中国散裂中子源
Chinese Spallation Neutron Source

Presentation on MELODY 2023 Workshop
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Physical Design and Simulation Study of Searching for MuMubar on MELODY

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2023. 11. 06

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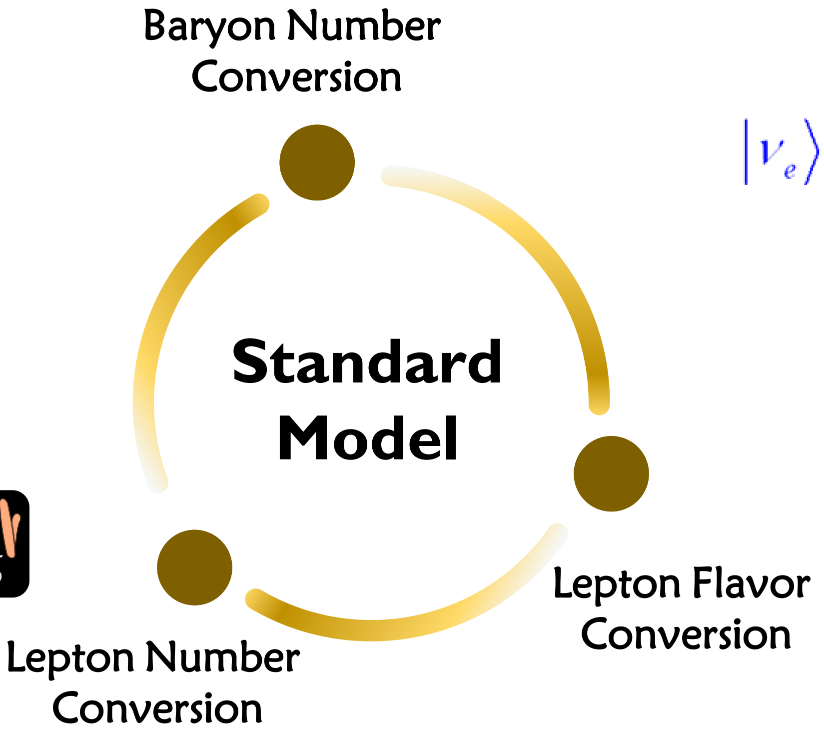
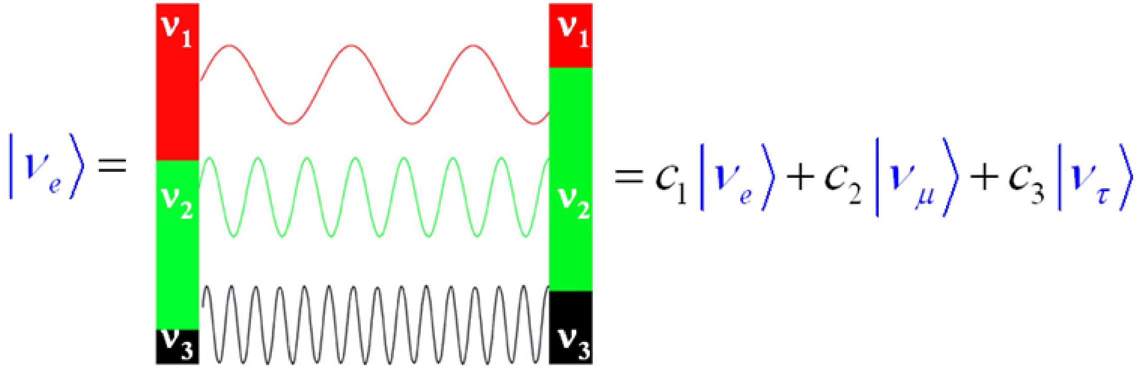
1.1 The cLFV prediction





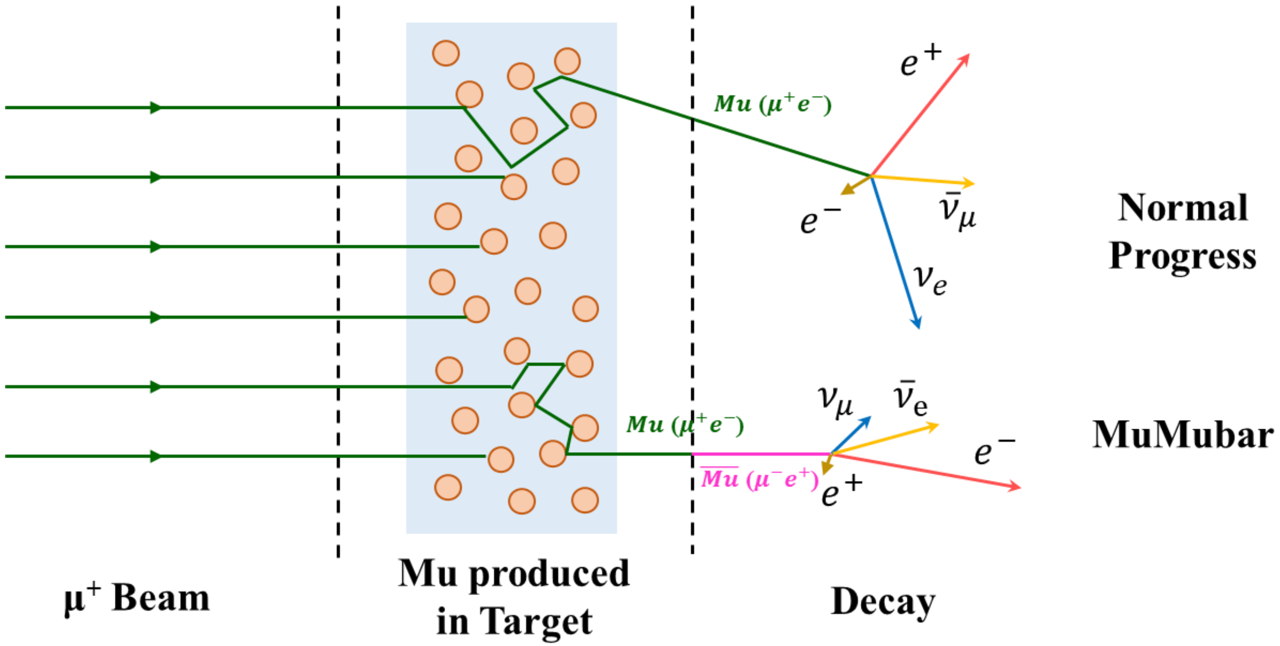
- Neutrino Oscillation indicated Neutral Lepton Flavor Violation.
- However, charged Lepton Flavor Violation (cLFV) is not observed so far.
- Searching for cLFV is an interesting topic.

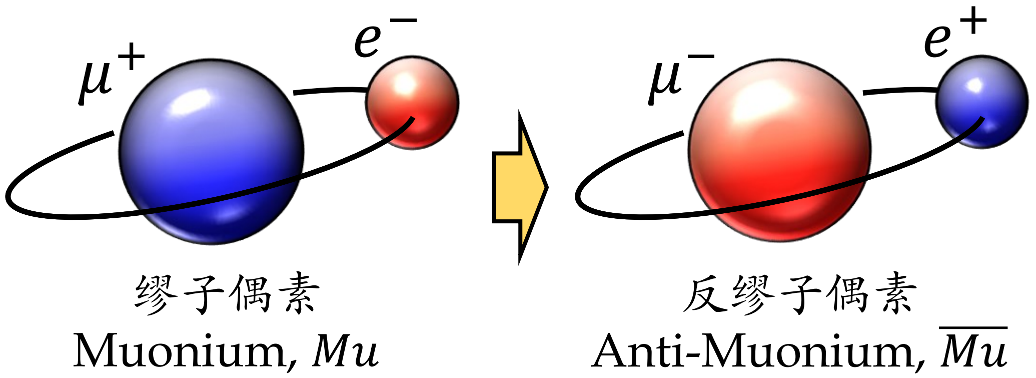
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$
- $\mu^+ \to e^+ e^+ e^- \nu_e \bar{\nu}_\mu$

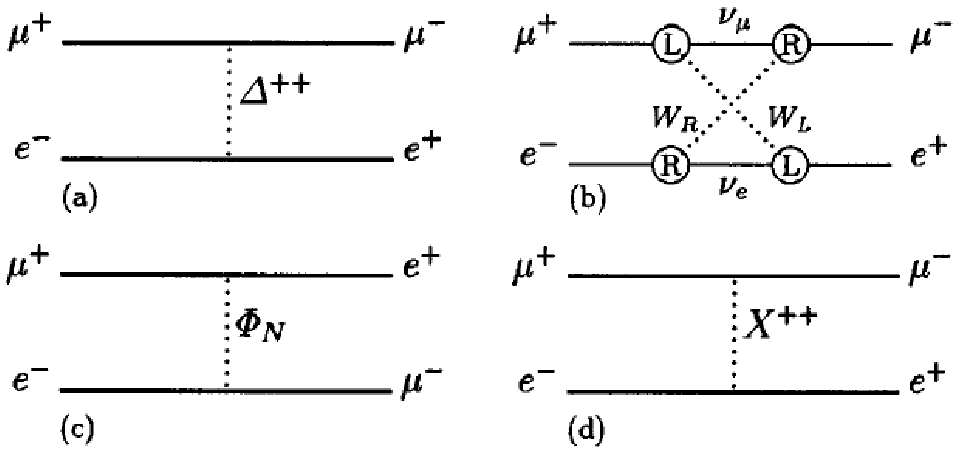
Beyond Standard Model

- $\mu^+ \to e^+ e^+ e^-$
- $\mu^+ \to e^+ \gamma$
- $\mu^- N \to e^- N$
- $\mu^+ e^- \to \mu^- e^+$

1.2 What is MuMubar?

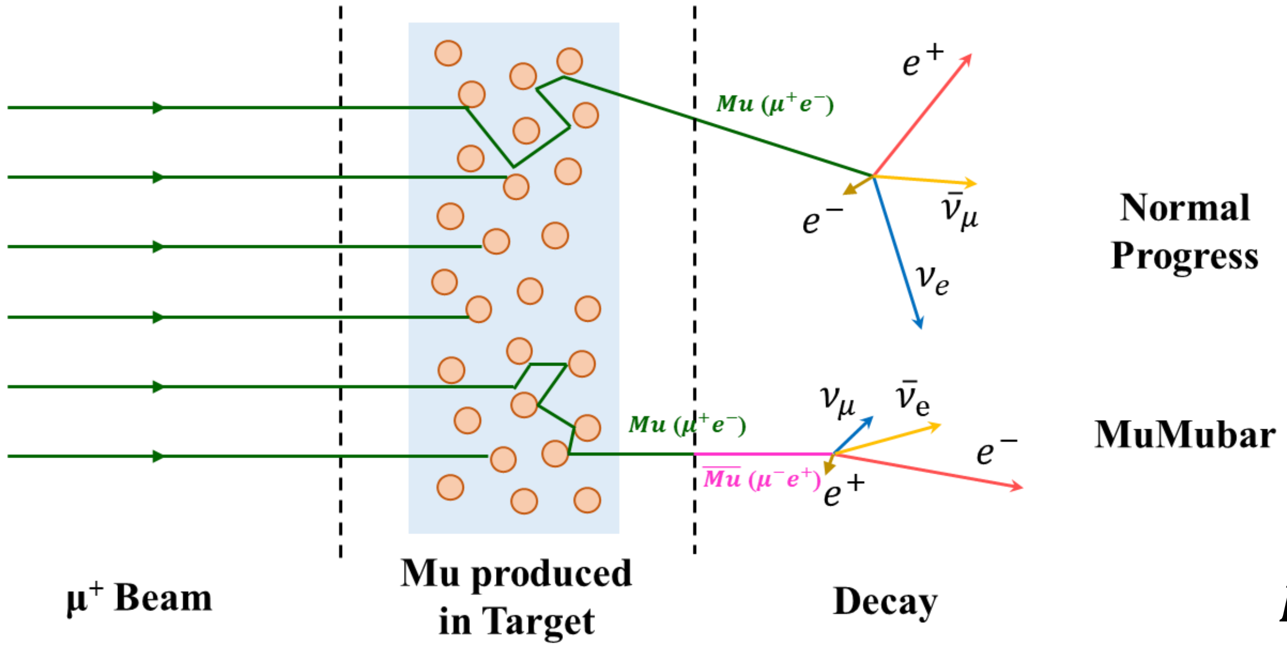


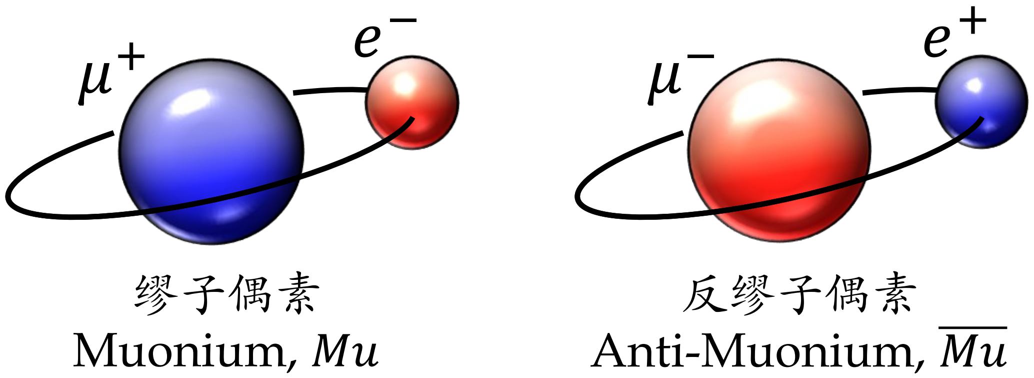




- MuMubar is one of possible way of cLFV.
- By capturing a e^-, μ^+ would become to muonium.
- Muonium might become to Anti-muonium if muon and electron exchange charge.
- Lepton flavor doesn't conserve in this progress. 2 units of lepton flavor are violated.

