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

5th XeSAT 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:

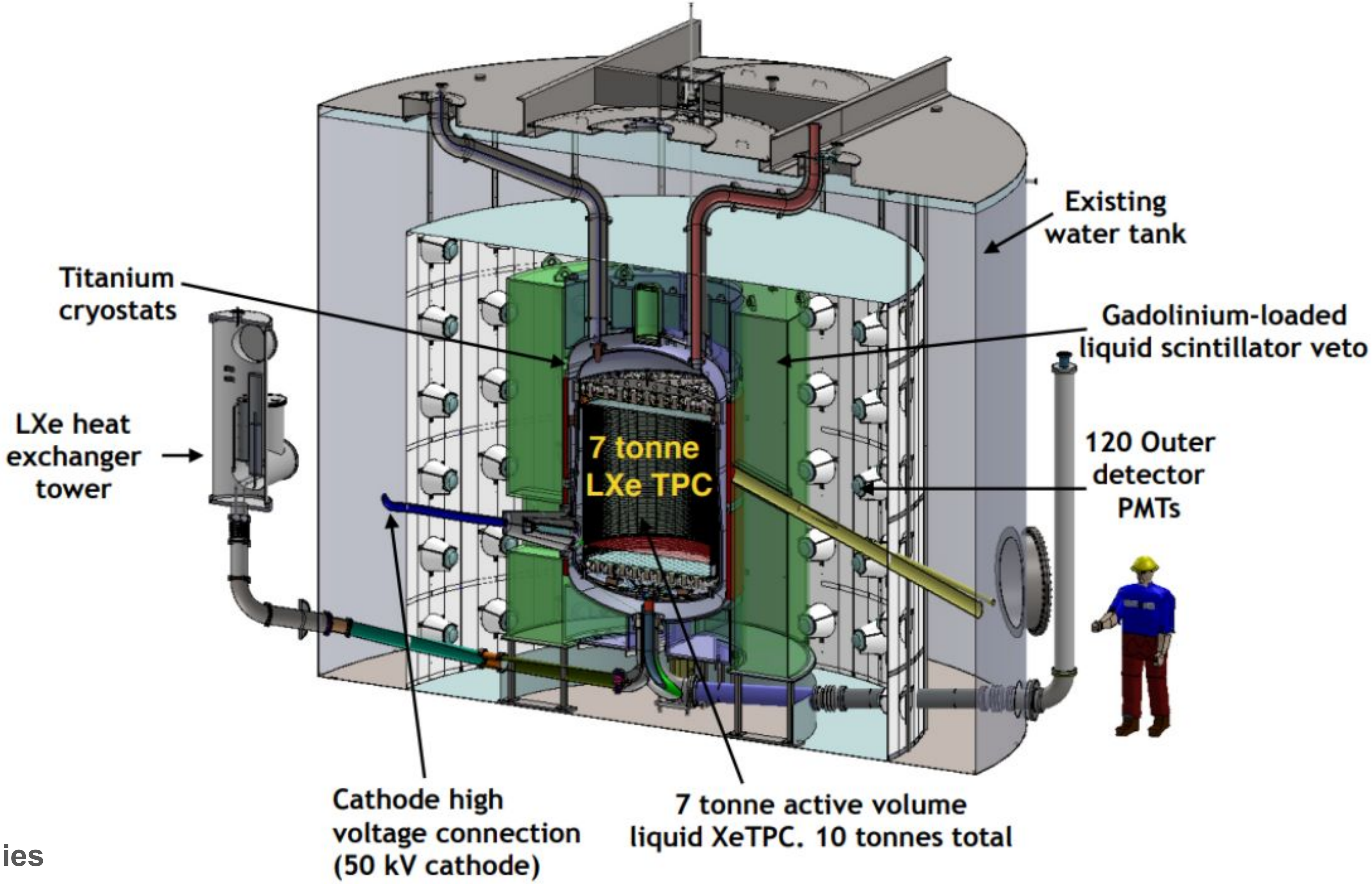
- 1.5 m diameter by 1.5 m height
- Active Mass: 7 t
  - 623 kg of ^{136}Xe
  - 741 kg of ^{134}Xe
- Fiducial: 5.6 t
- 494×3'' PMTs

3 components veto detector:

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

Scientific program

1. WIMP search
2. Neutrino physics searches
   - 2ν2β – $Q_{\beta\beta}$= 826 keV (^{134}Xe)
   - 0ν2β – $Q_{\beta\beta}$= 2458 keV (^{136}Xe)
     - **Requires good energy resolution for high energies**



In this presentation…

XY position reconstruction

Mercury Algorithm

LRF
(per PMT **L**ight **R**esponse **F**unctions)

New method for S2 Light Collection Correction

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

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

Valid for any subset of PMT

S2 from the bottom array for energy reconstruction

PMT phd calibration

- Non-invasive technique developed for ZEPLIN
- Time dependent corrections of gains
- Produced with Single Electron events

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

S2 & S1 spatial corrections with Rn-222 alphas

Measure g1 and g2 with Doke method

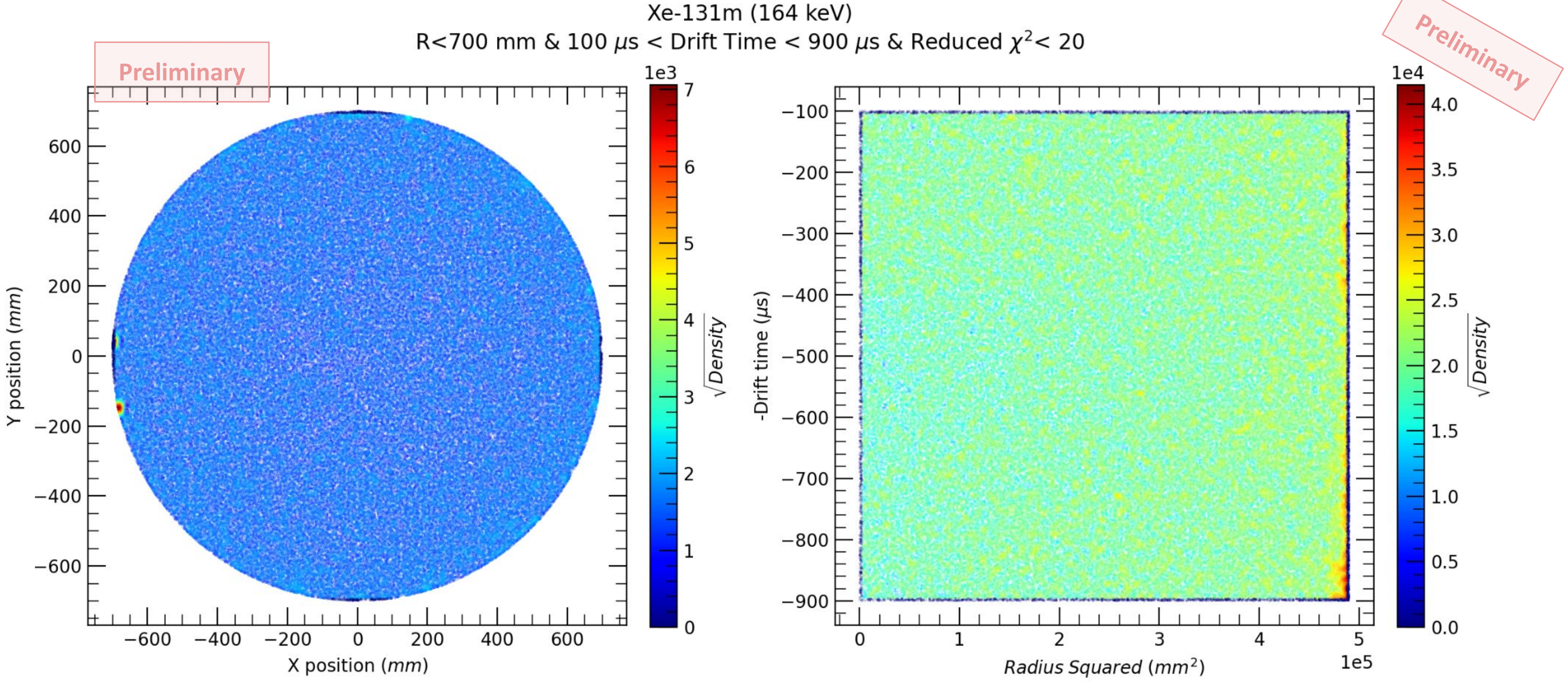
LZ Energy Resolution

Compare results

NEST simulation
(Noble Element Simulation Techniques Collaboration)

Position reconstruction results

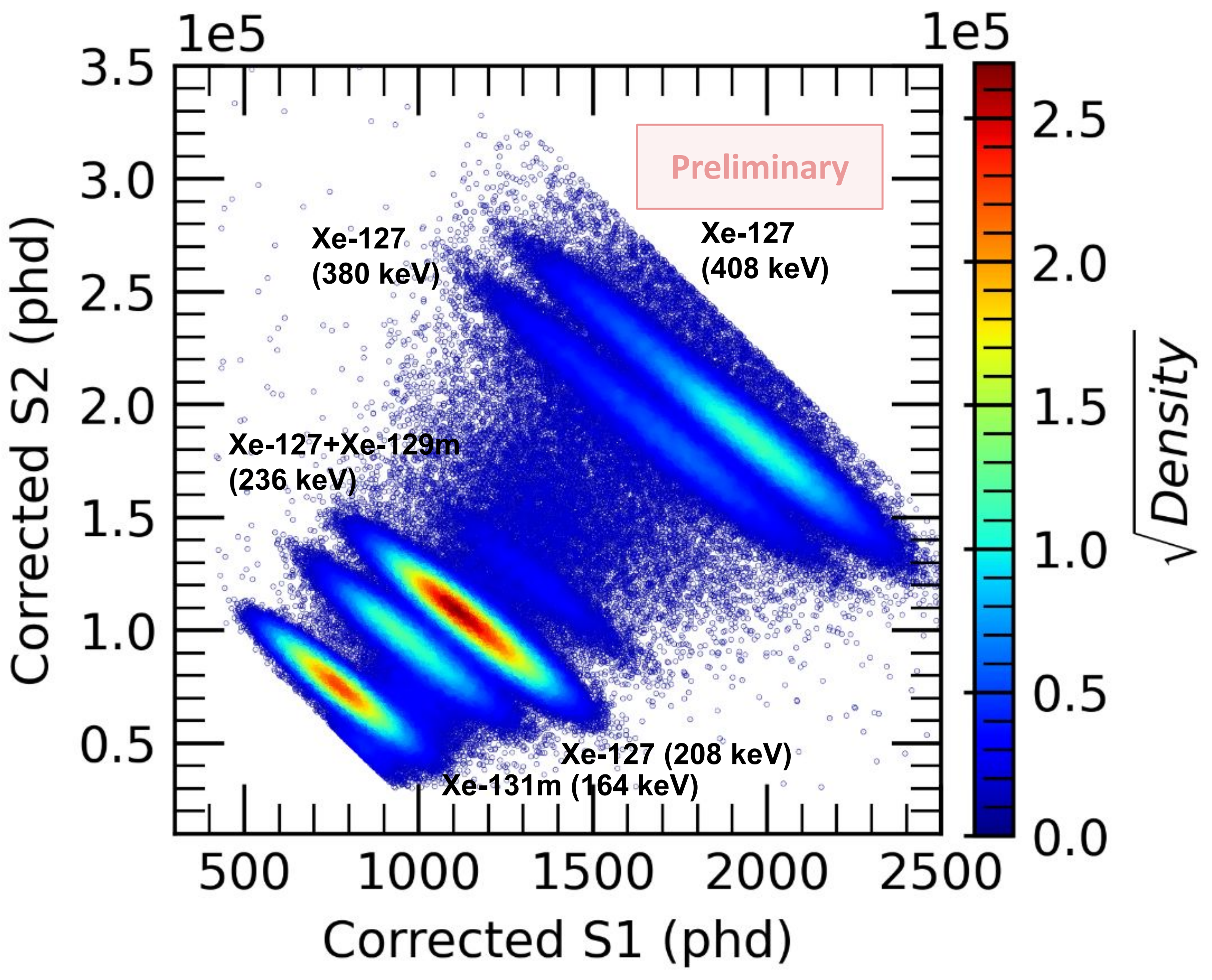
- Two main features:
  - Two hotspots on the left – most likely activity from two resistors located at the bottom of the detector (still under investigation)
  - Low event density regions in the periphery – boundary condition artifact of the density algorithm

