Hypernuclear Physics Meeting

Simulation study of the next hypernuclear spectroscopy experiments on ${}^{40,48}_{\Lambda}\mathrm{K}$ at JLab

Tatsuhiro Ishige
2nd year of MC, Tohoku University

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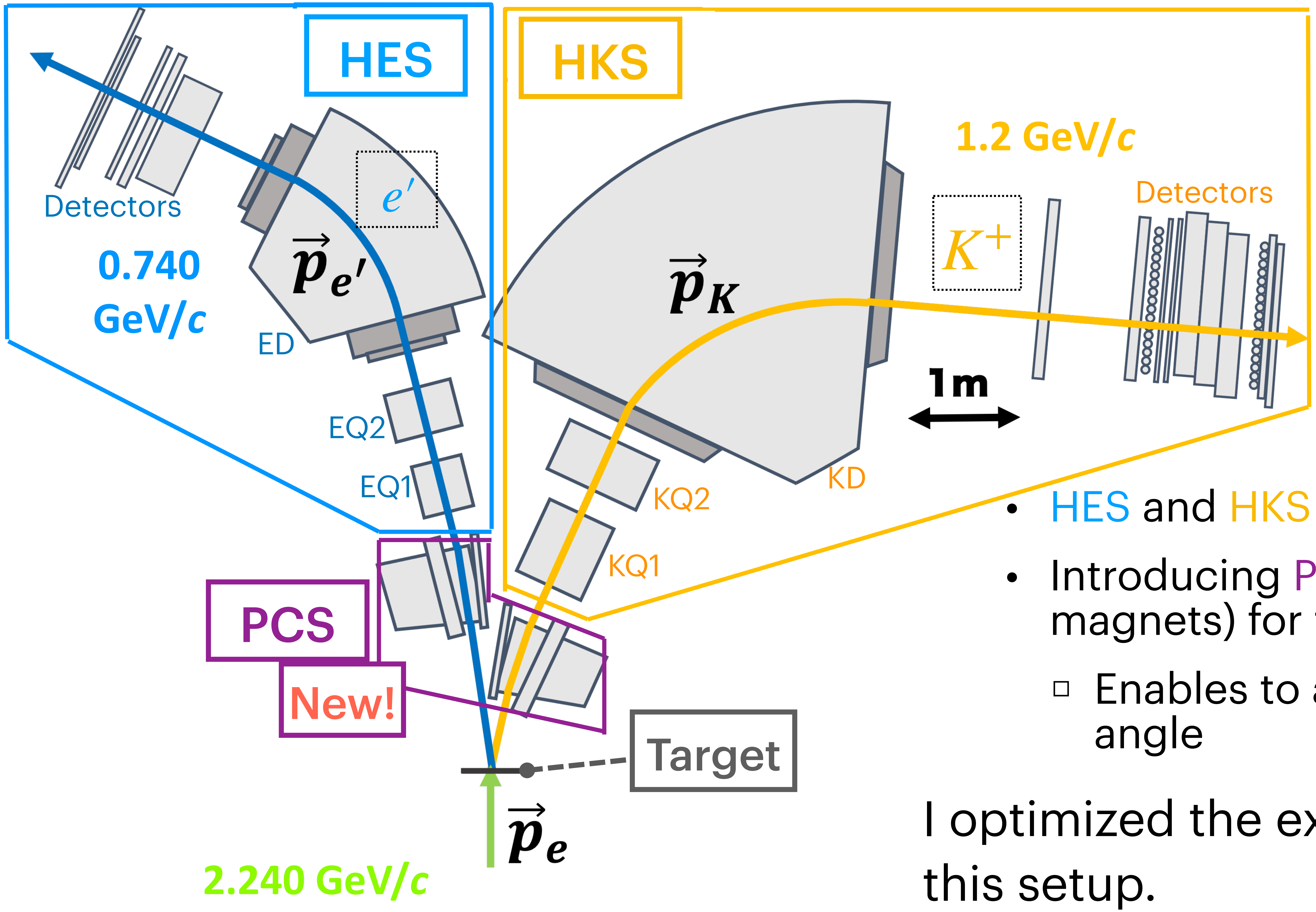
Contents

- Optimization of experimental conditions by Geant4 simulation
  - HES installed angle, target thickness, beam intensity
- Estimated missing mass spectrum of $^{40,48}_{\Lambda}\mathrm{K}$

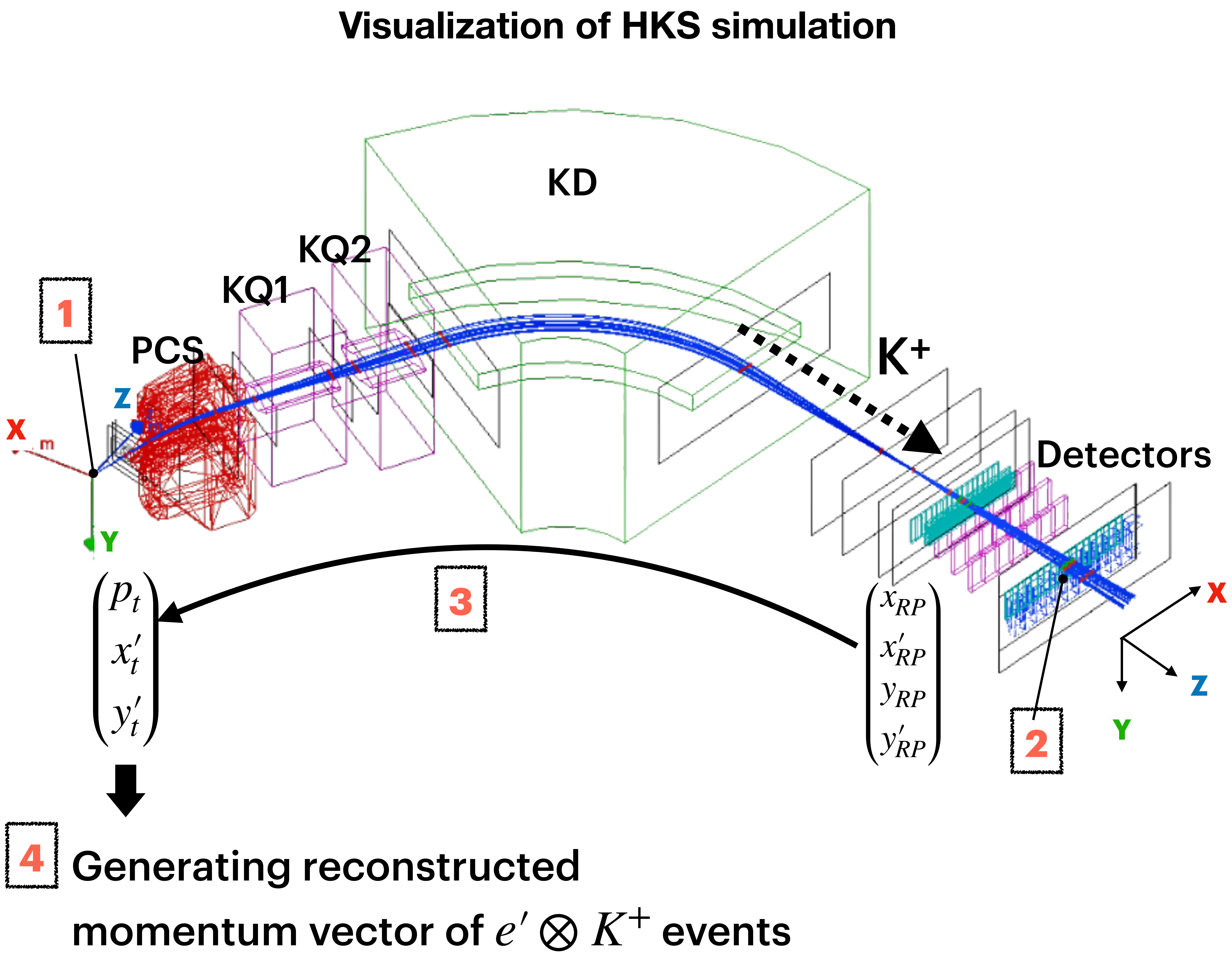
Setup of the next experiment



- HES and HKS used in previous experiment
- Introducing PCS (Pair of Charge Separation magnets) for the first time
  - Enables to avoid background with forward angle

I optimized the experimental conditions for this setup.

Geant4 simulation



- Simulation consists of particle generator, setup, and analysis
- It can reproduce dataset of reconstructed momentum
- Process of generating data goes from step 1 to step4

Experimental conditions to be optimized

- Developed estimating missing mass spectrum by Geant4 simulation (skip details)

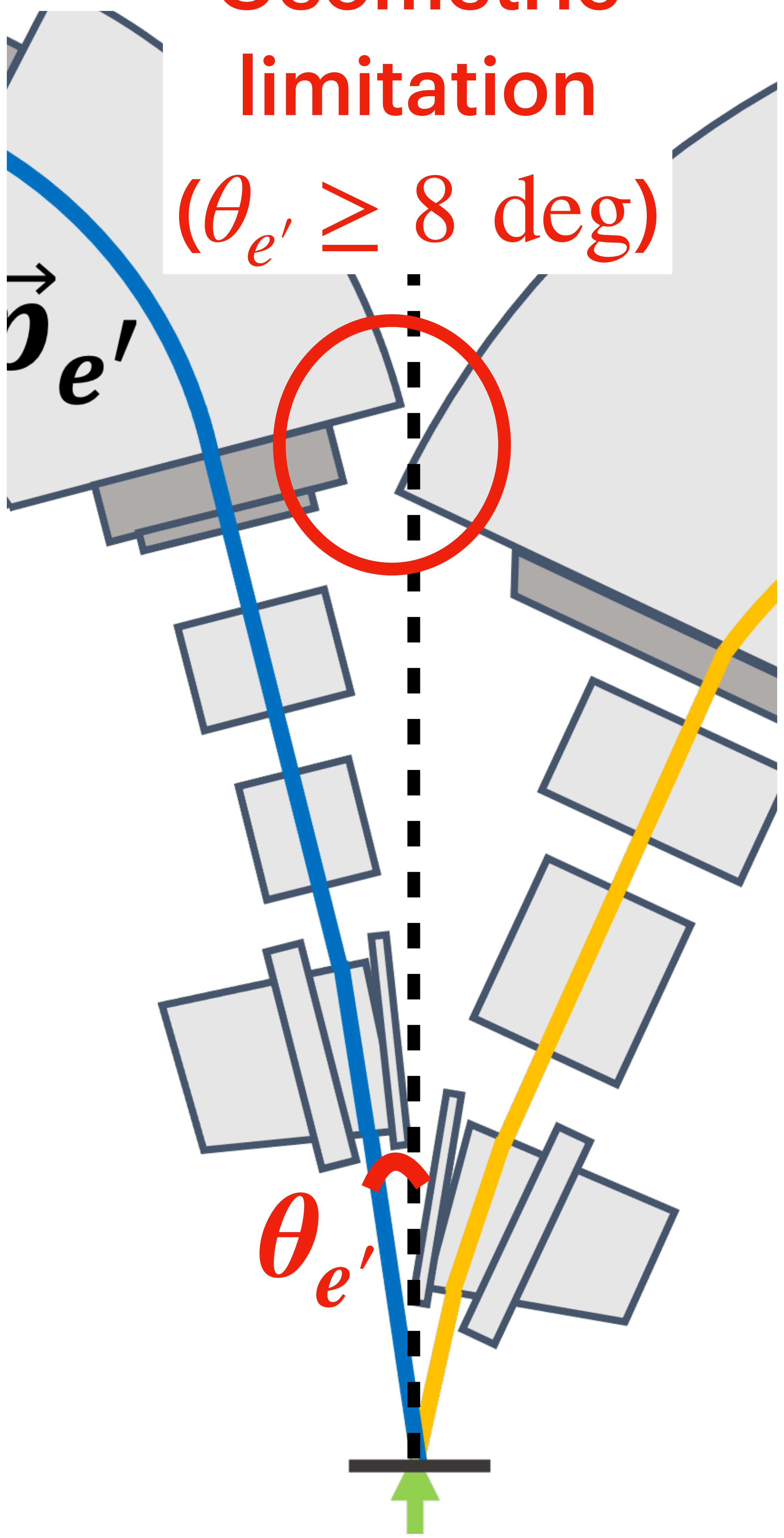
→ Optimized experimental conditions following tables

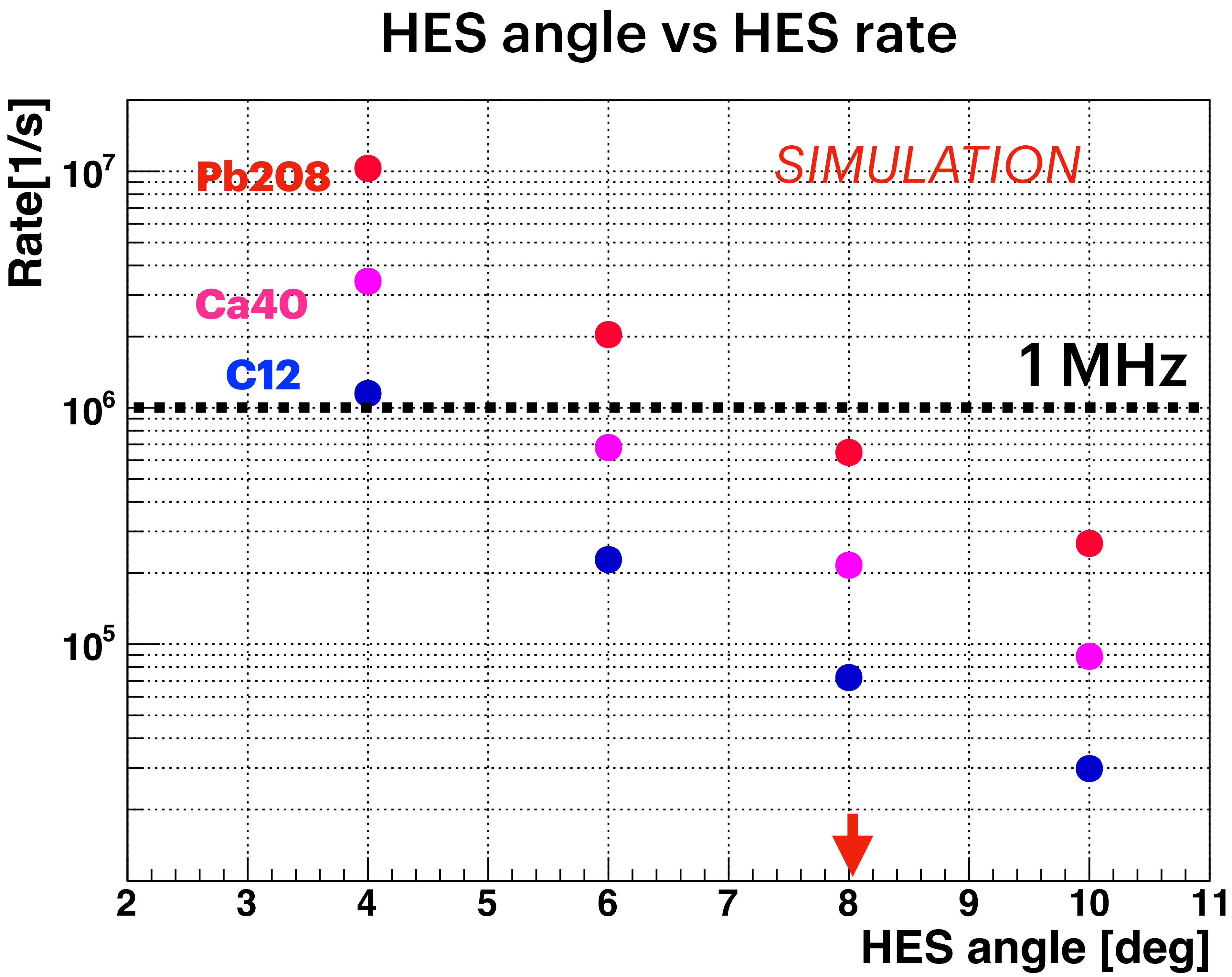
Condition	Advantage	Disadvantage
HES installed angle	Hypernuclear yield	Accidental background
Target thickness	Hypernuclear yield	B_Λ resolution , accidental background
Beam intensity	Hypernuclear yield	Accidental background

Condition 1. HES installed angle $\theta_{e'}$

- Bremsstrahlung background increasing at forward angle
- Virtual photon flux increasing at forward angle
- Evaluation by geometric limitation, HES single rate

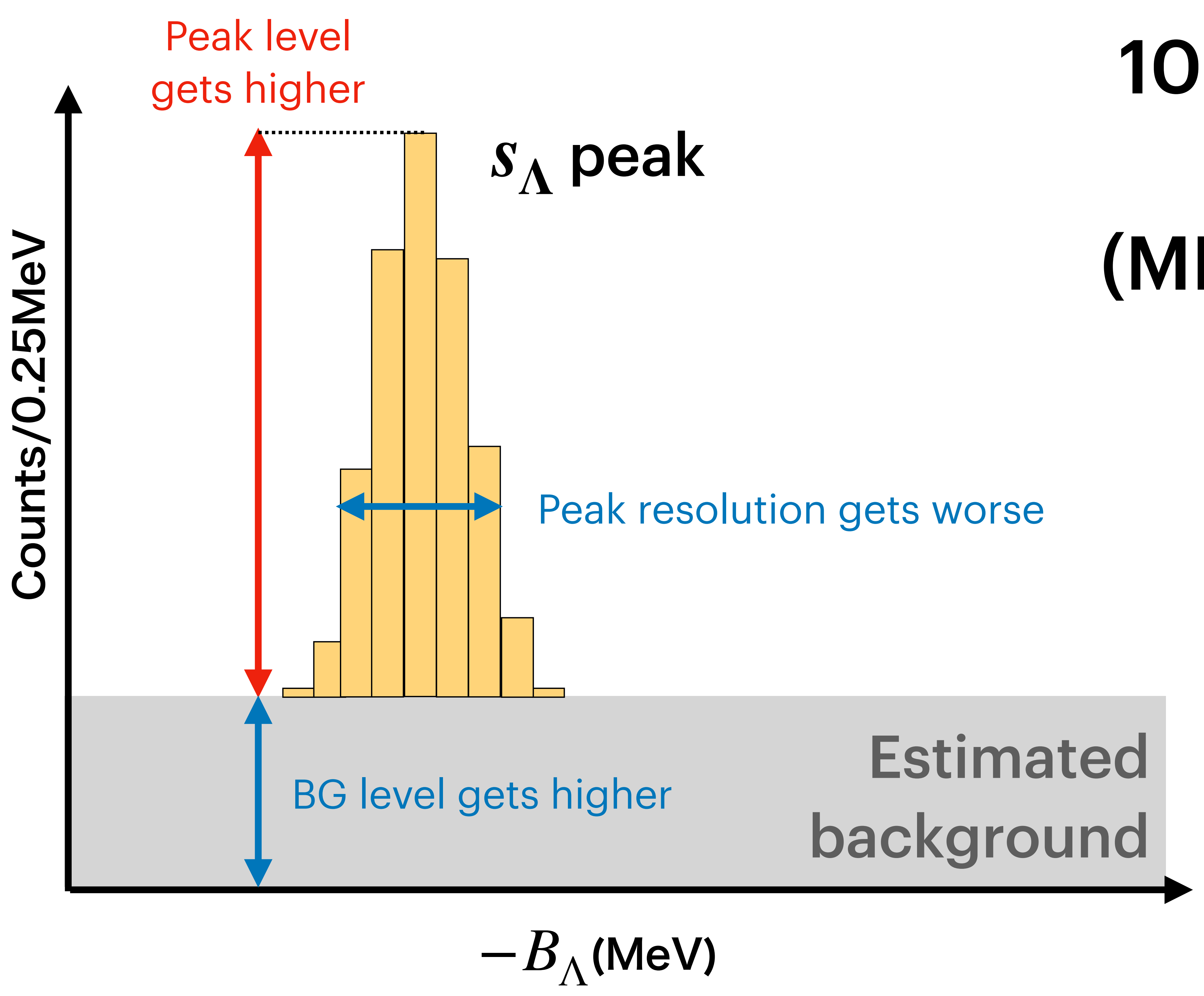
→ Adopted 8 deg.





