4D Track Reconstruction at sPHENIX

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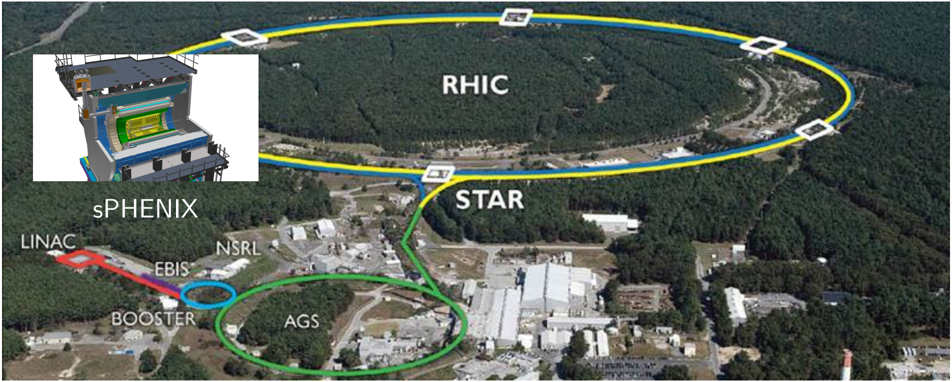
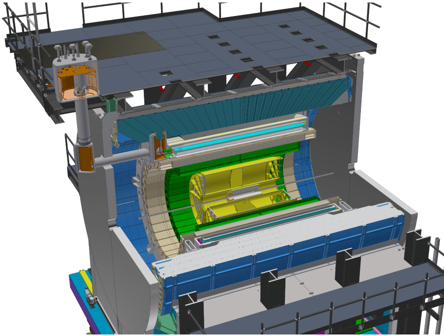
Next Generation of QCD at RHIC



The Relativistic Heavy Ion Collider (RHIC)
at Brookhaven National Laboratory

sPHENIX

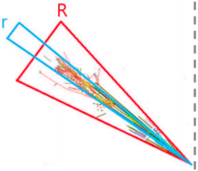
- sPHENIX is a new detector being commissioned this year at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory
- Jet and heavy flavor probes for precision hot and cold QCD measurement comparisons to LHC
- Reuse Babar 1.4T solenoid and introduce hadronic calorimetery for the first time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



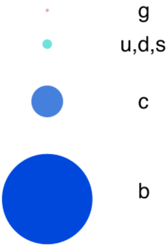
sPHENIX

Jet correlation & substructure

Vary momentum/ angular size of probe

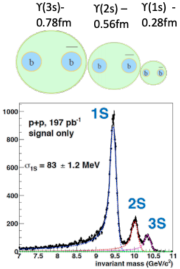


Parton energy loss
Vary mass/ momentum of probe



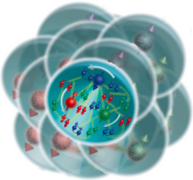
Upsilon spectroscopy

Vary size of the probe



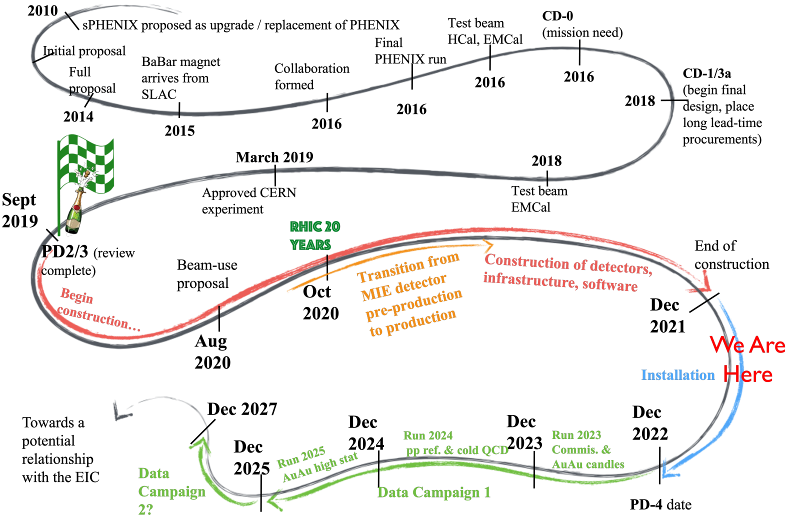
Cold QCD

Vary temperature of QCD matter



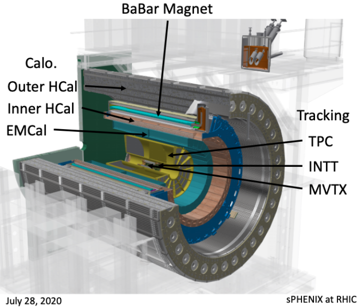
- Study QCD matter at varying temperatures for direct comparisons to LHC with rare probes
- Study partonic structure of protons and nuclei

