Energy resolution of the LZ detector for High-Energy Electronic Recoils

LIDINE 2022 conference

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on behalf of the LUX-ZEPLIN collaboration

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

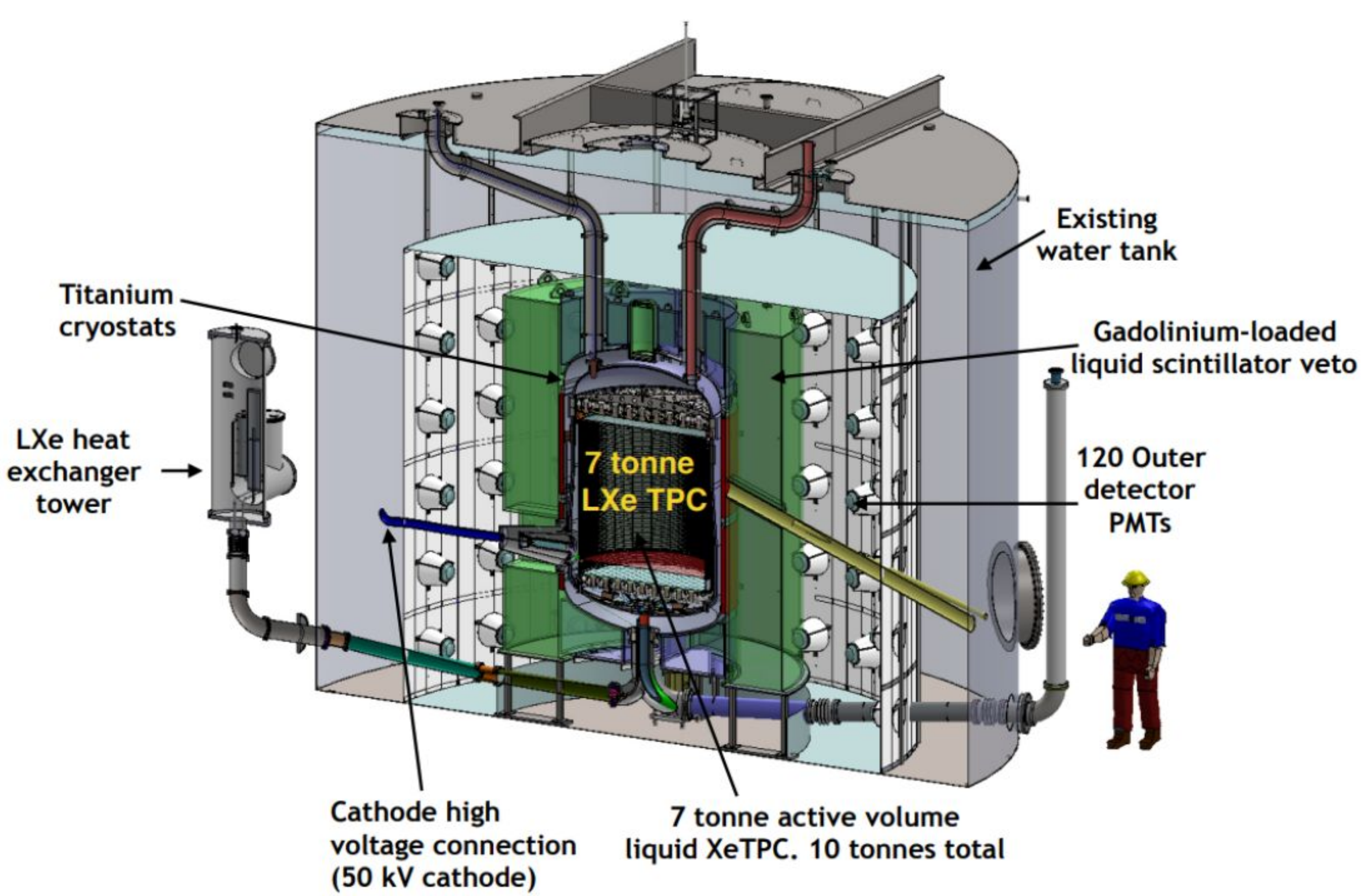
LZ Overview

Liquid Xenon TPC:

- 1.5 m diameter by 1.5 m height
- Active Mass: 7 t
  - 623 kg of ^{136}Xe
  - 741 kg of ^{134}Xe
- Fiducial: 5.6 t
- 494×3” PMTs

3 components veto detector:

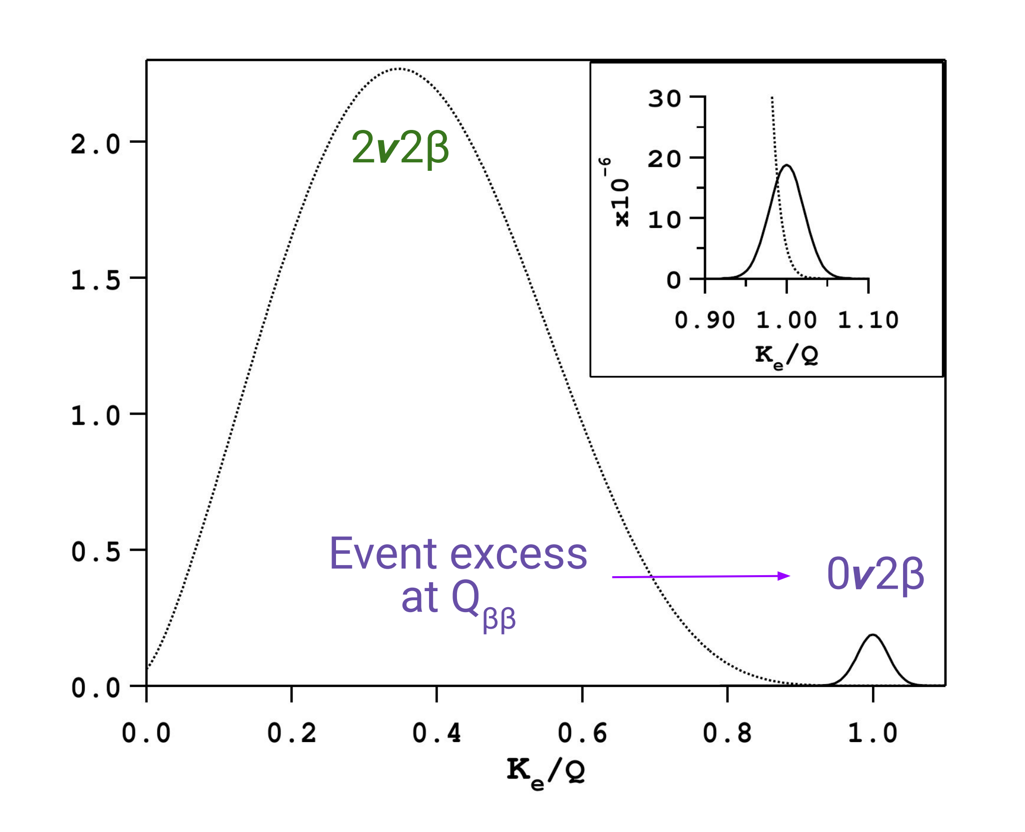
- Water Tank + Gadolinium-loaded scintillator
- Liquid Xe skin



LZ Scientific program

1. **WIMP search**
    - Better energy resolution
        - Better identification of the background sources
            - Better estimate for the background in the WIMP search region

2. **Neutrino physics searches**
    - $2\nu2\beta$ – $Q_{\beta\beta}$= 826 keV (^{134}Xe)
    - $0\nu2\beta$ – $Q_{\beta\beta}$= 2458 keV (^{136}Xe)



If a neutrinoless ($0\nu\beta\beta$) decay mode is measured then neutrinos are Majorana particles:

- Not yet observed;
- The two electrons carry the total energy of the decay, $Q_{\beta\beta}$;
- Look for the $0\nu\beta\beta$ decay by searching for an excess rate of events at $Q_{\beta\beta}$;

Better energy resolution for high energies ⇒ Improved sensitivity

Framework overview

XY position reconstruction

Mercury algorithm

Statistical method using LRFs (per PMT Light Response Functions)

New method for S2 Light Collection Correction

$$C_{lc}(x,y) = \frac{\sum_i \lambda_i(0{,}0)}{\sum_i \lambda_i(x{,}y)}$$

$\lambda_i(x,y)$ = *Light* ***R****esponse* ***F****unctions per PMT*

Valid for any subset of PMT
This work: S2 from the bottom array for energy reconstruction

S2 & S1 spatial corrections

Generated from Rn-222 alphas

Two easily identifiable α lines:

- 5.49 MeV (^{222}Rn -> ^{218}Po)
- 6.00 MeV (^{218}Po -> ^{214}Pb)

Uniform in the volume and with high S1 and S2 yield

Corrections consist in a linear combination of 2D and 3D Uniform cubic B-splines

PMT calibration

Non-invasive technique developed for ZEPLIN

- Time dependent corrections of gains
- Produced with Single Electron events
- Calibration outputs detected photons (phd) instead of photoelectrons (phe)

NEVES, F., et al. Calibration of photomultiplier arrays. *Astroparticle Physics*, 2010, 33.1: 13-18.

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Measure g1 and g2 with Doke method

LZ Energy Resolution

NEST simulation (Noble Element Simulation Techniques Collaboration)

S2 Corrections - Light Collection

$\boldsymbol{S2}$ = S2raw_area_phd × $C_{elt}(t_d, \tau)$ × $C_{lc}(x,y)$ × $C_y(x,y)$

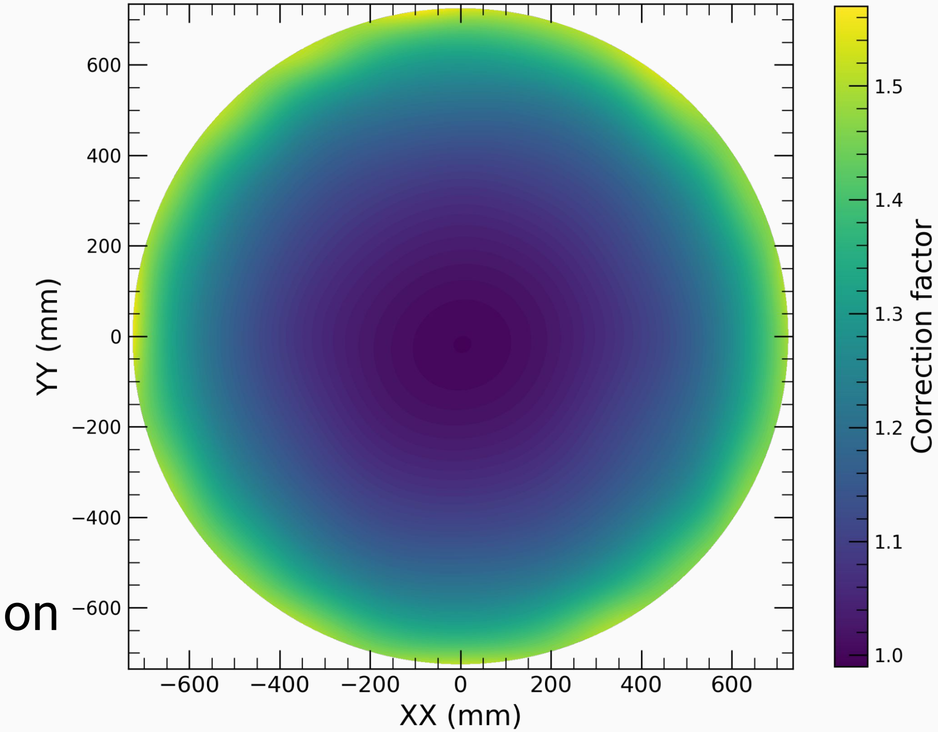
- C_{elt} - Electron lifetime
- **C_{lc} - Light collection efficiency**
- C_y - S2 yield (electron extraction and electroluminescence efficiency)