1.3 How to Search for MuMubar?





Track Electron Ek = 13.5 eV

***Mu* Decay** $\mu^+ + e^- \rightarrow e^+\nu_e\bar{\nu}_\mu + e^-$

$\overline{Mu}$ Decay $\mu^- + e^+ \rightarrow e^-\bar{\nu}_e\nu_\mu + e^+$

- Mu and $\overline{Mu}$ are unstable and will decay.
- Their decay products owns opposite charges.
- Searching for MuMubar is searching for the decay products with $\overline{Mu}$ decay characteristics.

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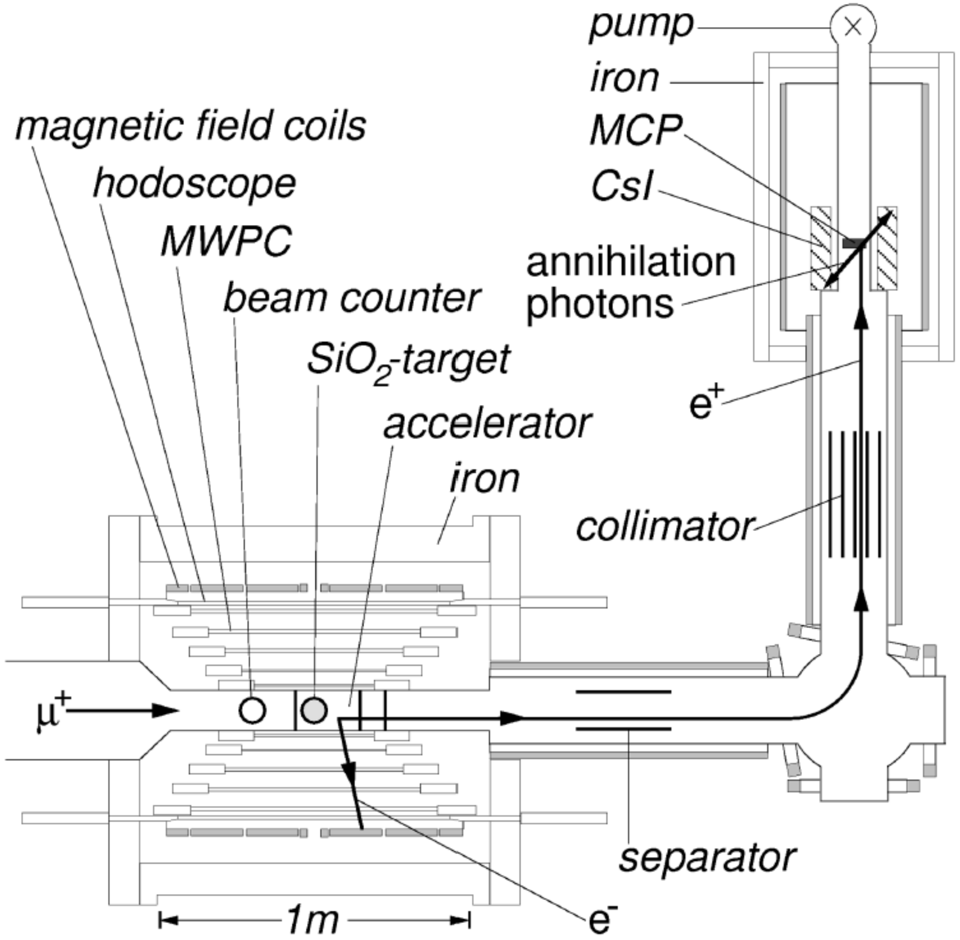
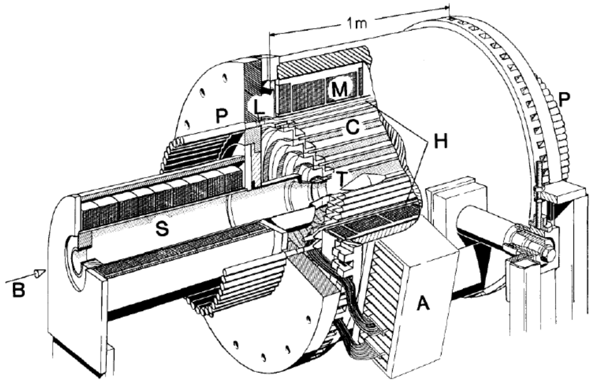
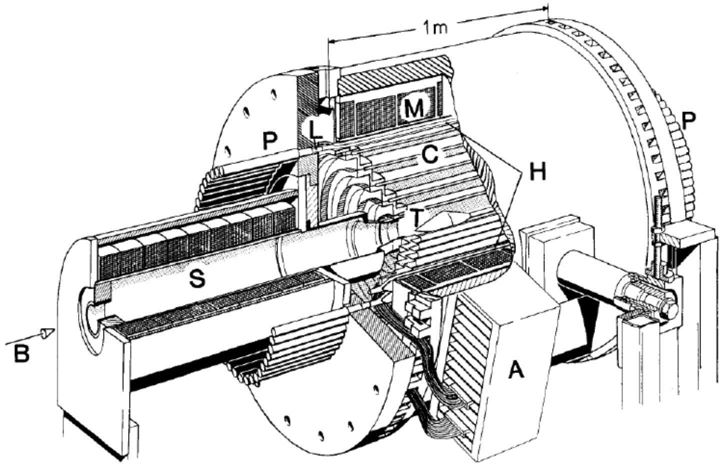




- MACS, 1998, @PSI-πe5， $8\times10^{6}\mu/s$， CM
- Decay Electron Spectrometer (DES):
  - ➢ MWPC + Scintillator + 0.1 T Mag Field
- Track Electron Spectrometer (TES):
  - ➢ MCP + Scintillator
- 0.1 T Mag Field guild track electron to TES
- $P < 8.3\times10^{-11}$ with 180 days observing.

2.2 Ways to improve MACS – muon source



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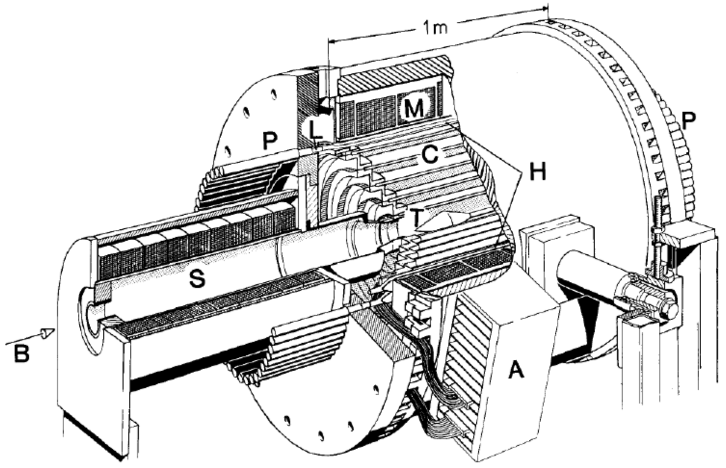
More Muon Exposure

- Longer observing time
  - ➢ 180 days to 3 years
- More intensive muon source
  - ➢ $8 \times 10^6\ \mu/s$ to $10^{10}\ \mu/s$

2.2 Ways to improve MACS – spectrometer



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More Muon Exposure

- Longer observing time
  - 180 days to 3 years
- More intensive muon source
  - $8 \times 10^6\ \mu/s$ to $10^{10}\ \mu/s$

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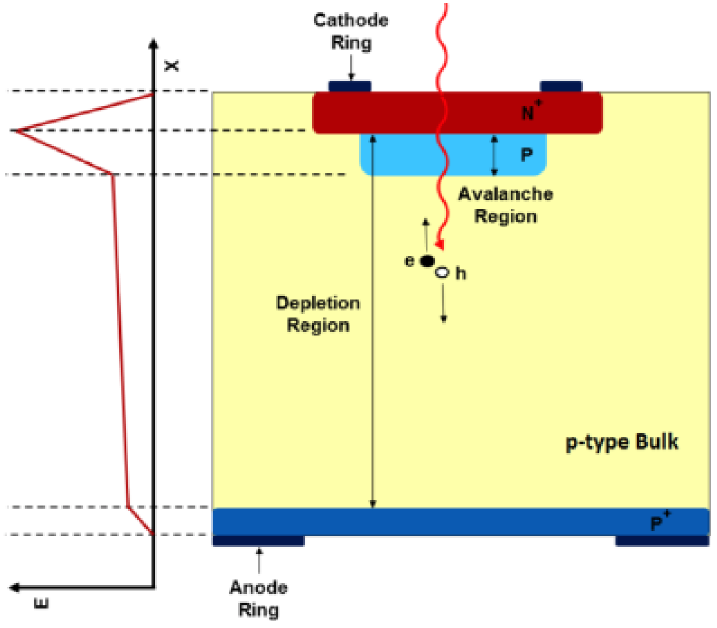
More Sensitive Detector

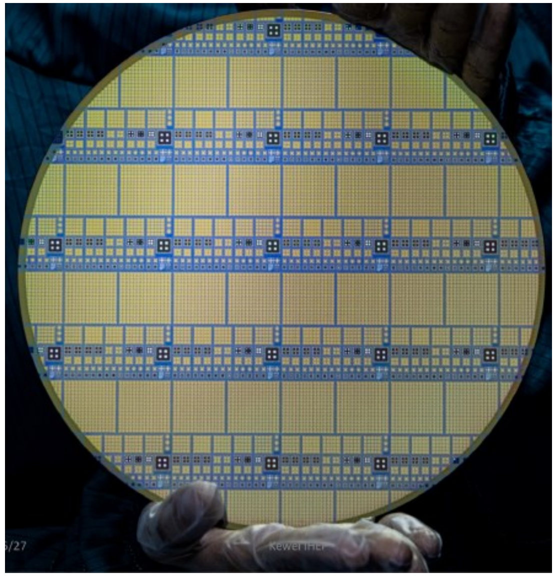
- Need a detector with:
  - Excellent timing sensitivity.
  - Small mass budget.

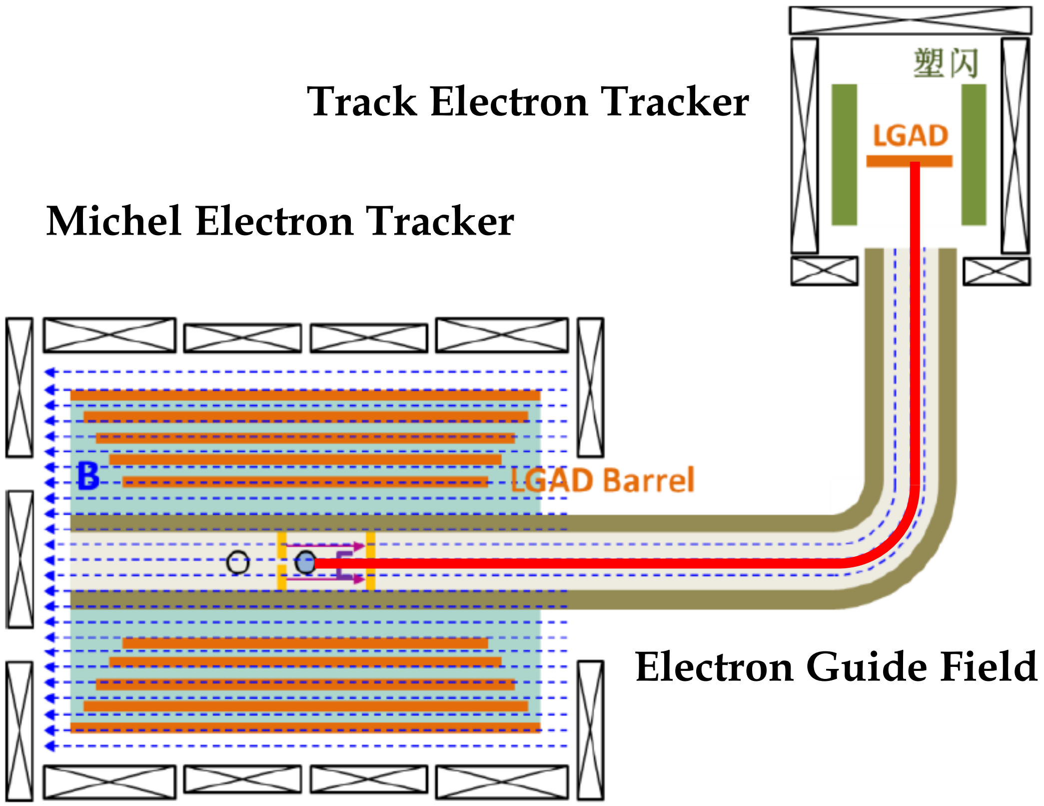
2.2 Ways to improve MACS – LGAD

- Low Gain Avalanche Diode (LGAD).
- Developed for ATLAS and CMS.

