4D Track Reconstruction at sPHENIX

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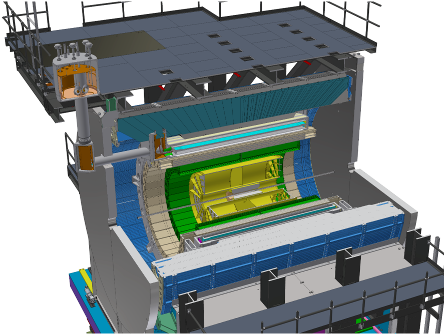
sPHENIX

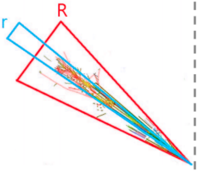
- sPHENIX is a new detector being commissioned this year at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory
- Jet and heavy flavor probes for precision hot and cold QCD measurement comparisons to LHC
- Reuse Babar 1.4T solenoid and introduce hadronic calorimetery for the first time at RHIC for full jet measurements



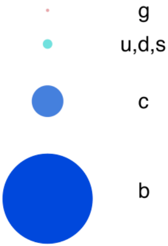
sPHENIX

Jet correlation & substructure

Vary momentum/ angular size of probe

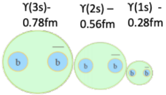


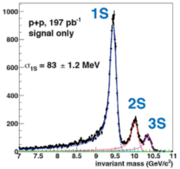
Parton energy loss Vary mass/ momentum of probe



Upsilon spectroscopy

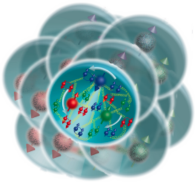
Vary size of the probe





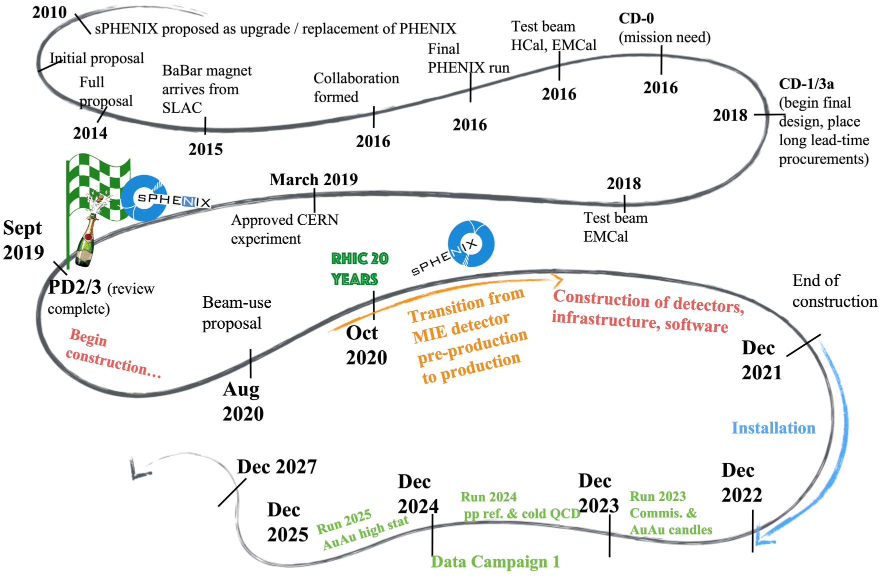
Cold QCD

Vary temperature of QCD matter



- Study QCD matter at varying temperatures for direct comparisons to LHC with rare probes
- Study partonic structure of protons and nuclei

sPHENIX Timeline



2010 sPHENIX proposed as upgrade / replacement of PHENIX

Initial proposal

Full proposal
2014

BaBar magnet arrives from SLAC
2015

Collaboration formed
2016

Final PHENIX run
2016

Test beam HCal, EMCal
2016

CD-0
(mission need)
2016

2018
CD-1/3a
(begin final design, place long lead-time procurements)

2018
Test beam EMCal

March 2019
Approved CERN experiment

Sept 2019
PD2/3 (review complete)

