Fermilab

EFFECT OF SYSTEMATIC UNCERTAINTIES ON NOνA FAR/NEAR EXTRAPOLATION USING FNEX

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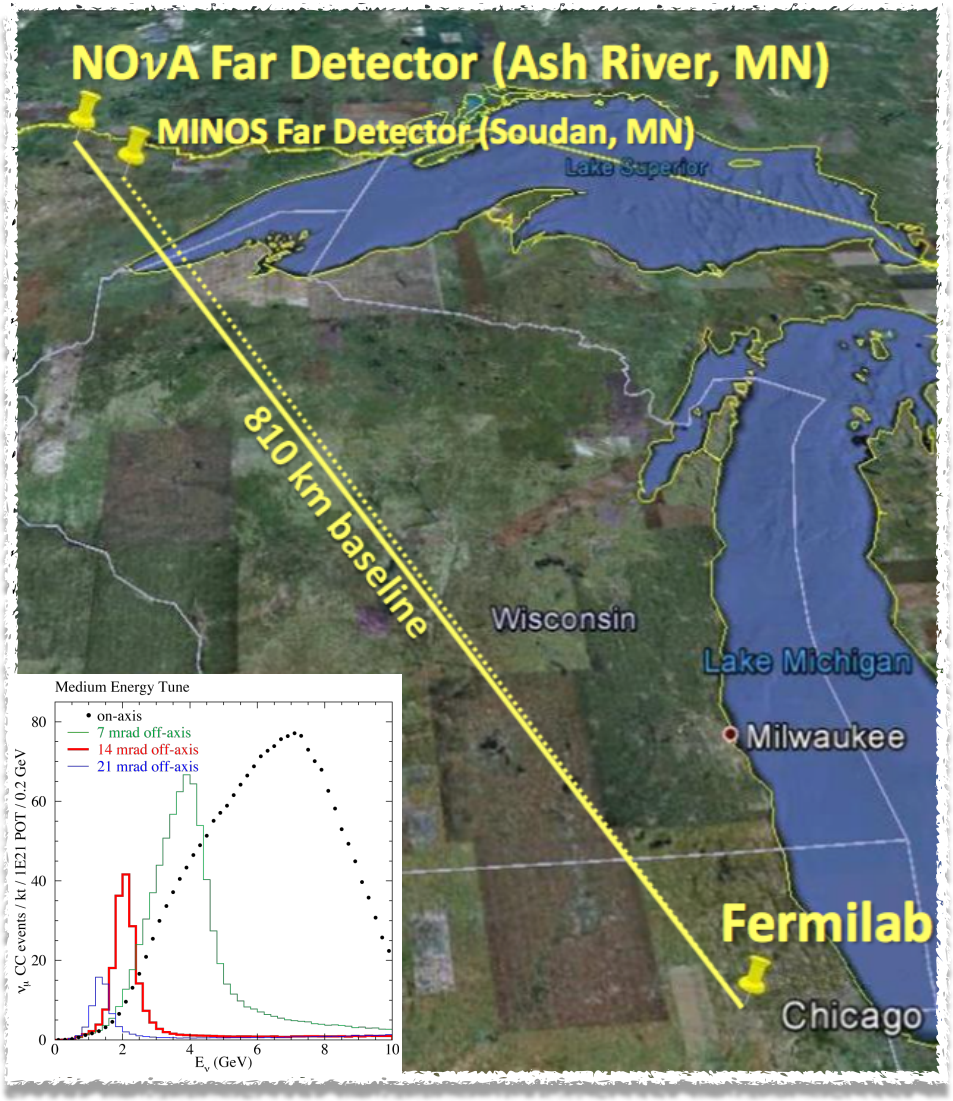
Supervisor **Keith Matera**

ABSTRACT

- Neutrino oscillations physics in the NOvA experiment
- Studying the effect of systematics using FNEX
- Implementation of the *OscPlots* class in FNEX
- Conclusions

THE NOνA EXPERIMENT

NUMI OFF-AXIS ν_e APPEARANCE

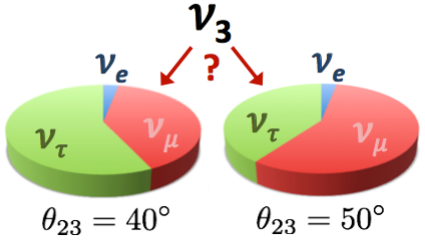


Study of the **neutrino oscillations** in the channels:

$$\nu_\mu \rightarrow \nu_e \qquad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$
$$\nu_\mu \rightarrow \nu_\mu$$

MAIN GOAL: get a measurement of

- θ_{13}
- **CP violation** in the leptonic sector



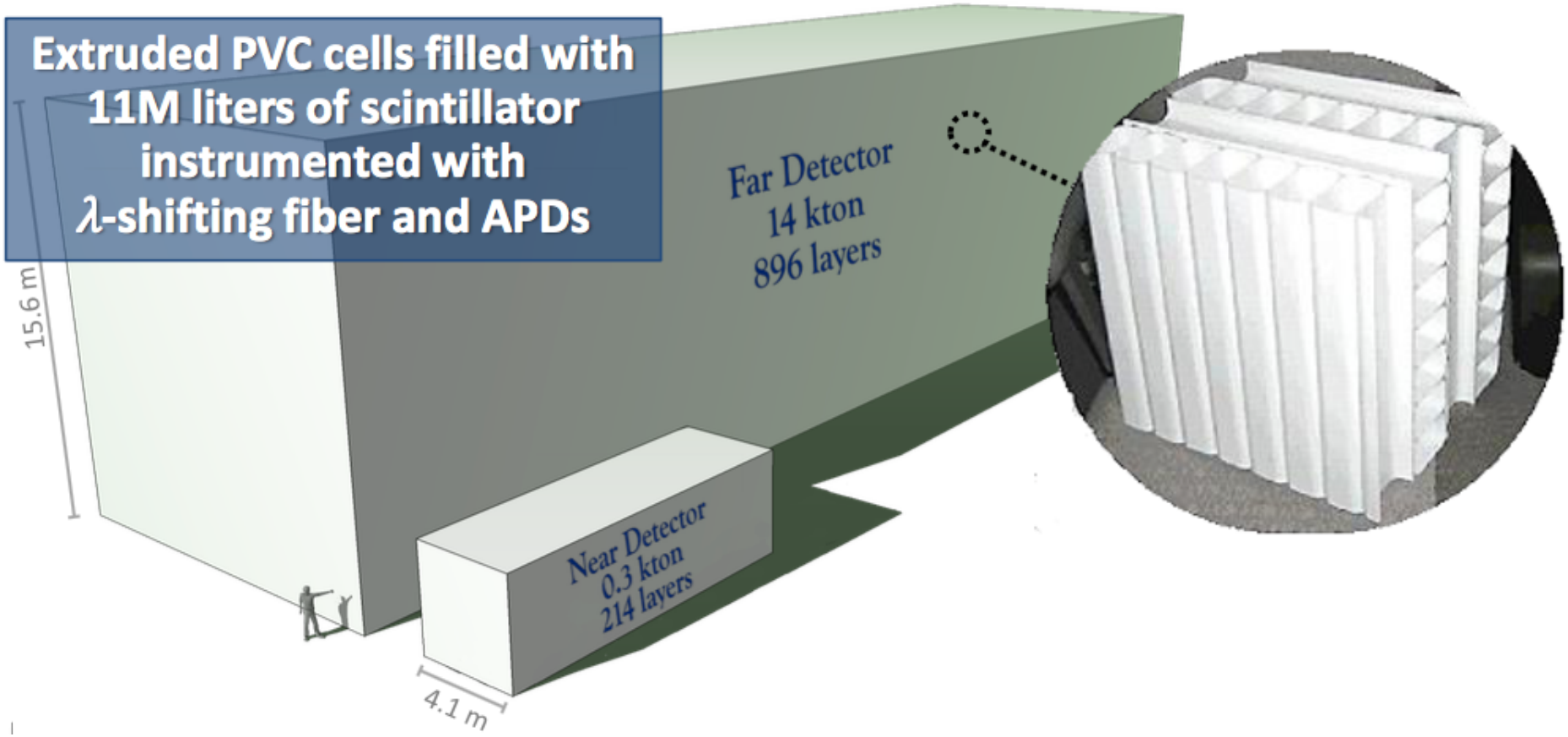
Furthermore…

→ Describe the **asymmetry** between matter/antimatter and solve the puzzling problem of the **ordering of neutrino mass states**

THE DETECTORS

12 km from the central axis of the NuMI beam

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs

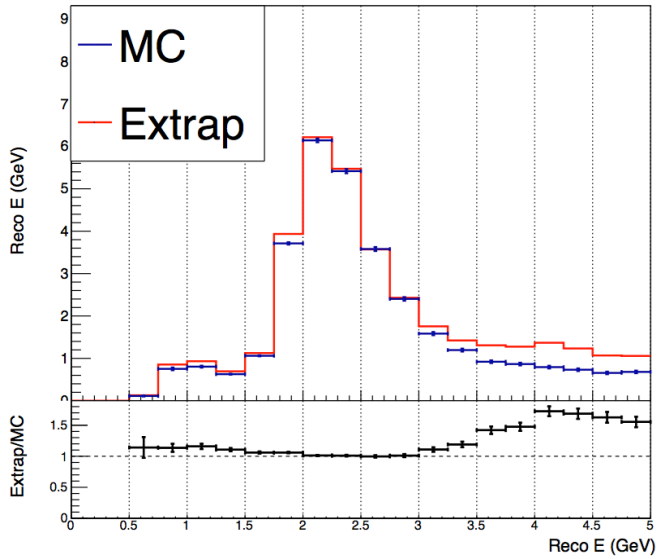


FAR/NEAR EXTRAPOLATION PACKAGE

FNEX package works in the *ART* framework and provides the tools to easily perform:

- First analysis cuts
- Full **FD/ND extrapolation**

$$FD_{(EXTRAP.)} = FD_{(MC)} \times \frac{ND_{(DATA)}}{ND_{(MC)}}$$



- Find best fit **oscillation parameters**

$$\chi^2 = \sum_{all\ bins,i} \left(N_{MC,i} + b_i - N_{DATA,i} \ln \frac{N_{DATA,i}}{N_{MC,i} + b_i} \right) + \sum_k \left(\frac{(\epsilon_k - <\epsilon_k>)^2}{\sigma^2_{\epsilon_k}} \right)$$

- **Confidence intervals** and much more…

SYSTEMATIC UNCERTAINTIES : how do they affect our final plots?

