Performance of hit, track, and vertex reconstruction of the Silicon Tracking System of the CBM experiment

Dario A. Ramirez Zaldivar

Goethe University Frankfurt - GSI

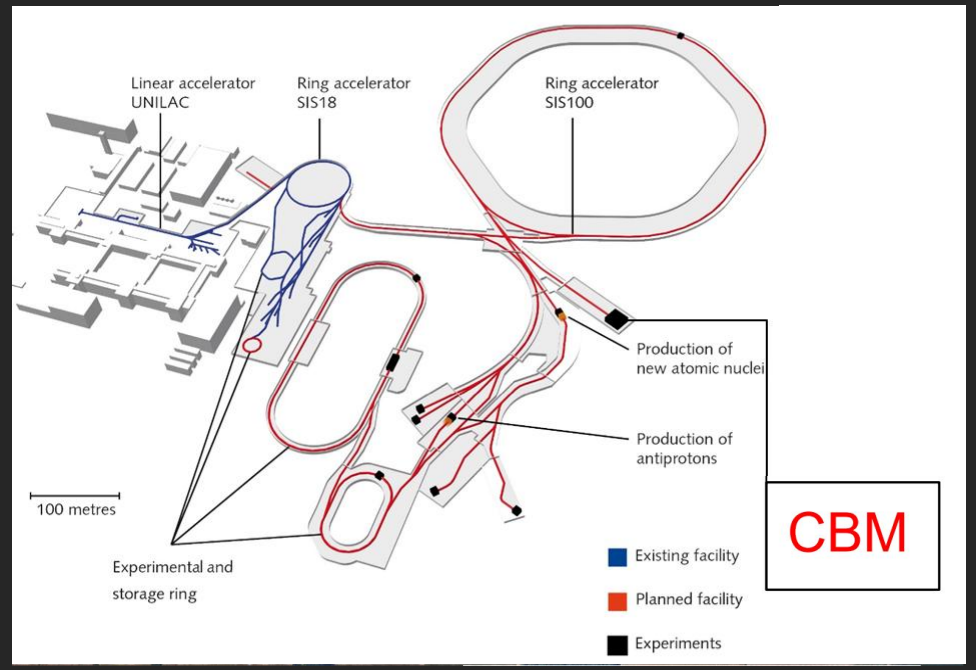
(CBM collaboration)

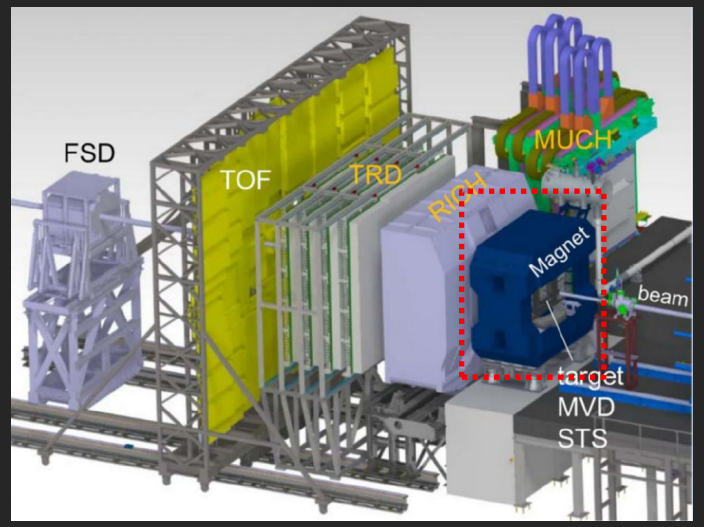
GSI - Facility for Antiproton and Ion Research (FAIR) - location

Facility for Antiproton and Ion Research (FAIR) - Construction site

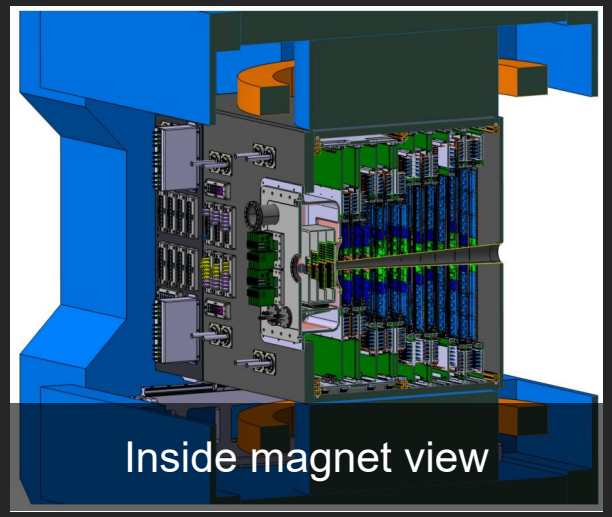
https://www.youtube.com/watch?v=x0RTwqa Rock

Facility for Antiproton and Ion Research - Compressed Baryonic Matter





CBM cave
- down-stream -



Inside magnet view

CBM

- Fix target experiment
- Heavy ion collisions
- 700 particles/event Au+Au 12 AGeV/c
- High interaction rates: 10 MHz
- 2.5^0 - 25^0 polar angle coverage
- Free-streaming data (software trigger)
- Online track reconstruction

CBM - Silicon Tracking System

Silicon Tracking System

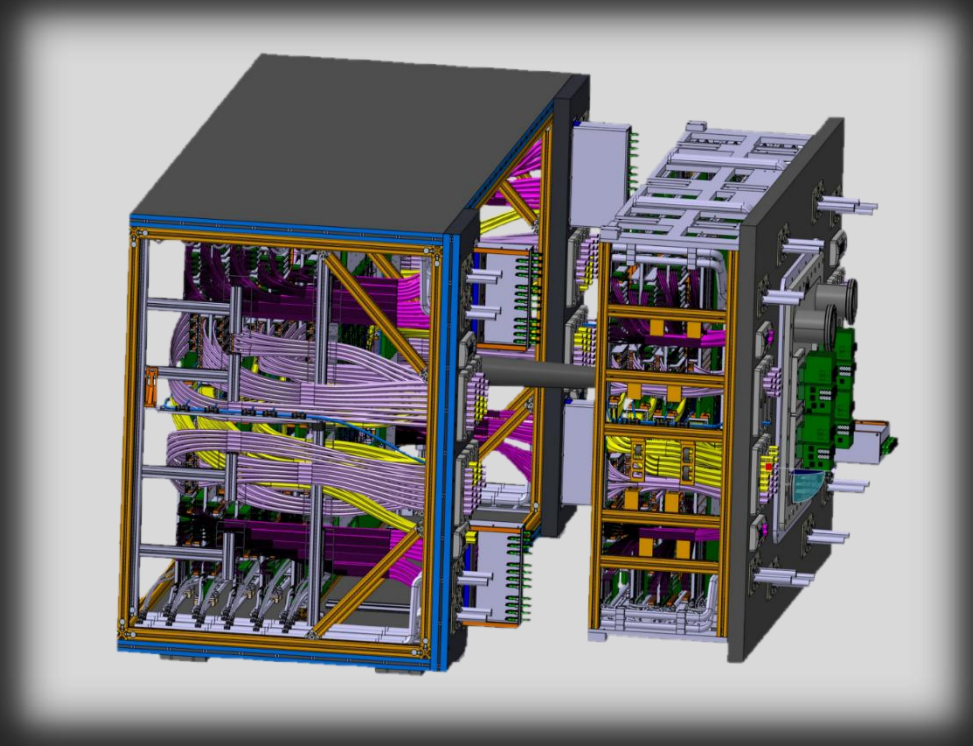
- 8 Stations / tracking layers
- 876 modules
- 1.8M channels

Challenges for tracker

- High rates → O (1000) tracks in aperture interaction

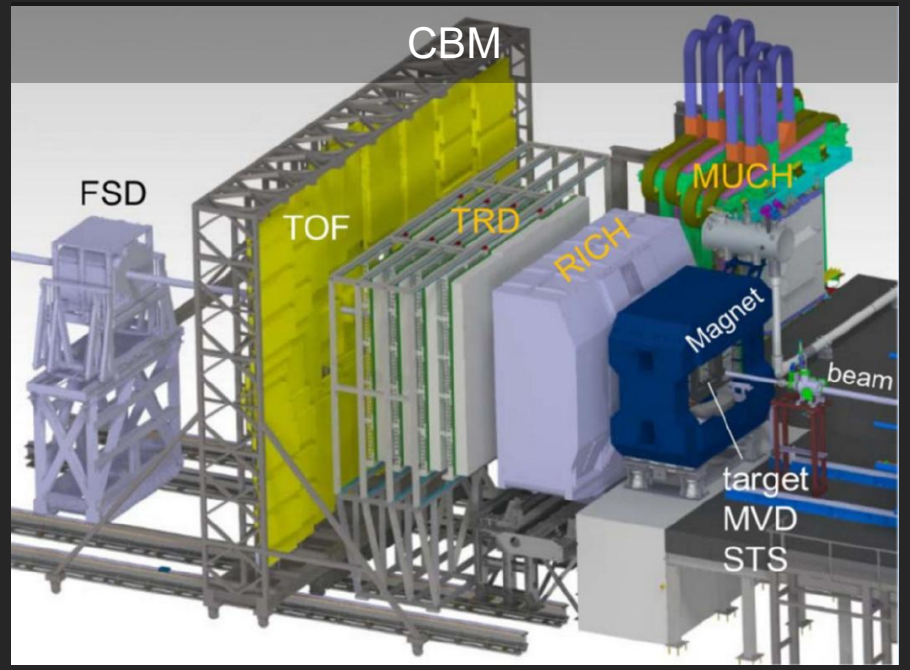
→ high granularity

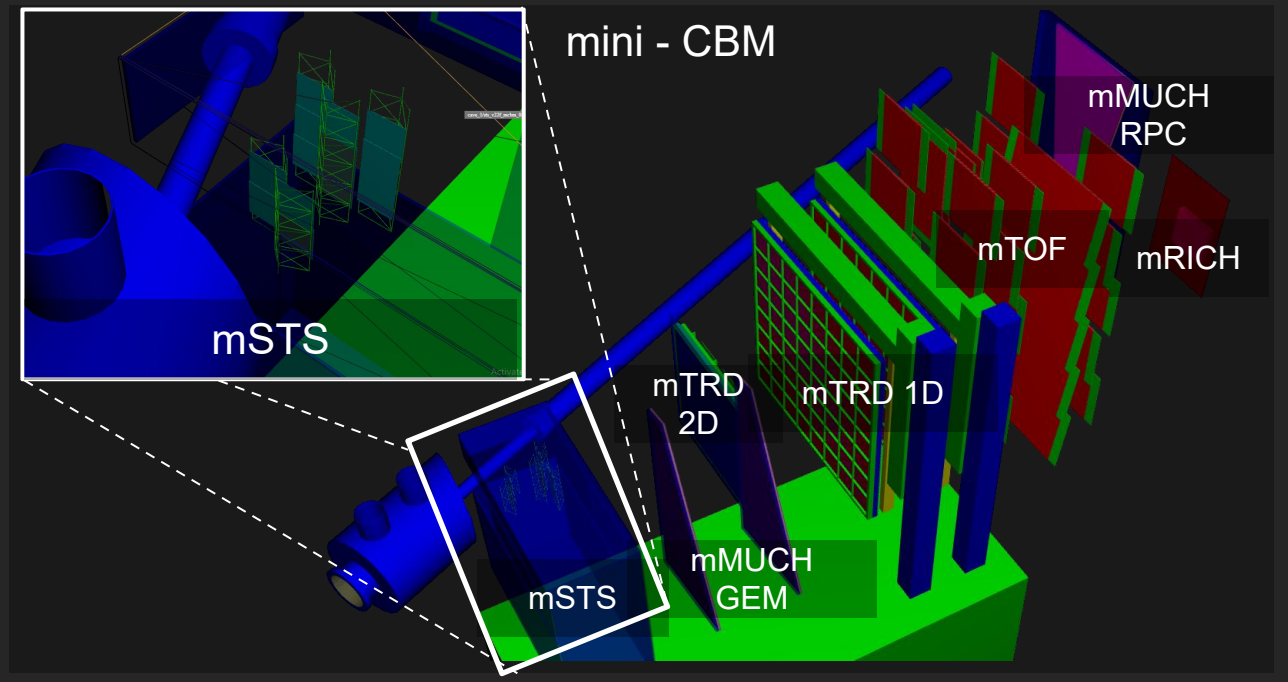
- low momenta → low material budget (2 − 8% X_0)
- $\Delta p/p$ = 1 − 2% (evt. in B=1T)
- spatial (< 30 µm) + timing (< 5 ns) + amplitude (15 fC, 5 bit) in free-streaming mode



Most demanding detector in term bandwidth and material budget!

CBM - Full scale prototypes: mini-CBM (mCBM) - mCBM@SIS18





mCBM@SIS18 goals:

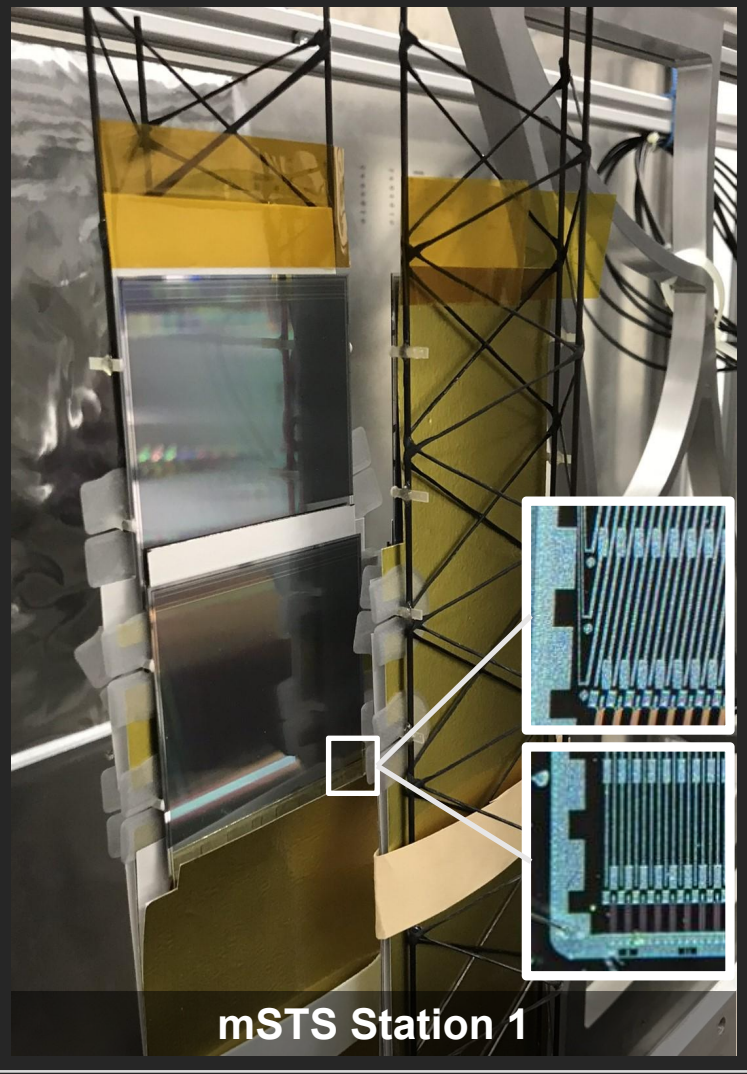
... test and optimize the operation of the full system (...) under realistic experiment conditions.

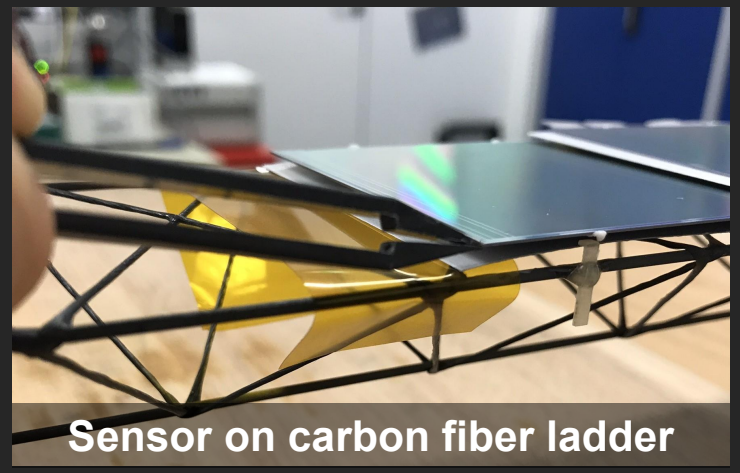
... the free-streaming data acquisition system ...

... the online track and event reconstruction ...

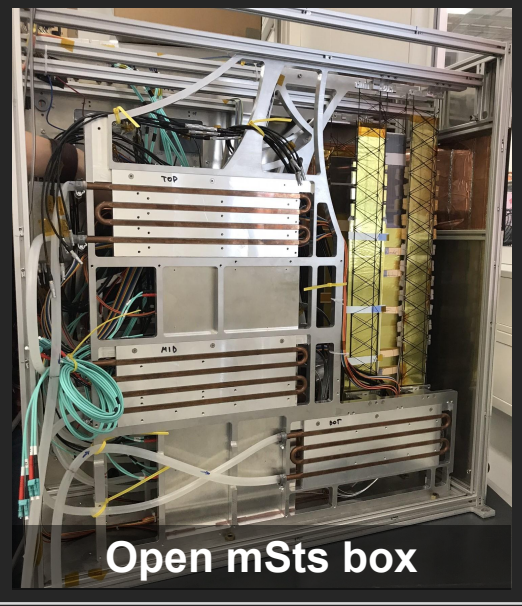
... the offline data analysis and the detector control system ...

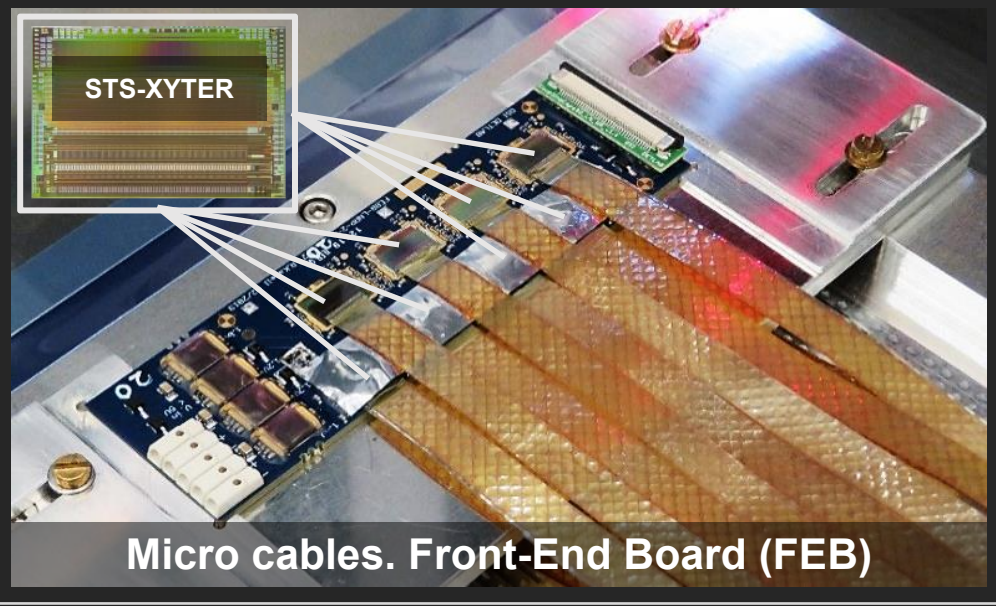
mini-STS(mSTS) Setup


mSTS Station 1


Sensor on carbon fiber ladder

- 2 tracking stations
- 11 modules (~1% full STS): double-sided double-metal micro-strip silicon sensors


Open mSts box

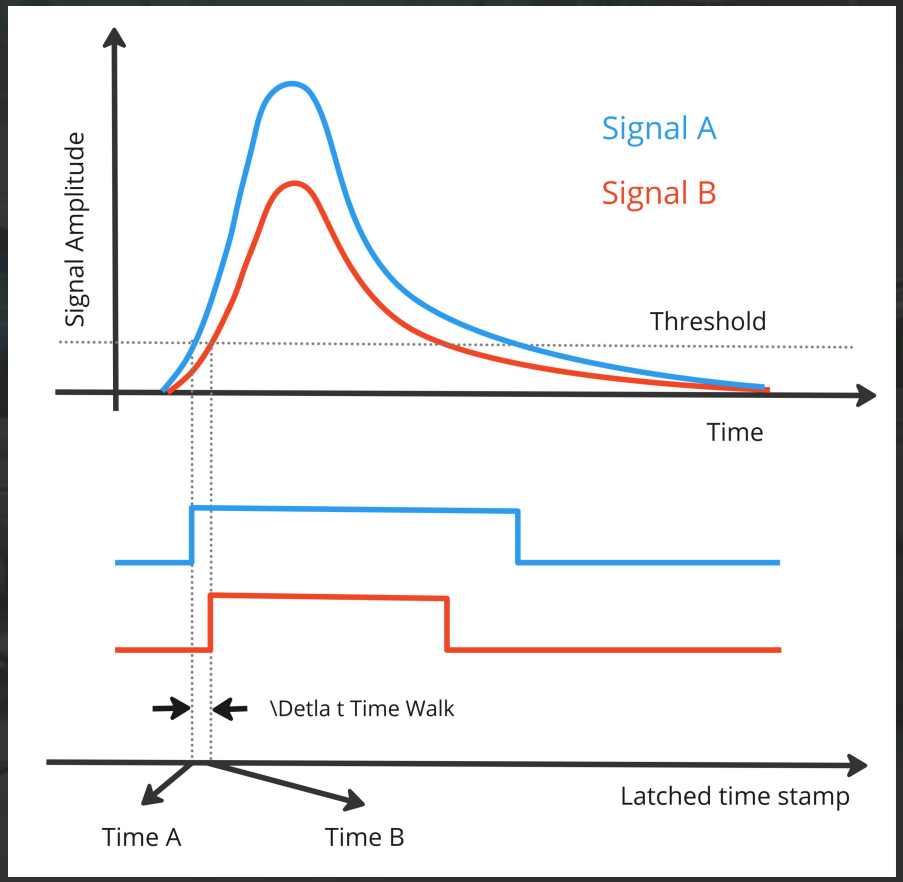


Micro cables. Front-End Board (FEB)

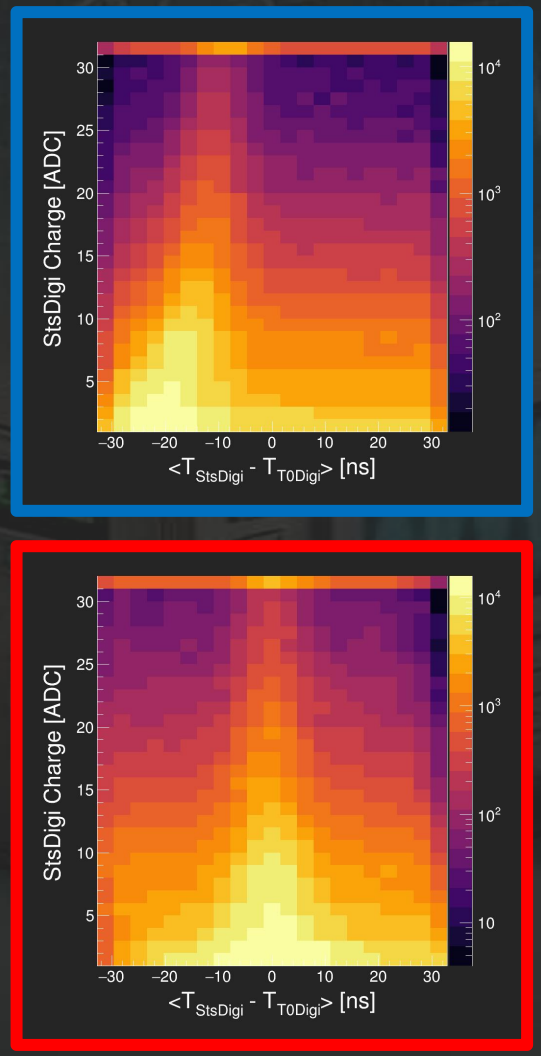
… time calibration …

mSTS Time calibration - Time calibration ??

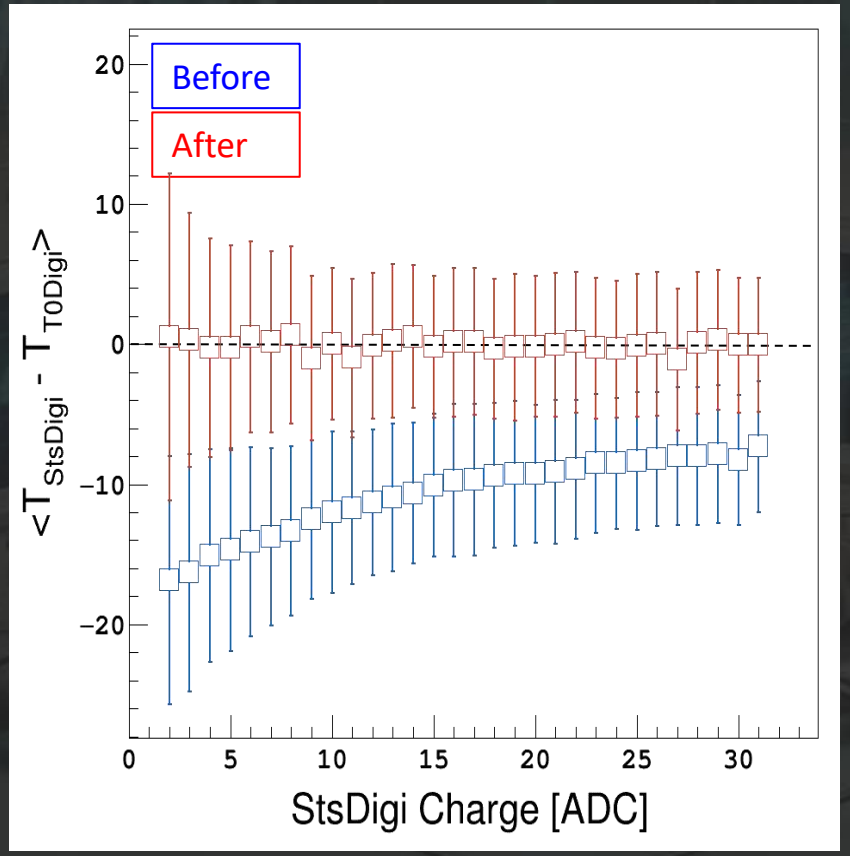
- Systems synchronization
- Signals correlated in time
- Signal amplitude dependence
- Time walk effect correction



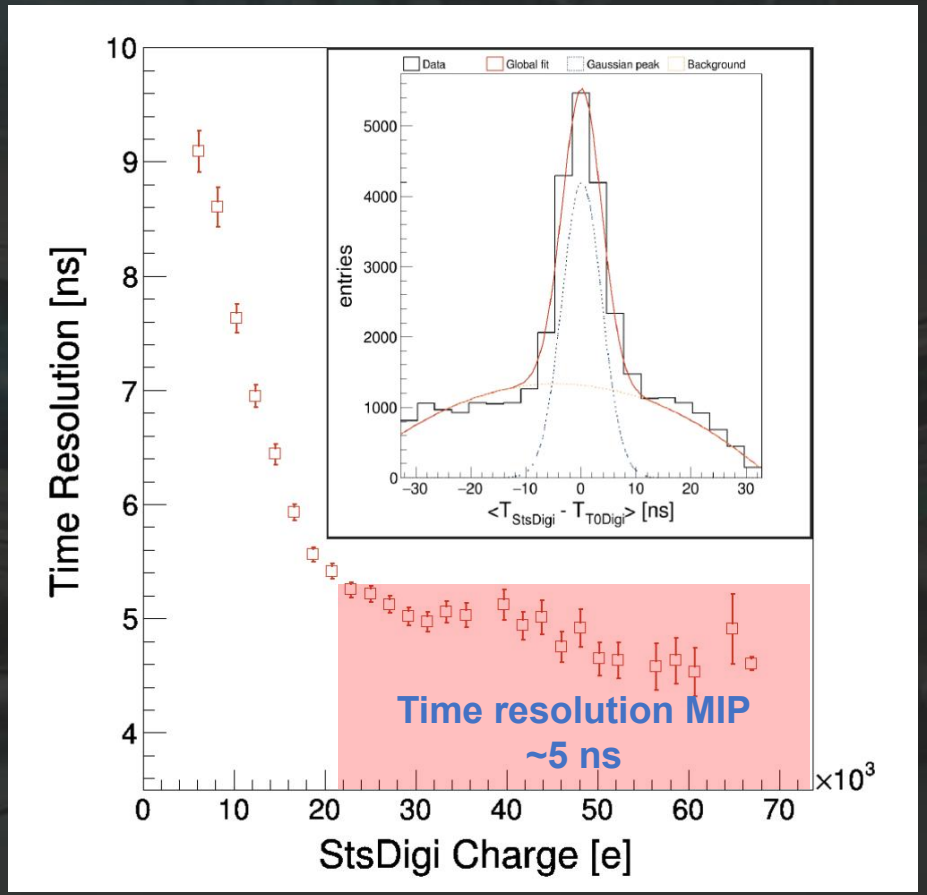
mSTS Time calibration - Time Resolution

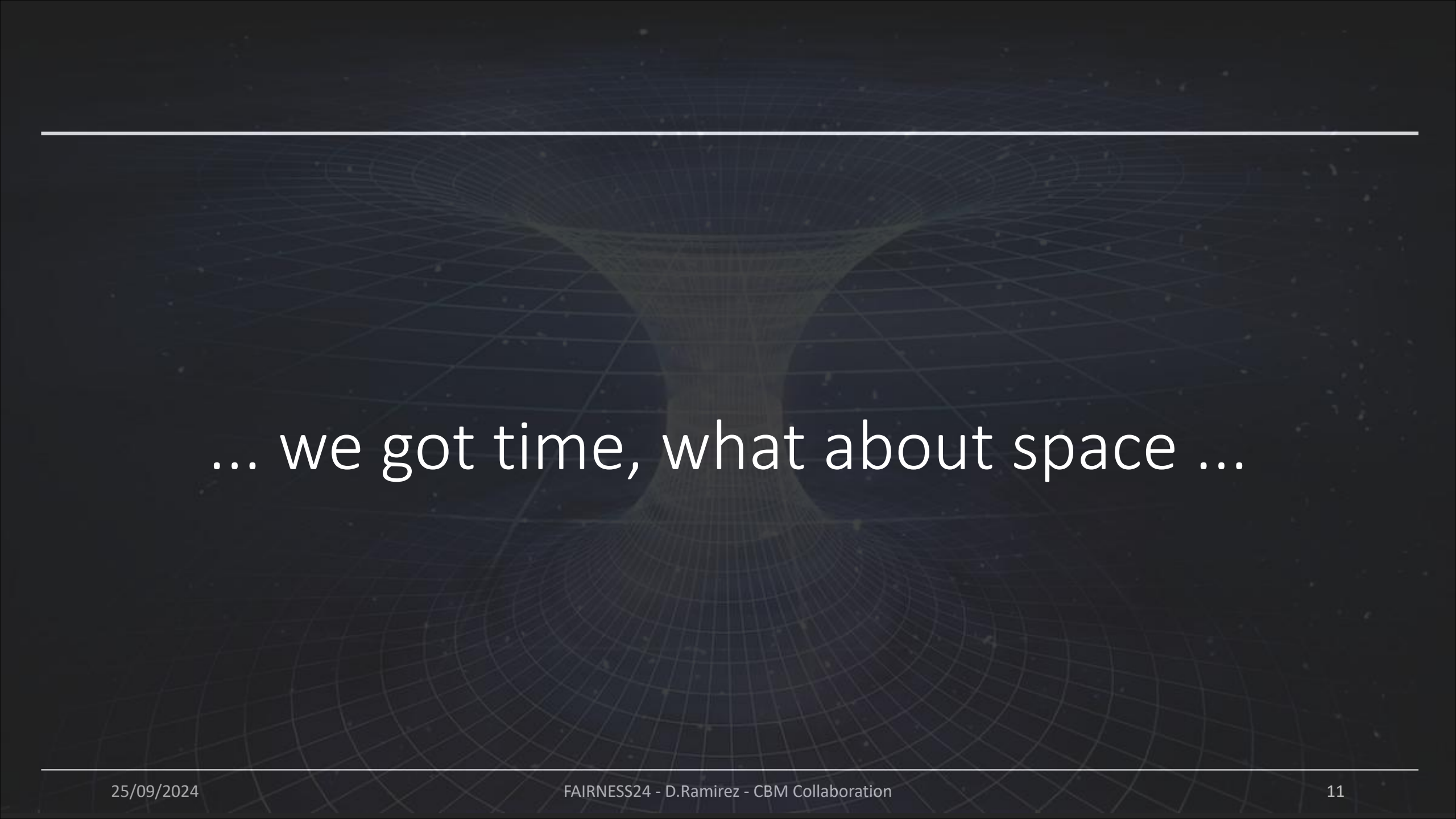


Robust time calibration procedure

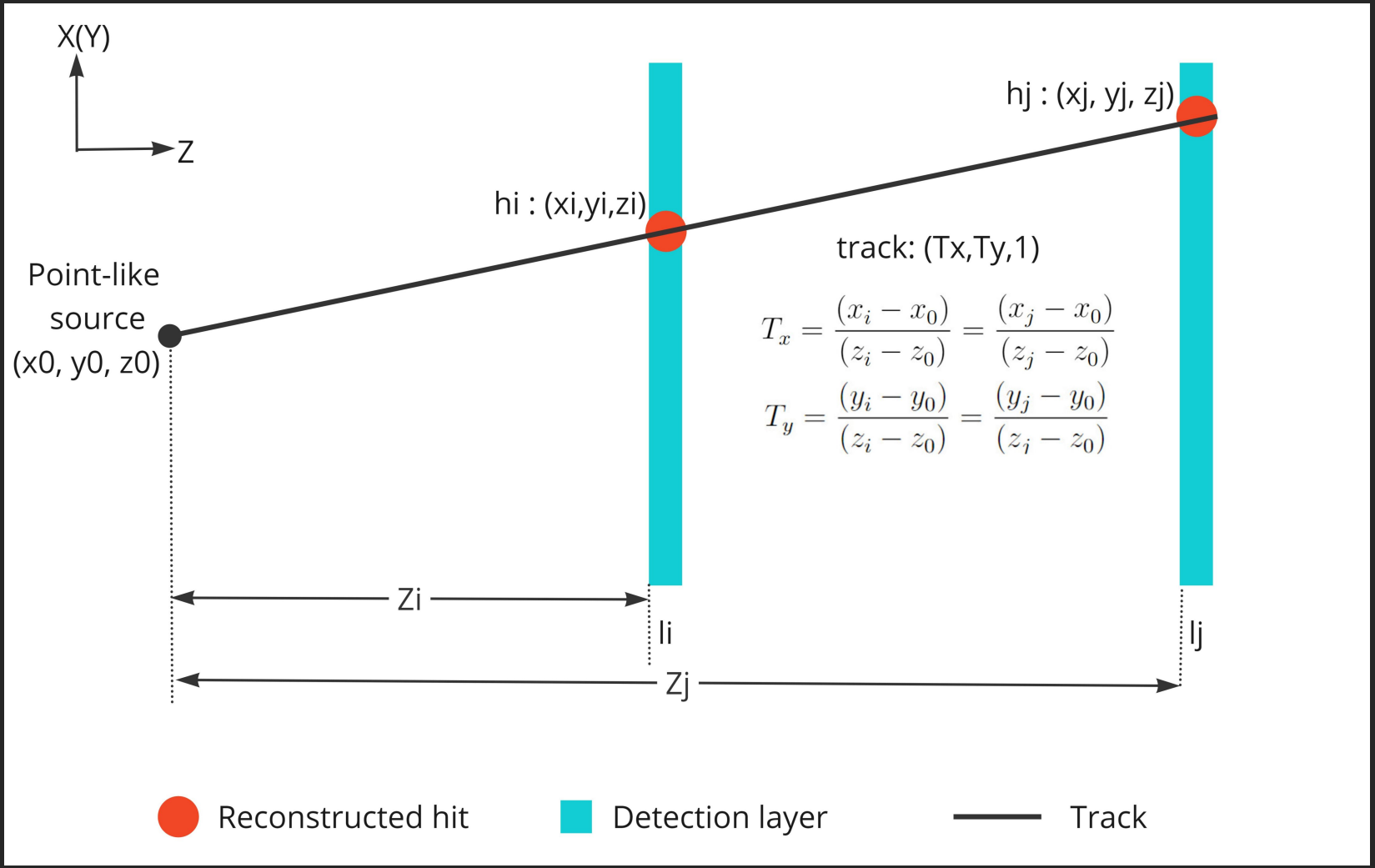


Time resolution 4.8 - 9.2 ns




… we got time, what about space …

STS Space Resolution - Geometrical background



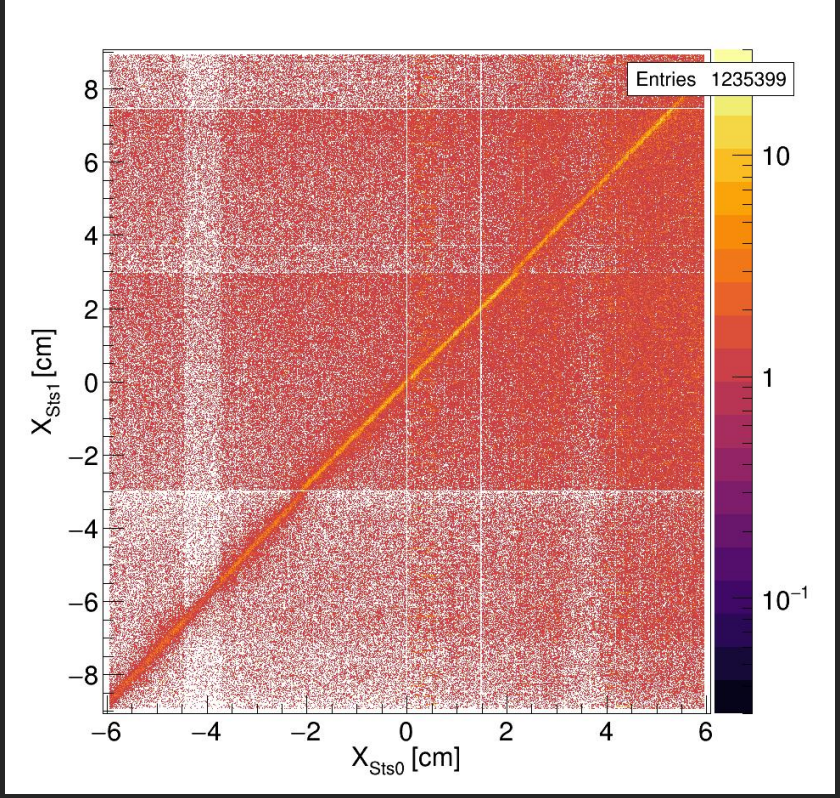
No magnetic field

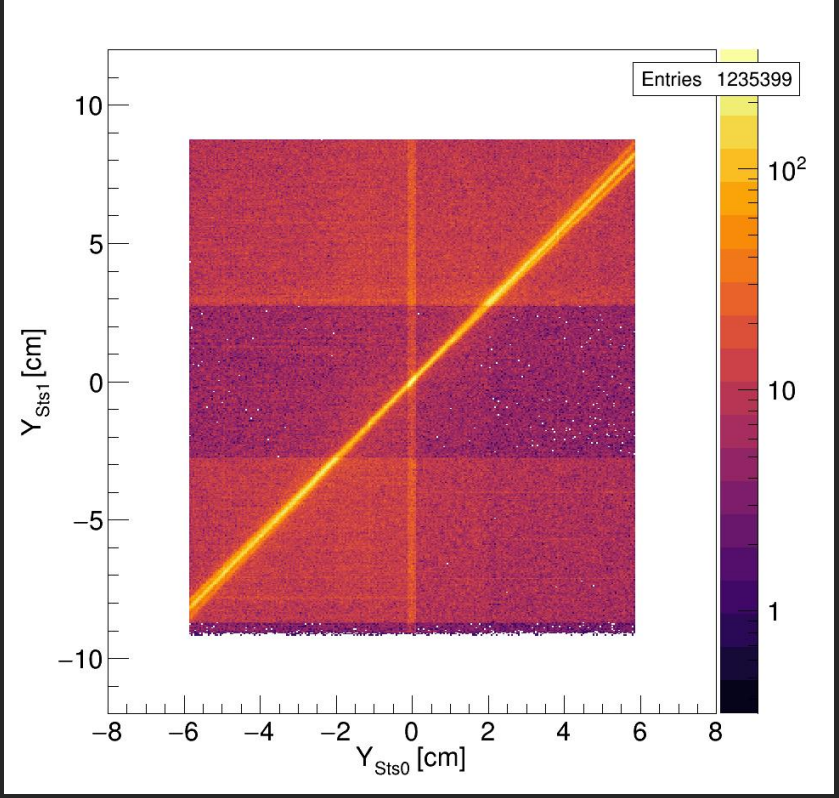
Straight tracks

Correlated hits

Line in X_iX_j (Y_iY_j) space

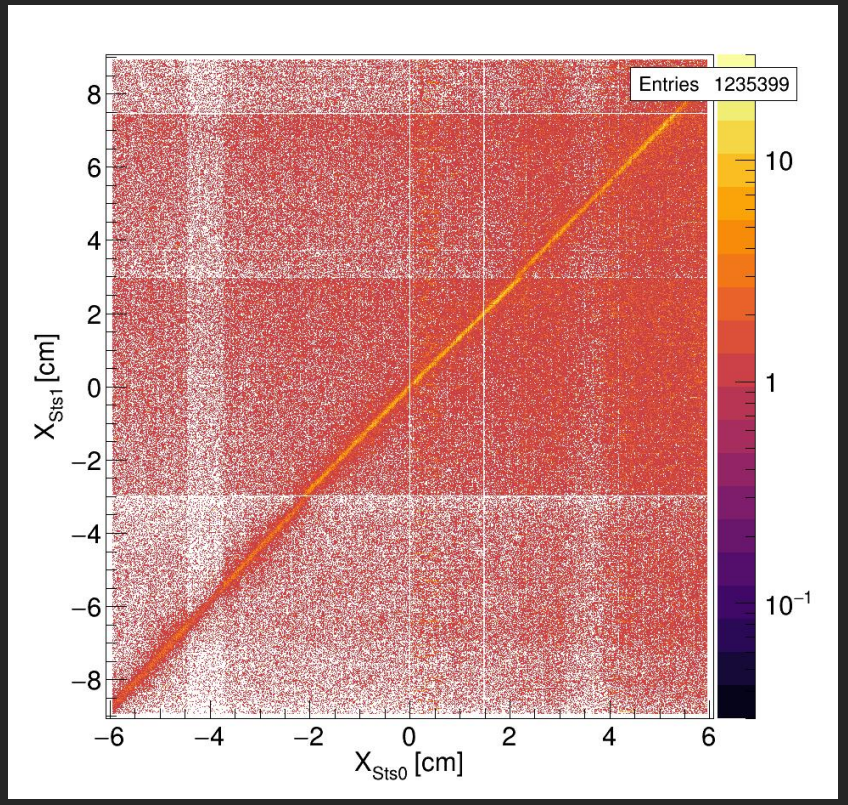
STS Space Resolution - NiNi@1.93 AGeV - Monte Carlo

