Response and discrimination of Low-Energy Electronic and Nuclear Recoils in Liquid Xenon

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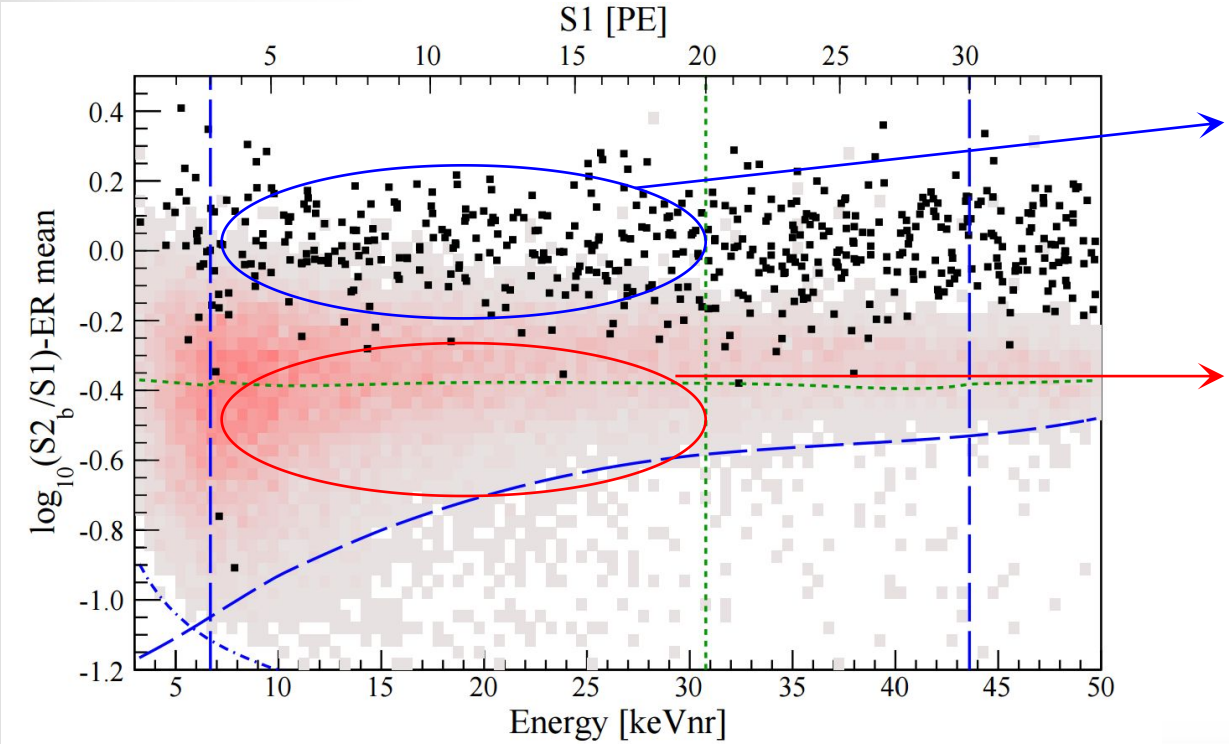
What to measure in LXe

E. Aprile (XENON100), Phys. Rev. Lett. 109, 181301 (2012)



Electronic Recoils (ER) ROI

Nuclear Recoils (NR) ROI

Gamma Background -> ER

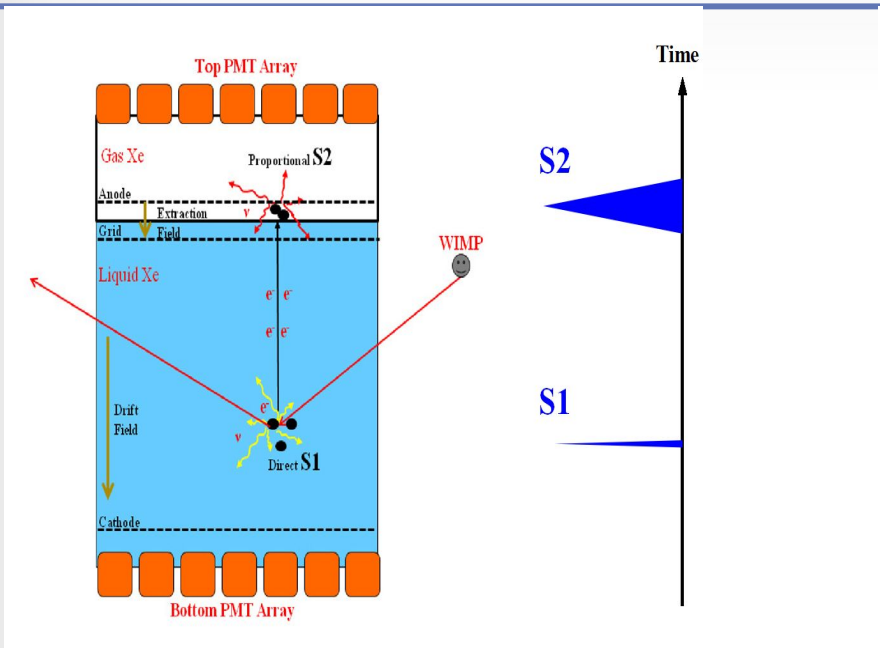
DM Candidate WIMP -> NR

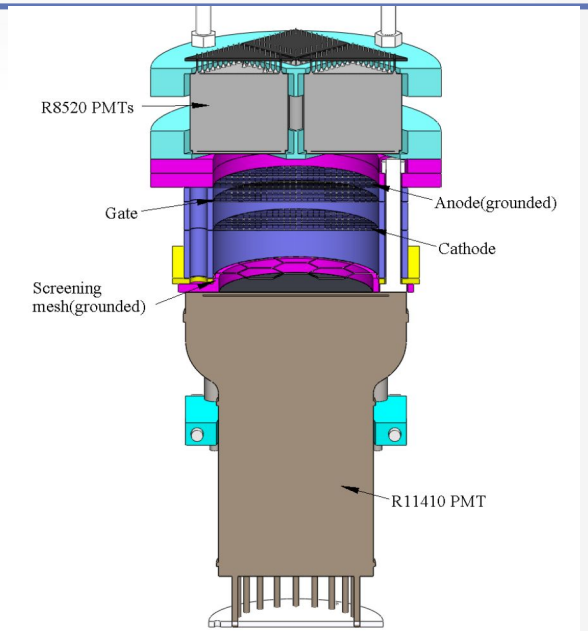
DM Candidate Axion -> ER

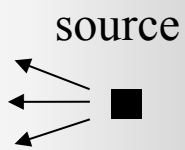
ER/NR discrimination

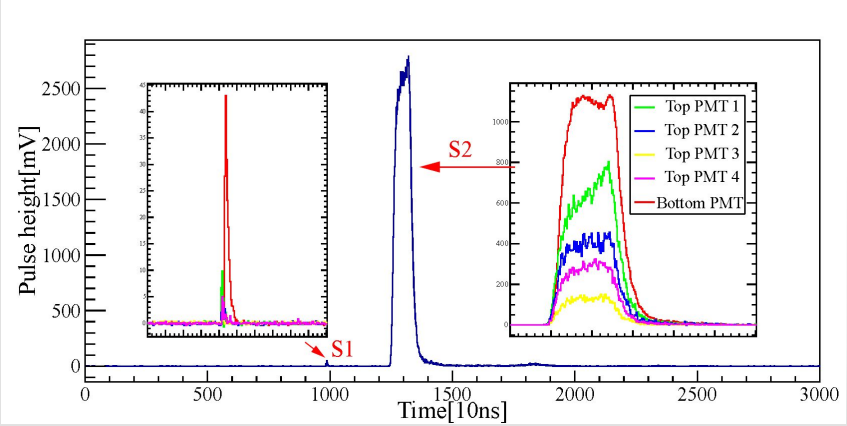
ER/NR signal response

Detector (LXe-TPC)



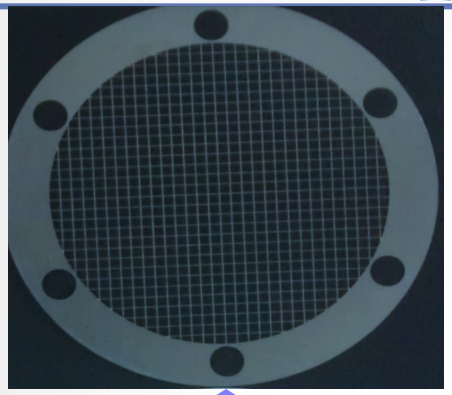


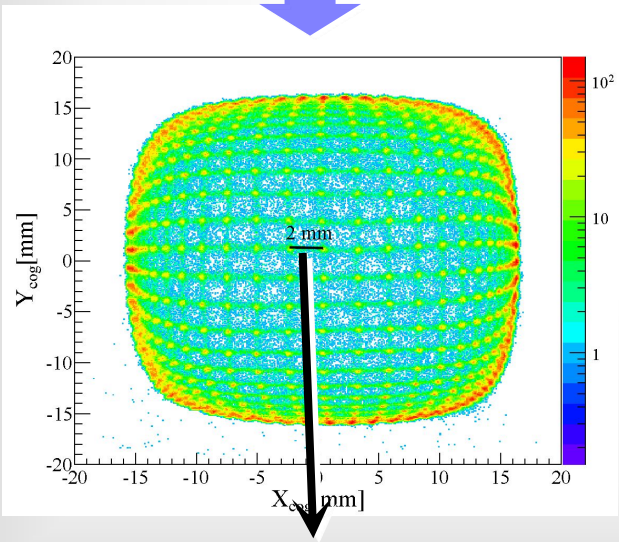




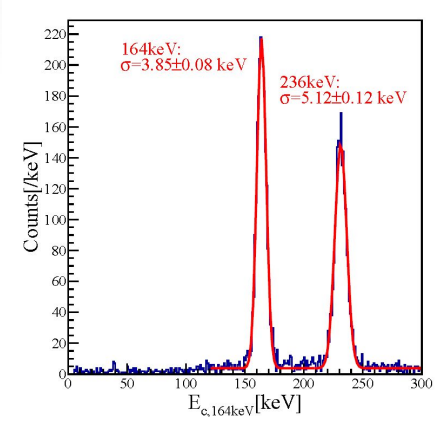
TPC Diameter[mm]	57
maximum drift length[mm]	10
Cathode-Screen[mm]	21
Anode-Gate[mm]	5
Sensitive Volume [g]	77
Fiducial Volume[g]	3
Top PMT number/Type	4/R8520
Bottom PMT number/Type	1/R11410

