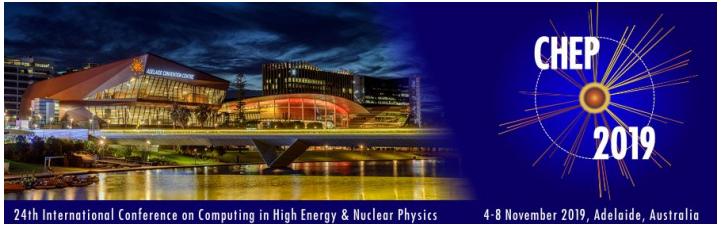
# Dealing with High Background Rates in Simulations of the STAR Heavy Flavor Tracker

*Jason Webb, Gene Van Buren, Jérôme Lauret, Sooraj Radhakrishnan, Xin Dong*

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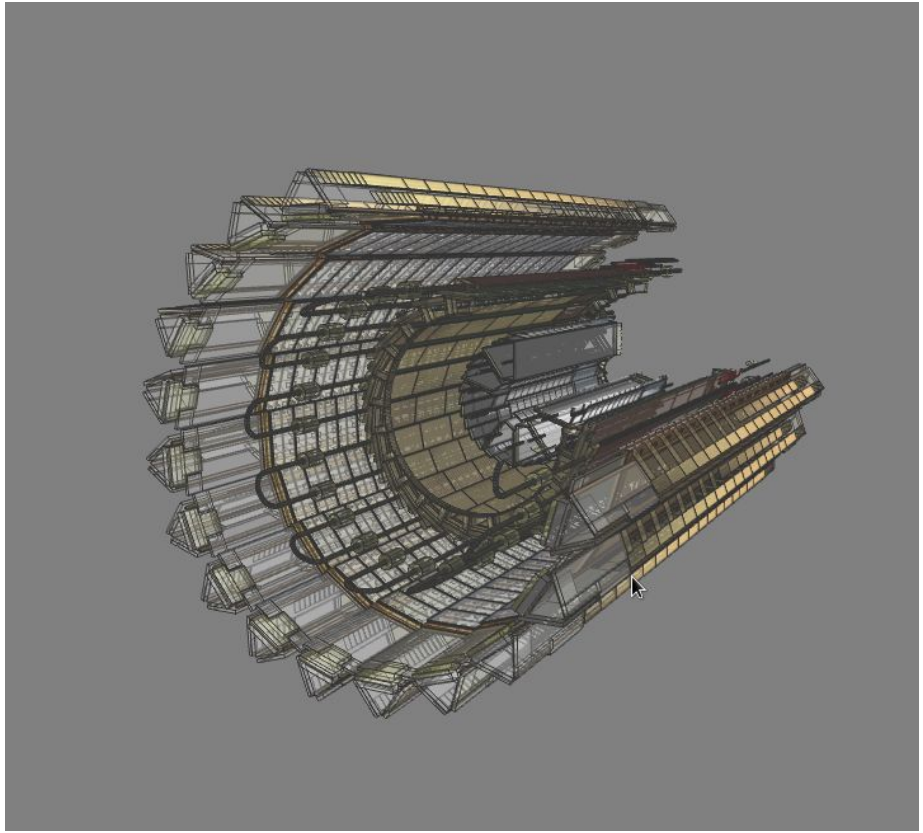
# Introduction

- The Heavy Flavor Program
- The STAR detector
- Background Environment
- Advantages of Embedding
- Making it work
- Summary



# Physics Motivation

## Charm quarks:

- Created early in heavy ion collisions through hard scattering
- Experience the full evolution of the system

## Physics:

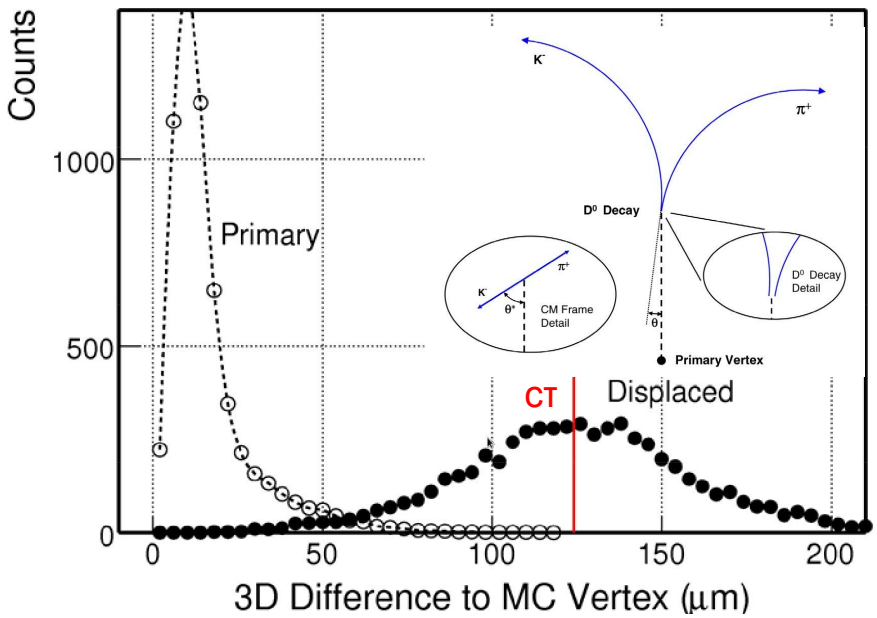
- High-$p_T$ provides test of energy loss mechanisms
- Low-$p_T$ extract medium properties from motion of heavy quarks

