Physics of the Intensity Frontier

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9/19/2011
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Outline

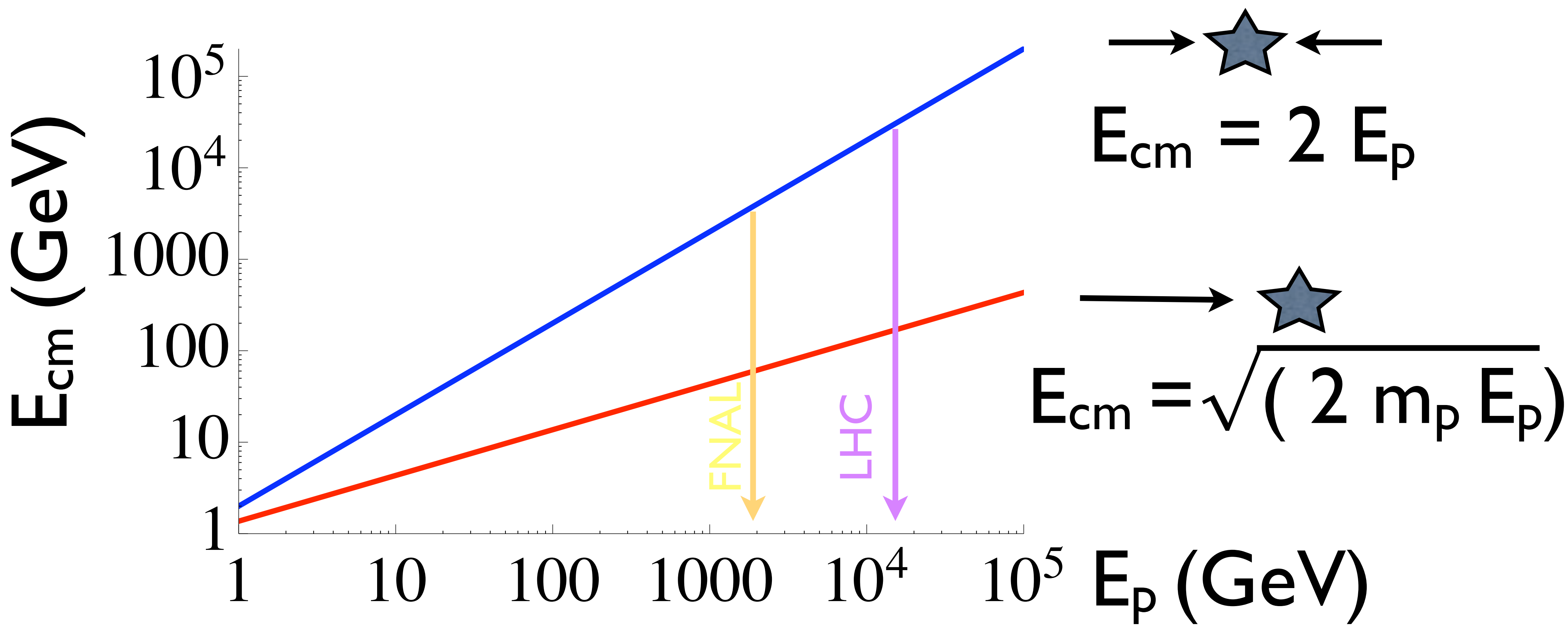
- Generalities
- Intensity Frontier Motivation
  - Kaon Physics
  - Muon Physics
  - Neutrino Physics
- Project-X at FNAL

For each topic there will be an introduction and a little more detail for the aficionados.

Particle Physics

- Deeper understanding of the constituents of matter and their interactions.
- The traditional approach has always been to either produce new particles by high energy accelerators or to look for rare signatures in decays, interactions, or asymmetries at low energies.

The collider technique

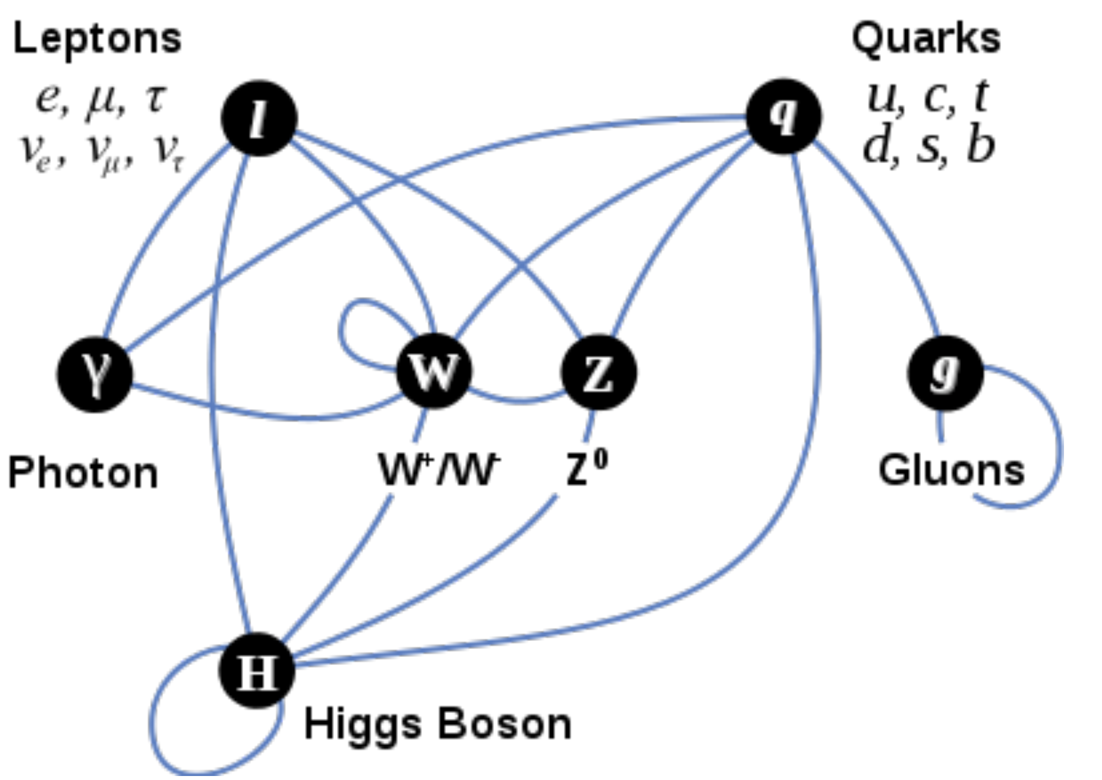


- The technique for making new particles had an extraordinary advance in ~1970s. The collider technique allowed several magnitude increase in available energy. Thus Tevatron and the LHC !
- There is no technological barrier to a 200 TeV collider.

Standard model of particles and interactions

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

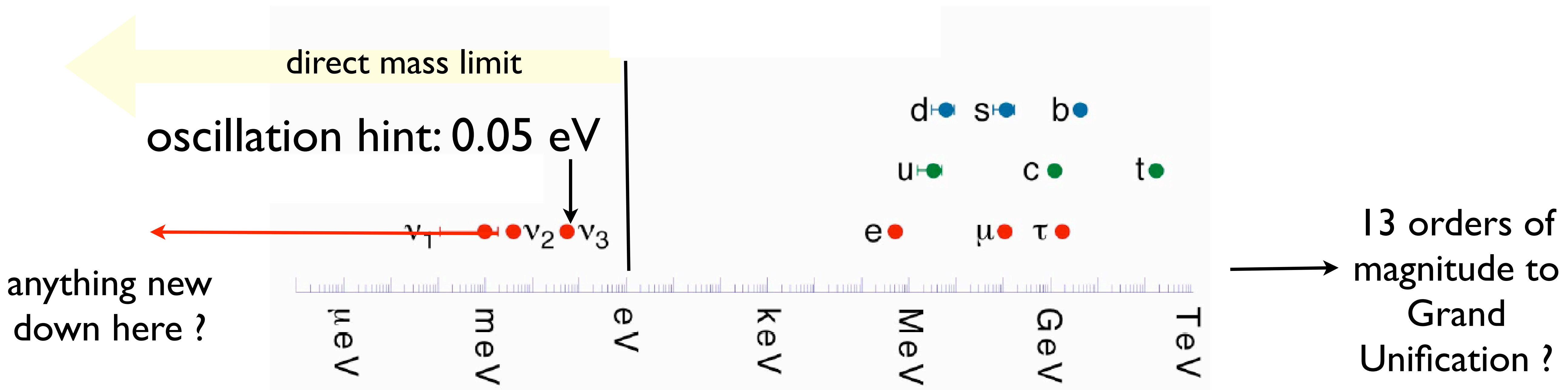
Leptons spin =1/2			Quarks spin =1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	(0–0.13)×10^{-9}	0	u up	0.002	2/3
e electron	0.000511	–1	d down	0.005	–1/3
ν_M middle neutrino*	(0.009–0.13)×10^{-9}	0	c charm	1.3	2/3
μ muon	0.106	–1	s strange	0.1	–1/3
ν_H heaviest neutrino*	(0.04–0.14)×10^{-9}	0	t top	173	2/3
τ tau	1.777	–1	b bottom	4.2	–1/3



gravity is separate for now

- There are elaborate rules that govern the interactions.
- They must respect QM, Kinematics, and symmetry principles that are not obvious. (Baryon and Lepton number)
- The quarks and neutrinos have been found to be QM superpositions of mass eigenstates.
- Without the Higgs particle this does not work. In any case, Neutrino masses are not easily accommodated.
- Suspected symmetry between matter and interactions requires doubling the entire spectrum (Supersymmetry) at high energies.

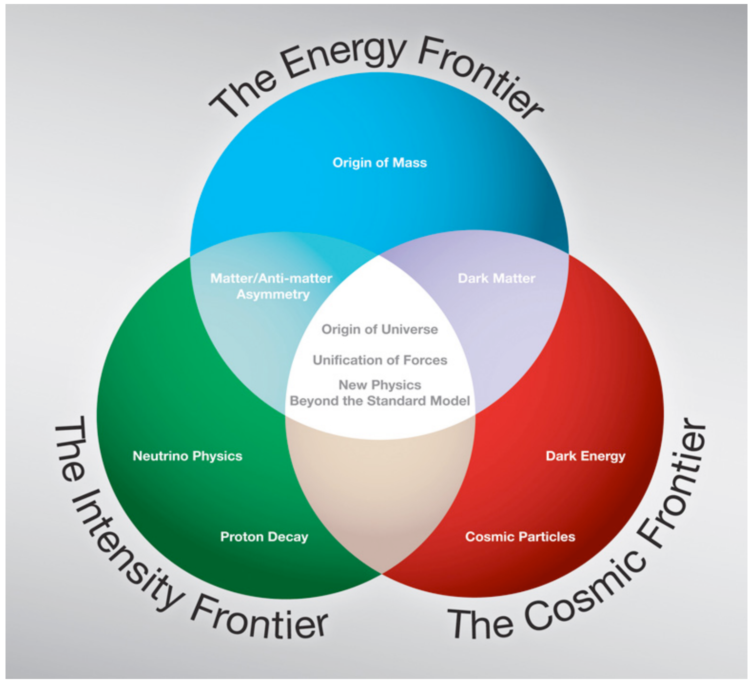
Current picture of neutrino masses points to another mass generation mechanism.



Mass is a coupling of the left and right components of the Fermion field,
unless it is a neutral fermion in which case mass can couple fields of same handedness.

Themes in particle physics

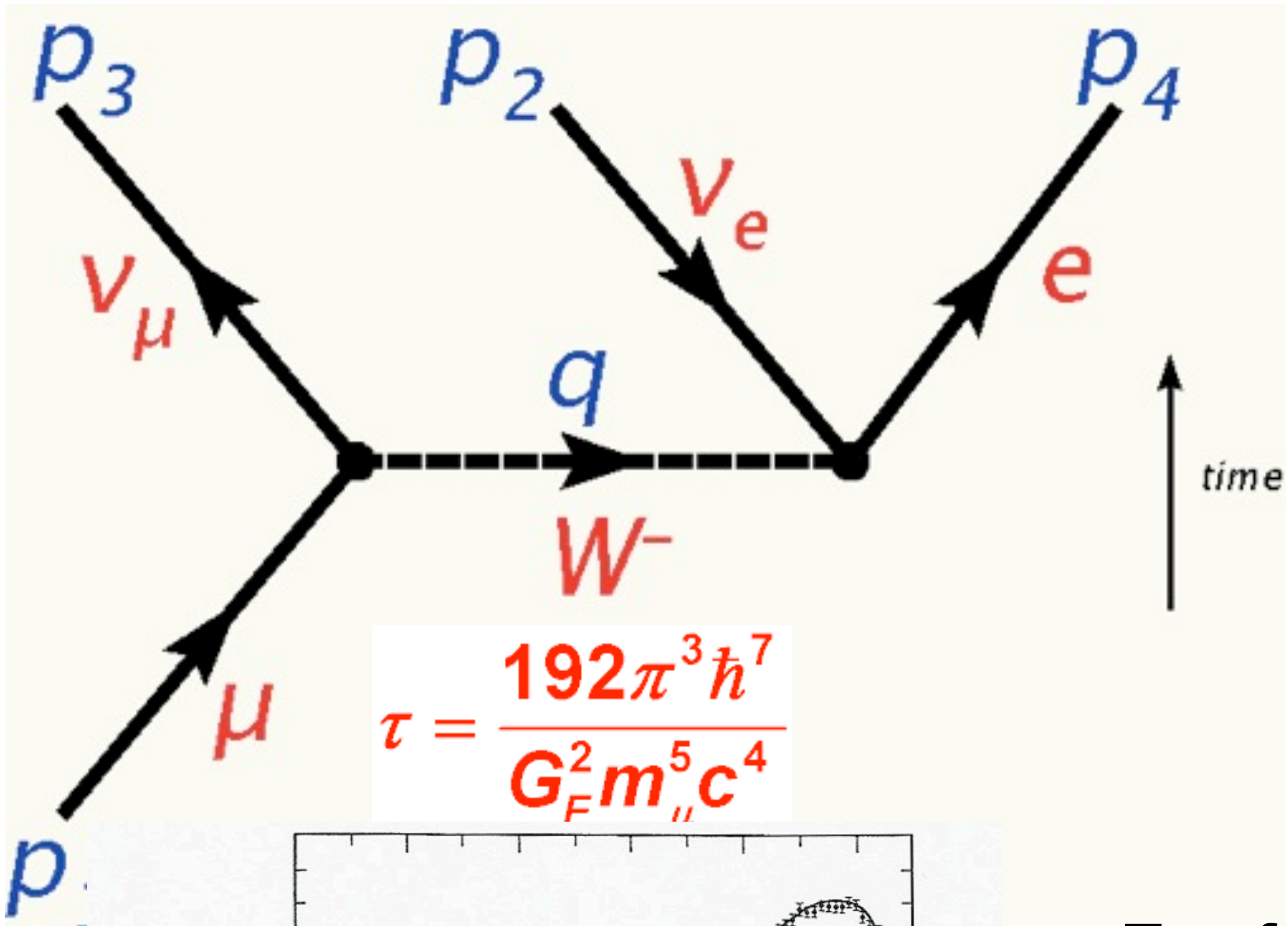
2008 Particle physics panel report



Problem	Key observations	Tools
Dark matter	Direct detection Missing energy	Underground Detect. Collider Detectors
Dark Energy	Accelerating Universe	Astronomical surveys
Neutrino Mass	Double beta decay Neutrino oscillations	Underground Detect. Neutrino beam/det.
Matter/antimatter asymmetry	CP violation Baryon, Lepton num.	K and B meson decay Neutrino Oscillations Proton/muon decay
Three generations	Quark mixing Neutrino mixing	K and B meson decays Neutrino oscillations
Unitarity at the TeV scale	Higgs particle Supersymmetric particles	Collider Detectors Muon dipole moments, Electric Dipole Moments. Rare decays

Focus of the talk will be Kaons, Muons, and Neutrinos

Muon decay

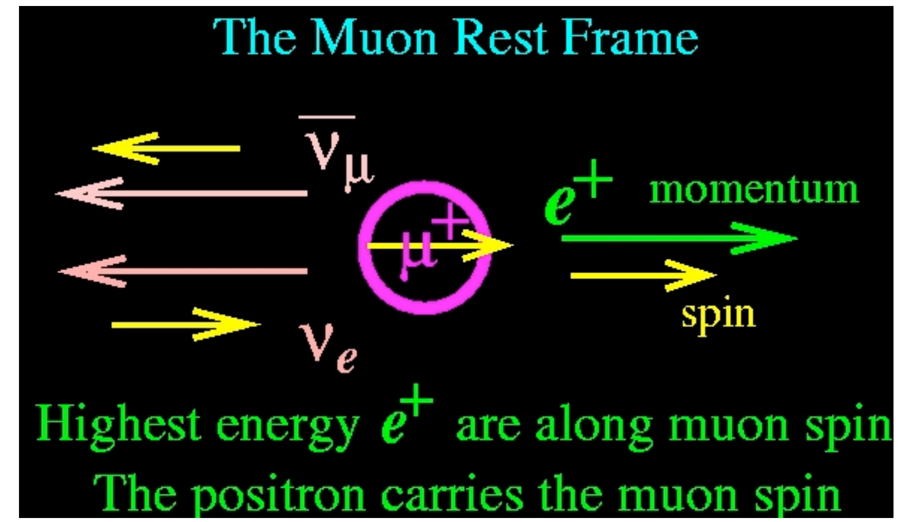


$$\tau = \frac{192\pi^3\hbar^7}{G_F^2 m_\mu^5 c^4}$$

$$\mu \rightarrow e + \nu_\mu + \bar{\nu}_e$$

mass: 105.658367(6) MeV

Lifetime: 2.197034(21) micro-sec



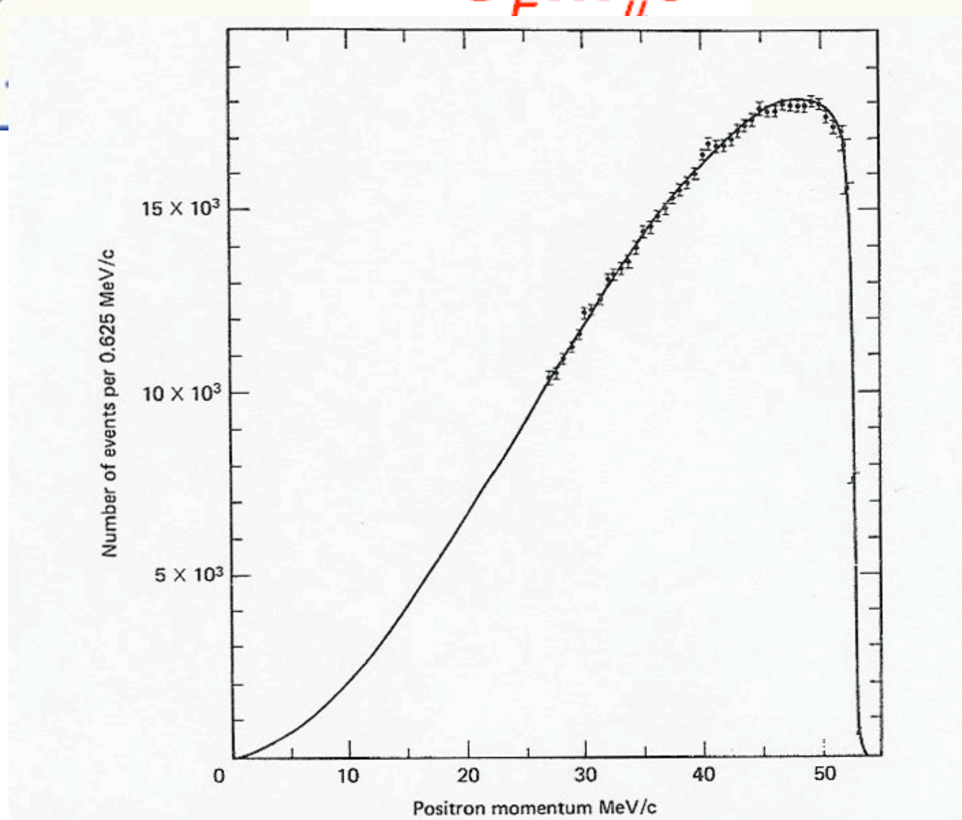


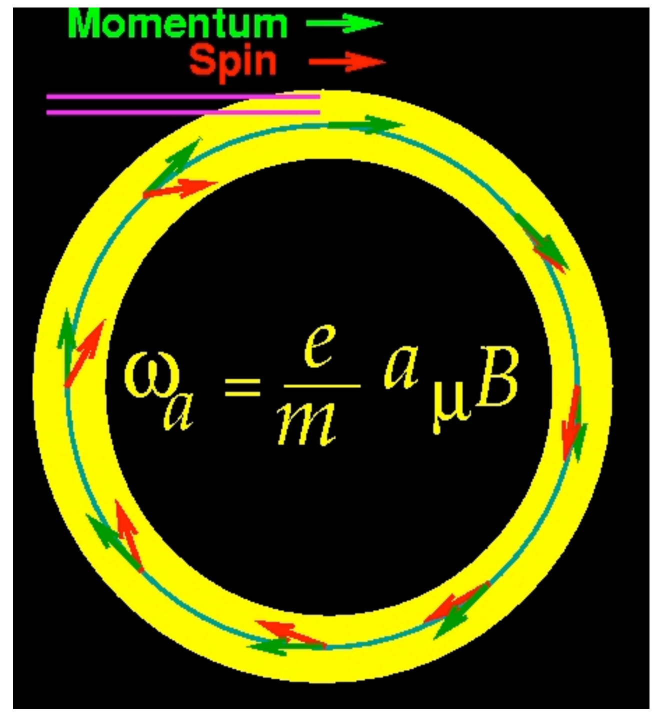
Figure 10.1 Experimental spectrum of positrons in $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. The solid line is the theoretically predicted spectrum based on equation (10.35), corrected for electromagnetic effects. (*Source:* M. Bardon et al., *Phys. Rev. Lett.* **14**, 449 (1965).)

- For free muons the highest energy electrons are E=m/2
- Decay violates parity. The electron (positron) is emitted anti (parallel) to the direction of the mu-spin.
- Negative muons can go into atomic orbits and decay while interacting with the nucleus.

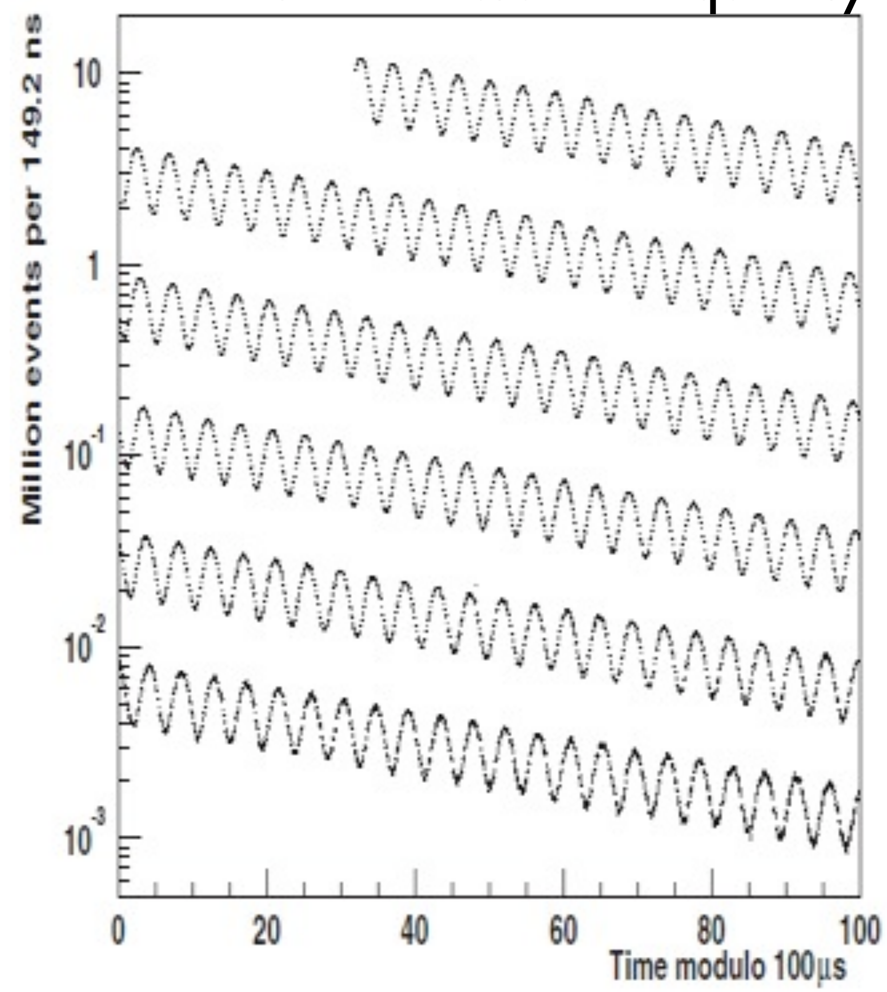
Muon (g-2)

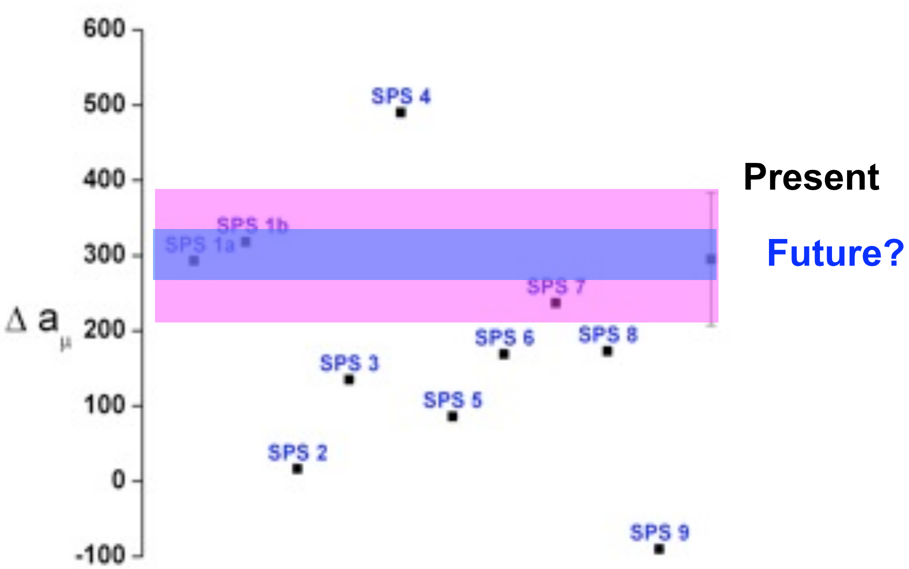
Dirac equation predicted g = 2;
use s=1/2 => ~0.000058 eV/Tesla
Loop effects make a = (g-2)/2 > 0

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$



BNL-821 measure frequency





New physics (susy) benchmarks

$$a_\mu = 11\,659\,208.0(6.3) \times 10^{-10}\ (0.54\ \text{ppm})$$

- The long muon lifetime, polarized parity violating decay means that the spin precession in a ring measures deviation from g=2.At FNAL this can be improved to 0.1ppm.

