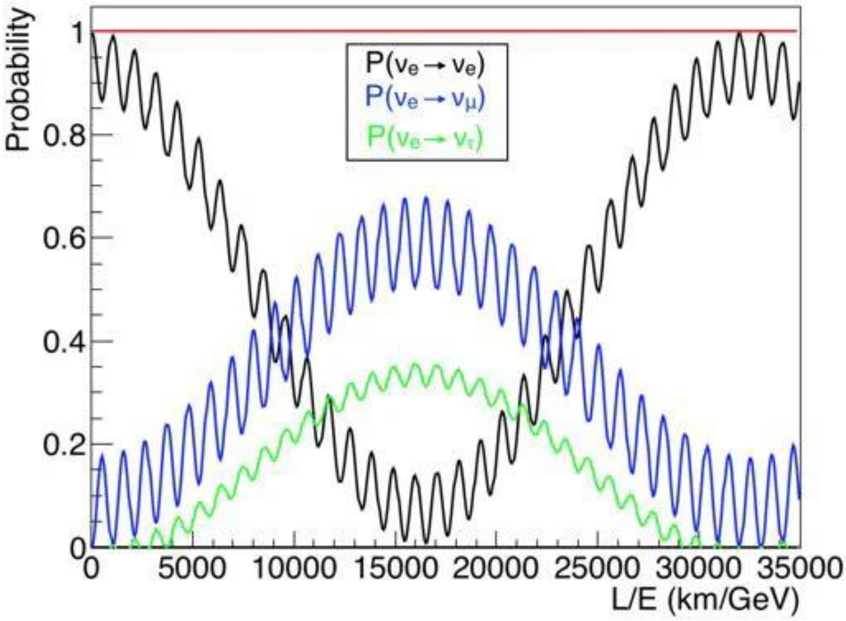
Reactor antineutrinos at DANSS

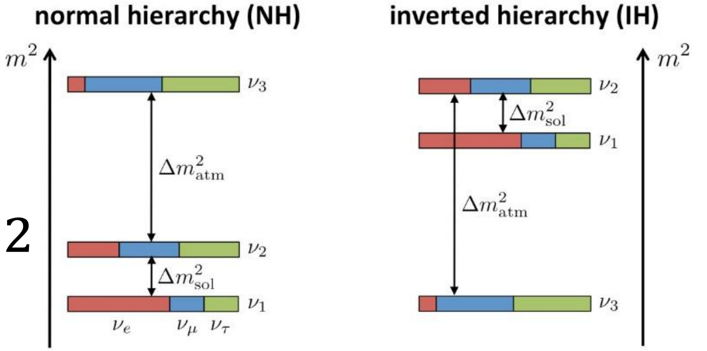
Petr Gorovtsov, 21.04.2026

Neutrino oscillations



- 2 generations:

$$P(\alpha \to \beta) = \sin(2\theta)^2 \sin(1.27 \cdot \frac{\Delta m^2[eV]L[m]}{E[MeV]})$$



- 3 generations (parameters depend on mass ordering):

$$\sin^2\theta_{12} \approx 0.30;\ \sin^2\theta_{23} \approx 0.57;\ \sin^2\theta_{13} \approx 0.022$$

$$\Delta m_{12}^2 \approx 7.41 \cdot 10^{-5}\, eV^2;\ \ |\Delta m_{32}^2| \approx (2.4 - 2.5) \cdot 10^{-3}\, eV^2$$

- By varying type, energies E and travel distances L for (anti)neutrinos one can increase sensitivity for oscillations between particular states

Some anomalies

LSND, MiniBooNE, 29.05.2013, Annual Review of Nuclear and Particle Science vol 63

- LSND & MiniBooNE result: ν_e in the ν_μ beam (6σ): $\Delta m^2 \sim 0.2 - 1 \text{ eV}^2$?
  - MicroBooNE does not confirm this anomaly

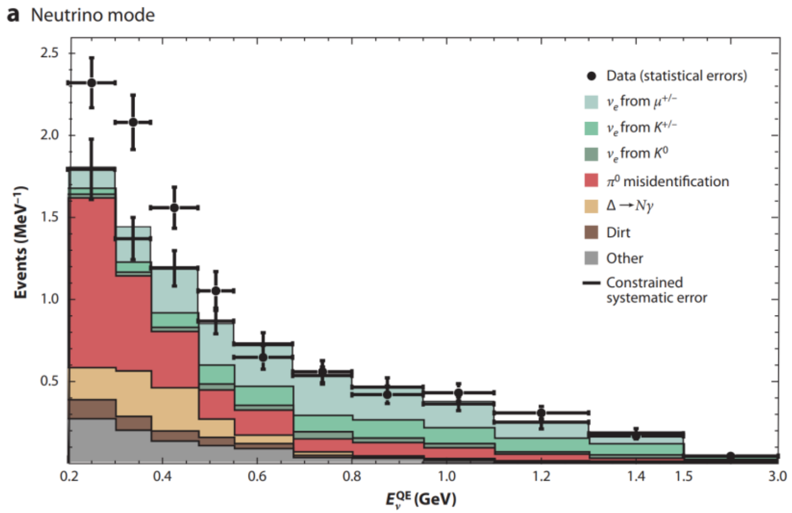
  P. Arbatenko et al., (MicroBooNE), Phys. Rev. Lett. 130, 011801, 2023

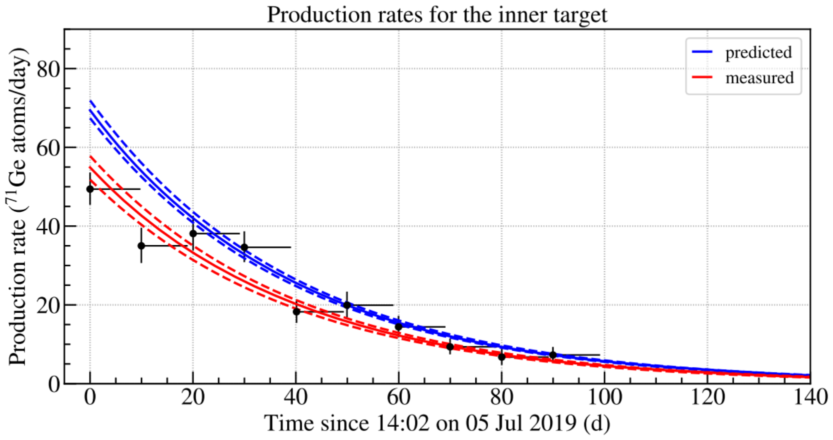
- Gallium anomaly (GA): deficit of ν events in the calibration measurements in gallium experiments SAGE, GALLEX and BEST (5σ)

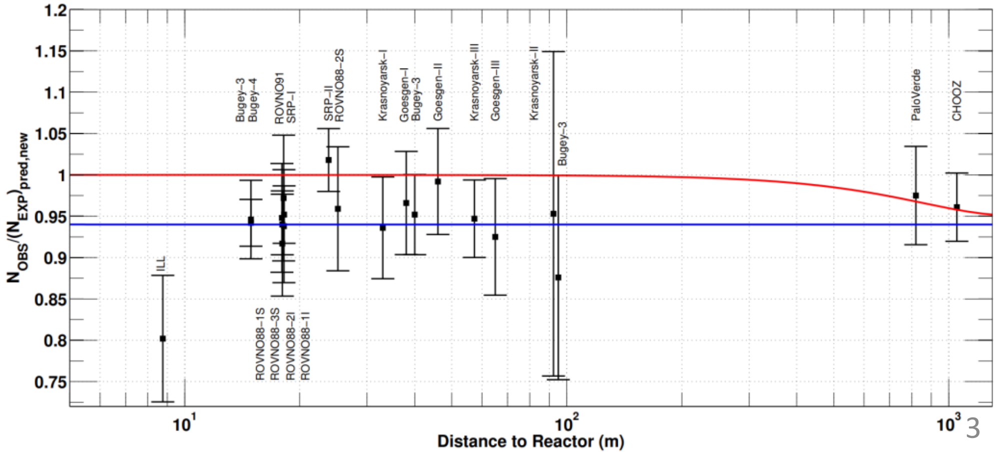
  V.V. Barinov et al, (BEST), Phys. Rev. Lett. 128, 232501, 2022

- Reactor Antineutrino Anomaly (RAA): deficit of $\bar{\nu}_e$ from the reactors in comparison with theoretical predictions (2.8σ), tends to decrease

  G. Mention et al, Phys. Rev. D 83, 073006, 2011







Searches for New Physics

- Sterile neutrinos: at short distances we can consider only oscillations to sterile state

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{ee}) \sin\left(1.267 \frac{\Delta m^2_{41}[eV^2] L[m]}{E[MeV]}\right)$$

$\sim 1\, eV^2$

- Large Extra Dimensions (LED) (N. Arkani–Hamed, S. Dimopoulos, G. Dvali, Phys. Let. B, vol 429, issues 3-4, pages 263-272, 1998)
  - Extra dimensions renormalize Planck mass: $M^2_{Pl} = (M^*_{Pl})^{2+n} a^n$
  - $n \geq 2$ needed for Hierarchy problem but one dimension can be bigger than others. In this approach survival probability for (anti)neutrino: $P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\sum_i |U_{ei}|^2 A_i\right|^2$

$$A_i = \left(1 - \frac{\pi^2}{6} m_i^2 a^2\right)^2 \exp\left(i \frac{m_i^2 L}{2E}\right) + 2 m_i^2 a^2 \exp\left(i \frac{m_i^2 L}{E}\right) \sum \frac{\exp\left(i \frac{n^2 L}{2Ea^2}\right)}{n^2}, ma \ll 1$$

Absolute mass scale

Size of the **dominant** dimension

Kaluza-Klein tower

Reactor antineutrinos

- $E \approx< 10\ MeV$, $L \sim 10 - 1000\ m$, sensitivity to $\theta_{13}, \Delta m^2_{31}$ and *hypothetic heavy states*

- Research reactors
  + Pure fuel (93% of ^{235}U)
  + Compact active zone

  - Lower power (50-100 MW)

