次世代$\mu^+ \to e^+\gamma$崩壊探索実験のための光子ペアスペクトロメーターの開発 ーシミュレーションによる性能評価ー

Development of Photon Pair Spectrometer for Next Generation $\mu^+ \to e^+\gamma$ Experiment - Performance evaluation by Simulation -

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Series talk

Detector R&D (Previous talk)

Simulation study (this talk)

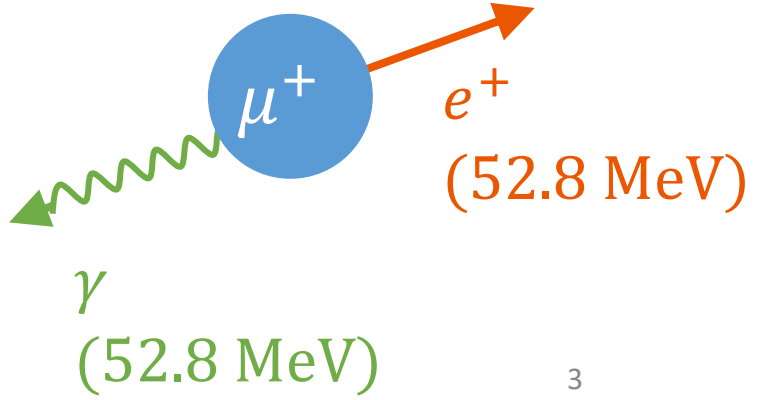
$\mu^+ \to e^+\gamma$ search

- Charged Lepton flavour violation decay
  - $\mathrm{Br}(\mu^+ \to e^+\gamma) \sim O(10^{-53})$ in SM + ν oscillation
  - $\mathrm{Br}(\mu^+ \to e^+\gamma) \sim O(10^{-11} \sim 10^{-15})$ predicted in BSM (e.g. SUSY)

Experiments

- MEG (2008 - 2013) & MEG II experiment (2021 – 2026 (planned)) @ PSI
  - Current UL : $\mathrm{Br}(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13}$ (90 % C. L.)
  - Target sensitivity : 6×10^{-14}

- Future $\mu^+ \to e^+\gamma$ experiment
  - Planning with the target sensitivity of $O(10^{-15})$



Future experiment for $\mu^+ \to e^+\gamma$ search

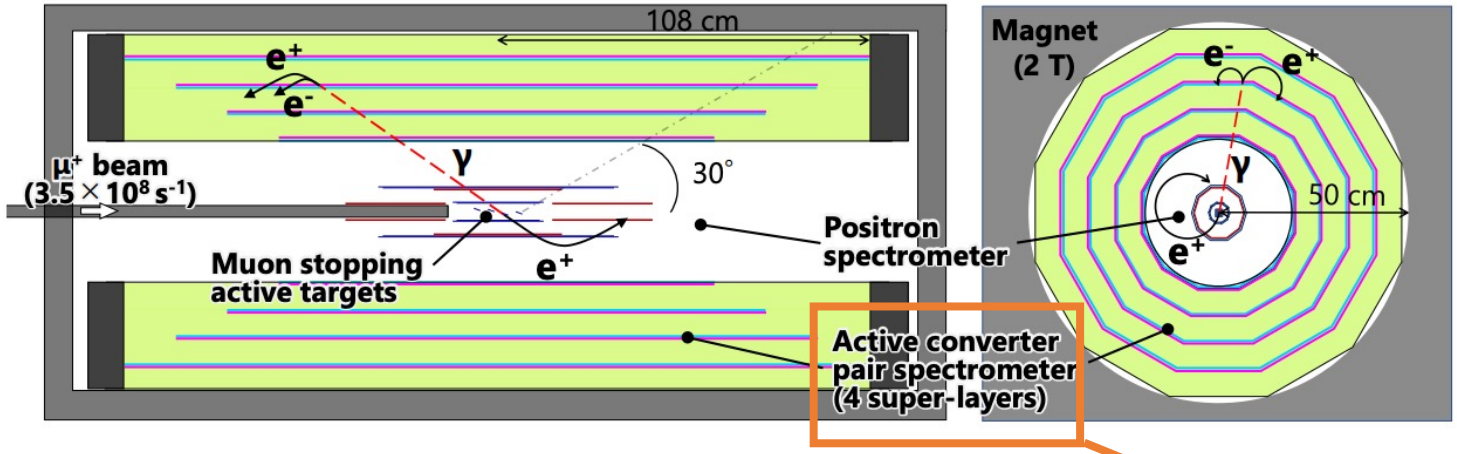
- Motivation
  - Further search for $\mu^+ \to e^+\gamma$ (if not found in MEG II)
  - Precise measurement of $\mu^+ \to e^+\gamma$ after discovery for BSM model selectio
- Muon beam increase at PSI (HIMB project)
  - $\times 100$ muon beam rate ($R_\mu \sim O(10^{10})$) available from 2027—2028
- Main background of $\mu^+ \to e^+\gamma$: accidental background

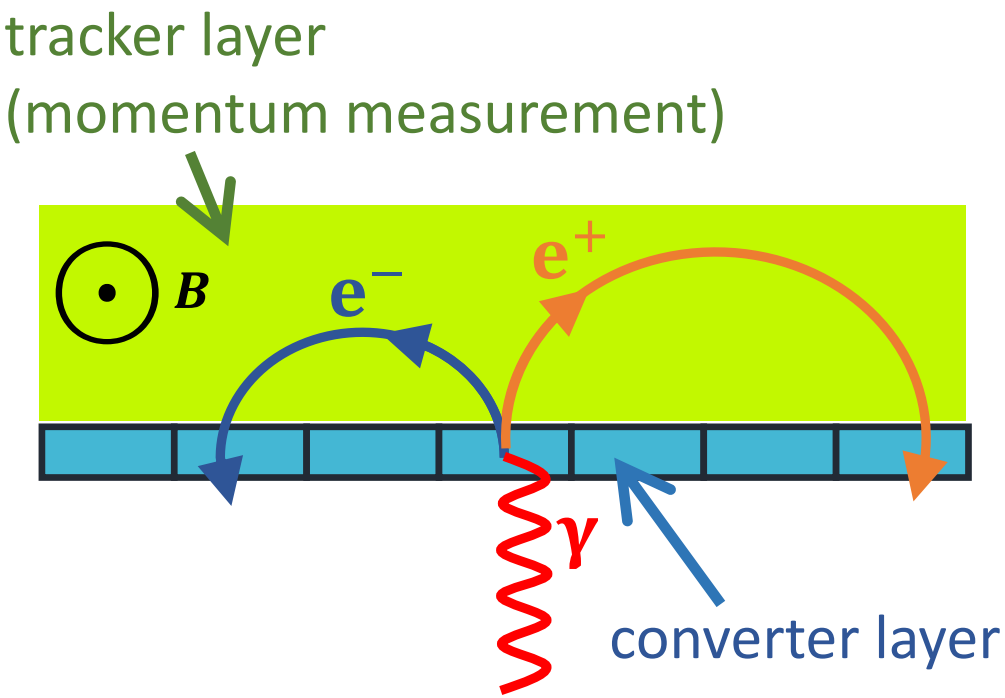
$$N_{\mathrm{acc}} \propto R_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta p_e \cdot \Delta \theta_{e\gamma}^2 \cdot \Delta t_{e\gamma} \cdot T$$

Detector resolution (especially γ) is important

to benefit from increased μ beam

Detector concept





- μ^+ stopping target … Active & split
- e^+ measurement … Silicon sensor (HV-MAPS)
- γ measurement … Pair-spectrometer

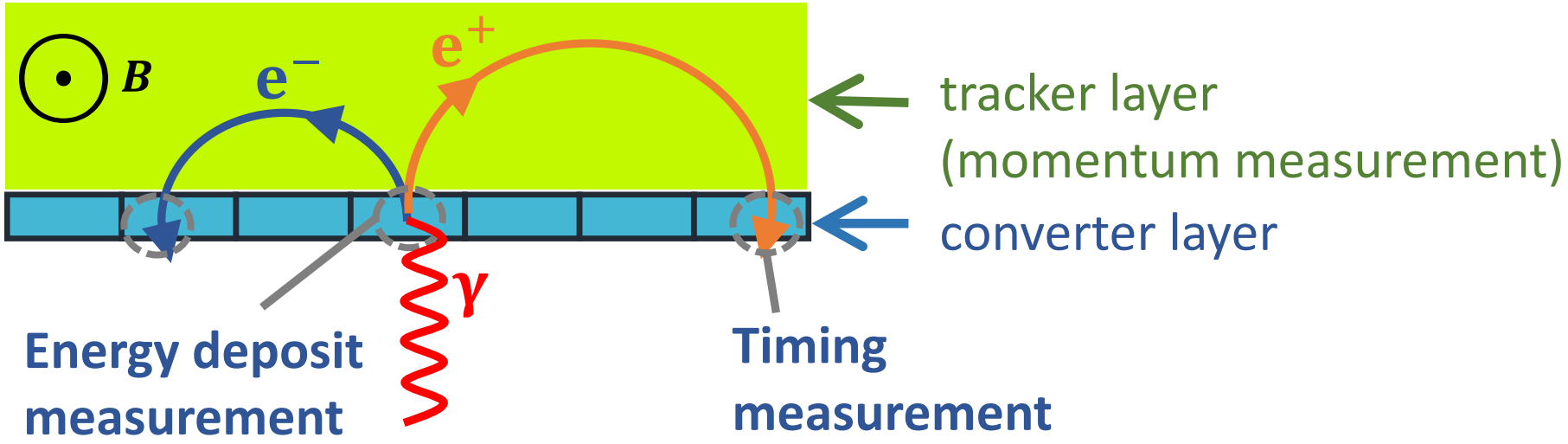
This talk!