sPHENIX Timeline



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



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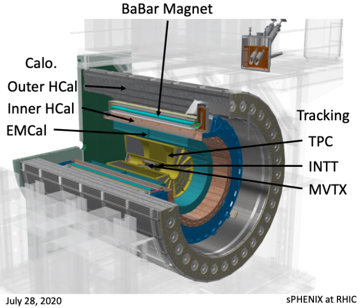
  - Intermediate silicon tracker (INTT) - 4 layers of silicon strips
  - Compact GEM-based TPC



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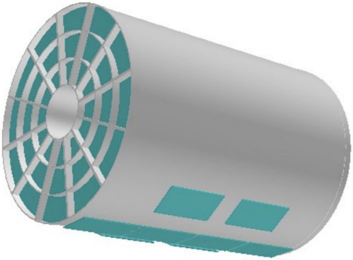

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sPHENIX Tracking

- 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

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Vertexing

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Timing

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Momentum

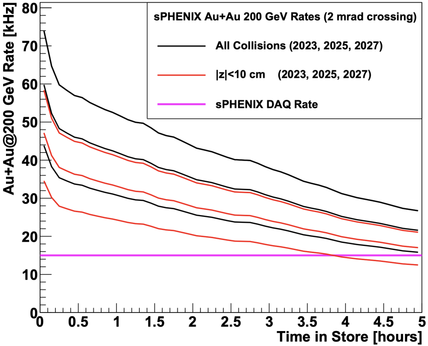
- TPOT - 8 modules of micromegas to provide additional $\mathcal{O}(100)$ micron space point

Calibration

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

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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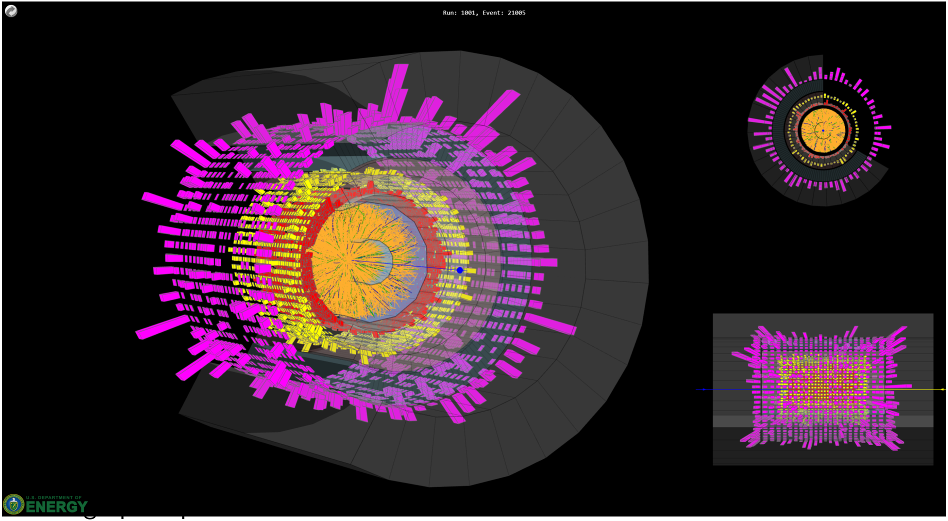

sPHENIX Computing Challenges

- In a 3 year, $\sim$24 cryo-week per year data taking campaign, sPHENIX will collect $\sim$ 250 PB of data
- Data will be processed on a fixed size computational farm at BNL - limited computational resources
- Necessitates fast, efficient track reconstruction
    - Goal is a CPU budget of 5 seconds-per-event on a single tracking pass
    - In reality, we will make two tracking passes including the TPC calibration workflow

sPHENIX-ACTS Track Reconstruction

- sPHENIX has implemented the A Common Tracking Software (ACTS) toolkit into our software stack
- ACTS is intended to be a modern, performant, flexible track reconstruction toolkit that is experiment independent
- Largely developed by ATLAS tracking experts; however, user/developer base has grown
  - sPHENIX, EIC, Belle2, ATLAS, FASER, ALICE...
- ACTS has modern development practices, e.g.
  - Semantic versioning/releases
  - Full CI/CD implemented in Github Actions
  - Issue tracking
  - Documentation
  - Unit testing