MAIN SOURCE → Likely mis-modeling of hadronic production in $\nu_\mu CC$ interactions

There exists discrepancy between Data and MC

Translating systematics into FNEX…

* *Hadronic Absolute Shift* (± 21 %)

  involves both ND and FD

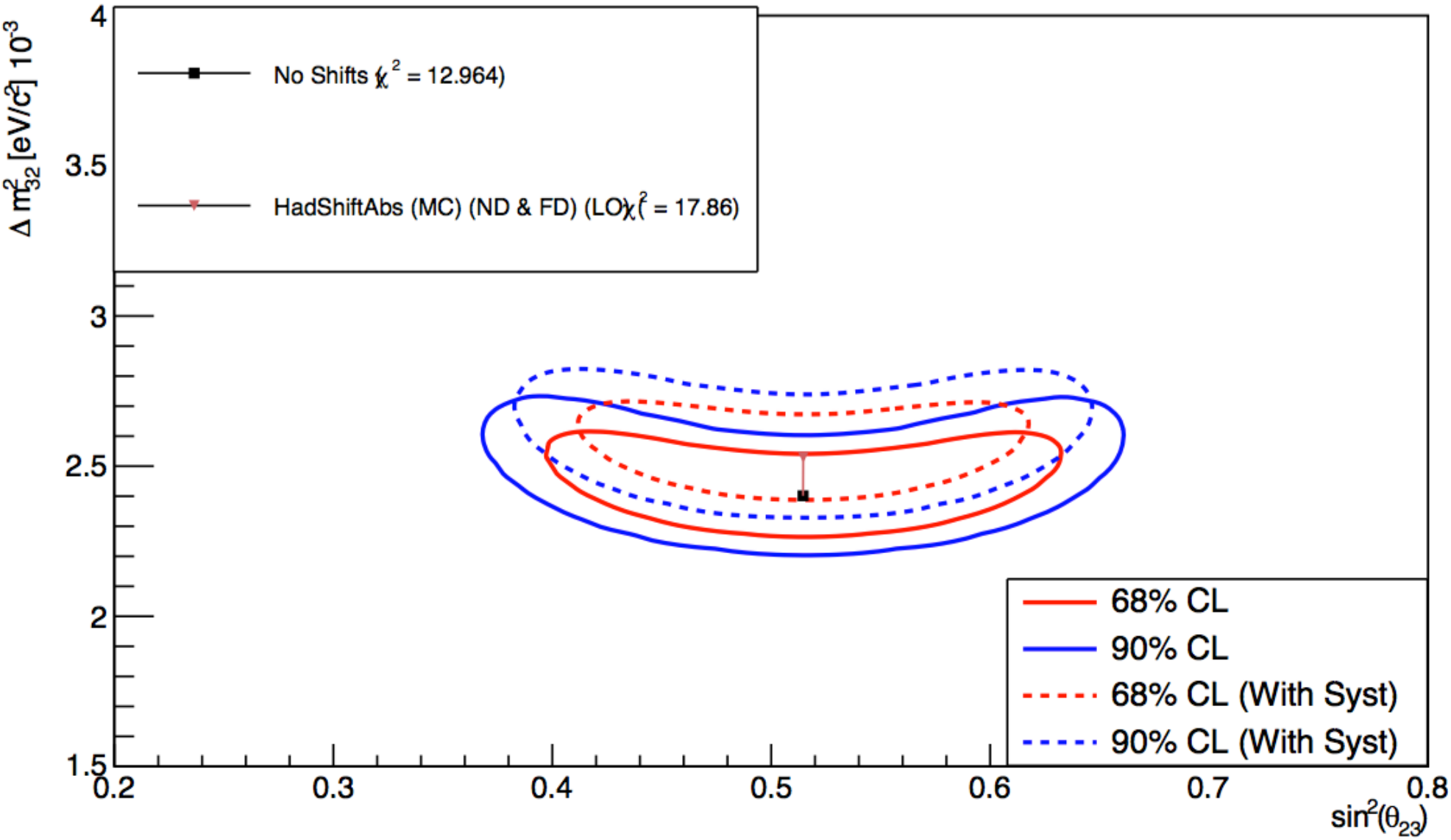
* *Hadronic Relative Shift* (± 6 %)

  FD only

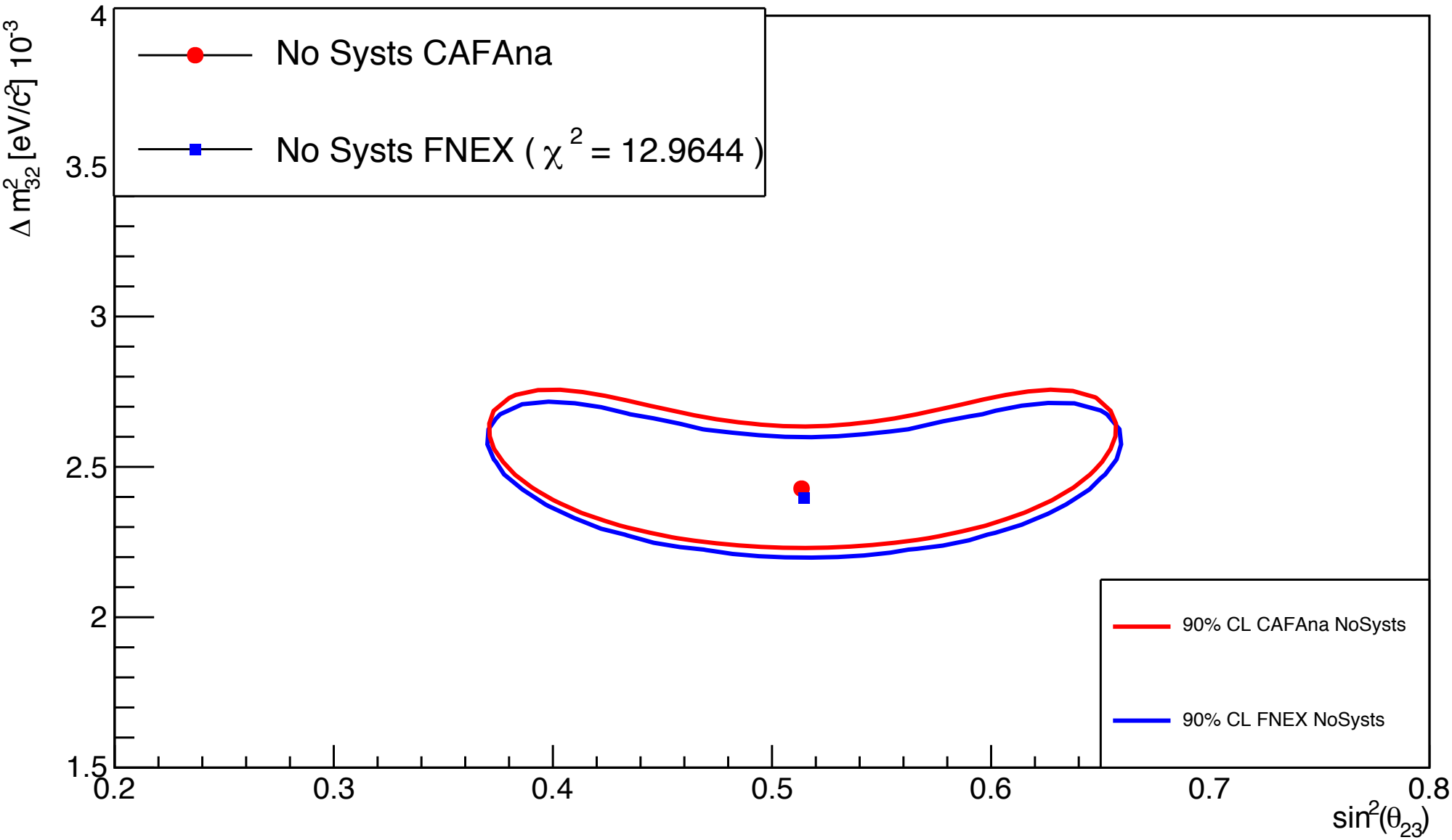
* *Hadronic Relative Normalization Shift* (± 2.2 %)

  FD only

HADRONIC ABSOLUTE SHIFT (LOW) MC



COMPARISON FNEX/CAFANA



Comparison New/Old Weights

Need to figure out why there exist discrepancies…

New weight

⋮

Find bin with E = TrueEnergy

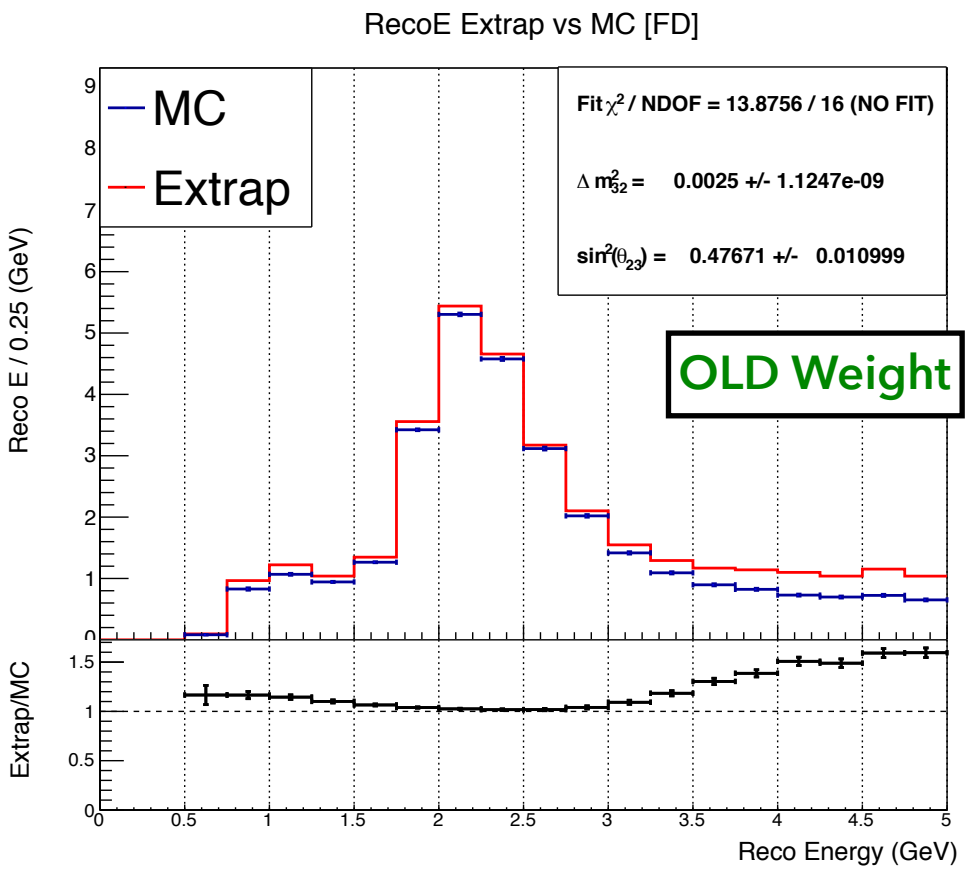
⋮

Evaluation of the bin center

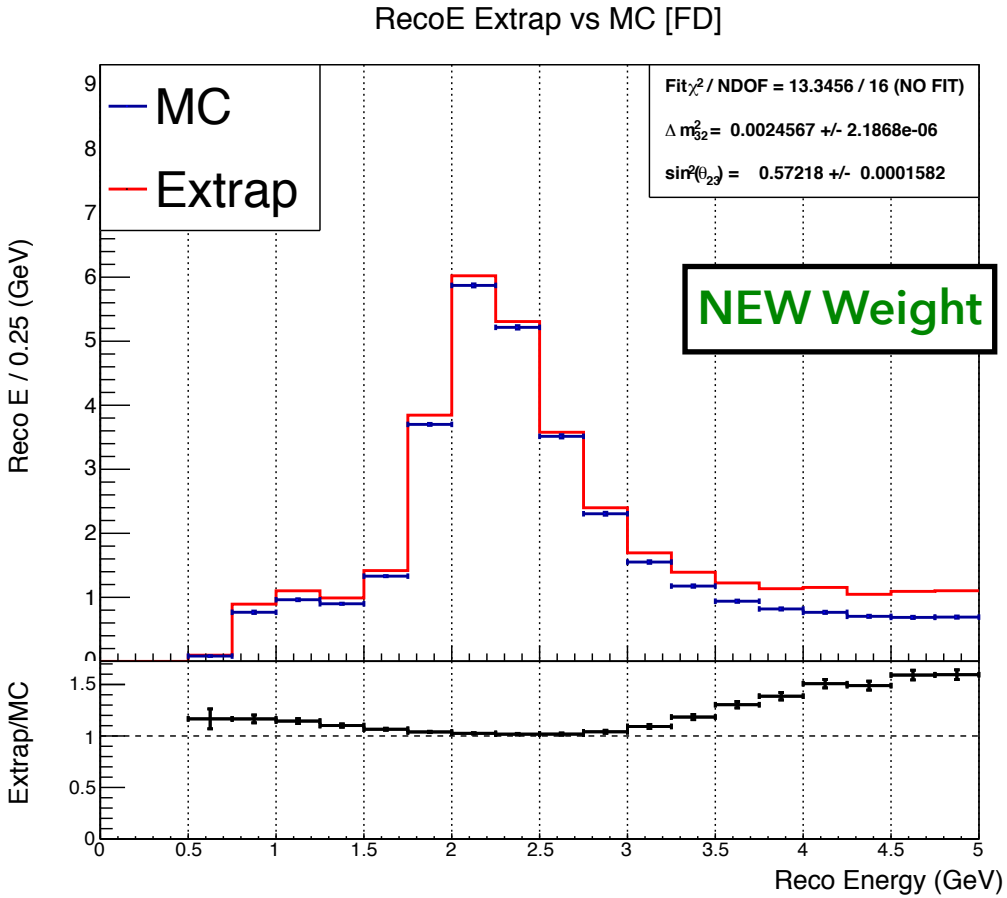
⋮

Determine the new oscillation rate for each pair $\nu_x \to \nu_y$

COMPARISON NEW/OLD WEIGHTS



Allowing to vary only $\sin^2\theta_{23},\ \Delta m^2_{32}$



Any difference must be due to :

