ΑΡΙΣΤΟΤΕΛΕΙΟ
ΠΑΝΕΠΙΣΤΗΜΙΟ
ΘΕΣΣΑΛΟΝΙΚΗΣ

Development of a Simulation Model and Precise Timing Techniques for PICOSEC-MicroMegas Detectors

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Outline

PICOSEC-MicroMegas Detector and its Performance

Alternative Timing Techniques

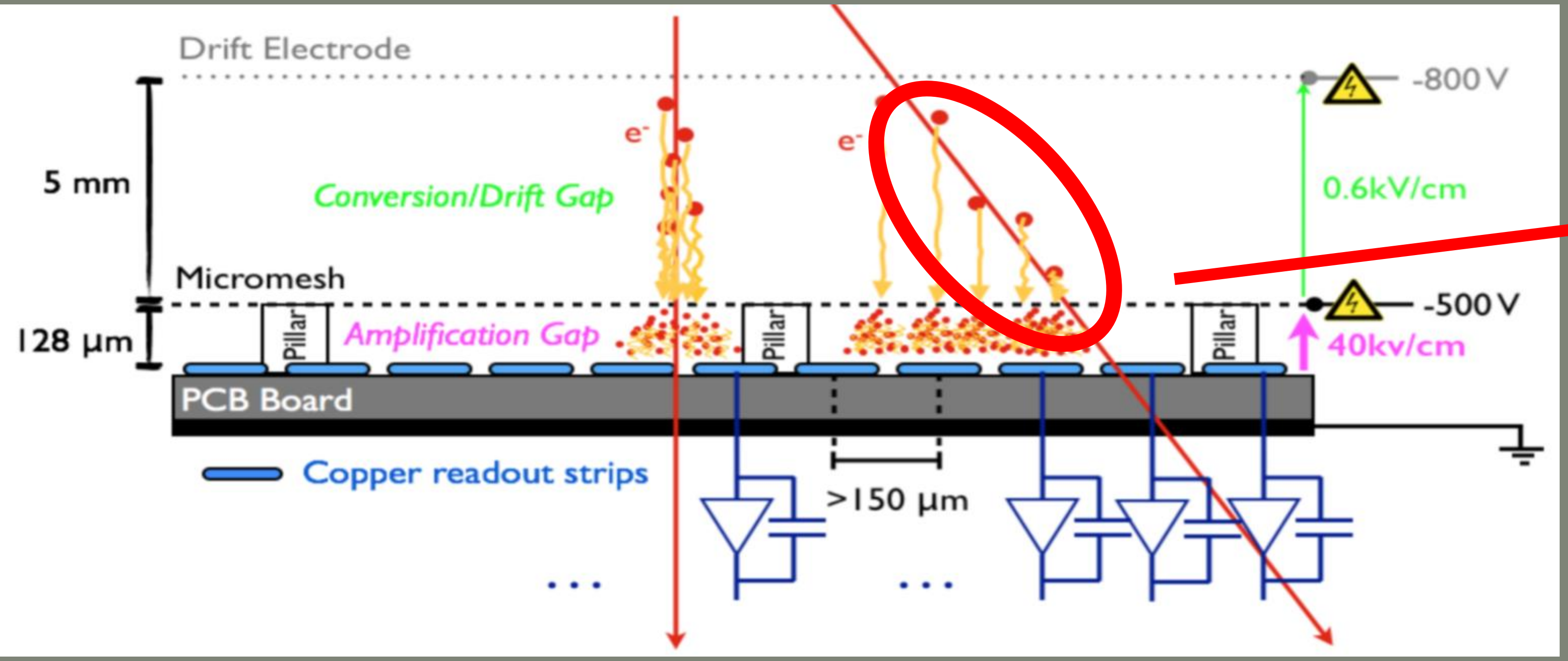
A Simulation Model to train Artificial Neural Networks for Precise Timing

Concluding Remarks

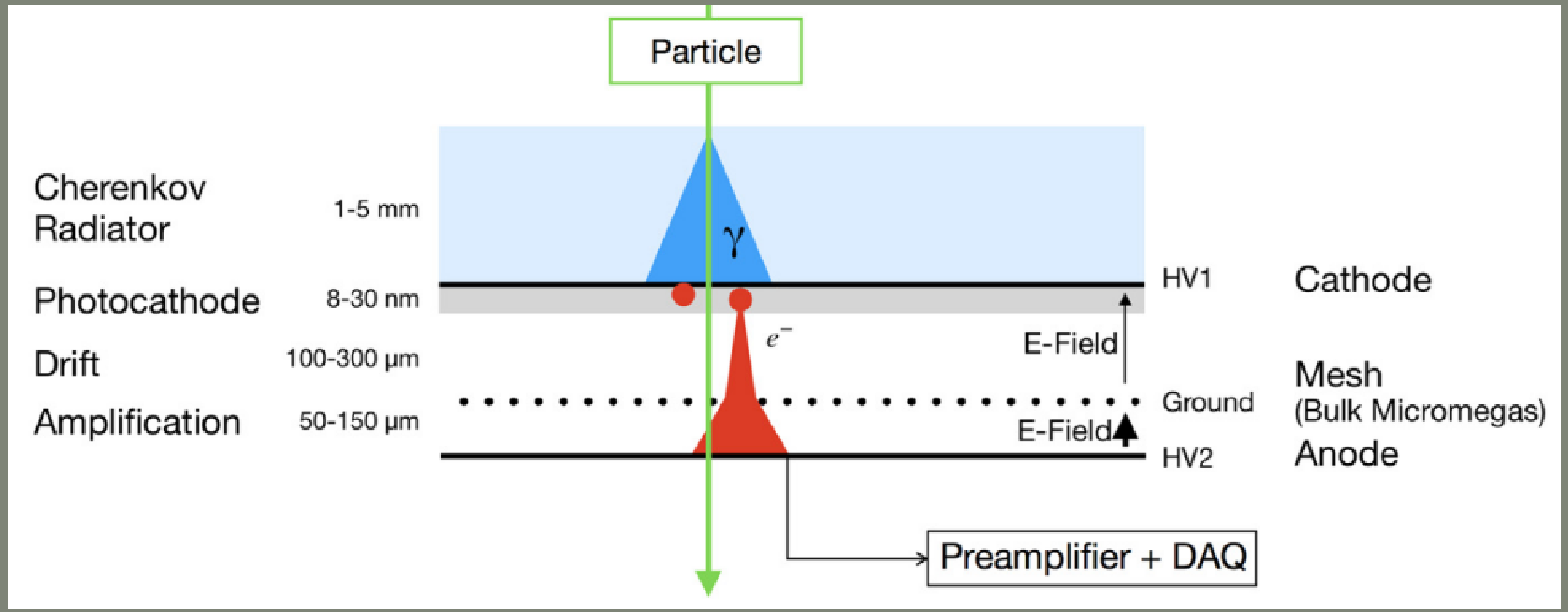
The PICOSEC-MicroMegas Detector

and its performance

Timing with MicroMegas Detectors



https://doi.org/10.1016/S0168-9002(97)00648-7



https://doi.org/10.1016/j.nima.2018.04.033

- Limitations of the MicroMegas Timing Potential
  - Stochastic nature of ionization
  - Randomness of the last ionization
  - Time jitter of a few ns

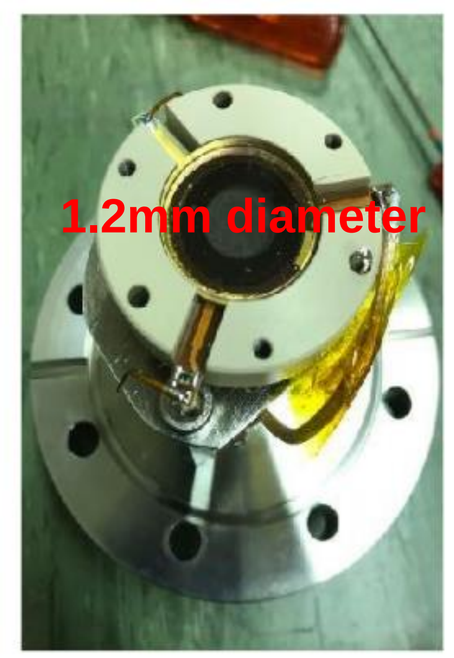
- The PICOSEC- Concept
  - Timing with tens of picosecond precision

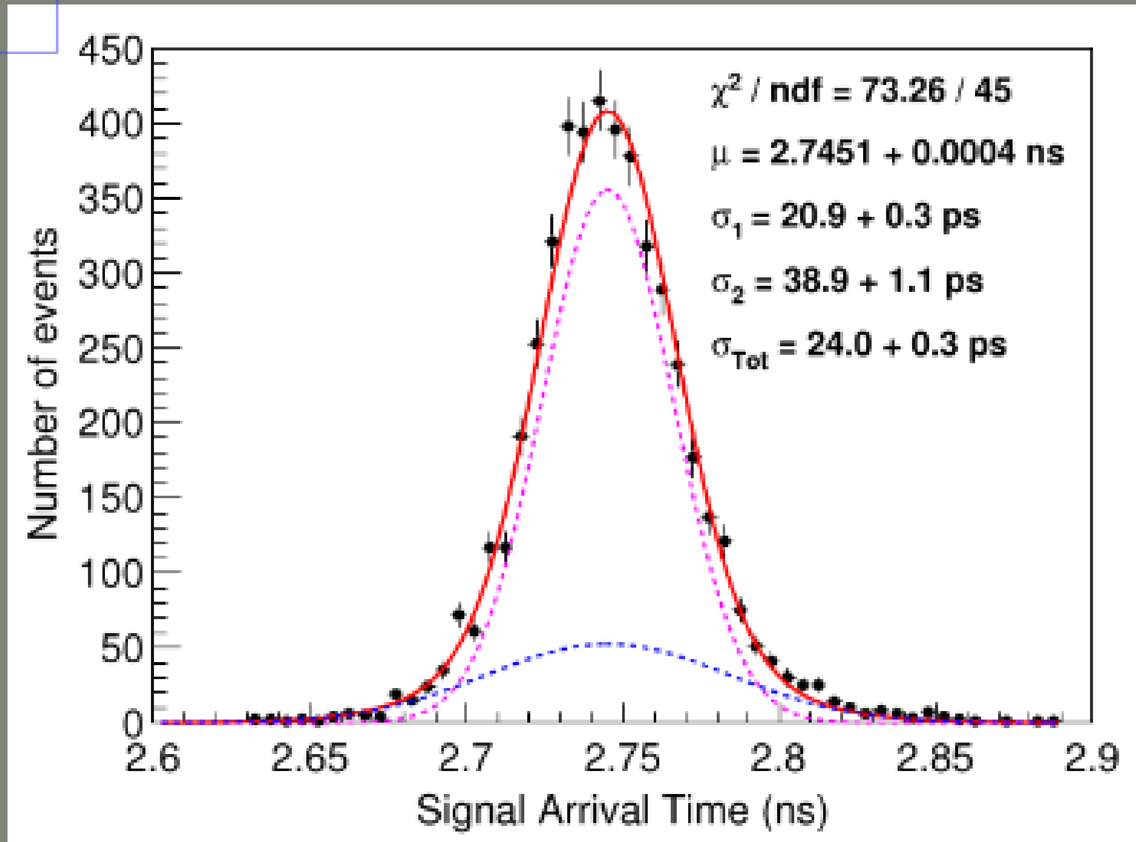
- Modifications of the MicroMegas geometry
  - Smaller conversion Gap (from 3mm to 200μm)
  - Elimination of the stochastic nature of ionization
  - Higher applied Drift Voltage-Preavalanche

- Additions to the classical MicroMegas
  - Cherenkov radiator
  - Photocathode, instead of simple cathode
  - Prompt photoelectrons

https://doi.org/10.1063/1.5091210

SinglePad

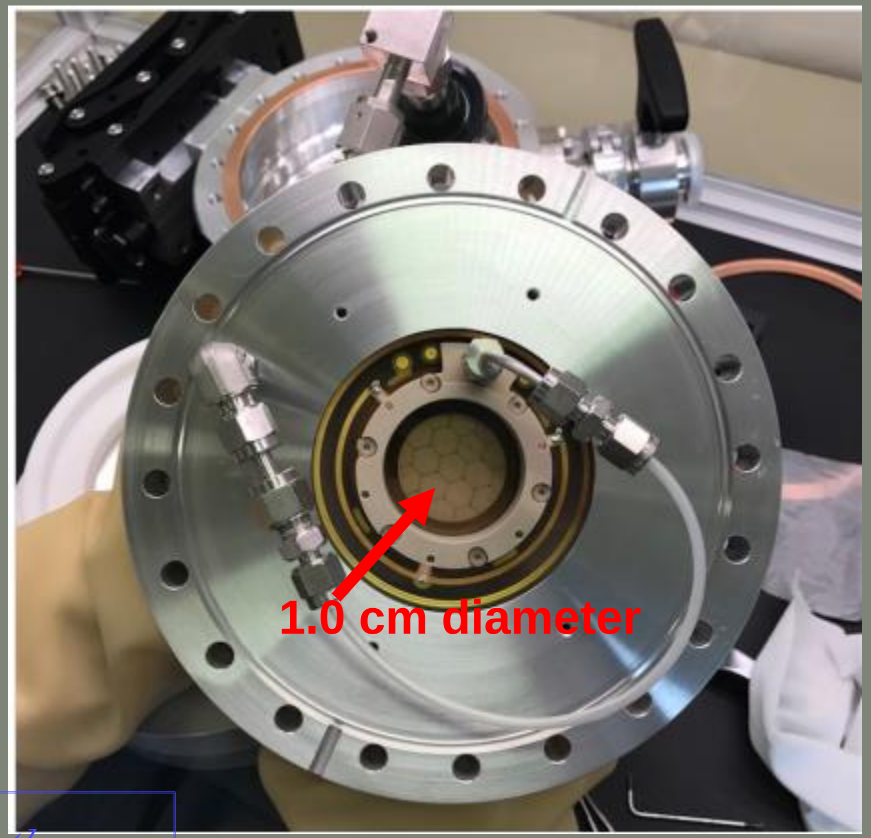


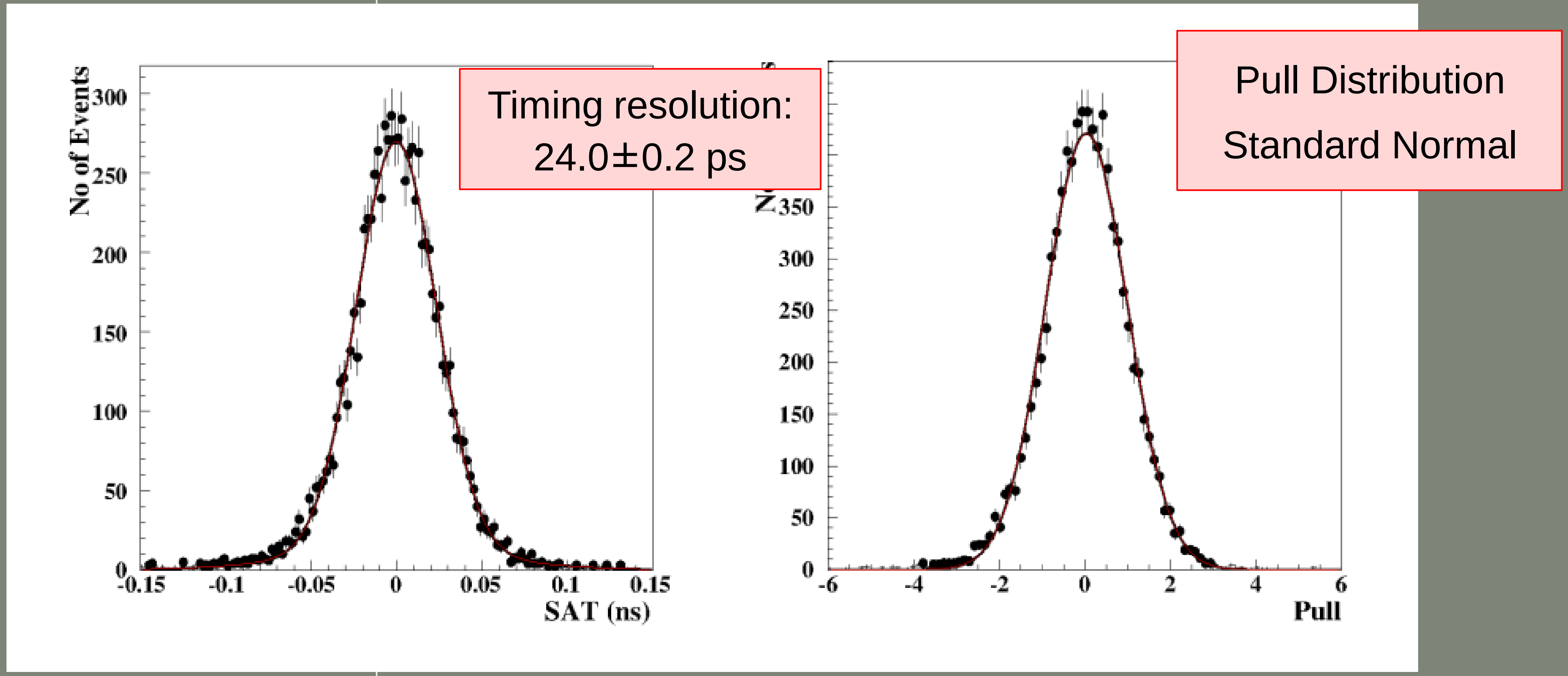


- PICOSEC Prototype
  - Test Beam with Muons of 150GeV
  - ~ 10 photoelectrons per track
  - Detailed studies resulted to Signal Arrival Time Distribution of 24.0 ± 0.3 ps fitted with Double Gaussian

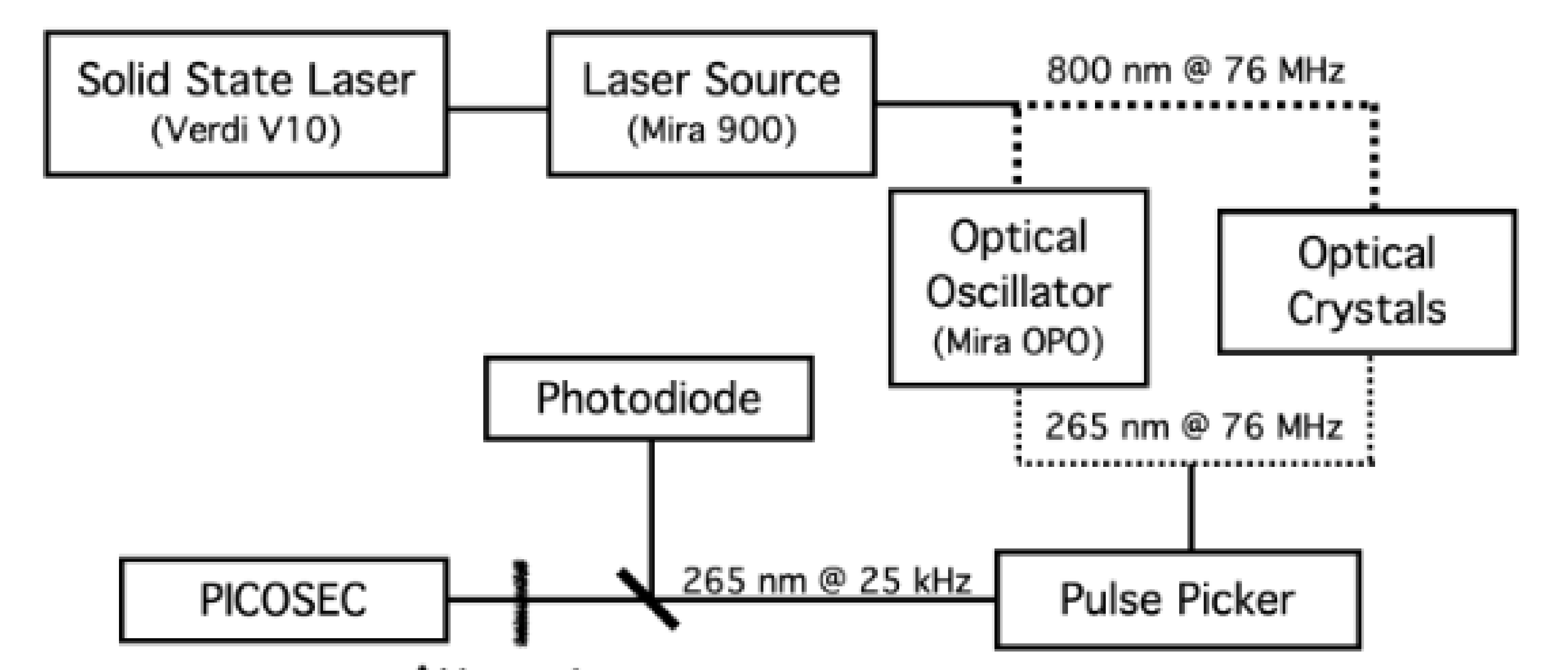
  - SAT → Signal Arrival Time
  - Timing Resolution → RMS of SAT distribution

Multipad





arXiv:1806.04395v1 [physics.ins-det]



