4D Track Reconstruction at sPHENIX

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Connecting the Dots 2022
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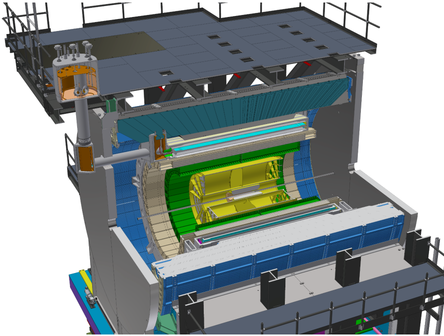
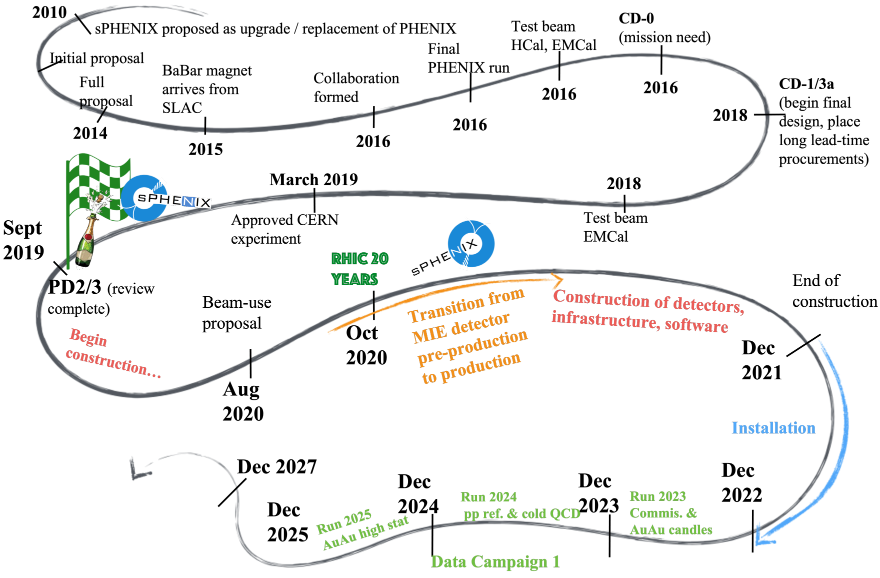
sPHENIX

- 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

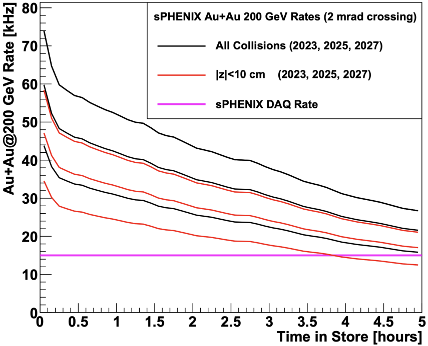


sPHENIX Timeline



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 in AuAu, similar to those expected at HL-LHC!
- Track reconstruction difficult in high pile up environments!



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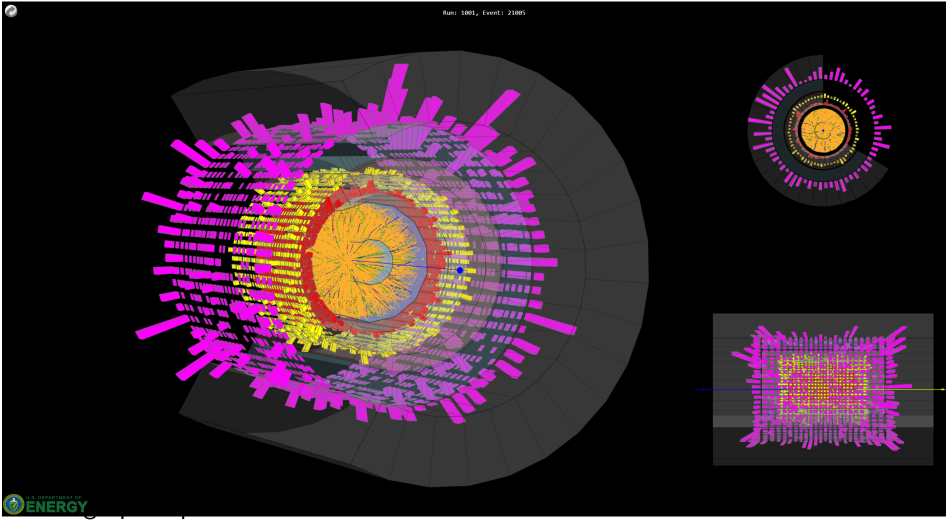
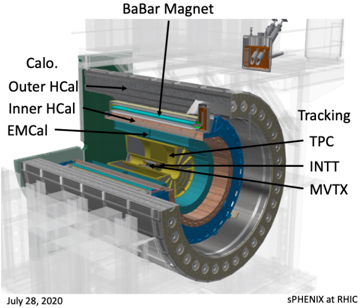


