Measurements of LGAD sensors at USTC & HGTD software and performance

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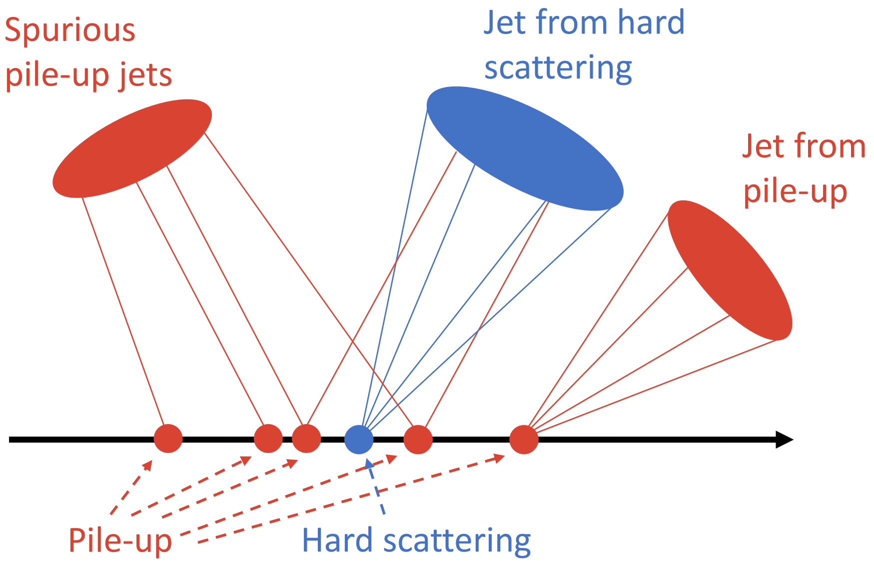
8th, Nov. 2020

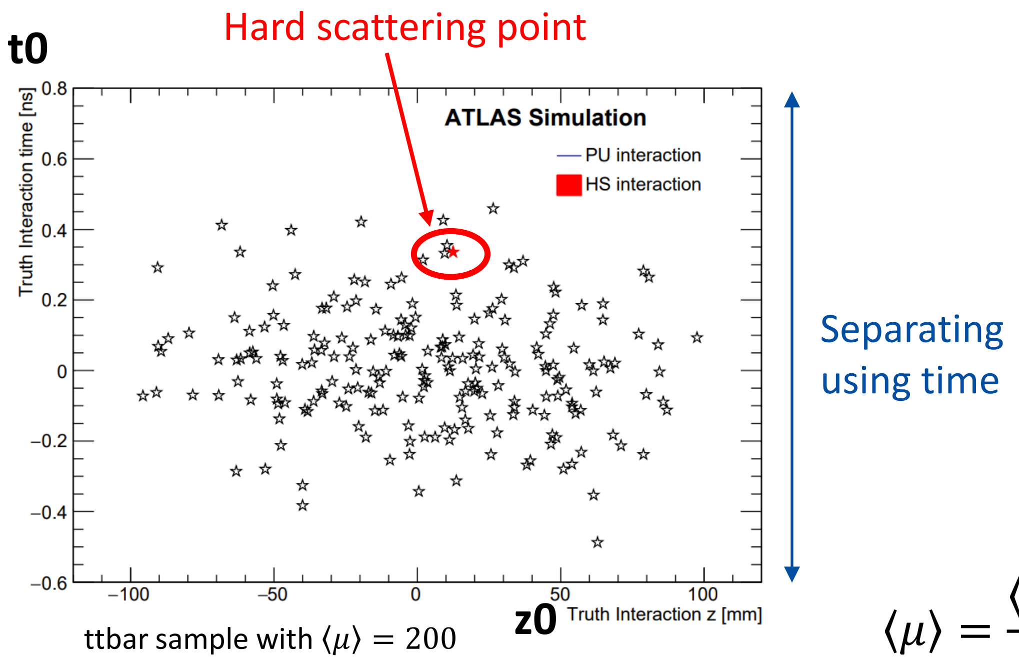
on behalf of USTC HGTD team

All the plots are from HGTD TDR except measurement results at USTC

Introduction | Pile-up

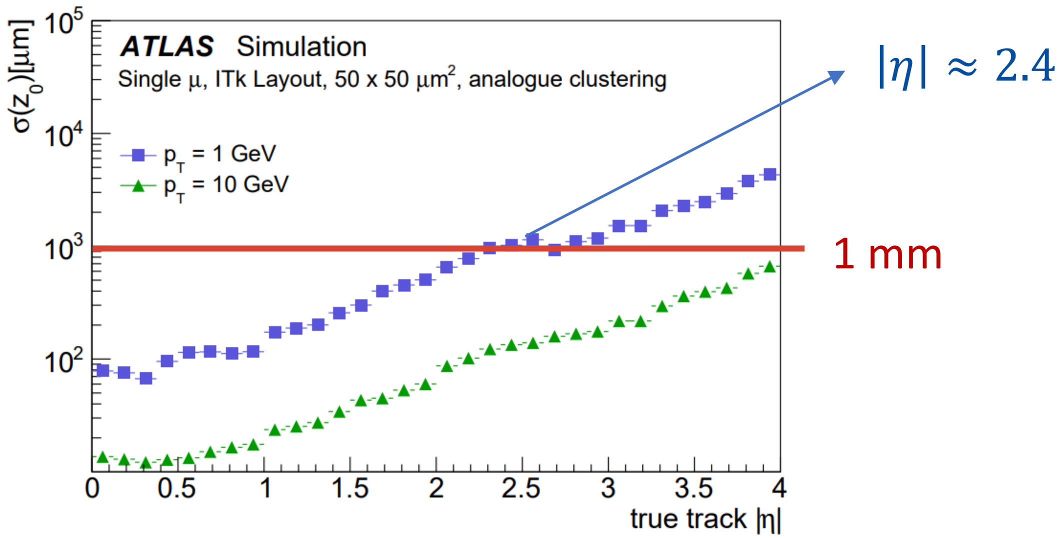


- **z0** and **t0** can both be used to separate pile-up from hard scattering
- **z0 resolution** in **high |η|** region is not good enough for ATLAS
- Adding **timing information** can improve the separation in the **high |η|** region



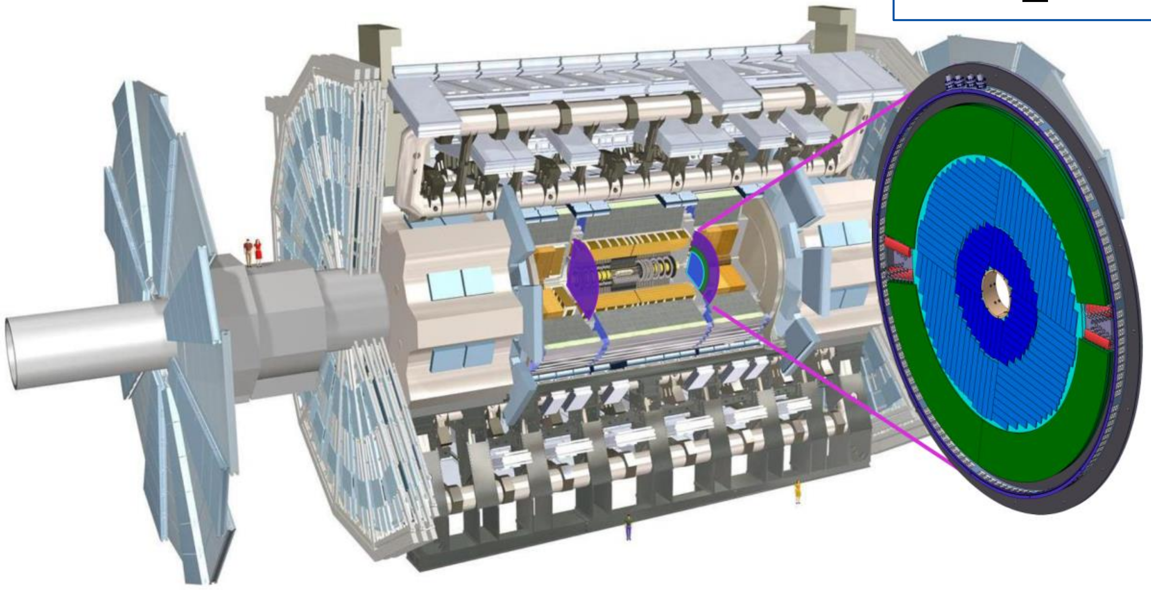
ttbar sample with $\langle\mu\rangle = 200$

$$\langle\mu\rangle = \frac{\langle\mathcal{L}_0\rangle\sigma_{\text{inelastic}}}{n_c f_{\text{rev}}}$$



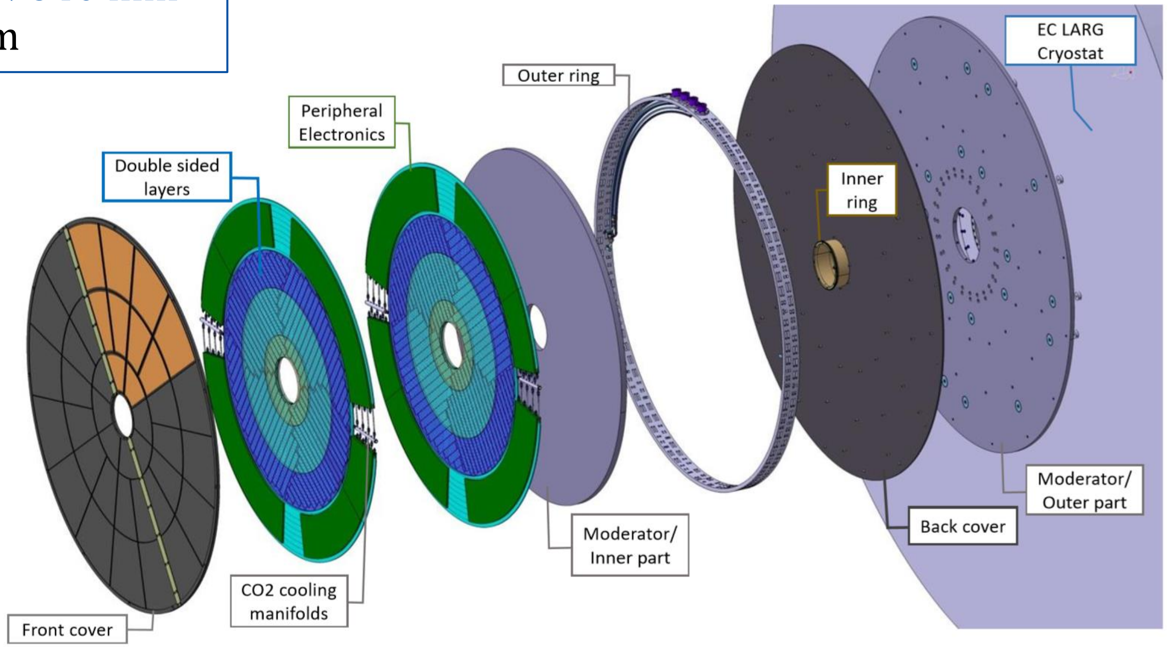
Introduction | HGTD

$2.4 < |\eta| < 4$
$120\ \mathrm{mm} < R < 640\ \mathrm{mm}$
$z = \pm 3500\ \mathrm{mm}$



ATLAS detector with HGTD
(**H**igh **G**ranularity **T**iming **D**etector)
installed