Begin construction…

Beam-use proposal
Aug 2020

RHIC 20 YEARS
Oct 2020

Transition from MIE detector pre-production to production

Construction of detectors, infrastructure, software

End of construction
Dec 2021

Installation

Dec 2022

Run 2023
Commis. &
AuAu candles

Dec 2023

Run 2024
pp ref. & cold QCD

Dec 2024

Data Campaign 1

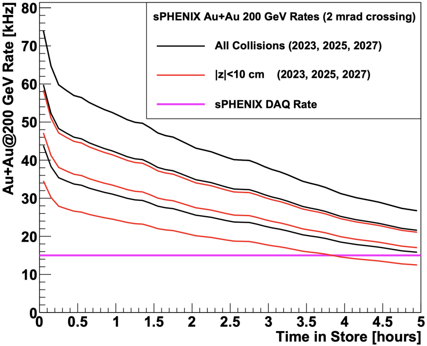
Run 2025
AuAu high stat

Dec 2025

Dec 2027

sPHENIX Run Conditions

- RHIC will achieve the highest luminosities in its history in 2023-2025
  - Average of 50 kHz Au+Au and 3 MHz $p+p$ collisions
- Translates to an average of 2-3 AuAu or $\sim$20 $p+p$ pileup collisions measured in sPHENIX
- Hit occupancies of $\mathcal{O}(100,000)$ expected, similar to those expected at HL-LHC!
- Track reconstruction difficult in high pile up environments!



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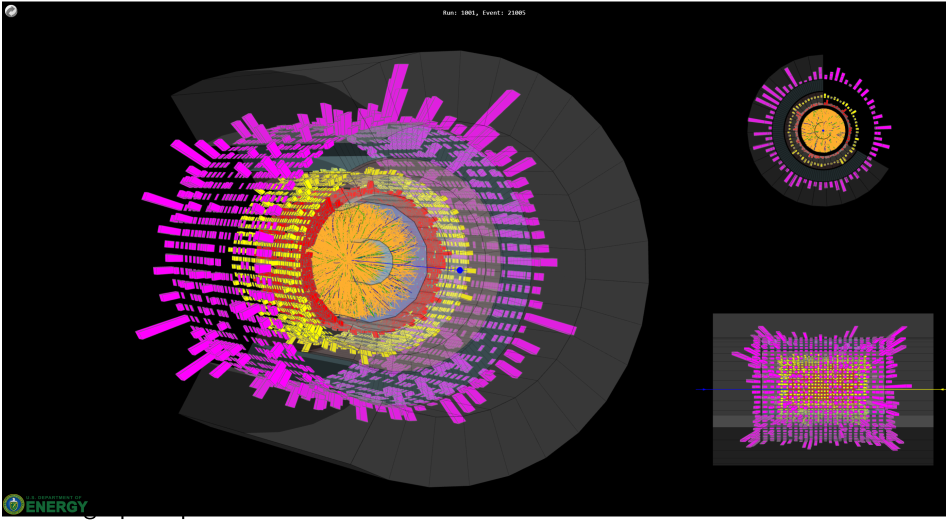
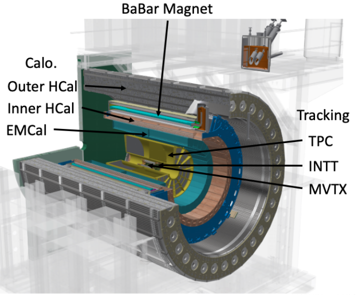


sPHENIX Detector

- sPHENIX detector designed for high precision tracking and jet measurements at RHIC
  - Large, hermetic acceptance
  - Hadronic calorimetery (first at RHIC)
  - Large offline data rate of ∼100 Gbit/s



July 28, 2020

sPHENIX at RHIC

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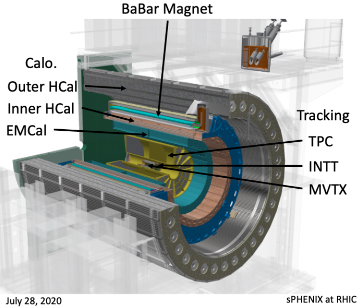
  - Intermediate silicon tracker (INTT) - 4 layers of silicon strips
  - Compact GEM-based TPC



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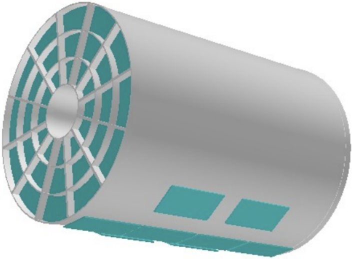

