Motivation

DUNEPrism

Easy Beam Options

Difficult Options

To Do

LBNF/DUNE Beam Options and ND Measurements

4th DUNE ND Workshop, Fermilab, March 22-24, 2018

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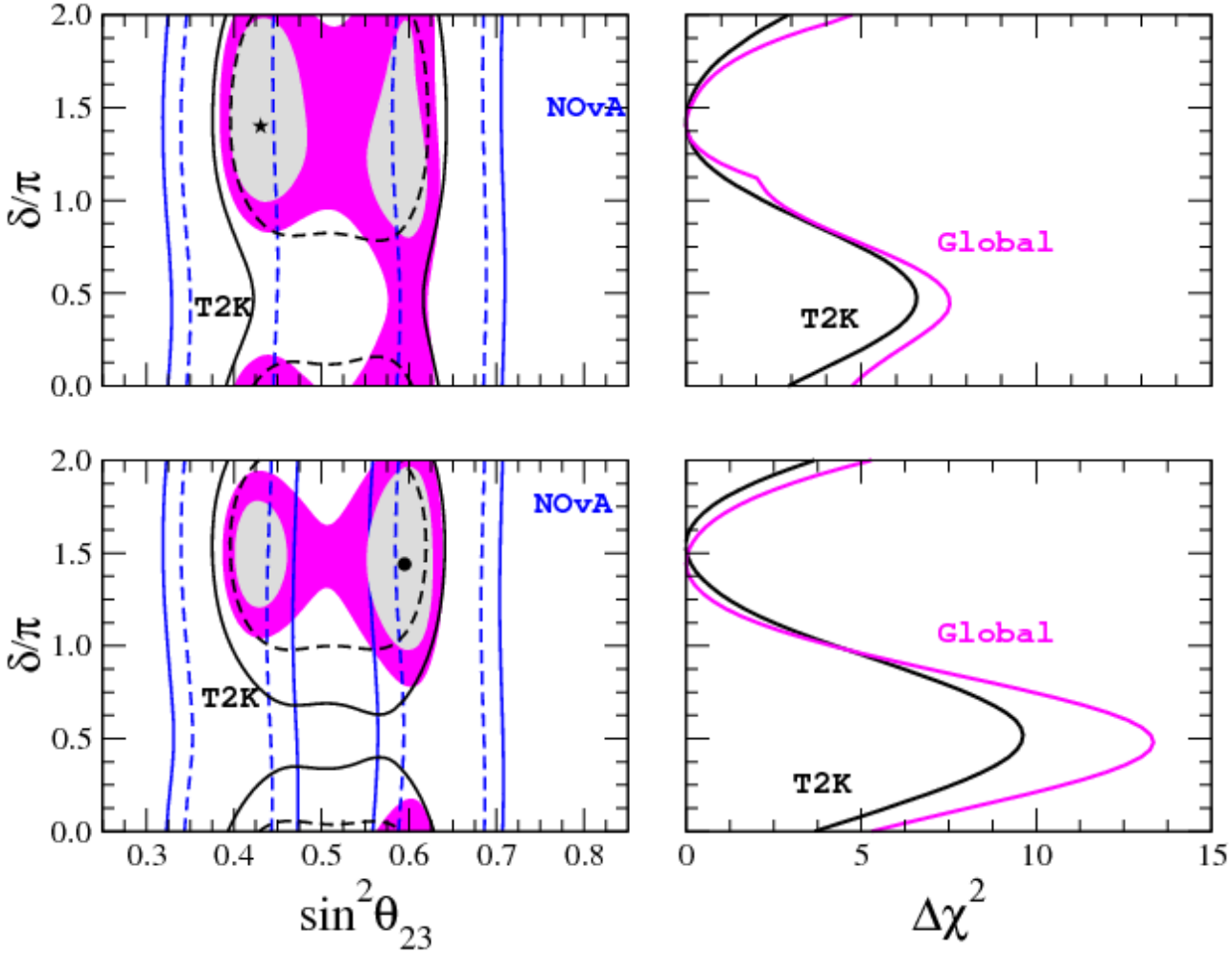
Brookhaven National Lab

March 23, 2018

Latest Results on δ_{cp} (Global Fits)

P. F. de Salas et. al. arXiv 1708.01186 (Aug 2017):

— 99% CL — 90% CL



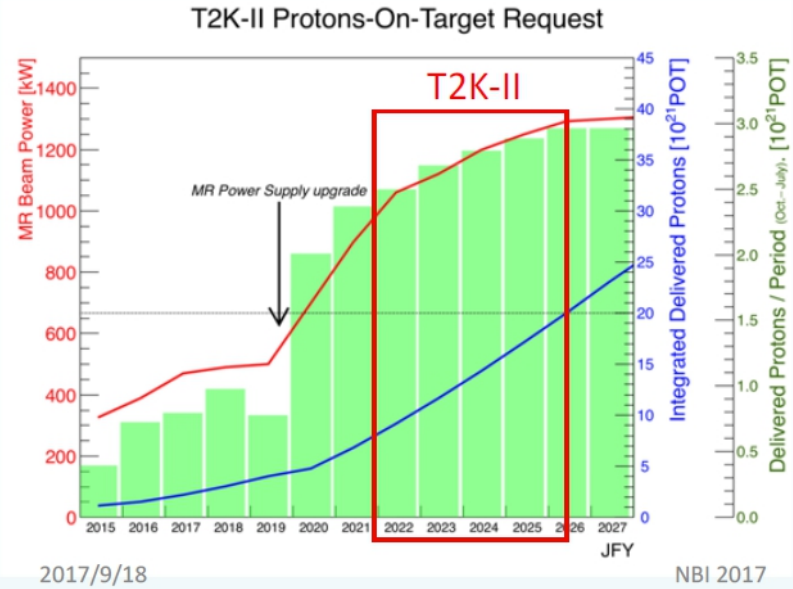
The current results favor maximal CP at NH

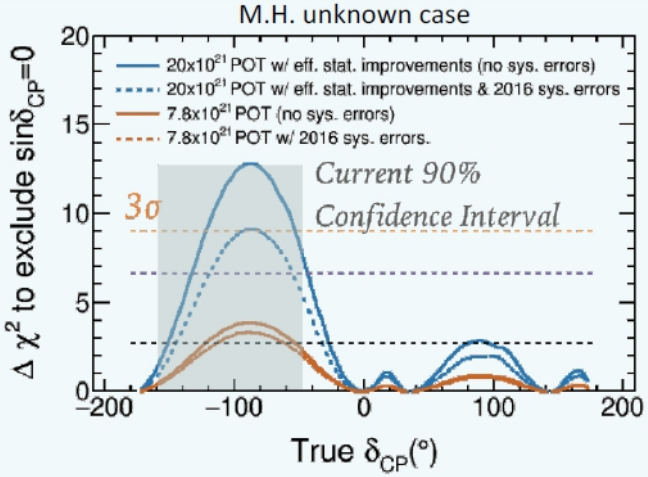
T2K II

Extension to T2K-II obtained stage-1 status at the J-PARC PAC of July 2016.

