



中山大學

SUN YAT-SEN UNIVERSITY

物理学院

SCHOOL OF PHYSICS

A TOFPET2-based Multichannel Readout System for Muon Beam Monitor and μ SR Spectroscopy

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Ai-Yu Bai, Yin-Yuan Huang, Liang Xian, Jing-Yi Zhang

Jian Tang, Yu Chen



SYSU MuOn and Optical TomograpHy

SMOOTH Lab, SCHOOL OF PHYSICS, SYSU

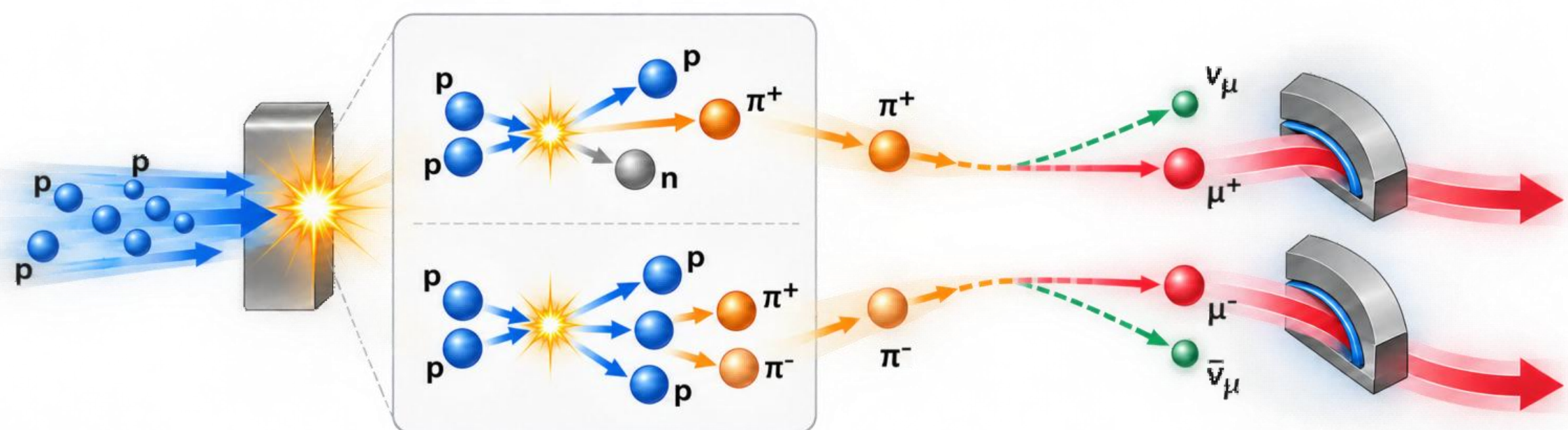
INSTR 2026 · Hefei



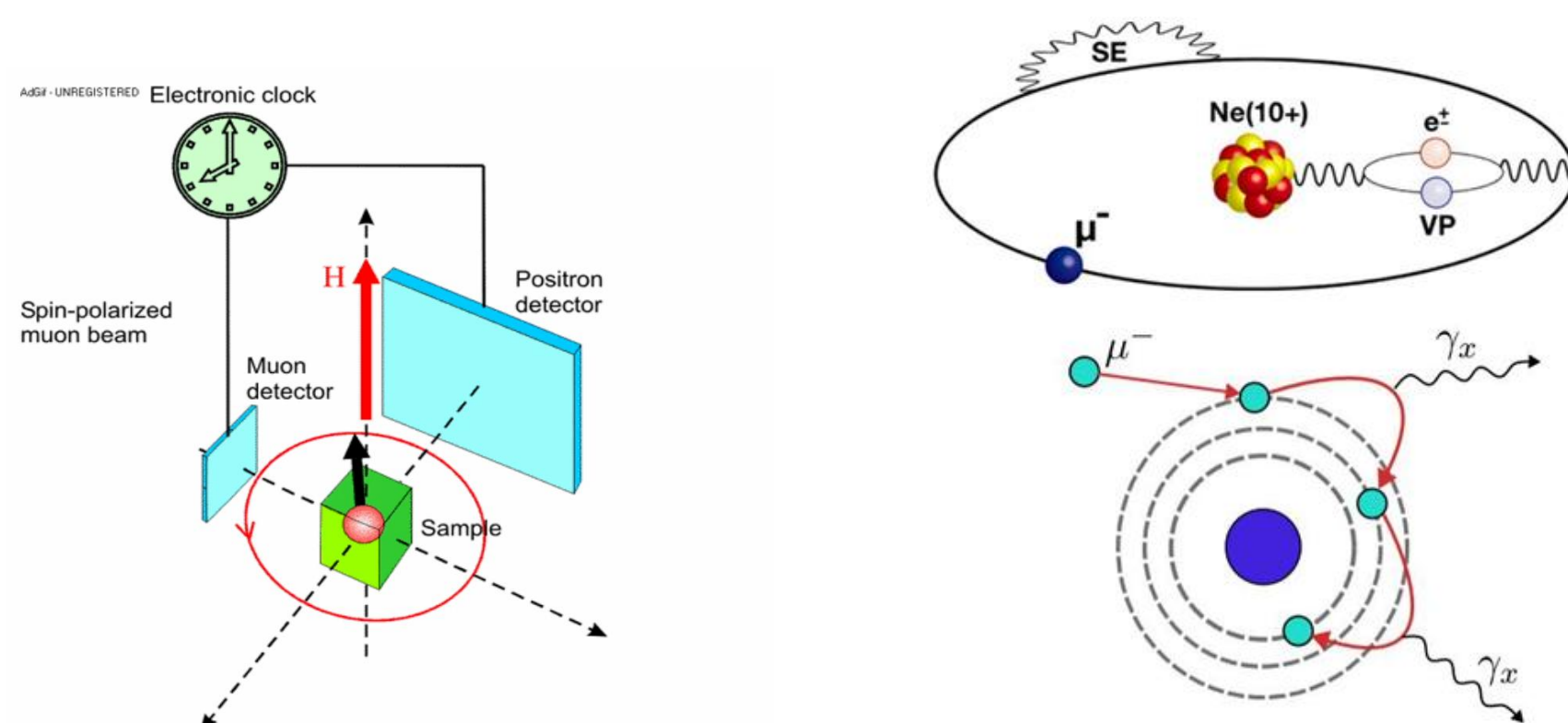
- **Muon Source and Applications**
- **Design of Muon Beam Monitor and μ SR Detector**
- **Multichannel Electronic Readout System (TMR)**
- **Outlook and Summary**



- **Muon Source and Applications**
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- Outlook and Summary

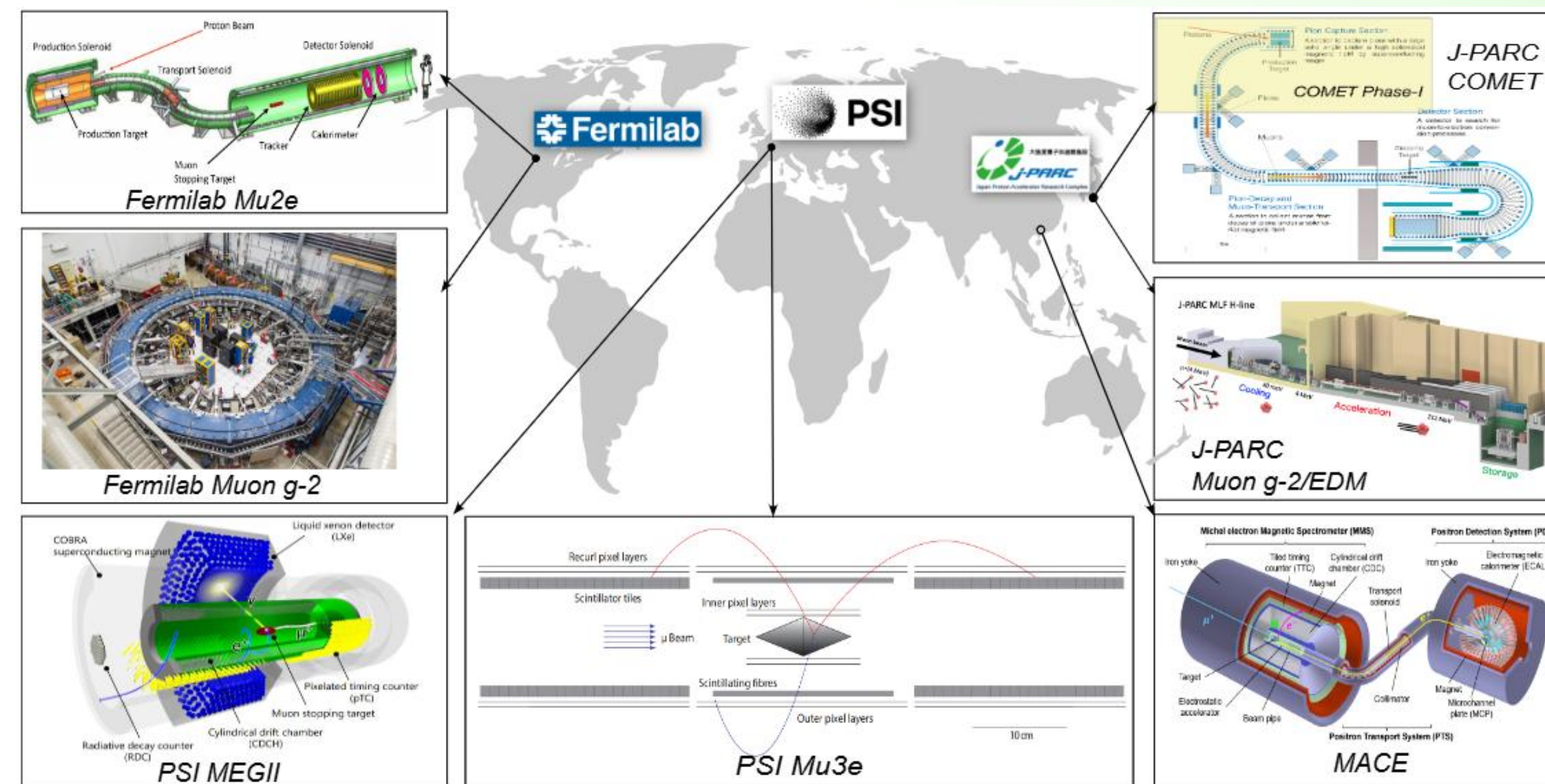


- **Muon Spin Rotation/Relaxation/Resonance(μ SR):**
Magnetic materials, superconductors, semiconductors, battery studies, biophysics, chemistry, etc.
- **Muonic Atom X-ray Applications:**
Precision tests of strong-field QED, nuclear structure, etc.
- **Muon-catalyzed fusion, etc.**



Multidisciplinary Applications

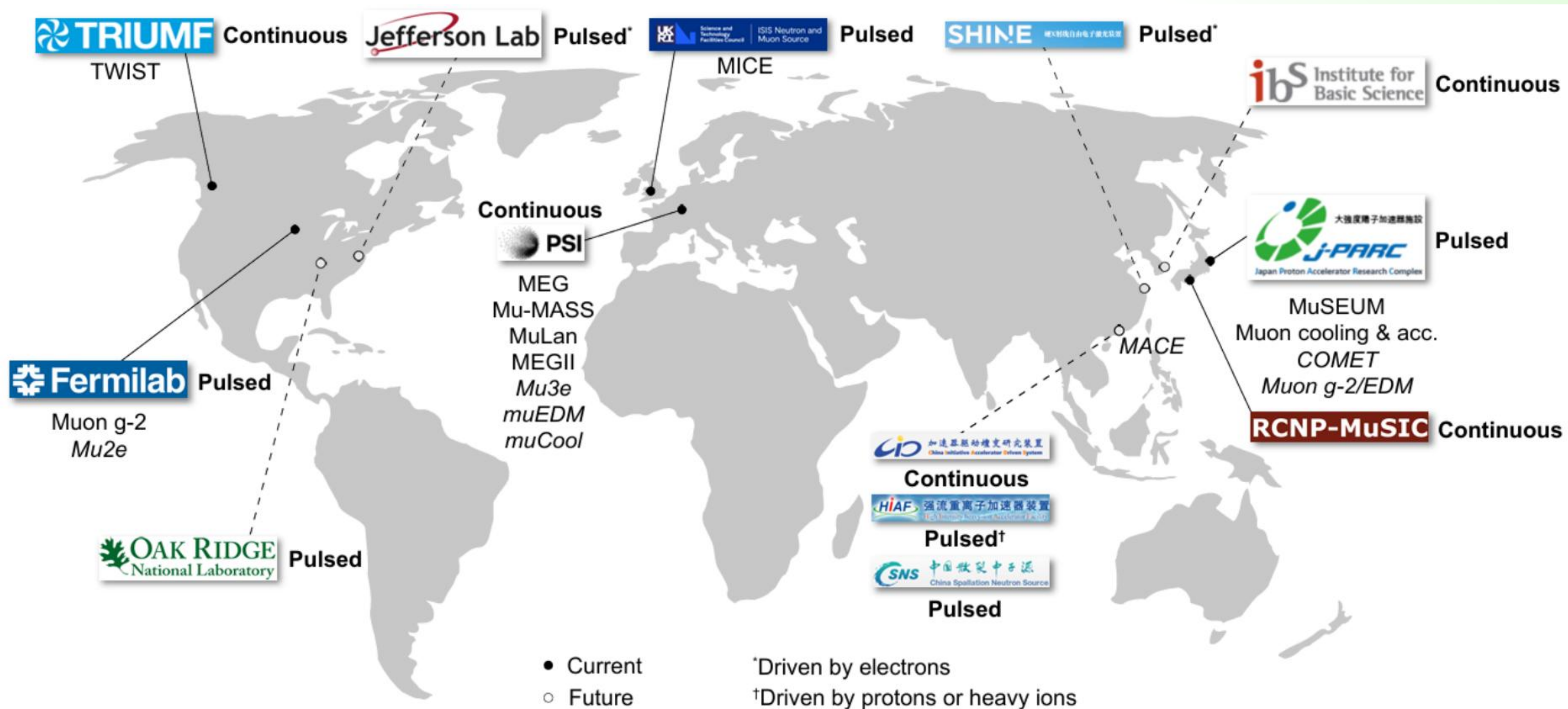
Frontiers of muon physics



arXiv:2609.25943

- **Charged-lepton flavor violation searches(cLFV):**
MEG($\mu^+ \rightarrow e^+ \gamma$), Mu3e ($\mu^+ \rightarrow e^+ e^- e^+$), Mu2e, COMET ($\mu^- N \rightarrow e^- N$), MACE($\mu^+ e^- \rightarrow \mu^- e^+$), etc.
- **Muon magnetic and electric dipole moments:**
Fermilab Muon g-2, J-PARC Muon g-2/EDM, etc.
- **Muonic atom spectroscopy:**
FAMU(RIKEN-RAL), QUARTET(PSI), etc.

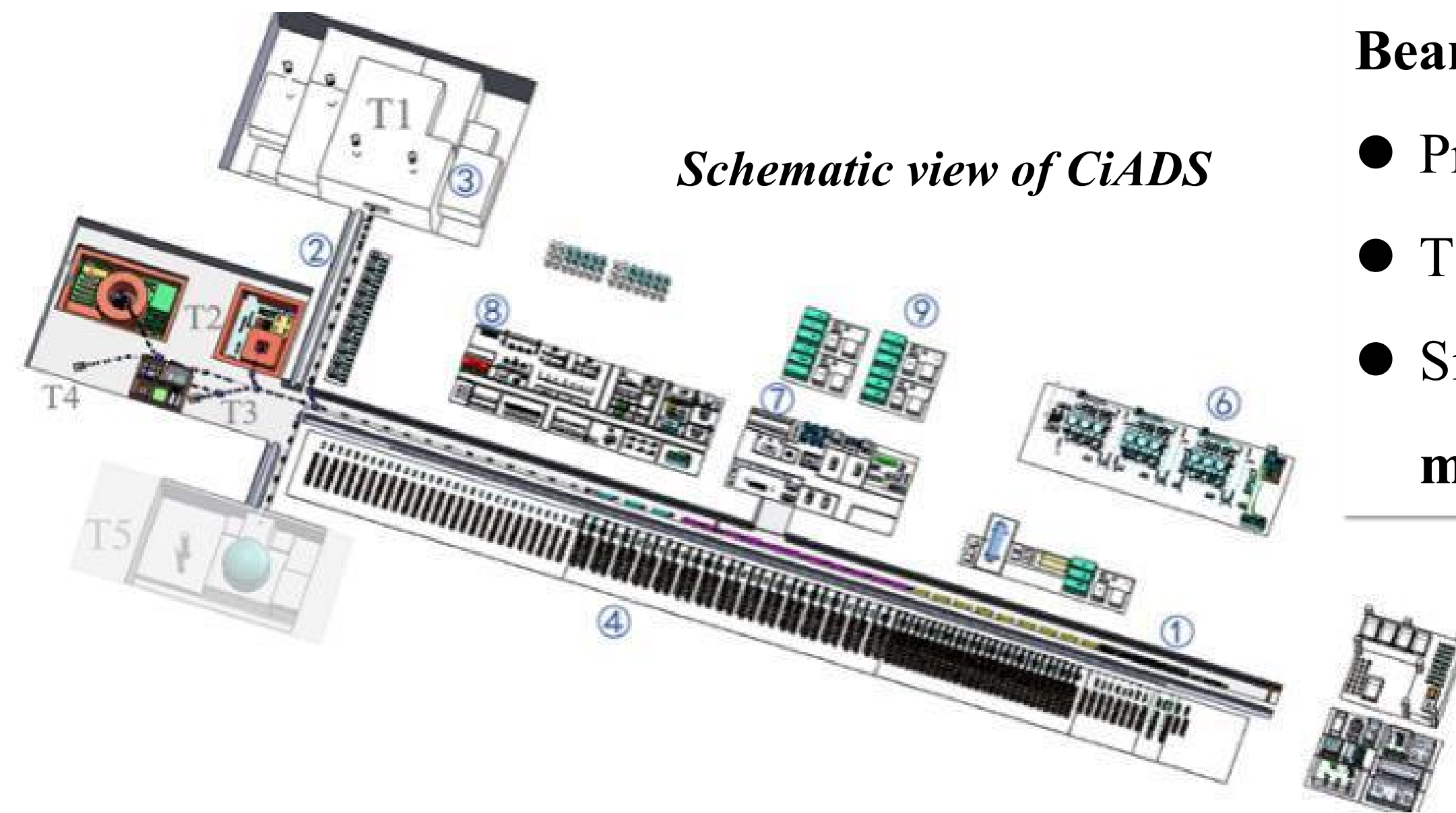
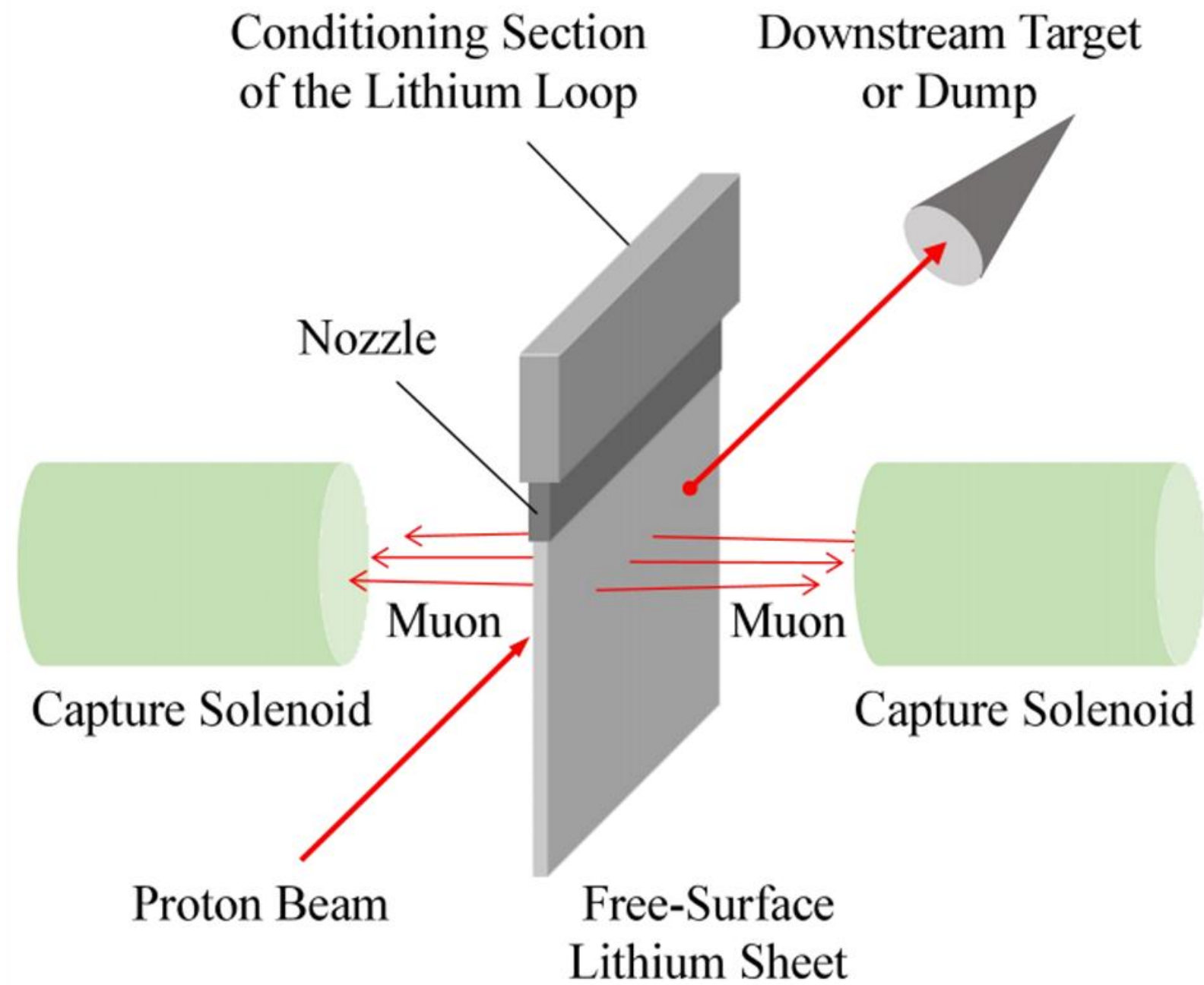
1 Muon Source



arXiv:2601.15818

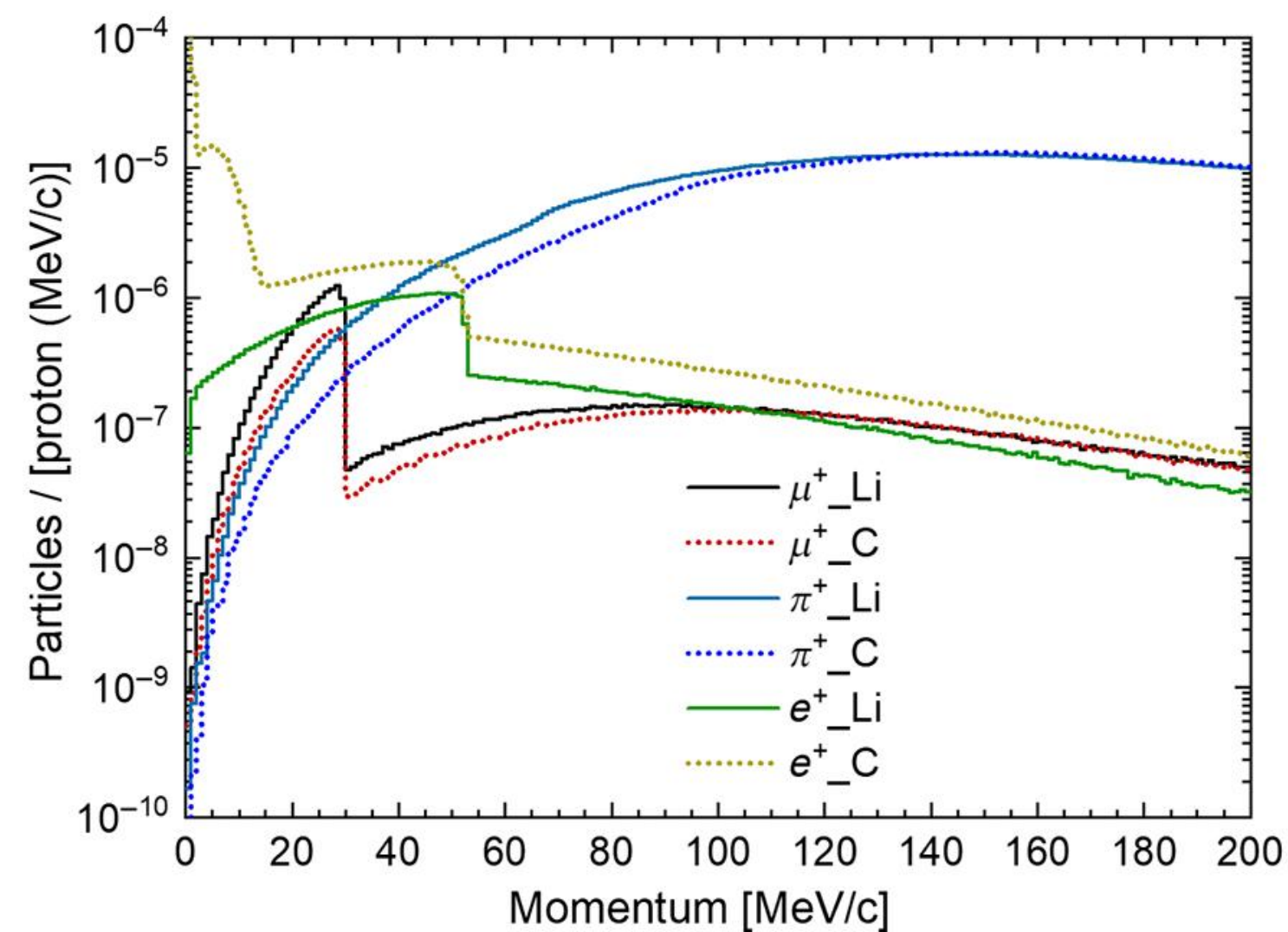
Several muon source projects are under development in China.

