Vertex Reconstruction at STAR

aka "Primary Vertex finding in the RHIC high precision measurement era enhancement and experience in STAR"

Dmitri Smirnov

J. Lauret, V. Perevoztchikov, G. Van Buren, J. Webb

Brookhaven National Laboratory

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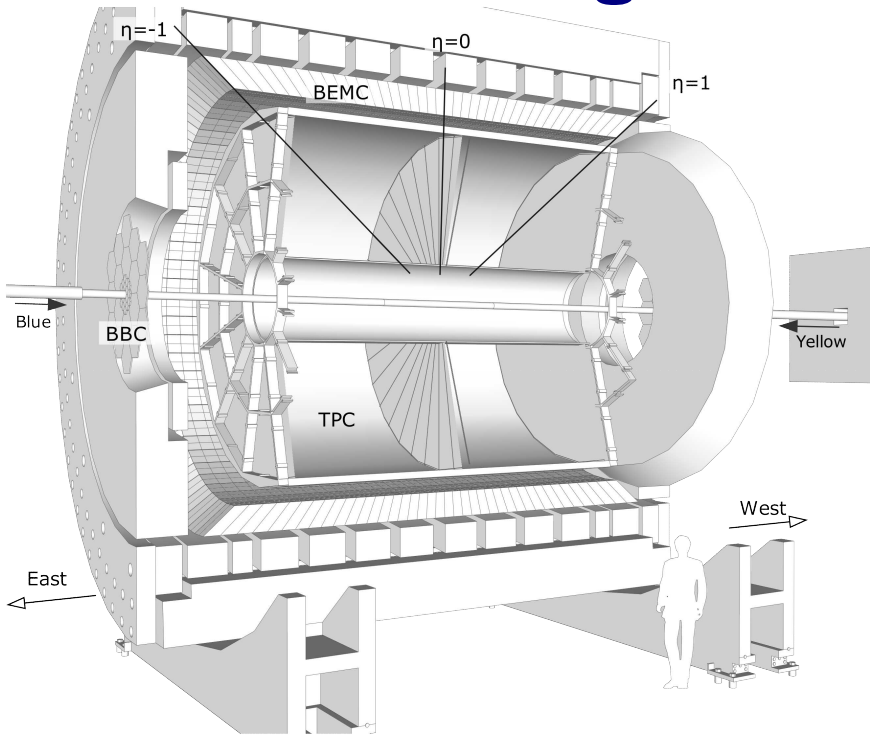
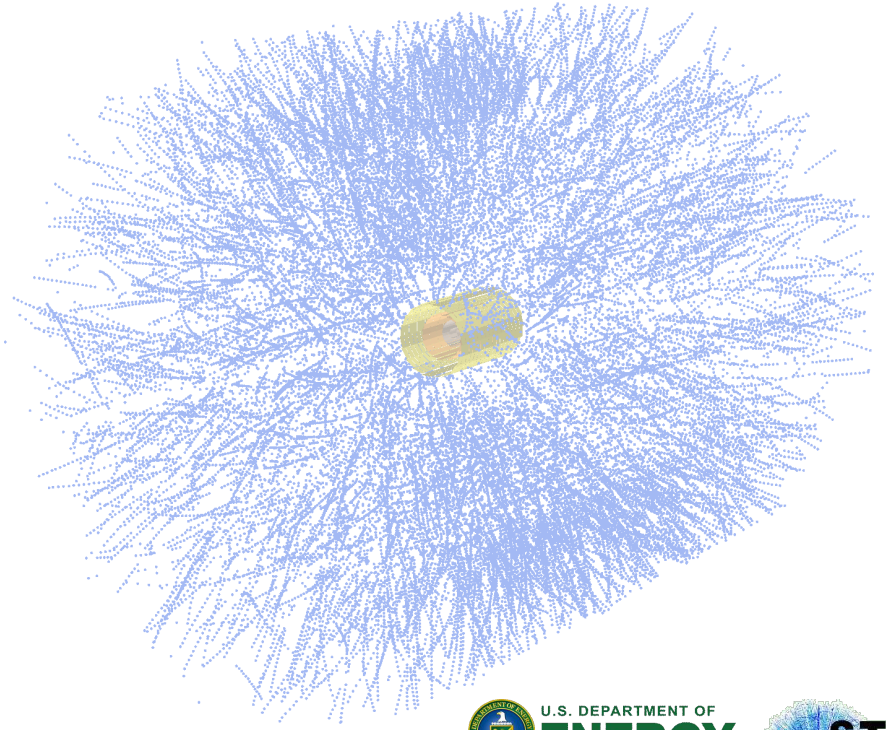
Tracking with STAR Detector at RHIC