Pair spectrometer with active converter

Problem with conventional pair spectrometer

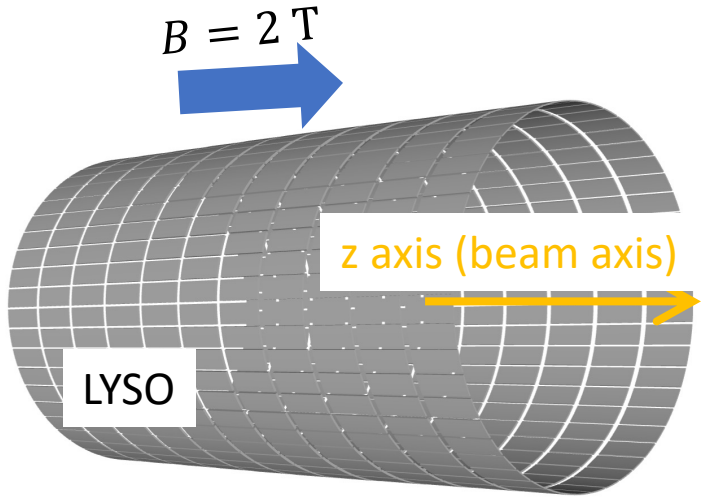
- Non-negligible energy loss inside the converter layer
- Too thin converter is not unacceptable… degradation of conversion efficiency

➡ Solution: energy measurement by converter itself (active converter)

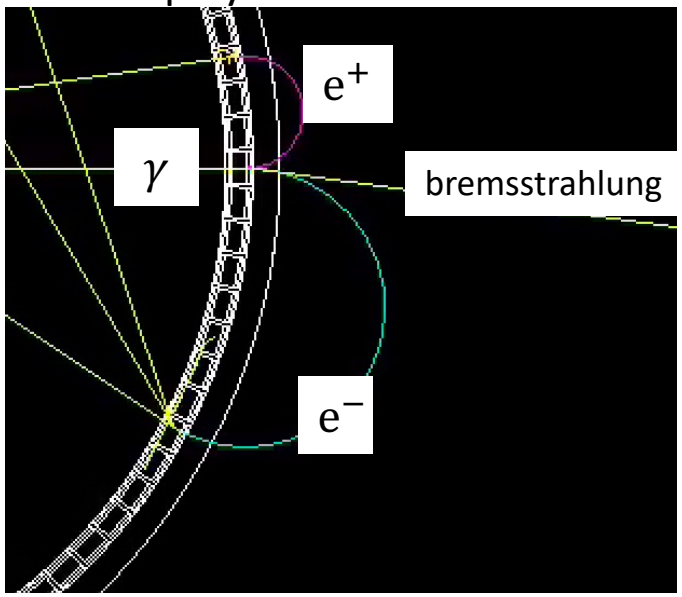


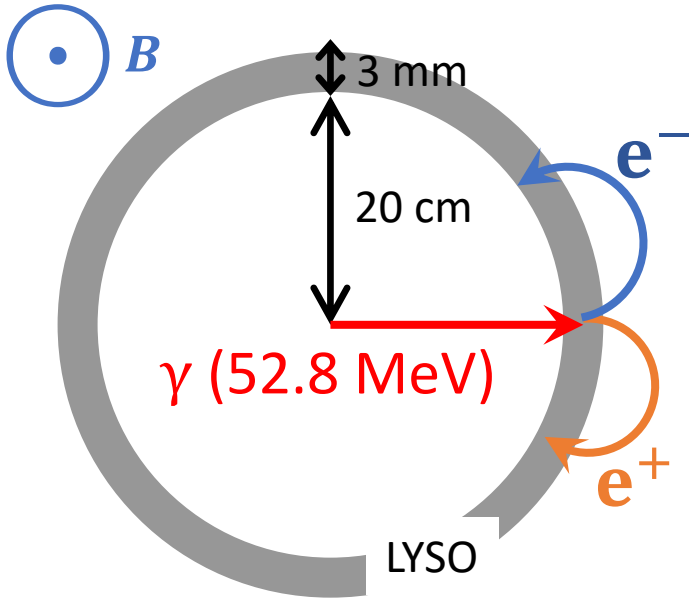
Simulation setup

- Only converter layer
  - No assumption for the conversion pair tracker (vacuum)
- Standard geometry:
  - Cell Size
    - width (ϕ direction) = 5 mm,
    - length (z direction) = 50 mm,
    - thickness(ρ direction) = 3 mm
- Uniform magnetic field (2T)
- 52.8 MeV gamma ray injection
  - Perpendicularly to LYSO (unless mentioned)



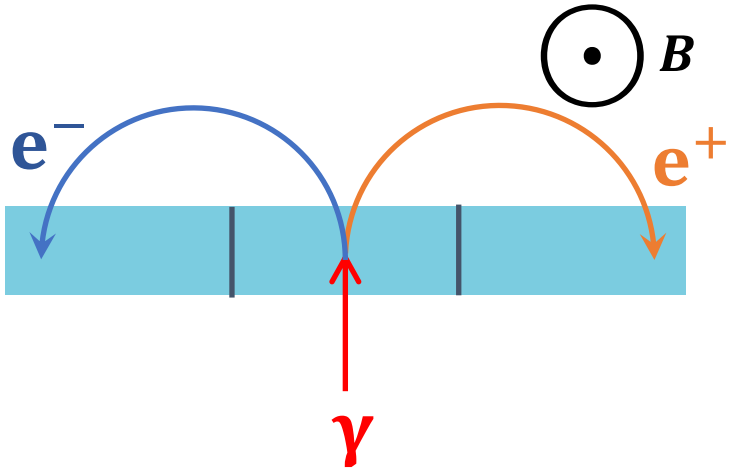
Event display of a conversion event





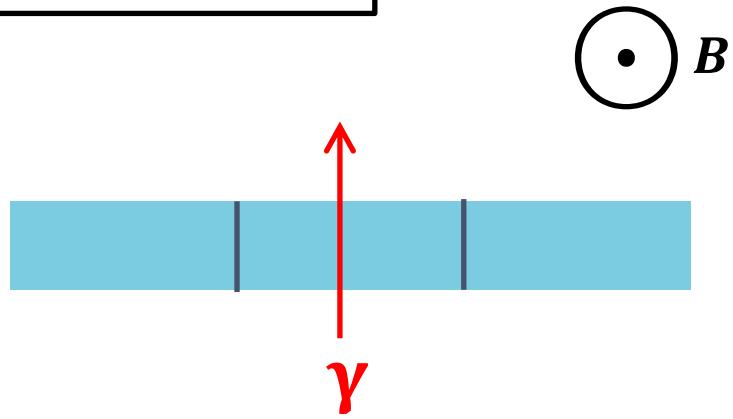
Event topology

Expected



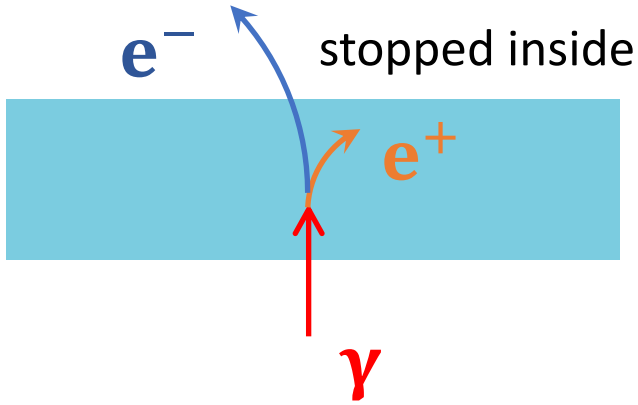
- Pair creation
- Large-enough momentum to track
- Return to different converter cell