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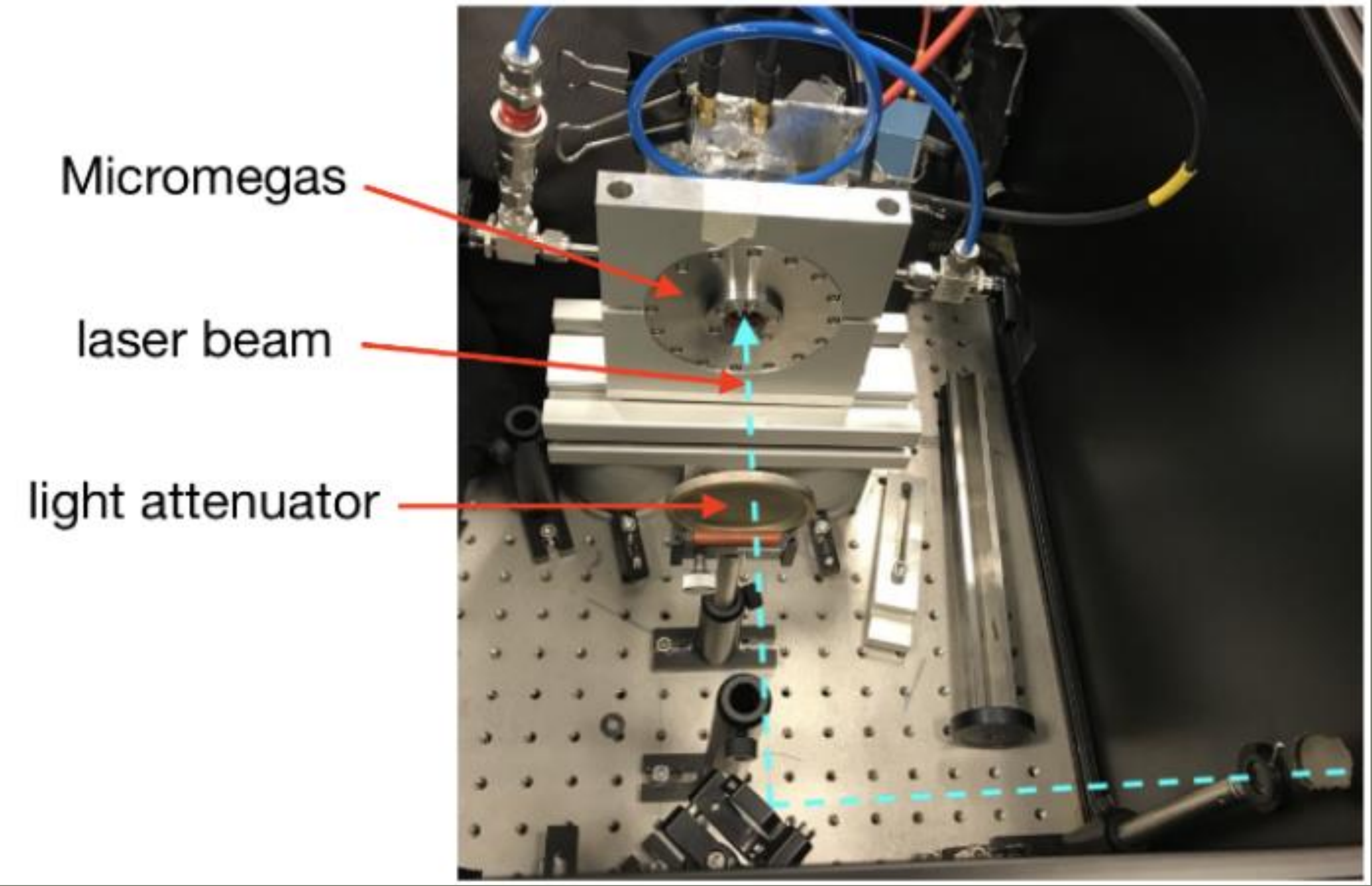


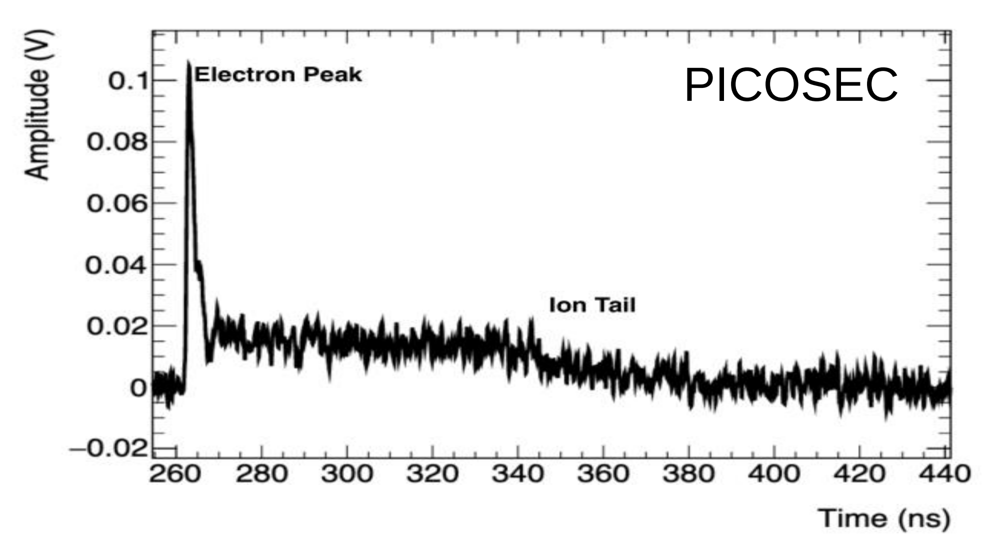
- First investigation of timing response
- Laser Beam Test (IRAMIS/SLIC, CEA Saclay)
- UV laser light
- Ultra short pulses with duration of a few ps το 120 fs

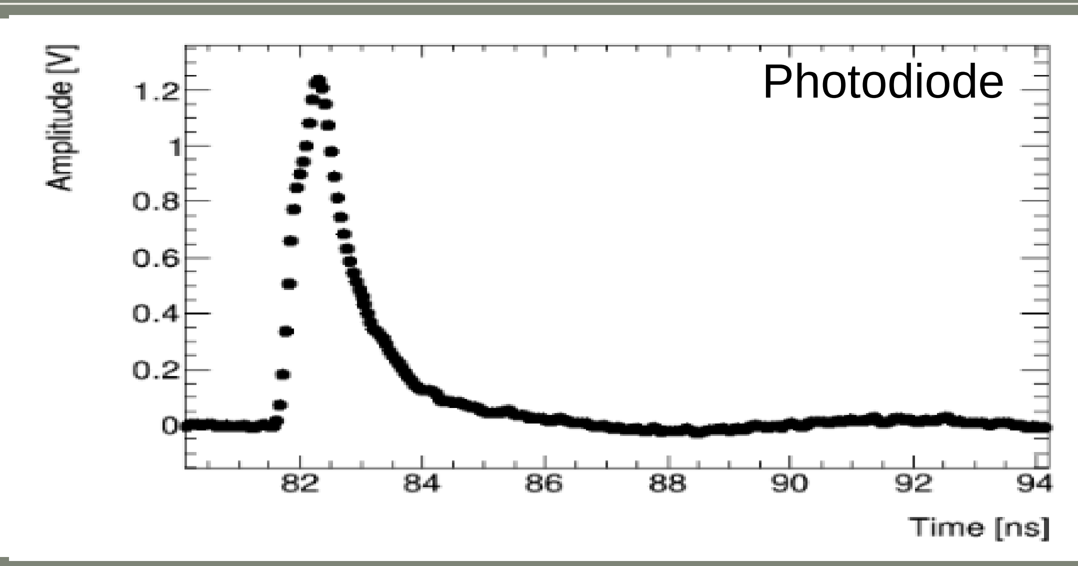
- Beam adjusted to 265nm
- Pulse Picker to adjust the repetition rate

- The beam is split between a PD0 and PICOSEC-MM
- Attenuator filters to control number of photoelectrons
- 2 Data-Set collected
  - SPE-set (single photoelectrons) & EXP-set (multi-photoelectrons)

PICOSEC-MM with a reduced gap of 119μm
CsI photocathode deposited on Al layer
1cm diameter

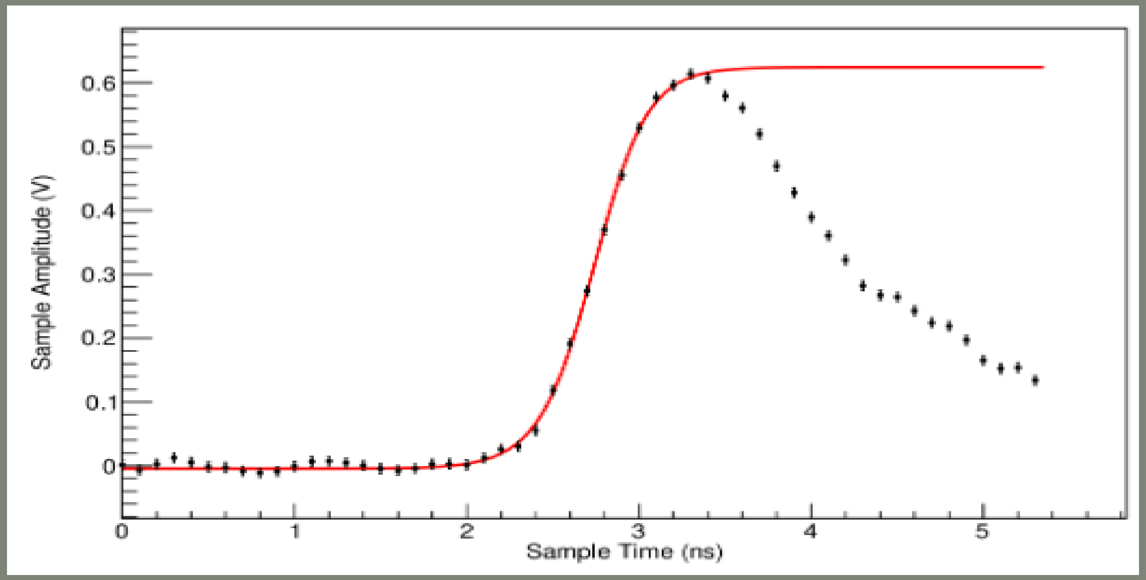
The Standard Constant Fraction Discrimination Technique (CFD)



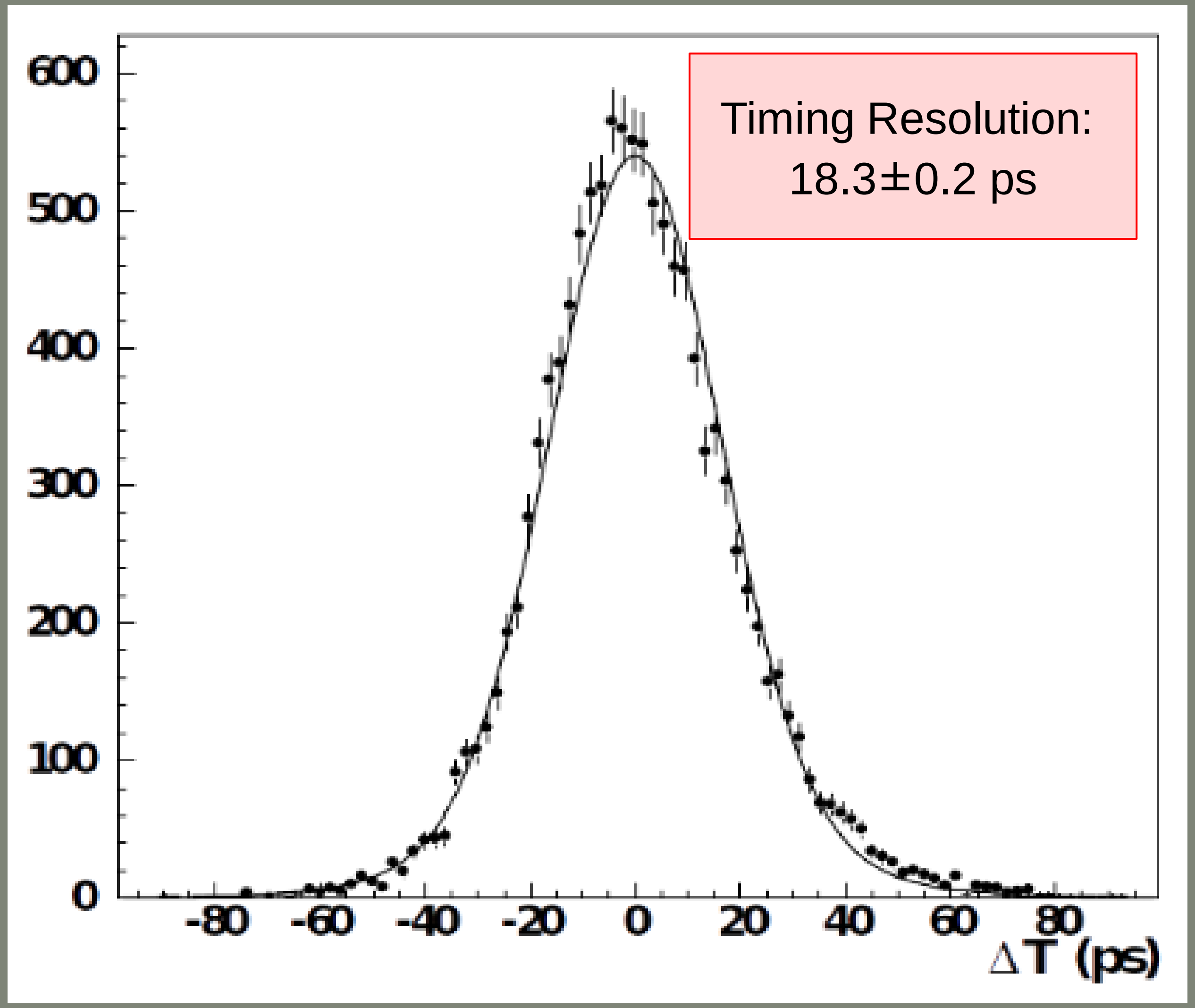


- Analysis of the EXP-set
- Adjust a curve to the experimental data
  → fitting the leading edge of
  the waveform with a logistic function

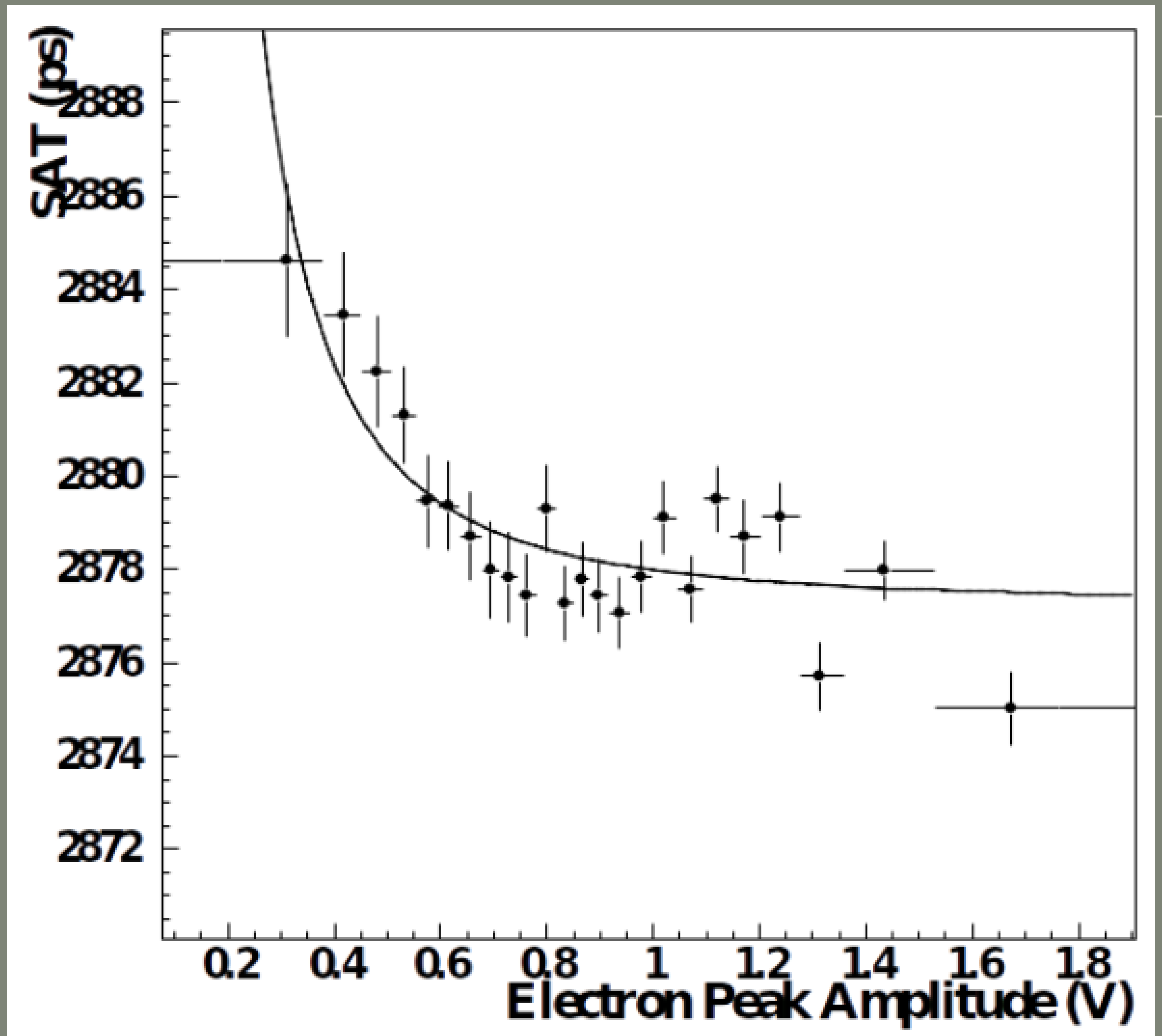
$$f(x; p_0, p_1, p_2, p_3) = V(t) = p_3 + \frac{p_0}{1 + e^{-(x-p_1)p_2}}$$



- Timing at 20% of peak amplitude both
  for the PD0 and PICOSEC signals



- Subtract the PICOSEC signal from the PD0 signal
- Create Calibration curves
- Correct for dynamical errors
- Timing resolution 18.3 ±0.2 ps



- In principle, CFD method DOES NOT suffer from time walk effect
- However, we observe a dependence of the SAT on the signal amplitude

- Its origin has nothing to do with the offline analysis procedure
- Results from the microscopic behavior of the avalanche and the fact that its photoelectrons drift with different velocity than the avalanche in total

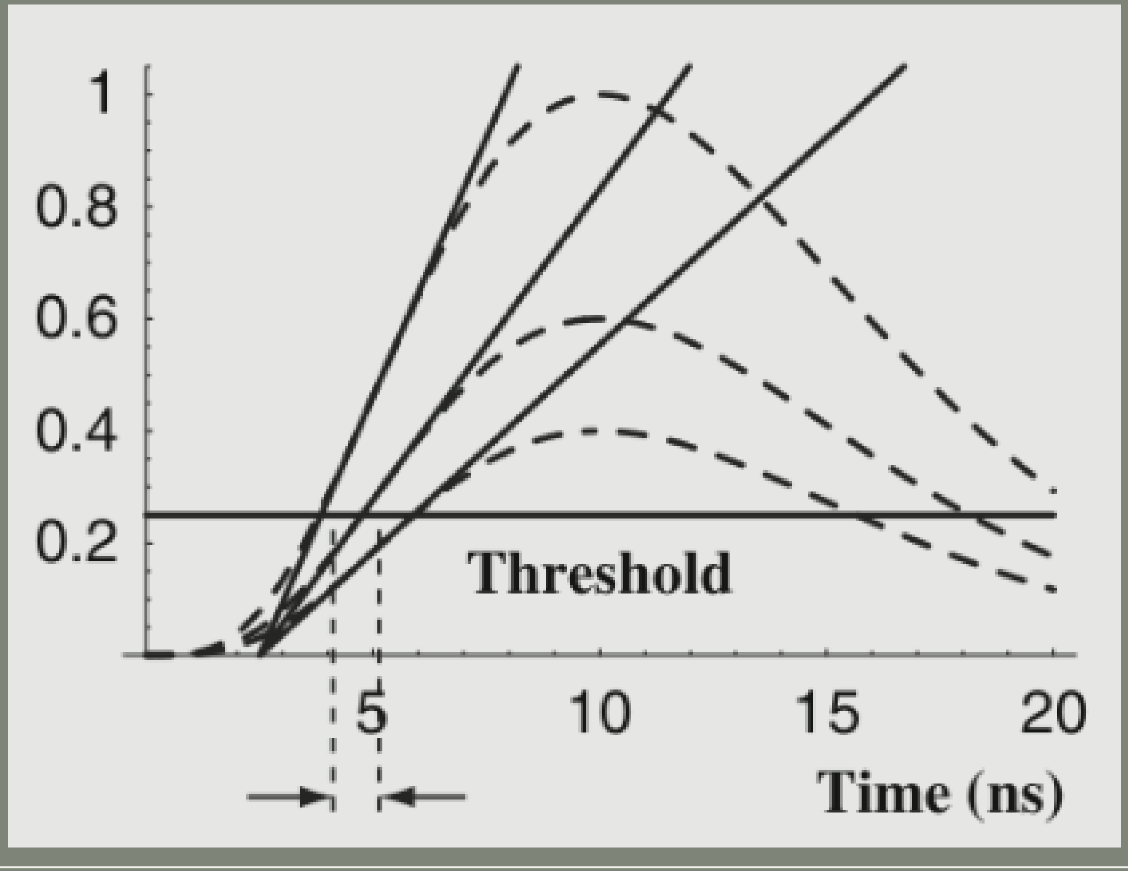
https://doi.org/10.1016/j.nima.2021.165049

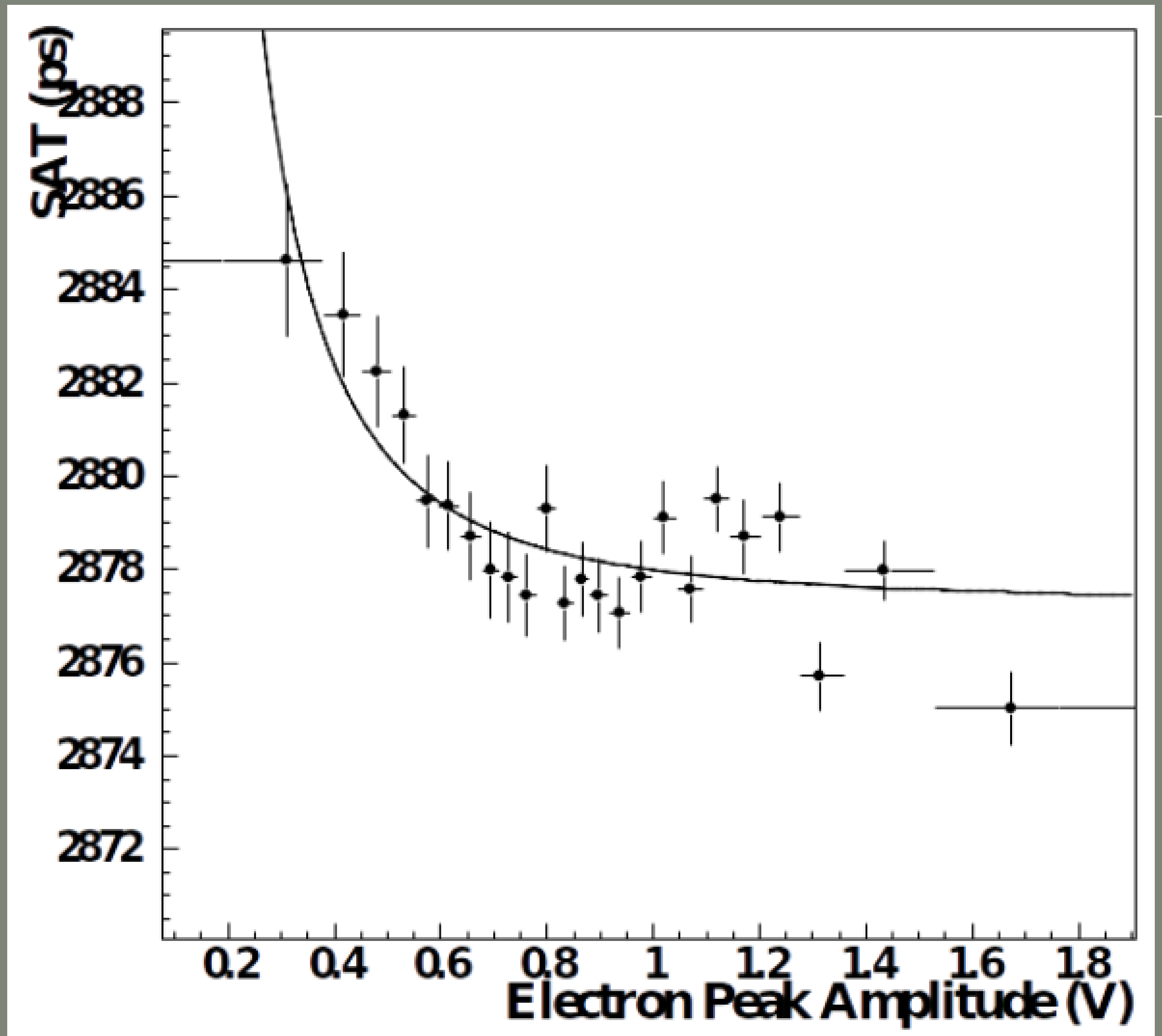
- Calibration curve $$g(x; a, b, w) = a + \frac{b}{x^w}$$

