Improving neutrino detection with double calorimetry in LArTPCs - Approval for LIDINE

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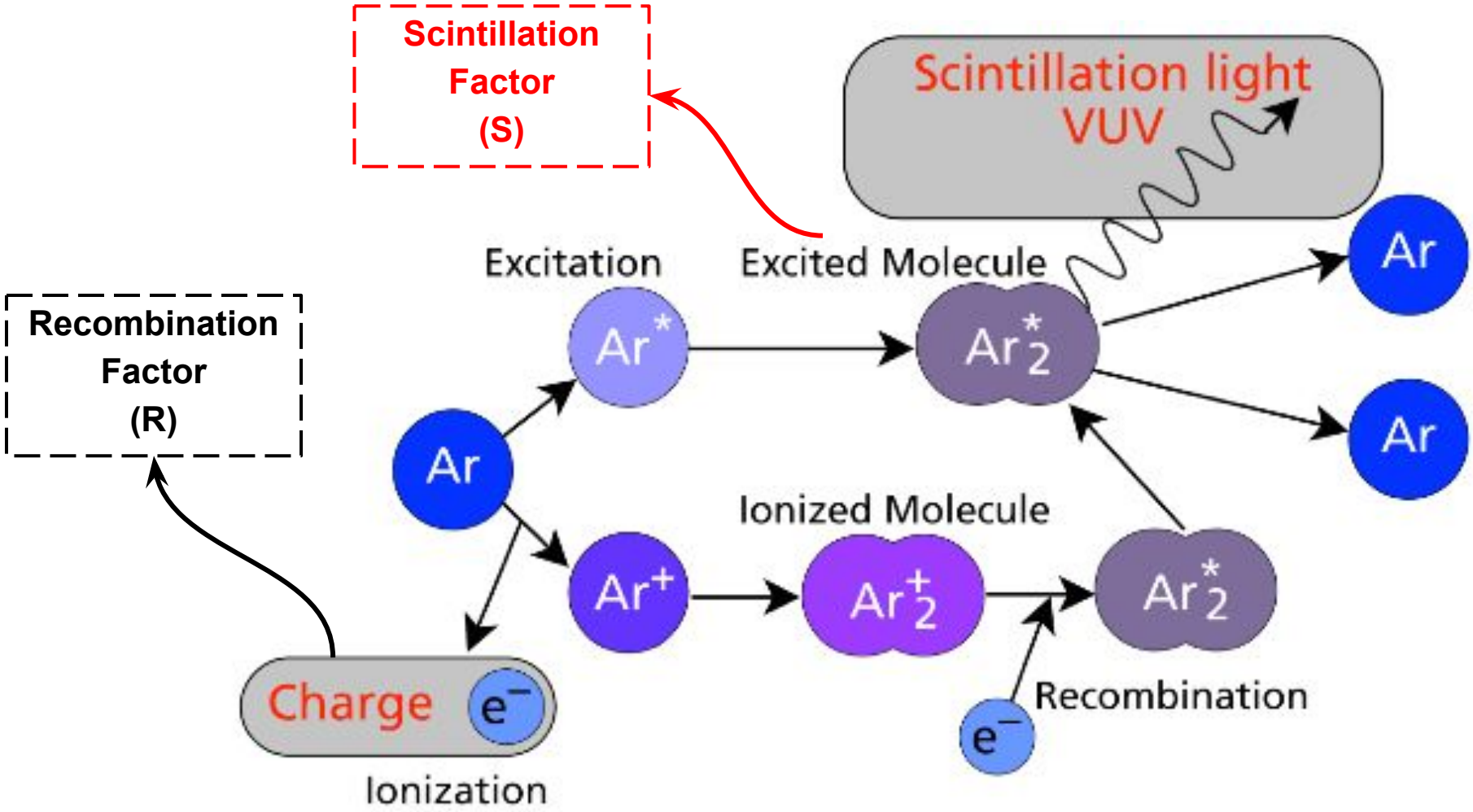
Outline

- **Main objective:** Learn and develop GLoBES software to analyse the oscillation parameters of the CPV and mass ordering for only charge and for both charge and light energy resolutions.
  - ❖ Ancillary files from the article: “Experiment Simulation Configurations Approximating DUNE TDR” - https://arxiv.org/src/2103.04797v2/anc
- **Sensitivity analyses in GLoBES** to validate with TDR using all data from ancillary - charge signal + smearing matrices.
- **Gaussian energy resolution function** into GLoBES to analyse CPV sensitivity and mass ordering:

  - Charge signal ~ 14% energy resolution;

  - Charge + Light signal ~ 8% energy resolution.

Charge and light signal in a LArTPC



Araujo, G. Wavelength Shifting and Photon Detection of Scintillation Light from Liquid Argon

Charge and light signal in a LArTPC

- **Electric Field in LArTPC ~ 0.5kV/cm**
  - **Recombination signal;**
  - **Scintillation signal.**

- **Charge signal (Q)**

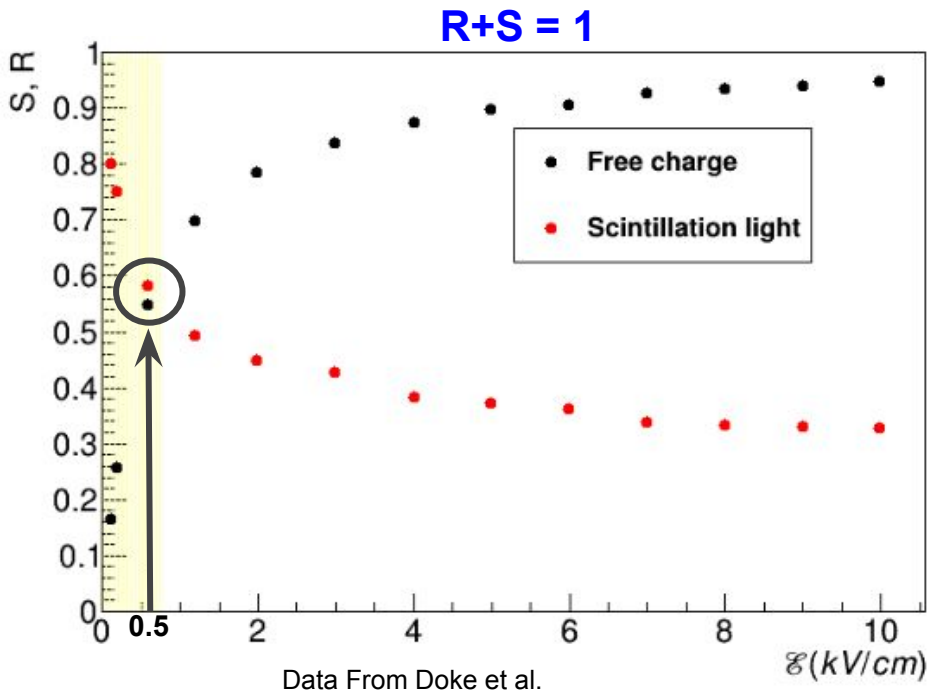
$$Q = N_e = N_i R$$

- **Light signal (L)**

$$L = N_\gamma = N_{ex} + N_i(1 - R)$$

- **Combination of charge signal and light (Q+L)**
  - **Improved energy resolution;**
  - **Independence of the recombination factor (R).**

$$L + Q = N_i + N_{ex} = \frac{\Delta E}{W_{ph}} \rightarrow \Delta E = (Q + L) W_{ph}$$



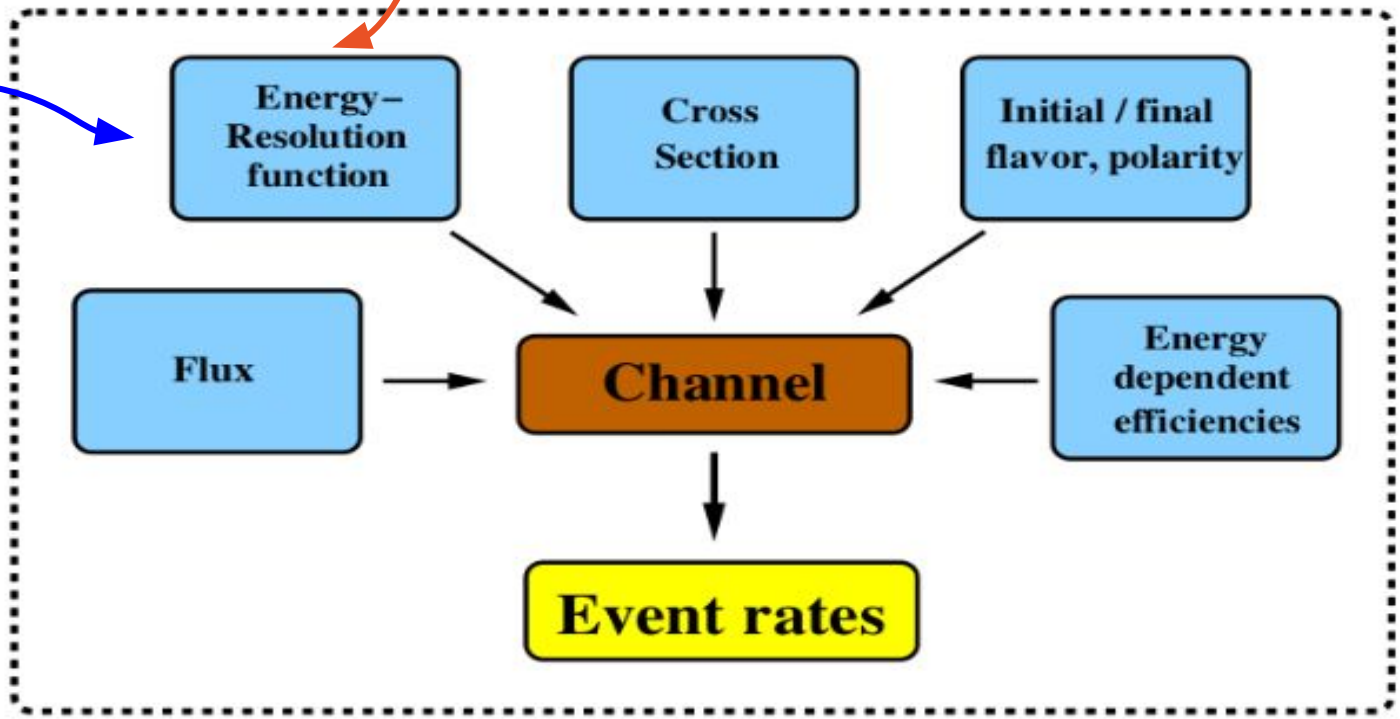
Data From Doke et al.