SoLid, STEREO, Prospect, Neutrino-4

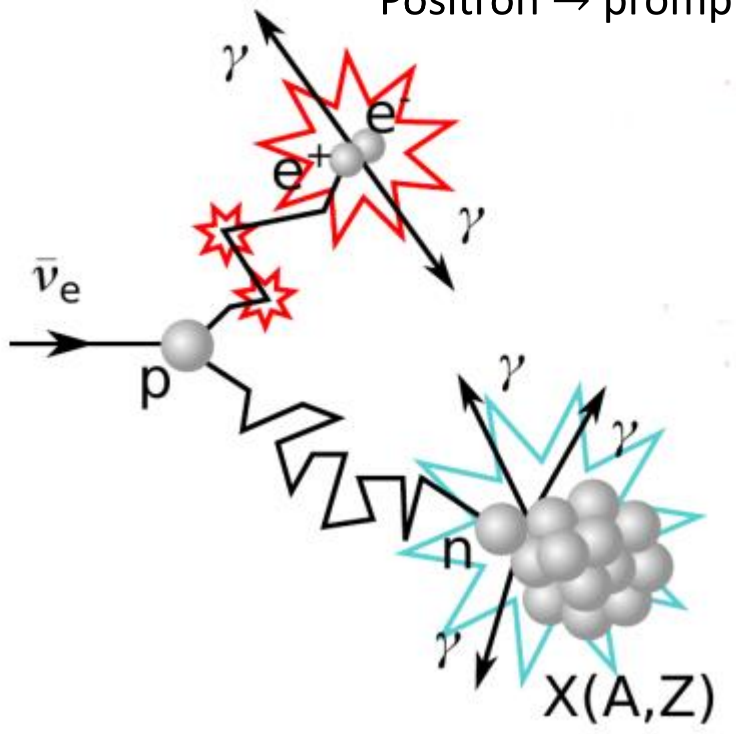
- Commercial reactors
  + High power and $\overline{\nu_e}$ flux (∼3000 W)

  - Uncertainties in fuel composition
  - Larger active zone, smearing of oscillations

DANSS, Daya Bay (long baseline), NEOS

Detector of AntiNeutrino based on Solid Scintillator

Positron → prompt signal



Neutron → delayed signal

- Detector is placed under the reactor core ($L \sim 11 - 13$ m) at Kalinin NPP and consists of nonflammable materials
- A movable platform → spectral ratio analysis not sensitive to detector efficiency and antineutrino spectrum
- The goal is to scrutinize the sterile neutrino hypothesis (and other BSM models)
- Antineutrinos are detected in the IBD reaction:
- The energy of antineutrino is determined by the energy of positron

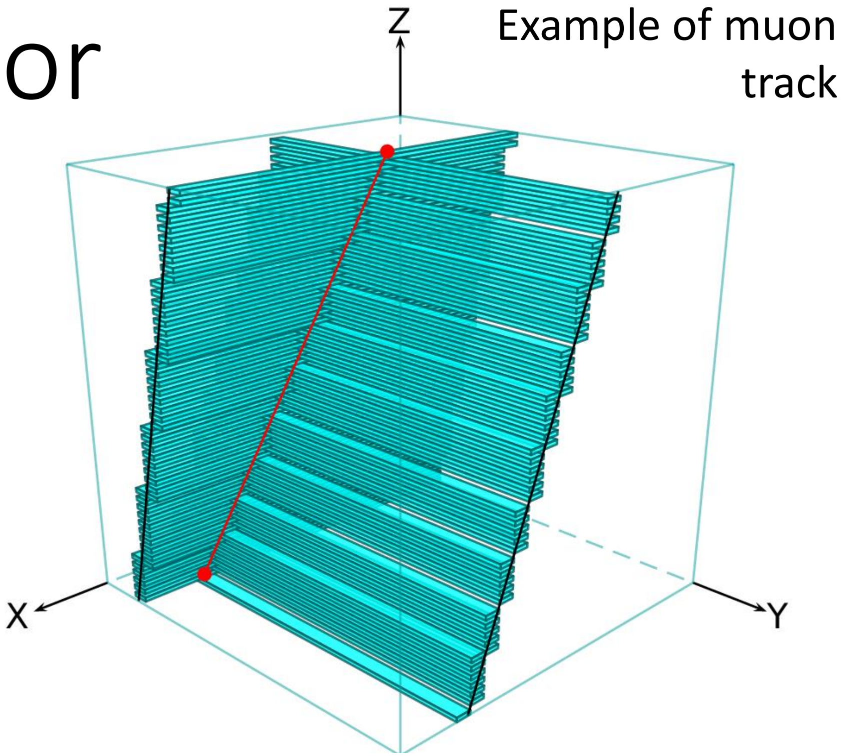
$$\overline{\nu_e} + p \rightarrow n + e^+$$

$$E_{\overline{\nu_e}} \approx E_{e^+} + 1.8MeV$$

$$\sim 5000\ events/day$$

Largest in the world antineutrino statistics, IBD is used

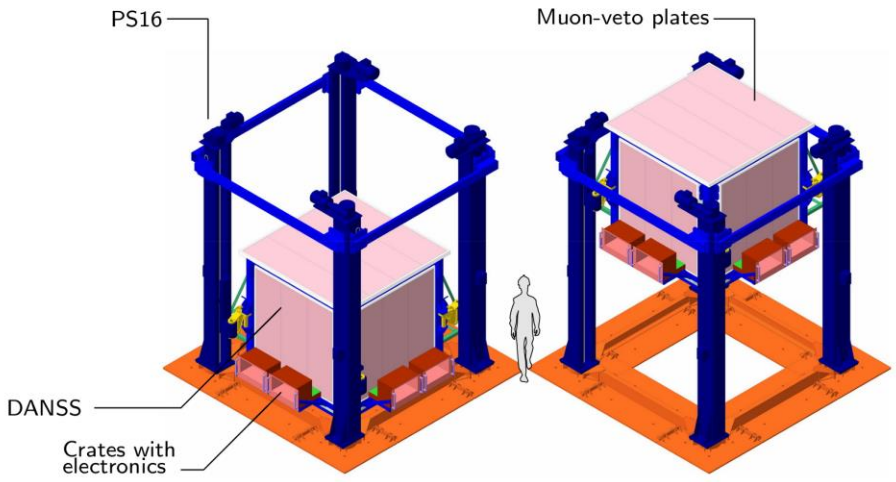
Design of the detector



- Shielding: muon veto, 8 cm of boron-doped polyethylene, 5 cm of lead, another 8 cm of boron-doped polyethylene, and a 5 cm layer of copper

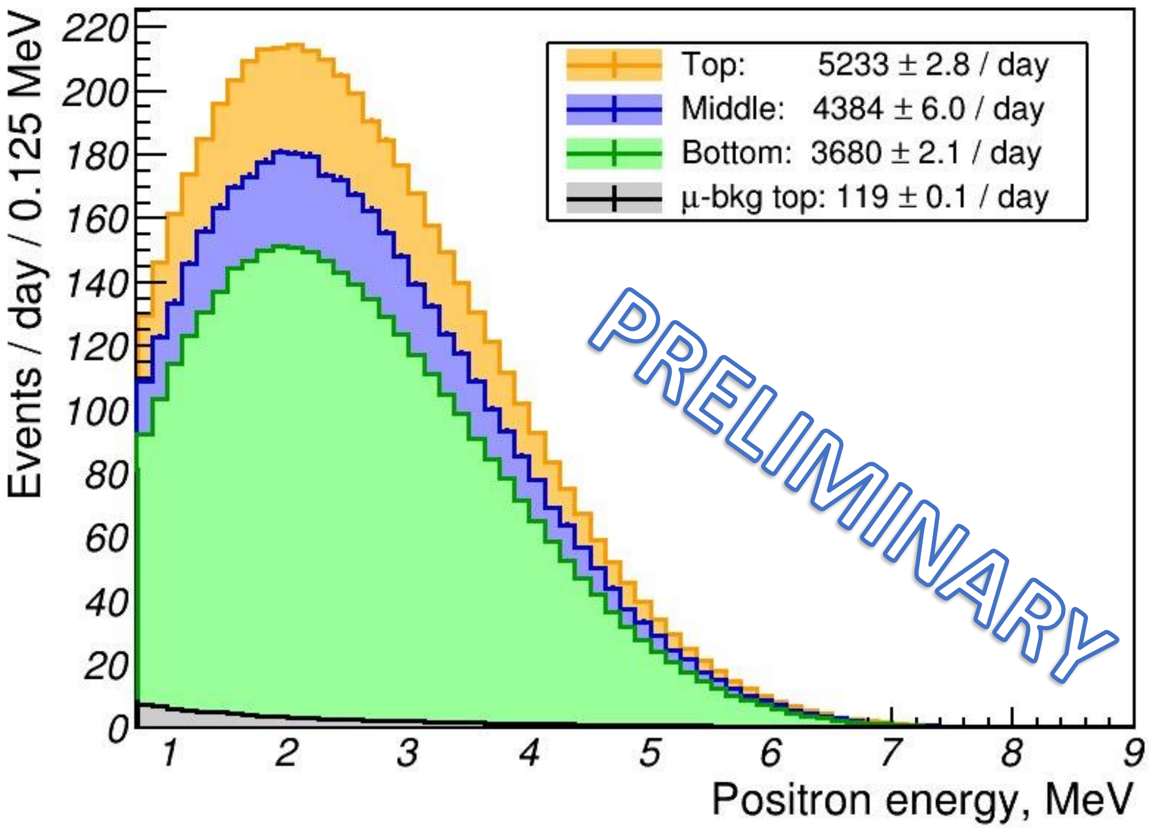
- 2500 scintillator strips coated with a gadolinium-containing layer for neutron capture. Light is collected with wavelength shifting fibers connected to SiPM and PMT