Rare muon decays

$$\mu^- N \rightarrow e^- N$$

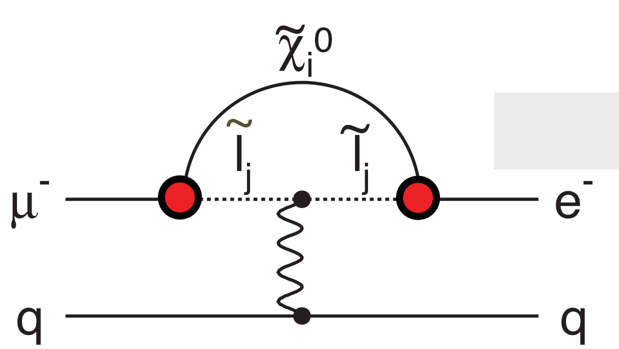
- Muon conversion in orbit of nucleus.
- Single monoenergetic electron.
- SINDRUM-II (PSI) limit for Ti: 4×10^{-12} Au: 7×10^{-13}
- Experimental signature allows very high sensitivity

$$\mu \rightarrow e\gamma$$

- Two body decay. Coincidence signature.
- MEG (PSI) Limit: $<10^{-11}$
- Becomes more difficult at higher rates due to accidentals.

Supersymmetry

rate ~ 10^{-15}



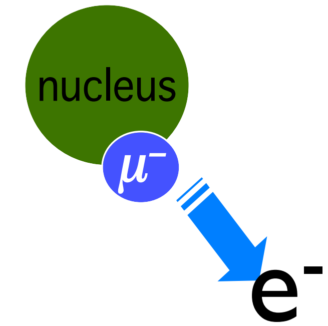
Terascale physics at the LHC implies CLFV at sensitivity of $>10^{-16}$

SM prediction due to neutrino mass

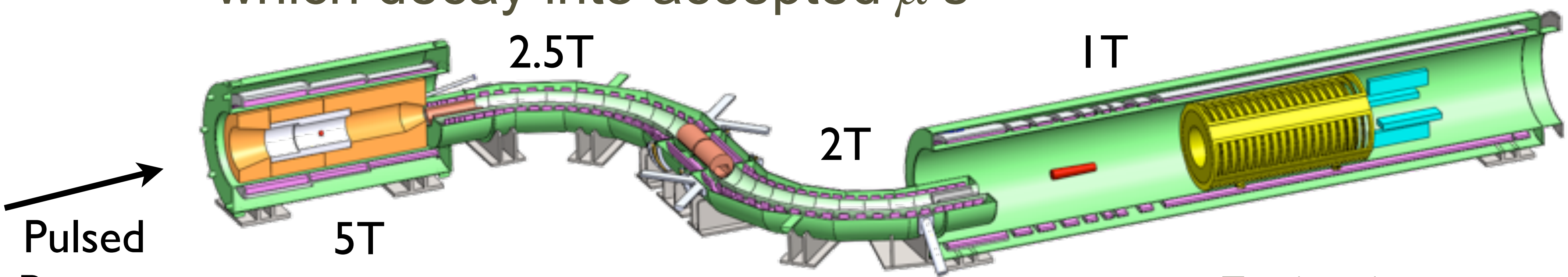
$$\propto \alpha\left(\frac{m_\nu}{M_W}\right)^4$$

- Only electrons, photons, and neutrinos are lighter than muons. Lepton number is an important probe, so muon decays to e's and gammas are a sensitive laboratory.

Mu2e experiment



- *Production*: Magnetic bottle traps π's, which decay into accepted μ's



- *Transport:* S-curve eliminates backgrounds and sign-selects
- *Detector:* Stopping Target, Tracking and Calorimeter

$\mu + Al \to \nu_\mu + Mg$	$\mu + Al \to e + Al$	$\mu + Al \to e + Al + \nu_\mu + \bar{\nu}_e$
Capture	conversion	Decay in orbit background

Mu2e will employ a pulsed proton beam with $<10^{-10}$ protons out of beam, and superconducting gradient solenoids to trap and select muons. Sensitivity ~ 10^{-16} is possible

Kaons

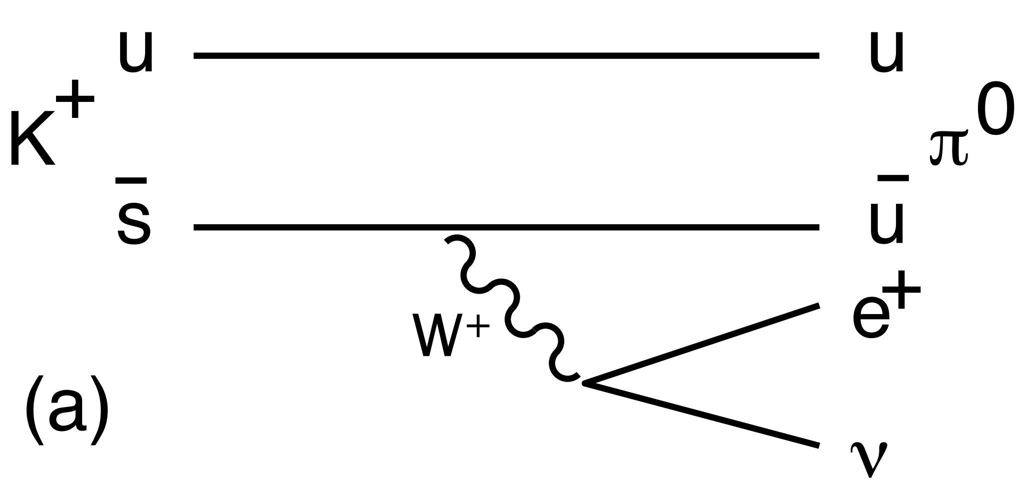
$K^+ = u\bar{s}, K^- = \bar{u}s$

- mass = 494 MeV
- lifetime = 12 ns
- Spin 0, odd parity

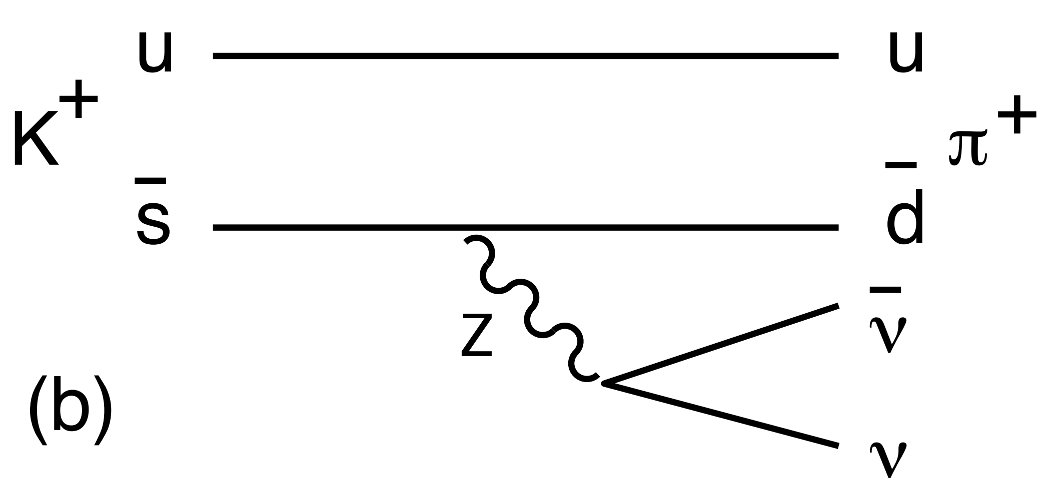
$K^0 = d\bar{s}, \bar{K}^0 = \bar{d}s$

$K_L \approx (K^0 - \bar{K}^0)/\sqrt{2}, K_S \approx (K^0 + \bar{K}^0)/\sqrt{2}$

- mass = 497 MeV
- T_L = 51 ns, T_S = 0.09 ns
- spin 0, odd parity



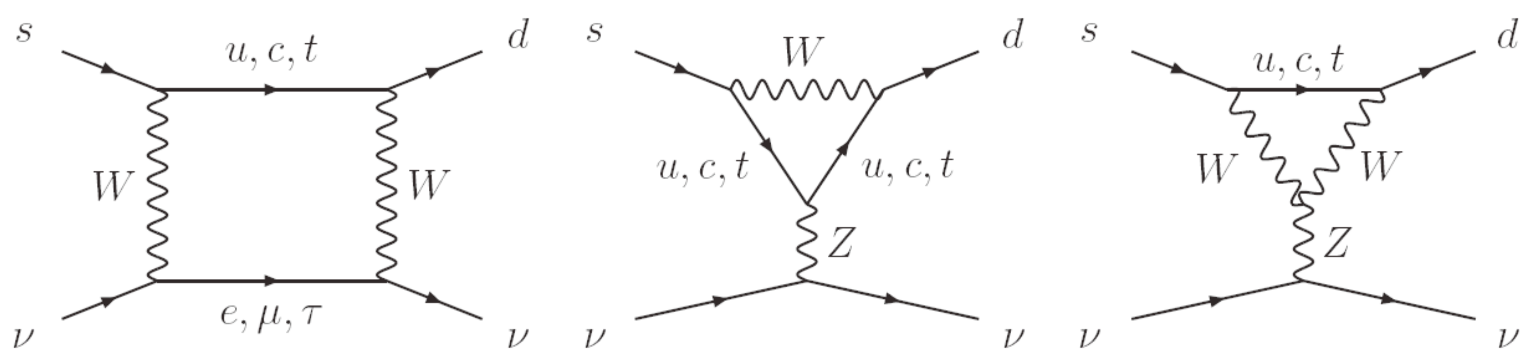
Allowed thru quark mixing: V_{us}



Not Allowed either through mixing or through loops (to first order)

Being spinless, and generation crossing particles the decays and dynamics of kaons have interesting properties. In particular, they can be made in almost CP eigenstates and they are forbidden to decay in the Flavor Changing and Neutral Charge (FCNC) modes.

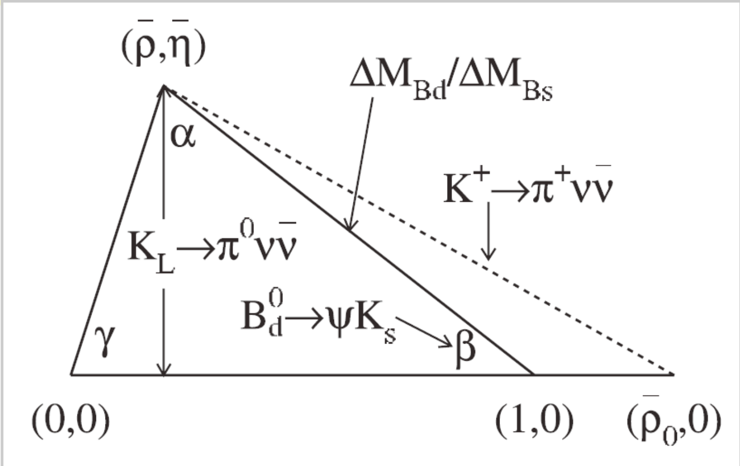
The $K \rightarrow \pi \nu \bar{\nu}$ decays are the most precisely precicted FCNC decays with quarks.



$$B_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \text{ x } 10^{-11}$$

$$B_{SM}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = (2.4 \pm 0.4) \text{ x } 10^{-11}$$

$$V_{CKM} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.9738 & 0.227 & 0.0039e^{-1.1i} \\ -0.227 & 0.9729 & 0.0422 \\ 0.008 & -0.0416 & 0.9991 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The uncertainty comes from CKM elements which continues to improve

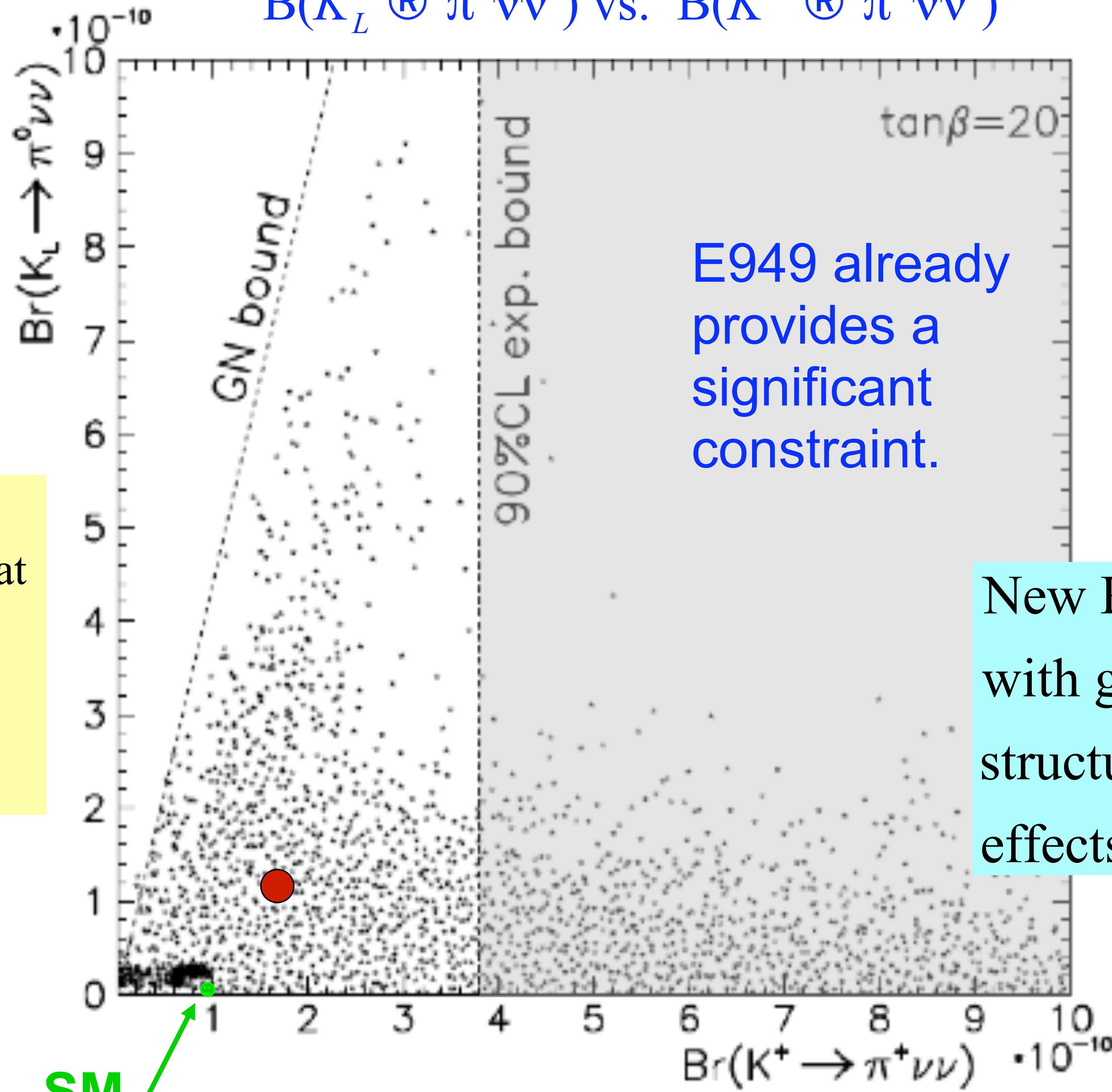
The entire heavy particle content of the standard model contributes to the decays and they are dominated by the Top quark contibution. If there are TeV scale particles they will contribute and easily cause a deviation.

General MSSM with R-parity

$B(K_L^0 ® \pi^0 \nu\bar{\nu})$ vs. $B(K^+ ® \pi^+ \nu\bar{\nu})$

Buras et al, NP B714,103(2005)

Points from a scan of MSSM parameters that satisfy experimental constraints except $B(K^+ ® \pi^+ \nu\bar{\nu})$



E949 already provides a significant constraint.

New Physics models with generic flavor structure induce large effects in $K ® \pi\nu\bar{\nu}$.

SM

R Parity: $R = (-1)^{2j+3B+L}$.

General MSSM with R-parity

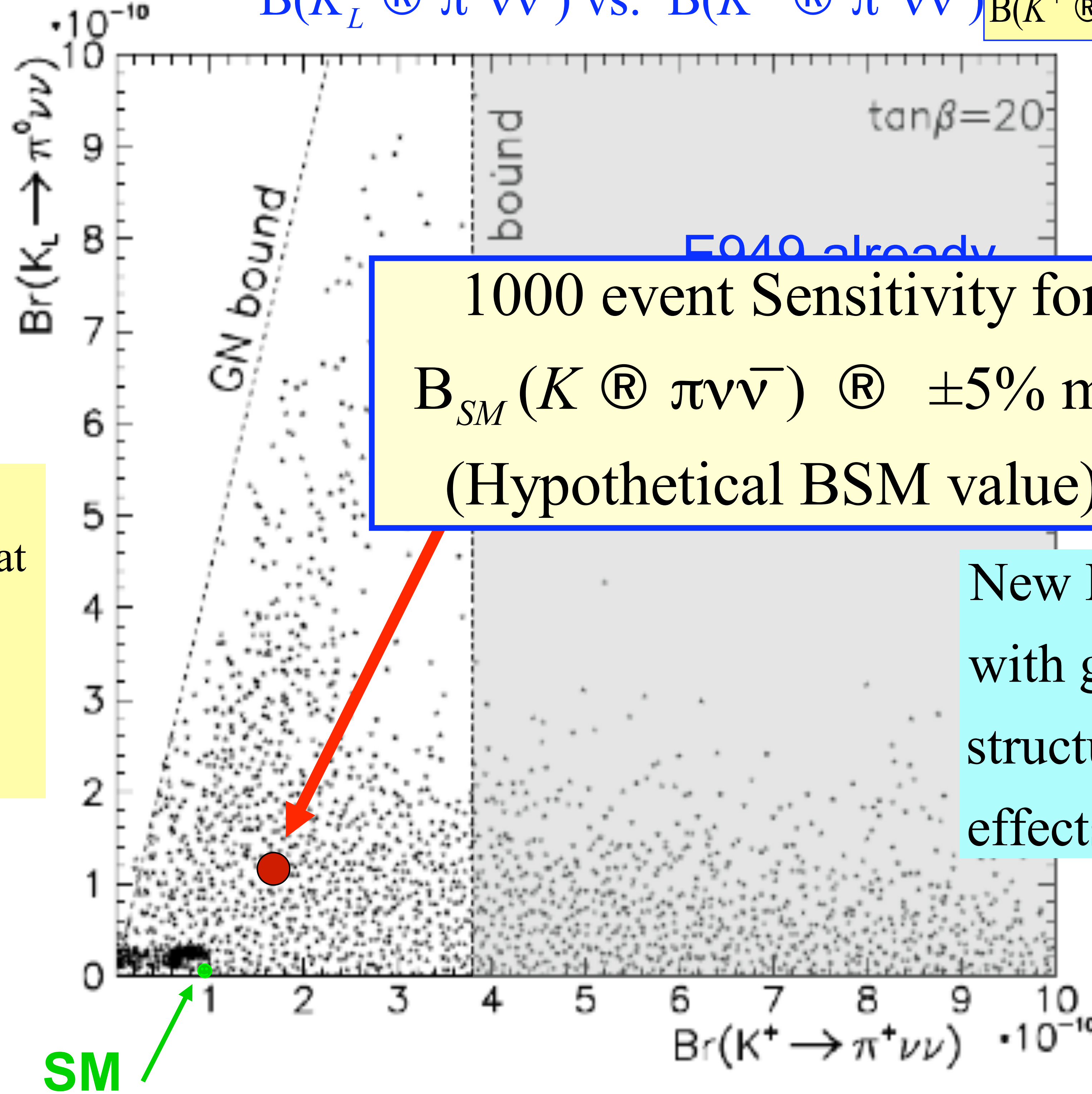
E787/E949 Final: 7 events observed

$B(K^+ ® \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

Standard Model:

$B(K^+ ® \pi^+\nu\bar{\nu}) = (0.78 \pm 0.08) x10^{-10}$

$B(K_L^0 ® \pi^0\nu\bar{\nu})$ vs. $B(K^+ ® \pi^+\nu\bar{\nu})$



Buras et al, NP B714,103(2005)

1000 event Sensitivity for

$B_{SM}(K ® \pi\nu\bar{\nu})$ ® ±5% measurement

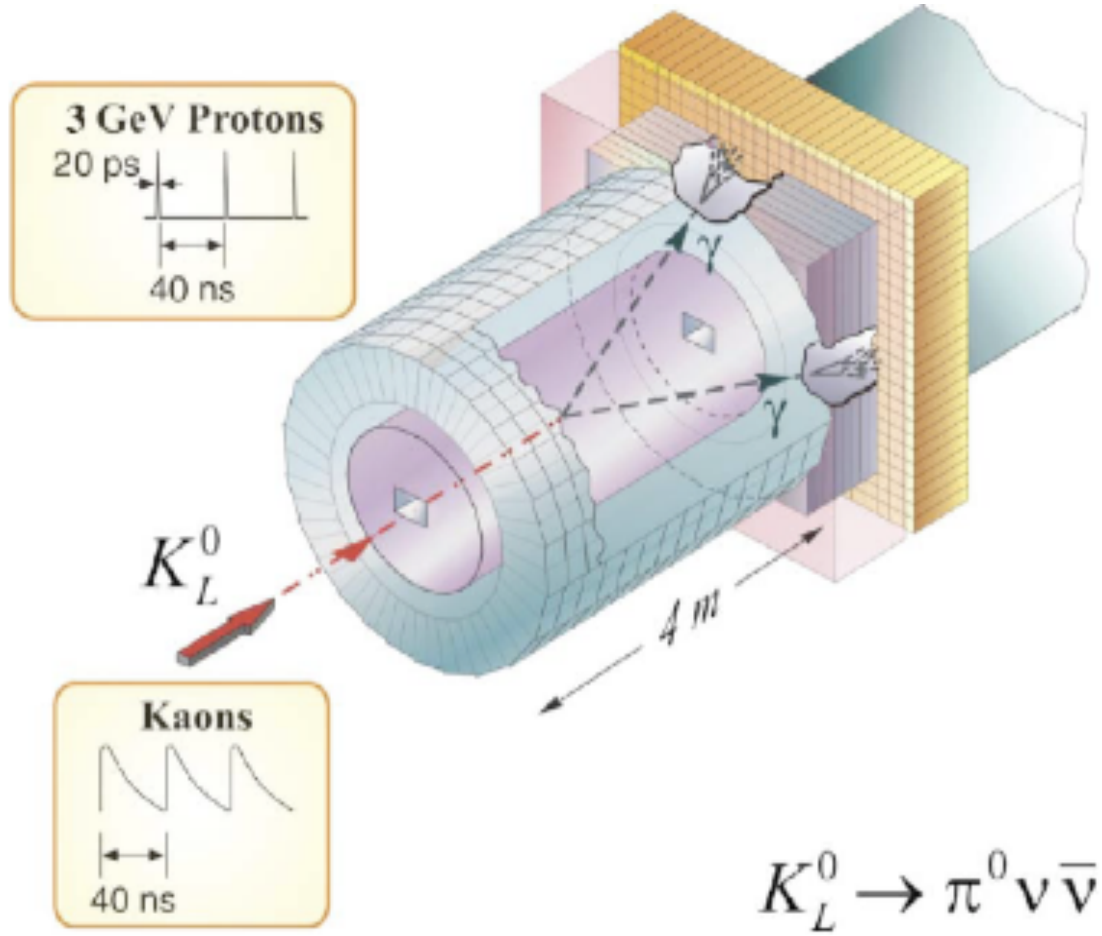
(Hypothetical BSM value)

Points from a scan of MSSM parameters that satisfy experimental constraints except $B(K^+ ® \pi^+\nu\bar{\nu})$

New Physics models with generic flavor structure induce large effects in $K ® \pi\nu\bar{\nu}$.