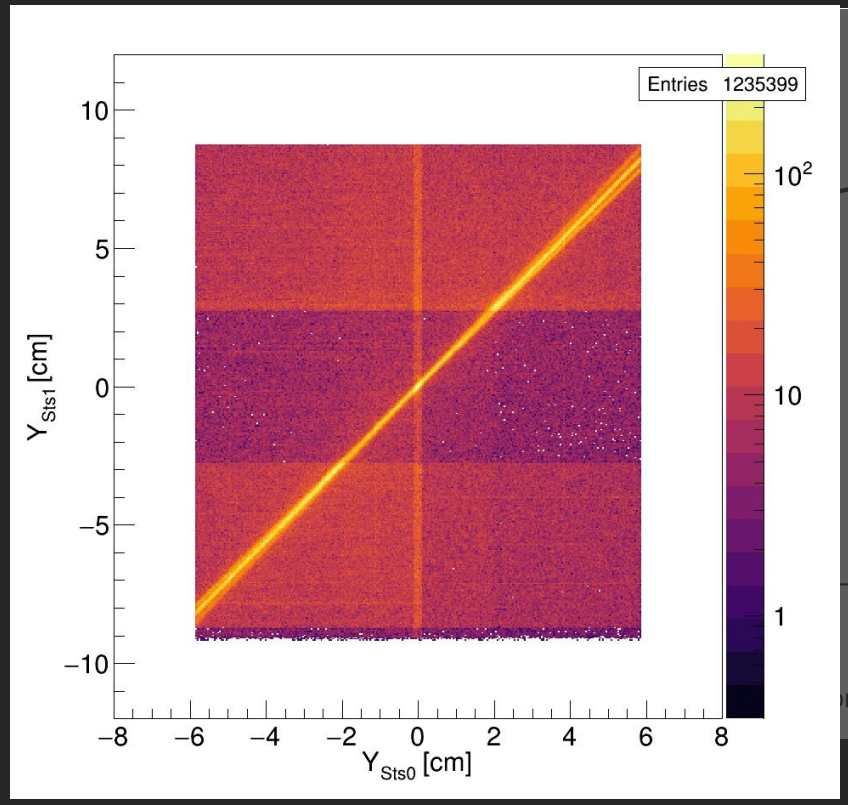




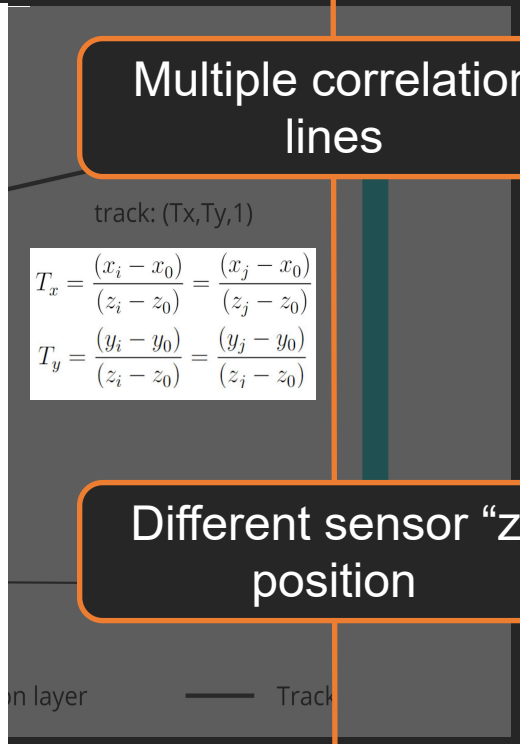
Multiple correlation lines

STS Space Resolution - NiNi@1.93 AGeV - Monte Carlo



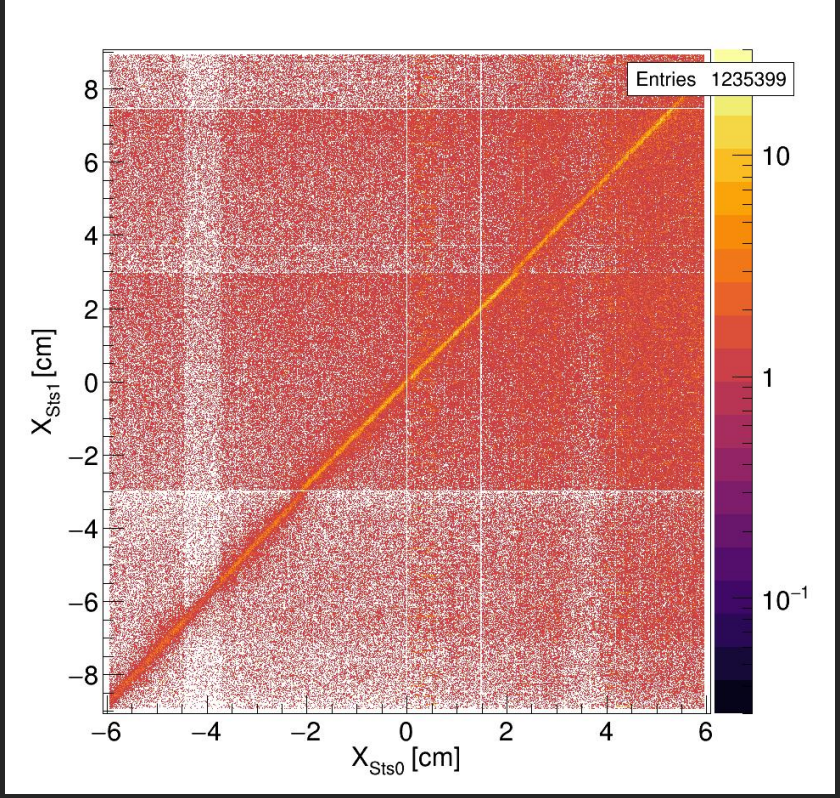


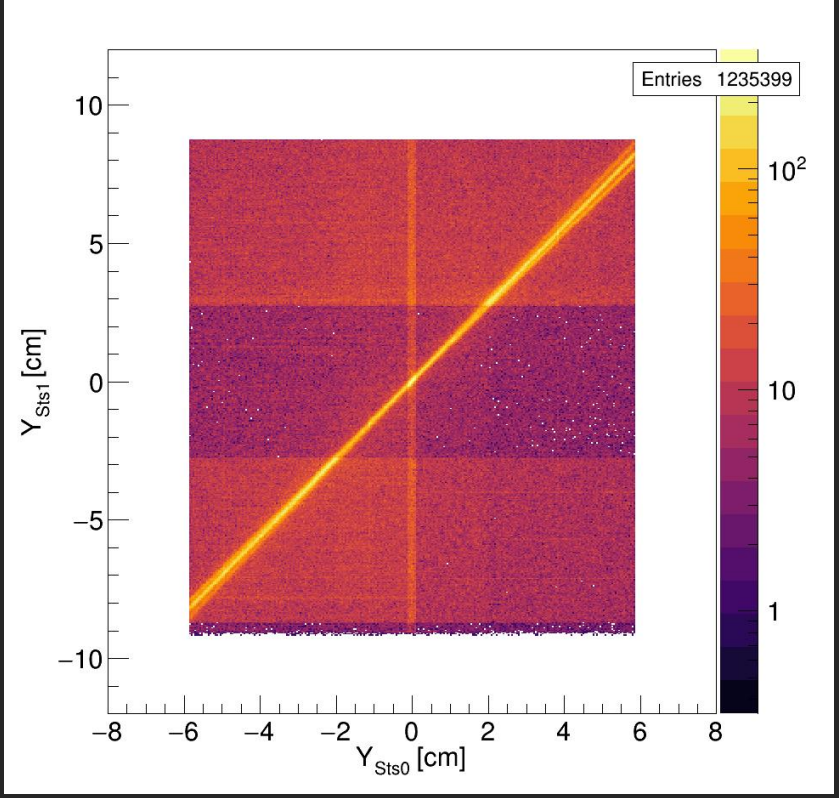
Multiple correlation lines



Different sensor “z” position

STS Space Resolution - NiNi@1.93 AGeV - Monte Carlo



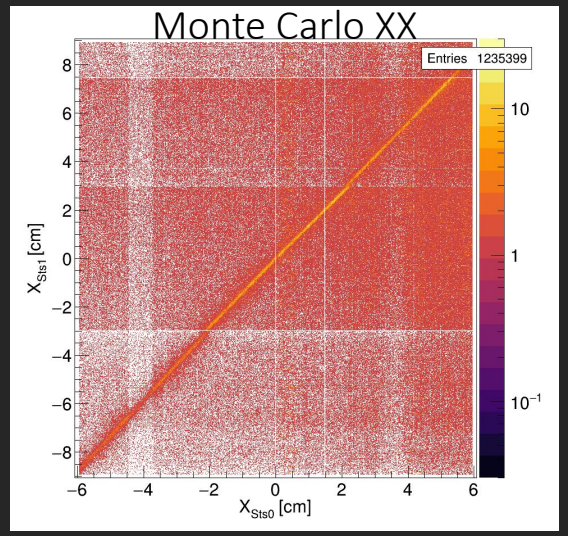


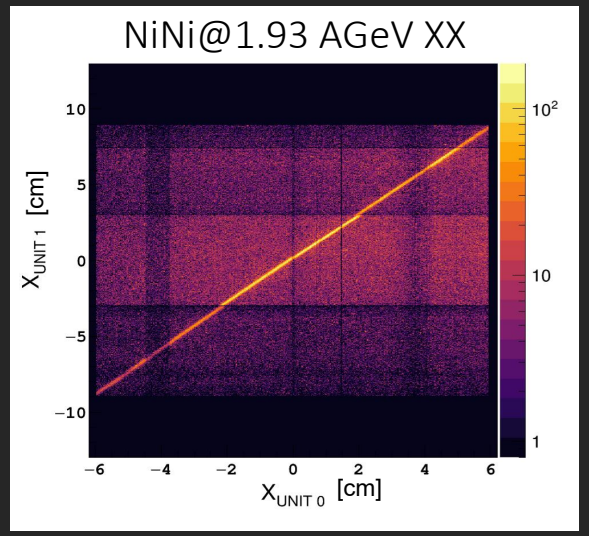
Multiple correlation lines

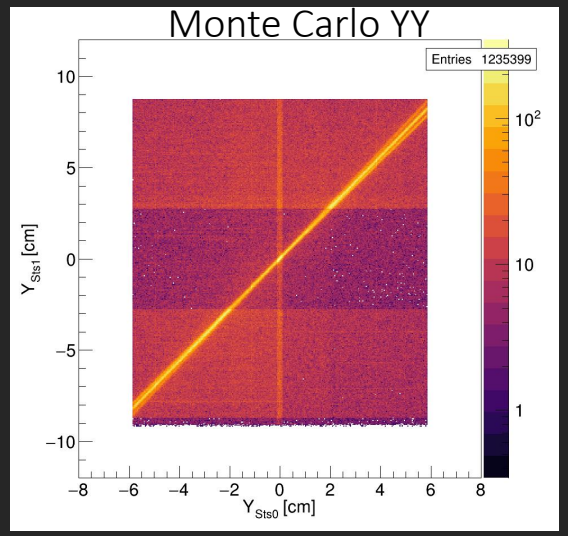
Different sensor “z” position

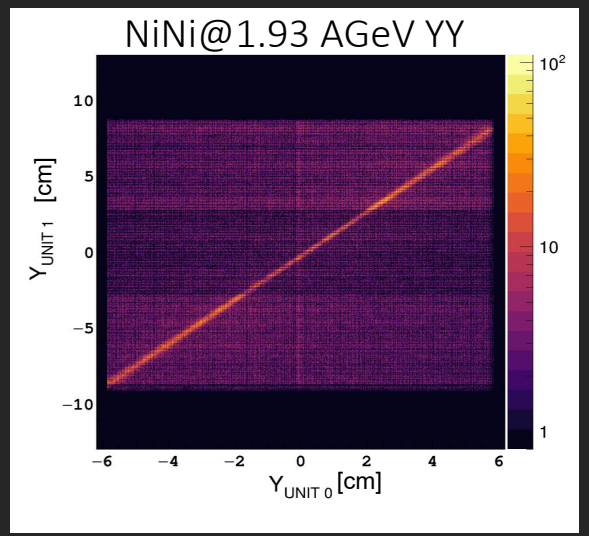
Split correlation by sensor pair

STS Space Resolution - NiNi@1.93 AGeV - mCBM@SIS18



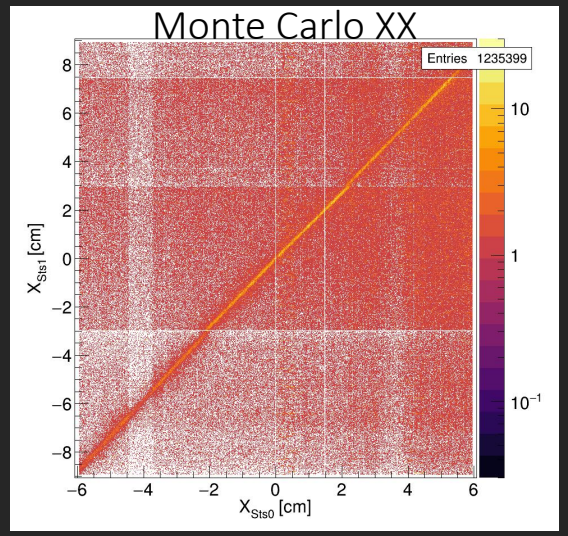


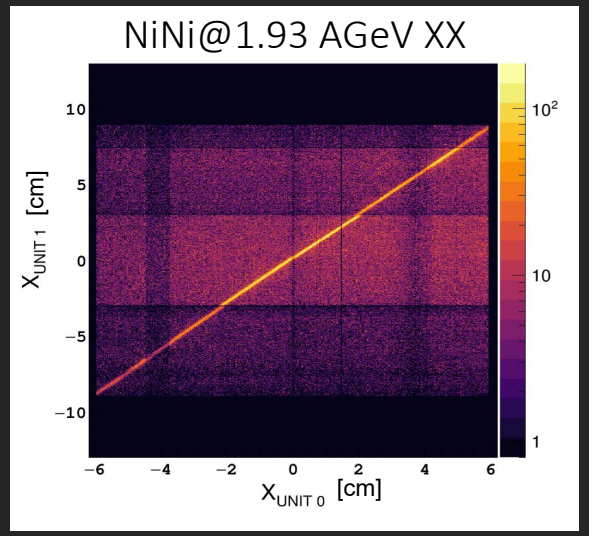


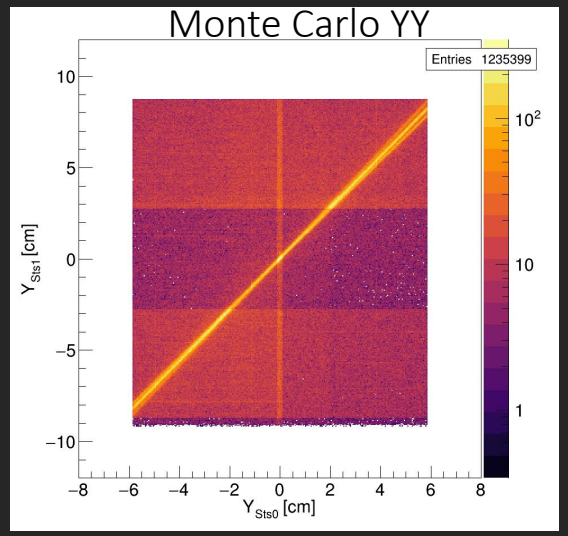


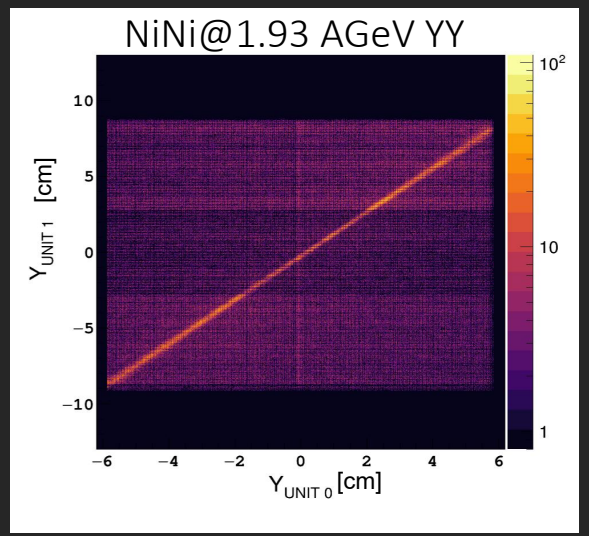
2D distributions are hard to compare

STS Space Resolution - NiNi@1.93 AGeV - mCBM@SIS18









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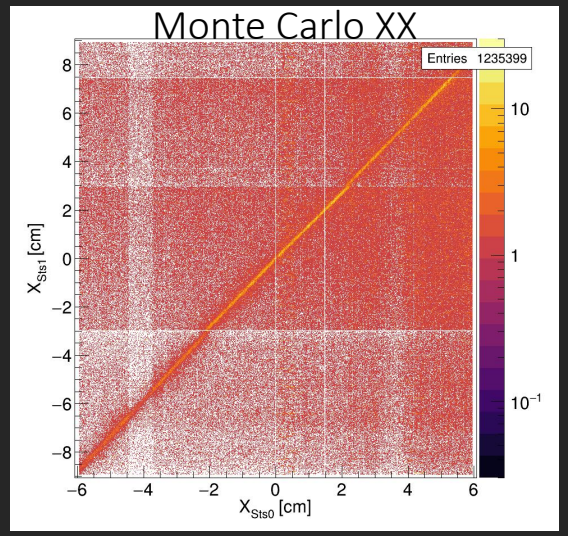
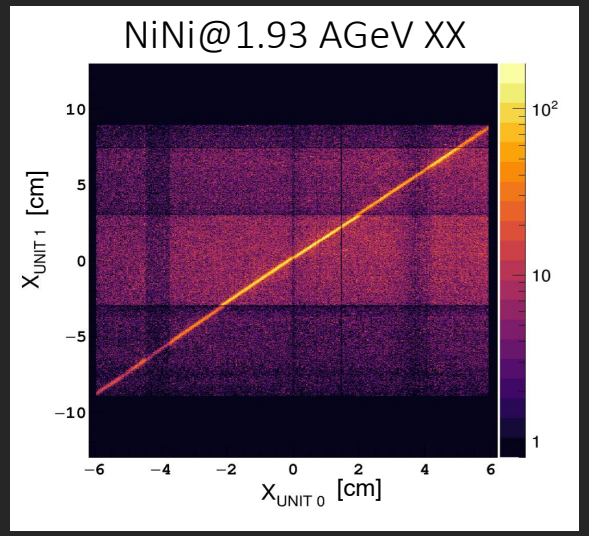
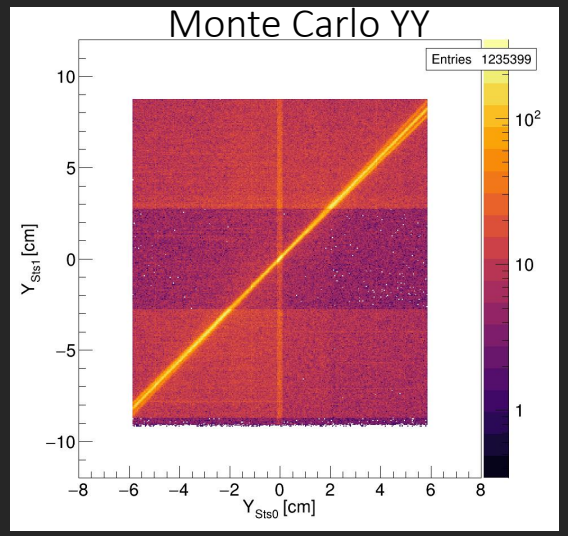
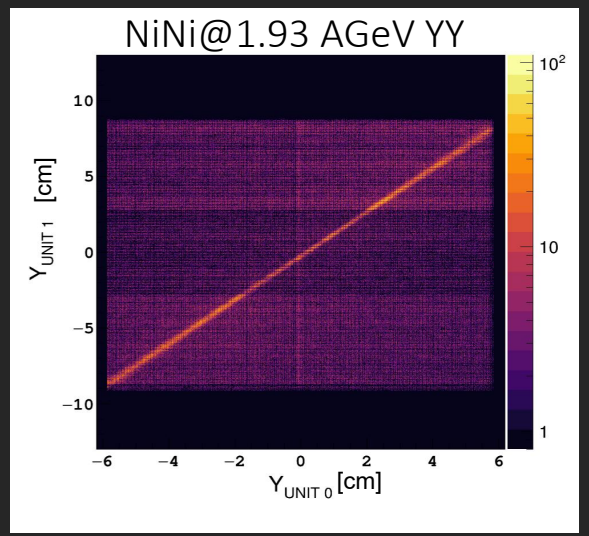
Correlation stength hard to quantify

STS Space Resolution - NiNi@1.93 AGeV - mCBM@SIS18









2D distributions are hard to compare

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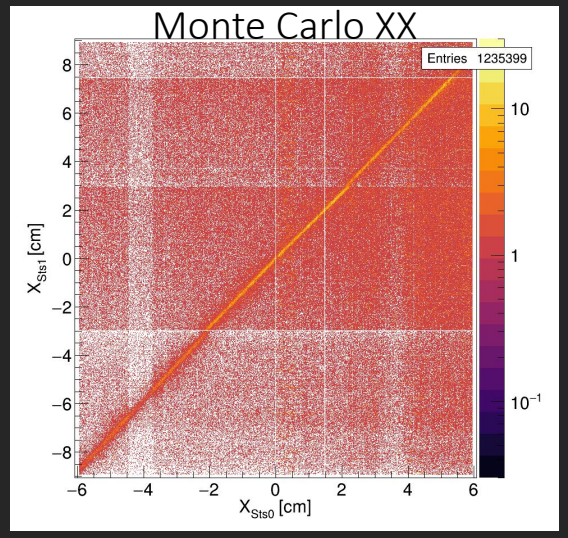
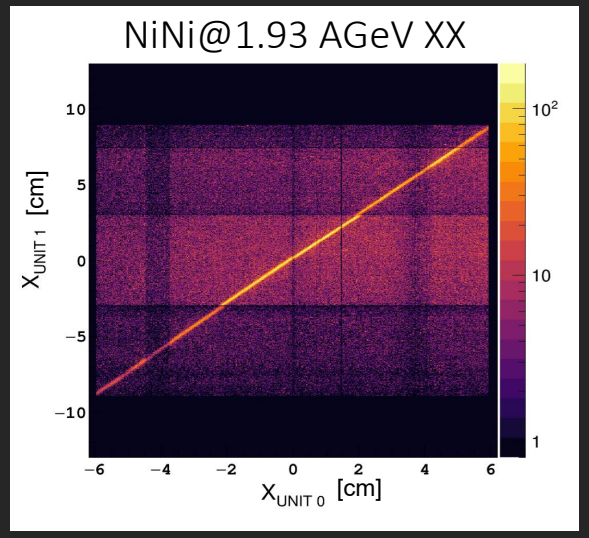
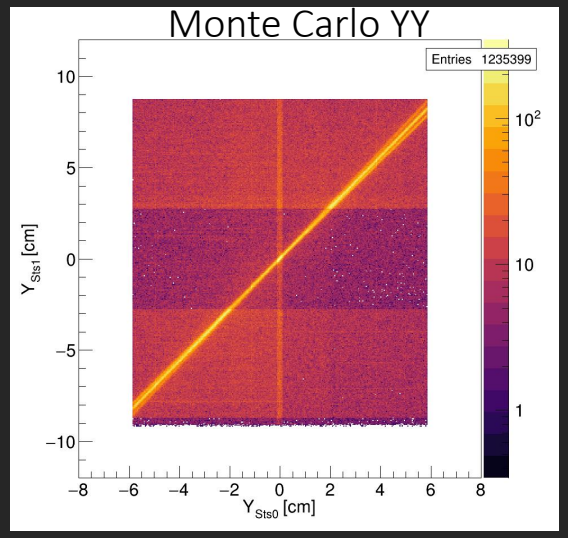
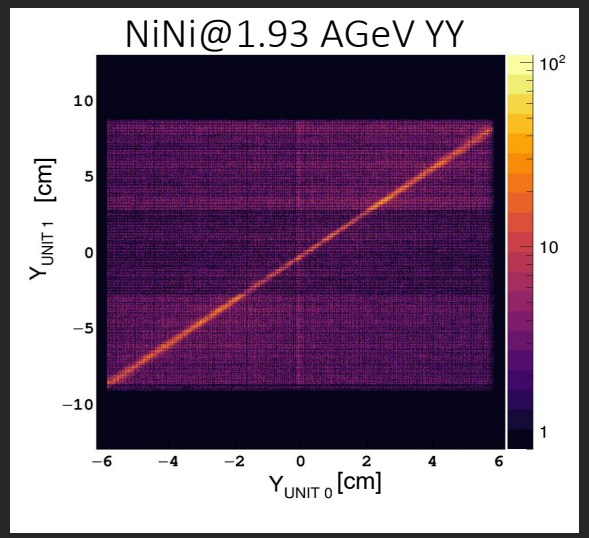
2D -> 1D ??

STS Space Resolution - NiNi@1.93 AGeV - mCBM@SIS18









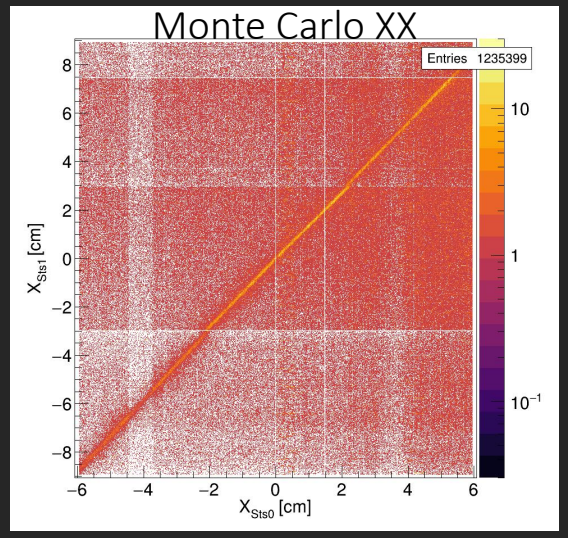
2D distributions are hard to compare

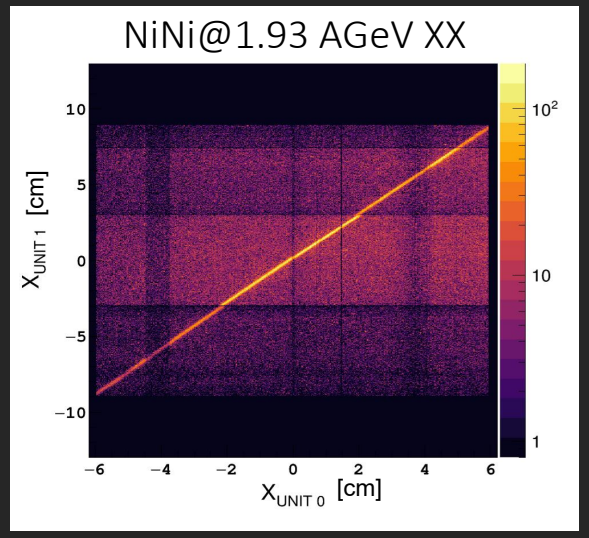
Correlation stength hard to quantify

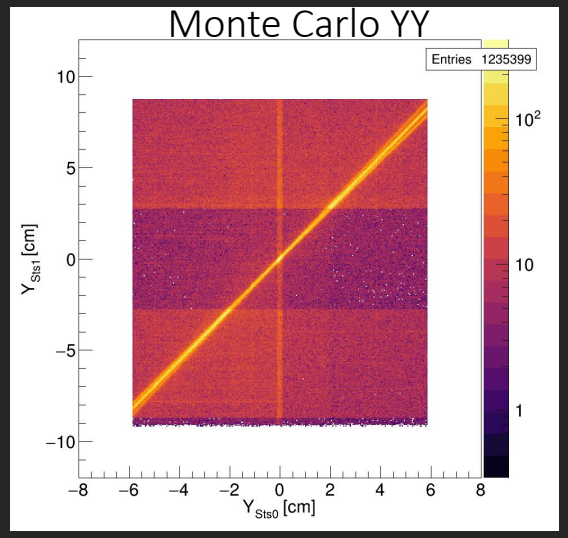
2D -> 1D ??

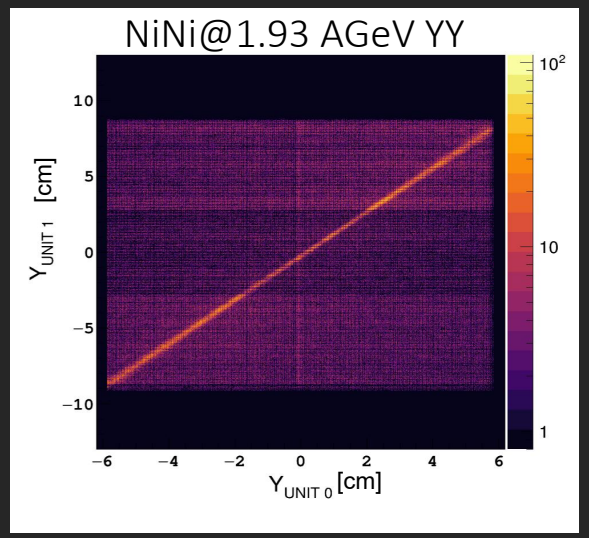
Distance point (x_i,x_j) to correlation line

STS Space Resolution - NiNi@1.93 AGeV - mCBM@SIS18









2D distributions are hard to compare

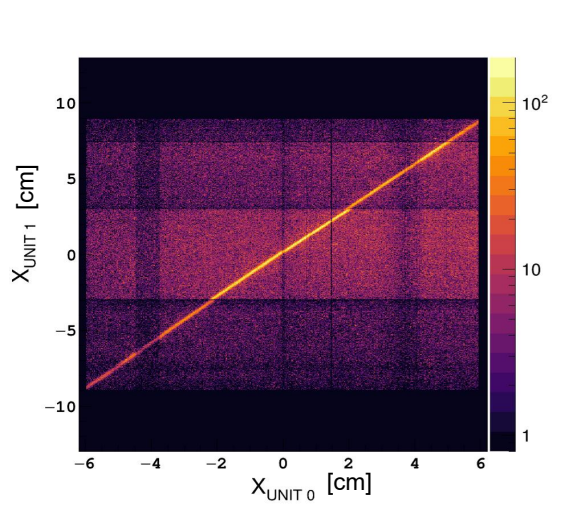
Correlation stength hard to quantify

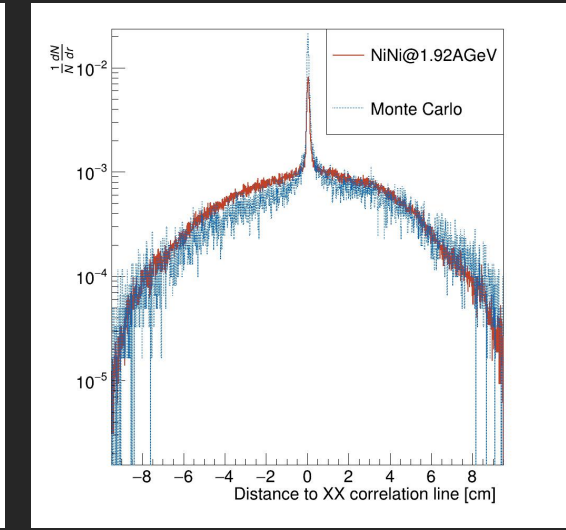
2D -> 1D ??

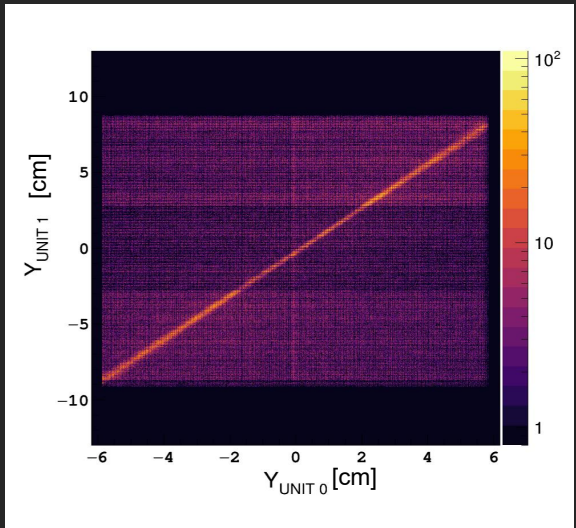
Distance point (x_i,x_j) to correlation line

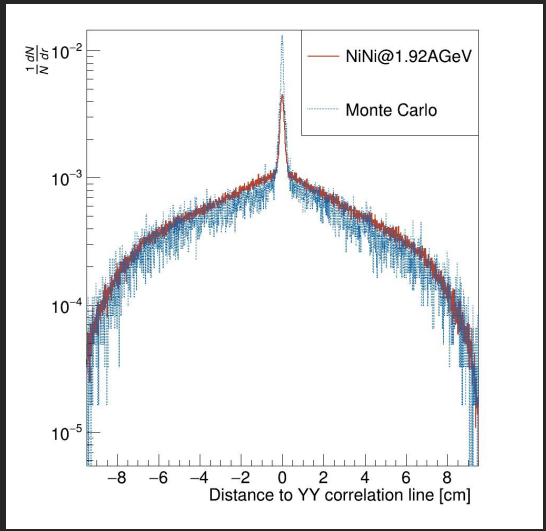
1D distribution
Gaussian + background

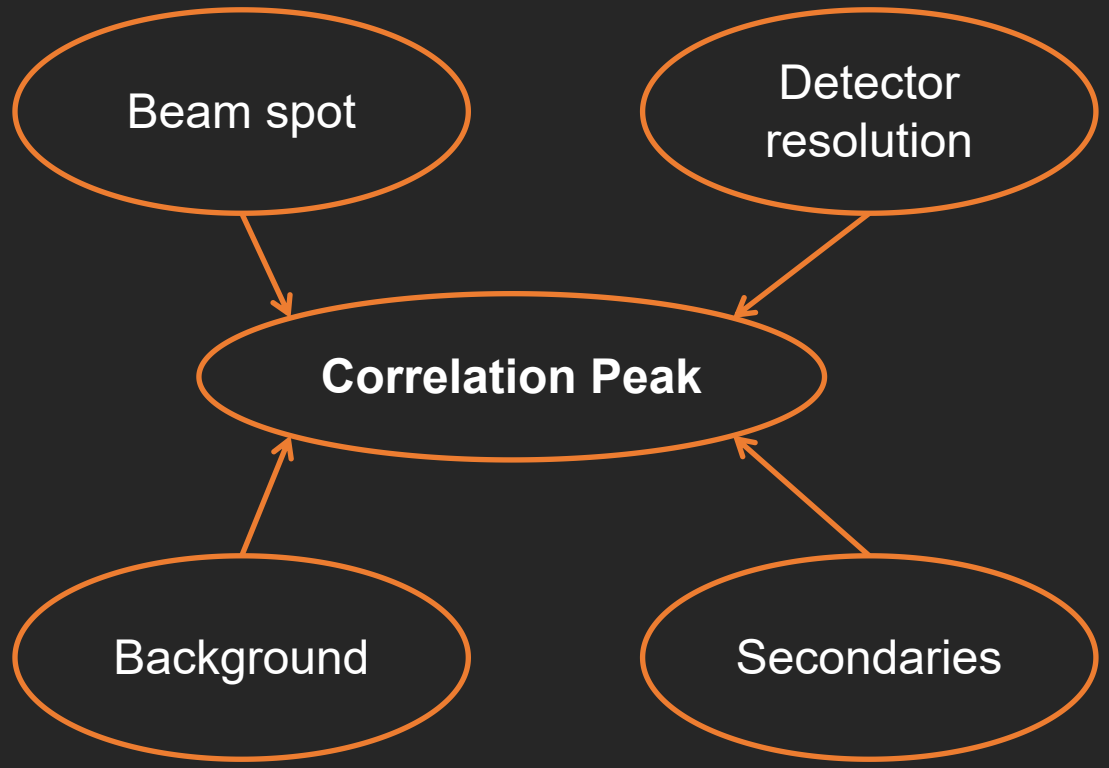
STS Space Resolution - NiNi@1.93 AGeV - mCBM@SIS18



