Proposal of An Alternative Active Target Design based on PIN

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BNL

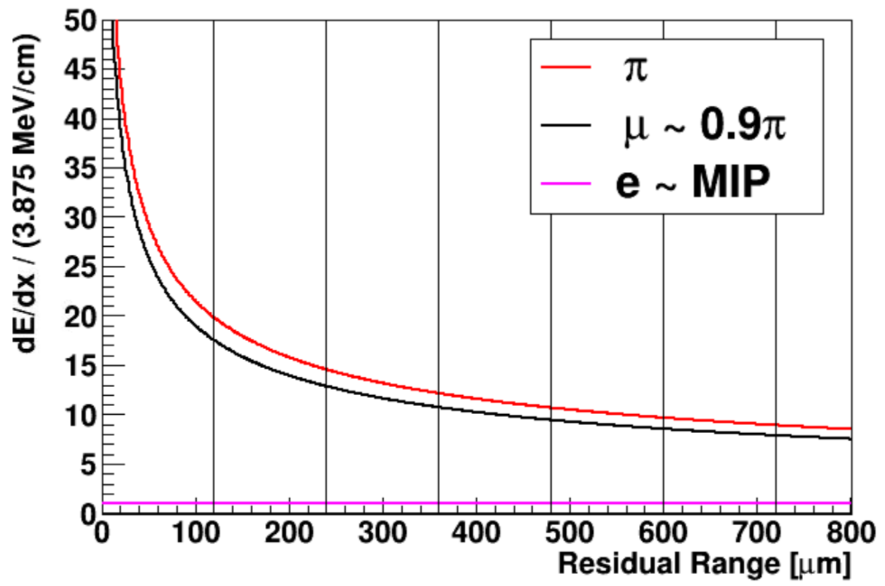
With fruitful discussions with Veljko Radeka, Sergio Rescia, Gabriele Giacomini, Vladimir Tishchenko, Chao Zhang and many others

Active Target (ATAR) Requirement for PIONEER

- **Excellent position resolution** (for π, μ, e) enabling pattern recognition capabilities to differentiate $\pi^+ \to e^+\nu$ from $\pi^+ \to \mu^+(e^+\nu\nu)\nu$
  - 2x2x0.6 cm^3 ATAR design with 200 um strip pitch and 120 um thickness demonstrated in simulation

- **Excellent timing resolution** for T_0 and two-hits separation
  - Capable of identifying $\pi \to \mu$ hits separated by 1.5 ns
  - Achieve a T_0 timing resolution that can handle 300 kHz rate (e) and rejecting beam background (for π ID)

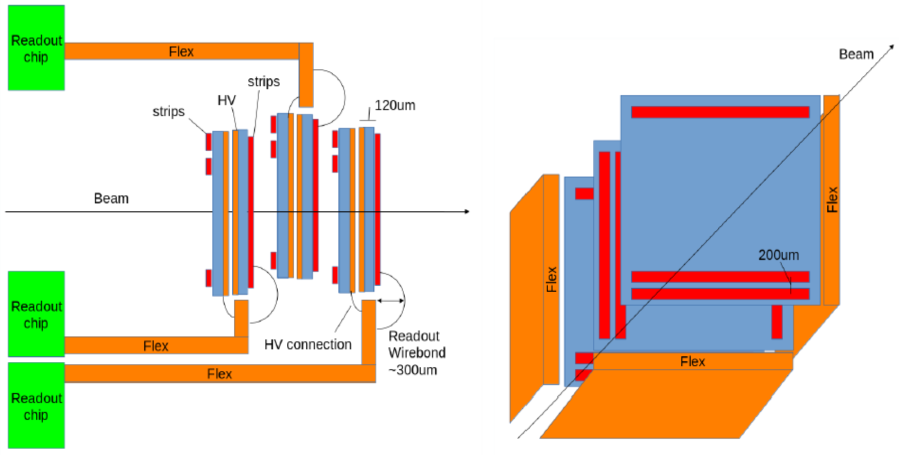
- **Excellent energy resolution**
  - Separating the stopping π from stopping μ
  - Measuring energy of e



ATAR Design in PSI Proposal

- **Position resolution**
  - for π, μ, e ensured by the excellent S/N ratio from LGAD
- **Timing resolution**
  - T_0 and 2-hits separation ensured by excellent S/N ratio from LGAD
- **Energy resolution**
  - R&D is needed, given LGAD is firstly proposed as a fast-timing detector
  - 'Gain' may create complications in energy measurement (stability, uniformity, topology dependence)

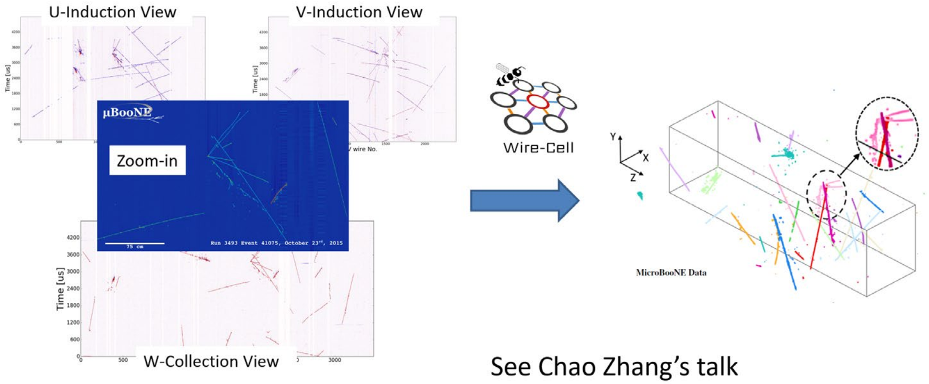
- Additional challenges
  - Excellent S/N ratio → non-trivial requirement on the dynamic range of the electronics
  - Energy measurement → non-trivial requirement on the linearity of electronics



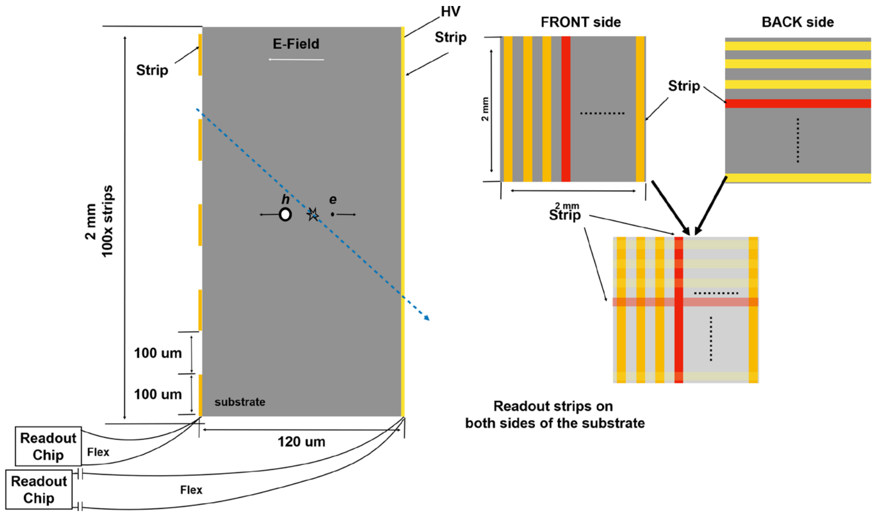
- 48 layers 1-side strip readout with 120 um thickness
- 100 strips with 200 um pitch covering 2x2 cm^2 area
- Sensors packed in stack of two with facing HV side and rotate 90^o
- AC or TI LGAD to ensure excellent Signal-to-Noise (S/N) Ratio

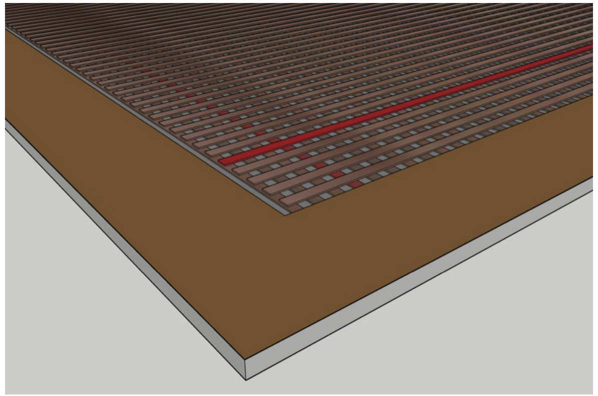
An Improved Design with 2-sided Readout

- Inspired by previous experience in Liquid Argon Time Projection Chamber
  → multiple projective 2D readouts enabling a 3D event reconstruction
  – For point-like energy deposition, same charge measurement in anode and cathode readout (Ramo theorem) → **double # of hits for an improved energy and timing resolution**, particularly beneficial for MIP electron
  – Expected to be beneficial to identify μ (-DIF) from the pion decay (~4 MeV, 750 um range)
    - **Allow track reconstruction within 1 layer**
  – For cathode readout, requiring capacitor (100 pF/up to 1 kV) to separate the bias voltage from readout (size ~ 2 mm x 1.2 mm integrating into the front-end board)



