Virtual Segmentation of a Small Contact HPGe Detector

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2024/05/09

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中国暗物质实验
China Dark matter EXperiment

Outlines

I. Introduction

II. Select Inner/Outer Layer Event via PSA

III. Determine Inner/Outer Layer Shape & Volume

IV. Background Suppression by Virtual Segmentation

V. Summary

I. Introduction

Introduction

☐ Search Ge-76 0νββ decay with HPGe detector:

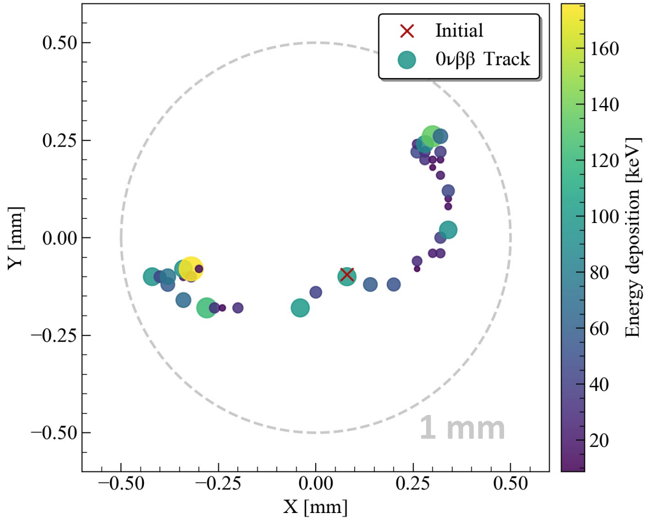
0νββ experiment requires ***Extreme Low Background*** (“0” Background in ROI for HPGe)

Small contact HPGe detector has ***Pulse Shape Analysis (PSA)*** for Background Suppression

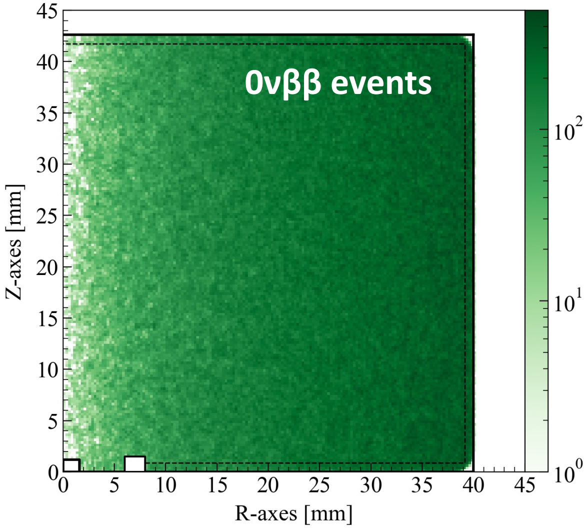
➢ *Identify Signal & Background by pulse shape features originating from their spatial difference*

Signal (2e⁻ from 0νββ)

Single-site event (SSE)



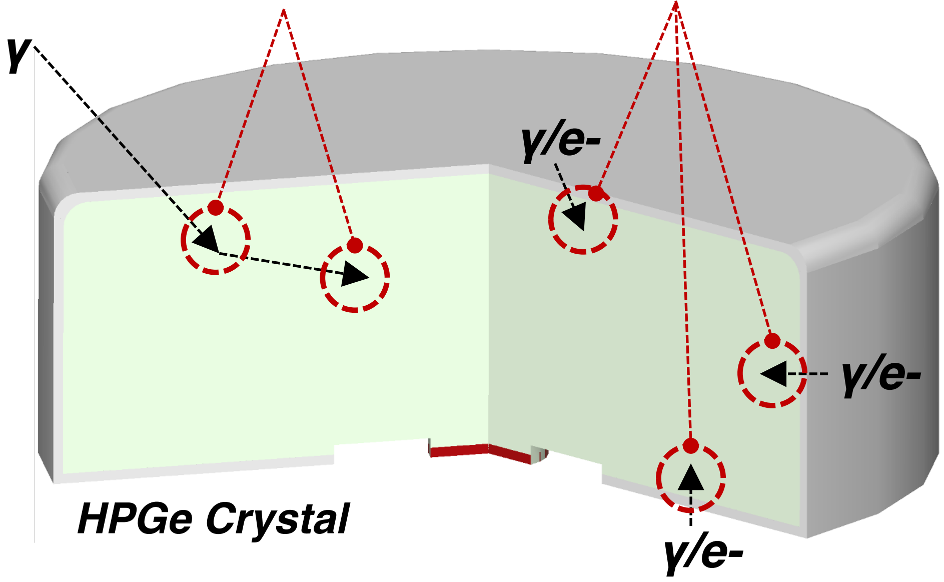
Uniformly distributed



Background (e-, γ from outside)

Multi-site event (MSE)

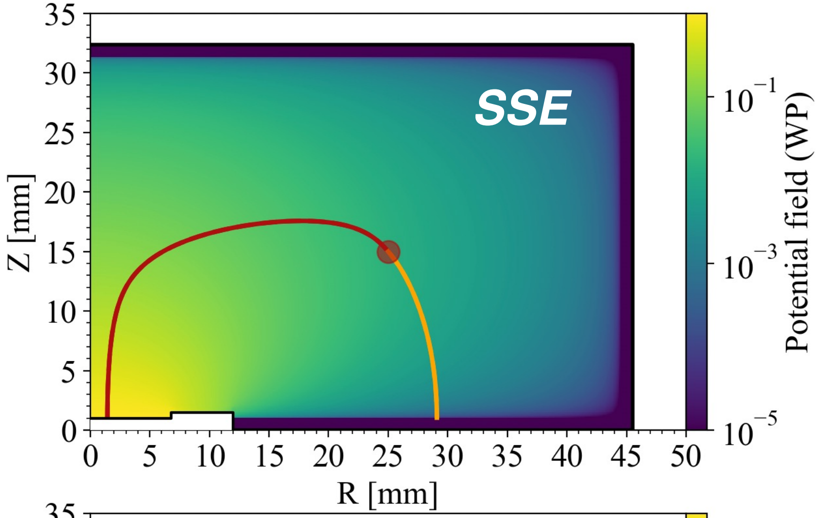
Surface event



Introduction

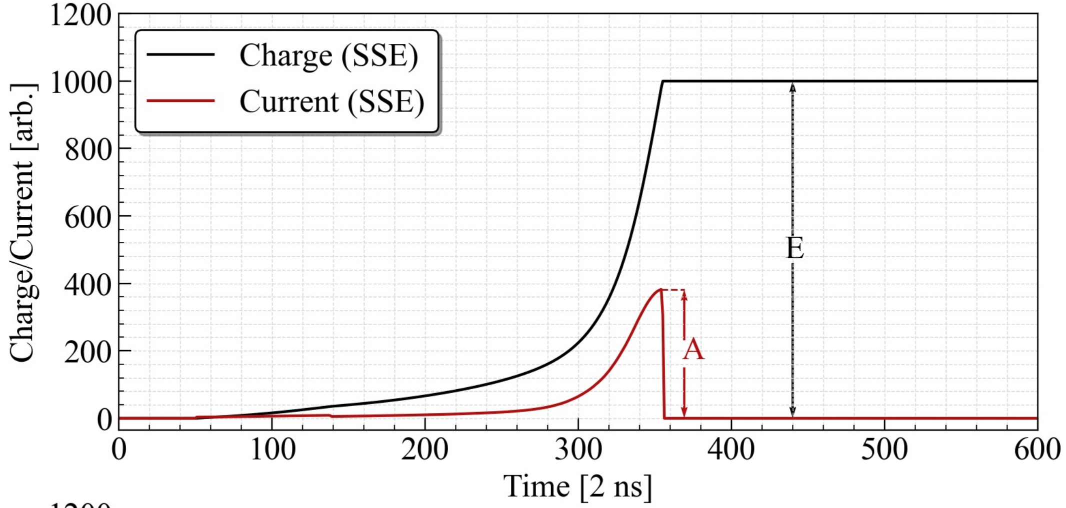
☐ Discrimination between SSE / MSE:

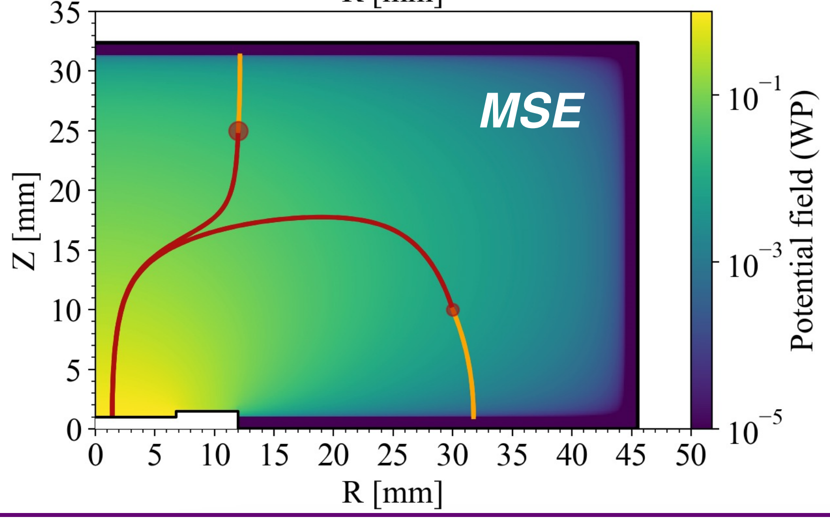
A/E method identifies ***single/multiple hits*** *using different drift times of the induced charge carriers*



Single hit

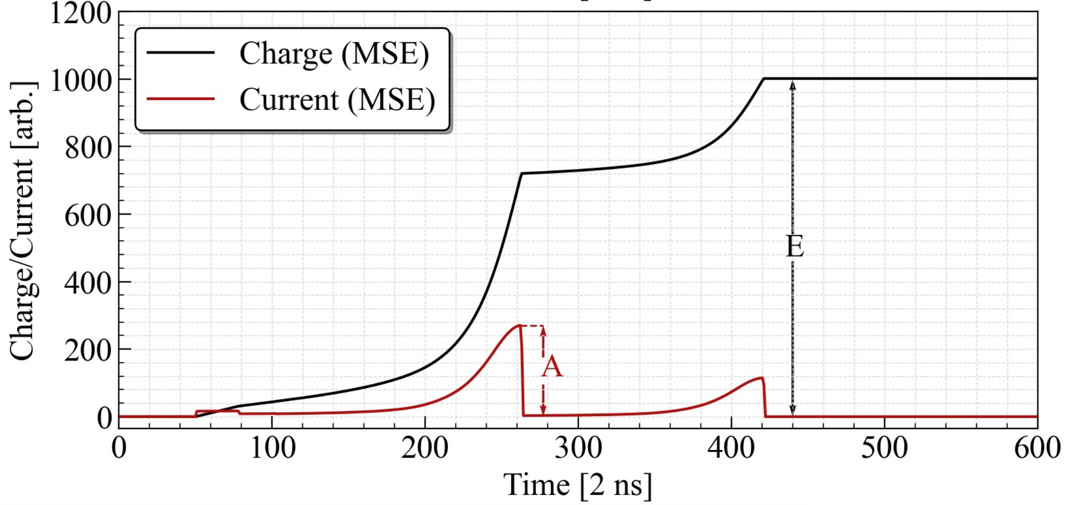
- ***One current peak***
- ***A∝E***





Multiple (two) hits

- ***Two current peak***
- ***(A1+A2)∝E***
- $(A/E)_{MSE} < (A/E)_{SSE}$



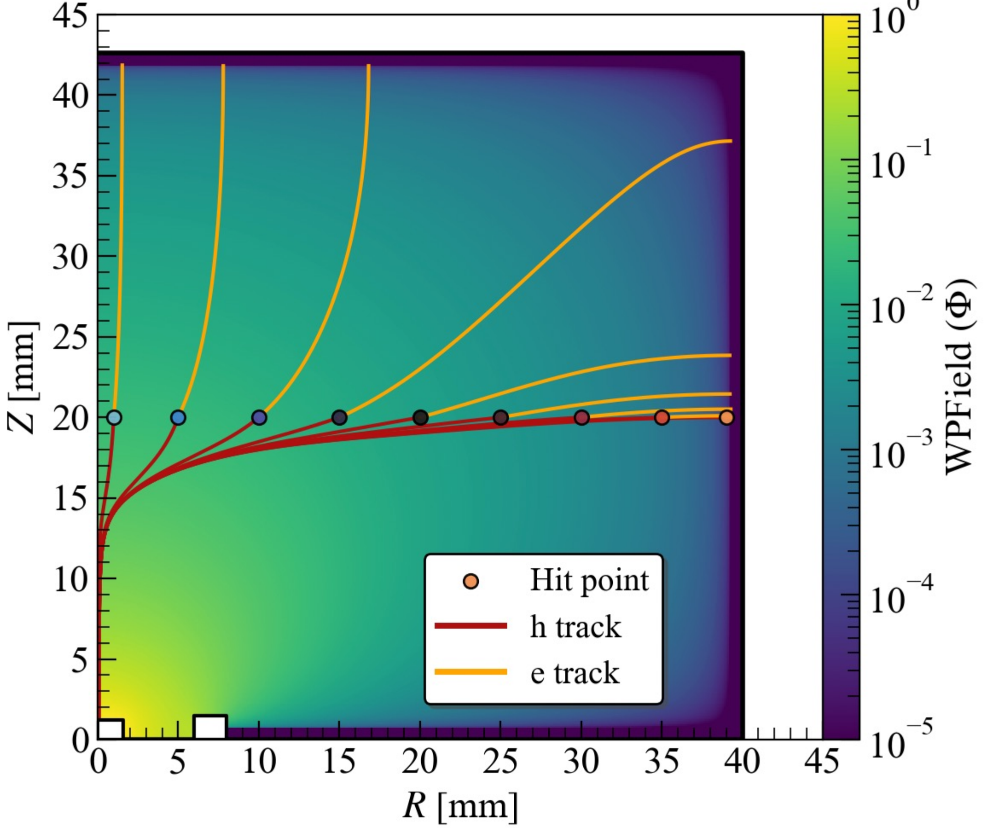
Introduction

☐ Idea of Virtual Segmentation:

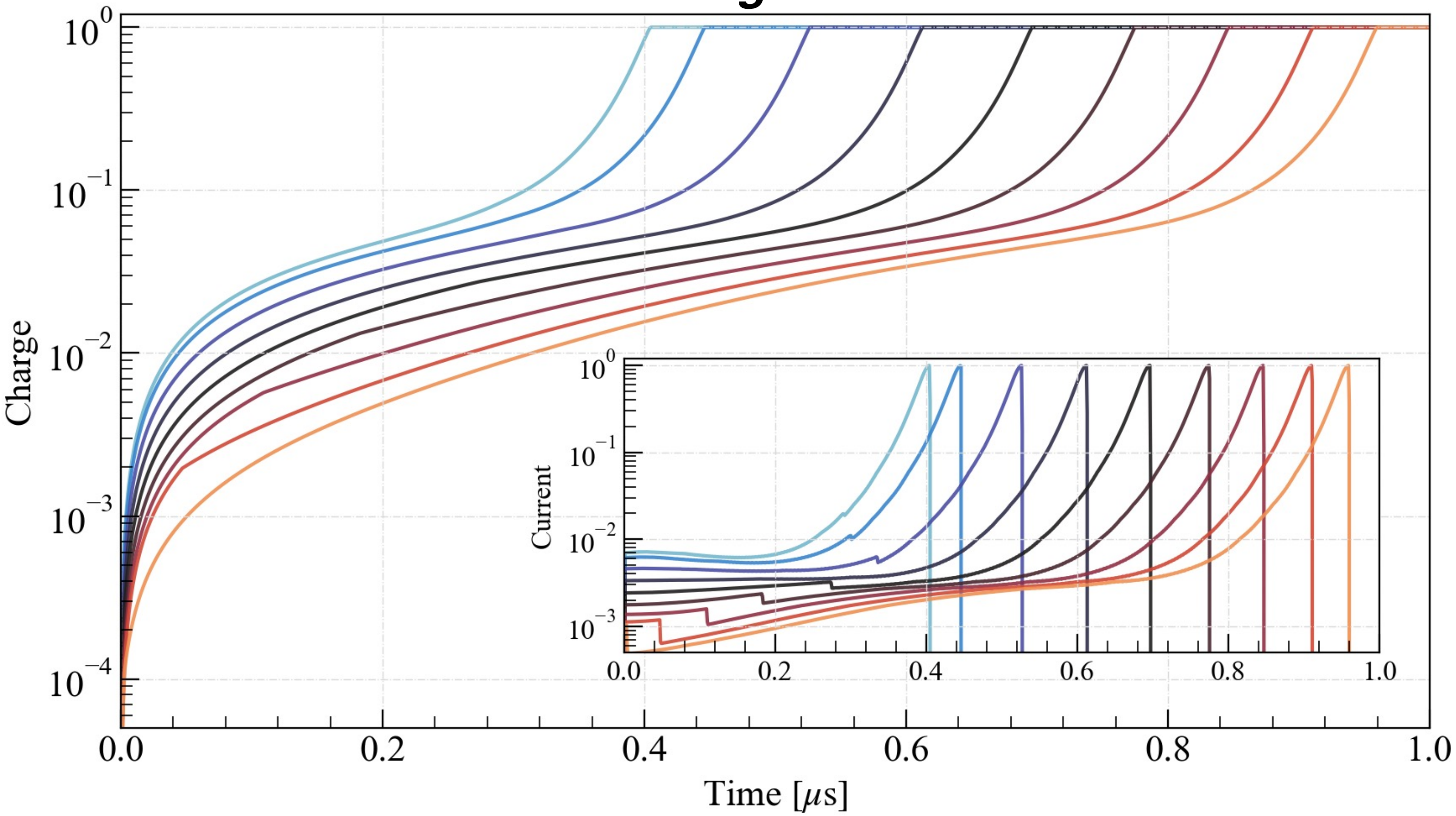
Hit position of SSE determines the ***drift time*** of induced charge carriers and its ***pulse shape***

Virtual Segmentation: Determine SSE position by Pulse Shape Analysis

SSEs in Different Positions



Simulated Charge & Current Pulse

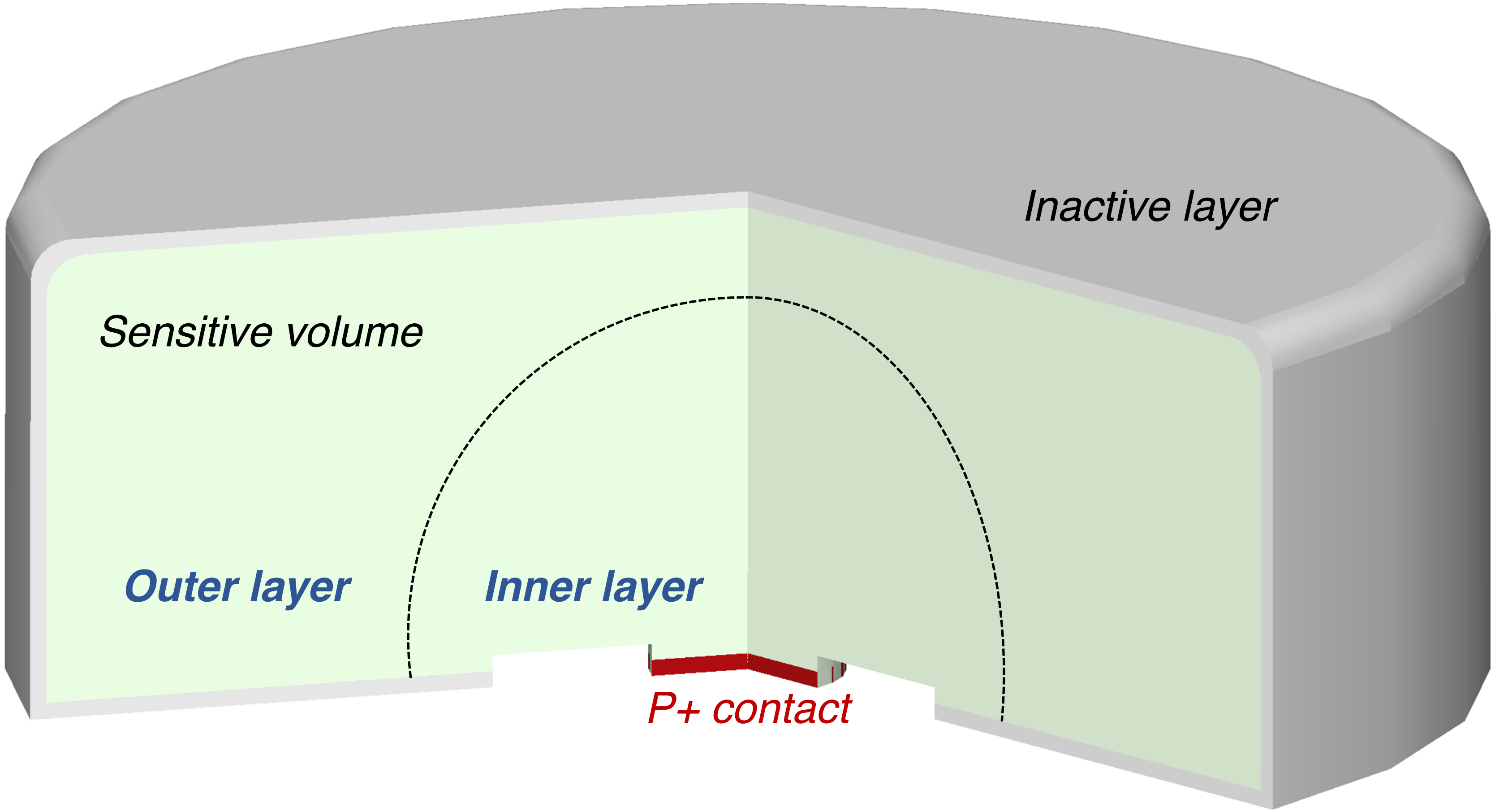


Introduction

Idea of Virtual Segmentation:

① *Identify SSE position by Pulse Shape Analysis*

② *Determine the Shape and Volume of the inner and outer layers by calibration*

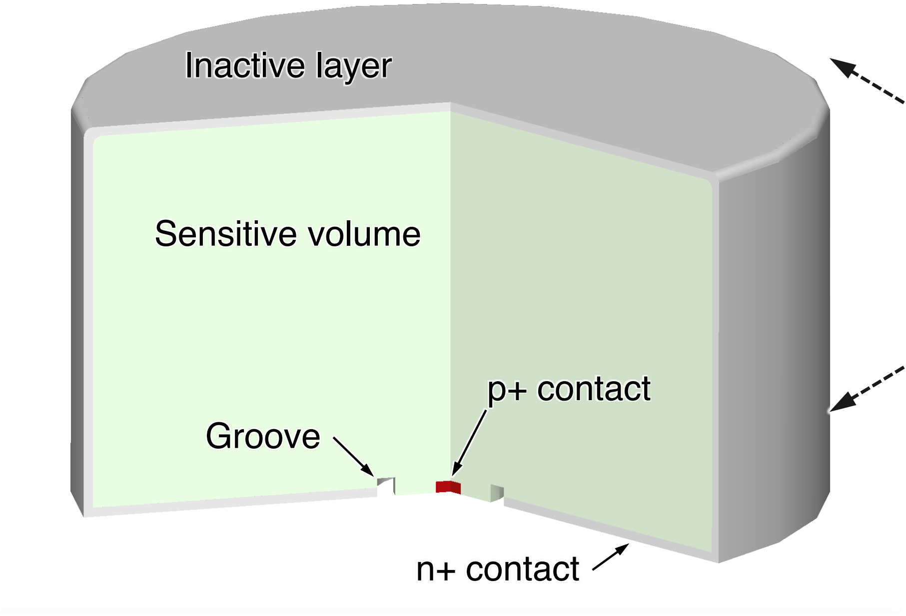


Introduction

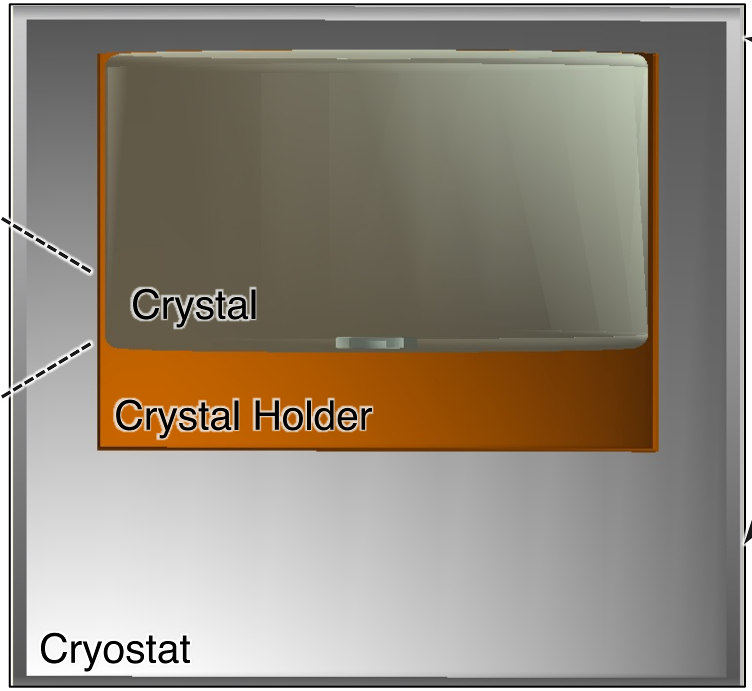
☐ Study on a single-readout BEGe detector:

- *Crystal size: 80 mm × 42.6 mm (Φ × H)*
- *Inactive layer thickness: 0.87±0.67 mm*
- *Sensitive volume (mass): 197.98±0.76 cm³ (1052.3±4.0 g)*

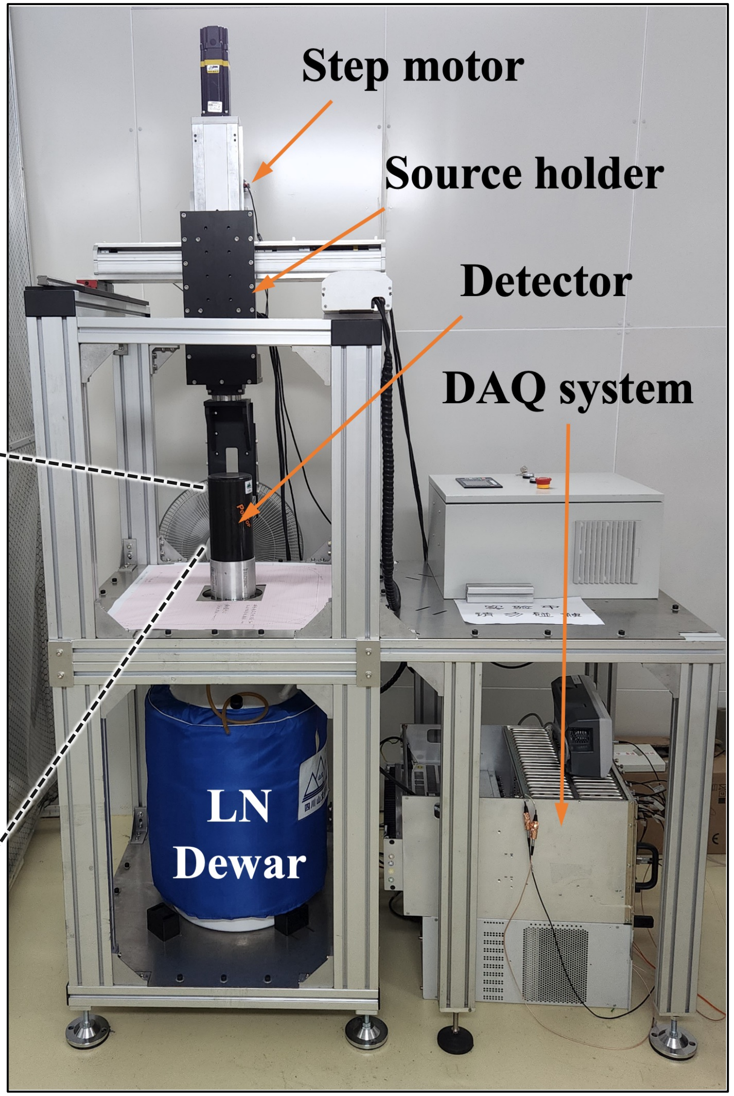
Ge Crystal



BEGe detector



Detector Scan Device @CJPL

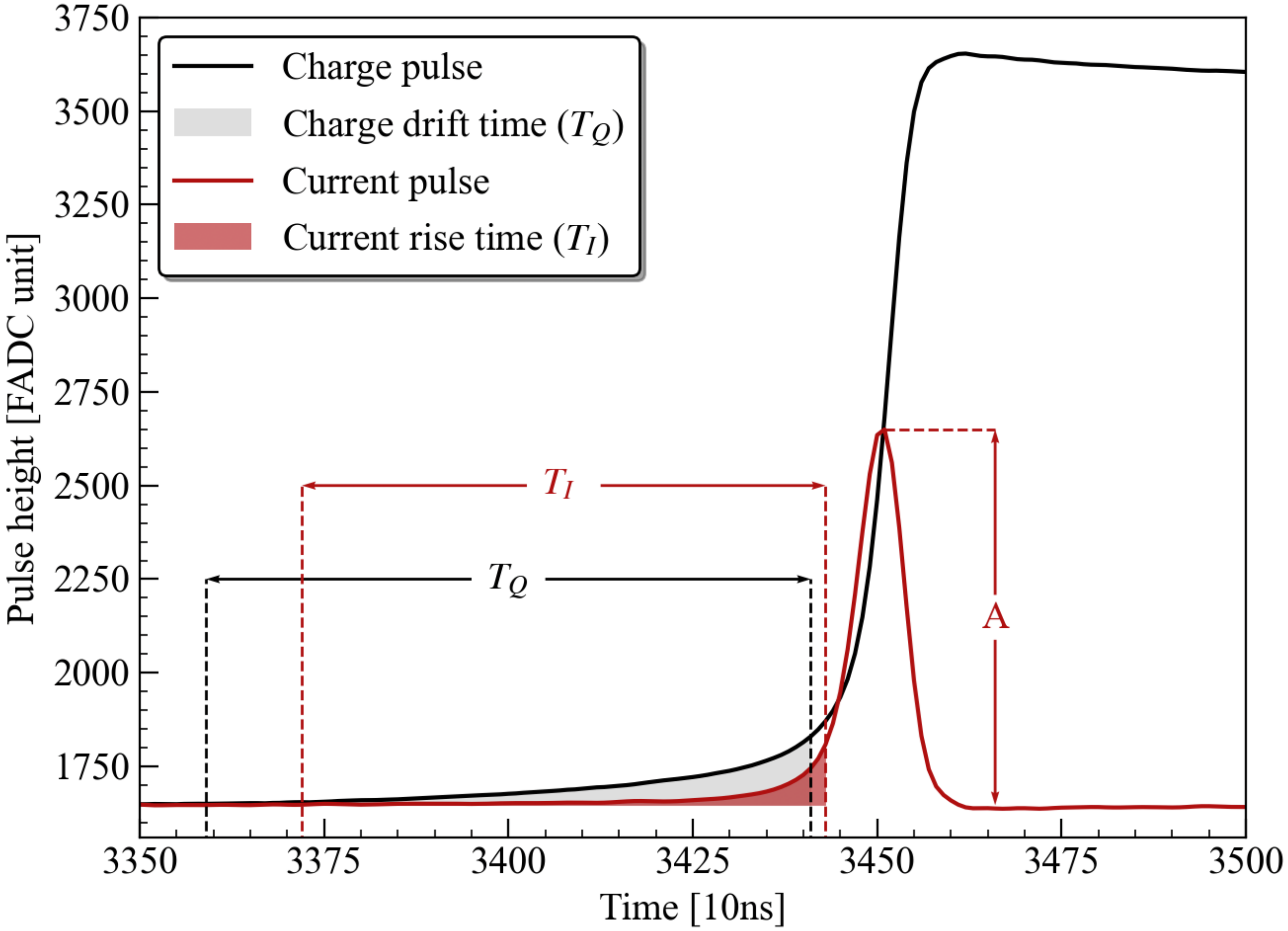


II. Select Inner/Outer Layer SSE via PSA

Select Inner/Outer Layer SSE via PSA

☐ Pulse Shape Parameters:

Three parameters ***(A, T_Q, T_I)*** are used to discriminate SSE/MSE & Inner/Outer Layer events



Current Amplitude (A):

- ➢ Get current by Moving-Average-Differential filter
- ➢ Select SSE by A/E method

Charge drift time (T_Q):

- ➢ 0.2% ~ 10% rise time of the charge pulse
- ➢ Applied to SSEs only

Current rise time (T_I):

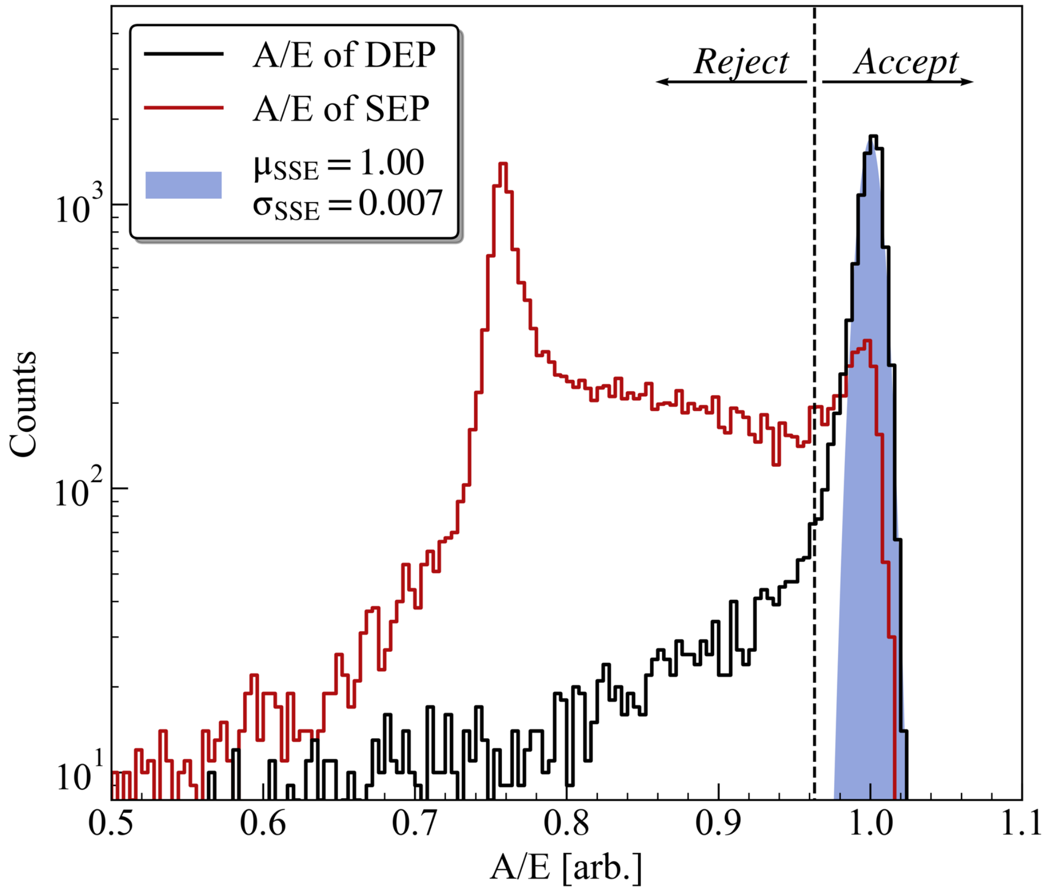
- ➢ 0.2% ~ 20% rise time of the current pulse
- ➢ Applied to SSEs only

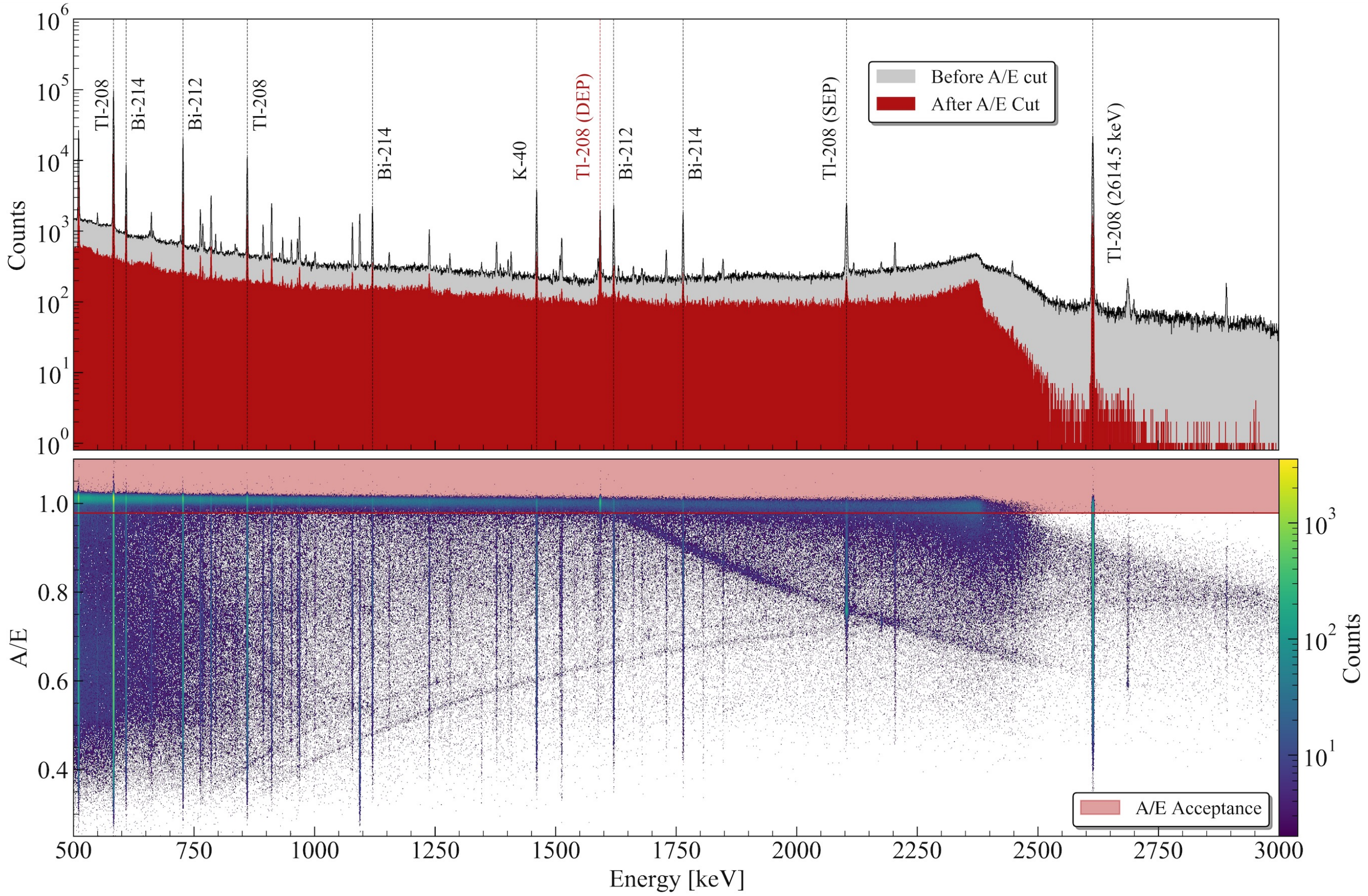
Select Inner/Outer Layer SSE via PSA

☐ Select SSEs by A/E method:

Cut determined by ***Double Escape Peak (DEP)*** events in Th-228 data: $(A/E)_{SSE} > \mu_{DEP} - 5\sigma_{DEP}$

➢ *80% survival for DEP events (SSE) and 9% survival for SEP events (MSE)*



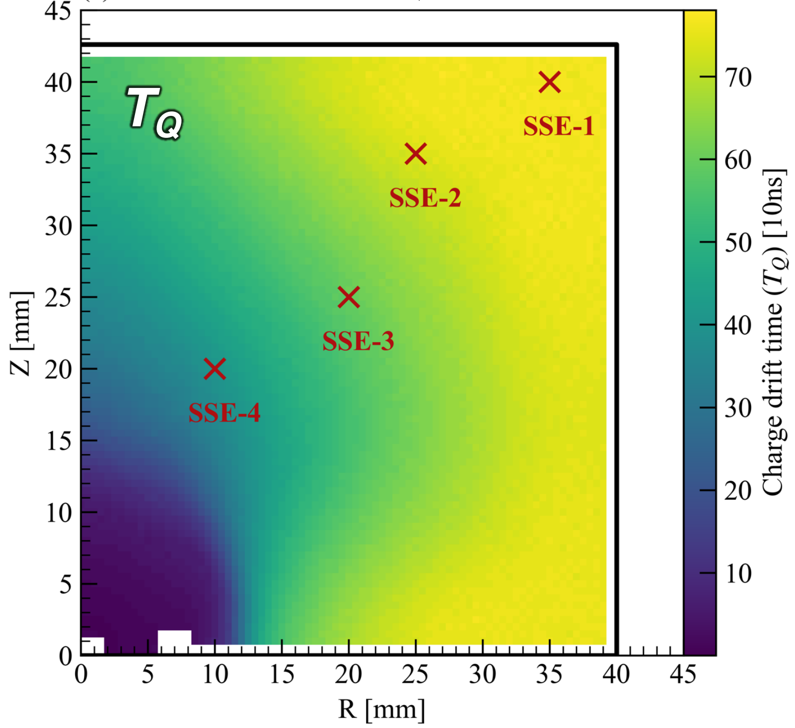


Select Inner/Outer Layer SSE via PSA

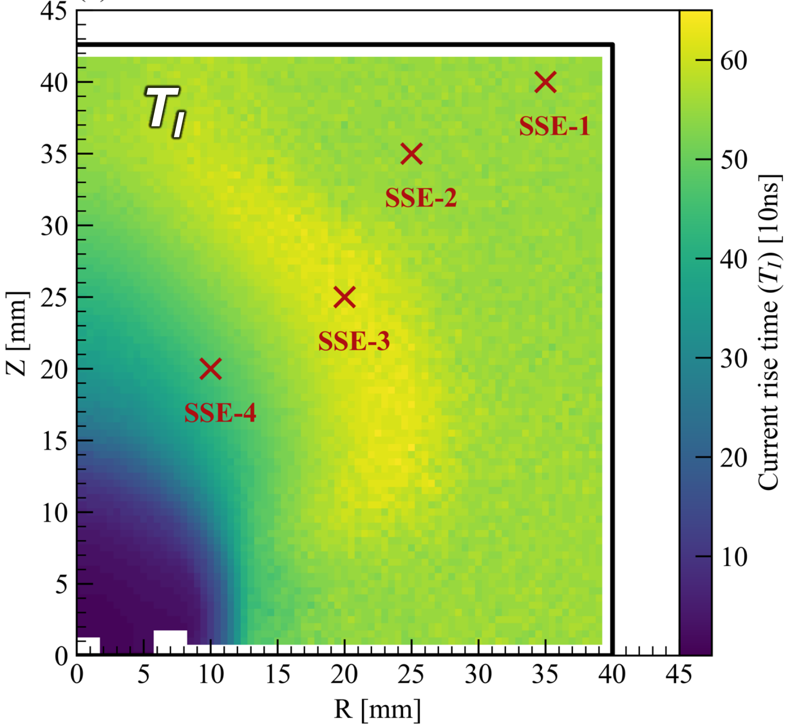
☐ (T_Q, T_I) Distribution for Inner & Outer Layer SSEs:

The ***Linear & Nonlinear*** relation between T_Q & T_I separates the ***Inner & Outer*** SSEs

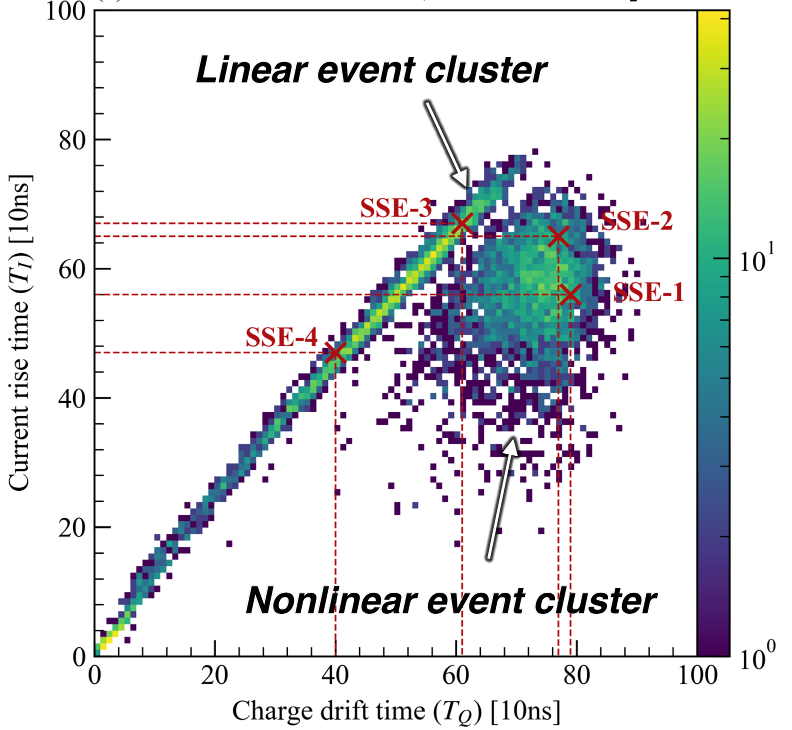
- ➢ *T_Q & T_I are both **proportional to charge carrier drift distance** for inner layer SSEs*
- ➢ *Charge/current signal **do not exceed T_Q, T_I threshold** when charge carriers drift in Outer layer*



Simulated T_Q for SSEs



Simulated T_I for SSEs



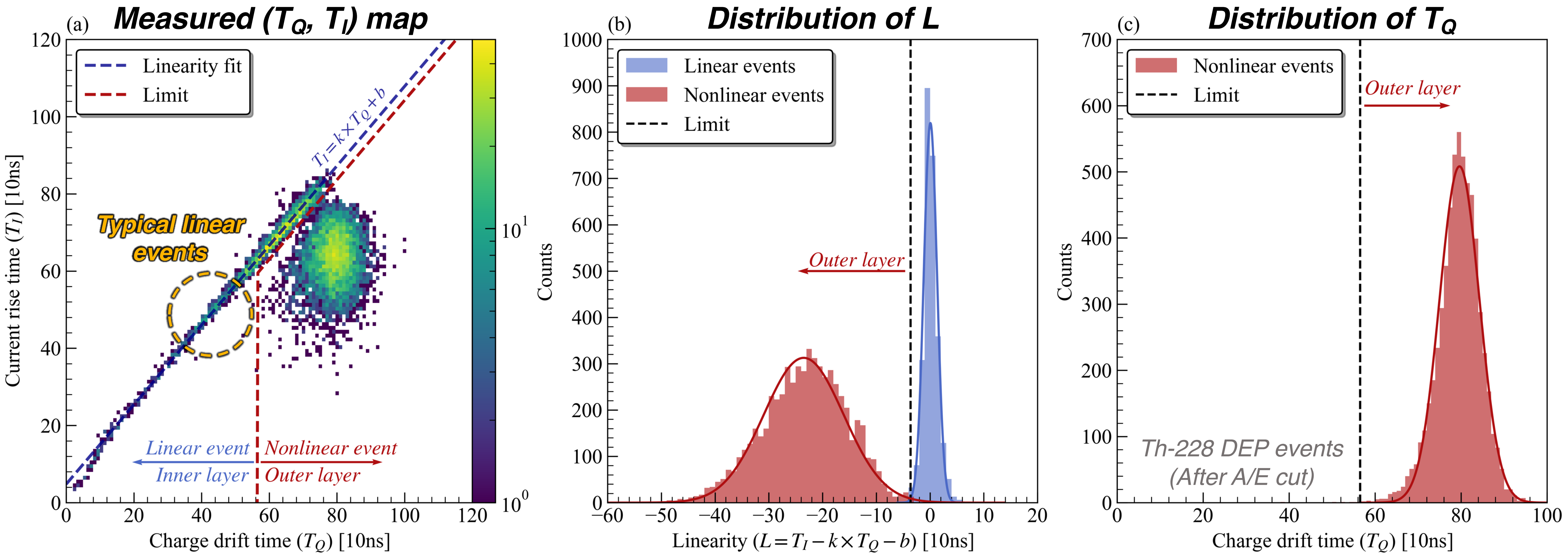
Simulated T_Q vs T_I map

Select Inner/Outer Layer SSE via PSA

- **Discriminate Inner / Outer SSEs via Linearity index:**

Linearity index between T_Q and T_I: $L = T_I - (k\cdot T_Q+b)$

➢ *Parameters k and b are fitted using* ***typical linear events***: $T_I = k \times T_Q + b$



