Study of high time resolution MRPC with the waveform digitizer system

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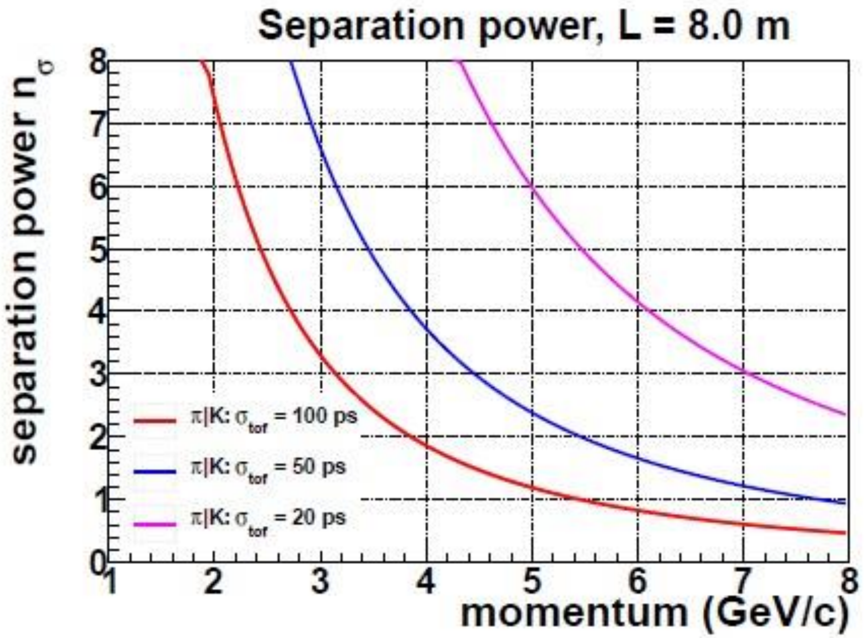
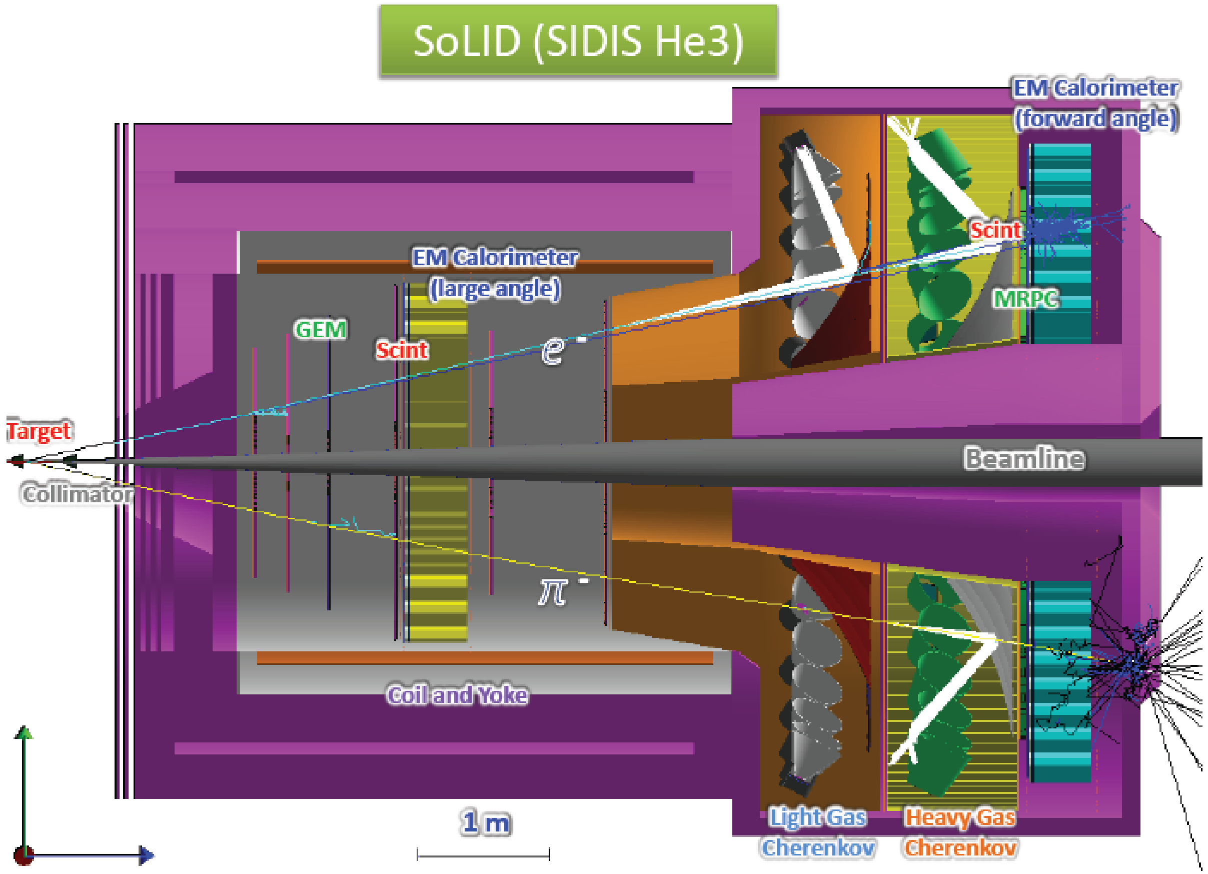
Outline

- ◆ **Motivation**
- ◆ **Experiment**
  - The structure of the high time resolution MRPC
  - Cosmic Test in Tsinghua
  - Preliminary Results
- ◆ **MRPC Simulation using Geant4**
- ◆ **Conclusion & Future Plan**

Motivation

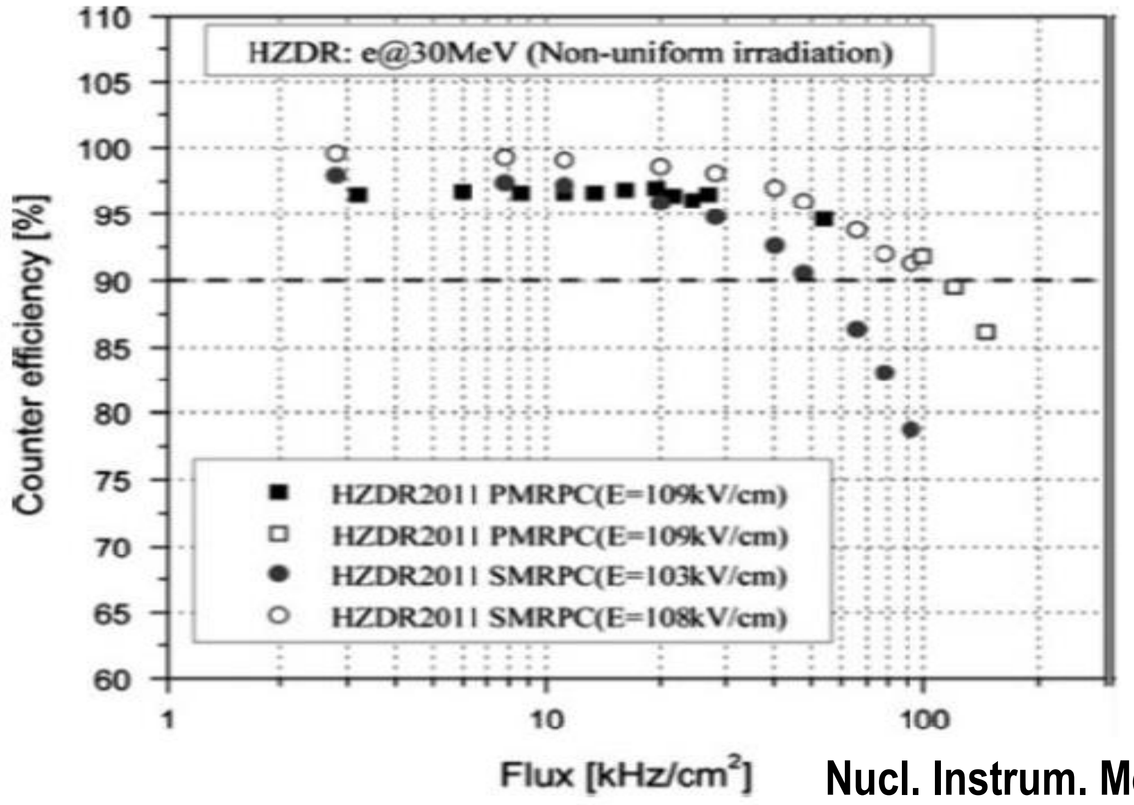
- Jefferson Lab (JLab) 12 GeV Upgrade
- Solenoidal Large Intensity Device (SoLID)
- The requirements for the TOF system are:
  - ✓ pi/k separation up to **7 GeV/c**
  - ✓ Time resolution < **20 ps**
  - ✓ Rate capability > **10 kHz/cm²**





Motivation

- The high time resolution & high rate MRPC for SoLID-TOF is proposed by Tsinghua
- High rate capability---- Low resistivity glass (10^{10} Ωcm)
  - ✓ Rate capability > 70 kHz/cm^2
  - ✓ Successfully used in CBM experiment (Germany)



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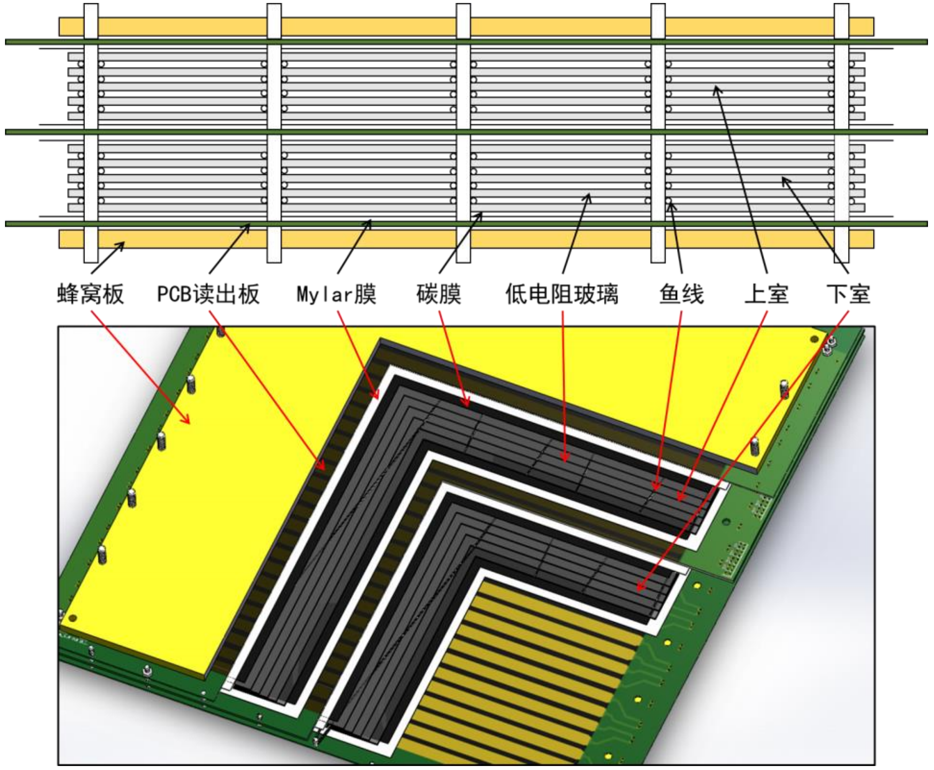


