Concepts Beyond the Neutrino Factory Baseline Design

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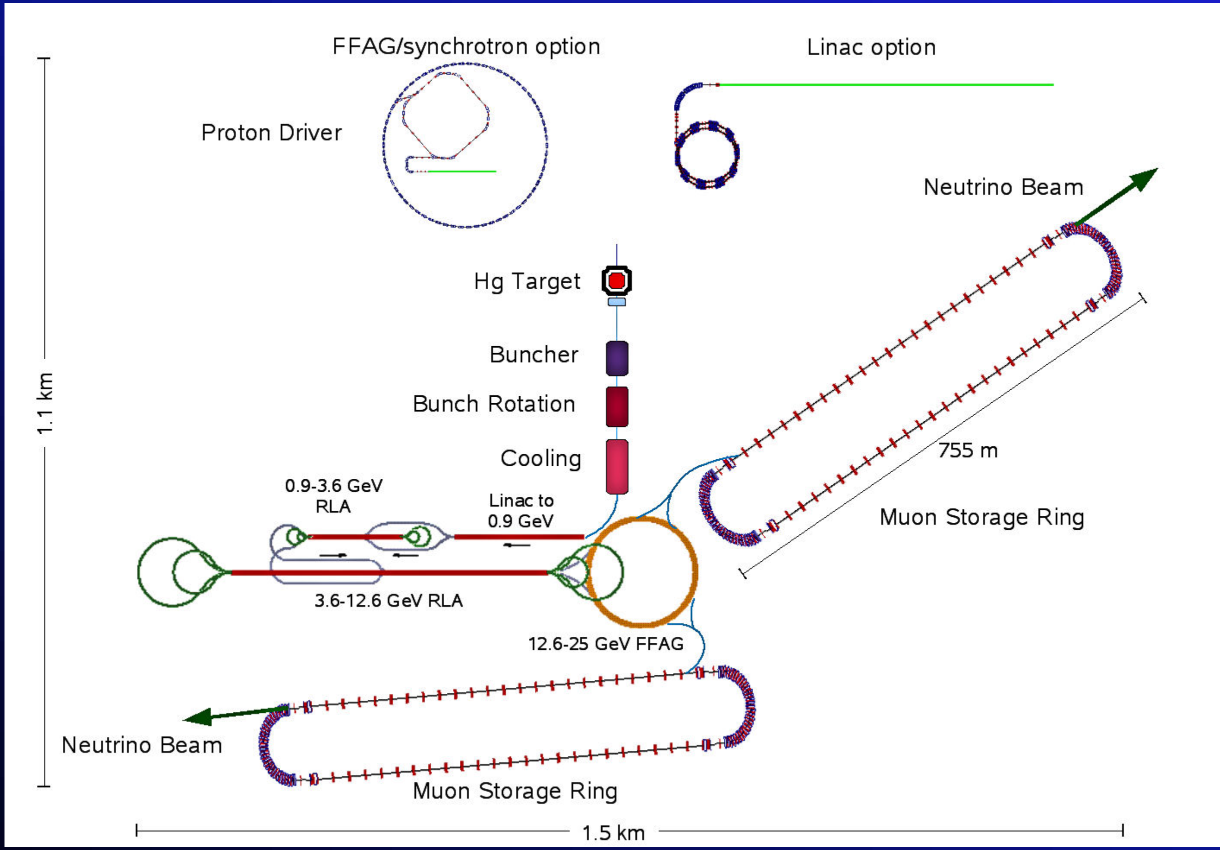
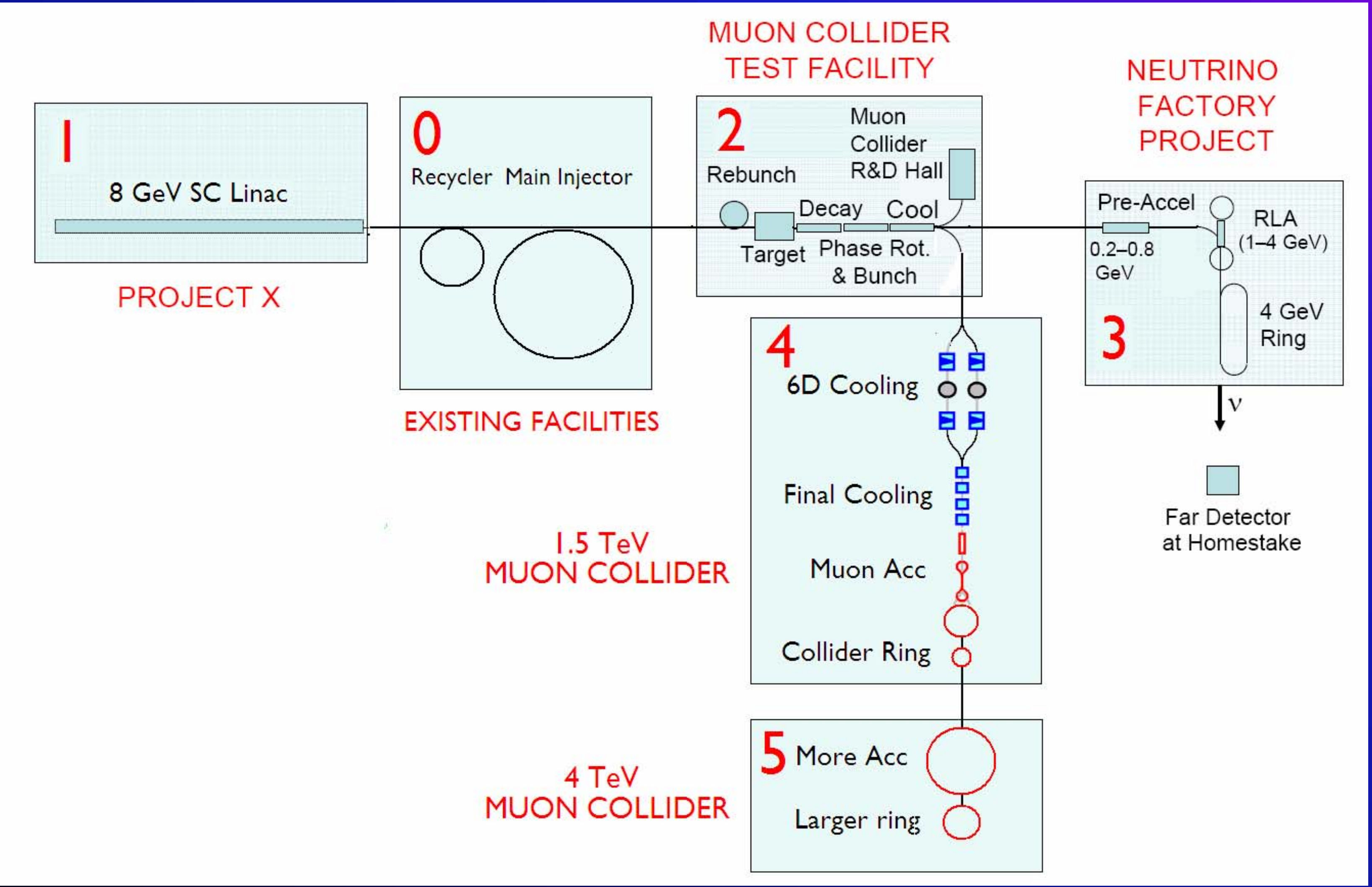
Neutrino Factory – IDS Starting Point