- Correction $$\text{Corrected SAT} = \text{SAT} - \frac{a}{(\text{Pulse Amplitude})^b} + c$$

Walter Blum, Werner Riegler, and Luigi Rolandi. Particle Detection with Drift Chambers. Springer-Verlag Berlin Heidelberg, 2008

- **Constant Threshold Timing suffers from Time Walk Effect**
  - Realistic case
  - Higher pulses arrive earlier
  - Dependence between timing and amplitude size
- The effect can be corrected on the off-line analysis





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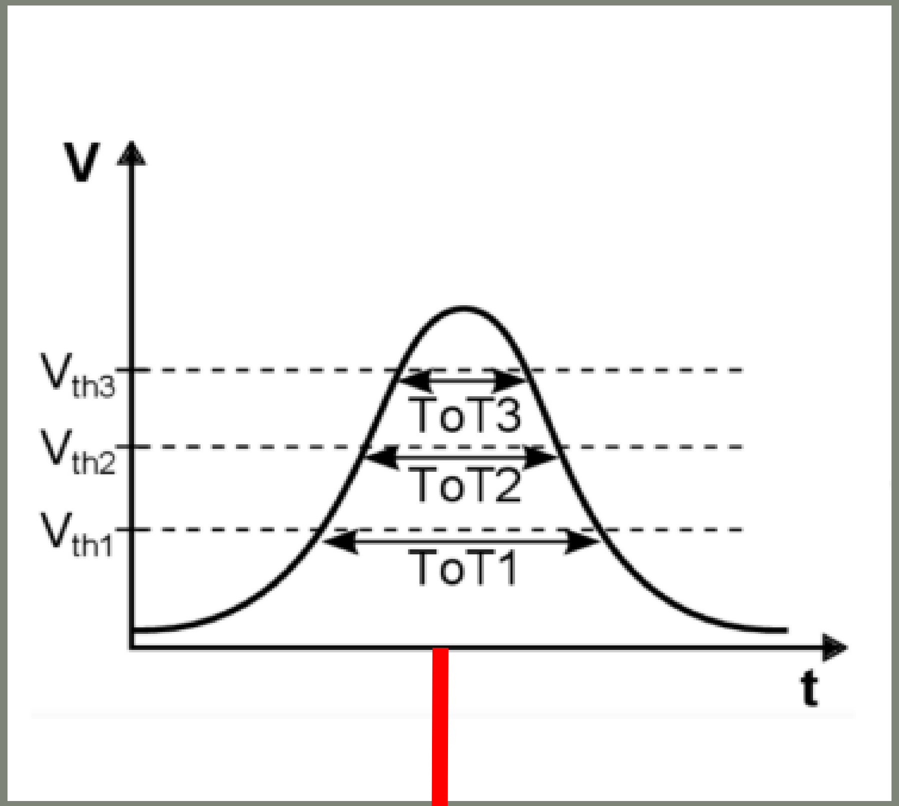
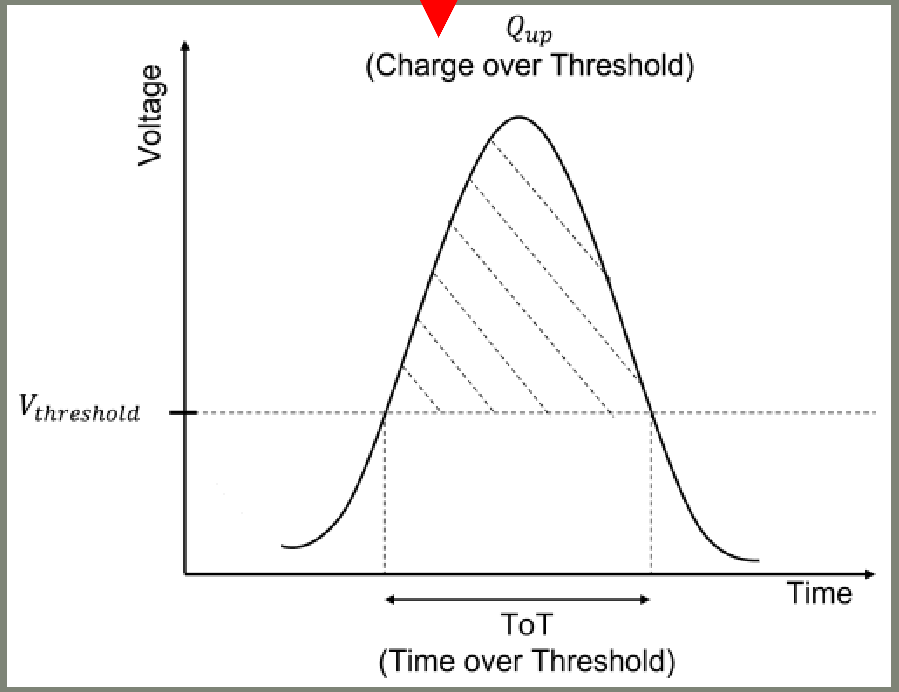
Alternative Timing Techniques

We aim to use existing electronics and if possible to have the timing information on real-time

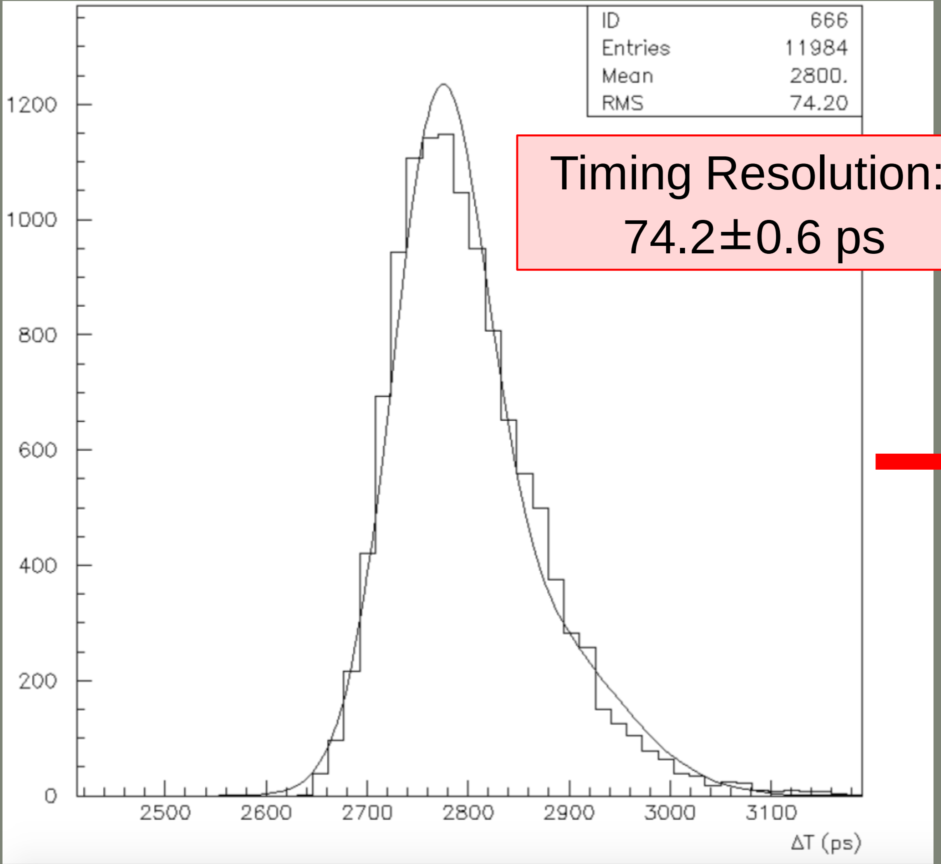
- **Constant Threshold Discrimination**
  - Take advantage of existing electronic devices:
    - NINO and NINO-2-chips – ToT information
      - Does not give precise timing resolution without extra corrections

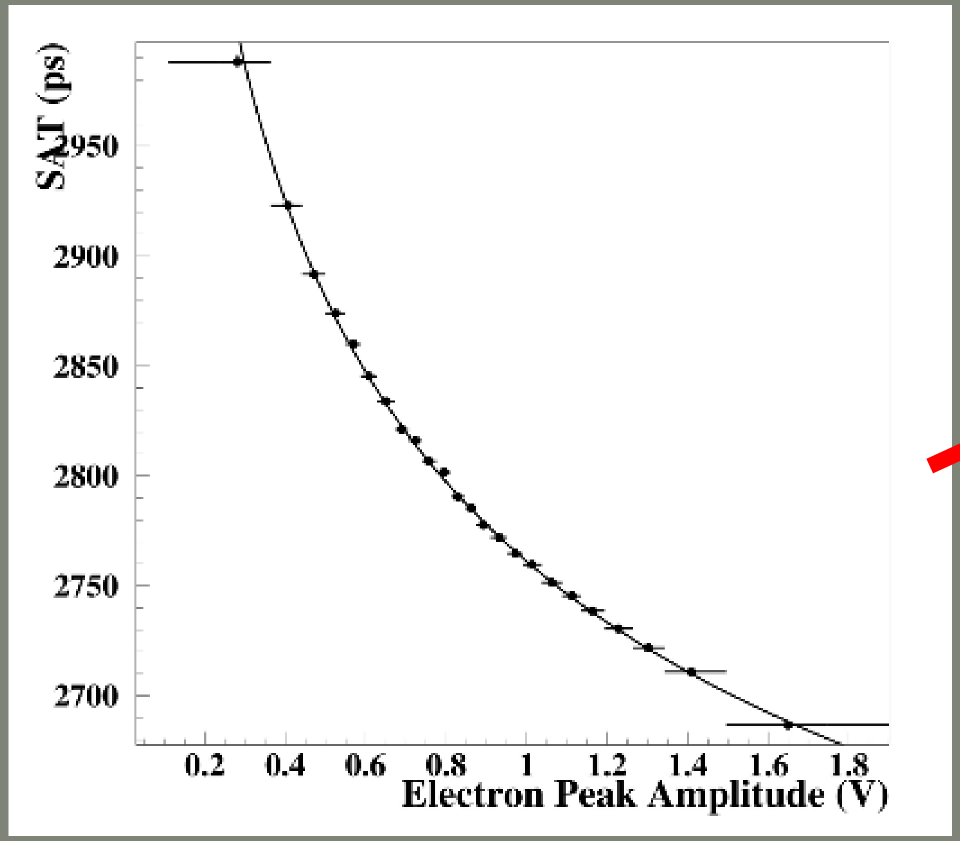


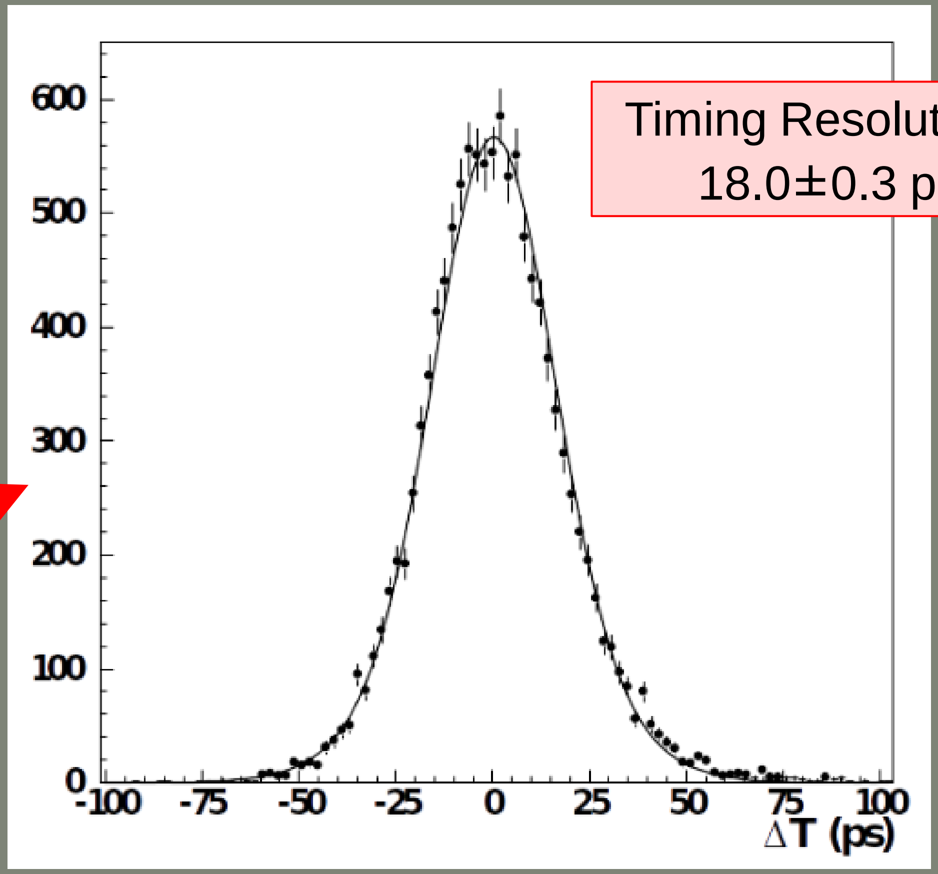
- **Multi-Charge over Threshold**
  - Use additional ADC devices
  - Single information the charge of the peak amplitude
  - Suffer from time walk effect

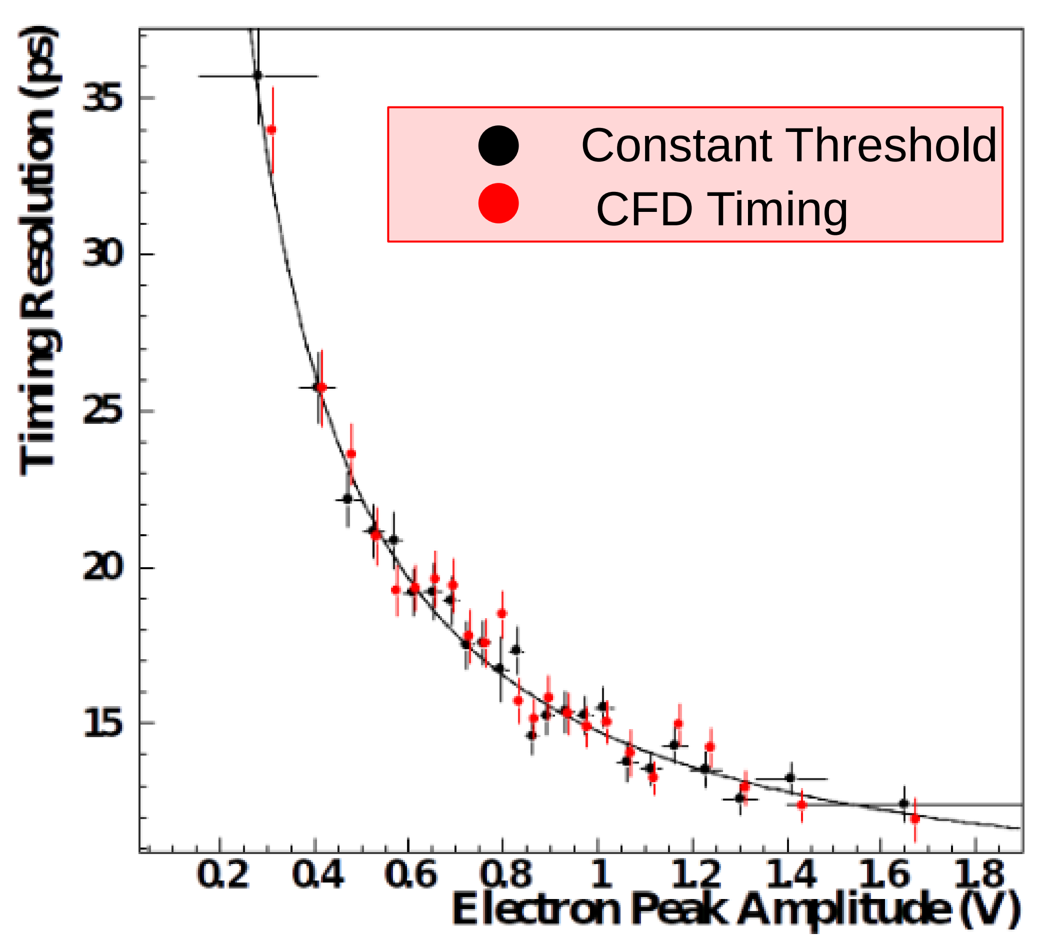


- **Signal Processing Algorithm Procedure**
- SAT defied at constant threshold of 100mV(timing)





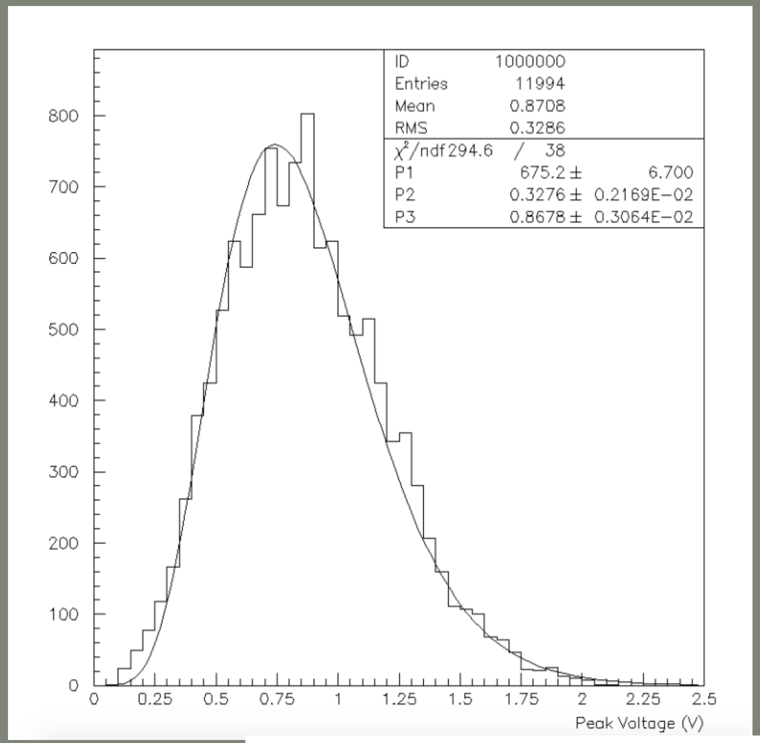


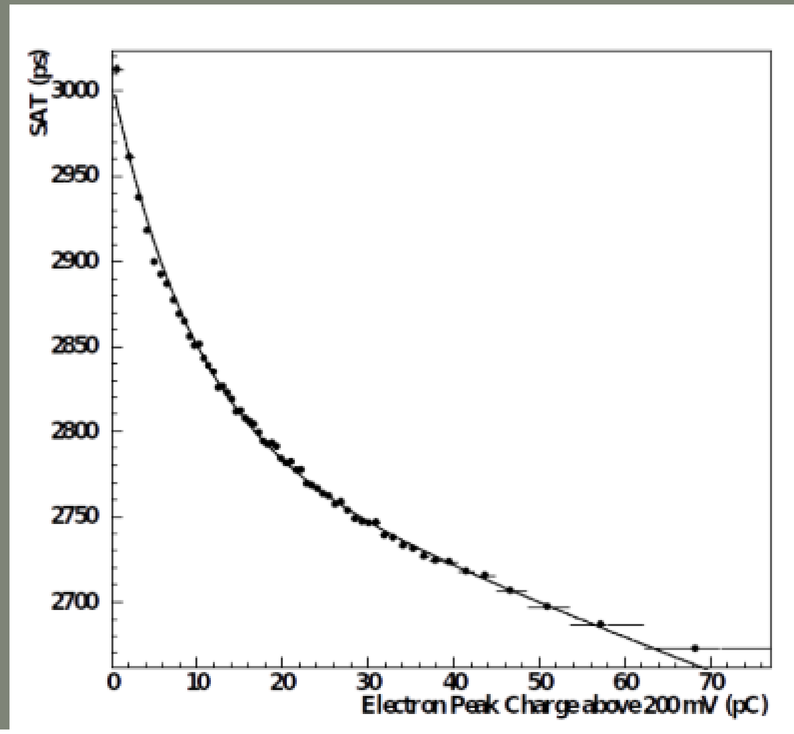


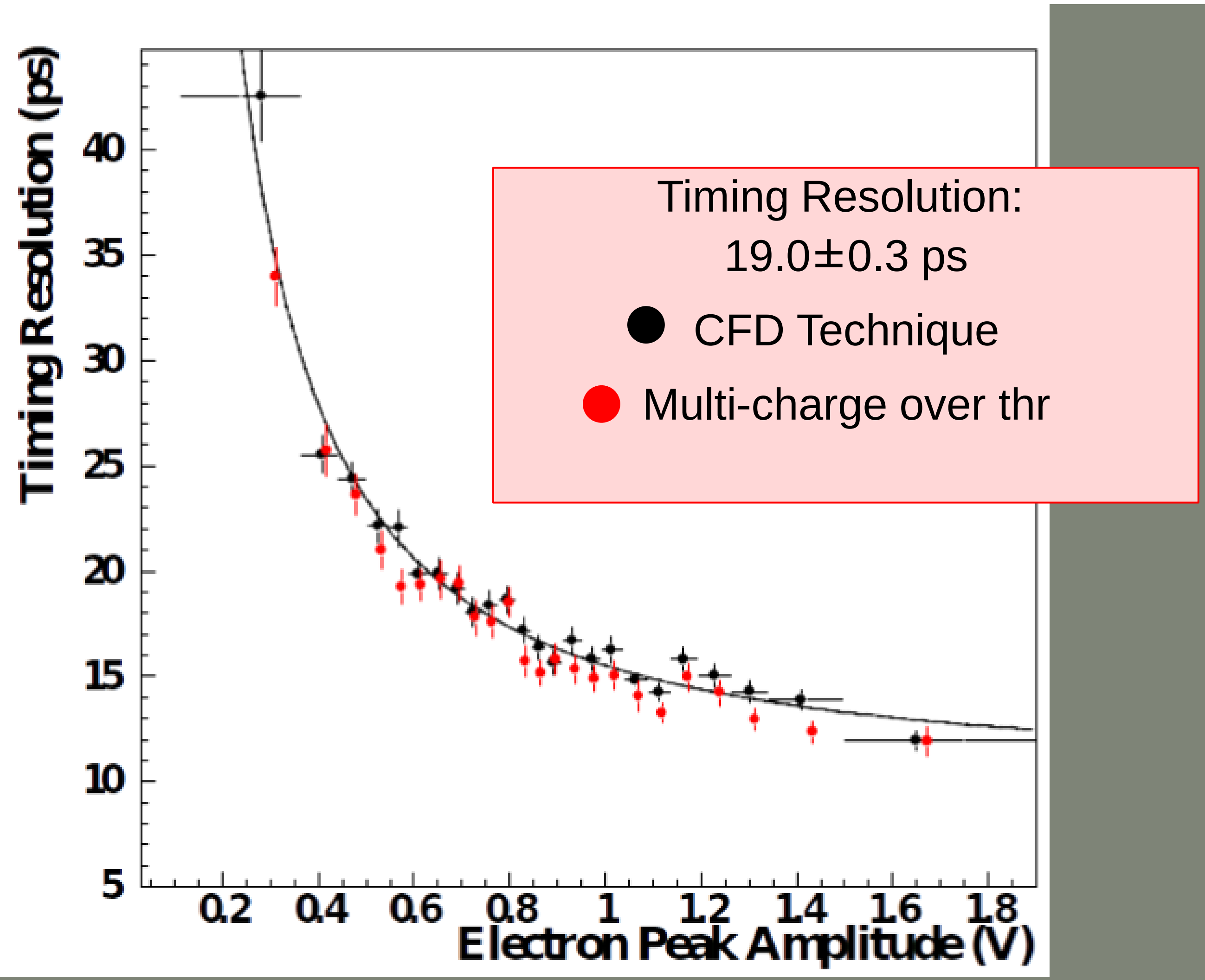
- Highly asymmetric Distribution
- Revealing time walk systematical error
- Create calibration curves for SAT corrections using **peak amplitude** as a parameter
- Comparison of CFD and Constant Threshold