2016 *JINST* 11 C08007

Motivation

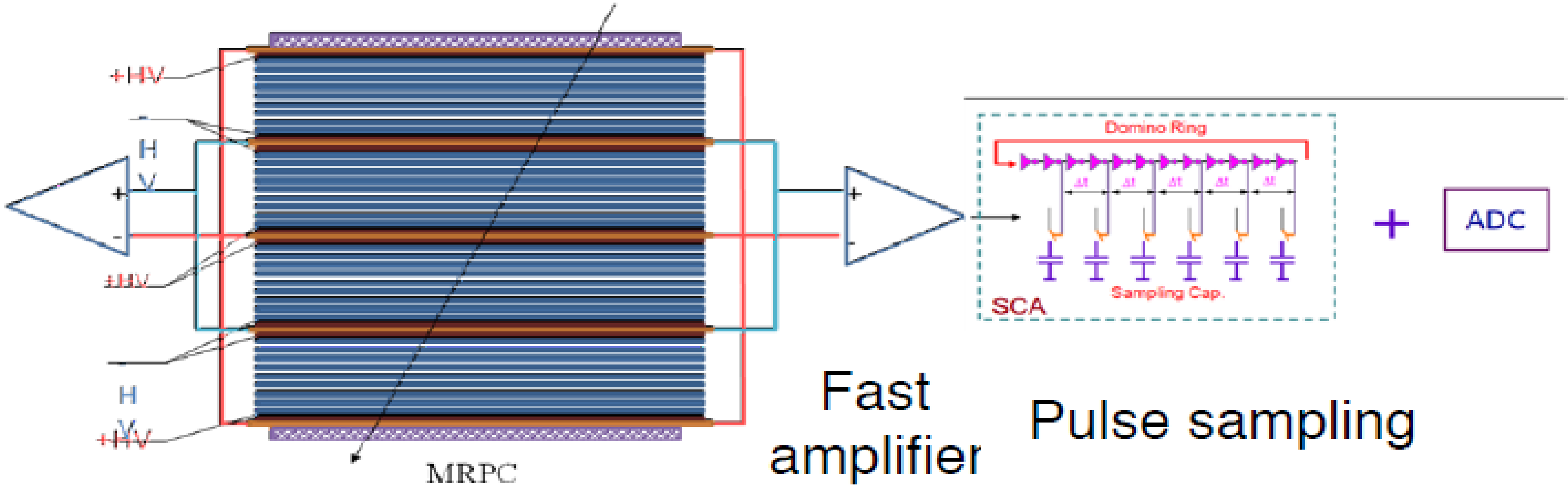
- Some typical MRPCs that are used in several high energy physics experiments

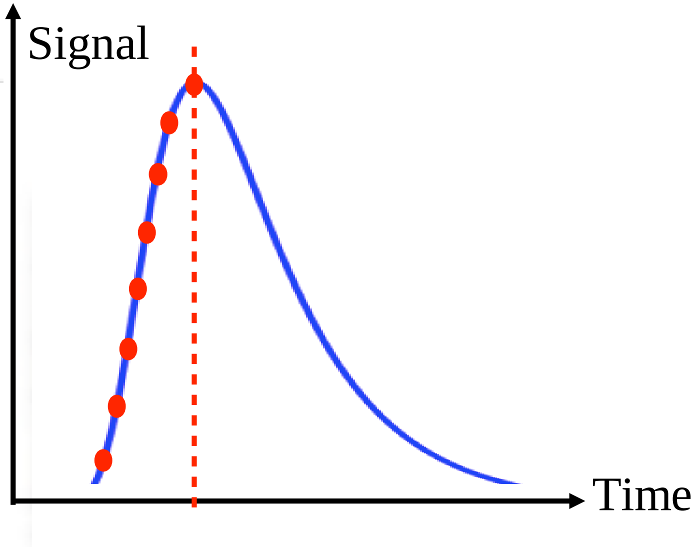
Experiment	StackNb	GapNb	Gap Thickness [um]	Working E [kV/cm]	Time resolution [ps]
ALICE	2	5	250	104	~60
STAR	1	6	220	114	~60
CBM	2	4	250	110	~60

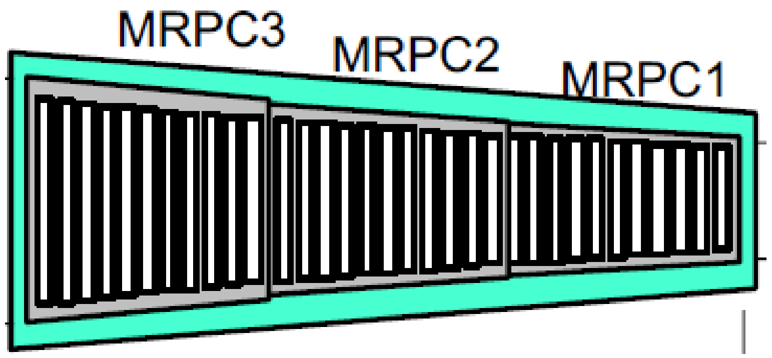
Exp.	Electronic	Time jitter/ps
ALICE	NINO Amplifier	~20
	HPTDC	~25
CBM	PADI	~10
	GET4	~25

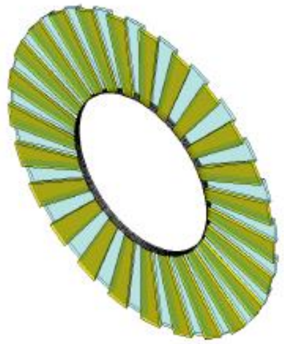
Motivation

- The high time resolution & high rate MRPC for SoLID-TOF is proposed by Tsinghua
- Thin gap MRPC + fast amplifier and waveform digitizer system (USTC)



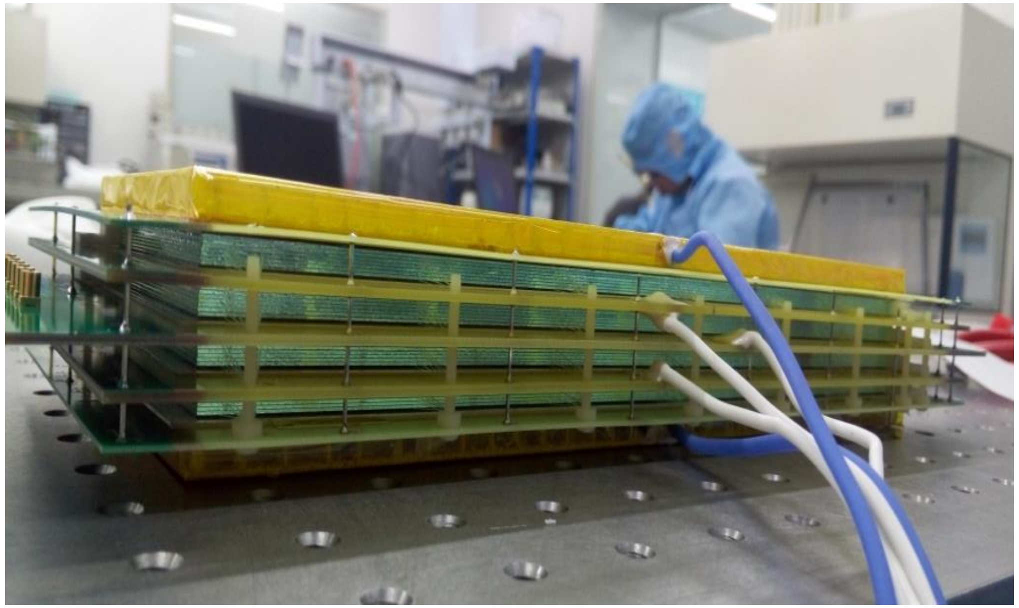






Experiment & Simulation

Experiment — MRPC Structure



Tsinghua Prototype	4-stack MRPC
Gas Gap Width	104 um (fishing line)
Number of Gas Gaps	4 stack × 8 layers = 32
Float Glass Thickness	500 um
Readout strip	7 mm × 270 mm (3 mm internal)
Readout	Single-ended

Equivalent noise charge:

$$\sigma_t = \frac{\sigma_V}{dV/dt} = \frac{t_{rising}}{V_{signal}/noise}$$

- **Narrower gap width** → fast charge dominant in the induced signal → Better timing resolution
- **More gas gaps** → Maintain the efficiency

Experiment — Electronics

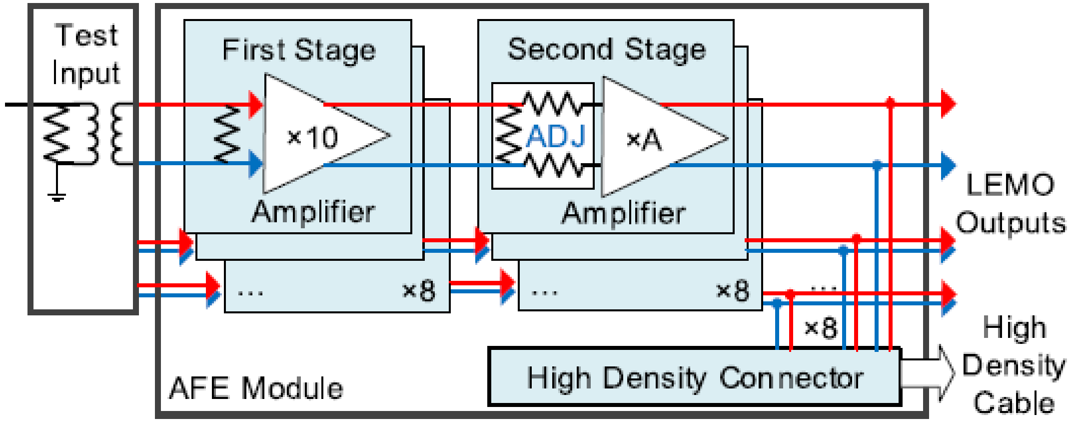
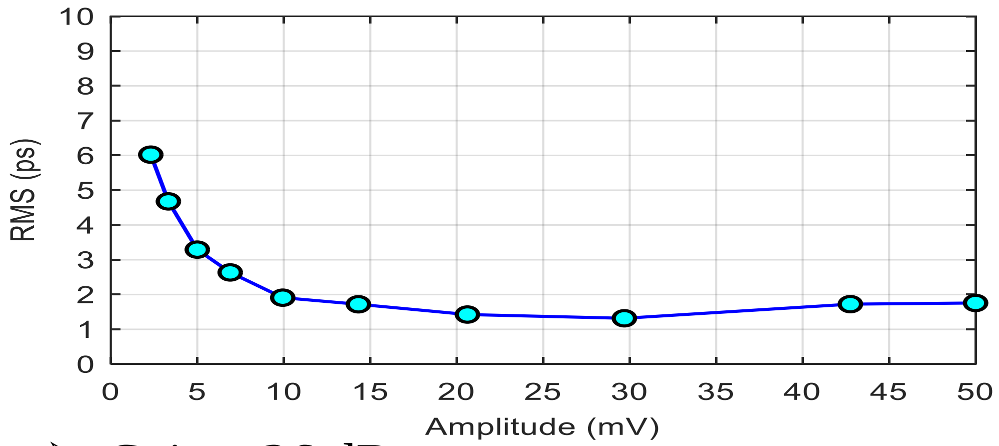
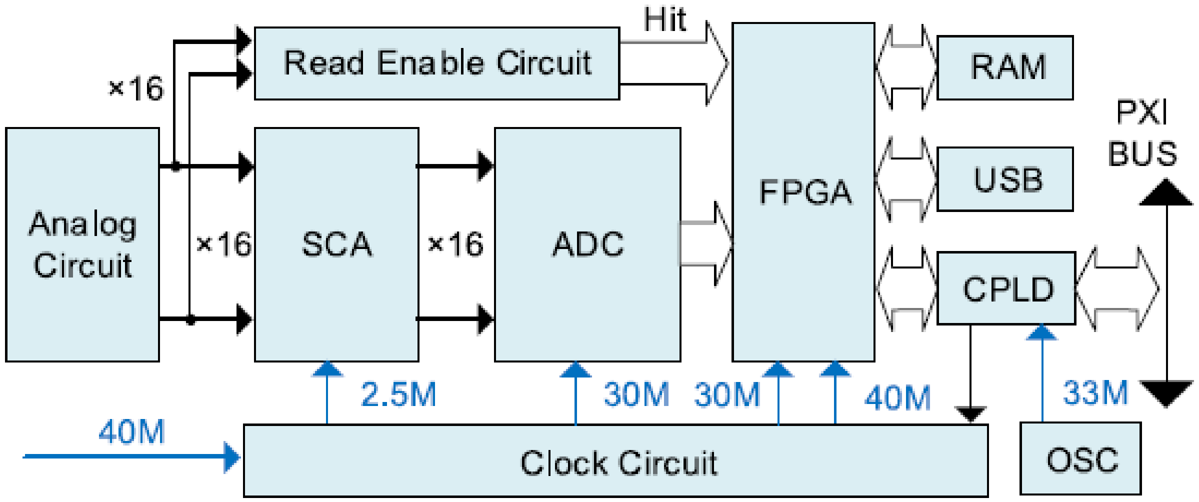