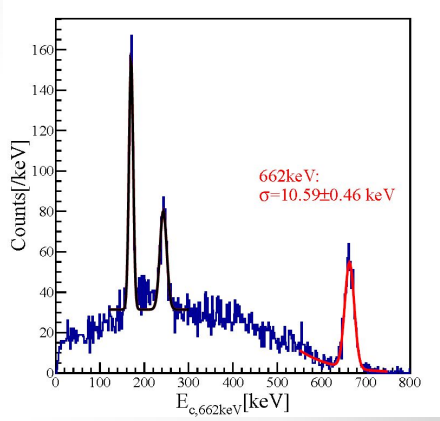
Detector performance

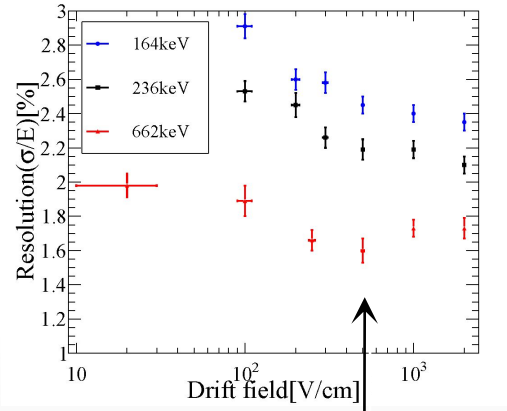




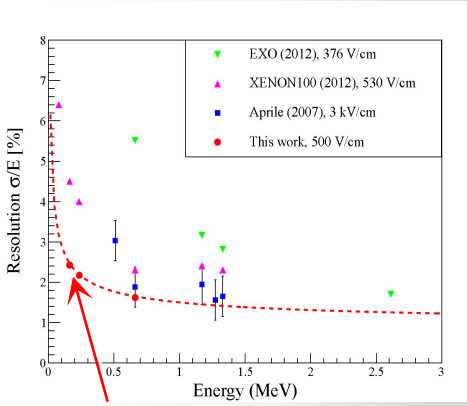
- Reconstrution resolution 0.37+-0.06mm





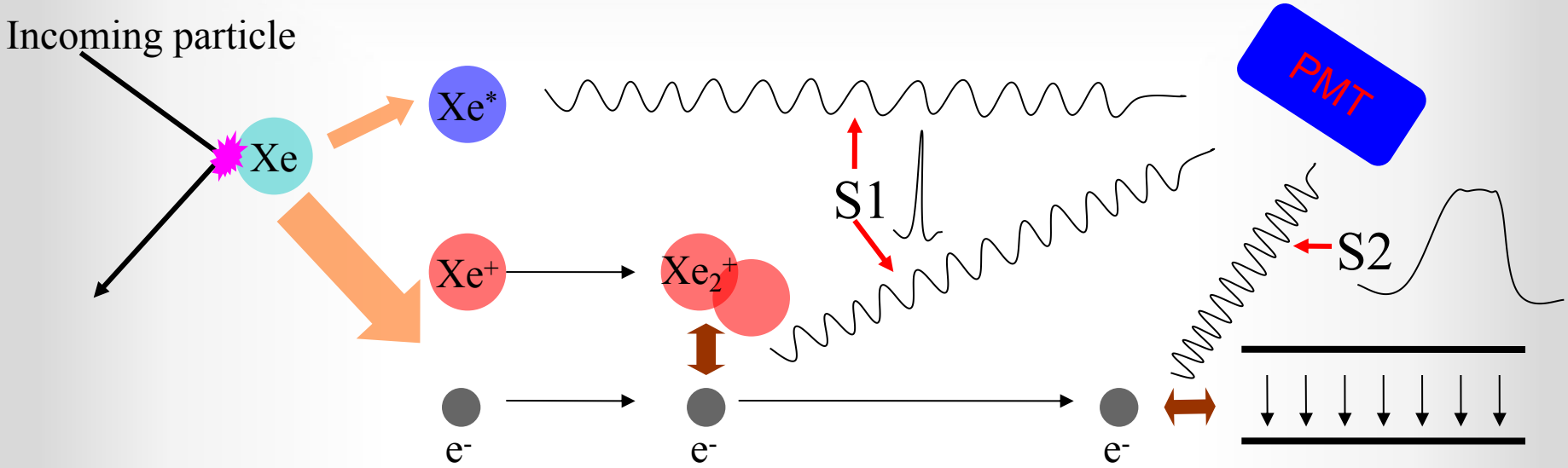


Best resolution (σ/E) = 1.60% @ 662keV @ 500V/cm



Very good energy resolution in LXe, meaning the systematic fluctuation of our detector is small

Signal model in LXe



$$\begin{cases} S1 = a \cdot N_{ph} = a\left(\dfrac{N_{ex}}{N_i} + r\right) N_i \\ S2 = b \cdot N_e = b(1 - r) N_i \end{cases}$$

N_i -- number of ion-electron pairs
a -- photon detection efficiency (PDE)
b -- electron amplification factor (EAF)
r -- recombination fraction

Recombination model

$$\frac{\partial N_+}{\partial t} = -\mu_+ \mathbf{E}\cdot\nabla N_+ + d_+\nabla^2 N_+ - \alpha N_+ N_- \quad \text{ION}$$

DRIFT **DIFFUSE** **RECOMBINE**

$$\frac{\partial N_-}{\partial t} = \mu_- \mathbf{E}\cdot\nabla N_- + d_-\nabla^2 N_- - \alpha N_+ N_- \quad \text{ELECTRON}$$

TIB model ← | → Birk-Doke law

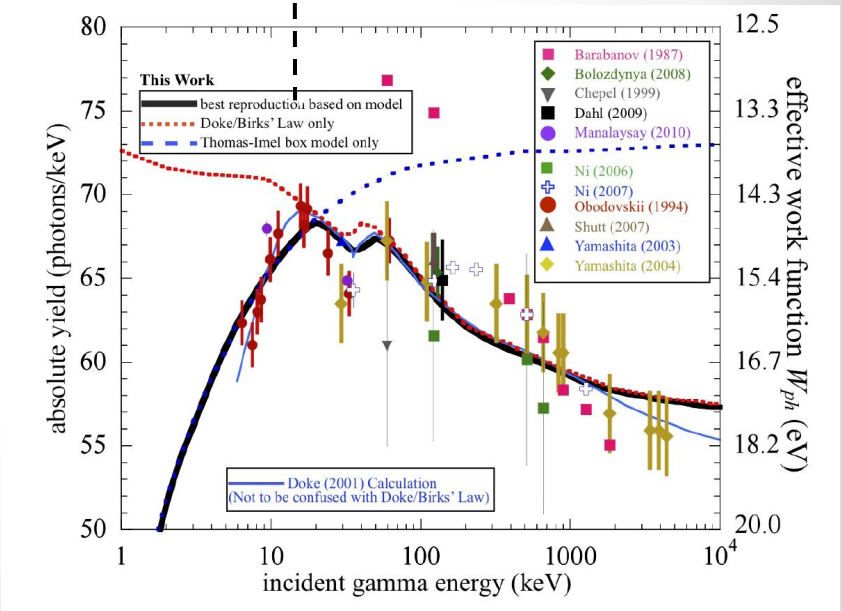
Birk-Doke Law (High-energy case, Drift and diffusion process neglected）：

$$r = \frac{A\cdot(dE/dx)}{1+B\cdot(dE/dx)} + C$$

A and B proportional to α, A/B+C=1

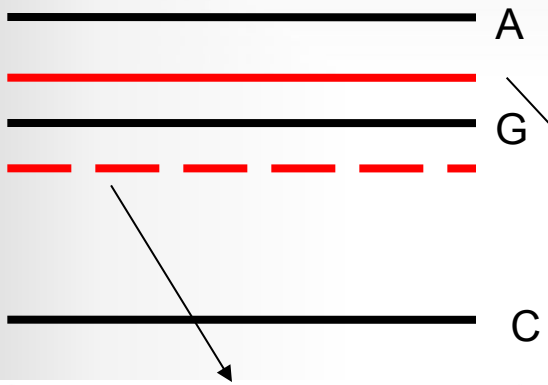
Thomas-Imel Box (TIB) model (Low-energy case, drift of electron taken into account）：

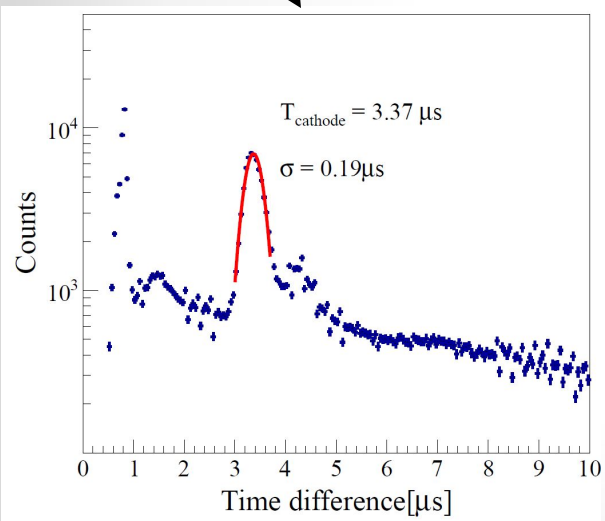
$$r = 1 - \frac{1}{\xi}\ln(1+\xi), \xi = \frac{\alpha N_i}{4a_0^2\mu E}$$

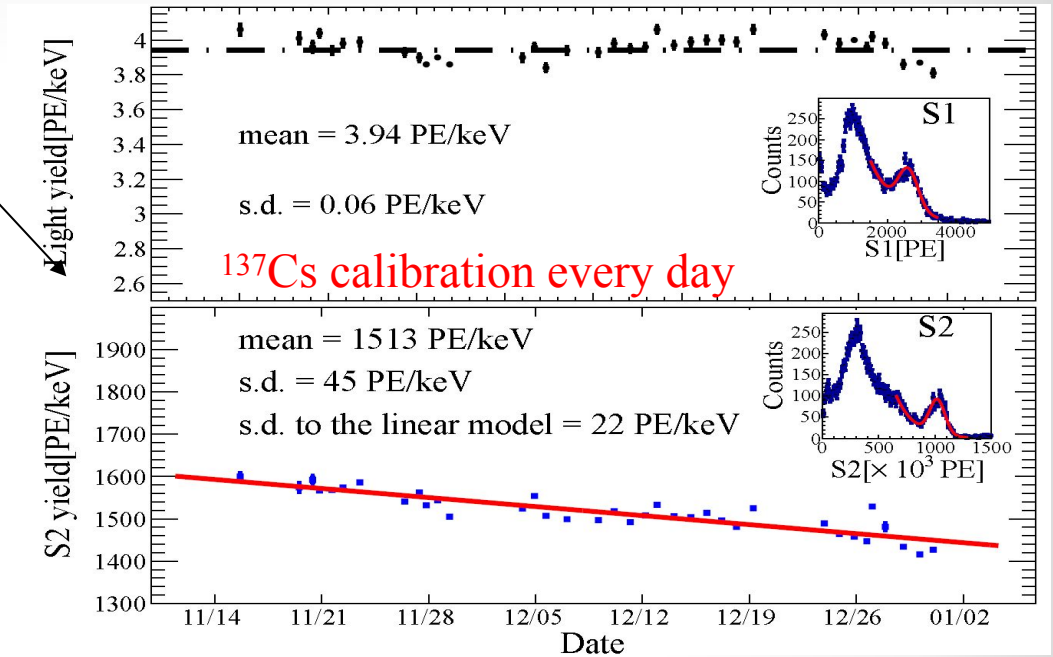


From NEST (JINST 6, P10002)