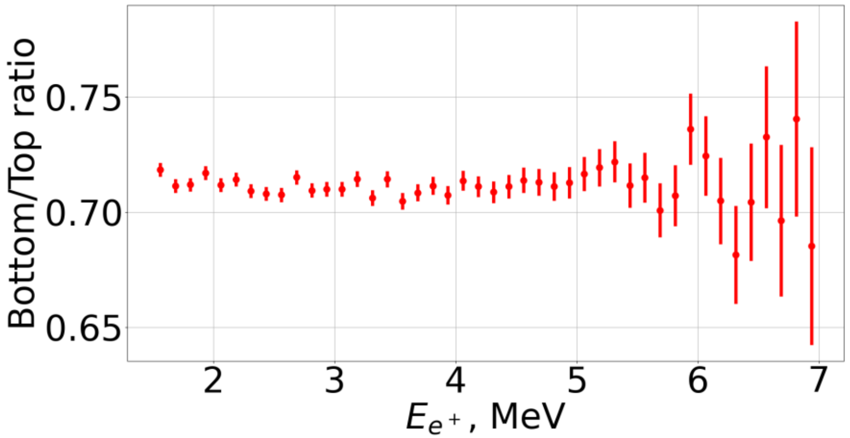
- Currently the detector's upgrade is coming: new scintillation counters, more of sensitive volume, better light collection



Acquired positron spectra

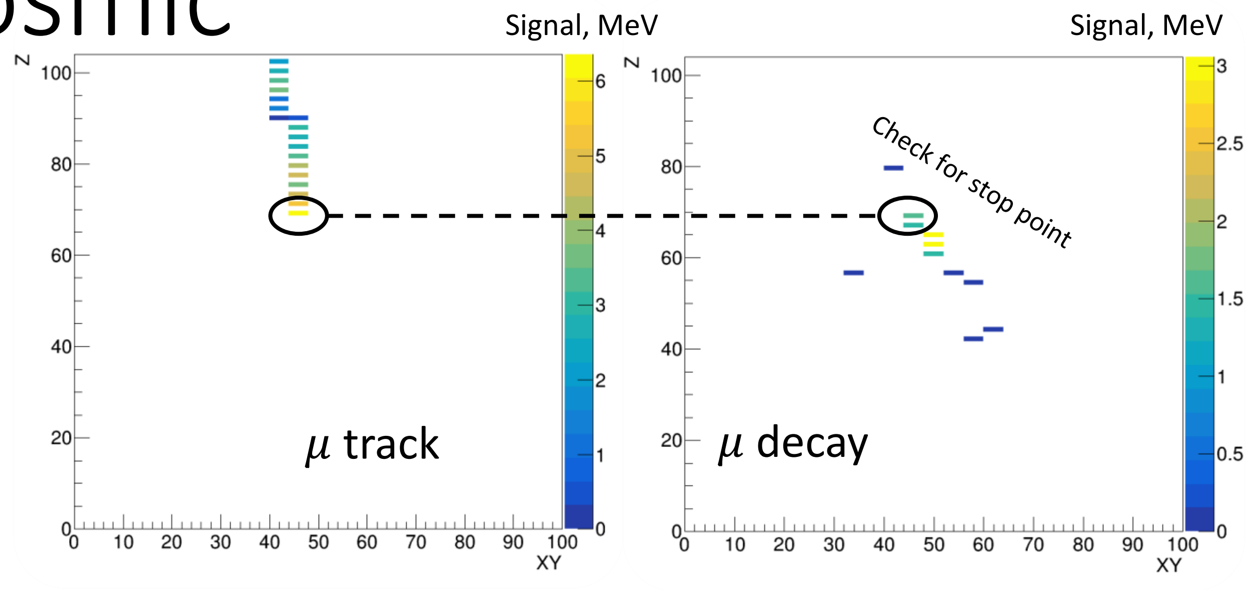
- October 2016 – May 2025
- 9.8×10^6 events in $[0.75 - 8]$ MeV
- DANSS is moved once in 5-7 days in order to average the result by the fuel composition
- Pure positron kinetic energy (no annihilation gammas)
- μ-induced background due to the veto inefficiency is 1.8% of the signal only

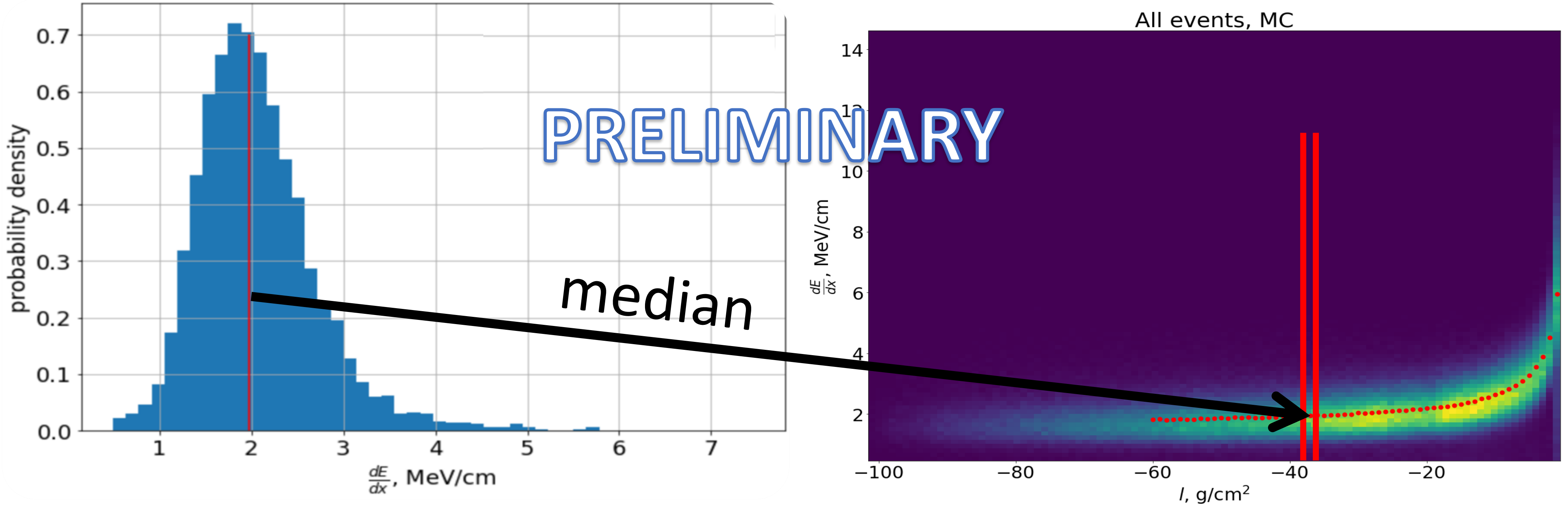




Calibration with stopped cosmic muons (my Bachelor)

- For muons stopped inside the sensitive volume it is possible to obtain median values of dE/dx as a function of distance to stop point – Bragg's curve





Calibration parameters

- Calibration scale K_E - proportionality between MC and Data

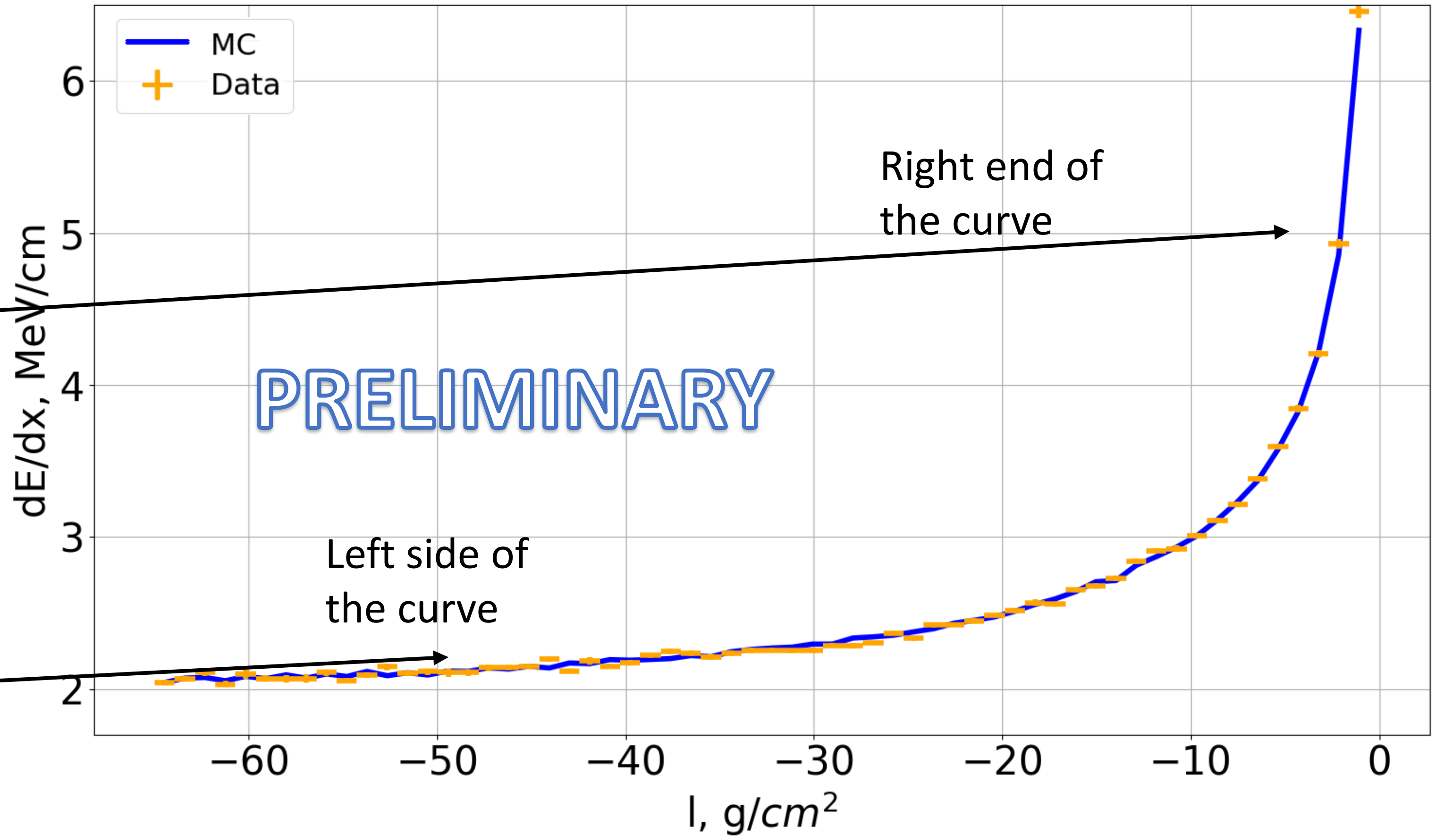
- Birk's coefficient:

$$\frac{dE}{dx}_{det} = \frac{dE/dx_{true}}{1 + \frac{dE}{dx} \cdot k_B}$$

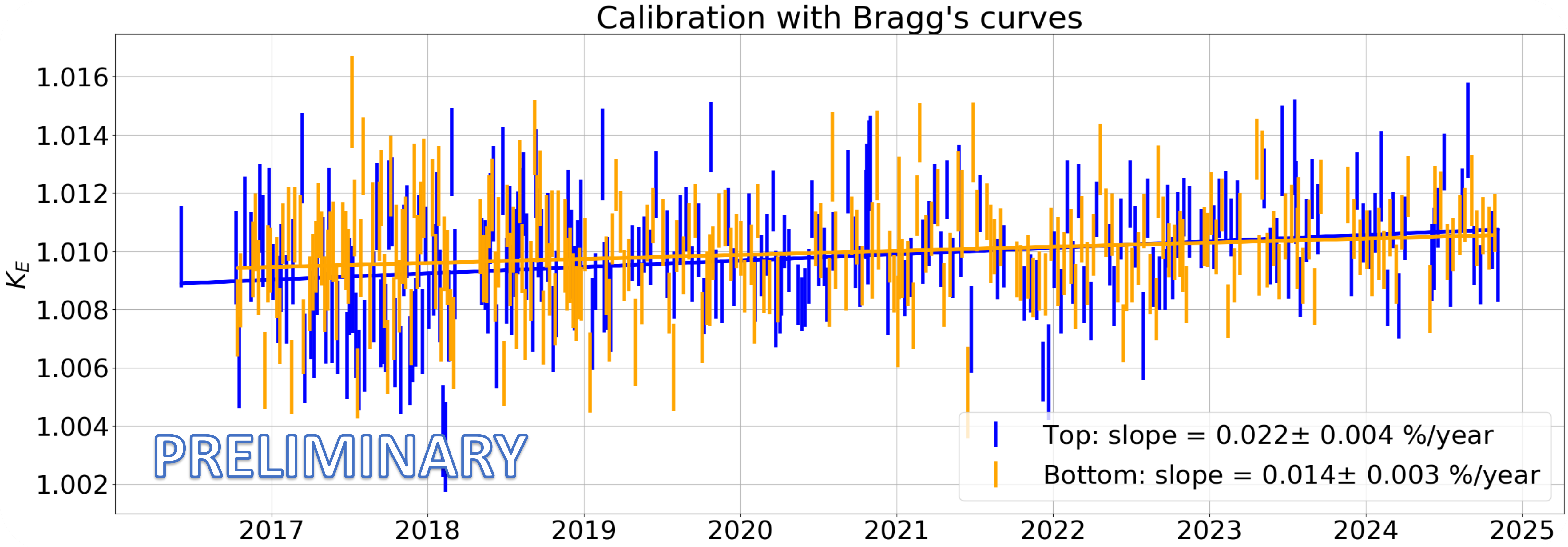
- Cherenkov radiation

$$\frac{dE}{dx} = K_{Ch}\left(1 - \frac{E^2}{n^2(E^2 - m^2)}\right)$$

- Cover layer thickness..



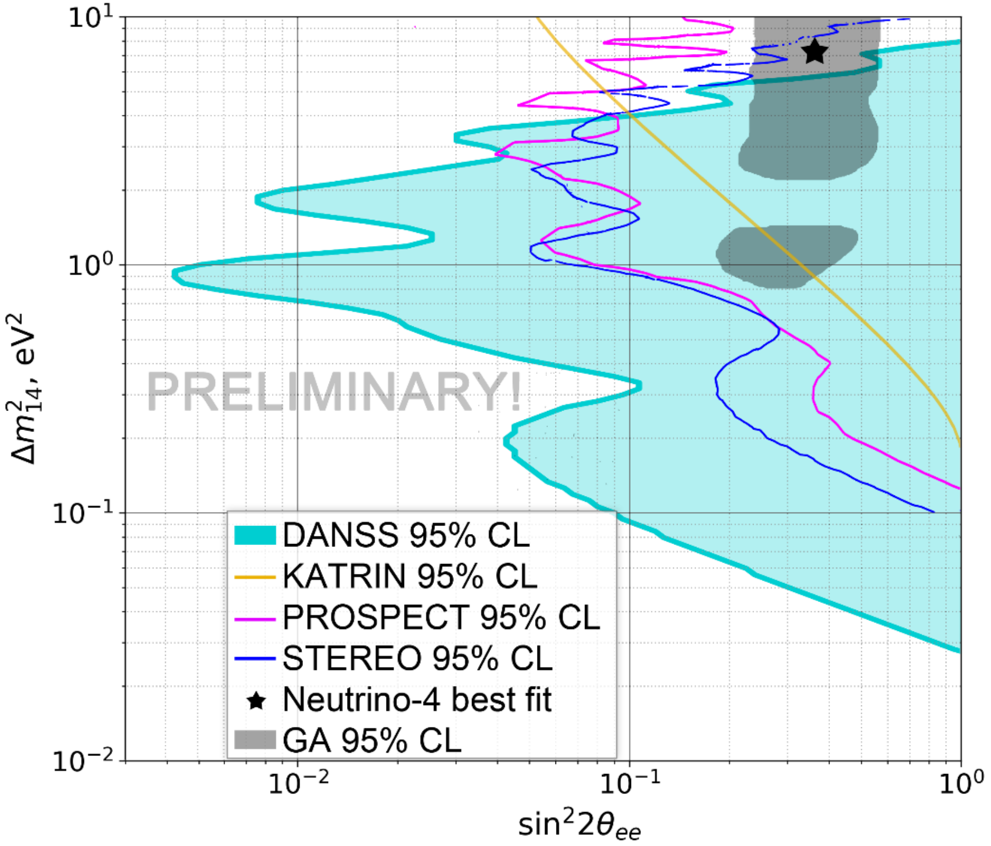
Time stability proven with Bragg’s curves



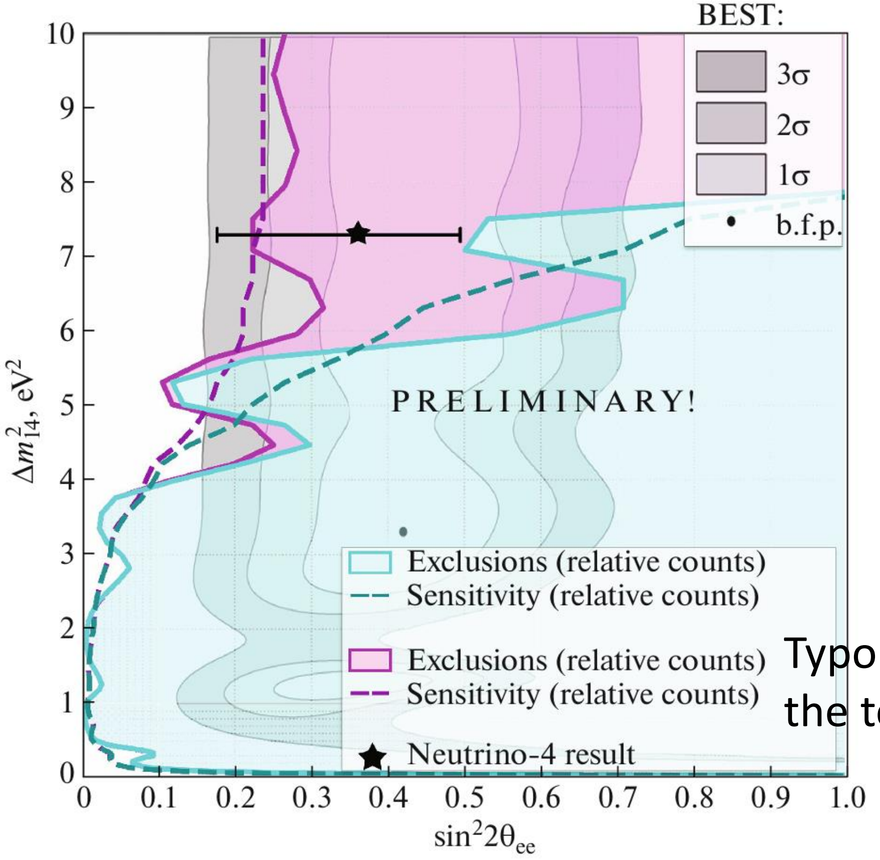
- Time stability during almost 10 years
- Good agreement between Top and Bottom detector positions – very important to searches for New Physics

Sterile neutrinos, N. Skrobova

- Only relative counts
- Analysis with Bottom/Top ratio



- With absolute counts
- Including information about total number of IBD events

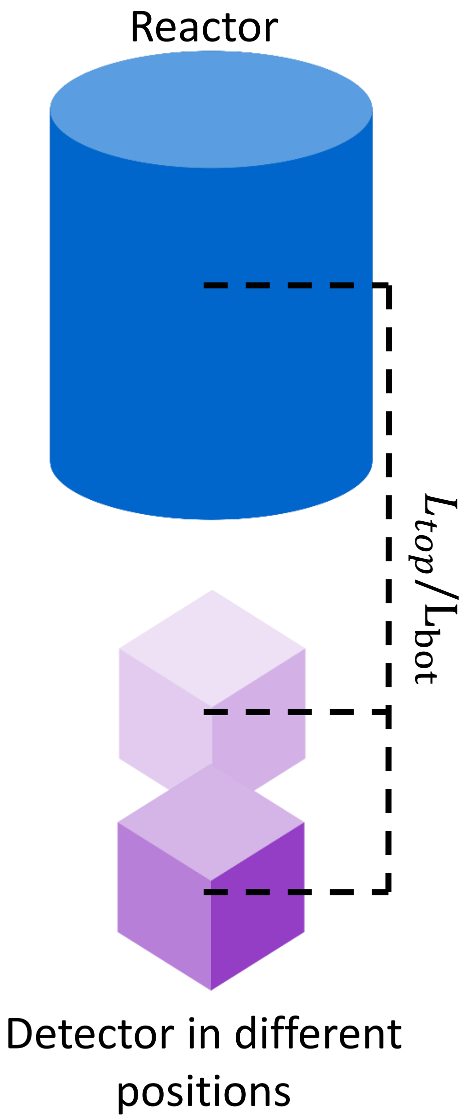


Typo in the text ☹

- The strongest limits in the world for some regions!
- Neutrino-4 result is excluded