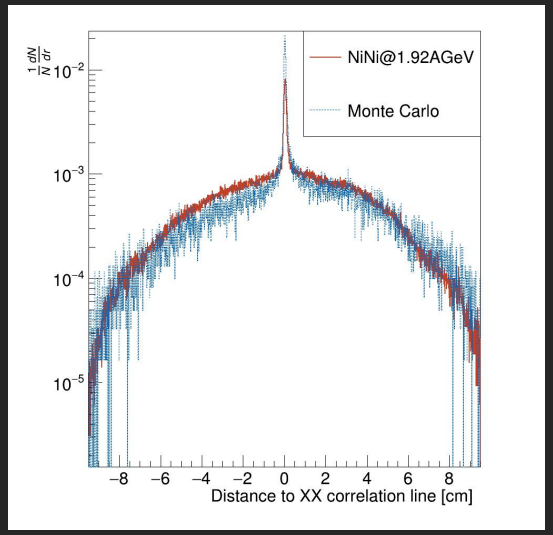


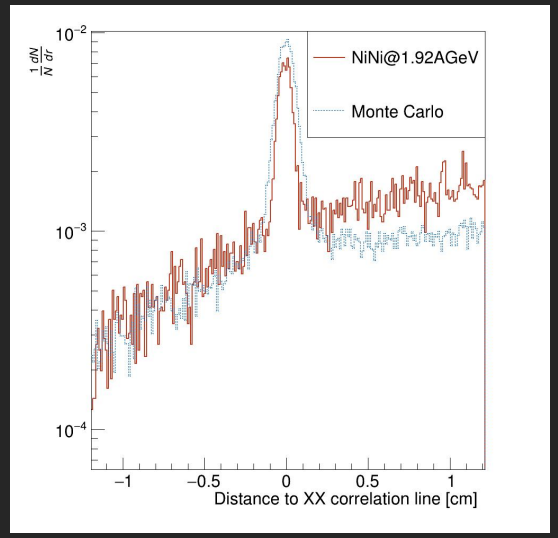


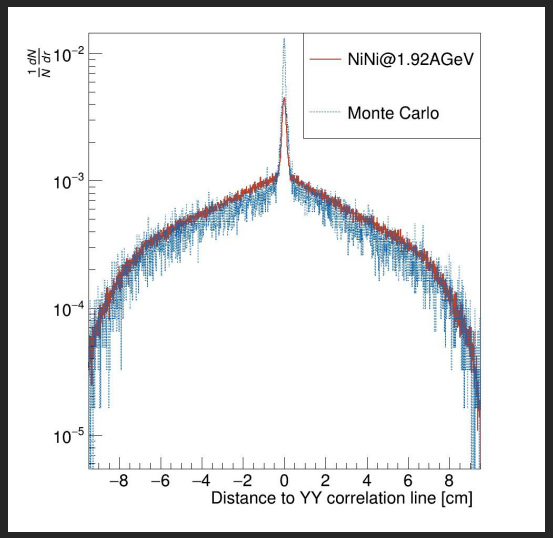


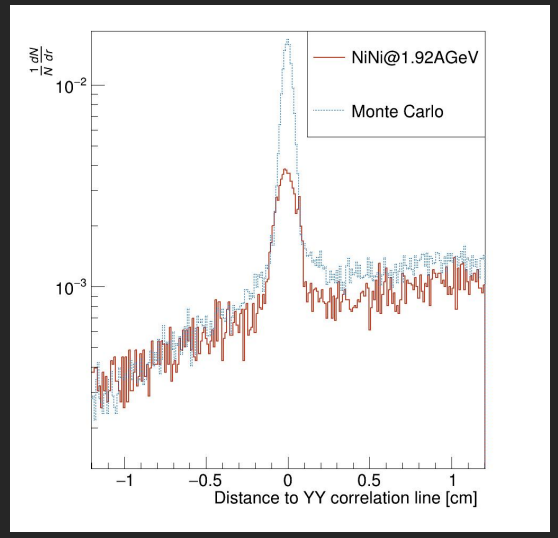


STS Space Resolution - NiNi@1.93 AGeV - mCBM@SIS18







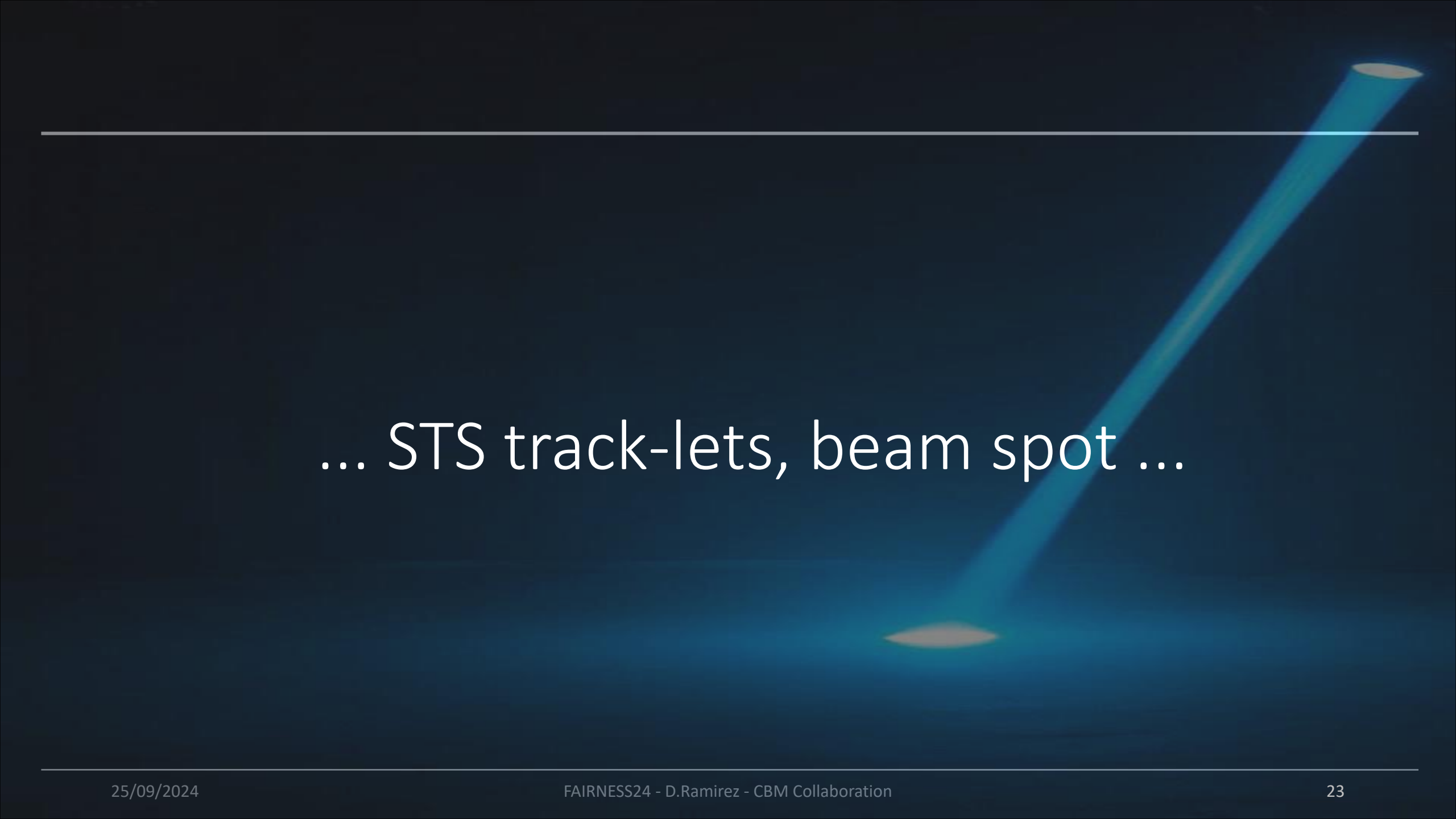


Detector resolution: ~10 um

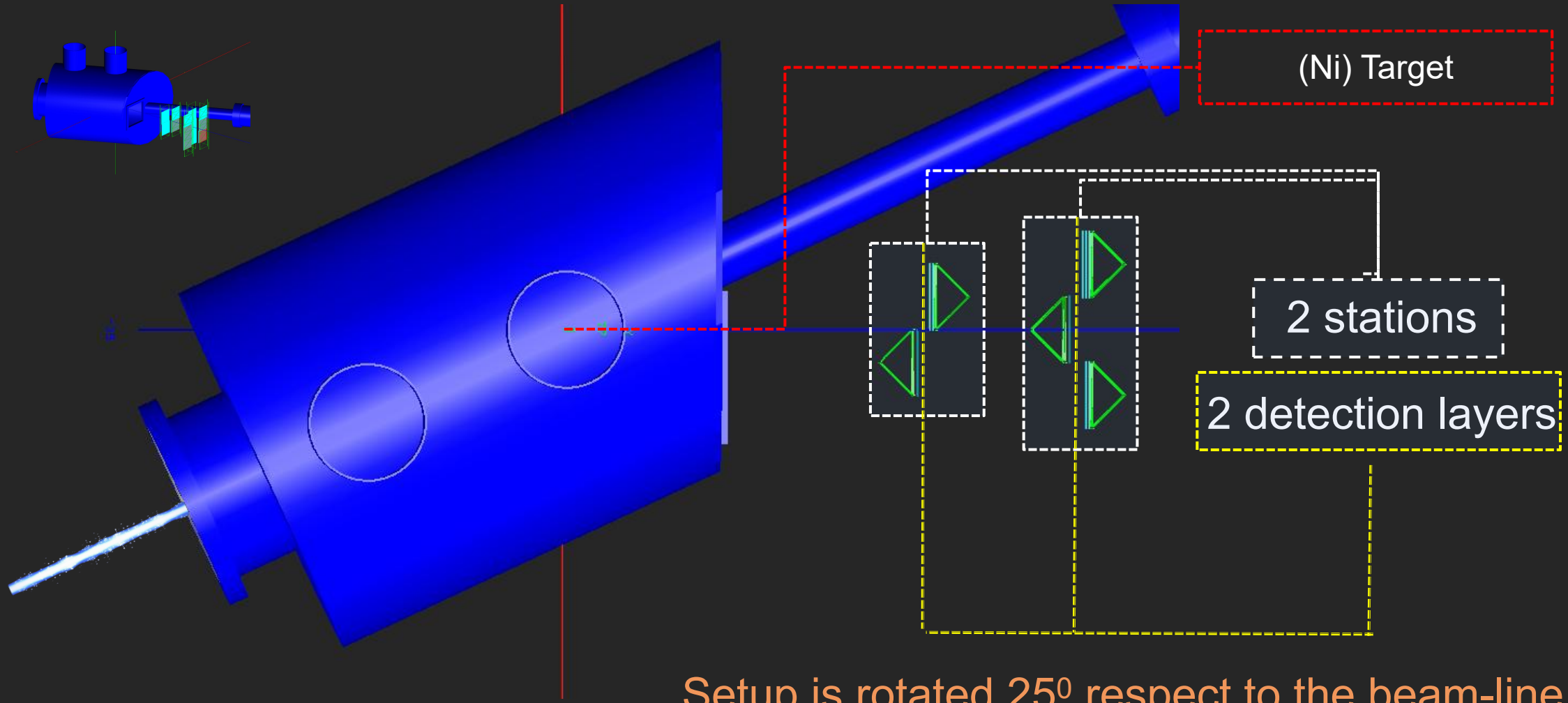
Beam spot extracted from data

Background is described in good measure

Secondaries: consistent peak baseline

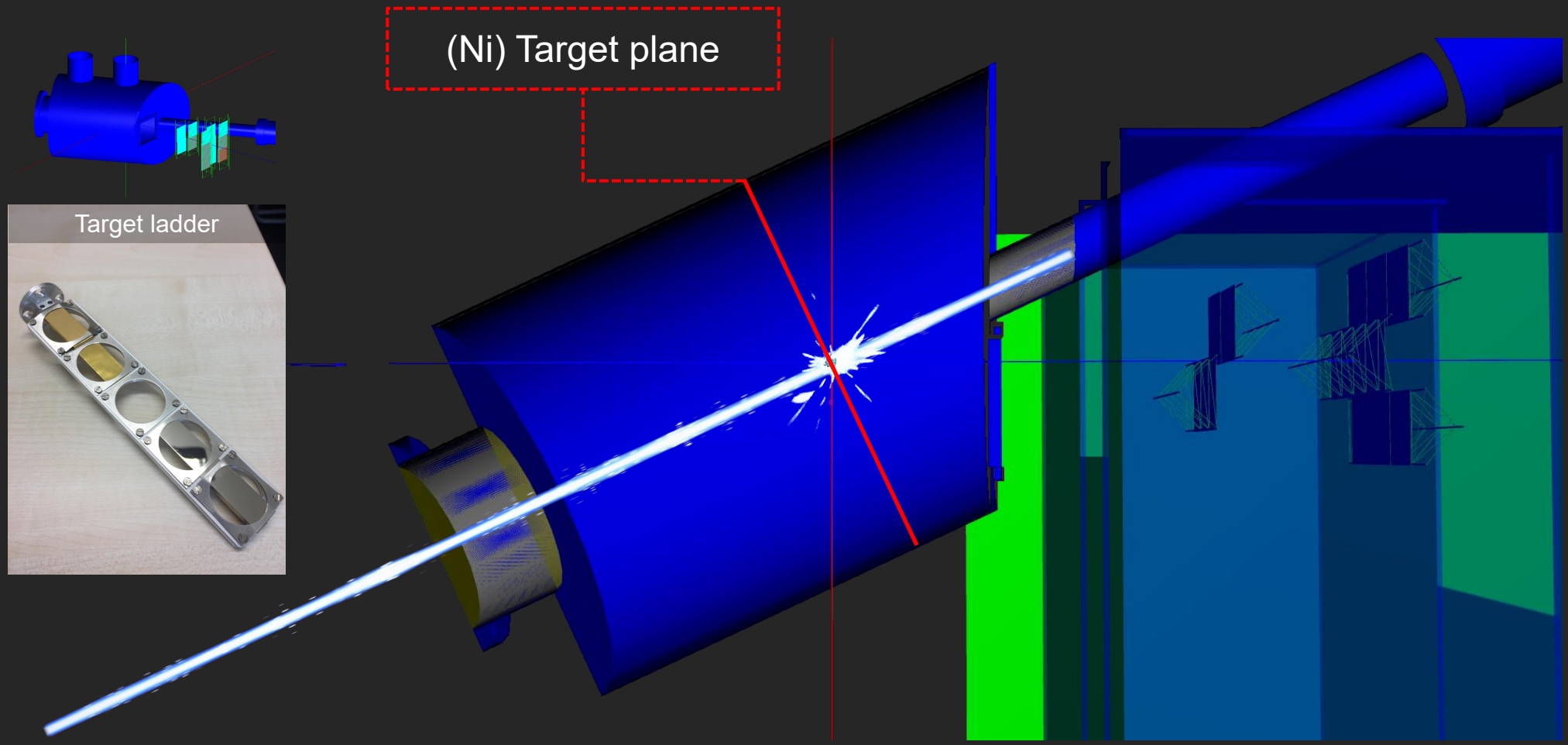

... STS track-lets, beam spot ...

mSTS Vertex Reconstruction (beam spot) - Setup: Top view

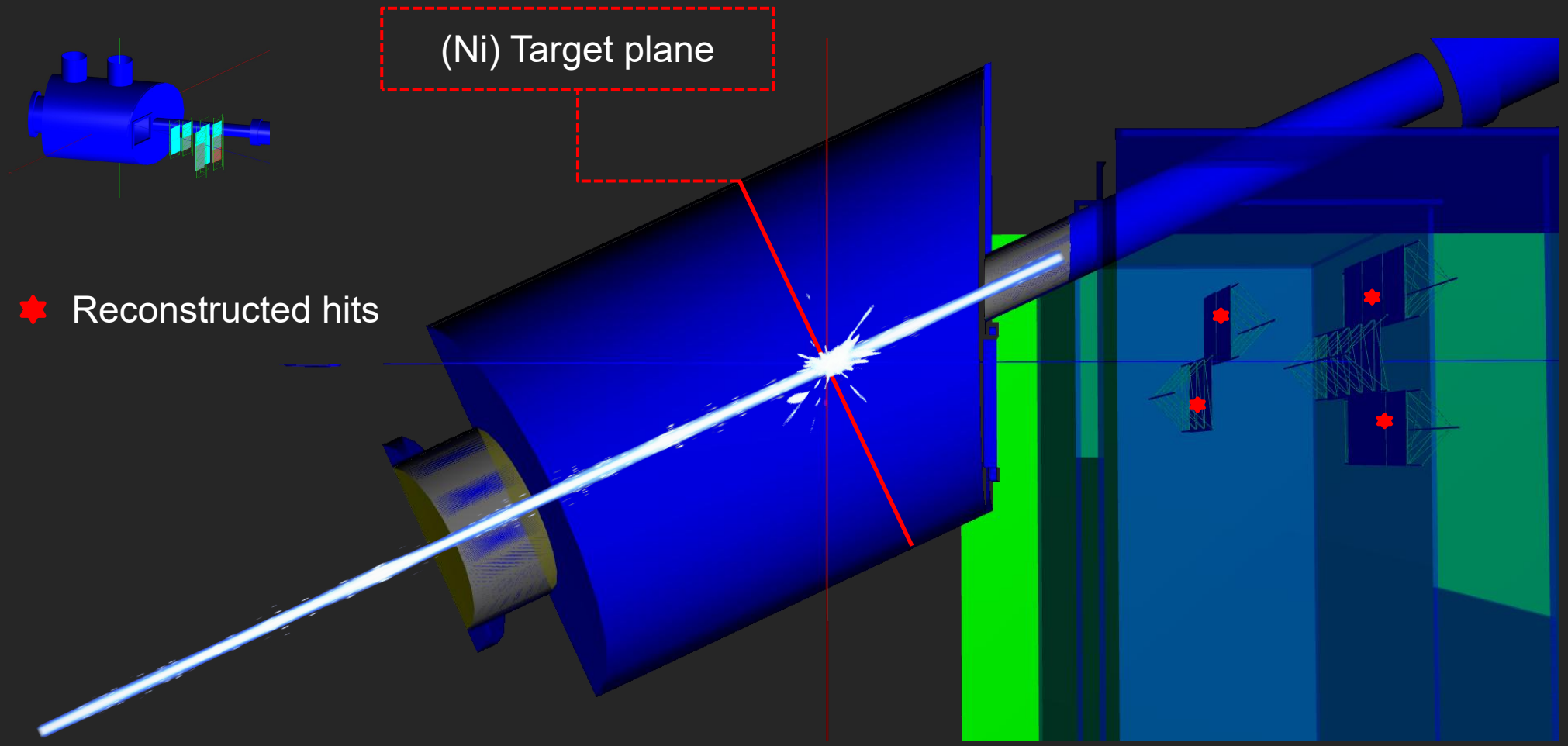


Setup is rotated 25^0 respect to the beam-line

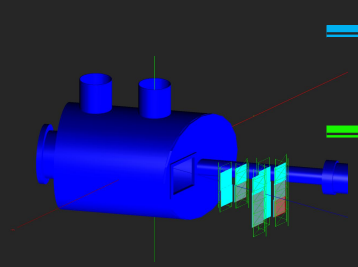
mSTS Vertex Reconstruction (beam spot) - Setup: Top view



mSTS Vertex Reconstruction (beam spot) - Setup: Top view



mSTS Vertex Reconstruction (beam spot) - Setup: Top view



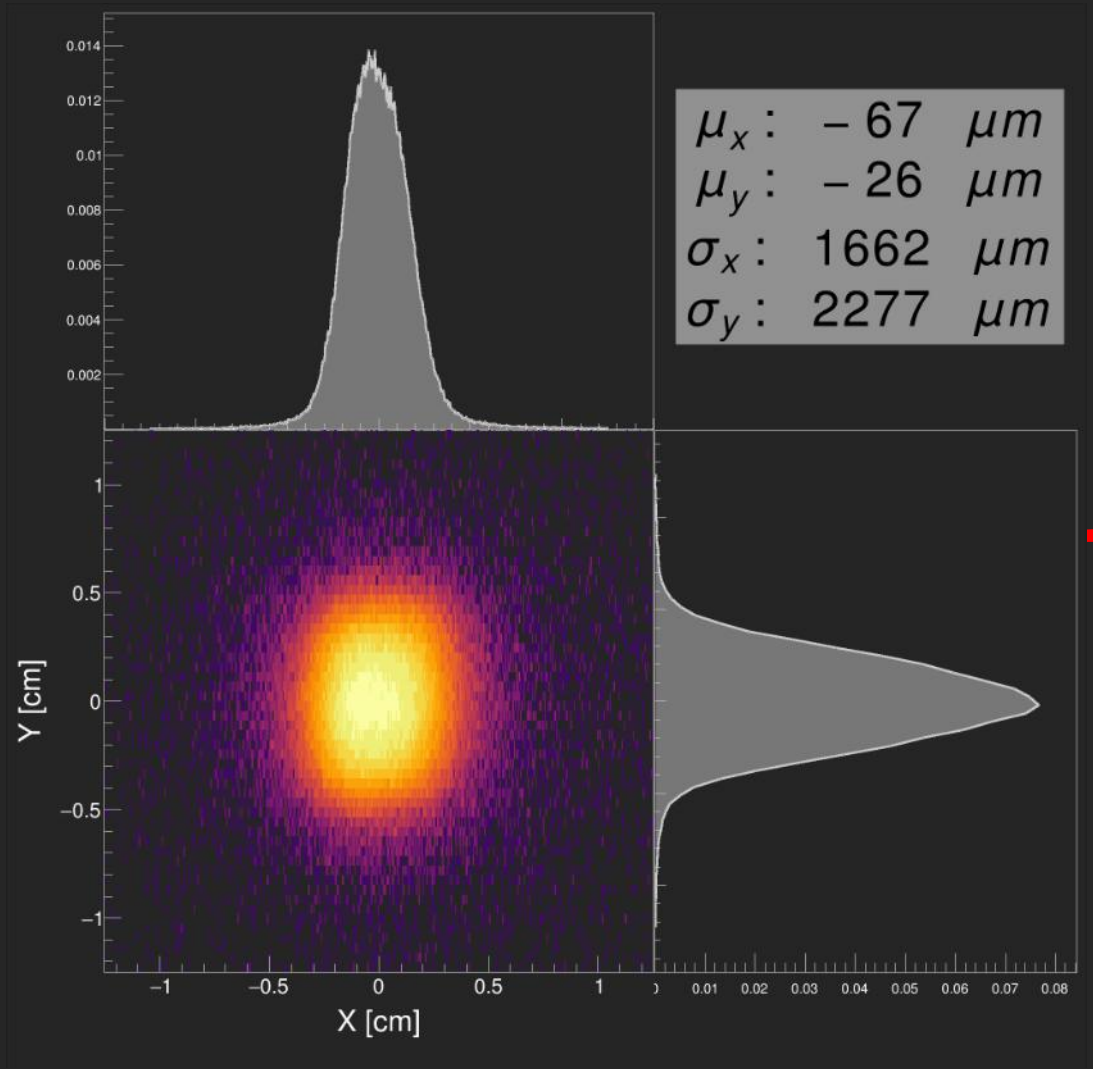
Combinatorial background

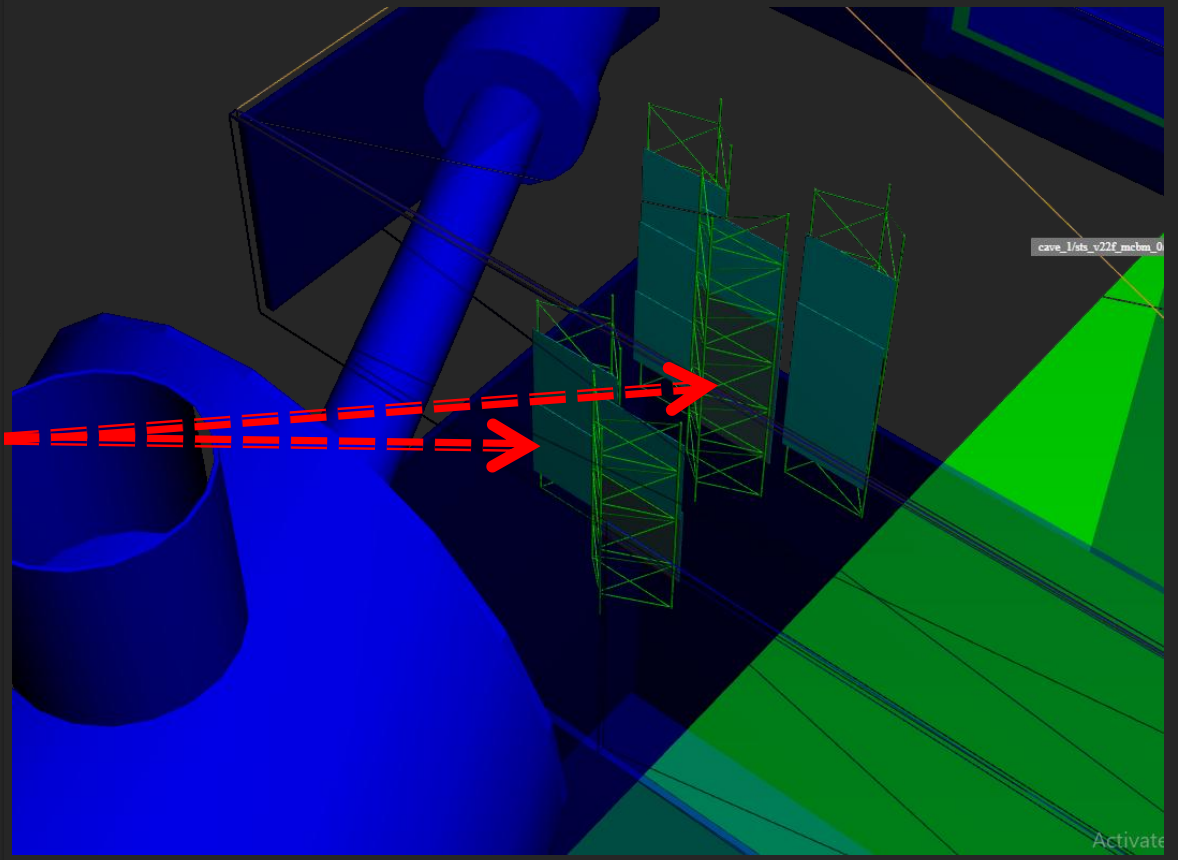
Real tracks

Reconstructed hits

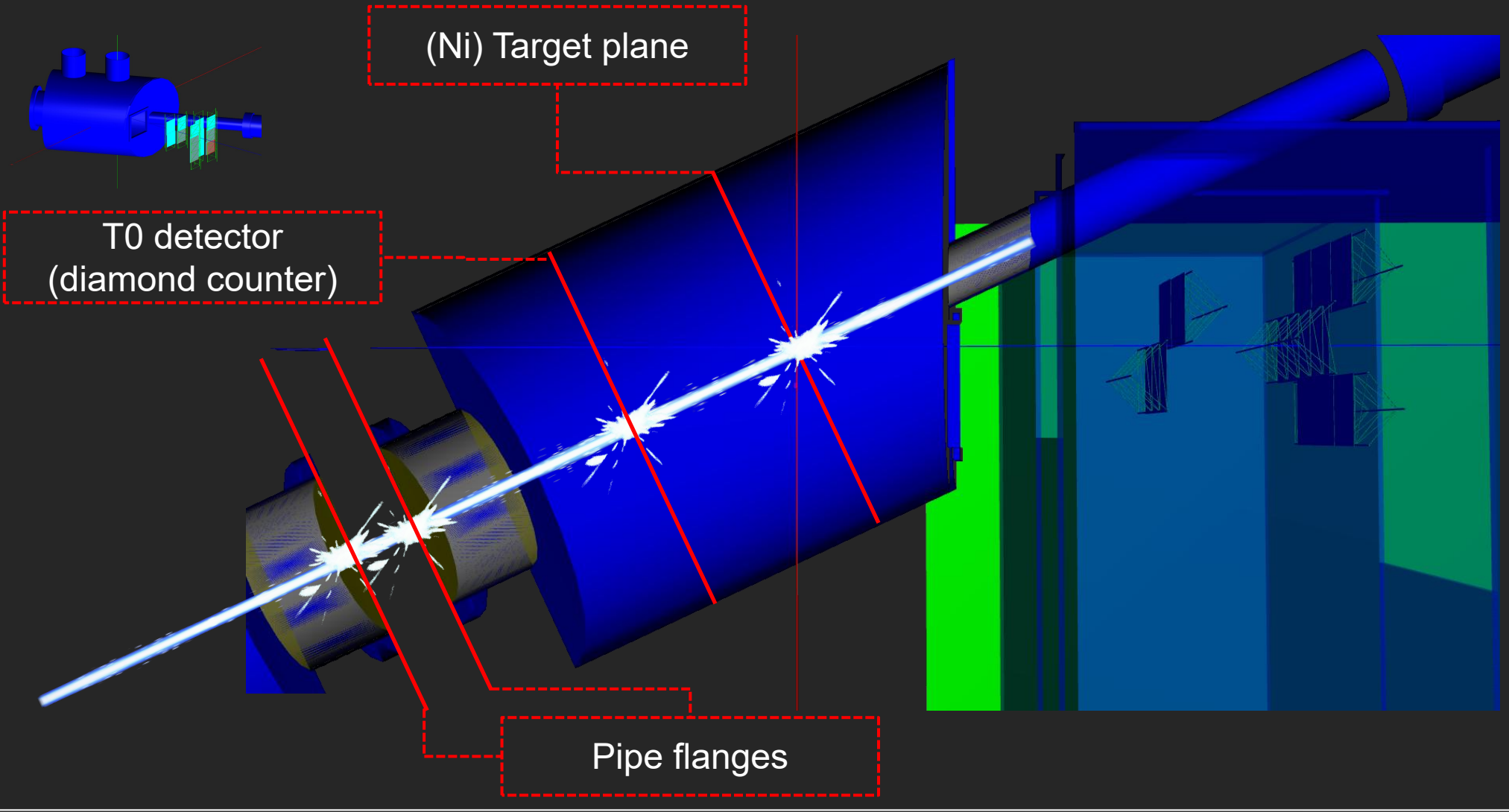
Straight lines defined by two STS hits

mSTS Vertex Reconstruction : beam spot at target plane

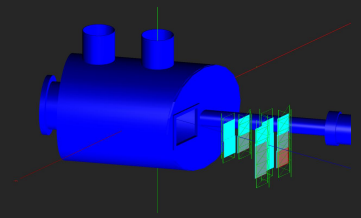




mSTS Vertex Reconstruction : secondary targets

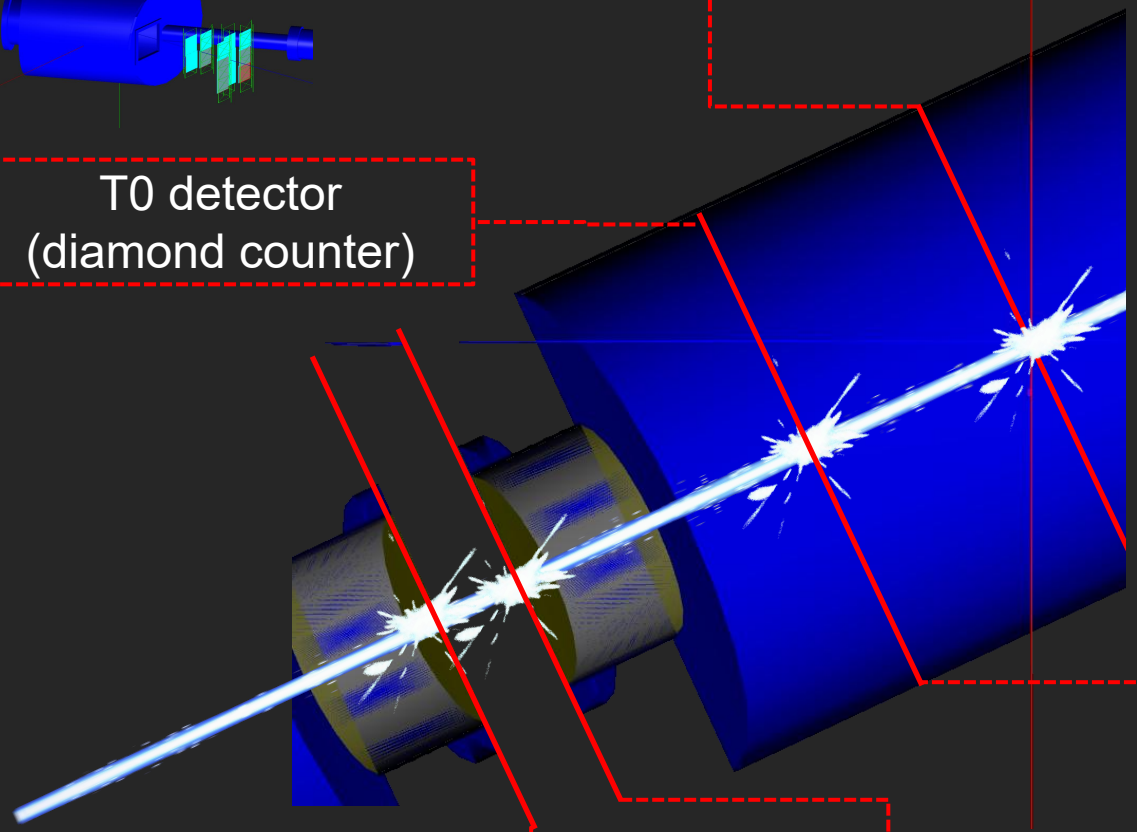


mSTS Secondary targets - Cave “tomography”

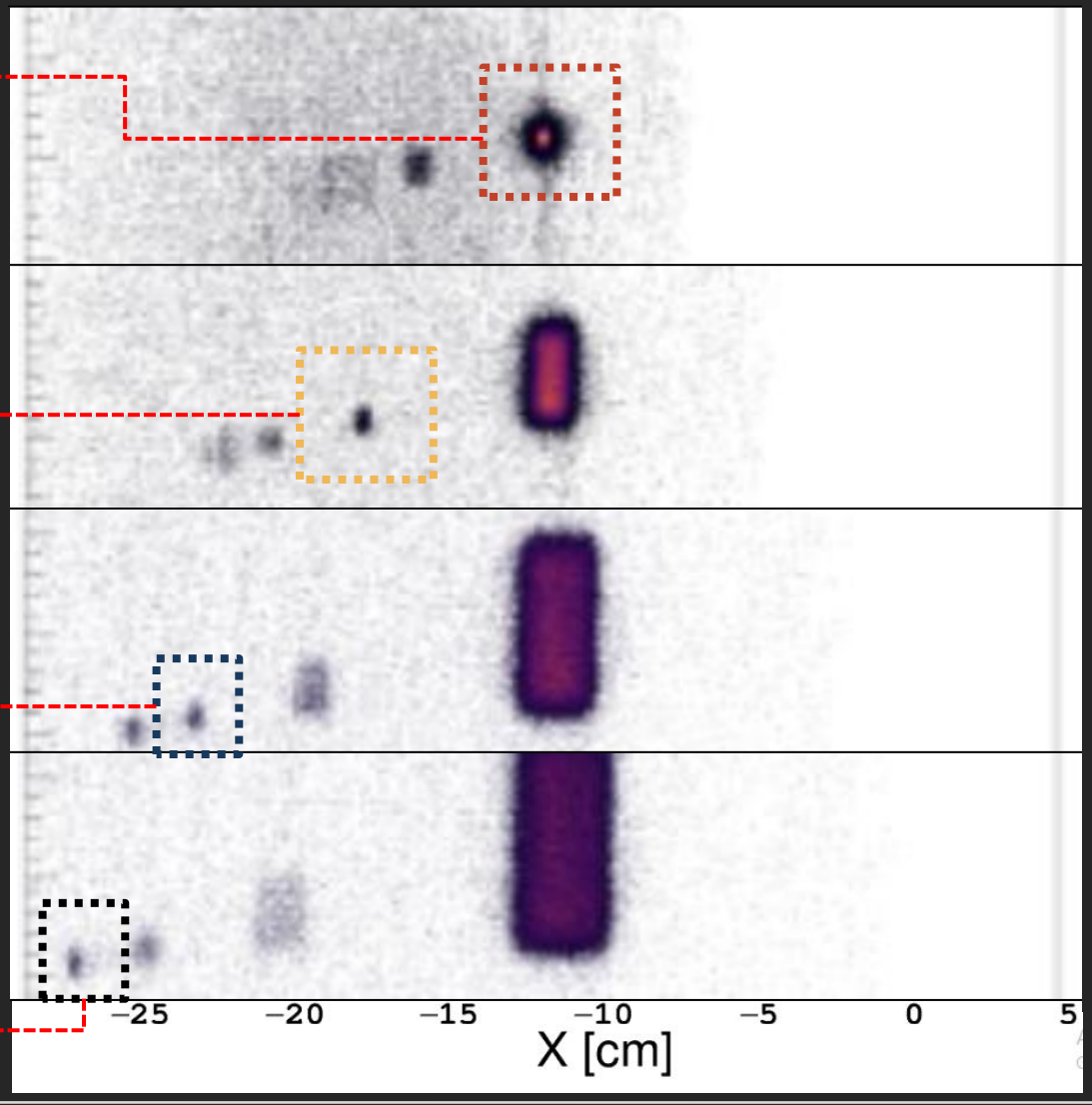


(Ni) Target plane

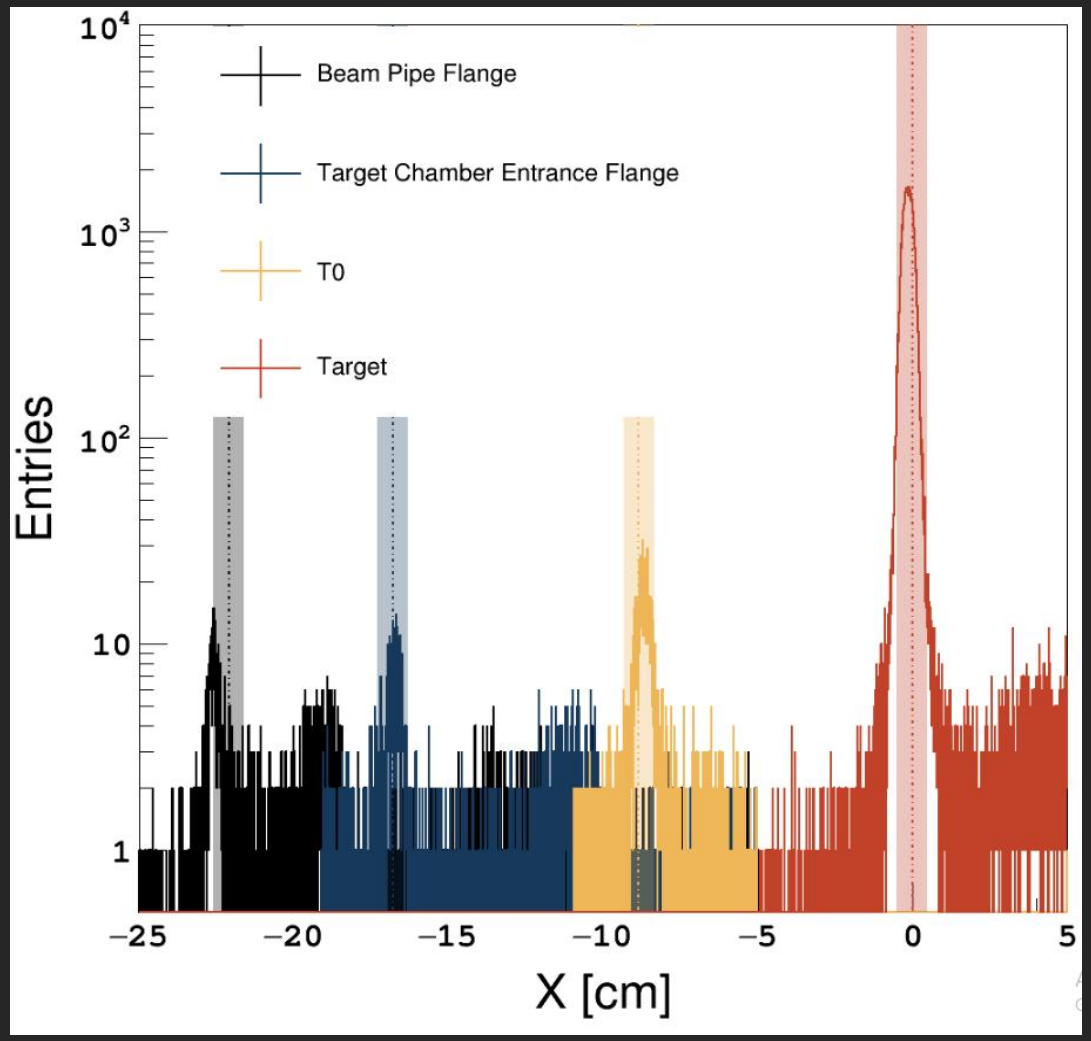
T0 detector
(diamond counter)

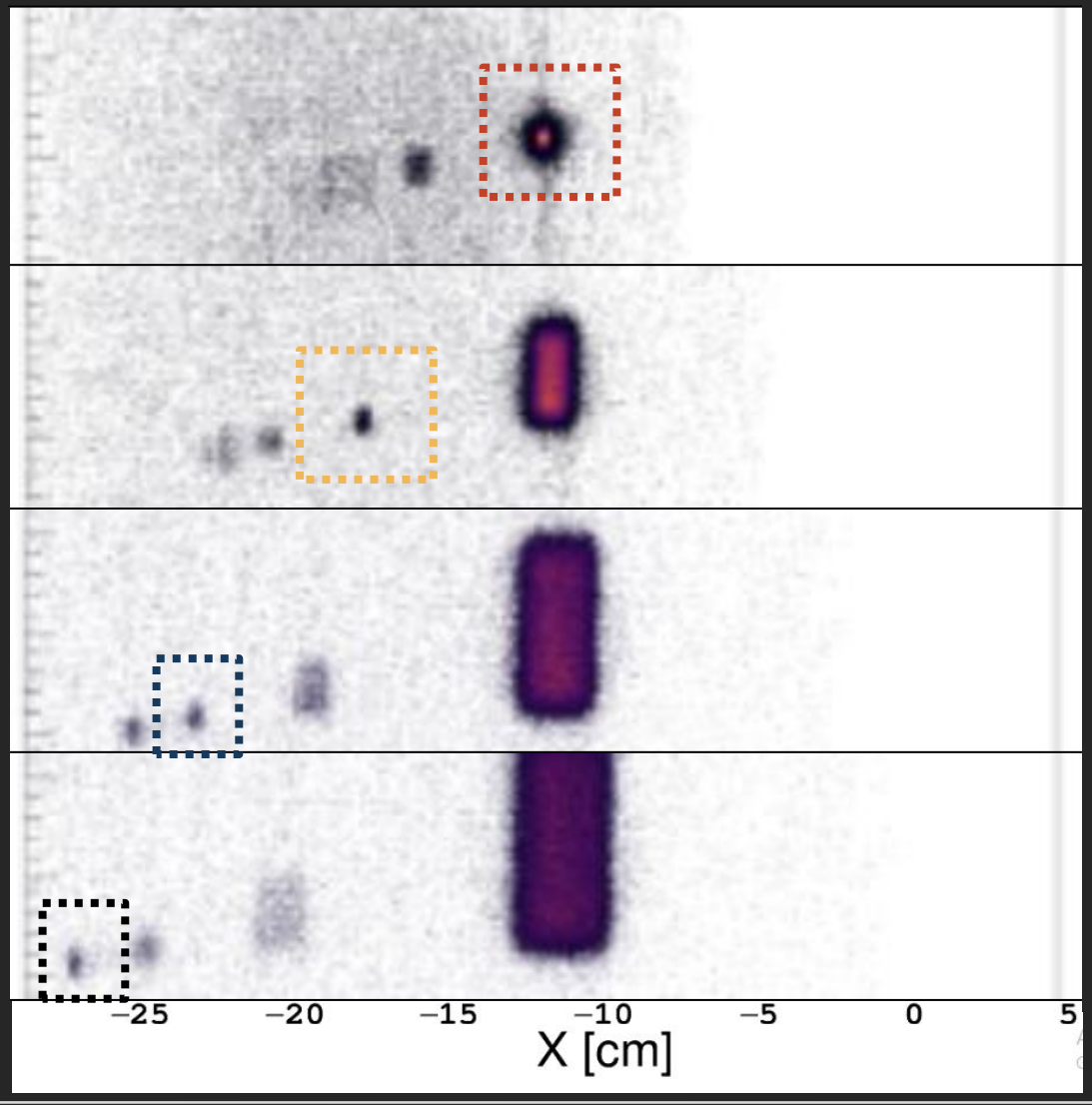


Pipe flanges



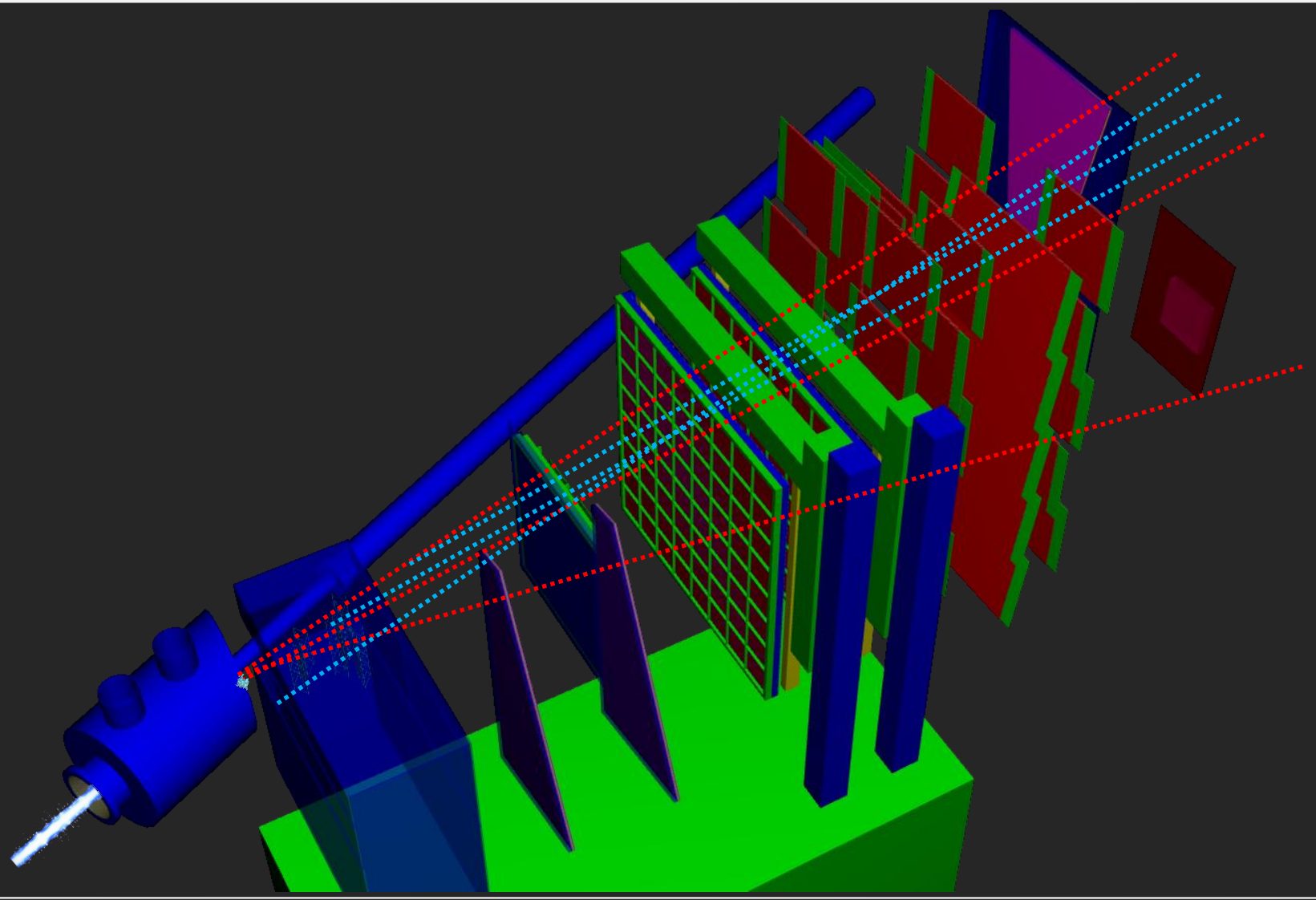
mSTS Secondary targets - Cave “tomography”





