

The **STAR** ☆ Heavy Flavor Tracker

Embedding Simulations into a High Multiplicity Environment

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U.S. DEPARTMENT OF
ENERGY

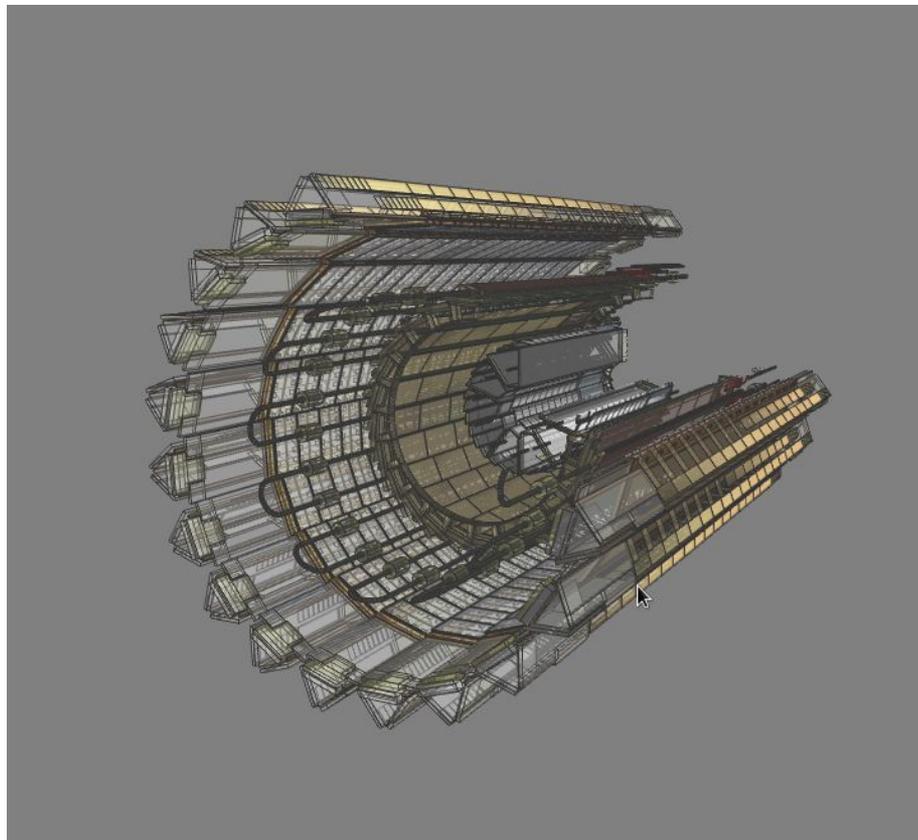
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Outline

- The STAR detector
- Physics Motivation
- The HFT Experience
- Towards Physics Results
 - Determining Efficiencies
 - The role of calibration
uncertainties
- Summary



EEMC

BEMC

Magnet

TOF

MTD

TPC

HFT

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- 0.5 T Solenoidal Magnetic Field
- Electromagnetic Calorimetry $-1 < \eta < 2$
- Time of flight $-1 < \eta < 1$
- Muon detector
- Time Projection Chamber $-1 < \eta < 1$
 - 4m length
 - $60 < r < 190$ cm
 - ~ 1 mm spatial resolution
 - Integrates over $40 \mu\text{s}$

Physics Motivation

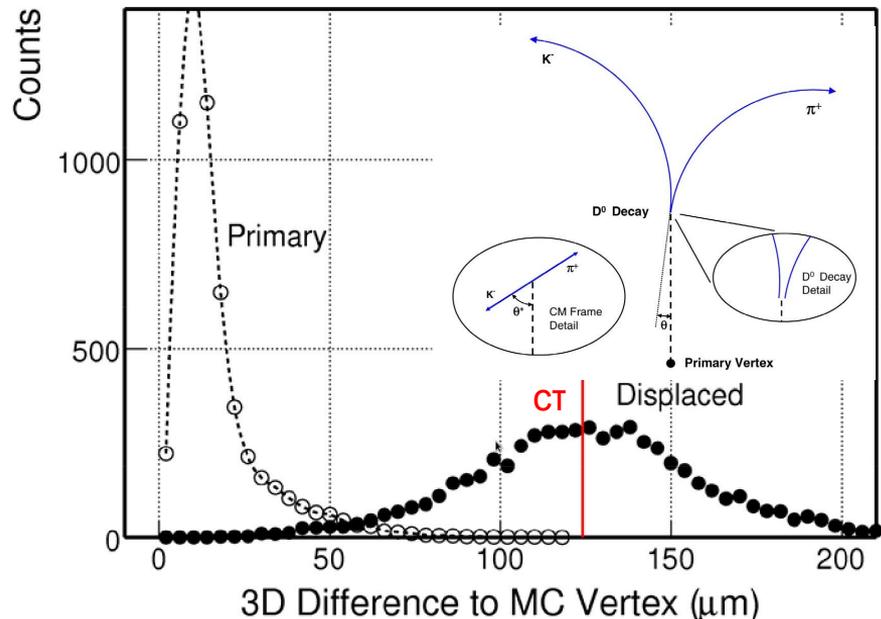
Charm quarks:

- 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

50 μm DCA pointing resolution for 750 MeV kaons



Particle	Decay Channel	$c\tau$ (μm)	Mass (GeV/c^2)
D^0	$K^- \pi^+$ (3.8%)	123	1.8645
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312	1.8694
D_s^+	$K^+ K^- \pi^+$ (5.2%) $\pi^+ \pi^+ \pi^-$ (1.2%)	150	1.9683
Λ_c^+	$p K^- \pi^+$ (5.0%)	59.9	2.2865

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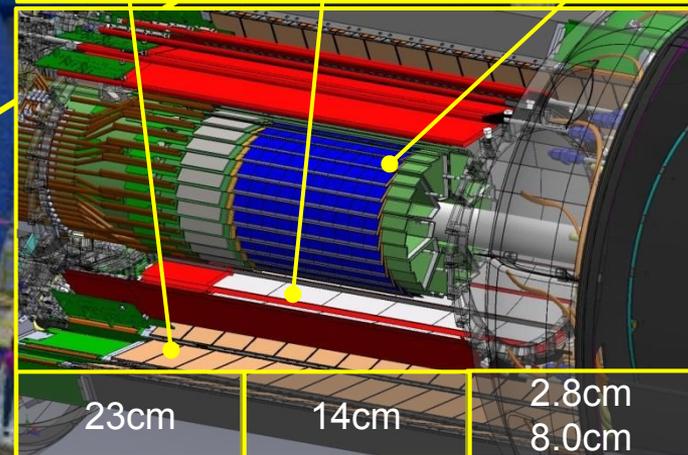
TPC

HFT

SST

IST

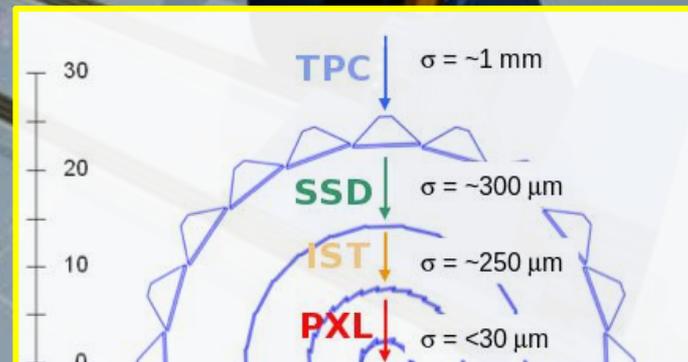
PXL



Heavy Flavor Tracker

- $-1 < \eta < 1$
- Silicon Strip Detector (SST)
 - Fast double-sided silicon strips
- Intermediate Silicon Tracker (IST)
 - Fast single-sided silicon strips
- Pixel Detector (PXL)
 - Two layers of $20.7 \times 20.7 \mu\text{m}$ MAPS (Monolithic Active Pixel Sensors)
 - Integrates over $186.5 \mu\text{s}$

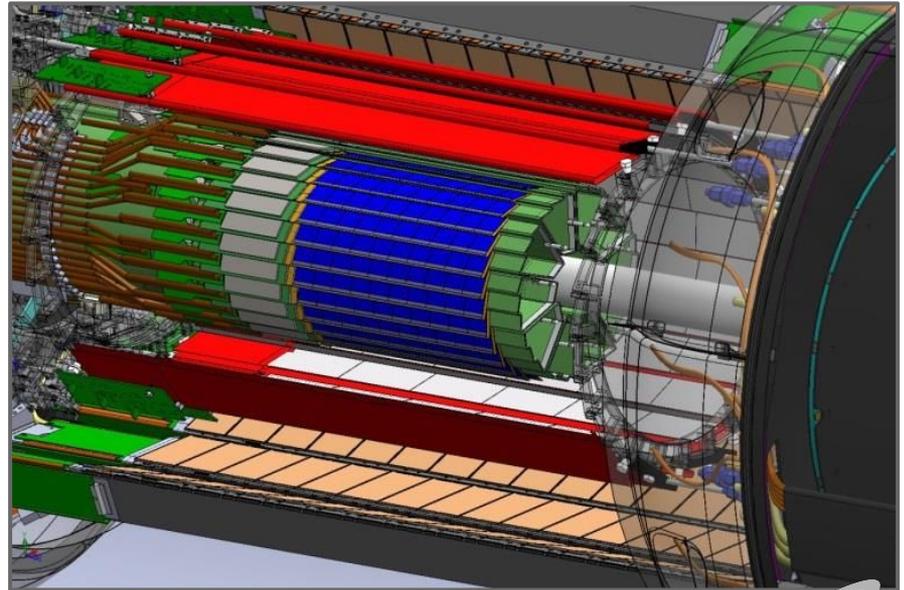
DOI: [10.1016/j.nima.2018.03.003](https://doi.org/10.1016/j.nima.2018.03.003)



