Charge and light sensitivity analysis on oscillation parameters in DUNE Far Detector

Luis Gustavo, Ettore Segreto and Laura Paulucci
UNICAMP and UFABC

DUNE LBL Meeting
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Outline

- Goal: simulation using GLoBES for determining the oscillation parameters of the CPV and mass ordering.
  - ❖ Ancillary files from the article: “Experiment Simulation Configurations Approximating DUNE TDR” - > https://arxiv.org/src/2103.04797v2/anc
- Validate event rate and sensitivity with TDR using charge signal and smearing matrix.
- Use the gaussian energy function in GLoBES and analyse CPV sensitivity and mass ordering:

  - Charge signal ~ 14% energy resolution;

  - Charge + Light signal ~ 8% energy resolution.
- This is a preliminary work and further developments are expected.

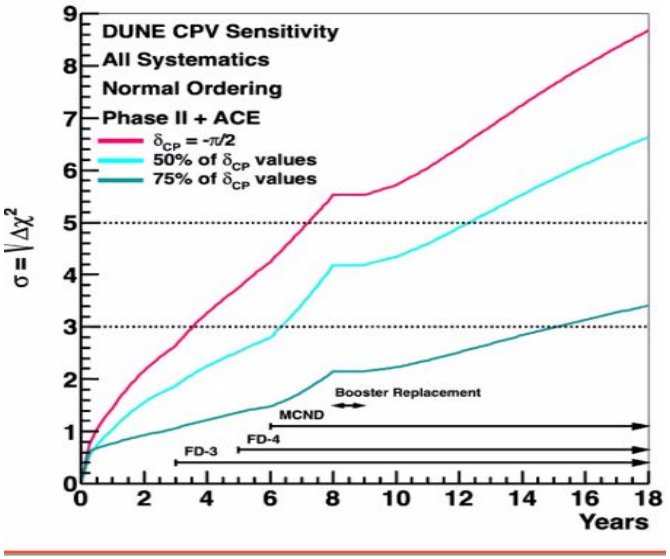
GLoBES Simulation

- First simulation: for validation with TDR - Nominal deployment plan and the oscillation parameters from NuFIT 4.0 (2018).
  - Start of beam run: two FD module volumes for total fiducial mass of 20 kt, 1.2 MW beam
  - After one year: add one FD module volume for total fiducial mass of 30 kt
  - After three years: add one FD module volume for total fiducial mass of 40 kt
  - After six years: upgrade to 2.4 MW beam

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

GLoBES Simulation

- Second Simulation: using the updated information about nominal deployment plan and implementation of the current value oscillation parameter from NuFIT 5.2 (2023).



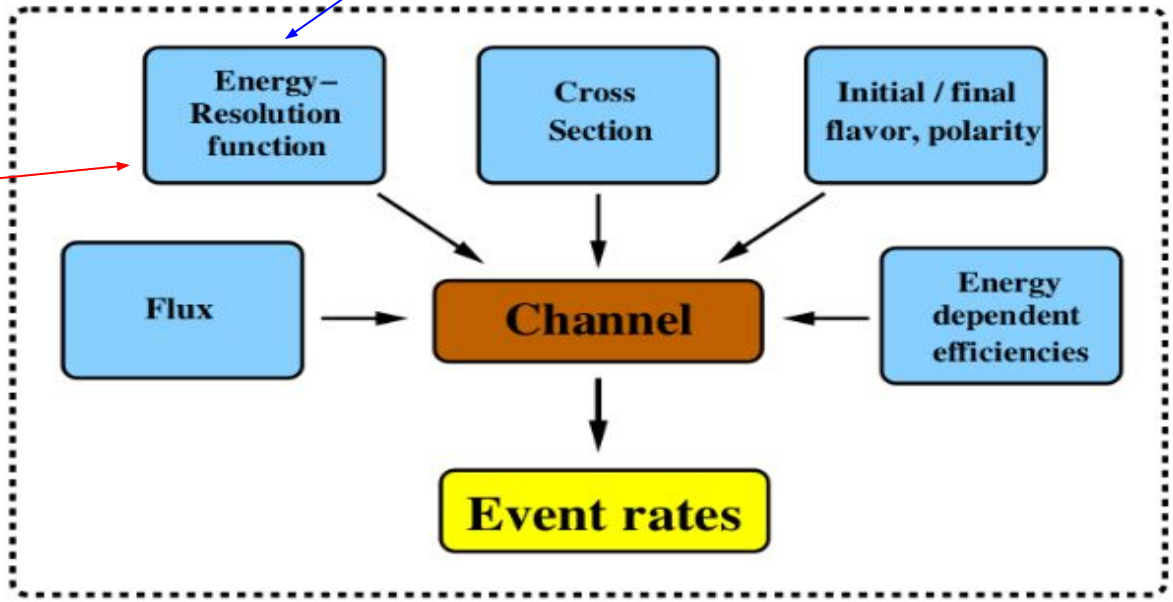
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

- **We do not take into account:**
  - **Near Detector configuration;**
  - **Approximately 1 year which the experiment could be stopped for the beam upgrade.**

Event rates

Updated data: Charge and Light signal - Gaussian function

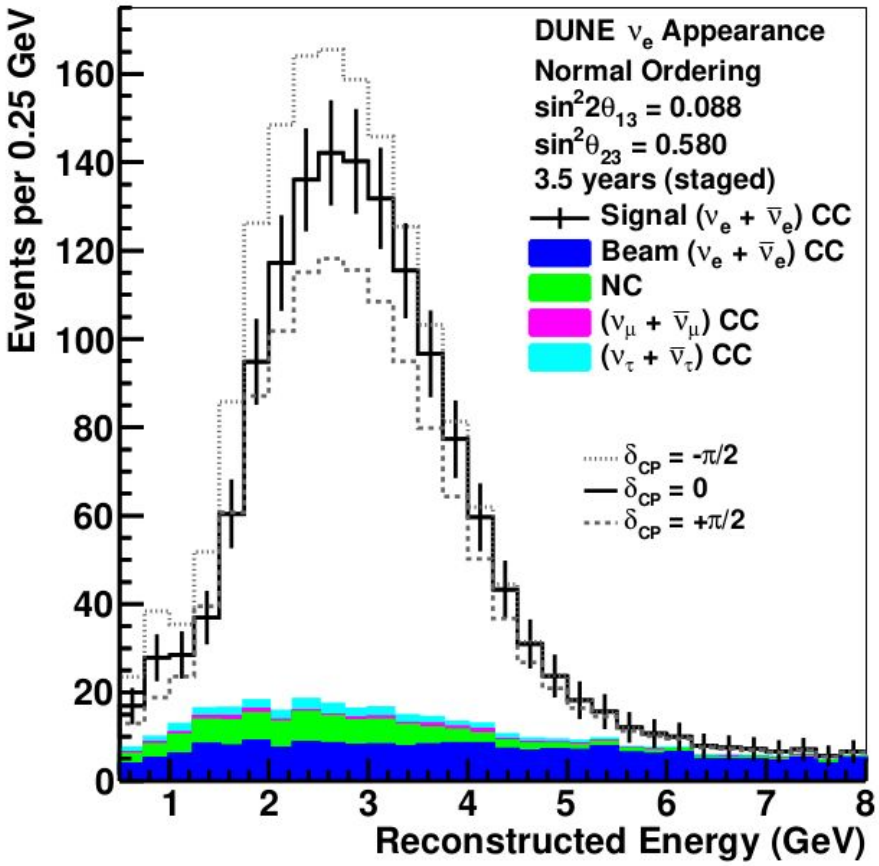
TDR only Charge signal - smearing matrices