… lets combine multiple tracks …

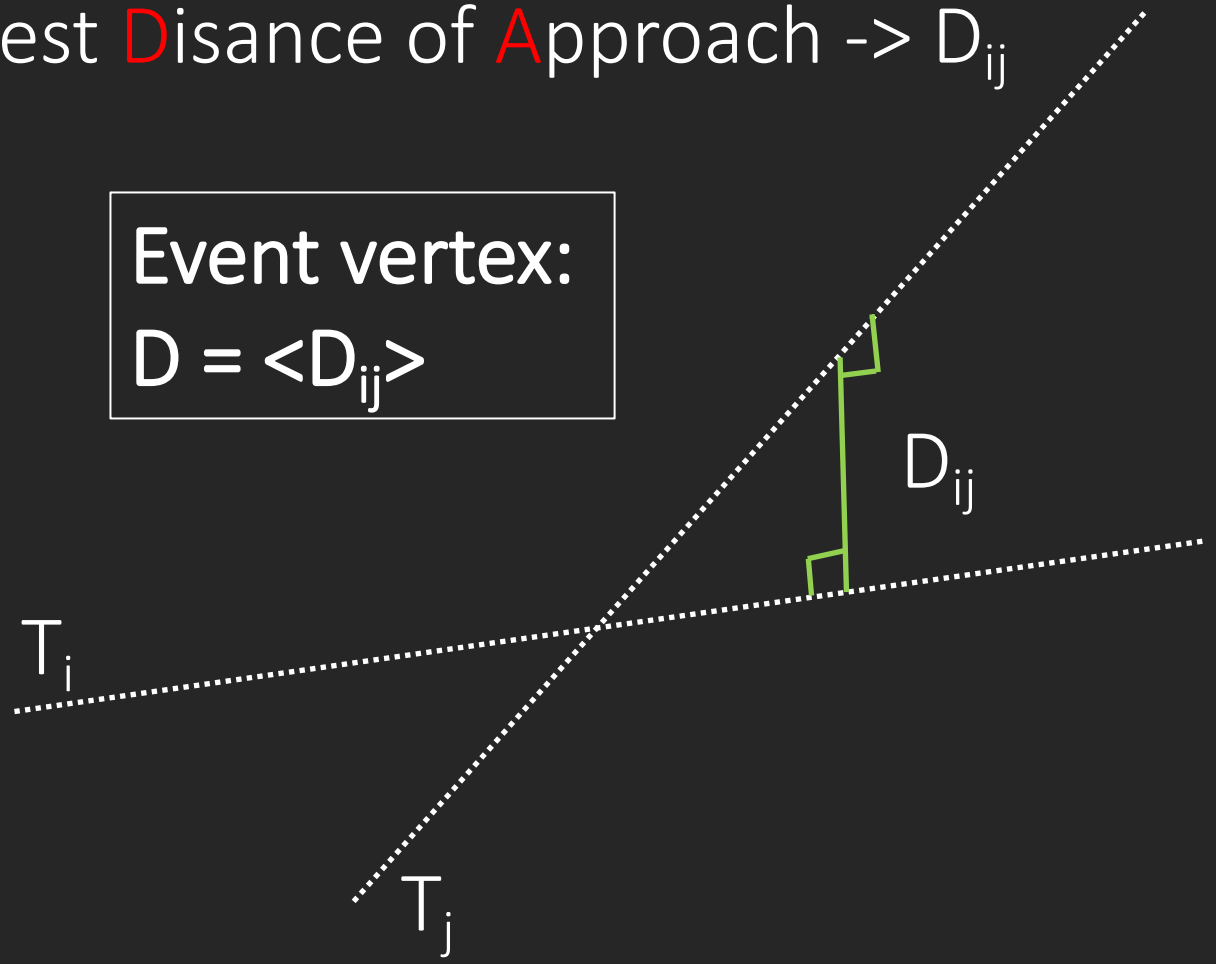
CDA Vertex reconstruction - Simplified apporach



CDA Vertex reconstruction - Simplified apporach

Closest Disance of Approach -> D_{ij}

Event vertex:
$D = \langle D_{ij} \rangle$



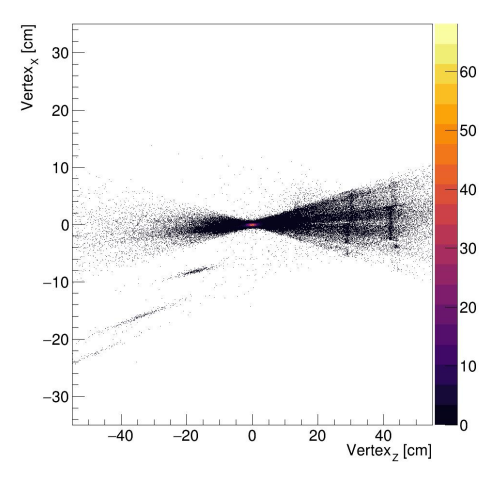
Event Vertex is biased by off-vertex secondary tracks

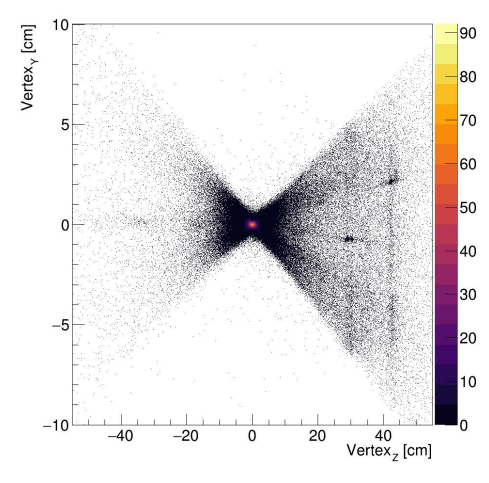
Background

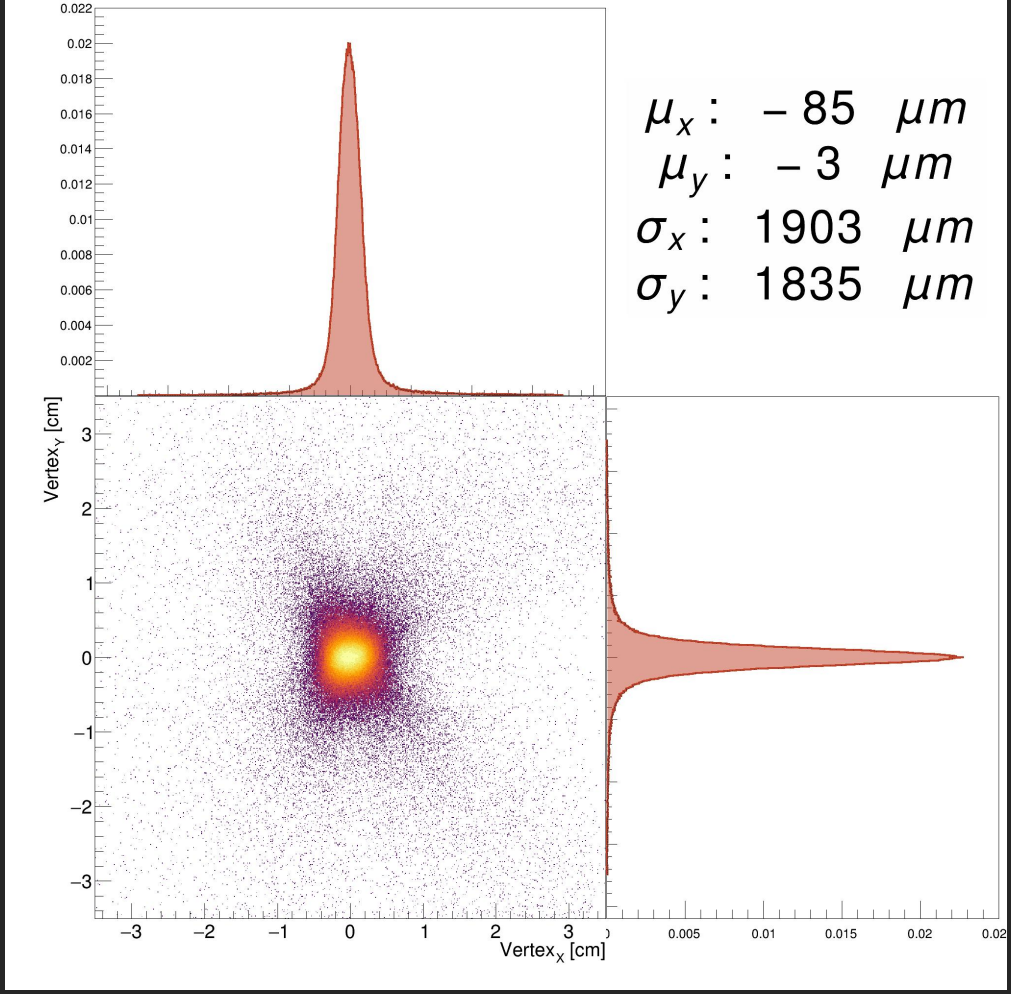
Off-vertex Primary+Secondary track mixing

DCA cuts

CDA Vertex reconstruction - Two STS hit tracks





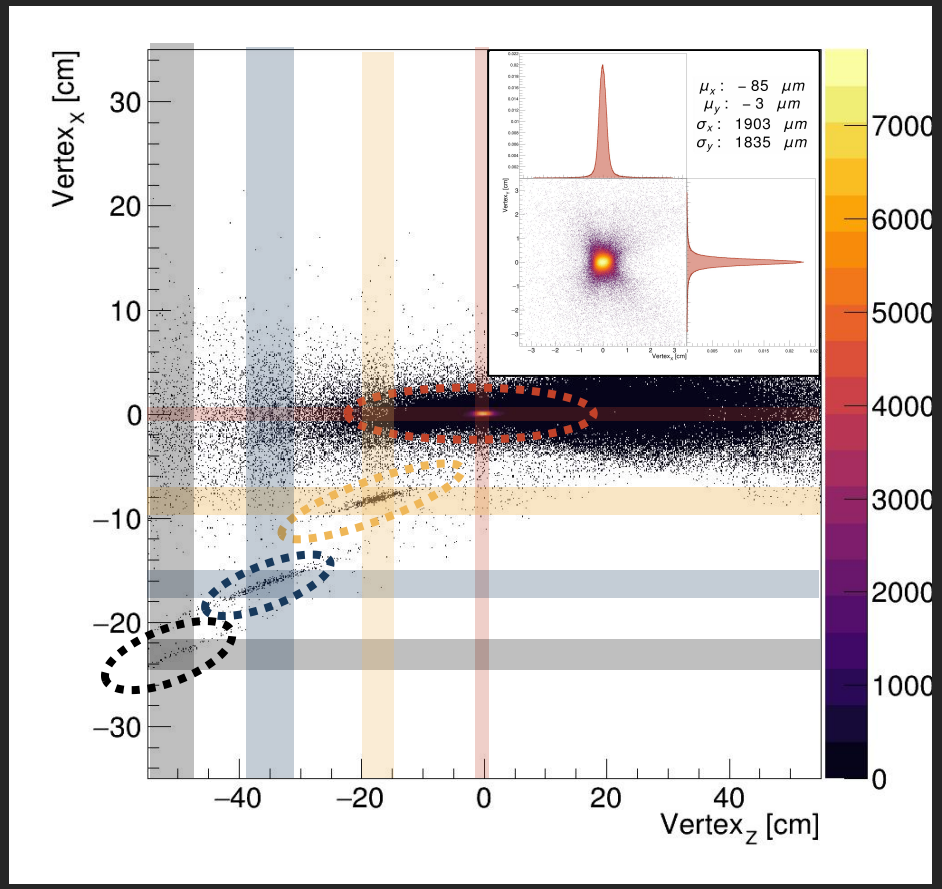


Structures appear at material budget location

Main structure produces by target

XOY picture coherent with beam spot studies

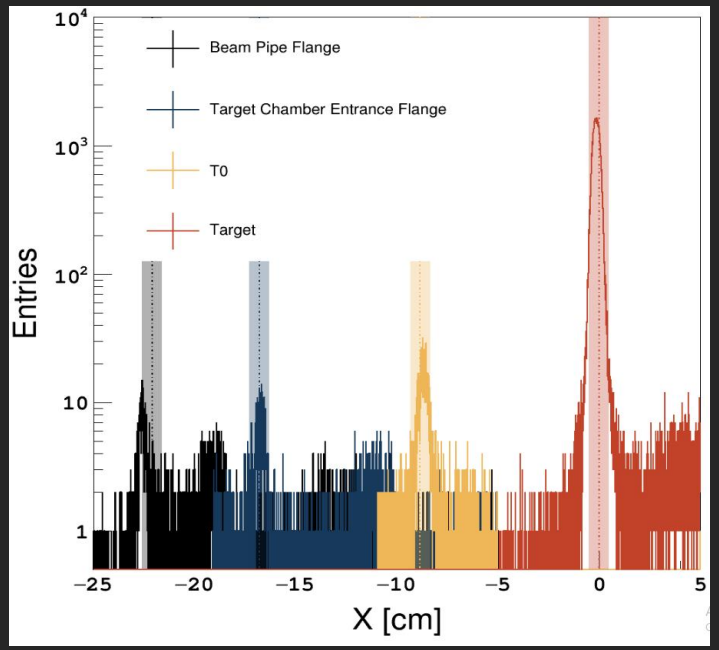
CDA Vertex reconstruction - Two STS hit tracks



Structures appear at material budget location

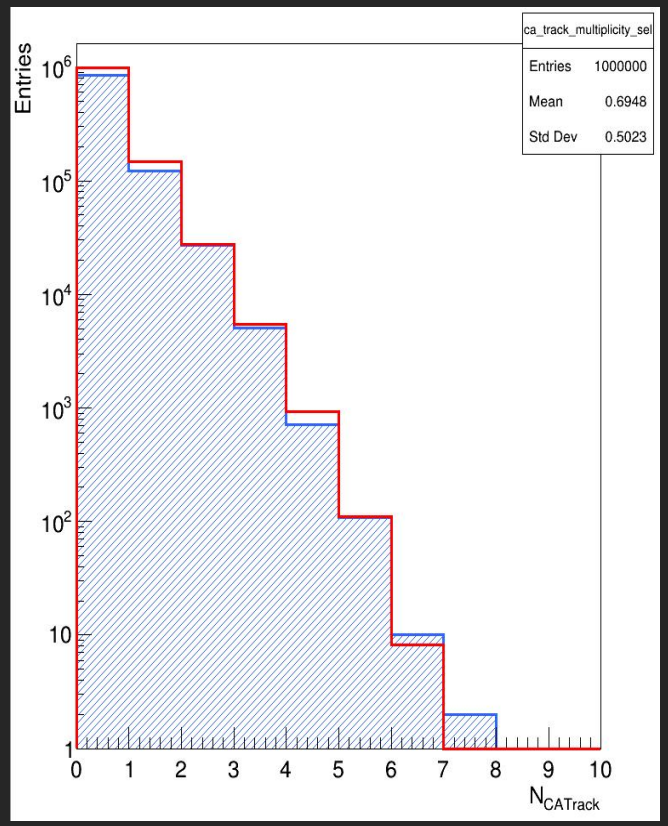
Secondary targets at mCBM@SIS18 cave

Consistent location



CDA Vertex reconstruction - DCA distributions - Track to vertex

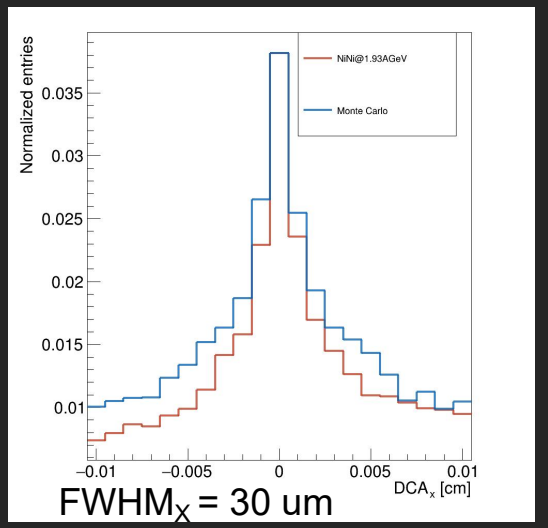
Consisent track selection

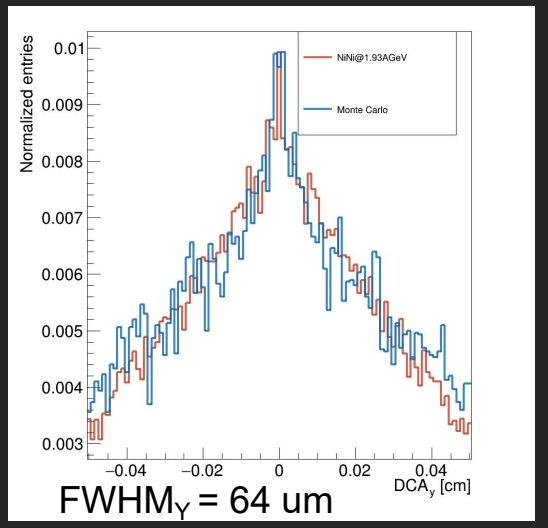


DCA component reflect vertex resolution capabilities

Analysis is biased by secondaries*

FWHM set a upper bound for vertex resolution

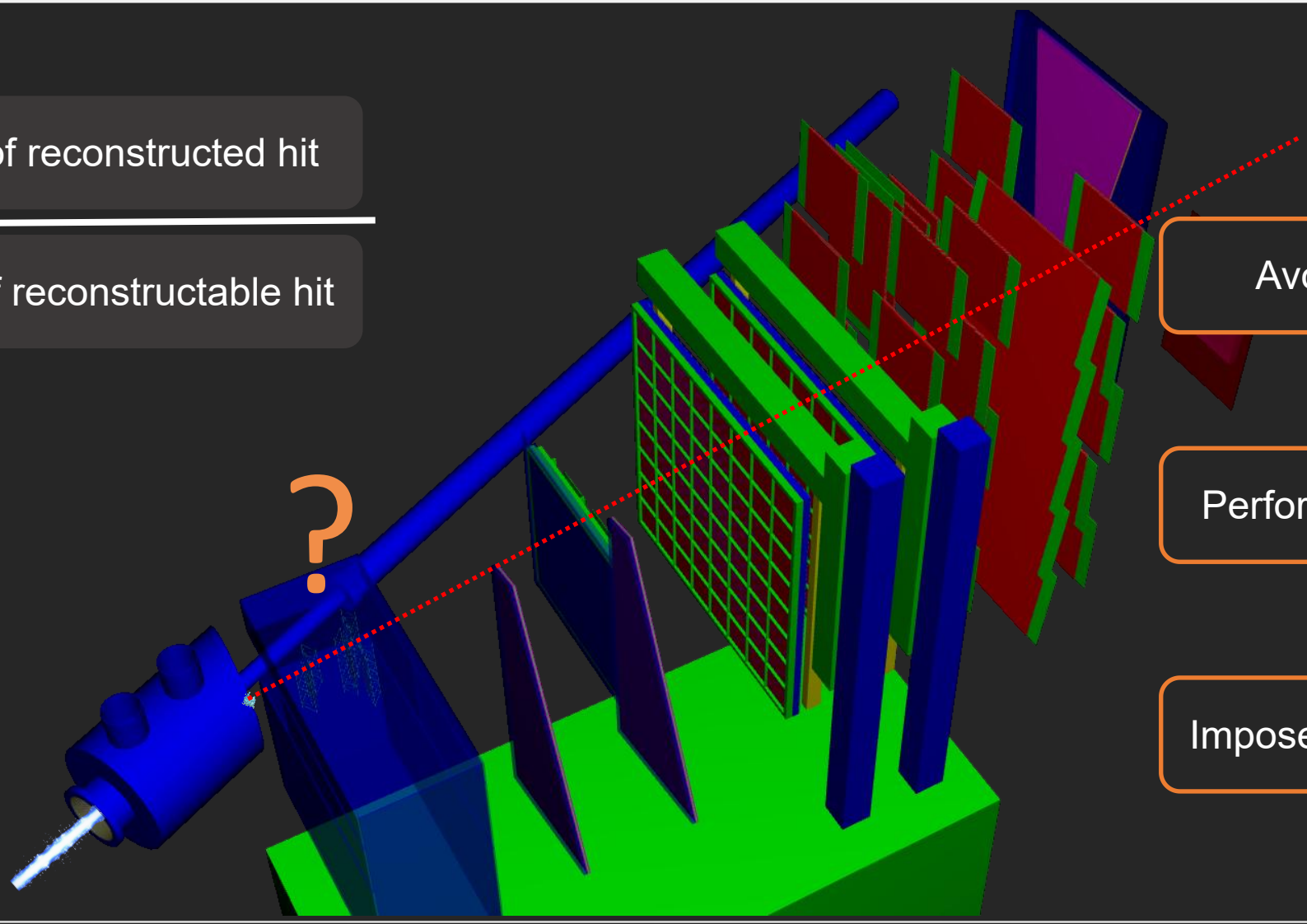




… hit reconstruction efficiency …

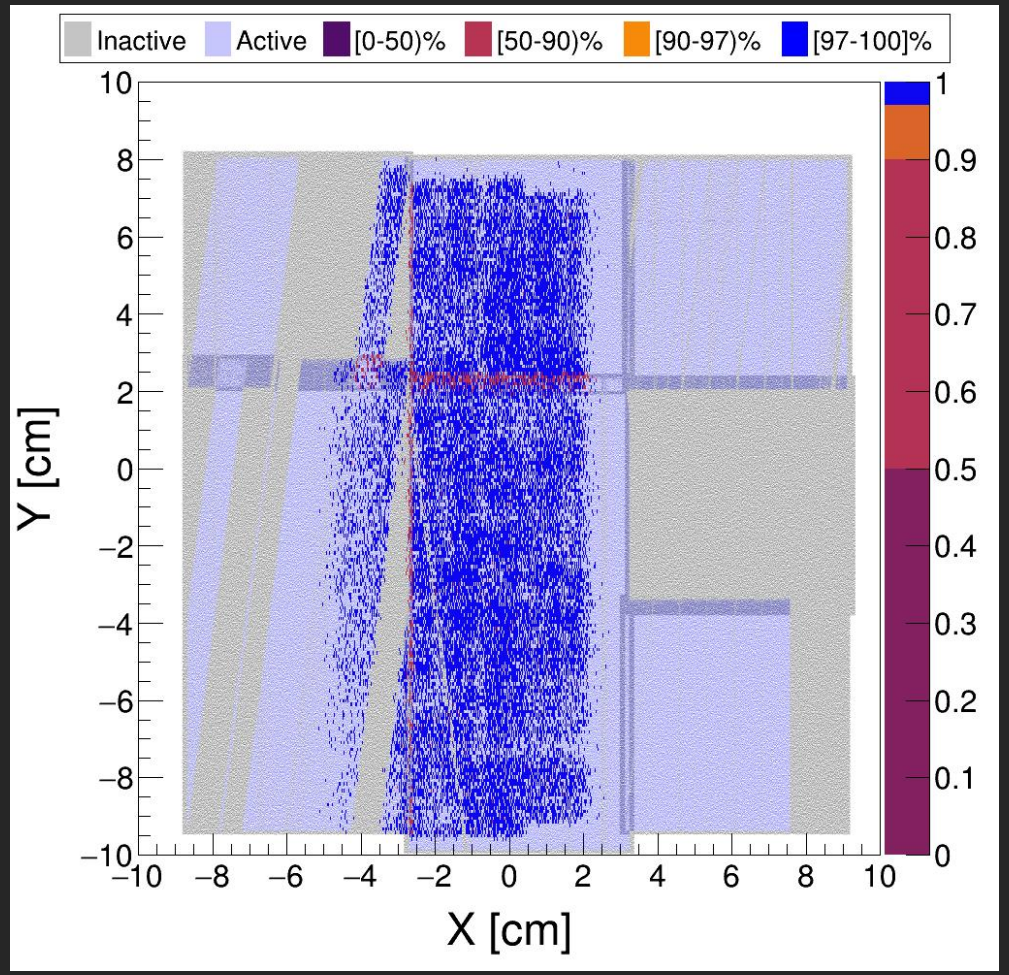
mSTS - Hit Reconstruction Efficiency - Definition

$$HRE = \frac{\text{No of reconstructed hit}}{\text{No of reconstructable hit}}$$



- Avoid bias cases
- Perform track selection
- Impose geometrical cuts

mSTS - Hit Reconstruction Efficiency

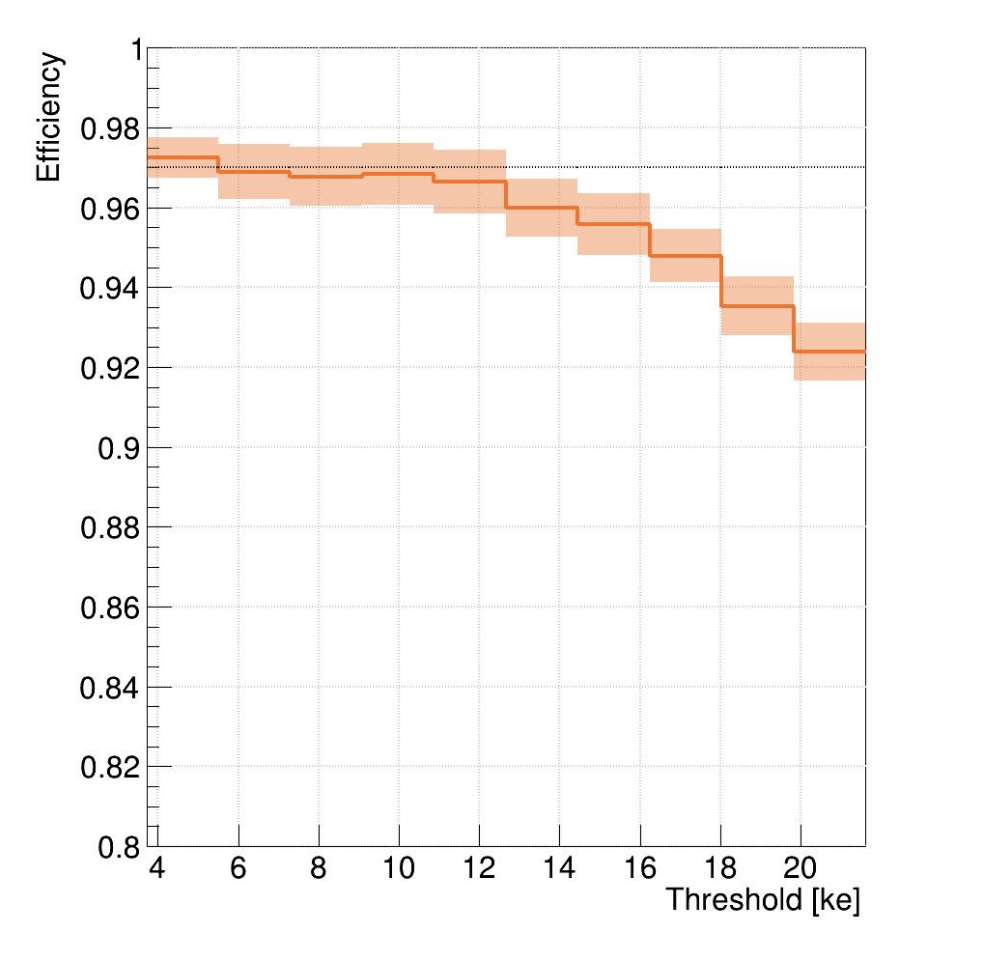


Bias cases were minimized

Reduced acceptance due to track selection

HRE remarkable on sampled area

mSTS - Hit Reconstruction Efficiency

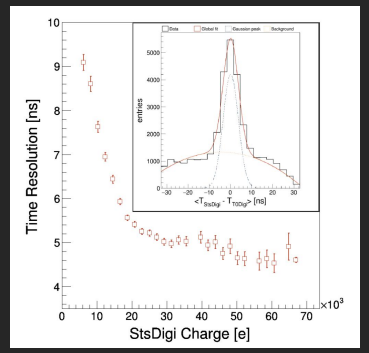


Average of sampled area

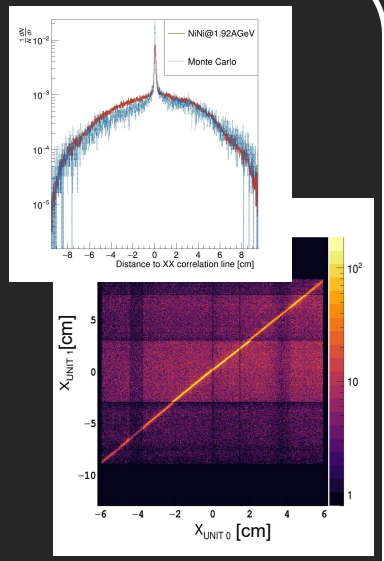
Threshold at Digi level

Large operational threshold before HRE drops significantly

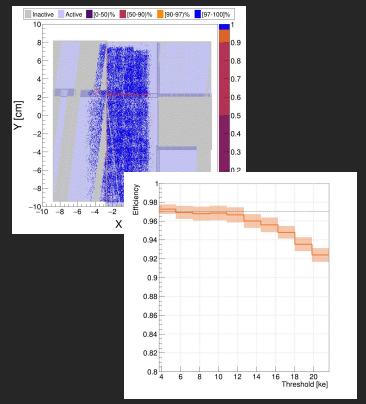
Summary



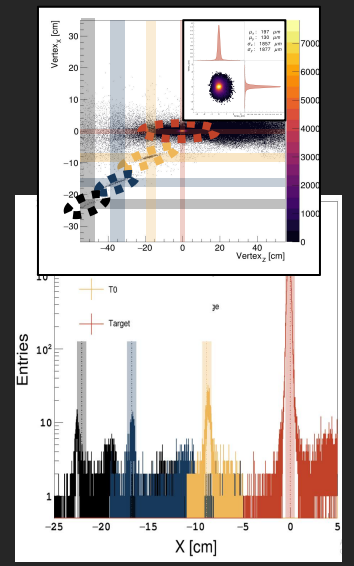
Robust time resolution procedure: 4.8 - 9.2 ns (6k-67k e)



Position measurement inline with MC expectations ~10 um



Hit reconstruction efficiency above 97% - small loss for high threhsold



Consistent vertex and beam spot reconstuction

Deep dive

M.Teklishyn From 3D to 5D tracking: SMX ASIC-based Double-Sided Micro-Strip detectors for comprehensive space, time, and energy measurements
TWEPP 2023 https://indico.cern.ch/event/1255624/contributions/5444008/attachments/2728888/4743371/smx_5d_tracking_teklishyn_06OCT2023.pdf

A. Rodriguez Rodriguez et al., Functional characterization of modules for the Silicon Tracking System of the CBM experiment
accepted by NIM

K. Agarwal, Thermal Management of the CBM-FAIR's Silicon Tracking System (STS) – Concept and Demonstrators
Forum on Tracking Detector Mechanics 2023
https://indico.cern.ch/event/1228295/contributions/5390887/attachments/2656554/4600811/20230531_Agarwal_FTDMT%C3%BCbingen.pdf

S. Mehta, Impact of air cooling on mechanical stability of silicon sensors in CBM-STS
Forum on Tracking Detector Mechanics 2023
https://indico.cern.ch/event/1228295/contributions/5390888/attachments/2656536/4600775/Vib_Tracking_forum_Mehta_1.pdf

I. Elizarov, Sustainable cooling supply for the STS detector electronics
Forum on Tracking Detector Mechanics 2023
https://indico.cern.ch/event/1228295/contributions/5401384/attachments/2656351/4600422/Elizarov-Pilot%20Cooling%20Supply%20for%20the%20CBM%20Silicon%20Tracking%20System%20Detector%20Electronics.pdf

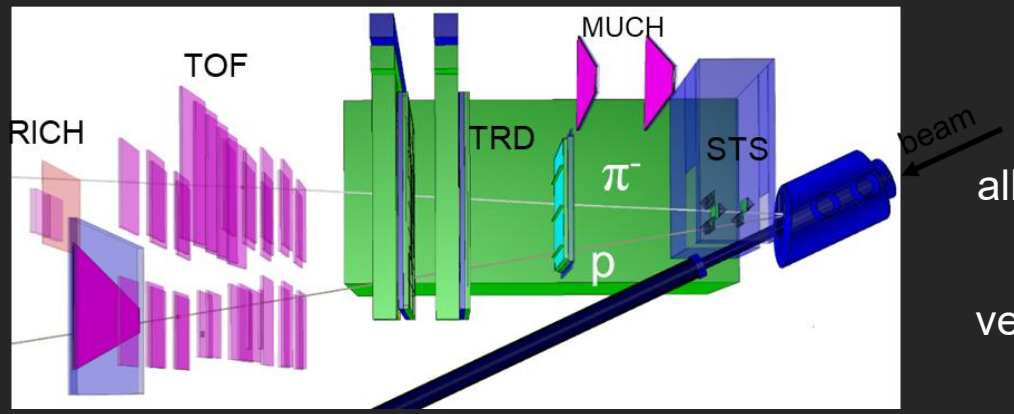
L.M. Collazo, Temperature calibration and thermal stress tests of the Front-End Electronics of the CBM Silicon Tracking System
Forum on Tracking Detector Mechanics 2023
https://indico.cern.ch/event/1228295/contributions/5394879/attachments/2656948/4601561/FTDM2023_Poster_Lady_Maryann.pdf

M. Teklishyn Detectors and Electronics for the CBM experiment at FAIR
ICPADGP 2023 https://events.vecc.gov.in/event/19/contributions/1009/attachments/198/411/teklishyn_cbm_detectorselectronics_07feb2023.pdf

... additional material ...

mCBM Benchmark Lambda reconstruction

Rare signal reconstructed: $\Lambda \rightarrow p\ \pi^-$

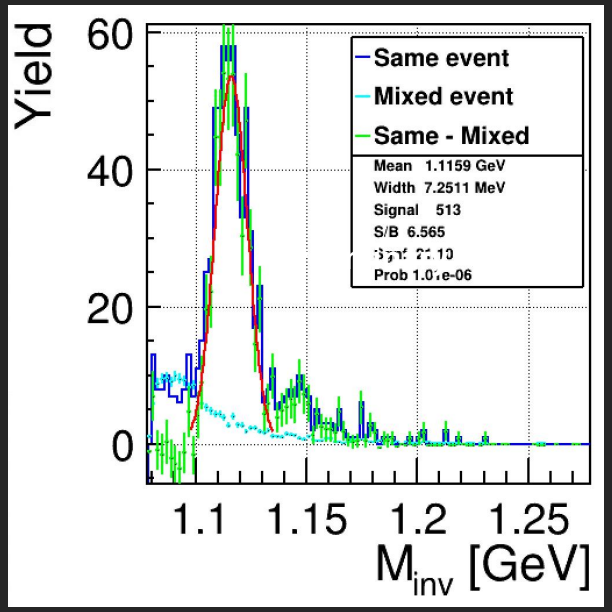


Ni+Ni 1.93 AGeV
run 2391 (May '22):
10^9 collisions, 1:57h
400 kHz av. coll. rate

all detector systems involved

secondary vertex

velocity windows for p and π^- candidate

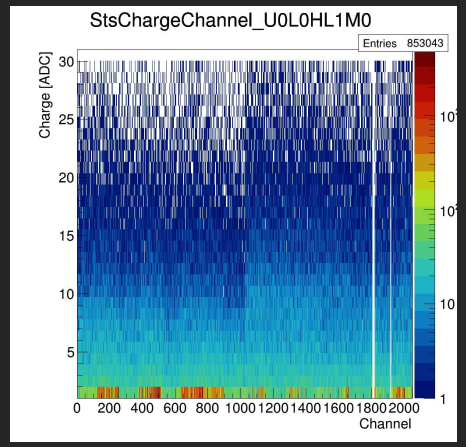


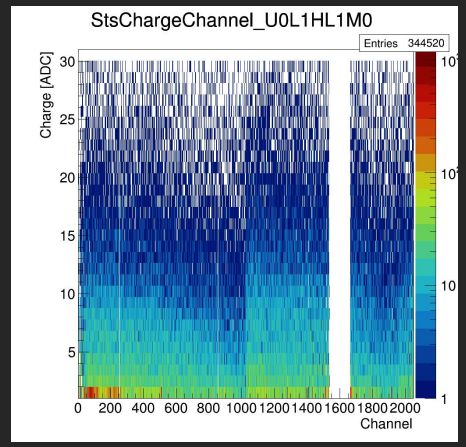
mSTS Signal Analysis - Charge vs Channel

