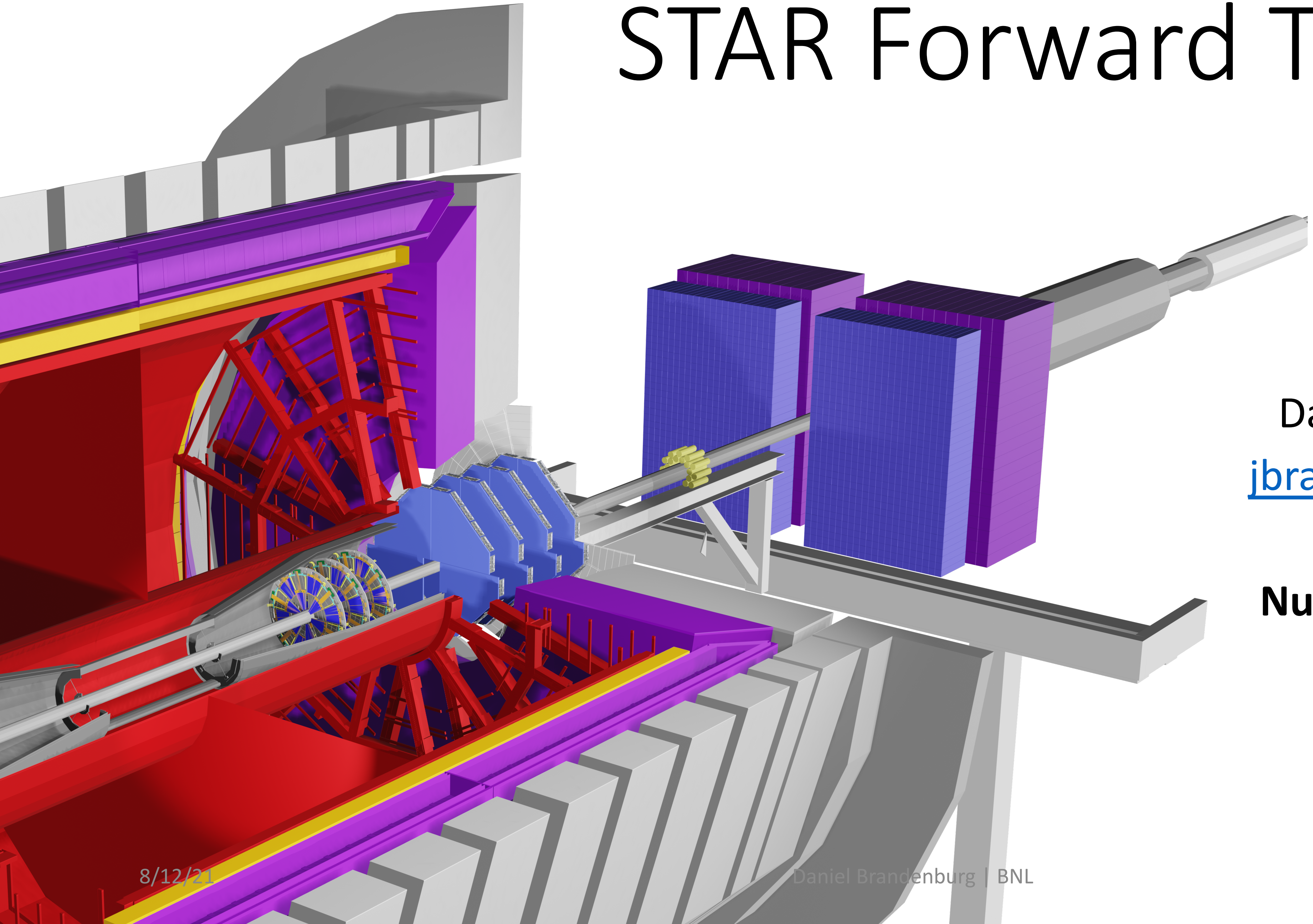

STAR Forward Tracking

Daniel Brandenburg

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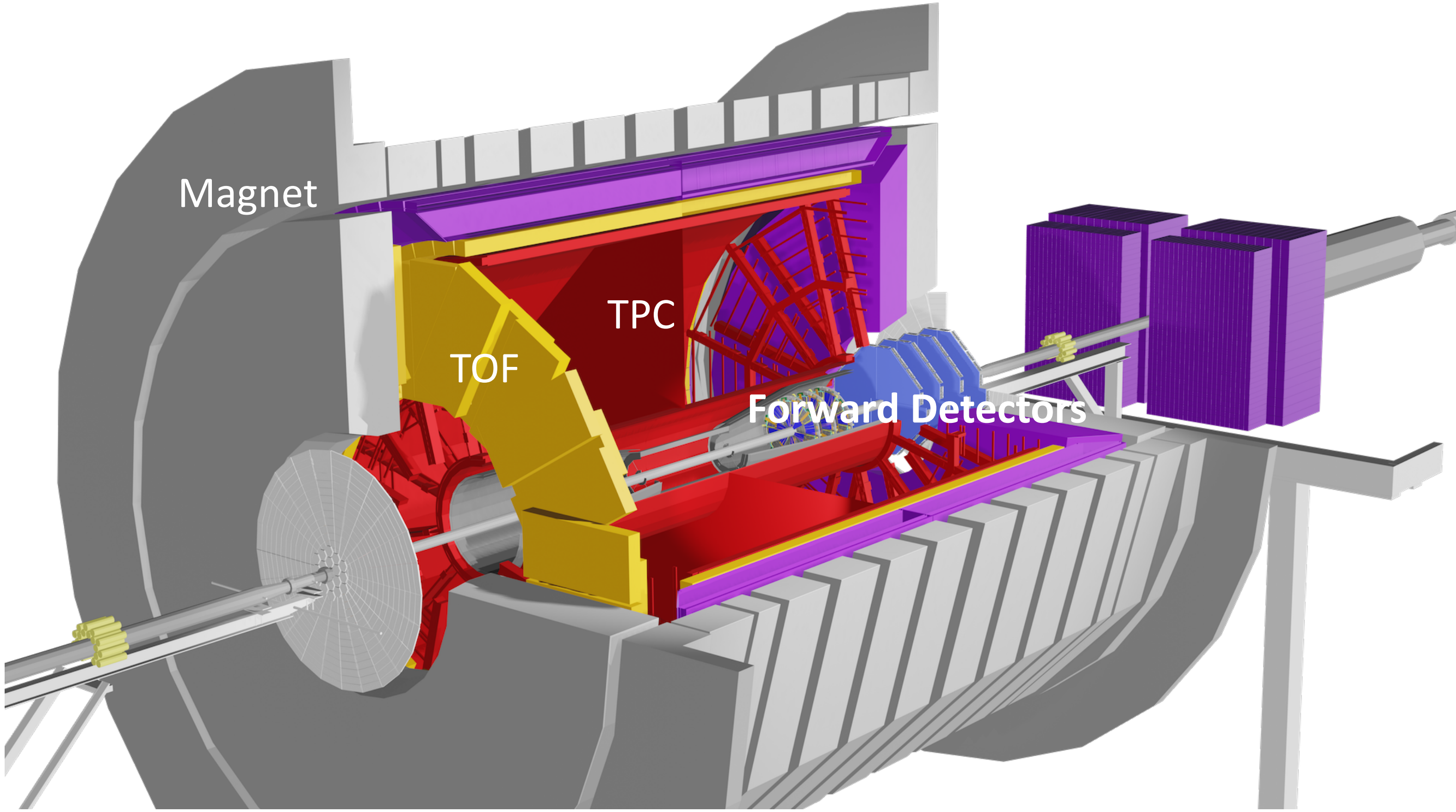
NuSTEAM@BNL 2021

Outline

- Introduction & History
- STAR Forward Detectors
- Tracking Concepts
- Track Finding and Fitting
- Performance
- Conclusions
- HW Questions

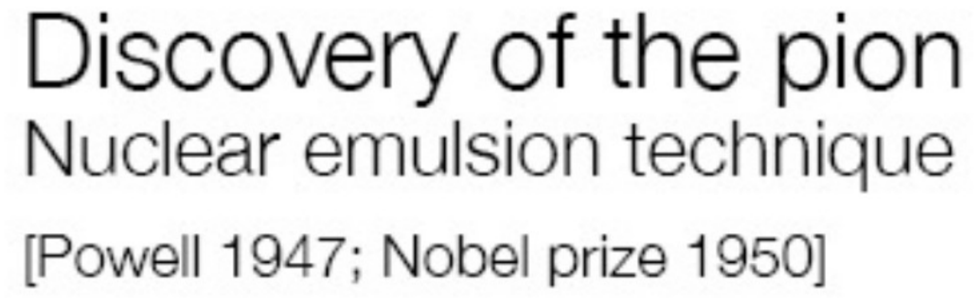


Detector Technology through the years

1906: Geiger Counter, H. Geiger, E. Rutherford
1910: Cloud Chamber, C.T.R. Wilson
1912: Tip Counter, H. Geiger
1928: Geiger-Müller Counter, W. Müller
1929: Coincidence Method, W. Bothe
1930: Emulsion, M. Blau
1940-1950: Scintillator, Photomultiplier
1952: Bubble Chamber, D. Glaser
1962: Spark Chamber
1968: Multi Wire Proportional Chamber, C. Charpak
1970es: Silicon era

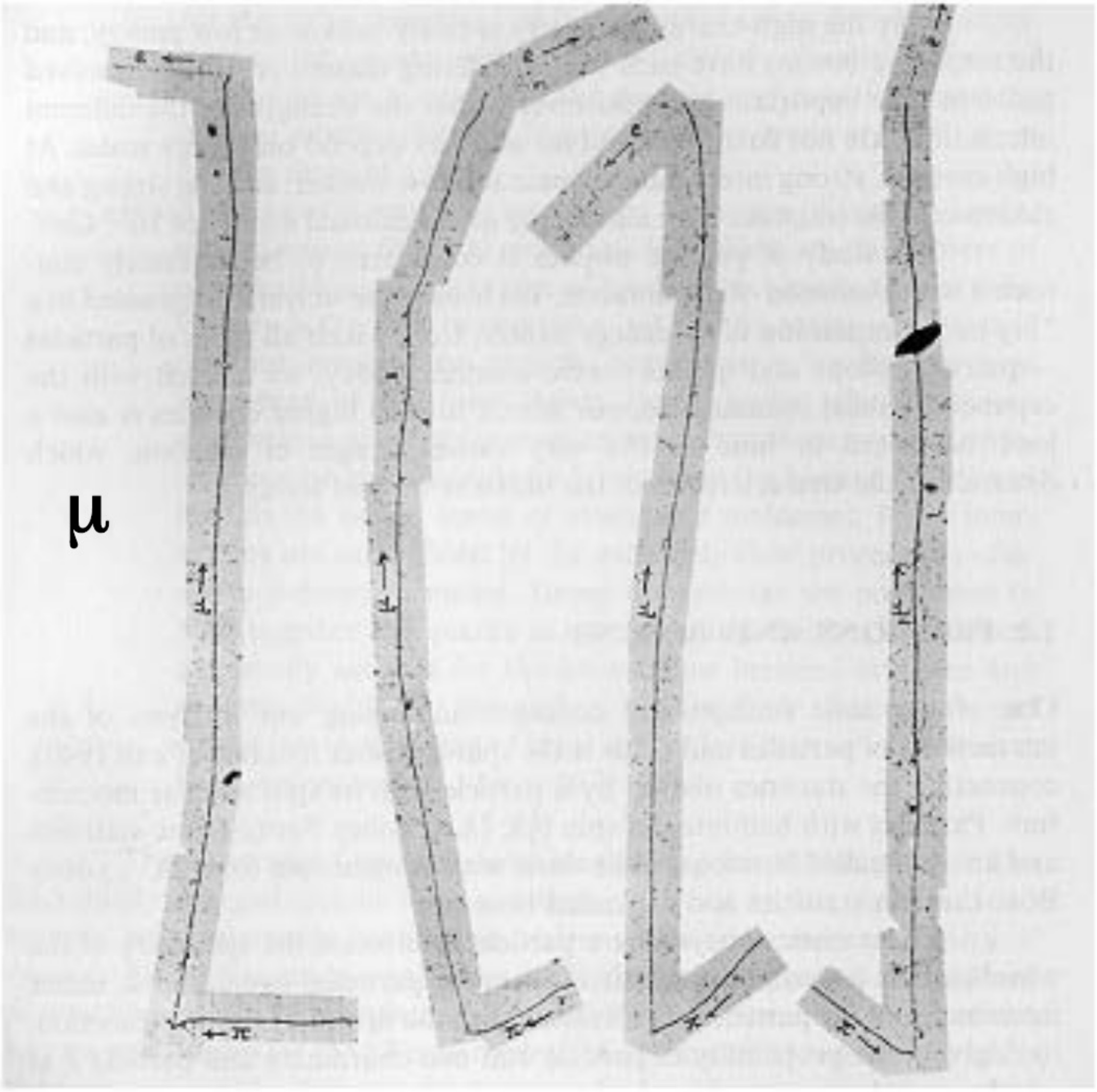
[lecture notes Erika Garutti]

Discovery of the π



Discovery of the pion
Nuclear emulsion technique
[Powell 1947; Nobel prize 1950]

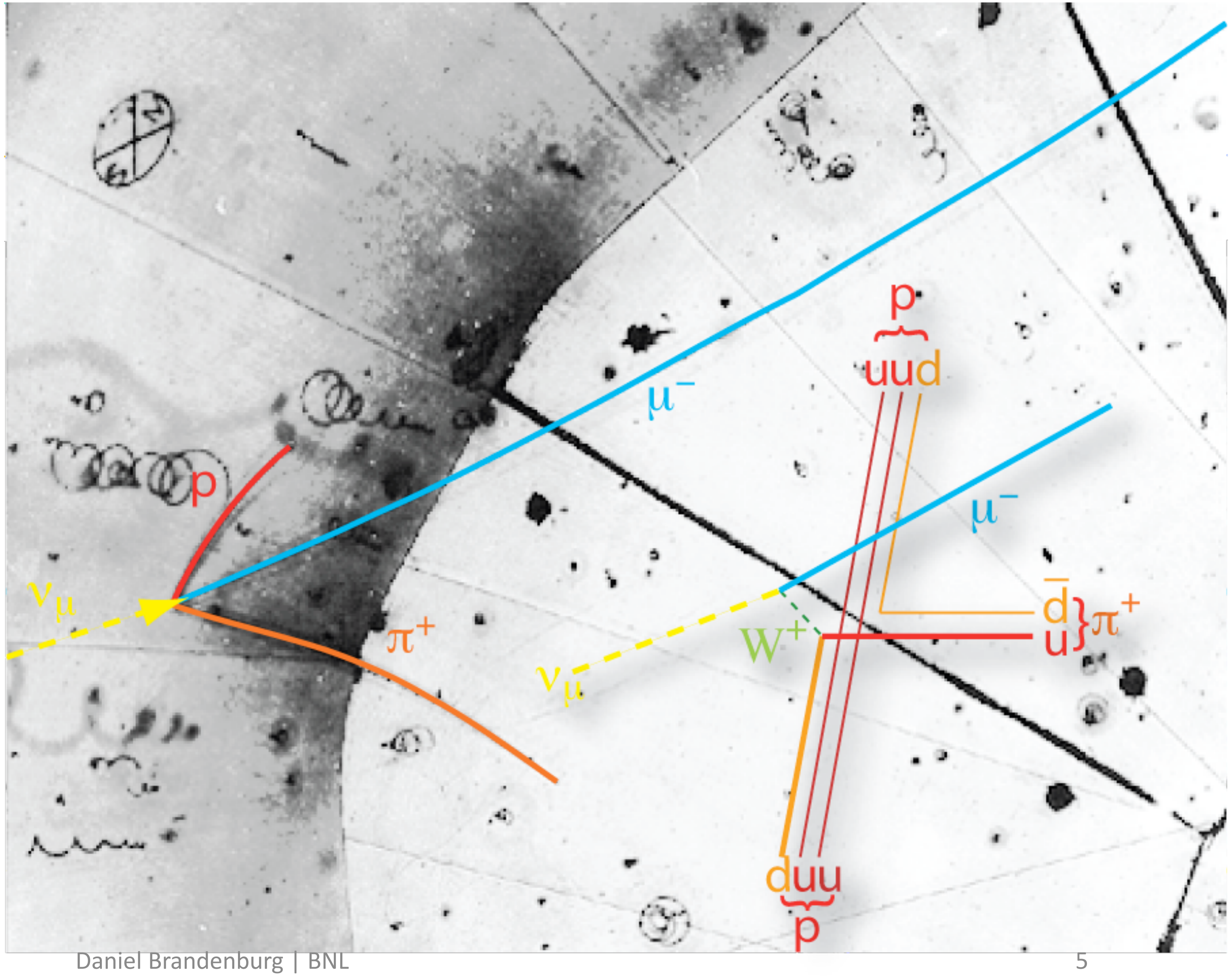
- Pion decays to a muon and an unseen particle, hence the sharp bend to the track



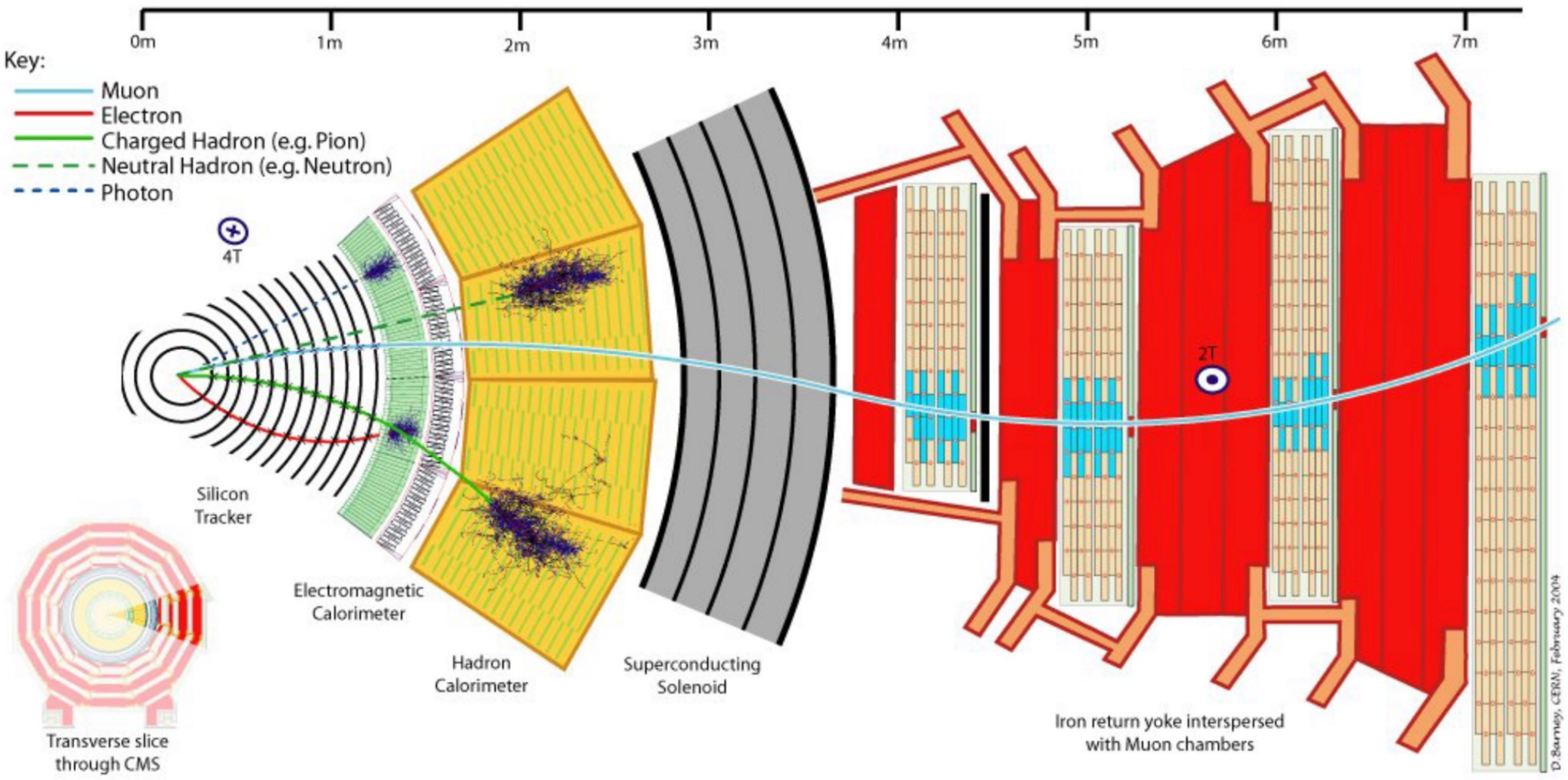
$$\pi \rightarrow \mu^- \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

The Neutrino Event

- Observation of a neutrino in a hydrogen bubble chamber - 1970
- Neutrino strikes a proton, converts into a muon
- It looks like 3 particles coming from nothing!
- Tracks were drawn by hand on photos of every event