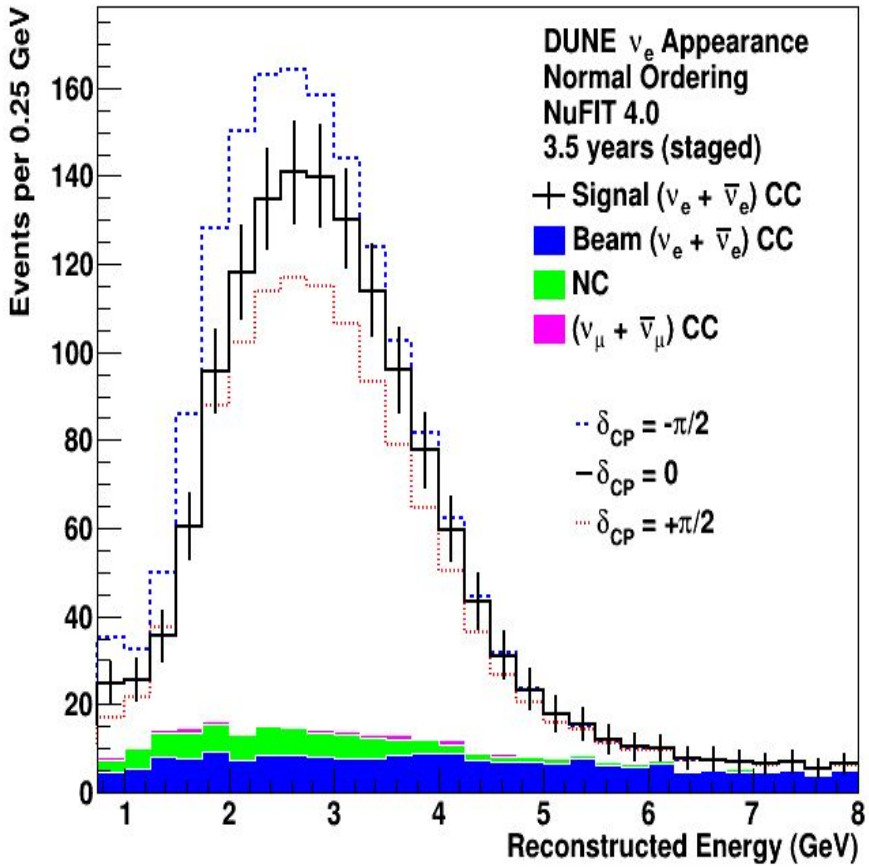
$$n_i^c = N/L^2 \int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE' \int_0^\infty \phi^c(E) P^c(E) \sigma^c(E) R^c(E, E') \epsilon^c(E').$$

