LBNE Experiment

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Beam ⇒

Measurement of the PMNS Matrix Elements

Θ_{13} δ_{CP} ν-Mass Hierarchy   Resolving degeneracies

⇒ Syst.Precision

(Nu -vs- NuBar ⇐ δ_{CP})

Beyond PMNS

Θ_{23} = 45^0 ?   CPT Violation ?   High Δm^2 Oscillation ?

⇒ *Phenomenon that defies the Zeitgeist*

The familiar, beautiful neighborhood

X-secs, Sin**2(Θ_w): precision comparable to Colliders?

Sum rules, Isospin Physics (Nu -vs- NuBar ⇐ δ_{CP})

Heavy neutrinos

....

Rewriting the ν text-book

non-Beam ⇒

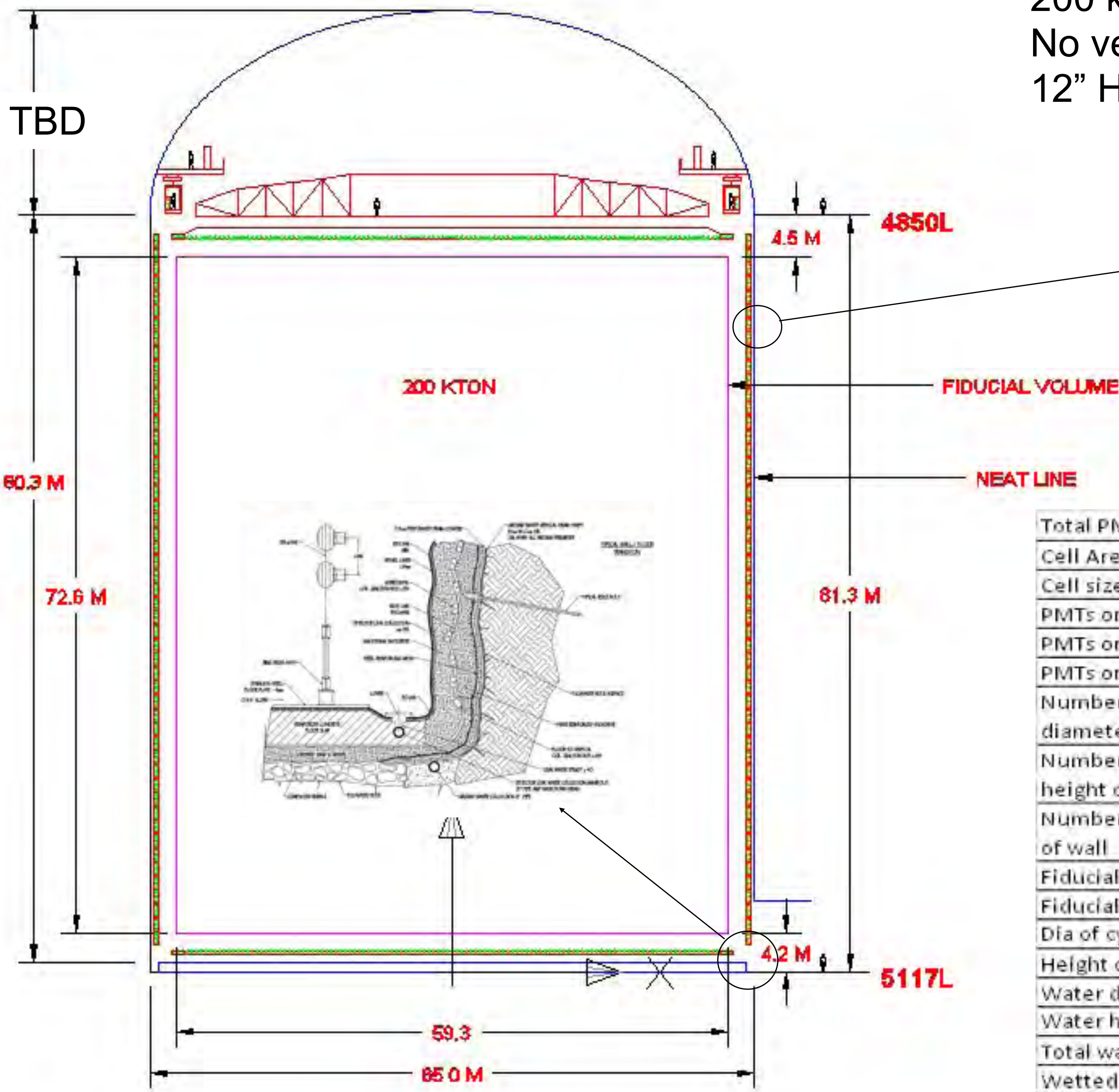
Proton Decay

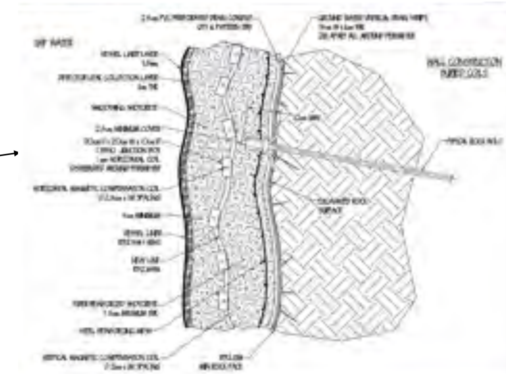
Supernovae ν Solar & Atmospheric ν ...

LBNE Experiment: Salient Parameters

- *Evolution:* MINOS ⤜ NOvA ⤜ LBNE
- ν *Source:* 700 kW upgraded to 2.3 MW (Project-X)
- *Distance:* 1300 km from the ν source (Fermilab ⇒ Homestake, SD) ⇐ Mass Hierarchy
- ν *Beam:* Maximize intensity at the 1st (2.5 GeV) and the 2nd. (0.75 GeV) Maxima ⇐ δ_{CP}
- *Far Detector:* 200 kT Water Cerenkov or 34 kT Liquid Argon
- *Depth:* 4850 ft for WC (possibly LAr)
- Comprehensive program to conduct precision measurements at the Near Detector, including ν-H_2O/Ar interactions ⇐ PMNS & non-standard

200 kton Known Tech: x4 SuperK
No vessel, liner on shotcrete
12” HQE PMTs

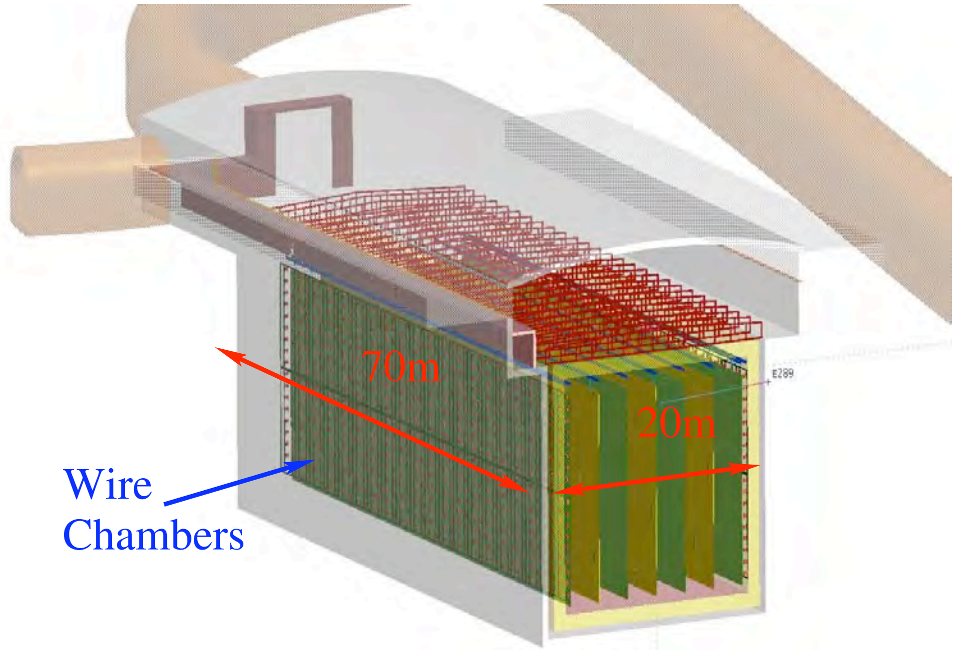




Total PMTs		28719
Cell Area	m^2	0.74
Cell size	m	0.86
PMTs on wall		20240
PMTs on Floor		4239
PMTs on Deck		4239
Number of cells across deck & floor diameter		73
Number of cells to traverse the height of wall		88
Number of cells around perimeter of wall		230
Fiducial diameter	m	59.30
Fiducial Height	m	72.60
Dia of cylinder at PMT equator	m	63.30
Height of cylinder at PMT equator	m	76.60
Water diameter	m	65.00
Water height	m	80.10
Total water volume	m^3	265796
Wetted Surface	m^2	19675
Surface to volume ratio	m^-1	0.074

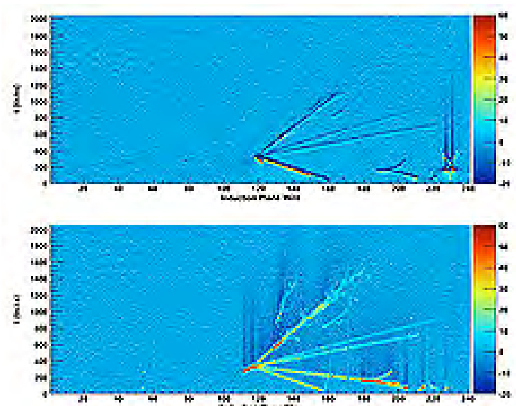
ICARUS : 0.6kt

LBNE LAr : 34 kt module X 2



LAR

ArgoNeuT (175 litre) prototype in the NuMI beam →

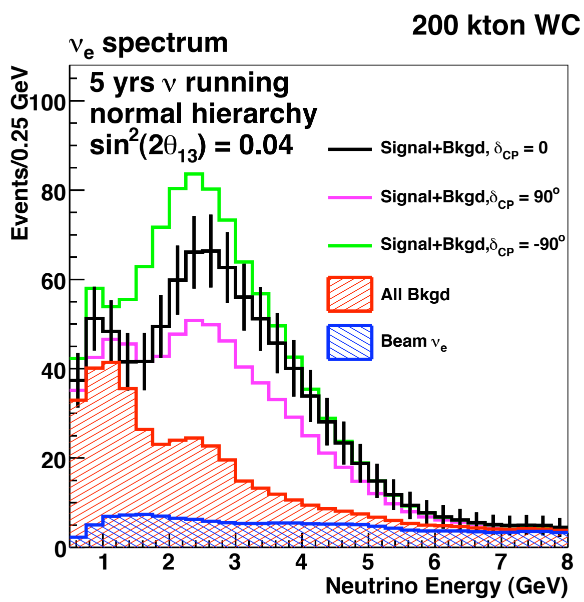


High efficiency and purity

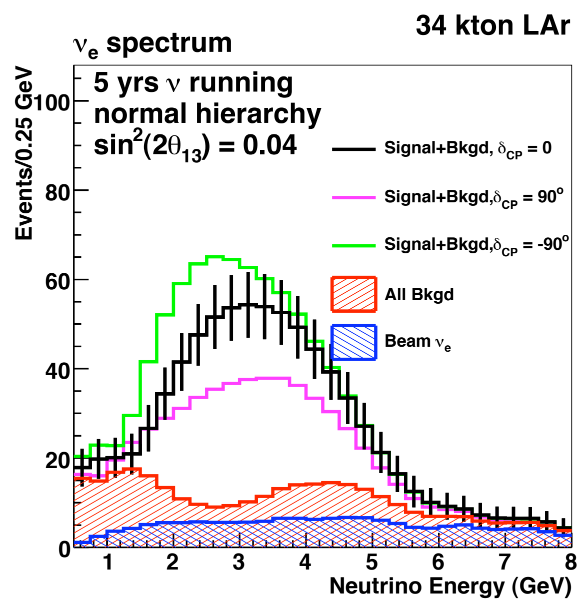
Requires 60 × scale-up - challenging.

On-axis wide-band beam (NuMI focusing). **Water Cerenkov response is based on the SuperK MC.** **LAr is modeled as a near-perfect detector.** *Exposure is 3.5 MW. yr ν with* $\mathbf{\sin^2 2\theta_{13} = 0.04}$*:*

200 kt WCD



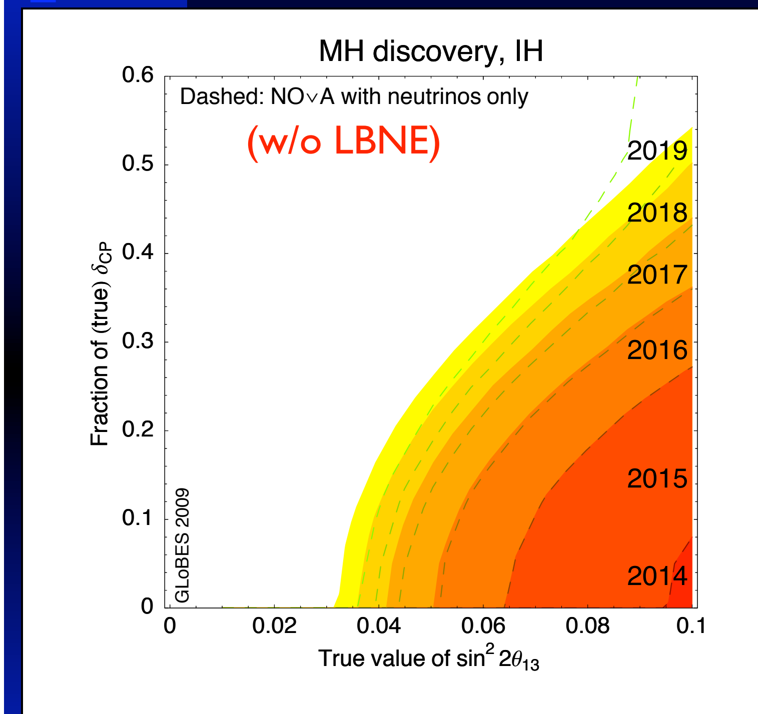
34 kt LAr



Interaction rates per 100kT.MW.yr ($0.5 < E_\nu < 20$ GeV)

ν_μ CC	ν_μ CC osc	ν_e CC beam	$\nu_\mu \rightarrow \nu_e$ CC	$\nu_\mu \rightarrow \nu_\tau$ CC
29K	11K	260	560	140

Mass hierarchy



PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009), arXiv:0907.1896.

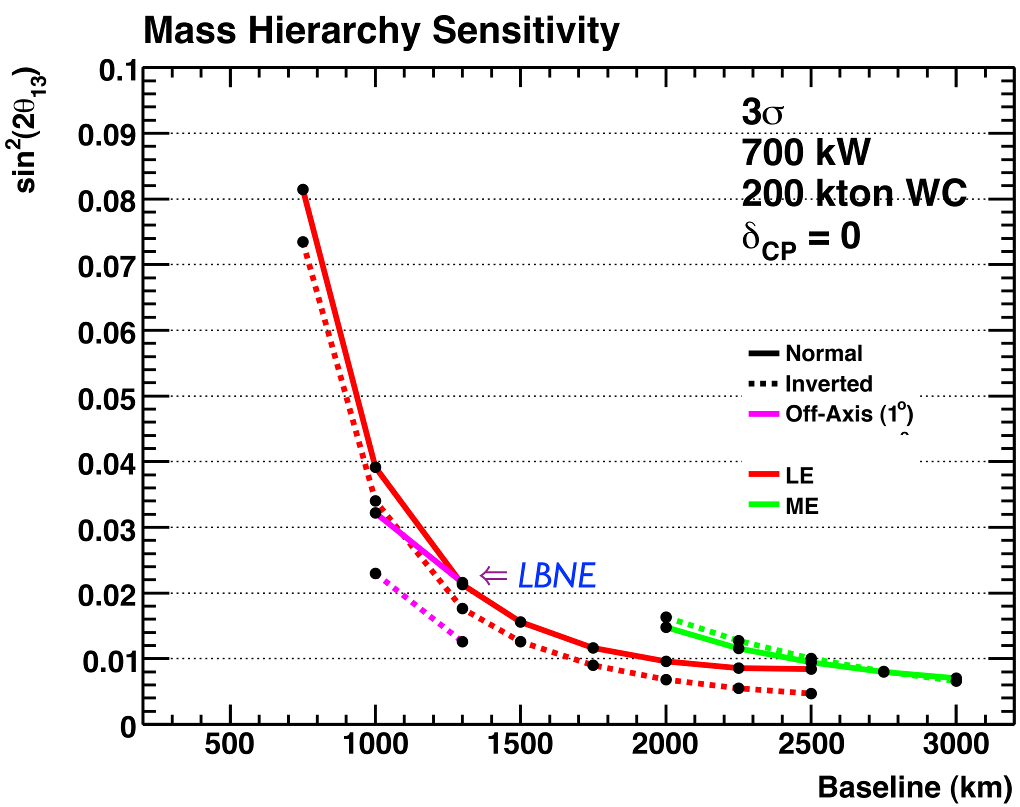
90% CL, combines T2K, NOνA, Daya Bay, Double Chooz and RENO At this CL MINOS and T2K have discovered $\theta_{13} \neq 0$!

At $3\,\sigma$ this plot would be essentially empty!

P. Huber – VT-CNP – p. 3

$\Rrightarrow$ Given the Δm^2_{13} and terrestrial medium ...

