Implementation of Acts at sPHENIX

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Brookhaven National Laboratory
2^{nd} Tracking in Particle Physics Workshop

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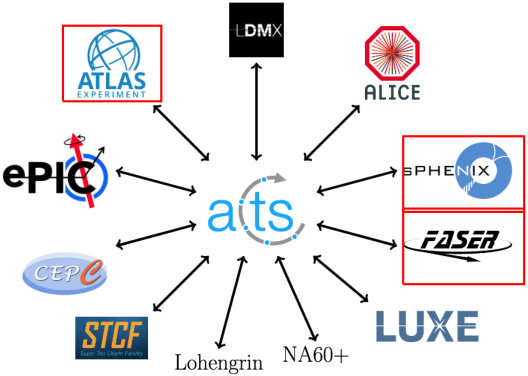
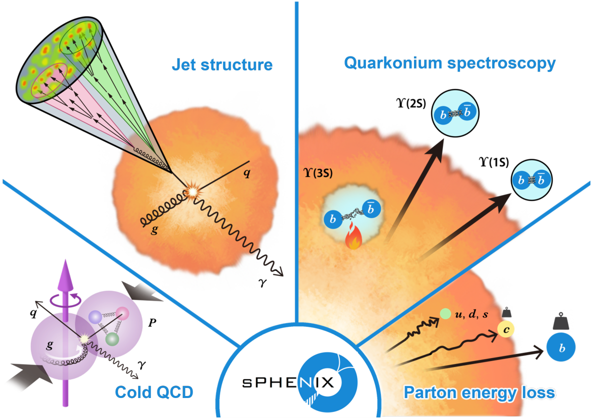
Acts in HENP

- A Common Tracking Software (Acts) is an experiment independent tracking toolkit used in high energy nuclear and particle physics experiments
- Contains production and R&D testbed
- Utilizes modern c++ development and tools
- sPHENIX was an early adopter, and is one of three experiments worldwide using Acts with real data

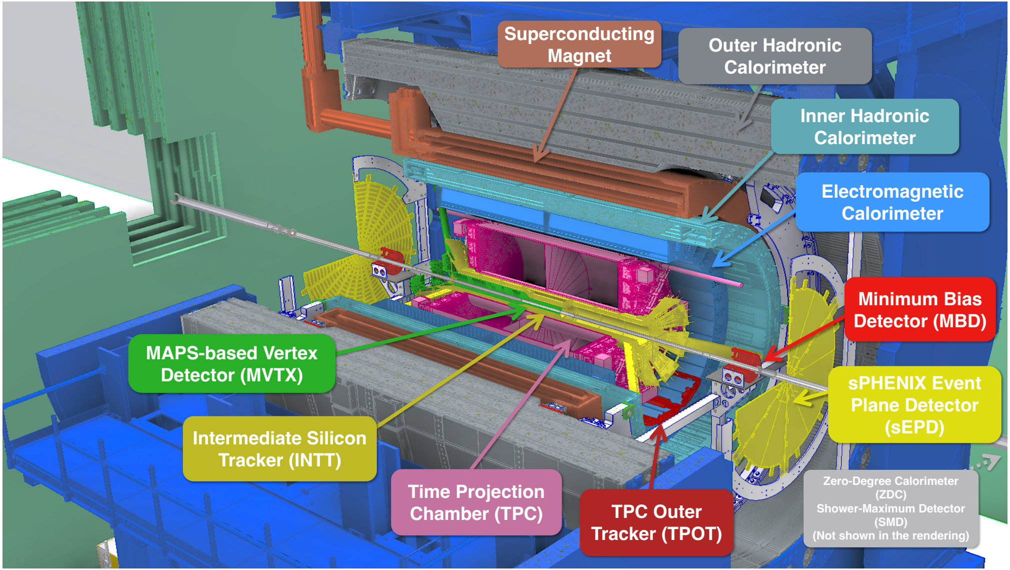


sPHENIX Physics

- 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 $\sim$100 Gbit/s
- Study QCD matter at varying temperatures for direct comparisons to LHC
- Study partonic structure of protons and nuclei