Channel's values in GLoBES

Event rates - TDR reference

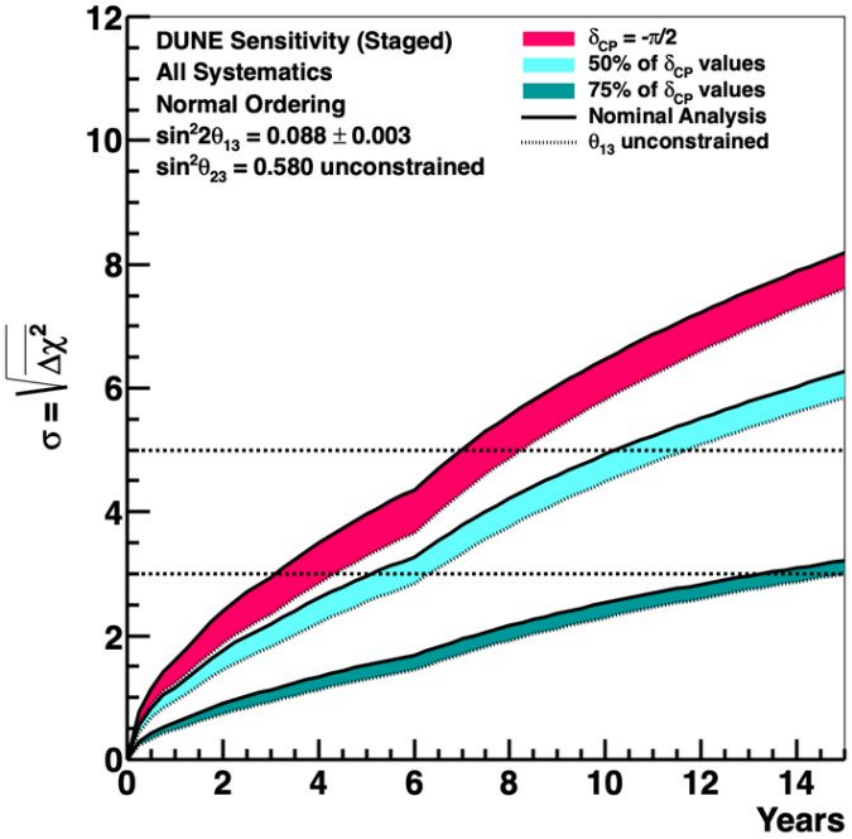


- Graph from TDR
- Include all systematics effects
- A full simulation chain

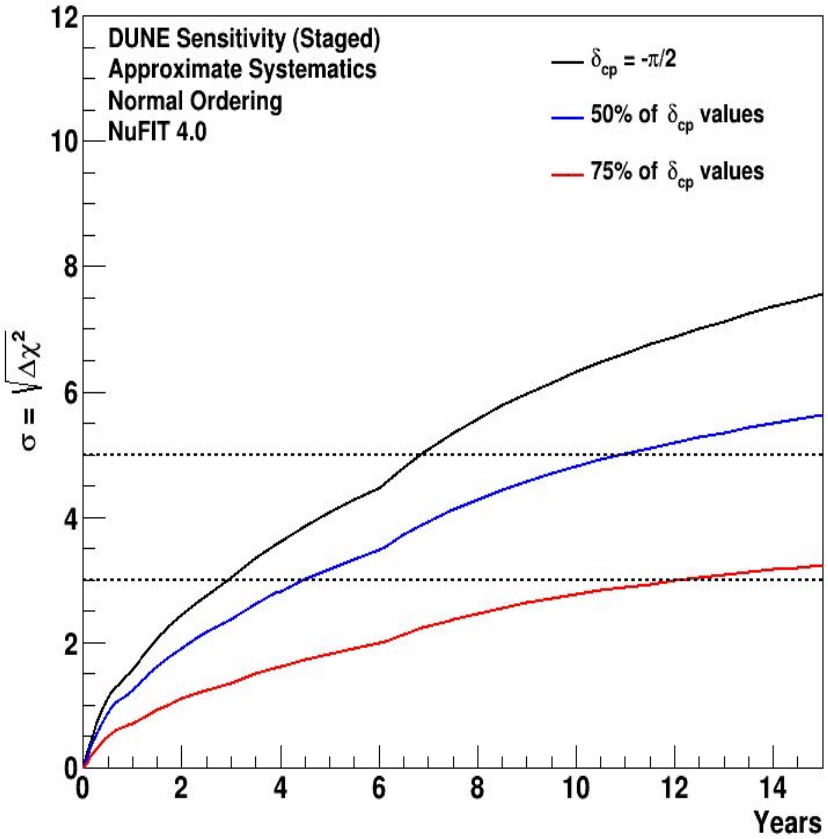


- Graph from our results
- Approximate systematics effects
- Approximate simulation

CPV Sensitivity - TDR reference

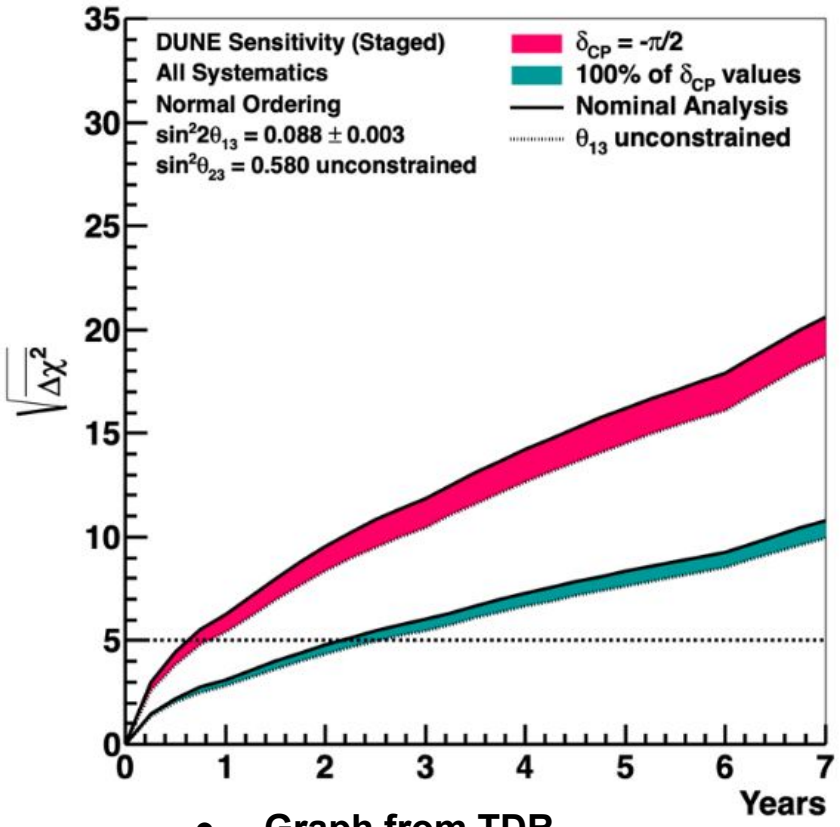


- Graph from TDR
- Include all systematics effects
- A full simulation chain
- Sensitivity analysis with Framework CAFAna

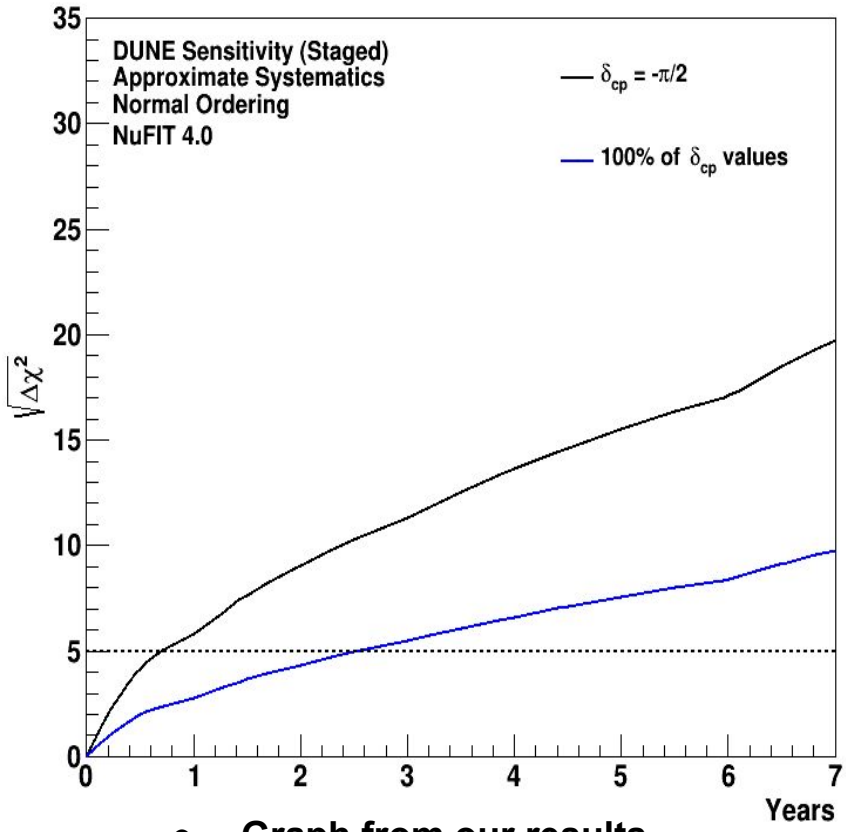


- Graph from our results
- Approximate systematics effects
- Approximation sensitivity analysis with GLoBES

Mass Ordering Sensitivity - TDR reference



- Graph from TDR
- Include all systematics effects
- A full simulation chain
- Sensitivity analysis with Framework CAFAna



- Graph from our results
- Approximate systematics effects
- Approximation sensitivity analysis with GLoBES

Energy Resolution Function

- In general, the energy resolution function is determined through a complete Monte Carlo simulation of the detector and expressed in terms of a smearing matrices.
- We define the “bin kernel” as

$$K_i^c(E) \equiv \int_{E_i-\Delta E_i/2}^{E_i+\Delta E_i/2} dE' \quad R^c(E, E')$$

- An example for a smearing matrices

$$K_{ij} = \underbrace{\begin{pmatrix} a_{00} & a_{01} & a_{02} & a_{03} & & & & \\ a_{10} & a_{11} & a_{12} & a_{13} & a_{14} & & & \\ & a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & & \\ & & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & \\ & & & a_{43} & a_{44} & a_{45} & a_{46} & a_{47} \\ & & & \uparrow & & \ddots & & \uparrow \\ & & & k_l^i & & & & k_u^i \end{pmatrix}}_{\texttt{\$sampling\_points columns}} \leftarrow \texttt{\$bins rows}$$

Energy Resolution Function

- Gaussian energy resolution function and energy resolution:

$$R^c(E, E') = \frac{1}{\sigma(E)\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2(E)}} \qquad \frac{\sigma(E)}{E} = \alpha + \frac{\beta}{\sqrt{E}} + \frac{\gamma}{E}$$

  - Flexibility to modify its variables α, β and γ, to achieve the expected energy resolution.