- Calculated as a ratio of sums of S2 LRFs in the following way

$$C(x,y) = \frac{\sum_i \lambda_i(0{,}0)}{\sum_i \lambda_i(x{,}y)}$$

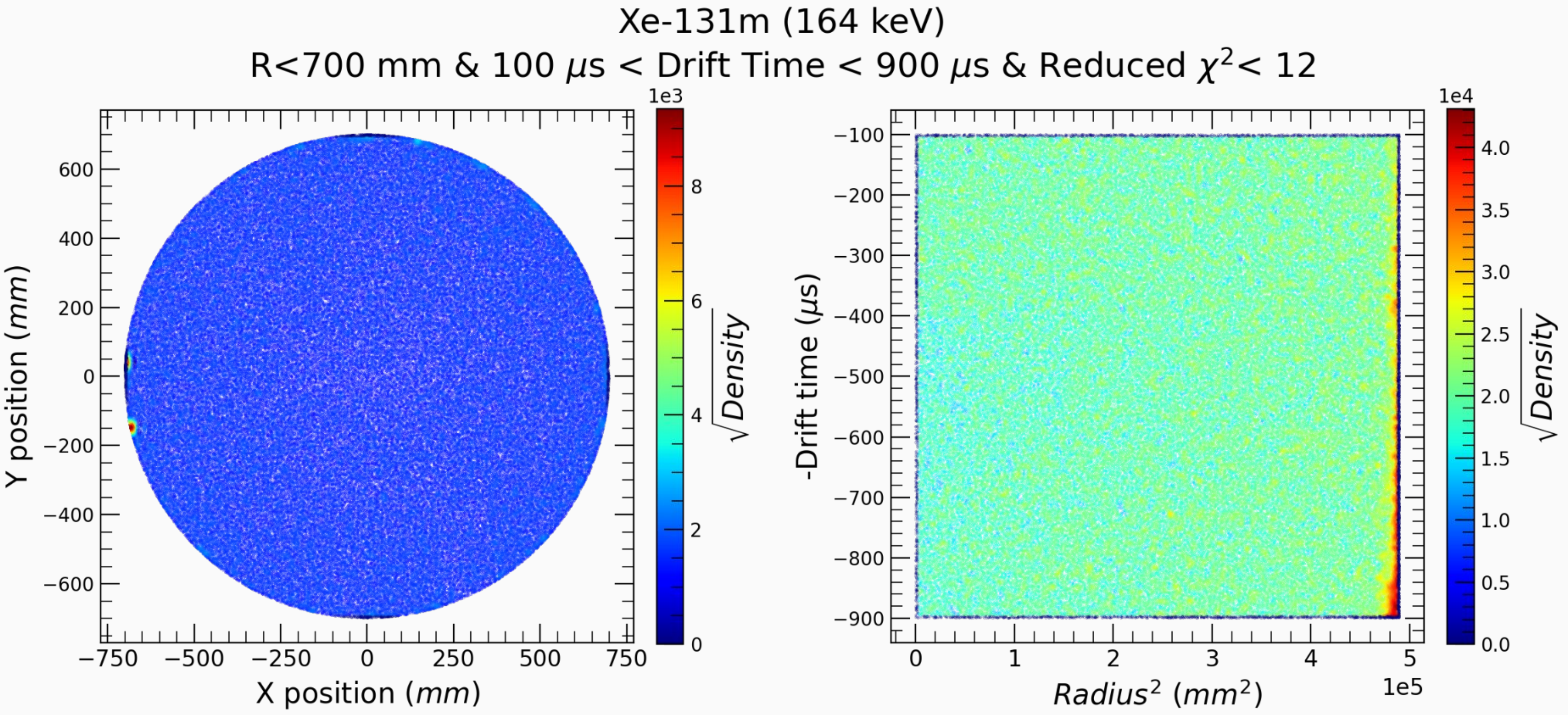
The subsets can be also made dynamic, varying from event to event.
Eg: dynamically exclude disabled PMTs

S2 bottom LC correction



Position reconstruction results

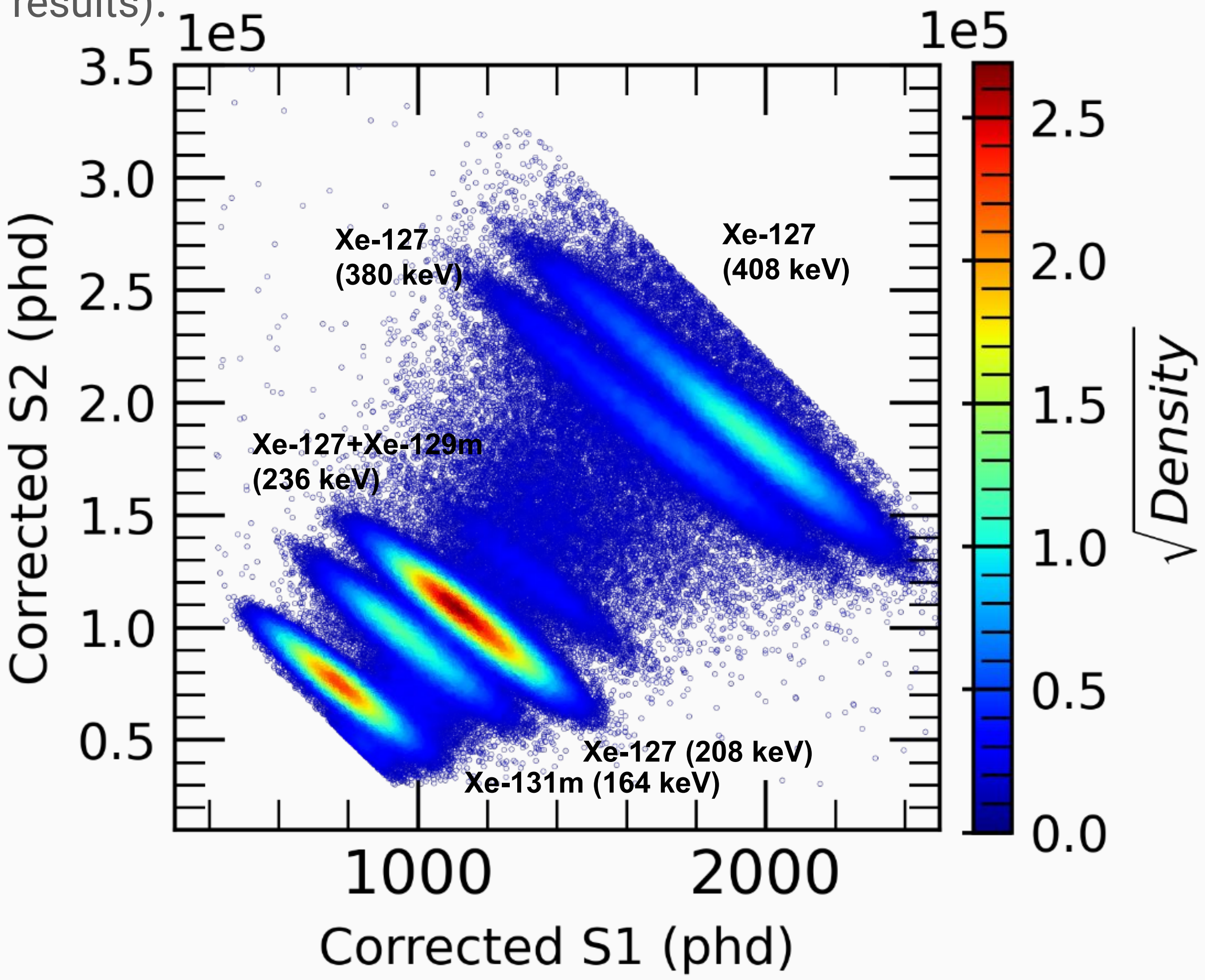
- Events uniform inside the TPC
- Two hotspots on the left – activity from two resistors located at the bottom of the detector

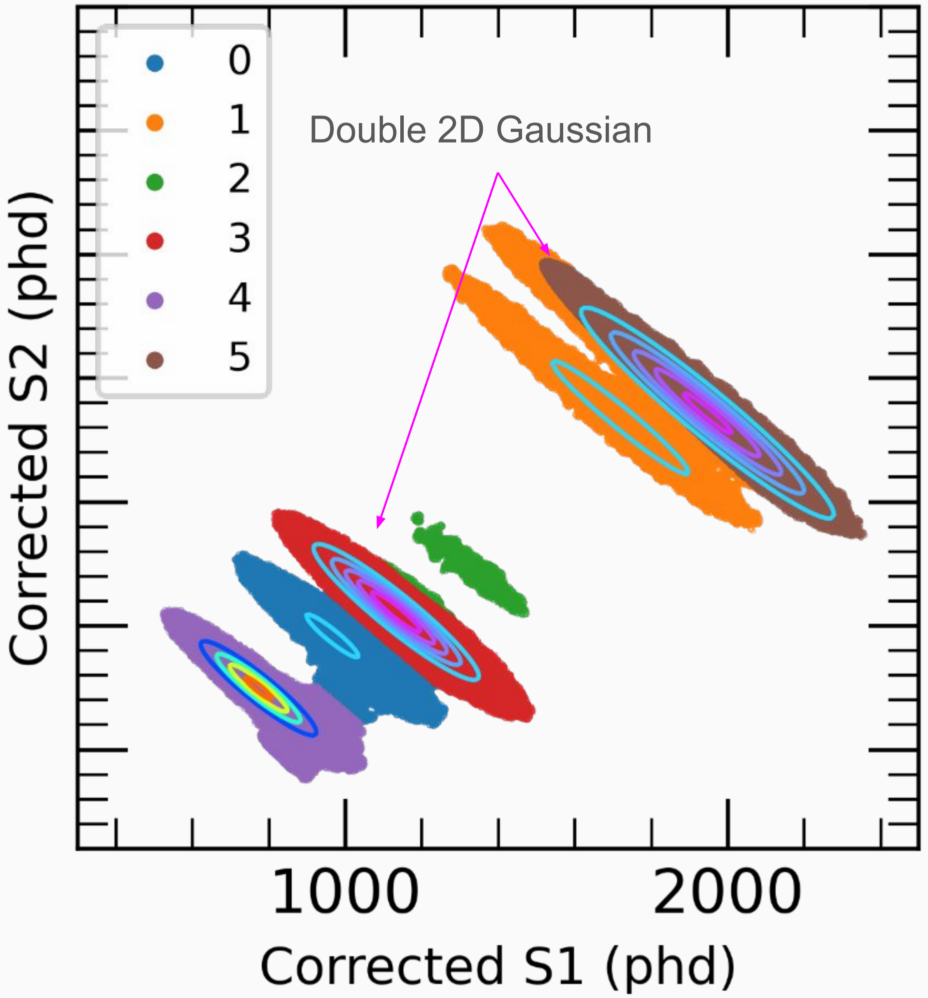


- Scatter plots with the color representing the interpolation of the respective 2D histogram bins – per event density

Doke plot - measure g1 and g2

- **S2 bottom only**
- Density cuts (clean clusters) + Gaussian Mixture Model (initial guess) + 2D Gaussian Fitting (final results).