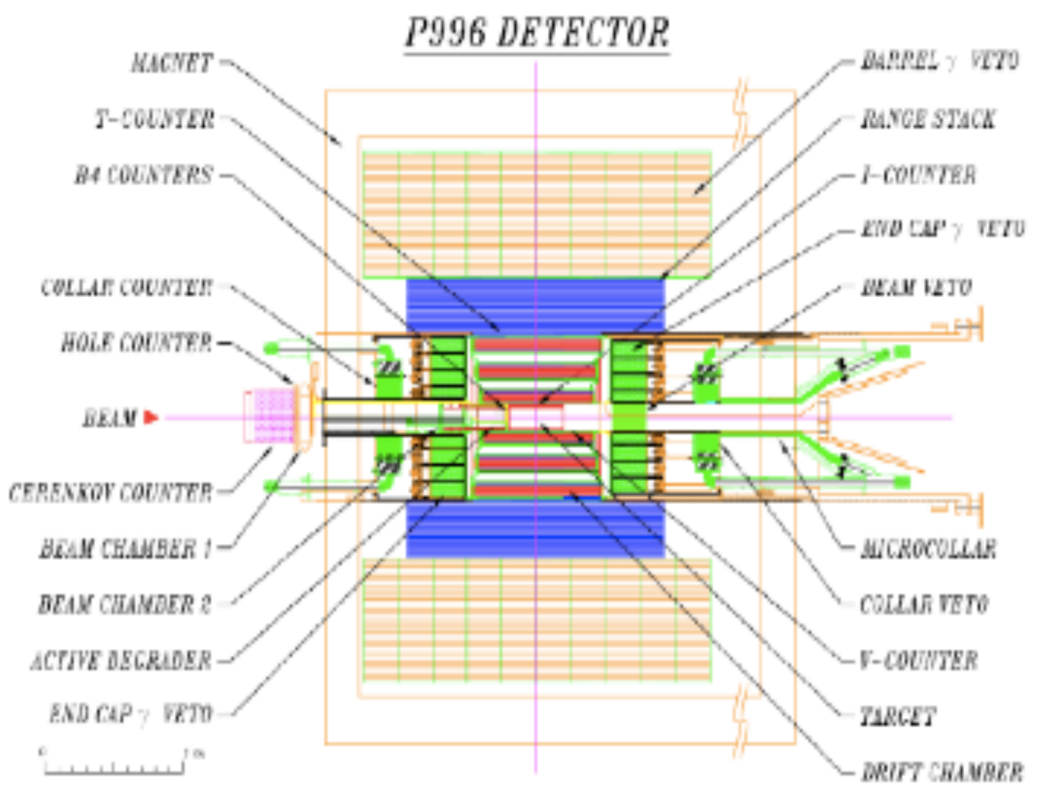
R Parity: R = $(-1)^{2j+3B+L}$.

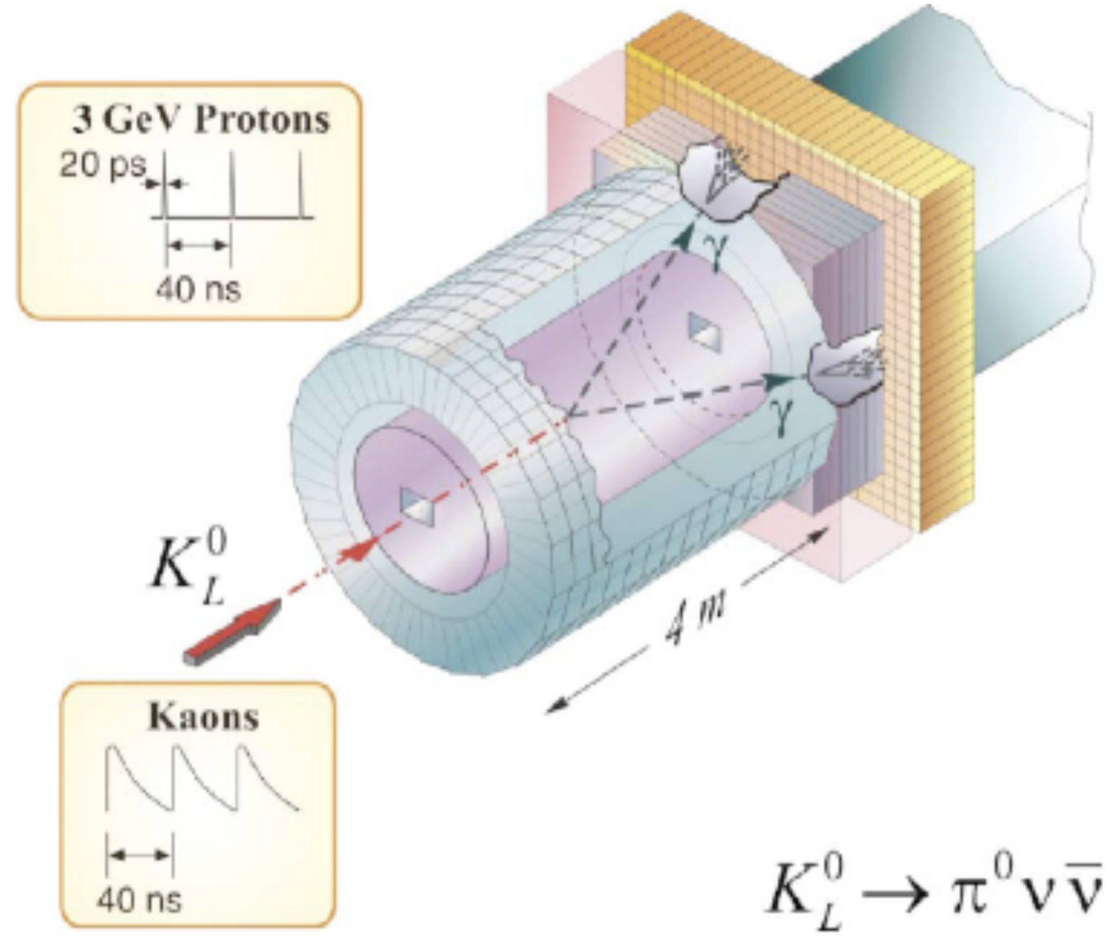
$K \rightarrow \pi\nu\bar{\nu}$ Experimental Issues



- Previous K^+ experiment was at BNL (E787/E949). It used kaons that stopped in the middle. Observed 7 events (2.5 backg).
- Currently two efforts: NA62 (CERN), KOTO(JPARC).
- Key experimental problems to get to 1000 events is flux. Must get huge flux. Project-X at Fermilab can provide this flux.
- Signature of a single pion in final state. Must suppress all other backgrounds.

$K \to \pi\nu\bar{\nu}$ Experimental Issues





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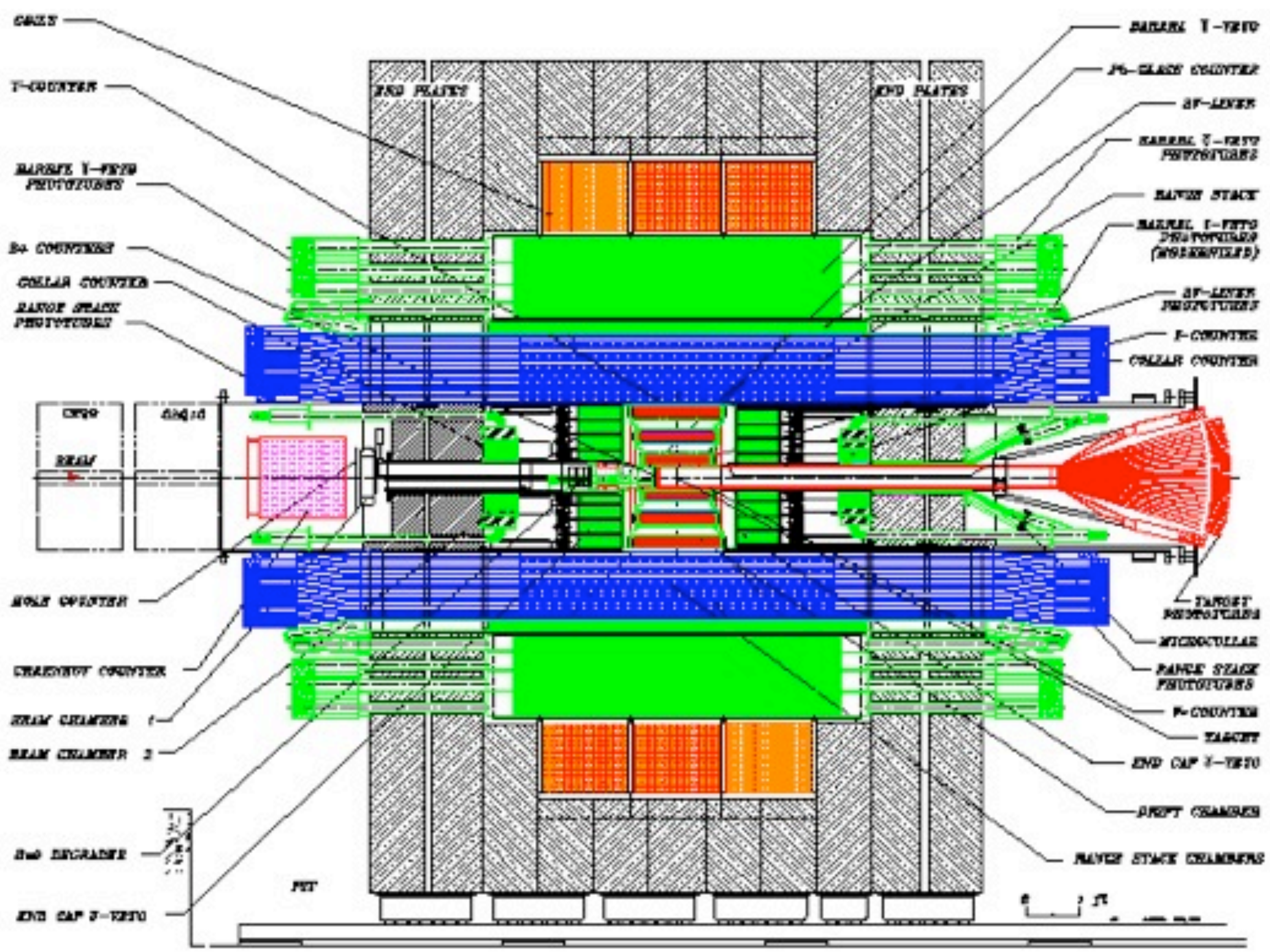
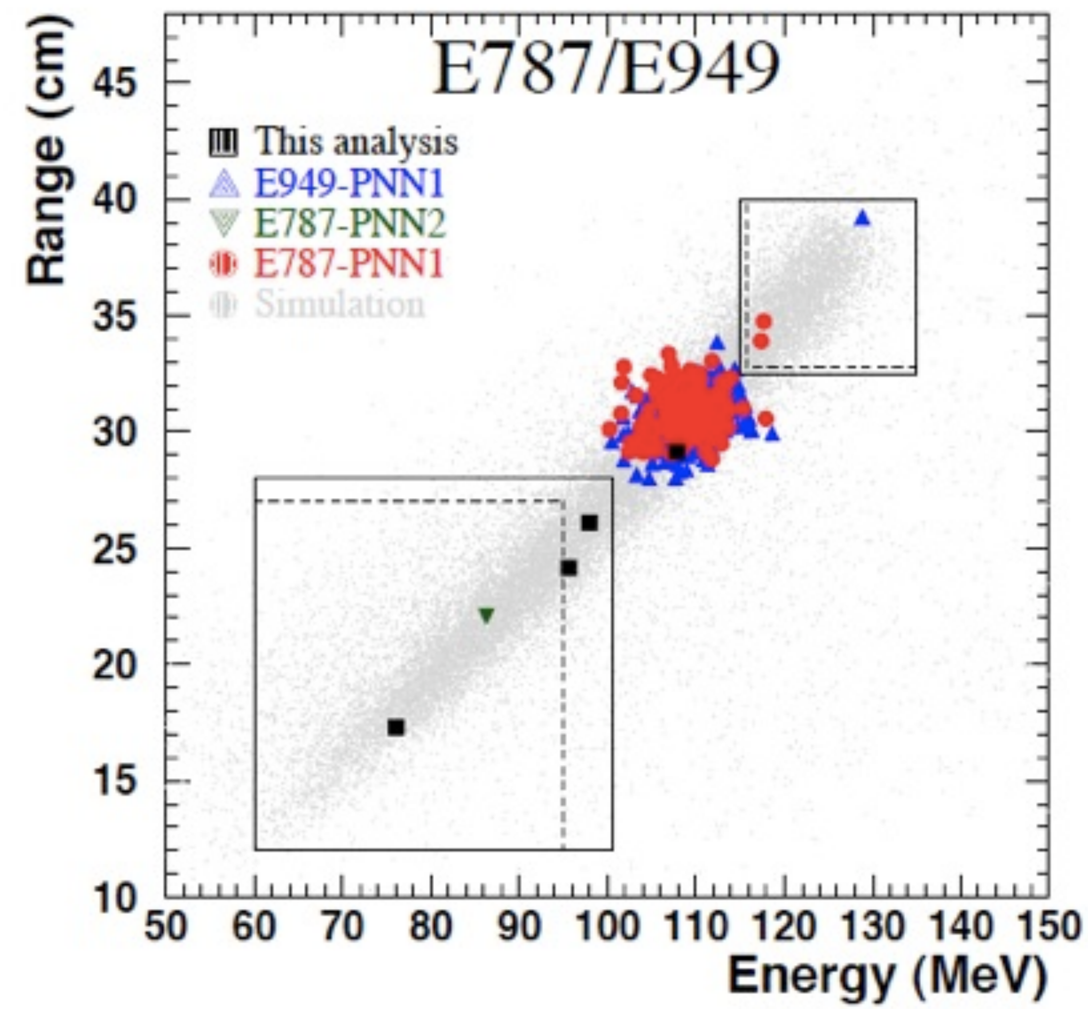
BNL E787/949 experiment

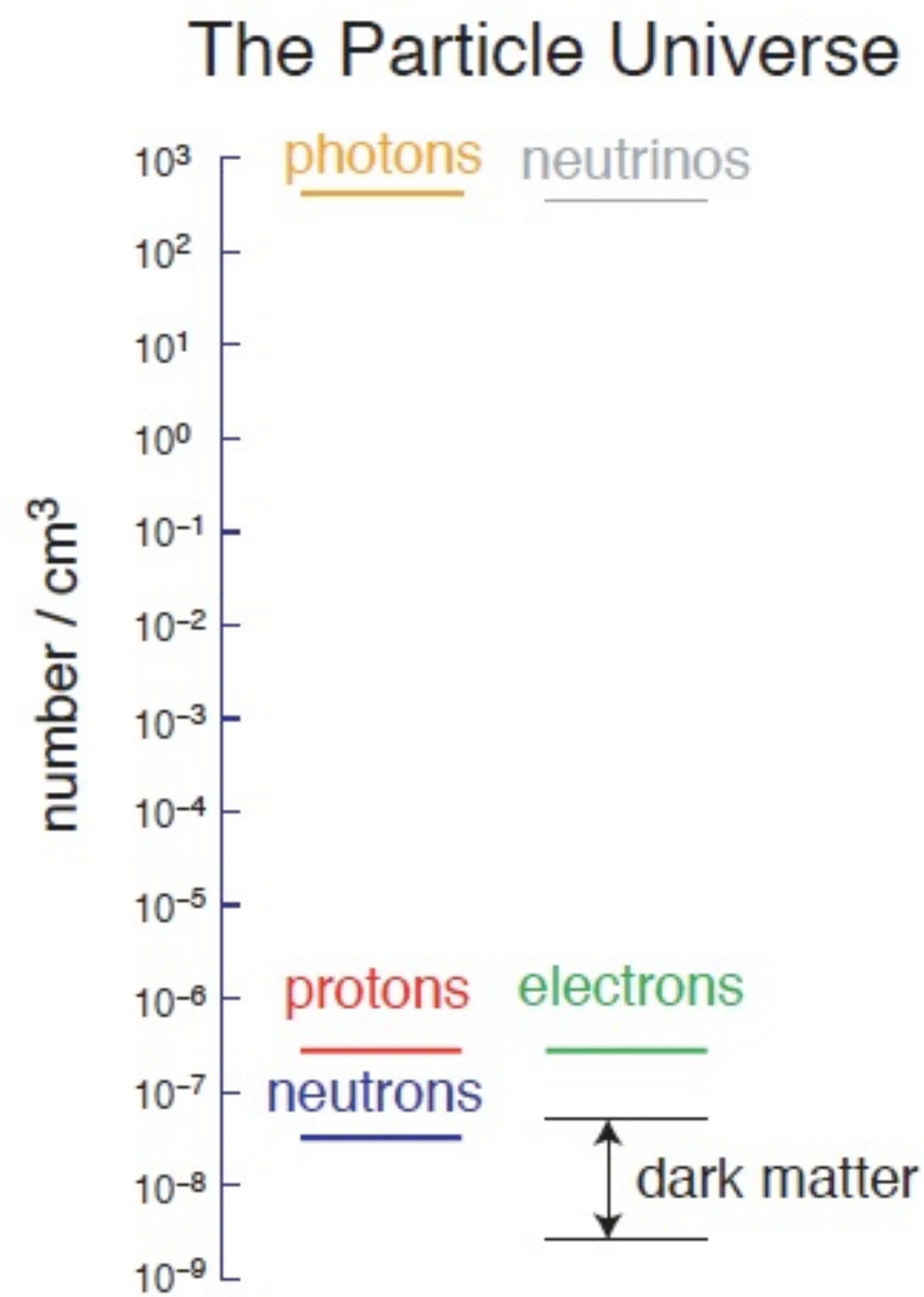




Technique for $K^+ \rightarrow \pi^+ \nu\nu$: Take intense low energy (~550 MeV/c) Kaon beam. Stop in scintillating target. Observe all decay products emerging. Eliminate events with photons. Identify pions from decay chain: $\pi \rightarrow \mu \rightarrow e$. Measure momentum, energy, range in scintillator of pion.

Neutrinos

- The most abundant particle is the photon: ~400/cc
- The most abundant matter particle is the neutrino at 56/cc of each type.
- CNB (1.95K) is a relic of the big bang similar to the CMB (2.725K). Neutrinos decoupled at 2 sec while photons decoupled at ~400,000 yrs.



If neutrinos have mass; the massive states need not be the same as the Weak interaction states.

This will lead to interference effects

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

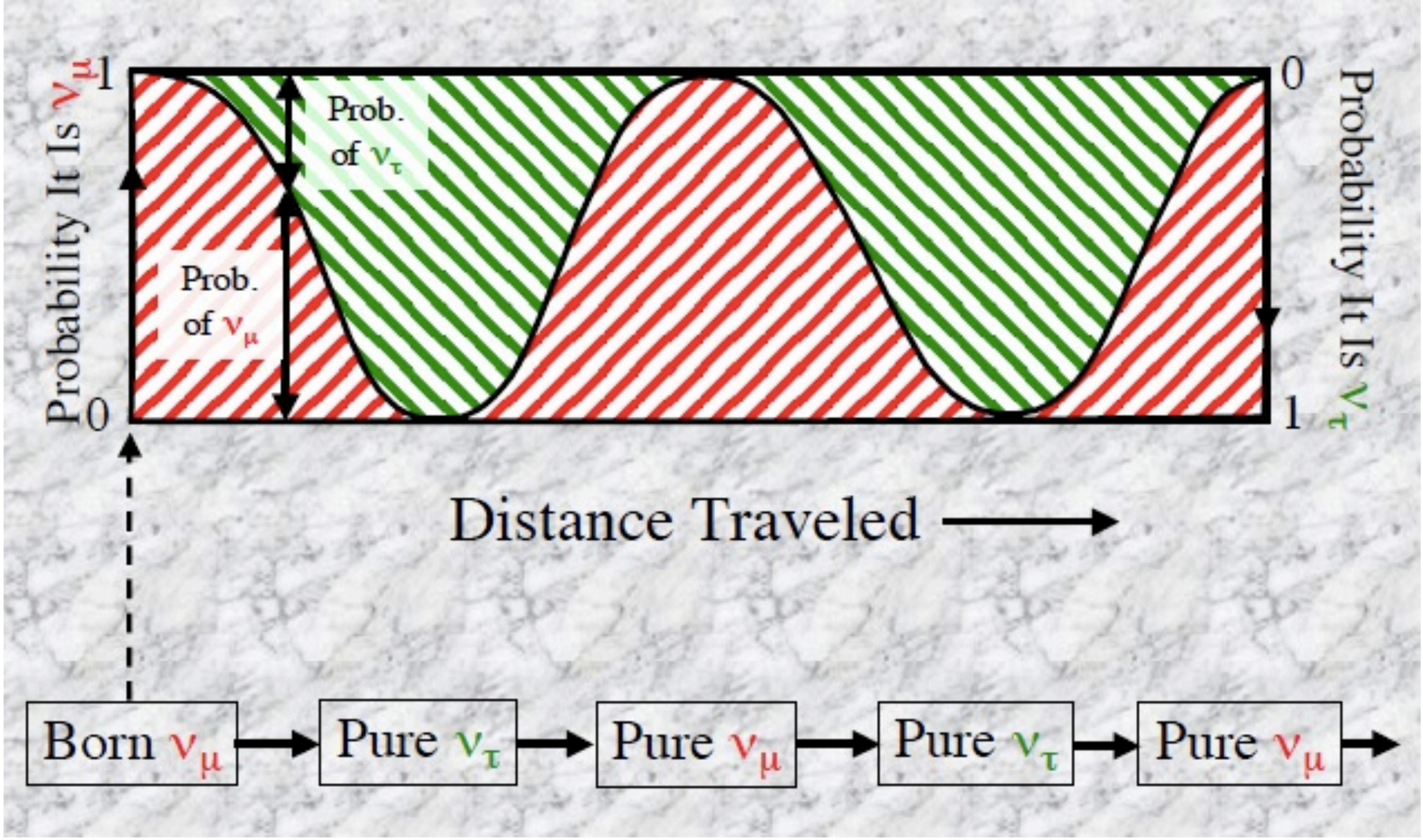
Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

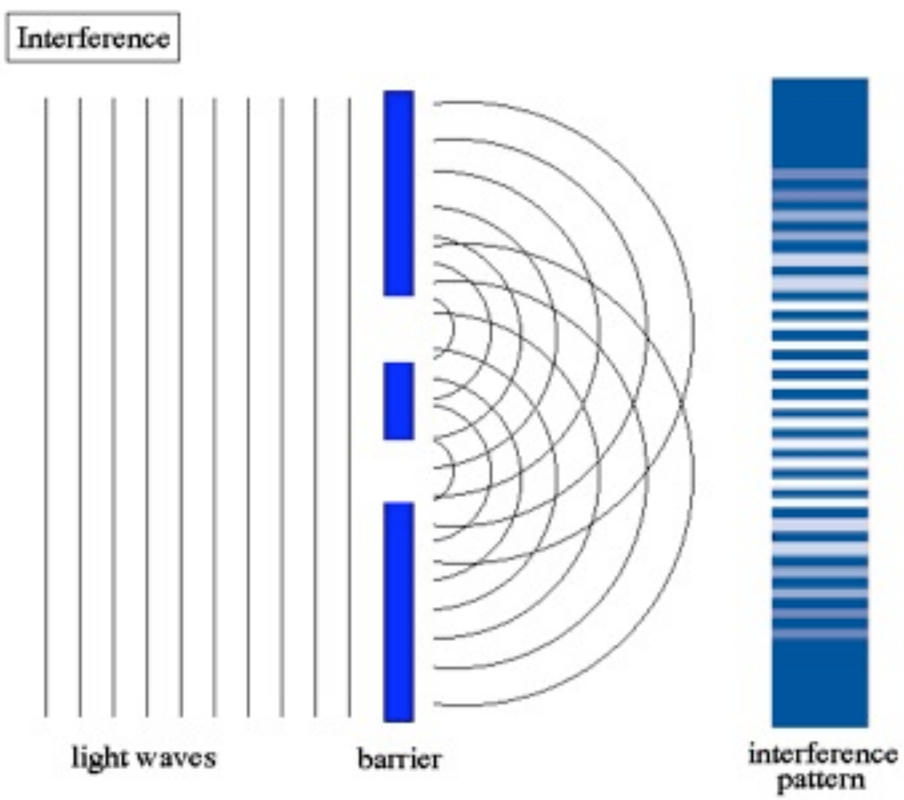
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ ($\pi/2$): $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

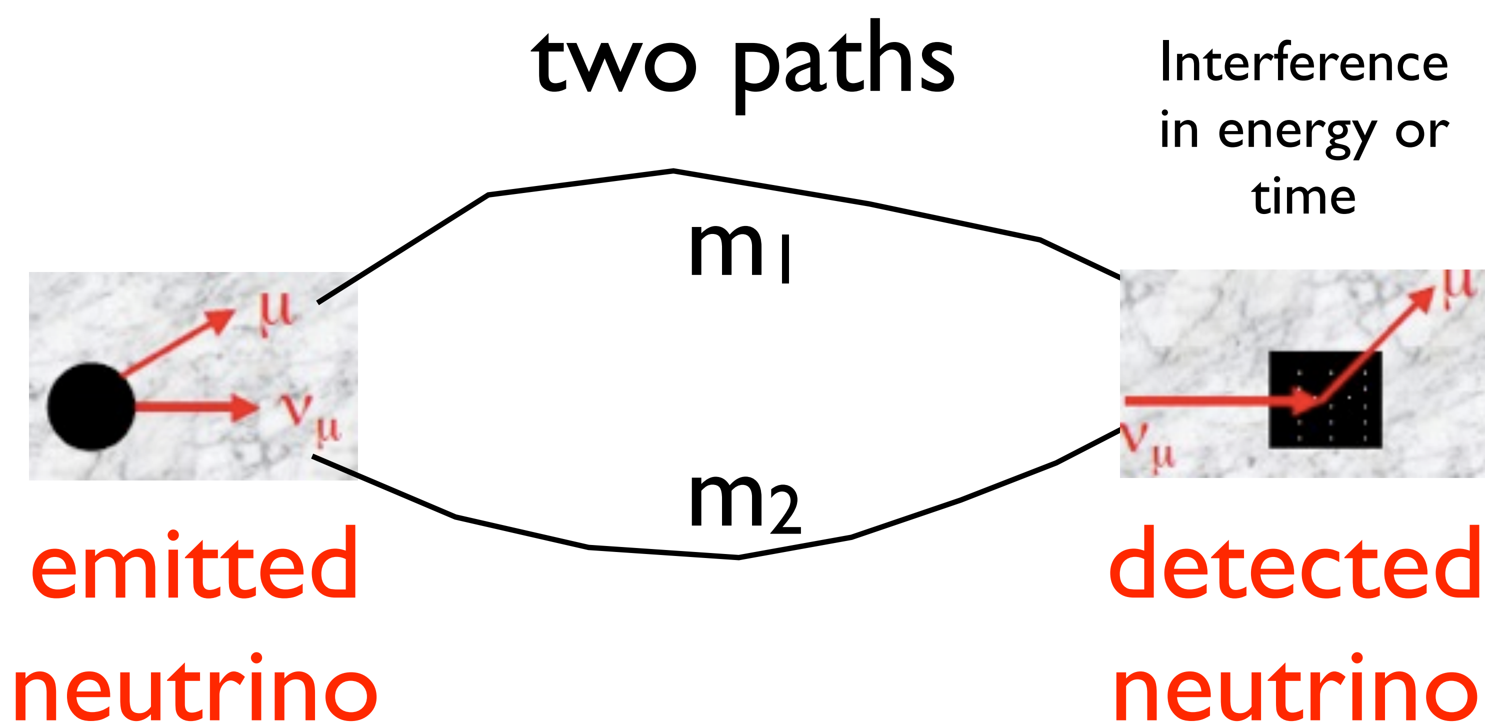
Picture with θ = 45 deg



Astonishingly this is reality

Oscillations is a new interferometry.





