

Timing Performance of the Mu3e Tile Detector Prototype

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Tiancheng Zhong

Kirchhoff-Institute for Physics, Heidelberg University



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Kirchhoff-
Institut
für Physik

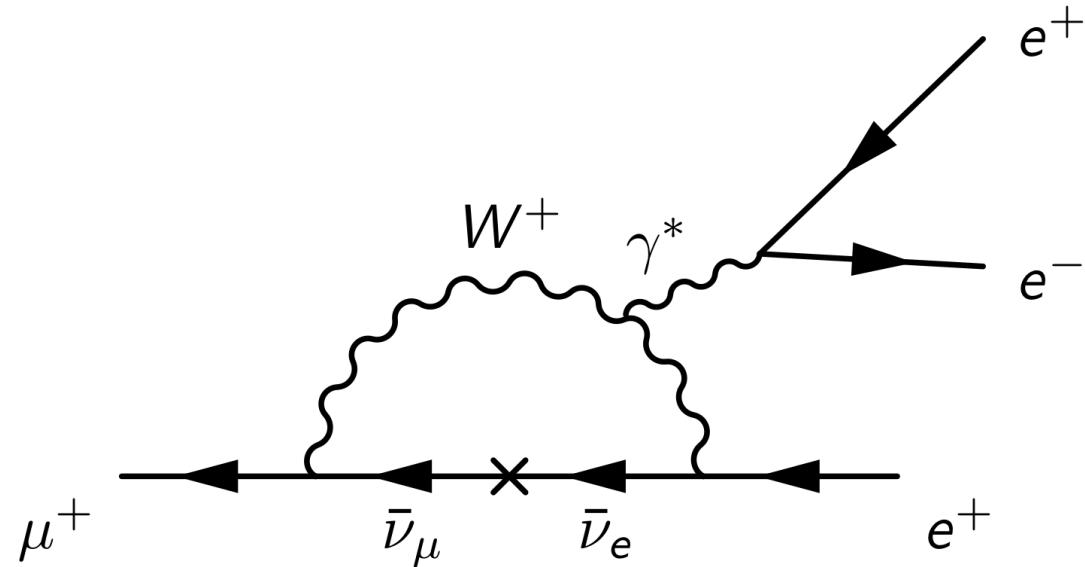


Contents

- Mu3e experiment
- Tile Detector and prototype
- Latest testbeam
- Summary

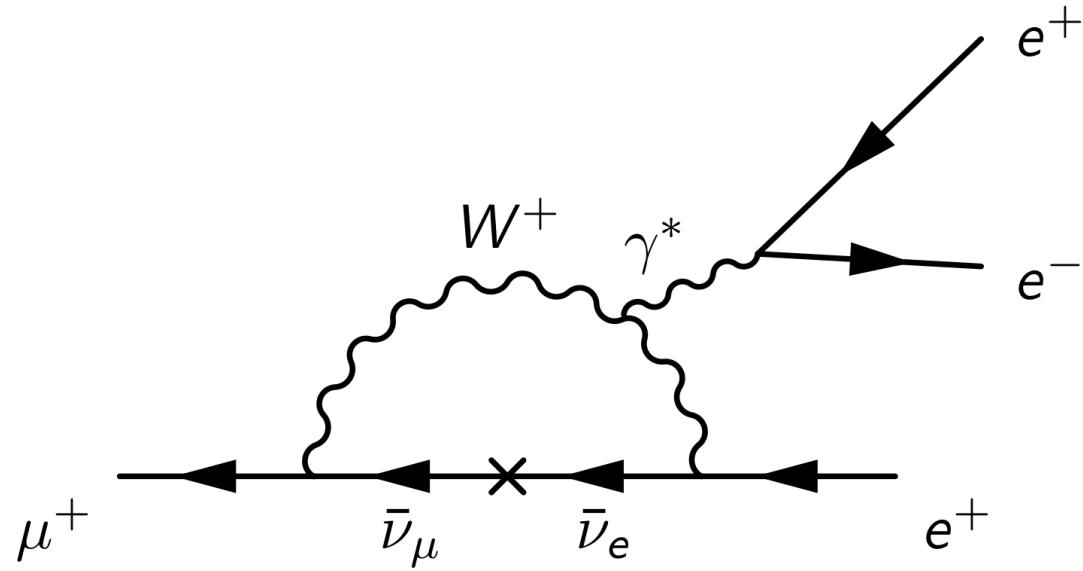
Motivation

- Mu3e: $\mu \rightarrow eee$
- Standard Model: $BR_{\mu \rightarrow eee} \sim 10^{-54}$



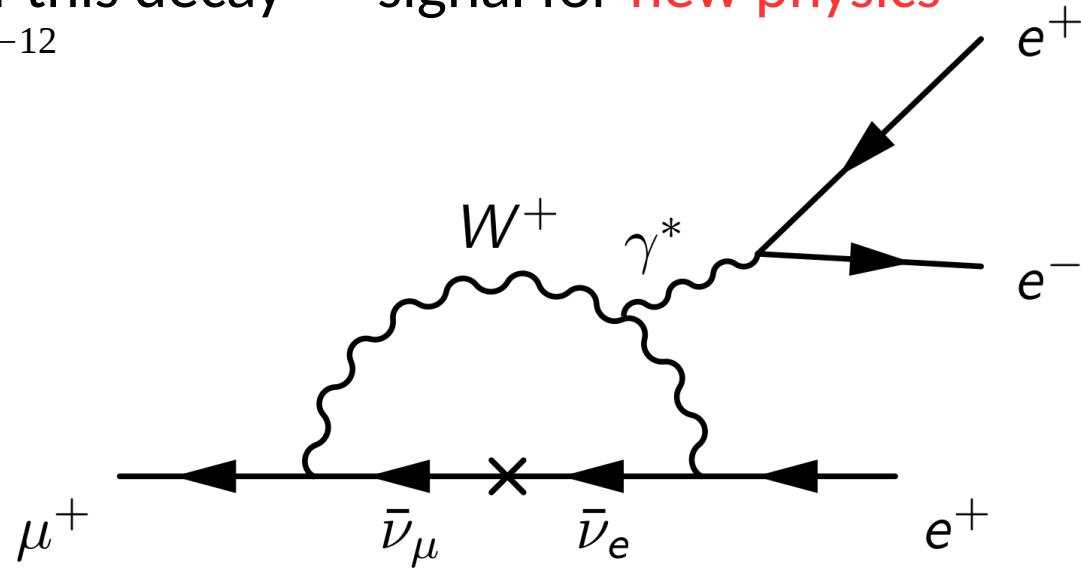
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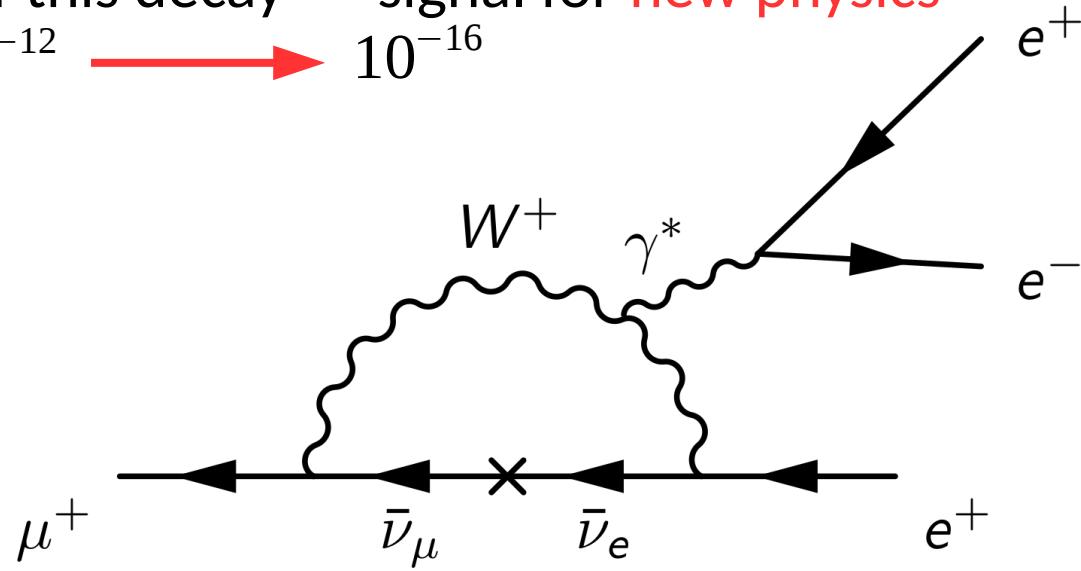
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- Observation of this decay => signal for **new physics**
- Sensitivity: 10^{-12}



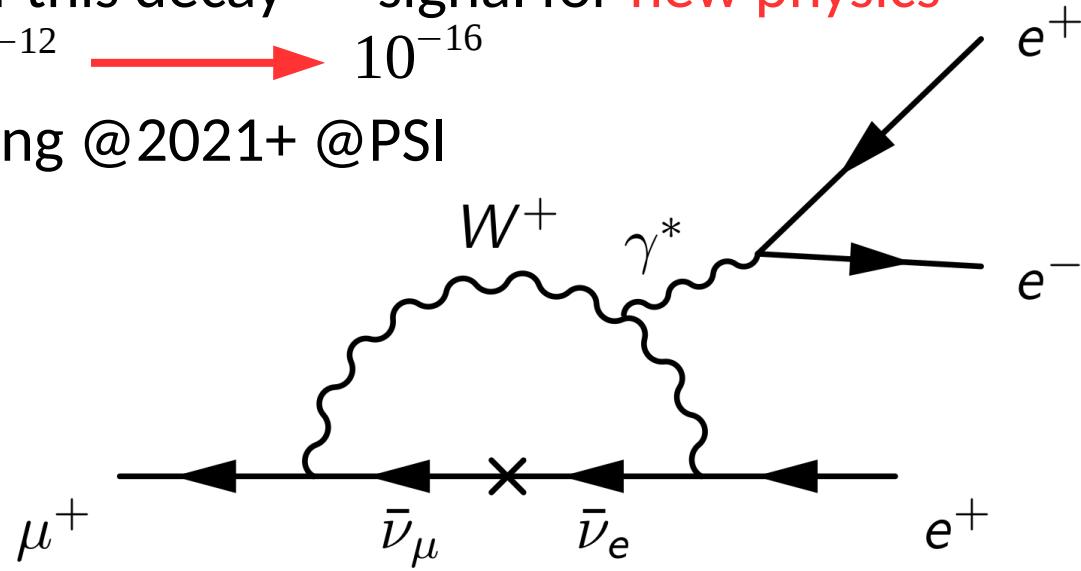
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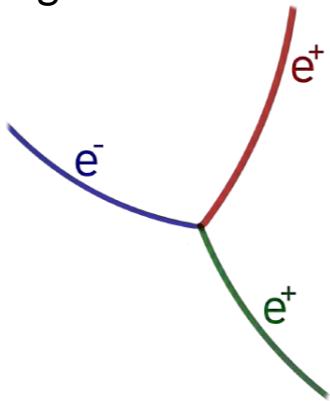
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- Plan: Data taking @2021+ @PSI



Background for $\mu \rightarrow eee$

Signal:

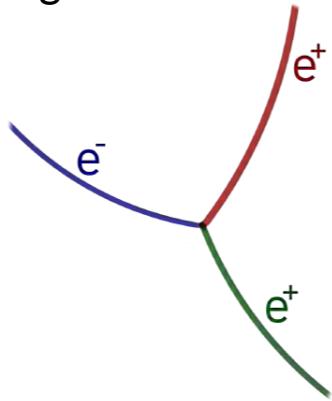


Common vertex

$$\sum E_e = m_\mu, \sum \vec{p}_e = 0$$

Background for $\mu \rightarrow eee$

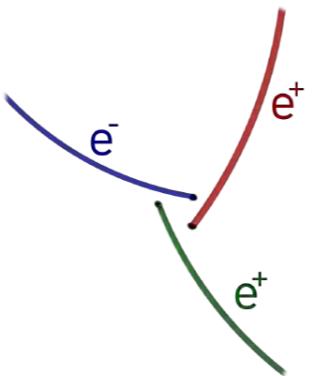
Signal:



Common vertex

$$\sum E_e = m_\mu, \sum \vec{p}_e = 0$$

Accidental background:

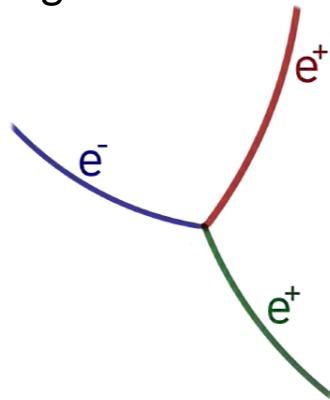


No common vertex
(No coincidence)

$\sum E_e \neq m_\mu, \sum \vec{p}_e \neq 0$
(Timing/Vertex resolution)

Background for $\mu \rightarrow eee$

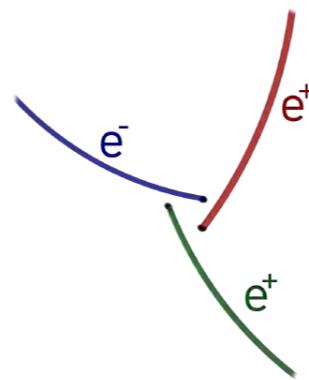
Signal:



Common vertex

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Accidental background:

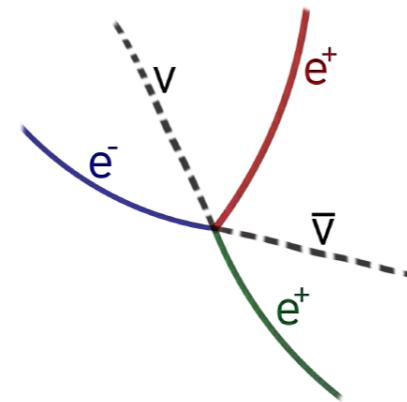


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$$\sum E_e \neq m_\mu, \sum \vec{p}_e \neq 0$$

(Timing/Vertex resolution)

Internal conversion decay:

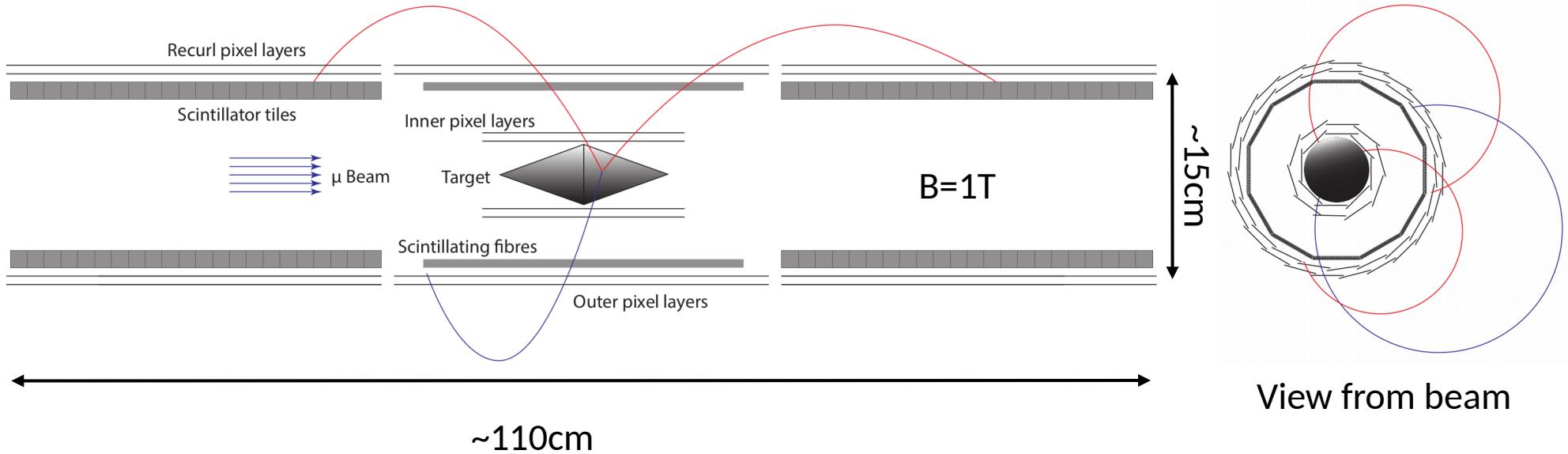


Common vertex

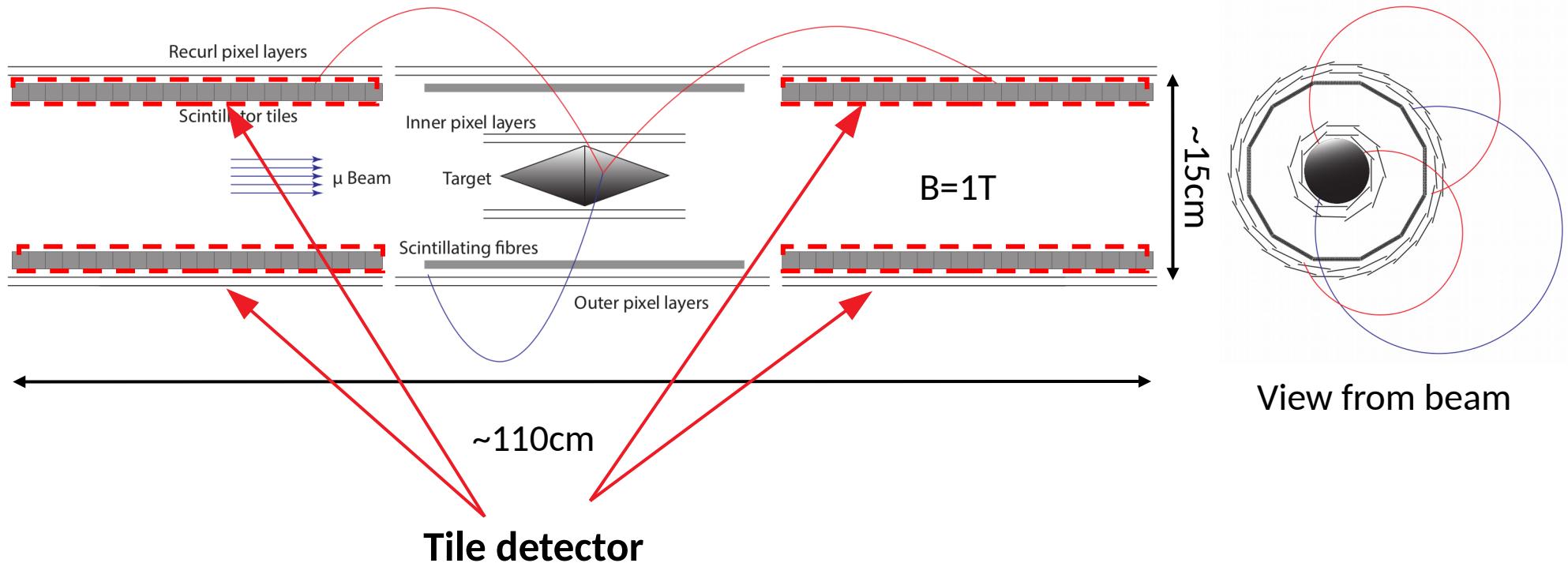
$$\sum E_e < m_\mu, \sum \vec{p}_e \neq 0$$

(Momentum/Energy resolution)

Mu3e experiment layout

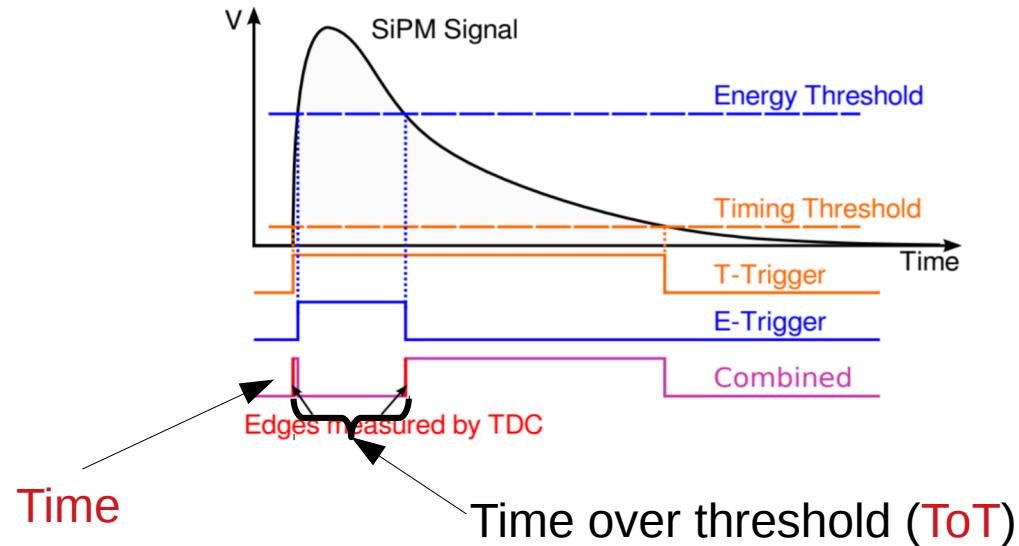
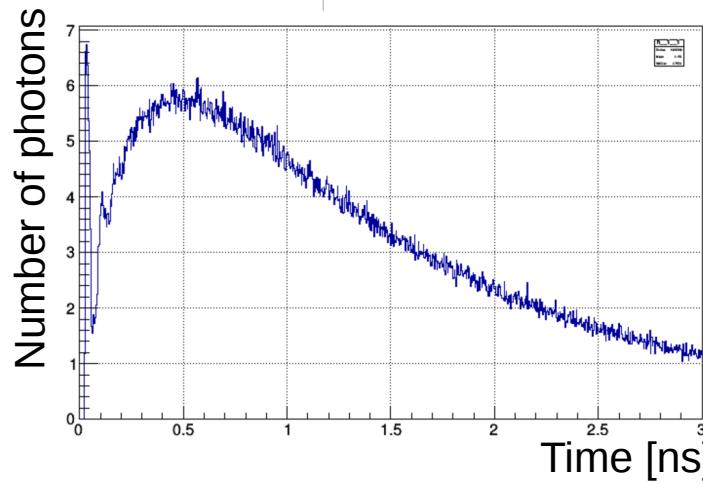
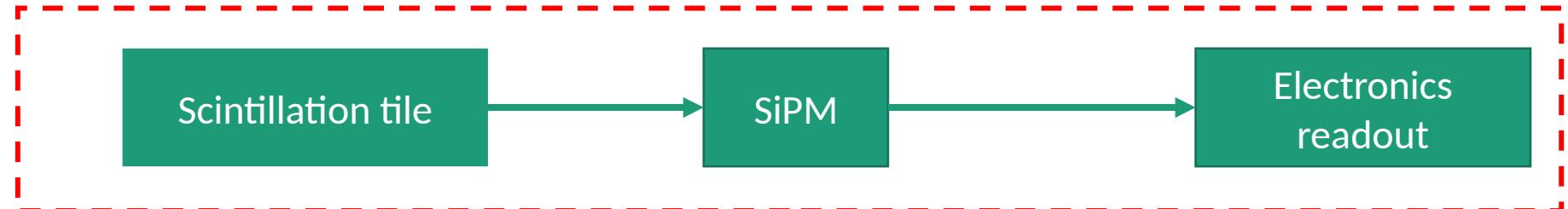


Mu3e experiment layout

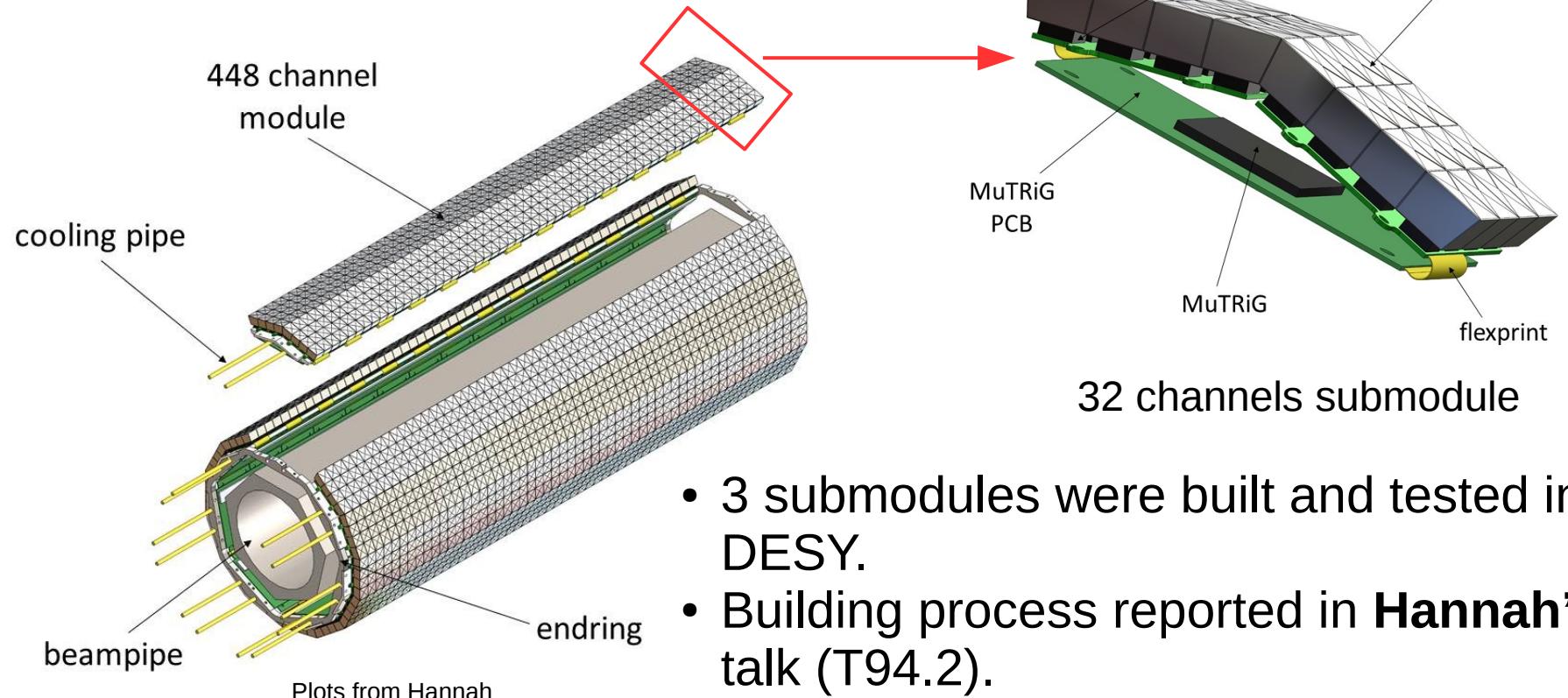


To suppress the accidental background; Time resolution <**100ps** is required!