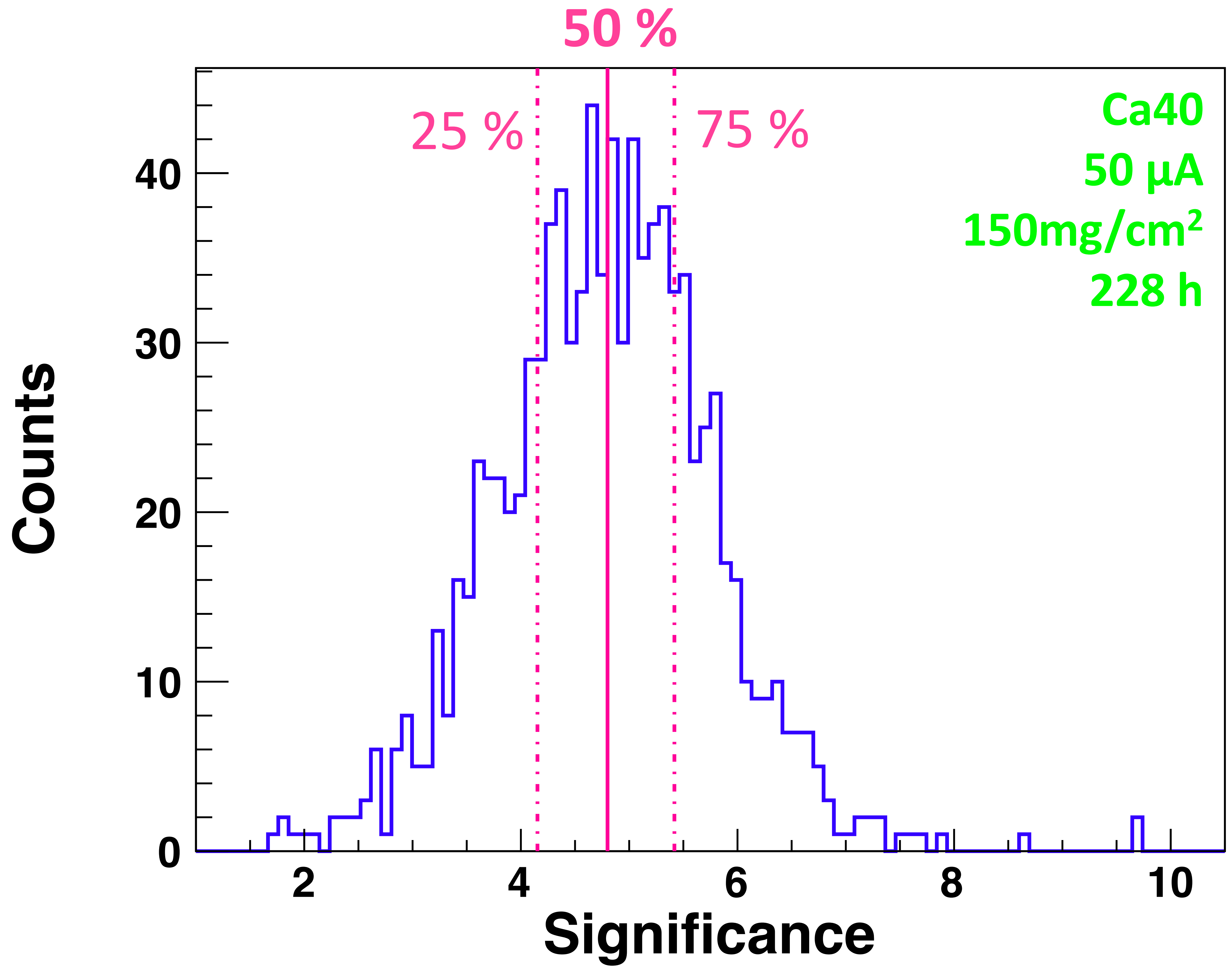
Condition 2. Target thickness

In case of thick target



1000 times loop (MM + Calc.)