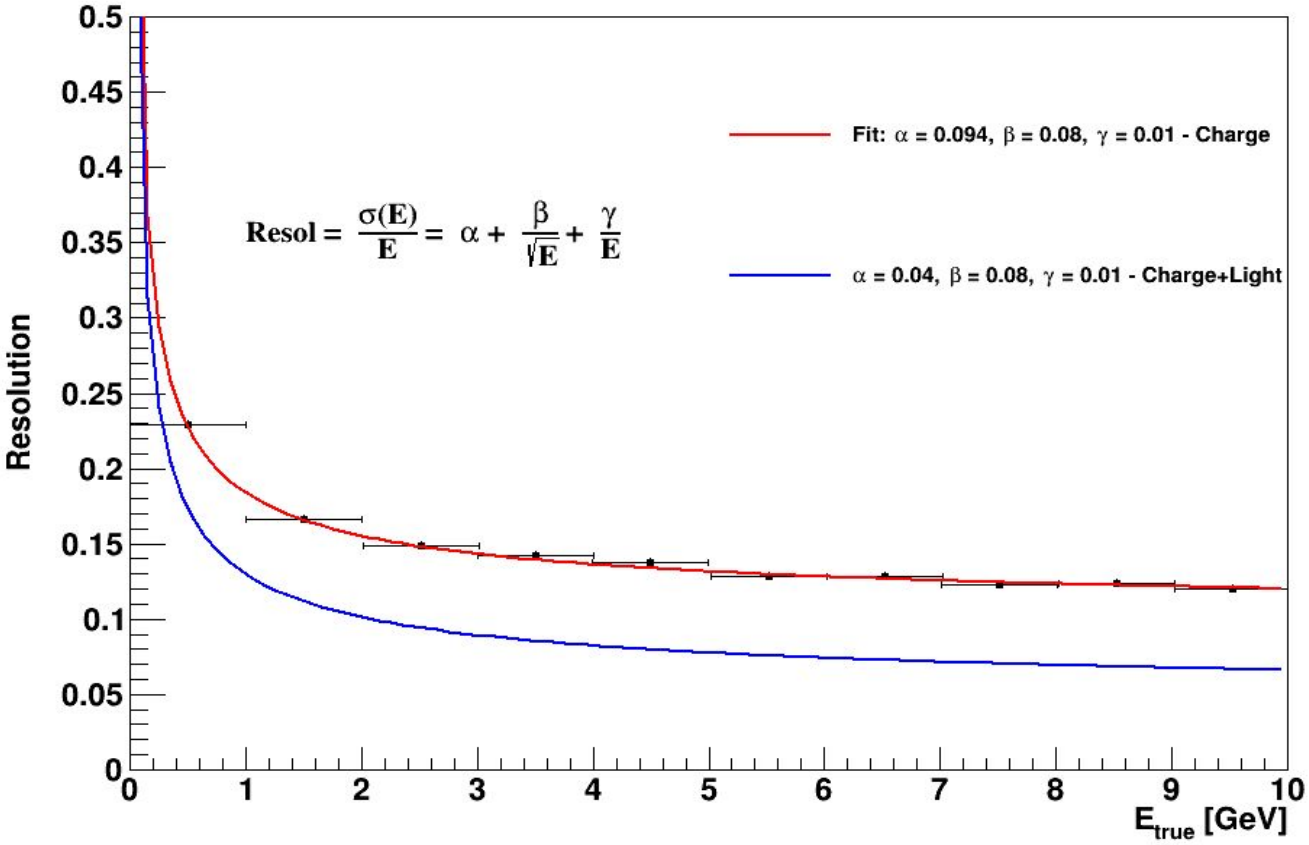
Energy Resolution Function

- Charge Energy Resolution (14% energy resolution)
  - Neutrino energy reconstruction in the Vertical Drift (Wenjie Wu) - CM 13 Sep, 2022 - > https://indico.fnal.gov/event/53964/contributions/250282/

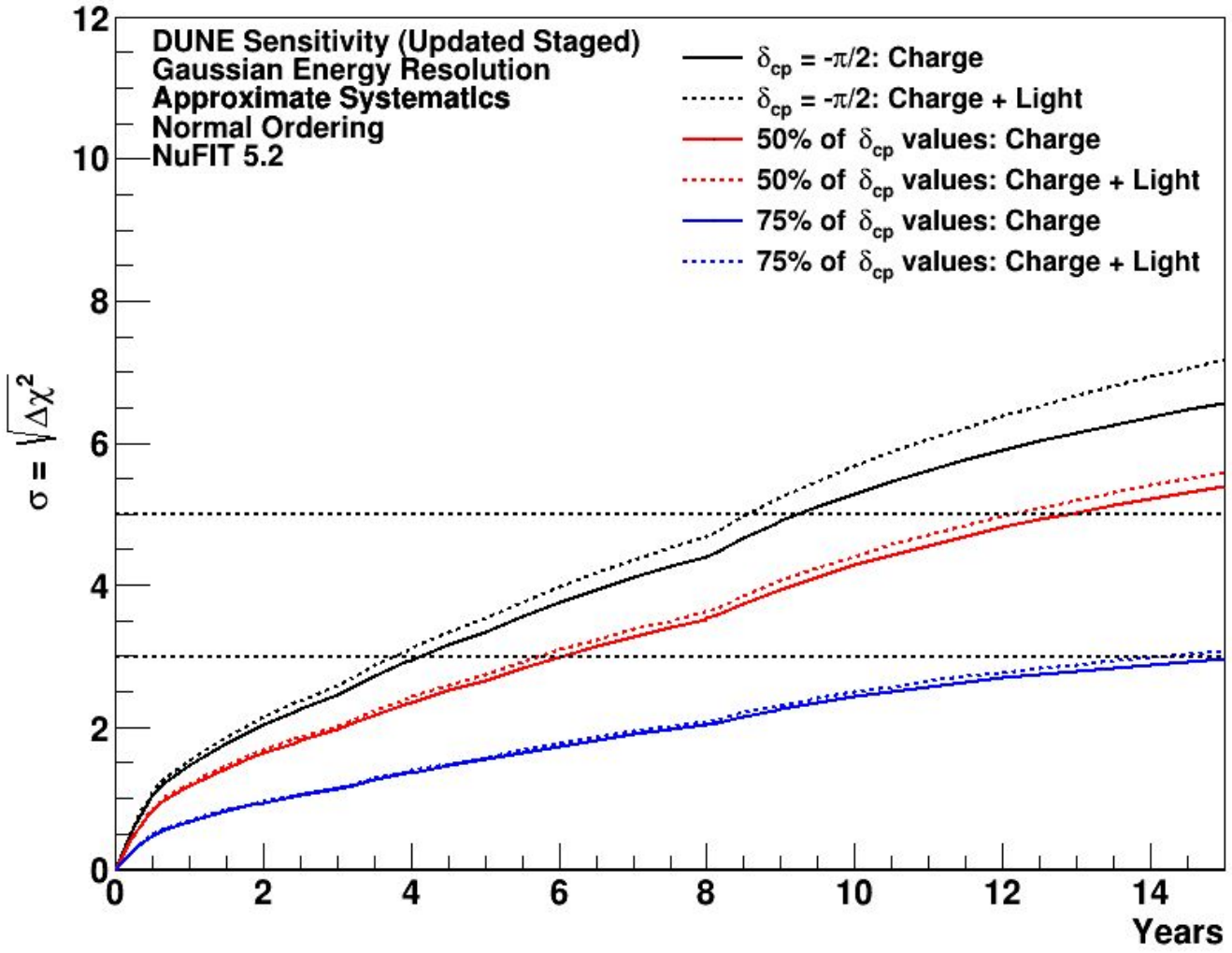
- Charge + Light energy resolution (8% energy resolution)
  - Charge and Light analysis in DUNE Far Detector HD (Marta Torti and Giulia Brunetti) - CM 25 May, 2023 - > https://indico.fnal.gov/event/57487/contributions/267200/
  - Energy resolution for electron neutrinos is around 6.5%, we assume 8% as an initial conservative analysis.