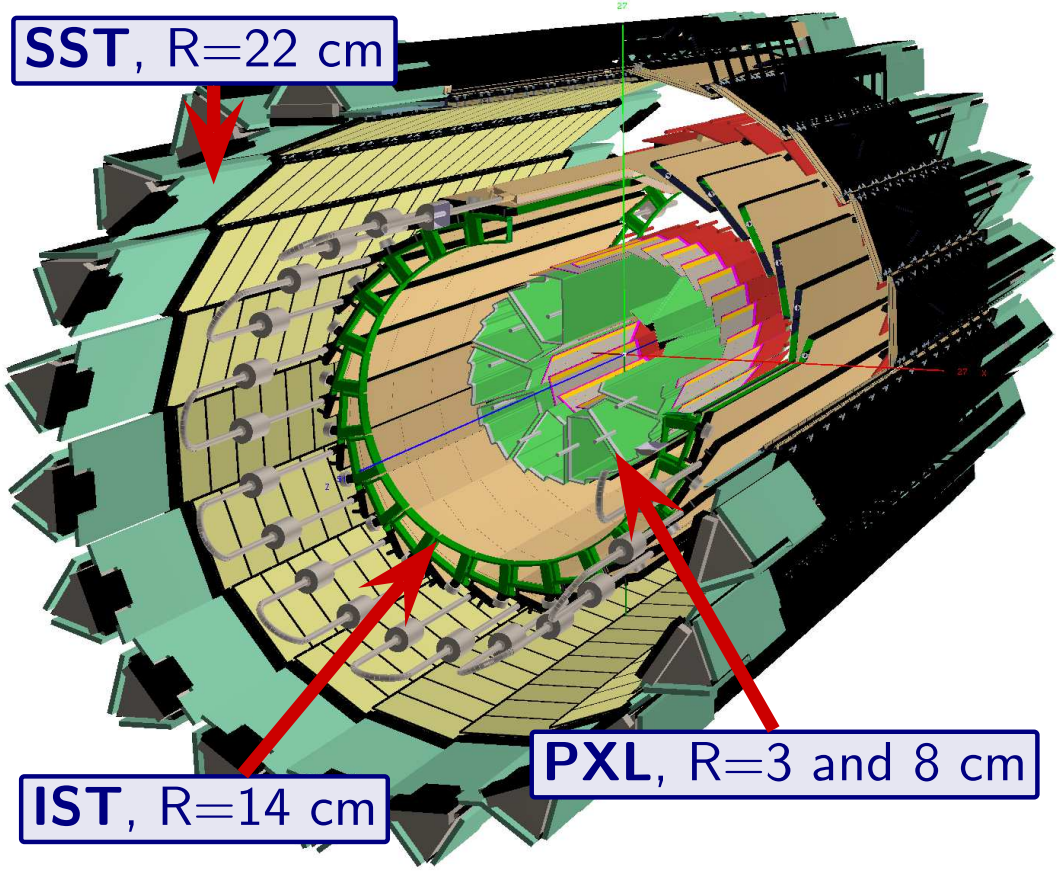


- **STAR** is a versatile collider detector capable of detecting products of hadronic interactions
- **RHIC** provides polarized $\mathbf{pp}$ and unpolarized **heavy ion** (Au-Au, d-Au, Cu-Au, U-U, . . .) beams with $\sqrt{s}_{NN}$ up to 510 GeV
- **Rich physics program:** quark-gluon plasma, spin asymmetries, strange and charm particle decays
- Tracking at STAR is done by means of **Time Projection Chamber** (TPC)

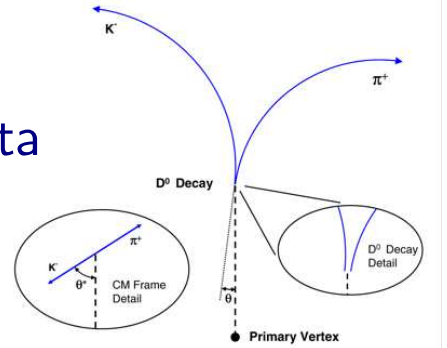
- STAR tracking delivered quality results for over a decade
  - STAR tracking is a robust deterministic algorithm consisting of seed finding stage followed by KF-based fitting
- For STAR tracking details see talk by Jason Webb (contribution #286)