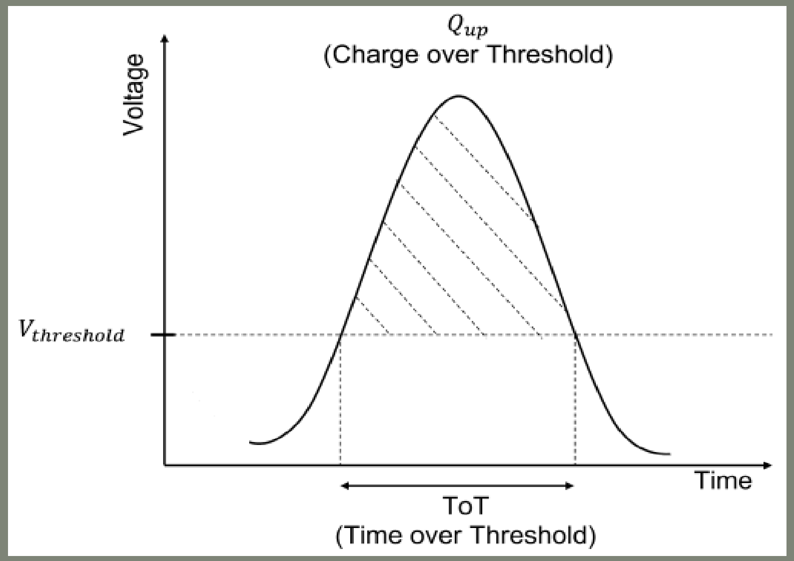
- **Signal Processing Algorithm Procedure**
- SAT defied at the constant threshold of 100mV (timing)
- Using multiple higher thresholds 200mV, 400mV, 600mV
- Alternative method of peak size estimation
- Create calibration curves for SAT corrections

  using **charges above thresholds** as a parameter
- Correct for time walk effects in the higher crossing threshold
- Comparison of CFD and multi-Charge over Threshold timing resolution
- Reaching the same timing resolution of 19.0 ± 0.3 ps



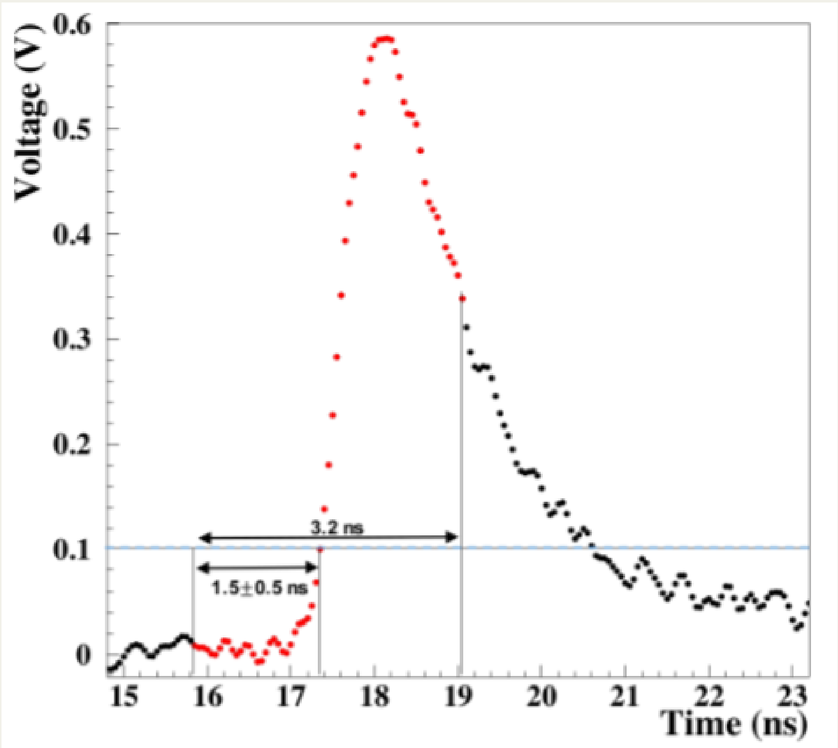






Timing using the digitized leading edge of the pulse and Artificial Neural Networks

e.g. feasibility test for the SAMPIC digitizer



- **Architecture**
  - Feed Forward Neural Network
  - One Input layer
  - Two hidden layers with 64 neurons each
  - Output layer
  - Activation function ReLU for all nodes
  - Cost function → mean squared error

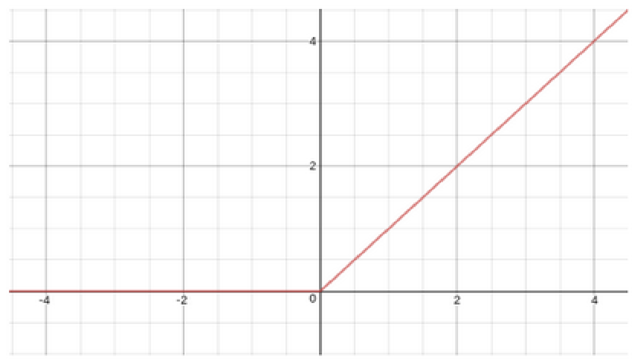
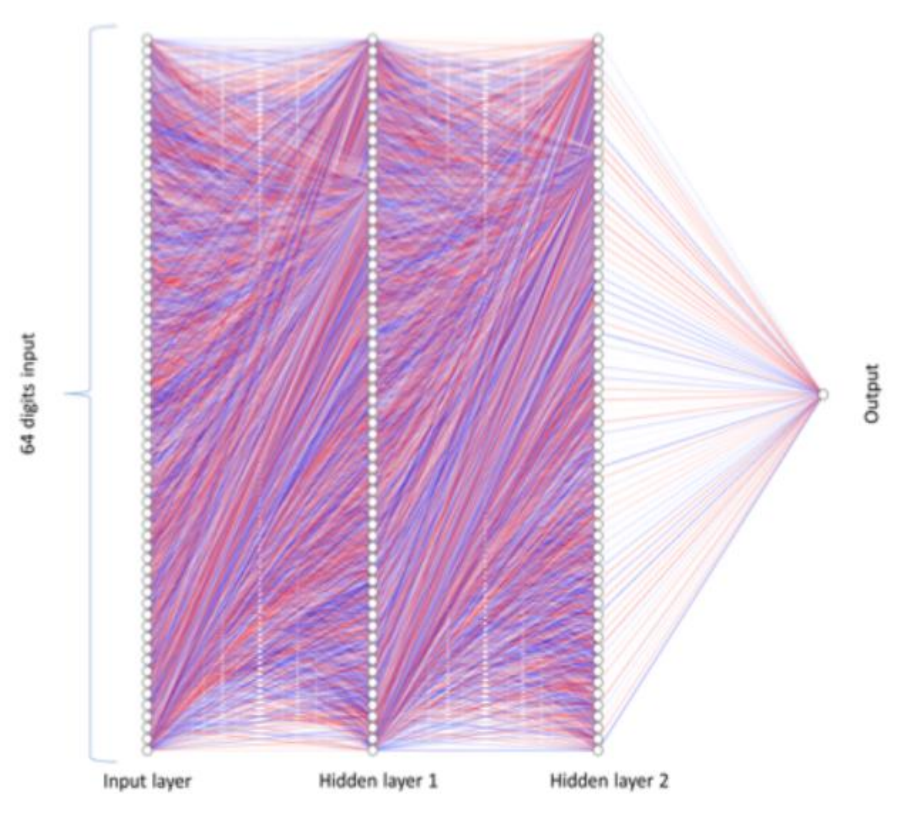
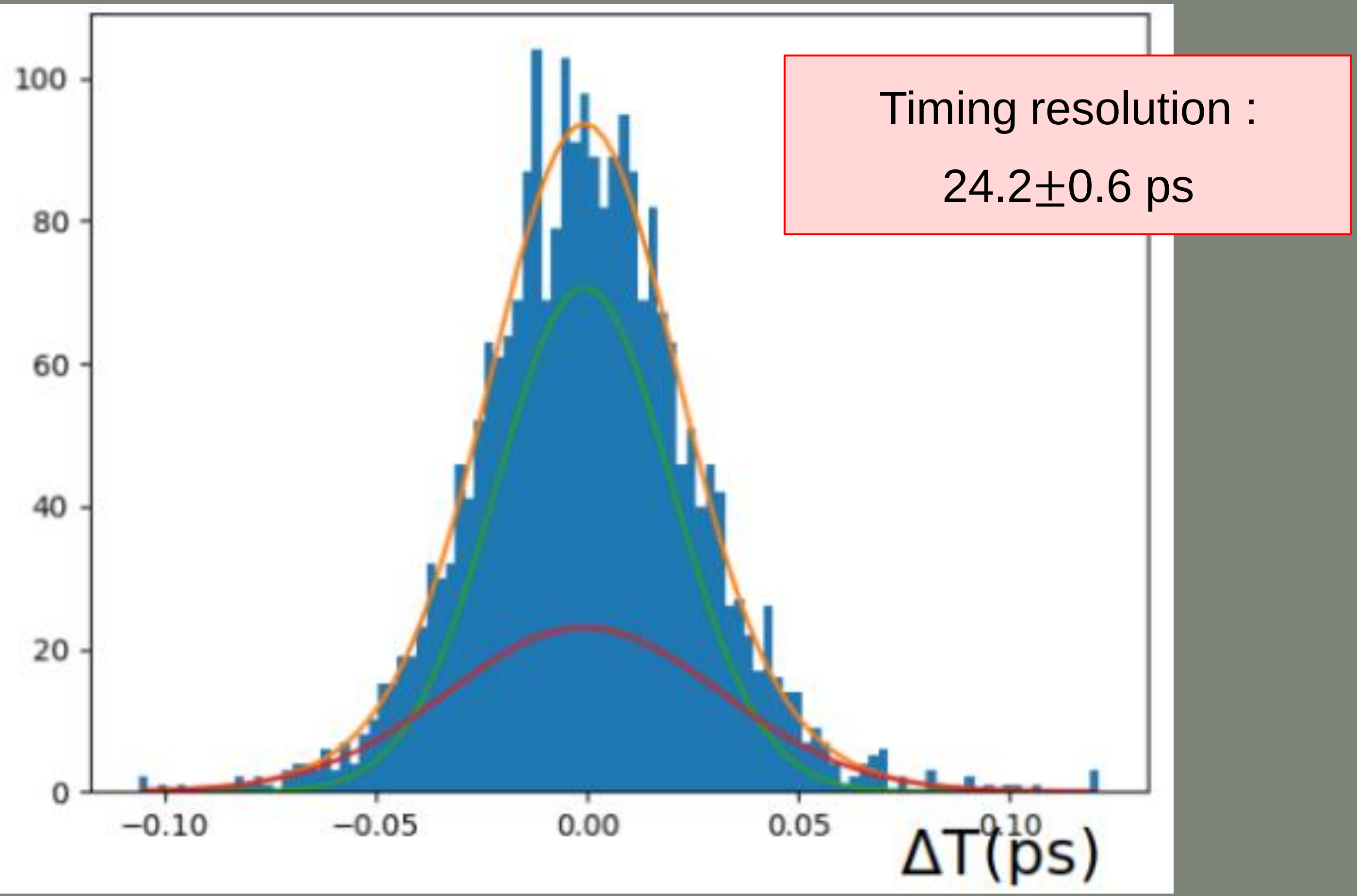


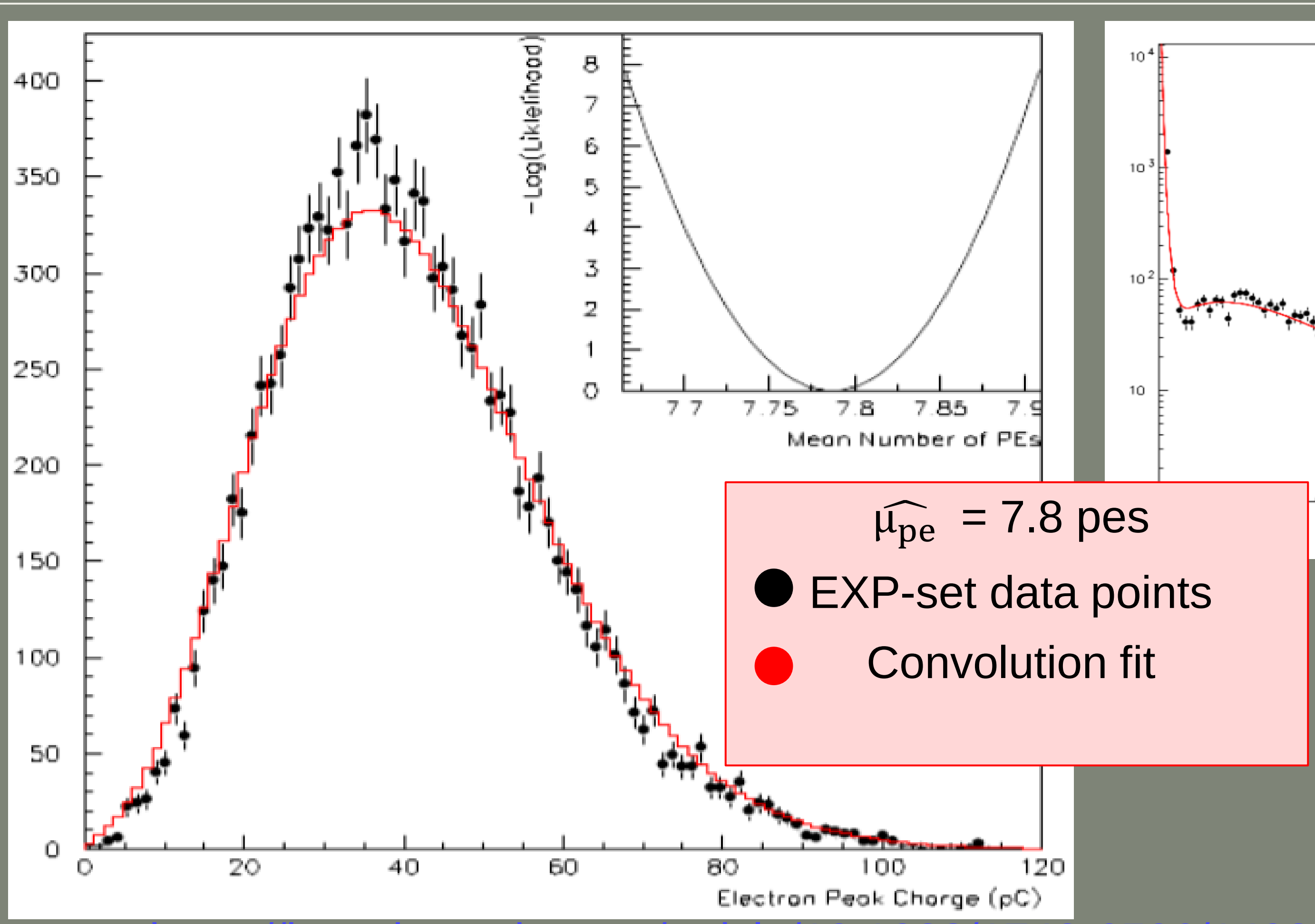
Figure 1: The Rectified Linear Unit (ReLU) activation function produces 0 as an output when $x < 0$, and then produces a linear with slope of 1 when $x > 0$.

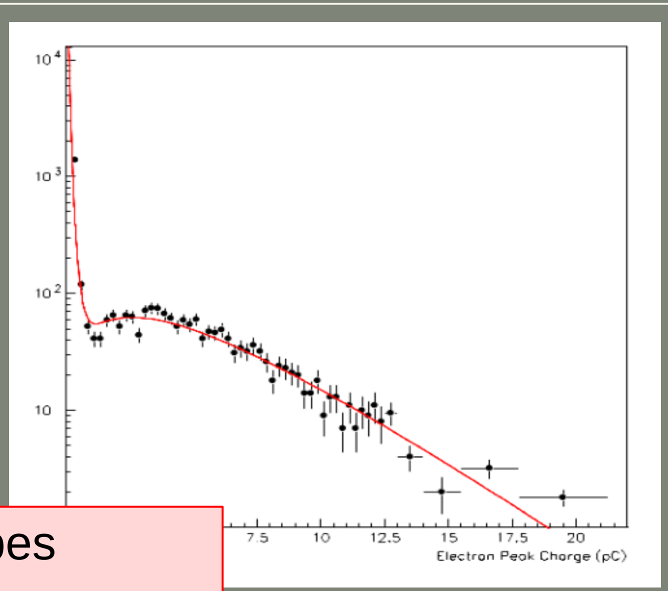




- **First indication**
  - Using Muon test beam data
  - Reproduce the same results as with the full offline analysis
  - K-fold validation technique to Train and Test the ANN
  - Reaching the same timing resolution of 24.2 ± 0.6 ps

- **Laser Beam Data**
- Two sets of Data ⟶ SPE-set & EXP-set
- Need for a wide sample of data for the Training process
- Train with emulated multi-pes pulses created from SPE-set
- Test with EXP-set
- Exp- Set contains ~7.8 photoelectrons
  - Log-Likelihood estimation method
  - Convolution fit of Poissonian X Polya distribution using $\widehat{\mu_{pe}}$
- **Creation of Multiphotoelectrons**
  - Multiplicity N, single pes chosen according to a Poissonian distribution with $\hat{\mu}_{pe} = 7.8\, pes$
  - N waveforms selected randomly among SPE-set
    - Each shifted in time to t-refference being zero
    - 3rd degree polynomial interpolation between digitization points





