# Reactor Antineutrino with the DANSS Detector

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# DANSS — Detector of reactor AntiNeutrino based on Solid-state Scintillator

**Unique location and movability**

- 50 m.w.e. overburden
- 10.9 – 12.9 m from the core center
- Regular movement every week

**Safety and fine segmentation**

- 1 m$^3$ of polystyrene based scintillator strips 10x40x1000 mm$^3$ with Gd coating and WLS fiber readout
- 25 strips in a layer, 100 layers with alternating direction
- Center fiber – SiPM (2500 channels)
- Two edge fibers from 50 strips of the same direction – PMT (50 channels)

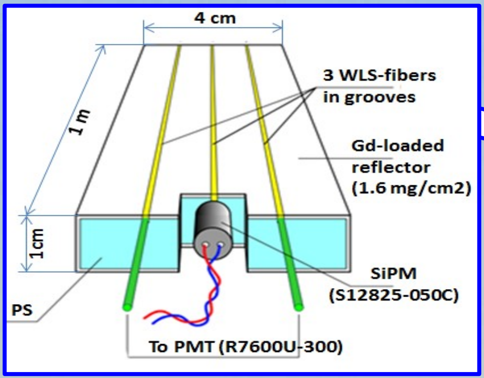
**Powerful shielding**

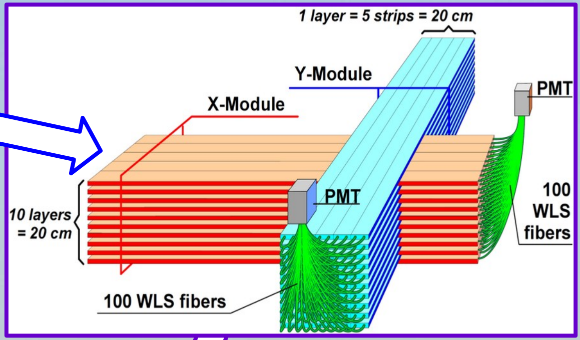
- Multilayer Cu (5 cm) + CHB (8 cm) + Pb (5 cm) + CHB (8 cm) closed passive shielding
- 2-layer μ-veto on 5 sides

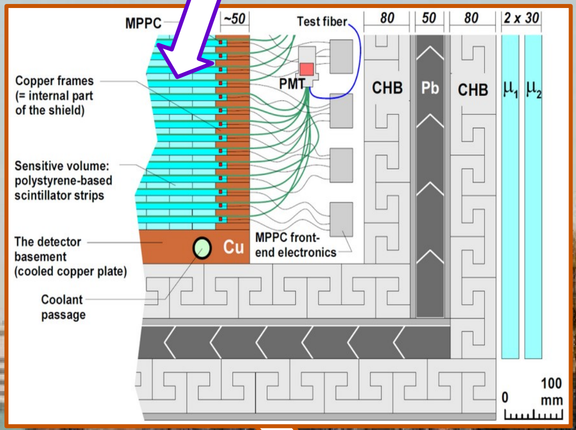
**Versatile DAQ**

- Dedicated WFD-based DAQ system

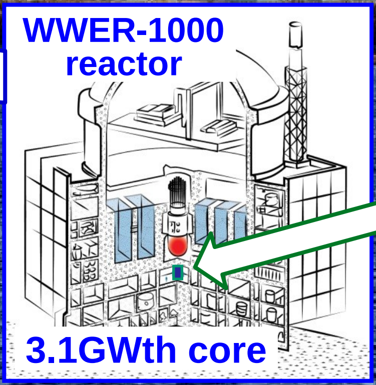
JINST 11 (2016) P11011

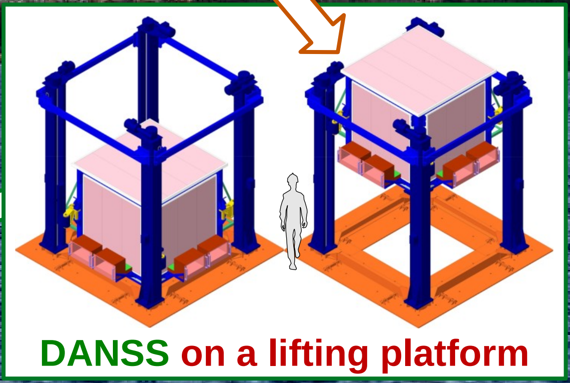


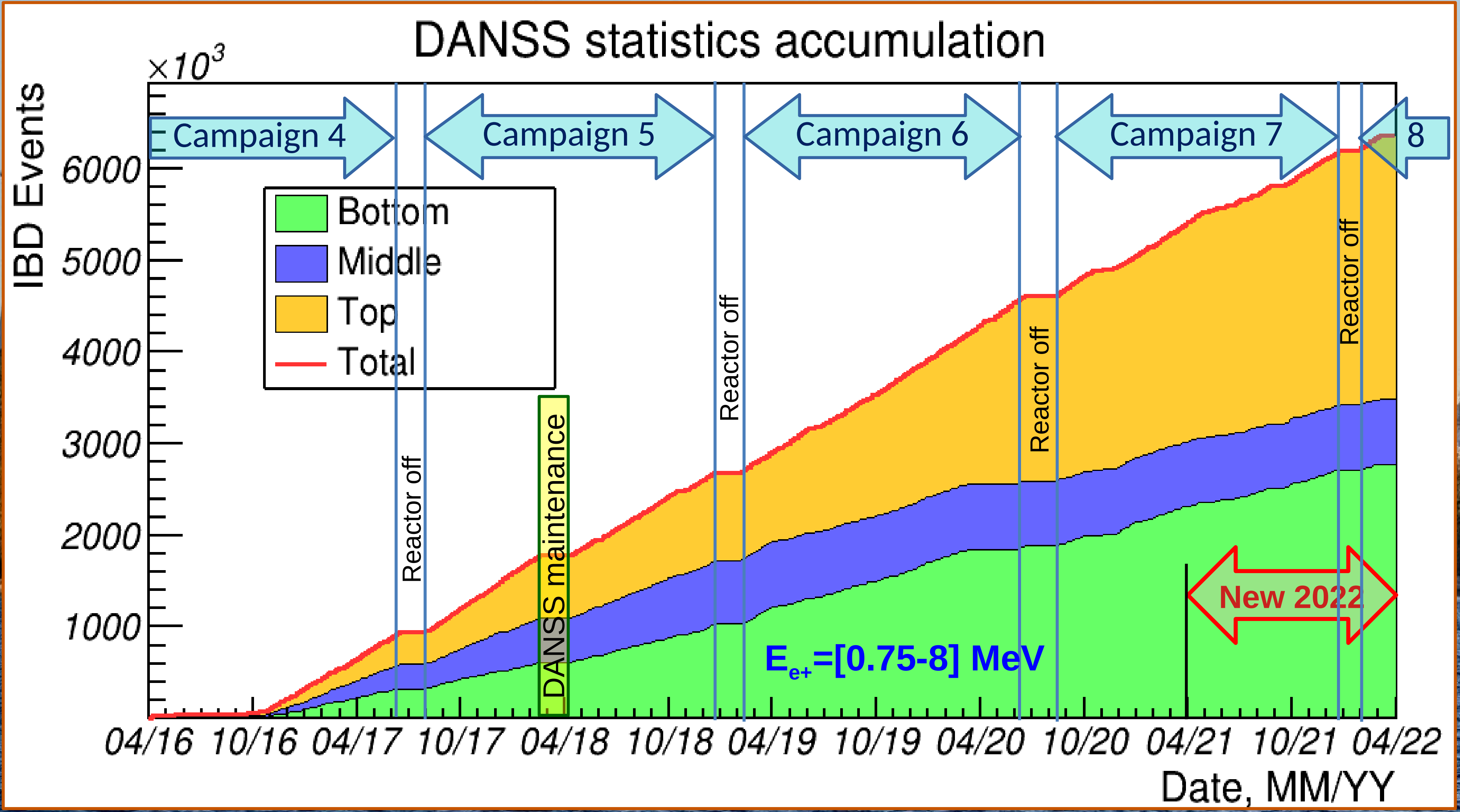

Kalininskaya NPP Unit 4



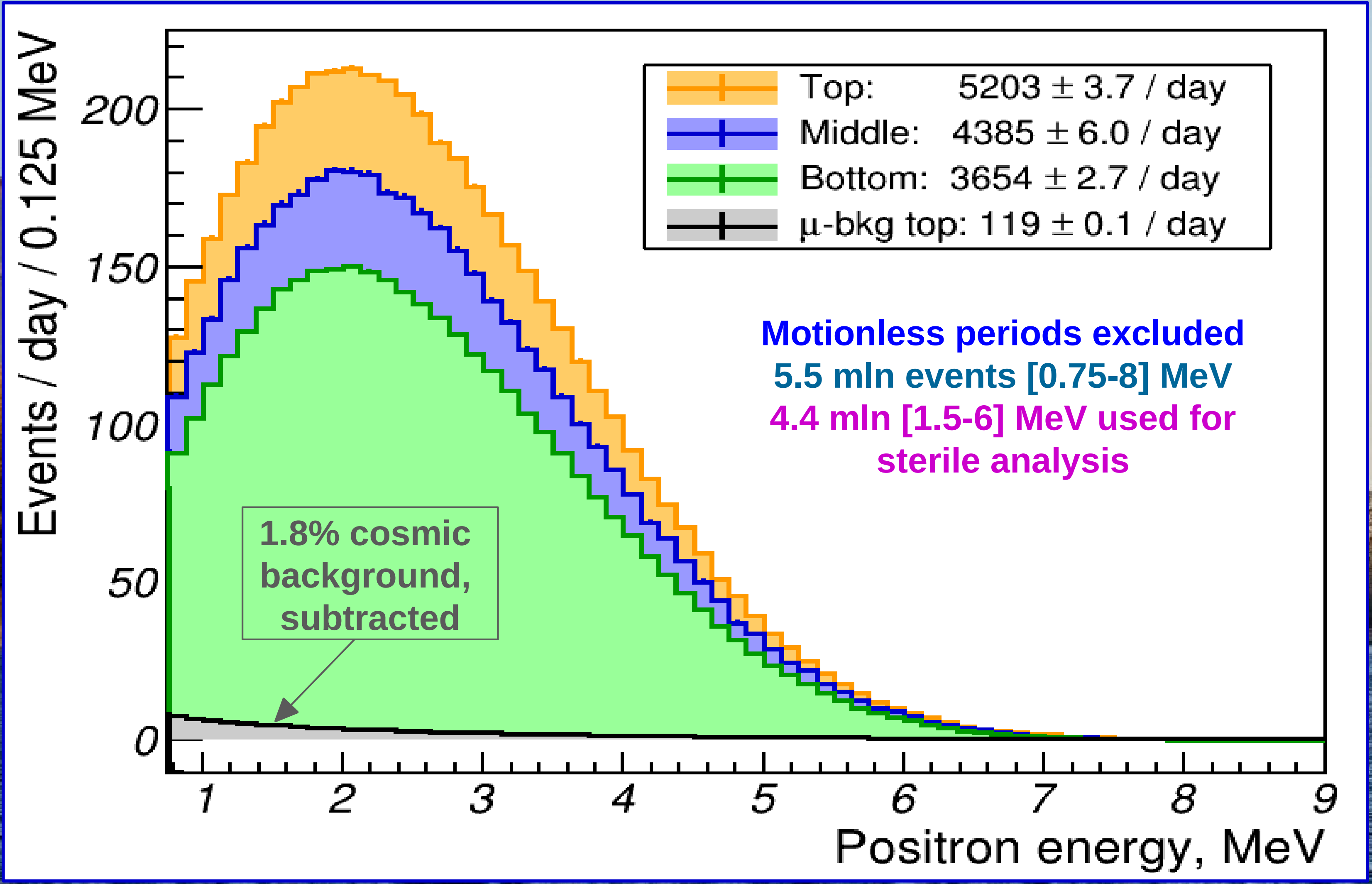
# Setting World Records, I

- **6 years of very stable and almost continuous running**
- **> 6 mln. neutrino events recorded and analyzed till April, 2022 (so far)**
- **3 full fuel campaigns, 4 reactor-OFF periods**