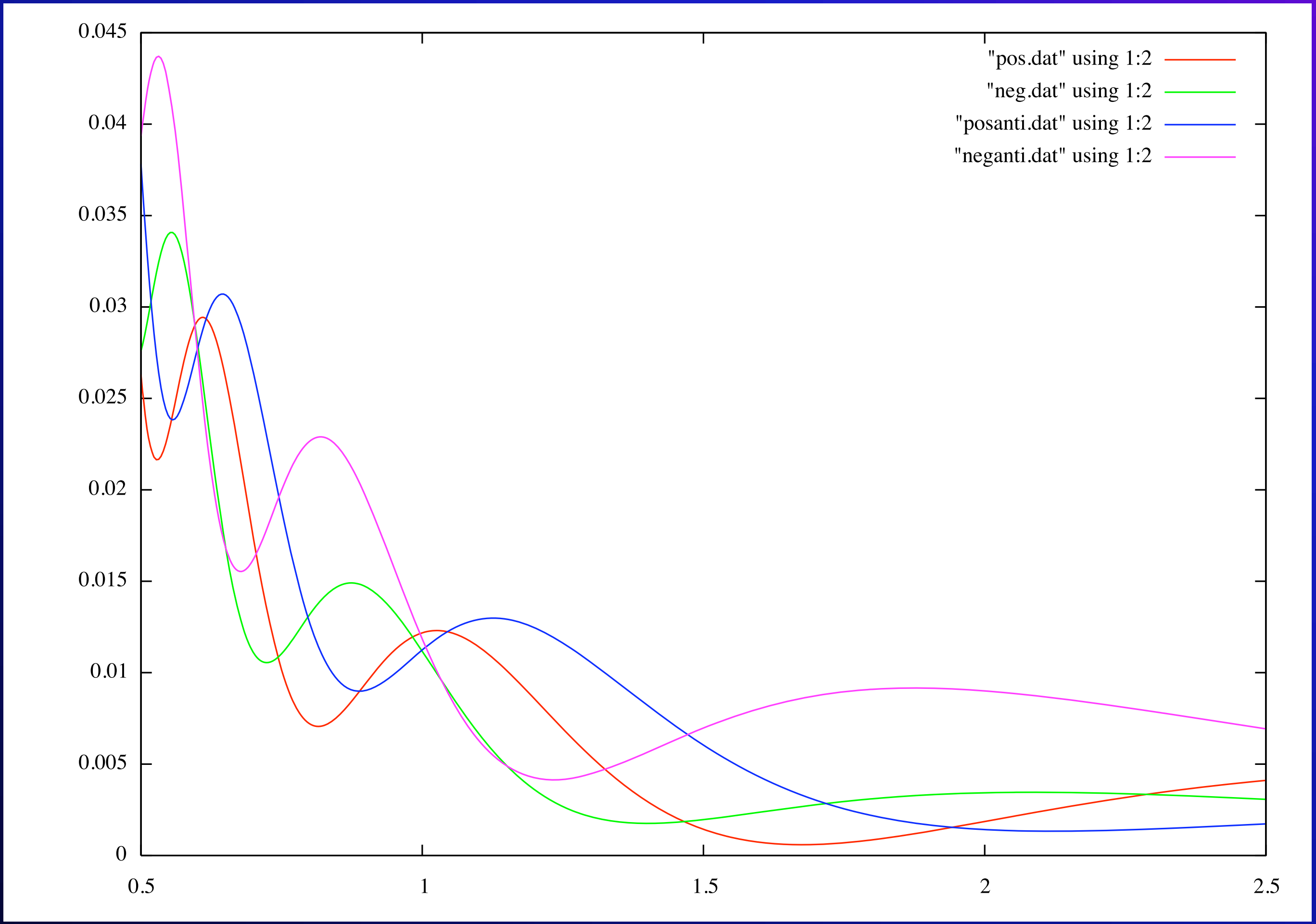


- Proton Driver
  - 4 MW, 2 ns bunch
- Target, Capture & Phase Rotation
  - Hg Jet
  - 200 MHz train
- Cooling
  - 30 pmm ($\perp$)
  - 150 pmm (L)
- Acceleration
  - 103 MeV $\rightarrow$ 25 GeV
- Storage/Decay ring

Muon Complex Evolution

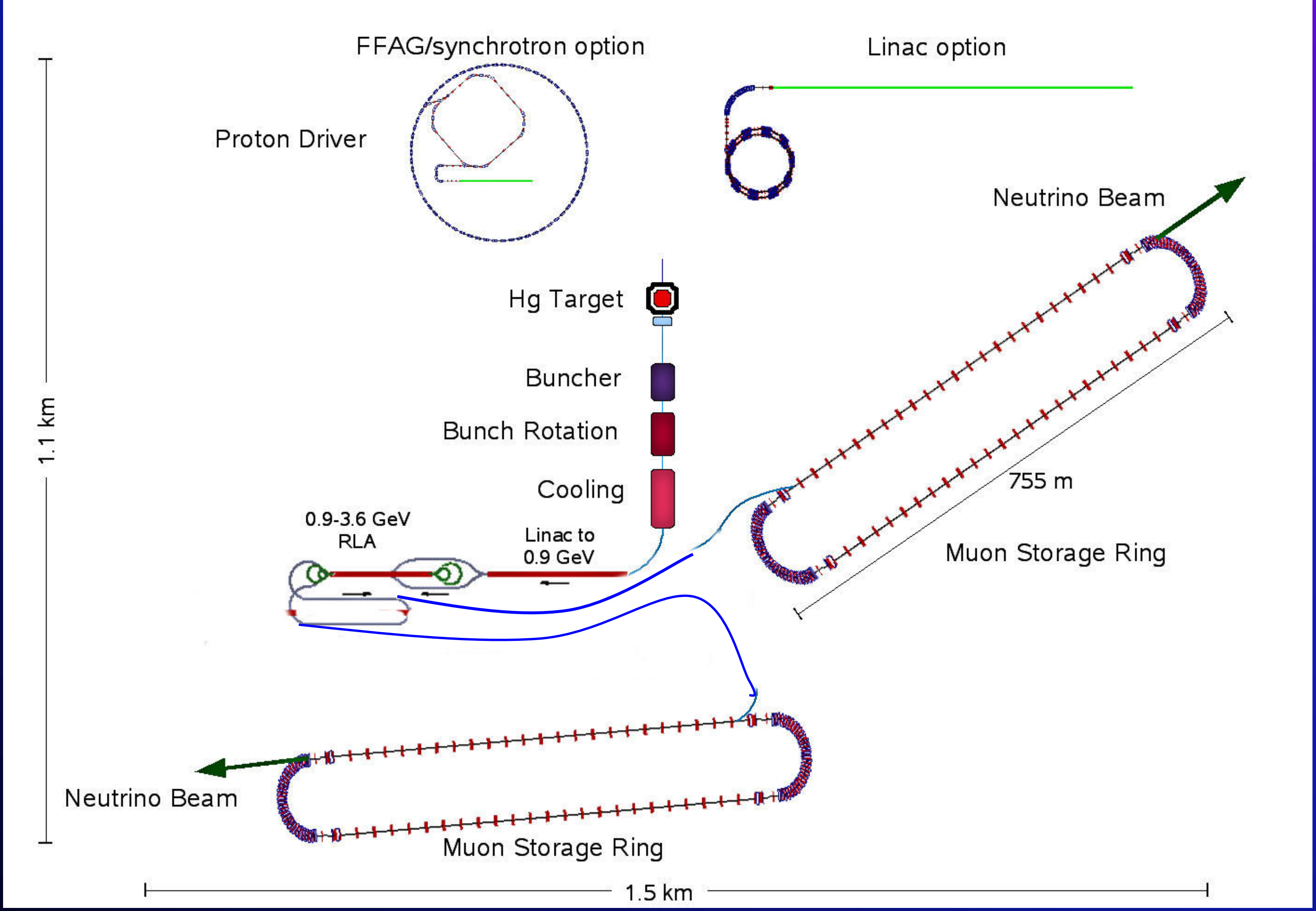


Extension of Analysis with estimated TADS σ_E



- If the TASD can fully exploit the rich oscillation pattern at low energy → 0.5 to 1.5 GeV (and go to E_ν threshold of 0.5 GeV)

IDS - Lite



FFAG/synchrotron option
Linac option
Proton Driver
Neutrino Beam
Hg Target
Buncher
Bunch Rotation
Cooling
1.1 km
0.9-3.6 GeV
RLA
Linac to
0.9 GeV
755 m
Muon Storage Ring
Neutrino Beam
Muon Storage Ring
1.5 km

But, Can the Physics Goals be Accomplished with a LE-NF?

