

Achieving TPC design resolution

NP-EXP Group Meeting

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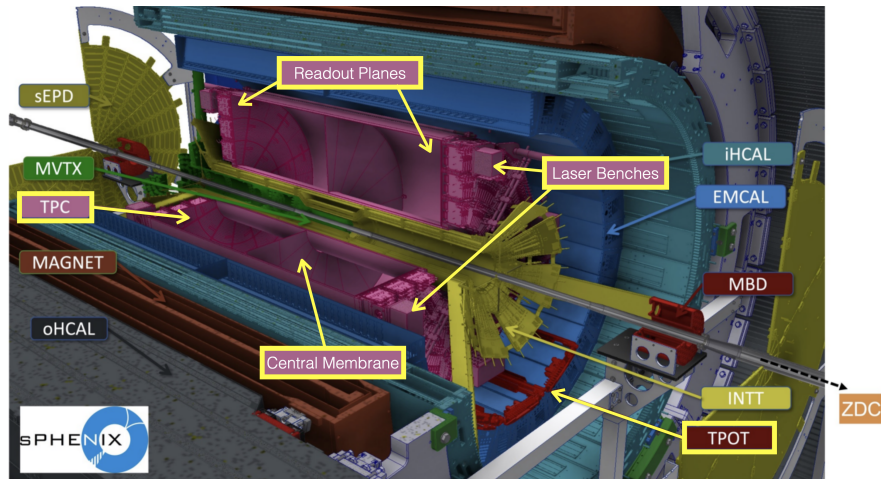
Stony Brook University



Outline

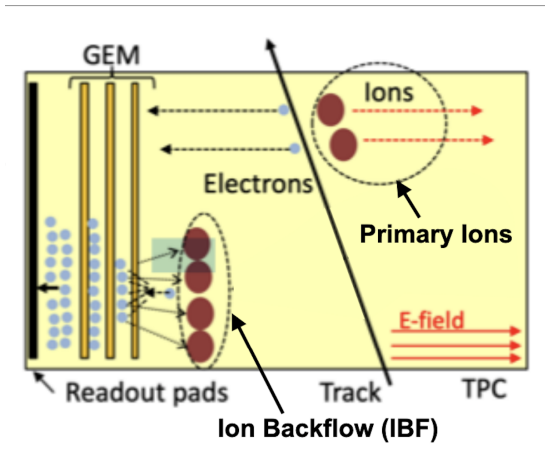
- sPHENIX detector
- TPC at sPHENIX
- TPC resolution
 - ▶ Electron drift and electronics response
 - ▶ Zig-Zag pad geometry (Hits) and Differential non-linearity (clusters)
 - ▶ Alignment
 - ▶ Distortions
- Steps towards achieving TPC design resolution
- Resonance reconstruction. Already inspiring results! Sometime here will be Υ as well!

sPHENIX detector



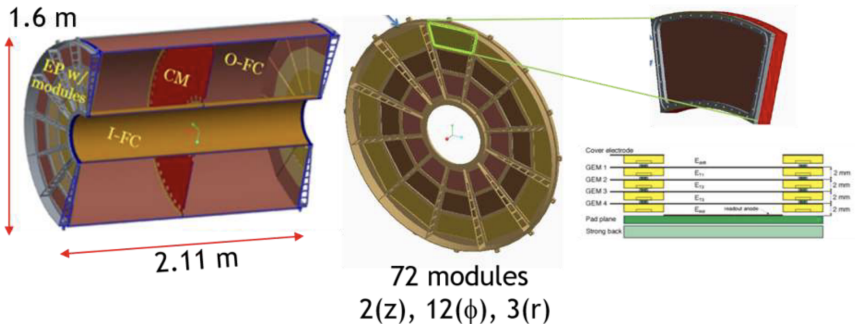
sPHENIX is the final experiment of the heavy ion era at RHIC.
Completion of the remaining measurements: Full Jets (HCAL); Open Heavy Flavor;
Resolved Upsilon

Time projection chamber



Particles ionize TPC gas, electrons drift to readout ions drift to Central Membrane $B=1.4$ Tesla controls diffusion $E = 400 \text{ V/cm}$ guides e^-