Particle Detectors have come a long way

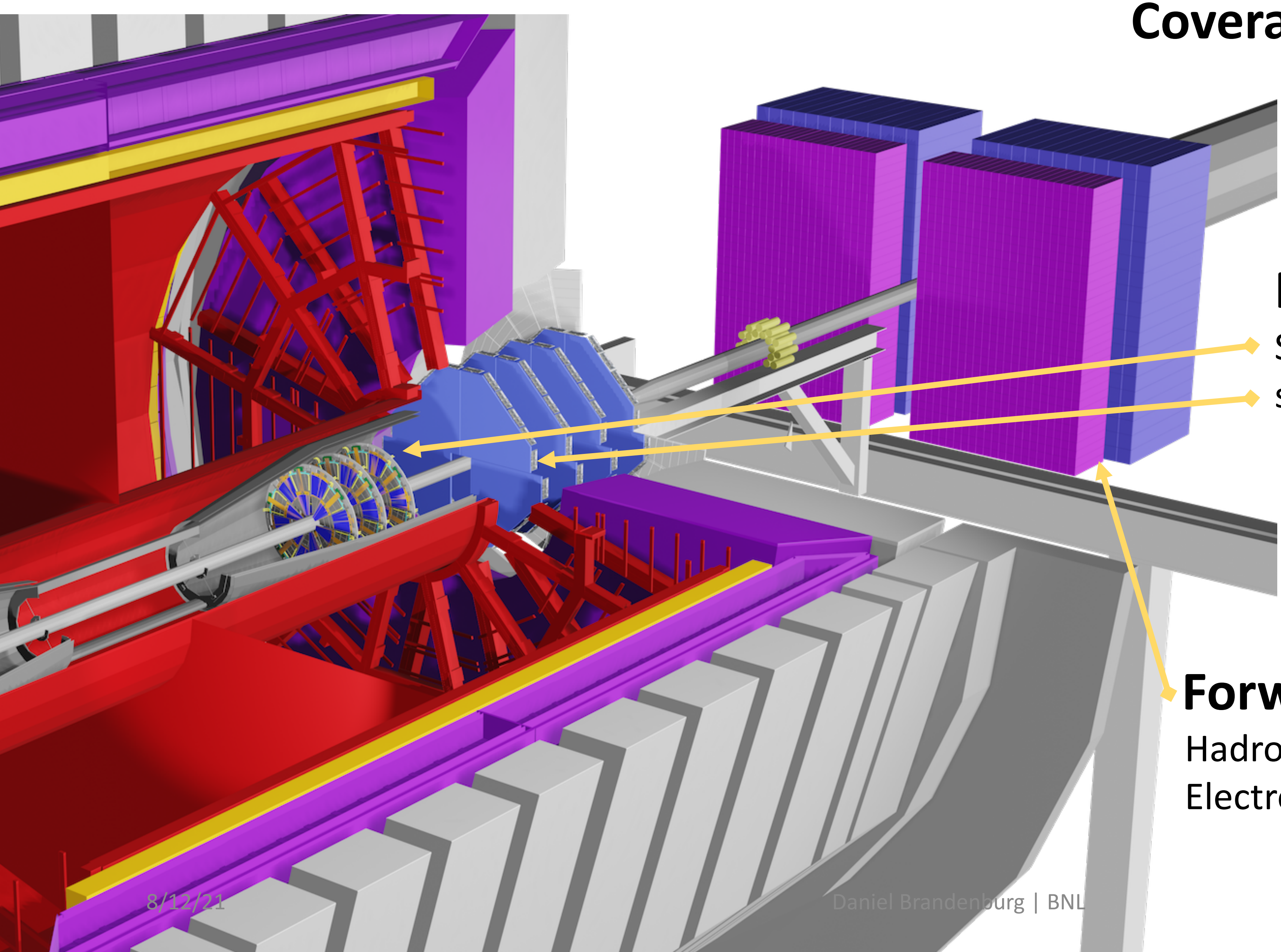


Slice of the CMS detector

Modern detectors are fully electronic with several special purpose sub-detectors

The STAR Forward Upgrade

Coverage: $2.5 < \eta < 4.0$



Forward Tracking System

Silicon microstrip sensors

small-Strip Thin Gap Chambers

Forward Calorimetry System

Hadronic Calorimeter

Electromagnetic Calorimeter

STAR Forward Rapidity Physics Program

Measurements planned for 2021+ with the STAR forward upgrade
→Address important topics in hot & cold QCD

Forward-rapidity $2.5<\eta<4$

pp, pA

Beam:

500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:

- TMD measurements at high x transversity → tensor charge
- Improve statistical precision for Sivers through Drell-Yan
- $\Delta g(x, Q^2)$ at low x through Di-jets
- Gluon PDFs for nuclei
- ➢ R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, g-Jets

Au+Au

Beam:

200 GeV: Au+Au

Physics Topics:

- Temperature dependence of viscosity through flow harmonics up to h~4
- Longitudinal decorrelation up to h~4
- Global Lambda polarization
  → Test for strong rapidity dependence

Forward Tracking System

	Requirement	Motivation
Momentum Resolution	< 30%	A+A goals
Tracking Efficiency	> 80% @ 100 tracks / event	A+A goals
Charge Separation	–	p+p / p+A goals

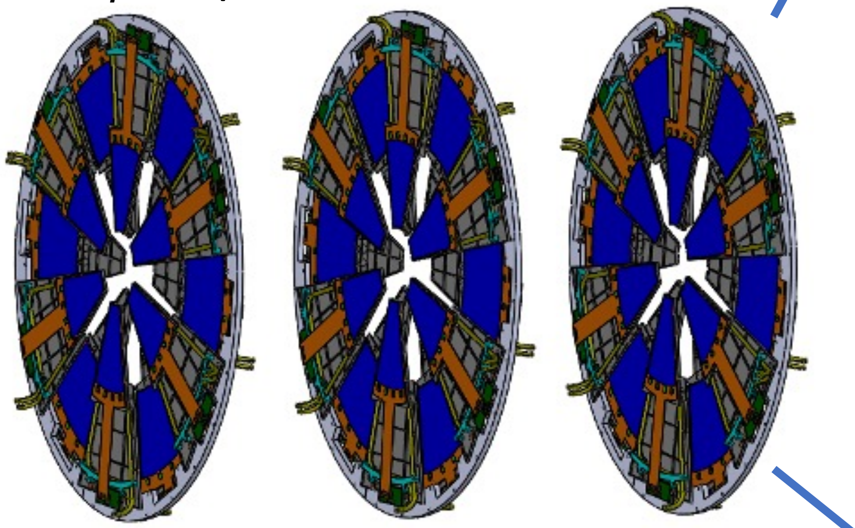
Forward Calorimeter System

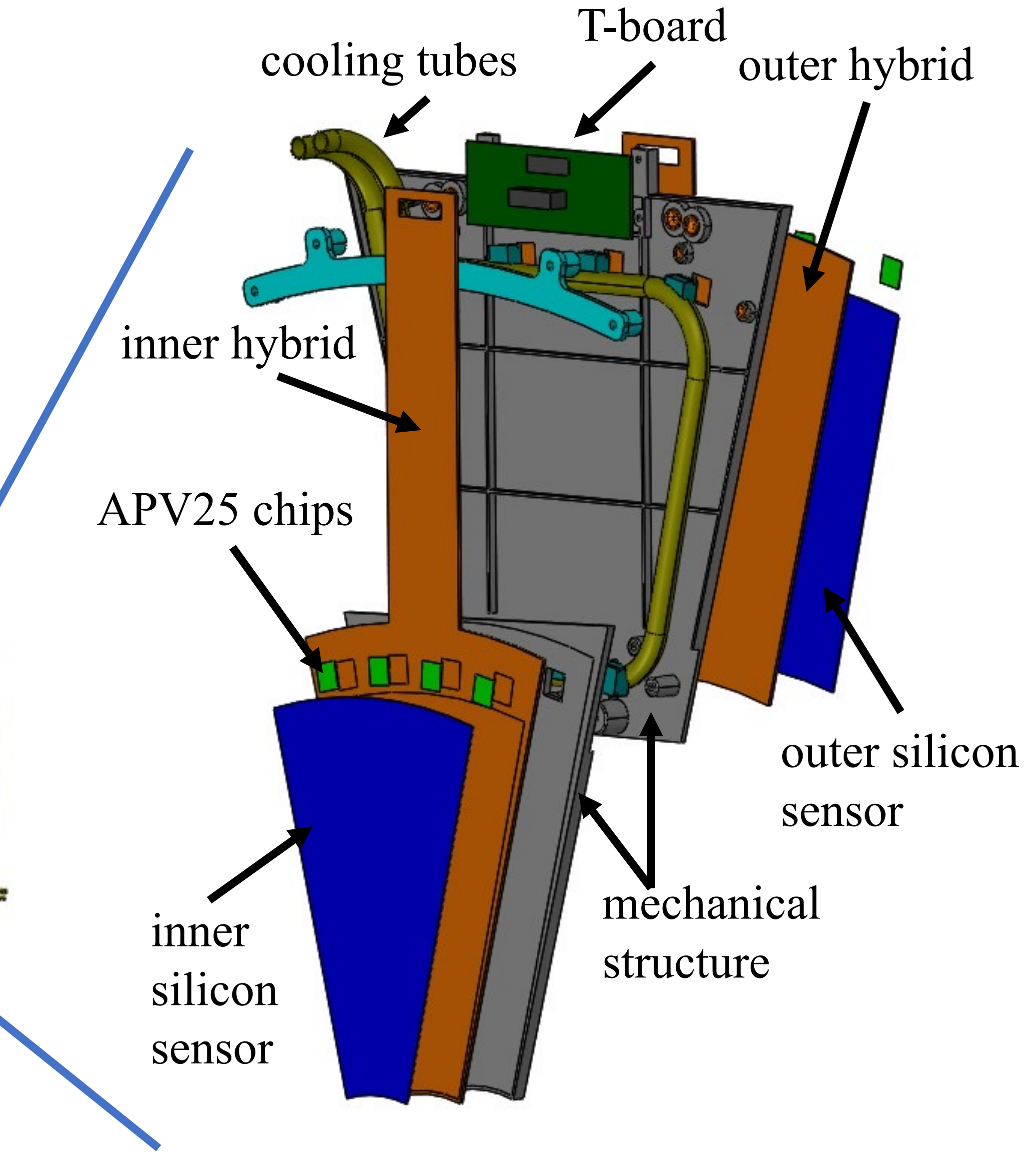
Detector	Resolution p+p and p+A	Resolution A+A
ECal	$\sim 10\%/\sqrt{E}$	$\sim 20\%/\sqrt{E}$
HCal	$\sim 50\%/\sqrt{E} + 10\%$	–

Lets review the technology used for the tracking detectors

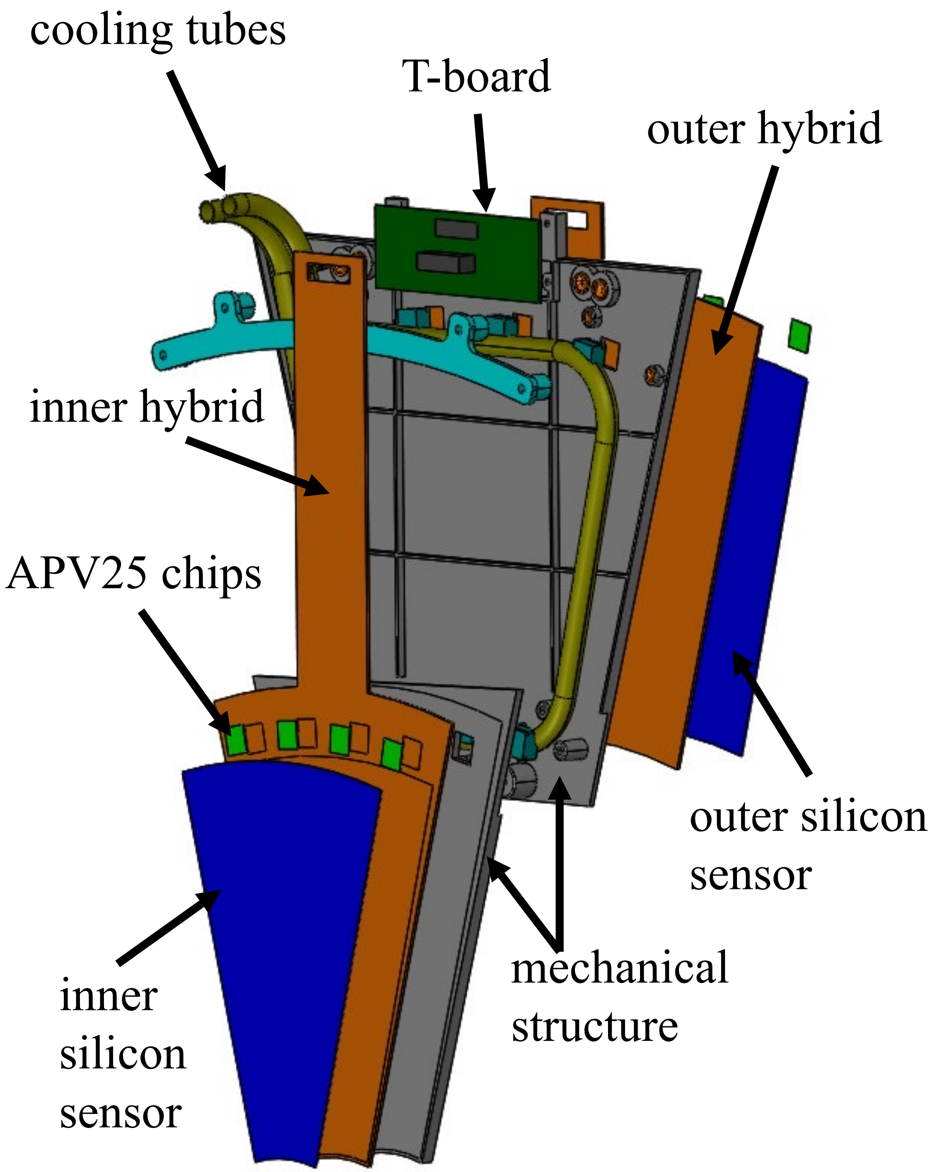
STAR Forward Silicon Tracker

- Full installation: 3 identical disks
  - Acceptance:
  - $\mathbf{0 < \phi < 2\pi,\ \ 2.5 < \eta < 4.0}$
- 12 wedge modules / disk
- APV25 frontend readout chips
- Flexible hybrid
- Precise ϕ, imprecise R measurement





STAR Forward Silicon Tracker - Prototype Module



cooling tubes

T-board

outer hybrid

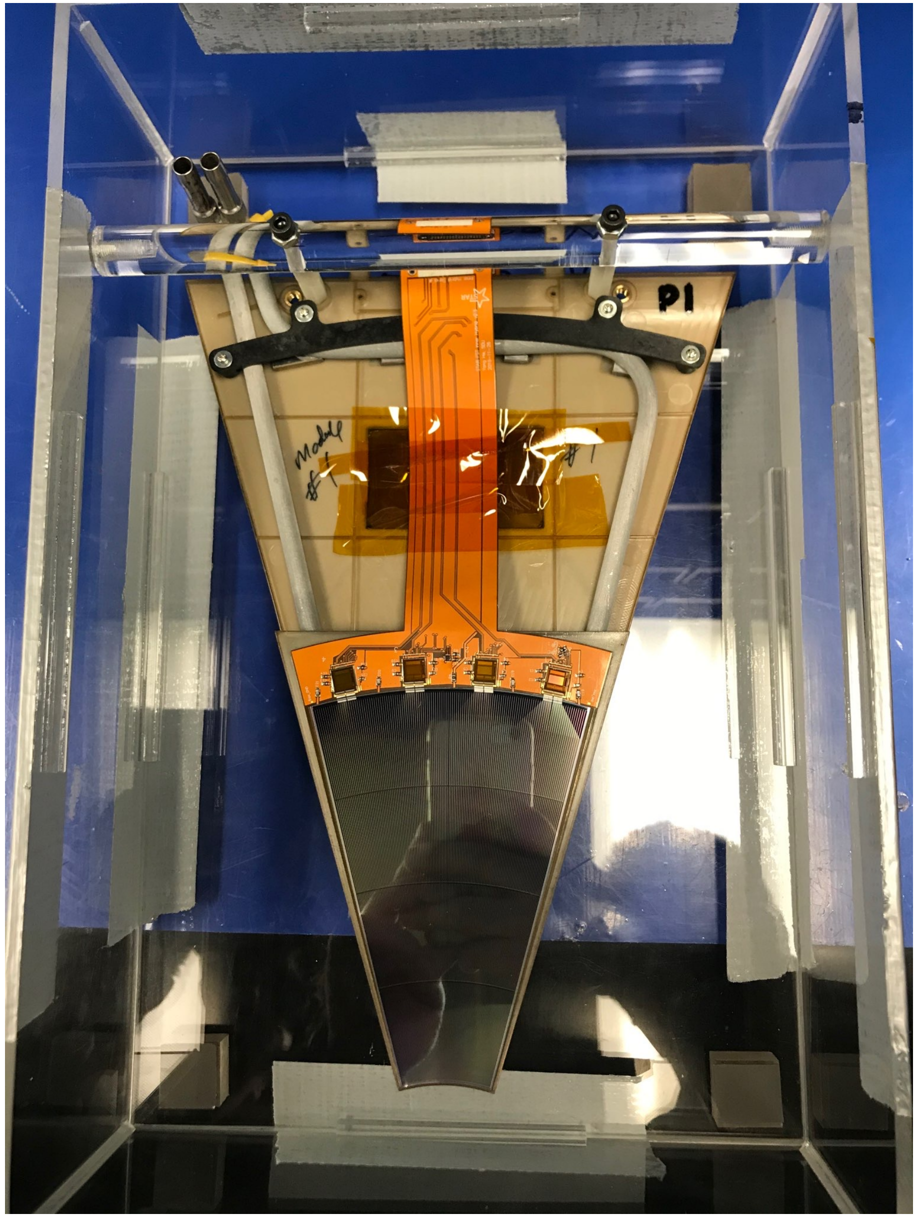
inner hybrid

APV25 chips

outer silicon
sensor

mechanical
structure

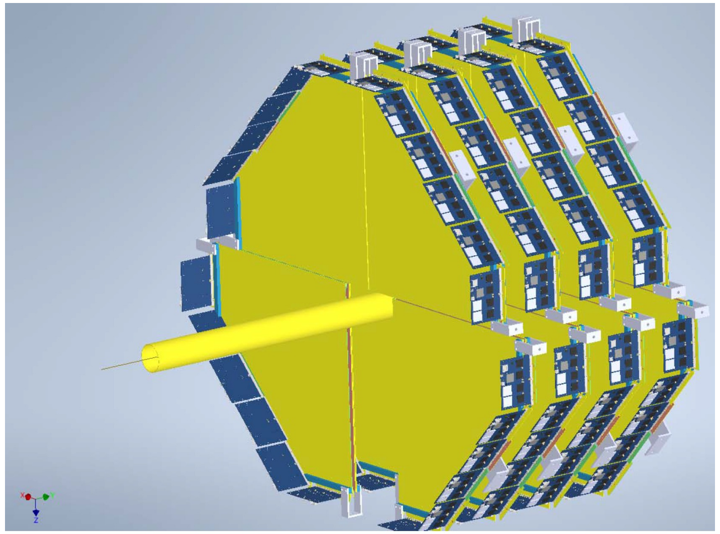
inner
silicon
sensor

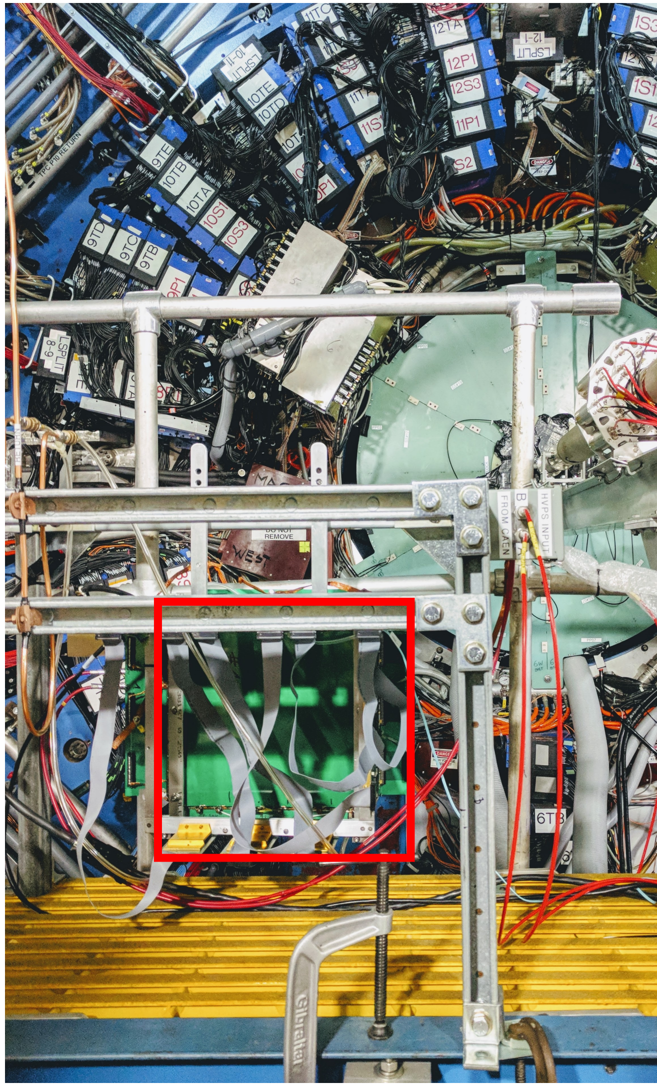


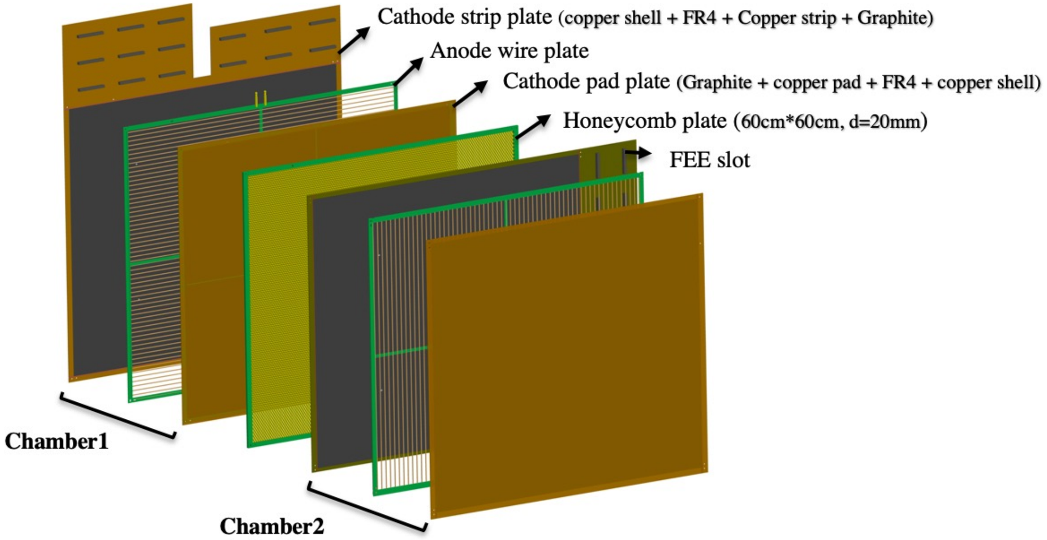
Small-Strip Thin Gap Chambers (sTGC)

Detector:

- Based on ATLAS sTGC design
- 4 layers in total
  - 4 modules/layer
  - 2 chambers/module
- Pentagon shape formed from identical modules
- Shandong University : sTGC R&D and production
- **Position resolution: $\sim$100 μm**







Wire: Au-plated tungsten wire
⌀ 50μm, 1.8mm pitch
Copper strip: 3.2mm pitch
Height of one layer: 5.8mm
Gas: 55% n-pentane+45%CO2
HV: 2900V

Requires dedicated gas system

Forward Tracking System

	Requirement	Motivation
Momentum Resolution	< 30%	A+A goals
Tracking Efficiency	> 80% @ 100 tracks / event	A+A goals
Charge Separation	–	p+p / p+A goals

Silicon mini-strip disks ×3

- Location : z = 90, 140, 187 cm from interaction point
- **Build on and utilize STAR experience of successful Intermediate Silicon Tracker(IST) detector**
- minimal material (≤1% X0/layer) in the acceptance

Small-Strip Thin Gap Chamber (sTGC) ×4

- Location : z = 270, 300, 330, 360 cm from interaction point
- **Significant reduction in cost (compared to all silicon)**
- Prototype at BNL, testing in STAR during 2019 run