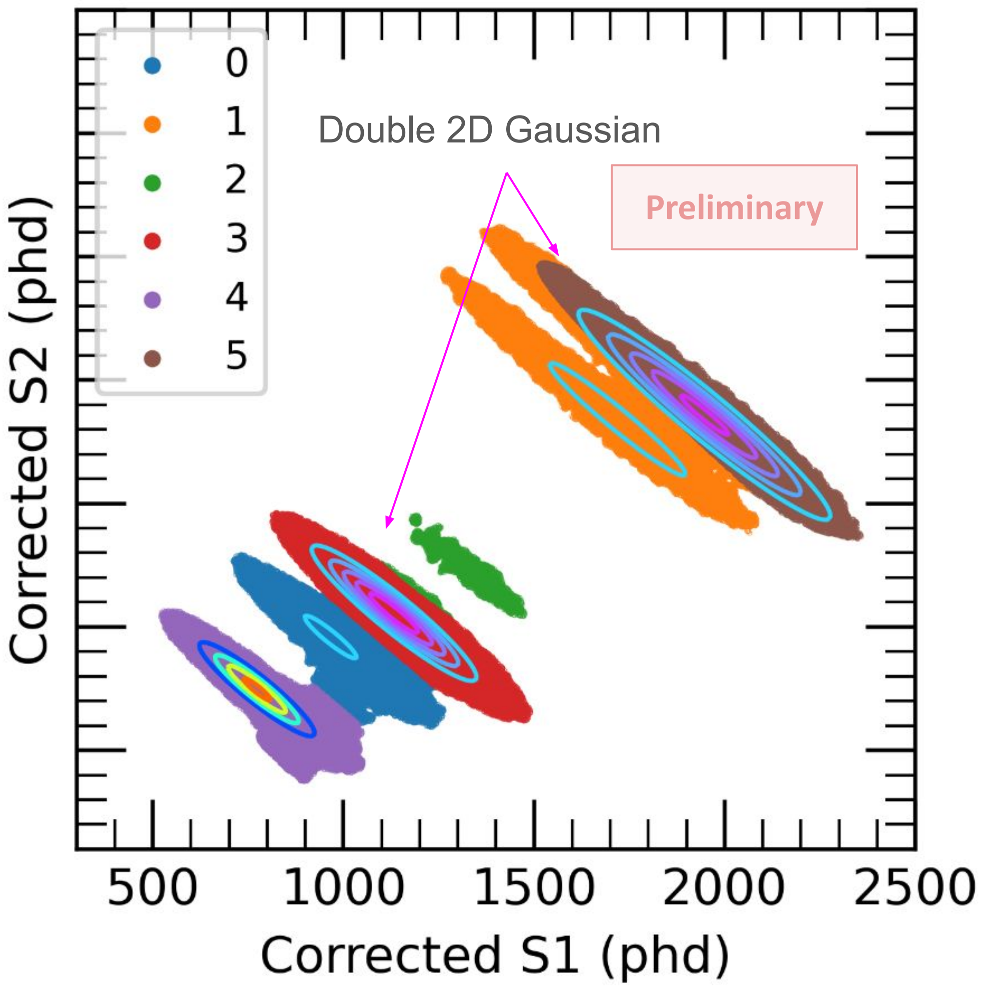


- Scatter plots with the color representing the interpolation of the respective 2D histogram bins – per event density

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

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

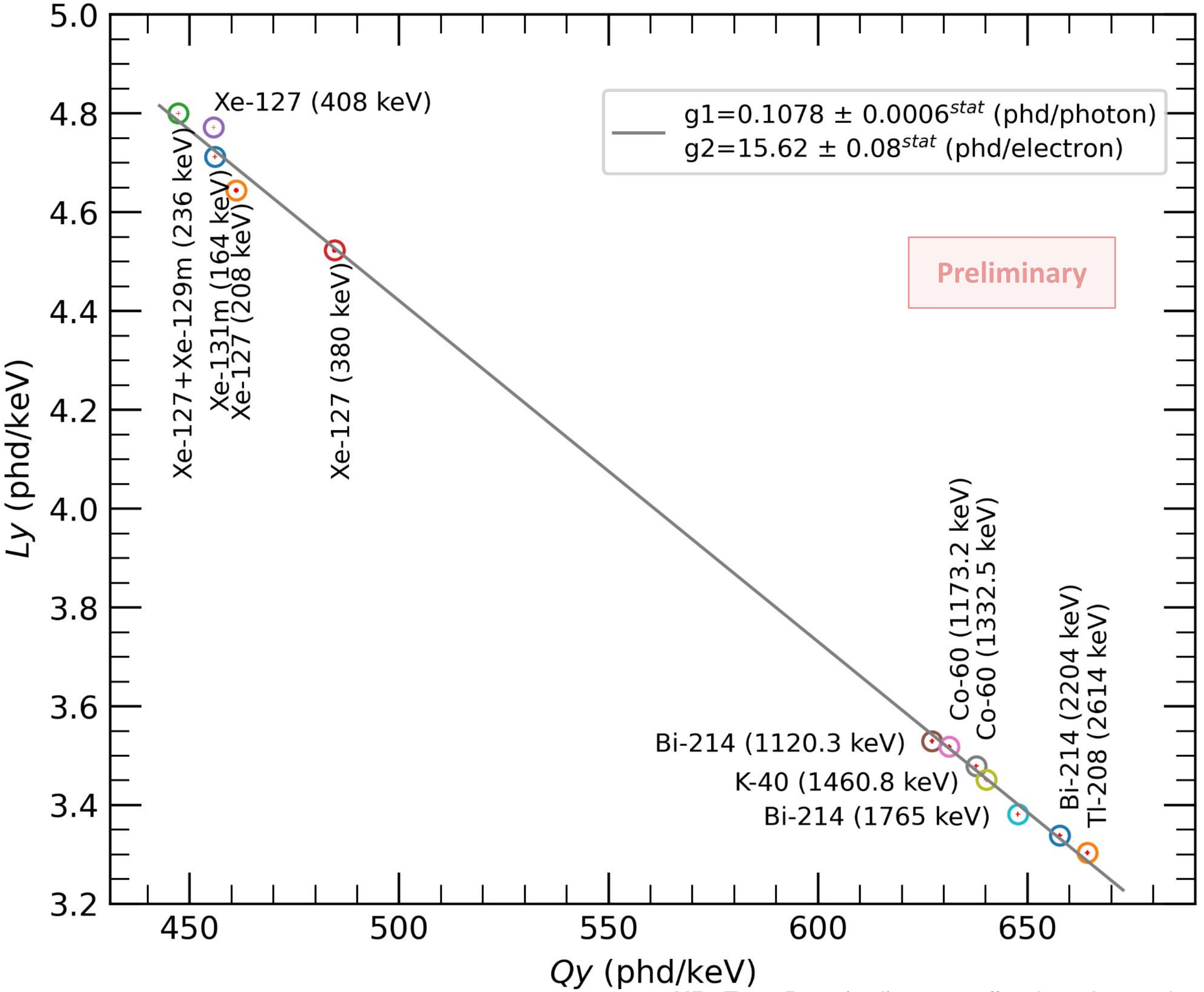
Valid only for Electronic Recoils

$$W = 0.0137\ keV$$

- These gains are not final and are subjected to change as we improve calibrations and analysis

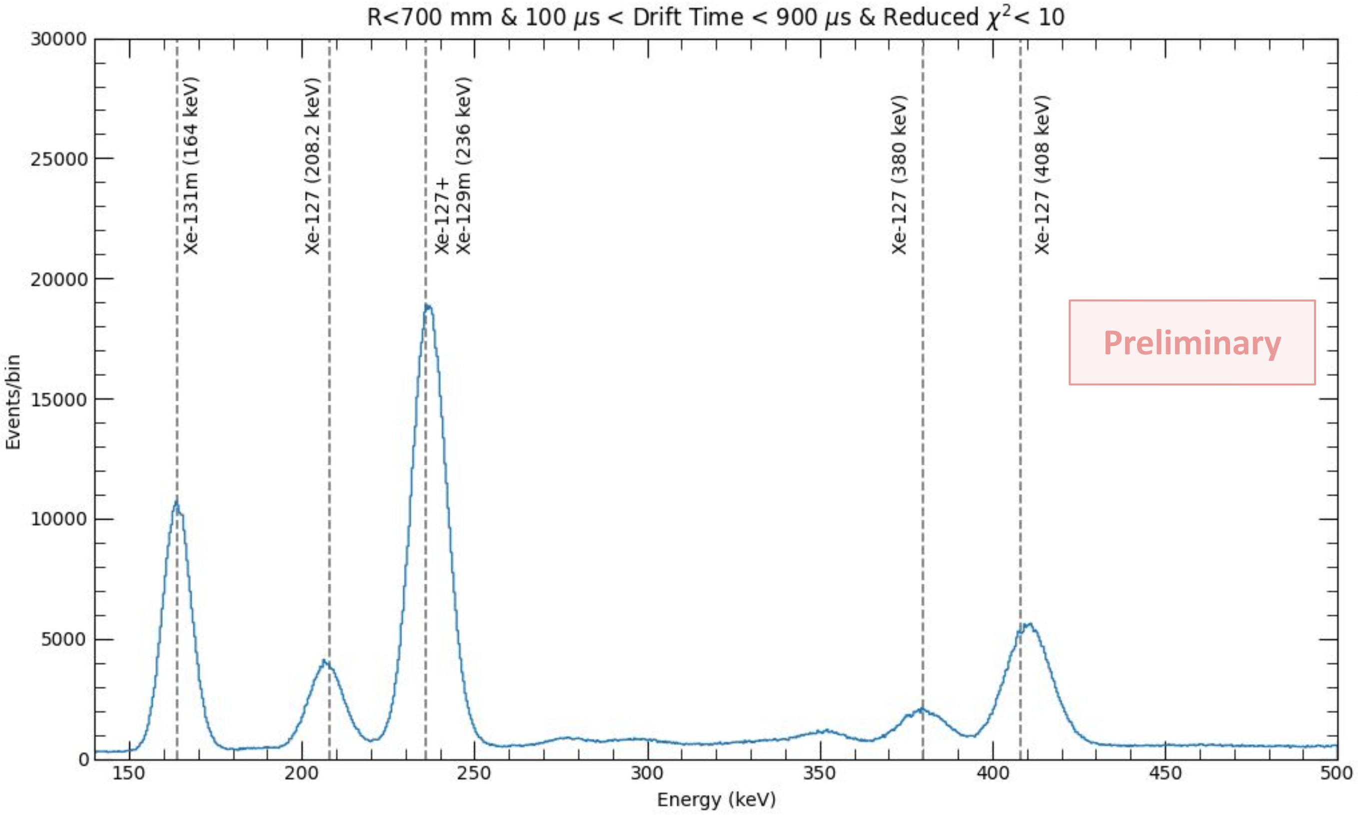
Xe-127 EC+Xray multi step processes cause a slight disagreement in the Doke fit