Detector operation



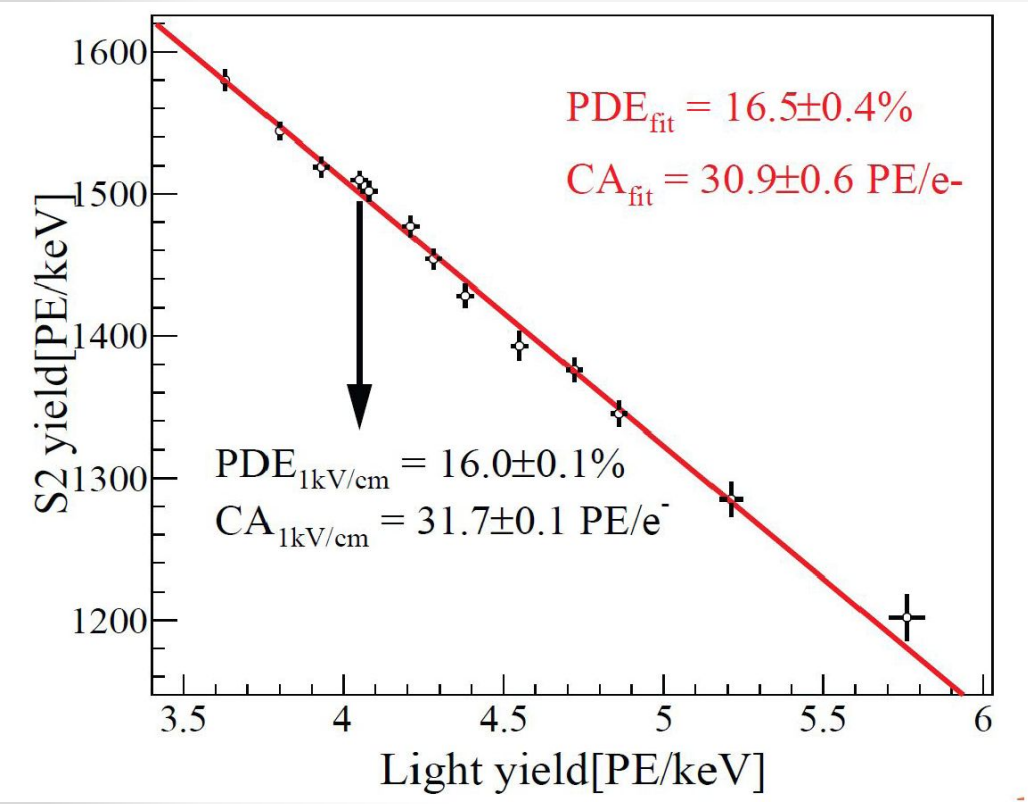




	Field[V/cm]	PDE[%]	EAF[PE/e-]
LS above gate	236 - 1920	15.5+-0.2	31.8+-0.5
LS below gate	3930	20.0+-1.7	20.0+-1.7

COMSOL simulation shows the field = **3.93kV/cm**.

Cross check of PDE and EAF using Anti-correlation



$$\begin{cases} \dfrac{S1}{\varepsilon} = a\left(\dfrac{N_{ex}}{N_i} + r\right)W_i \\ \dfrac{S2}{\varepsilon} = b(1-r)W_i \end{cases}$$

$W_q = W_i/(N_{ex}/N_i+1) = 13.7$eV

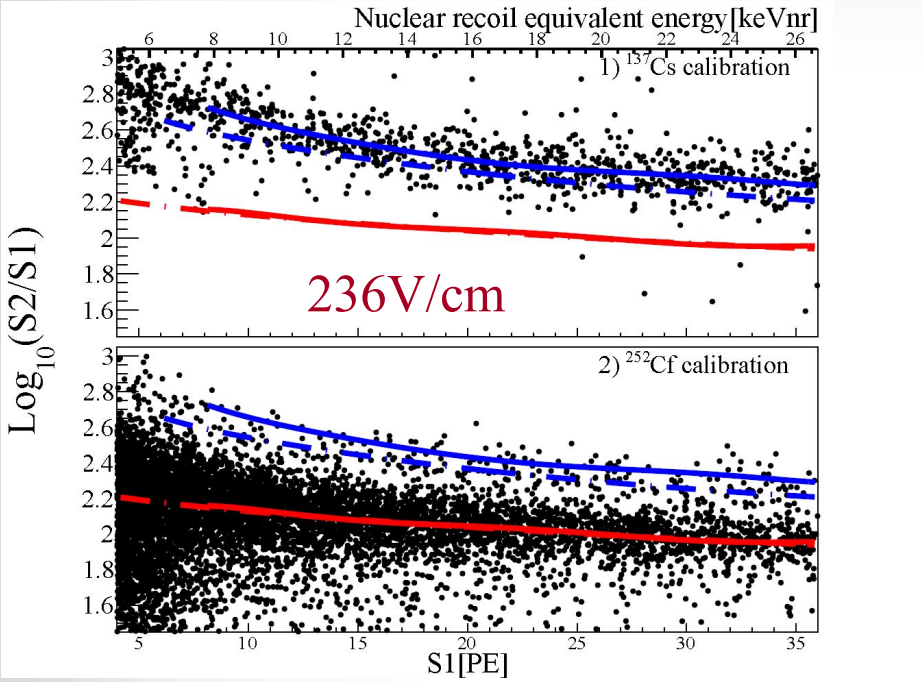
Slope = -b/a

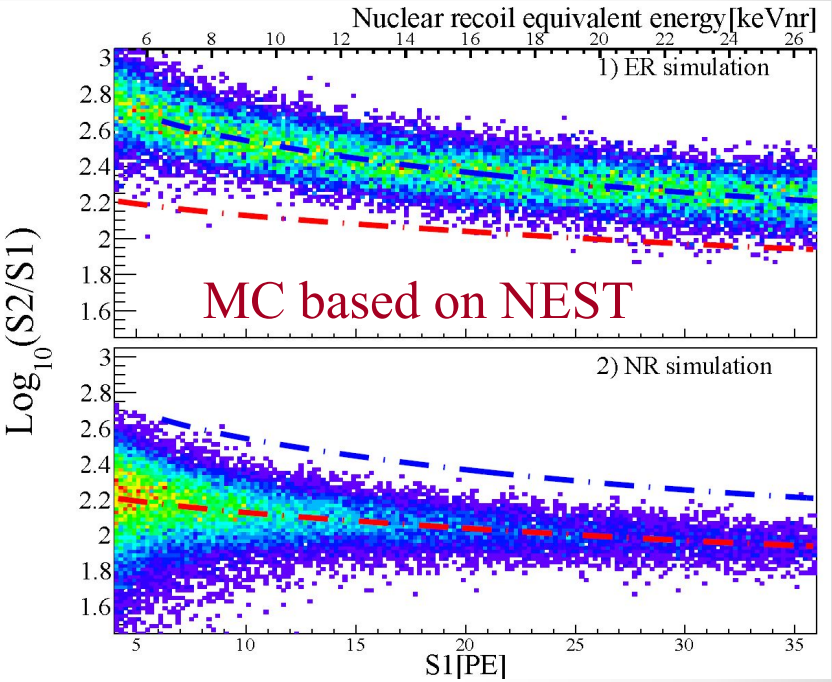
Intercept (Light yield) = a W_q

Intercept (S2 yield) = b W_q

The 3.0% and 2.6% varation of the PDE and EAF (CA), respectively, between anti-correlation and 1kV/cm data are within the 4% uncertainty of NEST.

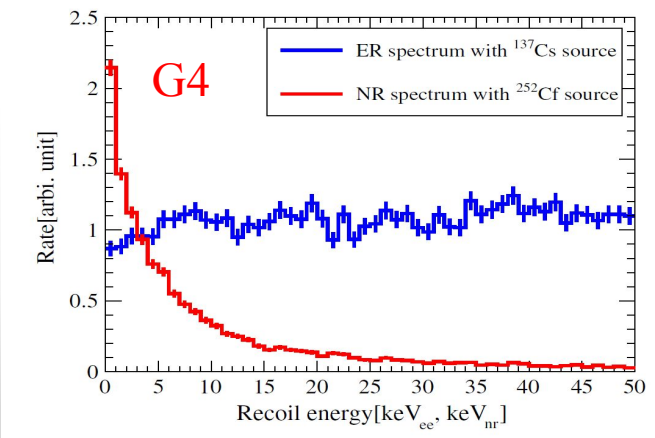
Measured recoils



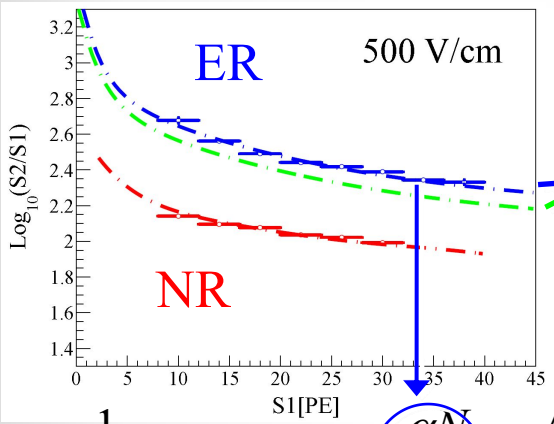


NR matches with NEST prediction.

ERs don't.