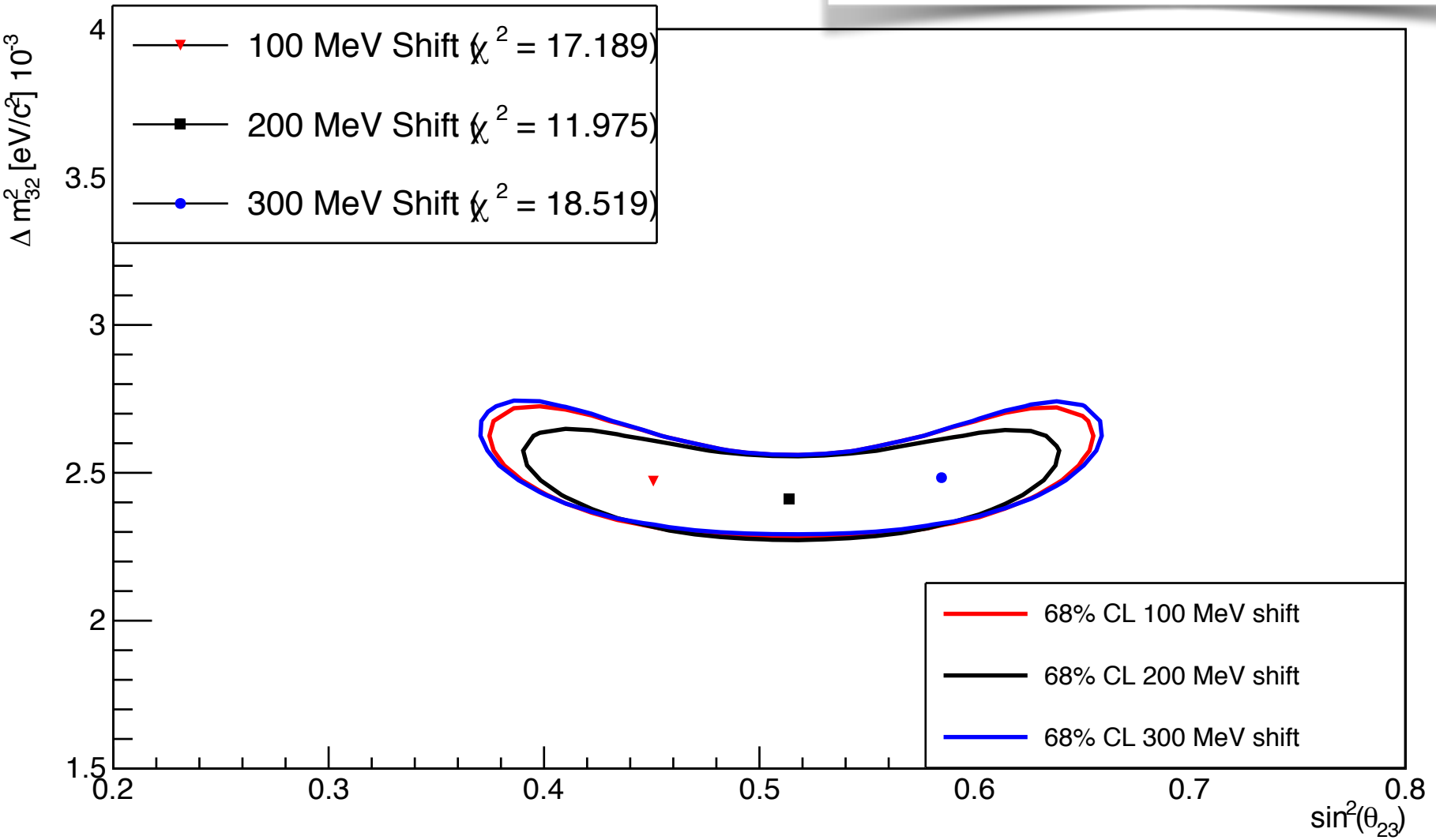
Different approach to the minimization procedure

Different extrapolation technique

TOWARDS THE UNBINNED BEST FIT : WALKING BINS

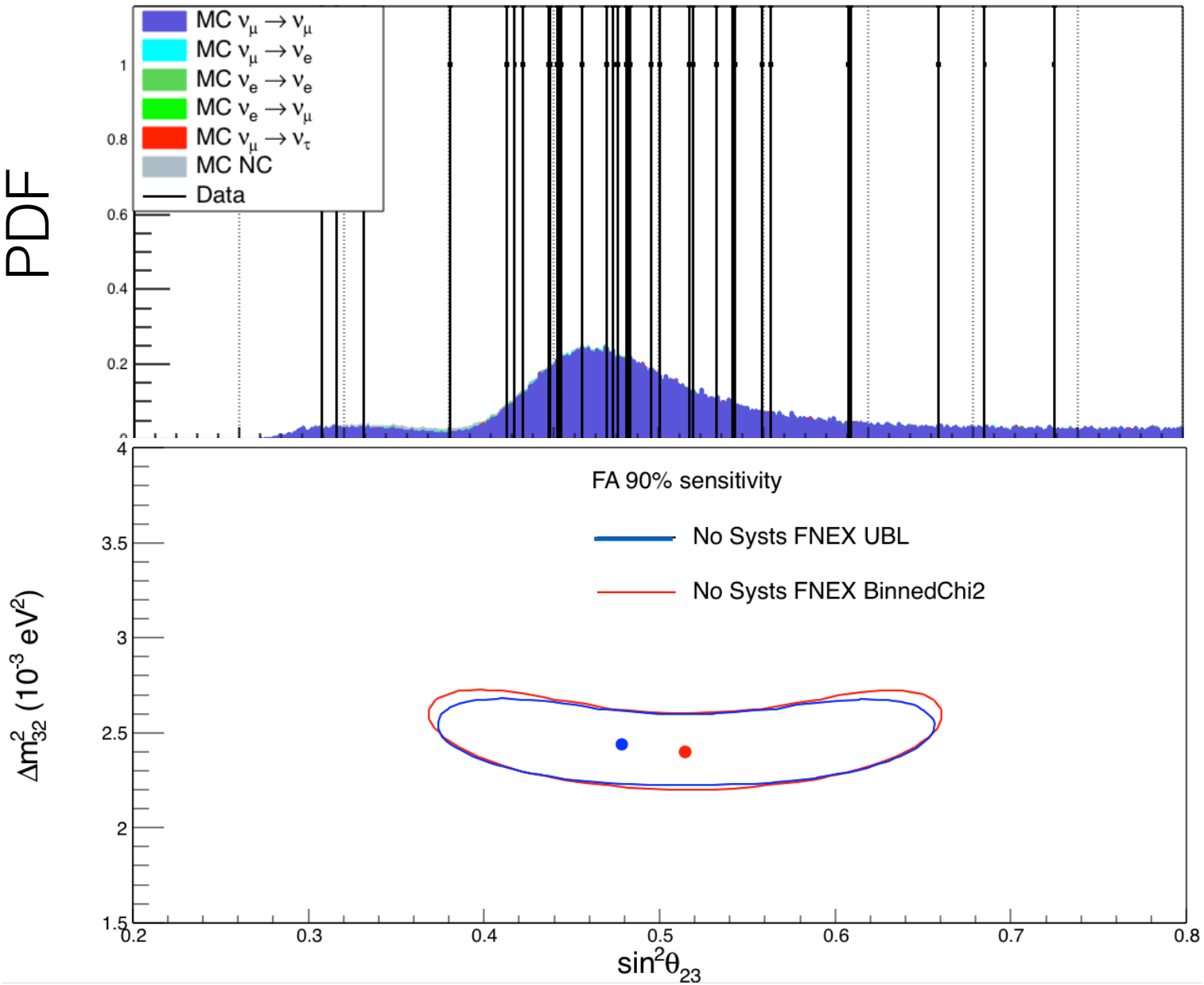
Allowing to vary only $\sin^2\theta_{23},\ \Delta m^2_{32}$

Shifting the Target Bin Range



UNBINNED LIKELIHOOD Numu FA Results

$$UBL = \sum_i -\log P_i(x_i, \vec{\theta})$$



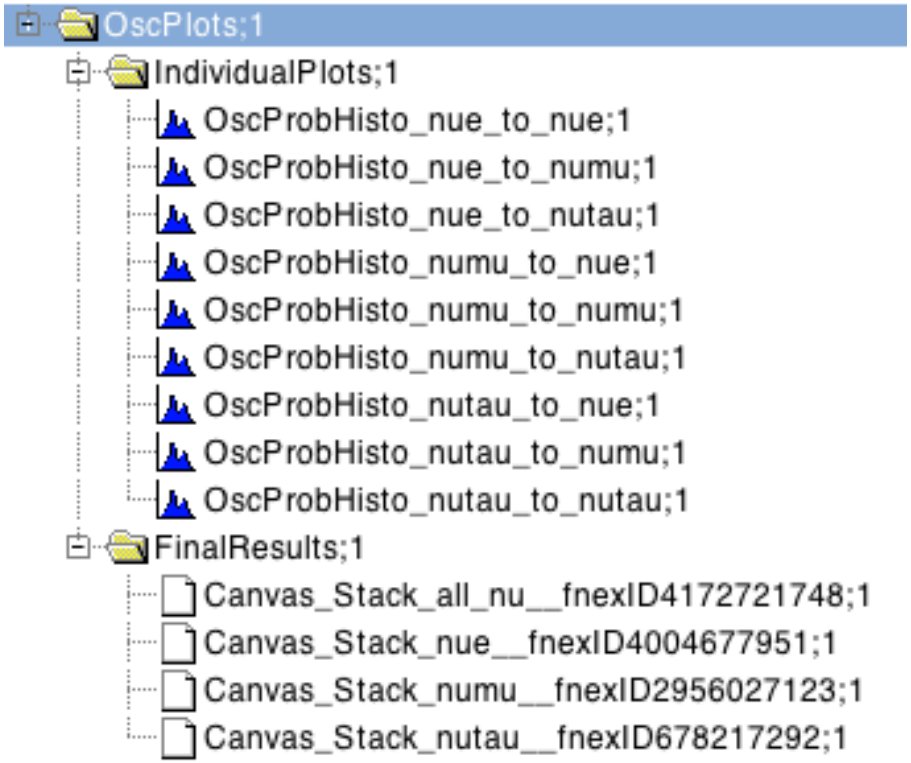
SOFTWARE IMPROVEMENTS : OSCPLOTS

- OscPlots::SetOscillationsParametersBF( )

  → FNEXFit , OscCalculator

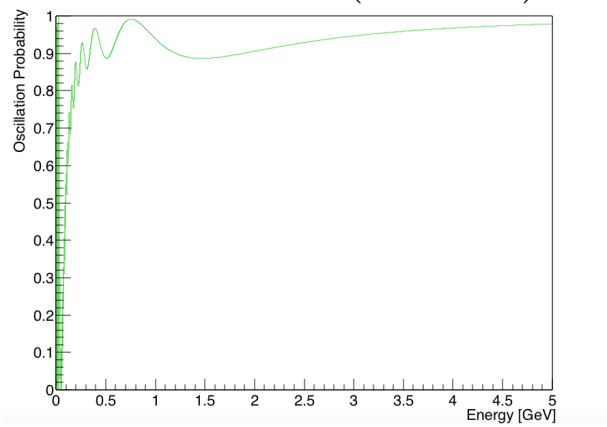
- OscPlots::MakeHisto( )
- OscPlots::MakeStacks( )