Marinho, F., et al. JINST C07009 (2022)

Event rates

Updated data: Q+L signals - Gaussian function

From TDR - Q signal and smearing matrices



Channel's values in GLoBES

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

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.

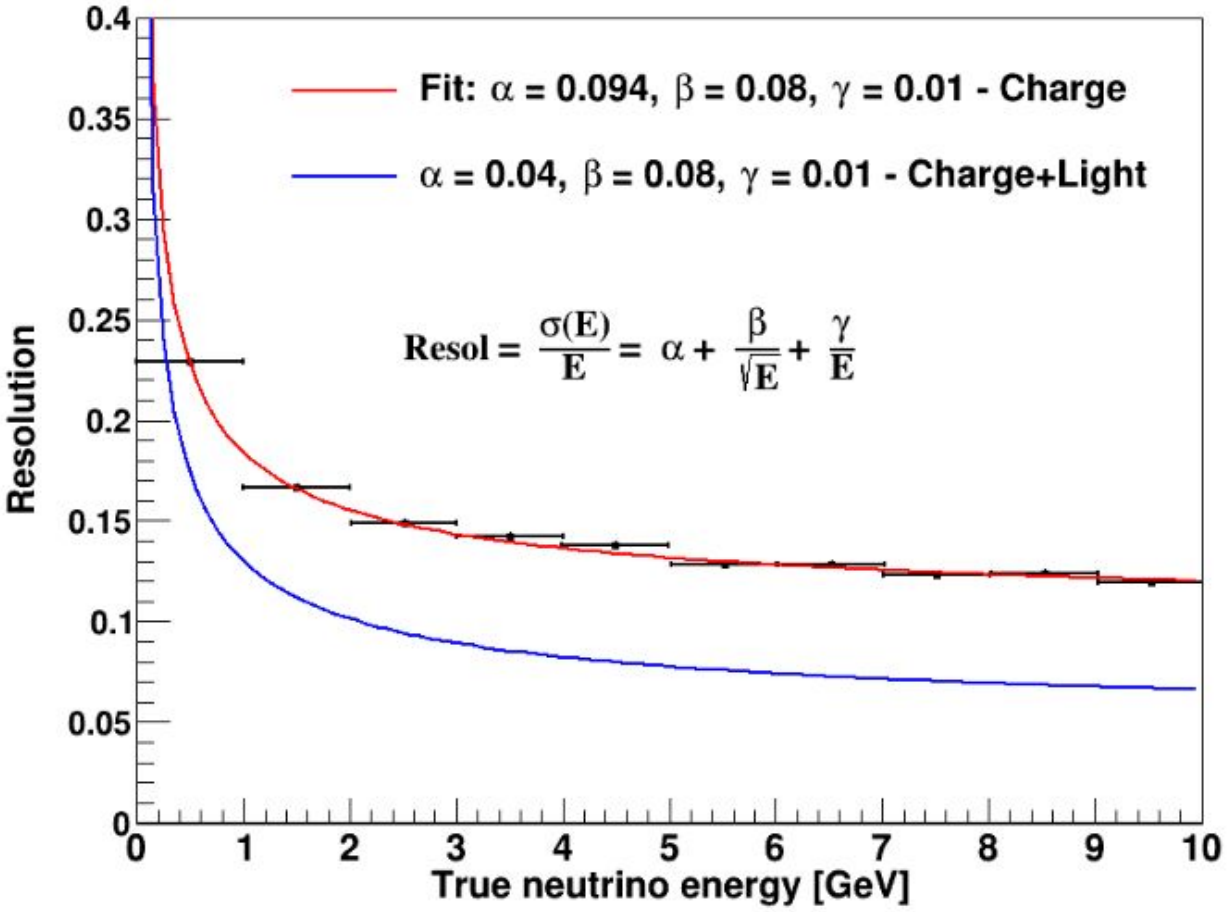
Energy Resolution Function

- **Q 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/

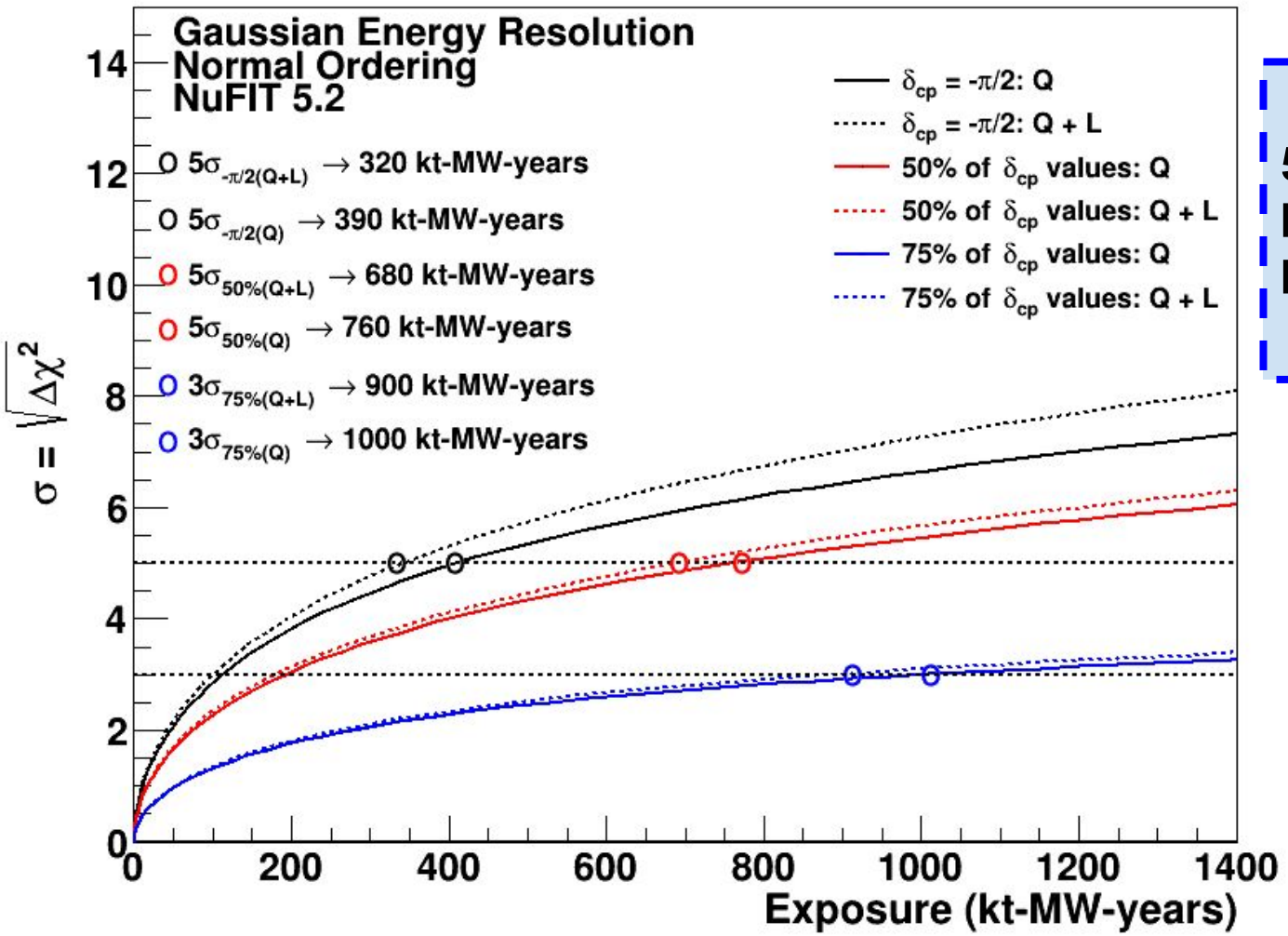
- **Q + L energy resolution** (8% energy resolution)
  - Charge and Light analysis in DUNE Far Detector HD (Marta Torti and Giulia Brunetti) - CM 25 May, 2023 - > https://indico.fnal.gov/event/57487/contributions/267200/
  - Energy resolution for electron neutrinos is around 6.6%, we assume 8% as an initial conservative analysis.
    - Preliminary results on simulated beam events CC Nue contained on Total Deposited Energy.