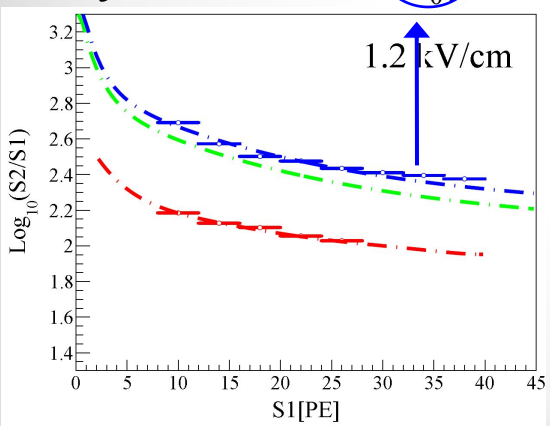
Update TIB parameters

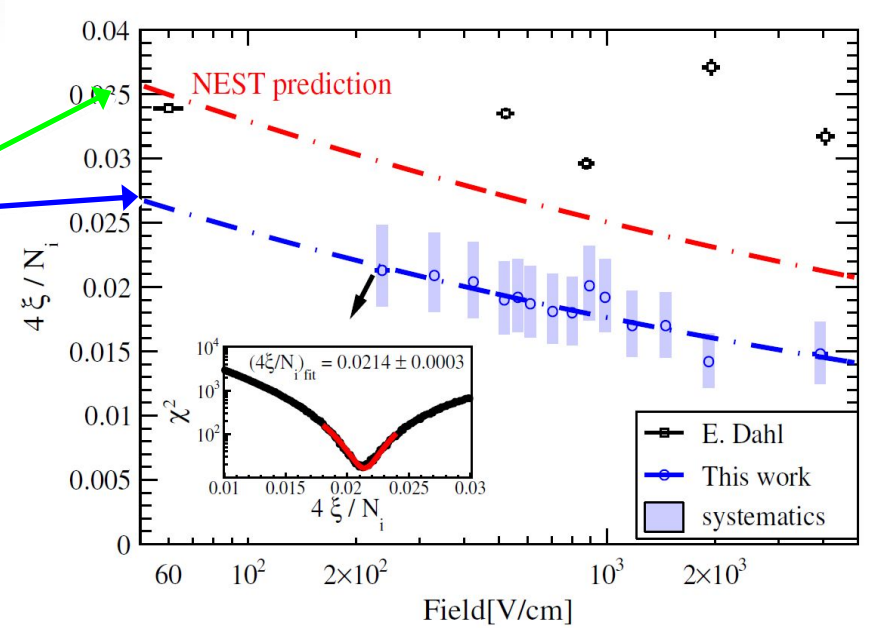


TIB

$$r = 1 - \frac{1}{\xi}\ln(1+\xi), \xi = \frac{\alpha N_i}{4a_0^2 \mu E}$$

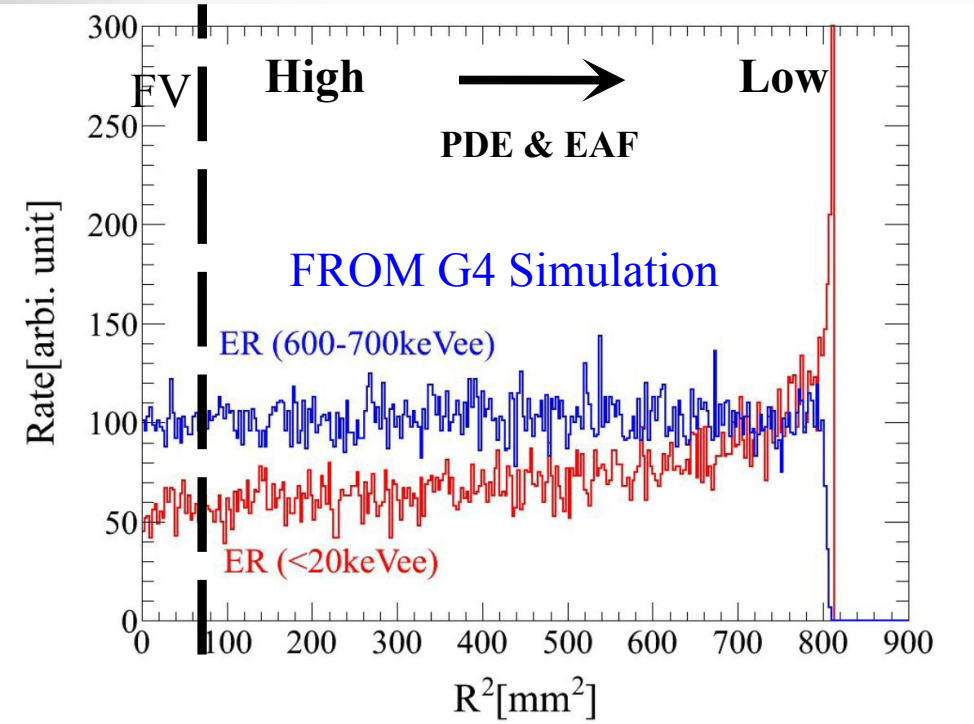
Adjust





Source of systematics	Value on (PDE and EAF)
Gain difference between ^{137}Cs calibration and recoil measurements	7.2%
PDE and EAF evolution	1.5%
NEST global uncertainty	4%
E-life induced S2 variation	1.2%

Edge effect



Data volume	Difference of photon yield to NEST[ph/keV]
FV	-5.0
Whole	-2.5

$$py' = \frac{S1}{(S1/a' + S2/b')\cdot W_q}$$

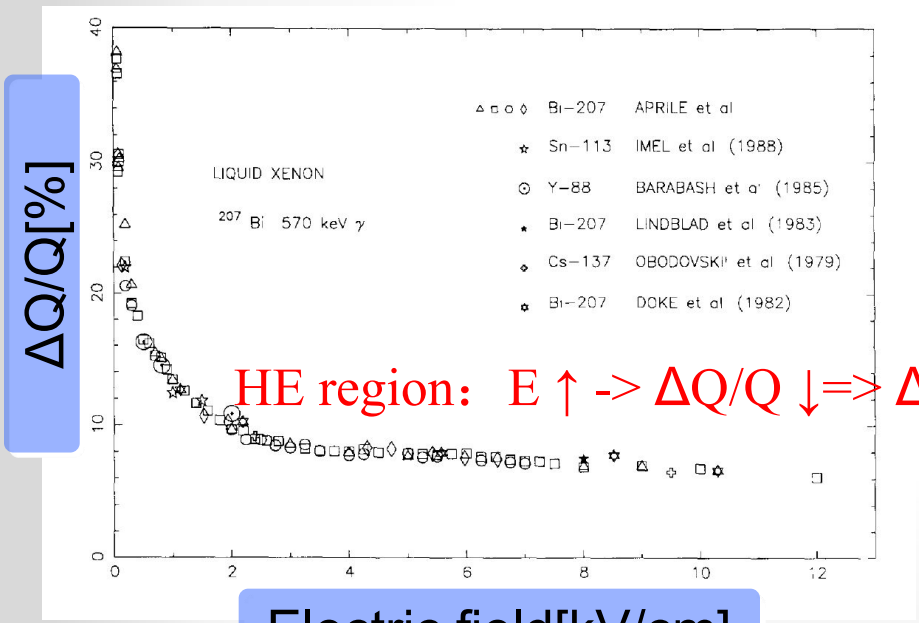
$$= \frac{1/W_q}{cy * \frac{b/b'}{a/a'} + py}\cdot py$$

$$\frac{b/b'}{a/a'} < 1 \Rightarrow py' > py$$

The PDE(EAF) is 4.5%(11.9%) lower if using whole volume than using FV in this work.

Discrimination observed in previous experiments

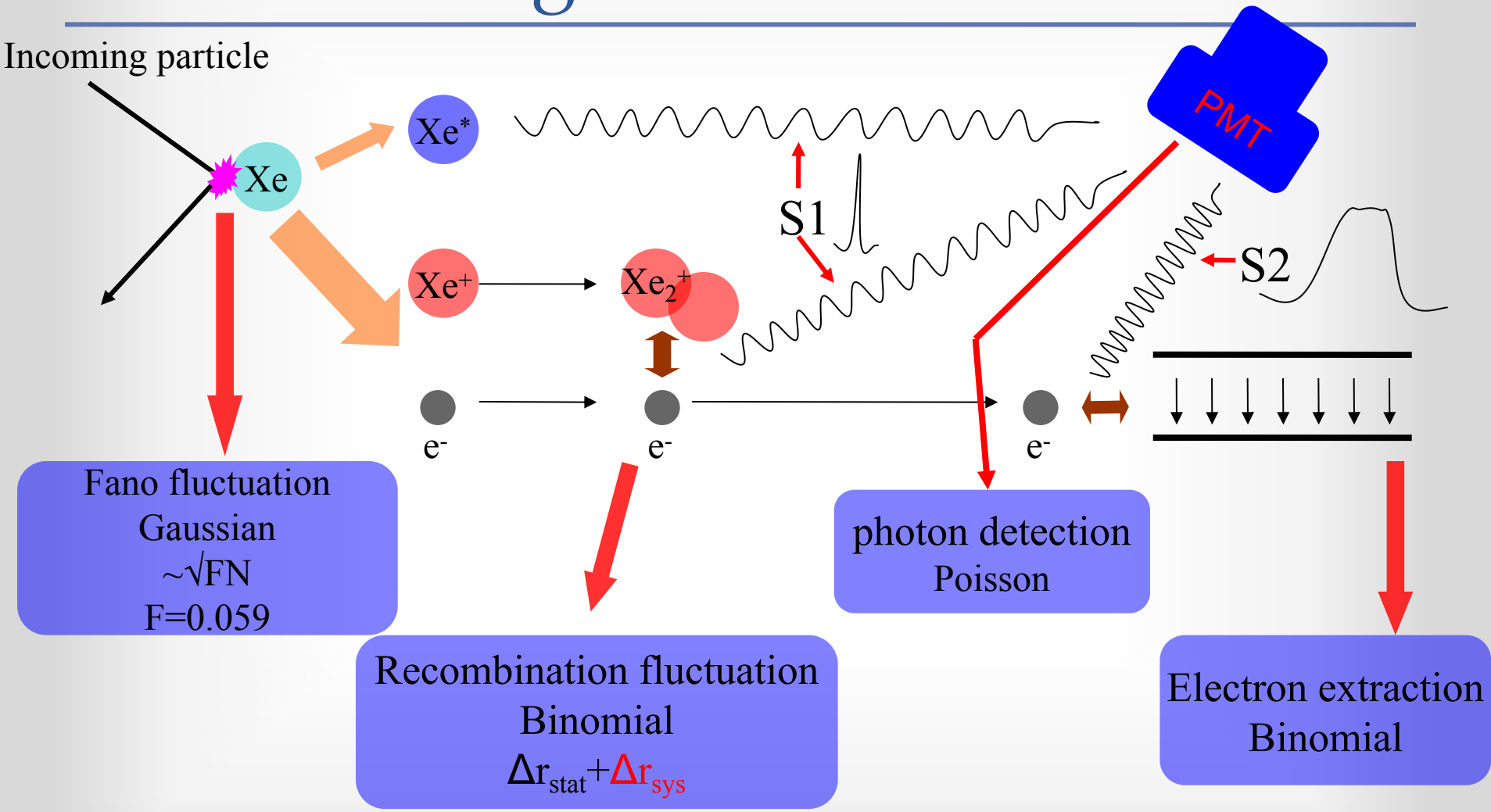
	Field[kV/cm]	PDE[%]	energy ROI	Gamma rejection power[%]	Nuclear recoil accepance[%]
ZEPLIN-II[14]	1.00	1.7	5–20 keVee	98.5	50
XENON10[9]	0.73	9.3	4.5–26.9 keVnr	99.86	45 ∼ 49
ZEPLIN-III[10]	3.90	8.1	7–35 keVnr	∼ 99.99	∼ 40
XENON100[7]	0.53	6.7	6.6–43.3 keVnr	99.75	20 ∼ 60
LUX[8]	0.18	14.0	3.4–25.0 keVnr	99.6	50
PandaX	0.67	9.6	4–10 keVnr	99.6	50



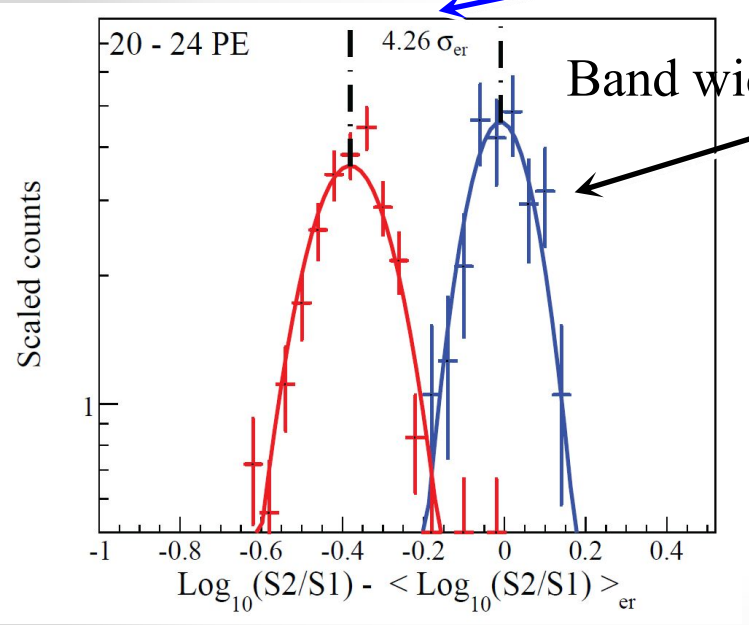
HE region: E ↑ -> ΔQ/Q ↓=> Δr ↓ → LE region: E↑ => Δr ↓ => σ_{er} ↓

?