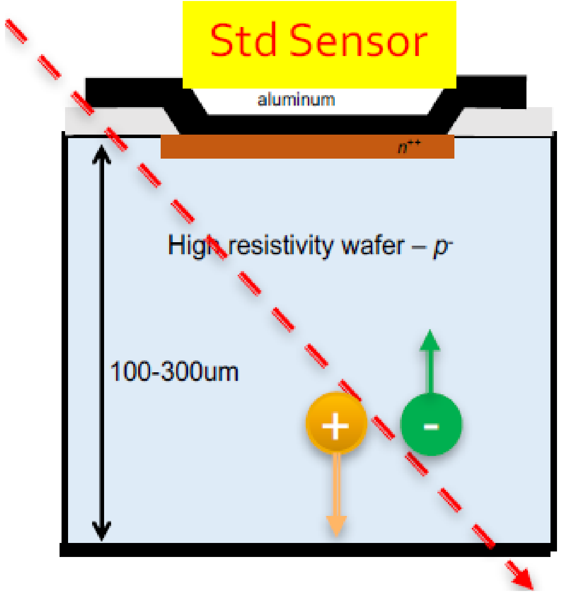
See Chao Zhang's talk



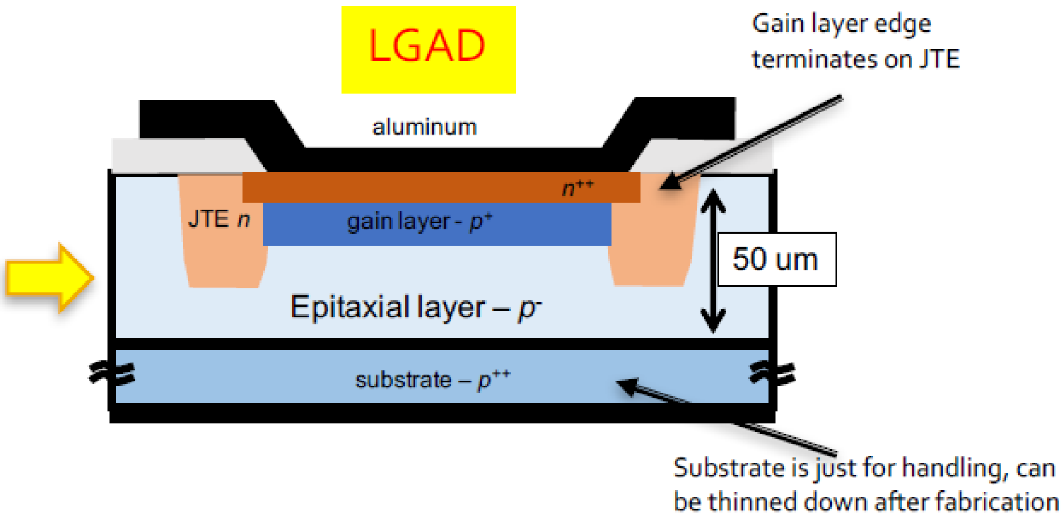


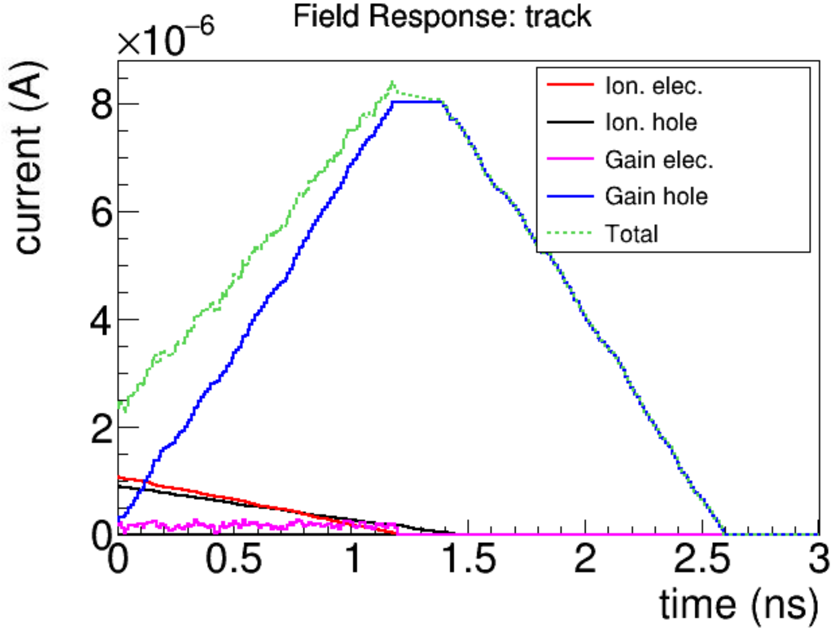
Alternative Design with a PIN Device

- Just like the Calorimeter (LXe vs. Crystal), it is desired to have an alternative design for the ATAR
  - Given the existing studies on simulations, a natural candidate for the alternative design is a PIN device
  - Compared to LGAD, PIN does not have the GAIN mechanism



PIN device





Pros and Cons for PIN-based 120 um-thick ATAR

Pros

- PIN is known to be **linear** in energy response to energy deposition from 1 to 100 MIP
  - Excellent stopping π/μ separation
- With the charge collection signal, much easier to calibrate the energy response (**uniform, stable and topology independent**)
- A single 12-bit (4096) digitizer is sufficient to cover the entire dynamic range

Cons

- Need a working design of **pre-amp electronics to achieve > 9:1 signal-to-noise ratio for MIP signal, which requires more power**
  - With FAST, the S/N ~ 5:1 for MIP signal
  - Also have impact in timing resolution (to be elaborated in details)

- Additional considerations for the alternative design
  - Keep the current geometry, possible to expand to 3x3 cm^2 with more channels
  - Given stopping π/μ ~ 10-35 MIP,
    - Good T0 timing resolution is expected
      - Handle 300 kHz rate (e) and rejecting beam background (for π ID)
    - Good 2-hits separation should be expected, but depending on electronics
      - π/μ separation for hits separated by 1.5 ns

Requirement of Electronics

- The (minimal) most probable value (MPV) charge for a MIP track in a 120-um thick Si is about 7800 electrons (1.25 fC)
  - **To reach a 9:1 S/N ratio, the equivalent noise charge (ENC) should be smaller than 860 electrons**
- 6 e- /pF@ 1 us shaping @ room temperature
  - "Signal Processing for Particle Detectors" Veljko Radeka
  - **@ 10 pF, 5 ns shaping time gives us 850 electrons**
  - At LXe temperature (~4 e/pF), ENC ~ 570

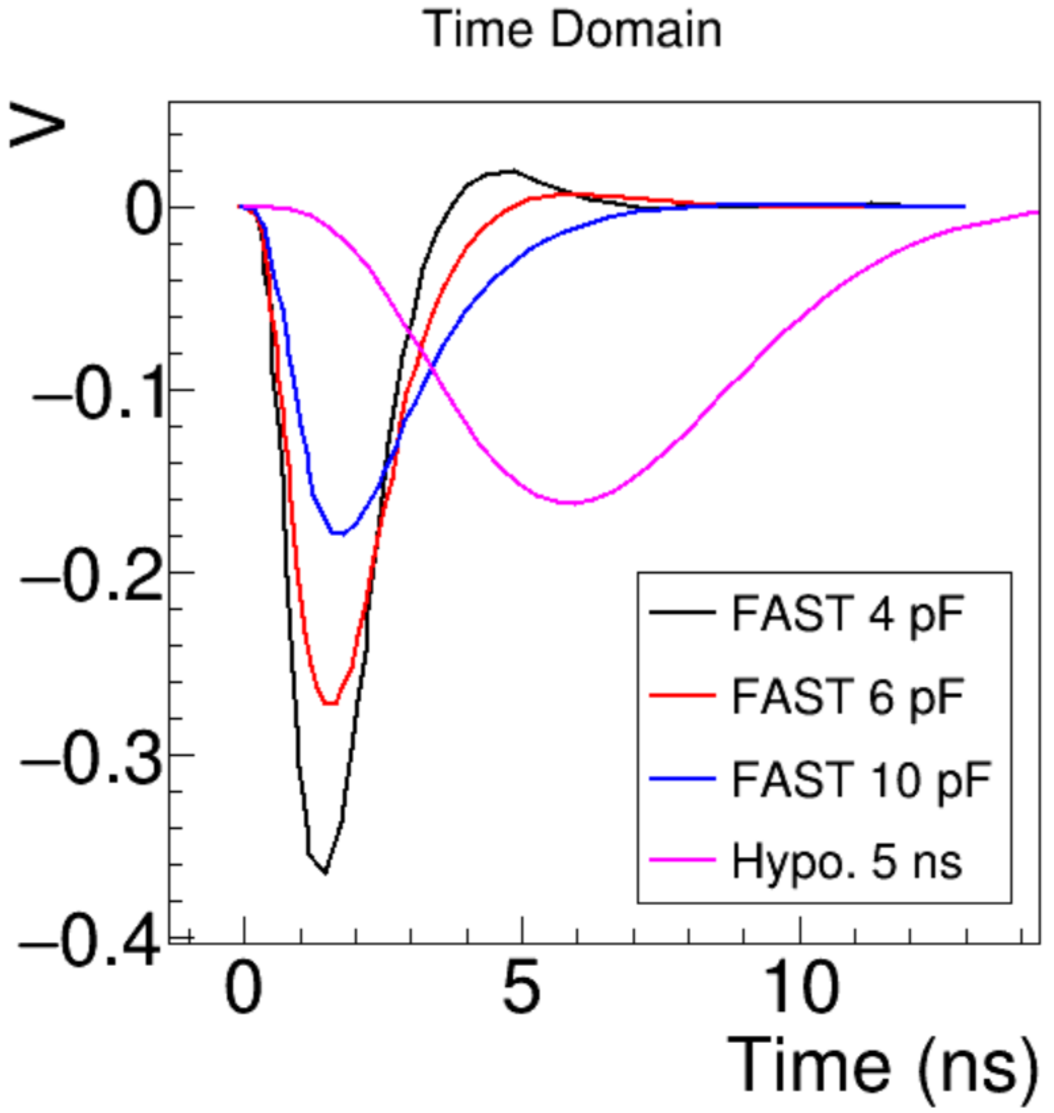
$$ENC \propto C_{in} \cdot \sqrt{\frac{1}{t_{shaping}}}$$

- ~ 5 mW/ch
- Better than 1% integrated linearity up to 100 MIP

200 um pitch, 100 um width	N-type strip (2 cm)	P-type strip (2 cm)
Interstrip capacitance	0.1 fF/um → 4 pF	0.04 fF/um → 1.6 pF
Back capacitance	0.08 fF/um → 3.2 pF	0.08 fF/um → 3.2 pF
FLEX cable	50-60 pF/m → 2.5 – 3 pF	
Total	~ 10 pF	~ 8 pF