1 Proposed Muon Source at CiADS China initiative Accelerator Driven System



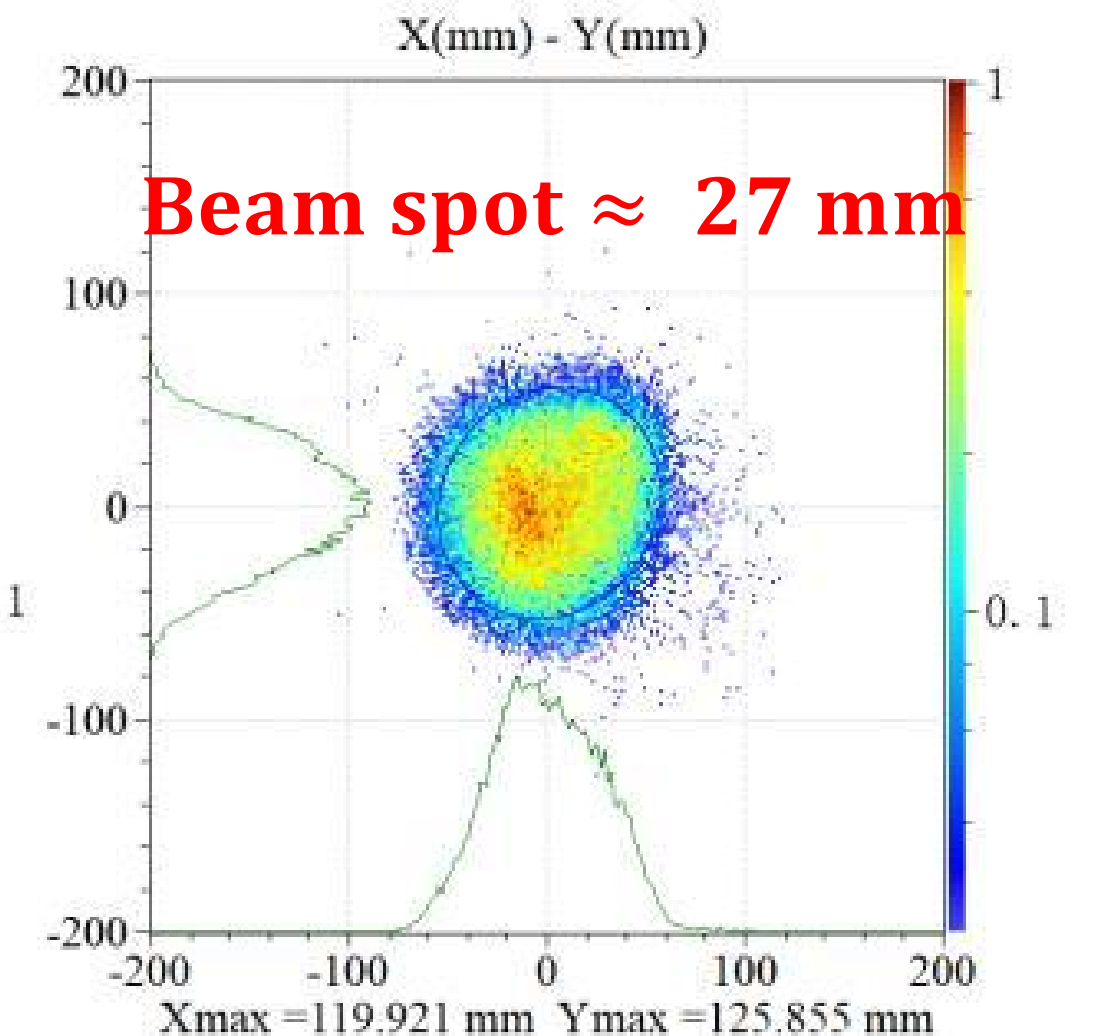
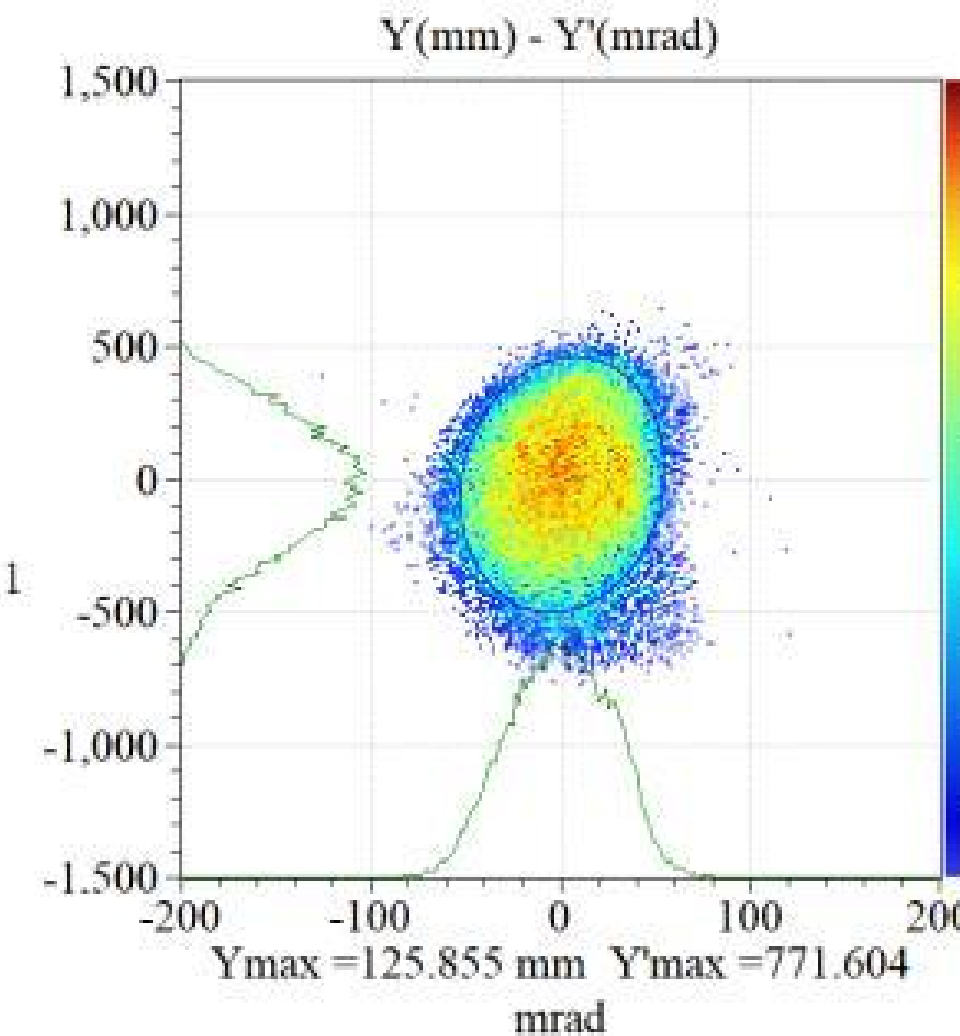
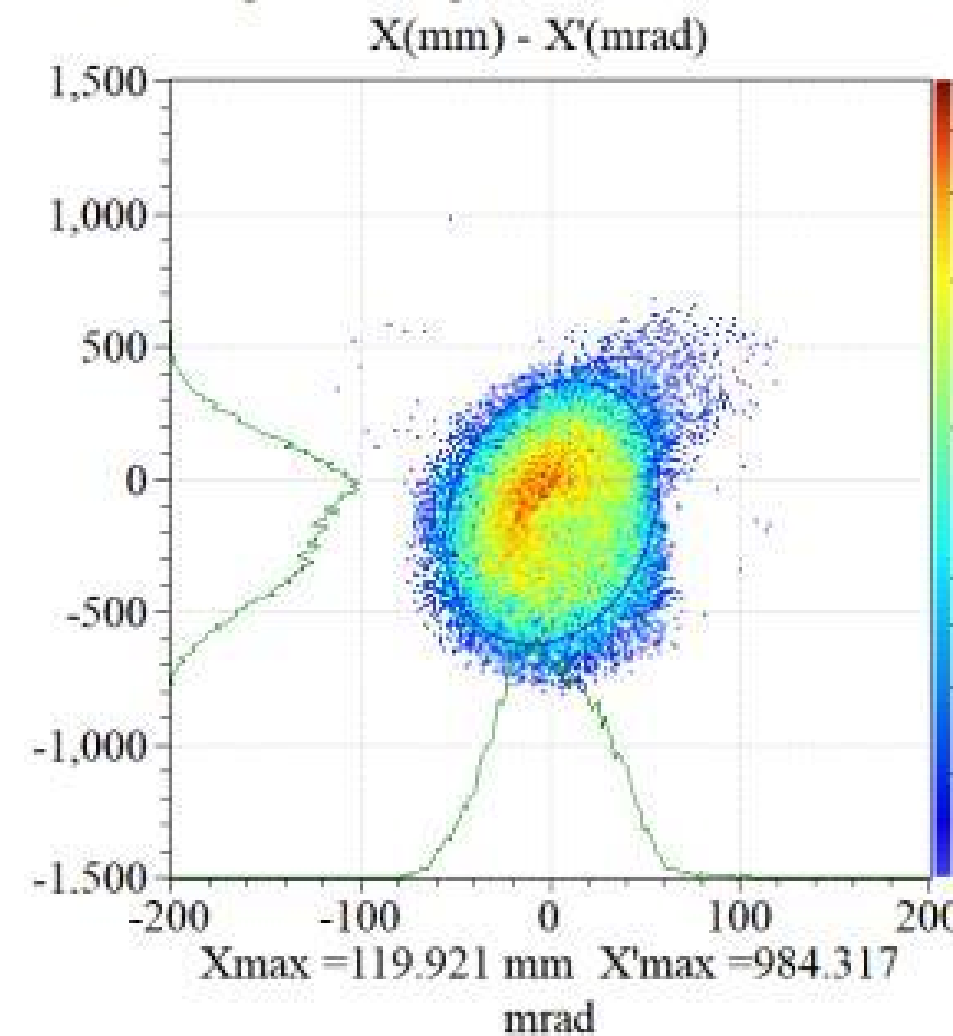
Beam Characteristics

- Proton beam energy: **500 MeV**
- Target: **Liquid-lithium sheet**
- Simulated beam spot: **RMS ≈ 27 mm**



Simulated Particle Momentum Spectra

Ele #2539 [14.2272 m] NGOOD : 42786 / 487609

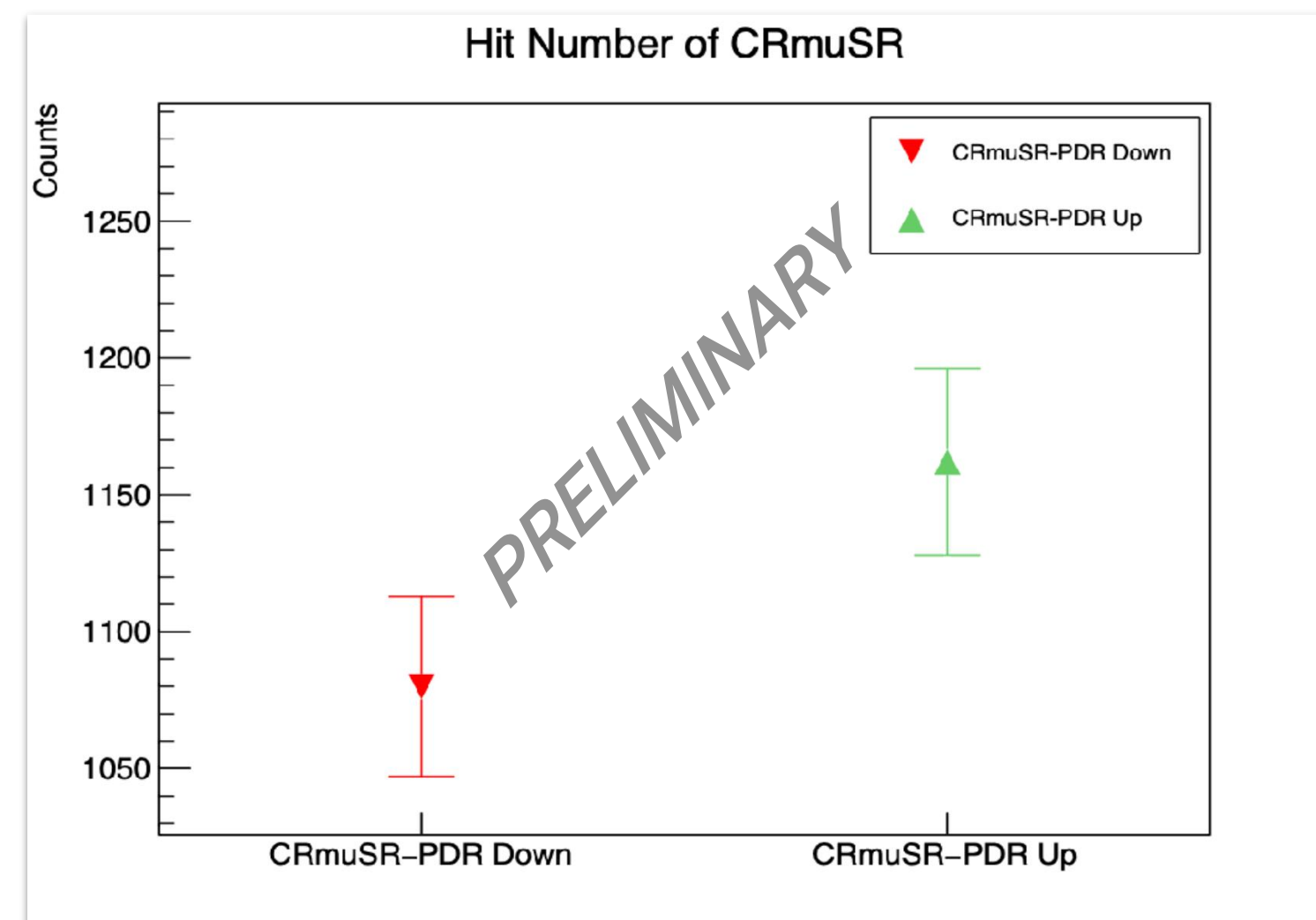
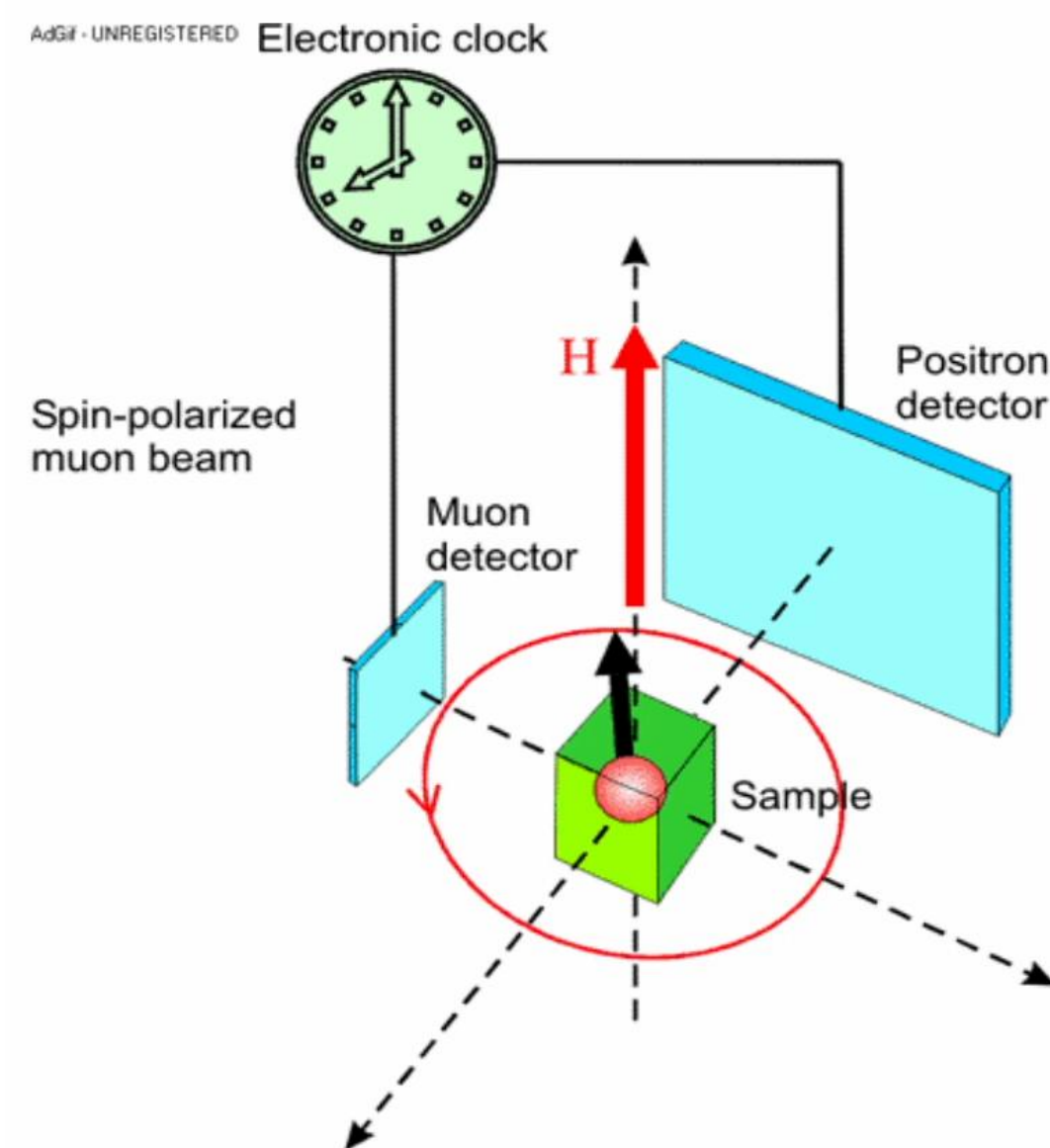


