A Neutrino Factory MIND at Large θ_{13}

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on behalf of the IDS-NF collaboration

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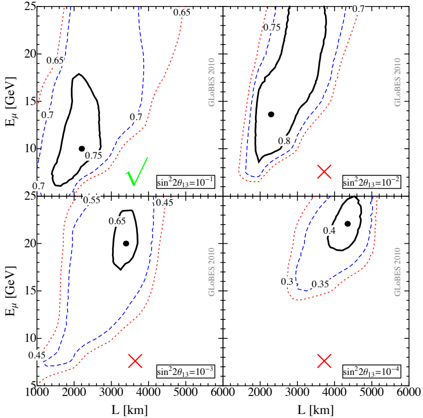
Consequences of Large θ_{13} on Neutrino Factory

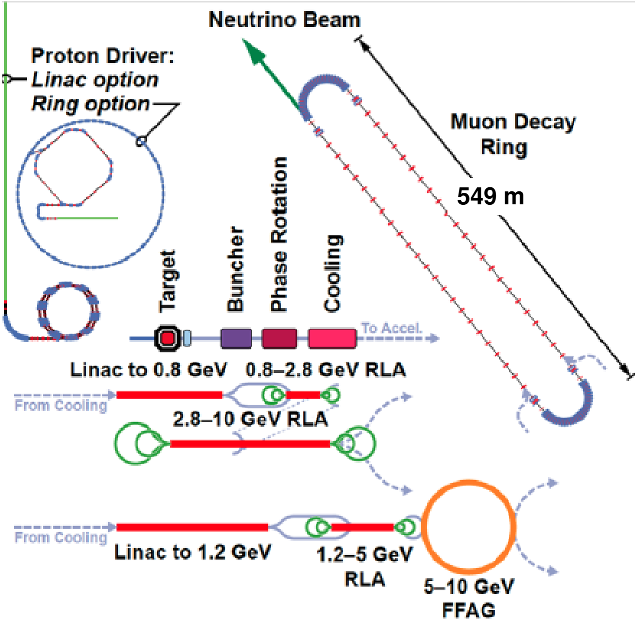
- Physics priorities shift to measurement of CP violation.
- For measurement of θ_{13} used
  - Two baselines: 4000 km and 7500 km
  - 25 GeV stored μ energy.
- Re-optimization of baseline and beam energy required
- Measurement of δ_{CP} achieved with
  - Single 2000 km baseline.
  - 10 GeV stored μ energy.



From IDS-NF-020, Interim Design Report

- MIND simulation used to examine sensitivities with these specifications.

New Baseline Neutrino Factory



- Single decay ring.
- Stores both μ^+ and μ^-.
- 10 GeV final muon energy.
- Either RLA or FFAG will be used in final design.

Physics at a Neutrino Factory

- Neutrino Factory provides neutrinos from μ^+ and μ^- decay.
- Will produce 5×10^{20} useful muons of both species per year.

ν Oscillation Channels

	Store μ^+	Store μ^-
Golden Channel	$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
ν_e Disappearance Channel	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
Silver Channel	$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$
Platinum Channel	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$
ν_μ Disappearance Channel	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$
Dominant Oscillation	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$

- MIND optimized for Golden Channel signal (wrong sign muon).

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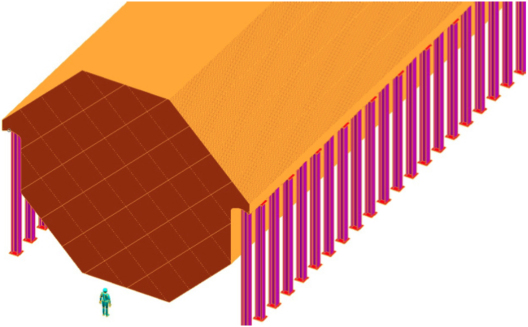
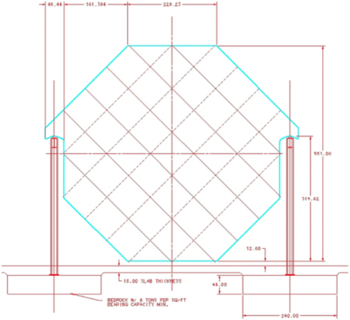
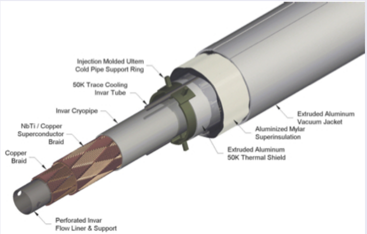
MIND Design for Neutrino Factory