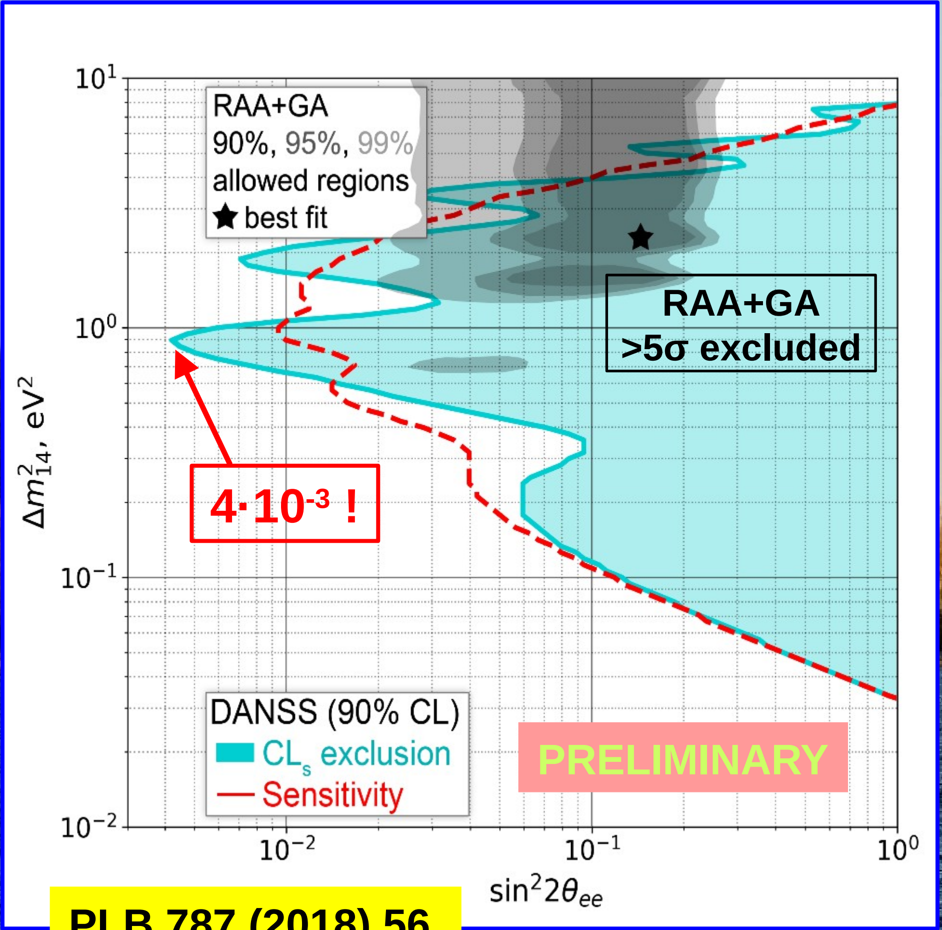
# Setting World Records, II

- > 5000 events/per day in the closest position
- > 50:1 signal to noise ratio
- Good statistics in positron spectra



# Sterile Analysis

- Gaussian CLs method for the exclusion limits, reaches $\sin^2 2\theta < 4 \times 10^{-3}$
- RAA+GA best point is deep in the exclusion region. 5σ exclusion already in 2018
- Two Feldman-Cousins allowed regions with close significance more than 2σ
- The best point 2.35σ is not significant enough to claim indication of 4ν

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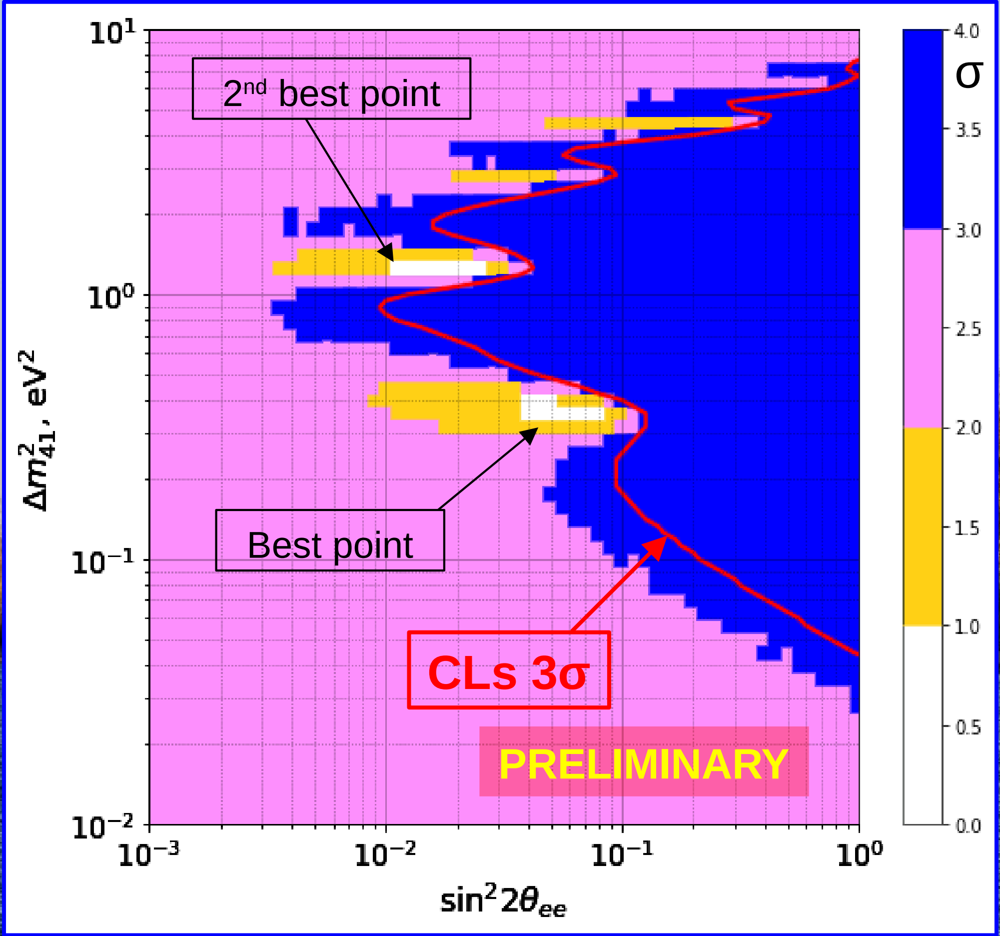
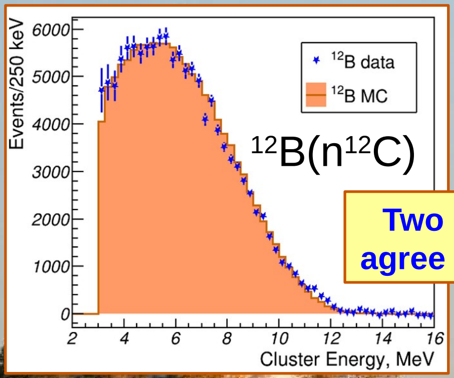
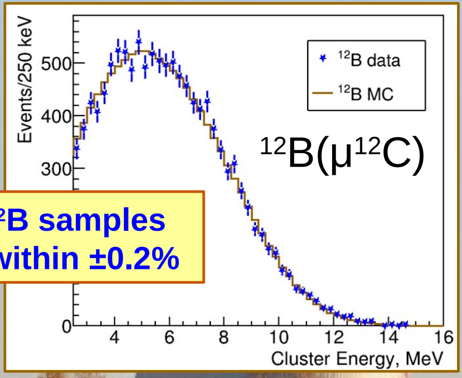


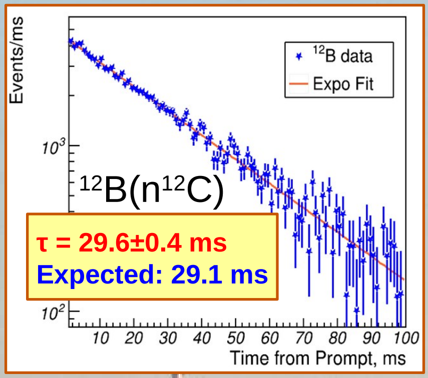
# Calibration and Monte Carlo

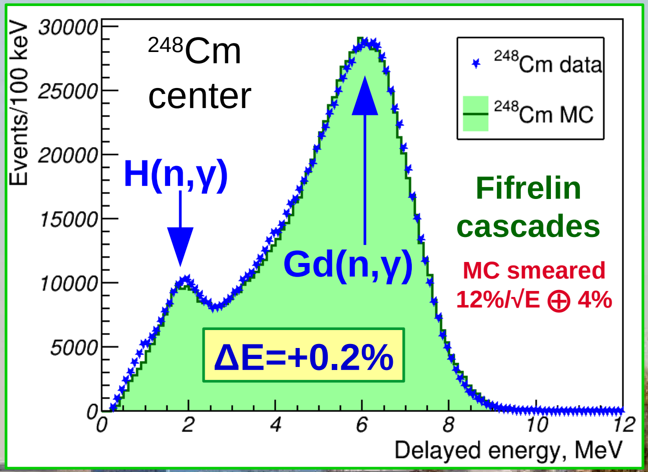
- Routine calibration, now using median of distributions:
  - SiPM by noise spectra every 30-40 min
  - All photo-sensors by cosmic muons every 2 days
- Global energy scale is fixed by $^{12}$B-decay, most similar to $e^+$ signal: −4.6% to the muon scale
- Good agreement ±0.2% of various calibration sources (except $^{22}$Na)
- Much progress in MC, including individual light yields for each SiPM and PMT