(a) ***Measured (T_Q, T_I) map***

(b) ***Distribution of L***

(c) ***Distribution of T_Q***

III. Determine Inner/Outer Layer Shape & Volume

Determine Inner/Outer Layer Shape & Volume

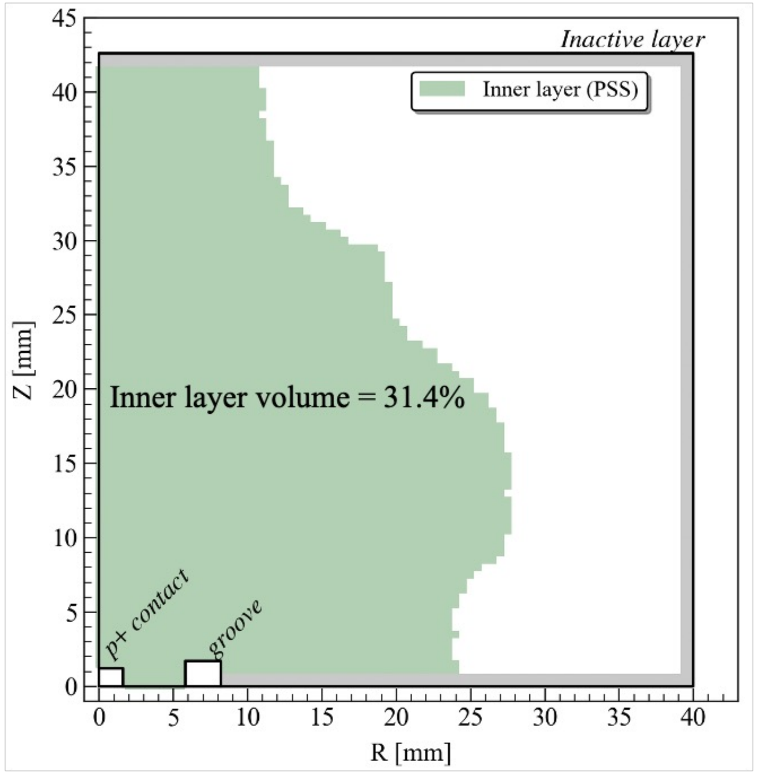
☐ Pulse Shape Simulation (PSS):

Inner layer Shape & Volume heavily rely on the ***crystal impurity profile***

- ➢ ***As precise impurity profile not known, Inner/Outer Layer is calibrated experimentally***

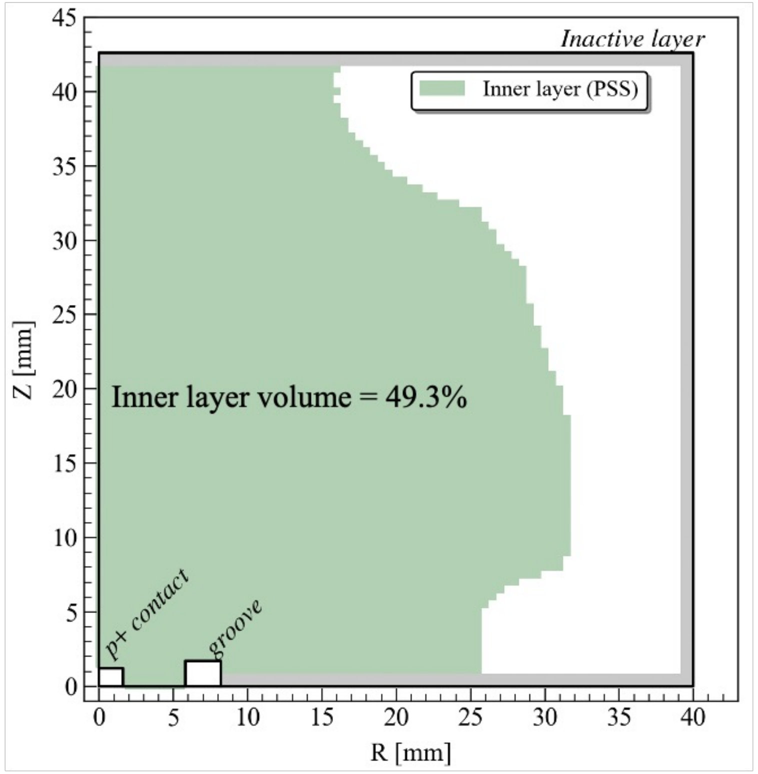
Impurity in Z-direction (10^{10} cm^{-3})

$Z_0 = 0.05$ $Z_1 = 0.22$



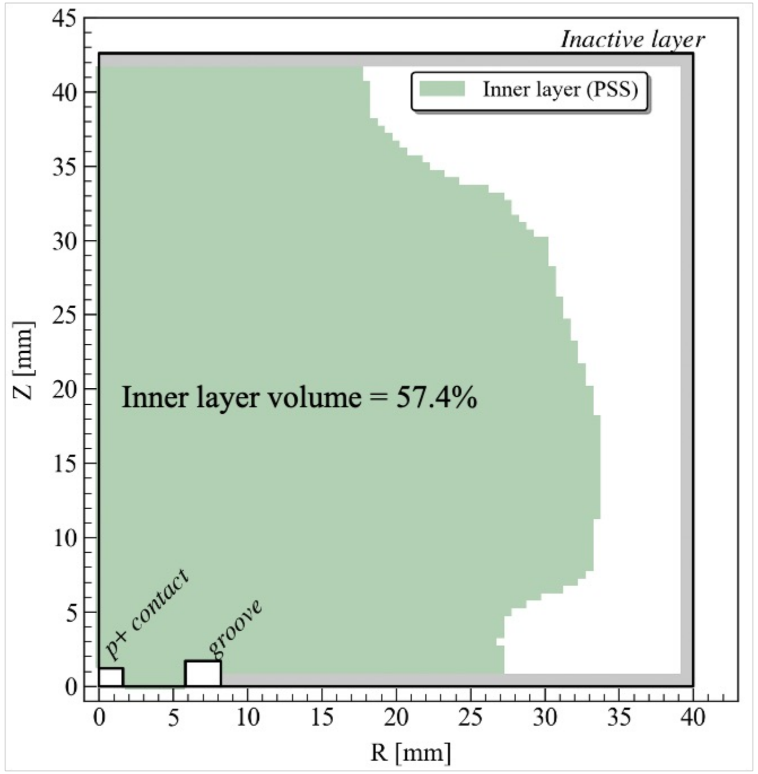
Impurity in Z-direction (10^{10} cm^{-3})

$Z_0 = 0.25$ $Z_1 = 0.38$



Impurity in Z-direction (10^{10} cm^{-3})

$Z_0 = 0.50$ $Z_1 = 0.44$



Determine Inner/Outer Layer Shape & Volume

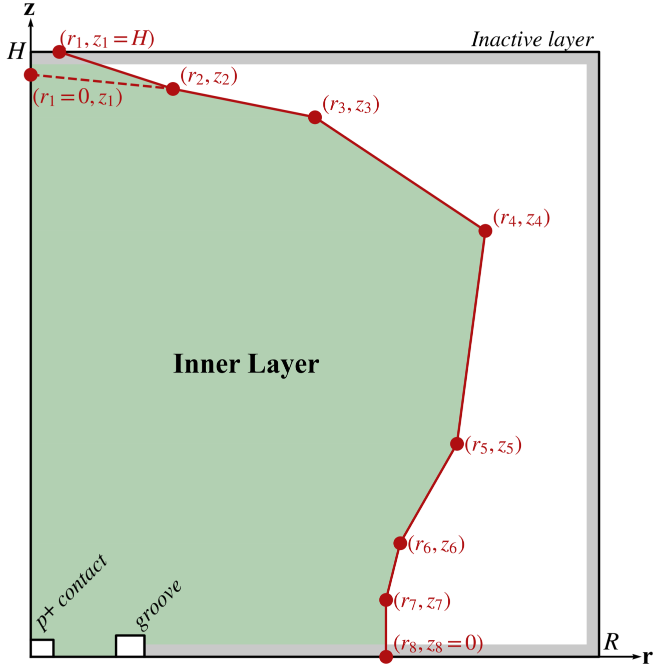
☐ Calibrate Inner/Outer Layer using Th-228 DEP Data:

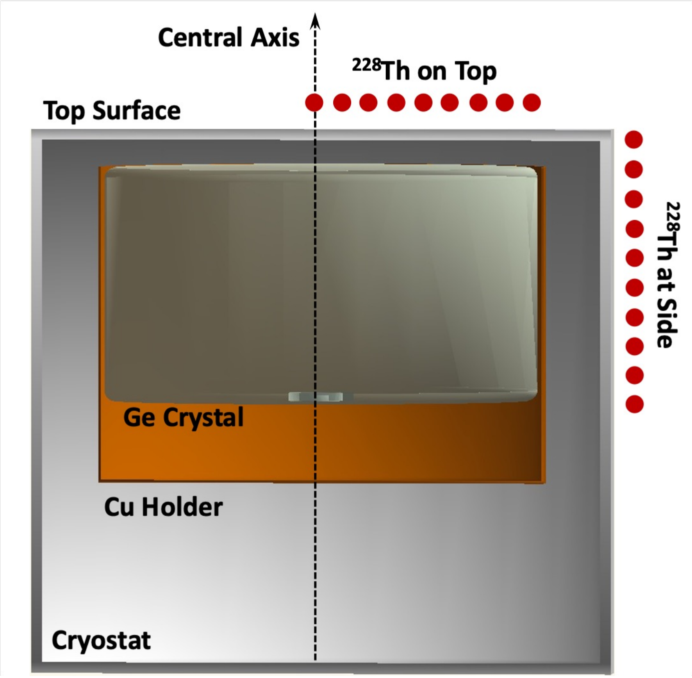
$$R_L = \iint M(r,z|\theta) \cdot F_{DEP}(r,z)drdz$$

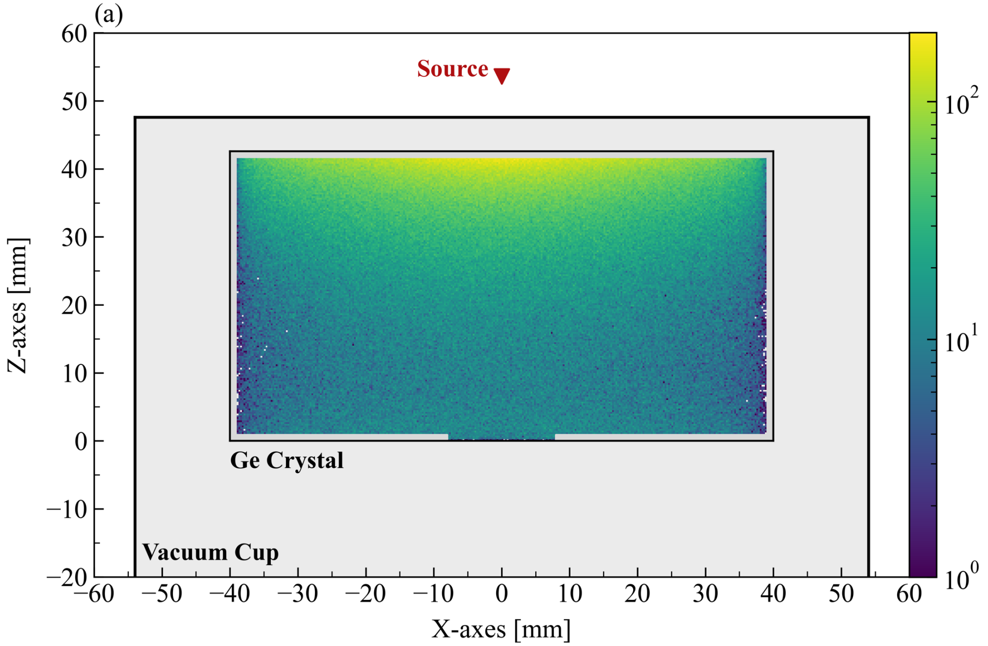
① Parameterized segment model ***M(θ)***: 8 points, 14 parameters

② Inner layer event ratio (***R_L***) in Th-228 scanning experiments: 19 positions on Top & Side

③ SSE spatial PDF (***F_{DEP}***): calculate via Geant4 simulation







Determine Inner/Outer Layer Shape & Volume

- ☐ **Measure R_L for different source positions:**

Linear events in background data

Linear events in Th-228 data

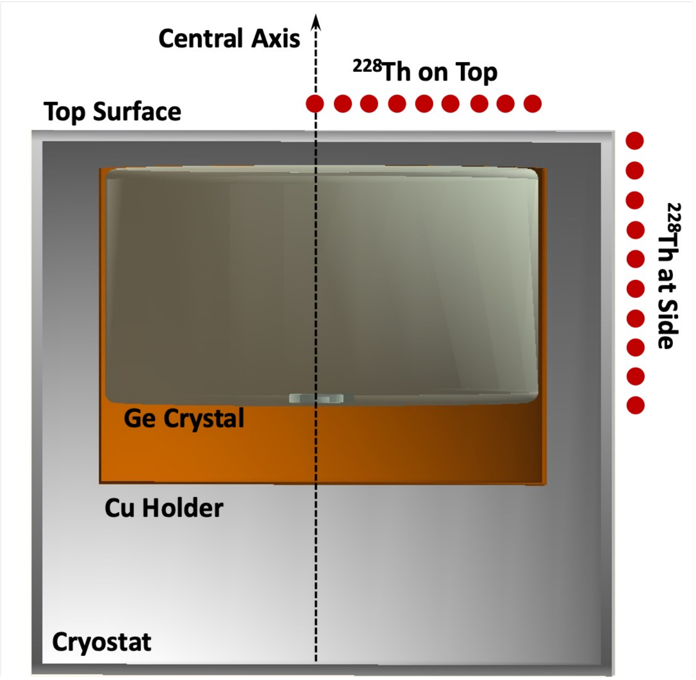
$$R_L = \frac{N_{L,S} - N_{L,B} \cdot t_S/t_B}{N_{T,S} - N_{T,B} \cdot t_S/t_B}$$

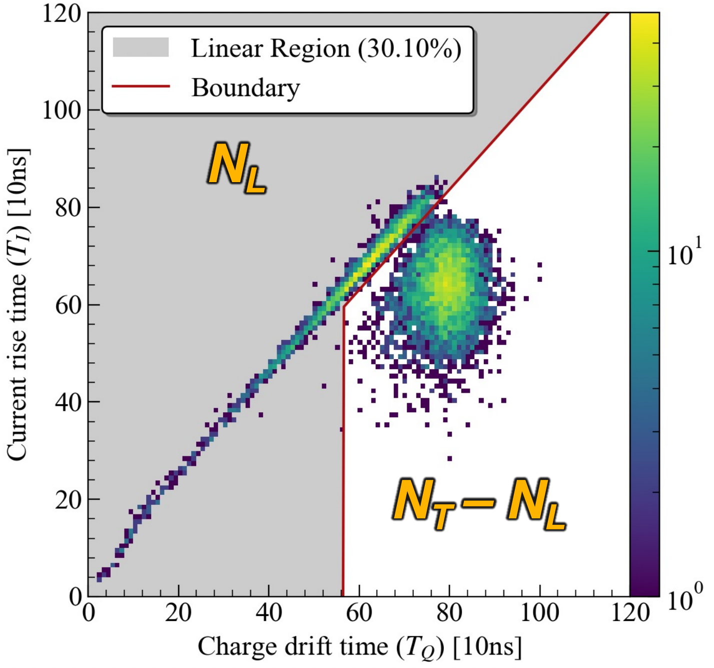
Total events in Th-228 data

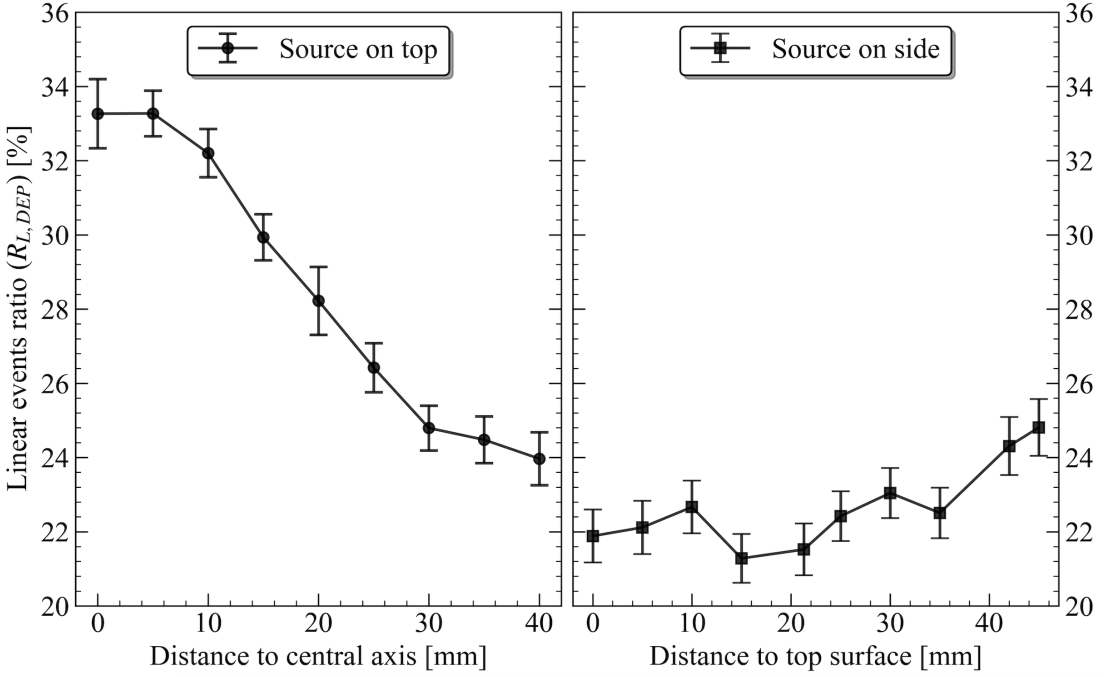
Total events in background data

t_S: source measure time

t_B: background measure time







Determine Inner/Outer Layer Shape & Volume

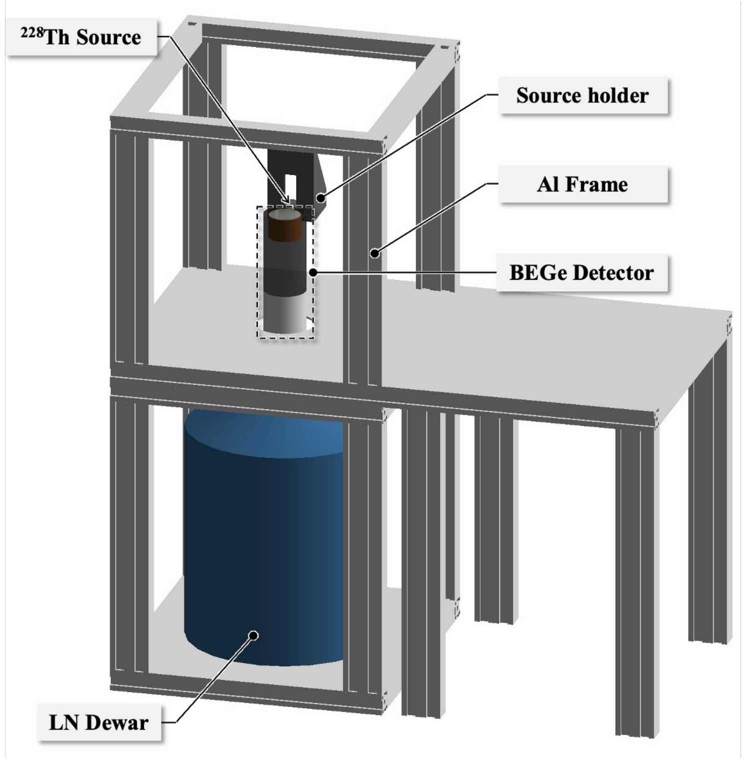
☐ Simulate Spatial PDF:

- Detailed detector model in Geant4
- Simulate energy deposition of DEP events
- Parameter δ_D to remove MSEs in simulation

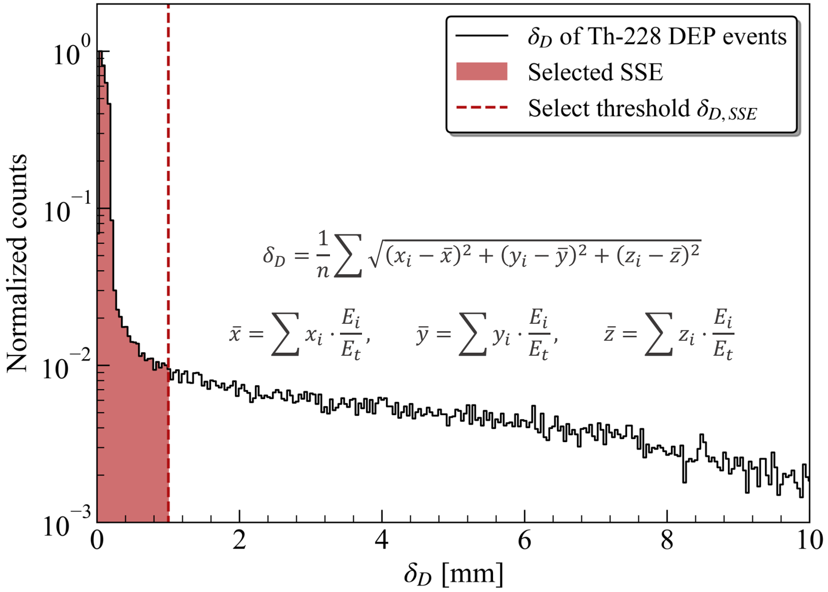
$$R_{L,M}(\theta) = \iint M(r,z\mid\theta)F_{DEP}(r,z)\,\mathrm{drdz}$$

$$M(r,z\mid\theta) = \begin{cases} 1 & (r,z) \in \text{Inner Layer} \\ 0 & (r,z) \in \text{Outer Layer} \end{cases}$$

Geant4 Model → ***Select SSE*** → ***Spatial PDF $F_{DEP}(r,z)$***



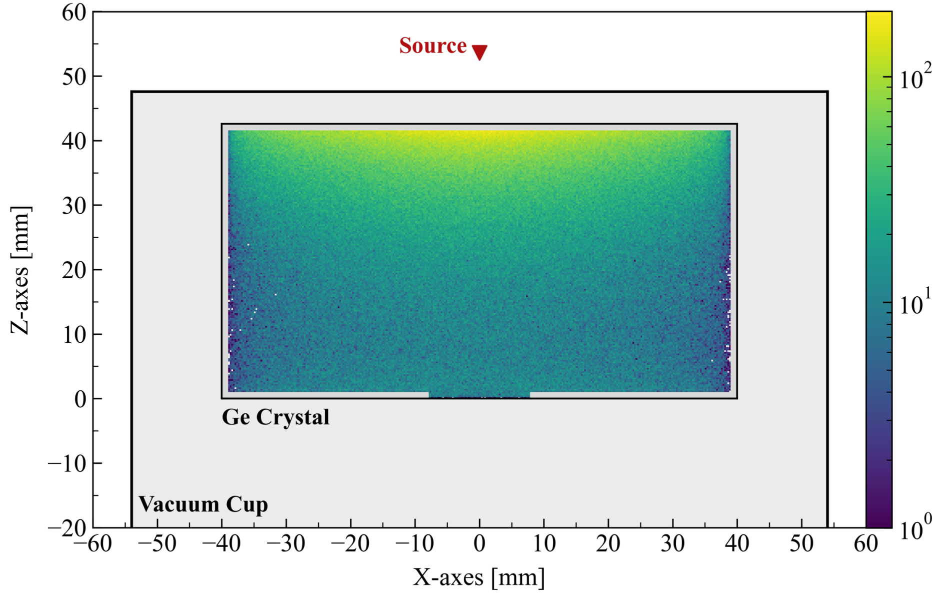
Same survival fraction with A/E cut



$$\delta_D = \frac{1}{n}\sum\sqrt{(x_i-\bar{x})^2+(y_i-\bar{y})^2+(z_i-\bar{z})^2}$$

$$\bar{x} = \sum x_i\cdot\frac{E_i}{E_t}, \qquad \bar{y} = \sum y_i\cdot\frac{E_i}{E_t}, \qquad \bar{z} = \sum z_i\cdot\frac{E_i}{E_t}$$

F_{DEP} for Th-228 DEP event



Determine Inner/Outer Layer Shape & Volume

☐ Fit Model Parameters:

Measured inner event ratio

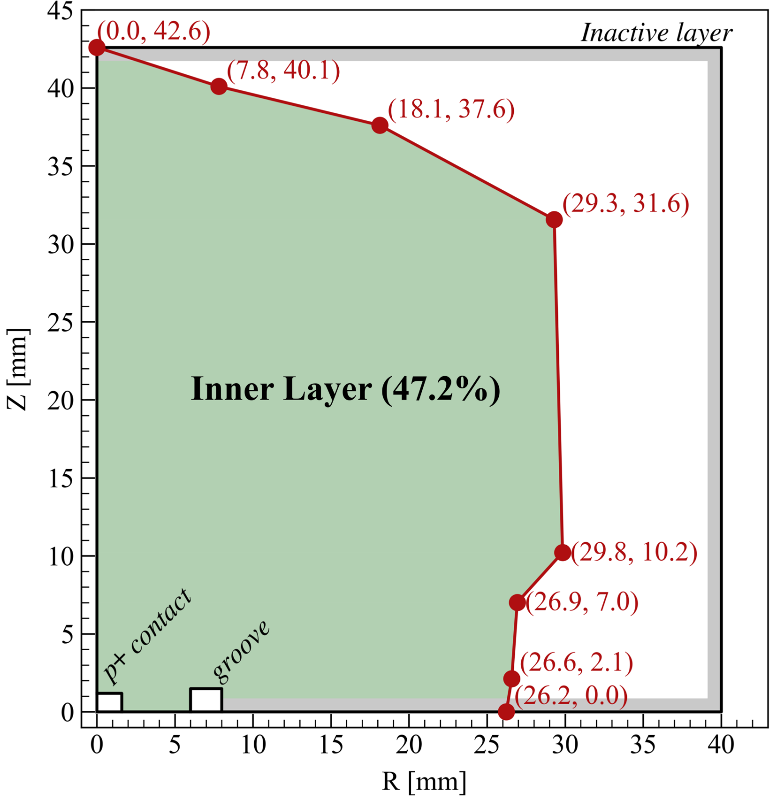
Segment model

Spatial distribution

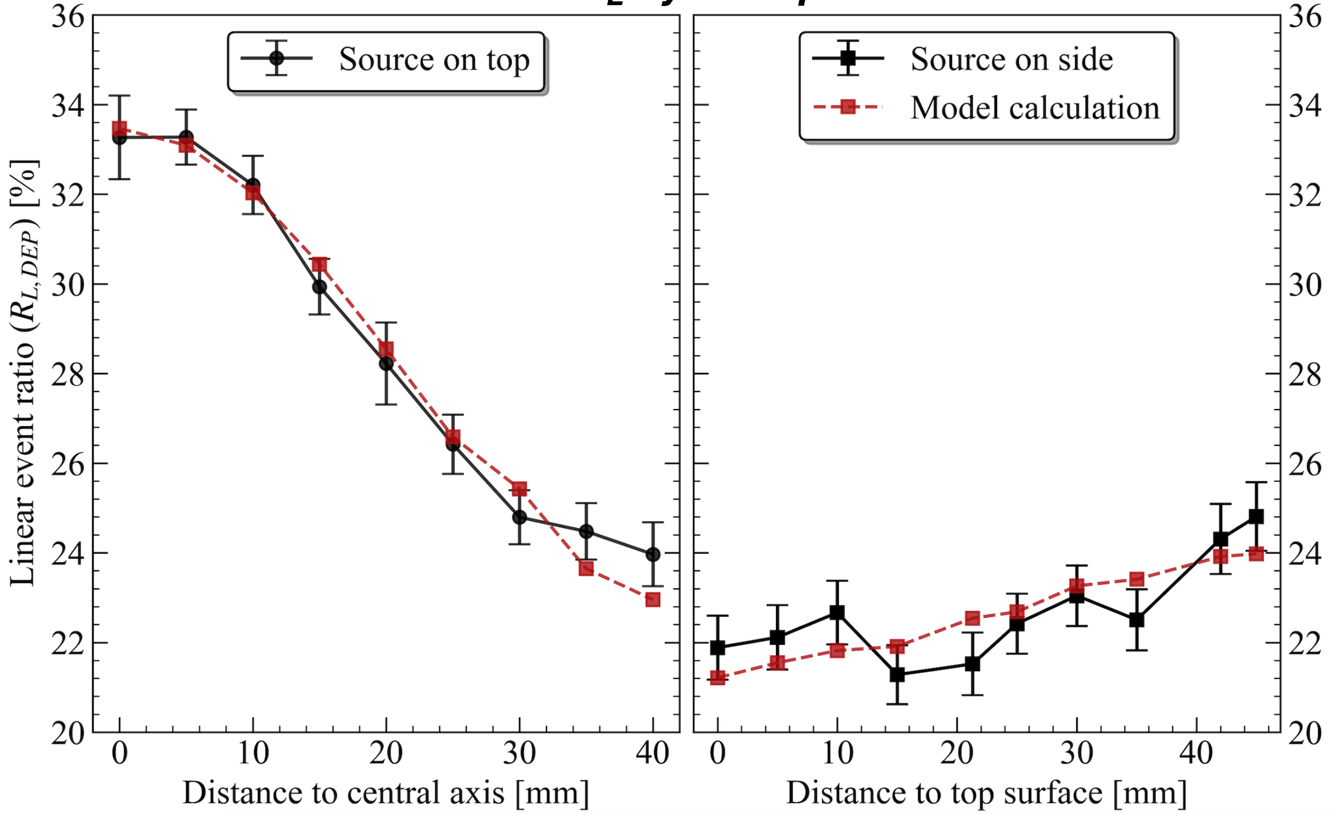
$$\chi^2 = \sum_{k=1}^{19} \frac{\left(R_{L,DEP} - \iint M(r,z \mid \theta) F_{DEP}(r,z) \mathrm{d}r\mathrm{d}z\right)^2}{\sigma_k^2}$$

Uncertainty of measured $R_{L,DEP}$

Optimized segment model



Reconstructed R_L by the optimized model



Determine Inner/Outer Layer Shape & Volume

☐ Uncertainty Assessment:

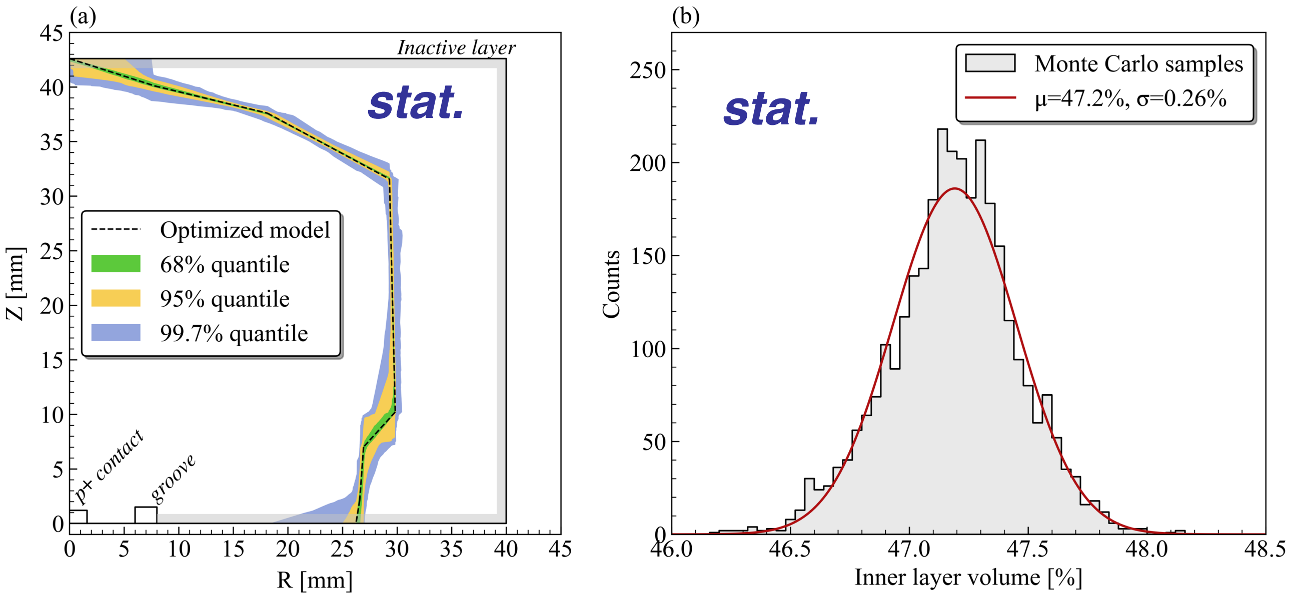
Inner layer in sensitive volume = 47.2% ± 0.26% (stat.) ± 0.22% (datasets) ± 0.18% (Inactive.)

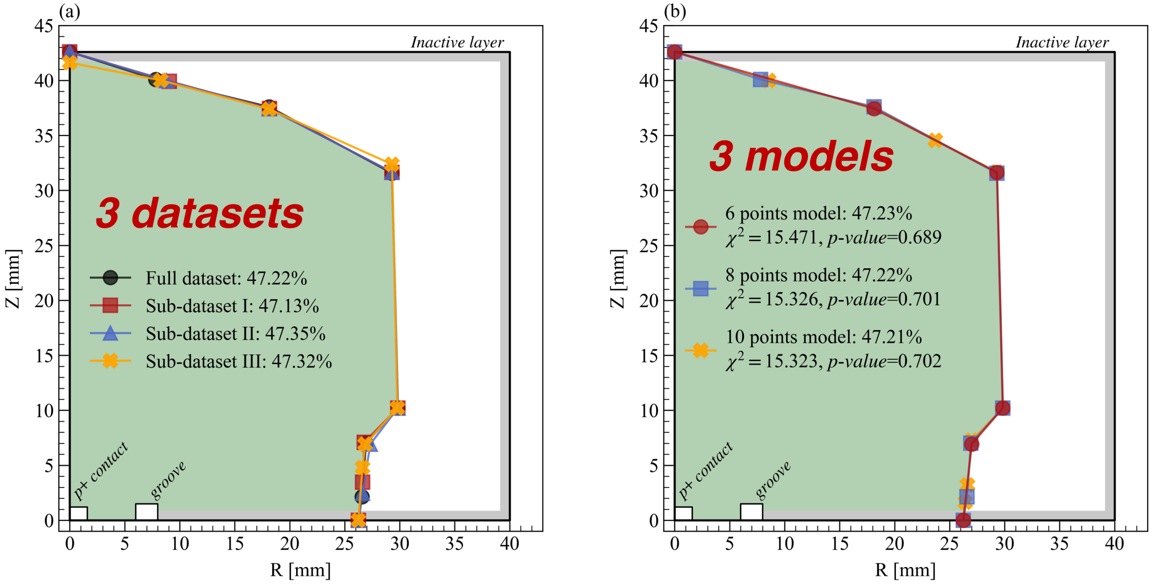
Statistic uncertainty:

- ➢ 3000 times toy-Monte Carlo sampling → **(±0.26%)**

Systematic uncertainty:

① Inactive layer thickness: measurement (870±67 μm) → **(±0.18%)**
② Dataset selection: re-fit model using 3 sub-datasets → **(±0.22%)**
③ Model construction: analyze 6, 8, and 12 points models → **(±0.02%, negligible)**

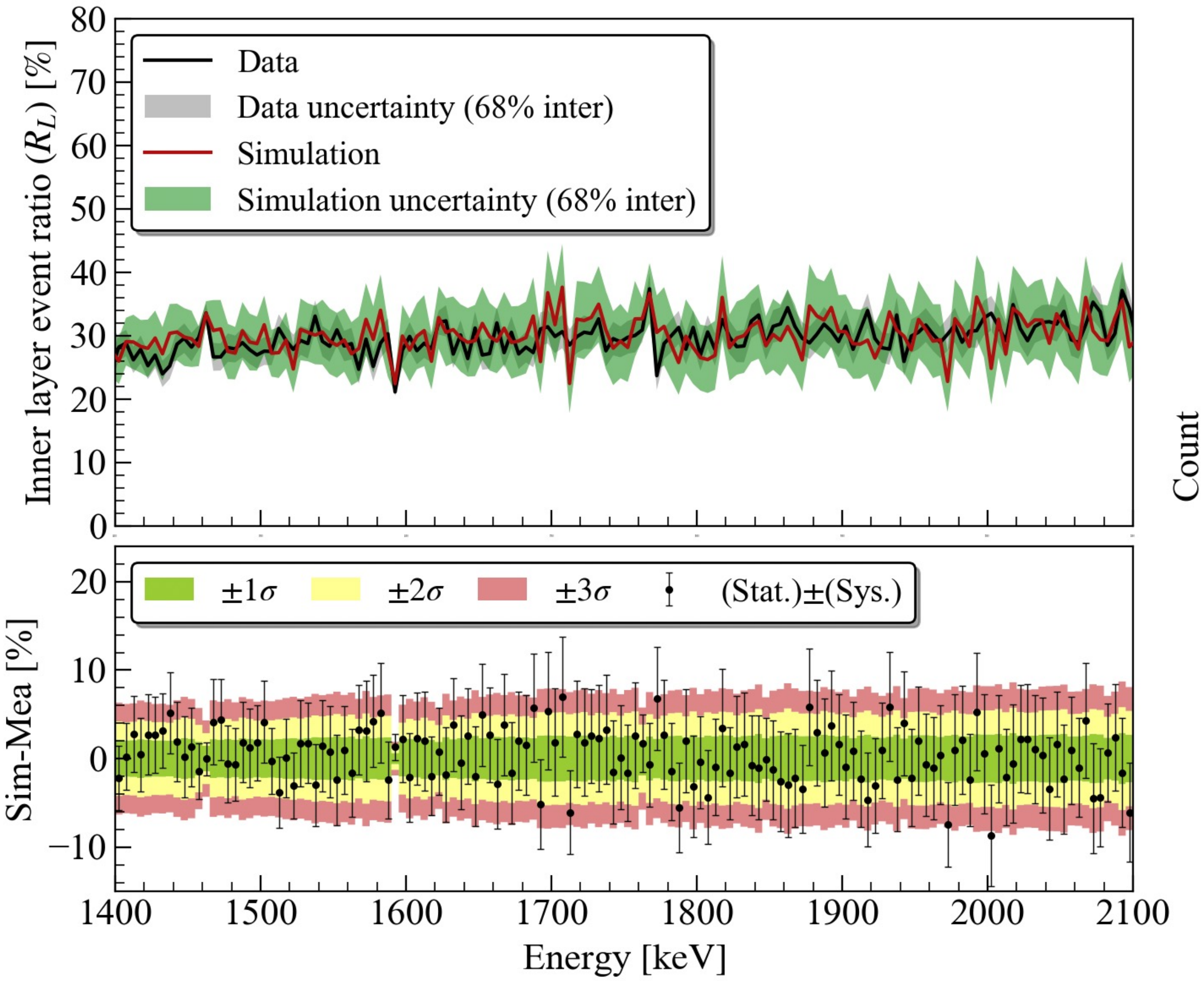


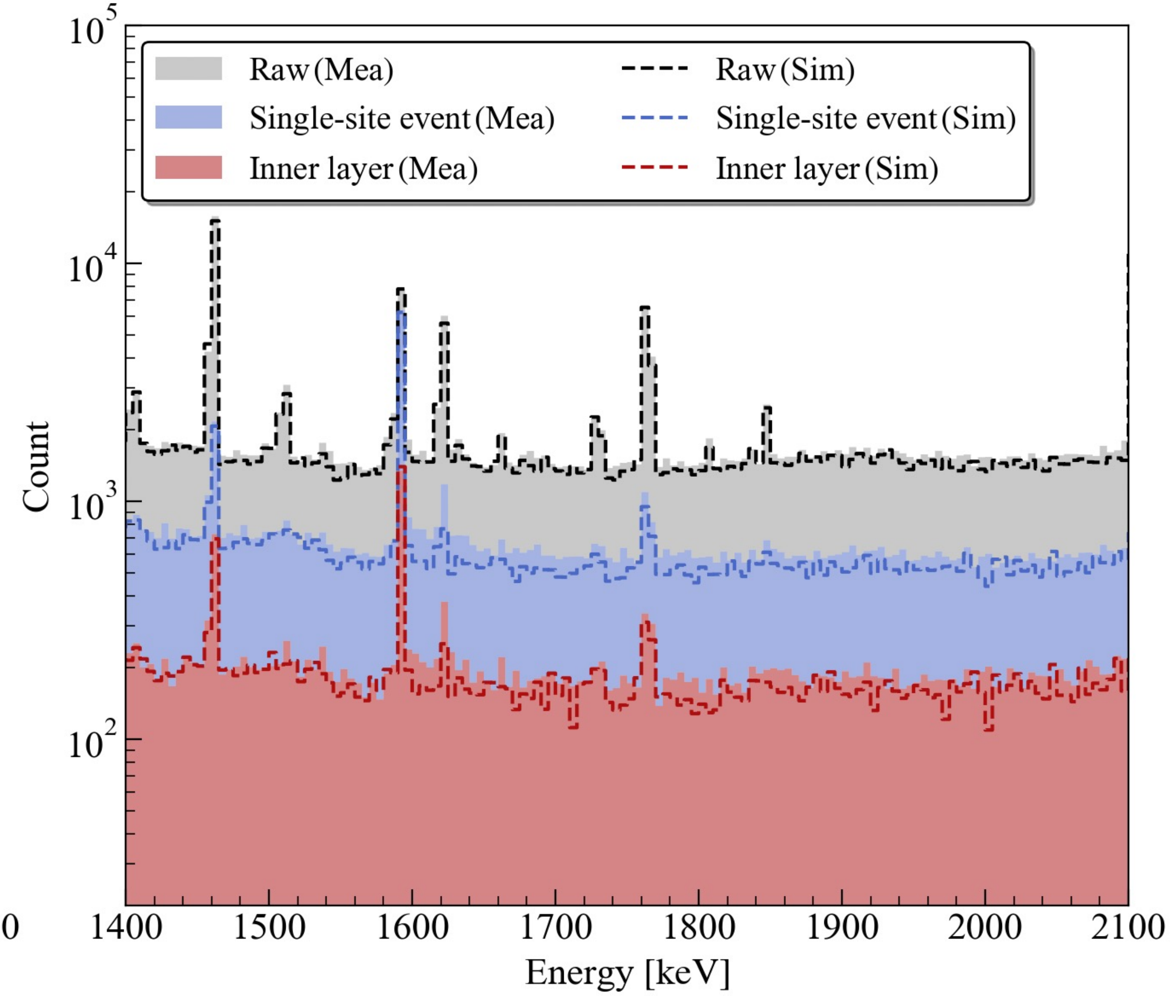


Determine Inner/Outer Layer Shape & Volume

- **Model Validation in Ge-76 0νββ signal region (2039 keV):**

Model optimized using 1592.5 keV DEP events and validated in 1400 ~ 2100 keV region





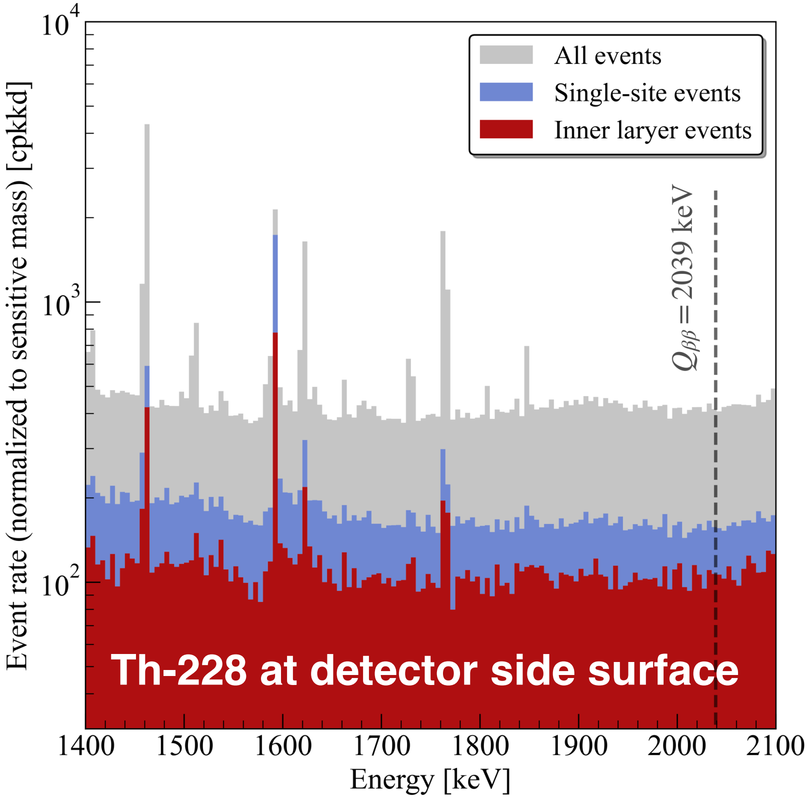
IV. Background Suppression by Virtual Segmentation

Background Suppression

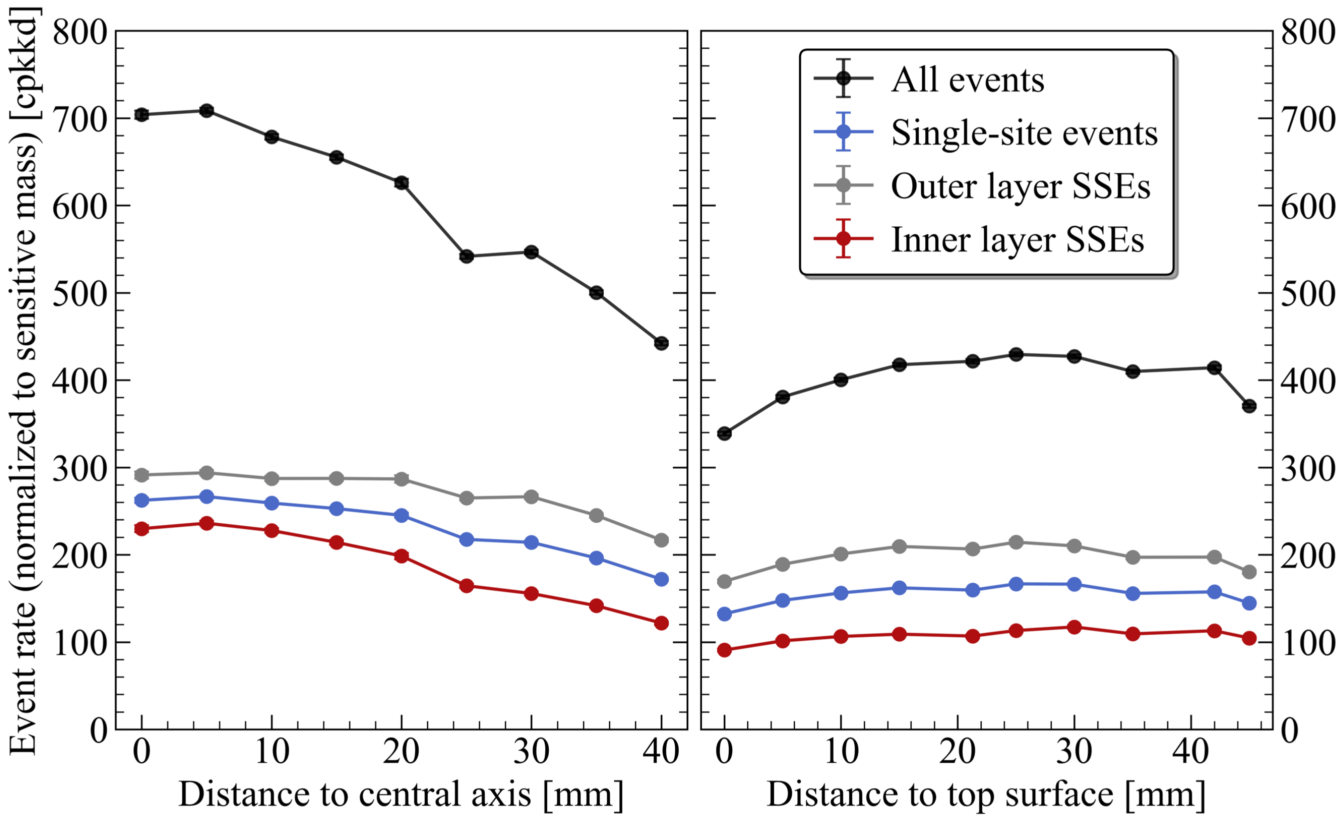
☐ High energy γ background in 0νββ signal region