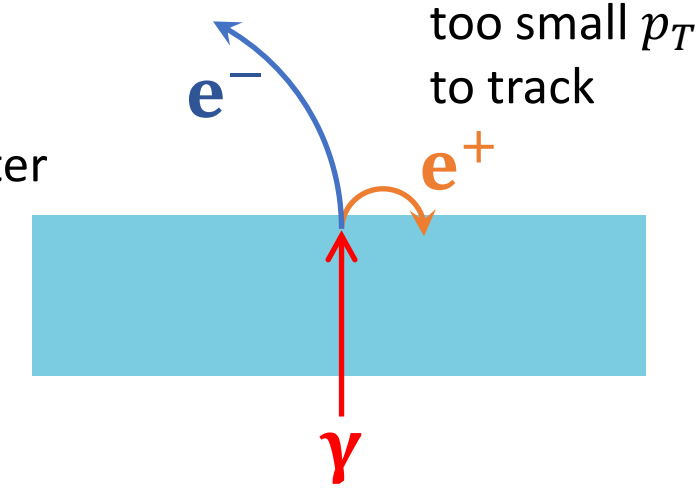
Not converted



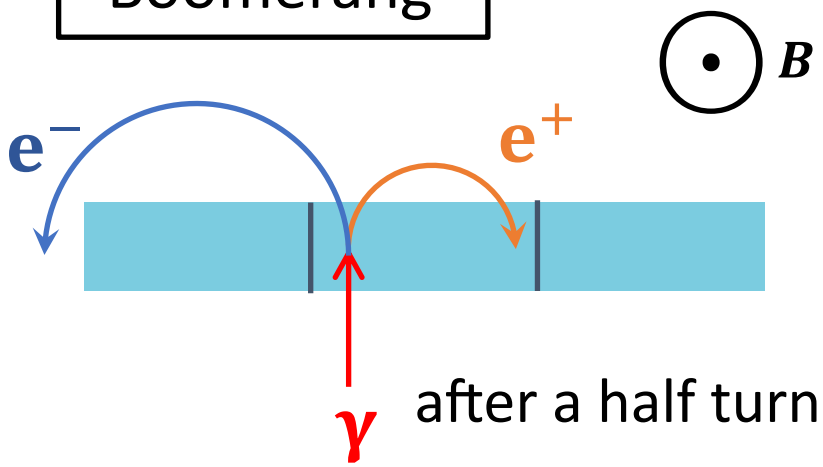
90 ~ 95 % of total events

Too small momentum

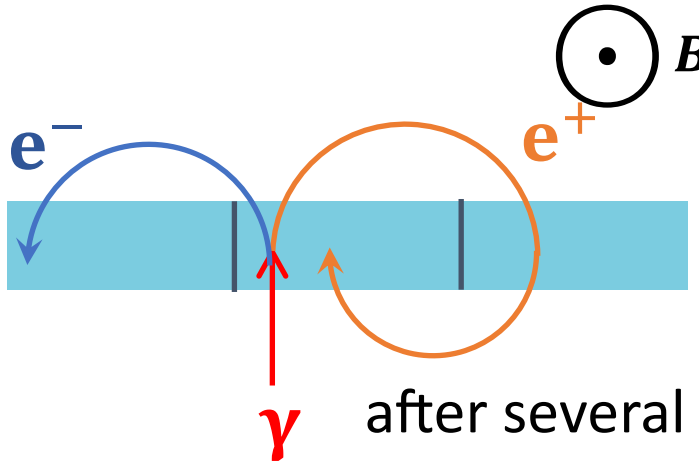




“Boomerang”



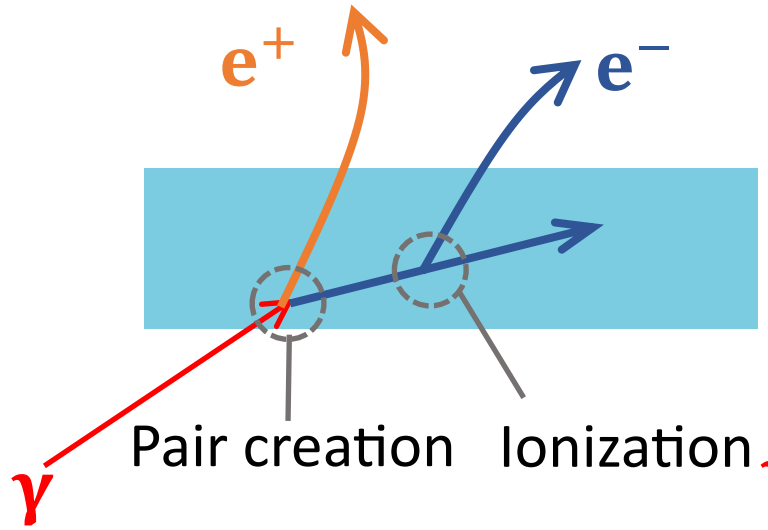
after a half turn



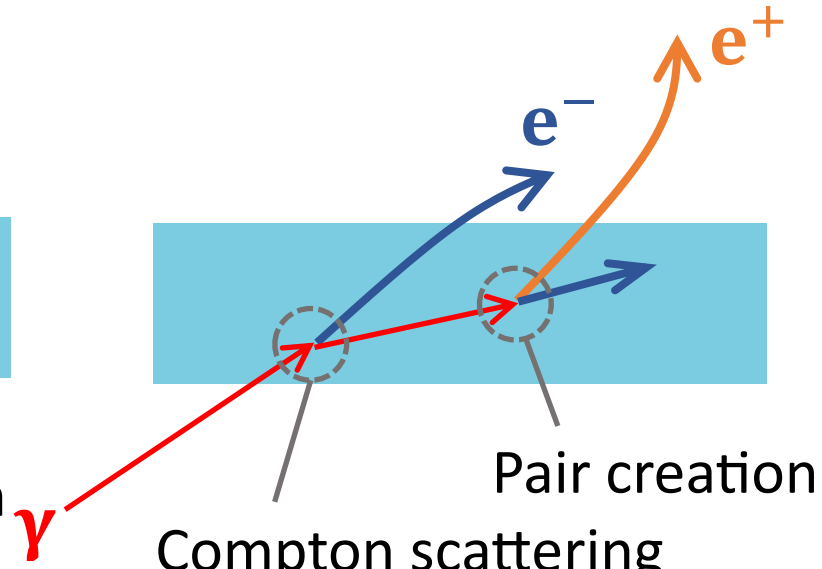
after several turns

Double-counting of energy deposit
→becomes inefficient by
wrong γ energy reconstruction

Fake conversion pair



Pair creation Ionization



Pair creation

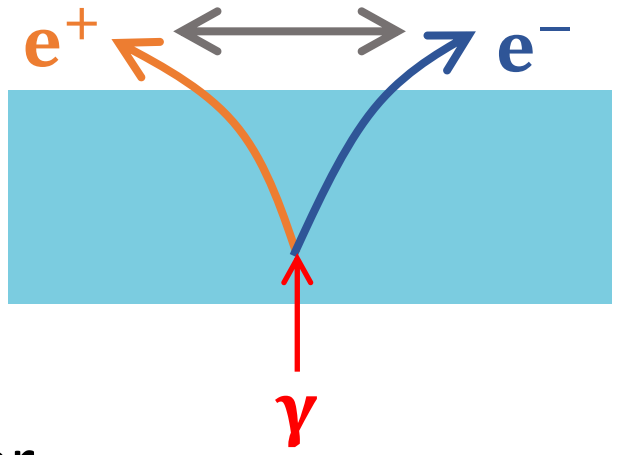
Compton scattering

- e^+&e^- from close point,
  not originating from
  one pair-creation
- With pile-up, also possible to have
  - one e^+ from signal γ
  - one e^- from pile-up γ

Pair selection

- Multiple electron & positron tracks are found
  → Selection of converted pair is not obvious

$\Delta t < t_{cut} = 150$ ps
$|\overrightarrow{\Delta r}| < r_{cut} = 2$ mm



- In this study, pair selection in the following steps:
  1. Selection of tracks
     - e.g. large enough p_T $(> 5\mathrm{MeV})$ to track with tracker
  2. Selection of $e^{\pm}$ pair from selected tracks
     - Condition: relative converter-leaving point distance smaller than cut value
     - Probability of selecting fake pair ~ 1 %

Energy reconstruction

Gamma energy reconstruction :

$$E_{\gamma,\mathrm{rec}} = \underbrace{p_{e^+} + p_{e^-}} + \underbrace{E_{\mathrm{dep}}}$$