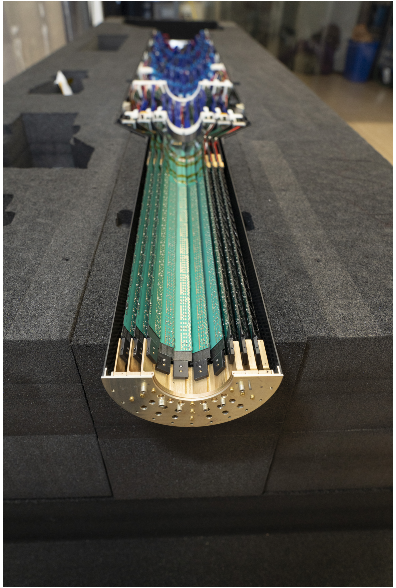


sPHENIX Experiment



Tracking Detectors

- MAPS based vertex tracker (MVTX)
  - Near copy of ITS2 inner barrel
  - Precision vertexing



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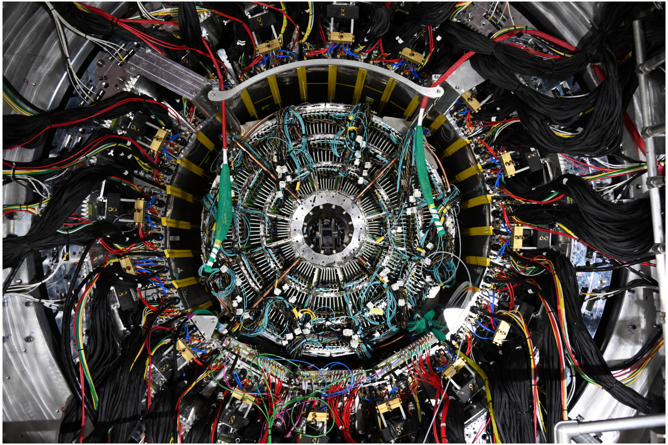

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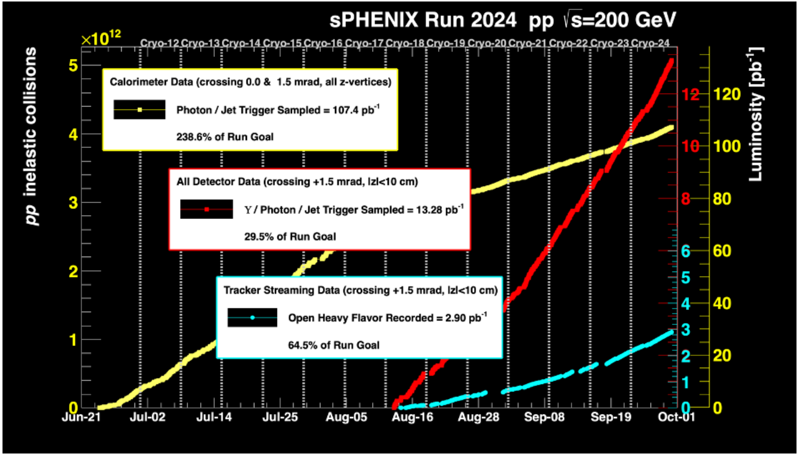
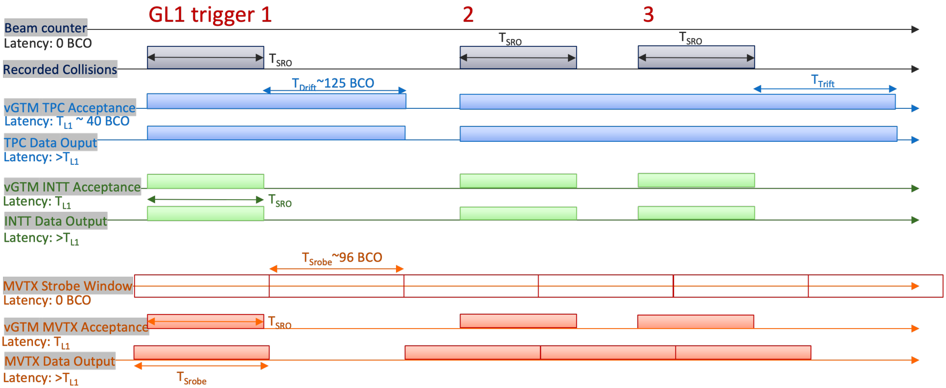
4D tracking to precisely reconstruct space and time structure of physics events

sPHENIX Run Plan

- Collected a sample of $p+p$ collision data at $\sqrt{s} = 200$ GeV in 2024, after an intense commissioning period
- Currently taking flagship Au+Au data at $\sqrt{s} = 200$ GeV, goal of $\mathcal{L}$=7nb^{-1}



