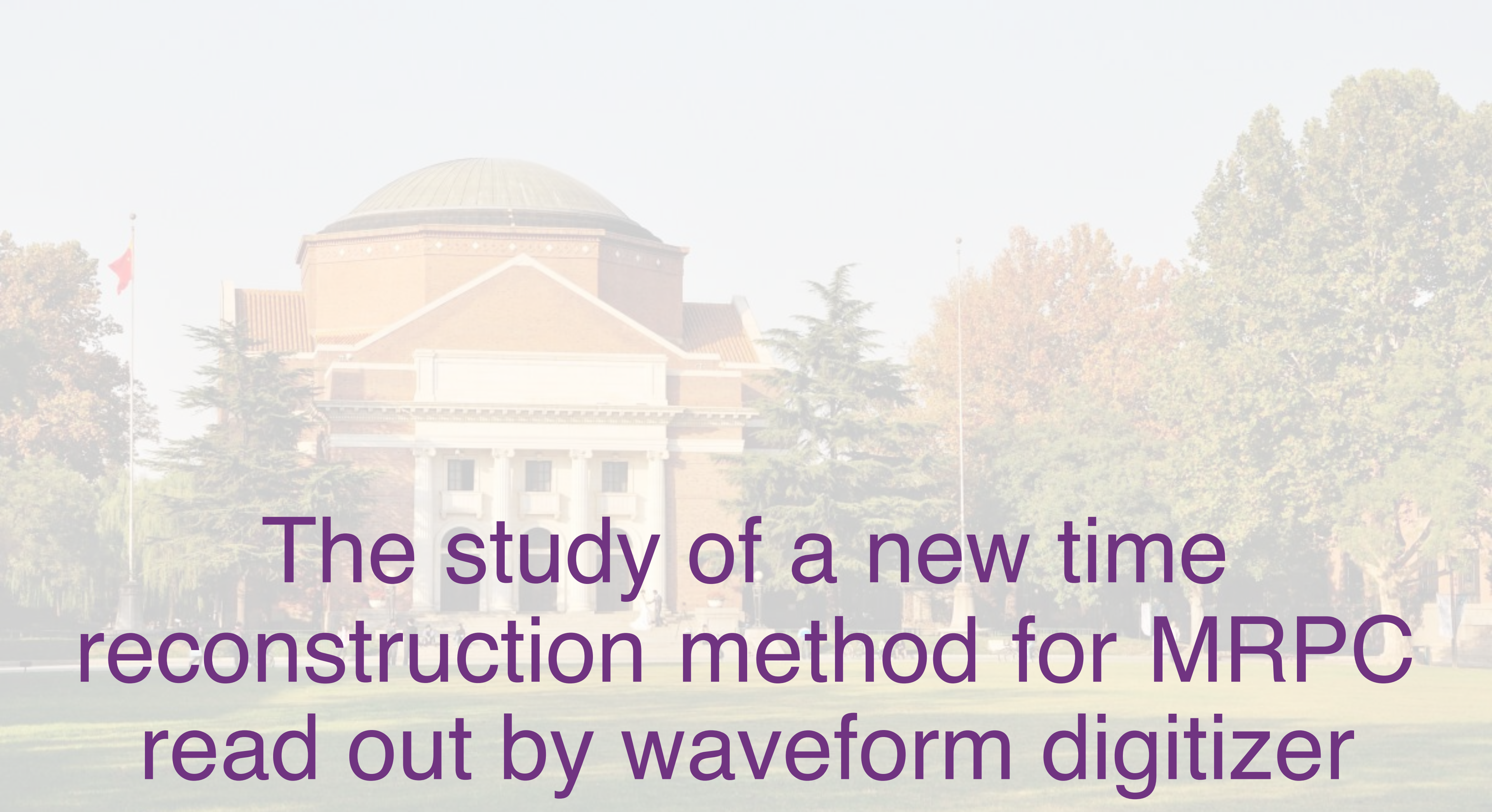

The study of a new time reconstruction method for MRPC read out by waveform digitizer

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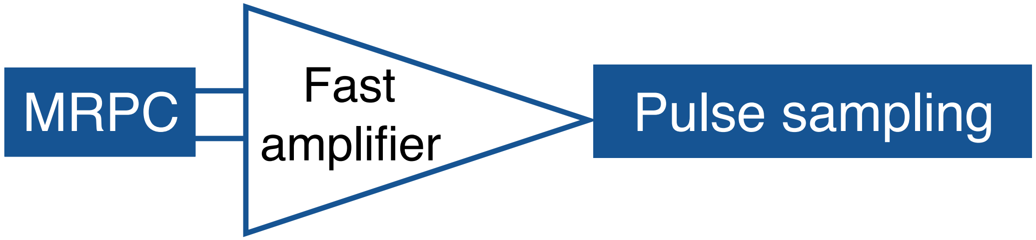
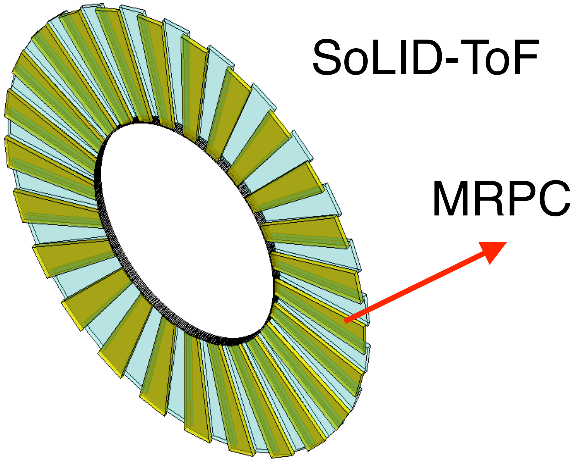
Outline

- Introduction and Motivation
- The framework of analysis method
    - MRPC detector simulation
    - Different neural networks
- The results
    - Simulation
    - Experiment
- Conclusions

Motivation

- Multi-gap Resistive Plate Chamber (MRPC)
- In physics experiments, MRPC is used in the Time-of-Flight(ToF) system as a timing detector
- In Solenoidal Large Intensity Device (SoLID) experiment:
  - pi/k separation up to 7GeV/c
  - Time resolution ~ 20ps





- Challenge for both MRPC and electronics.
- Electronics: Fast amplifier + pulse sampling
- New analysis method: take the advantage of the entire waveform

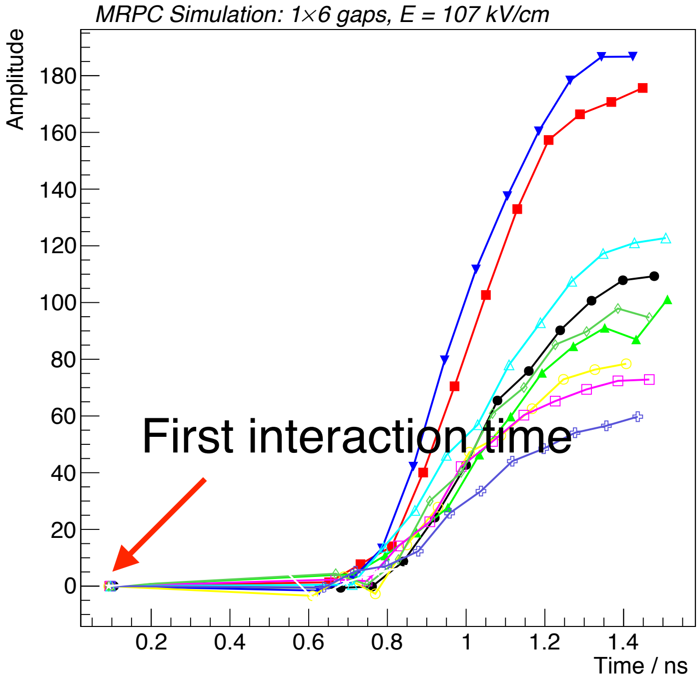
Analysis method

- The analysis method is based on the neural network.
- Artificial neural network(NN): powerful && widely used in high energy physics
- Introduce NN to obtain good time resolution:
  —— Find out the patterns from the MRPC signal and estimate the particle 1st interaction time more precisely.

Learn from the simulation waveforms

1 Test with simulation data

2 Test with experiment data



First interaction time

Analysis method

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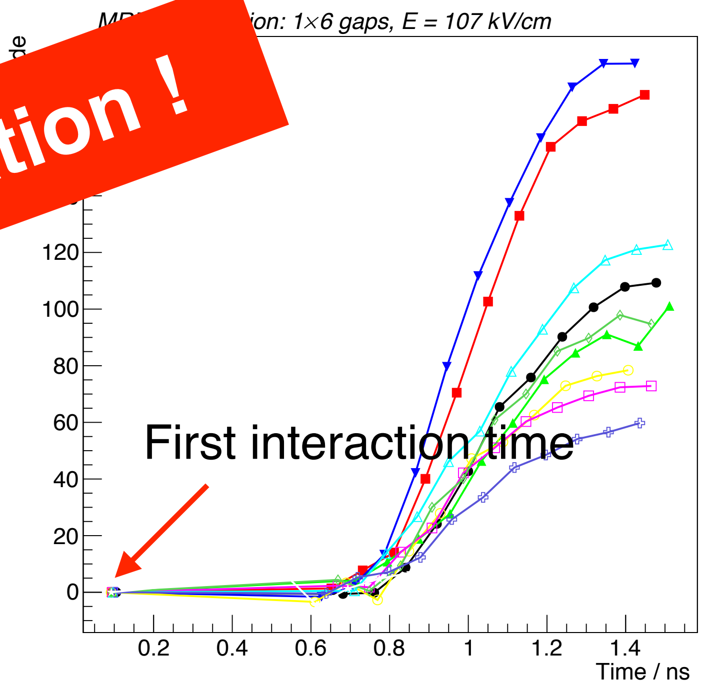
Learn from the simulation waveform

1 Test wit simulation data

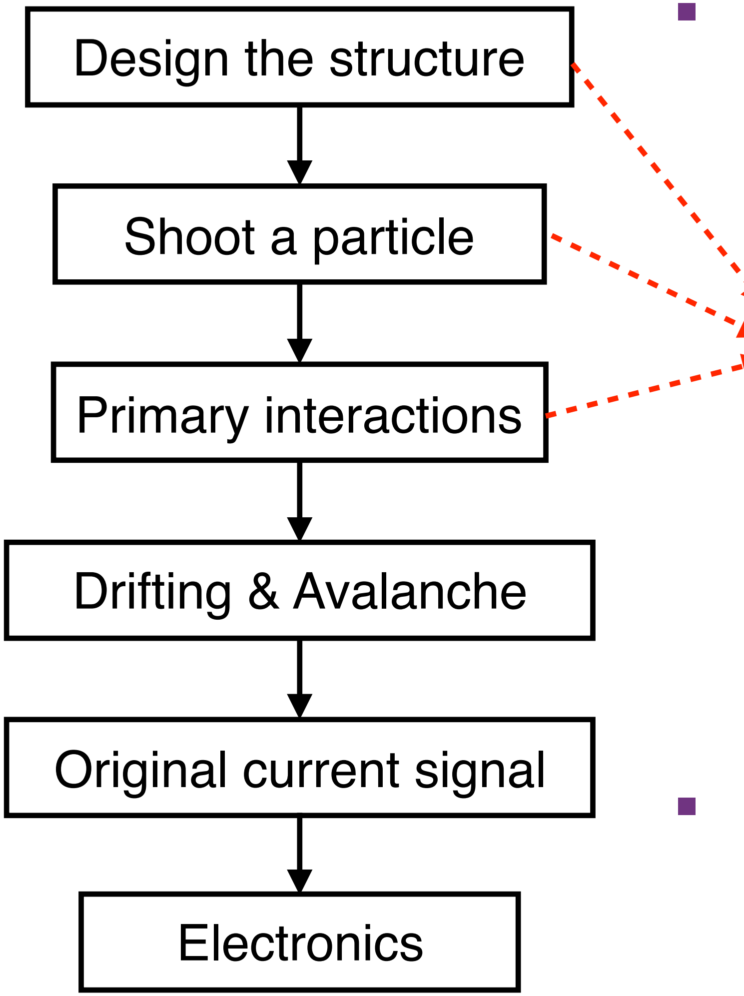
2 Test with experiment data

Simulation !



First interaction time

Waveform simulation

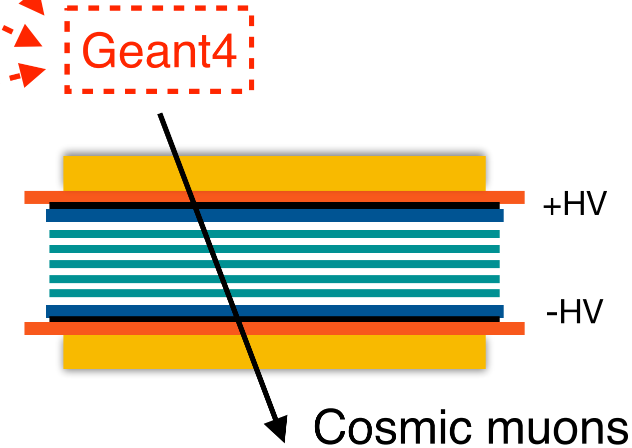


- MRPC structure

  6-gas MRPC

  Gap/glass thickness: 0.25/0.7 mm

  Gas: 90% $C_2H_2F_4$, 5% C_4H_{10} and 5% SF_6



Cosmic muons: ~ 4GeV

- Avalanche through drifting

$$\frac{d\bar{n}}{dx} = (\alpha - \eta)\bar{n}$$

α : Townsend coefficient
η : Attachment coefficient

*F. Wang, et al., A standalone simulation framework of the mrpc detector read out in waveforms, arXiv:1805.02387.

Waveform simulation

Design the structure
↓
Shoot a particle
↓
Primary interactions
↓
Drifting & Avalanche
↓
Original current signal
↓
Electronics

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

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

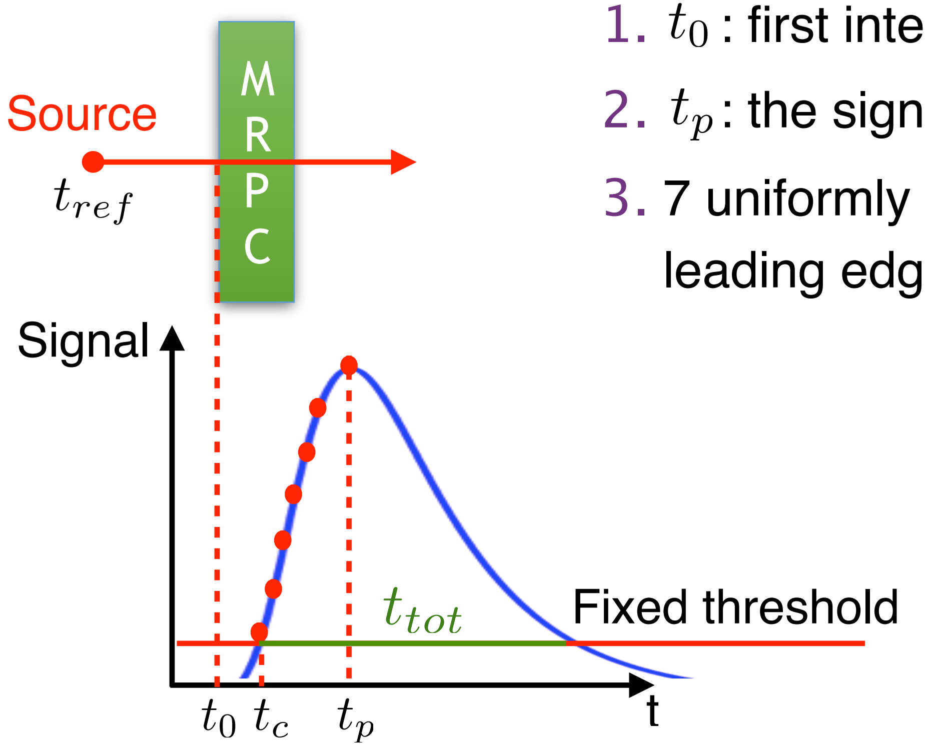
- Divide the gap into ~500 steps, and simulate the multiplication in every step
- Finally, avalanche growth like: $e^{(\alpha-\eta)x}$
- Space charge effect: ~10^6 electrons
- Induced current:

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

- Front-end electronics + noise

*F. Wang, et al., A standalone simulation framework of the mrpc detector read out in waveforms, arXiv:1805.02387.

Simulation data



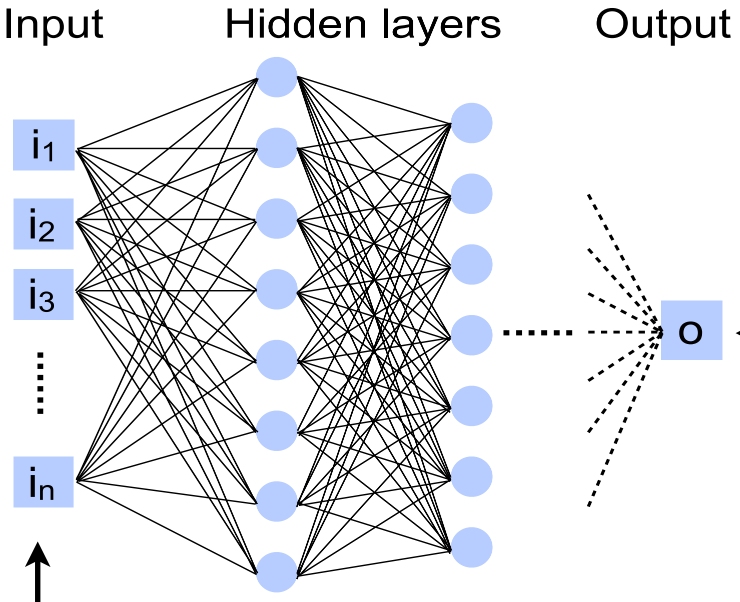
Simulation dataset :

1. t_0 : first interaction happens
2. t_p : the signal reach the peak
3. 7 uniformly distributed points along the leading edge

Multilayer perceptron (MLP)

- Multilayer perceptron (MLP)

$$\underset{\text{Output}}{\underline{F_i(\vec{x})}} = h(\sum_j(\omega_{ij}^2 g(...g(\sum_k(\omega_{jk}^1 g(\sum_l(\omega_{kl}^0 \underset{\text{Input}}{\underline{x_l}} + \chi_k^0)... + \chi_j^1) + \chi_i^2)$$



- Activation function: g and h —— tanh
- Weights: $\omega^{0,1...}$, $\chi^{0,1...}$
- “Dropout”: avoid overfitting

The length of the leading edge t_l

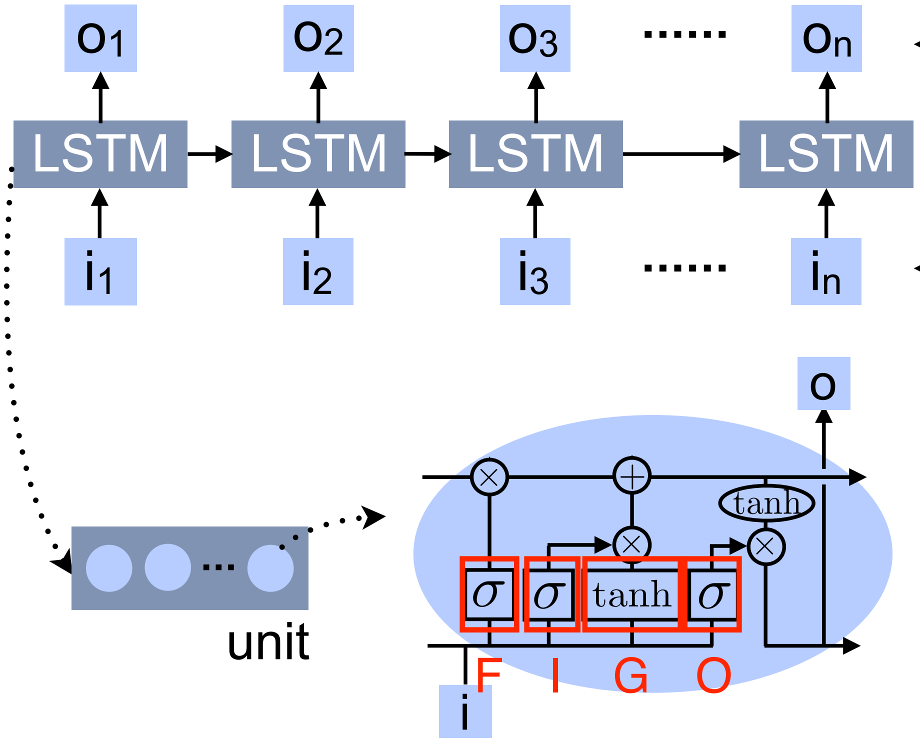
Time of the very first interaction: $t_0 = t_p - t_l$

Several uniformly distributed points along the leading edge

- Train/validate/test set: 20/10/10 k
- Tensorflow & GPU: GTX 1080 Ti
- ~ 10 mins for training

LSTM

- Recurrent neural networks(RNN): Long Short Term Memory network(LSTM)



The length of the leading edge t_l

Several uniformly distributed points along the leading edge

f : forget gate: Whether to erase
I : Input gate, whether to write
g: gate gate, How much to write
o: output gate, How much to reveal

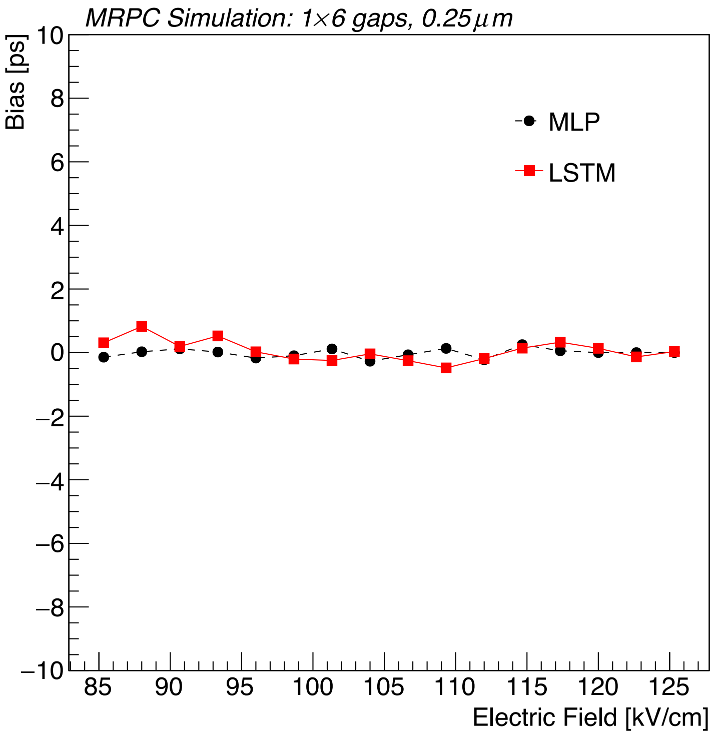
- Train/validate/test set: 20/10/10 k
- Tensorflow & GPU: GTX 1080 Ti

> 30 mins for training

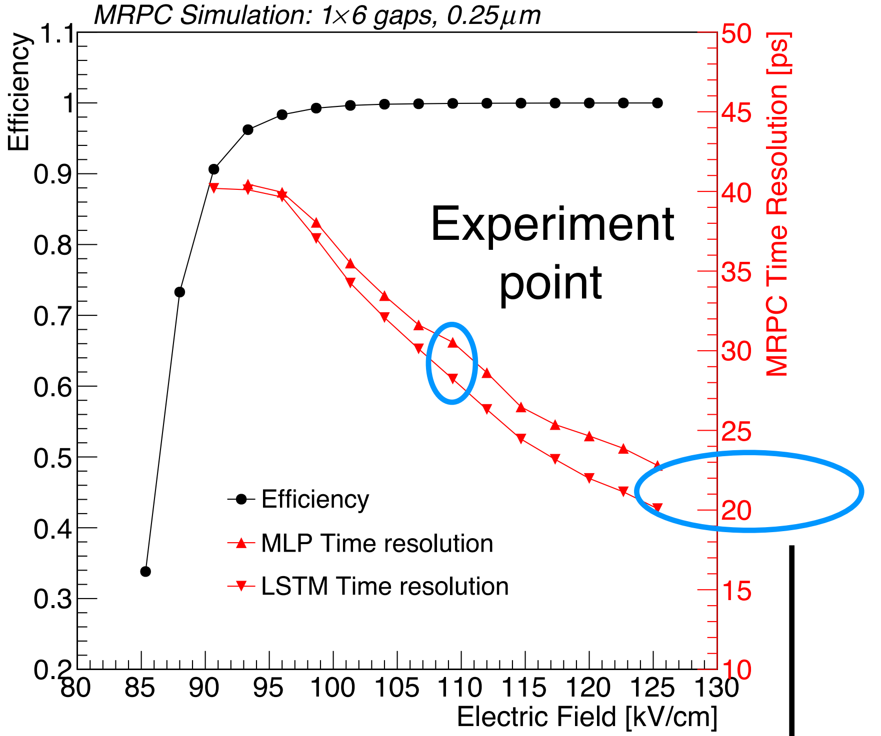
Results of simulation

- Define bias: $t_{estimate} - t_{truth}$

Accuracy



Precision



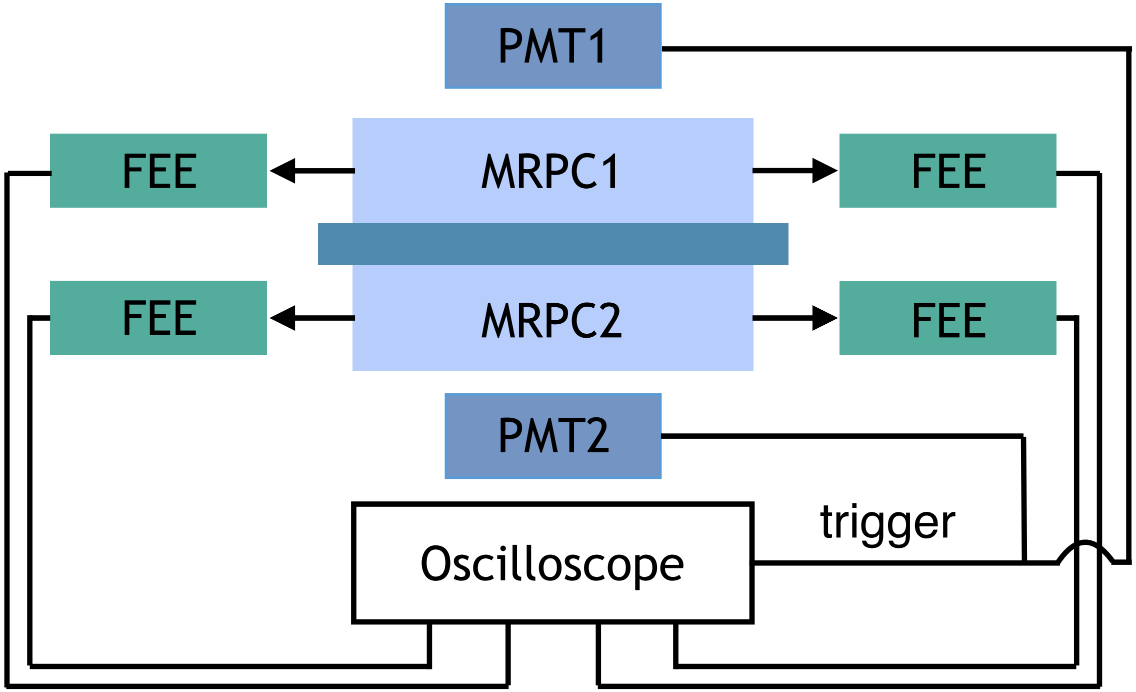
Experiment point

Streamer may happen

- Accuracy is good and stable
- The best time resolution can reach around 20 ps.

Experiment setup

- Experiment of the cosmic ray
- 2 identical MRPC: 6-gap, 0.25mm gap, working at E=109 kV/cm



PMT1

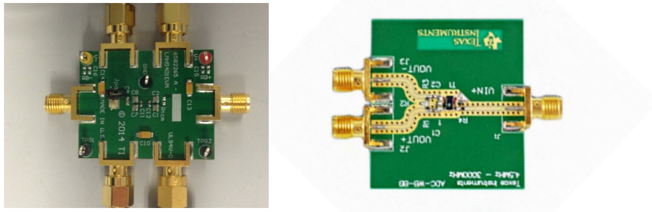
FEE MRPC1 FEE

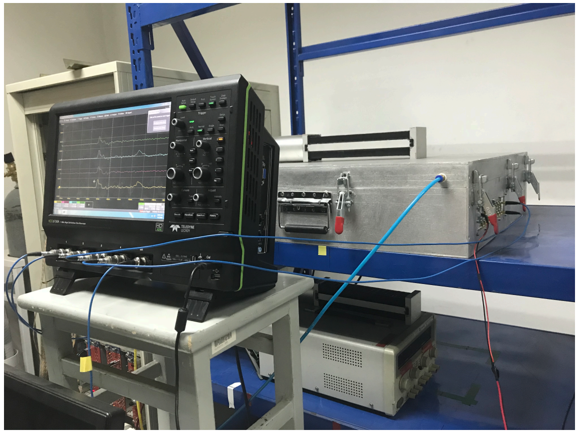
FEE MRPC2 FEE

PMT2

trigger

Oscilloscope





- Oscilloscope bandwidth: 1 GHz
- Sampling rate: 10 GS/s

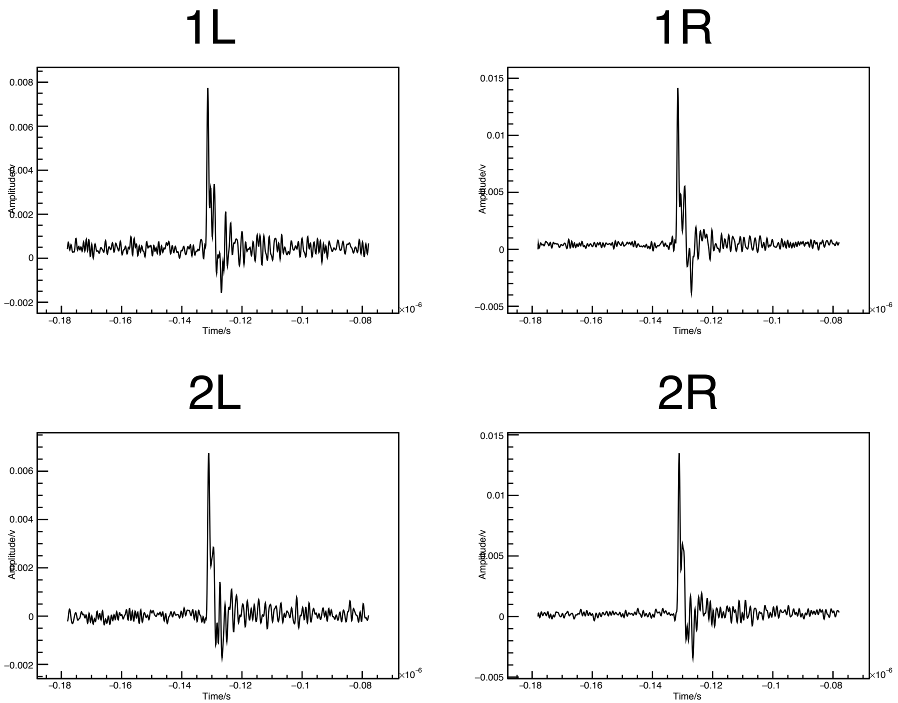
Leading edge: 700~800 ps

7~8 points along the edge

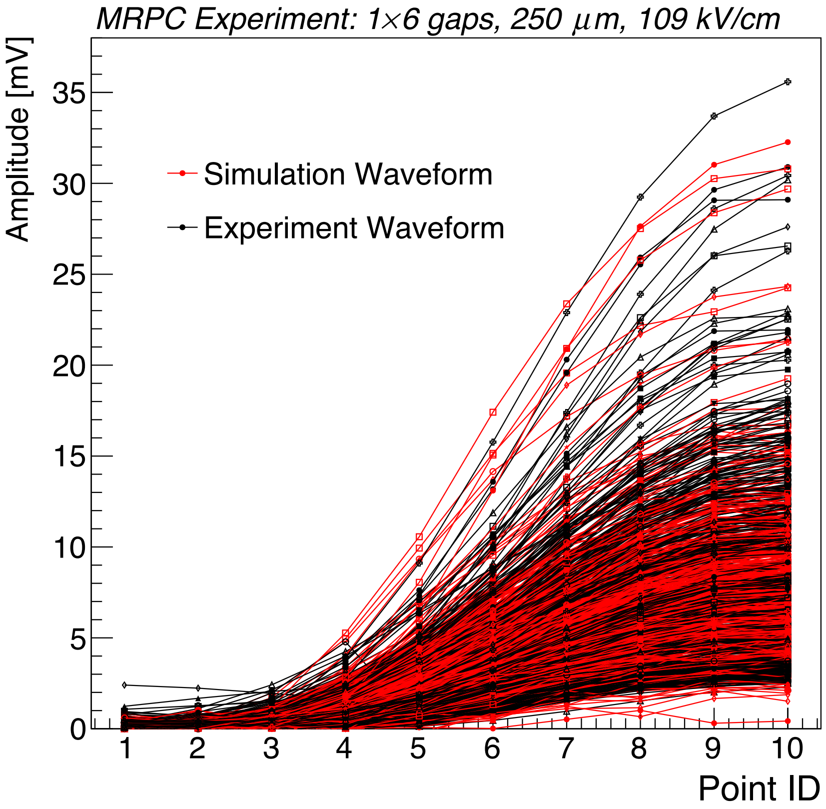
Tsinghua University

Experiment waveform

- Compare the waveform



Waveforms of 1 event



Nearly the same!

Still with differences!

Experiment result

- The 4 waveforms are estimated by the LSTM models separately
- Define: $\Delta t = t_{MRPC1} - t_{MRPC2}$ for vertical particles

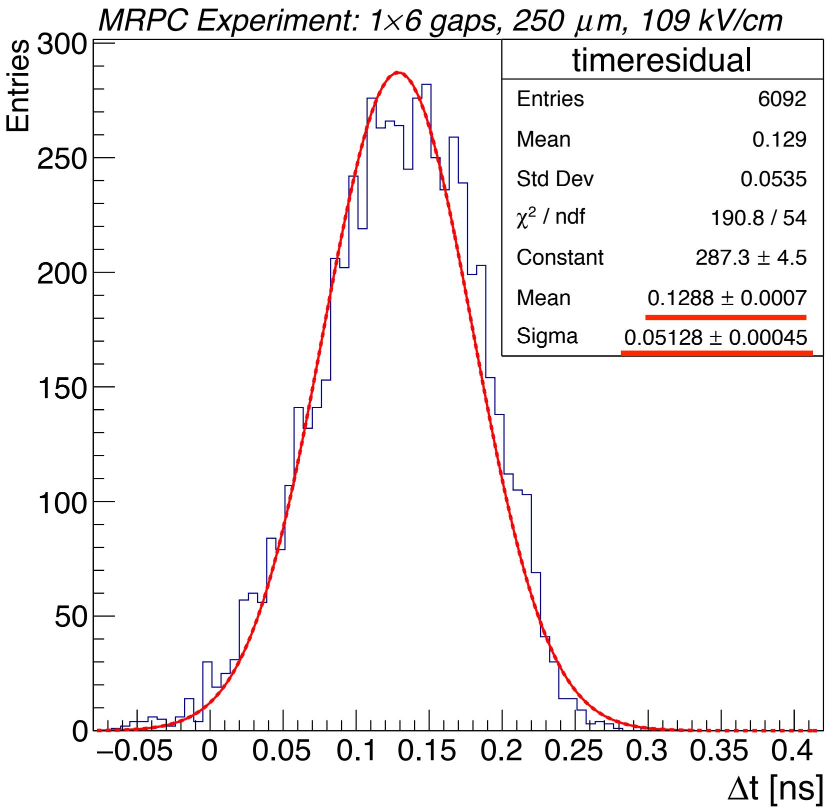
$$\Delta t_{true} = \frac{d_{MRPC} + d_{block}}{v} = \sim 130\ ps$$

- The time resolution of two MRPCs are independent:

$$\sigma_{MRPC} = \frac{\sigma(\Delta t)}{\sqrt{2}}$$

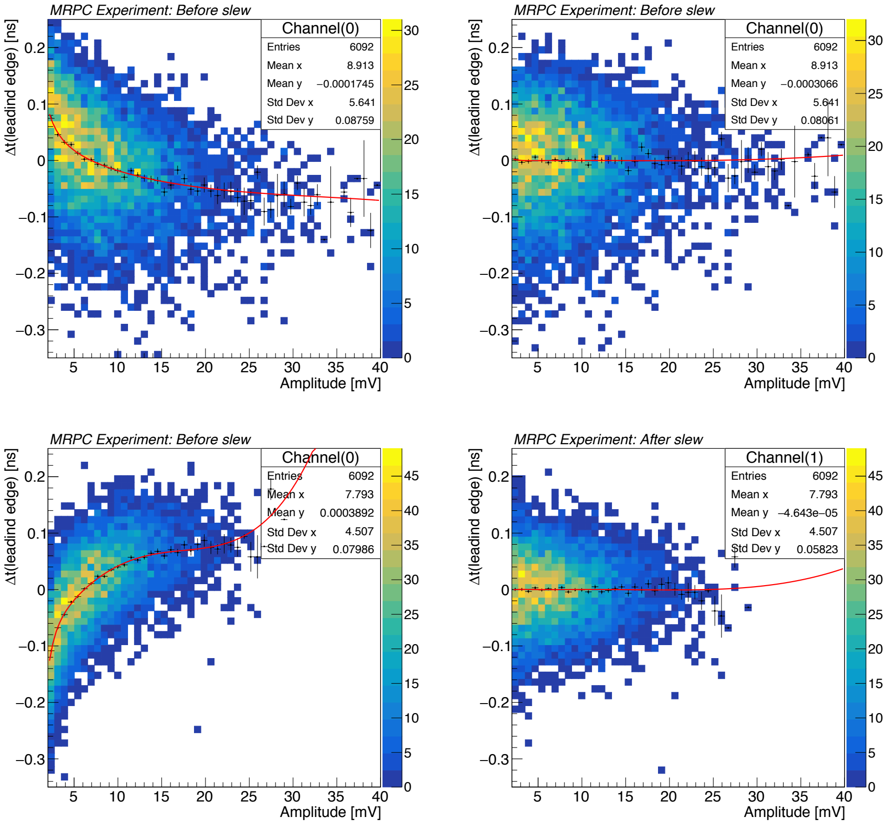
- With LSTM model, for vertical particles, the time resolution is:

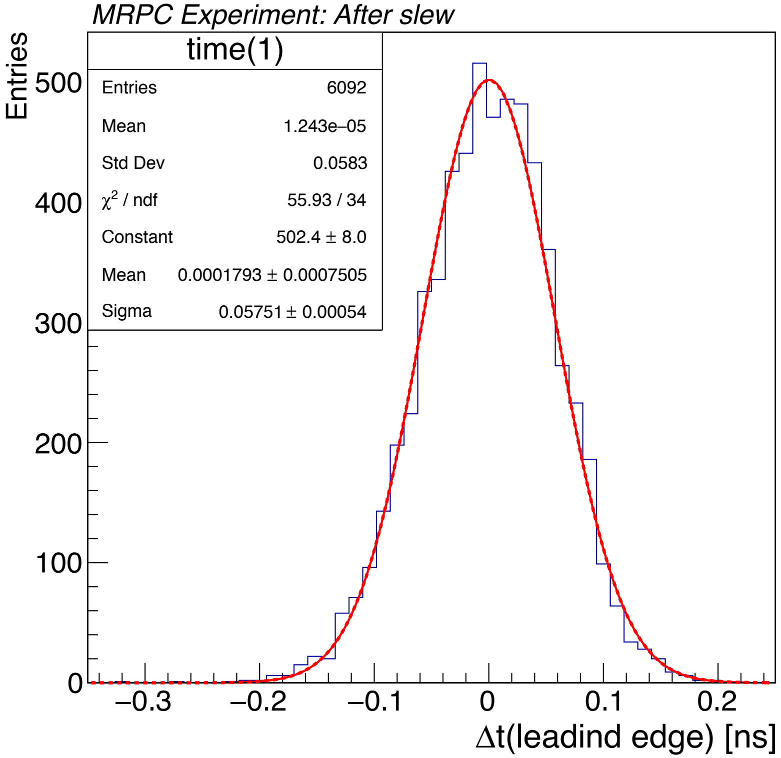
$$51.28/\sqrt{2} = 36.3\ ps$$



Experiment result

1. Much better than the typical time resolution of the 0.25 mm MRPC
2. Better than the state-of-the-art analysis method (Time over threshold (ToT) + slewing correction)





$$57.5/\sqrt{2} = 40.7\ ps$$

Conclusion

- A new time reconstruction method based on the neural network is proposed.
- Two sets of the networks(MLP and LSTM) are analyzed with the simulation data —— LSTM works better than MLP.
- The network models are also used in the experiment data, and the time resolution of 36 ps is achieved with 0.25mm thick MRPC.
  - Better than the typical time resolution
  - Better than the state-of-the-art analysis method
- Further studies on the thin gap MRPC is under consideration

Thank you

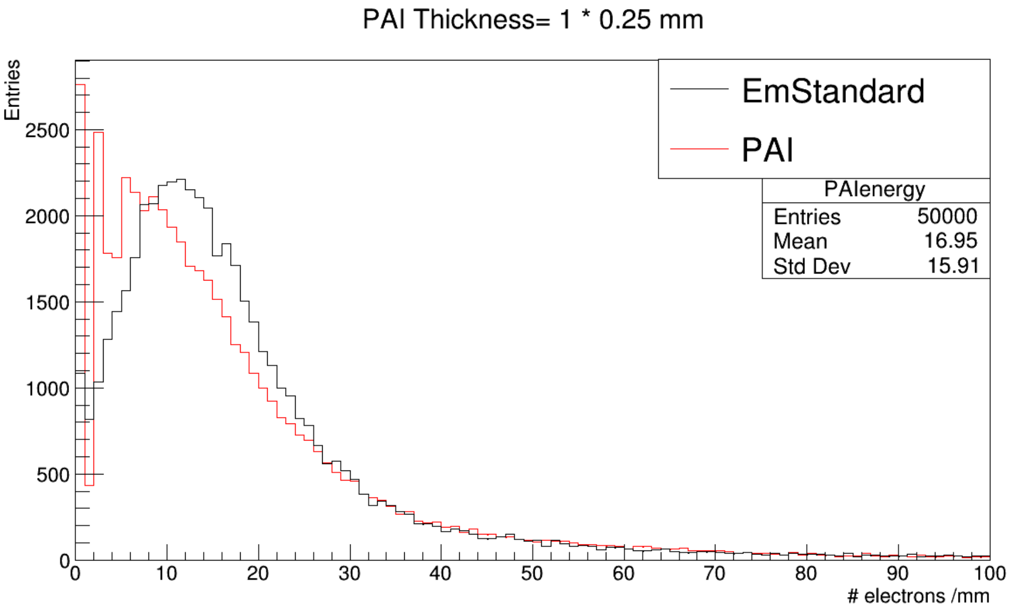
Fuyue Wang

Backup

Fuyue Wang

Physics List

- EMstandard: is most commonly used in LHC simulation,
- However, does not include shell electron effect —— only excellent for thick sensors.
- Photo Absorption Ionization (PAI) model: based on a corrected table of photo-absorption cross section coefficients and works for various elements.
- PAI: The simulated energy loss is in good agreement with the experiment data for moderately thin sensors*.



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*W. Allison, J. Cobb, Relativistic Charged Particle Identification by Energy Loss, Ann. Rev. Nucl. Part. Sci. 30 (1980) 253–298.

Charge Digitization

- Primary energy loss —— ionize electron-ion pairs. W = 30 eV
- Avalanche multiplication —— Townsend effect:

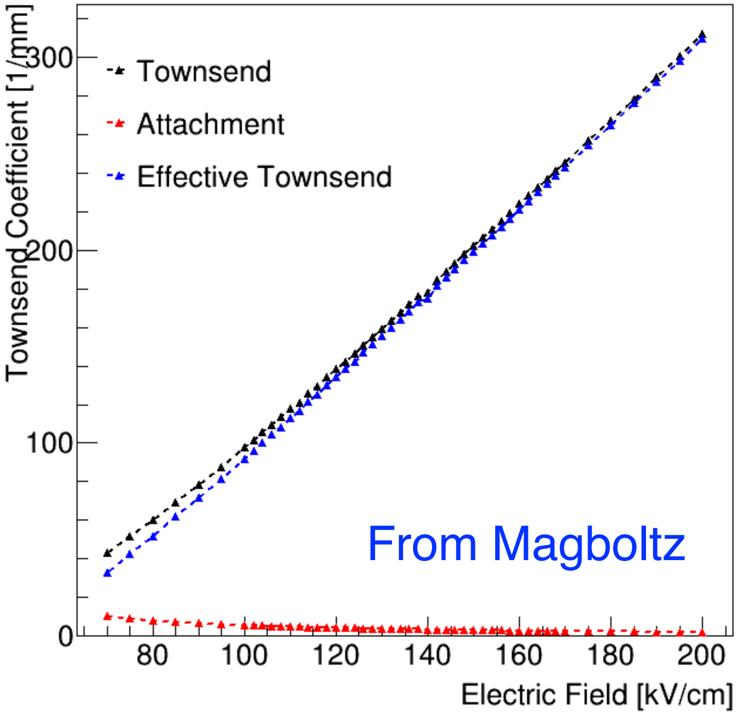
Assumptions:

1. Every step of the multiplication is independent
2. Uniform electric field

$$\frac{d\bar{n}}{dx} = (\alpha - \eta)\bar{n}$$

α : Townsend coefficient

η : Attachment coefficient



From Magboltz

Charge Digitization

Multiplication in a small step:

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

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

- 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: $e^{(\alpha-\eta)x}$

*W. Riegler, et al. NIMA 500 (1-3) (2003) 144-162.

Original signal current

- Electrons drifting in the electric field: induce a signal on the read out strips
- Ramo theory:

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

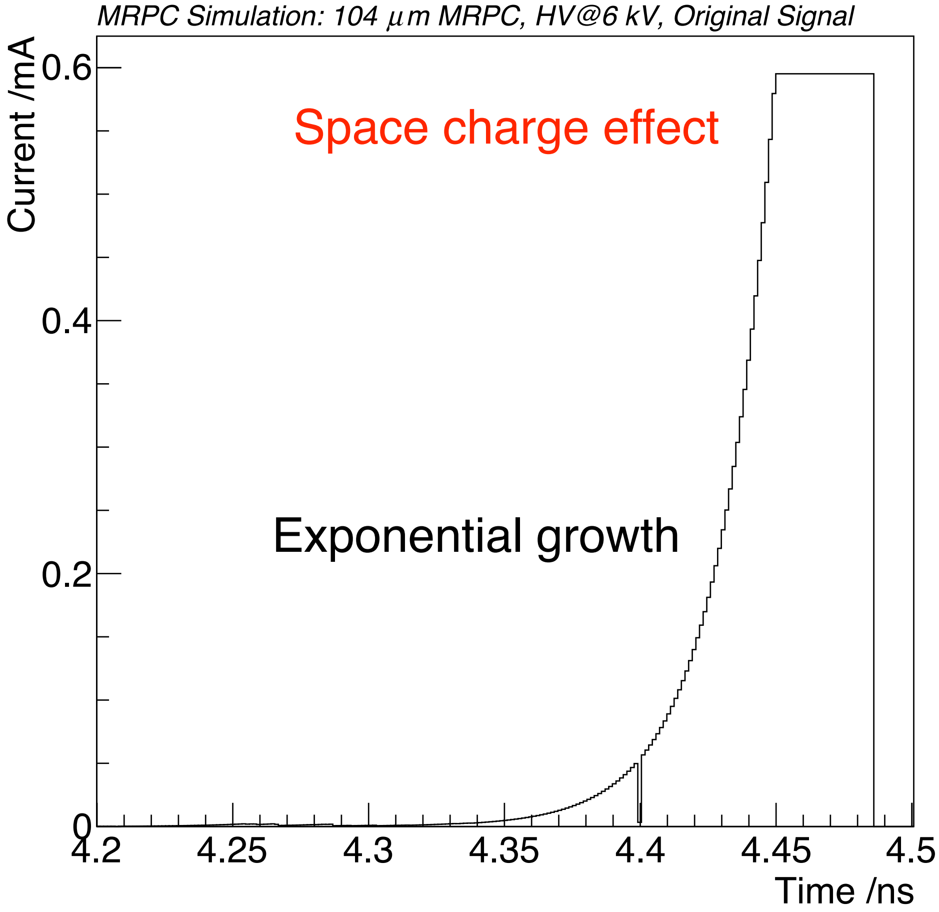
- Weighting field:

$$\frac{E_W}{V_W} = \frac{\varepsilon}{ng\varepsilon + (n+1)d}$$

0.71 mm^{-1}

- Space charge effect:

~10^6 electrons

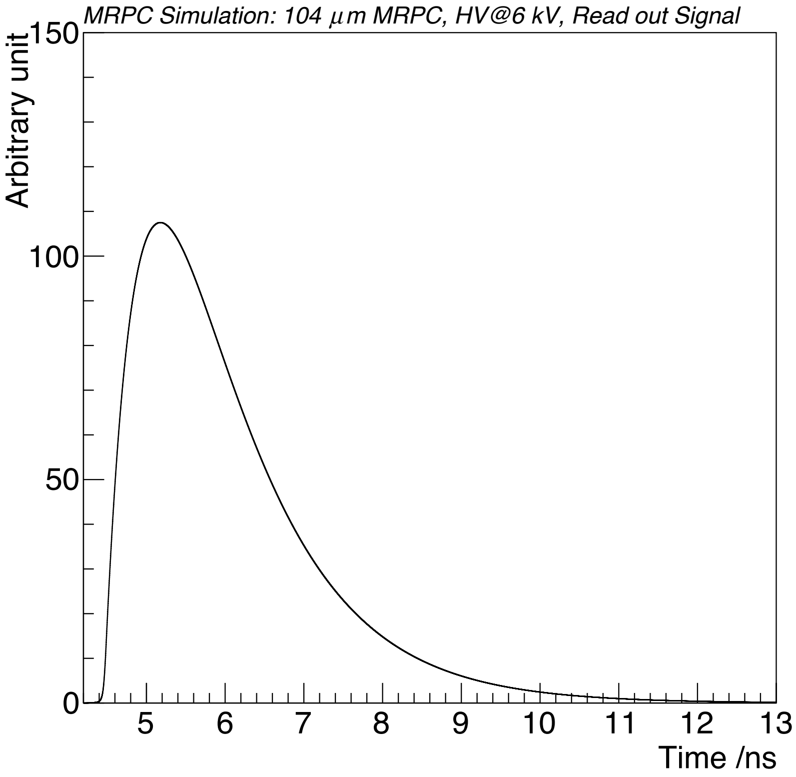


Electronics

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

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

- τ_1 : corresponds to the length of the leading edge
- τ_2 : corresponds to the length of the trailing edge
- Noise is introduced by adding a random number sampled from Gauss(0, σ) to every time bin
- The signal without noise

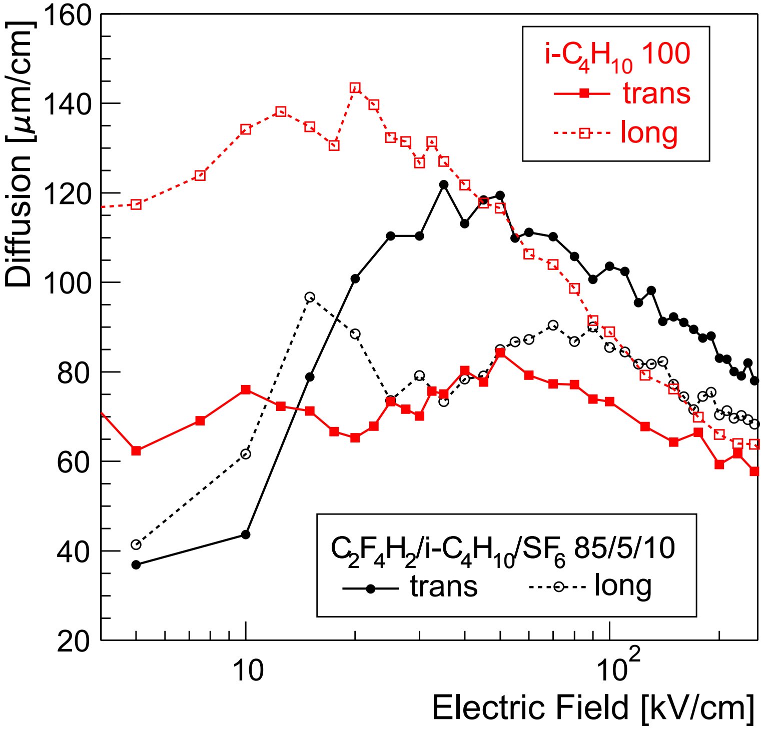


Space charge effect

- Assumption:
  —— the electrons cluster grows like a circle in the transverse direction
- transverse diffusion length: ~100 µm/√cm at E ≈ 100kV/cm
- In the surface, 10^6 electrons:

$$E = \frac{N e_0}{4\pi\varepsilon_0 r^2} = 50\, kV/cm$$

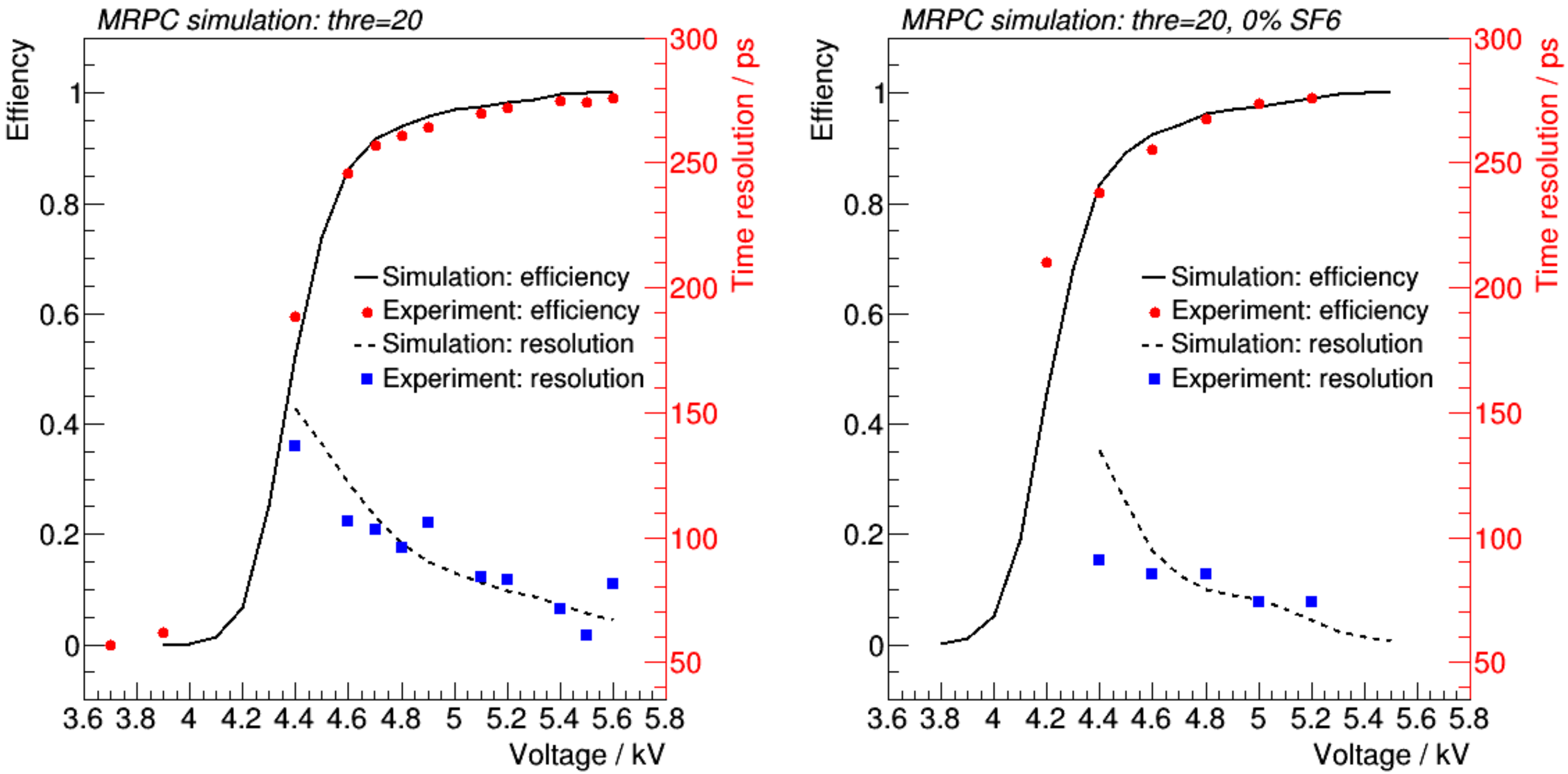
- Comparable to the applied electric field



*C. Lippmann, Detector physics of resistive plate chambers, Ph.D. thesis, Frankfurt U. (2003).

simulation result

- 2*4 gaps, 0.25 mm



Time resolution

- Since both of the MRPCs are read out at double end —— 4 waveforms for every signal: 1L, 1R, 2L, 2R.
- The estimate time $t_{est1,2}$ of each MRPC is the average of the left and right
- To eliminate the influence of the trigger, we calculate the difference of the two MRPC time:

$$\Delta t = t_{est2} - t_{est1}$$

- The difference of the 2 MRPC's truth time is a constant:

$$\sigma(\Delta t) = \sigma(t_{est2} \boxed{- t_{true2} + t_{true1}} - t_{est1}) = \sigma(t_{res1} - t_{res2})$$

- Then:

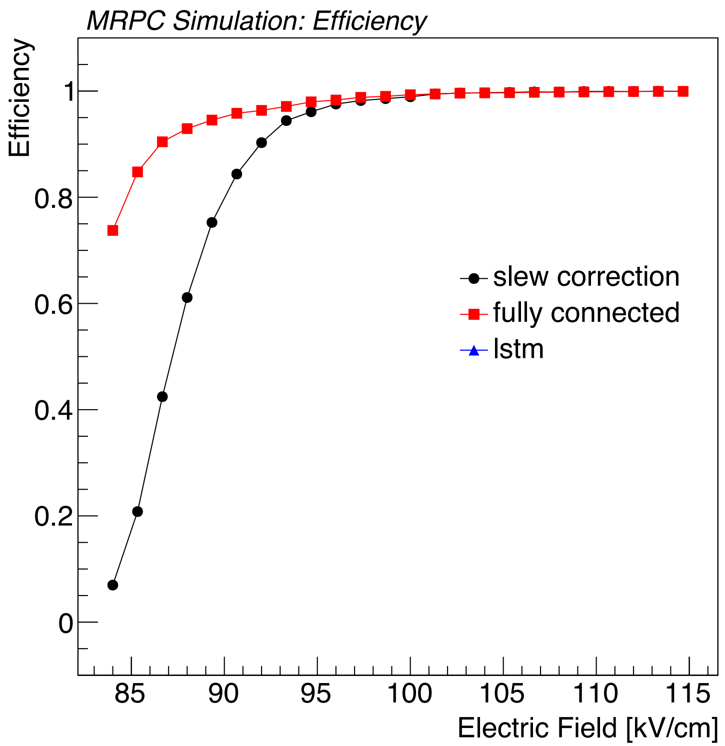
$$\sigma(\Delta t) = \sigma(t_{res1} - t_{res2}) = \sqrt{\sigma^2(t_{resi1}) + \sigma^2(t_{resi2})} = \sqrt{2\sigma^2_{MRPC}}$$

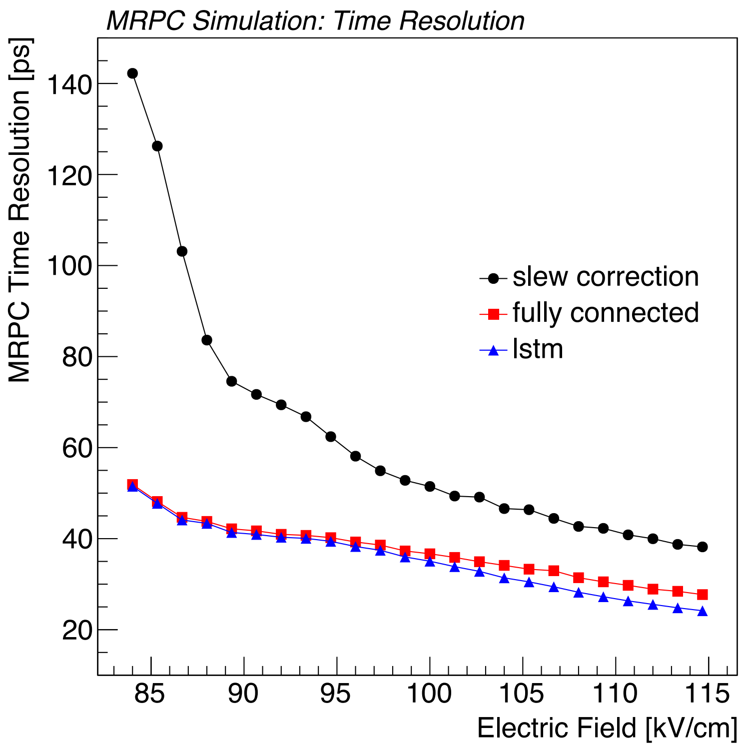
- Therefore:

$$\sigma_{MRPC} = \frac{\sigma(\Delta t)}{\sqrt{2}}$$

Previous method

- Read out with time-over-threshold(ToT) + slewing correction





	Single-stack MRPC
Gas Gap Width	250 um (fishing line)
Number of Gas Gaps	1 stack x 6 layers = 6
Float Glass Thickness	700 um
Readout strip	7 mm x 270mm(3 mm internal)
Readout	differential, both ends
honey	6mm
PCB	0.8mm
mylar	0.25mm