ACTS Github link

arXiv:2106.13593

ACTS Implementation Strategy

- ACTS requires geometry and measurement objects (that's all)
- sPHENIX objects store necessary information for ACTS objects
- Modules act as wrappers for calling ACTS tools and updating sPHENIX objects

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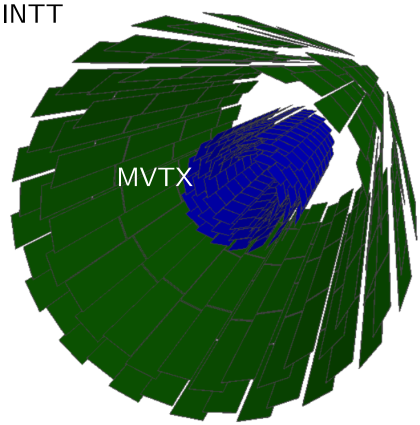
- Modules act as wrappers for calling ACTS tools and updating sPHENIX objects
- Eventually plan to move to a paradigm where sPHENIX objects == ACTS objects, for saving memory and time
- Fun4All-sPHENIX code available on Github - code is open source and containerized with Singularity. Ask questions if you are stuck!

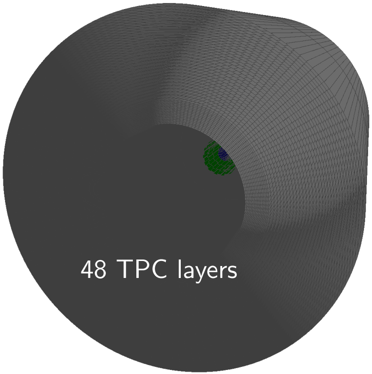
ACTS Geometry - Silicon+TPOT

- ACTS is able to perform material calculations quickly due to a simplified geometry model
- ACTS contains an available `TGeometry` plugin which takes `TGeoNodes` and builds `Acts::Surfaces`
- Any changes to sPHENIX GEANT 4 silicon or TPOT surfaces are then reflected in ACTS transparently

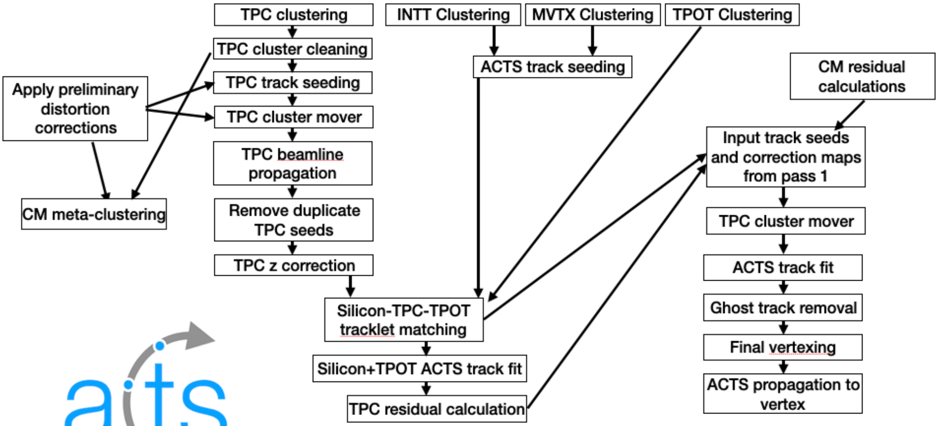


ACTS Geometry - TPC

- ACTS geometry model not immediately suited to TPC geometries, since surfaces are required
- With TPC, charge can exist anywhere in 3D volume
  - Side note: ongoing development within ACTS to allow for 3D fitting
- In place, create planar surfaces that mock cylindrical surfaces
- Surfaces are set at readout layers, so there is a direct mapping from a TPC readout module to *n* planar surfaces