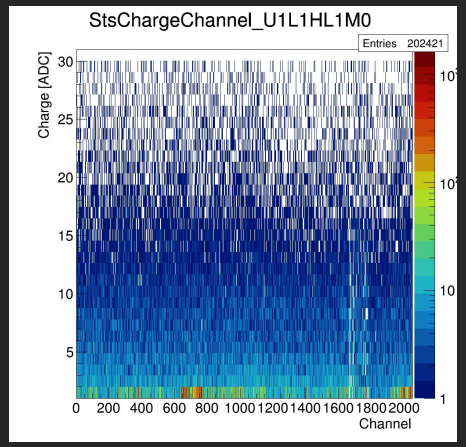
Station 1 **Station 2**

ladder 0 **ladder 1** **ladder 1**

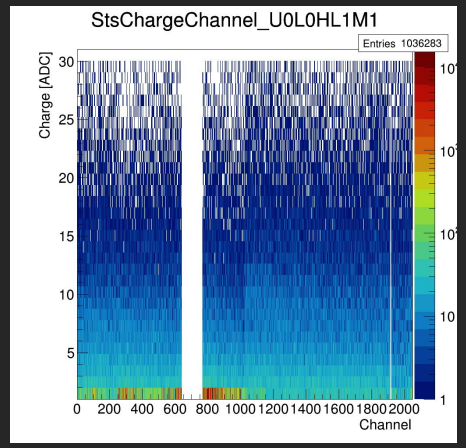
module 0

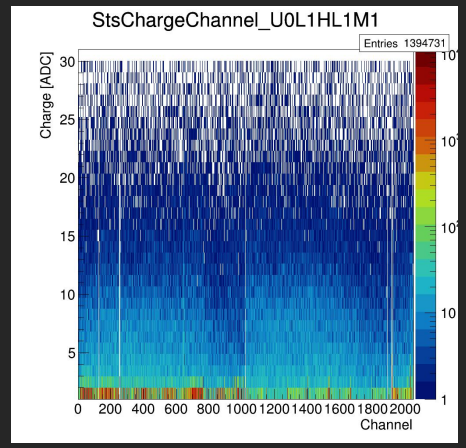


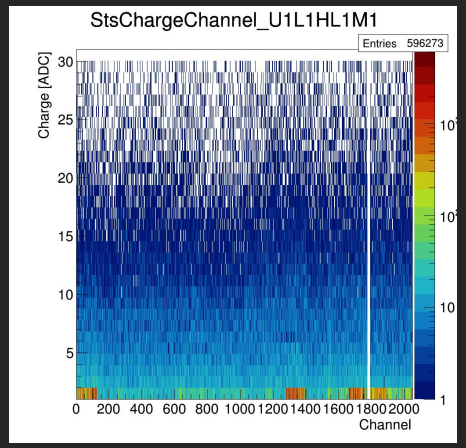




module 1

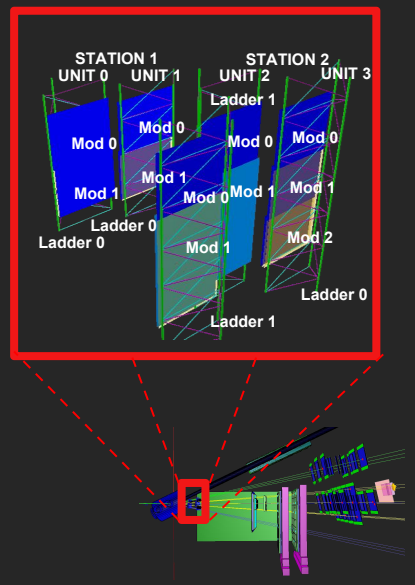






2 non functional ASICs

few dead channels

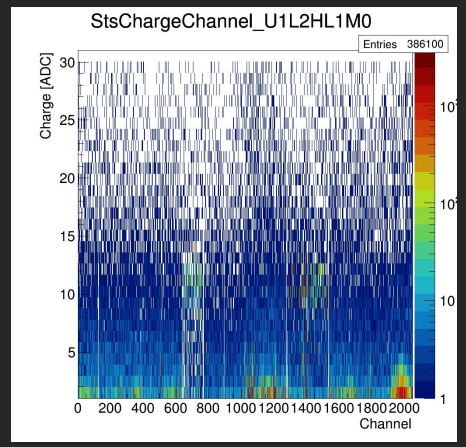


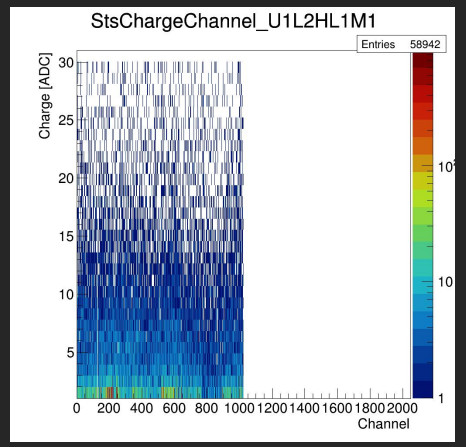
mSTS Signal Analysis - Charge vs Channel

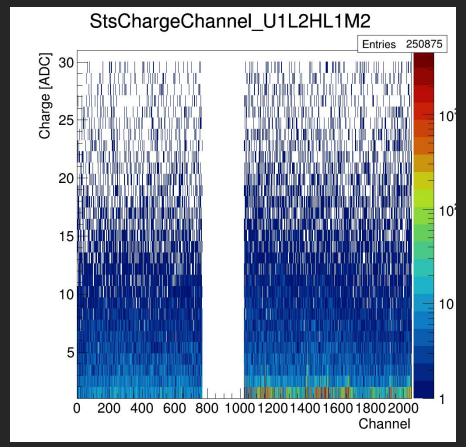
module 0 | **module 1** | **module 2**

Station 2

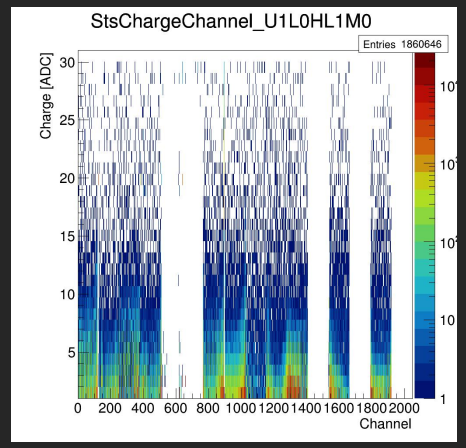
ladder 0

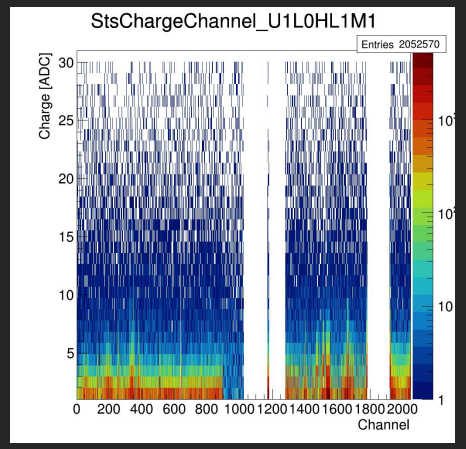






ladder 2

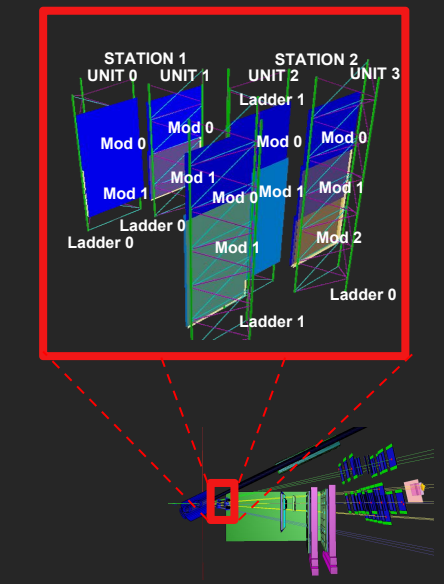




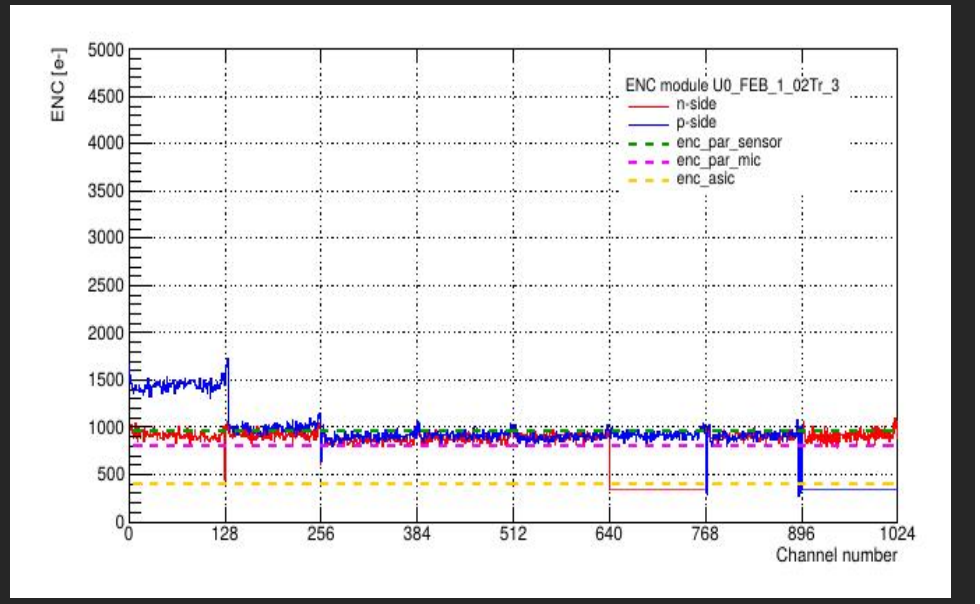
1 non functional FEB

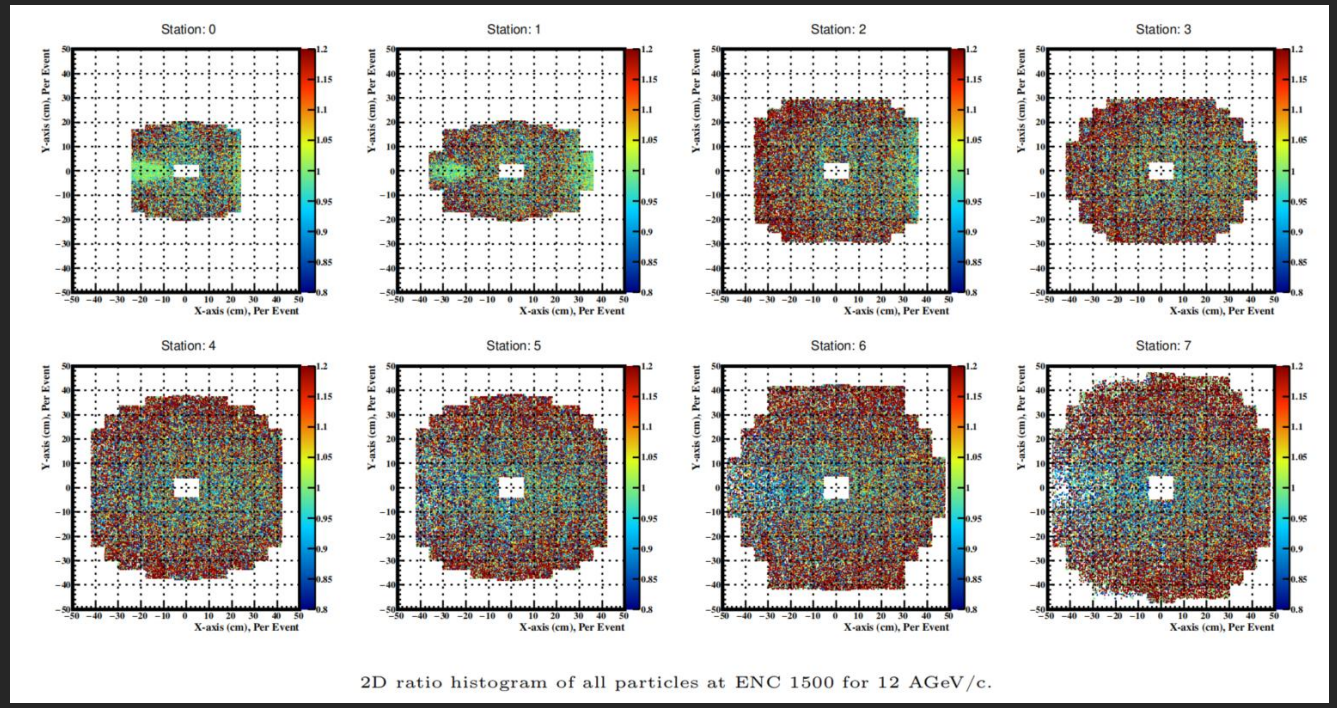
8 non functional ASICs

Calibration issues



STS Noise





2D ratio histogram of all particles at ENC 1500 for 12 AGeV/c.

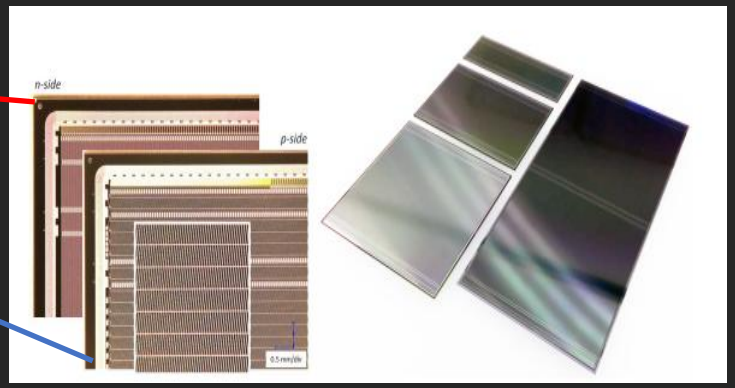
… from hardware to software …

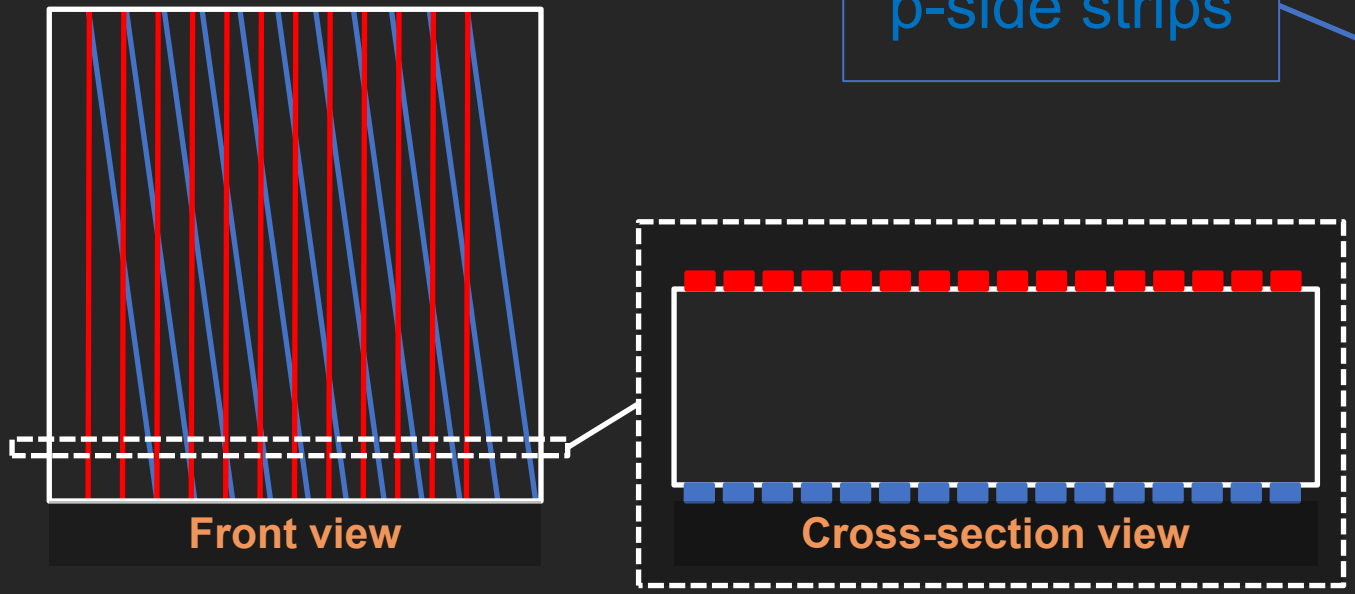
STS sensors strips

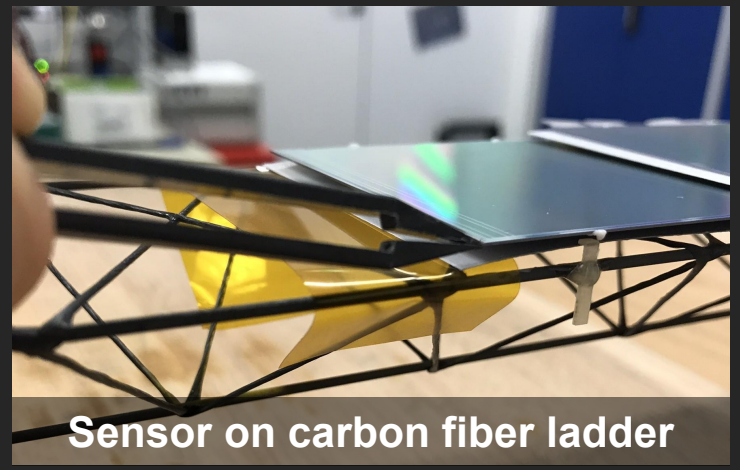
p-side strips tilted by 7.5^0

n-side strips

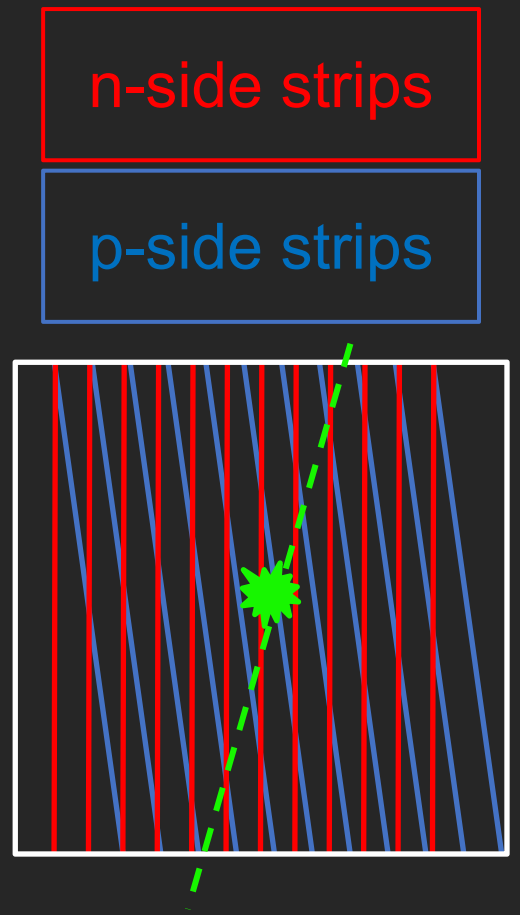
p-side strips

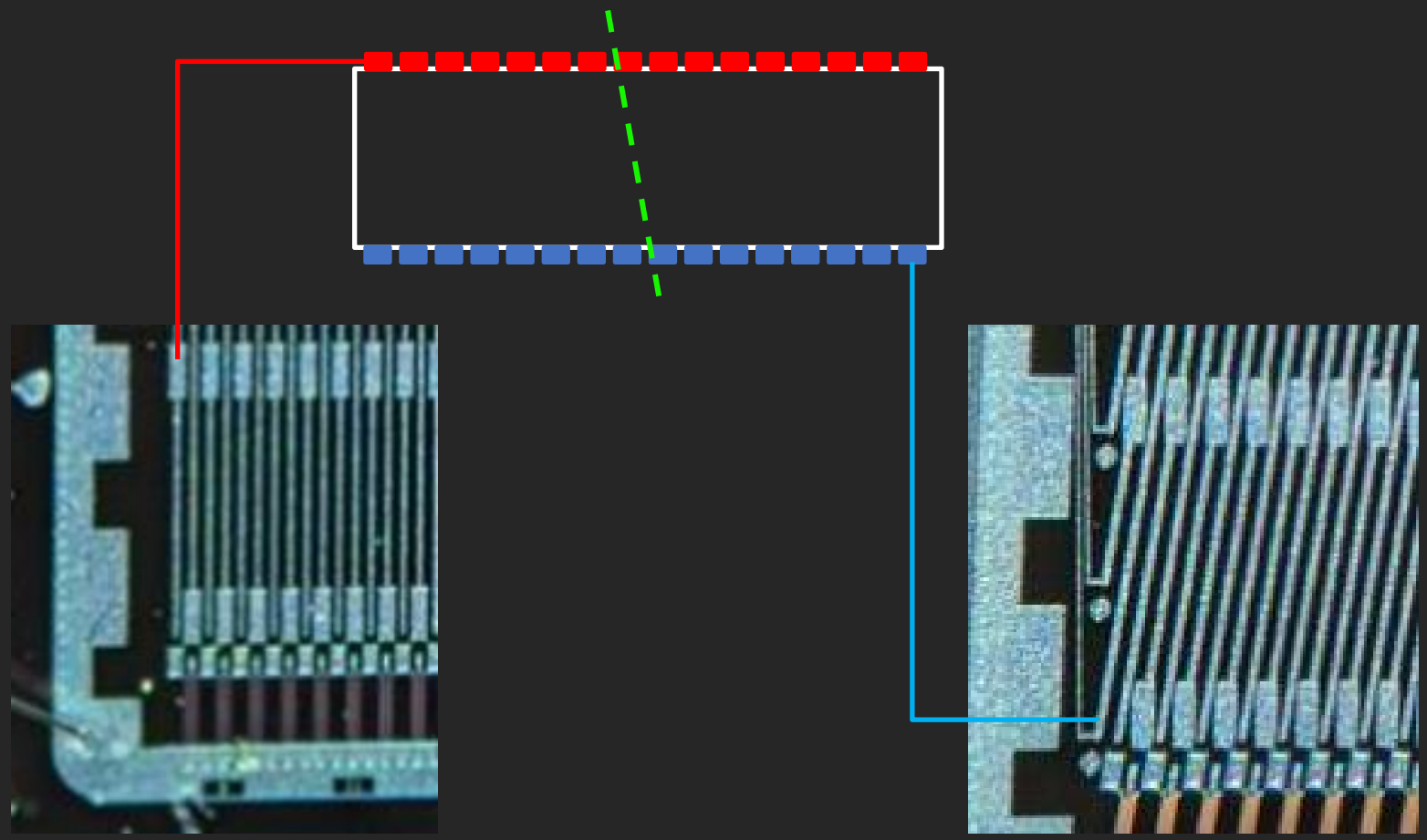






STS sensors strips

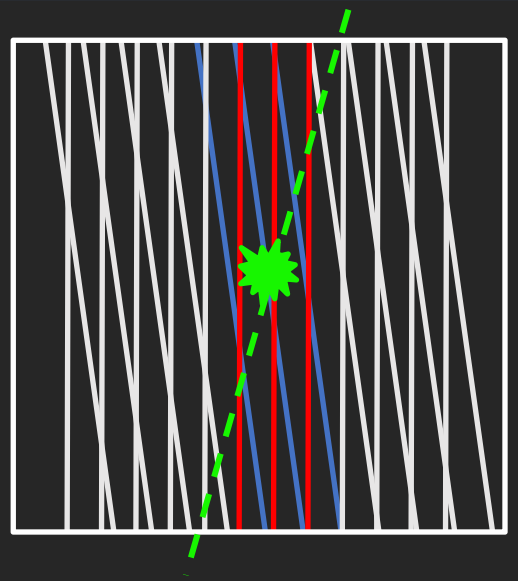


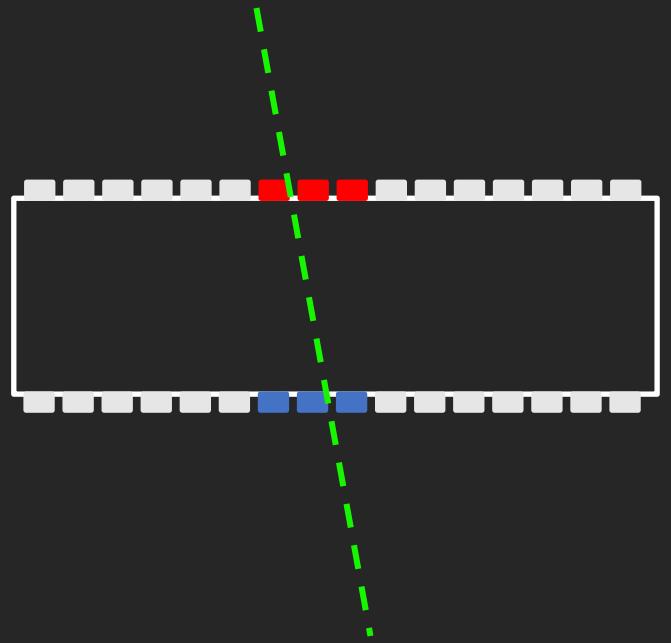


STS sensors fired strips

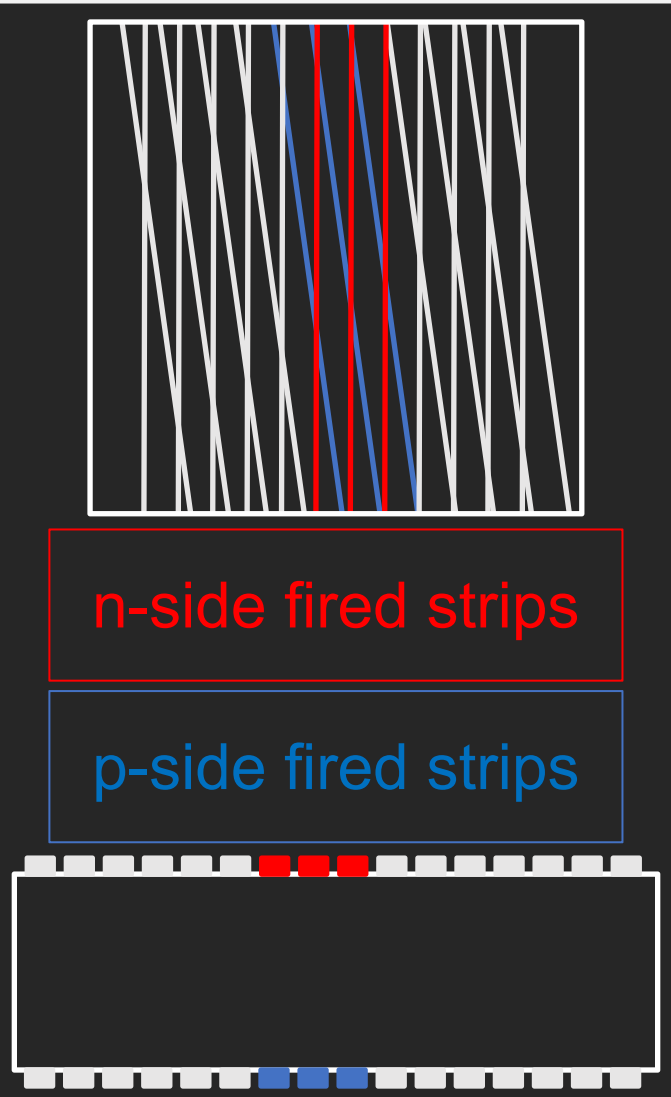
n-side fired strips

p-side fired strips

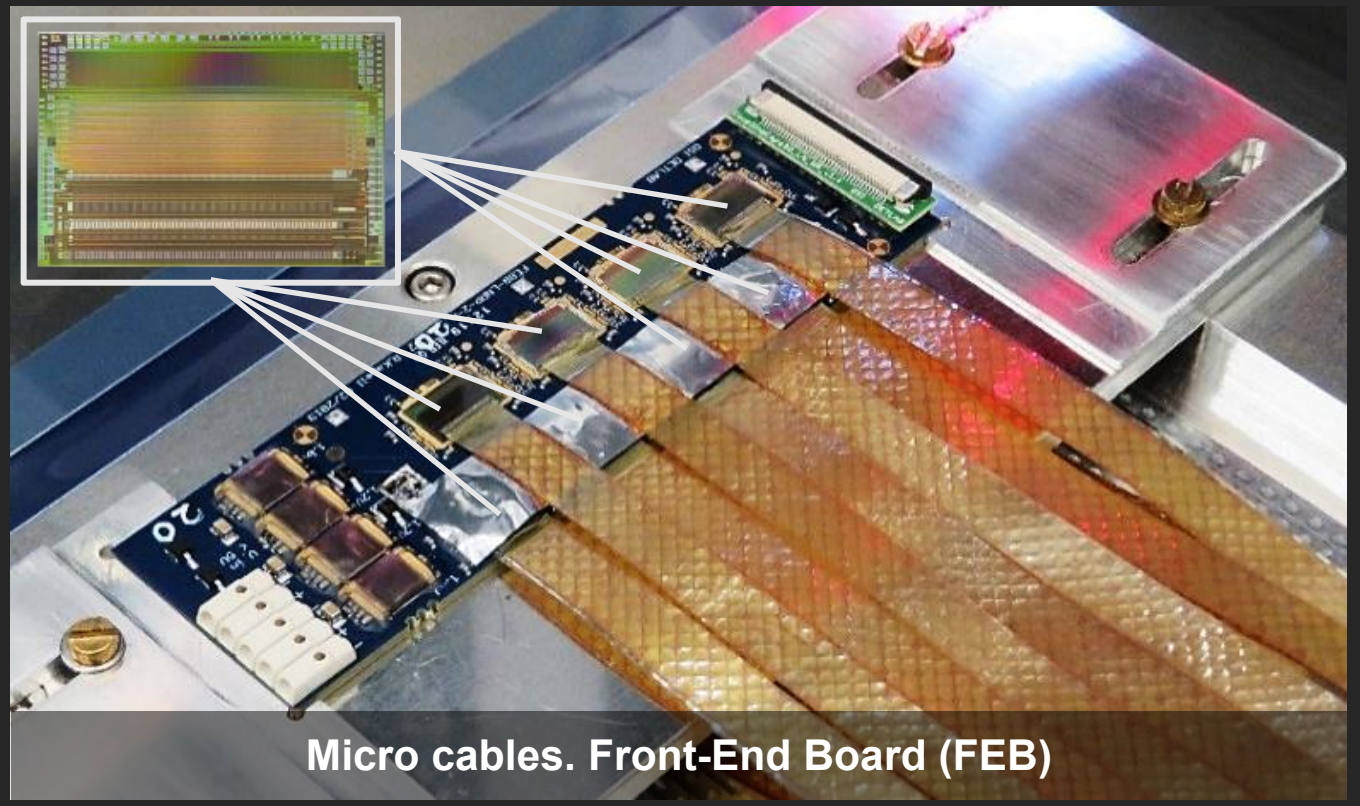




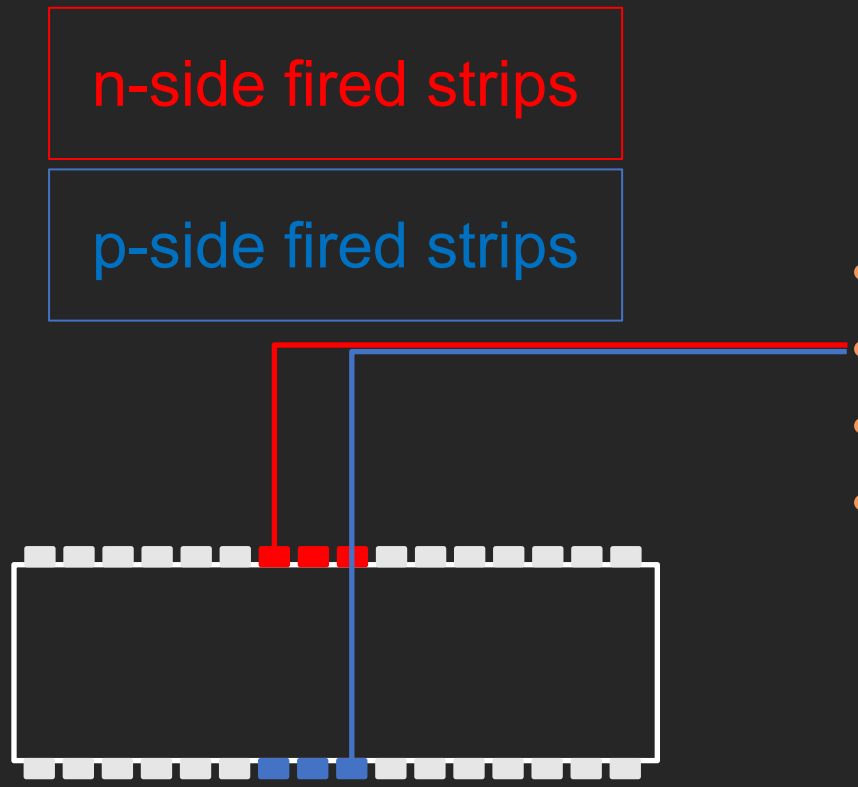
STS sensors strips



1 channel per strip
128 channels per ASIC
8 ASIC per side



Software objects: STS



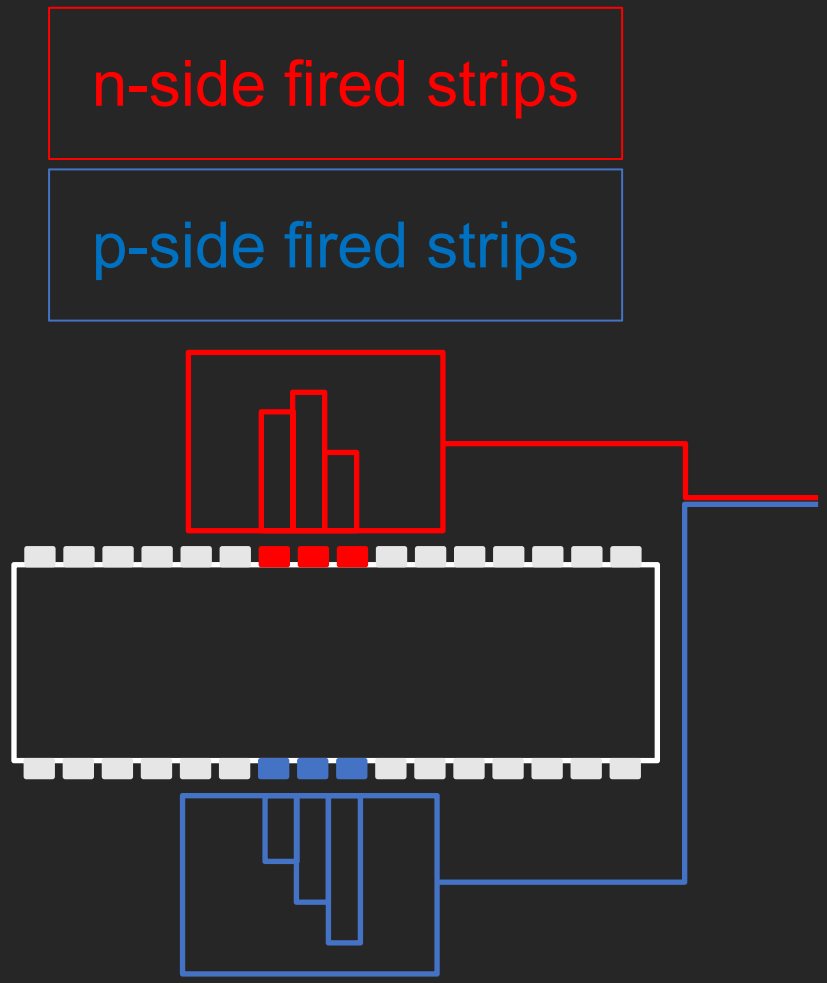
StsDigi

- Address (position of the sensor)
- Channel (position relative to the sensor)
- Time
- Charge (1-31 ADC)

StsCluster

StsHit

Software objects: STS



StsDigi

StsCluster

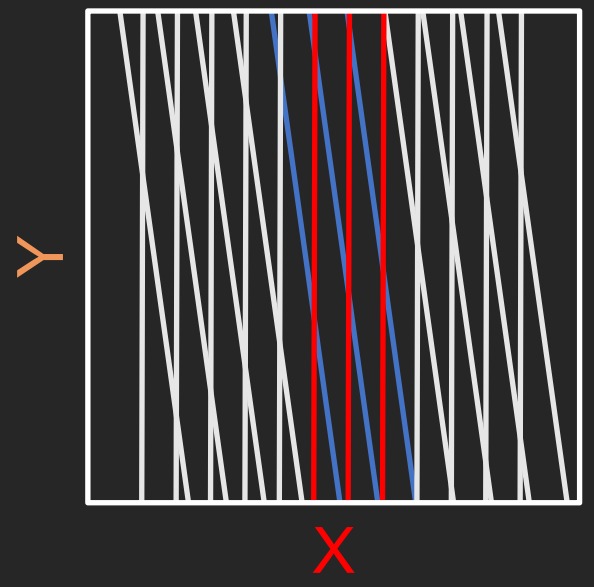
- Charge (1 - cluster size * 31)
- Position

StsHit

Software objects: STS

n-side fired strips

p-side fired strips



StsDigi

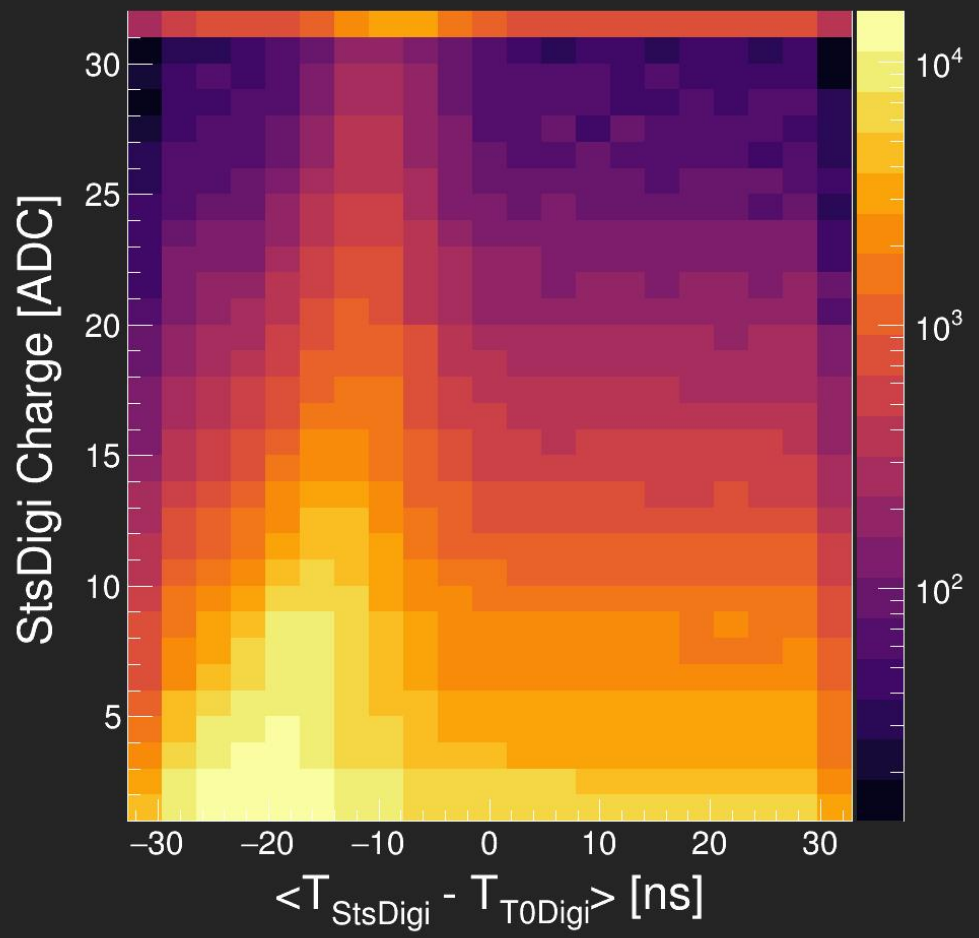
StsCluster

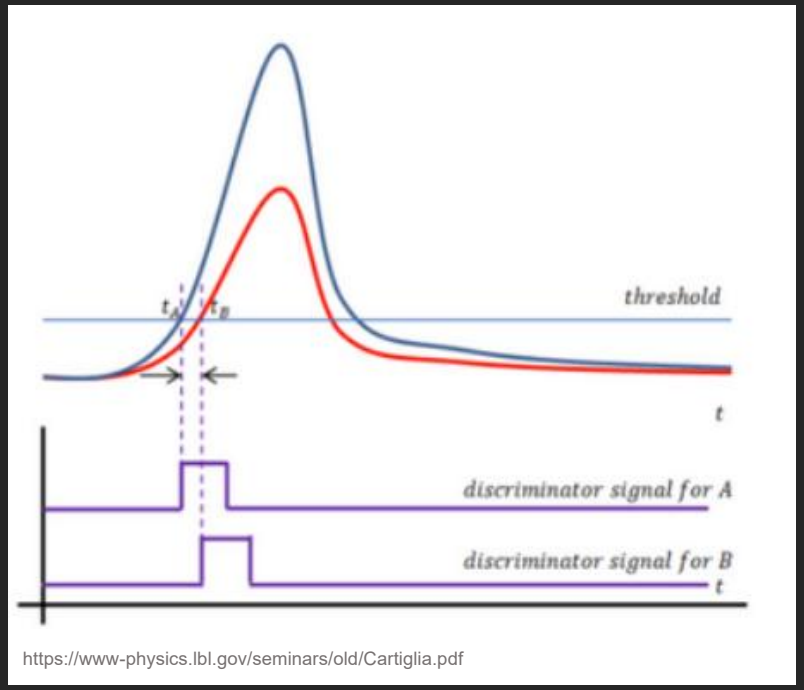
StsHit

- X, Y - cluster position
- Z - sensor position
- Time
- Charge

... time distributions ...