Momenta measured by the tracker layer

- Against the selected $e^{\pm}$ pair
- For now, use the MC truth

Energy deposit measured by the converter layer

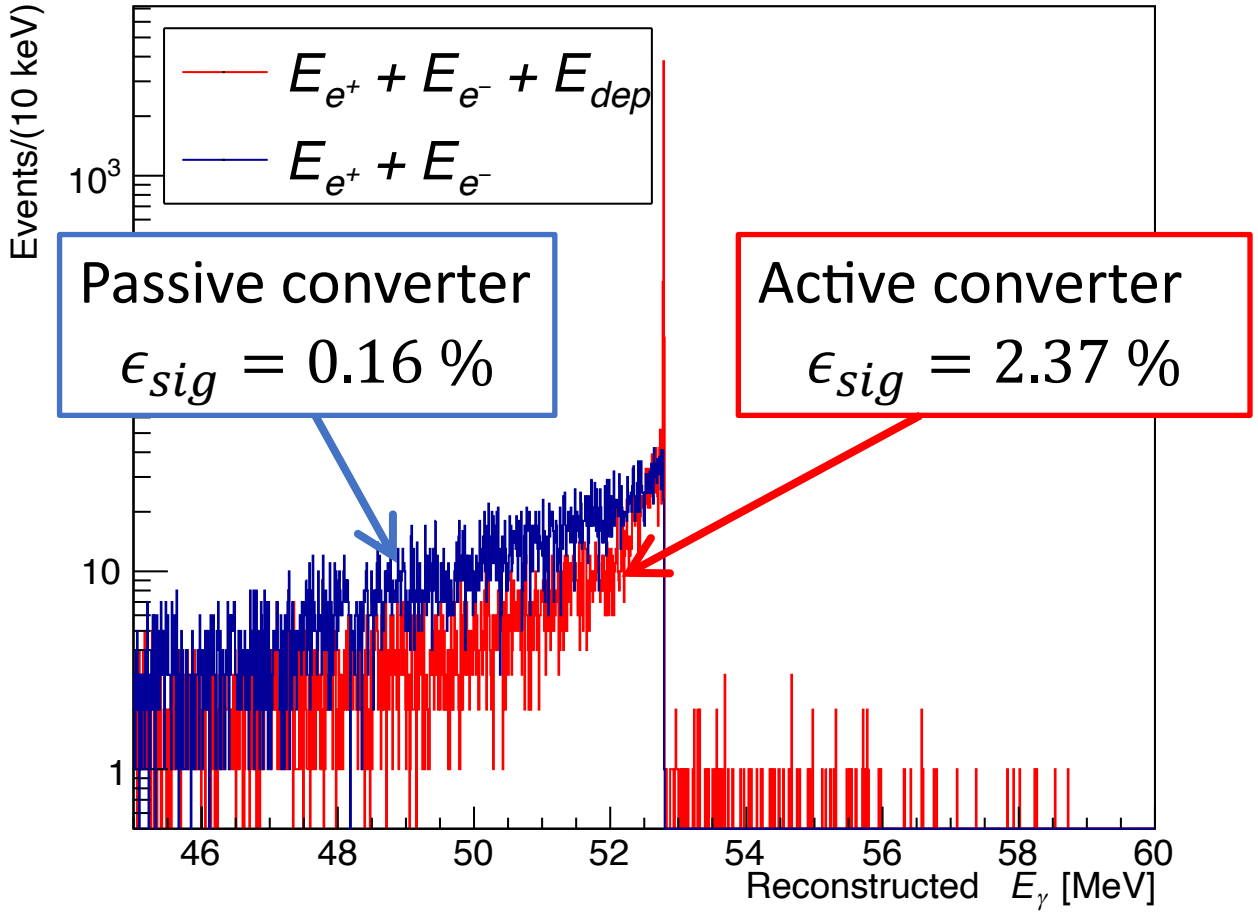
- Summed up within the same converter cell

target energy resolution for γ : 200 keV

Efficiency definition (in this study)

$$\text{signal efficiency} \equiv \frac{\#\text{ of events with } |E_{\gamma,\mathrm{rec}} - 52.8| < 100\ \text{keV}}{\#\text{ of signal events}}$$

Reconstructed signal energy spectrum

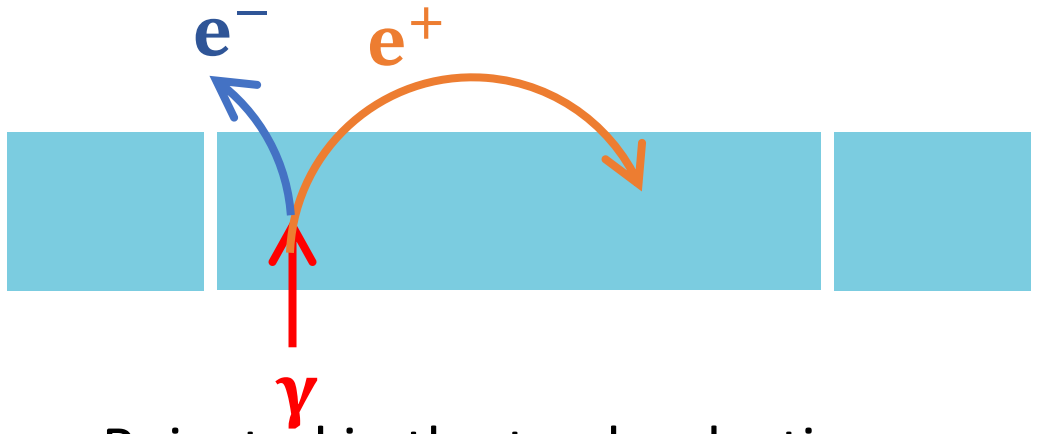


- Signal efficiency is improved by $\times 15$ by active converter
- High energy tail
  … Boomerang events
- Low energy tail
  … Energy escape by bremsstrahlung, ionization

"*Boomerang*" events

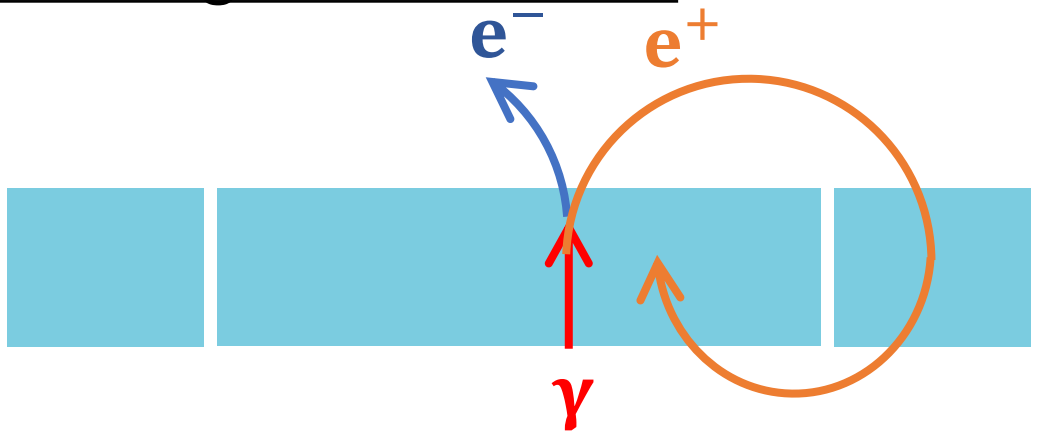
- E_{dep} … Energy deposit by conversion pair **until leaving the converter**
- Summing up energy deposit in the same converter cell
  → Returning to the same cell after several turns results in inefficiency
- Finer segmentation is effective to reduce them

