Advisor:
Prof. Alfredo Davide Ferella

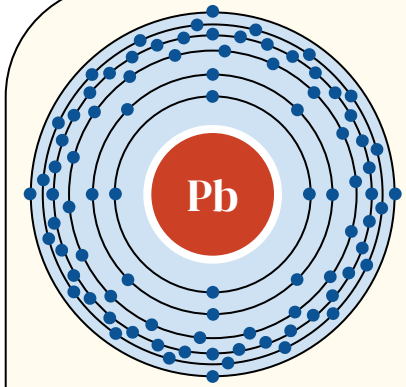
Pb studies in XENONnT

G S
S I

Ferrari Cecilia (XXXVI Cycle)
PhD Activity Report 2023

Outline

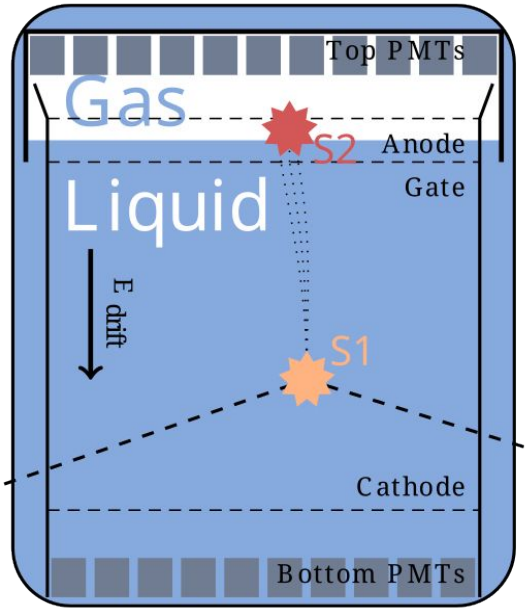
- XENONnT
- XENON WIMP searches backgrounds
- Wall background: the ^{210}Pb contaminant
- ER background
- ^{214}Pb GS BR uncertainty for LowER studies
- ^{212}Pb and ^{214}Pb branching ratios measurement

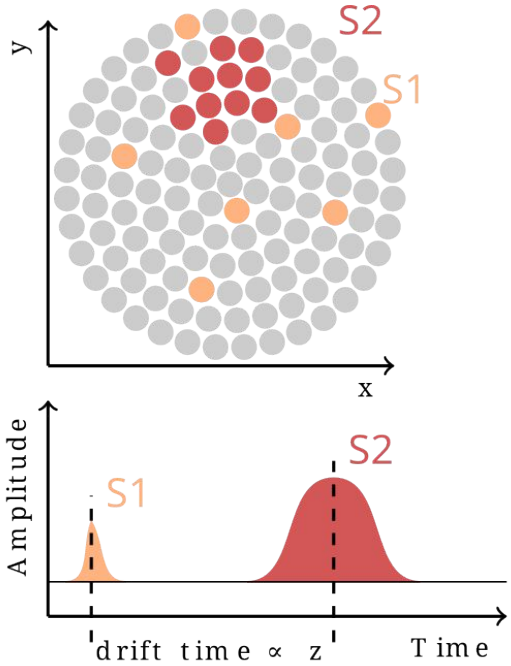


Lead

Major background for LXe TPC direct WIMP DM searches.

Isotope	half-life	decay	origin
210	22.20 y	β^-	^{238}U /^{222}Rn
212	10.64 h	β^-	^{232}Th/^{220}Rn
214	26.8 min	β^-	^{238}U /^{222}Rn





In LNGS Hall B. XENON core consists of 5.9 t LXe in a cylindrical TPC.

Particles scattering off the target produce:

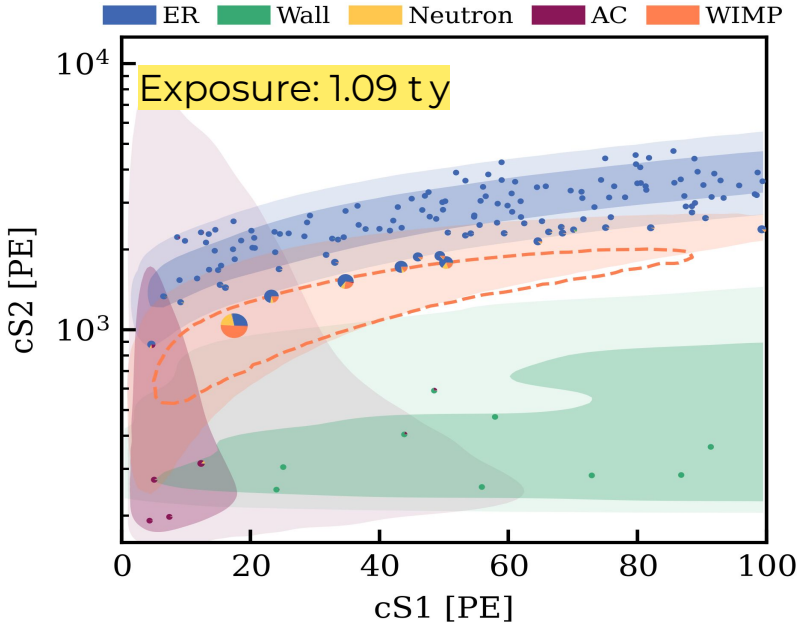
- Prompt scintillation light (S1)
- Delayed ionization signal (S2)

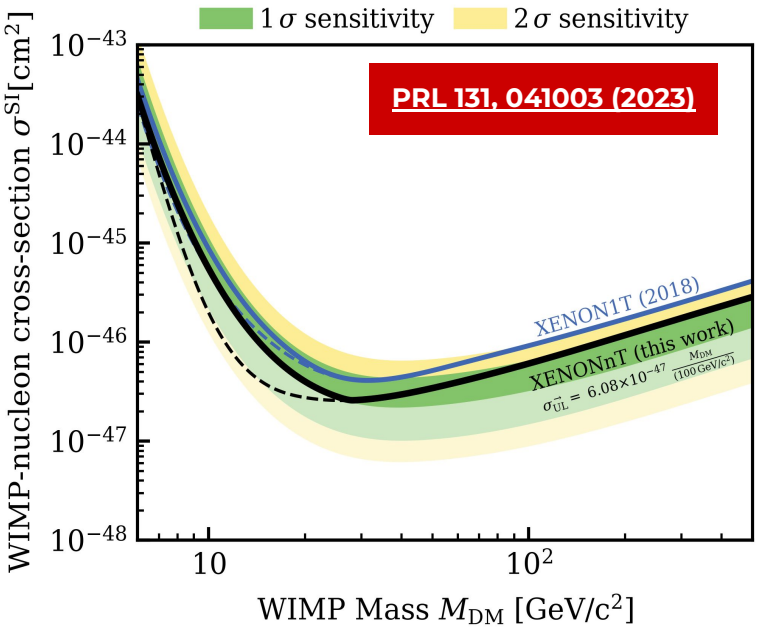
LXe TPC technology provides:

- Event position reconstruction
- Particle discrimination

XENONnT first WIMP searches result

- Wall background limits the exposure
- WIMP searches ultimately limited by AC (low M_{DM}) and ER (high M_{DM}) backgrounds



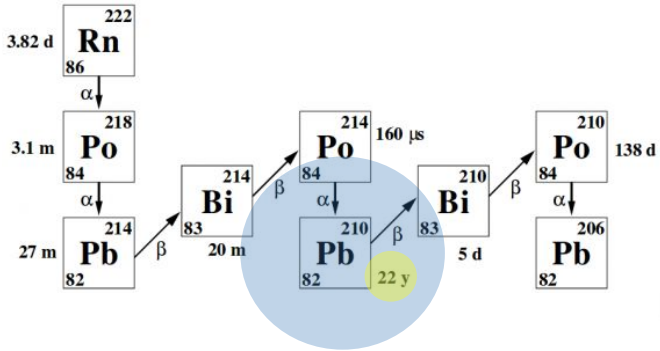


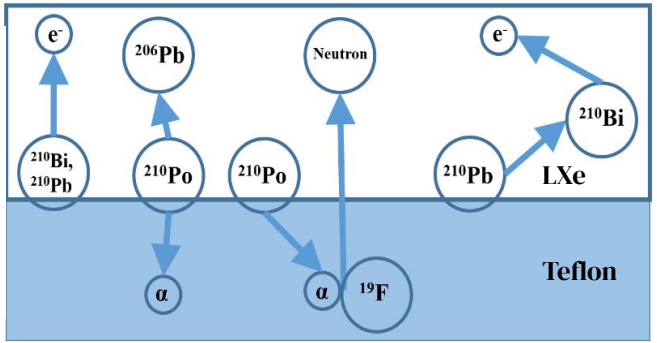

210Pb

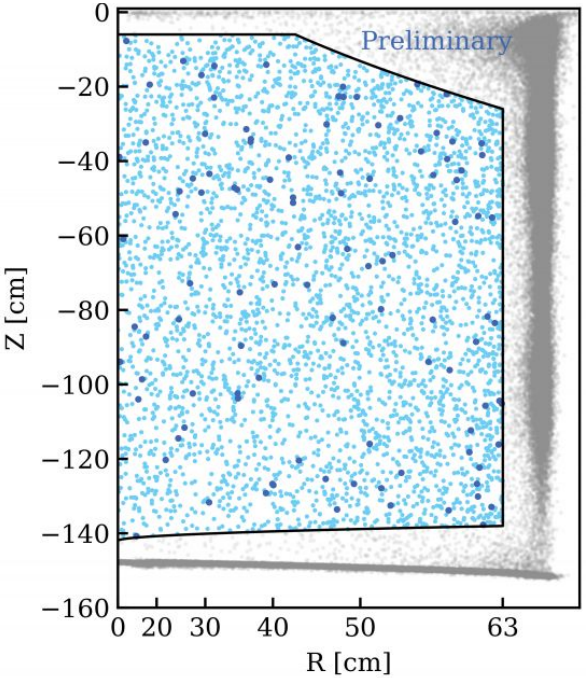
^{210}Pb and the wall background - the origins

Teflon surfaces surrounding the LXe active volume can be contaminated with Rn daughters due to "**plate out**".