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

Basics of Tracking

1. Find track candidates
   - Input: unsorted hits from detectors
   - Output: Possible tracks and their associated hits
2. Resolve ambiguities / conflicts
   - Input: Possible tracks (maybe with shared hits)
   - Output: Set of ”BEST” tracks
   - Considerations :
     - Can one hit be used by several tracks?
     - If so, how many shared hits are allowed?
     - If conflicts exists, what metric defines the “BEST” track?
3. Fit track model
   - Input: Set of tracks and their associated hits
   - Output: Momentum and charge information
   - Procedure : Fit points (+ Primary Vertex?) to track model
     - Track Model in uniform $\vec{B}$ = Ideal helix
     - Track Model in non-uniform $\vec{B}$ = helix modified by magnetic field variations (including zero field)

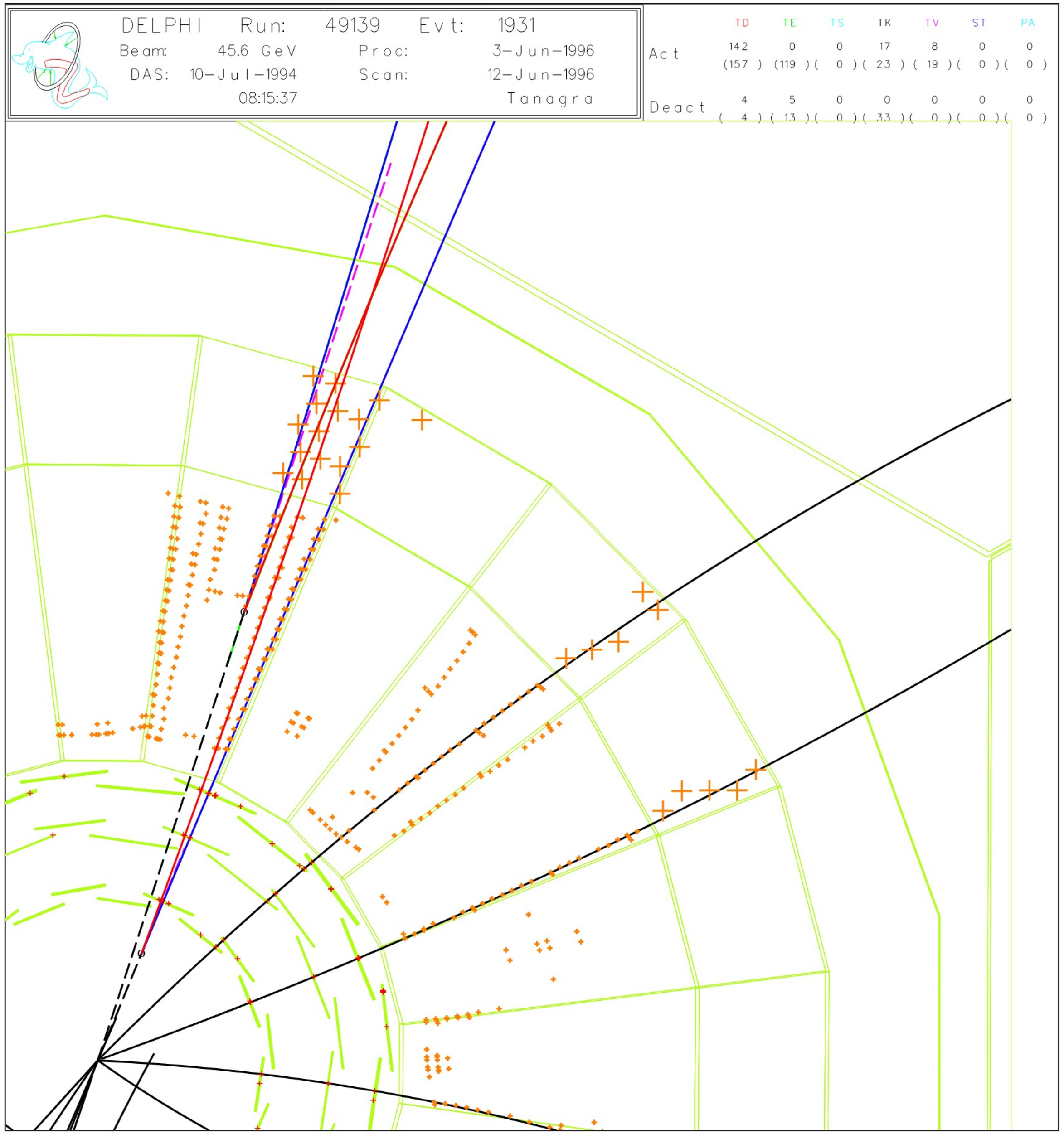
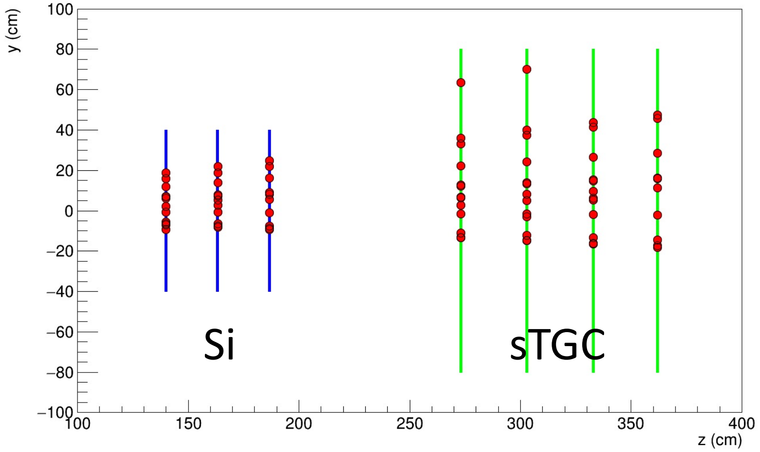


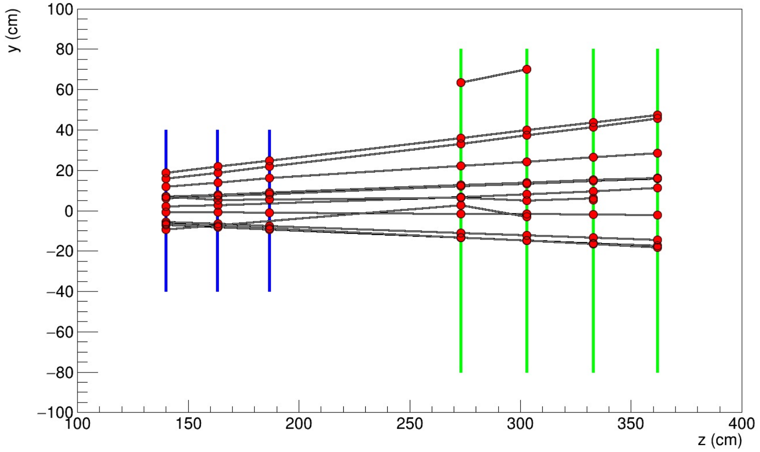
Figure 28: $e^- e^+ \rightarrow \Lambda \bar{\Lambda}$

Track Finding Procedure

- How do we go from this:



- To this:



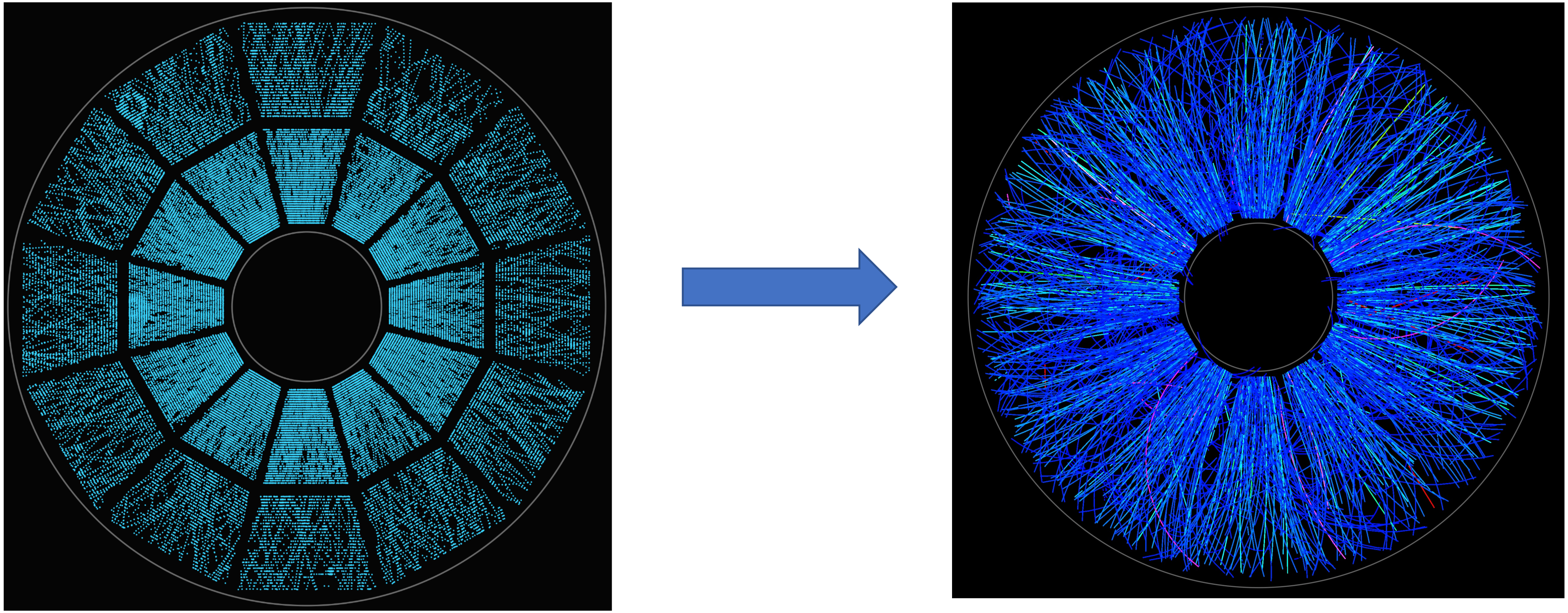
Naïve approach : make all possible connections

- Very slow due to combinatorial blow up
- Still need to distinguish real track segments from combinatorial

Cellular Automation

- Use simple “criteria” to build up longer segments of hits
- Build small segments, then grow them according to additional criteria
- Very performant & easily parallelized

Tracking in the STAR TPC (with iTPC upgrade)



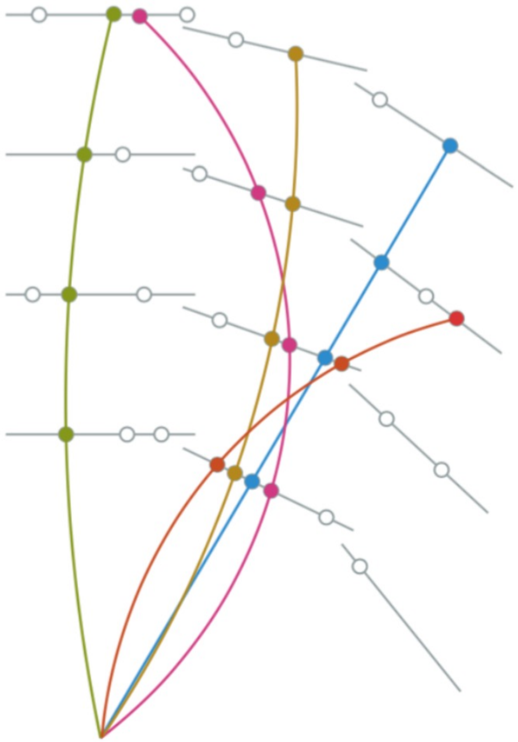
- Thousands of tracks per event (central collisions)

Conway’s Game of Life

A “glider” gun (Wikipedia)

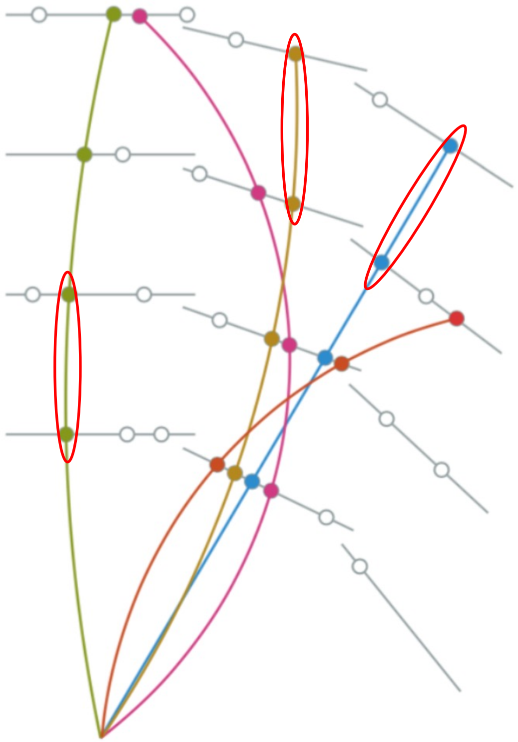
- Cellular Automation
  - System is in discrete states
  - “Update” state based on simple rules
  - Simple initial conditions and simple rules → complex emergent behavior
- But how can we use this for particle tracking?

Apply Cellular Automation to Tracking?



- How to apply Cellular Automation?
- How to express states of the system?
- How do we “update” to grow our tracks?

Apply Cellular Automation to Tracking?



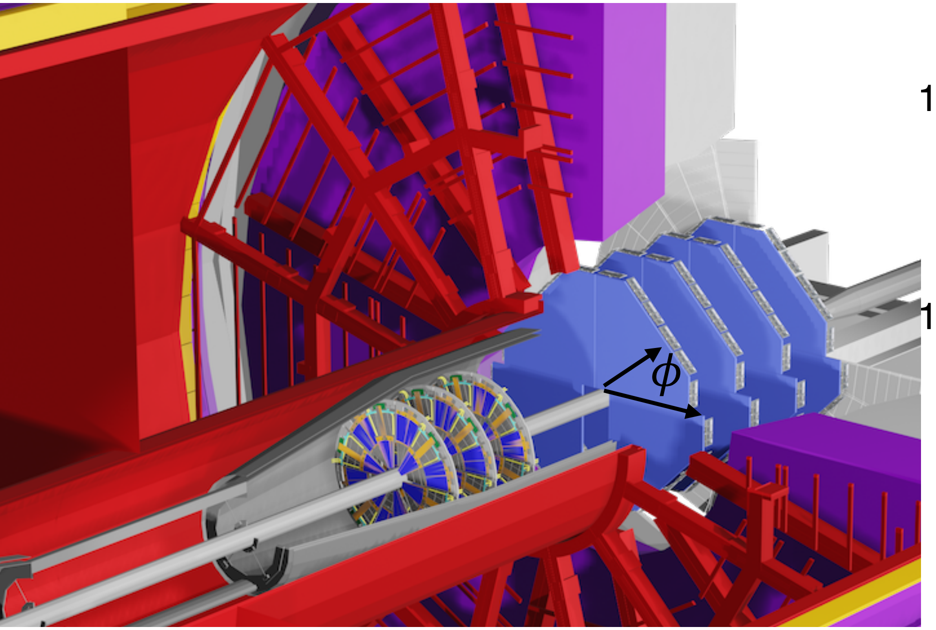
- First look at "hit pairs"
- Hits on neighboring detector planes
- How to distinguish "real" pairs (from a single particle track) from "fake" pairs?

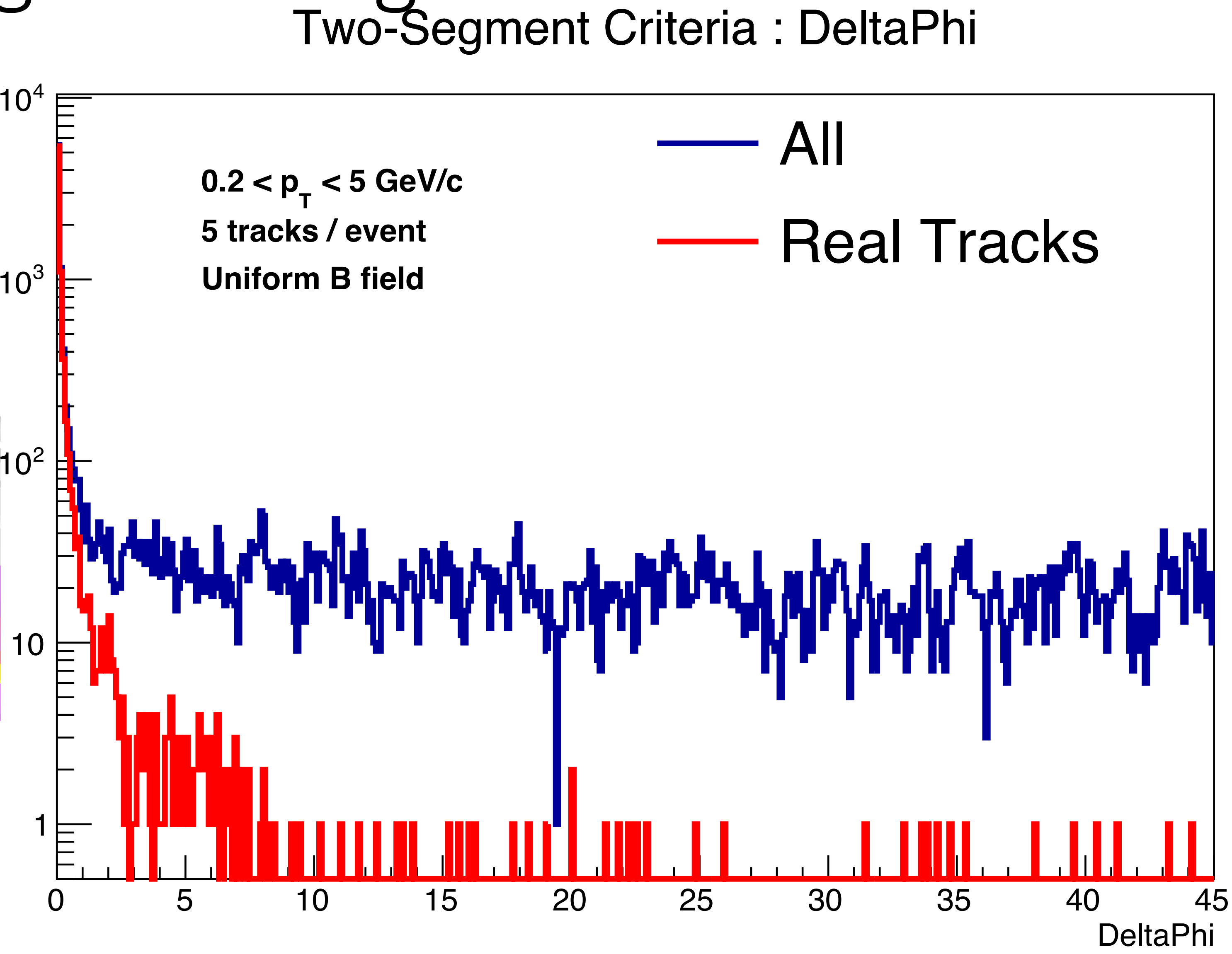
- Can we apply simple criteria for this?

Criteria for Finding Track Segments

Criteria DeltaPhi :

$$\Delta\phi = \phi_A - \phi_B$$



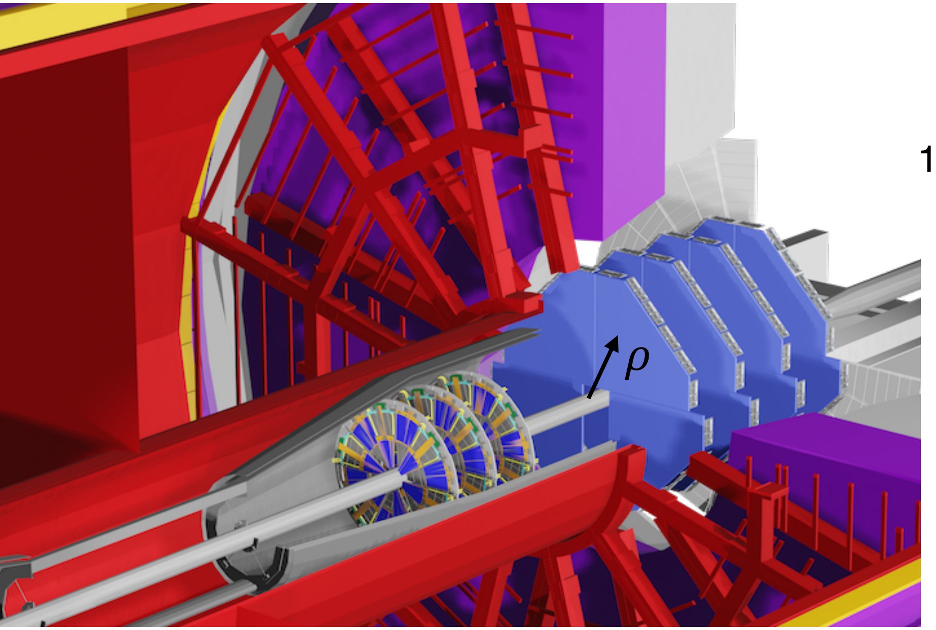


Hits at GEN level precision ($\sigma_x = \sigma_y = 0$)

Criteria for Finding Track Segments

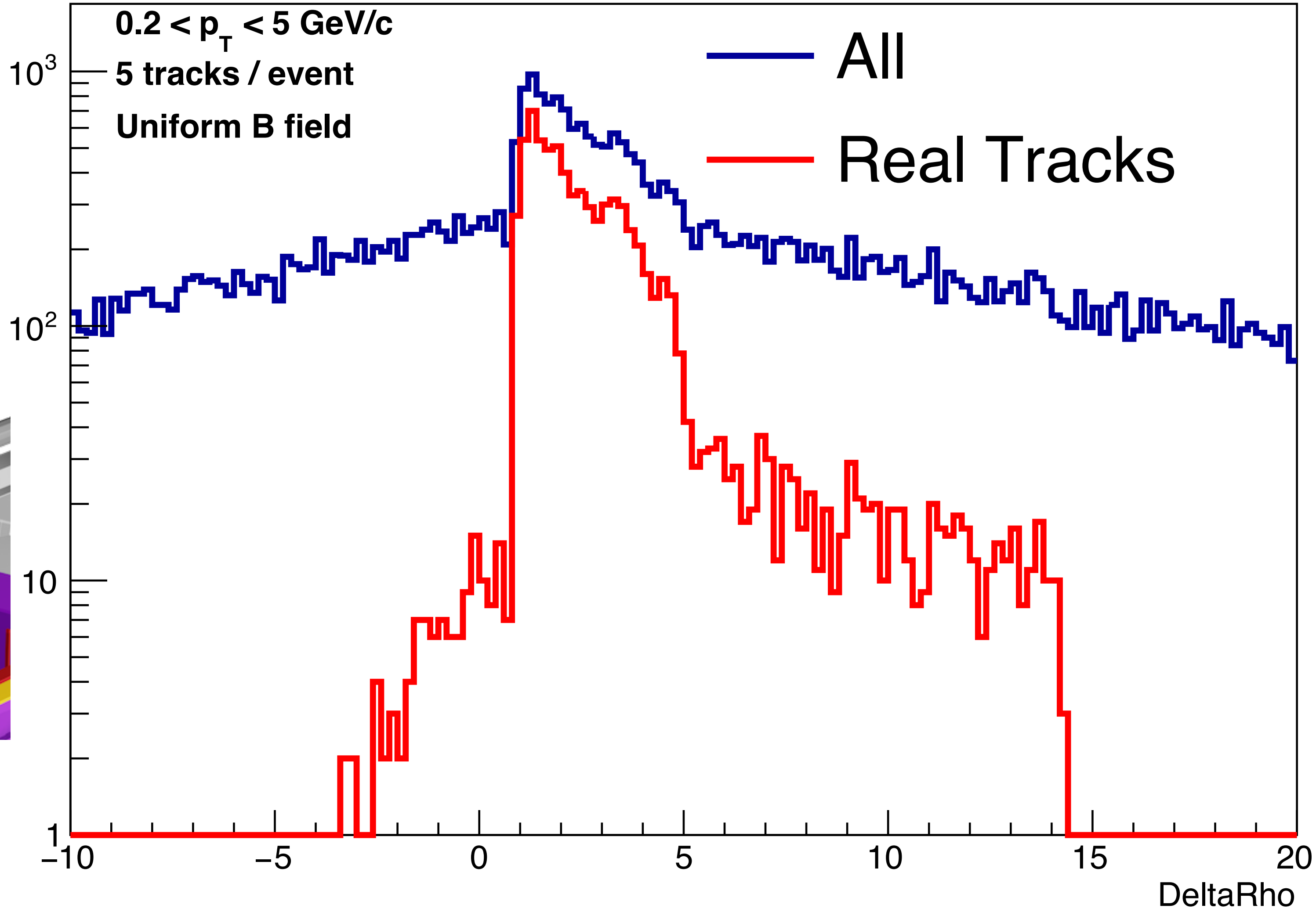
Criteria DeltaRho :

$$\rho = \sqrt{x^2 + y^2}$$
$$\Delta\rho = \rho_A - \rho_B$$



Hits at GEN level precision ($\sigma_x = \sigma_y = 0$)