Review of signal fluctuation

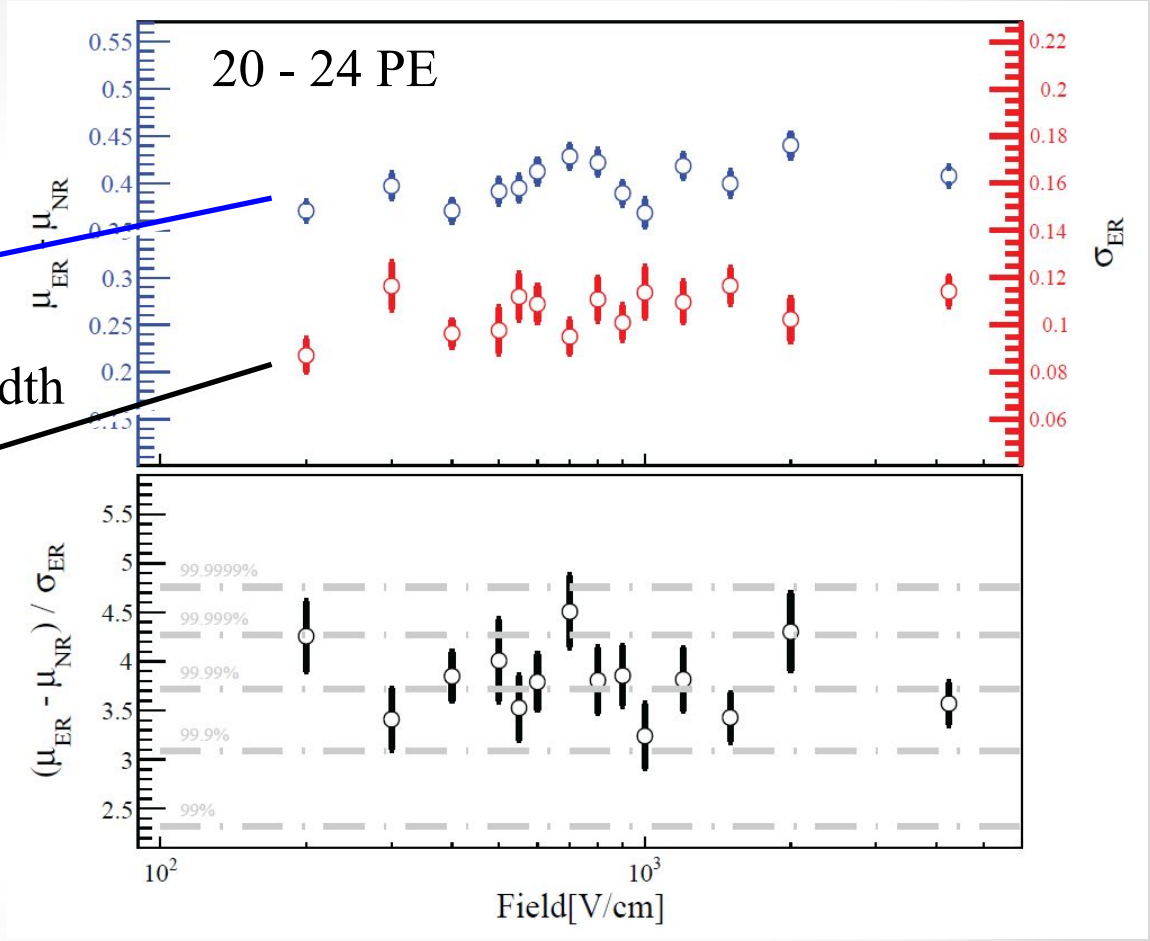


Discrimination measurement



Band separation

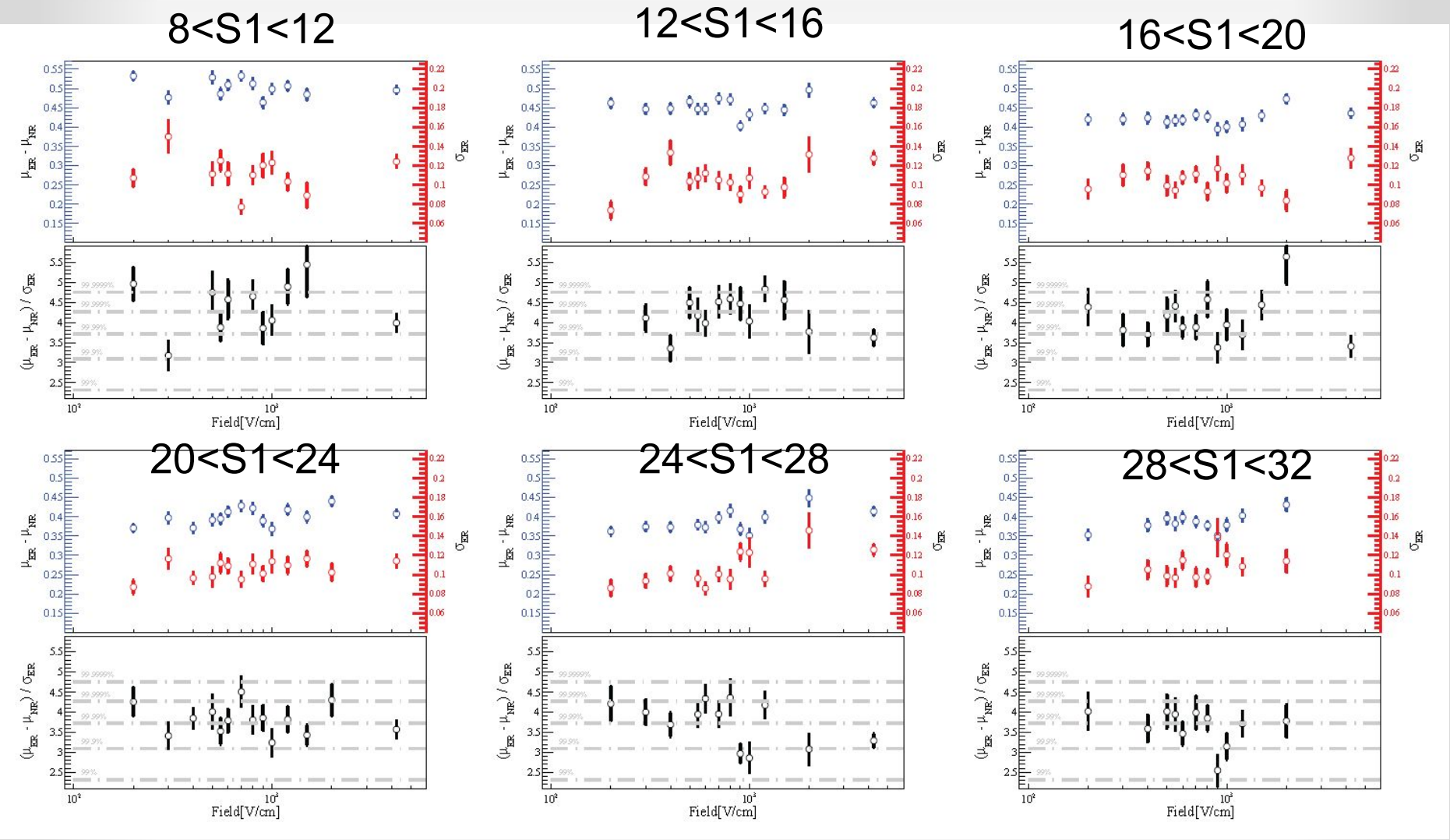
Band width



Probability of ER to appear below NR mean

No observation of discrimination level increasing as field!

Discrimination measurment



Δα for High energy ΔQ/Q

$$\frac{\partial N_+}{\partial t} = -\mu_+ \mathbf{E}\cdot\nabla N_+ + d_+\nabla^2 N_+ - \alpha N_+ N_-$$

ION

Drift Diffuse Recombine

Diffusion Eq

$$\frac{\partial N_-}{\partial t} = \mu_- \mathbf{E}\cdot\nabla N_- + d_-\nabla^2 N_- - \alpha N_+ N_-$$

Electrons

Birk-Doke Law：

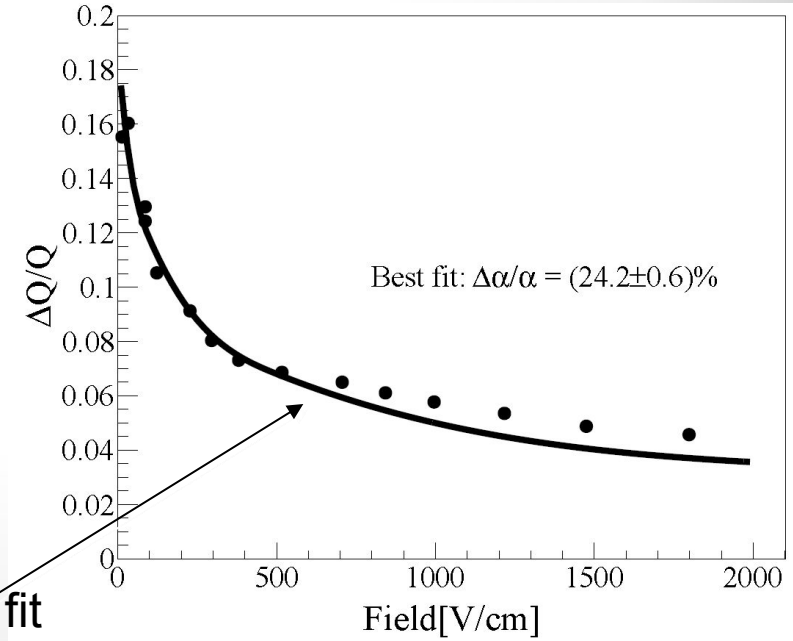
$$r = \frac{A\cdot(dE/dx)}{1+B\cdot(dE/dx)} + C$$