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sPHENIX Tracking

- MVTX - 3 layers of MAPS staves within $\sim 1 < r < 5$ cm
  - Precision space point identification for primary and secondary vertexing
  - $\mathcal{O}(1-10)$ micron precision in $r\phi$, z
  - Integration time $\mathcal{O}(\mu s)$
- INTT - 4 layers of silicon strips within $\sim 7 < r < 11$cm
  - $\mathcal{O}(10)$ micron precision in $r\phi$, 1cm in z
  - Fast $\mathcal{O}(100ns)$ integration time
- TPC - Compact, 48 layer, continuous readout GEM-based
  - $\mathcal{O}(100)$ micron precision
  - Long $\sim 13\mu$s drift time
- TPOT - 8 modules of micromegas to provide additional $\mathcal{O}(100)$ micron space point outside of TPC

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Vertexing

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Timing

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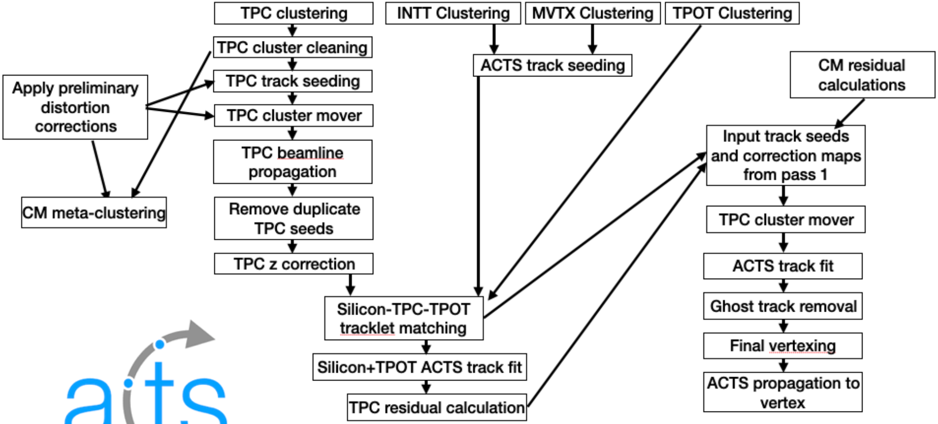
Momentum

- TPOT - 8 modules of micromegas to provide additional $\mathcal{O}(100)$ micron space point outside of TPC

Calibration

Each detector plays a critical role for the success of sPHENIX physics!

Track Reconstruction Workflow



TPC clustering

TPC cluster cleaning

TPC track seeding

TPC cluster mover

TPC beamline propagation

Remove duplicate TPC seeds

TPC z correction

Apply preliminary distortion corrections

CM meta-clustering

INTT Clustering

MVTX Clustering

TPOT Clustering

ACTS track seeding

Silicon-TPC-TPOT tracklet matching

Silicon+TPOT ACTS track fit

TPC residual calculation

CM residual calculations

Input track seeds and correction maps from pass 1

TPC cluster mover

ACTS track fit

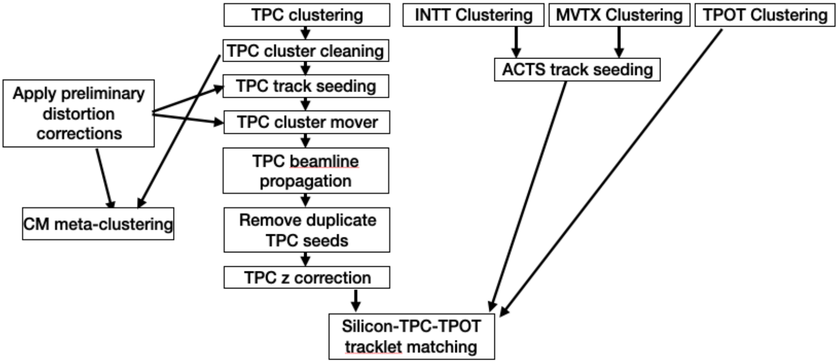
Ghost track removal

Final vertexing

ACTS propagation to vertex

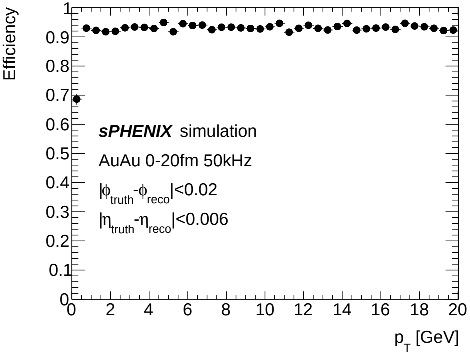
JDO et al., Computing and Software for Big Science 5, 23 (2021)
Acts Project, arXiv:2106.13593