⇛ Larger Flight Distance implies better MH sensitivity



Larger Θ_{13} ? ...& Measurement of δ_{CP}

- Larger Θ_{13} ⇛ Larger number of events:

  e.g. for 3.5 MW, 200 kT WC:

  $\sin^2(2\Theta_{13}) = 0.10$ ⇒ 1300 $\nu_\mu \to \nu_e$ events

  $\sin^2(2\Theta_{13}) = 0.01$ ⇒ 150 $\nu_\mu \to \nu_e$ events

  Measure δ_{CP} using:

- $$A(E_\nu) = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

- Whereas $P(\nu_\mu \to \nu_e)$ & MH improve with bigger Θ_{13}, sensitivity to δ_{CP} largely unaffected. As Θ_{13} increases the Asymmetry becomes smaller

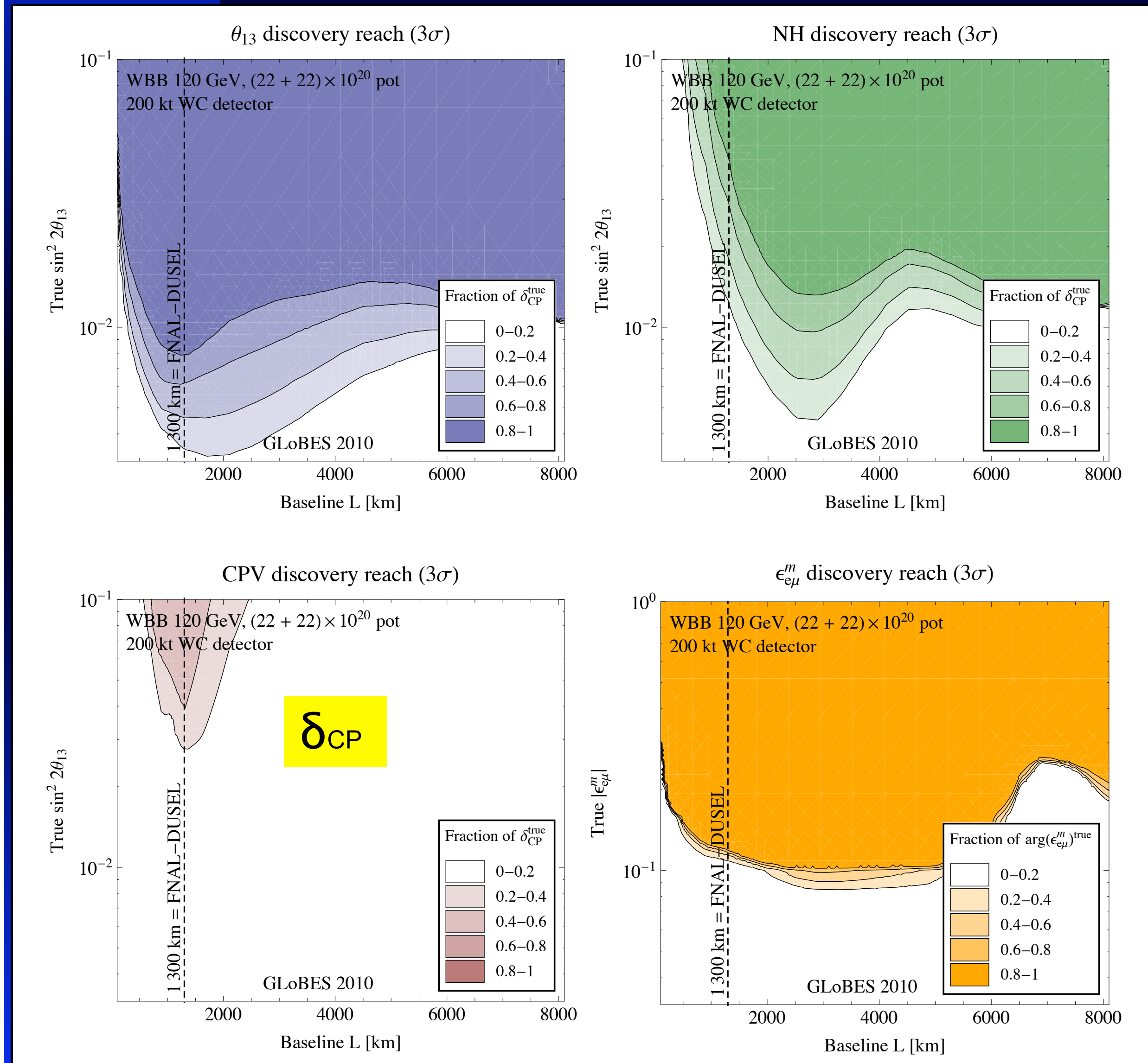
  ⇒ *Longer flight Distance*

  ⇒ *Asymmetry at the 2nd. Maximum*

  ⇒ *Better control of the Systematics*

Distance vs Sensitivity to δ_{CP}

Shorter Baseline?



1300 km is optimal for CP at all values of θ_{13}

The other measurements want a longer baseline

PH, J. Kopp, JHEP 1103:013,2011, arXiv:1010.3706.

P. Huber – VT-CNP – p. 6

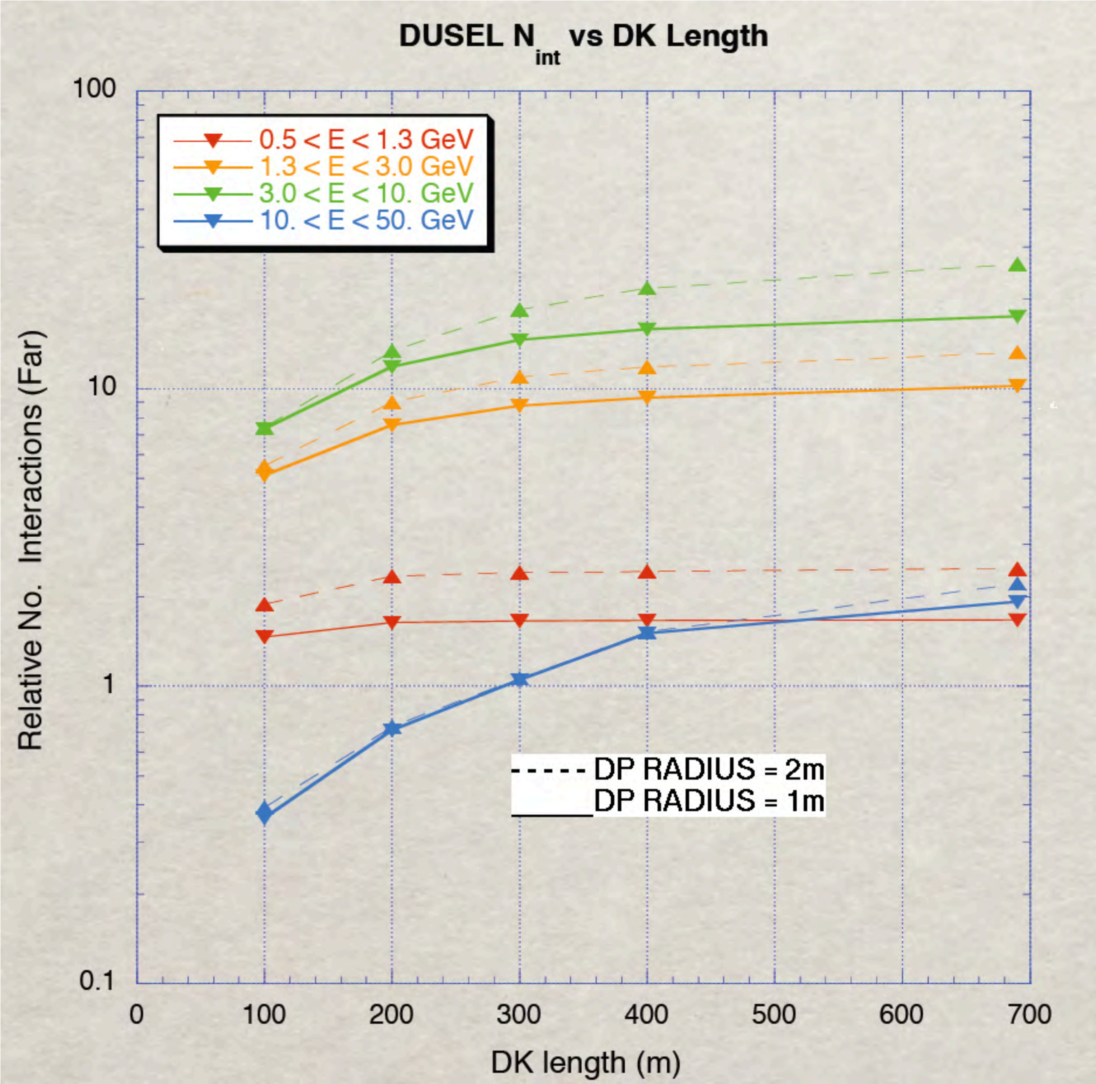
δ_{CP} vs Asymmetry at the 2nd. Oscl. Max ($E\nu \simeq 0.75$ GeV)

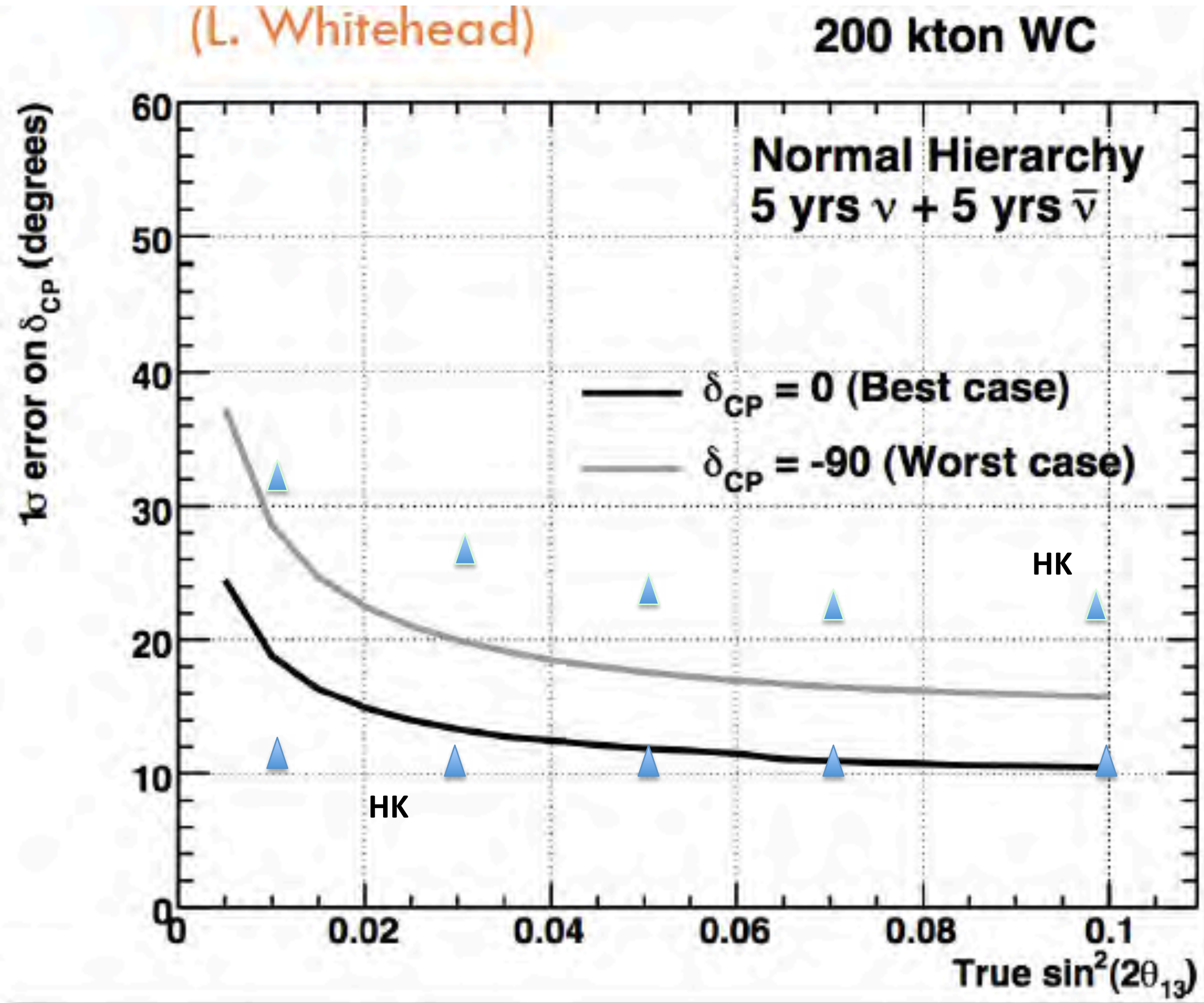
- For $\sin^2(2\Theta_{13}) \geq 0.02$, A(2nd.Max) is approx. 2*A(1st.Max)
  - $\Rightarrow$ Maximize the yield at $E\nu \simeq 0.75$ GeV

Note: Unless a new decay pipe is installed for NuMI, the flux will suffer from the small diameter beam pipe of the current setup.

This is true for both first and second oscillation

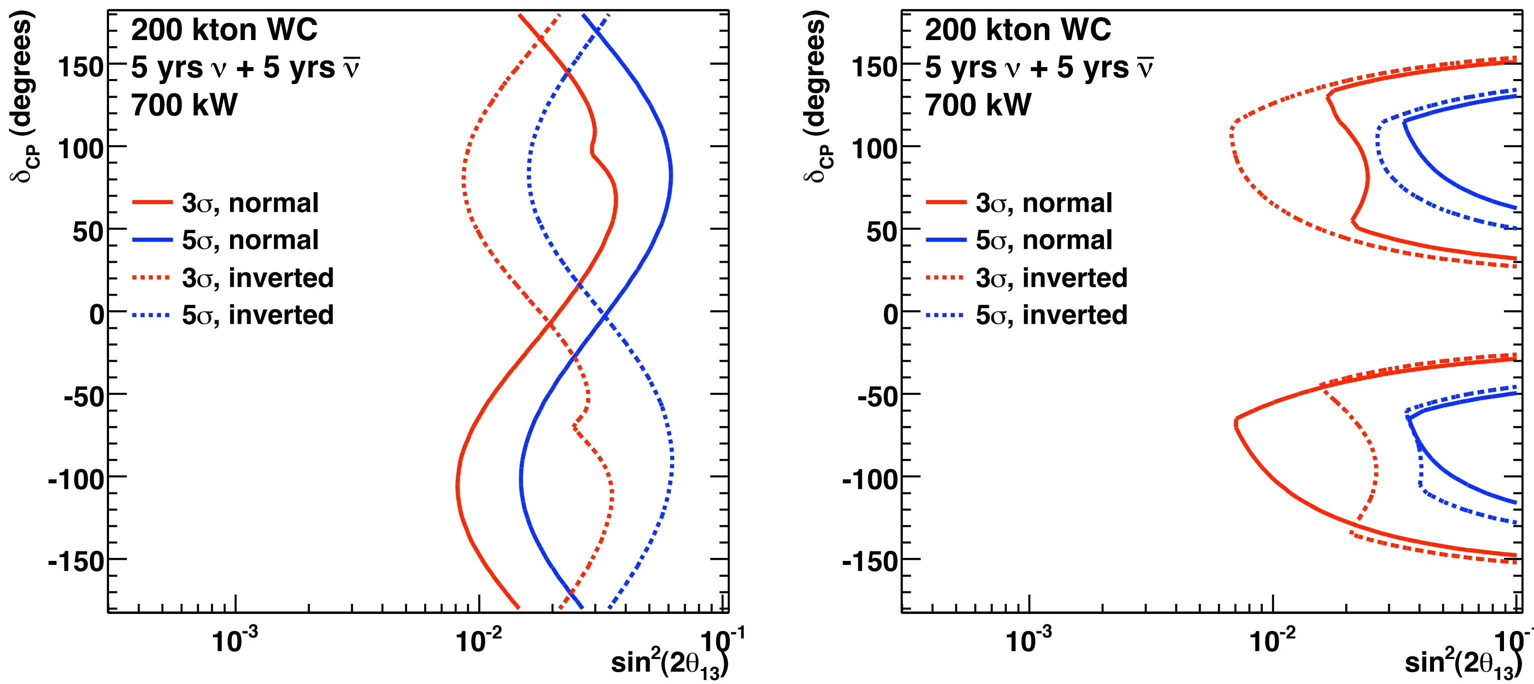
Need to keep this In mind.




(L. Whitehead)
200 kton WC
Normal Hierarchy
5 yrs ν + 5 yrs ν̄
δCP = 0 (Best case)
δCP = -90 (Worst case)
HK
HK
1σ error on δCP (degrees)
True sin²(2θ13)
0
10
20
30
40
50
60
0.02
0.04
0.06
0.08
0.1

200 kt WCD detector and 5 yrs of ν + 5 yrs of $\bar{\nu}$ running with 700kW:

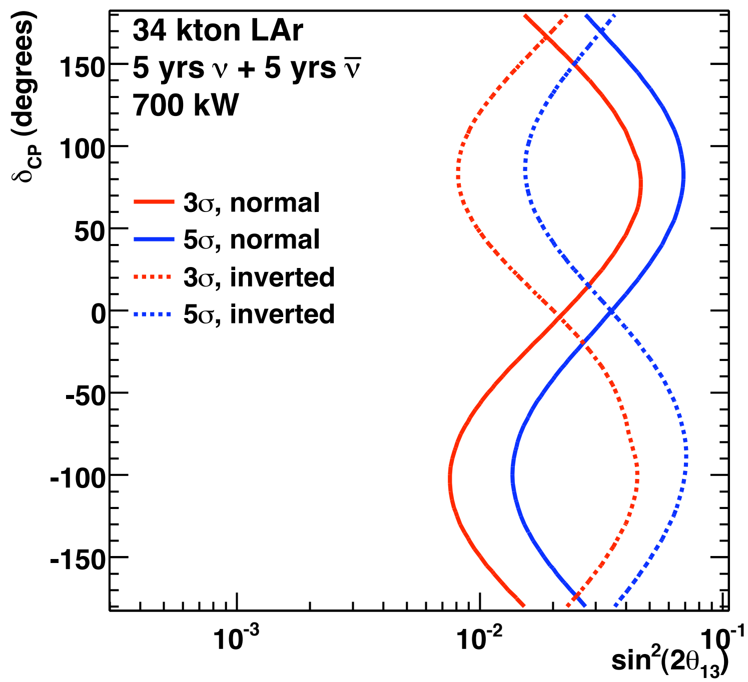
Mass Hierarchy **CP Violation**

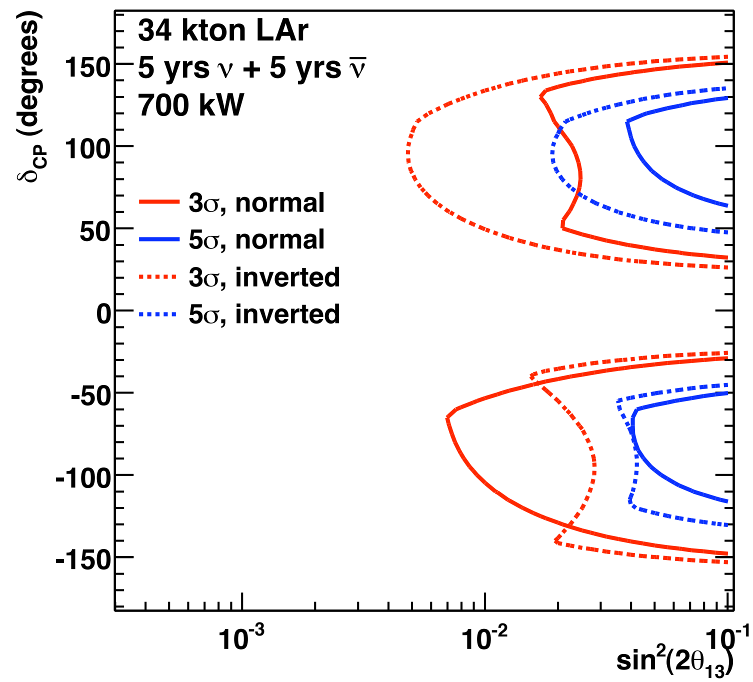


CPV and MH in LBNE 200 kT WC

34 kt LAr detector and 5 yrs of ν + 5 yrs of $\bar{\nu}$ running with 700kW:

Mass Hierarchy **CP Violation**

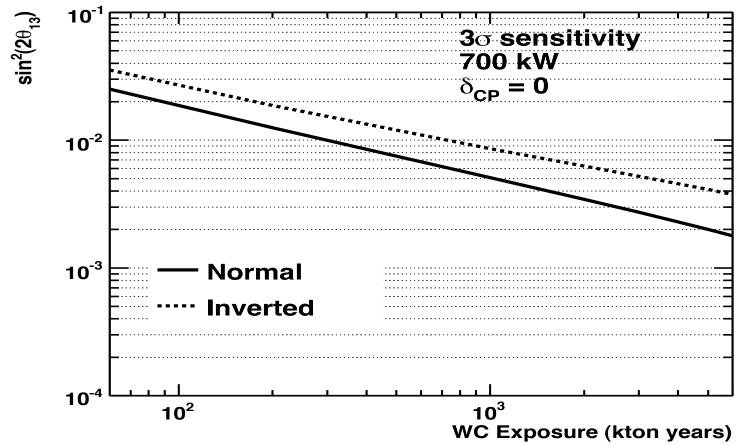




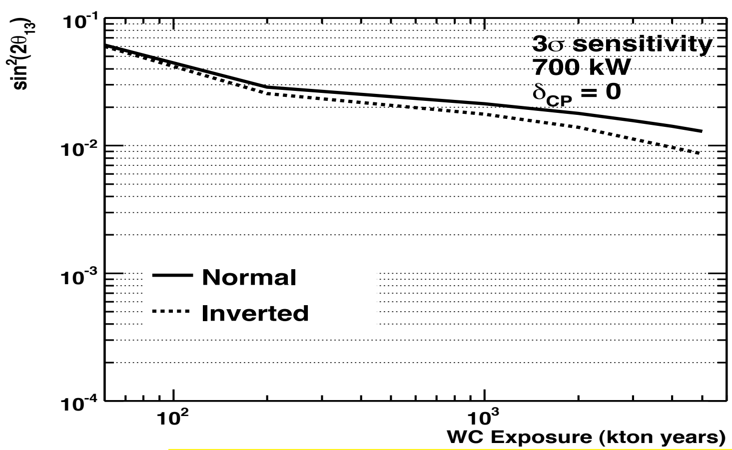
CPV and MH in LBNE 34 kT LAr

Sensitivity to the Trinity

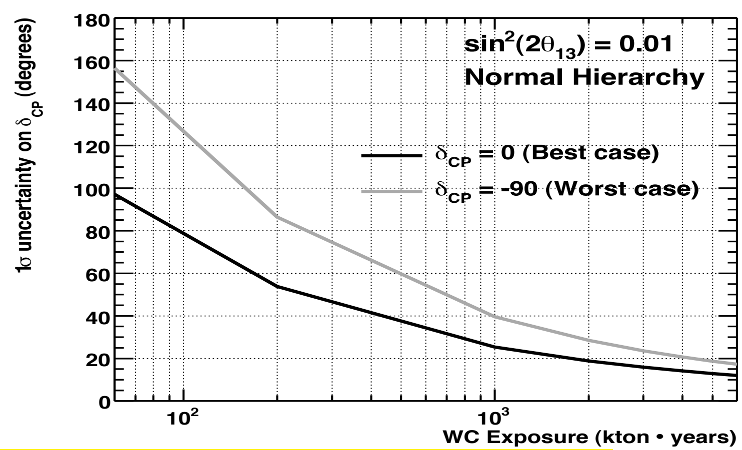
$\sin^2 2\theta_{13}$ Sensitivity at 3σ



MH Sensitivity at 3σ



Resolution of δ_{cp}



Sensitivity to MH and CPV at 3σ for $\sin^2 2\theta_{13} \geq 0.01$

Systematic Errors in ν Oscillation Experiments

Experiment	*L(km)/E(GeV)*	*ND?*	*Bkg* [Expt. Dependent]	*Error*	*$sin^2(2\theta)$*
BNL-E734	0.1/1.0	No	{418ν_e, 235NC}	From Data	3.4x10^-3
NOMAD {Very fine grain detector}	0.4/25	No	{6000-ν_e, 0-NC}	Small	1.3x10^-3
MiniBOONE	0.4/0.7	No	{249-ν_e, 137-NC}	9%	~3x10^-3
MINOS	735/3	Yes	{5-ν_e, 44-NC}	5.5%	~1x10^-1

$\Rightarrow$ Goal for LBNE is <5% systematic error
Try to achieve it in `Differential-bins' for NC and CC

Reinventing the Near Detector

✦ *Use of "identical" small detector at the near site is insufficient for future $\mathcal{LBL}$ experiments:*

- $\Phi^{\nu,\bar{\nu}}(E_\nu, \theta_\nu)$ *different at Near & Far sites;*
- *Impossible to have "identical" detectors, for $\mathcal{O}(100kt)$, at the projected luminosities;*
- *Different compositions of event samples ($\nu_\mu, \bar{\nu}_\mu, \nu_e$, NC, CC)*

$\Longrightarrow$ *Coarse resolution dictated by $\mathcal{O}(100kt)$ and different flux at Near-vs-Far tell us that the Identical Near Detector concept is insufficient*

✦ *Need a high resolution detector at the Near-Site to measure systematics affecting the Far-detector:*

- $\nu_\mu, \bar{\nu}$, $\boxed{\nu_e}$, $\boxed{\bar{\nu}_e}$ *content vs. E_ν and θ_ν;*
- *ν-induced $\pi^\pm/K^\pm/p/\pi^0$ in CC and NC interactions;*
- *Quantitative determination of E_ν absolute energy scale;*
- *Measurement of detailed event topologies in CC & NC.*

$\Longrightarrow$ *Provide an 'Event-Generator' measurement for $\mathcal{LBL}\nu$*

Measure over the full range of FD

Background to the ν(Bar)e/μ-Appearance

ν -vs0 ν(Bar) Interactions

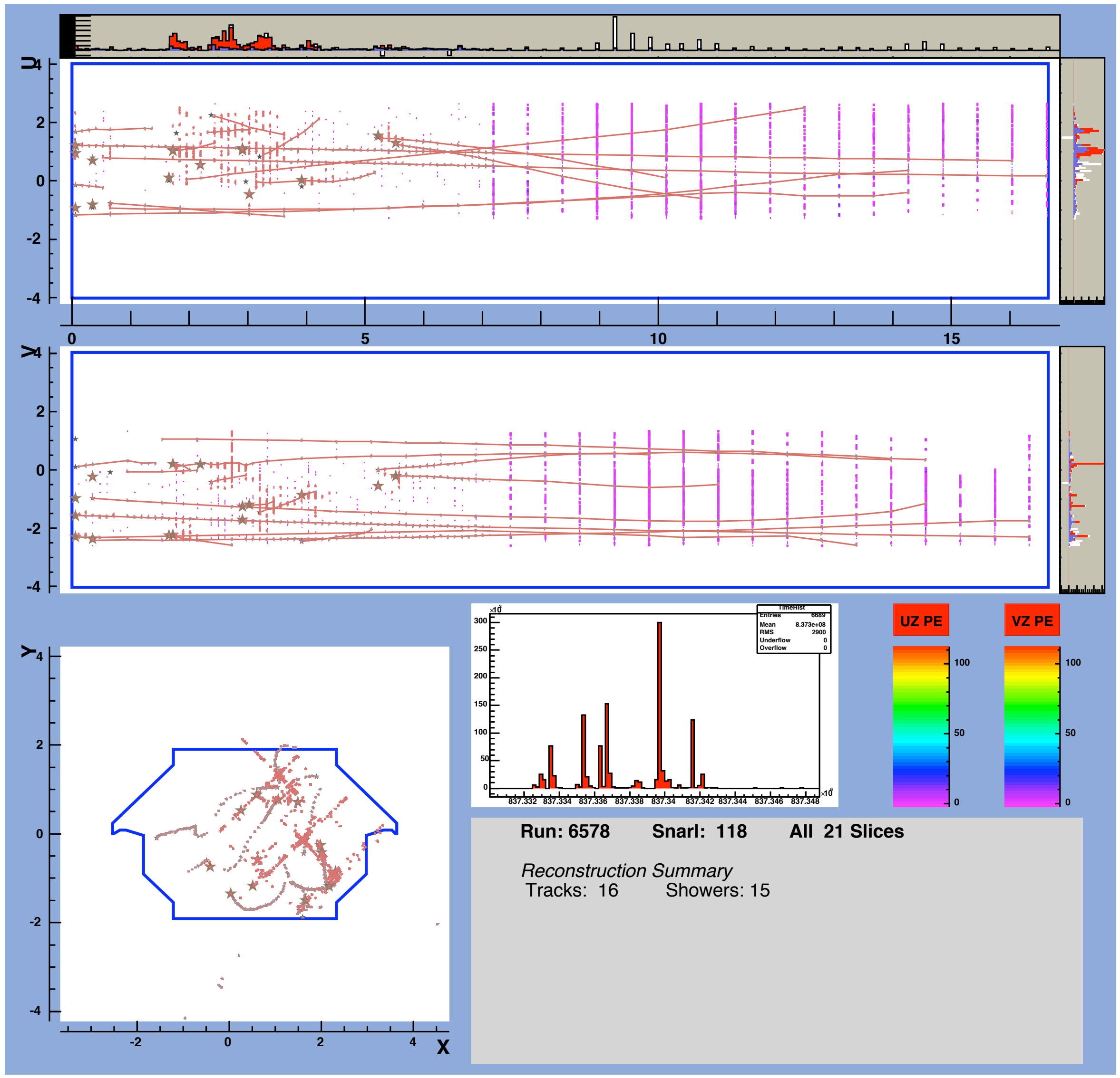
✦ *High Resolution near detectors at future $\mathcal{LBL}$ facilities are natural heirs to the precision neutrino scattering programme*

Can they achieve sufficient precision to complement the Colliders?

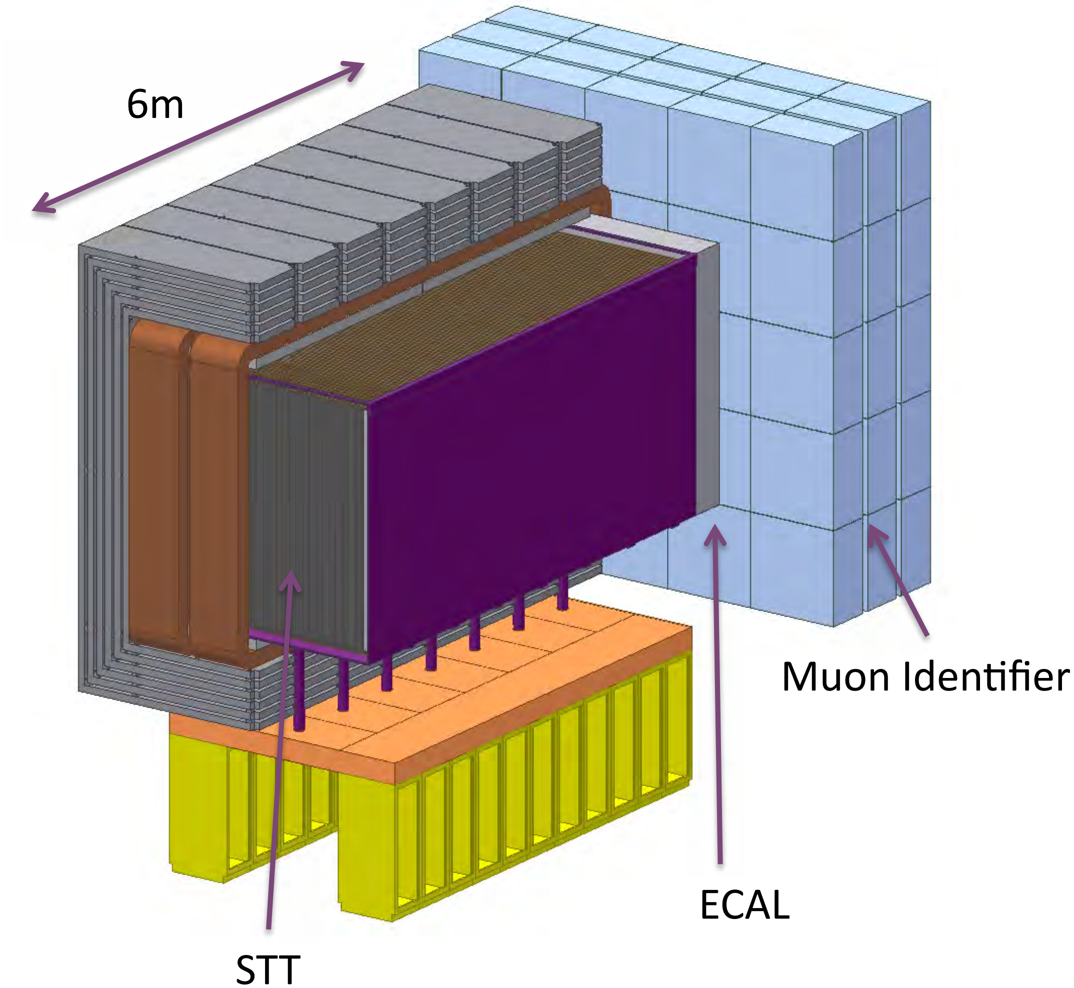
Events/Spill in MINOS-ND

≃2e13 PoT/Spill in MINOS(NuMI)

(Juxtapose against that expected from 3e14 PoT/Spill in ProjectX)



Straw Tube Tracker (STT)



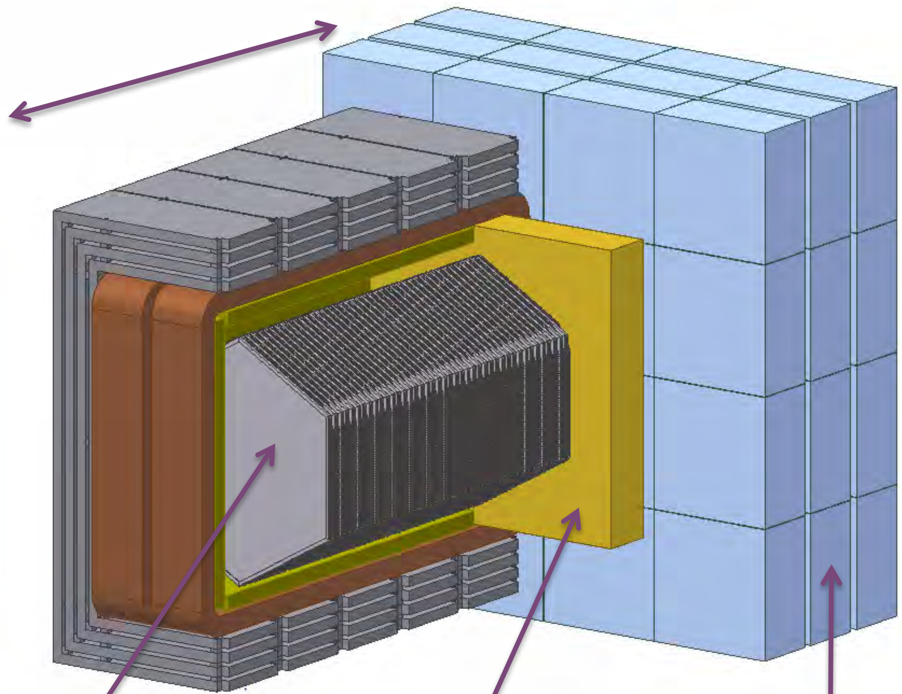
- Best performance of the 4-options
- 3.5m x 3.5m x 7m STT (7 tons; ρ≃0.1gm/cm^3)
  4π-ECAL
  Dipole-Field (0.4T)
  μ-Detector (RPC) in Dipole and Downstream

Transition Radiation ➽ e-/e+ ID ⇒ γ
dE/dx ➽ Proton, π+/-, K+/-
Magnet/Muon Detector ➽ μ+/-

- H2O & D2O Targets (≃x5 FD-Stat) ⇛ *WC-FD*
  {QE-Proton ID ⇛ Absolute Flux measurement}

- Pressurized Ar-target (≃x5 FD-Stat) ⇛ *LAr-FD*

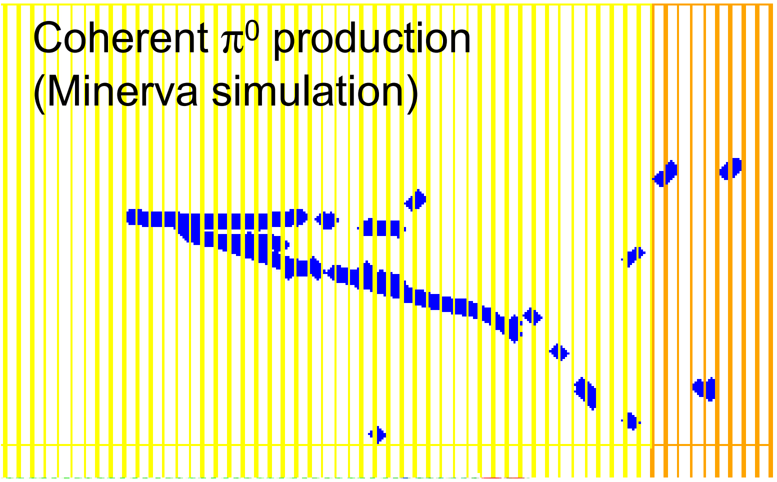
Scintillator Tracker (ST)



- 3m x 3m x 5m Sci-Tracker (7 tons; $\rho \simeq 1$gm/cm^3)
  4π-ECAL
  Dipole-Field (0.4T)
  μ-Detector (RPC) in Dipole and Downstream

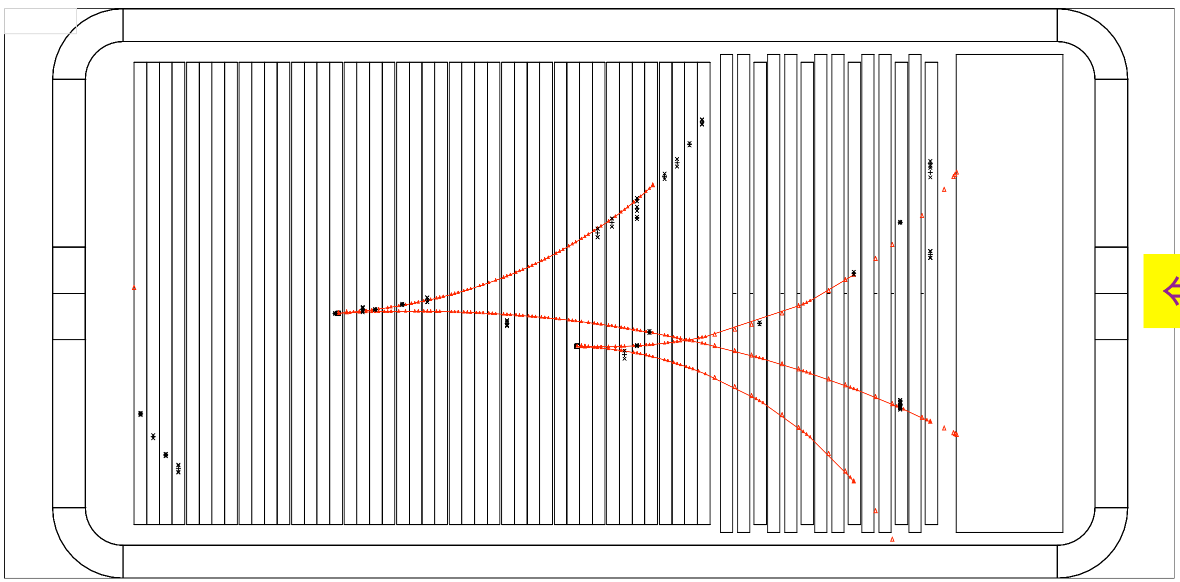
- H_2O Target ($\simeq$x5 FD-Stat) $\Rrightarrow$ *WC-FD*

Coh-π0



A Question of Resolution...