Hybrid Streaming and 4D Reconstruction

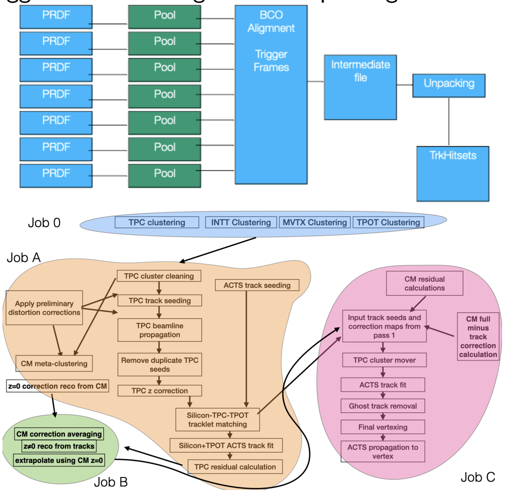


- Collected hybrid streamed data - silicon 100% streamed and TPC streamed 50μs of additional unbiased p+p collisions after every rare event trigger
- Collect large sample of unbiased p+p at $\mathcal{O}(200)$ kHz
- Assemble tracks in space and shift TPC track in time based on INTT measurements' time bucket

sPHENIX and Acts

- Implemented Acts in 2020 as production tracking toolkit
  - See CSBS 5, 23 (2021)
- Currently using Mid-Point seeding, KalmanFilter, and a variety of propagation tools (e.g. for vertices, track states at calorimeters, etc.)
- Running on Actsv34.1.0 - consumed by commissioning/operations, need to update
- Tracking production workflow in advanced stage - regularly producing fully fitted tracks

Trigger frame building and hit unpacking



Clustering, seeding, track fitting, vertexing

General Worfklow

1. Trigger frame building - associate hits to global timing unit trigger time in trigger time range
2. Associate hits to GL1 with relative bunch crossing
3. 4D (space+time) clustering in each subsystem
4. Track seeding - associate subsystem independent seeds to each other in space+time, apply distortion corrections
5. Fit tracks and determine vertices, determing track/vertex/crossing associations

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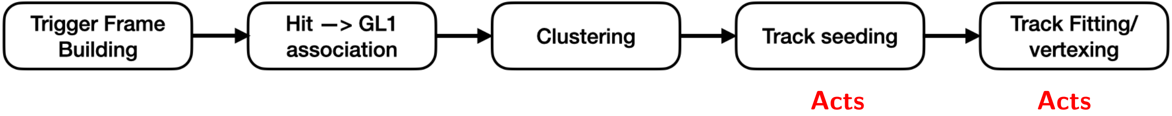

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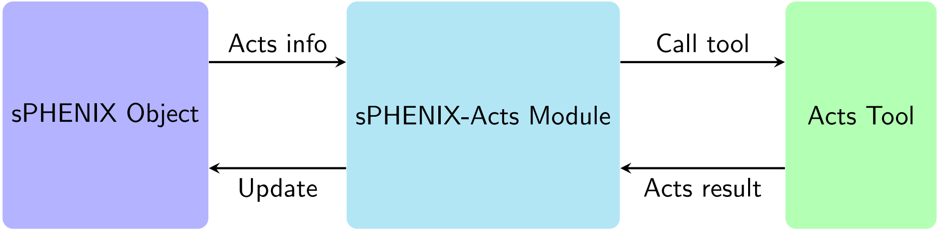
Acts Implementation Strategy



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

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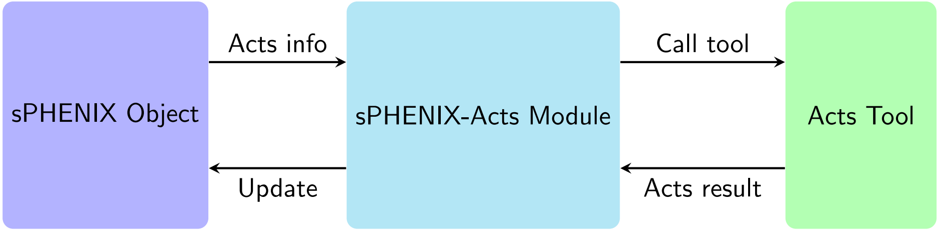

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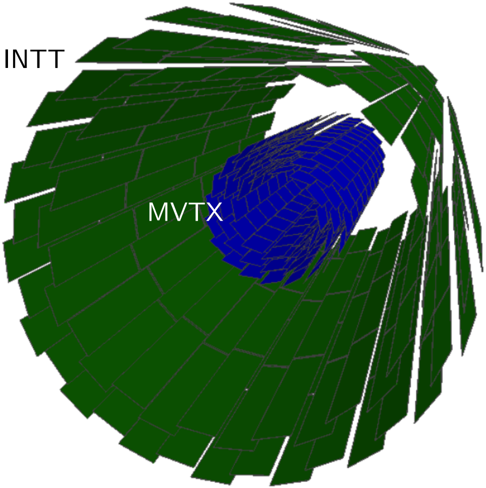
- Fun4All-sPHENIX code available on Github - code is open source and containerized with Singularity. Feel free to ask for more details!