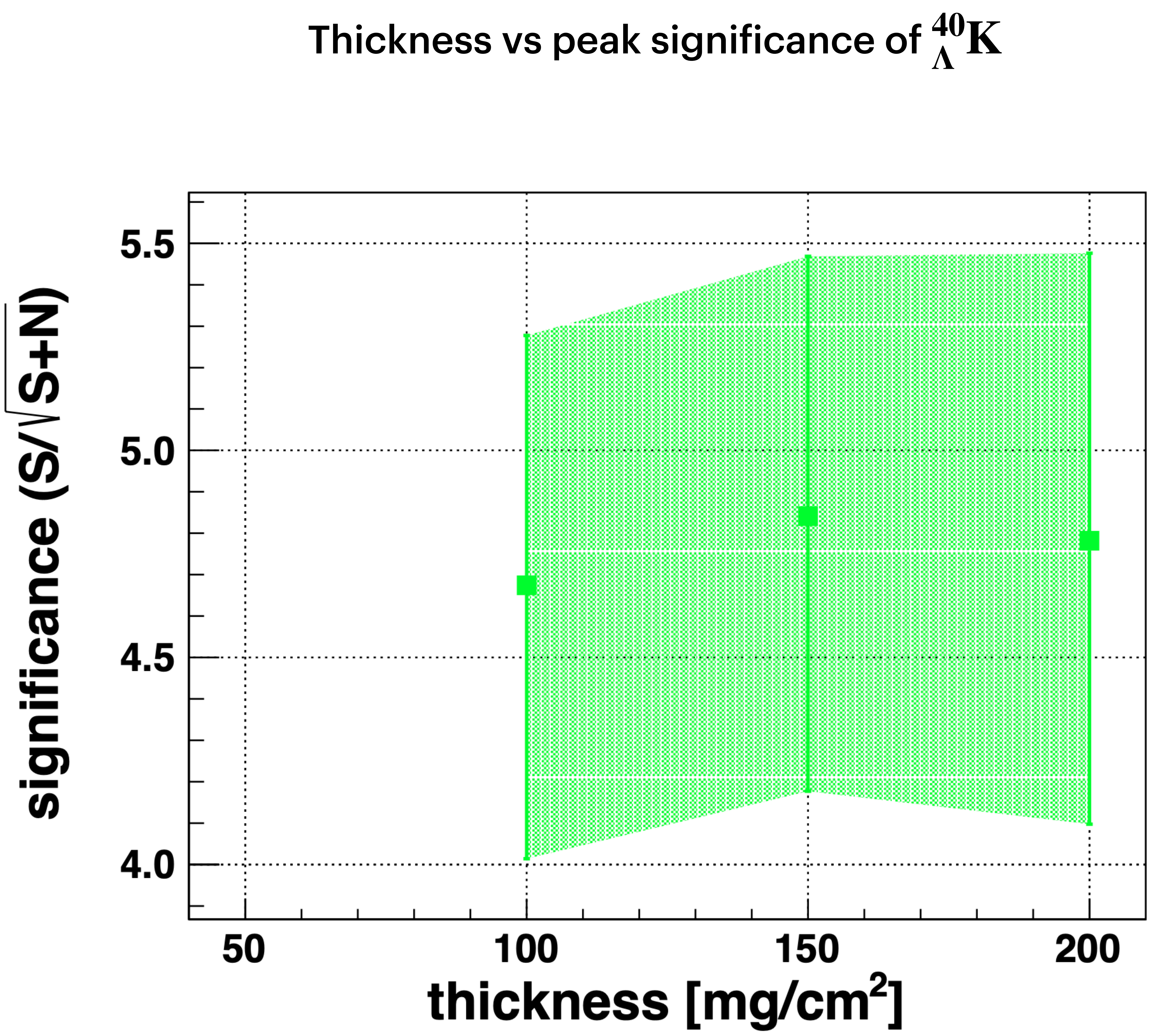
Peak significance distribution

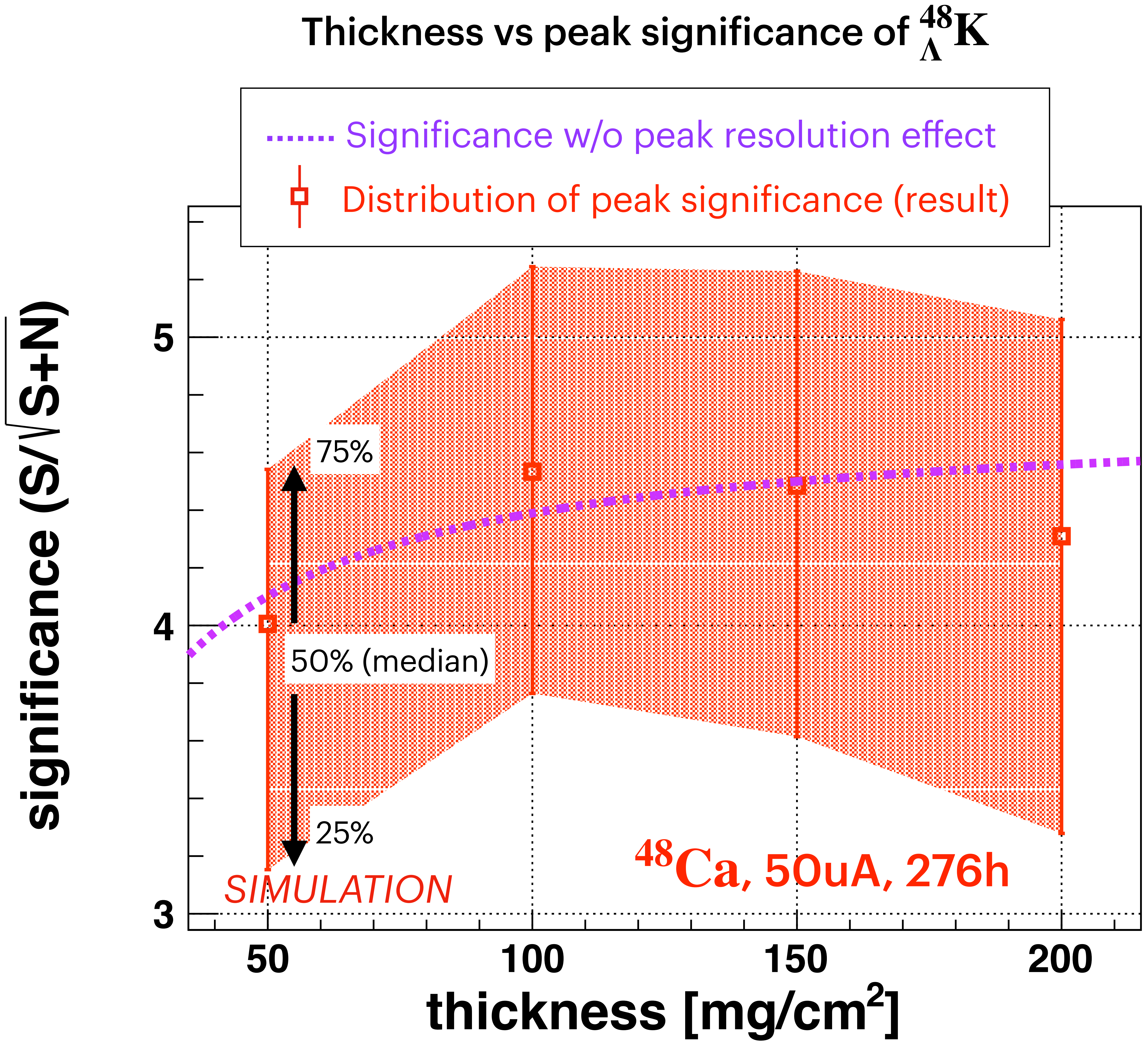


- Evaluation by peak significance of s_Λ

- Applied this analysis to other target thickness

Condition 2. Target thickness

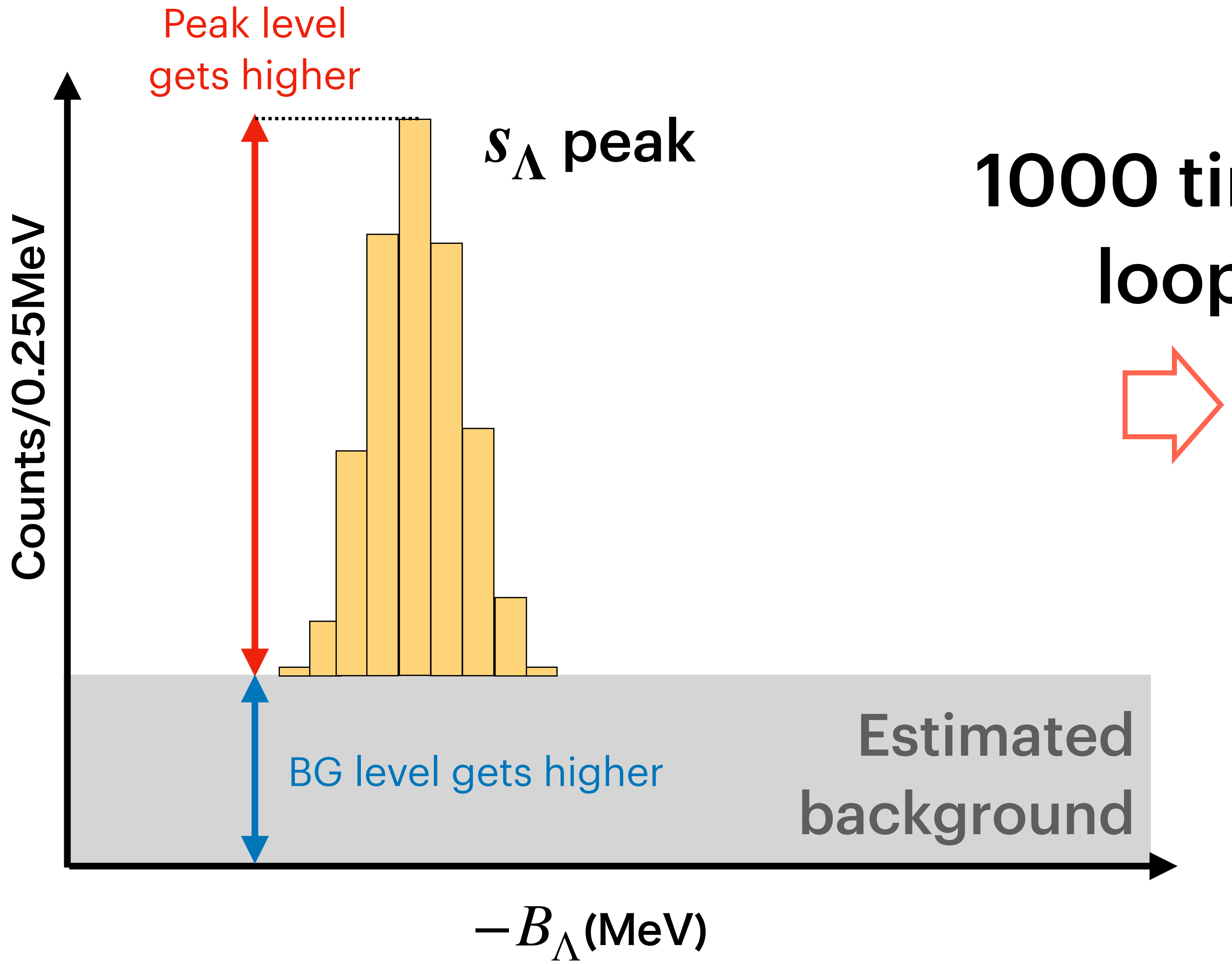


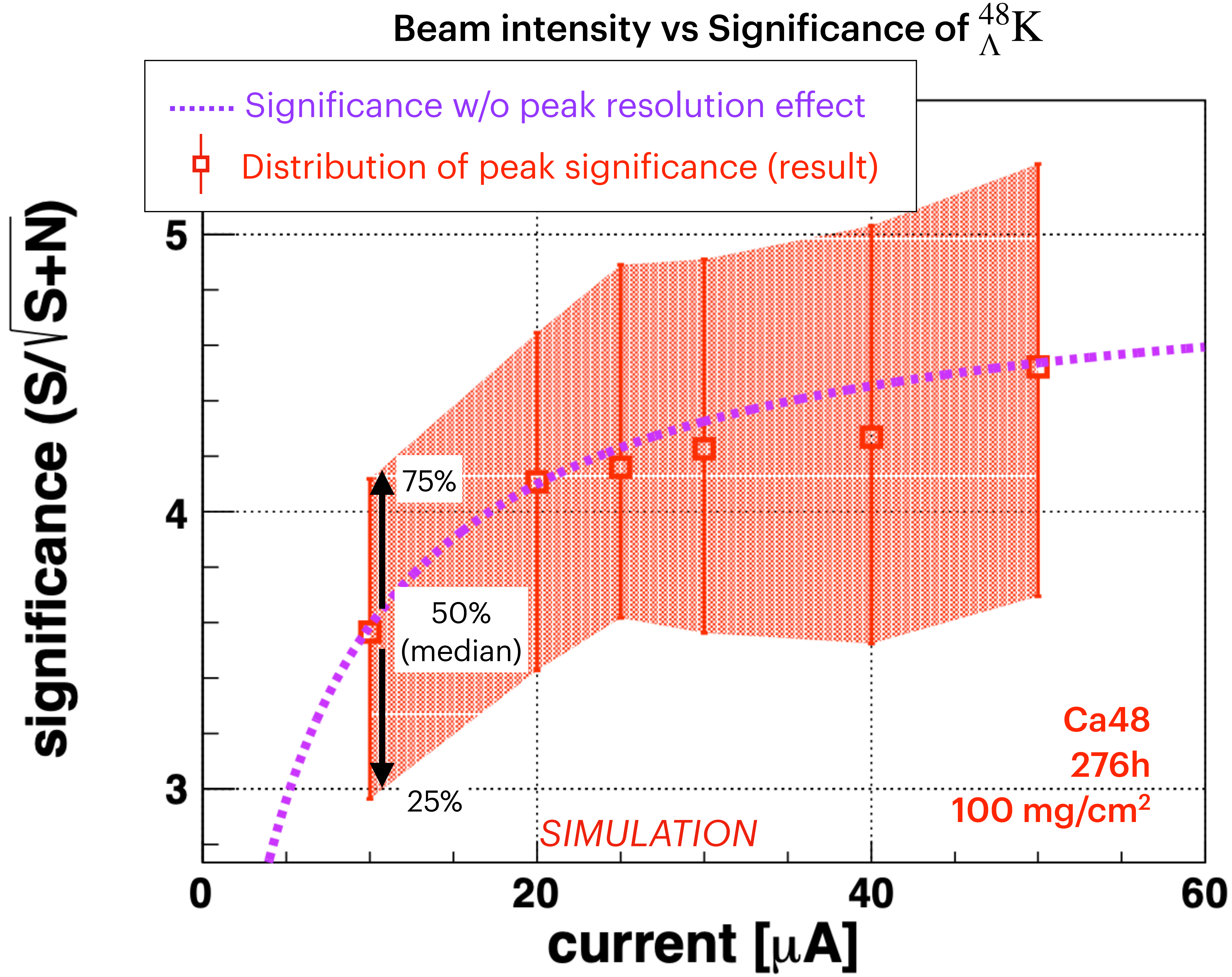


→ Maximum at $100 - 150\ \mathrm{mg/cm^2}$ for ${}^{40,48}_{\Lambda}$K

Condition 3. Beam intensity

In case of high intensity

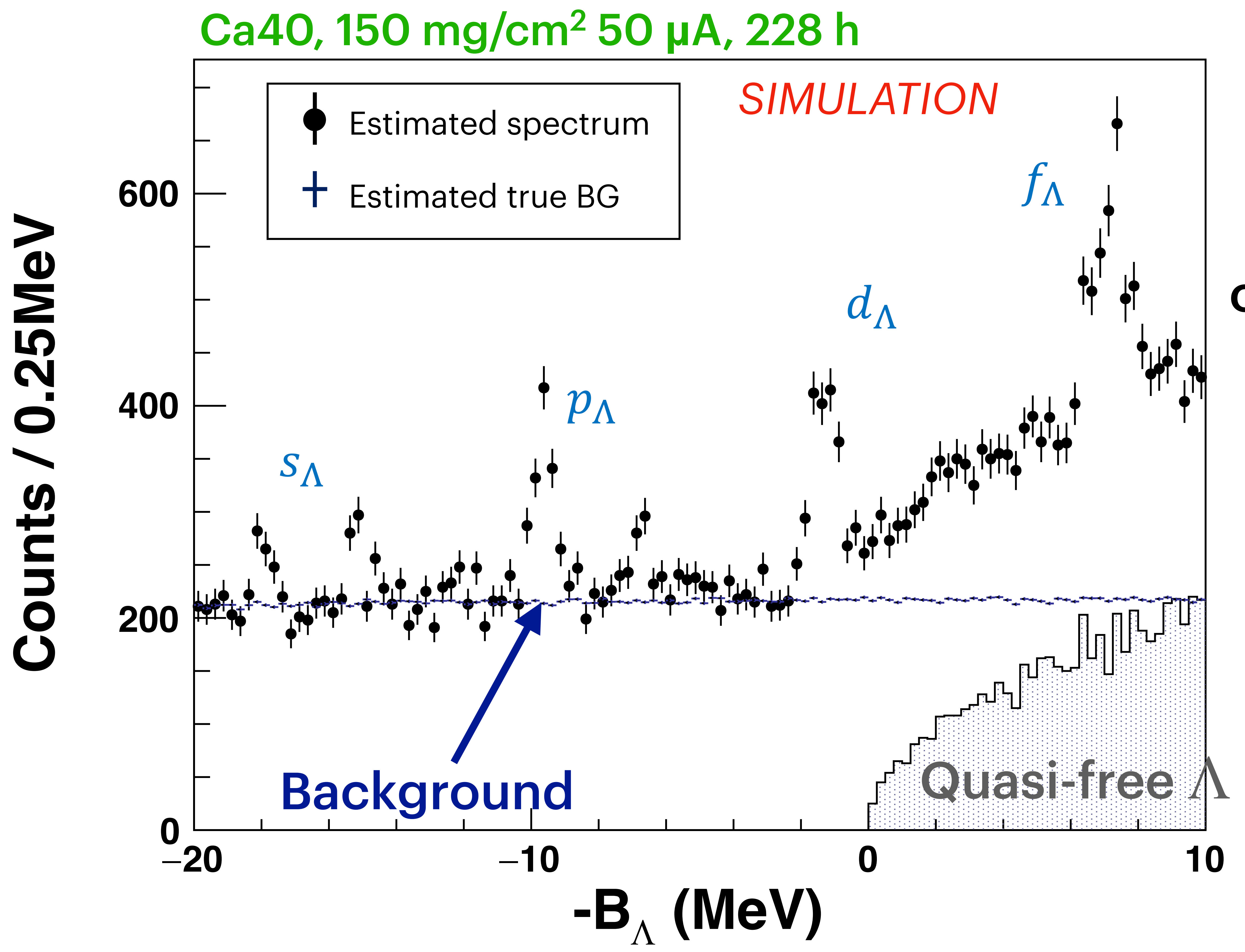




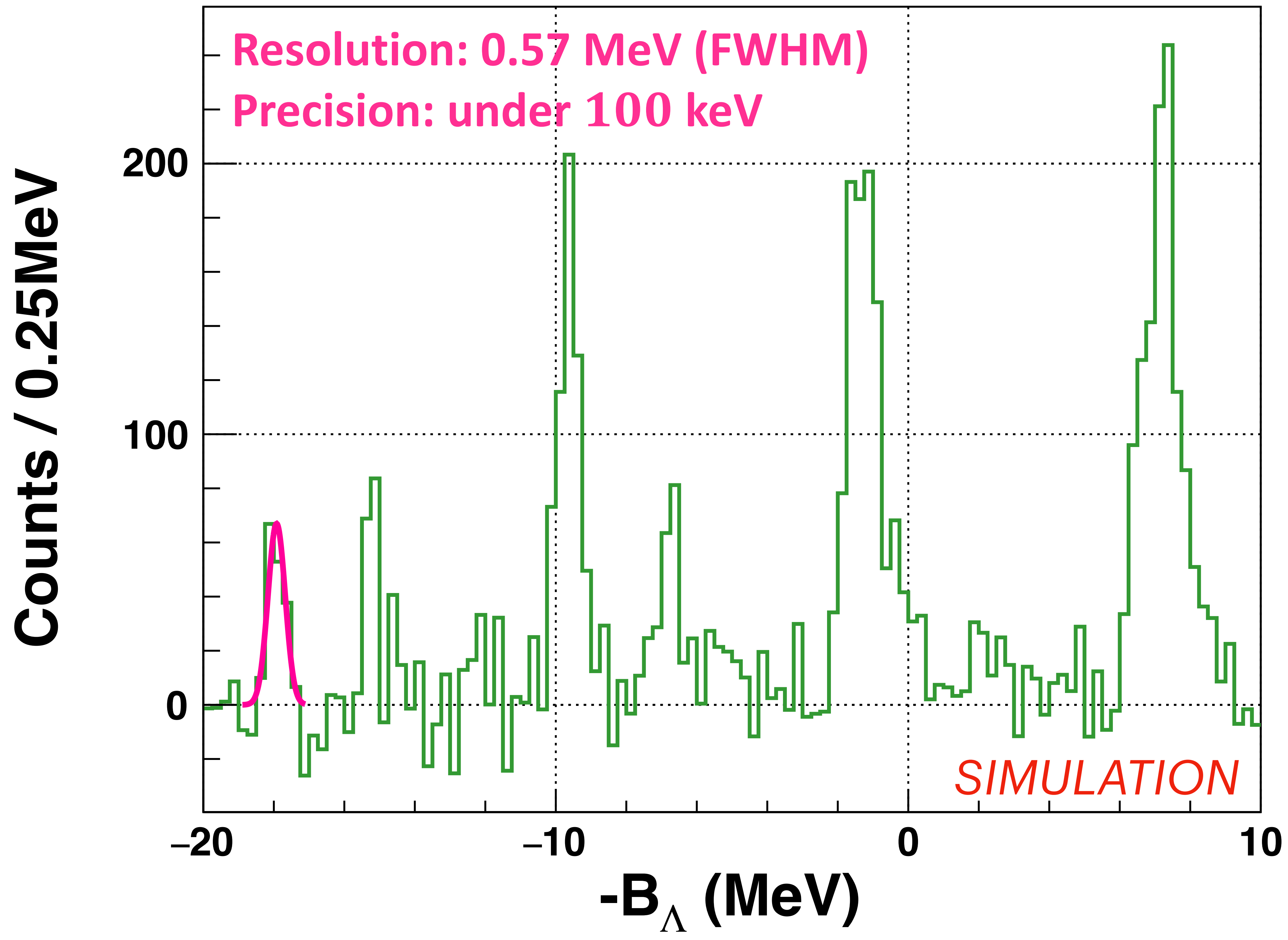
- Same peak evaluation as in condition2
- limitation of detector rate up to 1 MHz ($\leq 50\ \mu$A)

→ Adopted 50 μA for $^{40,48}_{\Lambda}$K

Missing mass spectrum of ${}^{40}_{\Lambda}\mathrm{K}$ after optimization

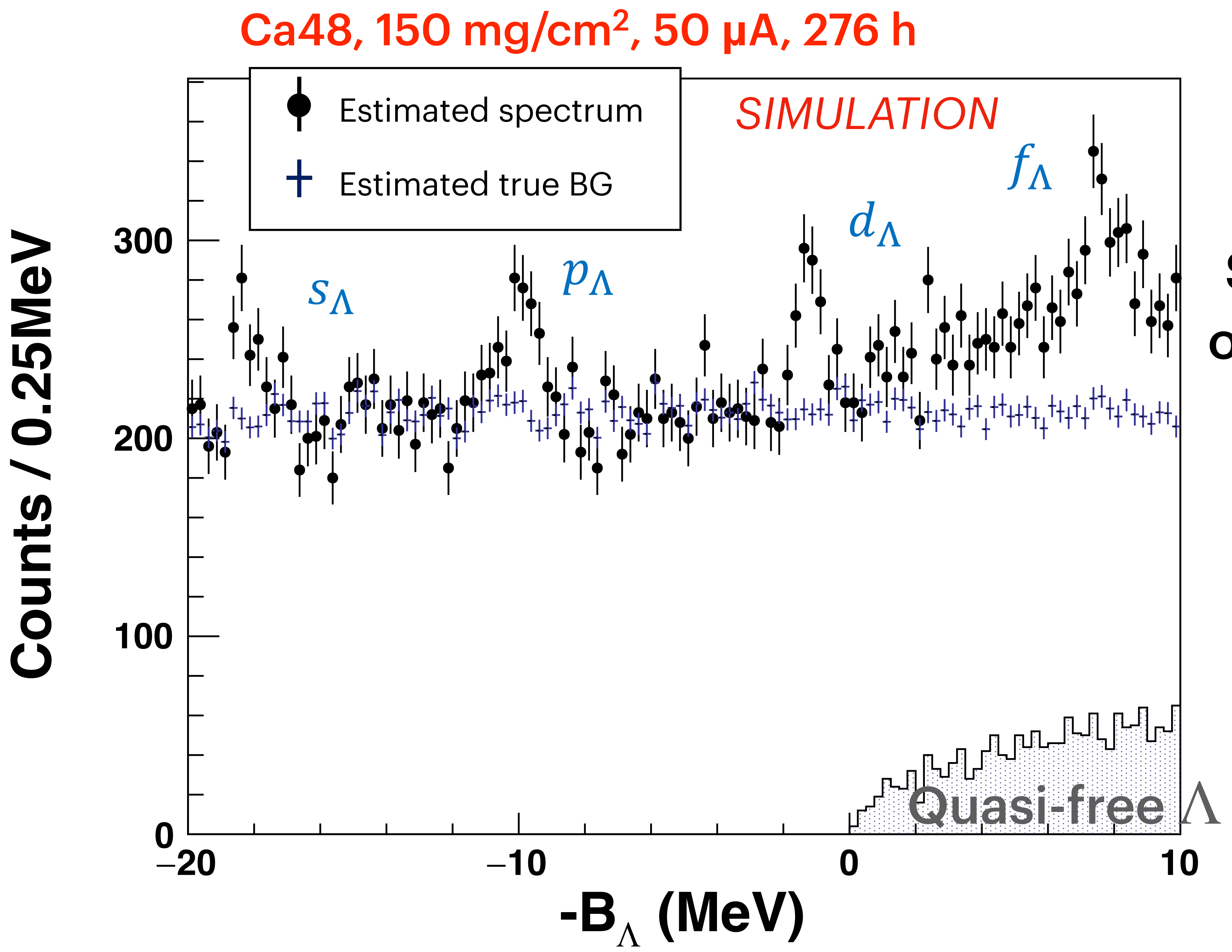


Subtraction of BG and QF

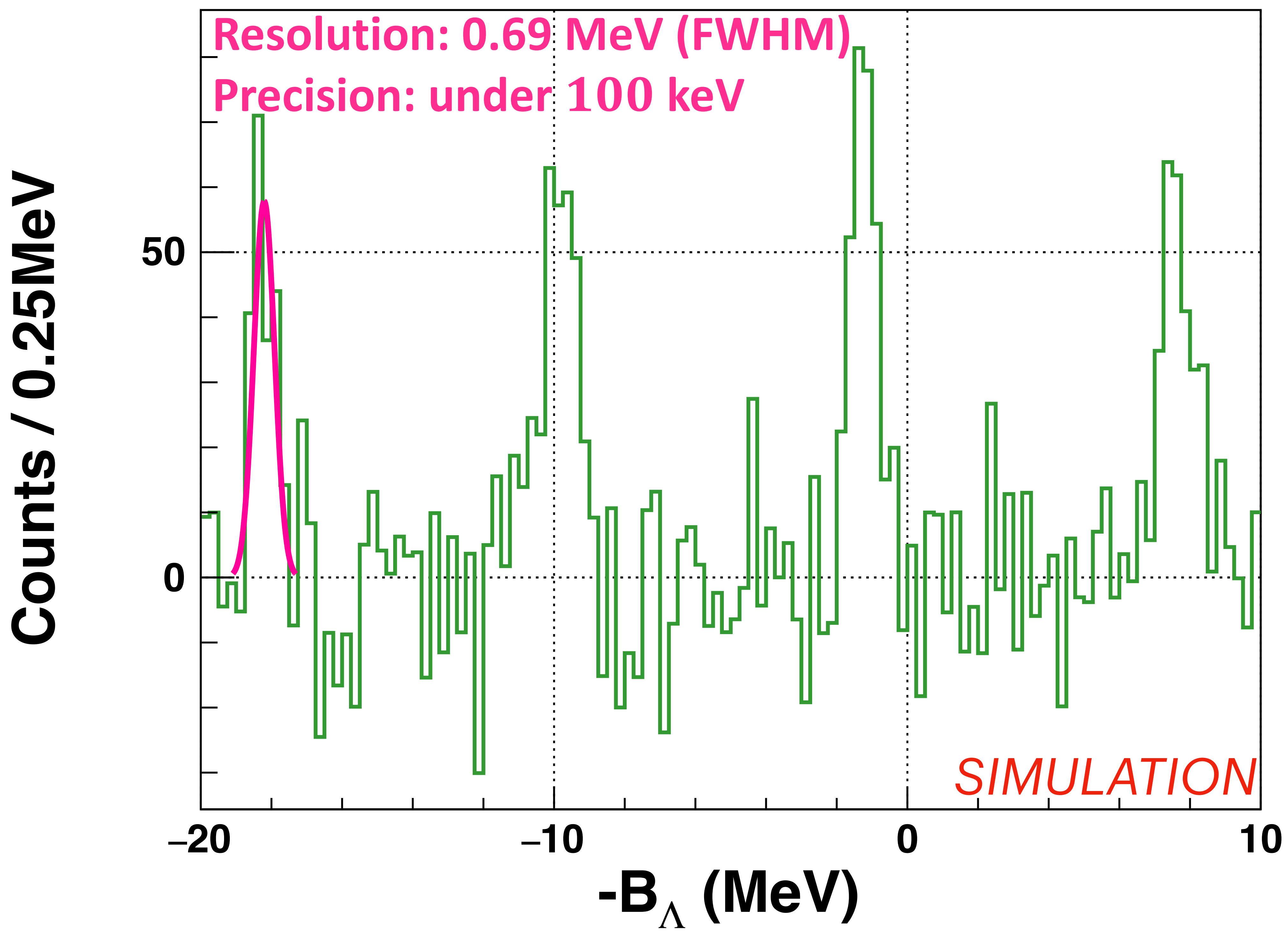


- For peak of s_Λ
  - Energy resolution: 0.57 MeV (FWHM)
  - Energy precision (32 keV from energy loss correction + 20 keV from fitting) : below 100 keV

Missing mass spectrum of ${}^{48}_{\Lambda}\mathrm{K}$ after optimization



Subtraction of BG and QF



- For peak of s_Λ
  - Energy resolution: 0.69 MeV (FWHM)
  - Energy precision (32 keV from energy loss correction + 30 keV from fitting): below 100 keV

Summary

- Optimized the experimental conditions
  - HES angle: 8 deg
  - Target thickness: 100 - 150 mg/cm2
  - Beam intensity: 50 μA

- Estimated missing mass spectra
  - Precision for Peak of s_Λ of ${}^{40,48}_{\Lambda}\mathrm{K}$: below 100 keV
  - Energy resolution: 0.6 - 0.7 MeV
  - Peak significance: less than 5σ

