

MEG II 実験における陽電子タイミング カウンターの3次元アラインメント

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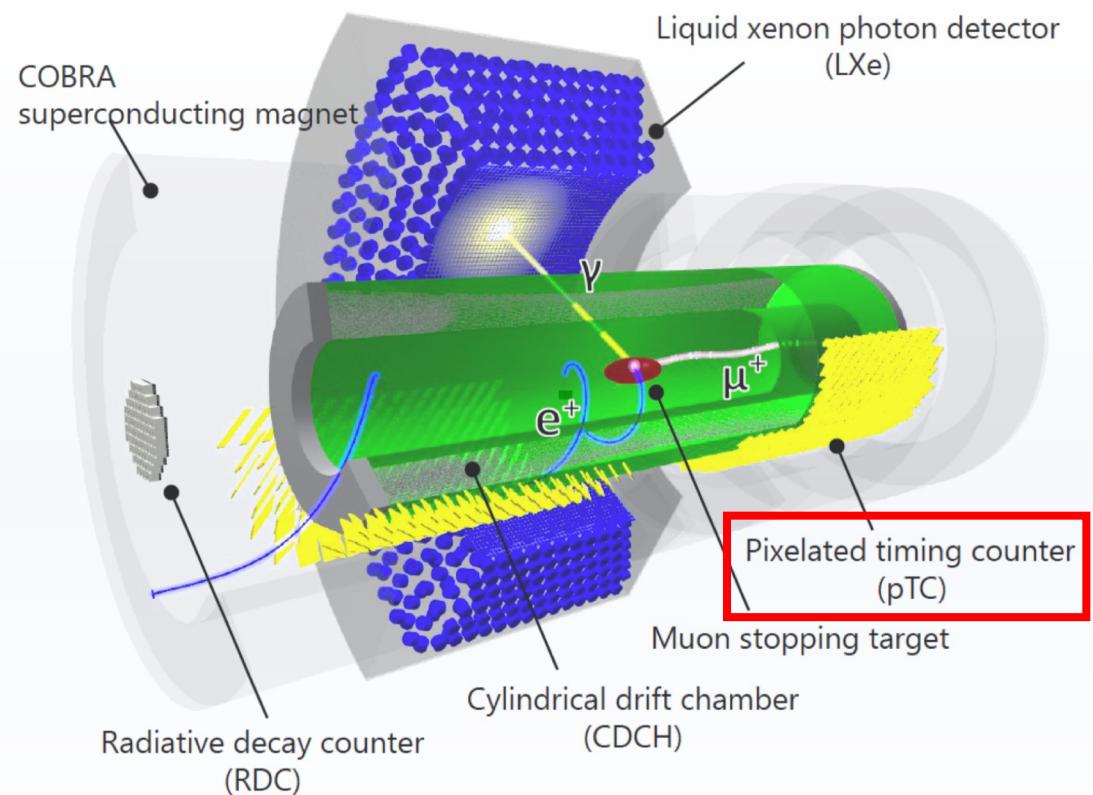
- Introduction
 - ... What is MEG II ?
 - ... Positron timing counter (pTC)
 - ... 3D alignment
- Methods & Results
- Summary & Prospects

What is MEG II ?

Upgrade of MEG experiment

- The search for $\mu^+ \rightarrow e^+ + \gamma$
 μ^+ : most intense beam at PSI
 γ : detected by LXe
 e^+ : detected by **pTC** & CDCH
- expected sensitivity: 6×10^{-14}
(higher than ever before searches)

“The design of the MEG II experiment”,
Eur. Phys. J. C (2018) 78:38

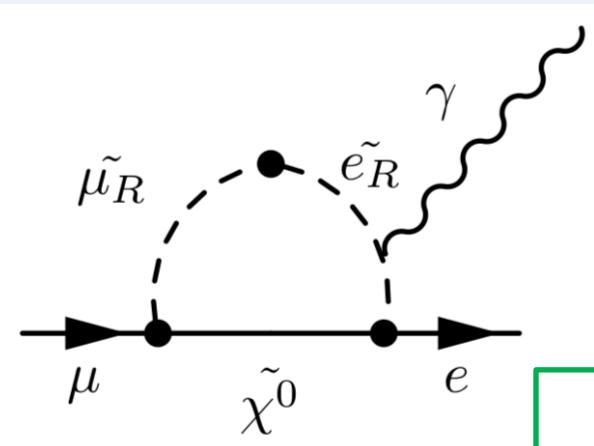
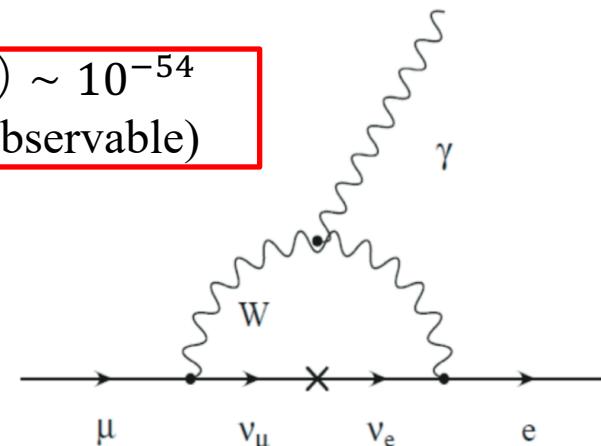


What is MEG II ?

- $\mu^+ \rightarrow e^+ + \gamma$ is a rare muon decay which is a charged lepton flavor violation process prohibited in the Standard Model.

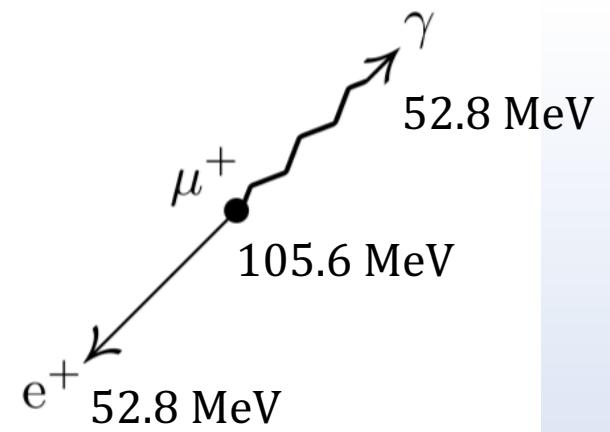
$$\mathcal{B}(\mu^+ \rightarrow e^+ + \gamma) \sim 10^{-54}$$

prohibited (unobservable)



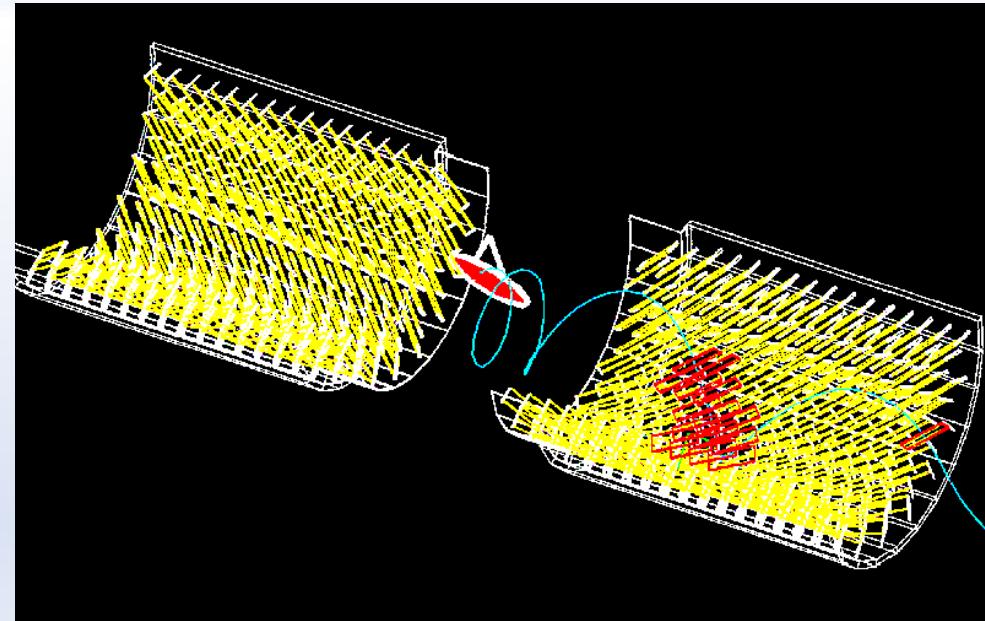
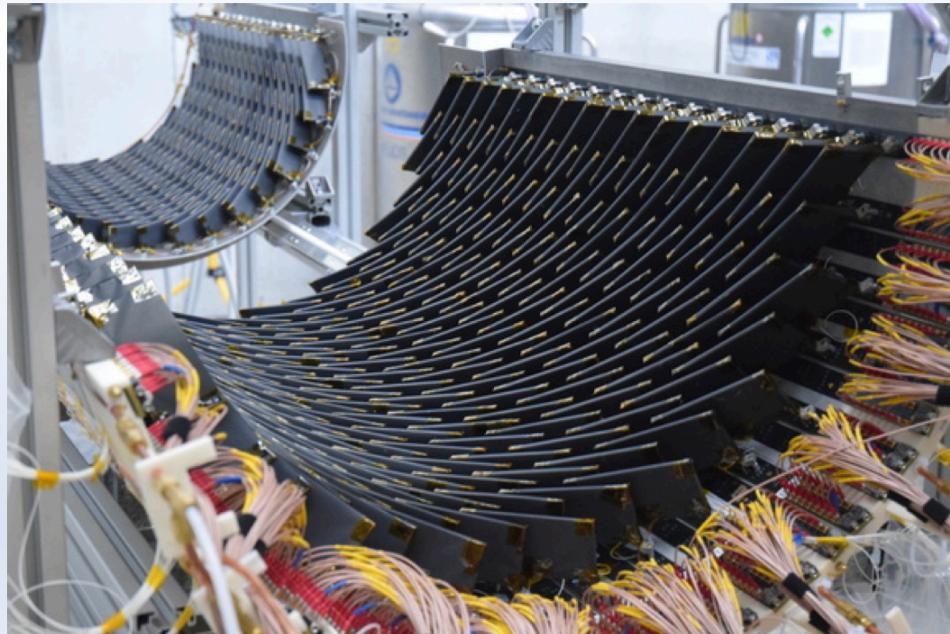
$$\mathcal{B}(\mu^+ \rightarrow e^+ + \gamma) \sim 10^{-12} - 10^{-14}$$

permitted (observable)



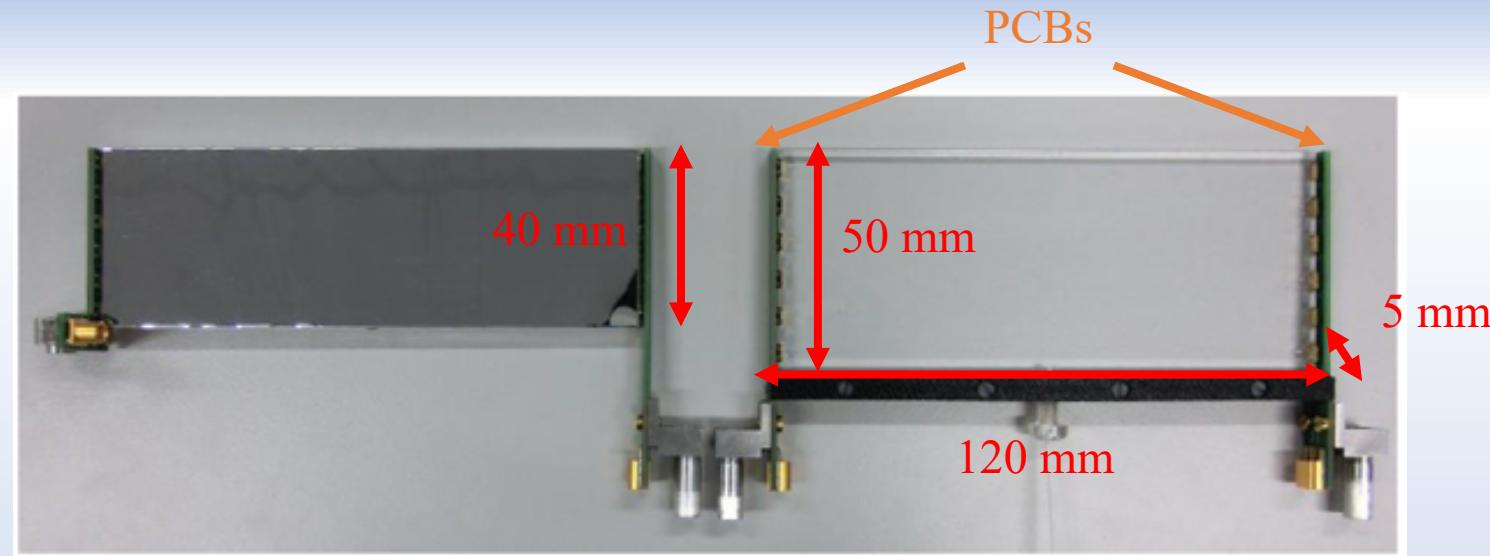
- Assuming supersymmetric particles, the decay can be observable.