Two-Segment Criteria : DeltaRho



Criteria for Finding Track Segments

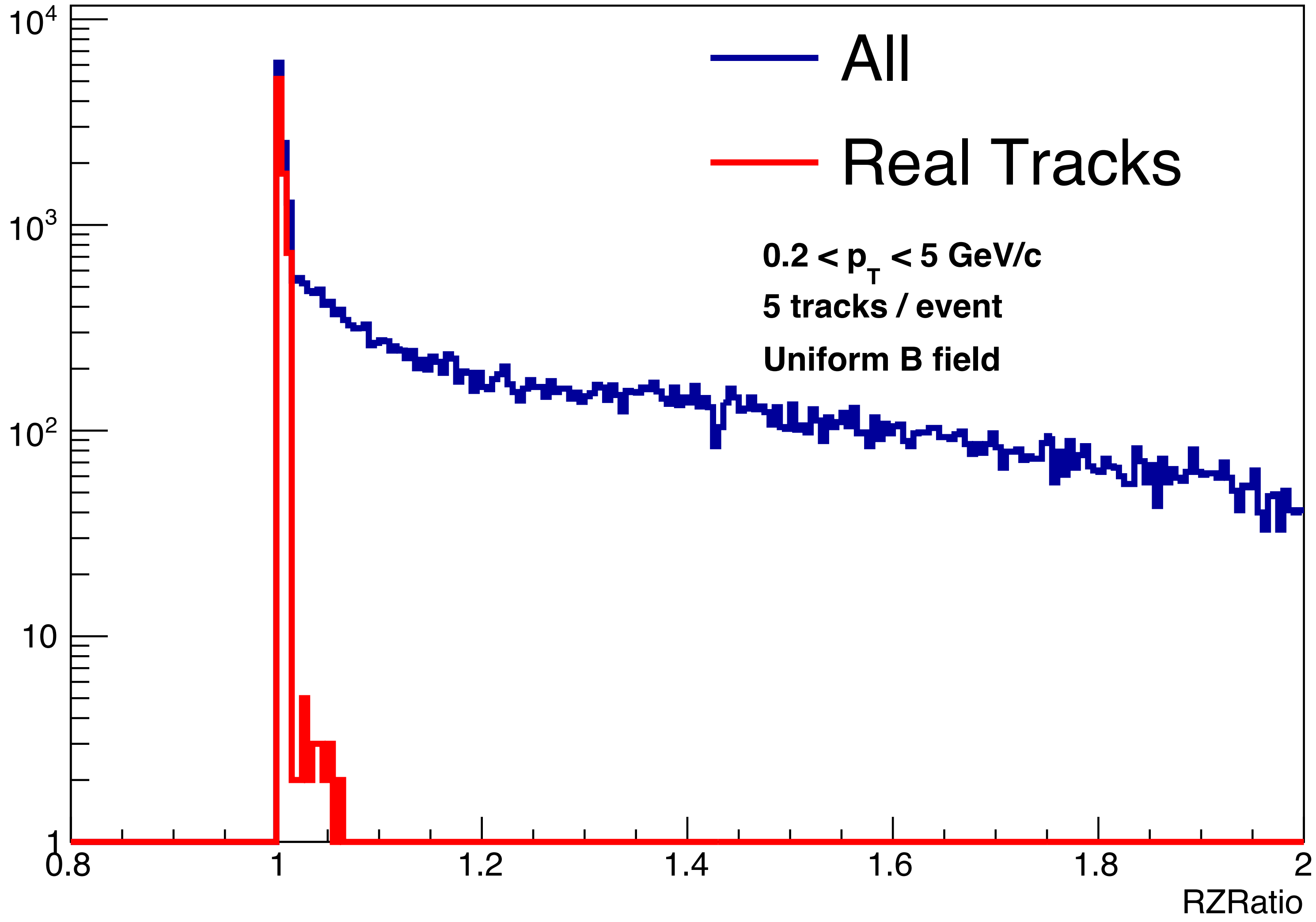
Criteria RZRatio :

$$\left(\frac{\Delta R}{\Delta z}\right)^2 = \frac{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}{(\Delta z)^2}$$

Strong discriminator for forward tracks

Hits at GEN level precision
$(\sigma_x = \sigma_y = 0)$

Two-Segment Criteria : RZRatio



$0.2 < p_T < 5$ GeV/c
5 tracks / event
Uniform B field

Criteria for Finding Track Segments

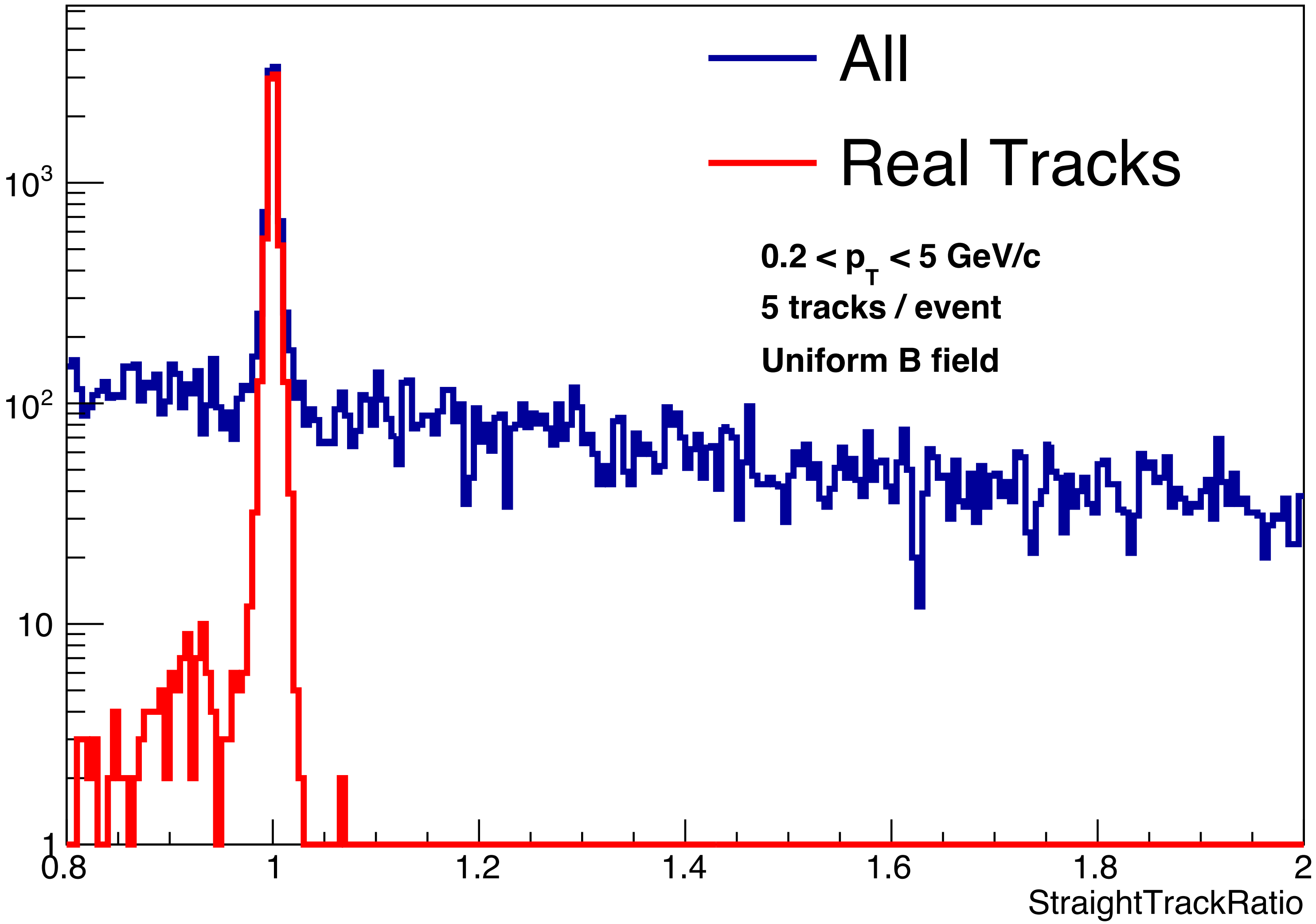
Criteria
StraightTrackRatio :

$$\frac{\rho_A * z_B}{\rho_B * z_A}$$

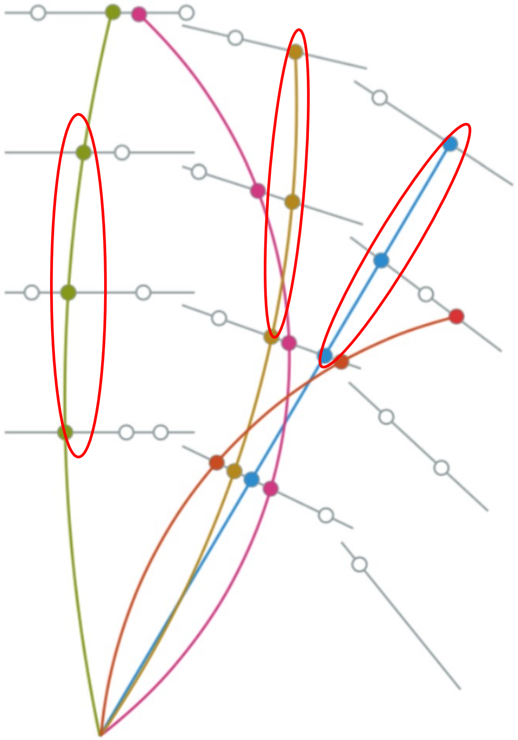
Strong discriminator for forward tracks

Hits at GEN level precision $(\sigma_x = \sigma_y = 0)$

Two-Segment Criteria : StraightTrackRatio



Apply Cellular Automation to Tracking?



- Next look at “hit triplets”
- Hits on neighboring detector planes connected by one hit
- How to distinguish “real” pairs (from a single particle track) from “fake” pairs?

- Can we apply simple criteria for this?

Criteria for Finding Track Segments

Criteria 2DAngle :

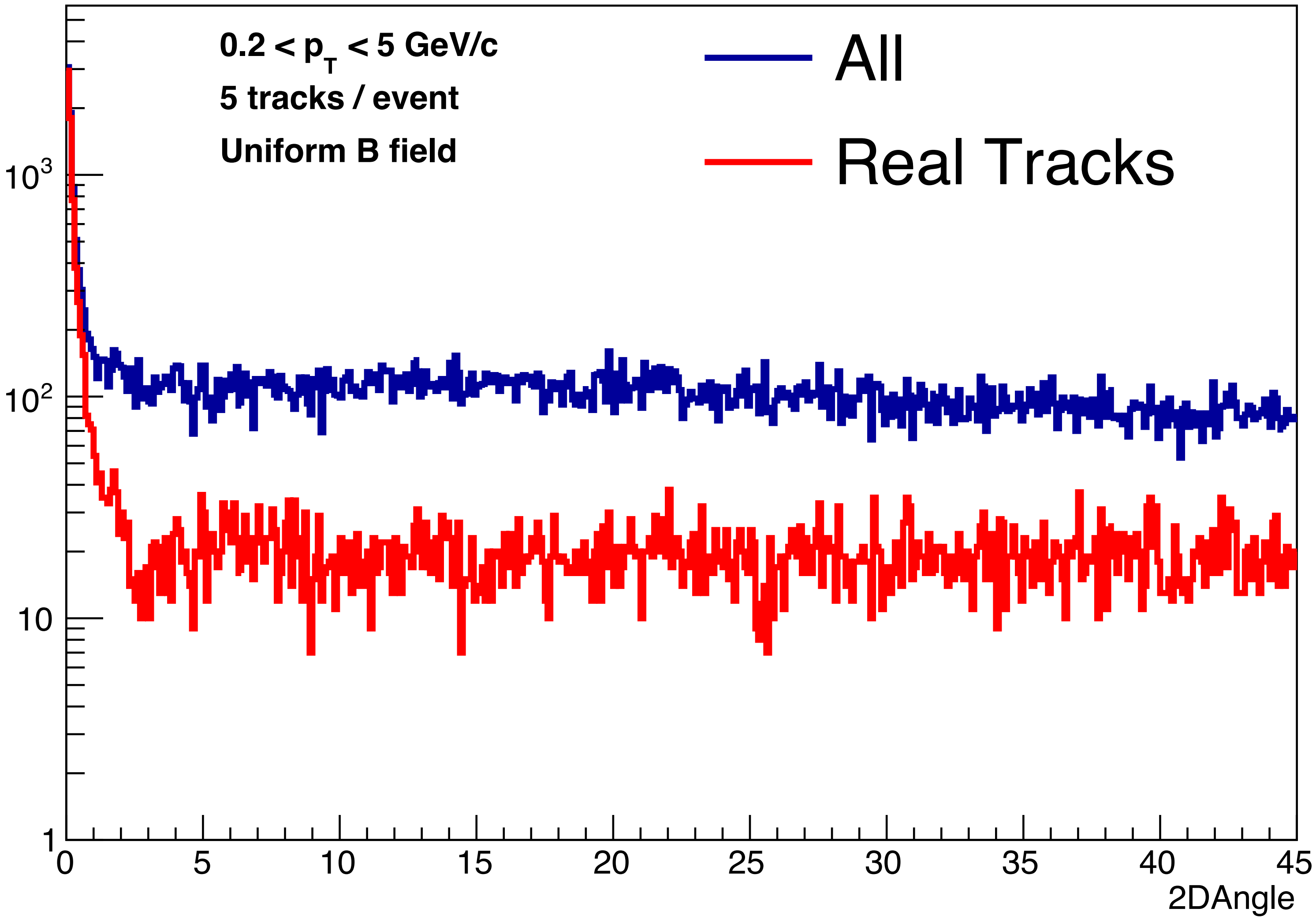
$$\Delta x_1 = x_B - x_A$$
$$\Delta y_1 = y_B - y_A$$

$$\Delta x_2 = x_C - x_B$$
$$\Delta y_2 = y_C - y_B$$
$$u = (\Delta x_1)^2 + (\Delta y_1)^2$$
$$v = (\Delta x_2)^2 + (\Delta y_2)^2$$

$$\cos^2(\theta) = \frac{\Delta x_1 * \Delta x_2 + \Delta y_1 * \Delta y_2}{u * v}$$

Hits at GEN level precision ($\sigma_x = \sigma_y = 0$)

Three-Segment Criteria : 2DAngle



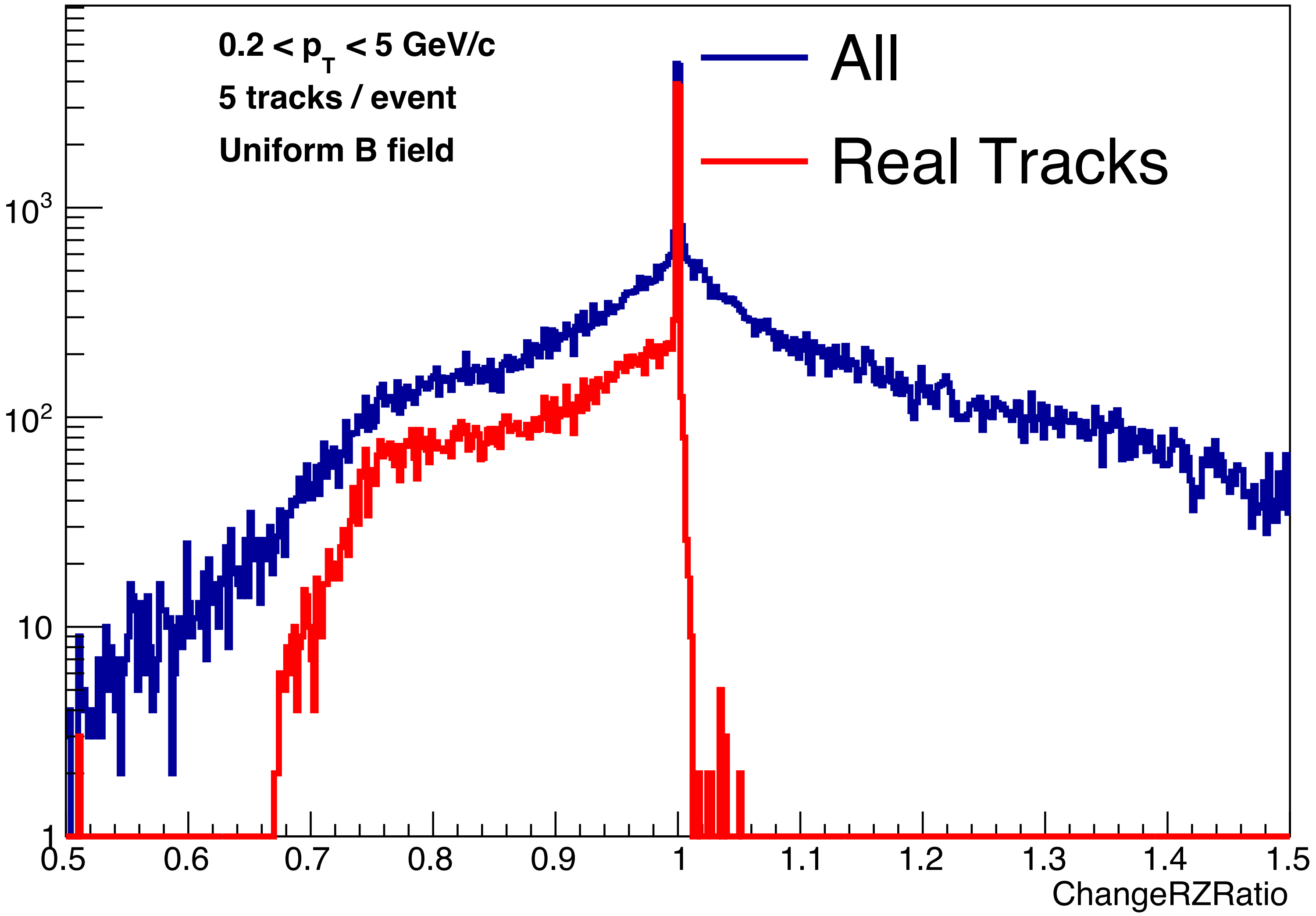
Criteria for Finding Track Segments

Criteria ChangeRZRatio :

$$\Delta RZ = \left(\frac{\Delta R}{\Delta z}\right)^2_{BA} - \left(\frac{\Delta R}{\Delta z}\right)^2_{BC}$$

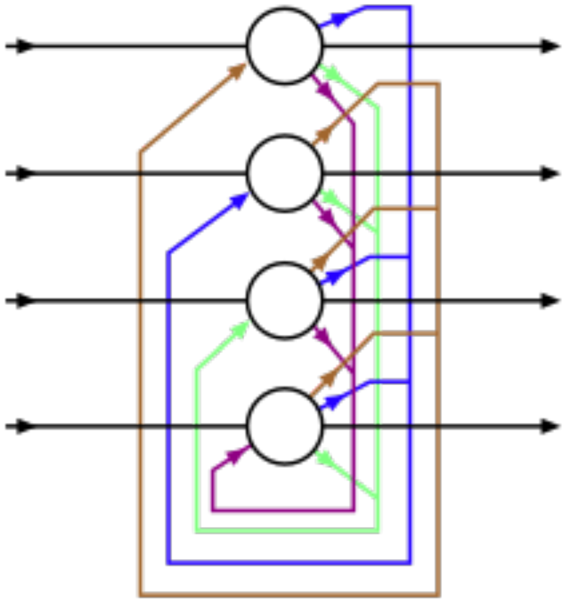
Hits at GEN level precision
$(\sigma_x = \sigma_y = 0)$

Three-Segment Criteria : ChangeRZRatio



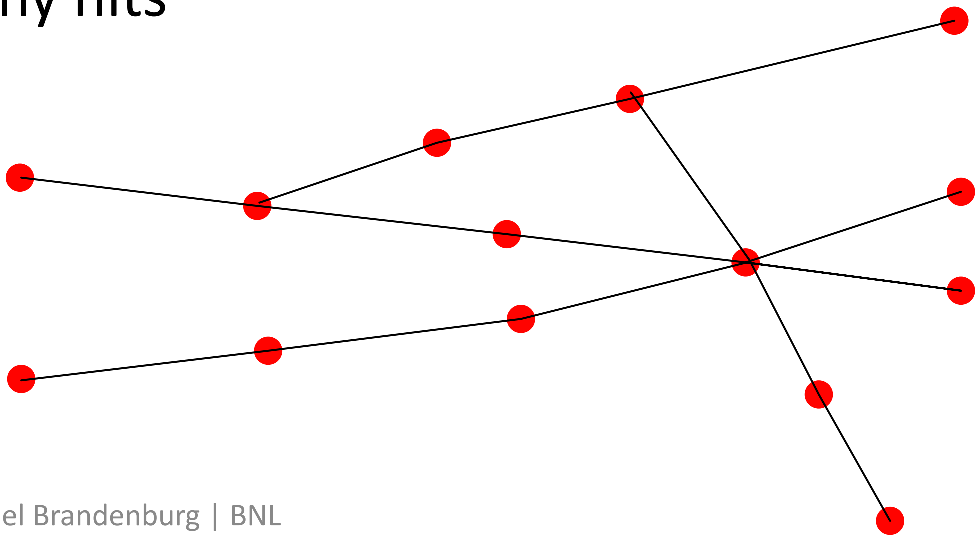
Cleaning the Cellular Automata output

- After Cellular automata, we have all possible tracks
- Use Hopfield Neural Network to find "Best Tracks"