Searches for Large Extra Dimensions (my Master)

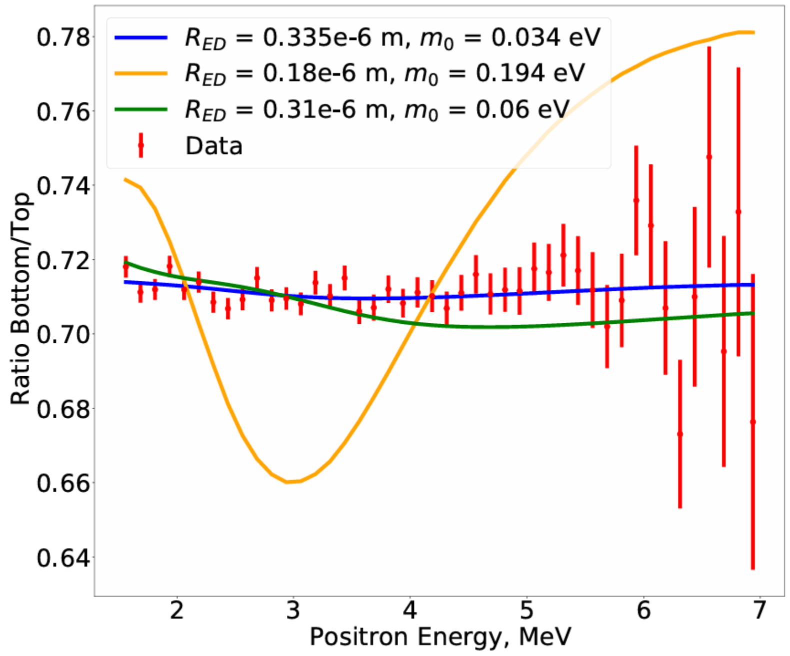
- Toy MC (no GEANT) of antineutrino in random
  - Point in the reactor $\boldsymbol{r_r}$
  - Point in the detector $\boldsymbol{r_d}$
  - Energy E
- Modelling accounts for
  - Oscillation into LED
  - Geometry of reactor and detector
  - Distribution of fission points in the reactor
  - Model of reactor antineutrino spectra (Huber-Mueller)
- Final step – conversion to positron spectra with the response matrix modelled in GEANT



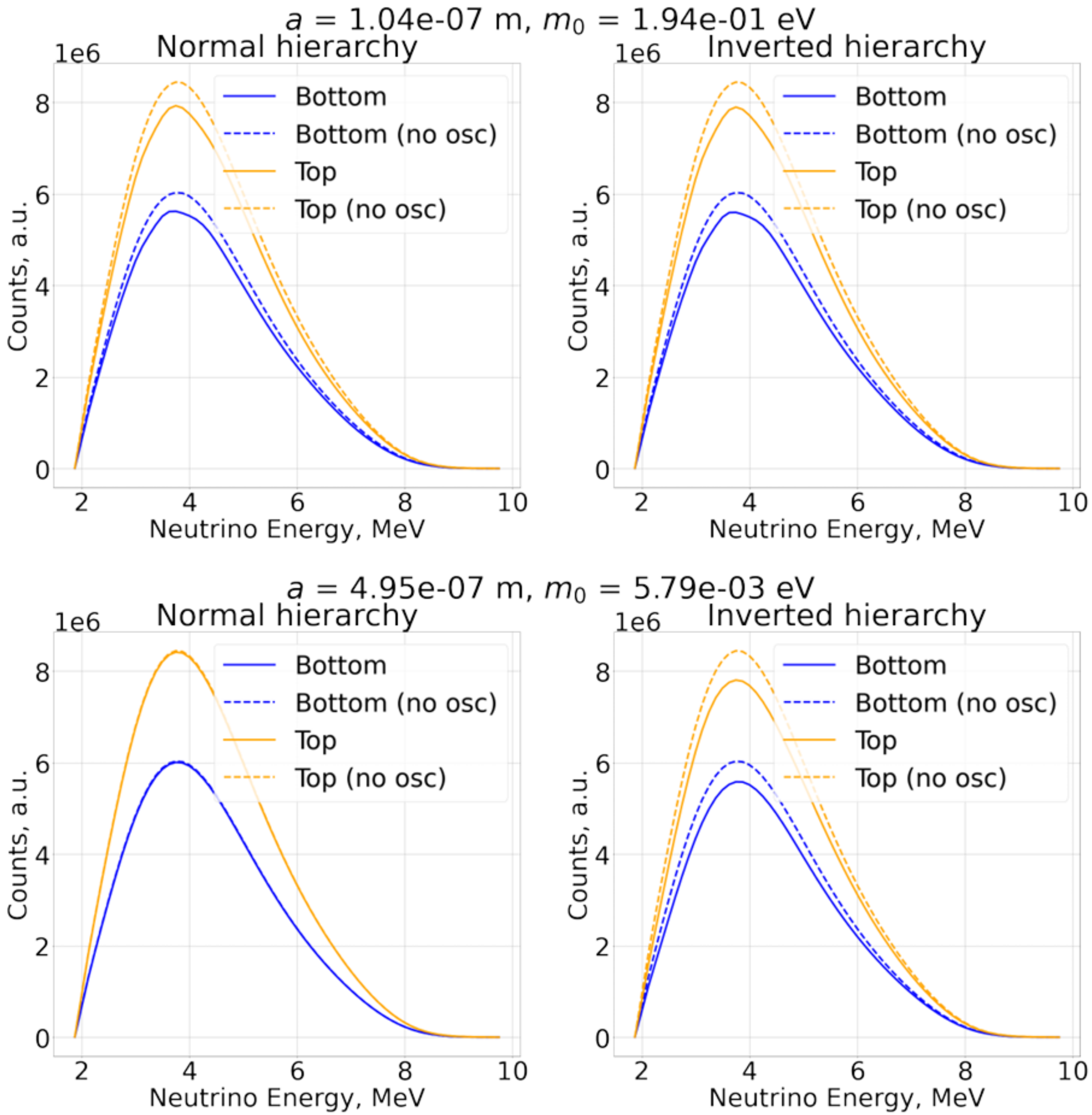
$$dP_{ee} = |A_{ee}(a, m_0, E, L)|^2 \times profile(\vec{r}_r) \times HM(E)dE \times \frac{1}{L^2} d^3\vec{r}_r d^3\vec{r}_d,$$

Modelled spectra

- No normalization for antineutrino flux, however, all other factors are included

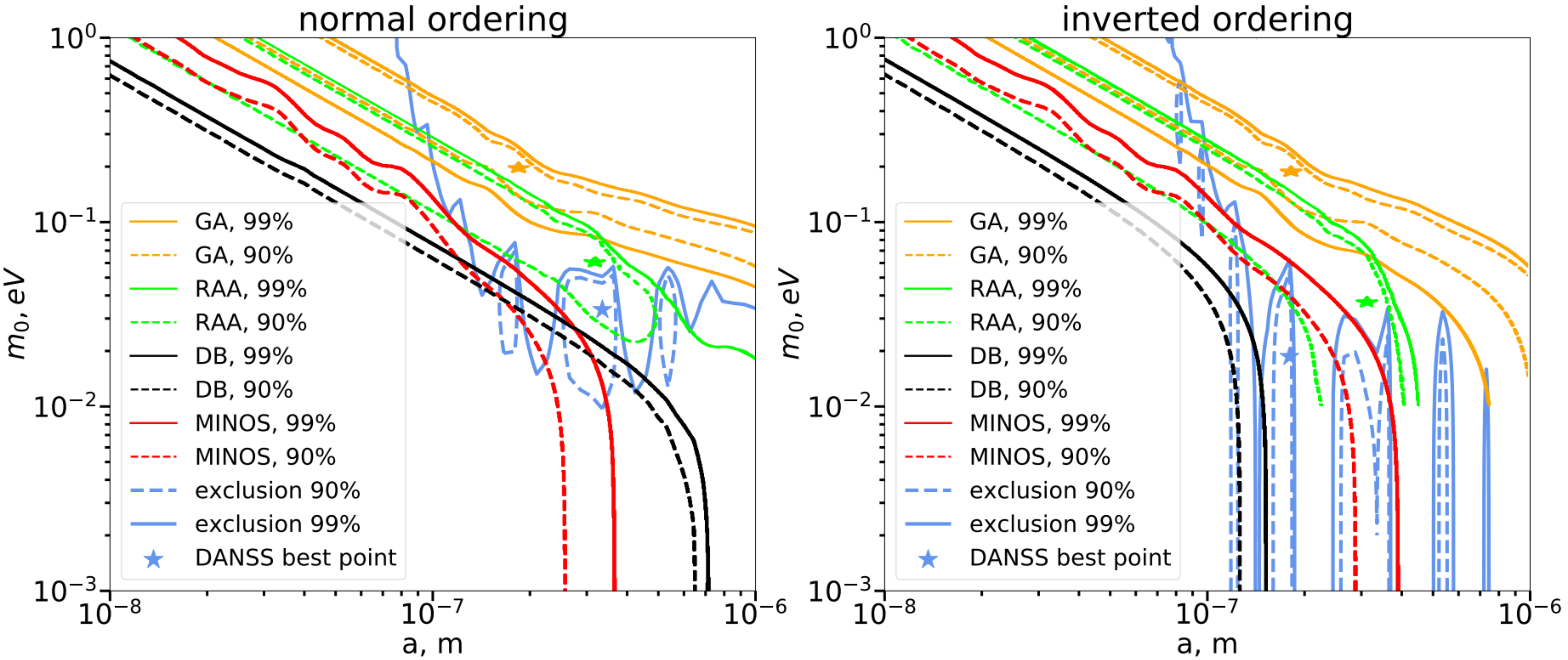


Observed (red) and predicted for DANSS (blue), GA (orange), RAA (green) b.f.p spectra ratios