Output

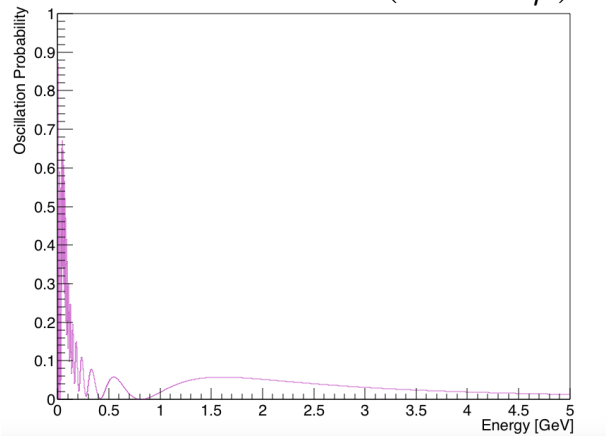


SOFTWARE IMPROVEMENTS : OSCPLOTS

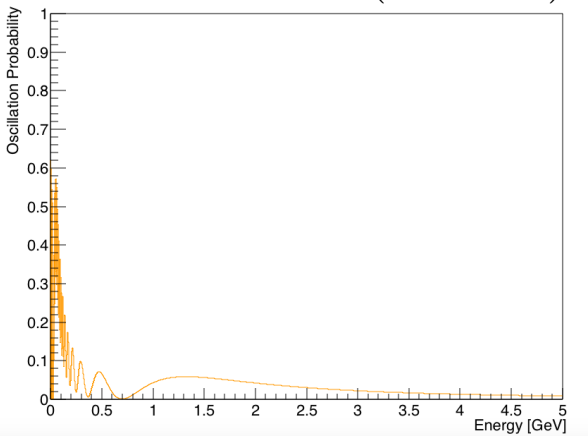
$P(\nu_e \to \nu_e)$



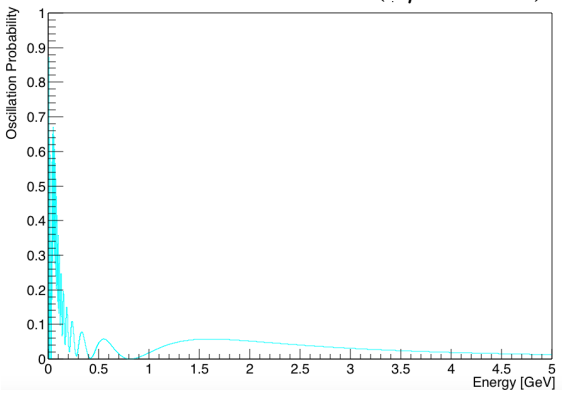
$P(\nu_e \to \nu_\mu)$



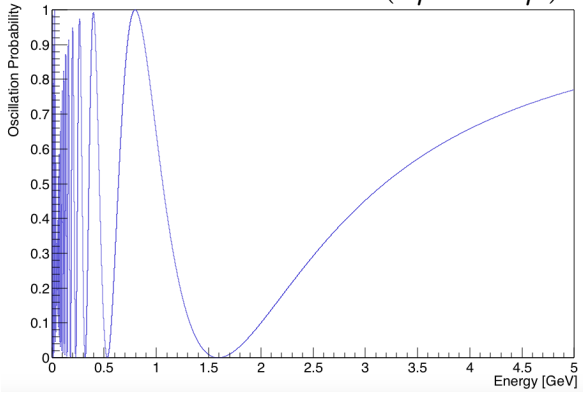
$P(\nu_e \to \nu_\tau)$



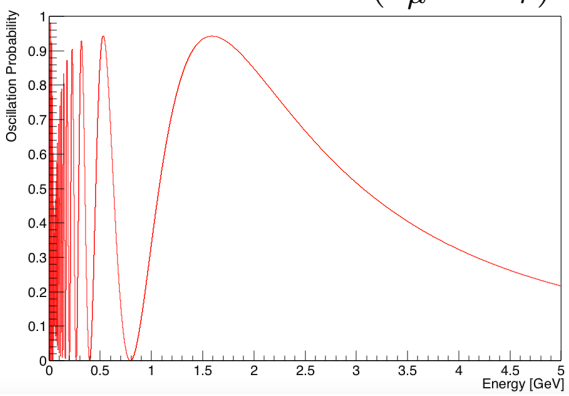
$P(\nu_\mu \to \nu_e)$



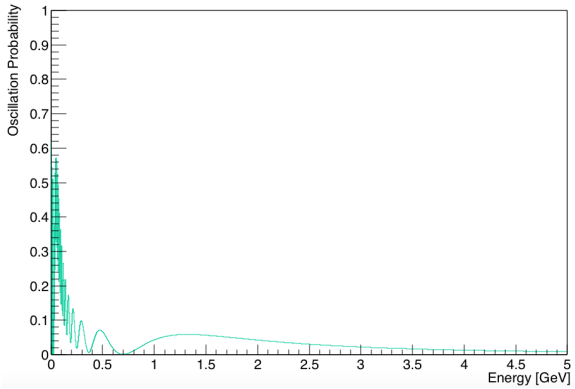
$P(\nu_\mu \to \nu_\mu)$



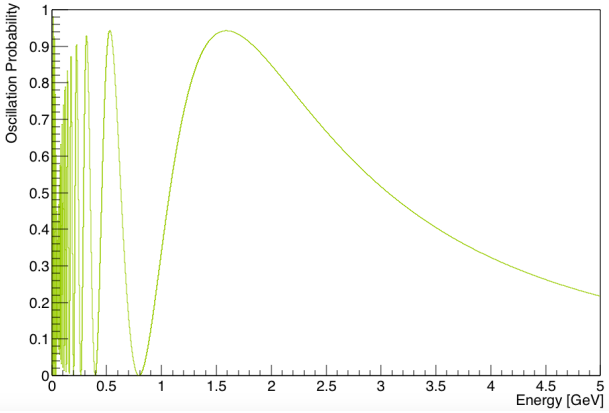
$P(\nu_\mu \to \nu_\tau)$



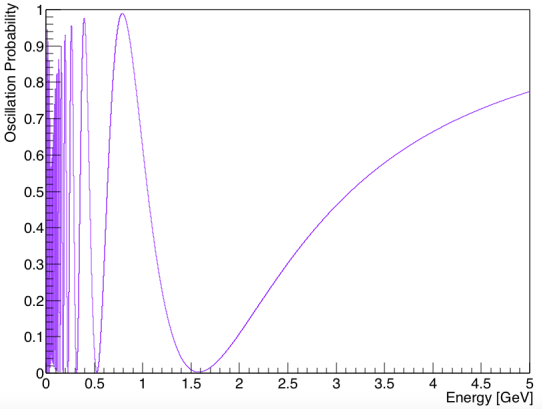
$P(\nu_\tau \to \nu_e)$



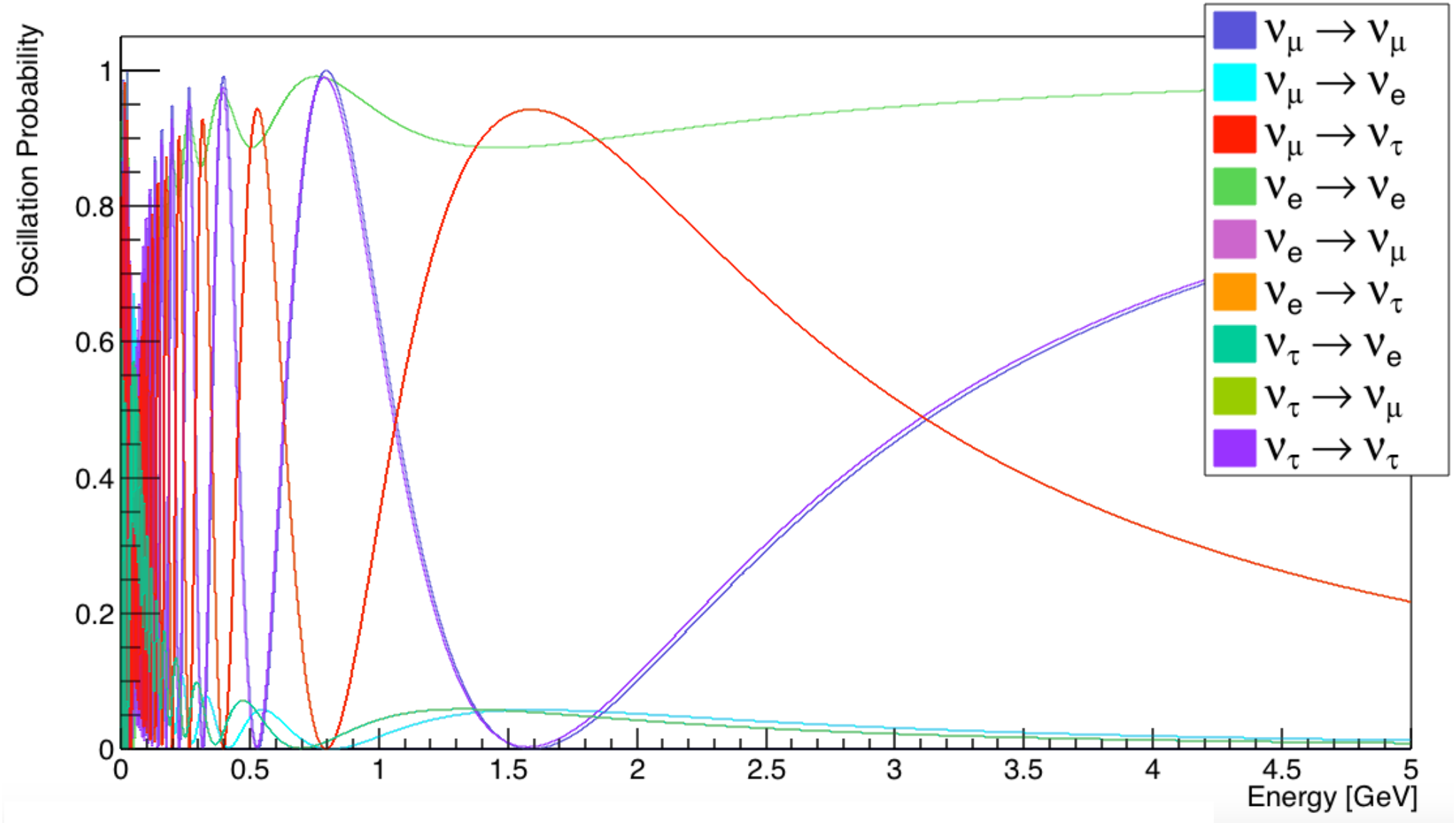
$P(\nu_\tau \to \nu_\mu)$



$P(\nu_\tau \to \nu_\tau)$



SOFTWARE IMPROVEMENTS : OSCPLOTS



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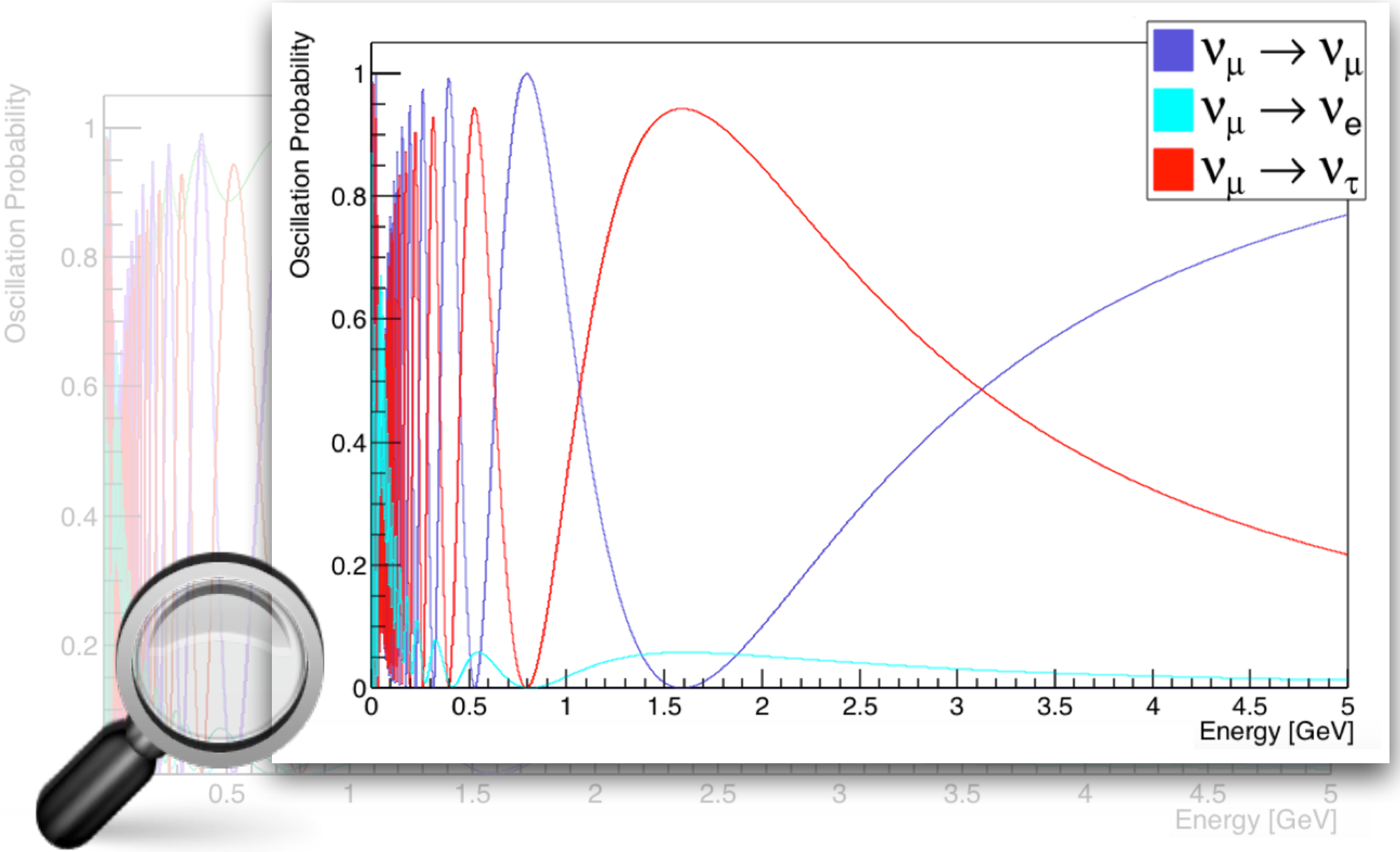