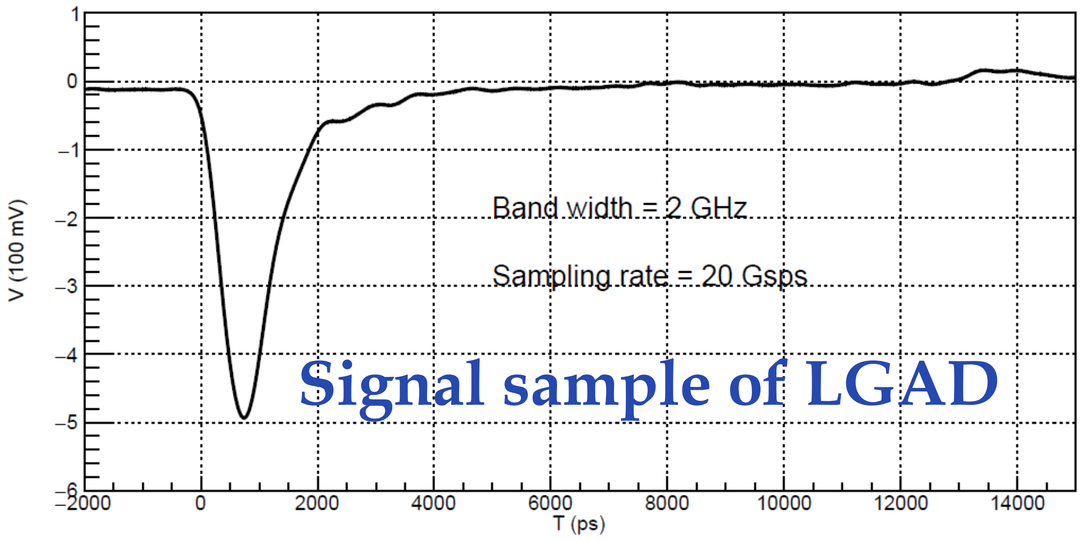
Depth	Signal Width	Temporal Res.	Seperation Size
50μm	2~3ns	30 ps	$1.3 \times 1.3\ mm^2$







Construction of Novel MuMubar Spectrometer
（Not to scale）



- Replace the MWPC with LGAD as the Michel Electron Tracker (MET).
- The Advantages：
  - 2 order of magnitude better on temporal resolution.
  - High feasibility, no risk of strike.

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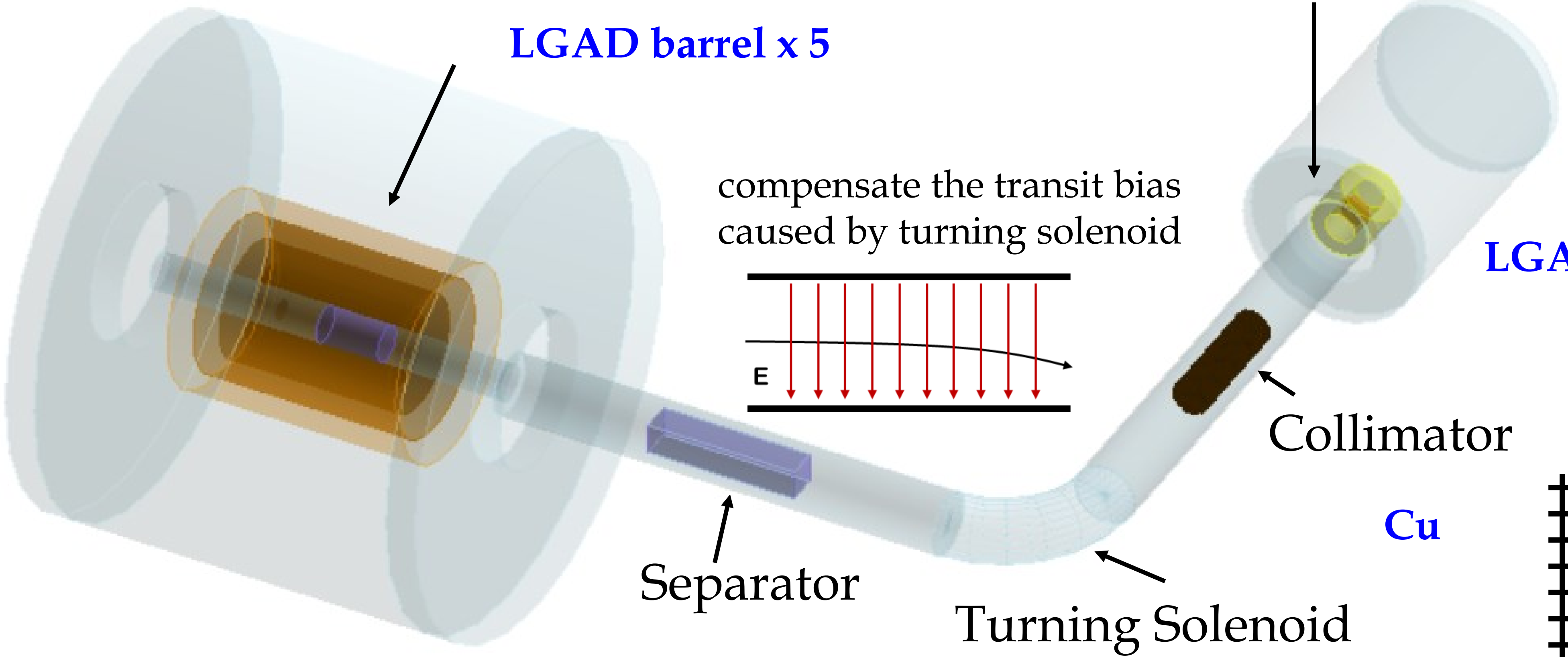
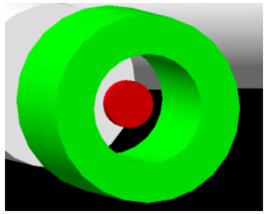
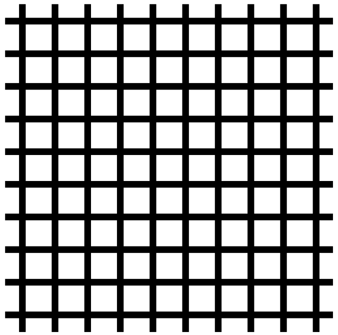
3.1.1 Geant4 Modeling

