Internal Calibration of the Stereo Detector

STEREO

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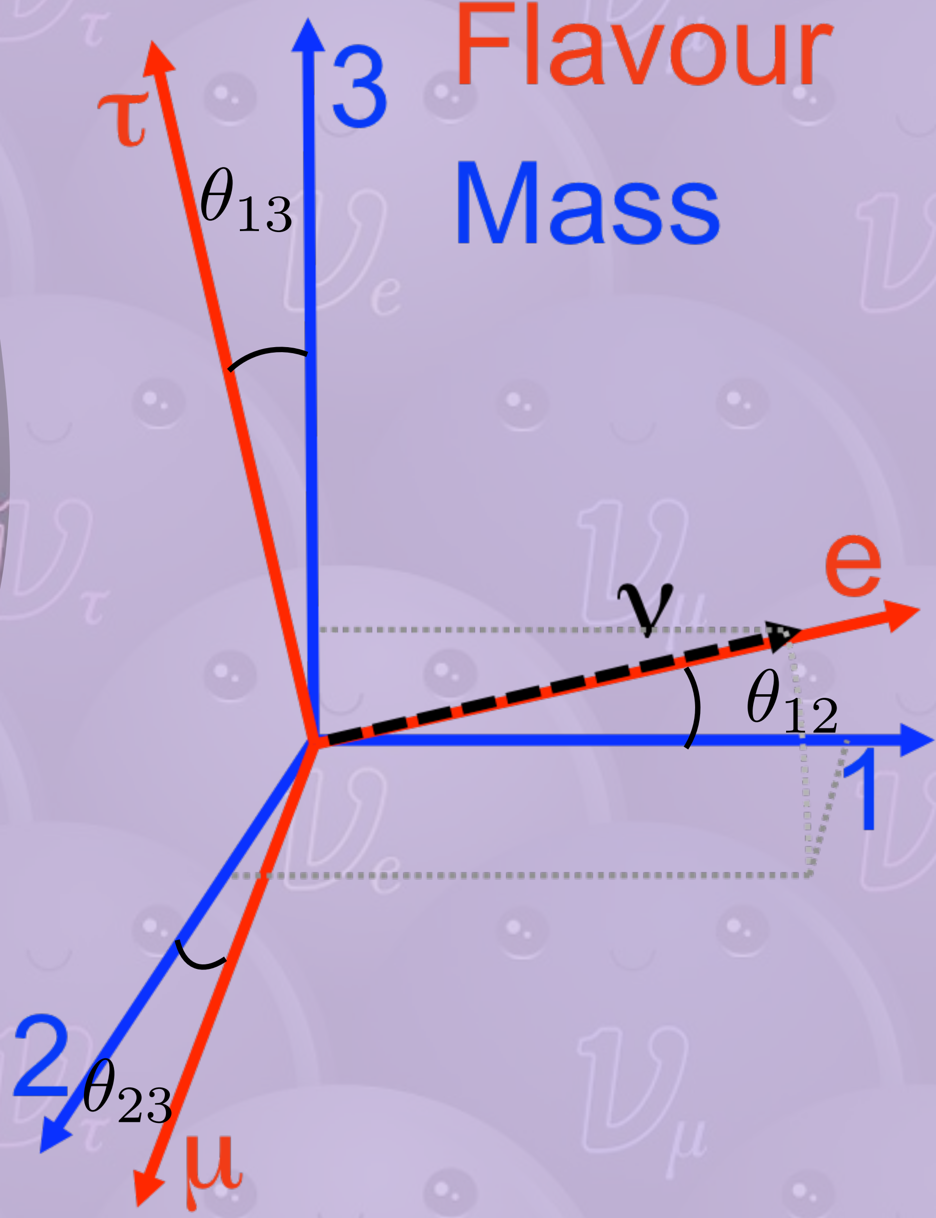
Neutrino Oscillations 101



* angles not at scale

Flavour eigenstates do not correspond to **mass** eigenstates

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \neq \begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \end{pmatrix}$$

Defined flavour
(production /detection)

Defined kinematics
(propagation)

Transformation of basis through unitary matrix U

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Matrix elements in U contain:

Oscillation angles

θ_{23} θ_{12}

θ_{13}

Are oscillation amplitudes

Squared mass splittings

m^2_{23} m^2_{12}

m^2_{13}

Are oscillation frequencies

Reactor Antineutrino Anomaly

Reactor plants are powerful sources of $\bar{\nu}_e$ and are commonly used to study neutrino oscillations

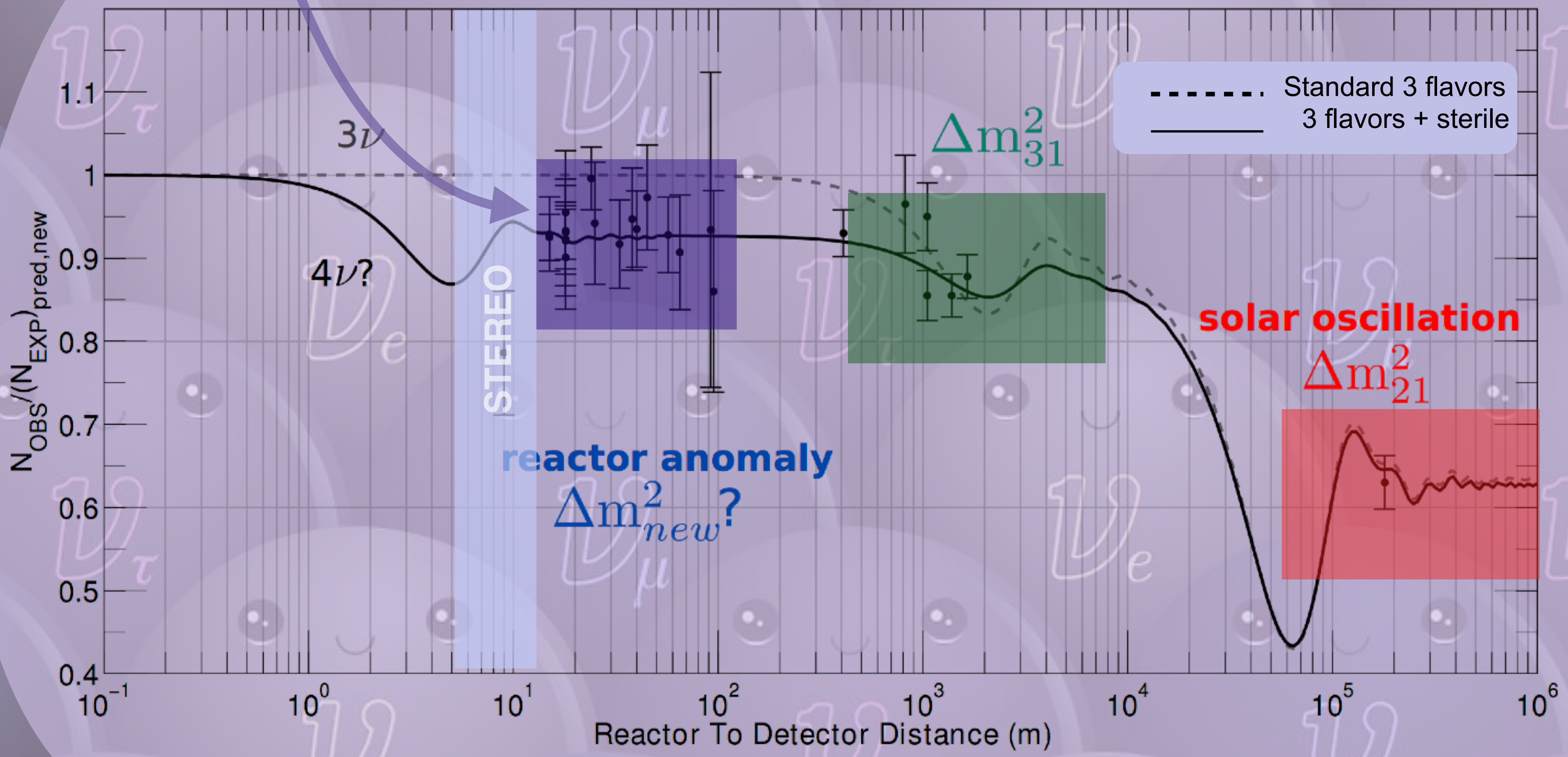
- Reactor Antineutrino Anomaly -

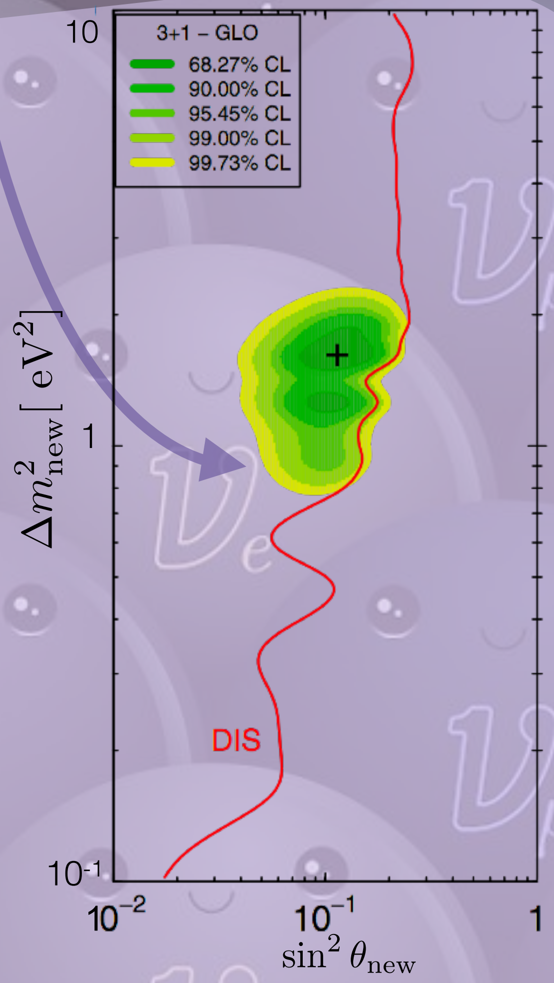
- Reevaluation of reactor $\bar{\nu}_e$ spectra +6% [1]
- Survival $P_{\bar{\nu}_e \to \bar{\nu}_e} = 0.940 \pm 0.024$ is $\sim 3\sigma$ from 1
- Why the deficit? New oscillation into a sterile state?