Beam spot ≈ 27 mm

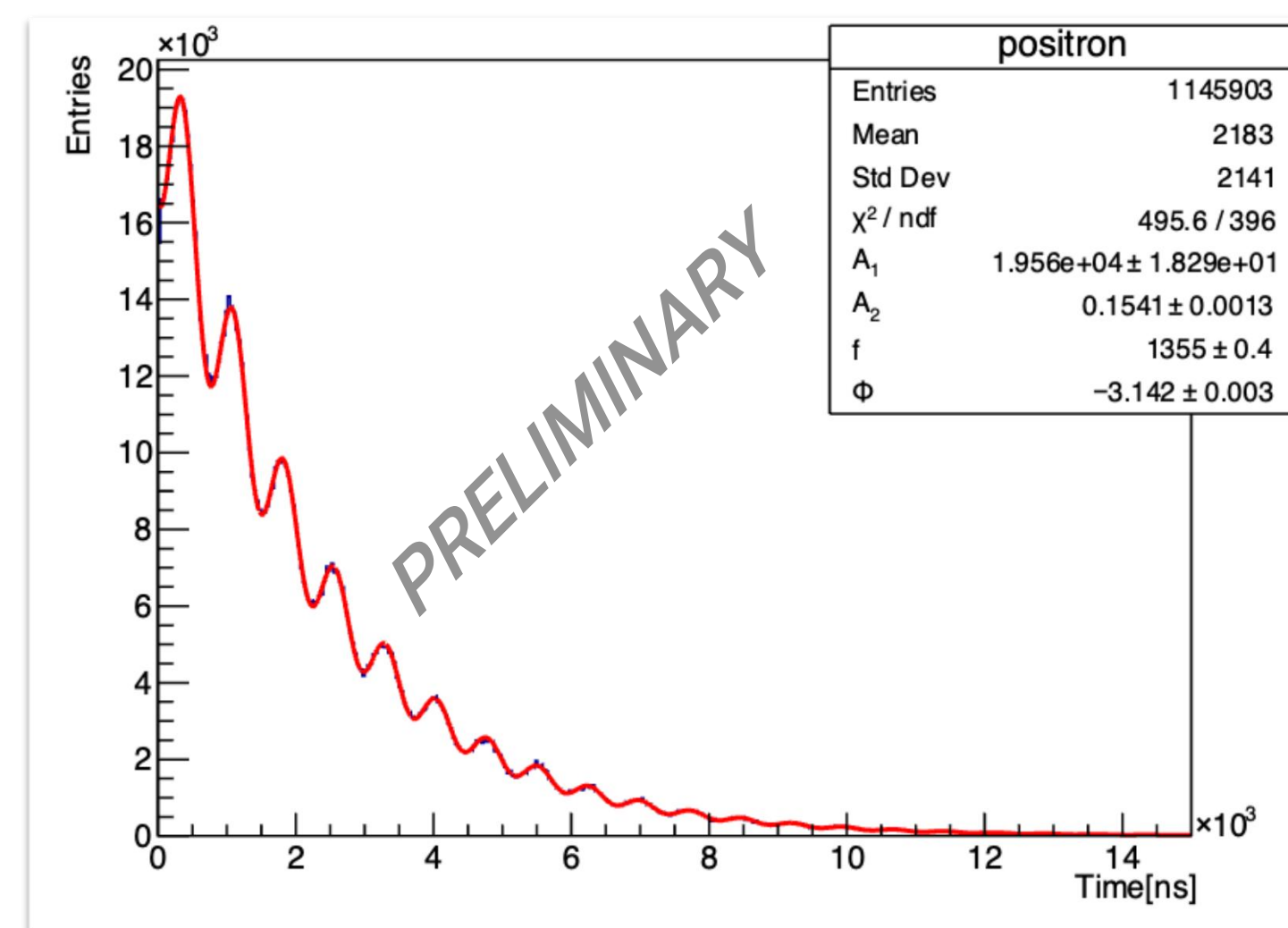
Simulated Beam Phase Space and Profile



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- Outlook and Summary



Preliminary Analysis of Michel-Electron Hits

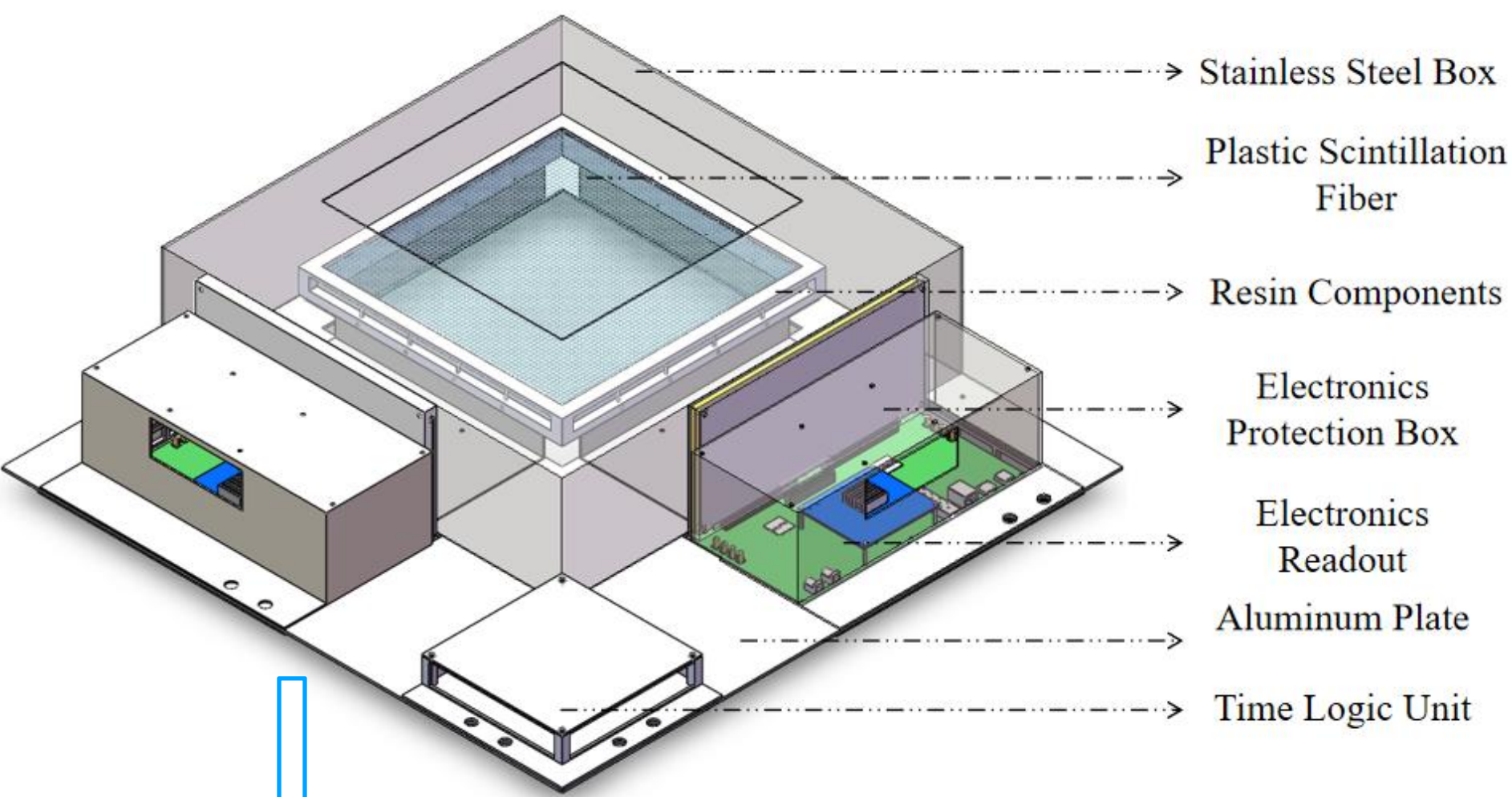
GEANT4 simulated μ SR Spectrum $B_{\text{sim}} = 100 \pm 0.02\text{Gs}$.Design of μ SR Detector

Beam-side requirements:

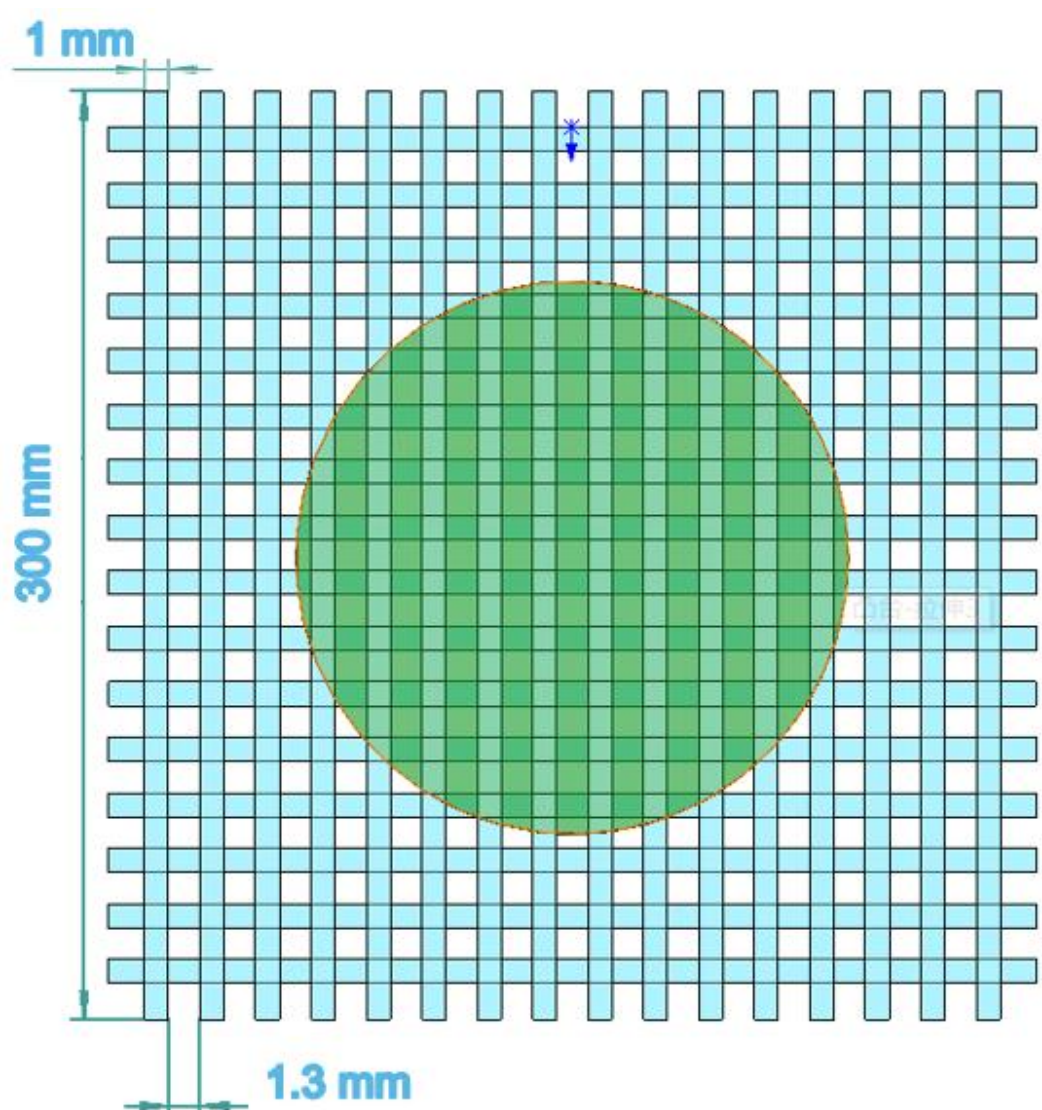
- Centimeter-scale beam spot size
- Tunable muon momentum
- High muon polarization
- Precise muon arrival timing

μ SR technology and MACE experiment requires high-quality beam

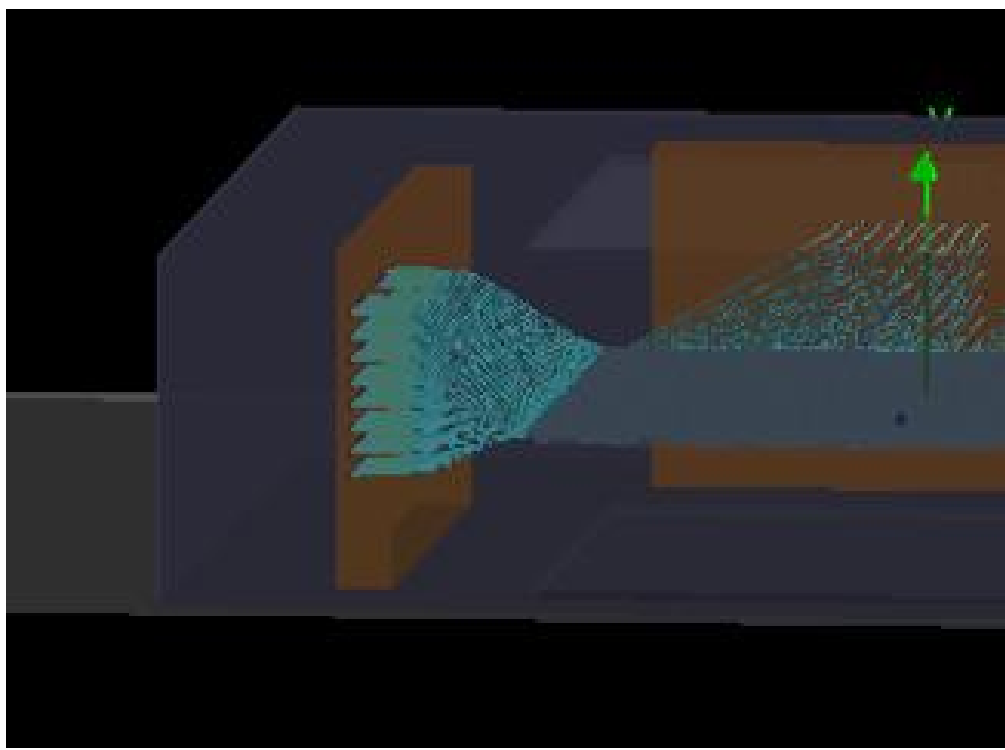
2 Design of Muon Beam Monitor Prototype



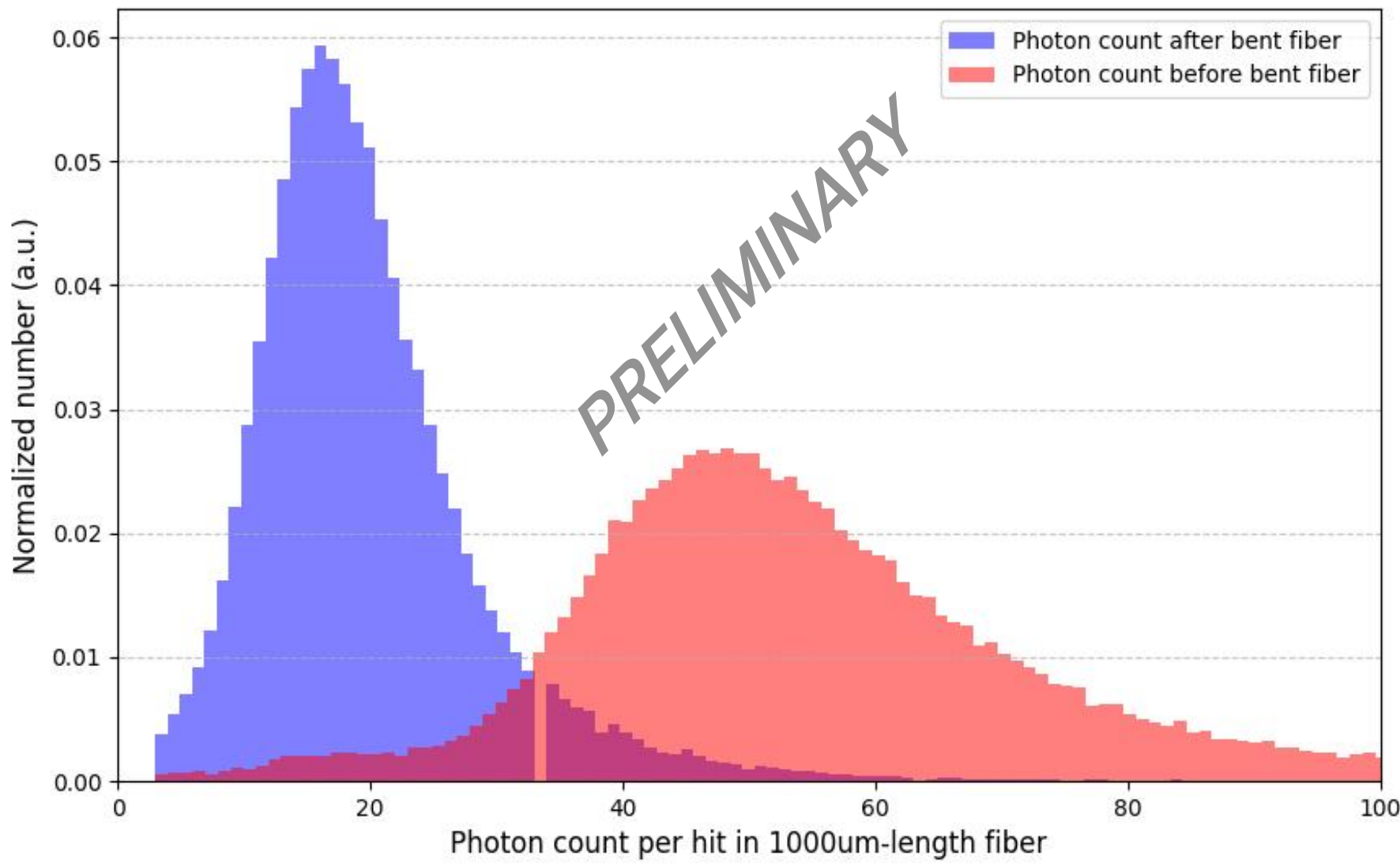
Design of Muon Beam Monitor



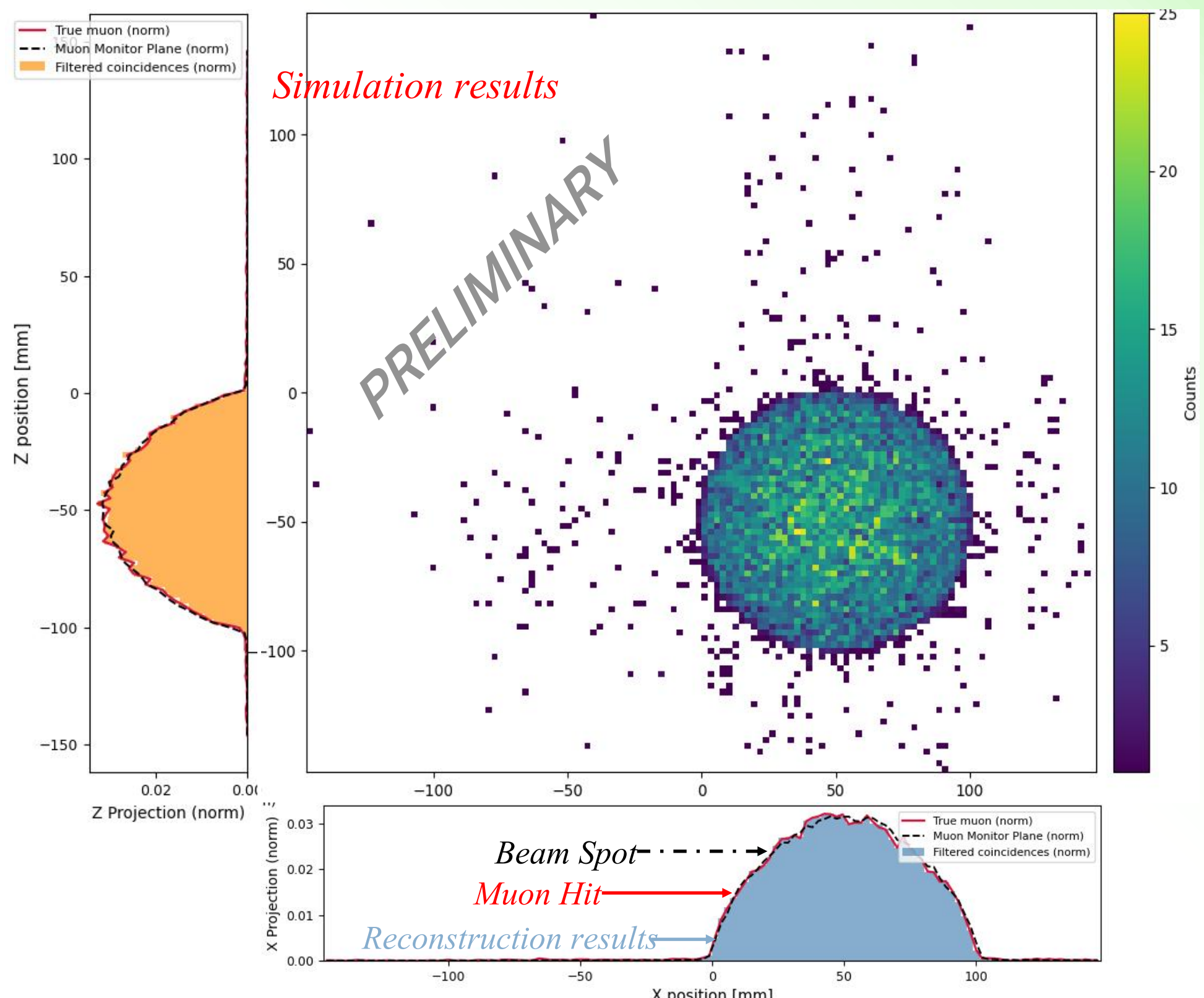
Schematic diagram



Due to the SiPM array, the fiber needs to be bent for connection



Bending fibers can lead to a reduction in the photon number

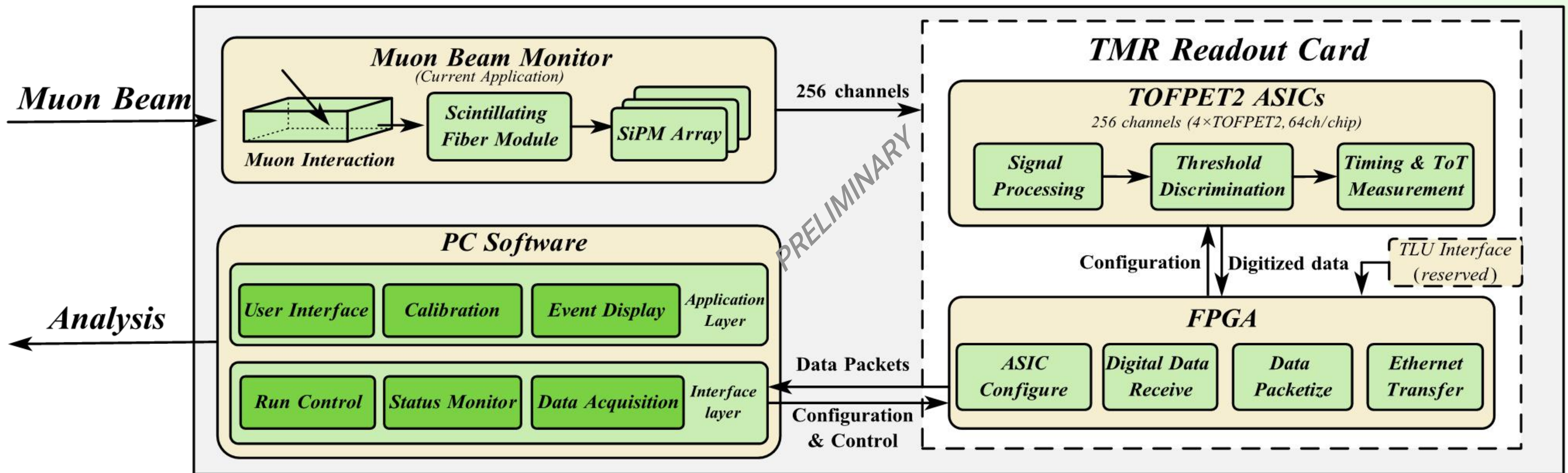


Performance requirements for detectors

Parameter	Specification
Readout channels	256
Time Resolution	< 500 ps
Beam Window Size	> 20×20 cm ²
Maximum Rate per Channel	400 kHz
Event Rate	10 MHz (up to 85 MHz aggregate 108 μ/s)



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<https://www.petsyselectronics.com/>