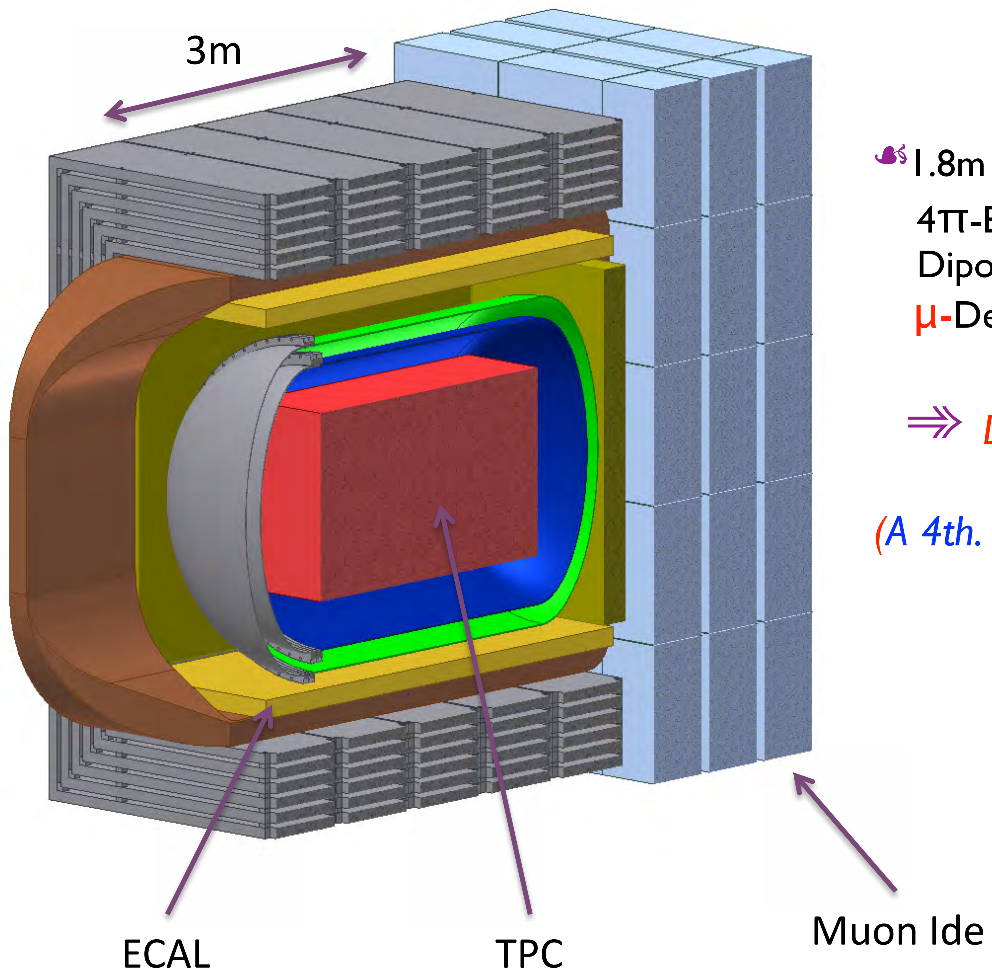
NOMAD DATA



⇐ x12 more hits in STT

(Hits shown by `x' are not used in the track-fit)

LAr TPC Tracker (TPCT)



- 1.8m x 1.8m x 3m LAr (13 tons)
  4π-ECAL
  Dipole-Field (0.4T)
  μ-Detector (RPC) in Dipole and Downstream

⇛ *LAr-FD*

(A 4th. option with larger LAr with membrane cryostat B-Field)

Why Tracker (ECAL/*μ-Detector)* within a B-Field?

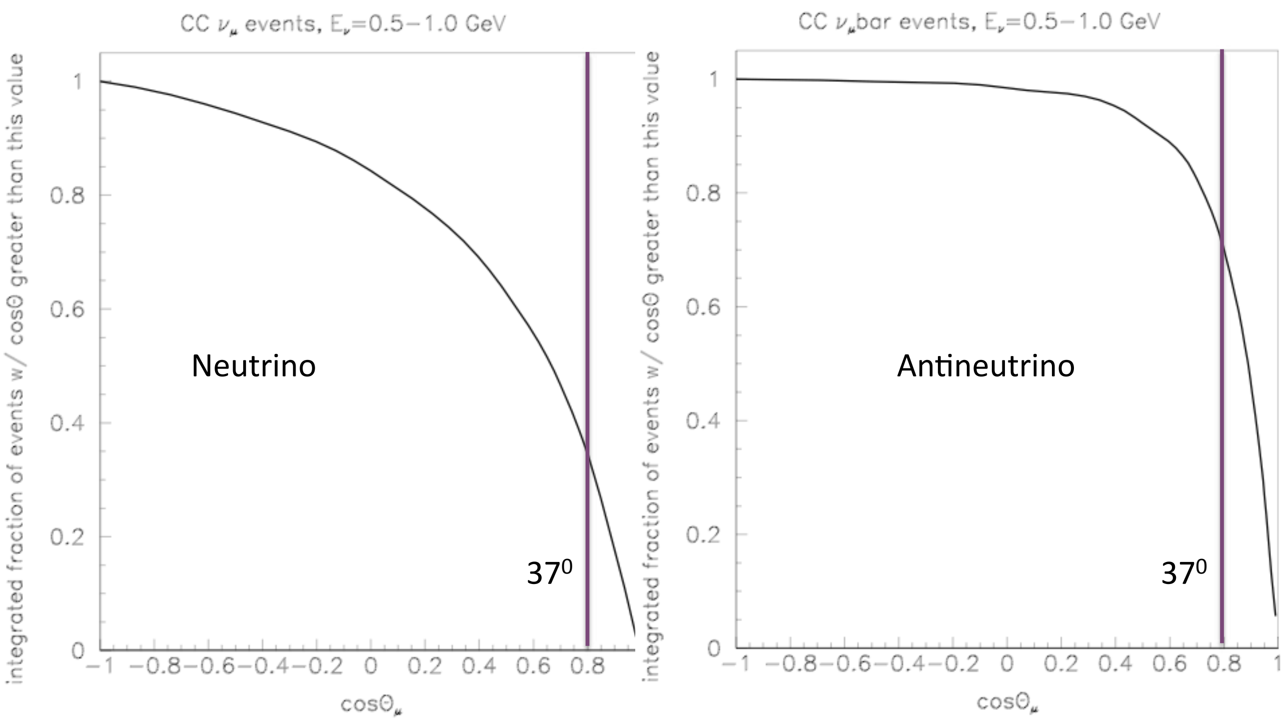
- Constrain E_ν-scale
- ND must measure the full range of E_ν & θ_ν else the sensitivity of FD will be compromized
- In $0.5 \le E_\nu \le 1$ GeV, the Acceptance ≃ 35% for $\theta_\mu \le 37^0$

  In $2.0 \le E_\nu \le 3$ GeV, the Acceptance ≃ 75% for $\theta_\mu \le 37^0$
- For LBNE, the Maximal sensitivity for δ_{CP} is $E_\nu \simeq 1.5$ GeV

  Measure differences in ν & Anti-ν *interactions which might fake a "* δ_{CP} *"*
- STT will be able to distinguish *μ-/μ+* down 0 ~0.3 GeV

⇛ *ND must measure and ID leptons (at least μ) emerging at large angles;*

0.5-1 GeV



Why track protons?

- Precision determination of ν_μ-QE requires proton-tracking.

⇒ QE in H_2O & D_2O will provide an Absolute-Flux measurement:

Need proton-tracking & resolution to point to the H_2O & D_2O vertex

⇒ (μ^-, p) provide an *in situ* constraint on the Fermi-motion and hence on the E_ν-scale

⇒ QE interactions dominant in Low-E_ν: Need accurate parametrization of QE *[see σ(QE) Fig.]*

- STT option will have a large proton sample from $\Lambda \to p\pi$

- If an ND is able to accurately measure proton, it will be able to measure the π^- & π^+ in NC and CC:

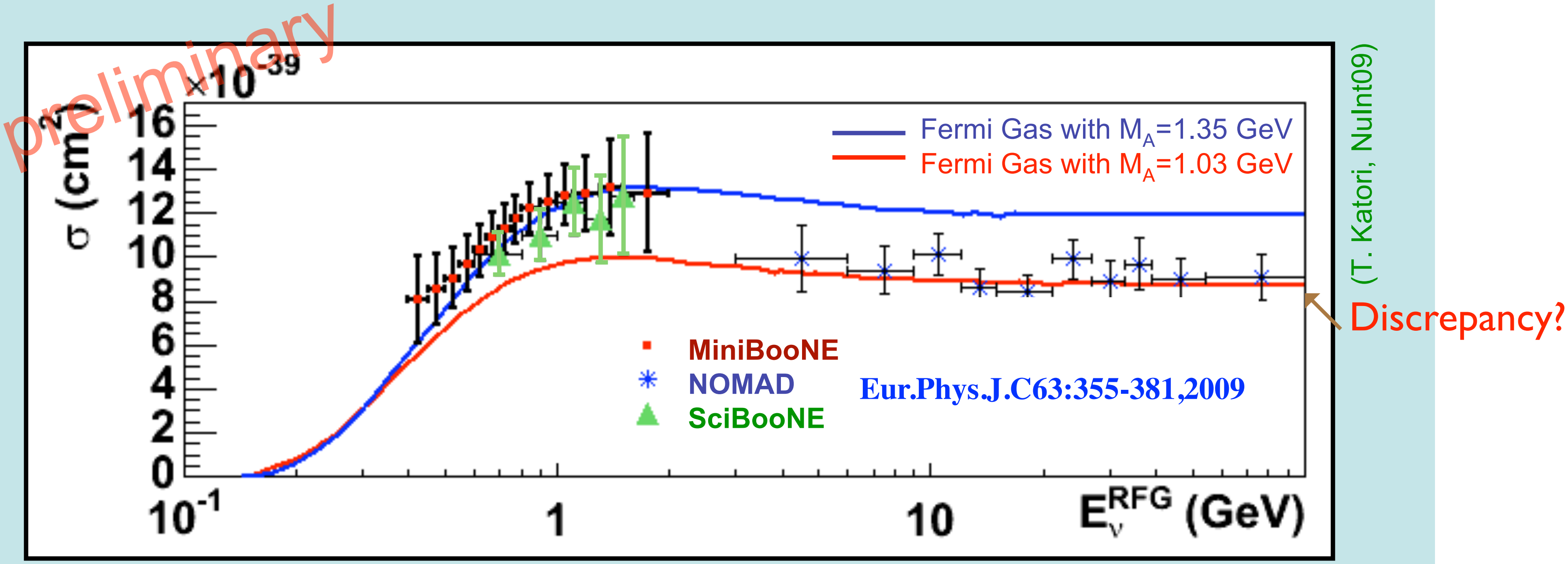
the largest source of background to the ν_μ & Anti-ν_μ disappearance

⇒ *ND must track & ID QE-protons*

QE

Quasi-Elastic Scattering

- new, modern measurements of QE σ at these energies (on ^{12}C)



~ 30% difference between QE σ measured at low & high E on ^{12}C ?!

?

ν_μ-QE Sensitivity Calculation

- Example of a ν-interaction in a high-resolution ND as a calibration of FD

- Key is 2-Track (μ, p) signature *Proton reconstruction: the critical issue* (*dE/dx in but not used in the analysis*)

- Use Nomad data/MC as calibration

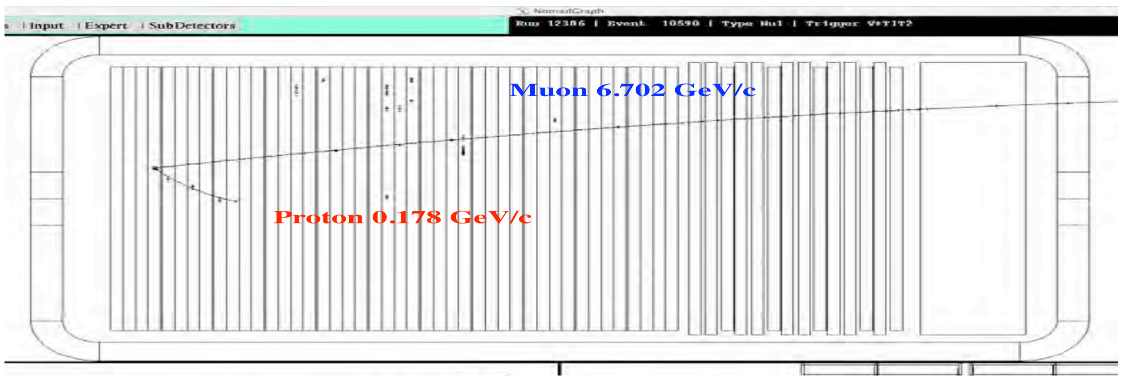


Figure 14: A ν_μ-QE candidate in NOMAD

QE Candidates in NOMAD: STT will have x6 more points for protons

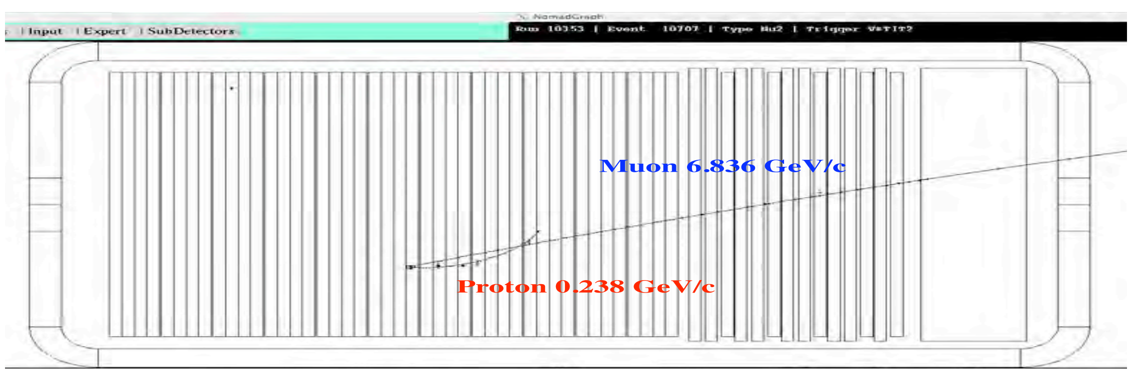
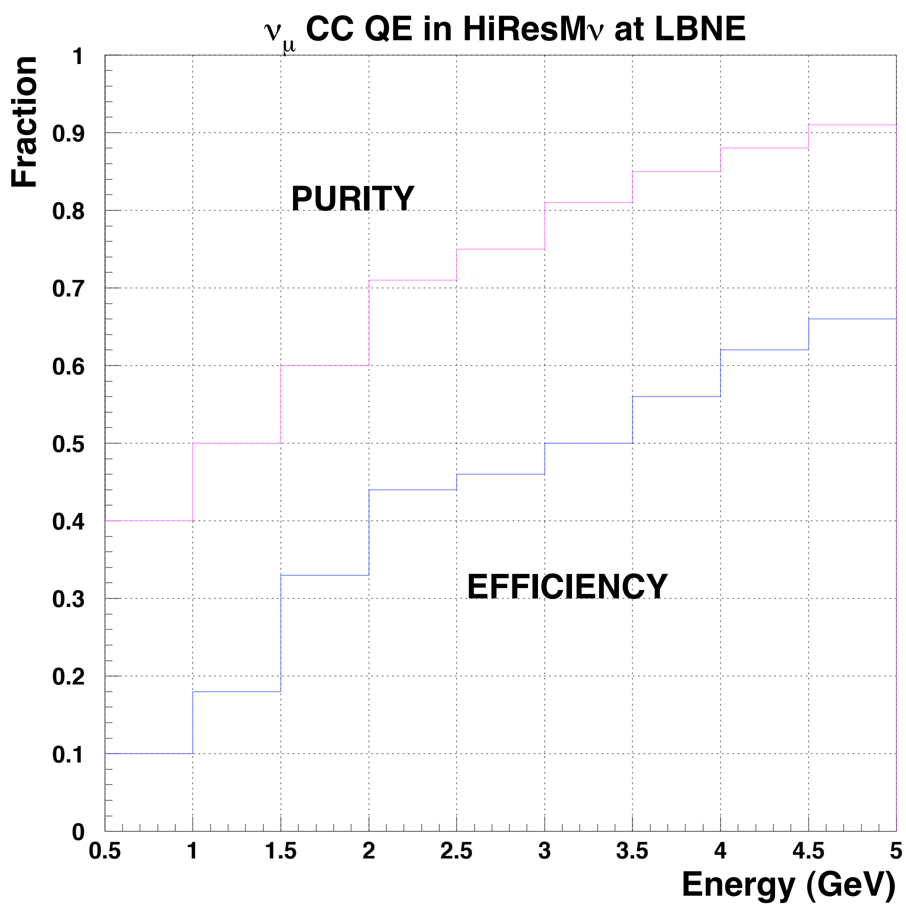


Figure 15: A ν_μ-QE candidate in NOMAD

RECONSTRUCTION OF CC QUASI-ELASTIC INTERACTIONS



- *Protons easily identified by the large dE/dx in STT & range*

  $\Longrightarrow$ *Minimal range to reconstruct p track parameters 12cm* $\Rightarrow 250\ MeV$

- *Analize BOTH 2-track and 1-track events to constrain FSI, Fermi motion and nuclear effects*

- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject DIS & Res backgrounds*

  $\Longrightarrow$ *On average* $\varepsilon = 52\%$ *and* $\eta = 82\%$ *for CC QE at LBNE*

Why measure and ID *e-* & *e+*?