Backup

Spectrometer

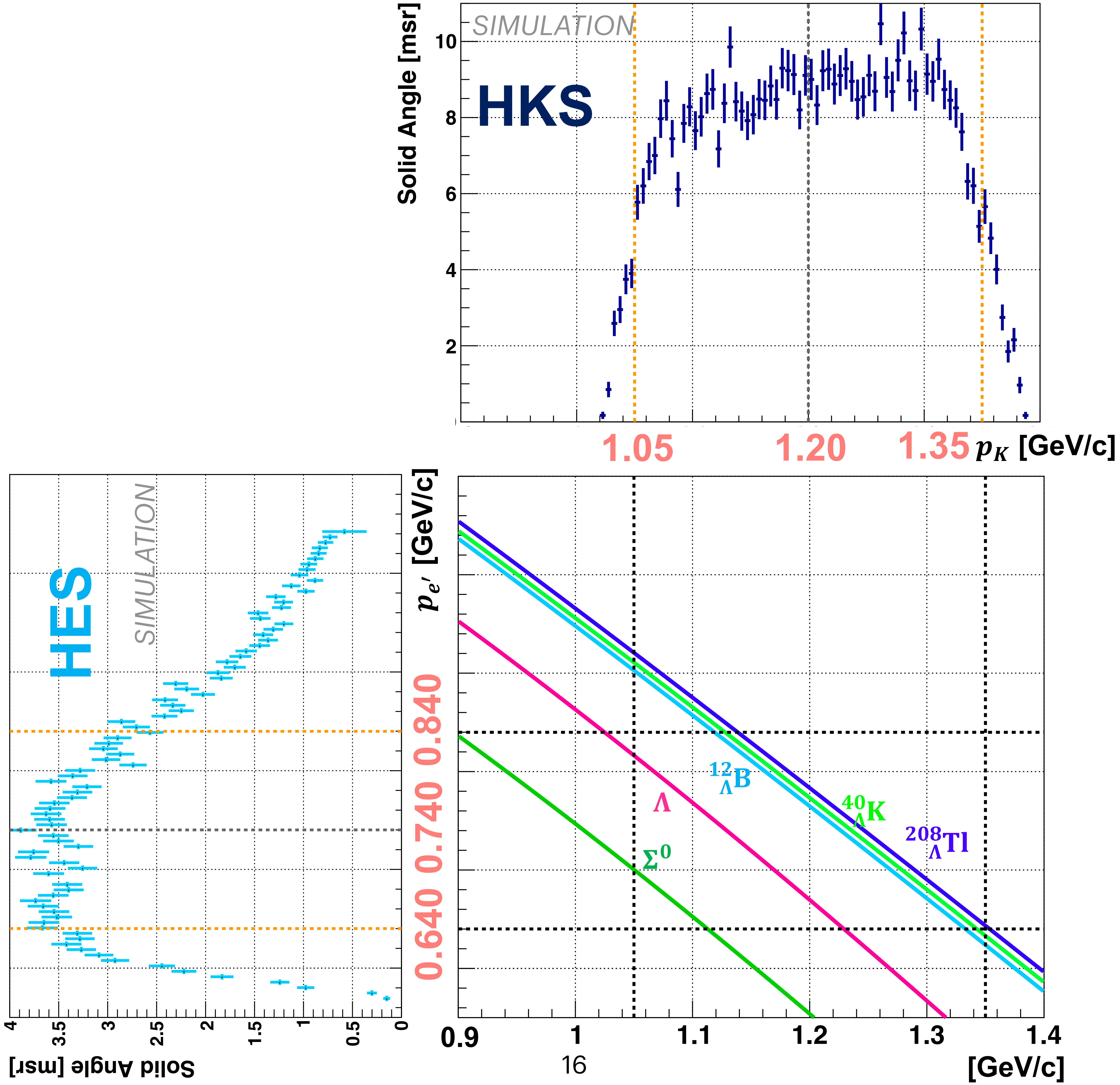
Optimal magnetic field

	PCS [T]	Q1 [T/m]	Q2 [T/m]	D [T]
HES	*	3.12	3.16	1.01
HKS	*	3.67	1.87	1.61

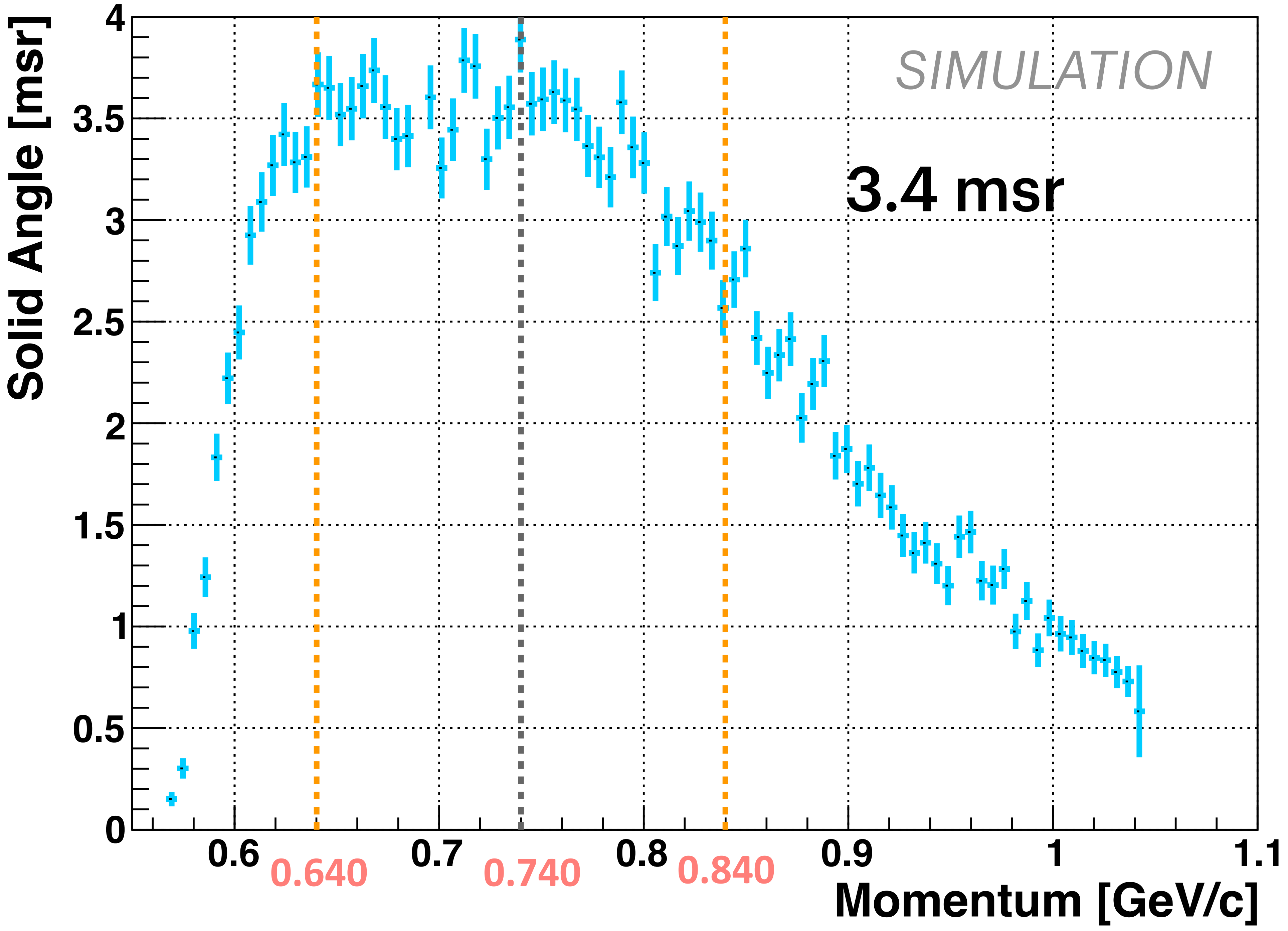
* Calculation is on-going for PCS field

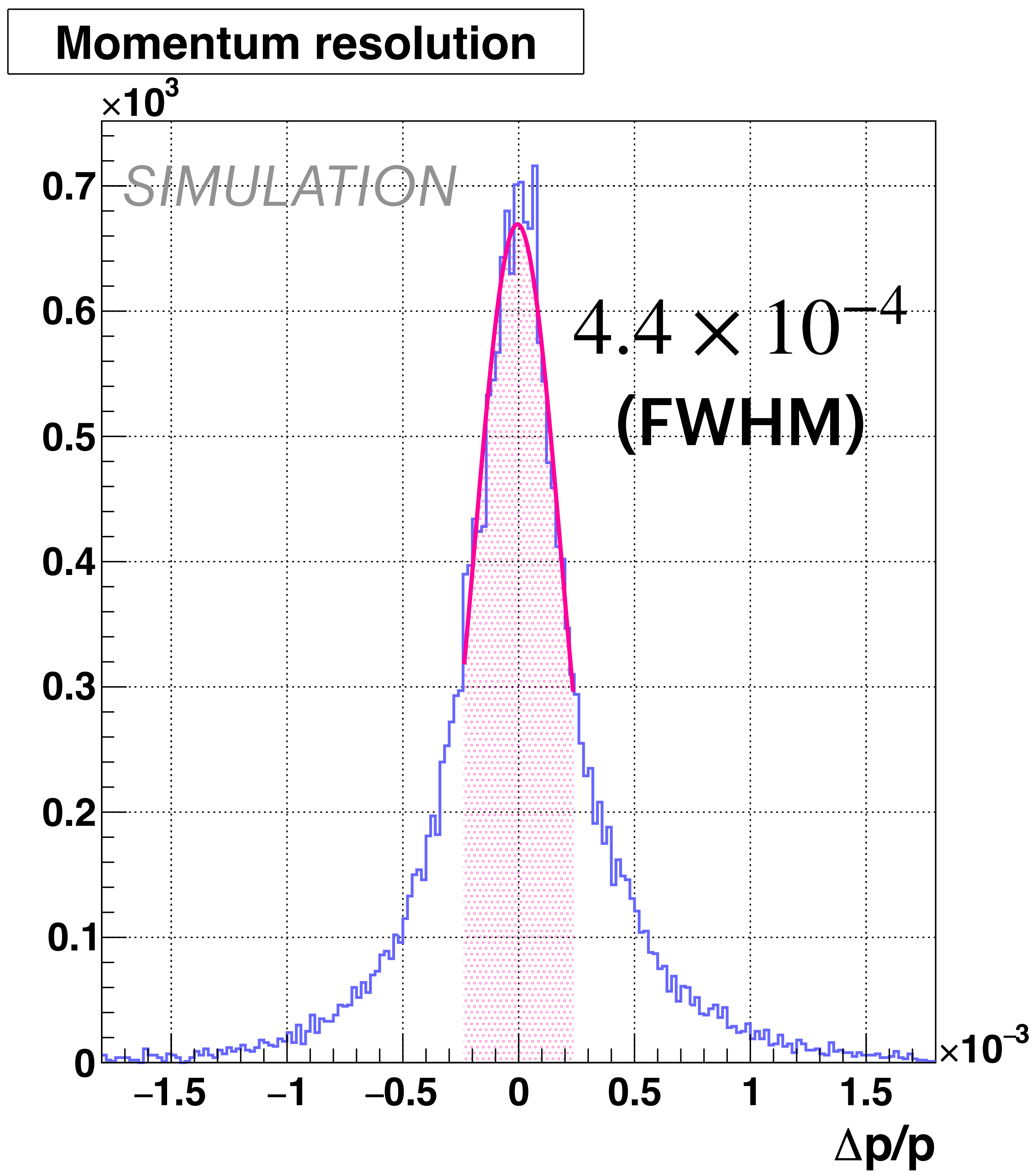
- Standard mag. field of each magnets are defined as max. at y=0 (center in vertical direction)
- Optimal mag. fields is defined as (standard filed) x (optimal scaling value)