TOFPET2 ASIC

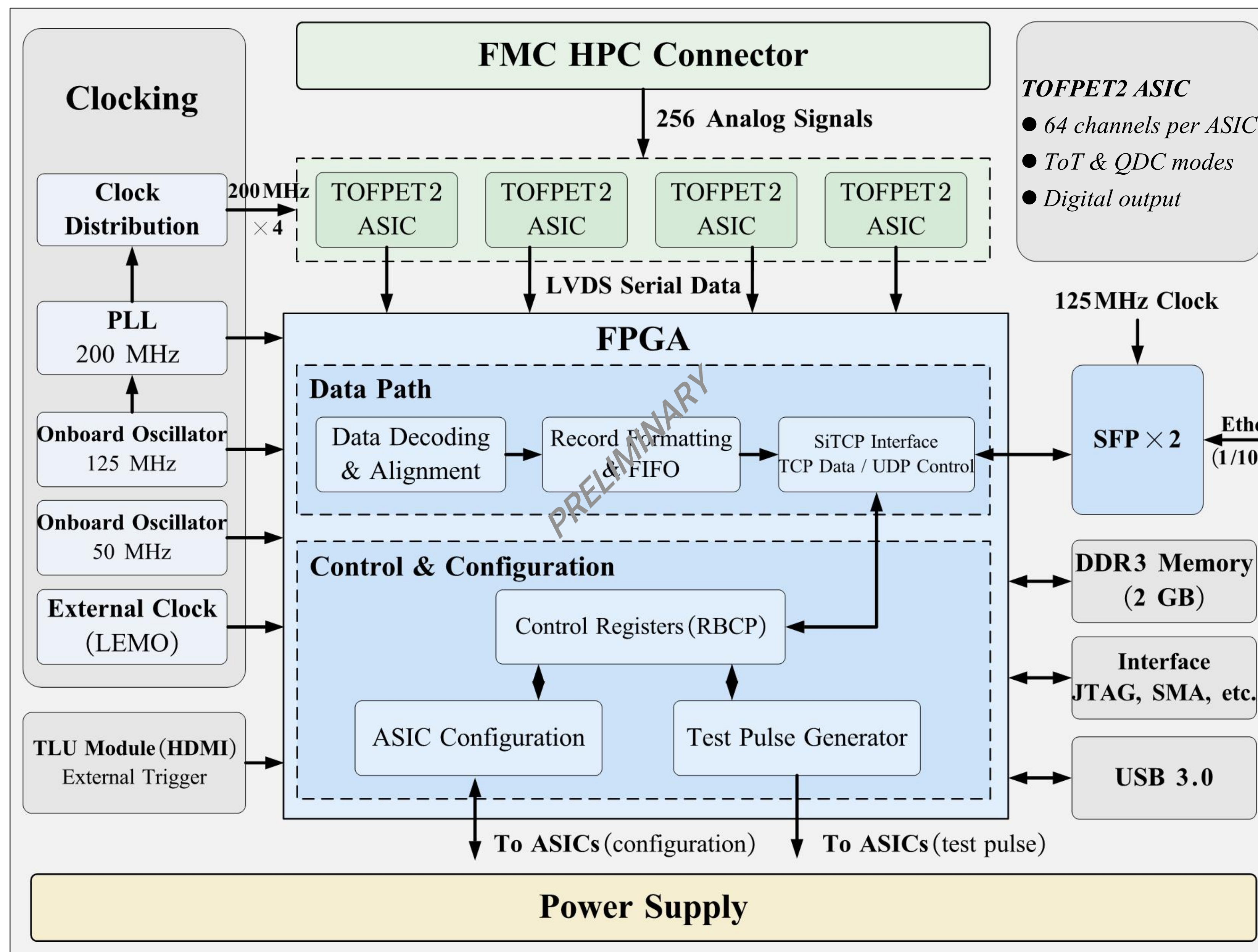
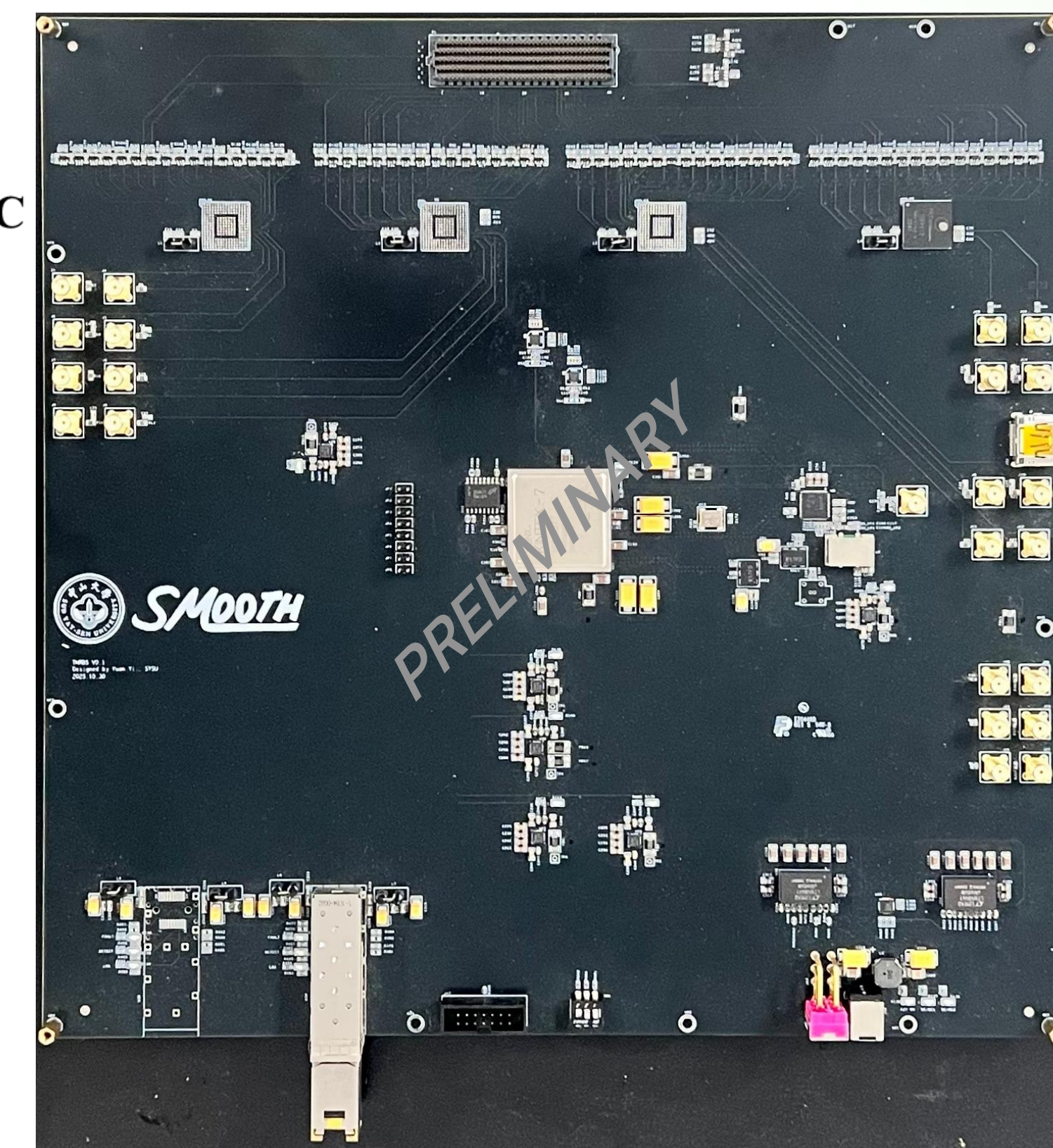
- 64 channels per ASIC
- Integrated timing and ToT measurement
- Individually configurable thresholds
- TDC binning: 30 ps

TMR Design Targets

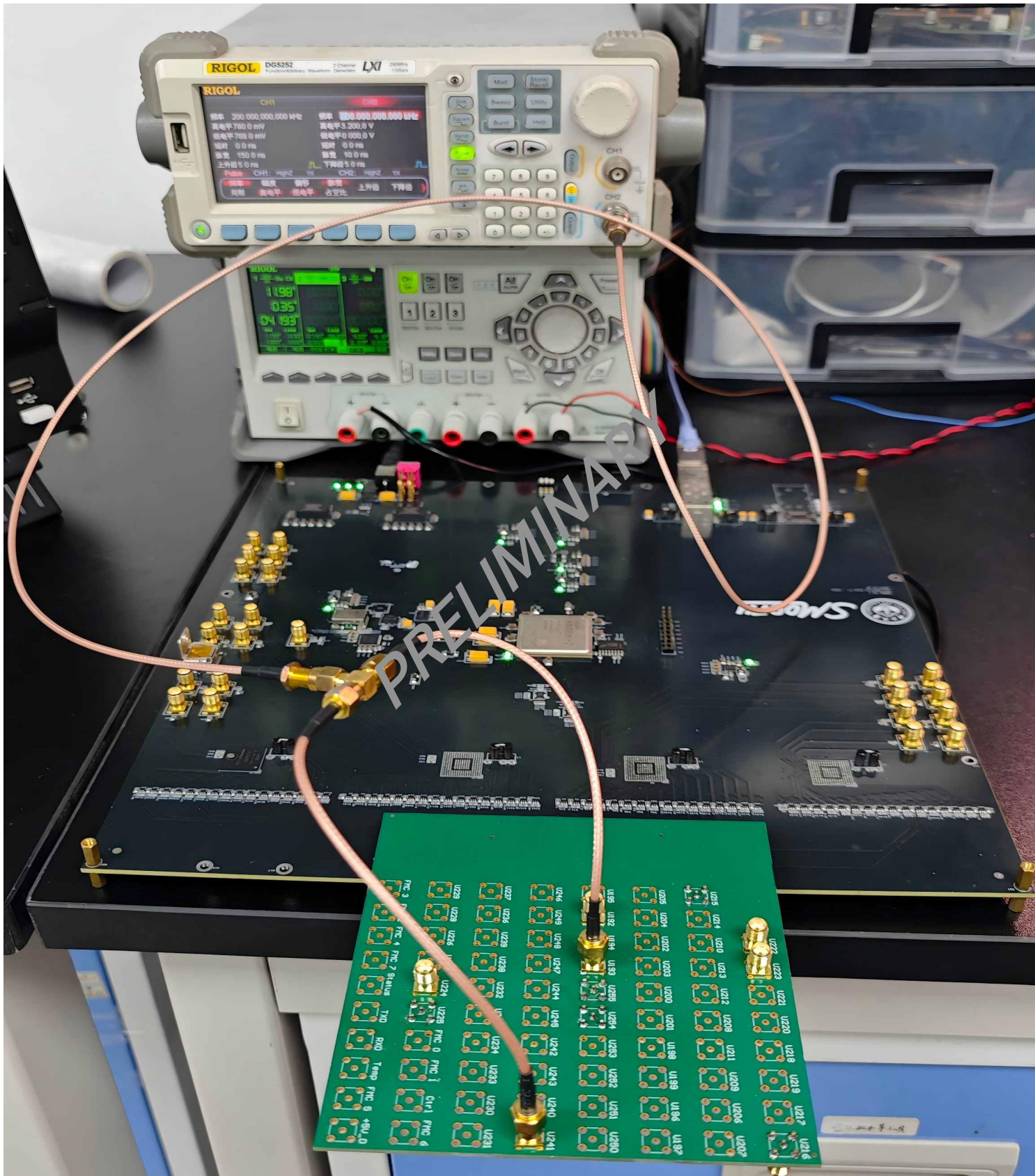
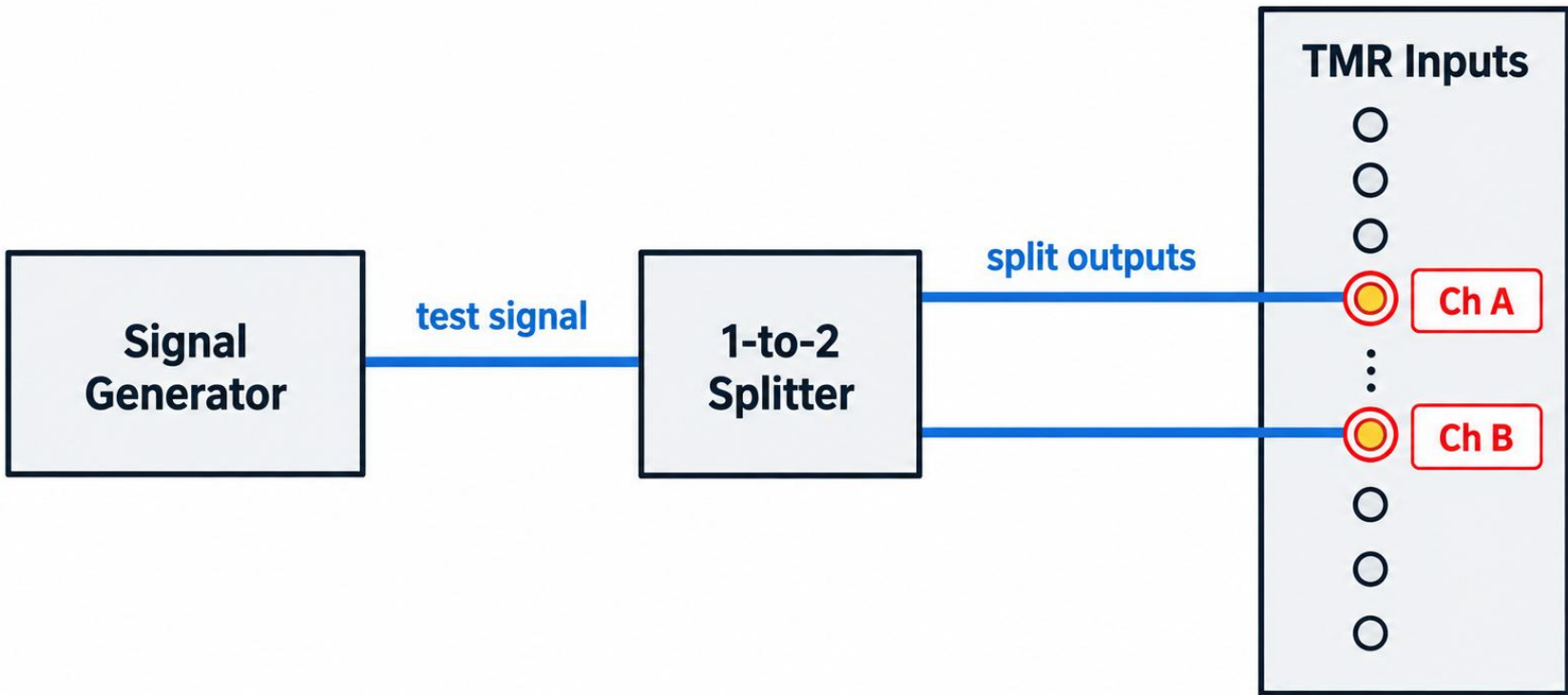
Parameter	Specification
Readout channels	256
Time Resolution	< 500 ps
Maximum Rate per Channel	450 kHz
Custom event formats and configurable trigger logic	

TMR System

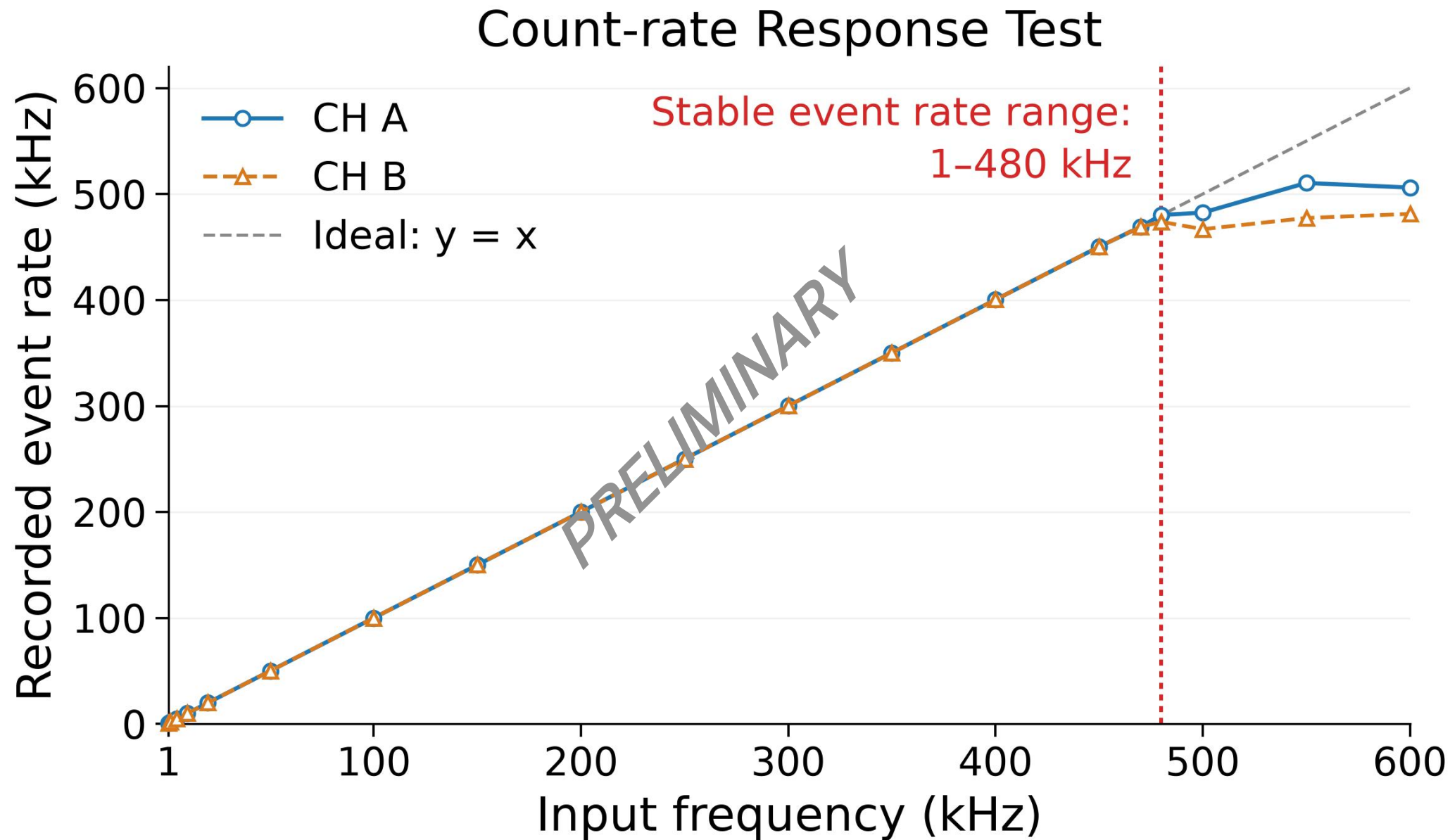
- 256-channel readout with TOFPET2 ASICs and FPGA.
- Detector-specific calibration, control, and event building
- Reserved TLU interface for multi-board synchronization and trigger coordination.



Count-rate and Timing Performance

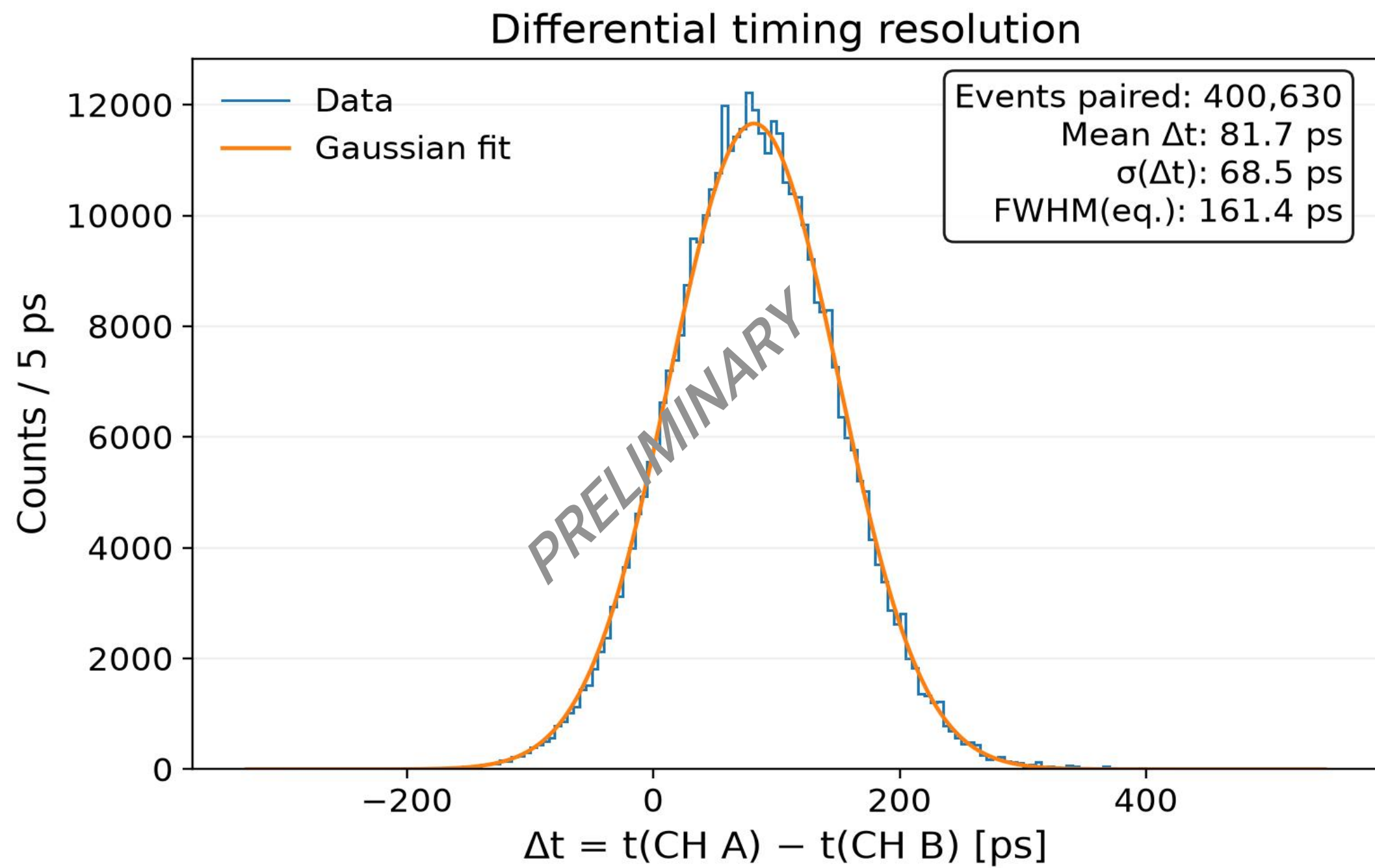


Pulse-Injection Test Setup with 1-to-2 splitter



Count-rate Response Test

- Pulses injected from a signal generator
- Input frequency scan: 1–600 kHz
- Linear response up to **≈480 kHz/channel**



Differential Timing Test

- Pulses split into two channels via 1-to-2 splitter
- Time difference:
 $\Delta t = t_a - t_b$
- Differential timing resolution: **68.5 ps(σ)**
- $\sigma_{ch} = 68.5 / \sqrt{2} = 48.4 ps$
- Mean offset: 81.7 ps,