Positron timing counter (pTC)



- a highly segmented ($256 \text{ tiles} \times 2$) scintillation counter, consists of two semi-cylindrical super-modules mirror symmetric to each other
- expected time resolution is 38 ps

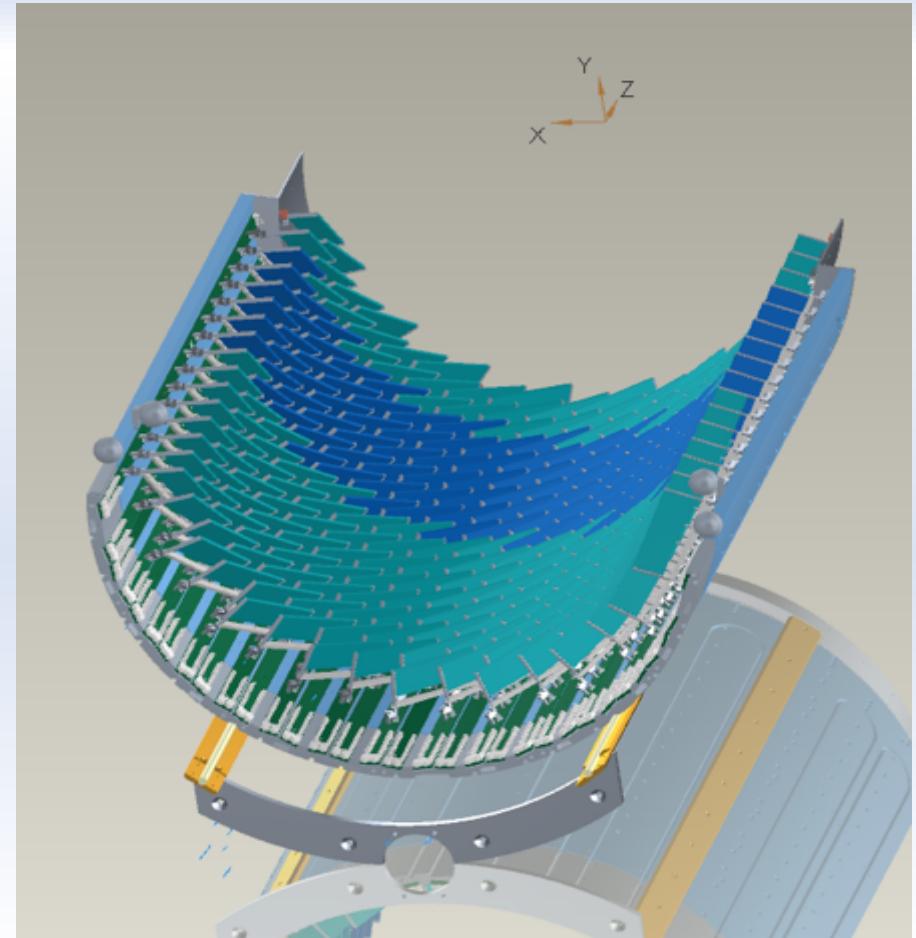
pTC - Pixel counters



- 120mm × 40mm (50mm) × 5mm plastic scintillator (BC422)
- Read by 6 SiPMs on each PCB attached to both side of the scintillator
- Two types (40mm, 50mm) for positrons moving spirally with various radii.

3D alignment - Necessity

- Real value of 3D positions and direction are **critical** to
 - detection efficiency
 - Time-of-Flight among hit pixels
- for positrons bent by COBRA magnet.



3D alignment - Goal

- Random uncertainty added up every pixel hit and a systematically bias

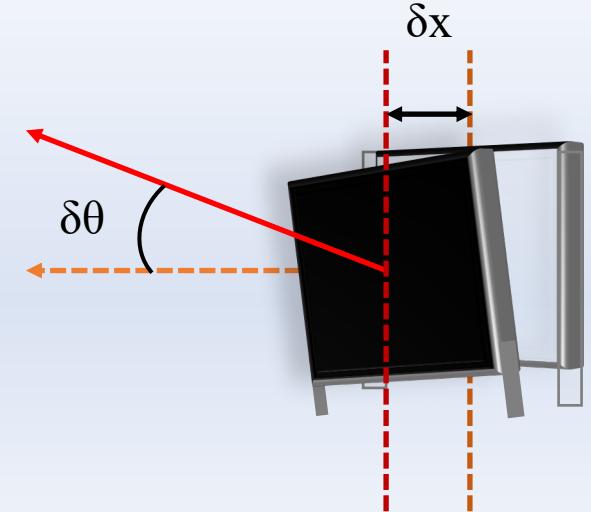
$$\sigma_{\text{alignment}} = \sigma_{\text{random}} \times \frac{1}{\sqrt{N_{\text{hit}}}} \times N_{\text{hit}} + \sigma_{\text{bias}} \leq 17 \text{ ps (Goal)}$$

(N_{hit} : number of hitted pixels ~ 9)

$$\sigma_{\text{random}} \leq (\delta x_{\text{random}} + 60\text{mm} \times \sin \delta\theta_{\text{random}})/c$$

$$\sigma_{\text{bias}} \leq (\delta x_{\text{bias}} + 60\text{mm} \times \sin \delta\theta_{\text{bias}})/c$$

(devided by c for positrons moving at light speed)



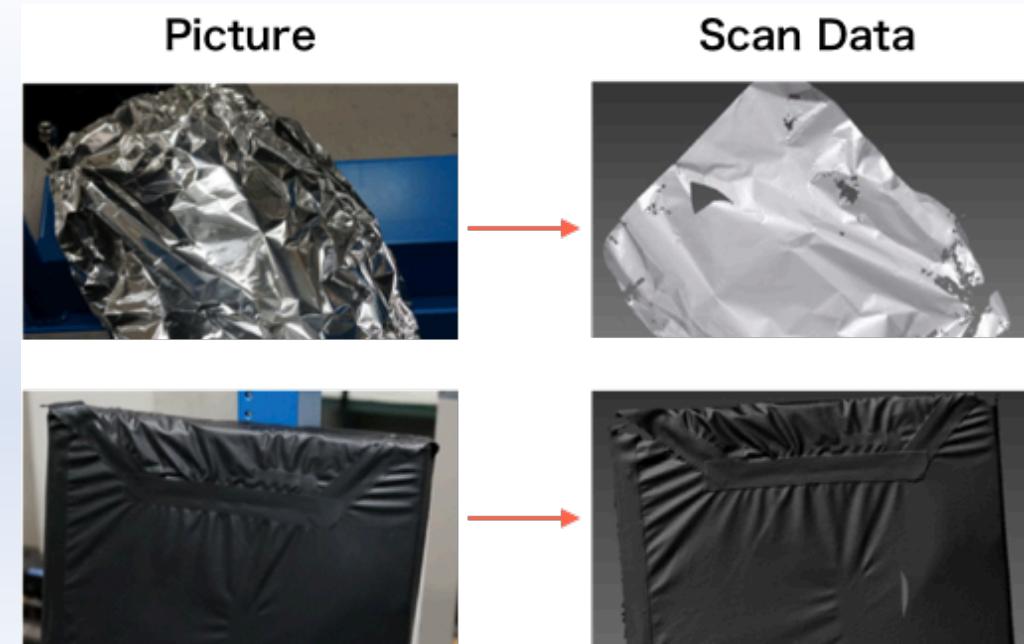
Propagation of 17 ps error makes pTC time resolution 38ps → 42ps
added in 4 ps $\sim 10\%$.

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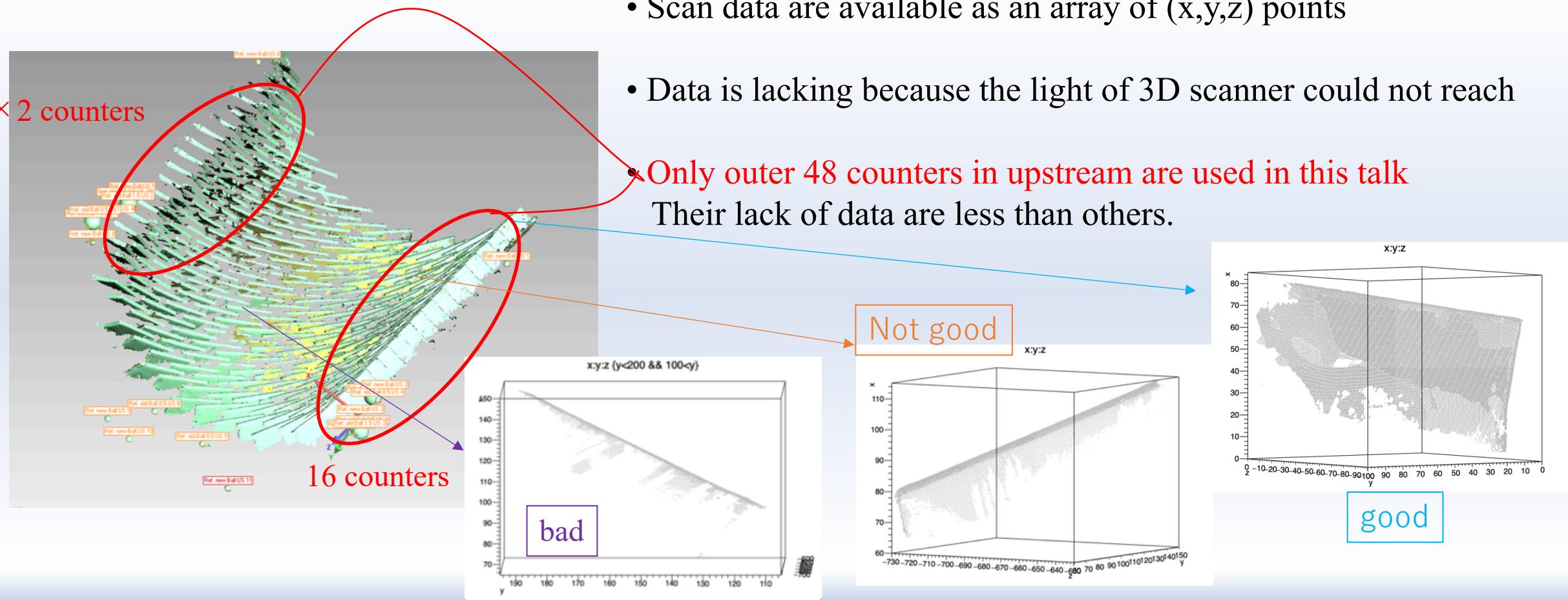
3D Scan - Scanner

3D Scanner (FARO Edge ScanArm HD)