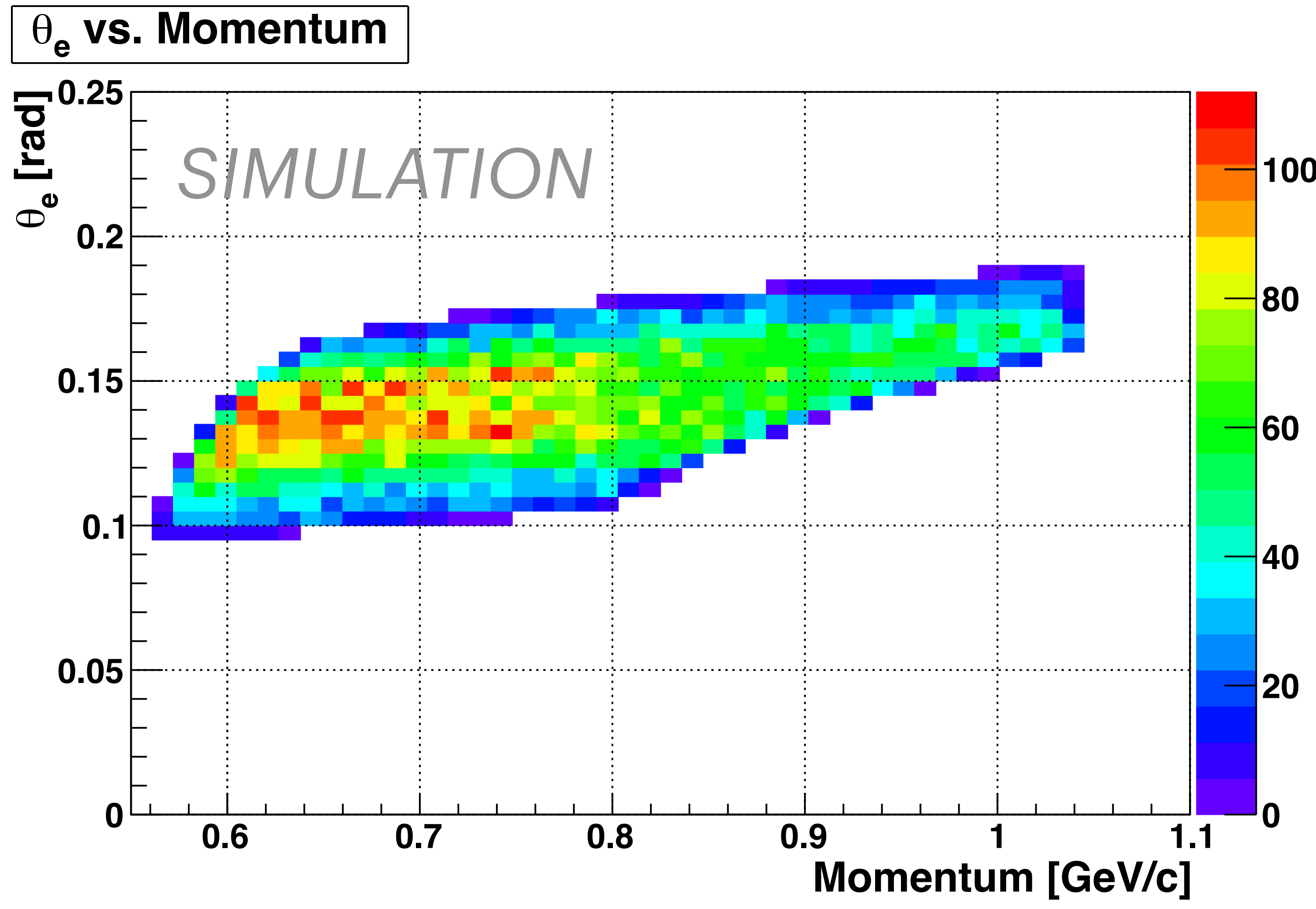
Momentum acceptance for all targets



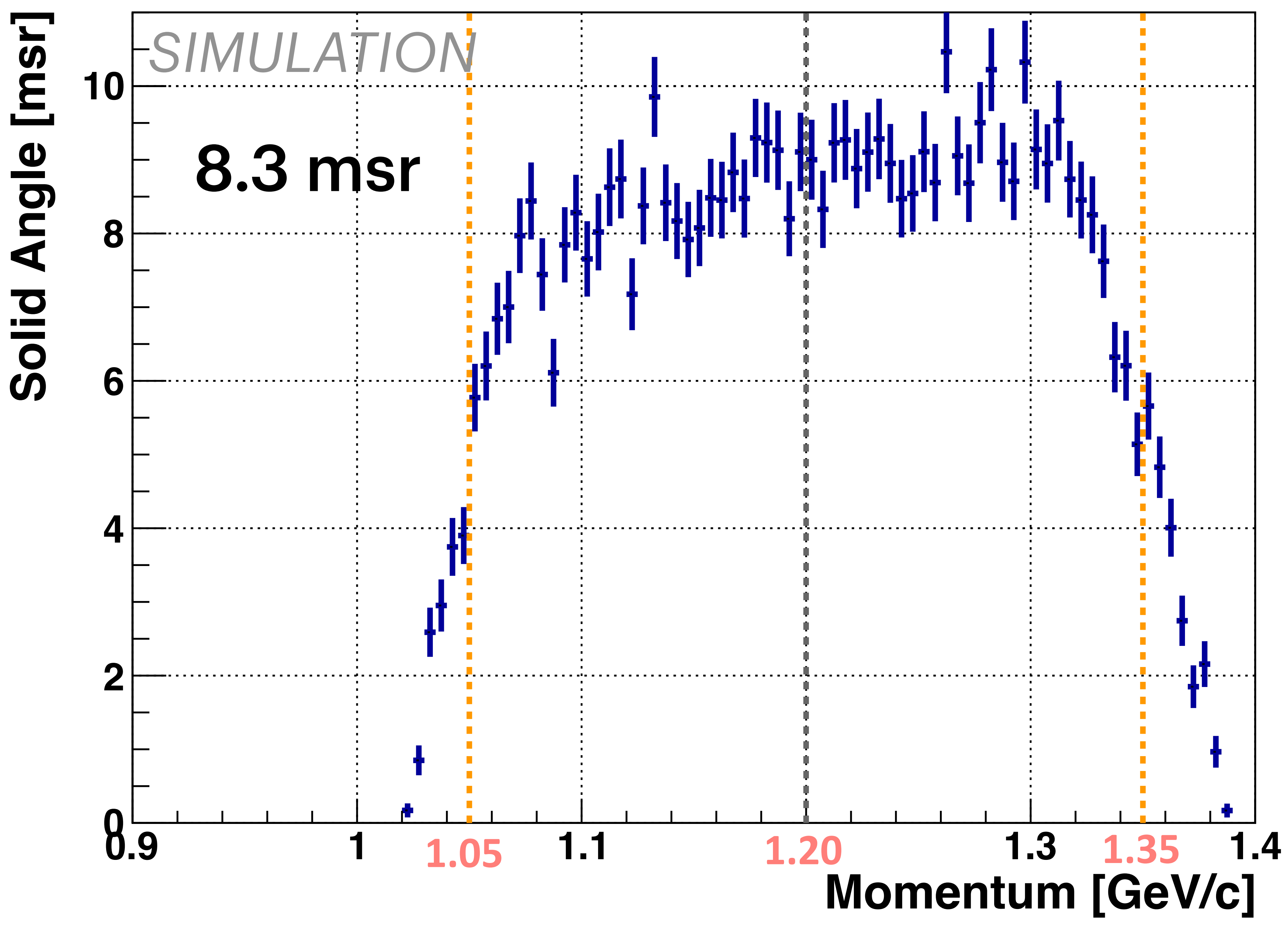
HES performance

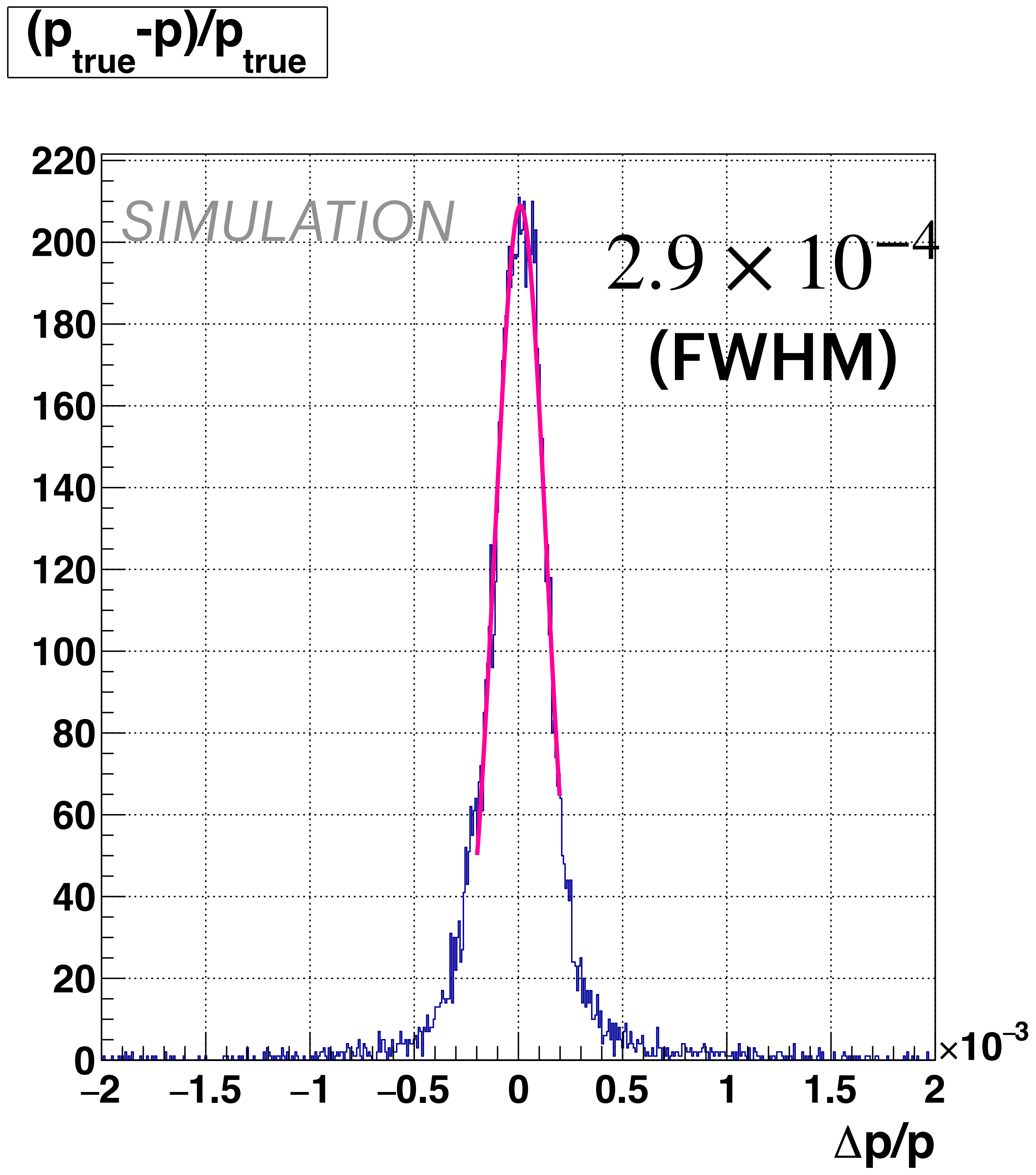


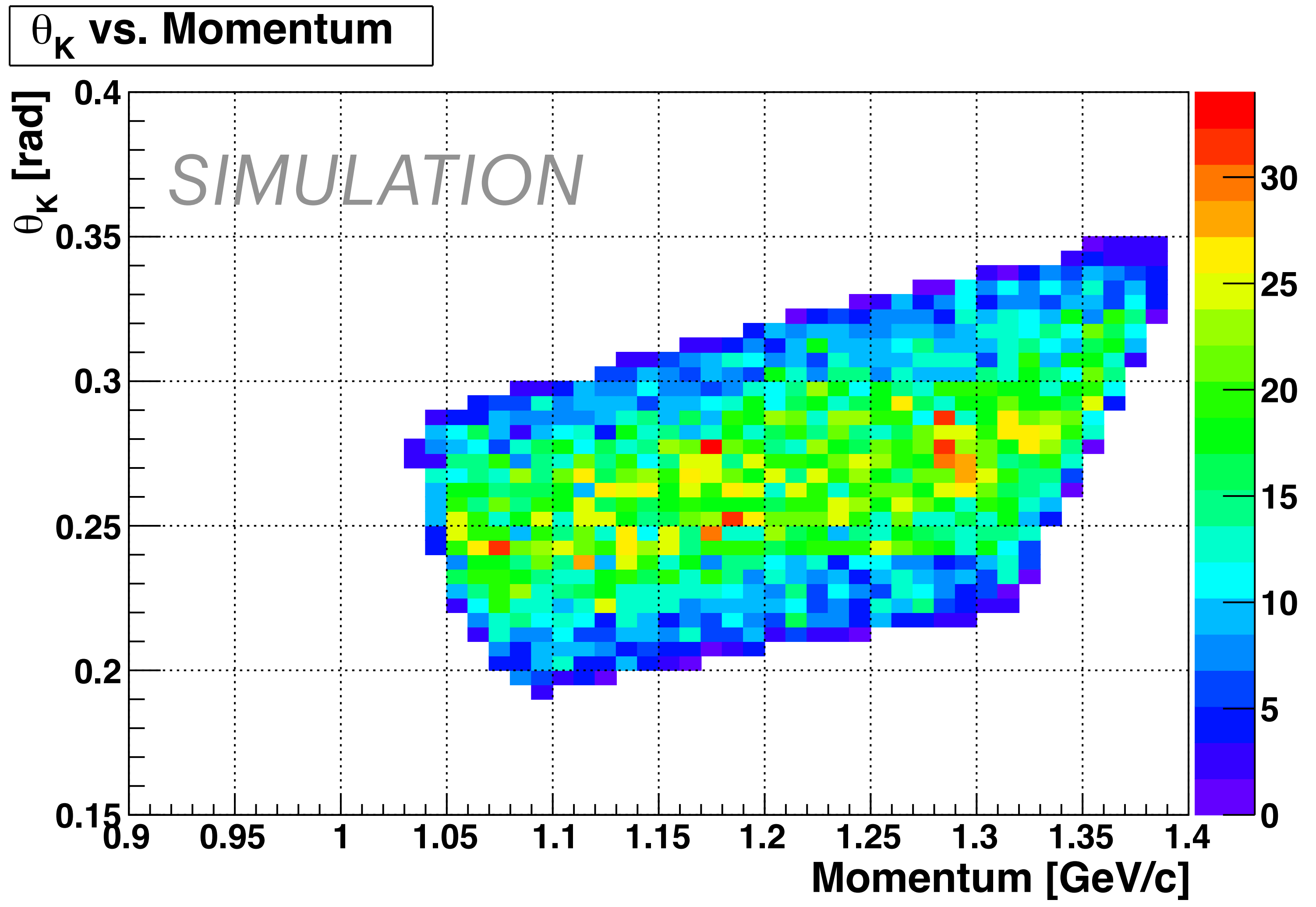




HKS performance

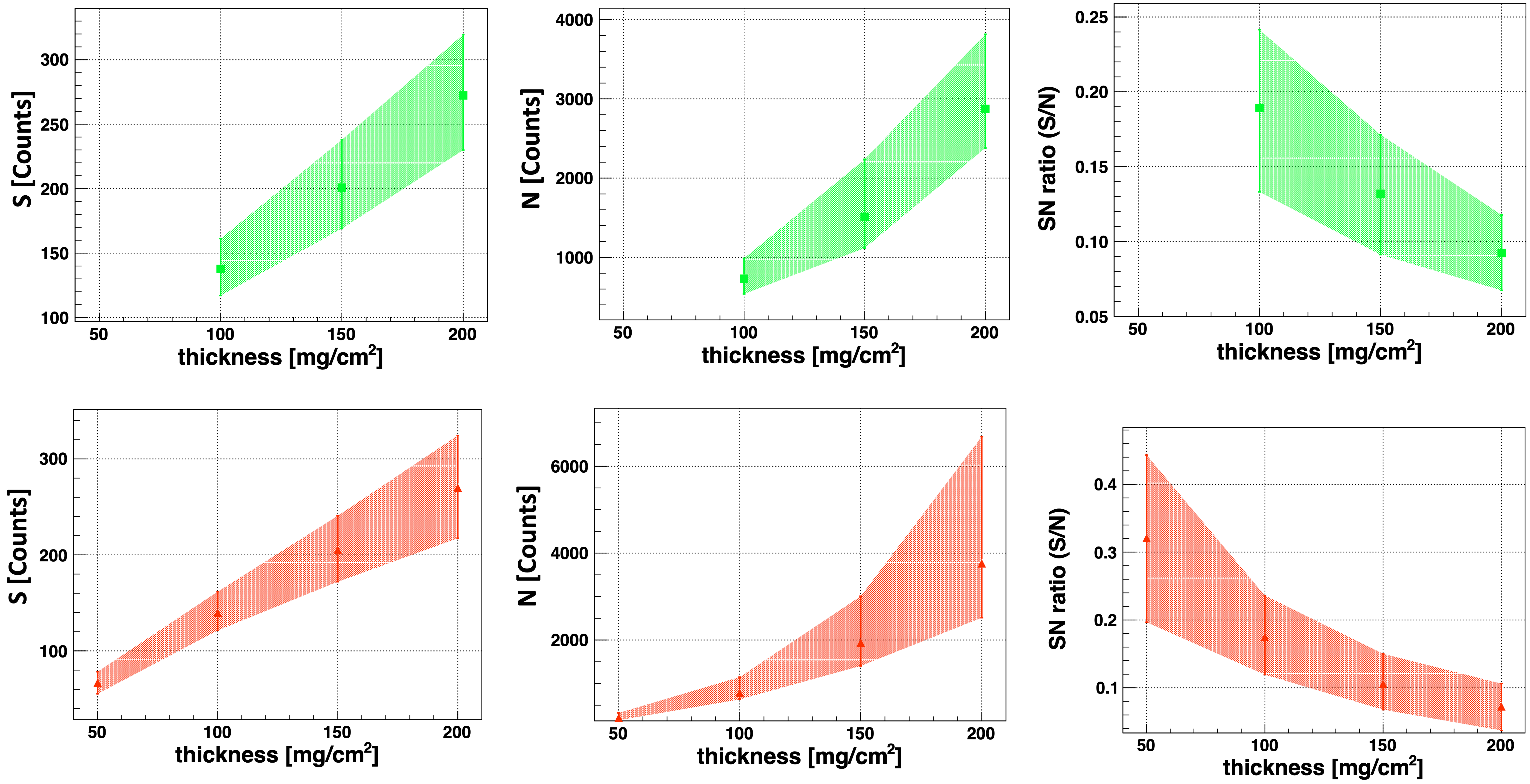




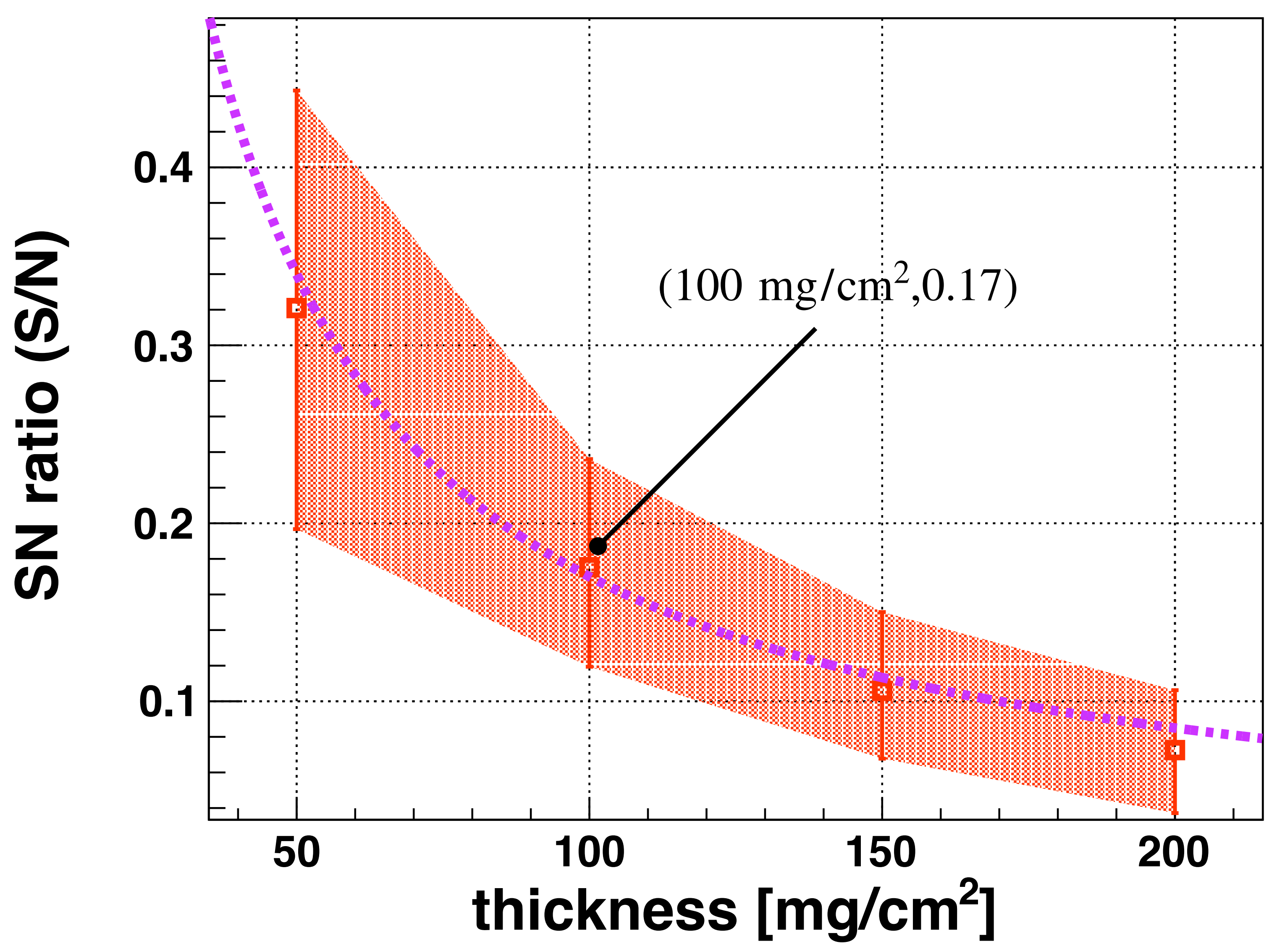


Result details

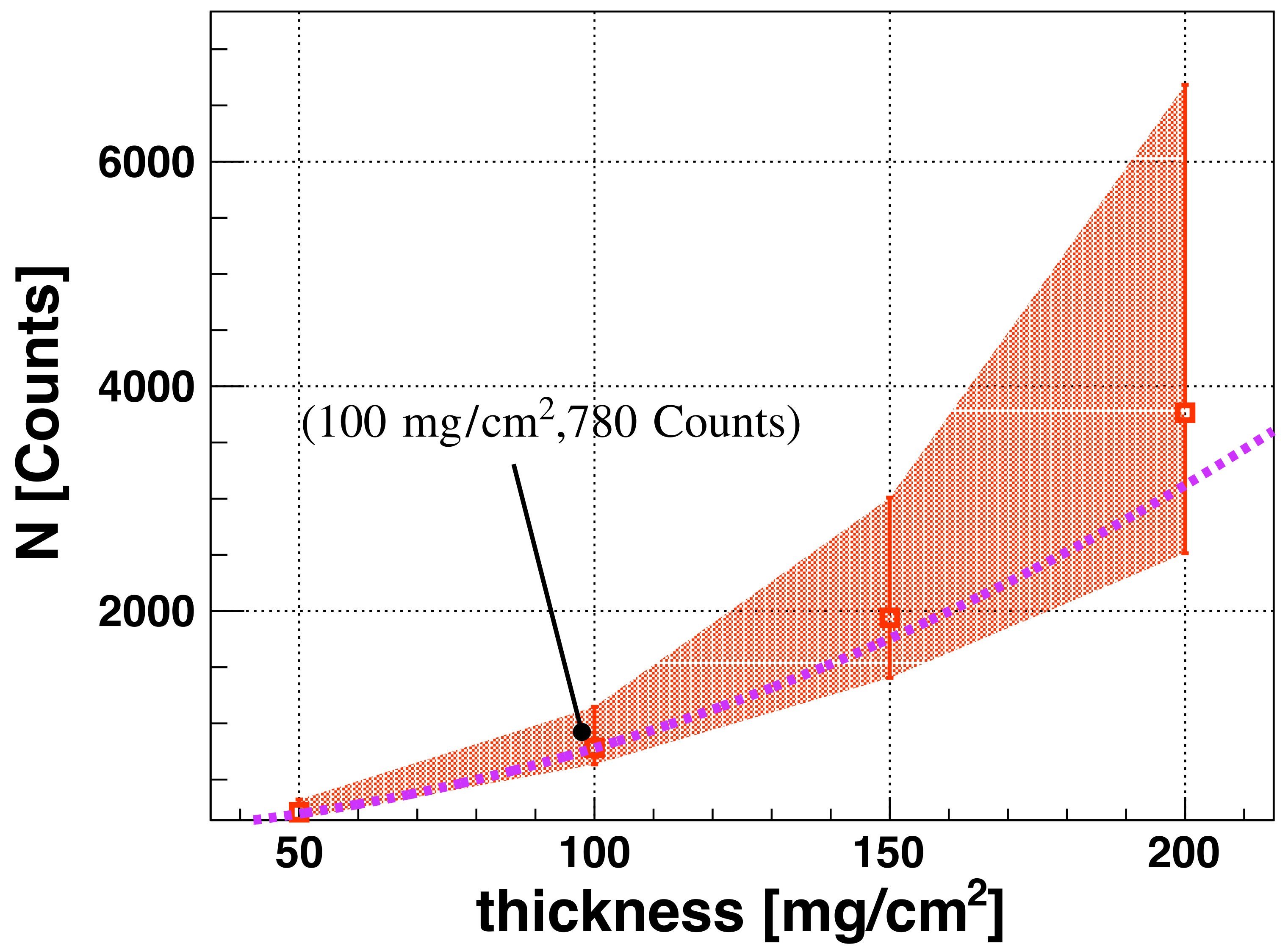
Condition 2. Thickness - S, N, S/N



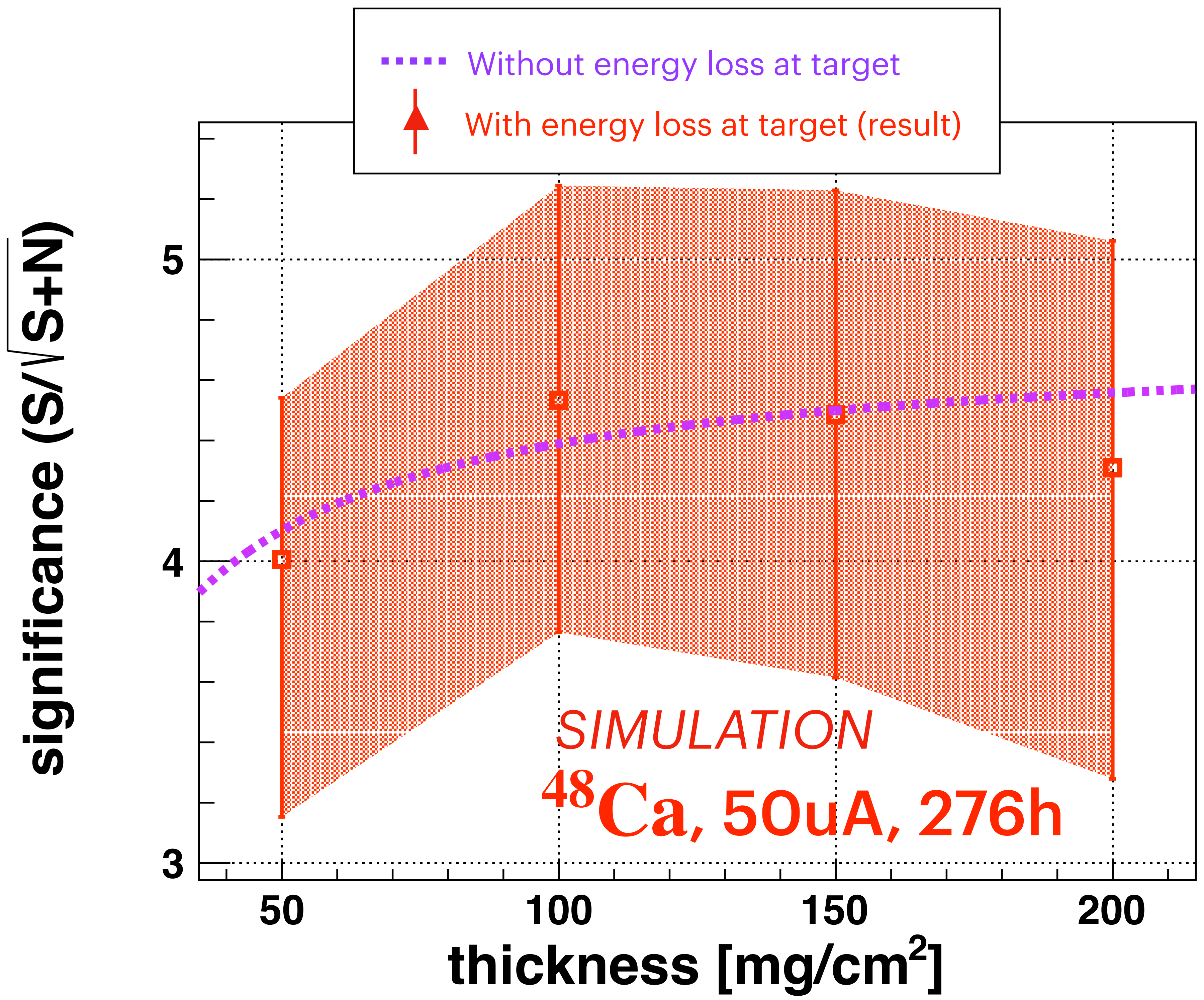
Condition 2. Thickness - Purple line



- Definition of S, N:
  - $S = ax$, $N = bx^2$, where x is thickness
- Signal to noise ratio passing at $(100\ \mathrm{mg/cm^2}, 0.17)$
  - $\frac{S}{N} = \frac{a}{b}\frac{1}{x} = 17\frac{1}{x}$

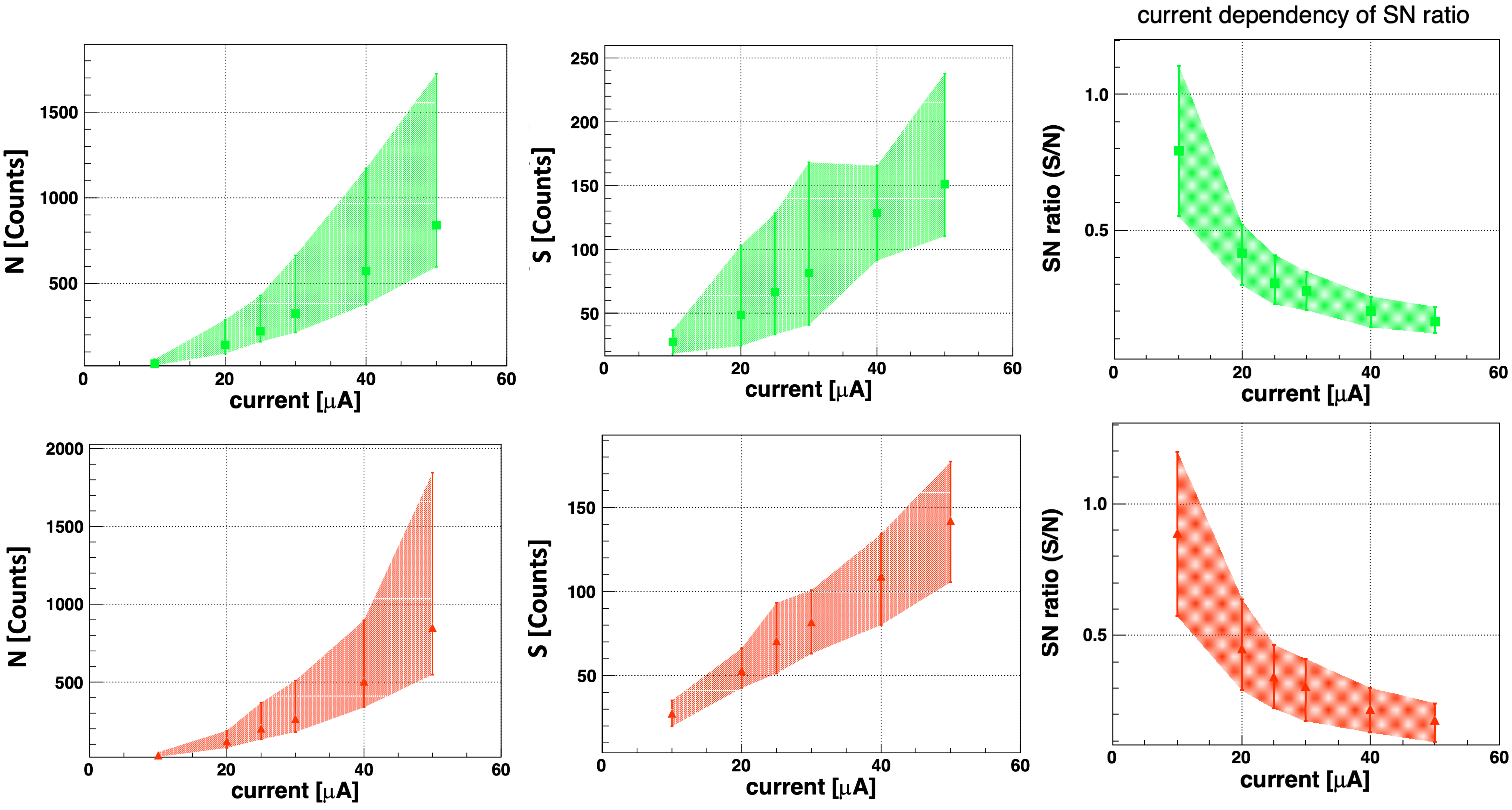


- Noise passing at $(100\ \mathrm{mg/cm^2}, 780\ \mathrm{Counts})$
  - $N = bx^2 = 0.078x^2$

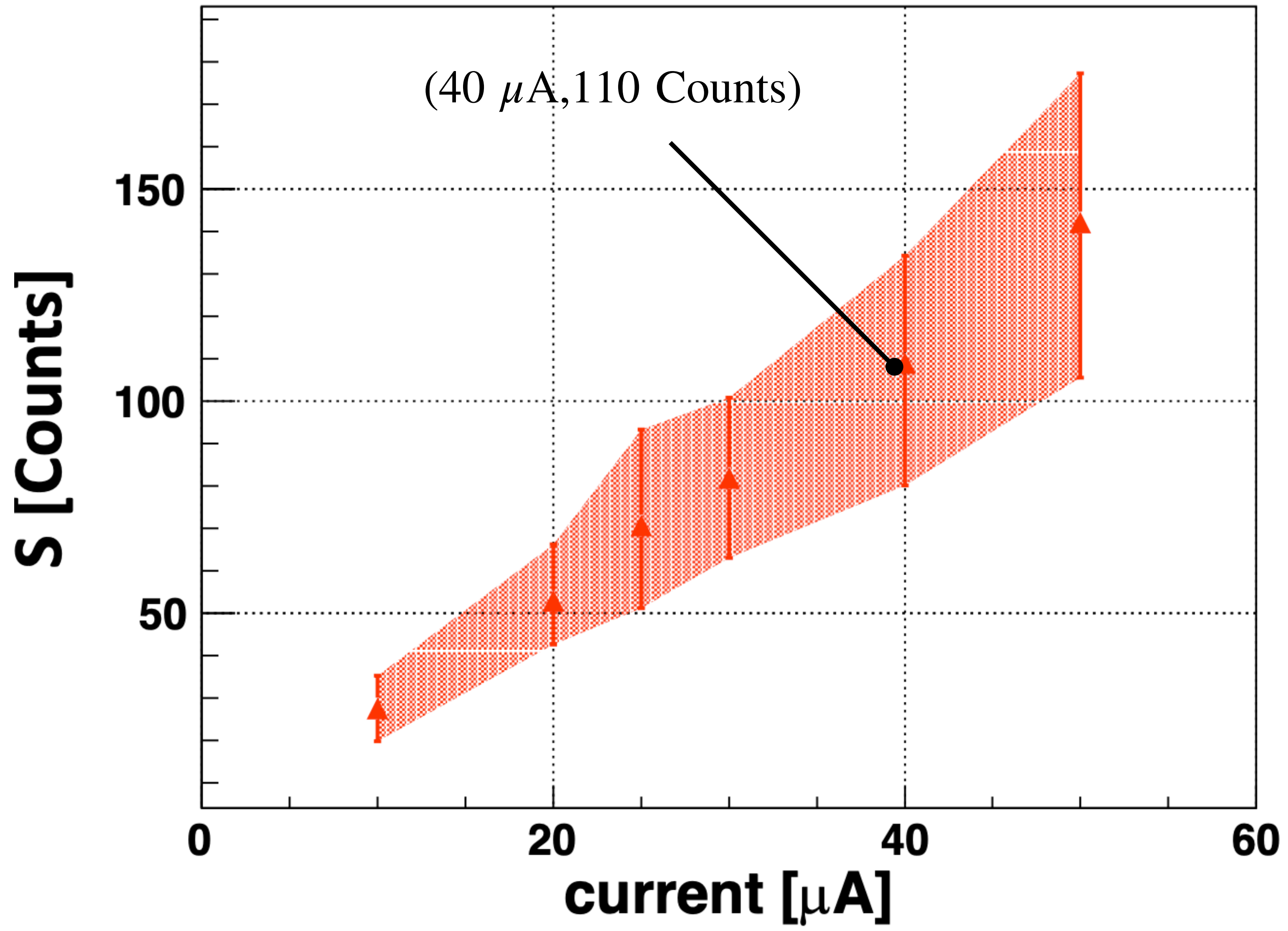


- So $a \simeq 1.3$, then peak significance(purple line) becomes
  - $\frac{S}{\sqrt{S+N}} = \frac{ax}{\sqrt{ax+bx^2}} = \frac{1.3x}{\sqrt{1.3x+0.078x^2}}$
- This function comes from only rate calculation formula
- → It doesn't consider energy straggling at target