- Up to now, the NFMCC has focused on neutrino factories with energies of 20-50 GeV

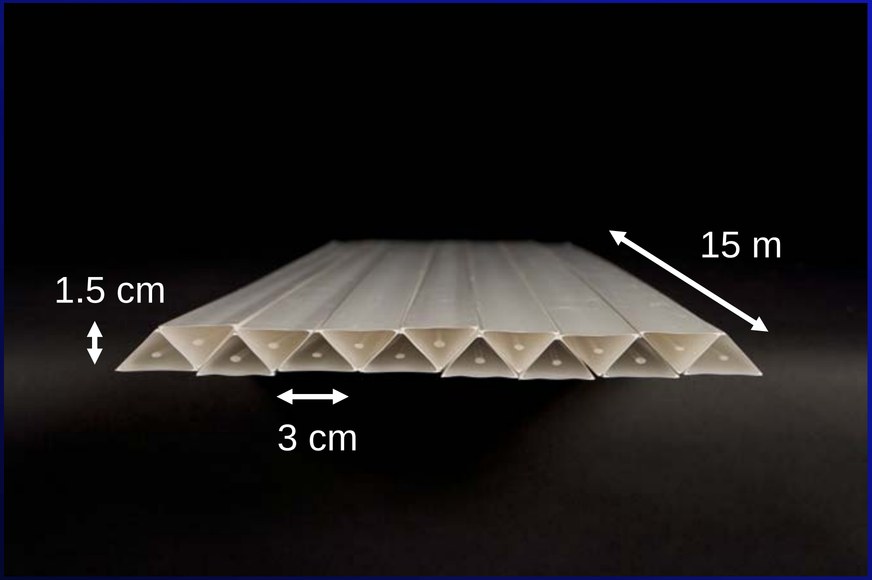
- The collaboration has not studied lower energy neutrino factories because, until recently, the proposed NF detectors have had muon energy thresholds (for measuring wrong-sign muons with adequate background rejection) of a few GeV, which imposes a minimum threshold on the desirable neutrino energy, and hence a minimum NF energy → ~25 GeV (current IDS baseline).

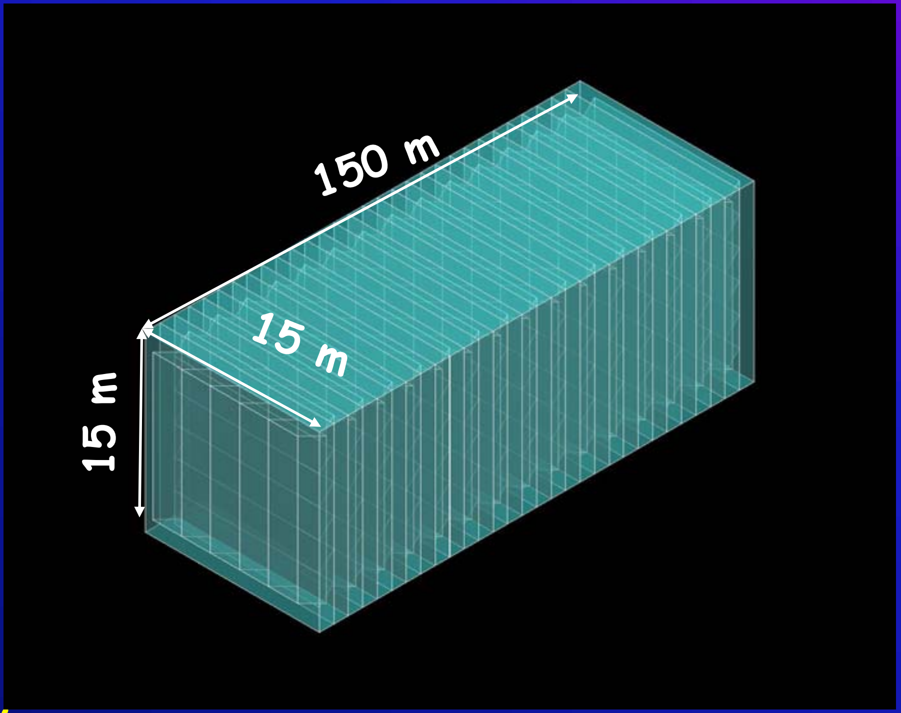
- During the ISS there was progress on understanding how to reduce the detector thresholds for measuring wrong-sign muons … so we can now consider lower energy neutrino factories.

Fine-Resolution Totally Active Segmented Detector

Simulation of a Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts with Geant4