CONCLUSIONS

- Biggest effect on the CL contours and BF point due to the *HadAbsShift* (Hi&Lo) and *HadRelShift* (Lo)

- *New weights* and *walking bins* have a tiny effect on the final distributions and CL contours

→ *As expected. Confident in our answer!*

WHAT'S UP NEXT

- FNEX upgrade for a complete ν_e first analysis


Thank you for your attention!
Many thanks to my supervisor Keith Matera
...And thank you Fermilab

Backup Slides

NEUTRINO OSCILLATIONS 1957 B. Pontecorvo

$|\nu_\alpha\rangle$: flavor eigenstates of the Weak Hamiltonian

$|\nu_k\rangle$: mass eigenstates of the free Hamiltonian

Mixing

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

$U_{\alpha k}$ PMNS matrix 3x3 $\quad k = 1,2,3 \quad \alpha = e, \mu, \tau$

- *Probability of oscillation*

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{12}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

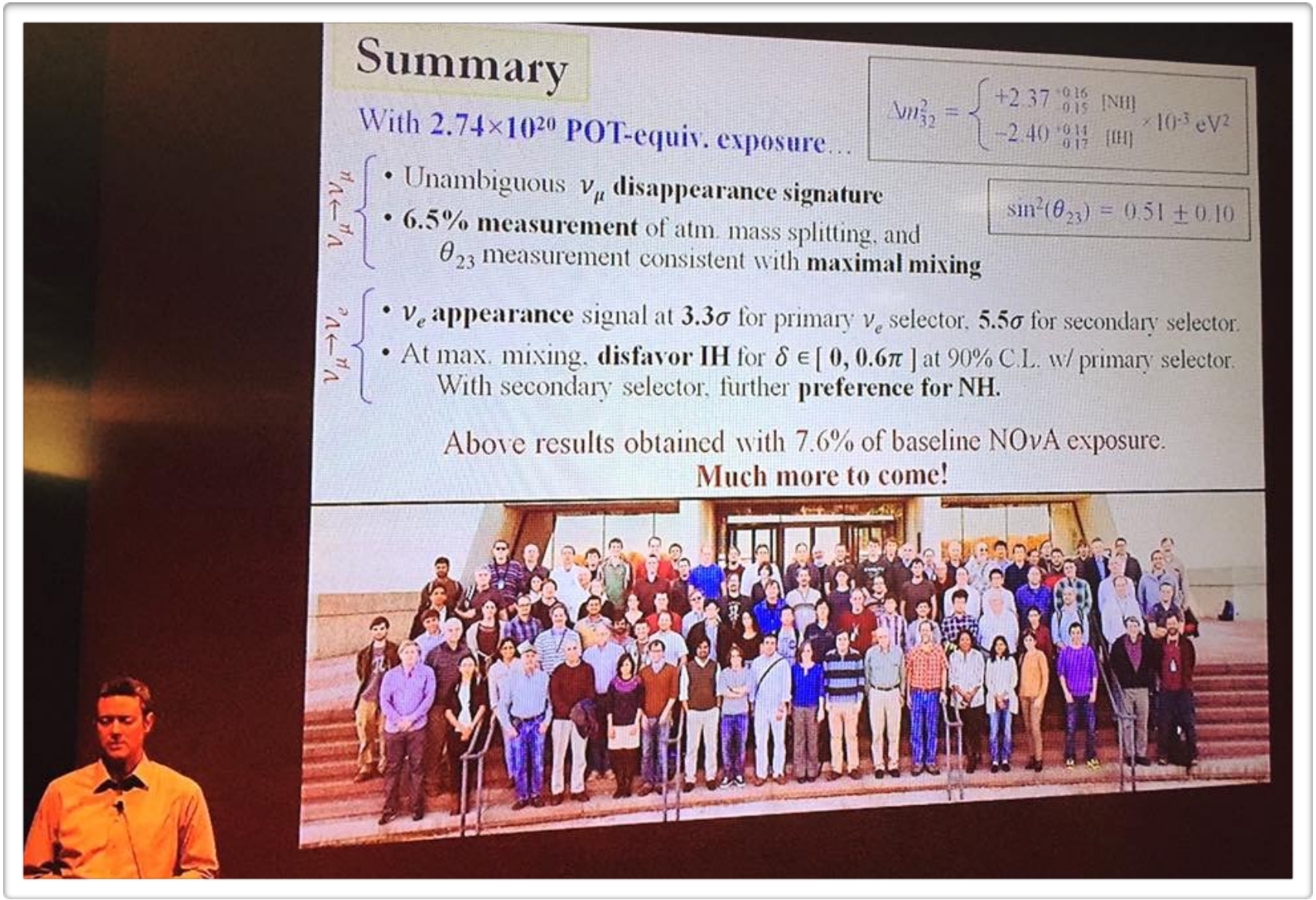
The observation of neutrino oscillations leads to the conclusion that neutrinos are massive and not degenerate

$$P(|\nu_\mu\rangle \to |\nu_e\rangle, L) \equiv |\langle \nu_e | \nu_\mu \rangle|^2 =$$

$$\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(1.27 \frac{\Delta m^2_{32}(eV^2) L(km)}{E(GeV)}\right)$$

From the Presentation of NOvA First Oscillation Results

Fermilab, Aug. 6th 2015



CONFIDENCE INTERVAL

Assume that the Likelihood could be approximated as a 2-dim. Gaussian and that

$$x = \frac{(\sin^2 2\theta - \sin^2 2\theta_{best})}{\sigma_{\sin^2 2\theta}}, \qquad y = \frac{(\Delta m^2 - \Delta m^2_{best})}{\sigma_{\Delta m^2}}$$

Then, Likelihood becomes: $\mathscr{L} = Ae^{-\frac{(x^2+y^2)}{2}}$

and for a given set of parameters

$$\chi^2 = -2\ln\mathscr{L} = (x^2 + y^2) + \chi^2_{min}$$

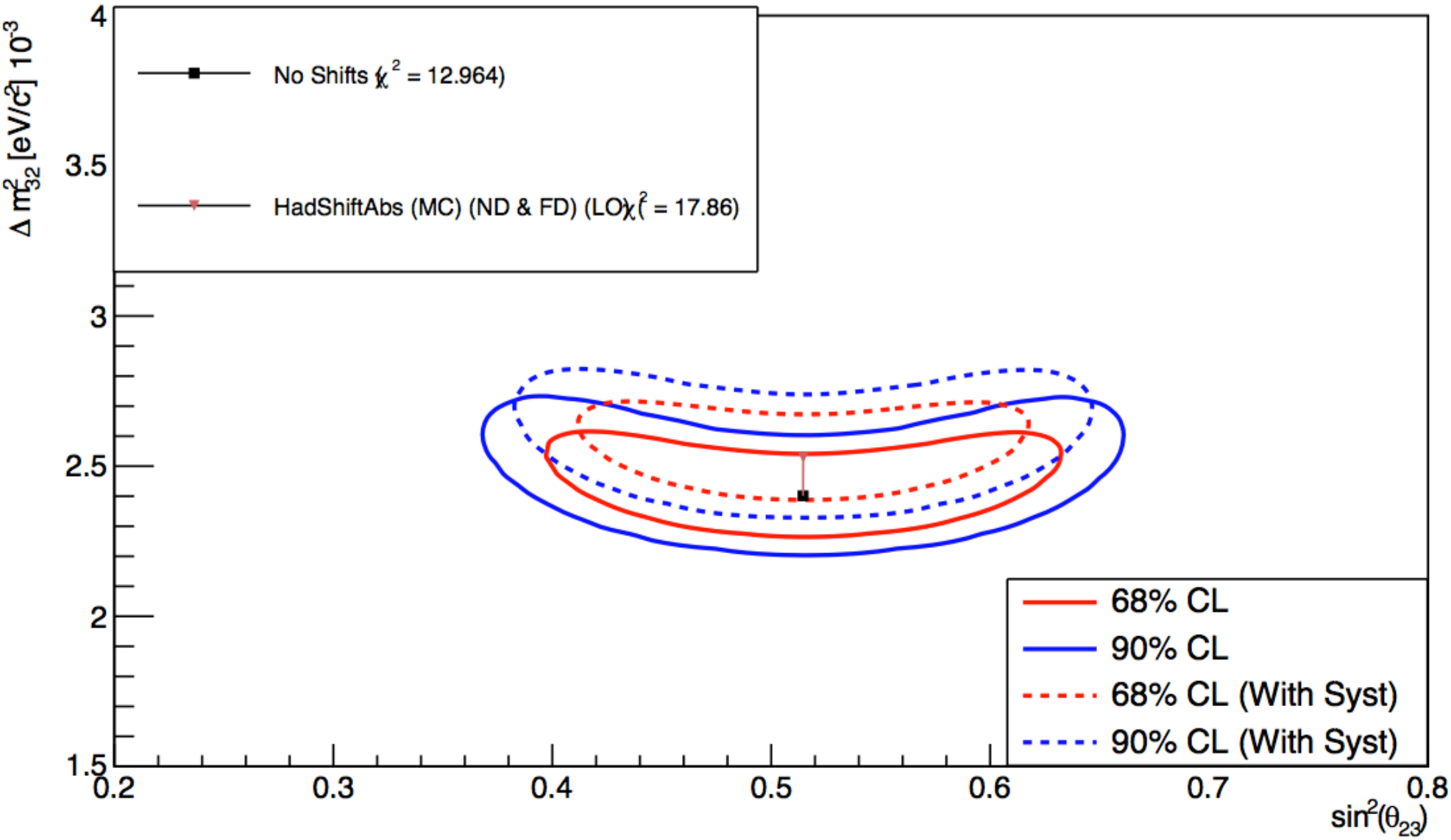
If one expresses $\chi^2_b = \chi^2_{min} + b$ then, in the entire space:

$$\Delta\chi^2 = \chi^2_b - \chi^2_{min}$$

the ***Confidence Interval*** is defined as

$$\lambda = 1 - \int_{-\infty}^{+\infty}\int_{-\infty}^{\sqrt{\Delta\chi^2}} \frac{e^{-\frac{(x^2+y^2)}{2}}\Theta\left(\chi^2(x,y) - \chi^2(x',y')\right)dxdy}{\Gamma}$$