Demonstration of the ATAR Performance with 5 ns Shaping

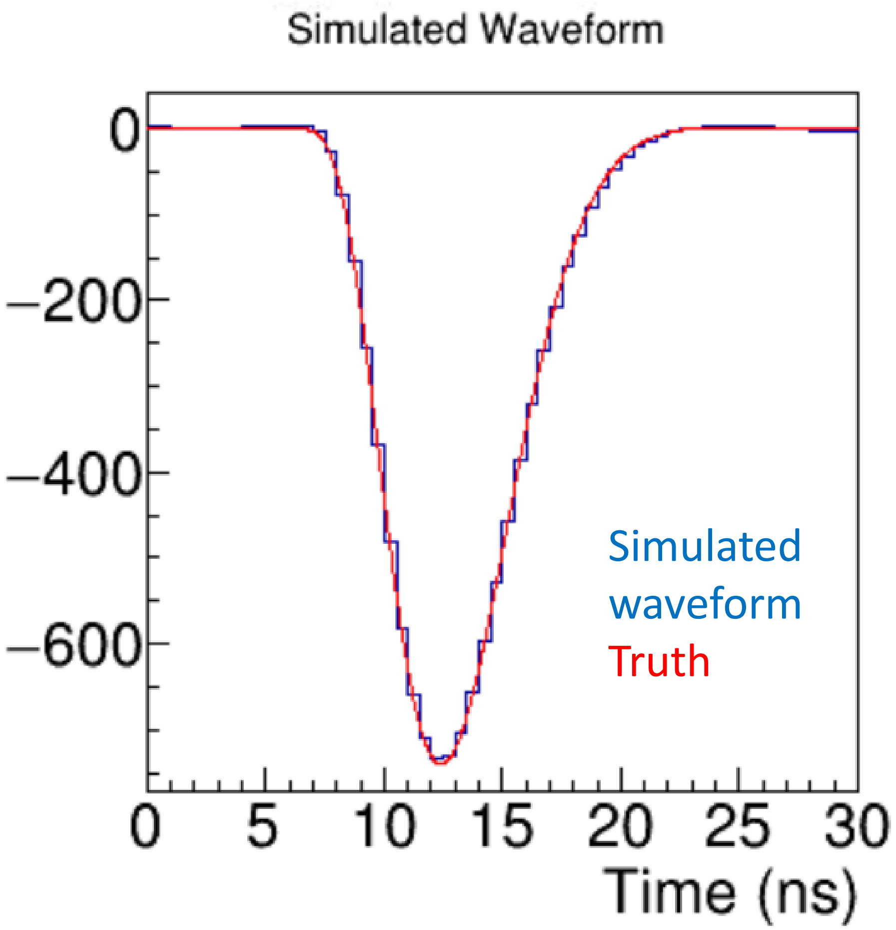
- Based on existing studies
  - Simulation: db-98
  - T0 timing resolution: db-104
  - Two-peak separation: db-106
  - Charge resolution: db-105
- Simulation:
  - Signal fluctuation + Random Electronics Noise
- Reconstruction assuming known electronics response function
  - Deconvolution with FFT
  - Compressed sensing with L1 regularization



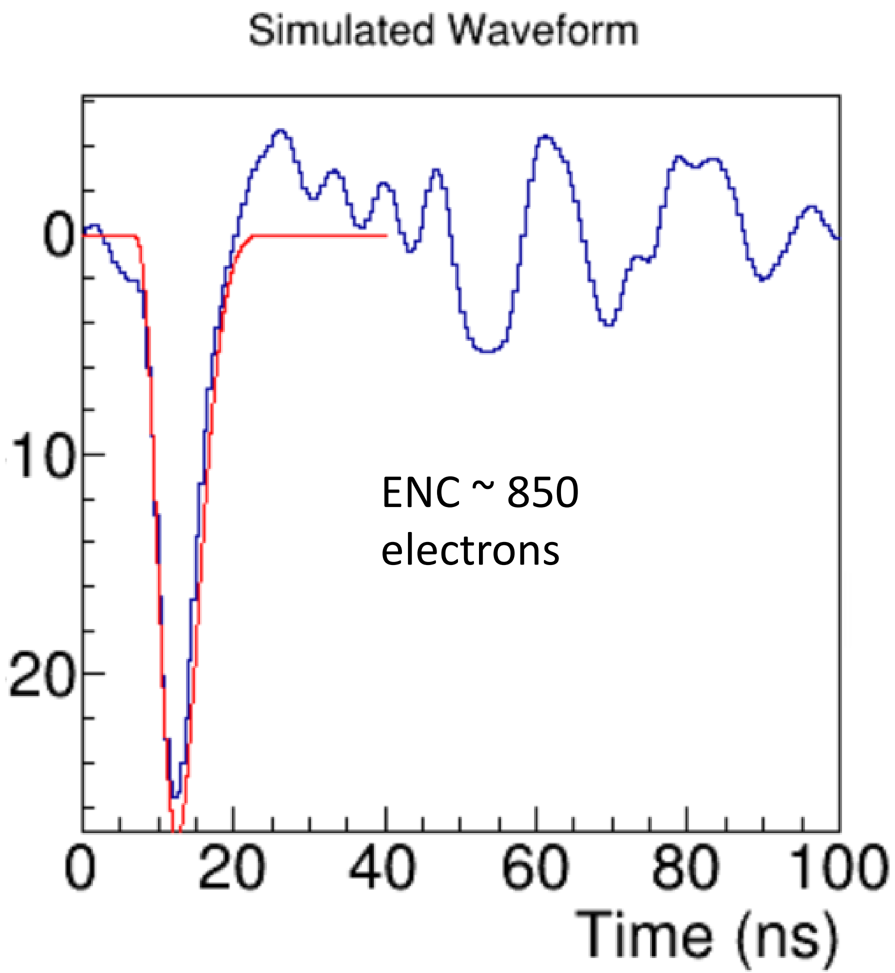
Hypothetical electronics response with 5 ns shaping utilized the functional form of LArASIC

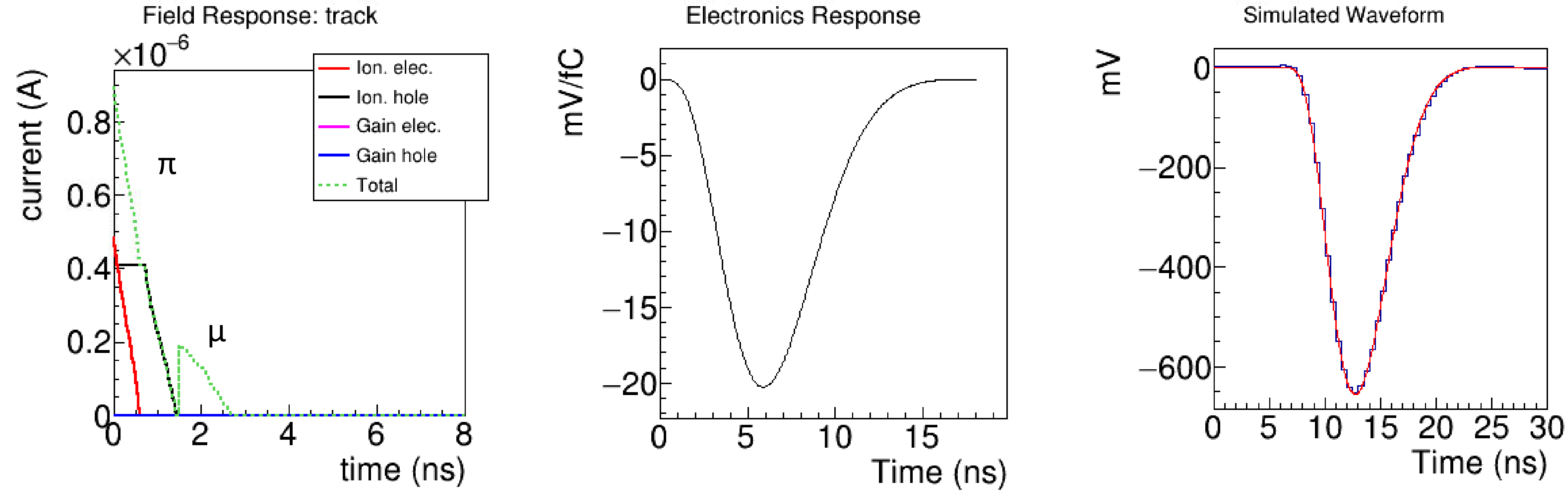
Example of Simulated Waveform with Noise @ 2 GHz digitization