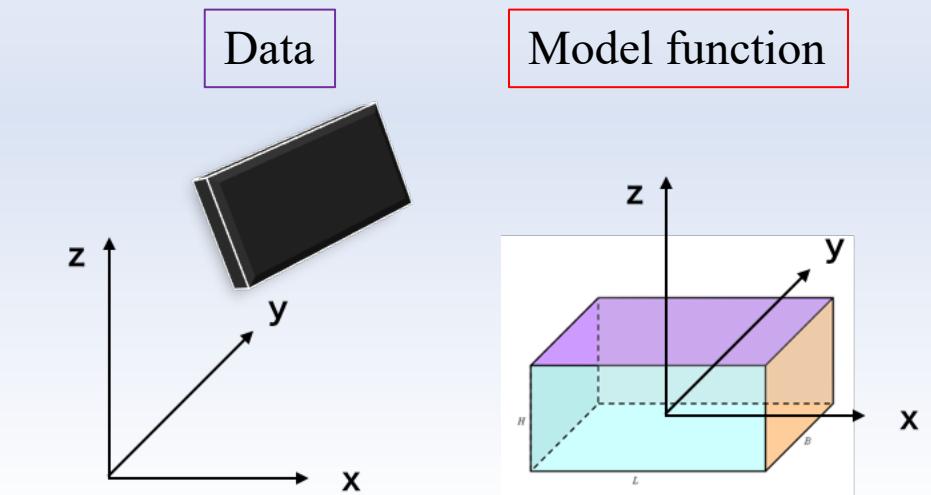
- Accuracy $\pm 25\mu\text{m}$
- Scan rate : 560,000 points/sec
- Cited from <https://www.faro.com/resource/faro-edge-scanarm-hd/>

3D Scan - Data



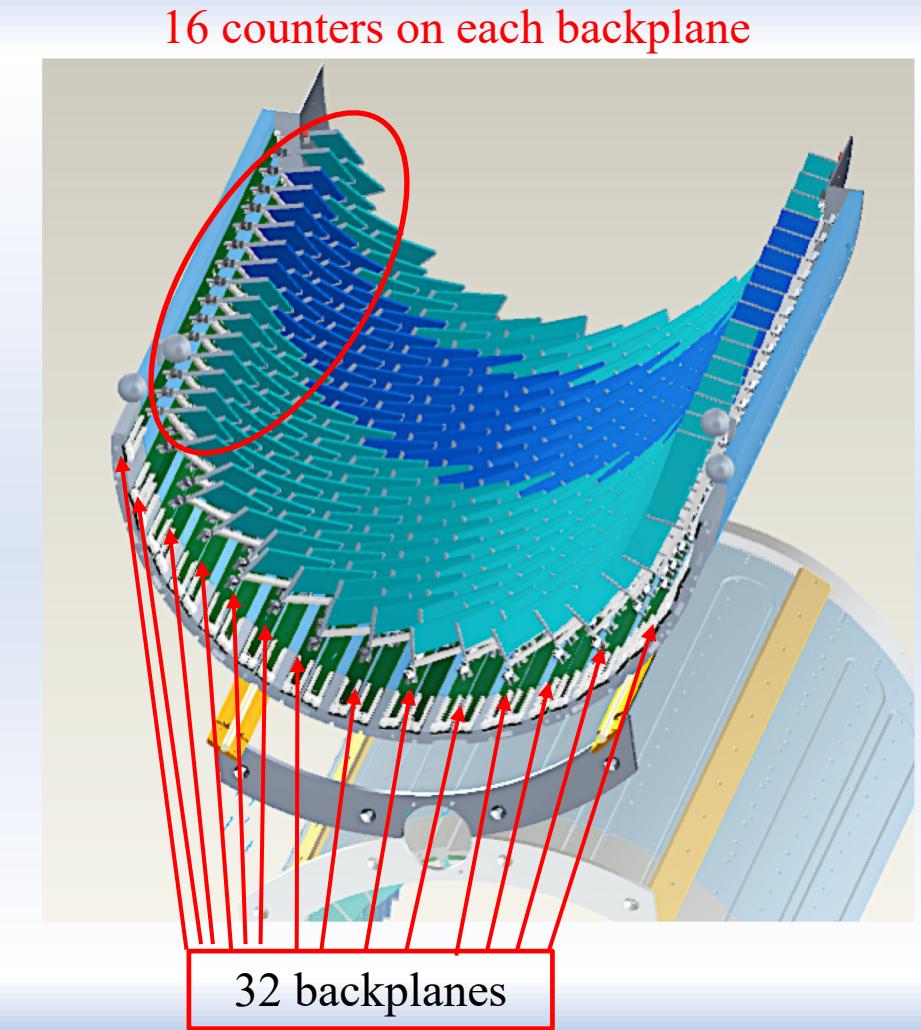
3D Scan – Fitting

- Each counter position and direction can be described by **6 parameters**.
 - center position (x, y, z)
 - rotation angle about each axis ($\theta_x, \theta_y, \theta_z$)
- are adopted here.
- Find a set of 6 parameters which **minimize sum of distance** between data points and model function.



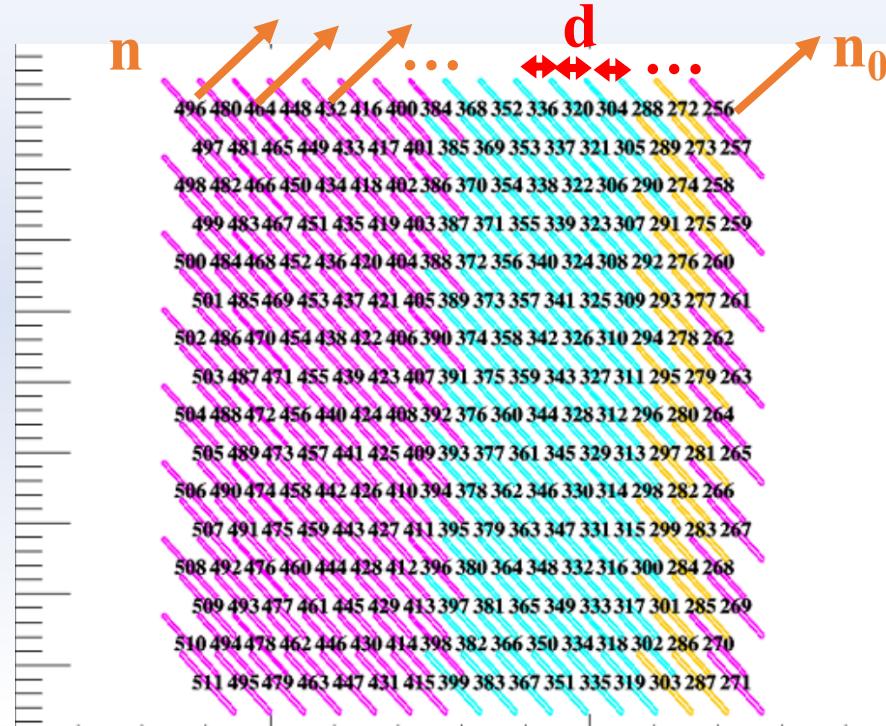
Analysis

- The coordinate system of scan data is different from that of CAD.
- Only relative values can be compared.
- Each 16 counters on the same backplane are designed to line up at regular intervals and in the same direction.



Analysis

- d_{cv} [mm] : 15×3 intervals of center position b/w neighborhood
- $\text{Arccos}(n \cdot n_0)$ [degree] : 15×3 angles formed by normal vectors



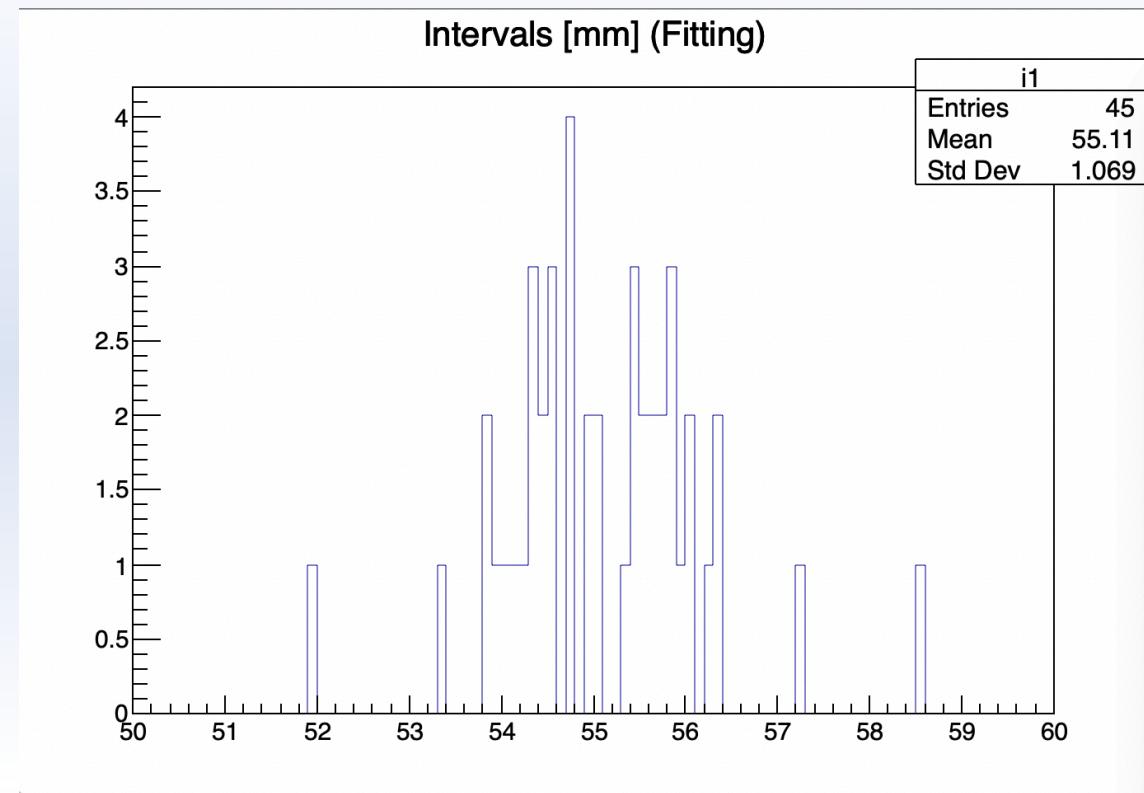
Analysis

- Fitting error
 - 3D scan error
 - Deviation from design value
- } misalignment

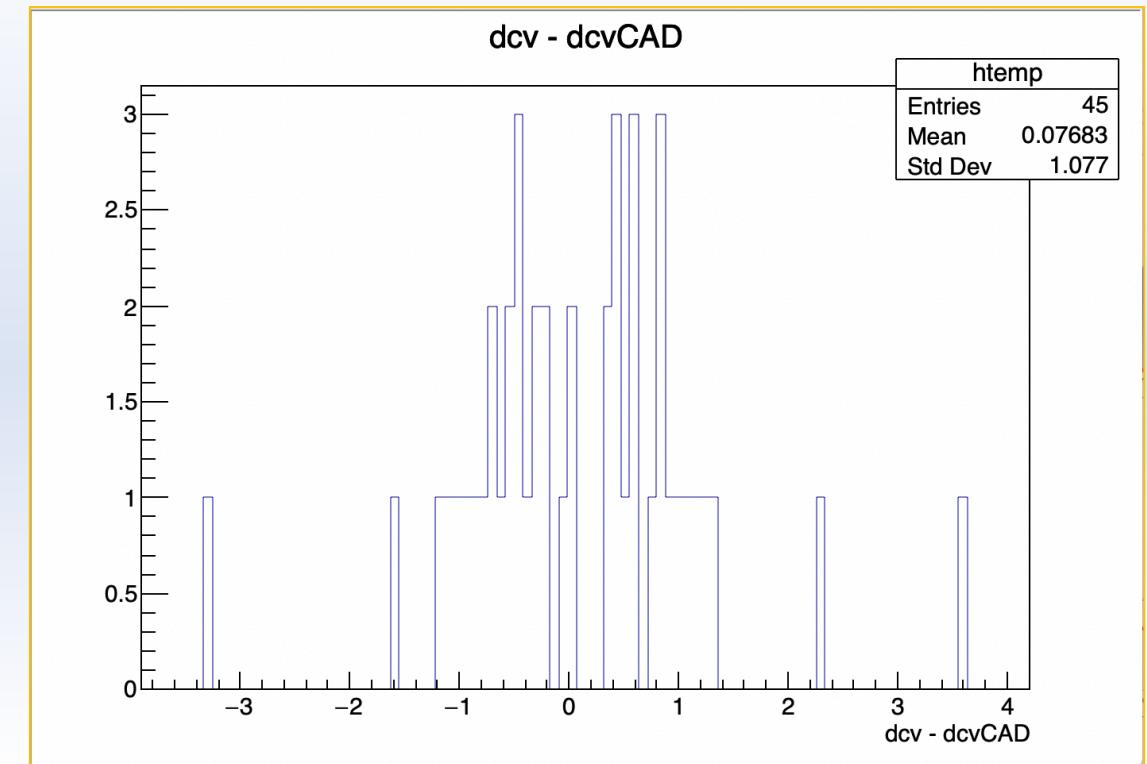


Analysis - intervals

(d_{cv} [mm] : 15×3 intervals of center position b/w neighborhood)