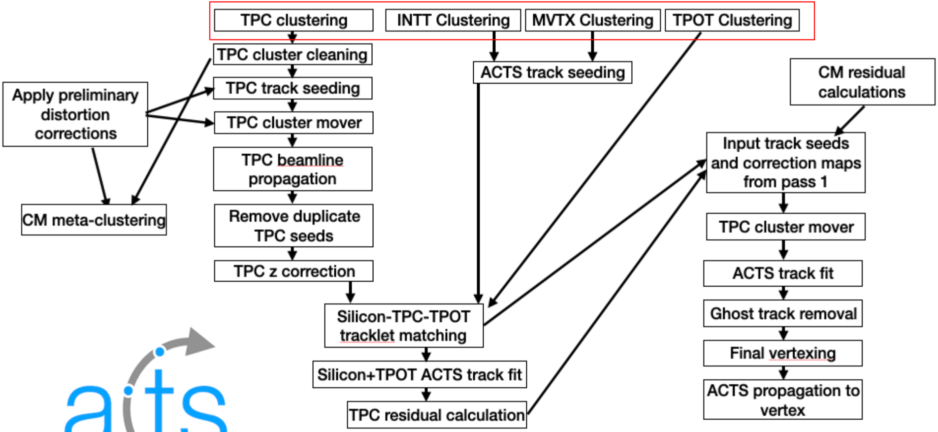


Track Reconstruction Workflow



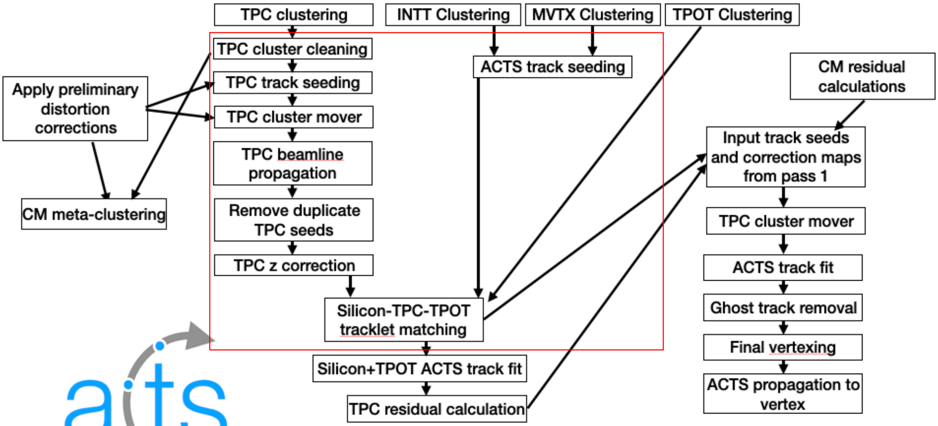
JDO et al., Computing and Software for Big Science 5, 23 (2021)

Track Reconstruction Workflow: Clustering



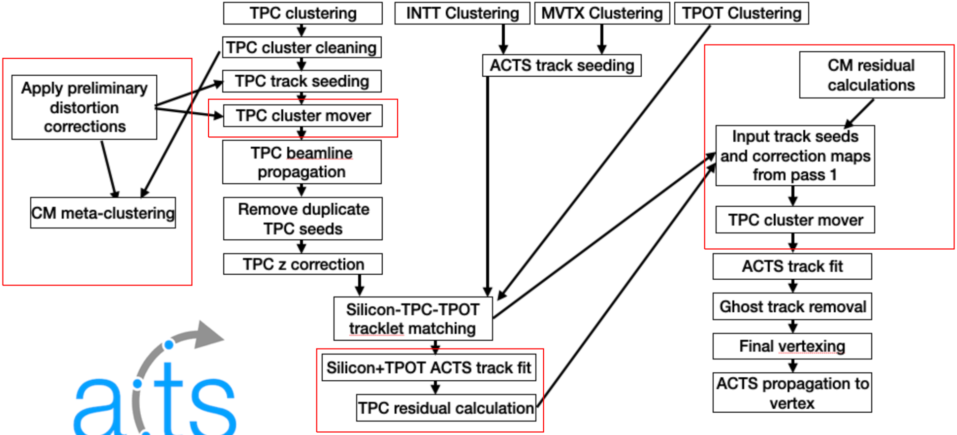
Start with clustering digitized hits to form clusters