Part of ATLAS Phase II upgrade

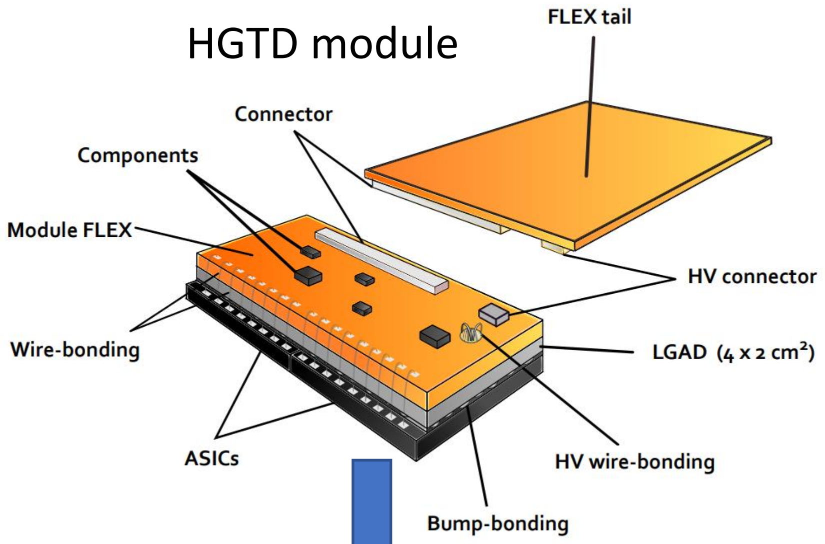


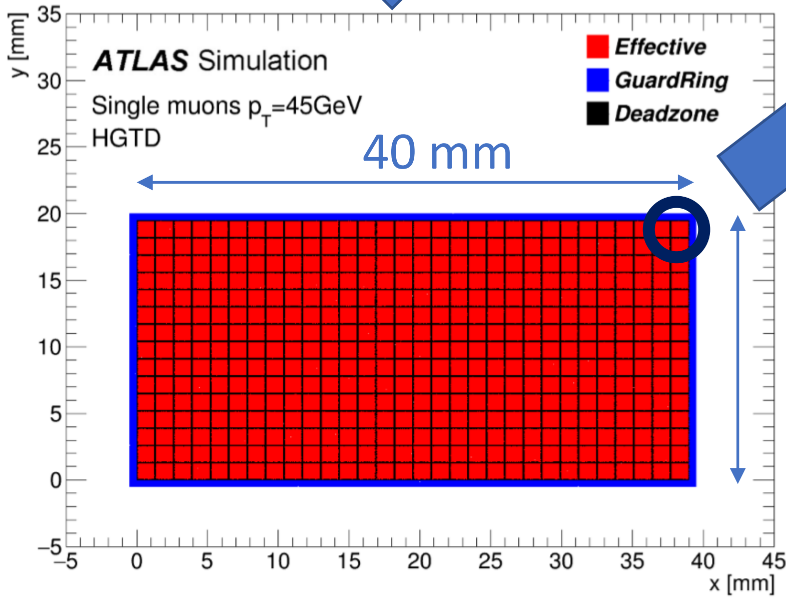
2 double-sided plates
4 layers, **8000** modules
3.6 million LGADs (**L**ow **G**ain **A**valanche **D**etector)

High granularity

Introduction | LGAD

HGTD module

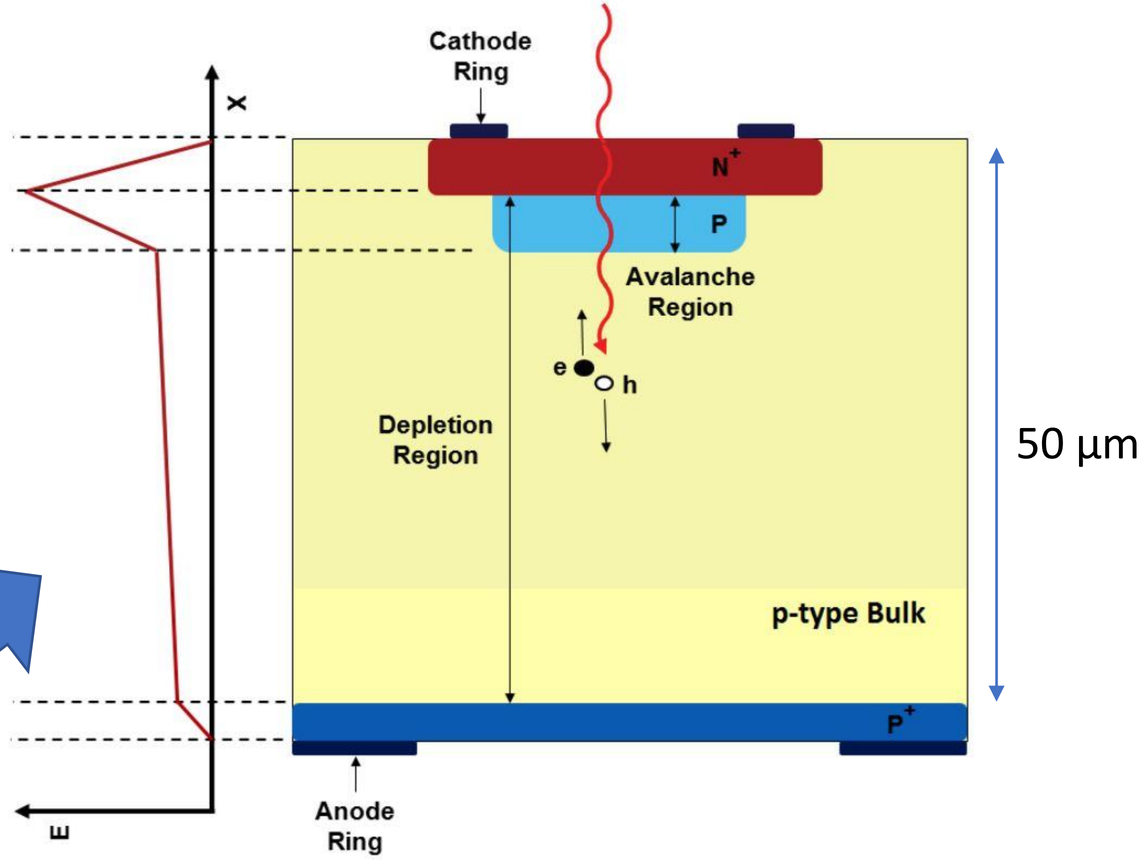




20 mm

15x30 array

1.3x1.3 mm each



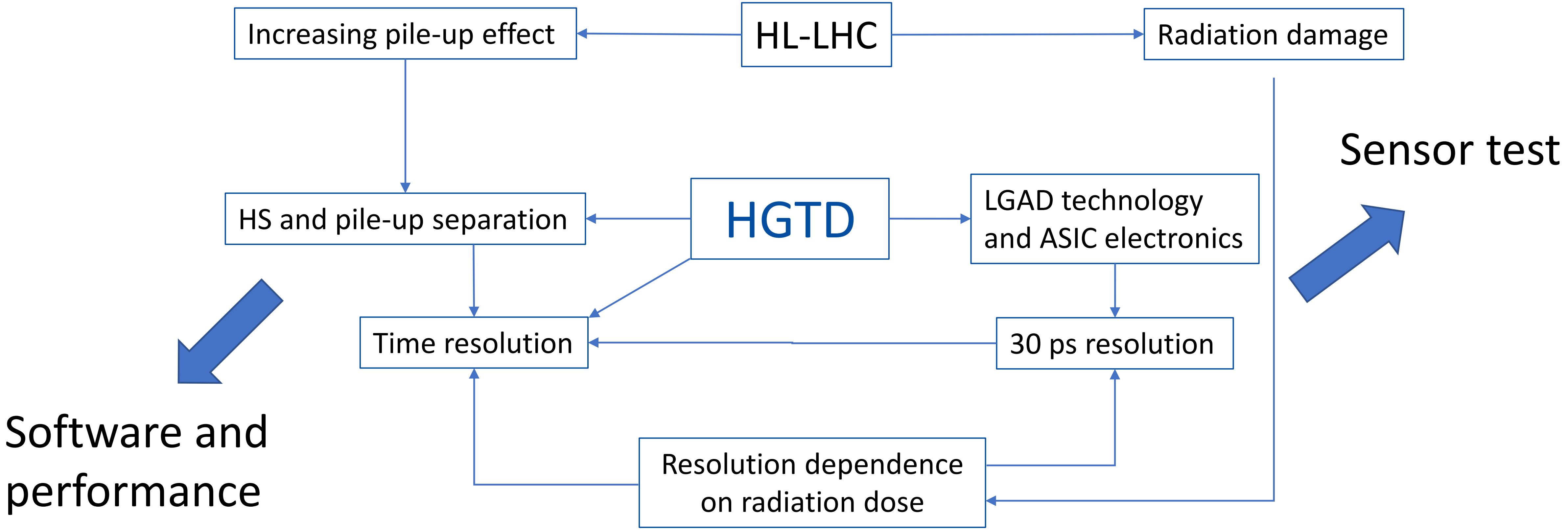
LGAD use the n^{++} (N^{+}) - p^{+} (P)- p structure

High E-field can provide ~20 gain

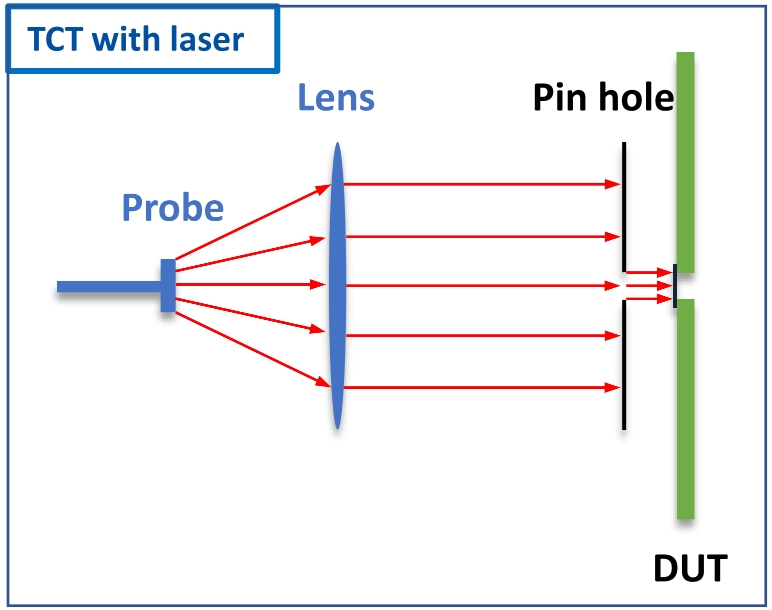
Dedicated ASIC electronics for HGTD

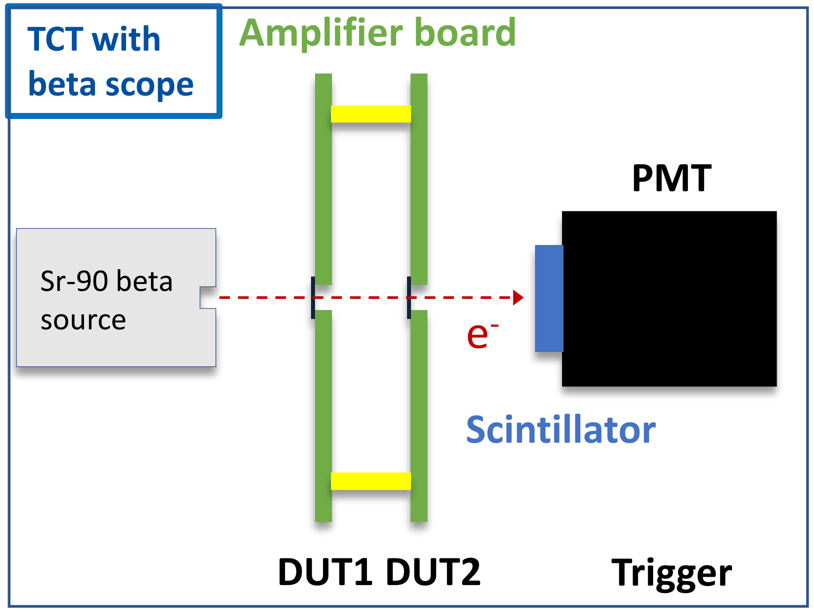
⇒ **30 ps resolution** for MIPs (before irradiation)

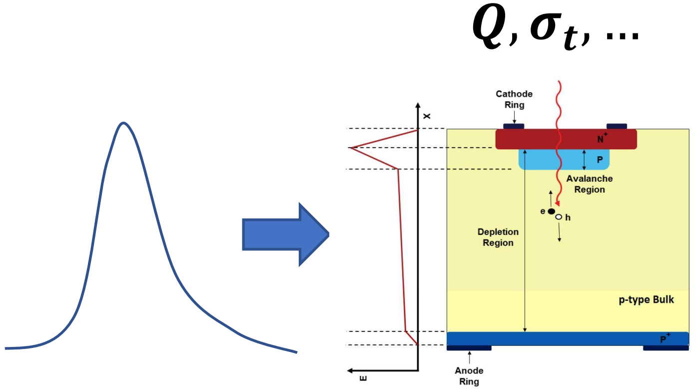
Introduction | Overview



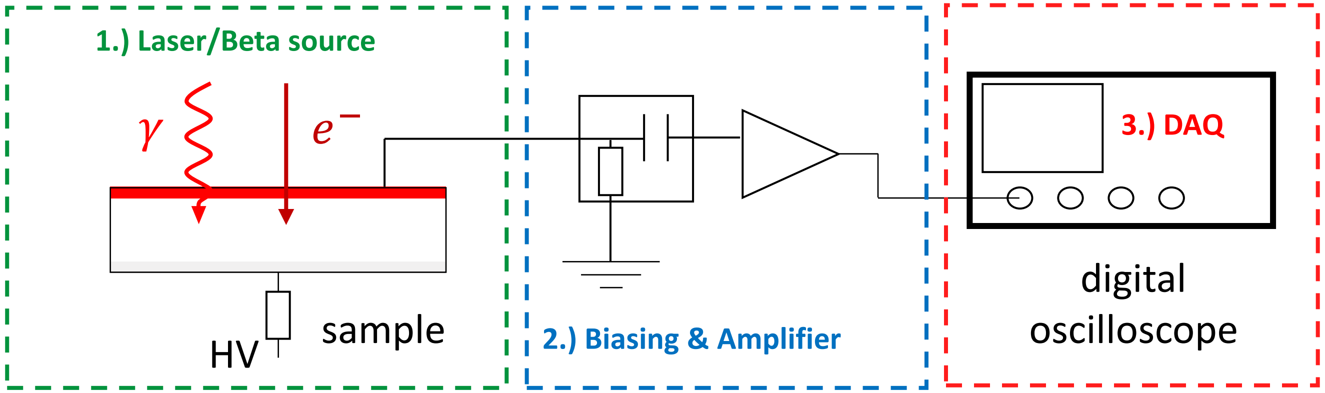
Sensor test | TCT measurement set up @USTC