The **long-lived** ($t_{1/2} \sim 22$y) **^{210}Pb isotope** gives rise to the wall background, constant throughout the whole experimental lifetime







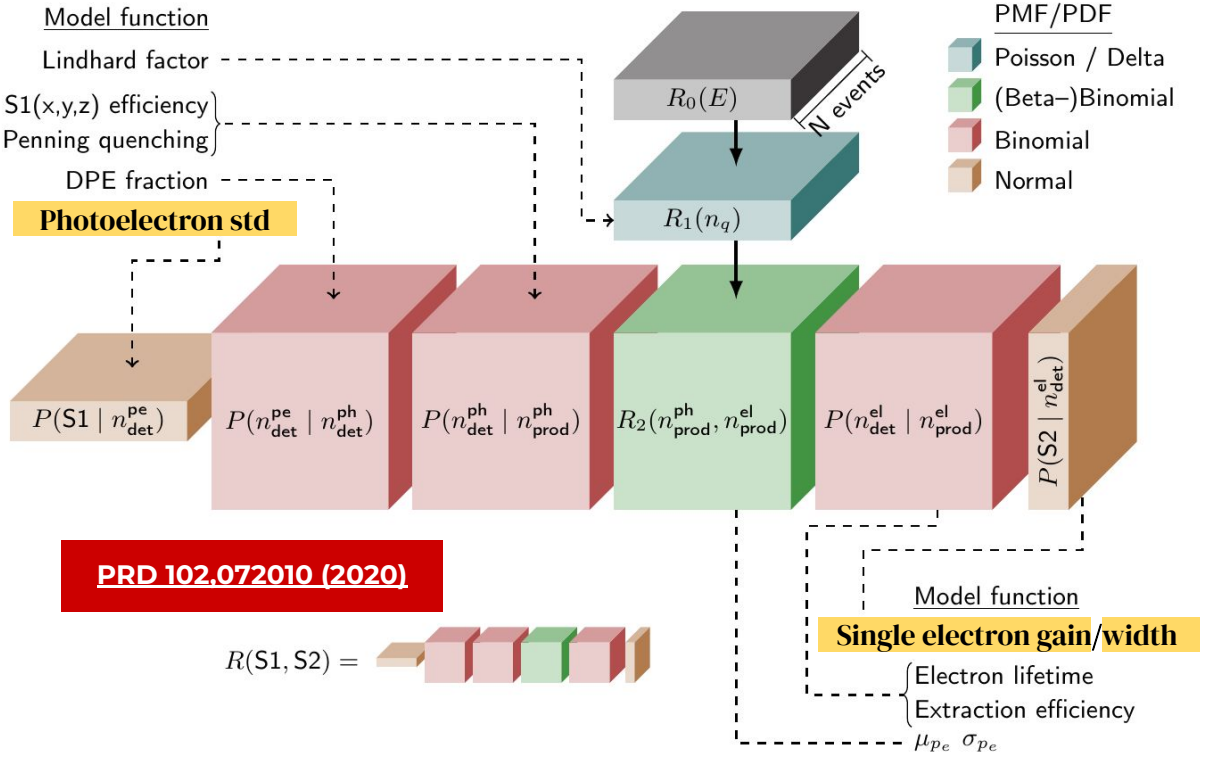
AIP Conf. Proc. 1921, 090002 (2018)

^{210}Pb and the wall background - the method

The study exploits the **flamedisx** software which permits a **multidimensional (6D) analysis** of the data.

Moreover, the explicit likelihood method reduces the computational costs

$$L = \text{Poisson}(N_{\text{tot}}|\mu) \prod_{i}^{\text{events}} \sum_{j}^{\text{sources}} \frac{R^j(\boldsymbol{s}_i)}{\mu}$$

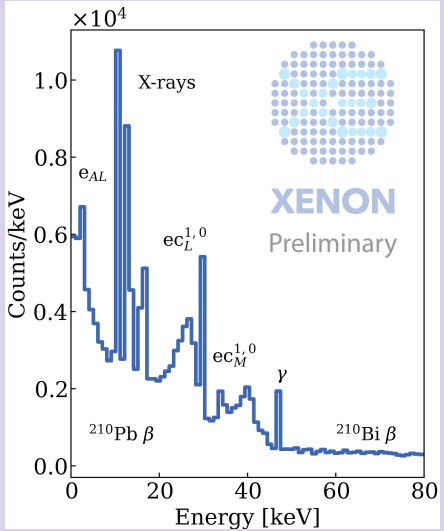


^{210}Pb and the wall background - the model

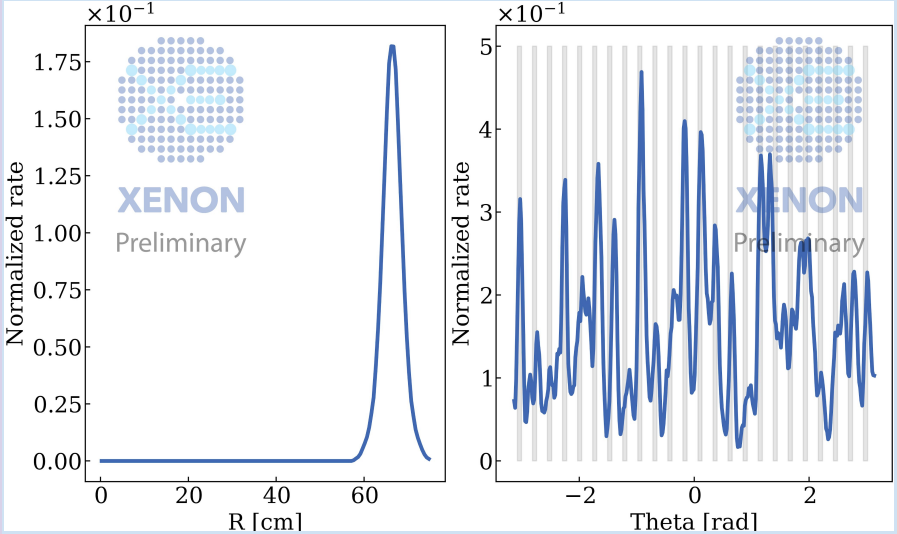
Poster @TAUP

The model needs: Energy input, Spatial input, Reduced S2 detection efficiency

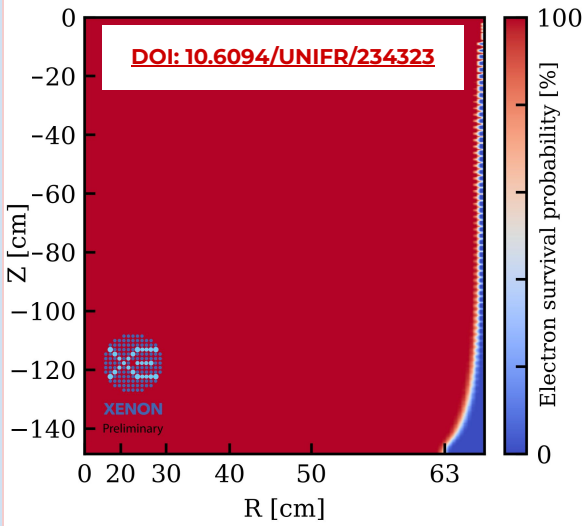
^{210}Pb chain in Teflon (G4)



data -driven R,Theta distributions and flat Z



Teflon charge up (pyCOMes)



electron_detection_eff = extraction_eff*exp(-drift_time*p0 /e_lifetime)*survival_probability(r,z)

^{210}Pb and the wall background - the results

Poster @TAUP

GSSI

The fit of a random sample of 150 events, returns the following best fit values.

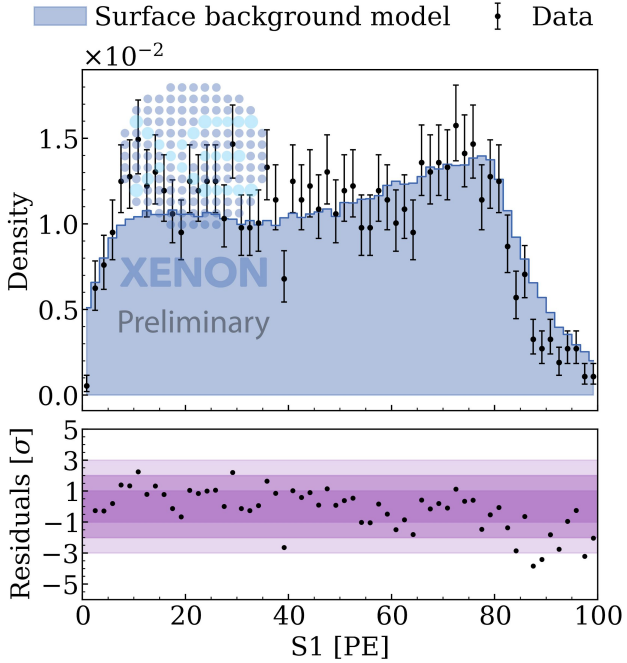
p0: 20.2 ± 0.2

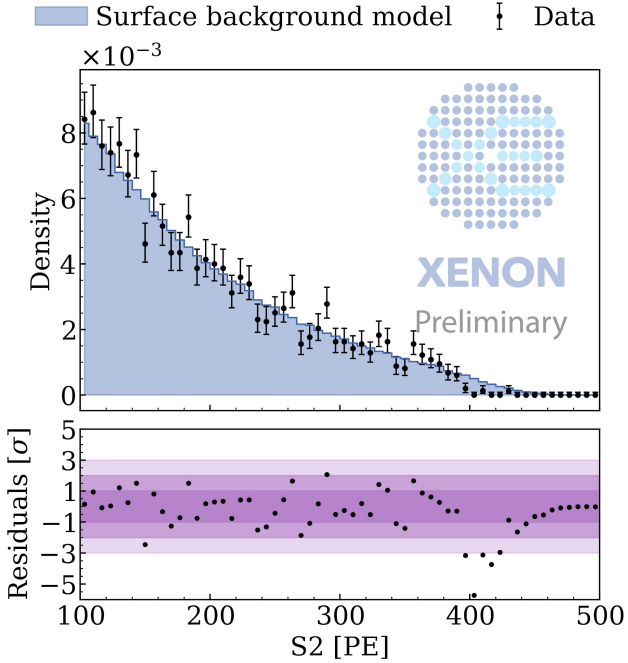
Single electron gain: (4.25 ± 0.07) PE/electrons