Returning after half-turn



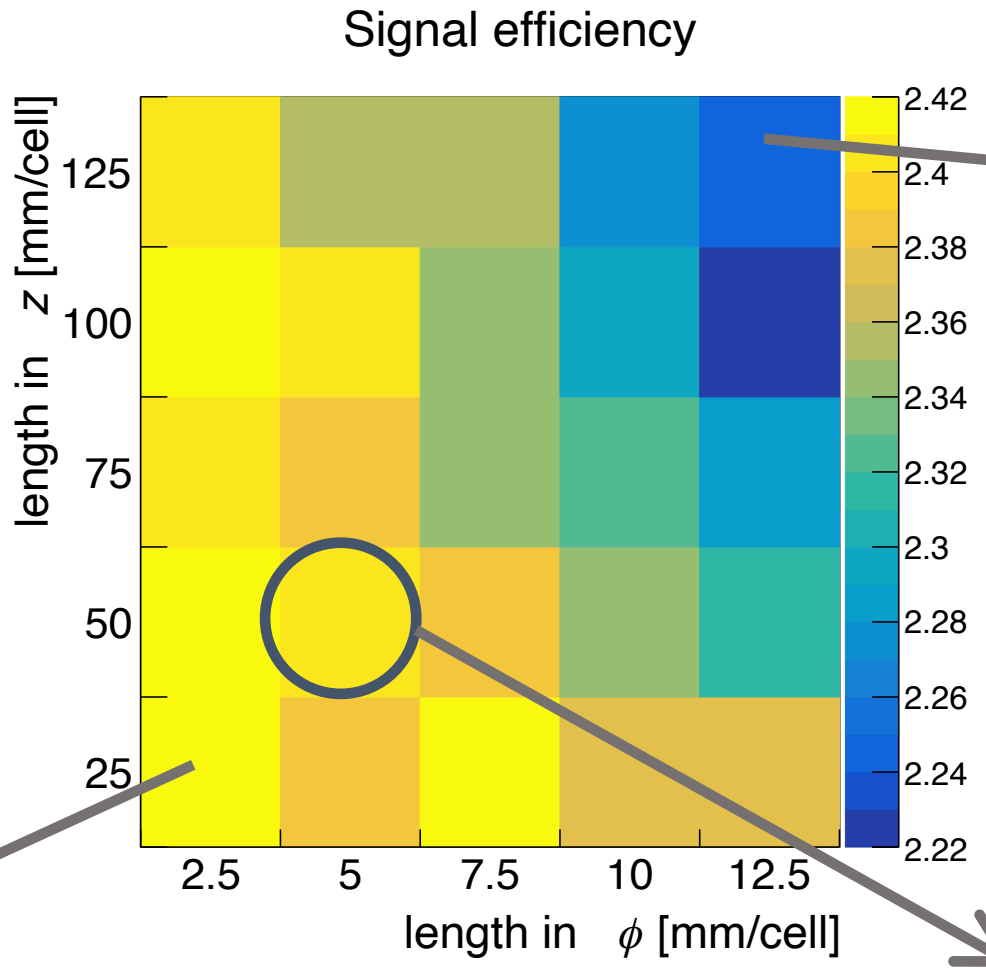
→ Rejected in the track selection

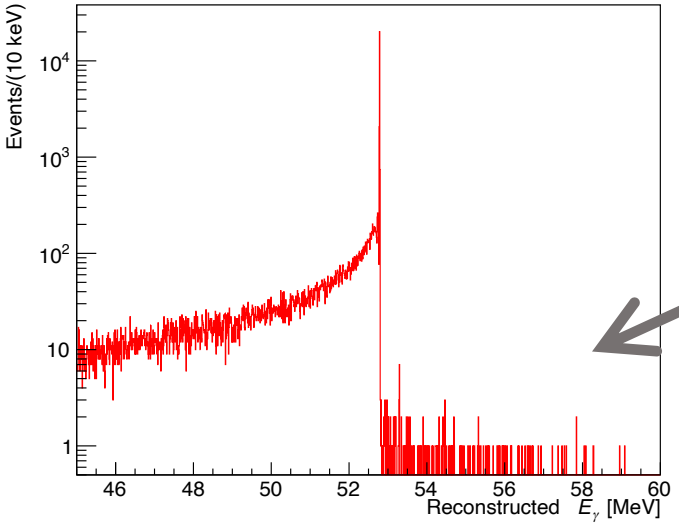
Returning after one turn

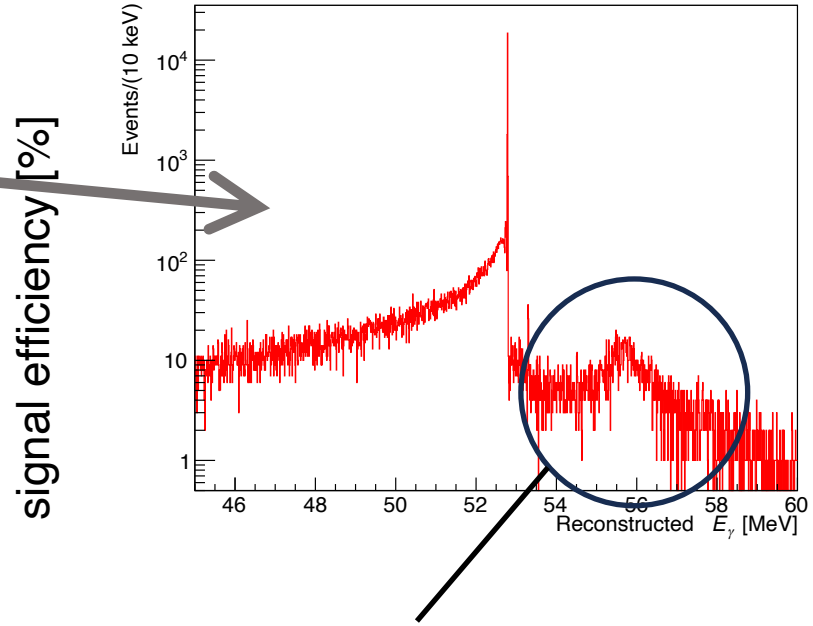


→ Energy overestimation

Geometry optimization: segmentation



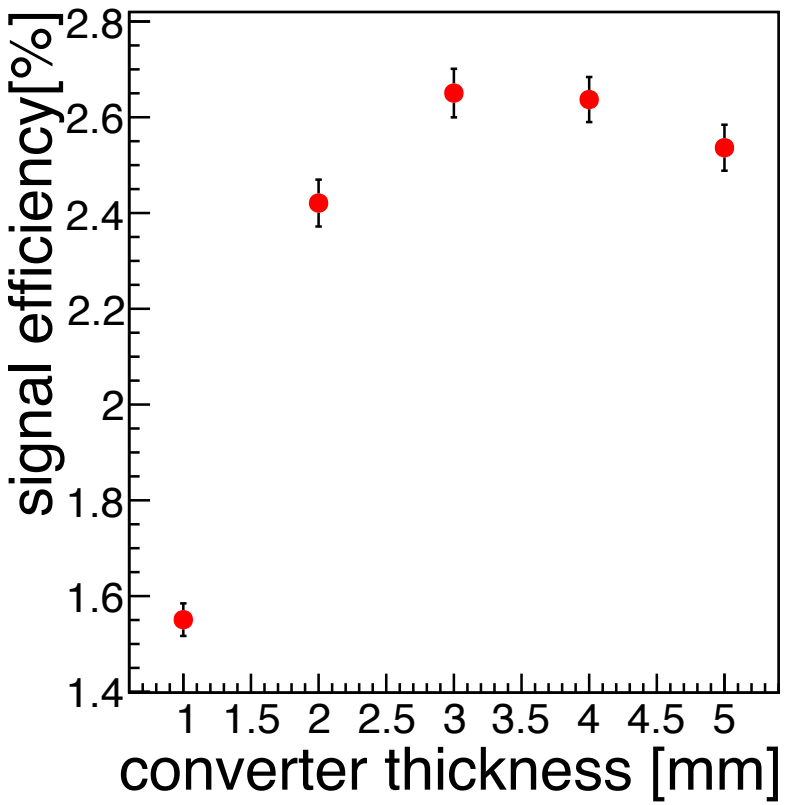


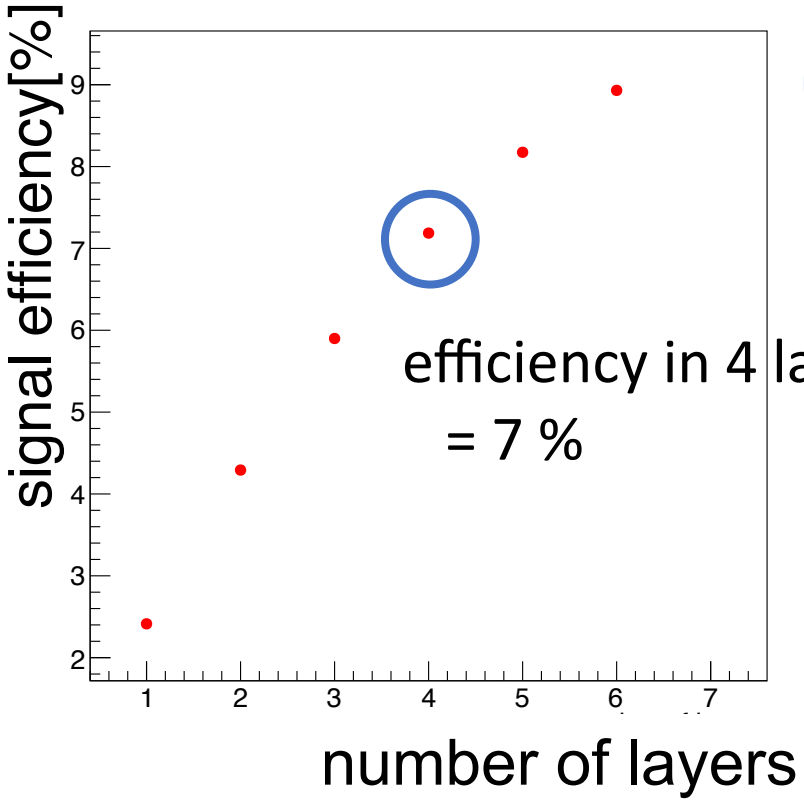


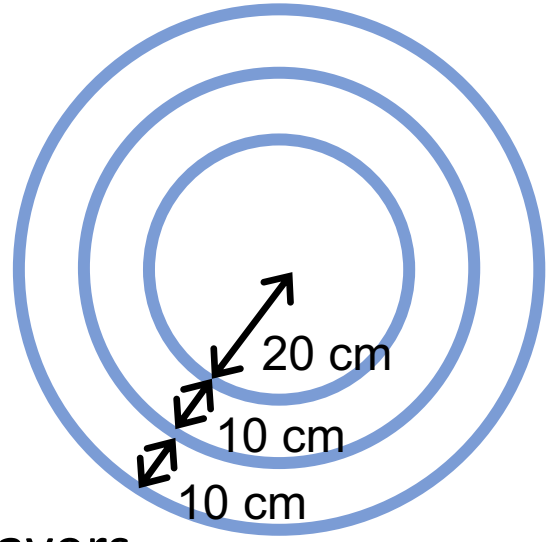
Course segmentation
will increase boomerang events