Based on MACS

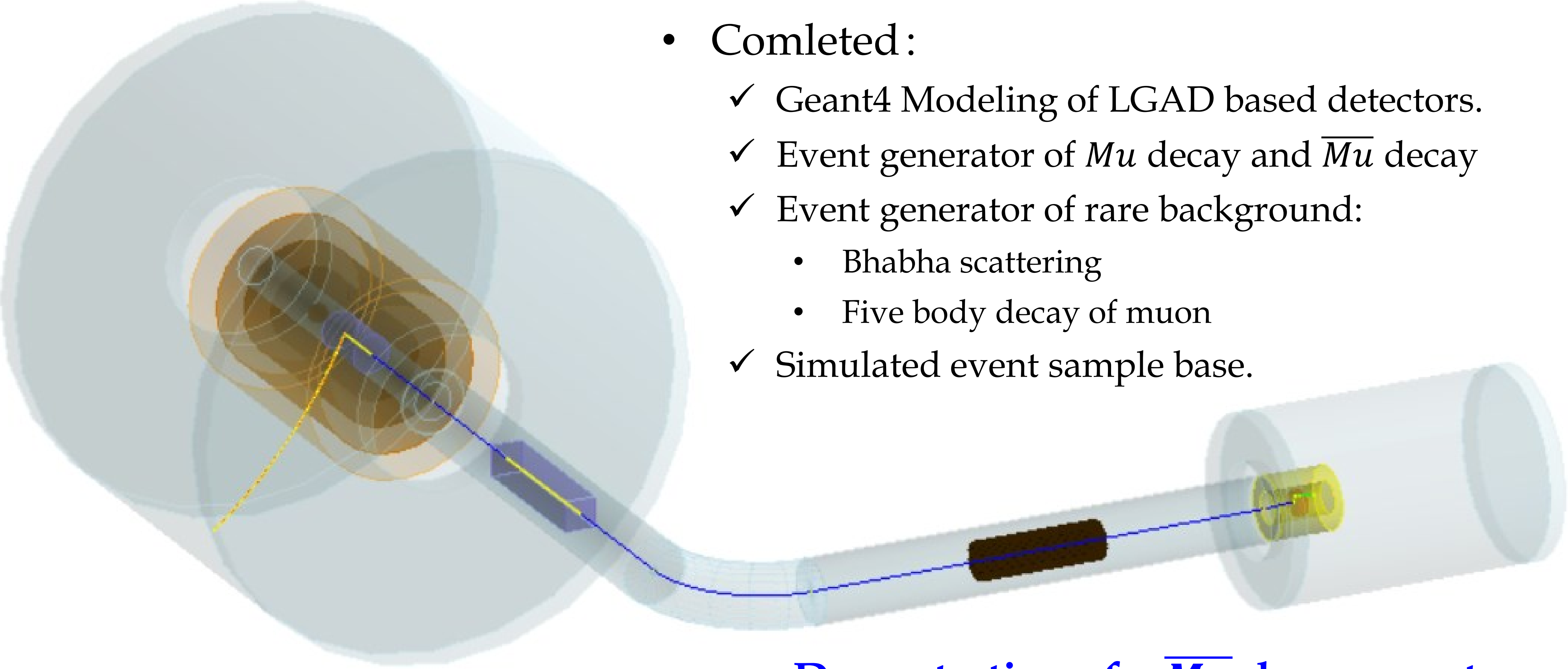






- EM field： 0.1T guide Mag-field + 8 kV static Elec-field

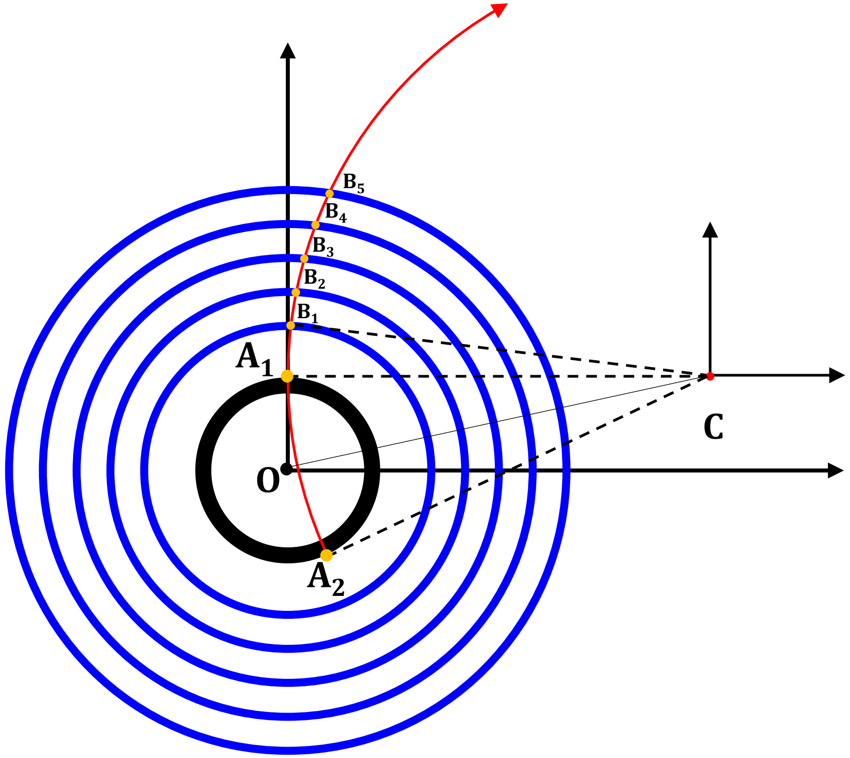
3.1.2 Simulation Study

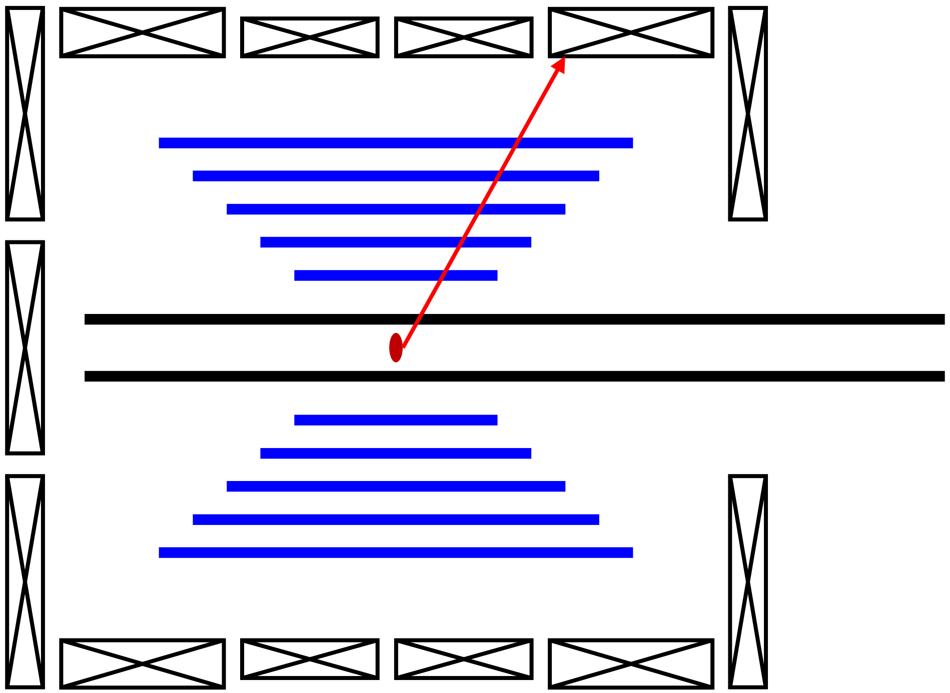


- Comleted：
  - ✓ Geant4 Modeling of LGAD based detectors.
  - ✓ Event generator of Mu decay and $\overline{Mu}$ decay
  - ✓ Event generator of rare background:
    - Bhabha scattering
    - Five body decay of muon
  - ✓ Simulated event sample base.

Demostration of a $\overline{Mu}$ decay event

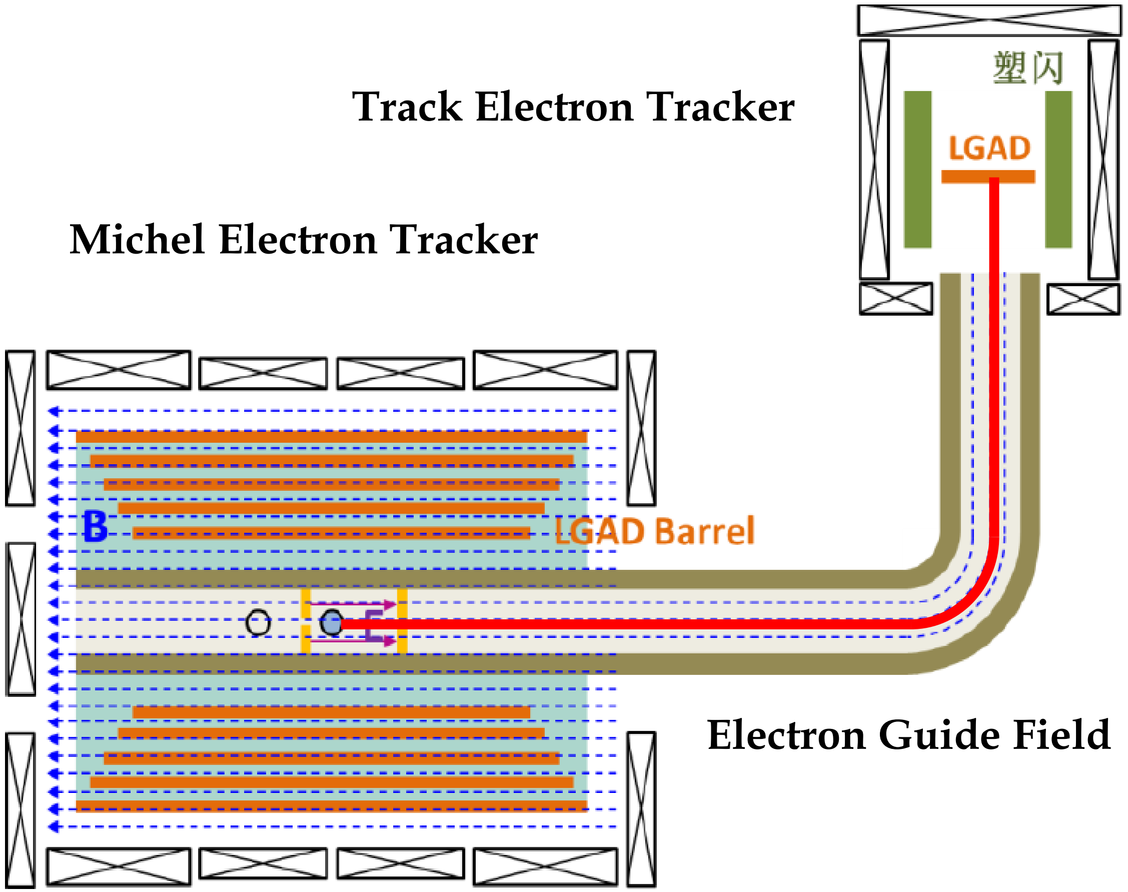
3.2.1 DE track reconstruction

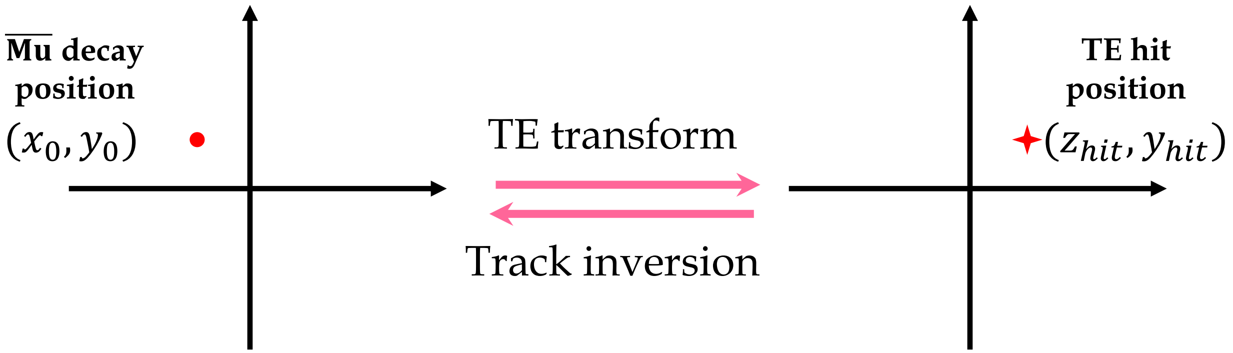




The decay electron is reconstructed by the hits on MET barrels.

3.2.2 TE Track Reconstruction





The TE track is reconstructed by the inversion of hit on TE detector

3.3 Performance of the spectrometer

Items		Performance
Michel Electron Tracker (MET)	MET volume efficiency	~76%
	MET positioning resolution	1 mm
	MET hit time resolution	30 ps
Track Electron Guide Tube	Positron transformation efficiency	~80%
Track Electron Detector (TED)	TED detection efficiency	~70%
	TED positioning resolution	1 mm
	TED hit time resolution	30 ps
Electrons vertex reconstruction	Michel electron energy rec resolution	1.6 keV
	Track electron vertex rec resolution in XY	1.3 mm
	Track electron vertex rec resolution in Z	1.6 mm

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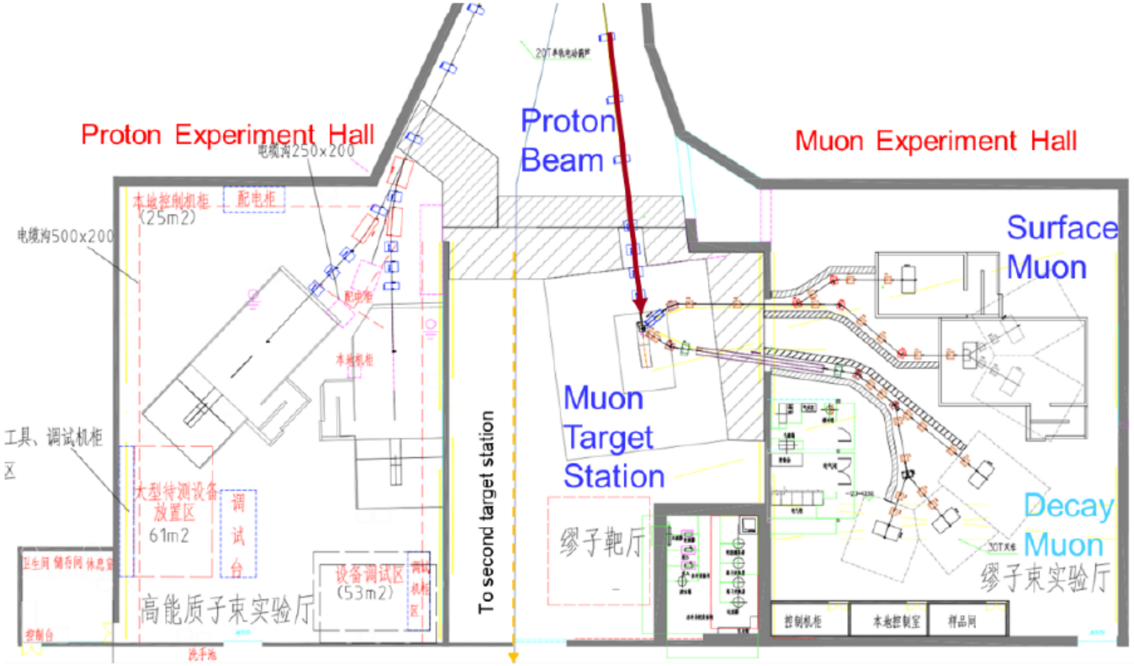
4.1 The MELODY