A&B proportional to α

$$\Delta r = \left[(r-C) - \frac{(r-C)^2}{1-C}\right]\cdot\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta Q}{Q} = \left[\frac{r-C}{1-r} - \frac{(r-C)^2}{(1-C)(1-r)}\right]\cdot\frac{\Delta\alpha}{\alpha}$$

fit

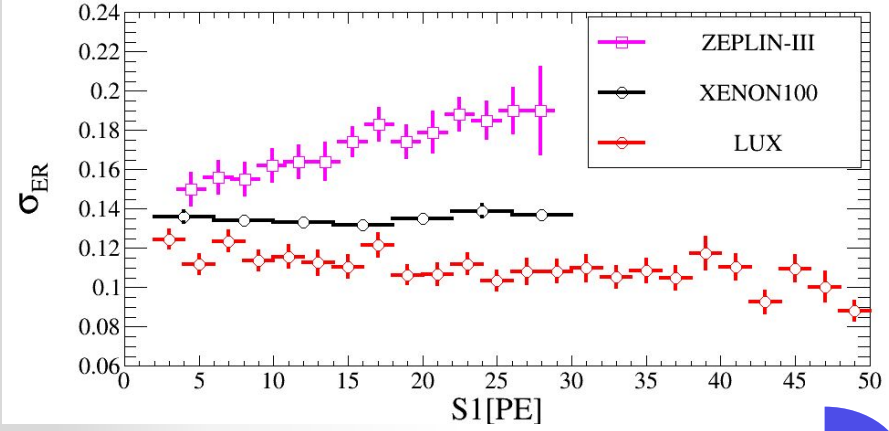


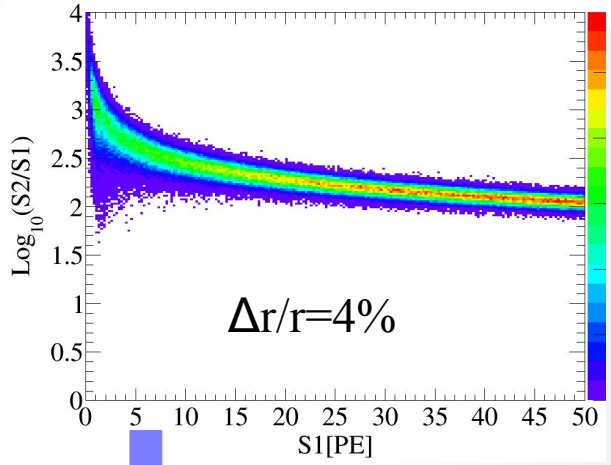
Low energy Δα

$$r(\xi) = 1 - \frac{1}{\xi}\ln(1+\xi), \xi \equiv \frac{N_i \alpha}{4a^2 \mu E}$$

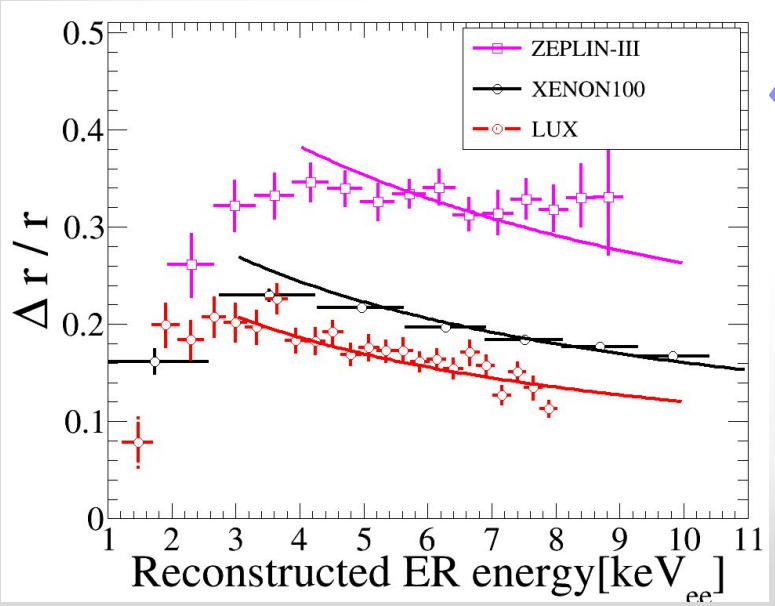
E↑ => Δr ↑

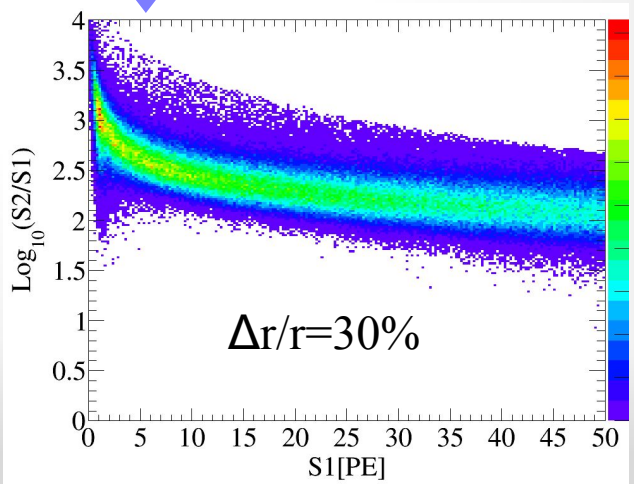
$$\Delta r = \left[\frac{1}{\xi} ln(1+\xi) - \frac{1}{1+\xi}\right]\frac{\Delta\alpha}{\alpha}.$$





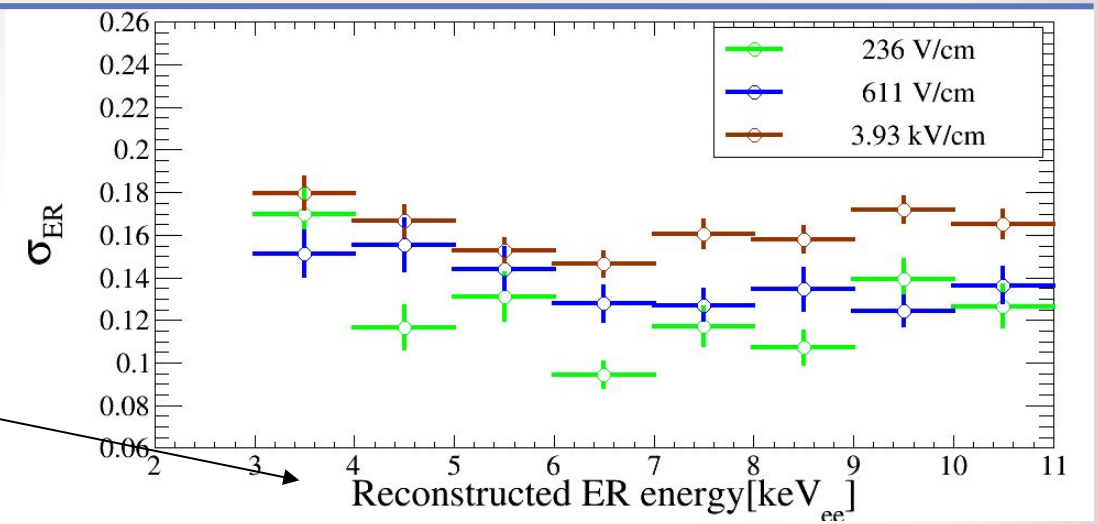
scan

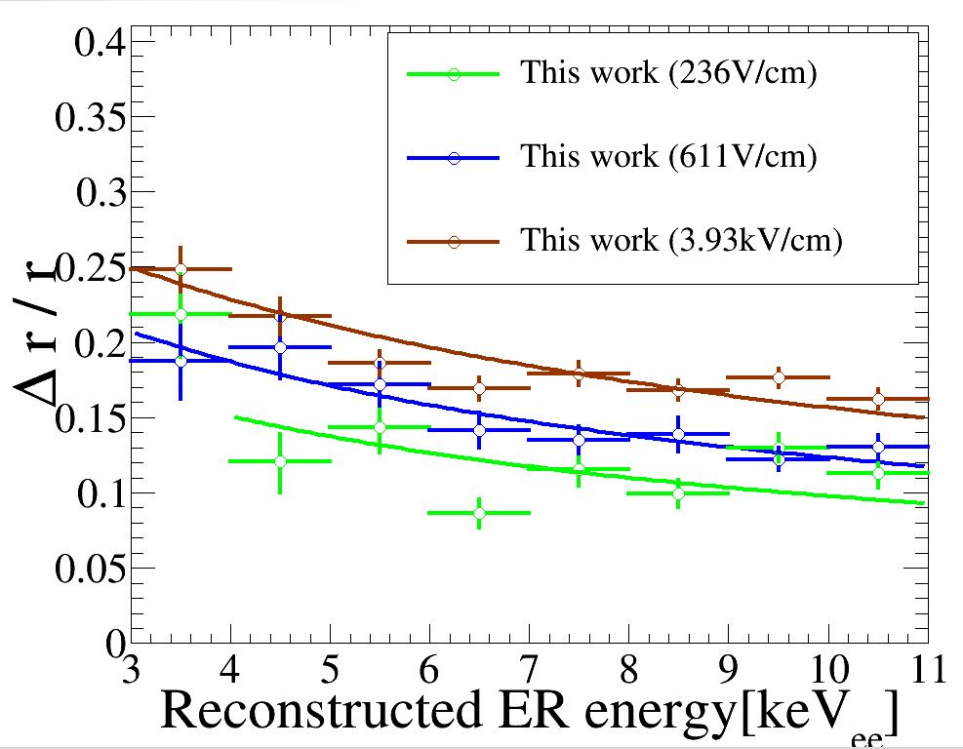




Low energy Δα

$$E_c = \left(\frac{S1}{PDE} + \frac{S2}{EAF}\right) \cdot W_q$$

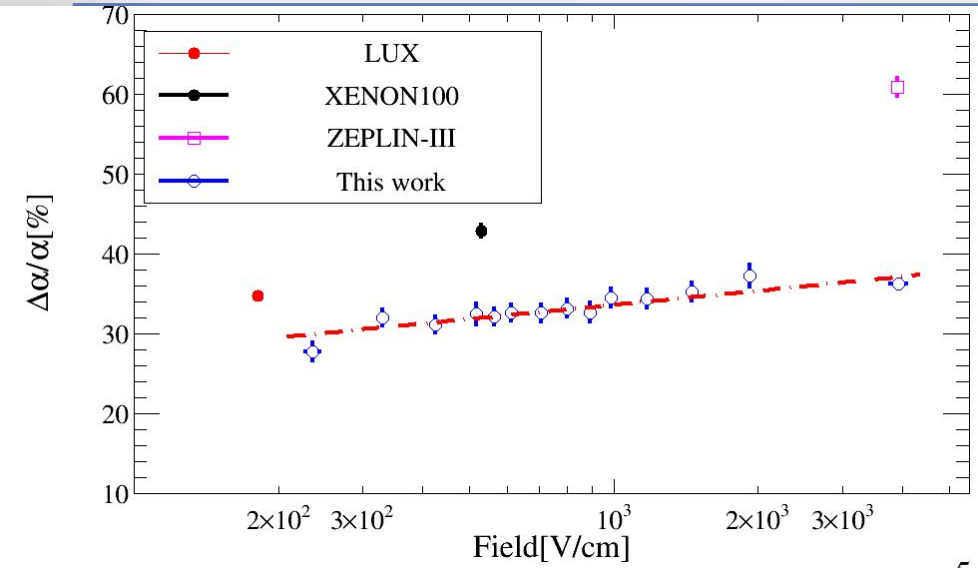




Solid lines:

$$\Delta r = \left[\frac{1}{\xi} ln(1+\xi) - \frac{1}{1+\xi}\right] \frac{\Delta\alpha}{\alpha}.$$