- Best Fit Parameters -

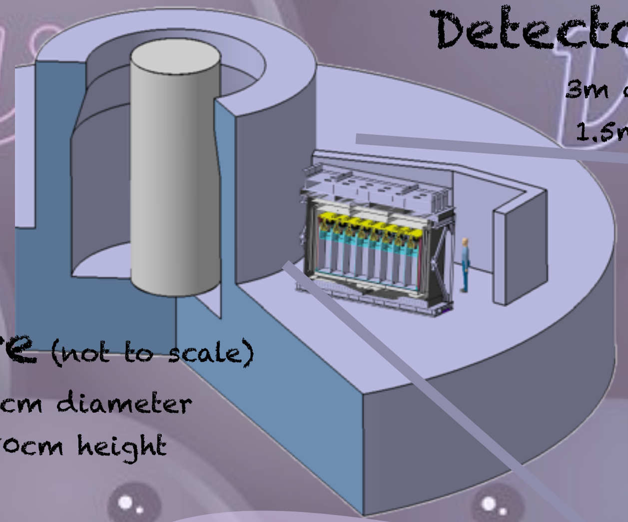
$$\sin^2(2\theta_{\text{new}}) = 0.11$$

$$|\Delta m^2_{\text{new}}| = 1.6\ \text{eV}^2$$





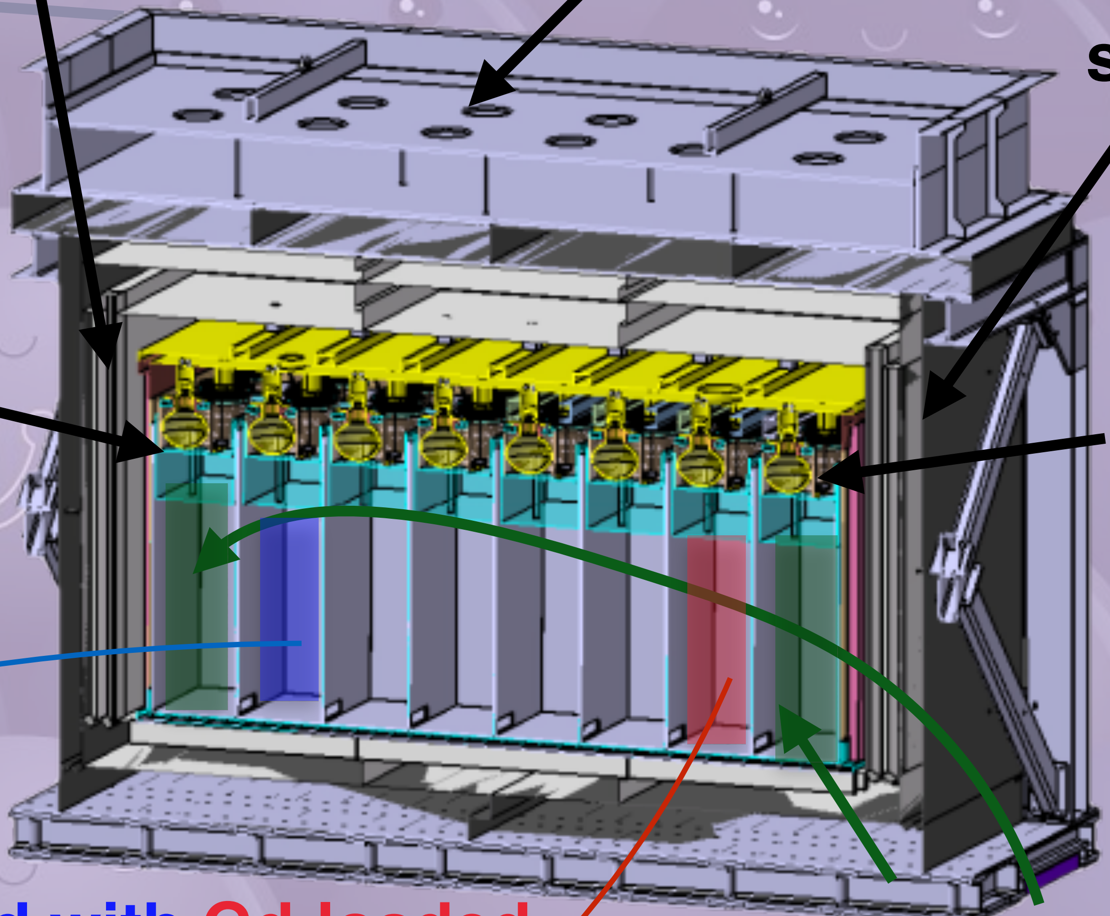
Stereo Detector



ILL nuclear reactor

Detector (not to scale)
3m diameter
1.5m height

Core (not to scale)
40cm diameter
80cm height



borated polyethylene shielding

water Cherenkov muon veto

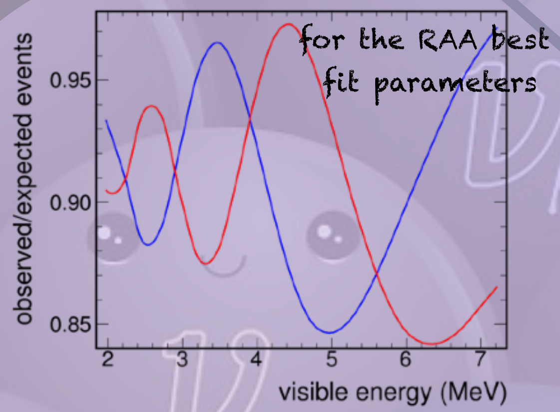
lead shielding

acrylic buffer

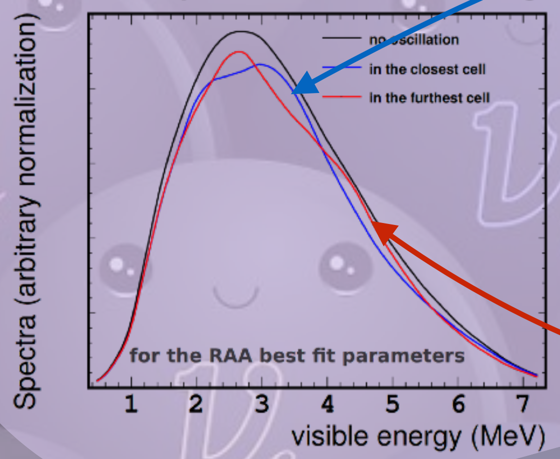
48 PMTs

6 cells filled with Gd-loaded liquid scintillator (2m³)