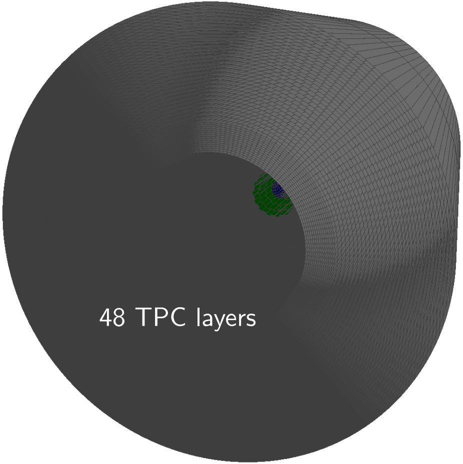
Acts Geometry - Silicon

- Acts is able to perform material calculations quickly due to a simplified geometry model
- Acts contains an available `TGeometry` and `DD4Hep` plugin which takes `TGeoNodes` and builds `Acts::Surfaces`
- Any changes to sPHENIX GEANT 4 silicon surfaces are then reflected in Acts transparently



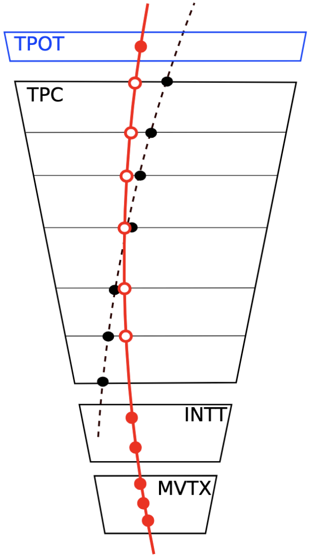
Acts Geometry - TPC

- Acts geometry model not immediately suited to TPC geometries, since surfaces are required
- With TPC, charge can exist anywhere in 3D volume
- 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

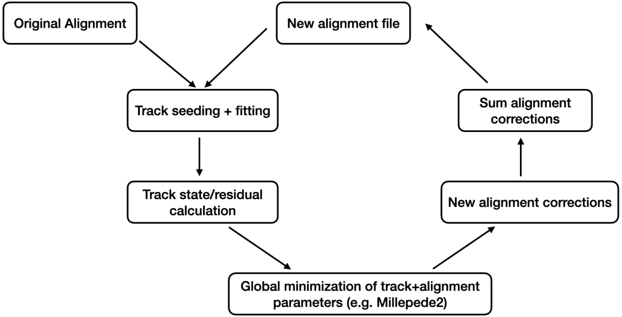


Acts Tools

- Acts tools described so far are “pre-packaged”
- Versatility of Acts - tools are templated, flexible, and can be adapted to your use case
- Example: use propagator to identify track states for TPC space charge distortions and track-to-calorimeter projections
- Example: unique `Acts::GeometryContext` to apply distortion corrections on track by track basis

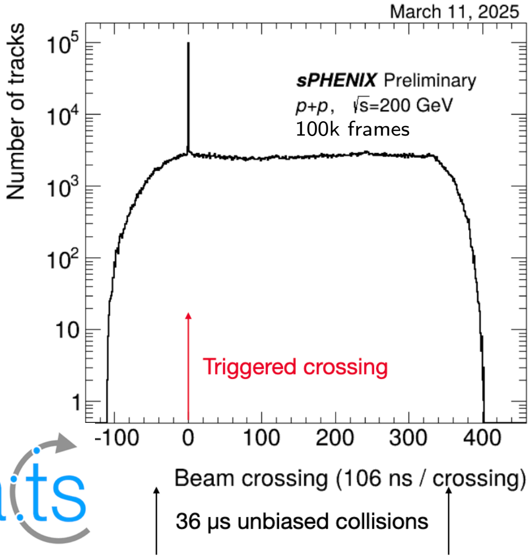


Alignment with Acts



- Alignment of MVTX to $\mathcal{O}(5)\mu$m necessary
- Acts has state jacobian information available to develop an alignment workflow with the (Combinatorial) Kalman Filter
- We have recently started exercising this machinery after using a simple helical fit method to do the initial $\sim$100 micron alignment.