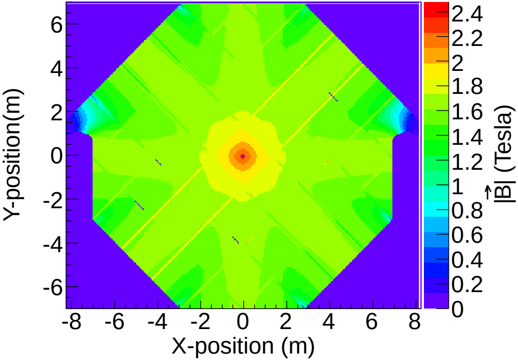
- 100 kTon detector
- 14 m×14 m×140 m.
- X and Y views from 2 cm thick lattice of 1 cm×3.5 cm scintillator bars.
- $\vec{B}$ field from 3 cm Fe plates, induced by 120 kA current carried by 7 cm diameter SCTL

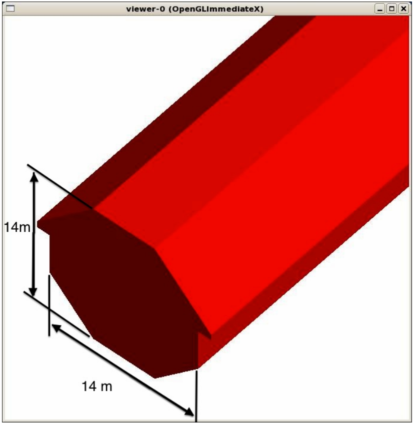
Superconducting Transmission Line



MIND Simulation

- Events simulated with GENIE.
- Full geometry & $\vec{B}$ field in GEANT 4
- Realistic field map generated by Bob Wands at FNAL
  - default positive focussing.



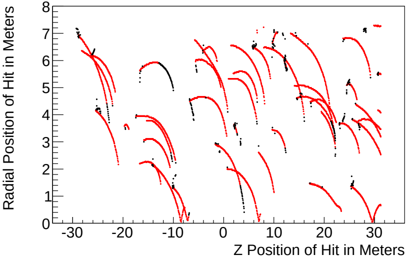


- Dimensions of detector easily altered for
  - optimization.
  - testing variations.

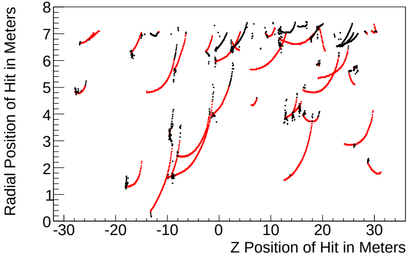
MIND Event Reconstruction

- Simulated events digitized.
  - Hits positions smeared and energy deposition attenuated.
  - Edep clustered into 3.5 cm×3.5 cm units.
- Tracks identified by Kalman Filter or Cellular automata.
- Kalman fitting used to determine momentum and charge.
- Algorithms from RecPack.
  - supported by Cervera-Villanueva *et al.*

- 50 $\bar{\nu}_\mu$ CC events.



- 50 ν_μ CC events.



- Fitted hits in red others in black.

Cuts Based Golden Analysis

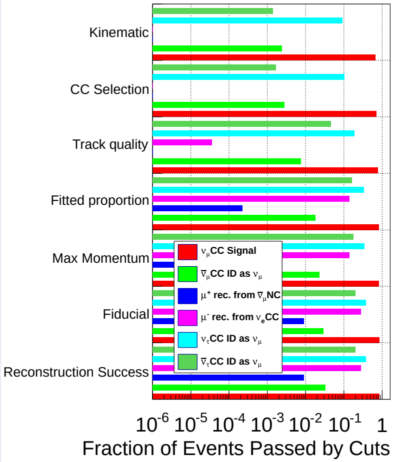
Described in detail in IDR.

- Separates NC like from CC like events.
- CC backgrounds are reduced as they are partially NC like.

Departures from IDR Analysis

- Quadratic and displacement cuts removed.
- Kinematic cuts replaced by a uniform requirement $Q_t > 0.15$ GeV

μ^+ or μ^- Focussing Magnetic Field



Consider ν_μ and $\bar{\nu}_\mu$ appearance.