Hopfield Recurrent Artificial Neural Network

- Can process "corrupt" data, reconstructing true data
- Recurrent network – exhibits temporal behavior "memory"
- For tracking, ideal for finding **unique tracks**
- It is generally a good assumption that real tracks do not share any hits



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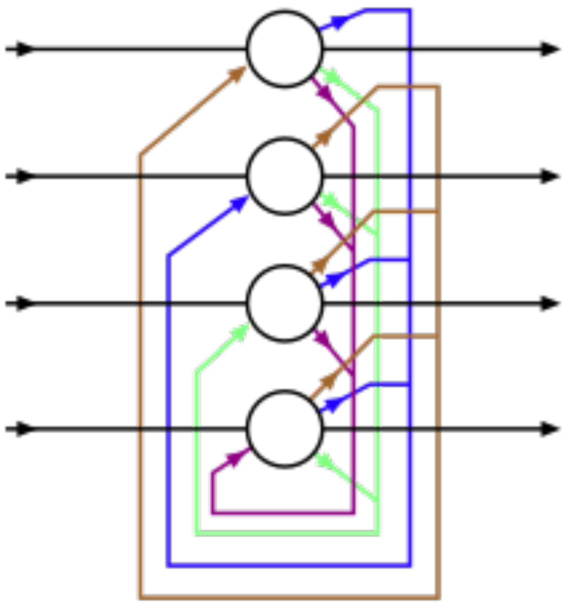

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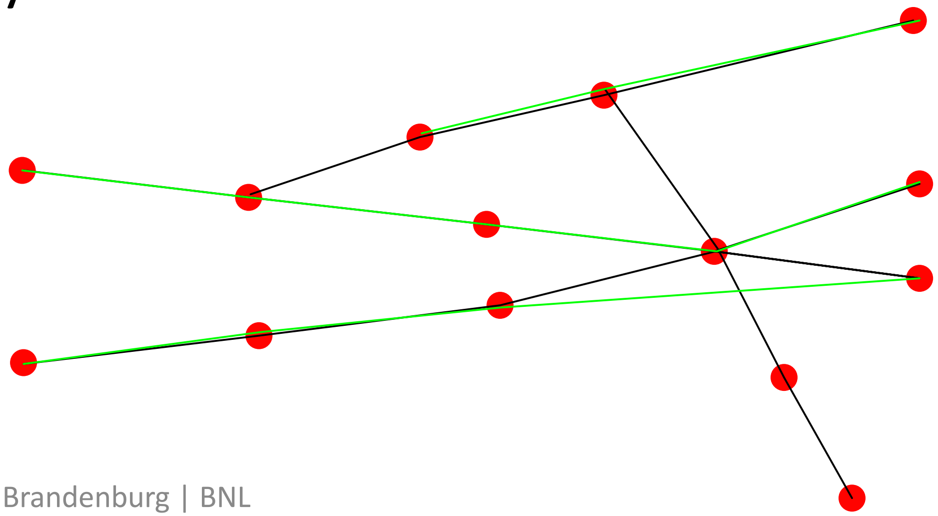
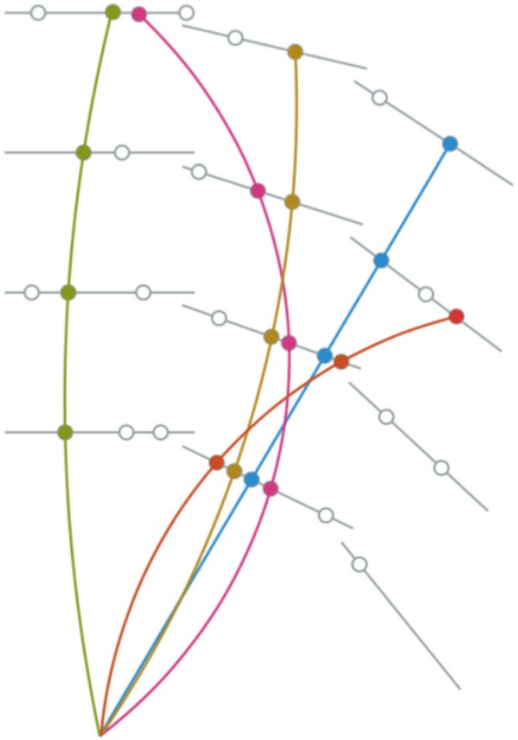


Goal of Track Finding

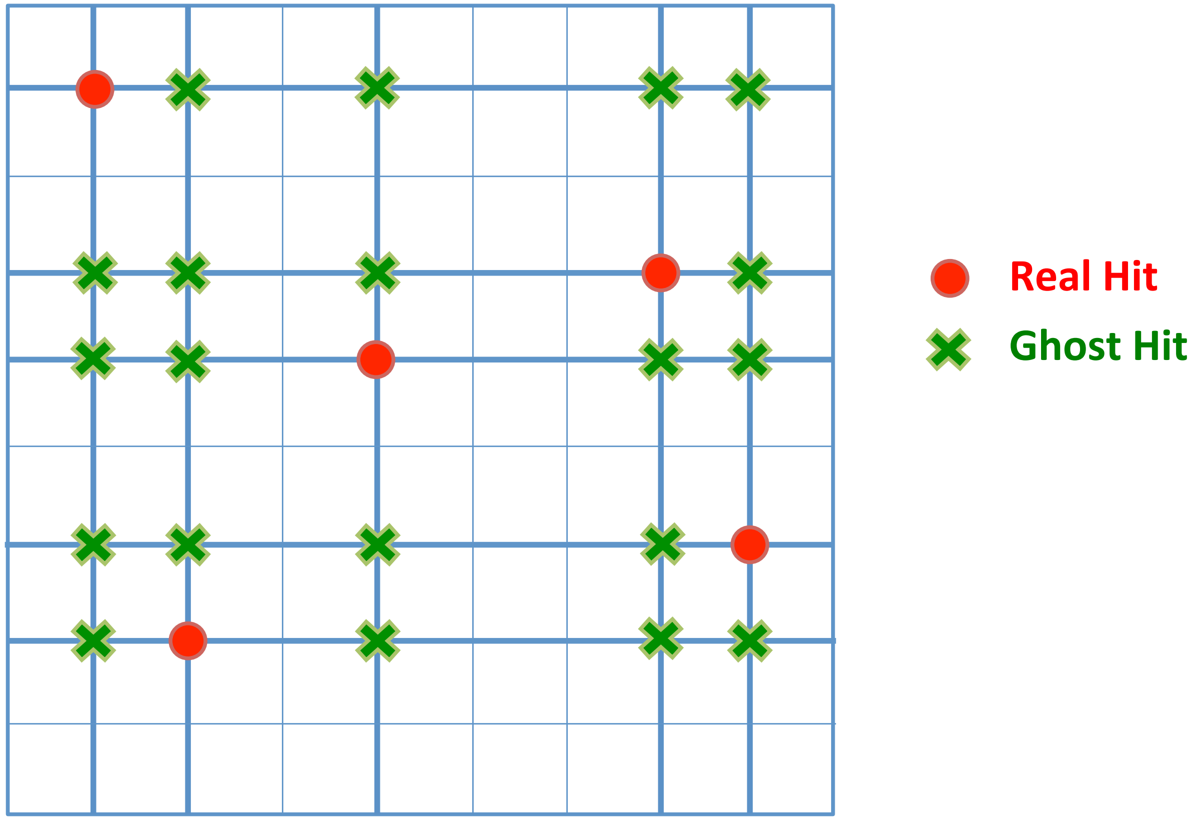


1. Efficiency
   - Find every track that exists – criteria cannot be too specific or inflexible

2. Purity
   - Don’t find tracks that shouldn’t be there
   - Caused by mismatching hits from one track with hits from another (previous slides)
   - Ghost hits!

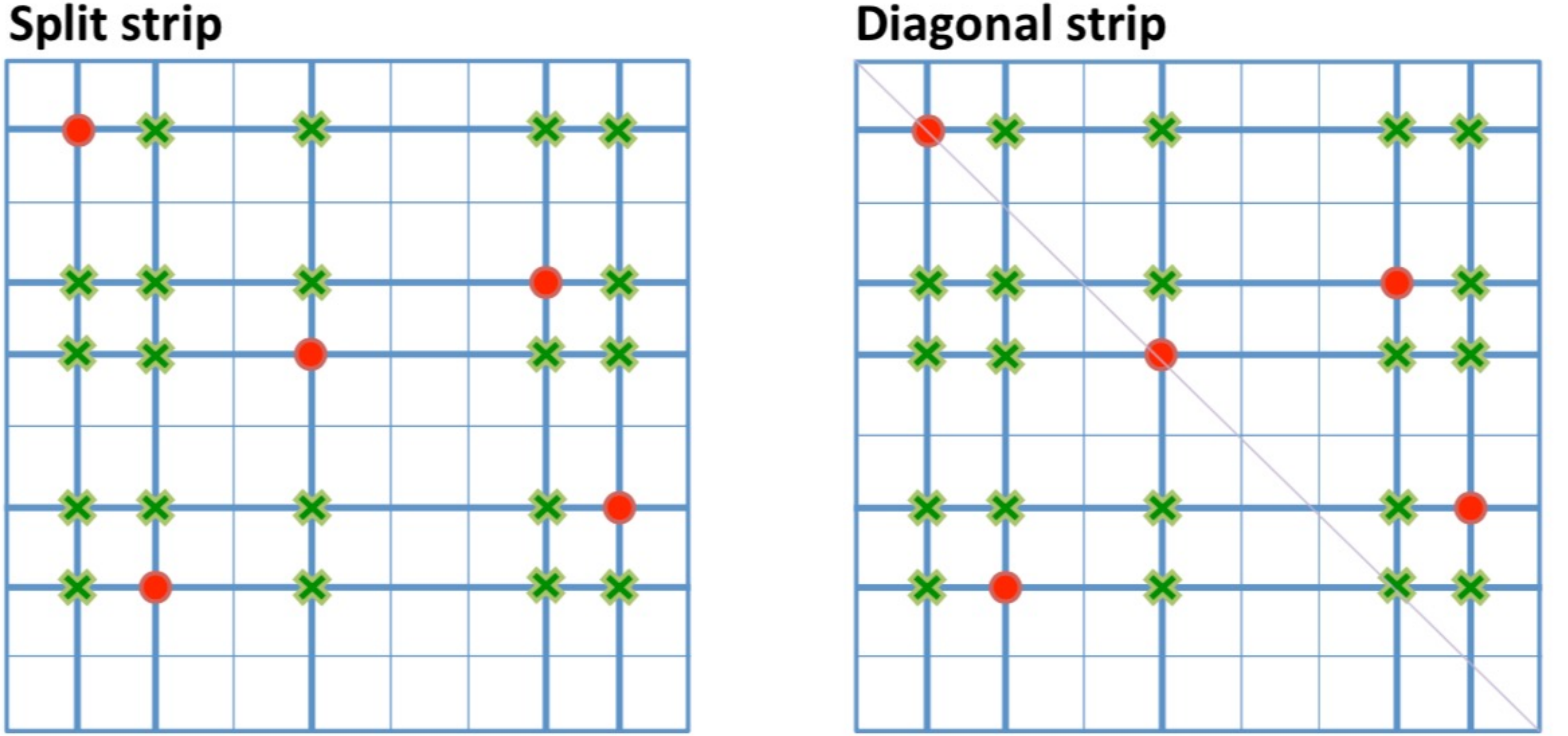
sTGC Ghost hits

sTGC ghost hits



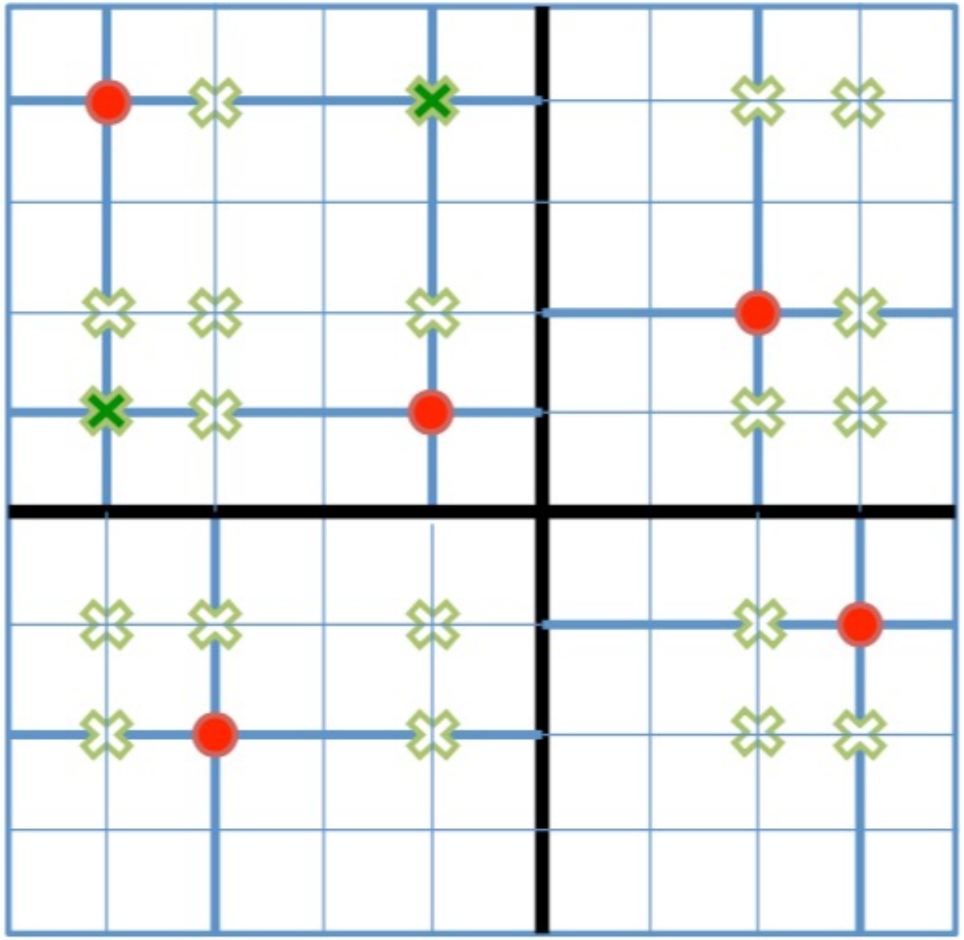
- sTGC is basically a sandwich of two 1 dimensional detectors
- Ambiguity exists when multiple hits occur
- Leads to “ghost” hits
- Major problem for high multiplicities