- to further explore through analysis of multi-scatter events



NB: Error Bars (red) are smaller than the marker

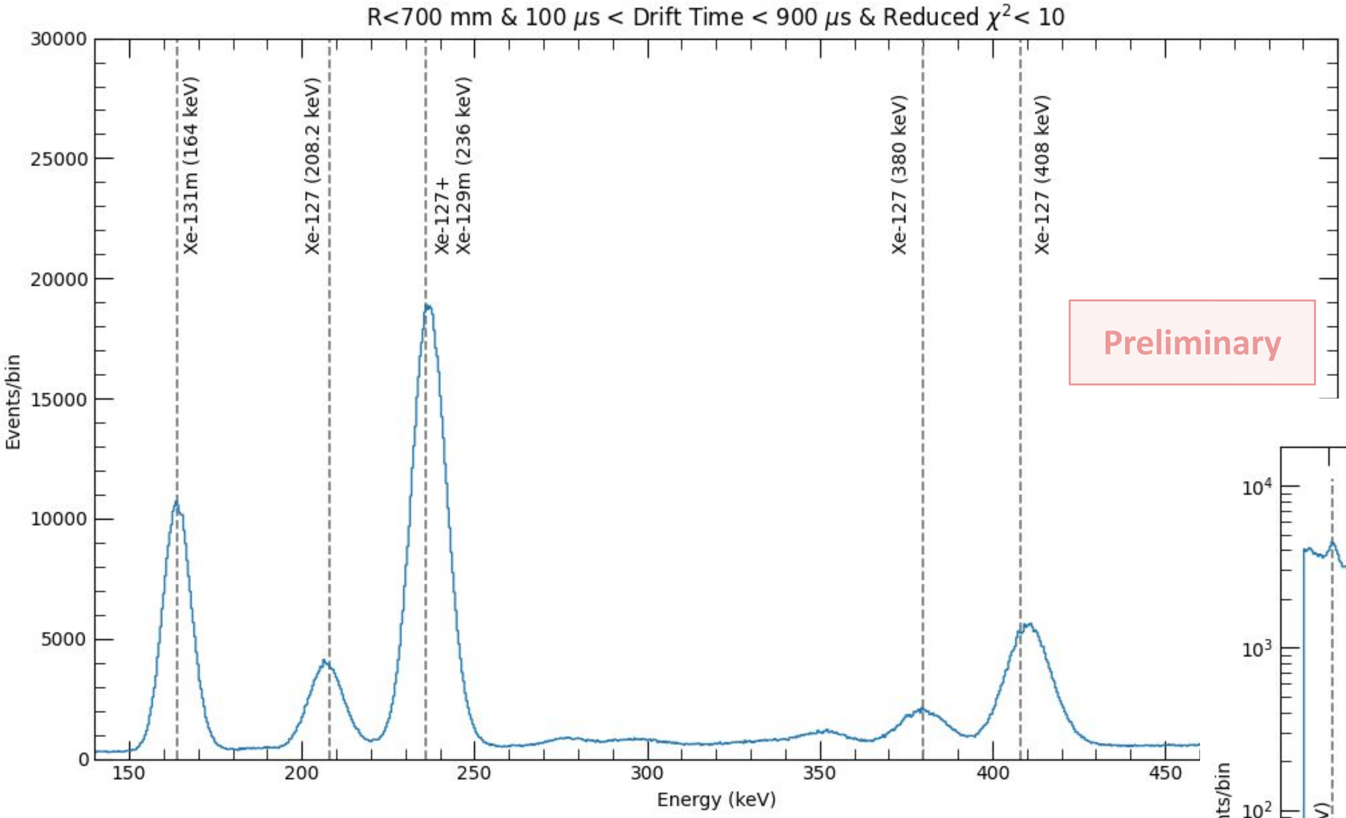
Energy spectrum



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

Energy spectrum



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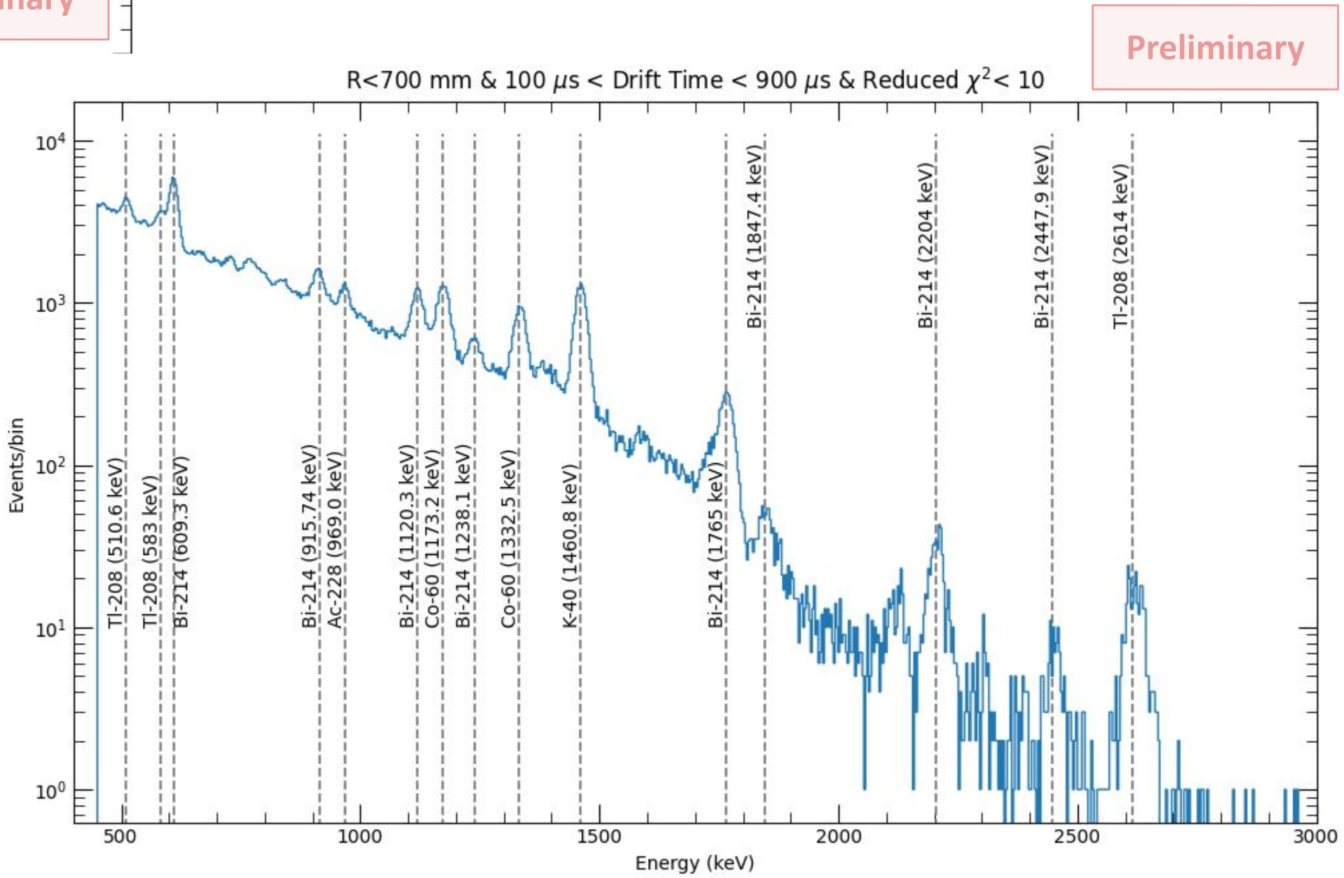
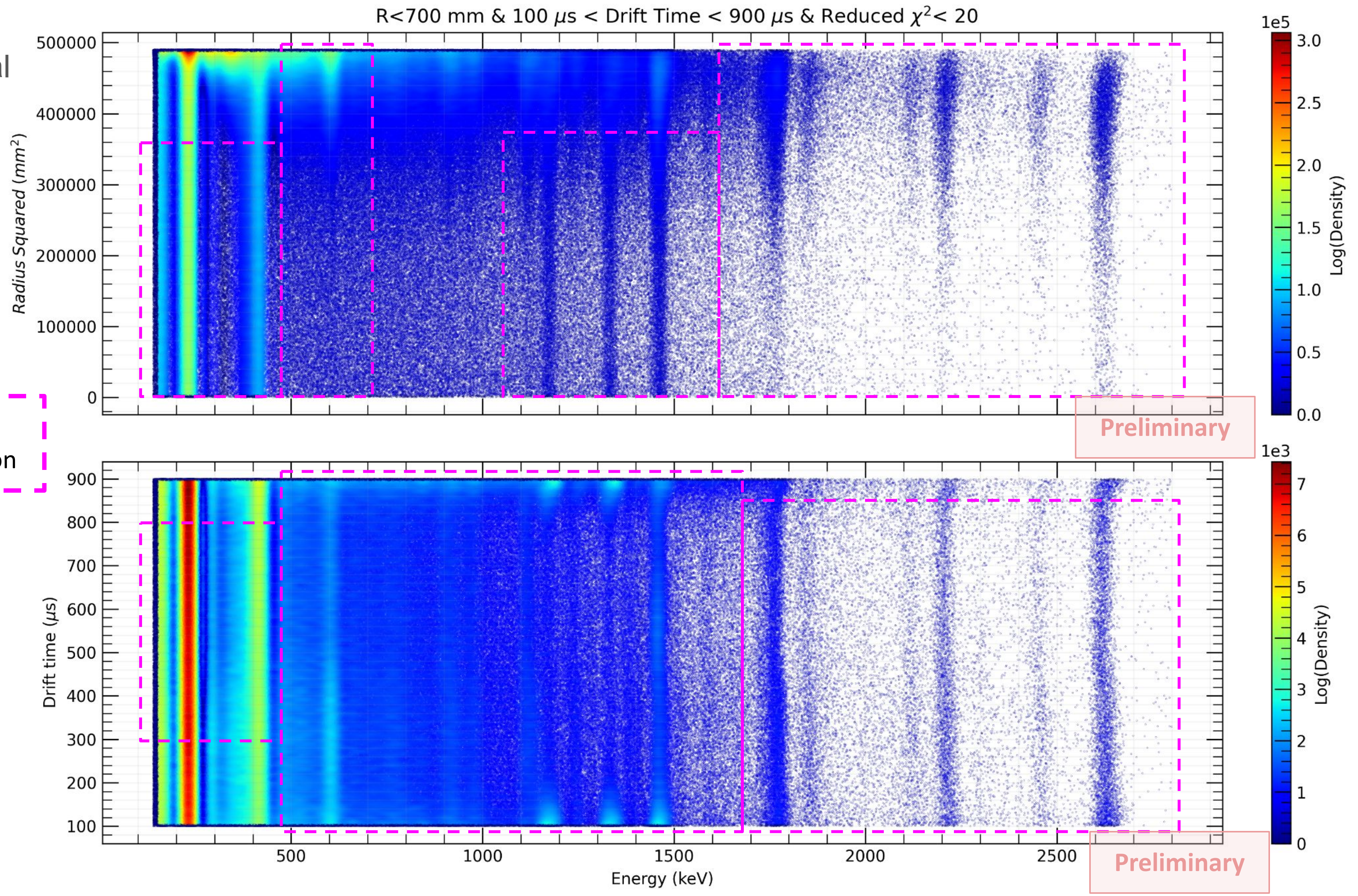