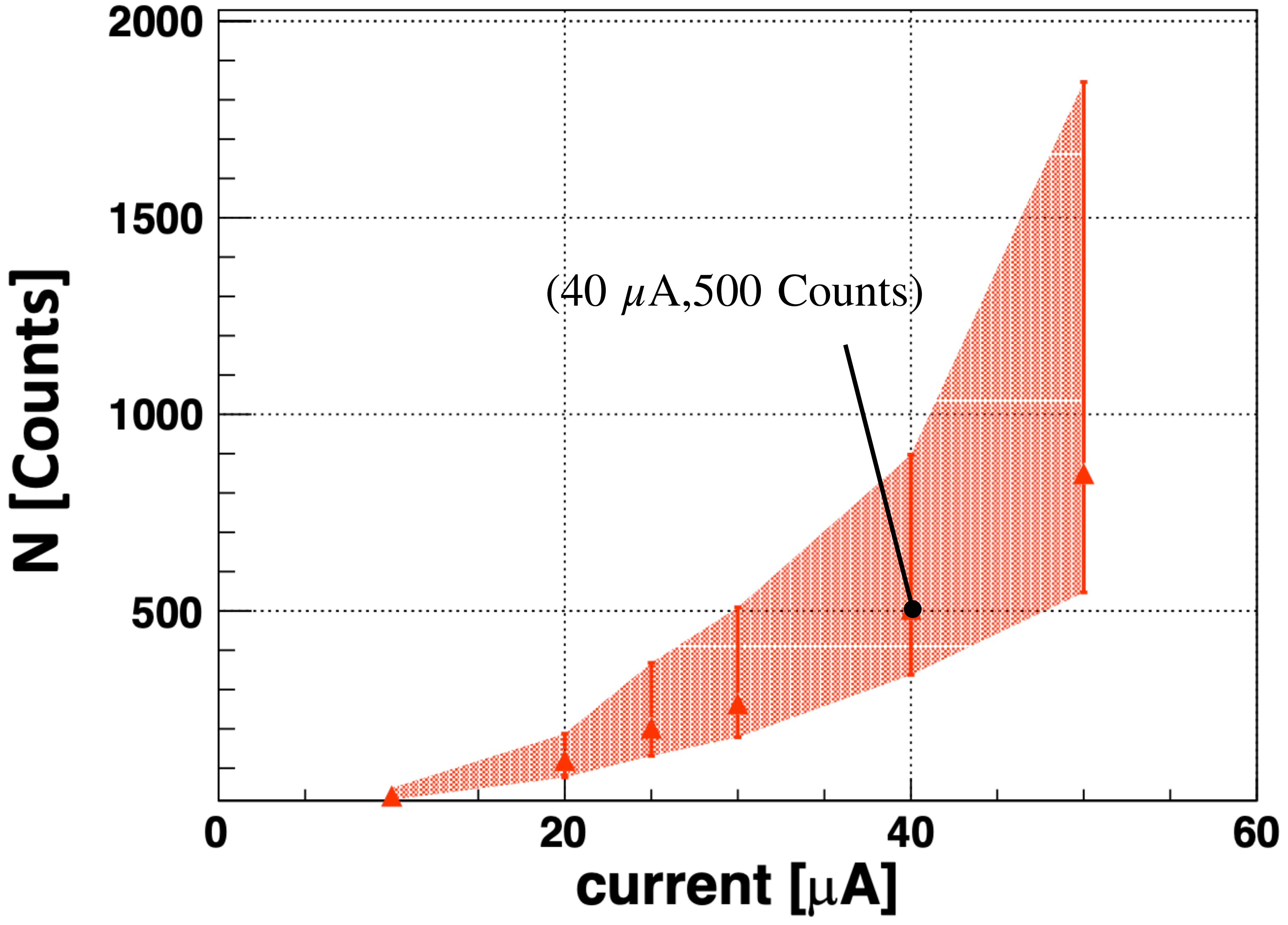
Condition 3. Beam intensity - N, S, S/N



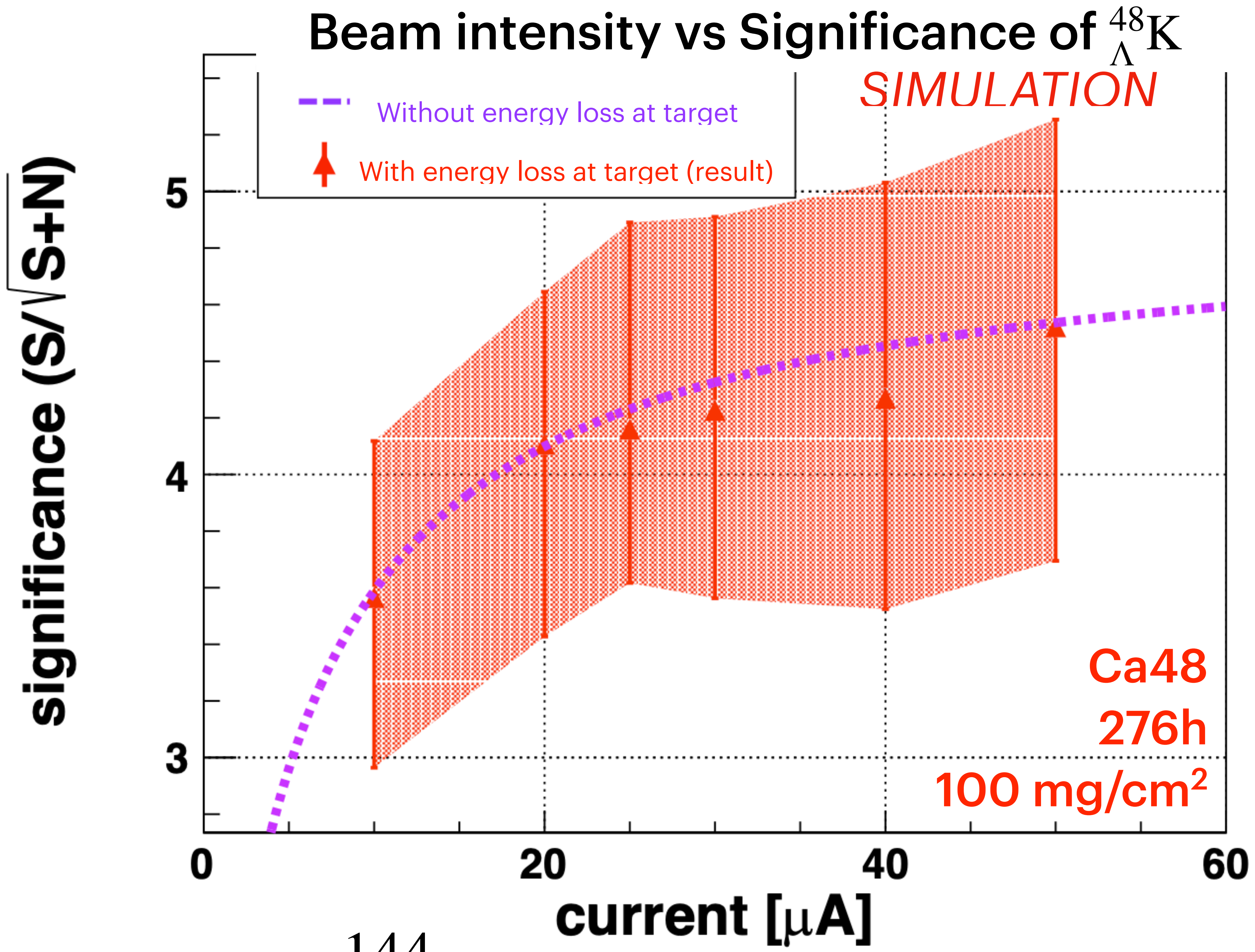
Condition 3. Beam intensity - Purple line



- Definition of S, N:
  - $S = cI, N = dI^2$, where I is current
- Signal to noise ratio passing at (40 μA,110 Counts)
  - $S = cI = \frac{11}{4}I$



- Noise passing at (100 mg/cm^2,900 Counts)
  - $N = dI^2 = \frac{5}{16}I^2$



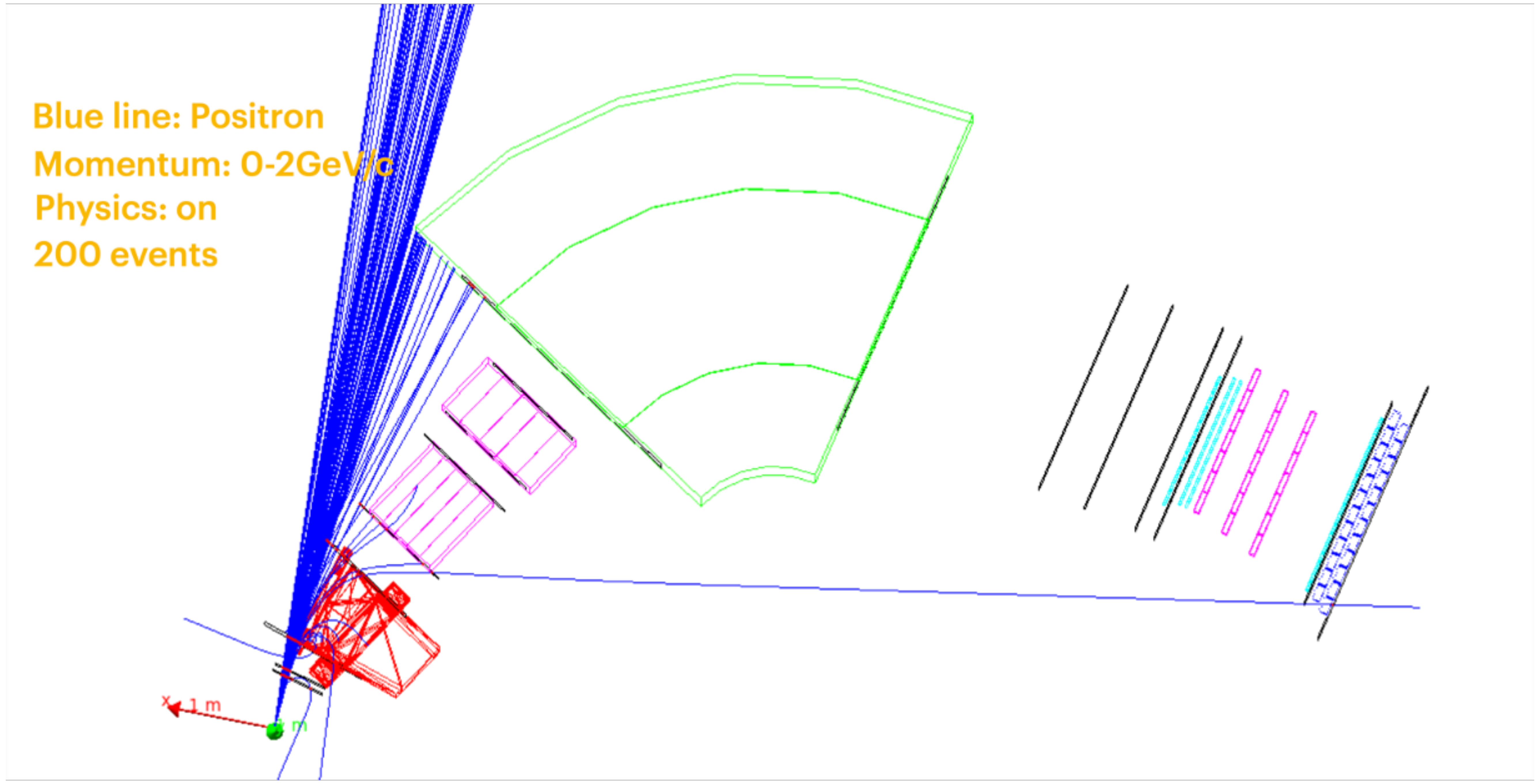
- So $a = \frac{144}{100}$, then peak significance(purple line) becomes
  - $$\frac{S}{\sqrt{S+N}} = \frac{cI}{\sqrt{cI+dI^2}} = \frac{\frac{11}{4}x}{\sqrt{\frac{11}{4}I + \frac{5}{16}I^2}}$$
- This function comes from only rate calculation formula
- → It doesn't consider energy straggling at target

Simulation details

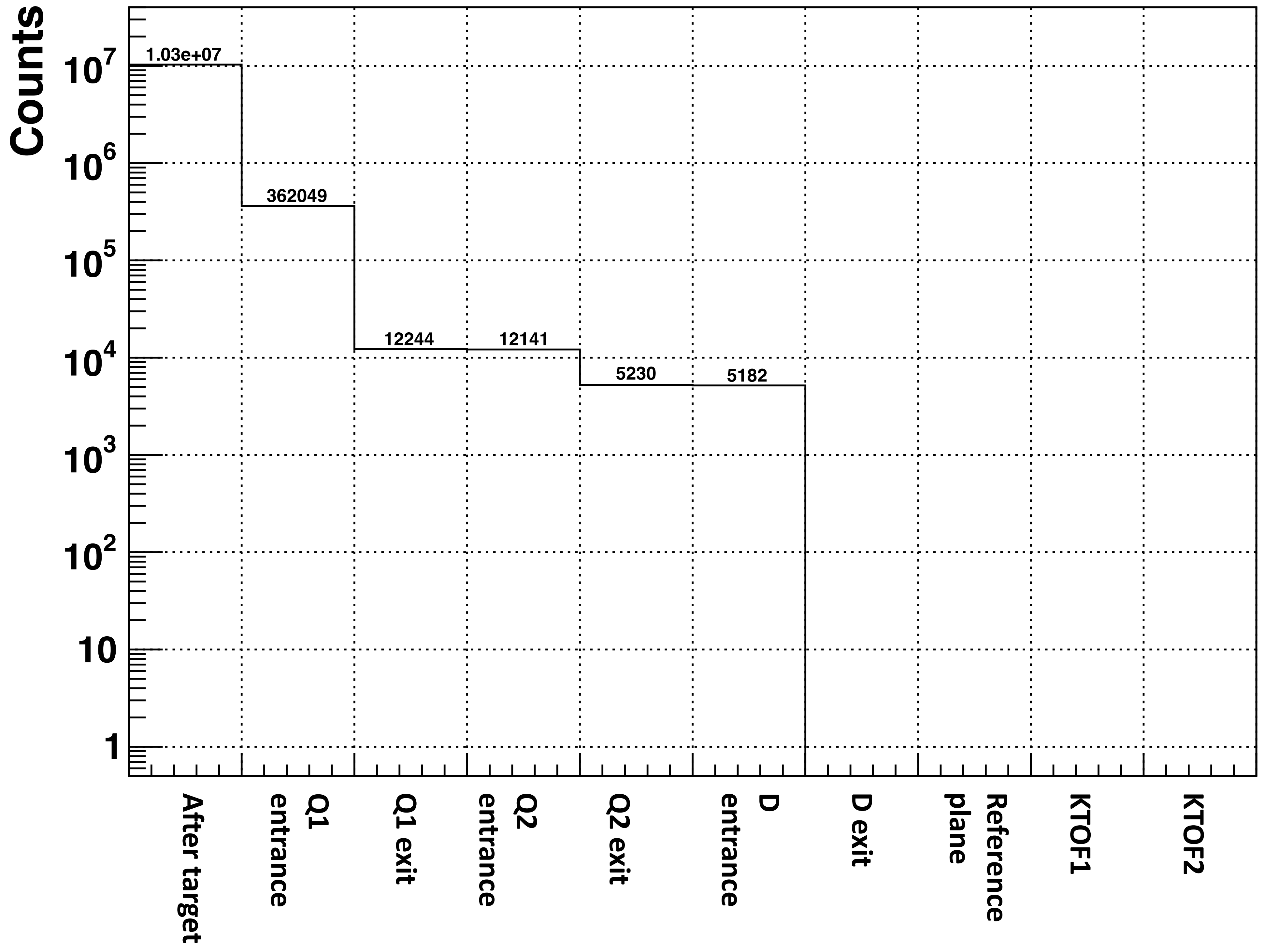
Checking positron contamination

- Check positron background found in the previous experiment by visualization and number of hit
- Positrons have the same condition as in the previous experiment