Reduce Ghost hits with Diagonal strips

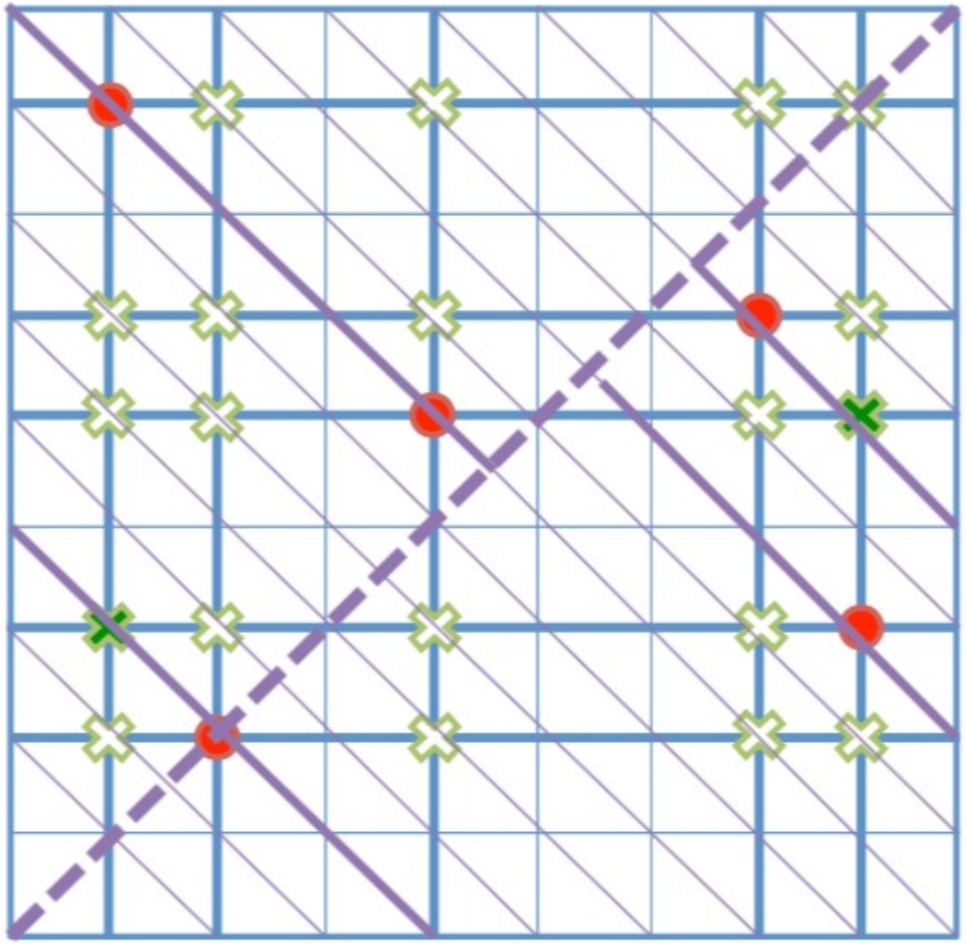


Reduce Ghost hits with Diagonal strips

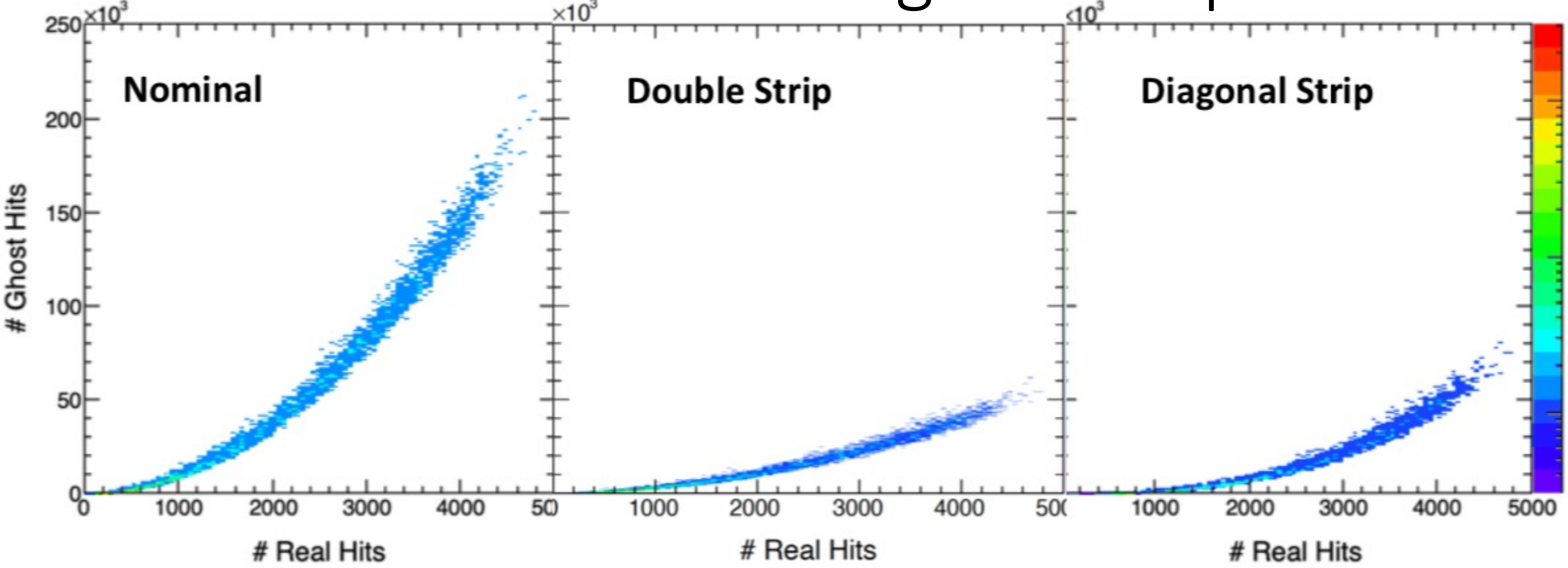
Split strip



Diagonal strip

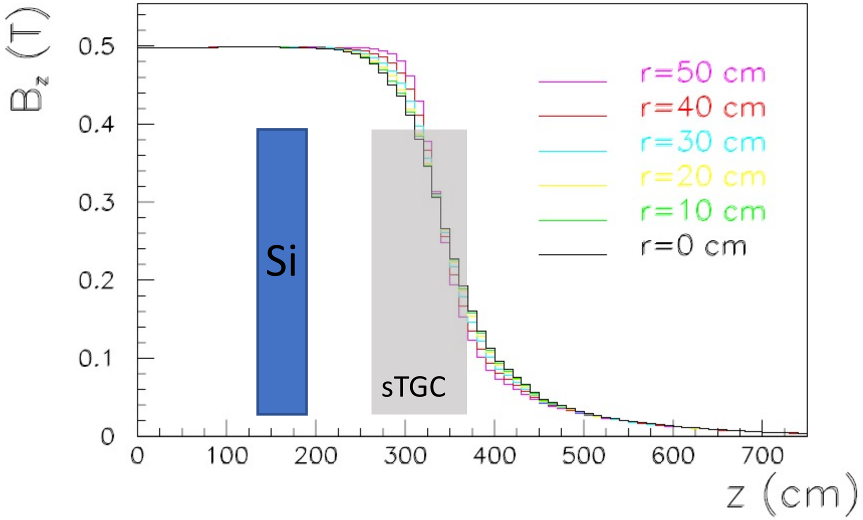


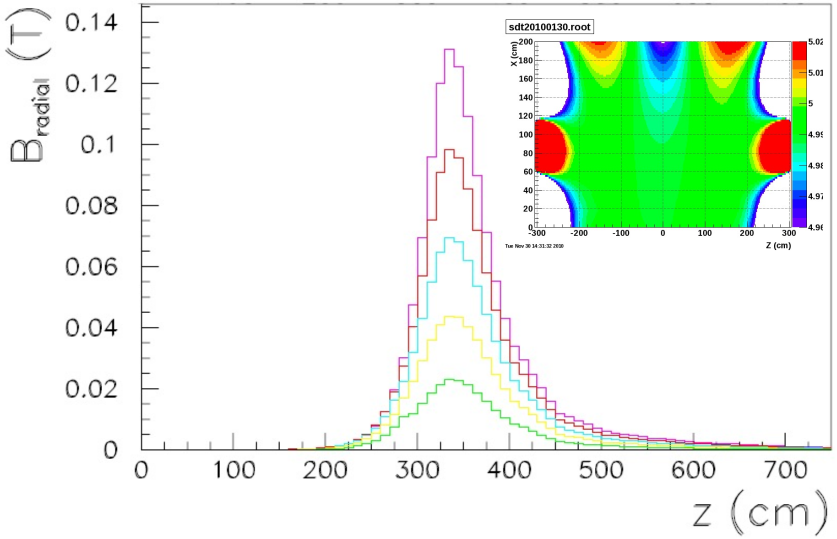
Reduce Ghost hits with Diagonal strips

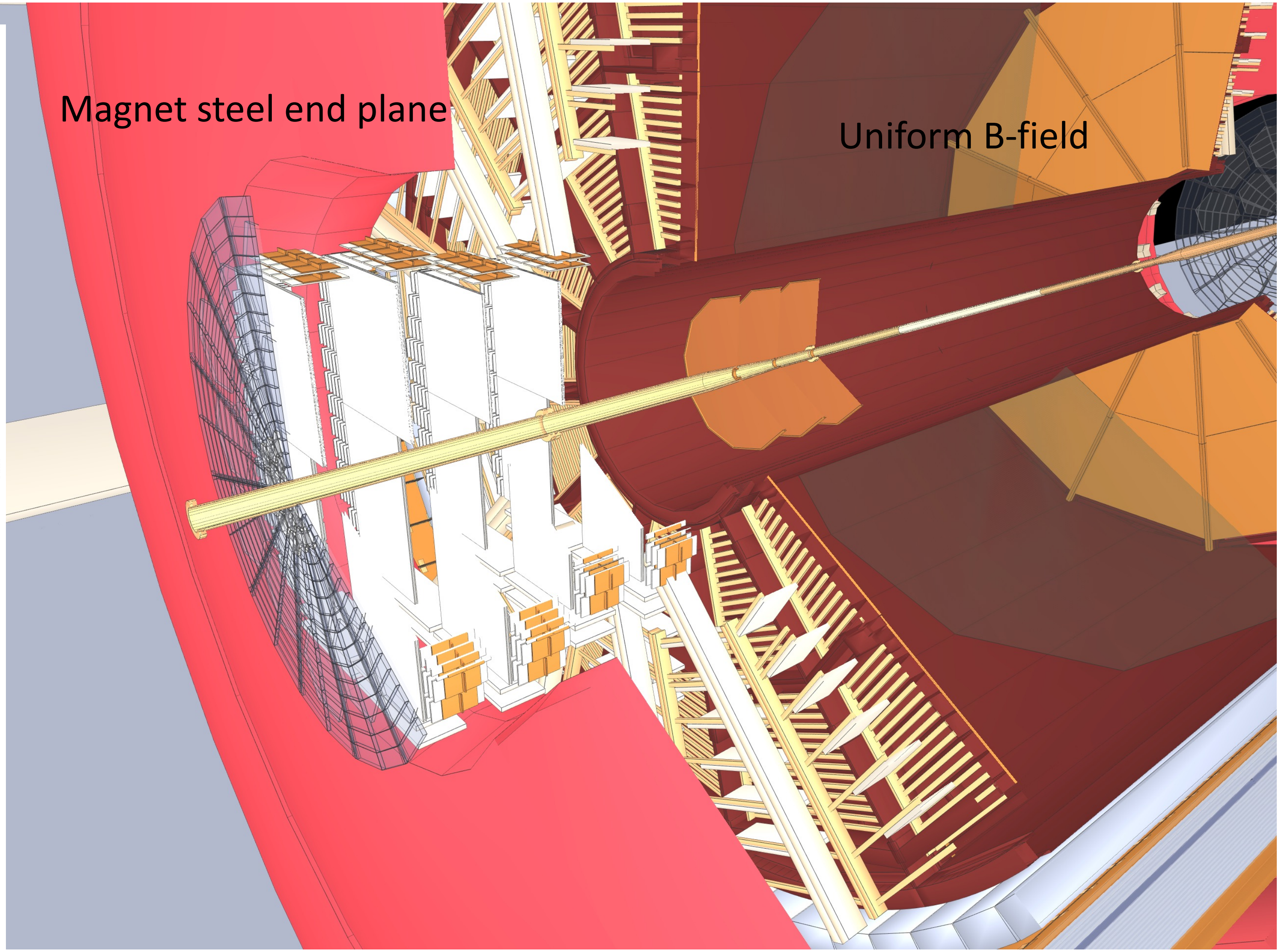


Significant reduction of ghost hits

Challenges: Magnetic Field in Forward Region





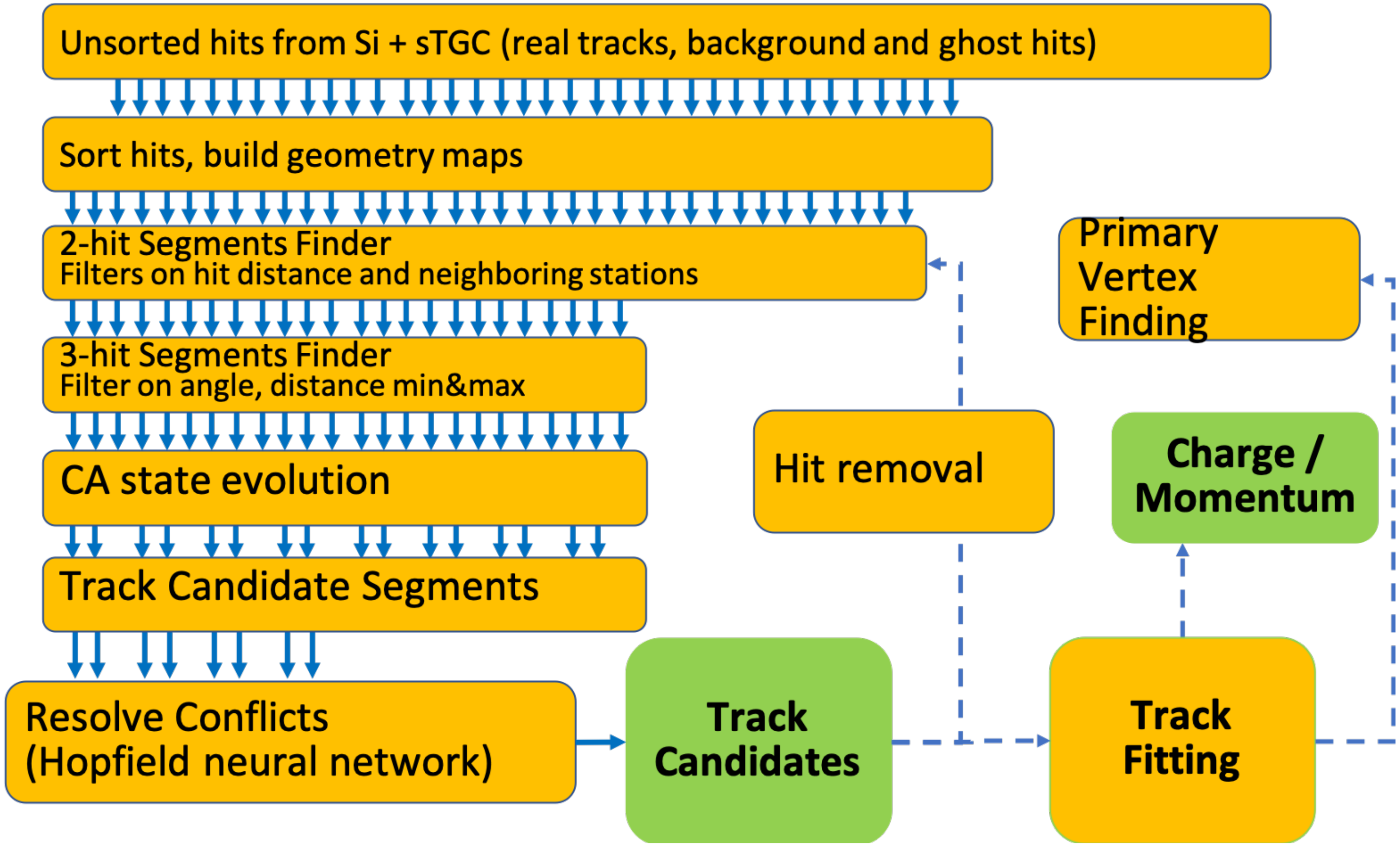


Forward Tracking

Unique Challenges:

- Combination of detector technologies: Silicon & sTGC
- Changing magnetic field
- Large hit density

- Track finding:
  - Cellular Automata
- Track Fitting:
  - GENFIT2 (a multi-experiment tracking framework)



Unsorted hits from Si + sTGC (real tracks, background and ghost hits)

Sort hits, build geometry maps

2-hit Segments Finder
Filters on hit distance and neighboring stations

3-hit Segments Finder
Filter on angle, distance min&max

CA state evolution

Track Candidate Segments

Resolve Conflicts
(Hopfield neural network)

Track Candidates

Hit removal

Track Fitting

Primary Vertex Finding

Charge / Momentum

Tracking Efficiency

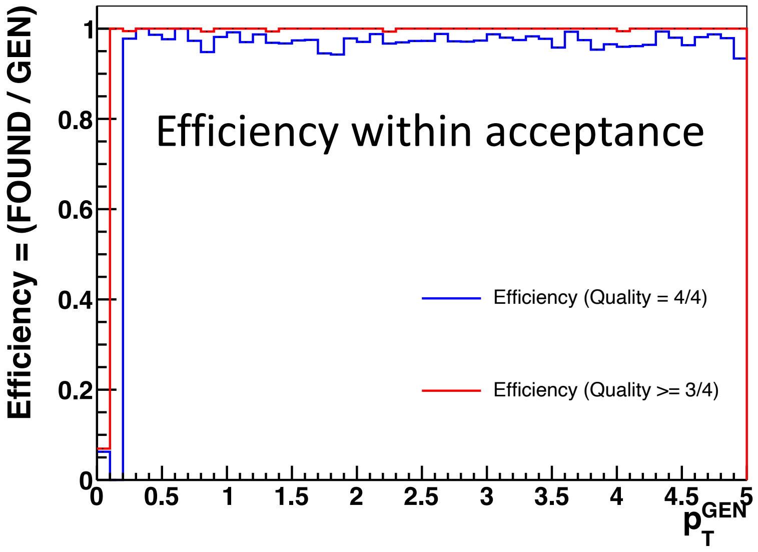
Evaluate performance under ideal conditions

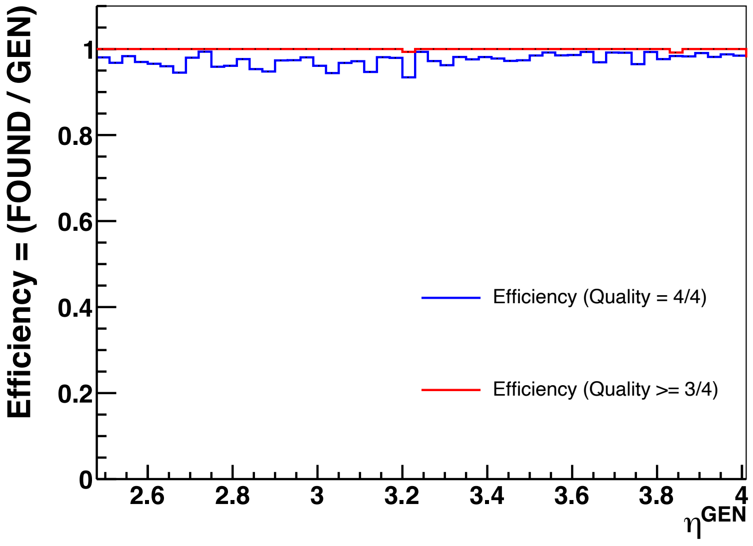
- Track finding efficiency (perfect 4/4 correct hits) is ≈ 98%
- Track finding efficiency (3/4 or more correct hits) is ≈ 99.5%
- **Full material effects**
- **Real STAR B-field**

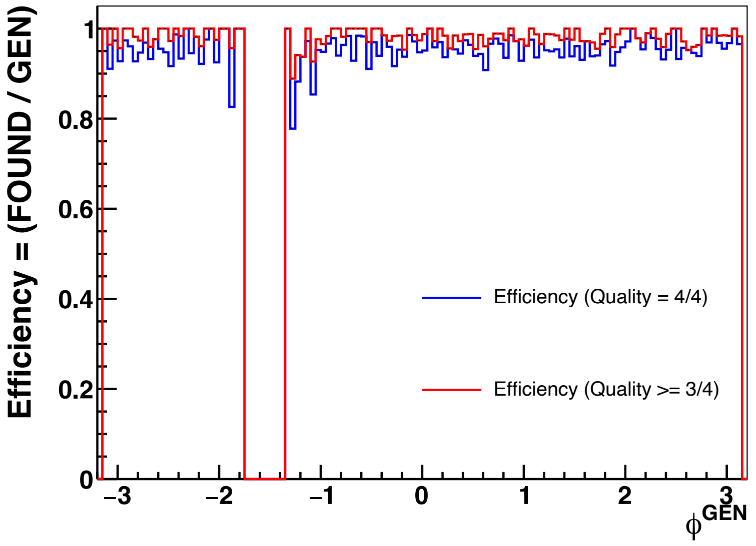
GENERATOR (“GEN” or “MC” hits):

- $1\ \mu^+$ / Event
- $2.45 < |\eta| < 4.05$
- $0.2 < p_T < 5\ GeV/c$
- B Field : **REAL** (StarMagField)
- Primary Vertex distribution $\mu = (0, 0, 0)$, σ =(0.05, 0.05, 5) cm.