Energy spatial dependency

Demonstration of the detector spatial stability

- Small deviation towards larger radius from decrease in position reconstruction performance

Cuts for final energy resolution plots.
Trade-off between statistics and resolution



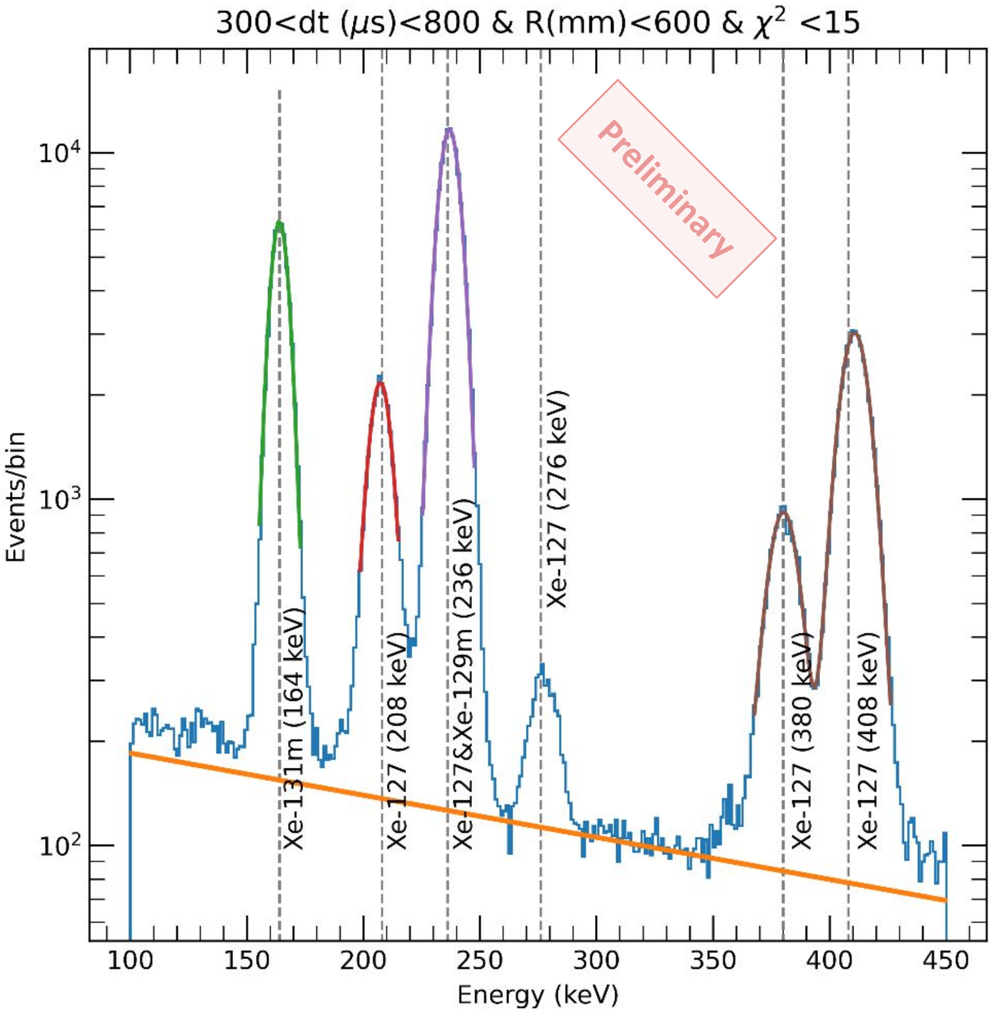
Peak Fit

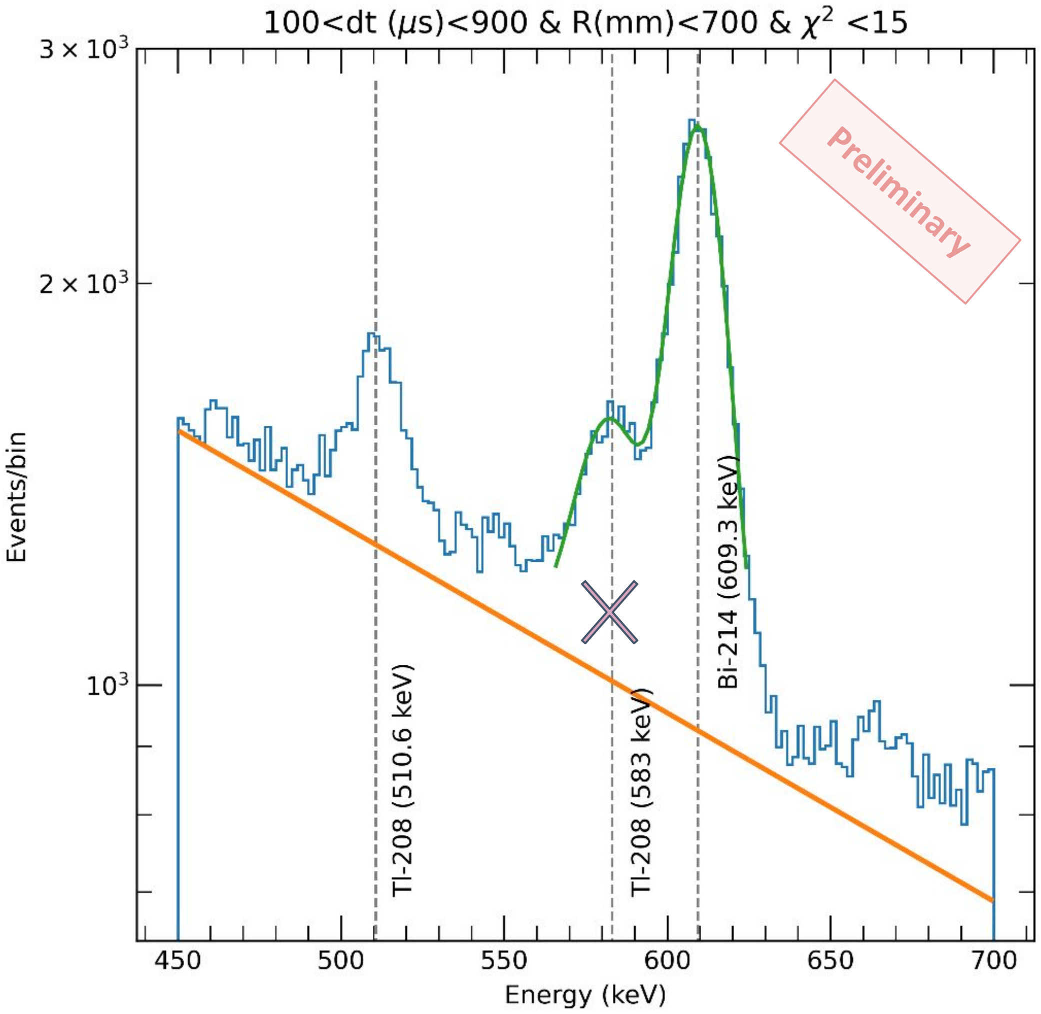
- Peaks fitted with gaussian

- Simple background model with exponential curve

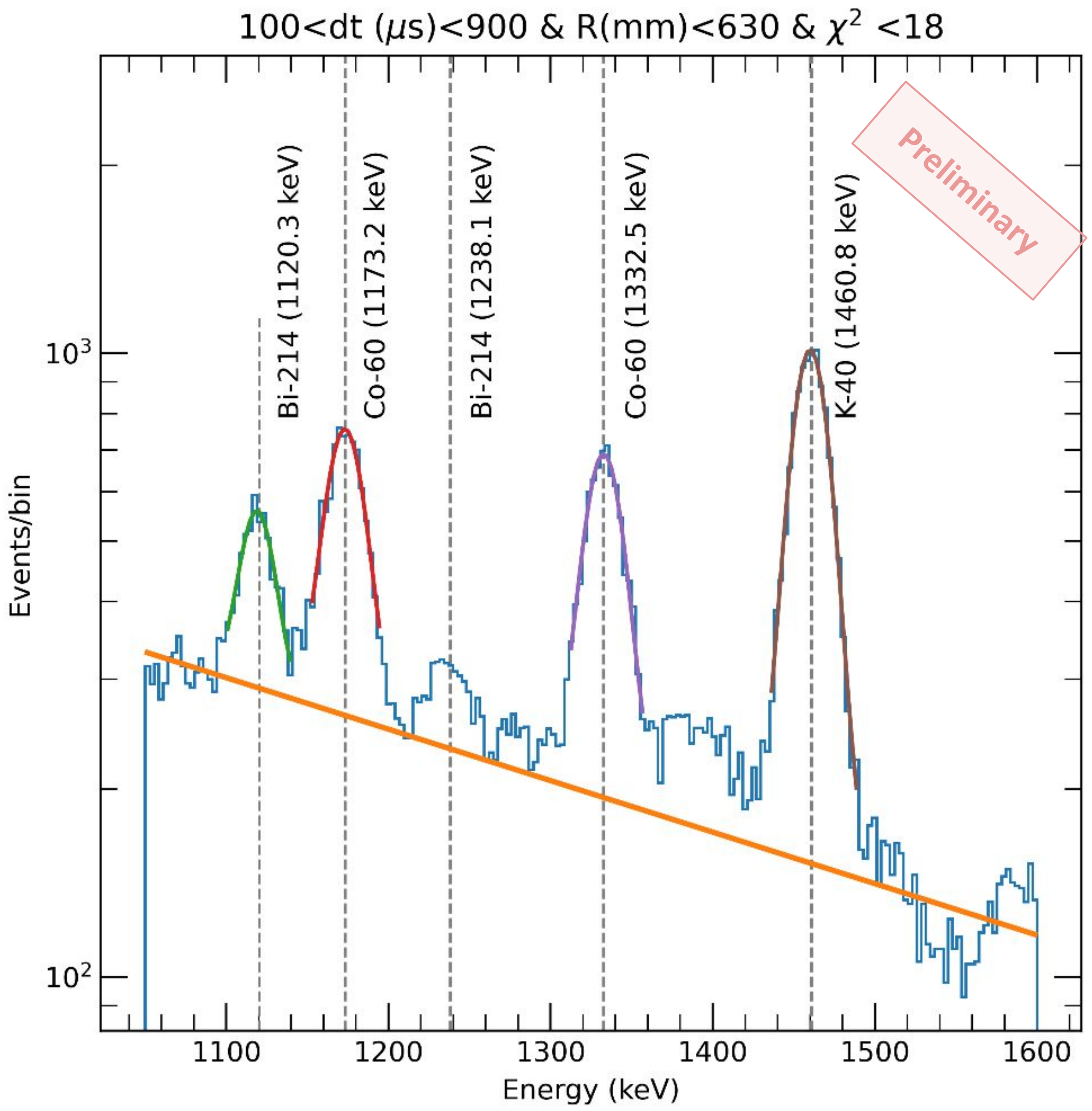
NB: logarithmic scale

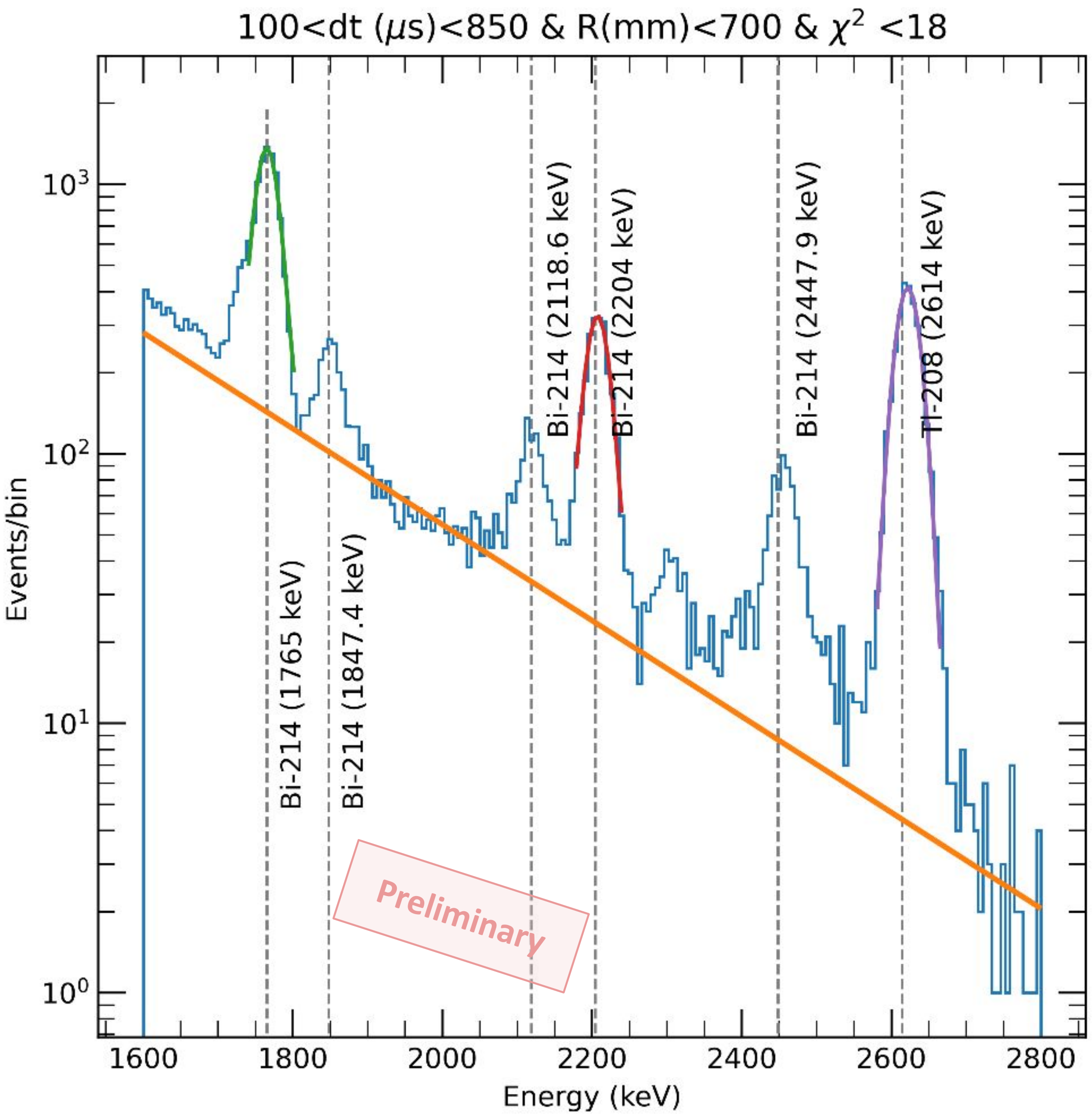
- Peaks with **low statistics not included** due to unknown contribution of the background and associated systematic errors