- Just as classic optical interferometry has led to new precision, neutrino interferometry has potential to be sensitive to new scales.

- e.g. Measure extremely small masses or interactions.

Neutrinos and the Standard Model

Massive neutrinos have several implications beyond just lepton flavor oscillations:

- A possible non-zero magnetic moment?
- Heavier neutrinos could decay into lighter ones
- They will have an effect on the CMB spectrum
- CP violation in early universe?
- Hint of unification scale below GUTs
- but still a lot we don't know…

The "seesaw" mechanism (there are many variations!)

LH Light neutrinos may have heavy RH partners that may mix via couplings that link LH and RH

The mass of the light neutrino goes roughly as:

$$m_\nu \sim m^2/M$$

Where m is the mass associated with our low energy EW scale (~246 GeV) and M is the mass of the heavy RH partner.

Oscillation measurements imply $M \sim 10^{15}$ GeV

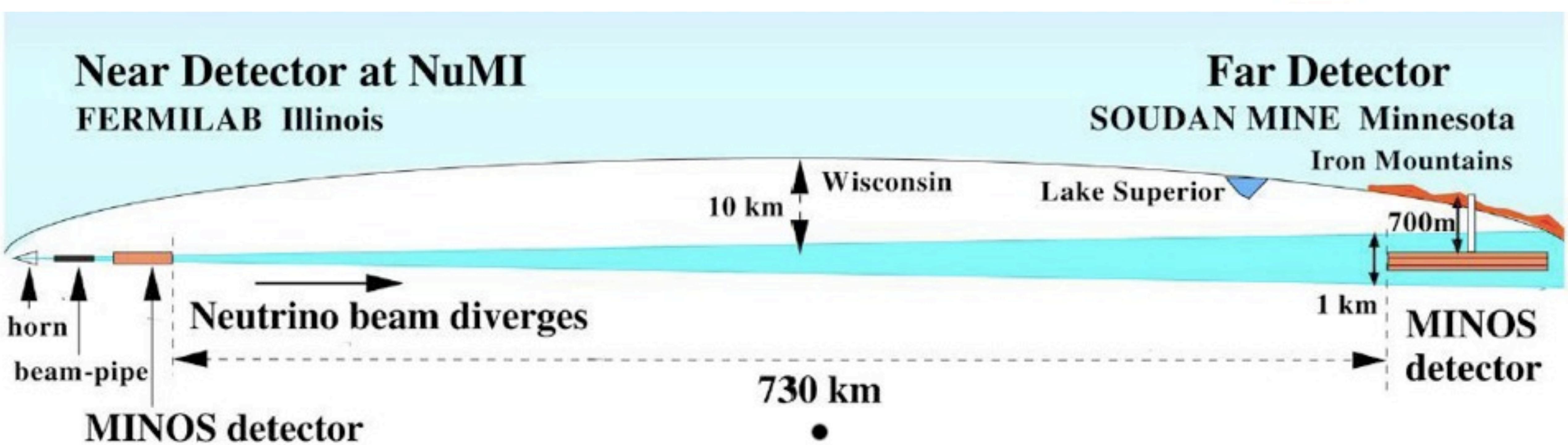
Leptogenesis

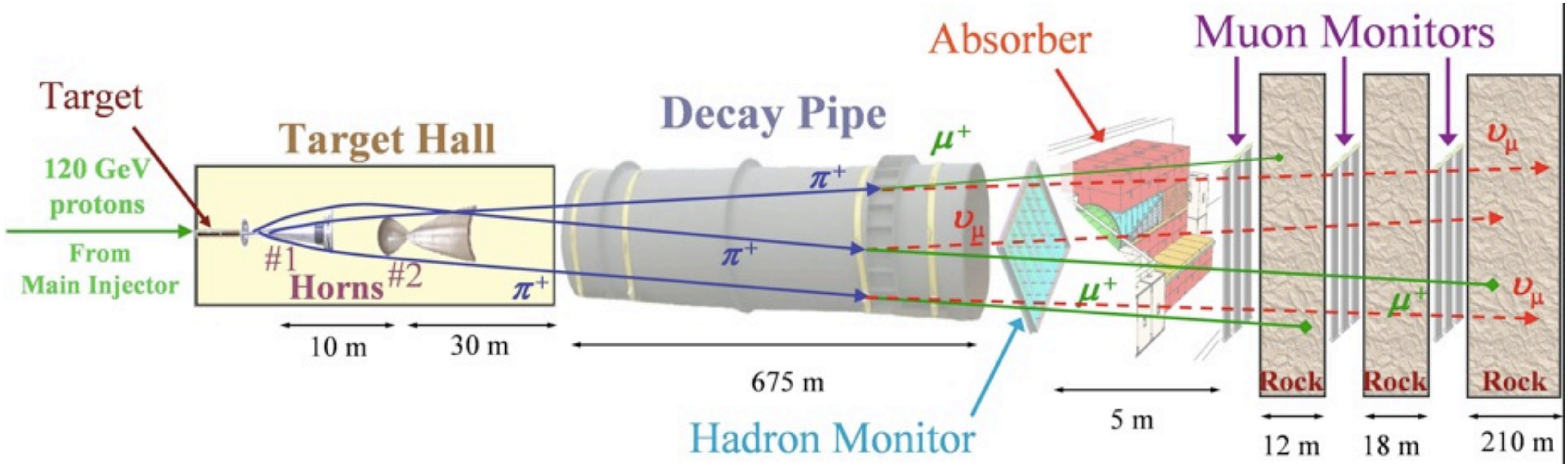
- If there does exist a RH heavy partner for the LH neutrinos, and if such a partner violates CP in its decay, it could influence the baryon/anti-baryon symmetry of the universe
- CP violation in the light neutrinos does not prove that neutrinos have a heavy CP-violating partner, but it is strong circumstantial evidence
- Knowing the absolute neutrino mass and structure would also help!

New Age of Accelerator Neutrinos

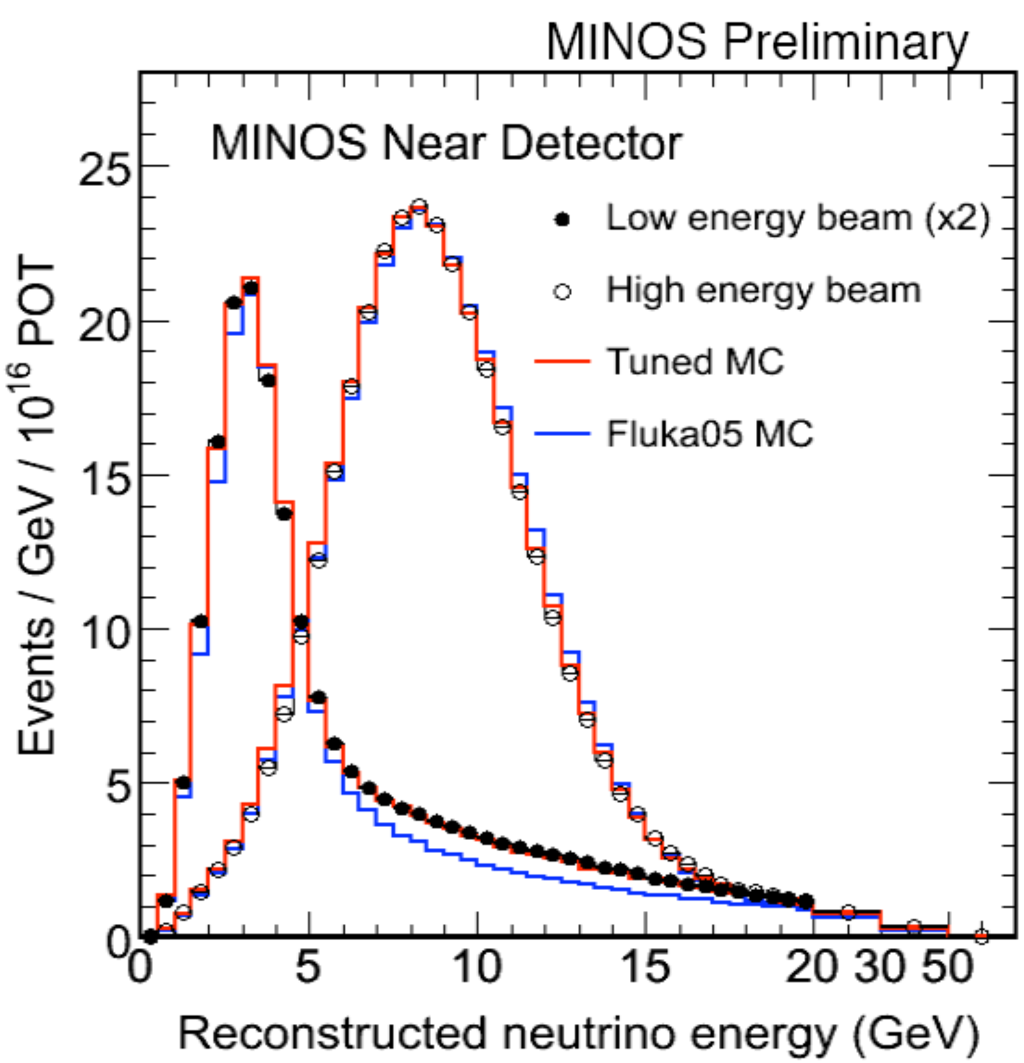
- For more precise experiments need pure beams of muon type neutrinos (or anti-neutrinos)
- Better controlled characteristics: energy, spectrum, backgrounds, pulsed.
- High energy (>1 GeV) to provide events with long muons. Better resolution.
- Generally called Long Baseline Experiments.

- Prepare a pure beam of muon neutrino beam.
- Aim it towards a large muon detector.
- Observe spectrum of muon neutrinos to see oscillations in energy.



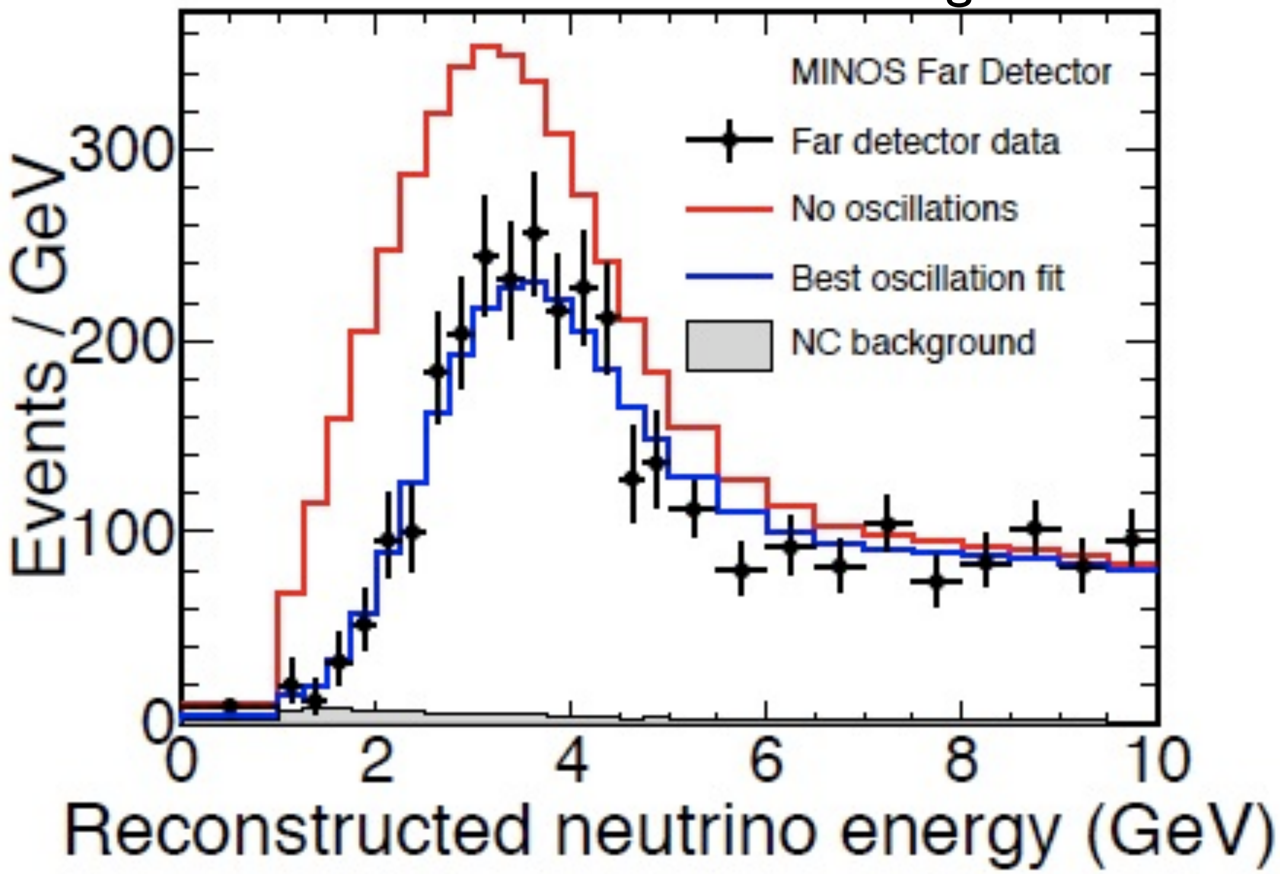


- 120 GeV protons from Main Injector
- Parabolic magnetic horns to sign select pions. Target can be moved to change beam energy.
- 10 μsec pulses/2.2 sec, 3.3×10^{13}protons/pulse
- Beam: ν_μ ~ 91.7%, anti-ν_μ~7%, ν_e~1.3%
- ν_μ and anti-ν_μ measured. ν_e constrained to ~10% with tuned Monte Carlo.

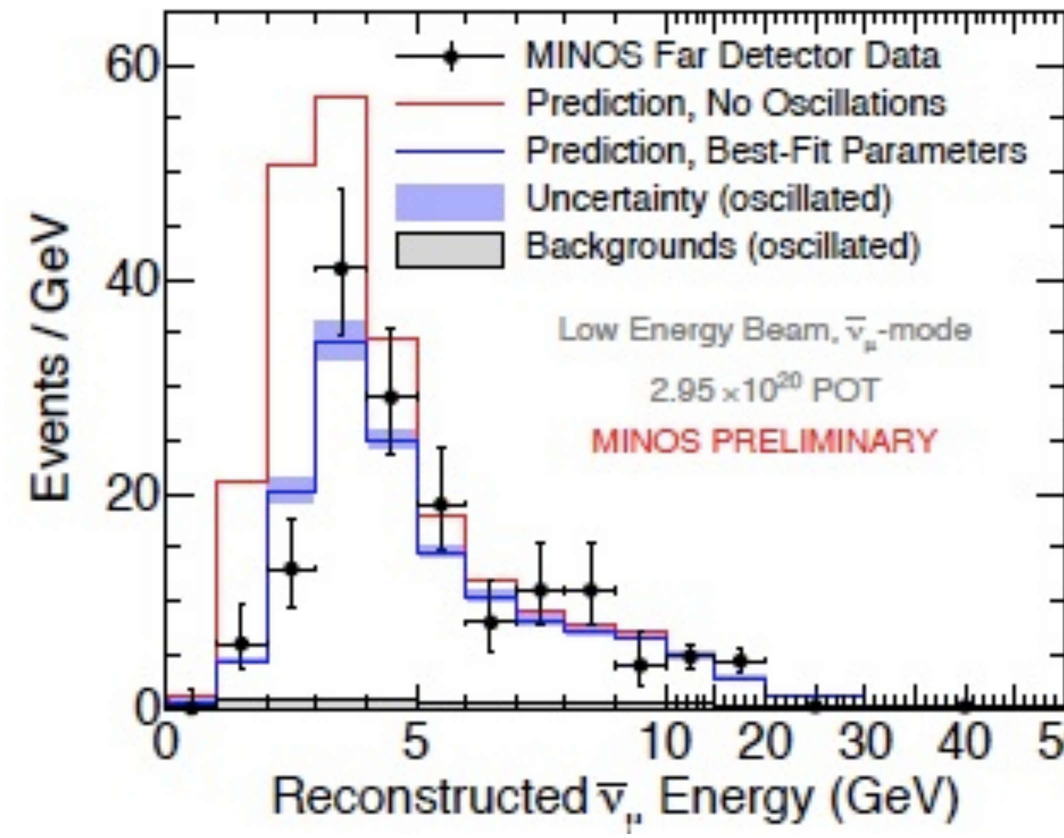


MINOS data

7.24x10[20] POT neutrino running



2011 Analysis, 2.95x10[20] POT



Expect: 2451

Observe: 1986

$$|\Delta m^2_{atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$$
$$\sin^2(2\theta_{23}) > 0.90 \ (90\% \ C.L.)$$

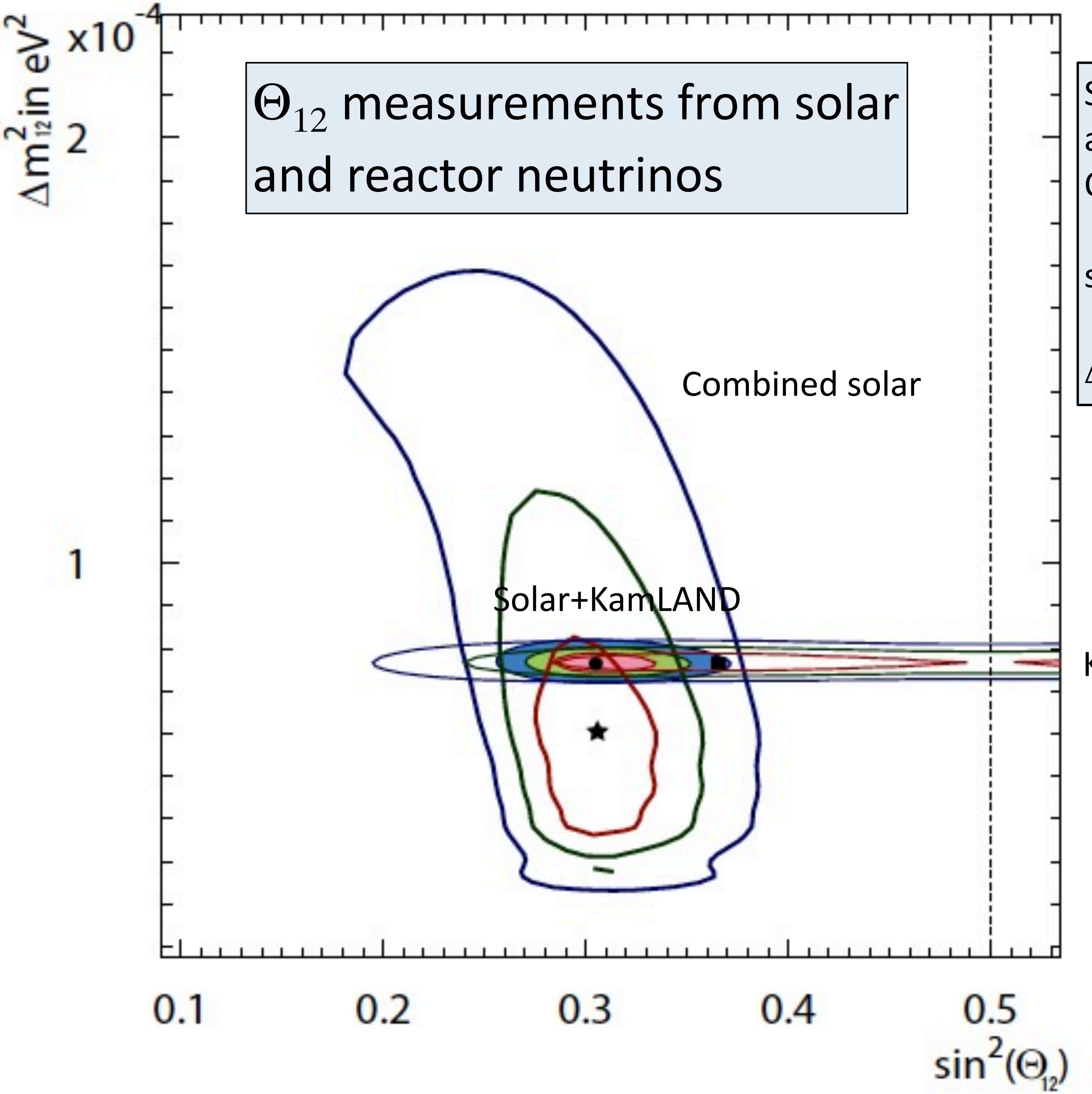
Expect: 273

Observe: 193

$$|\Delta \overline{m}^2_{atm}| = 2.62^{+0.31}_{-0.28} \times 10^{-3} eV^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}$$

Newest update

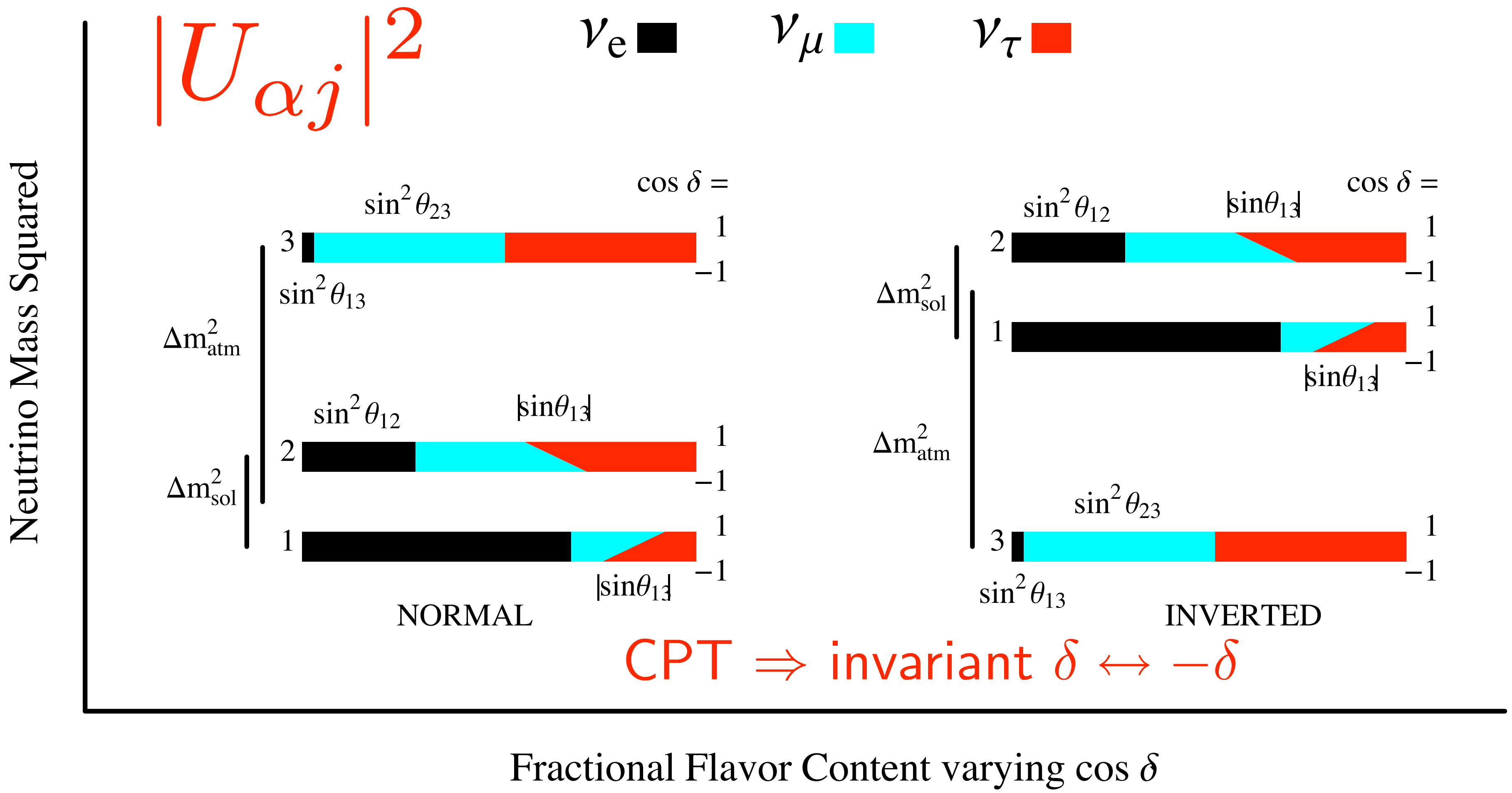
Θ_{12} measurements from solar and reactor neutrinos



Super-K
arXiv:1010.0118 hep-ex
Oct 1, 2010

$\sin^2\theta_{12} = 0.31^{+0.03}_{-0.02}$

$\Delta m^2_{12} = 7.7 \pm 0.3 \times 10^{-5}$ eV^2



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

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

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

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

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

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

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

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

Don't know

parke

The Mixing Matrix

For neutrinos

Atmospheric — Cross-Mixing — Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana ~~CP~~ phases

$\theta_{12} \approx \theta_{sol} \approx 34°,\ \theta_{23} \approx \theta_{atm} \approx 37\text{-}53°,\ \theta_{13} \lesssim 10°$

δ would lead to $P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. ~~CP~~

Since there are 3 neutrinos, there must be a 3X3 matrix with 3 angles and 1 phase (observable) and 2 Δm^2. We must determine if this holds true.