## Experimental Requirements:

- Topological reconstruction due to large combinatorial backgrounds
- 50 μm pointing resolution for 750 MeV kaons

## Computing Challenges:

- Combinatorial backgrounds in AuAu collisions
- Pileup events in detectors with long readout times




| Particle | Decay Channel | cτ (μm) | Mass (GeV/c$^2$) |
|---|---|---|---|
| $D^0$ | $K^- \pi^+$ (3.8%) | 123 | 1.8645 |
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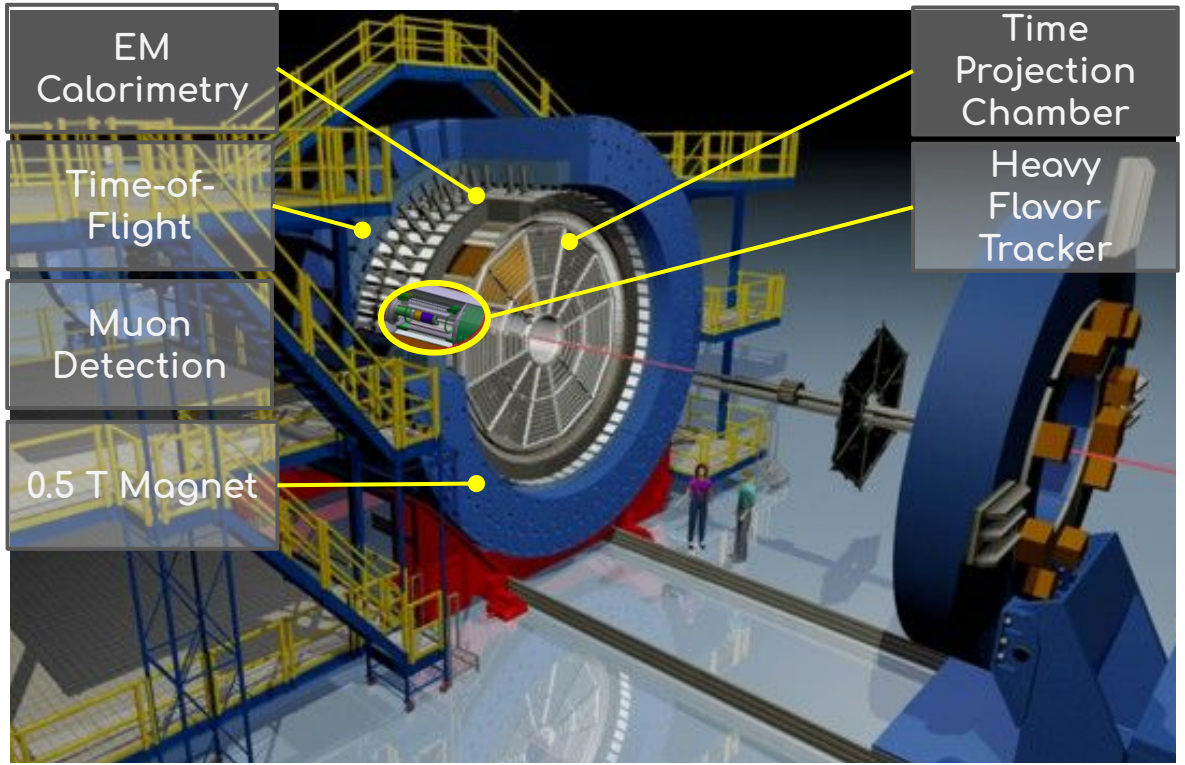
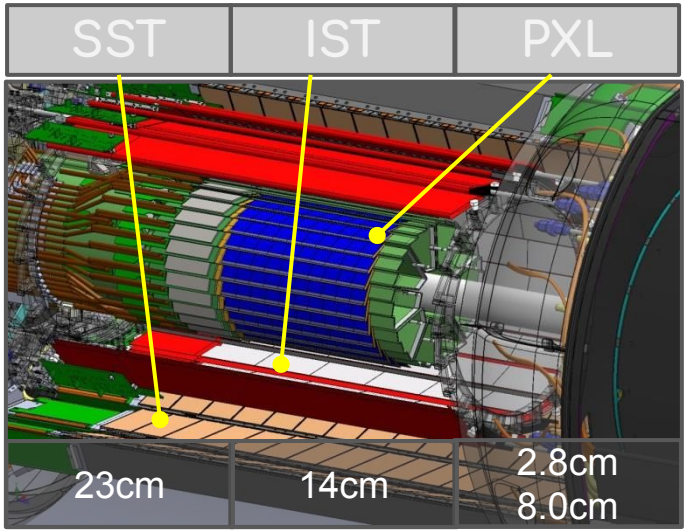
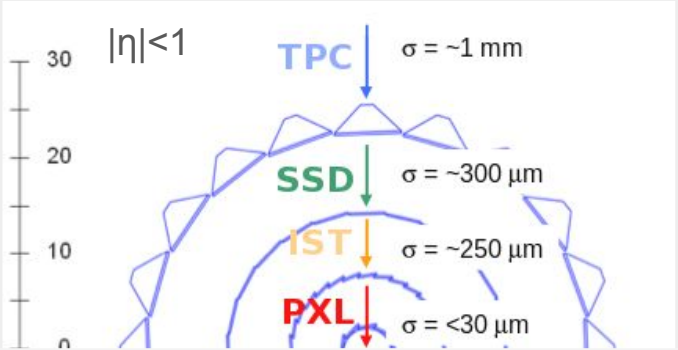
| $\Lambda_c^+$ | $p K^- \pi^+$ (5.0%) | 59.9 | 2.2865 |