Energy Resolution Function

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

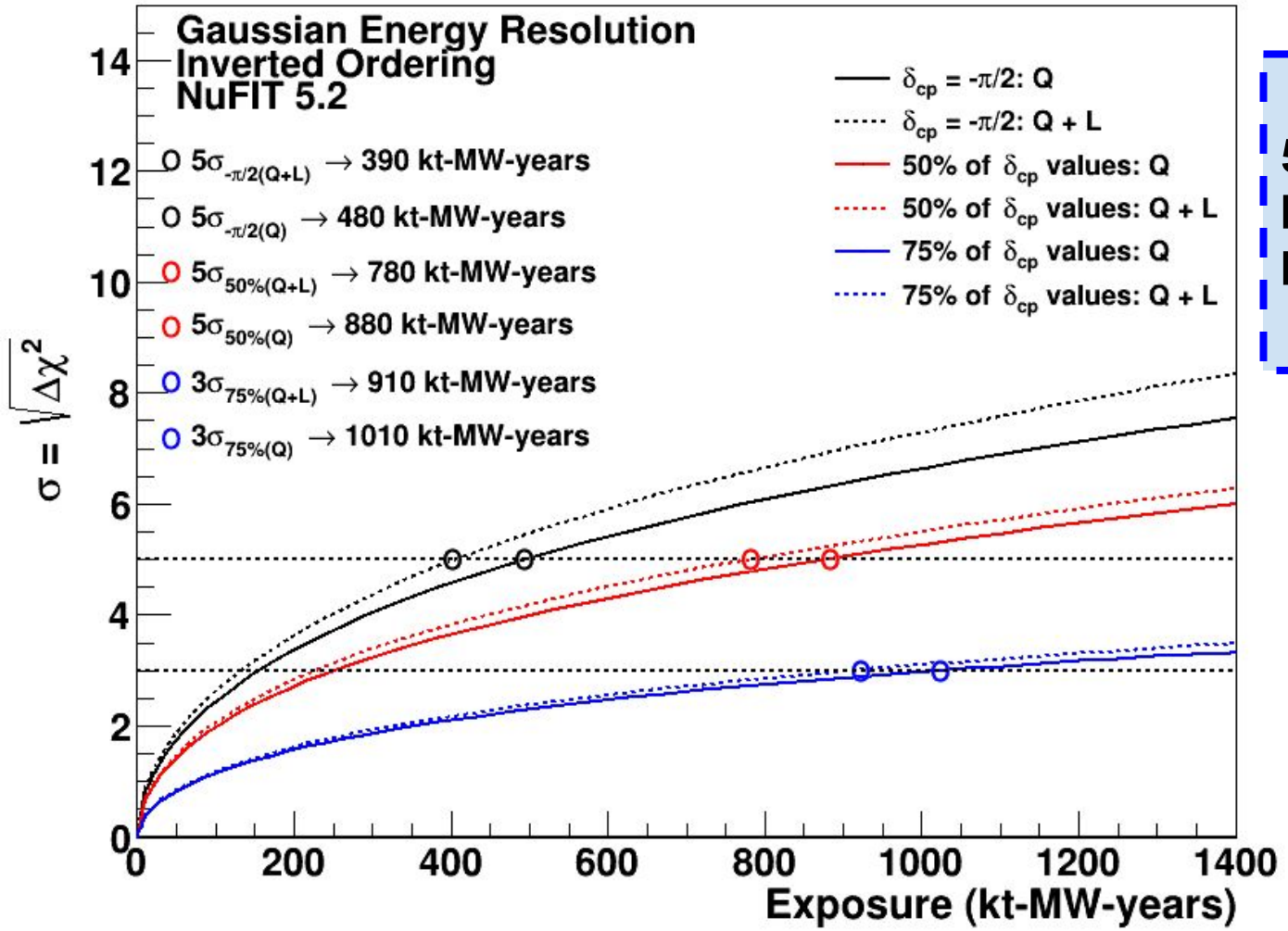


CPV Sensitivity for Q and Q+L



RESULT!
5σ sensitivity can be reached ~ 70 kt-MW-years earlier!

CPV Sensitivity for Q and Q+L



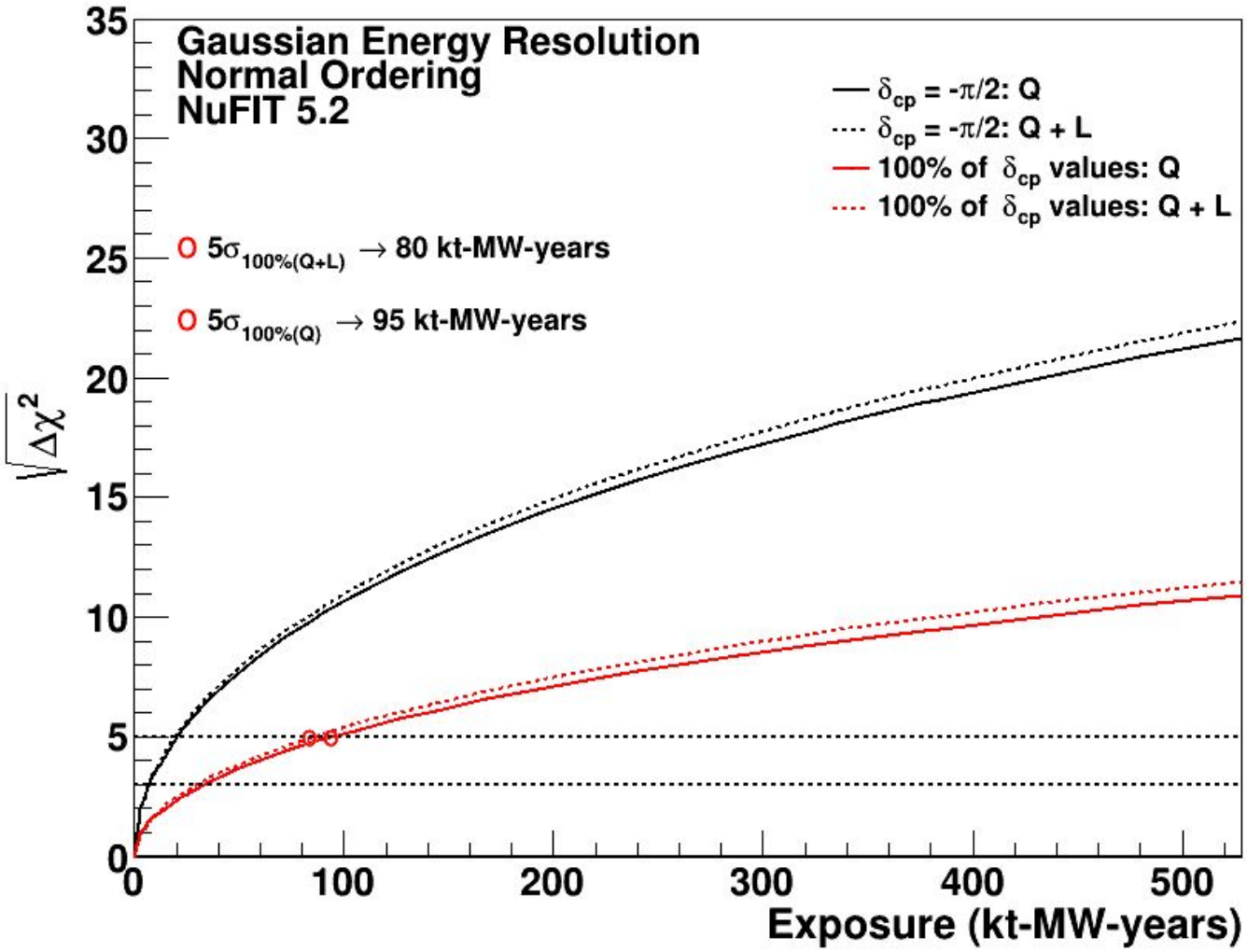
RESULT!
5σ sensitivity can be reached ~ 90 kt-MW-years earlier!

Approx. Improve CPV for Q+L

Improve CPV	-π/2	50% of δcp	75% of δcp
Normal Ordering	18%	15%	10%
Inverted Ordering	19%	11%	10%

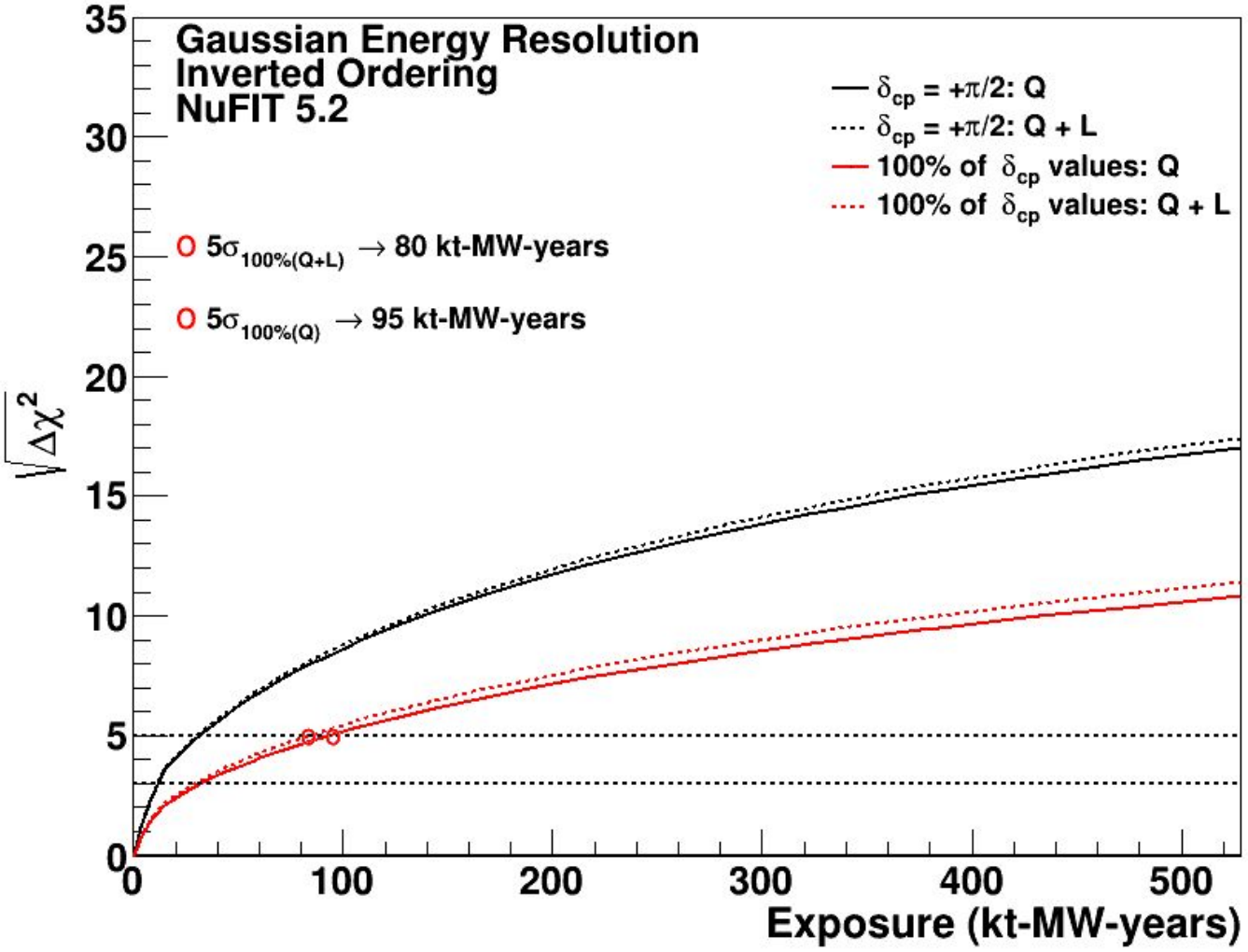
Tab 1: Reduction in Exposure obtained by comparing the Q+L signal with the Q signal for CPV.