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels



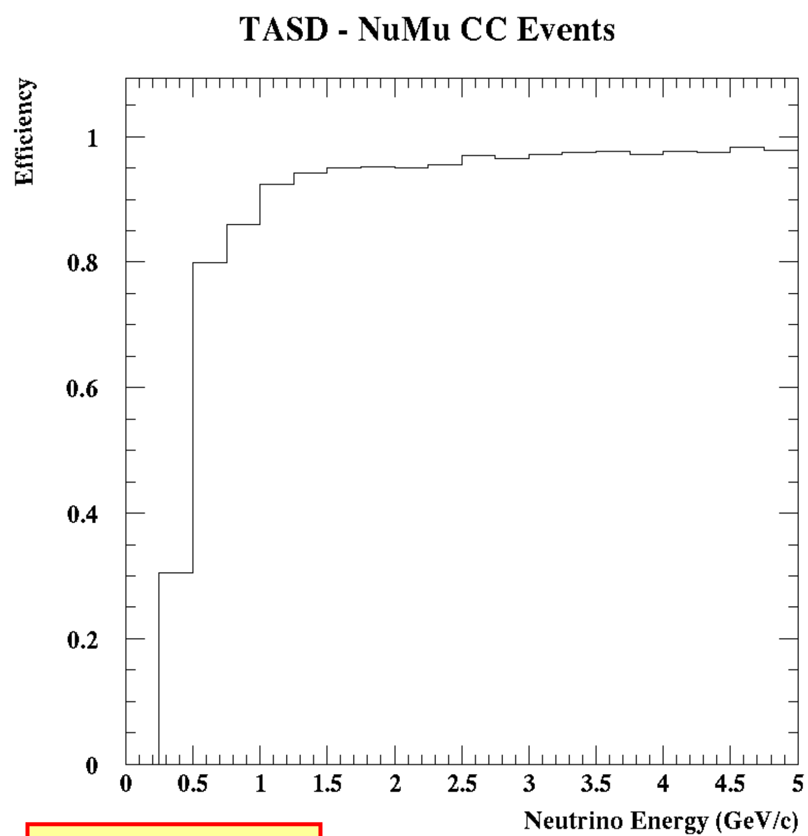


- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

B = 0.5T

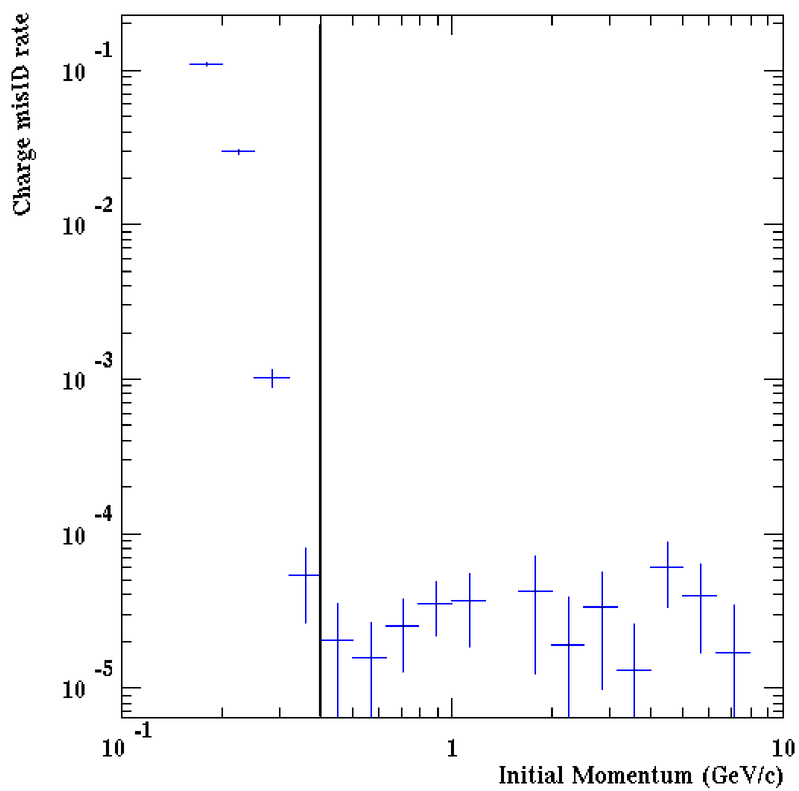
TASD Performance

ν Event Reconstruction Efficiency

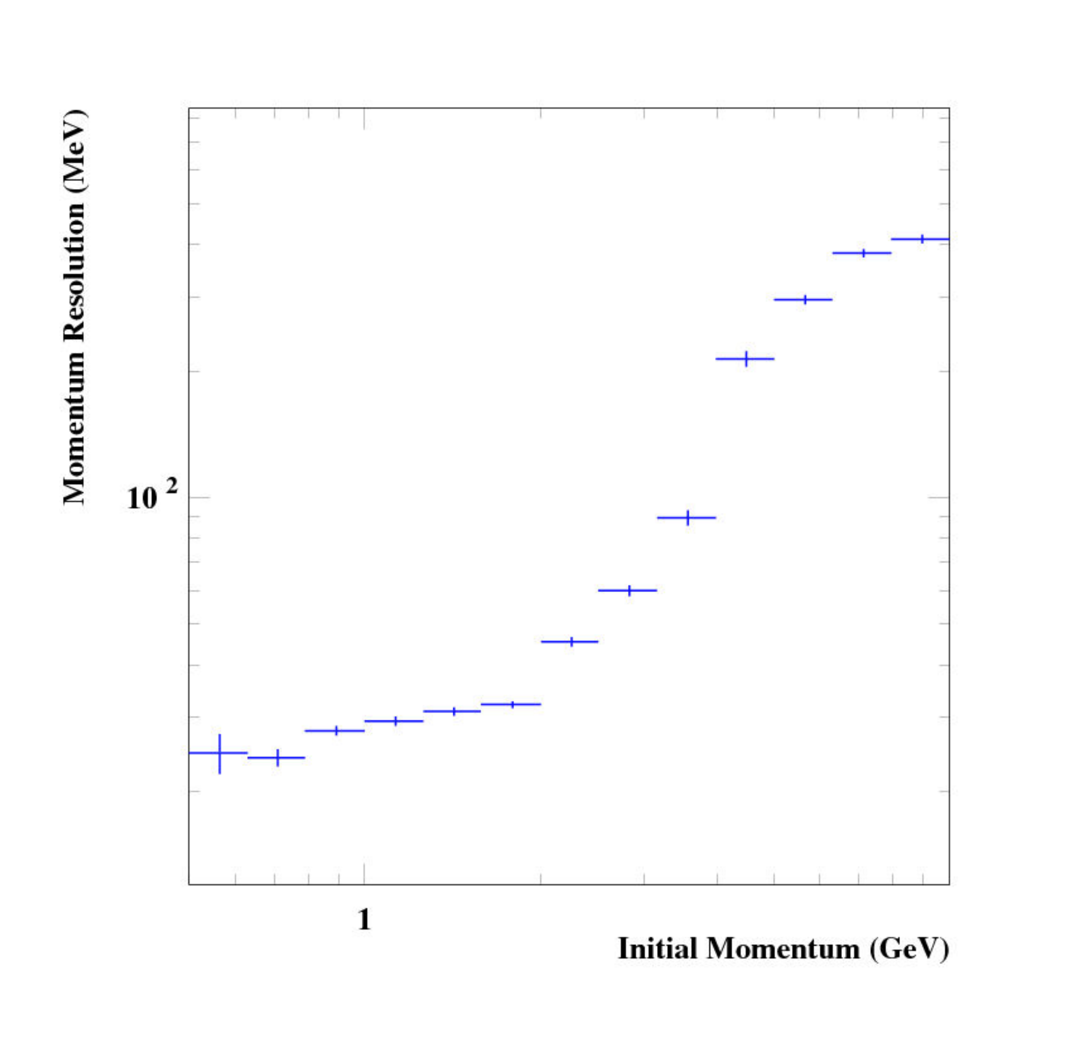


Excellent σ_E

Muon charge mis-ID rate



TASD Performance II



- Momentum resolution excellent
  - Neutrino Event energy reconstruction from tracking
  - EM component from hit counting possibly
- Simplifies electronics
  - No calibration needed
  - Hit efficiency is only consideration

4 GeV NF Physics Study

- Baseline: 1480km (FNAL-Henderson)
  - Also did Homestake to Fermilab
- Choose NF Energy ~ 4 GeV (Actually 4.12 GeV). This is motivated by the realization that for baselines O(1000km), if θ_{13} is not very small, the oscillation pattern is extremely rich below ~4 GeV.
- Will divide the simulated data into 3 energy bins, and fit the wrong-sign muon rates for each bin with positive- & negative-muons stored in the ring (6 rates to fit). Can also fit 6 right-sign muon rates.
- Energy bins: $E\nu$ = [0.8,1.5], [1.5,3.5], [3.5,4.12] GeV.
- Bins chosen to optimize ability to resolve degenerate solutions.

IPPP/06/85; DCPT/06/170; Roma-TH-1443; FERMILAB-PUB-07-021-E (Geer, Mena, Pascoli)

Input Parameters

- NF performance:

BASIC: (5 years) × (3 × 10^{20} useful decays/yr) × (2 signs) × (20Kt fid. Mass) = 3×10^{22} Kt-decays ×(2 signs)

BETTER: (10 years) × (5 × 10^{20} useful decays/yr) × (2 signs) × (20Kt fid. Mass) = 1×10^{23} Kt-decays ×(2 signs)

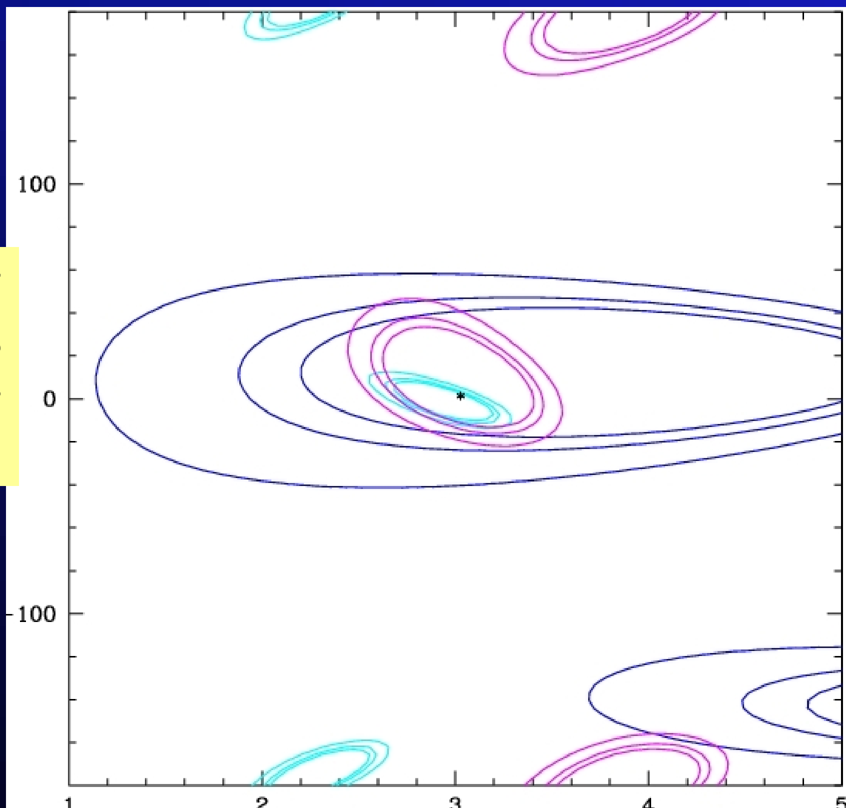
- Detector efficiency ε =0 for E_n < 0.8 GeV; ε =1 for E_n > 0.8 GeV

- Do not explicitly implement energy resolutions or cross-section uncertainties but include a 2% systematic uncertainty in the covariance matrix.