- Accumulate 20x10^{21} POT by 2026 for **3σ sensitivity** to CP violation in neutrino oscillation.
- With >MW accelerator & neutrino beam-line, ND-upgrade, and Gd-added SK

ND upgrade in progress with CERN SPSC EoI-015.





T2K-II improved feature

- MR beam power to 1.3MW with
  - 1.16s operation cycle with new P.S.
  - reinforced RF system
- Neutrino beamline upgrade for
  - cooling capacity improvement
  - radio-active water disposal
- Install new detectors in ND280
- SK tank refurbishment and adding Gd

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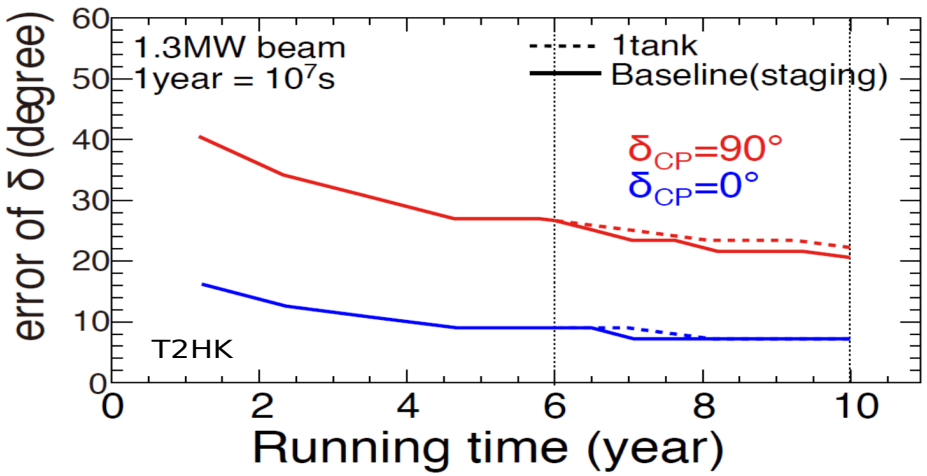
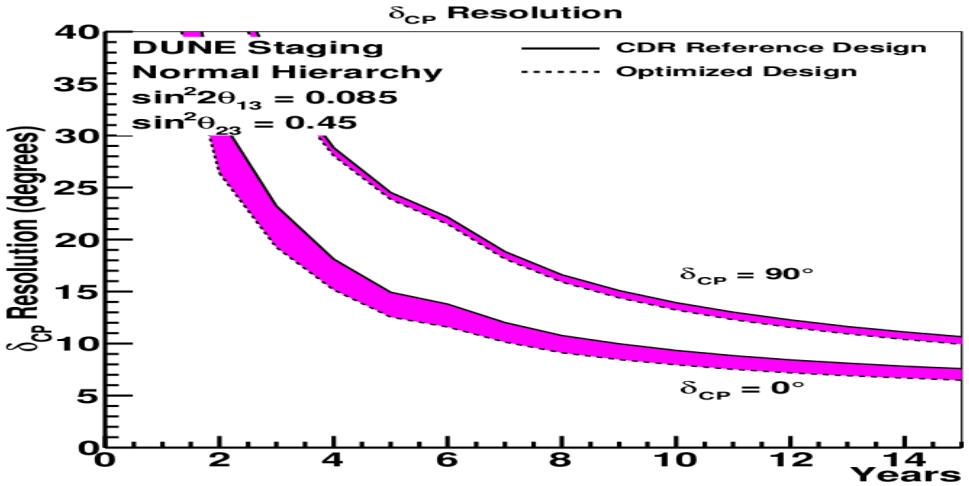
Maxmimal CPV $> 3\sigma$ within our sights!

Y, Fujii, NBI2017

How does this change the physics goals for DUNE

How well do we need to know δ_{cp}?