Visualization of HKS

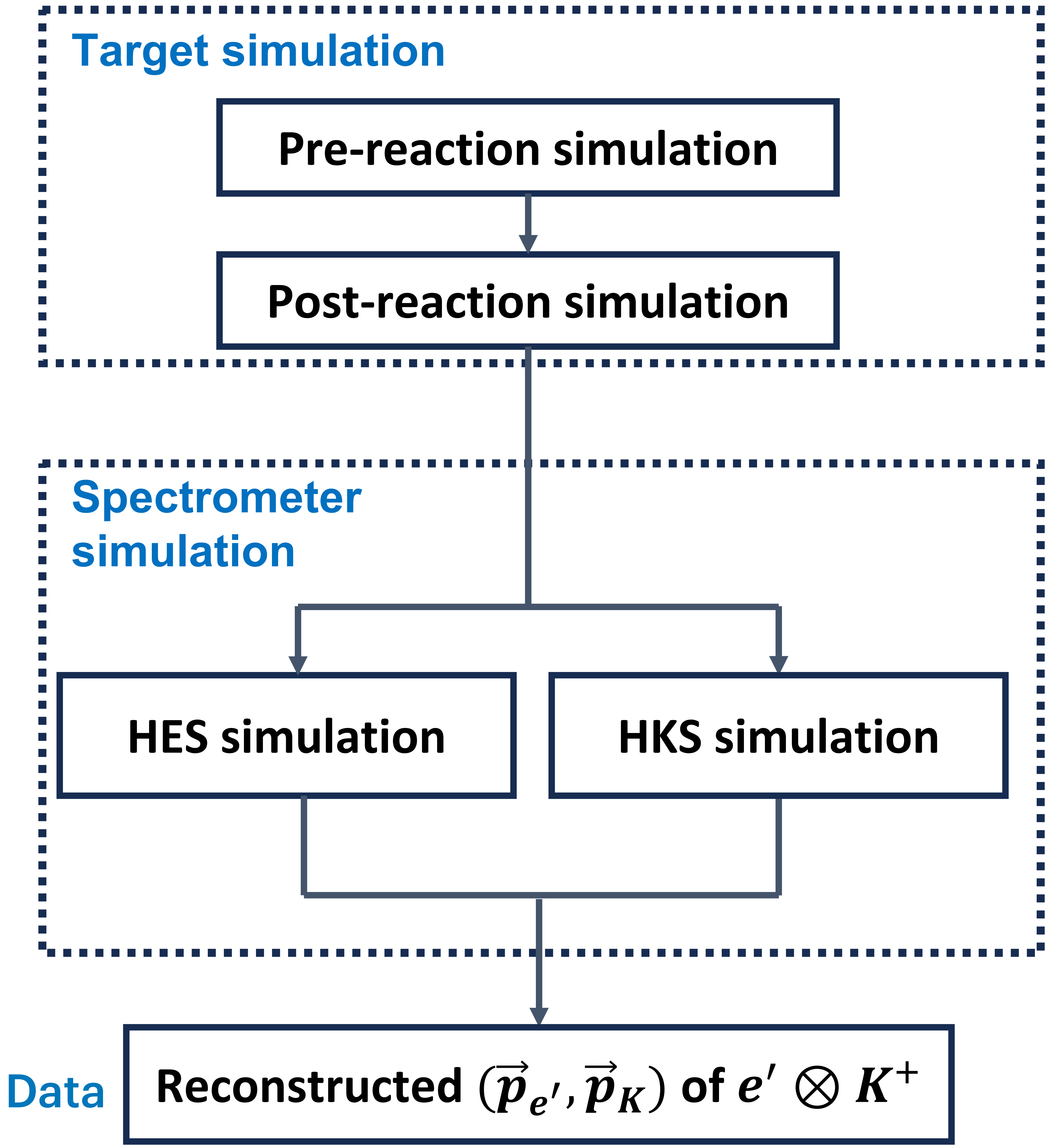


Number of hit of positron



- No hit at downstream
  - 0 events/ 10M events
  - Need to run more events

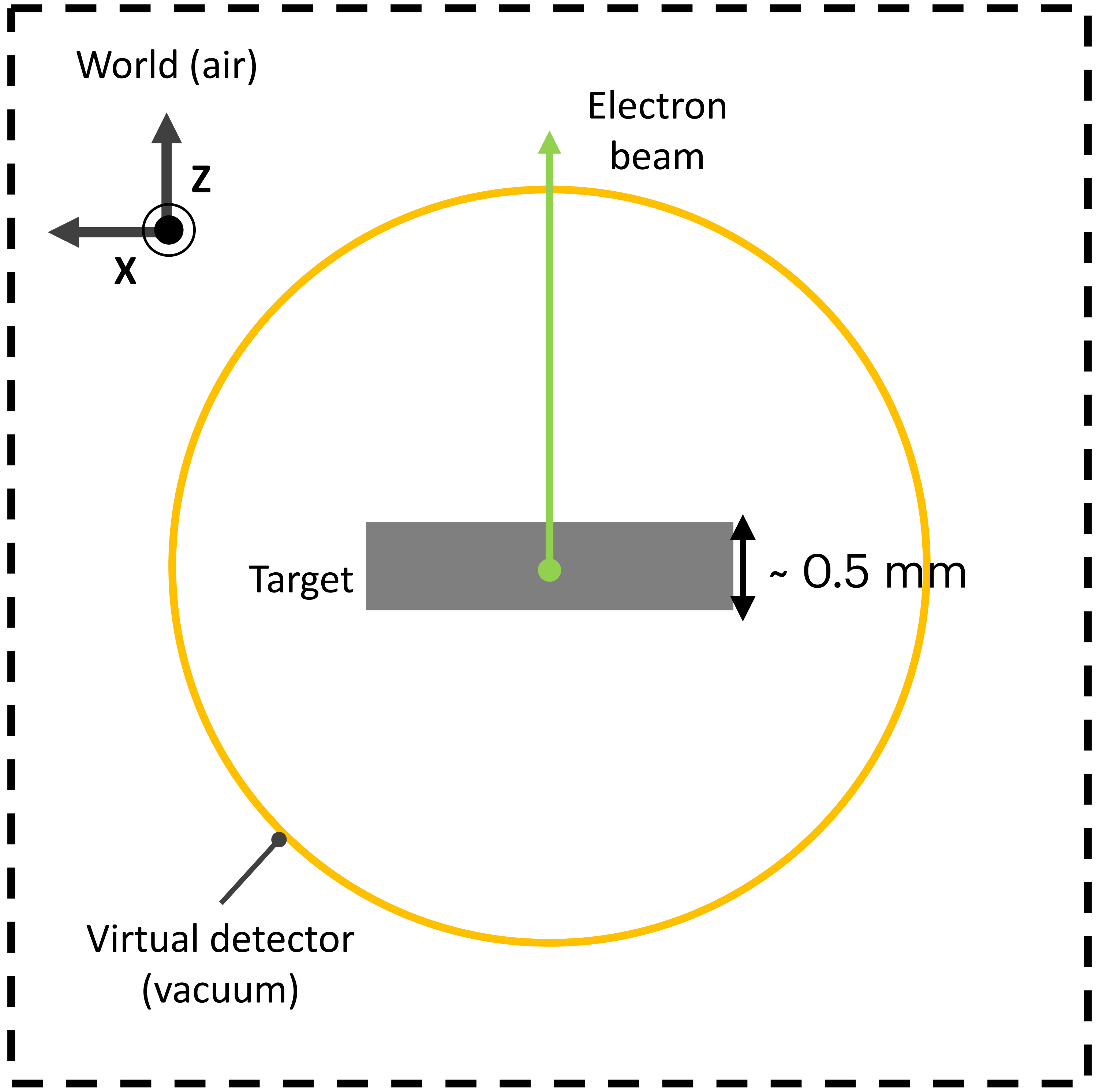
Simulation (detailed)



- The aim of simulation is to reproduce actual experiment and analysis data
- Simulation = Target part + Spectrometer part
- All simulations are made of Geant4 code
- Target simulation (generator)
  - Pre-reaction simulation … Process of e beam
  - Post-reaction simulation … Process of e' & K^+
- Spectrometer simulation (detect + momentum reconstruction)
  - HES simulation … Process of measuring e'
  - HKS simulation … Process of measuring K^+

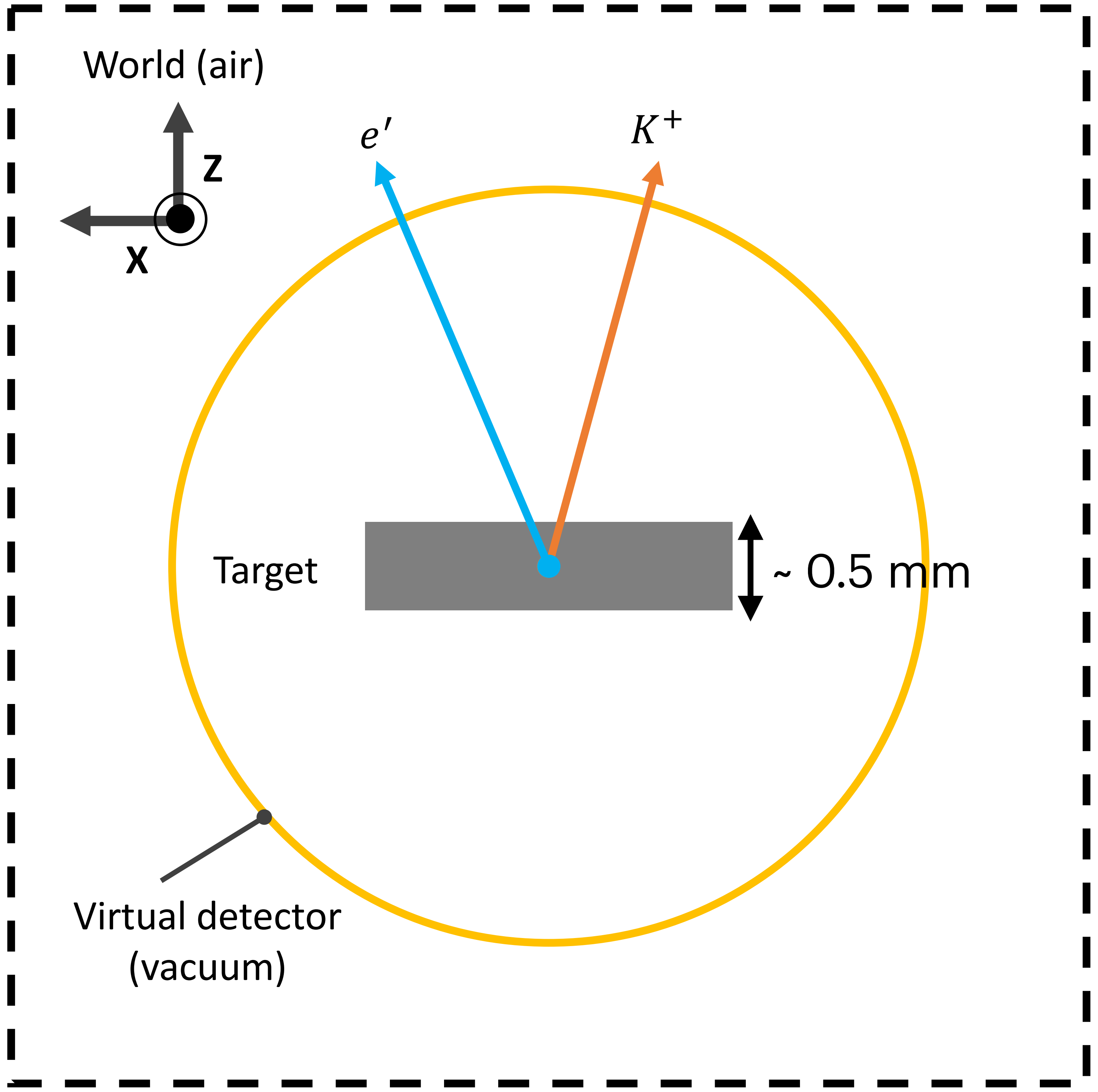
Target simulation

Schematics drawing of pre-reaction



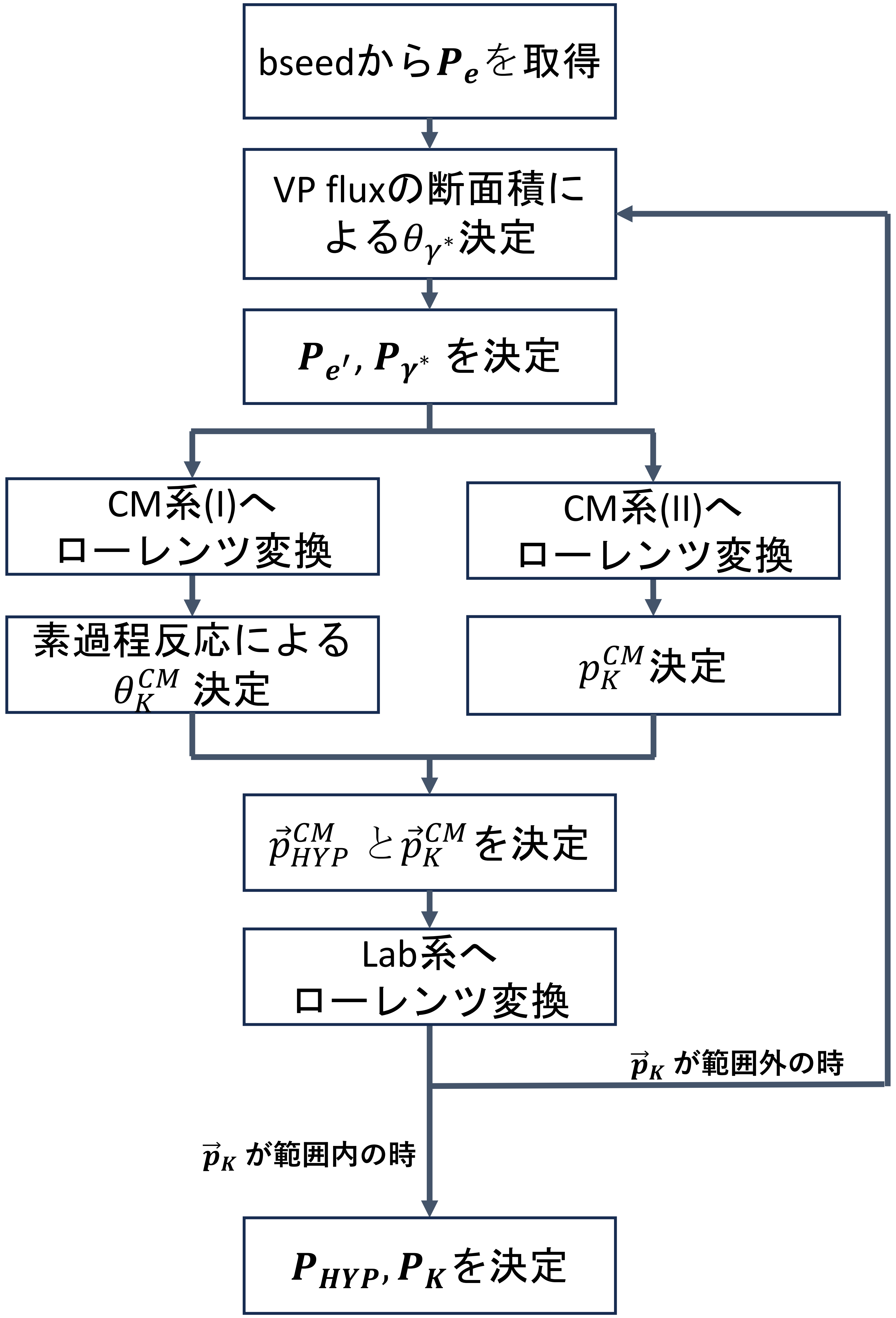
- Implementation
  - Energy loss & Energy straggling of e

Schematics drawing of post-reaction

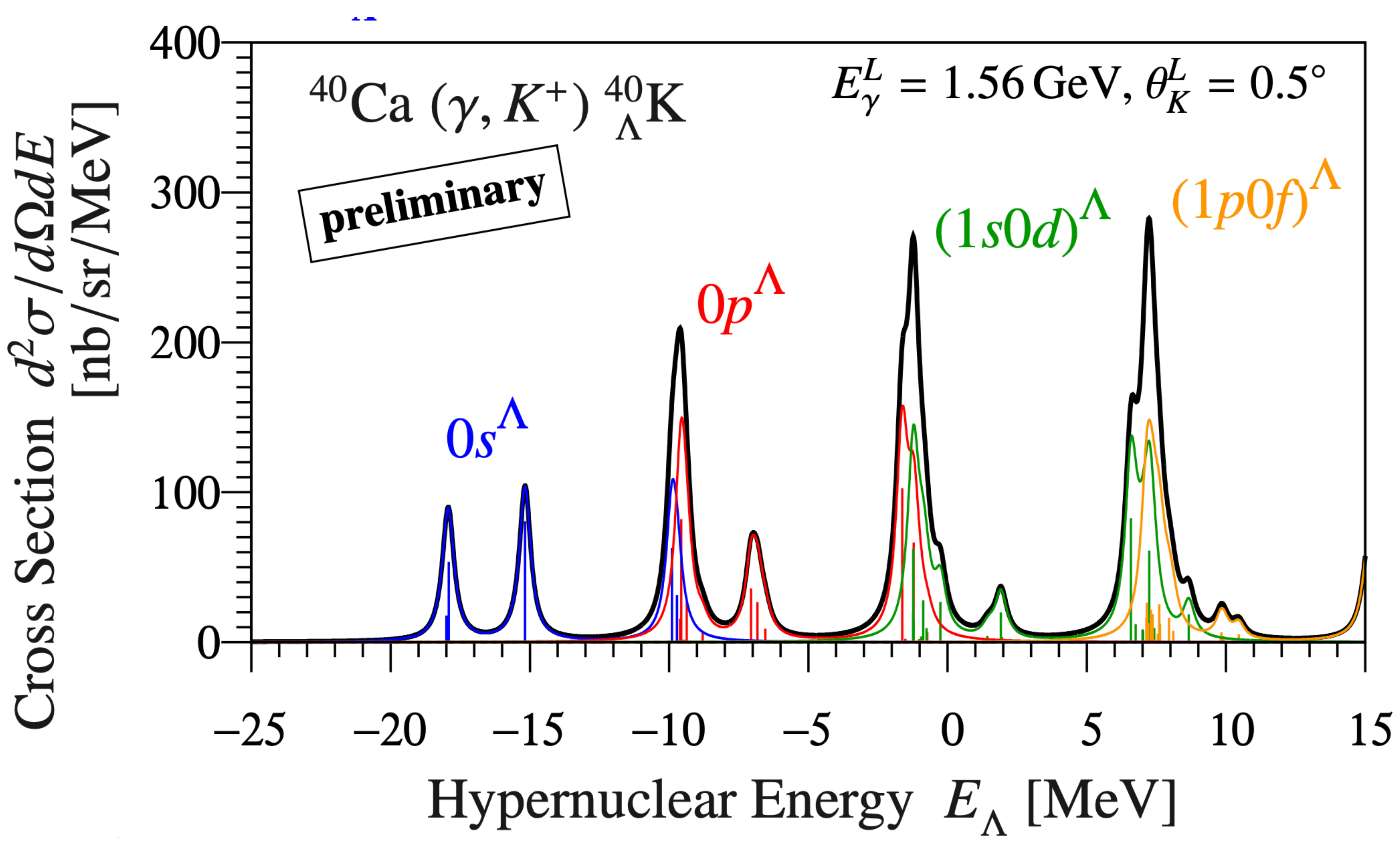


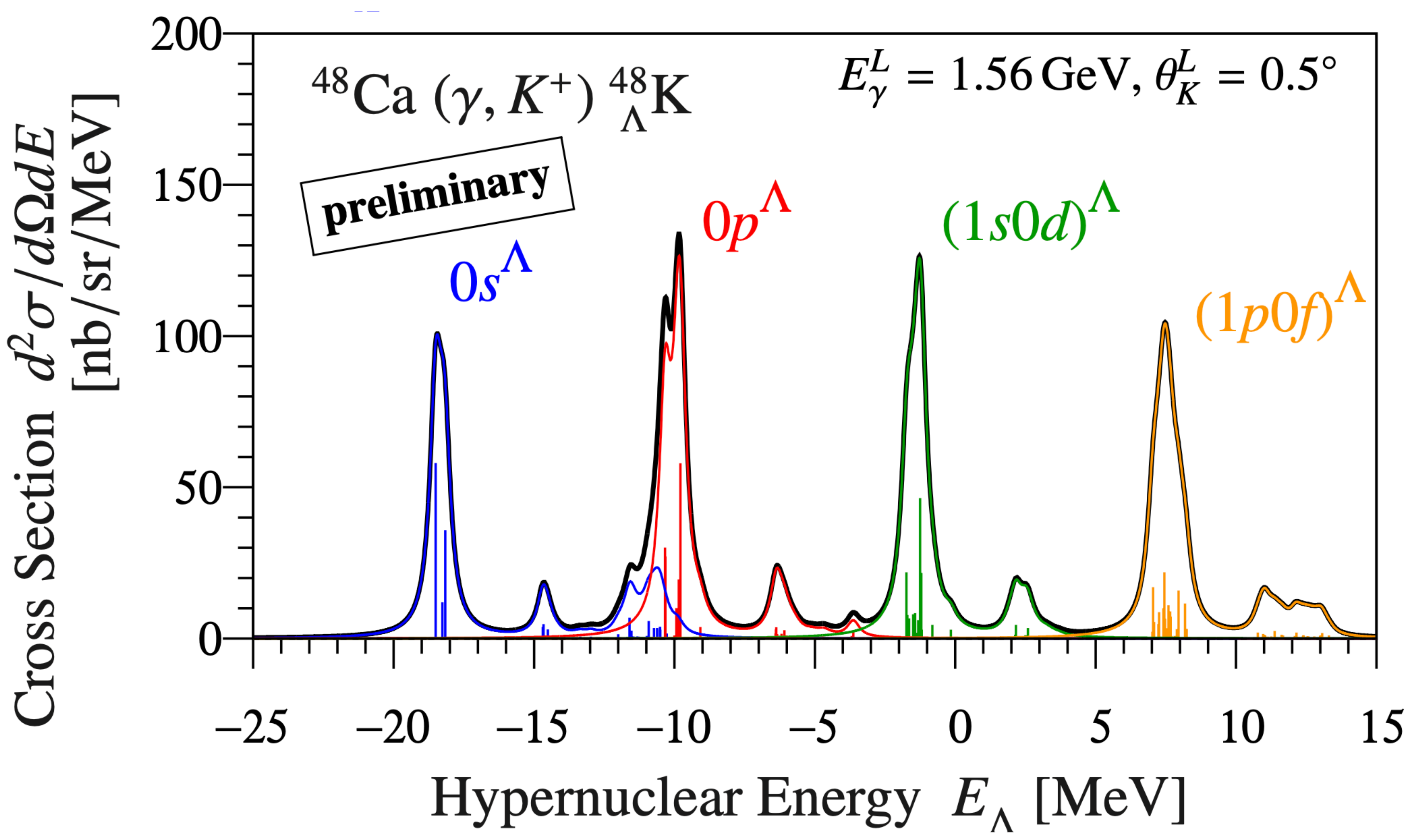
- Implementation
  - Energy loss & Energy straggling of e', K^+
  - Angular dependency of virtual photon flux
  - Angular dependency of (γ^*, K^+) reaction
  - Hypernuclear cross section (Shell model calc.)