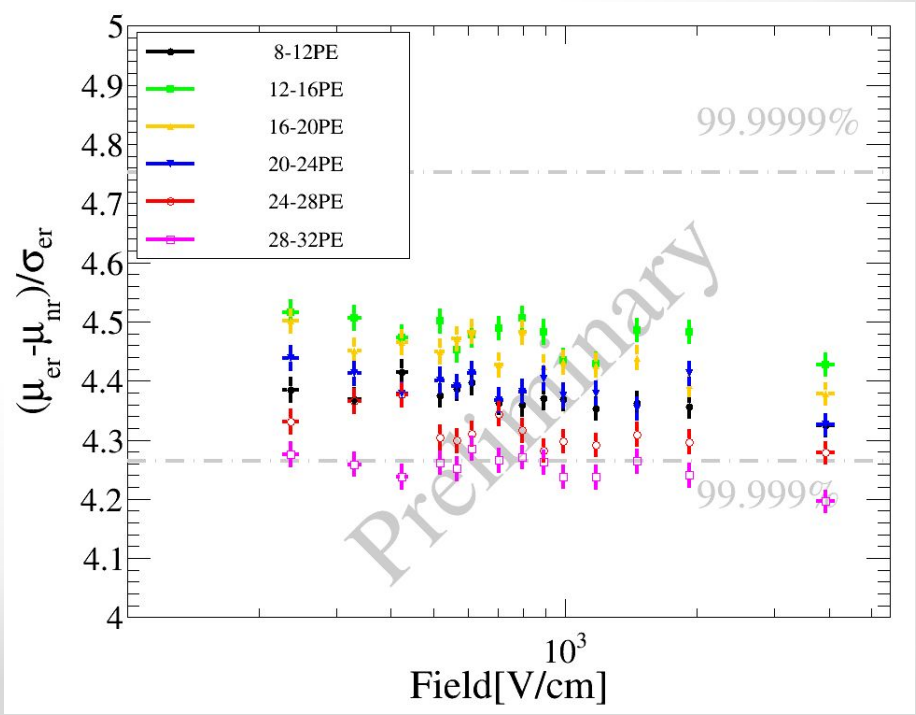
Expected Leakage fraction with the model



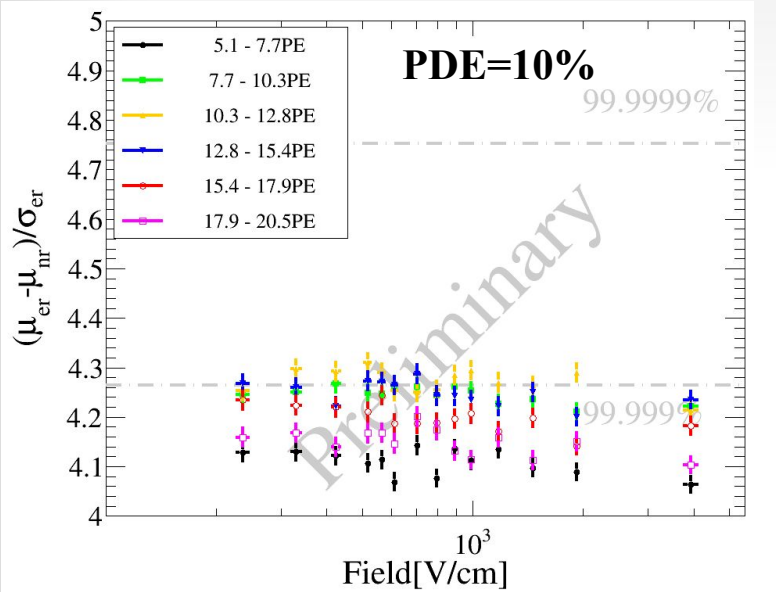
If assume a log linear Δα/α on field.

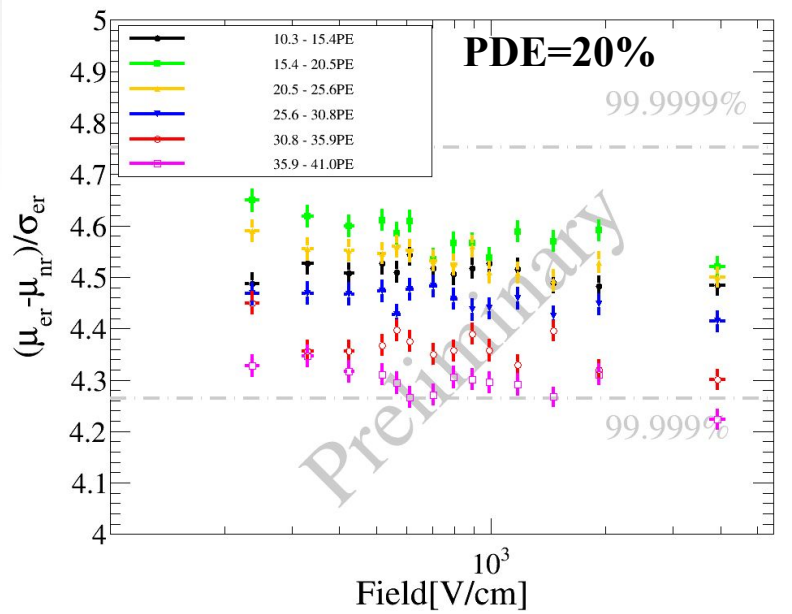
PDE=15.6%

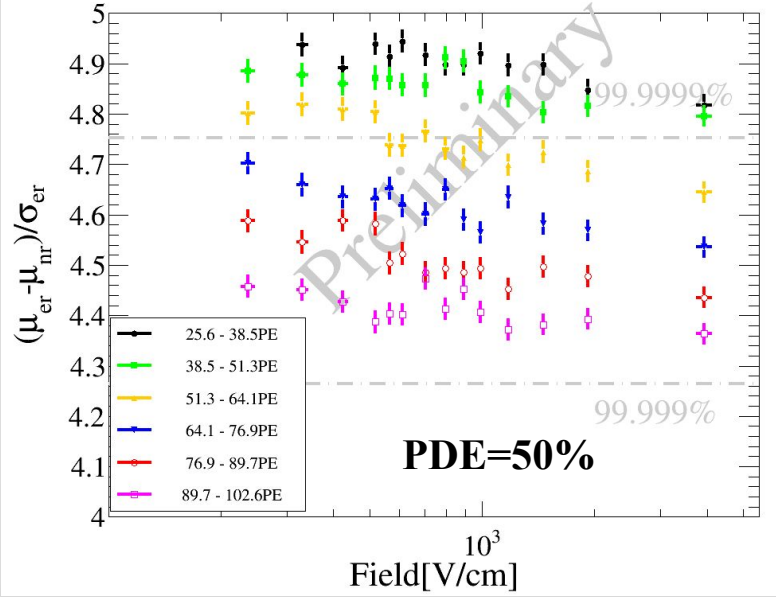
There's no field dependence of the rejection.

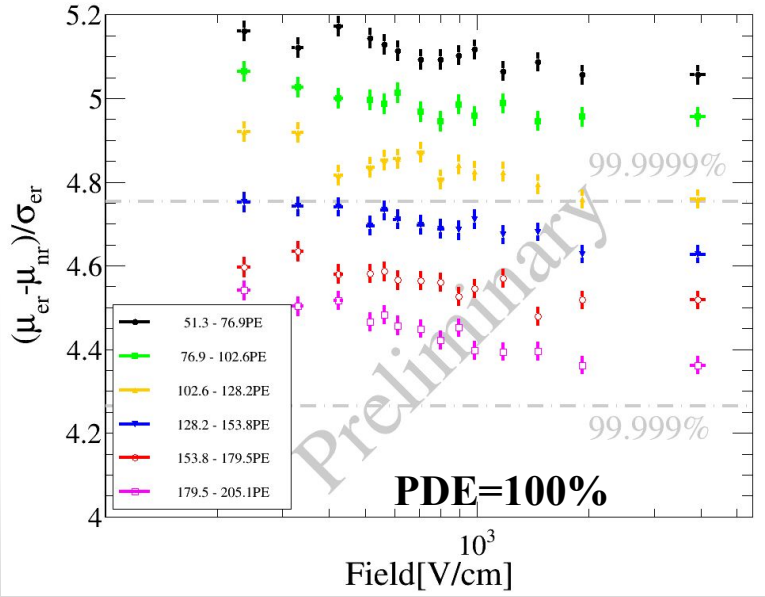


Expected Leakage fraction with the model









Summary

1. Response of low energy NR and ER in LXe at different fields (236V/cm - 3.93kV/cm) were measured. NR data are consistent with NEST, while ER showed a deviation of photon yield by 5ph/keVee from NEST (Q. Lin et al., Phys. Rev. D 92, 032005, 2015).

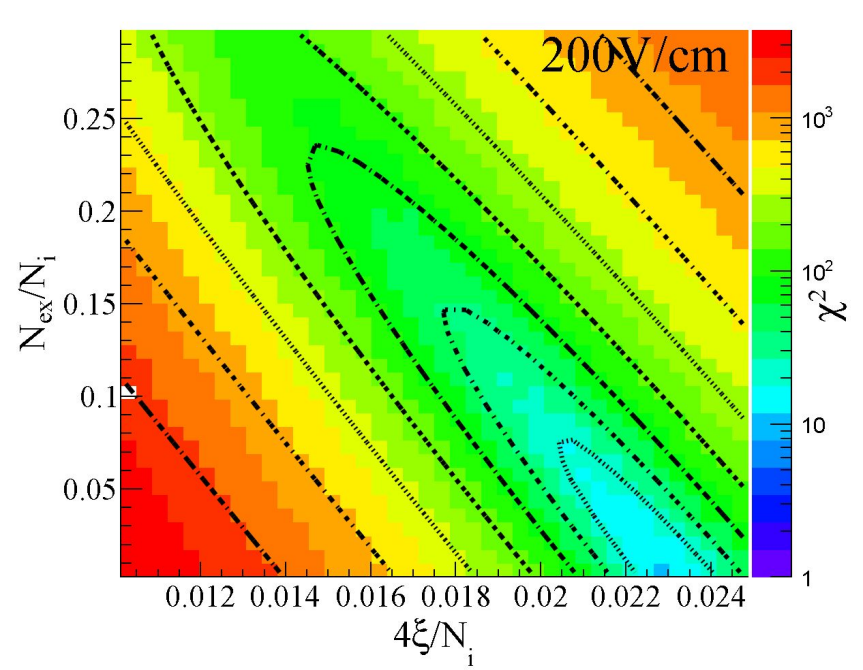
2. An average ER rejection around 99.99% (with 50% NR acceptance) was achieved at different fields.