# The STAR ☆ Detector




Heavy Flavor Tracker [2014-2016]

- Silicon Strip Detector (SST) Fast double-sided silicon strips
- Intermediate Silicon Tracker (IST) Fast single-sided silicon strips
- Pixel Detector (PXL) Two layers of 20.7x20.7μm MAPS

Integrates over 186.5 μs DOI:10.1016/j.nima.2018.03.003

# Background Environment

**TPC integration time of 40 μs**

- ➢ Out-of-time "pileup" tracks from ~2 minbias 200 GeV AuAu collisions drifting through TPC during collision of interest
- ➢ ~40 @200 GeV pp, ~400 @510 GeV pp

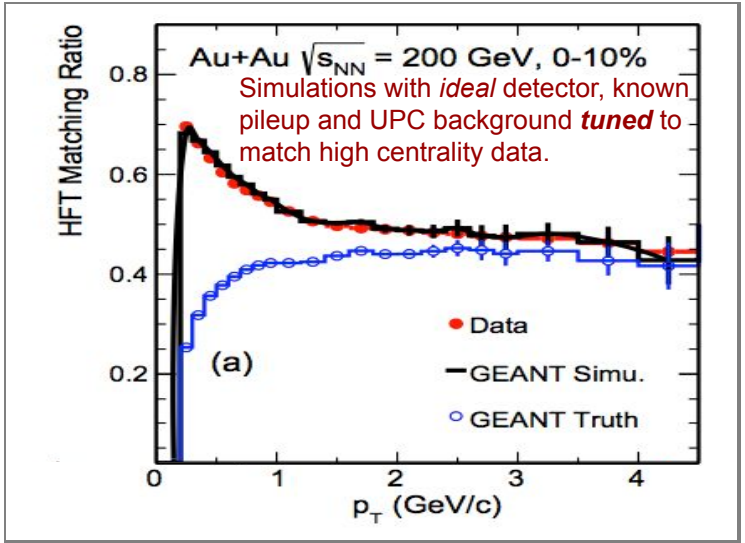
**IST and SST are "fast" detectors**

- ➢ Matching hits partially mitigates pileup

**PXL continuous readout over 185.6 μs**

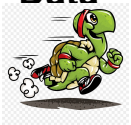
- ➢ Hits from ~10 minbias events in PXL during collision of interest
- ➢ Comparable flux of low-energy (~70 MeV) electrons from ultra-peripheral collisions (*difficult to model*)
- ➢ Source of accidental matches to TPC pileup tracks

$$HFT\ Matching\ Ratio = \frac{N\ Tracks\ with\ HFT}{N\ Tracks\ in\ HFT\ acceptance}$$




**Issues with pure Simulation**

1) **CPU time required to simulate / digitize (expensive *TPC digitization*)**
2) **Tuning of the detector response simulation to match the data**
3) **Fidelity of the event generation, and the relative contributions of the backgrounds**

| | Requirements | Cons | Pros |
|---|---|---|---|
| **Pure Simulation**  | Detailed understanding of the primary and background events<br><br>Full simulation (pedestals, noise) of tracking detector electronics | *Only as good as physics and background understanding*<br><br>Simulating backgrounds exceeds available CPU resources | Contains full MC truth information<br><br>Can work well even if detector alignment not fully understood |
| **Data Driven (aka Parameterized) Simulations**  | Input data distributions representing the relative performance of the HFT-to-TPC tracking and its DCA resolution | No MC truth information, secondaries not modeled<br><br>Vertex resolution not correct, and fails for single tracks | Captures the acceptance and effects of real background<br><br>FAST (7000 times faster than standard simulation chain) |
| **Embedding Simulations in Real Data**  | Detailed detector simulations merged channel-by-channel with real data representative of the background<br><br>Careful application of misalignments | Additional effort to understand alignments, corrections and uncertainties | Same as pure simu, plus…<br><br>Speed: x3 to x60 faster<br><br>Backgrounds measured *in situ* during actual data taking |

# Initial Expectations...

Historically, STAR has used *ideal* geometry in simulation, and applied detector misalignments during event digitization

- Time Projection Chamber
  - hits are simulated at their ideal position in gas volume
  - electrons created according to photoabsorption model
  - propagated to the *misaligned* detector planes for readout
    - space charge and grid leak distortions applied
- Silicon Vertex Detector (SVT) pre-2008
  - hits are simulated at their ideal position on the detector
  - moved along the track trajectory to the misaligned detector plane
  - worked well for the SVT, but fails for the HFT, which operates with higher precision and in a more challenging background environment