Mass Ordering Sensitivity for Q and Q+L



RESULT!
5σ sensitivity can be reached ~ 15 kt-MW-years earlier!

Mass Ordering Sensitivity for Q and Q+L



RESULT!
5σ sensitivity can be reached ~ 15 kt-MW-years earlier!

Approx. Improve Mass Ordering for Q+L

Improve Mass Ordering	100% of δcp
Normal Ordering	16%
Inverted Ordering	16%

Tab 2: Reduction in Exposure obtained by comparing the Q+L signal with the Q signal for Mass Ordering.

Conclusions

- Impact of including the charge and light signal into GLoBES
  - For determining CPV;
  - For determining Mass Ordering.
- 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;
  - Updated analyses of the improvement in energy resolution and the impact on oscillation parameters will be made in my PhD.

Next steps for the PhD

- Improve the oscillation analysis using better methods with MaCh3.
- In collaboration with the group of the Charge and Light analysis will employ the Monte Carlo simulation + ProtoDUNE data to build a better energy resolutions for Q+L signals.

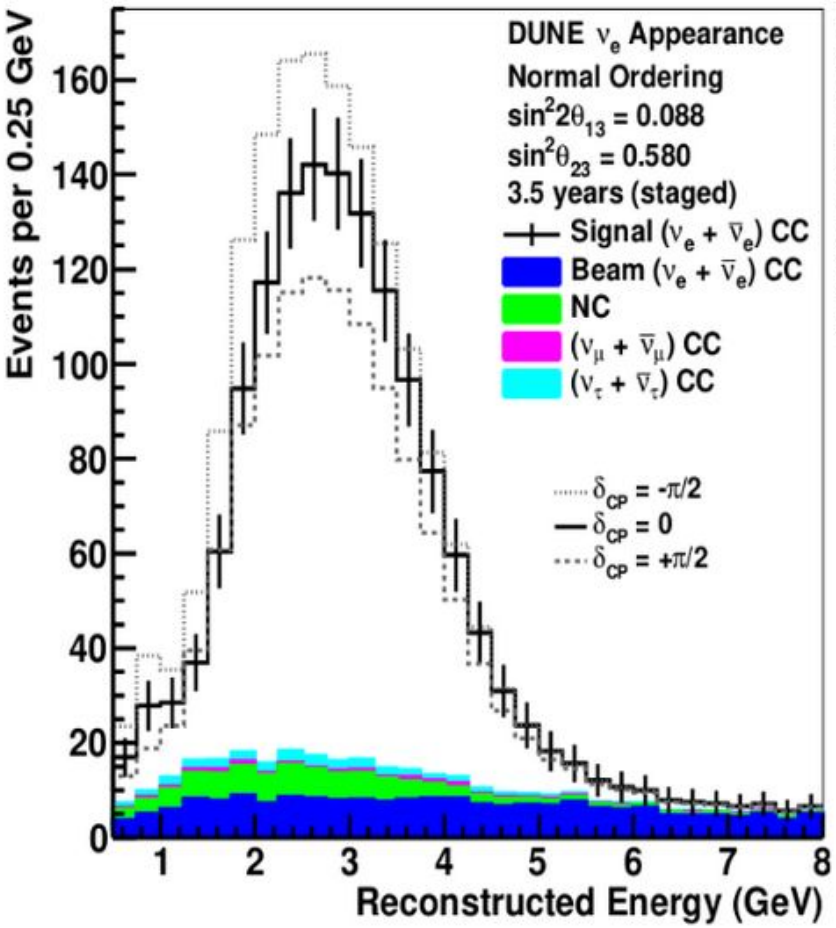
Back up

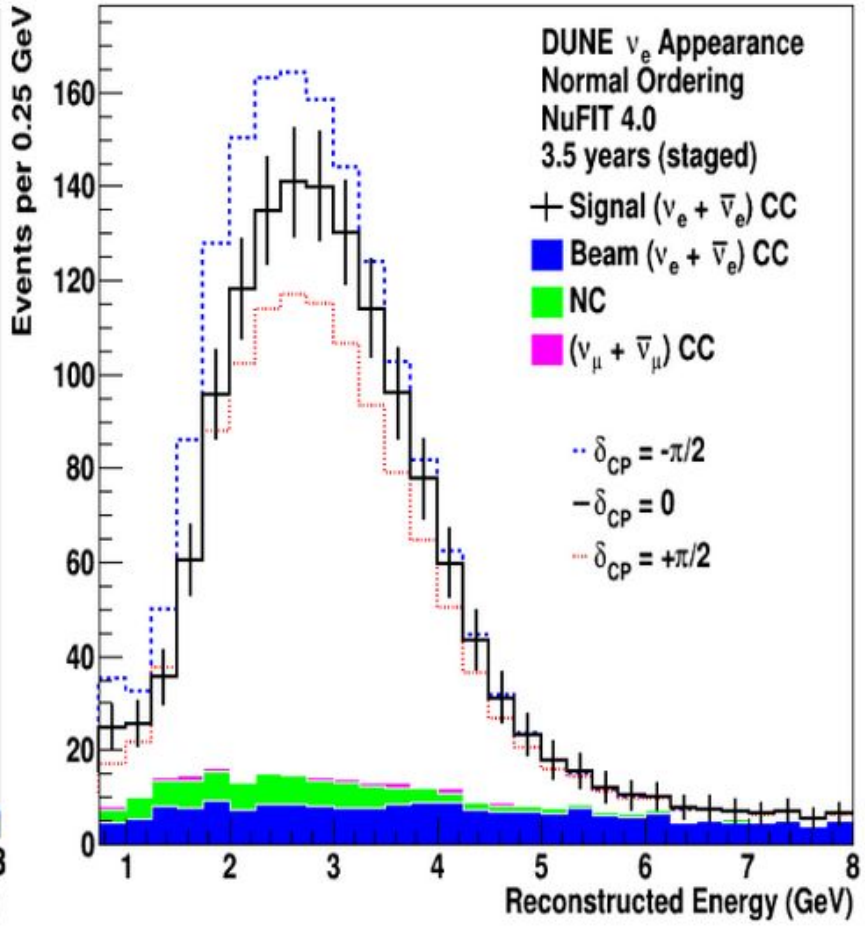
First step - Validation results

- **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}	$196 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