Doke plot - measure g1 and g2

$$E = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

Valid only for Electronic Recoils

$$W = 0.0135\ keV$$

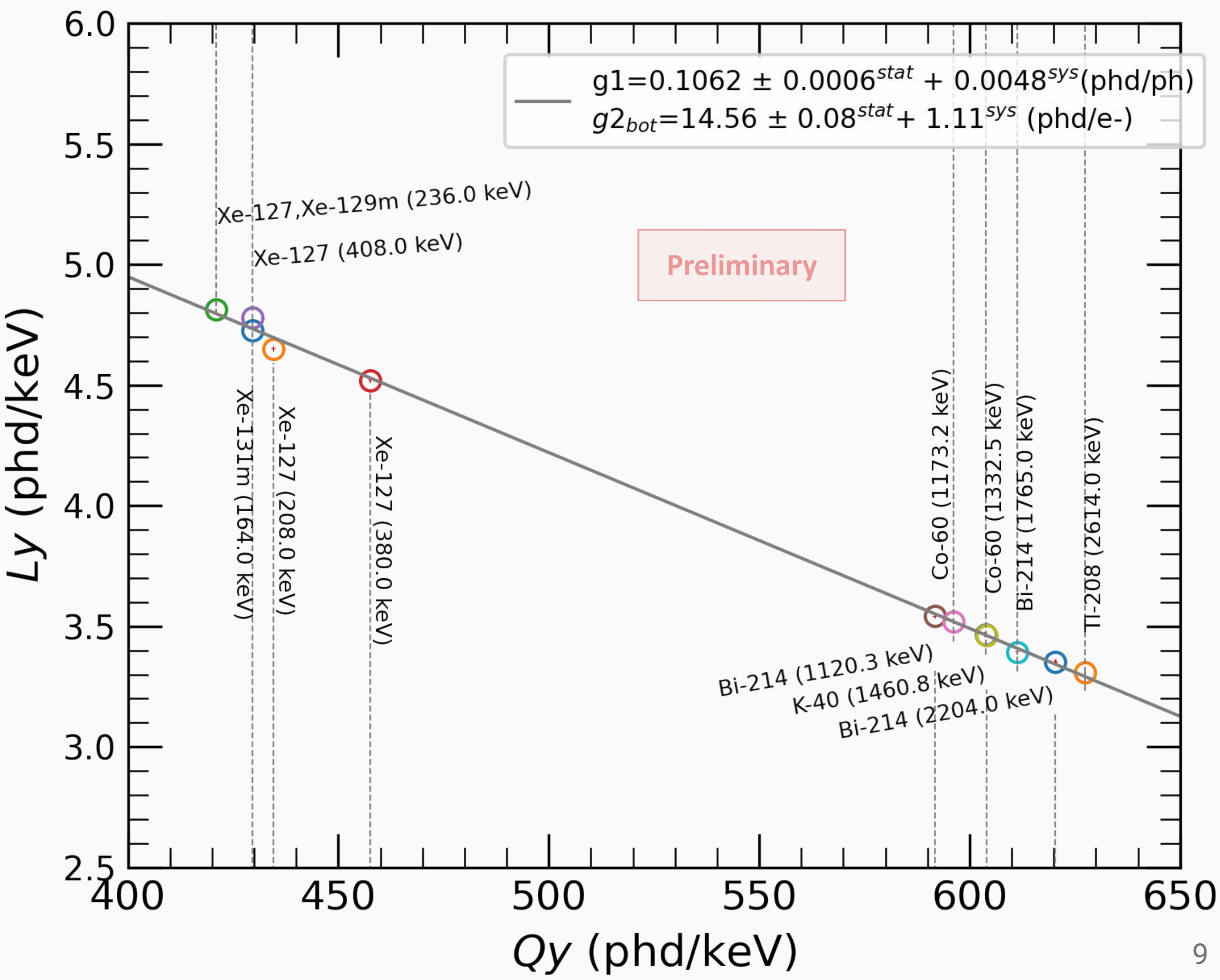
$$T = 174.1\ K; P = 1.791\ bara$$

$(Xenon\ working\ conditions)$

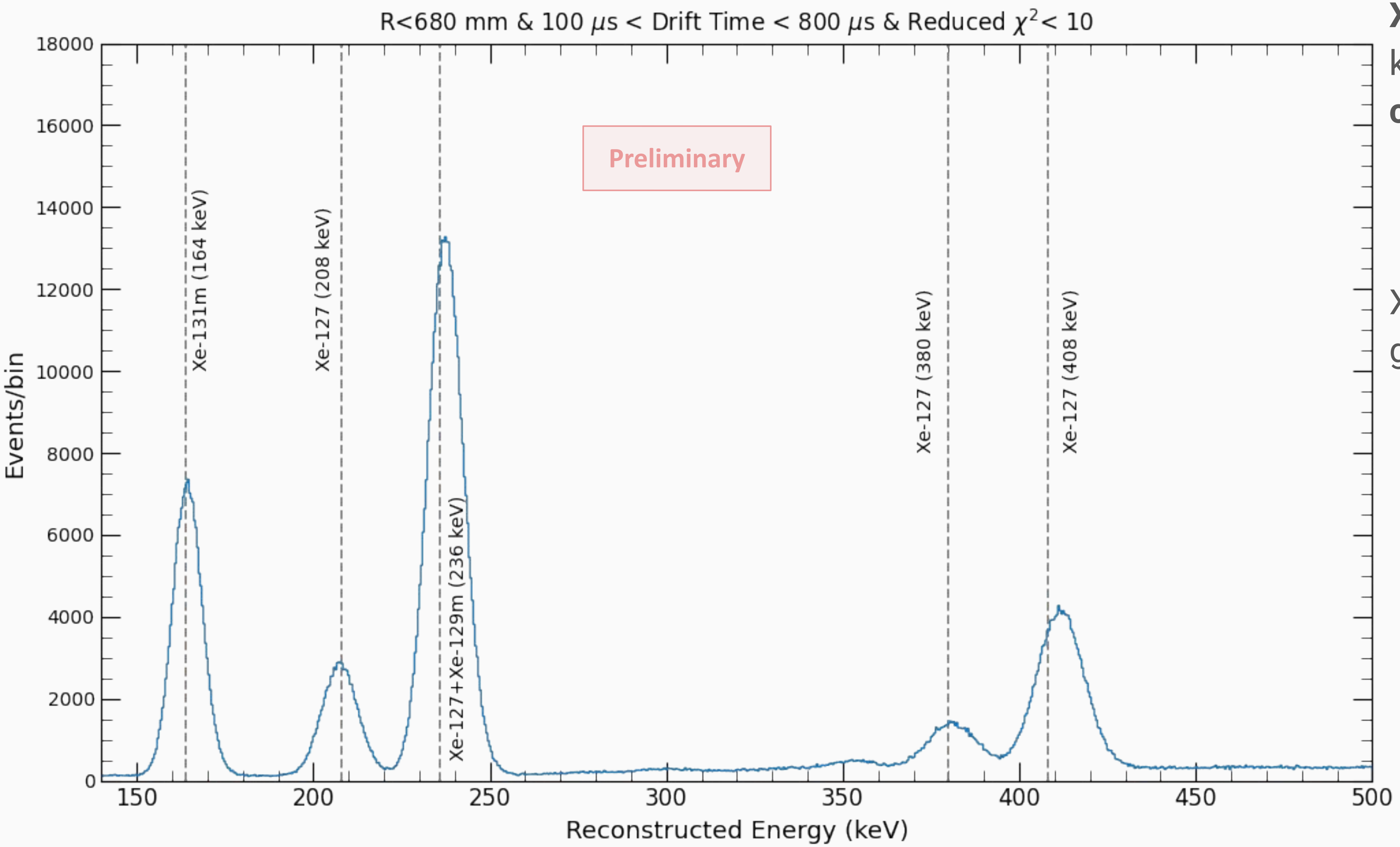
- Error bars calculated from the covariance matrix of the fit algorithm (sklearn curve_fit)
- Systematic calculated by splitting the doke in low and high energies.