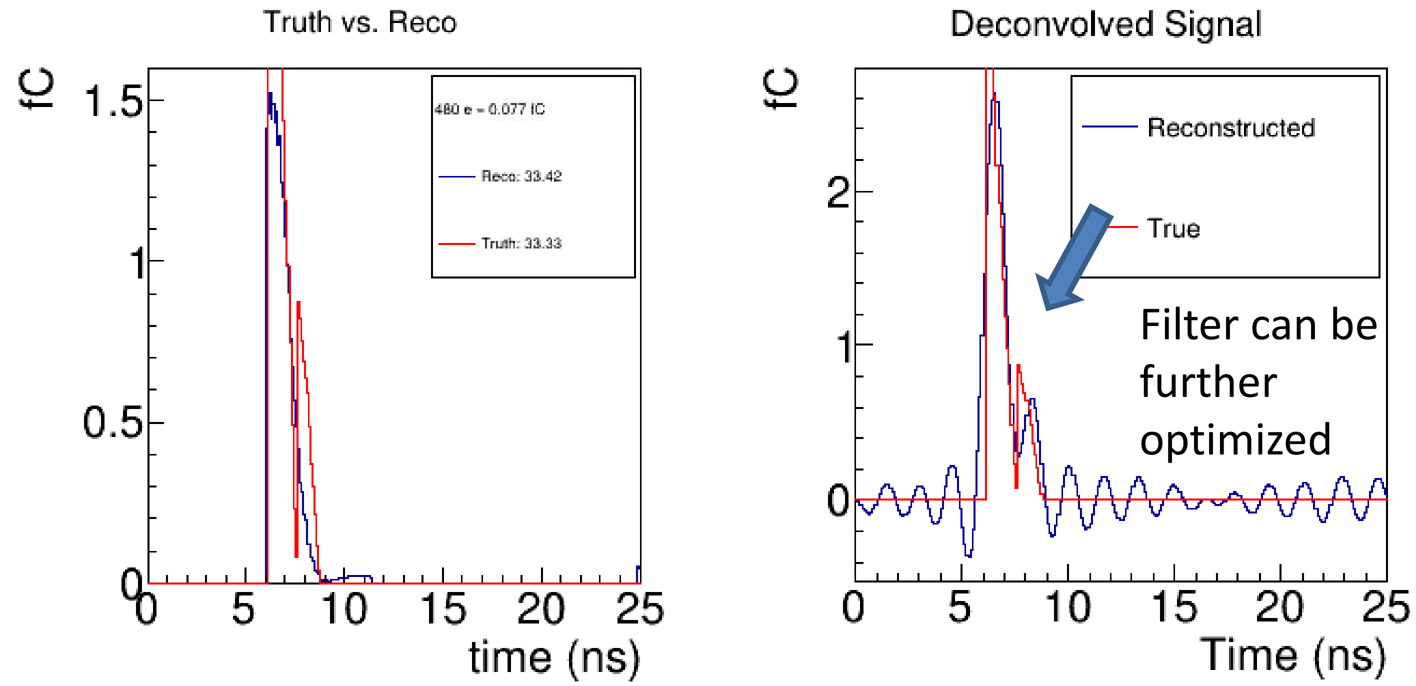
30xMIP ~ stopping pions/muons



MIP ~ electrons



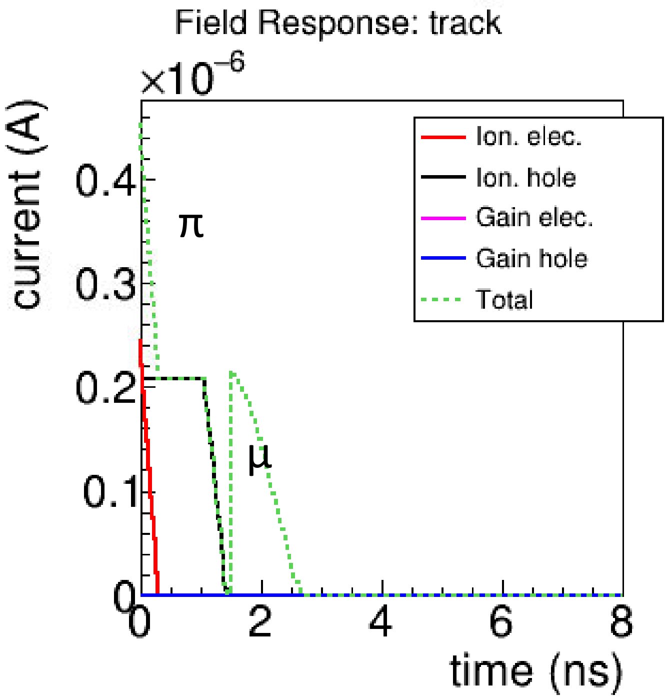


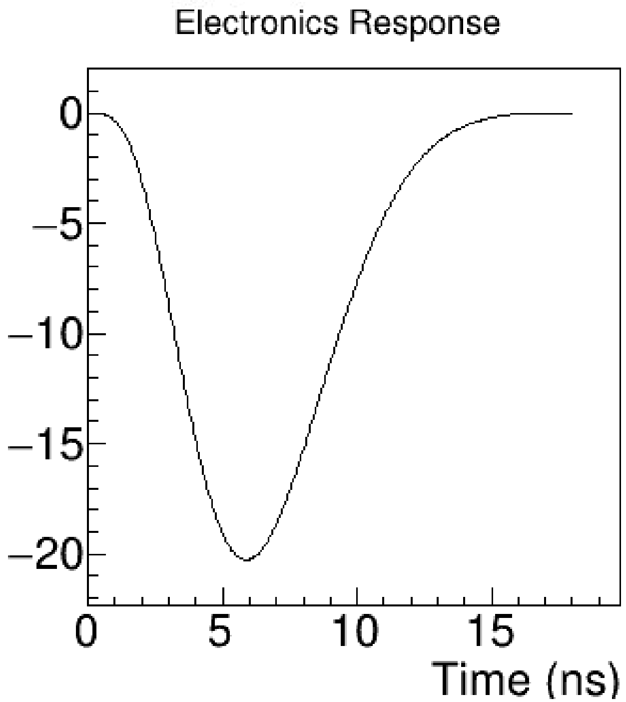


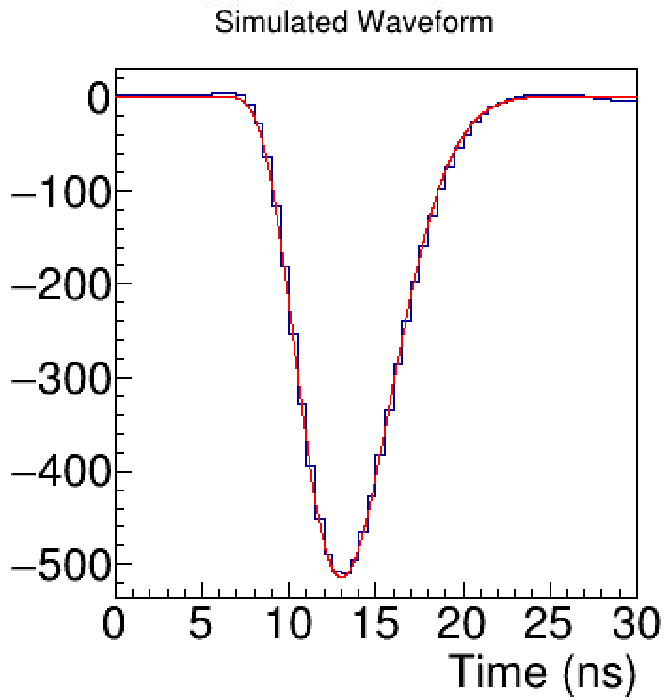
2-peak Separation

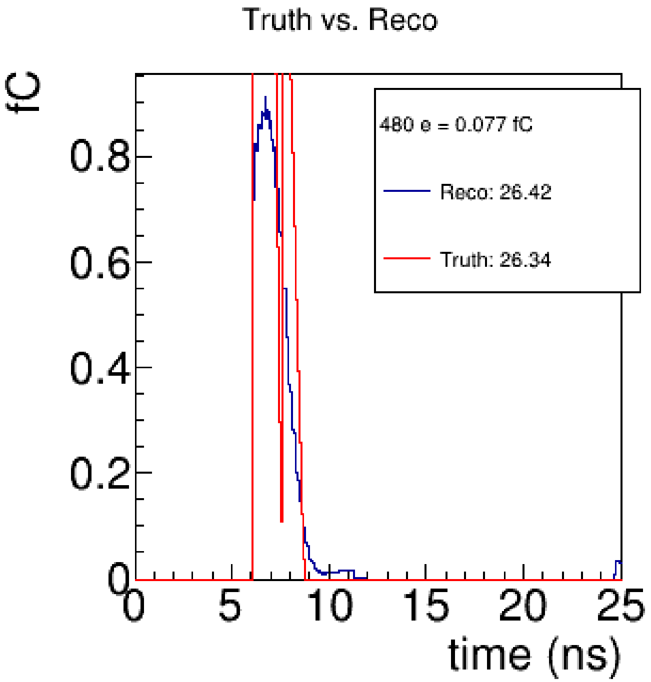
π (47 MIP)-μ (9 MIP)

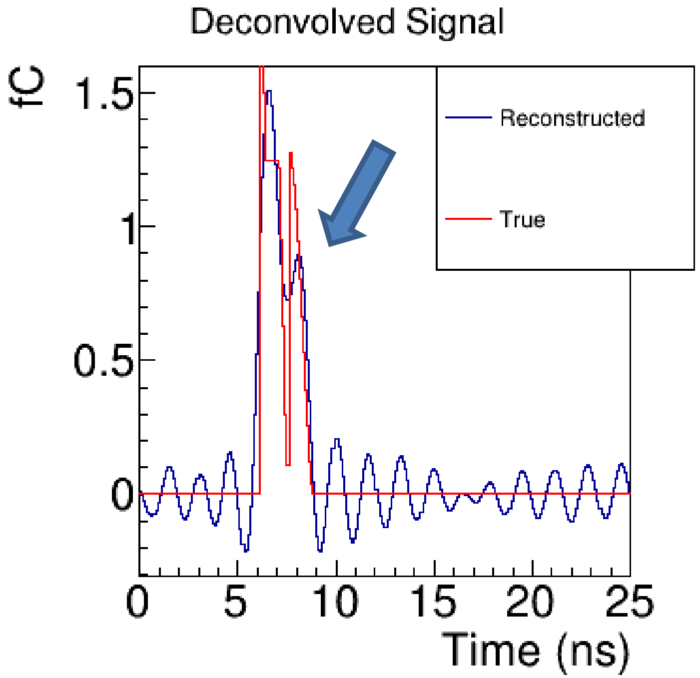
@ 60-60 um + 1.5 ns)