Mu3e tile detector design



Mu3e tile detector



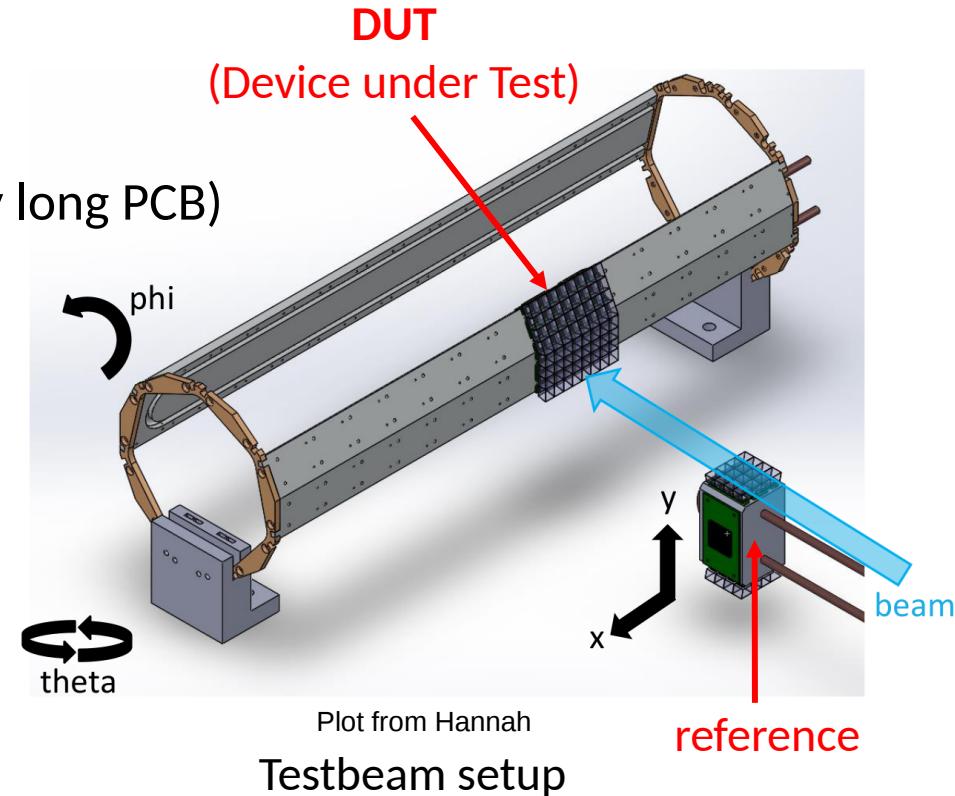
- 3 submodules were built and tested in DESY.
- Building process reported in **Hannah's talk (T94.2)**.

Latest testbeam

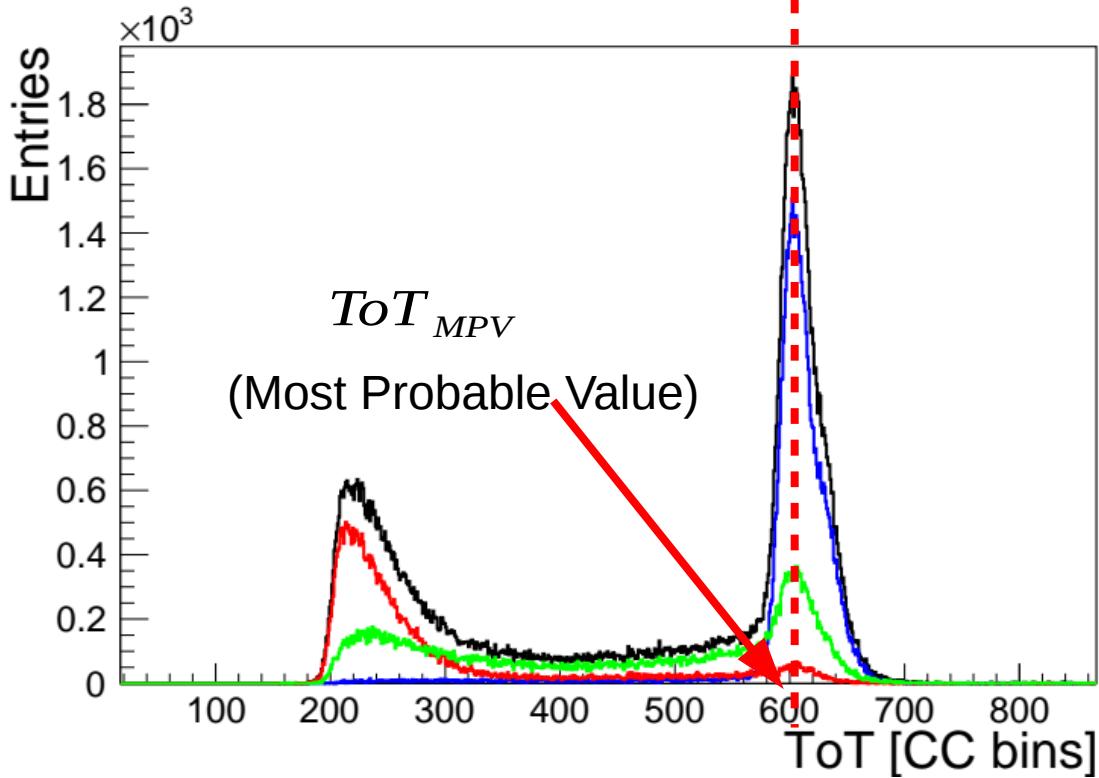
- Time: June 2018
- DUT: 64 channels (2 submodules, read out by long PCB)
- Reference: 16 channels (1/2 submodule)
- Electron beam: 2.6GeV @DESY



Long readout PCB

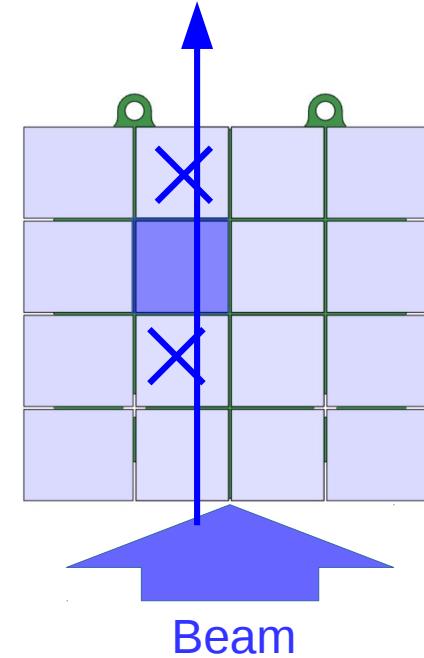


ToT spectrum

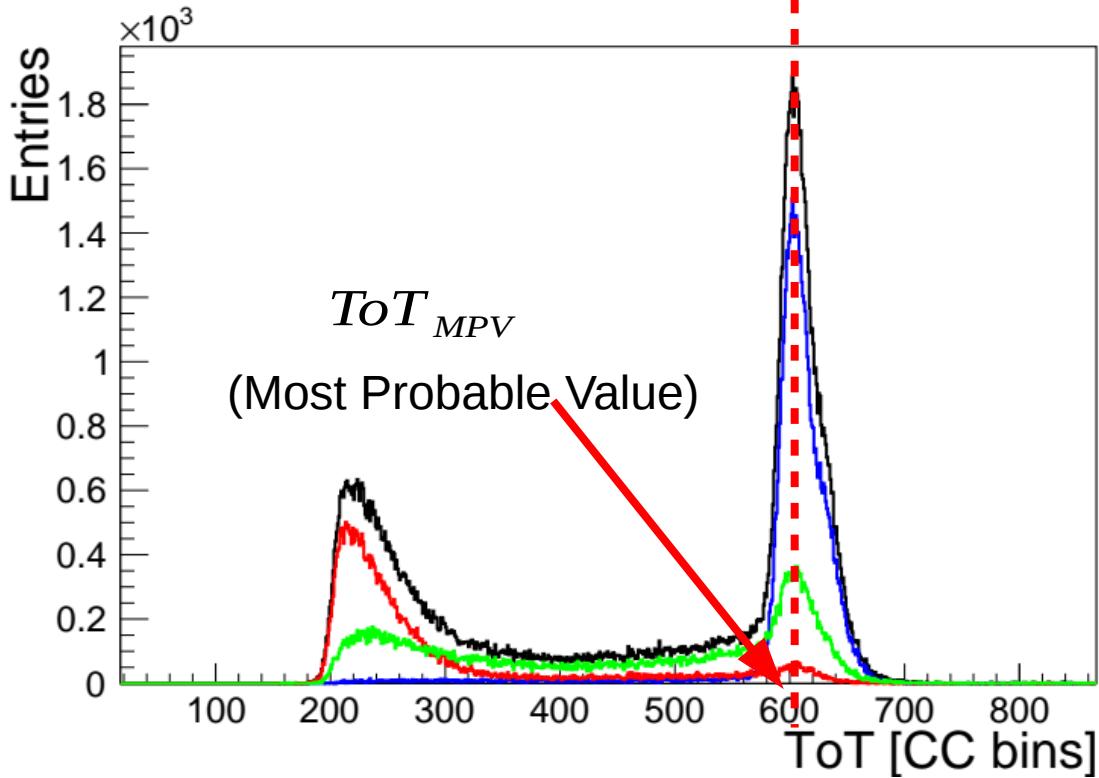


Feature of ToT:

- Black: total
- Blue: fully traverse the tile

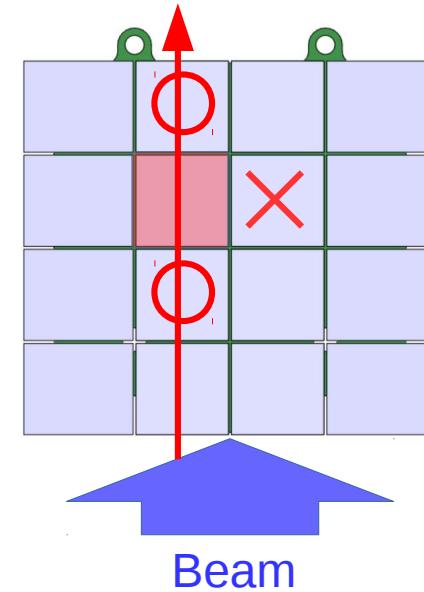


ToT spectrum

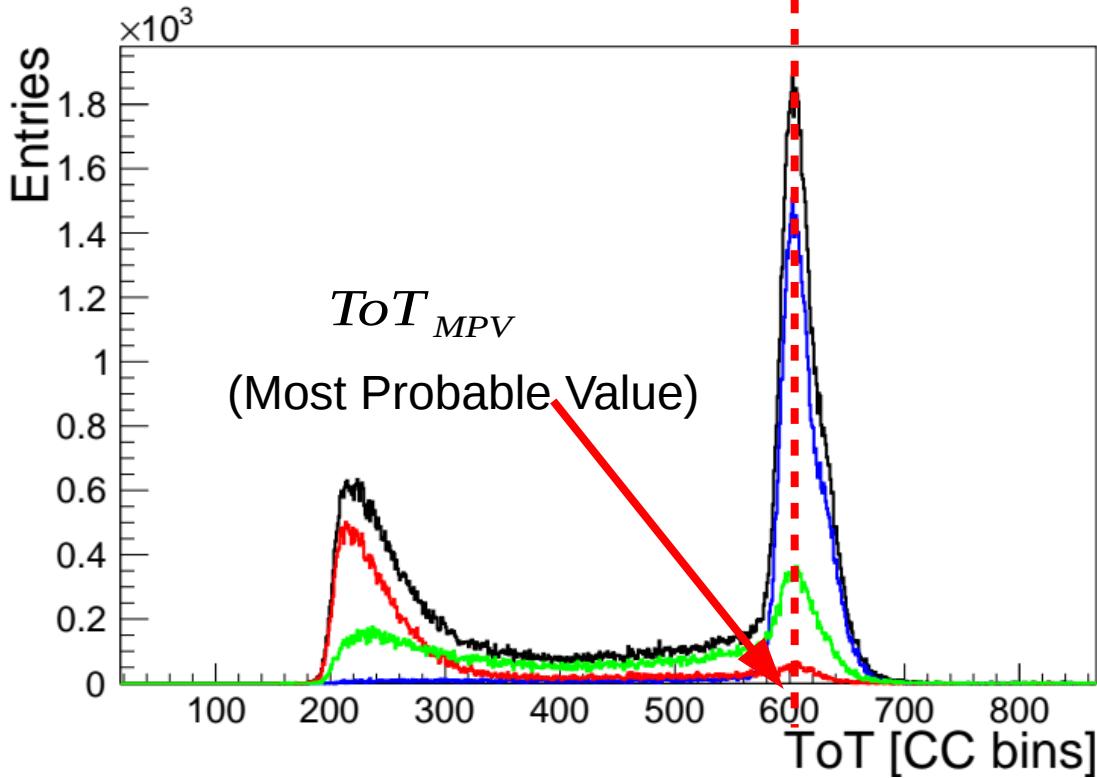


Feature of ToT:

- Black: total
- Red: cross talk

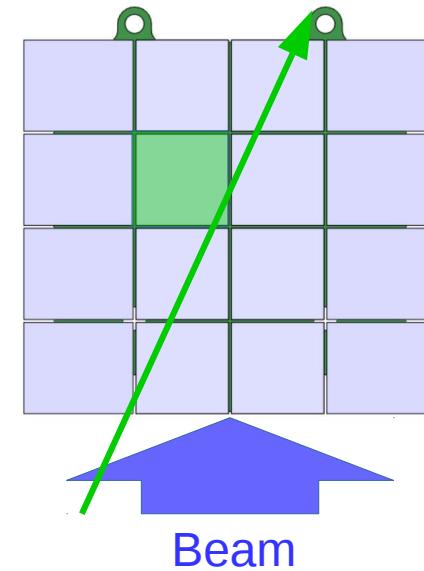


ToT spectrum



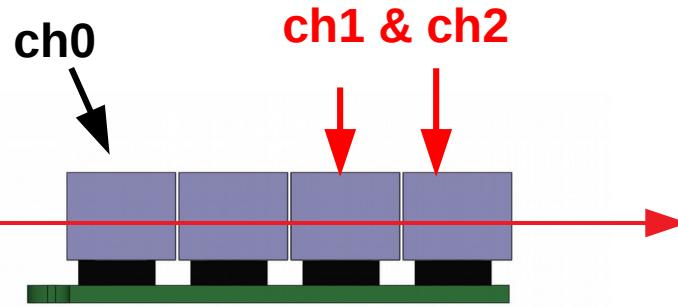
Feature of ToT:

- Black: total
- Green: rest events
- Partial go through



Single channel resolution

Time resolution of **ch0** (ref: ch1 & ch2)

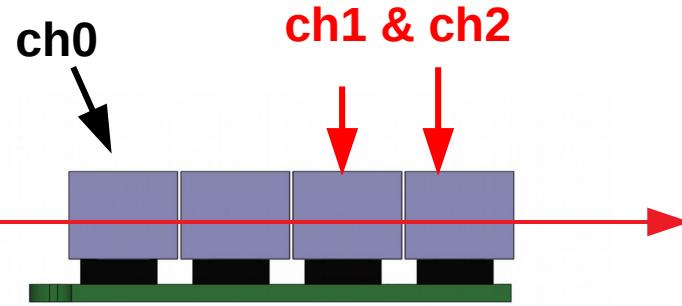


$$\sigma_0 = \frac{1}{\sqrt{2}} \sqrt{\sigma_{0,1}^2 + \sigma_{0,2}^2 - \sigma_{1,2}^2};$$

$$\sigma_{i,j}^2 = \sigma_i^2 + \sigma_j^2$$

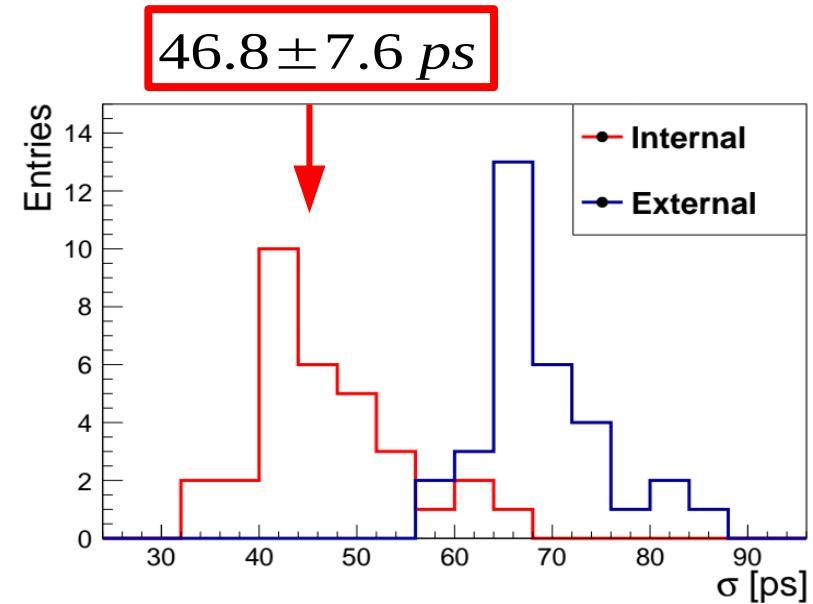
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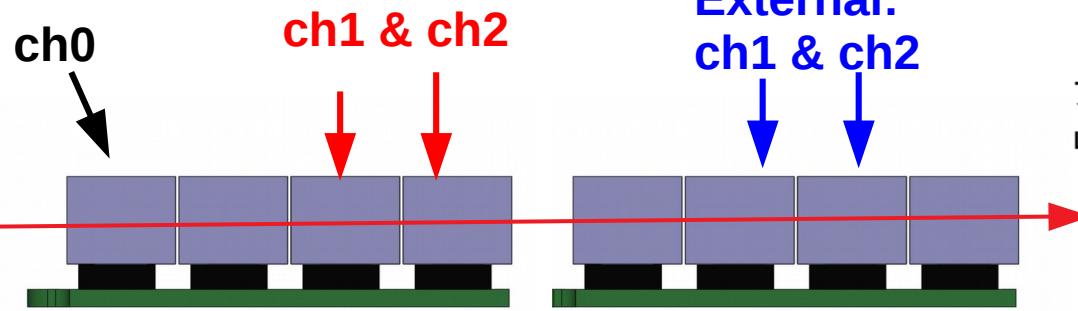
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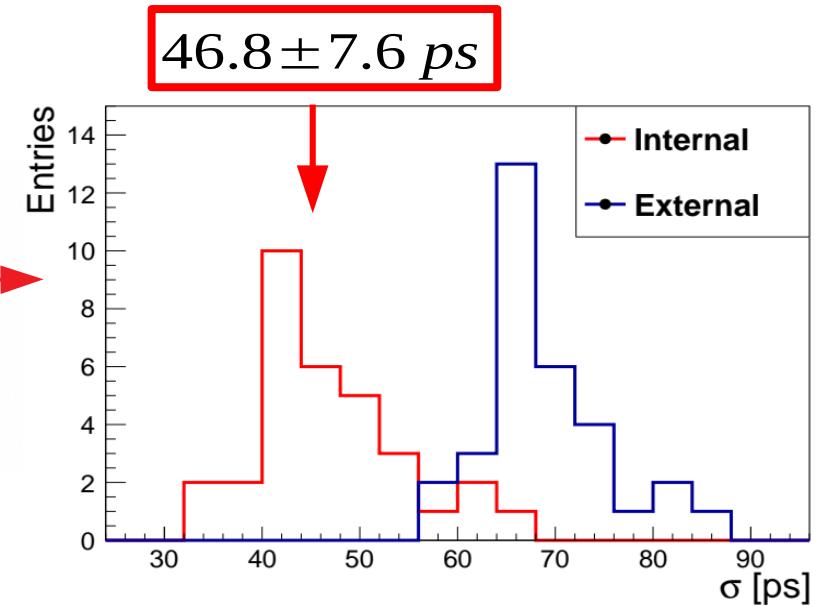
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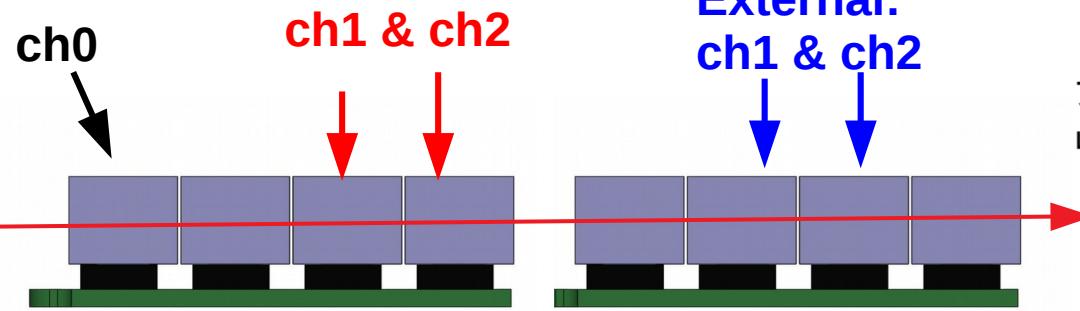
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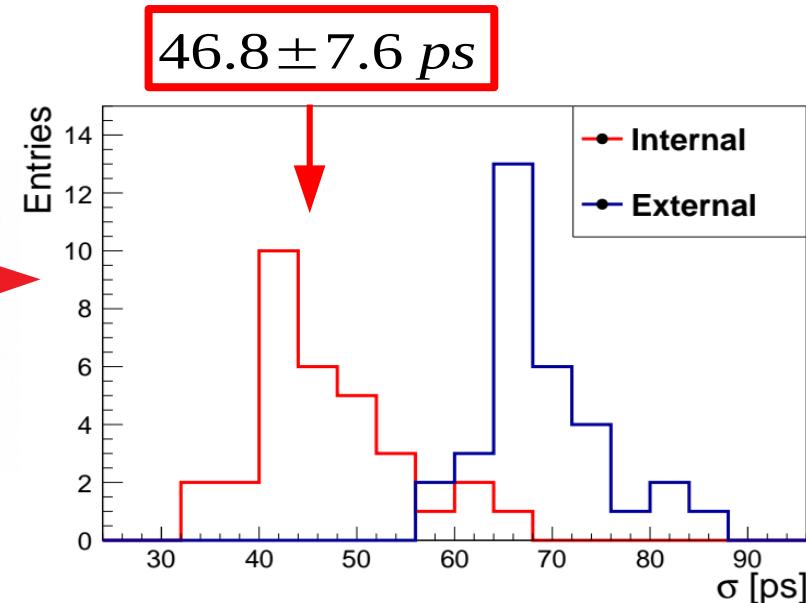
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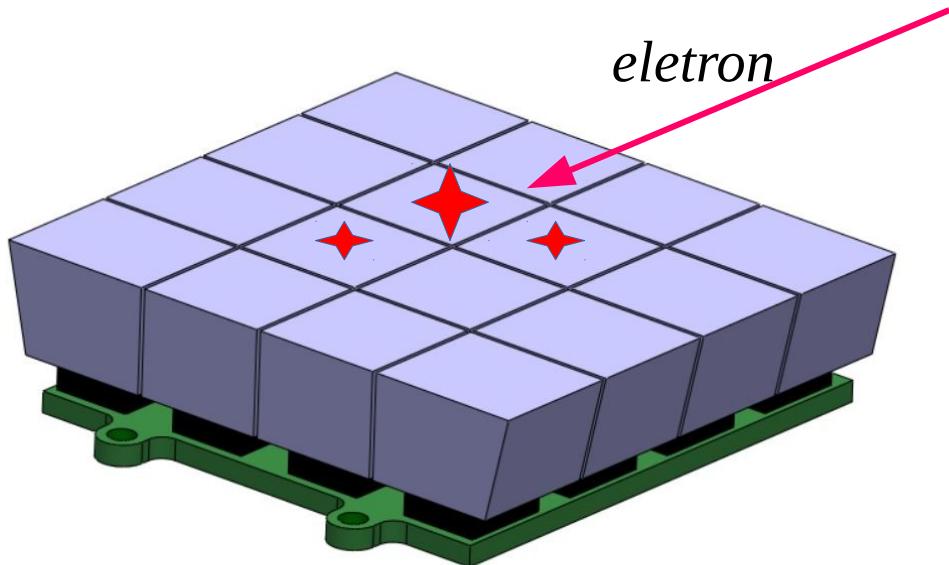
$$\sigma_{i,j}^2 = \sigma_i^2 + \sigma_j^2$$



Extra jitter between DUT and reference:
about $(45.5 \pm 3.2 \text{ ps})$

Timing resolution of module

- **Module resolution** is more important in real experiment

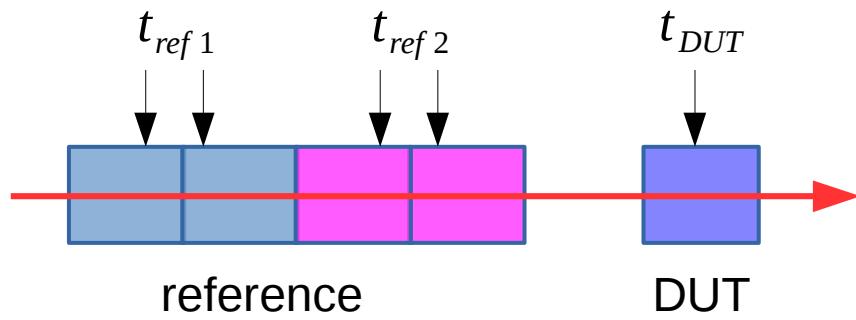


$$t_{module} = \sum_i w_i \times t_i$$

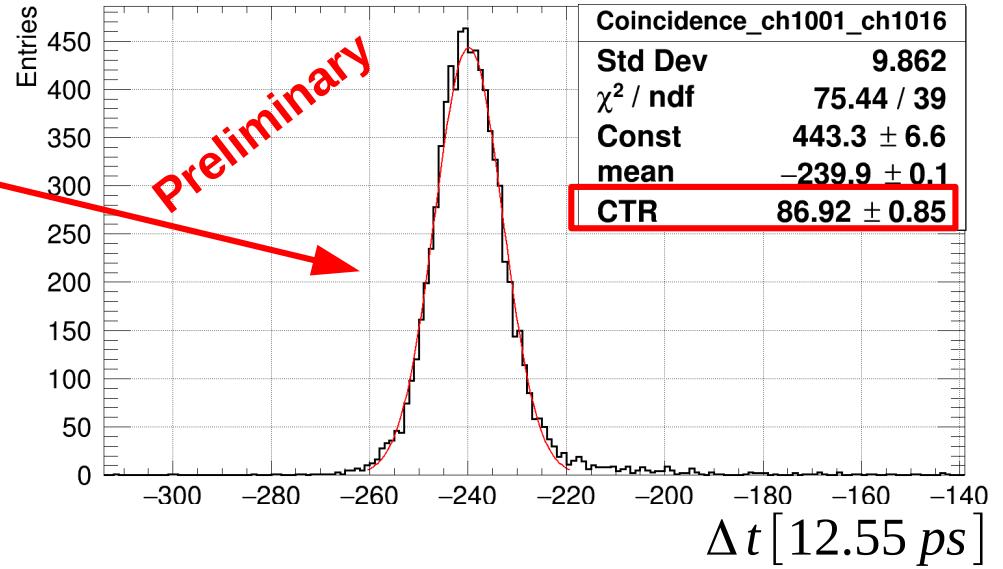
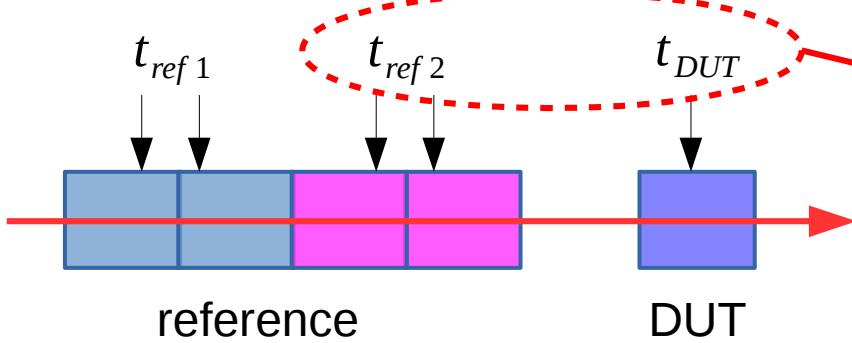
w_i :Weight for channel i