Resolving Degeneracies

Solutions corresponding to correct sign Δm^2

90%, 95%, 99% CL Contours



δ (degrees)

θ_{13} (degrees)

<u>Illustration of how it works:</u>

- L=1480 Km
- Simulate $\theta_{13}=3^o$, $\delta=0$ then

fit $\nu_e \rightarrow \nu_\mu$ & $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ rates

- Fits for 3 neutrino energy bins:

Dark: 0.8 – 1.5 GeV

Cyan: 1.5 – 3.5 GeV

Magenta: >3.5 GeV

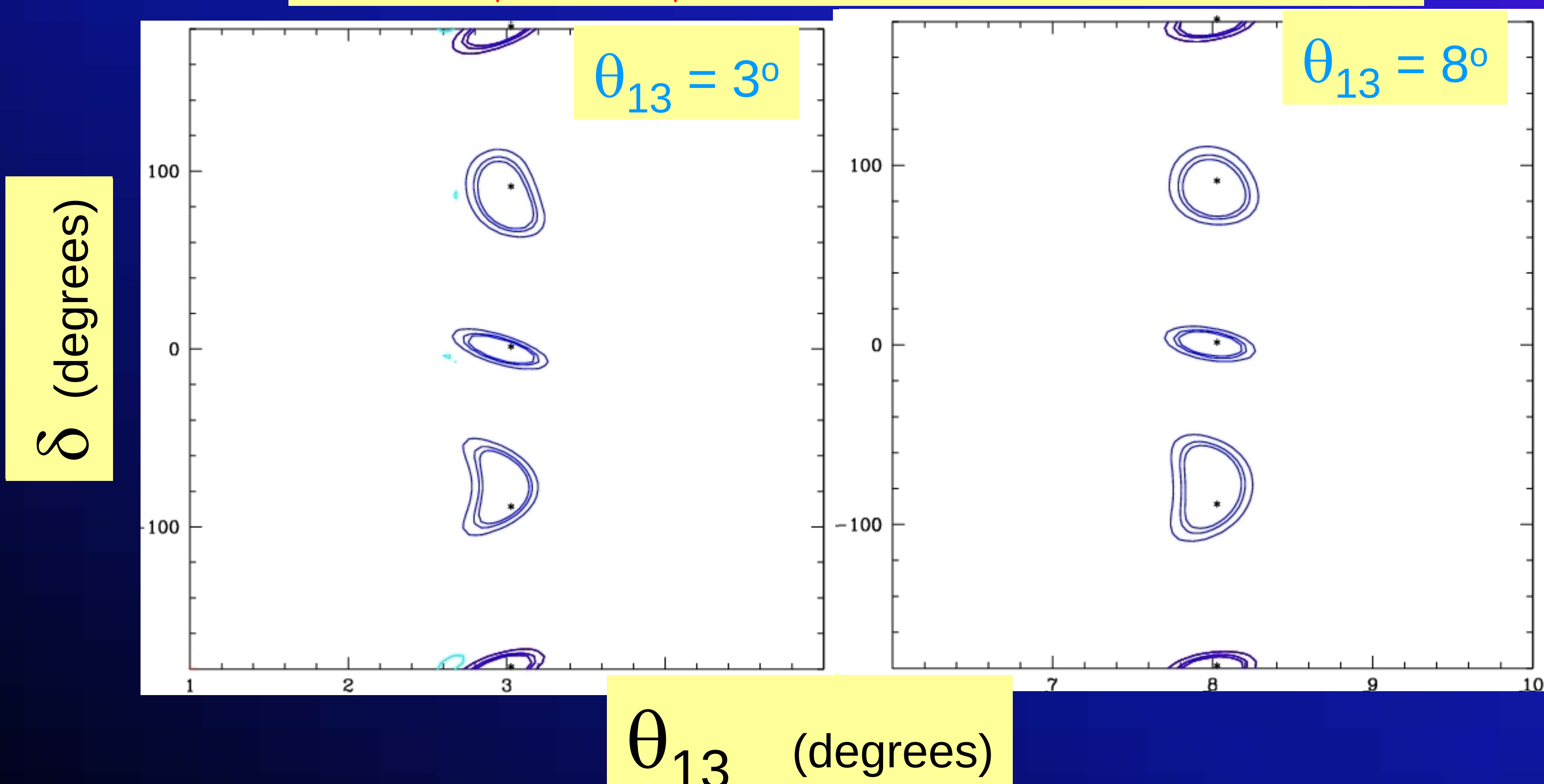
- Each fit yields one correct & one additional (“intrinsic degeneracy”) solution … but the additional solutions for the 3 bins do not overlap

$\rightarrow$ **Unique Solution !**

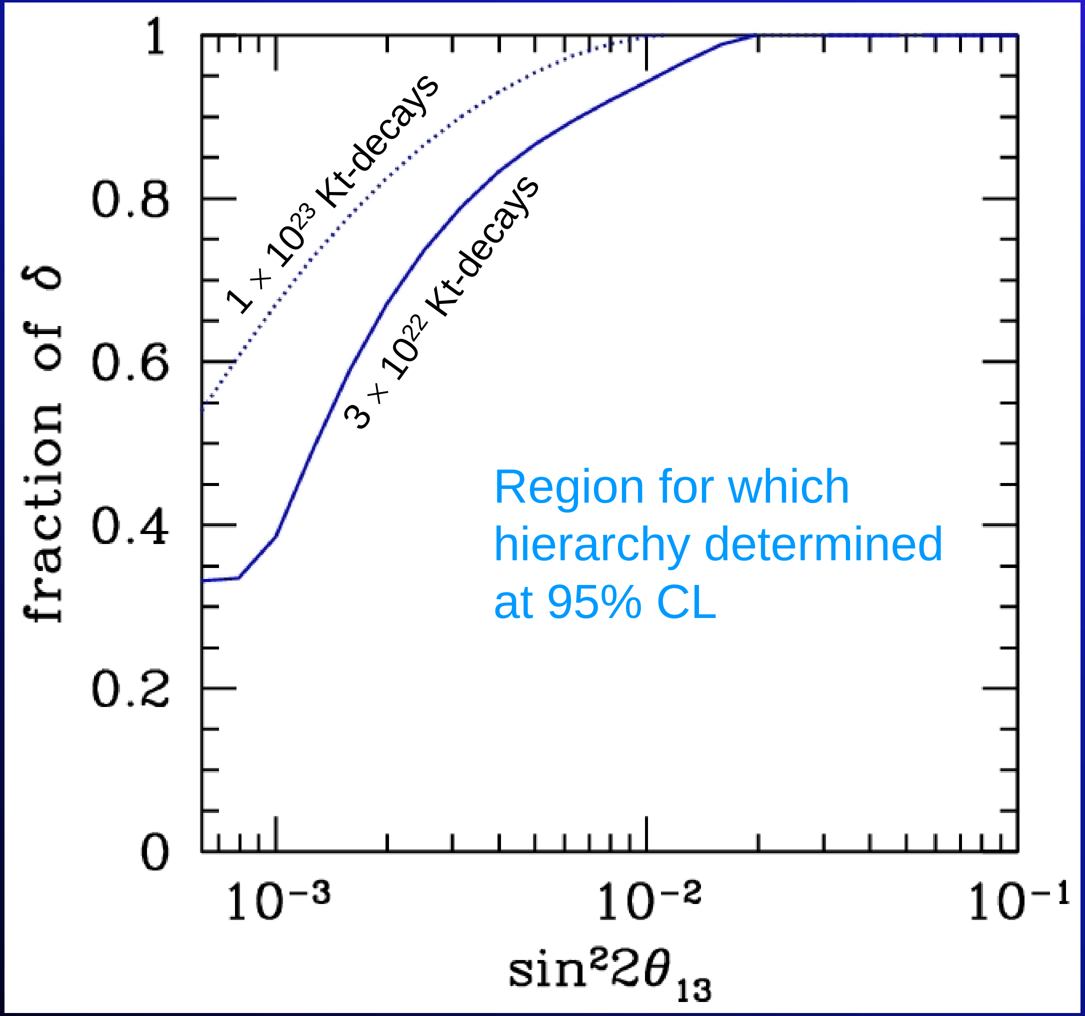
RESULTS: $\nu_e \rightarrow \nu_\mu$ $(3 \times 10^{22}$ Kt-decays)

- <u>Simulate 8 cases</u>: $\theta_{13} = (3^o \ \& \ 8^o)$ & $\delta = (0, \pi/2, -\pi/2, \pi)$ with $\sin^2\theta_{23} = 0.40$, $\Delta m^2_{13}=2.5\times10^{-3}$ eV^2, and L=1480 Km

Fit $\nu_e \rightarrow \nu_\mu$ & $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ rates (90%, 95%, 99% CL Contours)



Mass Hierarchy



L=1480 Km

Mass hierarchy can be determined for all δ, if $\theta_{13} > 3^o$ ($\sin^2 2\theta_{13} > 0.01$)