- CA Track finding uses sTGC only, fast & generic


Efficiency within acceptance





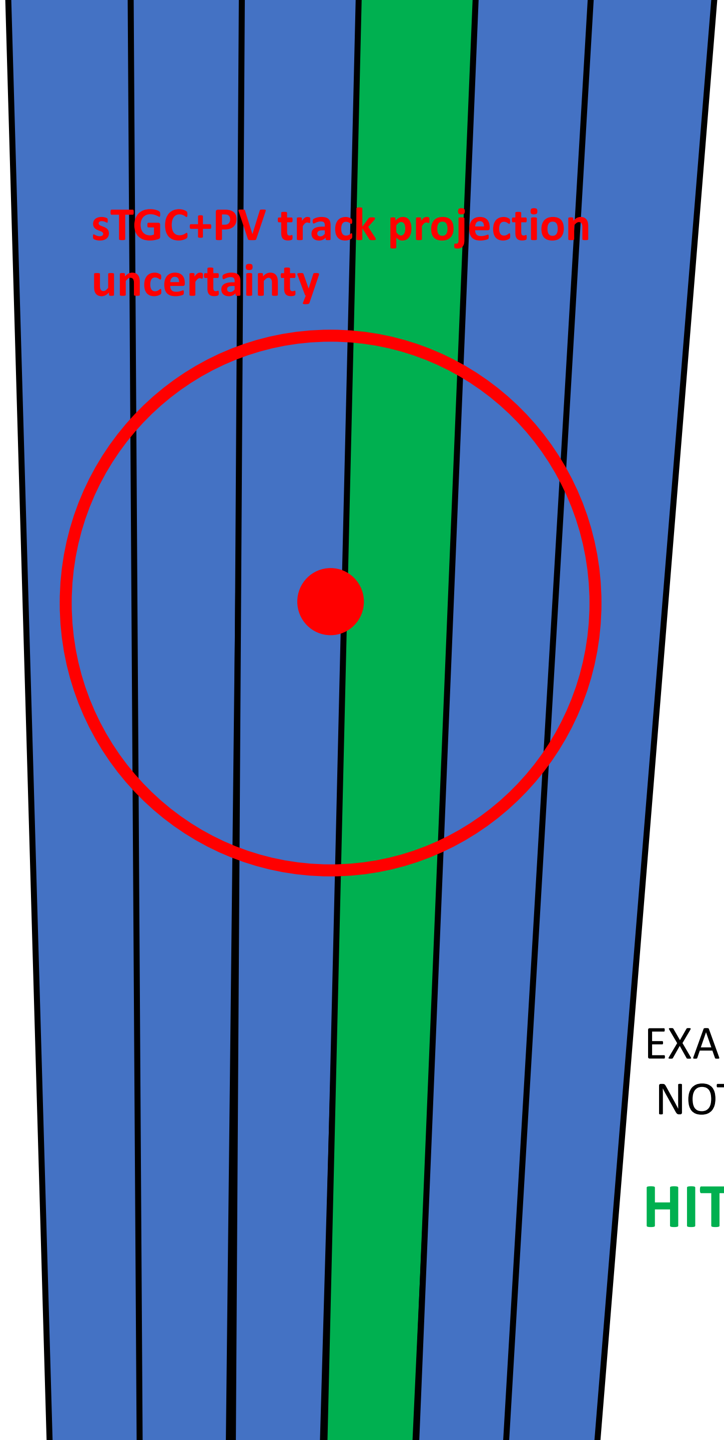
Tracking Algorithm

Track Finding

- Cellular Automata based
- Uses hits from sTGC detector

Track Fitting procedure

1. Fit primary vertex + sTGC hits
2. Swim along track, find hits in Si planes
3. Refit with primary vertex + Si + sTGC

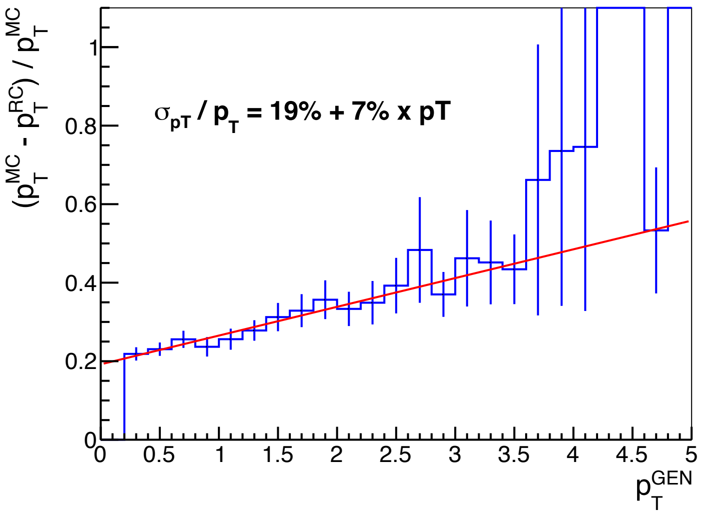


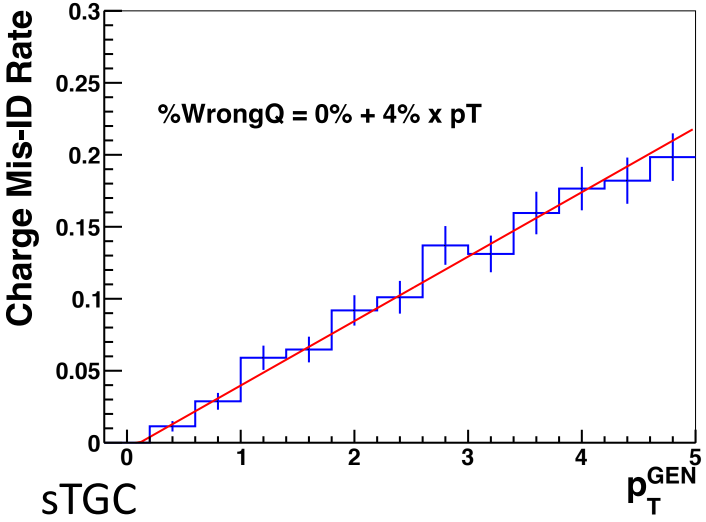
EXAMPLE ONLY:
NOT to SCALE

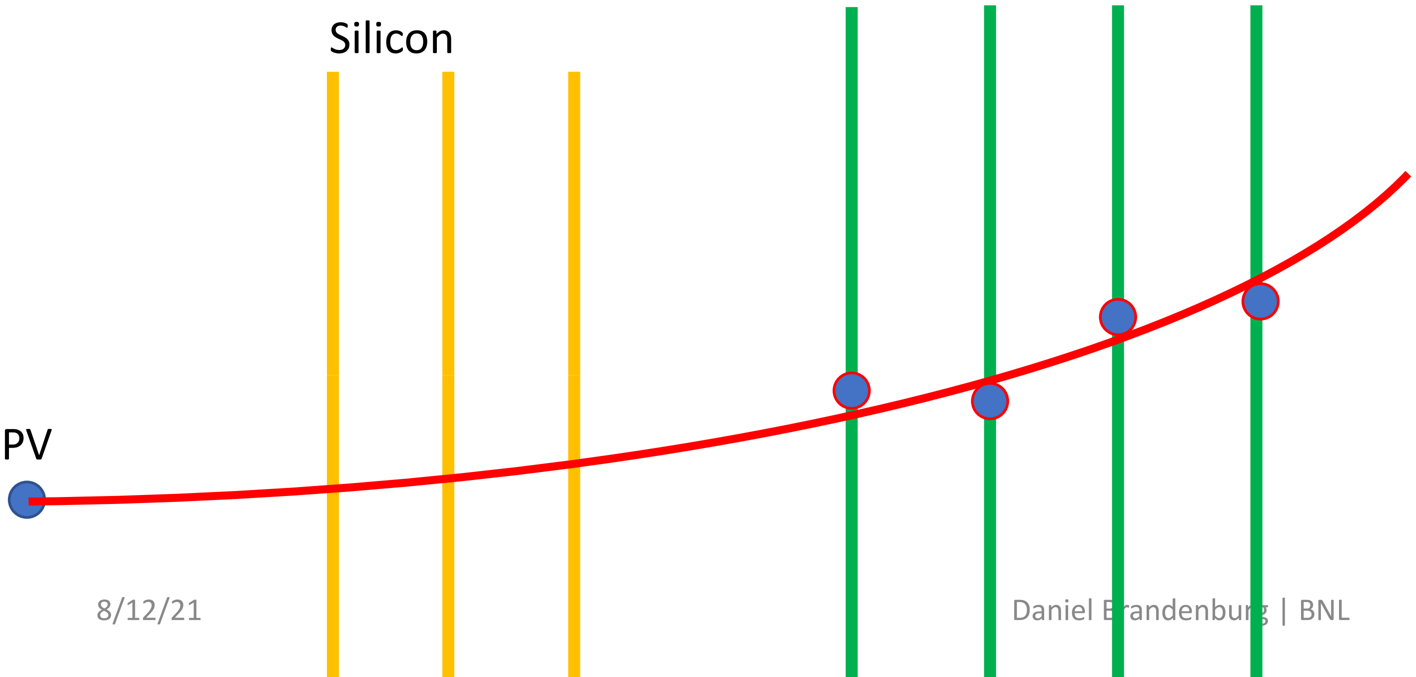
HIT Strip

Track Fitting and performance

sTGC + PV





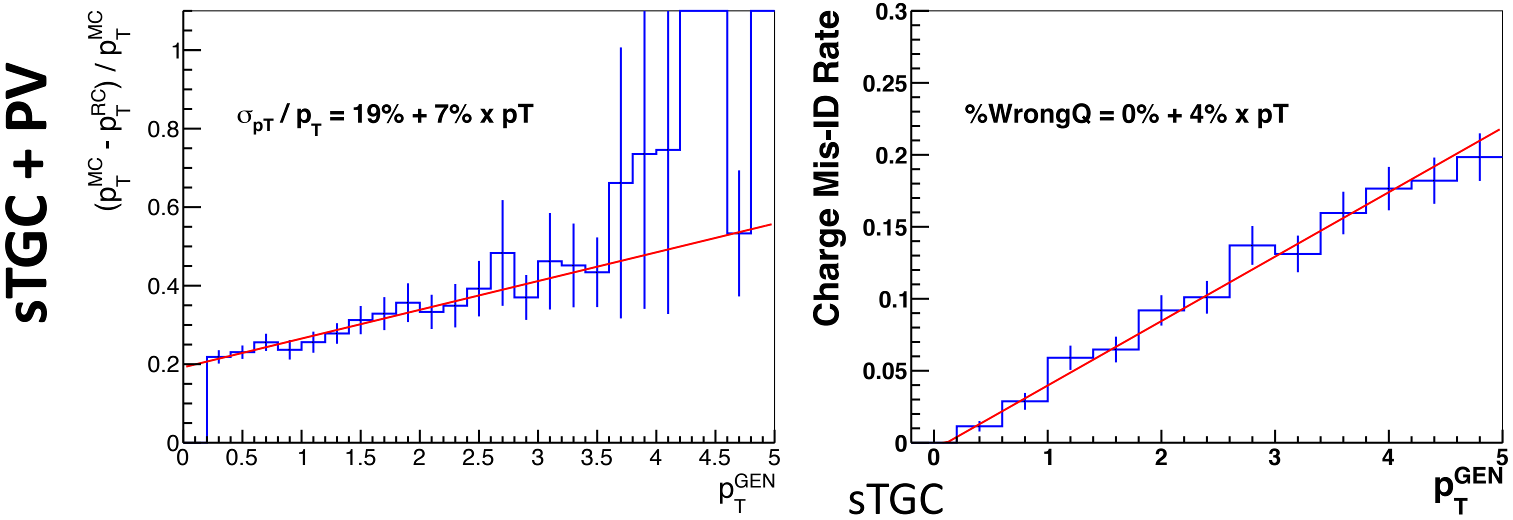


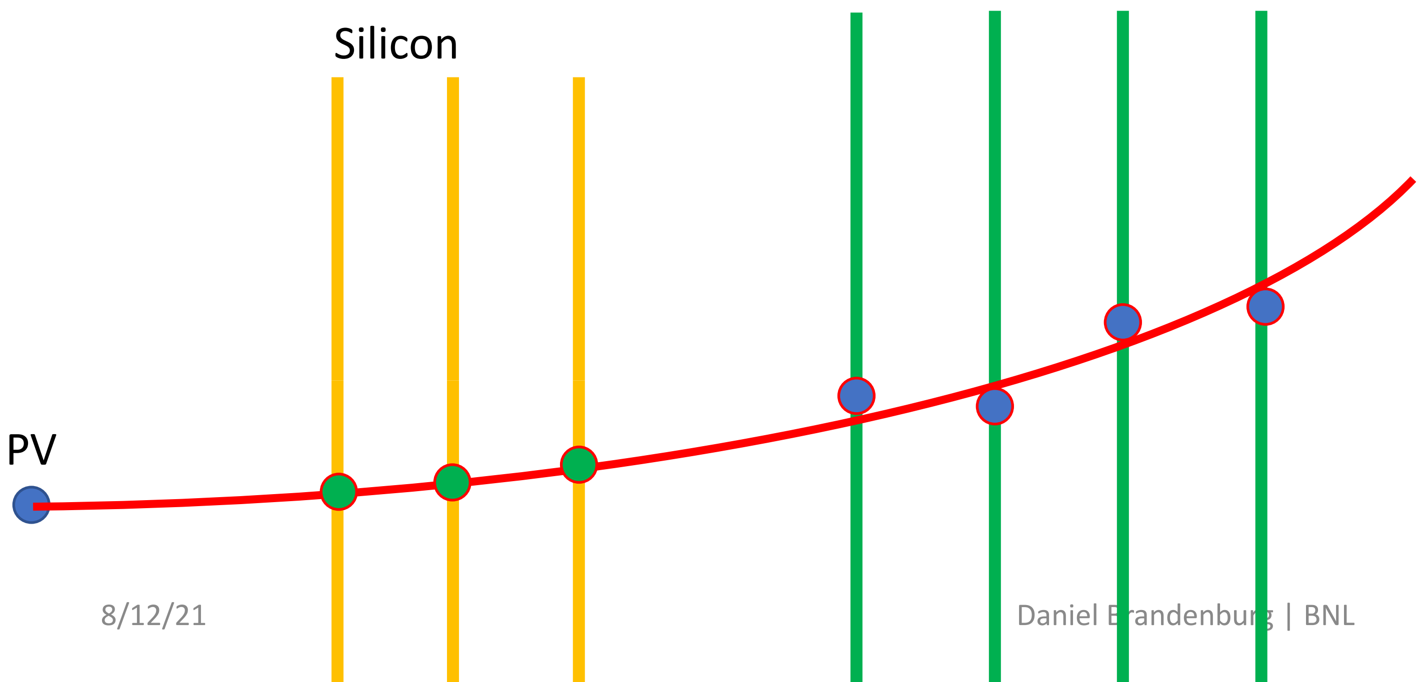
1. Fit with sTGC and primary vertex
2. Project tracks to Si disks and search for hits along track
3. Refit tracks with PV + sTGC + Si

Primary Vertex $\sigma_{XY} = 500\ \mu m$

- Beamline constraint should provide $\sigma_{XY} = 500\ \mu$m or better

Track Fitting and performance





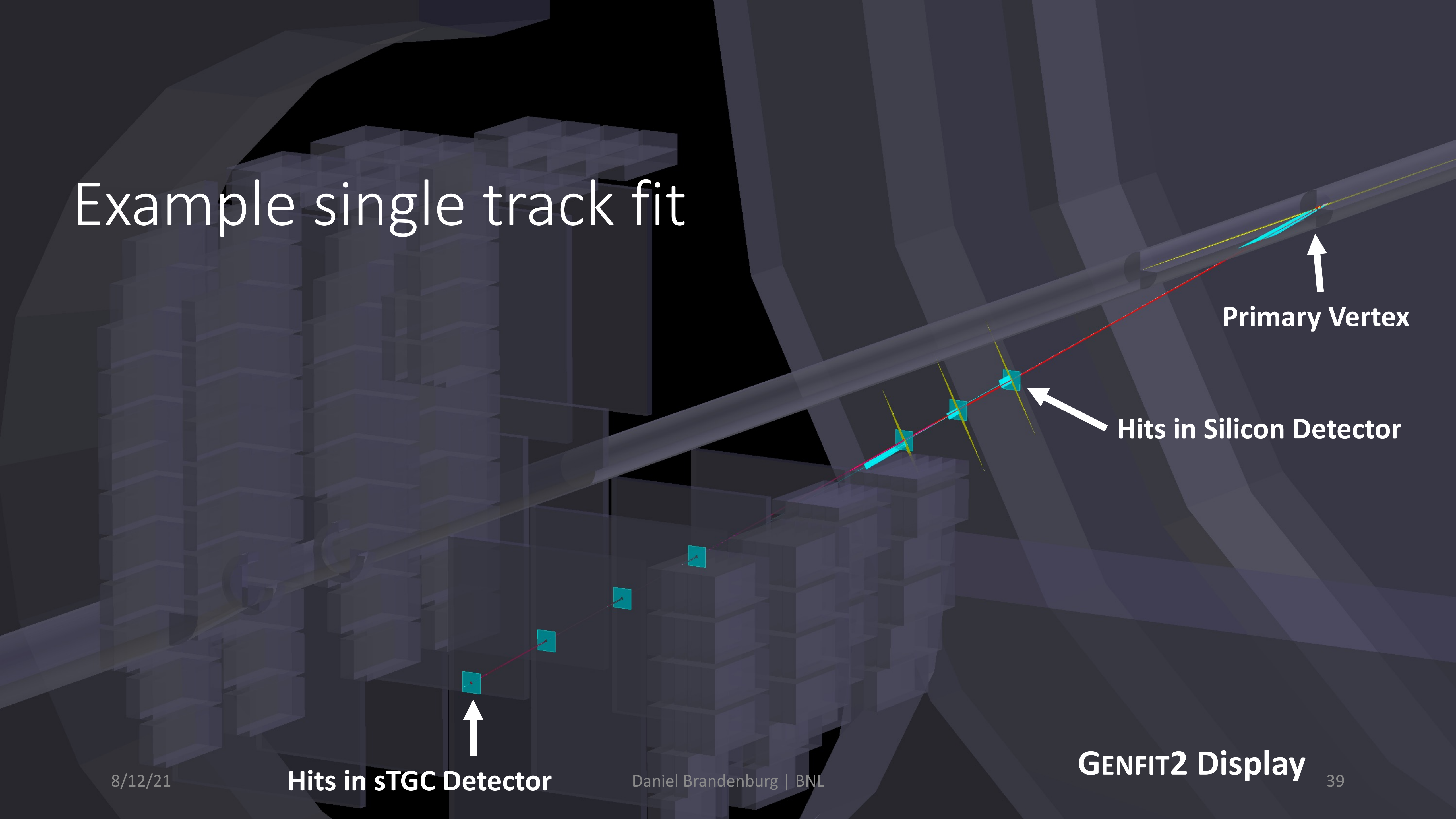
1. Fit with sTGC and primary vertex
2. Project tracks to Si disks and search for hits along track
3. Refit tracks with PV + sTGC + Si

Primary Vertex $\sigma_{XY} = 500\ \mu m$

- Beamline constraint should provide $\sigma_{XY} = 500\ \mu$m or better

- Combine projected R-position @ silicon with very high-precision phi-measurement

Example single track fit



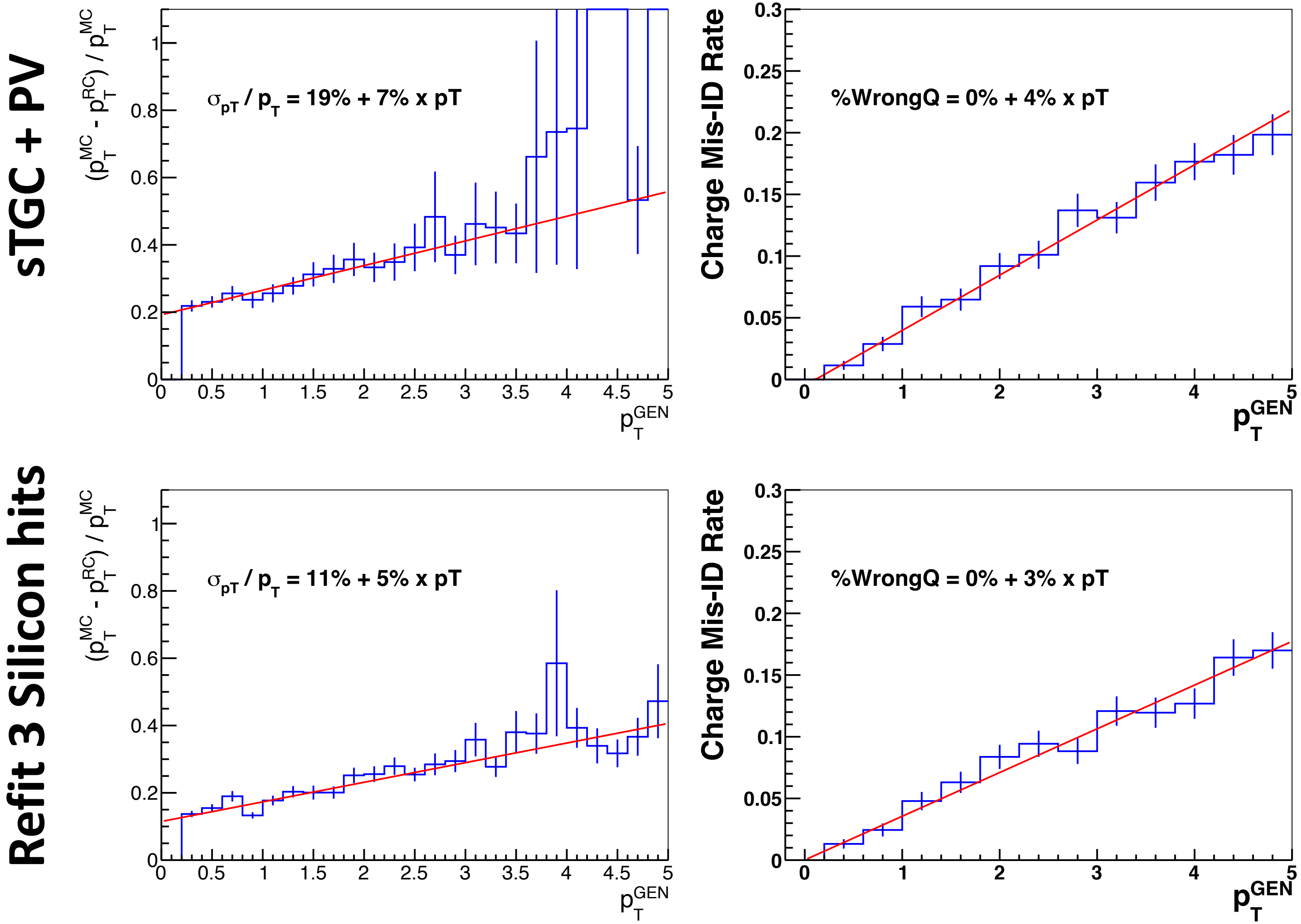
Primary Vertex

Hits in Silicon Detector

Hits in sTGC Detector

GENFIT2 Display

Track Fitting and performance



1. Fit with sTGC and primary vertex
2. Project tracks to Si disks and search for hits along track
3. Refit tracks with PV + sTGC + Si

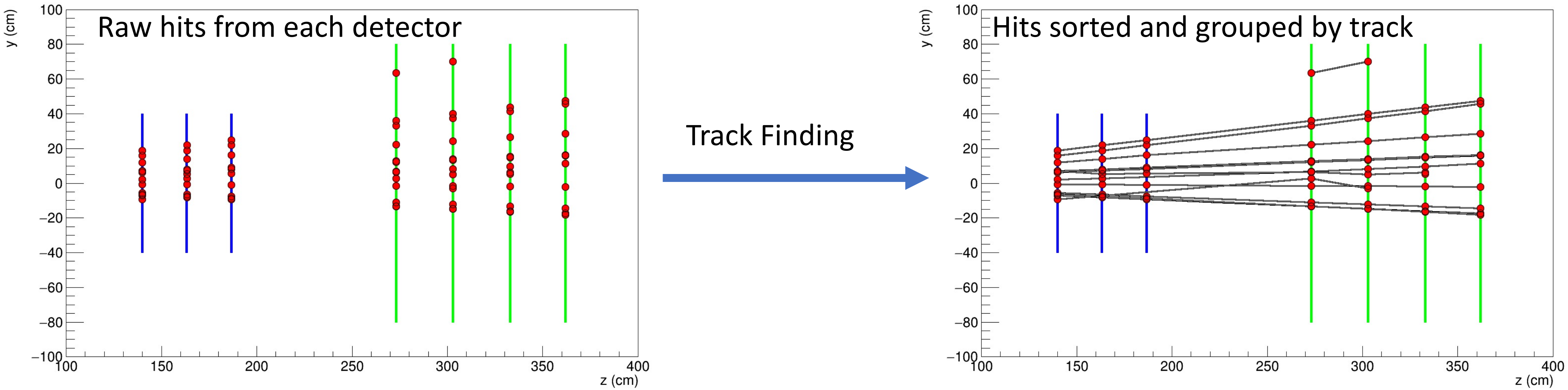
Primary Vertex $\sigma_{XY} = 500\ \mu m$

- Beamline constraint should provide $\sigma_{XY} = 500\ \mu$m or better

- Refit with Si provides significantly improved momentum resolution (x2) + charge identification (especially at higher pT)

Understanding the track fitting

- Study track FITTING only → assume **PERFECT** track finding, i.e.
- Why do this: Study track fitting independent of track finding



- **If we have perfect information of track hits, how well can we determine track momentum and charge?**

MC Closure test: verify the tracking procedure

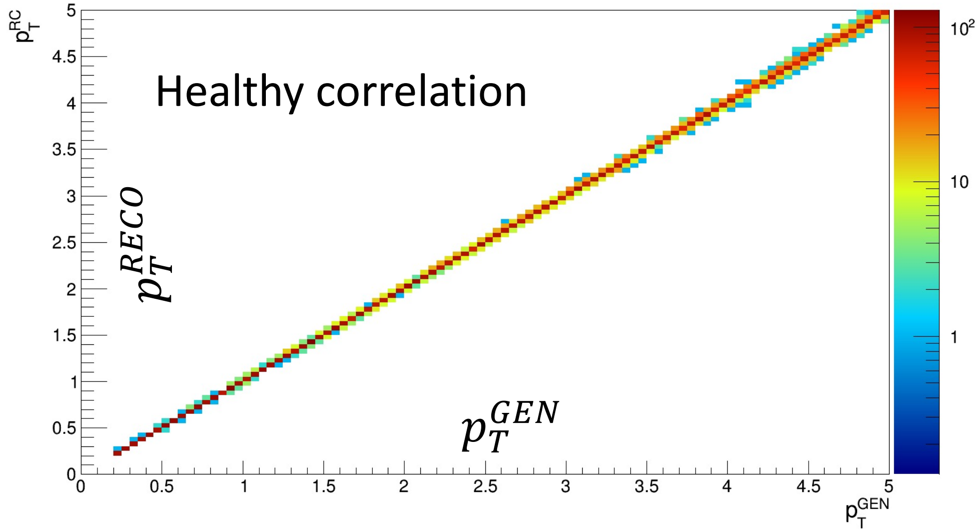
- MC Closure to prove that the tracking code “works”

1. Generate tracks / propagate with GEANT
   - Physics_OFF = Multiple scattering, hadronic interactions, etc. turned OFF
2. Use GEANT hits, blur position by $\sigma_{XY} = 1\ \mu m$ (could be anything)
3. Assign hit covariance matrix according to σ_{XY}
4. Fit tracks using GENFIT2 implementation

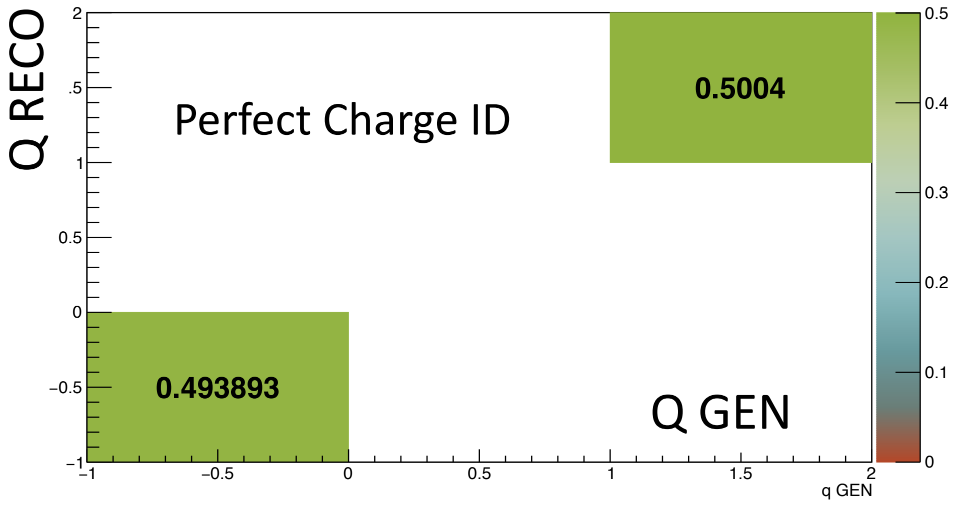
Thank you to Jason / Victor for help turning OFF multiple scattering etc.