Single electron width: (29.1 ± 1.9) PE/electrons

Photoelectron std: (2.3 ± 1.2) PE/PE

$A^{\text{effective}}_{^{210}\text{Pb-chain}}$: (1.97 ± 0.11) mBq/m^2

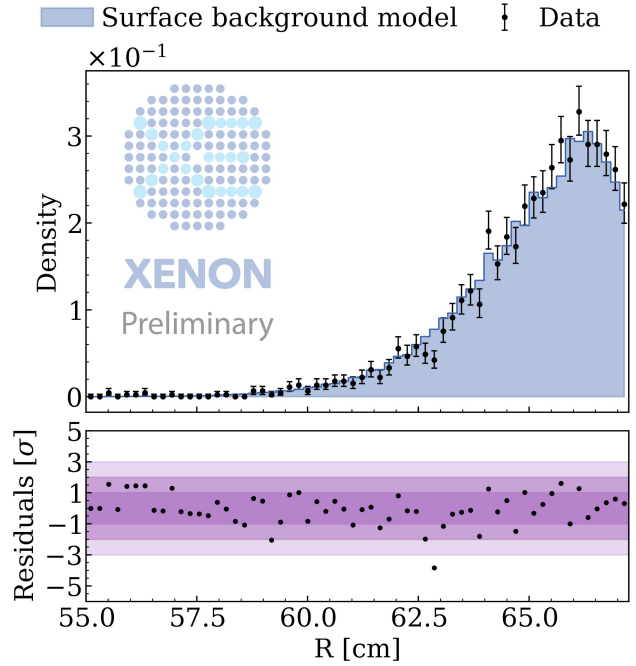


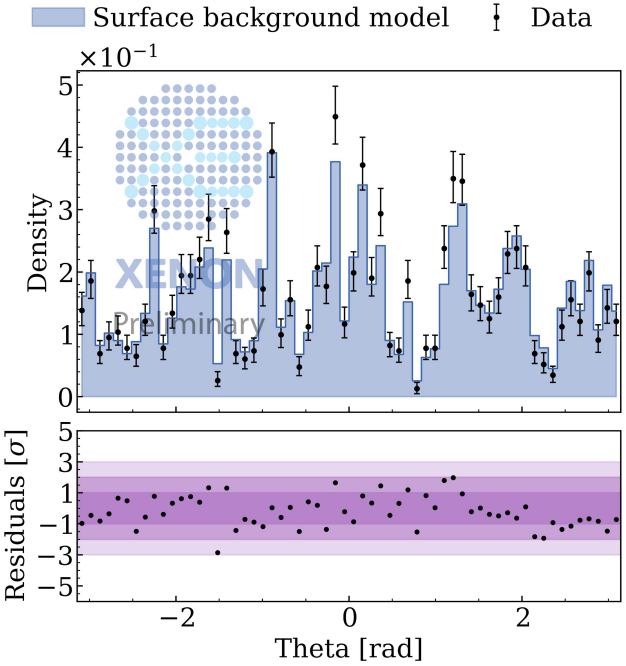


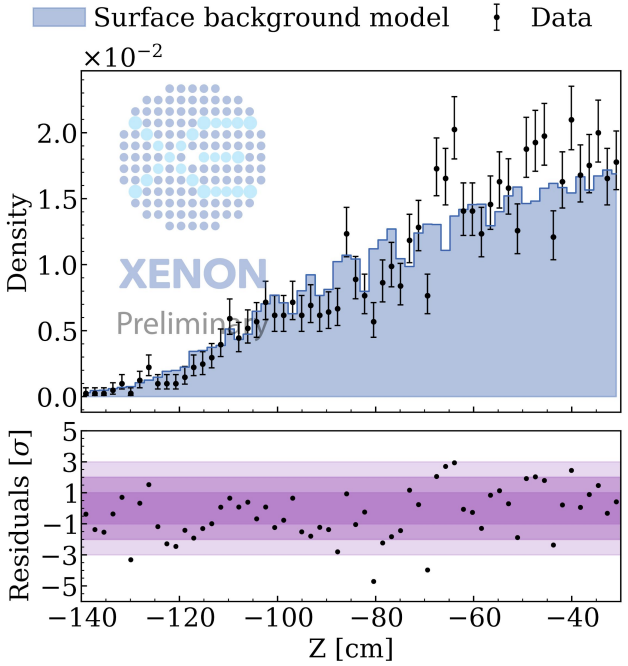
^{210}Pb and the wall background - the results

Poster @TAUP

Z non-flat distribution is a pure consequence of the S2 reduction.



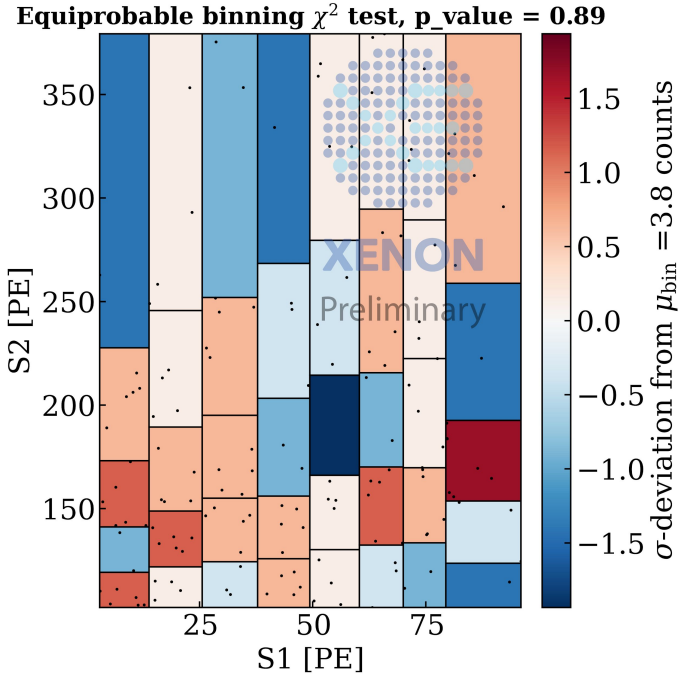


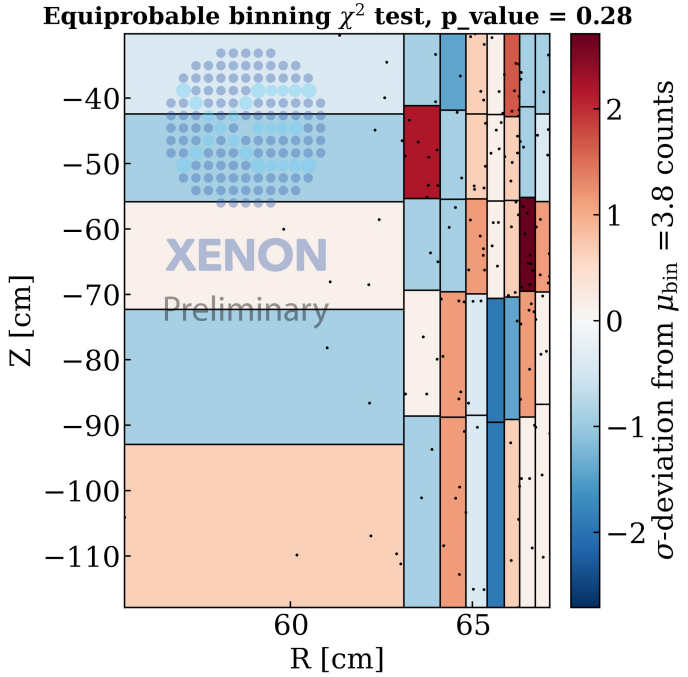


^{210}Pb and the wall background - GoF tests

Poster @TAUP

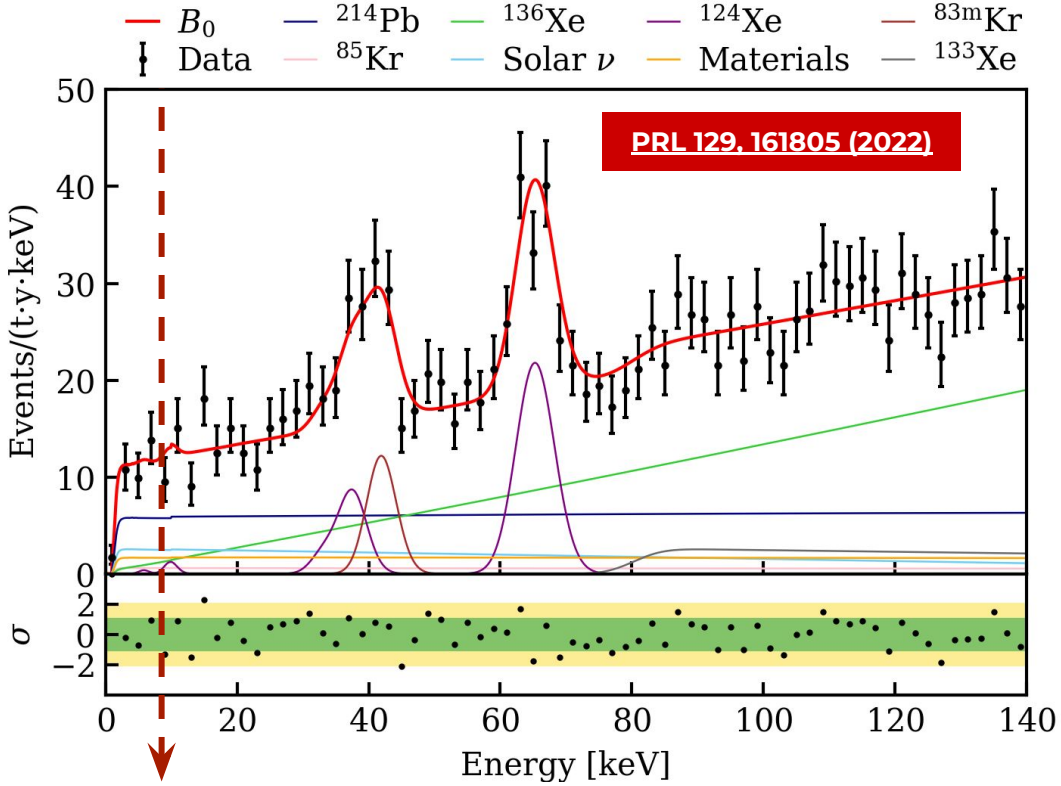
Goodness of fit equiprobable binning Chi-square tests in 2D ((S1,S2)&(R,Z)) reveal good agreement between model and fit data.