sPHENIX Detector

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



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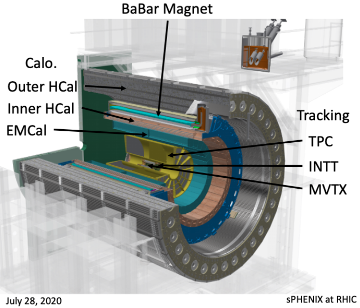
  - Micro vertexing (MVTX) - 3 layers of MAPS staves
  - Intermediate silicon tracker (INTT) - 4 layers of silicon strips
  - Compact GEM-based TPC



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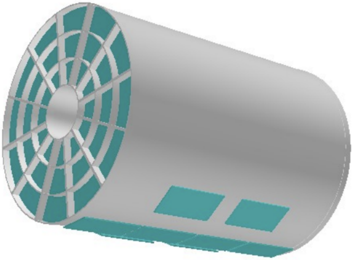

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sPHENIX Tracking

- 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
  - $\mathcal{O}(10)$s 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

- TPC - Compact, 48 layer, continuous readout GEM-based
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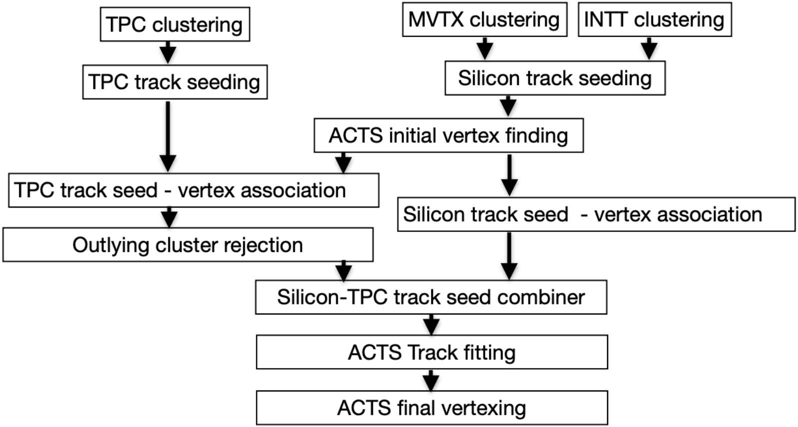
Momentum