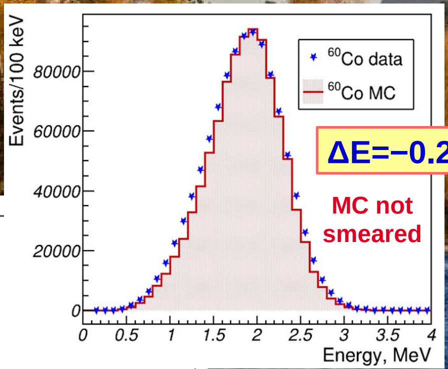


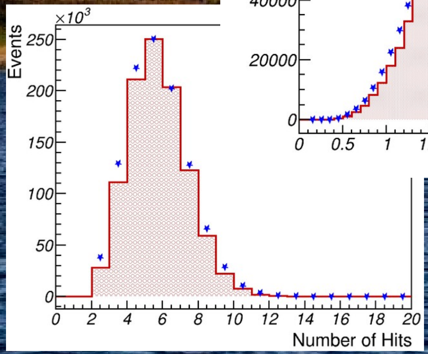



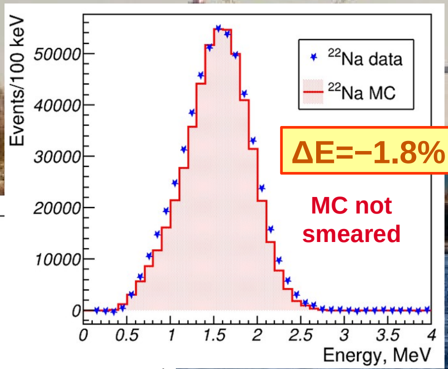

Two $^{12}$B samples agree within ±0.2%

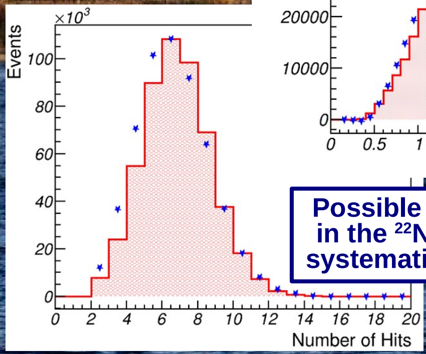


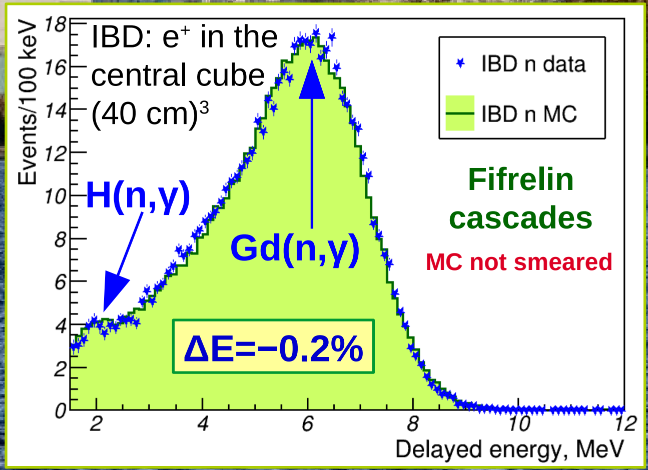



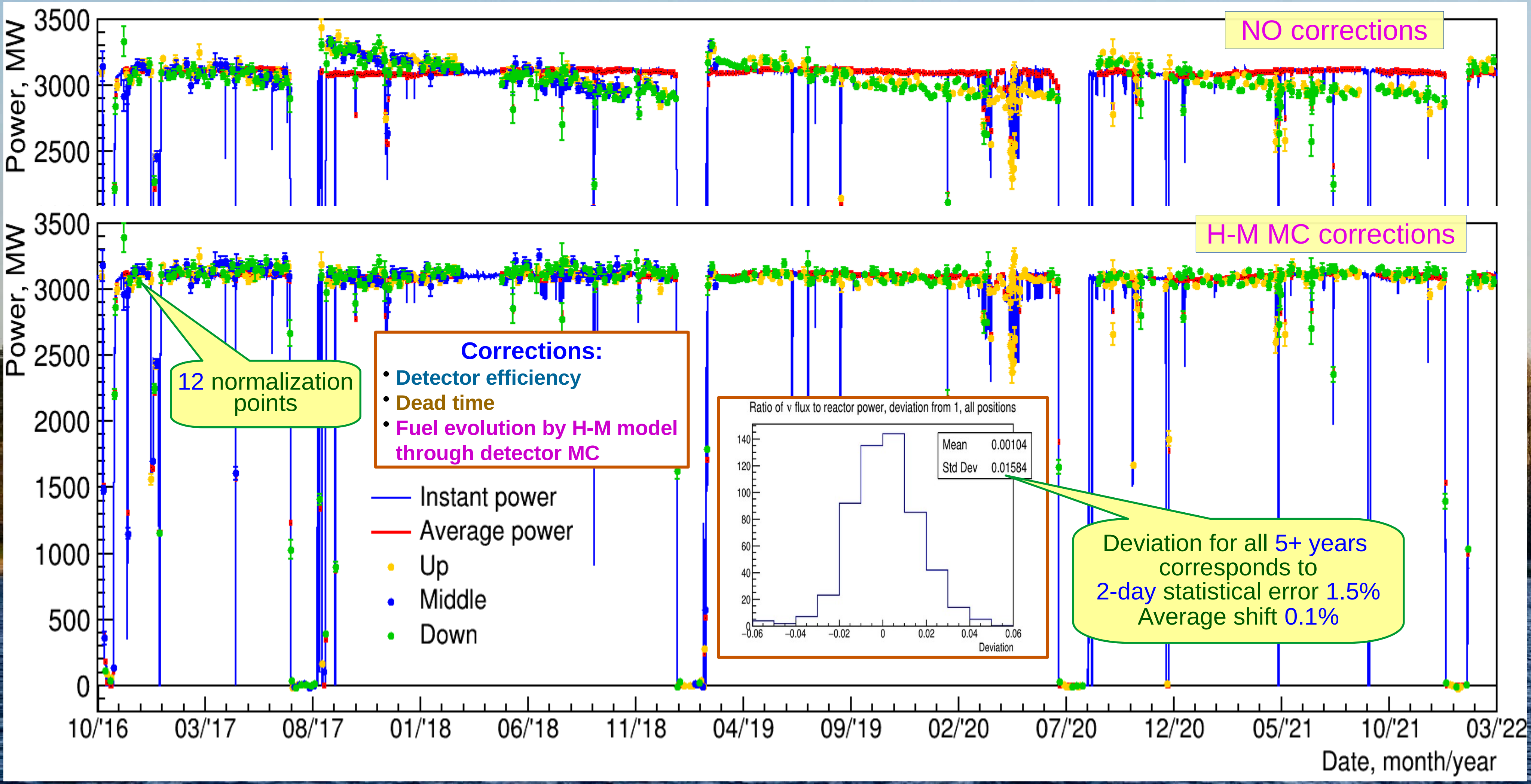




Possible $^{26}$Al contamination in the $^{22}$Na source. Keep 2% systematic error for the scale



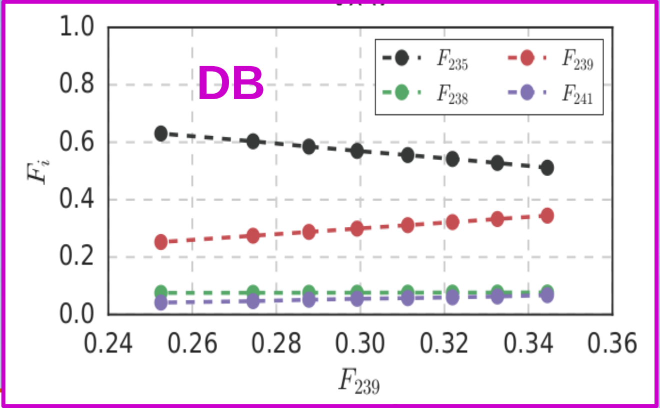
# Reactor Power Monitoring

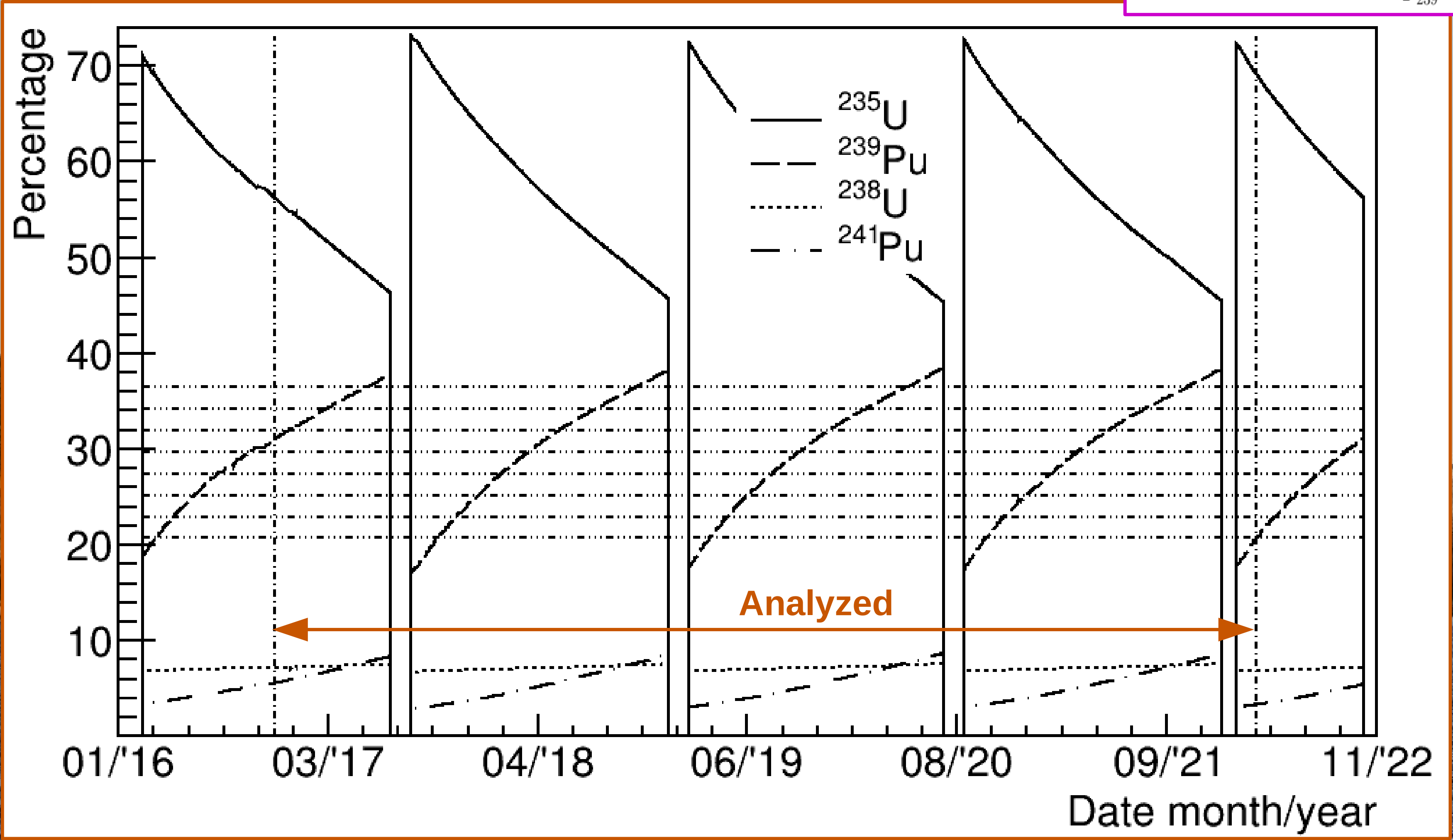
- Dependence on fuel evolution clearly seen
- Various detector positions equalized by toy MC of both the core and the detector
- Single common normalization by 1 month in October, 2016
- Absolute detector efficiency known with accuracy better than 1% during 5.5+ years