212Pb & 214Pb

^{212}Pb & ^{214}Pb branching ratios measurement - intro 1

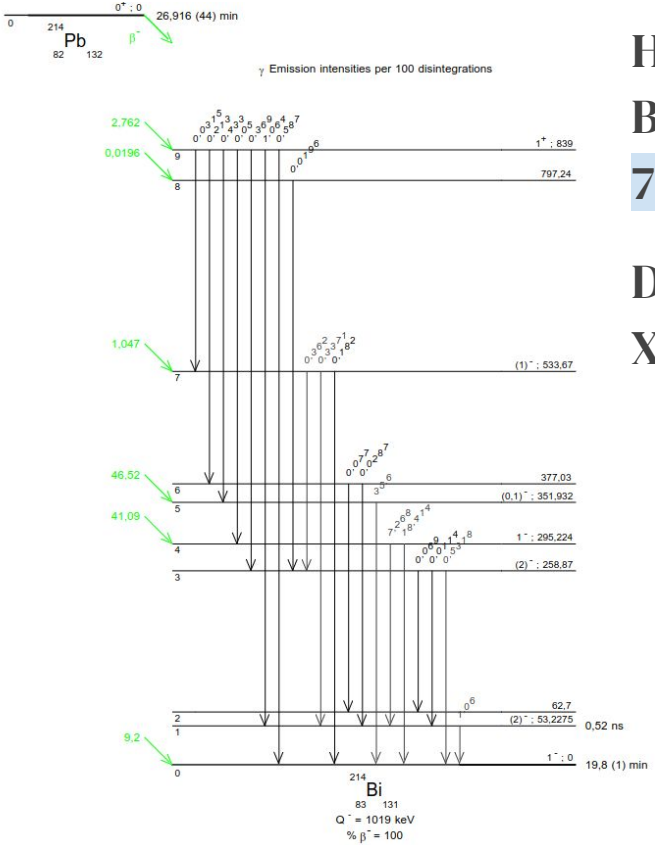


Below 35 keV the dominating ER background is ^{214}Pb.

This background could in principle be constrained by studying the alpha peaks of the ^{222}Rn chain.

Constraining ^{214}Pb background is of fundamental importance for Low ER studies, such as solar-pp neutrinos searches.

^{212}Pb & ^{214}Pb branching ratios measurement - intro 2



However, the ^{214}Pb Ground State Branching Ratio (GS BR) is reported in literature with an uncertainty of 7-10% according to the selected reference.

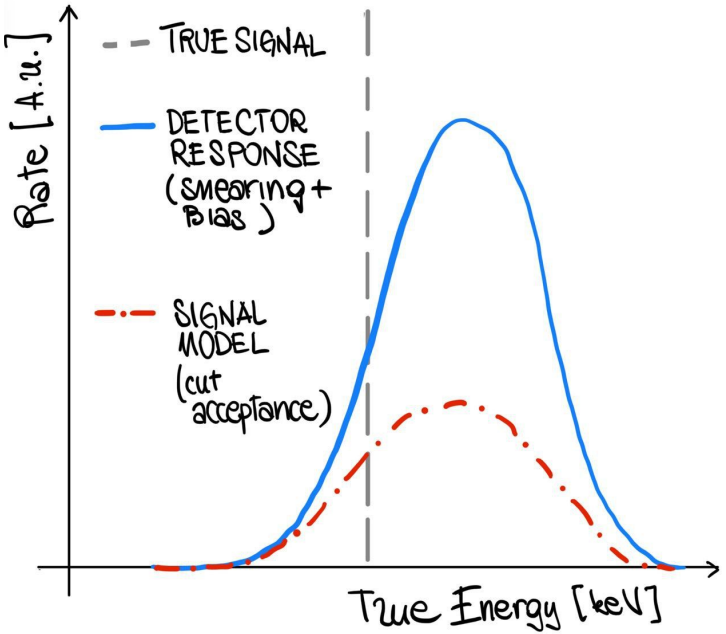
Data collected with the ^{222}Rn Calibration Campaign in XENONnT, will help in improving this measurement

	Energy keV	Probability × 100	Nature	lg ft
$\beta^-_{0,9}$	180 (11)	2,762 (22)	Allowed	4,5
$\beta^-_{0,8}$	222 (11)	0,0196 (27)	Allowed	6,9
$\beta^-_{0,7}$	485 (11)	1,047 (17)	1st Forbidden	6,2
$\beta^-_{0,5}$	667 (11)	46,52 (37)	1st Forbidden	5,1
$\beta^-_{0,4}$	729 (11)	41,09 (39)	1st Forbidden	5,2
$\beta^-_{0,0}$	1019 (11)	9,2 (7)	1st Forbidden	6,3

^{212}Pb & ^{214}Pb branching ratios measurement - method

Ingredients for the fit

- True spectra of the sources
  - G4/theoretical models for continuous bkg
- Detector response:
  - Smearing and bias
- Signal model:
  - Cut acceptance curves from simulations

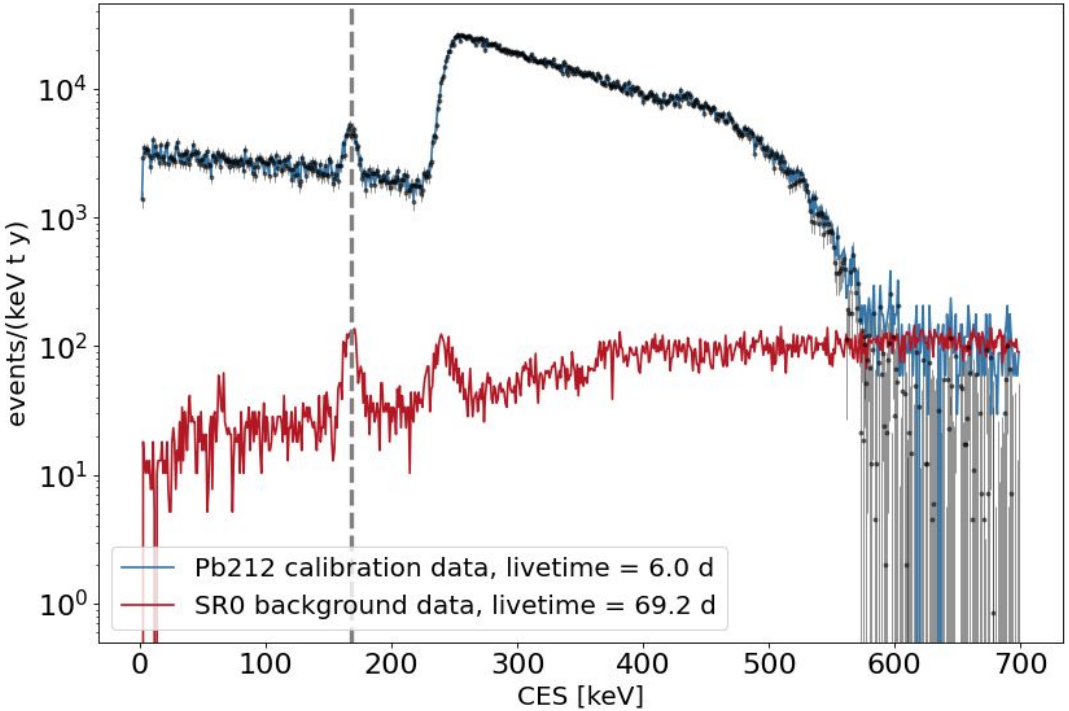


^{212}Pb branching ratios measurement - data

In SR0 a ^{220}Rn calibration was performed.

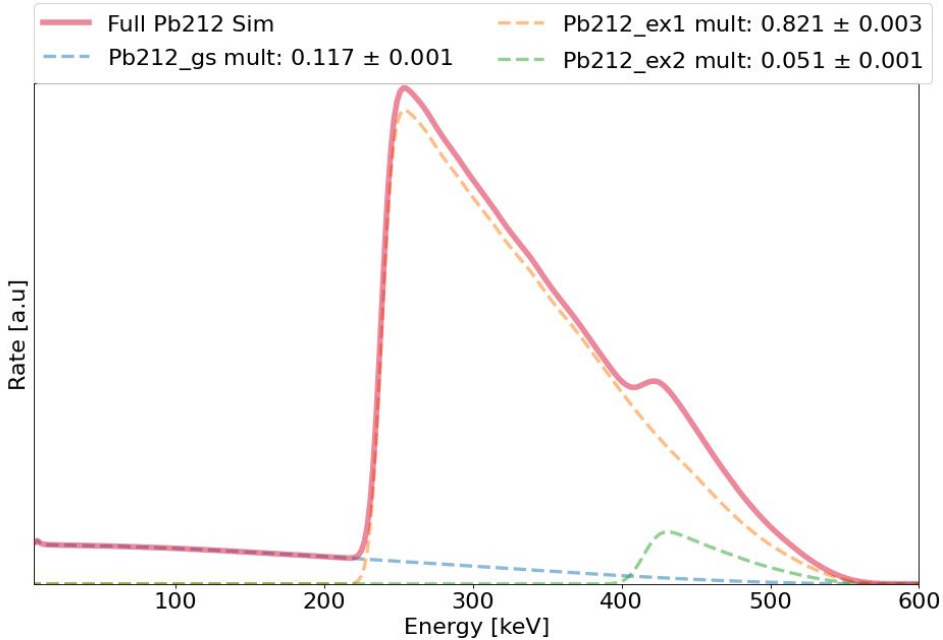
By subtracting from this data-set the SR0 background, a clean ^{212}Pb sample can be obtained.