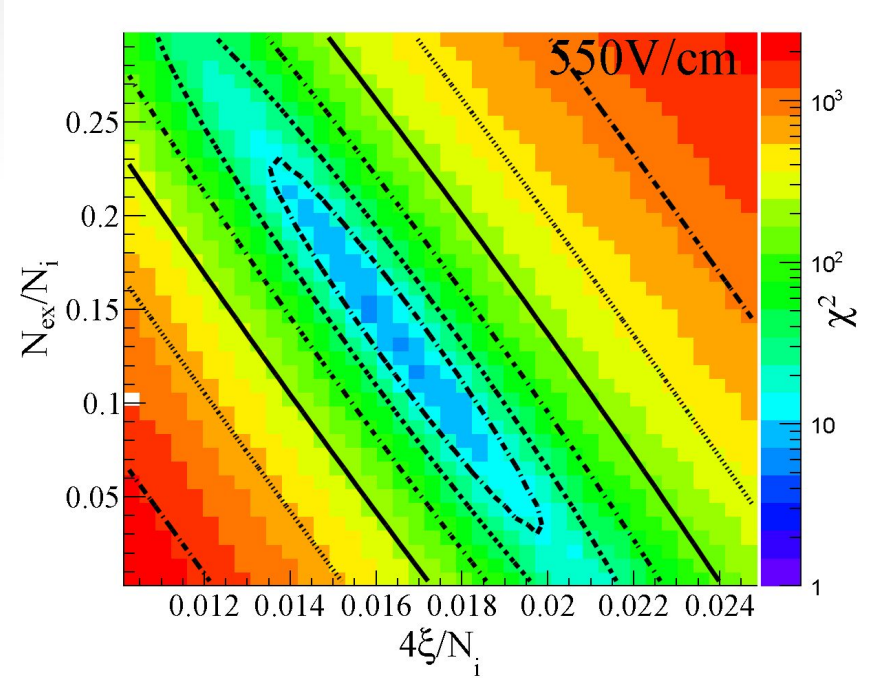
3. Preliminary study shows the ER rejection doesn't depend significantly on the field, while $\Delta\alpha/\alpha$ follows a log-linear dependence with field in our measurement.

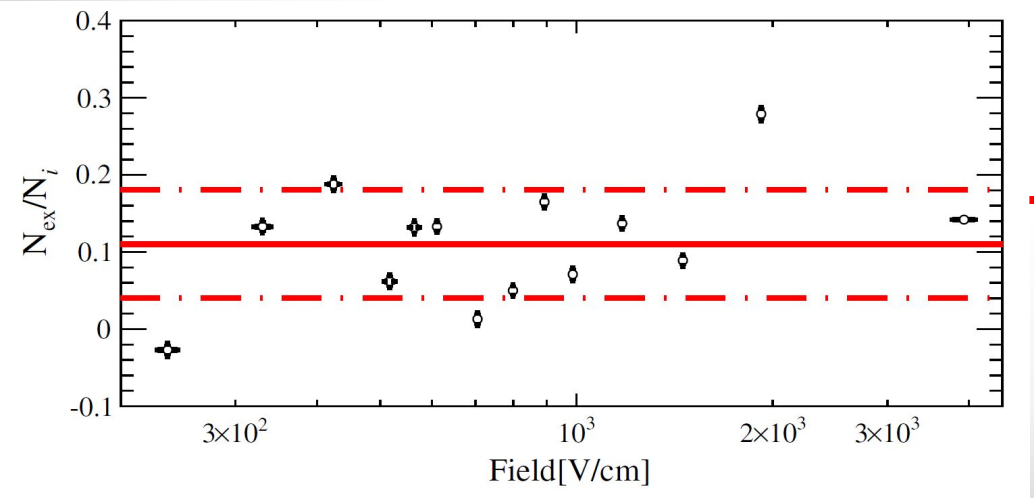
Thank you!

Backup

Float also N_{ex}/N_i

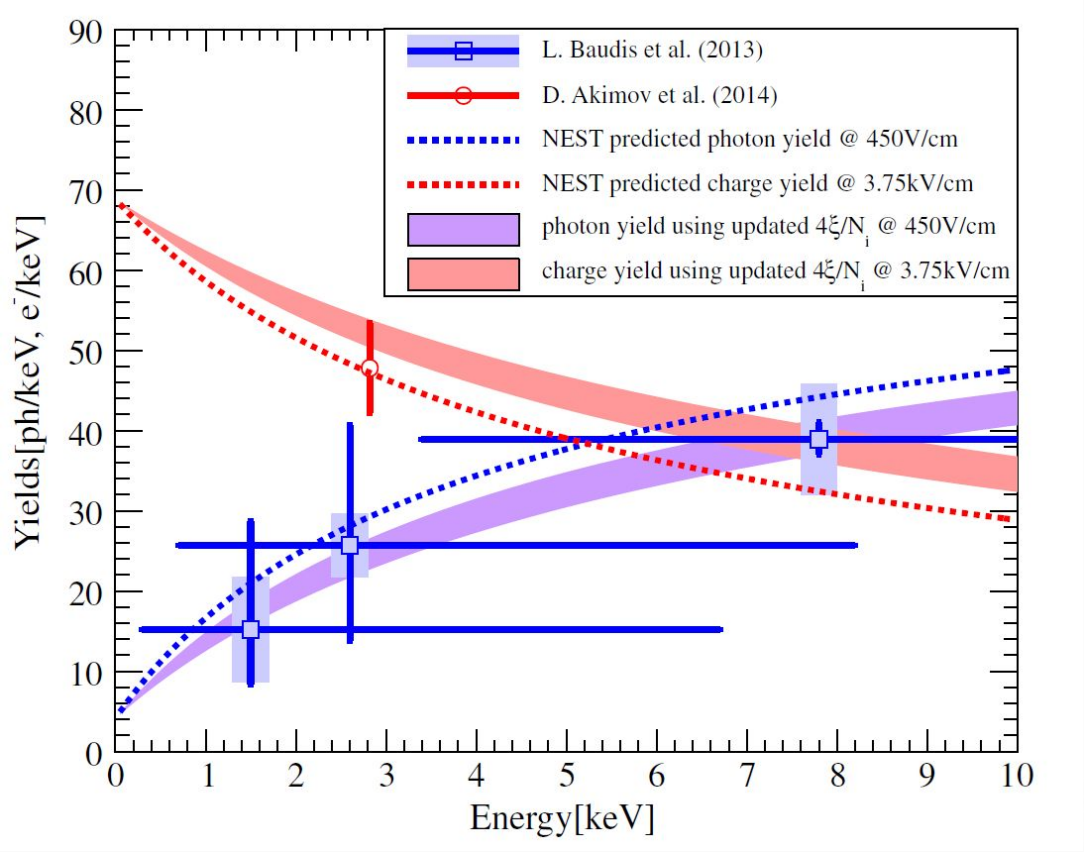






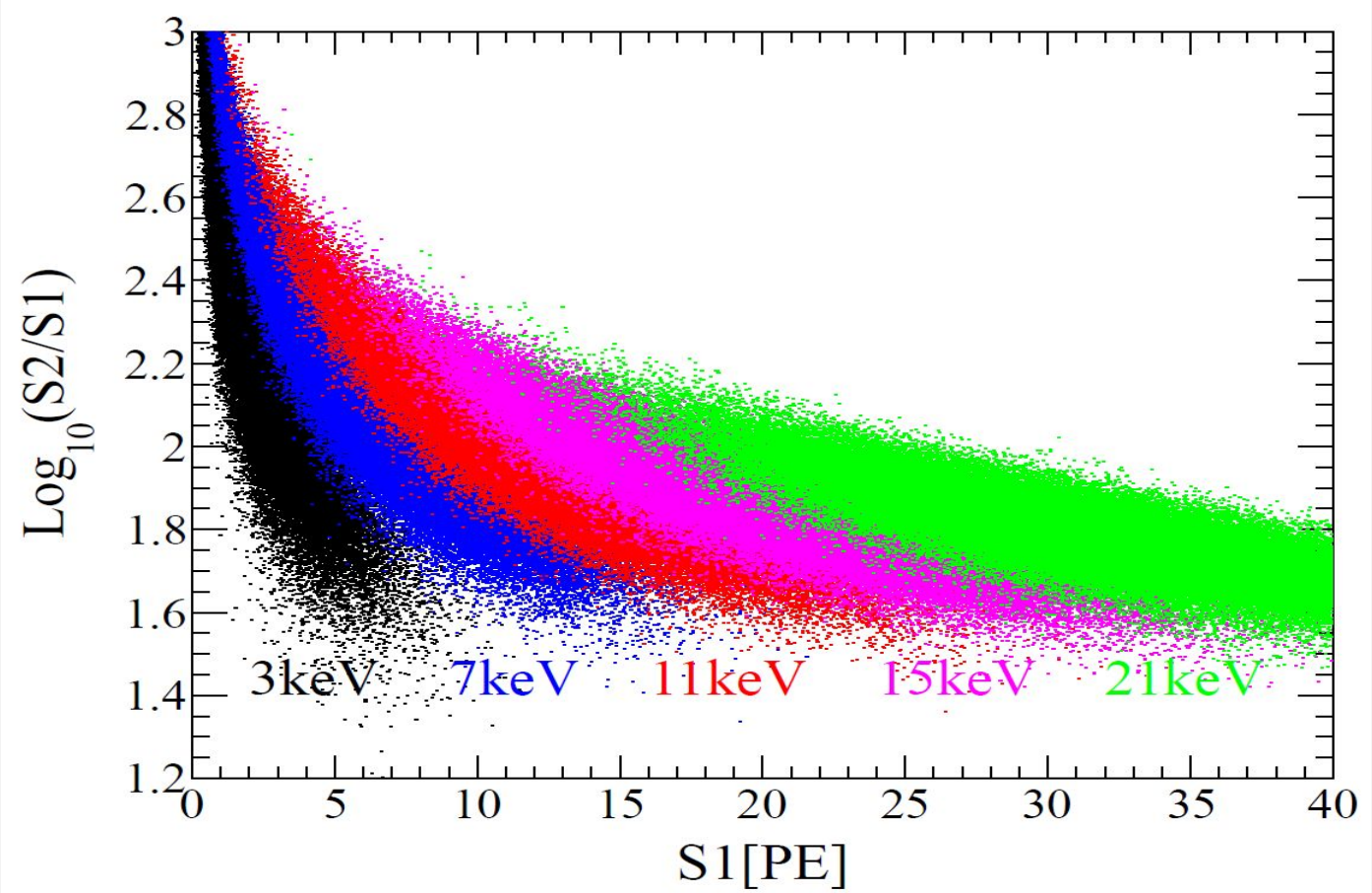
→ $N_{ex}/N_i = 0.11 +- 0.07$

Compare to existing measurements



Need more measurements of low energy ER to confirm

energy spectrum dependence of signal response



3-D simulation result (with liquid level 2mm below gate mesh)