outer crown with unloaded liquid scintillator



Oscillation phase shift inside the target



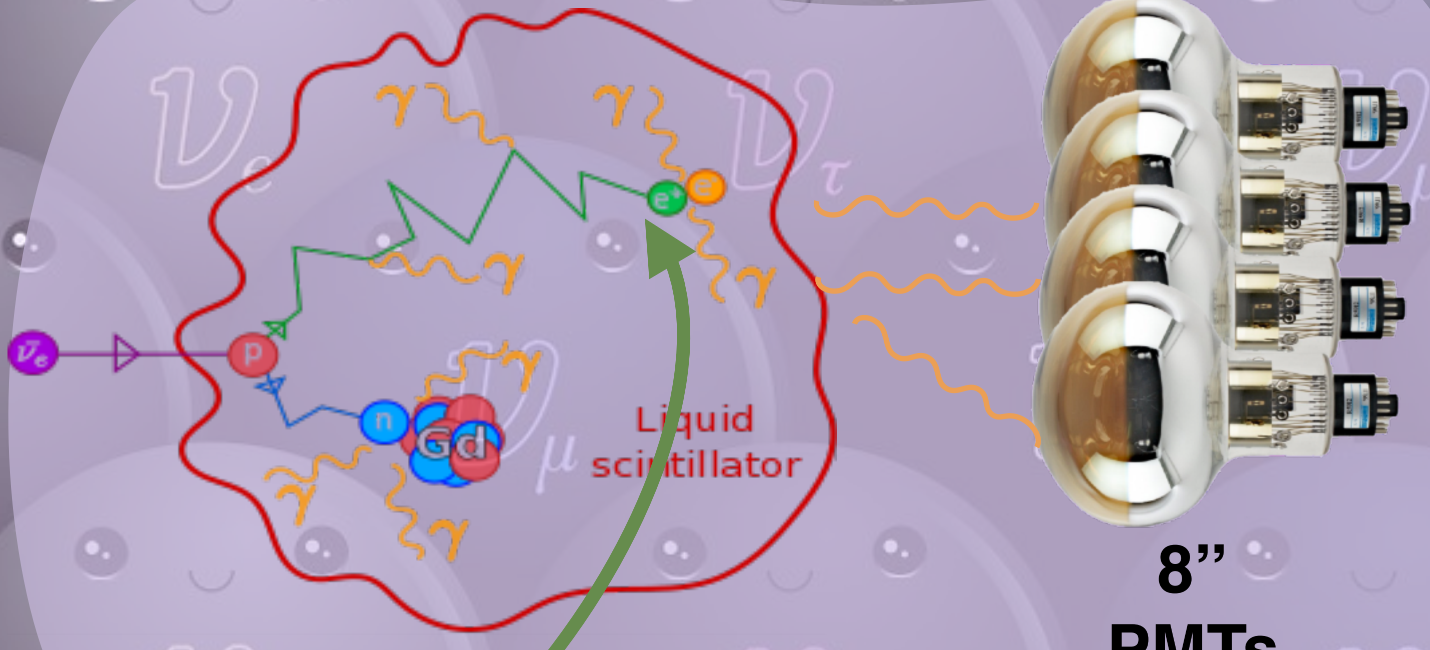
Detection process - Inverse Beta Decay (IBD)

Neutrinos interact via IBD:

$$\bar{\nu}_e + p \longrightarrow e^{+} + n$$

Two signals in coincidence:

- Prompt signal: energy reconstruction
- Delayed signal: coincidence with prompt guarantees IBD



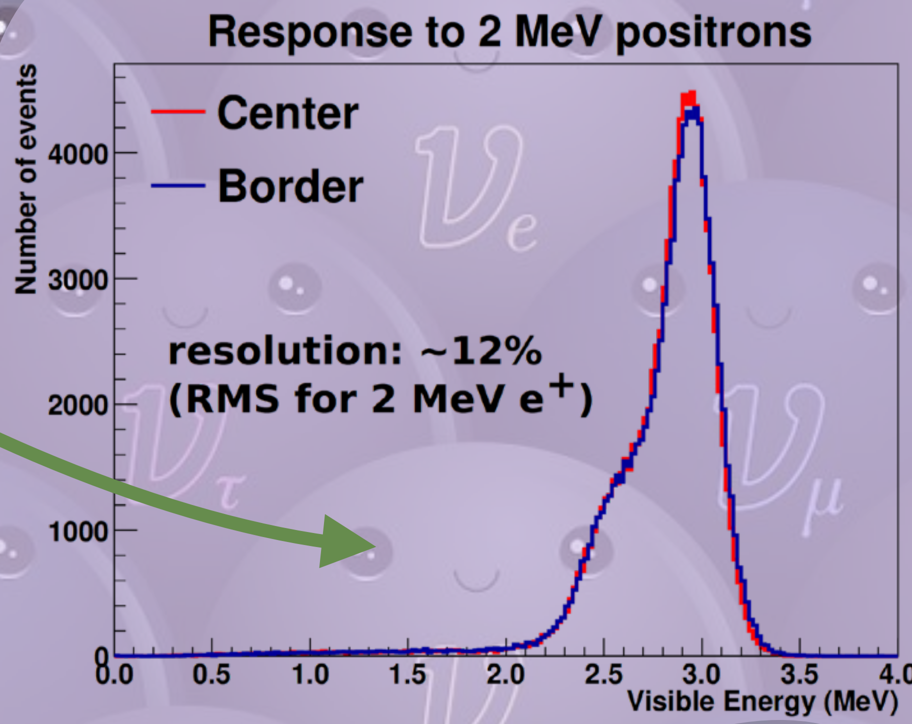
8” PMTs

- Prompt Signal -

- e⁺ ionisation + annihilation $E_{e^+} = [1, 8]\ \mathrm{MeV}$
- Oscillation depends on $E_{\nu} = E_{e^+} + 0.8\ \mathrm{MeV}$

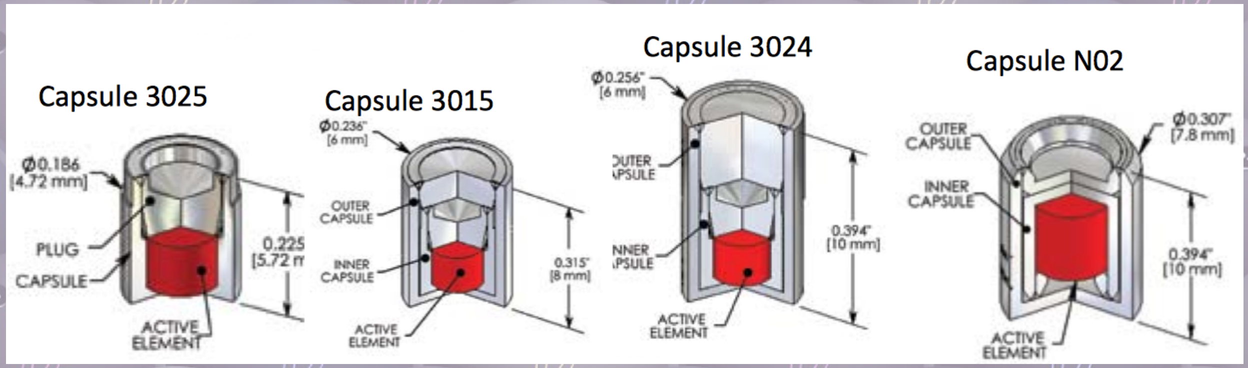
- Delayed Signal -

- n-capture on Gd releases γs : $\sum E_{\gamma} = 8\ \mathrm{MeV}$
- time separation from prompt $\Delta t \sim 15 \mu s$



Calibration in Stereo

Different gamma emitters are used in Stereo as calibration sources



- Three different calibration systems -

- **Internal tubes inside target cells.**
- External mechanical system.
- Rail underneath the detector.