Diagram of the **AFE module**



- Gain：26 dB
- Bandwidth：1.4 GHz
- Time resolution: better than 4 ps



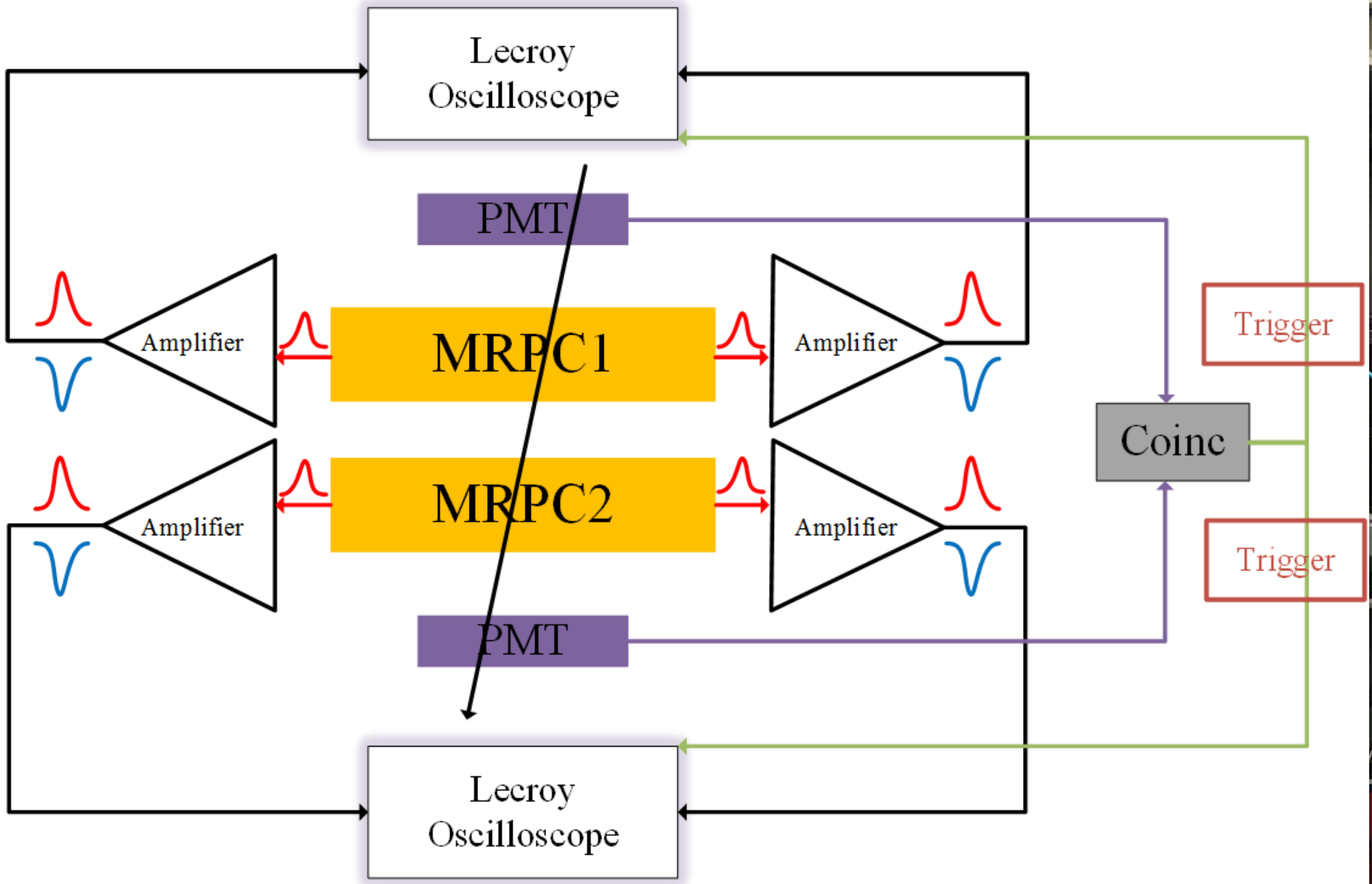
Block diagram of the **waveform digitization module**

Nucl. Instrum. Meth. A 925 (2019) 53.

- 1024 sampling capacitors of the Switched Capacitor Array (SCA)
- Sampling frequency of 5.12 GHz
- 0.5 mV rms & 3 ps time jitter
- DT5742 & Oscilloscope for the preliminary test and comparison

Experiment — Cosmic Ray Test

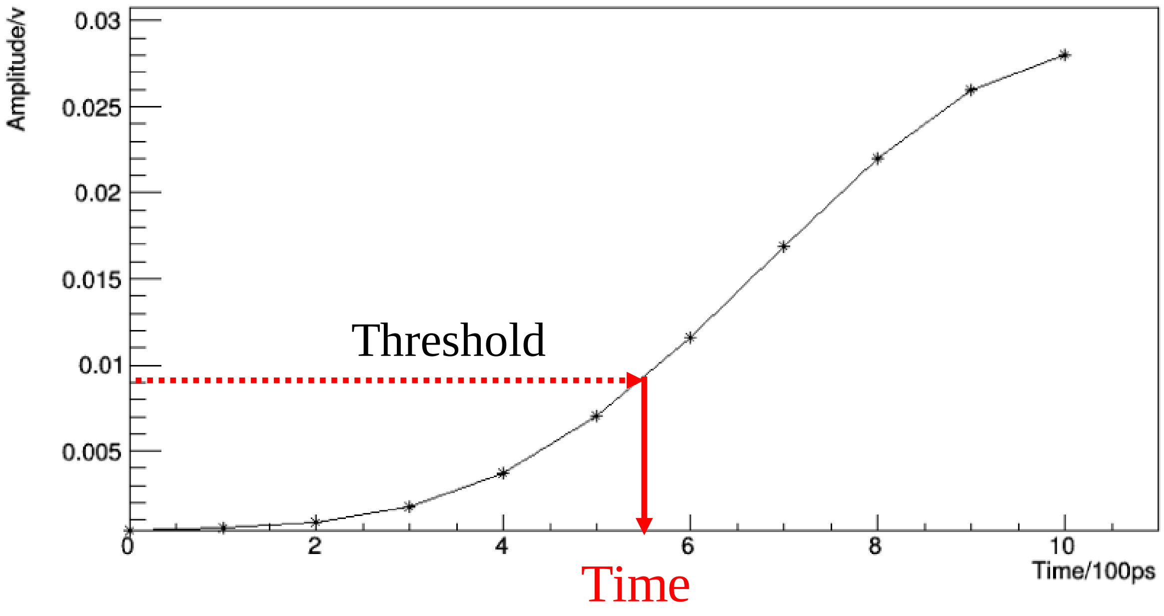
Gas component: **90% $C_2H_2F_4$ + 5% i-C_4H_{10} + 5% SF_6**