Event rates - TDR reference

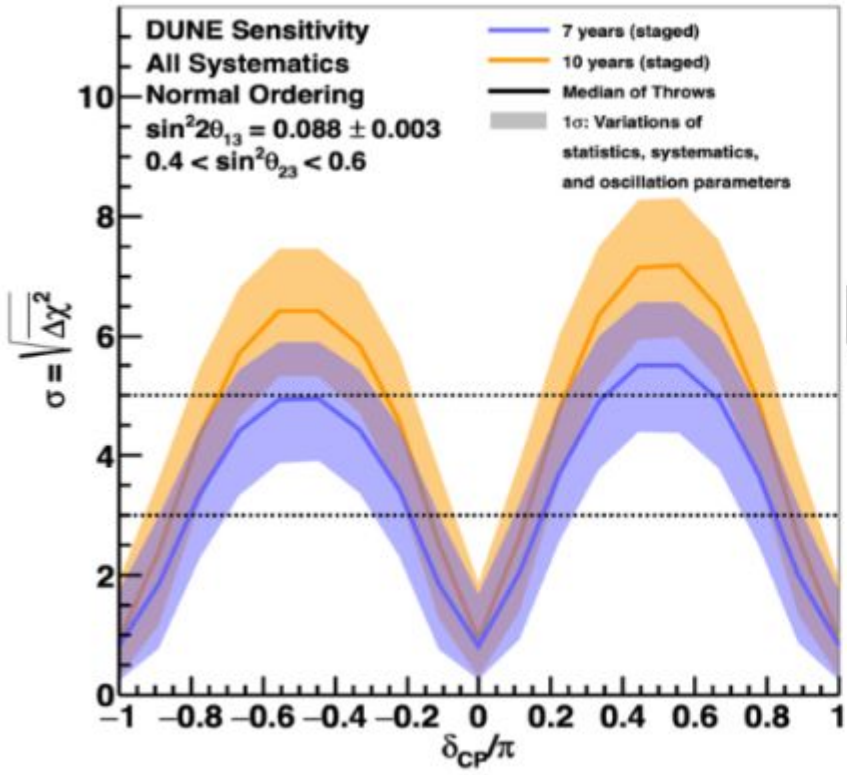


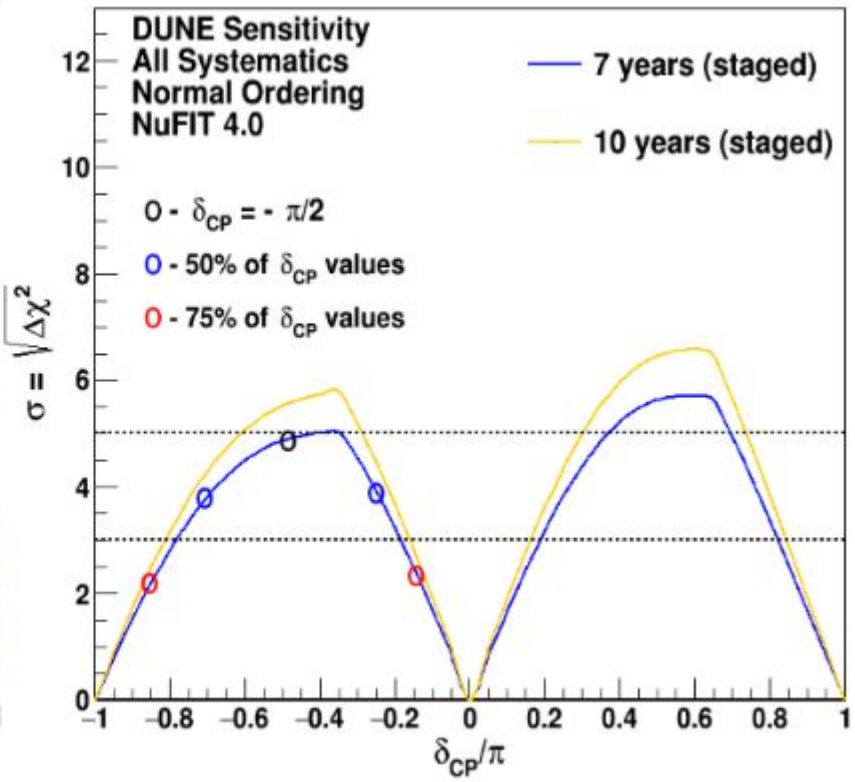


- **Graph from TDR**
- **Graph from our results using GLoBES**

Back up

- **Sensitivity CPV**

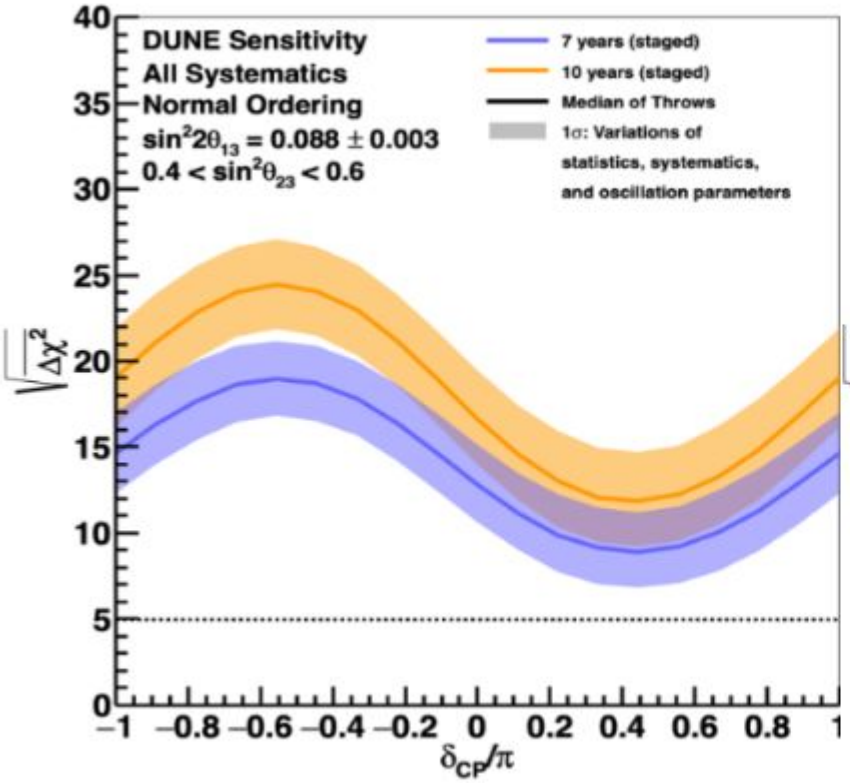


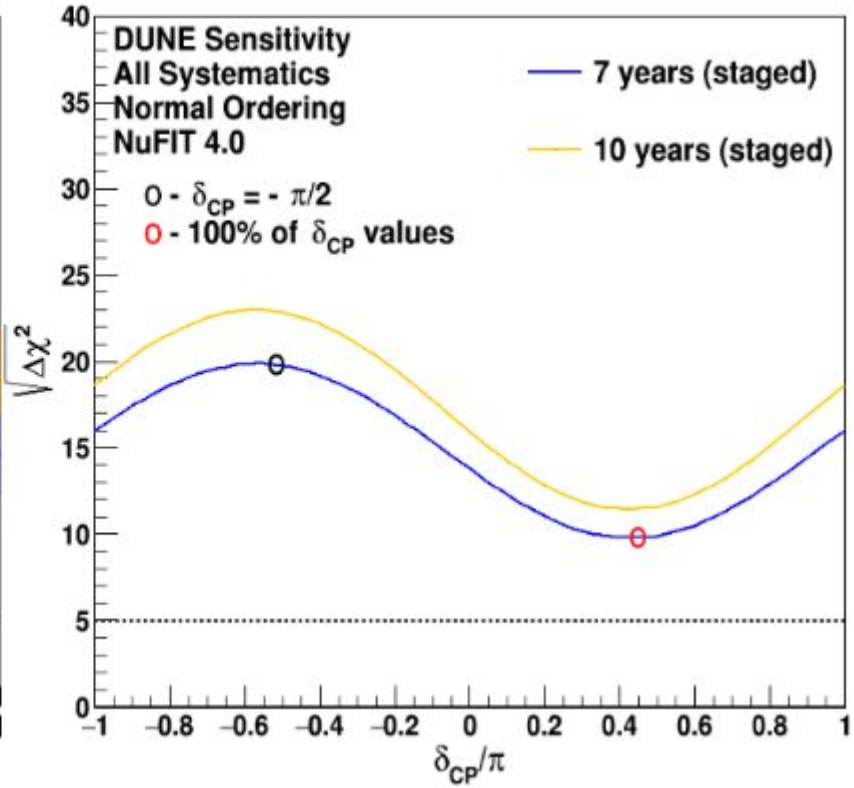


$$\Delta\chi^2_{CPV} = Min[\Delta\chi^2_{CP}(\delta^{test}_{CP} = 0), \Delta\chi^2_{CP}(\delta^{test}_{CP} = \pi)]$$