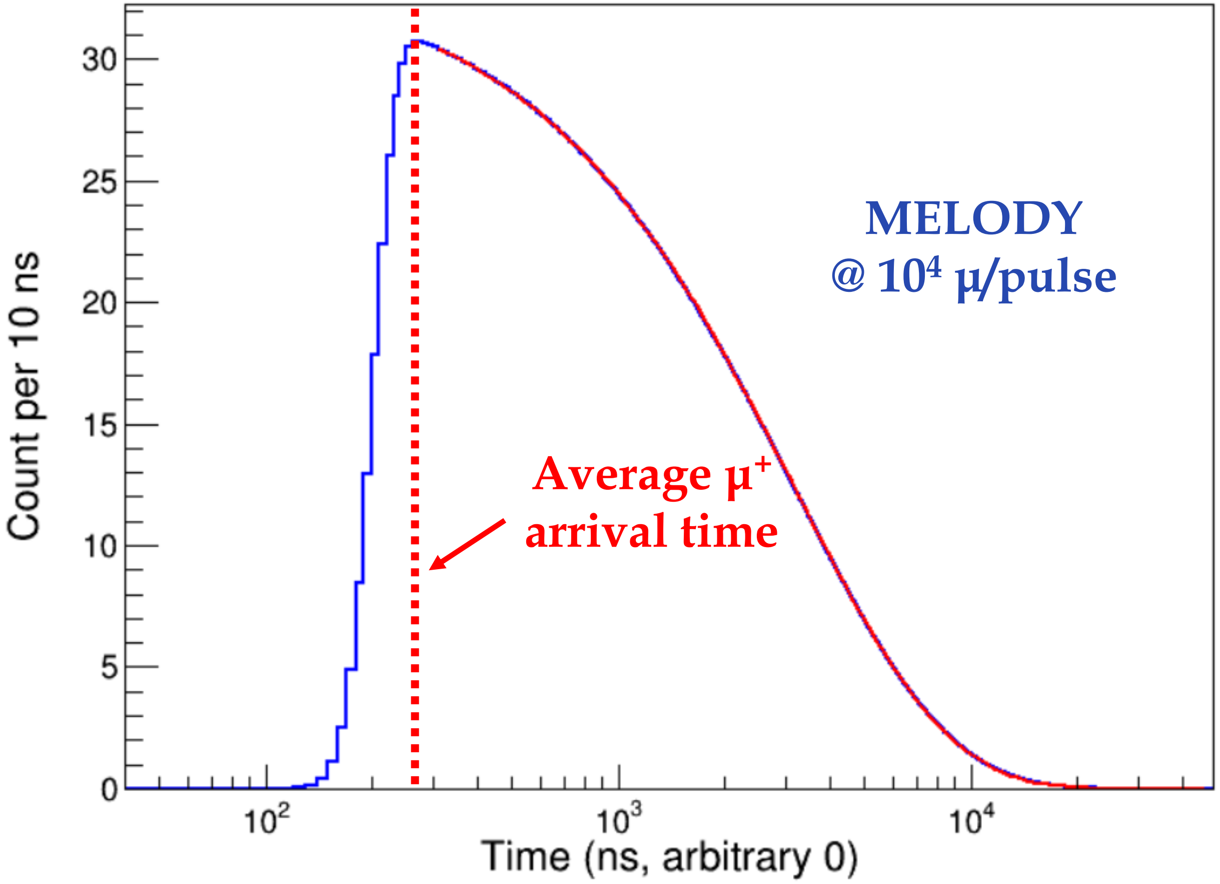
Parameters	Values
Pulse Frequency	1Hz
μ rate in single pulse	10^5 ~ 10^7, adjustable
Full width of single pulse	150 ns



- One of the test beam to be built in CSNS-II project.
- Pulsed surface muon source， 1Hz.
- We hope to test and tune our spectrometer on MELODY.
- Deal with the pile-up signals applying intensive μ source.

4.2 The Piled-up Signals

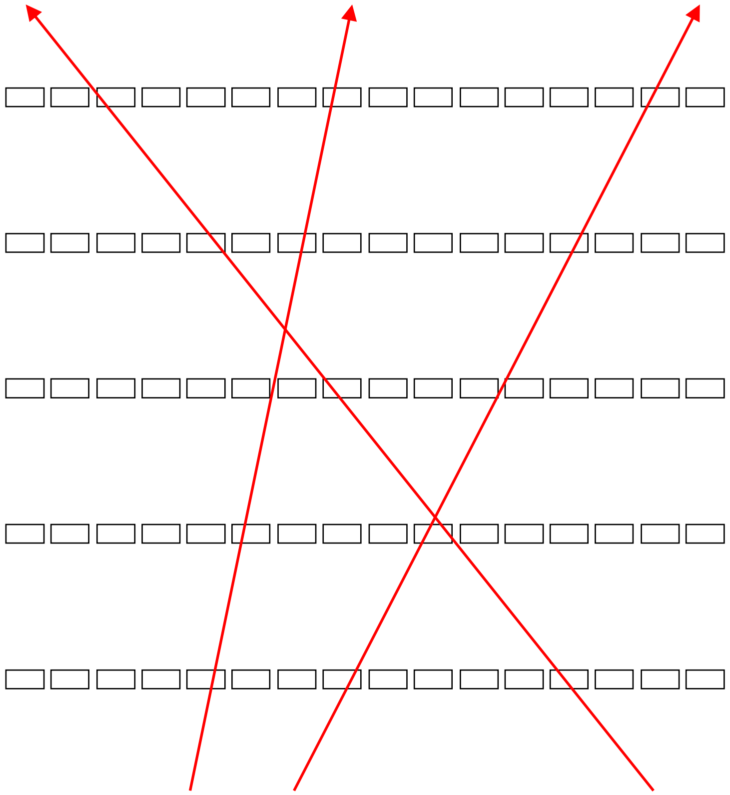
Time of Michel Electron Produced



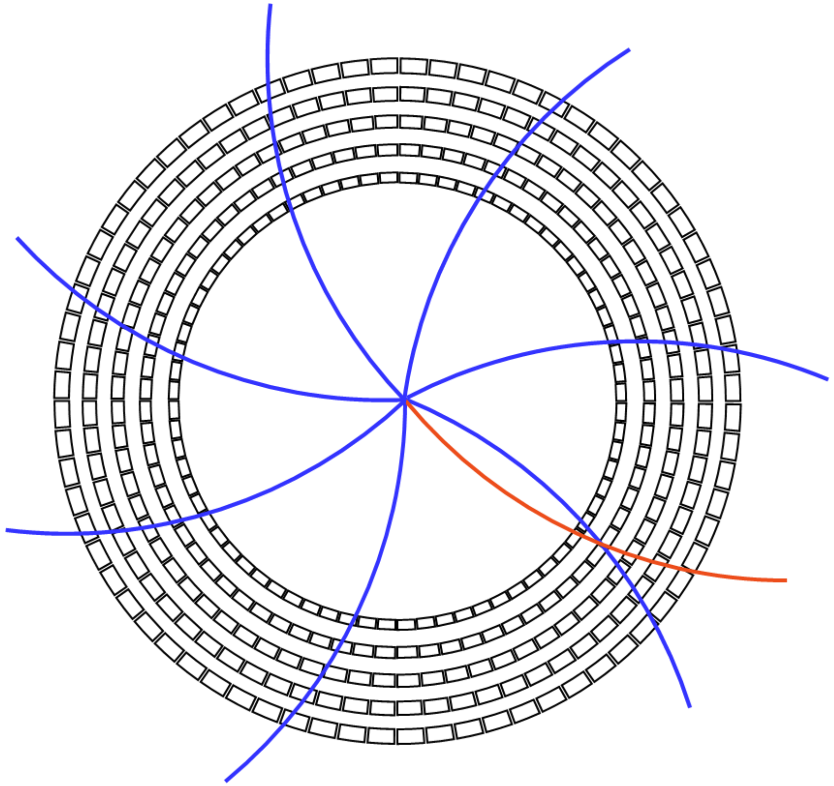
- Signals of Michel electron are too intensive, and pile up on the MET.
- Have to find the e^- from the massive e^+ signals.
- The gaseous detectors will be blind in this condition.
- The LGAD can provide high temporal resolution measurement, which is necessary to discriminate the massive piling up signals.
- **This is an important issue in this study.**