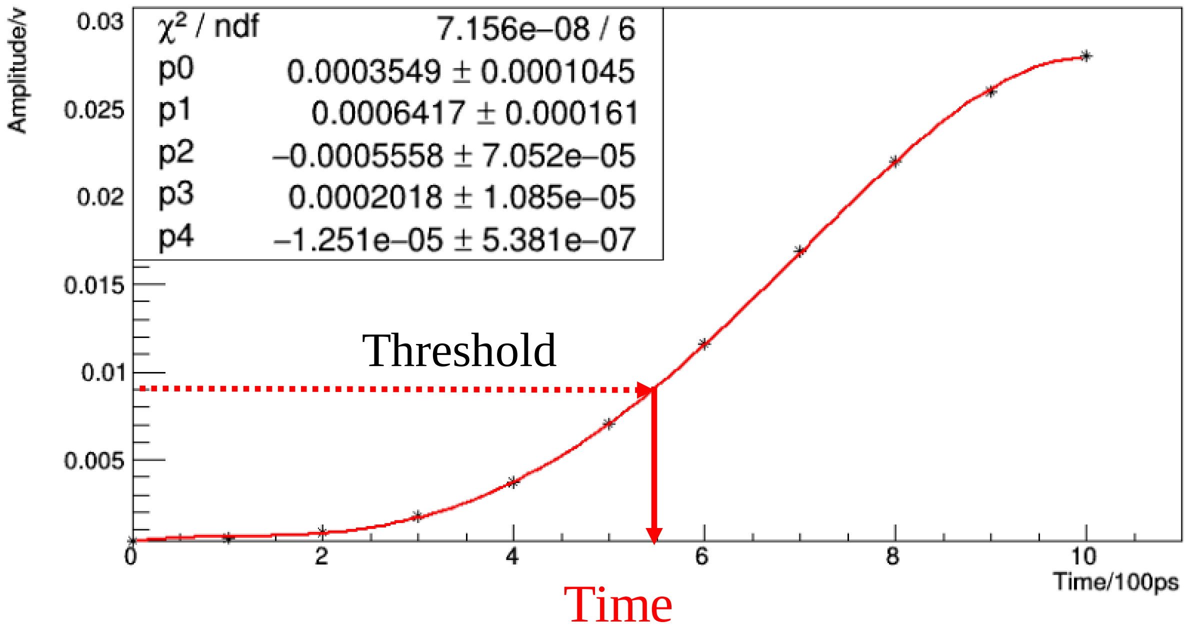


Experiment — Timing Method

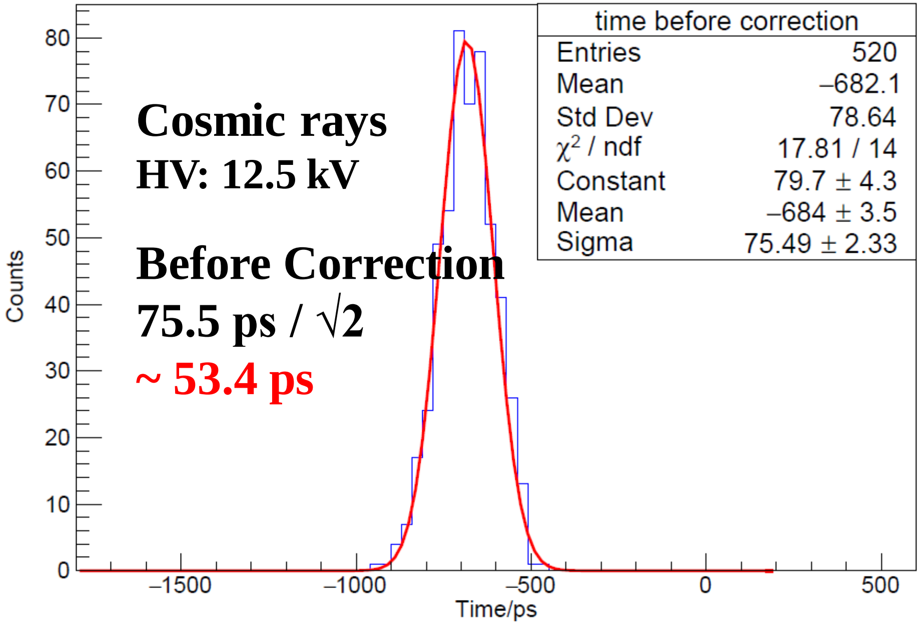
Algorithm to find a ref. time T (Fixed threshold)