Energy Resolution Function

- Fit the MC charge resolution with a proper function;
- Modify one of the parameters to reproduce the expected charge+light resolution.

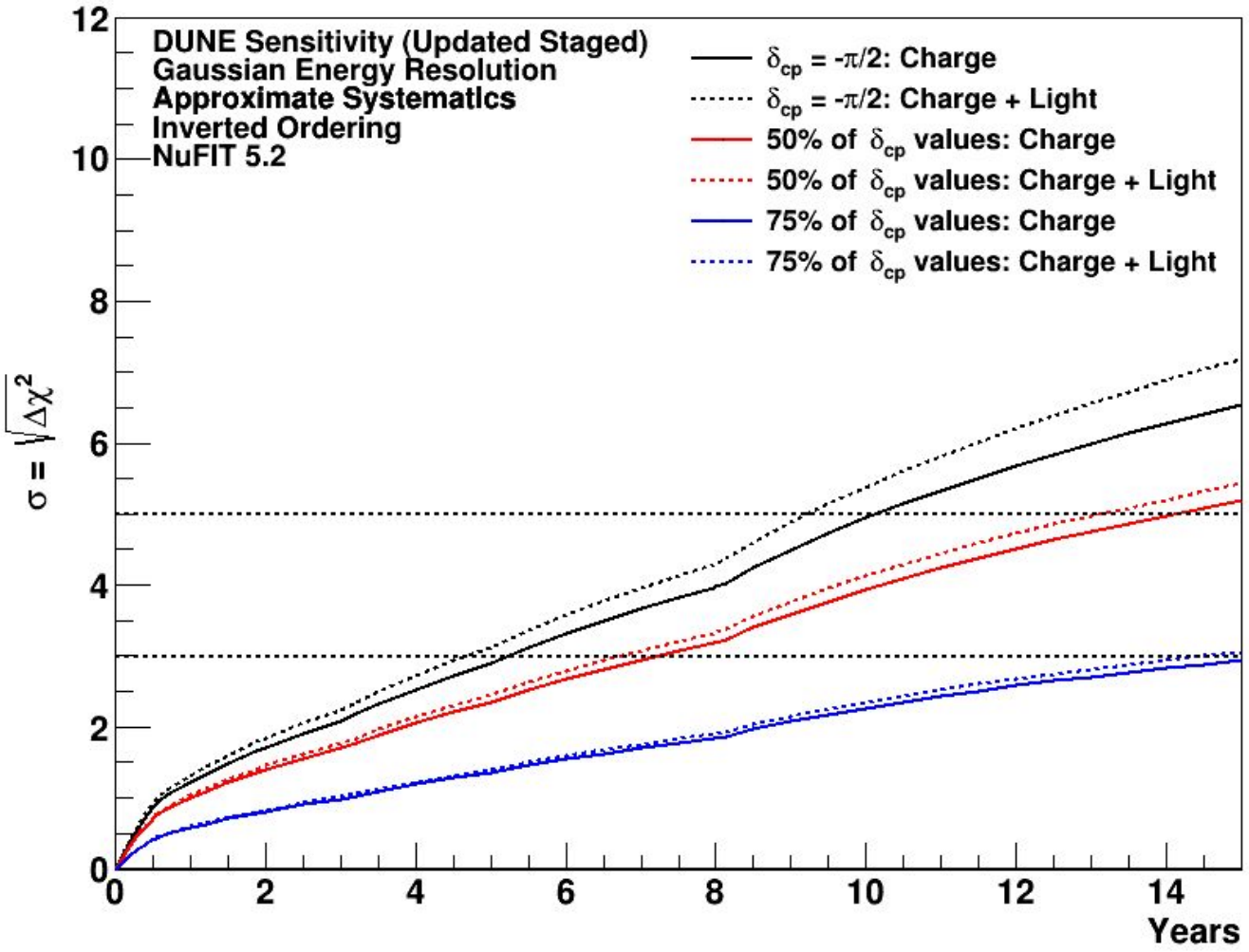


CPV Sensitivity for Q and Q+L



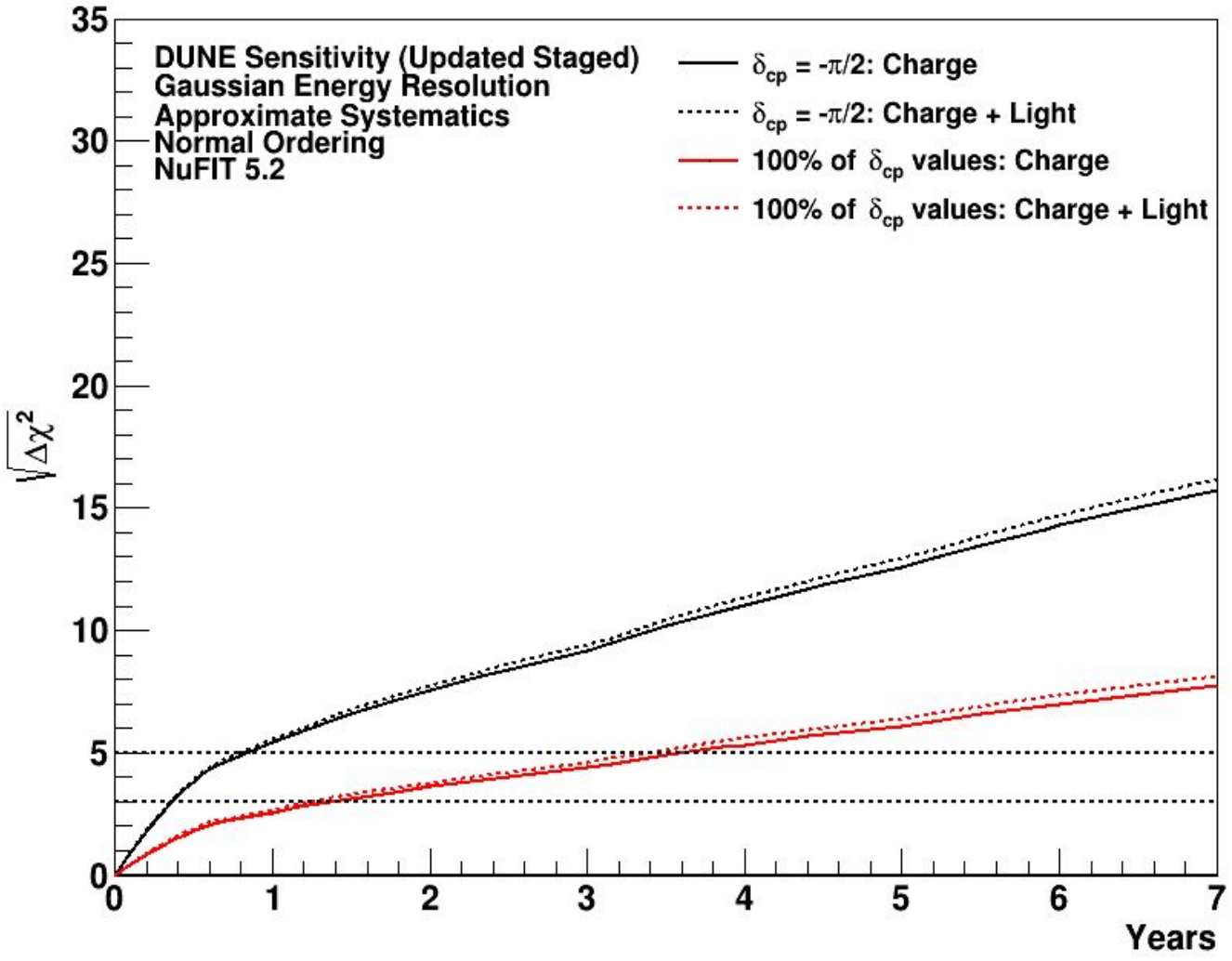