- Measurement of π^0 in NC and CC via $\gamma \Rightarrow e^- e^+$ measured in the tracker

{π^0 is the largest background to (anti)ν_e-appearance}

- Measure beam ν_e and Anti-ν_e

⇒ Difference between (ν_e from μ) & (anti-ν_e from K0L) extrapolations to FD from ND

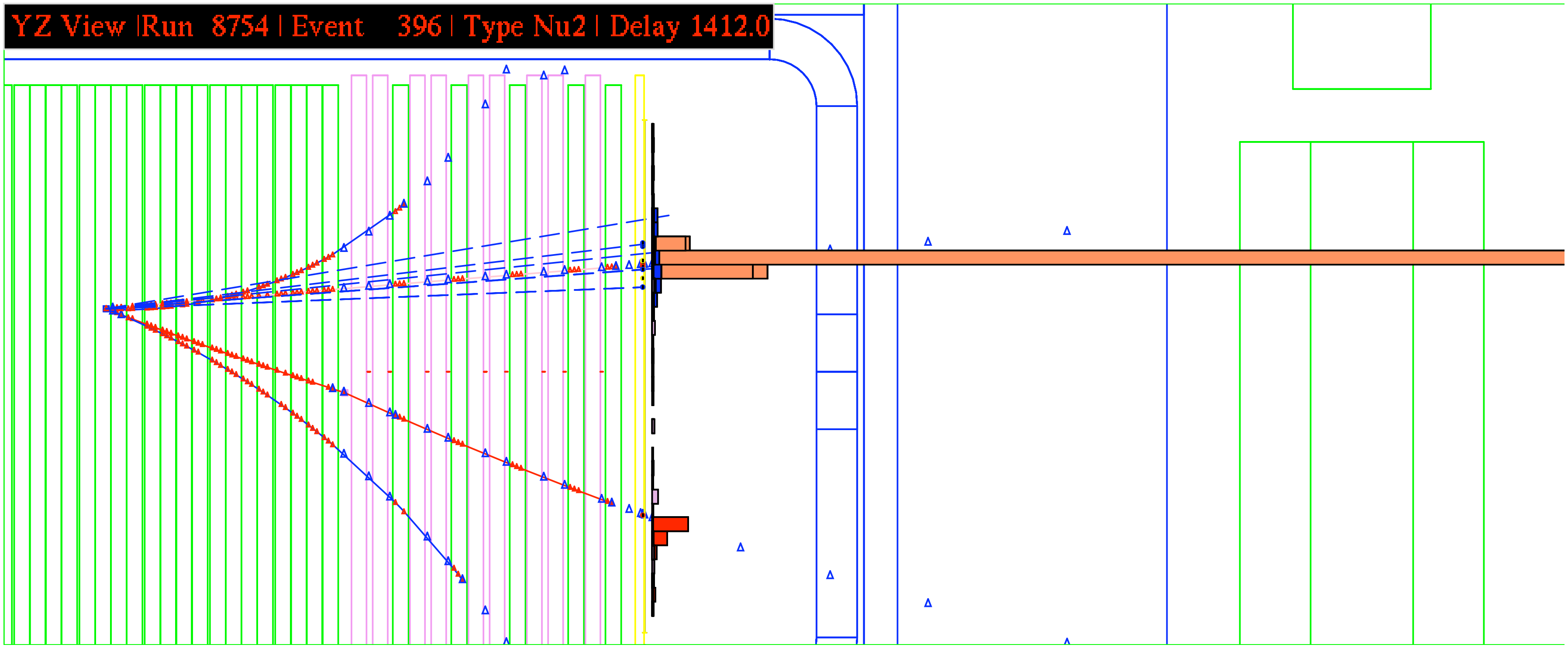
⇒ A must if there are large-Δm^2 oscillations

- Measurement of absolute flux

- To discover δ_{CP} we ought to ensure that ν_e & anti-ν_e events are as expected

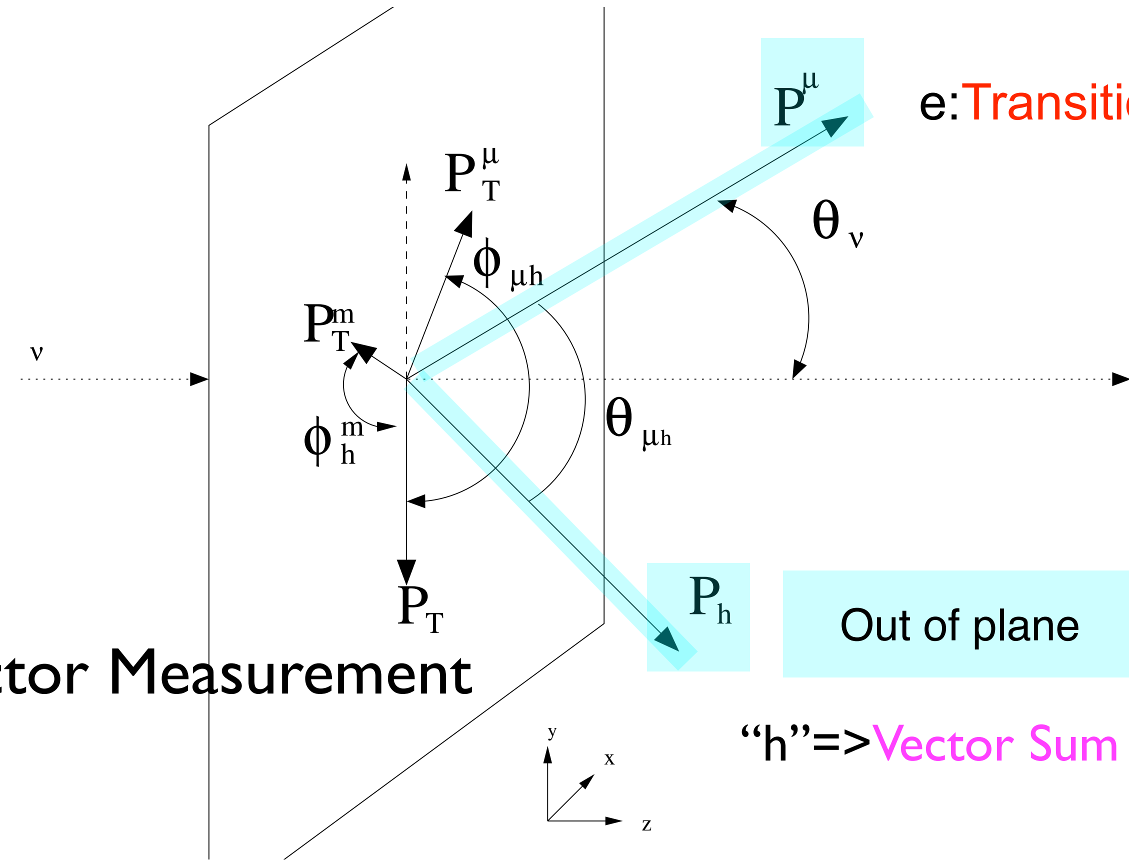
⇛ *ND must measure π^0 and ν_e & anti-ν_e* ➧ *e- -vs- e+*

A $\bar{\nu}_e$ CC candidate in NOMAD



- x12 higher sampling in STT (HiResMnu)
- x4π calorimetric and μ converage

Kinematics in STT



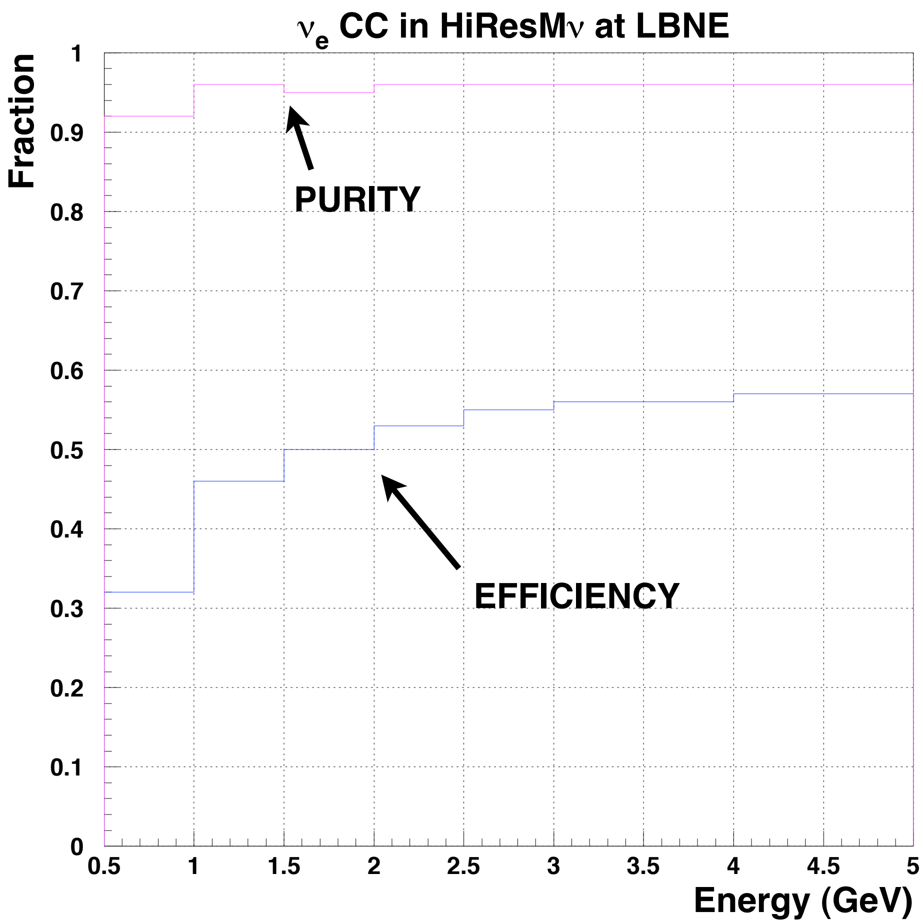
e:Transition Radiation

Out of plane

⇛ Pt-Vector Measurement

“h”=>Vector Sum of Tracks

IDENTIFICATION OF ν_e CC INTERACTIONS



- *The HiResMν detector can distinguish electrons from positrons in STT*

  $\Longrightarrow$ *Reconstruction of the e's as bending tracks NOT showers*

- *Electron identification against charged hadrons from both TR and dE/dx*

  $\Longrightarrow$ *TR π rejection of 10^{-3} for $\varepsilon \sim 90\%$*

- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject non-prompt backgrounds (π^0 in ν_μ CC and NC)*

  $\Longrightarrow$ *On average $\varepsilon =$ 55% and $\eta =$ 99% for ν_e CC at LBNE*

VeBar-CC *Sensitivity:*

If we keep the signal efficiency at ~55%, then purity is about 95%

Absolute Flux using ν-e Elastic NC Scattering

- Using the Weak Mixing Angle (0.238) at Q~0.1 GeV (known to ≤1% precision)

⇒ $\sigma(\nu_x e\text{-NC})$ known ⇒ Absolute-$\phi(\nu_x)$

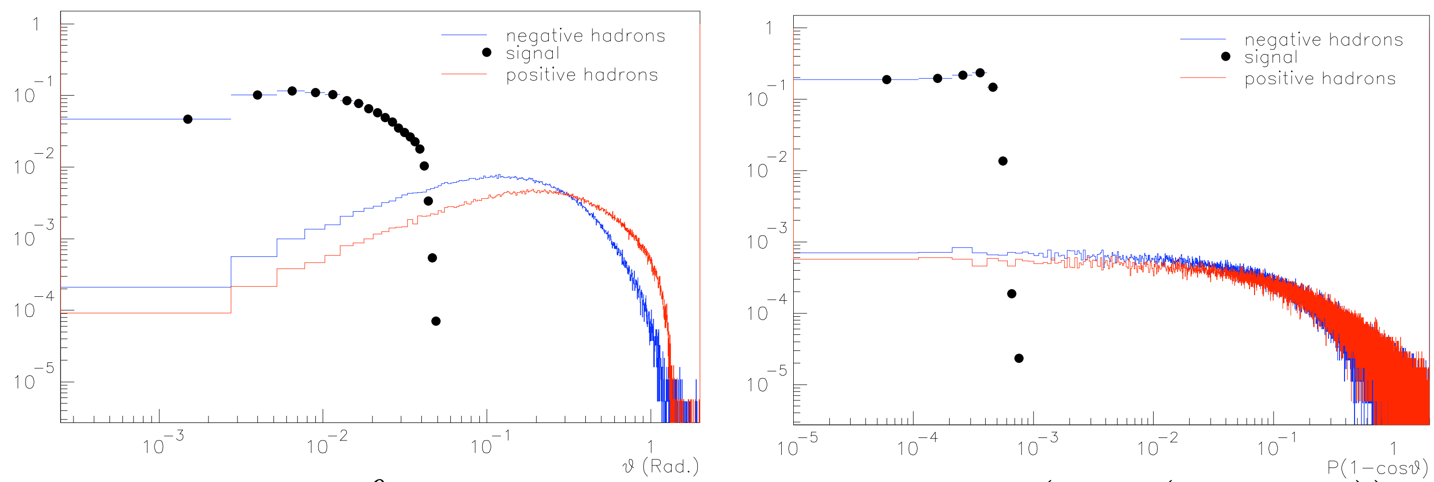
- ν-e ➽ Signal: Single, forward e-

Background: NC induced π_0 ➽ γ ➽ e- (e+ invisible): charge-symmetric

- Two-step Analysis: ✹Electron-ID: TR ✹Kinematic cut: ζ=Pe(1-cosΘe)

Simulation of charged hadron background.

(use LBNE Flux)



θ $\qquad$ $\zeta\ (\equiv P_e(1-\cos\theta))$

Background charge symmetric & benign

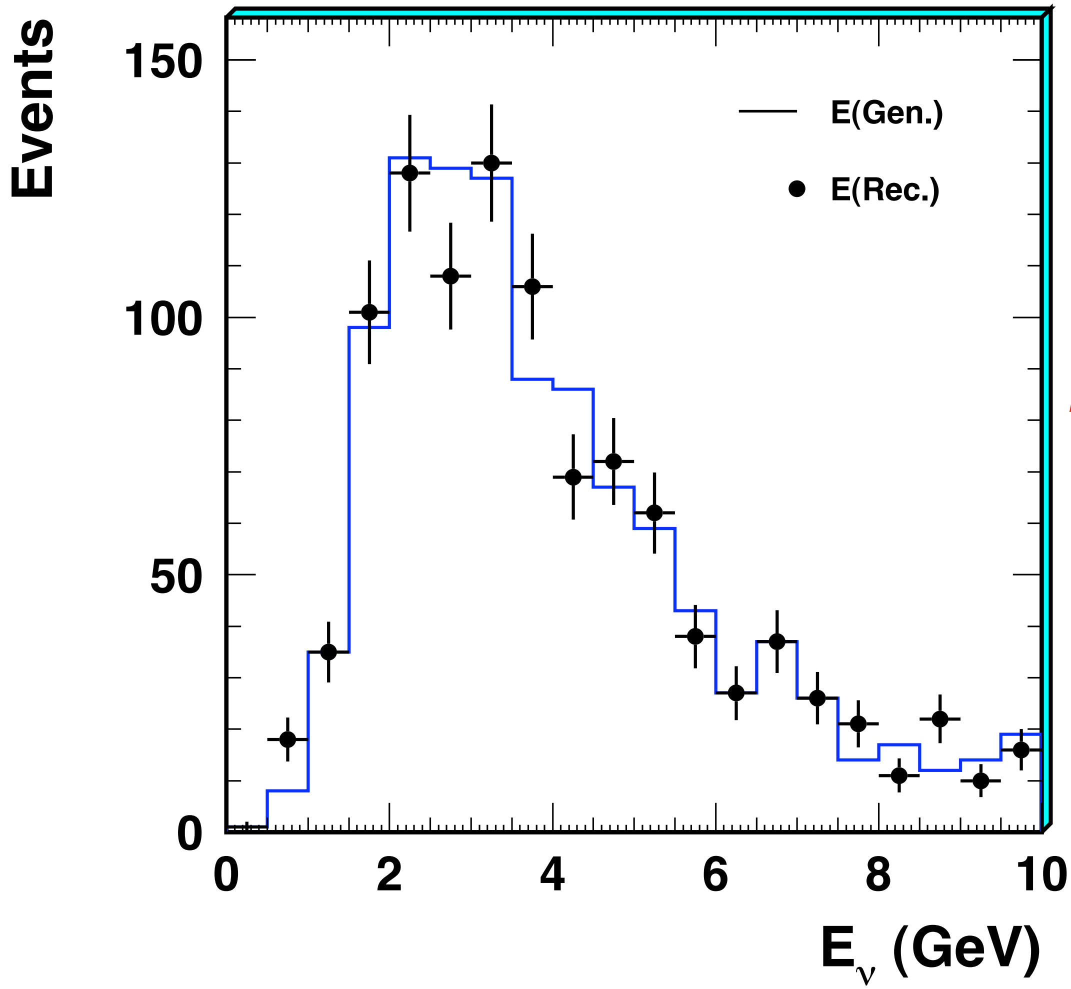
Eff➢64%
Bkg➢ ≤10**(-6) ⇐ Measured

⇐ Conclusion

Absolute Flux using ν-e Elastic Scattering

ॐ Shape of Enu using (Ee, θe):

ॐ The precision on relative ν-flux (shape) is worse than in that determined using Low-ν0 technique



1<Enu<4 => 1000 events

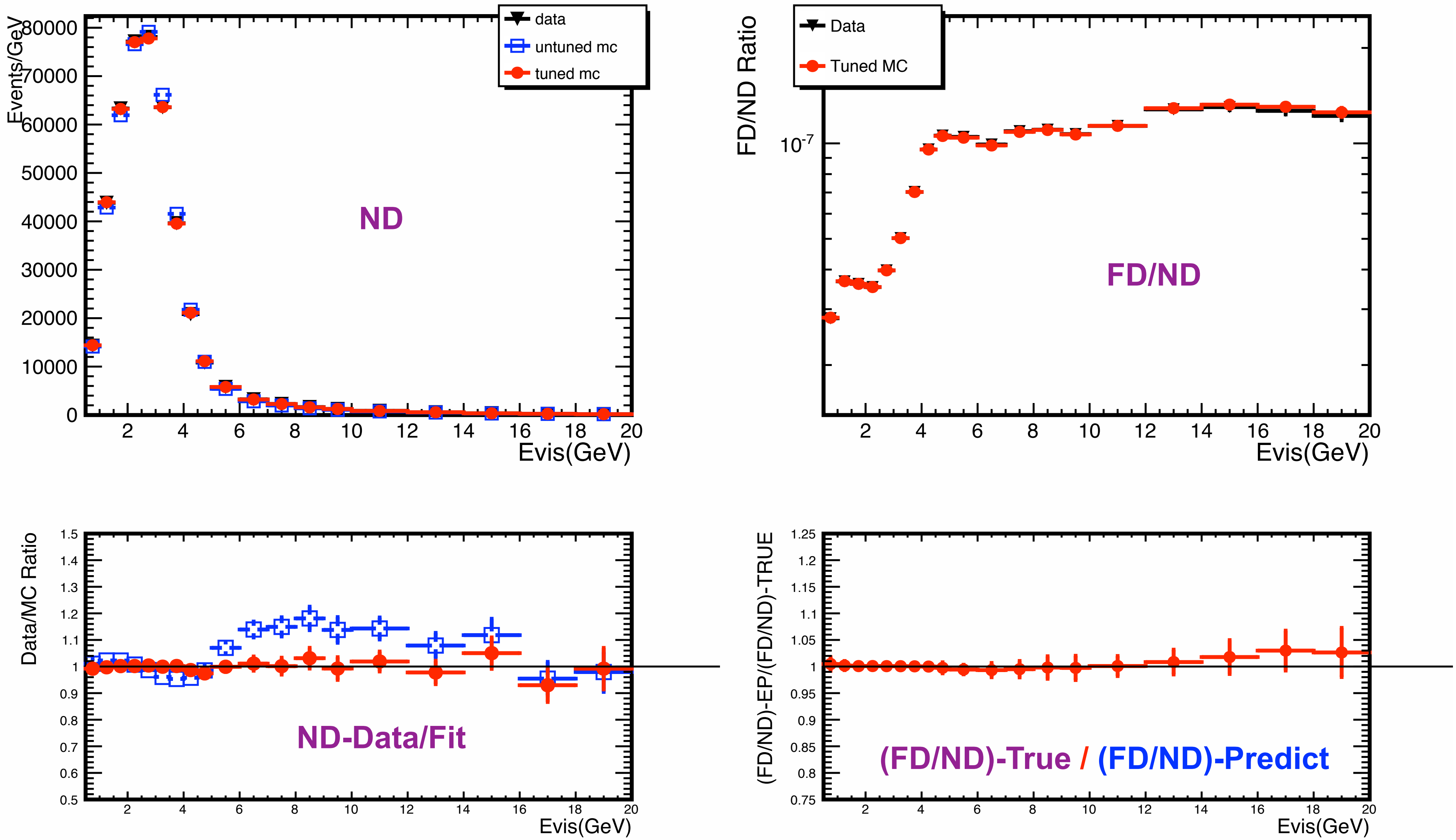
700kW; 3Yr Nu-Run

⇛ *ND will provide ~3% precision on Absolute-ν_μ*

Shape of ν_μ or Anti-ν_μ Flux using Low-ν_0 Method

ν_μ, Low-Nu0 Fit, ND at 500m

Relative ν_μ-Flux Measurement using Low-ν_0 @ LBNE



Conclusion ⇛
Predict FD/ND flux-ratio with high precision

π0-Reconstruction

ༀ Clean π0- and γ-signatures in HiResMnu(STT)