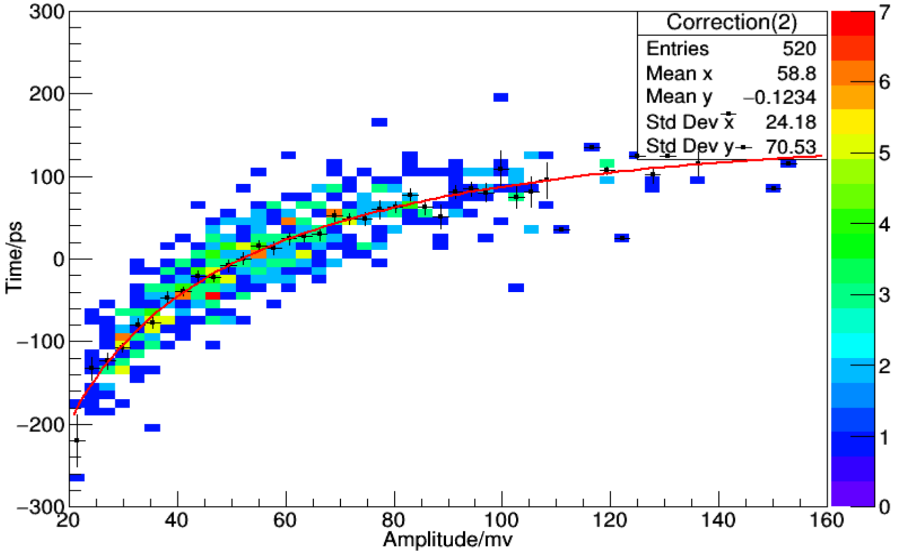
- Linear interpolation
- Polynomial fit

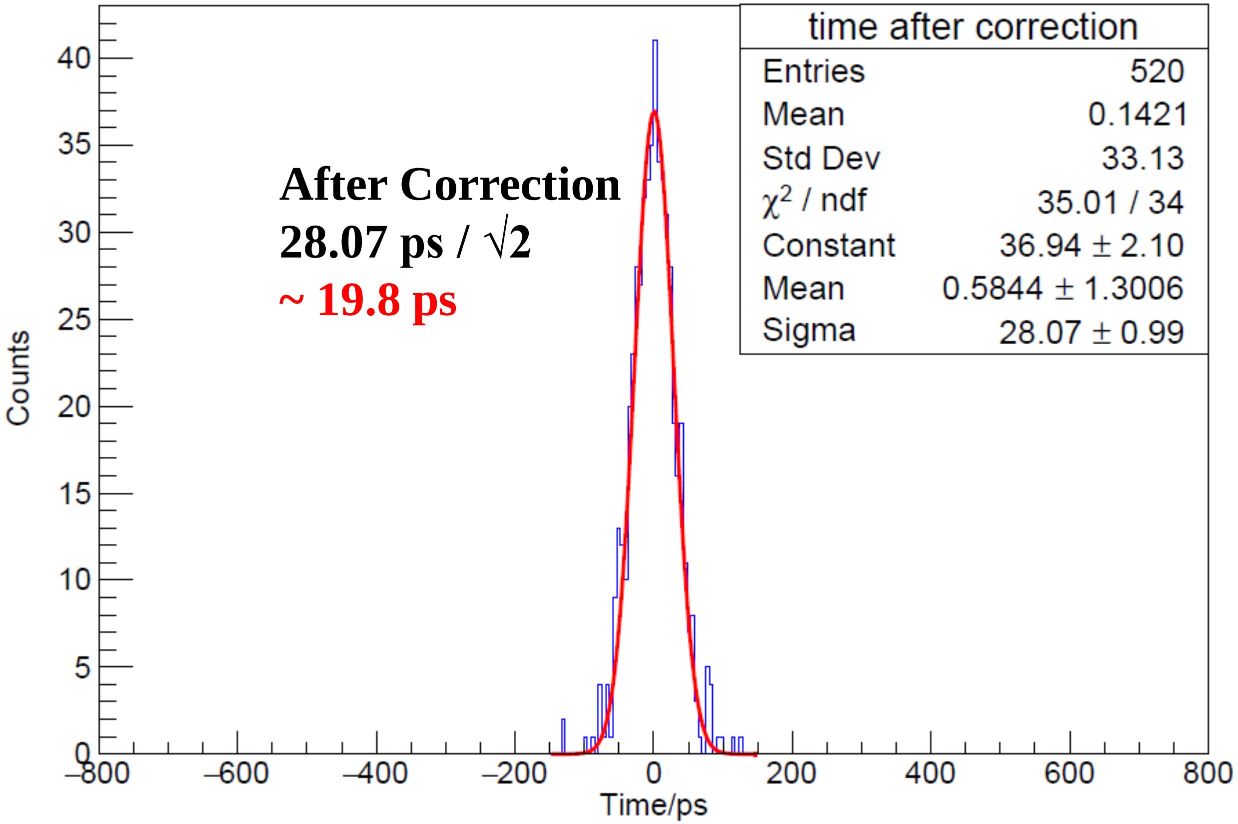




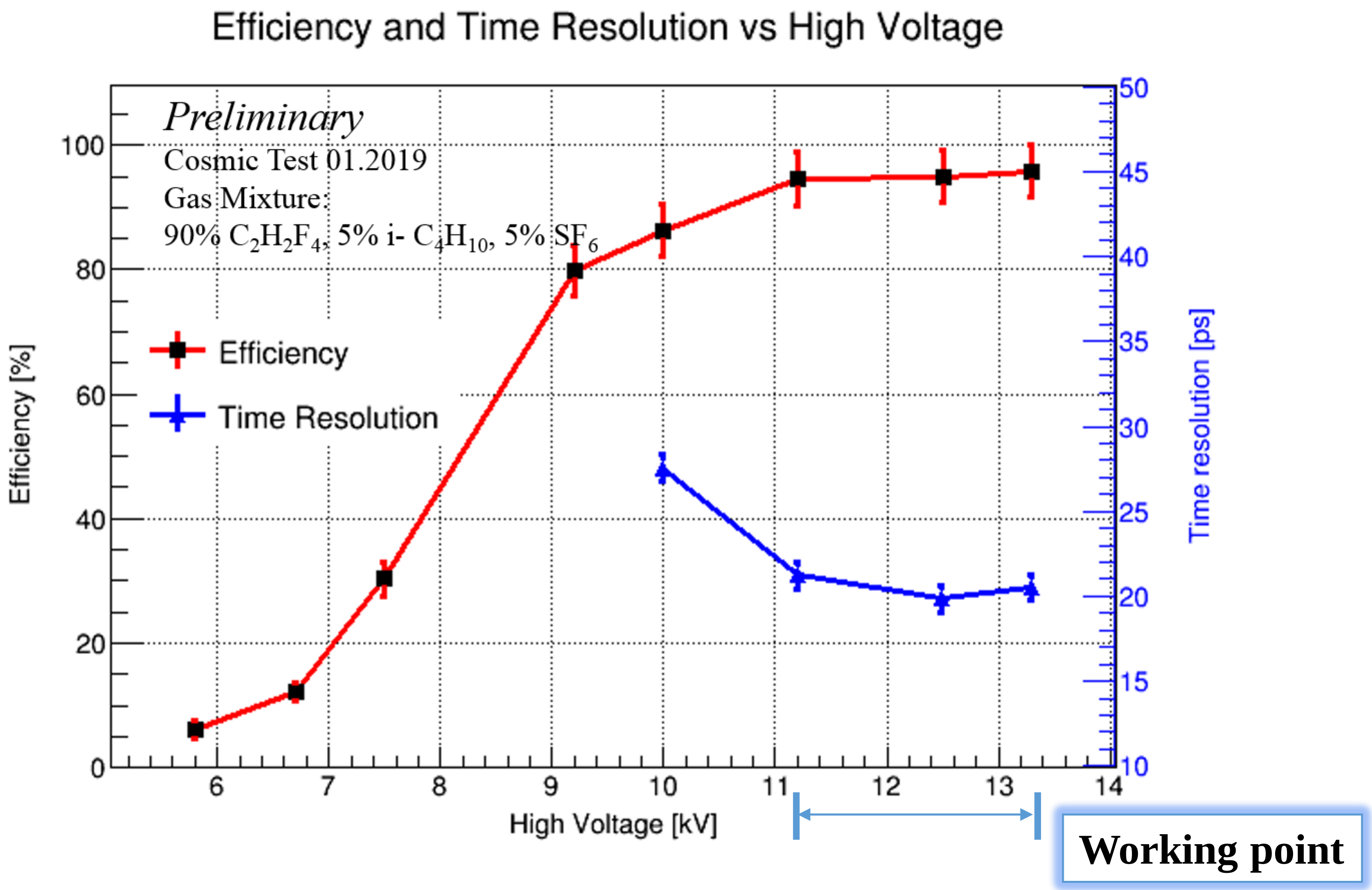
Experiment — Preliminary Results







Experiment — Preliminary Results



MRPC Simulation

Design a MRPC

↓

Shoot a particle

↓

Simulate the primary energy deposition with PAI model

↓

Digitize the charge of the avalanche

↓

Original current signal

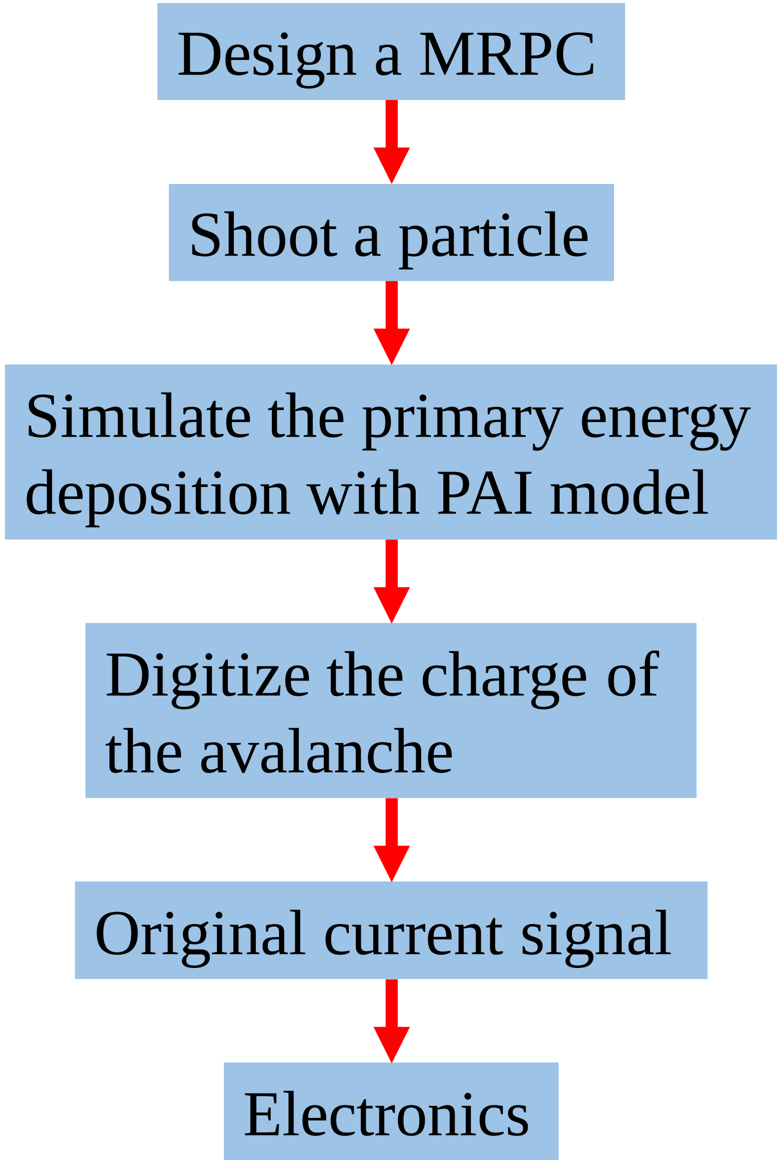
↓

Electronics

- MRPC structure
  - ✓ Materials
  - ✓ Gap/glass thickness, stack/gap number
  - ✓ Gas: **90% $C_2H_2F_4$ + 5% i-C_4H_{10} + 5% SF_6**
- Particle source: 4 GeV mu-
  - ✓ perpendicular to the MRPC
- **PAI** model is used to simulating the primary energy deposition*, rather than **Emstardard**

*W. Allison. Ann. Rev. Nucl. Part. Sci. 30 (1980) 253.
2018 JINST 13 P09007.

MRPC Simulation



- Primary energy loss
  - ✓ Ionize electron-ion pairs
  - ✓ W = 30 eV
- Avalanche multiplication — **Townsend effect**
  - α: Townsend coefficient
  - β: Attachment coefficient (by **Magboltz)**
- Electrons drifting in the electric field: induce a signal on the read out strips
- ***Ramo theory:**

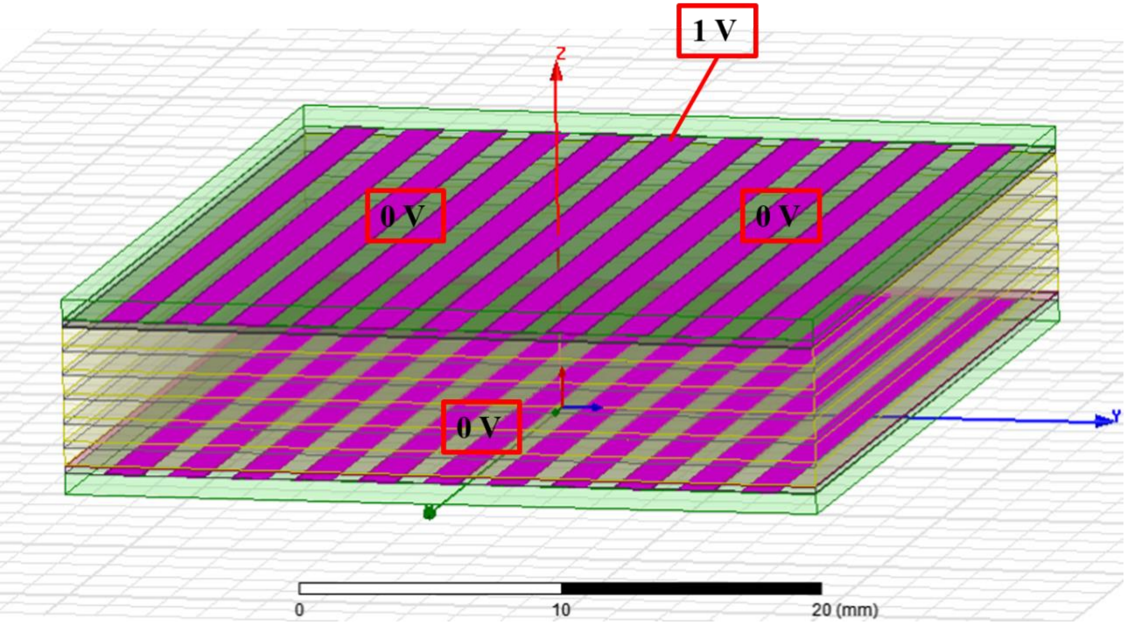
$$i(t) = \frac{E_W \cdot v}{V_W} e_0 N(t)$$

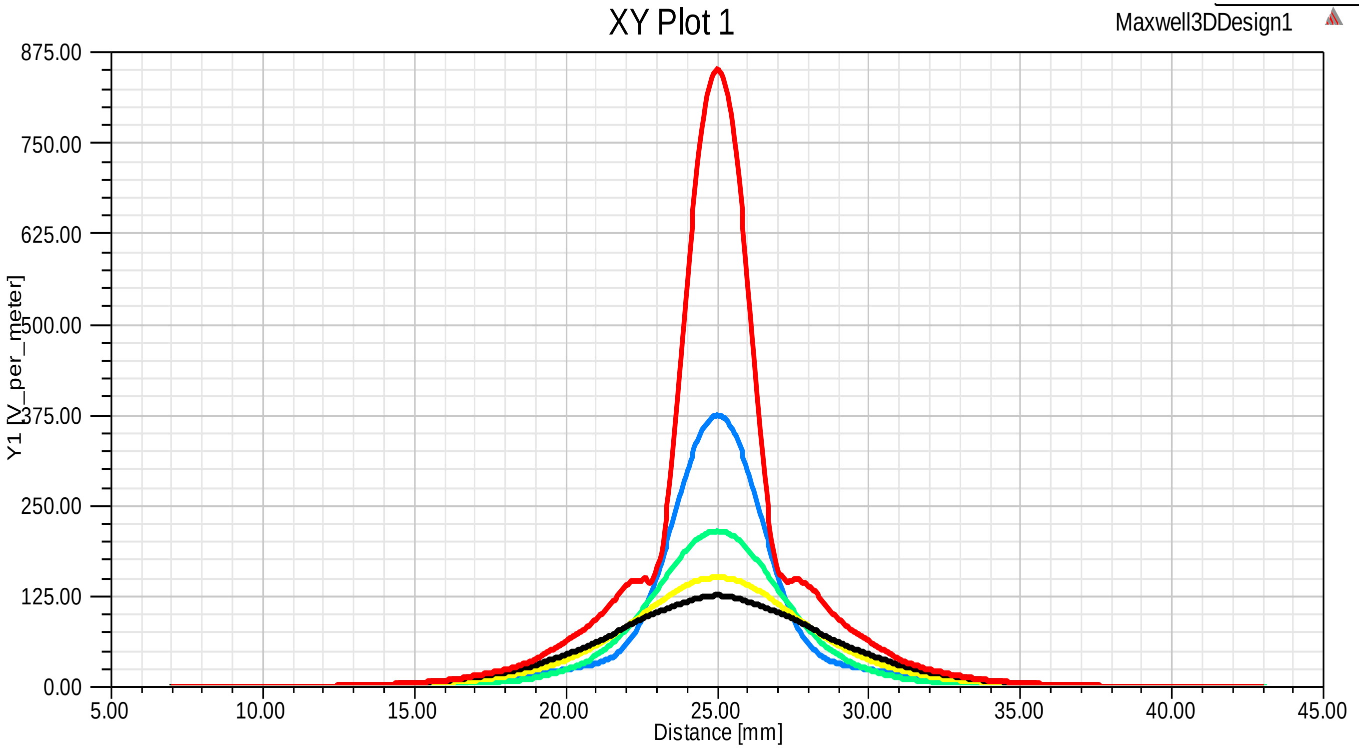
*S. Ramo, Currents induced by electron motion, Proc. IRE 27 (1939) 584.

MRPC Simulation

Weighting field

- ✓ E_W is the weighting field which is the electric field when setting the potential of the read out electrode to be V_W and others 0.





2019 JINST 14 P07020

MRPC Simulation

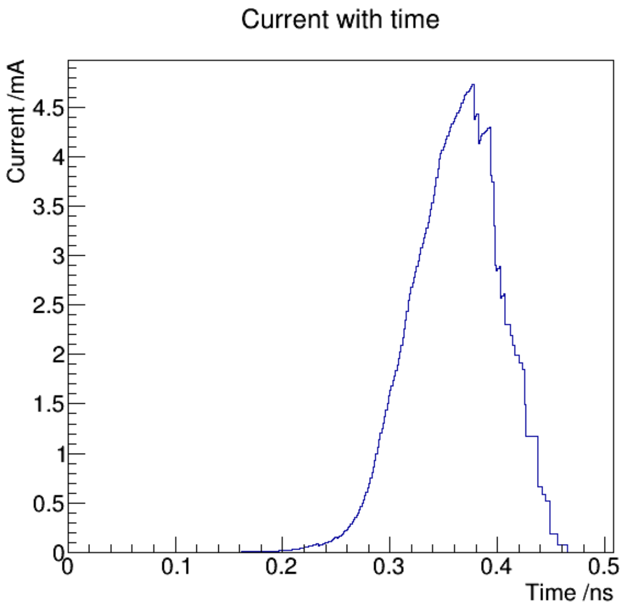
- Space charge effect: $\sim 10^7$ electrons

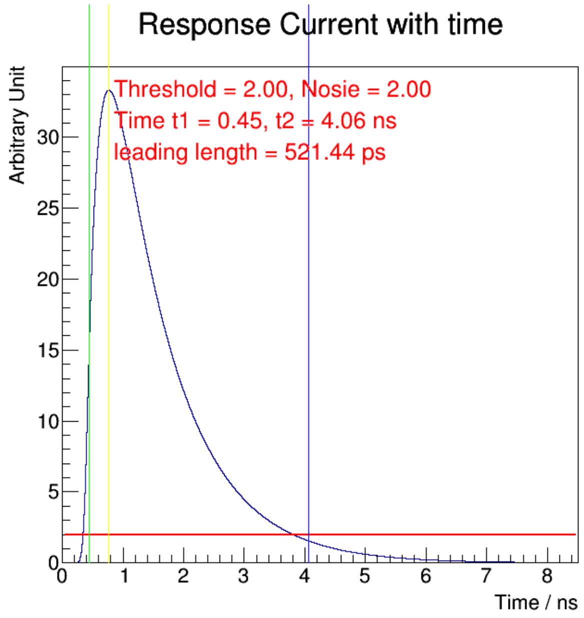
Werner Riegler, Christian Lippmann. Nucl. Instrum. Meth. A 500 (2003) 144.