STS Time Calibration (Time Walk correction)

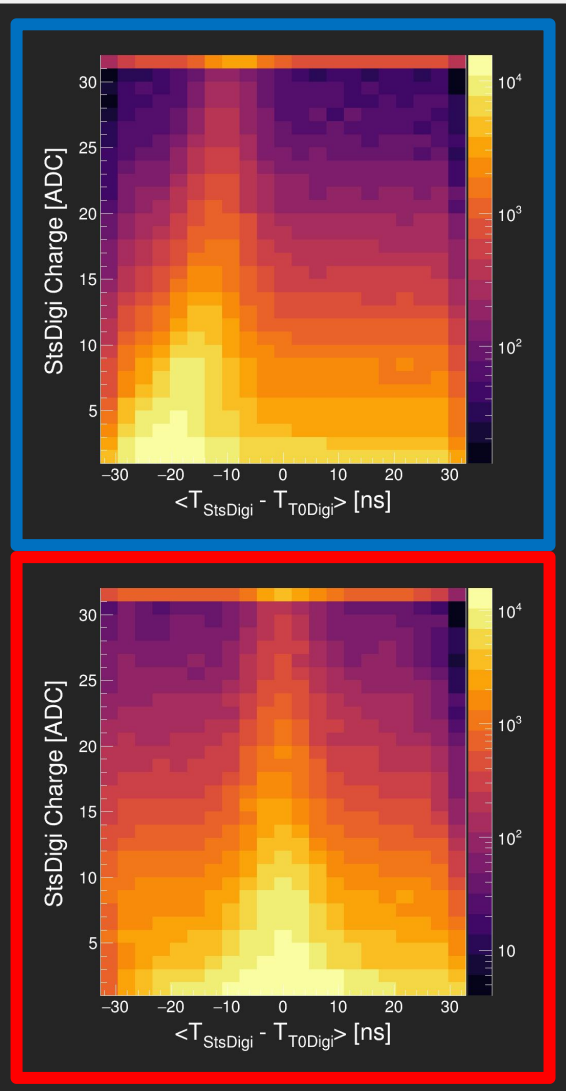


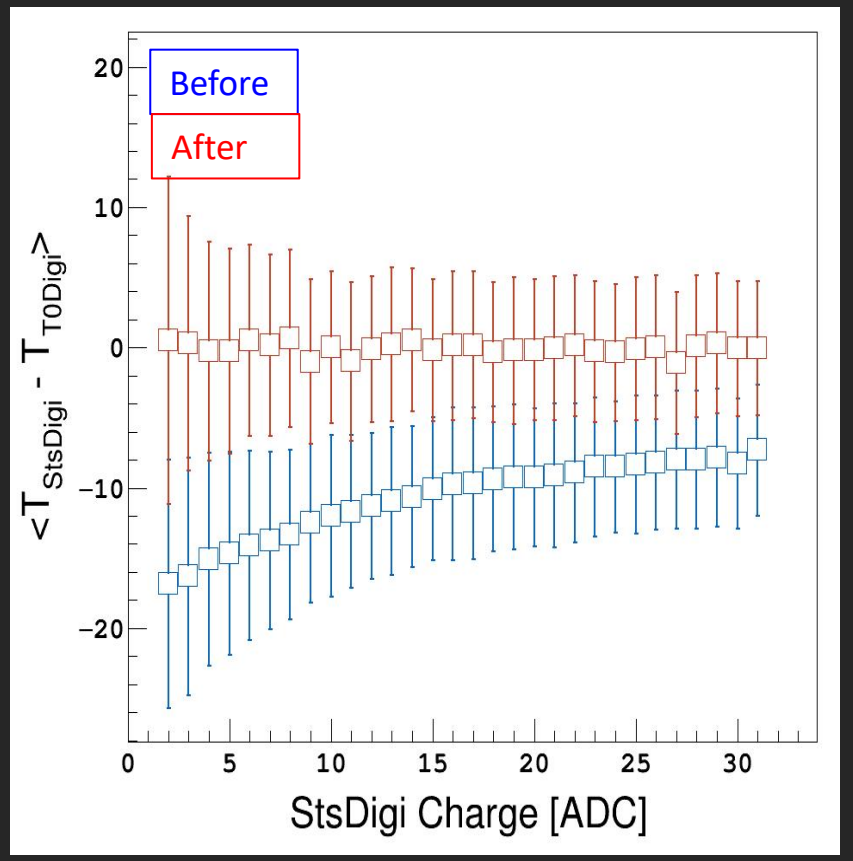


https://www-physics.lbl.gov/seminars/old/Cartiglia.pdf

Signal of different amplitudes are timed differently

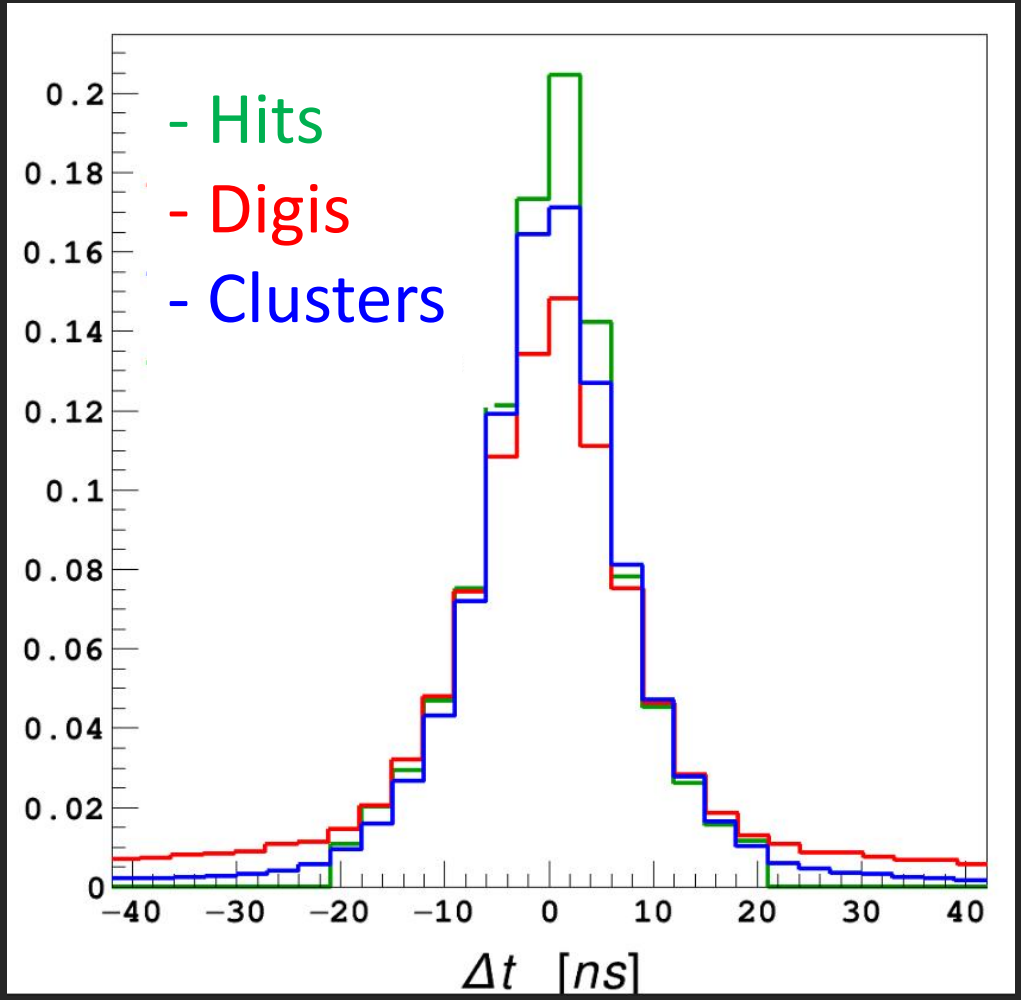
STS Time Calibration (Time Walk correction)





Correction is ASIC dependent

mSTS Time Resolution



Consistent time calibration across ASICs, Modules & Stations

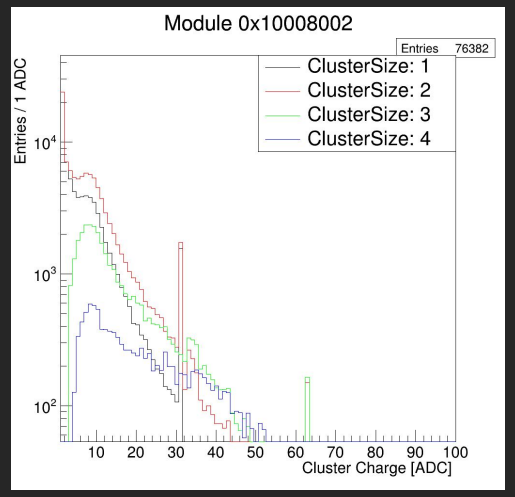
Removal of combinatorial

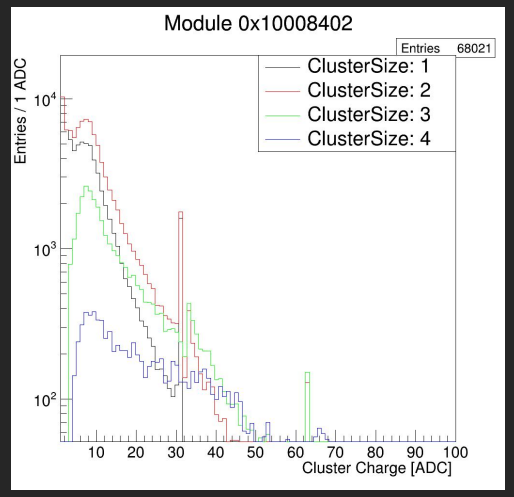
... cluster distributions...

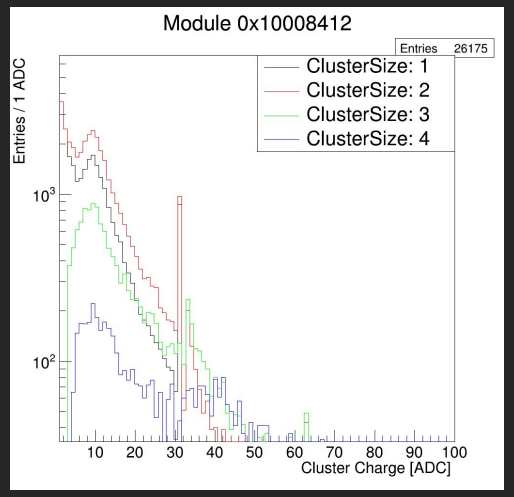
mSTS Signal Analysis - Cluster charge distribution

UNIT 0 | **UNIT 1** | **UNIT 2**

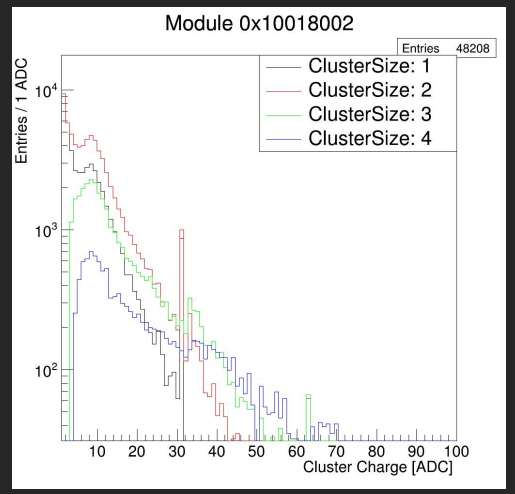
MODULE 0

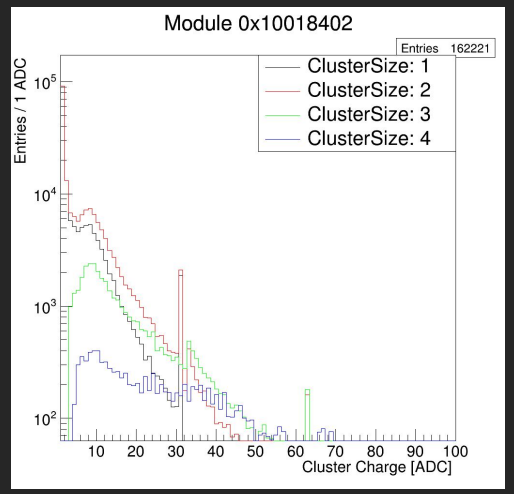


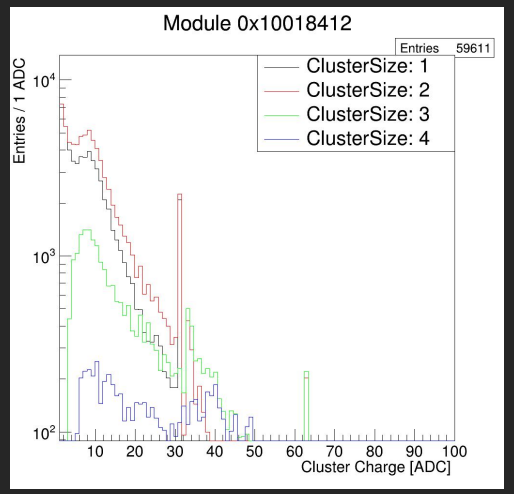




MODULE 1



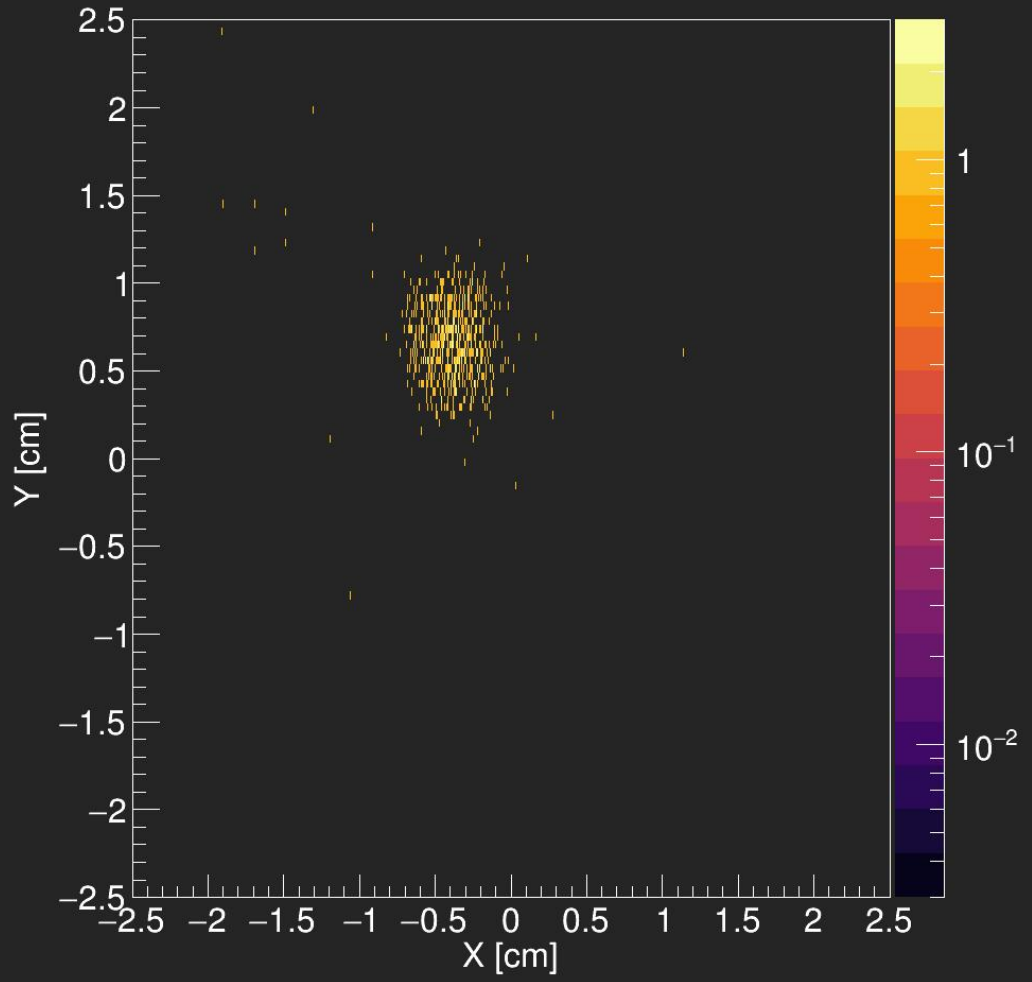


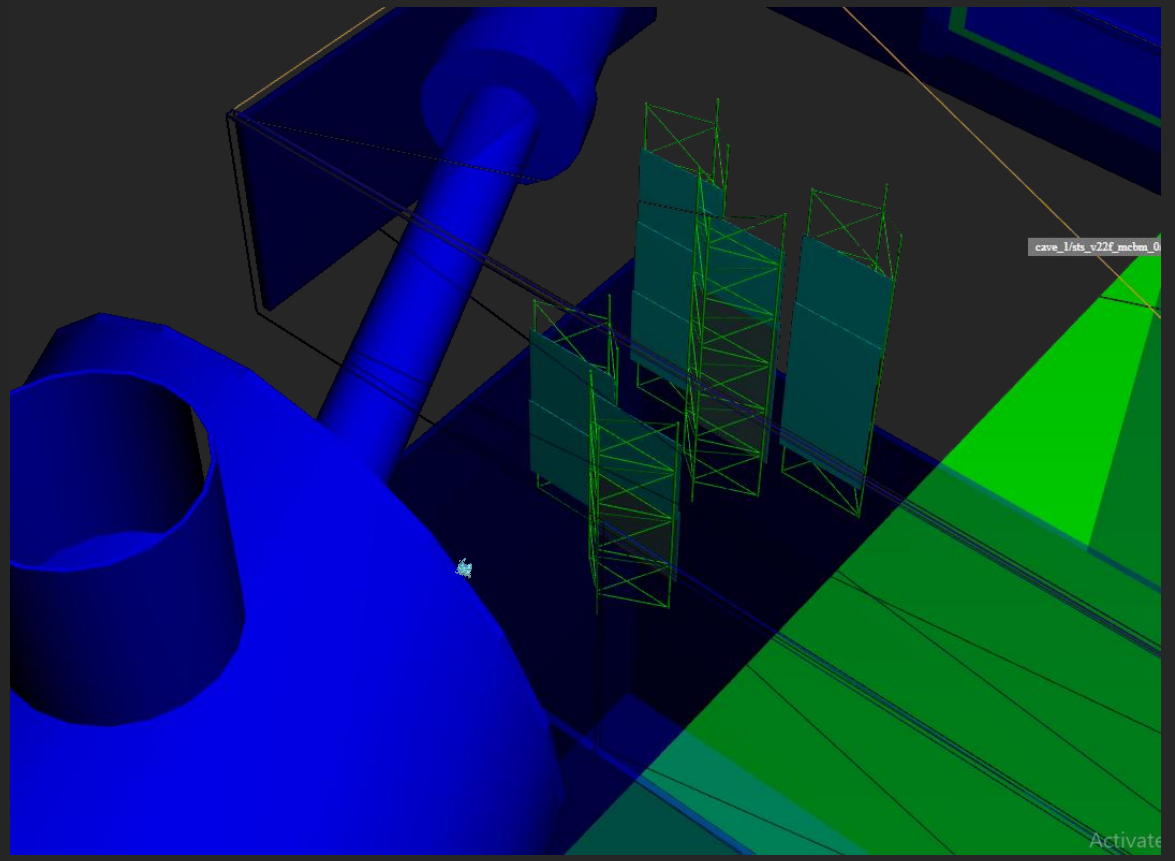


Charge distribution is consistent along different cluster size

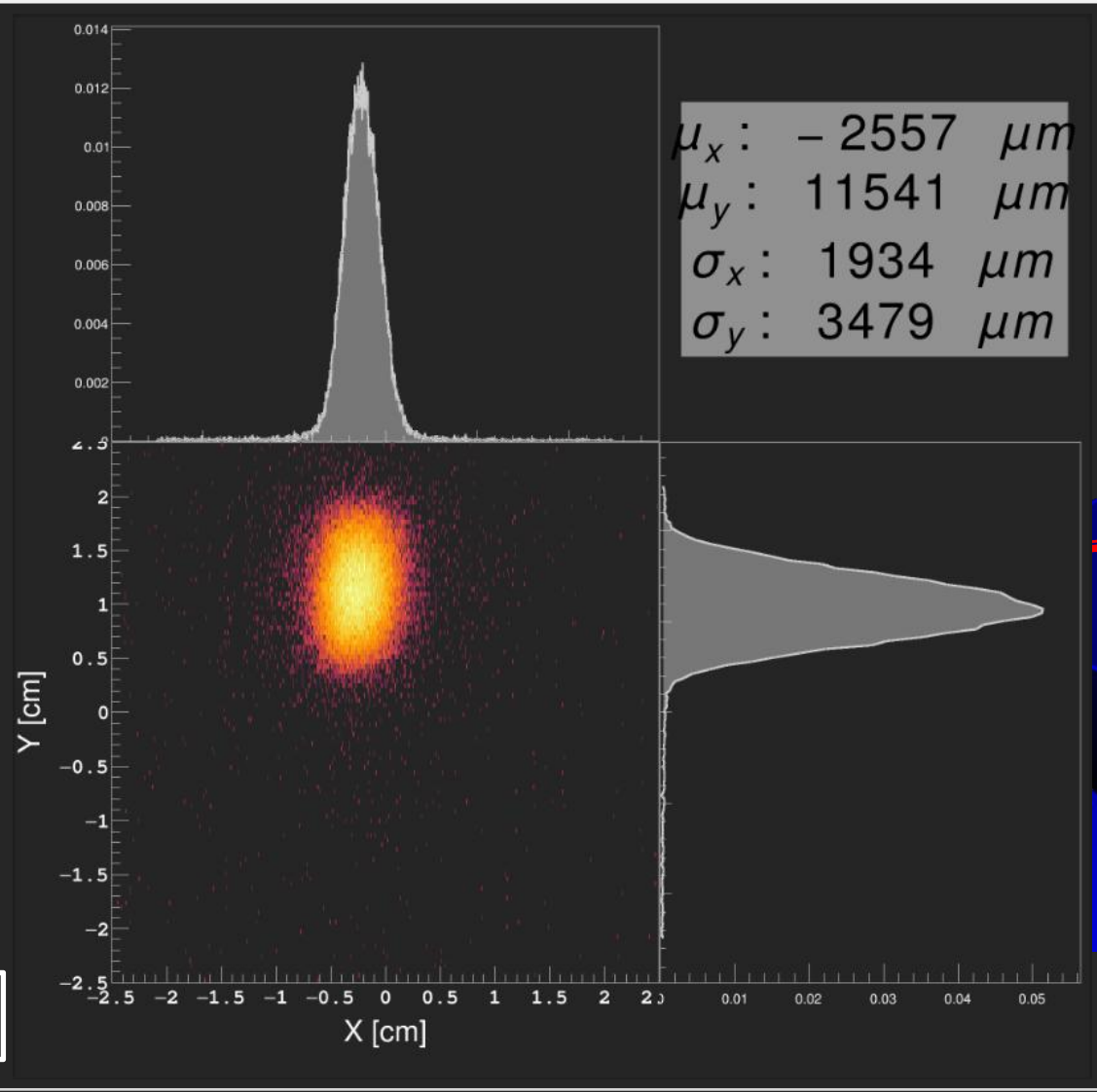
... preliminary alignment ...

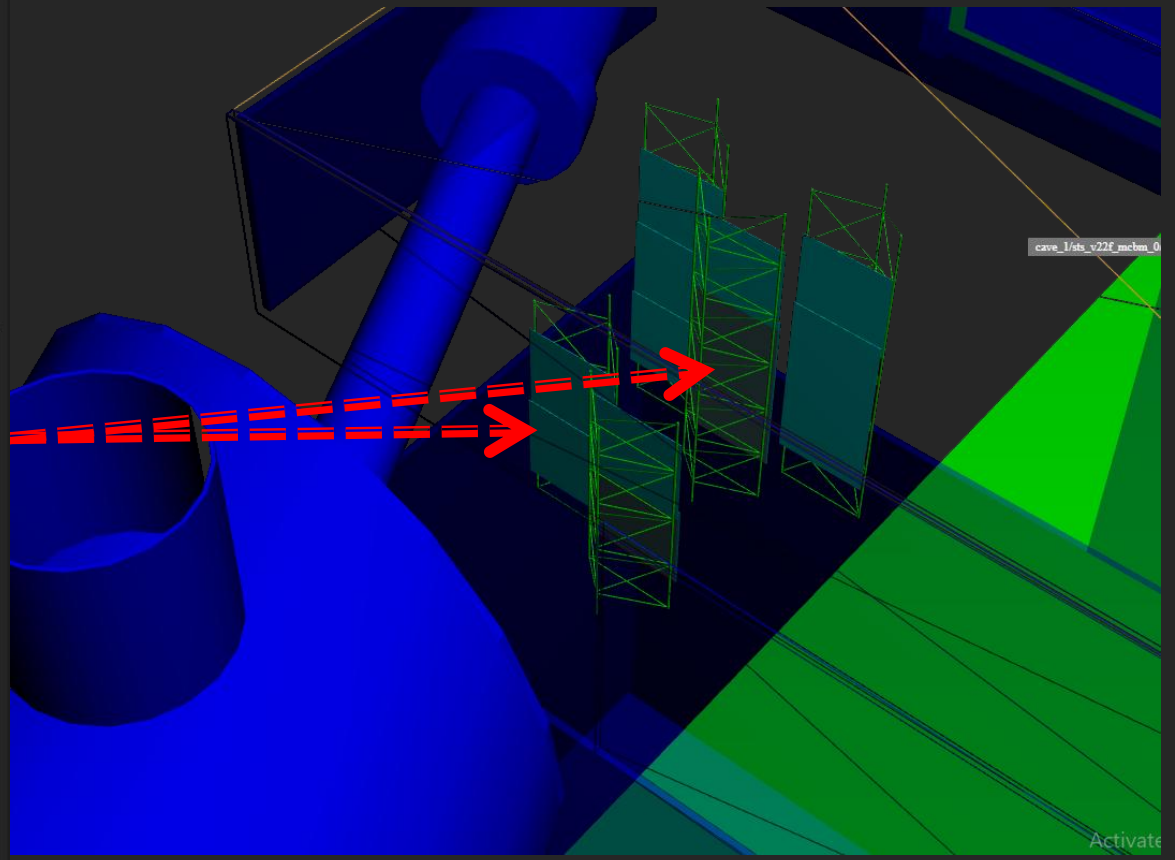
mSTS Vertex Reconstruction - Setup: Top view



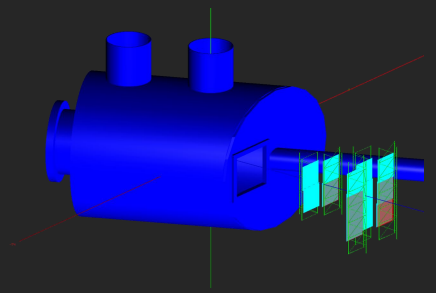


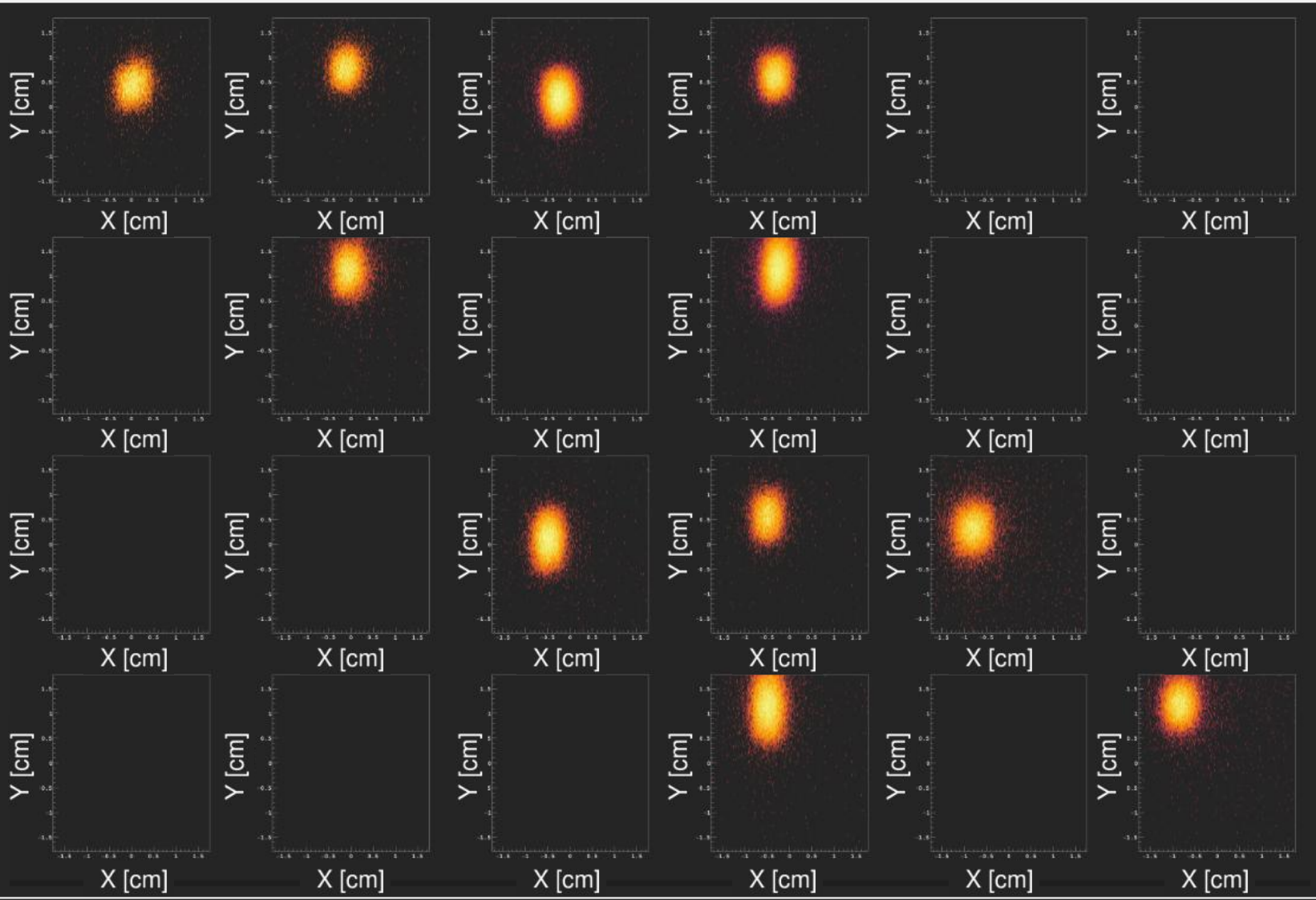
mSTS Vertex Reconstruction - Setup: Top view



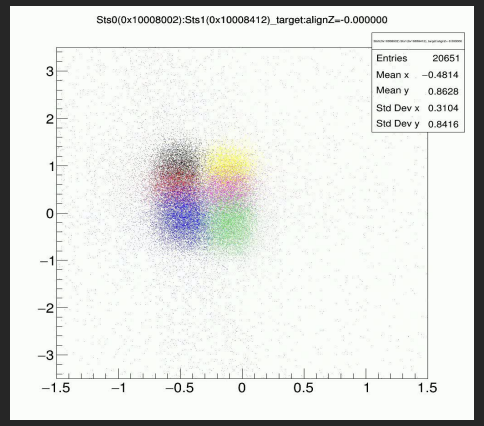


mSTS Vertex Reconstruction - Splitting contributions



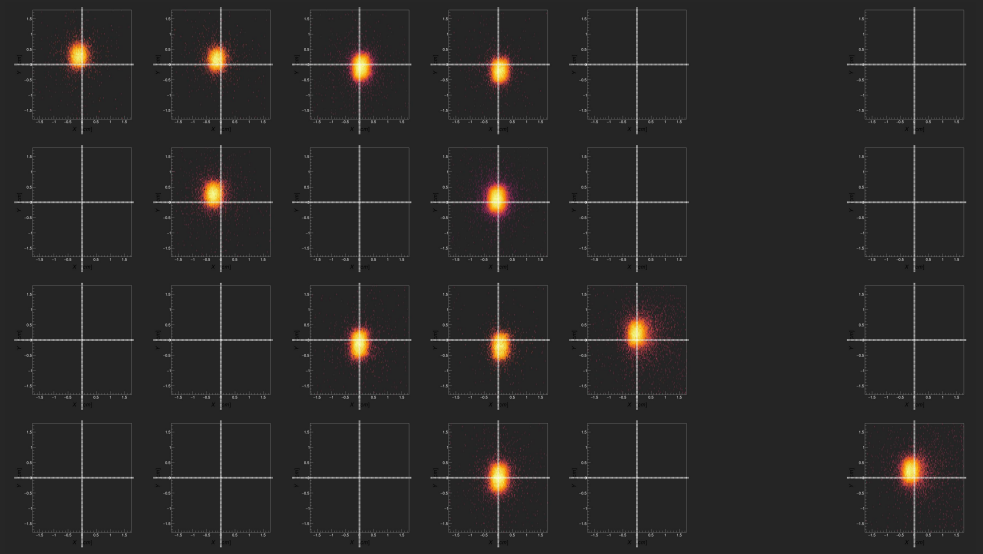


mSTS Self alignment



Run minimization: Vertex Spread

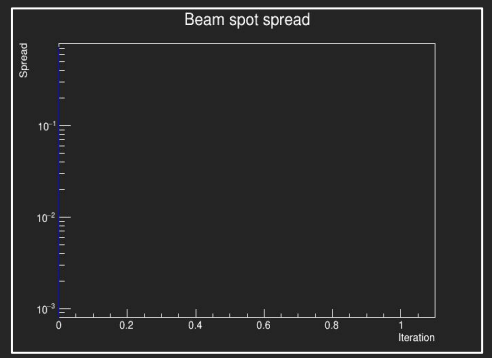
$$S = \sqrt{\frac{\sum_{ij} (v_{ij} - \bar{v})^2}{N_{pairs}}}$$

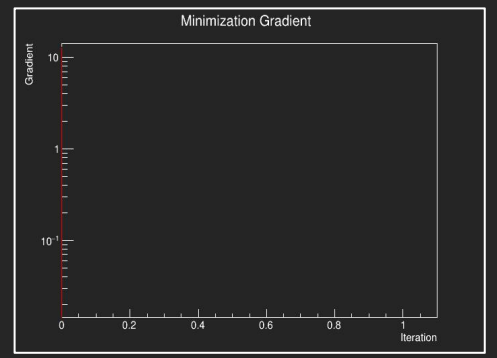


Minimization: Gradient decedent

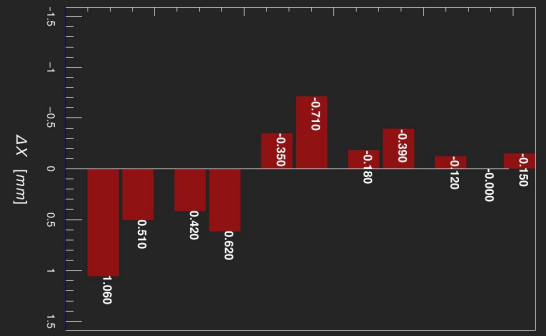
v_{ij} : vertex position for sensor_i, sensor_j

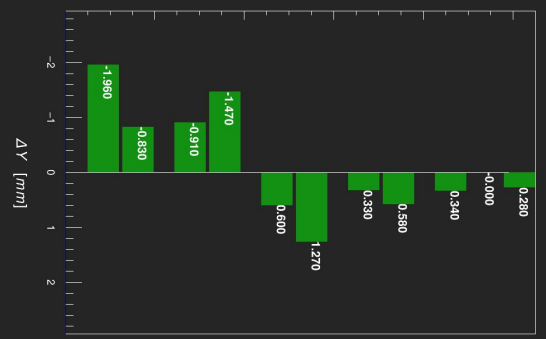
(currently, only translations - easily extended)

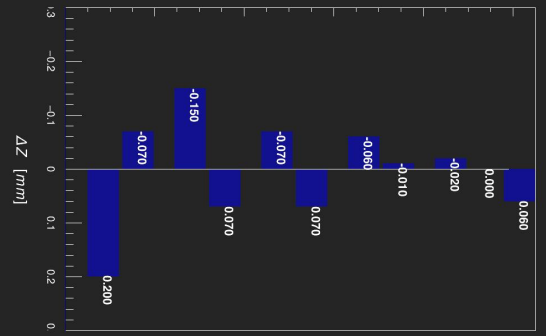


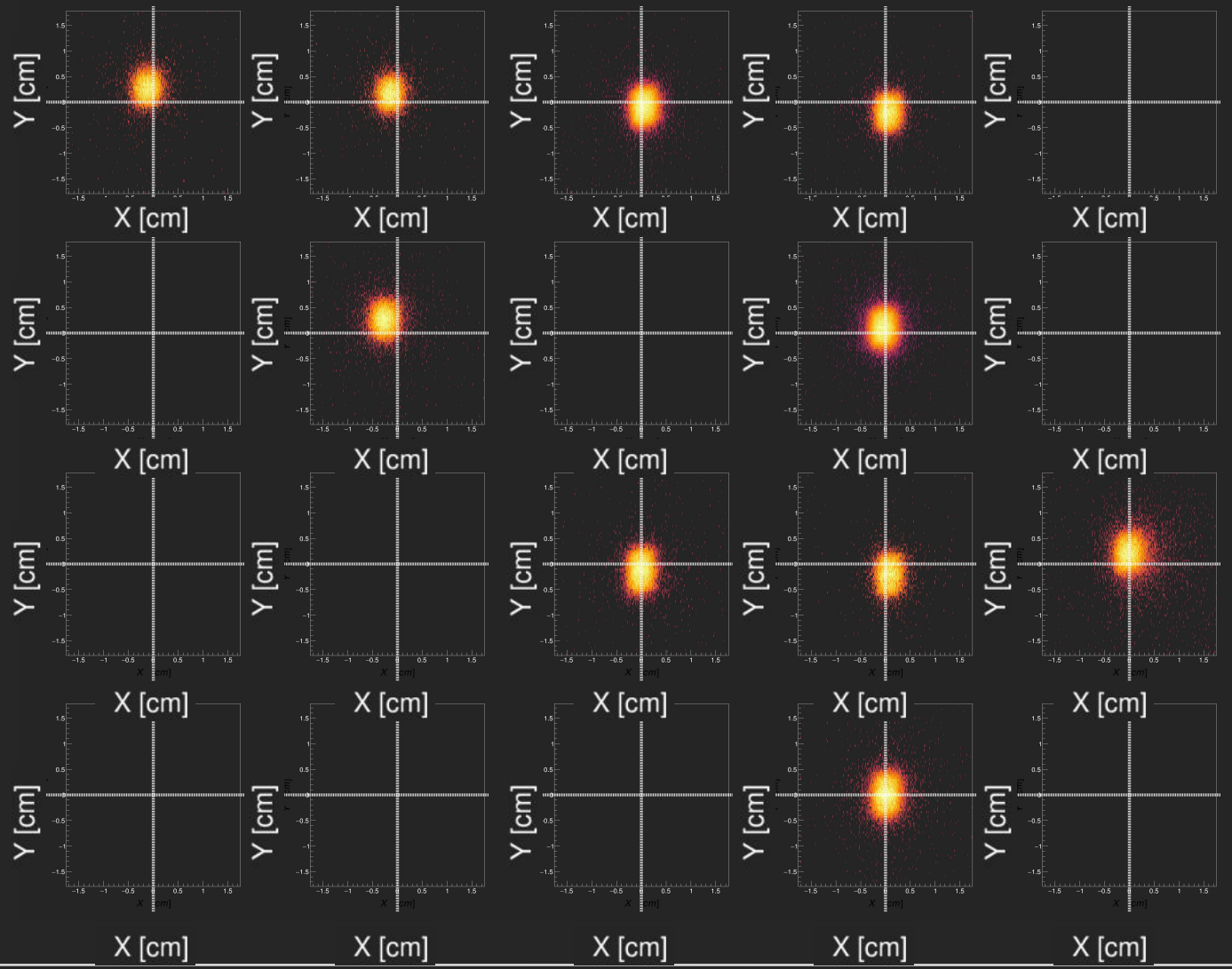


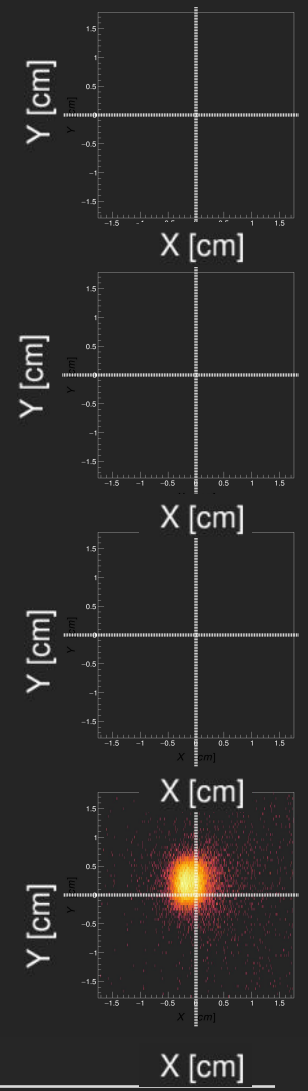
mSTS Vertex Reconstruction - Splitting contributions