^{212}Pb branching ratios measurement should result easier since it features only 2 excited states and data analysis corrections are well known for SR0.

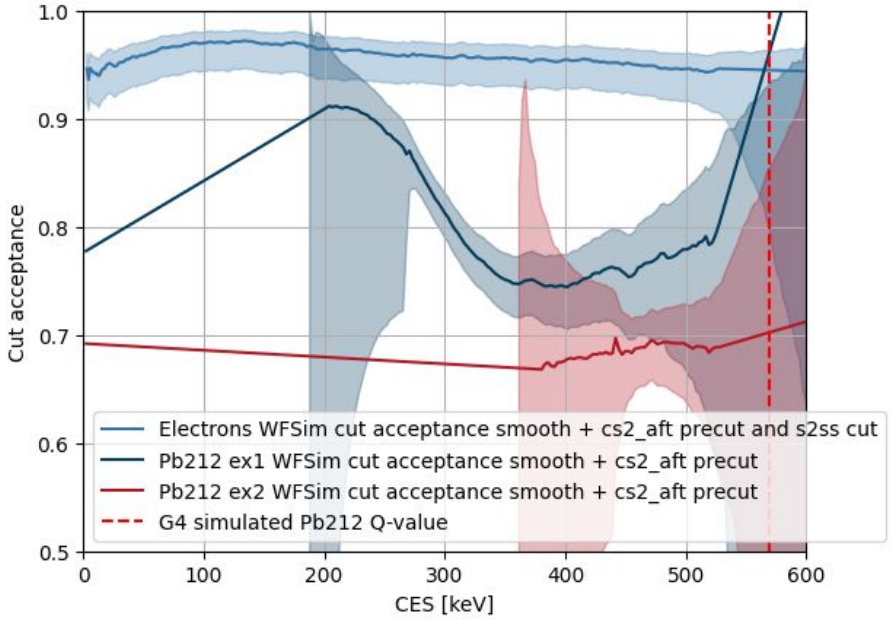


^{212}Pb branching ratios measurement - cut efficiency

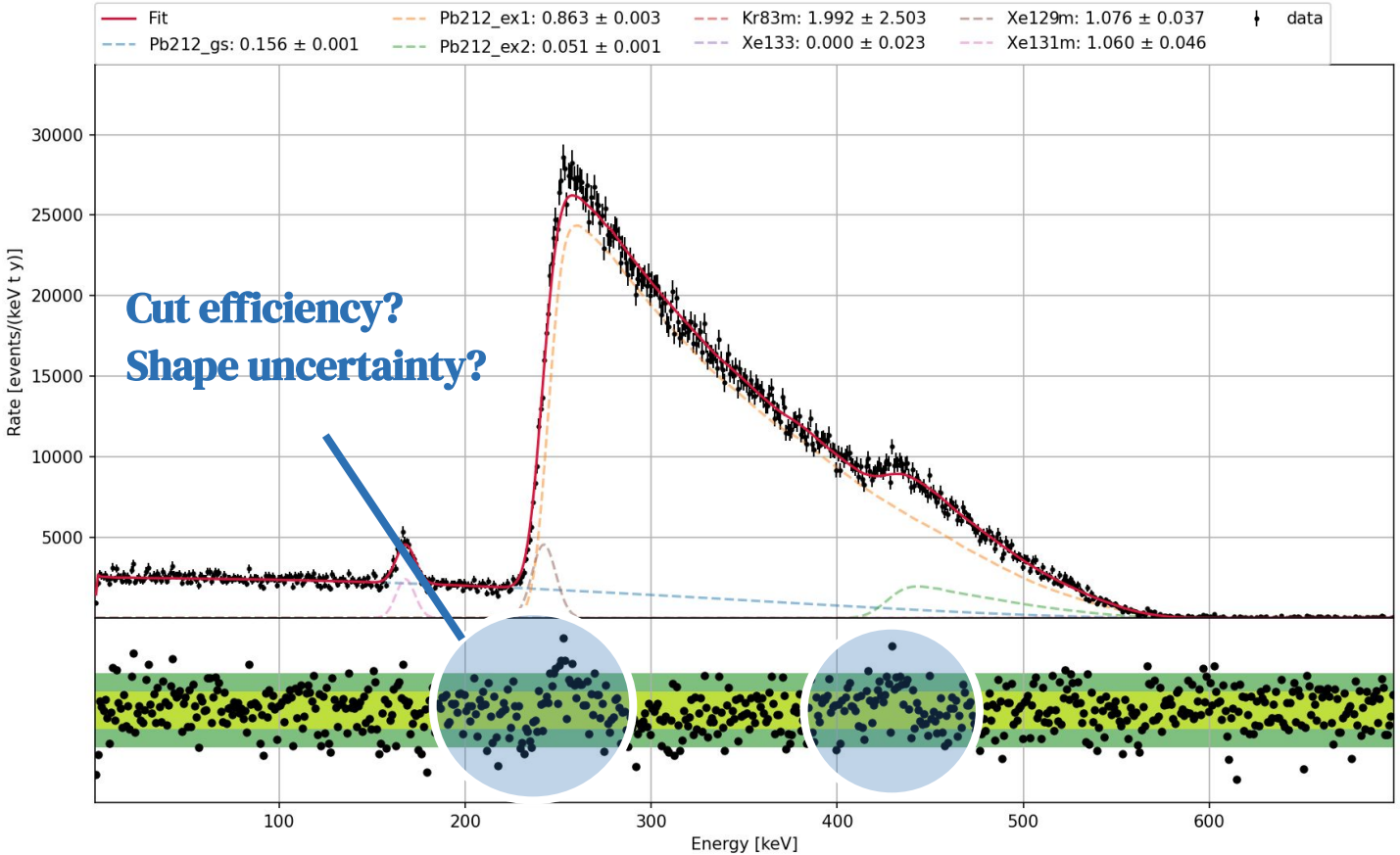
^{212}Pb simulated detector responses



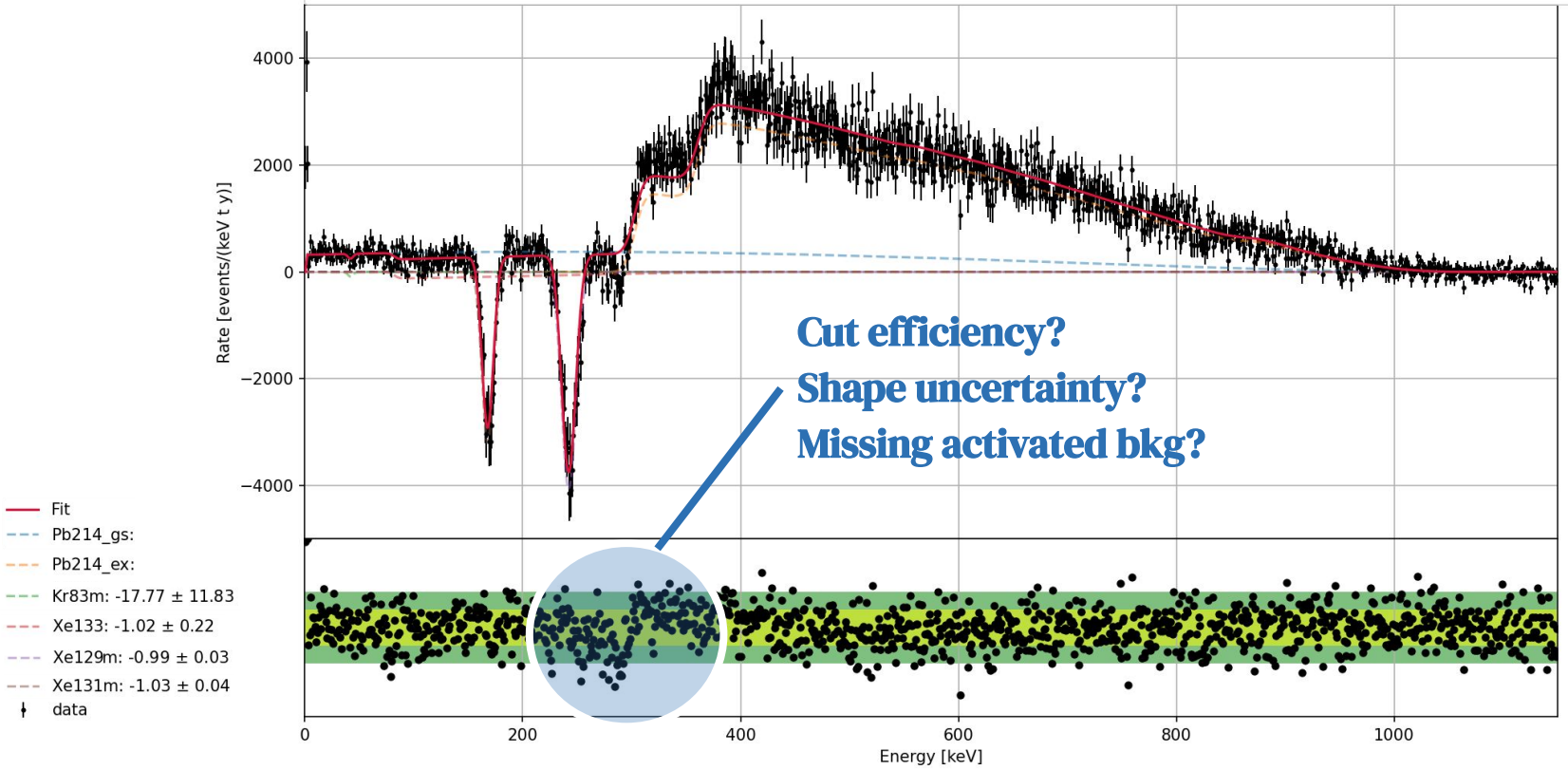
^{212}Pb Cut efficiency curves from sim



^{212}Pb branching ratios measurement - preliminary



^{214}Pb branching ratios measurement - preliminary



Prospects

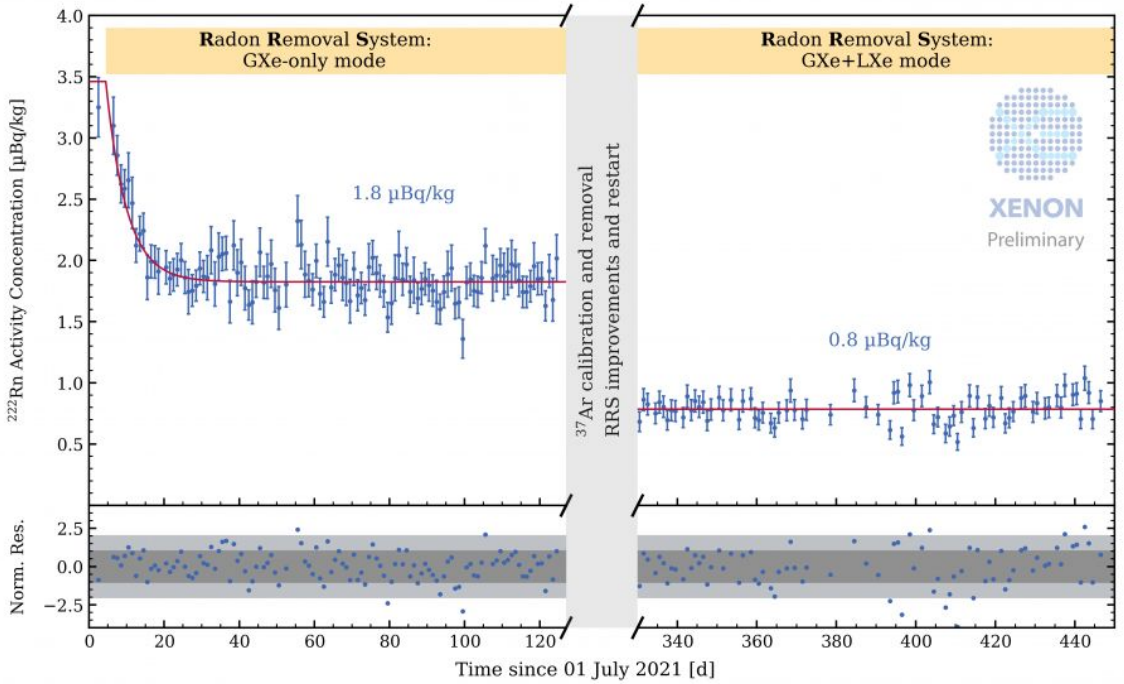
Legend:
- Why is my work important?
- What I plan to do next year

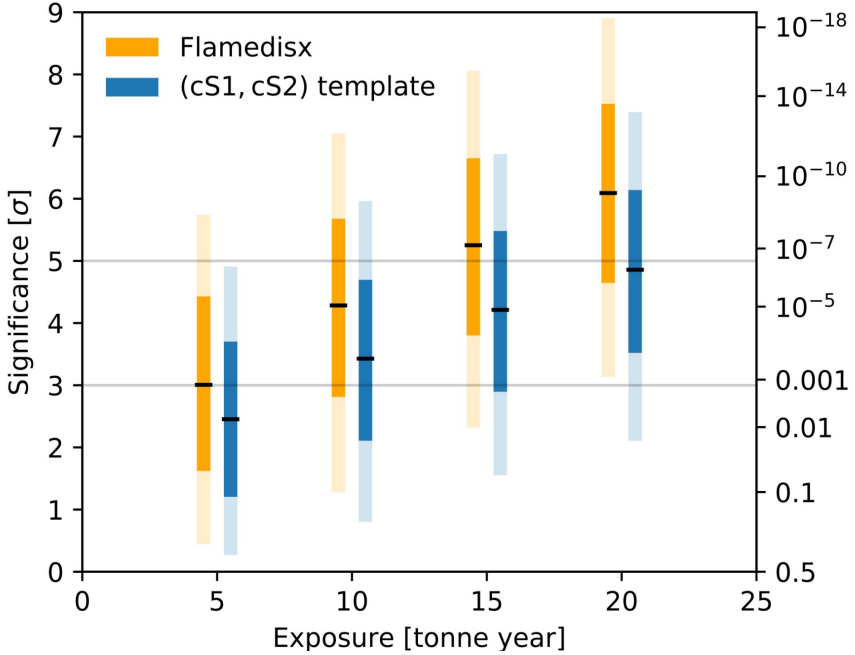
^{210}Pb
- **First time** a physics-driven model for the wall bkg in LXe TPC is made
- With flamedisx team support, refitting SR0 background for WIMP searches: first time in 6D.

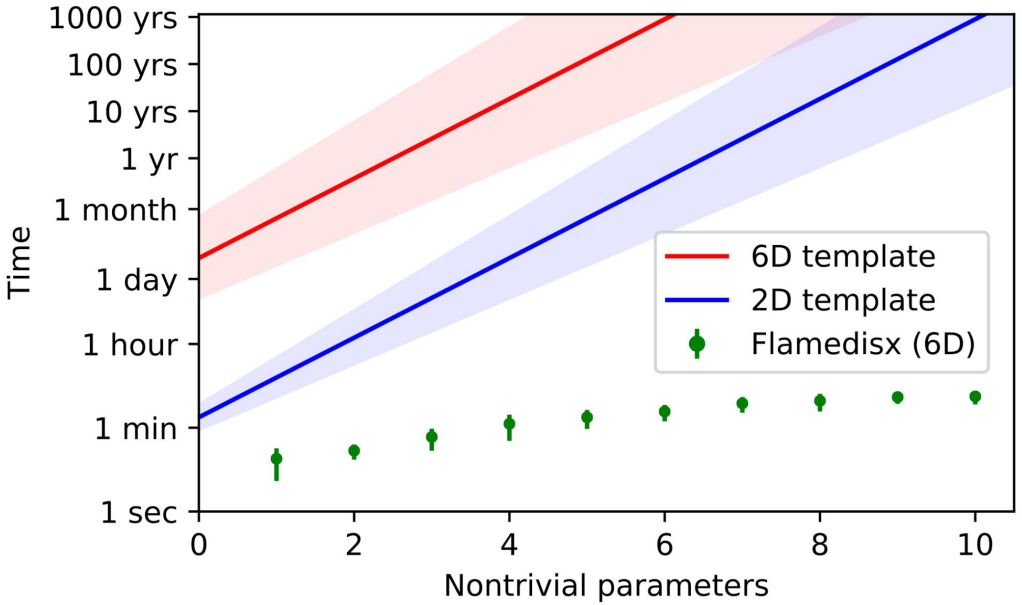
^{212}Pb
- Expected **improved precision** wrt literature values
- Benefit for solar-pp studies and other experiments low energy studies

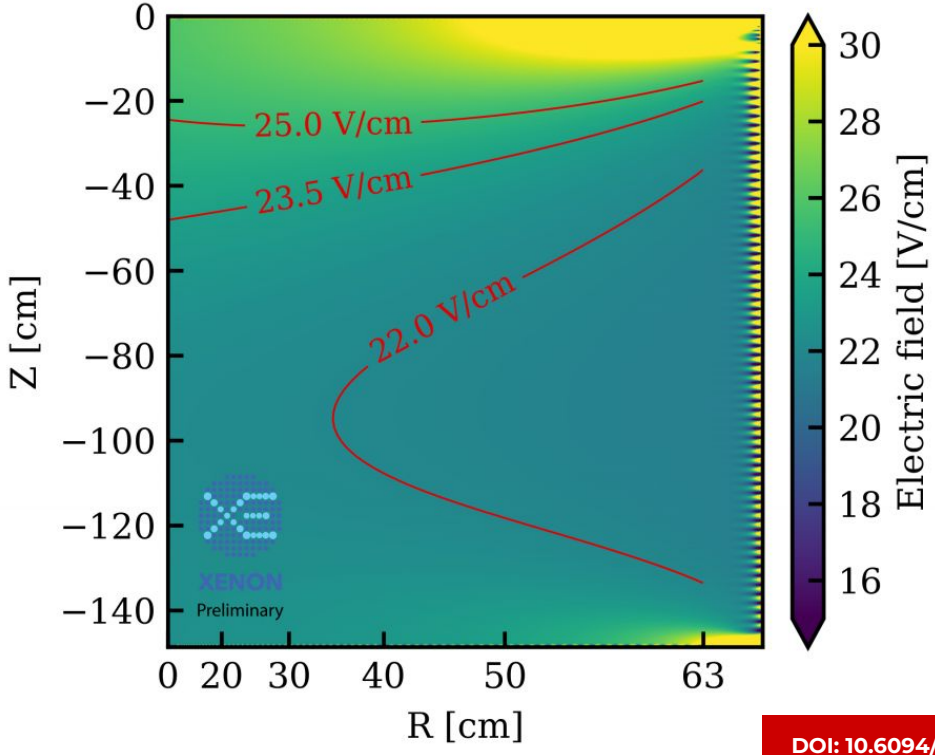
^{214}Pb
- Multiple scatter events integration to increase statistics
- Understanding mismodeling origin