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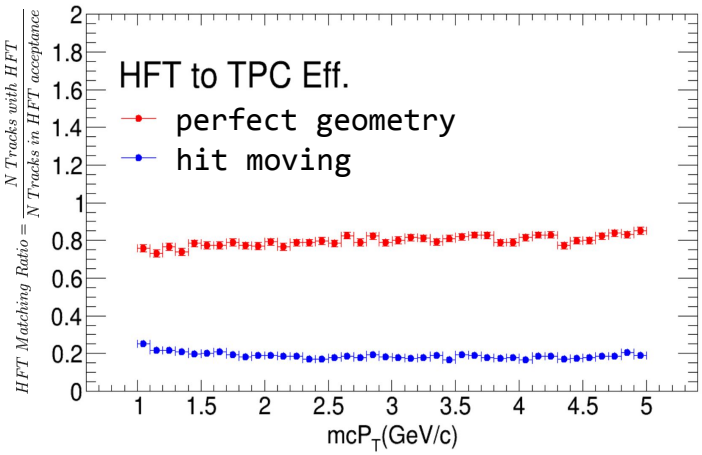
Expectation when we first integrated the HFT that hit moving would work, at least reasonably well.

It did not.



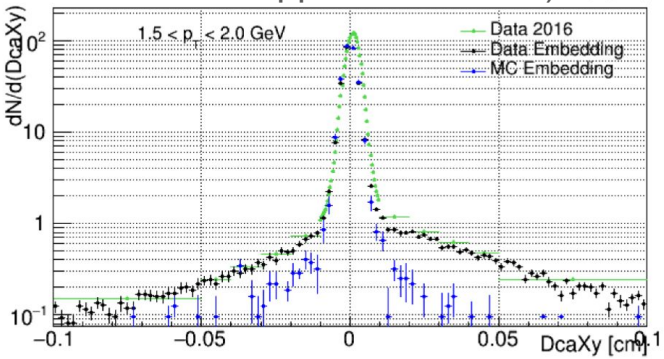

Comparison of HFT ratio for single pions in simulation using ideal position of hits (red) and hits moved to the real position of the detector (blue).

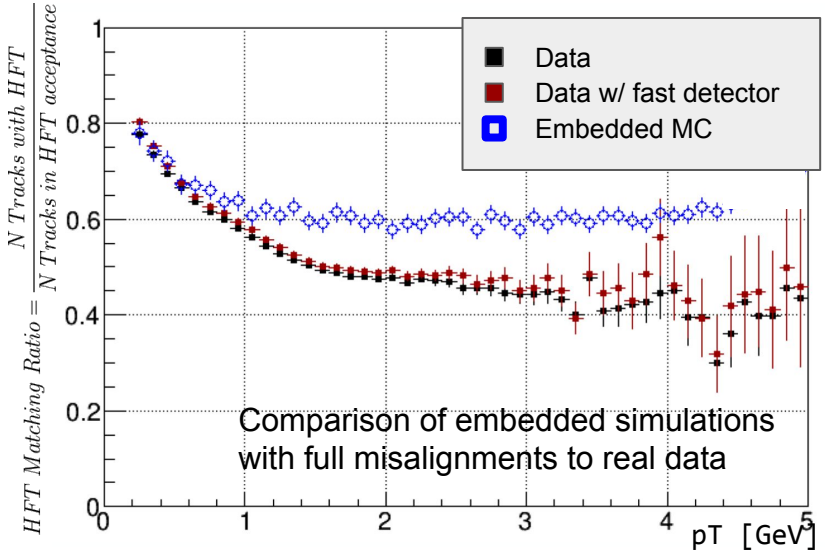
Demonstrated the need for full misalignment in the HFT simulations [doi:10.1088/1742-6596/898/4/042036].

# Misalignments: Necessary, but not Sufficient

Even with a full application of the detector misalignments to the simulated geometry, adding Monte Carlo hits on top of the measured background does not reproduce the data.

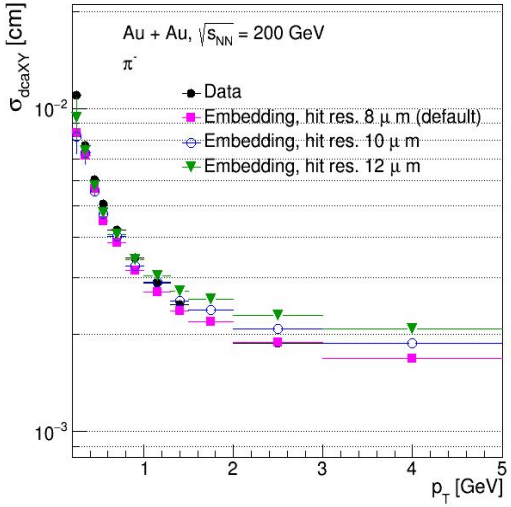
Pointing Resolution (aka Distance of Closest Approach or DCA)