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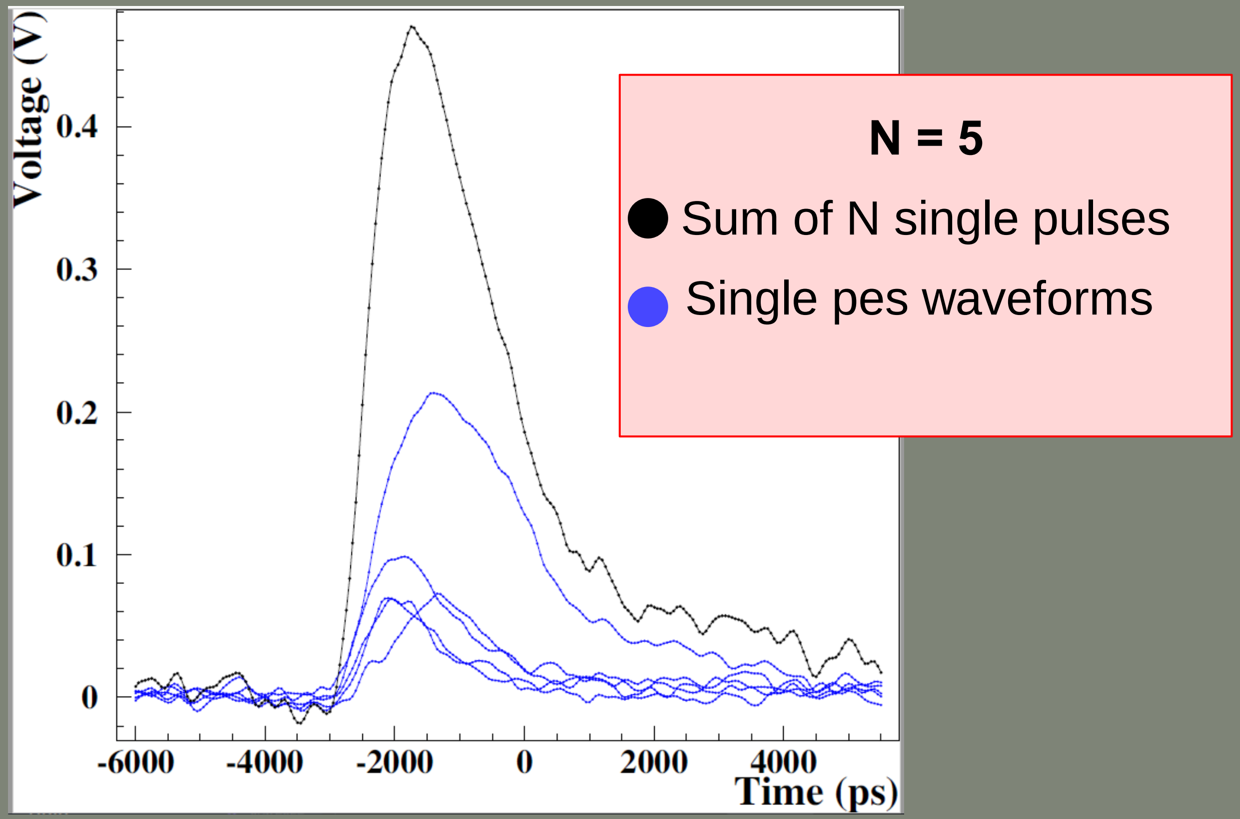
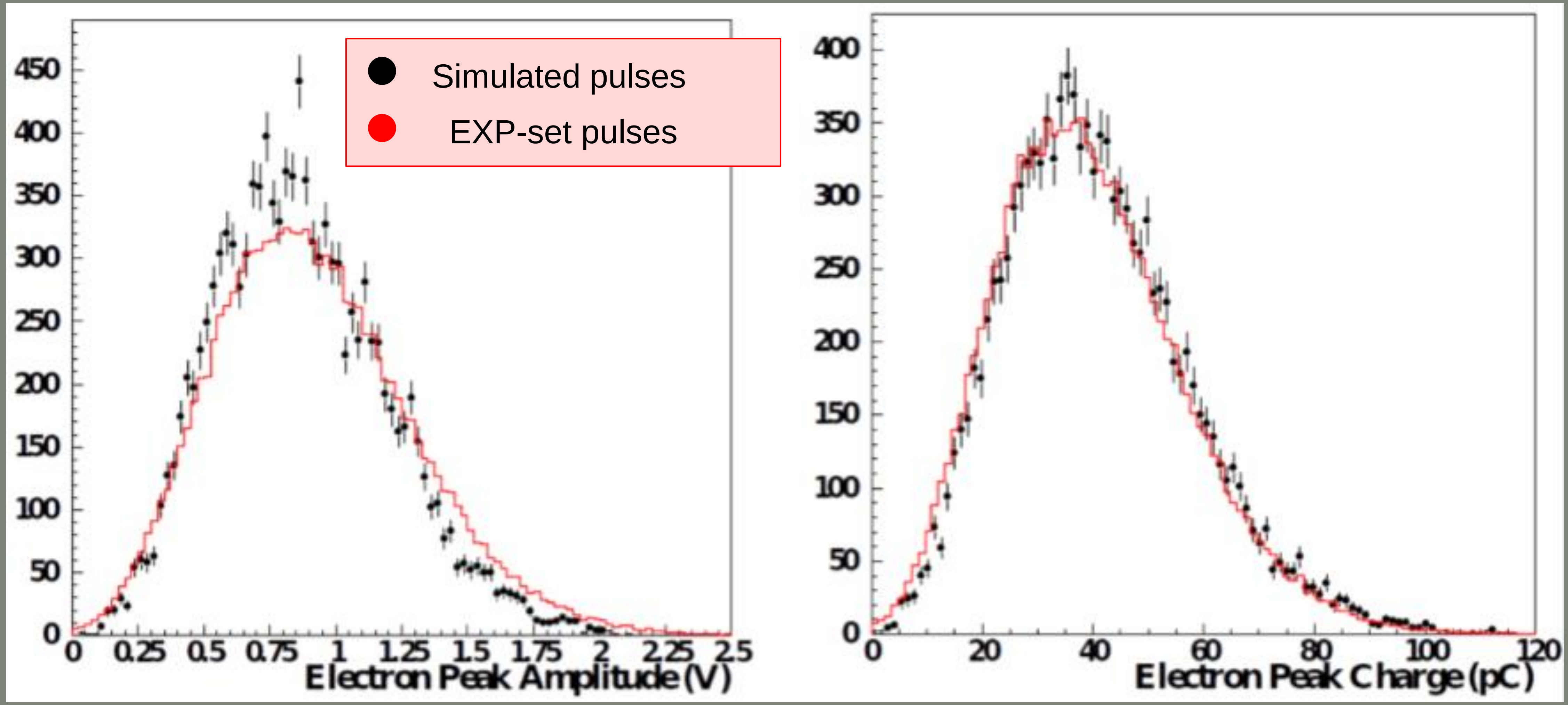
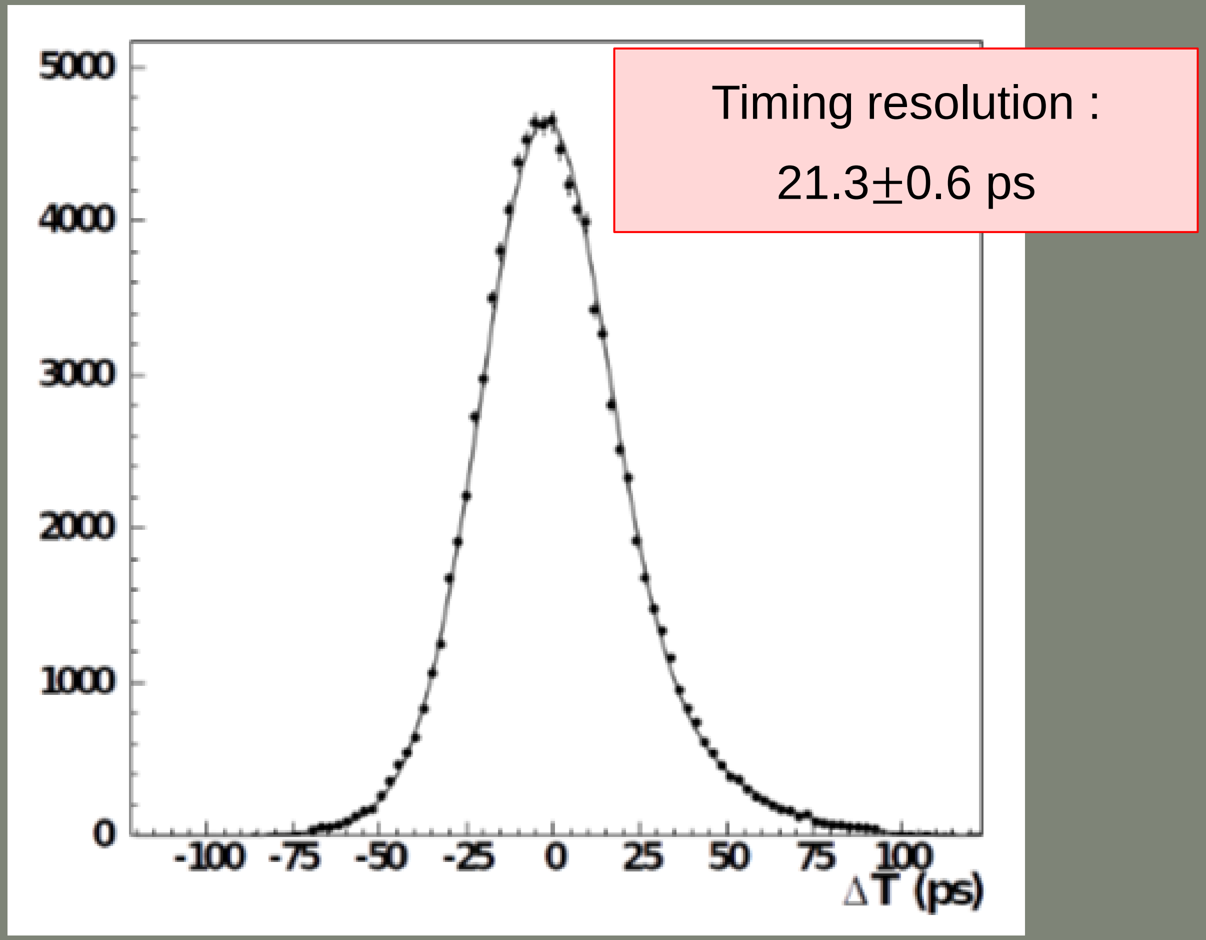


- Limited number of single pulses
- The Simulated pulses share the same SPE waveforms
- Should follow the same behavior as the EXP-set
- Reproduce and compare the distributions of electron peak size

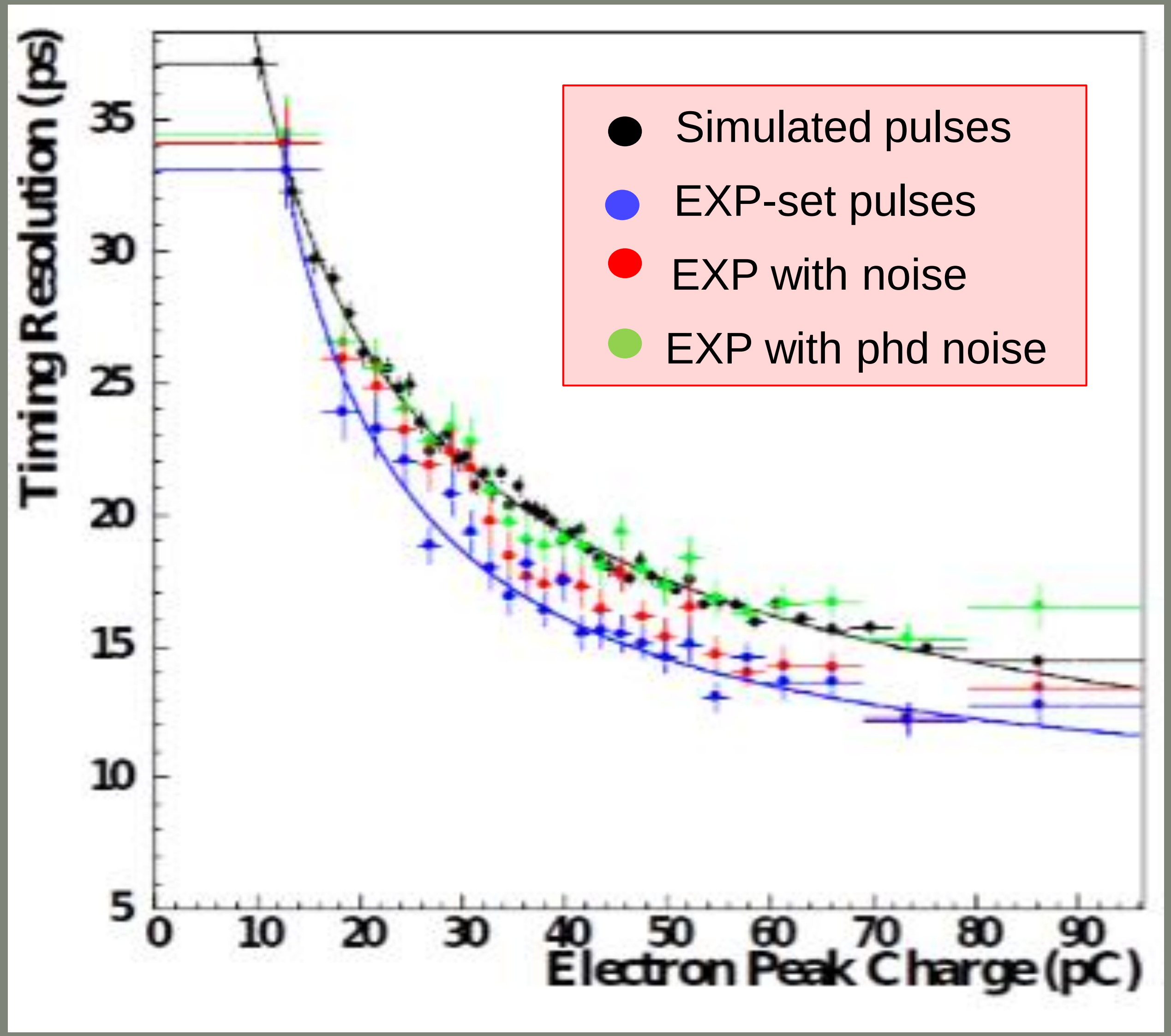


- **Noise contribution**
  - Has the cumulative property
  - Interpolation between digitization points

- **Timing properties**
  - Timing with CFD at 20% of peak amplitude



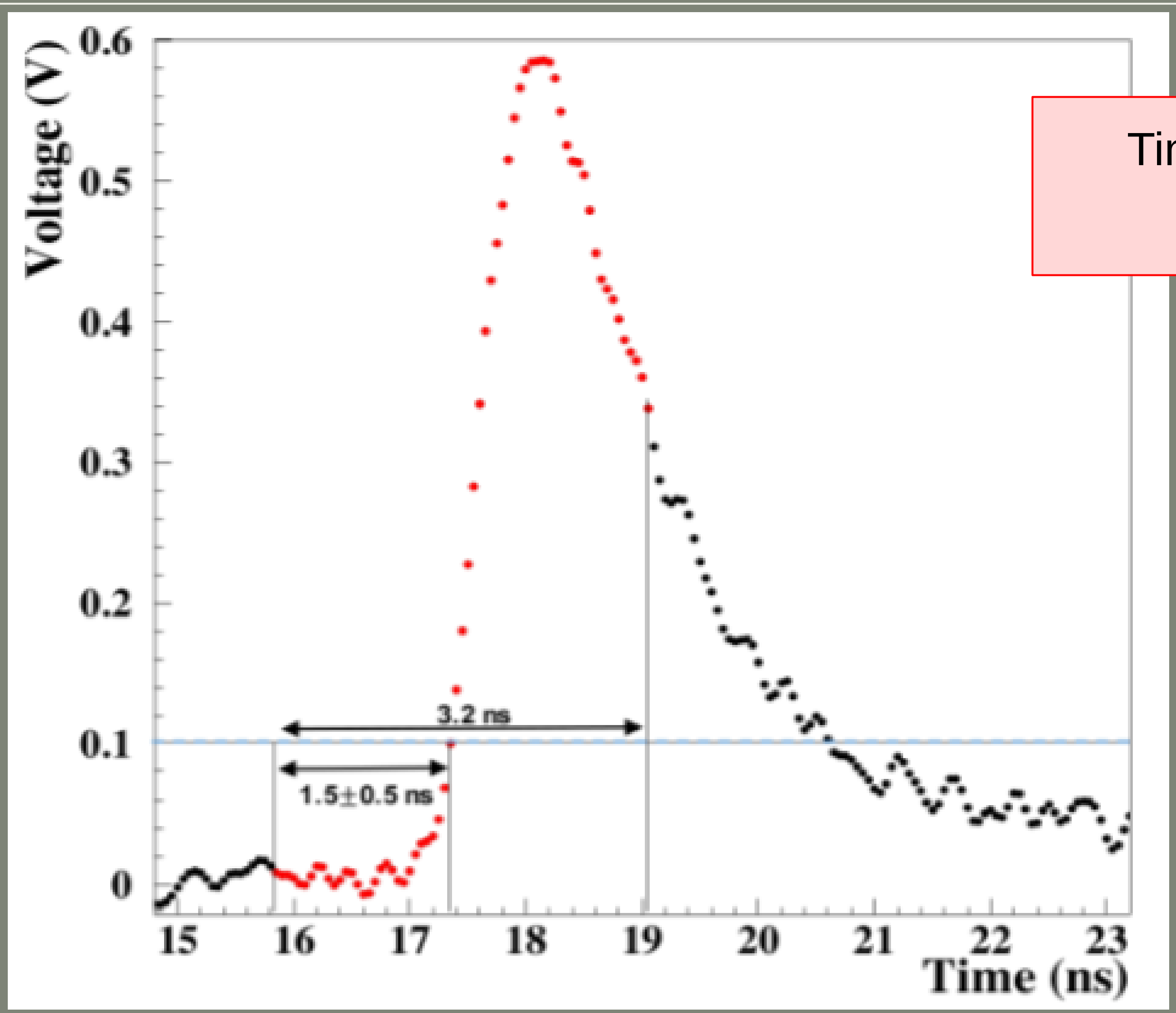
- Data with noise corresponds to RMS of random noise
- PDO noise corresponds to the resolution of Photodiode in which we are sensitive due to synchronization process

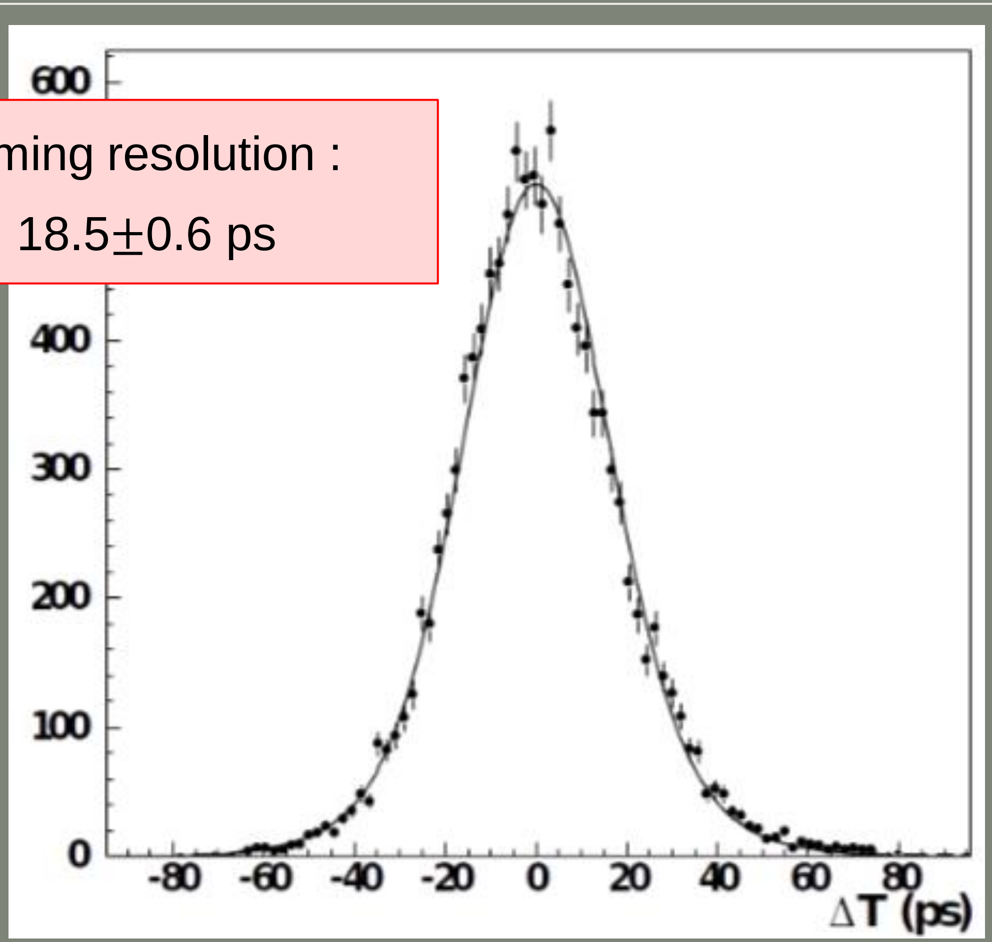


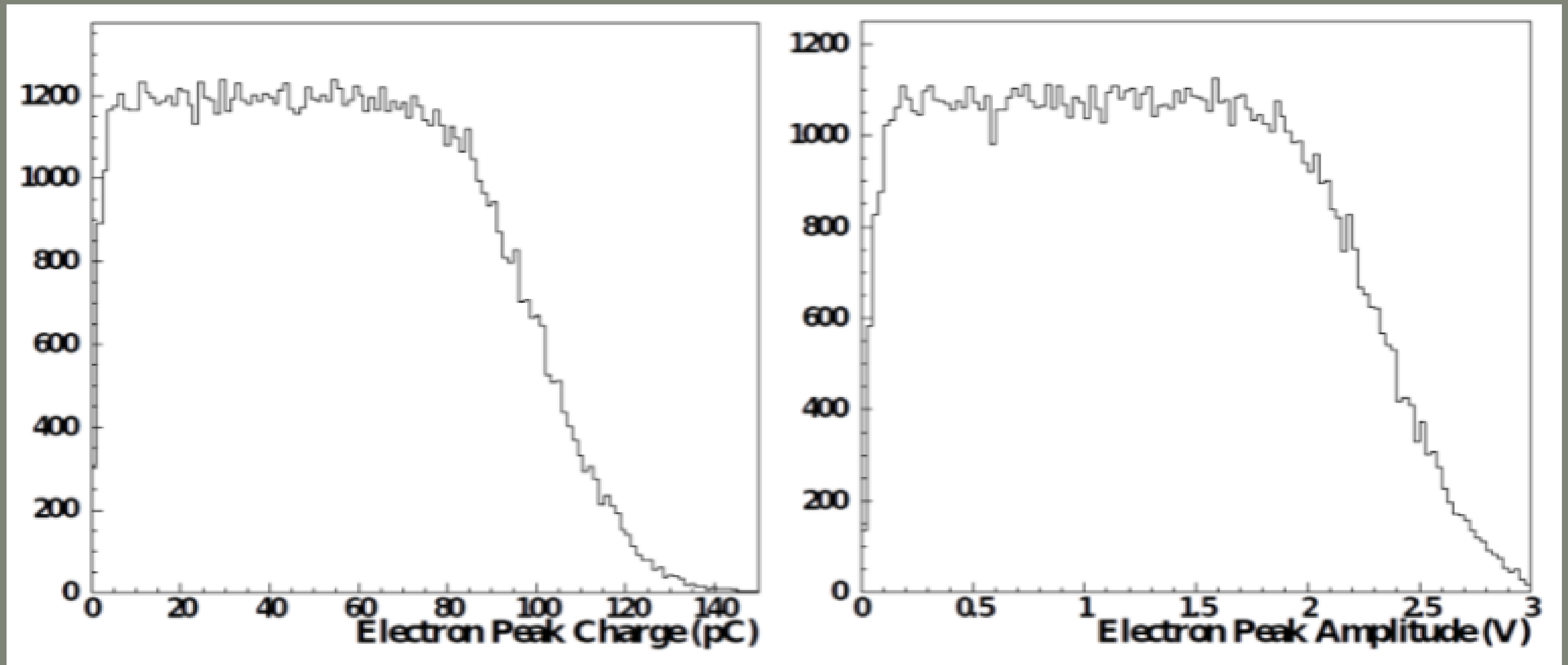
- Worse than the resolution of EXP-set by 3ps
- Noise affect the resolution

$$V[Data] = V[Data_{noise}] + V[\text{PDO}] = N_{pe} \cdot \sigma_{1pe}^2 + N_{pe}^2 \cdot \sigma_{phd}^2$$

- Red points represent the input layer (3.2ns)
- Threshold trigger at 100mV
  - Provide timestamp
- The starting point simulates the behavior of the SAMPIC starting digitization(64ch/sample)
- **Validation of ANN**
  - Use only of the EXP-set
  - Increase the danger of bias
- **Solution :**
  - Use unknown events for training
  - Use of the Simulation Model
- Reduce further the probability of bias
  - Generate pules with Uniform Npes