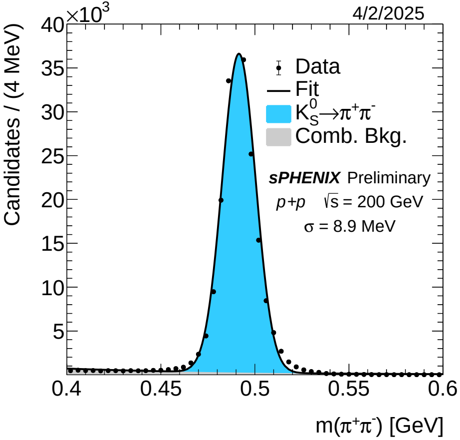
Streaming Readout Performance



- Tracking operates with unique extended streaming readout
- Enables collection of large unbiased $p+p$ dataset for open heavy flavor studies
  - Channels are untrigger-able $\Rightarrow$ requires streaming
- Tracks reconstructed with approximately constant efficiency as a function of crossing number

$\Rightarrow$ Streaming readout was successful

Light Flavor Reconstruction



- Early calibrations show clear K_s^0 peak after optimized cuts
- Reconstructible across all beam crossings

  $\Rightarrow$ Streaming readout and reconstruction successful!

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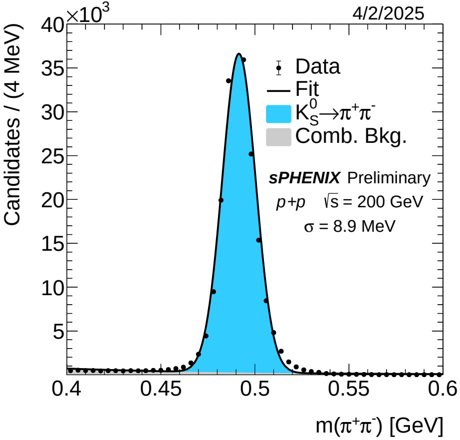

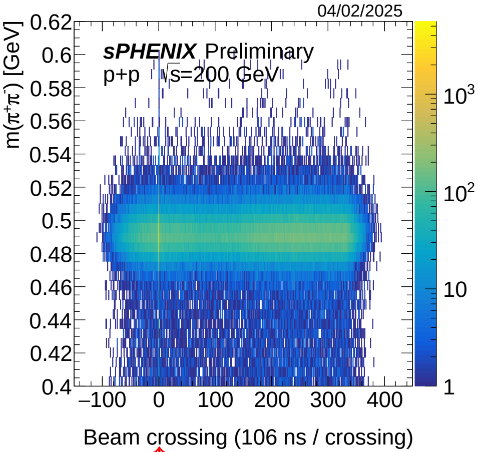

Triggered crossing

- Early calibrations show clear K_s^0 peak after optimized cuts
- Reconstructible across all beam crossings

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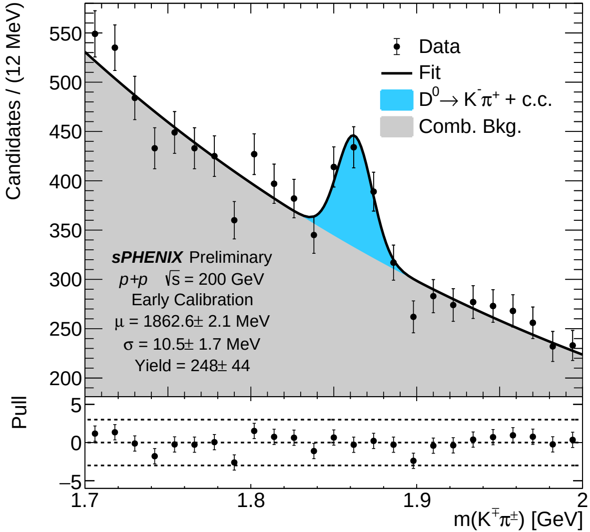
Heavy Flavor Reconstruction

- First D^0 invariant mass peak already measured!
- Focused analysis efforts corresponding to $\sim$ 1 hour of data (!)
- Ongoing effort to optimize selection efficiencies as feedback for improving yields and early calibrations