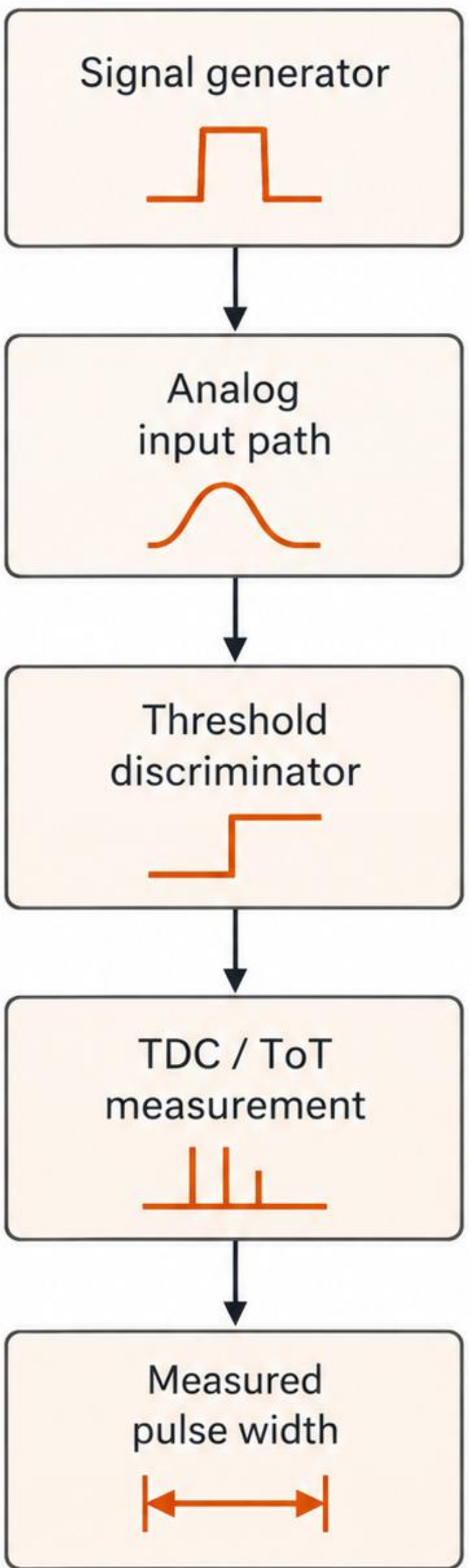
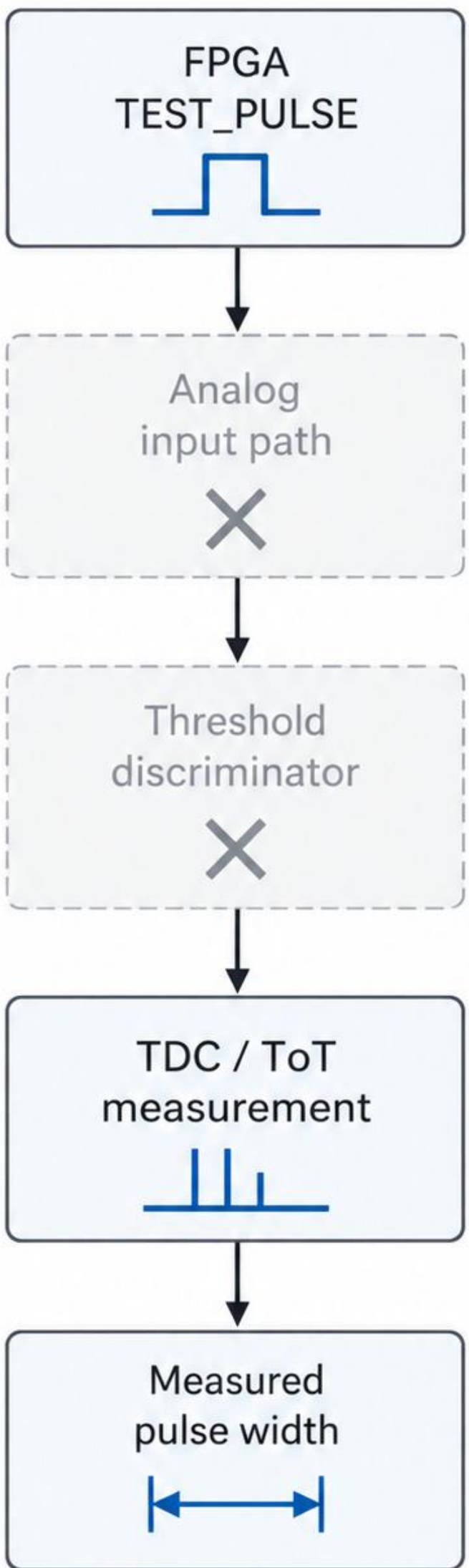
3 Pulse-width Measurement Comparison

A ToT pulse-width precision of ≈ 0.11 ns (σ) for analog pulses directly affects the achievable energy resolution.

- Pulse Width: 100 ns
- Event Rate: 200kHz

Digital TEST_PULSE

Input Pulse(Square)

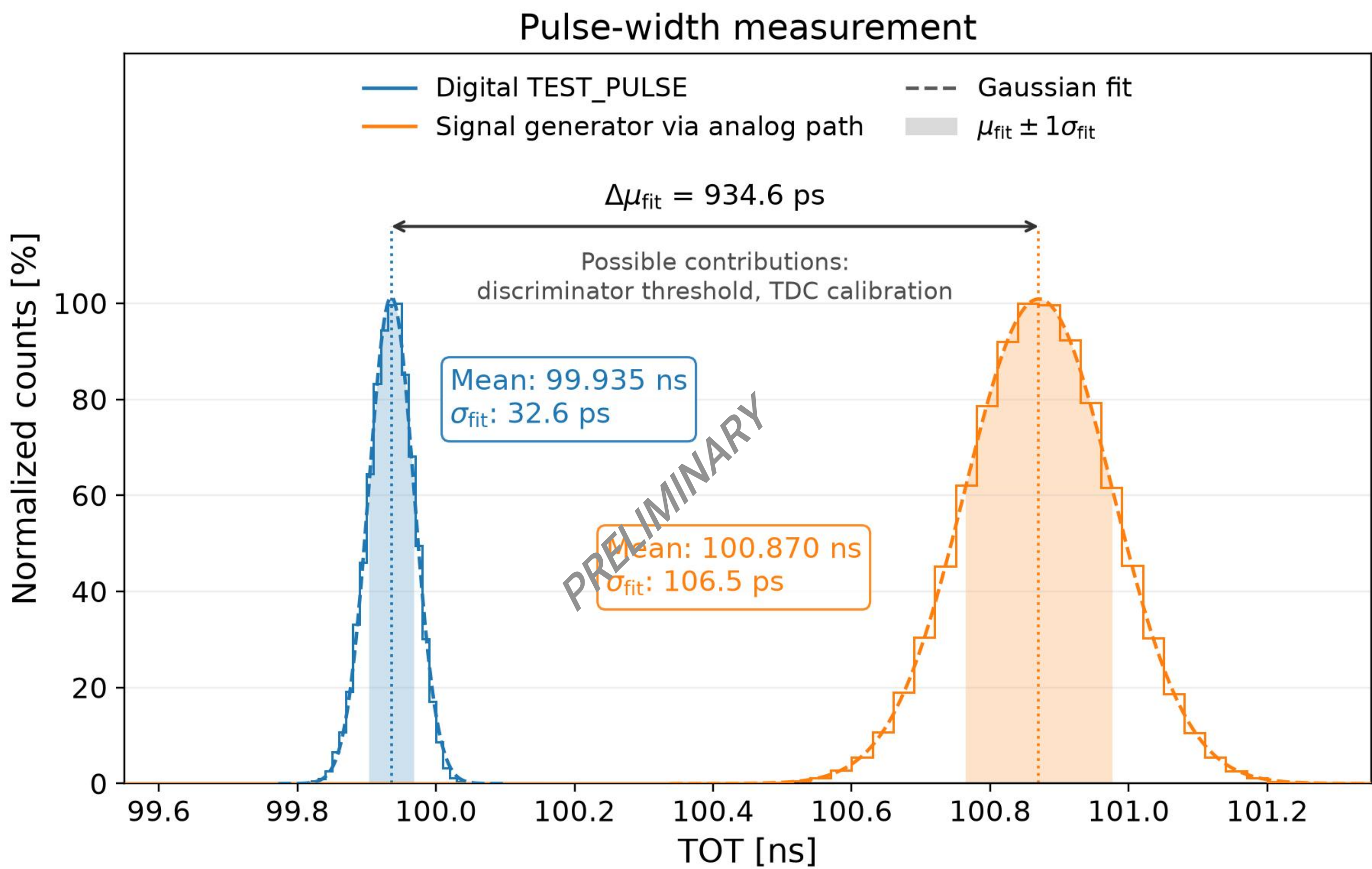


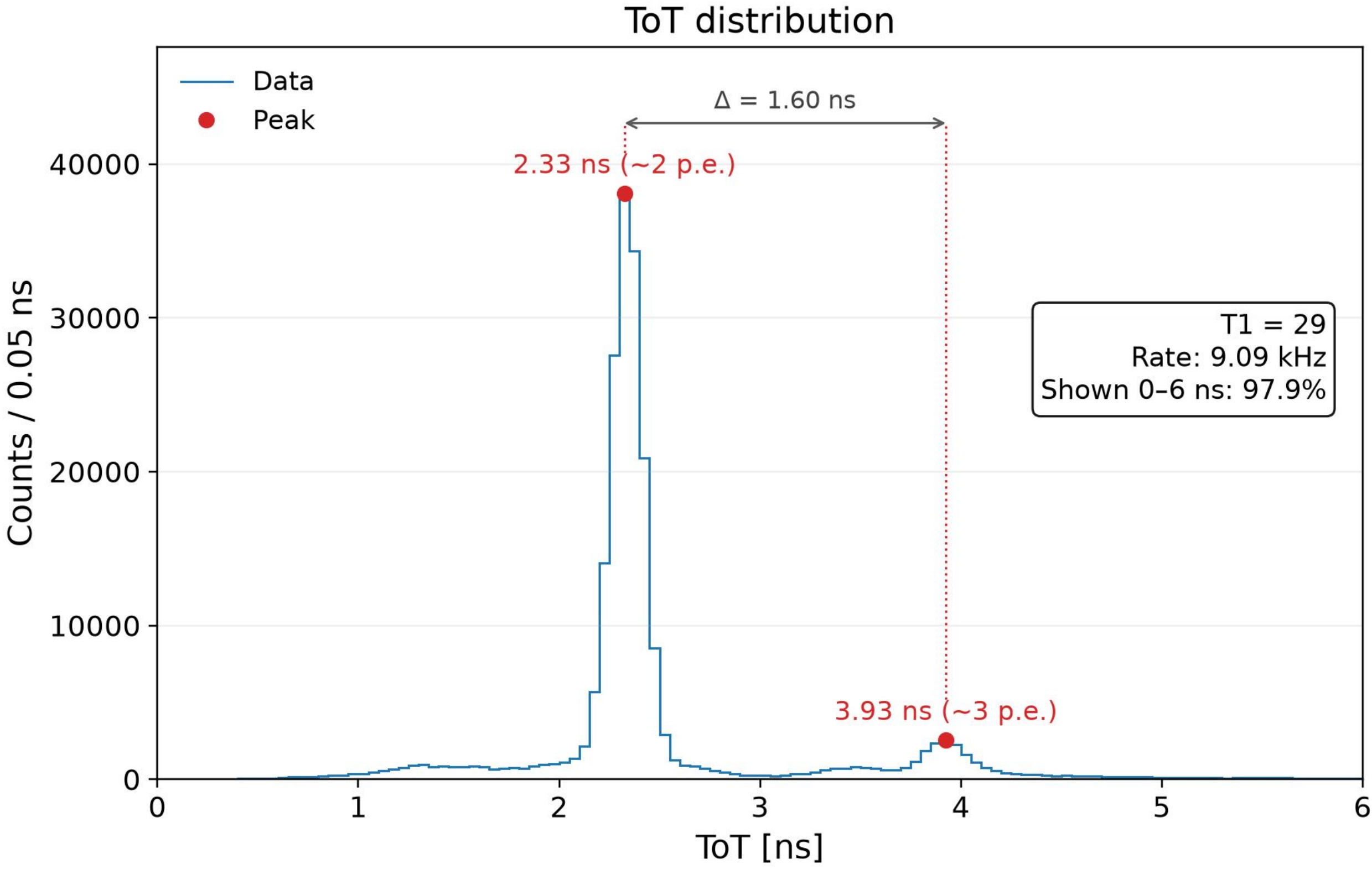
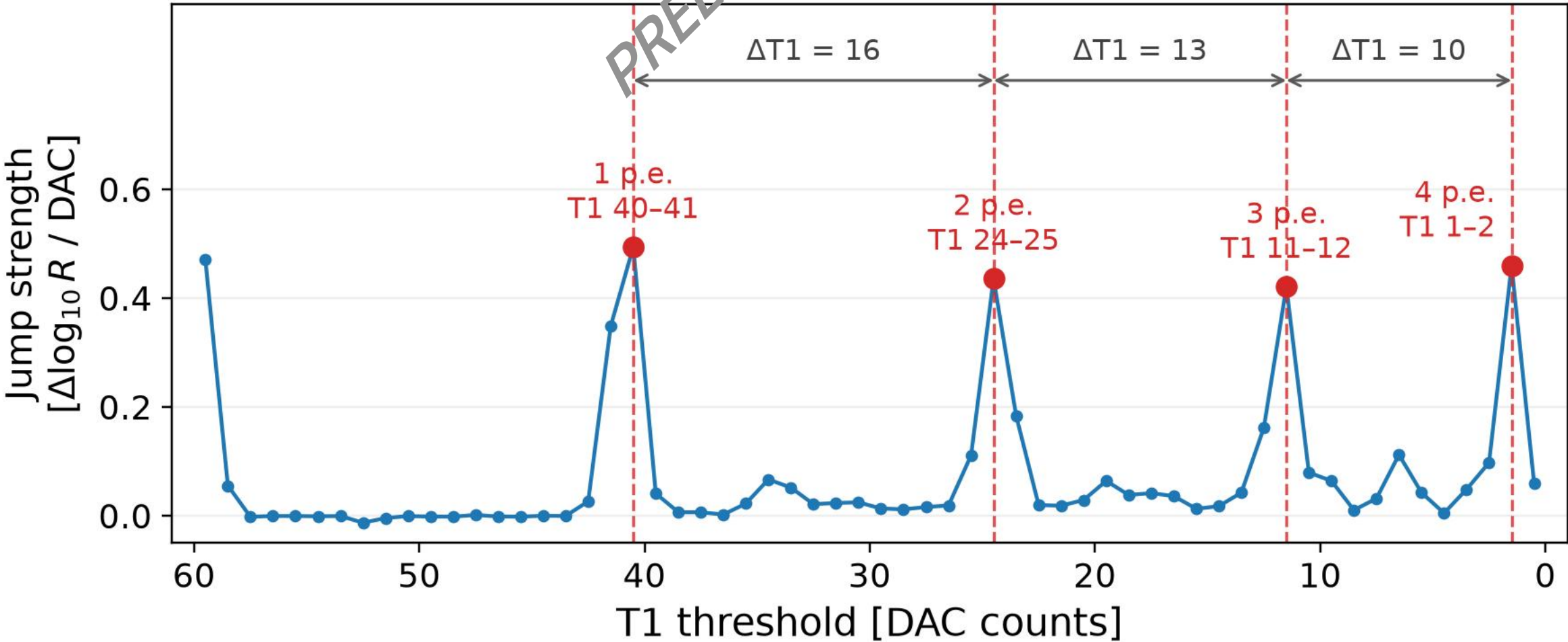
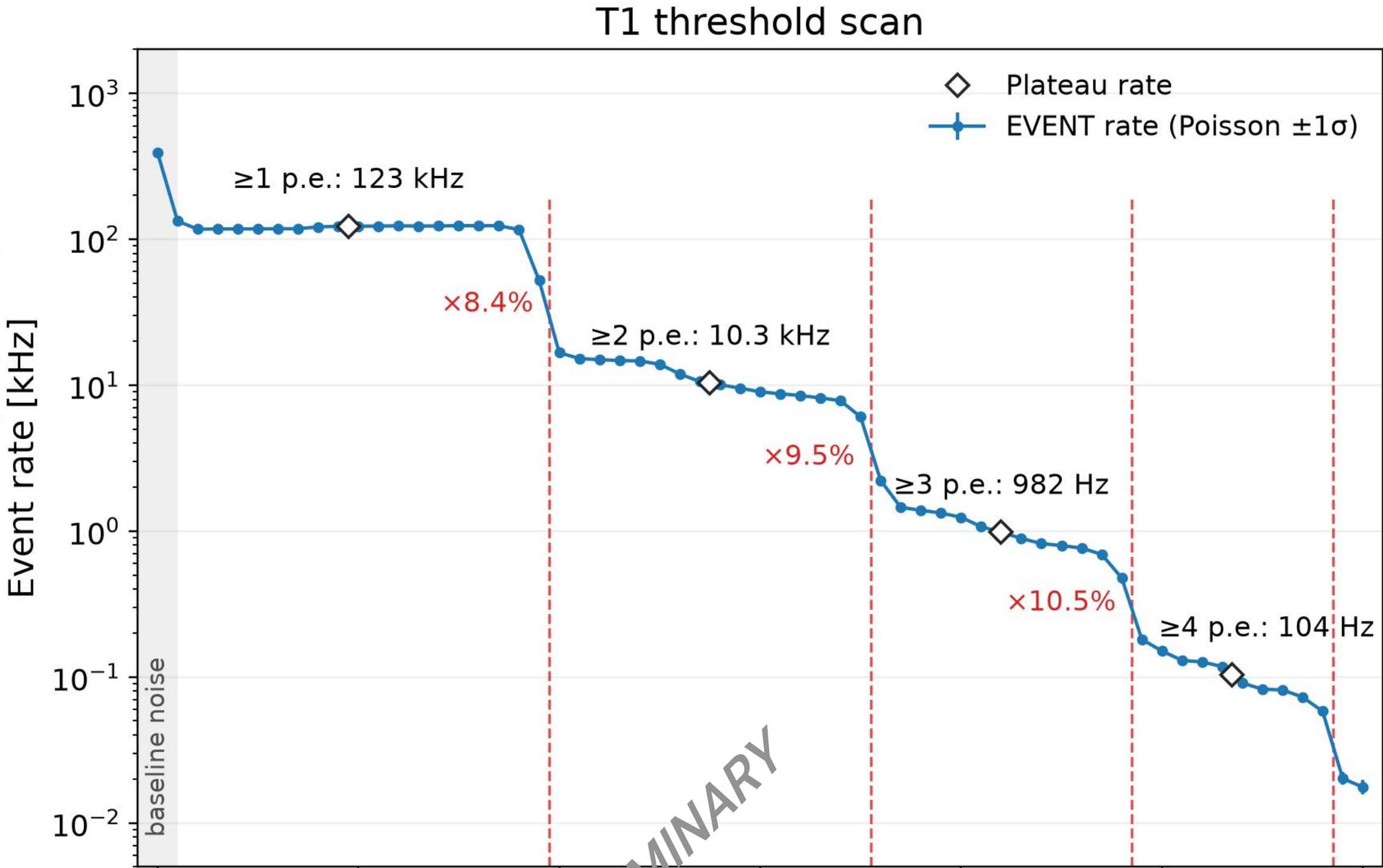
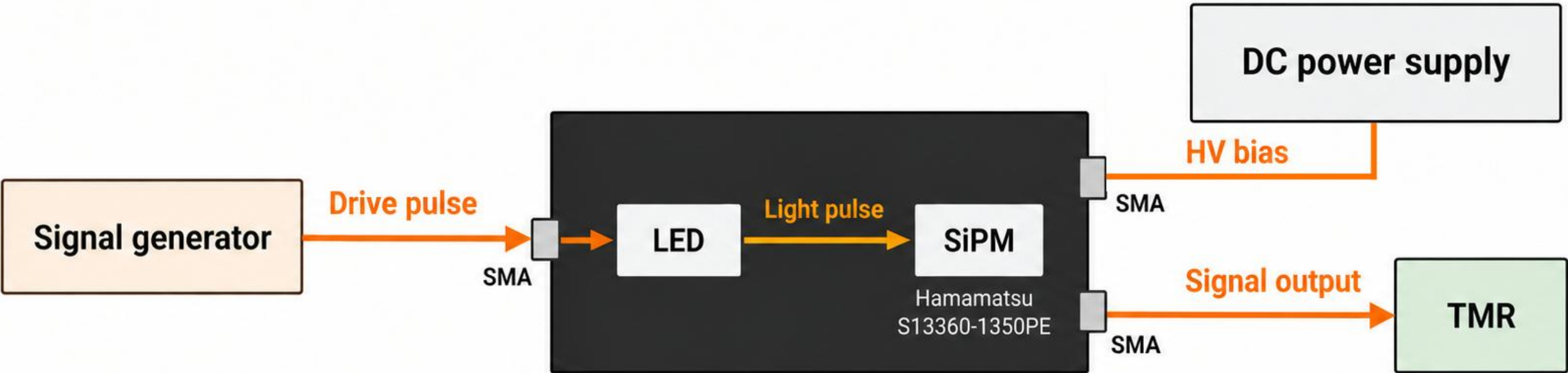
Digital TEST_PULSE

- FPGA-generated digital pulses.
- Analog front end and discriminator bypassed.
- Pulse-width spread: **32.6 ps(σ)**.

Analog Pulse Injection

- Pulses injected from a signal generator.
- Analog front end and threshold discrimination included.
- Pulse-width spread: **106.5 ps(σ)**.







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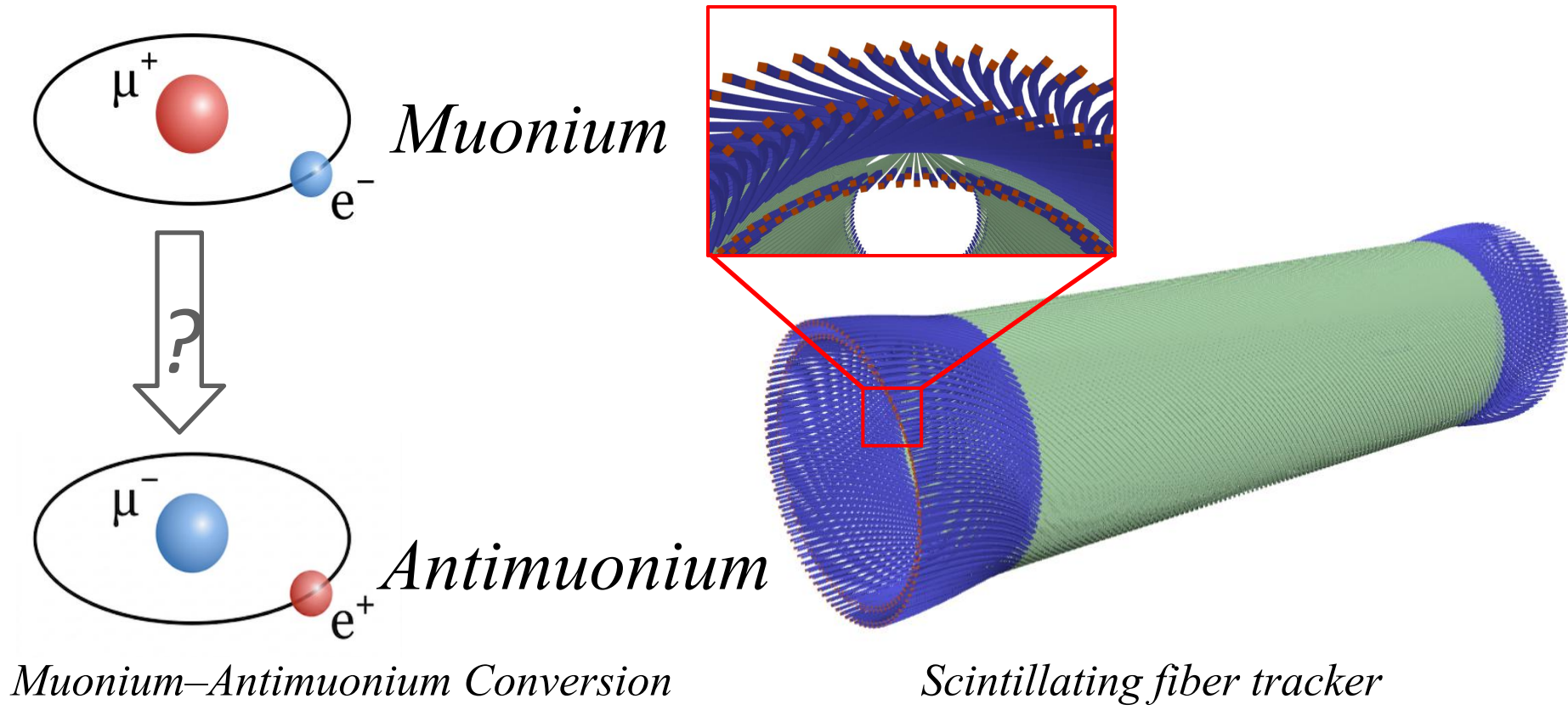
MACE requires readout of over 5000 channels and coordination across multiple detector modules. TMR plans to enable multi-board synchronization through a TLU, providing a scalable system for both μ SR and MACE.

μ SR Electronic performance requirements

Parameter	Specification
Channel Number	> 800
Time Resolution	< 1 ns

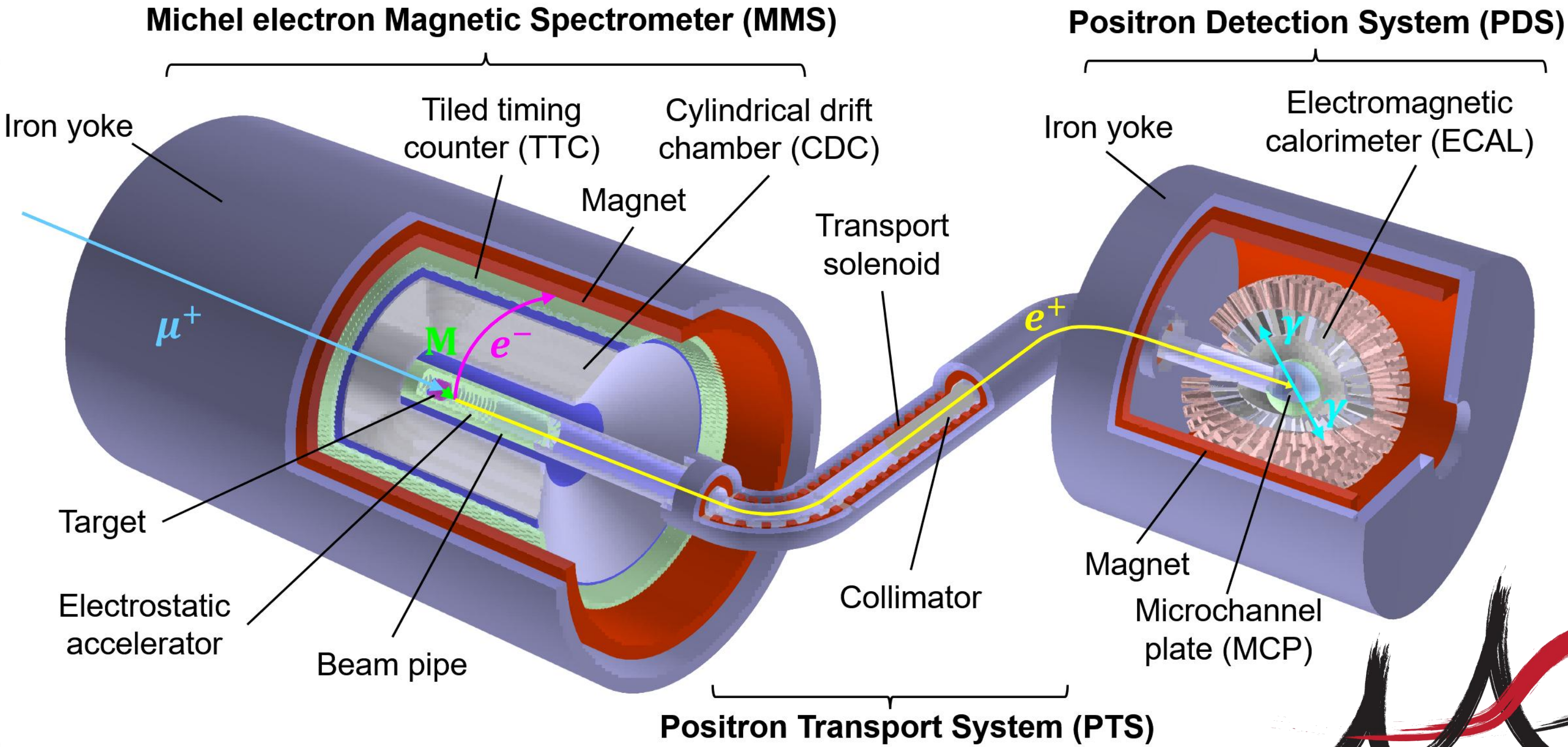


μ SR Prototype Design
arXiv:2505.13877



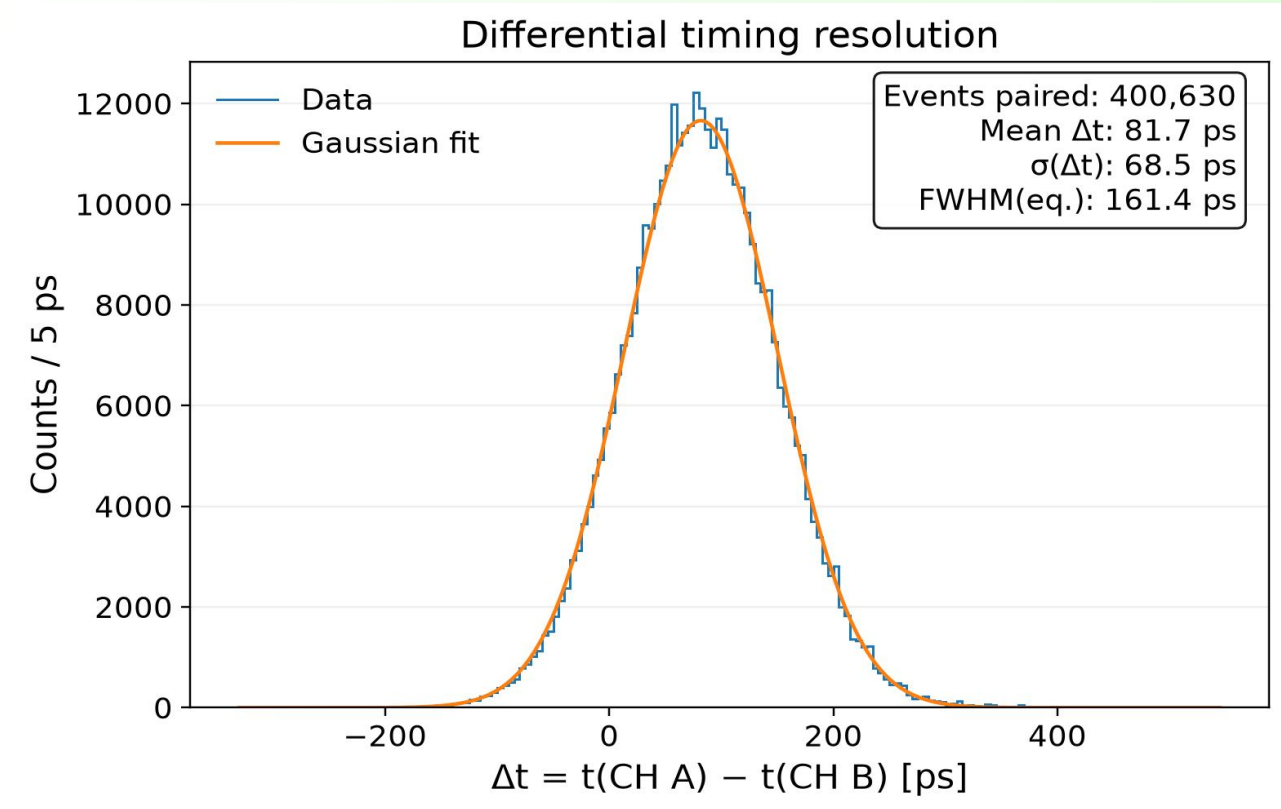
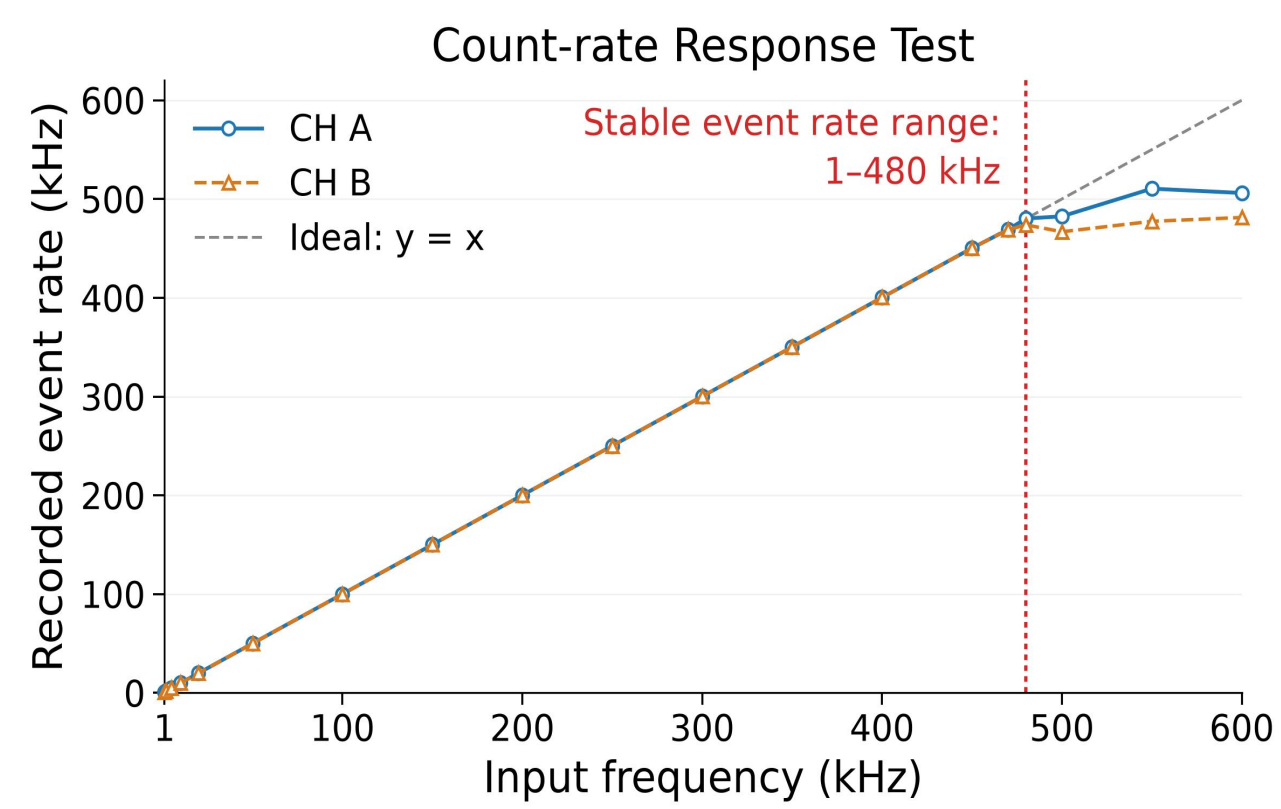
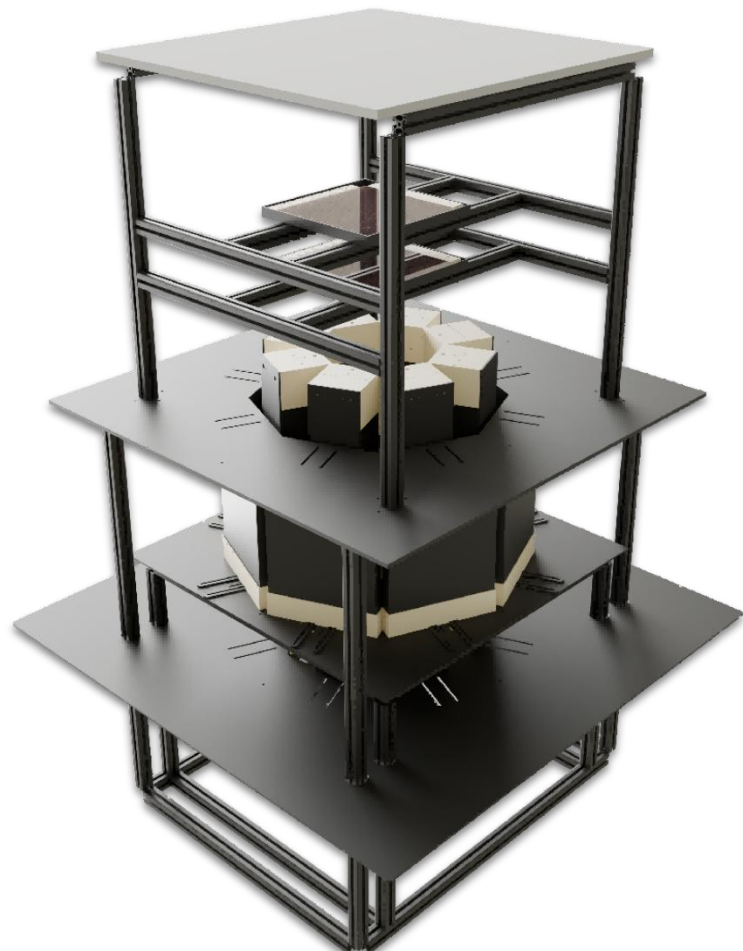
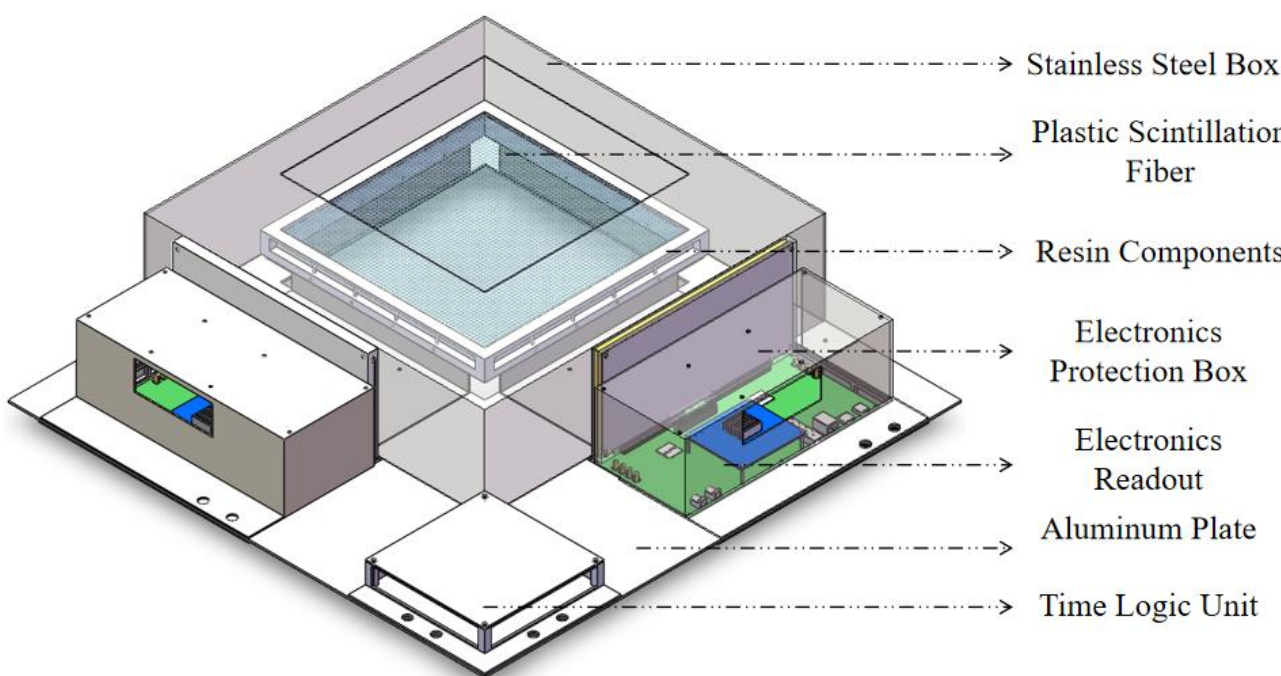
Scintillating fiber tracker
Electronic performance requirements

Parameter	Specification
Channel Number	2360
Trigger Rate	~ 100 kHz
Data Rate	56 Gbps



Nucl. Sci. and Tech. 37, 57 (2026), cover story MACE Concept Design





μ SR: beam-quality requirements
MBM : beam profile & arrival time

Motivation

Performance

TMR

Multichannel electronic readout

SiPM threshold steps & TOT readout

Linear response: 1-480 kHz/ch

Differential timing: 68.5 ps (σ)

256 channel TOFPET2 — based readout system

Flexible data structure & hardware control

Prototype

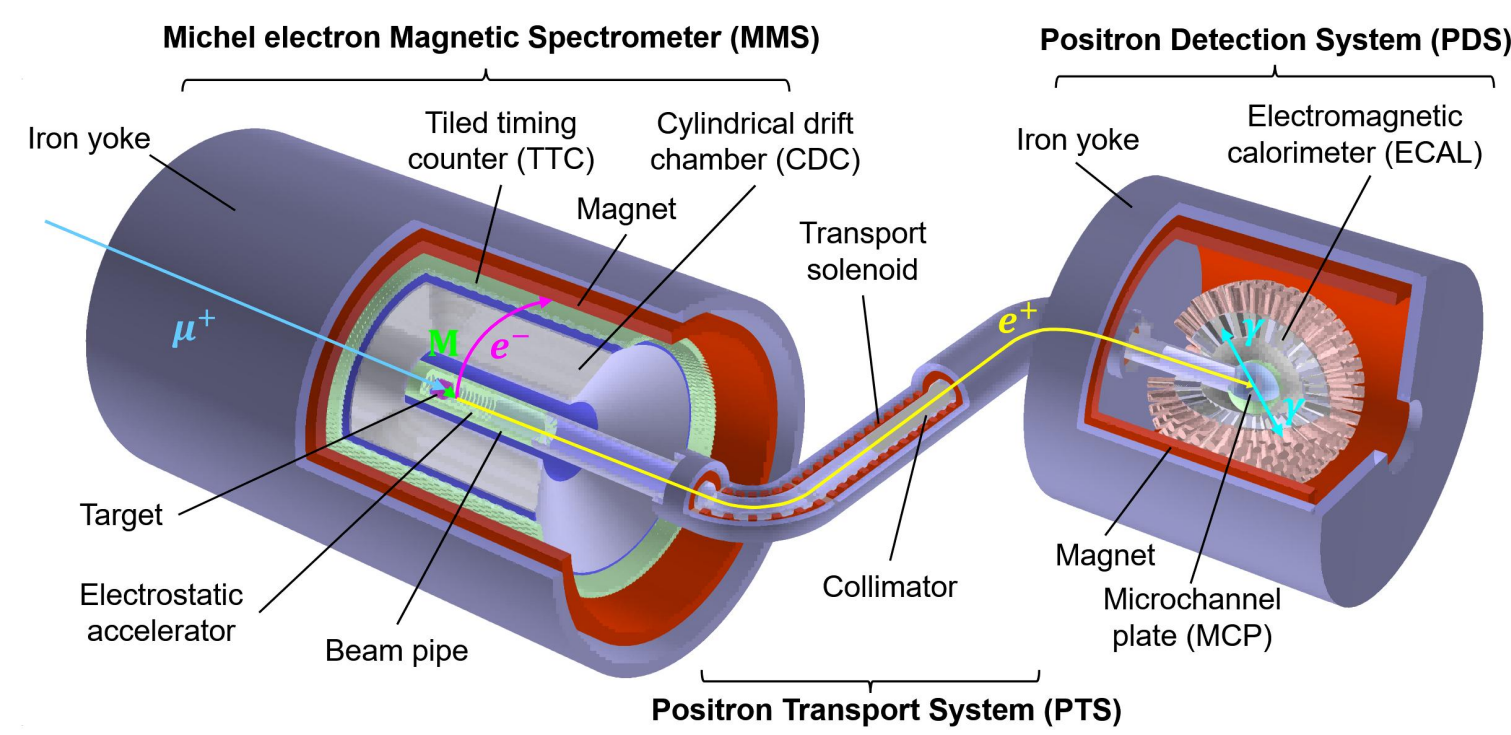
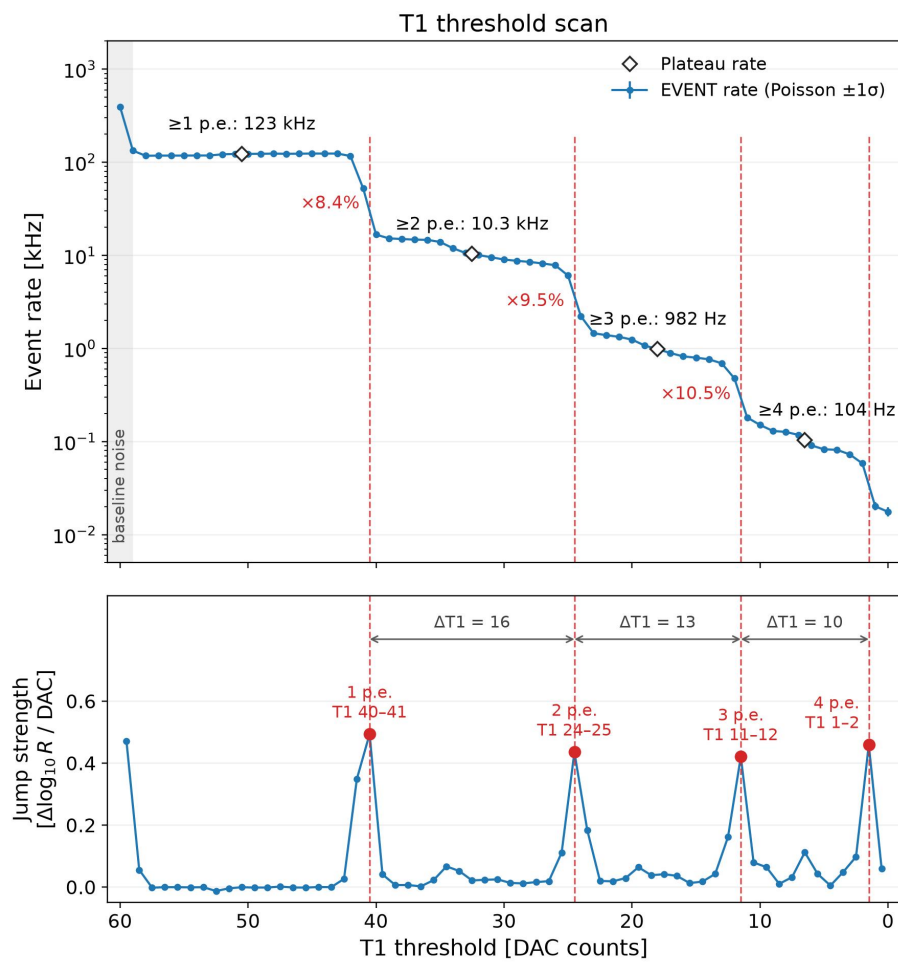
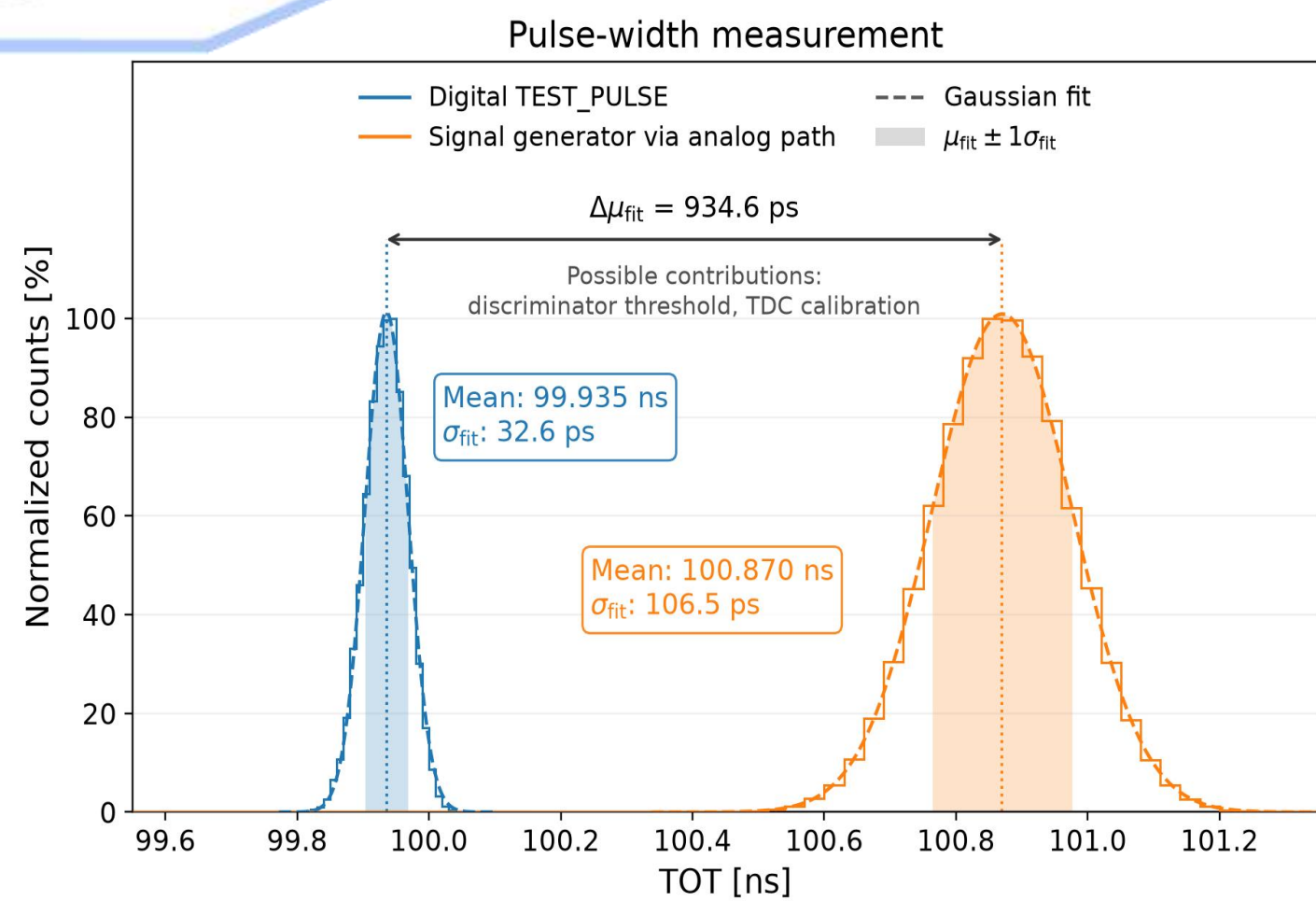
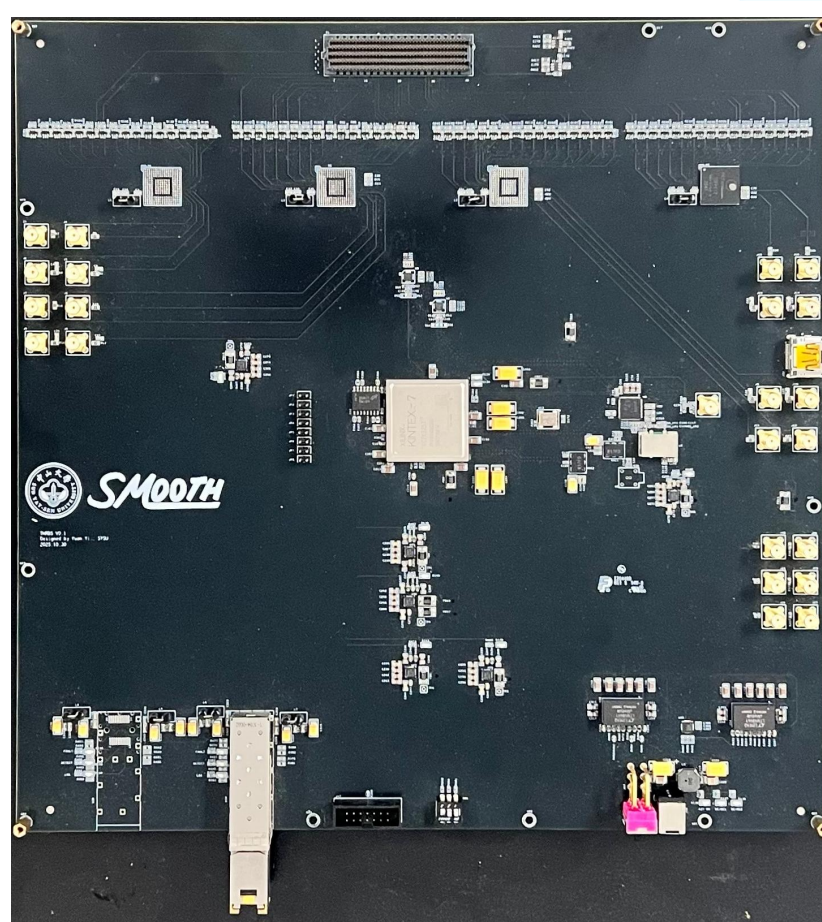
for muon detectors