Xe-127 EC+X-ray multi step processes cause a slight disagreement in the Doke fit

- to further explore through analysis of multi-scatter events



Energy spectrum

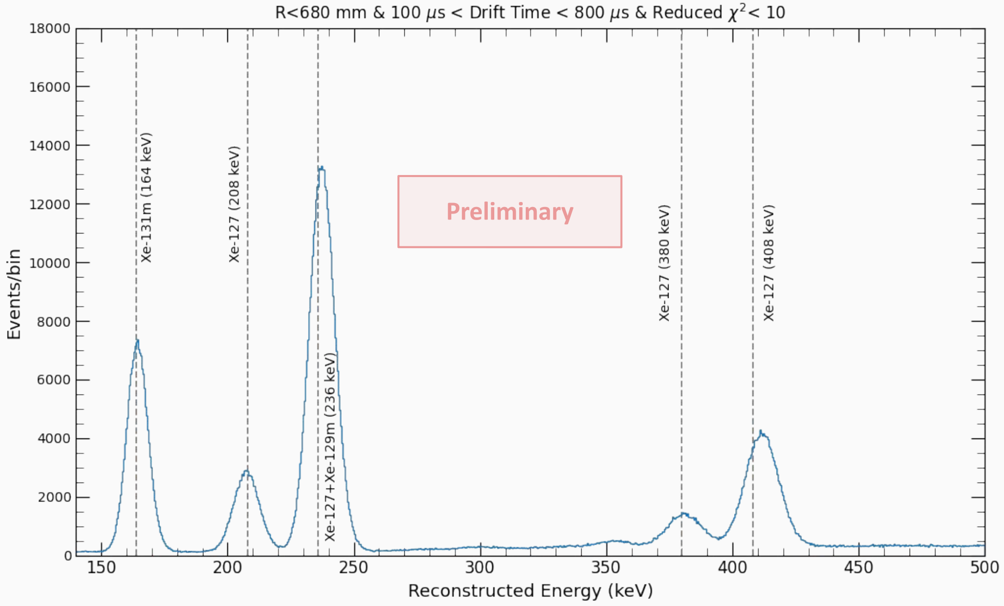


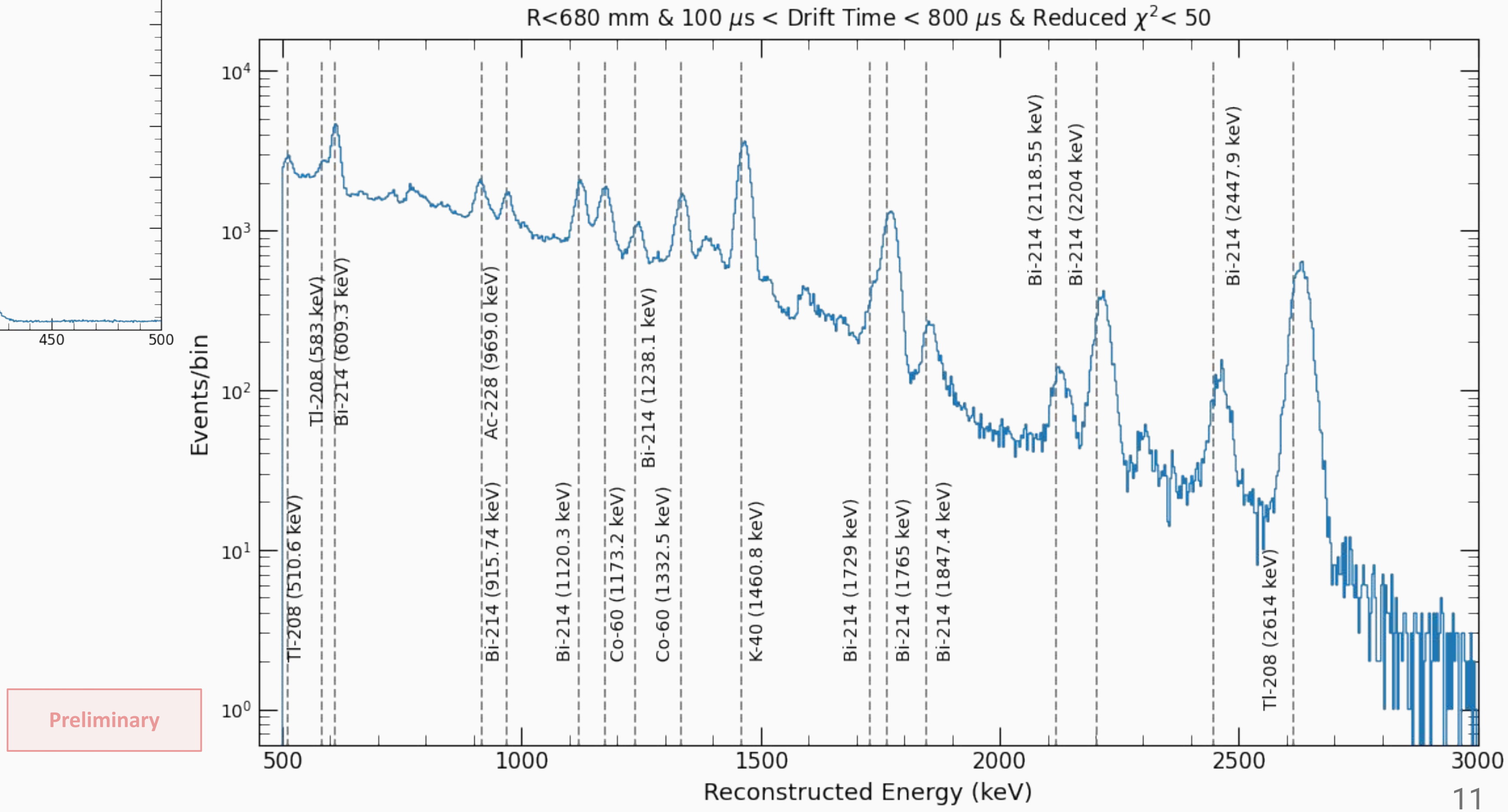
Xe-127 L lines (208.2 keV and 380 keV) have an **unresolved M shell contribution**.

- Its effects are handled in the final energy resolution results

X^2 = xy reconstruction goodness-of-fit

Energy spectrum

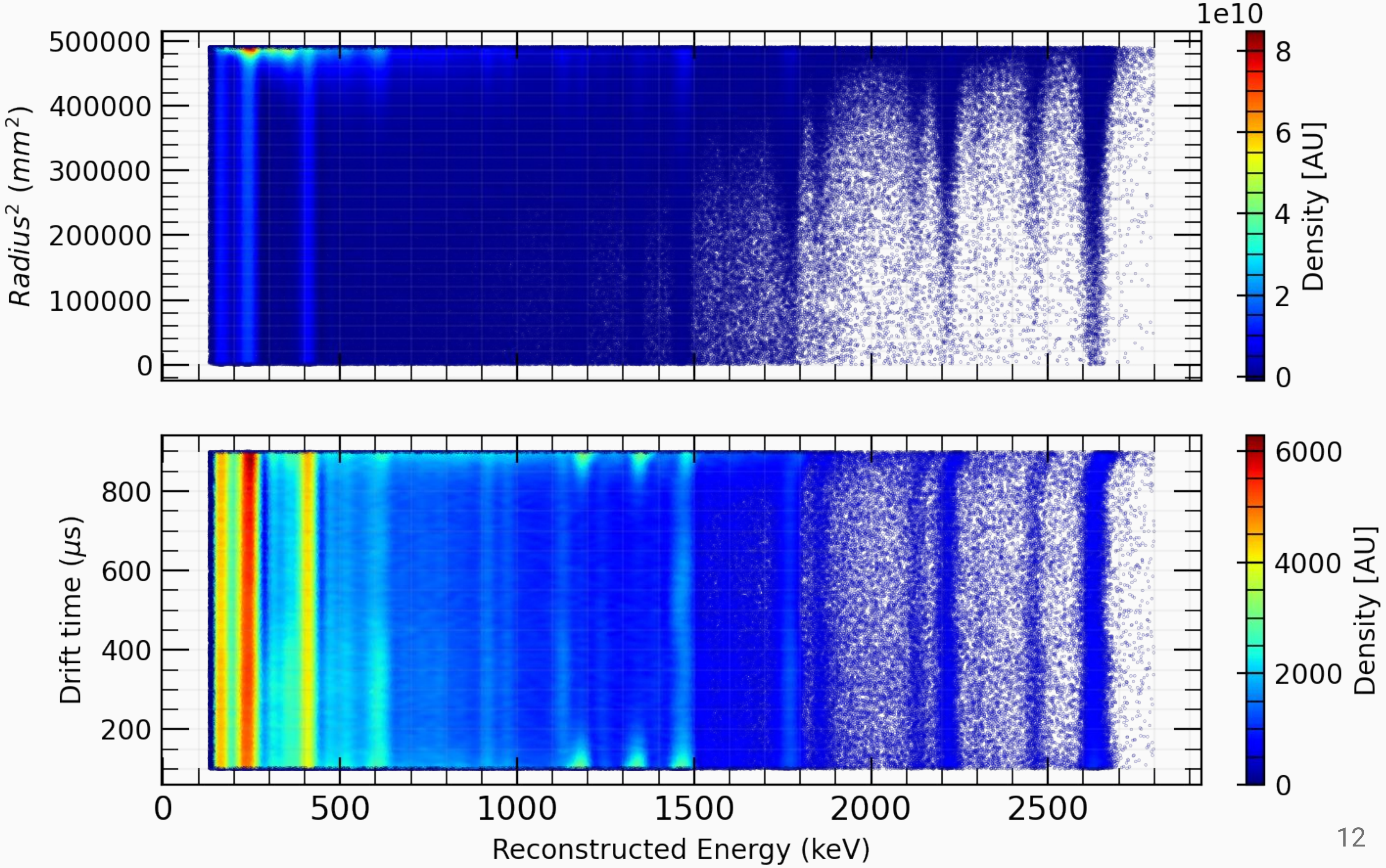




Energy spatial dependency

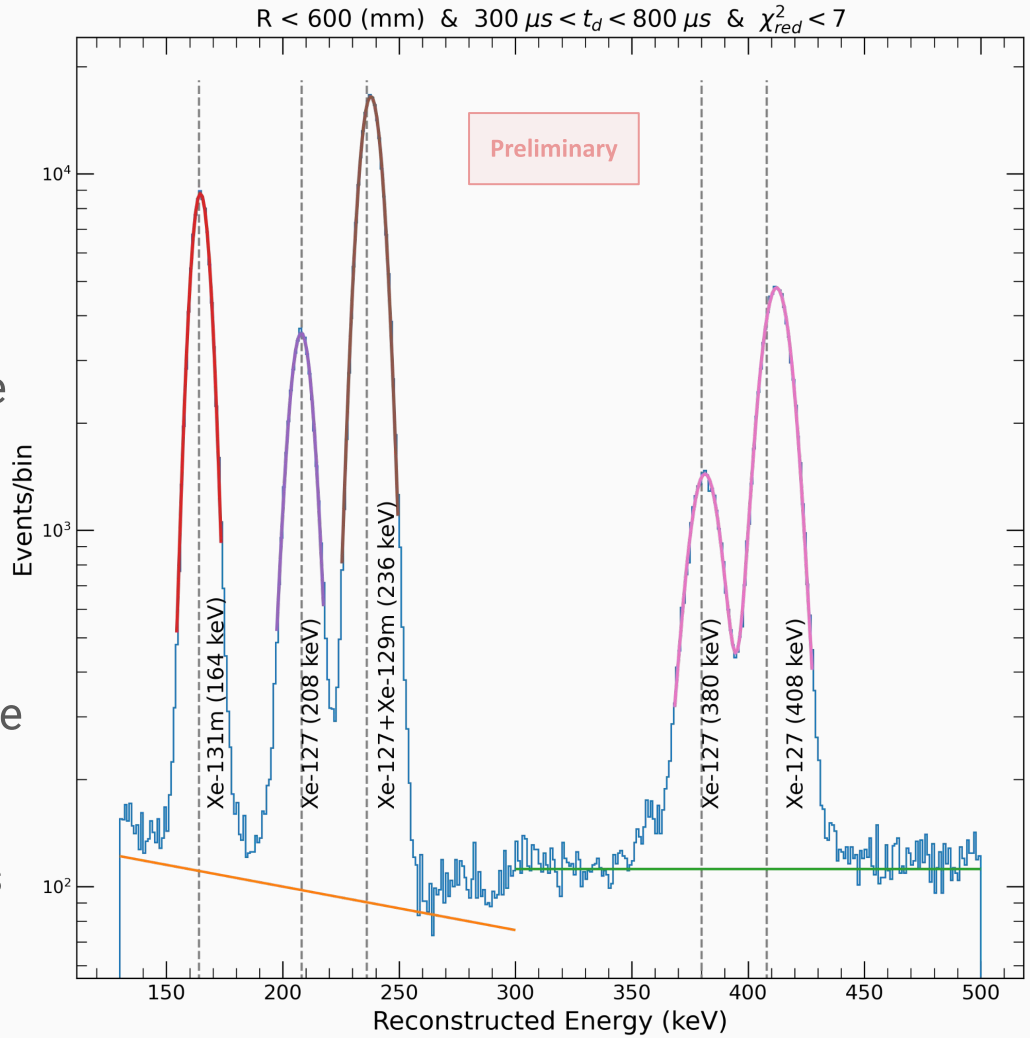
Demonstration of the detector spatial stability