Th-228 at different positions is a good proxy for external High energy γ background sources

- ➢ *Inner layer has a lower background rate* ***(5~12% BG suppression on top of the A/E method)***
- ➢ *Best background suppression for Th-228 at the side of the detector*



Th-228 at detector side surface

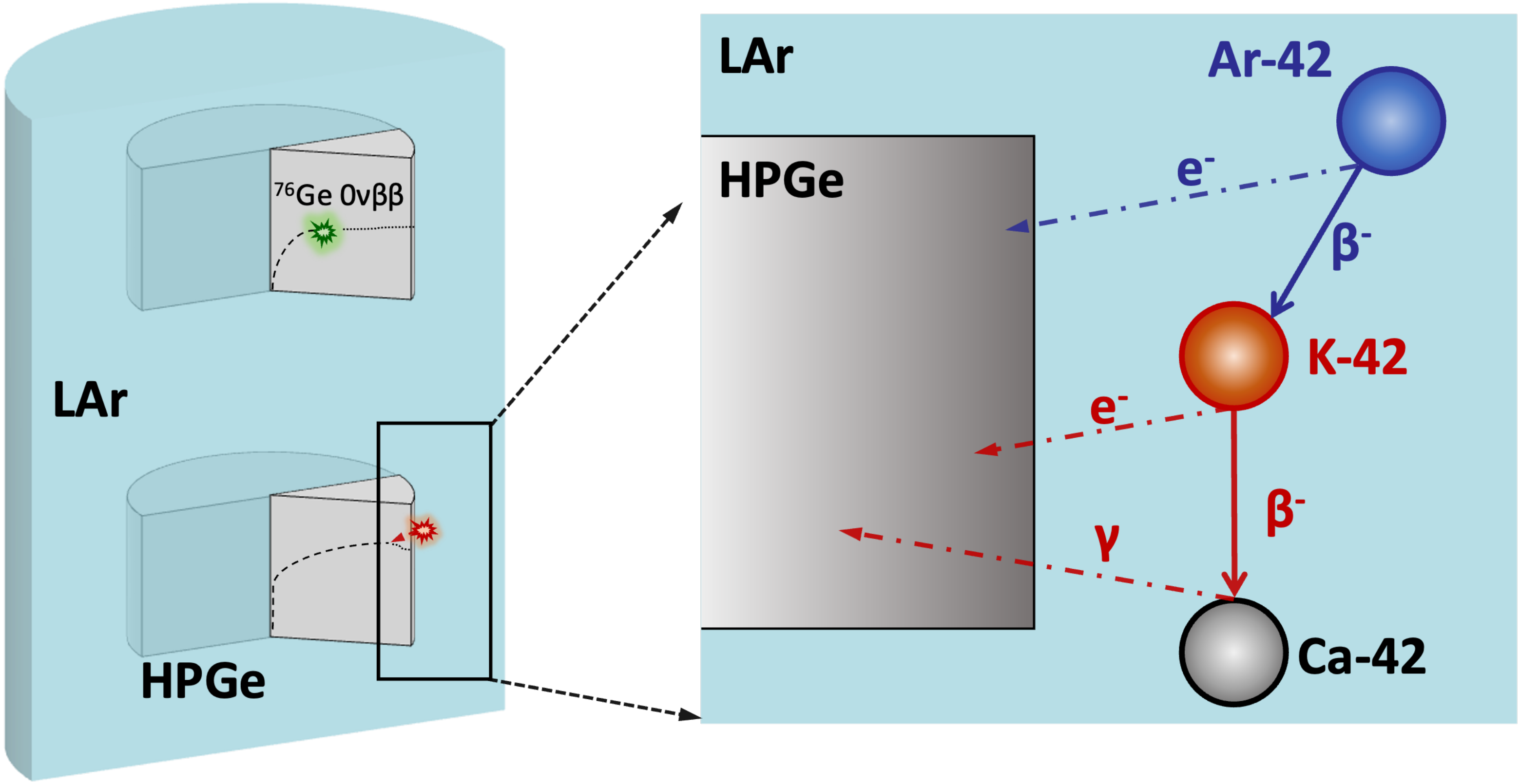


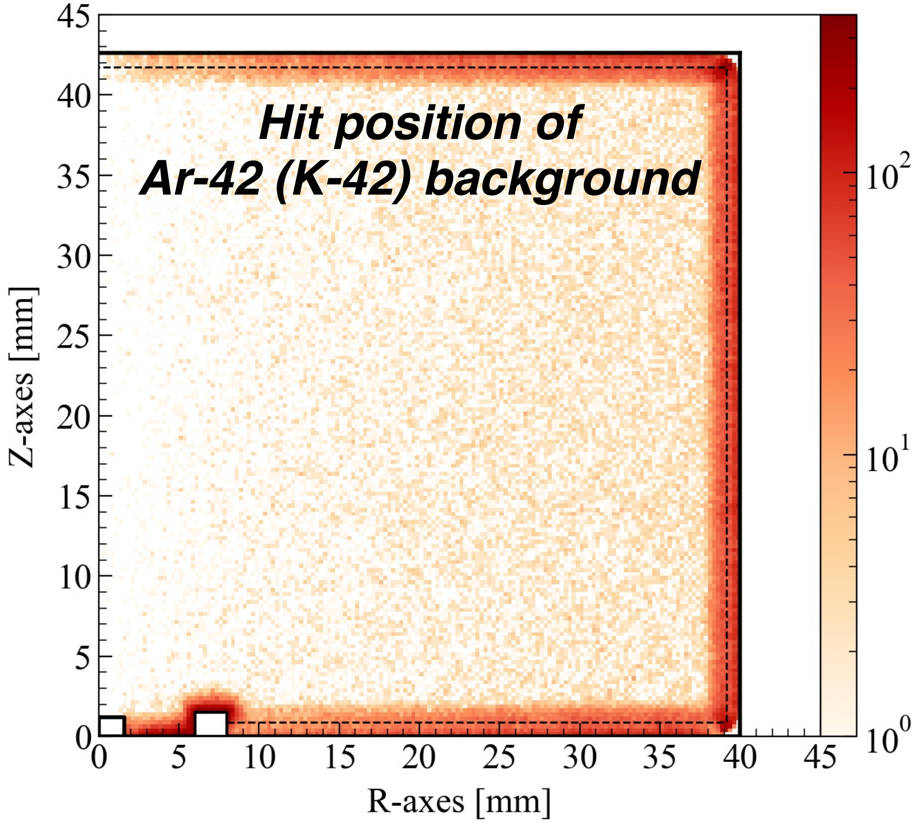
Background Suppression

☐ Surface background from Ar-42

When HPGe is immersed in LAr, background from Ar-42 (K-42) cluster on the detector surface

- *Ar-42 in Atmosphere Argon:* ***92 μBq/kg***
- *Background in ROI (2039 keV):* ***(16.8±0.9)×10^{-4} cpkky***



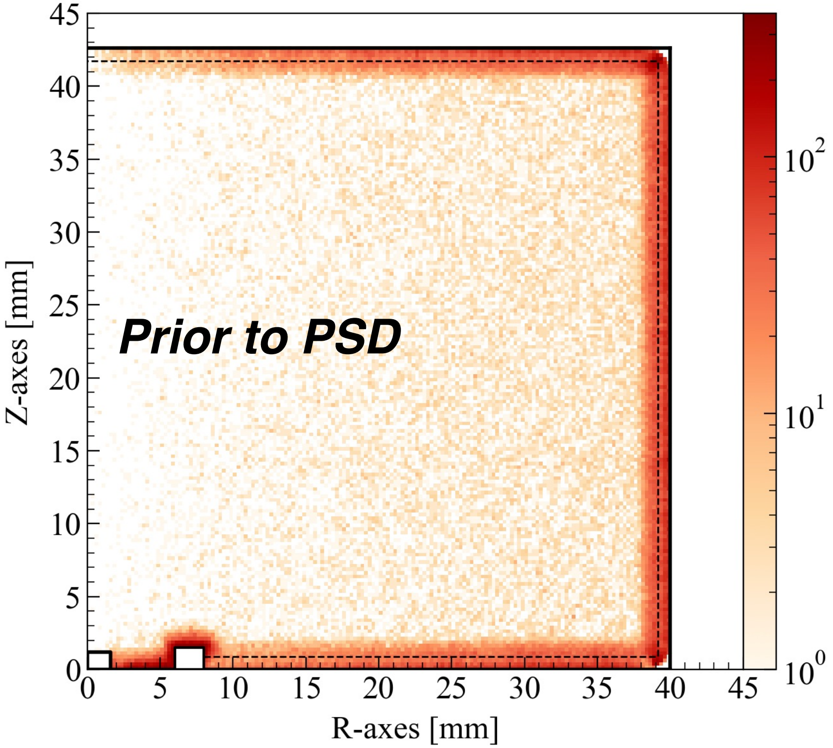


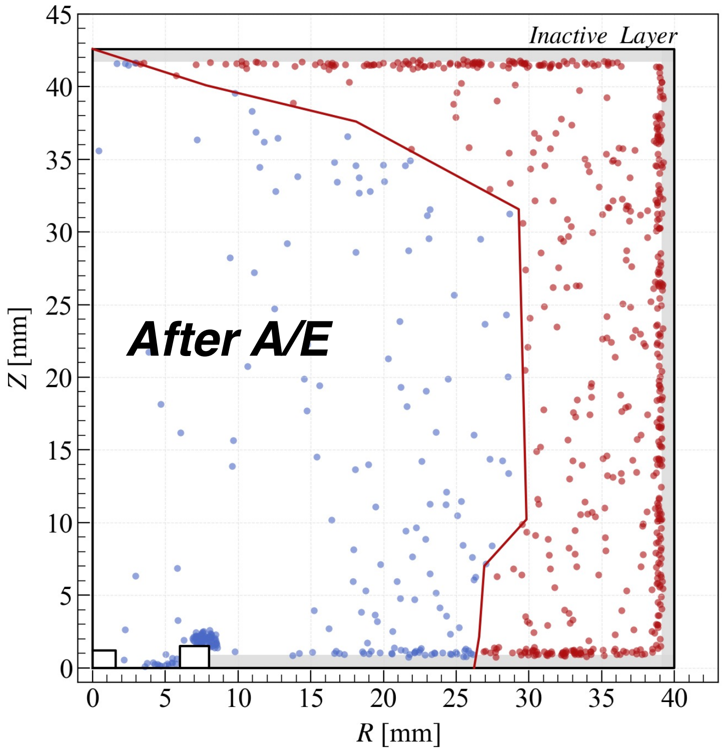
Background Suppression

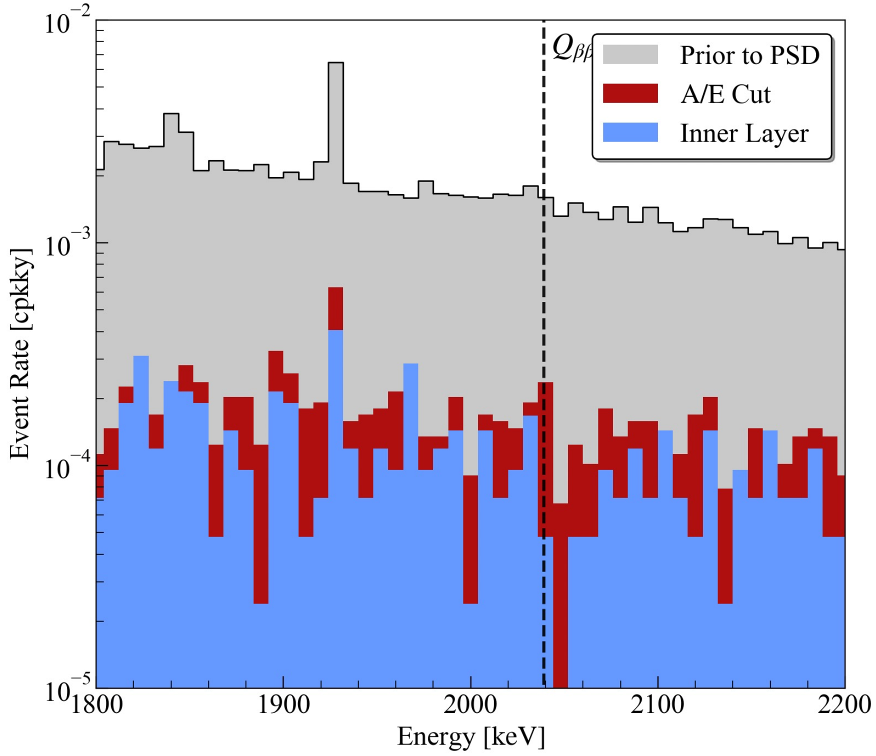
☐ Surface background from Ar-42

Assess PSD background suppression power by Geant4 + Pulse Shape Simulation

PSD Method	Prior to PSD	A/E Cut	**Outer Layer**	**Inner Layer**
Background [10^{-4} cpkky]	16.8±0.90	1.61±0.11	**2.10±0.15**	**1.05±0.09**







V. Summary

Summary

☐ Virtual segmentation of a small contact HPGe

Eur. Phys. J. C (2024) 84:294

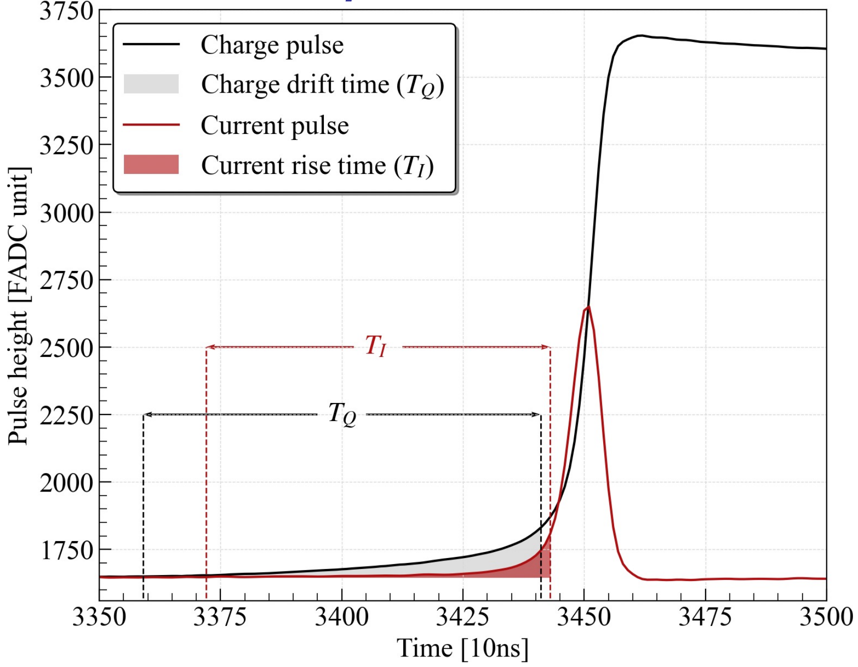
① *SSEs in Inner/outer segments are selected using pulse time feature T_Q and T_I*

② *Volume and shape of segments are calibrated by a Th-228 scanning experiment*

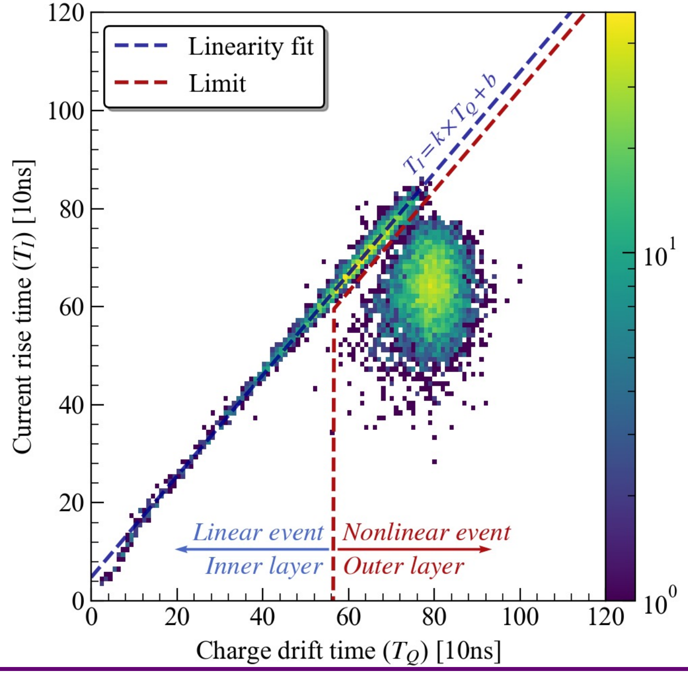
③ *Inner volume = 47.2% ± 0.26%(stat.) ± 0.22%(sys.) ± 0.18%(sys.)*