4/3/2025



Conclusions

- Acts toolkit is a flexible tracking toolkit that can (with some work) be deployed anywhere
- sPHENIX has been successfully using Acts in its tracking reconstruction workflow since 2020
- Streaming data readout and reconstruction with Acts demonstrated successfully with K_s^0, Λ^0, ϕ, Ξ, Σ, D^0, and Λ_c^+
- Some lessons learned
  - Geometry is the most challenging part - inherently experiment specific
  - Acts is flexible for a reason - not necessarily suited out of the box for your use case!
  - Valuable to have community of experts across wide range of high energy nuclear and particle physics, all addressing related problems
- Available geometries has expanded tremendously from community involvement - e.g. telescope like detectors

Back up

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 $\sim 100ns$ integration time
- TPC - Compact, 48 layer, continuous readout GEM-based
  - $\mathcal{O}(100)$ micron precision
  - Long $\sim 14\mu$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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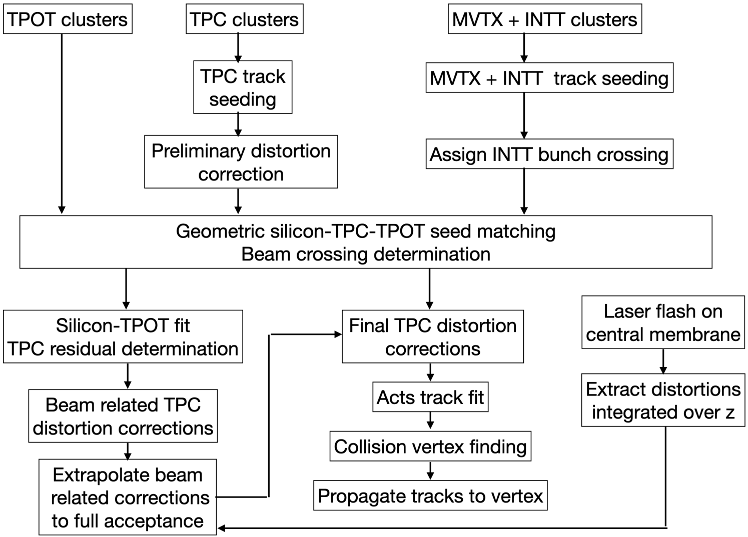
Momentum

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

Calibration

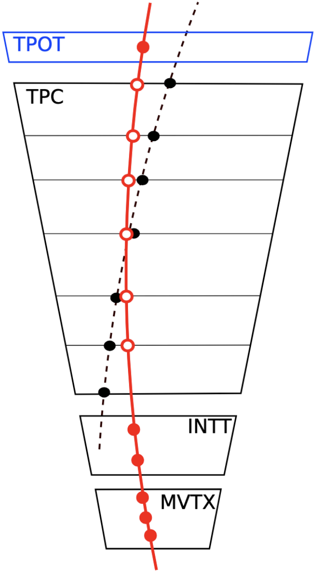
Each detector plays a critical role for the success of sPHENIX physics!

Reconstruction Workflow



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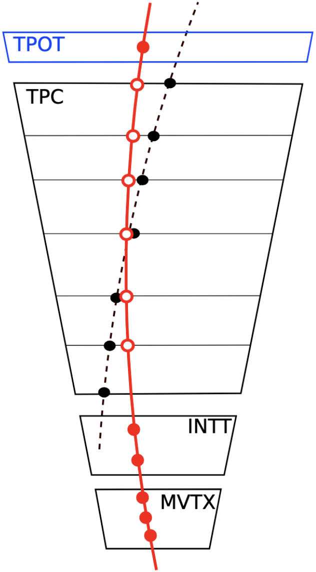
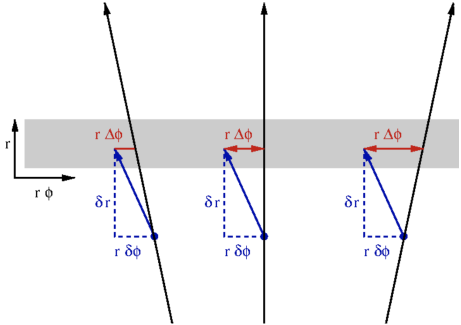
- Use MVTX+INTT+TPOT to define precisely timed in trajectory - then perform calibrations with TPC residuals