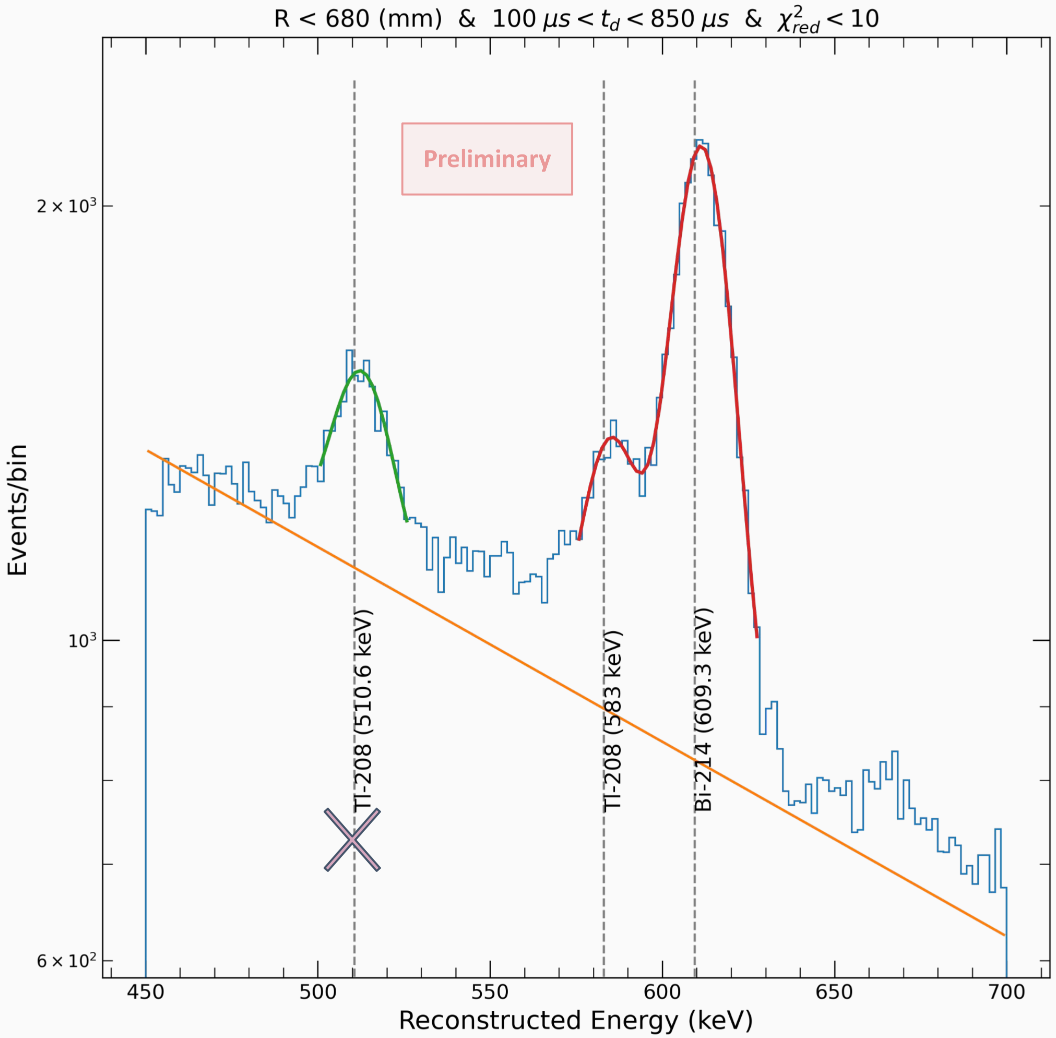
- Small deviation towards the bottom (high drift time) of the detector probably due to overestimation of S2 tail and a non-uniform mixing of liquid Xe.



Energy spectrum in 100—700 keV range

- Peaks fitted with gaussian
- Simple background model with exponential curve
- Peaks with **low statistics not included** due to unknown contribution of the background and associated systematic errors



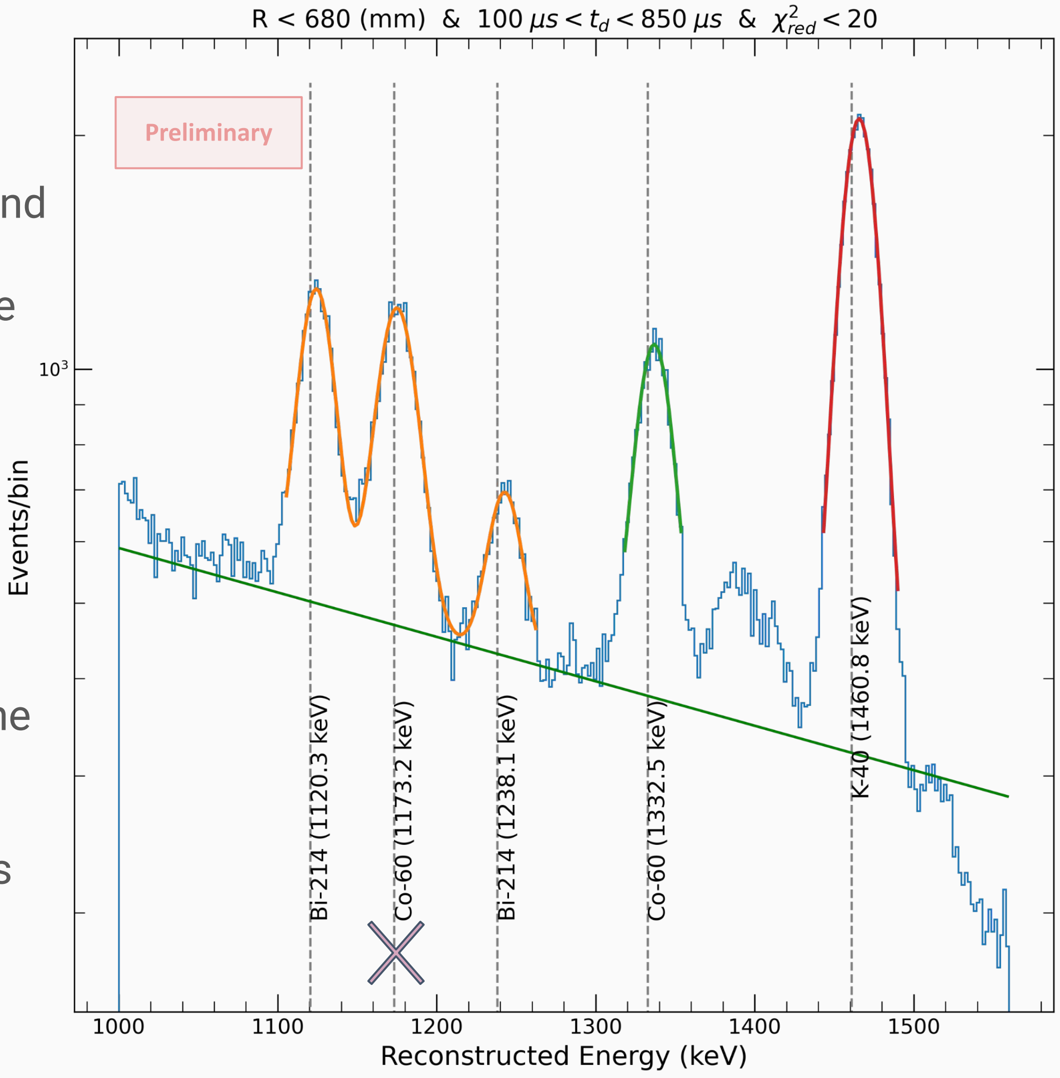


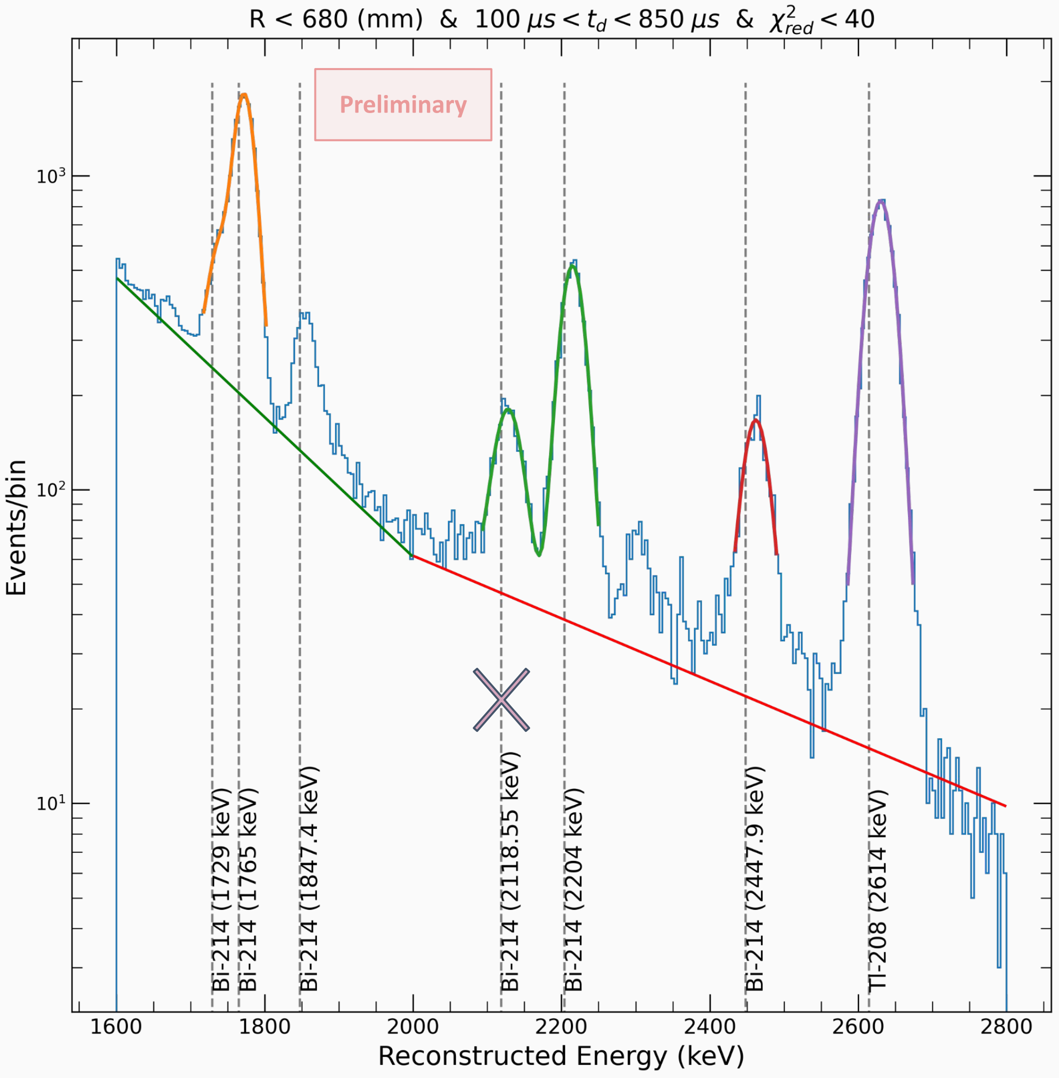
X_{red}^2 = position reconstruction goodness of fit (same as X^2)

X = Not included in final result

Energy spectrum in 1—2.8 MeV range

- Peaks fitted with gaussians
- Simple background model with exponential curve
- Peaks with **low statistics not included** due to unknown contribution of the background and associated systematic errors