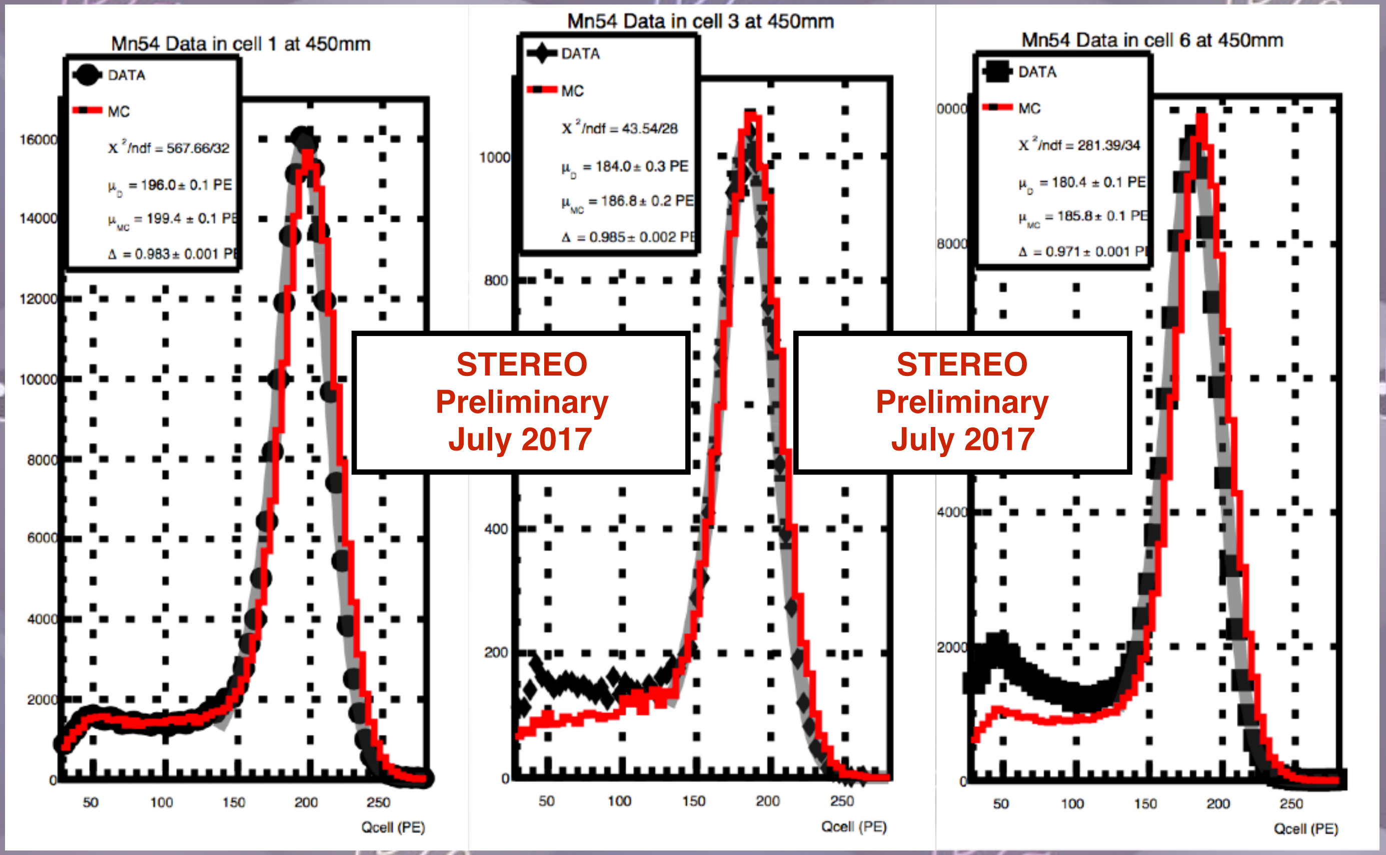
Today's topic

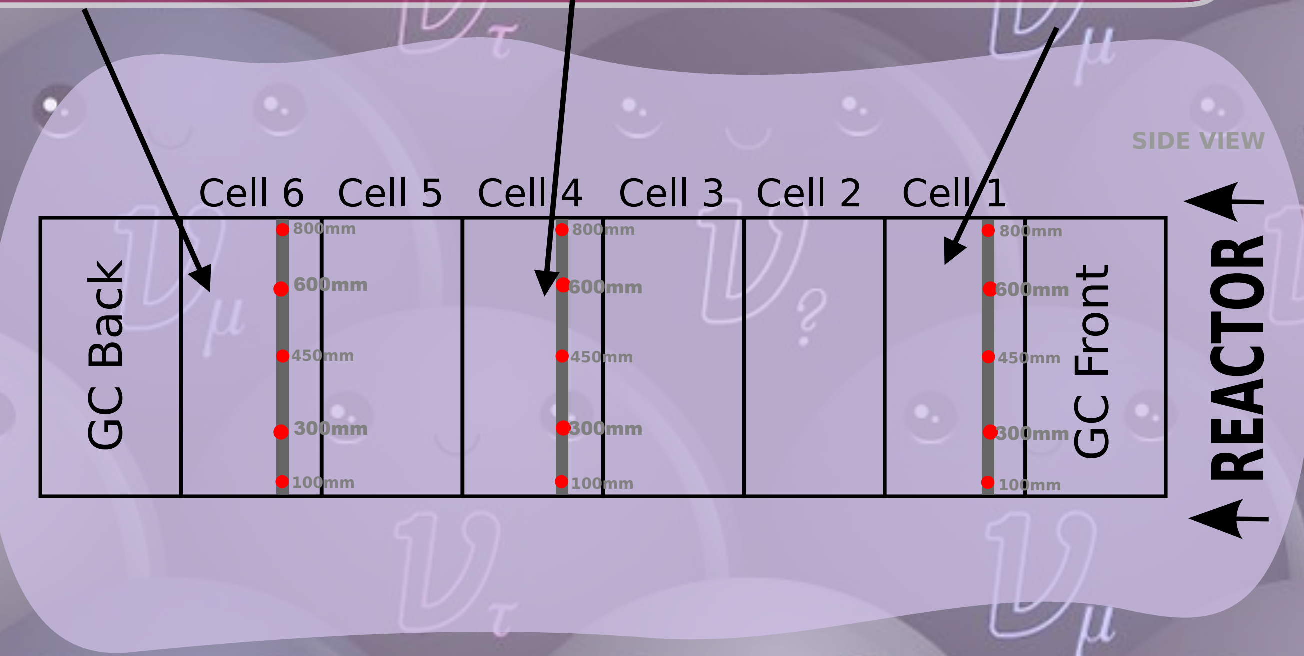
- Broad range of energies allow a good coverage of energy range.
- Low energy sources to account for quenching.
- High activity neutron emitter to calibrate for coincidence signals.

Isotope	Activity	γ - energy (keV)
Ge-68	90 kBq	2x511
Cs-137	37 kBq	660
Mn-54	**90 kBq**	**830**
Co-60	50 kBq	1170 & 1330
Zn-65	3.3 kBq	1120
Sb-124	2.4 kBq	600 & 1690
Na-24	5.9 kBq	1370 & 2750
AmBe	250 MBq (n ~kHz)	4400 + n
Cf-252	50 kBq (n ~kHz)	fission γ + n

Internal Calibration

3 tubes are placed in 3 different cells (1,4,6) inside the Target





For every tube, 5 different heights used as positions for the calibration sources: study z-axis

Response

- Attenuation length of the liquid scintillator above 6 meters - small z dependence.
- Target cells with very similar response, except for cell 4 which has a ~50% lower light collection efficiency due to leak of the buffer aquarium affecting the optical coupling of the PMTs.
- Intermediate cells (2,3,5) can be calibrated as well.

Energy reconstruction

To translate from Q collected at the PTMs to actual E, STEREO needs a dedicated energy reconstruction

- The charge collected in a cell i is proportional to the light produced in that cell and the light leaks from neighbouring cells:

$$Q_i = \sum_j E_j^{\mathrm{dep}} \times C_j \times L_{ji} = \sum_j E_j^{dep} M_{ji}$$

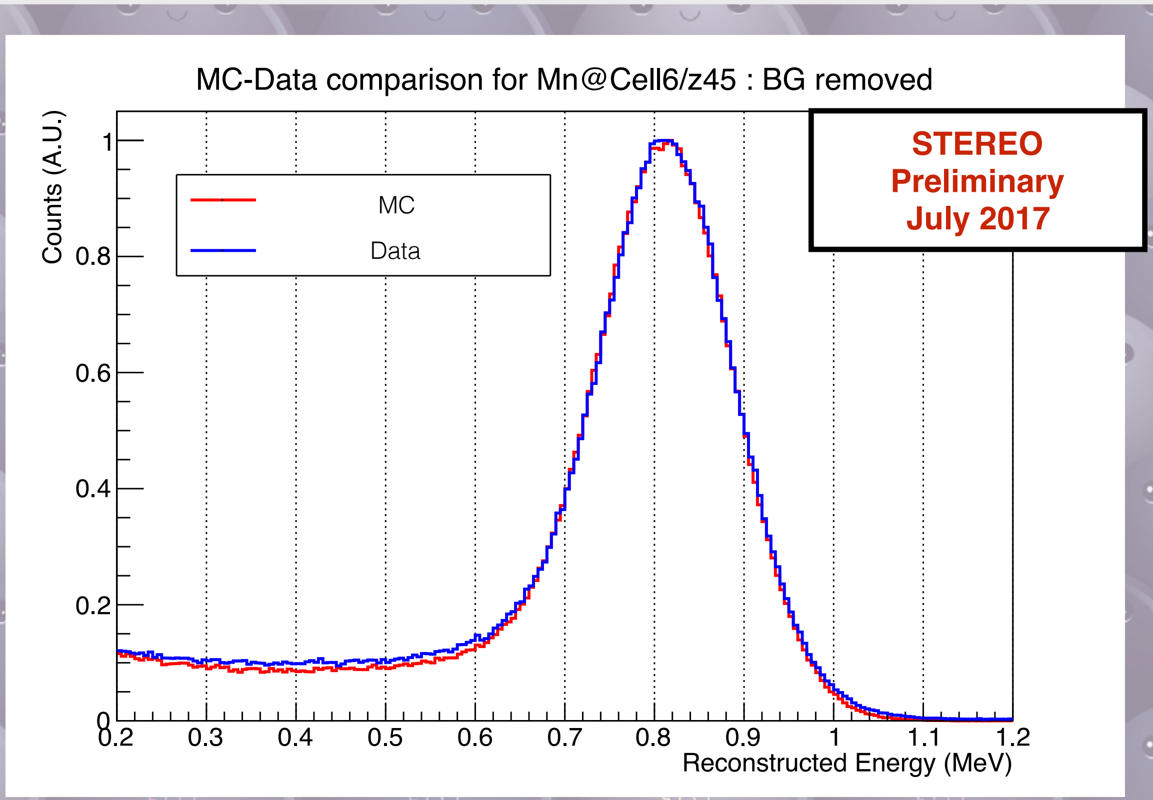
- Cj are the **calibration coefficients** for Cell j and Lji are the **Light Leaks** from Cell j to Cell i.
- Inverting Mji and solving the equation gives the final Edep as a sum of contributions of all cells.

- Advantages of Energy over Charge -

- Stabilise detector response
- Direct comparison Data-MC
- Allows topological cuts

How do we calculate Lji?

How do we calculate Cj?



General concepts to find CC

1. Use Light Leaks to create an Energy Leaks Cut (ELC) for Data and MC charge distributions. The main idea is to filter as many Full Energy Deposition events as possible.