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

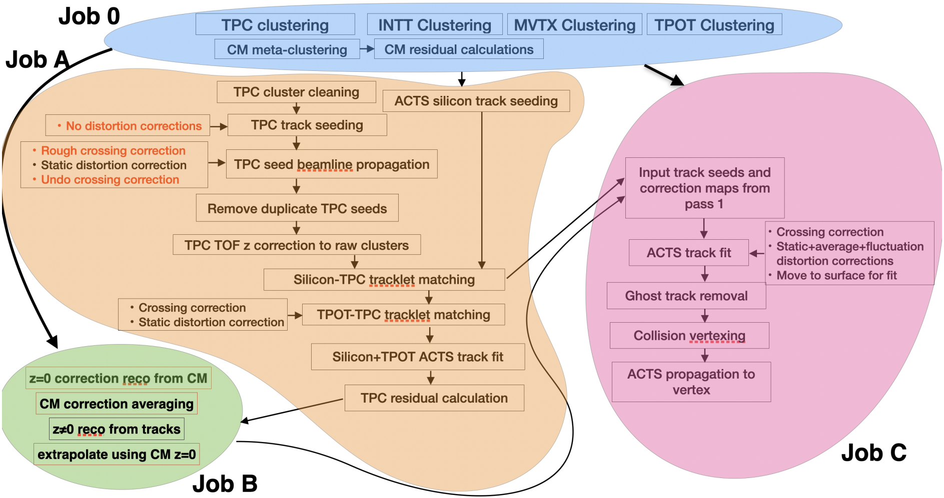
Calibration

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

Track Reconstruction Workflow CTD2020



Track Reconstruction Workflow CTD2022



JDO et al., Computing and Software for Big Science 5, 23 (2021)
X. Ai et al., Computing and Software for Big Science 6, 8 (2022)

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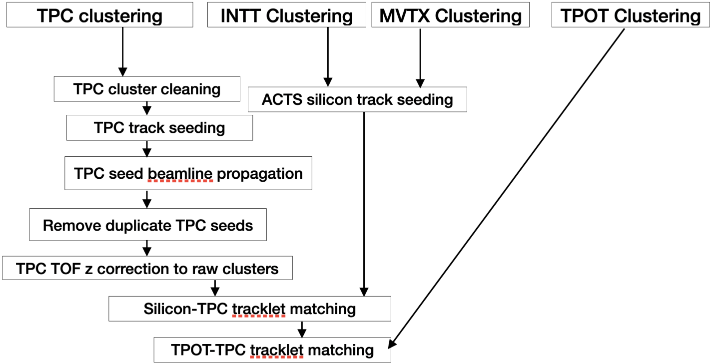
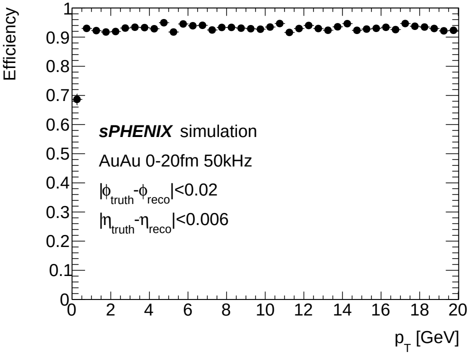


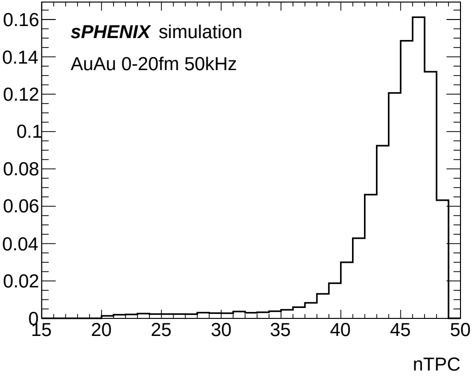
- 4D tracking strategy: reconstruct seeds in each detector individually
- Combine information at end of seeding
  - TPC seed contains most of the track defining curvature
  - Silicon seed contains precise vertex + timing information
  - TPOT measurement (if available) adds TPC calibration information

MVTX+INTT Seeding



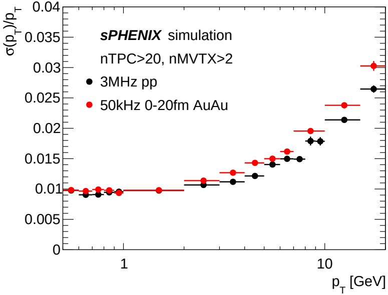
- Start with ACTS seeding algorithm in 3 layer MVTX
  - Finds triplets - reduce duplicates by deploying in MVTX only
- Propagate track seed to INTT layers to find additional matching measurements in tuned search windows