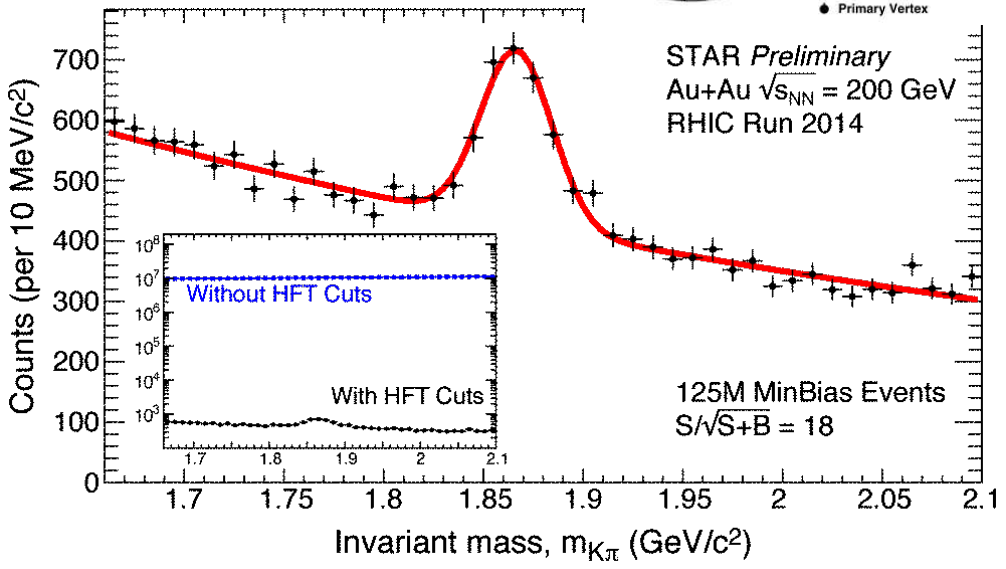
Precision Tracking with Heavy Flavor Tracker



- **HFT** includes three silicon detecors: SST, IST, and two layers of PXL
- **HFT** was installed to detect charm decays such as $D^0 \to K\pi$ with small decay length
- Direct topological reconstruction of D mesons is done by resolving displaced vertices (50–100 μm)
- **HFT** recorded physics data during three RHIC runs since 2014