2. Apply ELC and fit Data and MC cell's deposited charge spectra. Get deposited charge for Full Energy Deposition events $\bar{Q}_D$, $\bar{Q}_{MC}$

3. From MC, obtain True Edep ($E_{T,dep}$) corresponding to the deposited charge $\bar{Q}_{MC}$ calculated in 2.

4. If MC and Data match, calculating calibration coefficients is defined as CC= $\bar{Q}_{MC}$ / $E_{T,dep}$

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Energy Leak Cut

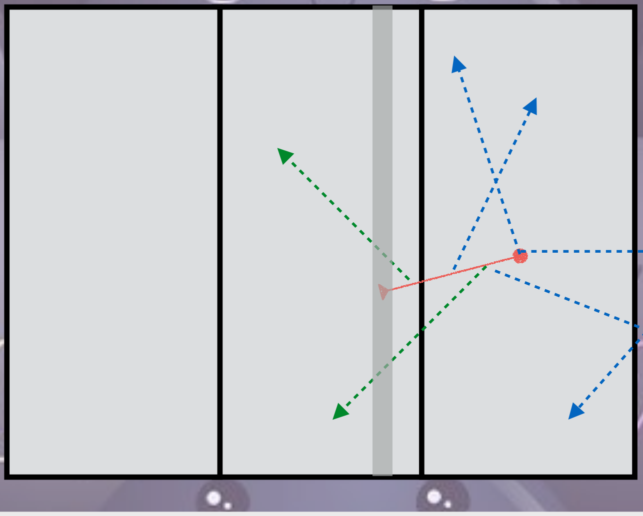
Charge collection in a cell can be affected by two different processes:

1. Gammas produced in cell A can escape to cell B and deposit energy there **- Energy Leaks (EL)**

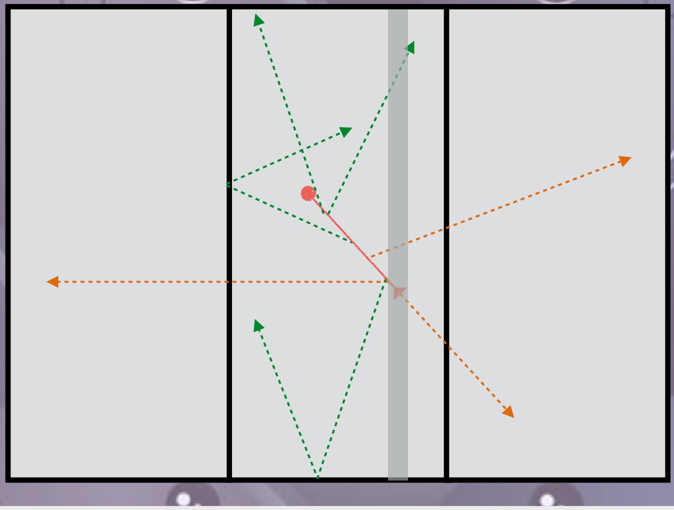
2. Scintillation light from produced in cell A can be collected in cell B **- Light Leaks (LL)**

Escaping gamma

No Full Energy Deposition!



Full Energy Deposition (FED)



1. When Energy Leaks happen there is no Full Energy Deposition (FED) in the cell

2. When only light leaks happen there is FED in the cell

A cut on Energy leaks helps rejection of events with no FED → **ENERGY LEAK CUT**

Energy Leak Cut

Charge collection in a cell can be affected by two different processes:

1. Gammas produced in cell A can escape to cell B and deposit energy there **- Energy Leaks (EL)**

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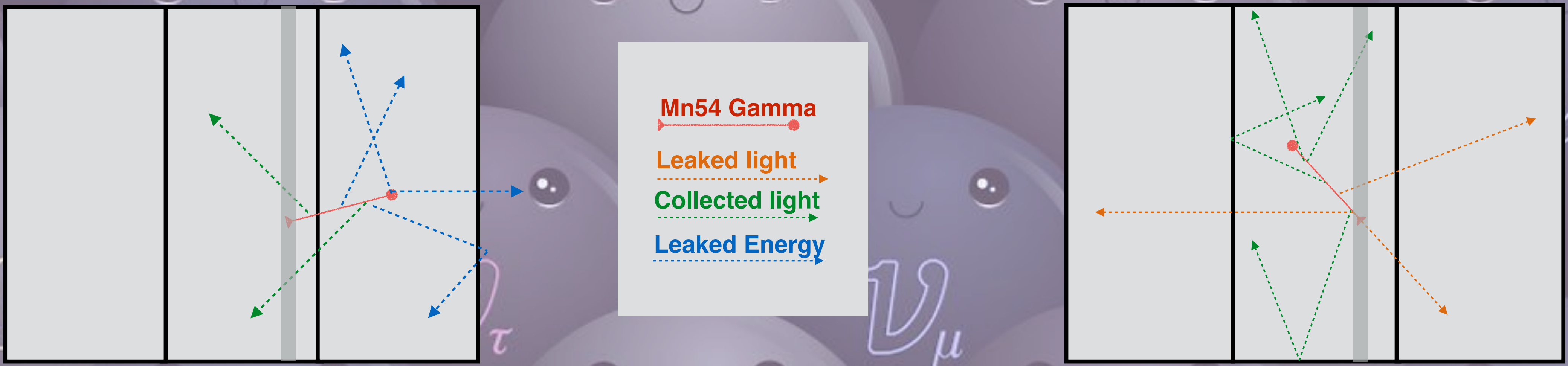
Escaping gamma

Full Energy Deposition (FED)

No Full Energy Deposition!



Pros of using a cut

- Cells with different LY do not contaminate each other.
- Direct comparison with FED events MC.
  - ·Allows intermediate cells to be calibrated.

Cons of using a cut

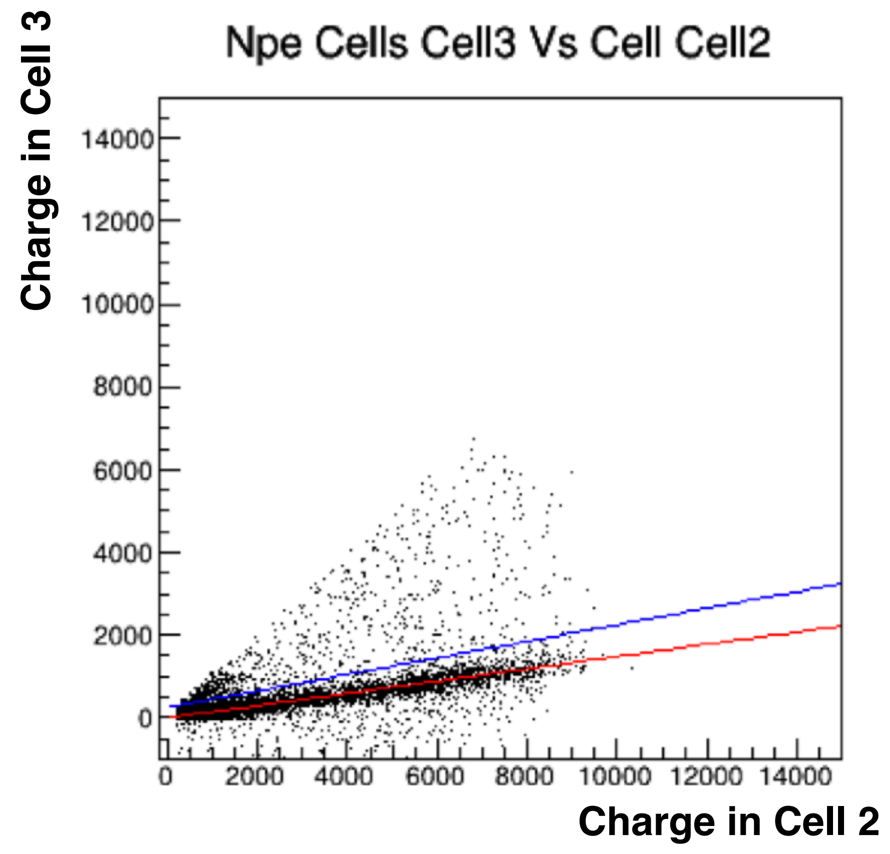
Since LLs and ELs are technically indistinguishable:

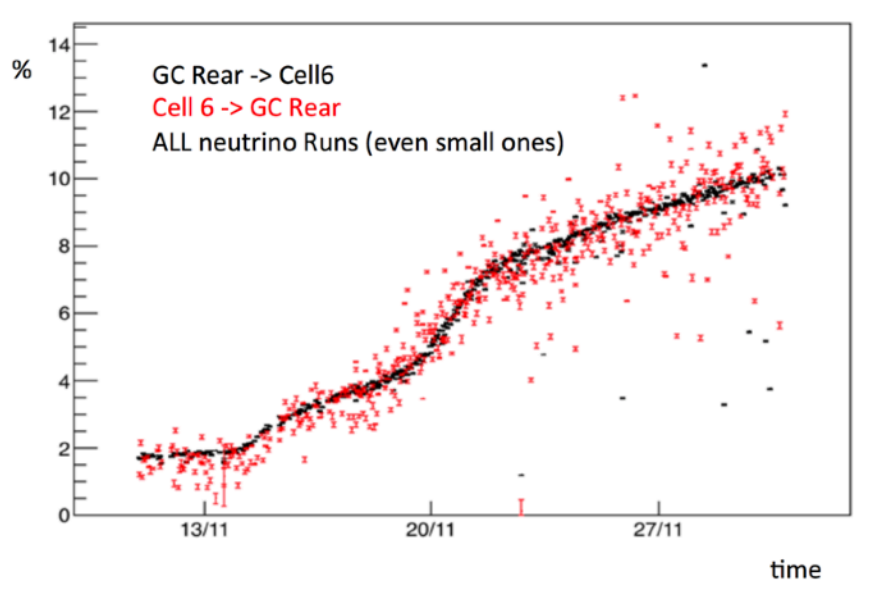
- Cutting too strongly will cut FED events that leak light away. Bias on the final spectrum.
  - ·How large are Light Leaks in Stereo?