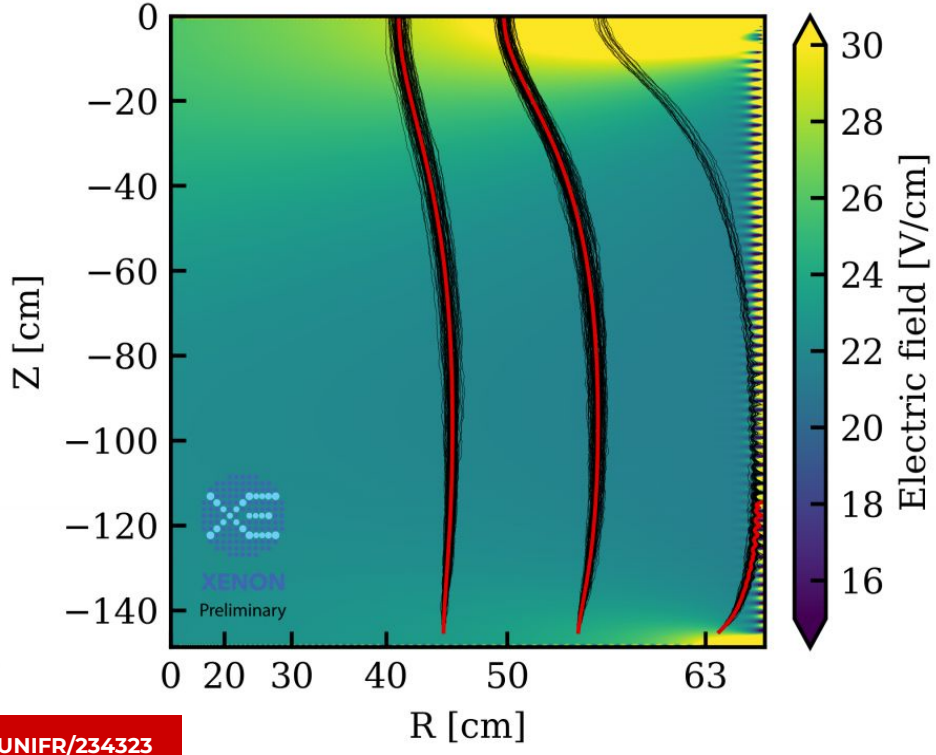
Thank you for your attention


Radon Removal System:
GXe-only mode
Radon Removal System:
GXe+LXe mode
1.8 µBq/kg
0.8 µBq/kg
XENON
Preliminary
37Ar calibration and removal
RRS improvements and restart
222Rn Activity Concentration [µBq/kg]
Norm. Res.
Time since 01 July 2021 [d]

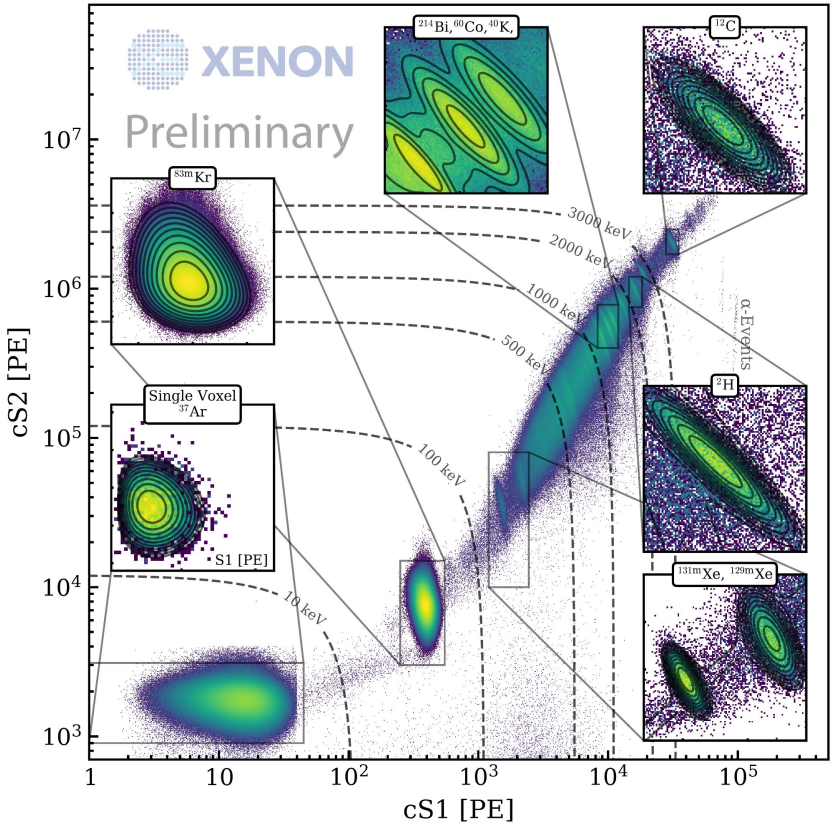

Flamedisx
(cS1, cS2) template
Significance [σ]
Exposure [tonne year]
0
5
10
15
20
25
1
2
3
4
6
7
8
9
10^{-18}
10^{-14}
10^{-10}
10^{-7}
10^{-5}
0.001
0.01
0.1
0.5

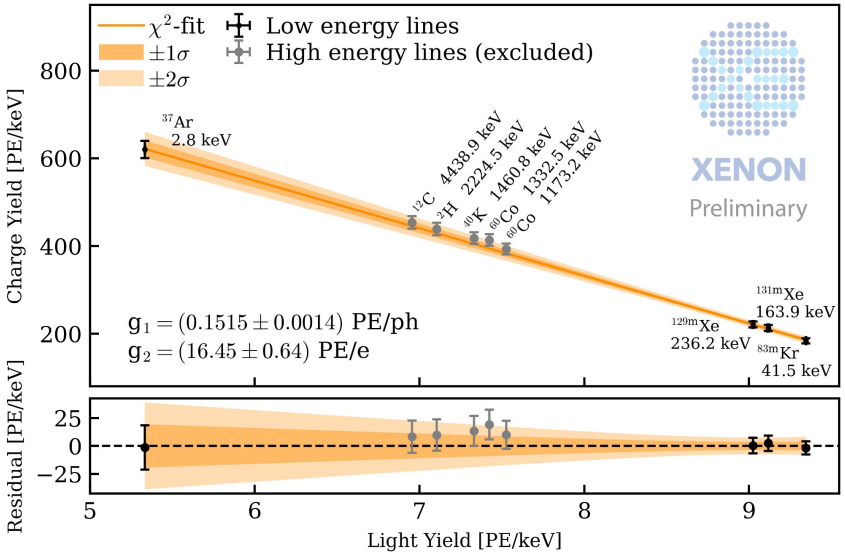

Time
1000 yrs
100 yrs
10 yrs
1 yr
1 month
1 day
1 hour
1 min
1 sec
6D template
2D template
Flamedisx (6D)
0
2
4
6
8
10
Nontrivial parameters