TCT (**T**ransient **C**urrent **T**echnique)

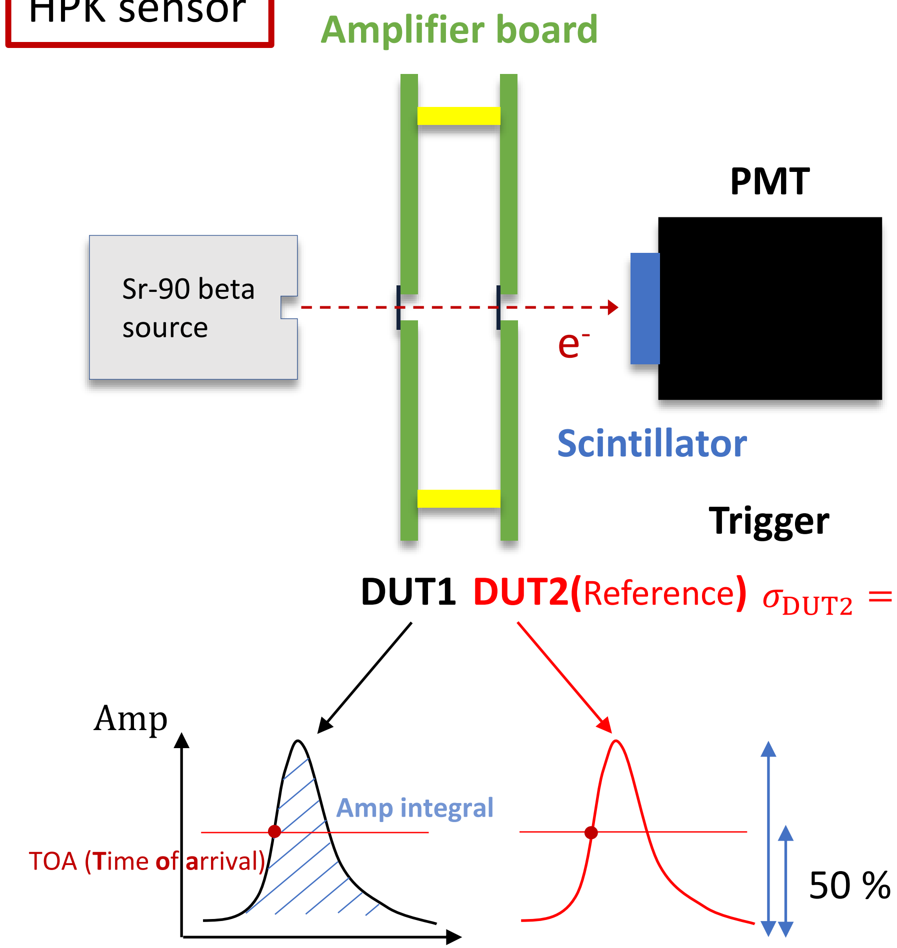


Established at USTC

HPK sensors

Sensor Test | Beta scope

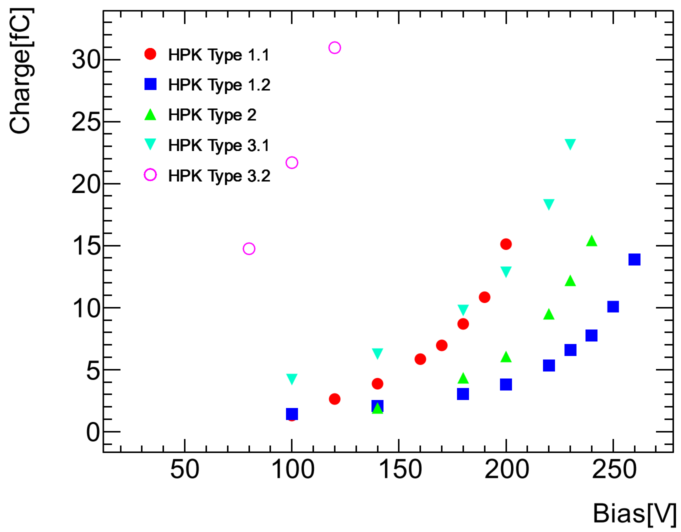
HPK sensor



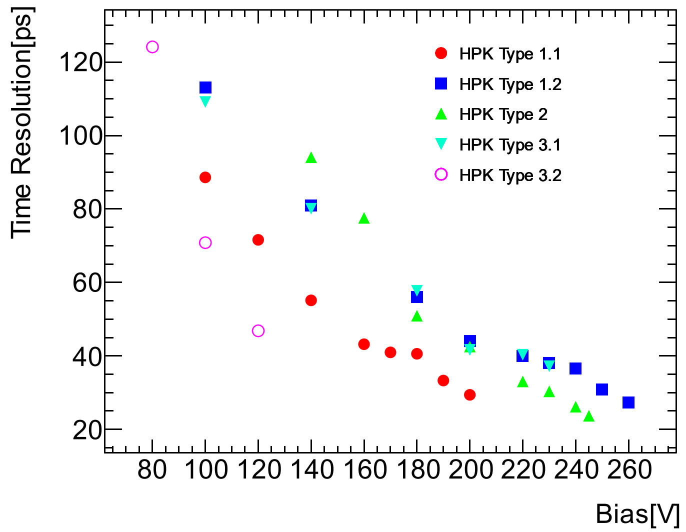
$\sigma_{\mathrm{DUT2}} = 35$ ps

t_1 t_2 CFD (Constant Fraction Discriminator) method

$$\sigma^2_{t_1-t_2} = \sigma^2_{\mathrm{DUT1}} + \sigma^2_{\mathrm{DUT2}}$$



Charge vs. Bias voltage

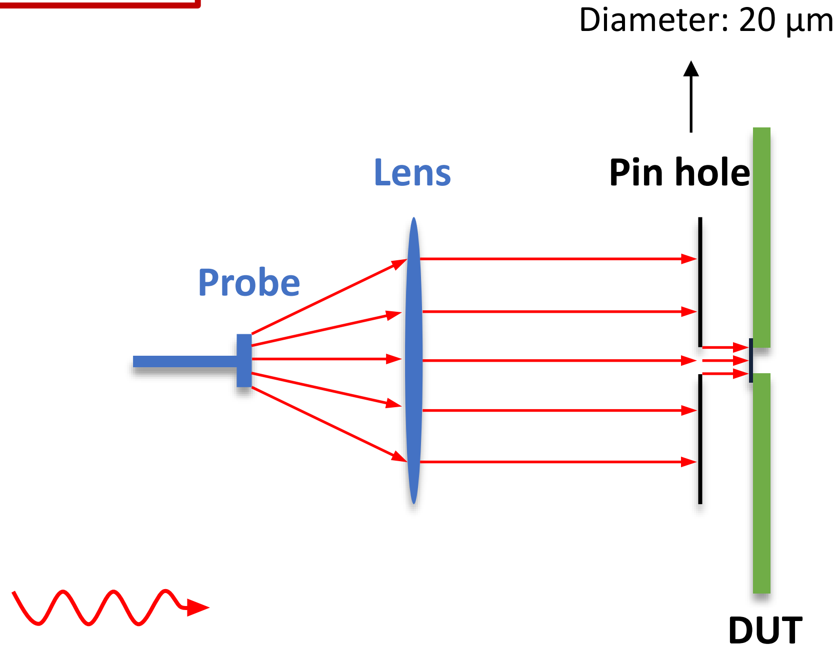


σ_t vs Bias voltage

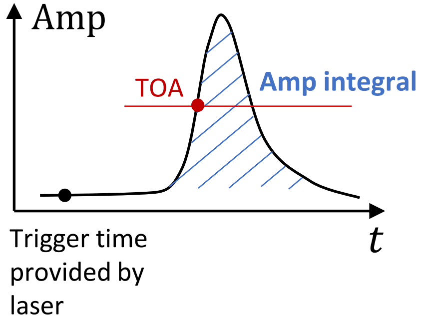
Consistent with results in TDR

Sensor test | Laser

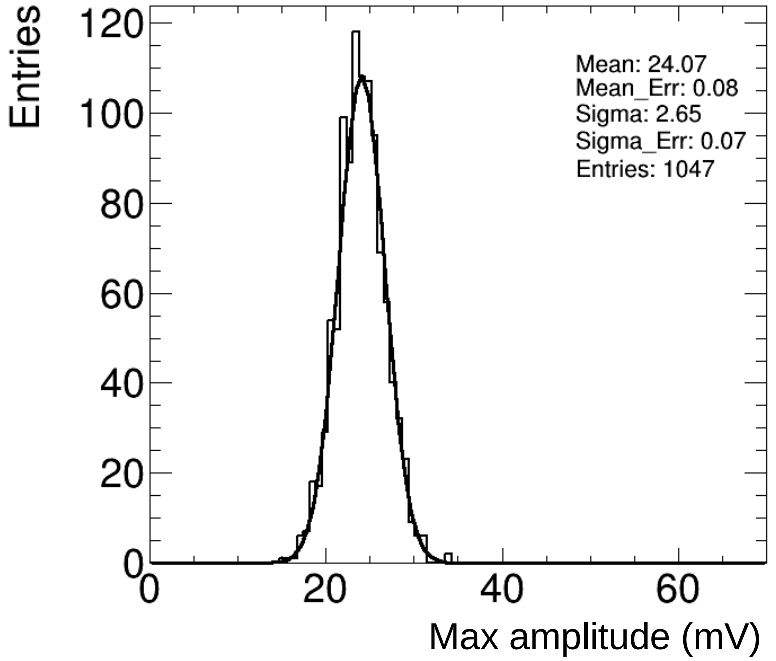
HPK sensor



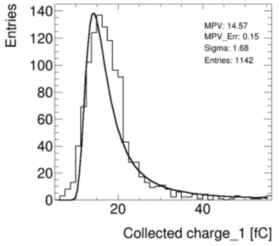
- Wavelength: 1064.29 nm
- Pulse width: 7.68 ps
- Pulse frequency: 21.9 MHz



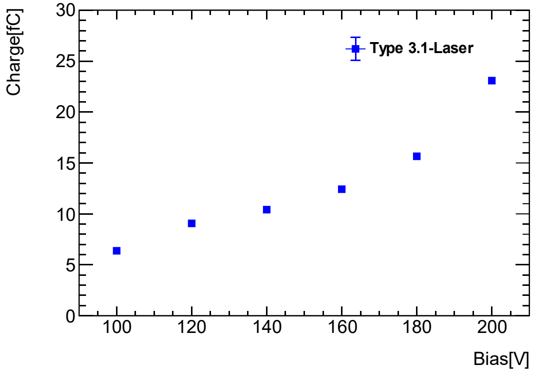
No Landau fluctuation in laser test in contrast with beta scope results