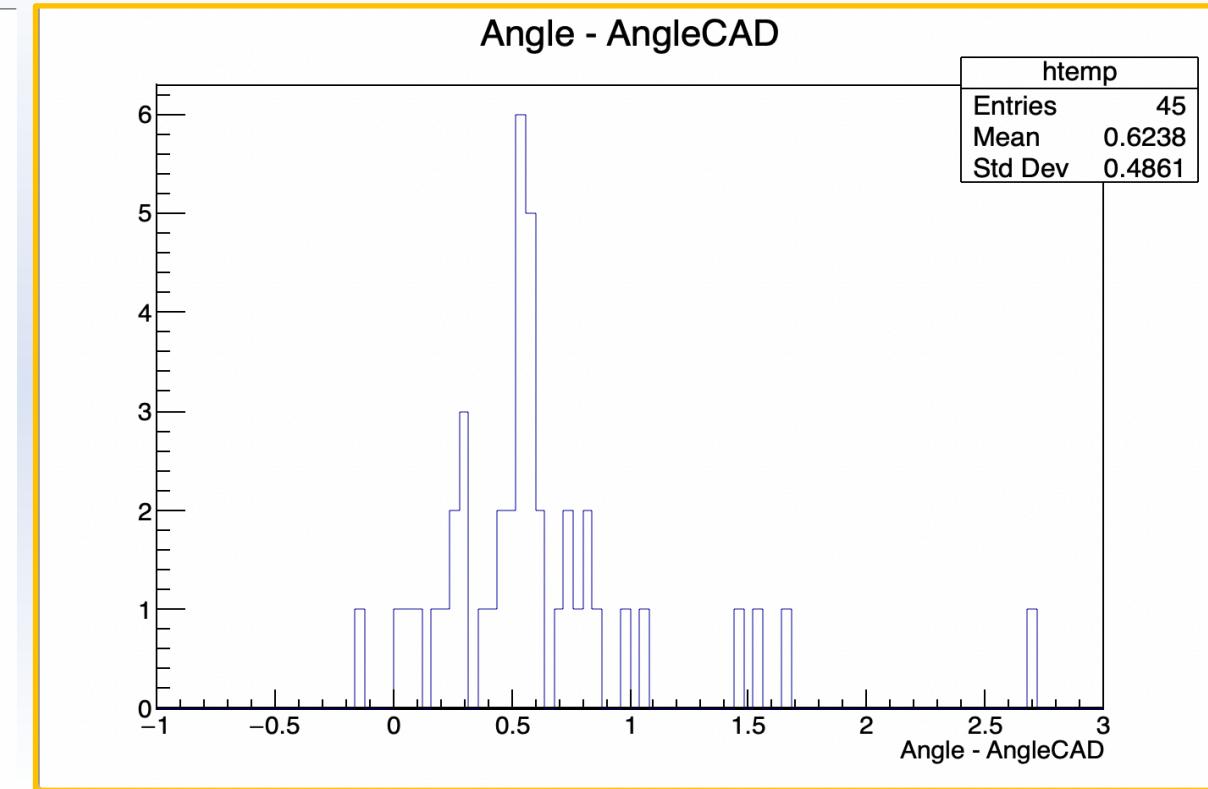
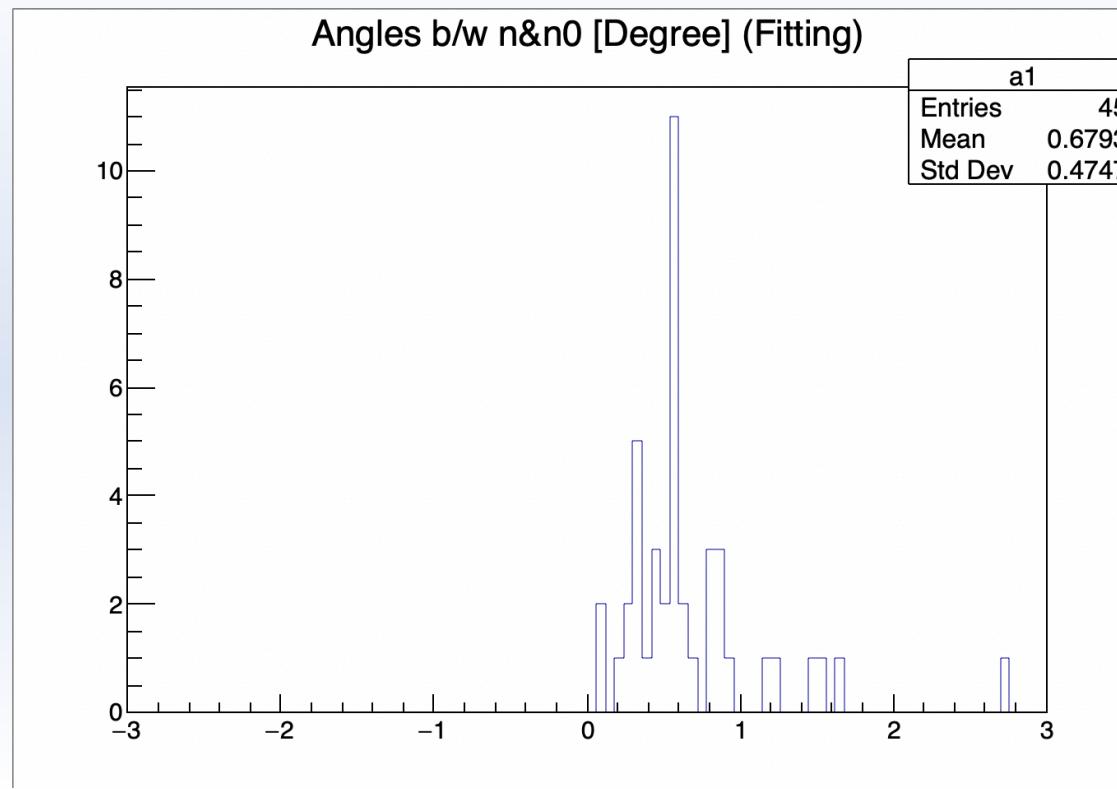


Mean ~ 0.1mm
Standard deviation ~ 1.1mm



Analysis - angles ($\text{Arccos}(\mathbf{n} \cdot \mathbf{n}_0)$ [degree] : 15×3 angles formed by normal vectors)

Mean $\sim 0.7^\circ$
Standard deviation $\sim 0.5^\circ$



Discussion

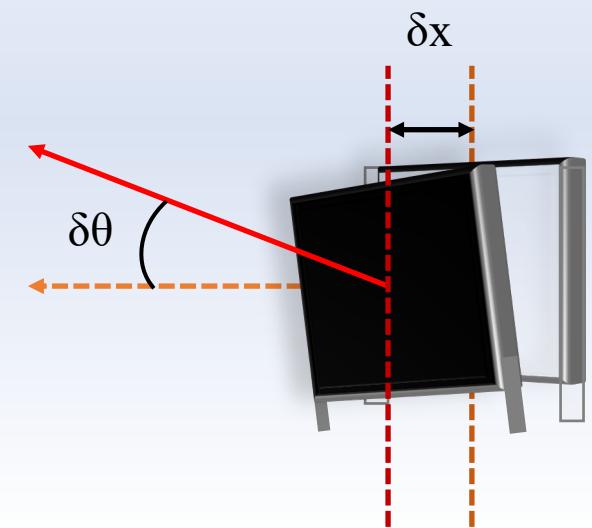
Assuming random error = std dev & alignment bias = mean value

- $\delta x_{\text{random}} = 1.1 \text{ mm}$, $\delta \theta_{\text{random}} = 0.5^\circ \rightarrow \sigma_{\text{random}} \leq (1.1 + 60 \times \sin 0.5^\circ)/c \cong 5.4 \text{ ps}$
- $\delta x_{\text{bias}} = 0.1 \text{ mm}$, $\delta \theta_{\text{bias}} = 0.7^\circ \rightarrow \sigma_{\text{bias}} \leq (0.1 + 60 \times \sin 0.7^\circ)/c \cong 2.7 \text{ ps}$

the maximum deviation b/w alignment and real position is

$$\sigma_{\text{alignment}} \leq \sigma_{\text{random}} \times 3 + \sigma_{\text{bias}} \cong 19 \text{ ps}$$

Propagation of 19 ps error makes time resolution of pTC
38ps \oplus 19ps $\sim 42.5 \text{ ps}$.



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Summary

- pTC, a highly segmented detector with complicated 3D structure, should be confirmed with each pixel position and direction.
- Preliminary alignment method with 3D scan data showed the error is at most 19 ps which influences the pTC time resolution 38ps by 4.5ps ~ 12%.
- The upper limit 19 ps is slightly over the alignment goal 17 ps, but deterioration of time resolution is ~12%, that is good enough.

Prospects

- Invisible biases of absolute positions & directions, will be eliminated by matching coordinate systems of 3D scan data & design value with reference points from laser tracker.
- An efficient alignment method for inner pixels is developed.
- To complete alignment for all 512 pixels.