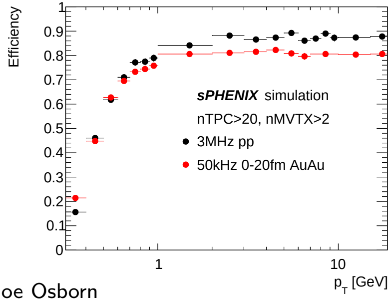
TPC Seeding



- 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

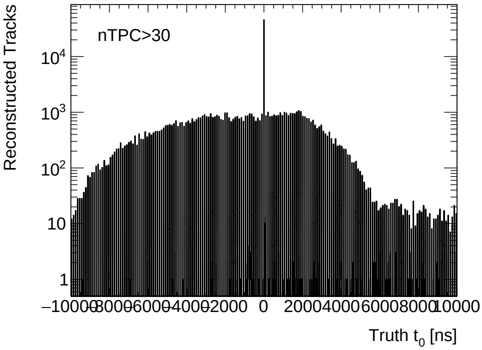




- Silicon tracklets are matched with TPC tracks
- Further propagation performed to TPOT layers to find compatible TPOT measurements (if any)
- Matching windows tuned to limit number of duplicates while also finding real matches
- Final track seed constructed with silicon tracklet position, TPC tracklet 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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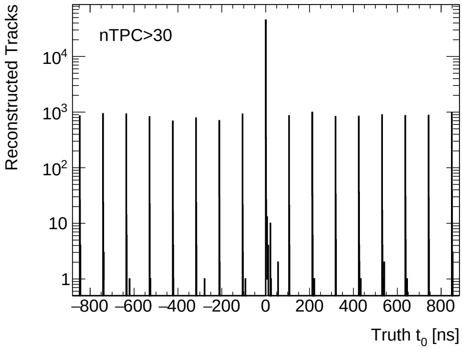

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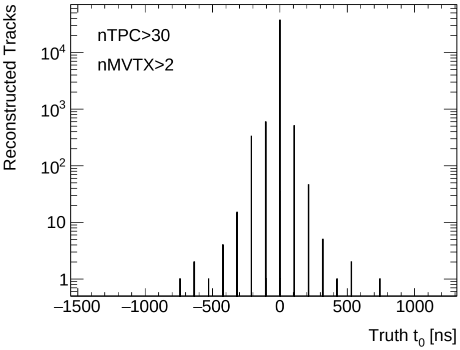
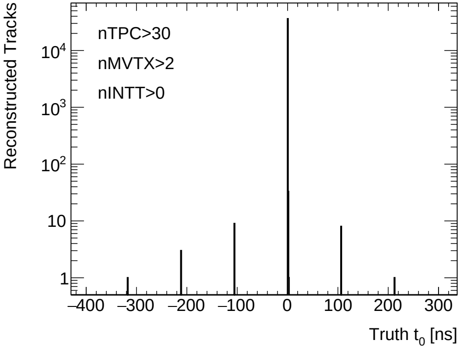
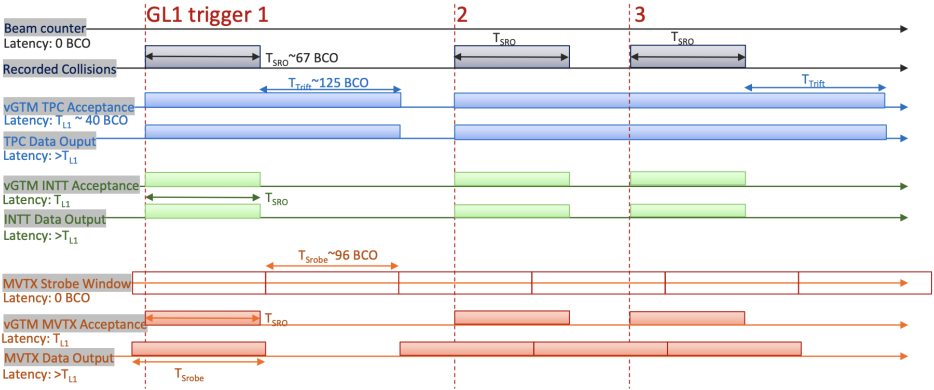