Back up

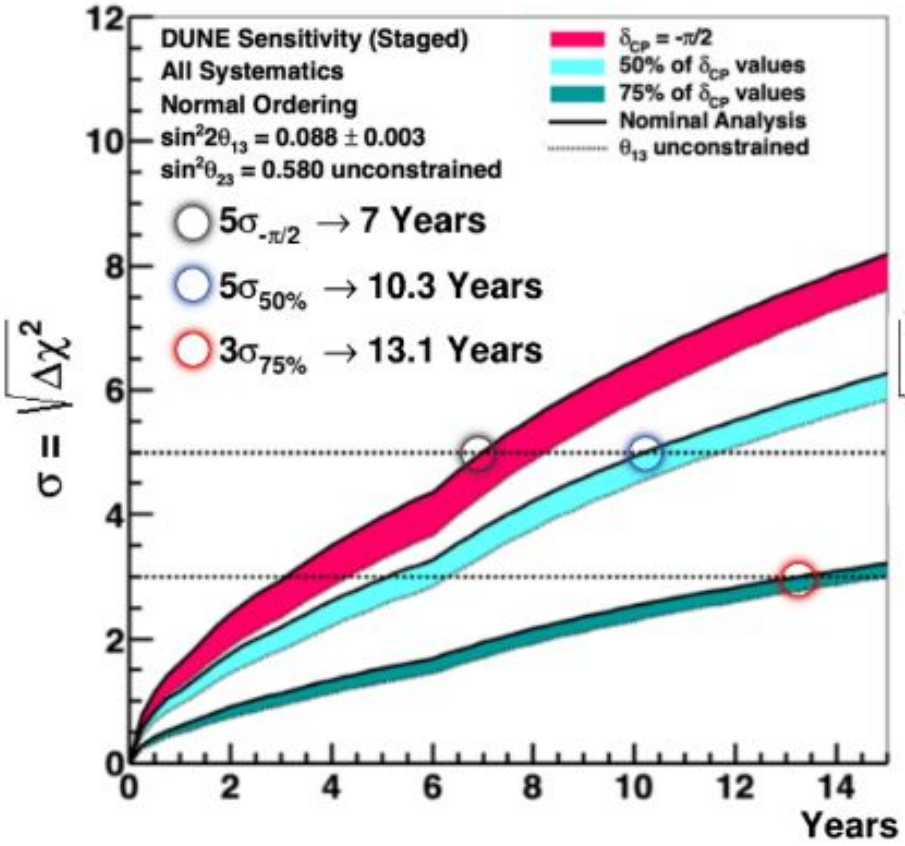
- **Sensitivity Mass Ordering**

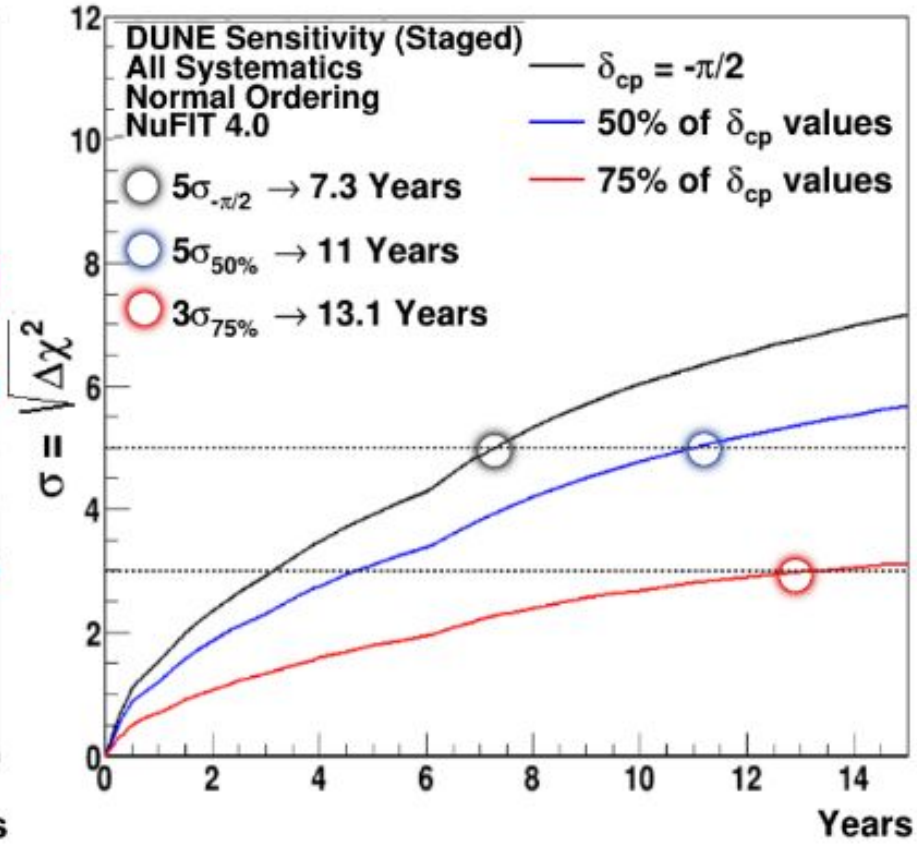




$$\Delta\chi^2_{ordering} = \chi^2_{opposite} - \chi^2_{true}$$

CPV Sensitivity - TDR reference

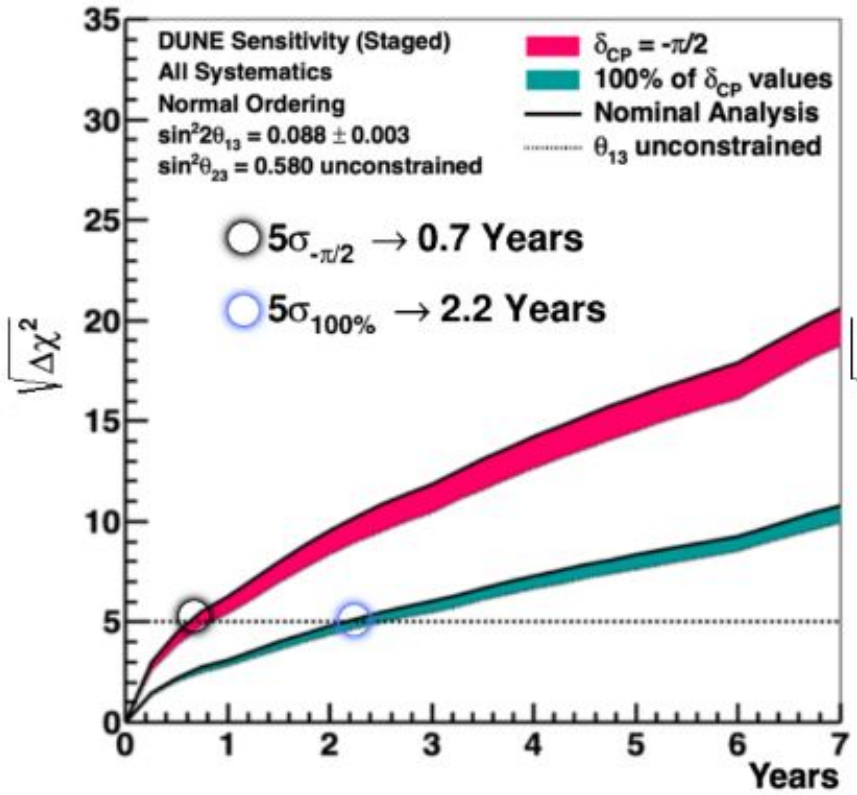




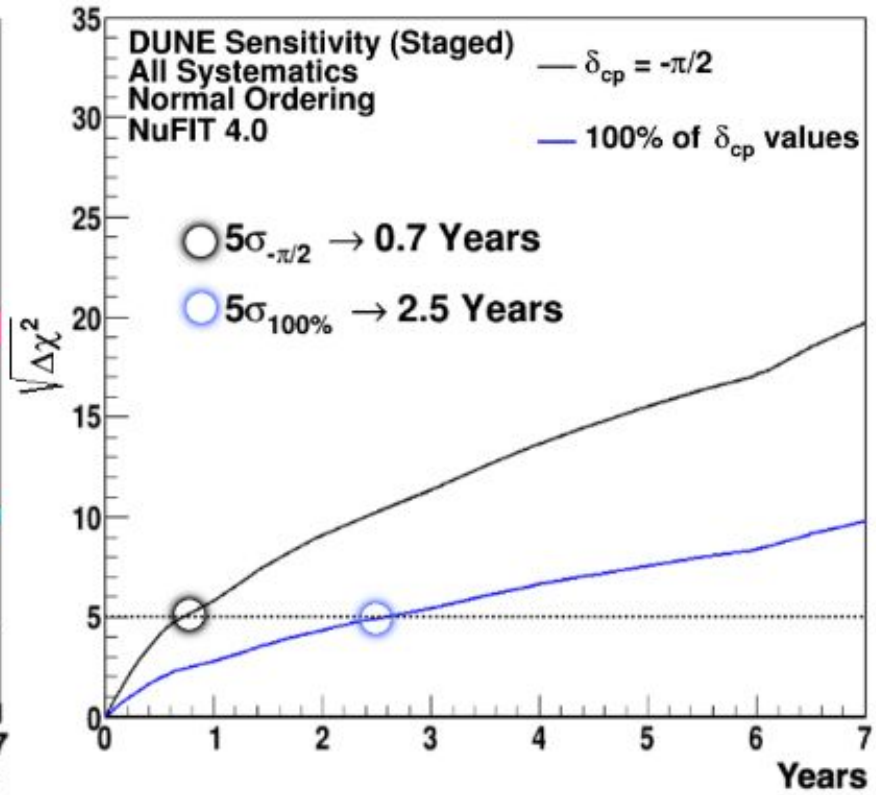
- Graph from TDR
- Sensitivity analysis with Framework CAFAna

- Graph from our results
- Sensitivity analysis with GLoBES

Mass Ordering Sensitivity - TDR reference



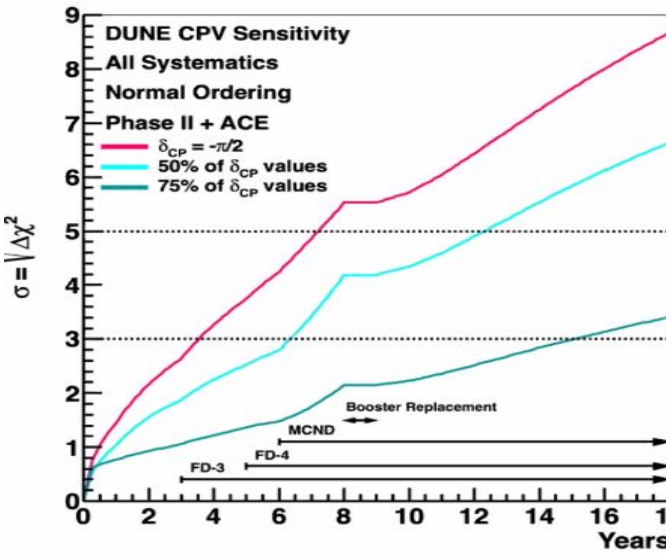
- Graph from TDR
- Sensitivity analysis with Framework CAFAna