How do we obtain a value for the Light Leaks in Stereo?

Obtaining the Light Leaks

- Cosmic rays crossing one cell leak light to neighbours proportionally.
- Fitteable correlation between light produced in FED cell and neighbour.
- Events below cutoff (blue line) correspond to Light Leaks.





1. Non-calibration runs of the detector are partially used to monitor cosmic rays. Light Leaks information over time can be used to estimate time evolution.

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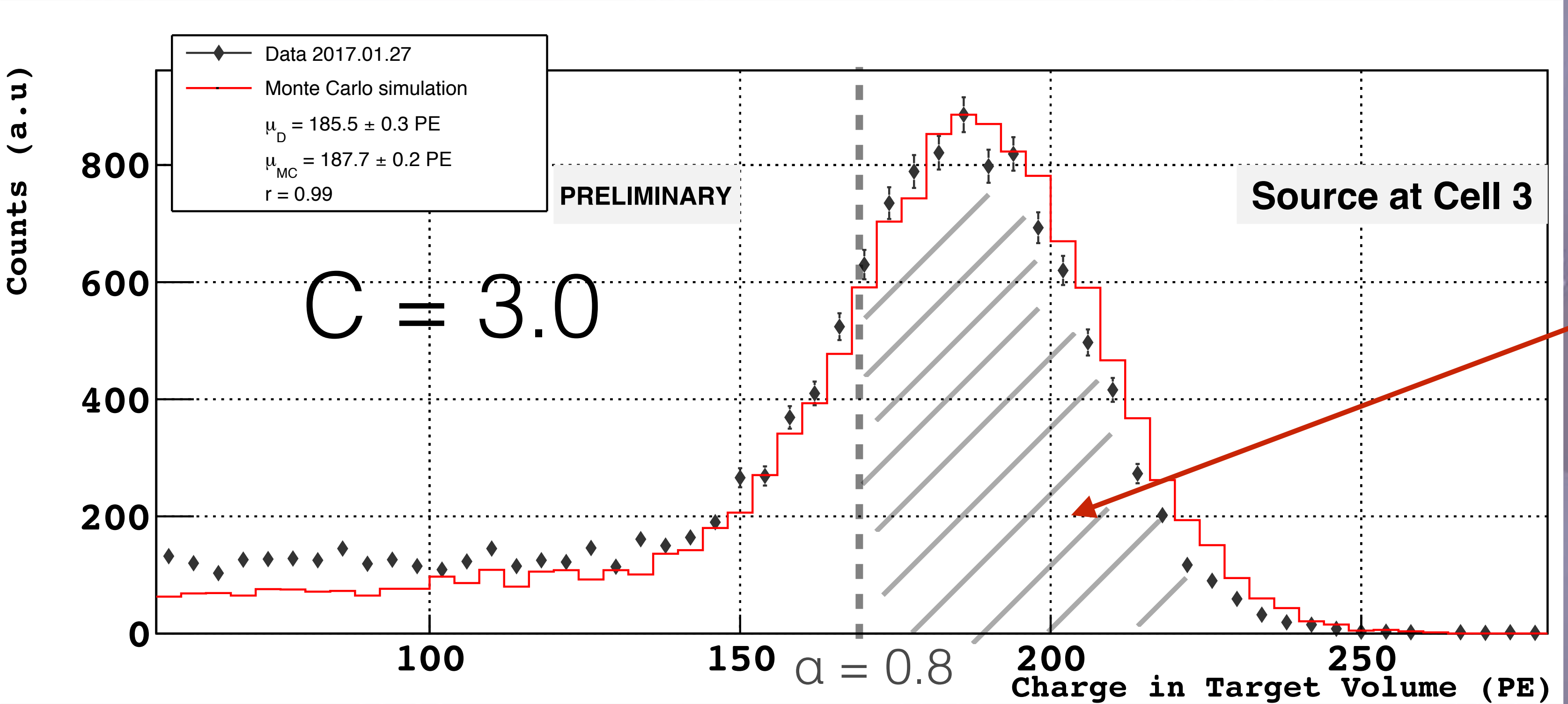
Applying Energy Leak Cut

1. Choose as Energy Leak Cut to reject events:

$$Q_i > \frac{Q_{det}}{(1+\sum_{i\neq j} \mathrm{LL}_{ij}+\mathrm{C}\sigma_{ij})}$$

- Where i is the cell being calibrated.
- C is a variable parameter to scan.
- LLij are the correspondent LL from cell i to cell j

- **The ELC depends majorly on the amount of LLs that Stereo has at the moment of calibration.**
- **Use normal statistical deviation $\sigma_{ij} = \sqrt{LL_{ij}}$**
- **As C increases, the cut loosens up allowing more events. Tuning C is crucial.**



2. Calculate $\bar{Q}_D(\mathrm{C},\alpha)$ and $\bar{Q}_{MC}(\mathrm{C},\alpha)$ as average of charge within the range {α·μ$_D$, ∞}, with α = [0.1, 1.0] to be scanned.

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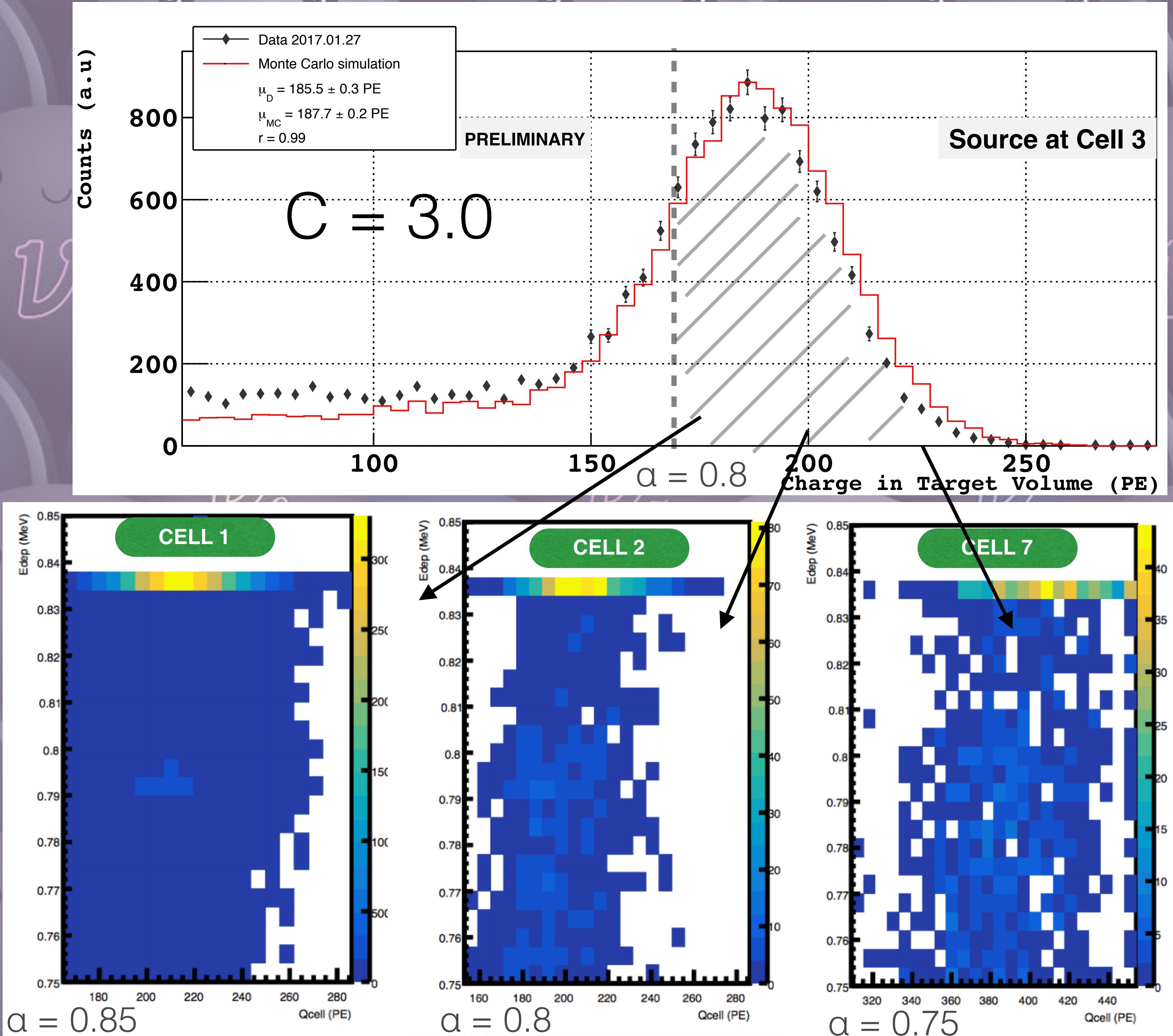
Obtaining True Deposited Energy