This size was tested with
electron beam
(previous talk)

Geometry optimization : thickness





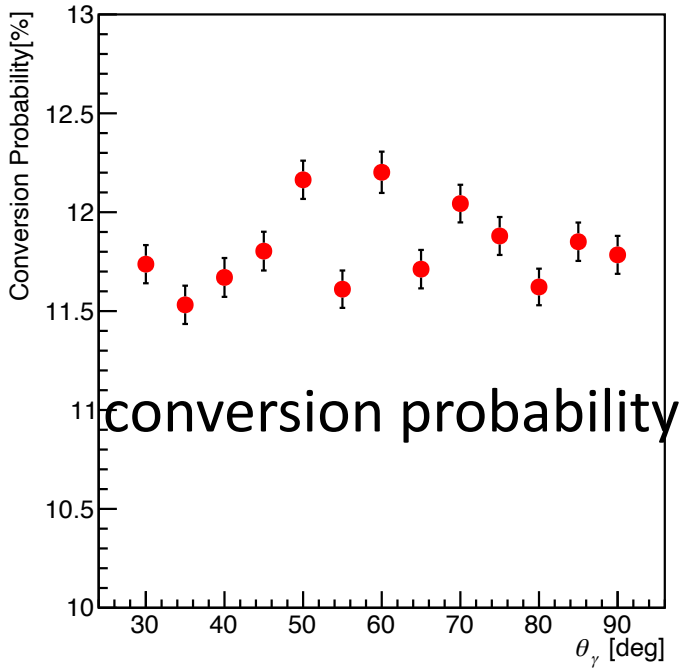


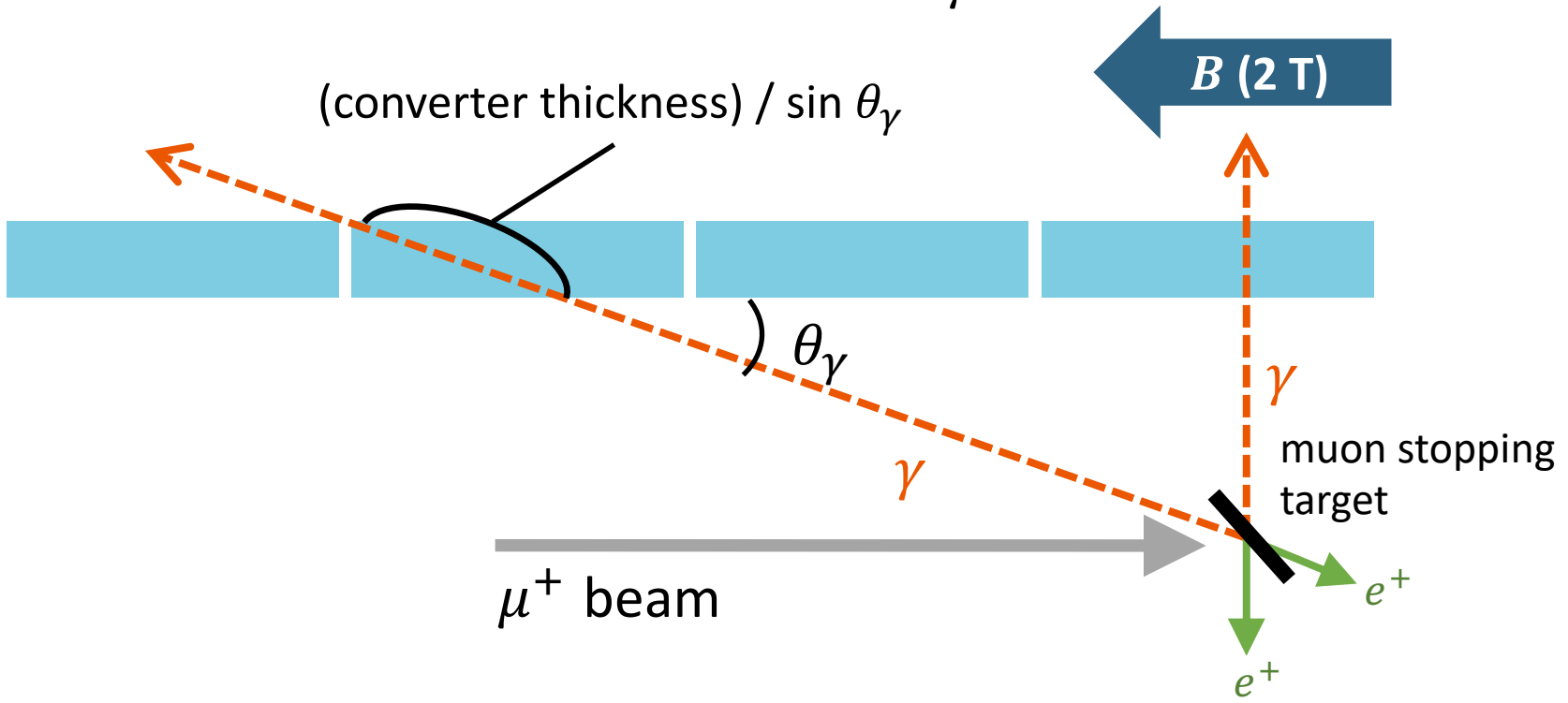
- Conversion probability = 4 % / layer
- Signal efficiency saturates at certain thickness → Increased energy escape
- Optimal thickness was found to be 3 mm

θ_γ dependence

- The converter is made thinner in the outer segment
  …To make the effective path length independent of θ_γ

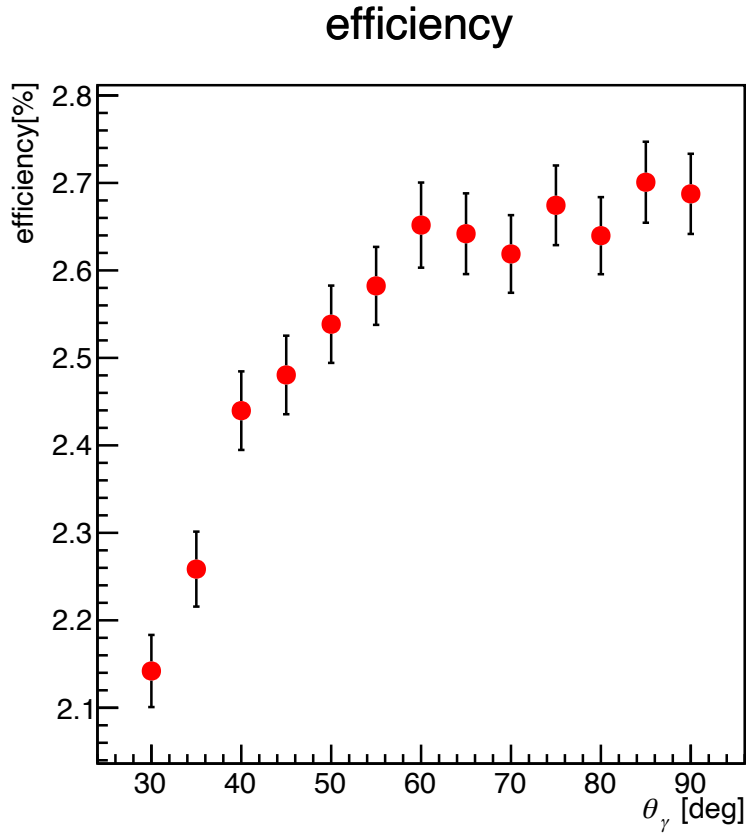
- So, the conversion probability roughly independent of θ_γ

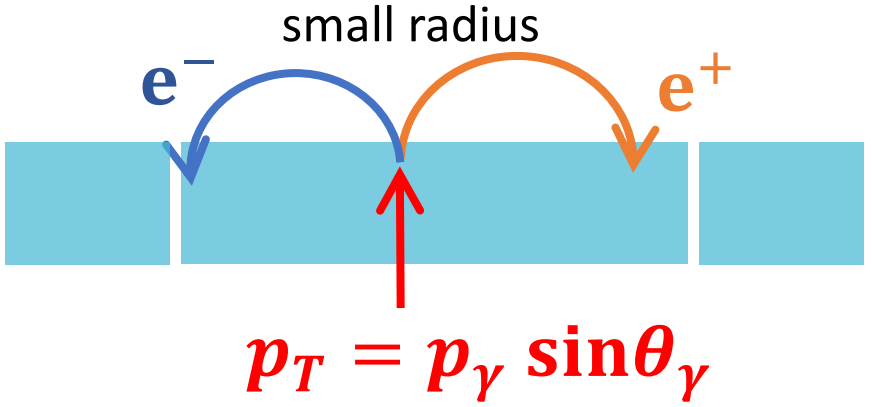




θ_γ dependence of signal efficiency

- However, signal efficiency was found to be θ_γ dependent
- This is mainly due to the larger boomerang probability