- Graph from our results
- Sensitivity analysis with GLoBES

Charge + Light analysis

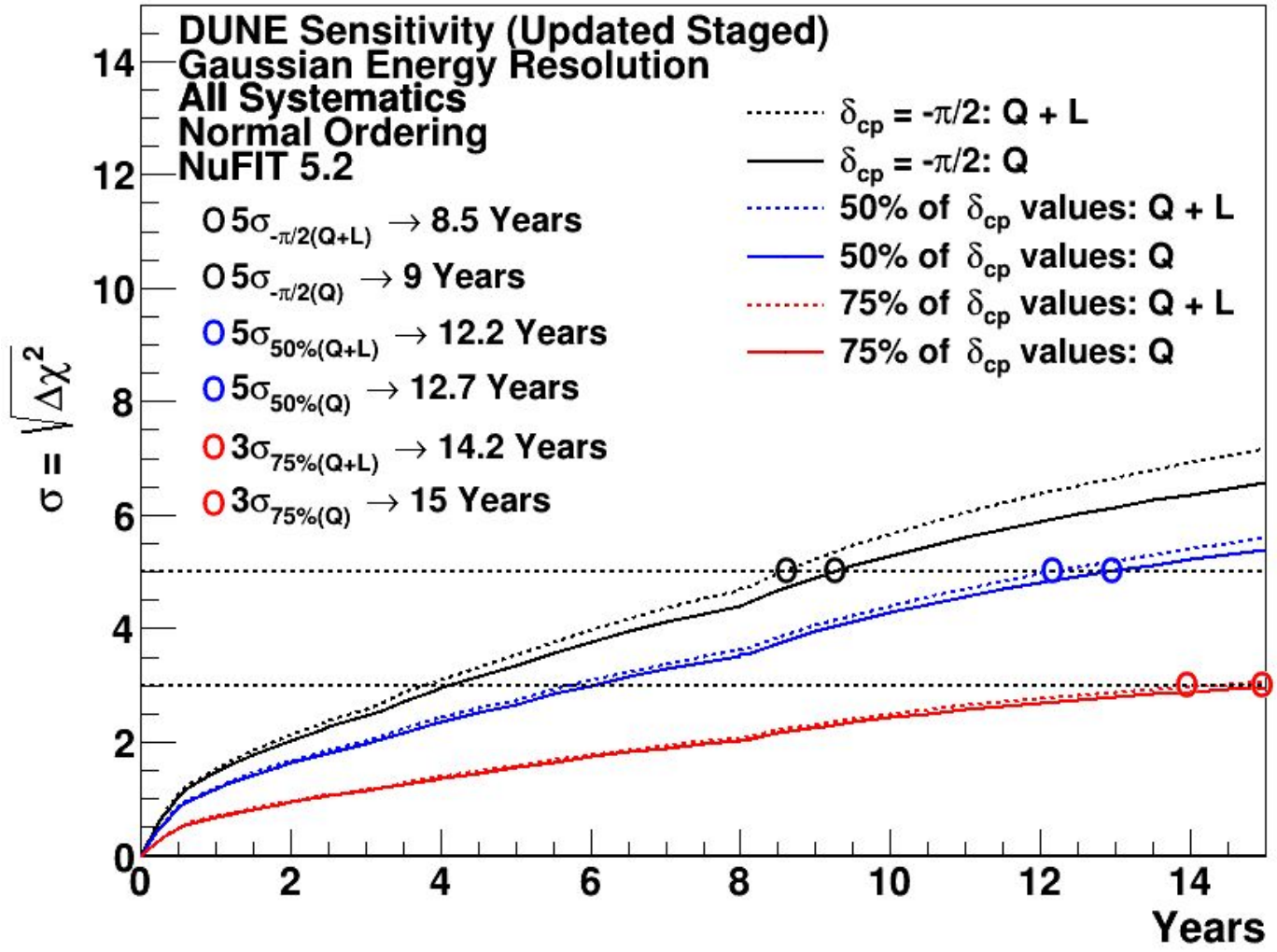
- **After validation:** using the updated information about nominal deployment plan (P5) and implementation of the current value oscillation parameter from NuFIT 5.2 (2023).



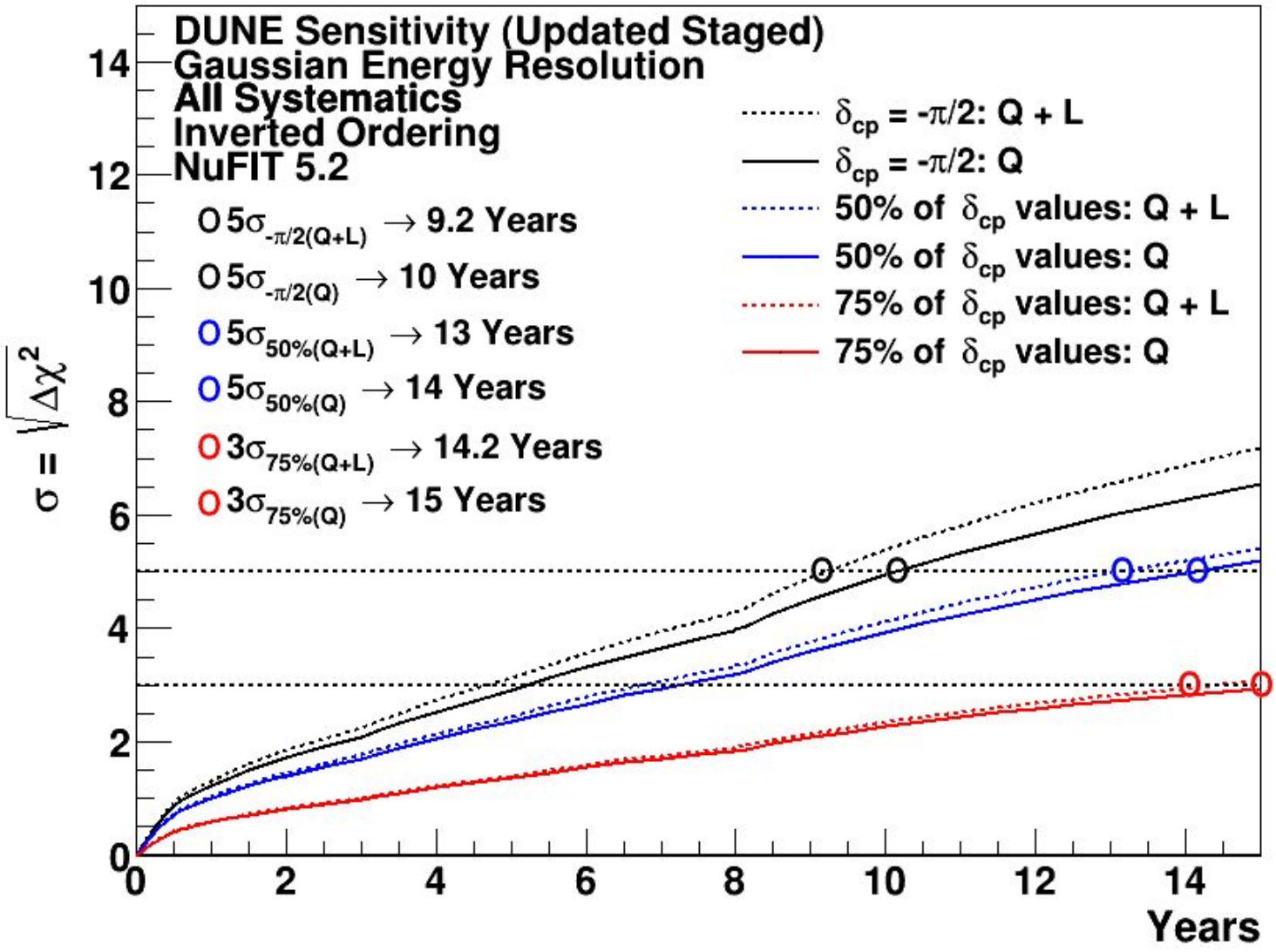
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	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.**