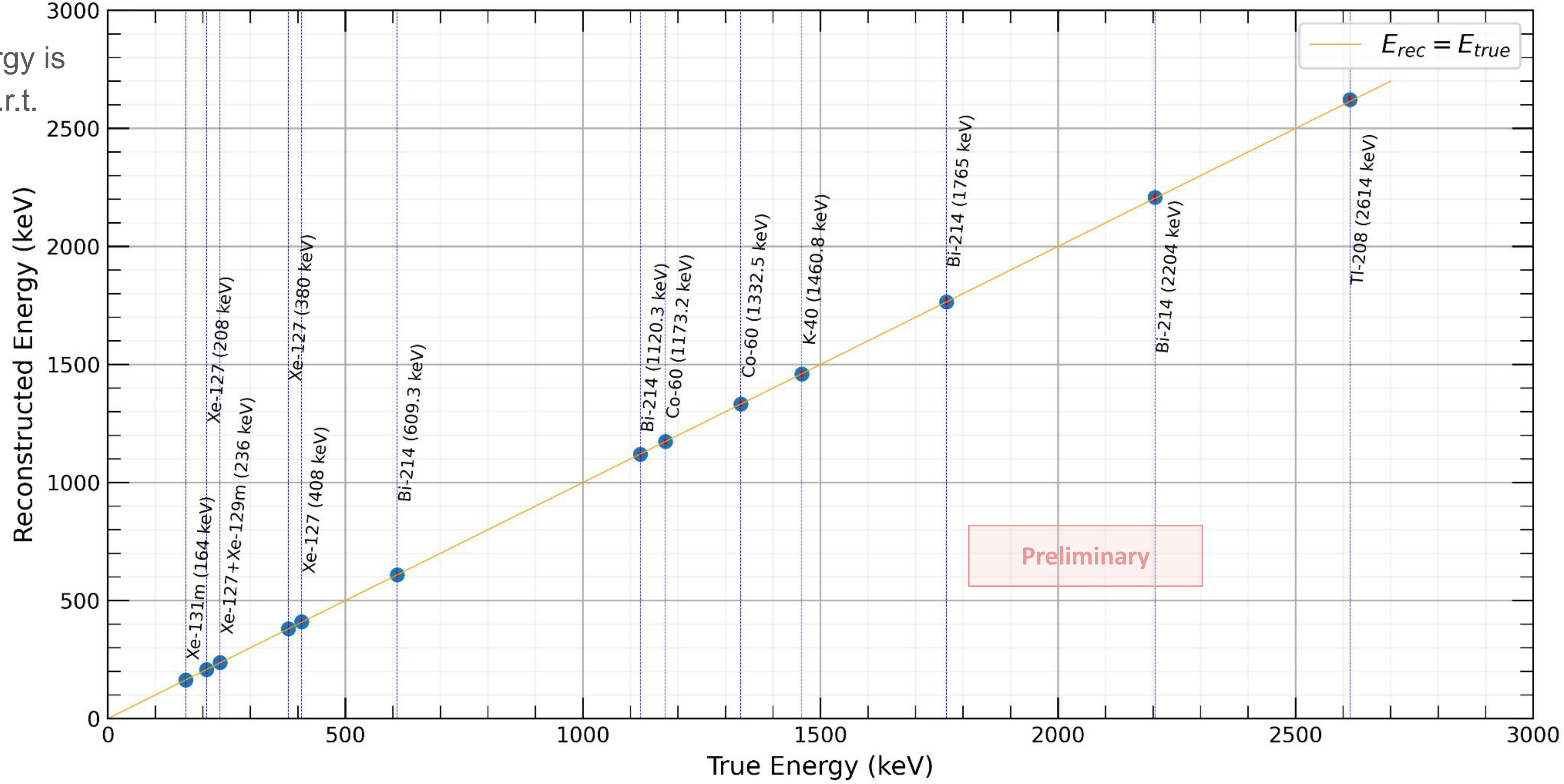
Peak Fit


100<dt (μs)<900 & R(mm)<630 & χ² <18
Bi-214 (1120.3 keV)
Co-60 (1173.2 keV)
Bi-214 (1238.1 keV)
Co-60 (1332.5 keV)
K-40 (1460.8 keV)
Preliminary
Events/bin
Energy (keV)


100<dt (μs)<850 & R(mm)<700 & χ² <18
Bi-214 (1765 keV)
Bi-214 (1847.4 keV)
Bi-214 (2118.6 keV)
Bi-214 (2204 keV)
Bi-214 (2447.9 keV)
Tl-208 (2614 keV)
Preliminary
Events/bin
Energy (keV)

Energy Reconstruction

Reconstructed energy is **linear within 1%** w.r.t. true energy



Energy Resolution

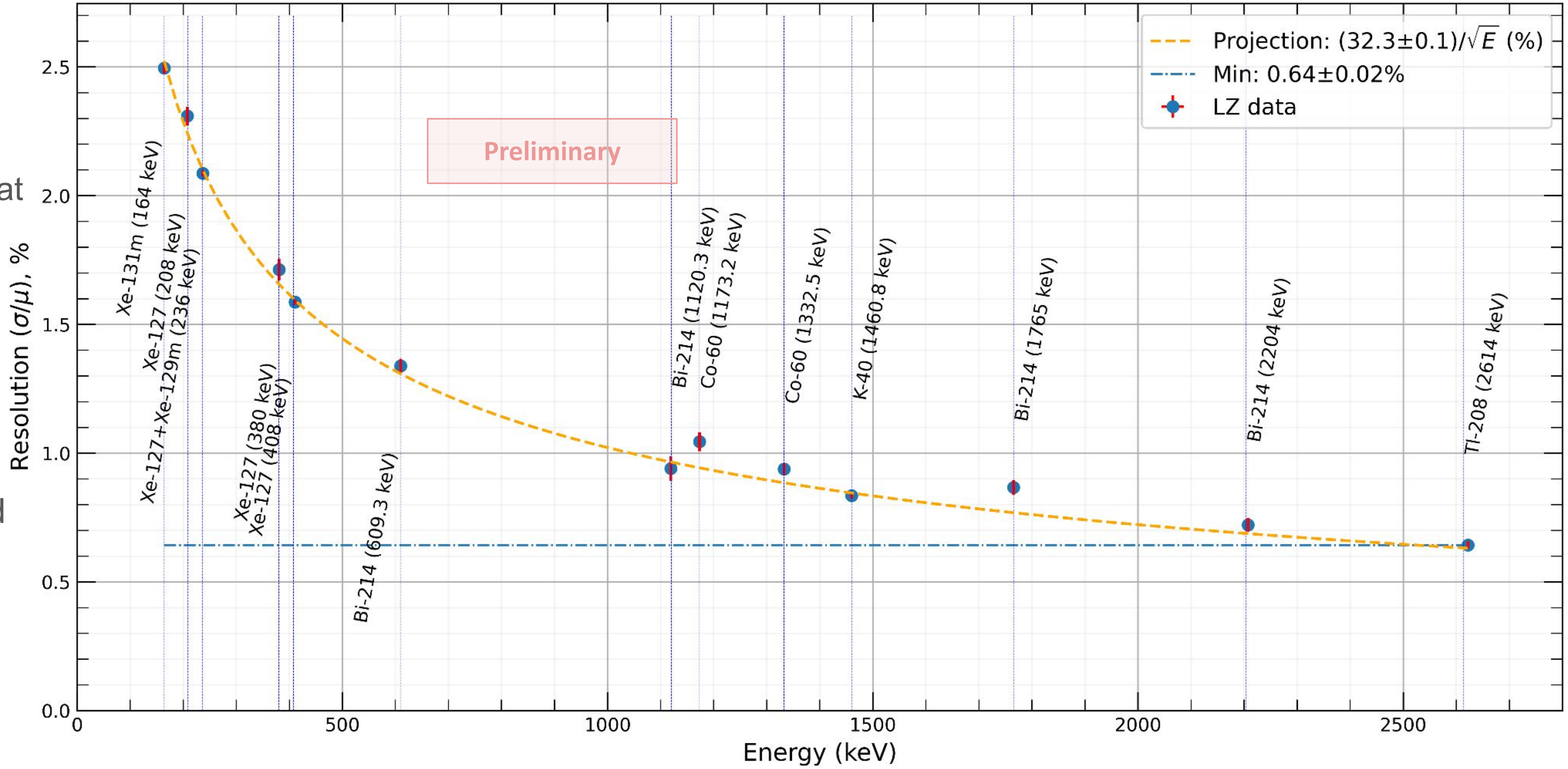
To our best knowledge we obtain an unprecedented energy resolution for LXe at high energies.