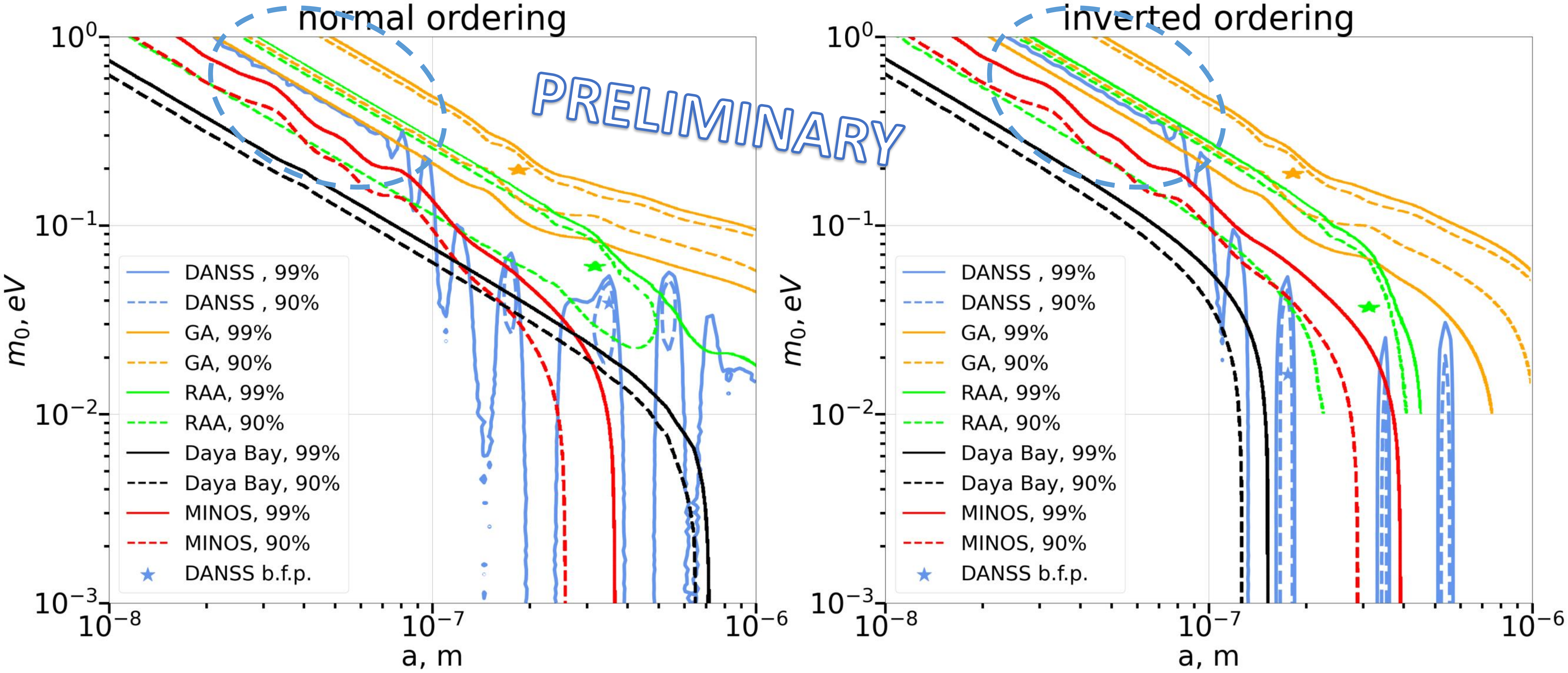
Results and comparison

I. Alekseev et al., DANSS, Letters to JETP, vol 122, issue 1, page 3, 2025



- GA, RAA and DB analysis from D.V. Forero et al, Phys. Rev. D 106, 035027, 2022
- MINOS from P. Adamson et al, (MINOS), Phys. Rev. D 94, 111101(R), 2016

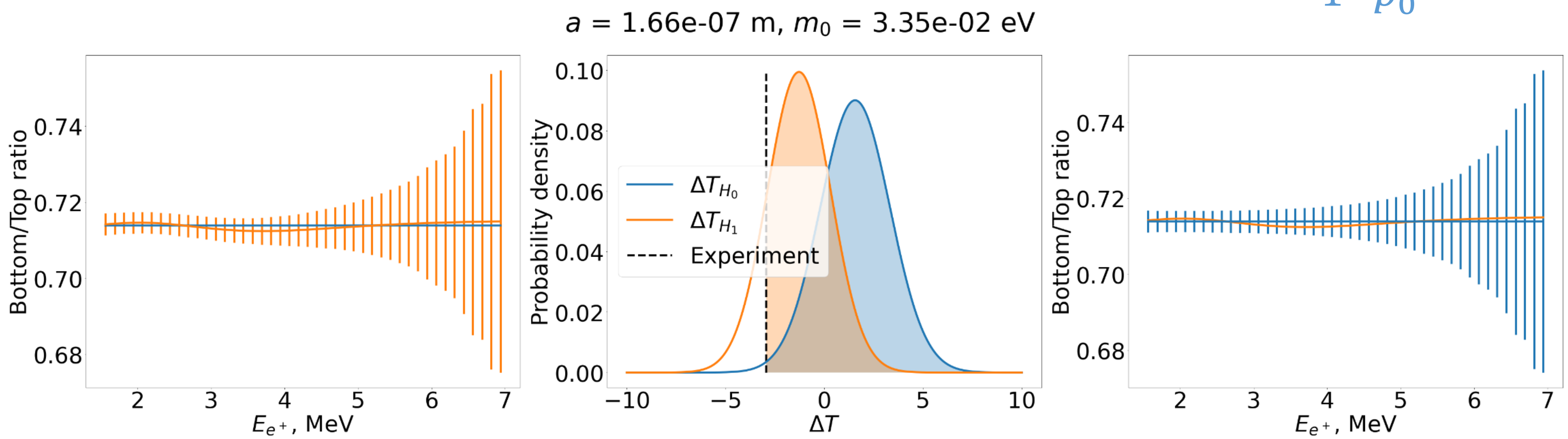
Improvements with absolute counts



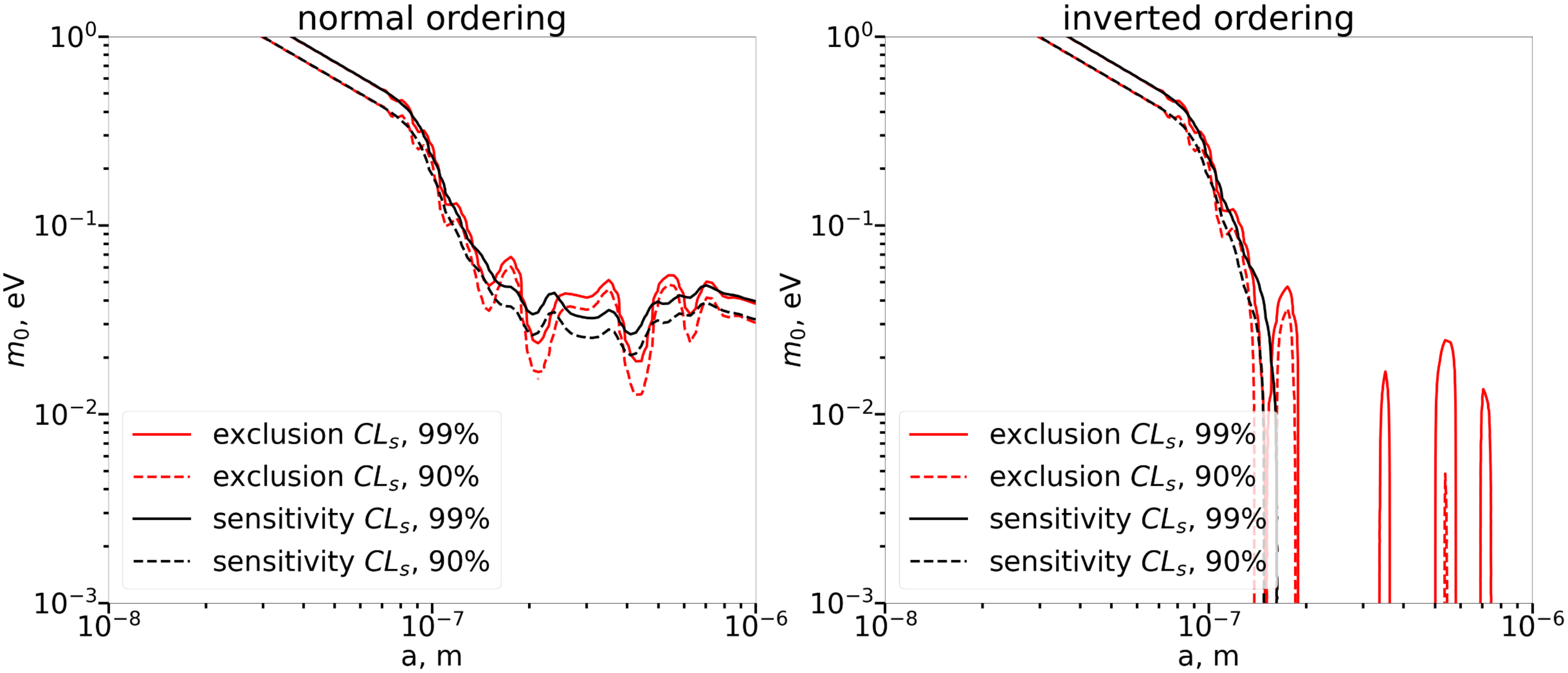
- Larger statistics + absolute counts
- Blue circles – area of largest impact from the absolute counts

Some Statistics

- Previously shown contours obtained with Wilk's theorem: *$\Delta\chi^2$ statistics is distributed with the χ^2_k distribution, if true hypothesis is not on the border of the parameter space. k is the number of parameters in the fit*
- Another method for studying exclusion of parameters is the Gaussian CL_s method: it compares each hypothesis with the null one independently, assuming the null hypothesis to be true
  - $\Delta T = \chi^2(a, m_0) - \chi^2_{null}$ distributed normally with the parameters determined by the Asimov dataset
  - Confidence level (relative to the null hypothesis) is given by $CL_s = \frac{1-p_1}{1-p_0}$