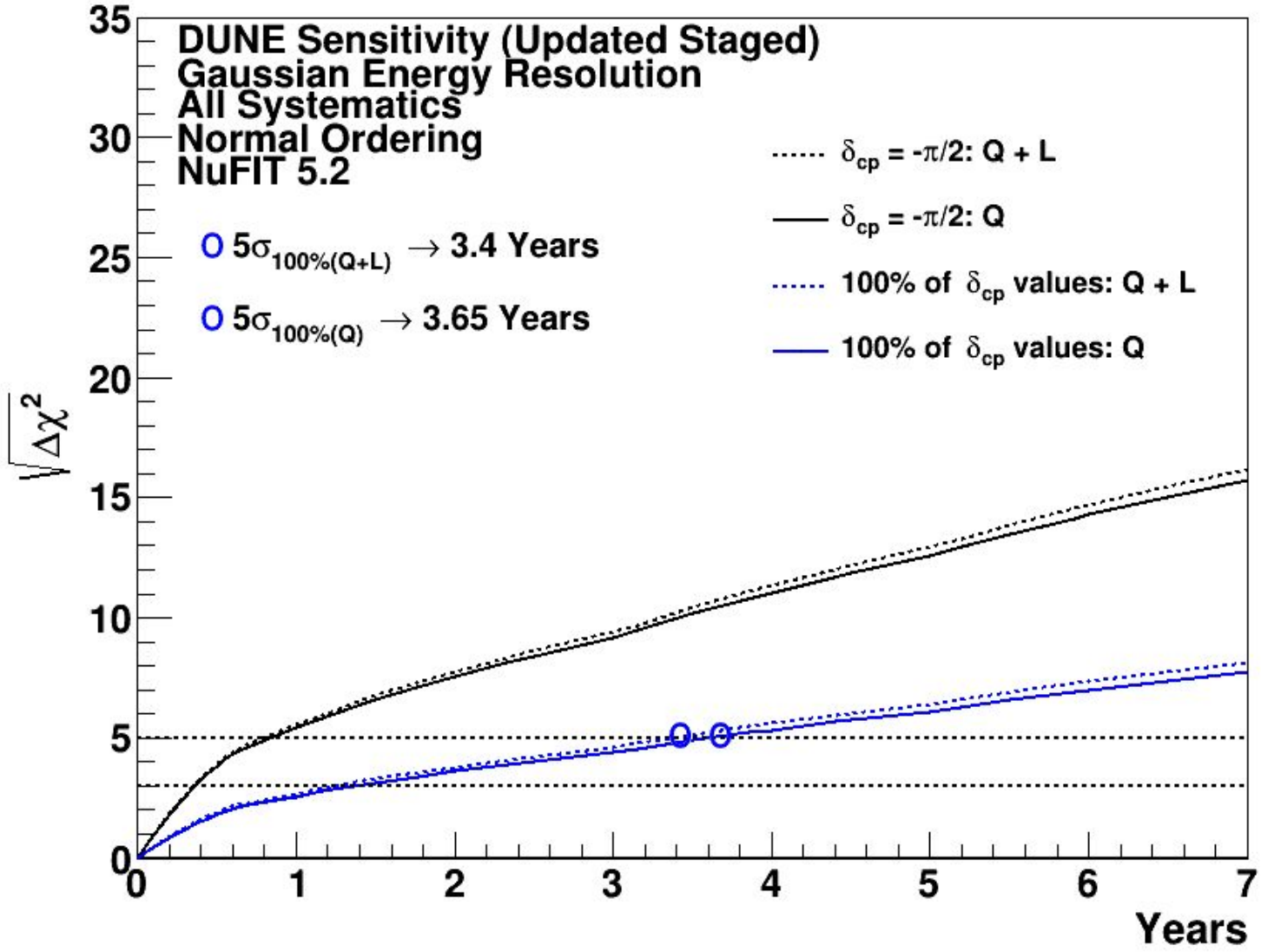
CPV Sensitivity - Updated reference



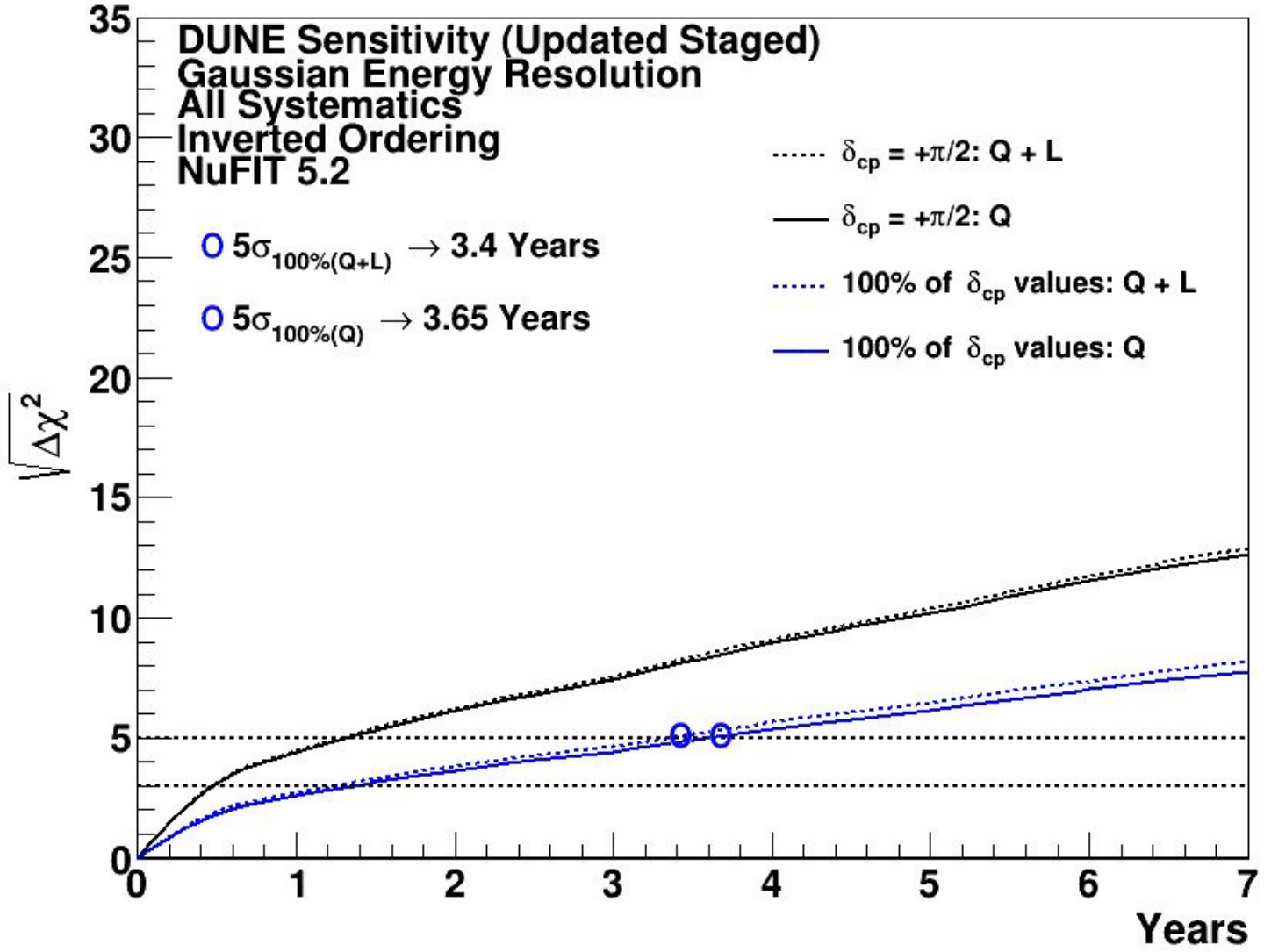
CPV Sensitivity - Updated reference



Mass Ordering Sensitivity - Updated reference



Mass Ordering Sensitivity - Updated reference



Back up

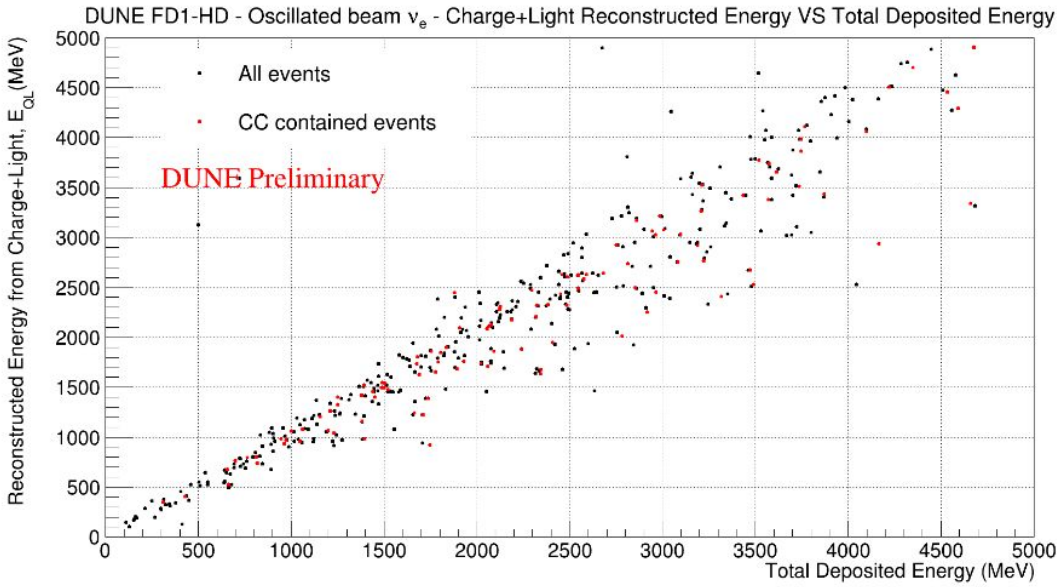
- **Energy Resolution Function:**
  - Charge signal - > Results from Wenjie Wu Presentation.

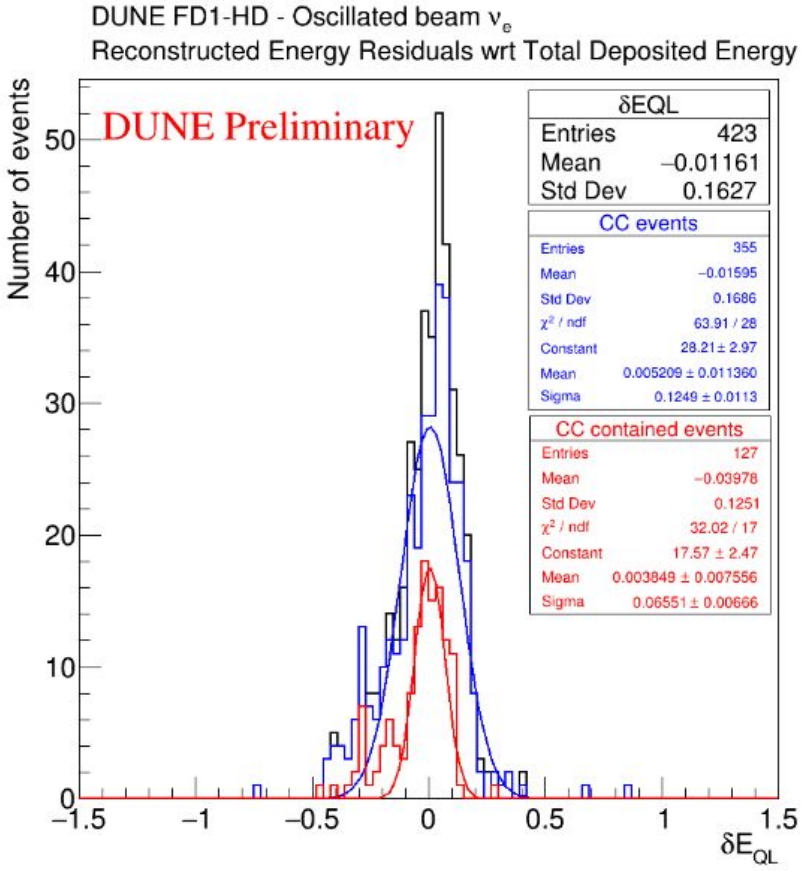
Resolution	3view_30deg	3view_30deg (anti-nu)	HD (tech-note)
Numu CC events (contained)	20.3%	17.2%	18%
Numu CC events (exiting)	18.3%	17.8%	20%
Nue CC events	14.1%	12.0%	13%

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.





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