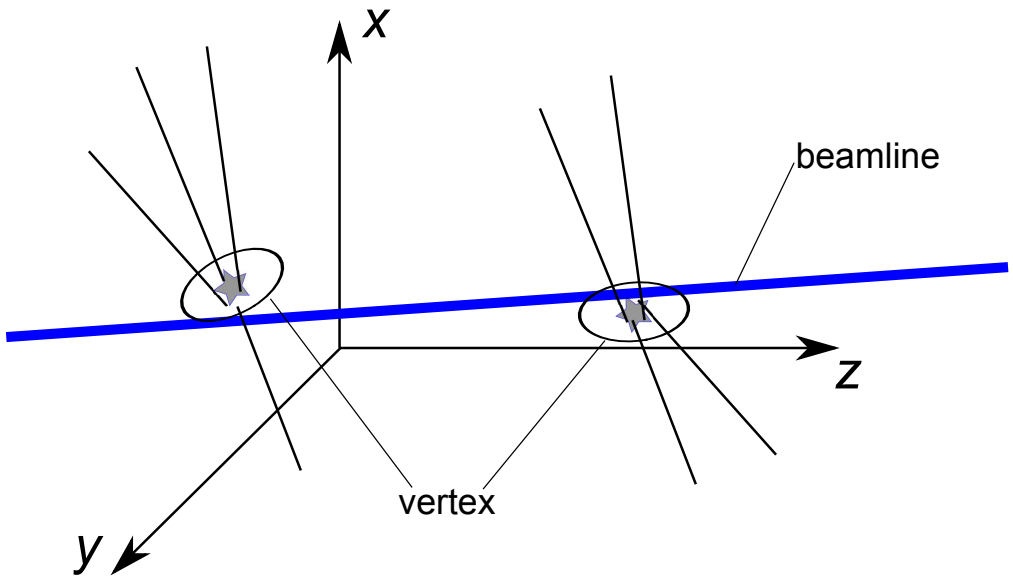


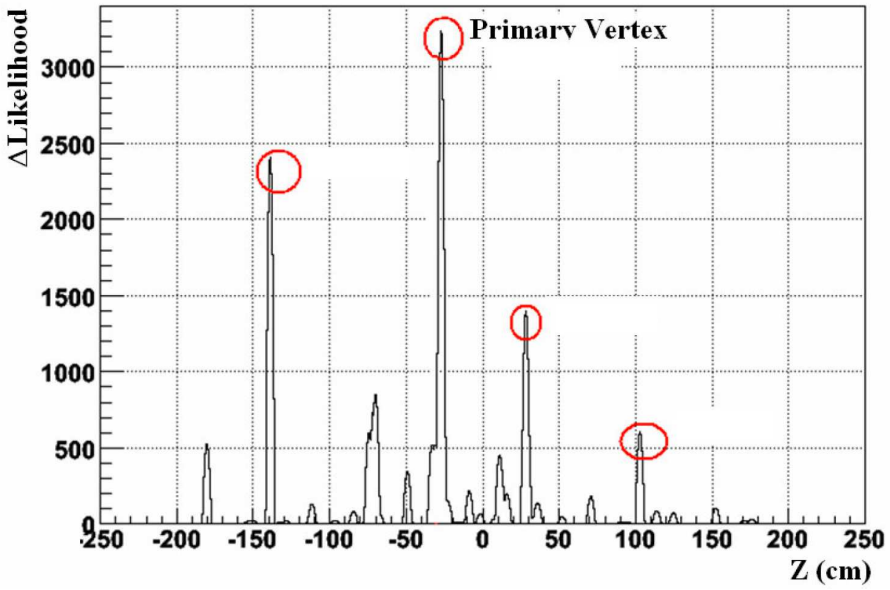
- HFT hits significantly improve resolution of TPC track projections to beam from 1–2 mm to ~ 30 μm
- **High precision tracking with HFT prompted us to revisit STAR tracking and vertexing algorithms**



Vertex Reconstruction Algorithms at STAR

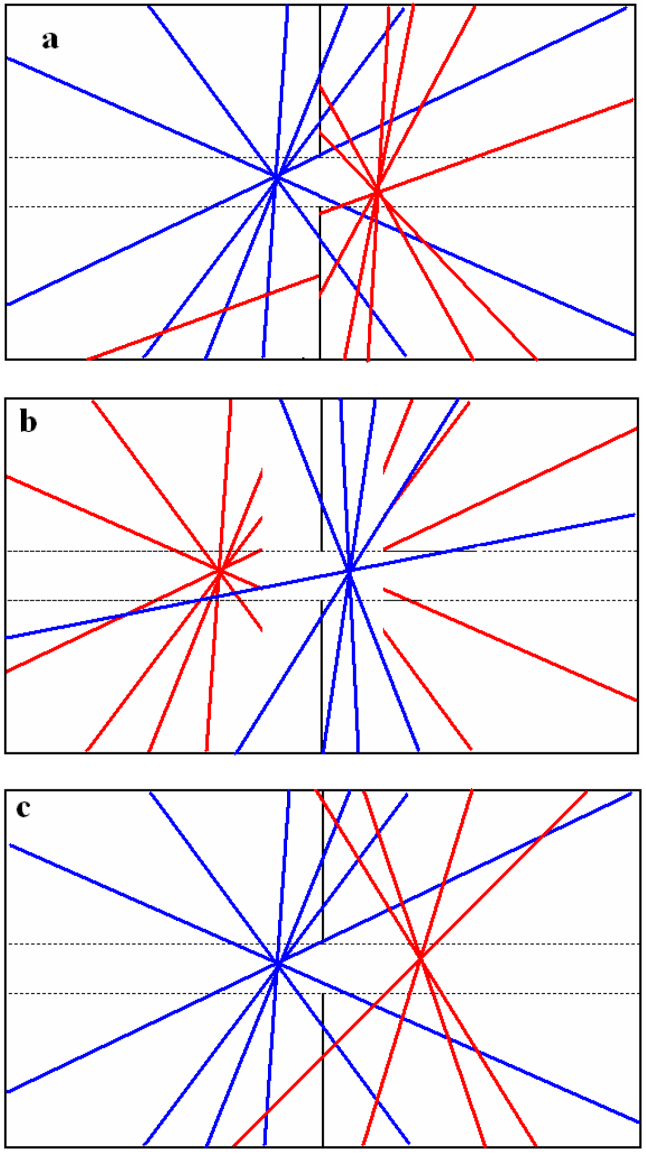
- Two vertex reconstruction algorithms:
  Pile-up Proof Vertexer (PPV)
  Minuit-based Vertex Finder (MinuitVF)
  - STAR is also evaluating an adaptive vertexer, KFV, based on Kalman Filter
- **PPV** and **MinuitVF** are traditional algorithms with dominating seeding/finding stage
  - Rely on similar track preselection
  - Seeding performed in 1D along the beam with predetermined initial binning
  - **PPV** and **MinuitVF** reconstruct different event topologies: pp and **heavy ion** collisions respectively