Sensitivity and exclusions in CL_s method

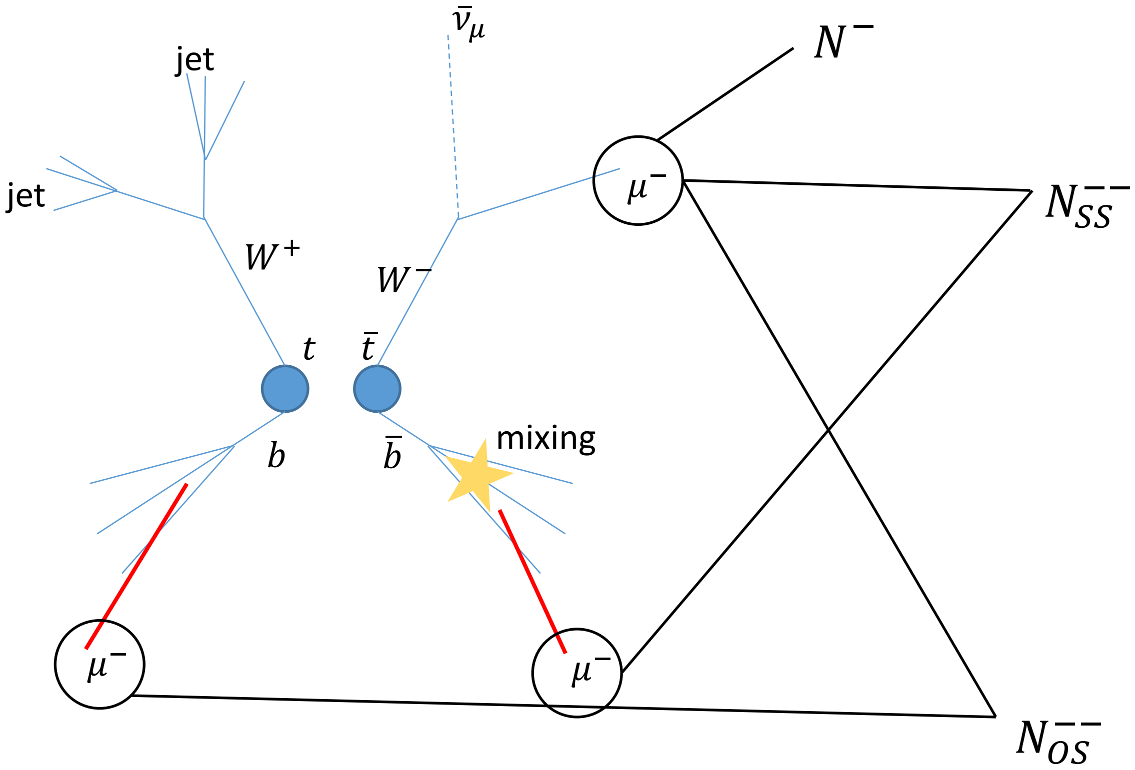


CPV measurement in CMS

Scheme of the analysis

- Goal is to measure A_{CP} separating it from the detector asymmetries
- $\bar{t}t$ events: high p_T of decay products
- Charge of hard muon → flavor of t (and, hence, b at production)
- Charge of soft muon → flavor of b at decay

$$A_{CP} = \frac{N_{SS}^{++} - N_{SS}^{--}}{N_{SS}^{++} + N_{SS}^{--}} = \frac{N_{OS}^{-+} - N_{OS}^{+-}}{N_{OS}^{-+} + N_{OS}^{+-}}$$



- There are detector-related asymmetries which should be taken into account and constrained from data

System of equation for asymmetries

- Asymmetries are obtainable from linear equations:

a) $$\frac{\mathcal{N}^{+} - \mathcal{N}^{-}}{\mathcal{N}^{+} + \mathcal{N}^{-}} = \Delta$$

b) $$\frac{\mathcal{N}^{++}{}_{SS} - \mathcal{N}^{--}{}_{SS}}{\mathcal{N}^{++}{}_{SS} + \mathcal{N}^{--}{}_{SS}} \simeq \Delta + \delta + \mathcal{A}_{CP}$$

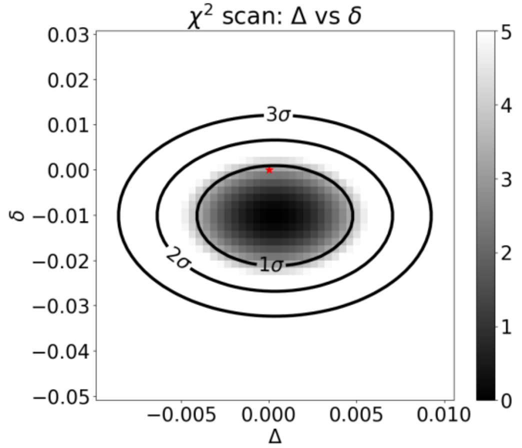
c) $$\frac{\mathcal{N}^{+-}{}_{OS} - \mathcal{N}^{-+}{}_{OS}}{\mathcal{N}^{+-}{}_{OS} + \mathcal{N}^{-+}{}_{OS}} \simeq \Delta - \delta - \mathcal{A}_{CP}$$

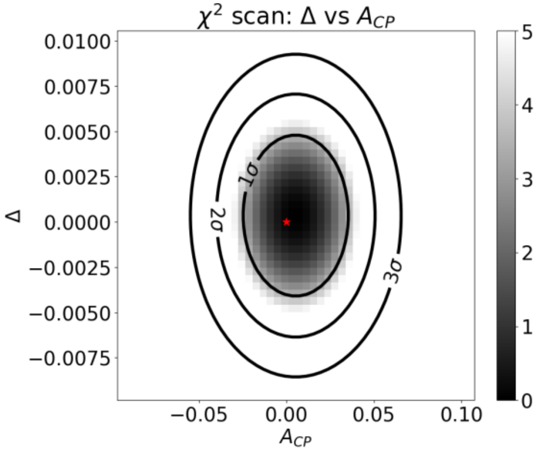
d) $$\frac{\mathcal{N}^{+-}{}_{SS} - \mathcal{N}^{-+}{}_{SS}}{\mathcal{N}^{+-}{}_{SS} + \mathcal{N}^{-+}{}_{SS}} \simeq \Delta - \delta - \frac{\bar{\chi}}{1-\bar{\chi}}\mathcal{A}_{CP}$$

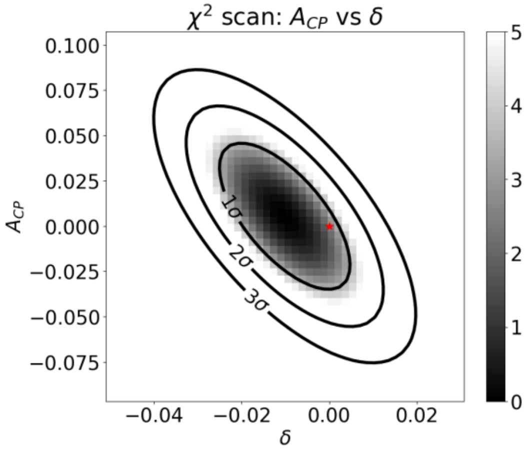
e) $$\frac{\mathcal{N}^{++}{}_{OS} - \mathcal{N}^{--}{}_{OS}}{\mathcal{N}^{++}{}_{OS} + \mathcal{N}^{--}{}_{OS}} \simeq \Delta + \delta + \frac{\bar{\chi}}{1-\bar{\chi}}\mathcal{A}_{CP}$$