4.3.1 Steps to Resolve the Piled-up Signals

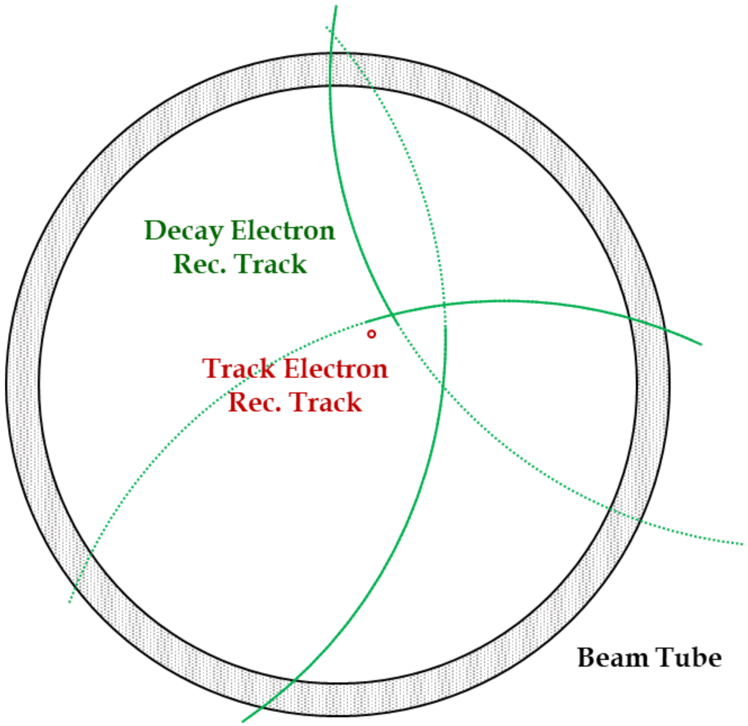
Track Separation

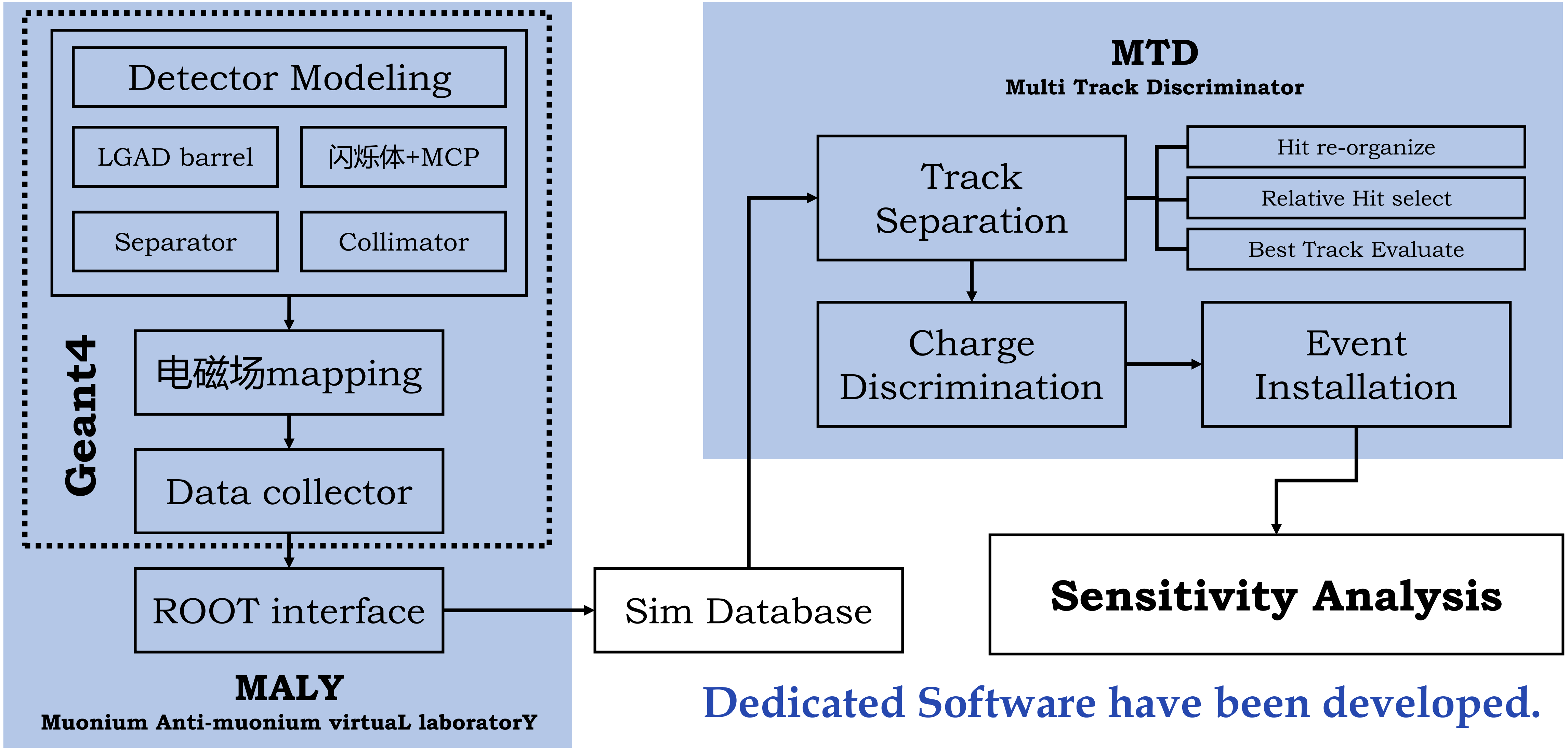


Charge Discrimination



Event Installation

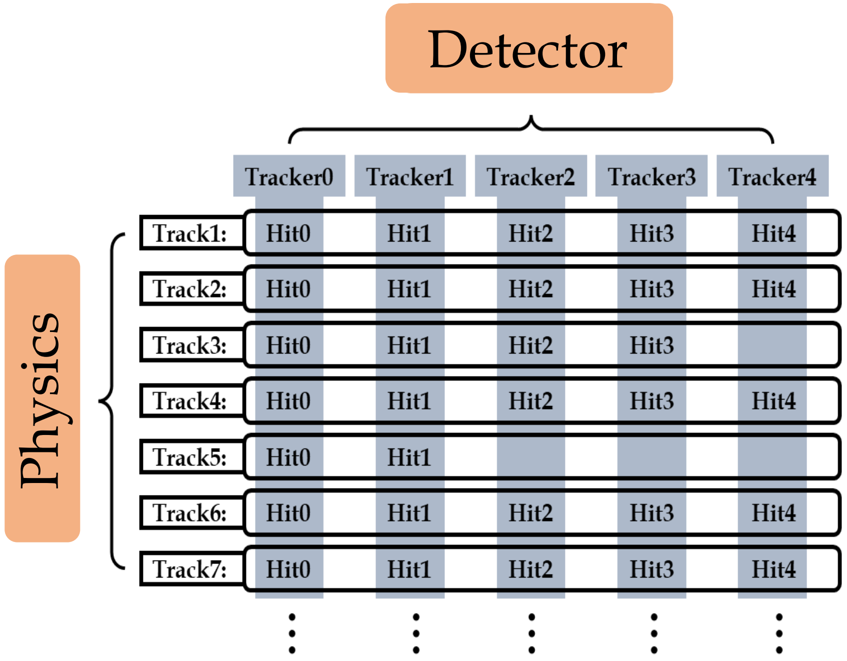


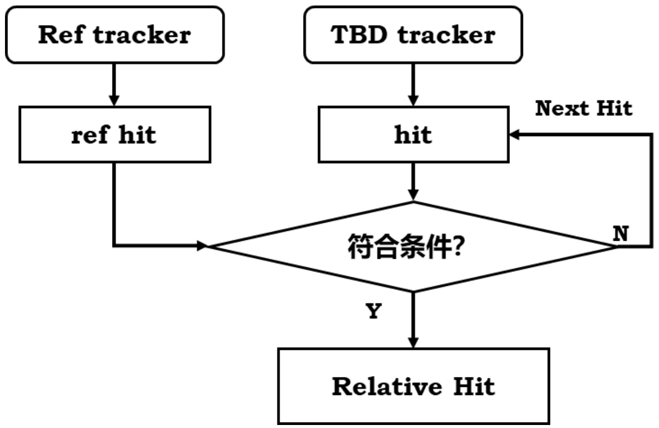


Dedicated Software have been developed.

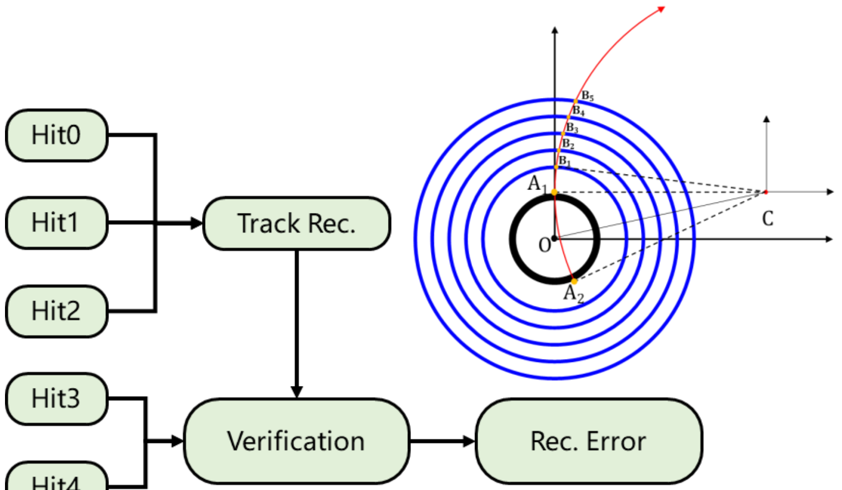
4.3.3 The Analysis Algorithm

Signal Transformation → **Hits Re-organization** → **Track Reconstruction**





- $0 < hitT - refT < 1.5$ ns
- $-15deg < hit\phi - ref\phi < 15$ deg



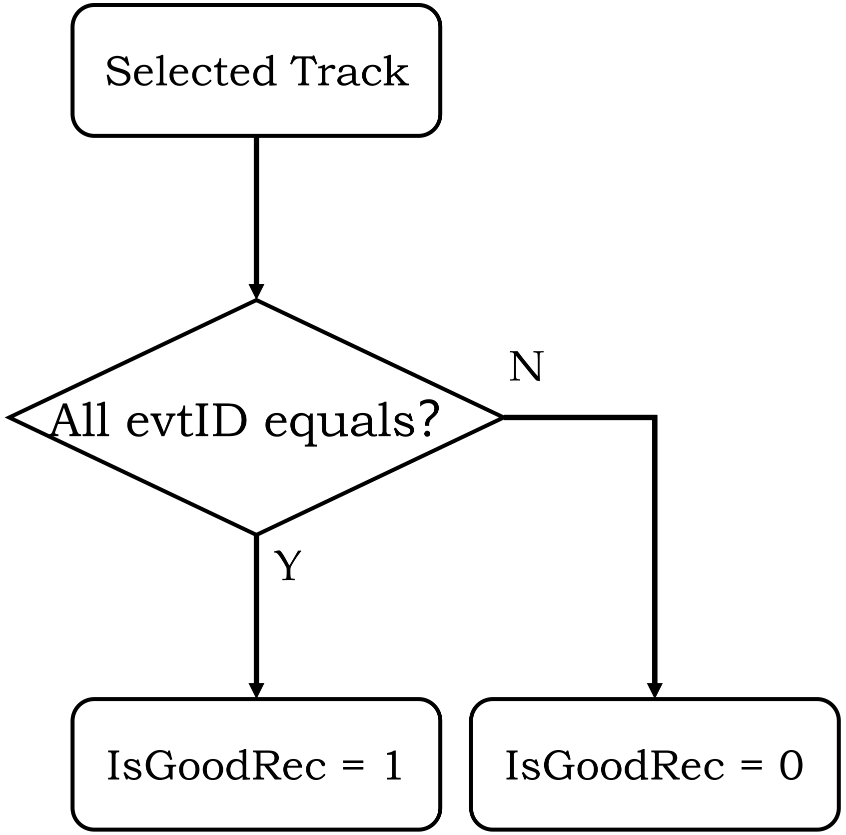
$$FOM_{rec} = \sqrt{\sum_{i=0}^{nHit}\frac{(Dist_i - R)^2}{nHit} + \sum_{i=0}^{nHit-1}\frac{(Z_i - Z_{trk})^2}{nHit-1}}$$

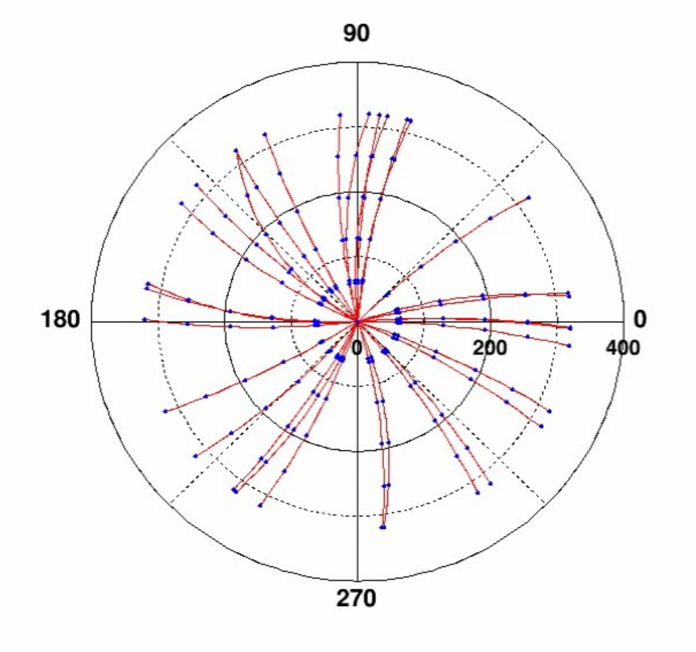
Transform MC to DET data | **Find the correlated hits** | **Select the best Rec. track**

4.4 Verification to the Reconstruction

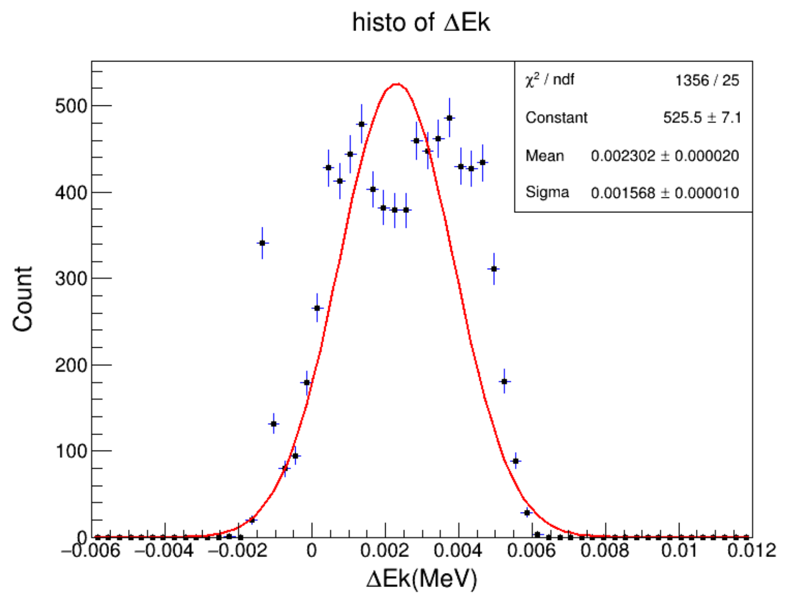
10000 ME/pulse

- The selected best rec. tracks are verified by event ID (MC truth).



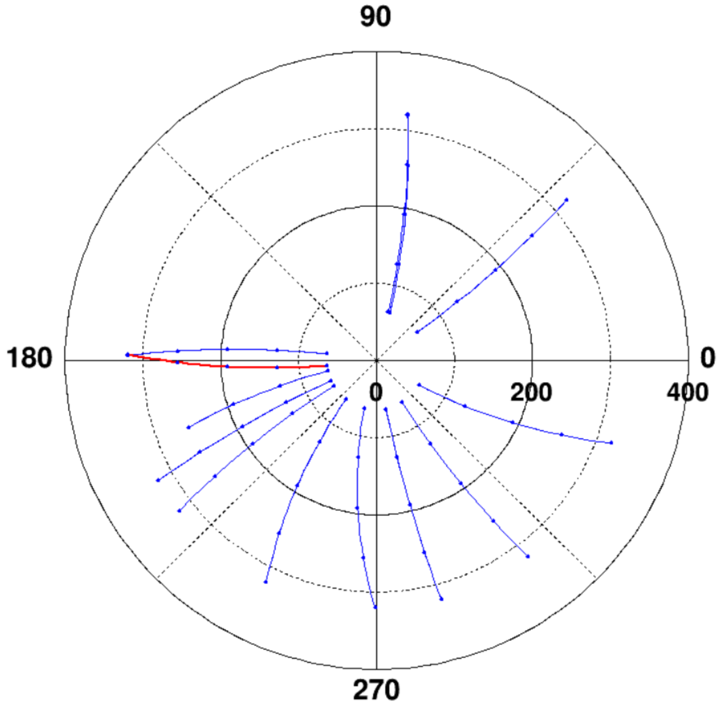


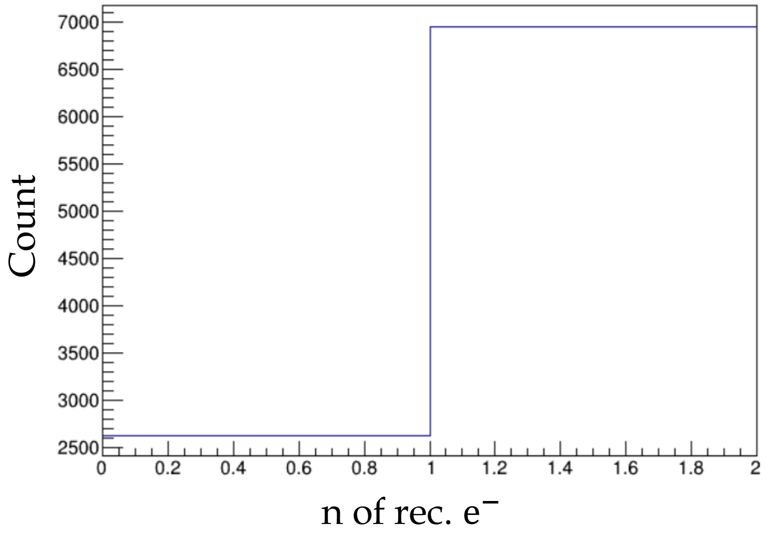
The Michel electron tracks are 100% well reconstructed



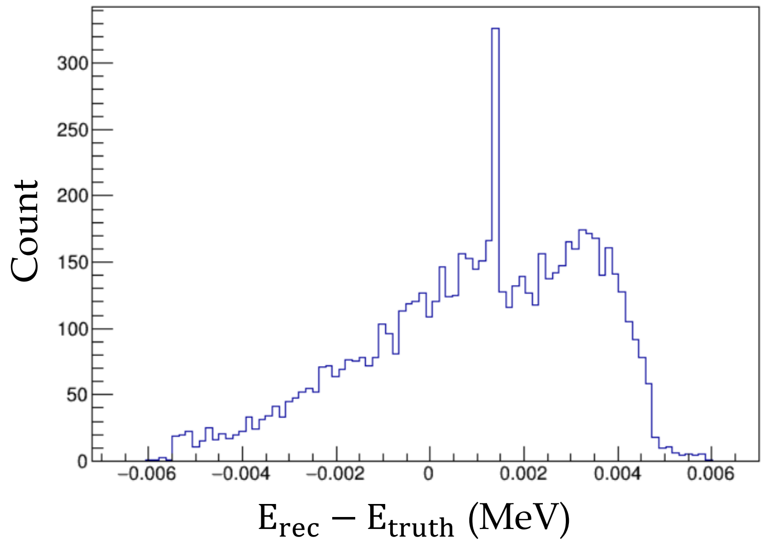
Rec. Michel electron Ek Bias: 2.3 keV, Res. 1.6 keV

- **(One $\overline{Mu}$ decay + 10000 Mu Decay) × 9576 pulse.**
- Totally 6945 in 7289 e^- tracks are successfully reconstructed. Eff = 95%.