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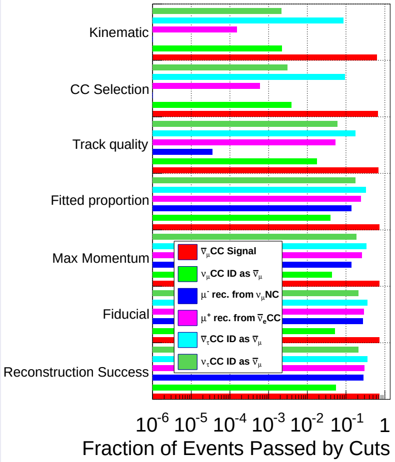

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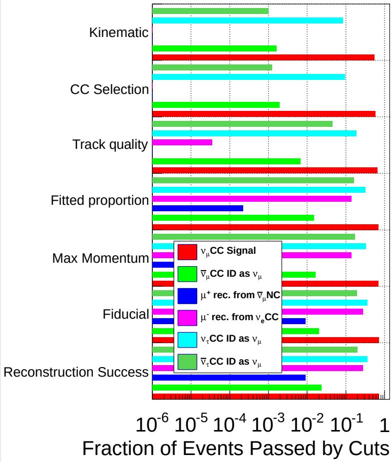

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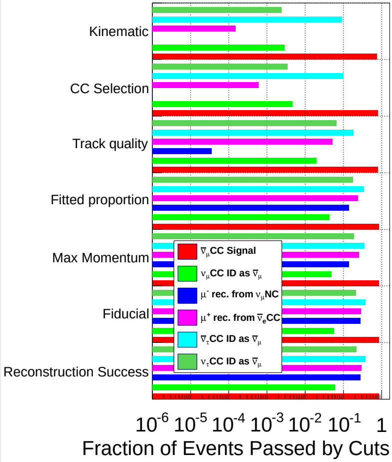

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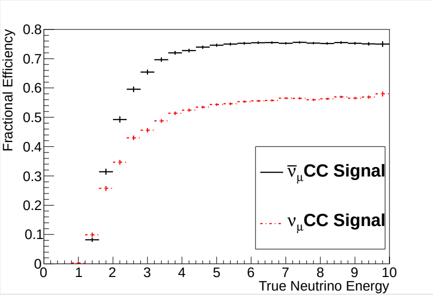
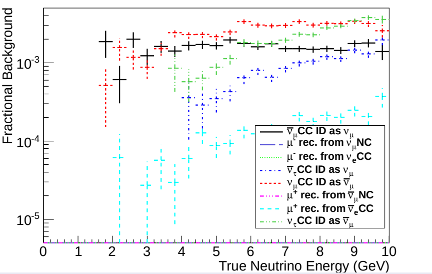
Charge Current Selection Efficiencies

Signal Efficiencies



Background



- All reconstruction efficiencies at or above 50%.
- Background suppressed by parts in 10^3.
- NC backgrounds completely suppressed.
- Efficiency behaviours different for positive and negative focussing.

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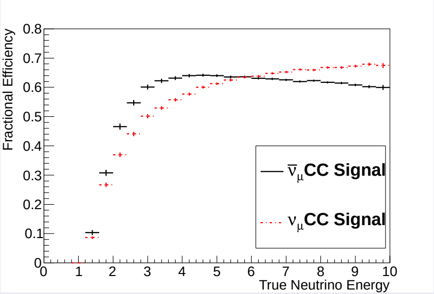

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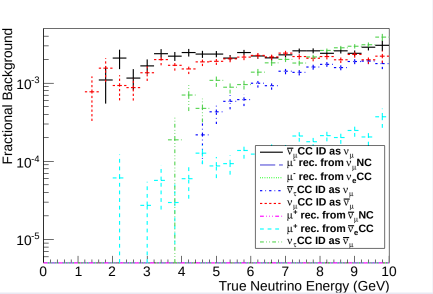

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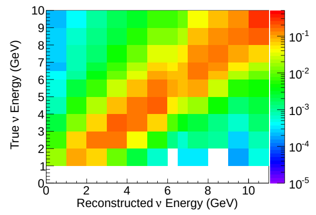
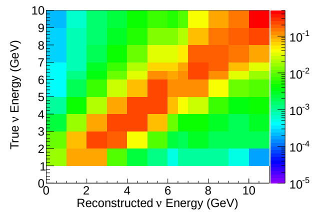
Energy Response in Octagonal MIND