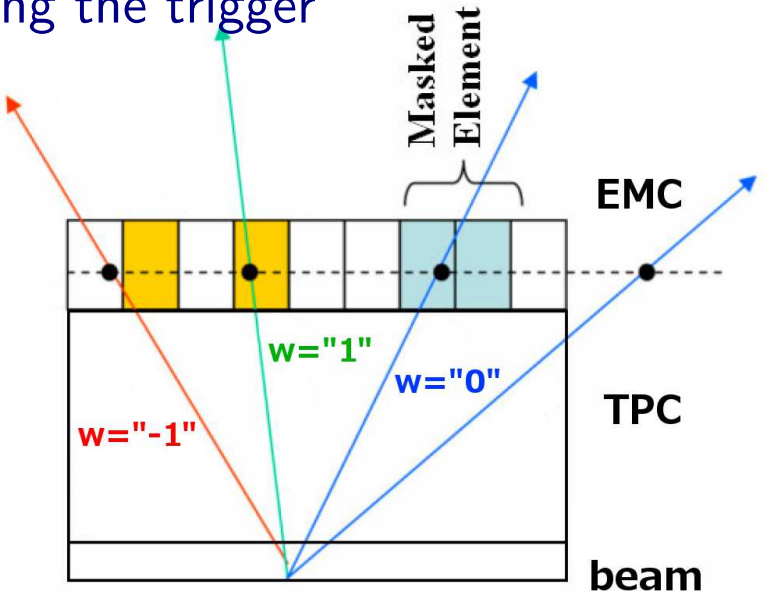


- A few areas for improvements have been identified:
  - **PPV** is lacking the final fitting stage
  - No beamline uncertainties utilized by either vertexer

Dealing with Pile-up Tracks: Vertex Ranking



- 400 bunch crossings per acquired STAR TPC event
  $\Rightarrow$ pile-up tracks
- When pile-up collisions occur before or after the triggered event the tracks in STAR TPC appear to be split
- Tracks are given weights based on the probability that they originated in the collision firing the trigger
  - Fast non-tracking detectors, e.g. EM calorimeter and Time of Flight detector, employed to mitigate the effect
  - Total weight is used in ranking tracks and vertices



- Identification of pile-up vertices produced in the same bunch crossing as the triggered one is left to analyzers

CHEP 2009 proceedings, J. Phys. conf. Ser. 219 032020

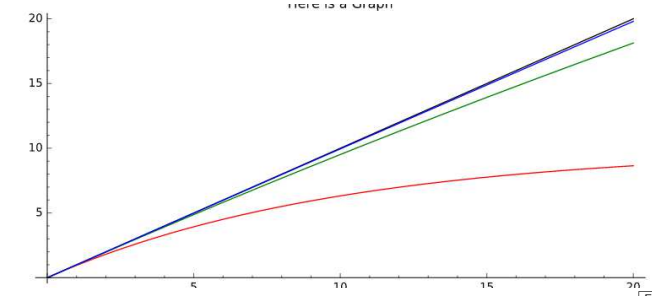
Dealing with Pile-up Tracks: Robust Potential

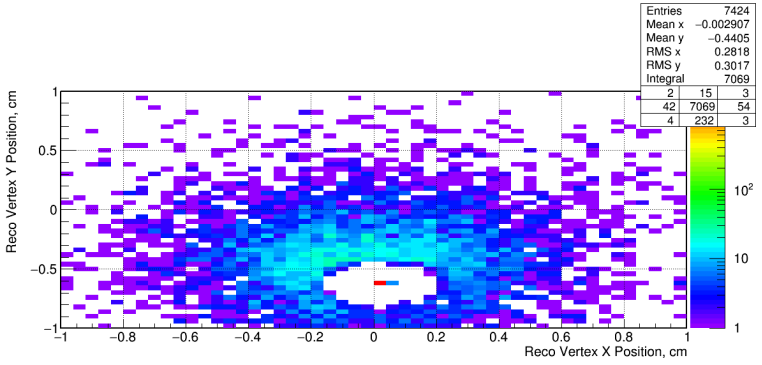
- In presence of HFT, high precision pile-up tracks can significantly bias primary vertex due to acceptance of such tracks at seeding phase
- This effect is alleviated by limiting contribution from measurements many sigmas away from the vertex candidate
- The usual χ^2 function is modified as

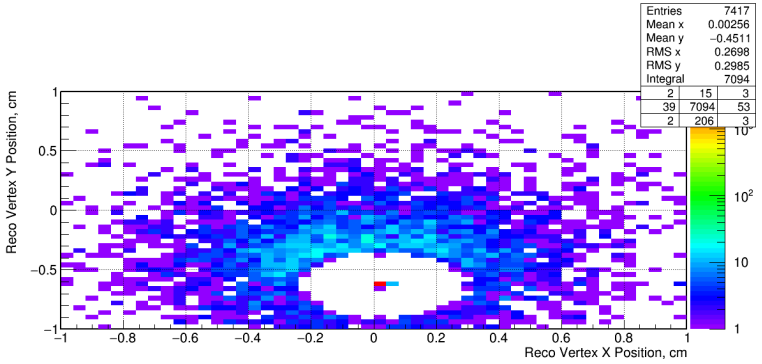
$$f = \sum_{\text{tracks}} k_{\text{seed}} \left(1 - e^{-\frac{\chi^2_{\text{track}}}{k_{\text{seed}}}} \right)$$