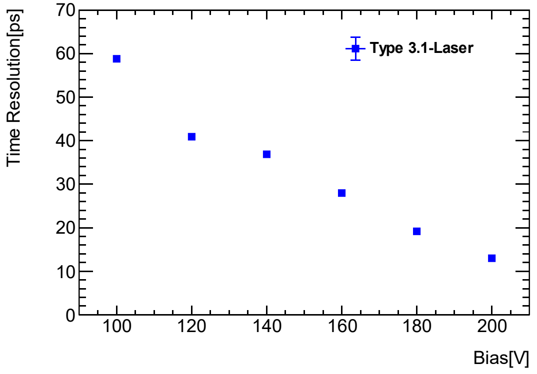
Beta scope results



Charge vs. Bias voltage

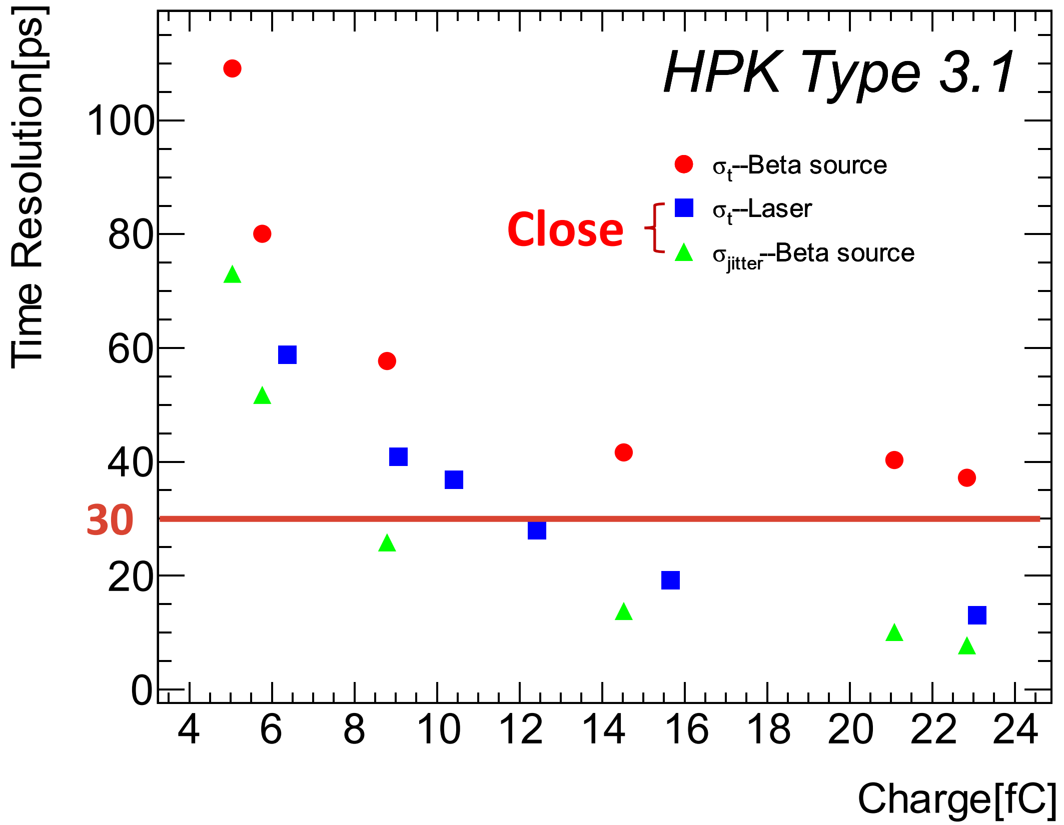


σ_t vs Bias voltage



Sensor test | Time resolution

HPK sensor type 3.1



$$\sigma_t^2 = \sigma_{\mathrm{Landau}}^2 + \sigma_{\mathrm{timewalk}}^2 + \boldsymbol{\sigma_{\mathrm{jitter}}^2}$$

$\sigma_{\mathrm{timewalk}}$ is corrected and reduced with CFD method

$$\boldsymbol{\sigma_{\mathrm{jitter}}} = \frac{N}{\mathrm{d}V/\mathrm{d}t} = \frac{N}{S/t_{\mathrm{rise}}}$$

N: noise

S: signal

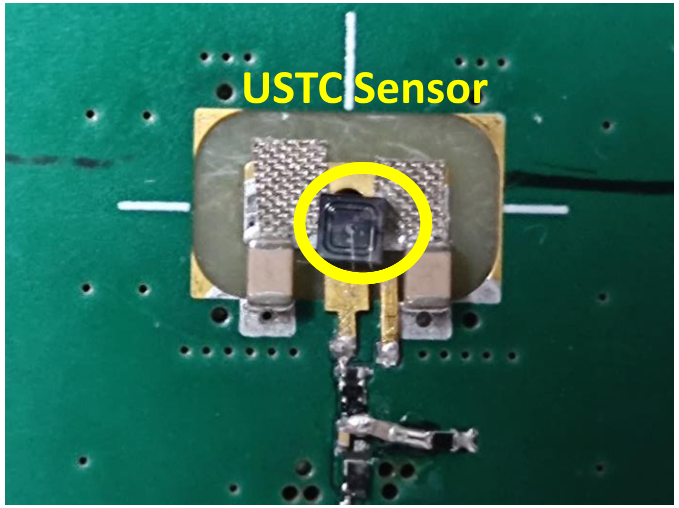
t_{rise}: rising time of signal

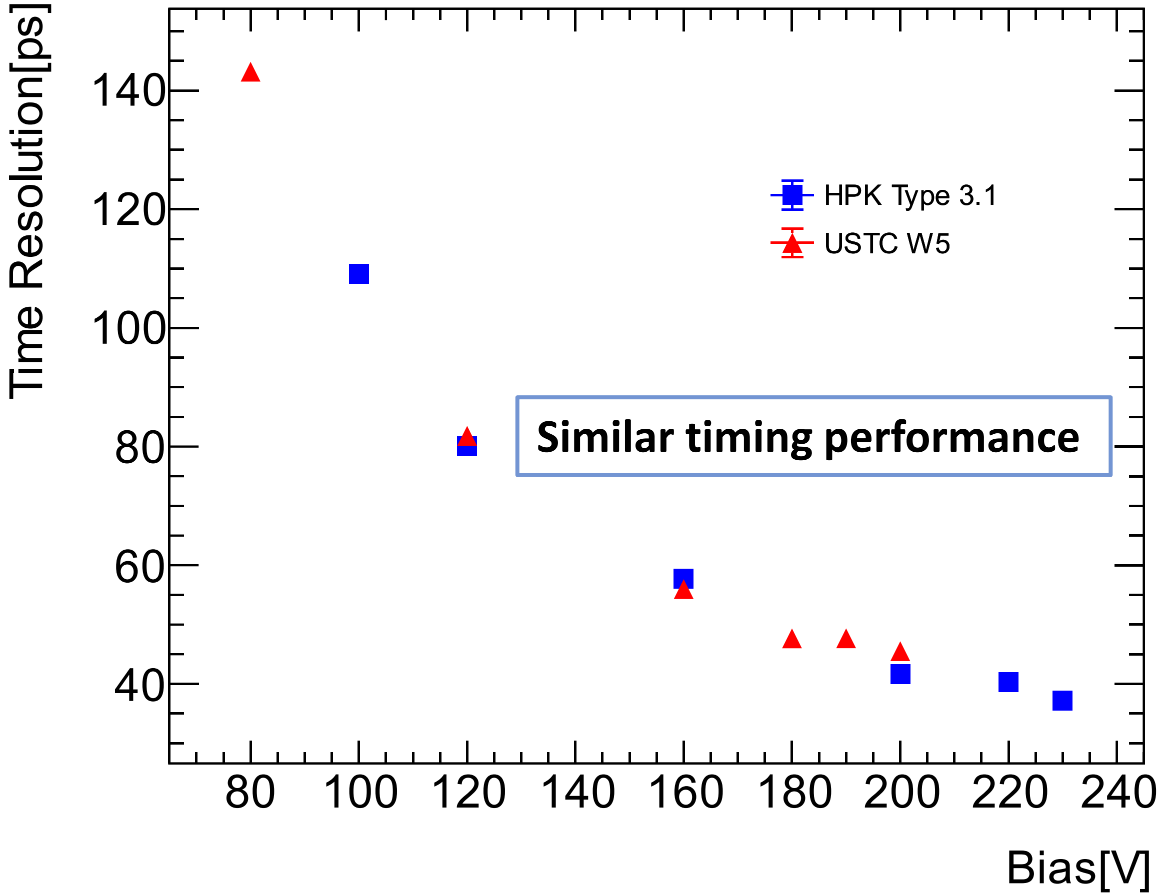
σ_t-laser is close to **σ_{jitter}-beta scope**

Time resolution at **10 fC** is about **30 ps**, which satisfies current specification

Sensor test | USTC sensor

USTC sensor



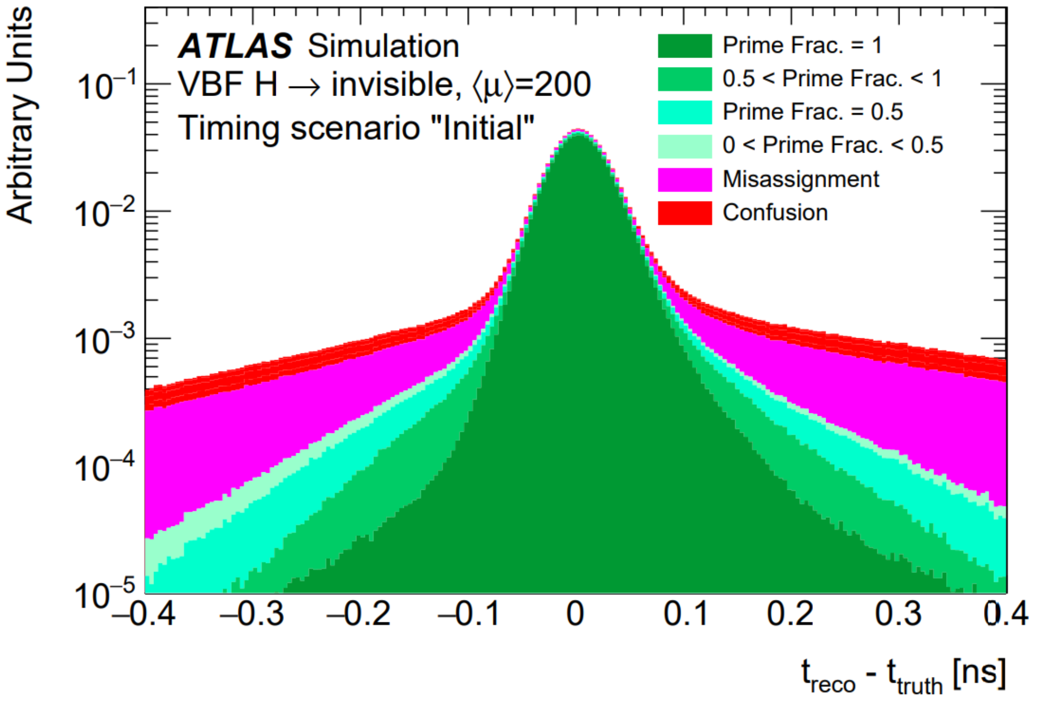


Designed by USTC and produced by IME

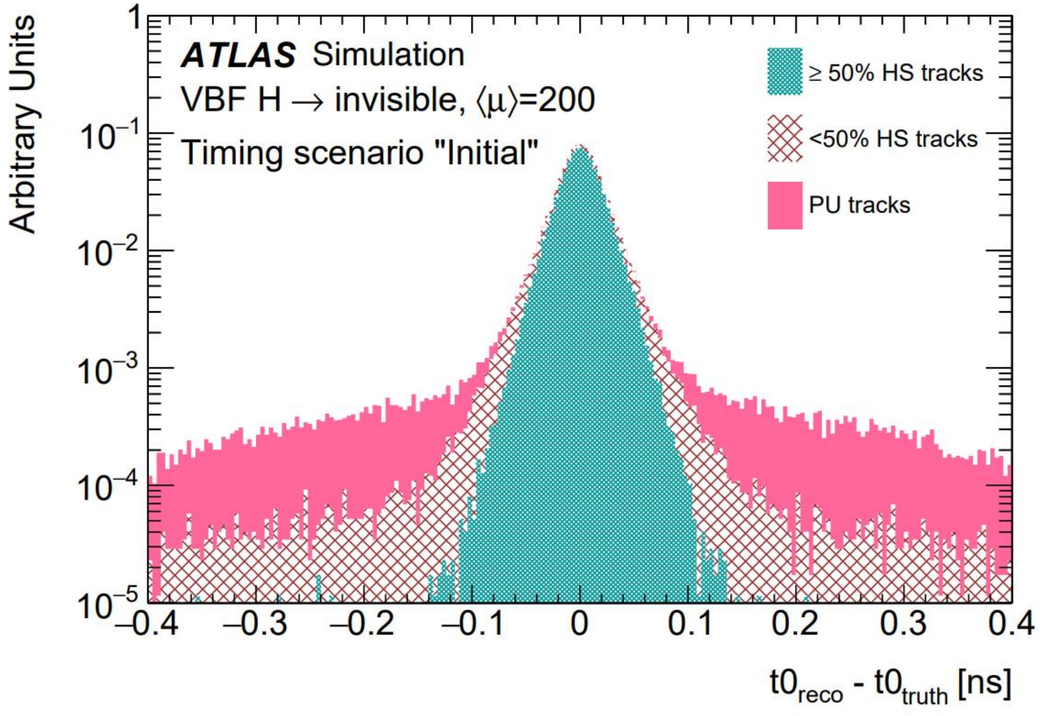
Also **satisfy** current specification for HGTD

More details **in Xiao Yang's talk** (link)