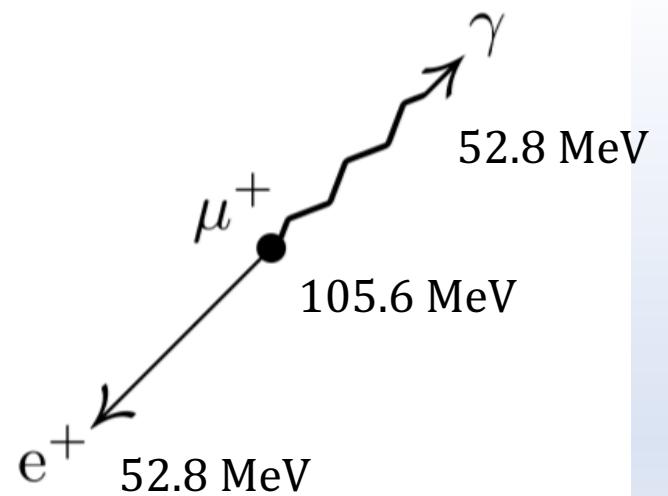
Back up

$$\mu^+ \rightarrow e^+ + \gamma$$

- $(m_\mu, \vec{0}) \rightarrow (p, \vec{p}) + (\sqrt{p^2 + m_e^2}, -\vec{p})$

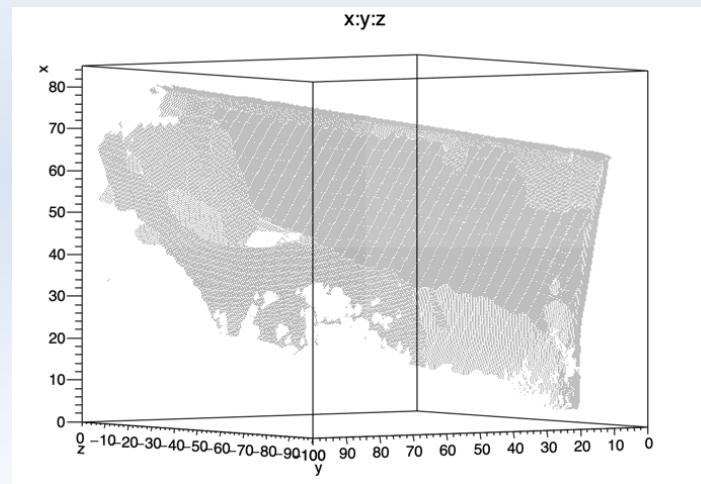
$$\therefore p = \frac{m_\mu^2 - m_e^2}{2m_\mu} \cong 52.8 \text{ MeV/c}$$

- $p = \gamma m_e \beta = m_e \sqrt{\gamma^2 - 1} \rightarrow \gamma \cong 10.2$
 $\beta \cong 0.9952$

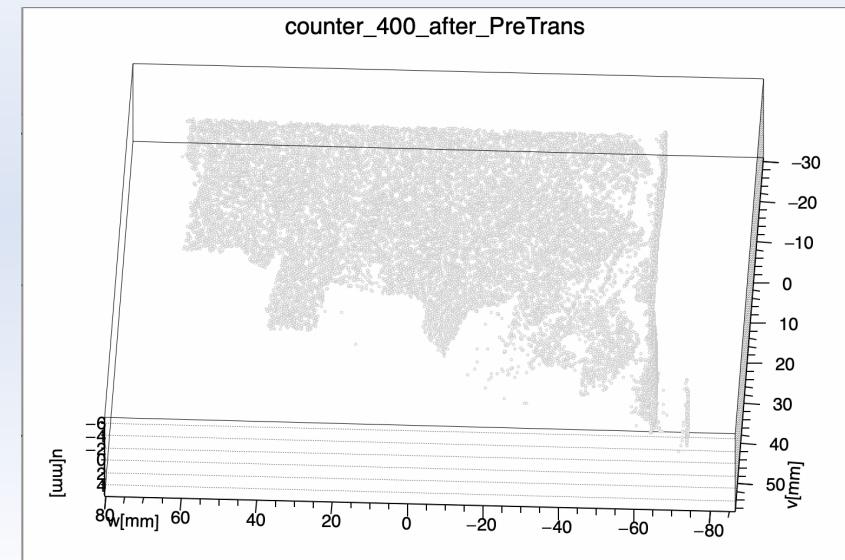


3D Fit - Initial value

- To find initial values, data points are **manually** moved and rotated data before fitting. (they will be replaced by design values)

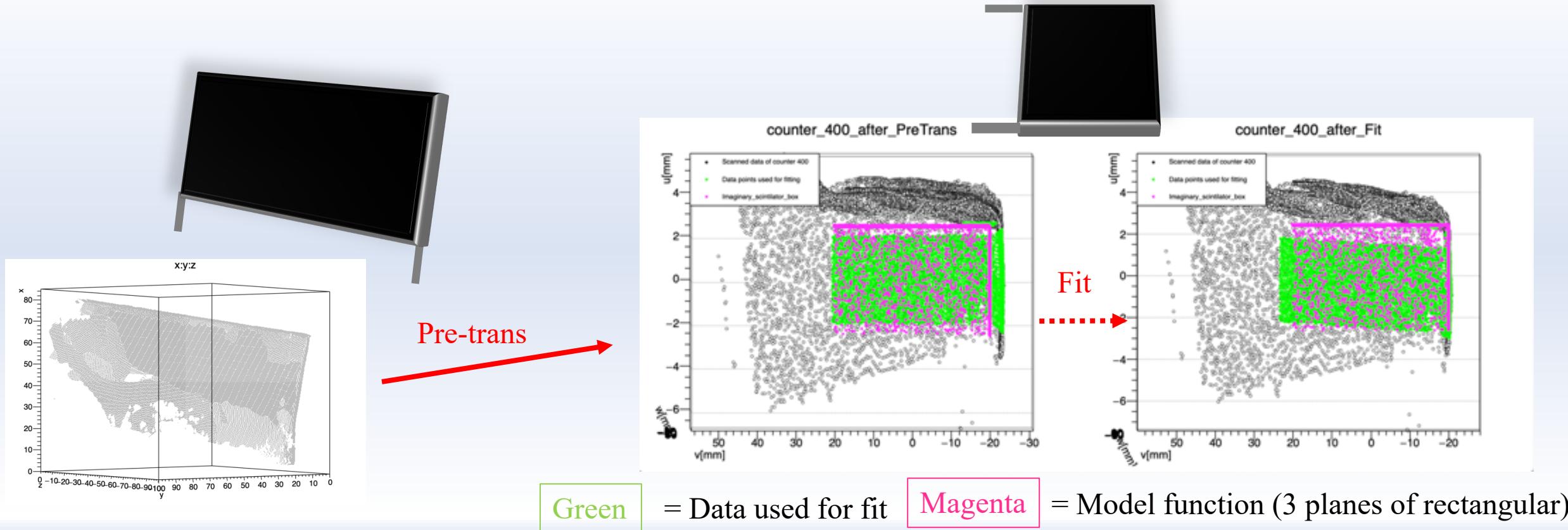


Pre-transformation
by initial values



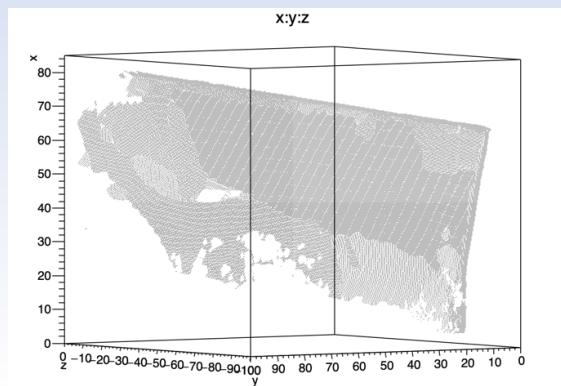
3D Fit - Data selection

- At least, 3 planes are needed

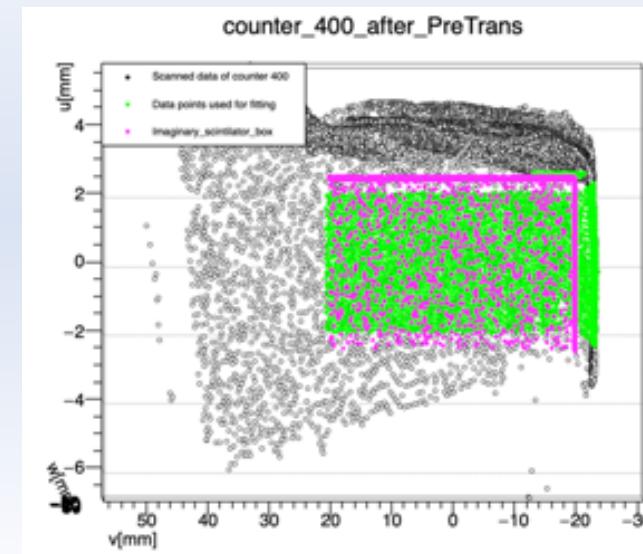


Data Selection

- A Top plane (5mm*120mm) & a small side plane (5mm*40mm)
- The most depressed points from a large side plane (40mm*120mm)