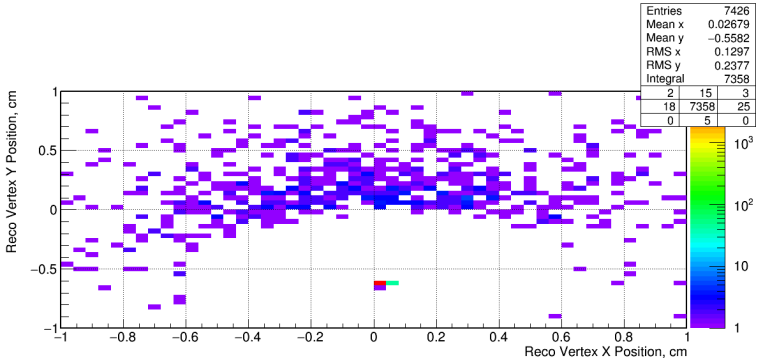
where $k_{\text{seed}} > 0$ is an adjustable scale factor

- **Similarly, vertex fits with high precision beamline contribution benefit from "robust potential" by avoiding track originated from secondarty vertices**

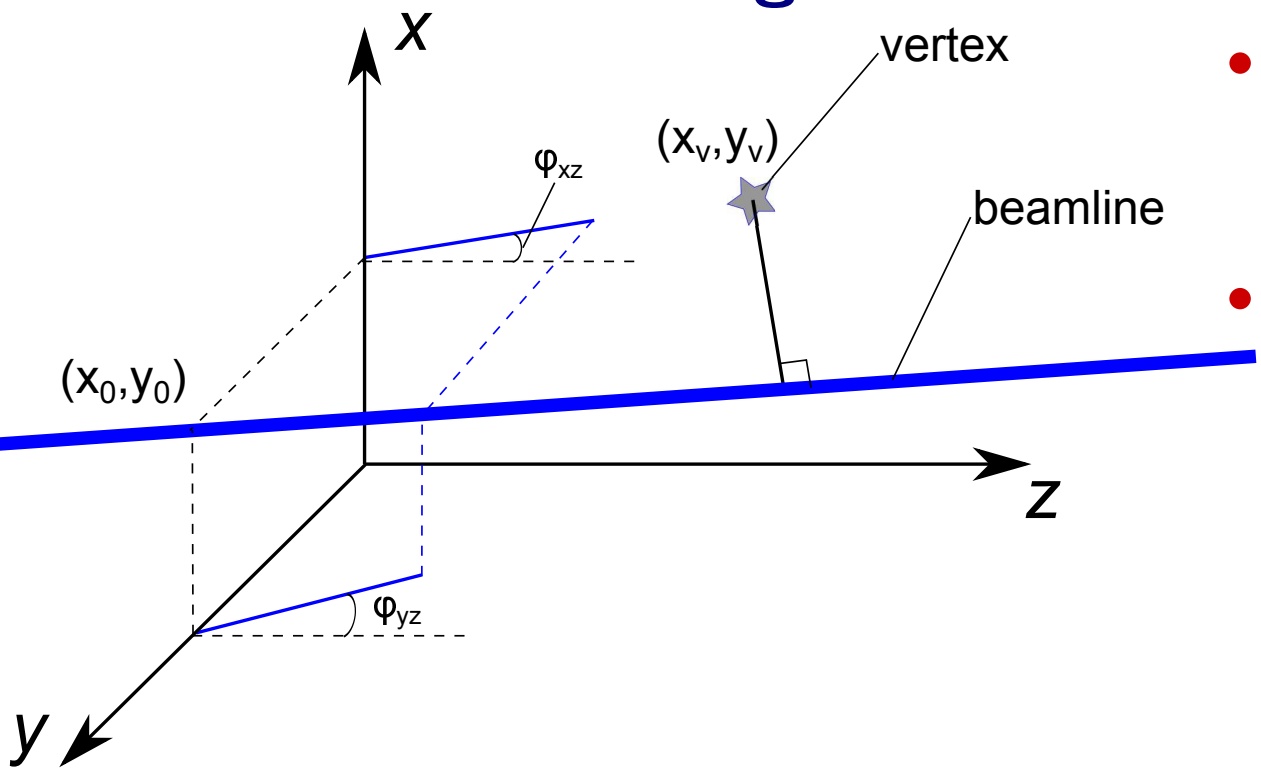








Using Beamline in Vertex Fit



- Beamline parameters with uncertainties extracted from a global fit to tracks projected to z axis
- Neglecting the correlation between the observables the beamline equation is trivial:

$$x = x_0 + k_{xz} z$$
$$y = y_0 + k_{yz} z$$

with corresponding uncertainties for intercepts and slopes: Δx_0, Δy_0, Δk_{xz}, Δk_{yz}

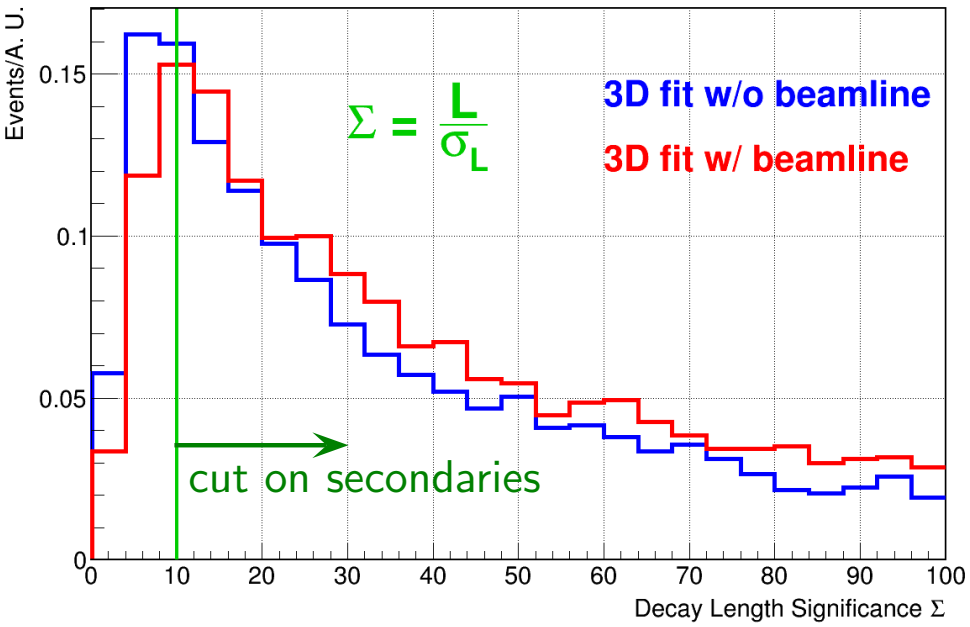
- The full covariance matrix for DCA is also easily calculated:

$$\Sigma' = J \Sigma J^T, \text{ with Jacobian for DCA w.r.t. the beamline parameters}$$

- Beamline can be optionally applied to vertex fit as additional constraint
- The precision in transverse plane is only limited by intrinsic beam width and beam shape systematics ($\lesssim 100\ \mu m$)

For implementation details see `https://github.com/star-bnl/star-vertex`

Secondary Decay Vertex



- We test the effect of improved uncertainty on vertex position by reconstructing $\Lambda \to \pi p$ and $K^0 \to \pi p$ in simulated pp collisions with pile-up
- We define decay length significance as $\Sigma = \frac{|\vec{v}_{\text{prim}} - \vec{v}_{\text{decay}}|}{\sigma_v}$
- An indication of improvement in S/B of $\approx 10\%$ is seen in reconstructed invariant mass of Λ cadidates

- **New for STAR:**

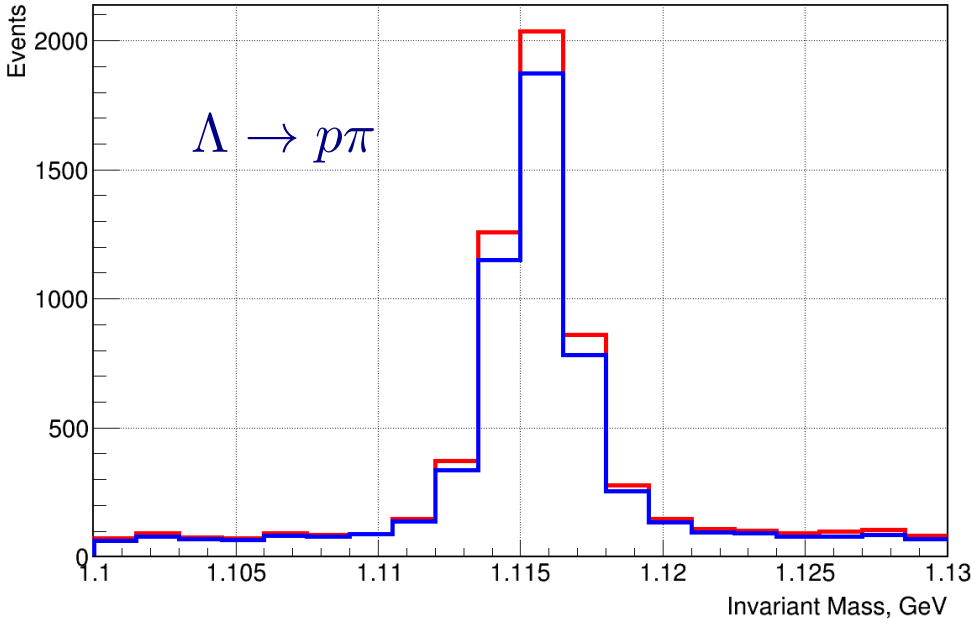
  3D fit w/o beamline: Only tracks used in the 3D fit (both VFs)