- 5 equations for 3 variables → parameters overconstrained in the fit

$$\chi^2 = (l - r)^T W (l - r)$$





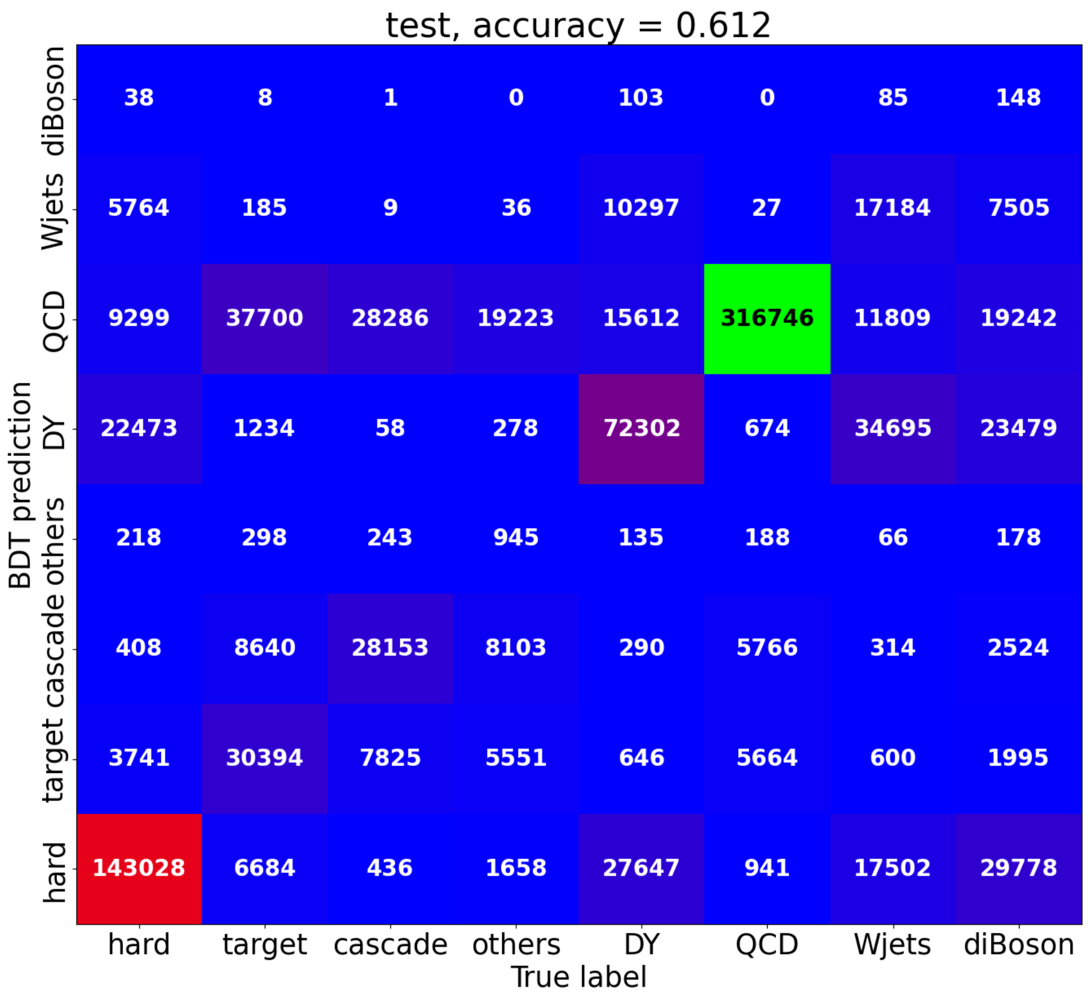


- Cross-sections of 3D $\Delta\chi^2$ profile
- Red point is $(0; 0; 0)$

Muon classification

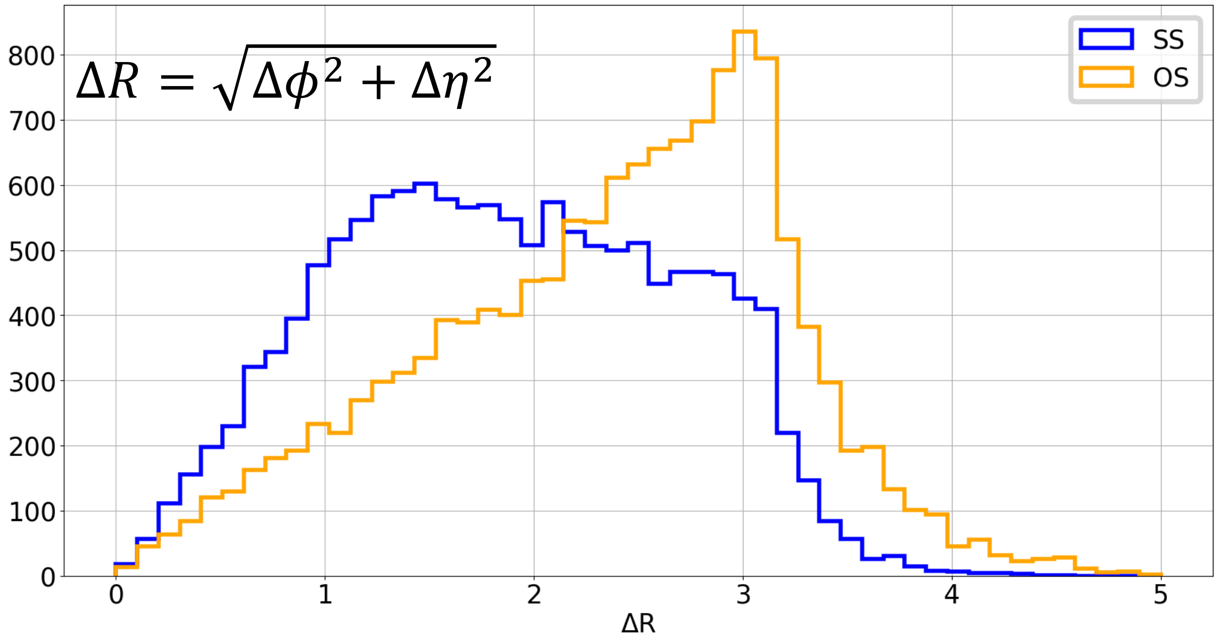
- Classifier is a forest of binary decision trees (BDT) and uses the kinematics of the muon and the closest jet

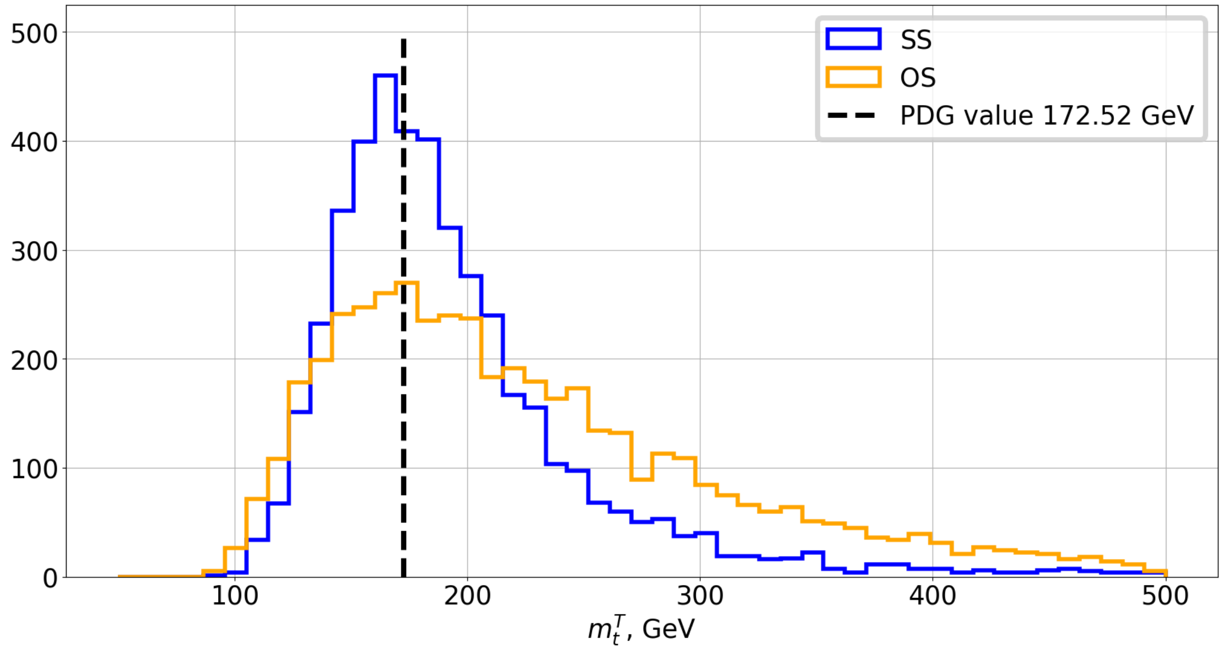
- Future plans – include info about whole event in order to discard more hard backgrounds



Tagging of soft muons

- For the event with both hard lepton and target muon reconstructed one should determine if they come from the same top or not
- Tagger is a forest of BDT trained on kinematics of two leptons, and the jet closest to the target muon. This jet is assumed to be b-jet coming from decay of top



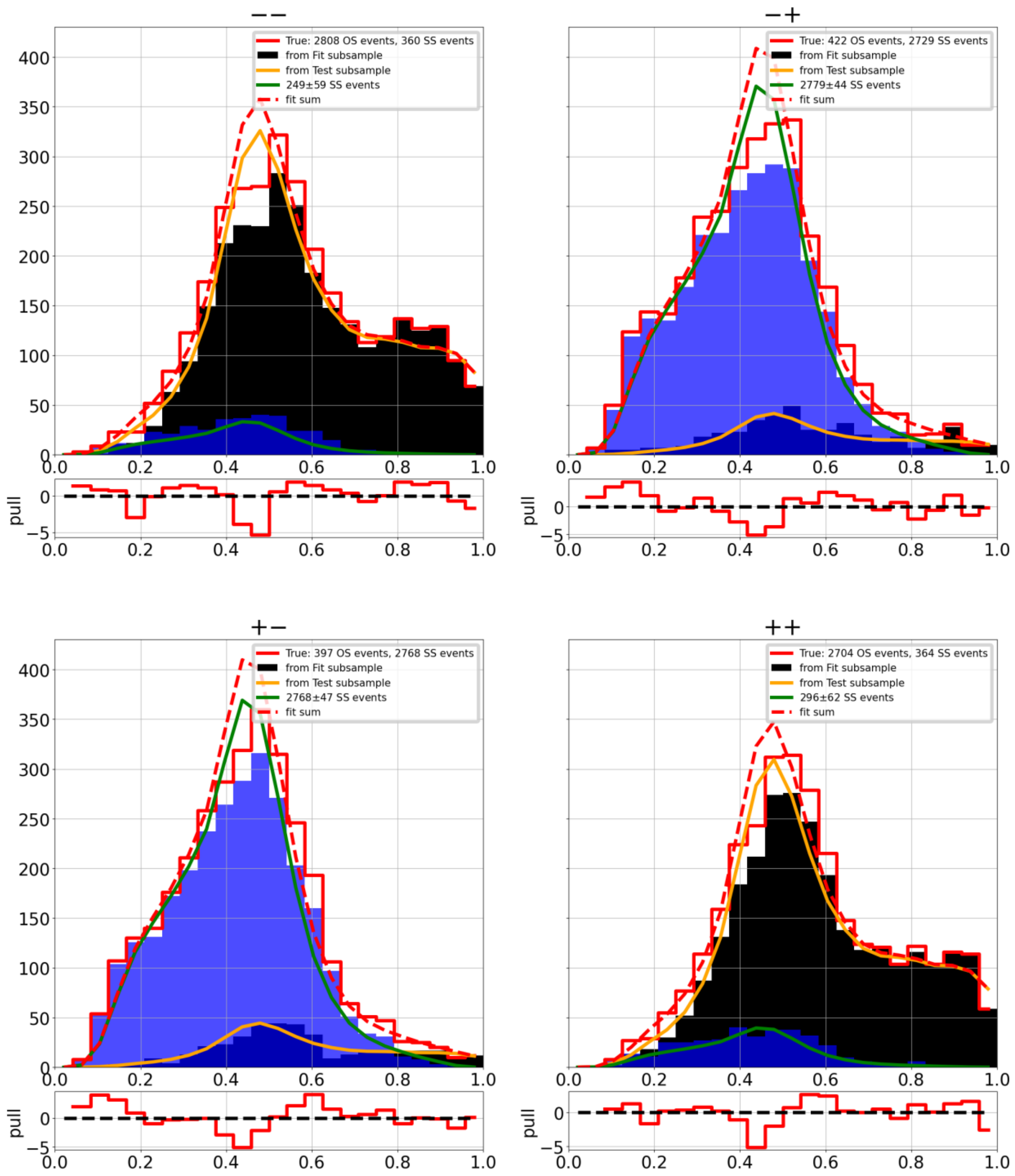


Performance of the fitter

- Fit data sample is divided in 4 subsamples depending on the charges of the hard and soft muons
- Shapes of tagger output is used in the fit
- Obtained $\bar{\chi}$:

$$\bar{\chi} = 0.129 \pm 0.026$$

$$\bar{\chi}_{MC} = 0.128$$



Thank you for your attention!