Order in fermion spectrum ?

Fermion masses in units of m_t at scale m_t

$$m_t = 1.0 \qquad m_b = 1.67 \times 10^{-2}$$
$$m_c = 3.6 \times 10^{-3} \qquad m_s = 3.1 \times 10^{-4}$$
$$m_u = 1.3 \times 10^{-5} \qquad m_d = 2.3 \times 10^{-5}$$

$$m_\tau = 1.0 \times 10^{-2} \qquad m_3 = 2.9 \times 10^{-13}$$
$$m_\mu = 6.2 \times 10^{-4} \qquad m_2 = 5.2 \times 10^{-14}$$
$$m_e = 3.0 \times 10^{-6} \qquad m_1 = < m_2$$

neutrinos

CKM | PMNS

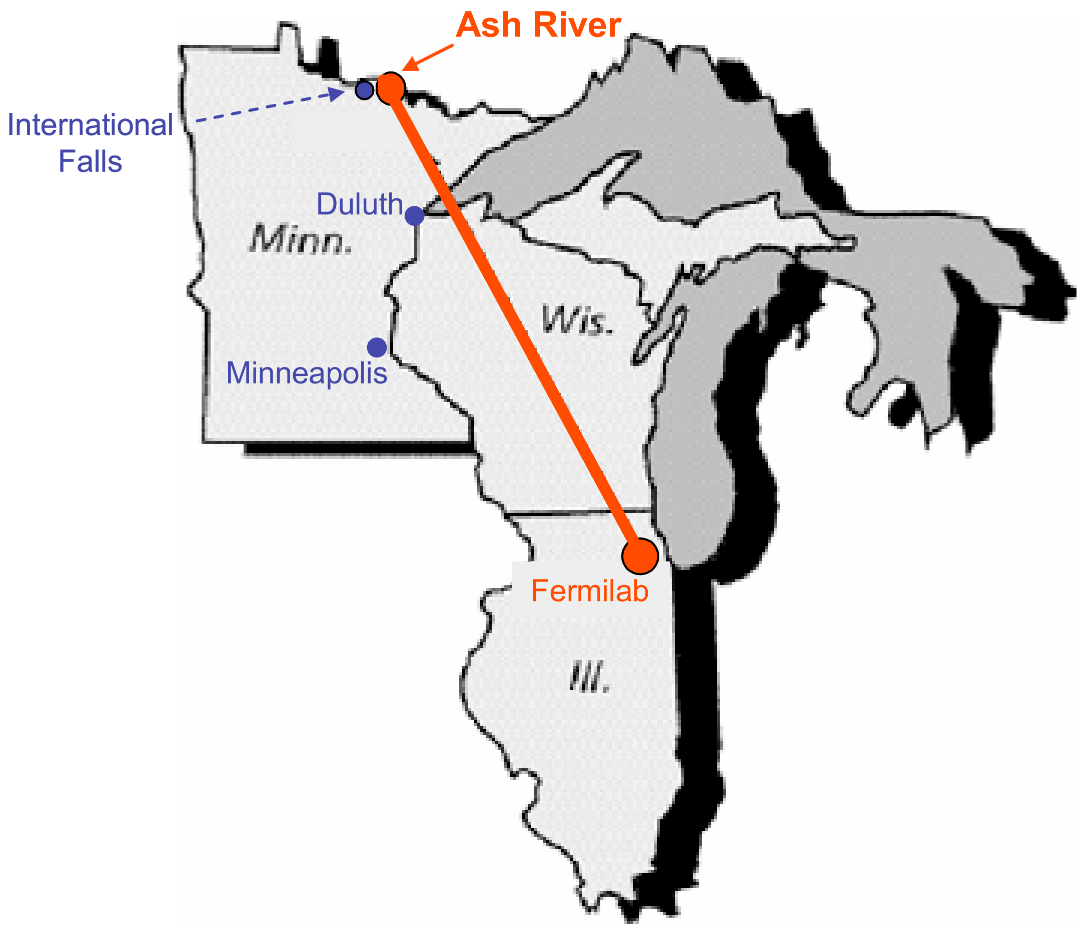
$$\begin{pmatrix} 0.9738 & 0.227 & 0.0039e^{-1.1i} \\ -0.227 & 0.9729 & 0.0422 \\ 0.008 & -0.0416 & 0.9991 \end{pmatrix} \begin{pmatrix} 0.8 & 0.6 & < 0.2e^{\delta i} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$

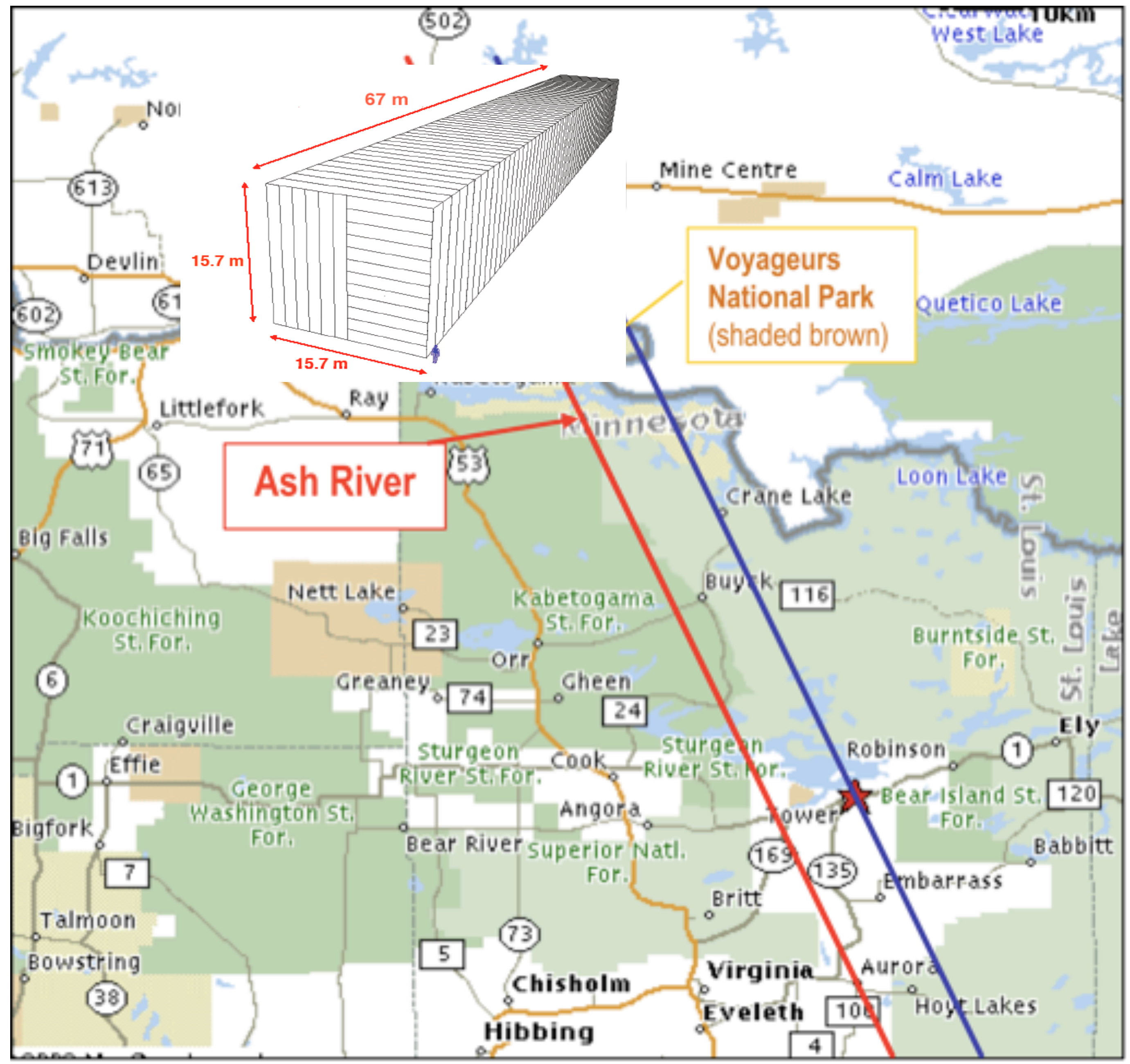
CKM: Cabbibo, Kobayashi, Maskawa
PMNS: Pontecorvo, Maki, Sakagawa, Sakata

Latest θ_{13} results have implications

- T2K sees 6 ν_e events with expected background of 1.5 +/- 0.3
- MINOS sees 62 events with expected background of 49.5 +/- 2.8 (sys) +/- 7.0 (stat)
- Combined, these exclude zero at the 90% c.l., and give a central value of $\sin^2 2\theta_{13}$ around 0.04-0.08 (depends on mass hierarchy)
- Double Chooz and RENO reactor, DayBay experiments should have results in **less than a year.**

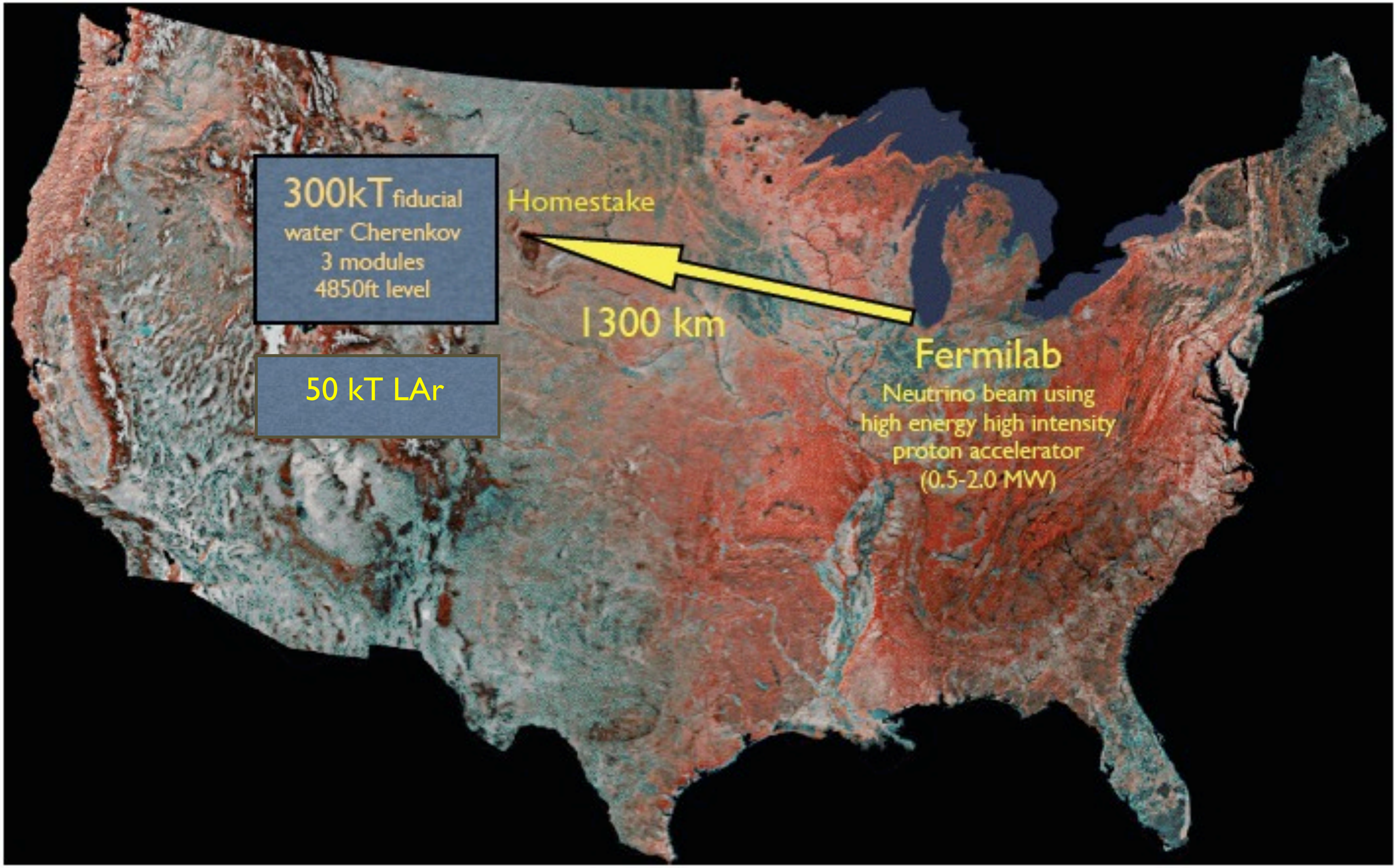
Progress of the NOvA experiment
15 kTon of scintillator fine grained FY 13
Far site construction competed. Start FY13-14





The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering.

Long-Baseline Neutrino Experiment

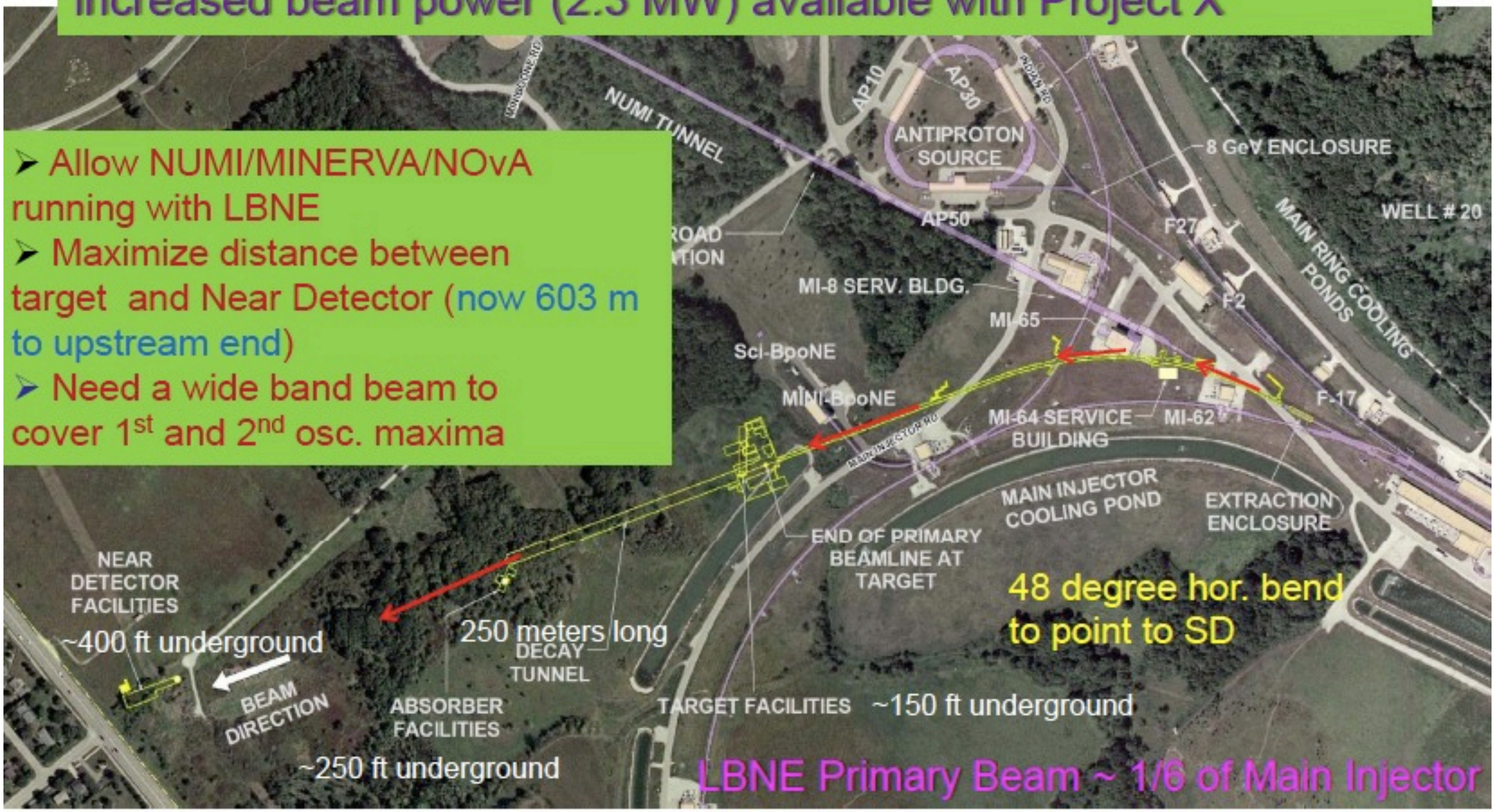


To make progress on CP violation needs very large detectors independent of the value of theta13.

The Neutrino Beam Facility at Fermilab

Start with a 700 kW beam, and then take profit of the significantly increased beam power (2.3 MW) available with Project X

- Allow NUMI/MINERVA/NOvA running with LBNE
- Maximize distance between target and Near Detector (now 603 m to upstream end)
- Need a wide band beam to cover 1st and 2nd osc. maxima



Primary beam energy (protons from the Main Injector) from 60 to 120 GeV

Design is becoming quite detailed and documented

New above ground design at FNAL

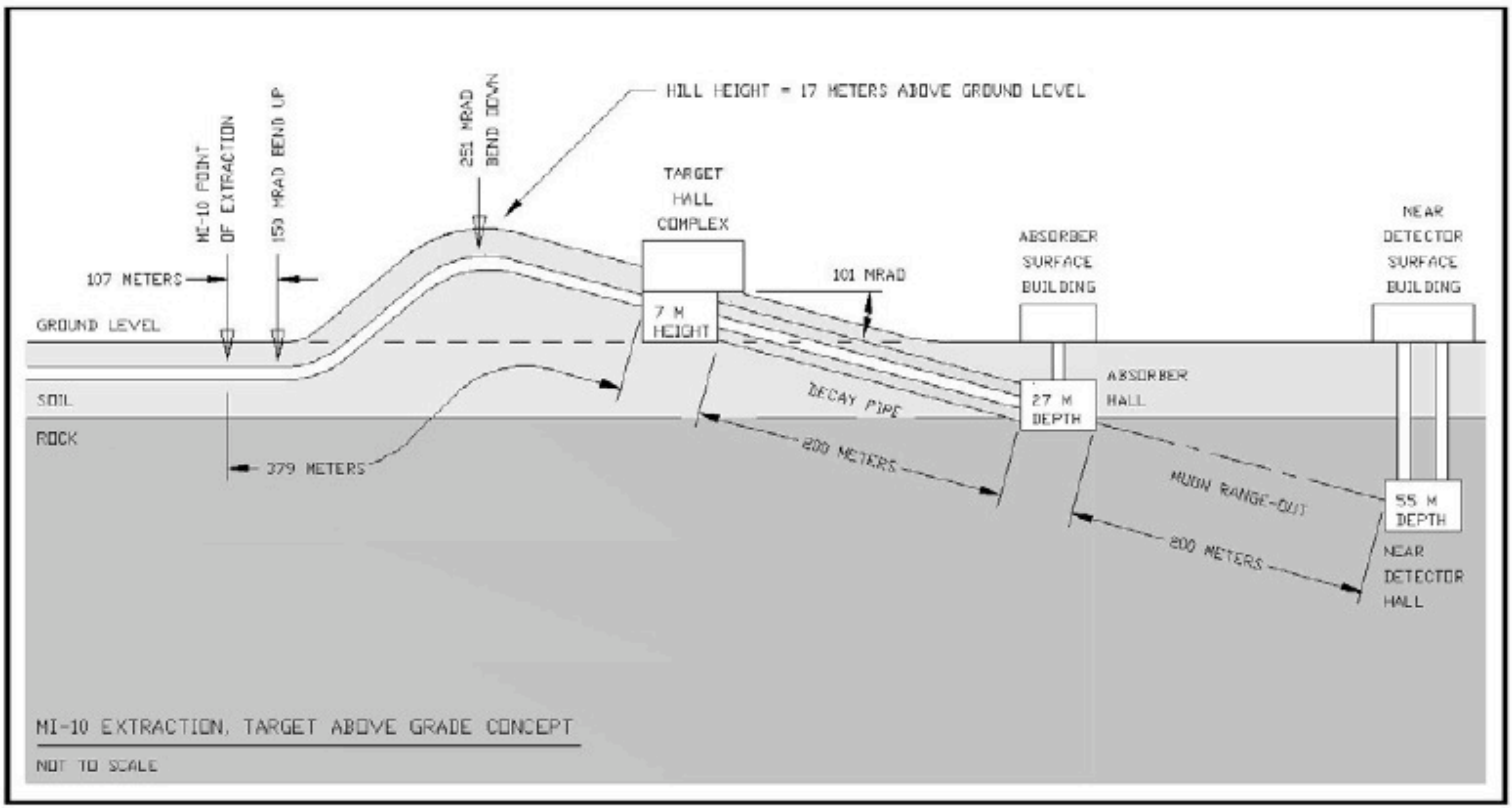
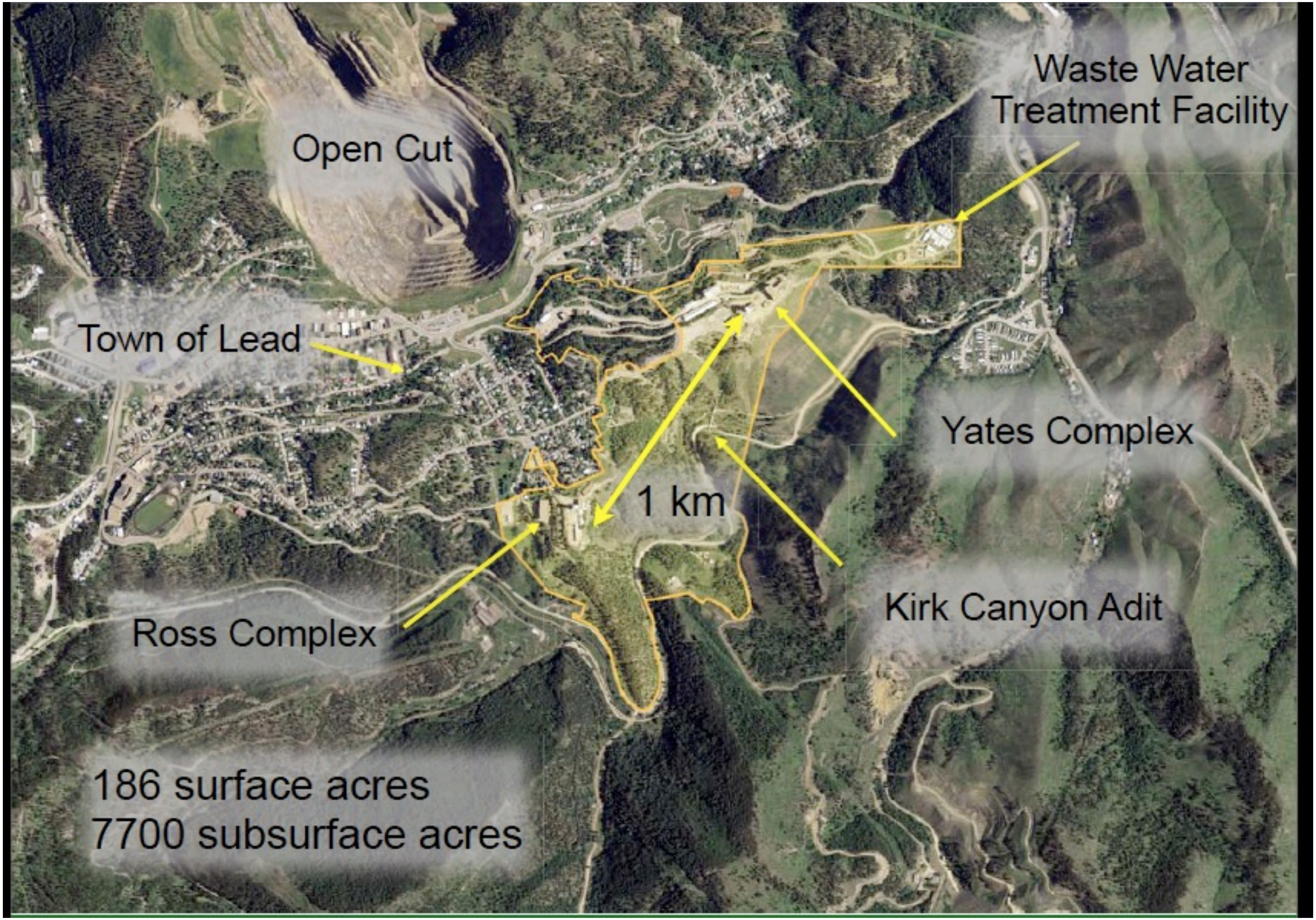


