Exp.!
- Long Term:
  - NuFactory as part of Muon Collider

Washington Post 1/25/2009



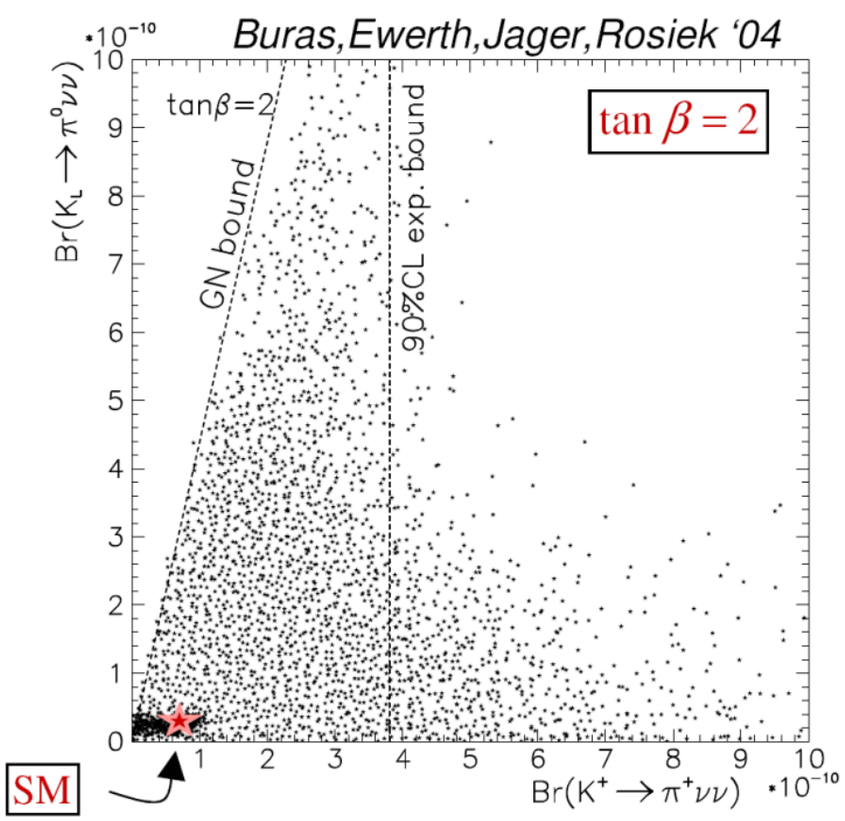
http://www.washingtonpost.com/wp-dyn/content/opinions/tomtoles/?name=Toles&date=01252009

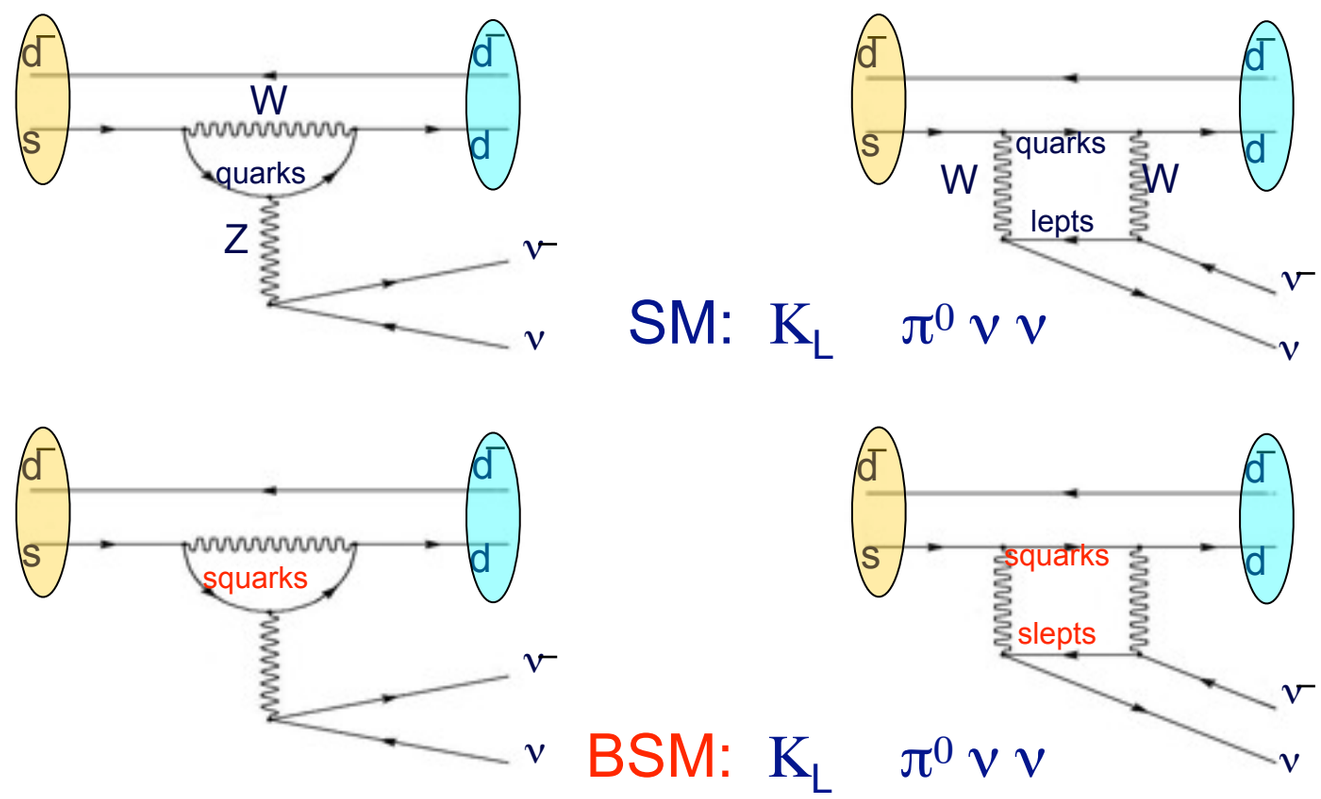
extras:

Kaons

$$K^+ \to \pi^+ \nu\bar{\nu}$$
$$K_L \to \pi^0 \nu\bar{\nu}$$

	Theo(SM)$\times 10^{10}$	Exp.$\times 10^{10}$	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}$	0.85 ± 0.07	$1.73^{+1.15}_{-1.05}$	BNL-E787/949
$K_L \to \pi^0 \nu\bar{\nu}$	0.28 ± 0.04	< 670	KEK-391





For Statistical Uncertainties $\approx$ Theoretical Uncertainties

$\sim$ 1000 events needed in K^+ and K_L !

Project X

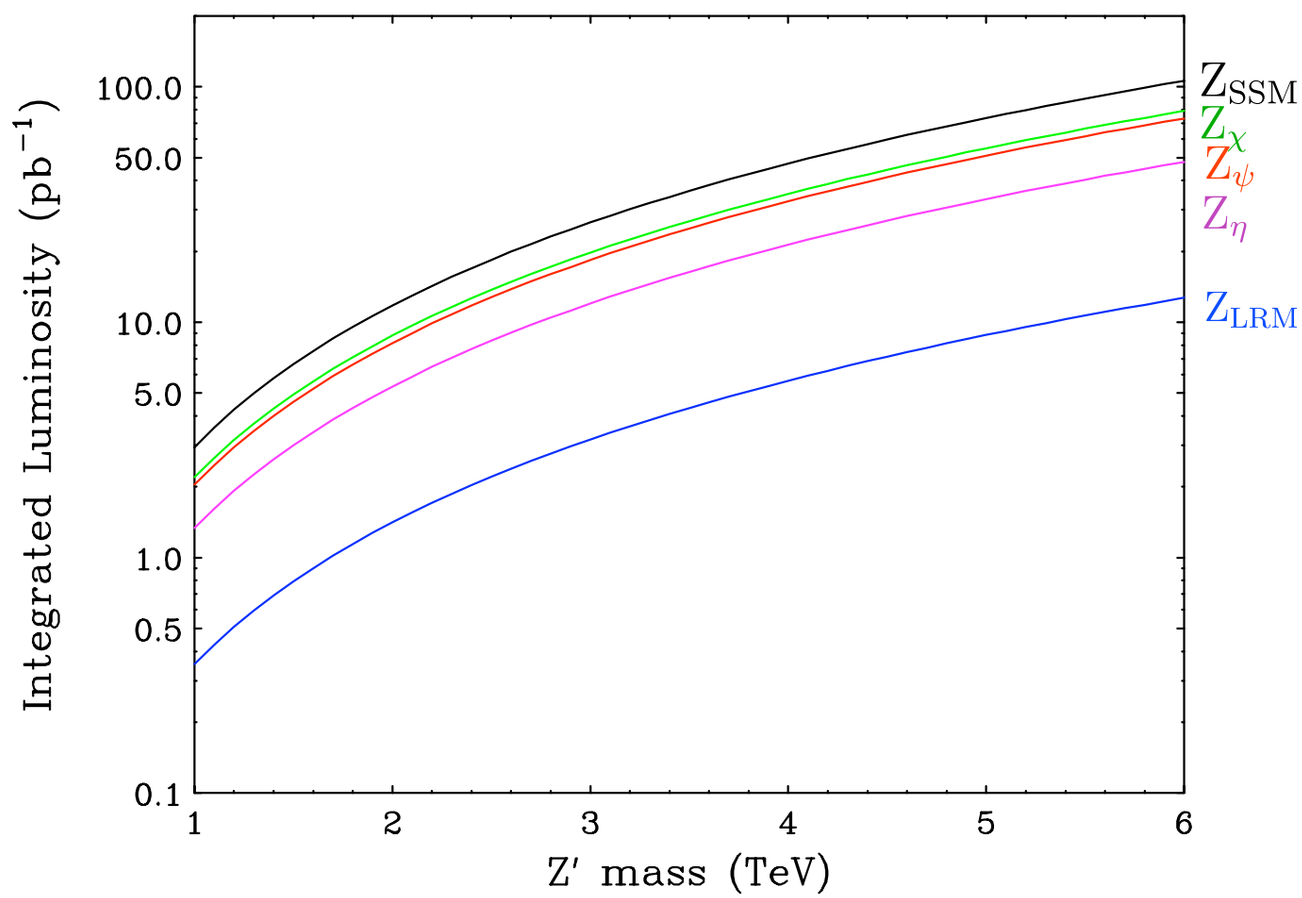
Minimum Luminosity for Physics:

- Assuming a new gauge boson: Z′
  - examples: SSM, E6, LRM
  - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

- For a narrow resonance with $2\Delta E_{beam} / \Gamma_{resonance} << 1$:

$$\rightarrow R_{\rm peak} = (2J+1)3\frac{B(\mu^+\mu^-)B(visible)}{\alpha^2_{\rm EM}}$$

The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z′ events on the peak



Hence minimum luminosity -> 0.5-5.0 x 10^{30} cm^{-2} sec^{-1}

for M(Z′) -> 1.5-5.0 TeV

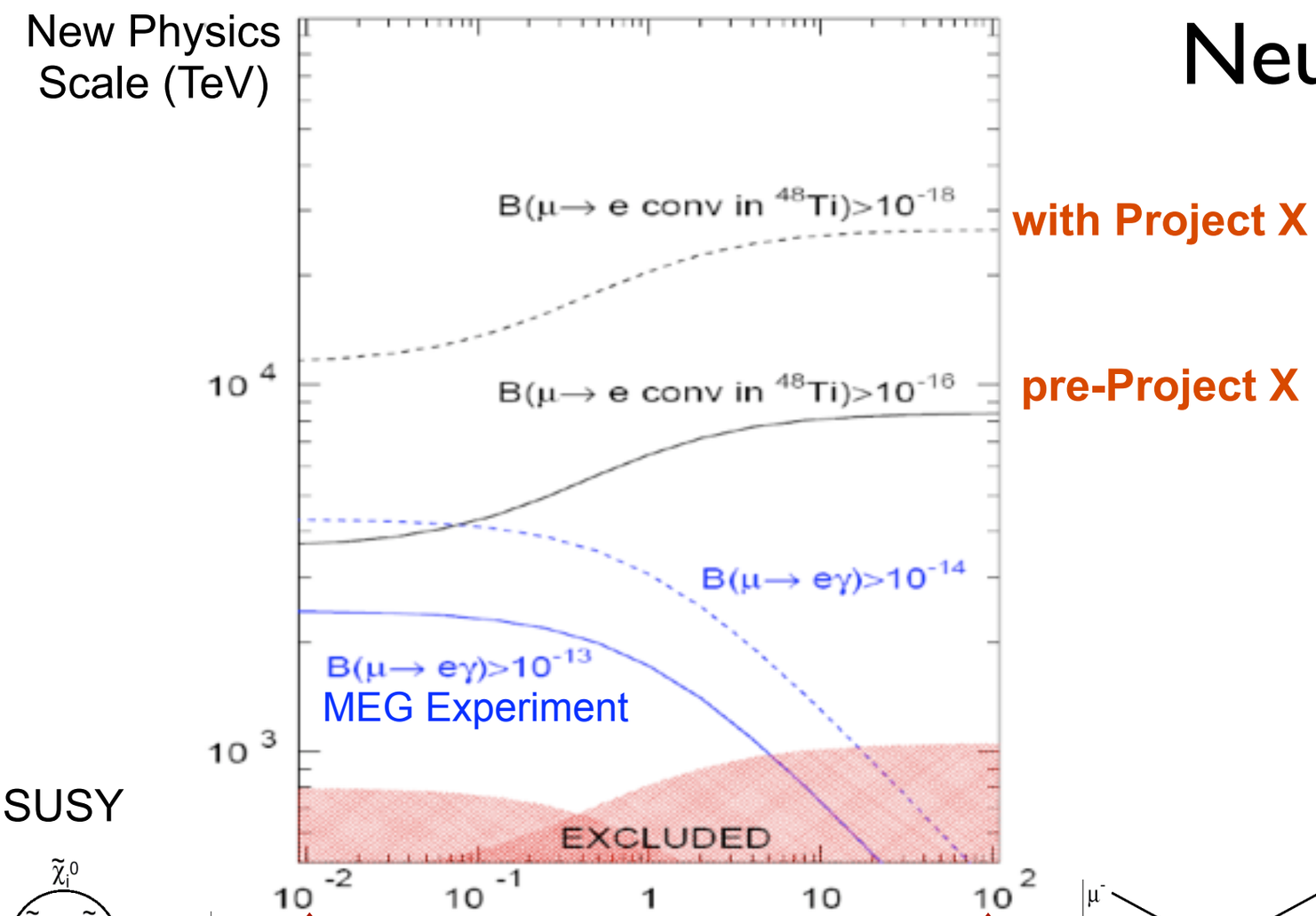
E. Eichten, "The Basics of Muon Collider Physics" (Fermilab-Pub-09-225-T)

• Muons

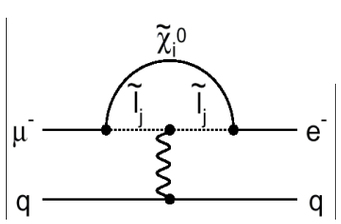
$$\mu + N \rightarrow e + N$$

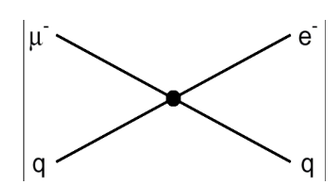
$$(g-2)_\mu$$

Neutrino Factory



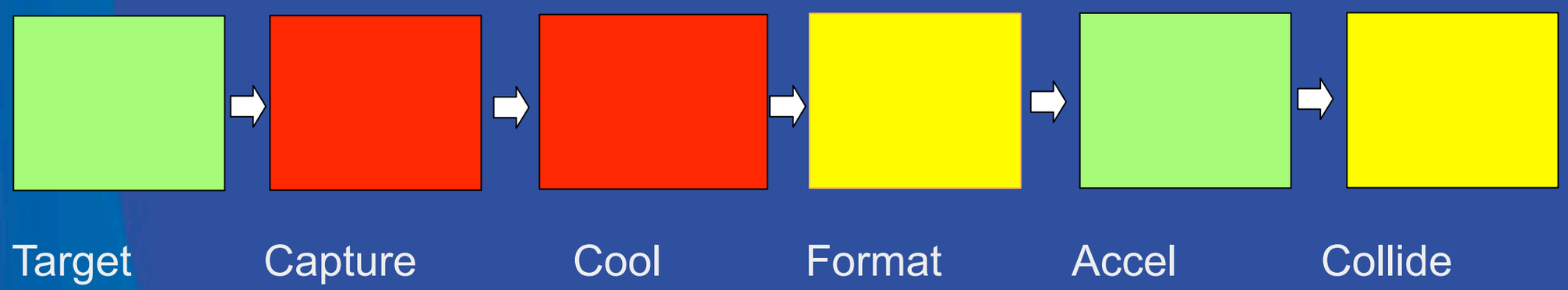
SUSY





Mu2e can probe 10^3 – 10^4 TeV

Muon collider functional layout



Color indicates degree of needed R&D (difficulty) and demonstration