t_i :Time for channel i

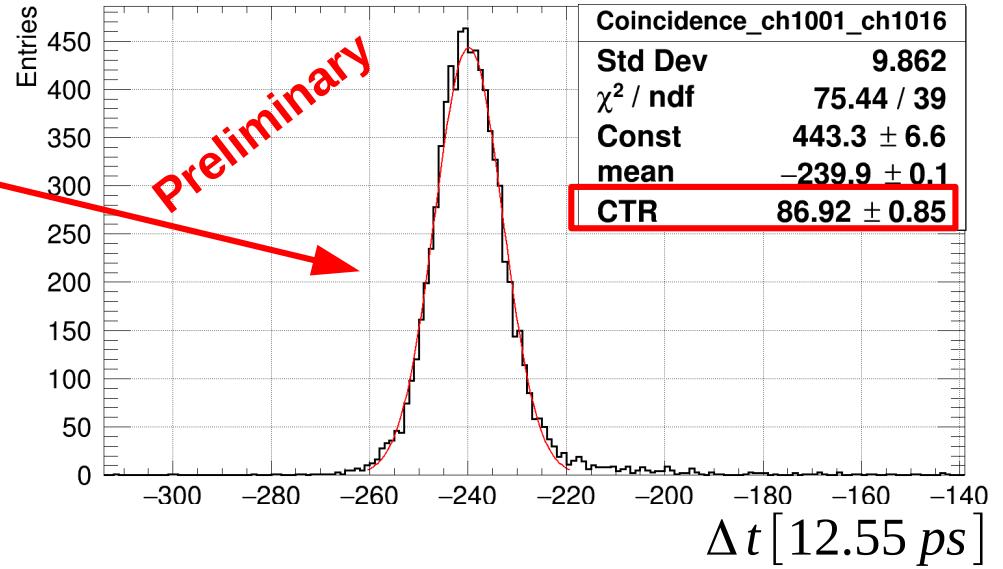
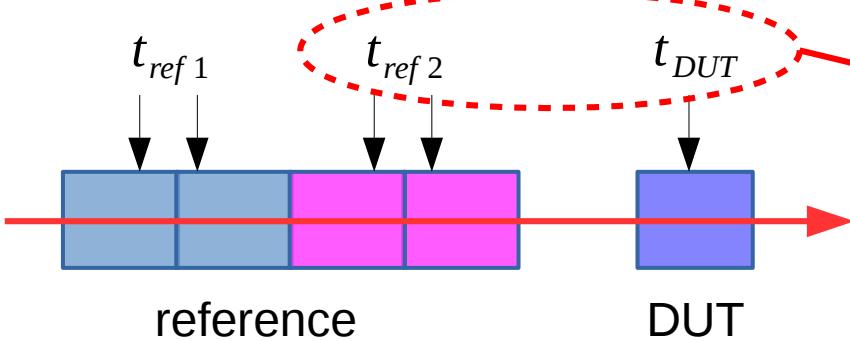
Timing resolution of module



Timing resolution of module



Timing resolution of module



- Coincidence Time Resolution (CTR): **86.92 ps**
- Estimated timing resolution of DUT: **~64 ps**

Summary

Summary:

- 3 submodules built in lab;
- First time to readout 3 submodules by same DAQ;
- Estimation of single channel resolution **~46.8 ps**;
- Preliminary estimated module resolution about **64 ps**.

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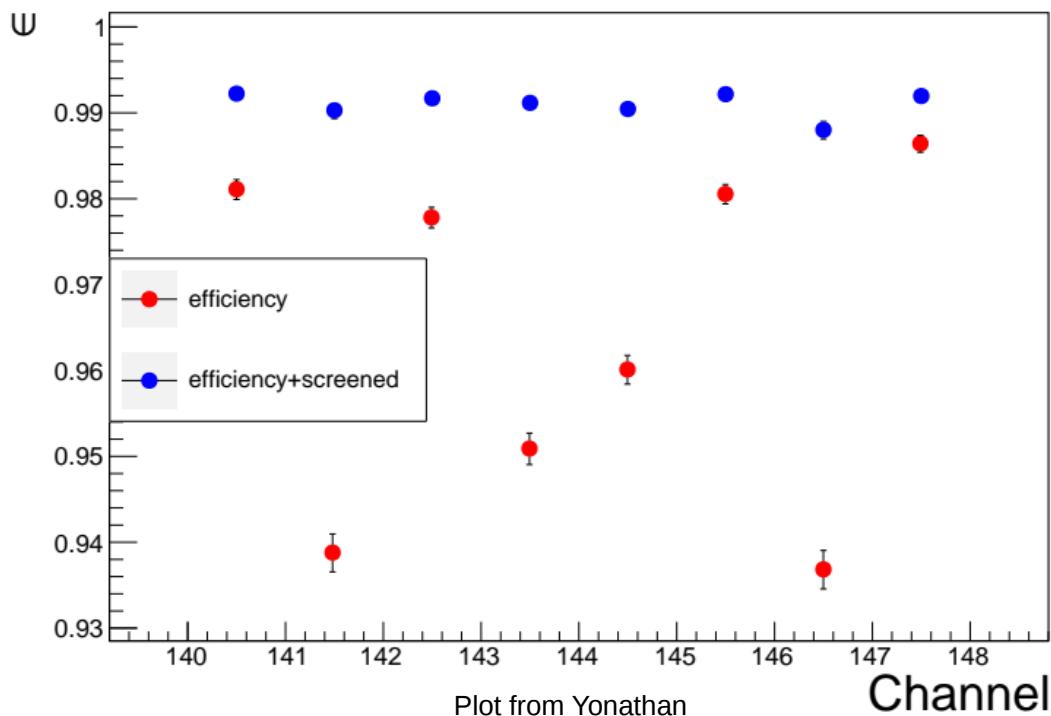
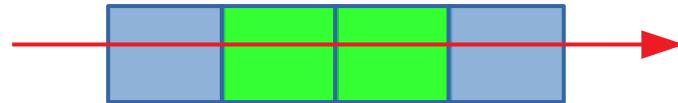
Outlook:

- Test with tracker => position of particle;
- Build prototype with more submodules.

Thanks for your attention!!

BK slides

Efficiency



Define:

- Big signal in edge tiles
- Possibility to have signal over cross-talk level in middle tiles.
- **Efficiency: 93.8%~98.7%**

Screen correction:

- Prior event observed and screened expected event
- After correction: >99%
better estimation can be got with tracker

Timing resolution of module

$$t_{module} = \sum_{i=0}^{N-1} w_i \cdot t_i + \left(1 - \sum_{i=0}^{N-1} w_i\right) \cdot t_N$$

$$t_{module} \rightarrow \sigma; t_i \rightarrow \sigma_i$$

$$\sigma^2 = \sum w_i^2 \cdot \sigma_i^2$$

Motivation

- The number of leptons of each family (lepton flavour) is **conserved** at tree level;
- Lepton flavour violation (LFV) has however been **observed** in the form of **neutrino** mixing;
- Lepton flavour violation is also **expected in the charged lepton** sector;
- Observation of cLFV would be a clear signal for **new Physics**;
- **Much** work has been done;
- Mu3e plans to search in a **lower sensitivity**.

DECAY CHANNEL	EXPERIMENT	BRANCHING RATIO LIMIT
$\mu \rightarrow e\gamma$	<i>MEGA</i>	$< 1.2 \cdot 10^{-11}$
	<i>MEG</i>	$< 2.4 \cdot 10^{-12}$
$\mu \rightarrow eee$	<i>SINDRUM</i>	$< 1.0 \cdot 10^{-12}$
$\mu Au \rightarrow eAu$	<i>SINDRUM II</i>	$< 7 \cdot 10^{-13}$

Timing resolution of module

$$t_{module} = \sum_{i=0}^{N-1} w_i \cdot t_i + \left(1 - \sum_{i=0}^{N-1} w_i\right) \cdot t_N$$

$$t_{module} \rightarrow \sigma; t_i \rightarrow \sigma_i$$

$$\sigma^2 = \sum w_i^2 \cdot \sigma_i^2$$

$$\partial \frac{(\sigma^2)}{w_i} = 0$$

Optimized weight:

$$w_i = \frac{\left(\prod_{j \neq i} \sigma_j \right)^2}{A_{normal}}, A_{normal} = \sum_i \left(\prod_{j \neq i} \sigma_j \right)^2$$

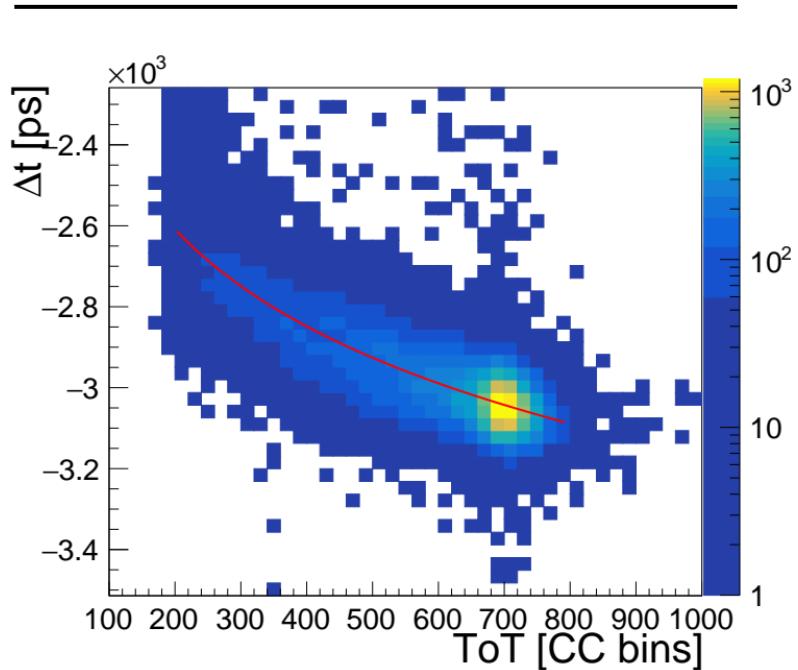
$$w_i = \frac{1/\sigma_i^2}{A_{normal}}, A_{normal} = \sum_i 1/\sigma_i^2$$

Minimum sigma:

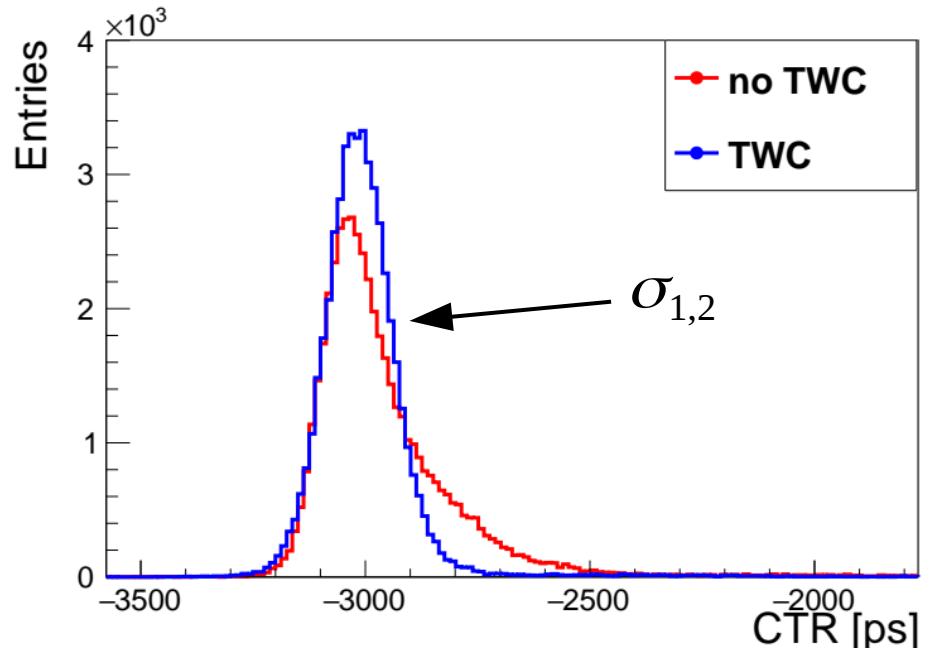
$$\sigma_{min}^2 = \frac{1}{A_{normal}}, A_{normal} = \sum_i 1/\sigma_i^2$$