Track Reconstruction Workflow: Seeding



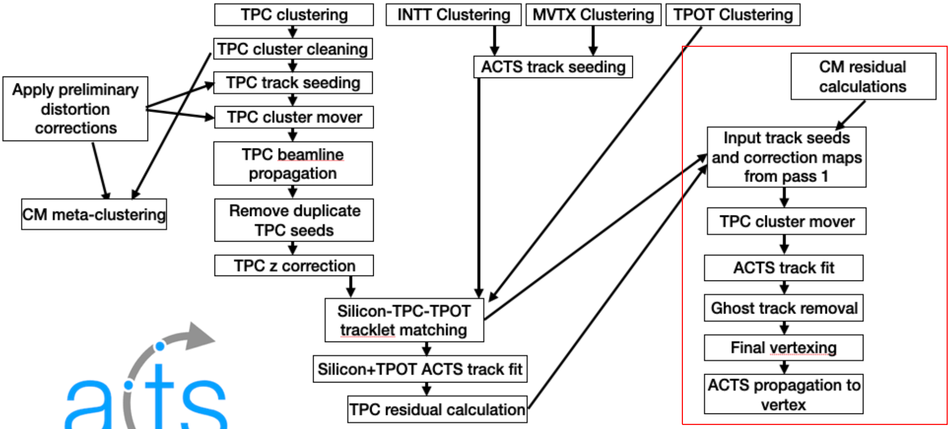
Combine measurements into track seeds (track finding)

Track Reconstruction Workflow: Distortions



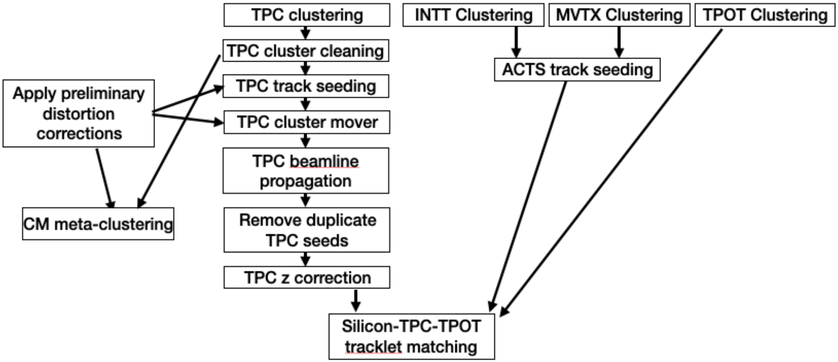
Determine/apply TPC distortion calibrations

Track Reconstruction Workflow: Fitting



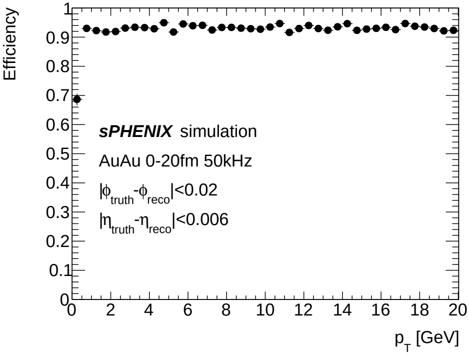
Perform final track fitting

Track Reconstruction Strategy



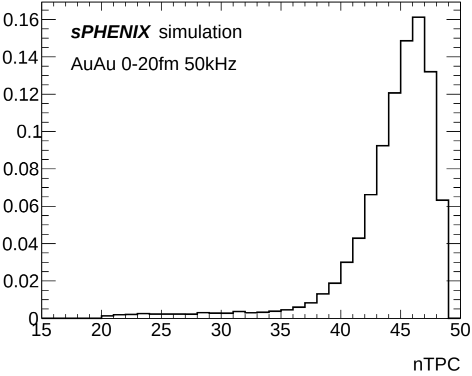
- 4D tracking strategy: reconstruct seeds in each detector individually
- Combine information at end of seeding
  - TPC seed contains most of the track defining curvature
  - Silicon seed contains precise vertex + timing information
  - TPOT measurement (if available) adds TPC calibration information