Hadronic Absolute Shift (Low) MC



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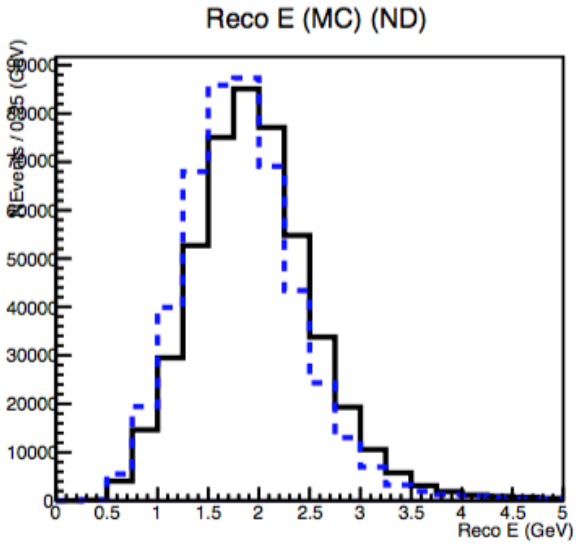
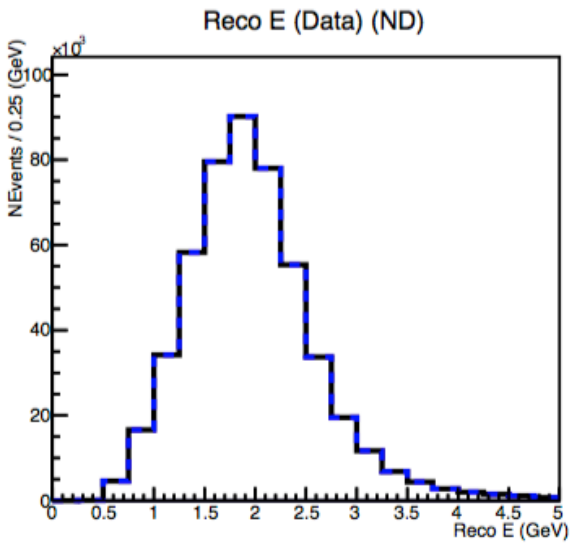
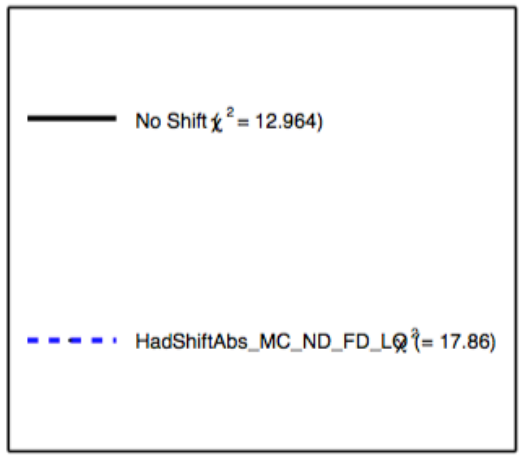
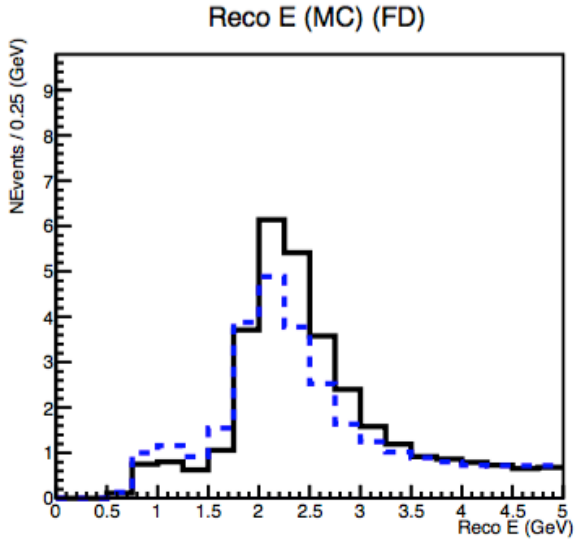
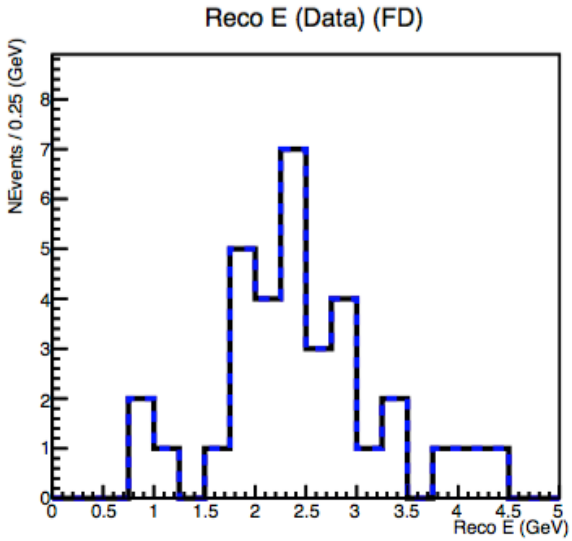
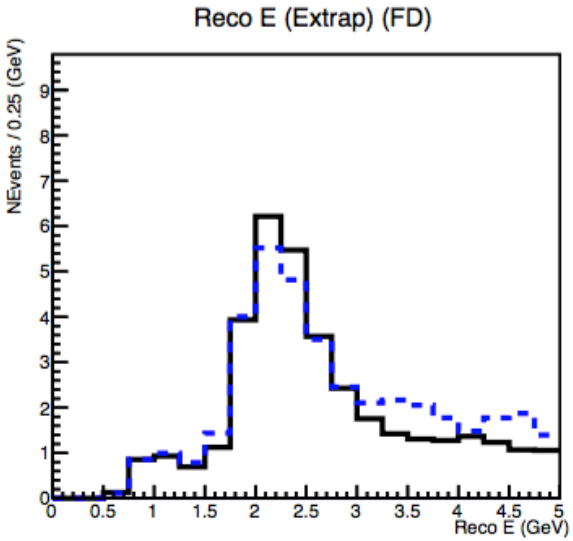