Variance weights

Time walk



$$f(x) = p_1 \cdot \ln\left(\frac{x}{ToT_{MPV}}\right) + p_0$$

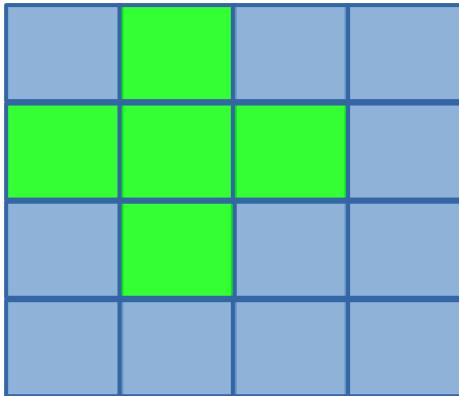


$$t_{corr} = t - (f(x) - f(ToT_{MPV}))$$

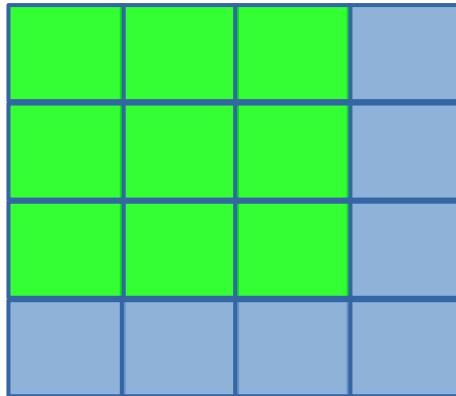
Timing resolution of module

Different ways to do cluster:

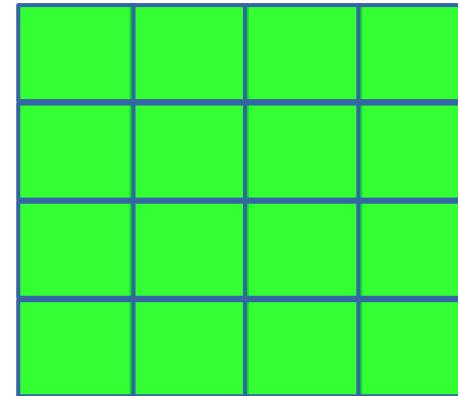
- Directly neighbors (cluster5);
- Nearby neighbors (cluster9);
- Full submodule (cluster16);



Cluster5

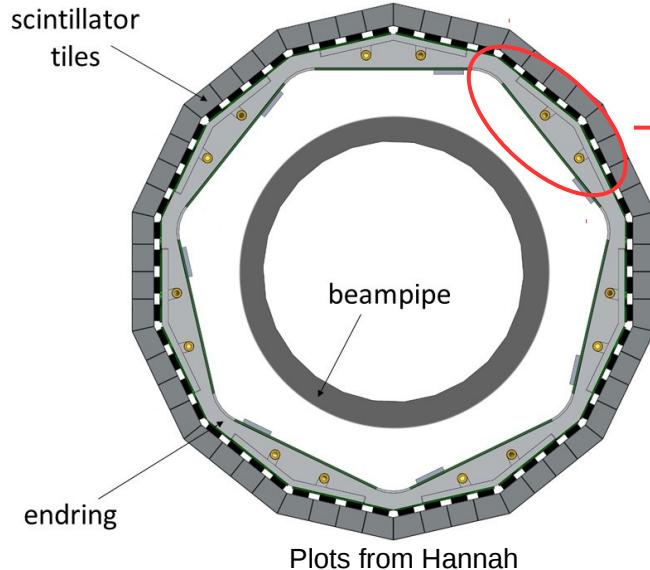


Cluster9

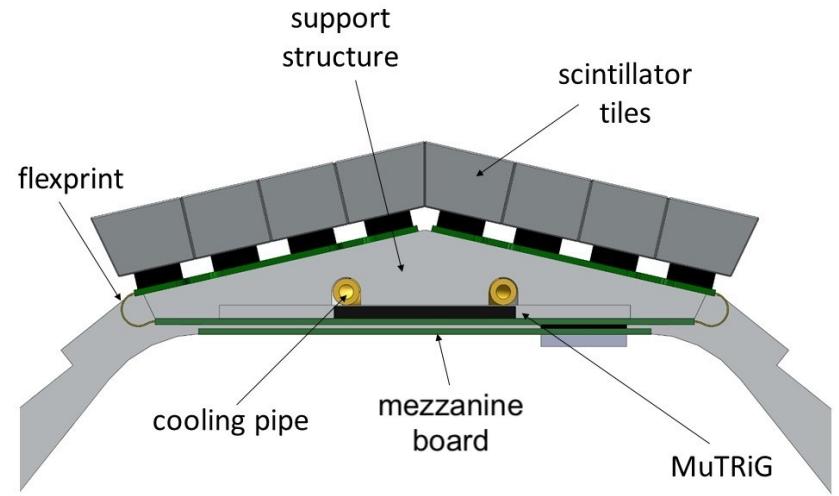


Cluster16

Mu3e title detector



$\frac{1}{2}$ Tile detector (7 modules)



Timing resolution of module

Example:

$$N=3 : t=w_1 \cdot t_1 + w_2 \cdot t_2 + w_3 \cdot t_3 ;$$

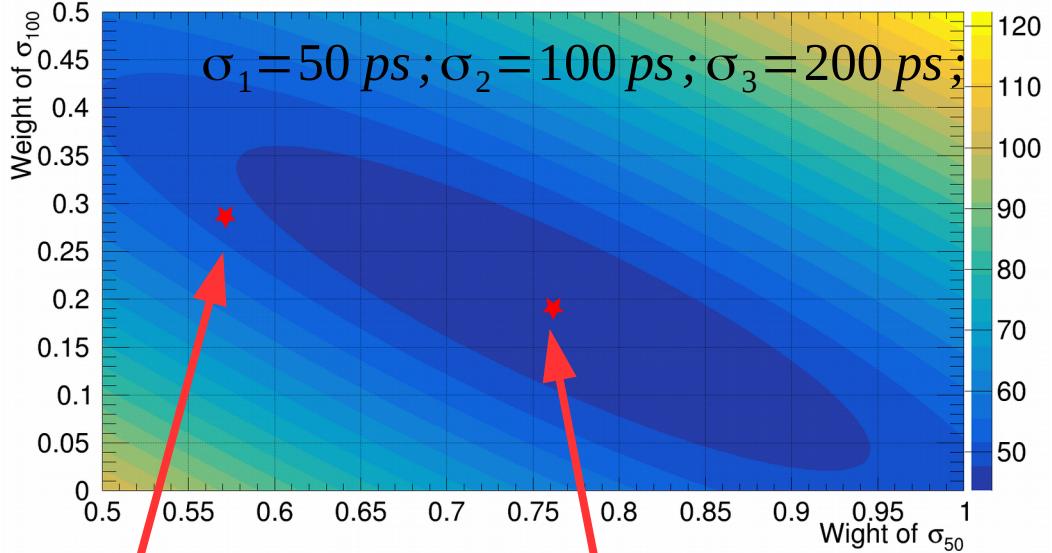
$$A_{normal} = (\sigma_1 \cdot \sigma_2)^2 + (\sigma_2 \cdot \sigma_3)^2 + (\sigma_1 \cdot \sigma_3)^2 ;$$

$$w_1 = \frac{(\sigma_2 \cdot \sigma_3)^2}{A_{normal}} ;$$

$$w_2 = \frac{(\sigma_1 \cdot \sigma_3)^2}{A_{normal}} ;$$

$$w_3 = \frac{(\sigma_1 \cdot \sigma_2)^2}{A_{normal}} ;$$

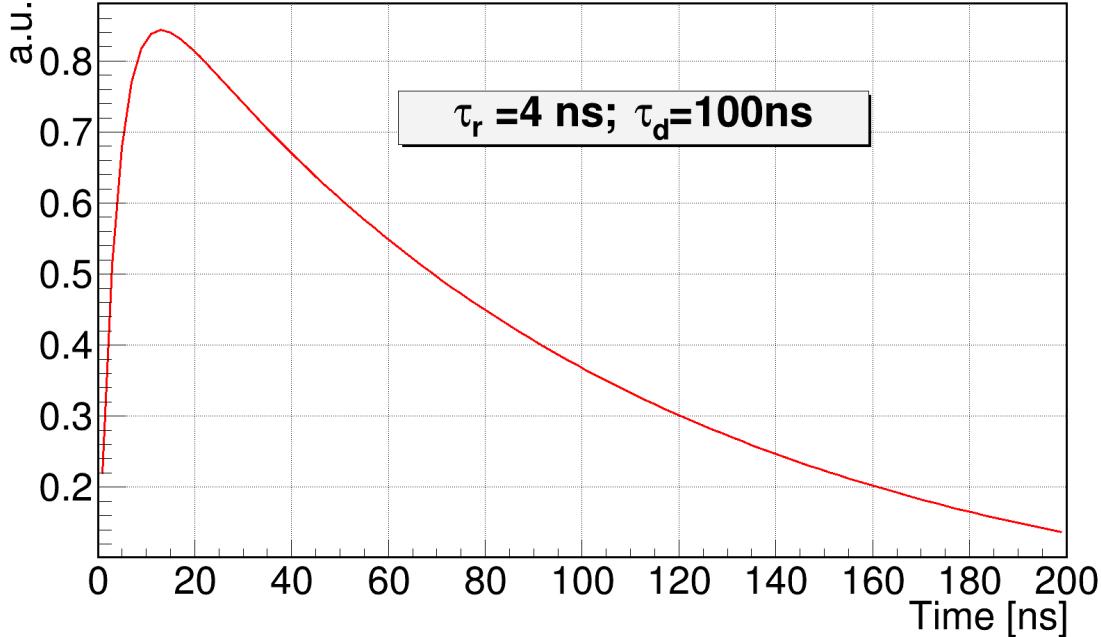
$$\sigma_{min}^2 = \frac{(\sigma_1 \cdot \sigma_2 \cdot \sigma_3)^2}{A_{normal}} = 1 / (\sigma_1^{-2} + \sigma_2^{-2} + \sigma_3^{-2})$$



$1/\sigma_i :$
 $\sigma = 49.49 \text{ ps.}$

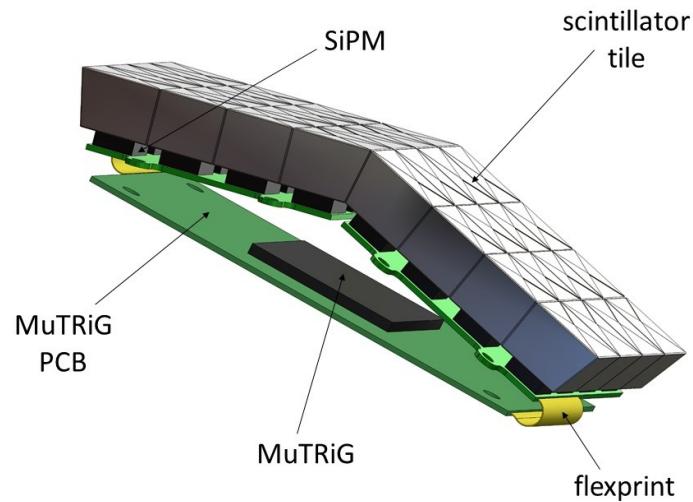
Optimized:
 $\sigma_{min} = 43.64 \text{ ps.}$

Time walk

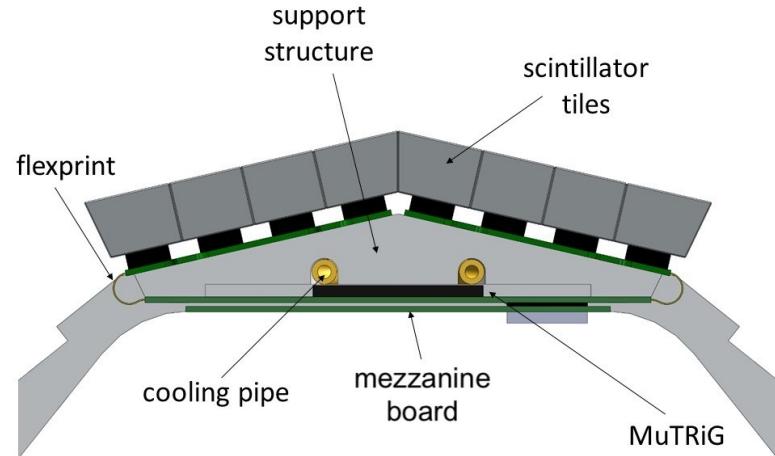


- Low time threshold: $Amp \sim e^t$
- different amplitude:
$$\Delta t \sim \ln(Amp)$$

Mu3e title detector

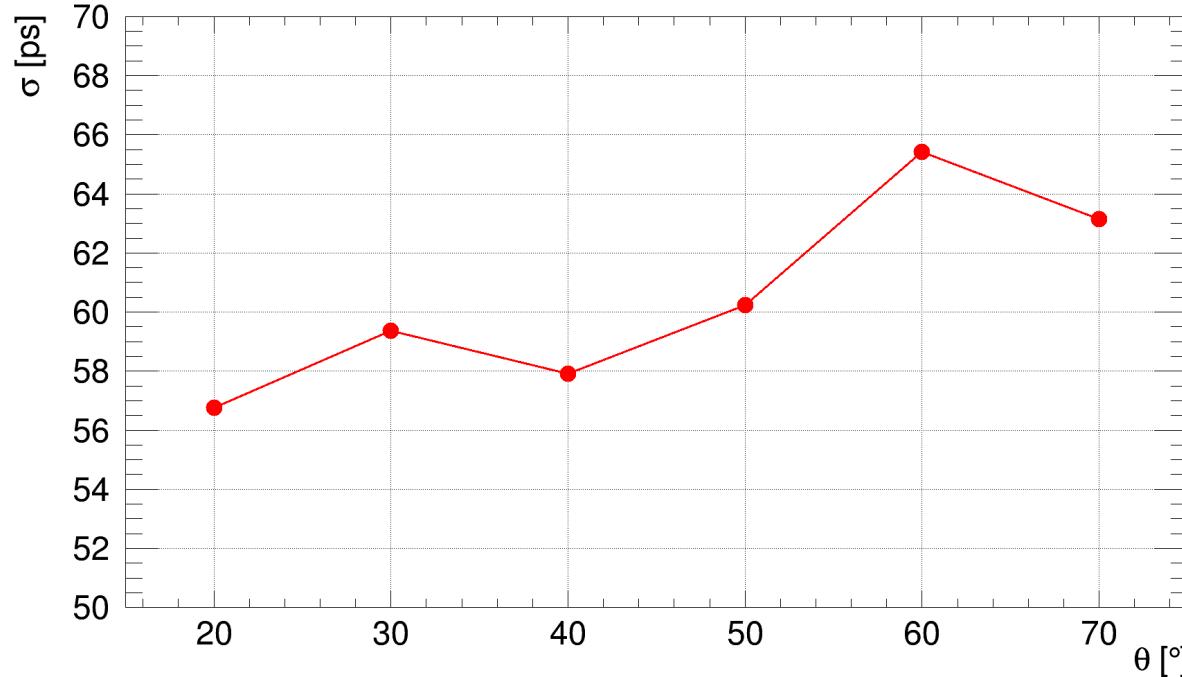


Submodule (32 channels)



Submodule (32 channels)

Timing resolution of module



Difference < 10ps observed between different theta.