Assuming 10 GeV factory

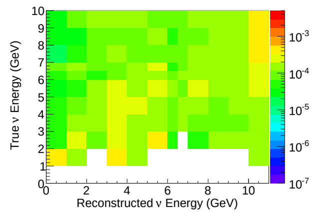
ν_μ Appearance Signal



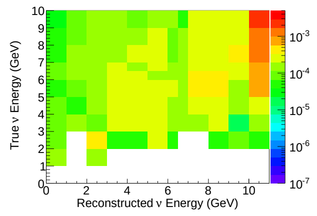
$\bar{\nu}_\mu$ Appearance Signal



ν_μ App. $\bar{\nu}_\mu$ CC Background



$\bar{\nu}_\mu$ App. ν_μ CC Background



- Two $\vec{B}$ settings.
- μ^+ Focussing.
- μ^- Focussing.
- Field settings run separately.
- Optimization still required

Energy Response in Octagonal MIND

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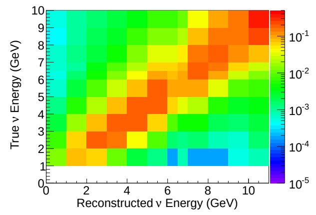

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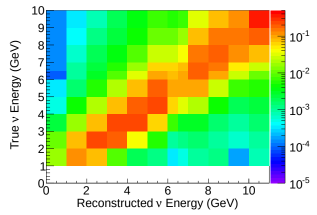

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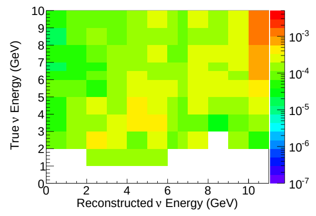

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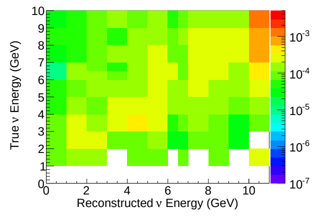

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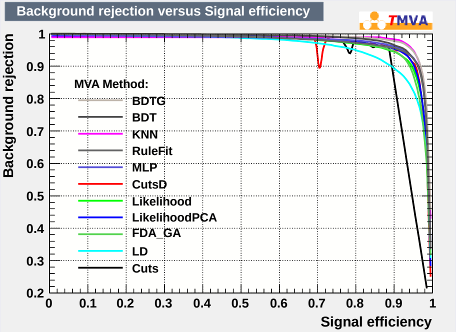
Multi-Variate Analysis

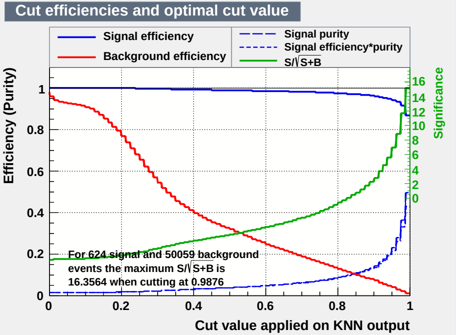
- A full multivariate analysis is under development.
  - Use a set of correlated variables to select signal from background.
- Should be able to achieve higher efficiency than existing analysis.
- Still a work in progress.

Variety of Methods Tested



Background rejection versus Signal efficiency

Example KNN Method



Cut efficiencies and optimal cut value

For 624 signal and 50059 background events the maximum $S/\sqrt{S+B}$ is 16.3564 when cutting at 0.9876

Extracting Sensitivities from Simulation

- Use the simulation to produce "migration matrices"
  - Relates true neutrino energy to reconstructed energy.
  - Contains efficiency, energy resolution, and response information.
- Run pseudo-experiments with simulation package (ie. NuTS).