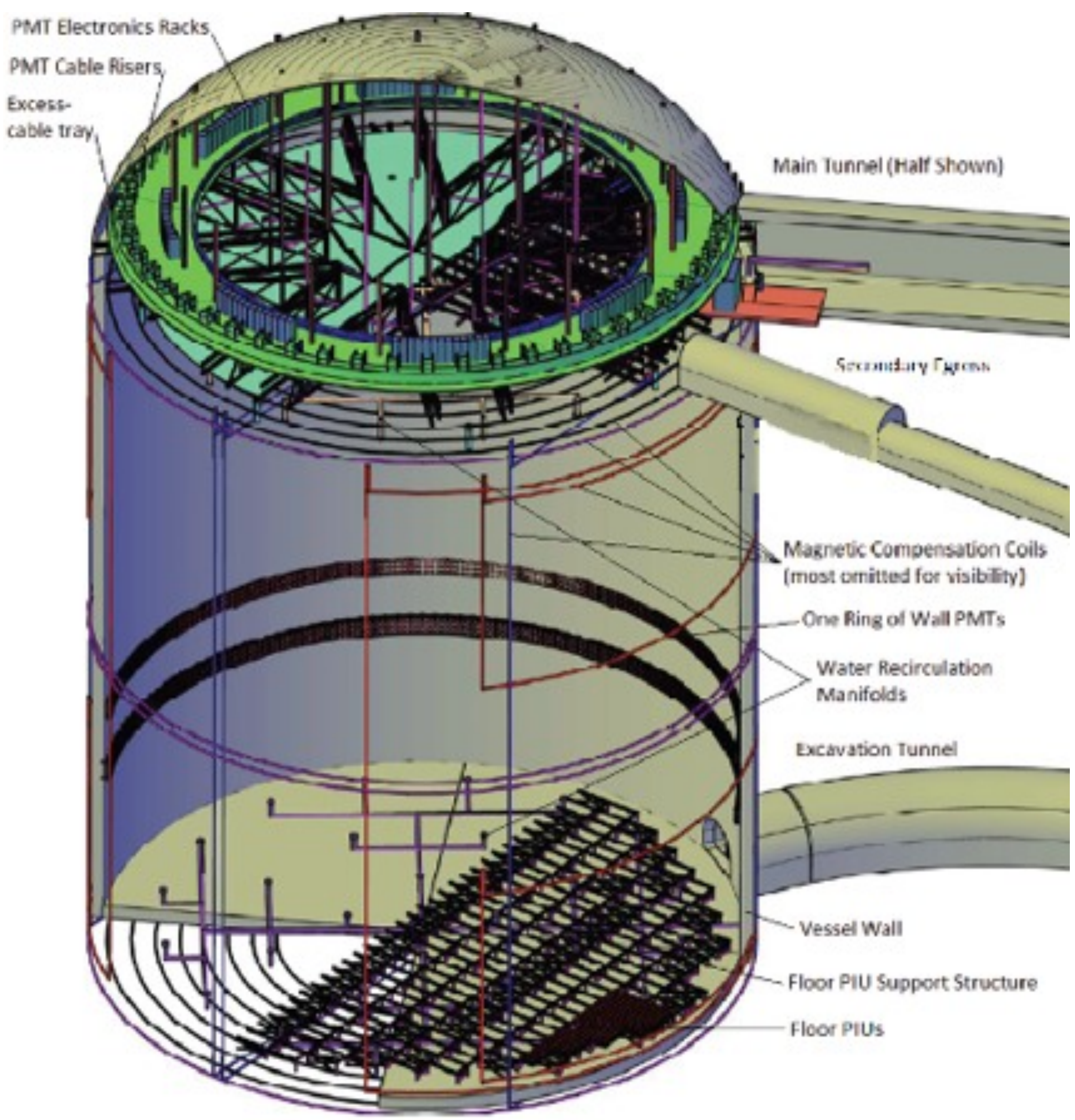
Fig. 1: LBNE neutrino beam configuration for extraction at MI-10 and the target hall above grade

Status of the Homestake site



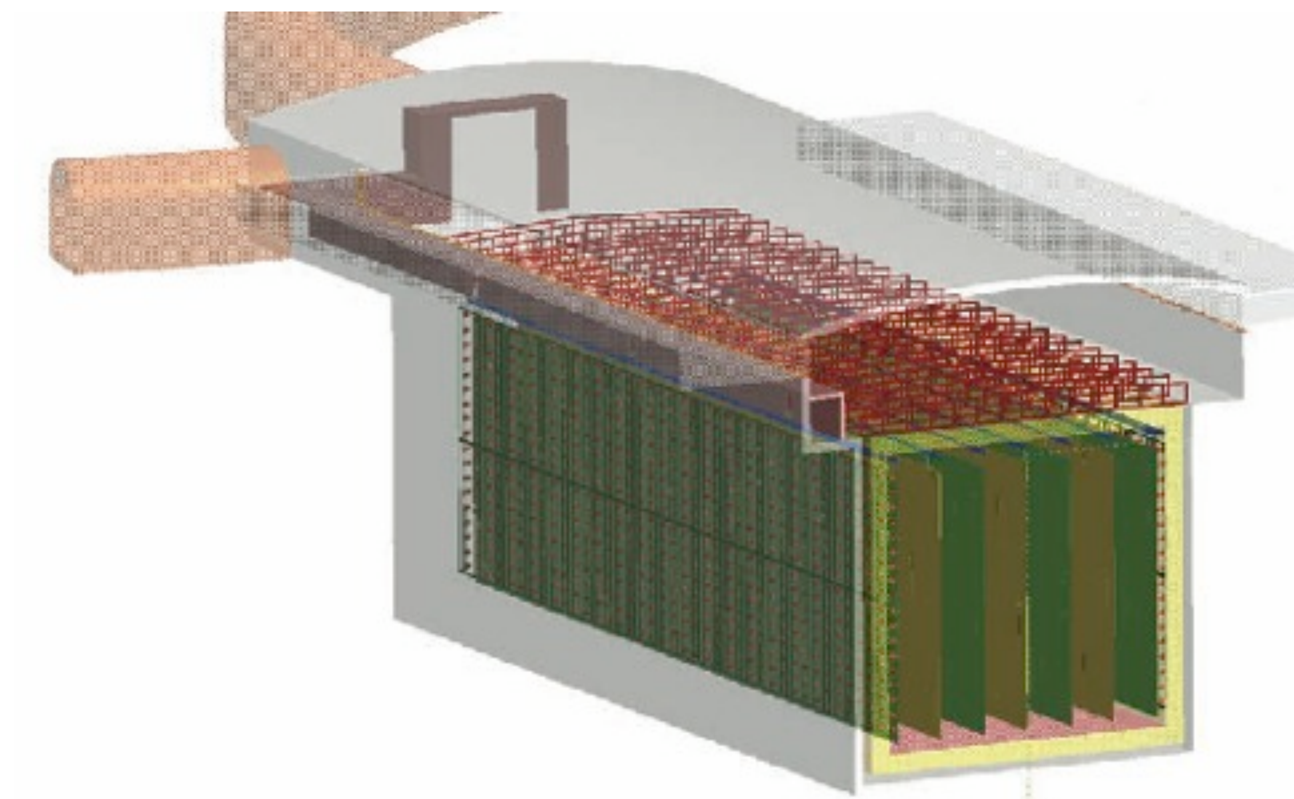
Two Far Detector Options

200 kT water Cherenkov



One 200 kT fiducial WC detector
Located at the **4850 foot level (0.2-0.3 Hz)**

34 kT liquid argon

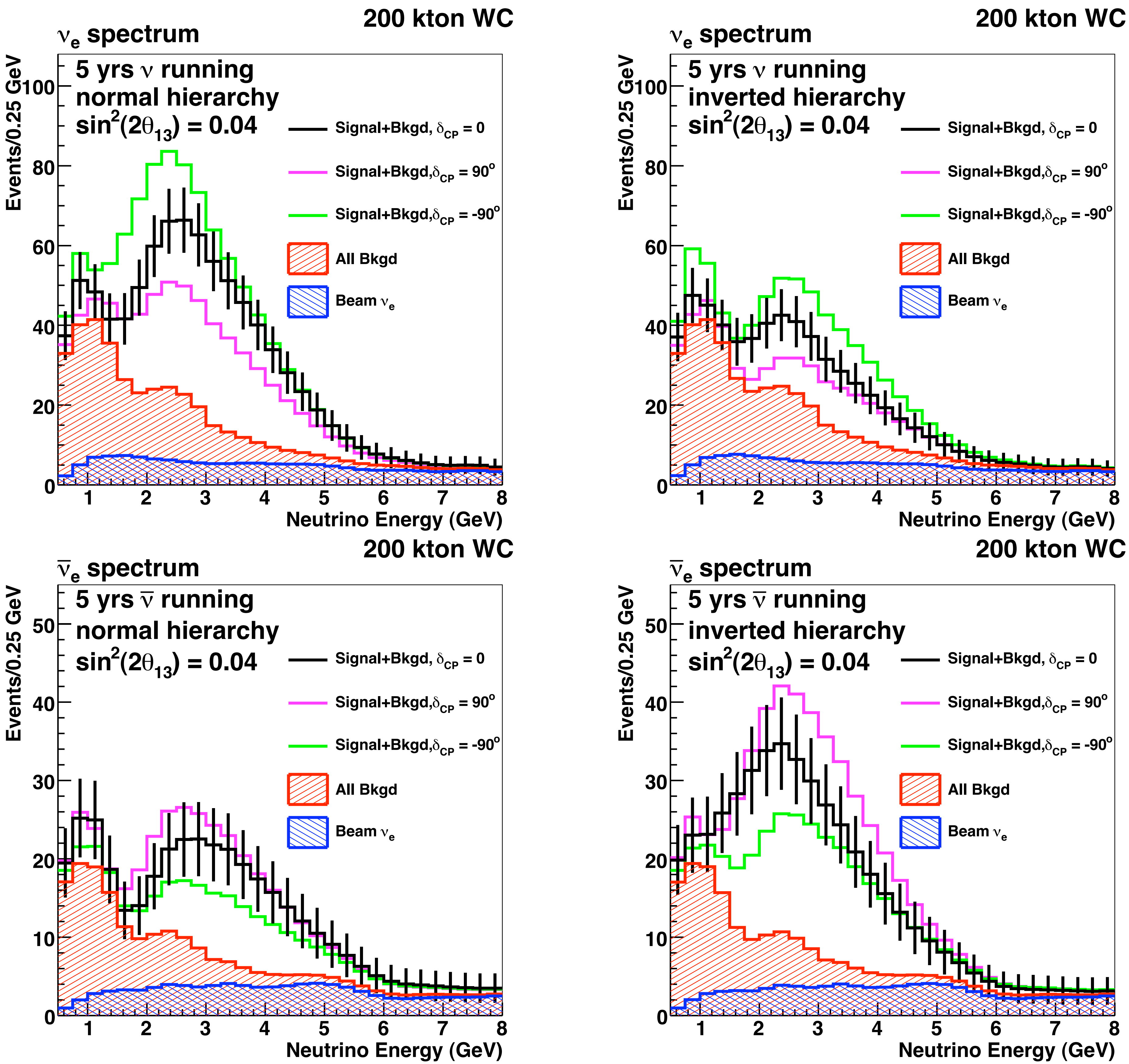


Two 17 kT fiducial LAr detectors
To be located at a new drive-in
site at **800 foot level**. (one detector
shown here) (~200 Hz)

normal | inverted

nu

anti-nu

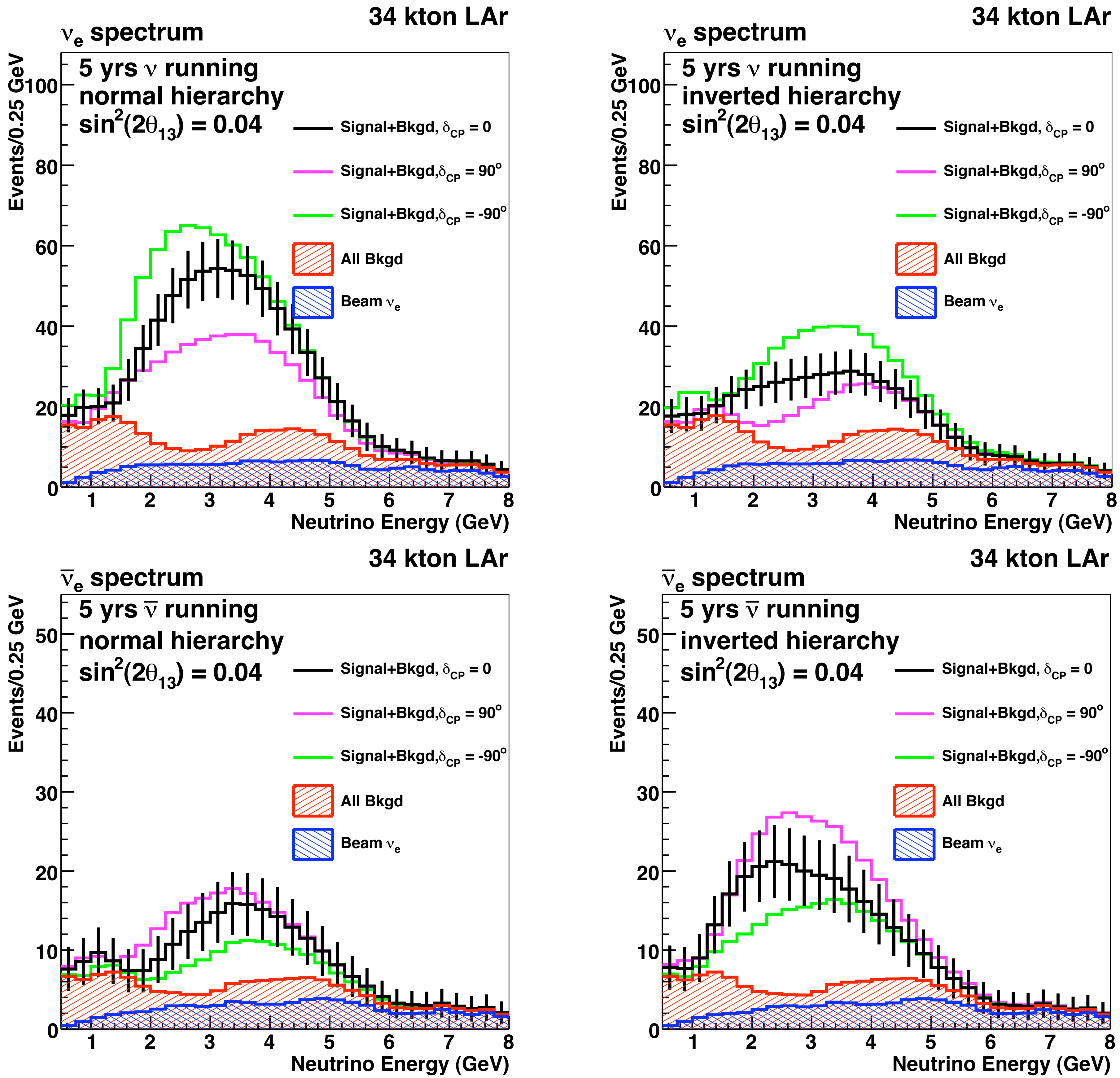


Lisa Whitehead

normal inverted

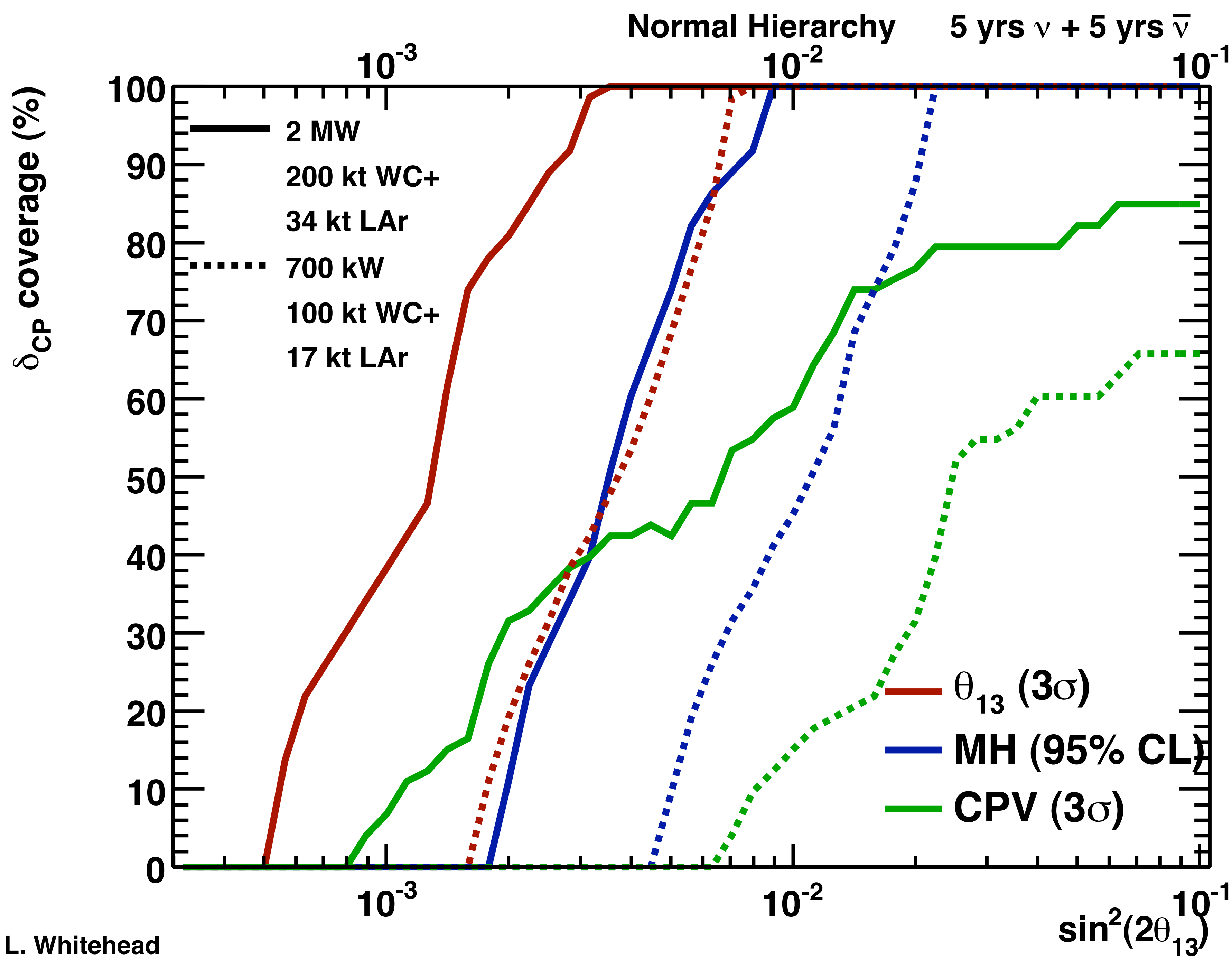
nu

anti-nu



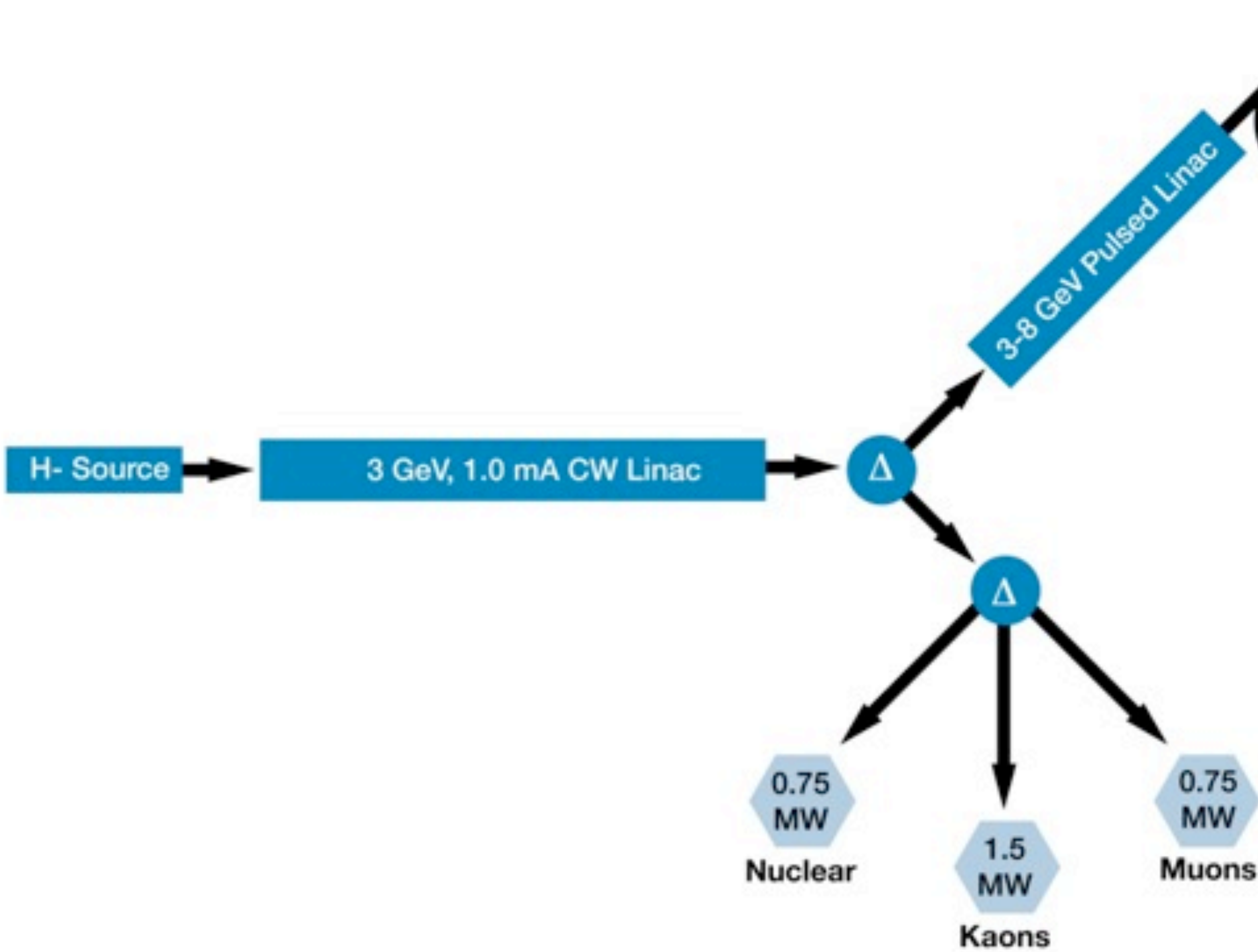
Lisa Whitehead

Sensitivity summary



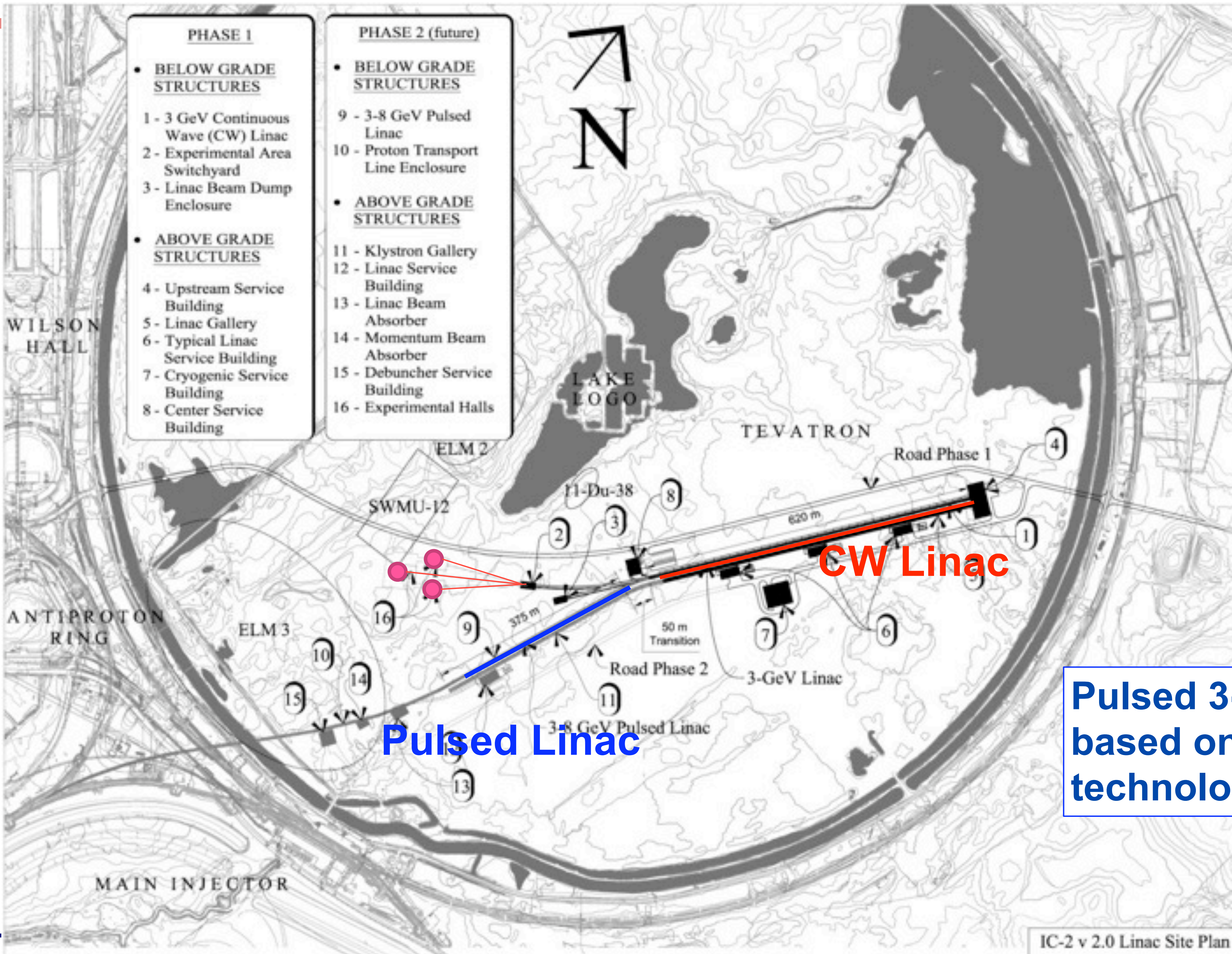
Project X Design at FNAL

Reference Design



	Energy	Current	DF	power
CW LINAC	3 GeV	1 mA	CW	2870 kW
Pulsed LINAC	8 GeV	40 μA	4.4 ms/ 10Hz	350 kW
Main Injector	120 GeV	20 μA	10 μS/ 0.7Hz	2200 kW