Detector R&D Issues

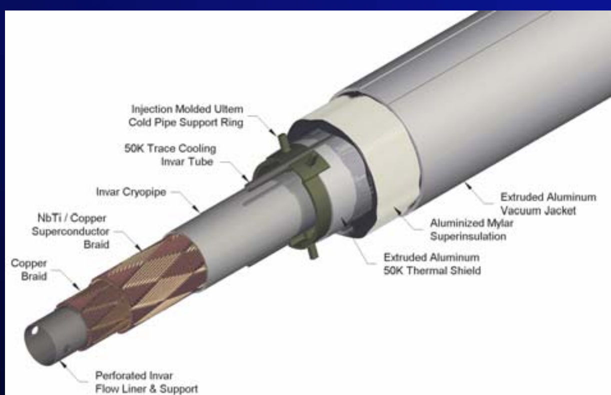
Detector R&D

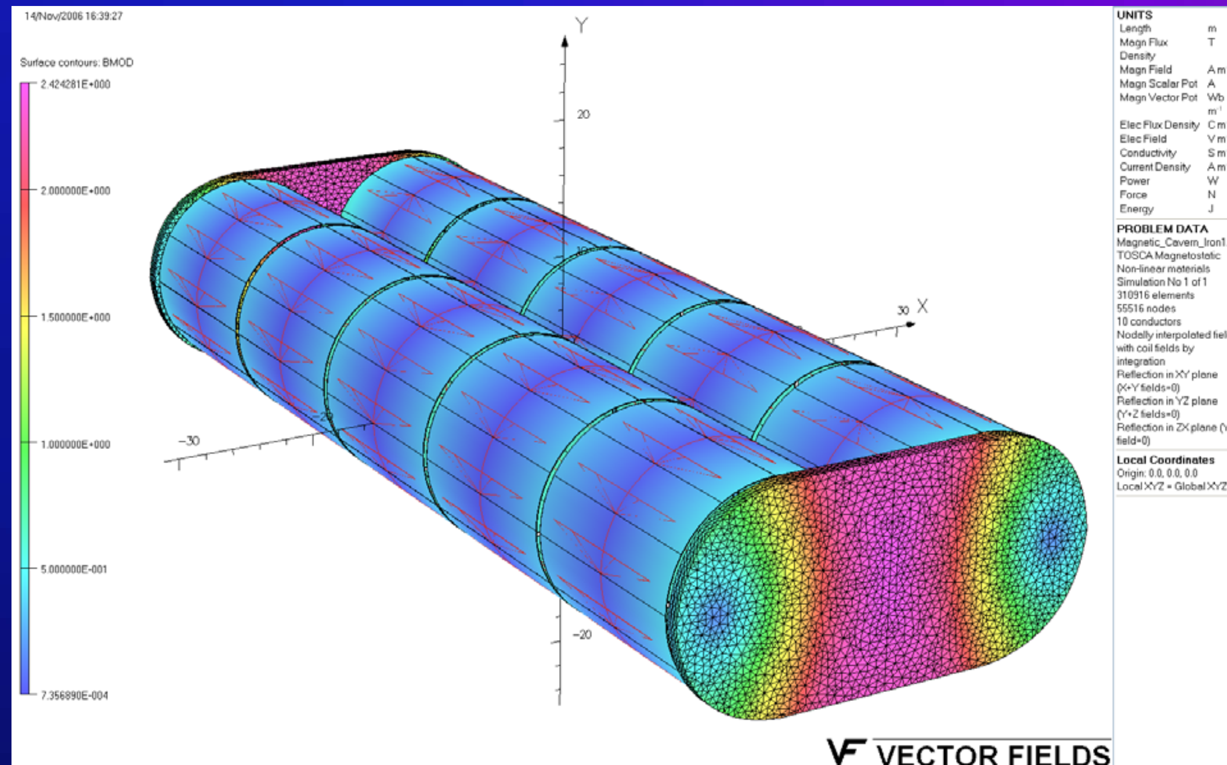
There are 3 components to this detector and their respective R&D

- Magnet
- Scintillator Production
- Photo-detector and electronics

Magnet

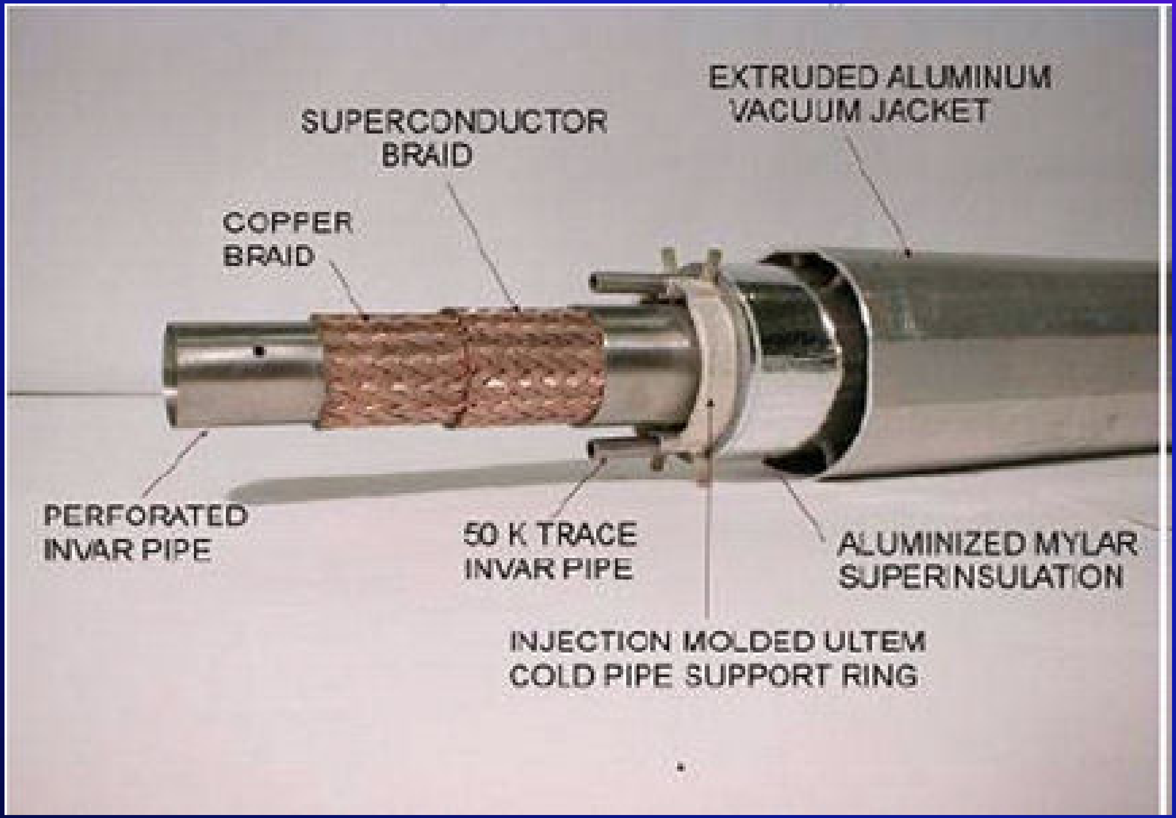
- **New Idea**
  - VLHC SC Transmission Line
    - Technically proven
    - Might actually be affordable





1 m iron wall thickness.
~2.4 T peak field in the iron.
Good field uniformity

Superconducting Transmission Line makes this concept possible *(affordable)*



- SCTL not a "concept" – prototyped, tested and costed for the VLHC Project at Fermilab