Negetive M.E.
Rec. eff. = 95%

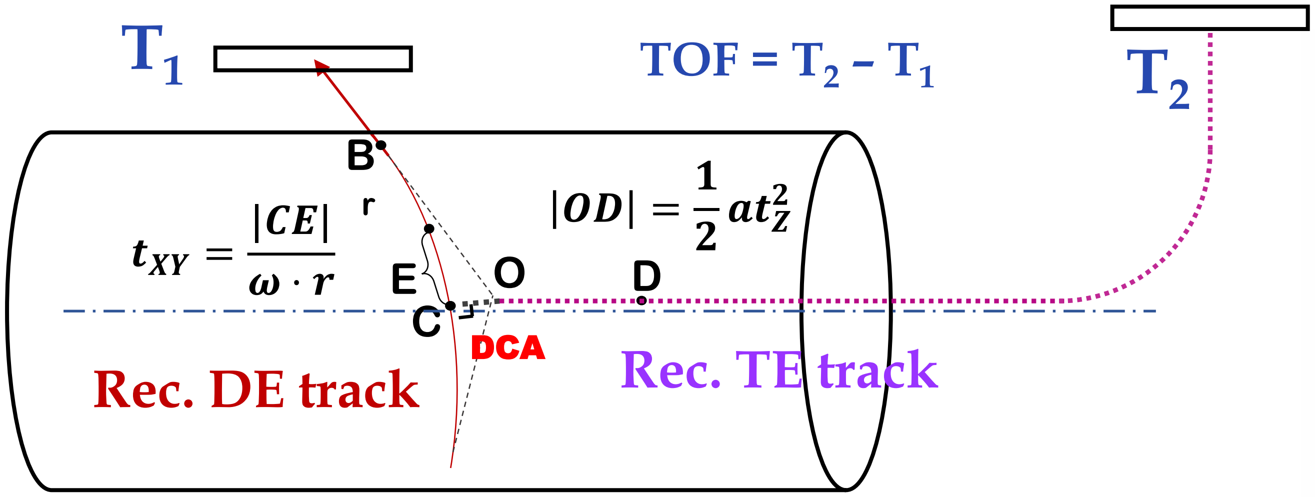


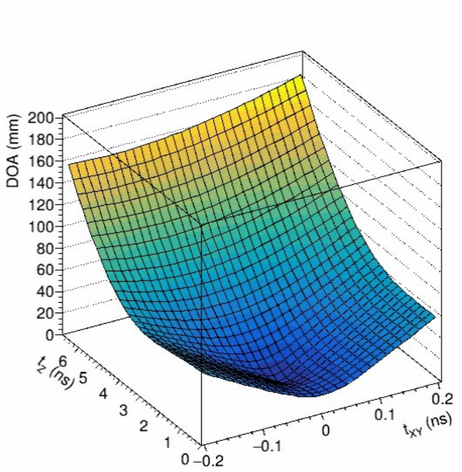
Negetive M.E.
Ek Rec. res. = 2.1 keV

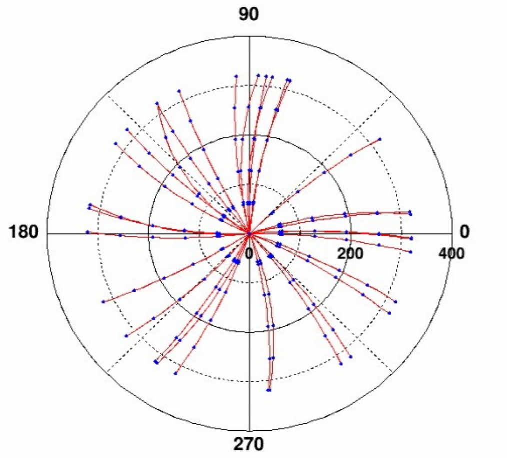
4.5.1 Selection Criteria

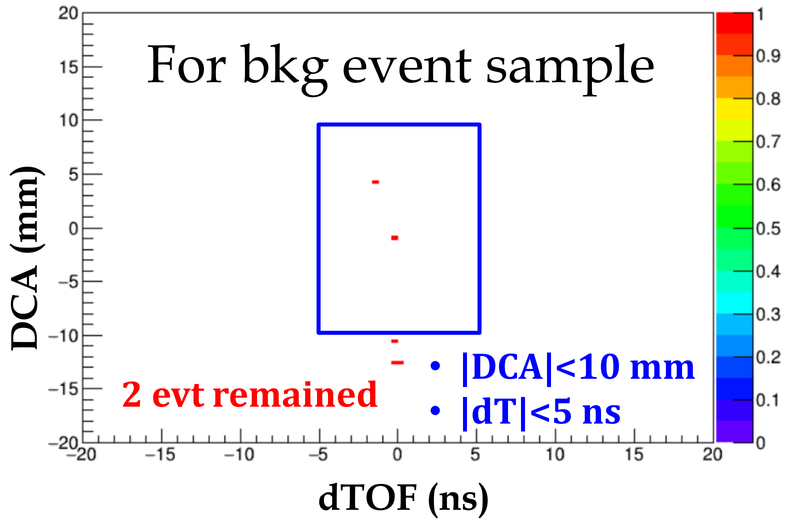
- Two Key criteria to suppress background :
  - Distance of Closest Approach (DCA)
  - Time of TE flight (TOF)

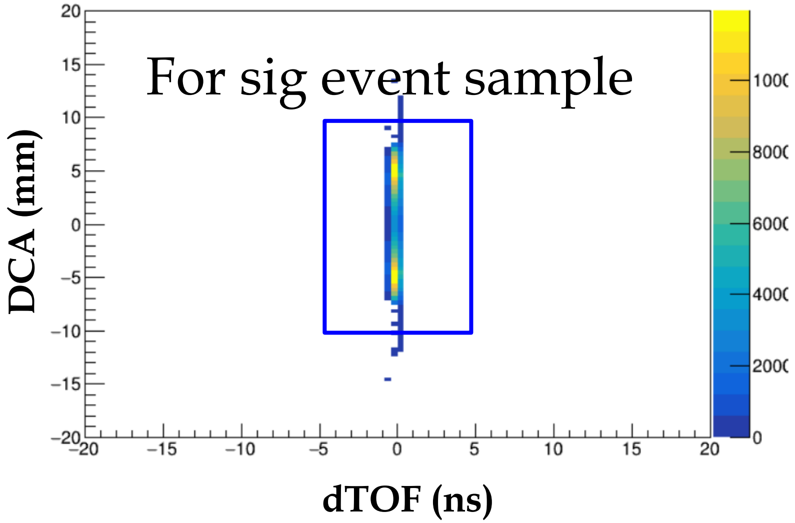
1. Bhabha Scattering
2. Five Body Decay of Muon











Criteria:

- nMWPCHit==5
- nMCPHit==1
- 1<=nCsIHit<=2
- CsIHitT<200
- CsIHitT-MCPHitT>0
- CsIHitT-MCPHitT<6
- CsIHitEk>0.4
- CsIHitEk<0.6

$$S = \frac{N_{90}}{N \cdot \varepsilon}$$

Parameters	Value
Detection Efficiency	39%
5-body bkg remained	2
Bhabha bkg remained	0
Equivalent observing time (year)	147 for 5-body bkg; 20 for Bhabha bkg;
Equivalent Bkg. Level	0.014

- **Sensitivity by Feldman-Cousins Approach:**
  - N_{90} , 90% C.L. upper limit (0 obs).
  - N , total count of Mu decay event.
  - ε , the detection efficiency.

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5.1 Discussion

- What sensitivity can we get on MELODY?
- Assumptions:
  - 1×10^4 μ/pulse, 1Hz repetition.
  - 3 years data taking, 2×10^7 s per year.
  - Spectrometer running stably.
  - 5% free muonium producing efficiency.

2.1×10^{-10} in 90% C.L.

(8.3×10^{-11} of MACS)

I（μ/s）	Time	Free Mu Exposure	Detection Efficiency	Background Level	Sensitivity (90% C.L.)
1×10^4	6×10^7 s	3×10^{10}	~39%	0.02	2.1×10^{-10}
1×10^5	6×10^7 s	3×10^{11}	~39%	If 0	2.1×10^{-11}

5.1 Discussion

- Could it perform better if a larger repetition muon source is applied?
- Assumptions:
  - 1×10^4 μ/pulse, **1 kHz repetition**.
  - 3 years data taking, 2×10^7 s per year.
  - Spectrometer running stably.
  - 5% free muonium producing efficiency.
- The intensity will reach 1E7 μ/s. Need more strict criteria to suppress the bkg level to ~0. Detection eff. will surely decrease.

I（μ/s）	Time	Free Mu Exposure	Detection Efficiency	Background Level	Sensitivity (90% C.L.)
1×10^7	6×10^7 s	3×10^{13}	If ~25%	If ~0	3.3×10^{-13}
1×10^7	6×10^7 s	3×10^{13}	If ~25%	If ~1	4.1×10^{-13}
1×10^7	6×10^7 s	3×10^{13}	If ~25%	If ~2	5.2×10^{-13}

5.2 Summary

- A preliminary design of novel MuMubar spectrometer has been proposed based on LGAD detector.
- The design has been studied by Geant4 simulation. Reconstruction Algorithms have been setup and tested:
  - Decay electron (DE) and Track electron (TE) track reconstruction.
  - Piled up Michel Electron track separation and reconstruction.
  - DE-TE installation under intensive muon source

Preliminary

- The detection efficiency is 39% and the background level is 0.014.
- For 3 years ($2 \times 10^7\ s/y$) observing on MELODY, the sensitivity is estimated to reach 2.1×10^{-10} (in 90% C.L.).
- This MuMubar spectrometer design ought to be potential for the future MuMubar experiment with intensive muon source.

致谢

承蒙厚爱

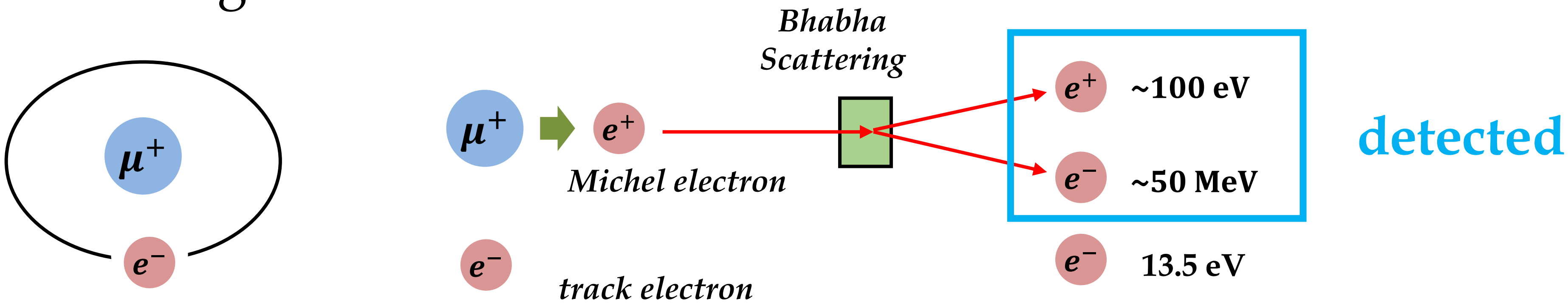
感谢倾听

Thanks!