GEN Level (Physics_off) $\sigma_{XY} = 0.1\mu$m

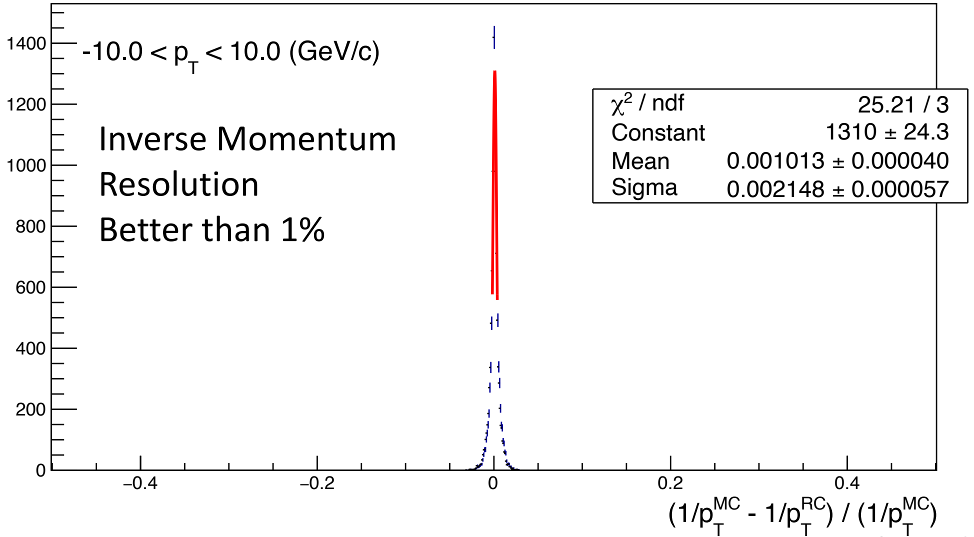
Physics_off = leave hit in detector, otherwise no interaction with material



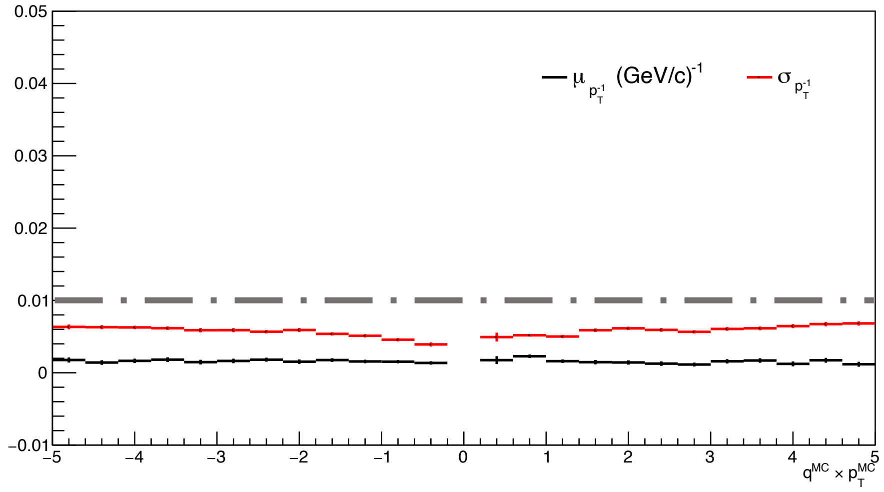
Healthy correlation



Perfect Charge ID



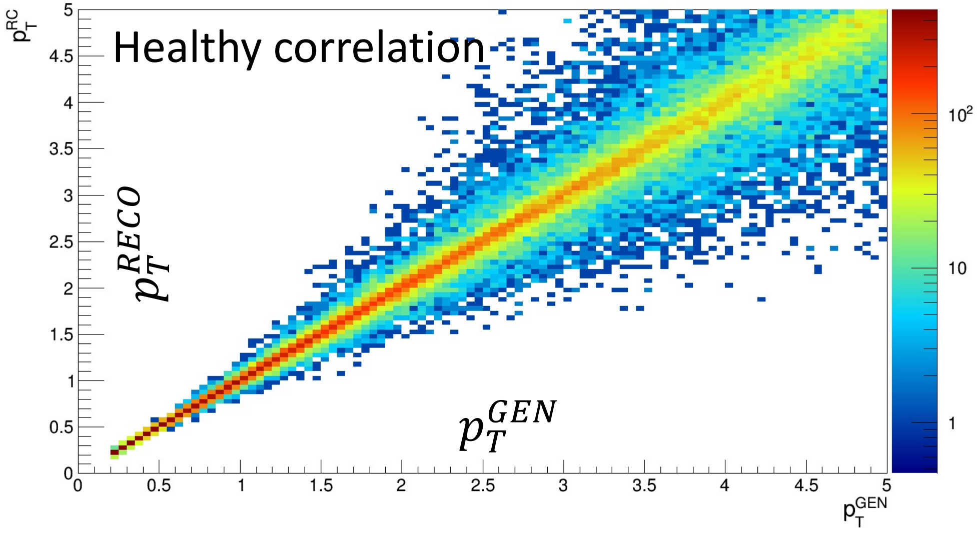
Inverse Momentum Resolution Better than 1%



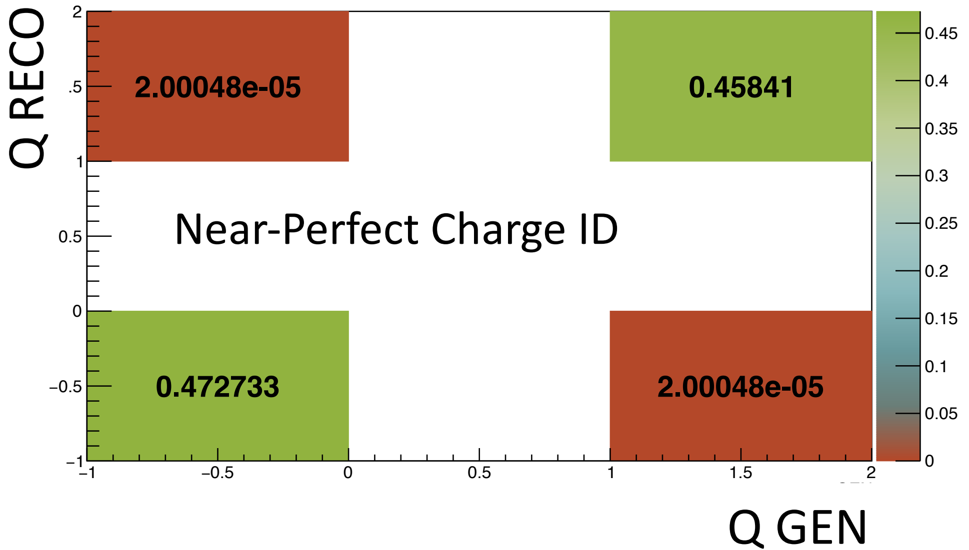
1%

➢ Proves tracking software works as expected

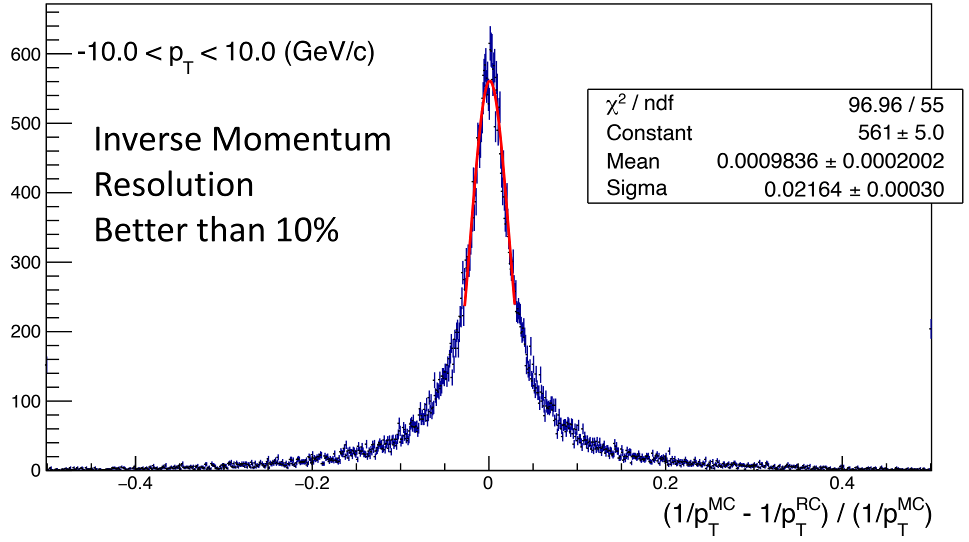
GEN Level (Physics_off) $\sigma_{XY} = 1\mu$m



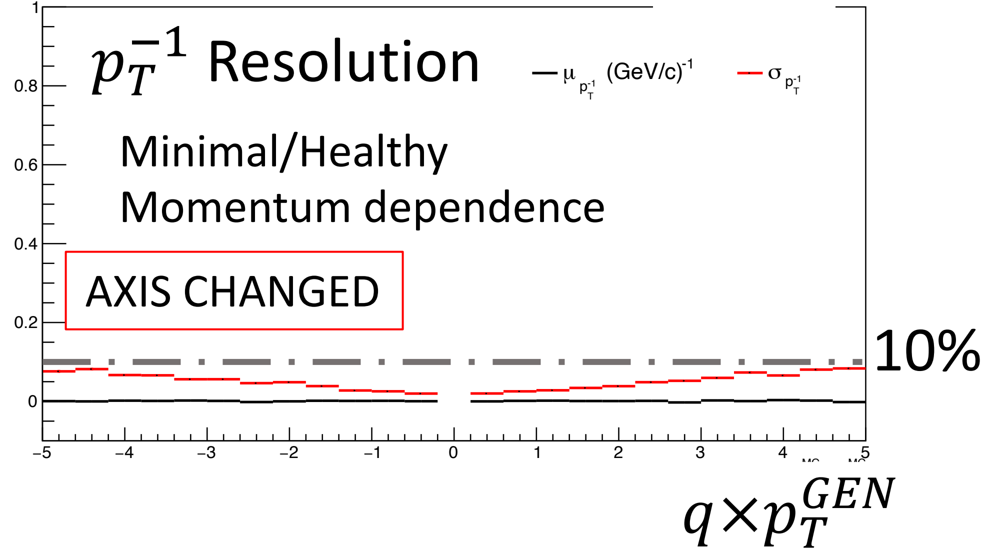
Healthy correlation



Near-Perfect Charge ID



Inverse Momentum Resolution Better than 10%



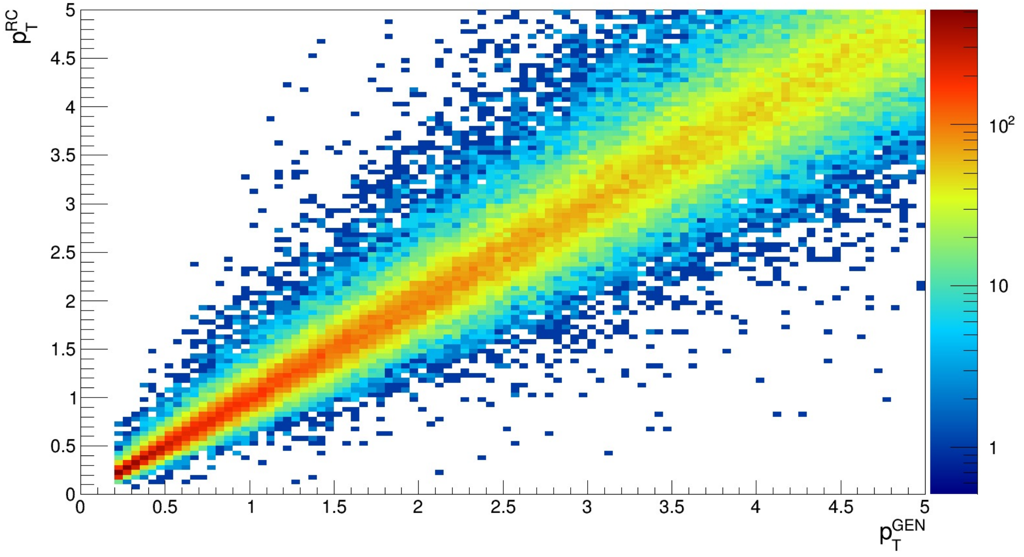
p_T^{-1} Resolution

Minimal/Healthy Momentum dependence

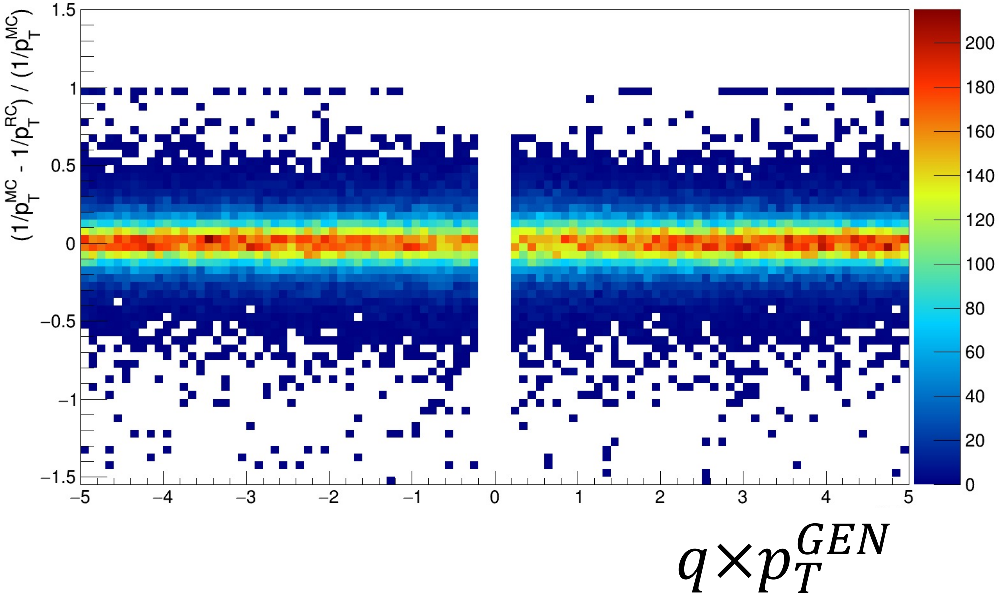
AXIS CHANGED

- ➢ Proves tracking software works as expected

GEN level ± 1μm (Physics ON)



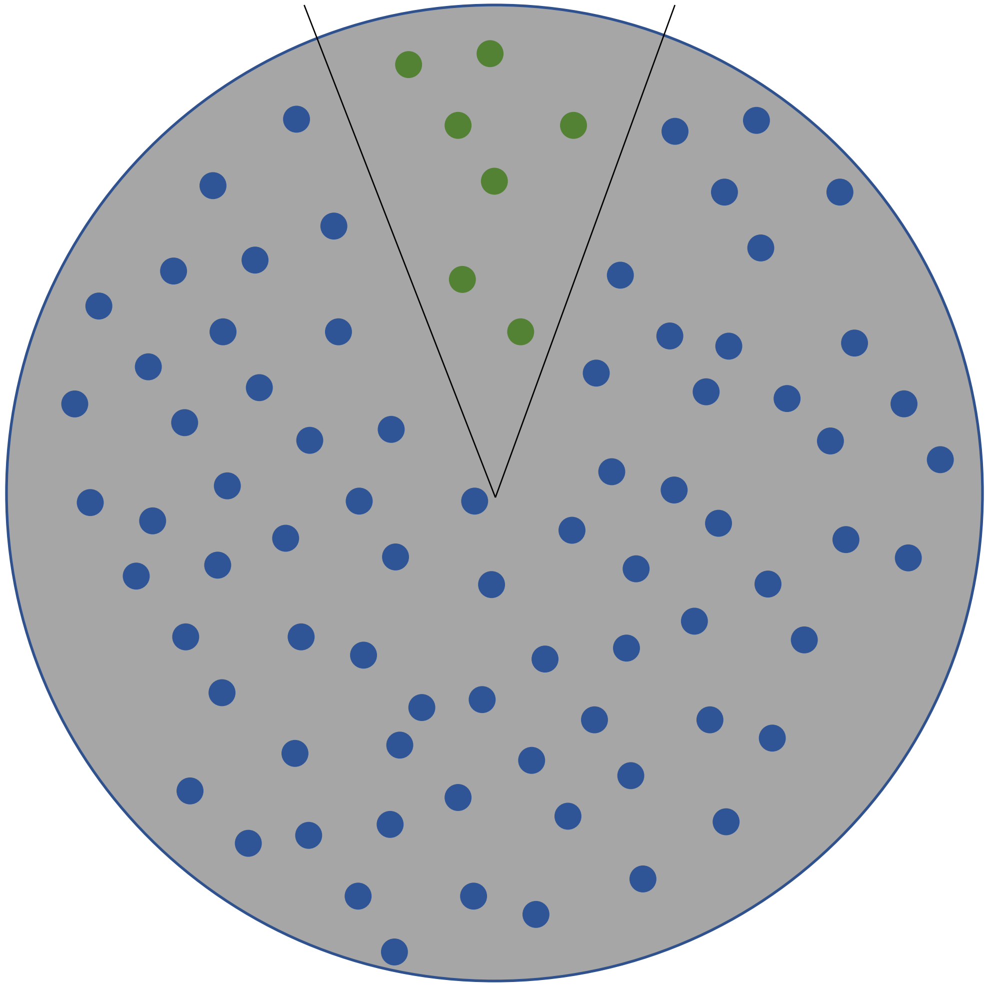
charge id good,
but a little worse



No p_T dependence, dominated by interactions

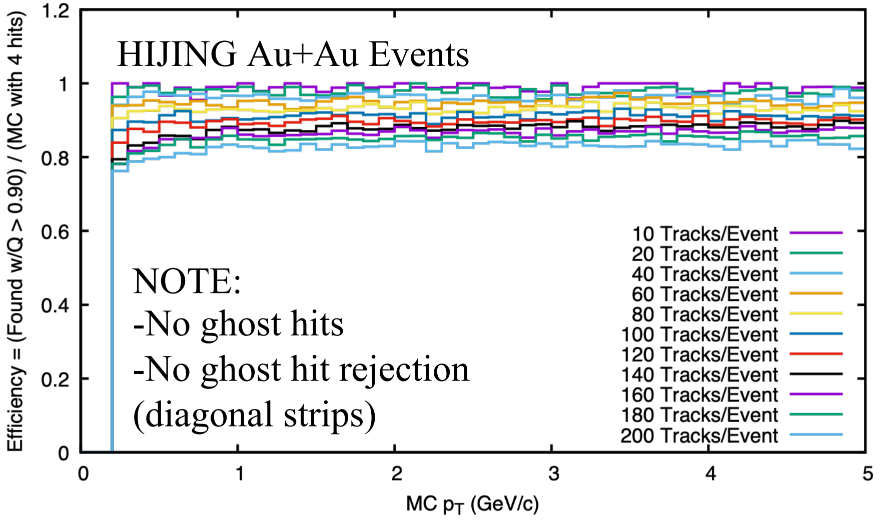
High Multiplicity Tracking

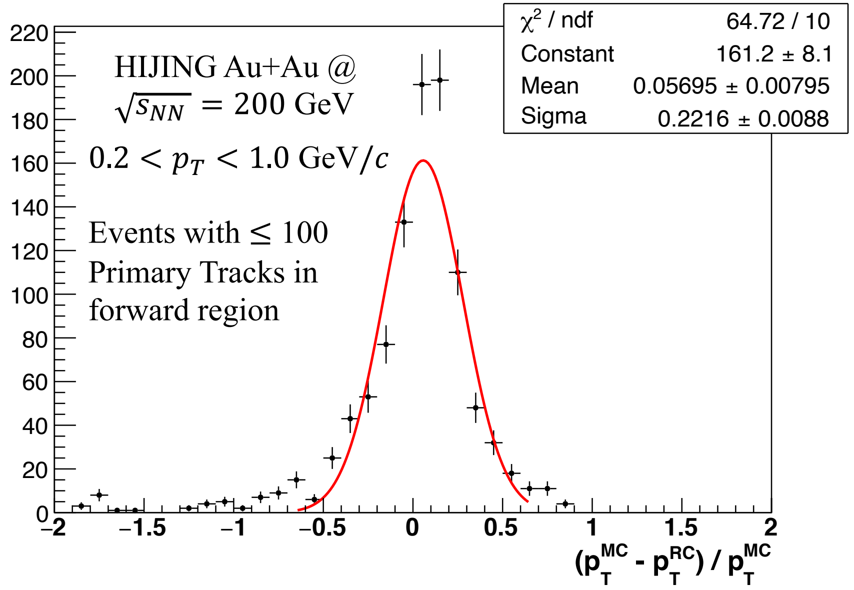
- Naïve CA implementation is <u>very</u> slow for high-mult events.
  - Scales with combinatorial pairs
  - Problem will be worse with ghost hits from sTGC in high-mult events
- CA is easily parallelizable / separable
  - Simplest approach: split hits from each station into slices in ϕ
  - Reduces combinatorial pairs
  - May reduce efficiency for low p_{T} tracks
    - ✓ Multiple iterations to recover hard-to-find track candidates



Tracking Performance at higher multiplicities

Track Finding Efficiency

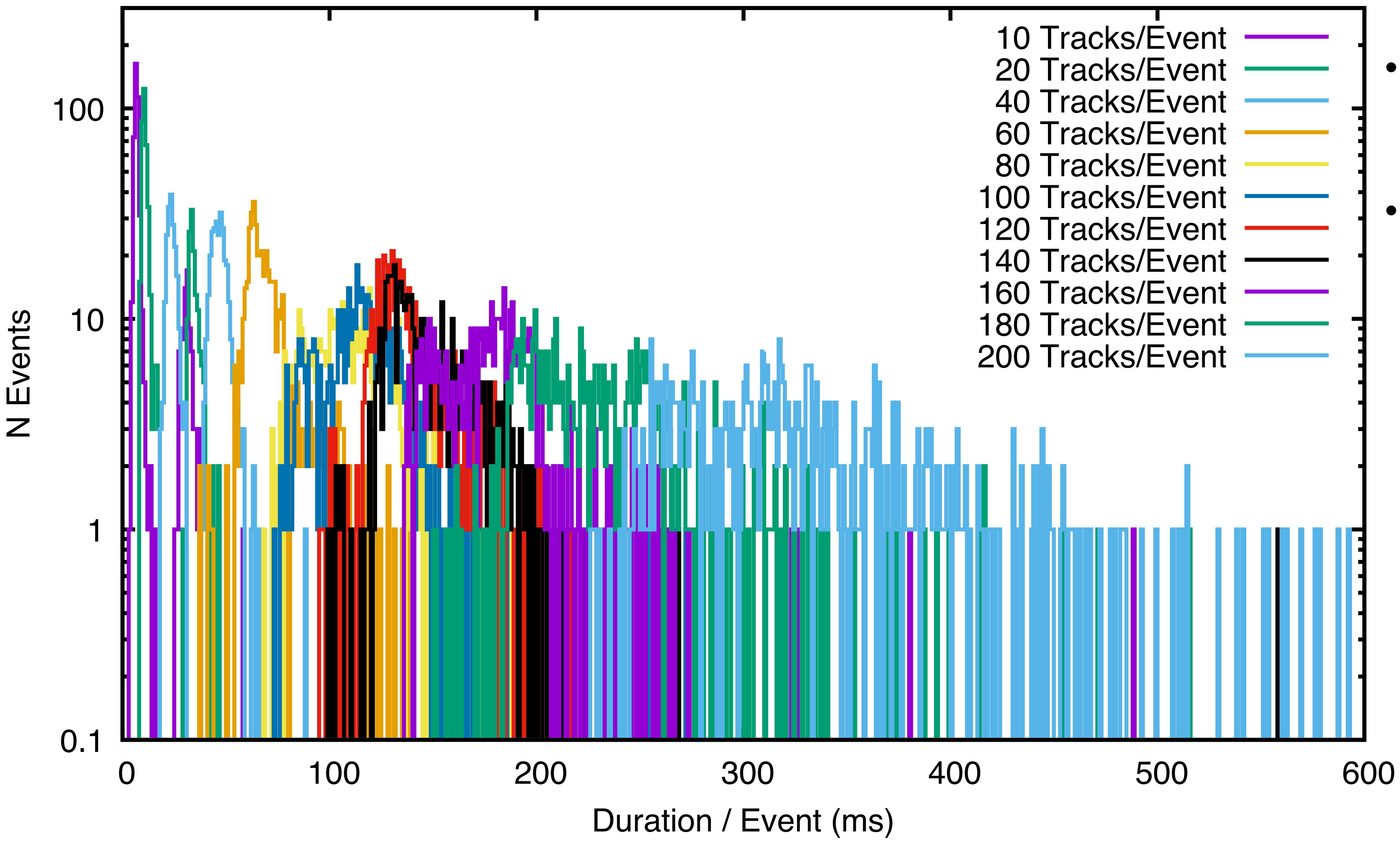




Tracking Performance:

- ✓Split/Parallelize high multiplicity events – speedup ~x1000
- ○ Track finding shows healthy behavior trending towards higher multiplicity
- ○ Detailed studies will be needed with ghost hits and diagonal strips
- ○ Preliminary study: momentum resolution peripheral Au+Au < 30%, meeting goals for physics in AA
  - ○ Note: resolution depends on η, p_T and multiplicity

Track Finding Efficiency vs. Multiplicity



- Healthy behavior with increased multiplicity
- Duration for high-mult event ~ 400 ms / Event

Conclusions

- Detector technology as been crucial for advancing our experiment reach and physical understanding
- STAR Forward upgrade uses modern tracking technology to achieve tracking in challenging situations : non-uniform B-field, various detector technologies...
- Tracking requires cutting edge mathematical algorithms for finding “real” tracks in the sea of background

Homework

- Read about particle detectors:
  - https://www2.physics.ox.ac.uk/sites/default/files/Detectors.pdf
- Read about track finding using machine learning:
  - https://arxiv.org/pdf/1904.06778.pdf
- Derive the relation between track curvature and the track momentum in a given B-field
- Write a ROOT/python code to compute/plot the number of ghost hits vs. real hits for an sTGC like detector. Can you come up with a mathematical expression for this?
  - If you break the area into 4 smaller independent detectors, how would that change the number of ghost hits?