Pre-trans
→

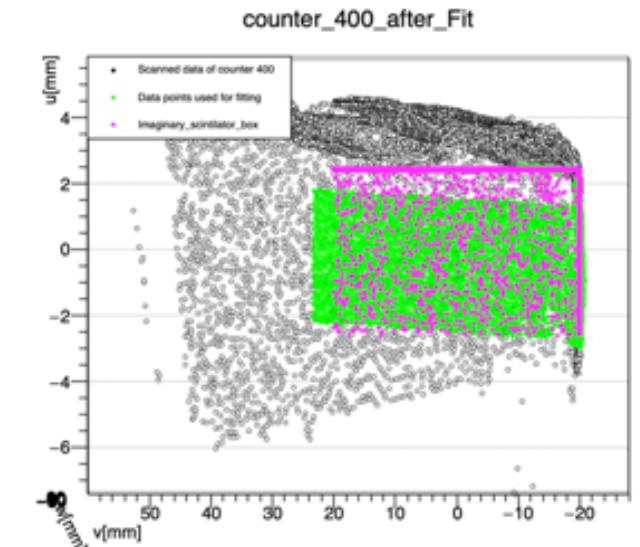


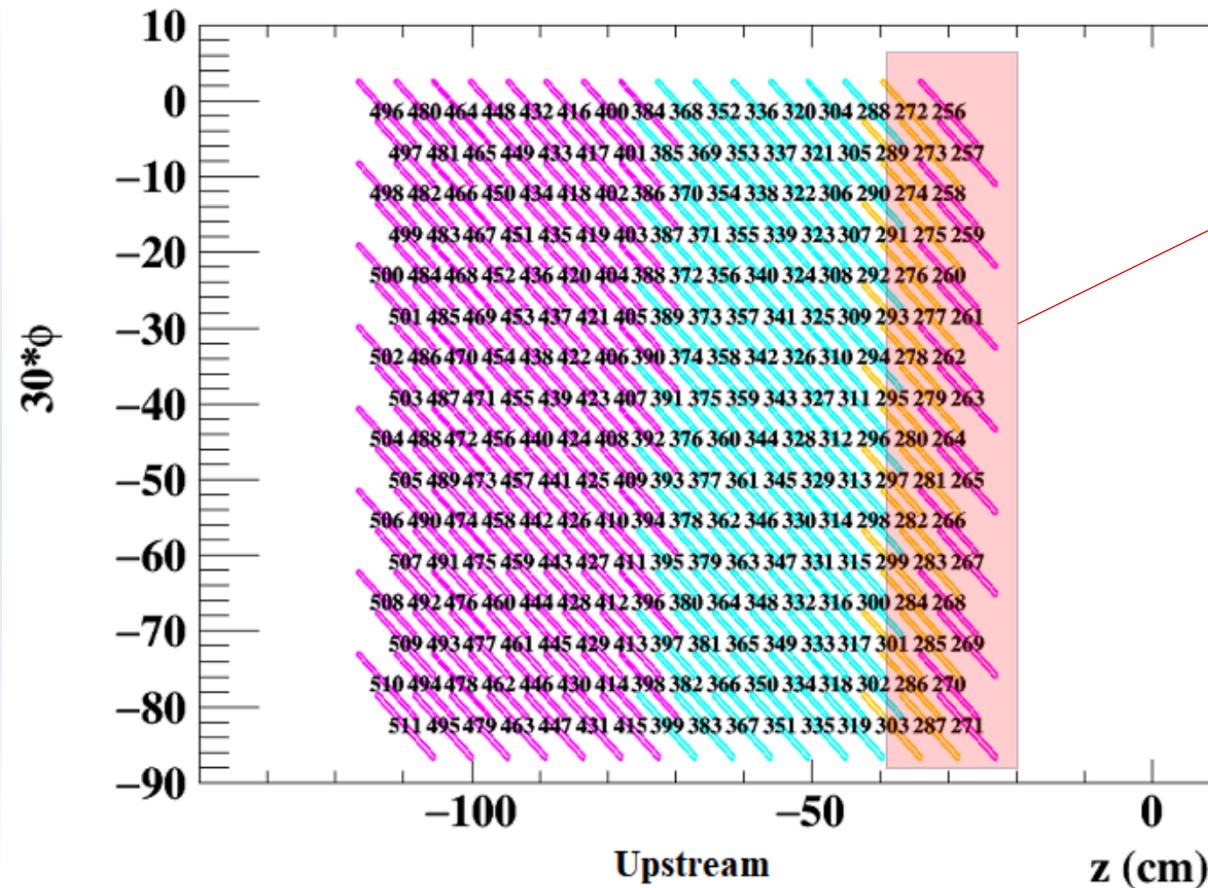
Green

= Data used for fit

Magenta

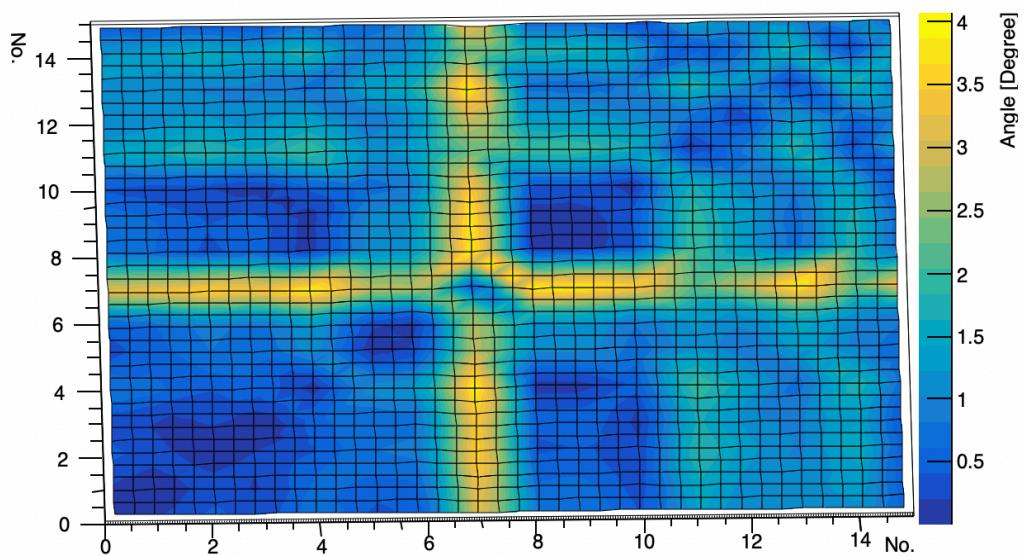
= Model function (3 planes of rectangular)



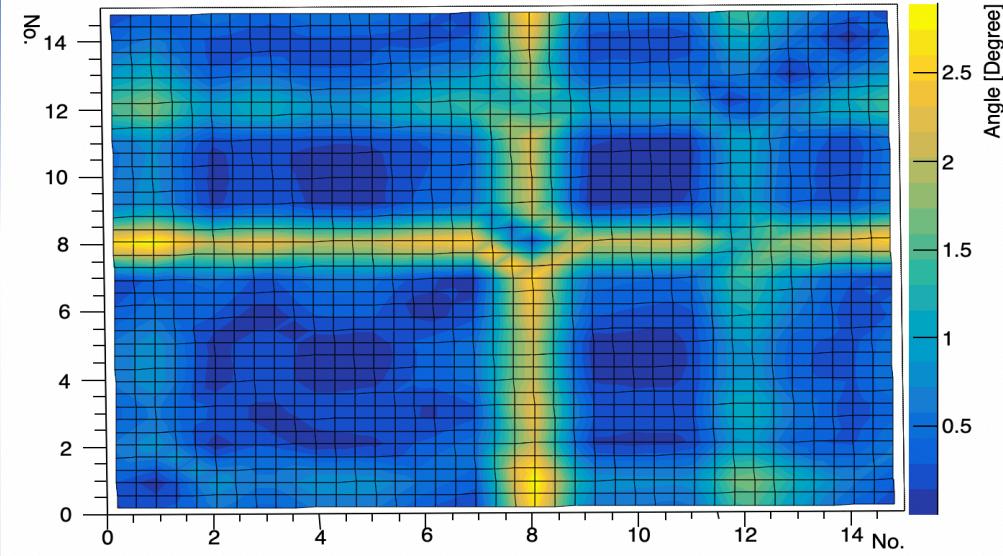


Inner radius of aluminum frame
Is smaller than large $|z|$
for docking to COBRA

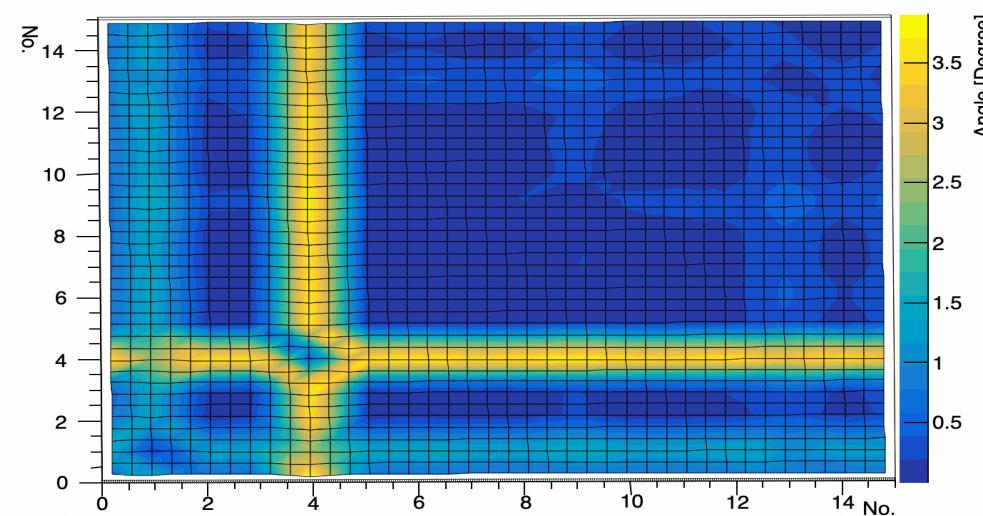
Angle b/w normal vectors BP0 from fitting

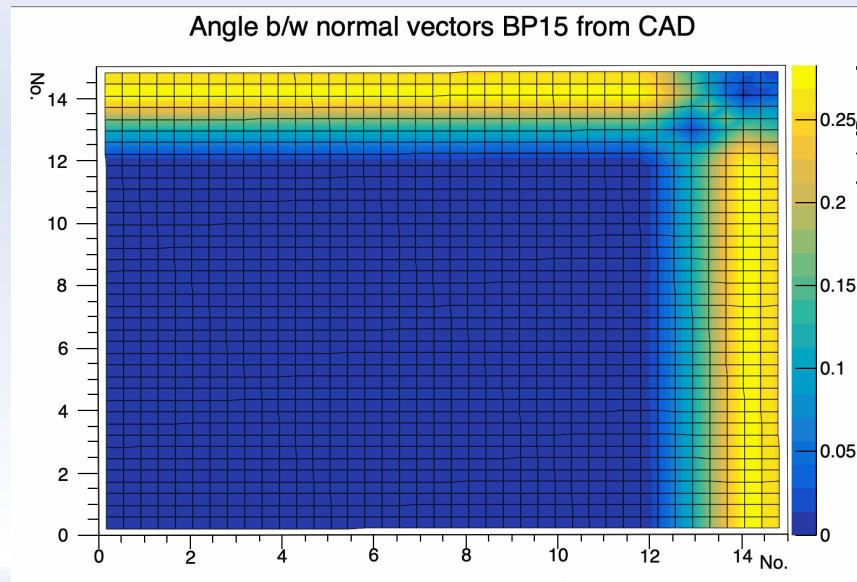
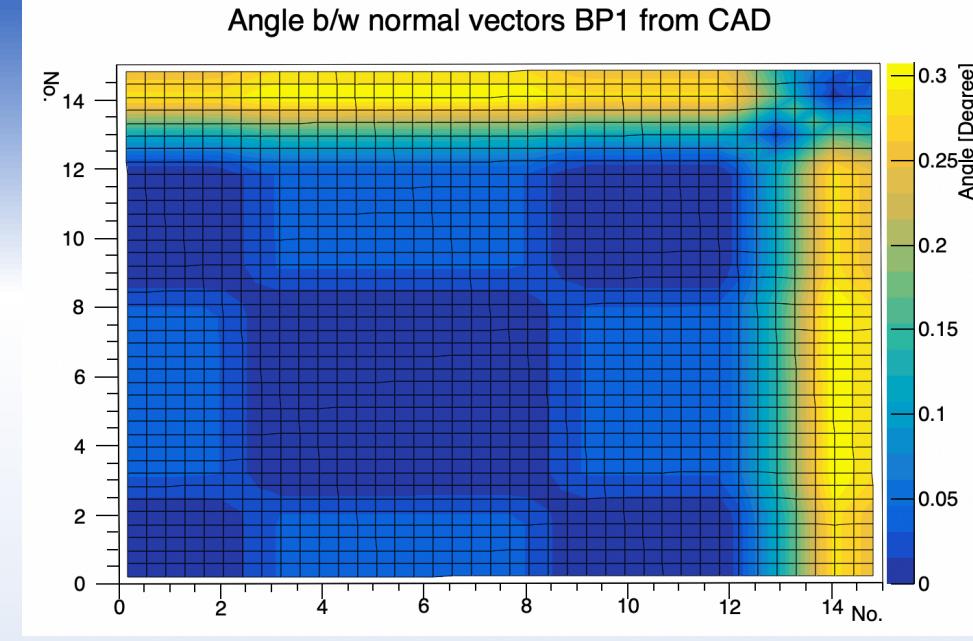
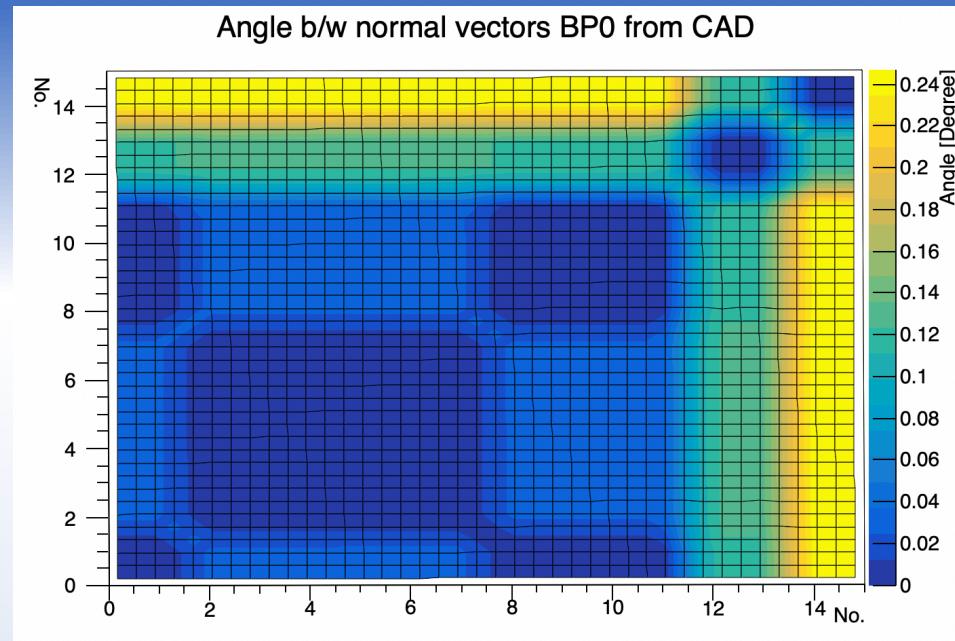