Software and performance | Performance overview



$t_{\mathrm{reco}} - t_{\mathrm{truth}}$ distribution for VBF H(inv) events

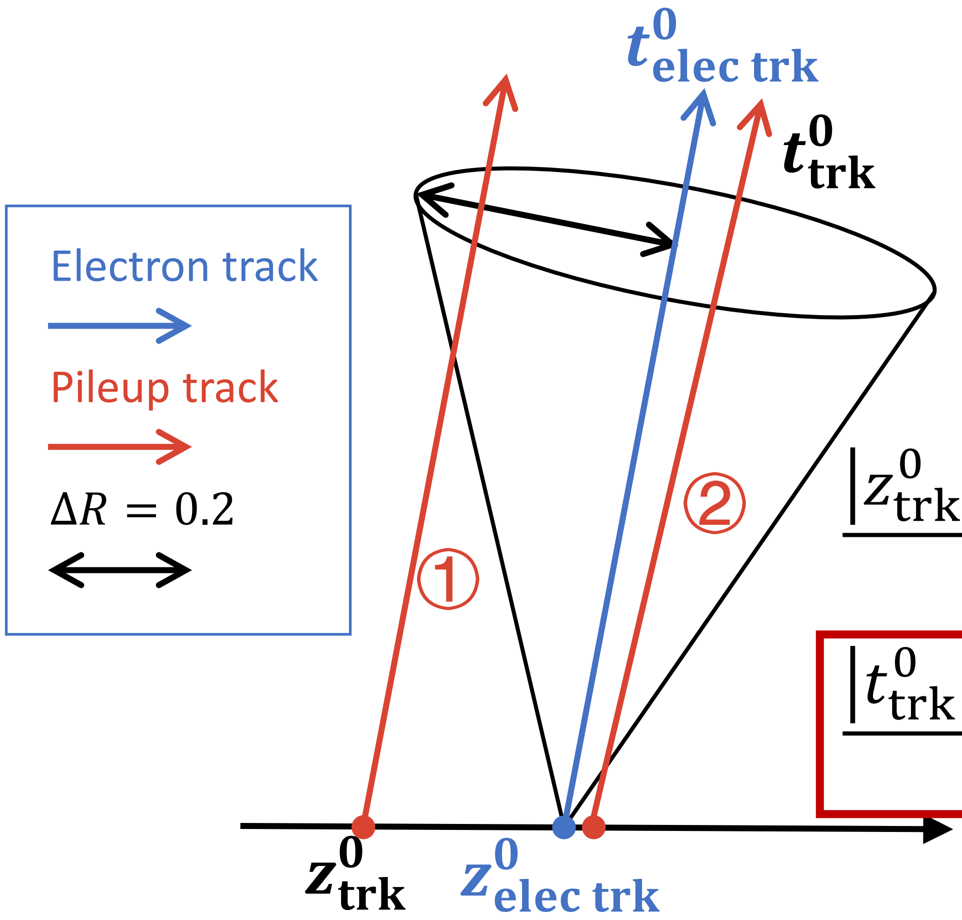


$t^0_{\mathrm{reco}} - t^0_{\mathrm{truth}}$ distribution for VBF H(inv) events

HGTD can provide a way to determine $\boldsymbol{t_0}$ (time of the **primary vertex**) information for tracks

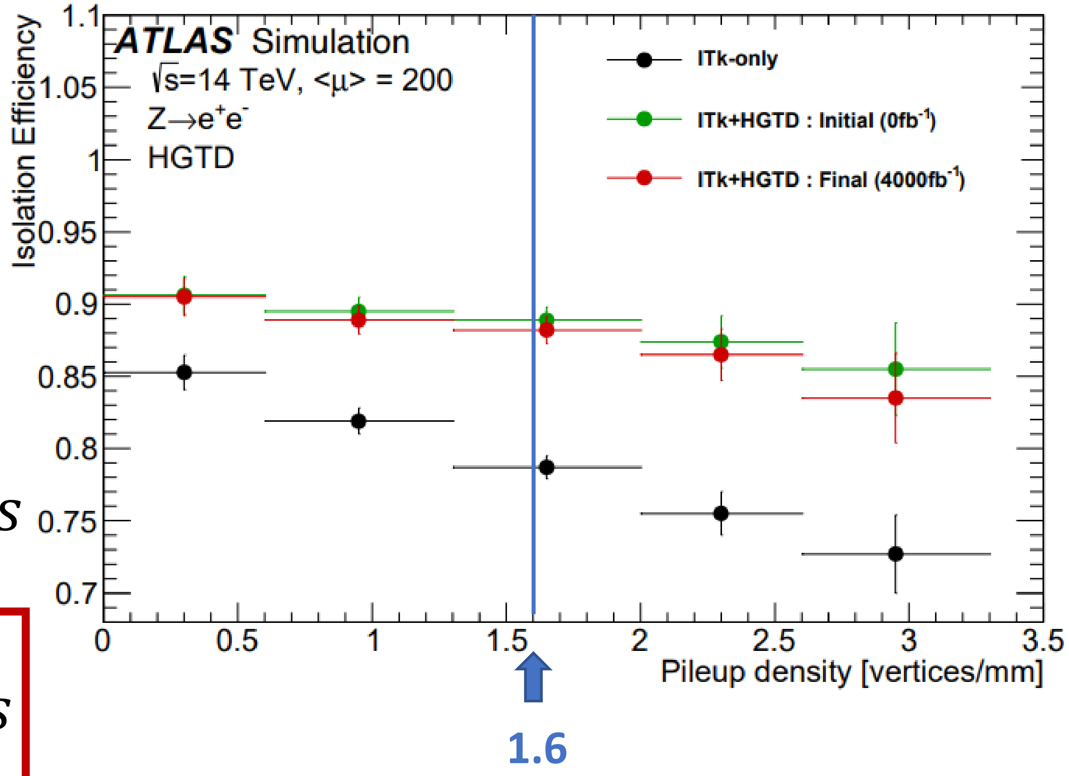
Software and performance | Lepton isolation

Identifying **pile-up** tracks ➡ **Un-isolated** electron relabeled as **isolated** electron



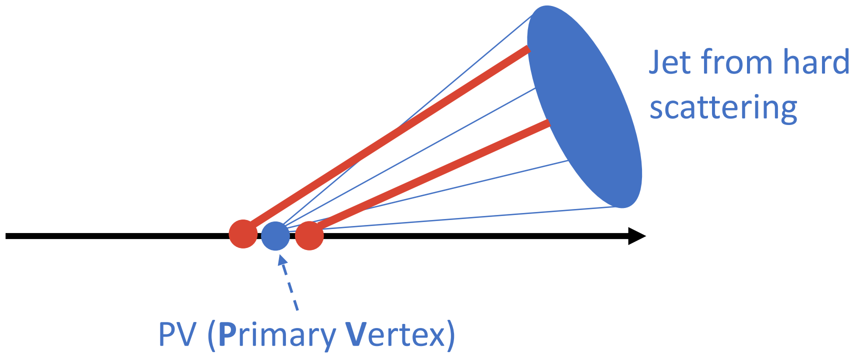
$$\frac{\left|z^0_{\text{trk}} - z^0_{\text{elec trk}}\right|}{\sigma_{z_0}} > s$$

$$\frac{\left|t^0_{\text{trk}} - t^0_{\text{elec trk}}\right|}{\sigma_t} > s$$



Improve about **10%** at **1.6** vertices/mm

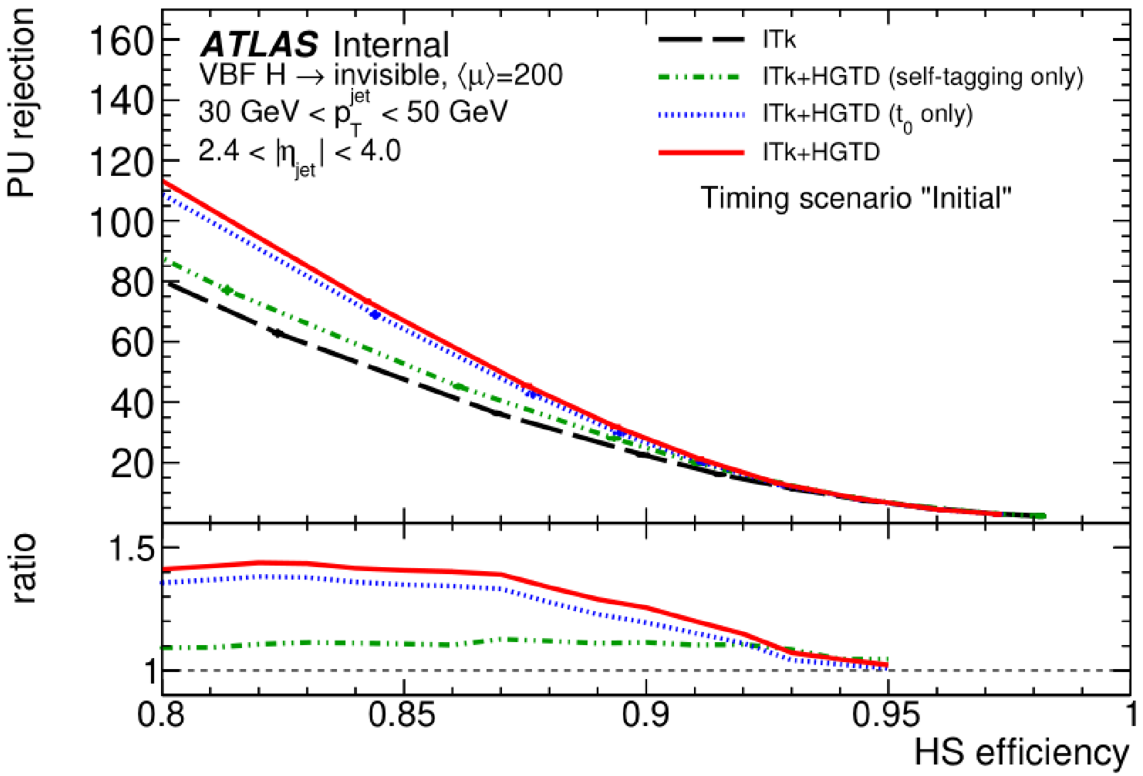
Software and performance | Pileup jet suppression



$$R_{p_T} = \frac{\sum p_T^{trk}(PV_0)}{p_T^{jet}} \quad \begin{cases} R_{p_T} > s, & \text{Hard scattering jet} \\ R_{p_T} < s, & \text{Pile-up jet} \end{cases}$$

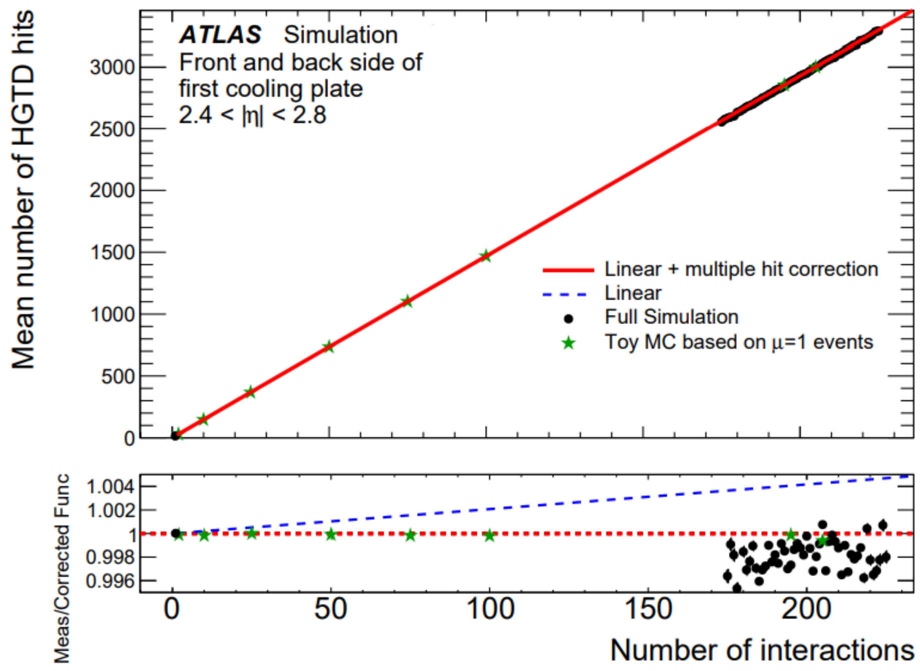
Timing information → **Enhance** → Subtract **pile-up** tracks → Correctly label mislabeled **HS** jet

Improve up to about **50%** at **85%** signal (HS) efficiency

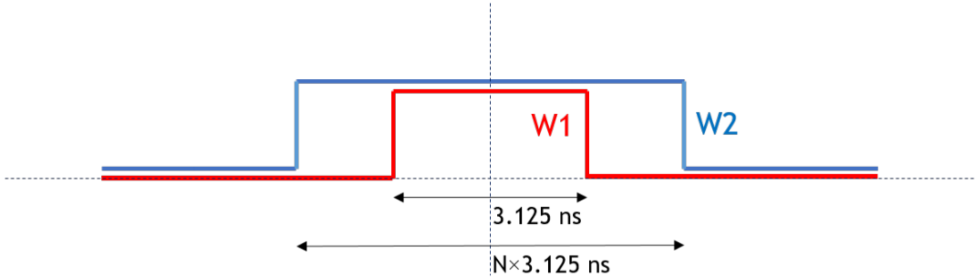


(a) Jets with 30 GeV $< p_T <$ 50 GeV.