3. From MC Charge distribution, select the corresponding True Deposited energy distribution.

3. Obtain $E_{T,dep}$ as the average of MC True Energy Deposition.



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4. If MC and Data match, calculating calibration coefficients is defined as CC= $\bar{Q}_D(C,\alpha)$/ $E_{T,dep}$

Calculating Calibration Coefficients

$$CC(C, \alpha) = \bar{Q}_D(C,\alpha) \,/\, E_{T,dep}$$

4. **To obtain CC find the most stable combination of {C,α}, follow some heuristic rules:**

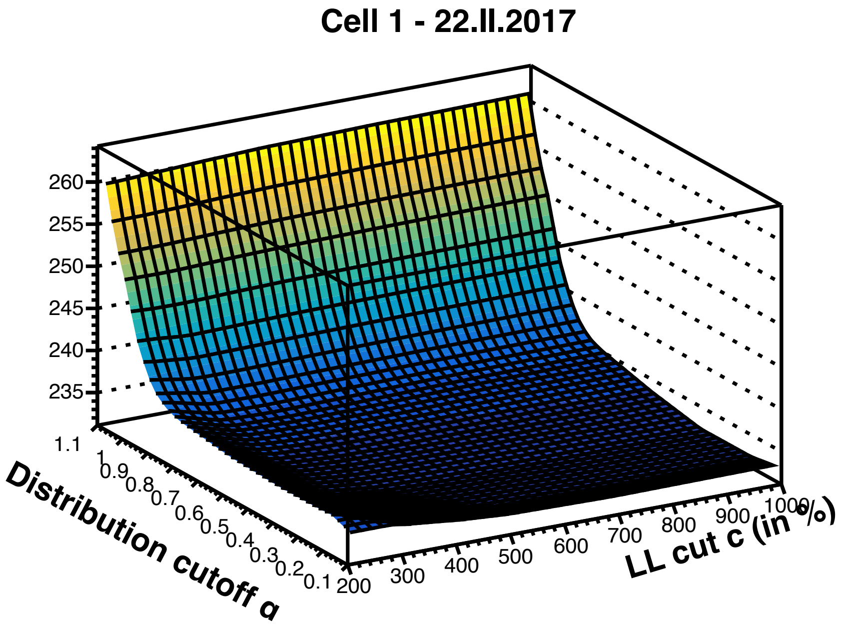
(I) Too strict ELC (**C < 2.0**) biases $\bar{Q}_D(C,\alpha)$ to high energies - cutting LLs asymmetrically.

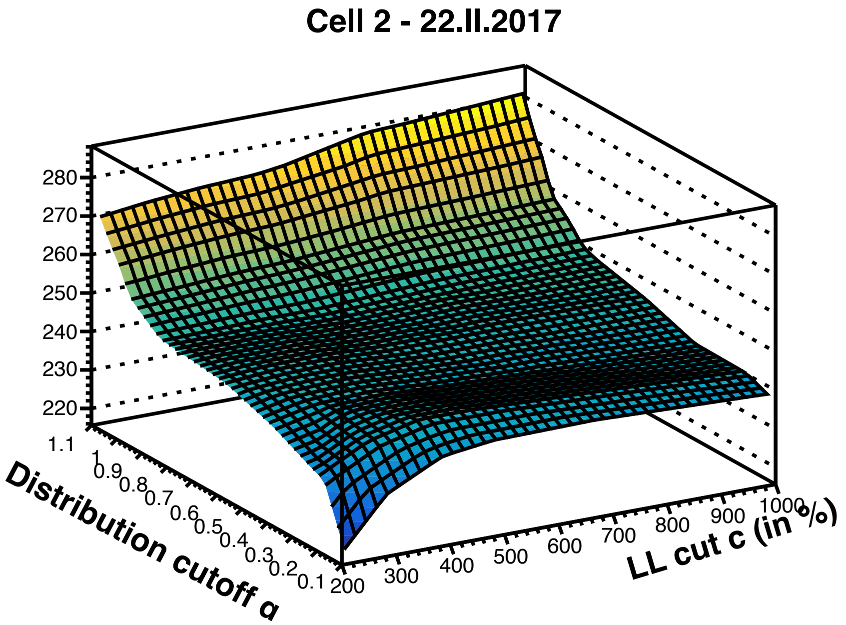
(II) Too loose ELC (**C > 5.0**) accepts too much Energy Leaks. Specially bad for intermediate cells where source is not deployed.

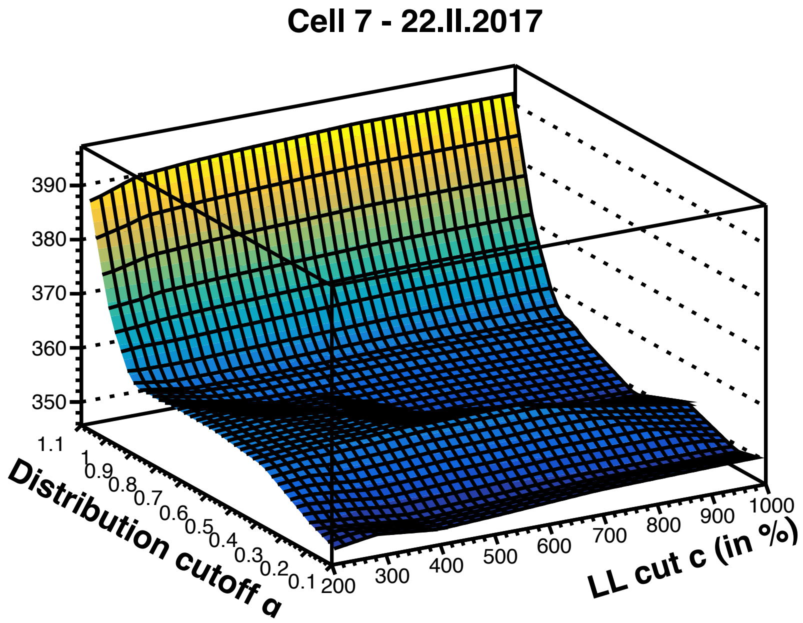
(III) Short cutoff on charge (**α > 0.9**) will cut FED peak and generates unstable CCs

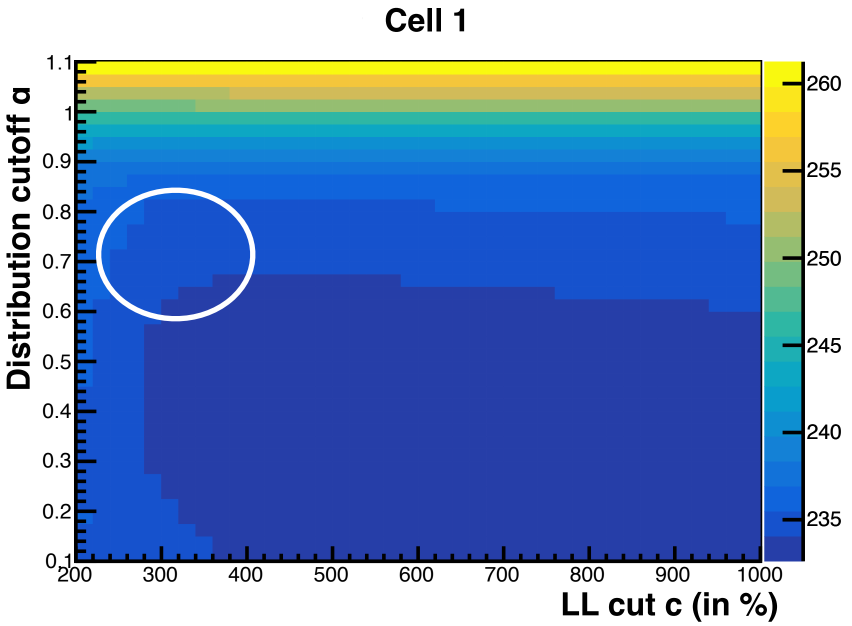
(IV) Long cutoff on charge (**α < 0.6**) includes too much non removed Energy leaks that is not present in true energy distribution