Reference Design
Provisional Siting



Pulsed 3-8 GeV Linac based on ILC / XFEL technology

$K \rightarrow \pi\bar{\nu}\nu$…Past, Present, Future

Facility (Experiment)	Proton Power	Kaon decay rate	Kaon Properties	$K \rightarrow \pi\nu\bar{\nu}$ Sensitivity
BNL AGS (E787/E949)	50kW	1×10^6 K^+/sec	Pure stopped K^+ source	7 events (charged)
CERN (NA62)	20kW	10×10^6 K^+/sec	Un-separated 1- GHz $K^+/\pi^+/p^+$ beam	80 events (charged)
Project-X $K^+ \rightarrow \pi\nu\bar{\nu}$	1500 kW	100×10^6 K^+/sec	Pure stopped K^+ source	>1000 events (charged)
JPARC (KOTO)	<300 kW	$<0.5 \times 10^6$ K_L/sec	Pencil beam	1 event (neutral)
Project-X $K_L \rightarrow \pi\nu\bar{\nu}$	1500kW	50×10^6 K_L/sec	Pencil beam & Precision TOF	1000 events (neutral)

$\mu^- A \rightarrow e^- A$ Conversion… Past, Present, Future

Facility (Experiment)	Proton Power	Stopped Muon rate	Muon Properties	$\mu A \rightarrow eA$ Sensitivity
PSI (SINDRUM II)	1000kW	10^7 μ/sec	"DC" (50 MHz cyclotron) 52 +/-1 MeV/c	3×10^{-13}
Booster & JPARC (Mu2e/COMET)	25kW	5×10^{10} μ/sec	1 MHz Pulsed 10-70 MeV/c	2×10^{-17}
Project-X (PRISM-like)	1000kW	$>10^{12}$ μ/sec	Pulsed, narrow-band (30 +/- 1 MeV/c)	$<10^{-18}$

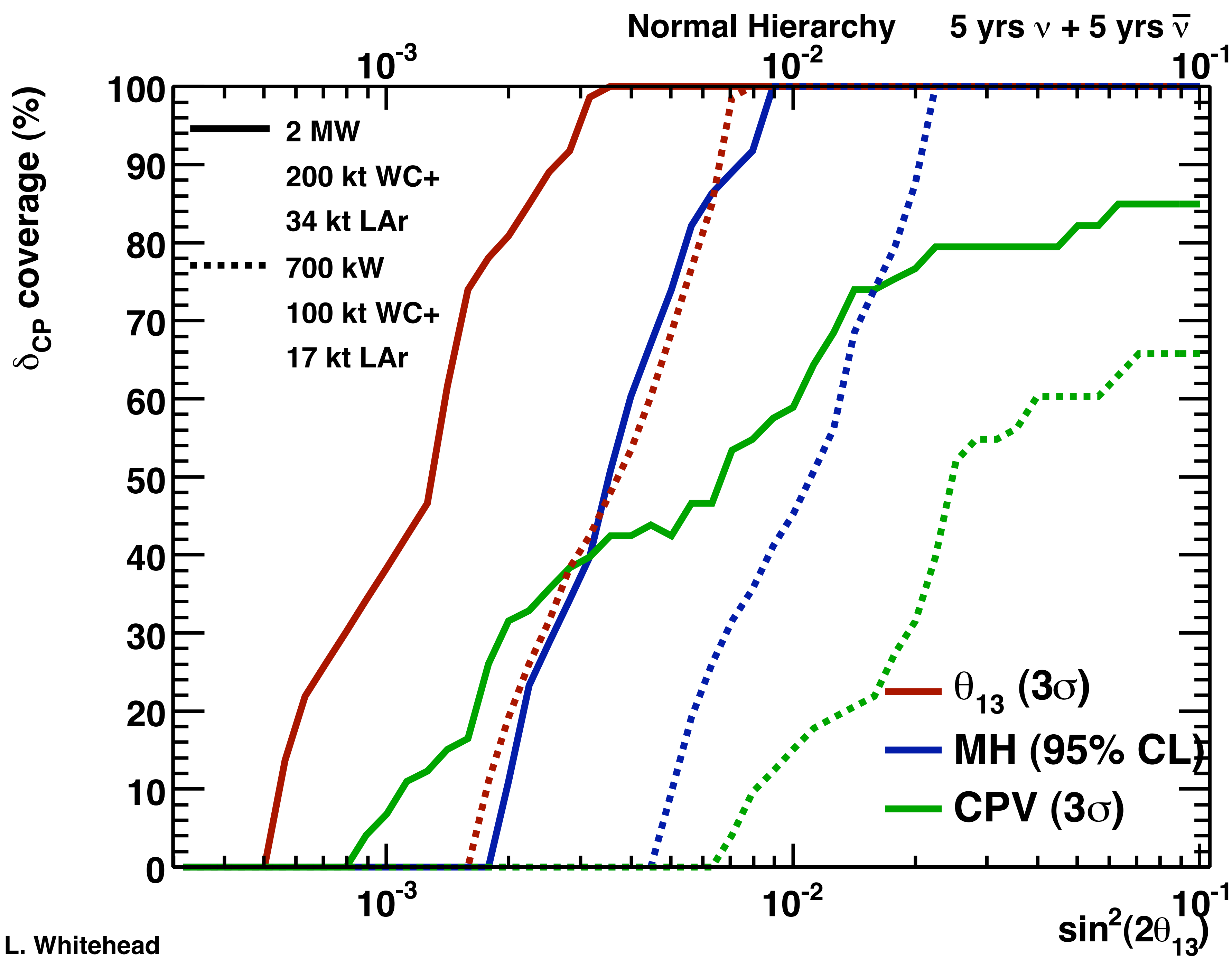
Mu2e/COMET breakthrough technology:

- Large muon yield from production target *inside* of high field solenoid.
- Pulsed beam strongly suppresses pion backgrounds.

Project-X breakthrough technology:

- Collapse the high flux wide-band muon beam to a narrow-band beam with cooling techniques.

Sensitivity summary



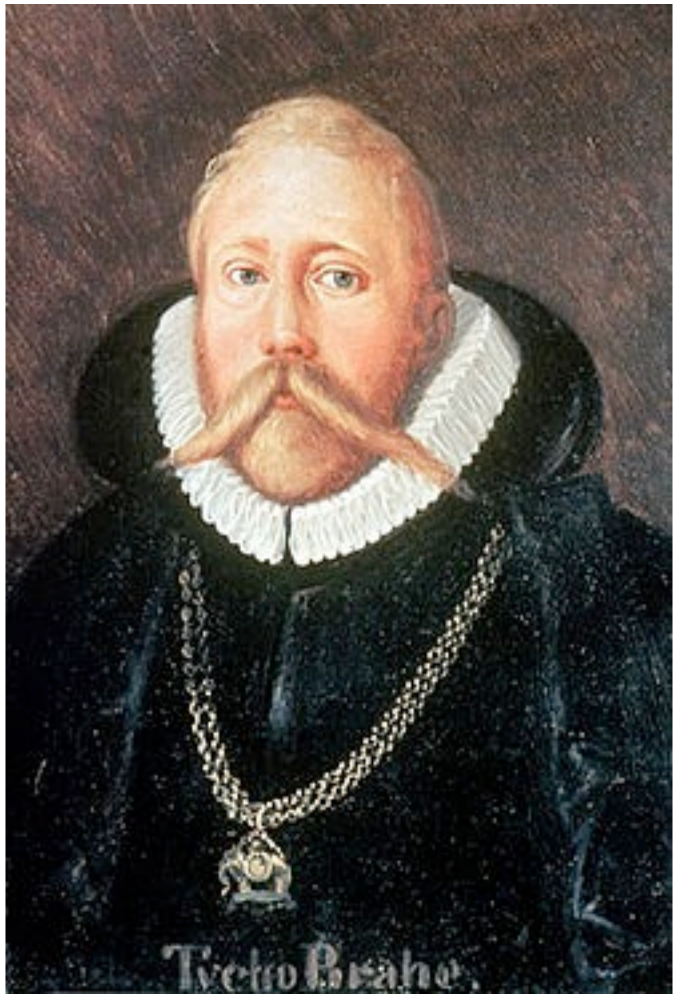
Fundamental Equation of Physics

Fundamental Equation of Physics

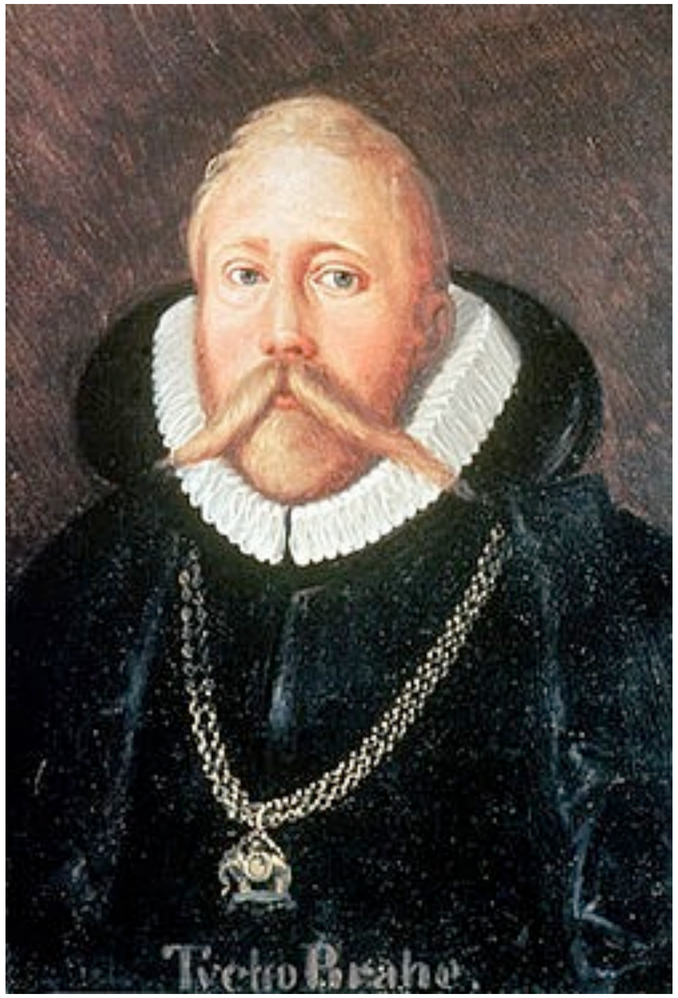
Money = Science

Fundamental Equation of Physics

Money = Science



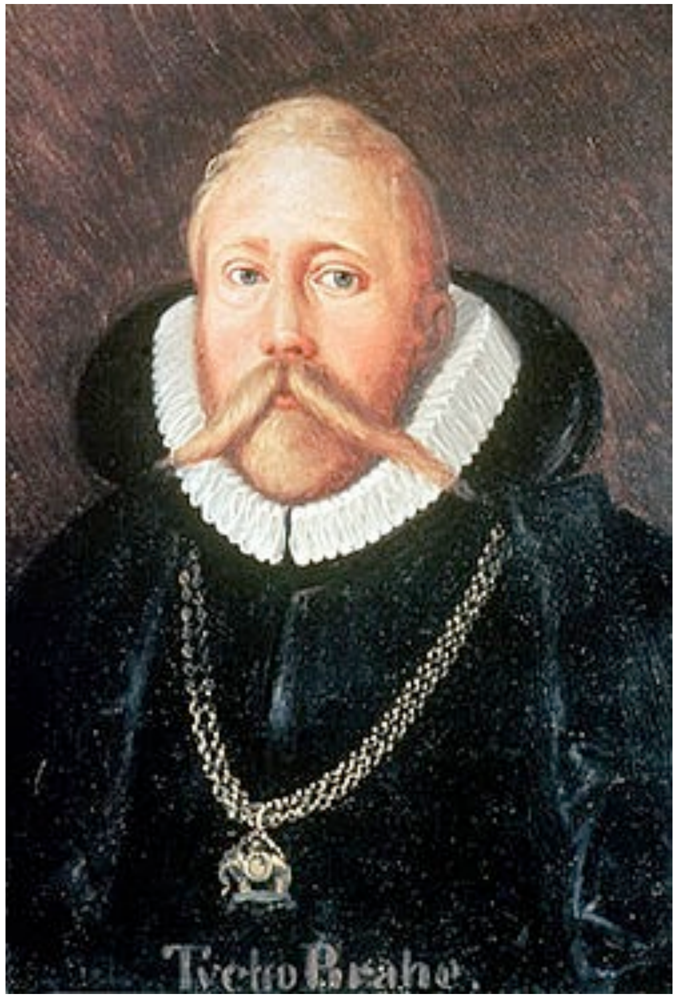
Fundamental Equation of Physics



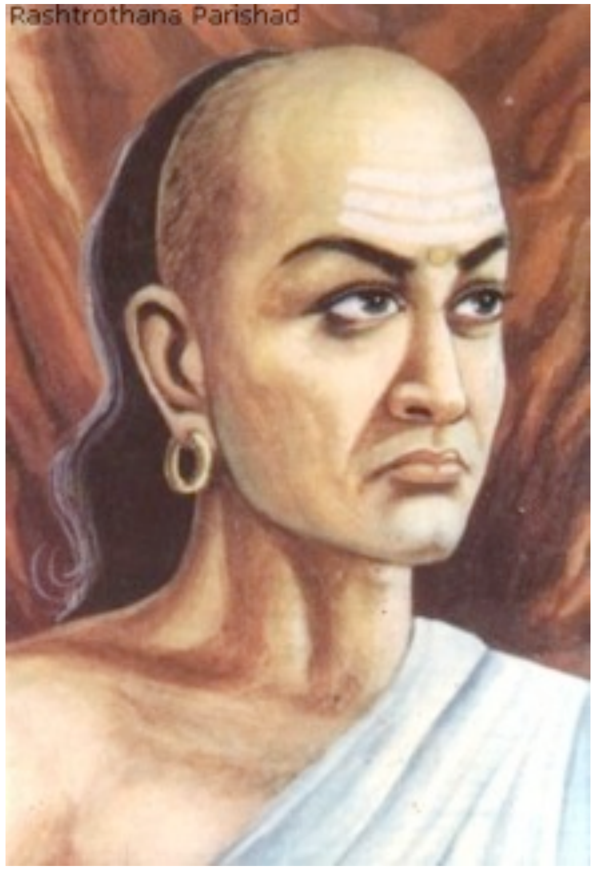
Money = Science

Kautilya: Check the King's treasury before starting a project.
(Koshpurvaa Sarvaarambha')

Fundamental Equation of Physics



Money = Science



Kautilya: Check the King's treasury before starting a project.
(Koshpurvaa Sarvaarambha')

Price tag

- LBNE has been costed (preliminary) at ~1.5 B including all contingency factors and site work at Homestake/Sanford Lab.
- The Project-X 3 GeV program comes at ~1.4B
- Additional cost from 3 to 8 GeV LINAC ~0.5 B
- There will be foreign contributions (already started on Project-X), but it will require consistent policy.
- We need to remain wisely optimistic and keep working at it.

Conclusion

- Measurements of the Standard Model in the last two decades have sharpened the key questions.
- Besides the important direct observation of electro-weak signatures, low energy observables can also contribute. e.g. the muons (g-2) anomaly has become central to new physics searches.
- New kaon, muon experiments should be launched. These are intricate, high technology experiments with great promise for new physics that is independent of the energy frontier.
- Neutrino physics is still going through a revolution and there is still much that we do not know. It will need new beam and detector facilities such as LBNE.

Backups

Reference Design Capabilities

- 3 GeV CW superconducting H- linac with 1 mA average beam current.
  - Flexible provision for variable beam structures to multiple users
    - CW at time scales >1 μsec, 15% DF at <1 μsec
  - Supports rare processes programs at 3 GeV
  - Provision for 1 GeV extraction for nuclear energy program
- 3-8 GeV pulsed linac capable of delivering 300 kW at 8 GeV
  - Supports the neutrino program
  - Establishes a path toward a muon based facility
- Upgrades to the Recycler and Main Injector to provide ≥ 2 MW to the neutrino production target at 60-120 GeV.
- Day one experiment to be incorporated utilizing the CW linac

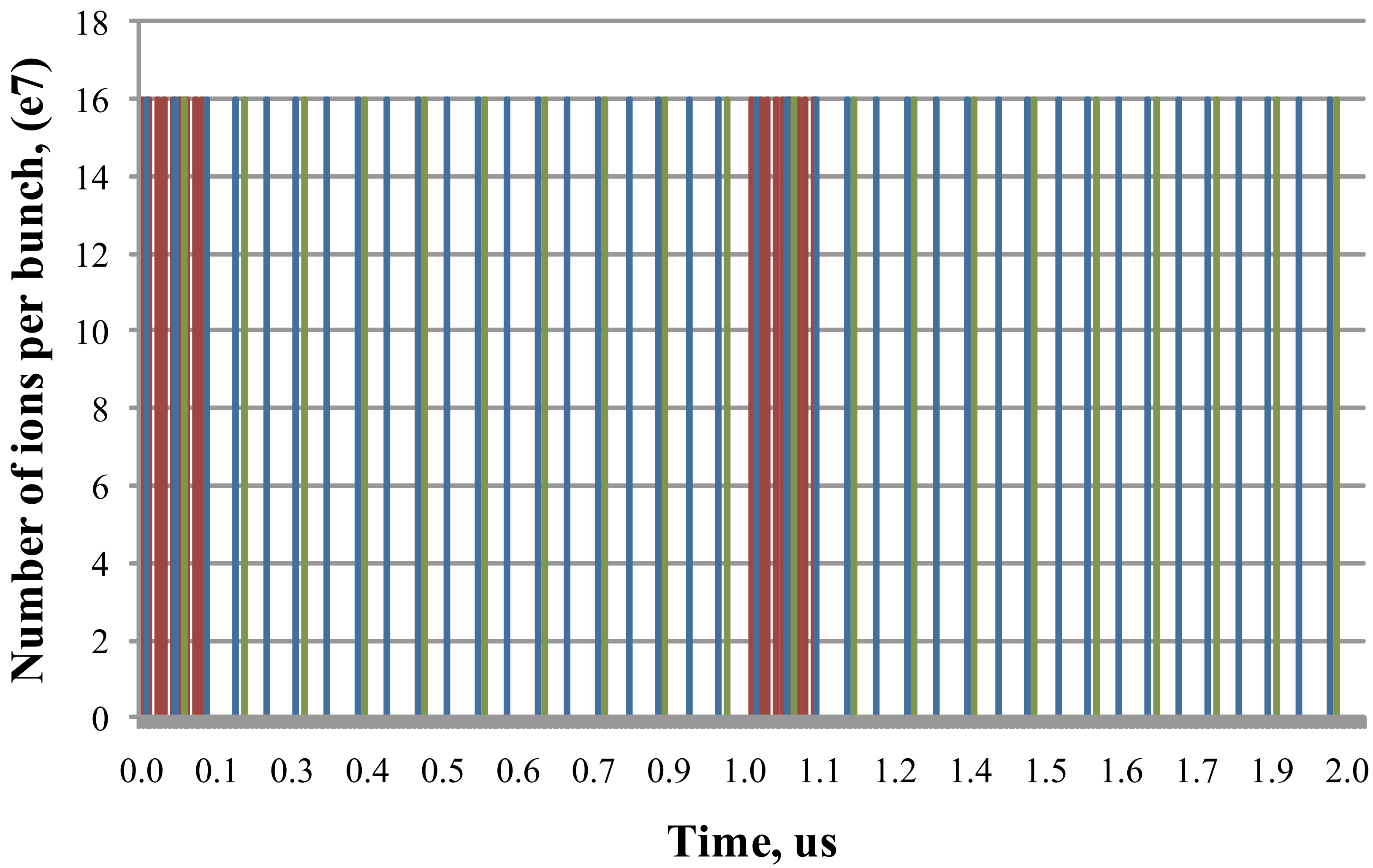
⇒Utilization of a CW linac creates a facility that is unique in the world, with performance that cannot be matched in a synchrotron-based facility.

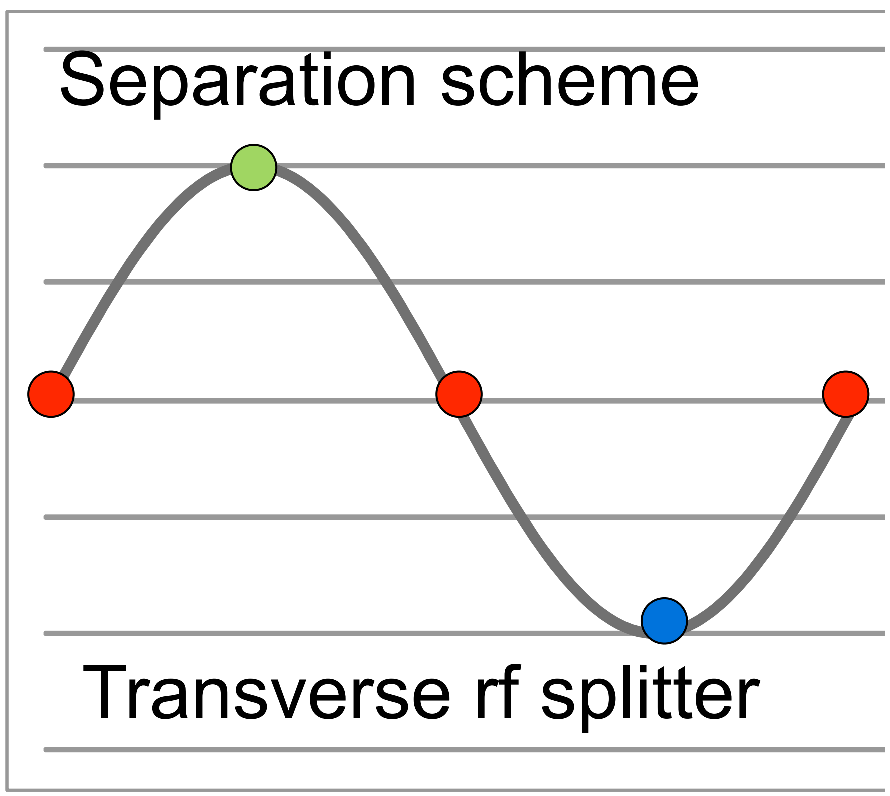
Chopping and splitting for 3-GeV

1 μsec period at 3 GeV

Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz	700 kW
Kaon pulses (16e7) 20.3 MHz	1540 kW
Nuclear pulses (16e7) 10.15 MHz	770 kW

Ion source and RFQ operate at 4.2 mA
75% of bunches are chopped at 2.5 MeV after RFQ





Performance Goals

Linac

Particle Type	H^-	
Beam Kinetic Energy	3.0	GeV
Average Beam Current	1	mA
Linac pulse rate	CW	
Beam Power	3000	kW
Beam Power to 3 GeV program	2870	kW

Pulsed Linac

Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	4.4	msec
Cycles to MI	6	
Particles per cycle to MI	2.6×10^{13}	
Beam Power to 8 GeV	350	kW
Upgraded Beam Power to 8 GeV	4 MW	

Main Injector/Recycler

Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per cycle	1.6×10^{14}	
Beam Power at 120 GeV	2200	kW