- Include the Front-end electronics response by convolving the original current with a simplified FEE response function:

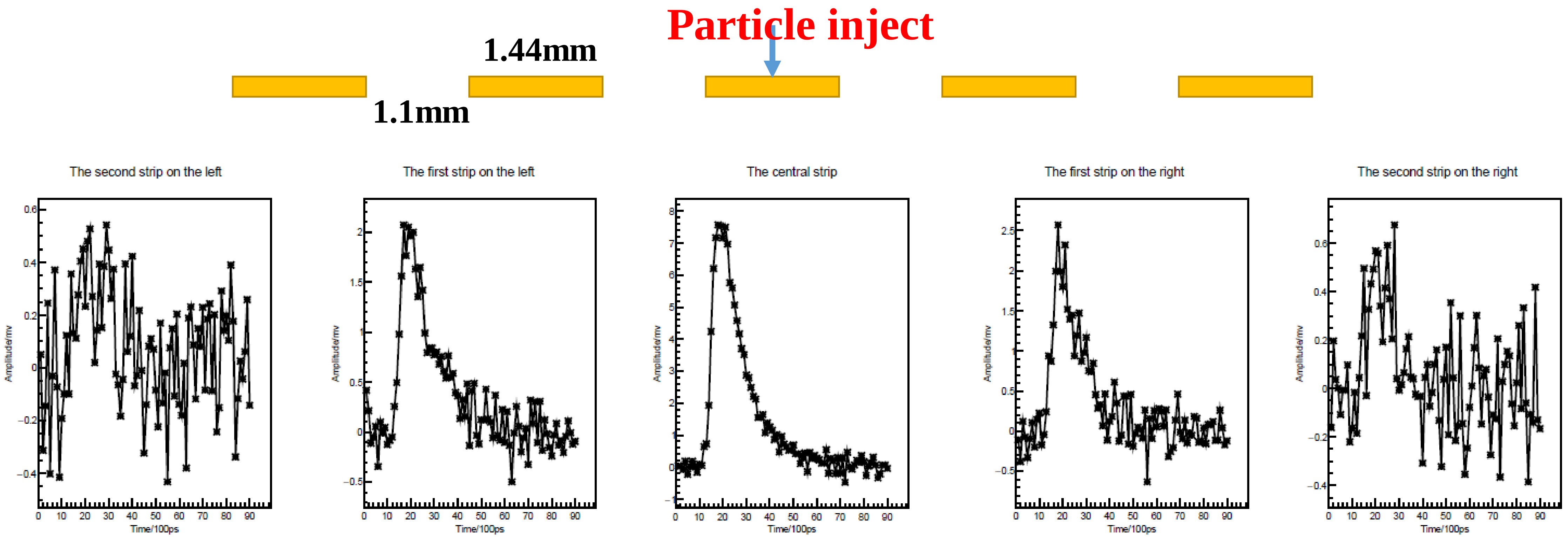
$$f(t) = A\left(e^{-t/\tau_1} - e^{-t/\tau_2}\right)$$

- Noise: by adding a random number sampled from Gauss(0, σ) to every time bin



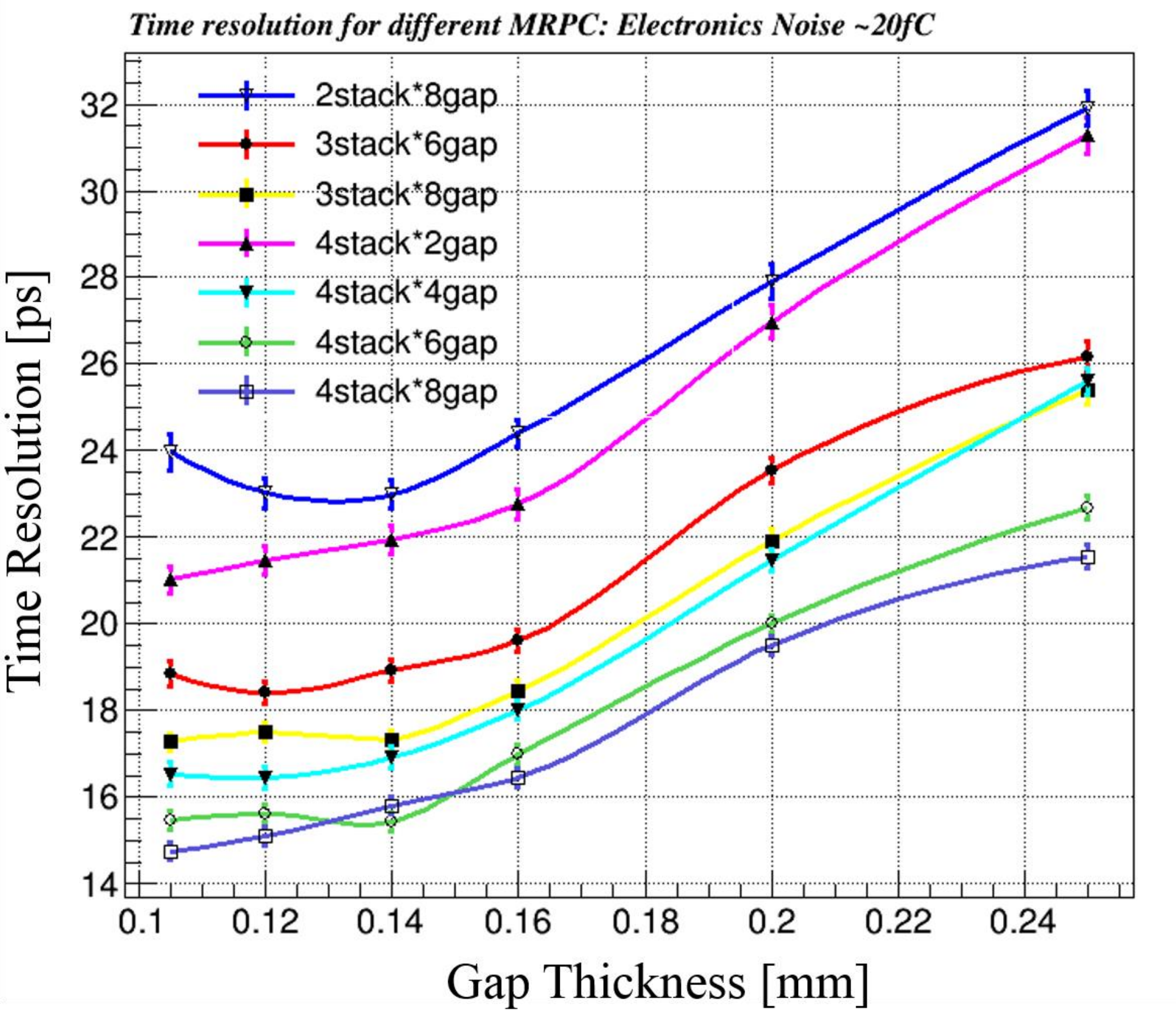


MRPC Simulation



- **Induced signals** generated by the energy deposition of **all sensitive areas**
- **Induced signals** on each readout electrode
- **Information** about time, charge, cluster size……
- **Position resolution --** with the center of gravity algorithm

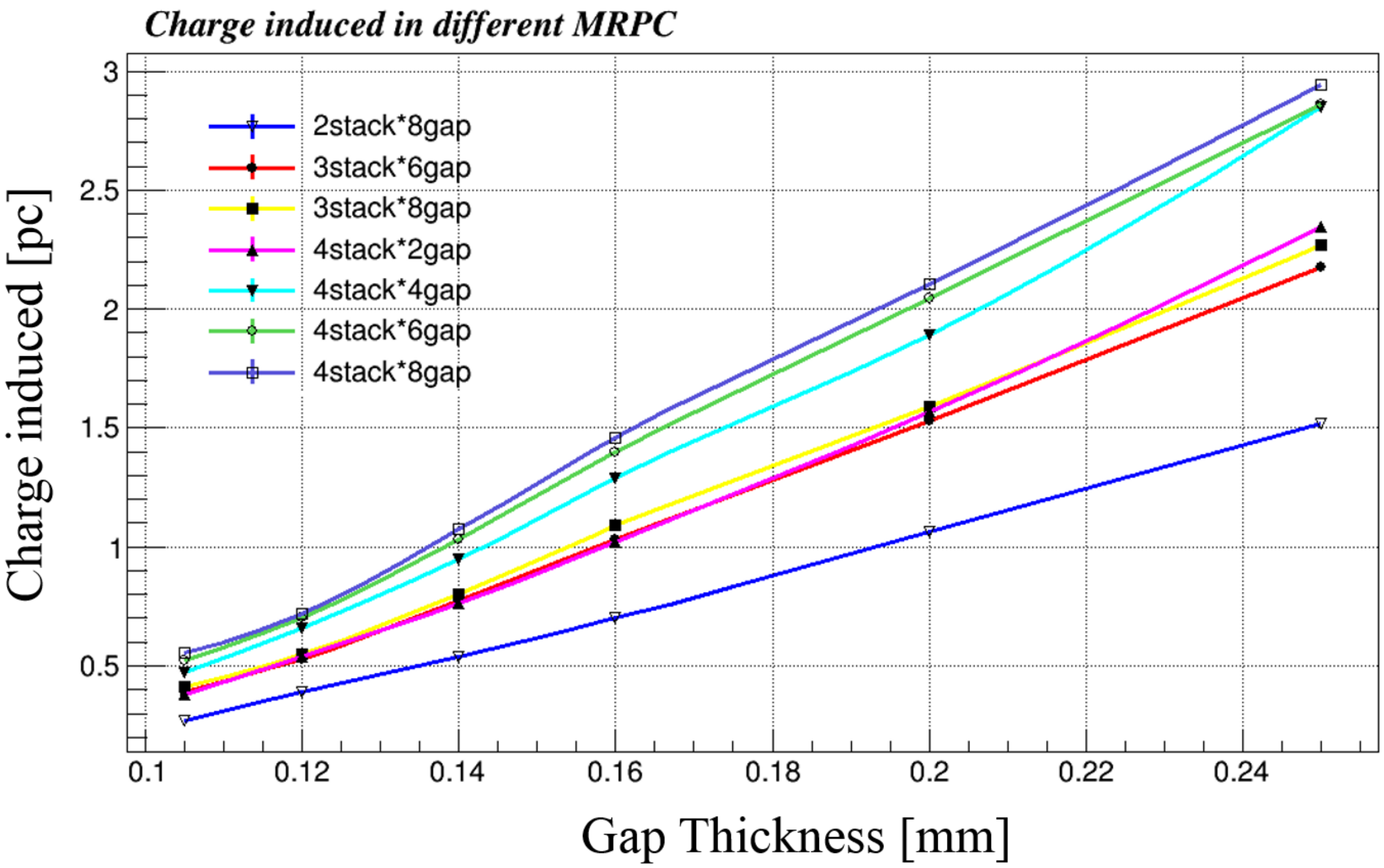
MRPC Simulation



In actual experiment, electronic noise and signal transmission should be considered carefully.