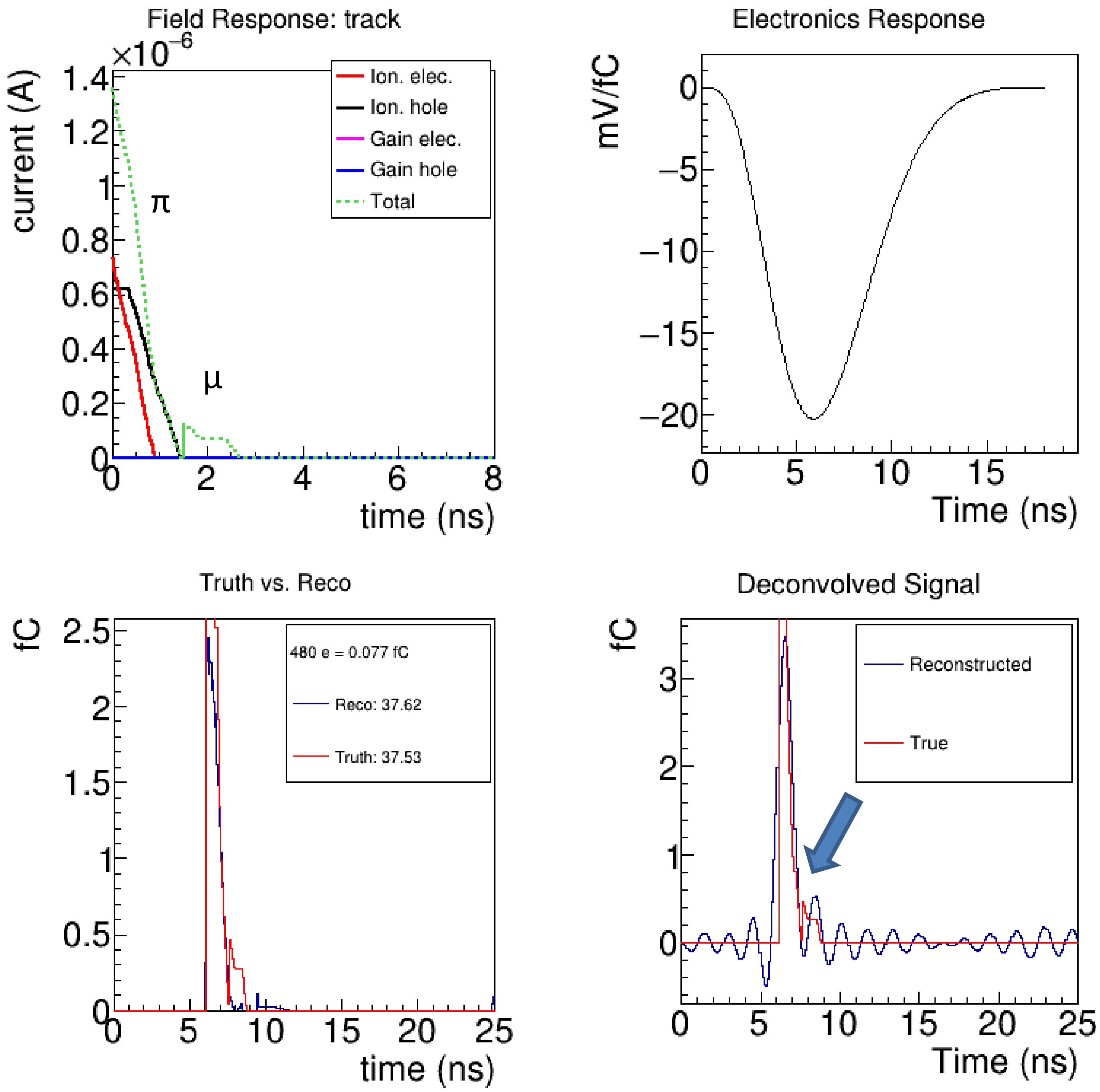






2-peak Separation

π (60 MIP)-μ (9 MIP) @ 30-90 um + 1.5 ns)



2-peak Separation π (39 MIP)-μ (9 MIP) @ 90-30 um + 1.5 ns)

2-sided readout limits the ambiguities a single 3D point in the decay layer

Summary of Timing and Charge Resolution

	MIP hit	MIP track (50 hits assumed with 2-sided readout)	10xMIP hit	30xMIP hit
T0 resolution	408 ps	408/sqrt(50) = 58 ps	103 ps	74 ps
Charge resolution (1024 e in 7 ns)	<13.1%	13.1%/sqrt(50) = 1.9%	<1.31 %	<0.44%
2-peak separation @ 3D point of the decay layer	N/A	N/A	Good with 1.5 ns separation, when delayed hit charge is not too small	

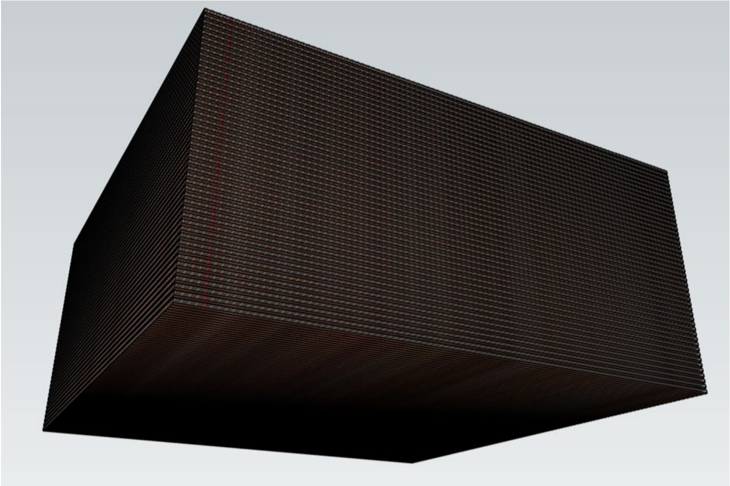
<u>PIONEER physics requirements satisfied!</u>

120 um PIN device, a 5 ns shaping time preamplifier + S/N ~ 10:1

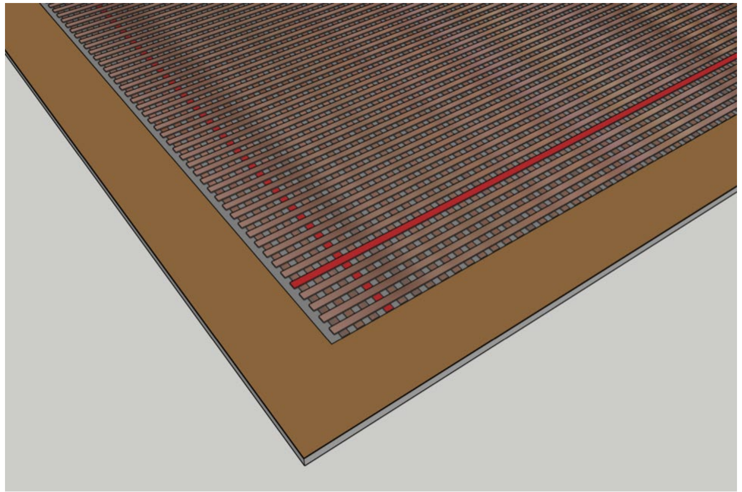
Discussions and R&D path

- Sensor and electronics design are related:
  - Thicker than 120 um ATAR PIN layer will allow for shorter (than 5 ns) shaping time
- Development of a new low-noise preamp electronics with shaping time ~ 5 ns
  - Can also be used for SiPM readout for PIONEER calorimeter
  - We may explore a readout scheme with E0, T0, and TOT instead of full digitization → simplified readout chain with a big saving on electronics power
- Demonstration of 2-sided PIN/LGAD fabrication (BNL LDRD scope, see Volodya and Gabriele’s talks)
- Engineering Design with proper cooling
  - Electronics Noise can be significantly reduced if using cold electronics (LXe temperature)