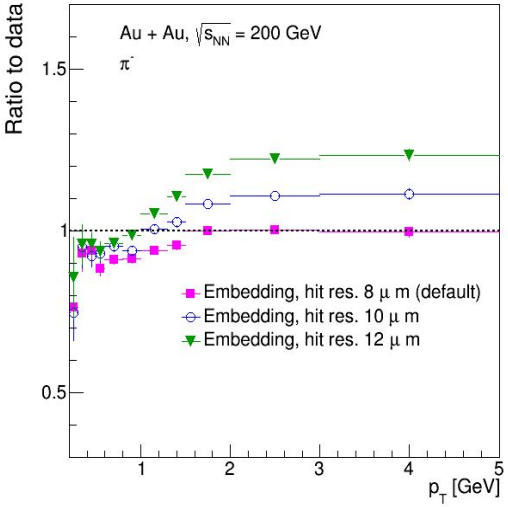



- Relative performance of the HFT is too good at large pT, compared w/ data
- Simulated DCA distributions are also too good (too narrow)

# Applying Misalignment Uncertainties

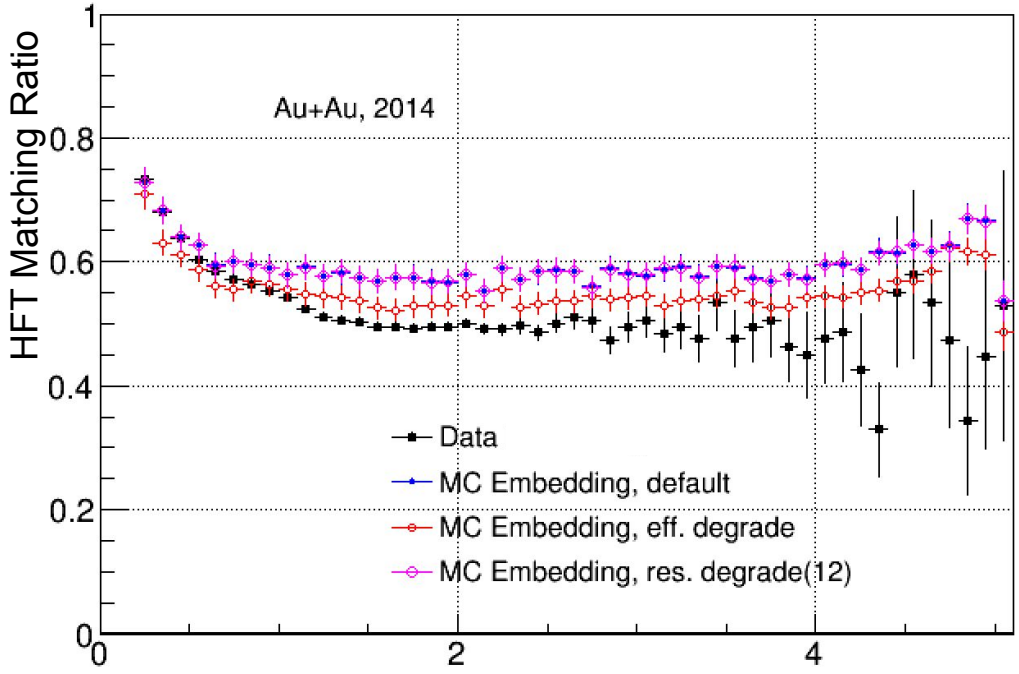



We know that we do not measure the detector alignments with perfect precision.

- Apply additional smearing of the hit positions to account for uncertainties in misalignments
- Expectations based on alignment studies of 8 μm, larger values not unreasonable
- DCA widths most sensitive, plot vs pT
- DCA peak broadens with degraded hit resolution, but no reasonable value matches the shape
- No perfect solution. 8 μm chosen as compromise.

# Impact on HFT performance




Additional smearing for the alignment uncertainties has virtually no effect on the HFT matching ratio

- ➢ Almost no change in the ratio going from 8 μm to 12 μm. And larger values deemed unreasonable.

What about degrading the single hit resolution in the HFT by few %?

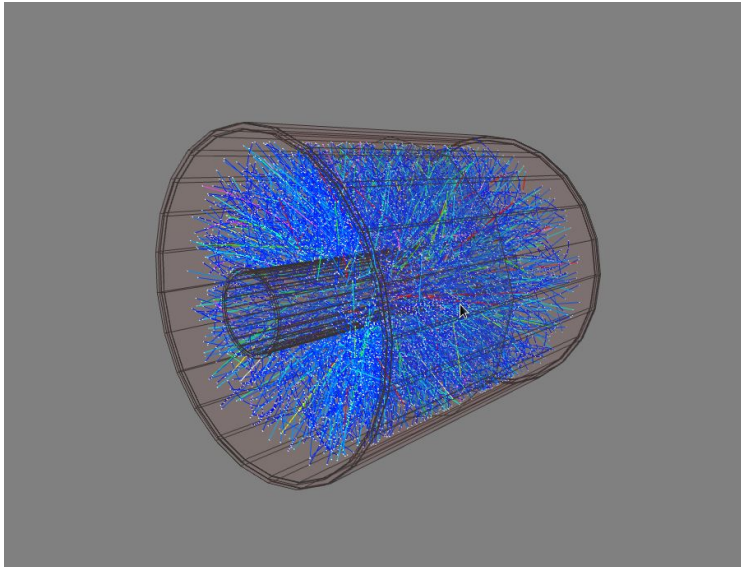
- ➢ Not fair, as this is highly constrained by test bench and cosmic rays.
- ➢ Worse, it failed to describe the shape of the HFT ratio described by changing HFT hit efficiencies.