MVTX+INTT Seeding



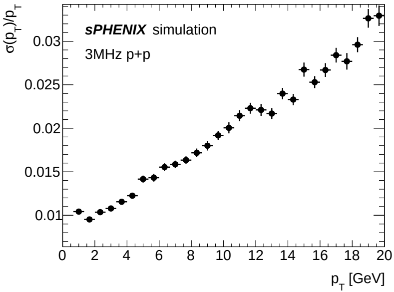
- Start with Acts seeding algorithm in 3 layer MVTX
  - Finds triplets - reduce duplicates by deploying in MVTX only
- Propagate track seed to INTT layers to find additional matching measurements in tuned search windows
- Iterative track finding is a future goal

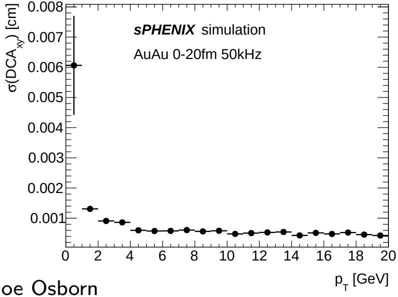
TPC Seeding



- Cellular Automaton seeding algorithm developed by ALICE collaboration deployed in TPC
- Chains links of triplets together in TPC layers
  - Needs improved performance at low p_T when chaining
- High efficiency and computationally fast

Track Matching and Fitting

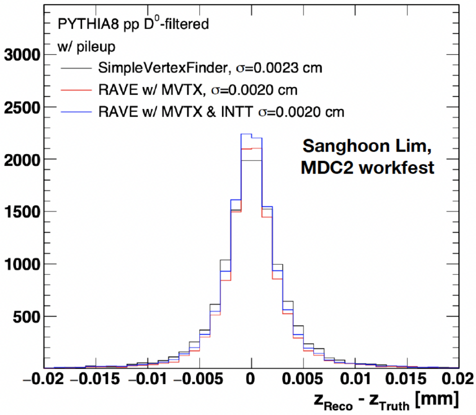




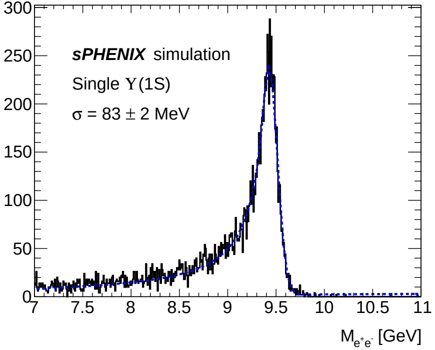
- Silicon tracklets are matched with TPC tracks
- Further propagation performed to TPOT layers to find compatible TPOT measurements (if any)
- Matching windows tuned to limit number of duplicates while also finding real matches
- Final track seed constructed with silicon tracklet position, TPC tracklet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

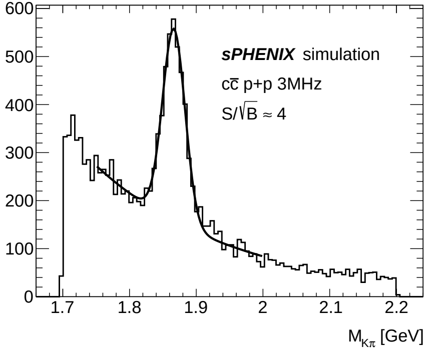
Vertexing

- Tracks are fit without any vertex information required
- Final fitted tracks are used to determine a list of all vertices in event
- Vertices are found by connected tracks with DCA less than 80 micron
- Outlier tracks are connected to closest vertex position



Final Tracks

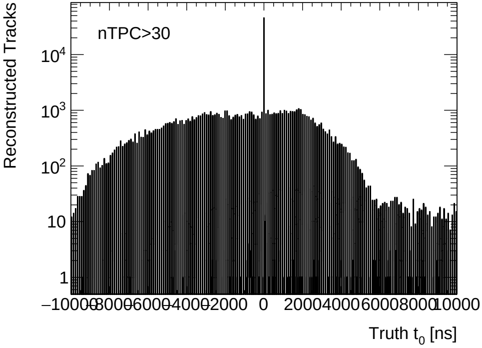




- Final fitted tracks are used for physics analysis

4D Tracking with time

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



MDC2 Workfest, Tanner Mengel

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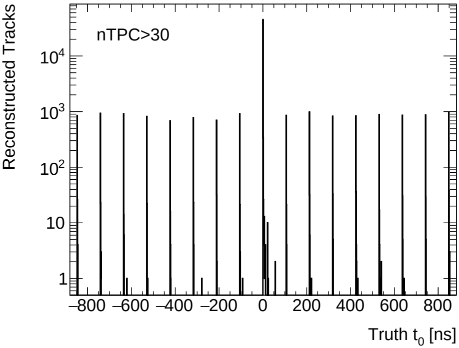