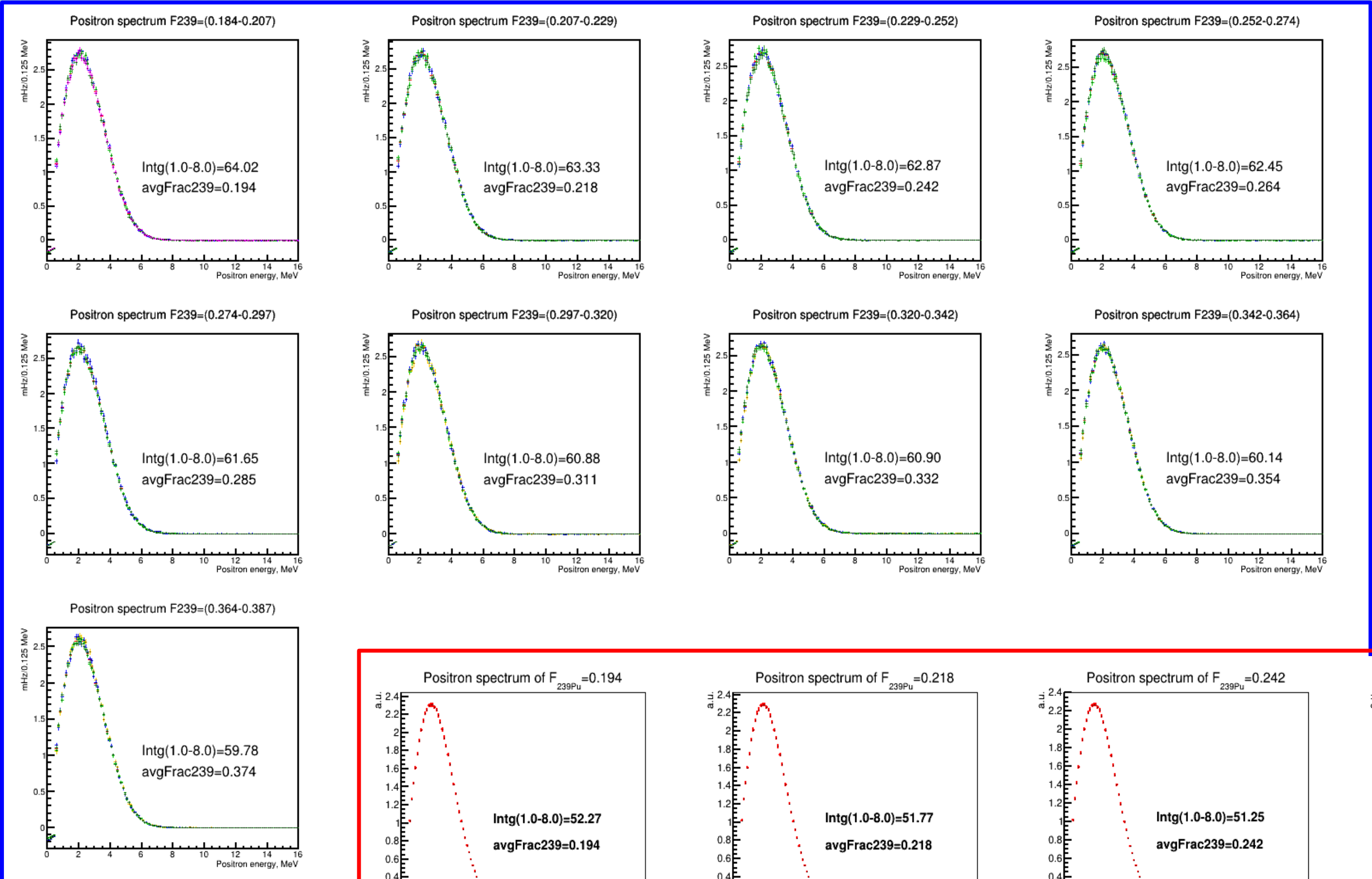
# Fission Fractions

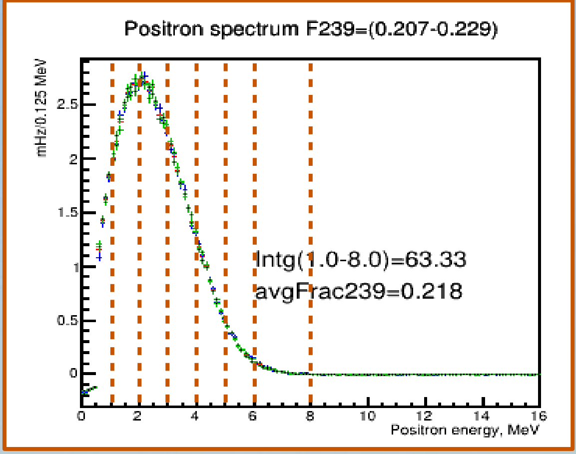
- ✔ New fission fractions from the NPP experts with common approach to all campaigns under analysis
- ✔ Following Daya Bay **Phys.Rev.Lett. 118 (2017) 25, 251801**
- ✔ 9 fission fraction intervals in $F_{239}$ ~(0.18–0.38)