ༀ ν-NC & CC ➺ π0 ➺ γγ

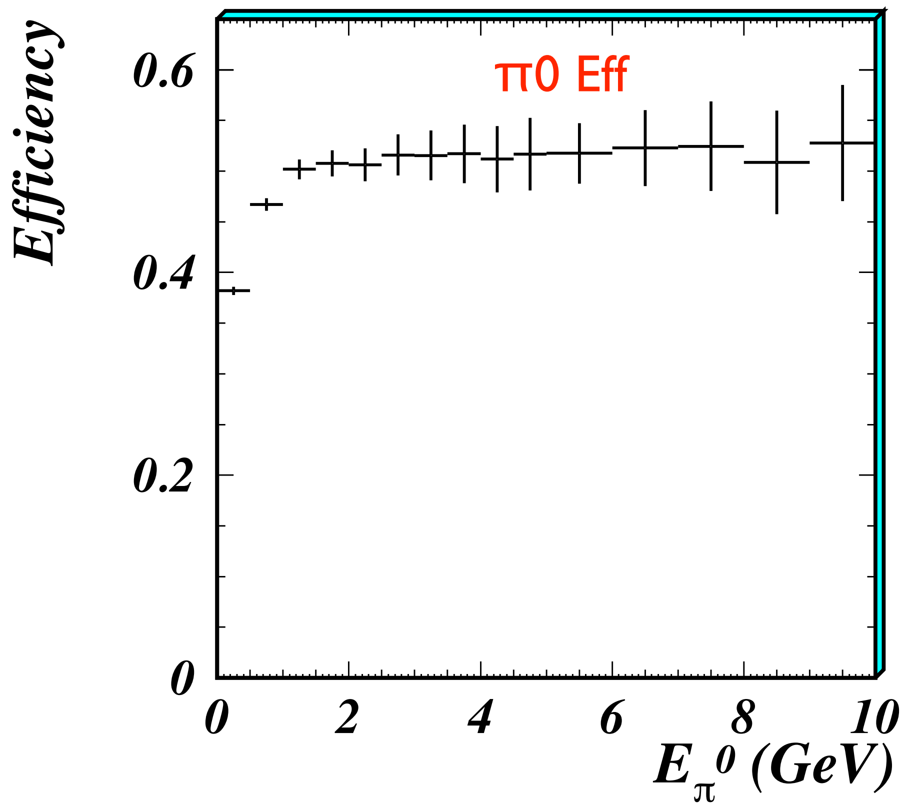
~50% of the γ ➺ e+e- will convert in the STT, away from the primary vertex. We focus on these

ༀ γ-Identification:

- e-/e+ ID: TR
- Kinematic cut: Mass, Opening angle

➢ At least one converted γ in STT
(Reconstructed e- & e+;
e- or e+ traverse ≥6 Mods)

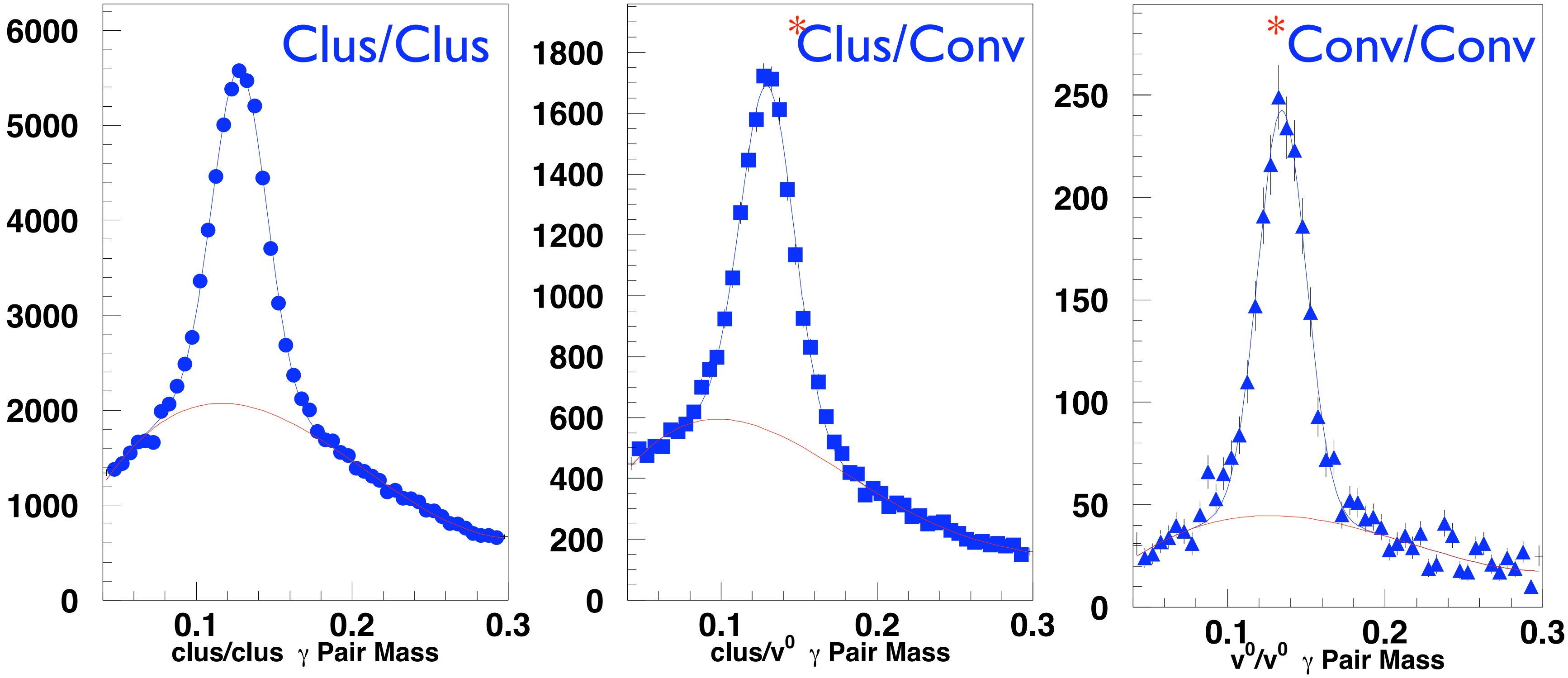
➢ Another γ in the Downstream & Side ECAL



Conclusion ⇛

π0's Very well constrained in CC and NC

Reconstructed π^0 in NC interactions in NOMAD



Overall more than 33k reconstructed events. Three topologies:

- *Cluster/Cluster 24k events*
- *Cluster/Conversion 7k events*
- *Conversion/Conversion 2k events*

[STT: expect similar resolution but much lower combinatorics]

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MEASUREMENT OF THE RATIO $\mathcal{R}_{e\mu}$ ⇐*Search/Impact of Large-Δm**2 Oscillation*

- *Independent analysis of neutrino data and anti-neutrino data due to possible differences following MiniBooNE/LSND results*

  $\Longrightarrow$ *Need a near detector which can identify e^+ from e^-*

- *Measure the ratio between the observed $\nu_e(\bar{\nu}_e)$ CC events and the observed $\nu_\mu(\bar{\nu}_\mu)$ CC events as a function of L/E_ν:*

$$\mathcal{R}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \nu_e N \to e^- X}{\#\ of\ \nu_\mu N \to \mu^- X}(L/(E\nu))$$

$$\bar{\mathcal{R}}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \bar{\nu}_e N \to e^+ X}{\#\ of\ \bar{\nu}_\mu N \to \mu^+ X}(L/(E\nu))$$

- *Compare the measured ratios $\mathcal{R}_{e\mu}(L/$ Eν *and* $\bar{\mathcal{R}}_{e\mu}(L/$ Eν *with the predictions from the low-ν_0 flux determination assuming no oscillations* ⇐ Benefit from External K+/π+, K-/π-, K0L/K+

- *Same analysis technique used in NOMAD to search for $\nu_\mu \to \nu_e$ oscillations.*

ainment of the events so reducing the usable statistics.

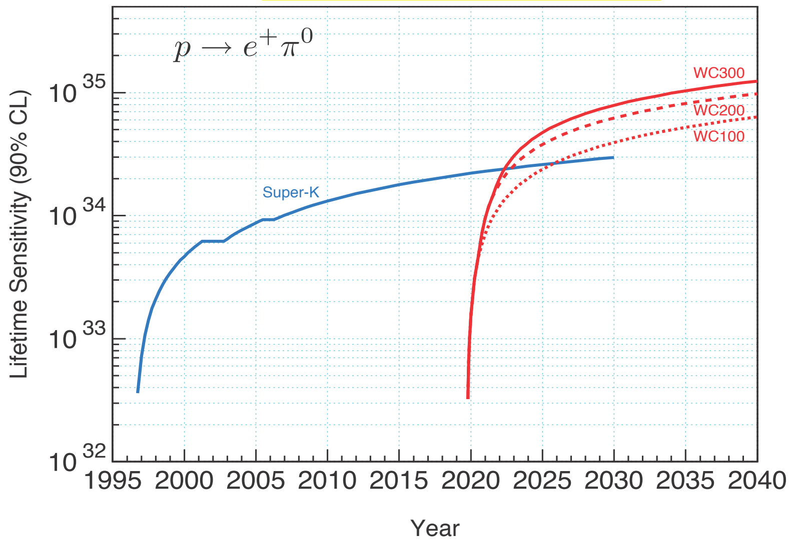
Measurement	STT	Sci+μDet	LAr	LArB	LArB+Sci+μDet	LAr+STT
In Situ Flux Measurements for LBL:						
$\nu e^- \to \nu e^-$	Yes	No	Yes	No	No	Yes
$\nu_\mu e^- \to \mu^- \nu_e$	Yes	Yes	No	Yes	Yes	Yes
$\nu_\mu n \to \mu^- p$ at $Q^2 = 0$	Yes	Yes	No	No	Yes	Yes
Low-ν_0 method	Yes	Yes	No	Yes	Yes	Yes
ν_e and $\bar{\nu}_e$ CC	Yes	No	No	Yes	Yes	Yes
Background Measurements for LBL:						
NC cross sections	Yes	Yes	No	Yes	Yes	Yes
π^0/γ in NC and CC	Yes	Yes	Yes	Yes	Yes	Yes
μ decays of $\pi^\pm, K^\pm$	Yes	No	No	Yes	Yes	Yes
(Semi)-Exclusive processes	Yes	Yes	Yes	Yes	Yes	Yes
Precision Measurements of Neutrino Interactions:						
$\sin^2\theta_W$ ν N DIS	Yes	No	No	No	No	Yes
$\sin^2\theta_W$ νe	Yes	No	Yes	No	No	Yes
Δs	Yes	Yes	Yes	Yes	Yes	Yes
νMSM neutral leptons	Yes	Yes	Yes	Yes	Yes	Yes
High Δm^2 oscillations	Yes	No	No	Yes	Yes	Yes
Adler sum rule	Yes	No	No	No	No	Yes
$D/(p+n)$	Yes	No	No	No	No	Yes
Nucleon structure	Yes	Yes	Yes	Yes	Yes	Yes
Nuclear effects	Yes	Yes	Yes	Yes	Yes	Yes

TABLE XXVIII: Summary of measurements that can be performed by different ND reference configurations.

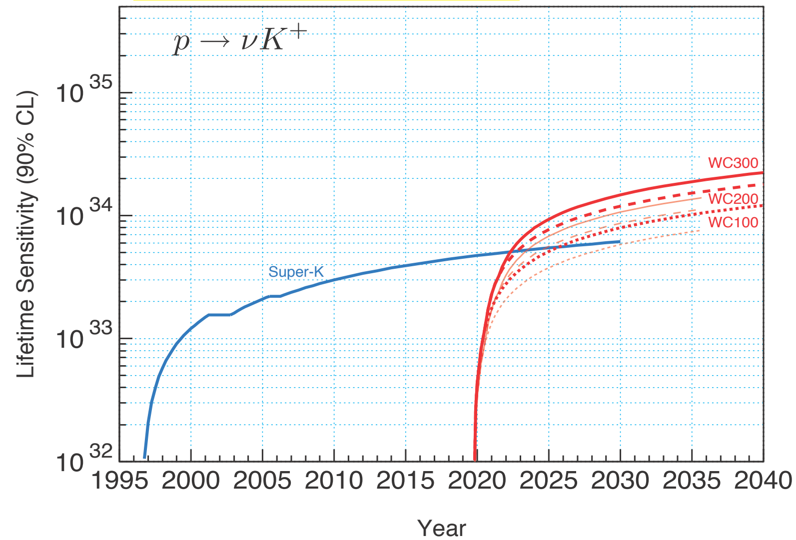
Summary page from the Short-Baseline Physics Report:

Proton Decay

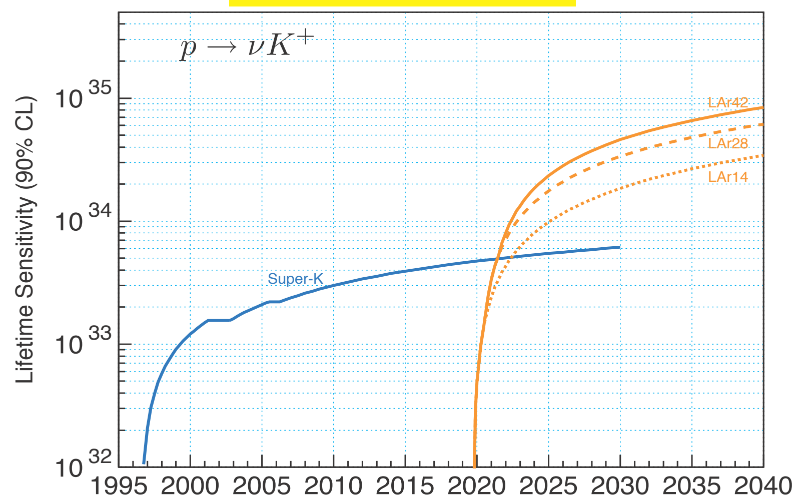
$p \longrightarrow e^+\pi^0$ WCD



$p \longrightarrow K^+\nu$ WCD

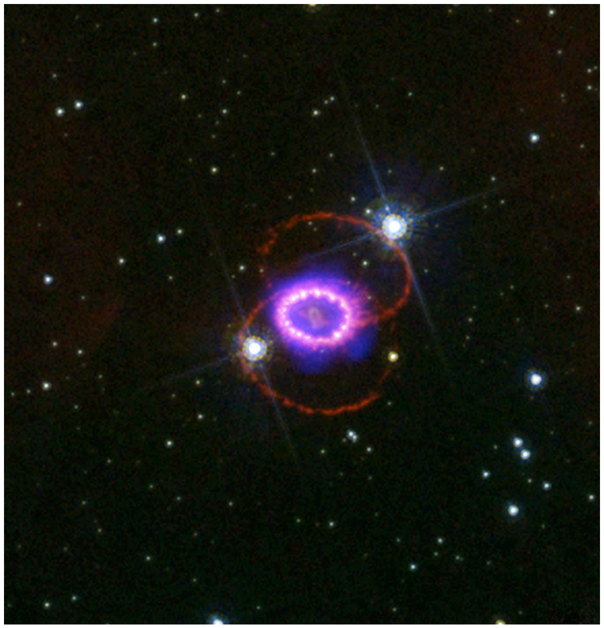


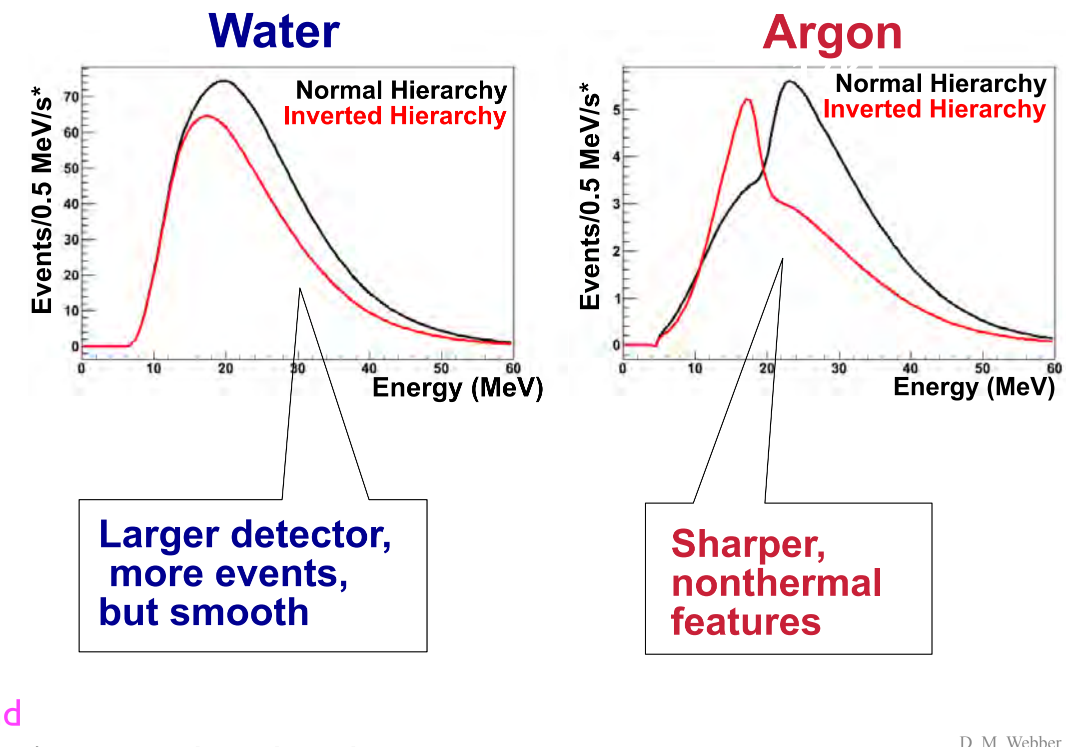
$p \longrightarrow K^+\nu$ LAr



SuperNova Burst

Observed features in water and argon





Features in energy, flavour, time evolution: Depend upon progenitor, model, SN-type, Oscl, ... ➢

* one-second late-time slice

Channel	LAr 17kt Events
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	1154
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	97
$\nu_x + e^- \rightarrow \nu_x + e^-$	148
Total	1397

Channel	WCD 100kt Events
$\bar{\nu}_e + p \rightarrow e^+ + n$	27116
$\nu_x + e^- \rightarrow \nu_x + e^-$	868
$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}$	88
$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}$	700
$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^*$	513
Total	29284

Outlook

- An comprehensive & ambitious ν program at Fermilab leading to LBNE

- Combination of L(Distance), Beam(1st & 2nd. Max), Far and Near Detectors
  - ⇛ Unique reach for the Mass Hierarchy and δ_{CP}, possibly, something new!
  - ⇛ Sensitivity to SuperNova & Relic-ν, Proton-decay, Atmospheric-ν, . . .