Timing of Reconstructed Tracks

- Example: bunch structure visible from reconstructed track sample in 3 MHz minimum bias $p + p$
- Reconstructed TPC tracks are found from nearly all 120 RHIC bunches. ∼100 ns bunch structure visible
- Reconstructed TPC+MVTX tracks are found from adjacent several bunches
- Reconstructed TPC+MVTX+INTT tracks are highly suppressed outside of the nominal t_0 bunch crossing



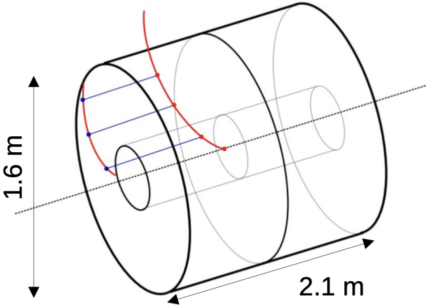
Streaming Readout



- 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 required complex track reconstruction workflow

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 : $\mathcal{O}(100\mu m)$, $\mathcal{O}(ms)$



Streaming Readout Tracking

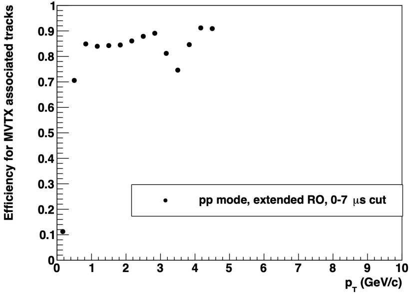
- Requirement: reconstruct tracks produced up to 7μs after the trigger
  - Provides minbias $p + p$ events for ∼67 bunch crossings
- TPC seeding performed without any distortion corrections
  - Without an explicit hardware trigger, we do not know where the TPC clusters are in z!
  - What we really measure is the drift time, not the z position! Without a t_0, the z position is undetermined
- However, we cannot match tracklets without reasonably precise beamline seed track parameters
  - Move clusters so the track points to $z = 0$
  - Make approximate static distortion corrections
  - Move clusters back by the same amount

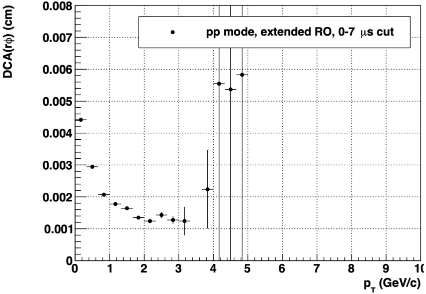
Streaming Readout Tracking

- After "artificially" moving TPC tracks, we can determine precise (enough) beamline track parameters
- Only the INTT clusters know the crossing number
- Determine beam crossing number by matching silicon/TPC tracks
  - Match tracklets using search windows in (η, ϕ, x_0, y_0)
  - Get crossing number from INTT clusters
  - Correct TPC cluster z positions for crossing time offset
  - Check for matching z_0 between tracklets

Streaming Readout Performance

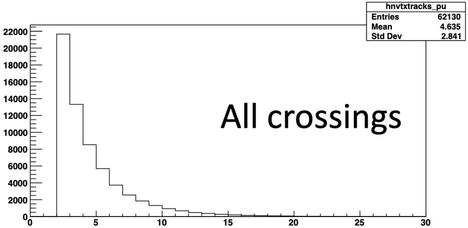
Note no uncertainties shown - become large after 3 GeV as in $DCA_{r\phi}$

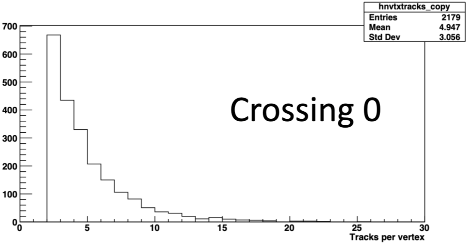




- Streaming readout track reconstruction performance shown in 3 MHz $p + p$ minimum bias collisions
- DCA largely limited by vertex reconstruction (low N_{tracks} per collision)