0.64 ± 0.02 % for Tl-208 (2.614 Mev)

Projection line calculated from fit on experimental data

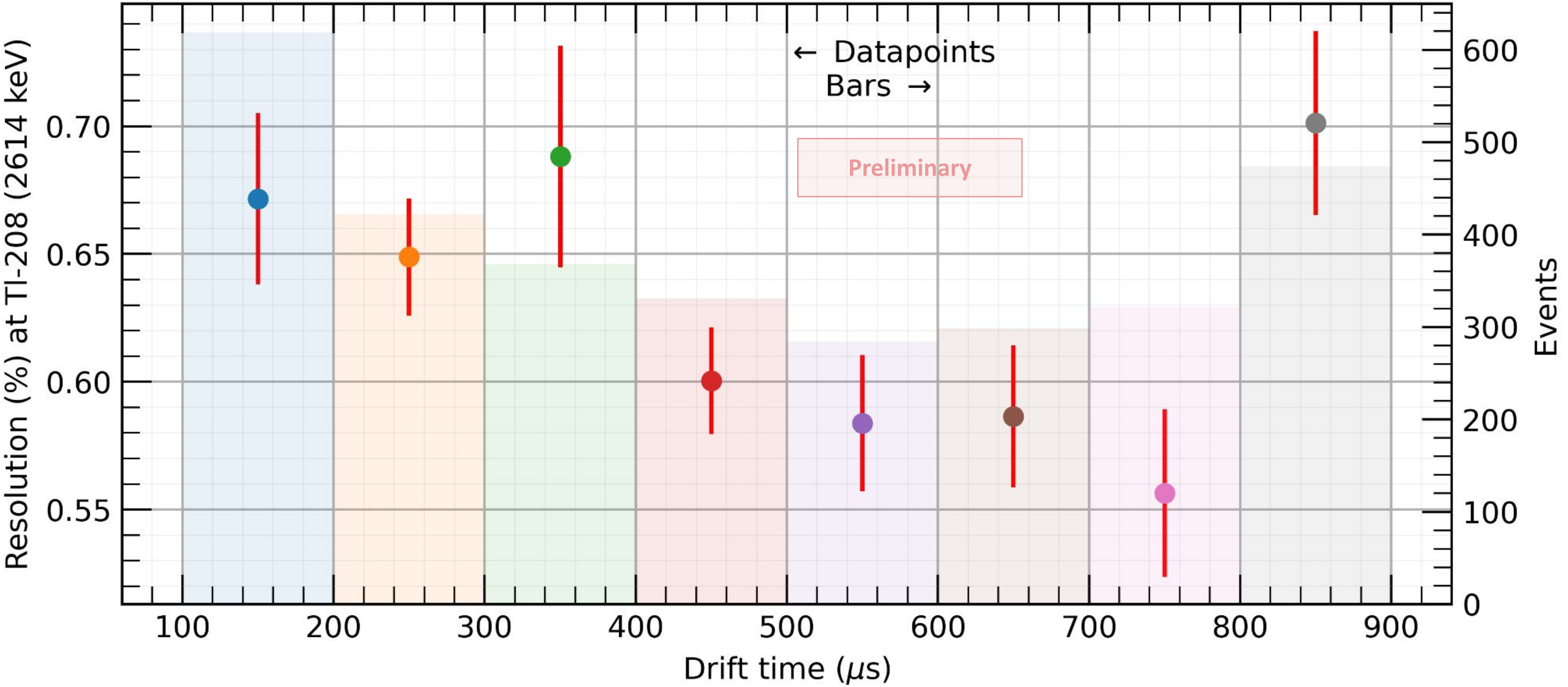
$$\sigma = K\sqrt{E}$$

$$K = 0.323 \pm 0.001$$



Energy resolution vs depth

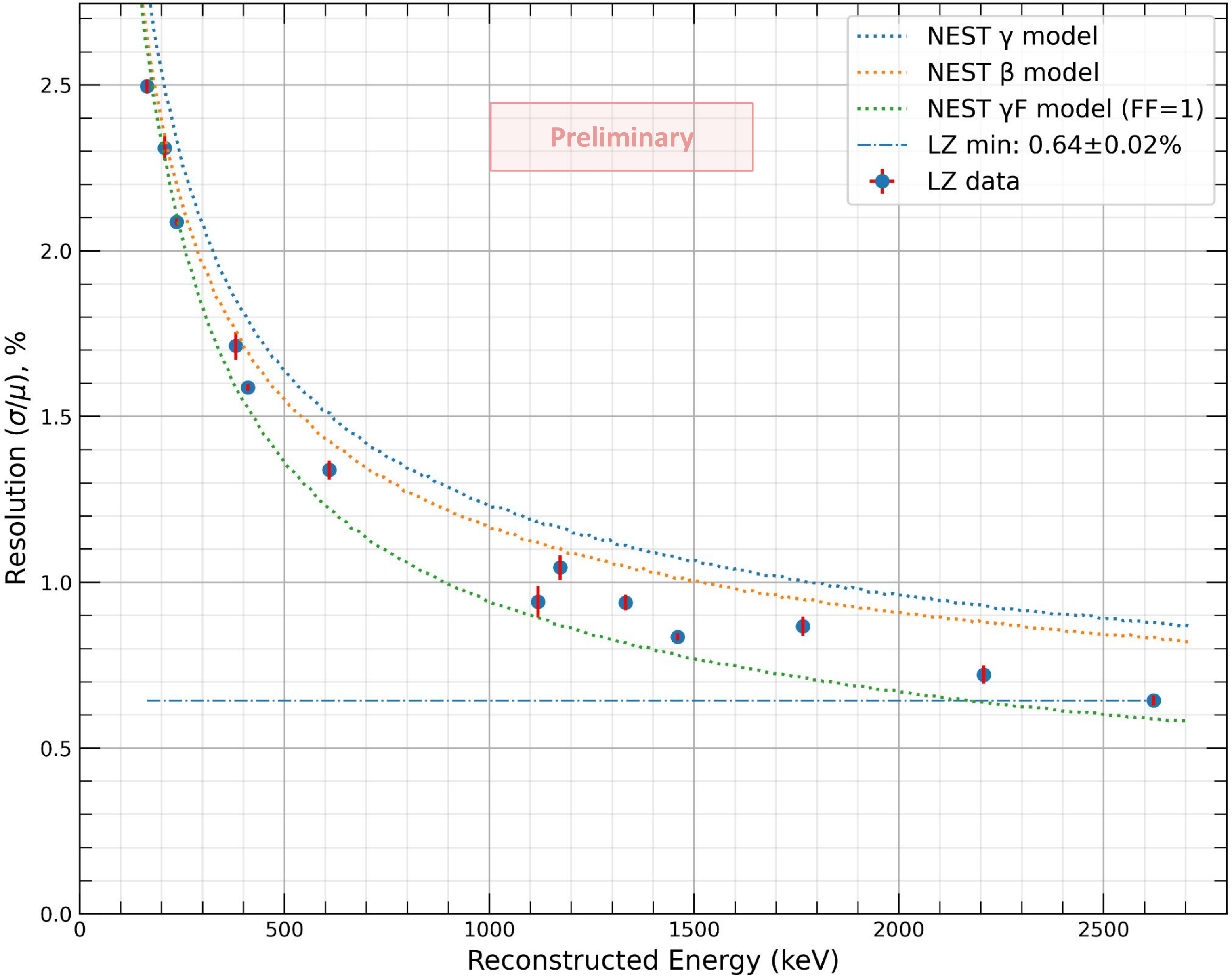
- Study of effects leading to depth-dependent variations of the resolution is still in progress



Comparing with NEST

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

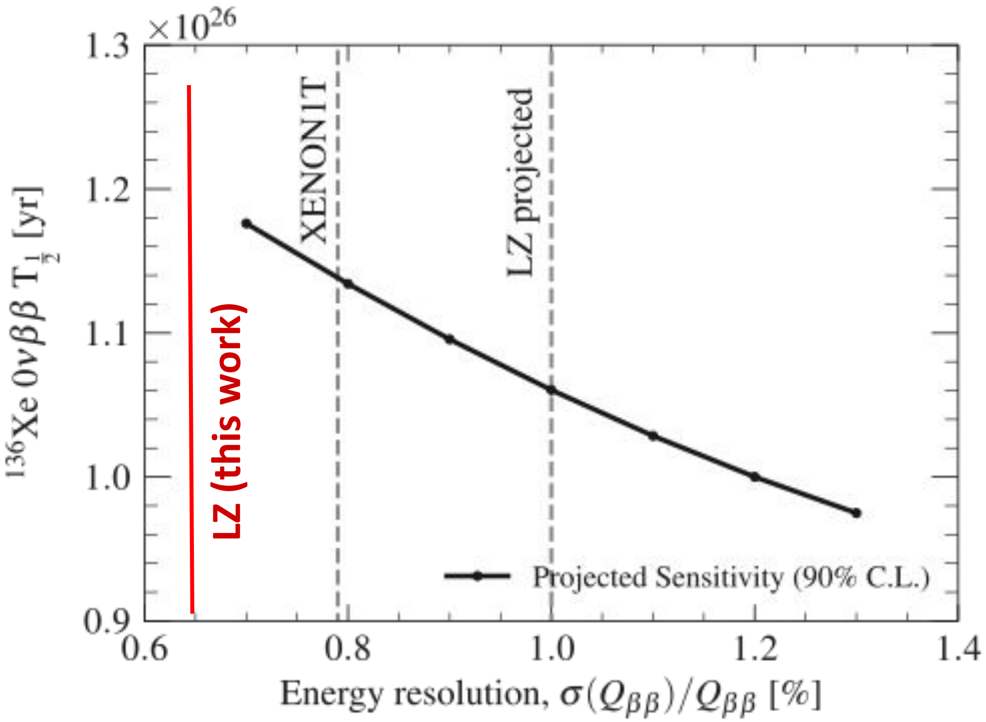
- Fano factor = 1
  - Initial fluctuations of the S1 and S2 given by a Poisson distribution