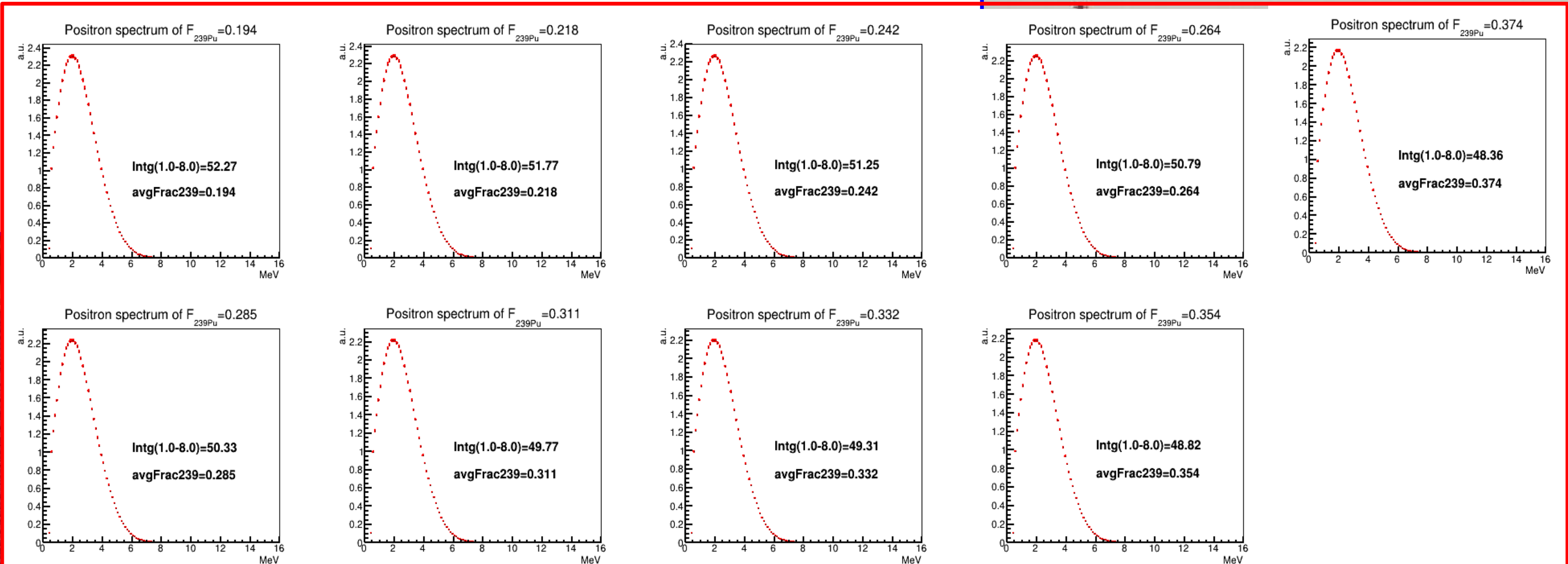



# $e^+$ Spectra for Fraction Intervals



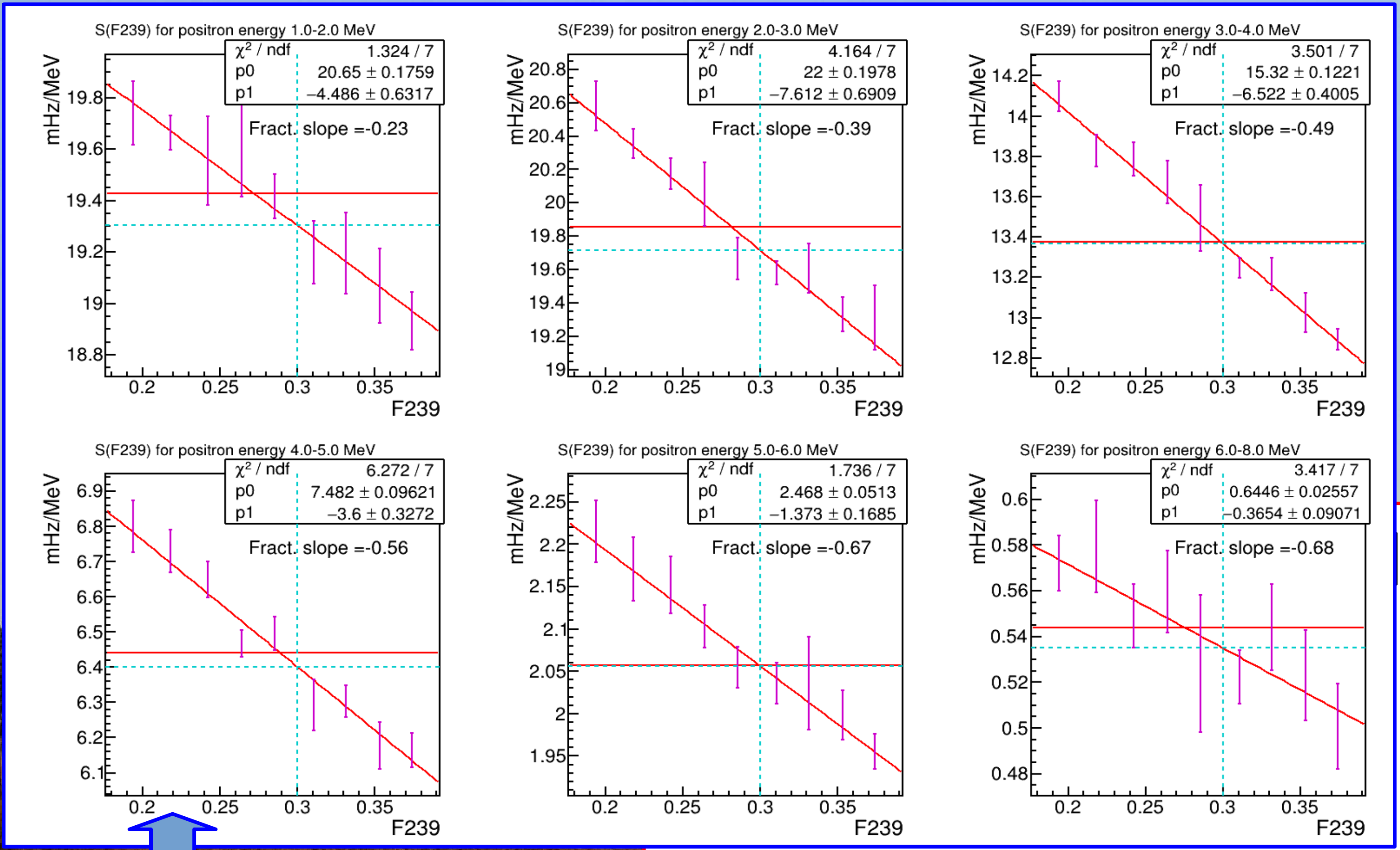



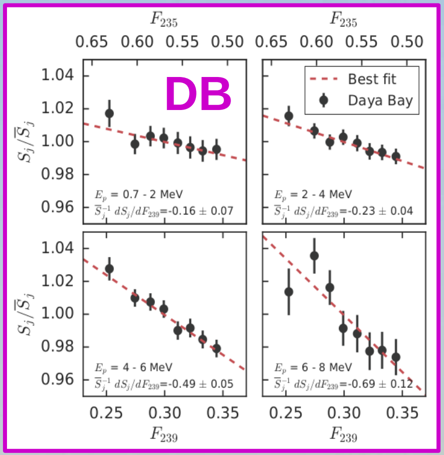

- ✔ **Each spectrum divided into 6 energy intervals**
- ✔ **Separate campaigns**



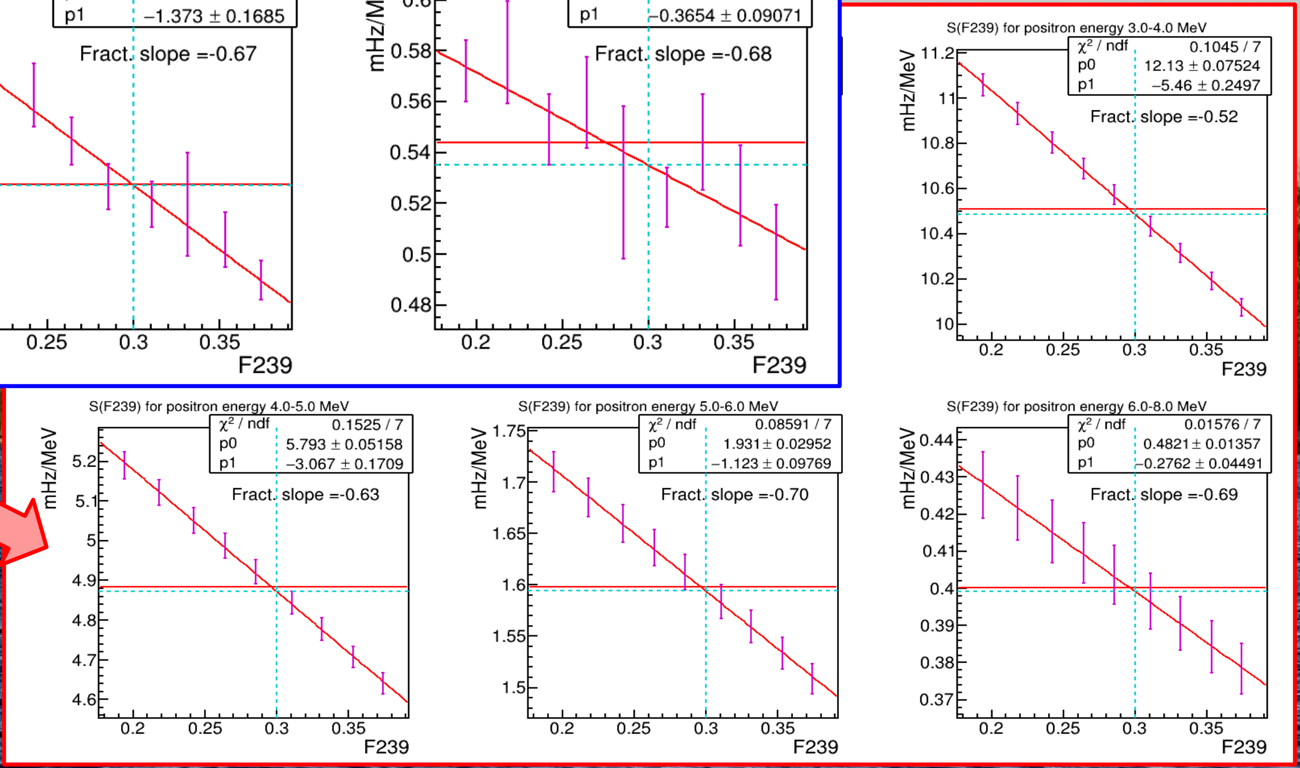

**Experiment & Monte Carlo H-M based**

# Fractional Slopes for Energy Intervals



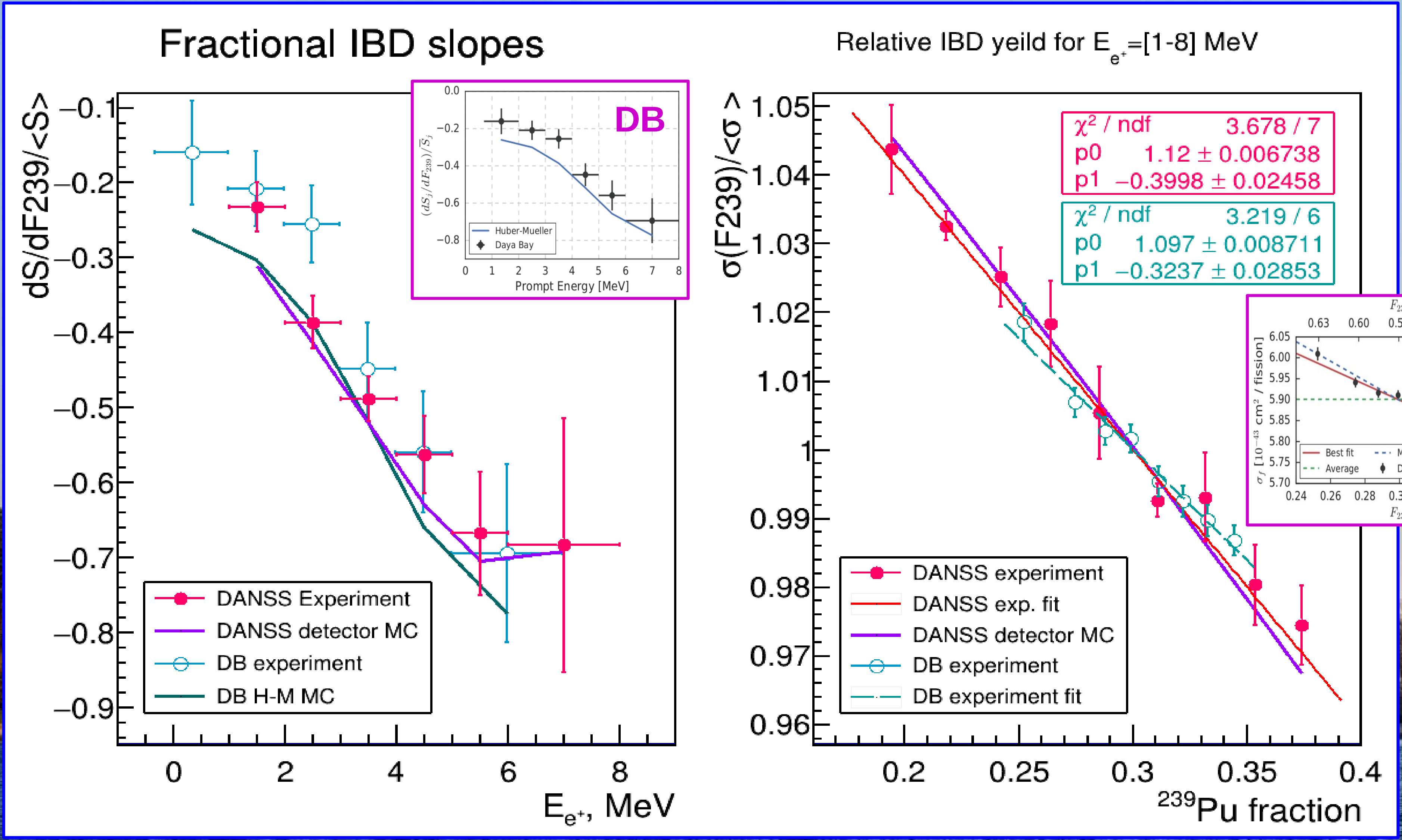




**Experiment & Monte Carlo**




- ✔ **Errors combine statistics and spread between campaigns – overestimated**
- ✔ **Normalized @$F_{239}$=0.3**