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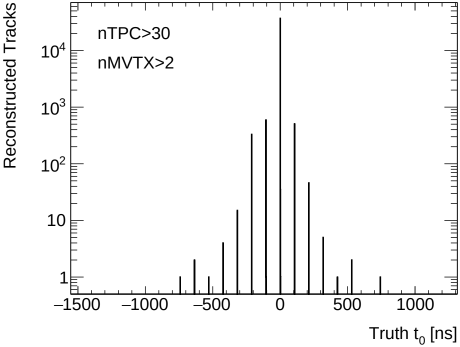

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4D Tracking with time

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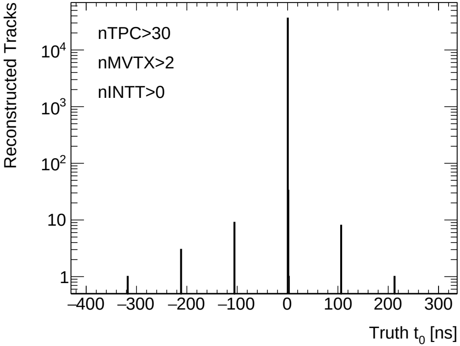
- Reconstructed TPC tracks are found from nearly all 120 RHIC bunches. ∼100 ns bunch structure visible
- Reconstructed TPC+MVTX tracks are found from adjacent several bunches
- Reconstructed TPC+MVTX+INTT tracks are highly suppressed outside of the nominal t_0 bunch crossing



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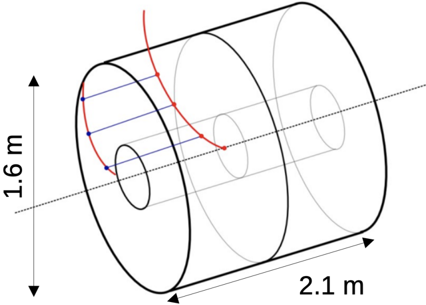
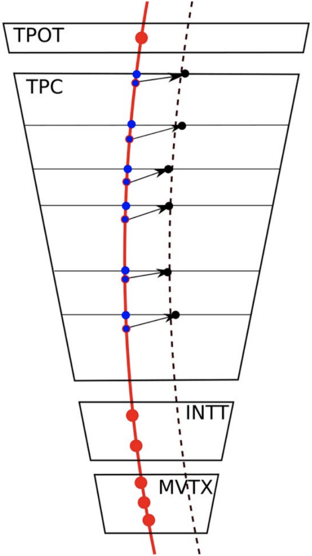
TPC Distortion Corrections

- Major effort of the last ∼year - TPC distortion correction implementation
- 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 : $\mathcal{O}(100\mu m)$, $\mathcal{O}(ms)$



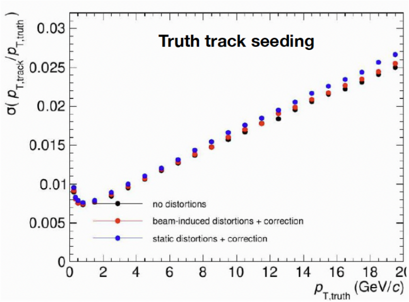
Distortion Corrections

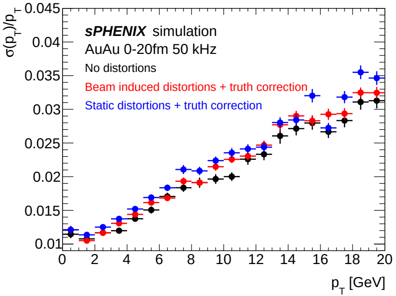
- $\mathcal{O}(cm)$ distortions reconstructed with pulsed laser system
- $\mathcal{O}(mm)$ distortions reconstructed with tracks with TPOT
- $\mathcal{O}(100\mu m)$ distortions reconstructed with diffuse laser