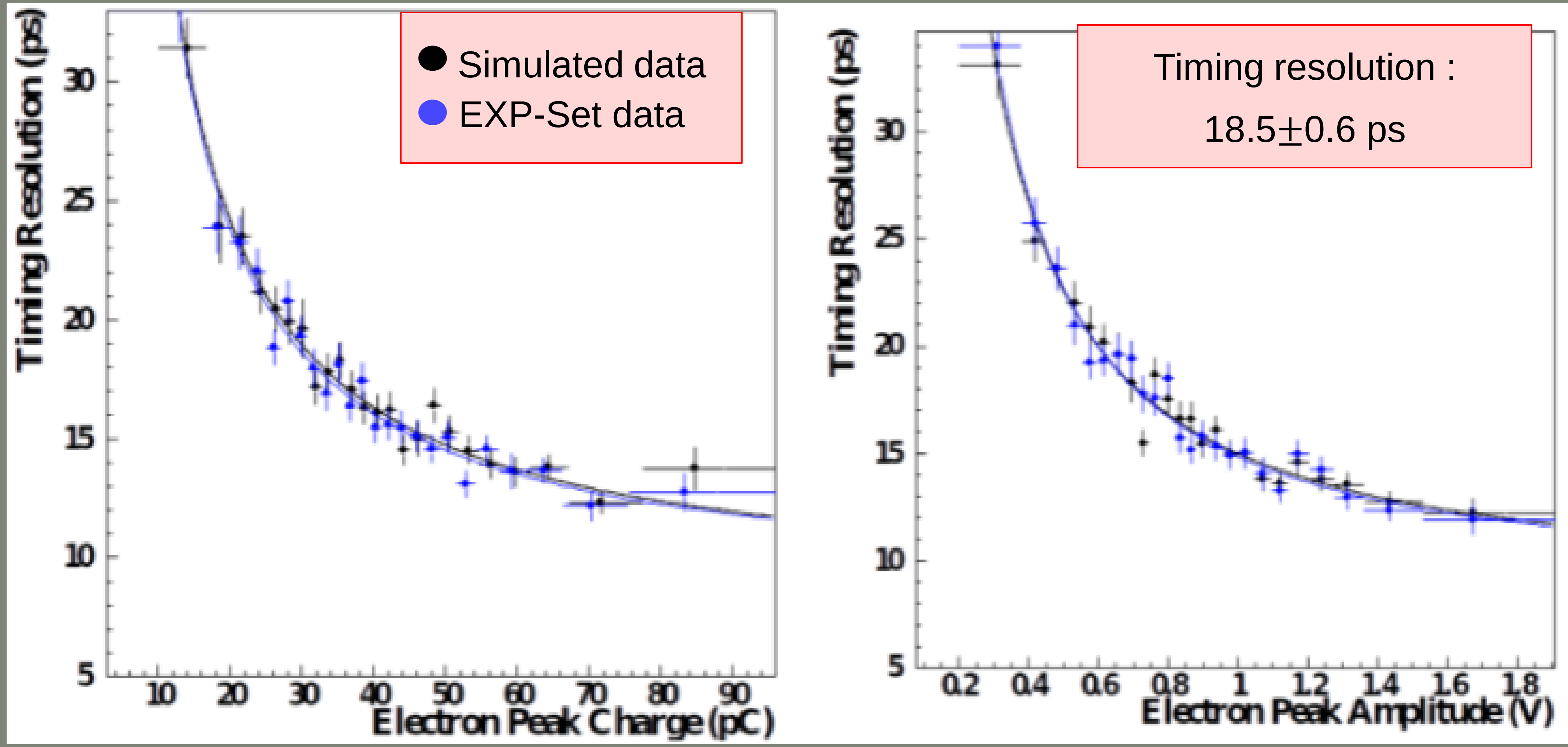




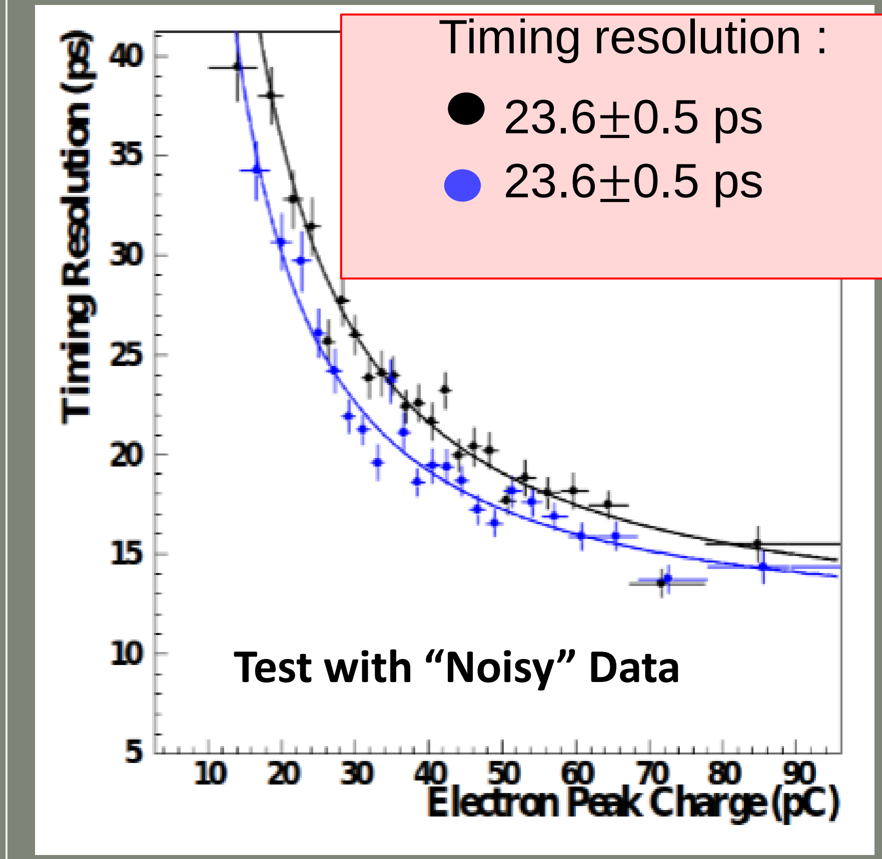


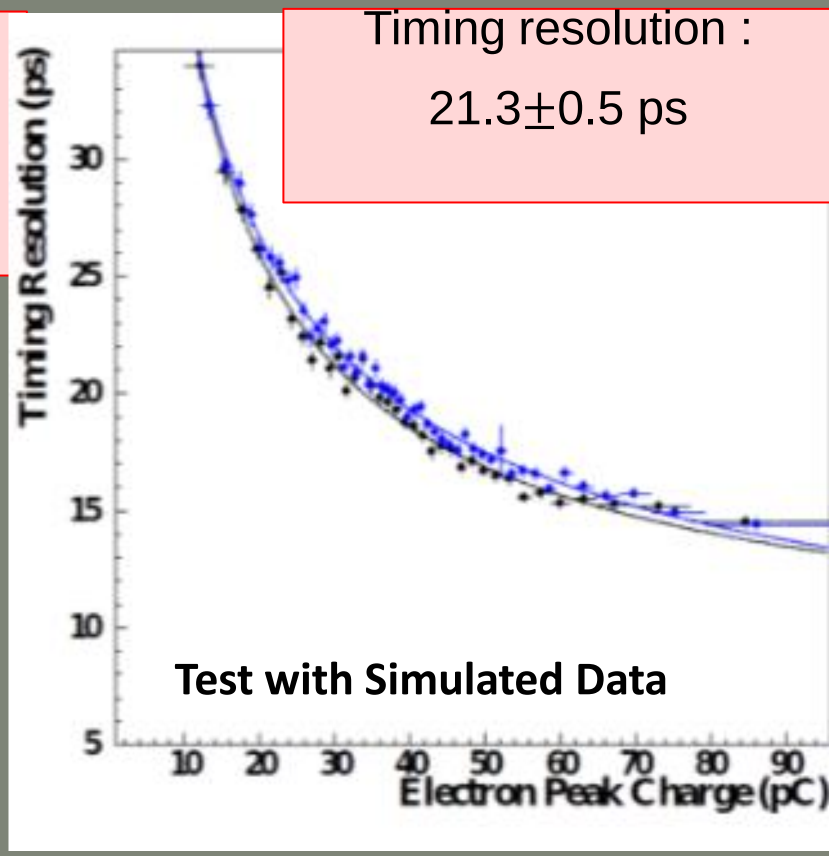
Prove that ANN is not a black box

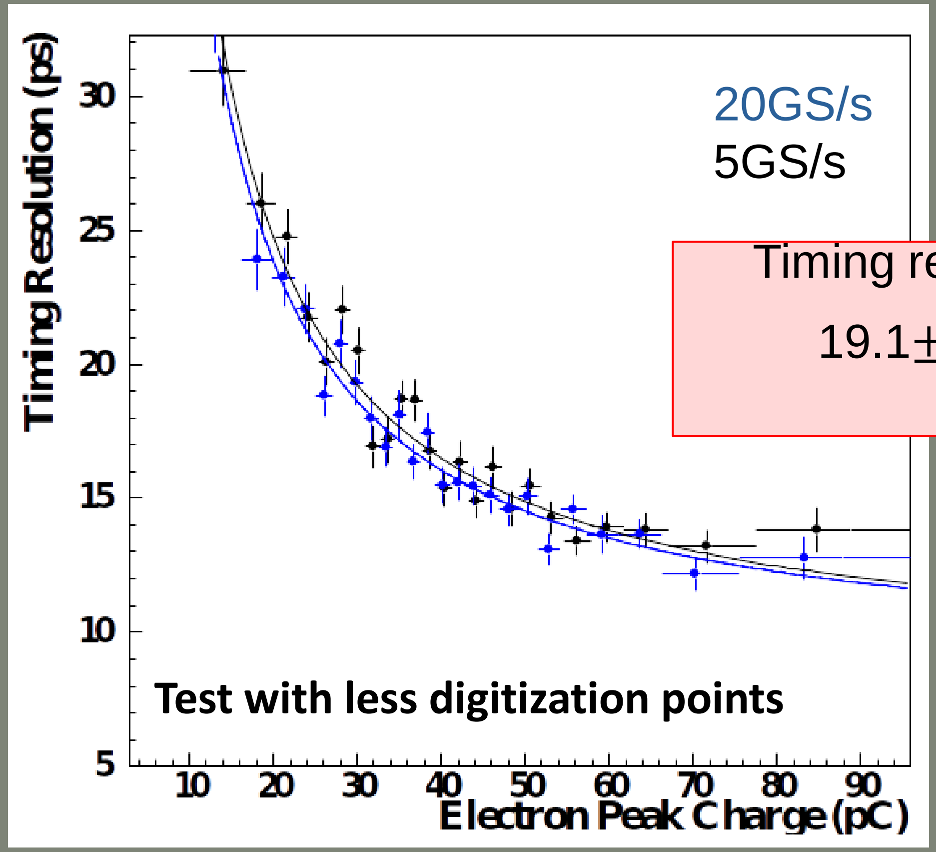
- **Train the ANN with uniform number of photoelectrons**
- **Test with real experimental data EXP-set**



Strong evidence that ANN works properly







Concluding Remarks

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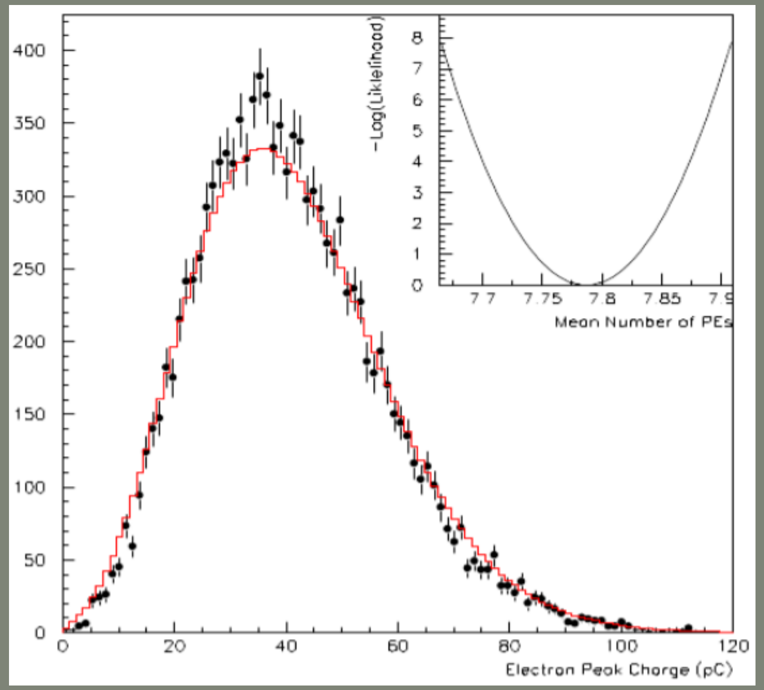
- The PICOSEC-MicroMegas Detector potential for precise timing, at a picosecond level, is demonstrated
- The development of signal processing algorithms explore the properties of the detector and offer the ability for online precise timing
- Using Laser Beam Test Data, analyzed offline (with CFD), results to a timing resolution of 18.3ps
- A signal processing algorithm based on Constant Fraction Discrimination, with Qup corrections, reaches the same timing resolution
- An ANN for real timing signal processing, is able to provide precise timing and can be used for fast event selection
- Main demand of adequate training samples → Simulation model
- It was proven that the ANN learns a signal analysis procedure and it is consistent and unbiased

Thank you!

Backup-slides

Deconvolution Process

- Assuming that the number of photons (n) in the Cherenkov radiator follows a Poisson distribution :



$$\text{Poisson}(n;\mu) = \frac{\mu^n e^{-\mu}}{n!}$$

- Each of these photons has either the probability to interact in photocathode or to escape :

$$\text{Binomial}(k;n,\epsilon) = \frac{n!}{k!(n-k)!}(\epsilon^k(1-\epsilon)^k)$$

- The probability to observe k photoelectrons is the convolution of the Poisson and Binomial resulting to a new Poissonian

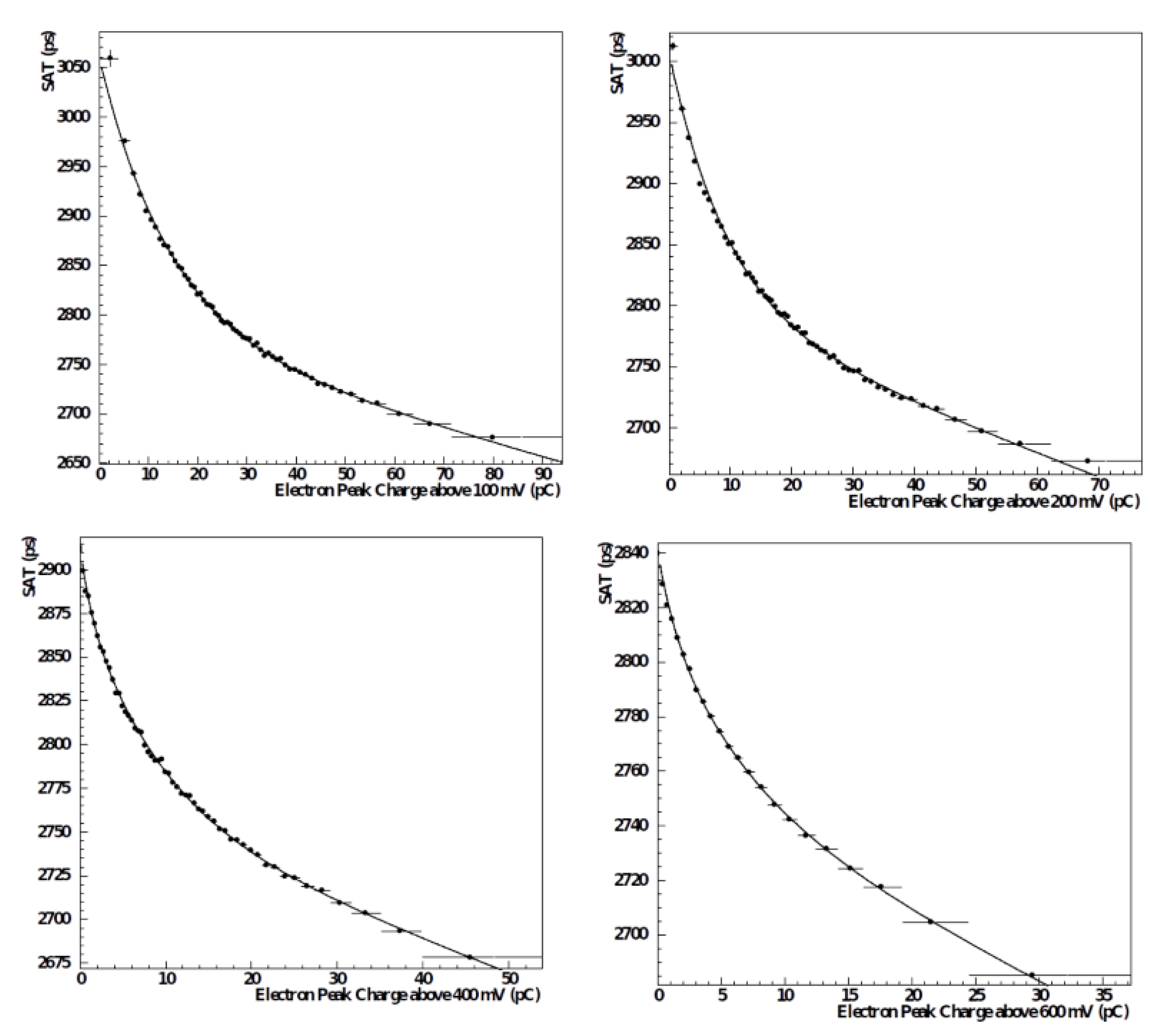
$$f(k;\mu,\epsilon) = \text{Poisson}(k;\mu\cdot\epsilon)$$

- Every single photoelectron is distributed via a Polya distribution, thus the multi-photoelectron charge distribution should be fitted with the convolution of Poissonian Distribution and N-Polya distribution

$$P_N(n;\bar{n},\theta,N) = \frac{(\theta+1)^{N(\theta+1)}}{\bar{n}\Gamma(N(\theta+1))}\left(\frac{n}{\bar{n}}\right)^{N(\theta+1)-1} e^{-(\theta+1)n/\bar{n}}$$

- Using Log-Likelihood estimation for the number of photoelectrons we conclude to the desired value of 7.8 photoelectrons

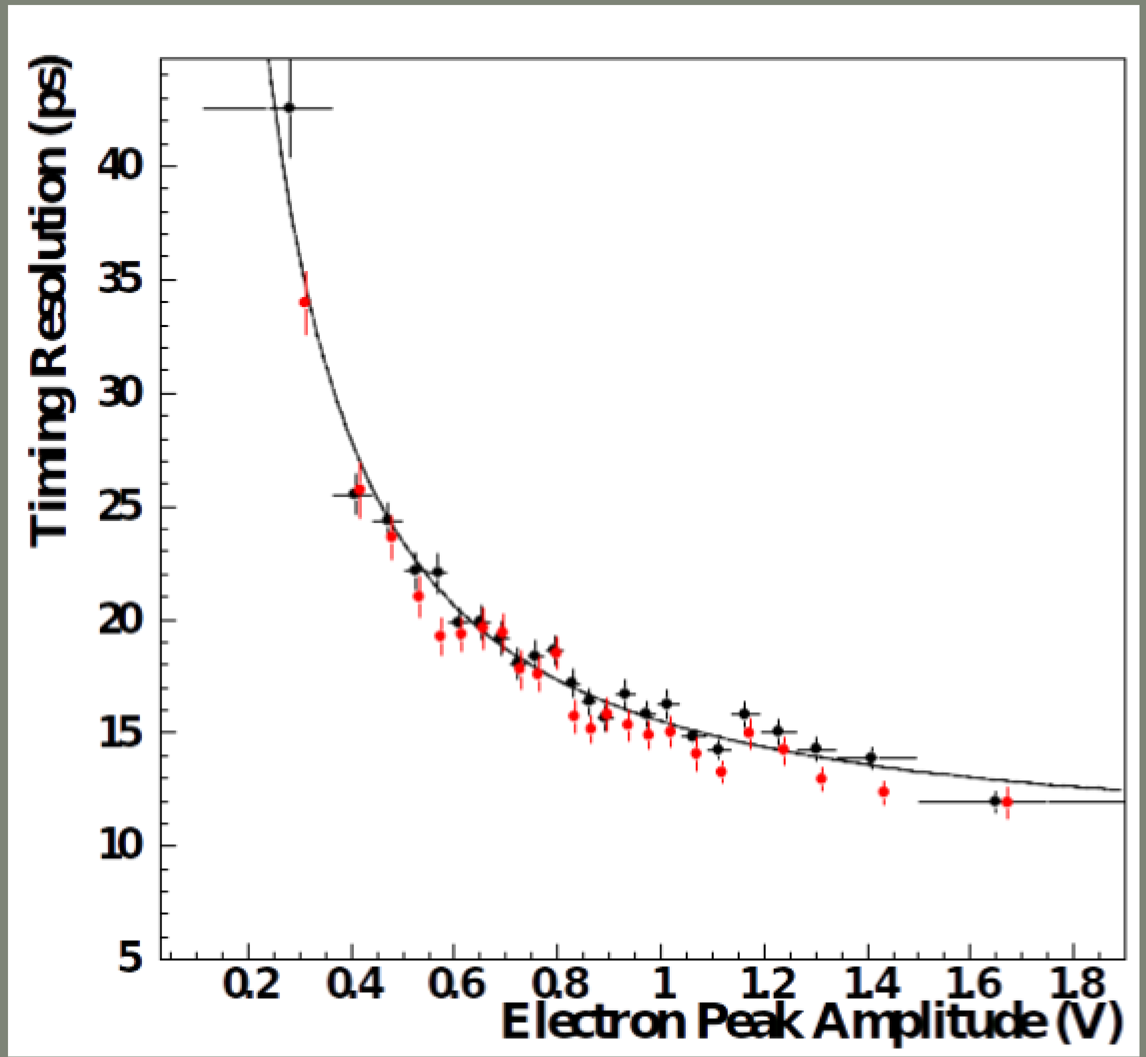
- **Signal Processing Analysis Procedure**
- SAT defied at constant threshold of 100mV (timing)
- Using multiple higher thresholds 200mV, 400mV, 600mV
- Alternative method of peak size estimation
- Create calibration curves for SAT corrections using charges above thresholds as a parameter
- Correct for time walk effects in the higher crossing threshold