Streaming Readout Performance

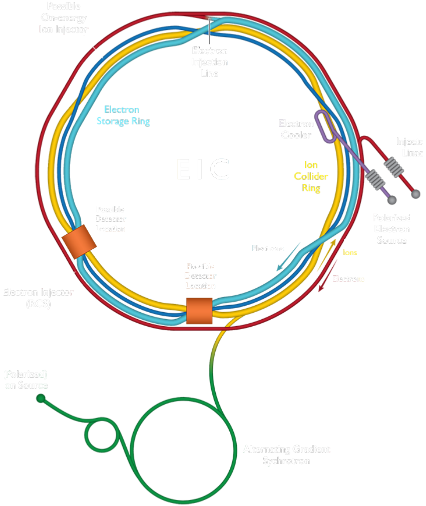




- Number of reconstructed vertices for all tracks in streaming readout ∼30x larger
- Places importance on track matching to silicon to properly identify bunch crossing

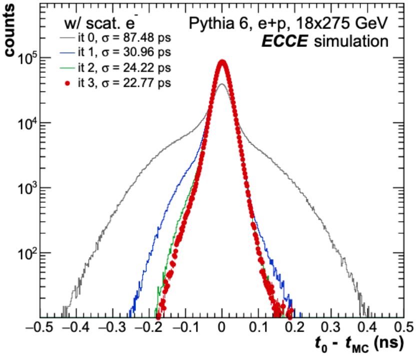
Towards the EIC

- 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

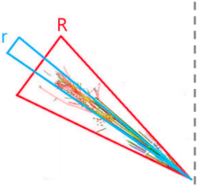
Conclusions

- 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

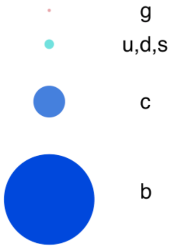
Extras

sPHENIX

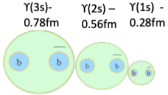
Jet correlation & substructure
Vary momentum/ angular size of probe

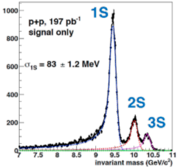


Parton energy loss Vary mass/ momentum of probe

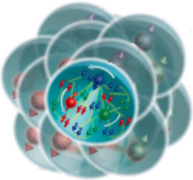


Upsilon spectroscopy
Vary size of the probe





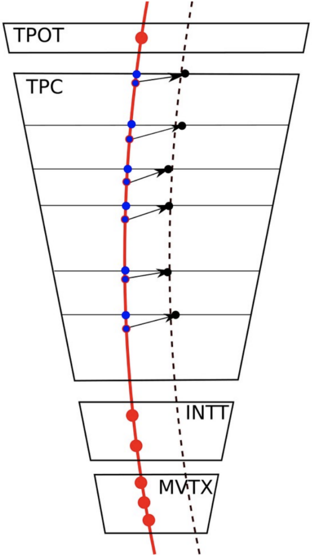
Cold QCD
Vary temperature of QCD matter



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

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



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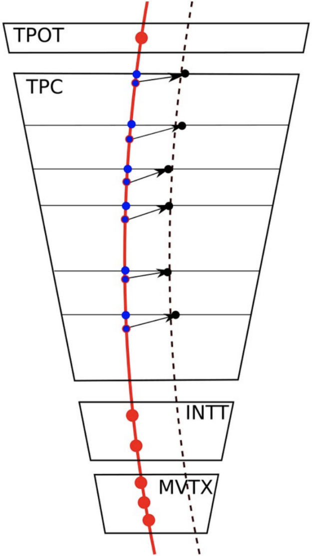
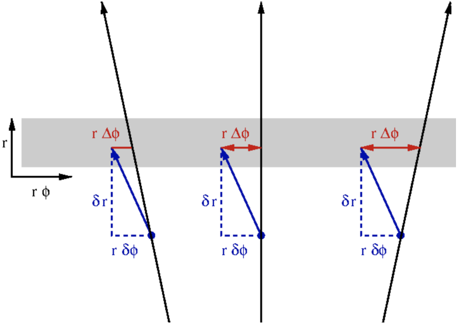
- Use MVTX+INTT+TPOT to define precisely timed in trajectory - then perform calibrations with TPC residuals



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