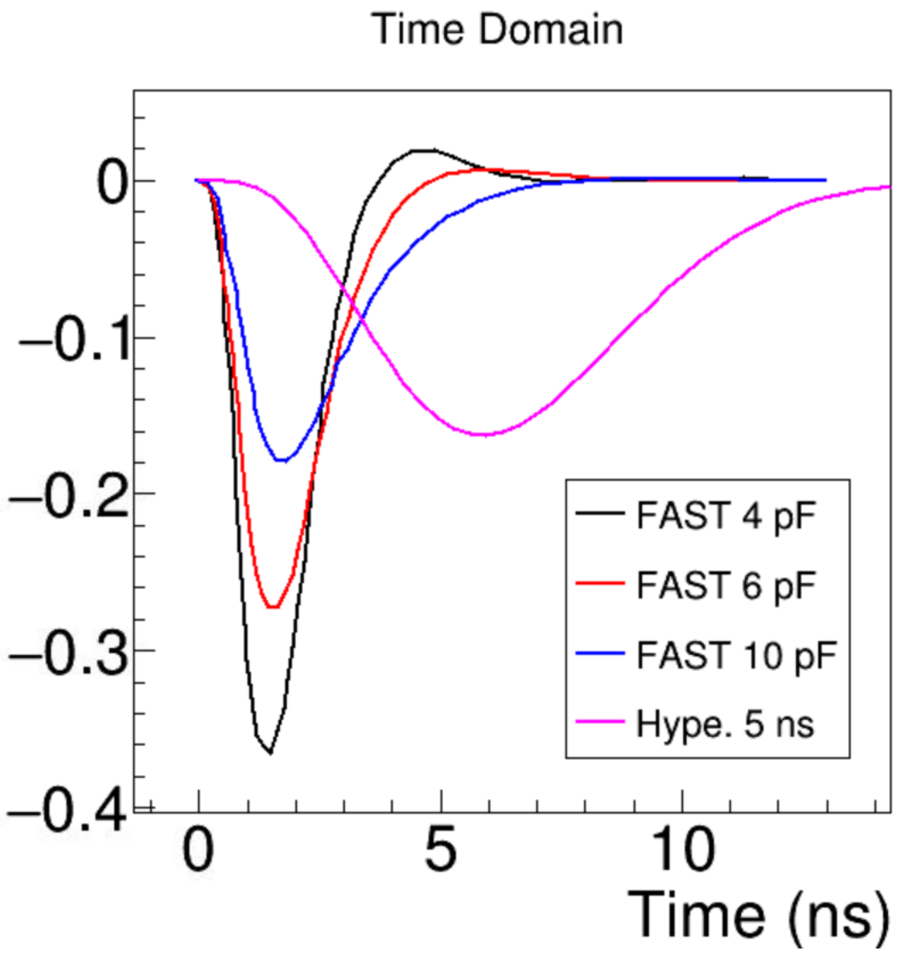
Summary

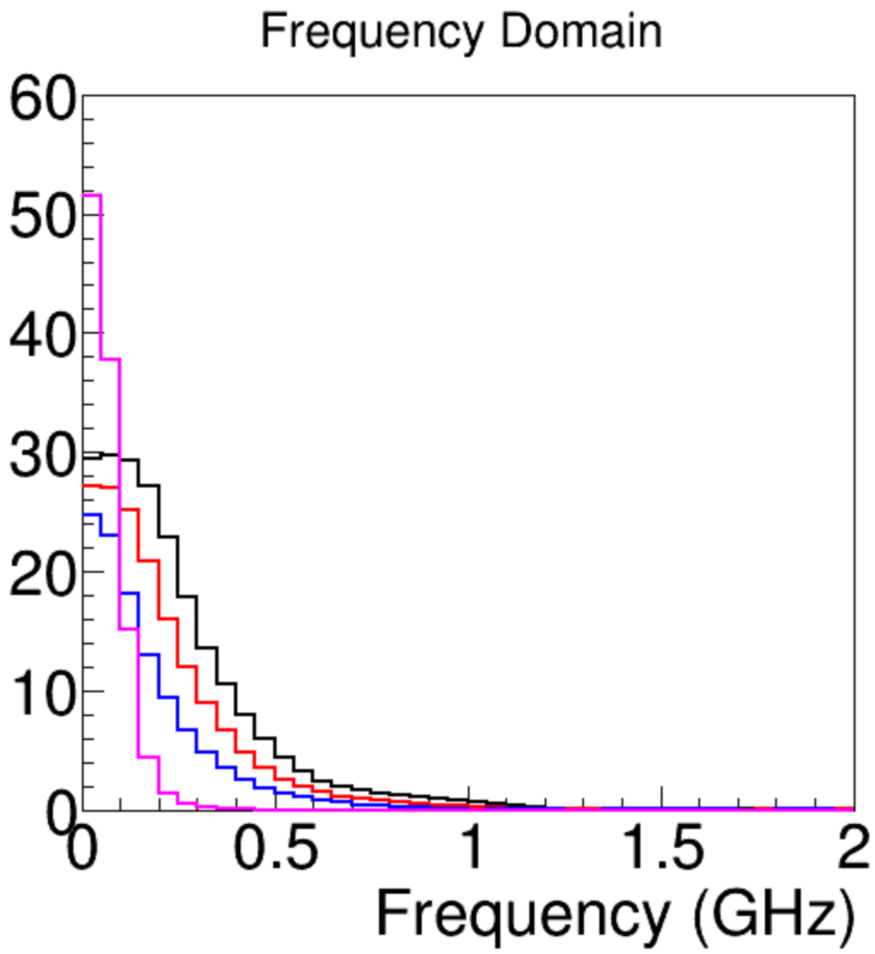


- We propose a 2-sided PIN-based ATAR for PIONEER
- With a 5-ns shaping time preamplifier, this alternative design enables
  - Excellent energy resolution (π/μ separation, electron energy)
  - Excellent timing resolution (<100 ps for stopping π/μ)
  - Excellent position resolution for precise 3D topology reconstruction (identify short muon even within one layer)

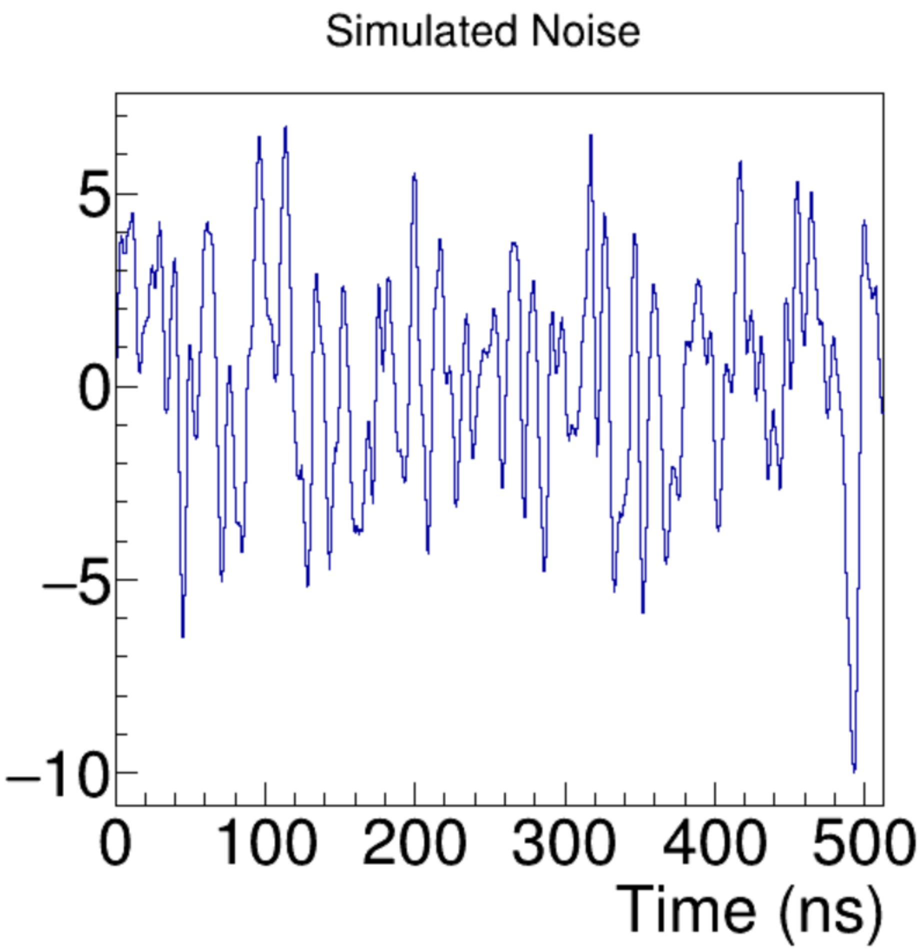


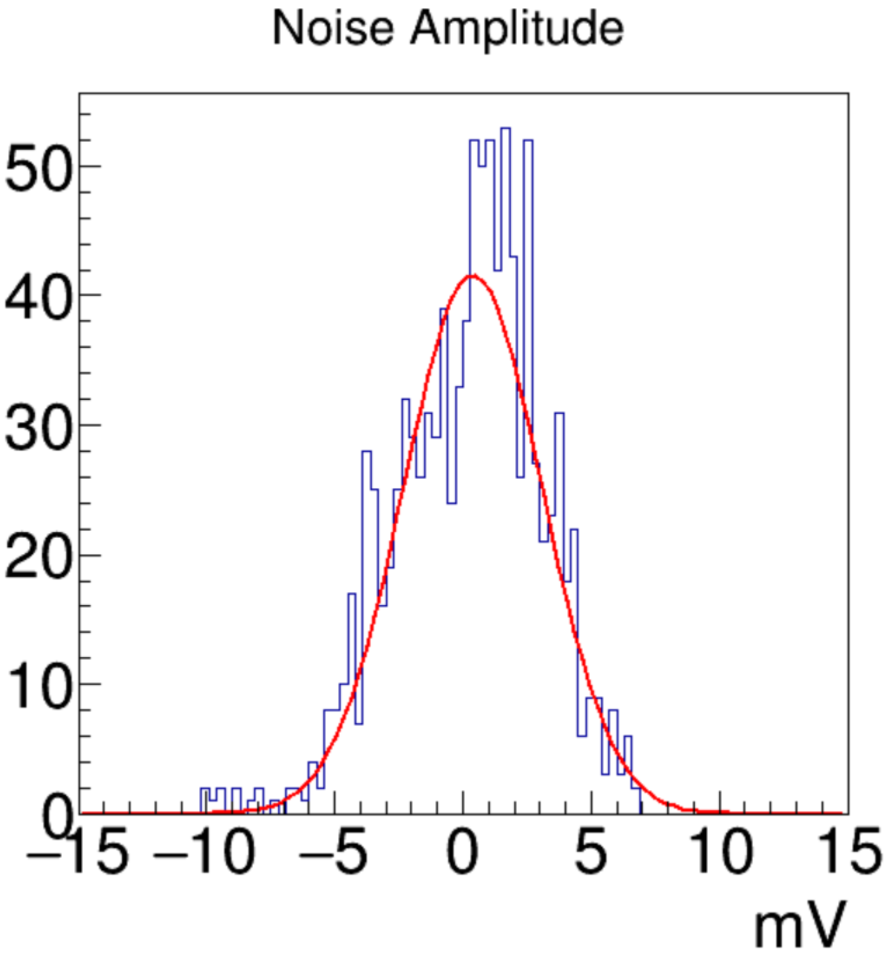
- R&D goals:
  - 2-sided 120 um PIN/LGAD fabrication (BNL LDRD)
  - Development of a new low-noise preamp electronics with a shaping time ~ 5 ns


Time Domain
0
−0.1
−0.2
−0.3
−0.4
0
5
10
Time (ns)
FAST 4 pF
FAST 6 pF
FAST 10 pF
Hype. 5 ns


Frequency Domain
60
50
40
30
20
10
0
0
0.5
1
1.5
2
Frequency (GHz)