- The LBNE-ND aims to provide precise constraints on the systematic errors affecting the ν oscillation physics:
  - ⇒ Flux of all 4 species: ν_e, ν_μ & Anti-(ν_e, ν_μ)
  - ⇒ Absolute Eν-scale
  - ⇒ Measurement of π0/+/- --- backgrounds to oscillation-signal --- in NC and CC
  - ⇒ Difference between ν & Anti-(ν) interactions
  - ⇛ *Provide a composite set of measurements which serve as the `Event Generator' for the Far Detector*

- A rich short-baseline ν-physics

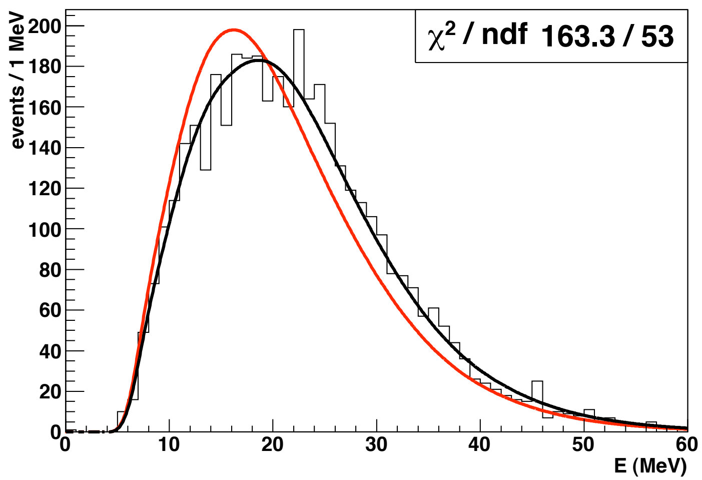
- We welcome, *and need*, new institutions/collaborators

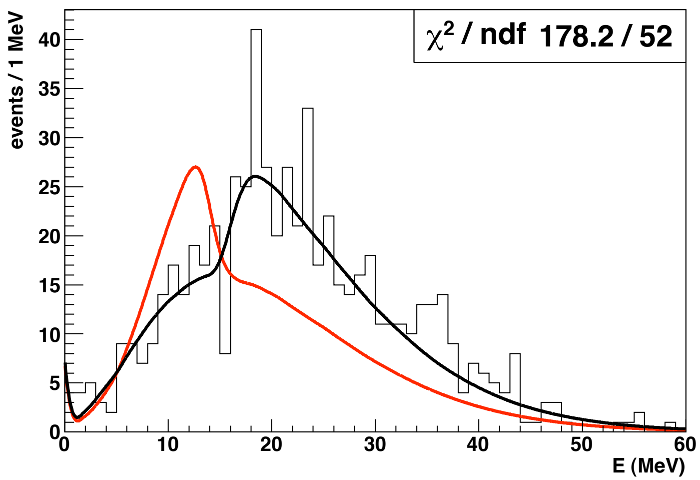
Backup Slides

SN ν-Spectra and MH

The SR neutrino spectra from 10 kpc observed in the LBNE detectors for normal hierarchy and the fit to the opposite hierarchy:

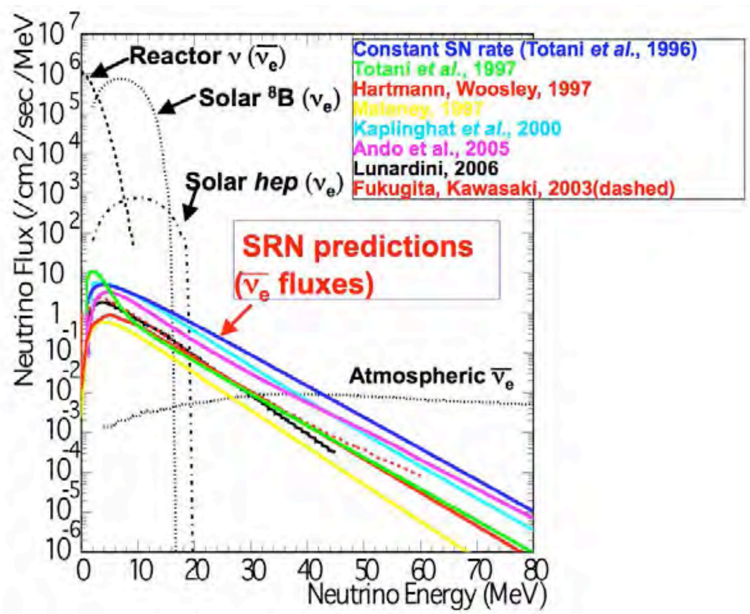
100 kt WCD - mostly $\bar{\nu}_e$ **17 kt LAr - mostly ν_e**

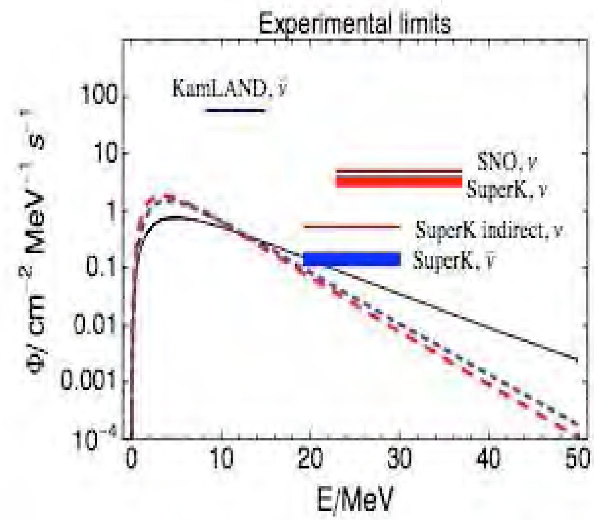




Some ability to distinguish the MH - backgrounds yet to be evaluated

Relic Supernova ν





Reference Configuration	Expected Annual SRN Signal (events/year)	Expected Annual Background (events/year)	Years of LBNE Data Needed for a 3.0-σ Signal Assuming Maximum/Minimum SRN Flux
300kt WCD 30%	5 – 52	320	1.3/144
300kt WCD 30% + Gd	13 – 74	64	0.13/0.9
100kt WCD + 100kt WCD-Gd + 17kt LAr	5 – 39	114	0.35/3
100kt WCD-Gd + 34 kt LAr	4 – 27	21	0.32/3

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Pionic correlations and meson-exchange currents in two-particle emission induced by electron scattering

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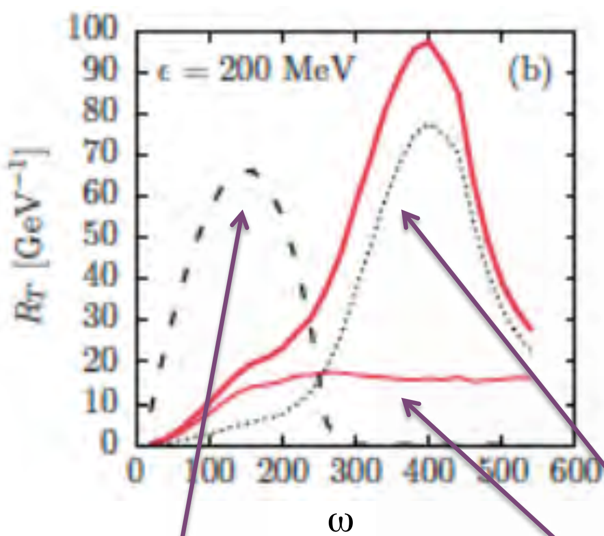


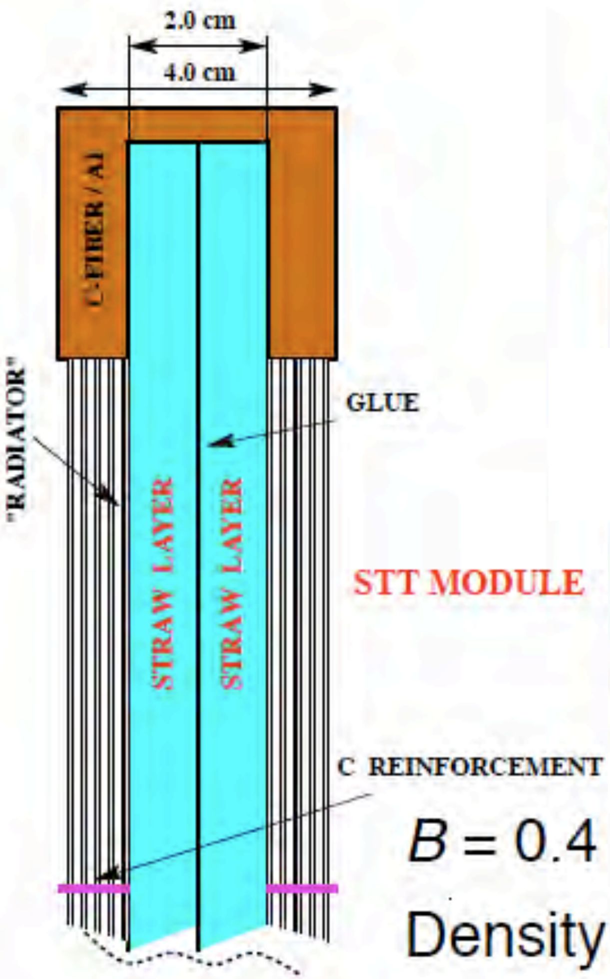
One body RFG

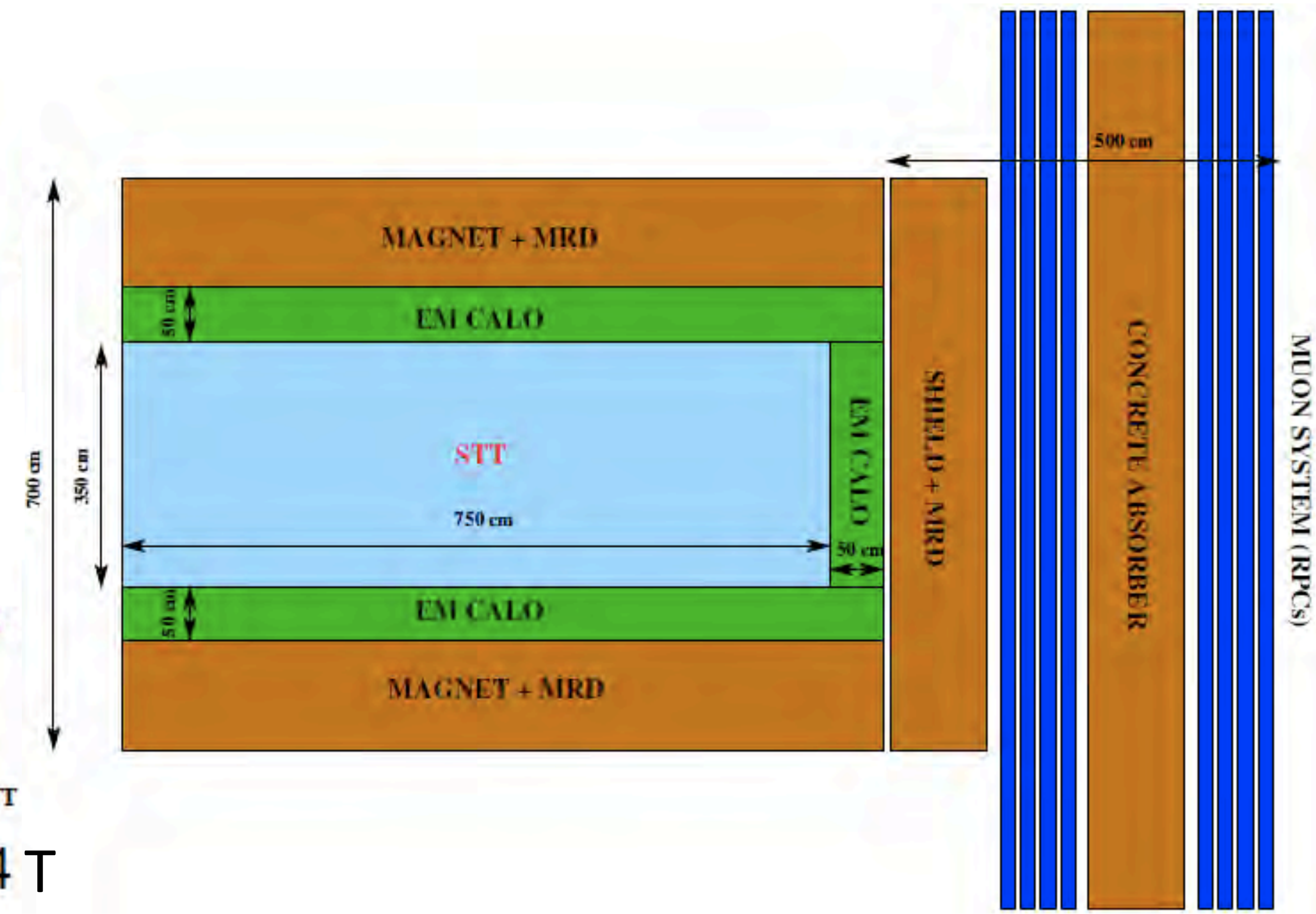
Meson exchange

Correlation

Meson-Exchange Currents predict a much larger fraction of the incident neutrino energy going into the hadron sector. Neutrino & antineutrino interactions may have different energy corrections up to ~300MeV and may create a spurious "CP-violating" effect, especially at 1.5 GeV where the sensitivity is maximum.

R_T = transverse response function





$B = 0.4$ T

Density = 0.1 g/cm3, 85% in the radiator foils.

Transition Radiation ⤜ e-/e+ ID ⇒ γ (w. Kinematics)

dE/dx ⤜ Proton, π+/-, K+/- ID

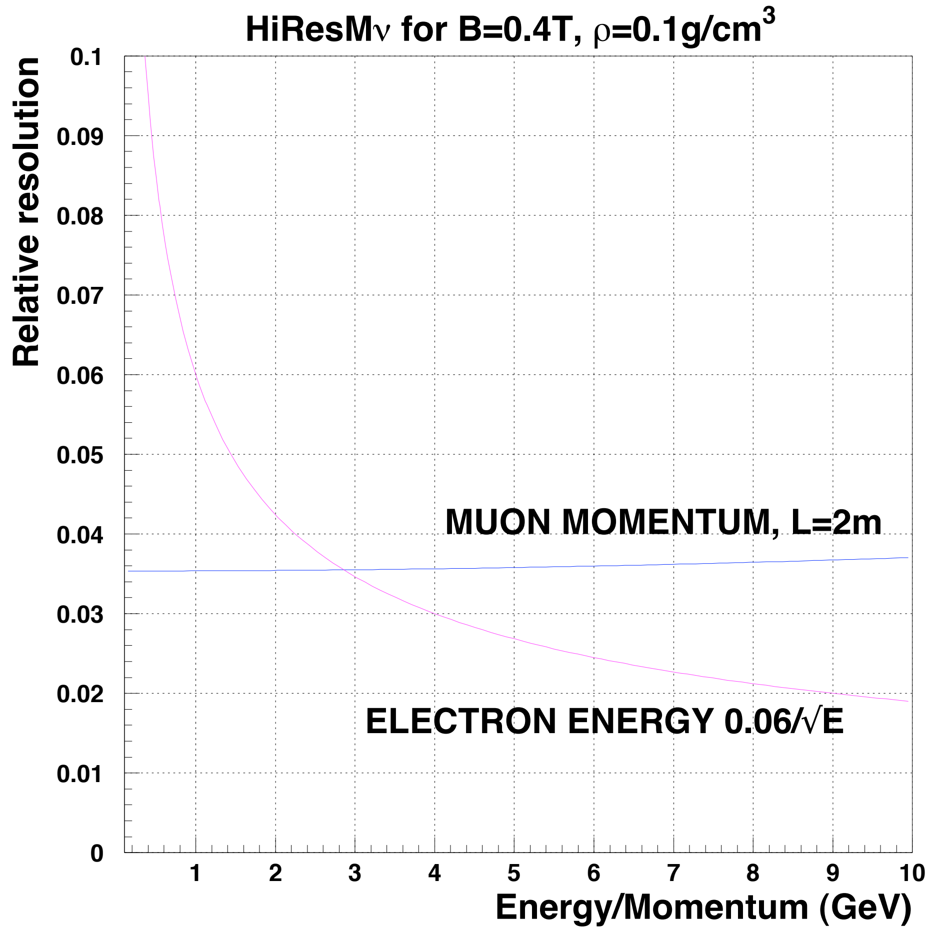
Magnet/Muon Detector ⤜ μ+/-

Resolutions in HiResMnu

- $\rho \simeq 0.1$gm/cm^3
- Space point position ≃ 200μ
- Time resolution ≃ 1ns

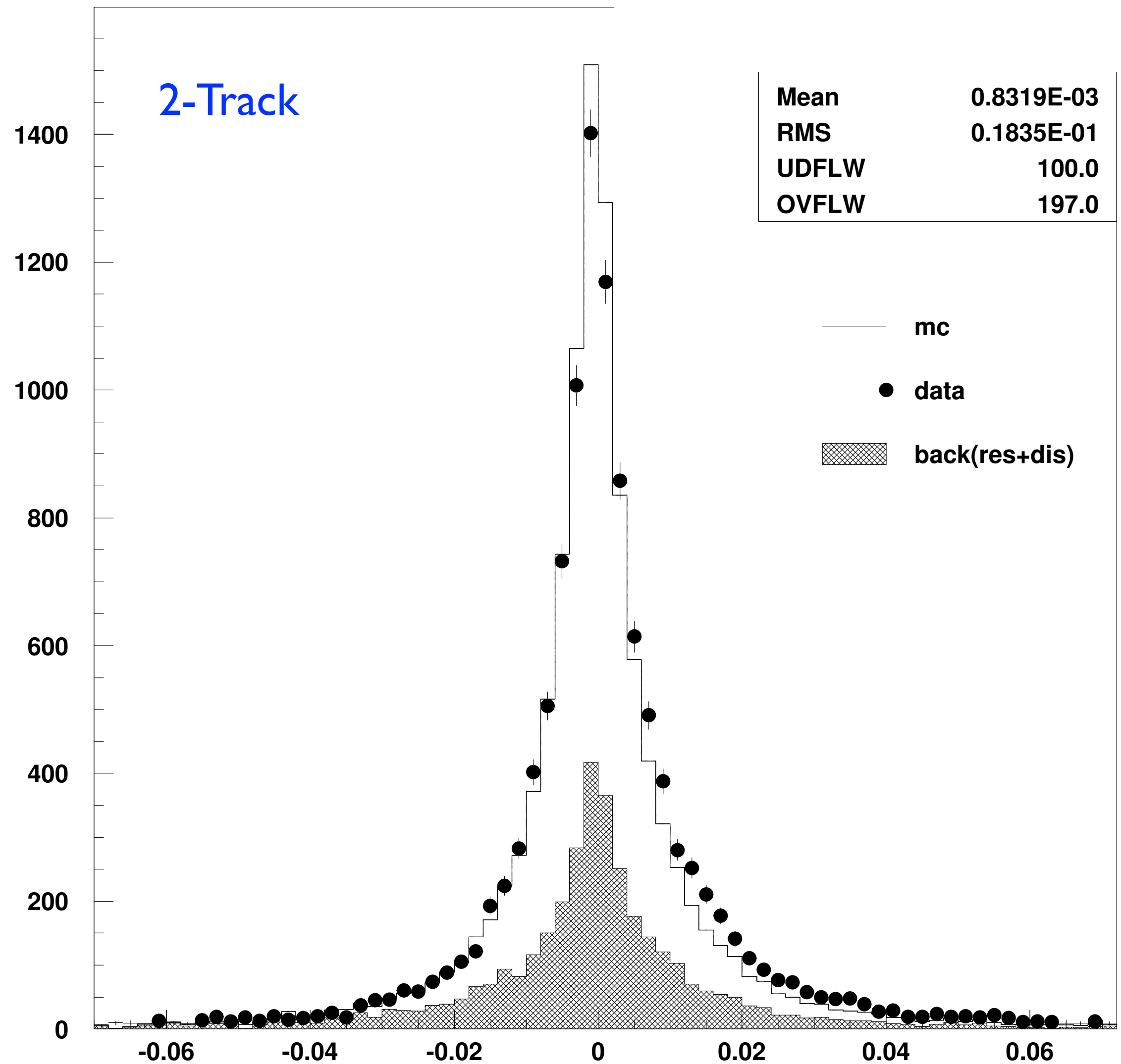
- CC-Events Vertex: Δ(X,Y,Z) ≃ O(100μ)
- Energy in Downstream-ECAL ≃ 6%/√E
- μ-Angle resolution (~5 GeV) ≃ O(1 mrad)