Software and performance | Luminosity measurement



(a) Linearity of $\langle n_{\text{hits}} \rangle$ as a function of μ.



- HGTD as a luminometer
  - **High granularity** gives **low occupancy** $\Rightarrow \langle n_{\text{hits}} \rangle \propto \langle \text{pp interaction} \rangle$
  - Special **two-timing-window scheme** at ASIC level to provide in-situ measurement for noise and afterglow
- Analysis channels can benefit from precise luminosity measurement:
  - ggH(→γγ)
  - ggH(→ZZ*)
  - ggH+VBF, H→ττ
  - …

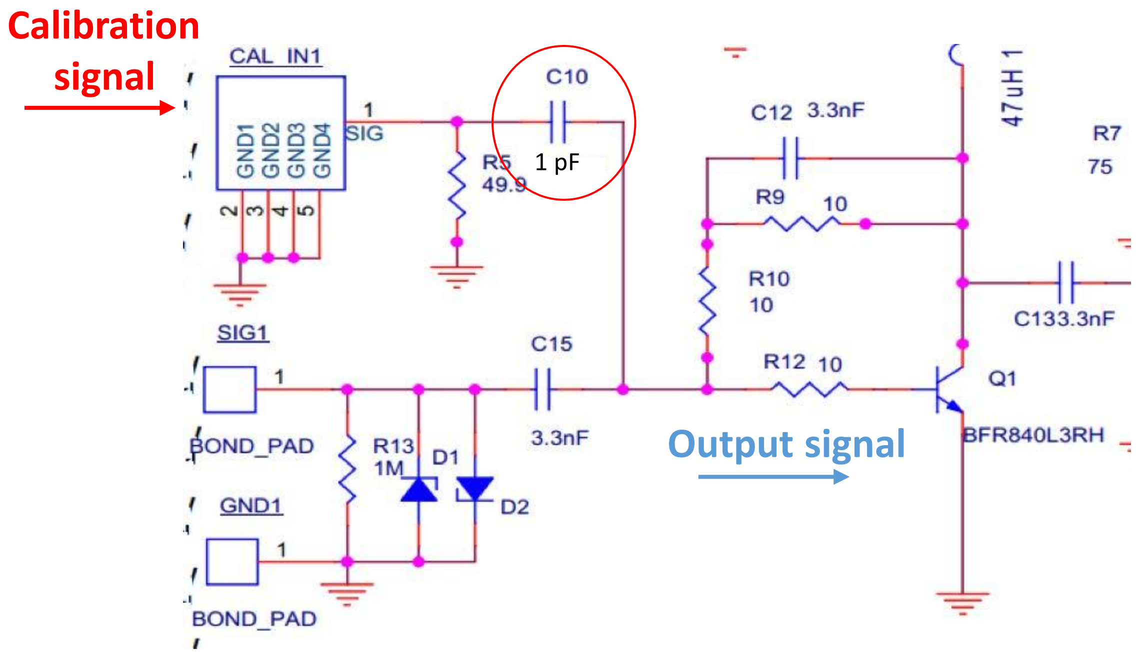
Summary

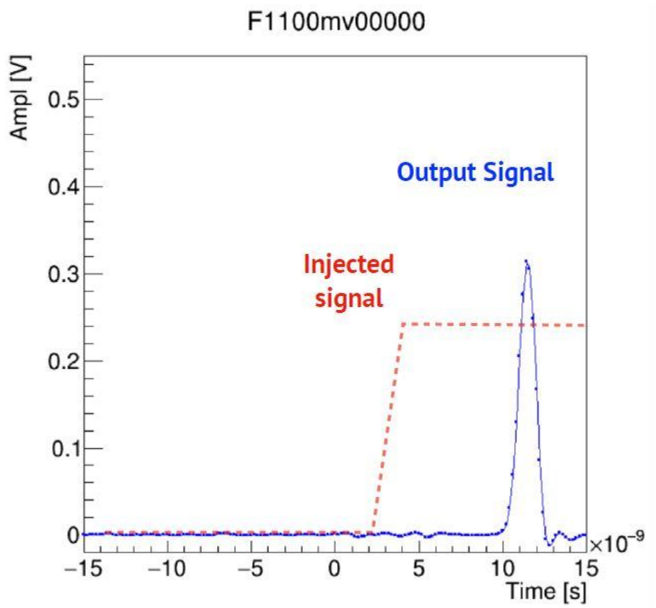
- HGTD, a **novel detector** to be installed on HL-LHC in the forward region, can provide **high-precision timing information** for charged particles;
- The **LGAD** technology is used, R&D work is being performed to measure the time resolution of the candidate sensors, and their characteristics **agree with** what's expected for un-irradiated sensors;
- Performance studies has been done to explore the full potential of HGTD, and it has been shown the timing information can improve physics studies in multiple ways
- More results coming!

Thanks for listening!

Backup

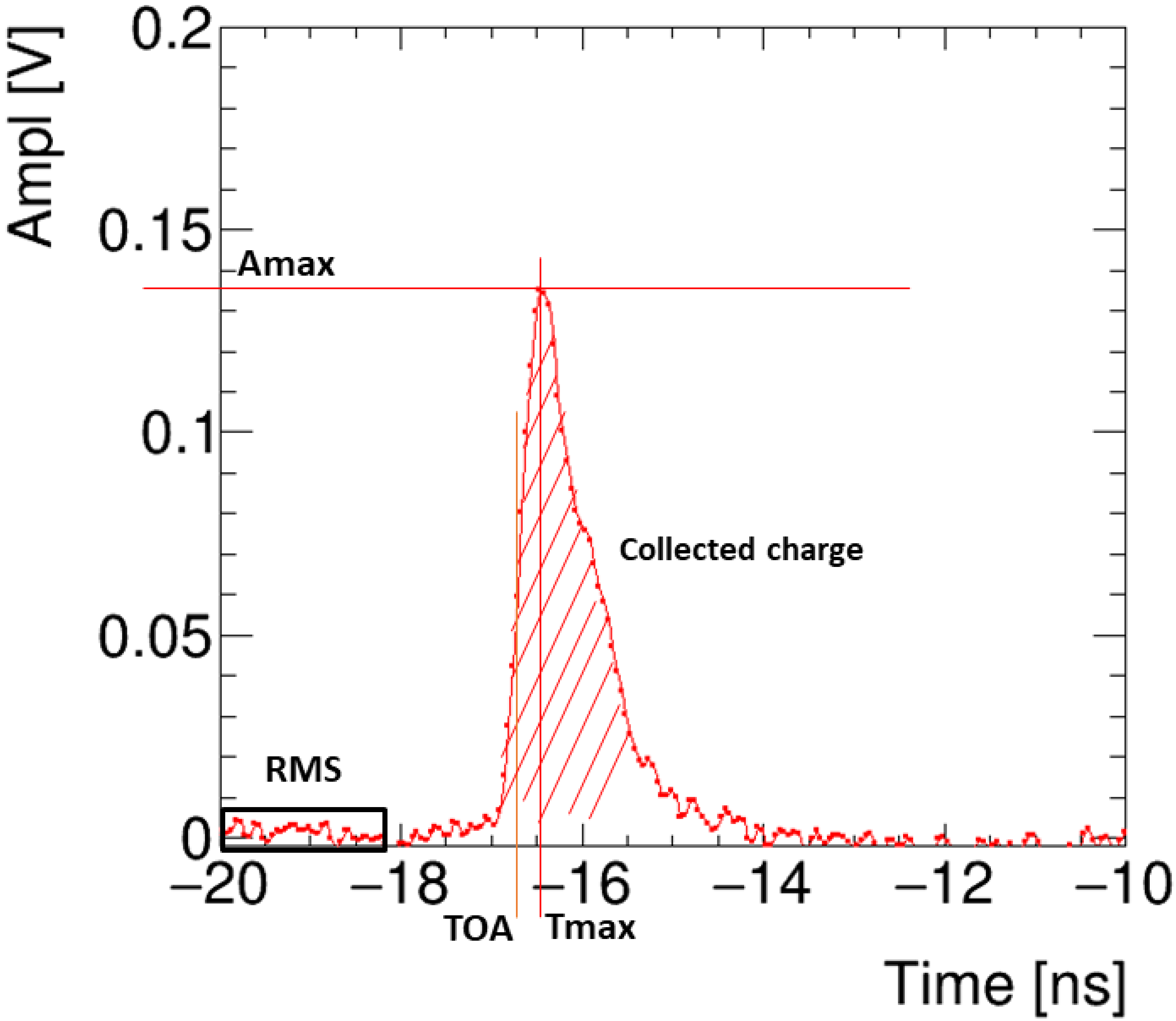
Calibration





- Calibration signal generated by signal generator with attenuator
- Injected signal leading edge ~1 ns
- Injected charge Q= ΔV*1 pF
- Average result of 1000 signals
- $\text{Calibration constant} = \frac{\text{Injected charge}}{\text{Voltage integral}}$

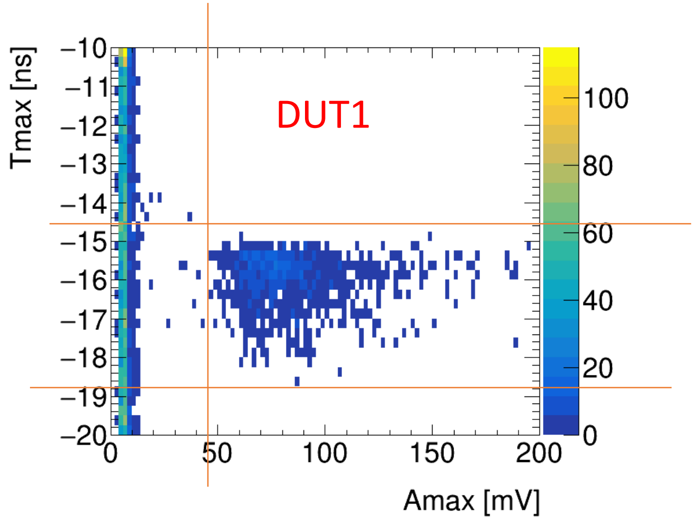
Waveform analysis

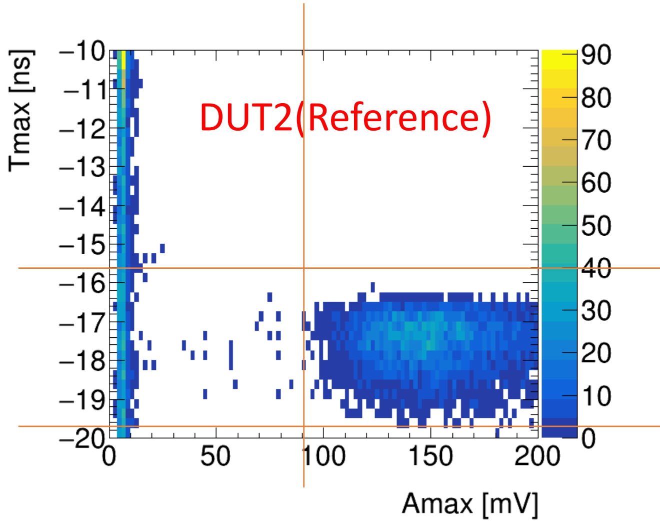


- **Amax**: the maximum amplitude of the waveform
- **Tmax**: time when the amplitude of the waveform is maximum
- **RMS**: RMS of the head part of the waveform (before the peak)
- **TOA**: time when the amplitude of the signal crosses 0.5*Amax
- **Collected charge**: the peak integral divide by the calibration constant