RESULT!
5σ sensitivity can be reached 6 months earlier!

CPV Sensitivity for Q and Q+L



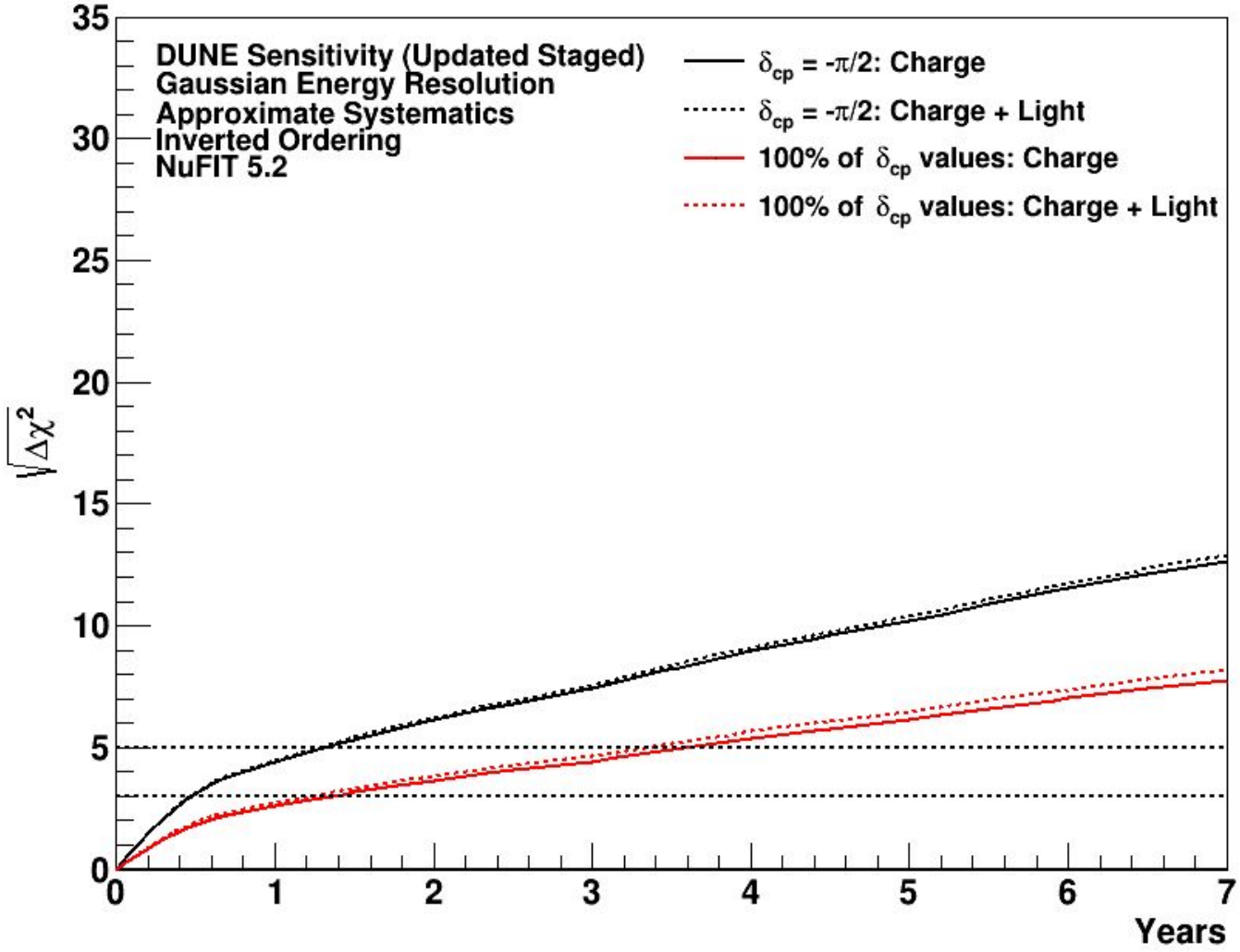
RESULT!
5σ sensitivity can be reached 9 months earlier!

Mass Ordering Sensitivity for Q and Q+L



RESULT!
5σ sensitivity can be reached 3 months earlier!