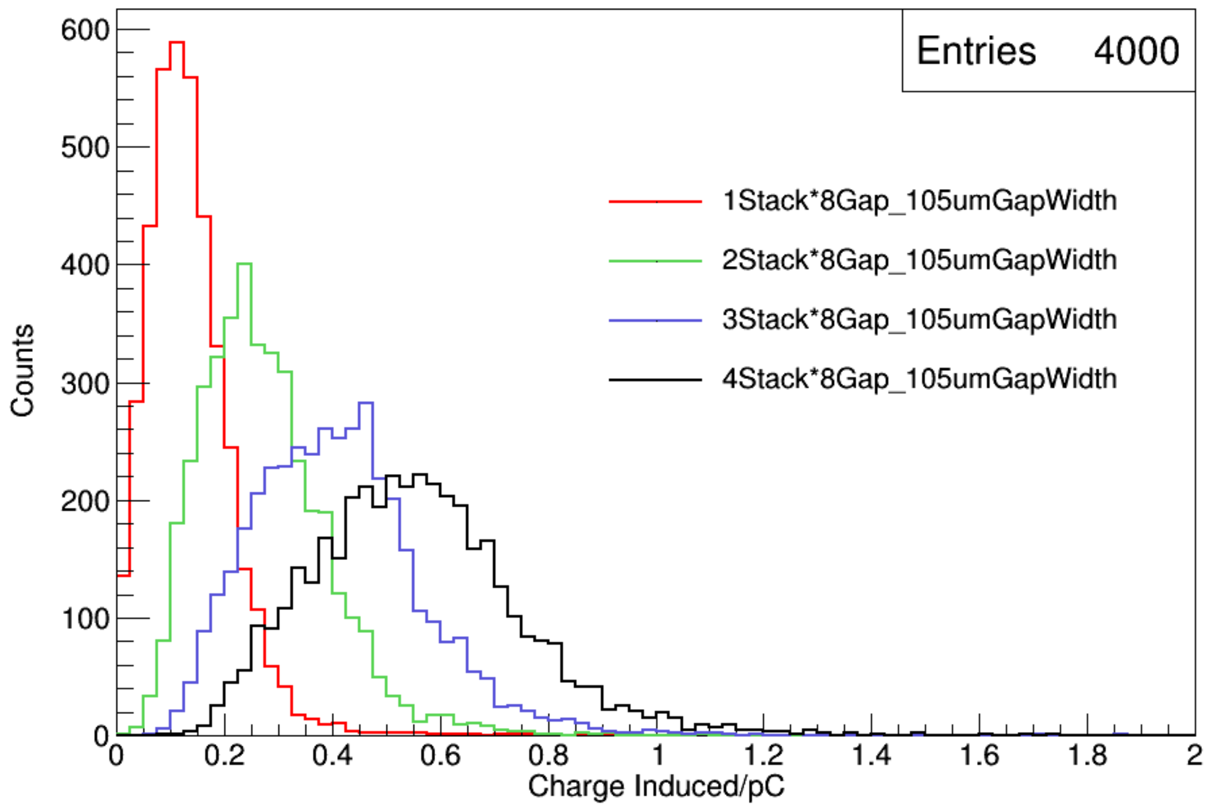
- Gap thickness below 160 μm, more than 3stacks, more than 4 gaps
  → 20 ps
- Thinner gap thickness, more gas gaps
  ?→ better time resolution

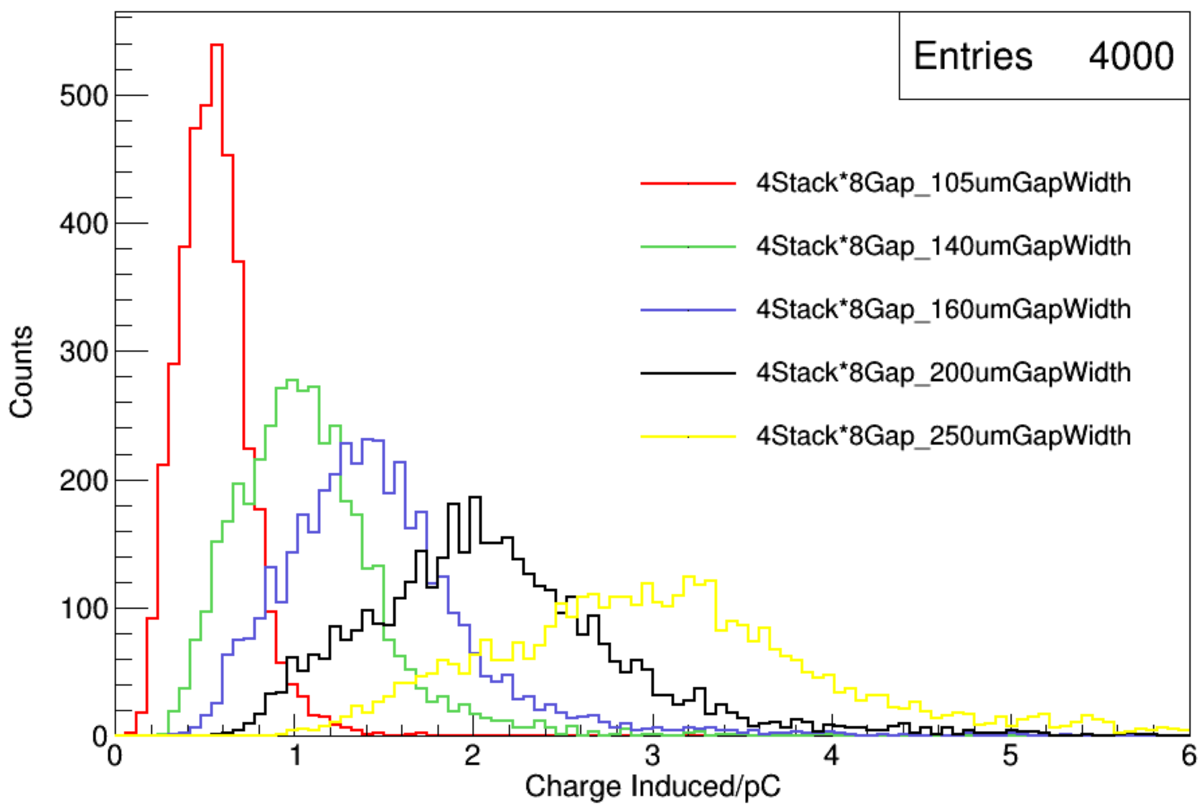
MRPC Simulation



- The charge induced increases with the increasing gap thickness significantly.
- The number of stacks has a great influence on the charge.

MRPC Simulation





- Charge distribution.
- Small signals worsen the time resolution.

Conclusion & Future Plan

Summary:

- ■ The 32-gap MRPC prototype with gap thickness of 104 μm has been developed.
  - ✓ Efficiency reaches 95% at ±6250 V.
  - ✓ Time resolution around 20 ps.
- ■ Detailed simulation of time resolution based on Geant4.
  - ✓ Different structure of MRPC.
  - ✓ Dependence on the thickness of gas gap.

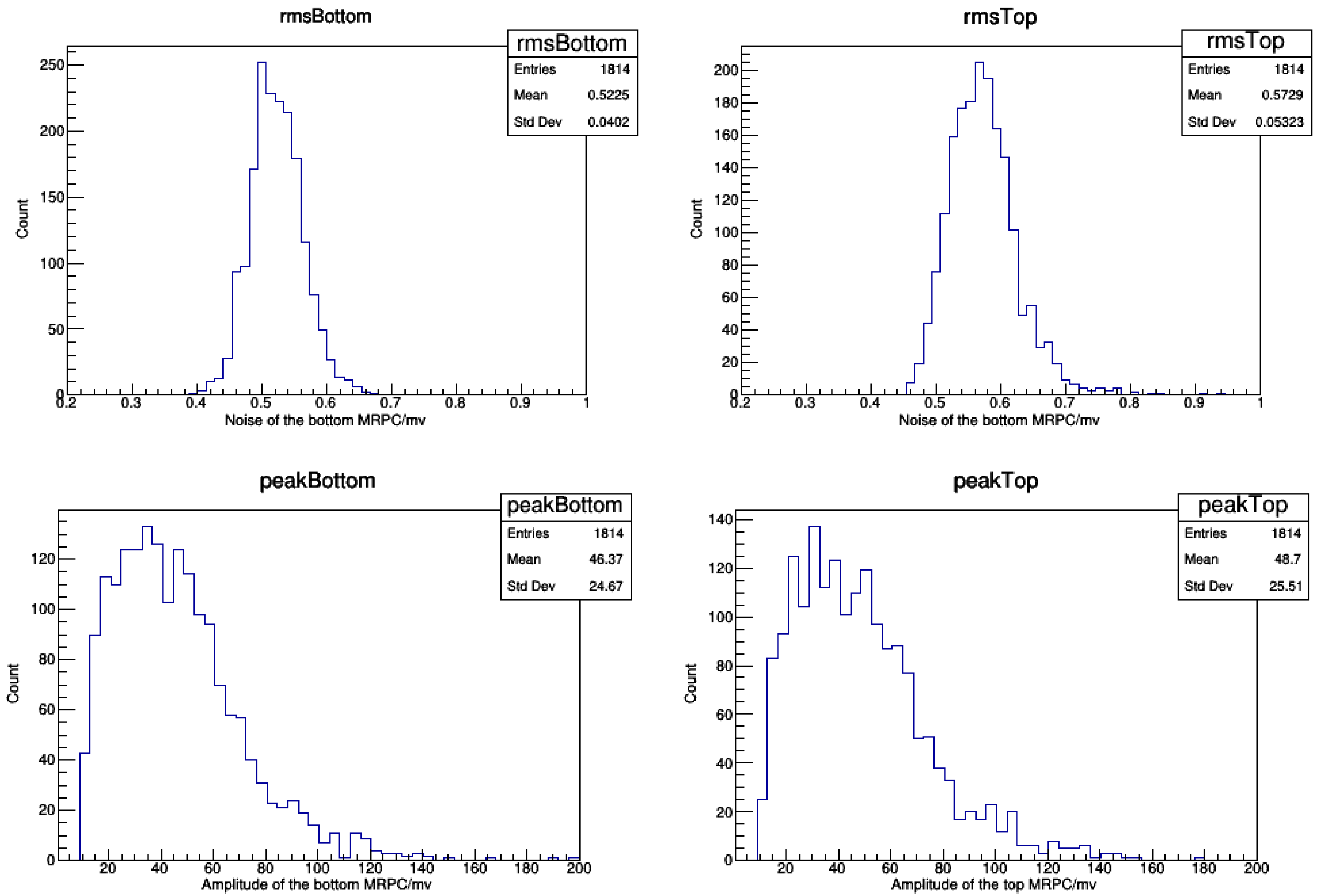
Future plan:

- ☐ Waveform digitization module will be ready soon (from USTC).
- ☐ New 24-gap MRPC is ongoing.
  - 4 stacks × 6 gaps, gap width ~140 μm.
  - Low resistive glasses.
  - Differential readout.
- ☐ Cosmic test & Beam test.