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

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

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

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

- $\Delta\phi$ 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

Tracking Timeline

RHIC failure ends
beam
commissioning

08/2023	09/2023	04/2024	05/2024	07/2024	08/2024

Tracking Timeline

RHIC failure ends beam commissioning

Cosmic commissioning

08/2023 | 09/2023 | 04/2024 | 05/2024 | 07/2024 | 08/2024

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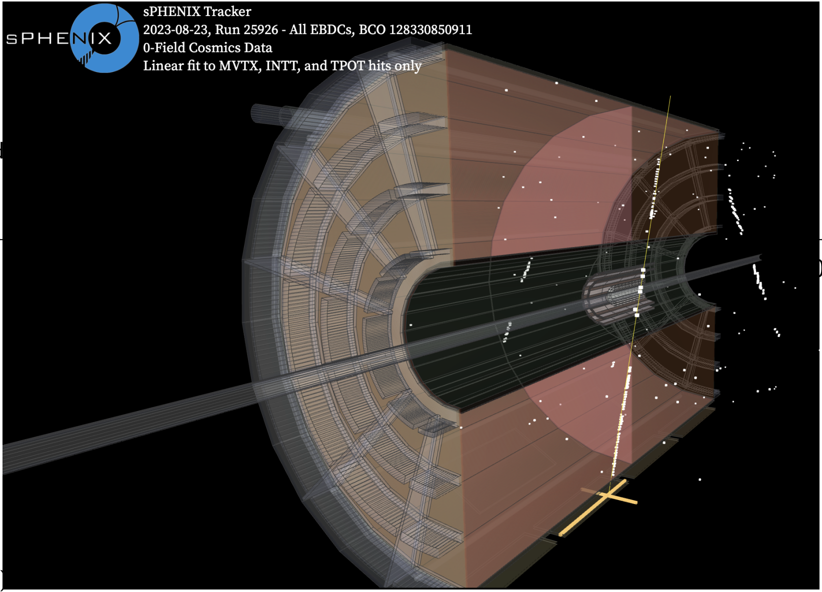
08/2023



08/2024

Tracking Timeline

08/2023	09/2023	04/2024	05/2024	07/2024	08/2024
RHIC failure ends beam commissioning	Cosmic commissioning	$p+p$ data taking begins			

Tracking Timeline

RHIC failure ends beam commissioning

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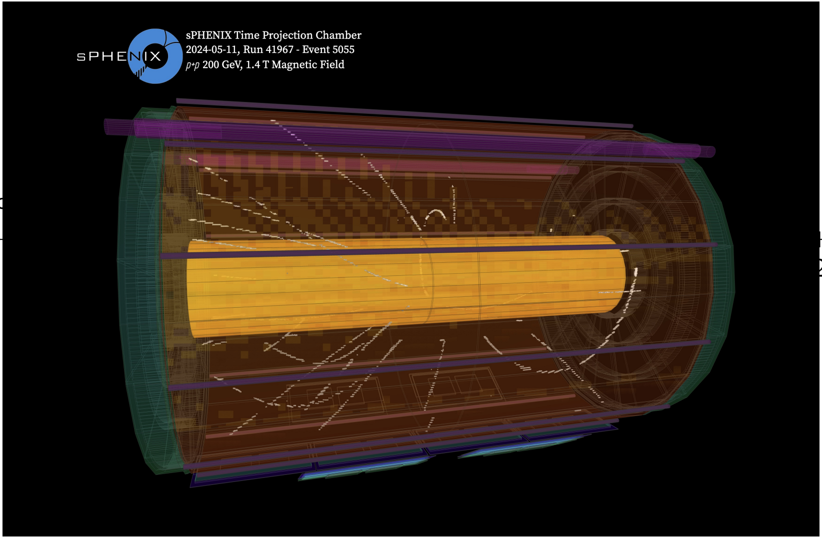
08/2023