Data is composed of sum

$$n_i^{data} = M_{ij}^{sig} \nu^{sig}(E_j) + \sum_k M_{ij}^{bkg,k} \nu^{bkg,k}(E_j)$$

Define a fit of θ_{13} and δ_{CP}, simultaneously

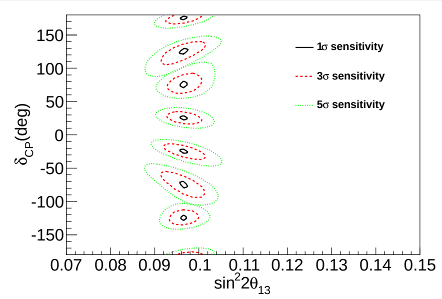
$$\begin{aligned} \chi^2 &= 2\sum_{i=0}^{L} \Bigg(AxN_{+,i}(\theta_{13}, \delta_{CP}) - n_{+,i}^{data} + n_{+,i}^{data} \ln\left(\frac{n_{+,i}^{data}}{AxN_{+,i}(\theta_{13},\delta_{CP})}\right) \\ &\quad + AN_{-,i}(\theta_{13}, \delta_{CP}) - n_{-,i}^{data} + n_{-,i}^{data} \ln\left(\frac{n_{-,i}^{data}}{AN_{-,i}(\theta_{13},\delta_{CP})}\right) \\ &\quad + \frac{(A-1)^2}{\sigma_A^2} + \frac{(x-1)^2}{\sigma_x} \Bigg) \end{aligned}$$

Preliminary Precision in δ_{CP} For Octagonal MIND

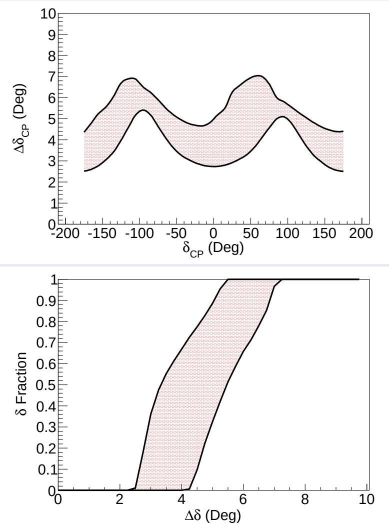
Assuming 10 GeV Factory, 10 years Running, 0.5×10^{21} μ^+ + 0.5×10^{21} μ^- per year

- Uses cuts-based analysis.
- Consider μ^+ and μ^- focussing
- Systematic variations shown (σ_A, σ_X)=(1%, 1%)→(2.5%, 3%).

χ^2 Contours; Arbitrary δ_{CP}, $\theta_{13} = 9°$



Error in δ_{CP} from 1 σ curves



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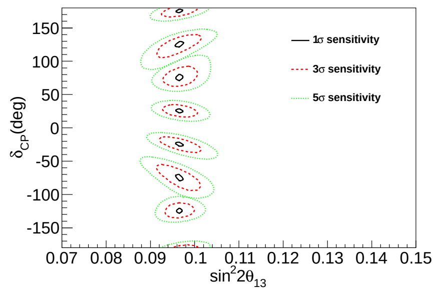

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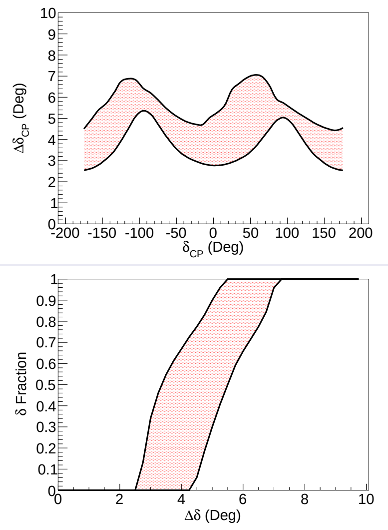


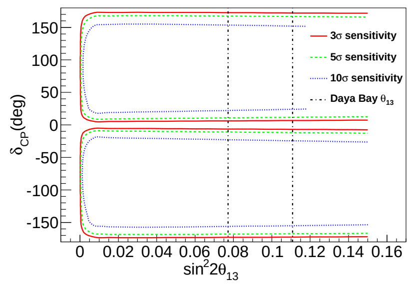
Preliminary Sensitivity to δ_{CP}

Assuming 10 GeV Factory, 10 years Running, 0.5×10^{21} μ^+ + 0.5×10^{21} μ^- per year

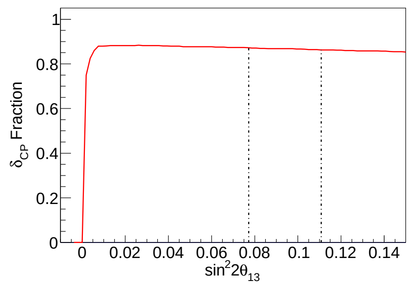
Contours determined using the expression

$$\max(\chi^2(\delta_{CP} = -180^\circ), \chi^2(\delta_{CP} = 0^\circ), \chi^2(\delta^0_{13} = 180^\circ)) - \chi^2_{min} \geq n^2$$

Sensitivity curves



5σ Discovery Potential



- Both normal and inverted hierarchy cases are considered.