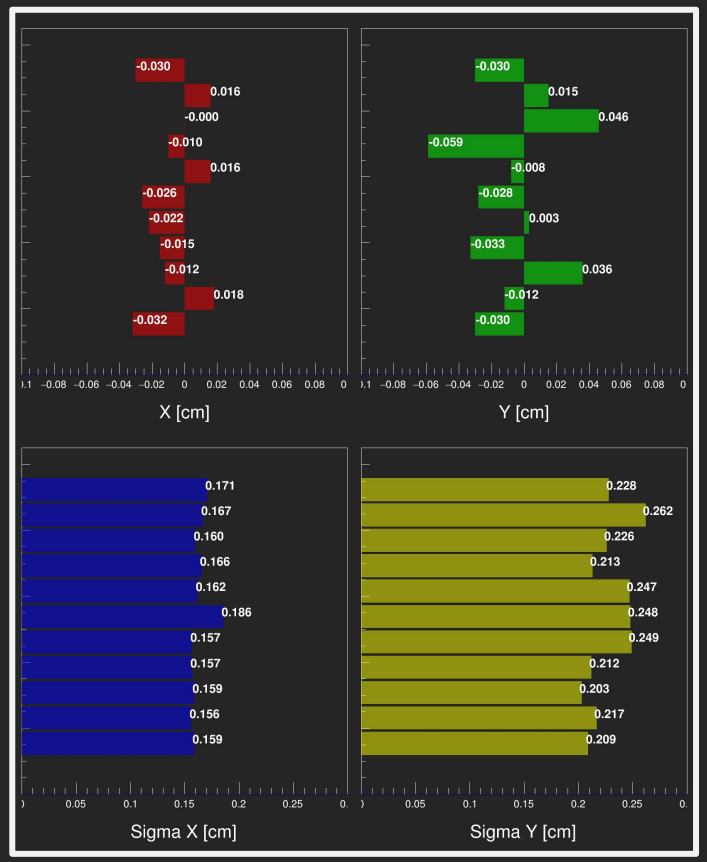




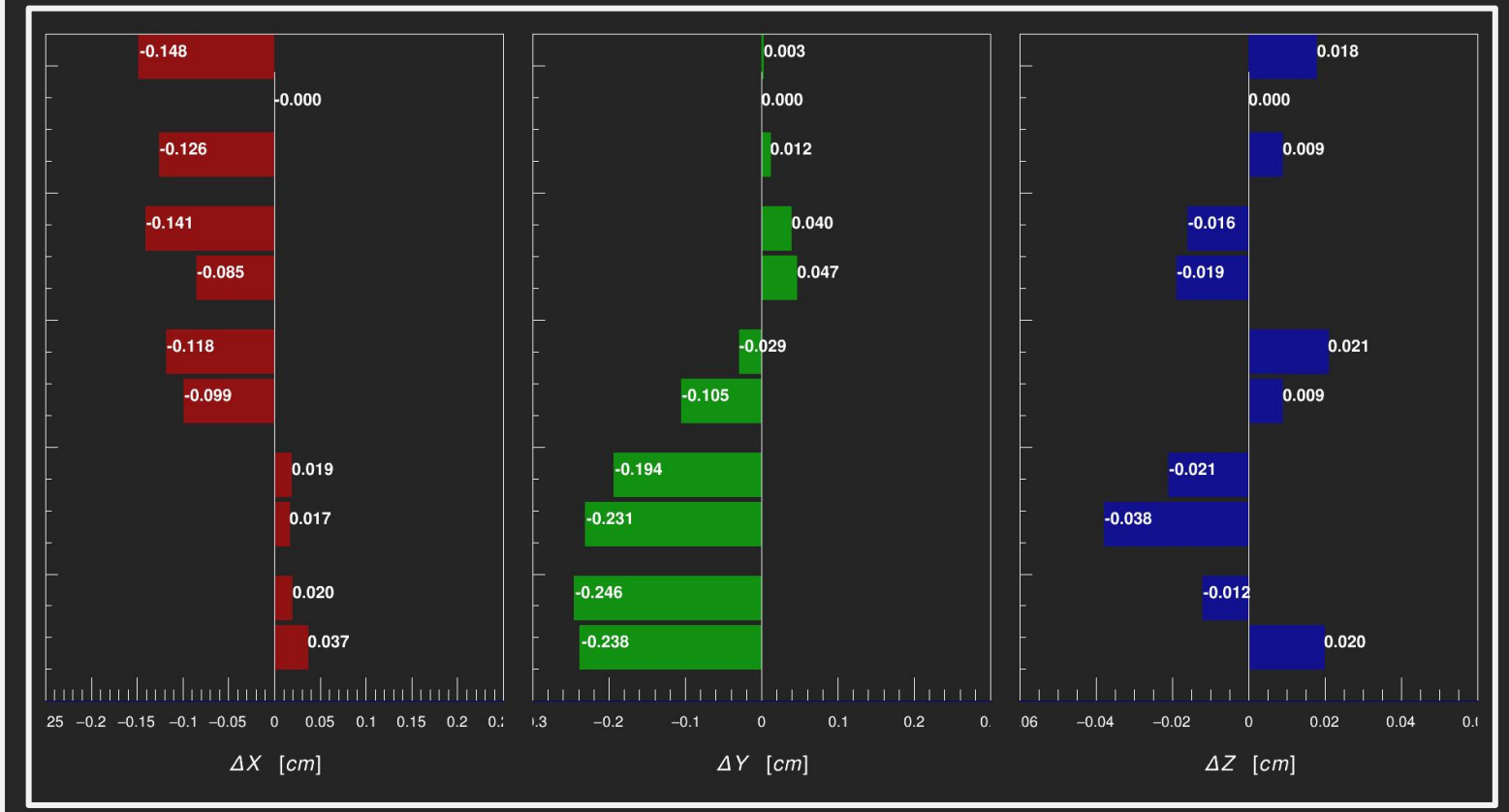


mSTS Vertex Reconstruction

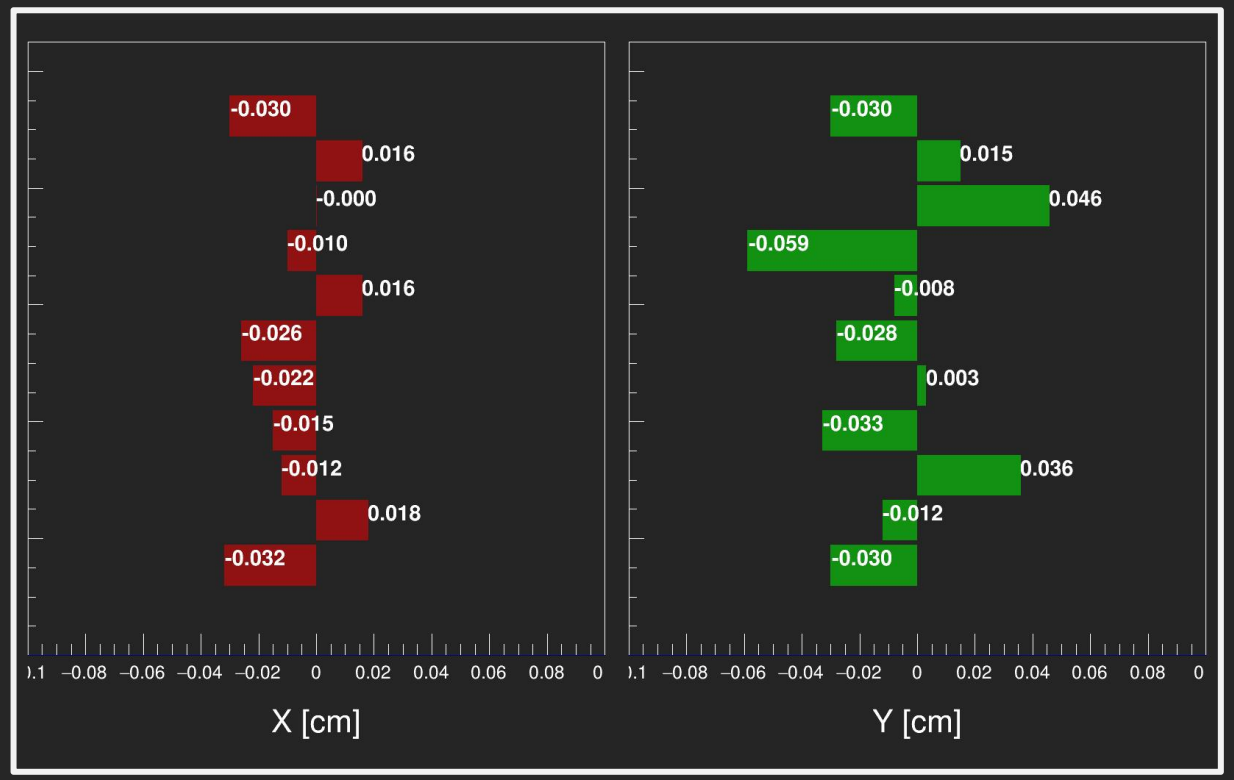
Aligned vertex



Sensor alignment parameters

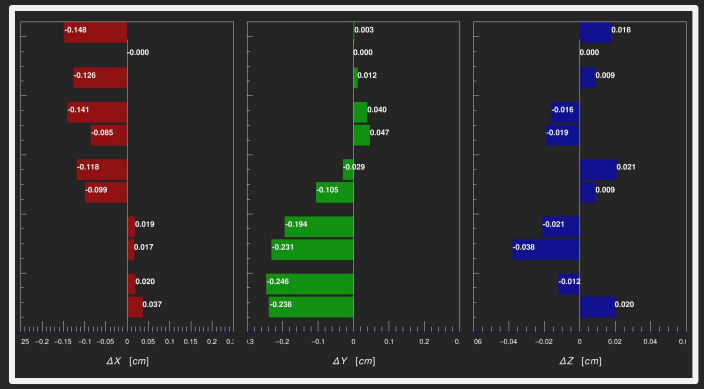


mSTS Vertex Reconstruction

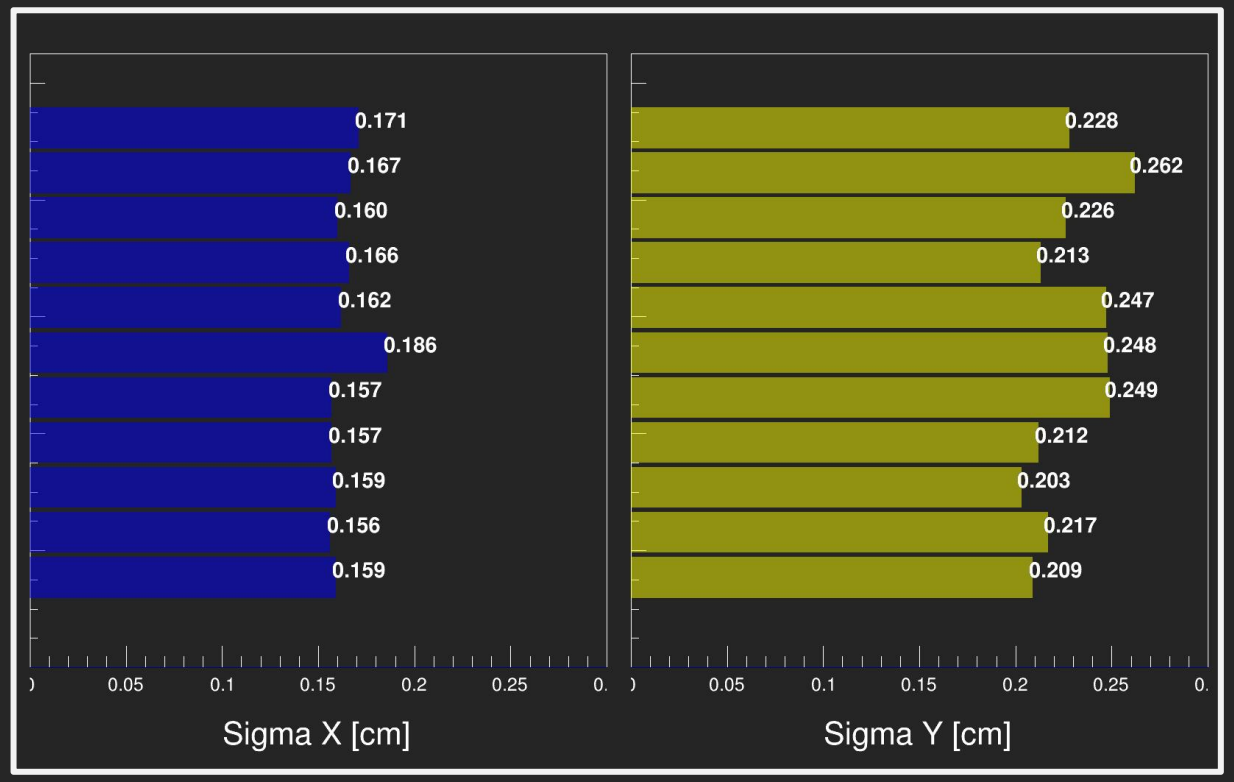


Different sensor pairs reconstruct beam spot at the same position

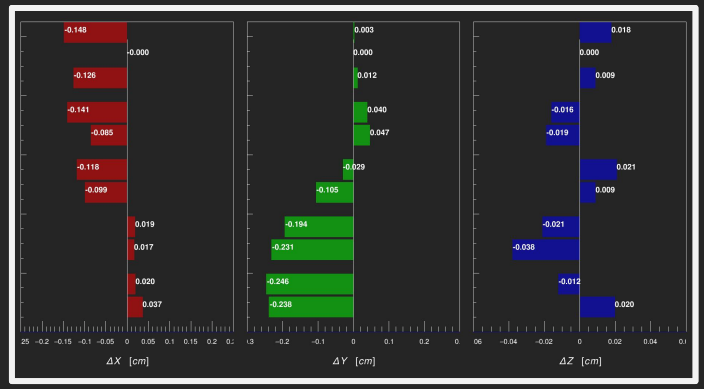
$$S = \sqrt{\frac{\sum_{ij} (v_{ij} - \bar{v})^2}{N_{pairs}}} = 300\ \mu m : 8\ iterations$$



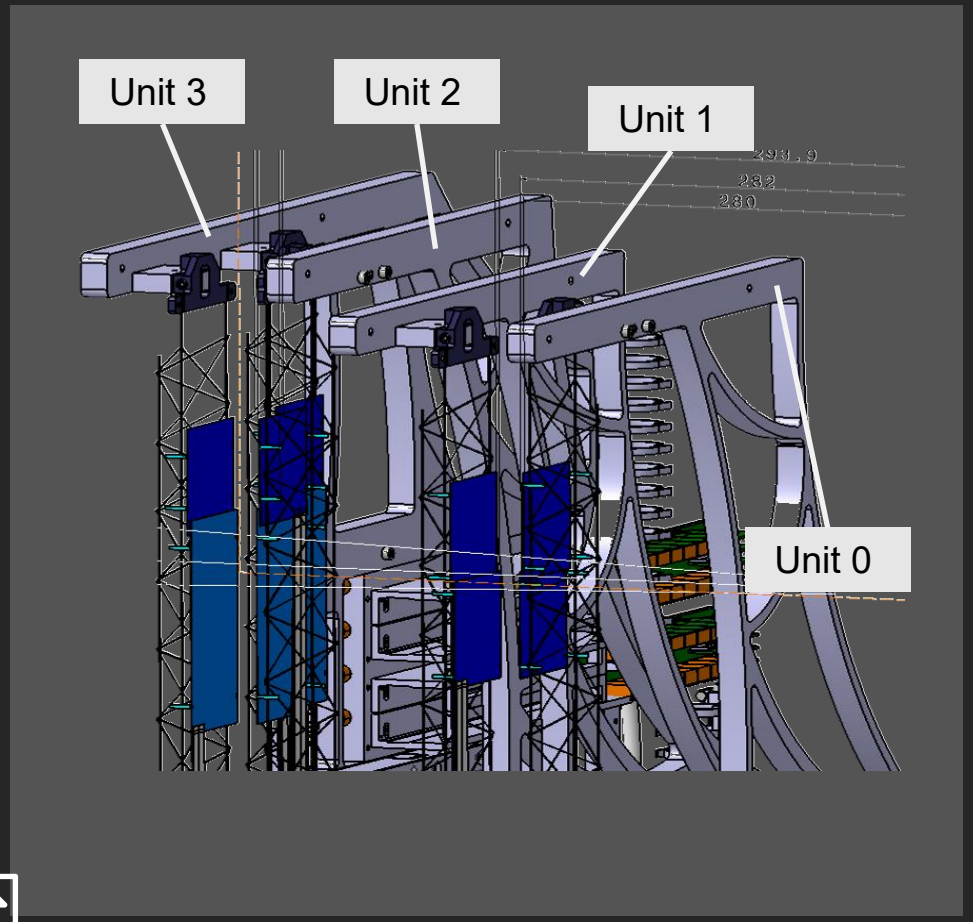
mSTS Vertex Reconstruction



Consistent vertex shape for different sensor pairs!

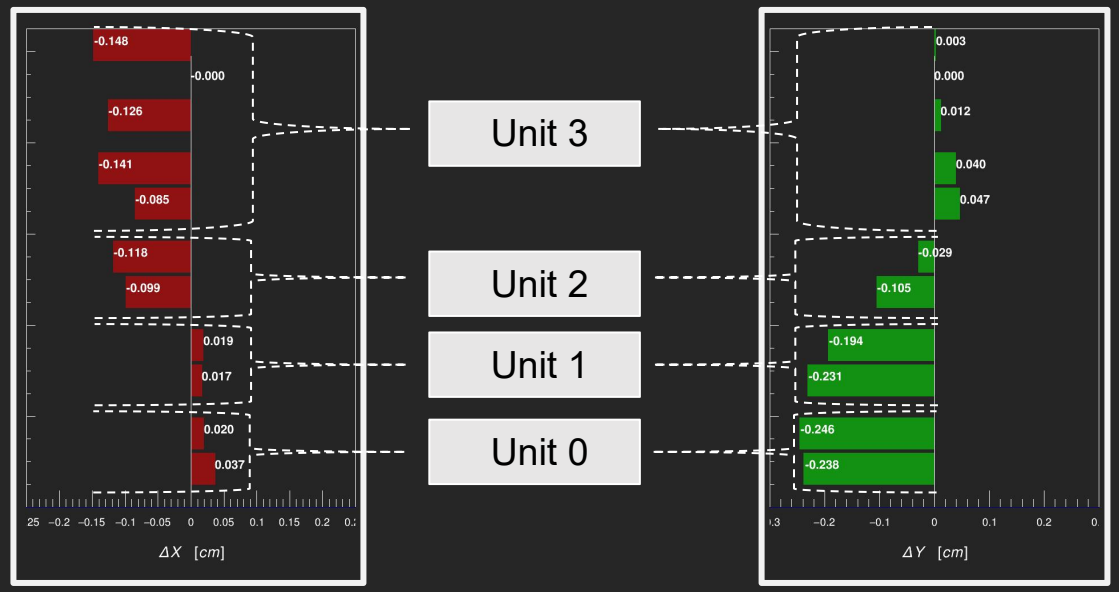


mSTS Vertex Reconstruction

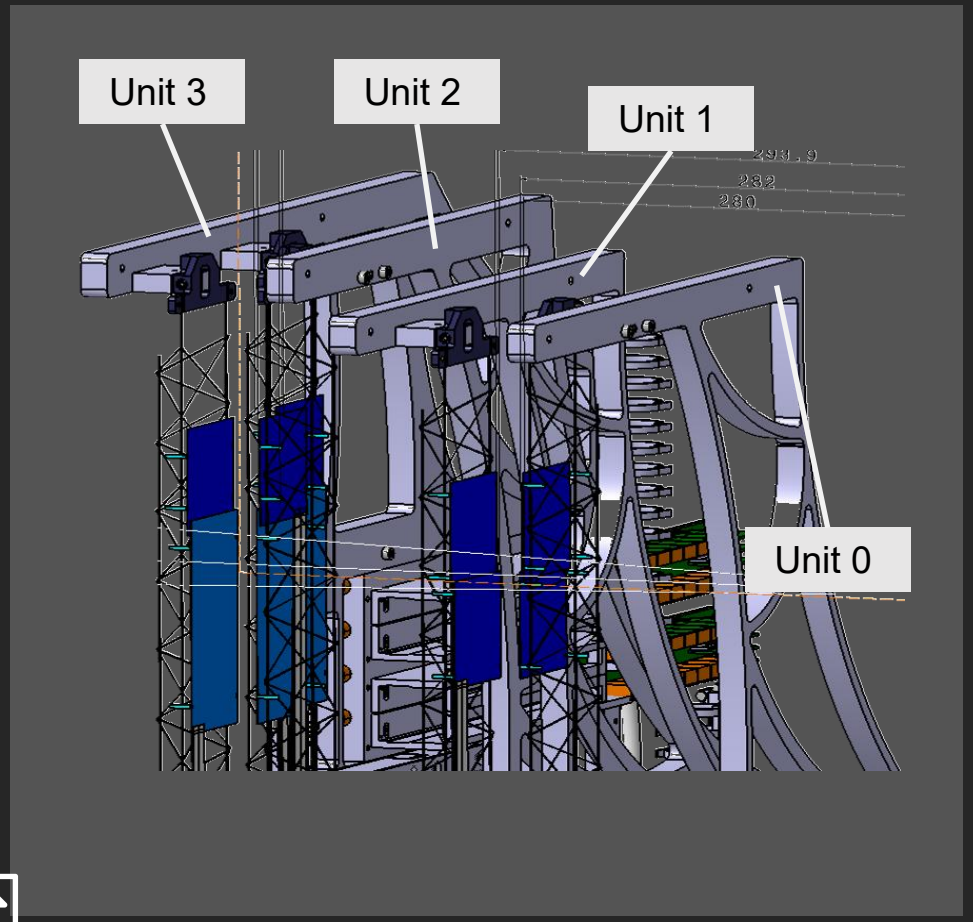


Sensor in the same mechanical structure move on the same direction

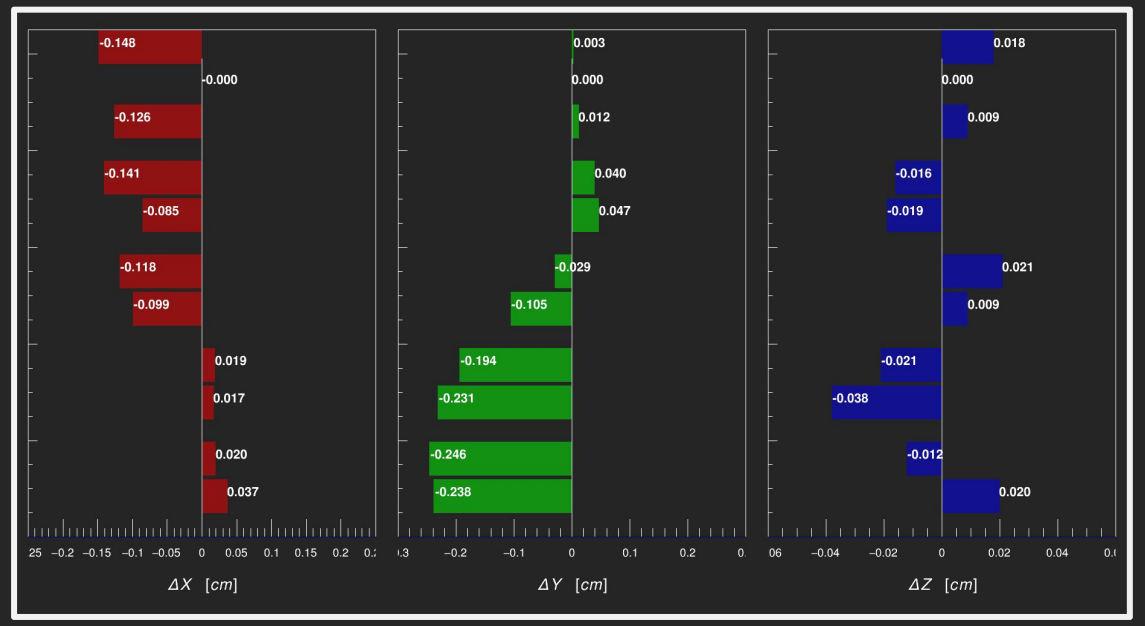
Rotations still need to be considered



mSTS Vertex Reconstruction

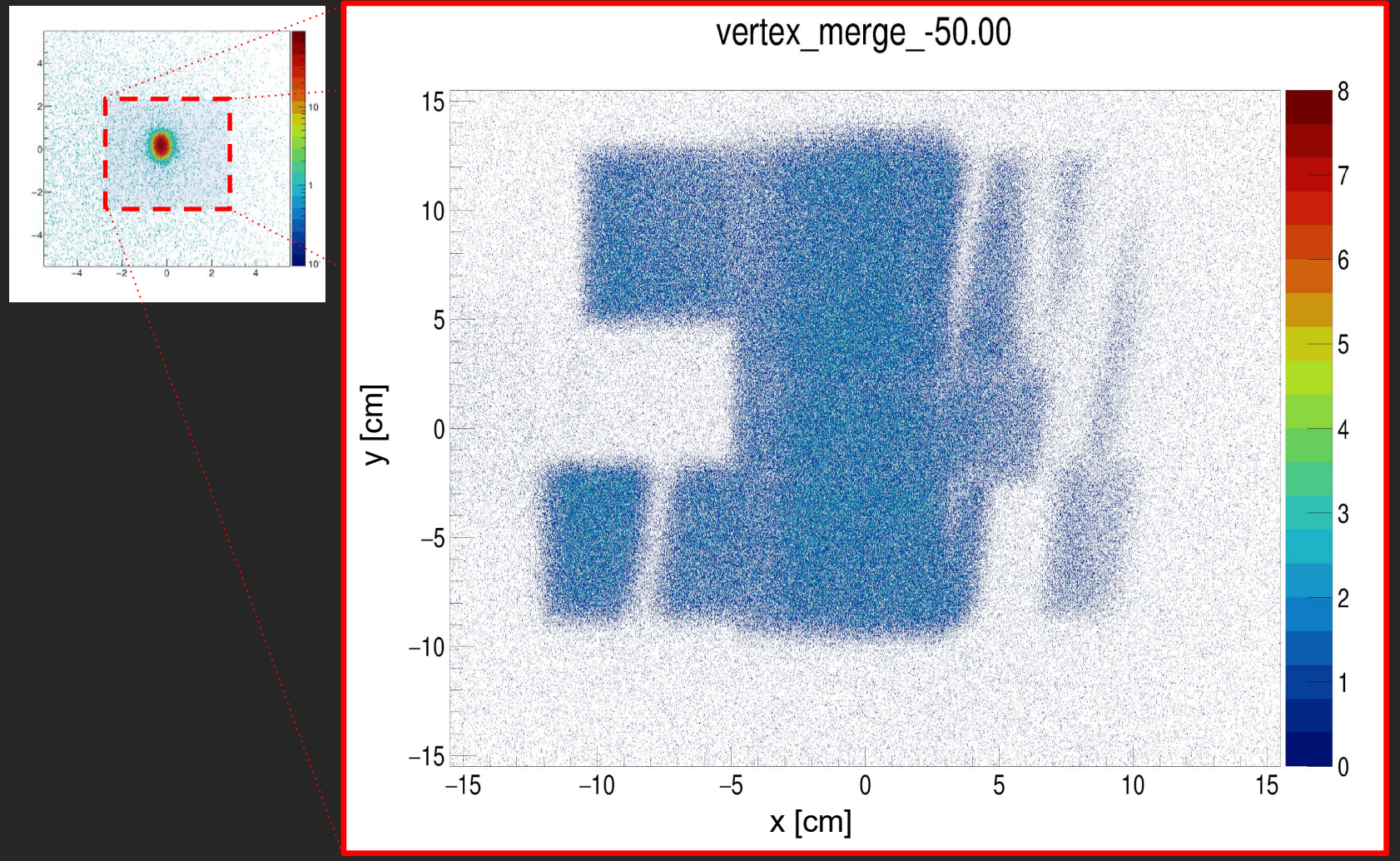


Sensor alignment translations are consistent with the mechanical assembly!



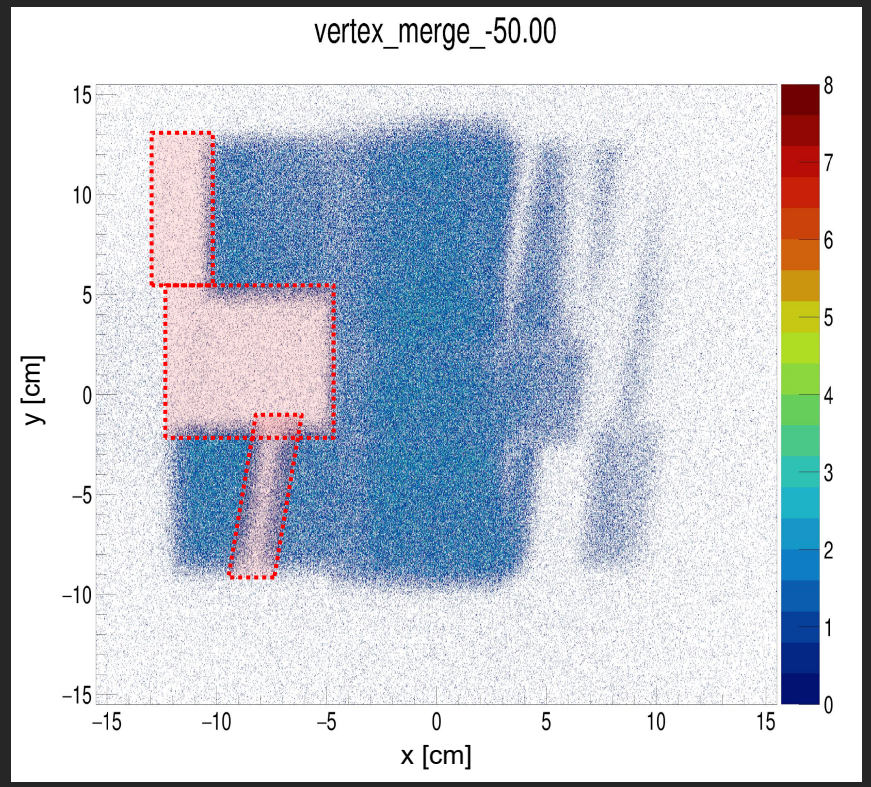
... zoom in the beam spot ...

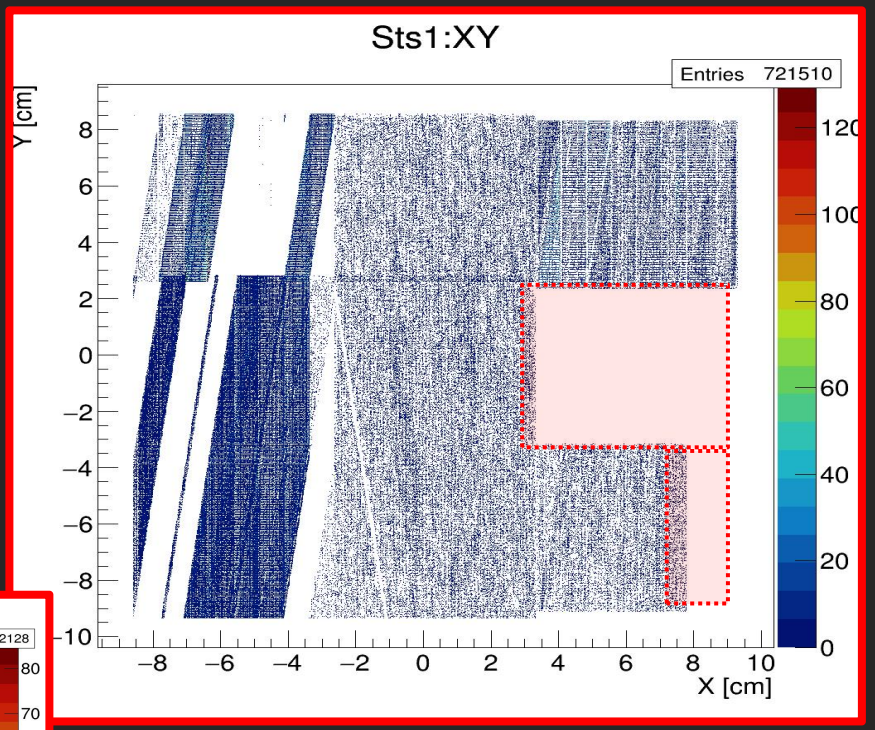
mSTS Vertex Reconstruction - Zooming the vertex

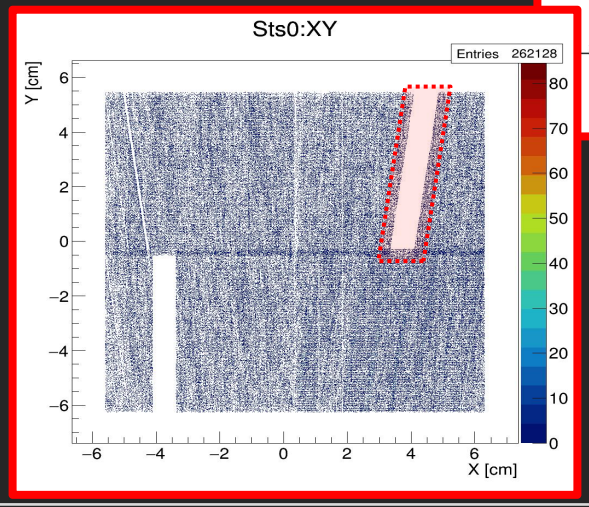


Extrapolating to large distance, detector structure shows up

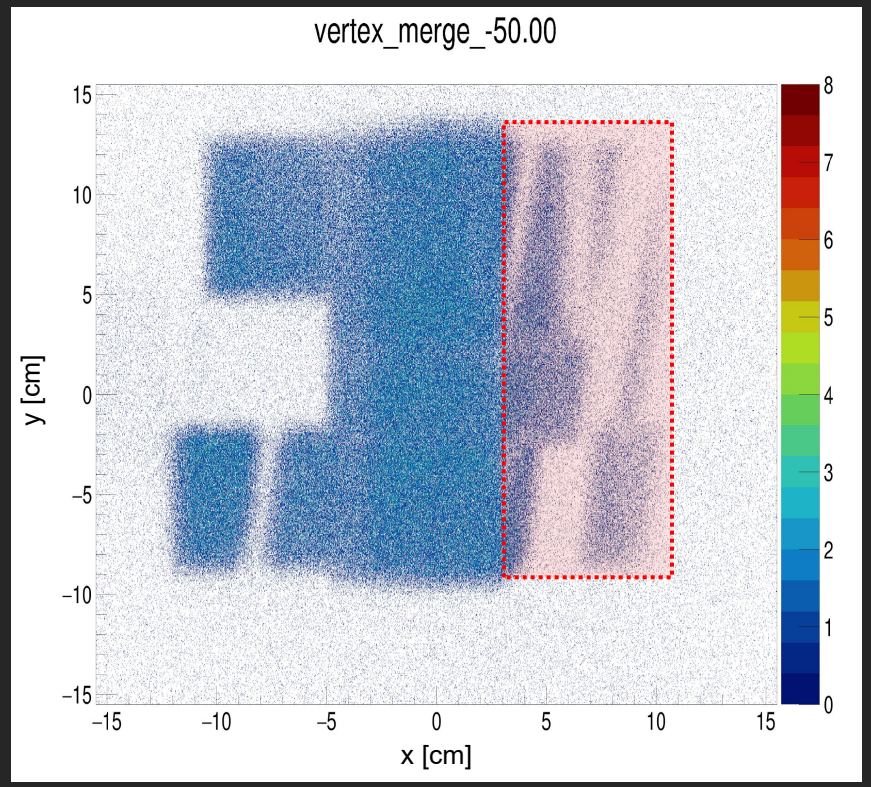
mSTS Vertex Reconstruction - Vertex structures

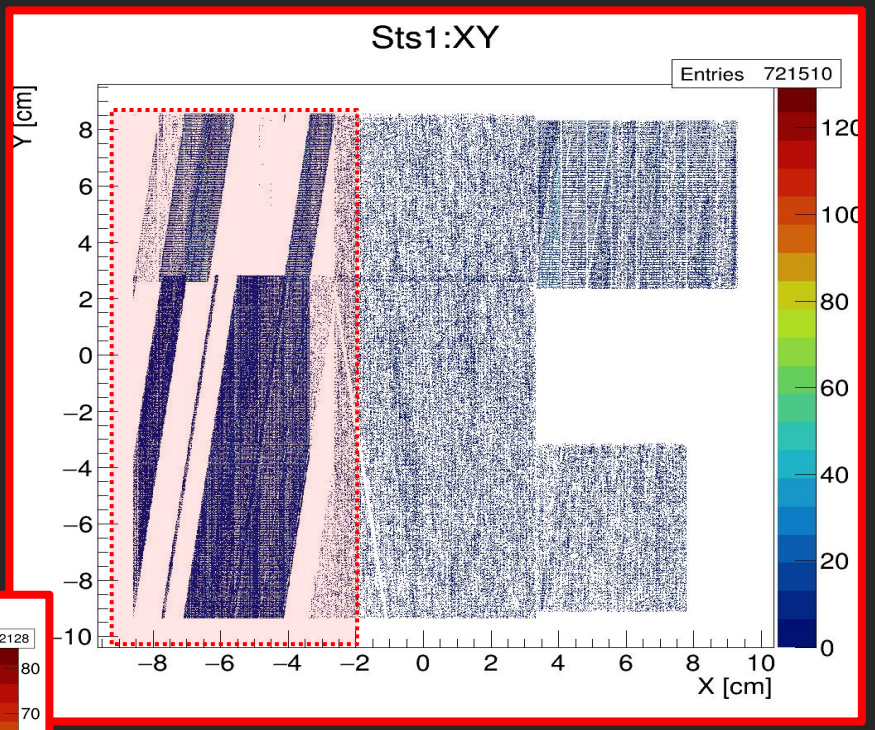


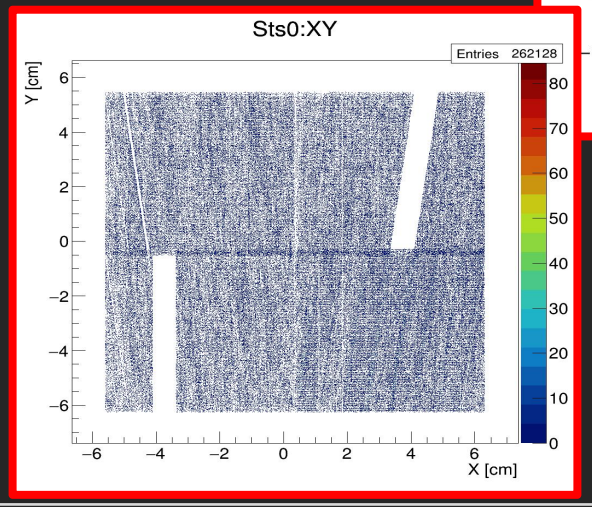




mSTS Vertex Reconstruction - Vertex structures

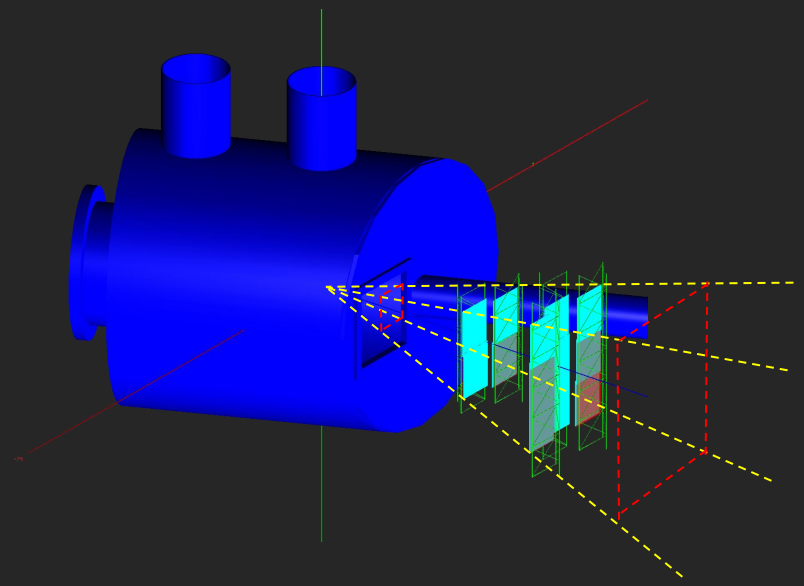






... Monte Carlo studies ...