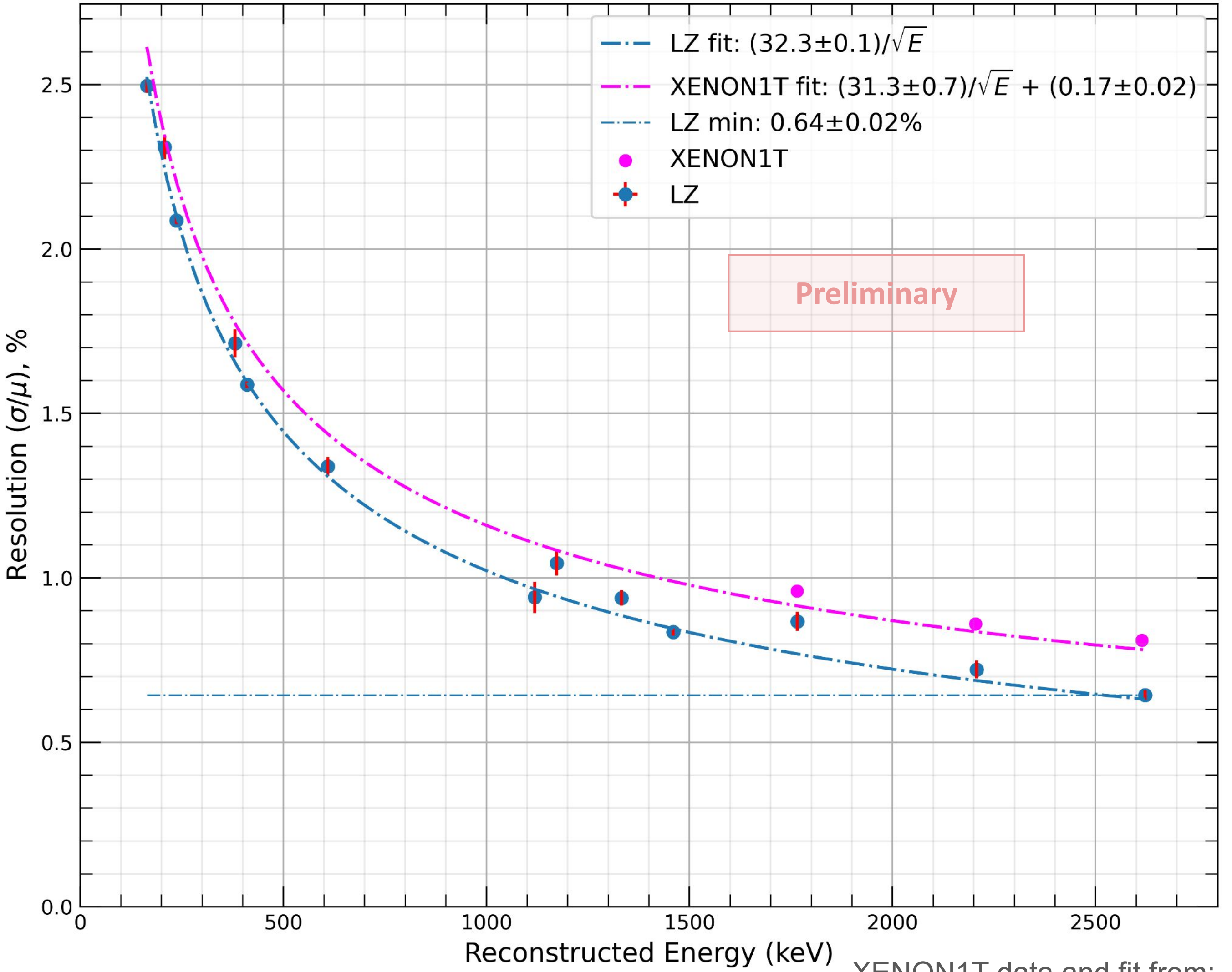
Comparing with XENON1T

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 0ν2β



COLLABORATION, LUX-ZEPLIN LZ, et al. Projected sensitivity of the LUX-ZEPLIN experiment to the 0νββ 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]

Summary

- 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 started taking science data, and extensive analyses are underway

- In this work we demonstrated the record energy resolution for any LXe detector
  - Resolution of **0.64 ± 0.02% at 2614 keV** for the full fiducial
  - Resolution of **0.56 ± 0.03% at 2614 keV for the bottom part** of the detector (due to improved S1 collection)

LZ (LUX-ZEPLIN) Collaboration

@lzdarkmatter

https://lz.lbl.gov/

35 Institutions: 250 scientists, engineers, and technical staff

- 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

Thanks to our sponsors and participating institutions!

U.S. Department of Energy
Office of Science

UKRI Science and Technology Facilities Council

Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

ibs Institute for Basic Science

Thank you!

Backups

LZ overview - with field values

Liquid Xenon TPC:

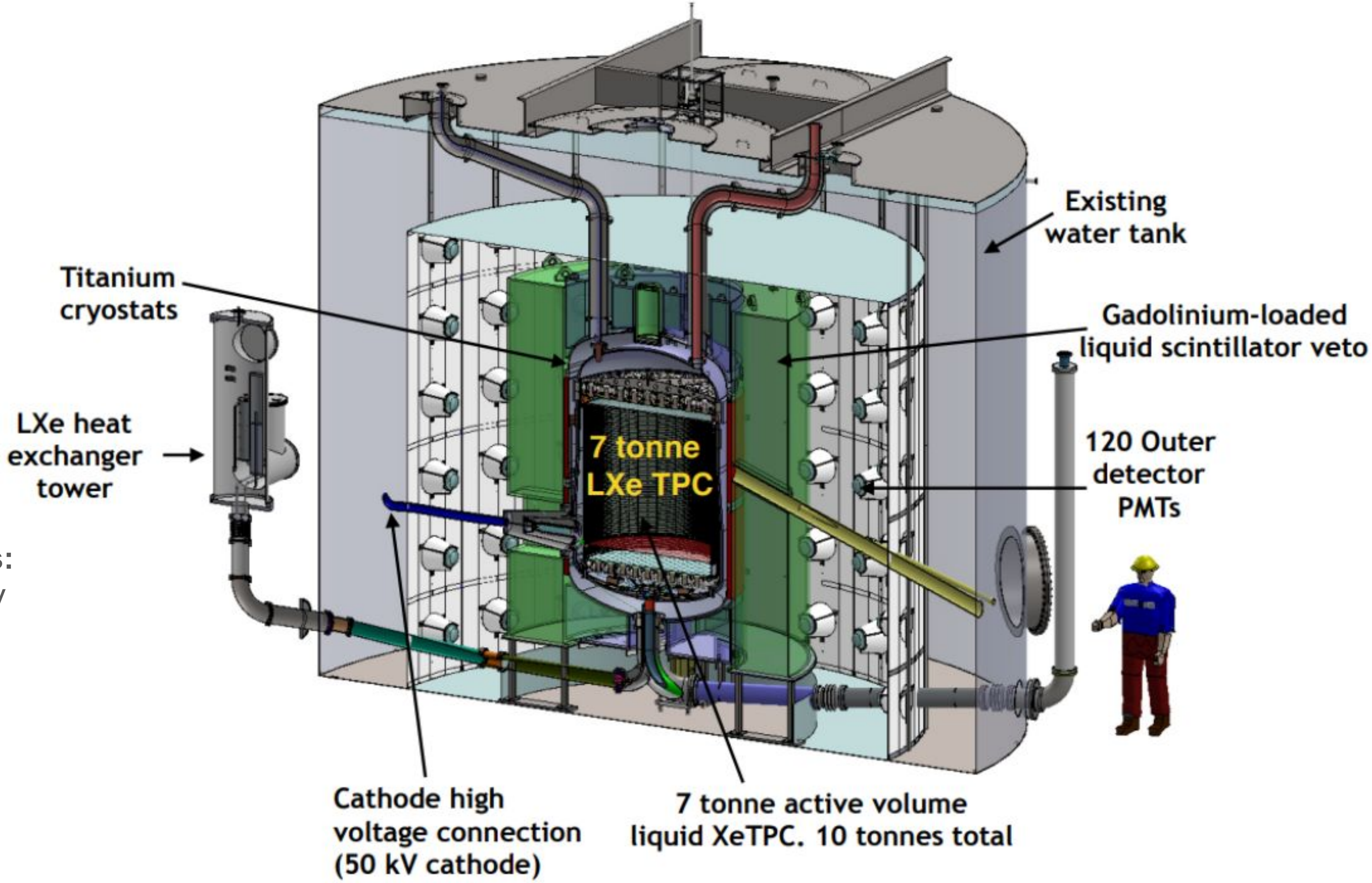
- 1.5 m diameter by 1.5 m height
- Fiducial: 5.6 T
- 494x 3'' PMTs

3 veto detector:

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

Electric field maintained by 3 electrodes:

- Cathode HV of 32 kV and G-A of 8 kV
- Extraction field: ~7.5 kV/cm
- Drift field: ~190 V/cm
    - Max drift time: 895 μs



Energy Reconstruction

$$E = W\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

$$W = 0.0137\ keV$$

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)

Light collection correction $C_{lc}(x,y)$ is applied w.r.t. position (0,0) and can be calculated as a ratio of sums of S2 LRFs in the following way:

$$C_{lc}(x,y) = \langle S2(0,0)\rangle / \langle S2(x,y)\rangle = \frac{\sum_i \lambda_i(0,0)}{\sum_i \lambda_i(x,y)}$$

$\lambda_i(x,y)$ = *Light Response Functions per PMT*

This correction is dynamically adjustable as summation can be taken over any subset of PMTs

S2 calculated from the bottom PMTs

Continuous PMT gain monitoring

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

- Non-invasive technique developed for ZEPLIN
  - Monitoring based on the Poisson distribution

- The mean signal, μ, measured by a given PMT from an SE event
  - varies with the distance between the SE and the PMT