TPC construction



- $20\text{ cm} < r < 78\text{ cm}$, $|\eta| < 1.1$ (2.11 meters long)
- 1022.88 cm drift length
- $\text{Ar} = 75\% \text{ CF}_4 = 20\% \text{ iC}_4\text{H}_{10} = 5\%$
- Metallized central “membrane” held at 40 kV
- Utilizes 4 stacked gas electron multipliers (GEMs) to produce signal from single ionized electrons

TPC resolution

Design TPC resolution $\sim 100 \mu m$

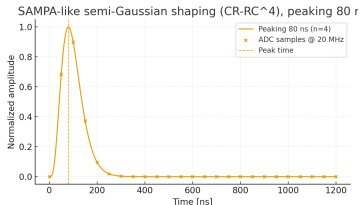
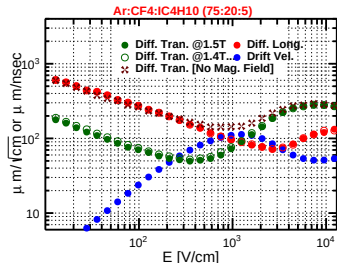
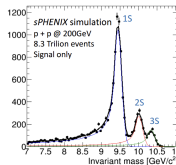
$$\sigma_{r\phi}^2 = \sigma_{pad}^2 + \frac{D_T^2 L}{N_{eff}} + \sigma_{resid}^2$$

- σ_{pad} is the intrinsic resolution of the pad plane
- With B -field and optimized gas smaller D_T (transverse diffusion)
- L - drift length
- N_{eff} - effective number of electrons
- σ_{resid} - uncertainty due to misalignment and $E \times B$

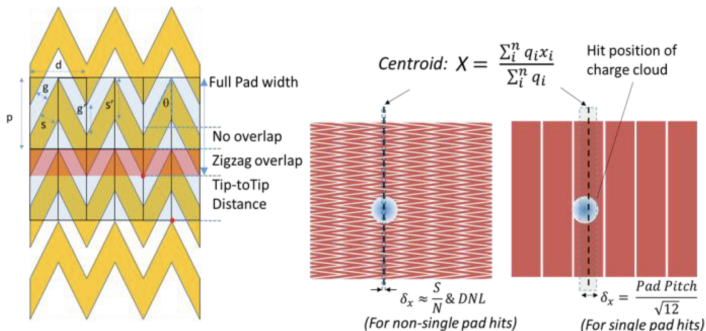
$$\sigma_z^2 = v_{drift}^2(\sigma_t^2) + D_L^2 L + \sigma_{timewalk}^2$$

$$\sigma_t^2 \approx \sigma_{sampling}^2 + \sigma_{shaping}^2$$

- σ_t - comes from the SAMPa shaping (80 ns) and the ADC sampling (20 MHz)



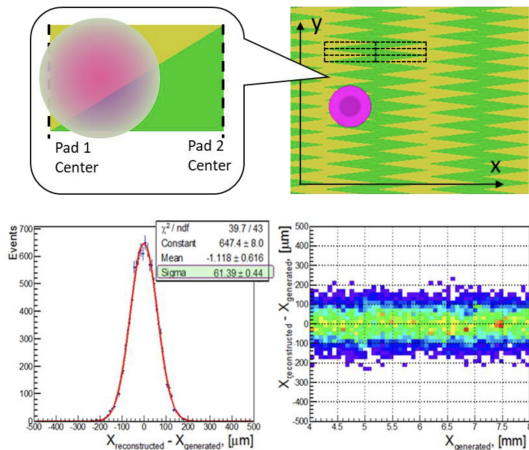
Zigzag pad geometry



- Zigzag pad edges increase overlap between neighbors $\Rightarrow$ induced charge is shared
- Fewer readout channels while keeping high spatial resolution via charge interpolation