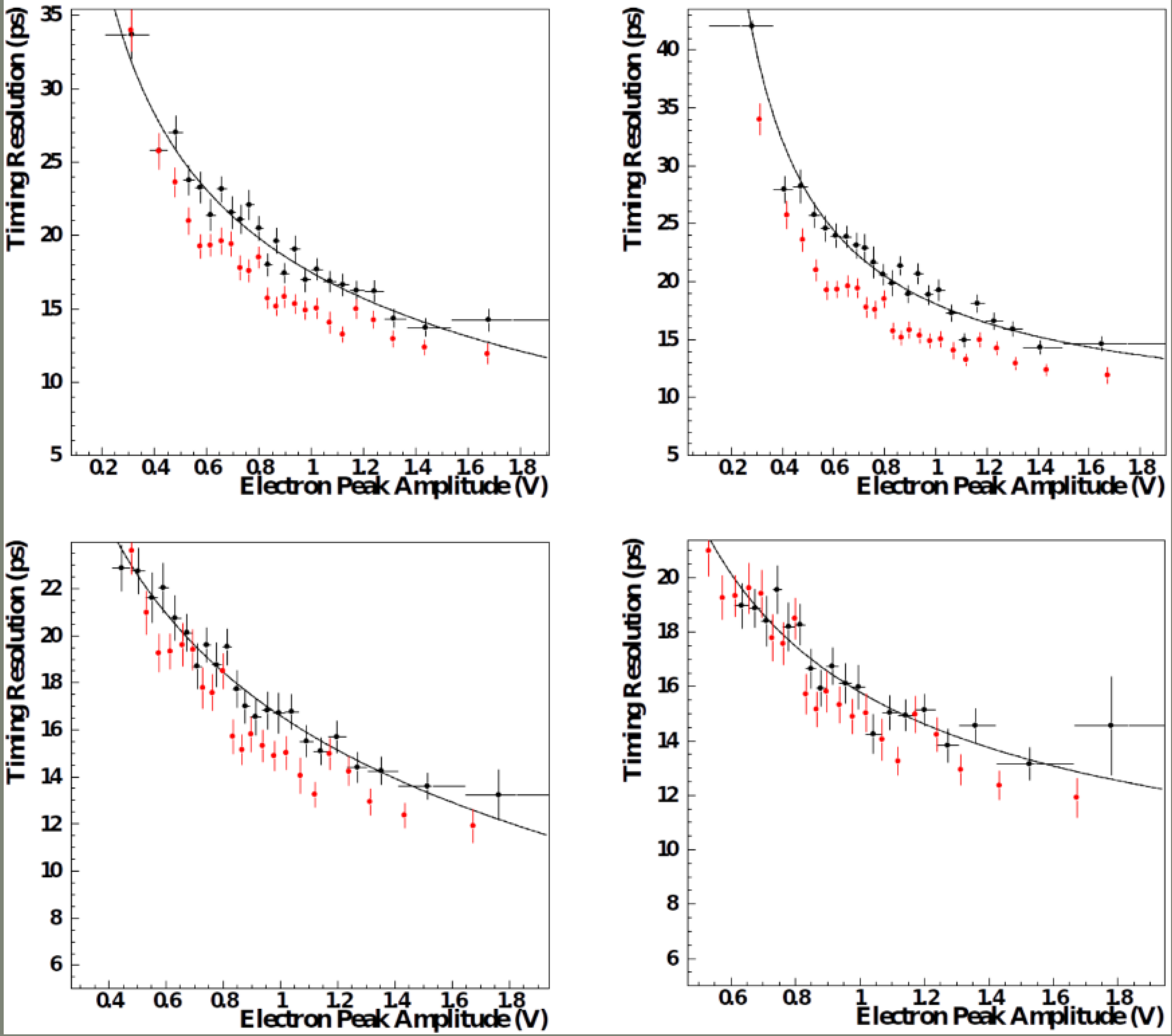


Alternative Timing Techniques – Multi-Charge over Threshold

- **Analysis Procedure**
- SAT defied at constant threshold of 100mV (timing)
- Using multiple higher thresholds 200mV, 400mV, 600mV

- Comparison of CFD and multi-Charge over Threshold timing resolution





- Reaching the same timing resolution of 19 ± 0.3 ps

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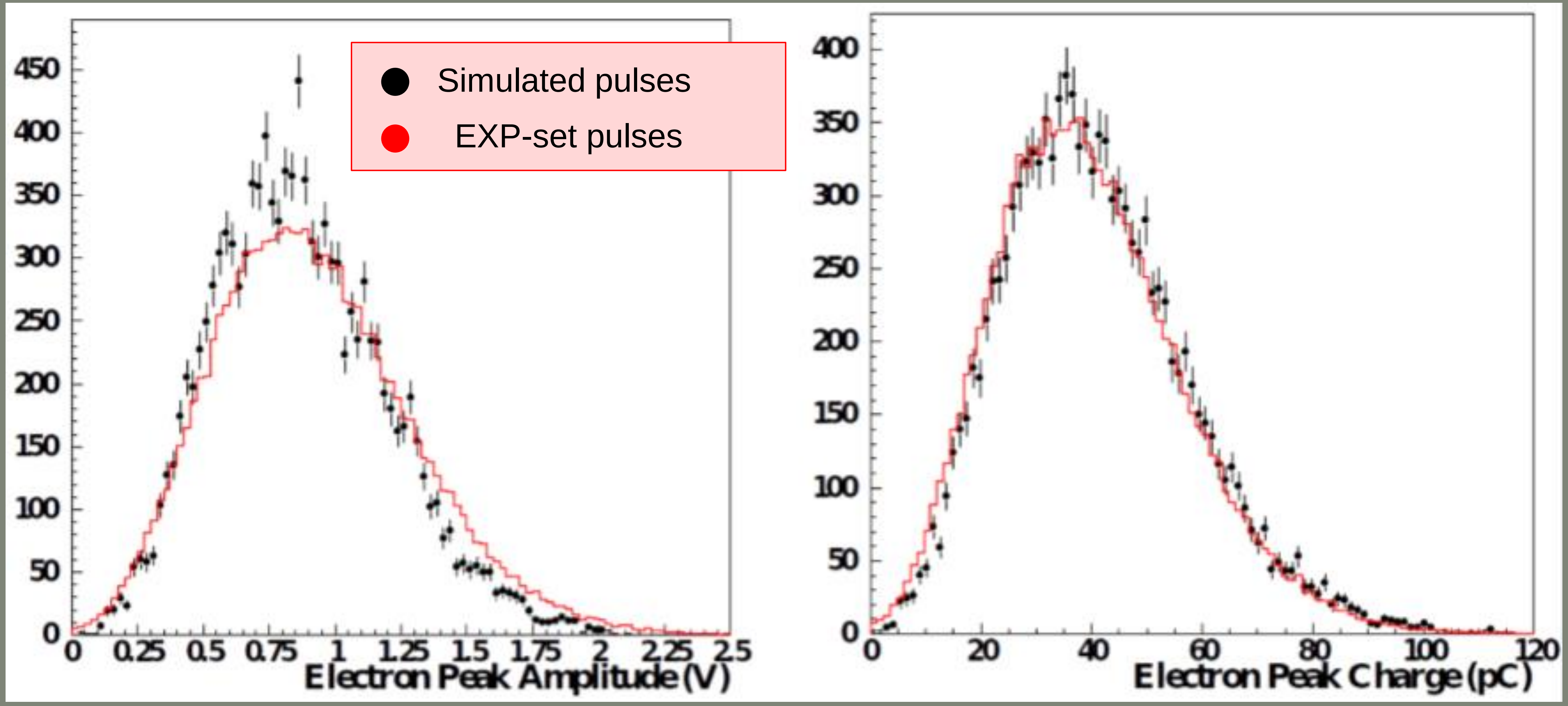
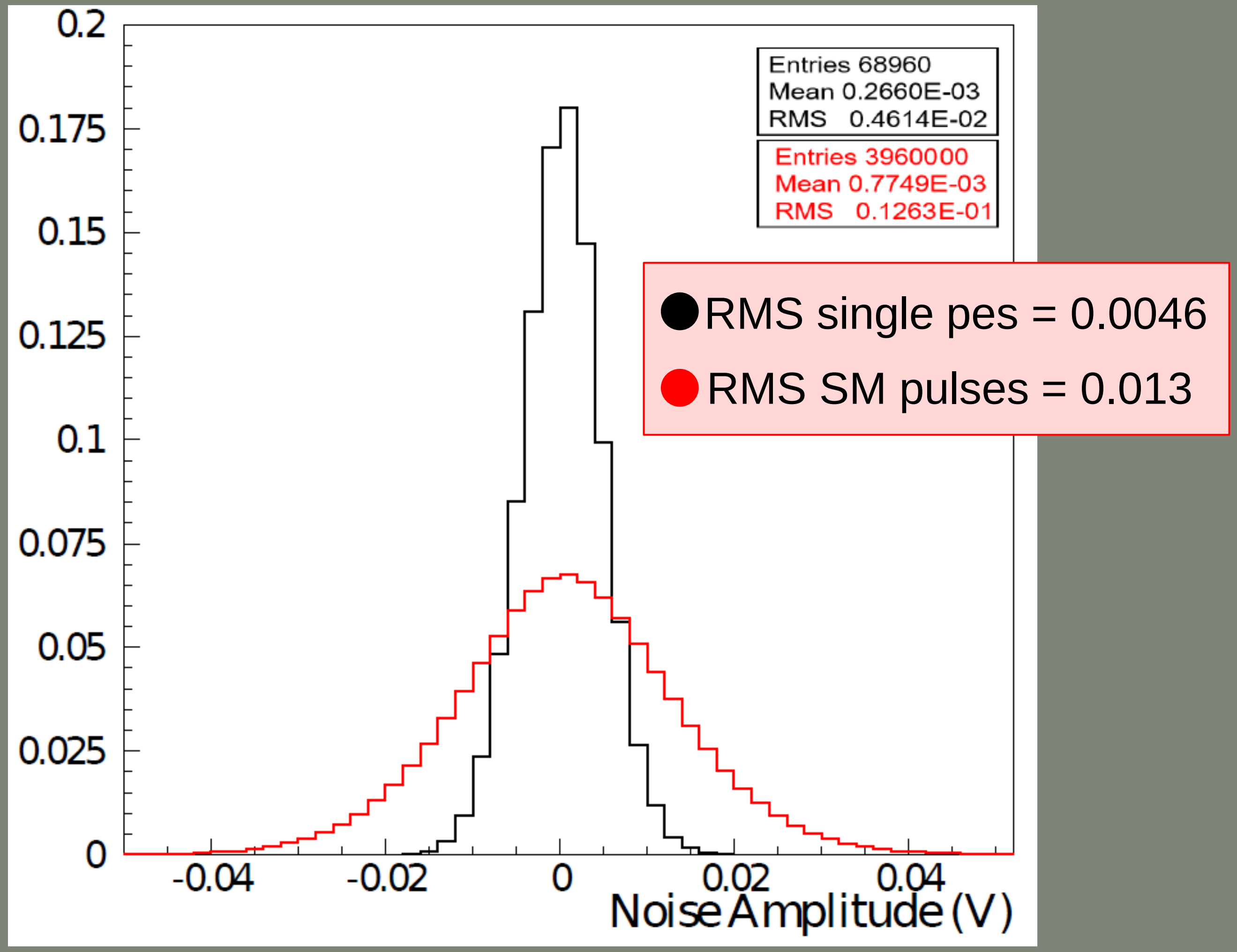
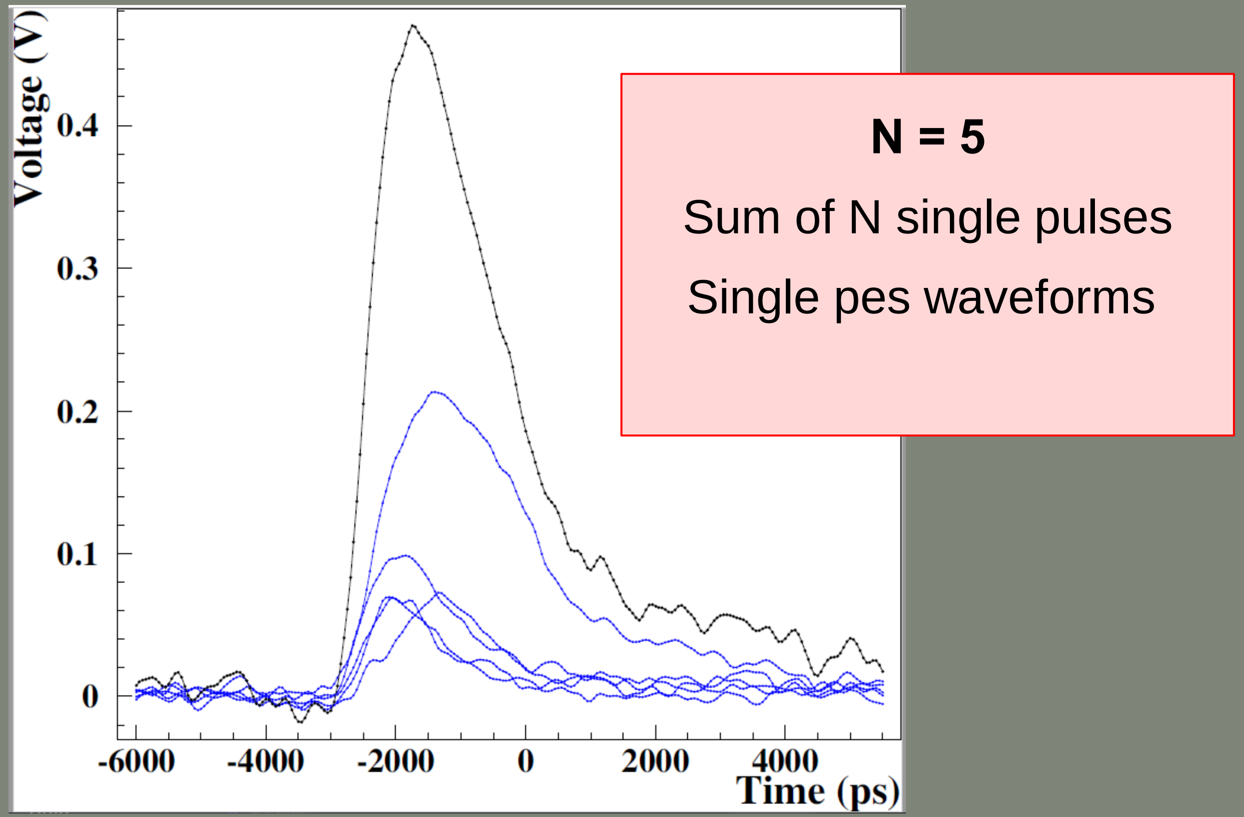
- Reproduce and compare the distributions of electron peak size



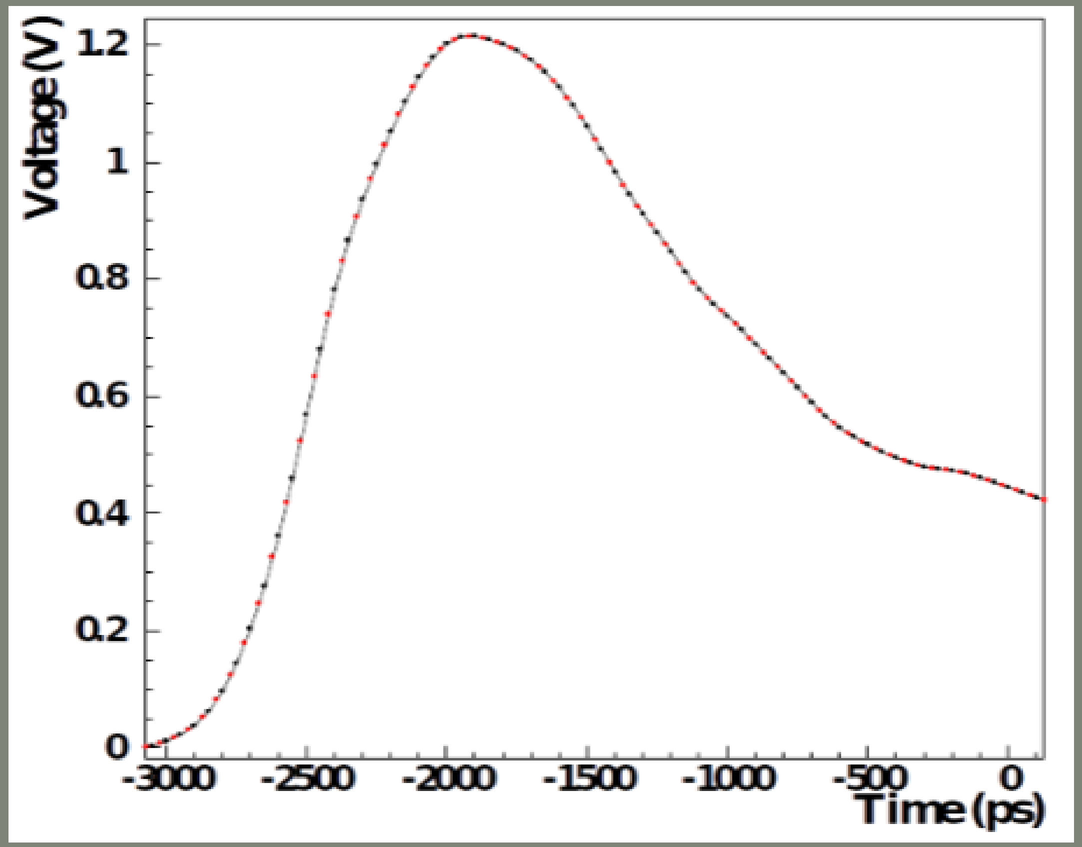


- **Noise contribution**
  - Noise has the cumulative property
- Affect the determination of E-peak maximum
- Adds a limitation in our model

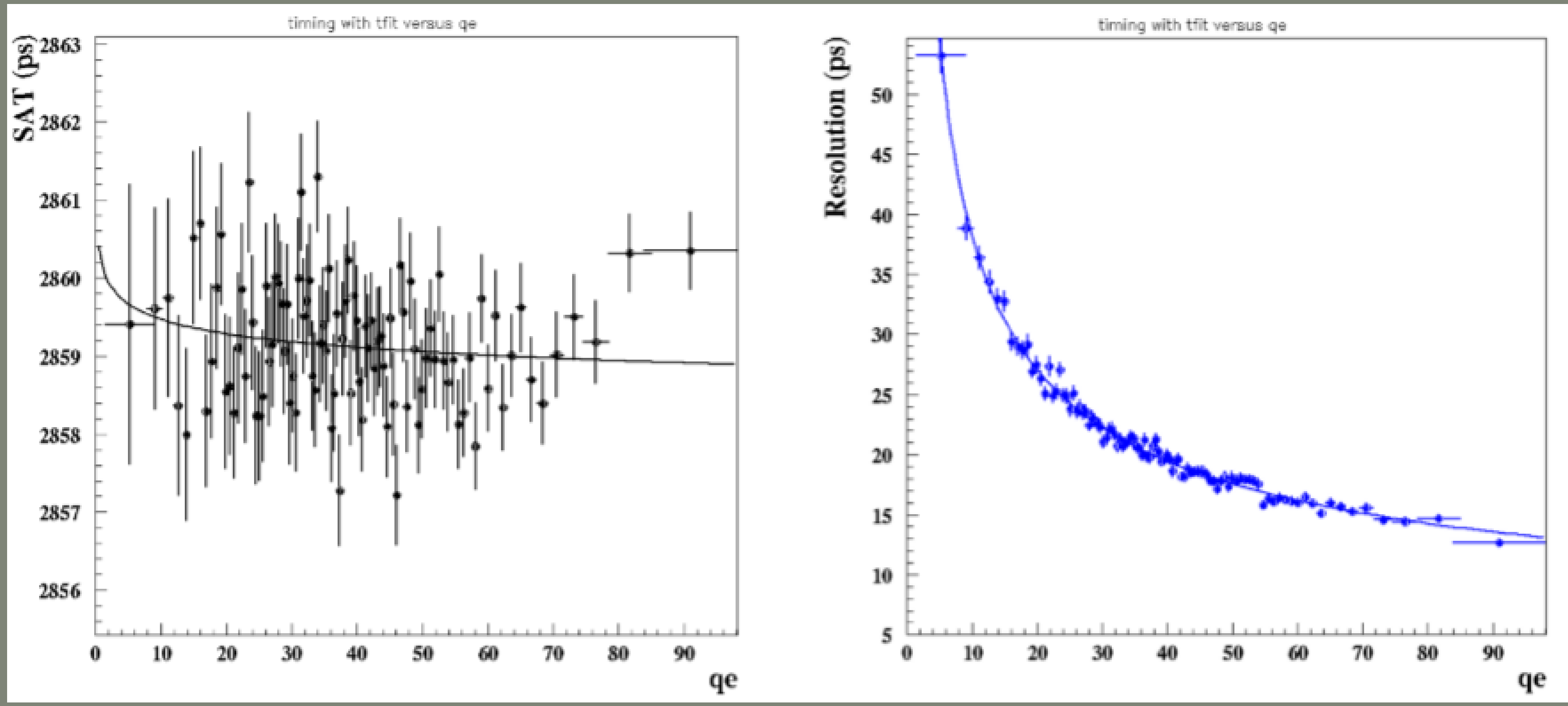
- **Creation of Multiphotoelectrons**
  - Multiplicity N, single pes chosen according to a Poissonian distribution with $\hat{\mu}_{pe} = 7.8\ pes$
  - N waveforms selected randomly among SPE-set
    - Each shifted in time to tref being zero
    - 3rd degree polynomial interpolation between digitization points