Timing resolution along E_{dep}

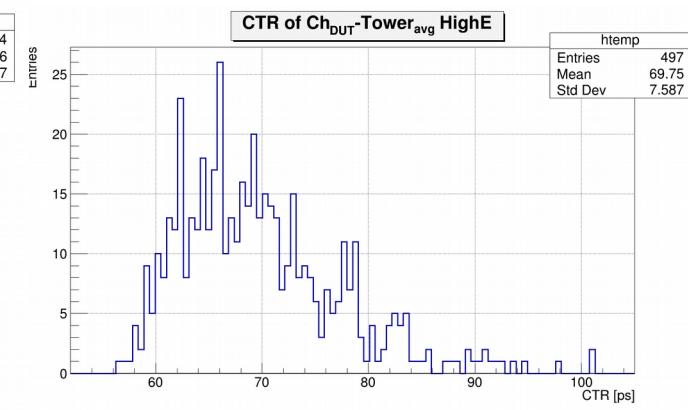
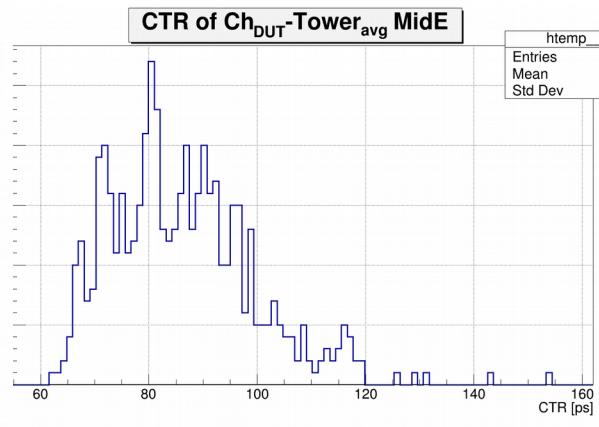
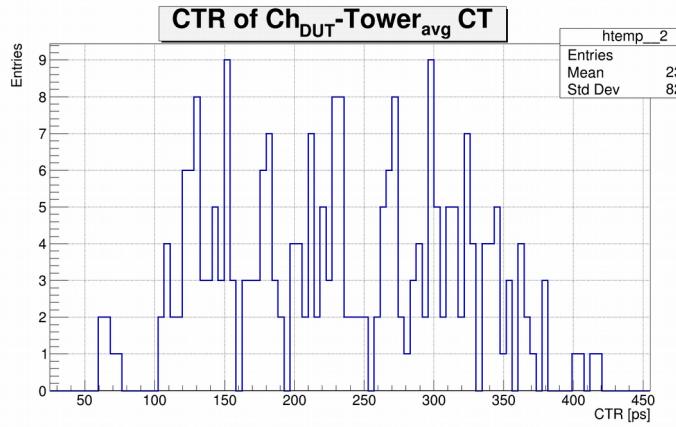
CTR :

- CT: 232.2 ps
- MidE: 86.2 ps
- HigHE: 69.8 ps

Jitter between module (45.5 ps);
TR of 4 channel average (25.8 ps).

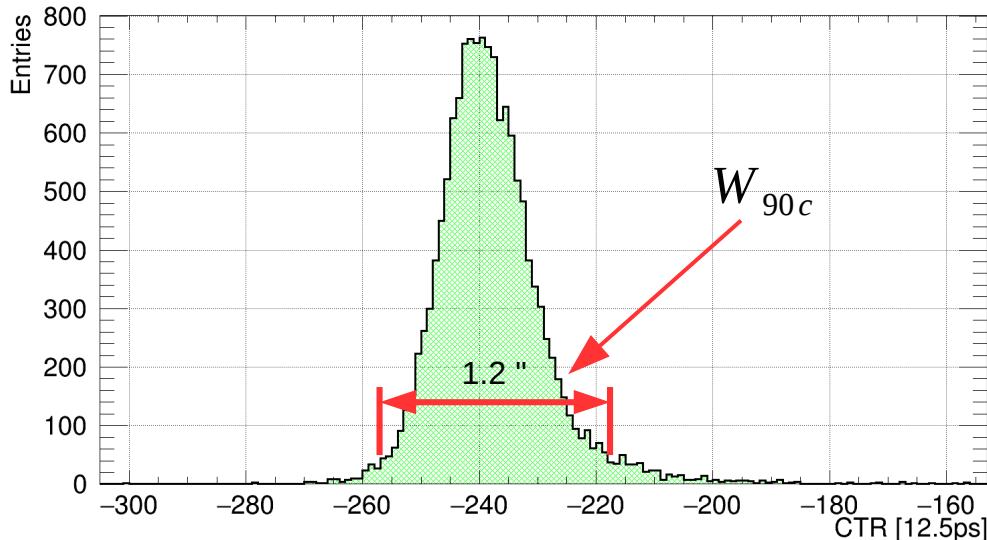
Timing resolution:

- CT: **226.2** ps
- MidE: **69.4** ps
- HighE: **46.2** ps



Timing resolution of module

Width @90% confidence



Weighted cluster16 vs. 2 channels average in trigger

$$W_{90c,min} = \min of W_{90c}$$

Equivalent timing resolution:

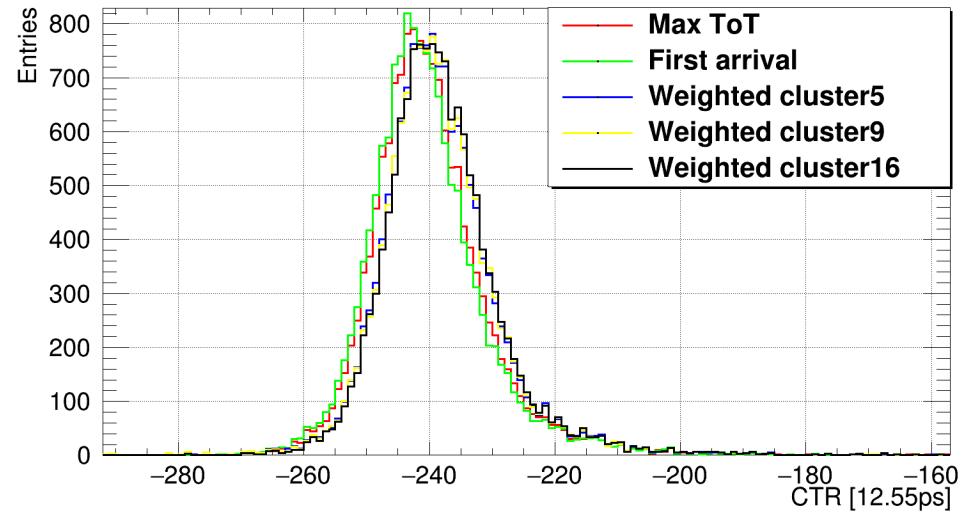
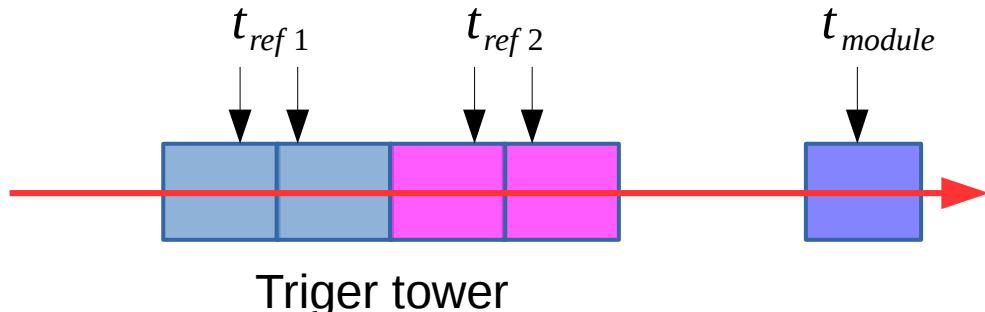
$$\sigma_{90c} = \frac{W_{90c,min}}{2 \times 1.658};$$

90%: gauss $\rightarrow 1.658 \sigma$

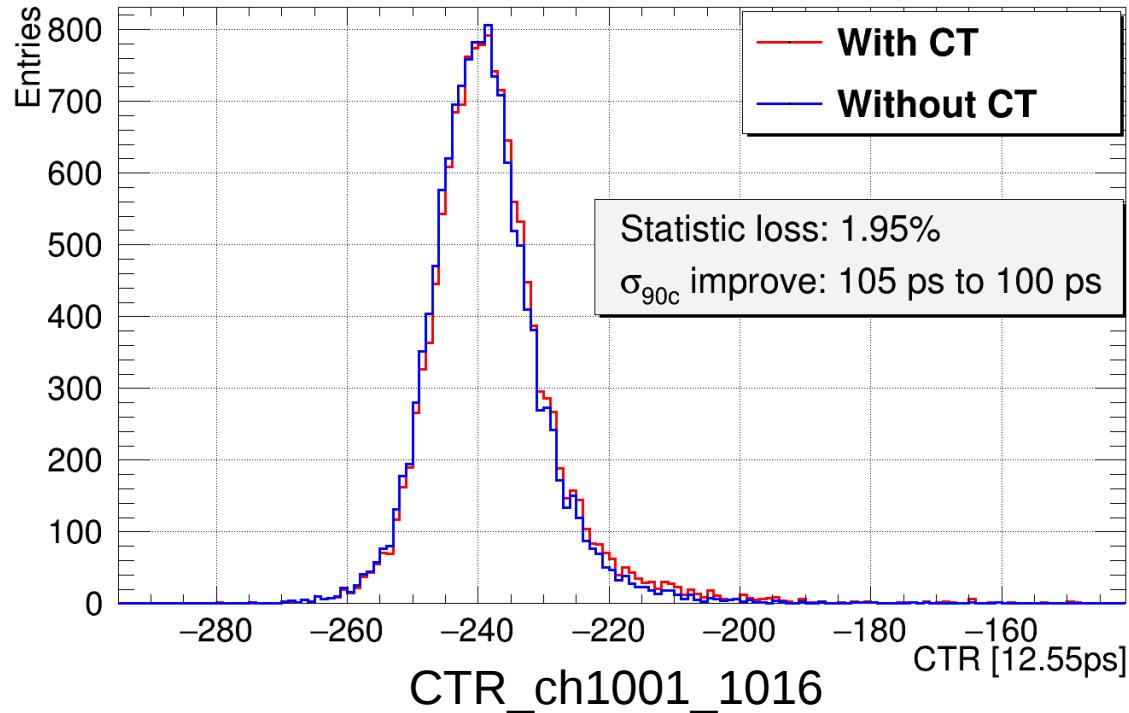
Timing resolution of module

- Narrow cut in Trigger
- No cut in DUT

$$\sigma_{90c, \text{module}} = \frac{1}{\sqrt{2}} \sqrt{\sigma_{90c, \text{ref } 1}^2 + \sigma_{90c, \text{ref } 2}^2}$$