Hit - an ADC, recorded by a pad in a time bin

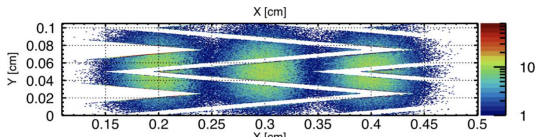
Zigzag pad geometry. Ideal zig-zags



- Pad pitch vs. charge cloud size (diffusion, drift)
- Zigzag period: should be small compared to pitch
- High conductor coverage fraction $\Rightarrow$ smoother charge collection
- Ideally, the collective response of all fired pads is linearly correlated to the hit position, with a differential non-linearity (DNL) ~ 0

Resultant resolution ($\sim 60 \mu\text{m}$) for a 2D Gaussian charge cloud (with $\sigma_x = \sigma_y = 400 \mu\text{m}$) and the pad response for 2mm pitch and a 0.5mm zigzag period, which incorporates a N/S = 2%

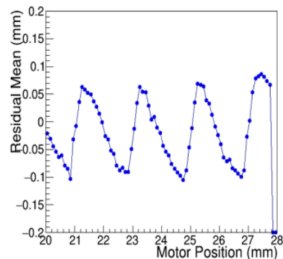
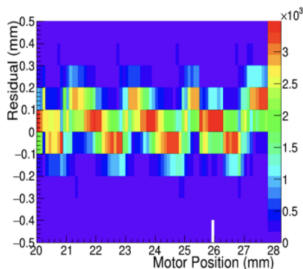
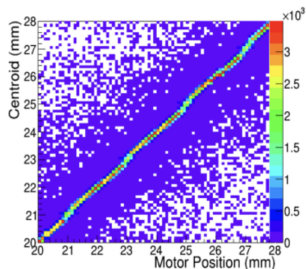
Differential non-linearity (DNL)



Cluster - set of hits, measured point on track

- Standard position:

$$\phi_{clus} = \frac{1}{N_{hits}} \sum_i^{N_{hits}} w_i \phi_i$$
 same for time bin
- Non-linear relation between electron true positions and the interpolated centroid



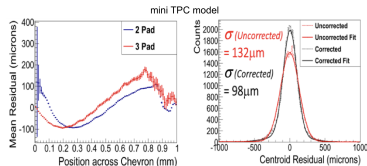
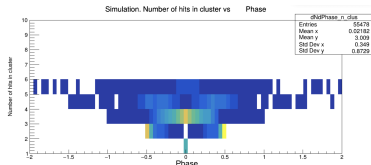
Resultant resolution ($\sim 60 \mu m$) for a 2D Gaussian charge cloud (with $\sigma_x = \sigma_y = 400 \mu m$) and the pad response for 2mm pitch and a 0.5mm zigzag period, which incorporates a N/S = 2%

Cluster Position Correction

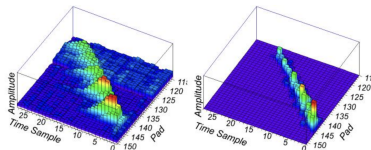
- Straight centroid $\Rightarrow$ non-linear response (DNL)
- Map reconstructed cluster position vs. true cluster position from simulation
- Phase variable

$$phase \equiv \frac{\phi^{reco} - \phi_{pad}^{maxADC}}{\Delta\phi_{pitch}}$$

- $\phi_{clust}^{truth} - \phi_{clust}^{centroid}$ vs $phase(\phi_{clust}^{centroid})$ - DNL correction
- Study how DNL depends on α and θ angles of the track
- Correction of an order of $\sim O(100 \mu m)$



DNL correction from mini TPC model

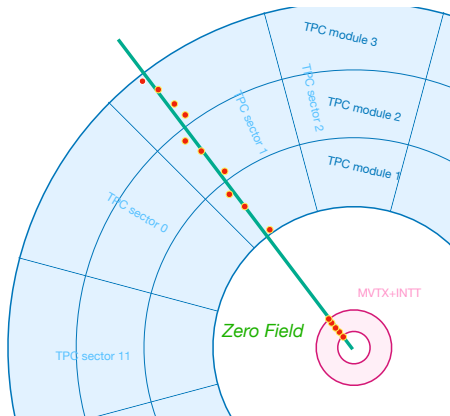


Residuals

Study of the $r\phi$ residuals in the tracking detectors, which are the difference between the measured cluster position and the expected cluster position (from the fit)

$$r\Delta\phi = r \left(\phi_{\text{meas}}^{\text{cluster}} - \phi_{\text{fit}}^{\text{cluster}} \right)$$