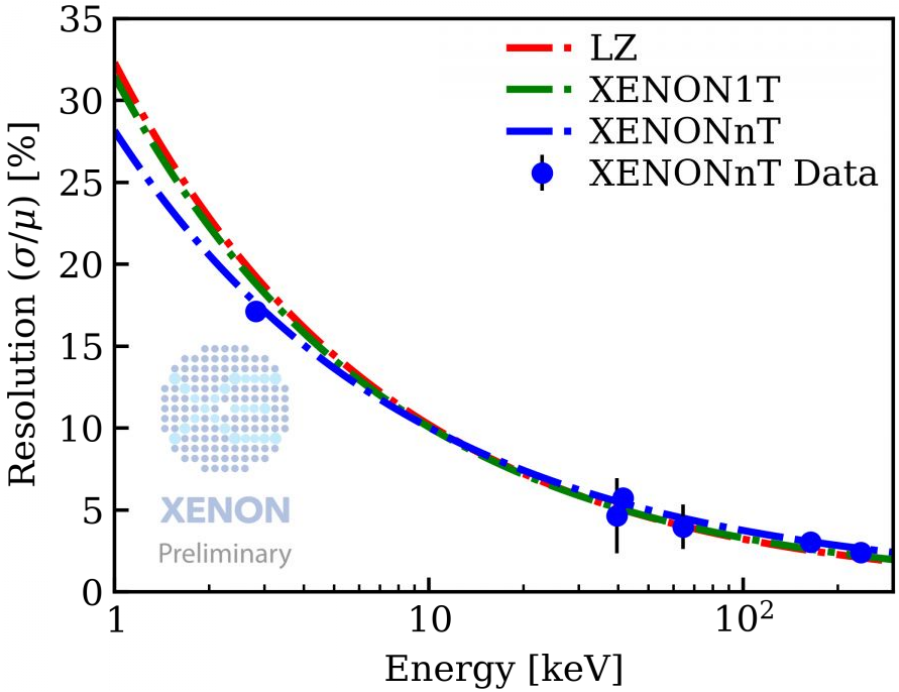


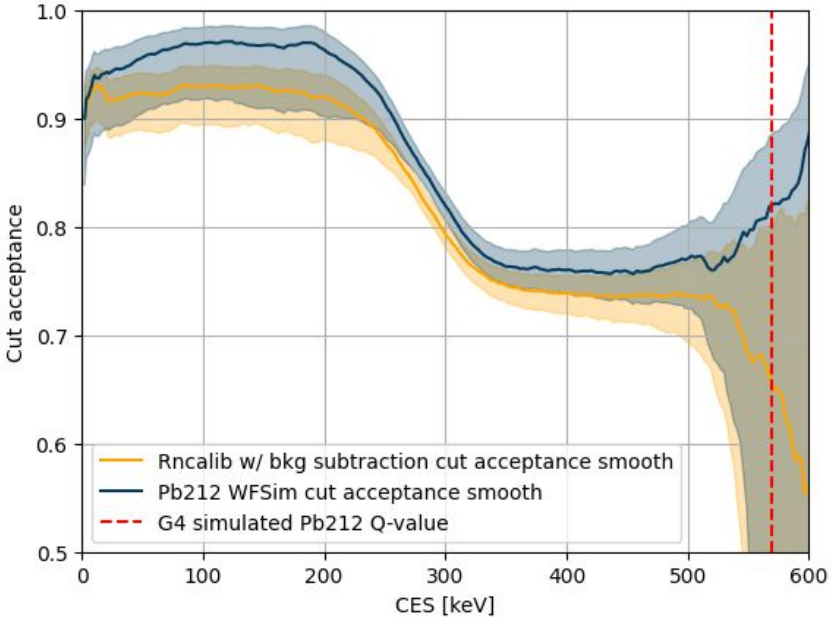


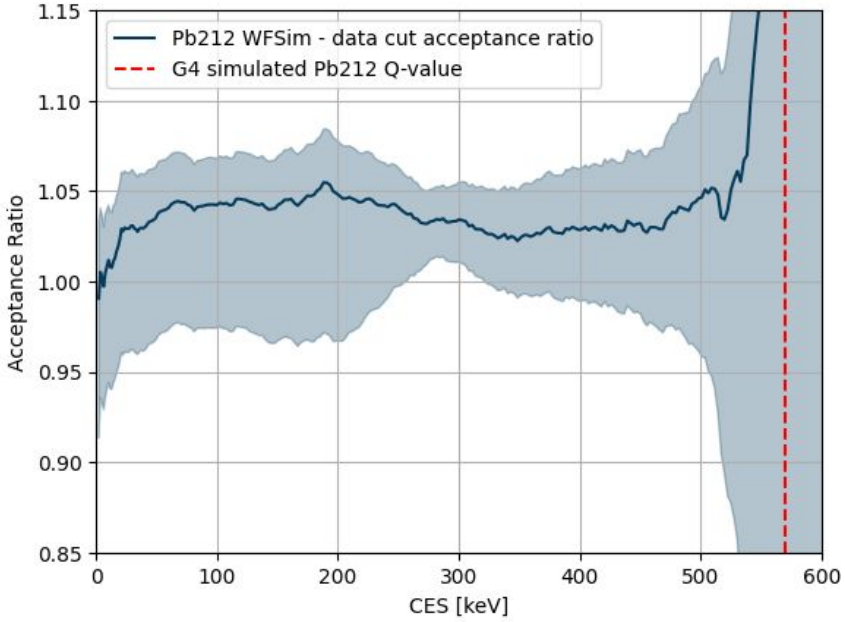
DOI: 10.6094/UNIFR/234323


XENON
Preliminary
^{214}Bi, ^{60}Co, ^{40}K,
^{12}C
^{83m}Kr
3000 keV
2000 keV
1000 keV
500 keV
100 keV
10 keV
α-Events
Single Voxel
^{37}Ar
S1 [PE]
^{2}H
^{131m}Xe, ^{129m}Xe
cS2 [PE]
cS1 [PE]

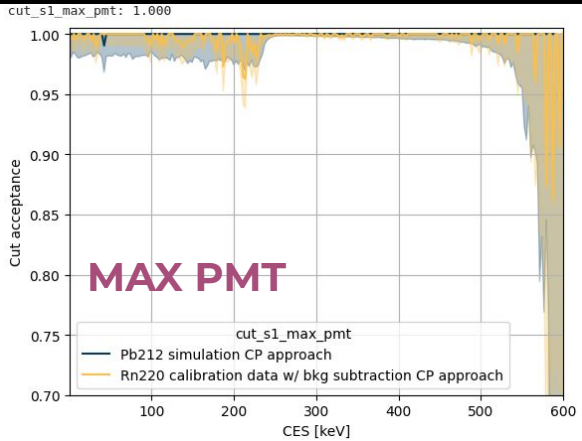

χ^2-fit
$\pm1\sigma$
$\pm2\sigma$
Low energy lines
High energy lines (excluded)
XENON
Preliminary
^{37}Ar
2.8 keV
^{12}C 4438.9 keV
^{3}H 2224.5 keV
^{40}K 1460.8 keV
^{60}Co 1332.5 keV
^{60}Co 1173.2 keV
^{131m}Xe
163.9 keV
^{129m}Xe
236.2 keV
^{83m}Kr
41.5 keV
$g_1 = (0.1515 \pm 0.0014)$ PE/ph
$g_2 = (16.45 \pm 0.64)$ PE/e
Charge Yield [PE/keV]
Residual [PE/keV]
Light Yield [PE/keV]

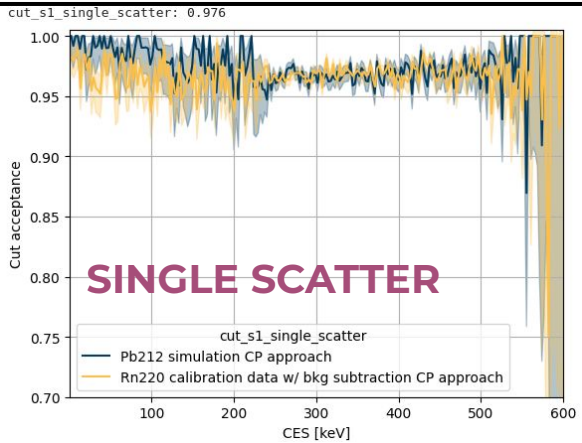

LZ
XENON1T
XENONnT
XENONnT Data
Resolution (σ/μ) [%]
Energy [keV]
XENON
Preliminary
0
5
10
15
20
25
30
35
1
10
10^2

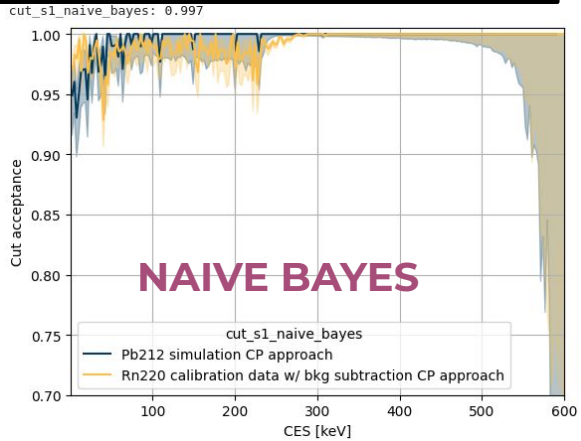

Cut acceptance
CES [keV]
Rncalib w/ bkg subtraction cut acceptance smooth
Pb212 WFSim cut acceptance smooth
G4 simulated Pb212 Q-value


Acceptance Ratio
CES [keV]
Pb212 WFSim - data cut acceptance ratio
G4 simulated Pb212 Q-value

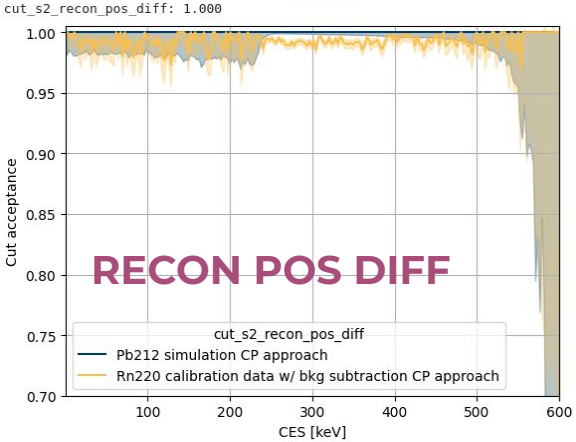
S1

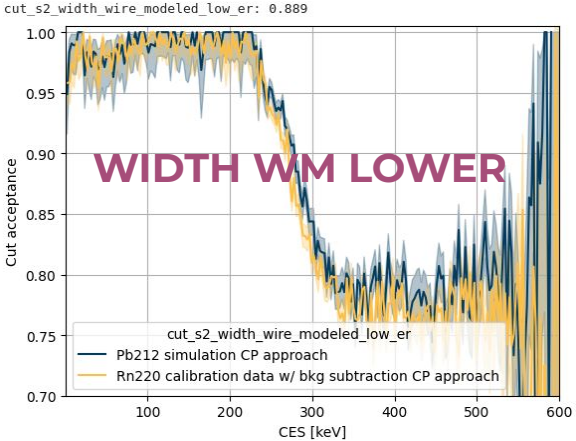

cut_s1_max_pmt: 1.000
MAX PMT
cut_s1_max_pmt
Pb212 simulation CP approach
Rn220 calibration data w/ bkg subtraction CP approach
Cut acceptance
CES [keV]

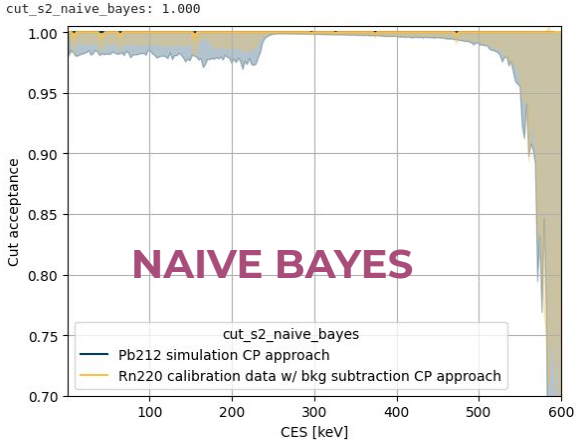

cut_s1_single_scatter: 0.976
SINGLE SCATTER
cut_s1_single_scatter
Pb212 simulation CP approach
Rn220 calibration data w/ bkg subtraction CP approach
Cut acceptance
CES [keV]


cut_s1_naive_bayes: 0.997
NAIVE BAYES
cut_s1_naive_bayes
Pb212 simulation CP approach
Rn220 calibration data w/ bkg subtraction CP approach
Cut acceptance
CES [keV]

S2


cut_s2_recon_pos_diff: 1.000
RECON POS DIFF
cut_s2_recon_pos_diff
Pb212 simulation CP approach
Rn220 calibration data w/ bkg subtraction CP approach
Cut acceptance
CES [keV]


cut_s2_width_wire_modeled_low_er: 0.889
WIDTH WM LOWER
cut_s2_width_wire_modeled_low_er
Pb212 simulation CP approach
Rn220 calibration data w/ bkg subtraction CP approach
Cut acceptance
CES [keV]


cut_s2_naive_bayes: 1.000
NAIVE BAYES
cut_s2_naive_bayes
Pb212 simulation CP approach
Rn220 calibration data w/ bkg subtraction CP approach
Cut acceptance
CES [keV]