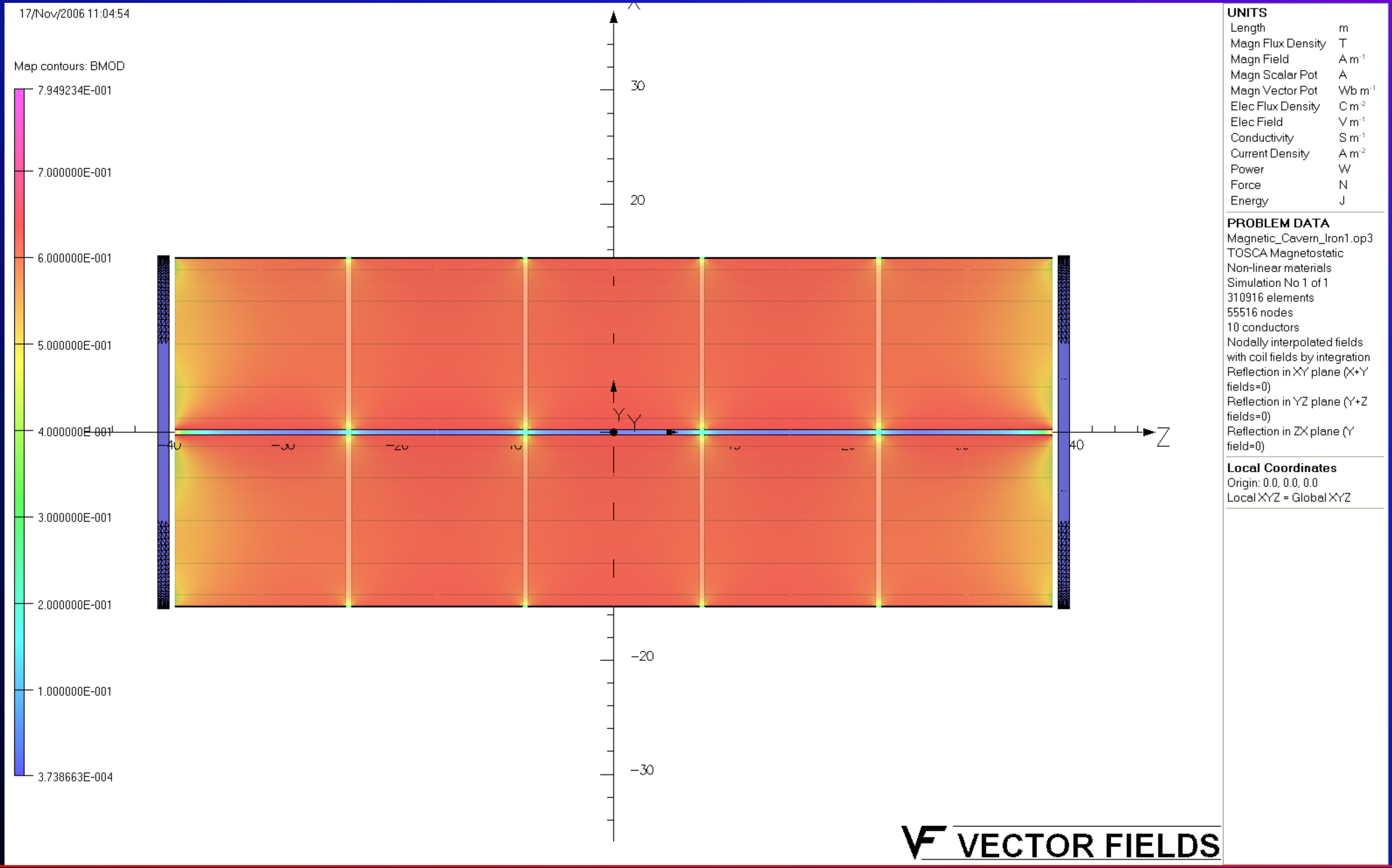
SCTL Parameters

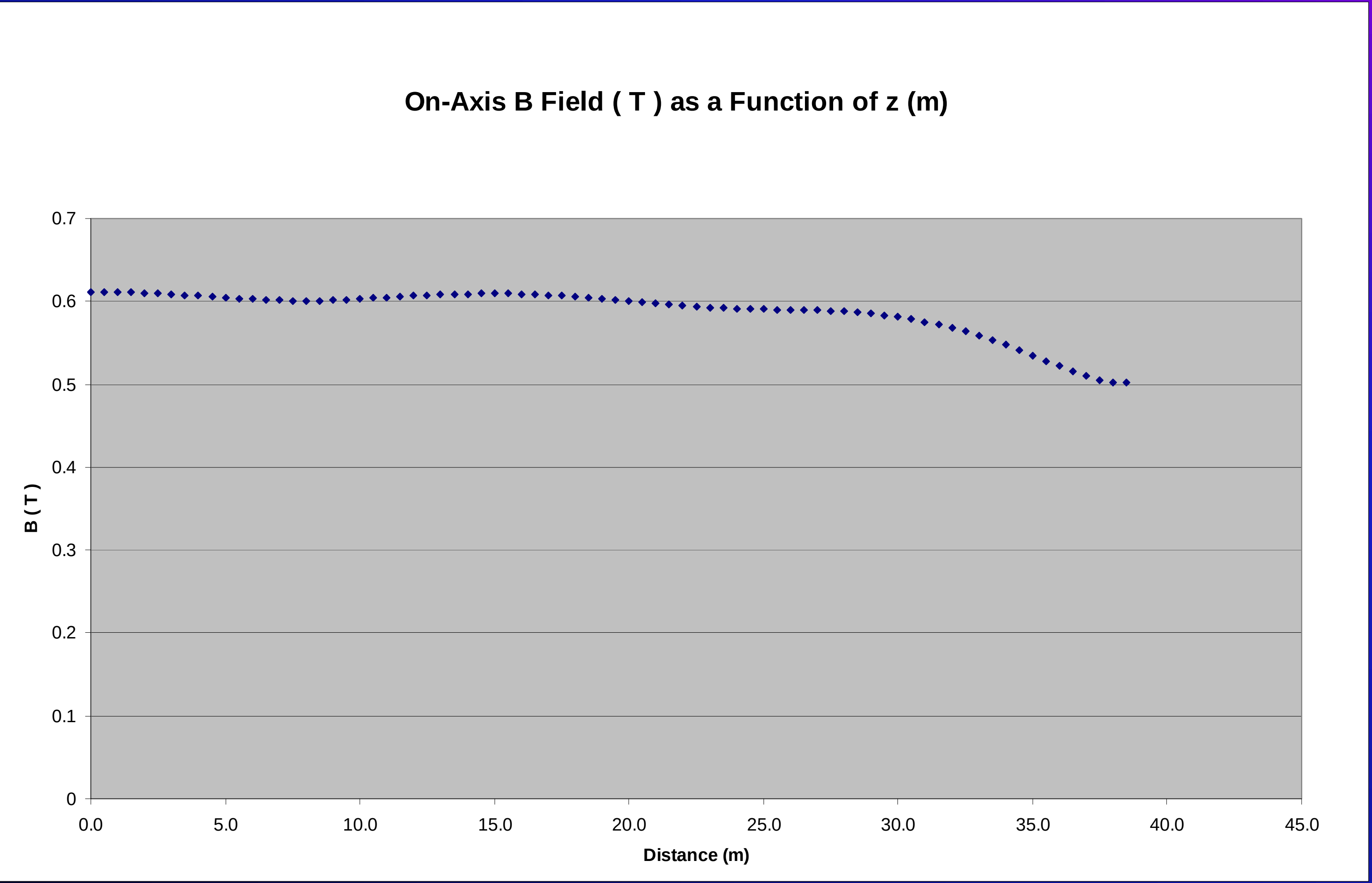
PARAMETER	UNIT	DESIGN	
		No iron	With iron
$I_{solenoid}$	MA	7.5	
N_{turns}/solenoid		150	
I_{turn}	kA	50	
$\|B\|_{average}$ in XZ	T	0.562	0.579
W_{total}	GJ	3.83	3.95
L_{total}	H	3.06	3.16
F_r maximum	kN/m	15.66	15.67
F_x maximum	kN/m	48.05	39.57