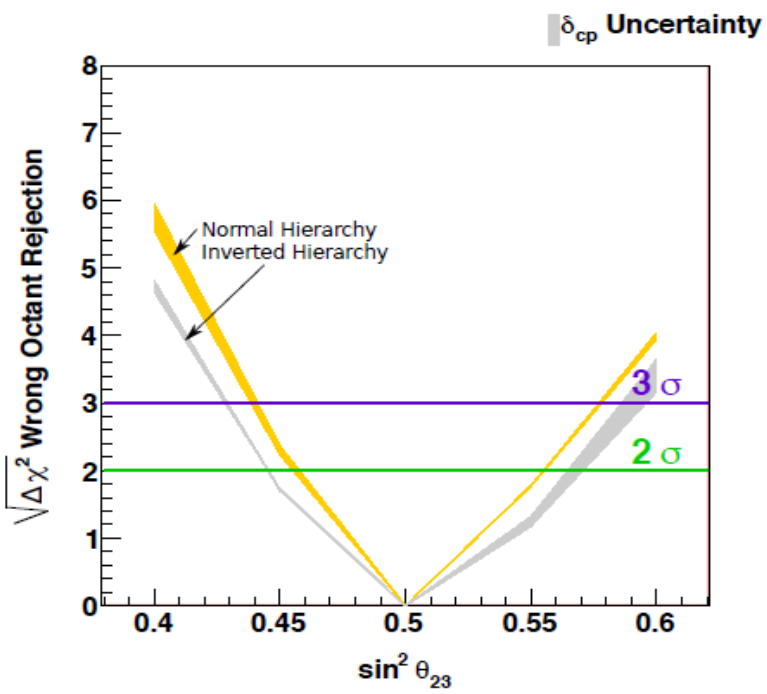




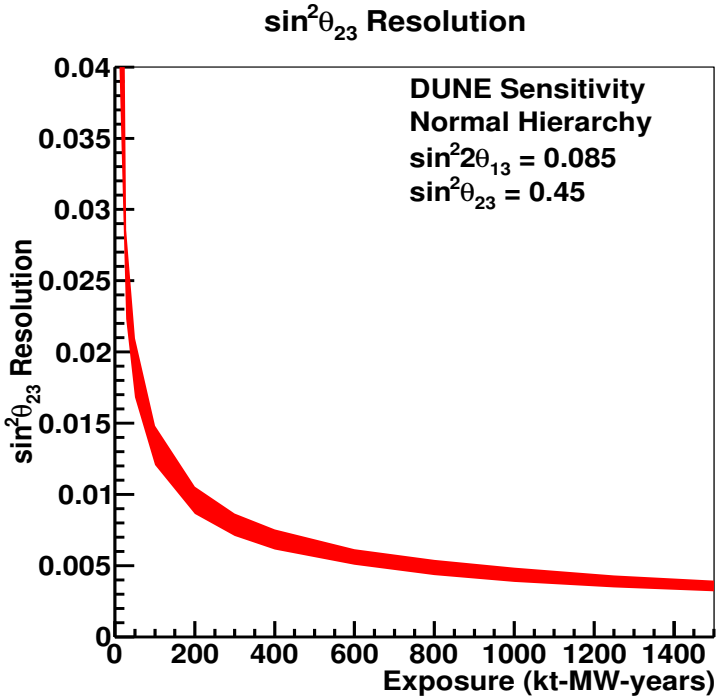
Theorists want 3° resolution on $\delta_{cp} = 3\pi/2$ to constrain baryogenesis.

A resolution of $\leq$ 10° should be our NEW goal

How well do we need to know θ_{23}?



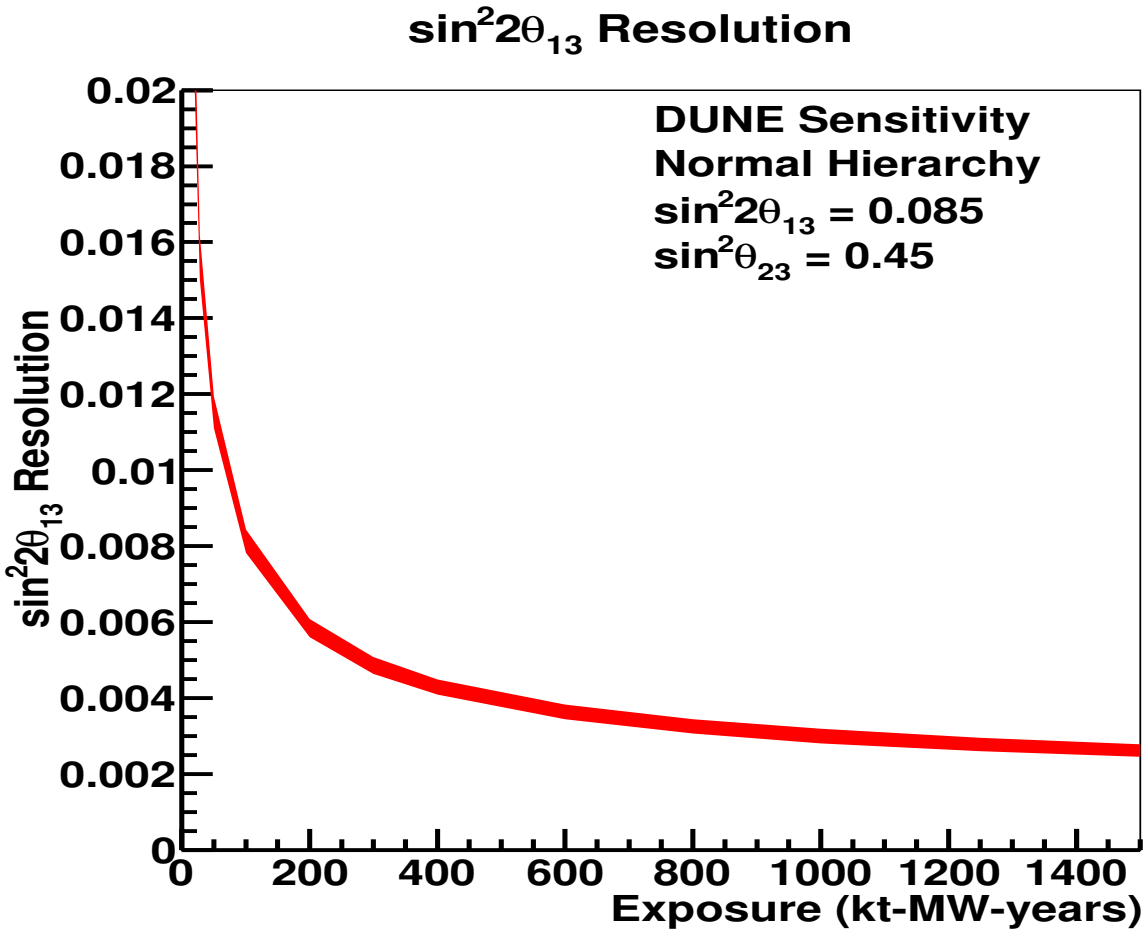
HyperK Octant (Atmospheric)



DUNE θ_{23} resolution (beam)

We need to resolve the θ_{23} octant - but what about the resolution?