  3D fit w/ beamline: Beamline and tracks used in 3D fit

- **Previously: 1D fit w/ beamline**

  Primary vertex is forced to be on the beamline

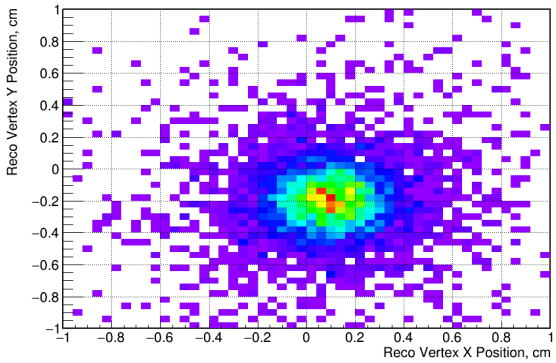
  $\Rightarrow$ no transverse uncertainties on primary vertex position

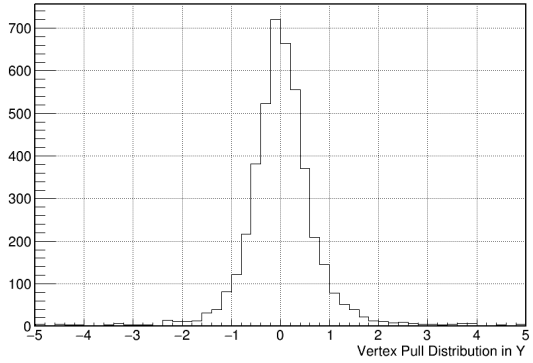


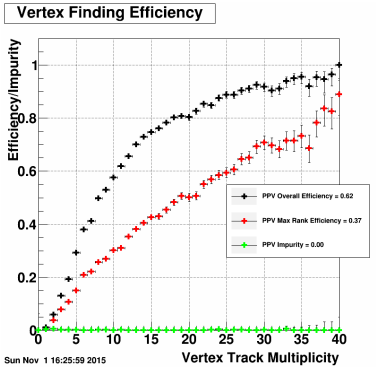
Common Tool for Performace Evaluation

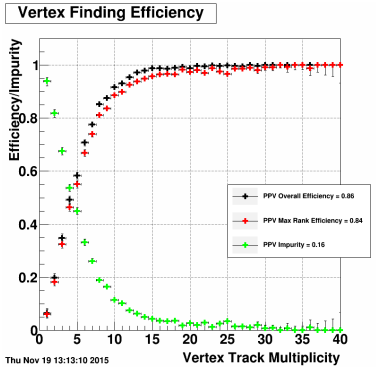
`Travex`: A toolkit for track and vertex reconstruction evaluation

- **Standalone.** No dependencies on specific event data format
- **Experiment independent.** Focus on common physical observables
  - Pull distributions, vertex position, resolution, etc.
  - Vertex finding efficiency, (im)purity based on dominant contributor matches in simulation









Source code openly available `https://github.com/plexoos/travex`

Summary

- STAR employs several techniques to overcome pile-up contamination in vertex reconstruction in TPC
  - Vertex ranking based on fast non-tracking detectors
  - Rejection of split tracks
- Developed tools and algorithms can be used by other experiments
  - Laid the groundwork for seamless comparison of vertex finders $\Rightarrow$ code
- **STAR vertex finders have been enhancement by implementing 3D fits to primary vertices with proper beamline constraint and reporting of real uncertainties**
  - Certain analyses relying on topology cuts may benefit from using the new vertex uncertainties
  - In Λ-enriched sample with realistic pile-up we observed an improvement in S/B of $\sim 10\%$