④ *Virtual segmentation could suppress surface background for 0νββ experiments*

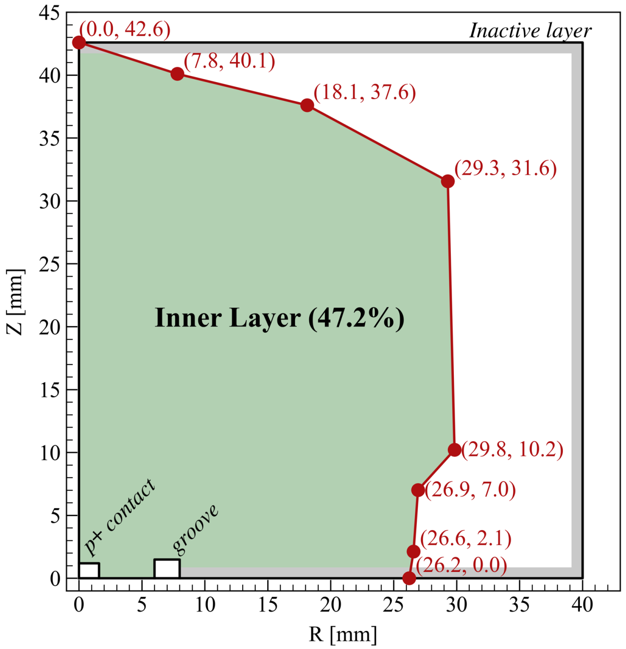
Extract pulse time features



Select of inner/out SSEs



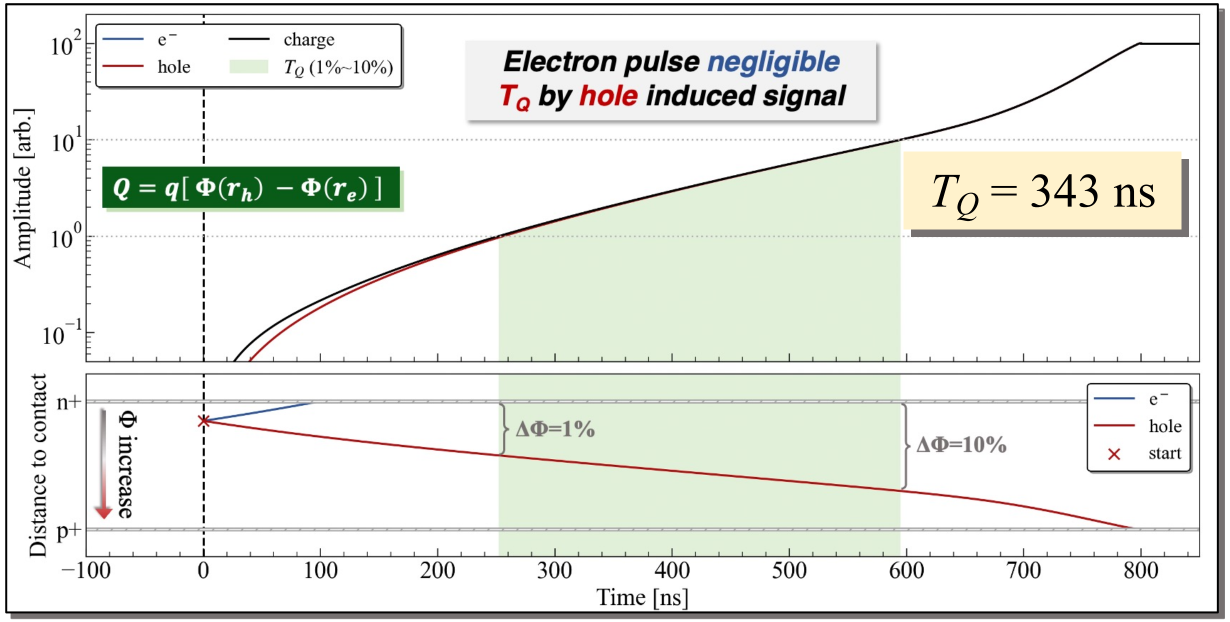
Optimized segments model



Thanks

Back up Materials

Back Up: Charge Pulses of SSEs in different Position

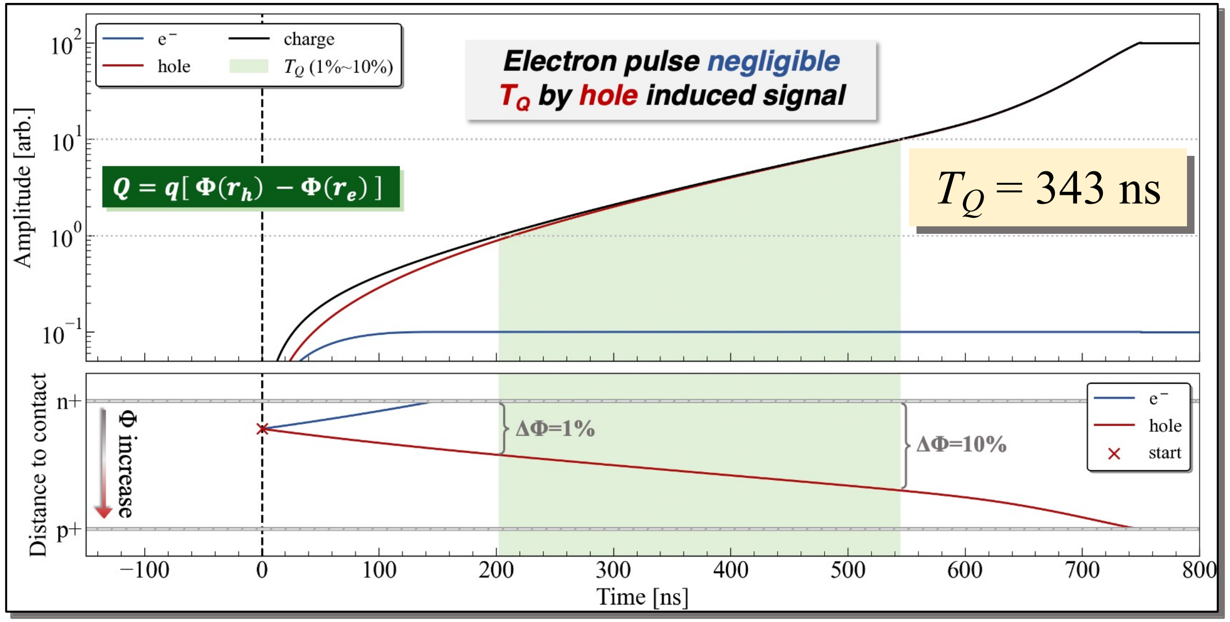


Electron pulse negligible

T_Q by hole induced signal

$Q = q[\,\Phi(r_h) - \Phi(r_e)\,]$

$T_Q = 343$ ns

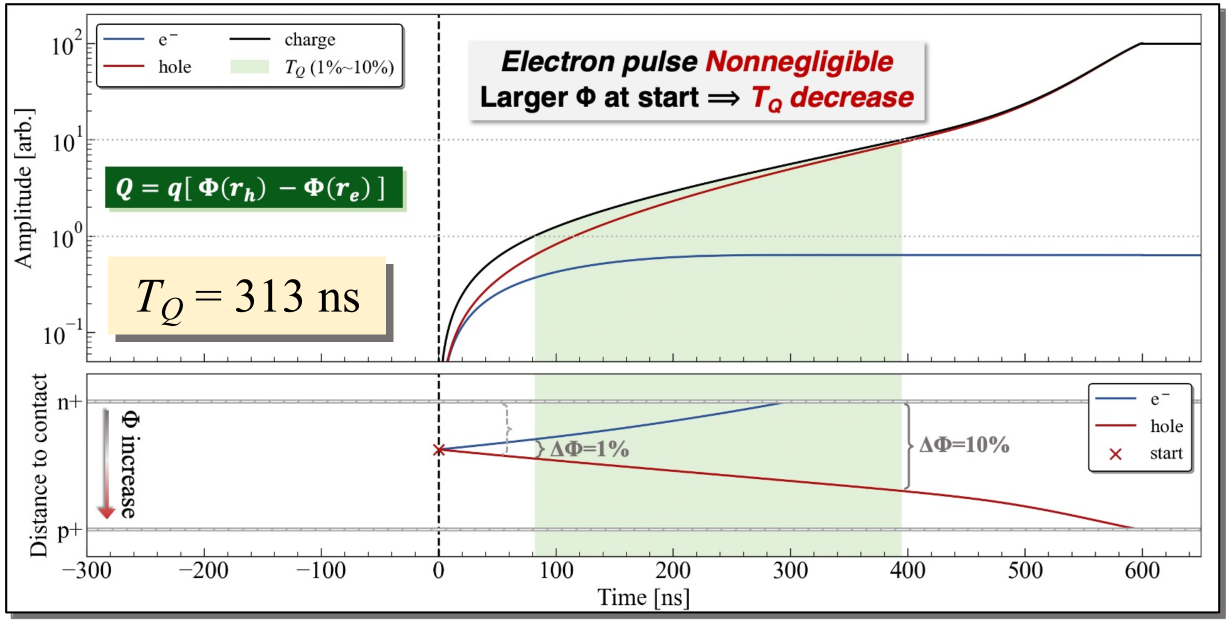


Electron pulse negligible

T_Q by hole induced signal

$Q = q[\,\Phi(r_h) - \Phi(r_e)\,]$

$T_Q = 343$ ns

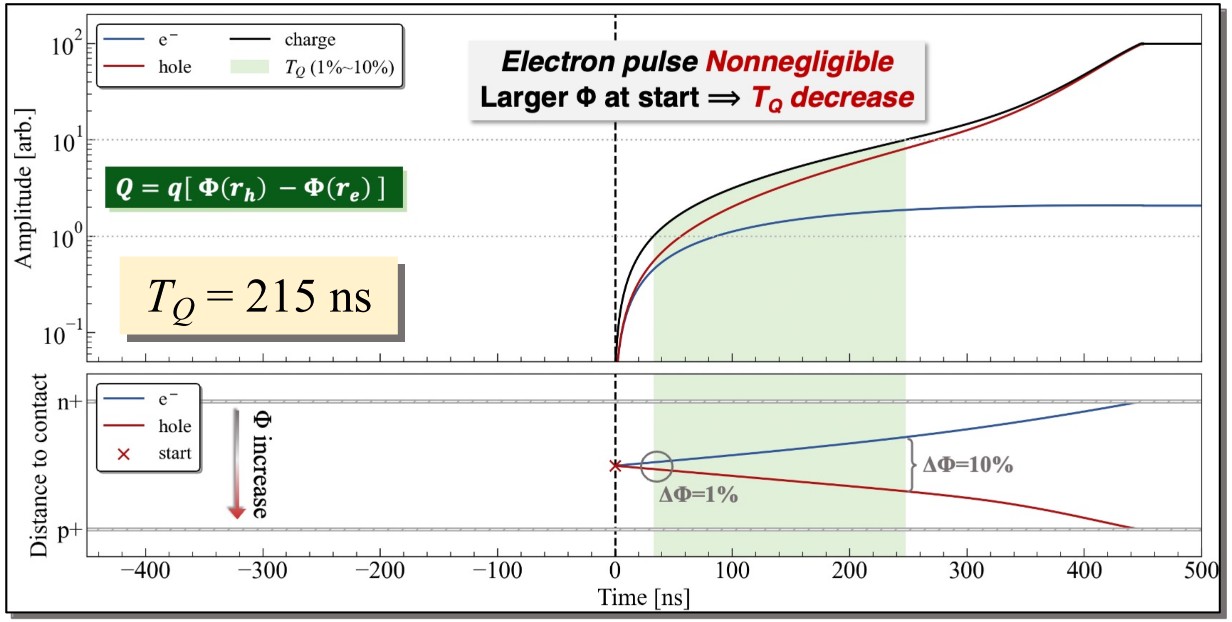


Electron pulse Nonnegligible

Larger Φ at start ⟹ *T_Q decrease*

$Q = q[\,\Phi(r_h) - \Phi(r_e)\,]$

$T_Q = 313$ ns



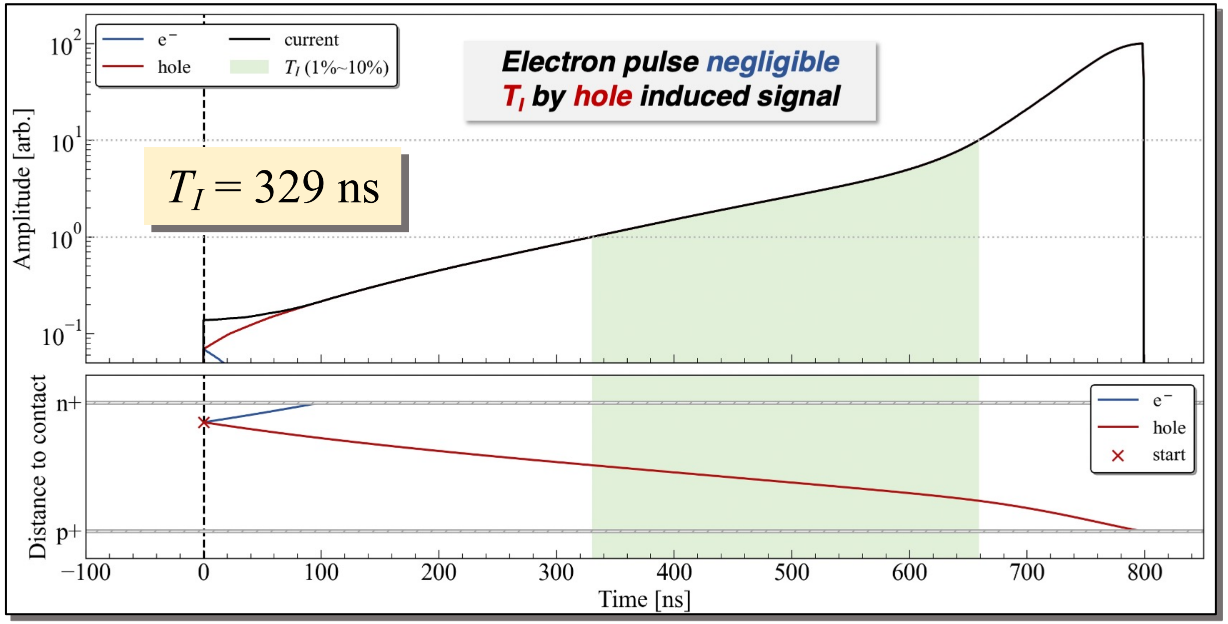
Electron pulse Nonnegligible

Larger Φ at start ⟹ *T_Q decrease*

$Q = q[\,\Phi(r_h) - \Phi(r_e)\,]$

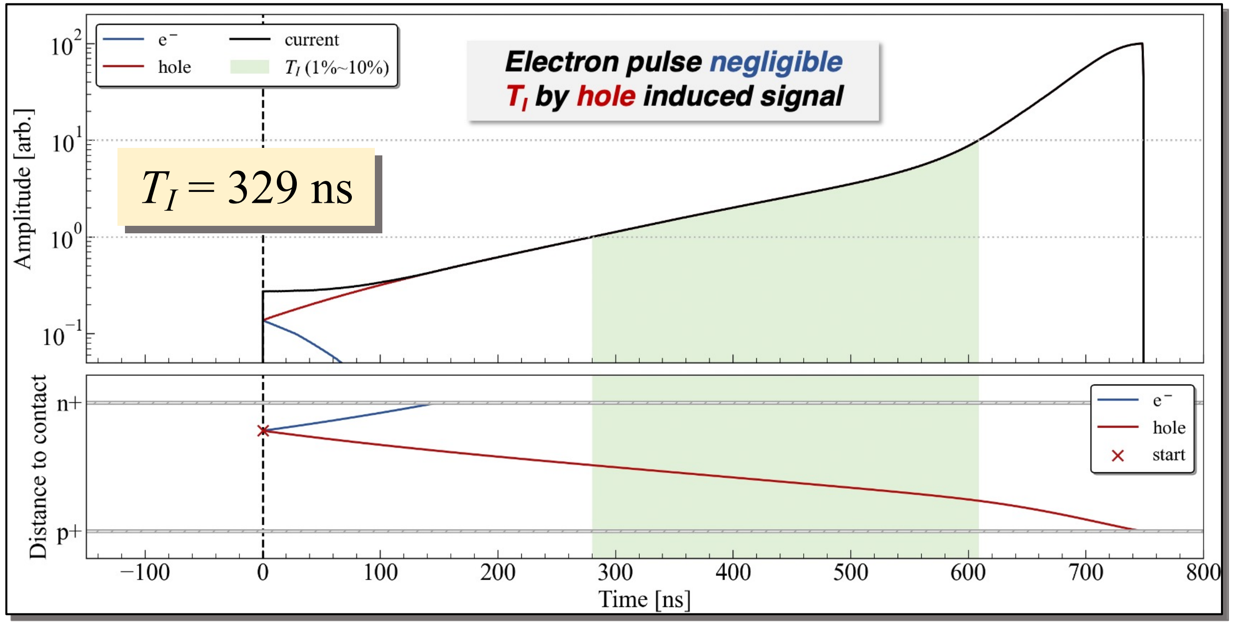
$T_Q = 215$ ns

Back Up: Current Pulses of SSEs in different Position



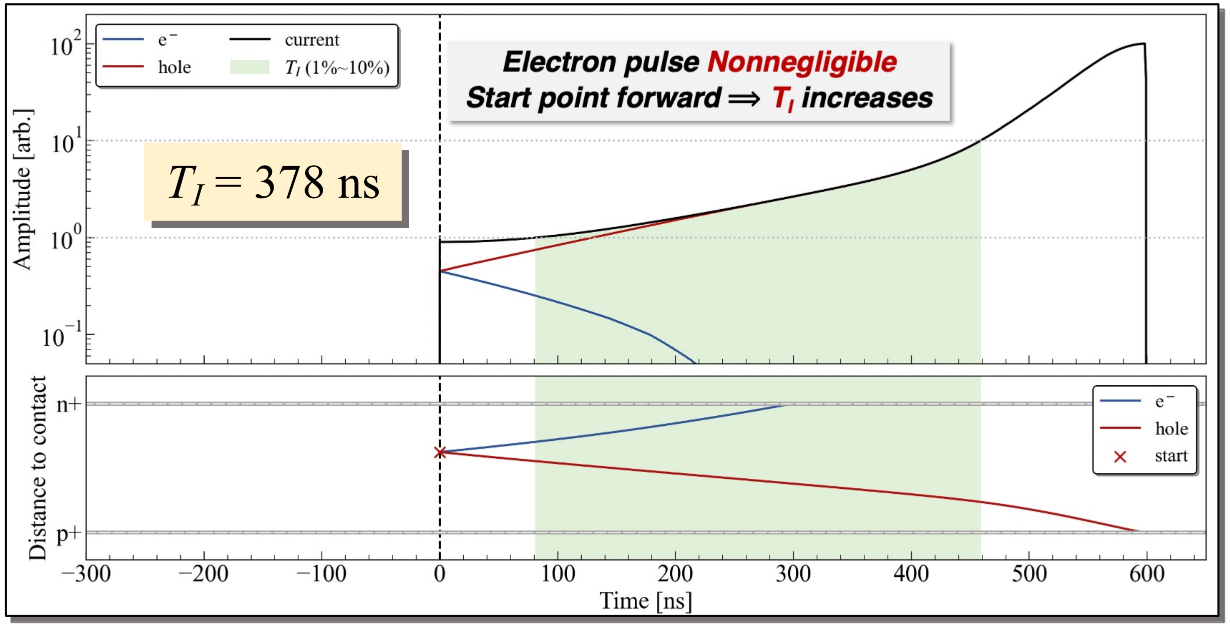
Electron pulse negligible
T_I by hole induced signal

$T_I = 329$ ns



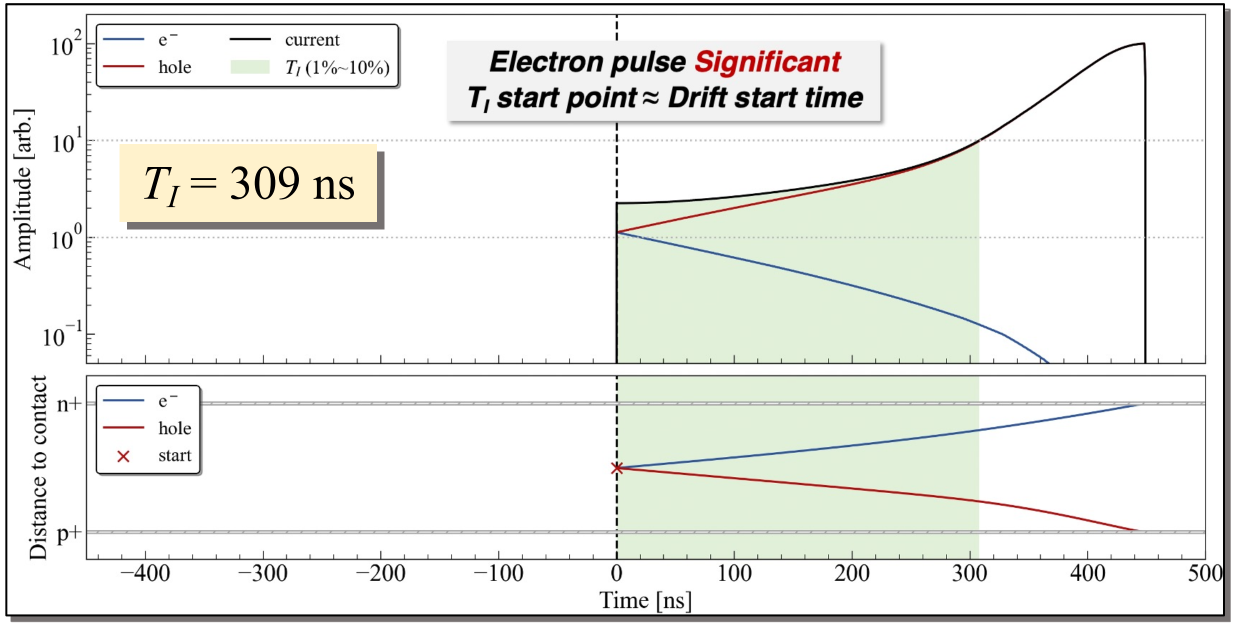
Electron pulse negligible
T_I by hole induced signal

$T_I = 329$ ns



Electron pulse Nonnegligible
Start point forward ⟹ T_I increases

$T_I = 378$ ns



Electron pulse Significant
T_I start point ≈ Drift start time

$T_I = 309$ ns

Background Suppression

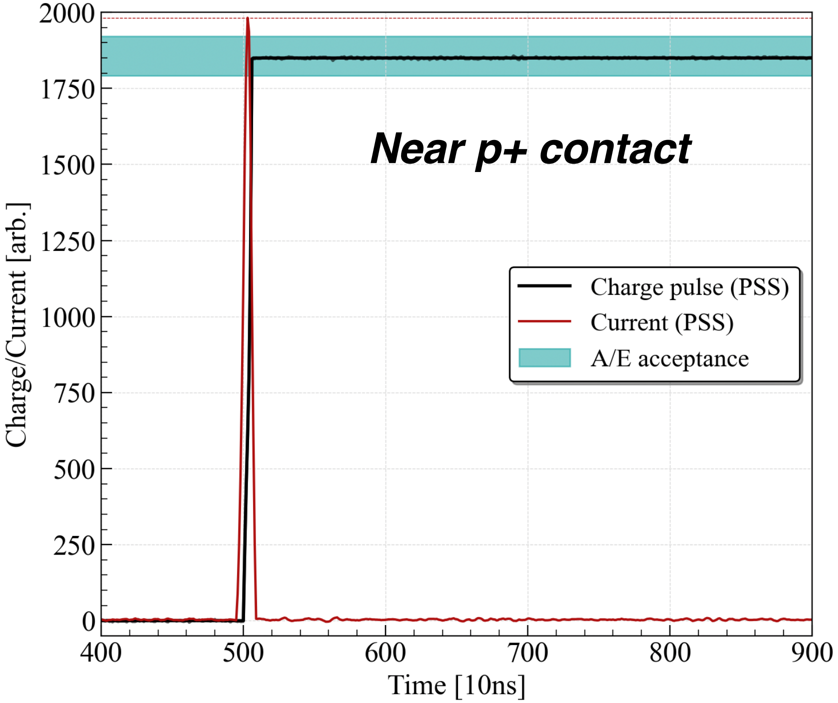
- **Pulse shape simulation for Ar-42 surface events:**

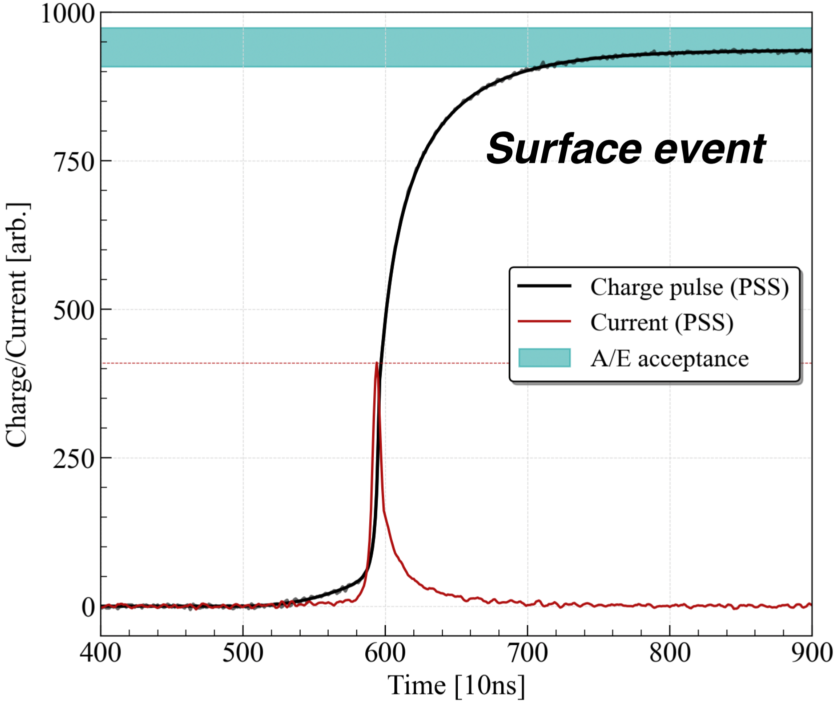
Three types of Ar-42 events could be removed by ***A/E cut****:*

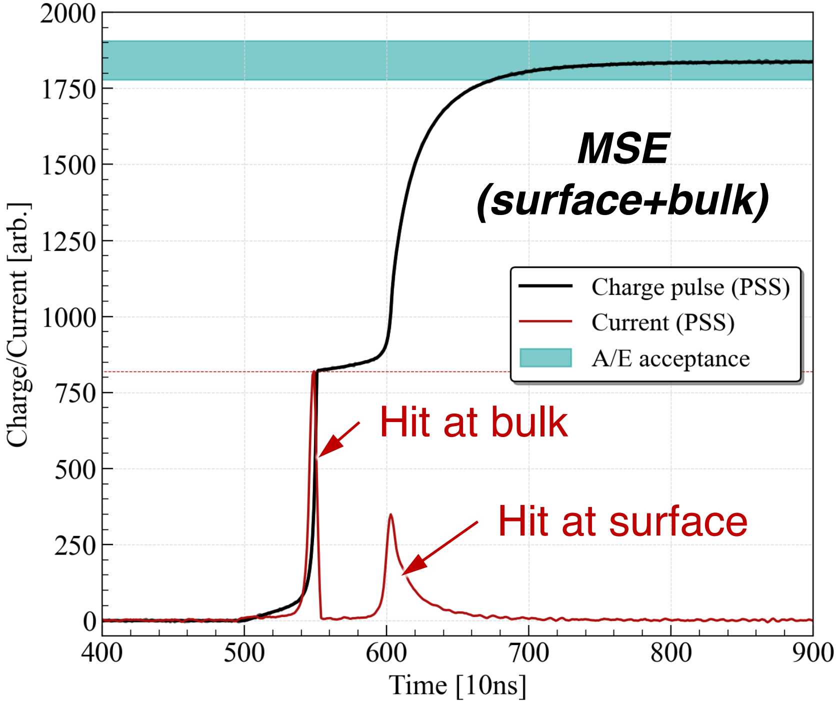
① ***Near p+ contact:*** *High A/E value than normal SSE*

② ***Surface events:*** *slow pulse and incomplete charge collection (lower A/E)*

③ ***Multi-site events:*** *a mixture of surface and surface/bulk hit position (lower A/E)*







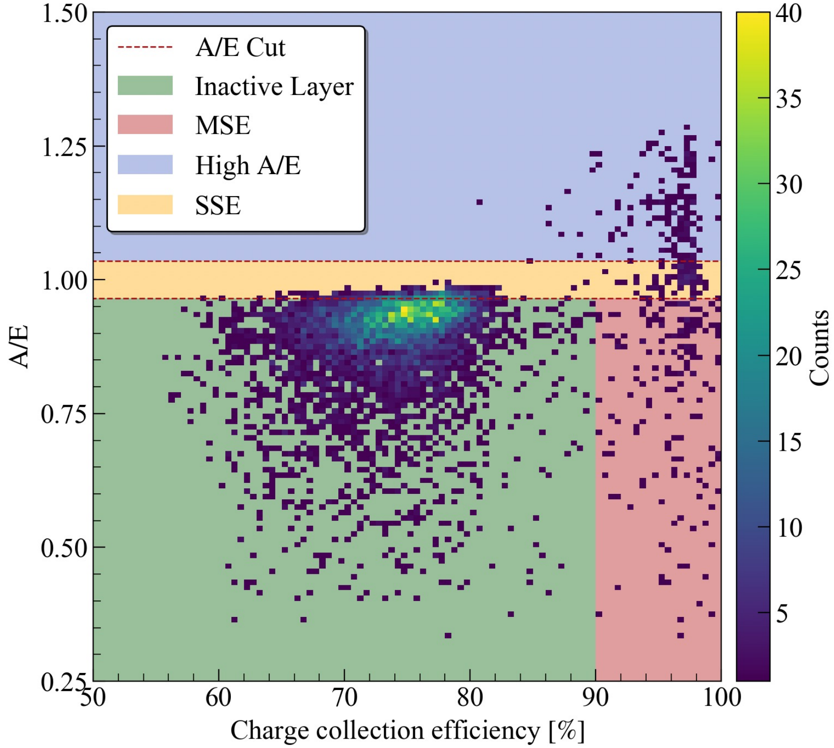
Background Suppression

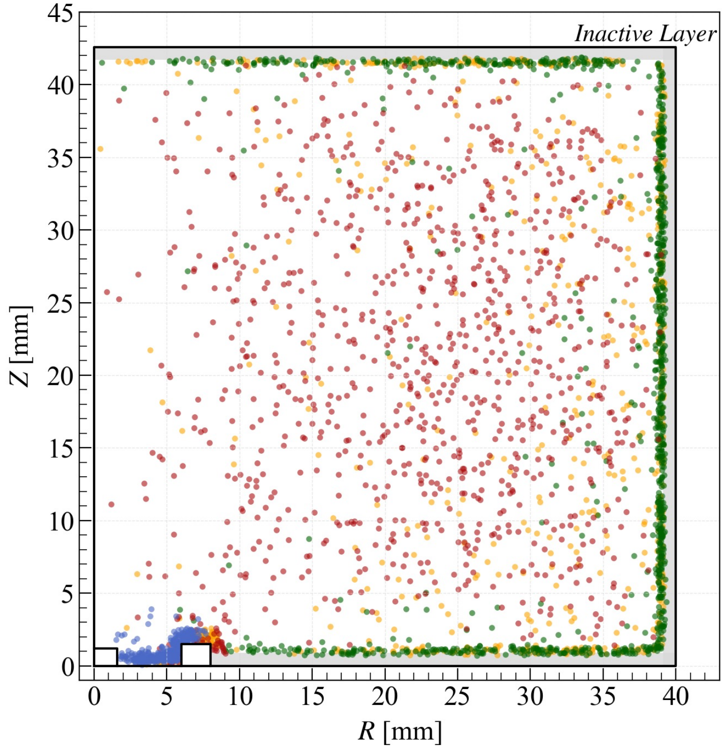
☐ A/E Cut for Ar-42 surface events:

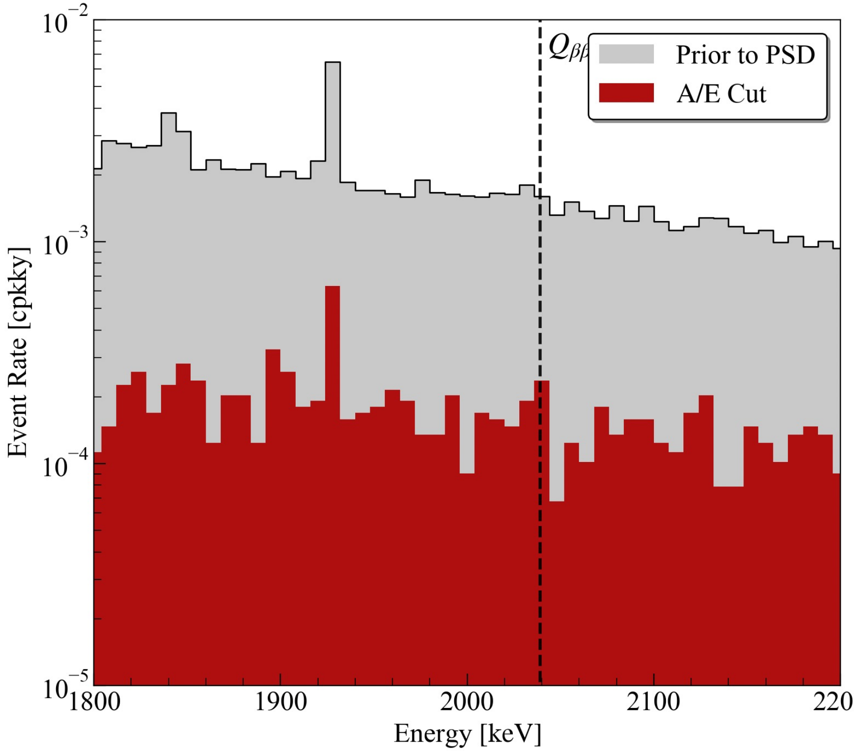
① *Most Ar-42 backgrounds are surface events and be removed by a low A/E cut*

② *When the background is near p+ contact, it can be removed by a high A/E cut*

A/E method could suppress Ar-42 background by ~10 times in $Q_{\beta\beta}$ region







Improve 0νββ Sensitivity by Virtual Segmentation

☐ Joint Analysis of Inner/Outer Layer Data

- Inner Layer has a ***lower Background*** while the Outer Layer ***shares ~1/2 sensitive mass***

Combine Inner/Outer Layer data to achieve better sensitivity

Joint Analysis

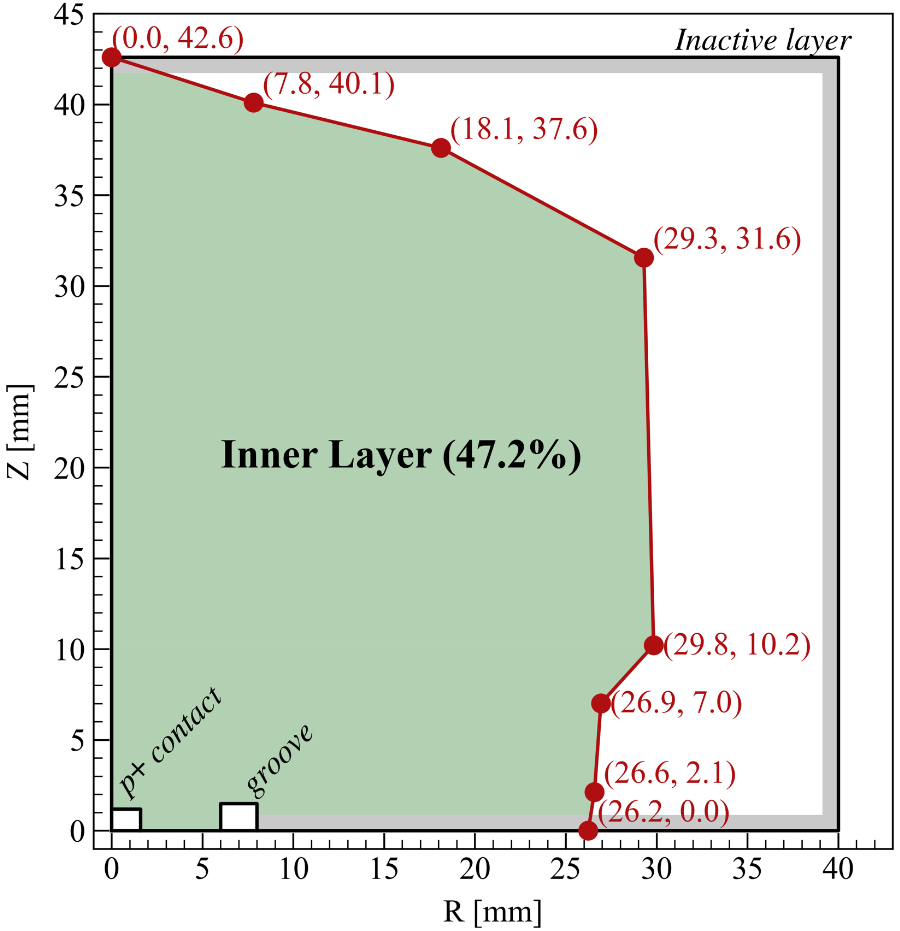
Likely hood Function for counts in 0νββ ROI:

$$L(N_{0\nu}) = \text{Poisson}(C_1|B_1 + S\cdot f_1\cdot\varepsilon_1)\times\text{Poisson}(C_2|B_2 + S\cdot f_2\cdot\varepsilon_2)$$

- **S is number of 0νββ signal**
- **C the counts、B the background,**
- **f the inner layer volume，*ε* the signal efficiency**
- **Index 1 (2) represents inner (outer) layer**

Estimate signal number ($\widehat{S}$) via Maximum likely hood:

$$\frac{\partial L(S)}{\partial S} = 0 \Longrightarrow \hat{S} = F(C,B,f,\varepsilon)$$



Improve 0νββ Sensitivity by Virtual Segmentation

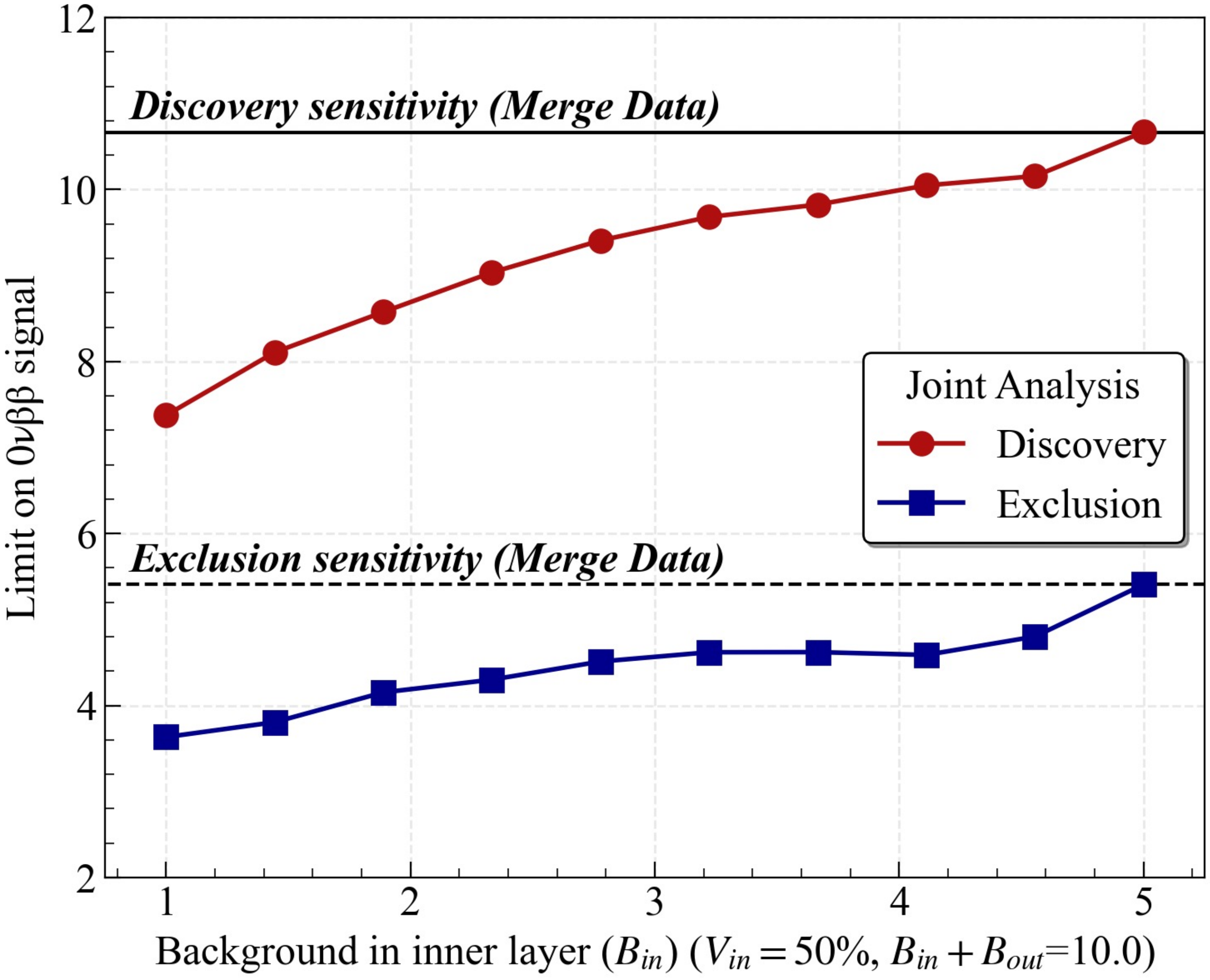
Discovery Sensitivity

$$\begin{cases} P(\hat{S}_{0\nu} \leqslant x \mid B_1, B_2, S_{0\nu} = 0) \geqslant 99.73\% \\ P(\hat{S}_{0\nu} \geqslant x \mid B_1, B_2, S_{0\nu} = S_{dis}) \geqslant 50\% \end{cases}$$

Exclusion Sensitivity

$$\begin{cases} P(\hat{S}_{0\nu} \leqslant x \mid B_1, B_2, S_{0\nu} = 0) \geqslant 50\% \\ P(\hat{S}_{0\nu} \geqslant x \mid B_1, B_2, S_{0\nu} = S_{exc}) \geqslant 90\% \end{cases}$$

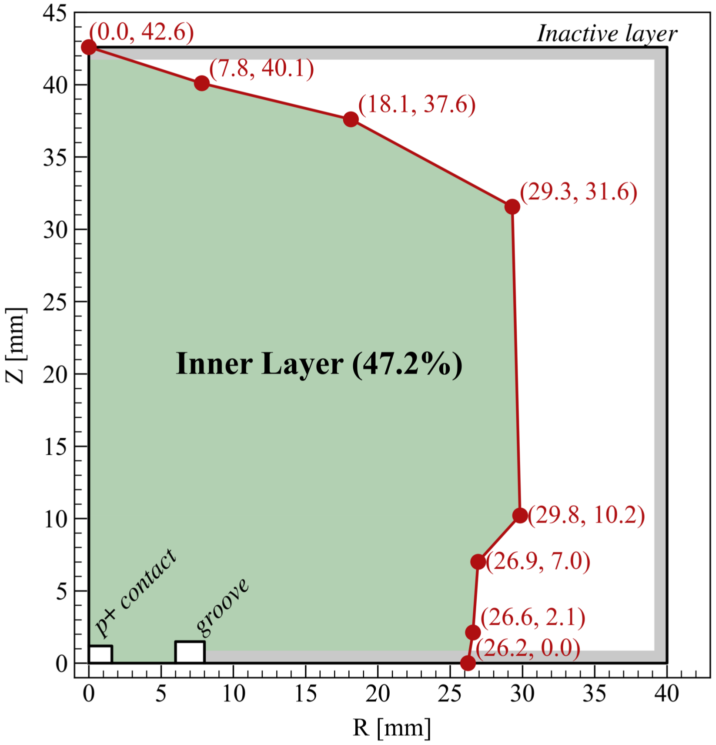
Joint analysis gives a **better sensitivity** for a **lower** inner layer background

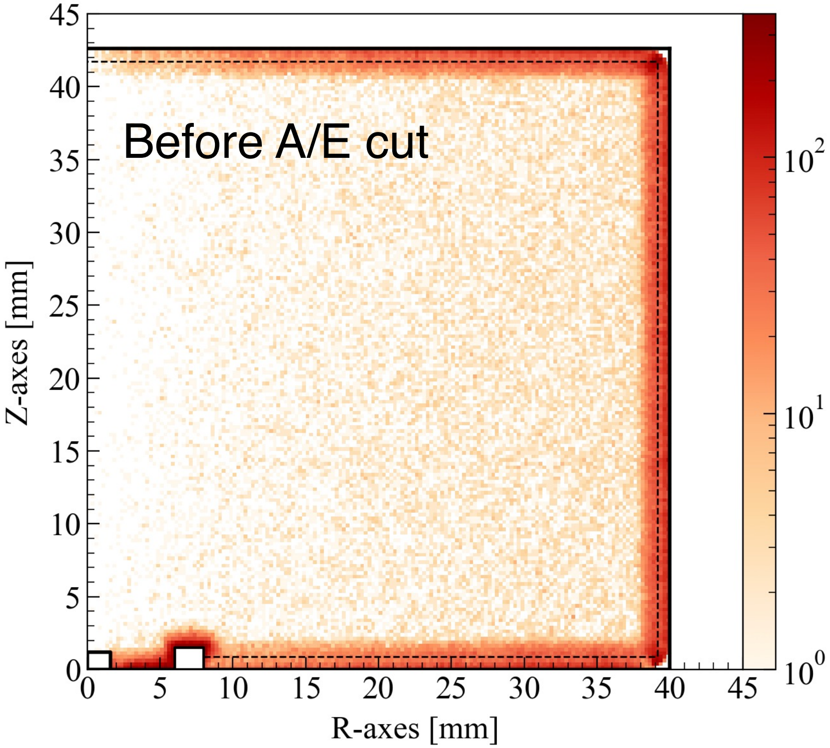


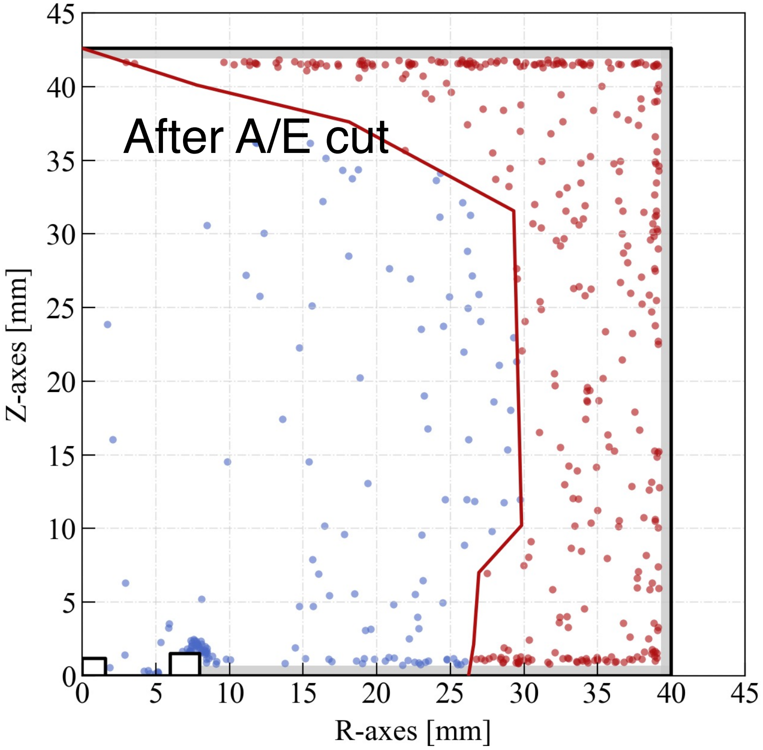
Improve 0νββ Sensitivity by Virtual Segmentation

☐ Apply Method on Ar-42 Background in CDEX-300:

PSD cuts	Before cut	A/E Cut	Outer layer	Inner layer
BI/10^{-4} cpkky	16.8±0.89	1.61±0.11	**2.10±0.15**	**1.05±0.09**
Background in 1-ton·yr	10.7	1.03	**0.71**	**0.32**



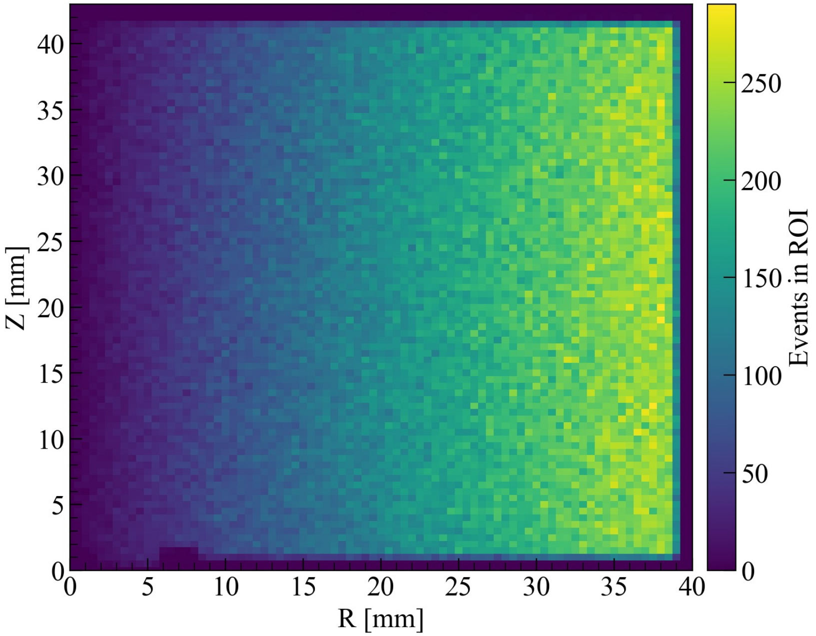




Improve 0νββ Sensitivity by Virtual Segmentation

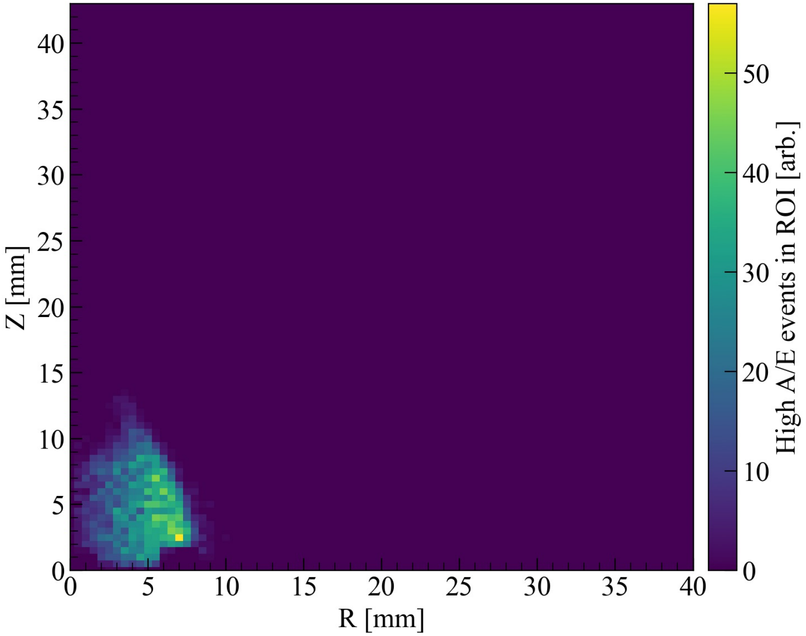
☐ Apply Method on Ar-42 Background in CDEX-300: Signal efficiency

PSD Cut	Sensitive Volume	0νββ Signal Loss			0νββ Signal Efficiency
		Energy Loss	Low A/E cut	High A/E cut	
Before cut	100.0%	16.6%	/	/	85.4%
A/E cut	100.0%	16.6%	10.67%	0.53%	72.2%
Inner layer	**47.2%**	**8.9%**	**16.50%**	**1.20%**	**73.4%**
Outer layer	**52.8%**	**22.8%**	**6.00%**	**0.00%**	**71.2%**



Events in Signal Region energy in ($Q_{\beta\beta}\pm 3\sigma$)

Events rejected by High A/E cut



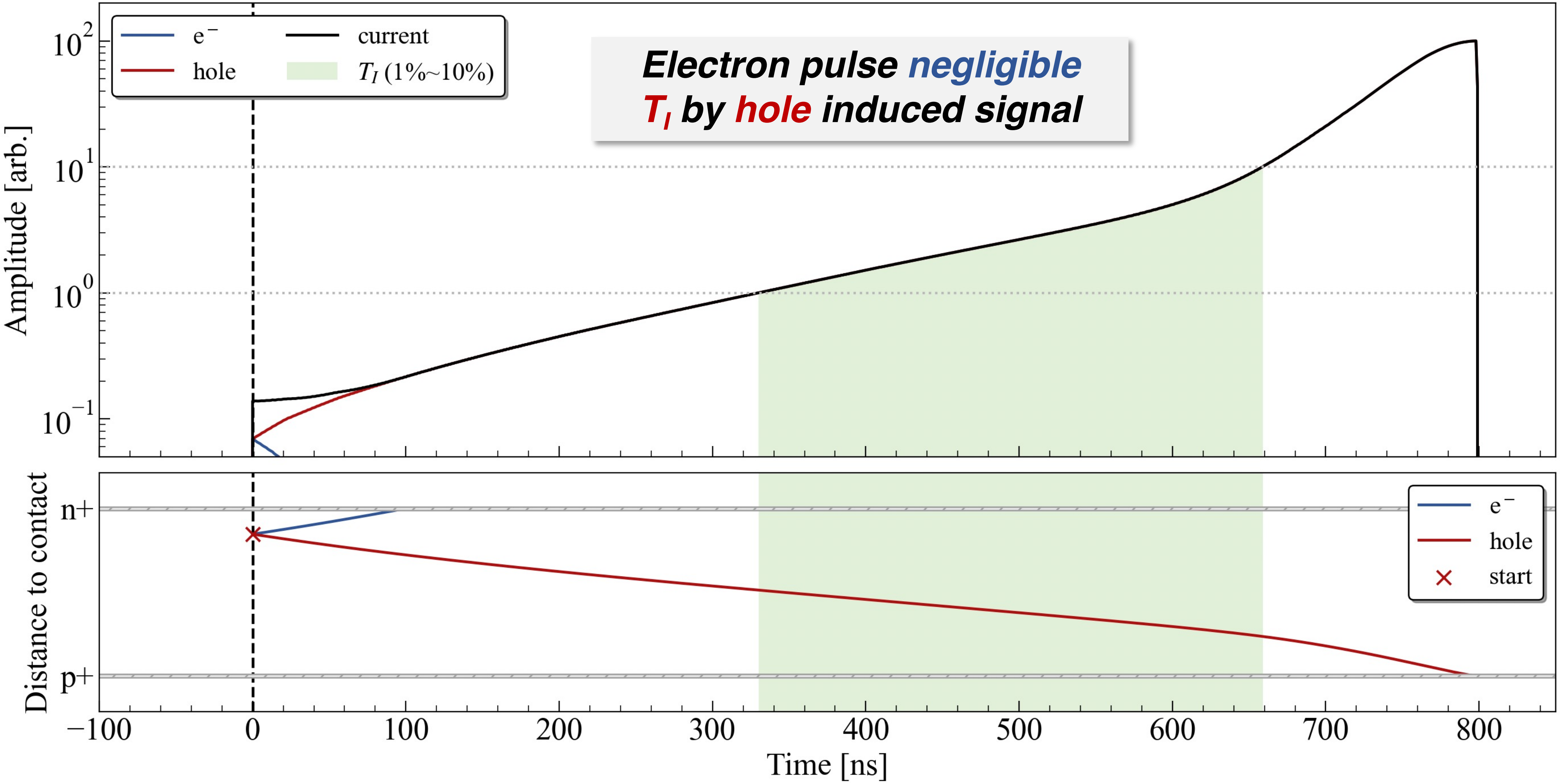
Improve 0νββ Sensitivity by Virtual Segmentation