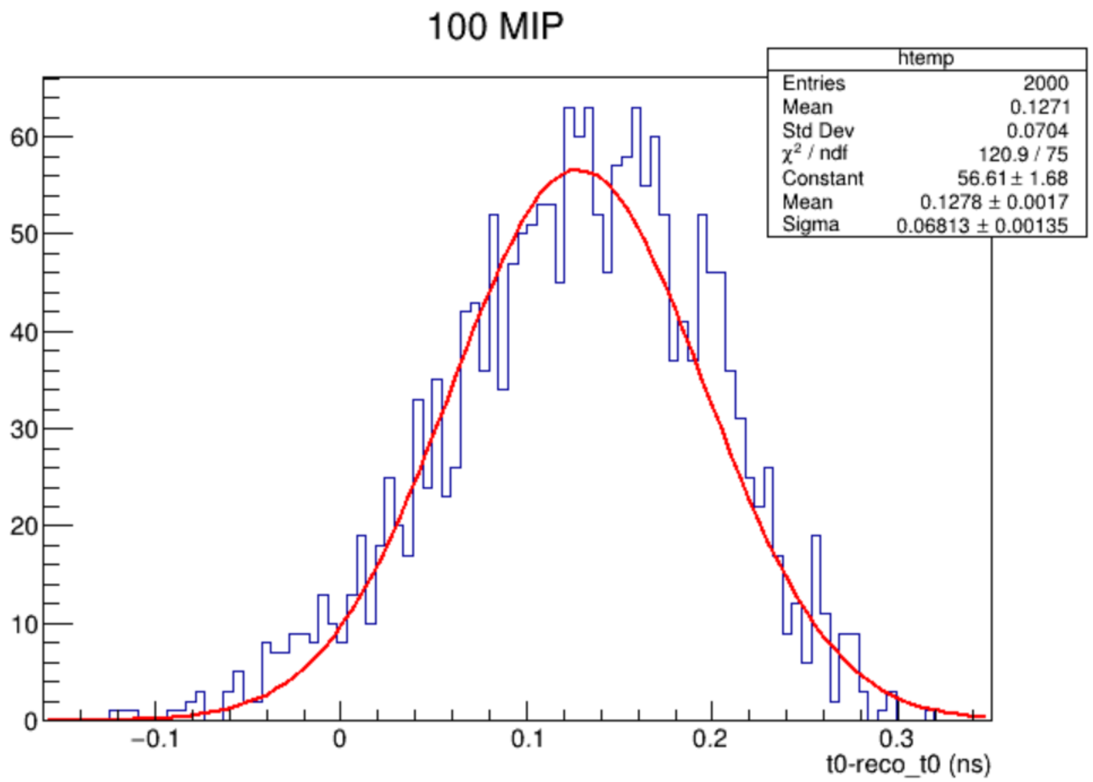
Simulated Noise (ENC ~ 860 e-)