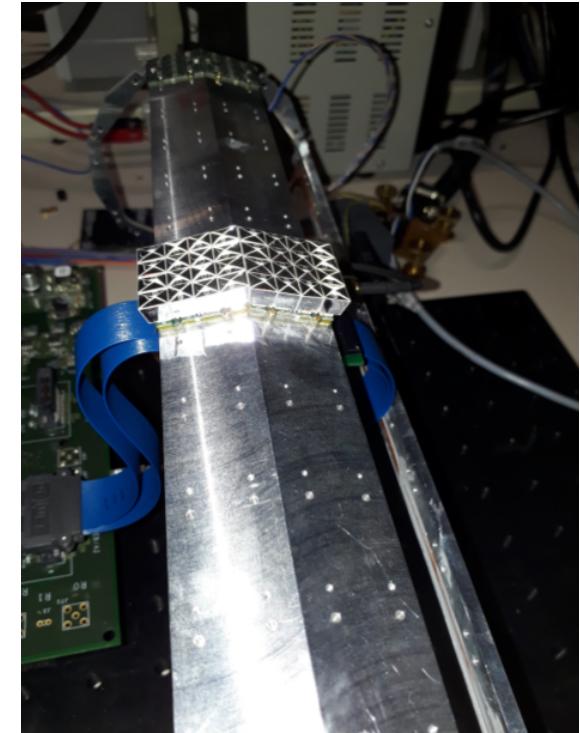
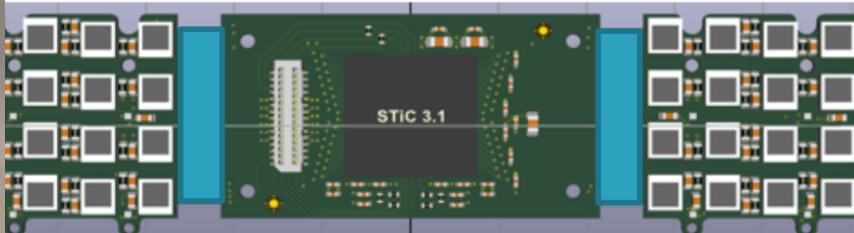
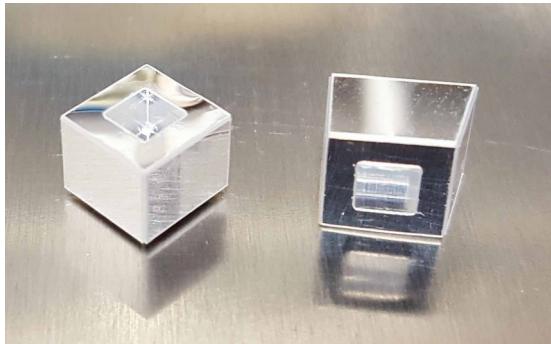


width @90% confidence



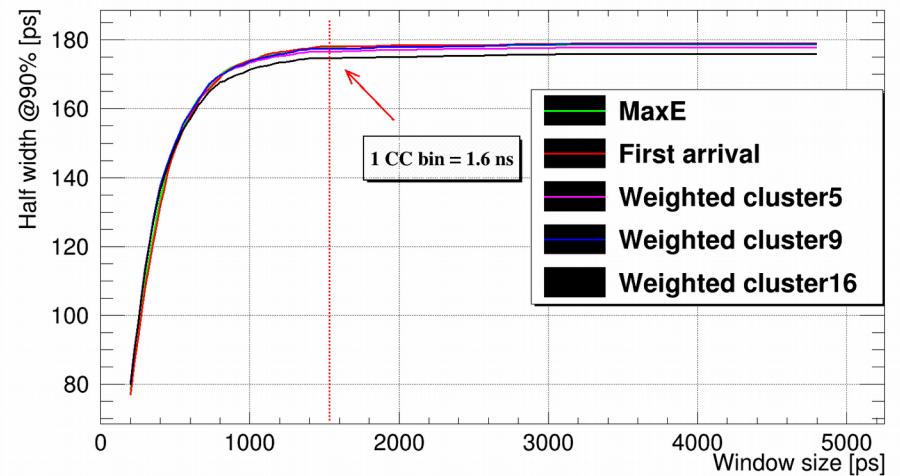
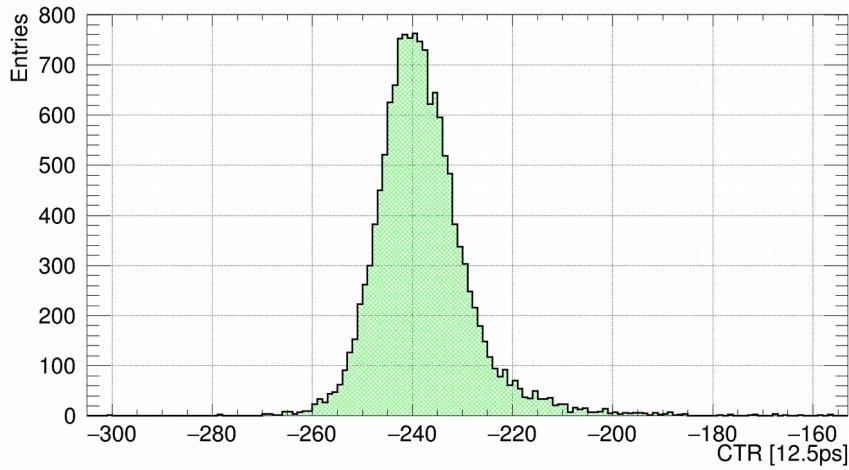
Mu3e title detector

- Individual wrapping
- Assembling 3 submodule (96channels)



Timing resolution of module

Width @90% confidence



Weighted cluster16 vs. 2 channels average in trigger

$\mu \rightarrow eee$: searching for cLFV

Standard Model (SM):

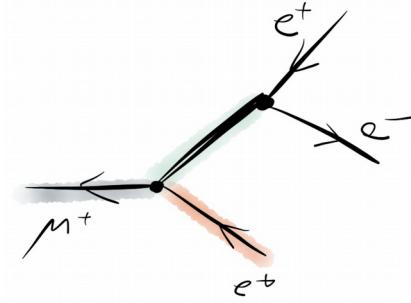
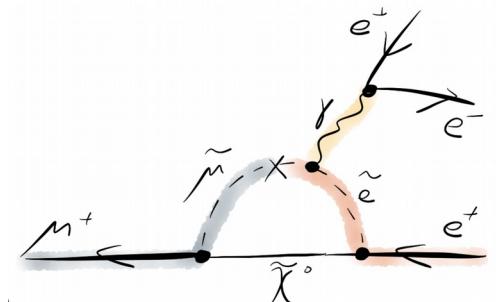
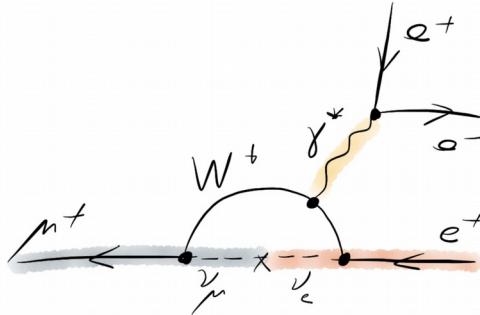
Br: $\sim 10^{-50}$

Unobservable

Beyond Standard Model (BSM):

Predict much larger branching fraction

Observable



Timing resolution of module

Module resolution:

$$\sigma_{module} = \frac{1}{\sqrt{2}} \sqrt{\sigma_{module, ref1}^2 + \sigma_{module, ref2}^2 - \sigma_{ref1, ref2}^2}$$

ref1 and ref2 are in same submodule



$$\sigma_{module} = \sigma_{pure} \oplus jitter$$

5 different ways define t_{module} :

Max ToT; First arrival; Weighted cluster5;
Weighted cluster9; Weighted cluster16.

Timing resolution of module

Module resolution:

$$\sigma_{module} = \frac{1}{\sqrt{2}} \sqrt{\sigma_{module, ref1}^2 + \sigma_{module, ref2}^2 - \sigma_{ref1, ref2}^2}$$

ref1 and ref2 are in same submodule



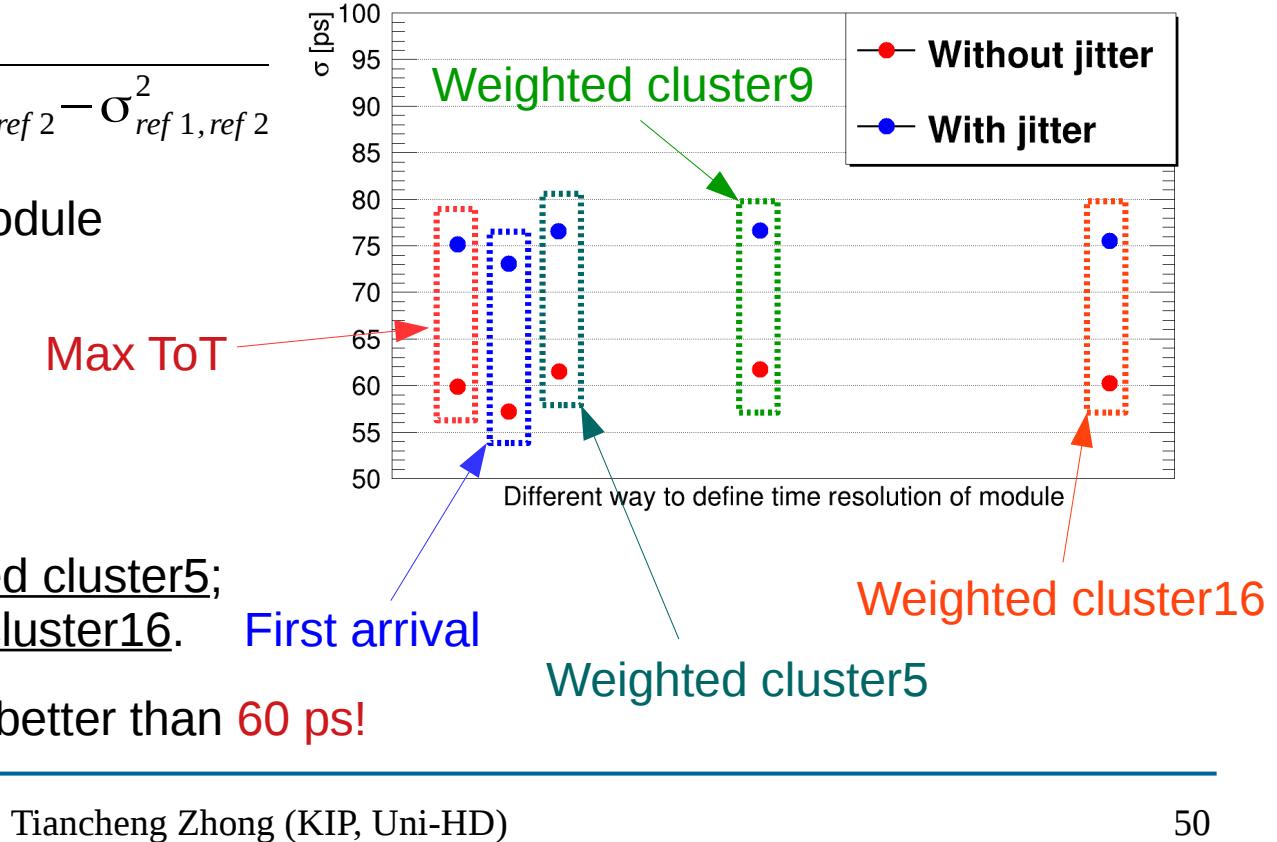
$$\sigma_{module} = \sigma_{pure} \oplus jitter$$

5 different ways define t_{module} :

Max ToT; First arrival; Weighted cluster5;

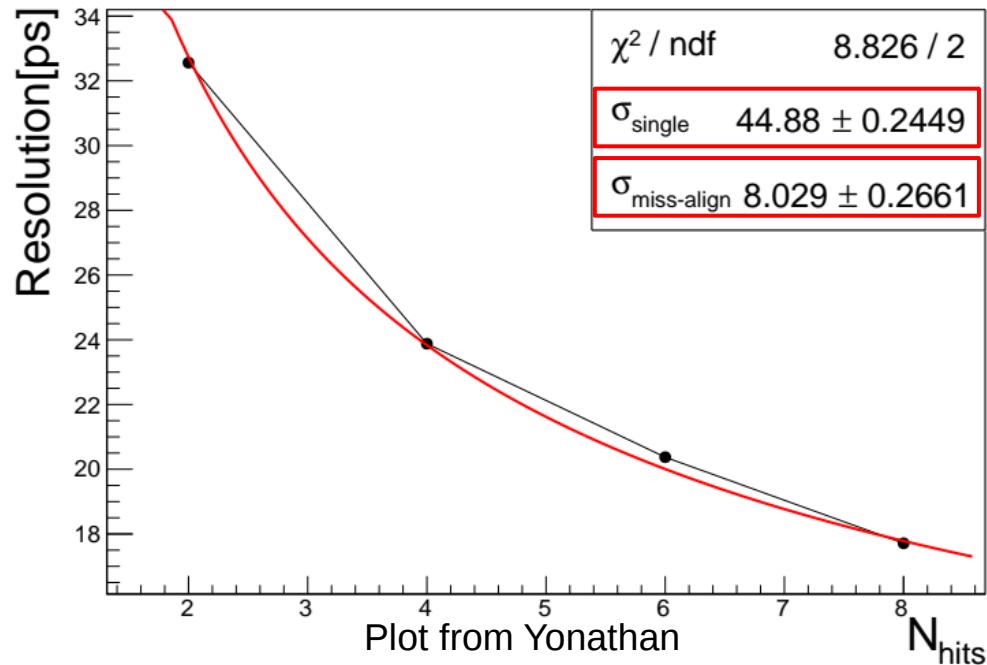
Weighted cluster9; Weighted cluster16.

Timing resolution of module is better than 60 ps!



Thanks for your attention!!

Single channel resolution



$$\sigma(N_{\text{hits}}) = \frac{\sigma_{\text{single}}}{\sqrt{N_{\text{hits}}}} \oplus \sigma_{\text{miss-align}}$$

single channel resolution:

$$\sigma_{\text{single}} = 44.88 \pm 0.24 \text{ ps}$$

Miss-alignment:

$$\sigma_{\text{miss-align}} = 8.03 \pm 0.27 \text{ ps}$$

Good agreement with internal results!