mSTS Acceptance - MCTrack

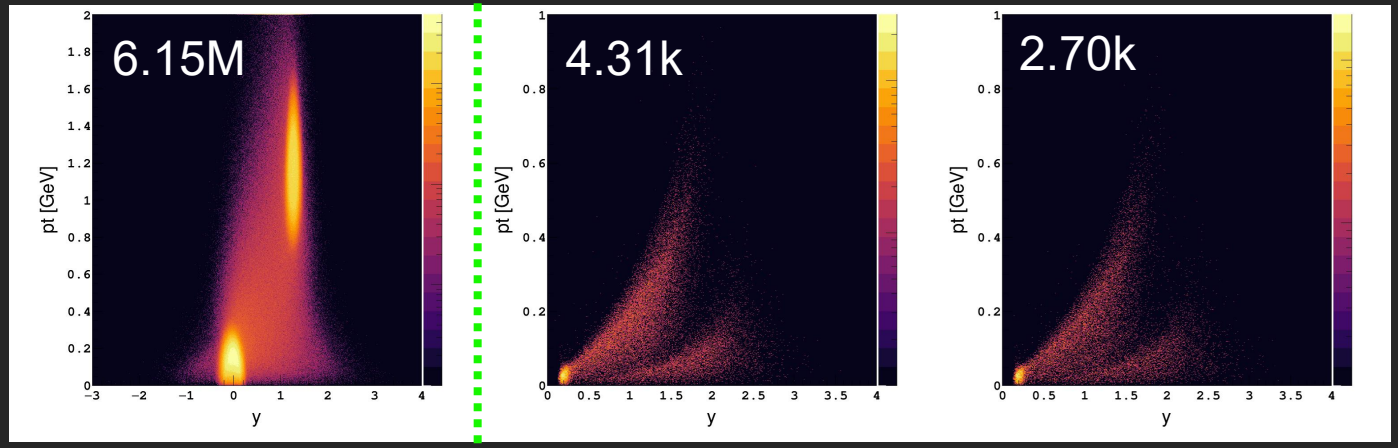


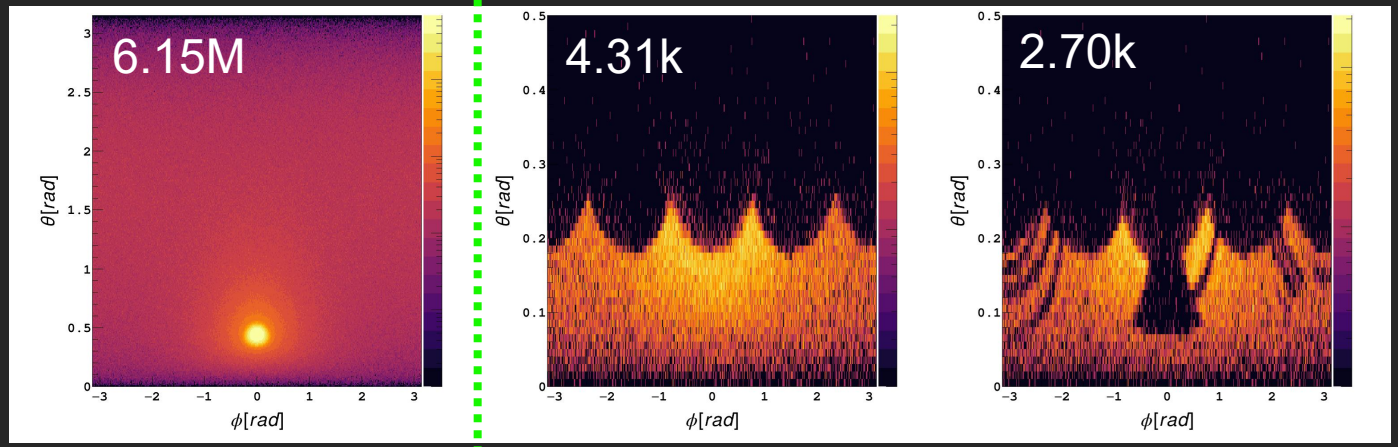
6.15M primary tracks

All tracks

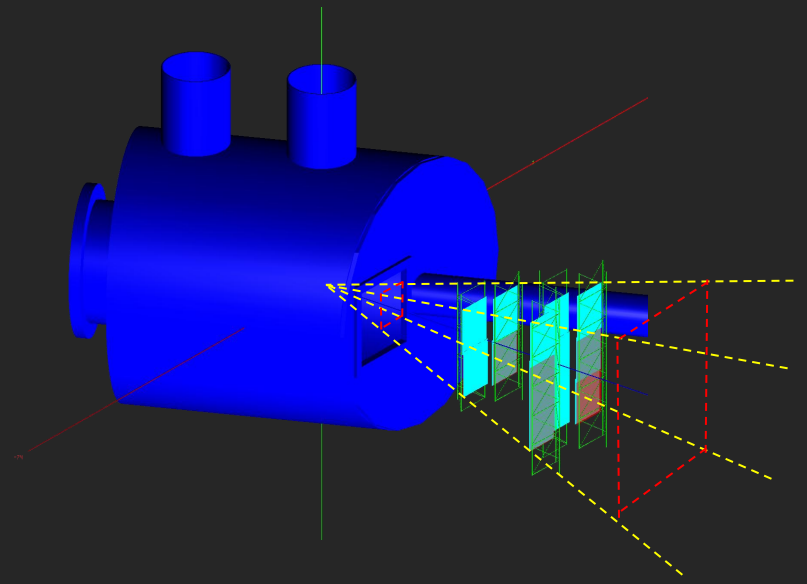
Hitting 2 Sts layers

2 Reconstructed layers



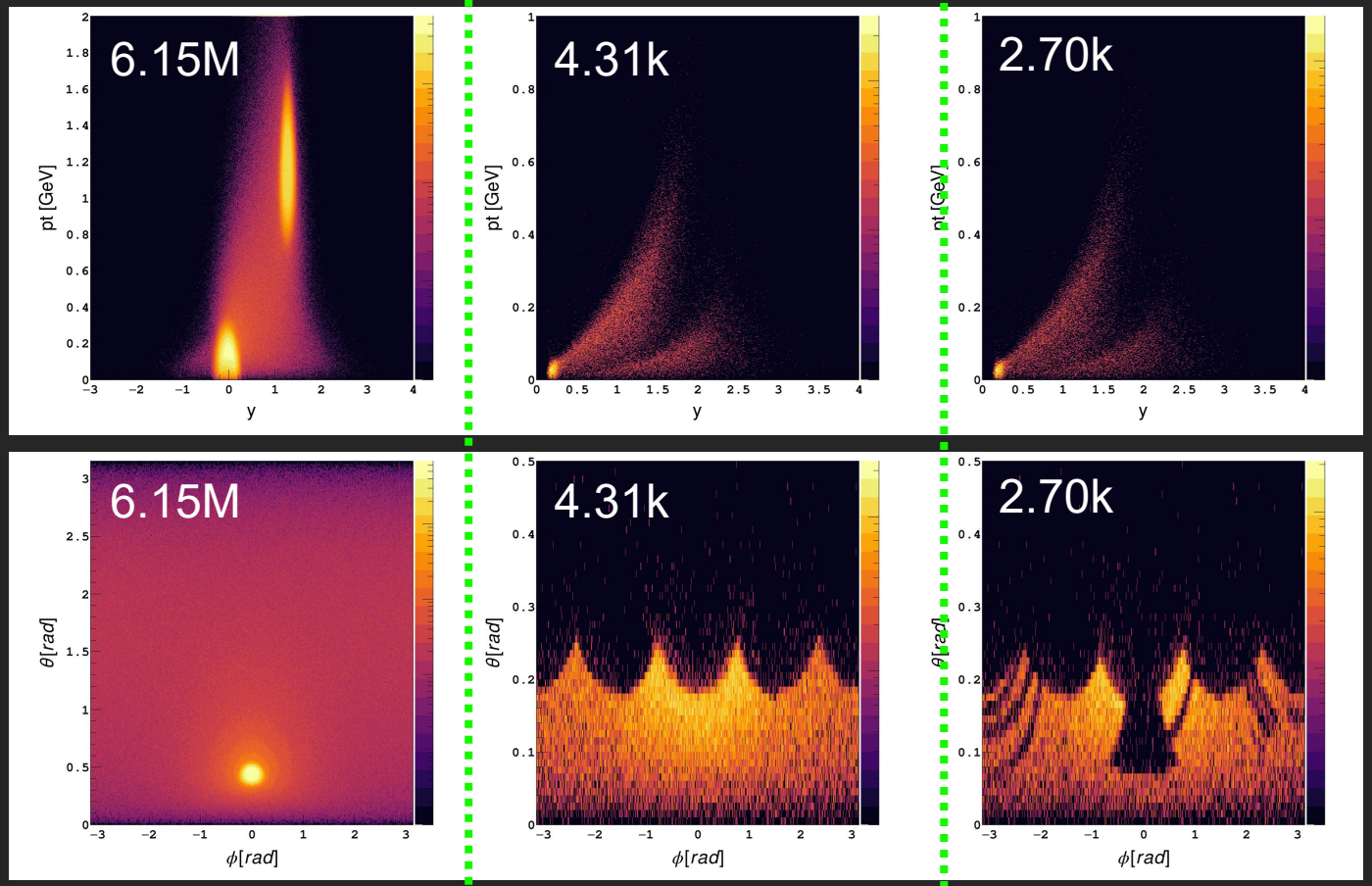


mSTS Acceptance - MCTrack

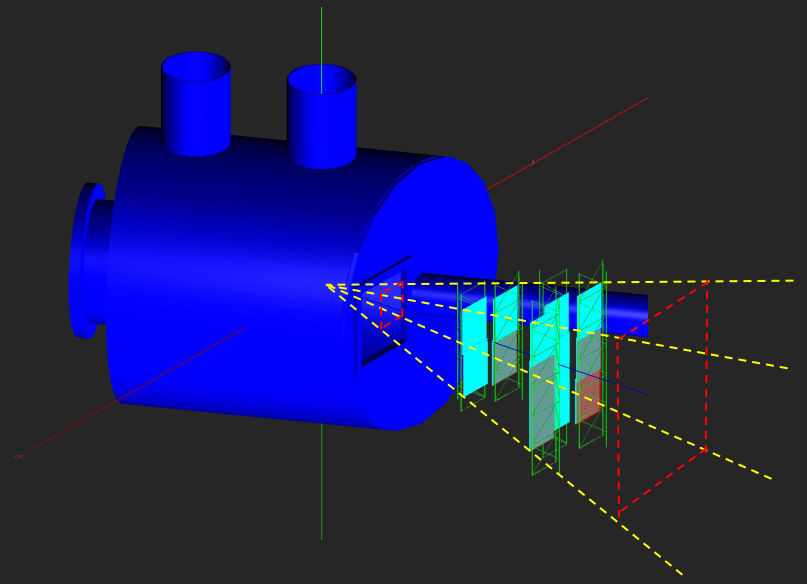


ACCEPTED / ALL:	7.00 %
RECO / ALL :	4.39 %
RECO / ACCEPTED:	62.64 %

All tracks | Hitting 2 Sts layers | 2 Reconstructed layers

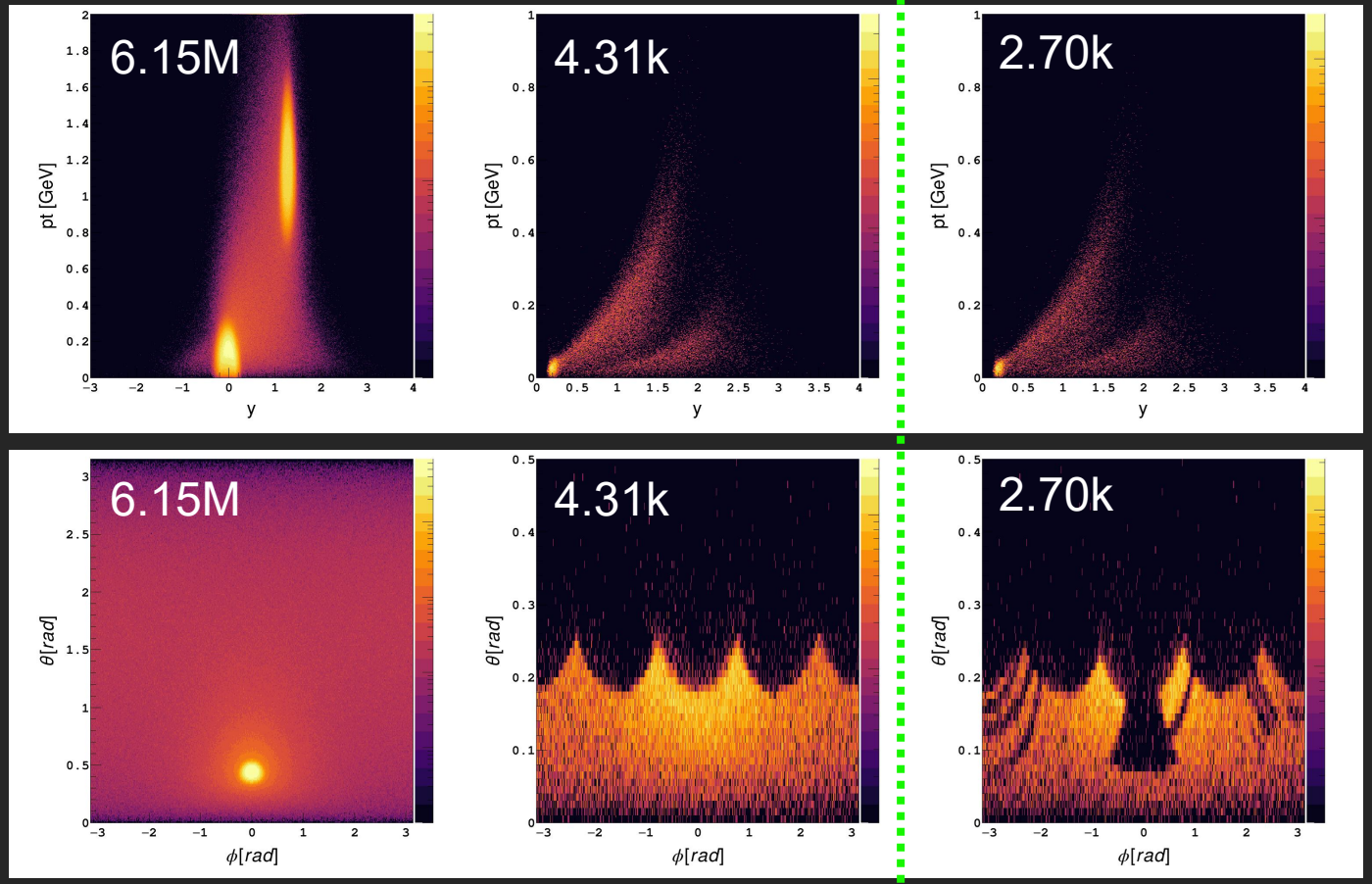


mSTS Acceptance - MCTrack

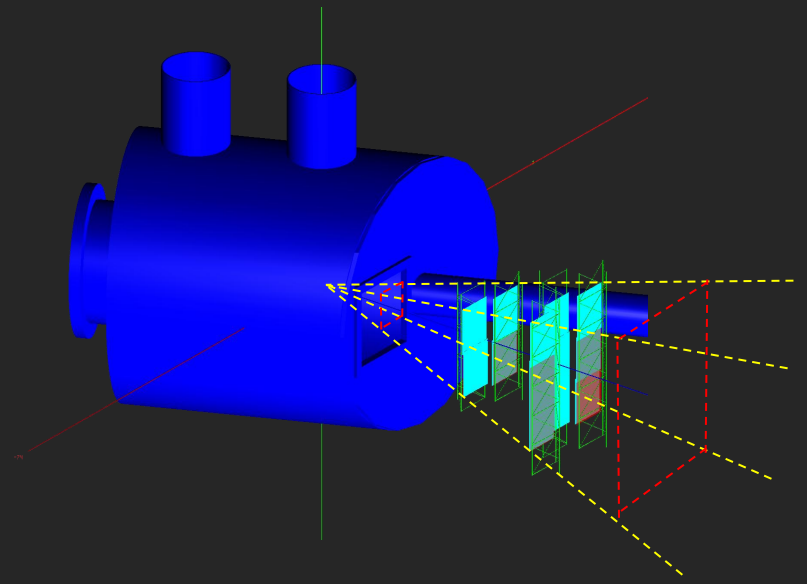


ACCEPTED / ALL: 7.00 %
RECO / ALL : 4.39 %
RECO / ACCEPTED: 62.64 %

All tracks | Hitting 2 Sts layers | 2 Reconstructed layers

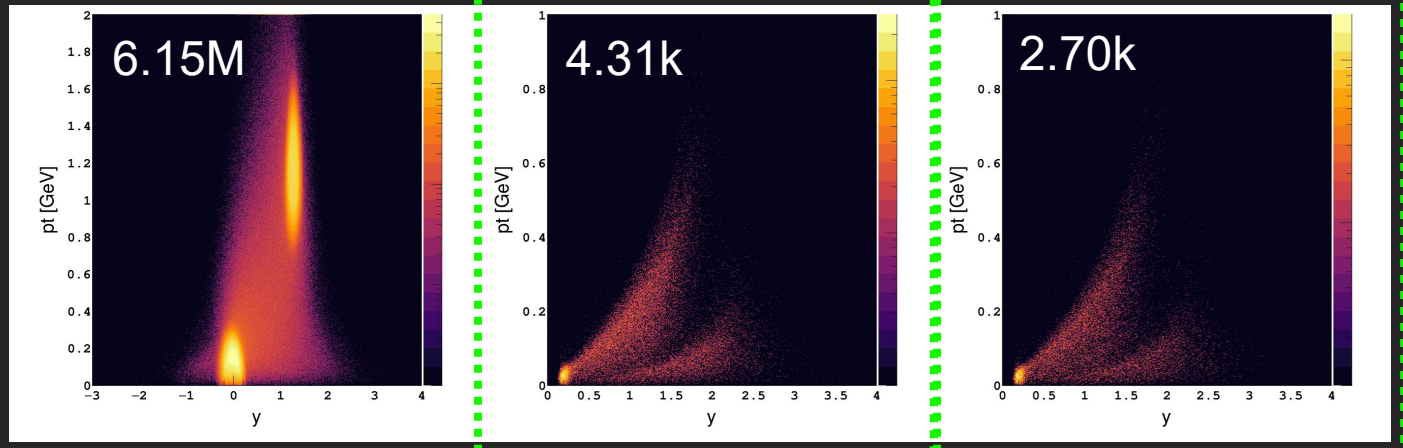


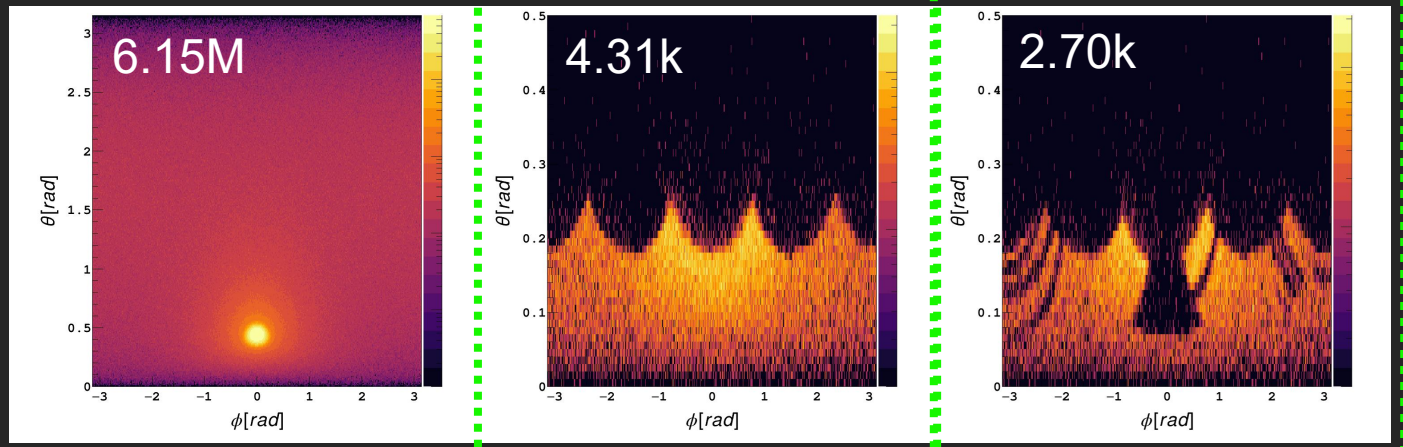
mSTS Acceptance - MCTrack



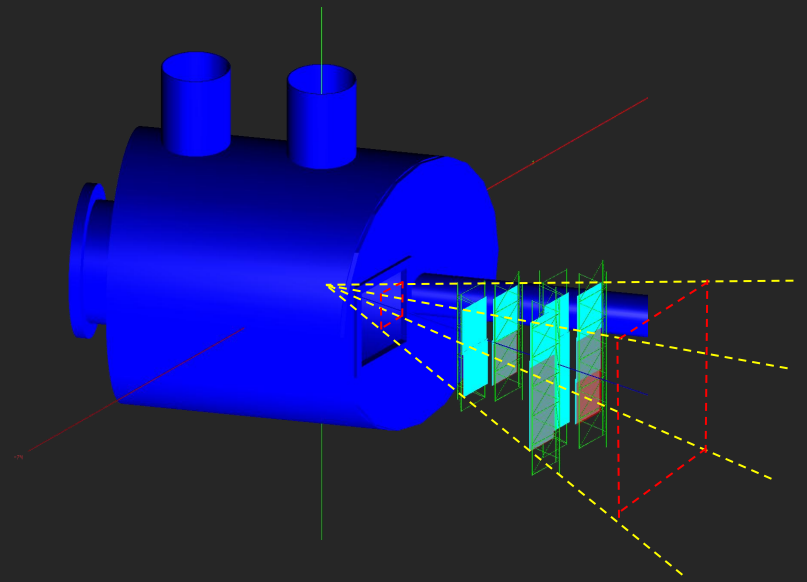
ACCEPTED / ALL: 7.00 %
RECO / ALL : 4.39 %
RECO / ACCEPTED: 62.64 %

All tracks | Hitting 2 Sts layers | 2 Reconstructed layers





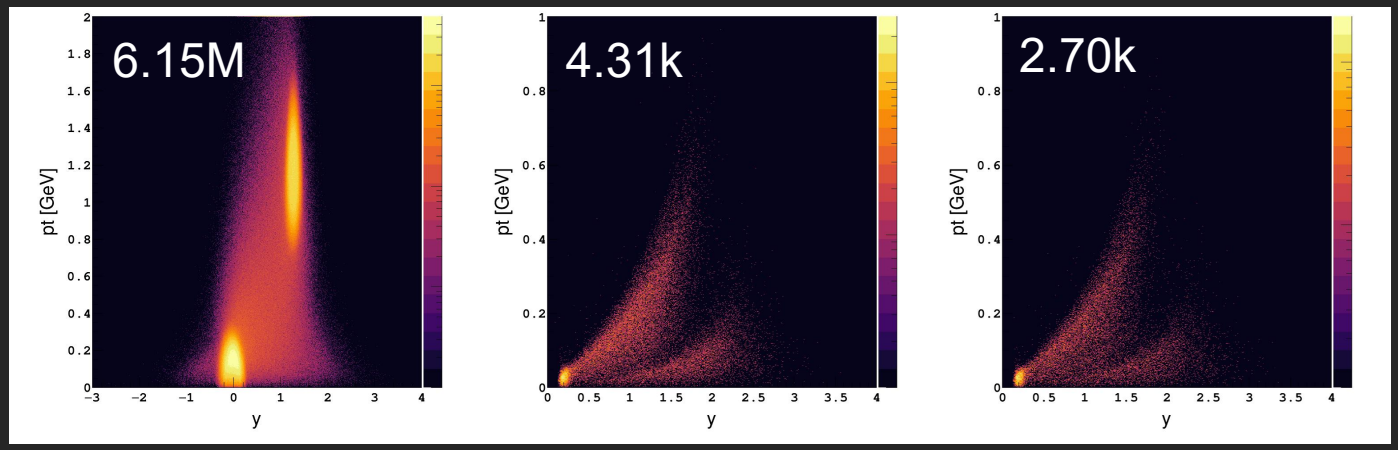
mSTS Acceptance - MCTrack

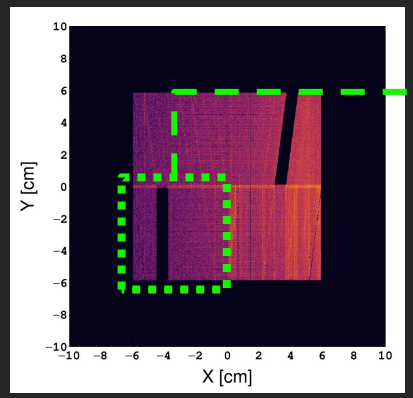


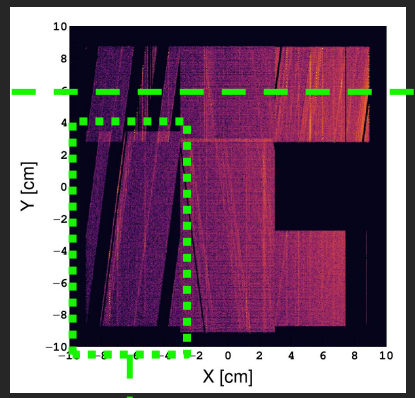
All tracks

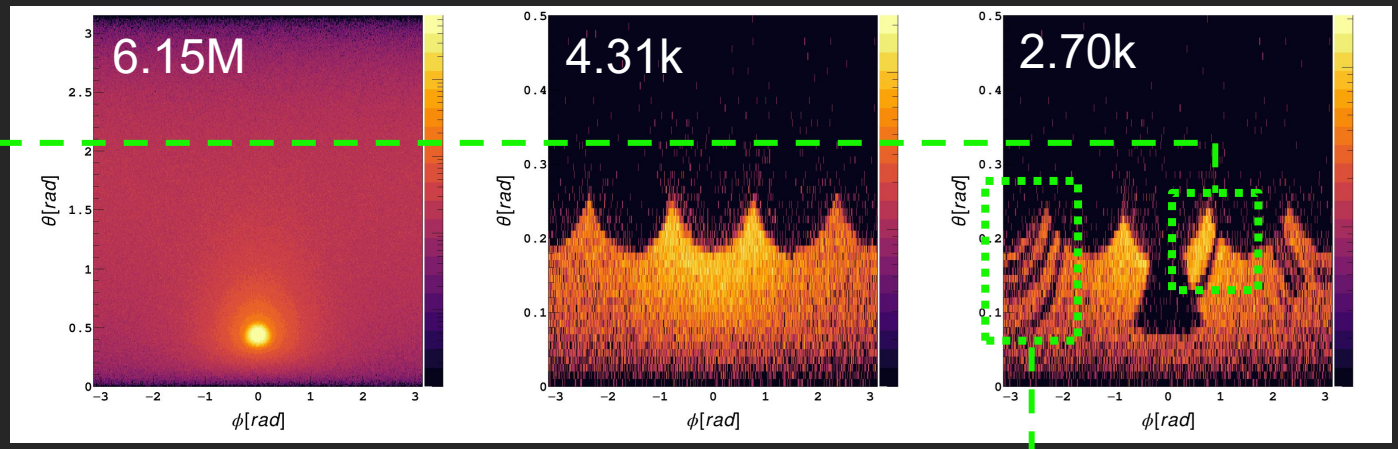
Hitting 2 Sts layers

2 Reconstructed layers

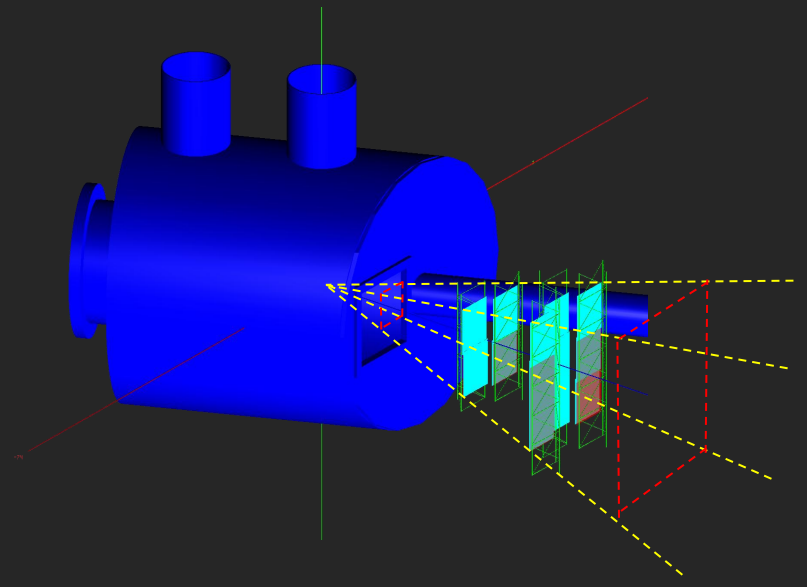


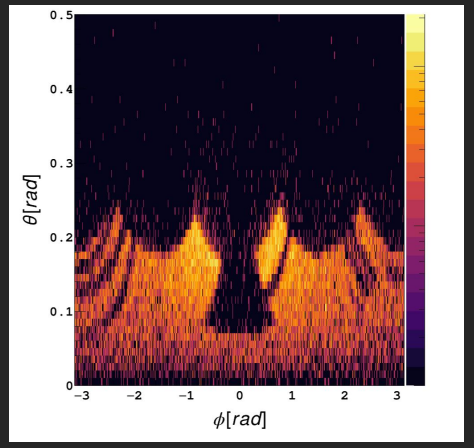




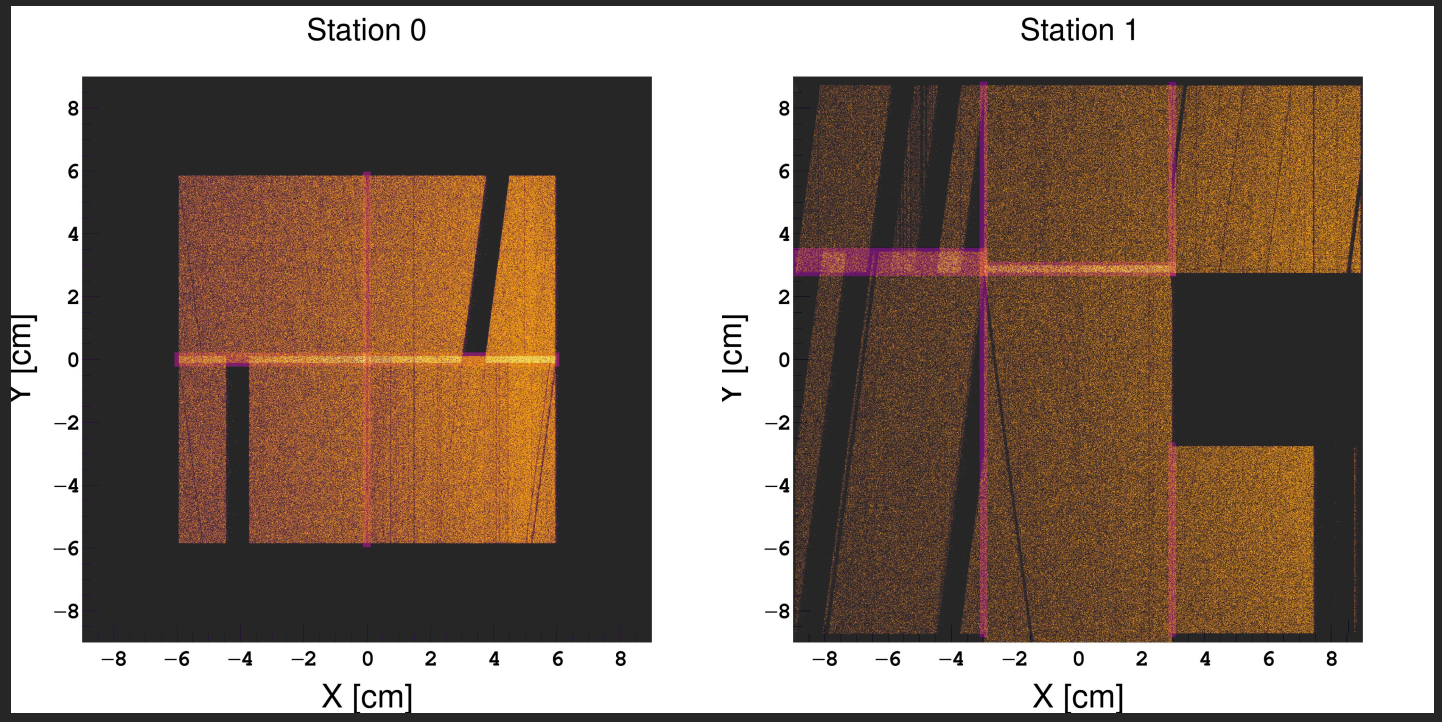


mSTS Acceptance - MC - Hit Reconstruction Efficiency





MC HRE >99.98%
Excluding inactive areas



mSTS Rates

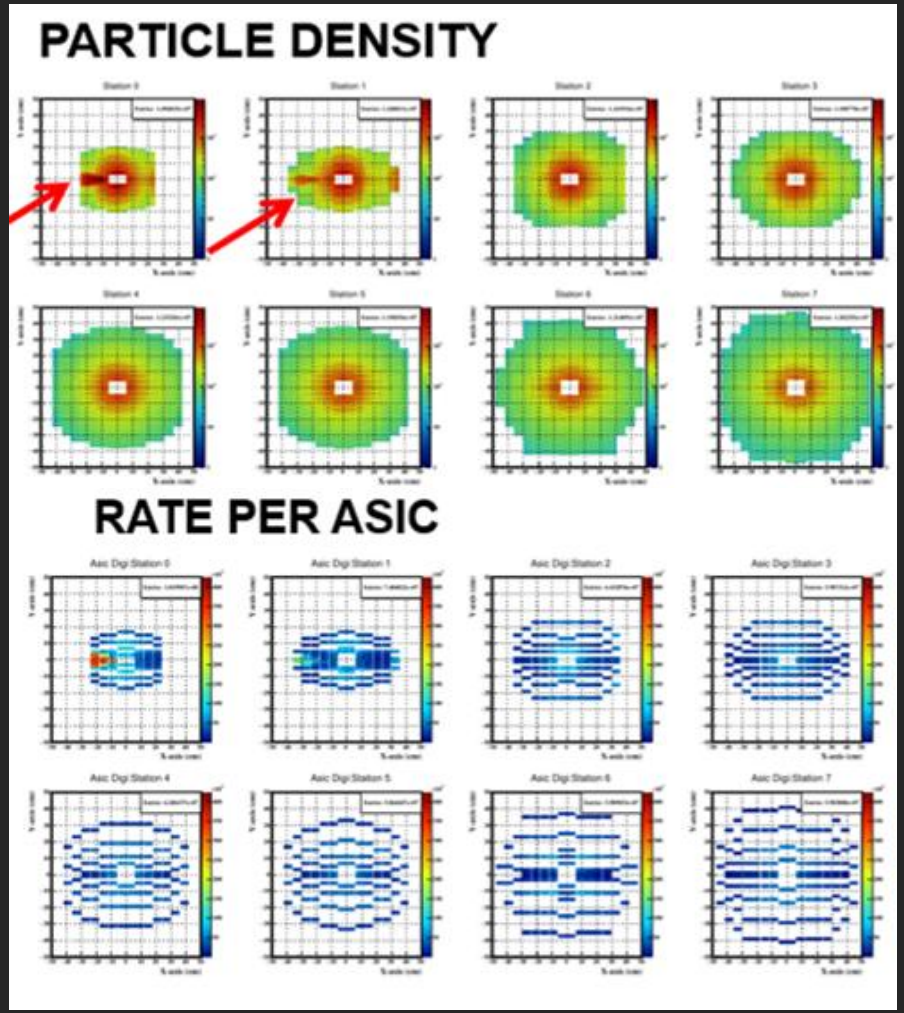
Expected rates STS - Worst Scenario - Monte Carlo

Au+Au - 12AGeV/c - 10MHz
Au-beam target interaction at 10^9 ions/s -> delta e
UrQMD Au+Au at 10^7 collisions/s

Delta e - low pT - B-field (1T): bent out or absorbed
The two first STS stations suffer the most

Digitization:
ENC = 1000 e,
Threshold: 4000 e

Max rate per channel: $150 \cdot 10^3$ digis /ch / s
few exceptions: 250 - $300 \cdot 10^3$ digis /ch / s

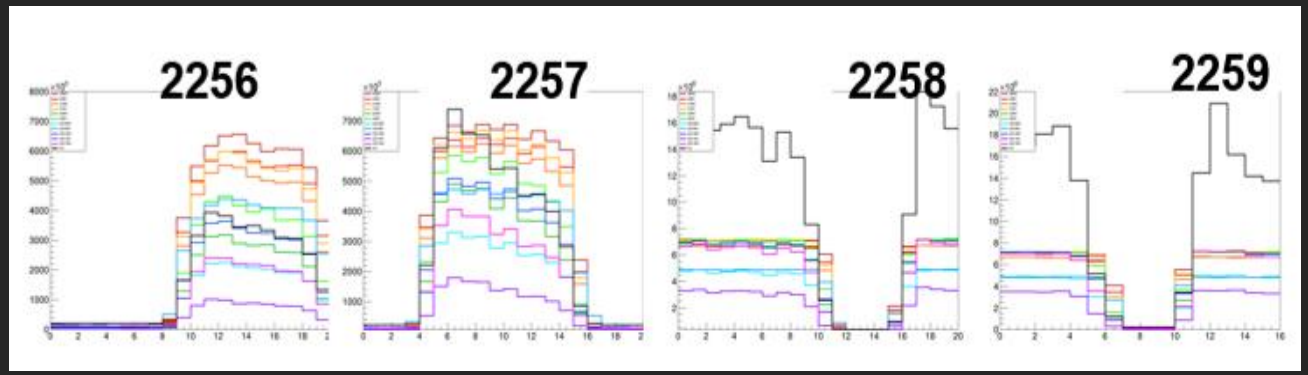


Observed rates mSTS

- Beam Intensity scan: U+Au
- micro-spill structures up to 1:10

STS can sustain rates up to:
27×10^3 digi/channel/sec

Run Number	Beam intensity (ions/spill)	Rate (digi/ch/s)
2256	$5 \cdot 10^7$	$25 \cdot 10^3$
2257	$1 \cdot 10^8$	$27 \cdot 10^3$
2258	$5 \cdot 10^8$	$28 \cdot 10^3$
2259	$1 \cdot 10^9$	$28 \cdot 10^3$



Observed rates mSTS

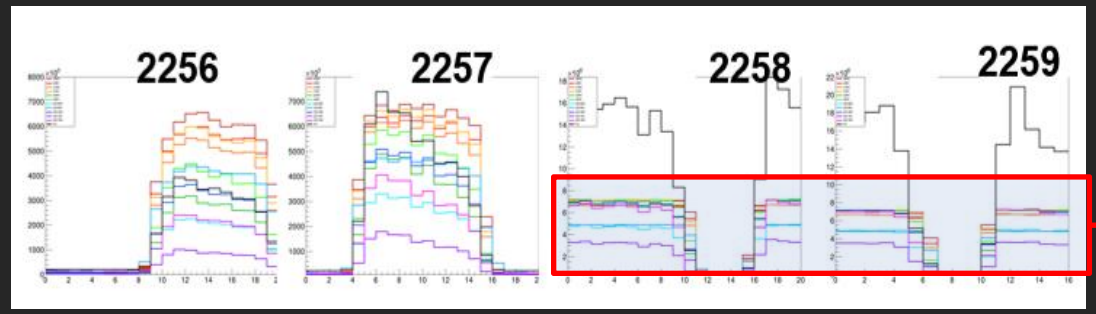
- Beam Intensity scan: U+Au
- micro-spill structures up to 1:10

STS can sustain rates up to:
28×10^3 digi/channel/sec

In mCBM saturation is reached
~ $5 \cdot 10^8$ ions/spill

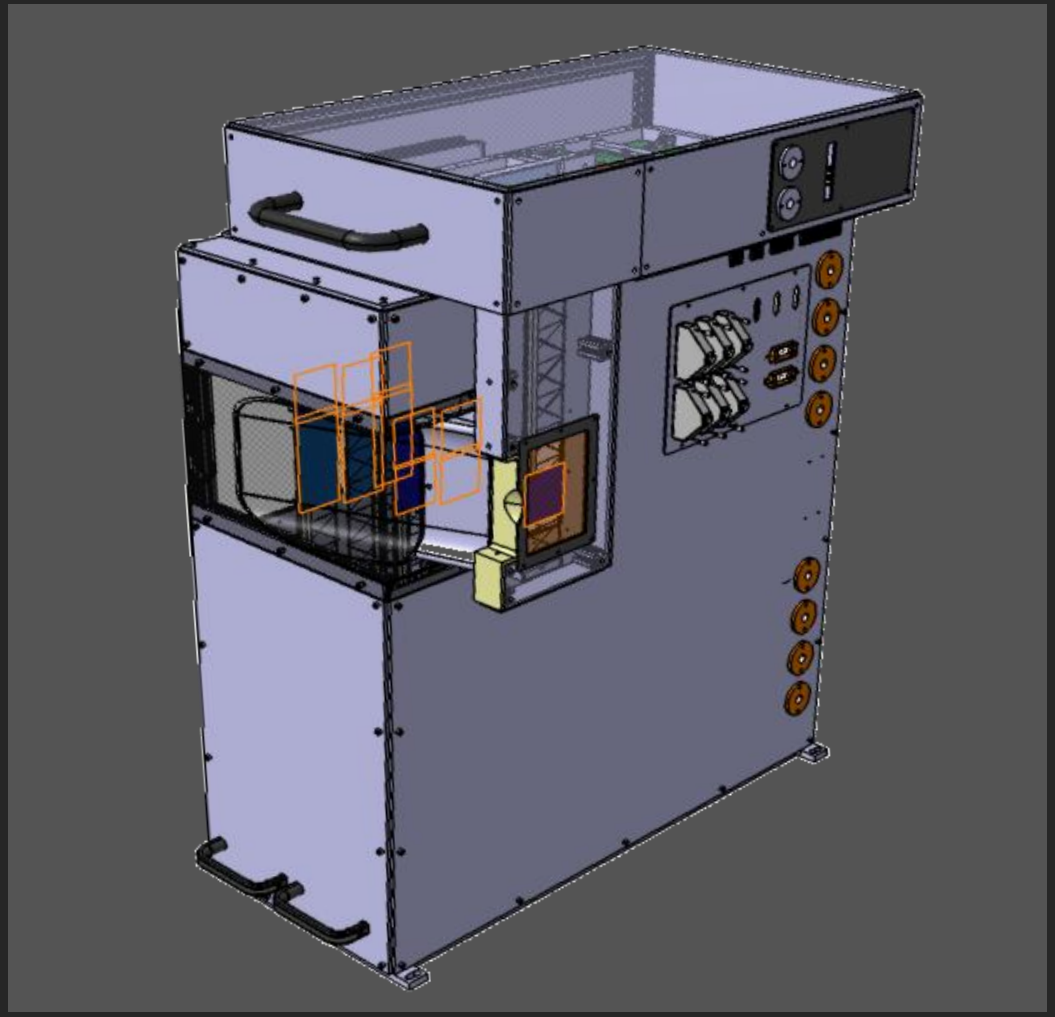
Run Number	Beam intensity (ions/spill)	Rate (digi/ch/s)
2256	$5 \cdot 10^7$	$25 \cdot 10^3$
2257	$1 \cdot 10^8$	$27 \cdot 10^3$
2258	$5 \cdot 10^8$	$28 \cdot 10^3$
2259	$1 \cdot 10^9$	$28 \cdot 10^3$

Saturated mSTS



Observed rates mSTS

Scaling bandwidth (to be tested!!!)
x5 FEB8_1 → FEB8_5:
$140 \cdot 10^3$ digi/ch/s

mSTS hardware update is coming to proof the linear scaling!

New module!!!
FEB8_5