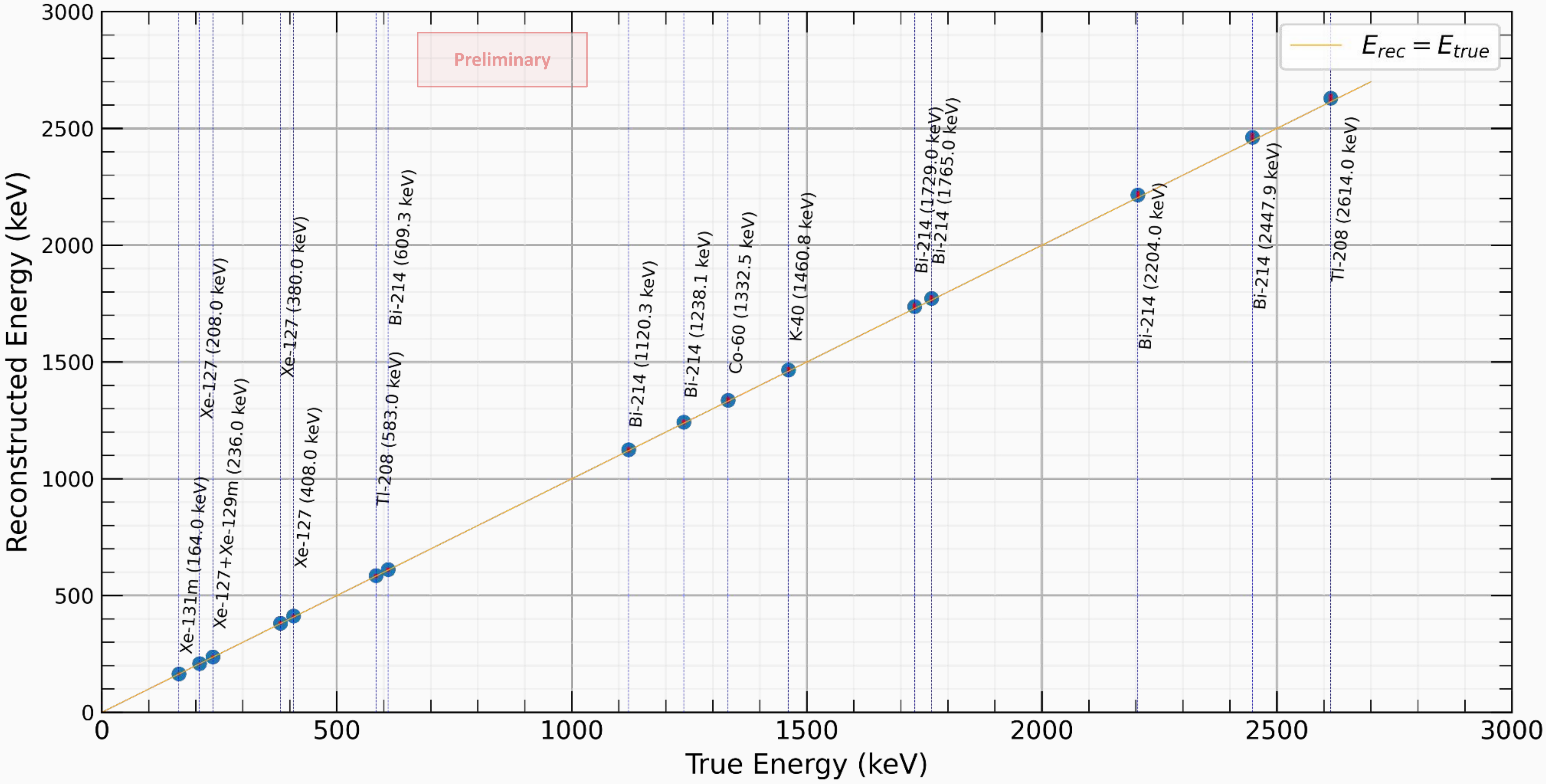




= Not included in final result

Energy Reconstruction

- Reconstructed energy **linearity within 1%** w.r.t. true energy



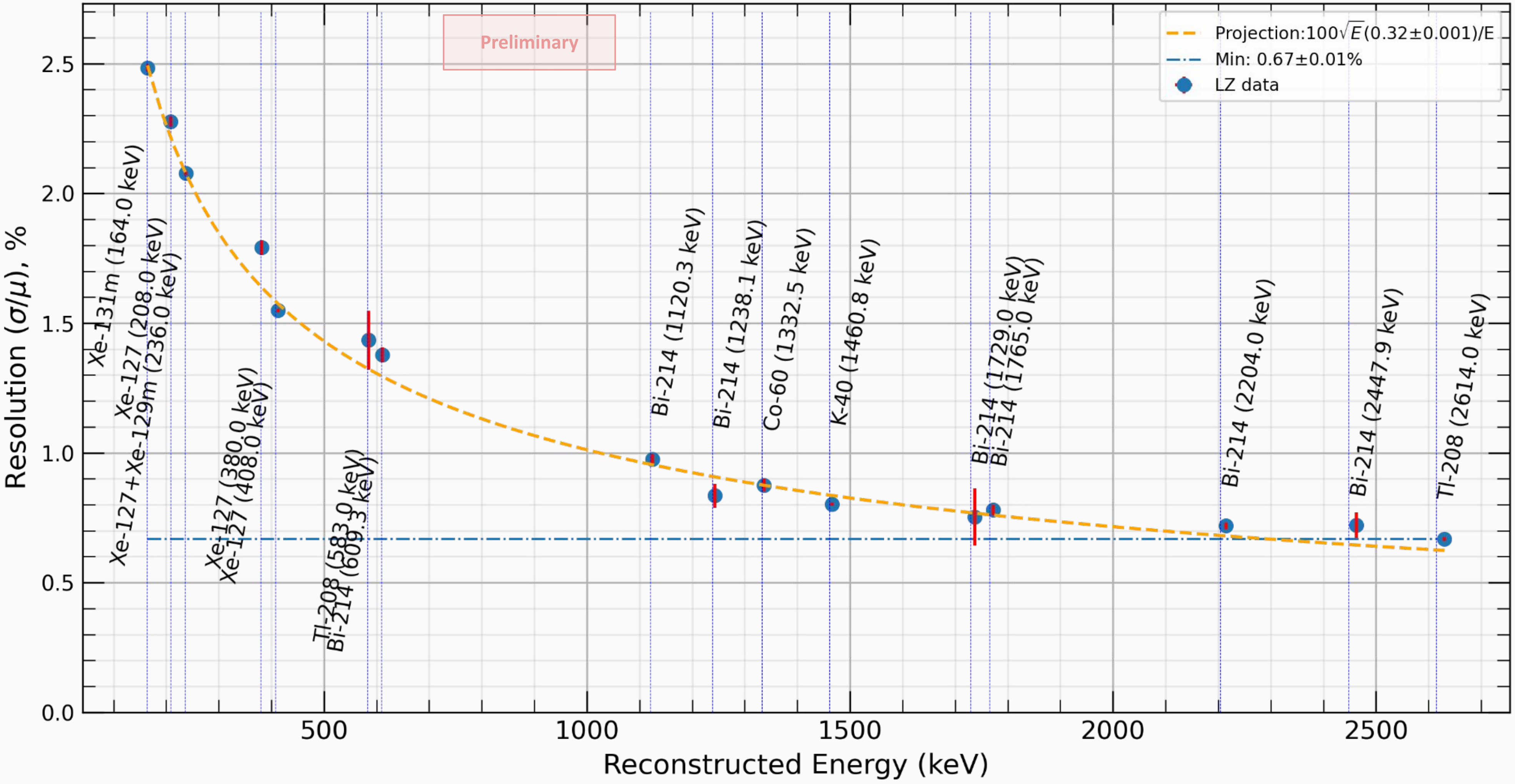
Energy Resolution

To our best knowledge, we obtain an unprecedented energy resolution for LXe at high energies.

0.67 ± 0.01 % for Tl-208 (2.614 MeV)

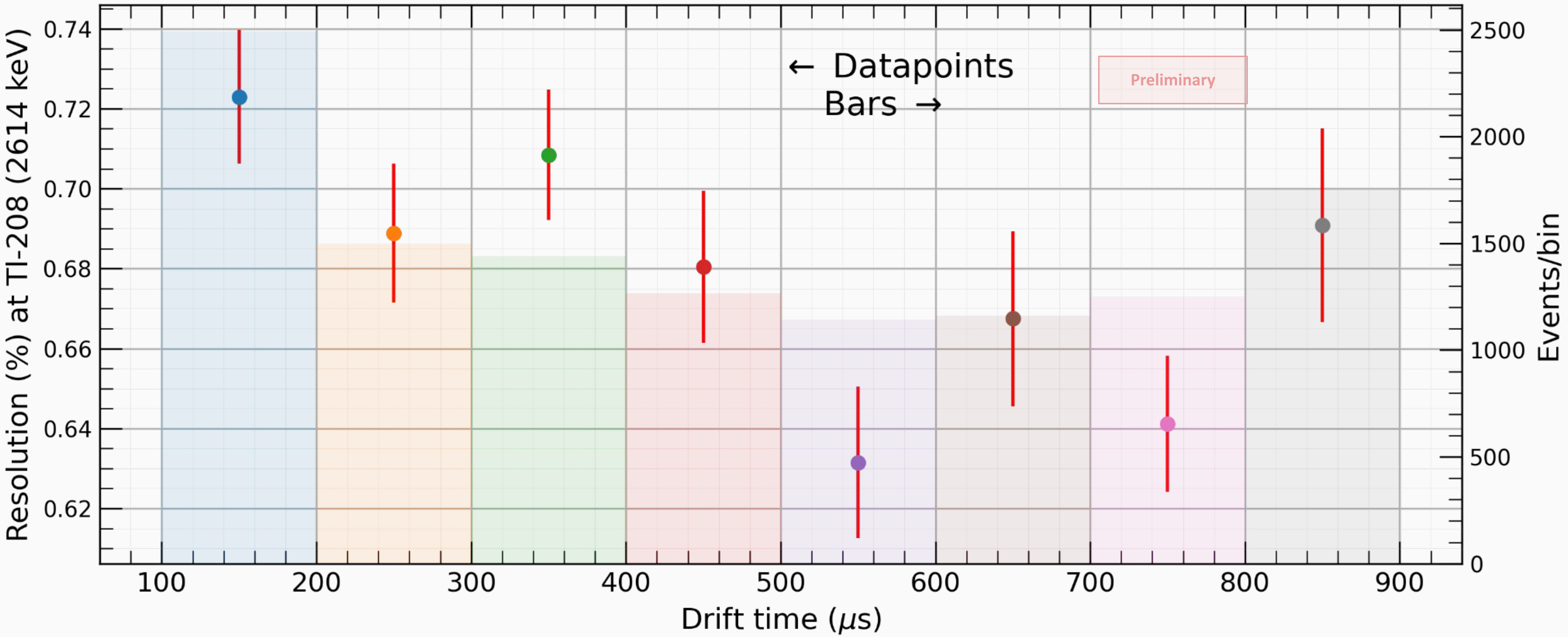
Projection line calculated from fit on experimental data