Mass Ordering Sensitivity for Q and Q+L



RESULT!
5σ sensitivity can be reached 3 months earlier!

Conclusions

- Impact of including the charge and light signal into GLoBES
  - 6 months less for NO and 9 months for IO for determining CPV.
  - 3 month less for determining Mass Ordering for both NO and IO.
- The simulations does not take into account all the systematic effects, including the ND and Gaussian function lacks details from the detector.
  - These results indicate that including the light signal may improve the sensitivity of CPV and Mass Ordering.

Next steps

- Dialogue with the LBL group to also include ND and others systematic effects in simulation.
  - Improve the sensitivity analysis using other methods (Mach3, CAFAna?).
- In collaboration with the group of the Charge and Light analysis will employ the Monte Carlo simulation data to construct smearing matrices.

Thank you for attentions!

Back up

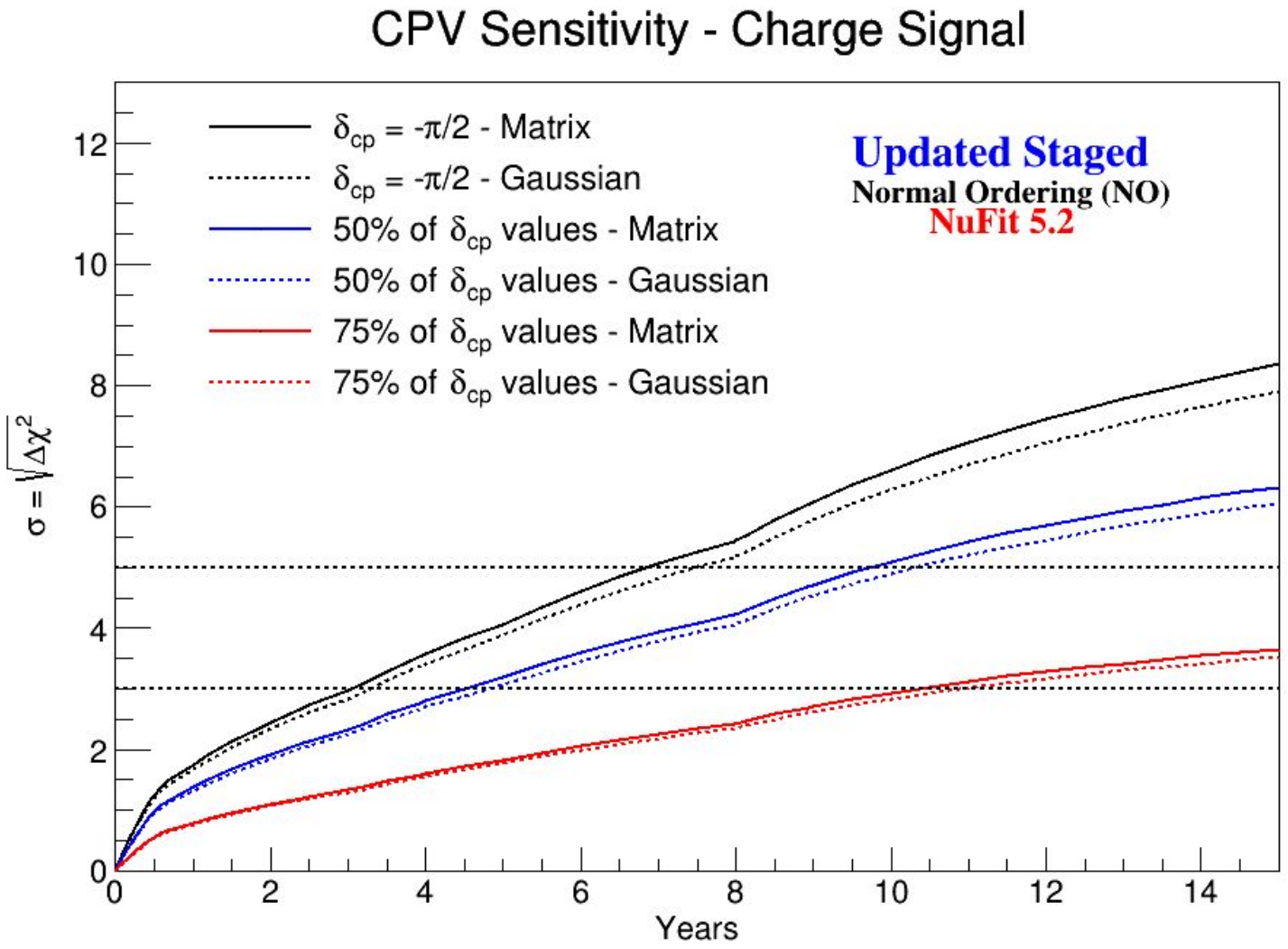
Back up

- Sensitivity CPV and Mass Ordering

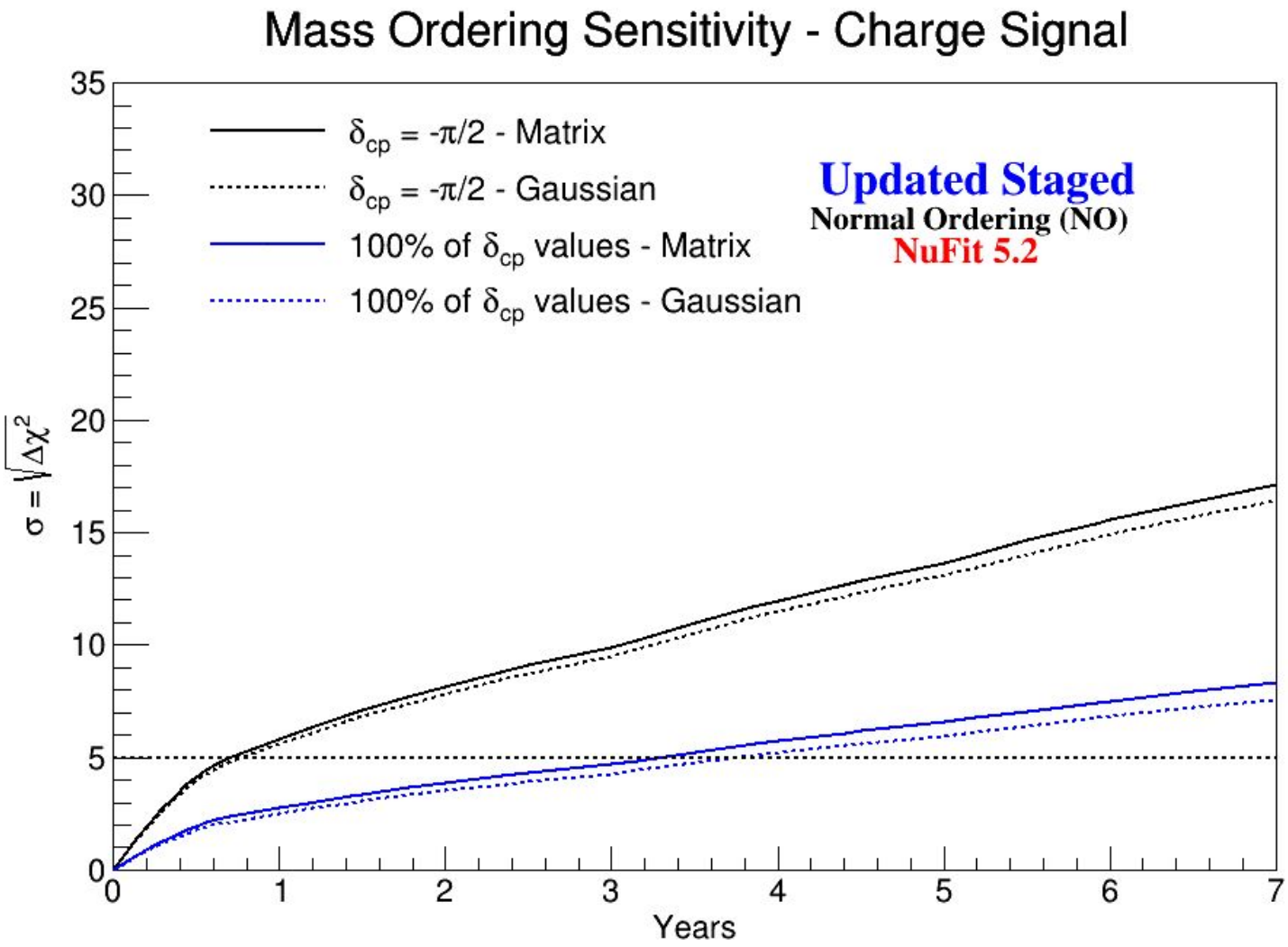
$$\Delta\chi^2_{CPV} = Min[\Delta\chi^2_{CP}(\delta^{test}_{CP} = 0), \Delta\chi^2_{CP}(\delta^{test}_{CP} = \pi)],$$