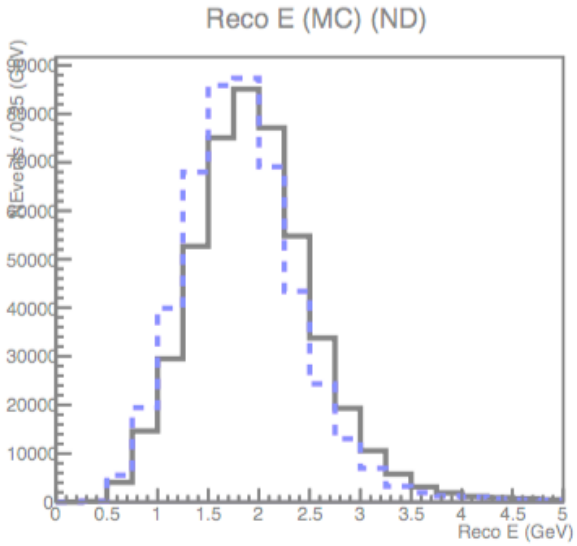


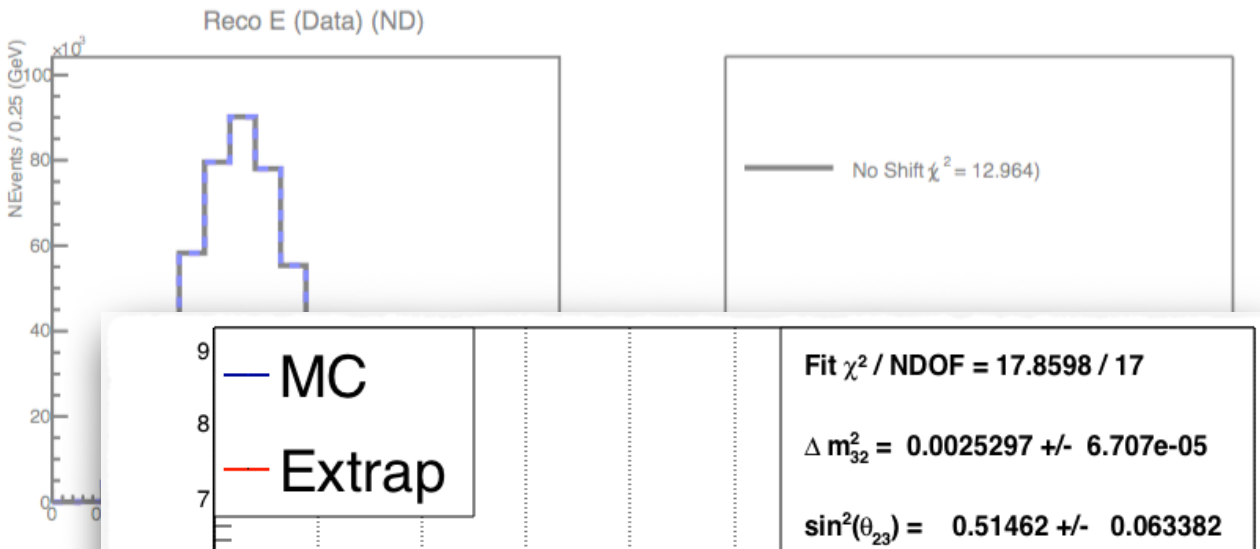


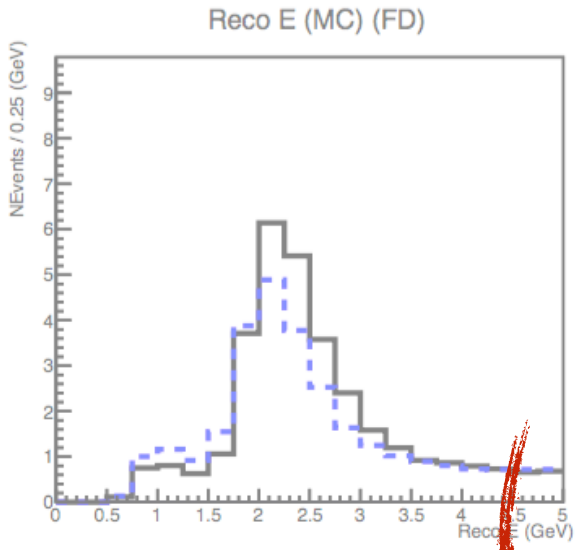


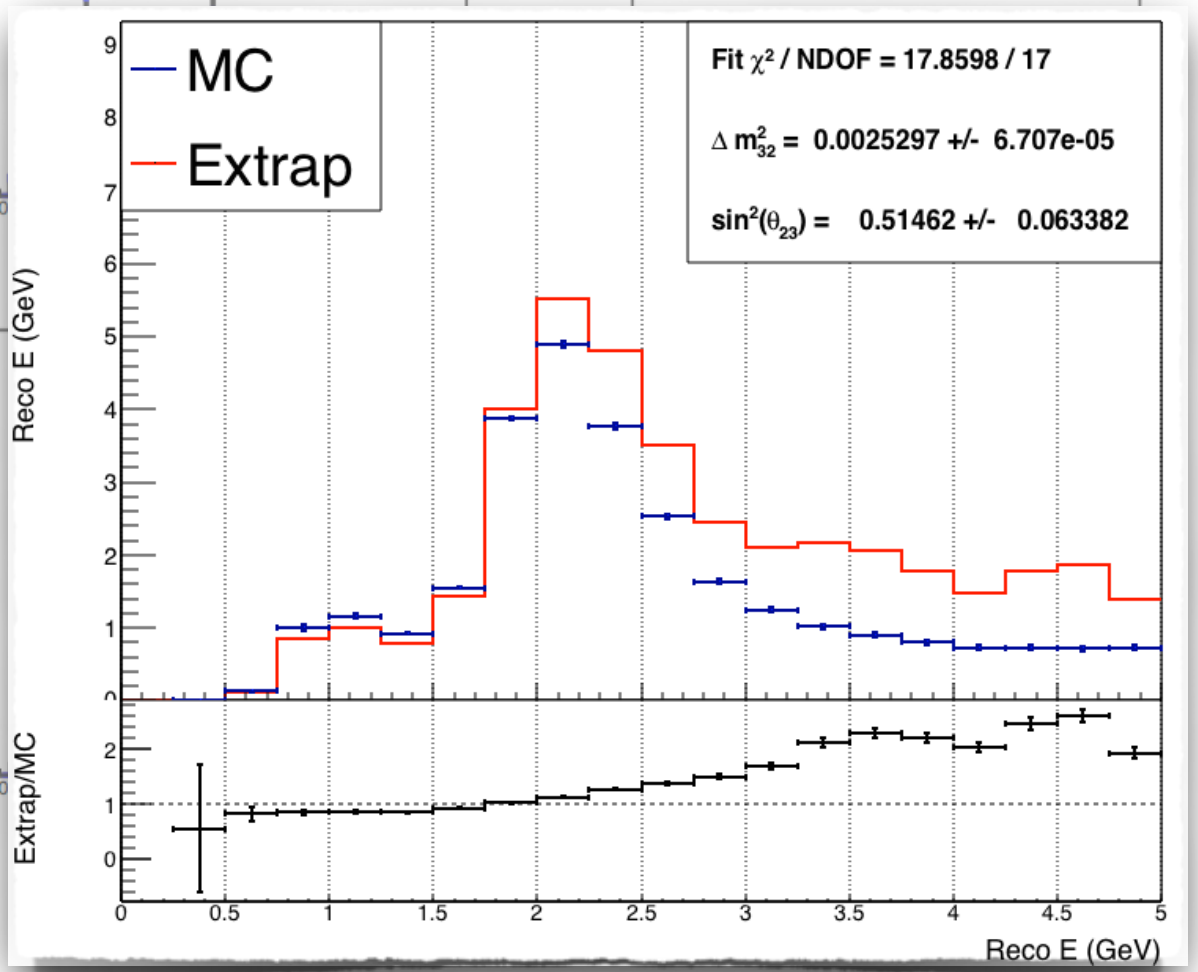


Hadronic Absolute Shift (Low) MC

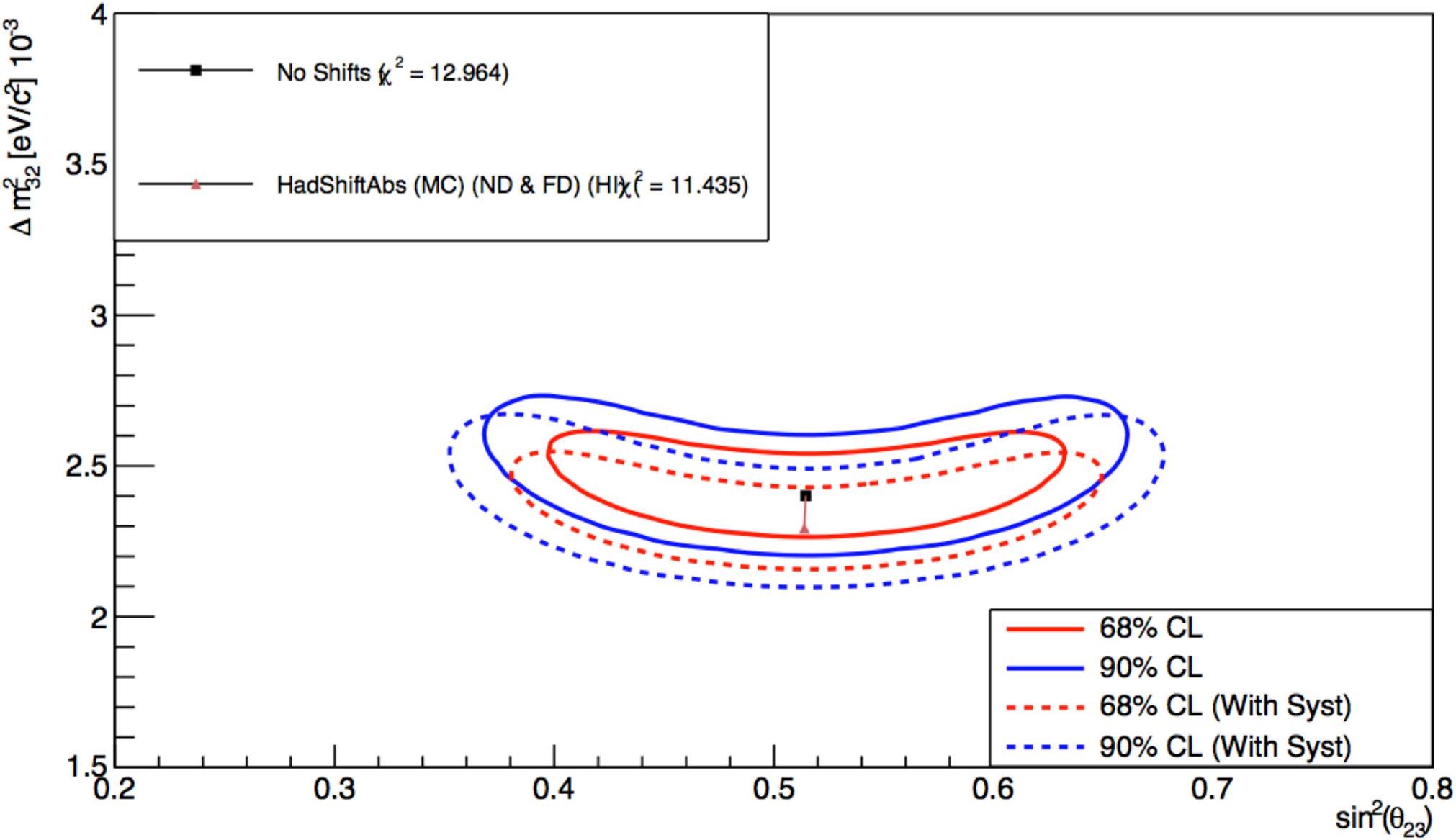




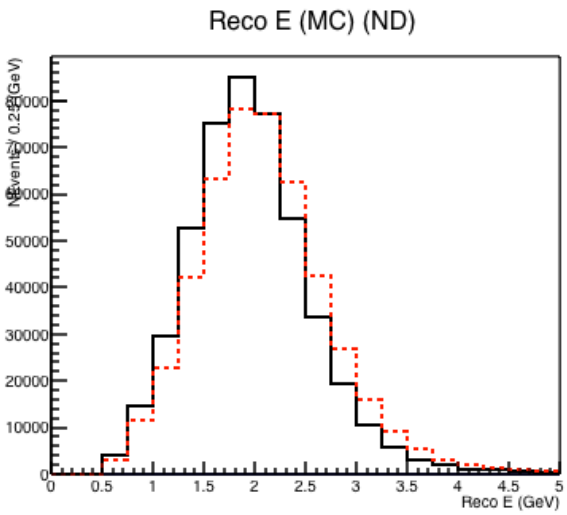


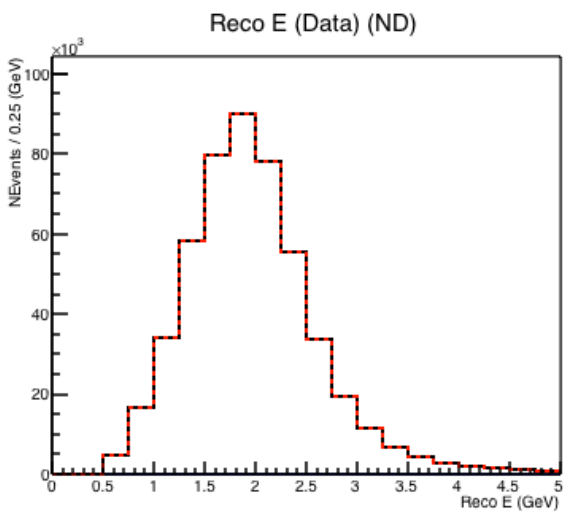


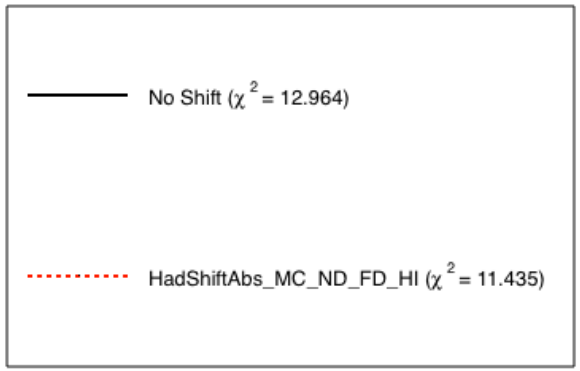
Hadronic Absolute Shift (High) MC

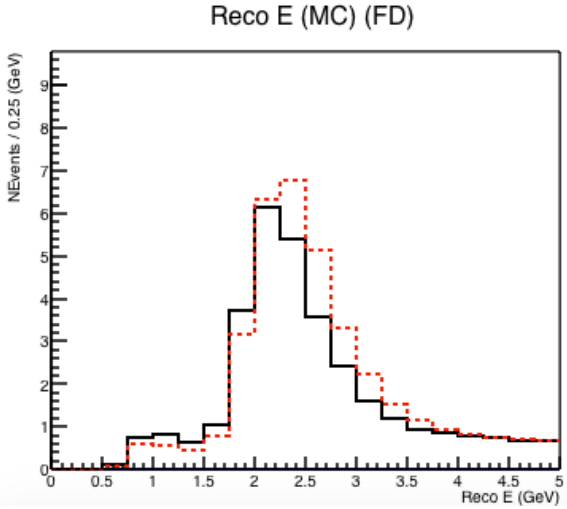


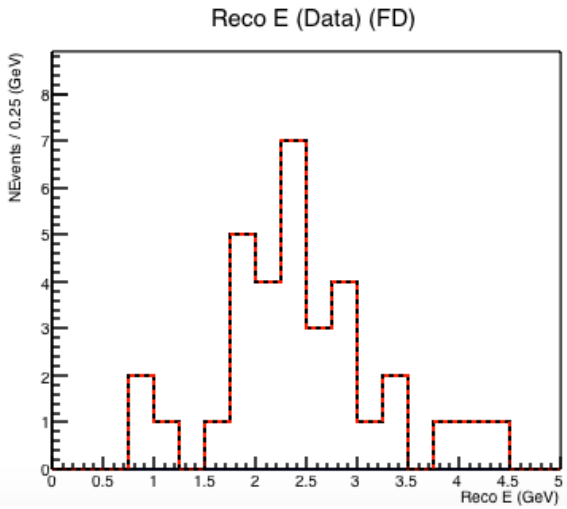
Hadronic Absolute Shift (High) MC