Kinematics algorithm of post reaction



Hypernuclear cross section considered





How to estimate in spectrometer simulation

Momentum resolution

$$p_t = a_1 x_{FP} + a_2 y_{FP} + a_3 x'_{FP} + a_4 y'_{FP} + a_5 x_{FP} y_{FP} + \ldots$$
$$= \sum_{a+b+c+d \le m} C(a,b,c,d)(x_{FP})^a (y_{FP})^b (x'_{FP})^c (y'_{FP})^d$$

Determine coefficients $a_i(i = 0 \ldots l)$ by solving coefficient vector from

Number of possible combination of (a, b, c, d)

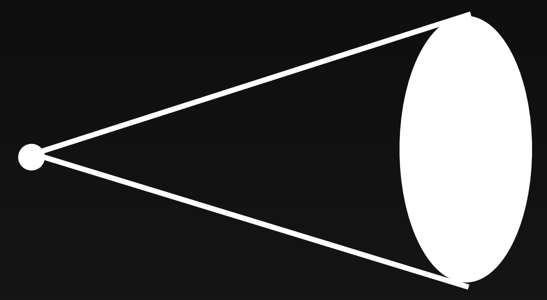
Number of event

$$\begin{pmatrix} p_t^{(1)} \\ p_t^{(2)} \\ \vdots \\ p_t^{(n)} \end{pmatrix} = \begin{pmatrix} x_{FP}^{(1)} & y_{FP}^{(1)} & \ldots & (y_{FP}^{'(1)})^6 \\ x_{FP}^{(2)} & y_{FP}^{(2)} & \ldots & (y_{FP}^{'(2)})^6 \\ \vdots & \vdots & \ddots & \vdots \\ x_{FP}^{(n)} & y_{FP}^{(n)} & \ldots & (y_{FP}^{'(n)})^6 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{pmatrix}$$

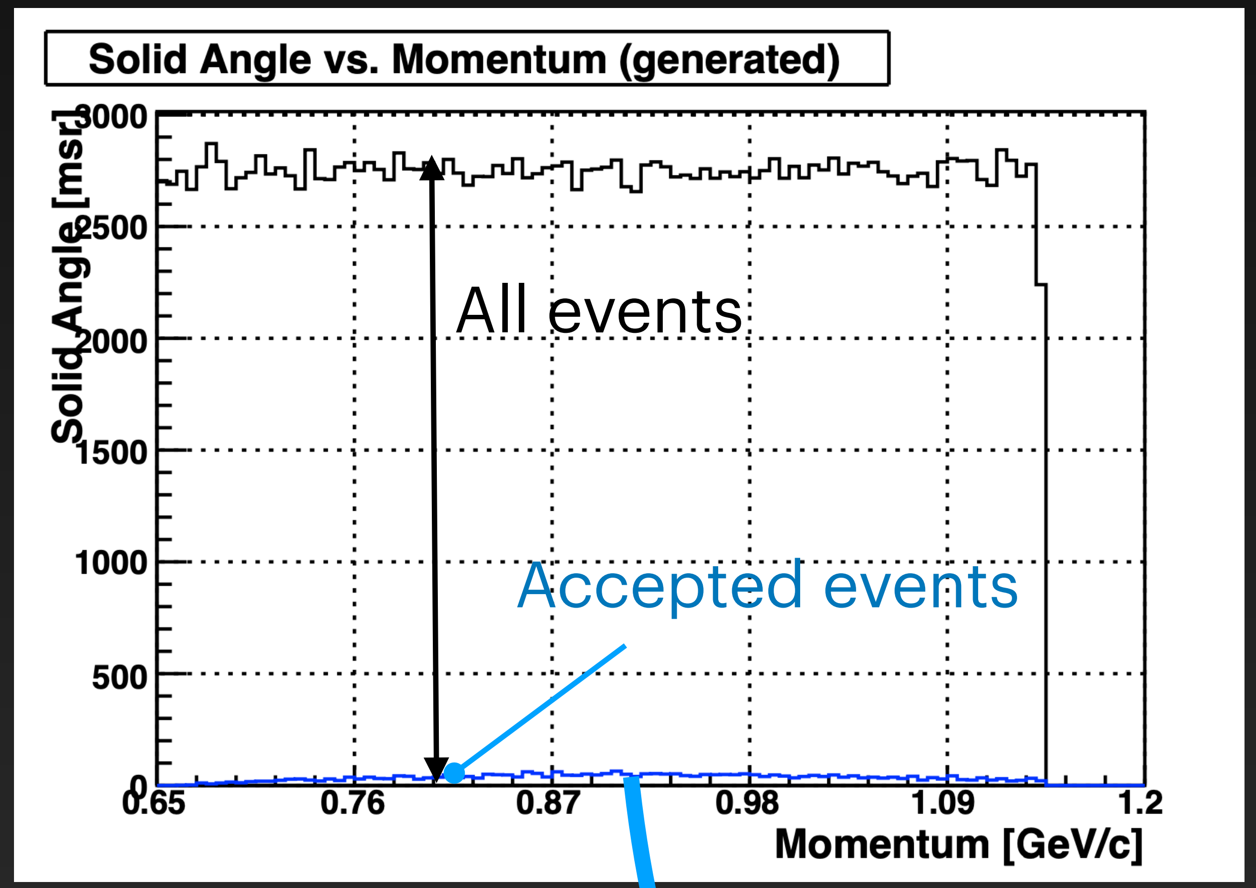
Actual value — Value calculated above

$$\frac{p_t^{true} - p_t^{calc}}{p_t^{true}} = \Delta p / p$$

Solid angle

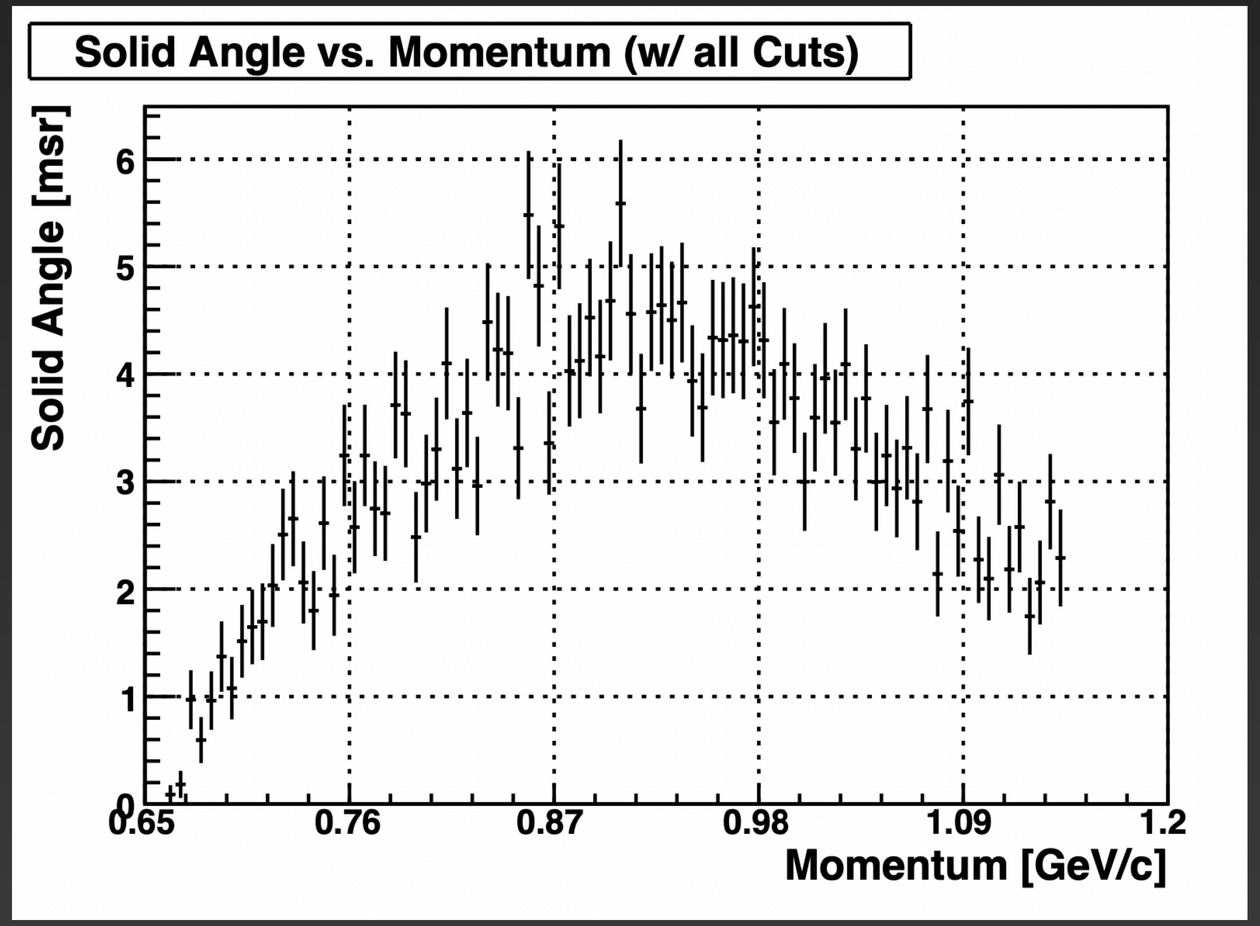


Cone range of emitted particles distributed uniformly in angle range $\Delta\theta$, $\Delta\phi$



In every momentum bin,

$$\sin\theta\ \Delta\theta\ \Delta\phi \times \frac{\text{accepted events}}{\text{all events}}$$



(II) Calculation of event rate- R_{BG}

Background(BG) rate: $$R_{BG} = R_{HES} \times R_{HKS} \times t_{\mathrm{window}} \quad (t_{\mathrm{window}} = 2\ [\mathrm{ns}])$$

HES rate **HKS rate** **Time window**

$$R_{HES} = R_{beam} \times N_{target} \times \frac{d\sigma_{brems}}{d\Omega} \times \Delta\Omega_{e'} \times \epsilon_{HES,track} \times \epsilon_{HES,trig}$$

R_{beam}: Number of beam electrons per sec

N_{target}: Number of atoms in target

$\frac{d\sigma_{brems}}{d\Omega}$: Cross section of bremsstrahlung

$\Delta\Omega_{e'}$: Solid angle of HES

$\epsilon_{HES,track}$: Tracking efficiency of HES (from past exp.)

$\epsilon_{HES,trig}$: Trigger efficiency of HES (from past exp.)

(II) Calculation of event rate - R_{BG}

Background(BG) rate: $$R_{BG} = R_{HES} \times R_{HKS} \times t_{\text{window}} \quad (t_{\text{window}} = 2\ [\text{ns}])$$

HES rate **HKS rate** Time window

$$R_{HKS} = \sum_{i \in (\pi^+, p, K^+)} R_i \times \epsilon_{HKS,track} \times \epsilon_{HKS,trig}$$

, where R_i is $$R_i = R_{beam} \times N_{target} \times \frac{d\sigma_i}{d\Omega} \times \Delta\Omega_K \times \epsilon_{i,reject} \quad i \in (\pi, p, K^+)$$

$\frac{d\sigma_i}{d\Omega} = \frac{d\sigma_i}{d\Omega}(^{10}\text{B data}) \times \left(\frac{A}{10}\right)^{2/3}$: Cross section of each particles scaled by past experimental data of ^{10}B

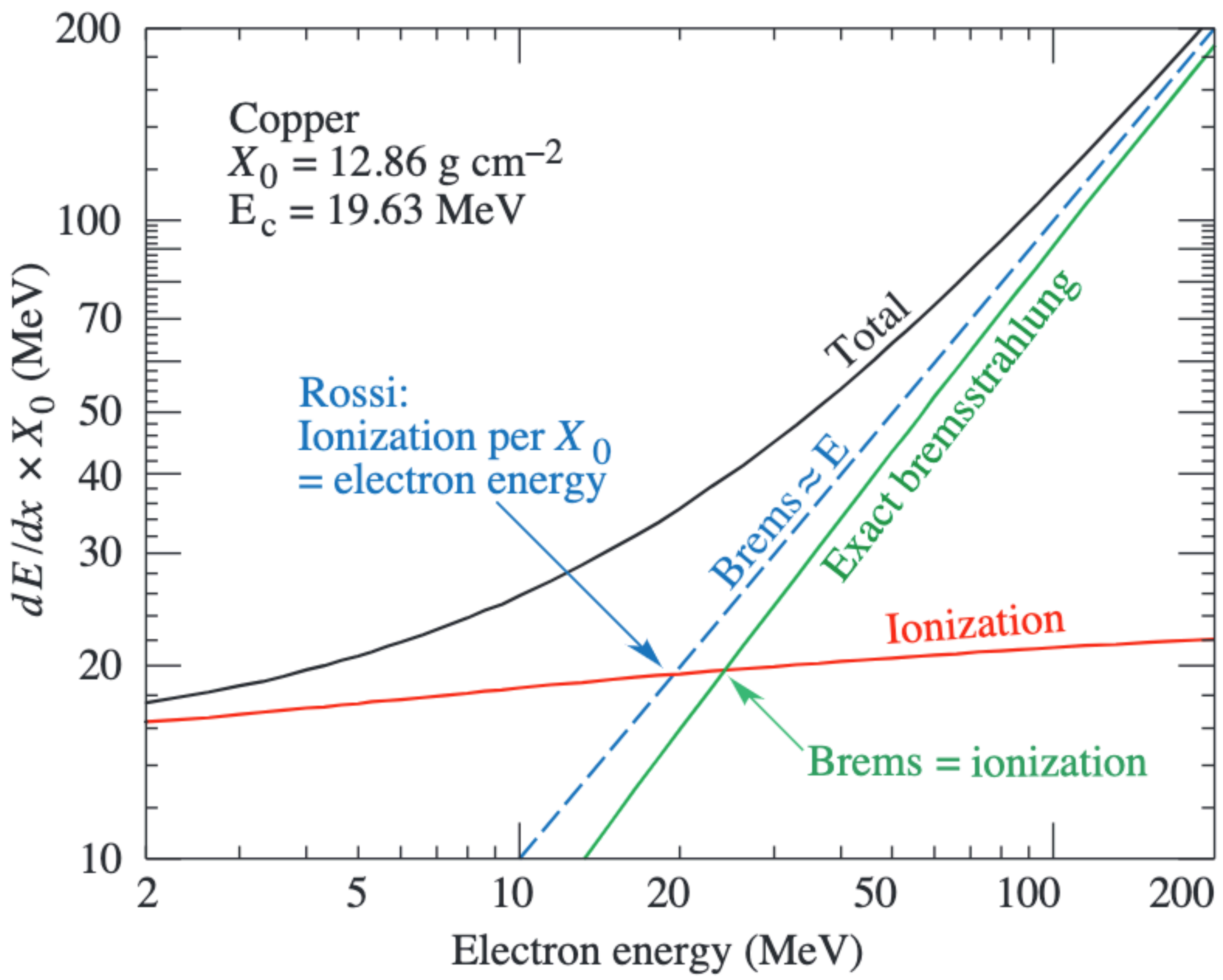
$\Delta\Omega_K$: Solid angle of HKS

$\epsilon_{i,rejcet}$: rejection efficiency for π^+, p and survival ratio for K^+

$\epsilon_{HKS,track}$: Tracking efficiency of HKS (from past exp.)

$\epsilon_{HKS,trig}$: Trigger efficiency of HKS (from past exp.)

Background at HES side



- Electron as background
  - Ionization of beam electron
  - Bremsstrahlung of beam electron

- The order of critical energy is 10 MeV
- →Since Ee=2.240 GeV, brems. electrons are dominant background

(2) Calculation of event rate - N_{HYP}

Hyprenuclear yield rate:

$$R_{HYP} = R_{\gamma*} \times N_{target} \times \frac{d\sigma_{(\gamma*,K^+)}}{d\Omega} \times \Delta\Omega_K \times \epsilon_{eff}$$

,where $R_{\gamma*} = R_{beam} \times \Gamma \times \Delta E_{e'} \times \Delta\Omega_{e'}$

Γ: Virtual photon flux $[1/(\mathrm{GeV} \cdot \mathrm{sr} \cdot \mathrm{electron})]$

$\Delta E_{e'}$: energy range of HES

$\Delta\Omega_{e'}$: Solid angle of HES

$\frac{d\sigma_{(\gamma*,K^+)}}{d\Omega}$: hypernuclear cross section by shell model calc.

$\Delta\Omega_K$: Solid angle of HKS

ϵ_{eff}: $\epsilon_{HES,track} \times \epsilon_{HES,trig} \times \epsilon_{HKS,track} \times \epsilon_{HKS,trig} \times \epsilon_{K,reject}$

Setup condition (now)

Beam	Energy Ee [GeV]	2.240
	Resolution ΔEe/Ee [GeV]	3×10^{-5}
PCS+HES	Cent. Moment pe [GeV/c]	0.744
	Cent. Angle θee′ [deg]	8
	Solid angle ΔΩe′ [msr]	3.4
	Momentum resolution Δpe′/pe′	4.4×10^{-4}
PSC+HKS	Cent. momentum pK [GeV/c]	1.2
	Cent. angle θeK [deg]	15
	Solid angle ΔΩK [msr]	8.3
	Momentum resolution ΔpK/pK	2.9×10^{-4}

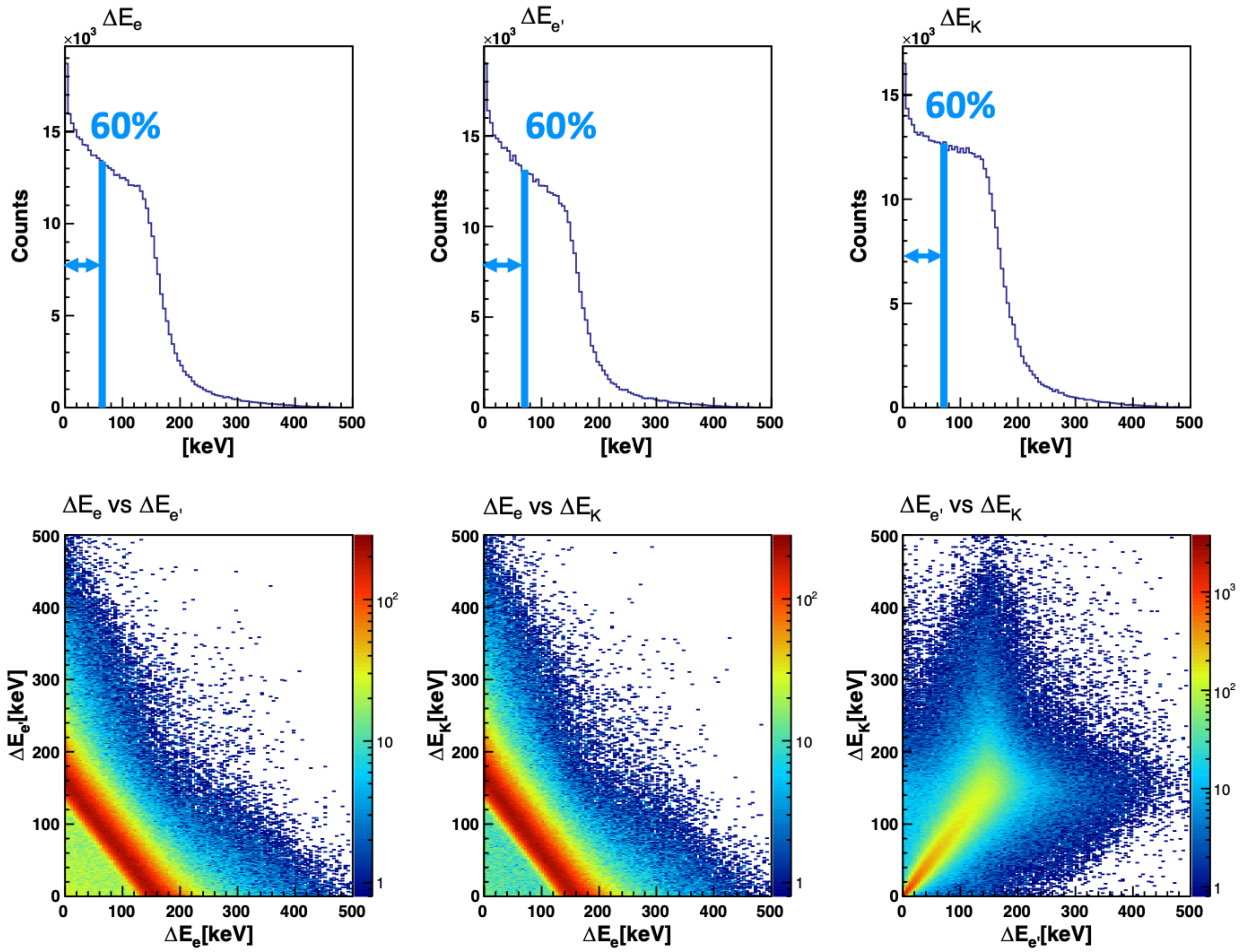
Event rate (2023May)

Table 6: Updated request of beamtime.

Target (Hyper Nucleus)	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected yield (/h)	Num. of events	Req. beamtime (hours)	B.G. rate (/MeV/h)	S/N	Comments
CH_2 (Λ, Σ^0)	2	500	1000	8.62	1000	120	0.03	290	Calibration
^{6}Li ($^6_\Lambda$He)	50	100	10	—	—	—	—	—	Separate LoI
^{9}Be ($^9_\Lambda$Li)	50	100	10	—	—	—	—	—	Separate LoI
^{11}B ($^{11}_\Lambda$Be)	50	100	30	—	—	—	—	—	Separate LoI
^{12}C ($^{12}_\Lambda$B)	50	150	90	6.79	1100	168	1.20	5.67	Calibration
^{27}Al ($^{27}_\Lambda$Mg)	50	150	60 *	1.98	330	168	1.77	1.87	Calibration
Subtotal						456			Calibration
^{40}Ca ($^{40}_\Lambda$K)	50	150	50	1.13	520	456	2.41	0.47	Physics
^{48}Ca ($^{48}_\Lambda$K)	50	150	50	0.94	520	552	1.89	0.50	Physics
Subtotal						1008			Physics
Total						1464			

* for $0s^\Lambda$ $9/2^+, 7/2^+$ doublet.

Energy loss correction (detailed)



標的	dE 分布の全体カウント数に対する割合	標的厚 [mg/cm^2]	δE_e [keV]	$\delta E_{e'}$ [keV]	δE_K [keV]	$\Delta E_{\mathrm{g.s.}}$ [keV]
^{40}Ca	60%	100	82	82	87	20
		150	123	122	131	-30
		200	162	161	177	6
^{48}Ca	62%	50	34	34	36	-9
		100	70	70	74	32
		150	107	106	113	-17
		200	141	140	153	3

Fit loop analysis