100 kA op demonstrated

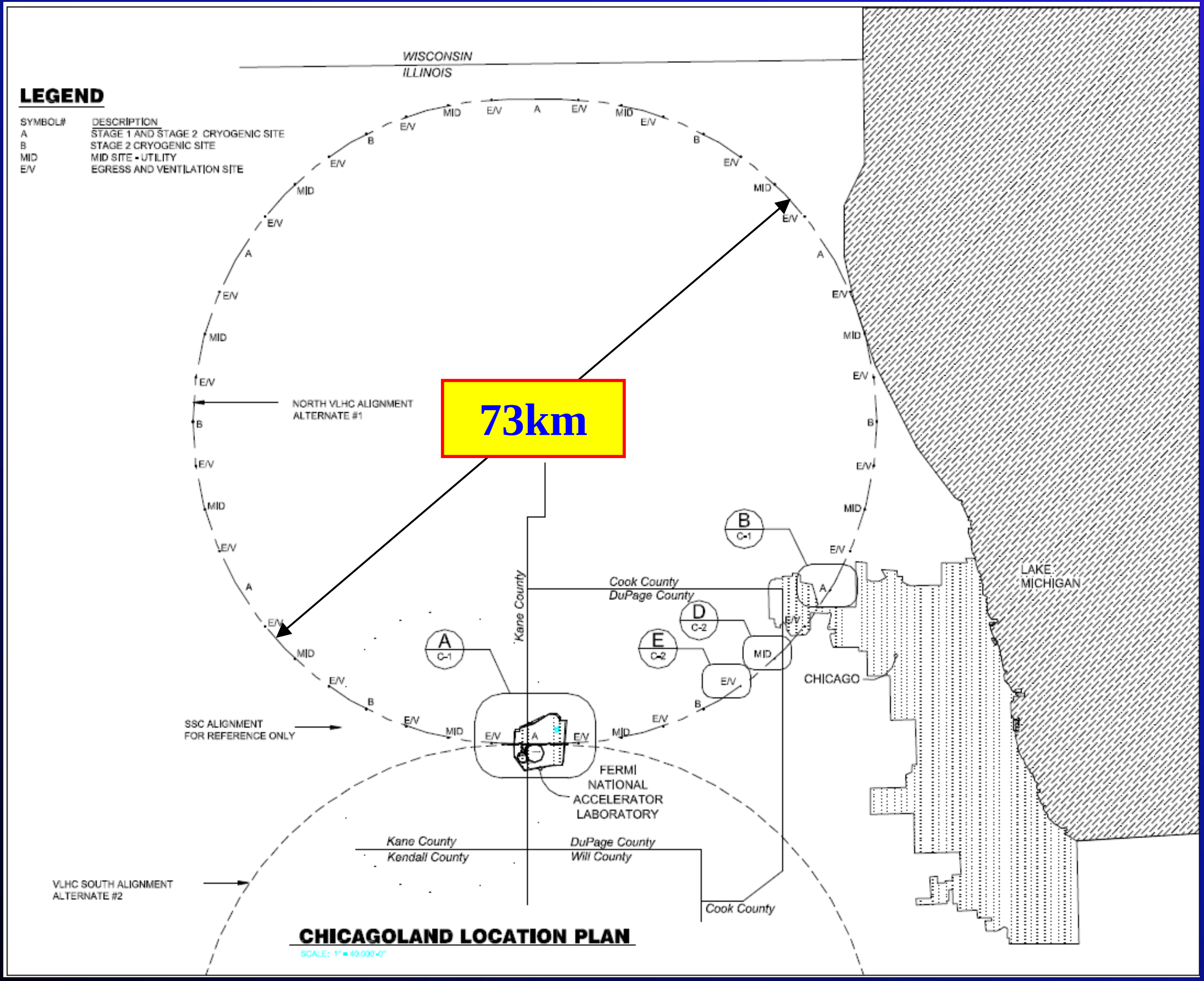
$1000/m ⇒ $50M

|B| in XZ cross-section



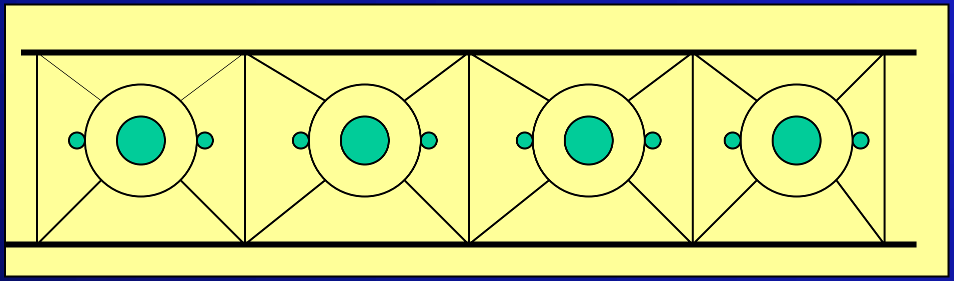

On-Axis B Field (T) as a Function of z (m)
B (T)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Distance (m)

R&D - VLHC and cable design



- Pipetron type cable
  - Needs modification to provide long length (~5-7 km) and flexibility (bending diameter 15 m)
- Solenoid Strong-Back
- Assembly procedure

New support structure and cable - Concept



Structure:

- Cable vacuum shell is now part of the solenoid support structure

LN shield is fabricated and installed independently:

- Two half-shells with LN pipes
- Super-insulation,
- Supports

Cable installed inside the LN shield:

- Thick LHe pipe with SC and Cu wires wound outside
- Thick Al or Cu tape (mechanical support and additional stabilizer) wrapped over SC/Cu wires
- Super-insulation
- Flexible (+/-2 mm dynamic range) supports

SCTL Approach to Large Solenoid – Conclusions

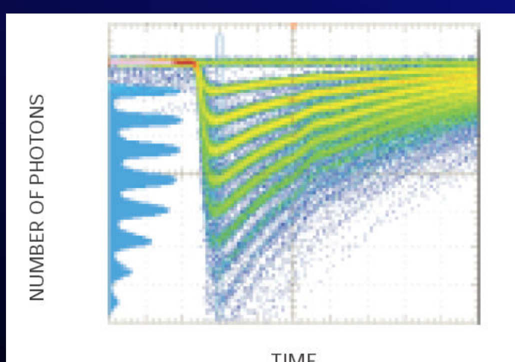
- The SCTL concept has been prototyped, tested and costed for the VLHC project
- Application for 15m diameter solenoids is different, however
  - Cost appears to be manageable (<$100-150M)
- R&D
  - Optimization of the SCTF for solenoid application
  - Engineering of fabrication process
  - Engineering of support structure
- R&D Program
  - Will discuss in session on TASD prototyping

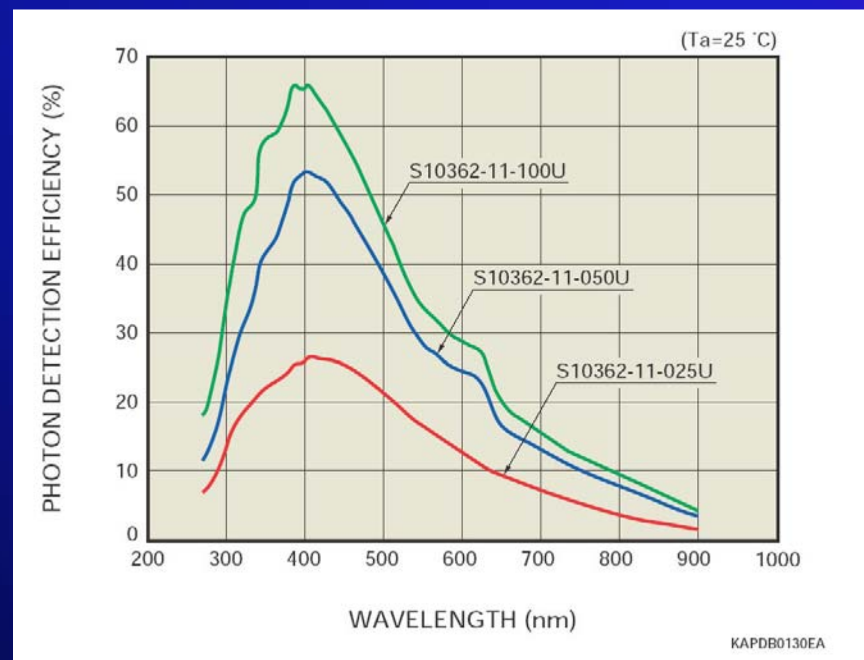
Scintillator

- There are really no technical show-stoppers here. It is just a matter of cost reduction
- Relatively small R&D Program ($250k)
  - Extrusion Die design to increase production through-put and efficiency
  - Extrusion Die Design to allow for co-extrusion of WLS fiber with scintillator profile
    - Has already been done successfully in tests on post-cladding Kuraray fiber with various polymers.
      - These were thin (100-300 μm), however

Photo-Detector and Electronics

- Here the R&D is already occurring all over the globe
- Silicon-PM, aka MPPD, aka MRSD
  - Hamamatsu, RMD
  - Potential to lower the channel cost to <$10/ch (Target $5)





Outlook

- A Low-Energy Neutrino Factory (coupled with the right detector) gives excellent capability in exploring the full neutrino mixing matrix and measure leptonic CP violation
- A finely segmented TASD is quite possible the right analysis tool for a Low-Energy NF
  - Much more simulation/study needs to be done, but the initial results are promising
  - Detector R&D program is well-defined
    - Magnet - $2-5M
    - Scintillator - $250k
    - Photo-detector – wait and see

Detector Cost
Magnet - $150M
Scintillator & Fiber - $150M
PD & readout - $100M

- A Low-Energy Neutrino Factory (4 GeV) is certainly cheaper than a 20 GeV facility.
- Plus with proper planning a Low-Energy Neutrino Factory might be upgradeable to higher energy