$$\sigma = K\sqrt{E}$$
$$K = 0.320 \pm 0.001$$



Energy Resolution vs depth

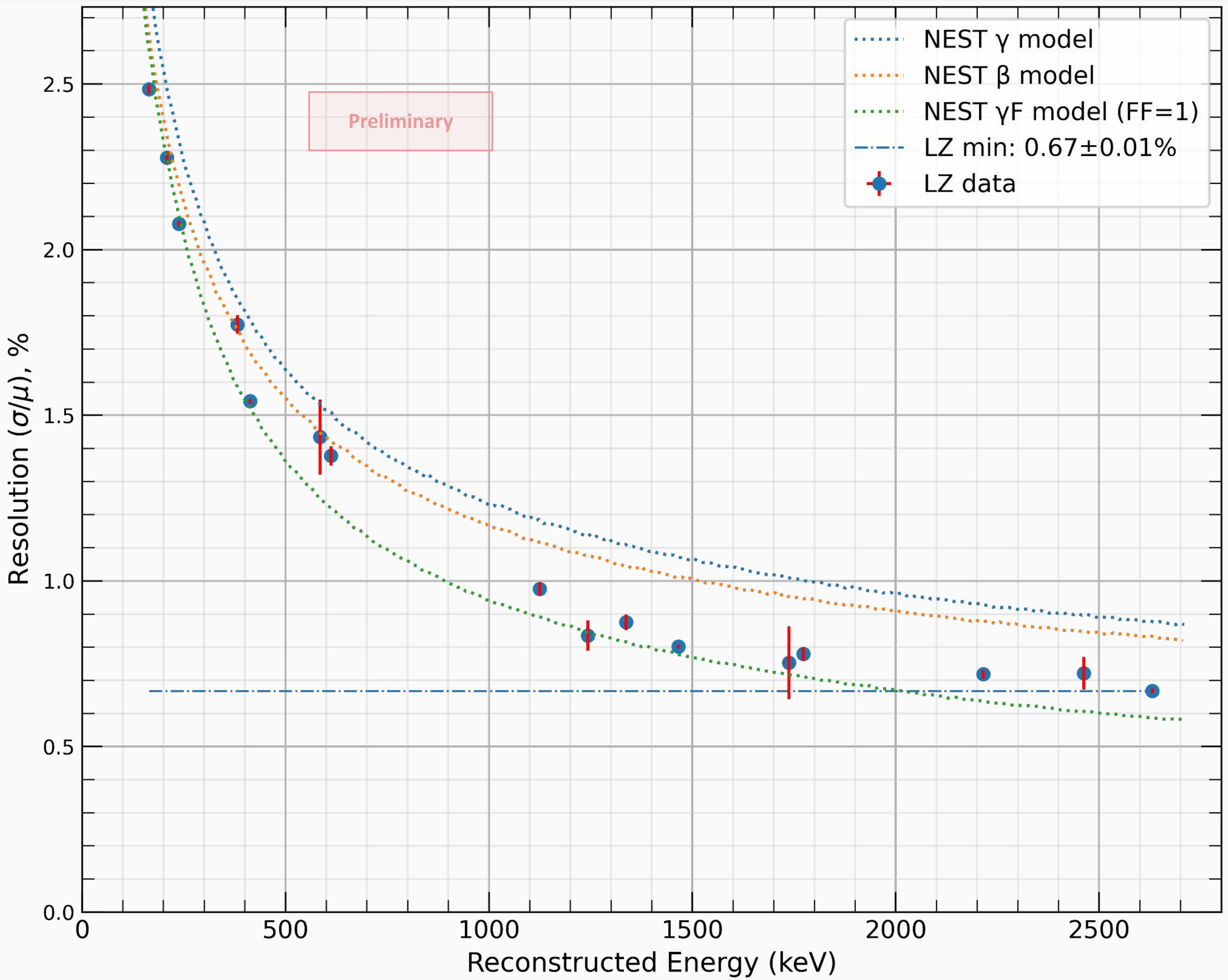
- Study of effects leading to depth-dependent variations of the resolution is still in progress



Comparing with NEST

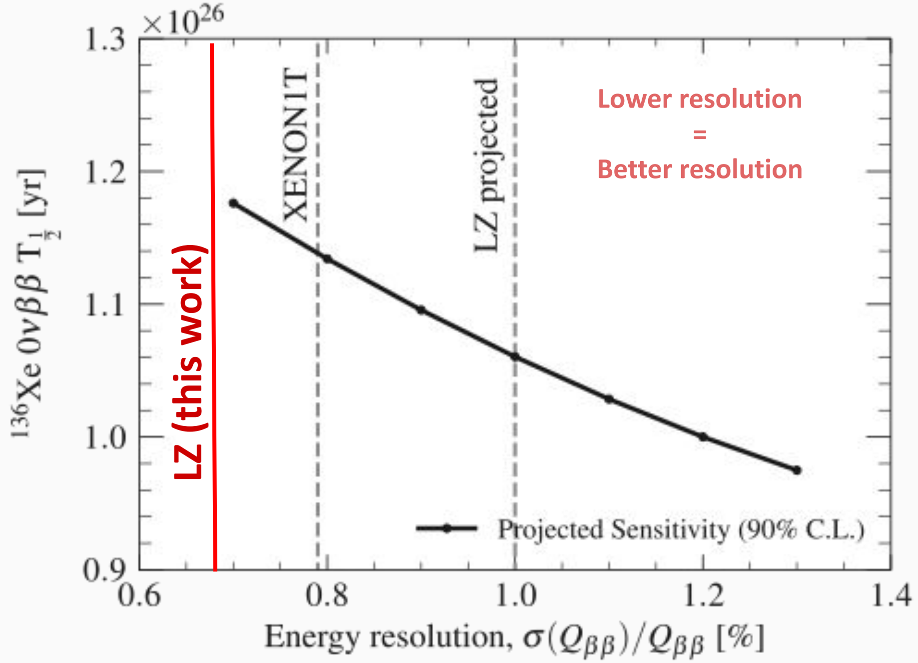
- Parameters used in NEST simulation ([v2.3.5]):
  - g1: 0.1057 phd/ph
  - E field gas = 8.1956 kV/cm

- NEST γF model assumes a Fano factor (FF) of 1:
  - Initial fluctuations of the S1 and S2 given by a Poisson distribution

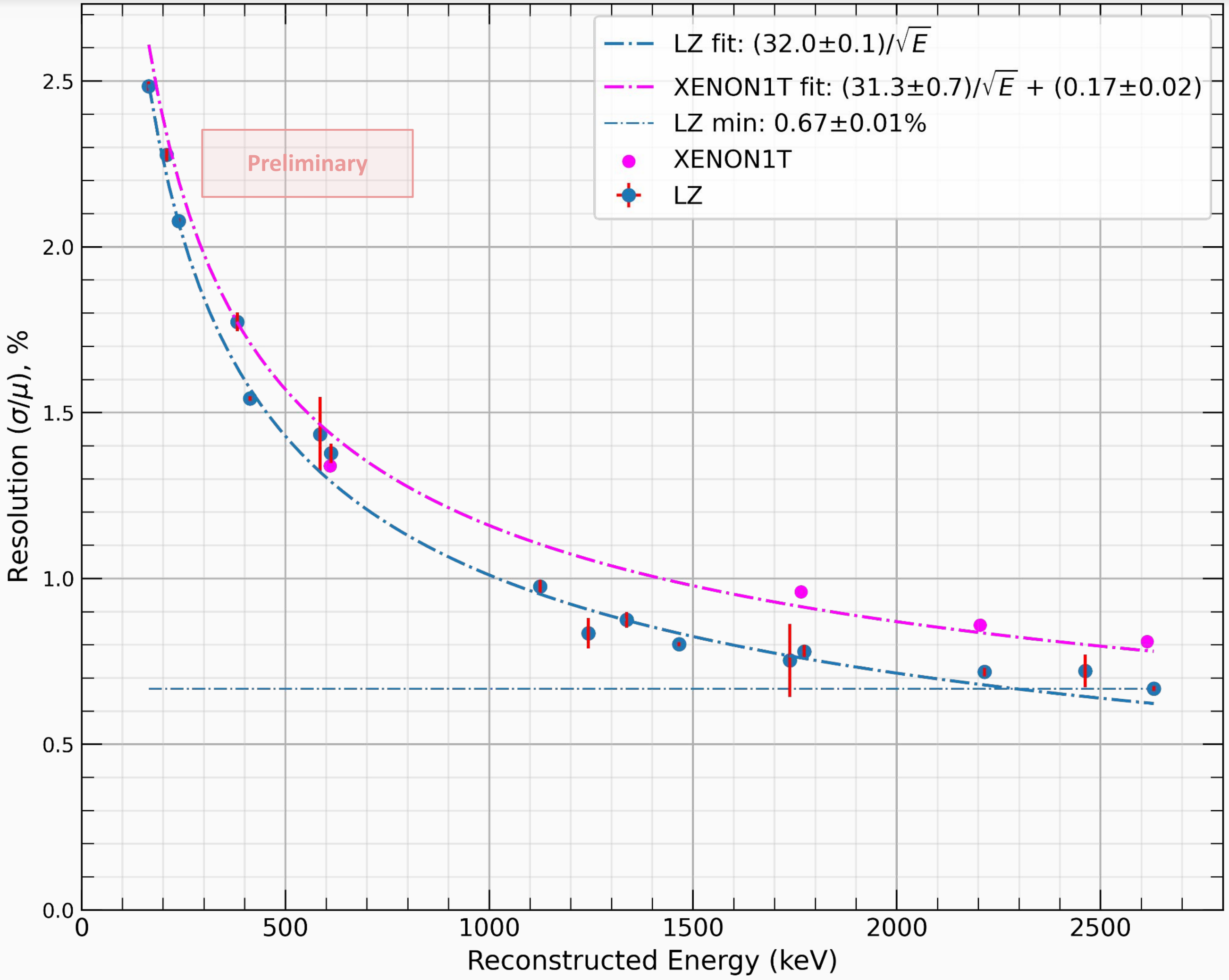


Comparing with XENON1T

- Both groups capable of demonstrating the excellent properties of LXe
  - LZ better by ~17% at 2.617 MeV
  - LZ performing better than the resolution used in the projected sensitivities for Xe-136 0v2β



COLLABORATION, LUX-ZEPLIN LZ, et al. Projected sensitivity of the LUX-ZEPLIN experiment to the 0vββ decay of Xe 136. Physical Review C, 2020, 102.1: 014602.



XENON1T data and fit from:
APRILE, E., et al. Energy resolution and linearity of XENON1T in the MeV energy range. The European Physical Journal C, 2020, 80.8: 1-9.
[Energy resolution and linearity of XENON1T in the MeV energy range]

Conclusions

- The LZ experiment, while primarily designed for a WIMP search, has a considerable sensitivity to neutrinoless double beta decay of ^{136}Xe and ^{134}Xe isotopes

- The experiment has ended its inaugural science run with 60 live days

  Aalbers et al., “First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment,” vol. 33, 2022. [Online]. Available: https://arxiv.org/pdf/2207.03764.pdf

- In this work we demonstrated the record energy resolution for any LXe detector
  - Resolution of **0.67 ± 0.01% at 2614 keV** for the full fiducial
  - Resolution of **0.63 ± 0.02% at 2614 keV for the bottom part** of the detector (due to improved S1 collection)

LZ (LUX-ZEPLIN) Collaboration

35 Institutions: 250 scientists, engineers, and technical staff

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- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Wisconsin, Madison

US UK Portugal Korea

LZ Collaboration Meeting – September 8-11, 2021

Thanks to our sponsors and participating institutions!