Outlook

TLU synchronization & expansion

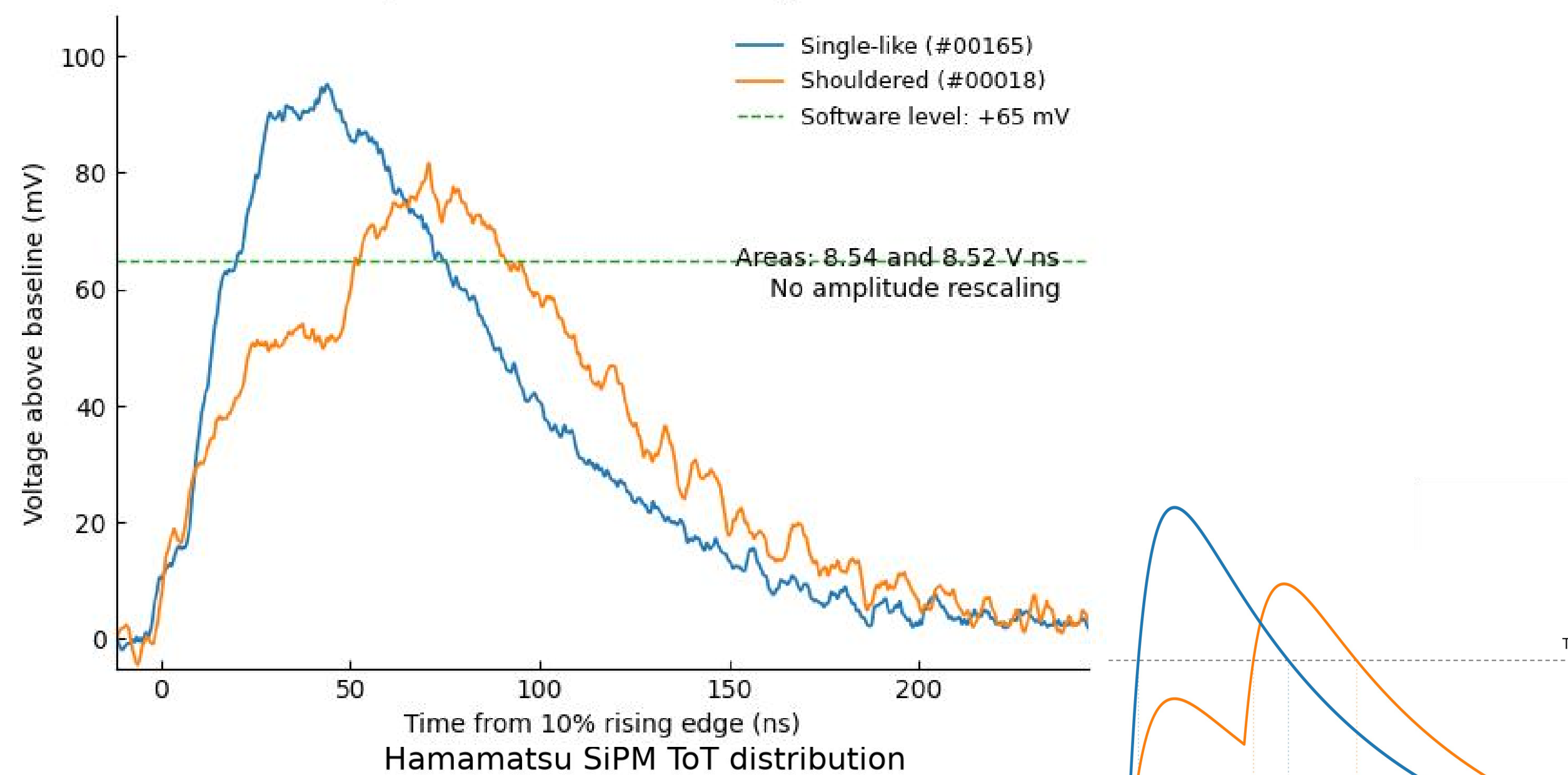
Adaptation to μ SR & MACE

TOT energy calibration & QDC mode

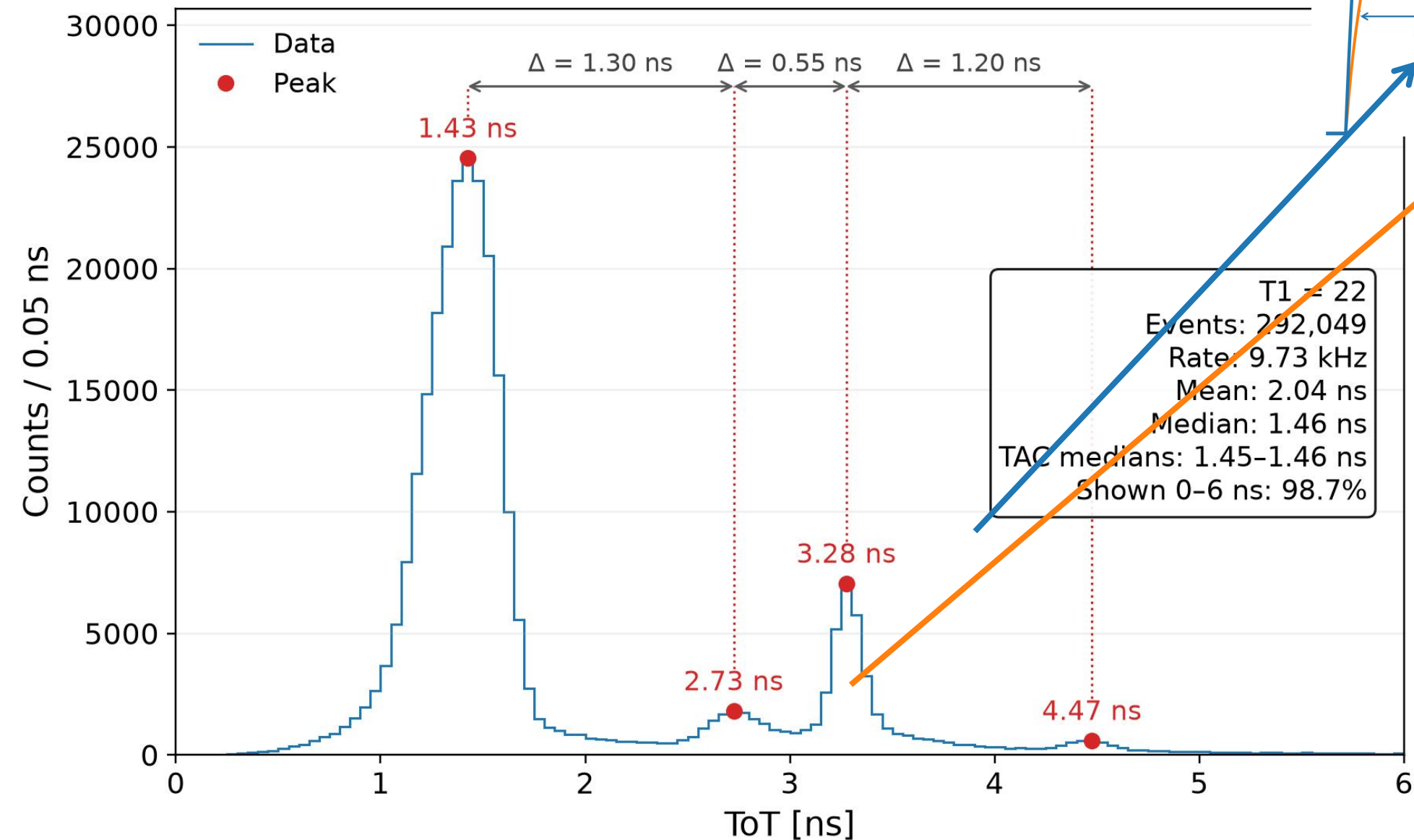


Thanks

Measured pulses with similar voltage-time area



Hamamatsu SiPM ToT distribution



T1 threshold scan

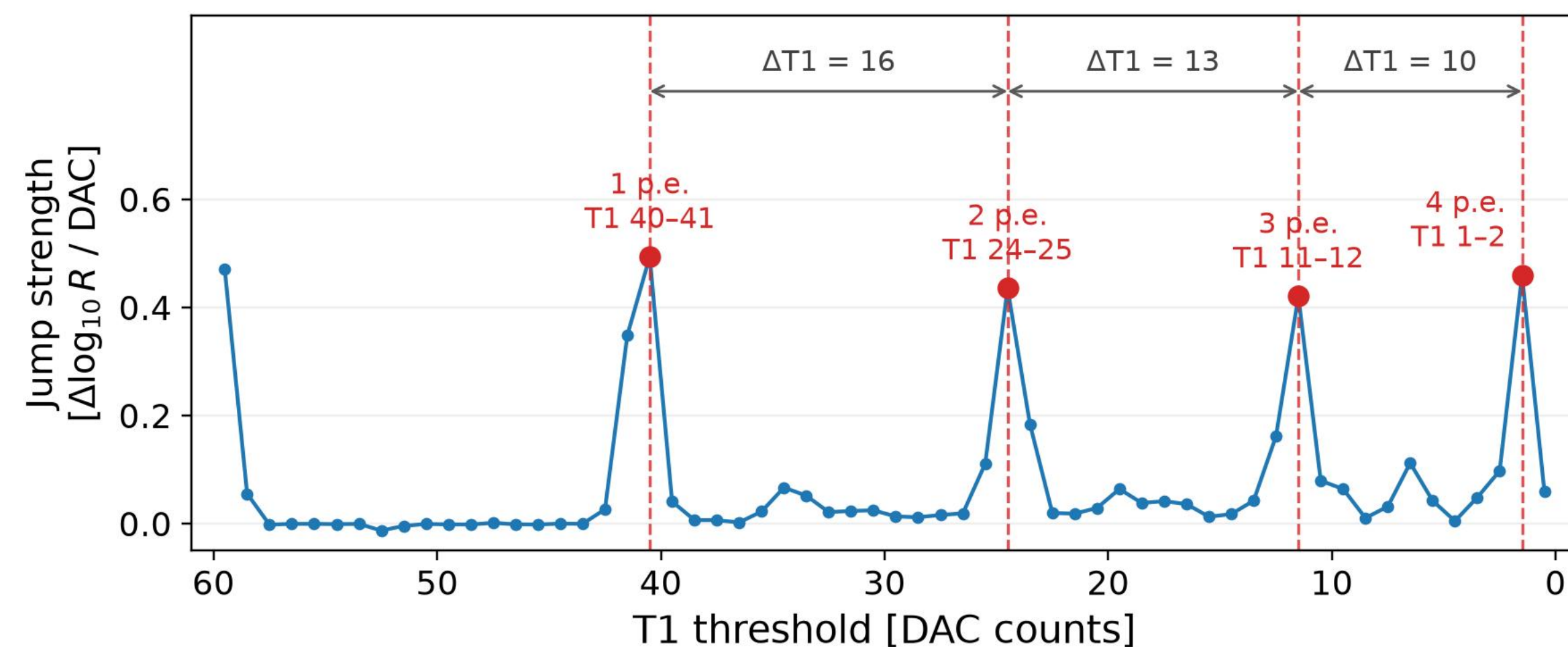
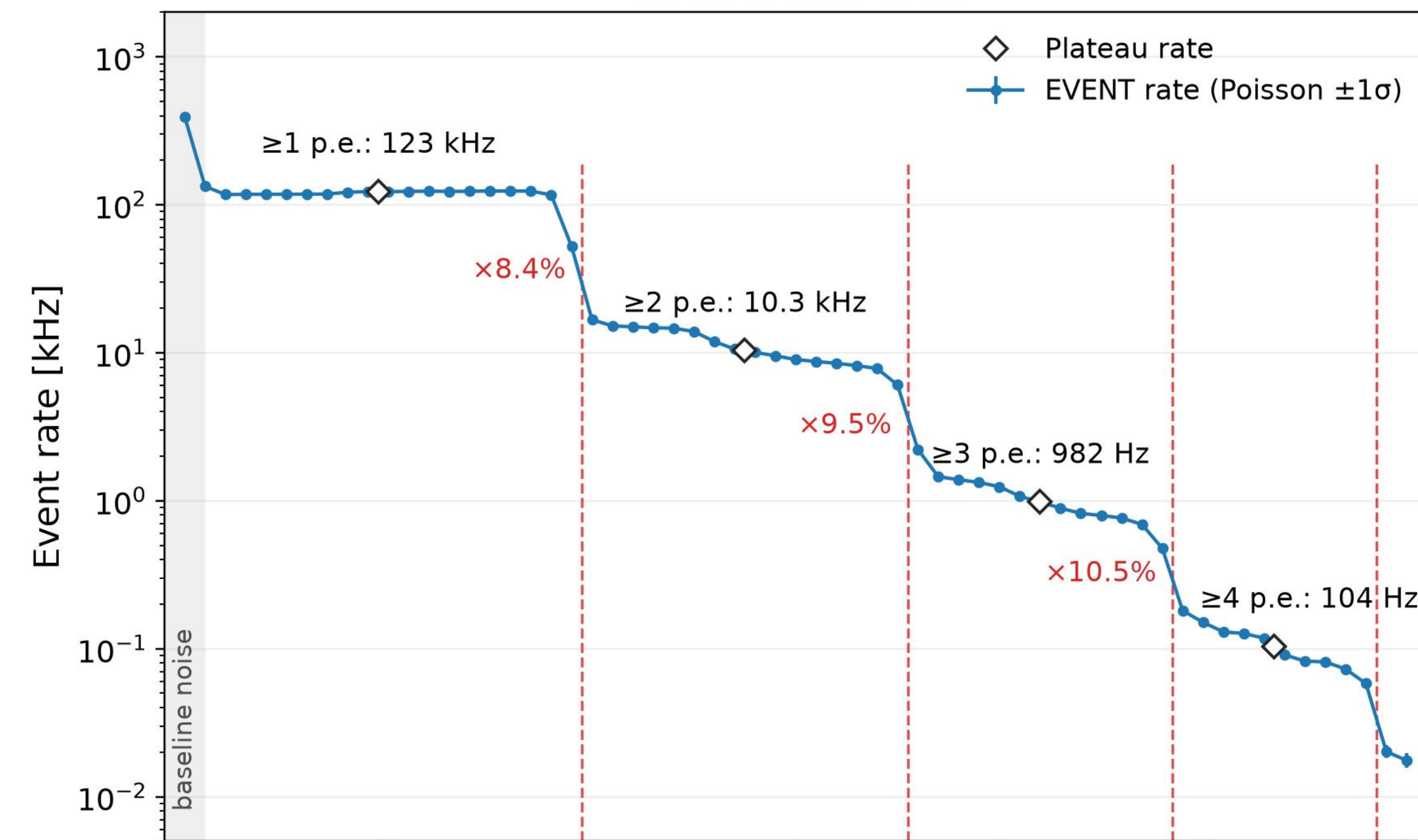
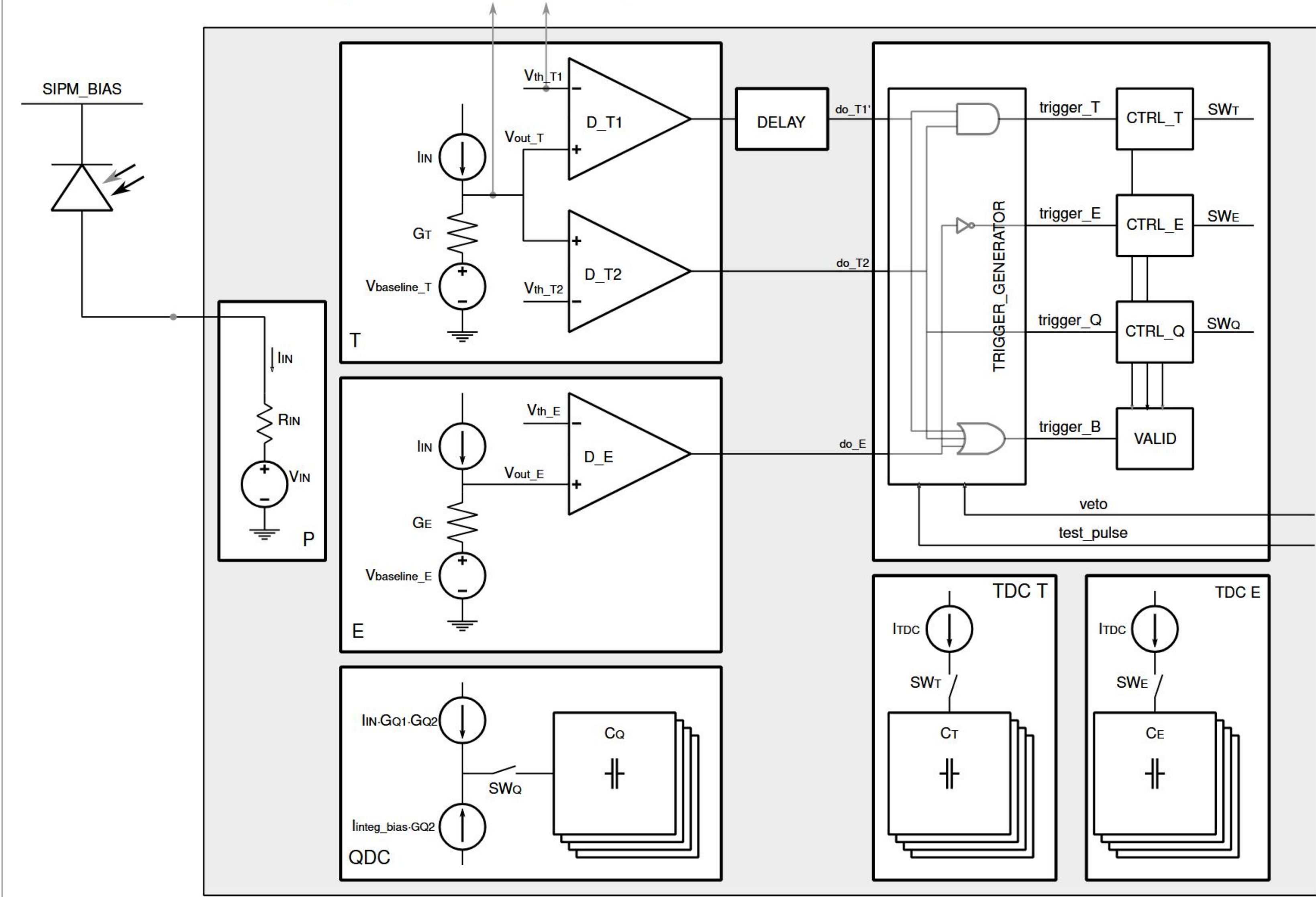
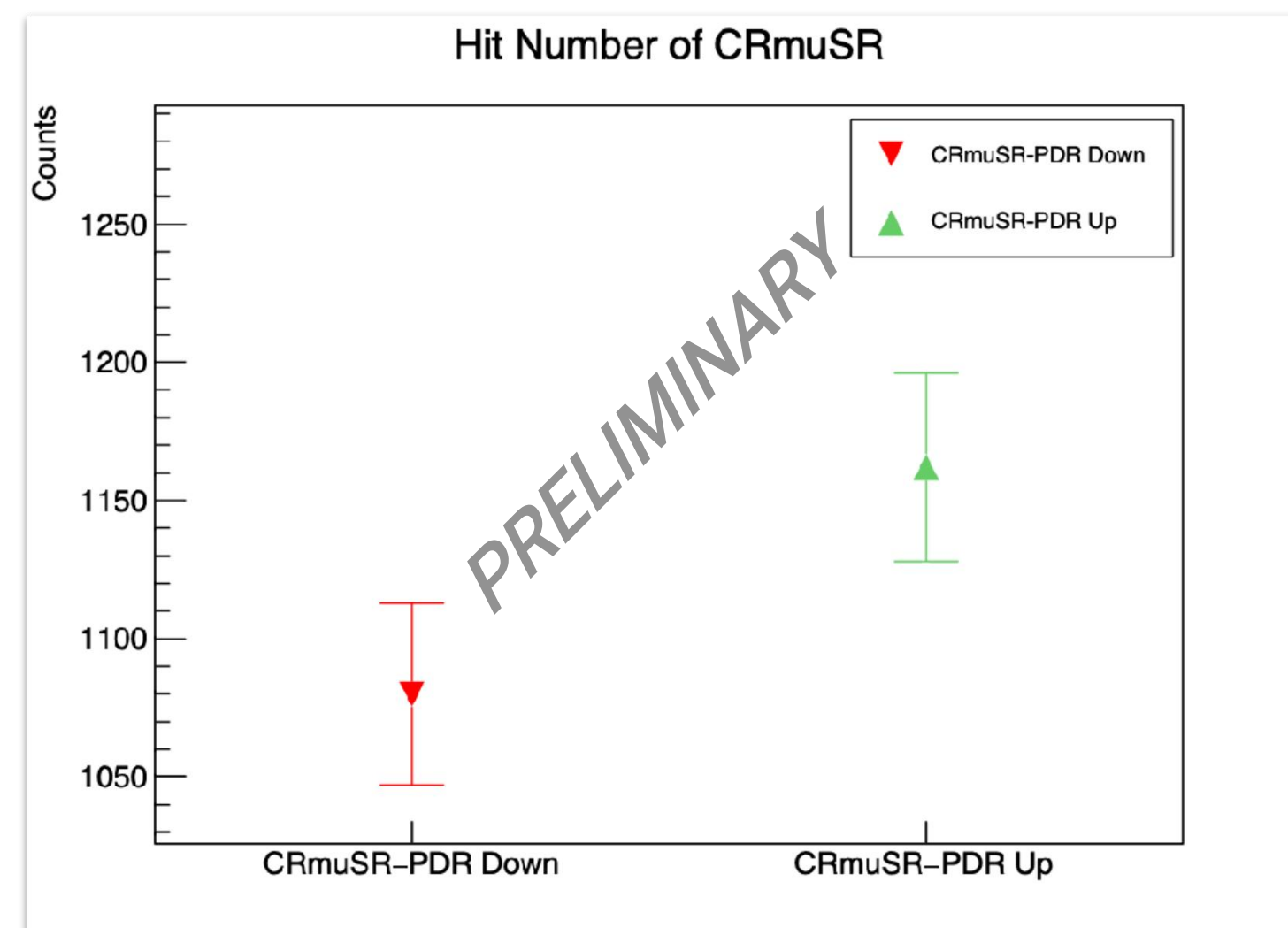
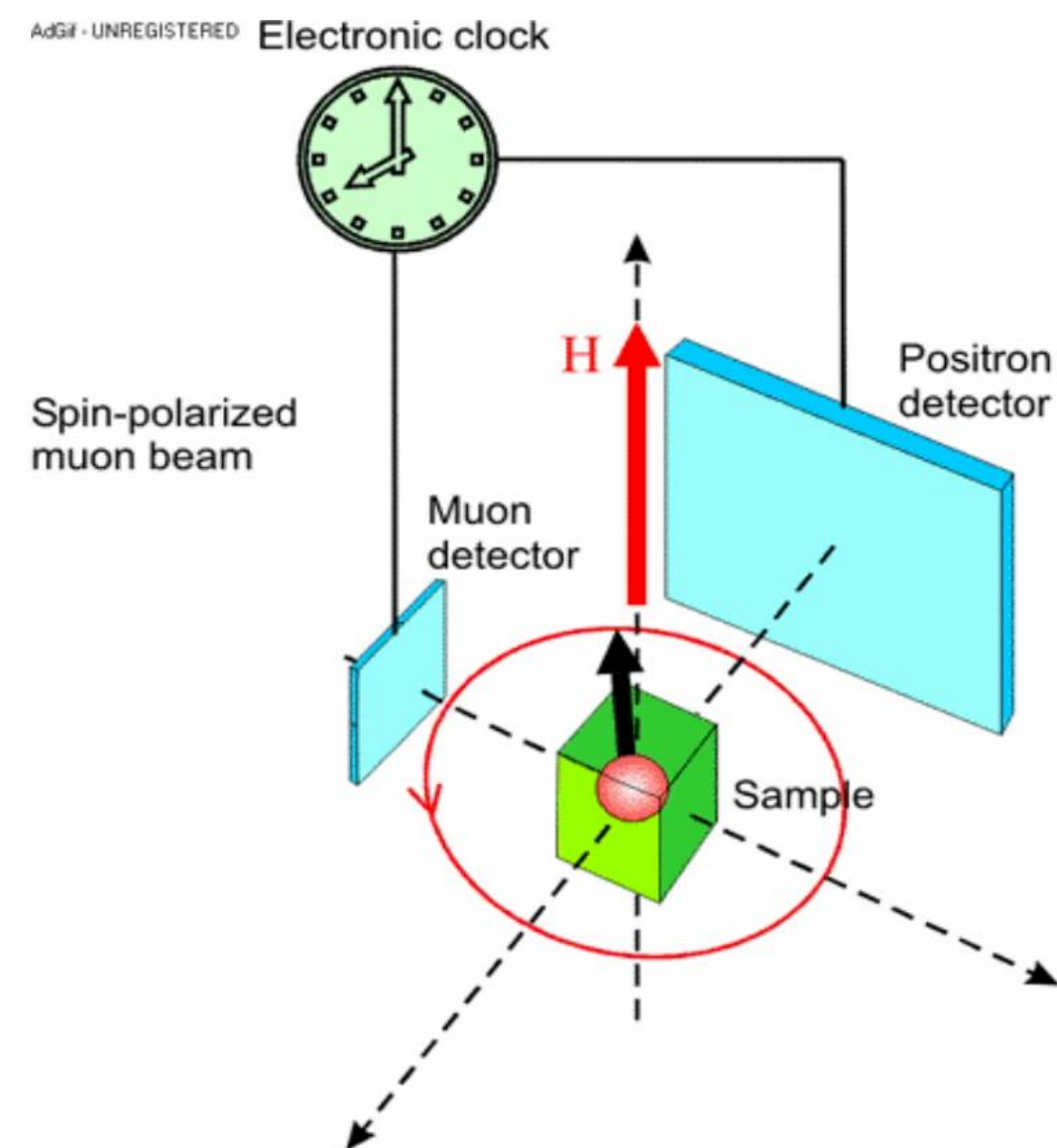


Figure 6: Simplified equivalent TOFPET 2C channel.

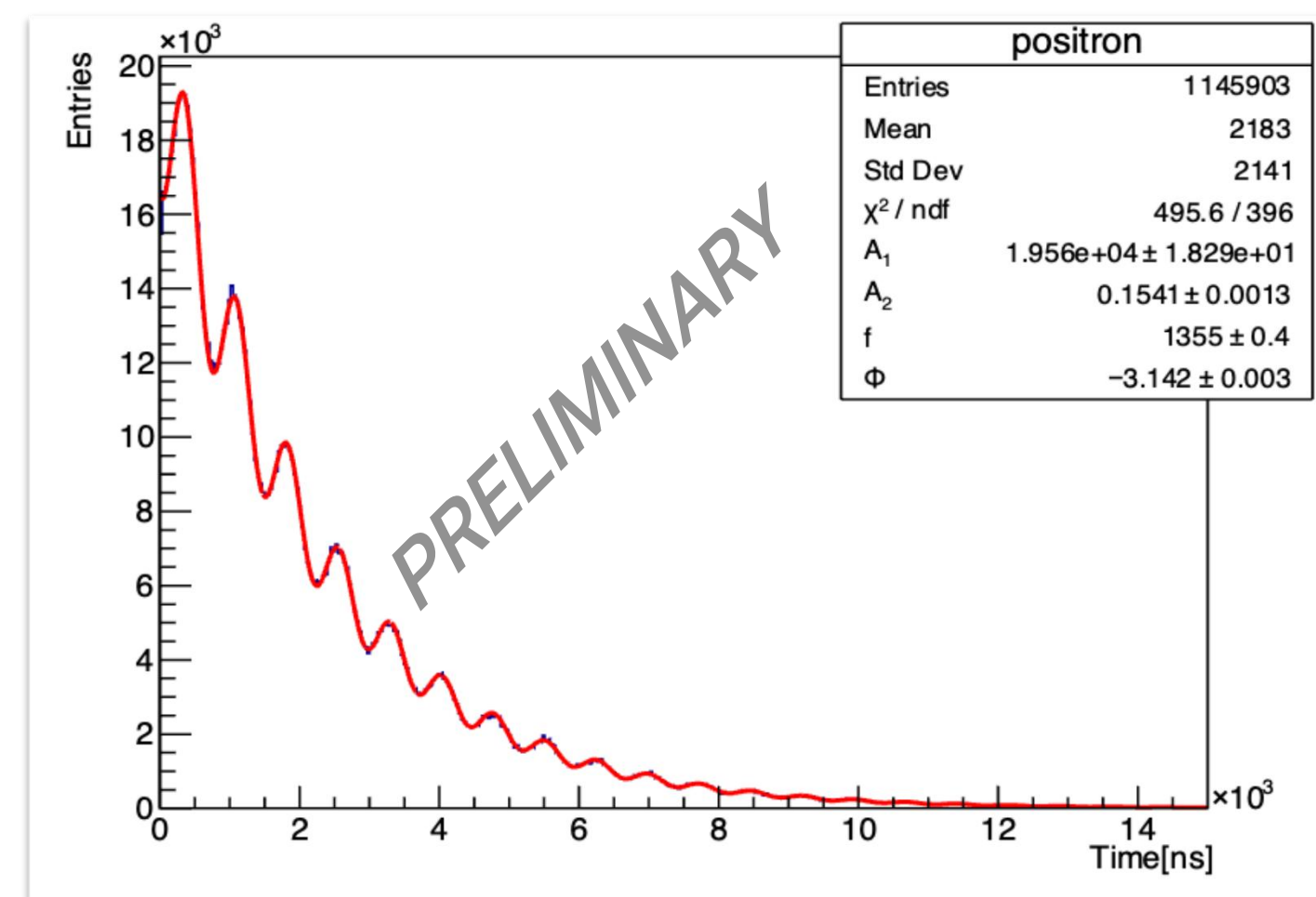
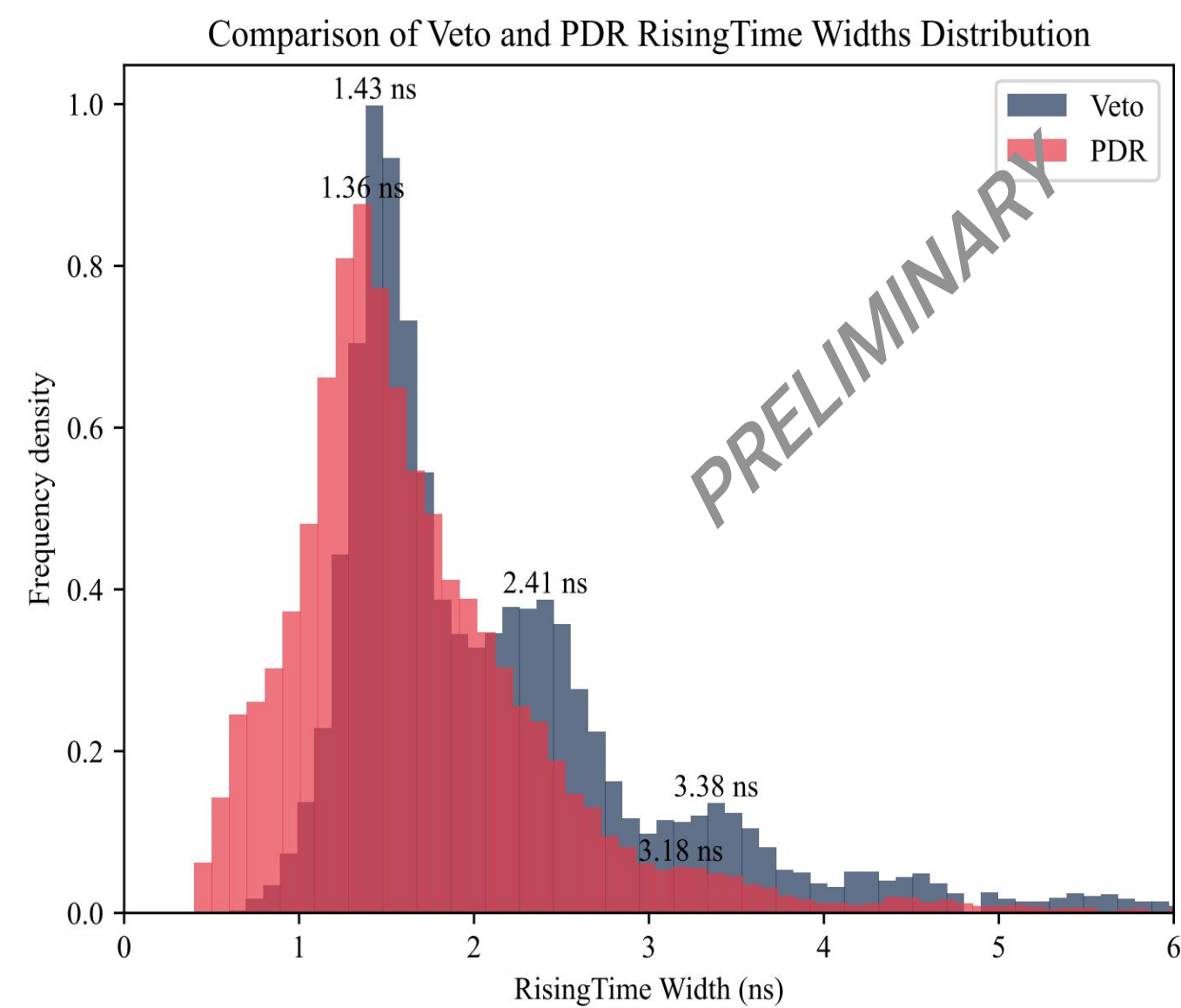


capture.root	
└ petsys/	PETsys singles-compatible fields
└ data	Selected events
└ index	Scan-step index
└ field_units	Field units and descriptions
└ calibration_note	Calibration status and limitations
└ tmrbs_metadata	Configuration, calibration, provenance, and statistics stored as JSON
└ tmrbs/	Full custom event representation
└ data	All EVENT records, including raw codes, converted values, and quality flags
└ index	
└ field_units	
└ calibration_note	
└ tmrbs_metadata	

5 Appendix



Preliminary Analysis of Michel-Electron Hits



GEANT4 simulated μ SR Spectrum $B_{sim} = 100 \pm 0.02$ Gs.



Design of μ SR Detector

TMRBS 实验控制台

配置

采集

实验

数据

工具

连接设置

操作记录 1

工作目录

C:\Users\YuanYi\Desktop\DATA1

更改...

目标设备

UDP 4660 · TCP 24

192.168.10.16

ASIC 工作时钟

200

MHz

TDC 200 MHz · tdc_clk_div=0 (×1)

工作配置

已保存

设备配置

未连接

当前任务

未连接

连接设备

读取并对比

请先连接设备。

工作配置

配置方案

工作配置操作

核对并应用到板子...

请先连接设备。

?

编辑通道

< Ch 63 >

模式作用范围

当前通道

设备快照

Ch 63 尚未核对

数值显示

十进制

撤销上次编辑

模式只更新 Ch 63。

测量方式

QDC

电荷积分

记录到达时间与积分电荷

ToT

脉冲宽度

记录上升沿与下降沿时间

触发方式

Only T1

单阈值 · T 支路

T1 同时负责计时和事件验证

Only E

单阈值 · E 支路

E 同时负责计时和事件验证

T1 + T2

双阈值 · T 支路

T1 计时, T2 验证事件

T1 + E

双阈值 · T / E

T1 计时, E 验证事件

T1 + T2

快速暗计数抑制

T2 参与触发门控, T1 保留计时

T1 + T2 + E

三阈值 · 快速抑制

T1 计时、T2 门控、E 验证

采集

?

保存目录

C:\Users\YuanYi\Desktop\DATA1\data

选择目录

文件名后缀

如 T149, 自动加日期时间前缀

.bin

☒ 定时采集

10

秒后停止并保存

☐ 保存后转换为 ROOT

开始采数

请先连接设备。

停止并保存

请先连接设备。

接收

宿主就绪

当前文件

-

平均写盘

0.00 Mbps

全局配置字段（184-bit payload）						
字段	位	值	bin	推荐	说明	
链路 3个						
tx_nlinks	[1:0]	4路 · 10₂ / 选项 10₂ = 2	10	10 4路	活跃链路数	
tx_ddr	[2]	DDR · 1₂ / 选项 1₂ = 1	1	1 DDR	SDR/DDR	
tx_mode	[4:3]	正常 · 10₂ / 选项 10₂ = 2	10	10 正常	链路模式	
系统 8个						
veto_mode	[11:6]	000000 二进制 000000₂ = 0	000000	000000	触发抑制	
r_clk_en	[15:13]	110 二进制 110₂ = 6	110	110	R时钟使能	
stop_ramp_en	[19:18]	00 二进制 00₂ = 0	00	00	停止斜坡使能	
counter_en	[20]	开 · 1₂ / 1 / 选项 1₂ = 1	1	0 开	事件计数使能	
counter_period	[23:21]	2²² · 110₂ / 选项 110₂ = 6	110	110 2 ²²	计数周期	
tac_refresh_en	[24]	开 · 1₂ / 1 / 选项 1₂ = 1	1	1 开	TAC刷新使能	
tac refresh period	[28:25]	1001 二进制	1001	1001	TAC刷新周期	

通道选择与批量操作

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35

36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63

当前:

<

Ch 63

>

复制当前 →

Ch 0 ~ 63

复制

→ ALL

推荐值(当前)

推荐值(全部)

未配置读回

清空全部

导出全部 JSON

通道 63 配置字段 (125-bit payload)							
字段	位序	值	bin	推荐	说明	Section	批量
系统 20个							
trigger_mode_1	[1...0]	00 / 二进制	00	00	设置触发模式	5.4	→ALL
		00 ₂ = 0					
sync_chain_length	[5...4]	00 / 二进制	00	00	—		→ALL
		00 ₂ = 0					
dead_time	[11...6]	000000 / 二进制	000000	000000	设置额外通道死区时间	5.8	→ALL
		000000 ₂ = 0					
counter_mode	[15...12]	0000 / 二进制	0000	0000	设置事件计数模式	5.9	→ALL
		0000 ₂ = 0					
tac_max_age	[20...16]	11110 / 二进制	11110	11110	—		→ALL
		11110 ₂ = 30					
tac_min_age	[25...21]	01010 / 二进制	01010	01010	—		→ALL
		01010 ₂ = 10					