# Applying TPC Calibration Uncertainties

Simulation of *hits* in the TPC readout requires careful accounting of effects which deflect electrons drifting through the gas volume...

- Accumulation of charges w/in the TPC during the events, and
- Leakage of ionization from the readout planes at the ends of the TPC

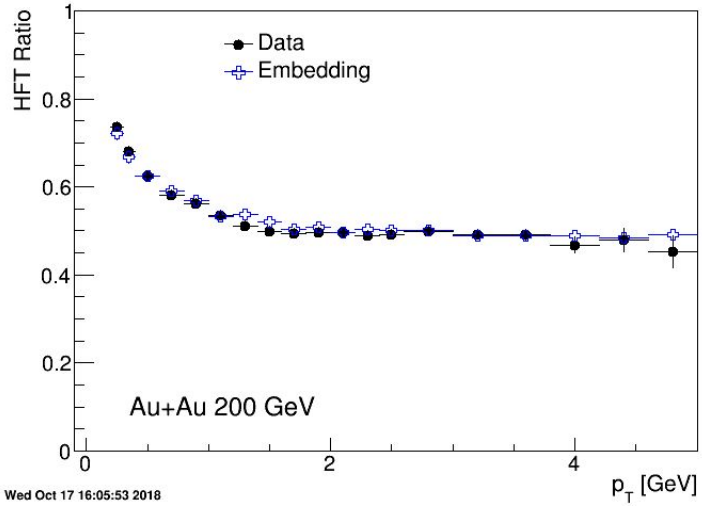
These are not known with perfect certainty. The degree of uncertainty is not known a priori, but could be measured by correlating with a second high precision detector, such as … the HFT.

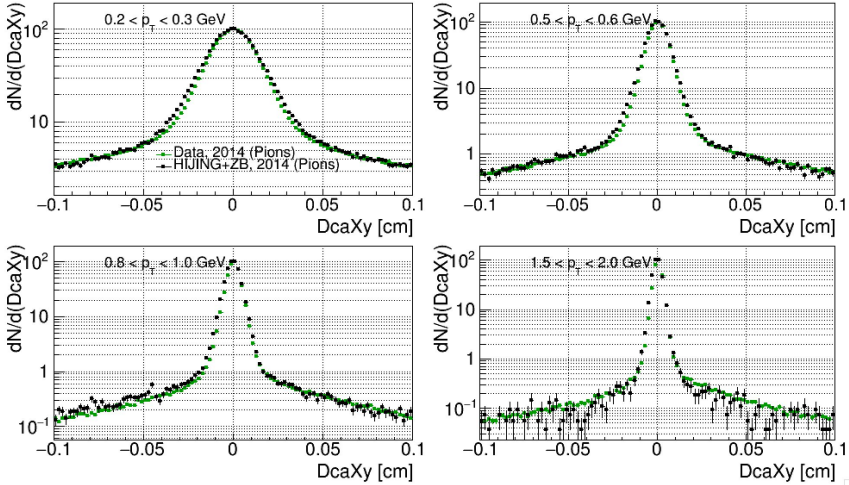


# Applying TPC Calibration Uncertainties

Can applying a reasonable (5%) fluctuation to the TPC distortions yield good agreement for the HFT ratio and DCA distributions?

Yes.



# Applying TPC Calibration Uncertainties

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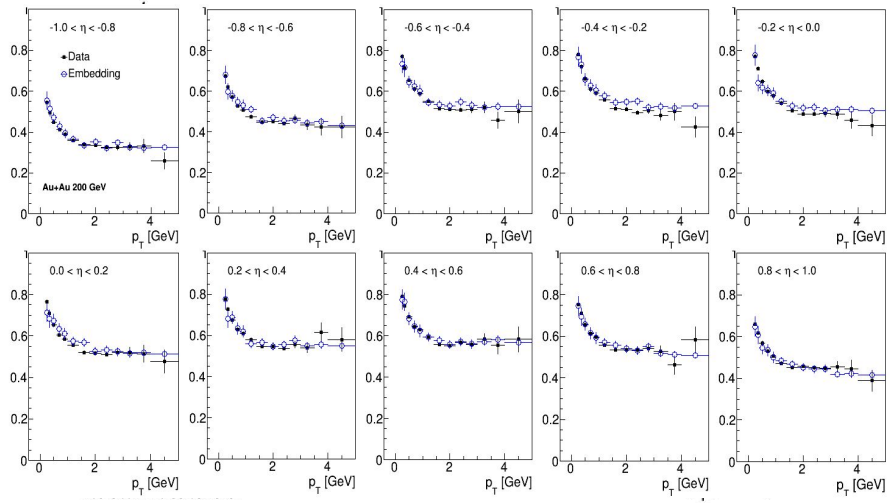
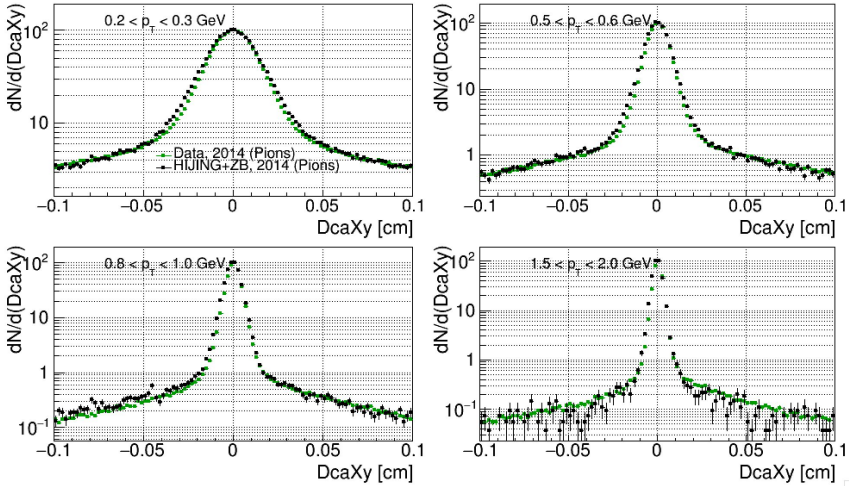
Yes. And in great detail, giving confidence in the efficiencies we want to extract.