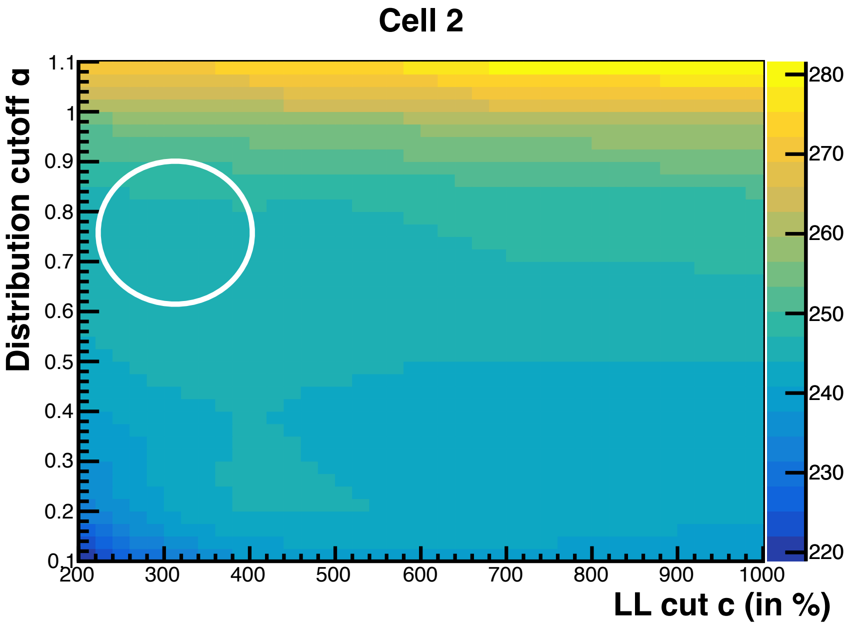
Calculating Calibration Coefficients

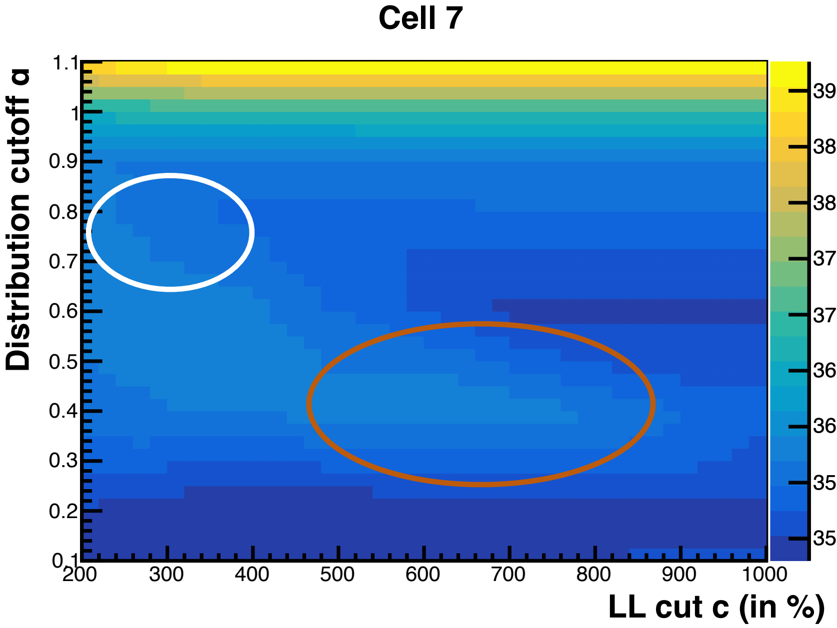












- **Look for the regions where CCs are most stable.**
- **Large α gives unstable CC for the different LL cuts c.**
- **Large LL cut c gives unstable CC for different cutoffs α.**

Relatively stable areas in parameter space

Contribution from lower scintillation cells

Conclusions

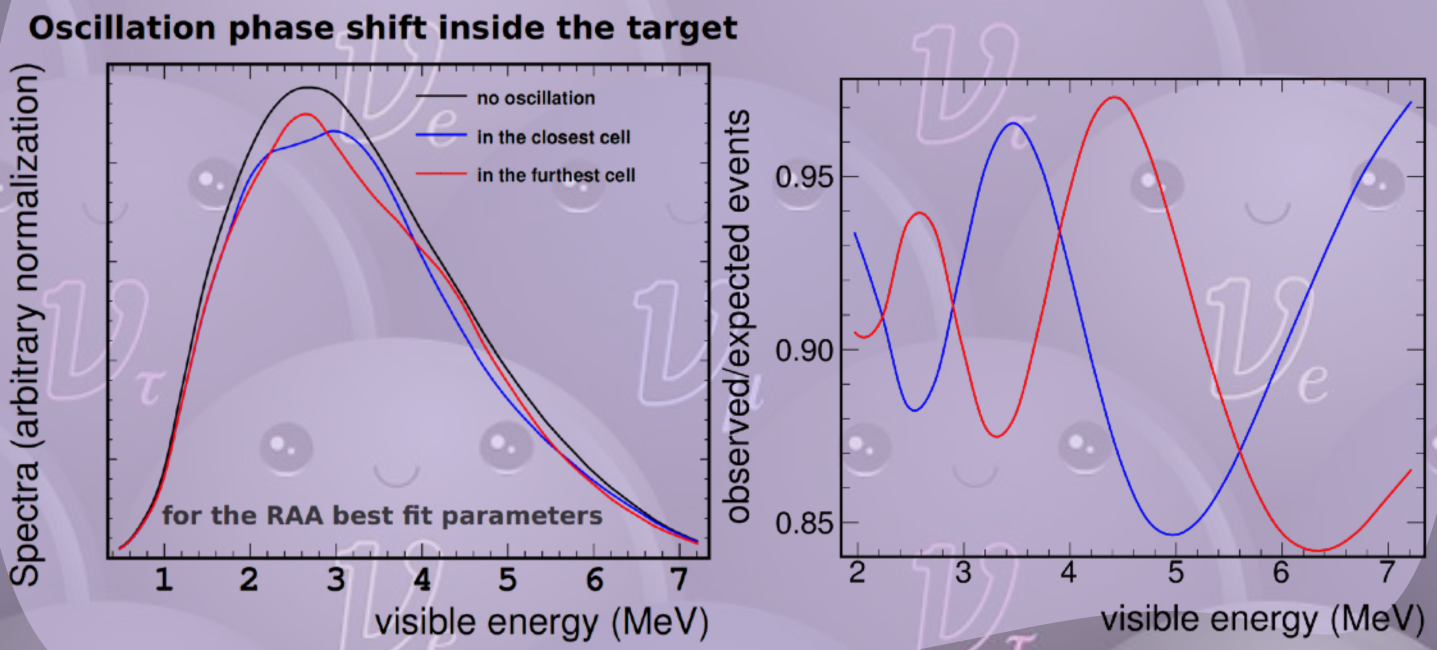
Stereo aims to observe a sterile neutrino oscillation signal. For this purpose, a dedicated Energy Reconstruction needs to be performed.

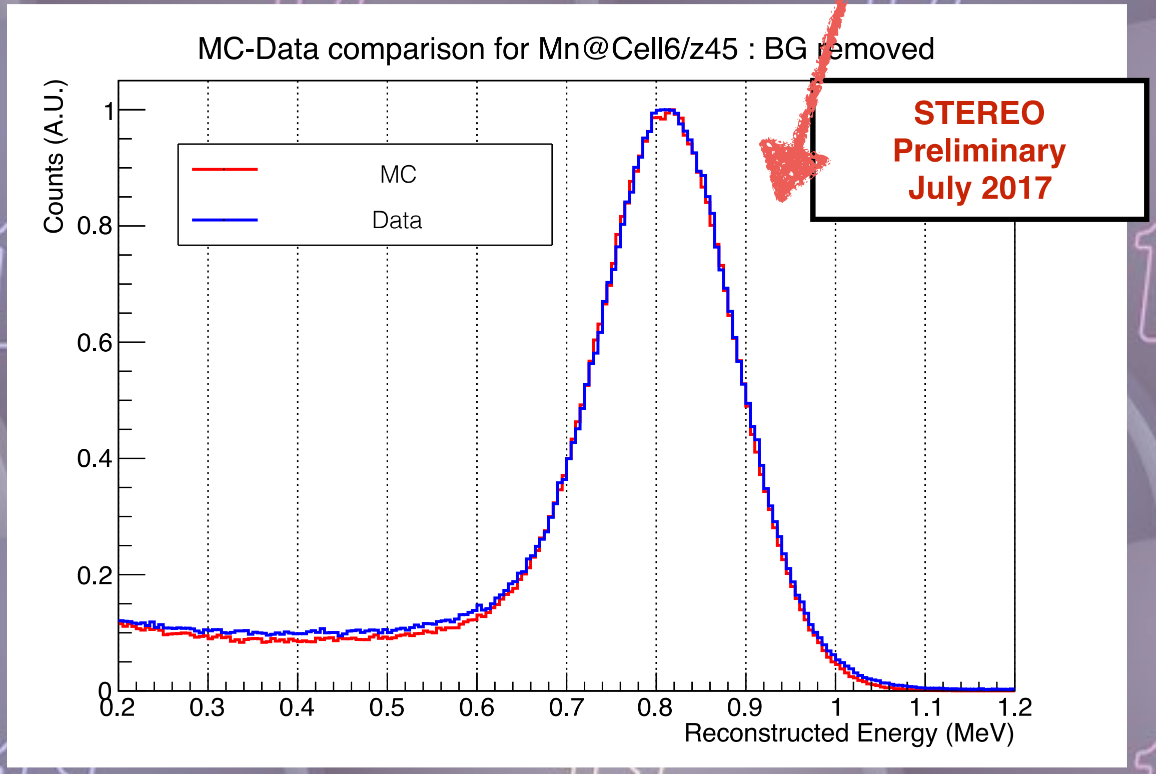
$$Q_i = \sum_j E_j^{dep} \times CC_j \times LL_{ji}$$

Heuristic arguments applied to find stable area in CC parameter space. Relative stable calibration coefficients found.

Calculated CCs give accurate Energy Reconstruction and low discrepancy Data / MC.

Good Energy Reconstruction is crucial





featuring STEREO experiment

Thanks for your attention - now BBQ is a little bit closer

DOGE APPROVED