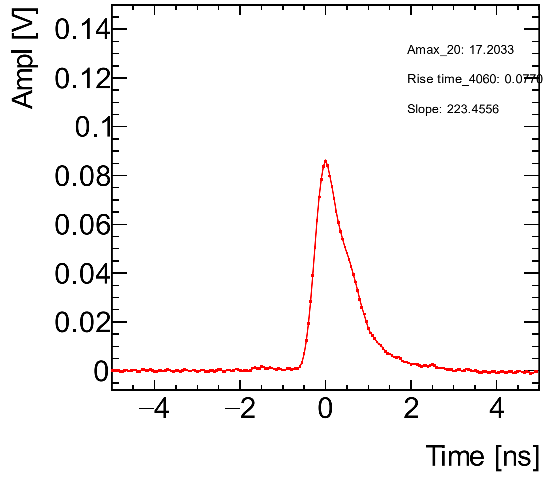
Events selection

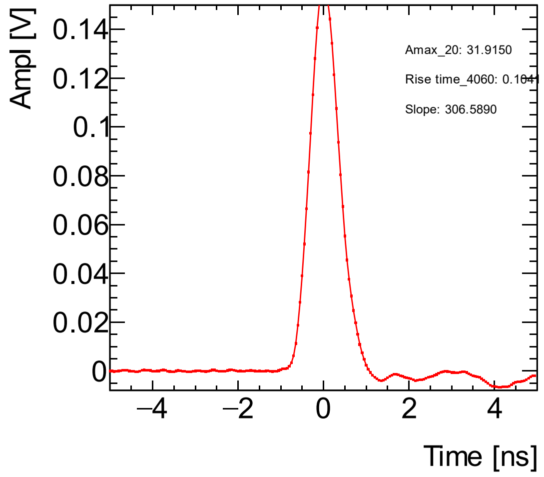
- Events recorded when the PMT is triggered
- Events chosen as the signal events while the events on both DUT1 and DUT2 are in the signal region (cut applied on the 2d distribution of Amax and Tmax)



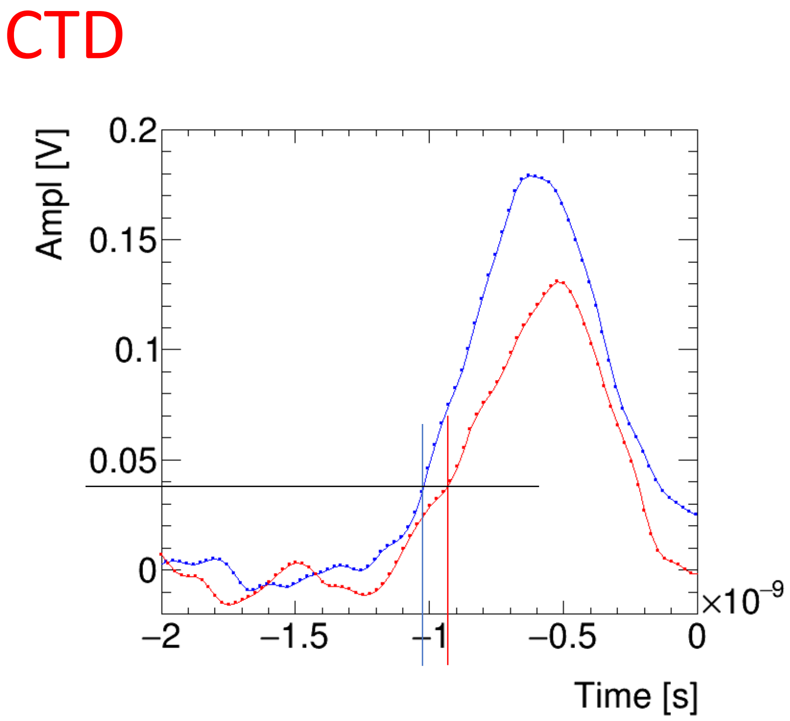


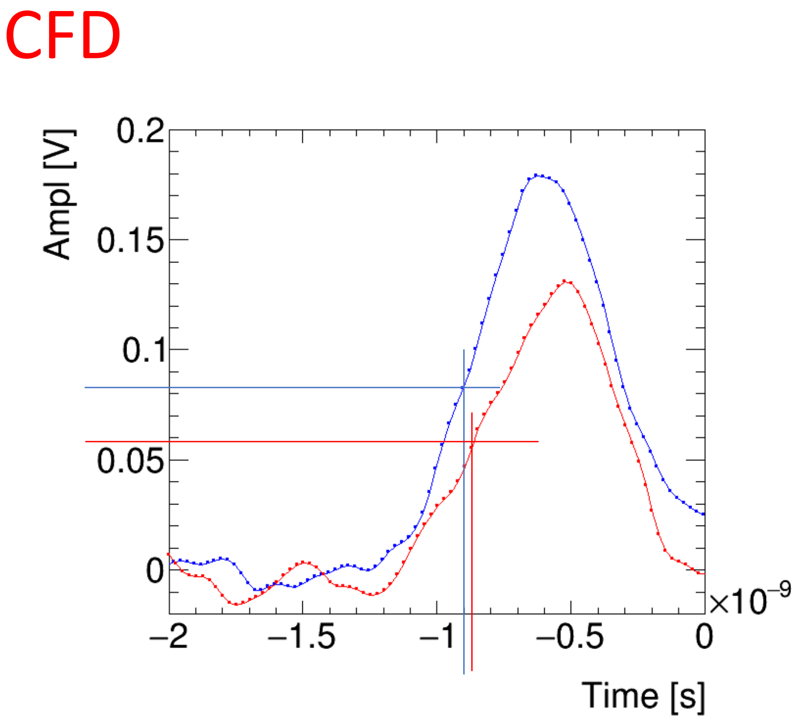
Tmax: time when the amplitude of the waveform gets maximum
Amax: the maximum amplitude of the waveform





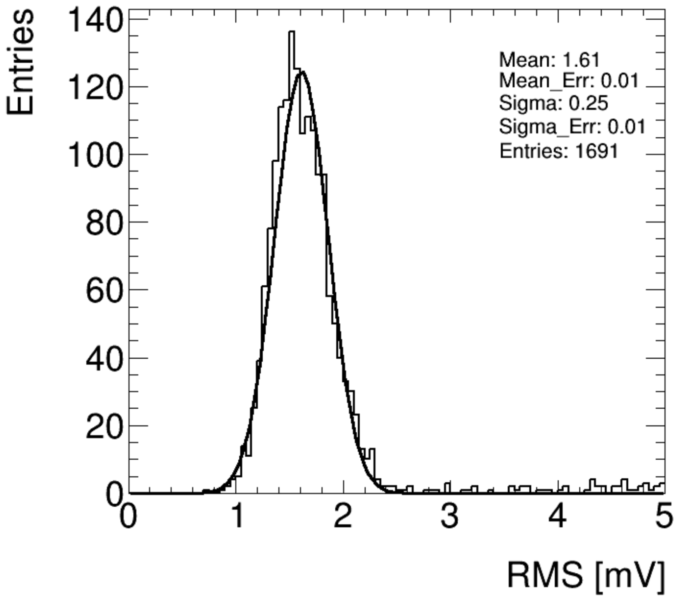
Time reconstruction

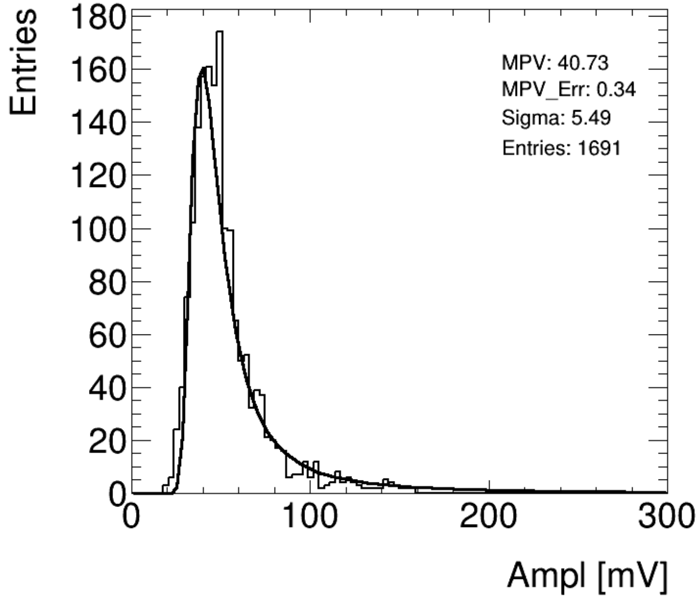


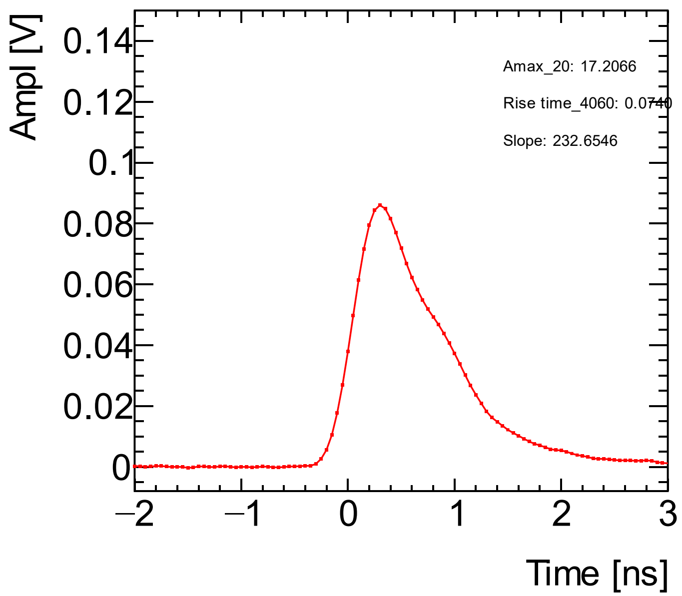


- CTD(Constant Threshold Discriminator): the time of arrival is defined as the time where the signal crosses a constant threshold. The effects of time-walk can be corrected if the signal amplitude is known.
- CFD(Constant Fraction Discriminator): the time of arrival is defined as the time where the signal crosses a constant fraction (f_{CFD}) of the maximum amplitude. However, since the threshold is crossed before the maximum amplitude is reached, this method cannot be implemented in the read-out electronics.
- CFD is used in the offline analysis.

Jitter estimation





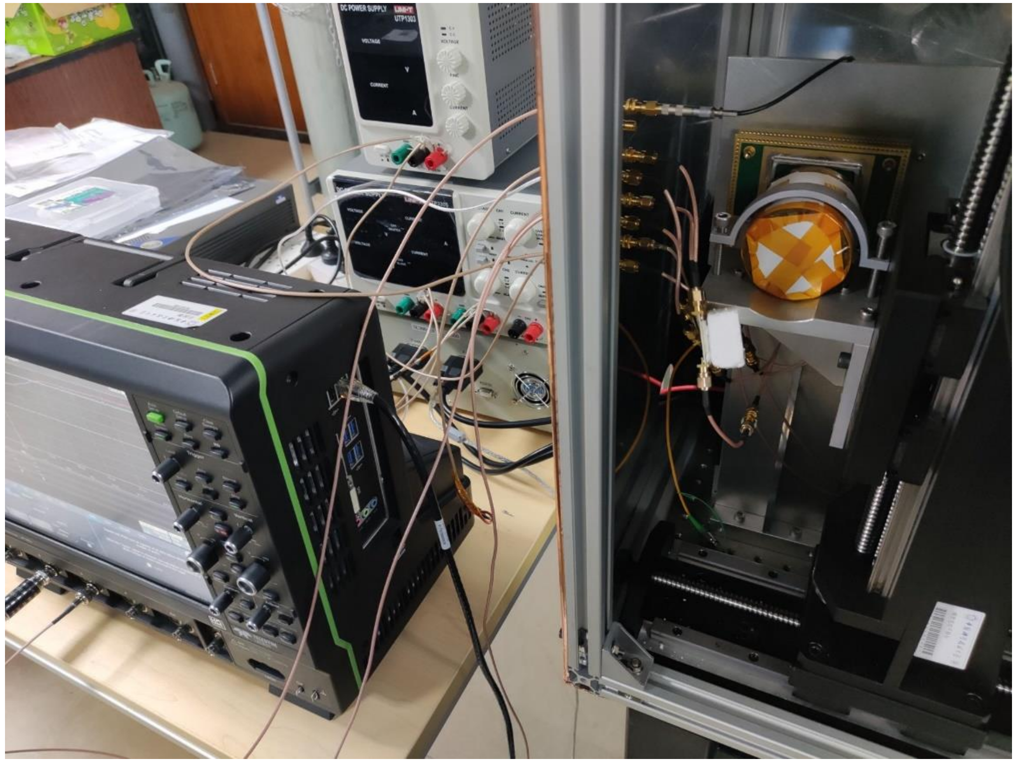


$$\sigma_{\mathrm{jitter}} = \frac{\mathrm{RMS}}{\mathrm{slope}} = \frac{\mathrm{RMS}}{\frac{\mathrm{Ampl} * 20\%}{T_{60\%} - T_{40\%}}}$$