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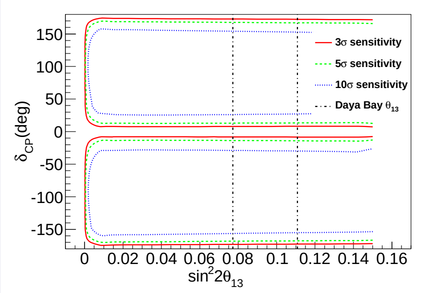

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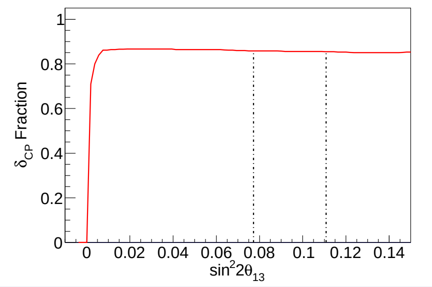

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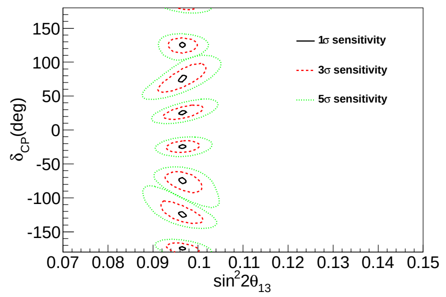
What About Dipole Geometry at 10 GeV?

Assuming 10 GeV Factory, 10 years Running, 0.5×10^{21} μ^+ + 0.5×10^{21} μ^- per year

- Achieved 10^{-4} background rejection in IDR
- Similar efficiency.
- Optimized for two baselines.

χ^2 Contours; Arbitrary δ_{CP}, $\theta_{13} = 9°$



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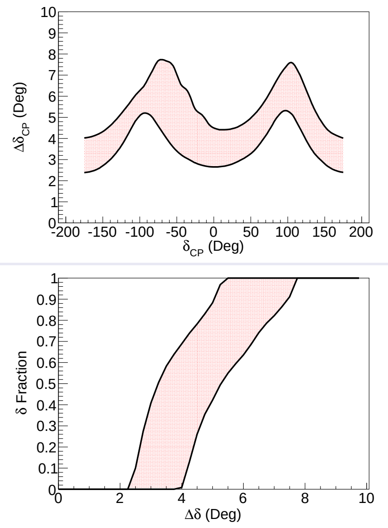
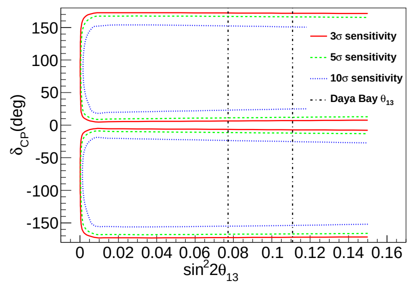


What does this tell us?

δ_{CP} Sensitivity curves



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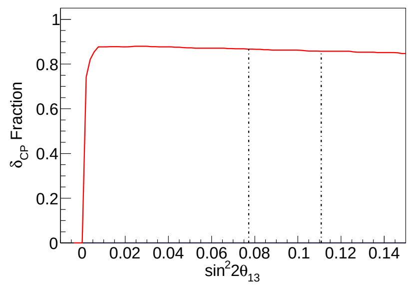

- δ_{CP} precision and sensitivity comparable between dipole and toroidal analyses for the same experimental conditions.
- Reduction of backgrounds does not increase sensitivity.
- Will reduction of energy threshold help?

Outlook

There has been great progress in the past year.

- Complete change to GENIE event generator.
- Introduction of realistic octagonal geometry
- Improvement of reconstruction to allow toroidal field.

Still work in progress

- Reconstruction of secondary, hadron tracks.
- Update to use multi-variate analysis.
- Optimize analysis for physics outcomes.

Early conclusions

- Preliminary precision of δ_{CP} between 2° and 8° with toroidal magnetic field.