Performance Goals

Linac		
Particle Type	H^-	
Beam Kinetic Energy	3.0	GeV
Average Beam Current	1	mA
Linac pulse rate	CW	
Beam Power	3000	kW
Beam Power to 3 GeV program	2870	kW
Pulsed Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	4.4	msec
Cycles to MI	6	
Particles per cycle to MI	2.6×10^{13}	
Beam Power to 8 GeV	350	kW
Upgraded Beam Power to 8 GeV	4 MW	
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per cycle	1.6×10^{14}	
Beam Power at 120 GeV	2200	kW

simultaneous

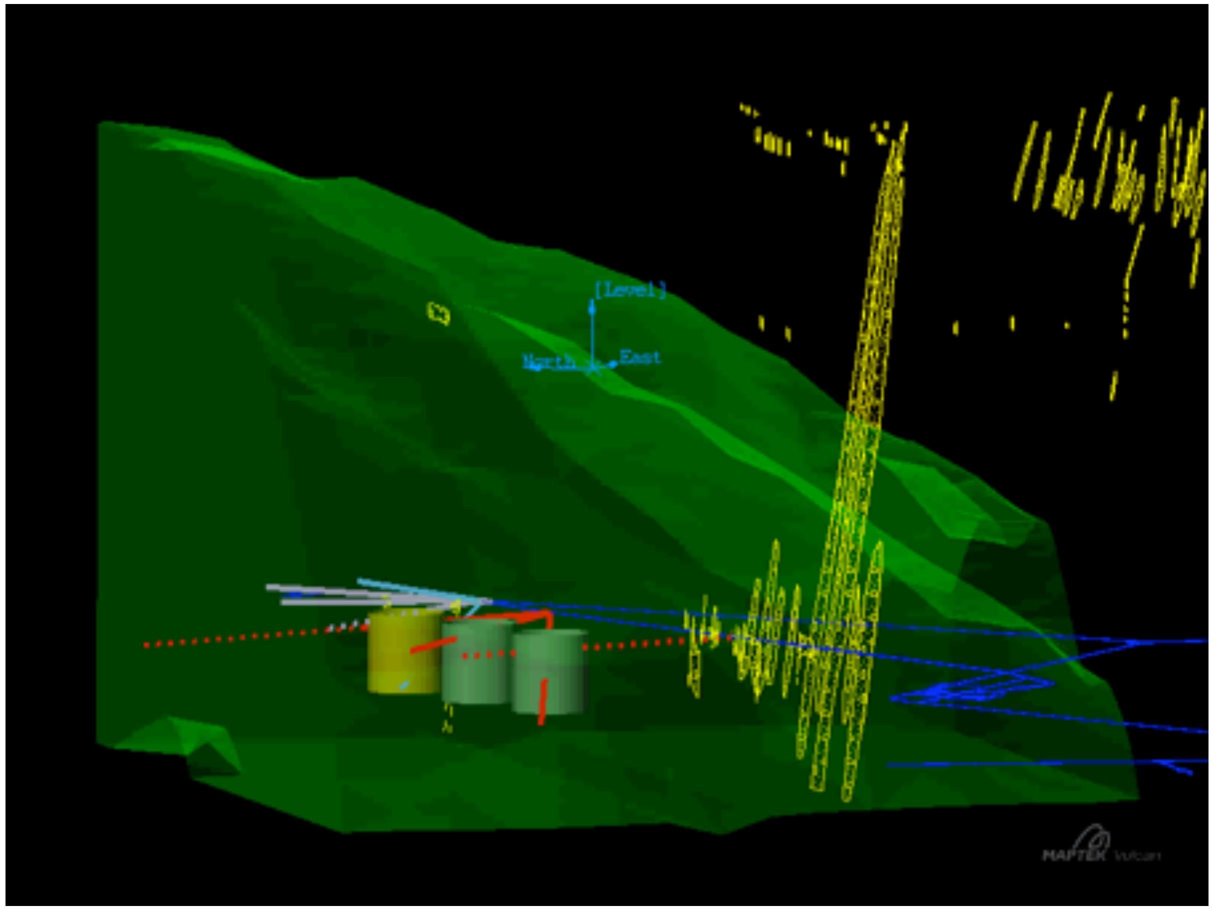
Steve Holmes

Fermilab

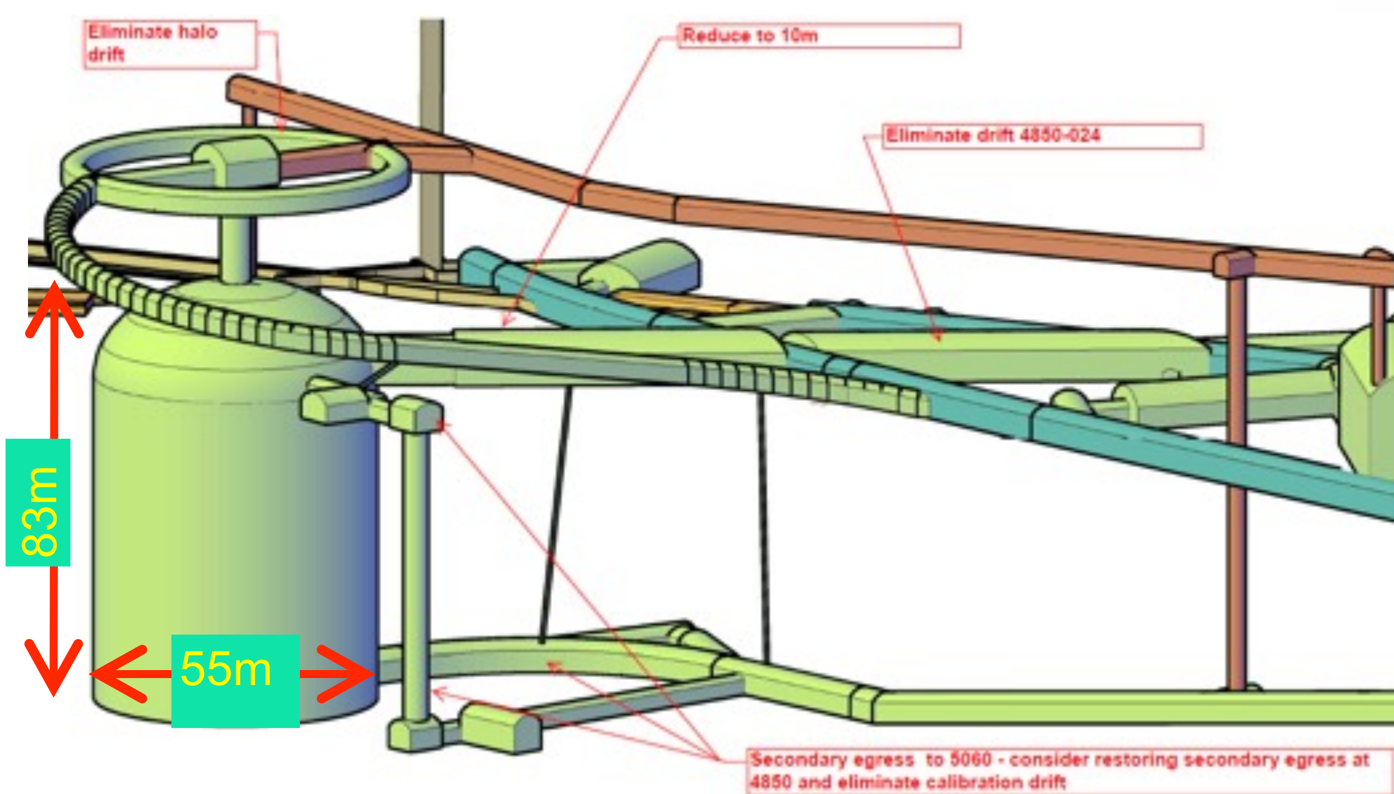
1. WILSON HALL - 16 WEST (BEFORE)

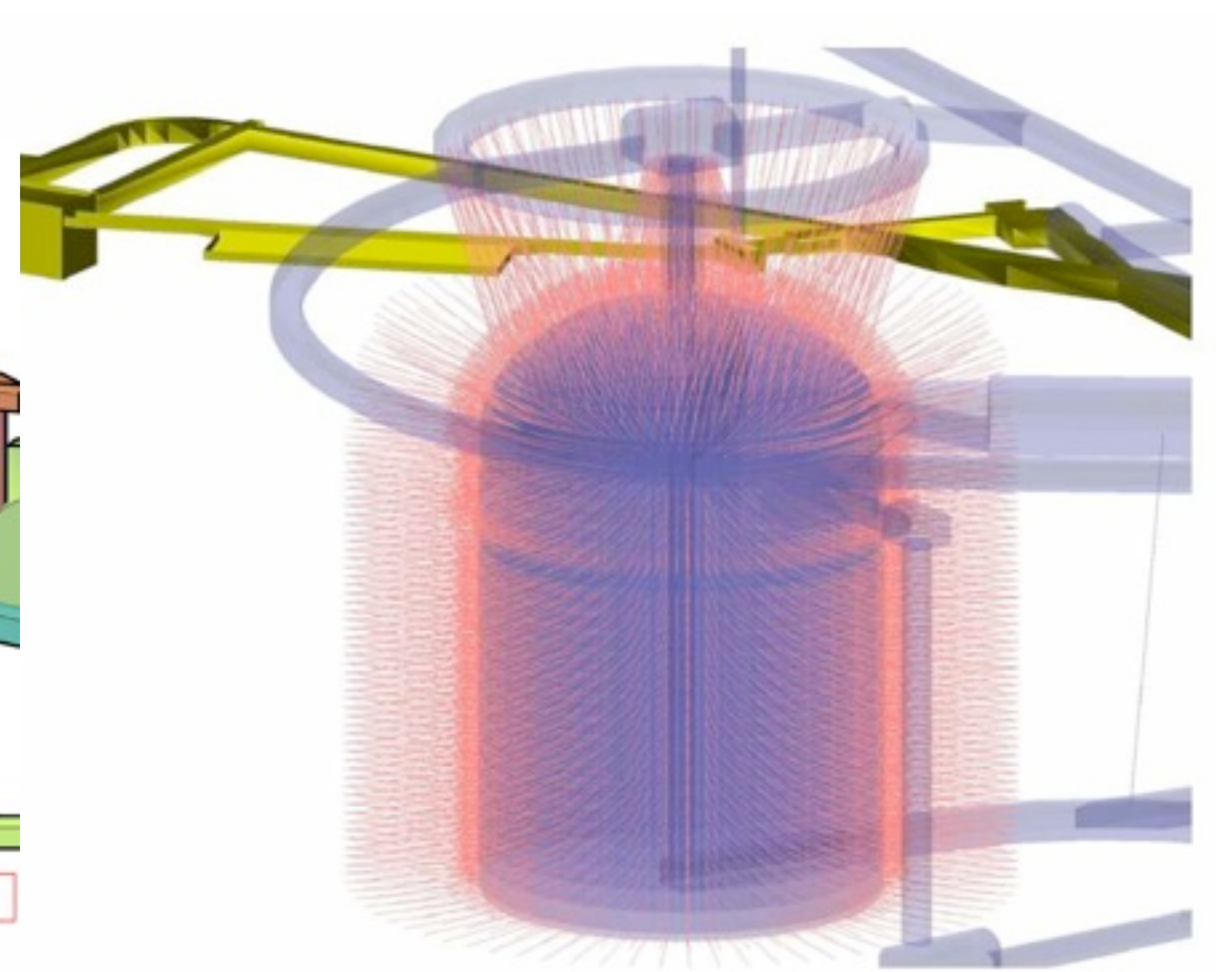
1. WILSON HALL - 16 WEST (AFTER)

Site investigation and preliminary design

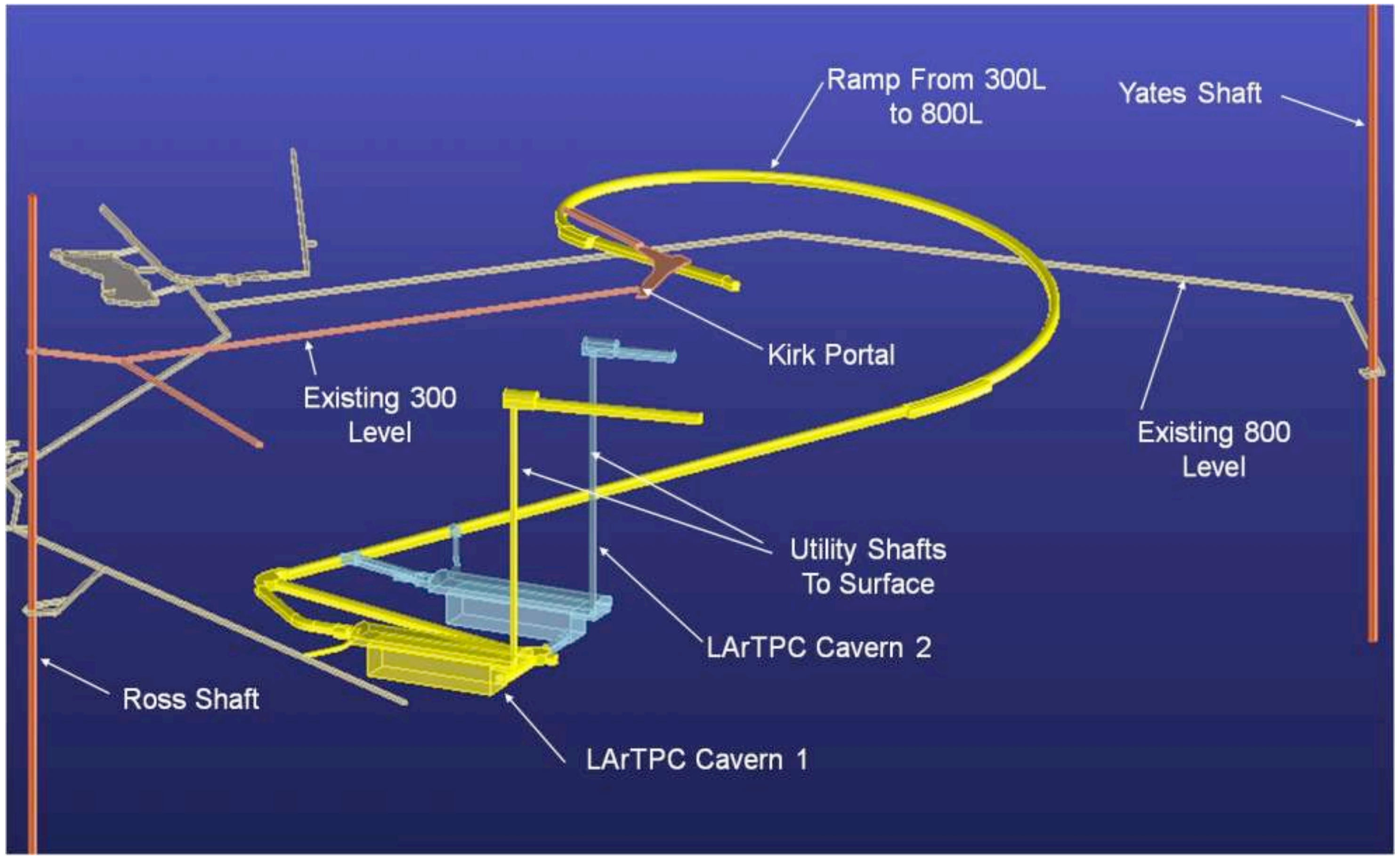


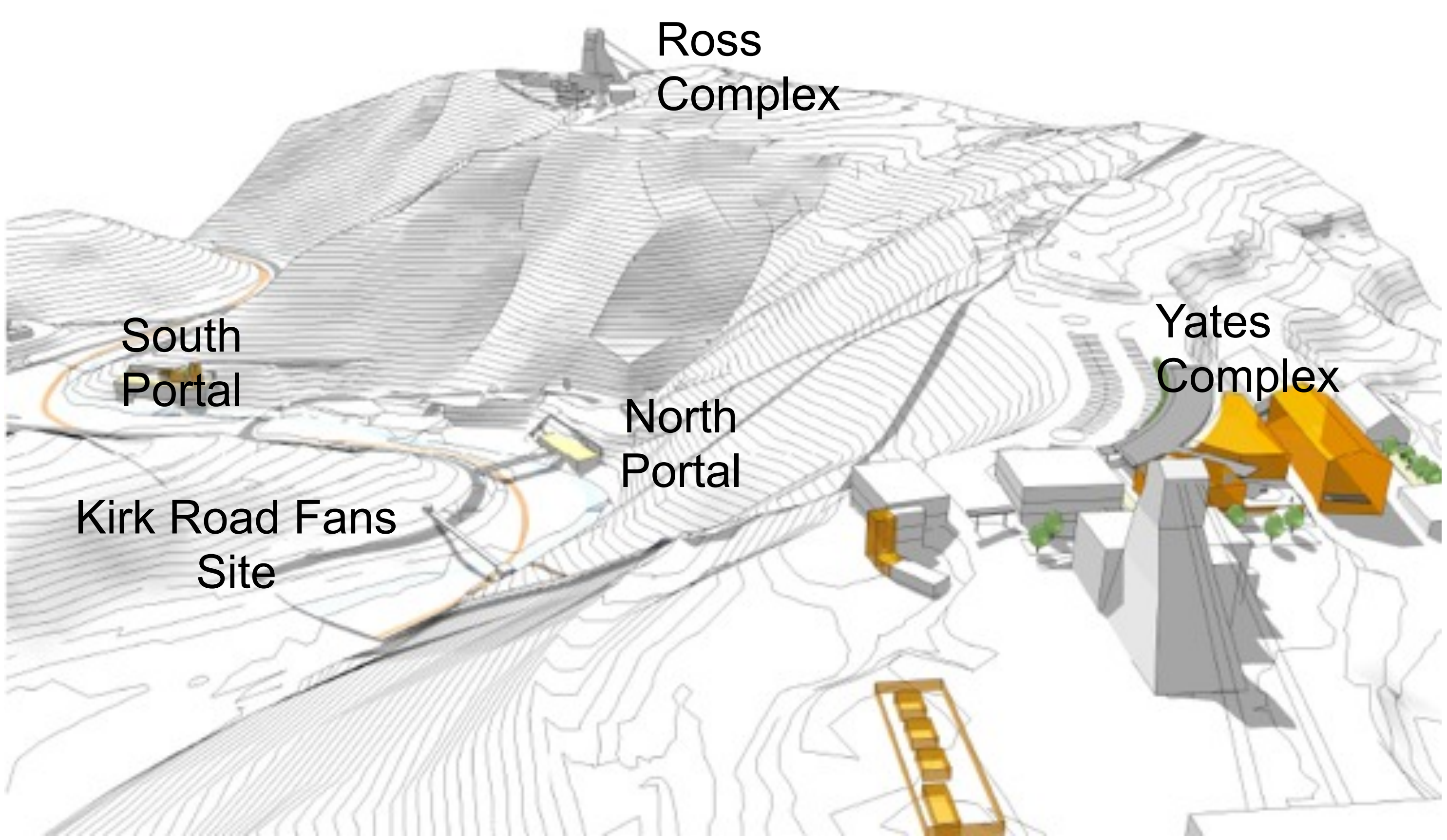
- Confidence in 55m span WCD cavity is high after much detailed design. (100kTon)
- Initial studies show that 200kTon could be possible





Site proposal for 34 kTon liquid argon

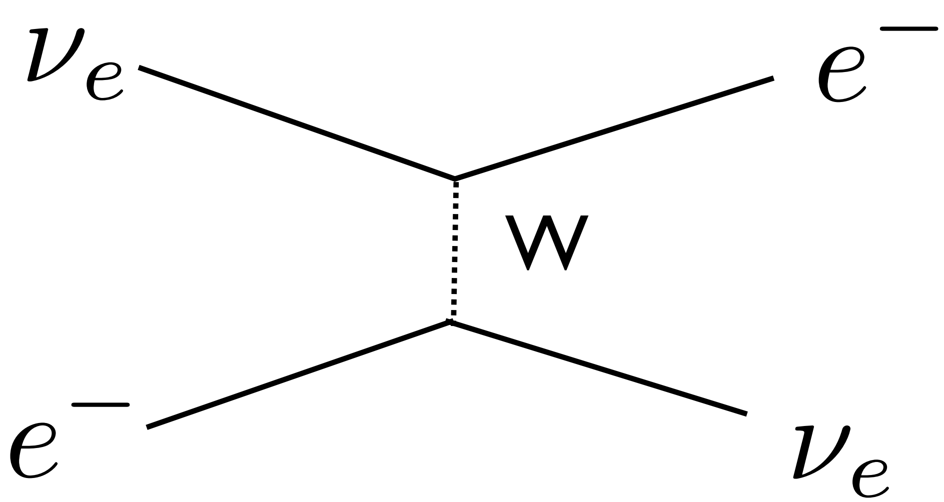




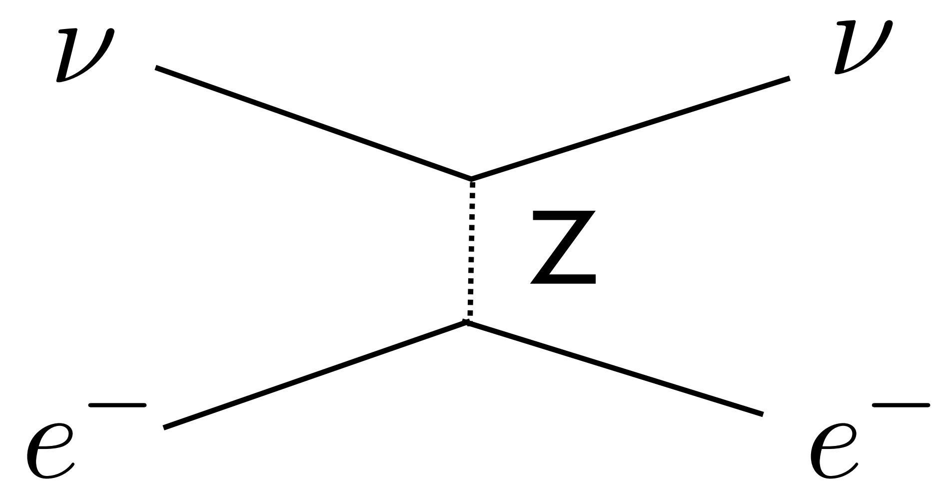
- Liquid Argon development is proposed to be at 800 ft level.
- Keep separated from rest of lab.
- Allow horizontal access through tunnel.
- Rock is not fully explored, but caverns are smaller.

$$i\frac{d}{dx}\nu_f = HR_\theta \nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.



Charged Current
for electron type only



Neutral Current
for all neutrino types

Additional potential for ν_e $(\bar{\nu}_e)$: $\pm\sqrt{2}G_F N_e$

N_e is electron number density.

An example of how additional phases come into the interferometry.

Oscillations in presence of matter

$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\left(R_\theta\begin{pmatrix}m_2^2-m_1^2 & 0\\ 0 & m_1^2-m_2^2\end{pmatrix}R_\theta^T + 2E\begin{pmatrix}\sqrt{2}G_FN_e & 0\\ 0 & -\sqrt{2}G_FN_e\end{pmatrix}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \quad (3)$$

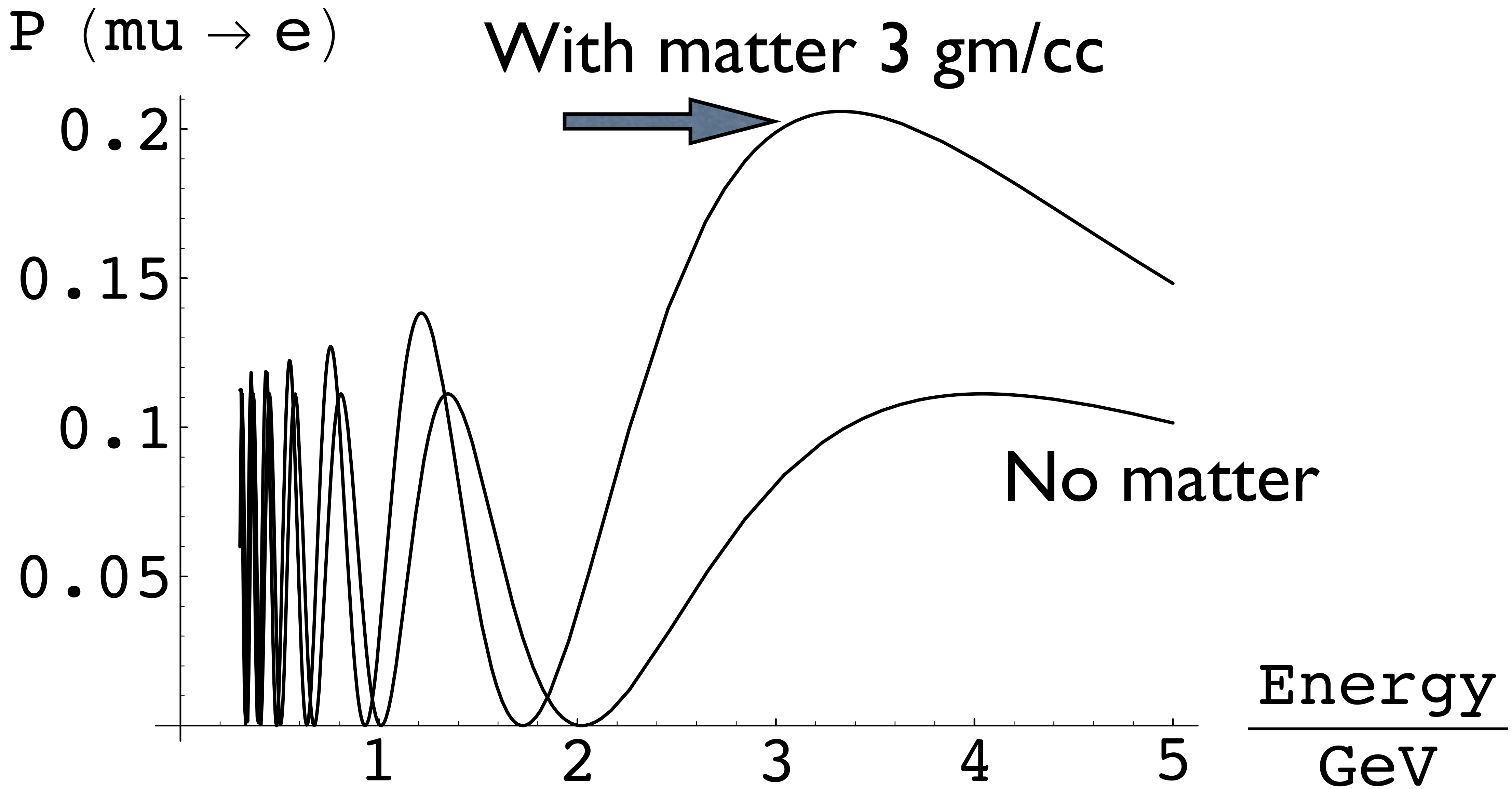
Looking at conversions of muon to electron neutrinos.

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta}\times\sin^2\frac{L\Delta m^2}{4E}\sqrt{(a-\cos 2\theta)^2+\sin^2 2\theta}$$

$$\begin{aligned} a &= 2\sqrt{2}EG_FN_e/\Delta m^2 \\ &\approx 7.6\times 10^{-5}\times D/(gm/cc)\times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \quad (4)$$

This effect present if electron neutrinos in the mix

2-neutrino picture



Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg