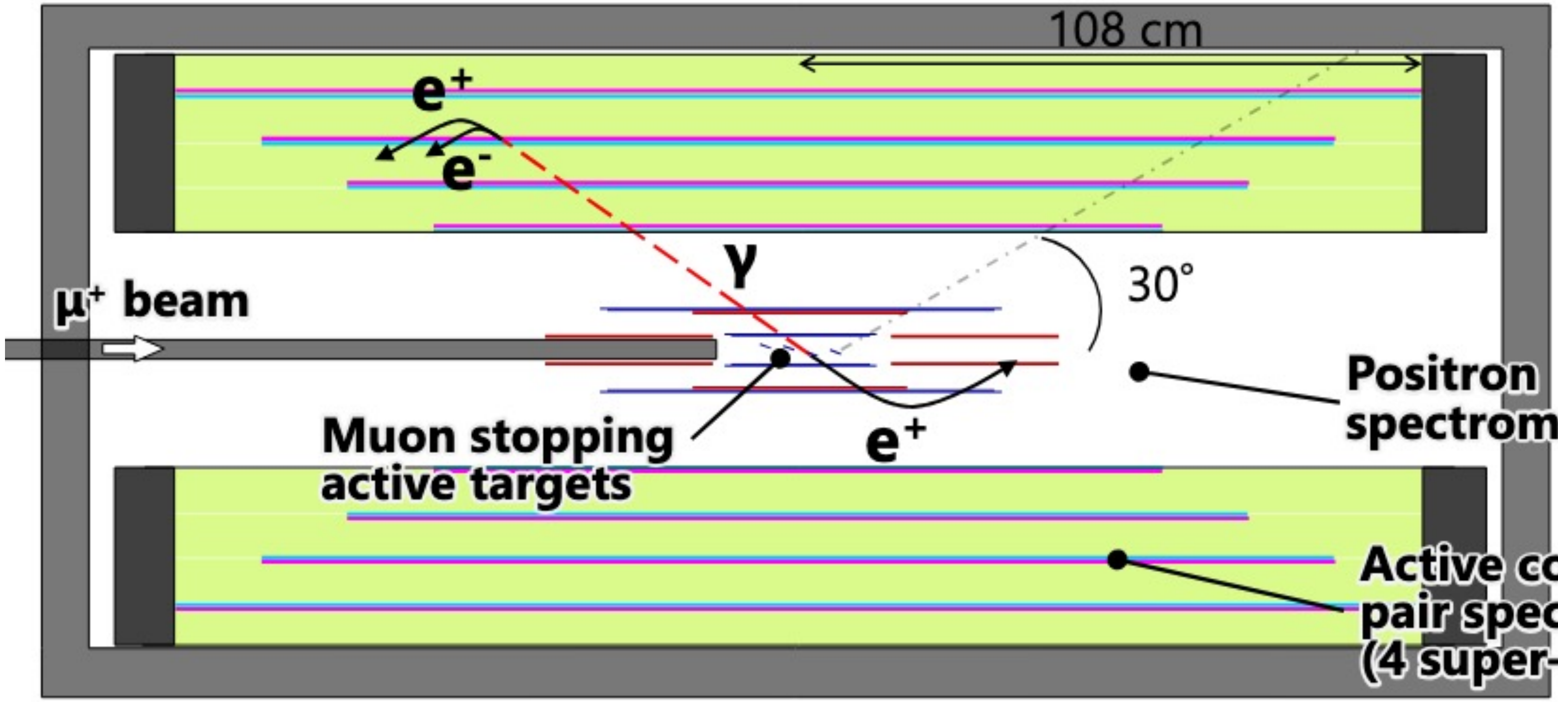
Introduction to activities in Tokyo for γ pair-spectrometer

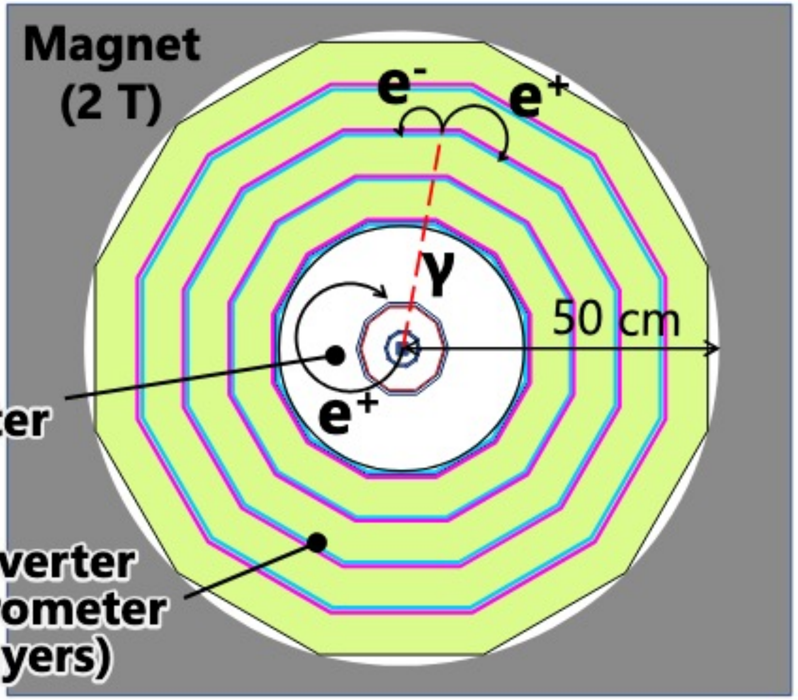
Atsushi Oya

12/Dec/2024

Reminder: Overview of design

- Photon detection with pair-spectrometer with active converter
  - Wide θ acceptance of $|\cos\theta| < 0.8 – 0.9$ (c.f. MEG II covers $|\cos\theta| < 0.35$)
  - Full ϕ acceptance (c.f. MEG II covers $|\phi| < \pi/3$)
  - Multi-layer design to have high efficiency



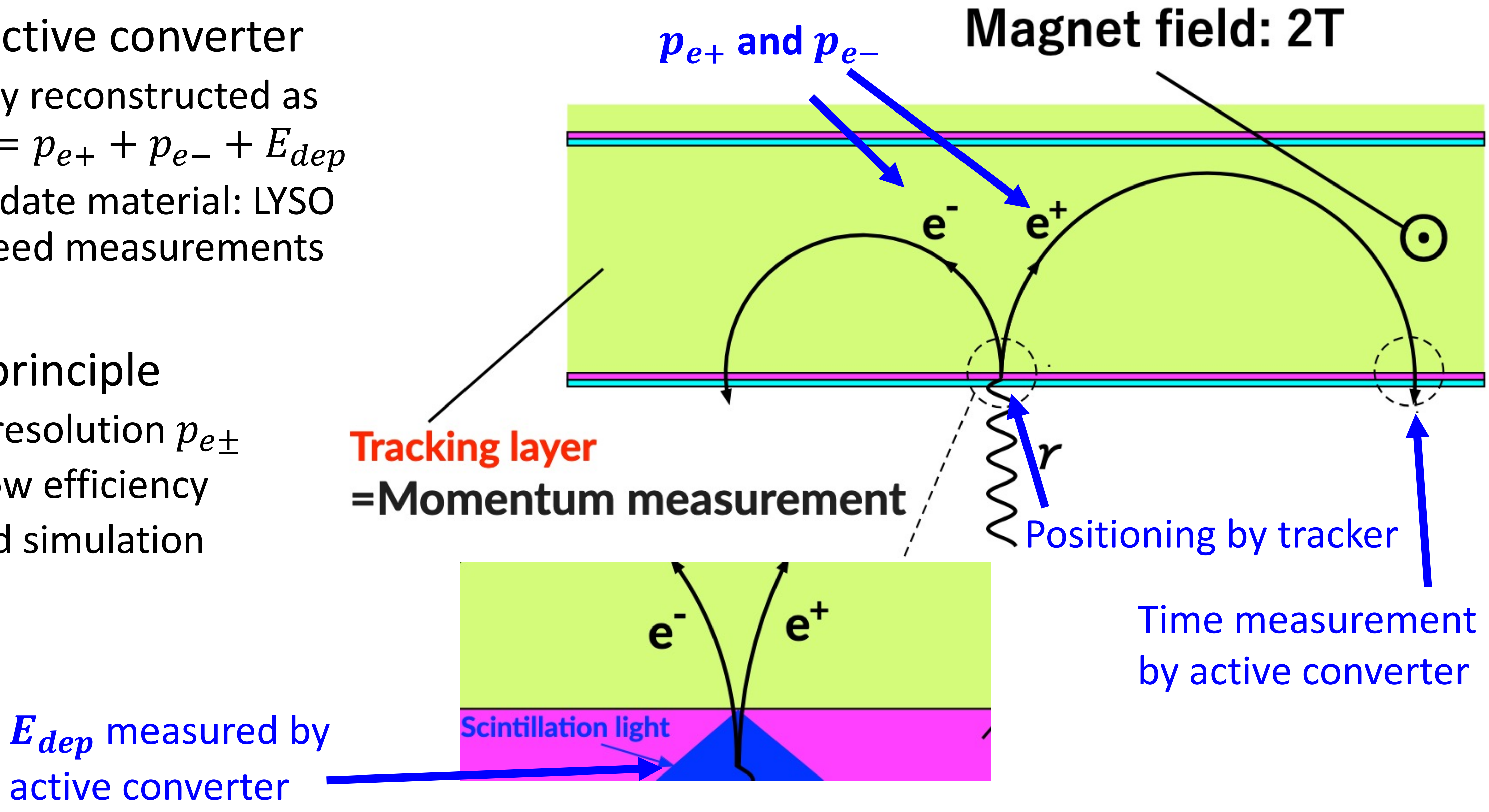


γ pair-spectrometer w/ active converter

- Use of active converter
  - Energy reconstructed as $E_{rec} = p_{e+} + p_{e-} + E_{dep}$
  - Candidate material: LYSO
    → Need measurements

- Design principle
  - High resolution $p_{e\pm}$
  - But low efficiency

  → Need simulation



Overview of activities

- Activities in Tokyo
  - Performance evaluation of active converter candidate
  - Simulation of photon measurement with active converter

Highlights from the past meetings:

- Simulation results reported Nov/2022
  - Reported 2.7% efficiency
  - Simulation only for signal w/o pileup & only γ conversion studied in detail

- LYSO performance reported last Oct
  - Beam test @KEK in 2023 (3 GeV electron beam)
  - Reported 30 ps time resolution & enough light yield of $O(10^3)$
  - Optimization of readout design
  - However, the data was not fully calibrated, leaving uncertainties on results

What news today?

- Simulation update
  - Better understanding in performance: Some additional effects found & incorporated
  - Rate-capability study: Simulation with event mixing
  - Effect of environmental materials: Material of tracker, mechanical support structure, etc
  - Background studies, as well as signal

- New measurement of LYSO performance
  - Beam test @KEK this Nov-Dec
  - Reflecting design optimization last year
  - Better calibrated dataset

Today's presentations

- My presentation: Simulations to compute sensitivity
  - BG photon simulation
  - Event mixing (pileup)
  - Effects of material around converters

  Aims to demonstrate what we should learn from simulation to compute sensitivity

- Rei's presentation: Simulations for detector effects & design optimization
  - Analysis of angle dependence
  - Possible use of angle measurement of pair tracks (context: BG studies)
  - Converter design optimization

- Fumihito's presentation: Reports on LYSO measurement
  - Explanation of configuration, purposes
  - Preliminary results & analysis plan

Sensitivity simulation

Atsushi Oya

12/Dec/2024

Outline

1. Signal simulation
    - Review of past simulation
    - Inputs for sensitivity calculation

2. BG photon simulation
    - Configuration of BG-photon simulation & spectrum

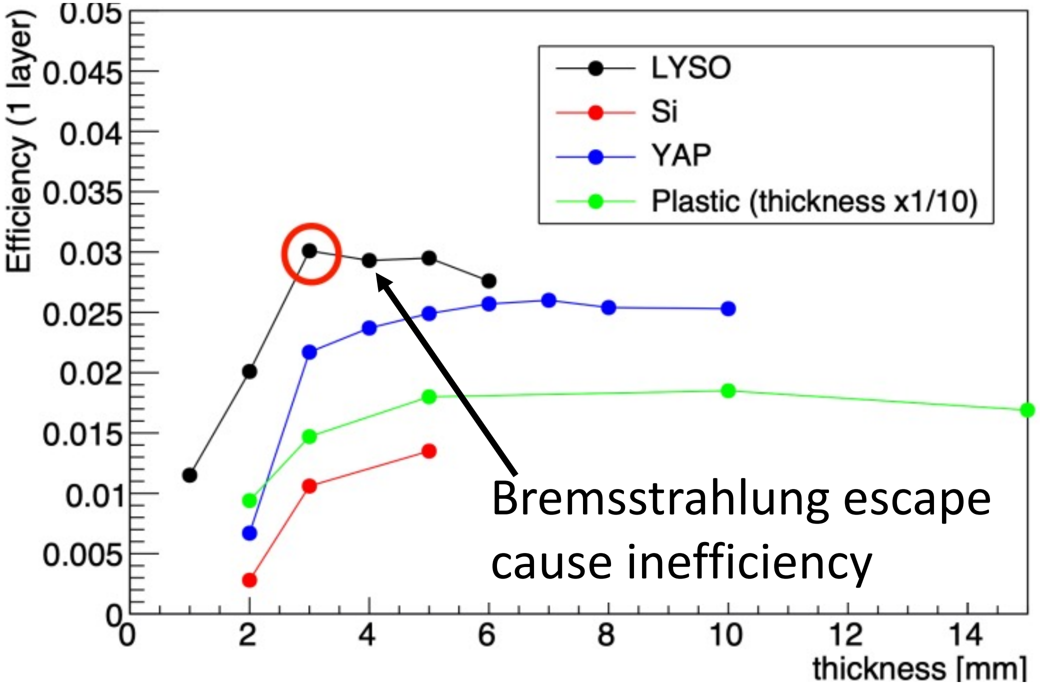
3. Event mixing: Performance at high rate

4. Environmental material: Impact on spectrum & efficiency

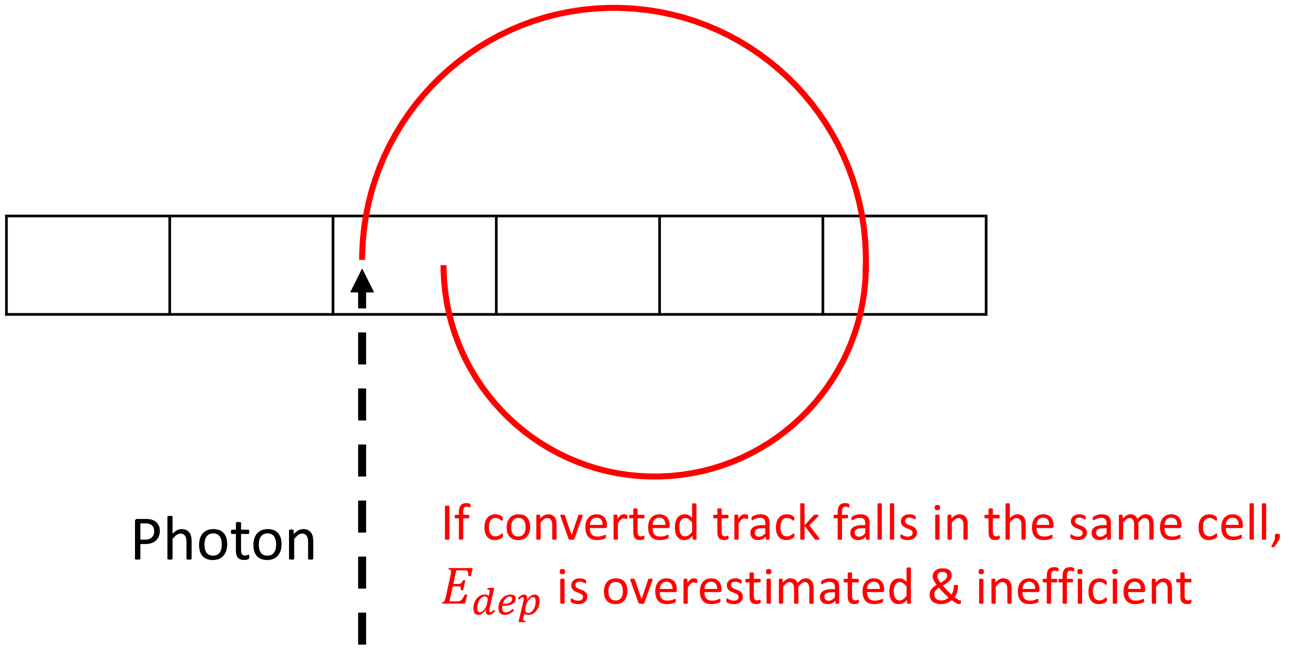
5. Preliminary sensitivity calculation

Review of studies so far

- Efficiency definition in the previous study
  - Simply evaluate # of events with $52.7 < p_{+}^{MC} + p_{-}^{MC} + E_{dep}^{MC} < 52.9$ MeV
  - Inefficient when some bremsstrahlung energy escapes out of converter
    → Efficiency saturation at 3 mm thickness
  - Multiple counting of E_{dep} by converter cell is already considered
    - "Boomerang inefficiency"

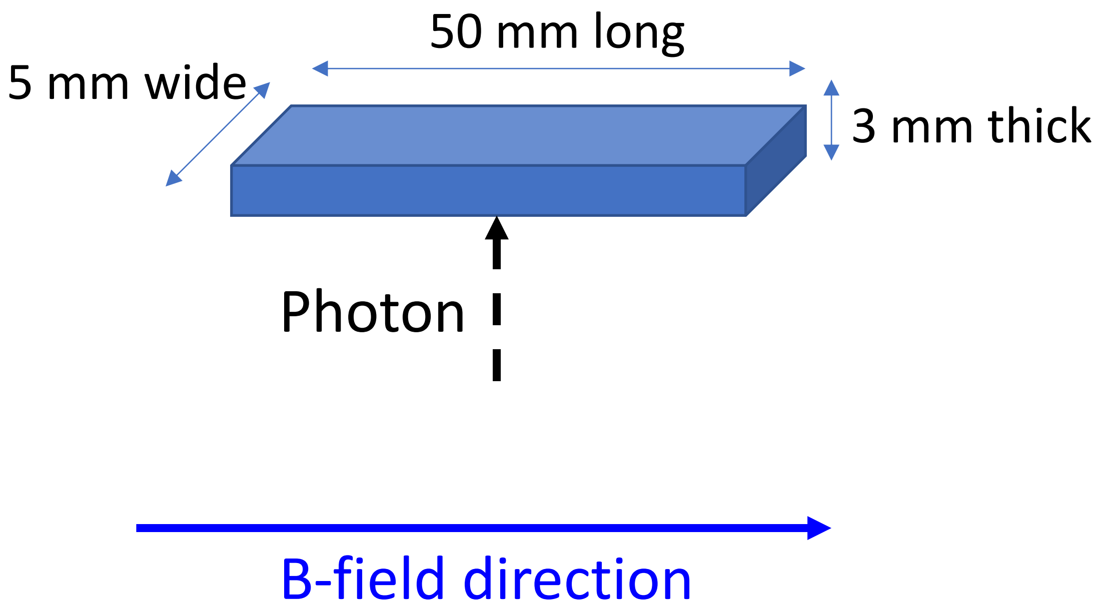


Topology of *Boomerang*



Review of studies so far

- Baseline choice of converter cell after optimization
  - Note: Width is sensitive to Boomerang



Baseline choice in performance measurement in beam test.

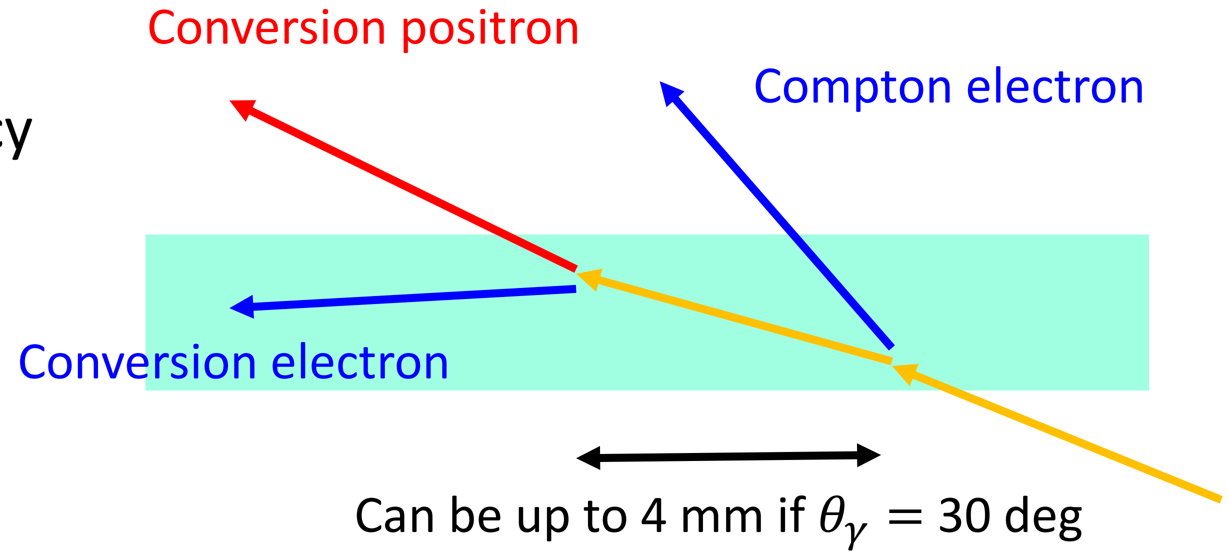
My presentation today is based on this configuration (if not explicitly mentioned).

→ Overall, 2.7% efficiency is reported

Additional considerations

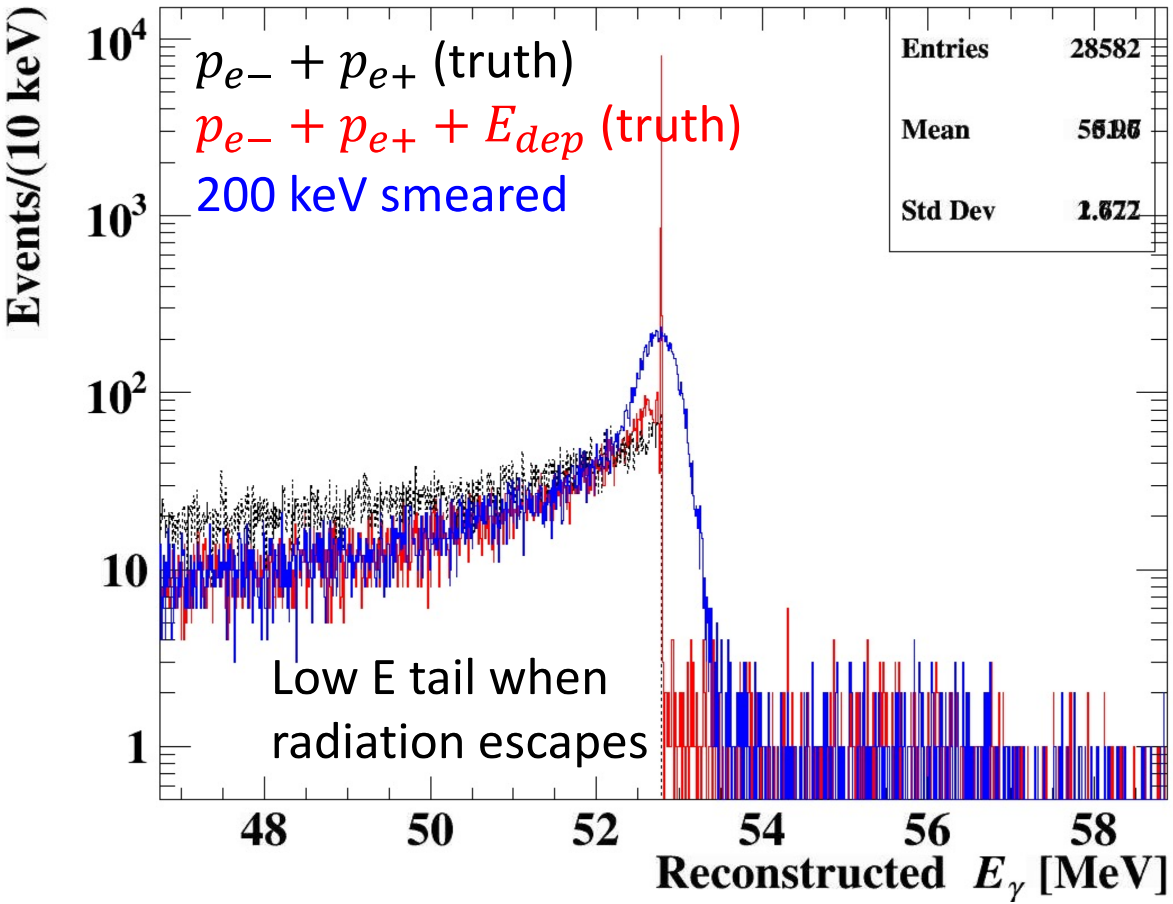
- Now, we think about pileup & tracking capability
  - Tracking may be inefficient for if momentum is too low
  → **$p_T > 5$ MeV cut** is assumed
  - With pileup, possible to have e^+ from signal & e^- from pileup
  → Introduced **cut to require vertices** (position getting out of LYSO) **are within 2 mm**
  - **N.B: Thresholds above are arbitrary choices now**

- Signal inefficiency? Other effects?
  - Small, but ~0.2% additional loss of efficiency
  - **Mainly from $p_T > 5$ MeV cut**
  - Impact of vertex cut is negligible
    (Rare: Event topology as shown right)
  - Rei will discuss more detail



Signal efficiency & Spectrum

- So far, cut applied to MC truth value, 52.7 – 52.9 MeV
- For sensitivity computation, cut should be re-defined w/ realistic resolution
  - Need realistic BG estimation, but then, cut is re-defined giving different ϵ_{sig}



Today, we assume 200 keV tracking ⊕ converter resolution for sensitivity calculation

3mm thick, 90° θ_γ efficiency w/ breakdown

Conversion probability: 11.81%
-> Vertex consistency cut: 7.15%
-> Energy cut:

CutA: Events with < 100 keV error on MC truth: 2.4% (cross-check purpose with past results)

CutB: Events with 52.2 < Eg < 53.4 w/ σ = 200 keV: 3.16% (In sensitivity calculation, we adopt this number)

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BG-γ simulation

- BG photon source in MEG II
    1. Muon radiative decay
       → Today's presentation
    2. Annihilation in flight of decay positron (flying e^+ annihilates in material, producing 2γ)
       → Difficult to study now without knowing material for muon target & positron detector

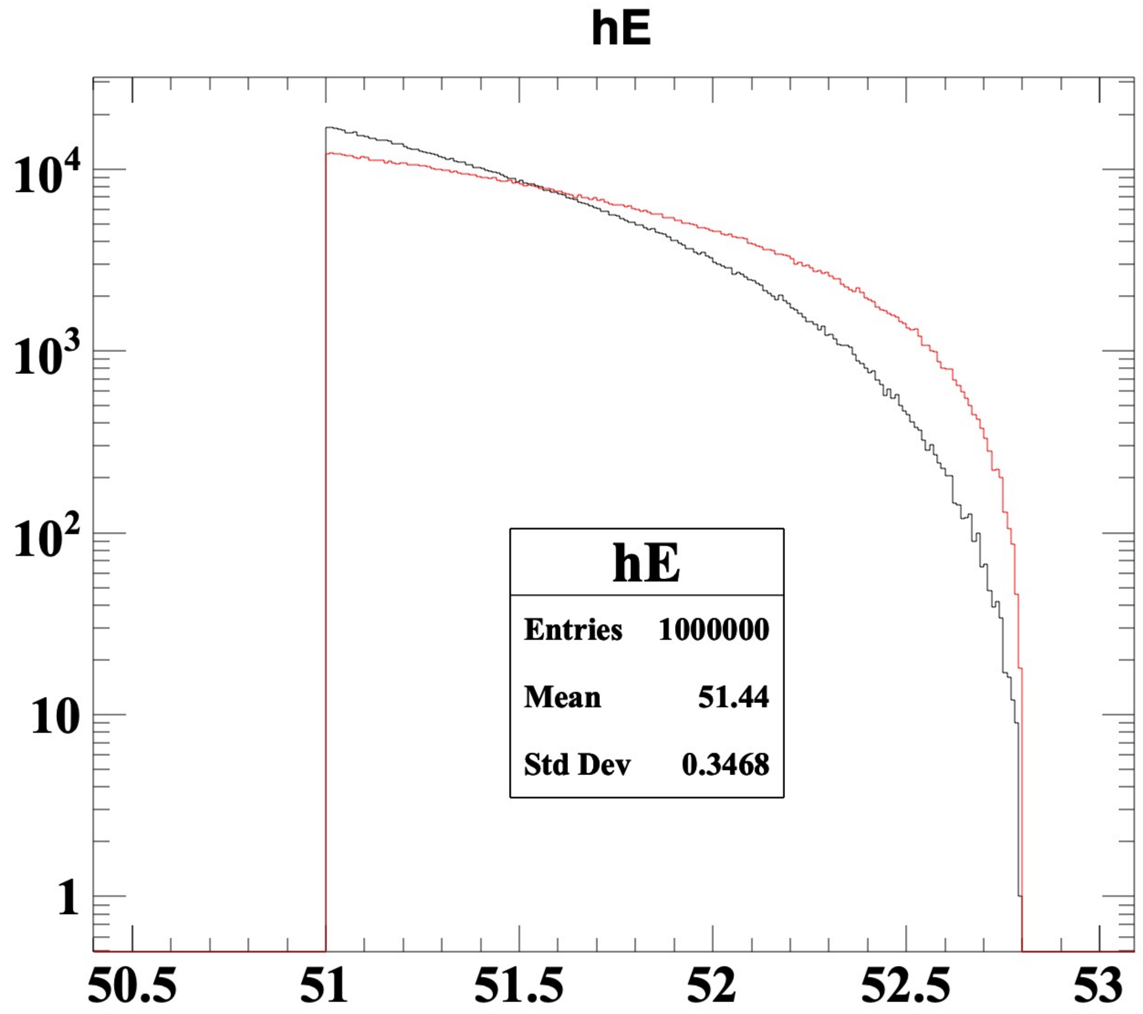
- Use of inclusive differential branching ratio of radiative decay
    - Given in Kuno, Okada (1998)

$$\frac{dB(\mu^\pm \to e^\pm \nu\overline{\nu}\gamma)}{dy d\cos\theta_\gamma} = \frac{1}{y}\left[J_+(y)(1 \pm P_\mu \cos\theta_\gamma) + J_-(y)(1 \mp P_\mu \cos\theta_\gamma)\right]$$

    - E_e and θ_e in full differential branching ratio are integrated out here

Generated RMD-γ spectrum

- Spectrum can be generated incl. polarization
  - (Below: IR cutoff is set at 51 MeV)



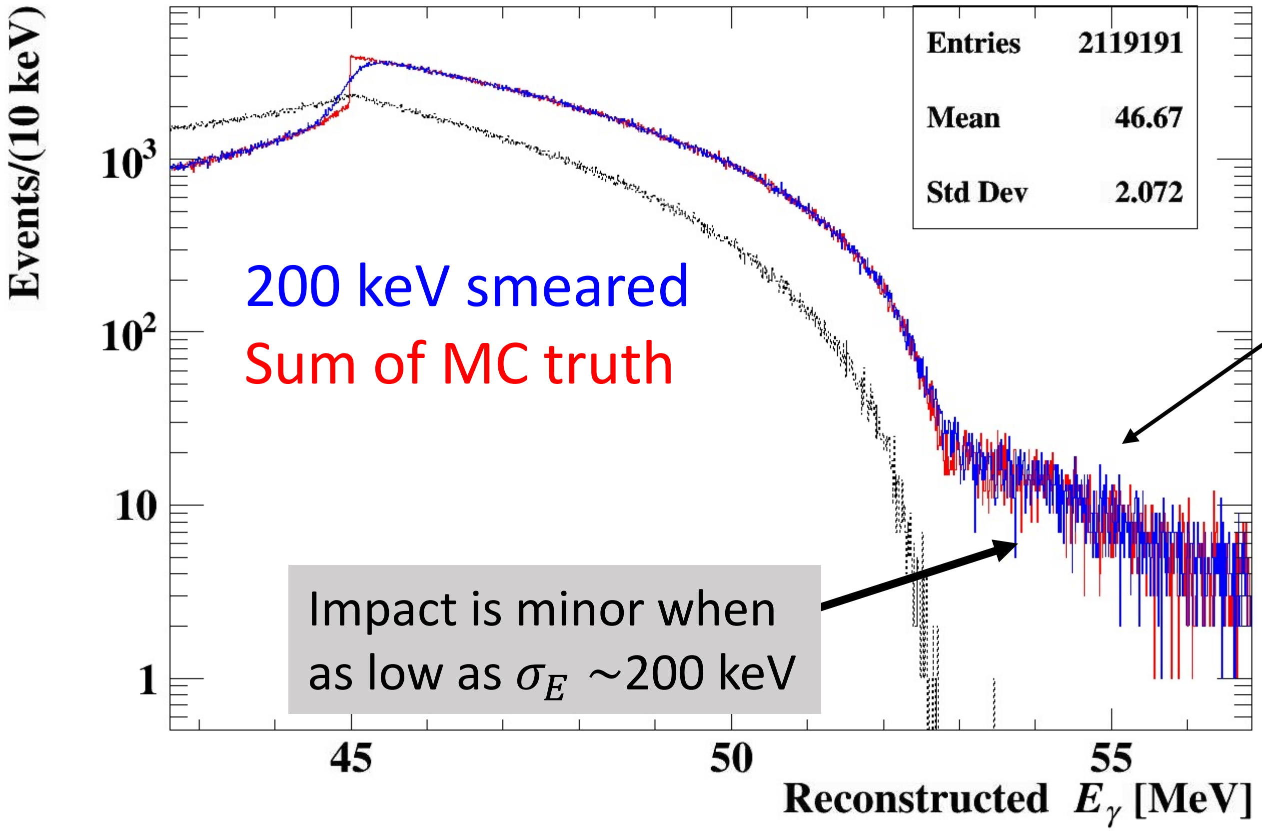
Full polarization assumed: $P_\mu = -1$

- Photons emitted to $\cos\theta_\gamma = -1$ direction
- Photons emitted to $\cos\theta_\gamma = 1$ direction

Simulated BG spectrum

- Evaluated spectrum with the same cuts discussed for signal
  - Apply track multiplicity cut, etc. , and then smear the sum of MC truth by 200 keV

RMD-originated BG spectrum



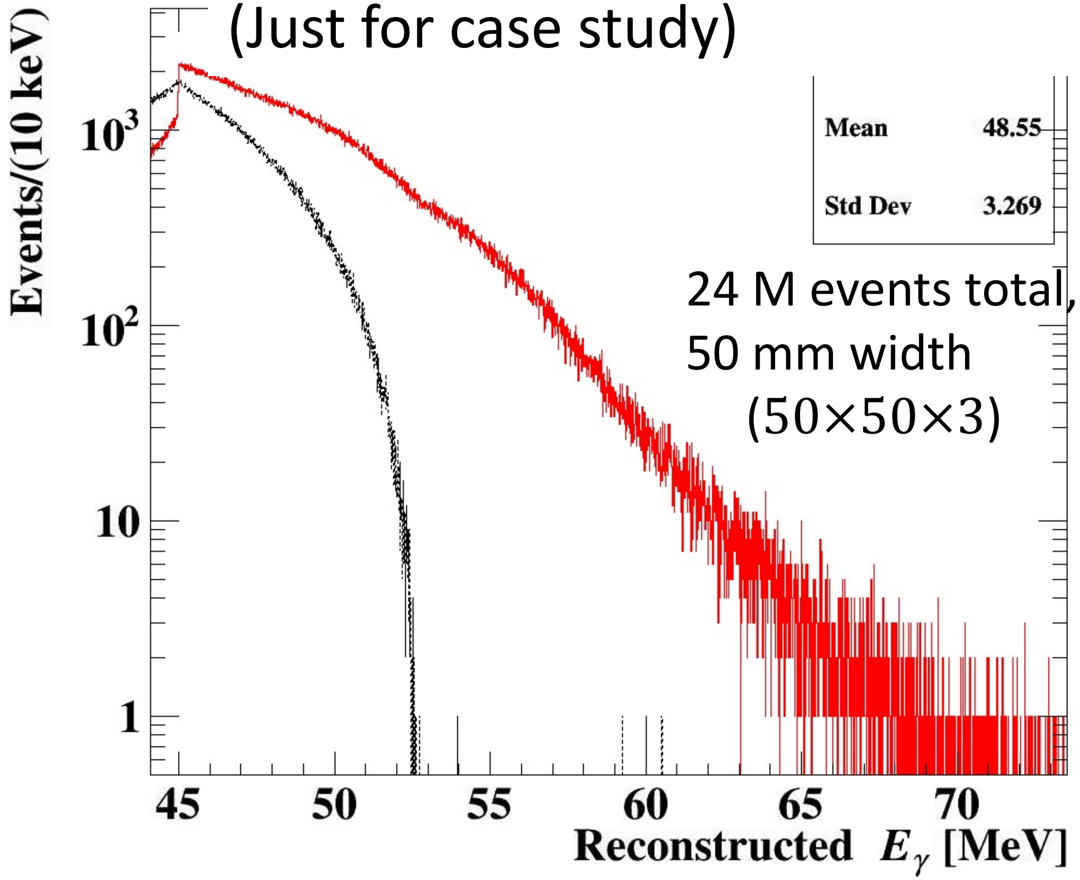
- Spectrum evaluated after applying vertex consistency cut & p_T cut.
- High-energy tail arise from Boomerang event topology.

In BG spectrum, Boomerang is more important than detector resolution itself

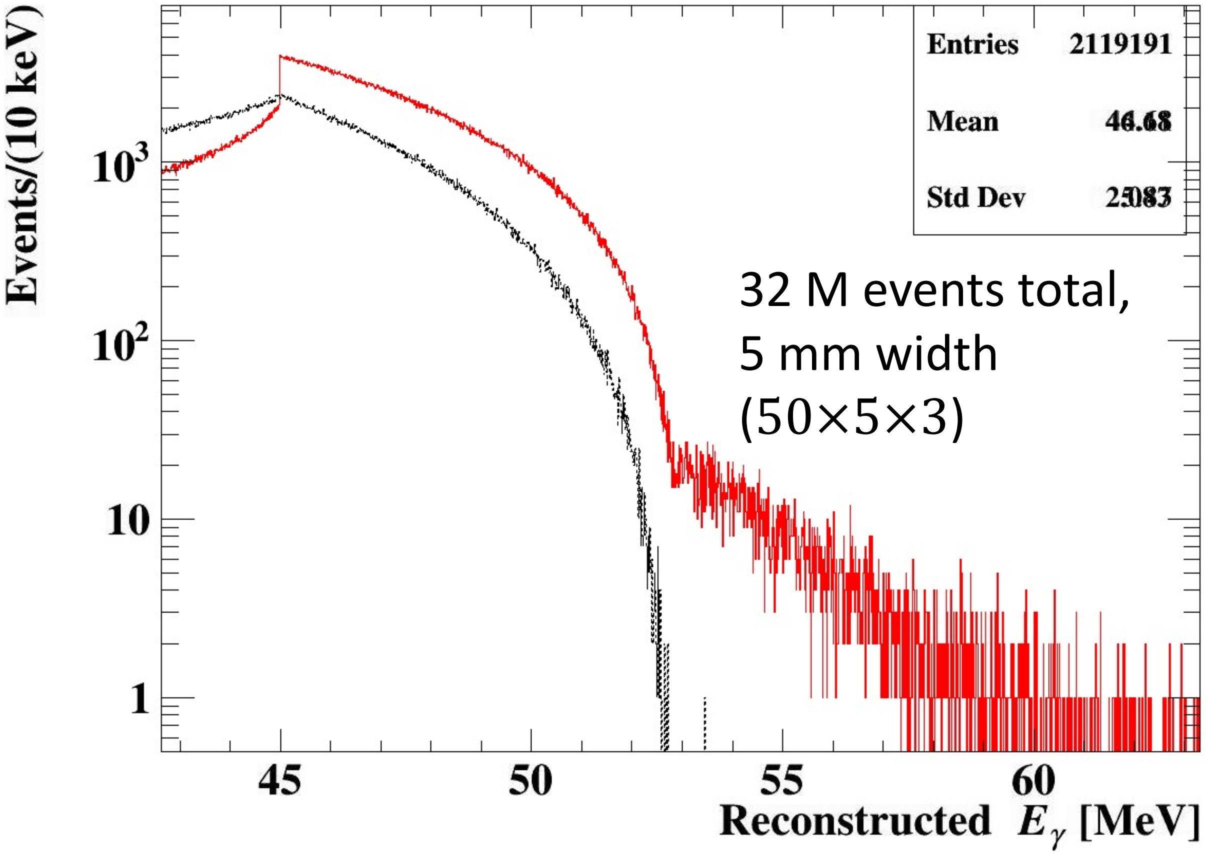
Boomerang in BG-γ: Case study

- Boomerang effect is also important in BG spectrum
  - Not just a matter of signal efficiency, but also high impact on N_{BG}

Boomerang-enhanced geometry
(Just for case study)

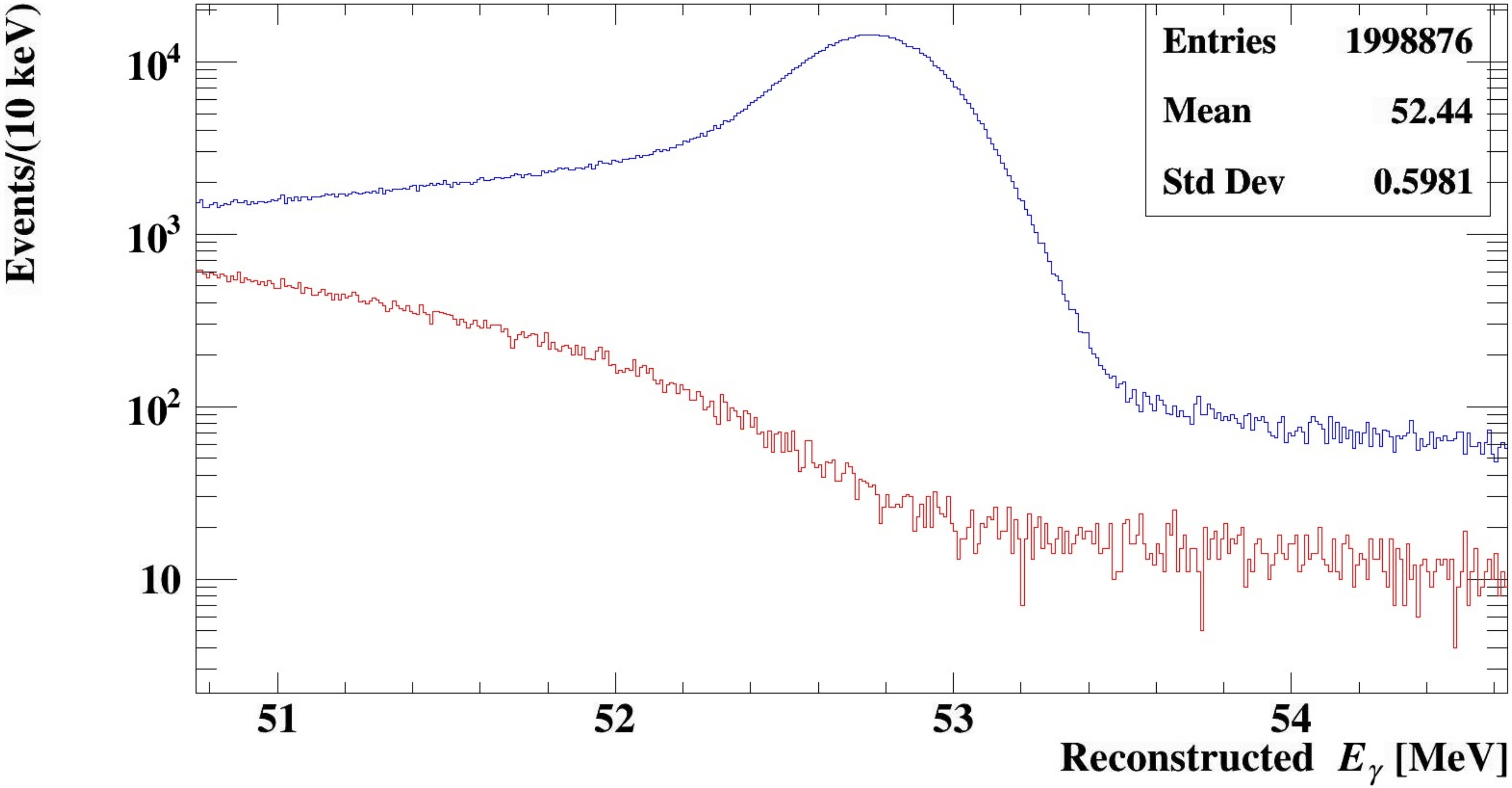


“Standard” converter cell geometry



Smeared spectrum comparison

- 27M signal photon vs 31M BG photon of $E_\gamma > 45$ MeV



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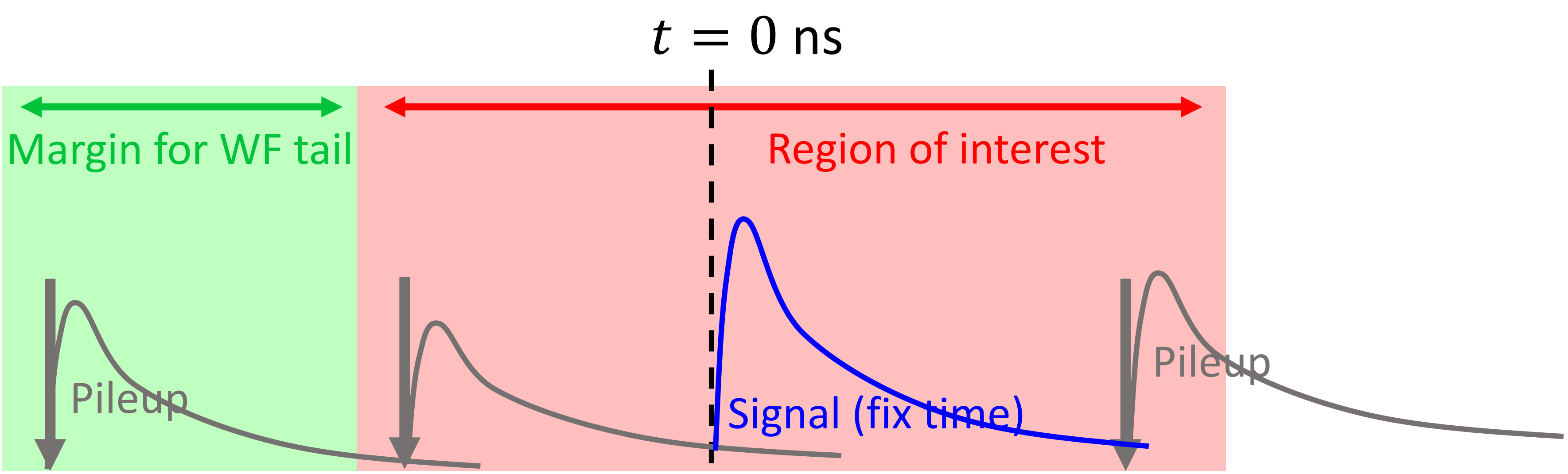
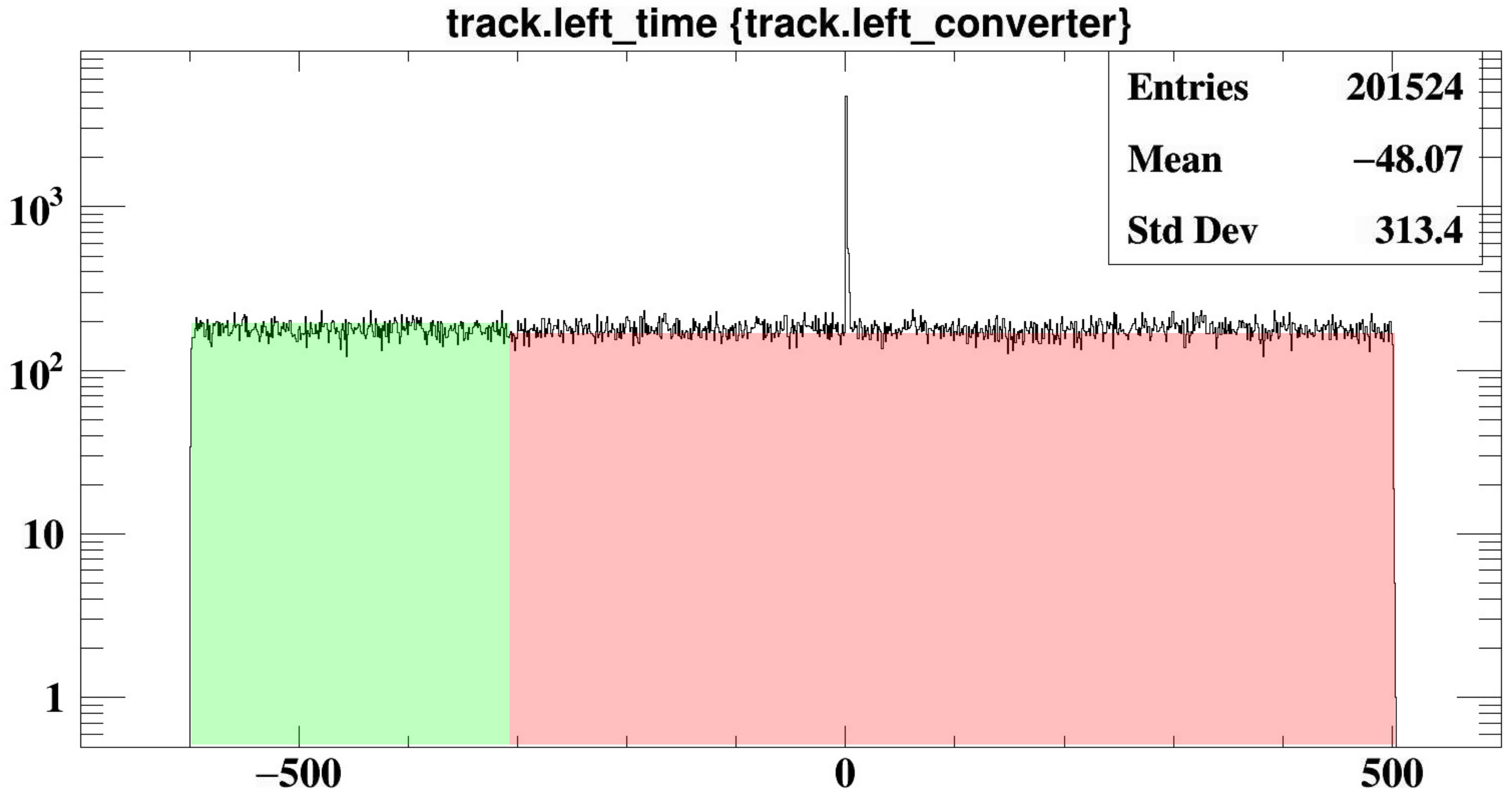
Event mixing implementation

- Algorithm of mixing
  1. First define time window (– 300 ns to 500 ns for discussions below)
  2. One sample placed at a fixed time if configured so (intended for signal)
  3. Pileup samples placed at a specified rate
     - Generation starts earlier than the start of time window (margin for waveform tail)
     - If margin is set to 300 ns, then pileup samples can come within – 600 ns to 500 ns
- N.B. Trigger judgment is not implemented now (not difficult to implement)



Example event mixing

- Below shows time distribution of tracks leaving converters



Analysis with pileup

- As I mentioned earlier today,
  - With pileup, possible to have e^+ from signal & e^- from pileup

  → Introduced **cut to require vertices** (position getting out of LYSO) **are within 2 mm**

- Also, timing cut is applied for tracks & converter energy deposit
  - Tracks: Grouped when timing & vertex are both consistent
  - Converter hit: E_{dep} counted when hit timing $\in [-200\text{ ns}, 200\text{ ns}]$ from track

    → **Pileup hits on converter result in high-energy tail**

- RMD$-\gamma$ of > 10 keV are mixed in this work
  - Mixing rate: Branching ratio with that cut × Muon stopping rate

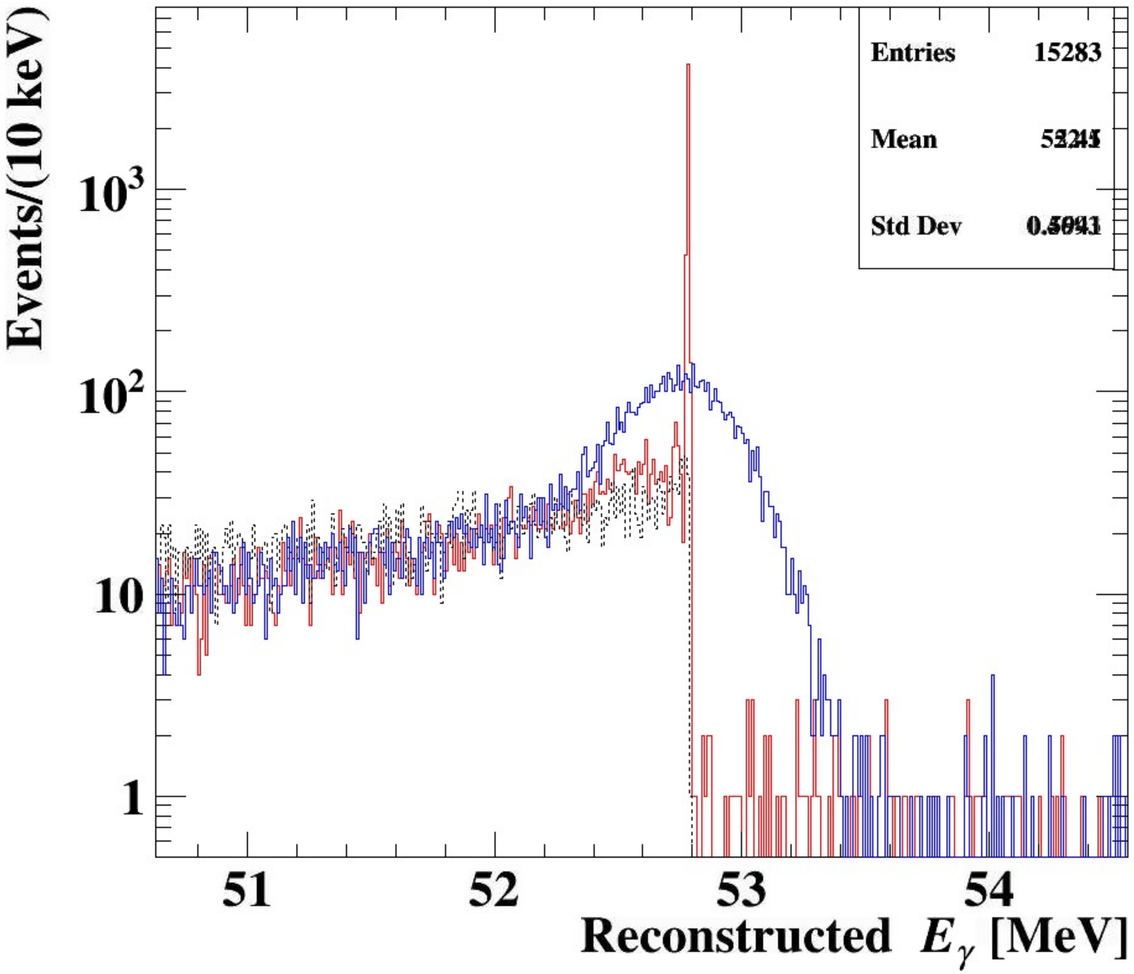
Signal spectrum at different rate

- aa

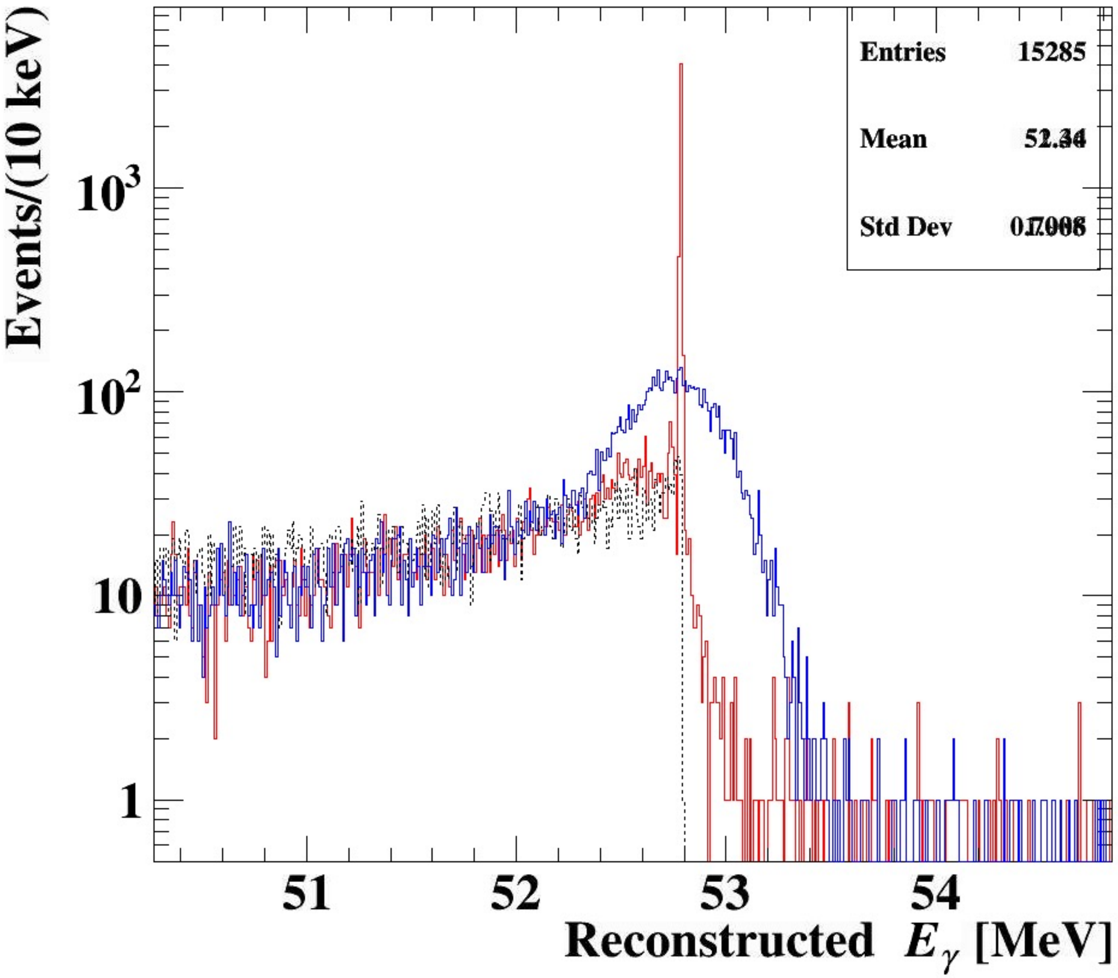
$p_{e-} + p_{e+} + E_{dep}$ (truth)

200 keV smeared

No event mixing



2e9 stopping rate



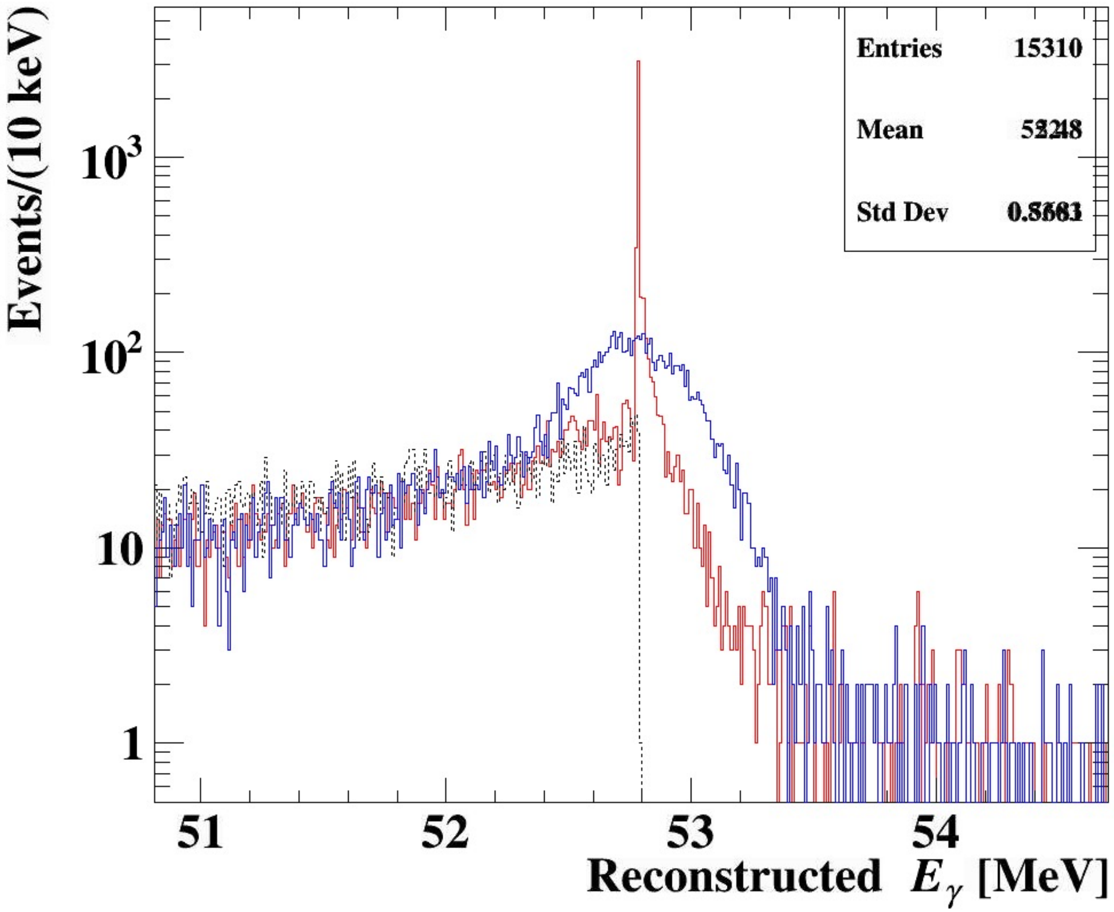
Signal spectrum at different rate

- aa

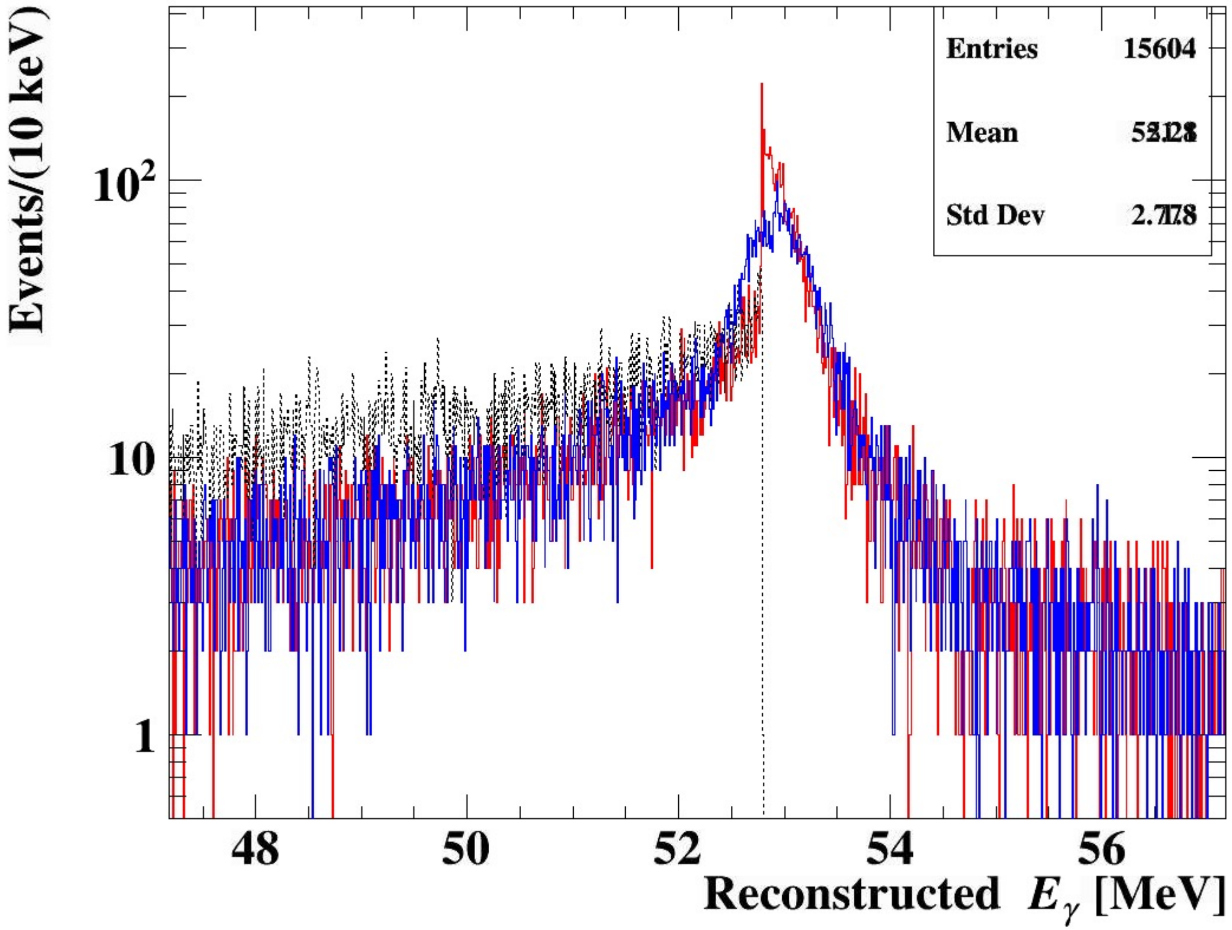
$p_{e-} + p_{e+} + E_{dep}$ **(truth)**

200 keV smeared

2e10 stopping rate



2e11 stopping rate



Discussion about pileup

- Impact of pileup with soft RMD-γ
  - Limited impact at $O(10^9/\,s)$ stopping
  - Impacts start to appear at $O(10^{10}/\,s)$
  - Clearly worsen spectrum at $O(10^{11}/\,s)$

- Today, I will present **sensitivity only up to $\mathbf{10^9/\,s}$ stopping**
  - Up to this point, we do not have to care about E_γ PDF change
  - If we want to discuss higher stopping rate, change in E_γ PDF should be incorporated

Technical information

- Event mixing is implemented with Gaudi
  - https://gaudi-framework.readthedocs.io/en/latest/user_guide.html
  - Development initiated for ATLAS, LHCb

- Use of Gaudi in our simulation
  - We just use algorithm switching feature
    (Implement algorithm ourself, which can be switched by runtime configuration file)
  - But, not use built-in reconstruction algorithm, etc

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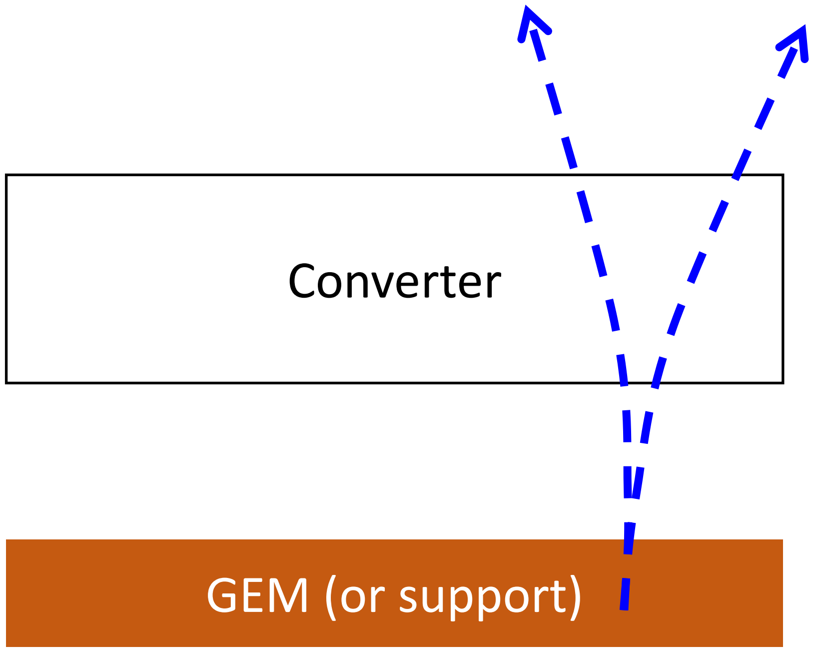
Our concern about material

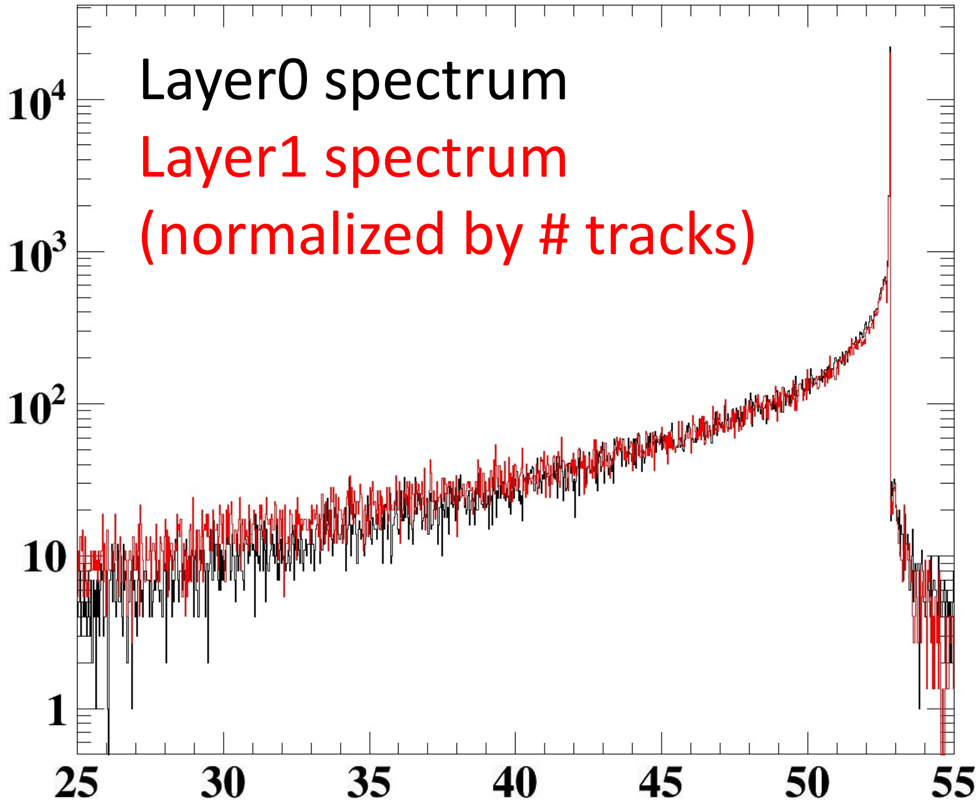
- Concerns about conversion in front of LYSO
    1. Conversion may happen at GEM detector for TPC readout
    2. Or at mechanical support structure for LYSO

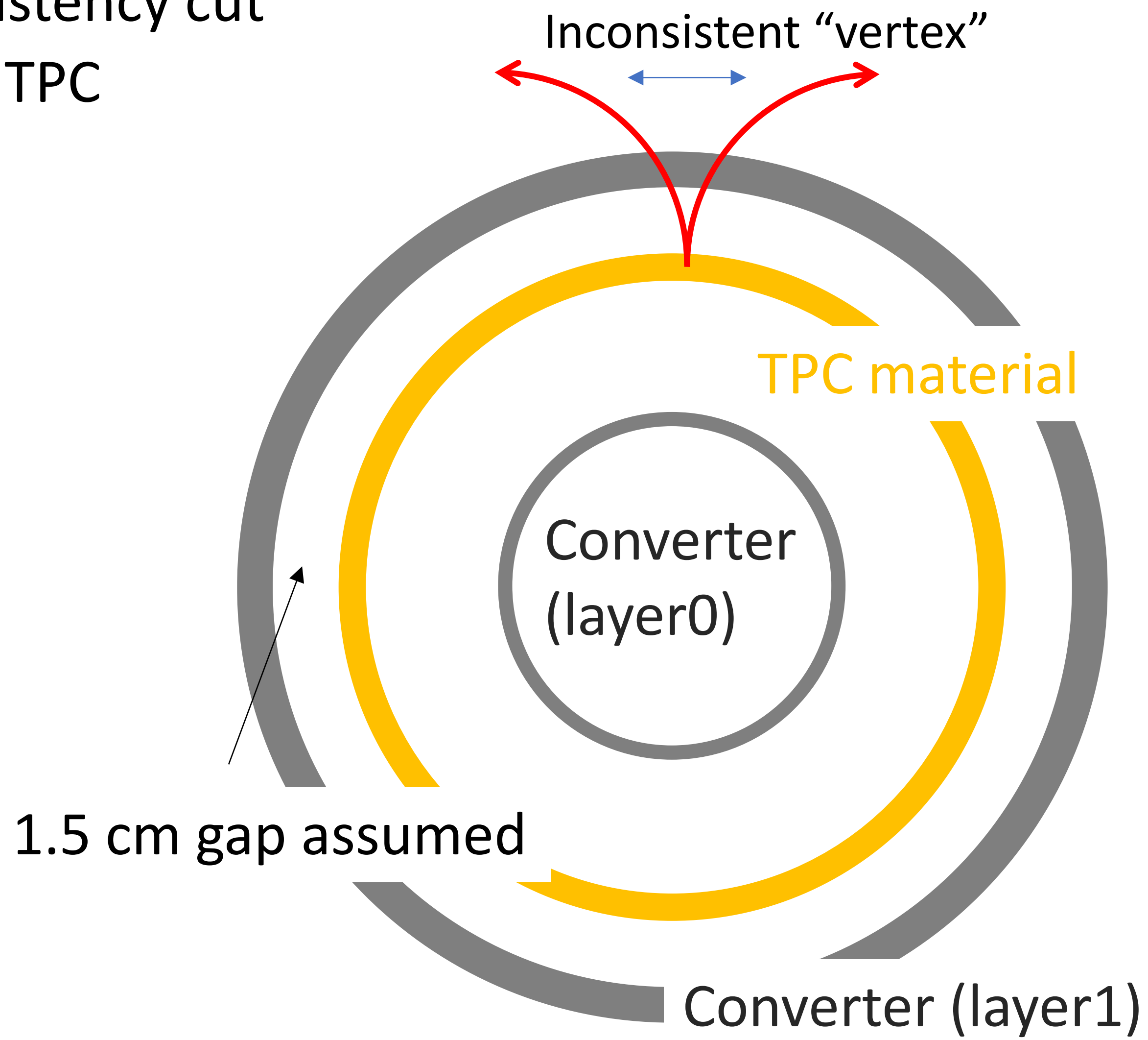
→ Trying to understand the impact on energy spectrum & efficiency



Case study with TPC-like material

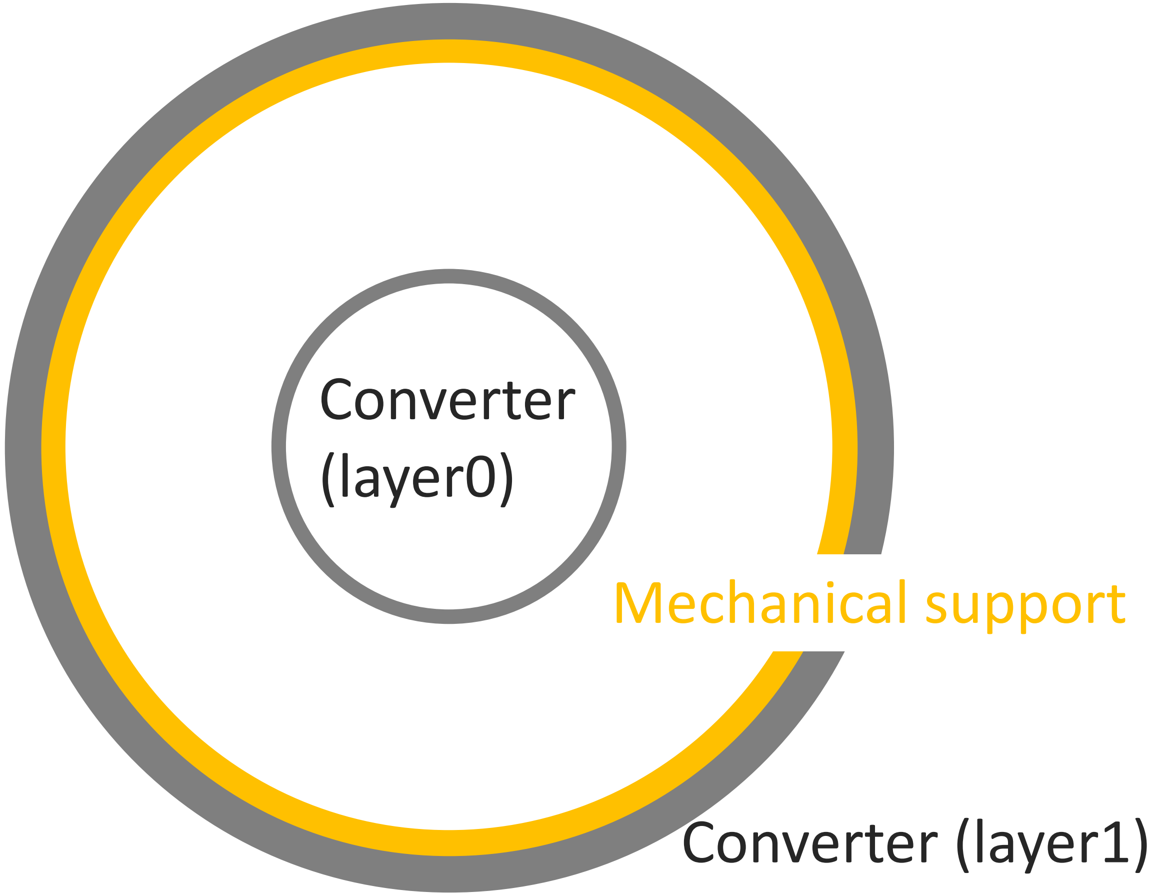
- With **gap b/w TPC material** & converter, **no impact on spectrum**
  - Because tracks are discarded by position consistency cut
  - Just results in inefficiency when converted on TPC
  - (Copper implemented in this case study)

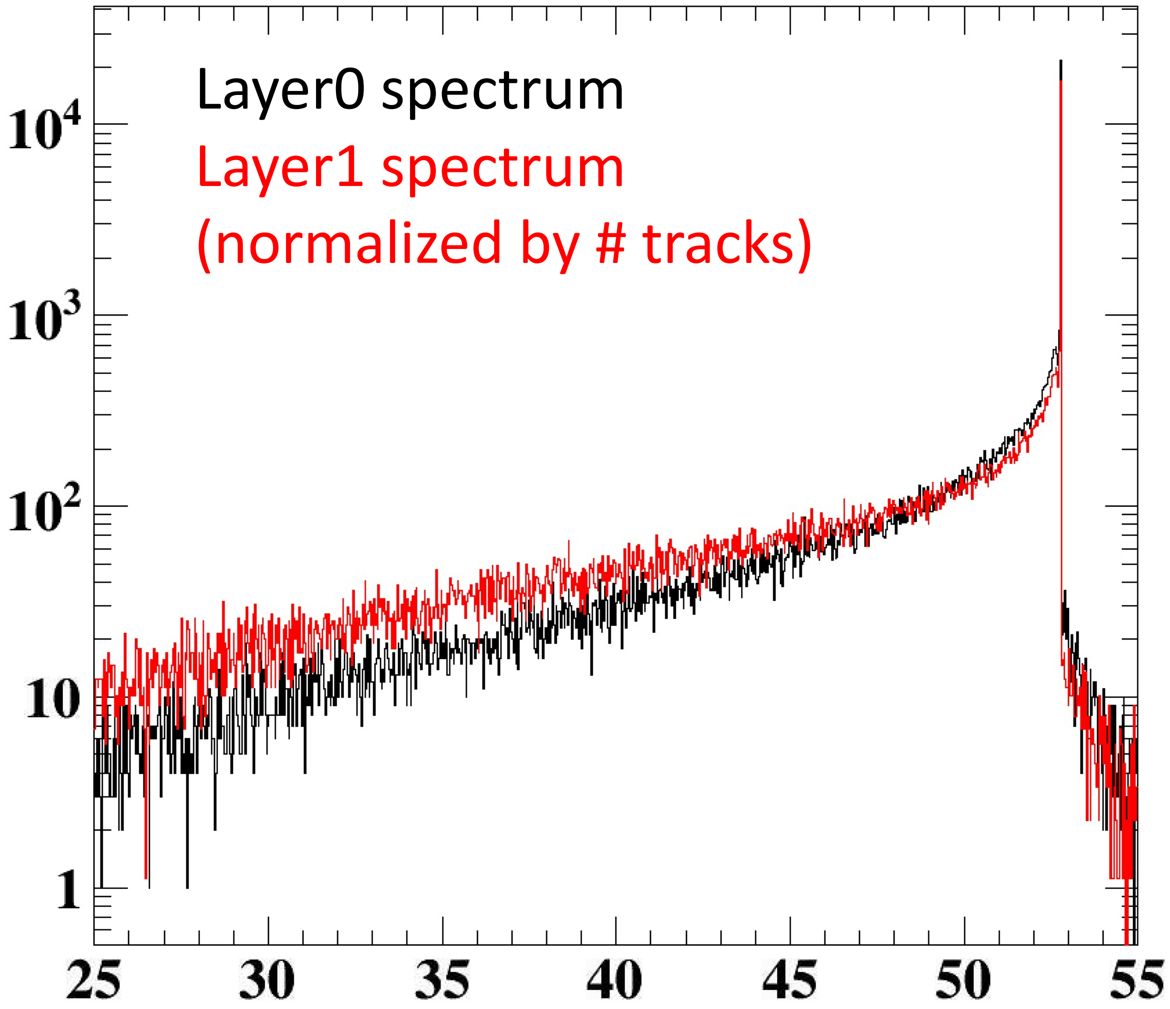




Case with support-like material

- Simulated with additional material **attached to** converter
  - Increase in the very long tail, though impact is limited on the main peak
  - Worth attention to mechanical structure





Efficiency breakdown for materialized layer

- Gap b/w material & converter changes tracking-based cut
- But, little impact on final energy-based cut

	Layer0	Layer1 1.5 cm gap	Layer0	Layer1 attached
All events	1000000 total		1000000 total	
Tracking cut	79182	**58665**	79484	**70457**
$\|\Delta E\|<100$ keV	25596	17552	25629	17590
$E_{smeared}$ in SR (52.2 – 53.4)	34146	23545	34064	23432

Our learnings here (though it is obvious once noticed):

- For spectrum study, we care only about mechanical support
- Other materials may only reduce the detection efficiency

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MEG II analysis in a nutshell

- Extended un-binned fit to estimate N_{sig}

Minor BG

$$\frac{e^{-(N_{\rm sig}+N_{\rm RMD}+N_{\rm Acc})}}{N_{\rm obs}!}\prod_{i=1}^{N_{\rm obs}}\left(N_{\rm sig}S(\vec{x_i}|X_{\rm TGT},\vec{q_i})+N_{\rm RMD}R(\vec{x_i}|\vec{q_i}))+N_{\rm Acc}A(\vec{x_i}|\vec{q_i}))\right)$$

  - List of observables: $E_e, E_\gamma, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}$ are essentially important

- To get branching ratio, normalize N_{sig} by k
  - $Br(\mu \to e\gamma) = N_{sig}/k$
  - k estimation by counting Michel positrons (and cross-checked by counting RMD samples)

Fit range in MEG II

- $|t_{e\gamma}| < 500$ ps
- $|\theta_{e\gamma}| < 40$ mrad, $|\phi_{e\gamma}| < 40$ mrad
- $52.2 < E_e < 53.5$ MeV
- $48 < E_\gamma < 58$ MeV

→ N_{Acc} is the number in this range
(This is NOT counting analysis)

Configuration for sensitivity study

- Software: Re-use of that for MEG
  - With only corrections for PDF parameters (i.e. resolution, spectrum, etc.)

- PDFs: Only E_γ PDF has been modified from MEG II so far
  - E_e, time, and angle distribution is assumed to be the same as MEG II (This clearly needs to be updated to be more realistic…To be discussed later)
  - E_γ PDF: Just used the spectrum presented earlier today (i.e. Naïve smearing with 200 keV is adopted)
  - Fit range is changed only for E_γ : $48 < E_\gamma < 58$ MeV → $52.2 < E_\gamma < 53.4$ MeV

- Sensitivity definition in MEG
  - Median of upper limits among pseudo-experiments with zero signal

Approach to estimate statistics

- N_{Acc} relies on experience in MEG II
  - But, need to correct for the change in fit range for E_γ
  - $\frac{N_{Acc}}{k \cdot R_\mu} \sim 7.5\times10^{-19}$ for $48 < E_\gamma < 58$
    ($N_{Acc} \propto R_\mu^2$, but one of R_μ already absorbed in k, which is $k = R_\mu\, \epsilon_{eff}$)
  - For $52.2 < \mathrm{E}_\gamma < 53.4$ MeV, estimated to be $\frac{N_{Acc}}{k \cdot R_\mu} \sim 9.2\times10^{-21}$ ($N_{Acc} \propto \delta E_\gamma^2$)

- k: Normalization factor for $Br(\mu \to e\gamma) = N_{sig}/k$
  - $k = R_\mu \cdot T_{DAQ} \cdot \Omega_{geom} \cdot \epsilon_e \cdot \epsilon_\gamma \cdot \epsilon_{trg} \cdot \epsilon_{sel}$
  - $\Omega_{geom} = 0.85$: $|\cos\theta| < 0.85$ and 2π for ϕ (was 11% for MEG II)
  - $\epsilon_e = 0.6$ (same efficiency as MEG II at 4e7)
  - $\epsilon_\gamma = 0.1$ (c.f. single-layer converter gives 3.2% in $52.2 < \mathrm{E}_\gamma < 53.4$ after smearing)
  - T_{DAQ}: 10^7 sec/year

Estimated statistics

- Normalization vs beam rate
  - $k = R_\mu \times 5.1 \times 10^5$ / year
  - So, at 2×10^8 (10^9) beam intensity, $k = 1\times10^{14}$ (5×10^{14}) / year

- N_{Acc} at 2×10^8 (10^9)
  - $\frac{N_{Acc}}{k \cdot R_\mu} \sim 9.2\times10^{-21}$
  - $N_{Acc} = 184$ (4600) / year

Evaluate sensitivity to N_{sig},
Not sensitivity to branch

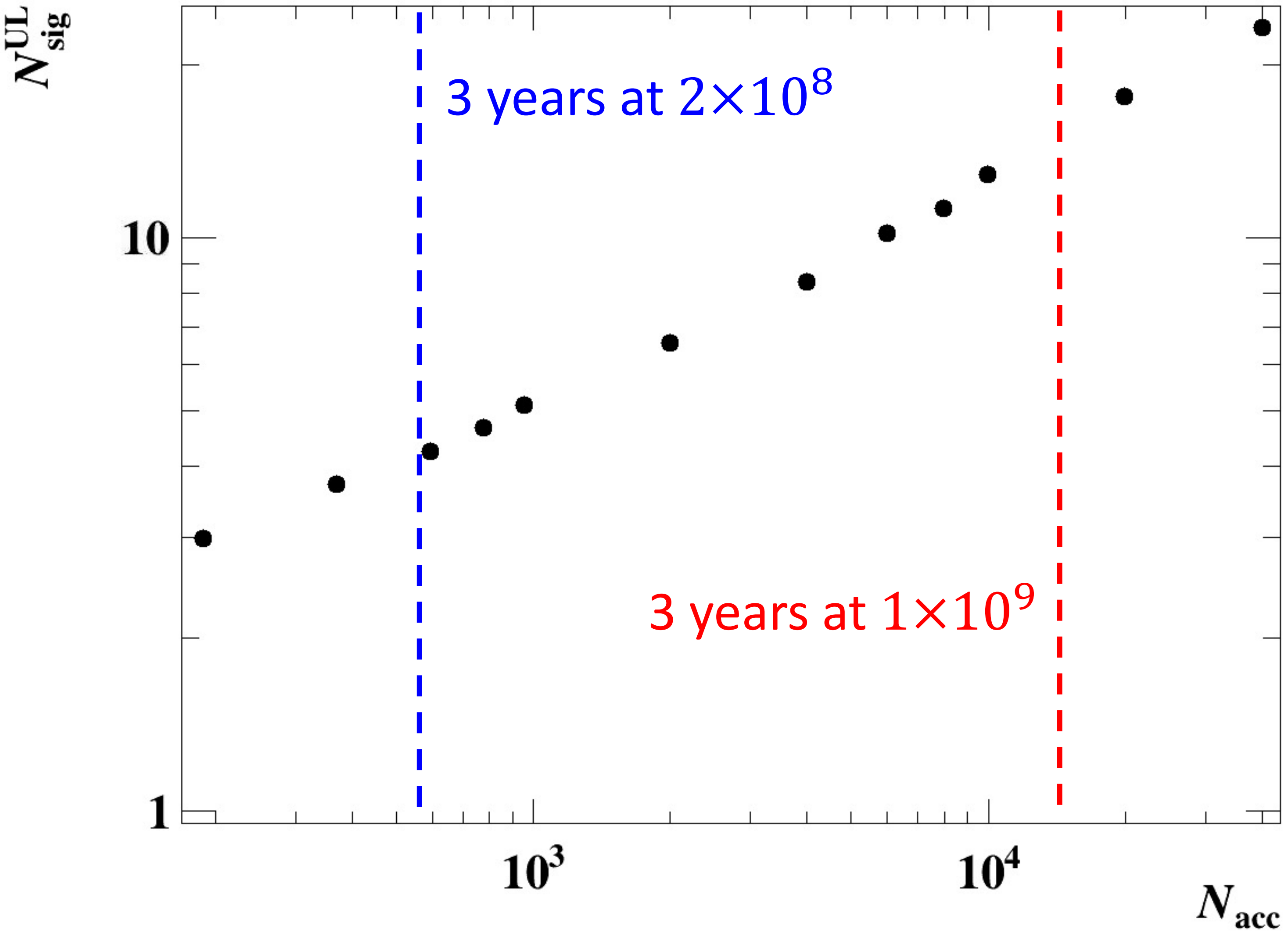
- Interpretable results at different rate
  - Above shows an example for 2×10^8 & 10^9
  - But, different rates can be similarly calculated once we obtain N_{sig}^{sens} vs N_{Acc} plot
  - In this way, not difficult to interpret with different efficiency assumptions

N_{sig}^{sens} vs N_{acc} calculation

- Interpretation depends on R_μ

- In 3 years at $2{\times}10^8$
  - N_{sig}^{sens} ~ 4.1 in 3 years at $2{\times}10^8$
  - k ~ $3{\times}10^{14}$
  - So, Br ~ $1.4{\times}10^{-14}$

- In 3 years at $1{\times}10^9$
  - N_{sig}^{sens} ~ 15 in 3 years at $2{\times}10^8$
  - k ~ $15{\times}10^{14}$
  - So, Br ~ $1{\times}10^{-14}$



Summary & Prospects

- Presented status of simulation works
  - Signal simulation with some new knowledge
  - Introduction of BG photon simulation
  - Introduction of event-mixing (pileup)
  - First look at material effects around converter
  - Sensitivity estimation

- Important studies/inputs to be more realistic
  - Pair tracker: Resolution for pairs & p_T cut assumption (5 MeV selected arbitrarily)
  - Active converter: E_{dep} resolution → Plan to include results of LYSO measurement
  - Positron performance (just MEG II performance is now assumed now)
  - Position distribution of muon decay (so far, only simulated muon decays at the origin)

Discussions towards strategy input

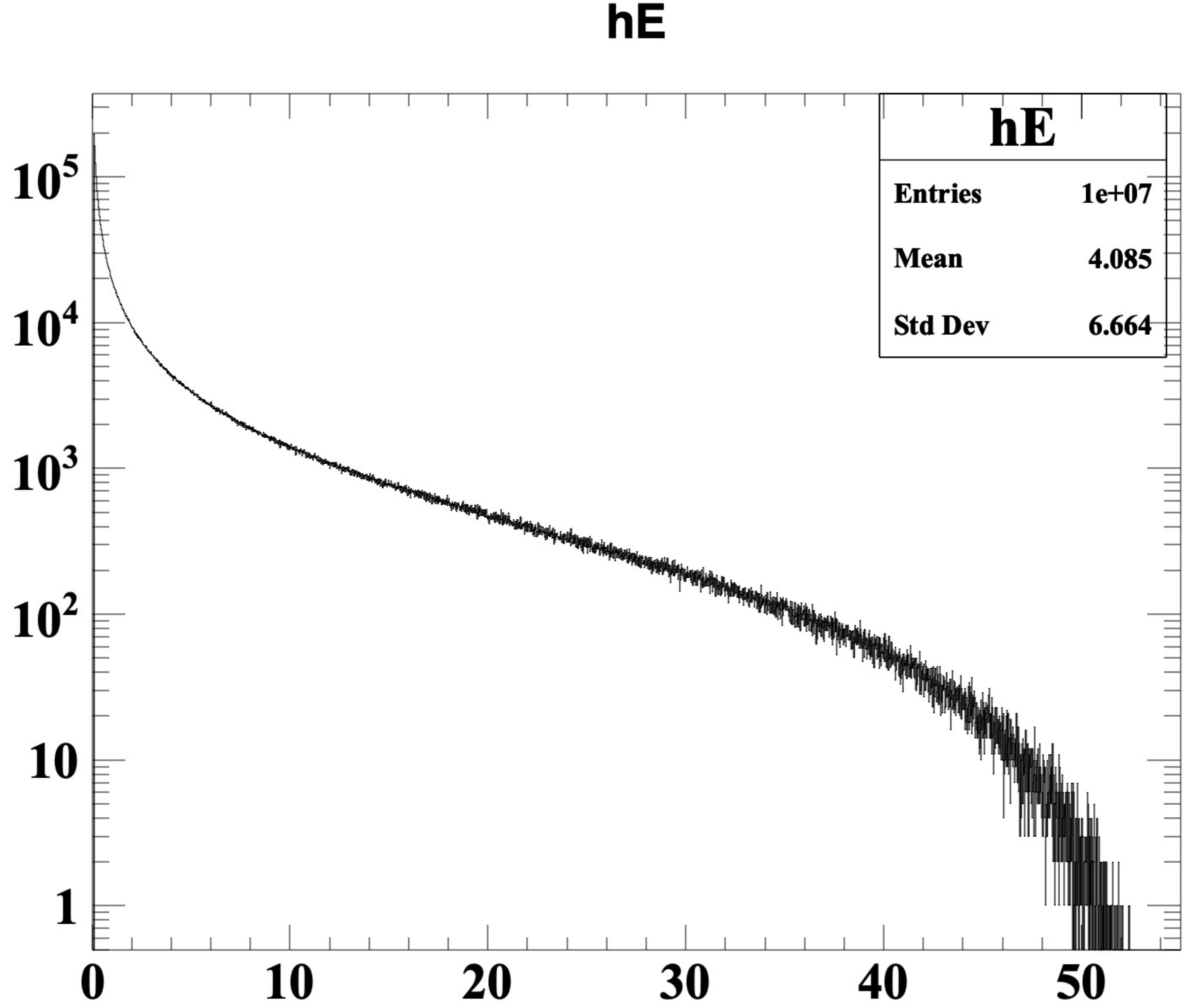
- Inputs to the community needed by Feb/Mar next year
  - What will we claim? (Will we include sensitivity, etc?)
  - How much sophistication will be desired with our simulation?
  - And how much can we do in reality?

- Time scale for our studies
  - To run from GEANT4 to sensitivity, at least one month would be necessary
    (And, of course, there are MEG II works as well)
  - By Jan, we aim to get some results from beam test data collected this year
  - What about tracker? Can we include tracker simulation in this time scale?
  - And what about positron resolution?: $\sigma_{t_e}, \sigma_{p_e}, \sigma_{\Theta_e}, \sigma_{x_e}$, etc.
  - Target? Beam profile?

Backup

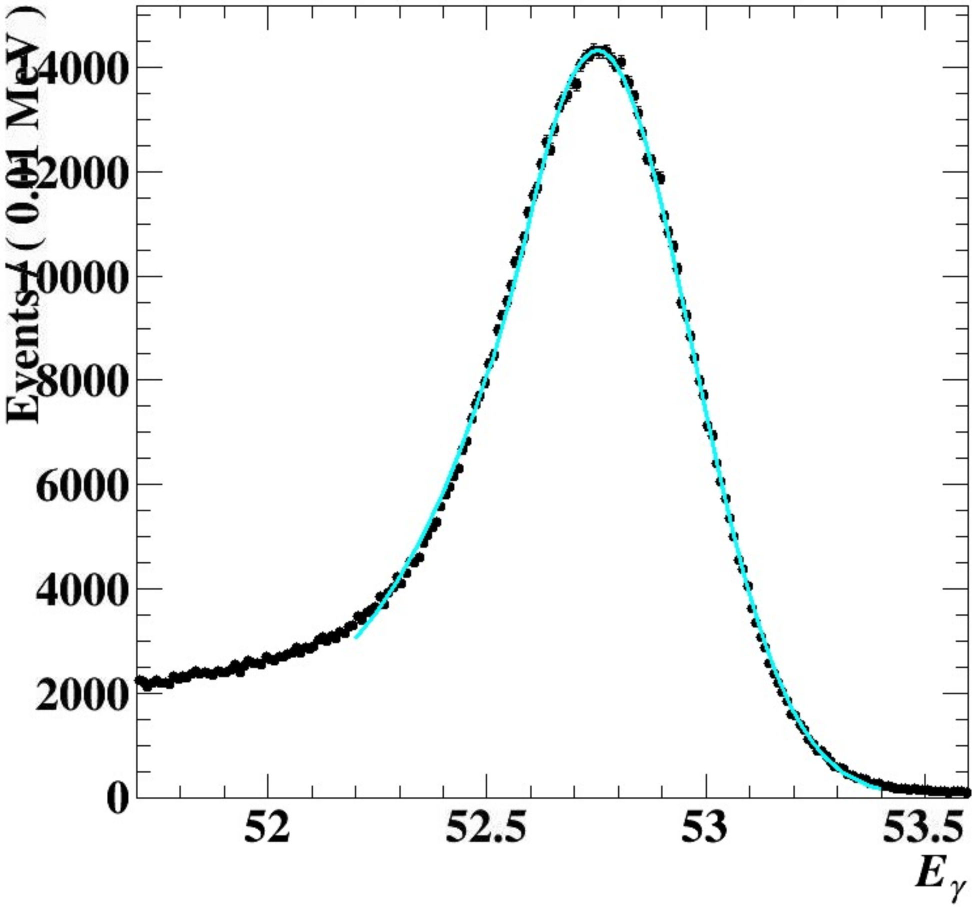
Generated RMD kinematics

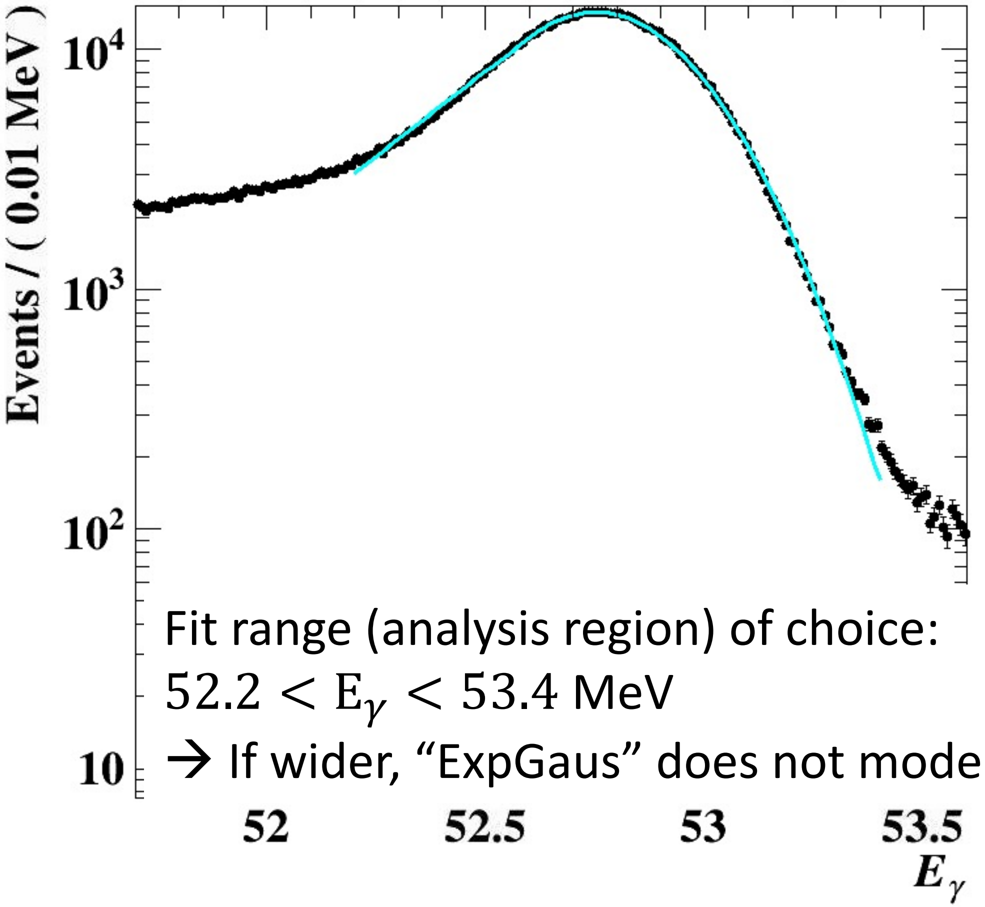
- 100 keV cut on E_γ



Fit region for sensitivity study

- Modeling: Working on the same framework for MEG II
  - Signal modeled with ”ExpGaus”: Gaussian + exponential low-energy tail
  - BG modeling based on MC spectrum + additional Gaussian smearing





Fit range (analysis region) of choice:
$52.2 < \mathrm{E}_\gamma < 53.4$ MeV
→ If wider, “ExpGaus” does not model well