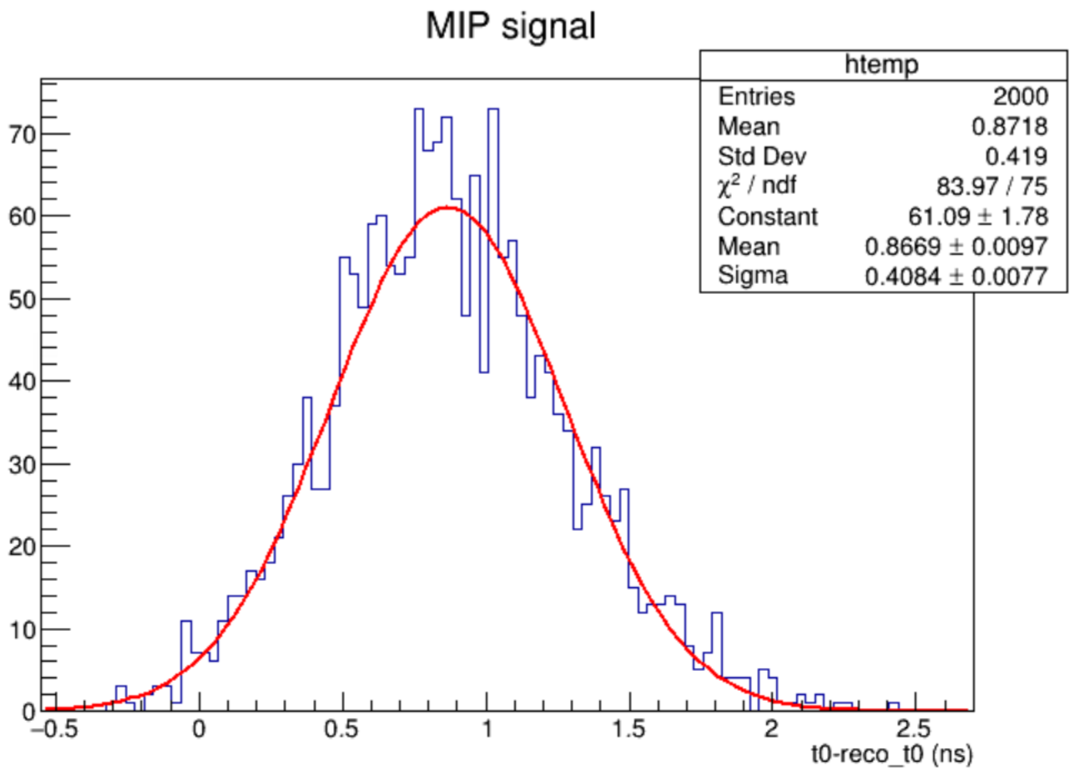


T0 resolution

100x MIP

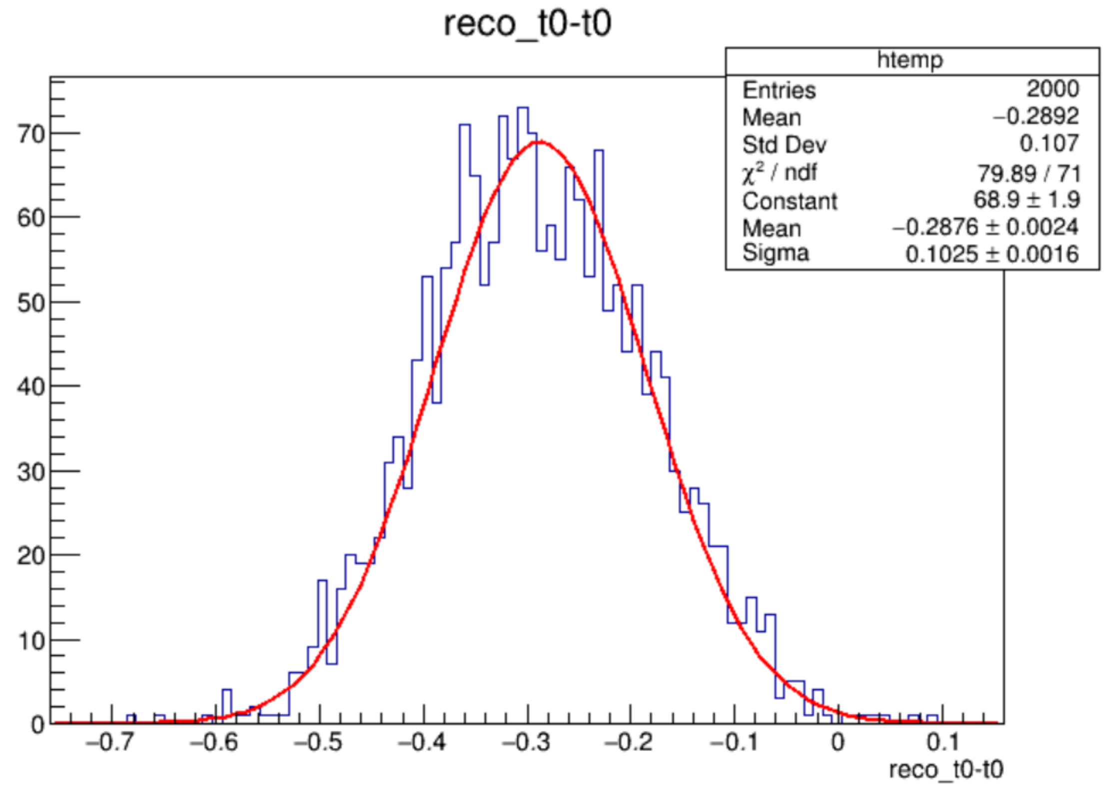


MIP

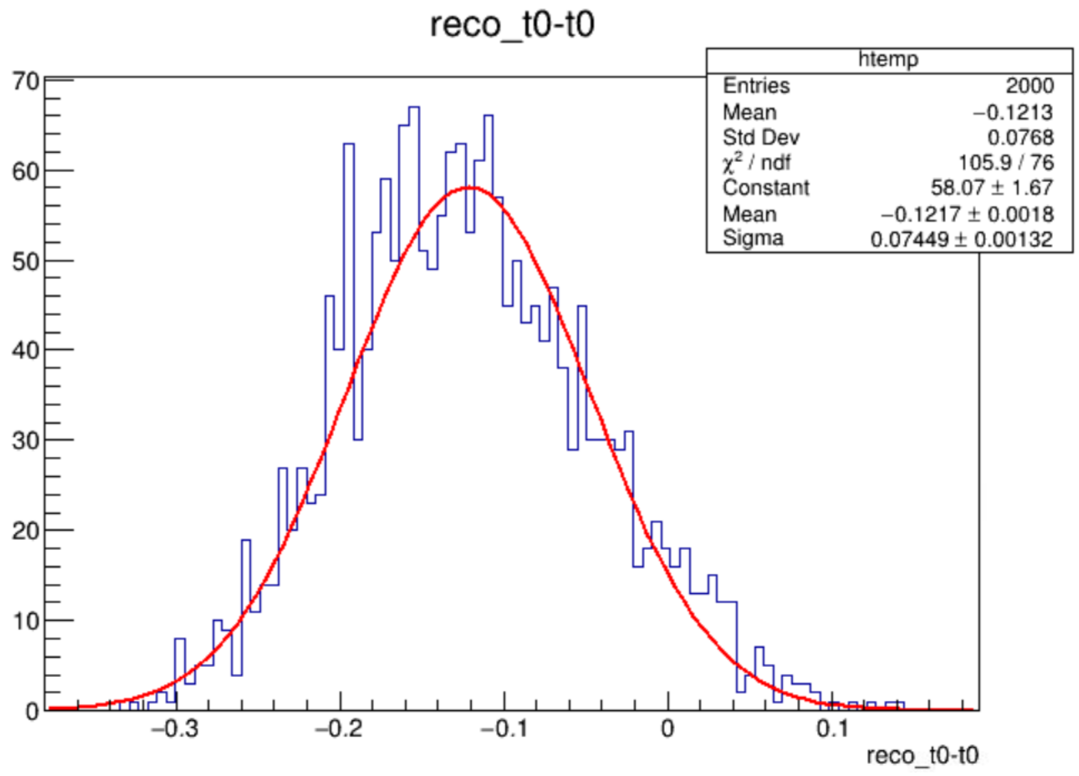


T0 resolution

10 MIP

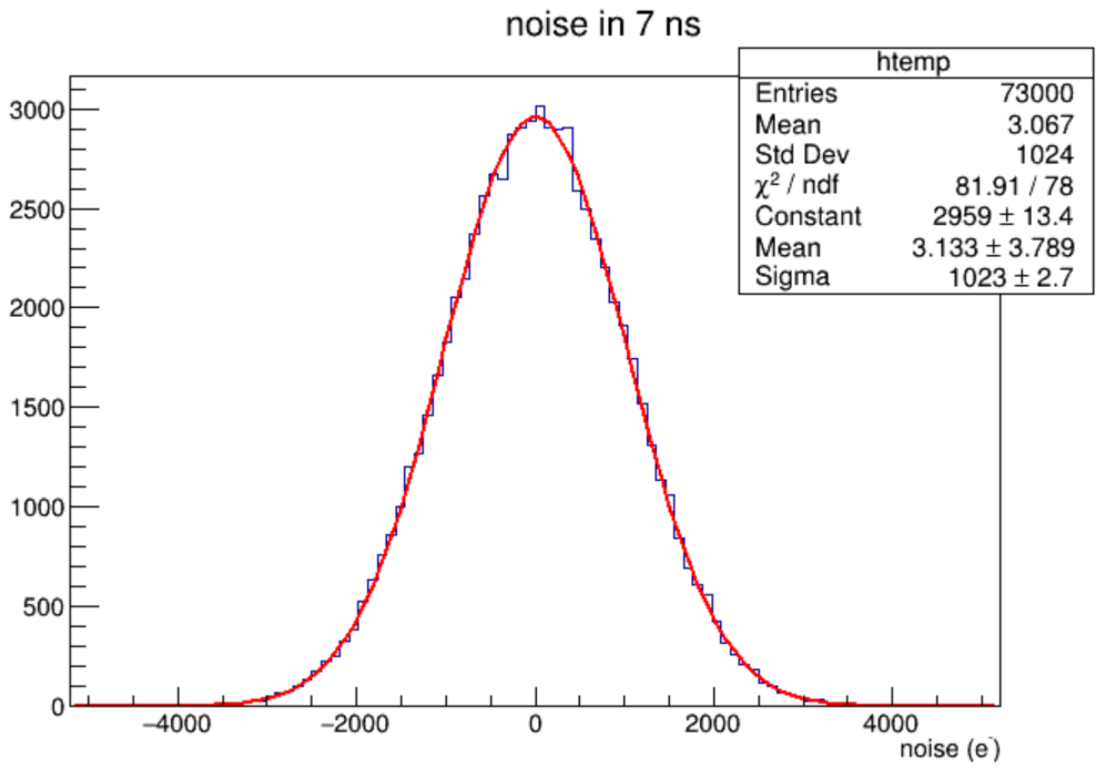


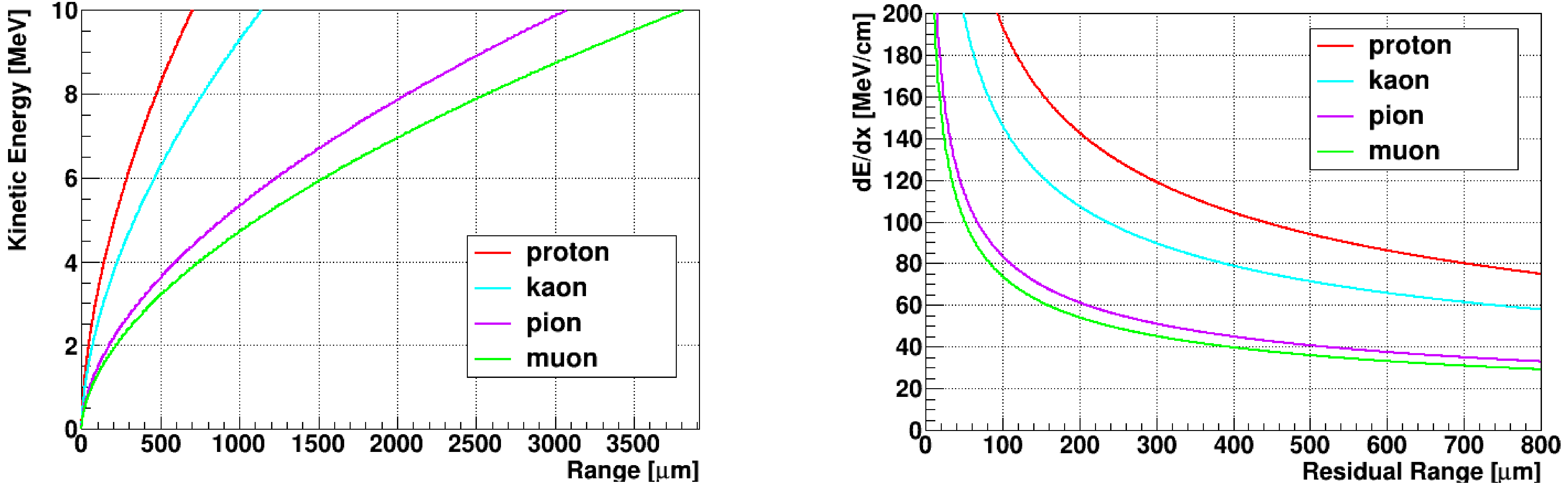
30 MIP

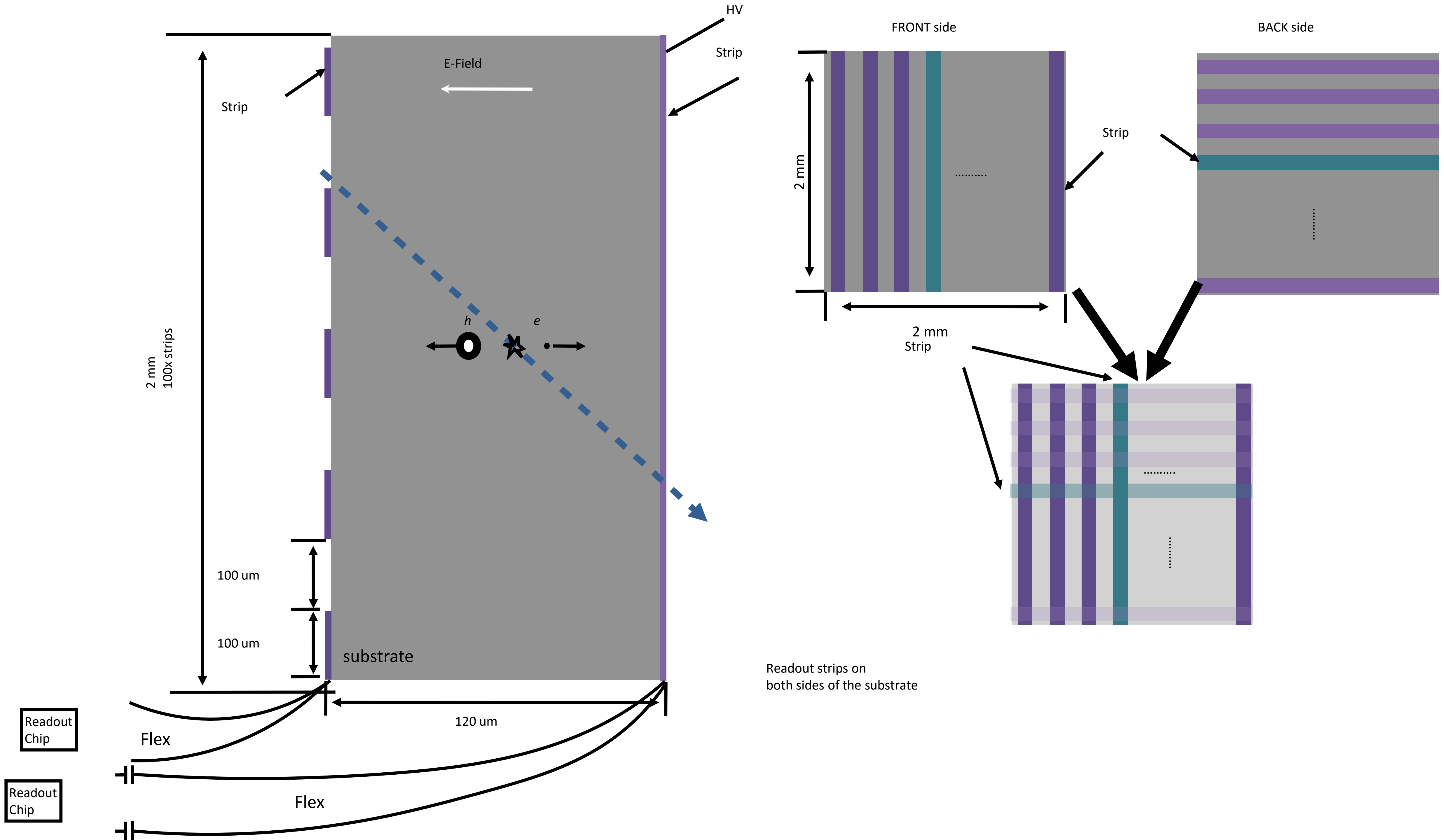


Charge Resolution (7-ns window)

- MIP
  - 13.1%
- MIP track with 50 hits
  - 1.85%
- MIPx100
  - 0.13%




Kinetic Energy [MeV]
Range [μm]
proton
kaon
pion
muon
dE/dx [MeV/cm]
Residual Range [μm]
proton
kaon
pion
muon


HV
Strip
E-Field
Strip
2 mm
100x strips
h
e
100 um
100 um
substrate
120 um
Readout Chip
Flex
Readout Chip
Flex
FRONT side
BACK side
2 mm
Strip
2 mm
Strip
Readout strips on
both sides of the substrate