Track Reconstruction Workflow



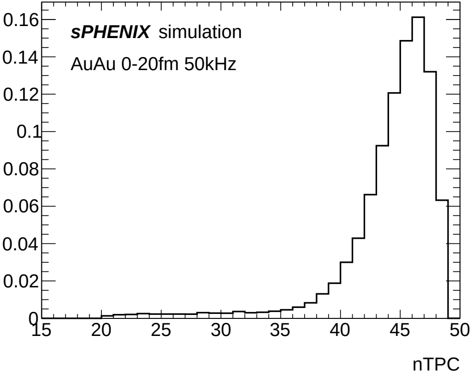
- 4D tracking strategy: reconstruct seeds in each detector individually
- Combine information at end of seeding
  - TPC seed contains most of the track defining curvature
  - Silicon seed contains precise vertex + timing information
  - TPOT measurement (if available) adds TPC calibration information

MVTX+INTT Seeding



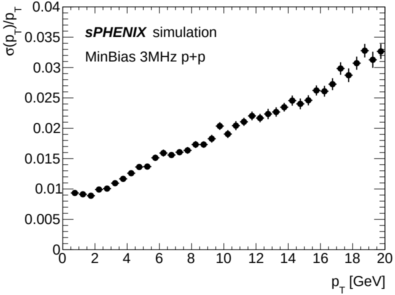
- Start with ACTS seeding algorithm in 3 layer MVTX
  - Finds triplets - reduce duplicates by deploying in MVTX only
- Propagate track seed to INTT layers to find additional matching measurements in tuned search windows

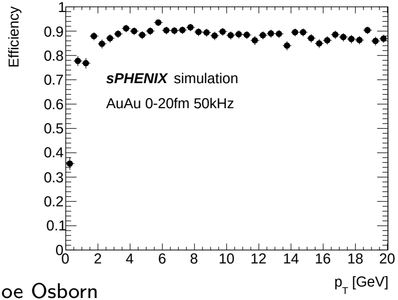
TPC Seeding



- Cellular Automaton seeding algorithm developed by ALICE collaboration deployed in TPC
- Chains links of triplets together in TPC layers
- High efficiency and computationally fast

Track Matching and Fitting

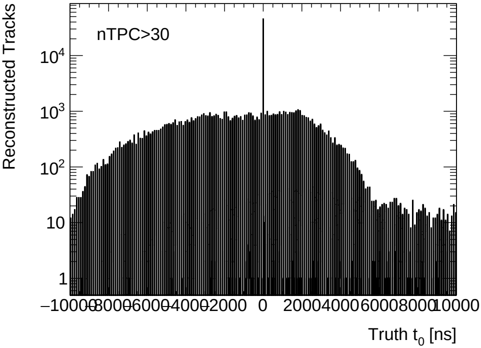




- Silicon tracklets are matched with TPC tracks
- Further propagation performed to TPOT layers to find compatible TPOT measurements (if any)
- Matching windows tuned to limit number of duplicates while also finding real matches
- Final track seed constructed with silicon tracklet position, TPC tracklet momentum, and INTT timing information
- ACTS track fitter and vertex propagation provides final track parameter determination

Timing of Reconstructed Tracks

- Example: bunch structure visible from reconstructed track sample in 3 MHz minimum bias $p+p$



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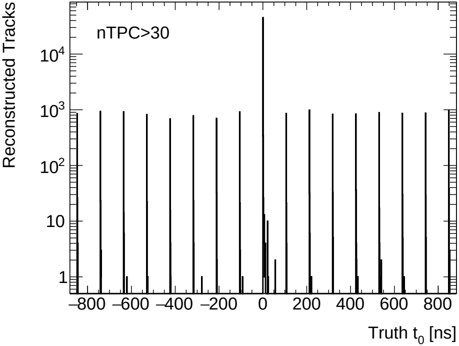

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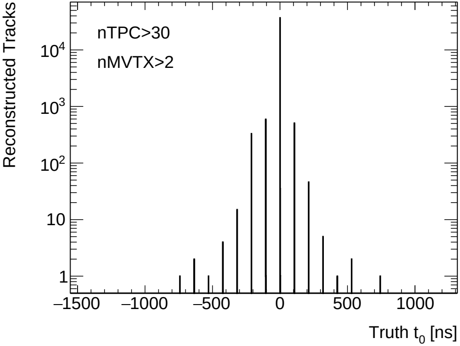