- ☐ **Apply Method on Ar-42 Background in CDEX-300:**

PSD Cut	Sensitive Volume	0νββ Signal Efficiency	Background	Sensitivity (Exclusion)	Sensitivity (Discovery)
Before cut	100.0%	85.4%	10.7	6.91	12.84
A/E cut	**100.0%**	**72.2%**	**1.03**	**3.97**	**6.44**
Inner layer	47.2%	73.4%	0.32	5.74	9.69
Outer layer	52.8%	71.2%	0.71	8.46	10.54
Joint analysis	**100%**	**/**	**/**	**3.26**	**5.40**

Back Up: Current Pulses of SSEs in different Position

☐ Start Point at Outer Layer: $T_I = 329$ ns

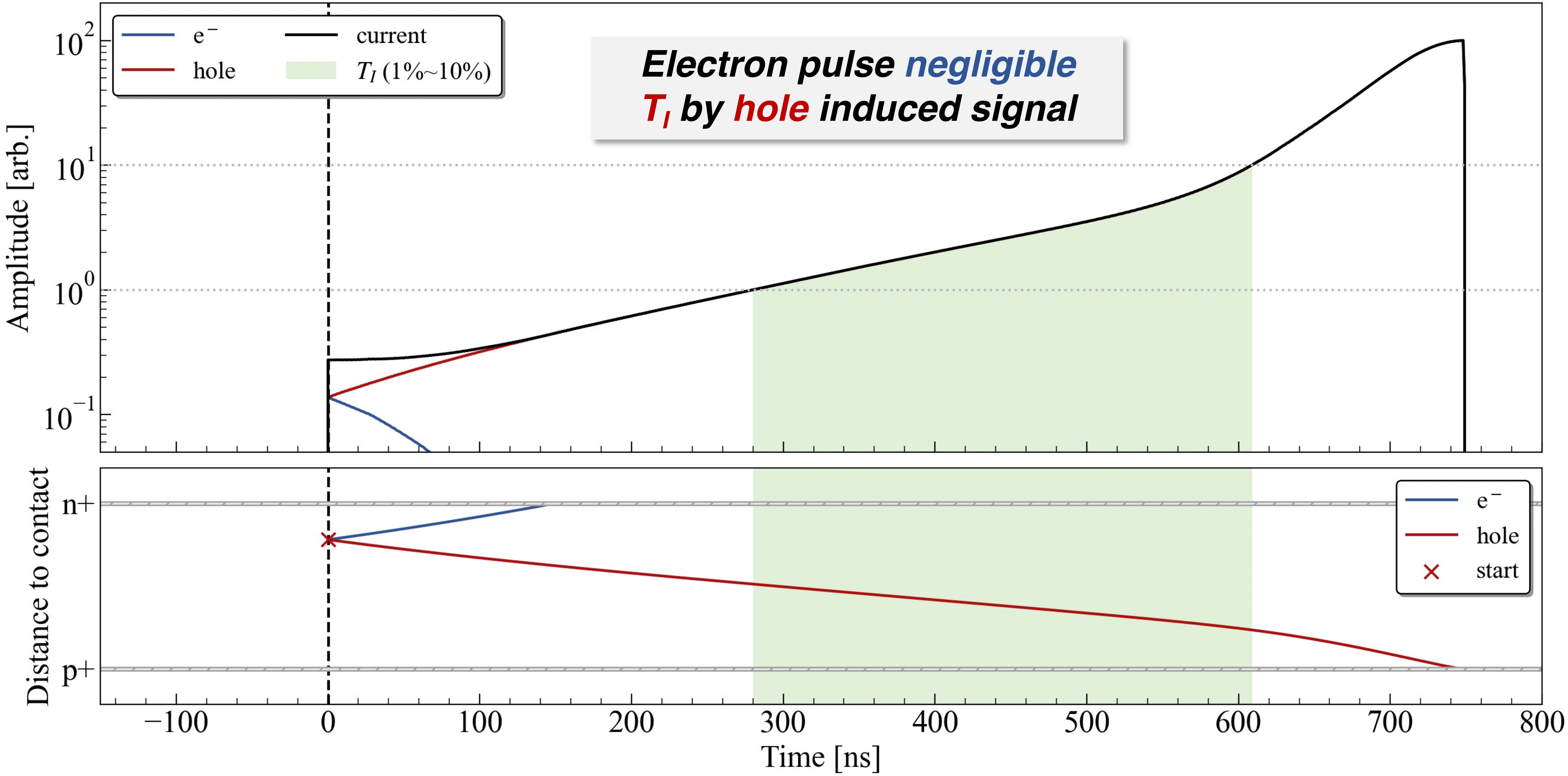


Electron pulse negligible

T_I by hole induced signal

Back Up: Current Pulses of SSEs in different Position

☐ Start Point at Outer Layer: $T_I = 329$ ns



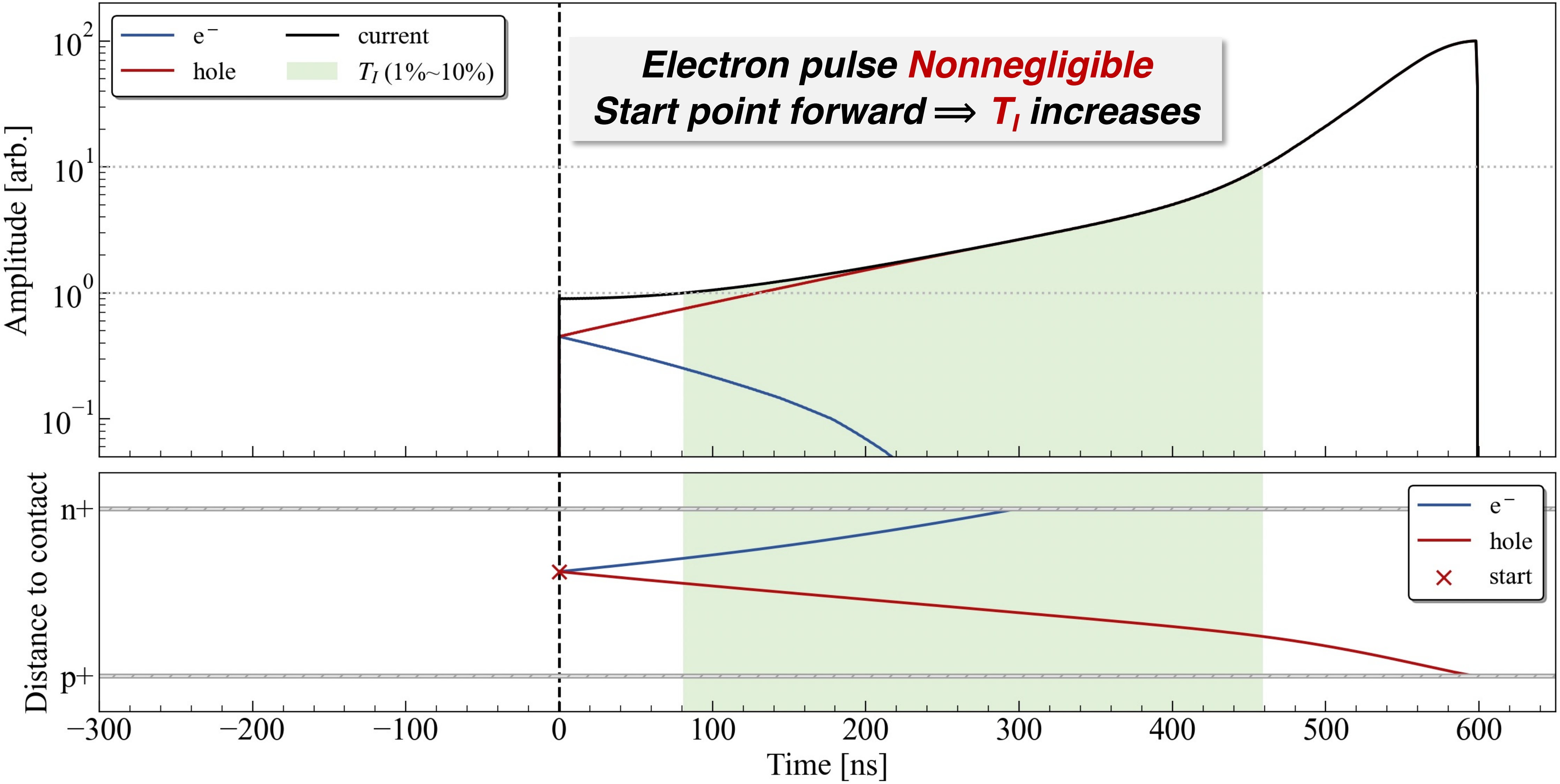
Electron pulse ***negligible***

T_I by hole induced signal

Back Up: Current Pulses of SSEs in different Position

☐ Start Point at Middle: $T_I = 378$ ns

Out $T_I = 329$ ns

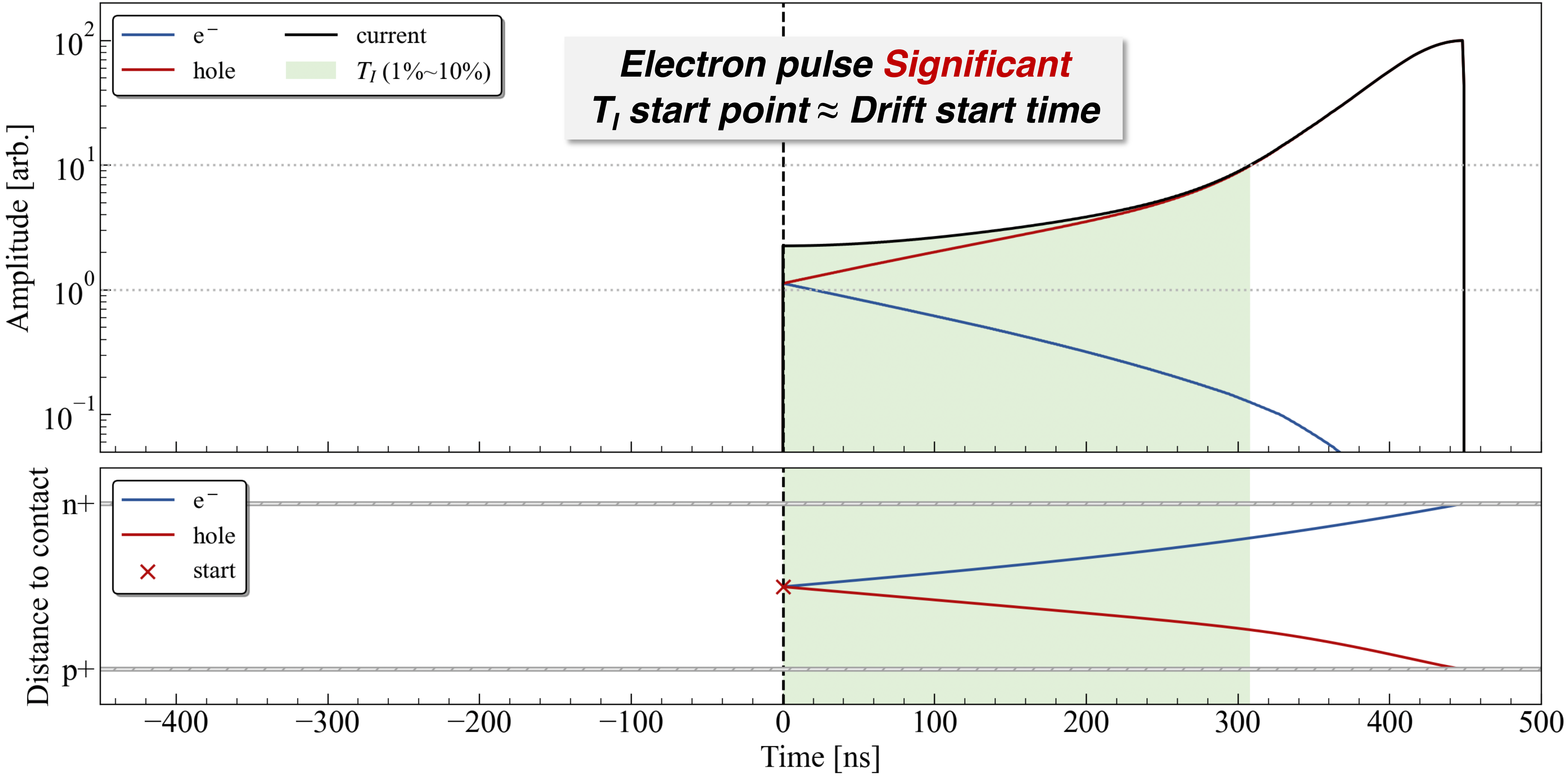


Electron pulse Nonnegligible

Start point forward ⟹ T_I increases

Back Up: Current Pulses of SSEs in different Position

☐ **Start Point at Outer Layer: $T_I = 309$ ns** Mid $T_I = 378$ ns Out $T_I = 329$ ns

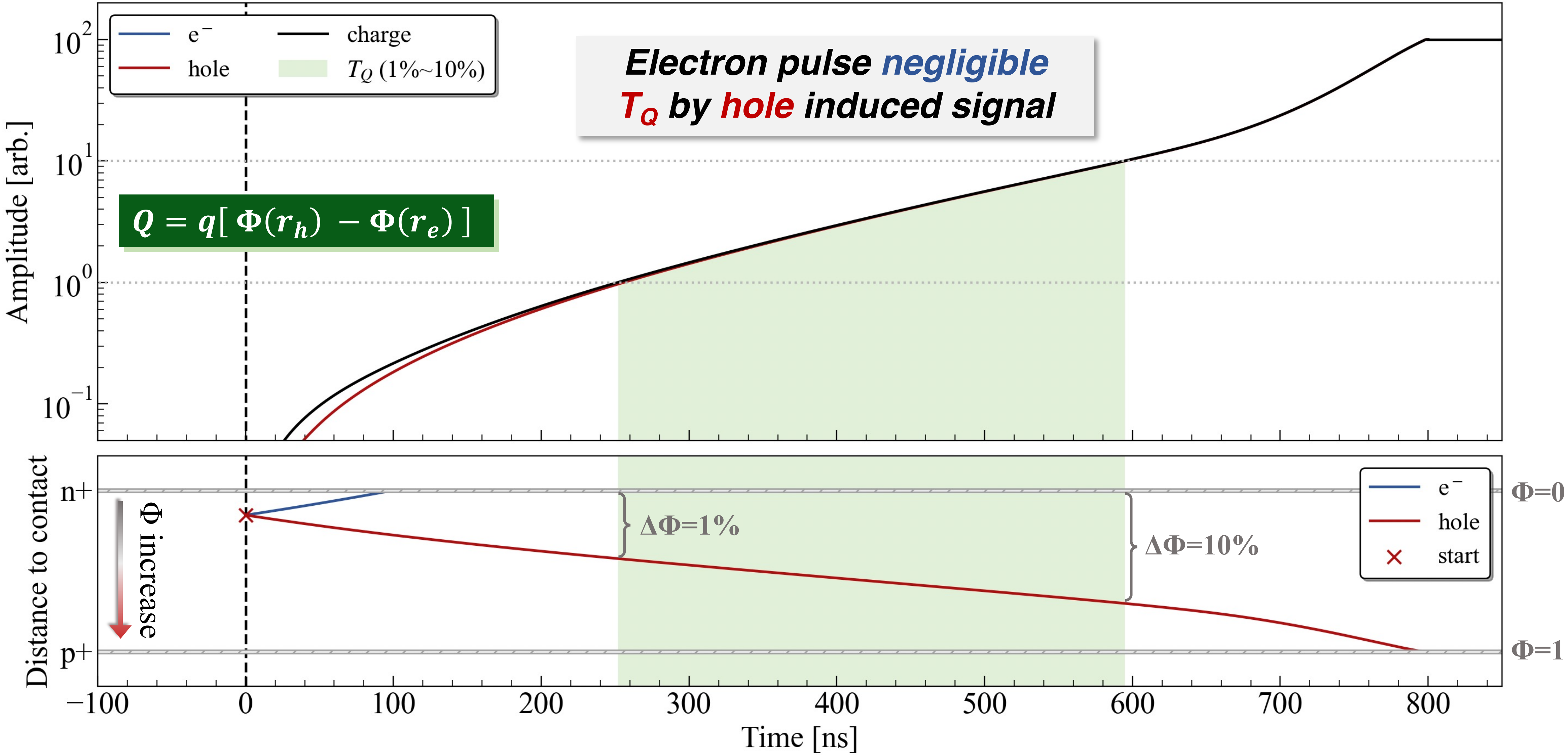


Electron pulse Significant

T_I start point ≈ Drift start time

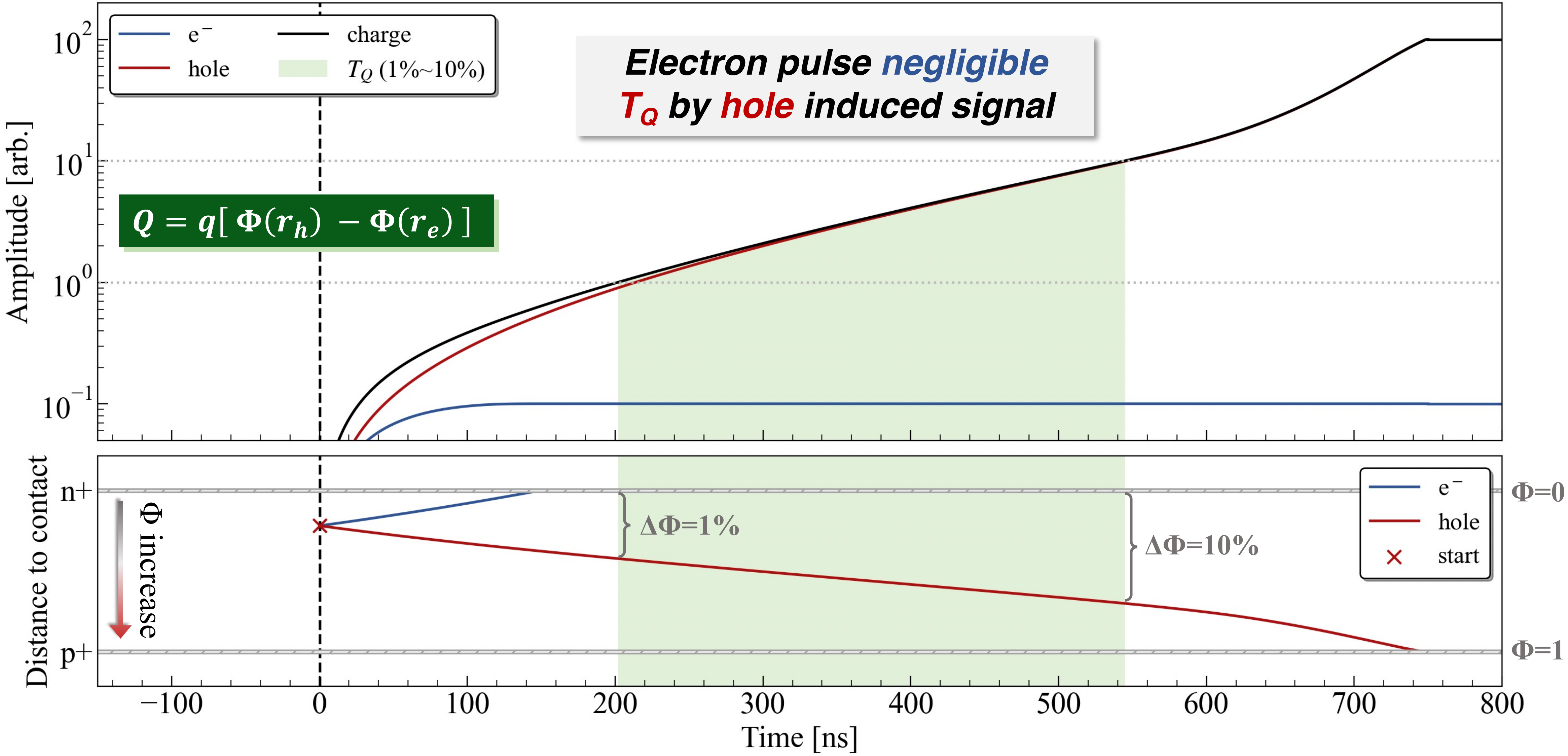
Back Up: Charge Pulses of SSEs in different Position

☐ Start Point at Outer Layer: $T_Q = 343$ ns



Back Up: Charge Pulses of SSEs in different Position

☐ Start Point at Outer Layer: $T_Q = 343$ ns



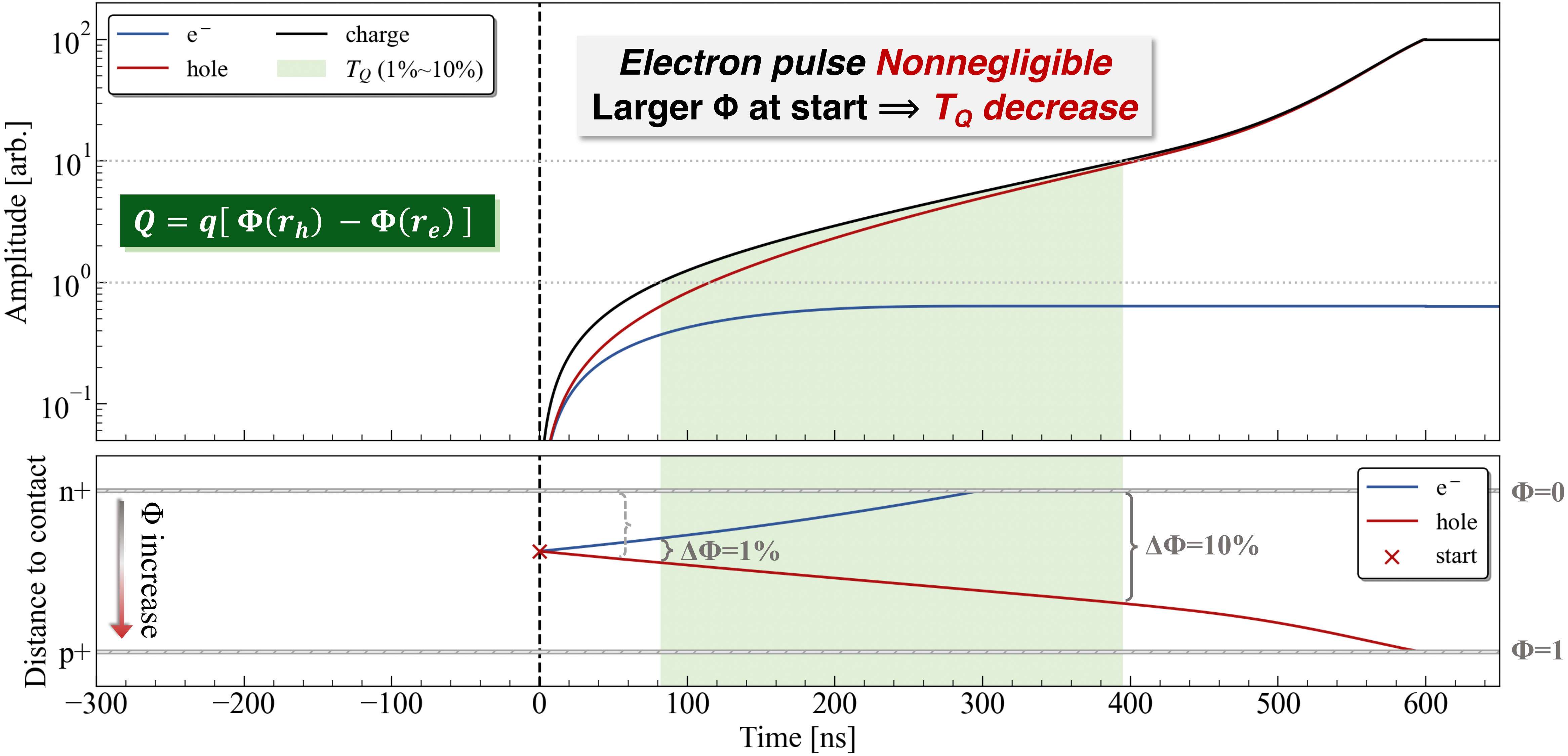
Electron pulse negligible
T_Q by hole induced signal

$$Q = q[\,\Phi(r_h) - \Phi(r_e)\,]$$

Back Up: Charge Pulses of SSEs in different Position

☐ Start Point at Middle: $T_Q = 313$ ns

Outer Layer $T_Q = 343$ ns



Electron pulse Nonnegligible

Larger Φ at start ⟹ T_Q decrease

$$Q = q[\,\Phi(r_h) - \Phi(r_e)\,]$$

Back Up: Charge Pulses of SSEs in different Position

☐ **Start Point at Inner Layer: $T_Q = 215$ ns** Mid $T_Q = 313$ ns Out $T_Q = 343$ ns