Angle b/w normal vectors BP1 from fitting

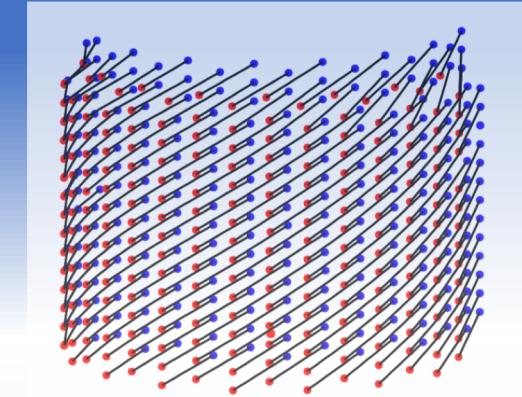
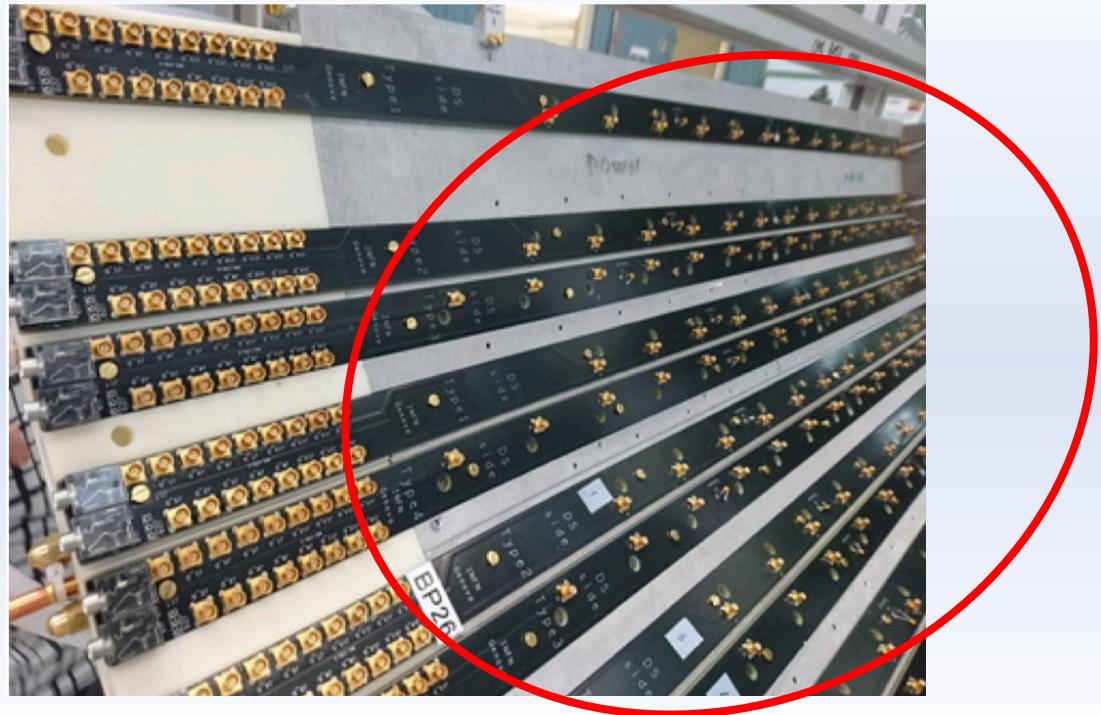