$$\Delta\chi^2_{ordering} = \chi^2_{opposite} - \chi^2_{true}.$$

Back up


CPV Sensitivity - Charge Signal
δ_{cp} = -π/2 - Matrix
δ_{cp} = -π/2 - Gaussian
50% of δ_{cp} values - Matrix
50% of δ_{cp} values - Gaussian
75% of δ_{cp} values - Matrix
75% of δ_{cp} values - Gaussian
Updated Staged
Normal Ordering (NO)
NuFit 5.2
$\sigma = \sqrt{\Delta\chi^2}$
Years
0
2
4
6
8
10
12
14

Back up


Mass Ordering Sensitivity - Charge Signal
δ_{cp} = -π/2 - Matrix
δ_{cp} = -π/2 - Gaussian
100% of δ_{cp} values - Matrix
100% of δ_{cp} values - Gaussian
Updated Staged
Normal Ordering (NO)
NuFit 5.2
$\sigma = \sqrt{\Delta\chi^2}$
Years
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7

Back up

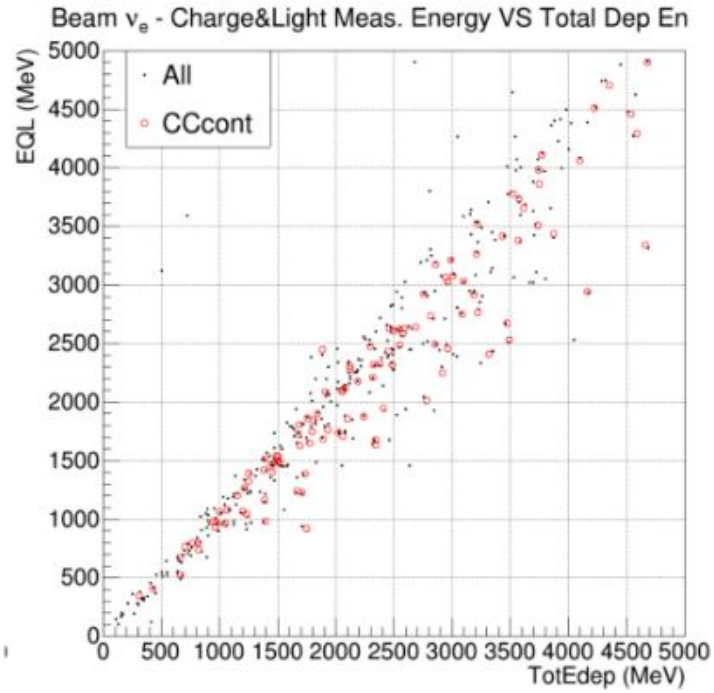
- Energy Resolution Function
  - Charge signal - > Results from Wenjie Wu Presentation.

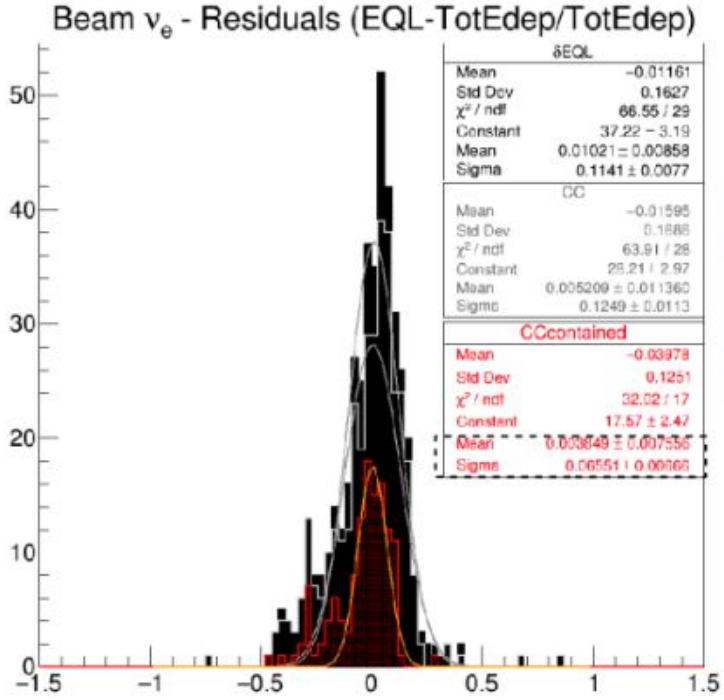
Resolution	3view_30deg	3view_30deg (anti-nu)	HD (tech-note)
Numu CC events (contained)	20.3%	17.2%	18%
Numu CC events (exiting)	18.3%	17.8%	20%
Nue CC events	14.1%	12.0%	13%

https://indico.fnal.gov/event/53964/contributions/250282/

Back up

- Energy Resolution Function
  - Charge and Light signal for electron neutrino - > Results from Giulia Brunetti/Marta Torti Presentation.





For CC contained events

Mean : 0.0038

Sigma: 0.0655

https://indico.fnal.gov/event/57487/contributions/267200/