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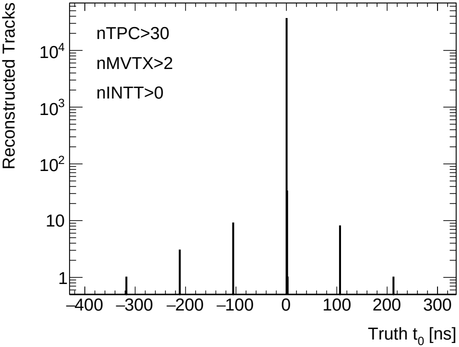
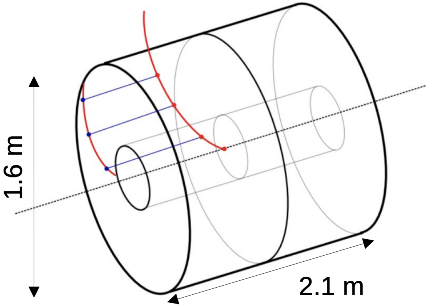
- Reconstructed TPC+MVTX+INTT tracks are highly suppressed outside of the nominal t_0 bunch crossing



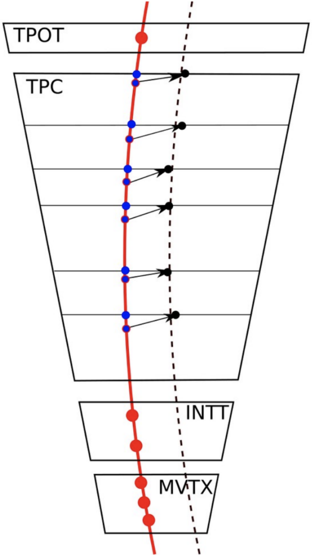
TPC Distortion Corrections

- Track reconstruction is further complicated by TPC distortions
- In an ideal TPC, primary electrons drift longitudinally at a constant velocity
- Sources of distortions from the ideal case:
    - Static due to $E \times B$ inhomogeneities : $\mathcal{O}(cm)$, $\mathcal{O}(months)$
    - Beam induced due to ion back flow: $\mathcal{O}(mm)$, $\mathcal{O}(min)$
    - Event-by-event fluctuations due to multiplicity : $\mathcal{O}(100\mu m)$, $\mathcal{O}(ms)$



Distortion Corrections

- $\mathcal{O}(cm)$ distortions reconstructed with pulsed laser system
- $\mathcal{O}(mm)$ distortions reconstructed with tracks with TPOT
- $\mathcal{O}(100\mu m)$ distortions reconstructed with diffuse laser



Distortion Corrections

- $\mathcal{O}(cm)$ distortions reconstructed with pulsed laser system
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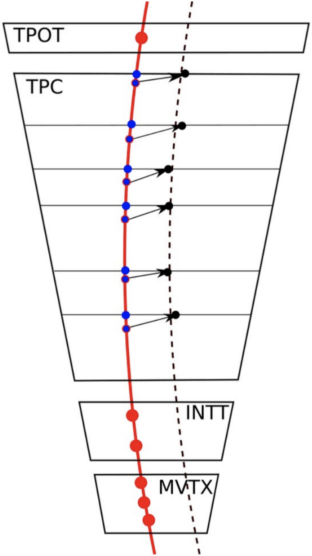
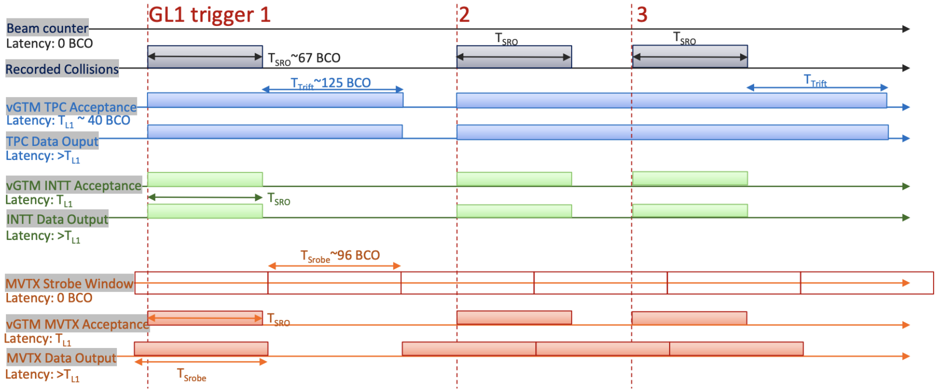
- Use MVTX+INTT+TPOT to define precisely timed in trajectory - then perform calibrations with TPC residuals