# Fractional Slopes and Relative IBD Yield




- DANSS results are slightly more sensitive for the fuel evolution, than DB, and slightly closer to H-M predictions, yet almost agree with both

# Cross-section Ratio $\sigma_{235}/\sigma_{239}$

$$N=\alpha\cdot\left(\sigma_8 f_8+\sigma_1 f_1+\sigma_5 f_5+\sigma_9 f_9\right) \quad (1)$$

N – IBD yield, per fission

- Take derivative with respect to $f_9$

$$\frac{dN}{df_9}=\alpha\cdot\left(\sigma_8\frac{df_8}{df_9}+\sigma_1\frac{df_1}{df_9}+\sigma_5\frac{df_5}{df_9}+\sigma_9\right) \quad (2)$$

$dN/df_9$ – slope of IBD yield in DB definition

- Divide (2) by (1)

$$Sl=\frac{\frac{dN}{df_9}}{N}=\frac{\frac{\sigma_8}{\sigma_9}\frac{df_8}{df_9}+\frac{\sigma_1}{\sigma_9}\frac{df_1}{df_9}+\frac{\sigma_5}{\sigma_9}\frac{df_5}{df_9}+1}{\frac{\sigma_8}{\sigma_9}f_8+\frac{\sigma_1}{\sigma_9}f_1+\frac{\sigma_5}{\sigma_9}f_5+f_9} \quad (3)$$

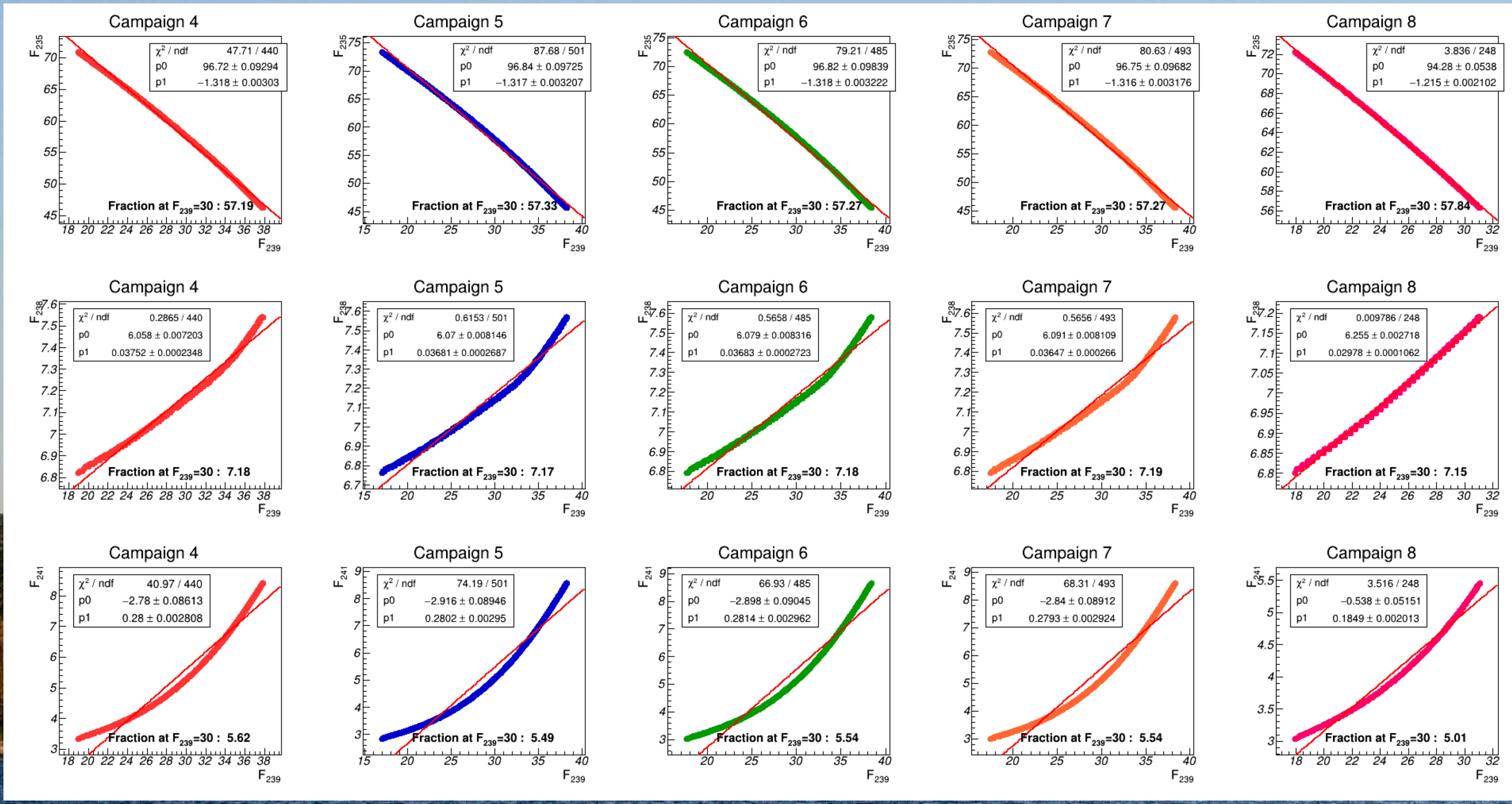
$(dN/df_9)/N$– relative slope of IBD yield in DANSS definition

- Express $\sigma_5/\sigma_9$ from (3)

$$\frac{\sigma_5}{\sigma_9}=-\frac{\frac{\sigma_8}{\sigma_9}\left(Sl\cdot f_8-\frac{df_8}{df_9}\right)+\frac{\sigma_1}{\sigma_9}\left(Sl\cdot f_1-\frac{df_1}{df_9}\right)+\left(Sl\cdot f_9-1\right)}{Sl\cdot f_5-\frac{df_5}{df_9}}$$

Unlike DB, $\sigma_5$ and $\sigma_9$ do not have to be calculated separately

# Fractions vs $F_{239}$ and Derivatives




- Campaigns 4-7 seem to be very similar
- Campaign 8 is taken only partly, resulting in slightly different numbers
- The difference between 4-8 and 4-7 is taken as the uncertainty estimate

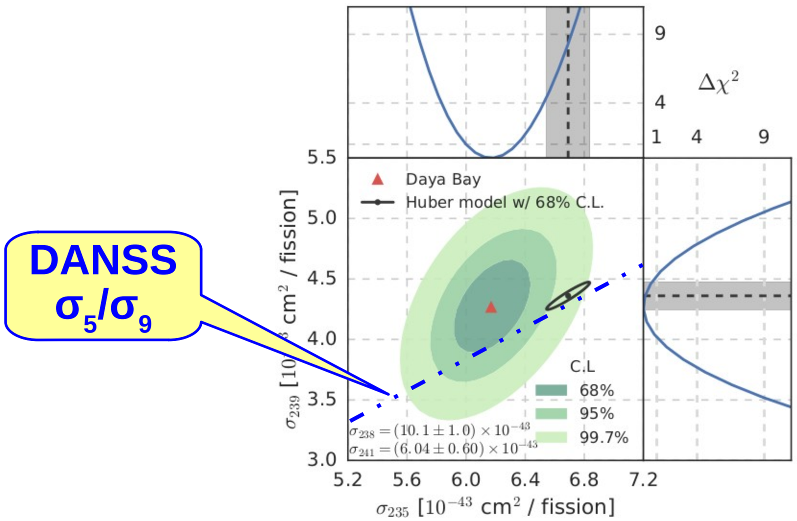
# Cross-section Ratio – Numbers

$$\frac{\sigma_5}{\sigma_9}=-\frac{\frac{\sigma_8}{\sigma_9}\left(Sl\cdot f_8-\frac{df_8}{df_9}\right)+\frac{\sigma_1}{\sigma_9}\left(Sl\cdot f_1-\frac{df_1}{df_9}\right)+\left(Sl\cdot f_9-1\right)}{Sl\cdot f_5-\frac{df_5}{df_9}}$$

$$\frac{0.152 + 0.420 + 1.120}{1.088} = \mathbf{1.555 \pm 0.052}$$

HM: 1.53 ± 0.05 DB: 1.445 ± 0.097

DB-Slope, our formula: 1.459 ± 0.052




Fractions $f_i$ taken at $f_9$=0.3, as in DB

Derivatives $df_i/df_9$ are slopes in linear fits

*Sl* = −0.3998±0.0246

Other cross-section ratios are from DB

Phys.Rev.Lett. 120 (2018) 2, 022503

| | DB[a] | Summation | H-M[b] |
|---|---|---|---|
| $\overline{\sigma}_f (10^{-43}\mathrm{cm}^2)$ | 5.9± 0.13 | 6.11 | 6.22±0.14 |
| $\frac{d\sigma_f}{dF_{239}} (10^{-43}\mathrm{cm}^2)$ | -1.86± 0.18 | -2.05 | -2.46±0.06 |
| $\sigma_5$ $(10^{-43}\mathrm{cm}^2)$ | 6.17± 0.17 | 6.49 | 6.69±0.15 |
| $\sigma_9$ $(10^{-43}\mathrm{cm}^2)$ | 4.27± 0.26 | 4.49 | 4.36±0.11 |
| $\sigma_8$ $(10^{-43}\mathrm{cm}^2)$ | 10.1±1.0 | 10.2 | 10.1±1.0 |
| $\sigma_4$ $(10^{-43}\mathrm{cm}^2)$ | 6.04±0.6 | 6.4 | 6.04±0.6 |
| $\sigma_5/\sigma_9$ | 1.445±0.097 | 1.445 | 1.53± 0.05 |