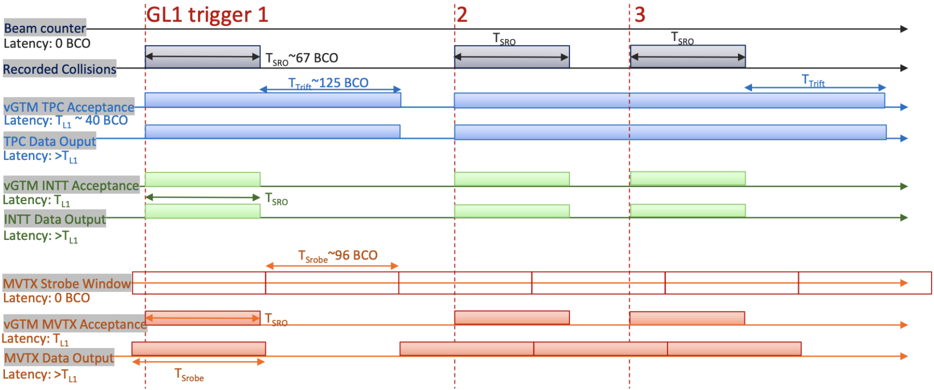
Applying Distortions

- Distortion corrections are determined
- Applied only to clusters on tracks by moving clusters to surfaces based on correction value
- Method functions as expected with truth seeding
  - Continuing to understand degradation of resolution from TPC clustering algorithm





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

Practical Matters

- Practical matters - how do I use the tracks in my analysis?
- SvtxTrack object is the primary track map class
- DSTs contain a map of SvtxTracks for analyzers to do with what they please
- Always available on the node tree - feel free to ask for help or more details if you need help!
- See AnaTutorial::getTracks for some initial guidance

```
SvtxTrackMap *trackmap =
findNode::getClass<SvtxTrackMap>(topNode,
"SvtxTrackMap");
for(const auto& [key, track] :  *trackmap) {
   float px = track->get_px();
   float py = track->get_py();
   float chisq = track->get_chisq();
   ...
}
```

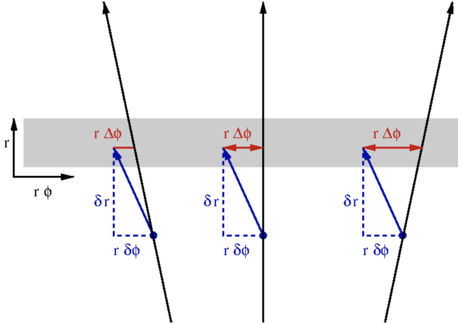
Conclusions

- 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

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

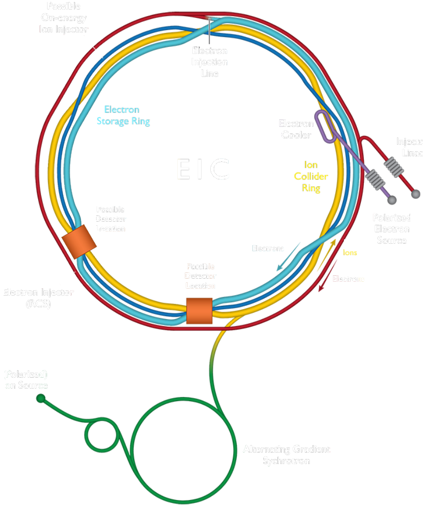
$$\Delta z = \delta z + \delta r \tan\beta$$

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

- $\Delta\phi$ 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

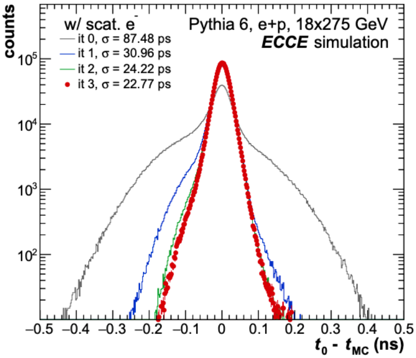
Towards the EIC

- 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, EIC, and (HL)-LHC