Angle b/w normal vectors BP15 from fitting

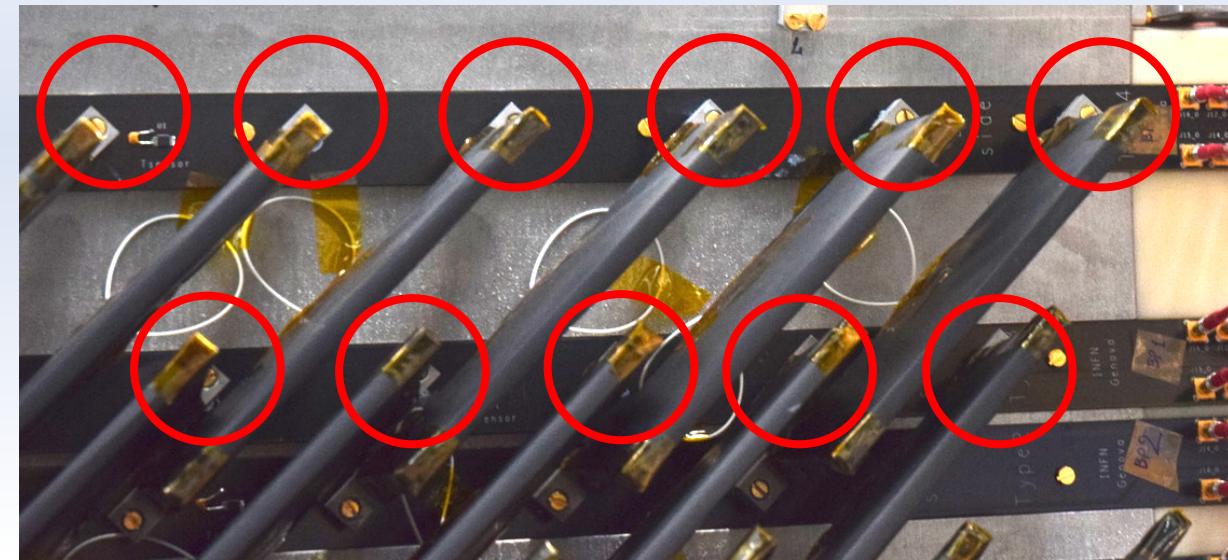




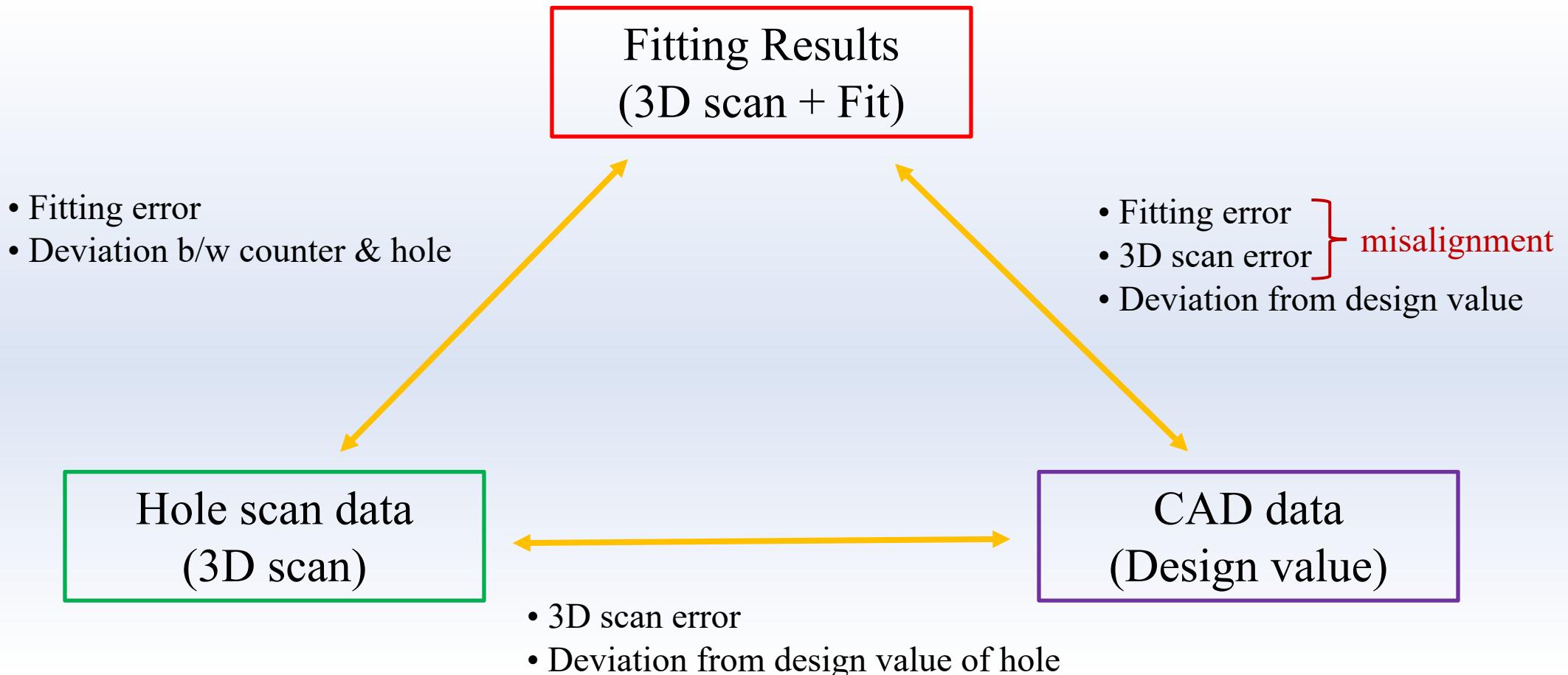
Backplane Holes Scan Data



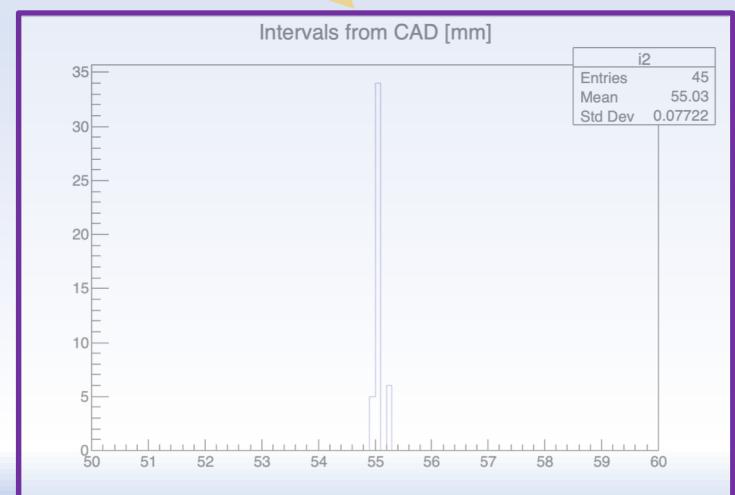
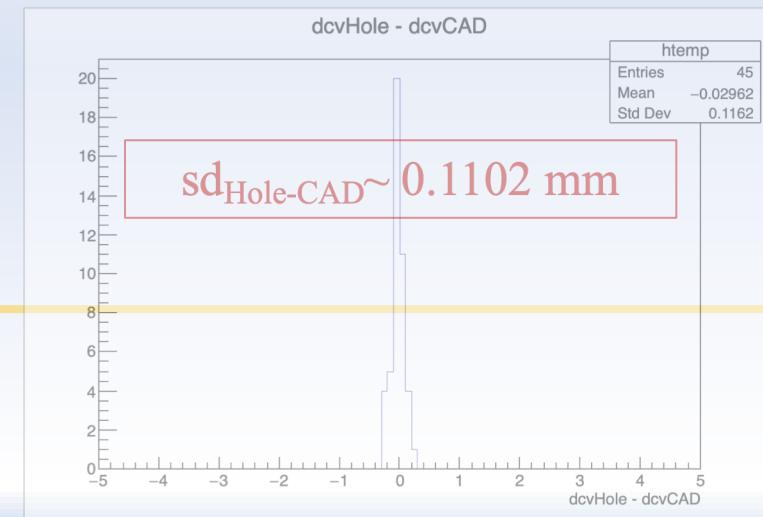
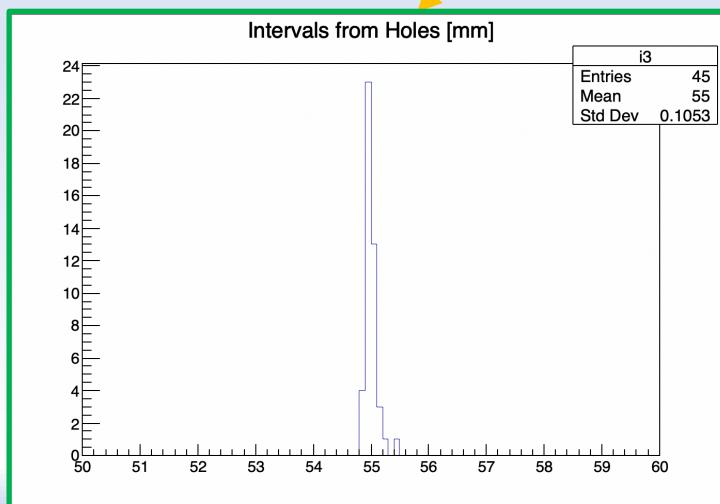
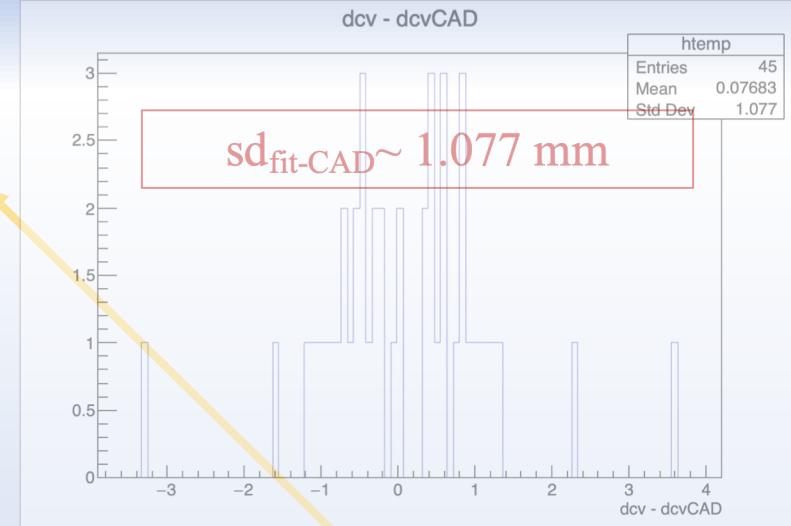
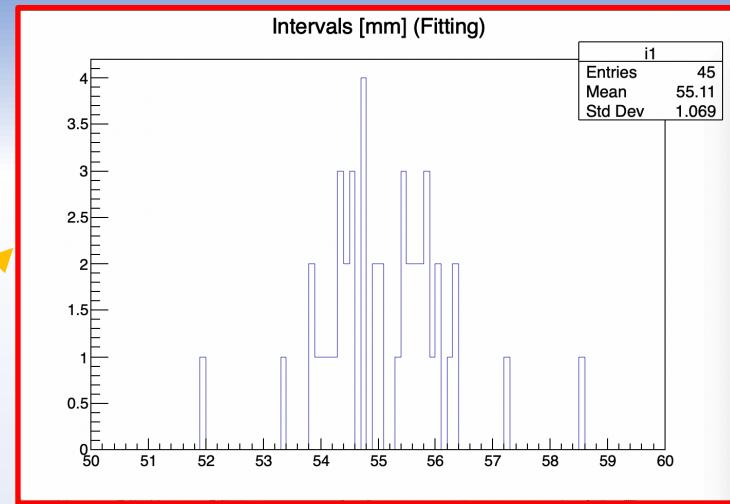
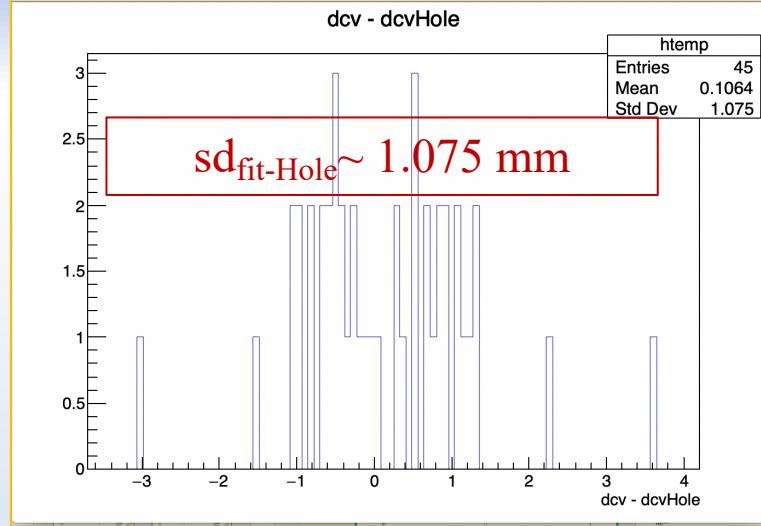
- Hole scan mode of 3D scanner was used
- These are used for intervals b/w counters



Analysis

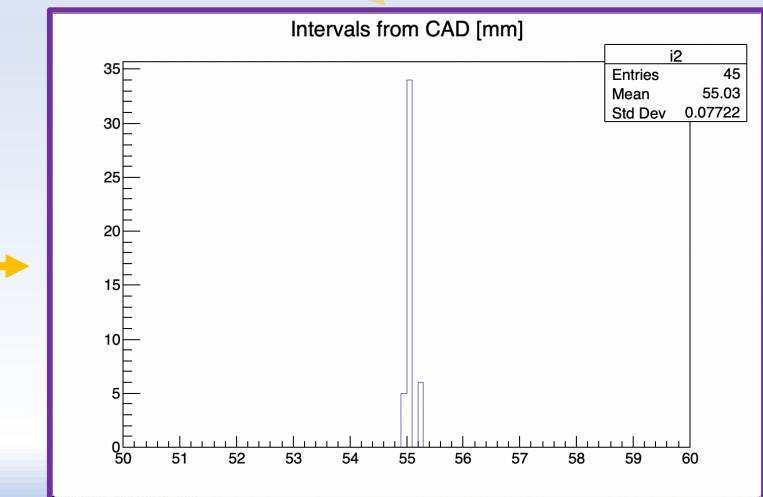
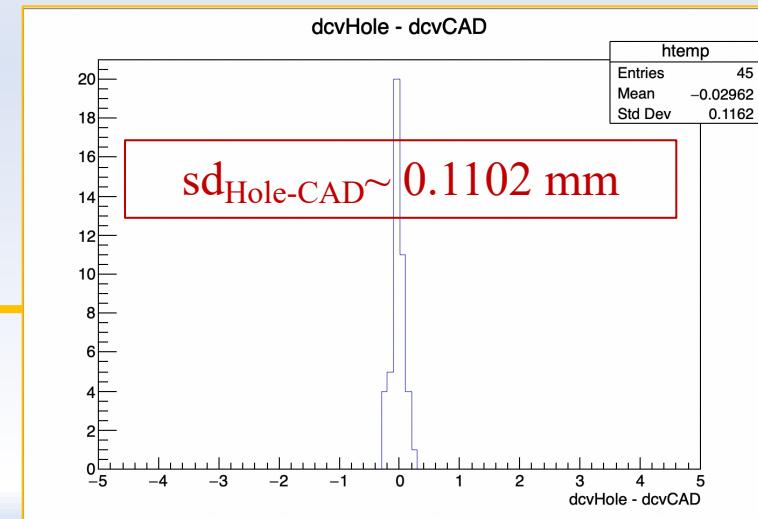
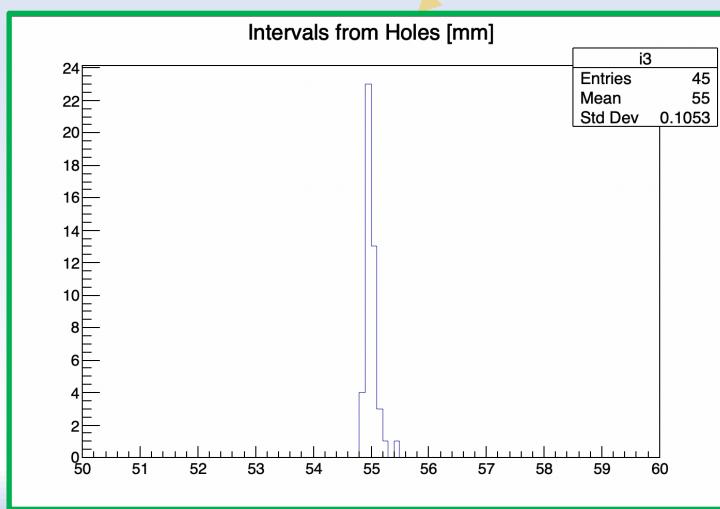
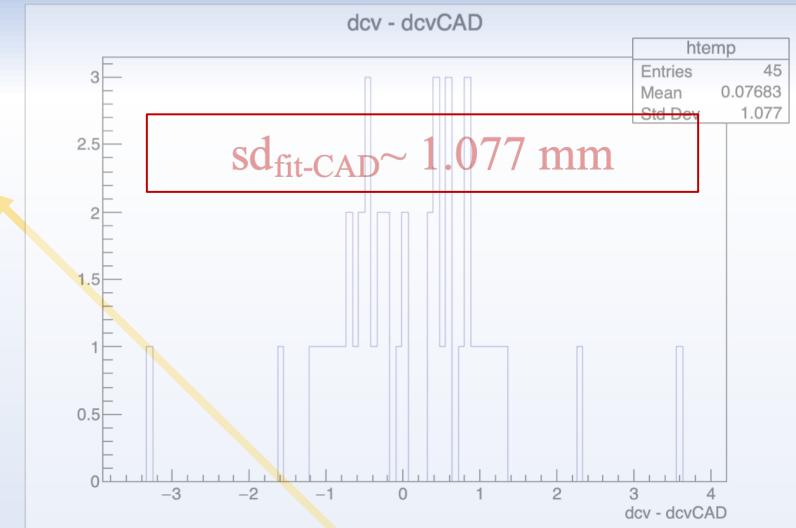
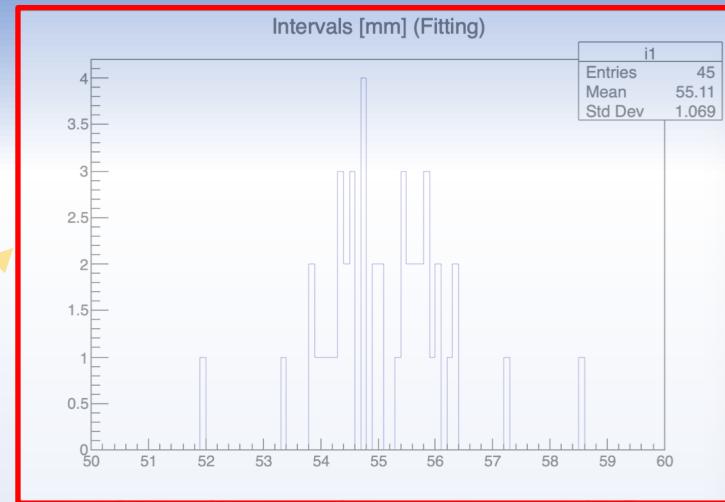
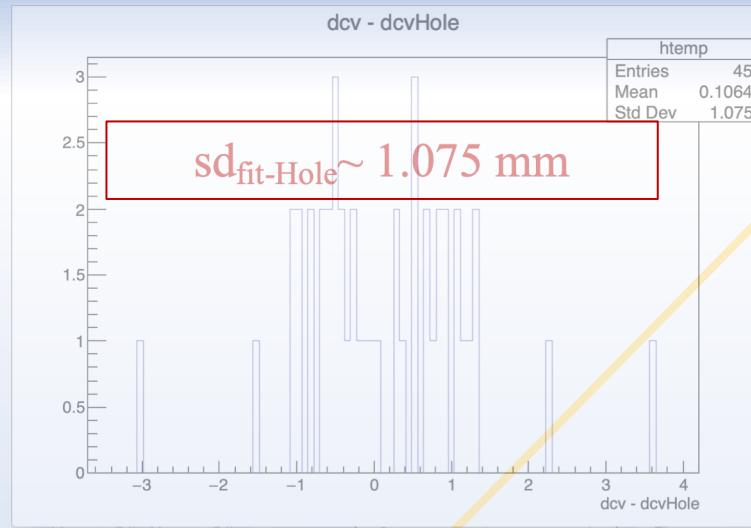


Analysis - intervals



Analysis - intervals

The bias ~ 0.1 mm
Standard deviation ~ 1.1 mm



Analysis – edge intervals

(16 intervals of **top side** of counters on each end of semi-cylinder)

Distances b/w top side of counters on each end are sharply ($sd \sim 0.46\text{mm}$) distributed but biased from CAD.

The bias (~2mm) contains

- Misalignment
- Deviation from design value