2024

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Tracking Timeline

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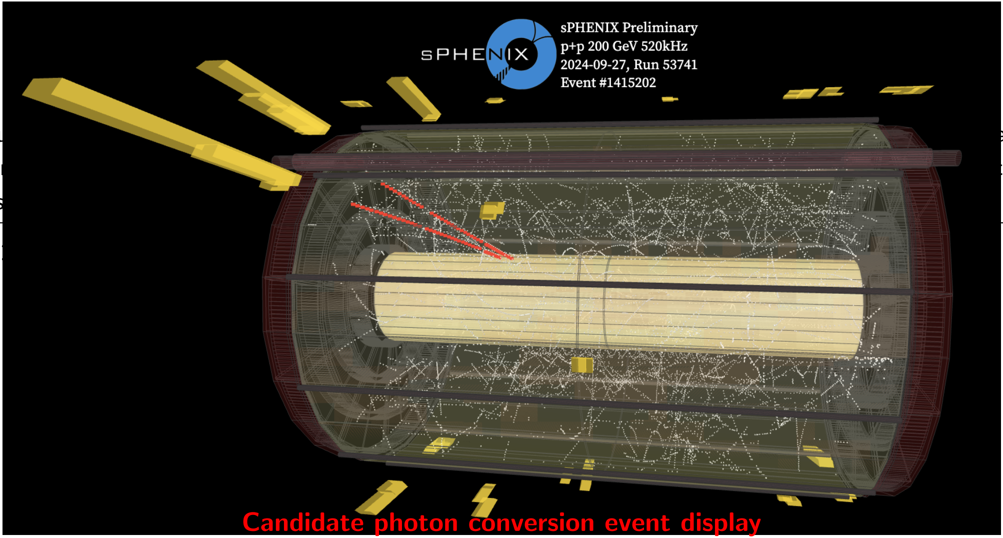
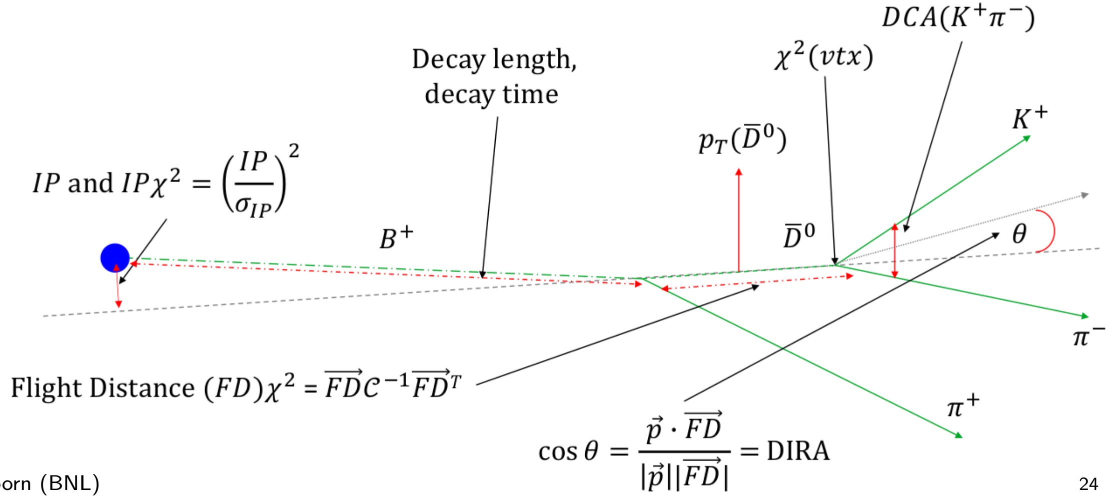


Candidate photon conversion event display

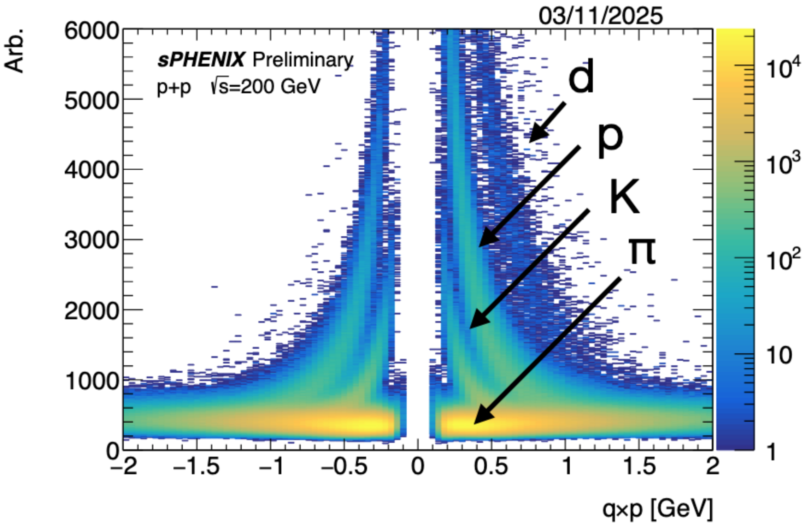
Selection definitions



Notes on Selection Criteria

- Cuts made on (for different states)
  - Track IP
  - Track PID estimate
  - Track-to-track DCA
  - N_{states} in subsystems
  - Transverse decay length
  - DIRA
  - Mother IP
  - Secondary vertex χ^2

TPC Performance



- TPC demonstrates stable performance with 5% isobutane
- PID separation with early dE/dx calibration (despite not being designed for this)
- Used for combinatoric background suppression at low momentum