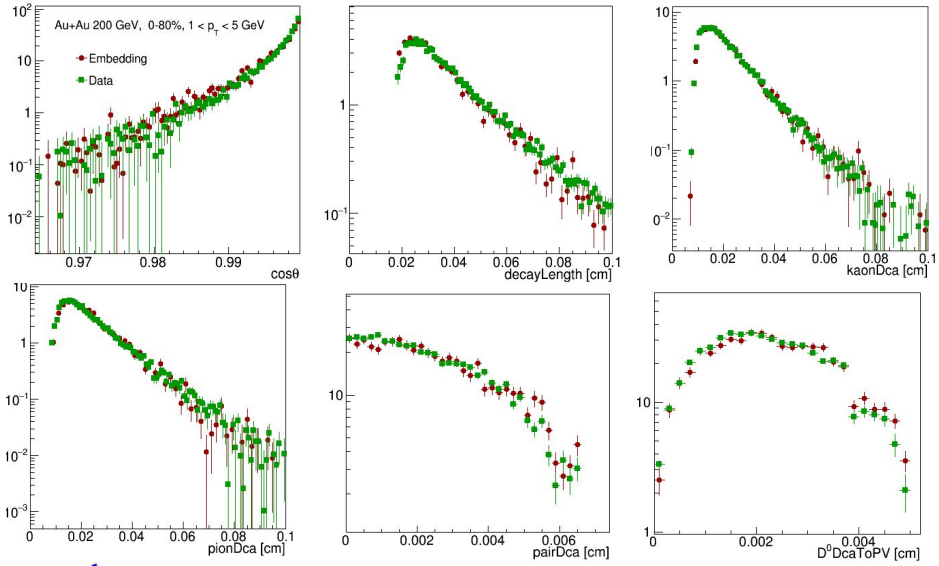


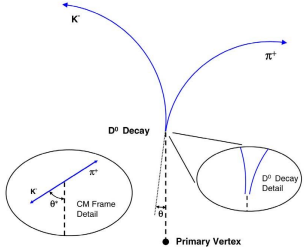



# Topological Parameters of D0 Decays

Once the relative performance of the HFT and the DCA distributions for single particles match the data, we verified the agreement between real and simulated D0 decay kinematics.

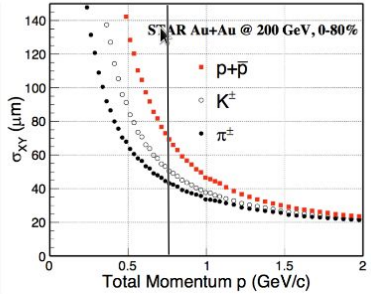
The agreement is quite good.

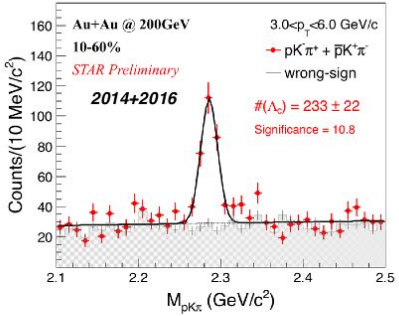


# $\Lambda_c$ production in heavy ion collisions

- $\Lambda_c/D^0$ yield ratio provide insight into charm hadronization mechanism in QGP
- HFT provides excellent vertex resolution, allows topological reconstruction of heavy flavor hadrons