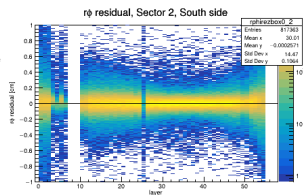
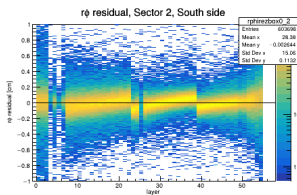
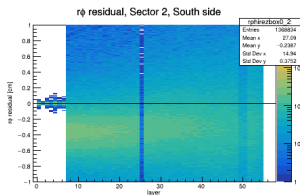
Knowing the residual values, one can extract the corresponding angles to align the tracking detector layer



Tracks without magnetic field. TPC alignment

No $E \times B$ effects - Tracks are straight lines

- Currently done - TPC alignment to the Silicon detectors (MVTX+INTT)



- Standalone TPC alignment
 - ▶ Internal alignment of the modules with respect to each other
 - ▶ TPC alignment to the beam axis

Tracks in magnetic field. Distortions

- Static Distortion

- ▶ external E, B fields: non uniformity and alignment
- ▶ expected to be $O(1 - 2\text{cm})$
- ▶ does not change
- ▶ mixes with module alignment, module edge effects, etc

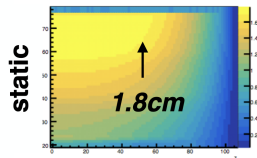
- Average Distortion:

- ▶ average spacecharge
- ▶ expected to be $O(1 - 2\text{mm})$
- ▶ changes slowly with lumi. and ambient conditions

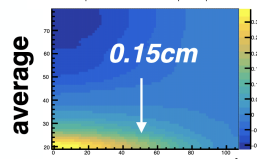
- Event-by-Event Distortion:

- ▶ fluctuations in spacecharge
- ▶ expected to be $< O(100\ \mu\text{m})$
- ▶ changes rapidly (78ms for full refresh)

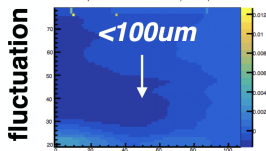
**simulated δr
in r-z slice**



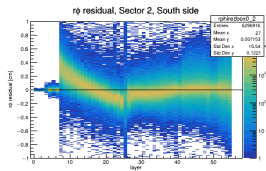
r component of int. distortion in zr plane at $p=3.102$



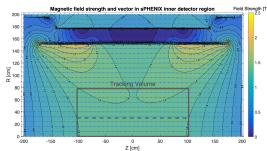
r component of int. distortion in zr plane at $p=3.102$



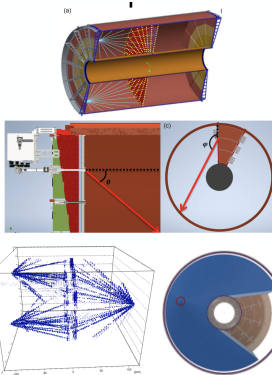
Distortion corrections



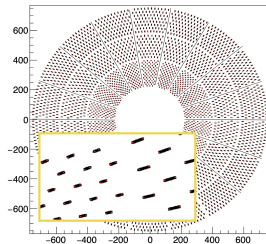
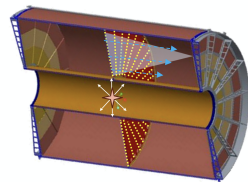
Residuals - Diagnostic tool



Static distortions from the magnetic field



Static distortions from Line laser



Average distortions from diffuse laser

Steps towards achieving designed TPC resolution

Simulation

- Implement zig-zag geometry for pads
- Correct pulse shape
- Verify gain normalization
- Zero suppression implementation
- Verify that track reconstruction software flow is the same as for real data