$\sigma_8/\sigma_9$=2.32±0.24 $\sigma_1/\sigma_9$=1.39±0.14

– All errors are included into the result

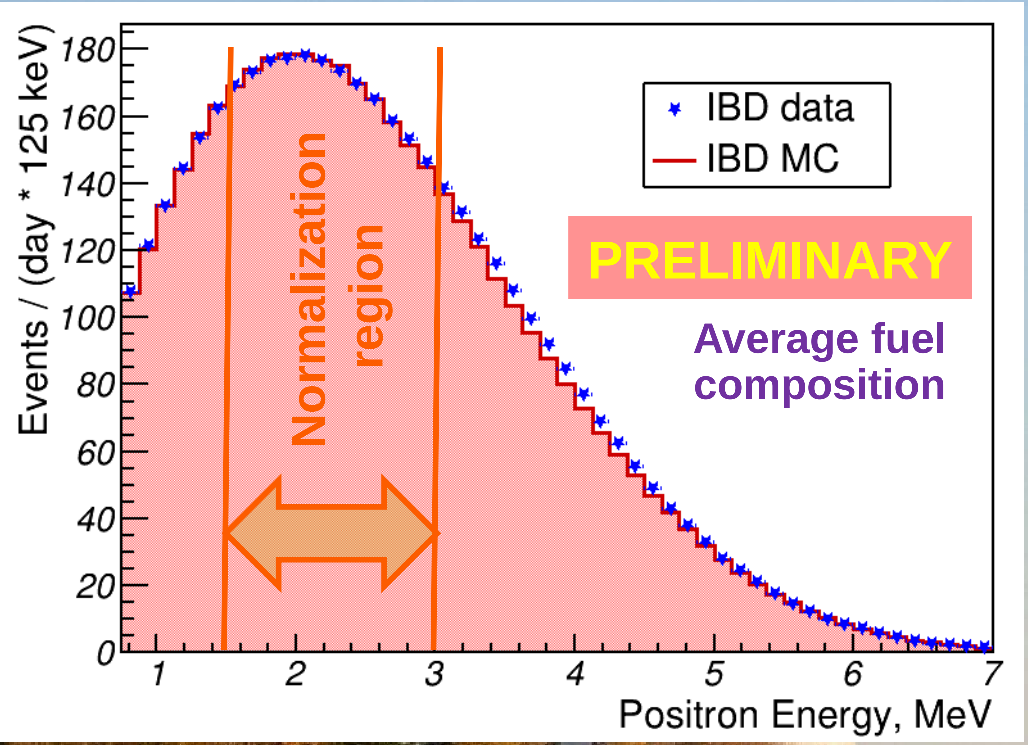
– Contributions from small fractions are not negligible

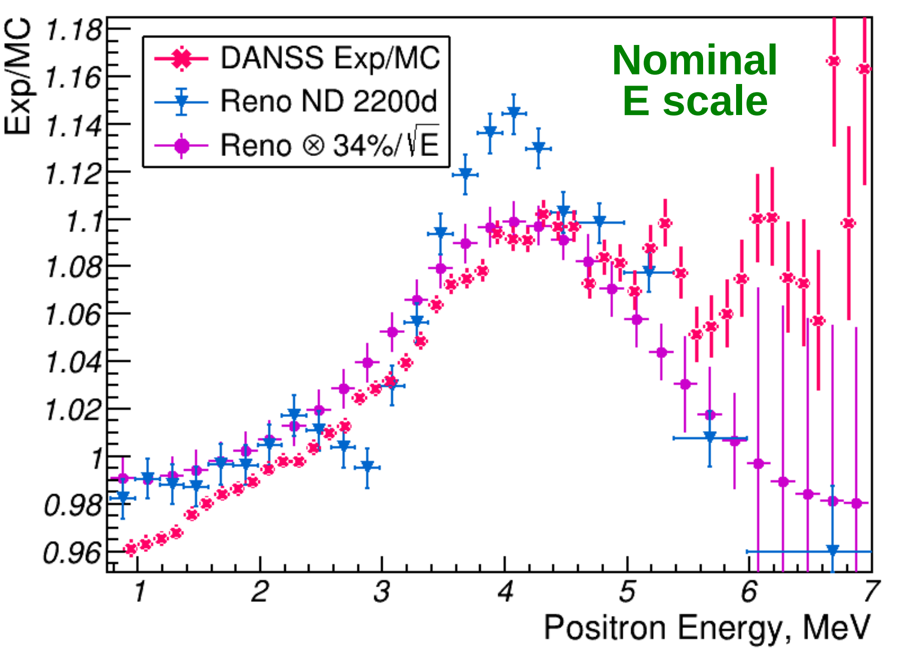
– Errors are smaller due to direct result

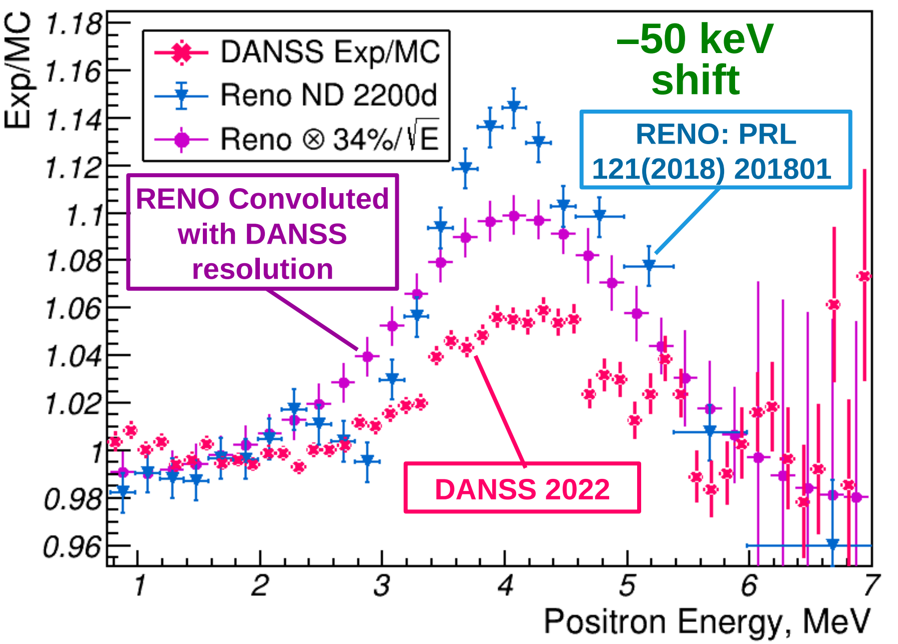
– DB slope gives good agreement

– DANSS result is closer to H-M and on the opposite side from DB

# The Bump: Experiment vs MC

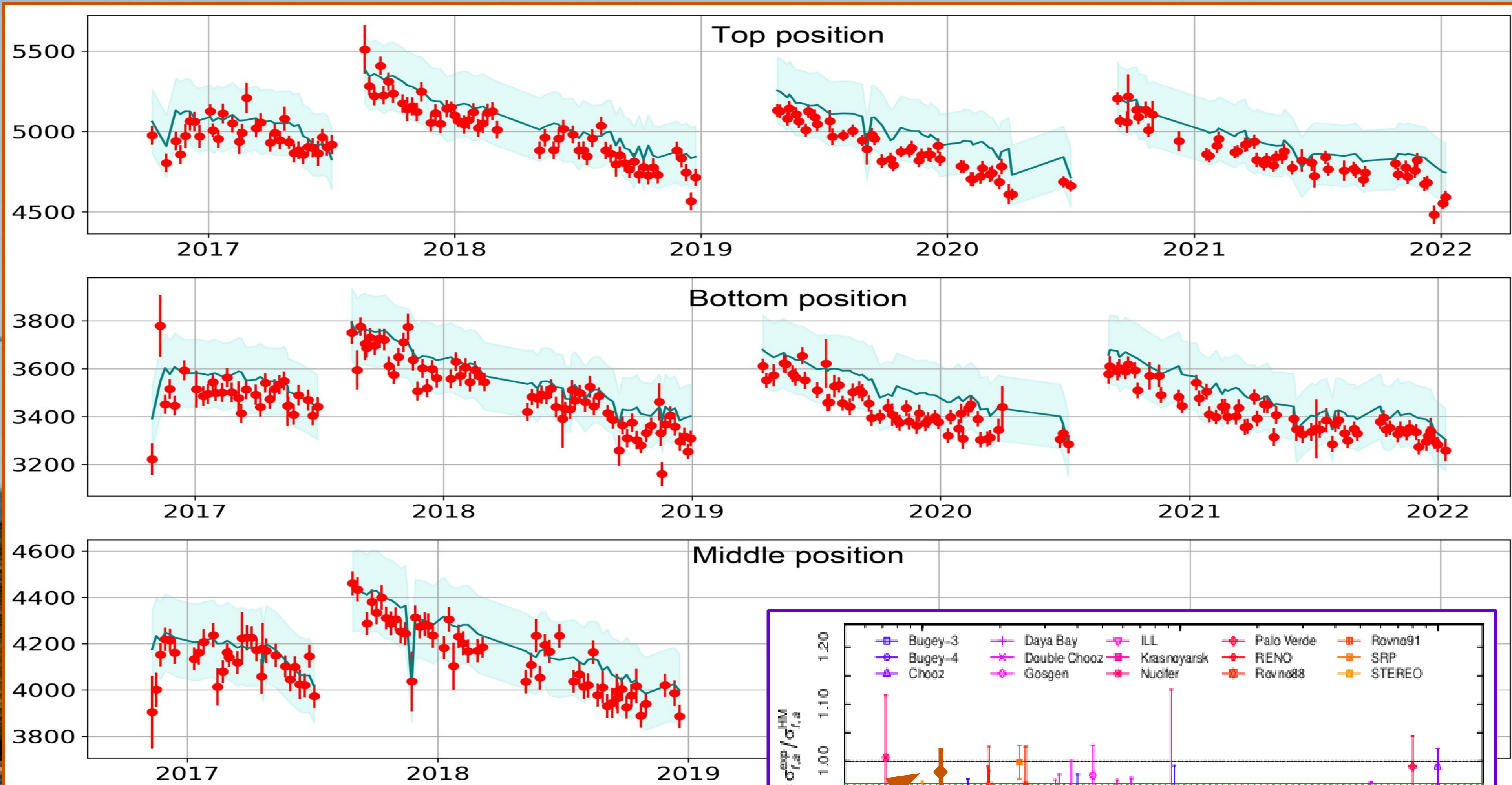


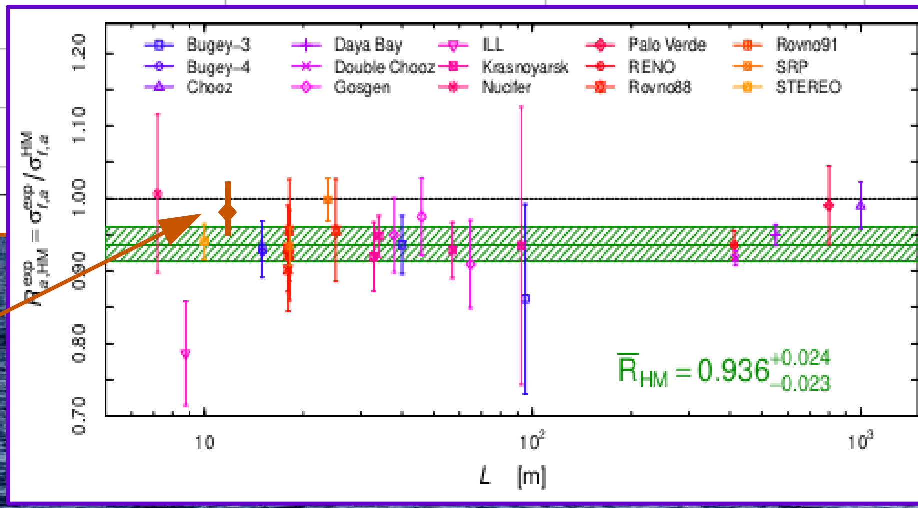




- Latest energy calibration
- Strong dependence on energy shift and scale
- Effect (if exists) looks twice smaller than expected from other measurements
- i.e. DANSS is closer to H-M than others