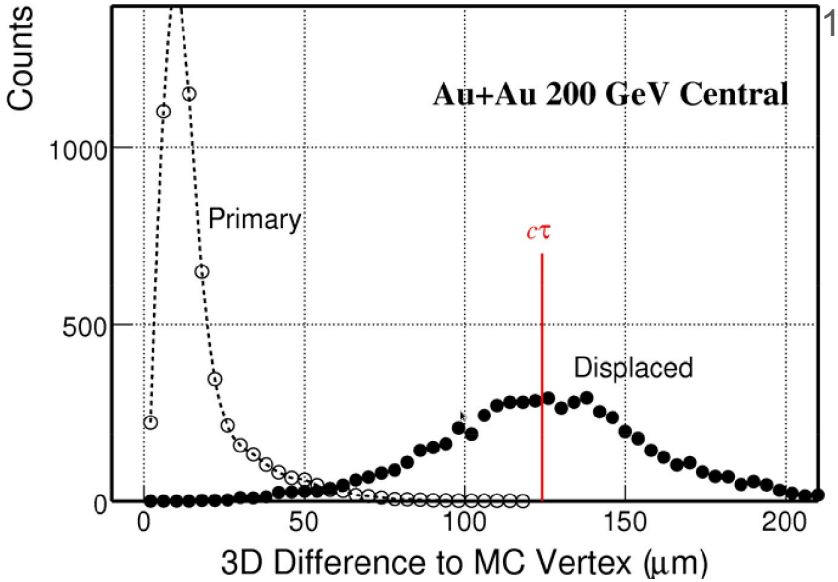



- $c\tau$ for $\Lambda_c$ = 60 μm!
- Supervised Learning Methods (BDT) used to improve signal-background separation for $\Lambda_c$ reconstruction

Talk by G. Xie: 04/10 Thu, 11.25 (P3)

Sooraj Radhakrishnan 4

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Recent Results @ Hard Probes 2018

More results coming at QM 2019

# Summary

- The STAR Heavy Flavor tracker [2014-2016] provides the precision tracking required to topologically identify charmed hadron decays, allowing important insights into the evolution of the dense medium created in heavy ion collisions
- Embedding provides increased simulation throughput, and precise modeling of the background environment by measuring backgrounds *in situ* with data taking
- The introduction of the new precision tracker required us to reevaluate long standing, successful procedures in our embedding workflow
  - Misalignments of the HFT had to be taken care of at the geometry level
  - Properly account for the uncertainties inherent in the measured alignments
  - Realize that the event-by-event fluctuations in the TPC distortions matter when correlating with a second set of high precision detectors
- The agreement between data and embedded simulations gives great confidence that we are properly measuring the efficiencies of our detectors, and has enabled us to address even the most challenging of the heavy flavor physics channels

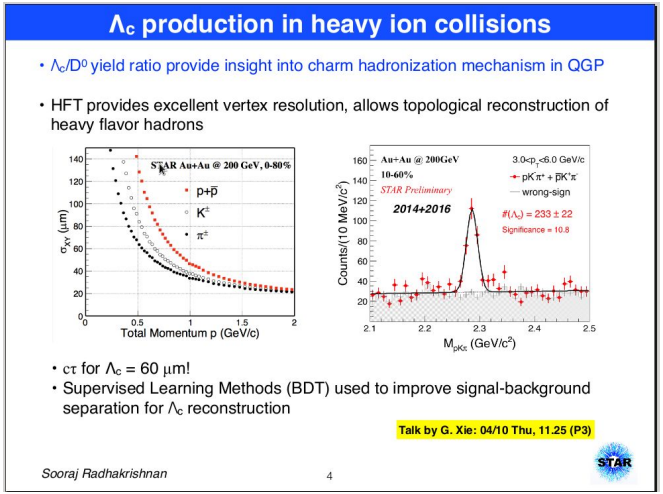
*Thank You for Your Attention*

# Dealing with High Background Rates in Simulations of the STAR ☆Heavy Flavor Tracker

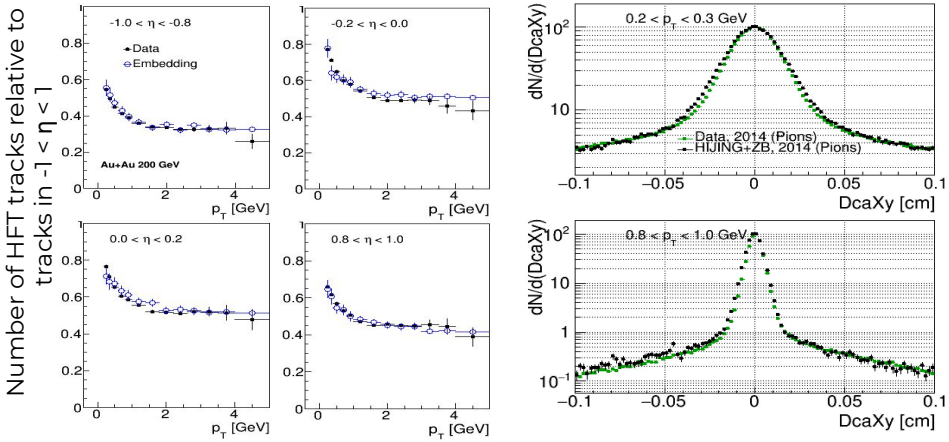
Pileup events in HEPNP detectors pose significant challenges to understanding tracking efficiencies.

- ➢ Simulating pileup events increases CPU cost
- ➢ Accuracy limited by level-of-knowledge of the experiment's background environment

Embedding simulated events into appropriate real data ensures realistic backgrounds for no additional CPU cost




*Detailed matching of relative tracking detector performance and vertex pointing between embedding simulations and data for single pions*




- ➢ Hit moving in simulation is insufficient with precision trackers. Embedding requires accurate, misaligned geometries in simulation.
- ➢ It also requires careful treatment of the *uncertainties* in misalignments and other hit calibrations.

Embedding improves simulation speed while accurately representing backgrounds, thus maximizing the impacts from physics programs.

# Embedding Workflow

Input *measured* backgrounds and *simulated* events

Merge real data with simulation channel-by-channel

Reconstruction software is identical to standard data production