- Finer segmentation in the Z direction
- coarser segmentation in ϕ direction

may be effective to reduce boomerangs in small θ_γ

Summary

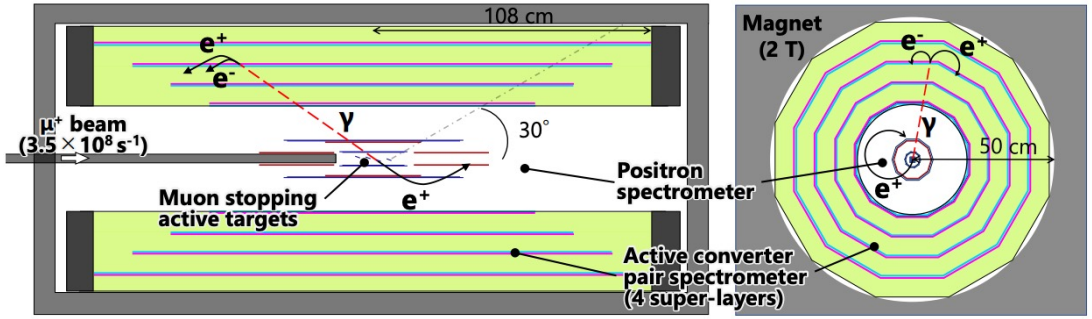
- Pair spectrometer with active converter is planned as a gamma detector for the future experiment for $\mu^+ \rightarrow e^+\gamma$ decay search.

- Various inefficiencies are expected in the experiment
  - Efficiency is up to 3 % / layer
  - Geometry has a large impact on them

- Signal efficiency was found to be dependent on photon incident angle, which can be mitigated by tuning of the segmentation

Prospects

- Improvement of the pair-spectrometer simulation
  - Incorporation of the conversion pair tracker layer
  - Incorporation of the LYSO performance based on beam test results
  - More realistic simulation with support structure



- Introduction of other components
  - Active & split muon stopping target
  - Positron measurement based on silicon sensor
  - Muon beam
  - …

Back up

Requirements for the future experiment

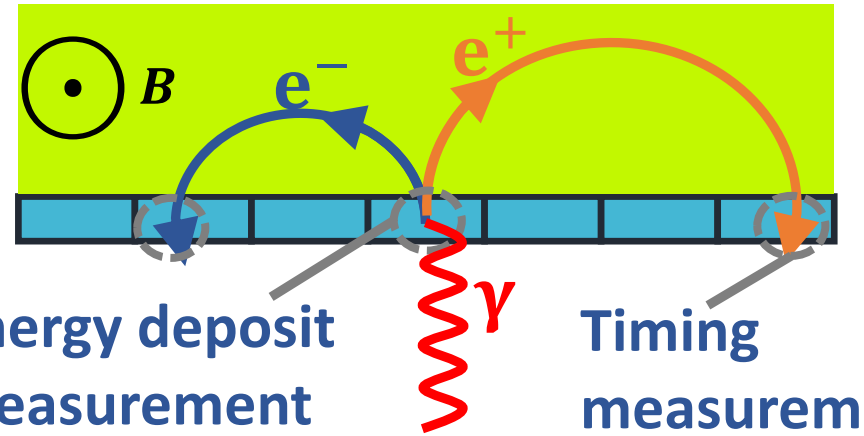
Energy resolution : 0.4% at signal energy (52.8 MeV)

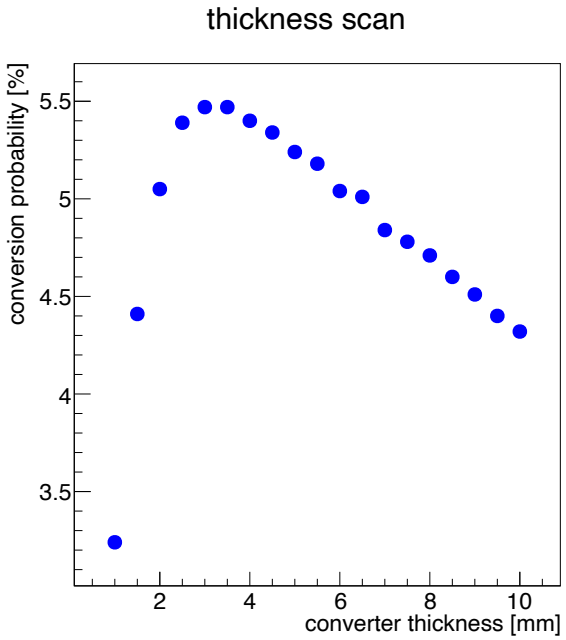
- $\frac{\Delta E}{E_{\mathrm{signal}}=52.8\ \mathrm{MeV}} = 0.4\ \%$ ➡ $\Delta E = 200$ keV required
- $\frac{\Delta E=200\ \mathrm{keV}}{2\times E_{\mathrm{deposit}}\simeq 7\ \mathrm{MeV}} = 3\ \% > \frac{1}{\sqrt{N_{\mathrm{p.e.}}}}$ ➡ $N_{\mathrm{p.e.}} > 500$ required per MIP

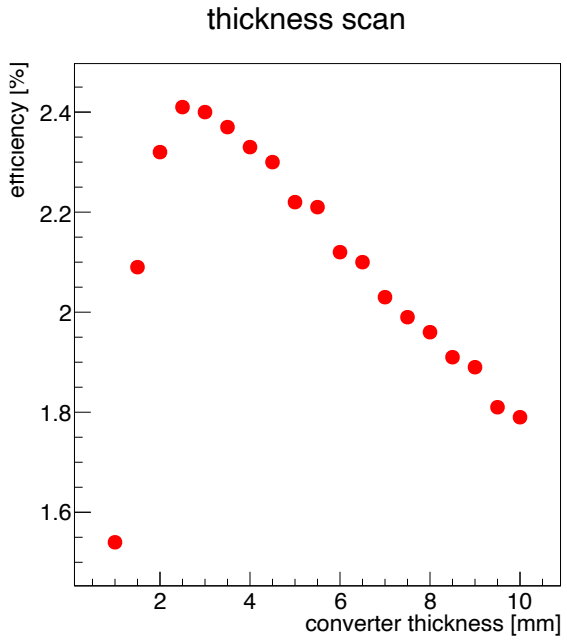
The fluctuation of energy includes (at least)
the fluctuation of light yield governed by Poisson statistics

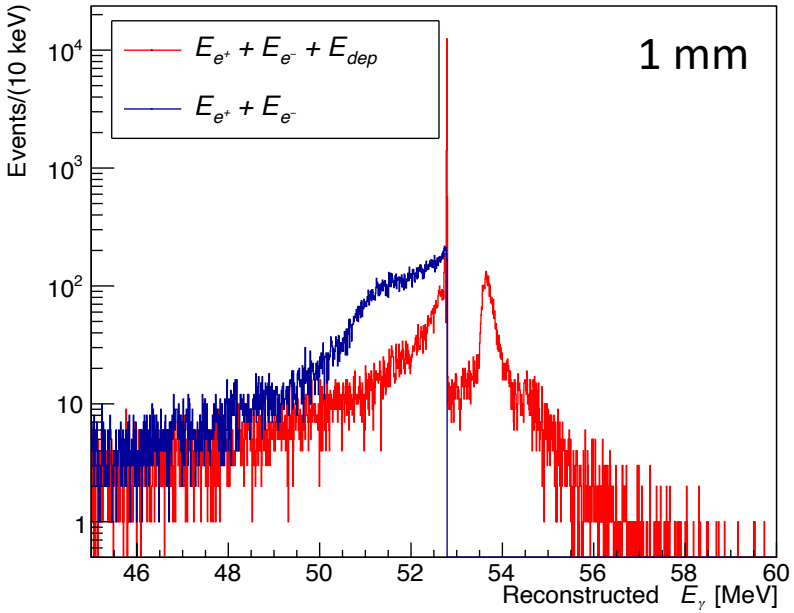
Time resolution : 30 ps for one gamma)