Streaming Readout



- Streaming readout DAQ will increase hard-to-trigger $p+p$ data sample (e.g. HF decays) by orders of magnitude
- Different detector integration times with varying tracklet precision leads to complex track reconstruction workflow

Streaming Readout Tracking

- In streaming readout mode, the timing information from the INTT plays a critical role
- Without an explicit hardware trigger, we do not know where the TPC clusters are in z
    - What we really measure is the drift time, not the z position! Without a t_0, the z position is undetermined

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  - Update TPC cluster z positions based on timing info provided by INTT match

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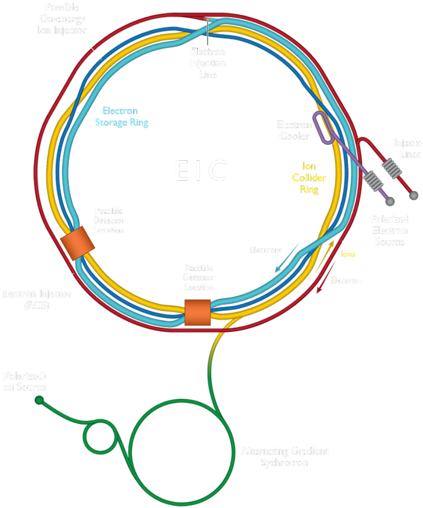
- Implementation in progress

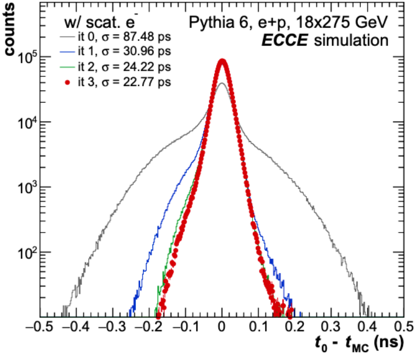
Towards the EIC

- The Electron Ion Collider (EIC) is the next generation precision QCD facility being constructed at Brookhaven National Laboratory
- Unique tracking challenges with planned streaming readout and high luminosity environment



4D Tracking at EIC

- Three major proposal efforts
  - ATHENA : athena-eic.org
  - CORE : eic.jlab.org/core
  - ECCE : ecce-eic.org
- **ALL** proposals included a layer of AC-LGAD detector technology for additional tracking space point + precise timing information for PID ($\mathcal{O}(10ps)$)
- **ALL** proposals included a streaming readout DAQ to collect complete unbiased data samples



  - 4D tracking essential for achieving physics at upcoming high luminosity facilities such as RHIC, (HL)-LHC, and EIC

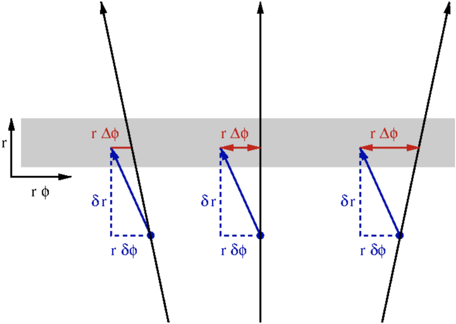
Conclusions

- sPHENIX experiment is designed to be a precision QCD jet and heavy flavor experiment
    - Requires robust track reconstruction in high occupancy environments
- Tracking detectors uniquely complement each other and provide important pieces for 4D track reconstruction
- Streaming readout data taking will increase heavy flavor data but will create even more complex reconstruction environment! 4D reconstruction necessary!
- Future facilities, e.g. HL-LHC and EIC, are already planning for 4D tracking. Continued progress being made

Extras

Reconstructing Distortions with Tracks

- Find tracks using all detectors
- Fit tracks with MVTX+INTT+TPOT
- Form cluster-track residuals in TPC in ϕ and *z*



Reconstructing Distortions with Tracks

- Divide TPC in to $\mathcal{O}(10,000)$ volume elements and form linear relationships between residuals and track angles

$$r\Delta\phi = r\delta\phi + \delta r\tan\alpha$$

$$\Delta z = \delta z + \delta r\tan\beta$$

$$\chi^2 = \sum \frac{r\Delta\phi - |r\delta\phi + \delta r\tan\alpha|^2}{\sigma_{r\phi}^2} + \frac{\Delta z - |\delta z + \delta r\tan\beta|^2}{\sigma_z^2}$$

- $\Delta\phi$ and Δz measured residuals in the TPC
- α, β local track angles measured in (ϕ, r), (z, r) planes
- δr, δz, $\delta\phi$ are unknown distortions
- Minimize and solve which gives three linear equations for three unknown average distortions