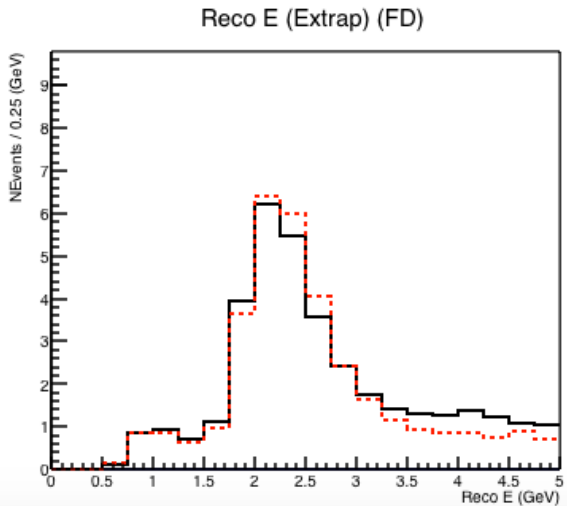




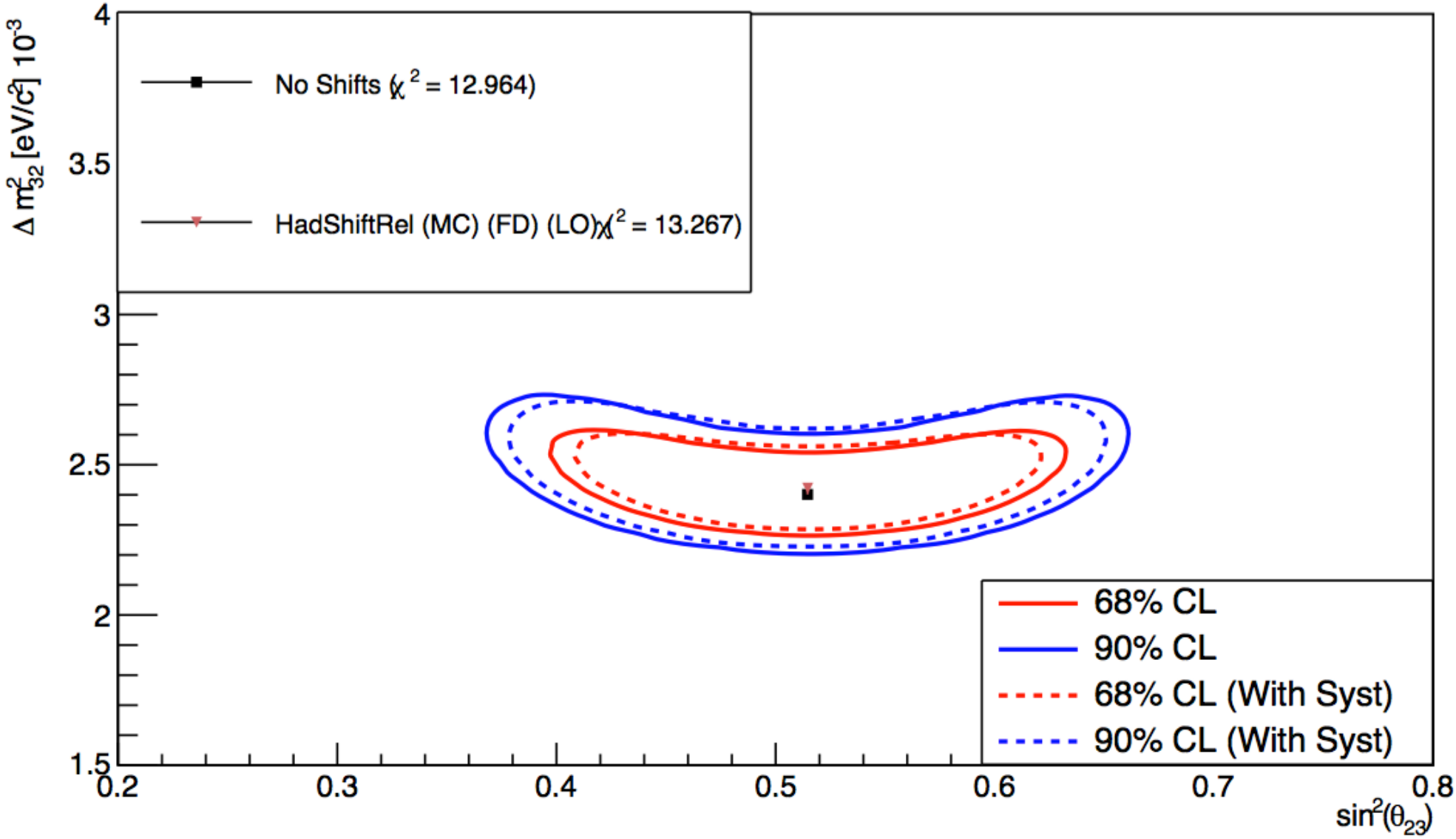




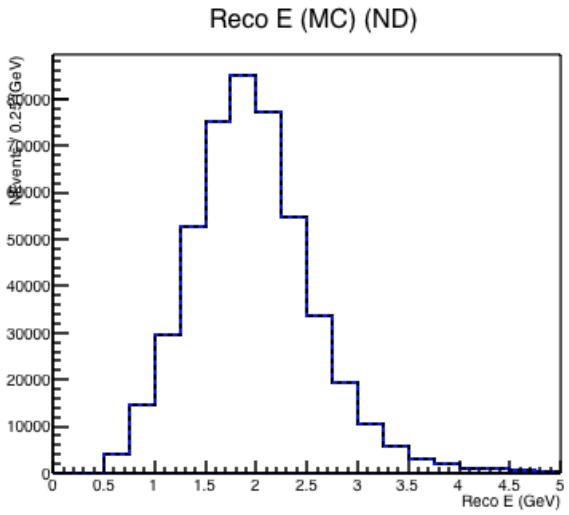


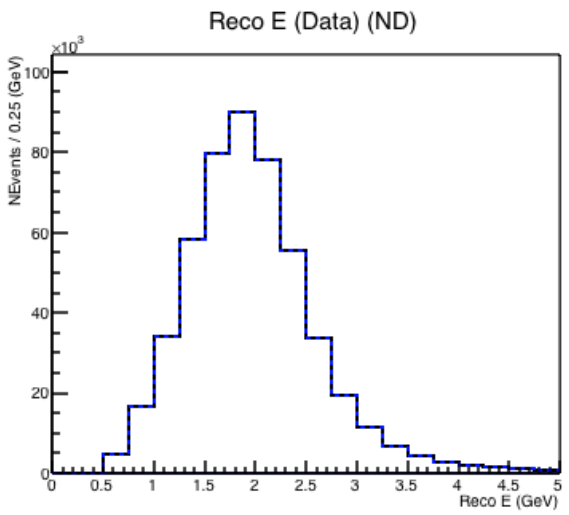


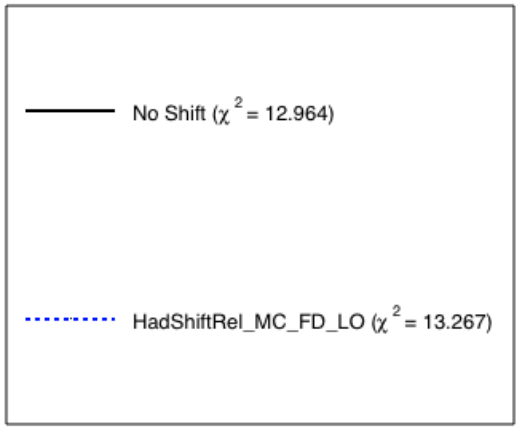
Hadronic Relative Shift (Low) MC

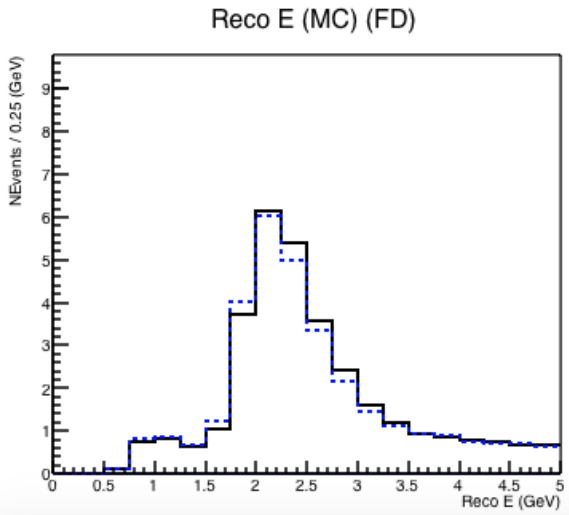


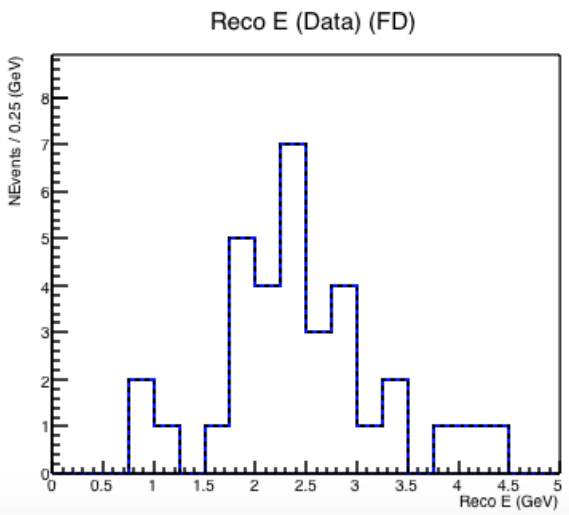
Hadronic Relative Shift (Low) MC

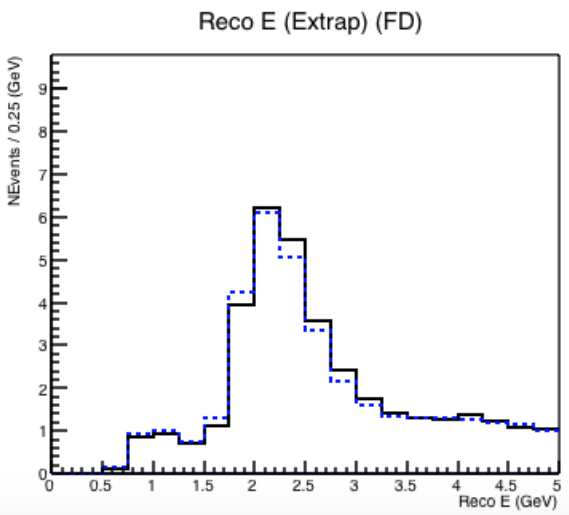




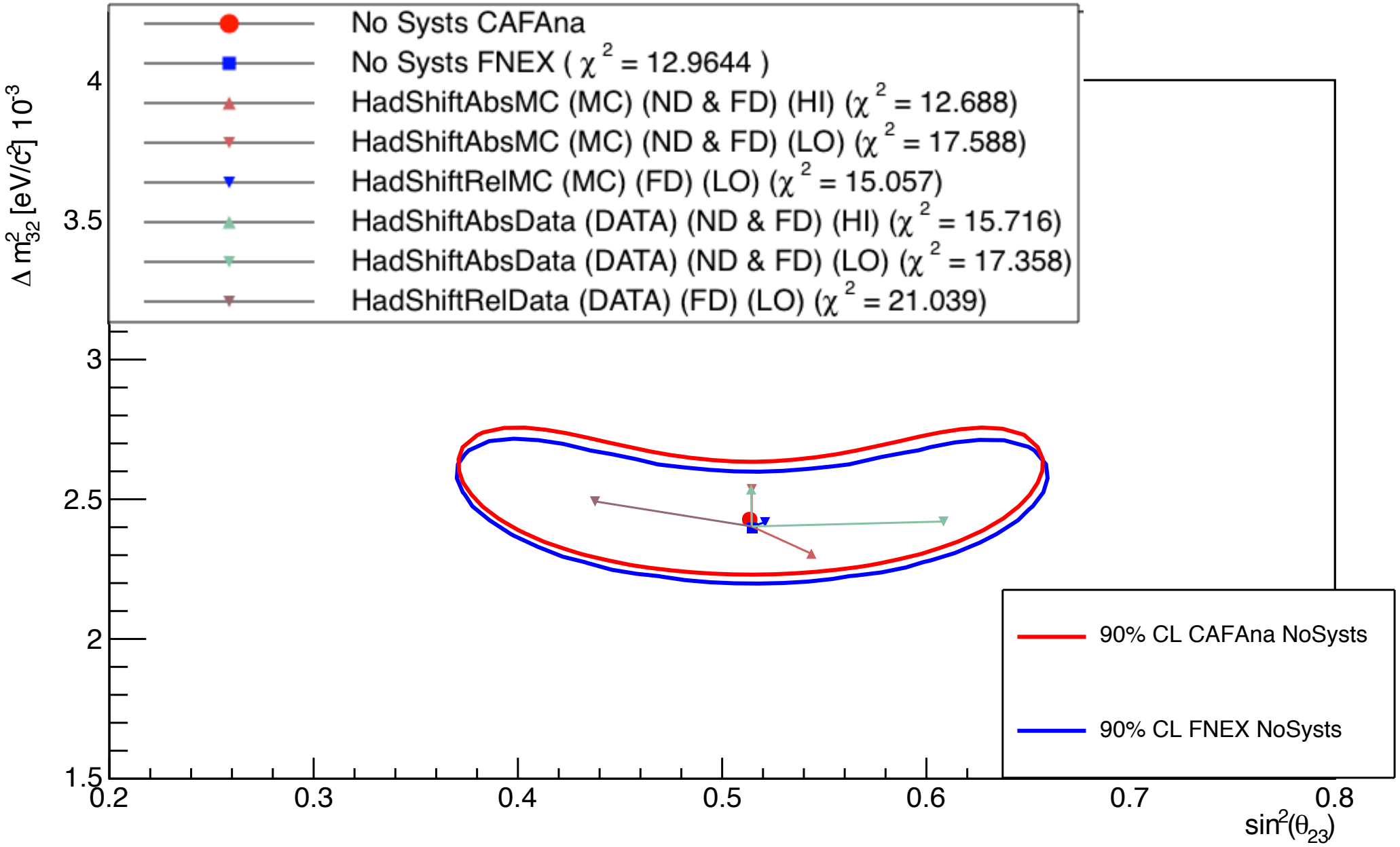








COMPARISON NEW/OLD WEIGHTS FNEX/CAFANA



RecoE vs Data FNEX/CAFAna