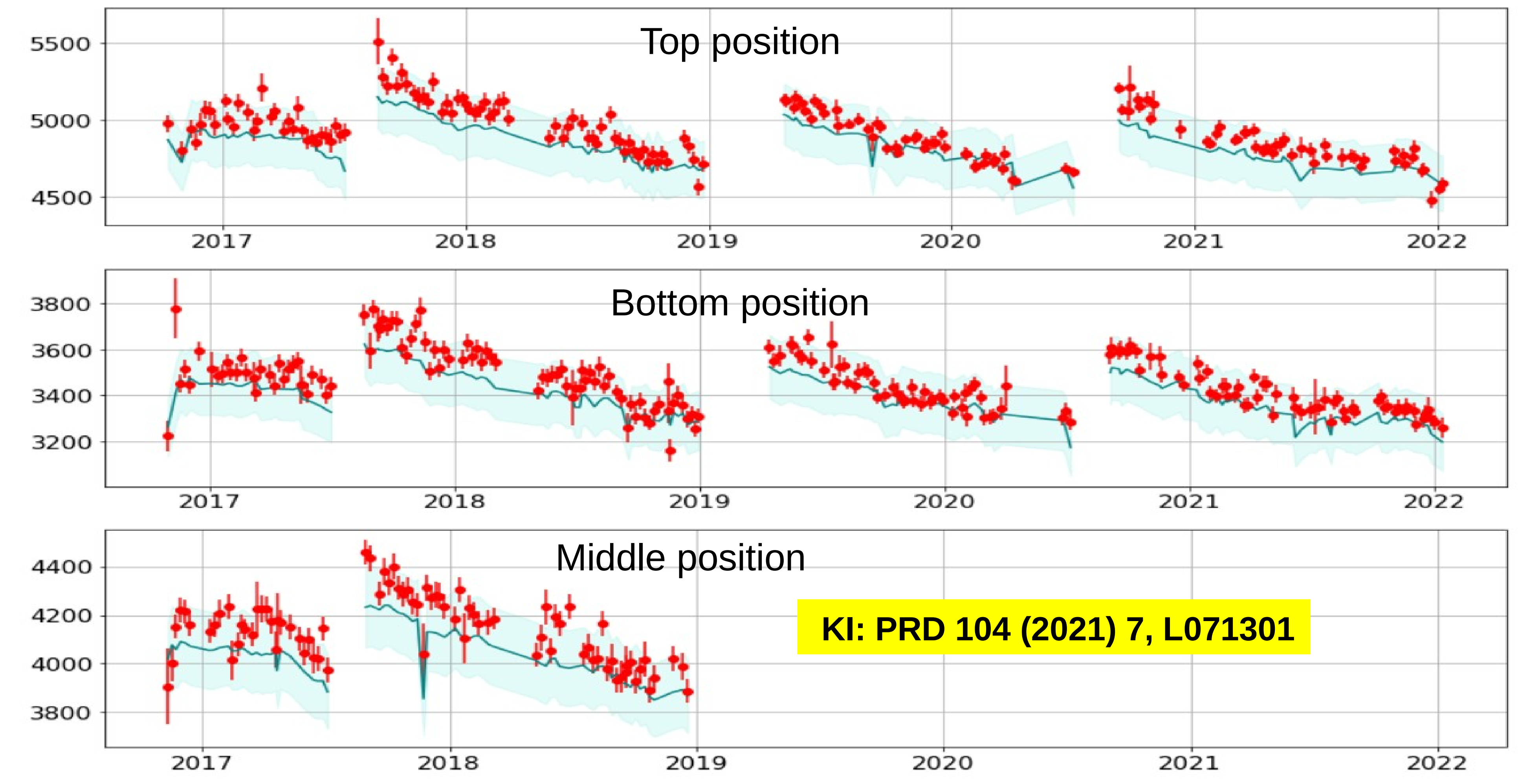
# First Steps towards Absolute Counts




- **DANSS results are below H-M predictions but within experimental uncertainties**
- **Average ratio: 0.98 ± 0.04**

# First Steps to Absolute Counts




- **Naturally, DANSS results are above KI predictions but within experimental uncertainties**
- **Not very informative**

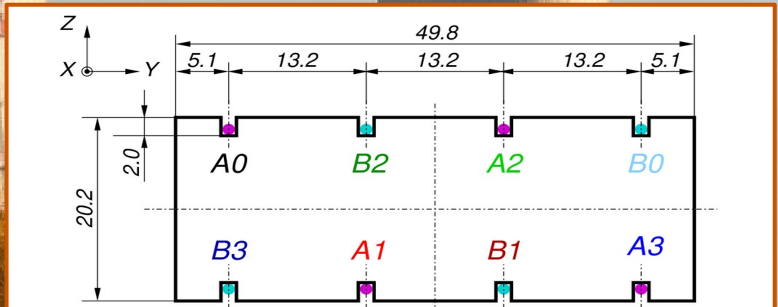
# Taking Data – Preparing Upgrade

**One but significant drawback:**

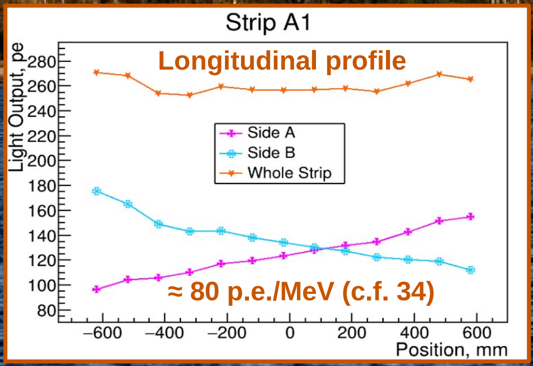
- Energy resolution 34% @ 1 MeV
- 18.9 (SiPM) + 15.3 (PMT) = 34.2 p.e./MeV, light collection nonuniformity 8% r.m.s.
- Other inhomogeneities, like fluctuations of Gd coating thickness
- Limits sensitivity to the sterile neutrino, though much is already achieved !

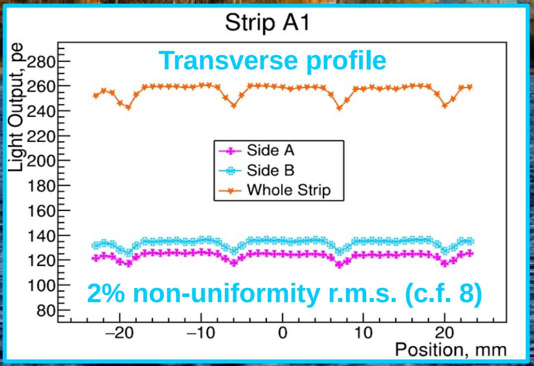
**Upgrade goals and expectations:**

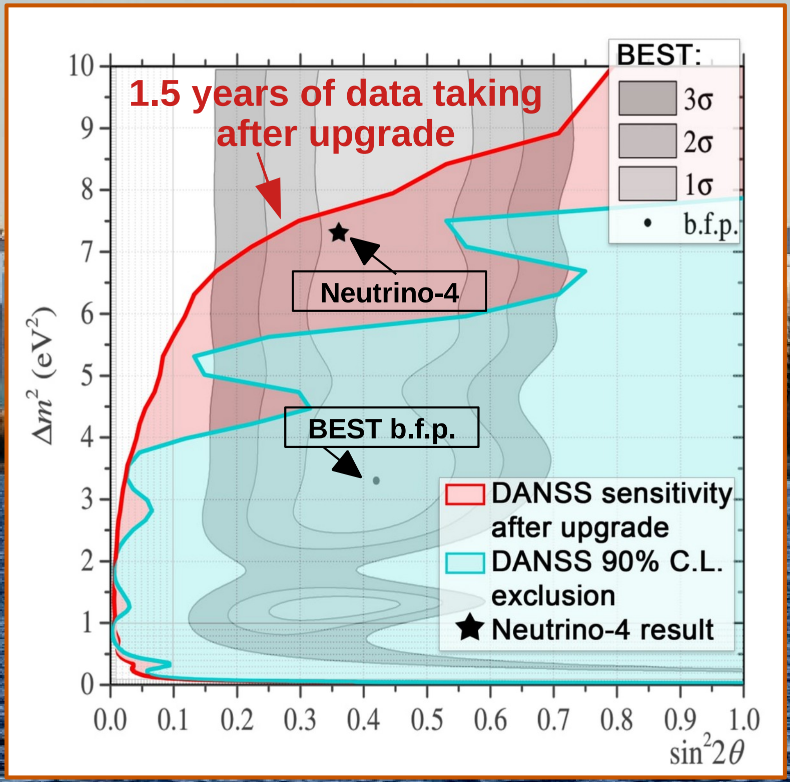
- Improve energy resolution to 12% @ 1MeV – expand sensitivity to higher $\Delta m^2$
- Increase sensitive volume – nearly x2 higher counting rates
- Longitudinal coordinate from timing – real 3D picture
- Probe Neutrino-4 and BEST results, already in 1.5 years of running



Strip cross-section with grooves and fibers



# Summary and Conclusions

- DANSS already recorded more tha 6 mln events and steadily continue taking data
- RAA+GA best point is deep in the exclusion region. 5σ exclusion already in 2018
- The FC best is not significant enough to claim indication of 4ν
- Several DANSS results indicate better agreement with H-M model than those from other experiments:
  - Reactor power monitoring is purely statistical after H-M correction
  - Fractional slopes and relative IBD yield are slightly more sensitive for the fuel evolution than DB, and closer to H-M predictions
  - Cross-section ratio $\sigma_5/\sigma_9$ coincide with H-M prediction, unlike DB
  - The bump, if any, is twice less pronounced than should be even with DANSS energy resolution
  - Absolute counts agree with H-M: average 0.98 ± 0.04 (very preliminary)
- Upgrade is under preparation with the main goal of 12%@1 MeV energy resolution
- New interesting things are coming !

# Thank you for your attention !