Q & A

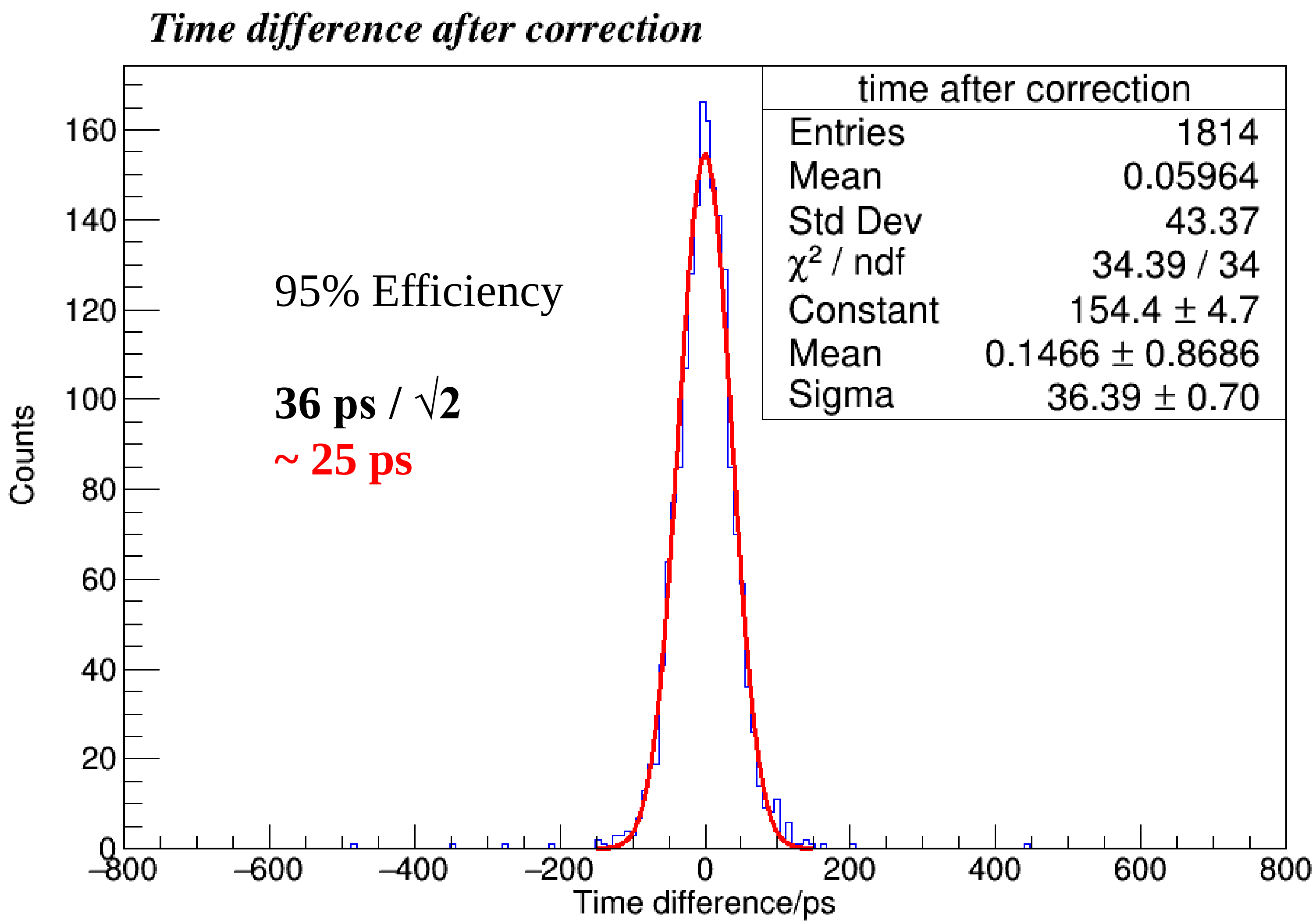
Thank you for your attention!

Backup



95% Efficiency:
20*SNR
1814events

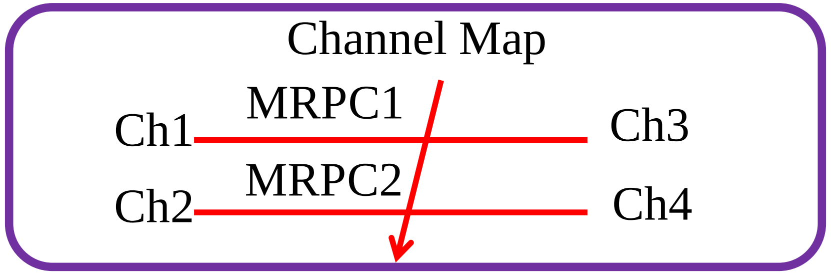
Backup



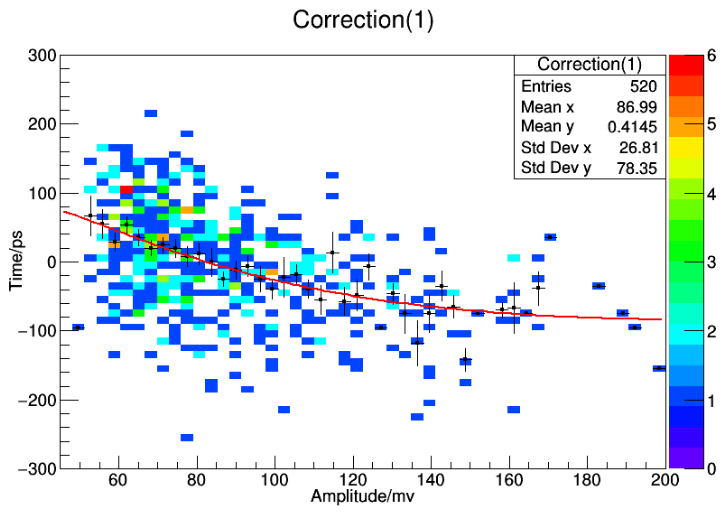
Time difference after correction
time after correction
Entries 1814
Mean 0.05964
Std Dev 43.37
χ² / ndf 34.39 / 34
Constant 154.4 ± 4.7
Mean 0.1466 ± 0.8686
Sigma 36.39 ± 0.70
95% Efficiency
36 ps / √2
~ 25 ps
Counts
Time difference/ps

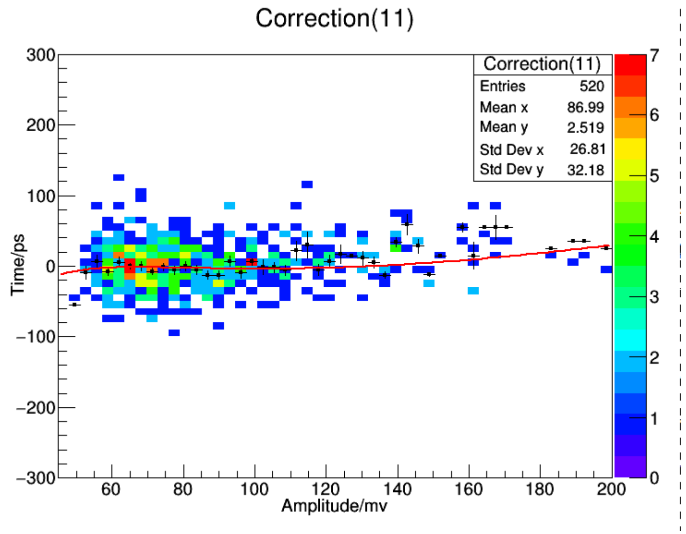
Experiment — Preliminary Results

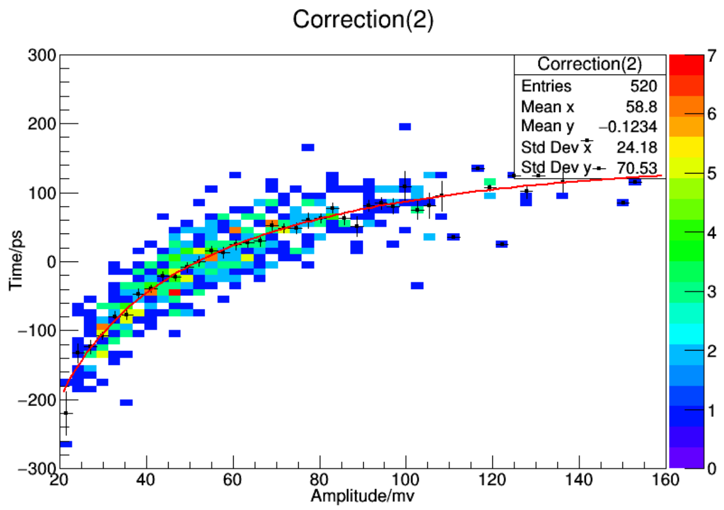
Time difference = (T_ch1 + T_ch3) − (T_ch2 + T_ch4)

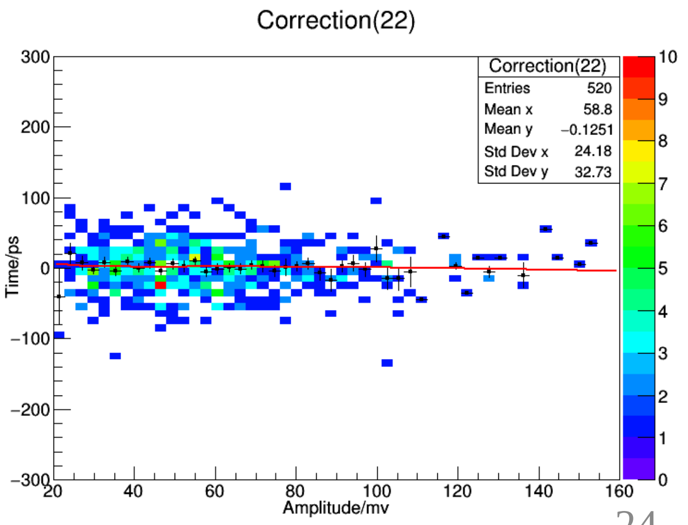


Cut:
(T_ch1 − T_ch3) − (T_ch2 − T_ch4)
→ Angle of incident particle









Simulation— Multiplication

Multiplication in a small step:

- P(n,x): Prob(one electron $\xrightarrow{x}$ n electrons)

$$
\begin{aligned}
P(n, x+dx) = & P(n-1, x)(n-1)\alpha\, \mathrm{d}x(1-(n-1))\eta\, \mathrm{d}x \\
& + P(n, x)(1 - n\alpha\, \mathrm{d}x)(1 - n\eta\, \mathrm{d}x) \\
& + P(n, x) n\alpha\, \mathrm{d}x\, n\eta\, \mathrm{d}x \\
& + P(n+1, x)(1-(n+1)\alpha\, \mathrm{d}x)(n+1)\eta\, \mathrm{d}x
\end{aligned}
$$

- Divide the gap into ~300 steps, and simulate the multiplication in every step
- Generate a random number according to P(n,x)*:

$$
n\begin{cases} 0, & s < k\frac{\bar{n}(x)-1}{\bar{n}(x)-k} \\ 1 + \mathrm{Trunc}[\frac{1}{\ln(1-\frac{1-k}{\bar{n}(x)-k})}\ln(\frac{(\bar{n}(x)-k)(1-s)}{\bar{n}(x)(1-k)})], & s > k\frac{\bar{n}(x)-1}{\bar{n}(x)-k} \end{cases}
$$

$k = \frac{\eta}{\alpha}$

s: uniform random number from (0,1)

- Finally, avalanche growth like: $e^{(\alpha-\eta)x}$