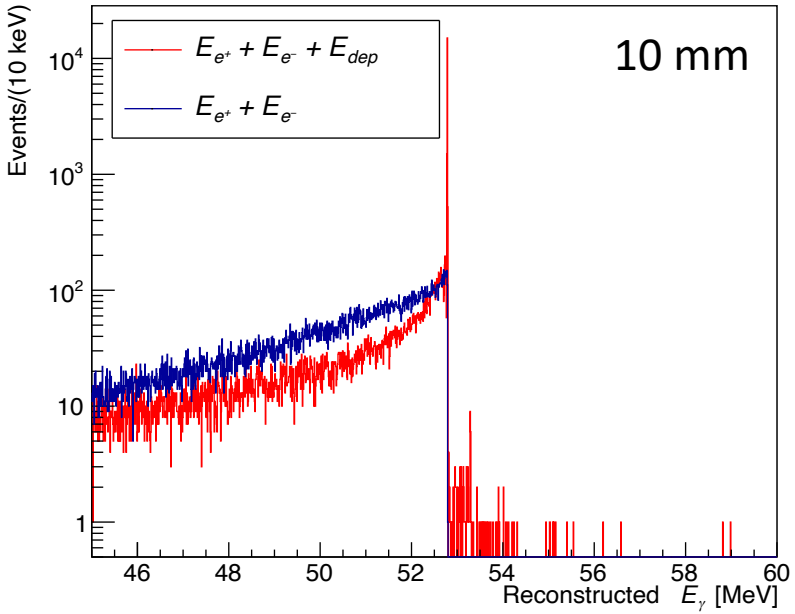
- $t_\gamma = (t_{e^+} + t_{e^-})/2$
- $\Delta t_\gamma < 30\ \mathrm{ps}$ ➡ $\Delta t_{e^\pm} < 30\ \mathrm{ps}\times\sqrt{2} = 40\ \mathrm{ps}$





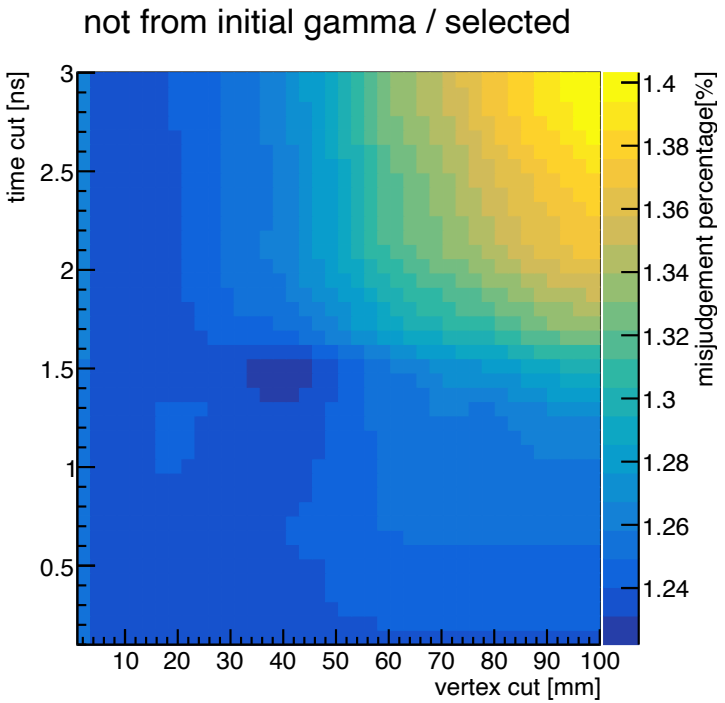


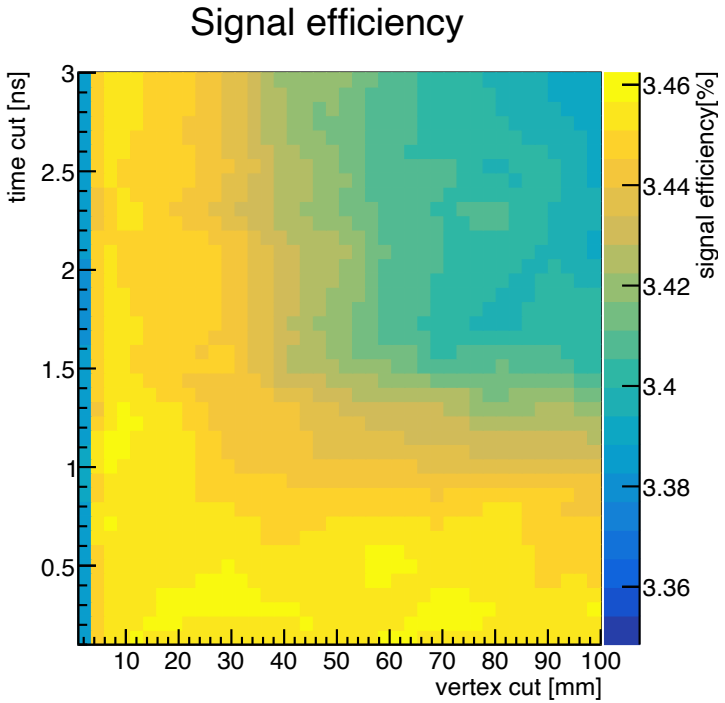




Conversion probability should scale with thickness …

Cut values for pair selection

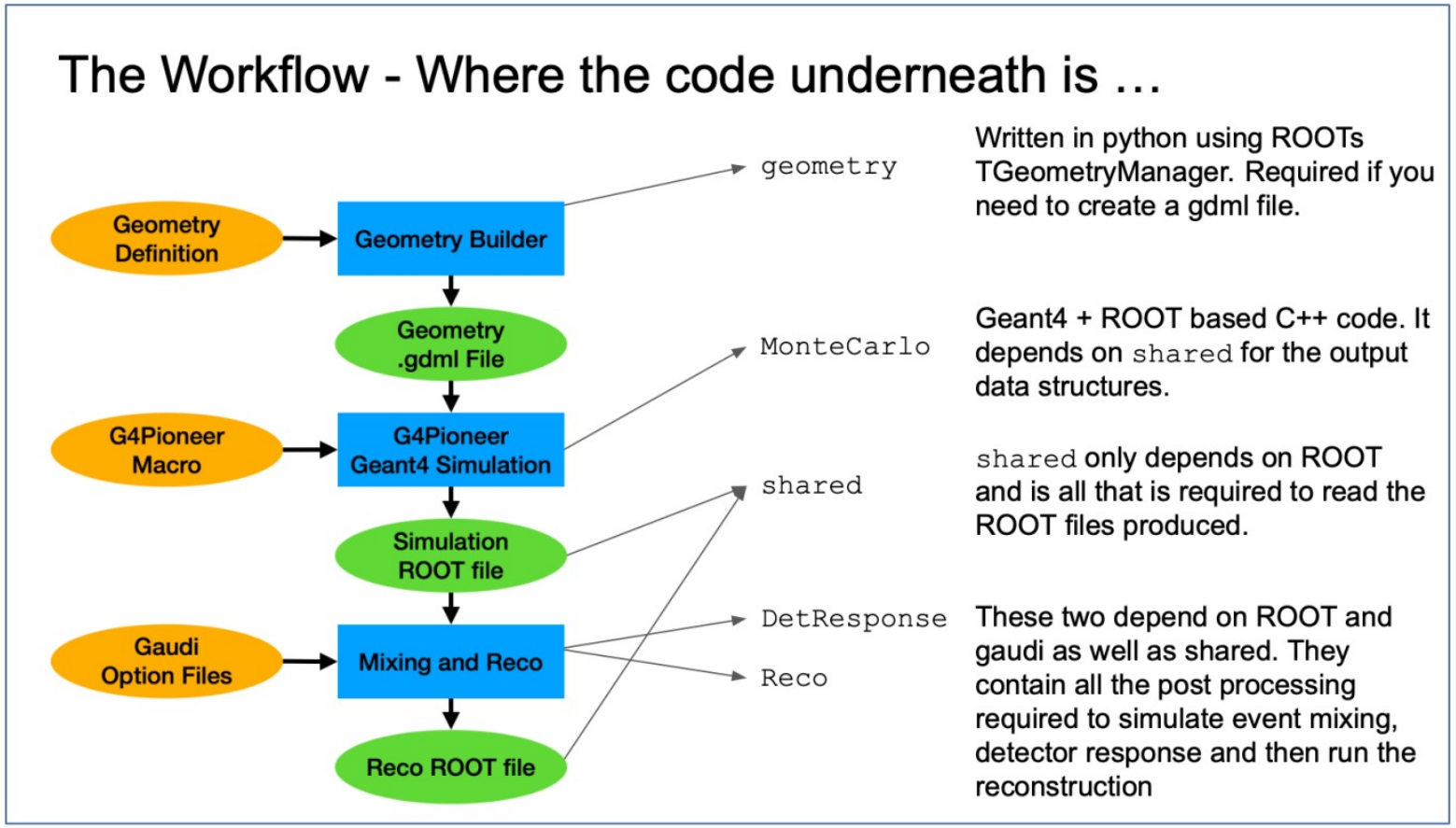




Physics model

- Reference Physics Lists: QGSP_BERT
  - Electromagnetic physics is G4EmStandard Physics
  - Photons:
    - pair production : BetheHeitler model with the LPM effect at high energies
    - Compton scattering : Klein-Nishina model
    - Photo-electric effect & Rayleigh scattering : Livermore model
  - Electrons and positrons:
    - multiple coulomb scattering : Urban model (0-100 MeV), WentzelVI model(100MeV-100TeV)
    - Bremsstrahlung : eBremSB model, eBremsLPM model
    - Ionization: Moller-Bhabha formulation
    - annihilation: eplus2gg model

PIONEER based simulation framework



https://indico.psi.ch/event/15146/overview