Unitarity tests: θ_{13} Measurements

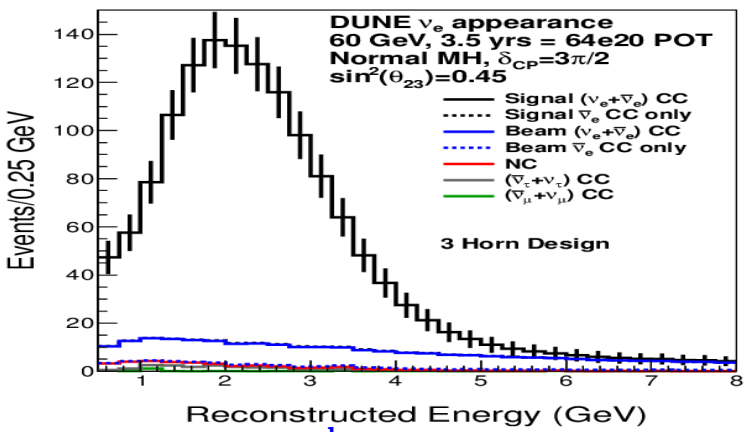


DUNE can eventually reach same $\sigma(\theta_{13})$ as reactors

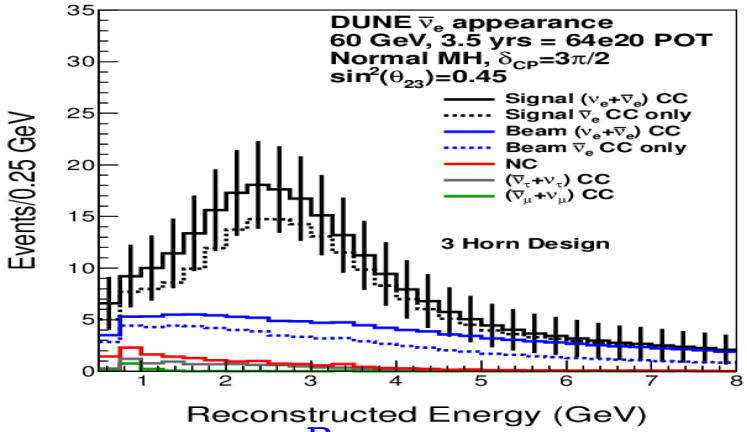
IF WE BELIEVE THE ASSUMPTIONS ON PERFORMANCE in CDR !!!

DUNE Event Spectra

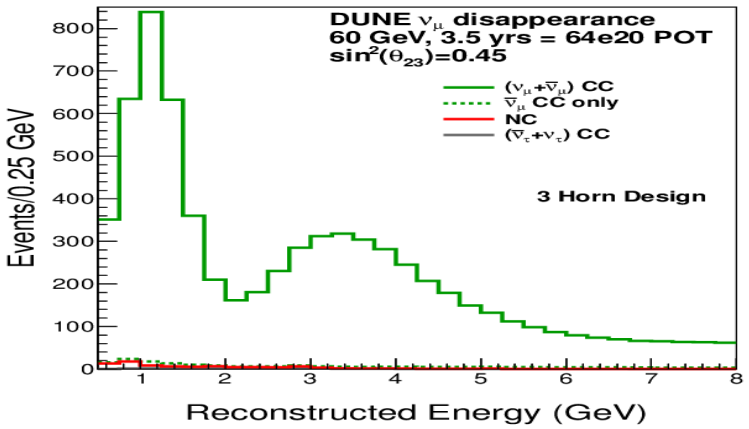
Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr $= 1 \times 10^{21}$ p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085$, $\sin^2\theta_{23} = 0.45$, $\delta m^2_{31} = 2.46 \times 10^{-3}$ eV^2)



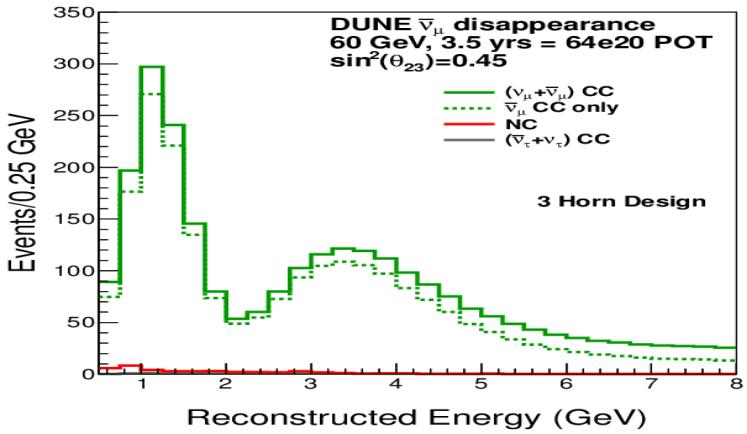
1171 ν_e,3 $\bar{\nu}_e$, 204 ν_e^{beam}, 17 NC, 19 ν_τ, 3 ν_μ



94 $\bar{\nu}_e$,39 ν_e, 98 ν_e^{Beam}, 7 NC, 8 ν_τ, 1 ν_μ



8329 ν_μ, 192 $\bar{\nu}_\mu$, 72 NC, 29 ν_τ



2420 $\bar{\nu}_\mu$, 791 ν_μ, 33 NC, 13 ν_τ

Spectral information in all 4 samples determines resolutions on parameters But asssumptions in CDR did not include energy scale uncertainties and spectral uncertainties due to ν interaction models!

Challenges for ND measurements

- **Wide-band beam poses problem for ND cross-section and flux measurements. Incoming neutrino energy is not known well and limits how well we can extrapolate to FD.**
- **Cross-section models of intra-nuclear effects and the modeling of neutrals produced (like neutrons) are difficult to nail down.**
- **ND measurements of neutrals produced in the interactions are difficult. In addition missing p_T techniques are not very accurate due to large scattering on heavy nucleus $\Rightarrow$ limited ability to reconstruct true neutrino energy accurately.**
- **A data-driven measurement of the ND reco to true neutrino measurement is needed**
- **Off-axis concepts like DUNEPrism require moving or building ND detectors within a limited range of angles, and depend somewhat on beam modeling uncertainties to predict incoming flux.**
- **Proposals to measure ν cross-sections on Ar with exactly known fluxes like NuSTORM (muon storage ring) are expensive to realize. And beam is still wide-band**
- **What calibration beam options available from LBNF beamline?**