Cluster positions

- Differential non-linearity
- z cluster position
- Correction of the cluster centroid in 3D using track angle

TPC standalone alignment

- Internal alignment of TPC modules with Field-off cosmic data
- Alignment of the TPC to the beam axis with low luminosity Au+Au Field off data
- Verify with line laser and diffuse laser pattern

Static distortions due to $E \times B$ effects

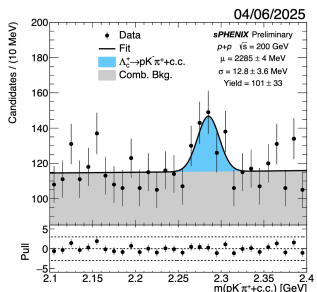
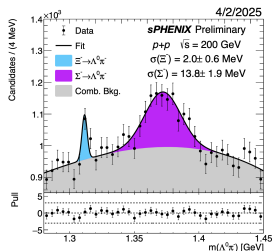
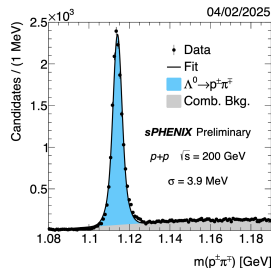
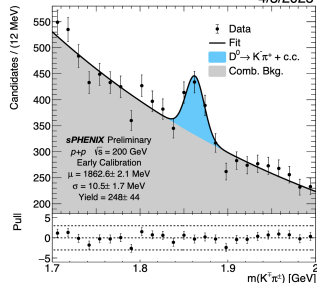
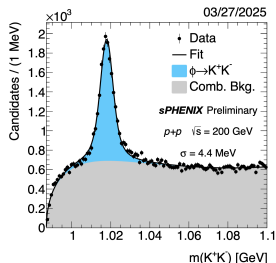
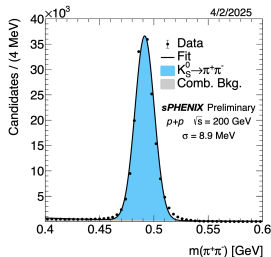
- Fine tune existing corrections based on simulation with known E and B field maps
- Produce data-driven static distortion corrections using line-laser data
- Produce a data-driven correction map of distortions at the edges of modules in r and ϕ .

Average and fluctuation distortions

- Derive average corrections from diffuse-laser data
- Other steps for distortion corrections

Resonance reconstruction. Already inspiring results!

4/3/2025



First run Au+Au 2025 results!

June 9th, 2025 - first collisions of Run 25!

June 16th, 2025 - first resonances reconstructed with full tracking system

Please, find all the public sPHENIX results here: <https://www.sphenix.bnl.gov/PublicResults>

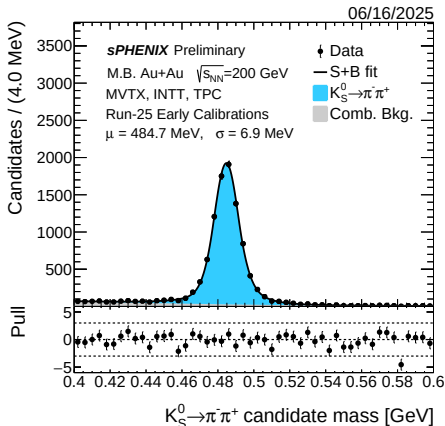


Figure: K_S^0 invariant mass

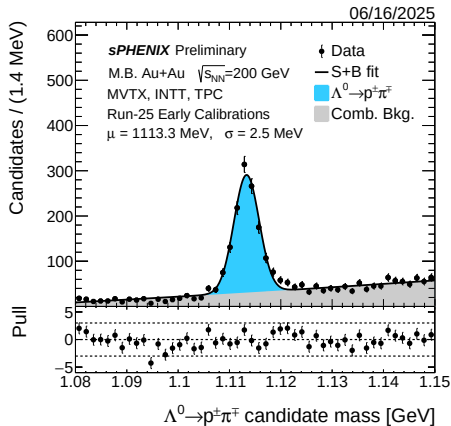


Figure: Λ^0 invariant mass