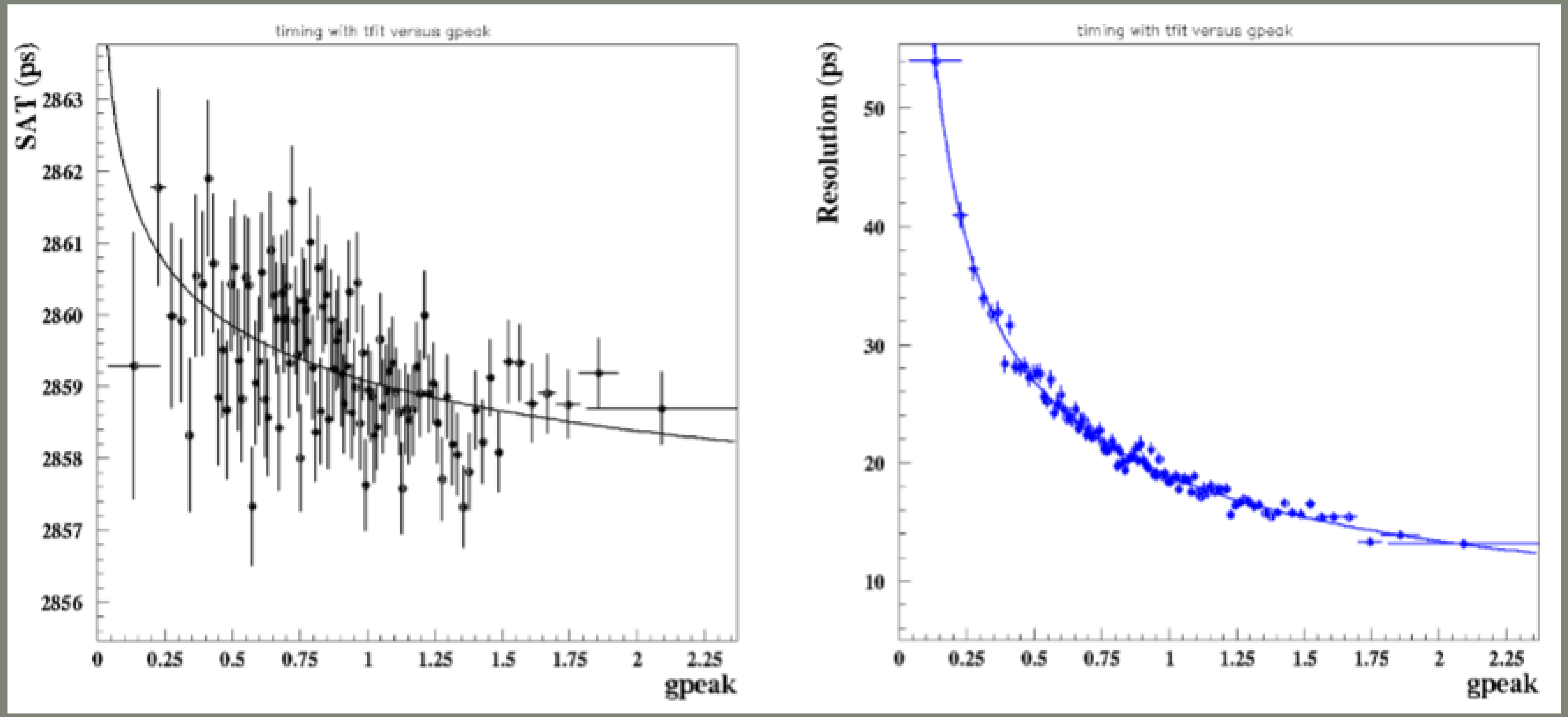


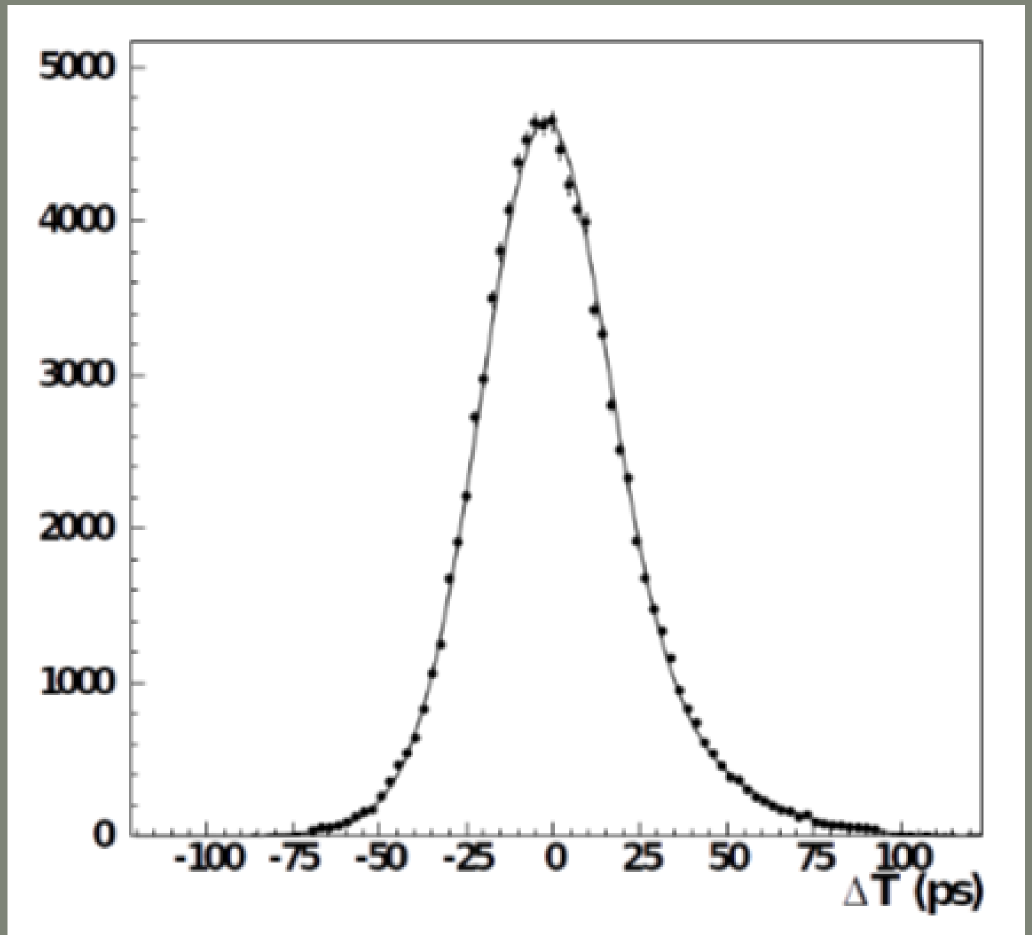
- Negative effect
  - Having the same digitization
  - Not real behavior
  - Trigger and digitization clock have no time jitter
  - Additional random digit shift ±50 ps



- **Timing properties**
  - Timing with CFD at 20% of peak amplitude

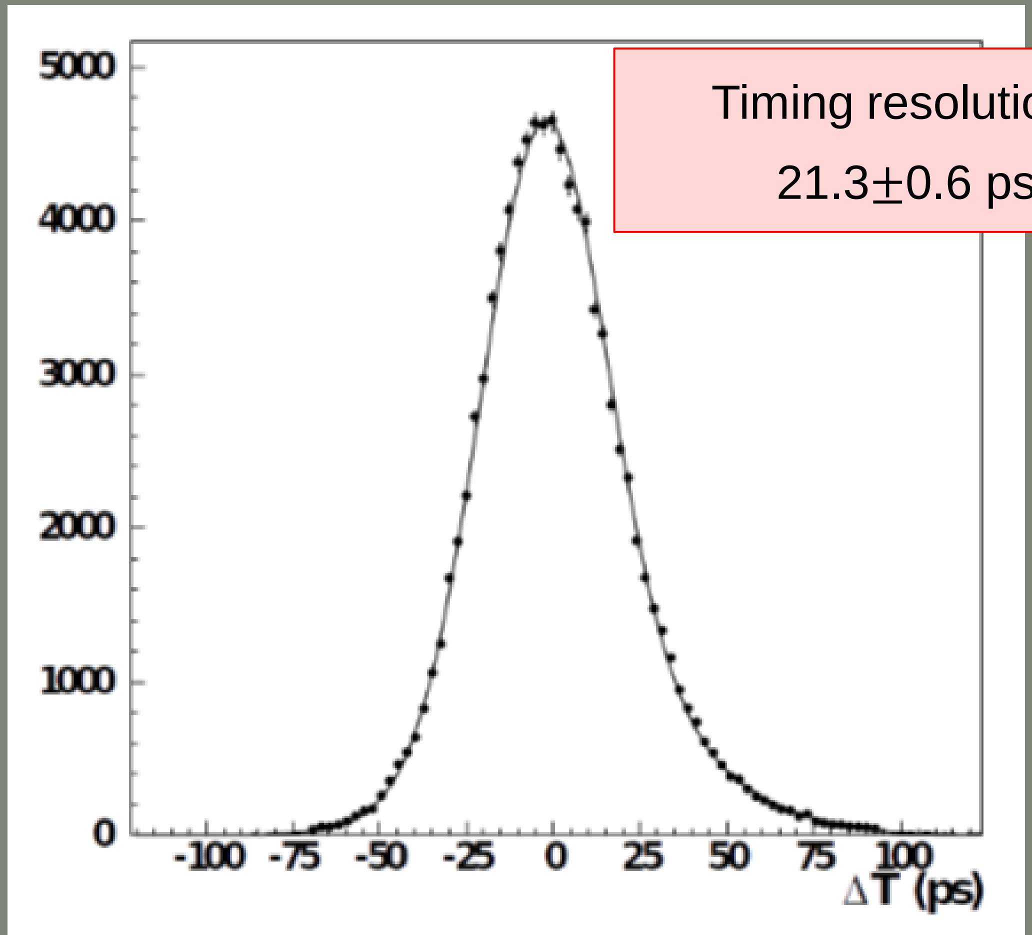


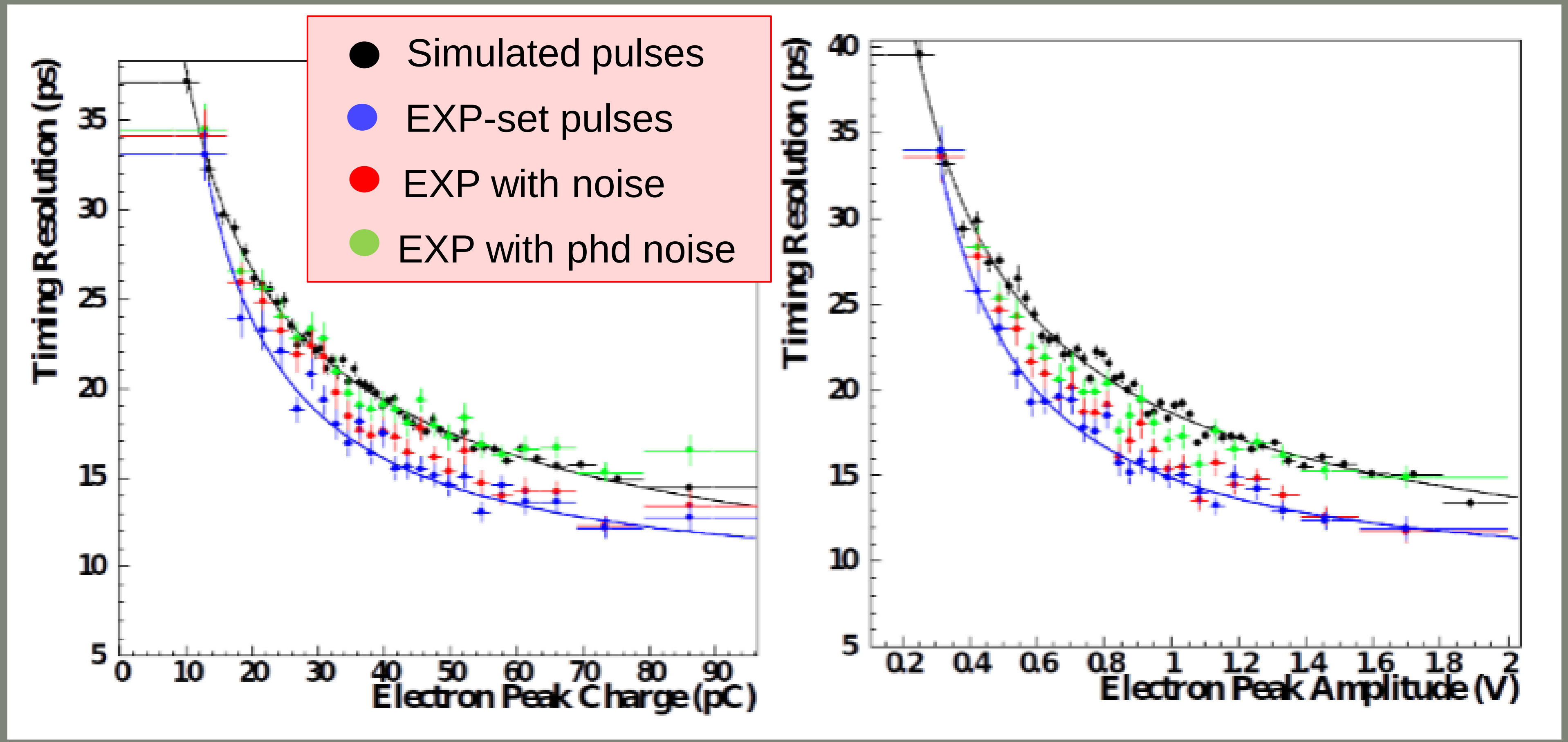




- Reaching timing resolution of 21.3 ± 0.6 ps
- Worse than the resolution of EXP-set by 3ps
- Noise affect the resolution

- **Timing properties**
  - Timing with CFD at 20% of peak amplitude



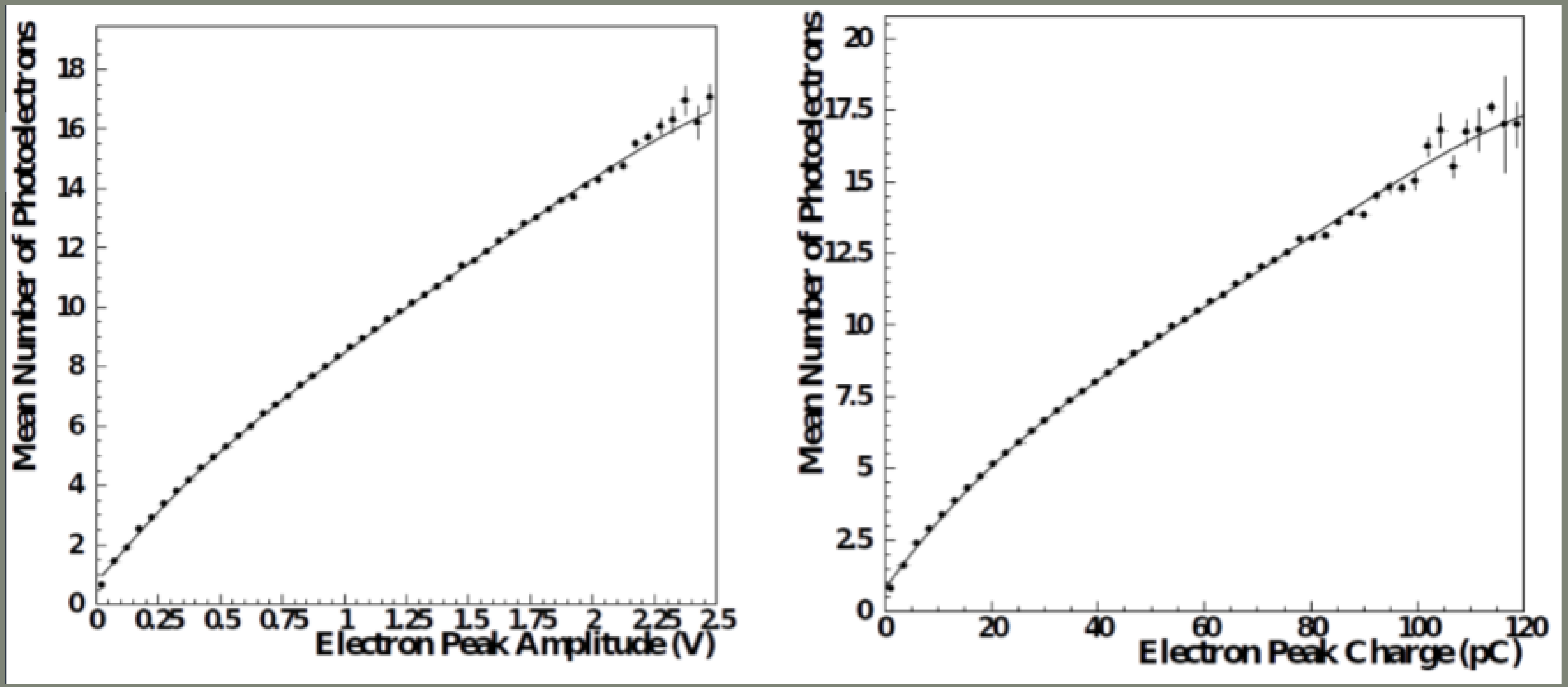


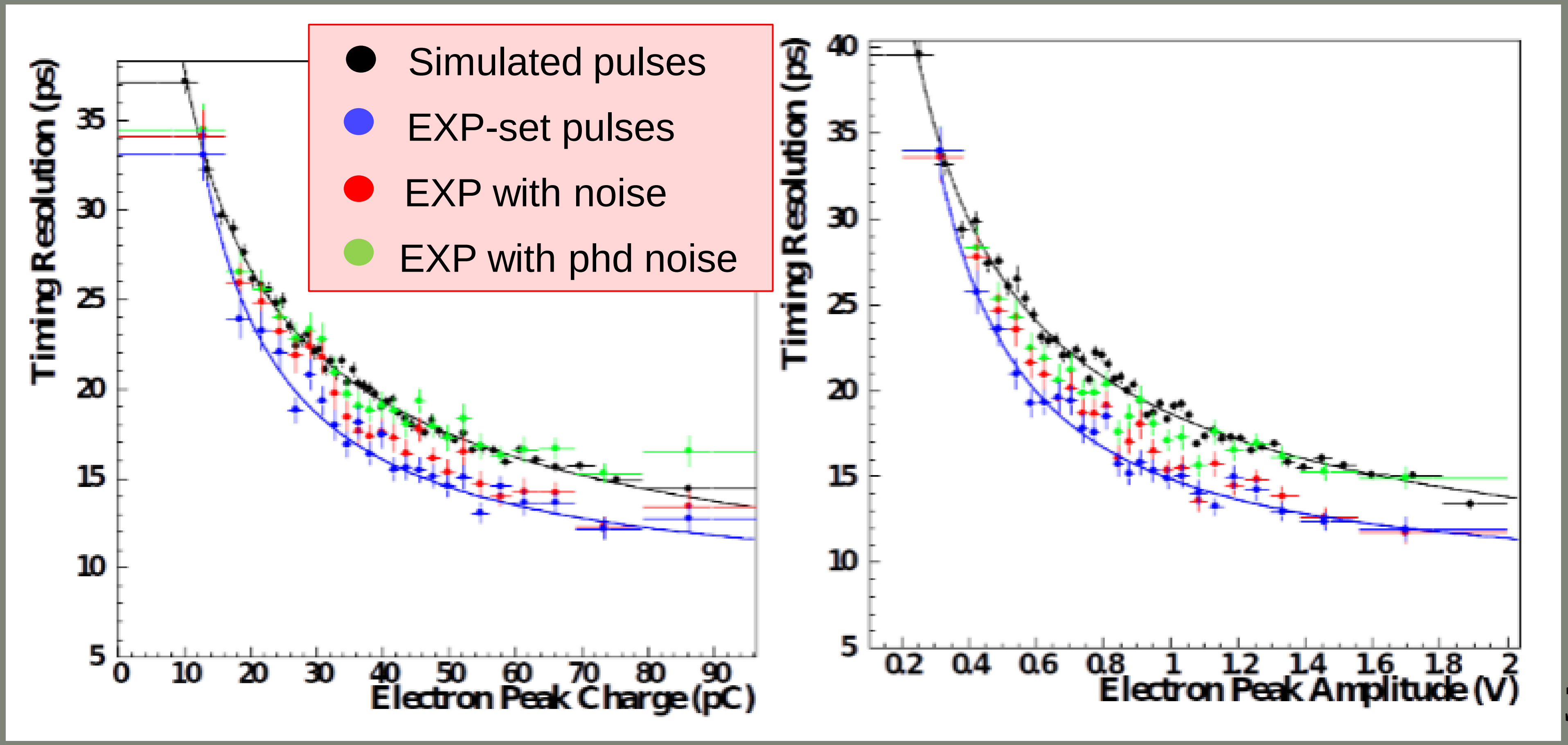
- Worse than the resolution of EXP-set by 3ps
- Noise affect the resolution
- Data with noise correspond to RMS of random noise

$$V[Data] = V[Data_{noise}] + V[phd] = N_{pe} \cdot \sigma_{1pe}^2 + N_{pe}^2 \cdot \sigma_{phd}^2$$

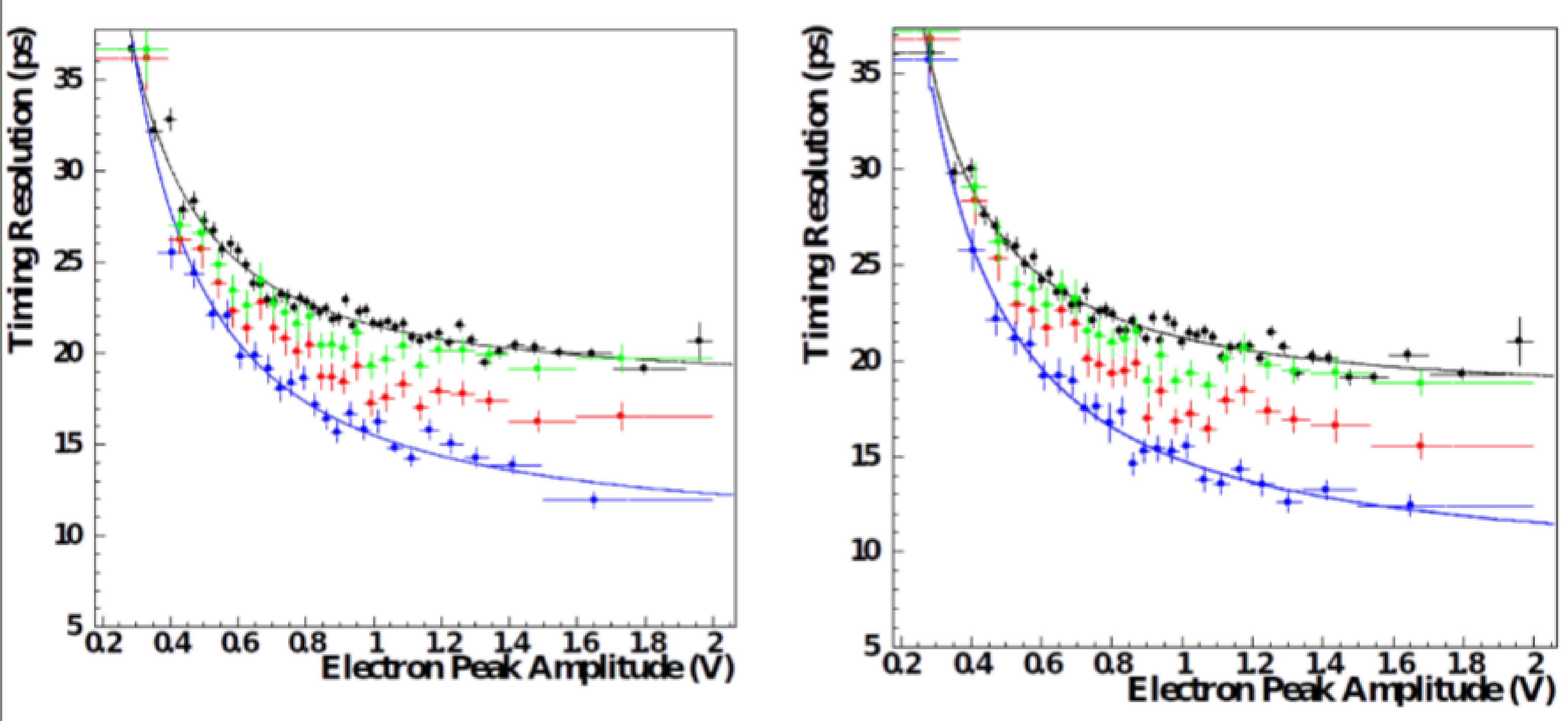
- phd noise corresponds to resolution of Photodiode in which we are sensitive due to synchronization process

- **Investigating the extra timing error**
  - Noise is added as a function of number of photoelectrons
  - Number of photoelectrons defines the size of the waveform
  - Fit with a 4rth degree polynomial
  - On an event-by-event basis and on digit-by-digit of every event the corresponding noise is added as $\sigma=\sqrt{N_{pe}}\cdot\sigma_{1pe}$ (red colored data points)
  - Synchronized with time reference at zero introduces an error proportional to the σ of the reference device as $\sigma=\sqrt{N_{pe}}\cdot\sigma_{phd}$ (green colored data points)





- **Timing properties**
  - Timing with Timing threshold at 100mV and multi-Charge over threshold corrections



- Reaching timing resolution of 23.2 ± 0.6 ps
- Worse than the resolution of EXP-set by 6ps
- Noise affect the Qup technique more