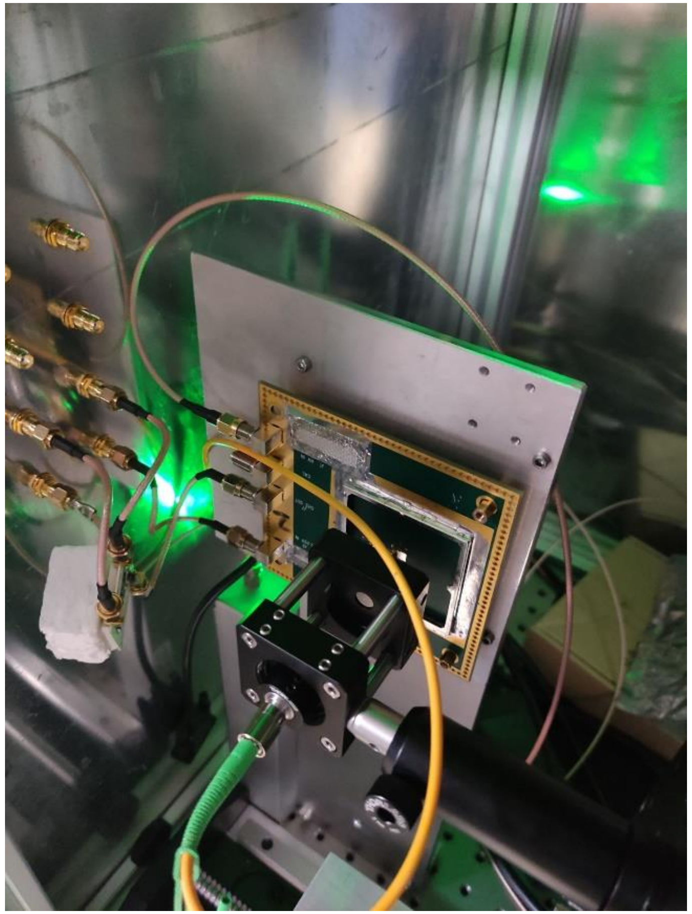
RMS: Mean of the RMS distribution

Ampl: MPV of the maximum amplitude distribution

$T_{40\%(60\%)}$: Time when the **average** waveform reach 40%(60%) of the maximum amplitude



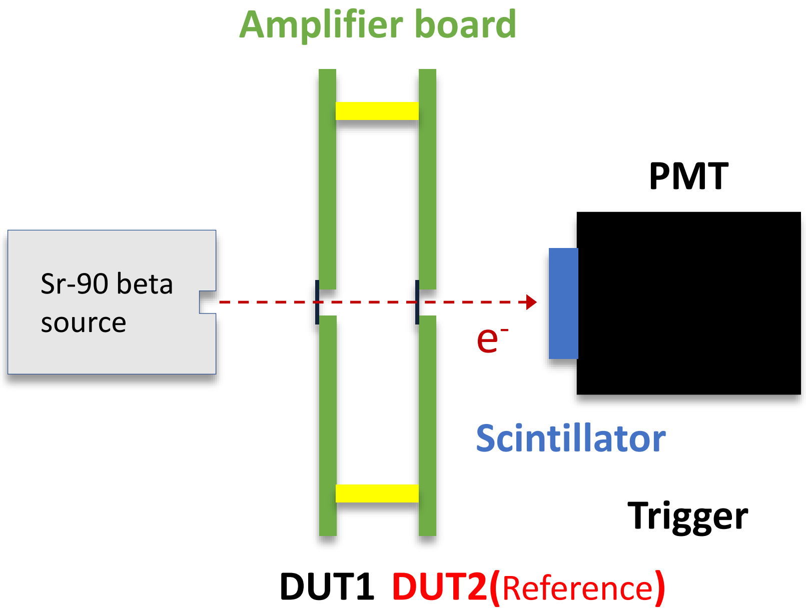
Beta scope test

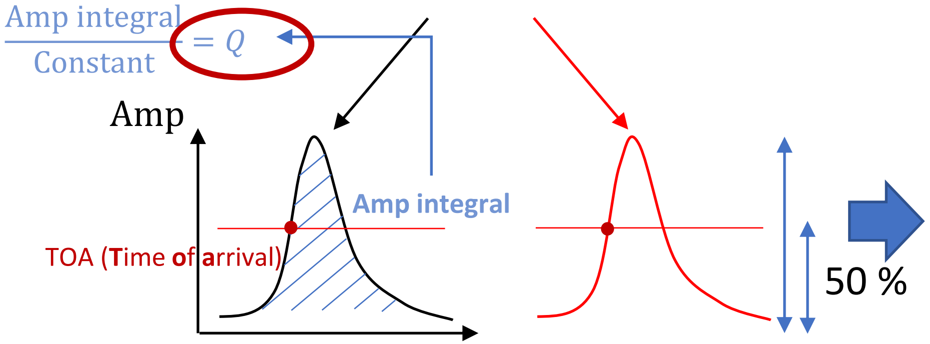


Laser test

Sensor Test | Beta scope

HPK sensor





t_1 t

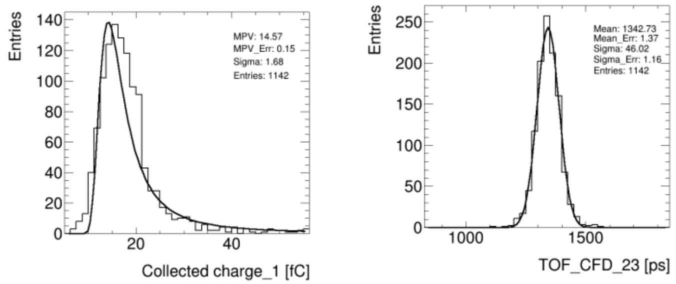
t_2 CFD (**C**onstant **F**raction **D**iscriminator) method

HPK Type 3.1 sensor at 230 V

$\sigma_{DUT2} = 35\text{ ps}$

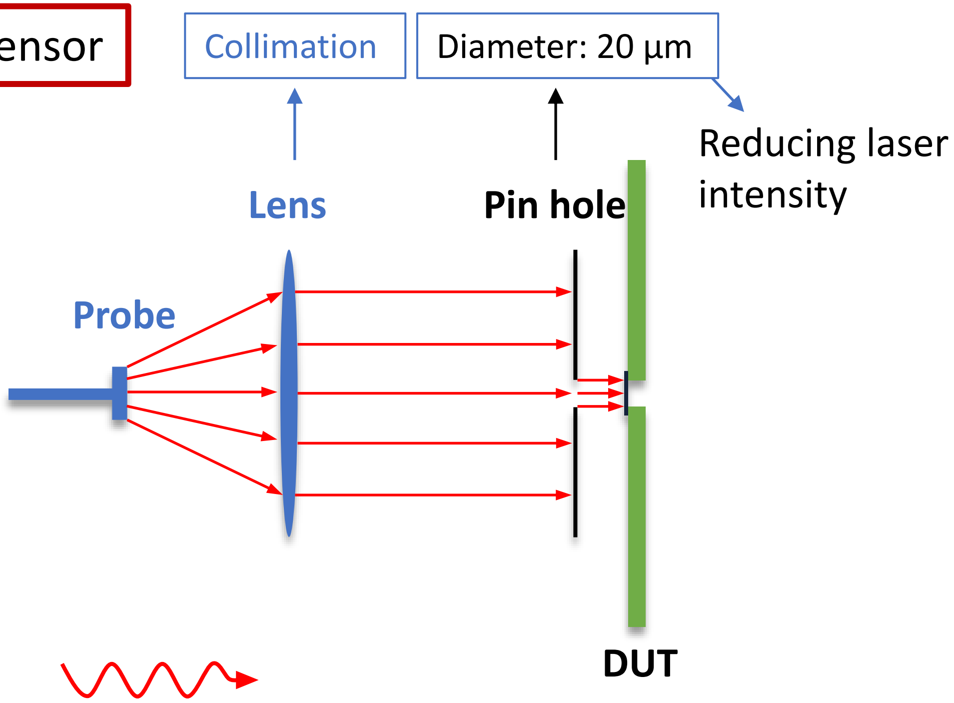
$t_{TOF} = t_2 - t_1 \quad \sigma^2_{t_{TOF}} = \sigma^2_{DUT1} + \sigma^2_{DUT2}$

Q t_{TOF}



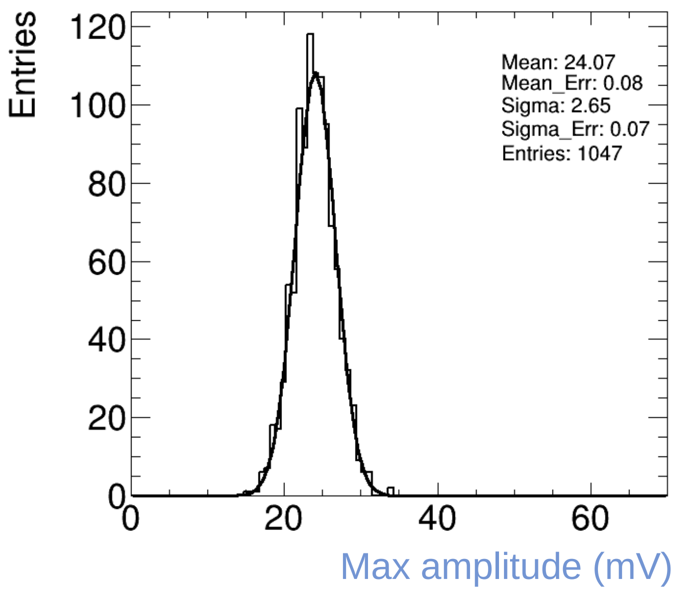
Sensor test | Laser

HPK sensor

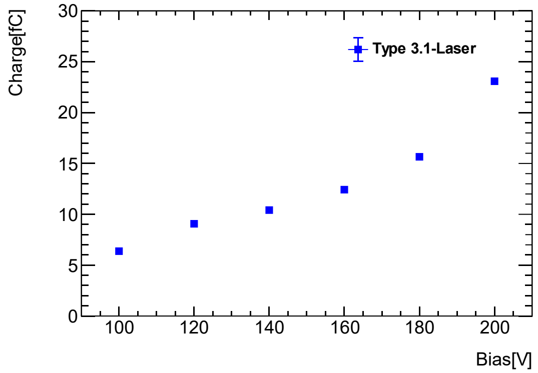


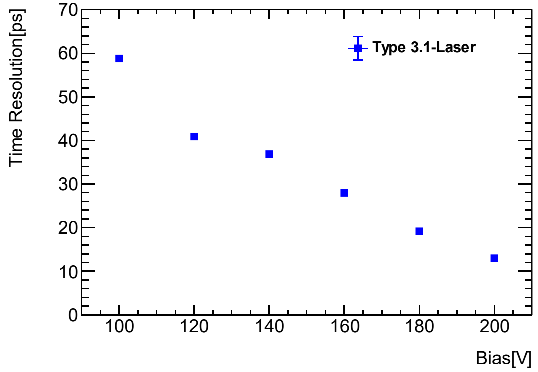
- Wavelength: 1064.29 nm i.e. 1.165 eV
- Pulse width: 7.68 ps
- Pulse frequency: 21.9 MHz

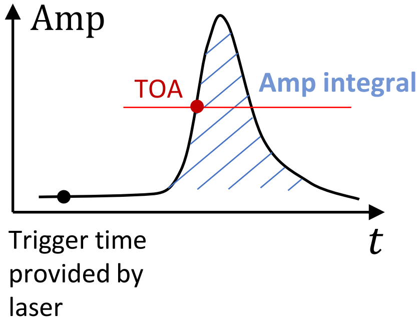
No Landau fluctuation in laser test



$$\frac{\text{Amp integral}}{\text{Max amplitude}} \approx \text{Const.} \Longrightarrow \frac{Q}{\text{Max amplitude}} \approx \text{Const.}$$







$$t_{\mathrm{TOF}} = t_{\mathrm{TOA}} - t_{\mathrm{trigger}}$$

$$\sigma^2_{t_{\mathrm{trigger}}} \approx 0$$

$$\sigma_{t_{\mathrm{TOF}}} \approx \sigma_{t_{\mathrm{TOA}}}$$

Luminosity measurement impact

Analysis channel	**Largest uncertainty**	$\Delta\sigma/\sigma_{SM}$
Cross section for $ggH(\to\gamma\gamma)$	Photon isolation efficiency	1.9%
Cross section for $ggH(\to ZZ^*)$	Electron eff. reco. total	1.5%
Cross section for $ggH+\mathrm{VBF}$, $H\to\tau\tau$	QCD scale ggH, $p_T^H \geq 120\,\mathrm{GeV}$	1.7%

Table 3.1: List of dominant uncertainties (excluding the uncertainty on the integrated luminosity) affecting various expected Higgs boson cross section results at the HL-LHC using $3000\,\mathrm{fb}^{-1}$ of data. An uncertainty on the luminosity measurement of 2% would be the dominant source of uncertainty for all these measurements.