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Sanford Underground Research Facility

South Dakota Science and Technology Authority

Institute for Basic Science

Thank you! (Obrigado)

Backups

Statistical fluctuation

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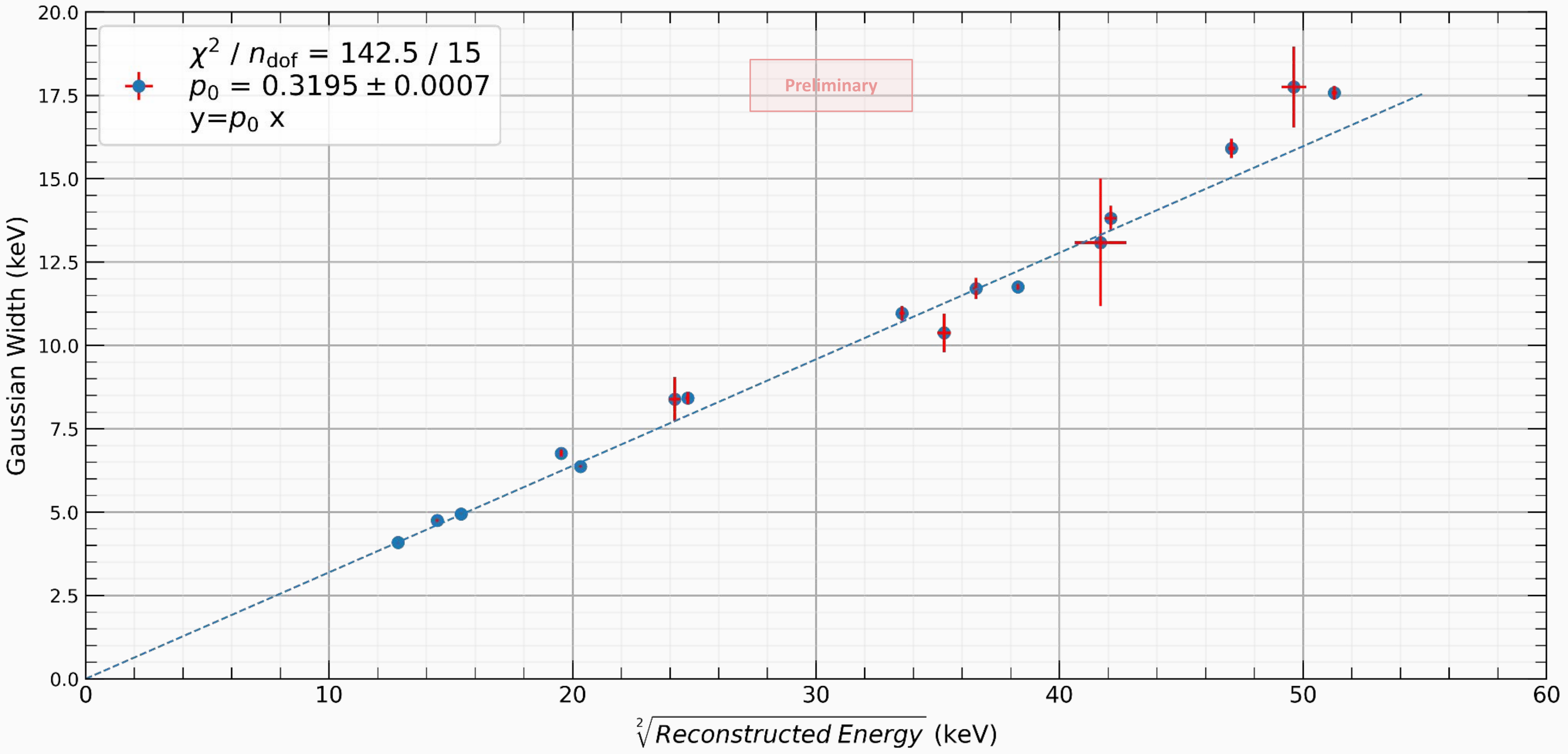


Statistical fluctuation

- Improved Xe-127 208 keV and 380 keV (L shells) results
  - Takes into account unresolved contribution from the M-shell EC
    - Two summed gaussians with a fixed energy difference of **4.1 keV** and relative contribution of **22%**
  - Improves results by 0.5σ

The observed intensities of K-, L-, M-, and N-shell EC X-rays as fraction of parent 127Xe decays

		Events	Amplitude	Expected (%)	Observed (%)
K	33.2 keV	2067	18200 ± 400	83.37	82.7 ± 2.4
L	5.2 keV	542	3090 ± 130	13.09	14.1 ± 0.7
M	1.1 keV	164	580 ± 50	2.88	2.6 ± 0.2
N	186 eV	31	133 ± 23	0.66	0.6 ± 0.1

Link: Xe-127 analysis in LUX

AKERIB, D. S., et al. Ultralow energy calibration of LUX detector using Xe 127 electron capture. *Physical Review D*, 2017, 96.11: 112011.

Spatial S1 & S2 Corrections

- Spatial Corrections calculated by a product of two splines:
  - 2D RZ spline ($C1_{rz}$) - a function of $\mathbf{R^2}$ = x^2+y^2 and $\mathbf{t_d}$ with a high number of bins (12)
  - 3D XYZ spline ($C1_{xyz}$) - a function of **XY** and $\mathbf{t_d}$ with a lower number of bins (6)
  - The corrections normalized at the center of detector - (0 mm, 0 mm, 475 μs)

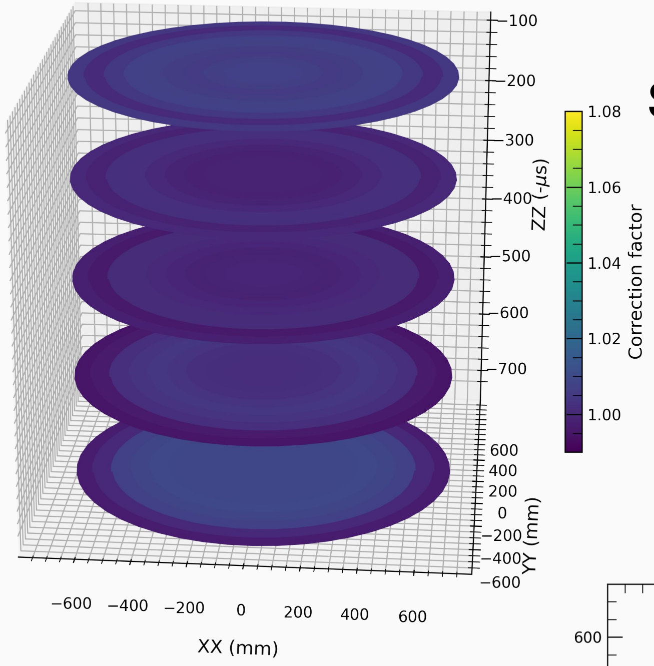
$$S1_c = S1_{raw} \frac{C1_{rz}(0{,}475)\ C1_{xyz}(0{,}0{,}475)}{C1_{rz}(r^2{,}t_d)\ C1_{xyz}(x{,}y{,}t_d)}$$

- Spatial Corrections calculated by a product of two splines:
  - 2D RZ spline ($C2_{rz}$) - a function of $\mathbf{R^2}$ = x^2+y^2 and $\mathbf{t_d}$ with a high number of bins (12)
  - 2D XY spline ($C2_{xy}$) - a function of **XY** with a high number of bins (15)
  - The corrections normalized at the center of detector - (0 mm, 0 mm, 475 μs)

$$S2_c = S2_{raw}\ C_{lc}(x, y)\ \frac{C2_{rz}(0{,}475)\ C2_{xy}(0{,}0)}{C2_{rz}(r^2{,}t_d)\ C2_{xy}(x{,}y)}\ e^{t_d/E_{lt}(t_s)}$$

t_d = drift time, μs
t_s = event trigger timestamp, unix time
E_{lt} = time dependent electron lifetime

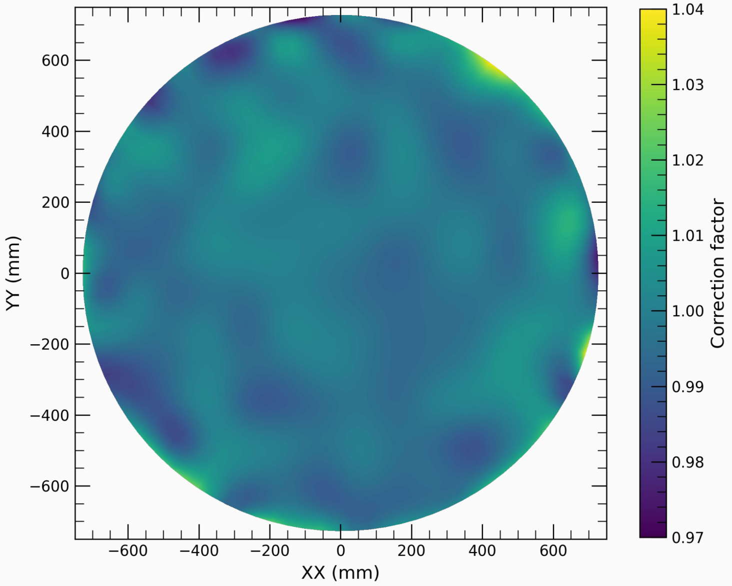
Spatial S1 & S2 Corrections



S2 for bottom PMTs

2D RZ spline

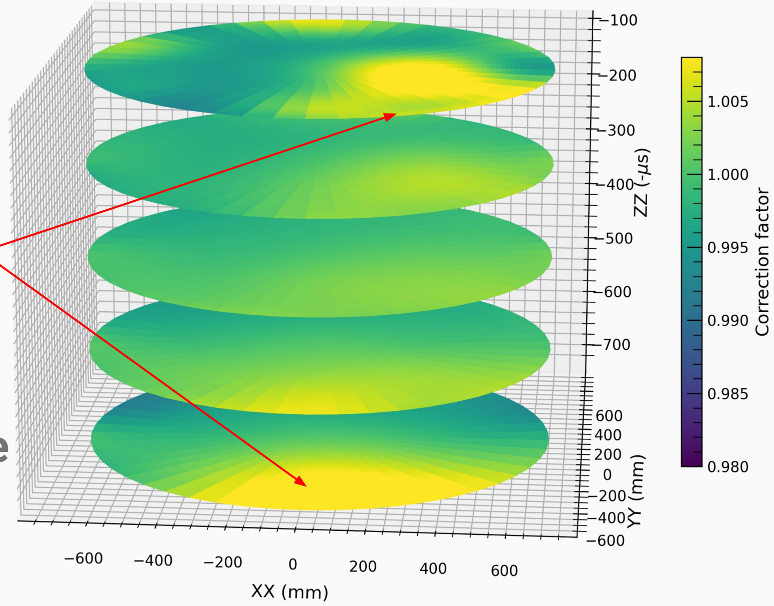
2D XY spline



S1 for all PMTs

Disabled PMTs

3D XYZ spline



2D RZ spline