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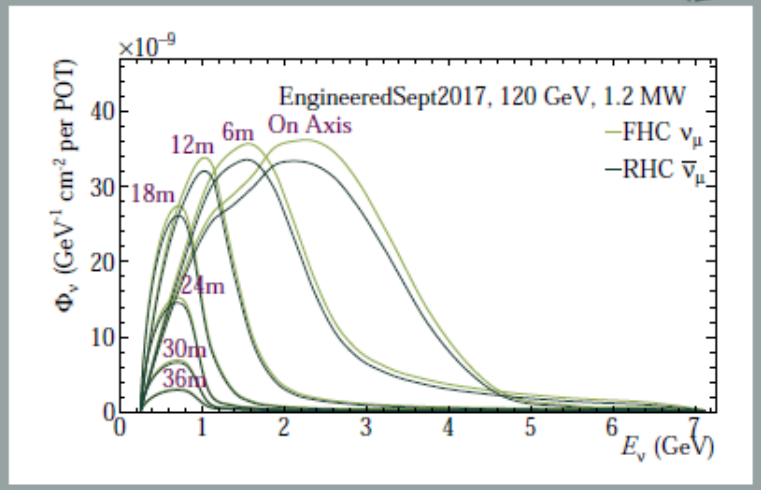
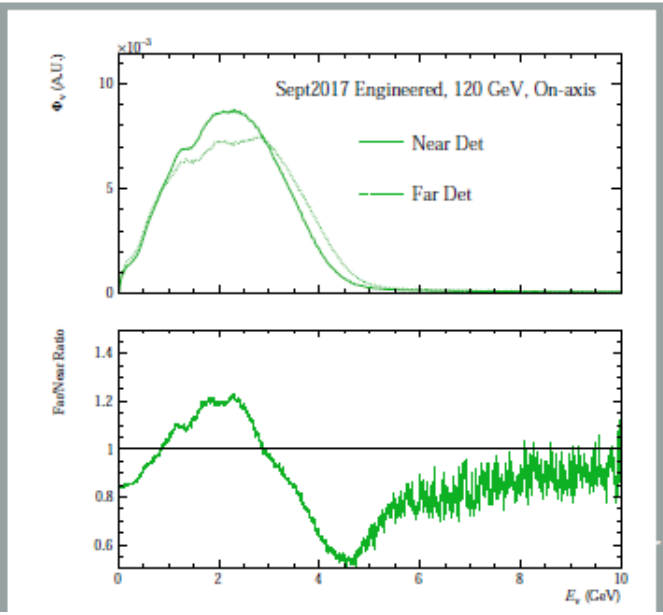
Beam simulation

- Beam simulation run using 1.5×10^8 POT.
- Uses `OptimizedEngineeredSept2017Review` `g4lbnf` macro.
  - 120 GeV, 1.2 MW proton beam
  - 1.1×10^{21} POT per year
- On axis predictions are in line with official beam group plots.





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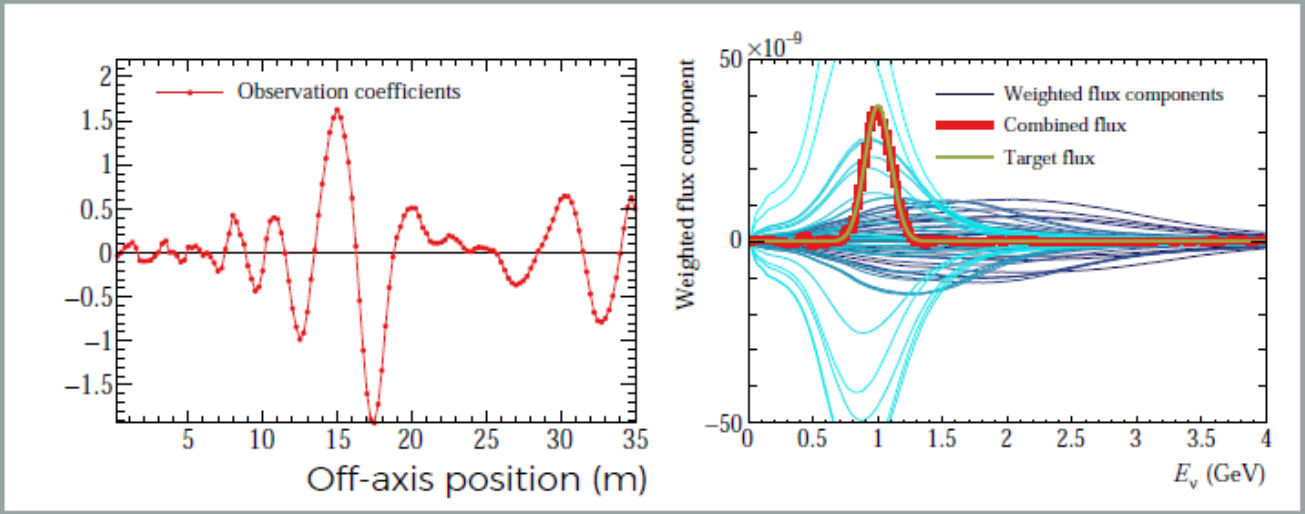
Linear combinations

- PRISM technique uses linear combinations of observations to construct a measurement of some observable under exposure to a chosen neutrino energy spectra.
- Coefficients needed to construct a given neutrino energy spectra are determined by fitting available fluxes.



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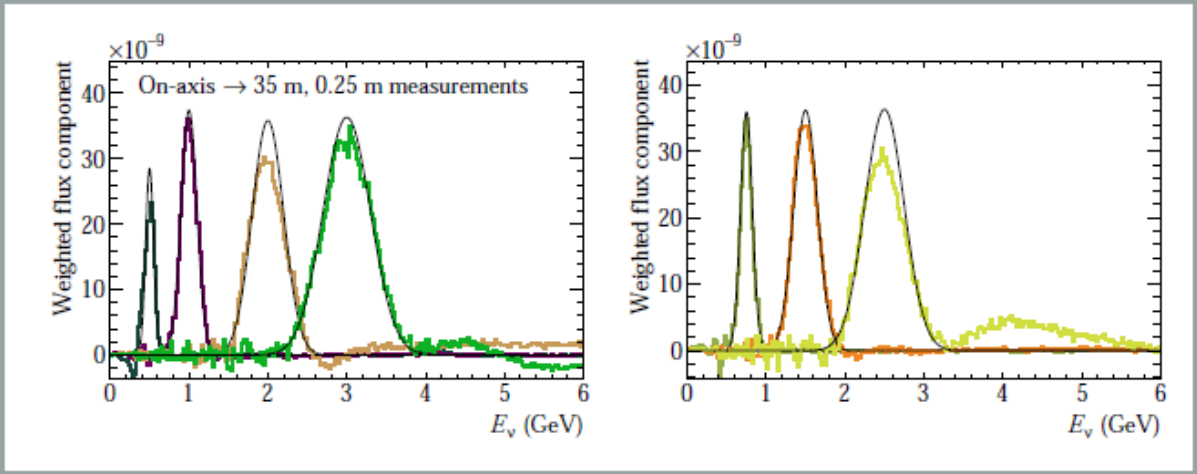
Fits to gaussian spectra

- Interaction models described as $\sigma\left(E_\nu, \vec{\mathbf{x}}\right) \rightarrow$ fitting for a given E_ν spectra allows measurements of any observable to be constructed: $E_{\mathbf{vis}}$, $p_{\ell pm}$, θ_π, ...
- Building quasi-monoenergetic fluxes: largely model-independent, *in situ* $E_{\mathbf{vis}}\left(E_\nu\right)$ measurements.
- Difficulty fully canceling high energy tail for Gaussian $\gtrsim 2.5\,\mathrm{GeV}$.