Backup 1. The background

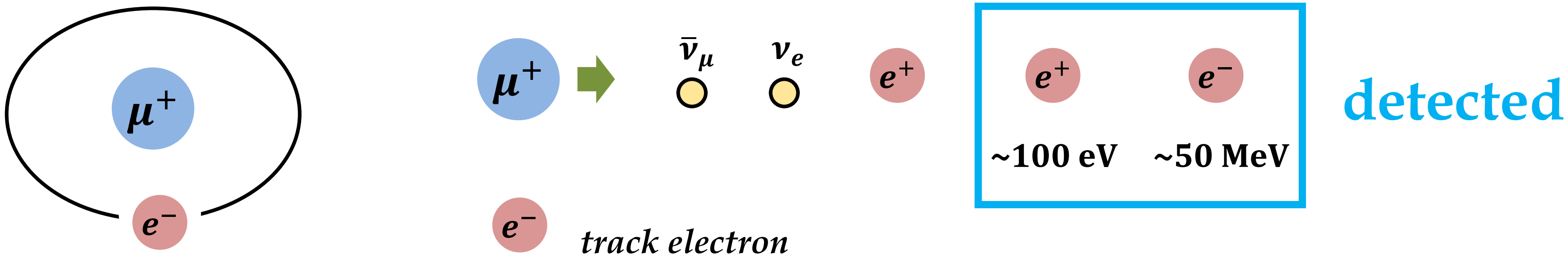
The MuMubar Searching is bothered by two types of Background:

1. Bhabha Scattering



2. Five Body Decay of Muon

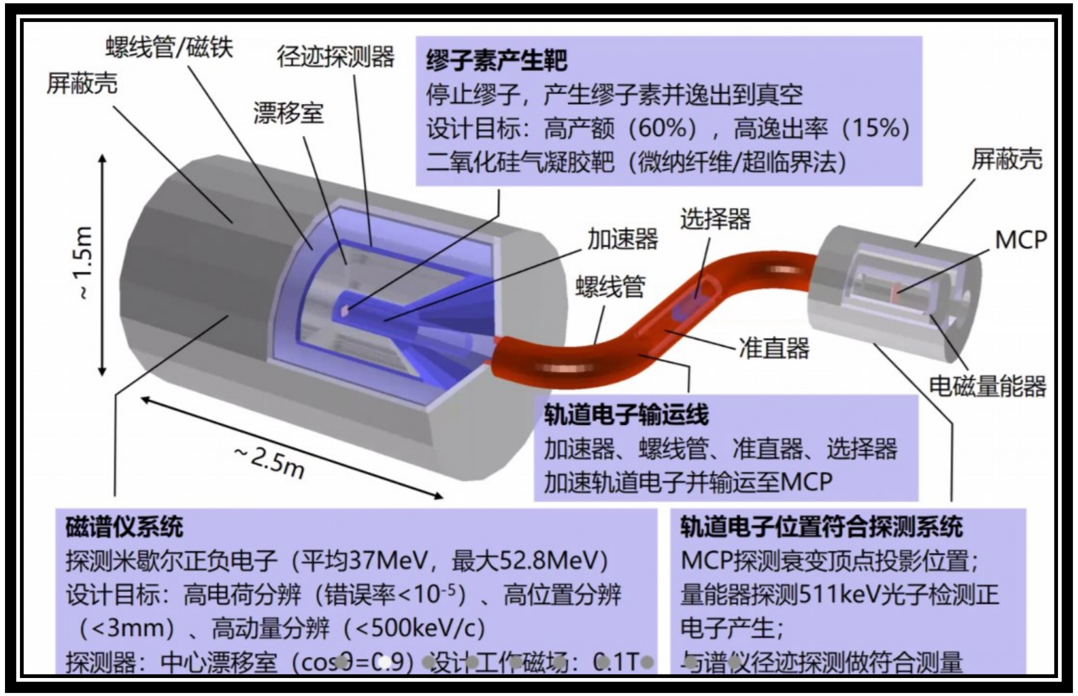
$$\mu^+ \rightarrow e^+ + e^+ + e^- + \bar{\nu}_\mu + \nu_e$$



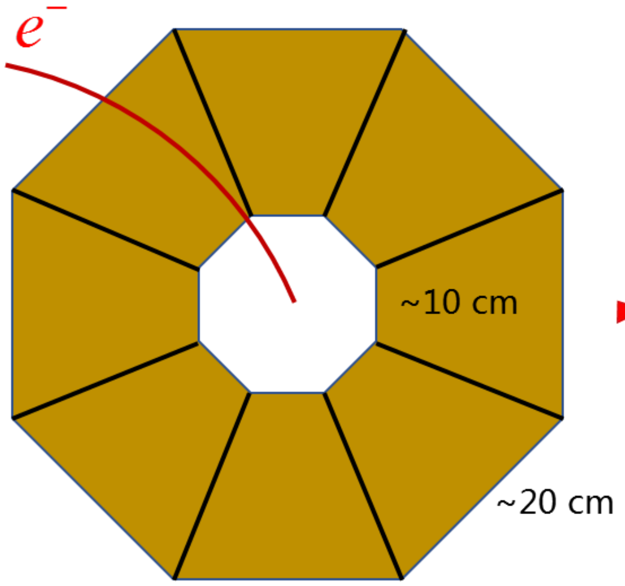
More Intensive Muon Source

参数	COMET-I	COMET-II	Mu2e
Institute	J-PARC		FNL
Proton pulse width	100 ns	100 ns	700 ns
Proton per pulse	2.9E6	5.12E7	1.02E7
Muon generation efficiency	4.7E-4	4.7E-4	1.9E-3
Muon generation per pulse	**1375 μ/pulse**	**24570 μ/pulse**	**19380 μ/pulse**
Muon Intensity	1.18E9 μ/s	2.1E10μ/s	1.14E10μ/s
Time to observe	~150 day	~180 day	~690 day
Total Muon to be observe	1.5E16	1.1E18	6.7E17
CLFV Sensitivity	7E-15	2.6E-17	2.3E-17

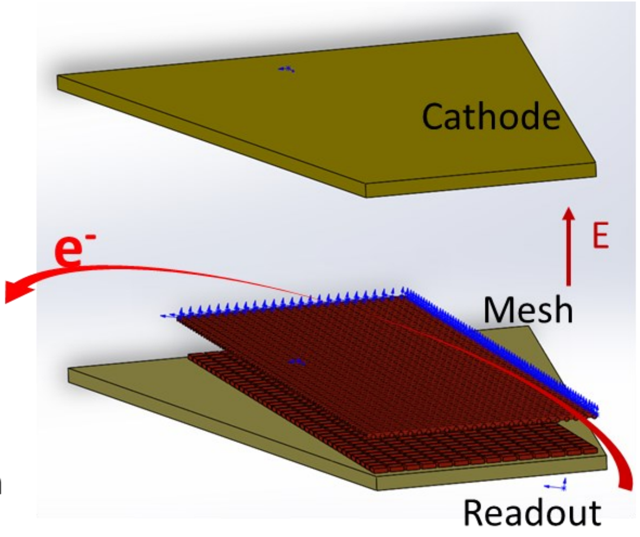
使用更灵敏的探测装置



中山大学/唐健团队/MACE实验



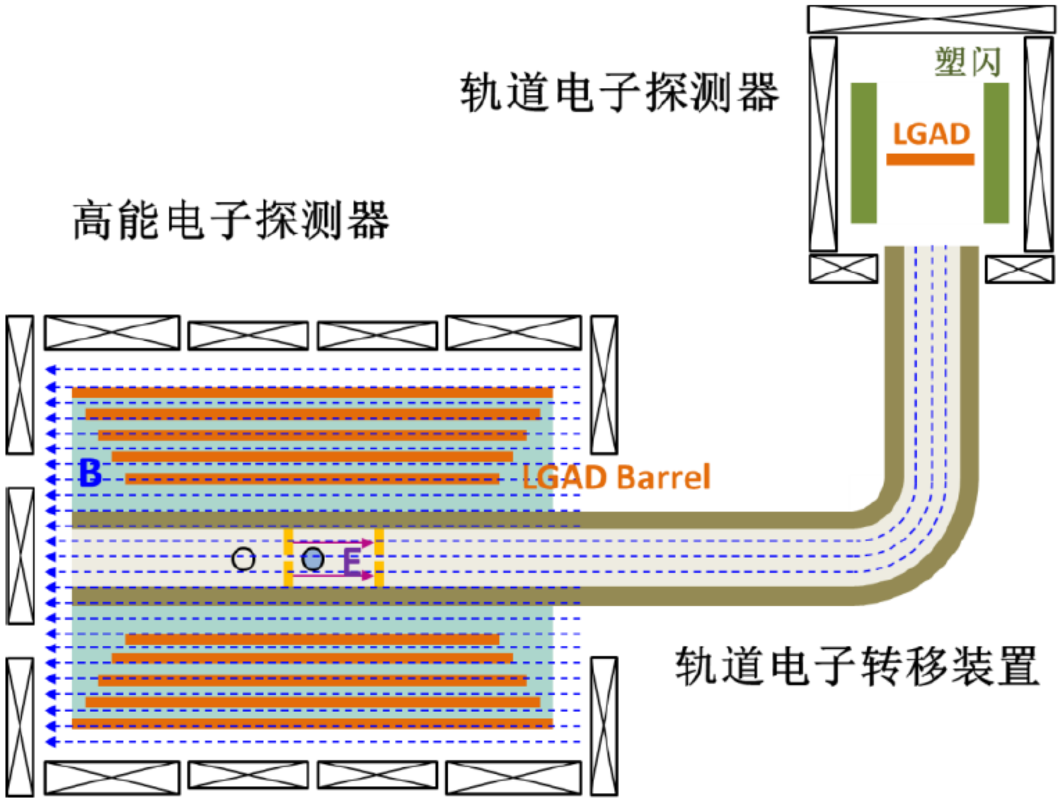
TPC探测器结构



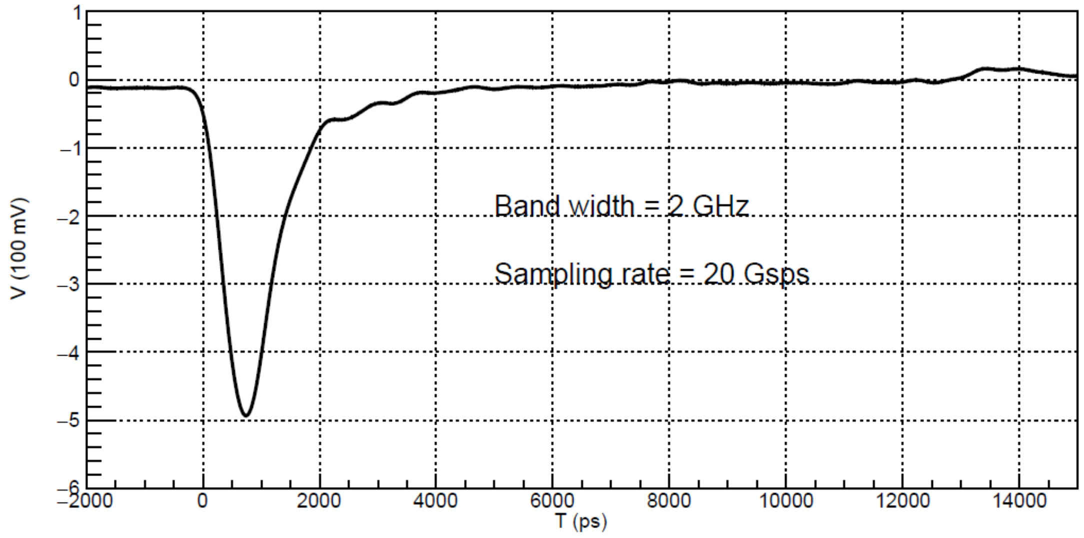
探测器扇形模块

高能所/鲍煜团队

Backup 3. Novel MuMubar Spectrometer Design



新型MuMubar谱仪结构
(Not to scale)



- LGAD优势：
  - 时间分辨率比气体探测器好2个数量级。
  - 安全可靠，不存在打火的风险。
- LGAD劣势：
  - 位置分辨率约1mm，比气体探测器稍差。
  - 然而MuMubar实验径迹探测对位置分辨要求不高。

预计该方案所能使用的μ子源强度比气体方案高两个数量级