- μ-Energy resolution (~3 GeV) ~ 3.5%
- e-Energy resolution (~3 GeV) ~ 3.5%



Sensitivity Calculations:

- Parametrized calculation
- Repeat with NOMAD configuration and checked against the Data and Geant-MC (Agree within 15%): ReWt



{Evis(2-Trak) - Enu(1-Trk w. PFermi=0)} / [Evis(2-Trak)]

⇒ *constraint on Eν Scale*

Flux: … Always the Flux

ॐ *Inverse Muon Decay*: ν_x + e- ↠ ν_x + μ- {Single, forward μ-}

- ν_μ (t-channel) or Anti-ν_e (s-channel)
- Elegant, Simple but steep threshold (calculable), $E\nu \geq 11$ GeV
- Systematic Advantage of STT lies in reducing systematic errors incurred by CCFR or CHARM-II in extrapolating the background to the signal $\zeta = P_e(1-\cos\Theta_e) \leq$ Cut

ॐ ν-*Electron Elastic Events*: ν_x + e- ↠ ν_x + e- {Single, forward e-}

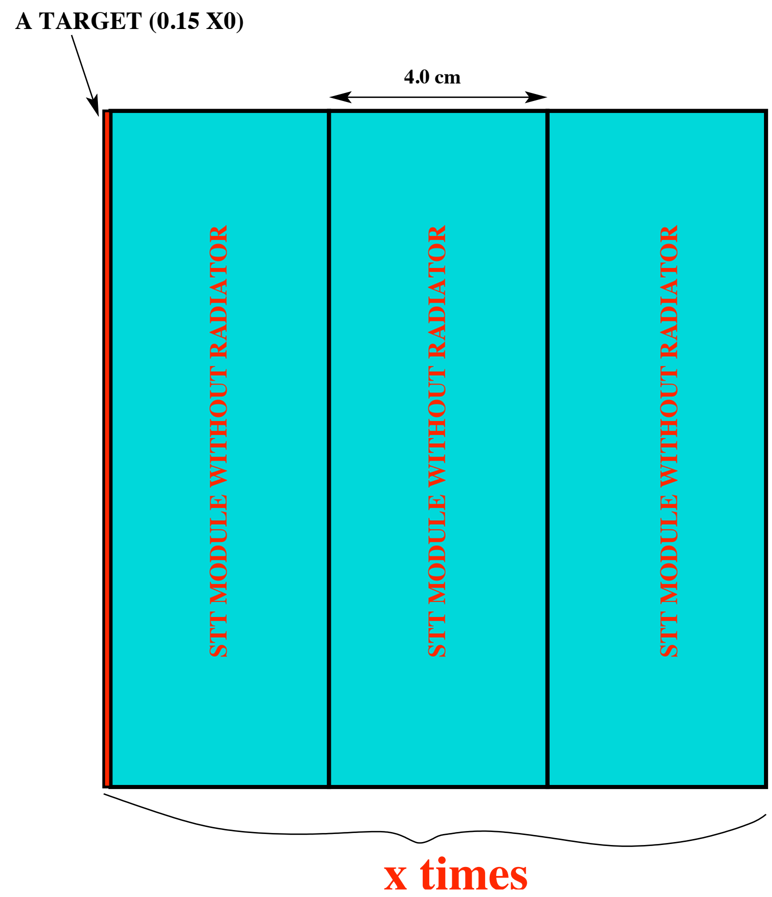
- Different processes: ν_ee-CC, Anti-ν_ee-CC, & all flavor ν_xe-NC
- Different Ee spectrum
- Focus on ν_μe-NC: Experimentally the most challenging
- The Weak Mixing Angle (0.238) at Q~0.1 GeV is known to ≤1% precision

⇒ $\sigma(\nu_x$e-NC) known ⇒ Absolute-$\phi(\nu_x)$

MEASURING NUCLEAR EFFECTS (Water, Ar, ..)

- *Measure the A dependence (Ca, Cu, H_2O, etc.) in addition to the main C target in STT:*
  - *Ratios of F_2 AND xF_3 on different nuclei;*
  - *Comparisons with charged leptons.*

- *Use 0.15X_0 thick target plates in front of three straw modules (providing 6 space points) without radiators. Nuclear targets upstream.*
  - *For Ca target consider $CaCO_3$ or other compounds;*
  - $\boxed{\text{OPTION}}$*: possible to install other materials (Pb, etc.).*



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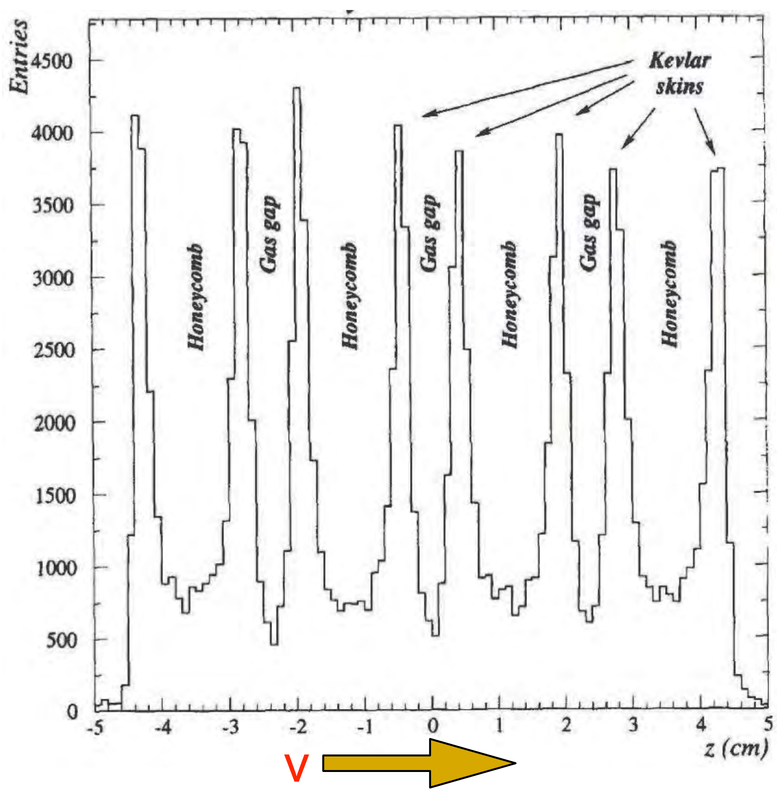
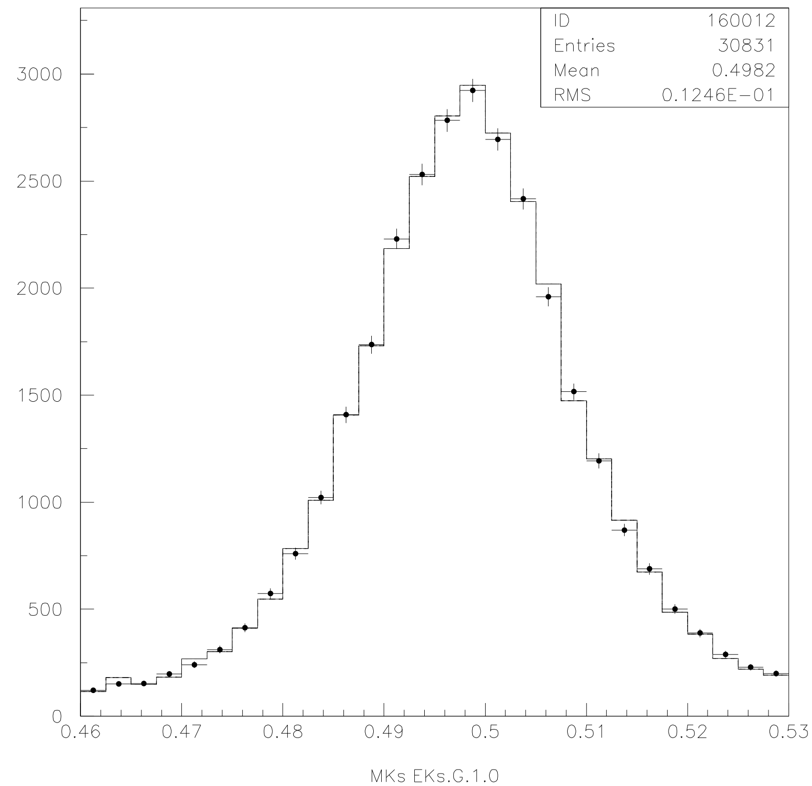
What we build on: NOMAD DATA



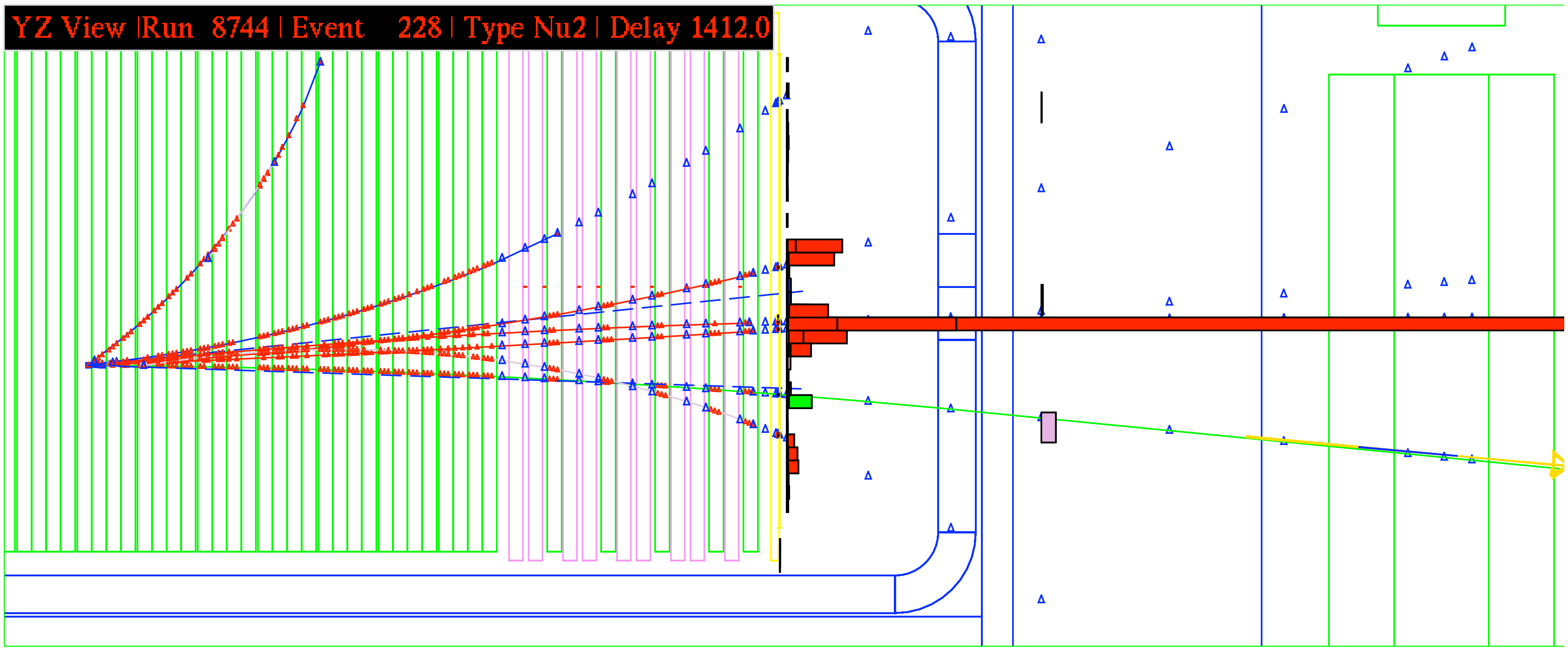
Neutrino radiography of one drift chamber



Reconstructed K^0 mass

- *NOMAD: charged track momentum scale known to* $< 0.2\%$
  hardonic energy scale known to $< 0.5\%$
- *HiResMν:* $\boxed{200\times}$ *more statistics and* $\boxed{12\times}$ *higher segmentation*

A ν_μ CC candidate in NOMAD



LOW-ν_0 METHOD ⇐Shape of ν_μ or Anti-ν_μ Flux

✦ *Relative flux vs. energy from low-ν_0 method:*

$$N(E_\nu : E_{\rm HAD} < \nu^0) = C\Phi(E_\nu) f(\frac{\nu^0}{E_\nu})$$

the correction factor $f(\nu^0/E_\nu) \to 1$ for $\nu^0 \to 0$.

$\Longrightarrow$ *Need precise determination of the muon energy scale and good resolution at low ν values*

✦ *Fit Near Detector $\nu_\mu, \bar{\nu}_\mu$ spectra:*

- *Trace secondaries through beam-elements, decay;*
- *Predict $\nu_\mu, \bar{\nu}_\mu$ flux by folding experiental acceptance;*
- *Compare predicted to measured spectra $\Longrightarrow \chi^2$ minimization*

$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F)g(P_T)h(x_F, P_T)$$

- *Functional form constraint allows flux prediction close to $E_\nu \sim \nu^0$.*

✦ *Add measurements of $\pi^\pm/K^\pm$ ratios from hadro-production experiments to the empirical fit of the neutrino spectra in the Near Detector*

USC

Systematic-Errors in Low-$\nu 0$ Relative Flux: ν_μ & Anti-ν_μ

- Variation in $\nu 0$-cut
- Variation in $\nu 0$-correction
- Systematic shift in Ehad-scale
- Vary σ(QE) ±10%
- Vary σ(Res) ±10%
- Vary σ(DIS) ±10%
- Vary functional-forms
- Systematic shift in Emu-scale

- Beam-Transport (ND at 1000m)

Includes:

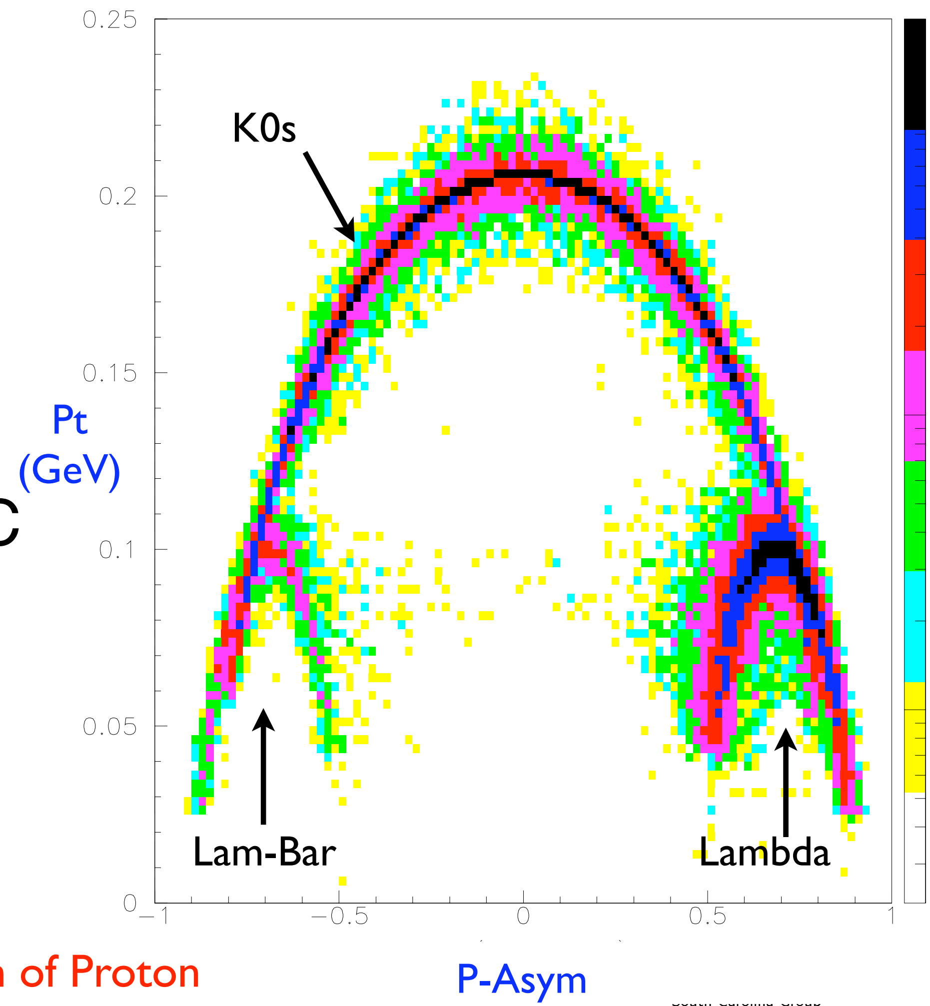
*Alignment (1.0mm)
*Horn Current (0.5%)
*Inert material (0.25λ)
*Proton spot size

⇒ Revisit these (?) & Investigate ND @ 500m

Measurement of exclusive topologies

- High resolution allows excellent reconstruction of exclusive decay modes
- NOMAD performed detailed analysis of strange particle production: $\Lambda, \bar{\Lambda}$
- Δ resonances in CC & NC are easier to reconstruct
- Constraints on NC decay mode $\Delta \rightarrow N\gamma$

CC-Data: Armenteros Plot



Lambda → Calibration of Proton Reconstruction