- Since the number of photons detected (phd) by a PMT follows a **Poisson distribution**, μ can be calculated from number of events that resulted in a **null signal** (below a given threshold)

$$\boxed{P(\mu, n) = \mu^n e^{-\mu} / n!}$$

$$\boxed{P(\mu, 0) = e^{-\mu} \Rightarrow \mu = ln(P_0)}$$

$$\mu = ln(N_0/N)$$

$$\sigma_\mu = \sqrt{\frac{1}{N_0} - \frac{1}{N}}$$

$$N = Total\ Number\ of\ events$$

The PMT gain correction is the ratio between average SE area and μ

Xe Peak Fit

- 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

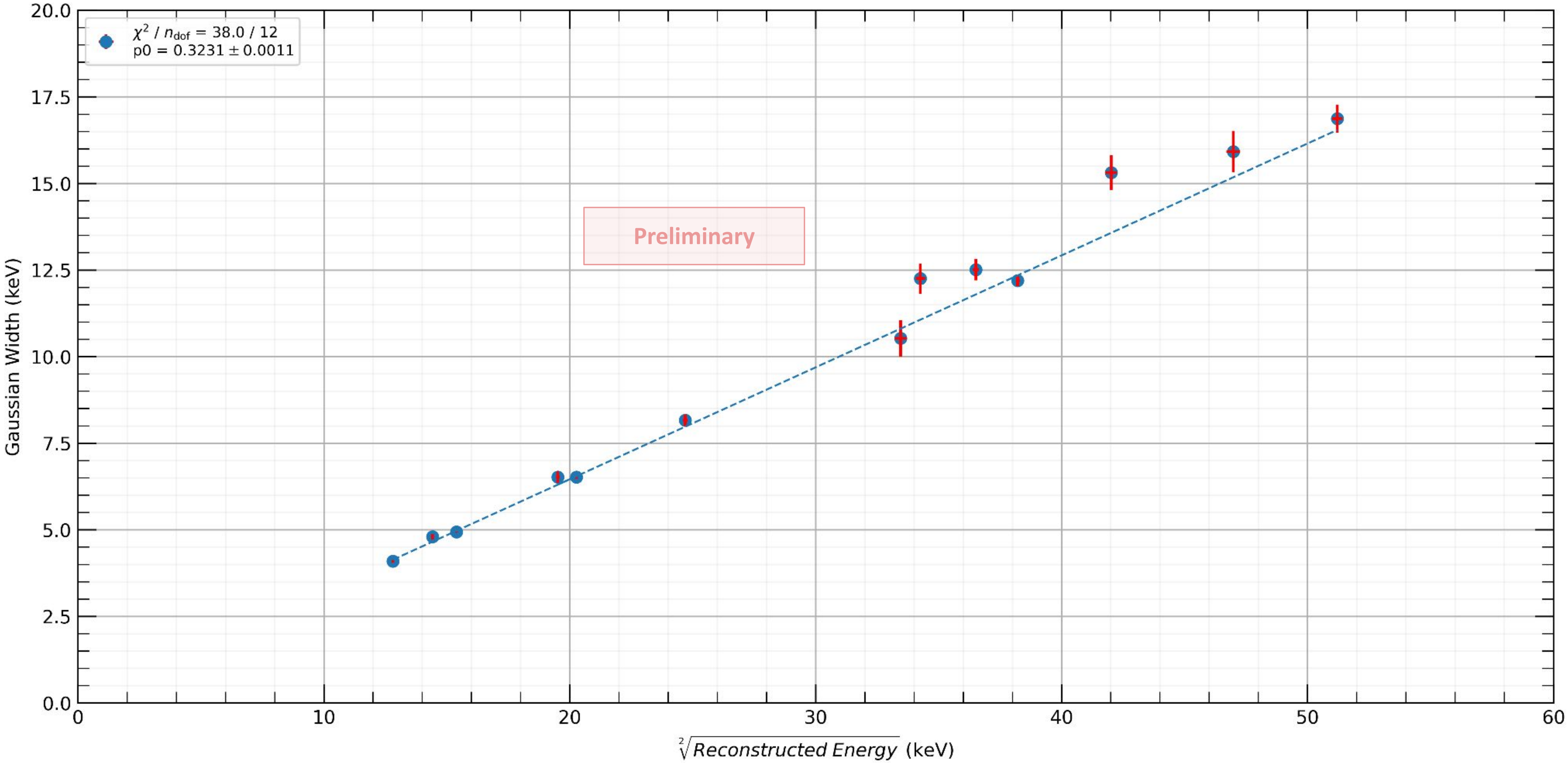
		Events	Amplitude	Expected (%)	Observed (%)
K	33.2 keV	2067	18200 ± 400	83.37	82.7 ± 2.4
L	5.2 keV	542	3090 ± 130	13.09	14.1 ± 0.7
M	1.1 keV	164	580 ± 50	2.88	2.6 ± 0.2
N	186 eV	31	133 ± 23	0.66	0.6 ± 0.1

[Link: Xe-127 analysis in LUX]

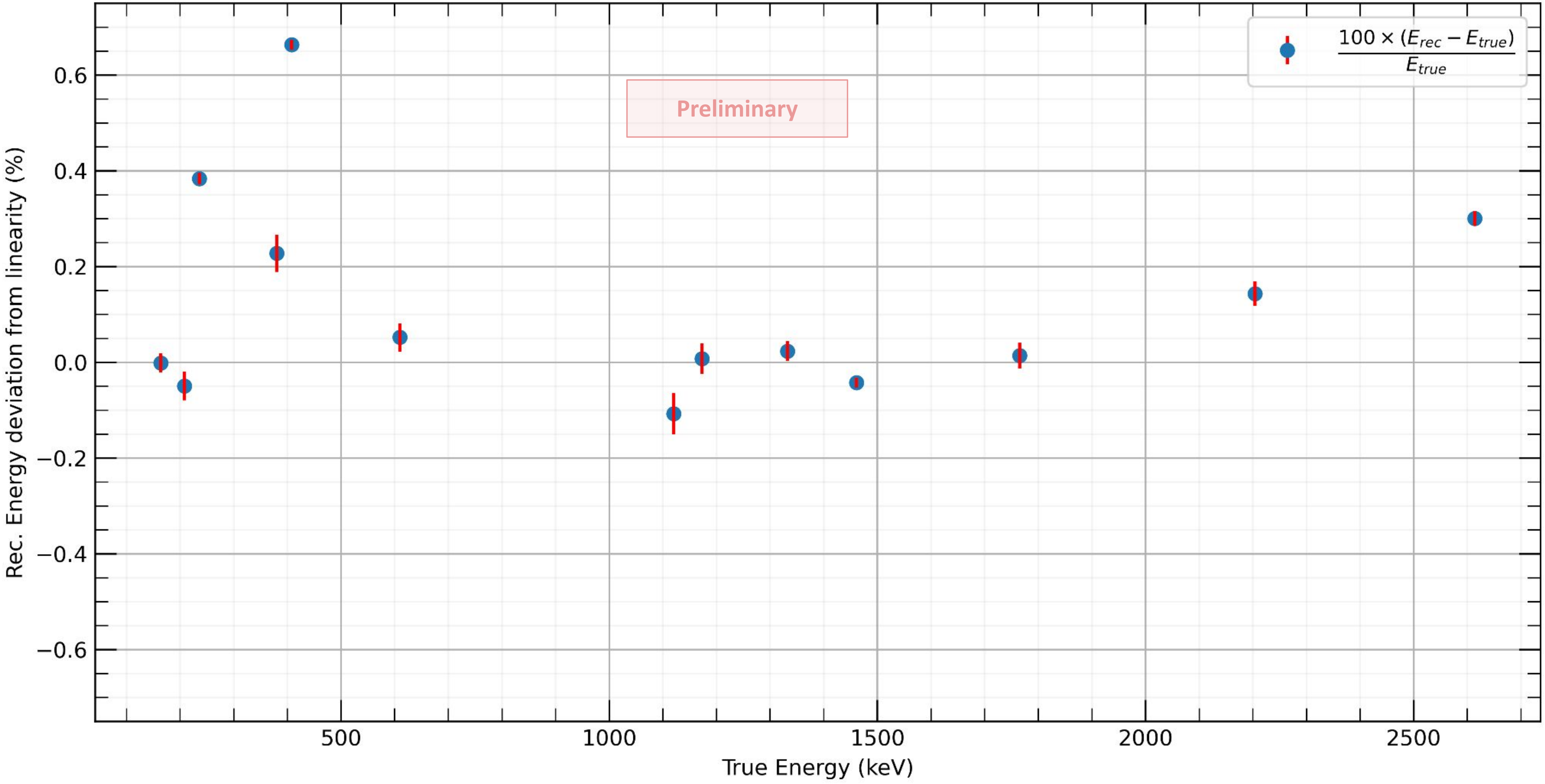
AKERIB, D. S., et al. Ultralow energy calibration of LUX detector using Xe 127 electron capture. *Physical Review D*, 2017, 96.11: 112011.

Statistical fluctuation

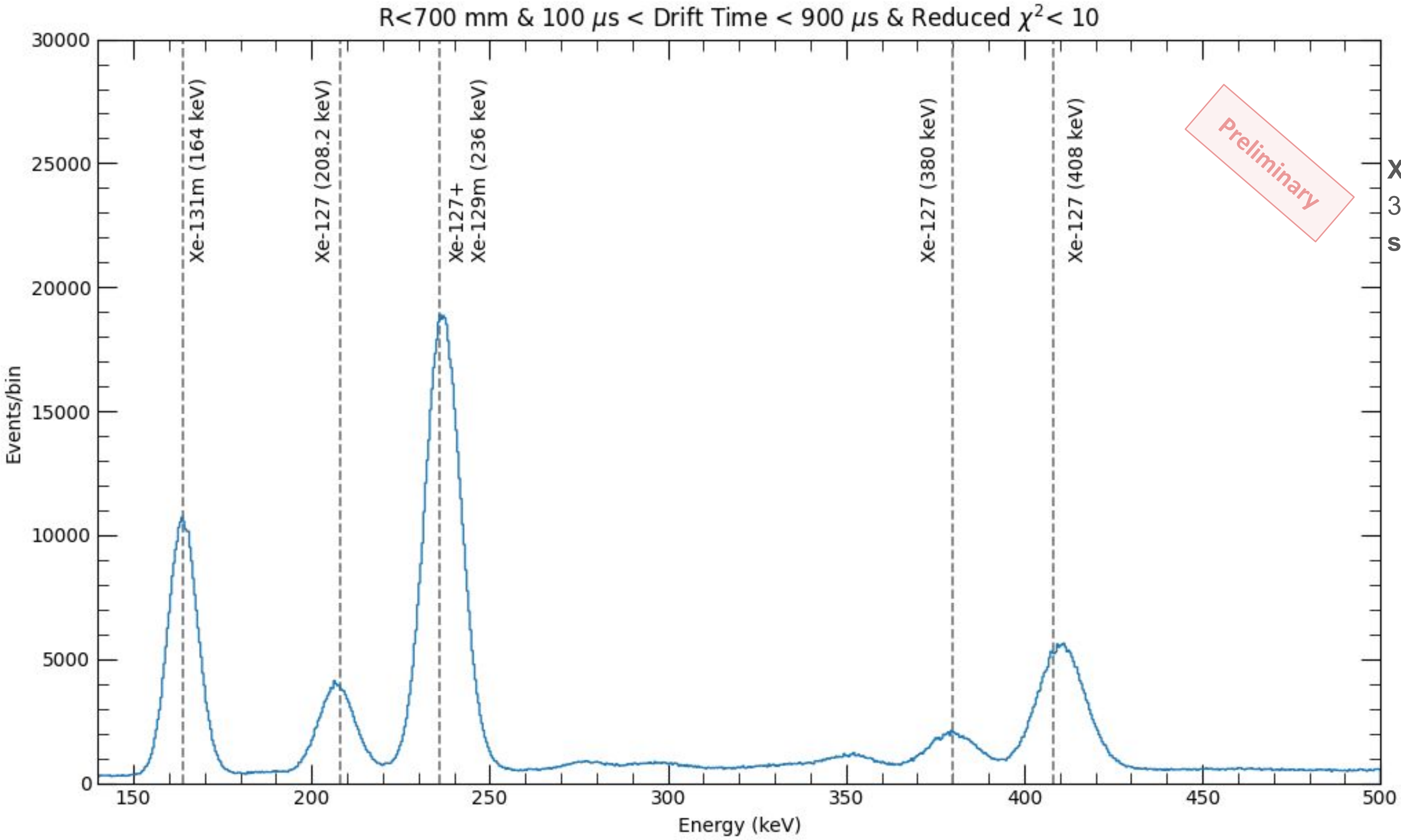
- Fit used to build a projection line in the following plot



Energy Reconstruction



Energy spectrum (Xe activation region)



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

Energy spectrum - High(er) region