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Varying Horn Configurations

From R. Zaki's (Radaboud Univ.) studies:

Study on different horn configurations

Simulation data: Neutrino fluxes

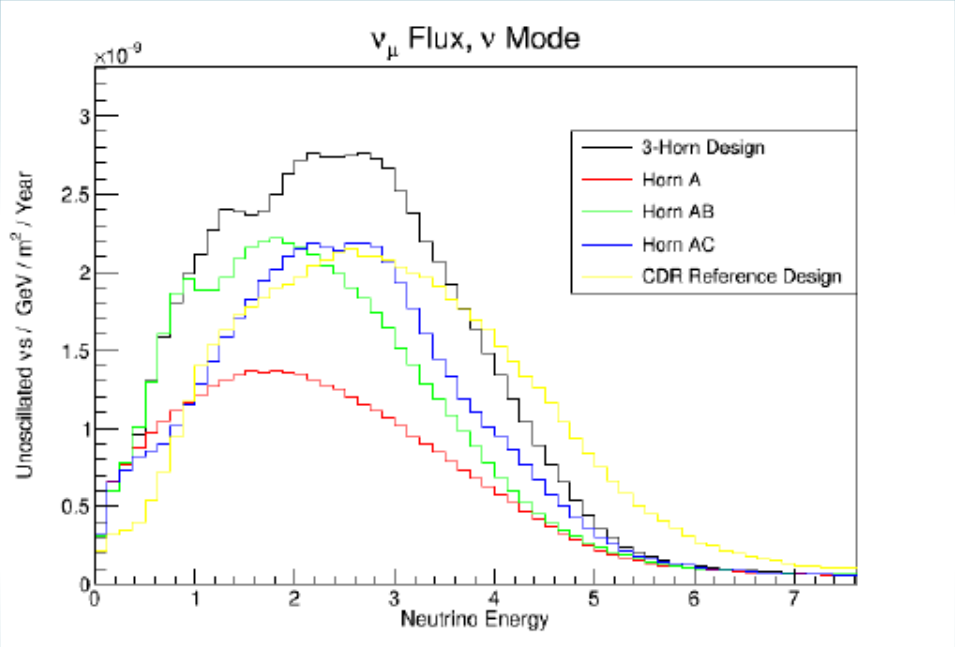


Figure: Neutrino flux for different Horn configurations

Important:

- Clear effect of separate horns on neutrino flux

Varying Horn Configurations

From R. Zaki's (Radaboud Univ.) studies:

Study on different horn configurations

Simulation data: Ratio of neutrino fluxes

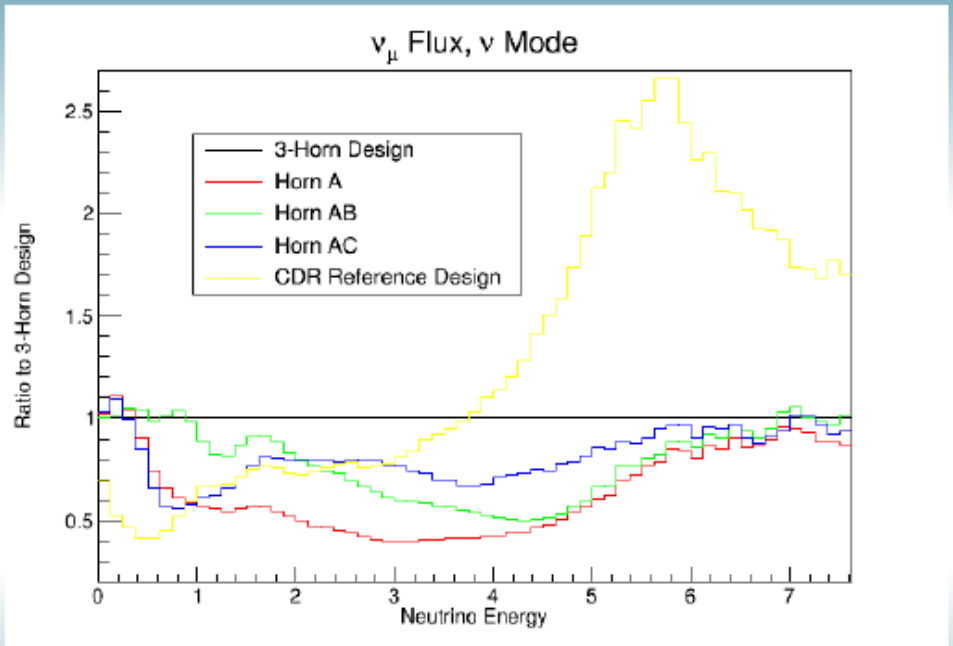


Figure: Neutrino flux ratios for different Horn configurations

Important:

- Large increase for higher energy neutrino flux in CDR design

Varying Horn Configurations

PROs:

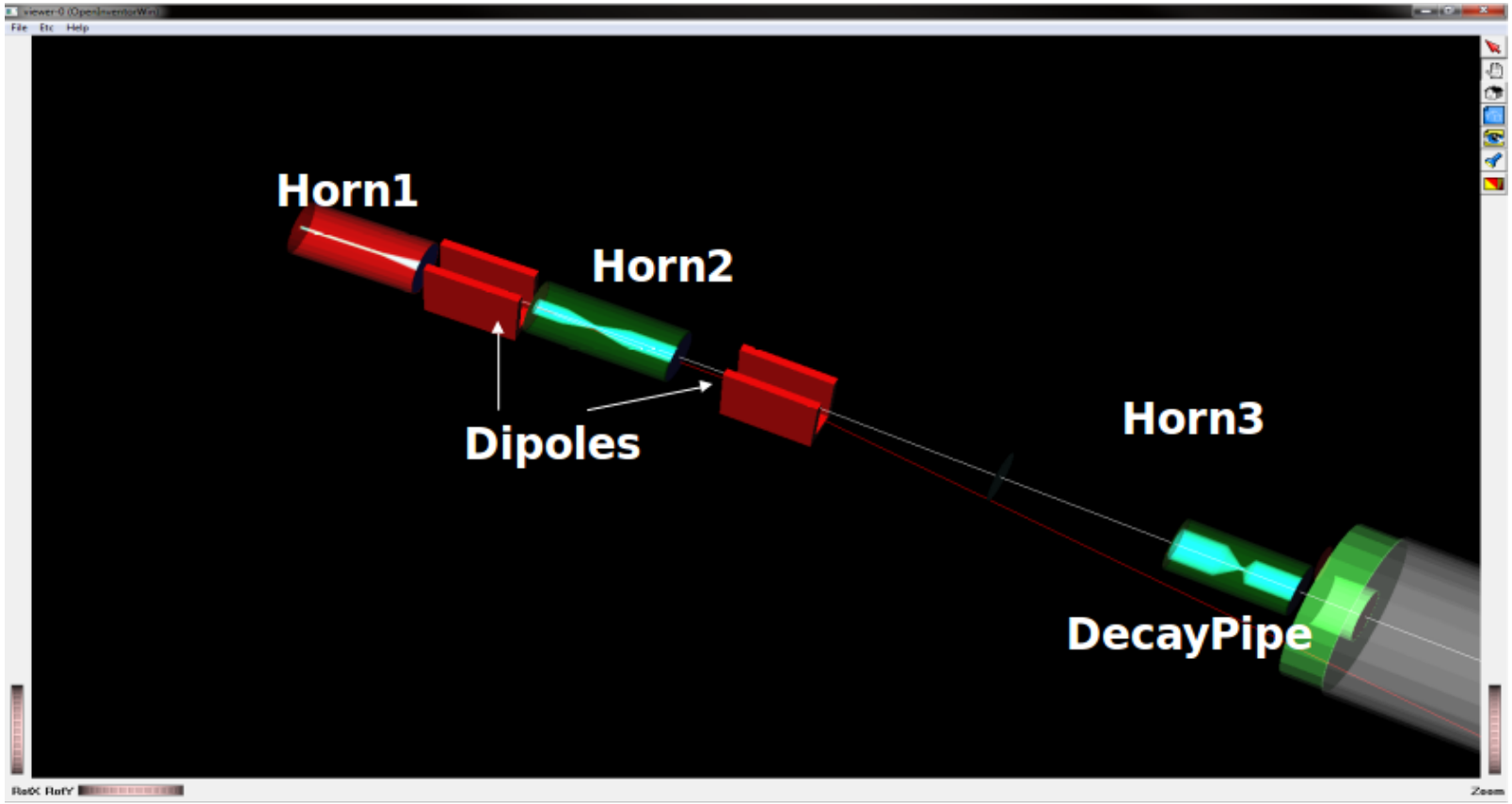
- **Scan different ranges of the beam spectra with full on-axis ND**
- **Combination of different horns running with different currents could provide a wide range of spectra.**
- **Modest modification to horn power supply (1 supply for all 3 horns) would enable individual horn off. This may also be desirable from an engineering point of view in case of horn failure (T2K experience).**
- **Could complement DUNEPrism measurements.**

CONs:

- **Modifications to PS could be of order $\sim$ 1$M.**
- **Downtime of few weeks (?) to disconnect a horn from PS.**
- **Difficult to get very narrow-band beams (but that may not be necessary), tunability is somewhat limited at lower energies**
- **Special runs would disrupt far detector running - depends on ND statistics how much.**
- **Still depends on knowing horn current modeling of horns**

Adding large Dipole Bending Magnets to LBNF Beamline inspired by A. Bross's NuPIL and M. Popovic's work

From M. Popovic's (Fermilab) studies:
Working Configuration (June 2016)



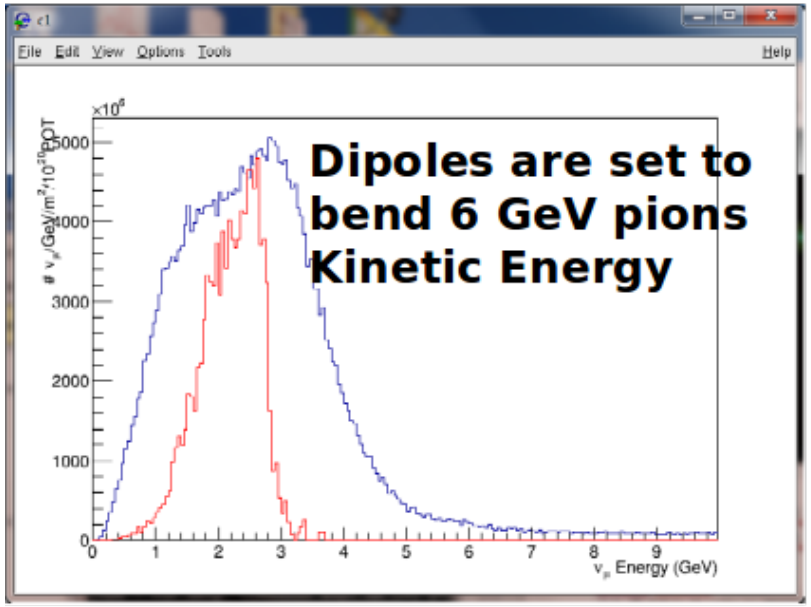
M. Popovic

Adding large Dipole Bending Magnets to LBNF Beamline

inspired by A. Bross's NuPIL and M. Popovic's work

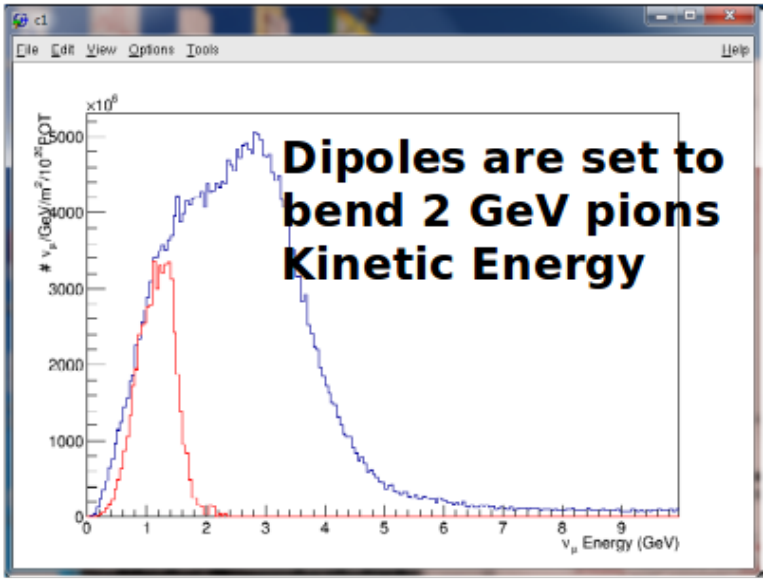
From M. Popovic's (Fermilab) studies:

Option 1, pions are bent for 5.7 degree



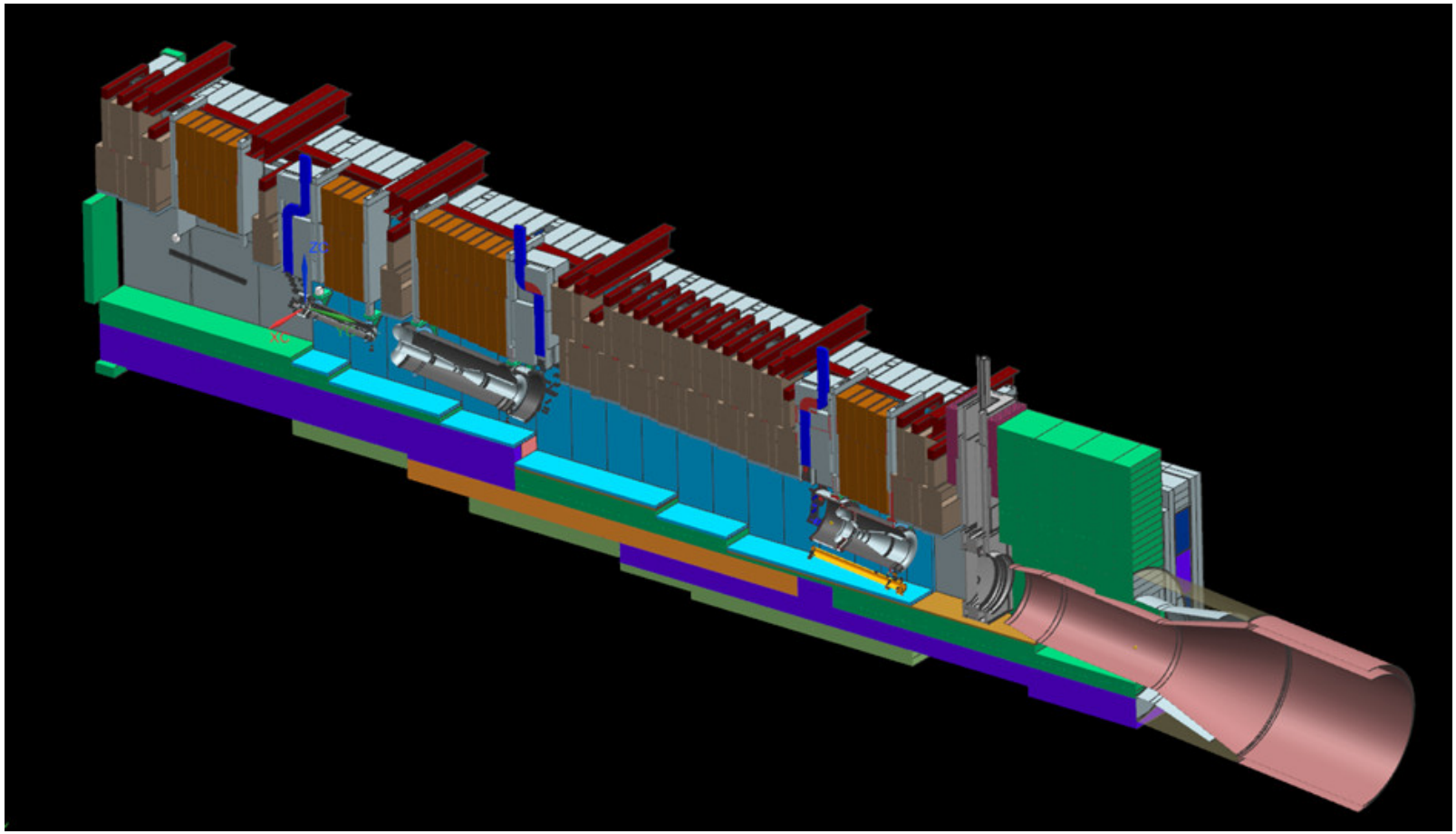
In presented concept, two bending magnets are identical, C-dipoles, conventional, iron dominated with field ~0.5T, ~2.4m long, gap 0.6 m and 1m field width. The first dipole is 0.2m separated from both horns. None of used parameters are optimized.

M. Popovic



Adding large Dipole Bending Magnets to LBNF Beamline inspired by A. Bross's NuPIL and M. Popovic's work

Current design for target chase:



Adding large Dipole Bending Magnets to LBNF Beamline inspired by A. Bross's NuPIL and M. Popovic's work

PROs:

- **Scan different ranges of the beam spectra with full ND**
- **Highly tunable with KNOWN π momentum bite**
- **Very "clean" beams - low wrong-sign contamination**
- **Could be accomodated as a special calibration run before shutdown for 2.4MW upgrade.**

CONs:

- **Highly disruptive to normal beam running (but see comment above)**
- **Requires large aperture rad hard dipoles to be built (existing technology is much smaller scale). Beam intensity could be lowered depending on ND target mass.**
- **Requires substantial ($$$) modifications to target facility**

  More shielding, larger crane capacity and power requirements,

  More RAW cooling capacity, beam window, bigger morgues....etc
- **Change from 2 to 3 horns required $34M extra... this could be more.**

To Do

- **Explore varying Horn currents as well as Horn on/off to assess the different range of beam spectra that could be available. Initiate a joint effort of Beam Interface and ND groups, particularly DUNEPrism to flush out needs.**
- **Explore further tunability/design of dipole option and possibility of narrower band beams. Right now the design was focused on getting a wide-band beam around 1st and 2nd maxima separately. This must be done soon because.....**
- **Any substantial modifications to beam infrastructure has to be determined NOW - even if chance of actual use is remote. Cant just "beef shielding up", need more quantative specifications for engineering team. While you dont need to install all extra capacity now, you need to engineer the facility** *to be upgradable* **NOW.**
- **NB: there is talk of 4MW beams .....**