HFT Operational History



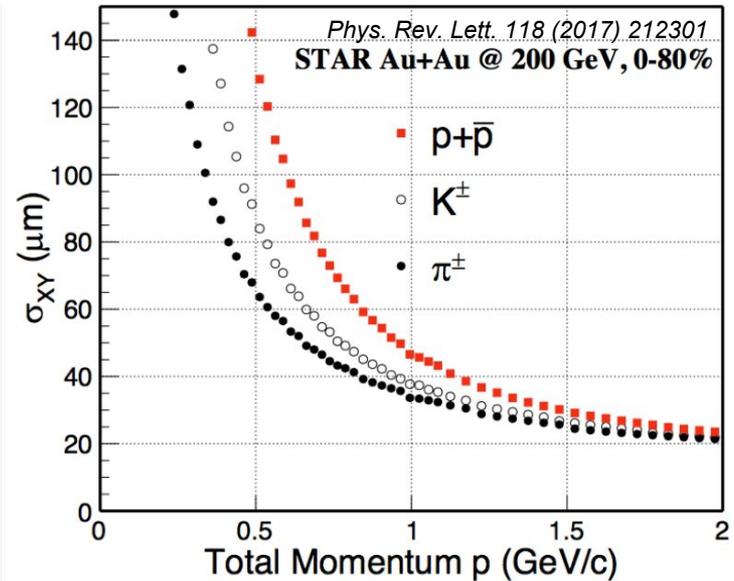
- Operational for physics from 2014 to 2016
- Decommissioned following 2016 run
- Typical trigger rates 0.8 to 1 kHz
- Accumulated significant data samples at $\sqrt{s_{NN}} = 200$ GeV
 - 2014 1.2B Au+Au
 - 2015 1.0B p+p, 0.6B p+Au
 - 2016 2.0B Au+Au, 0.3B d+Au



HFT Operational History

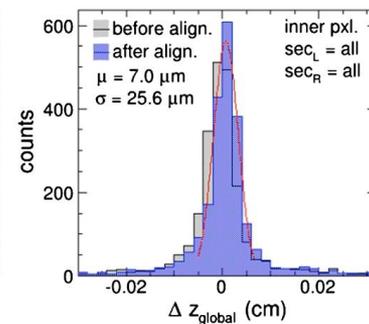
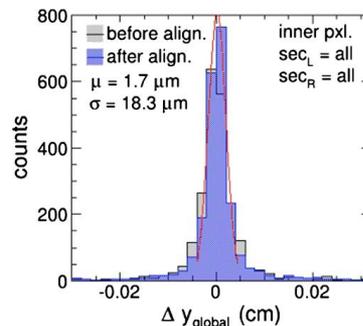
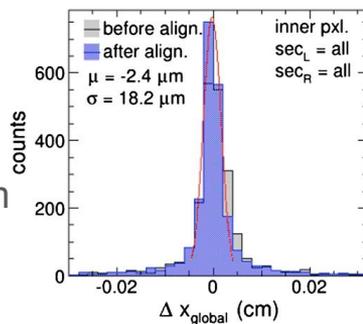
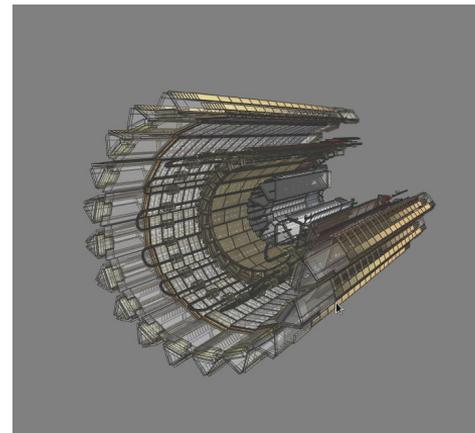


- Distance of Closest Approach (DCA) resolution met or exceeded design requirements
 - $\sim 50 \mu\text{m}$ for 750 MeV Kaons
 - $\sim 30 \mu\text{m}$ @ $p > 1 \text{ GeV}$
- Single hit detector efficiencies $\sim 97\%$ from cosmic ray runs



HFT Alignments

- Relative alignment of the HFT subsystems performed using zero-field cosmic rays
- Pixel sectors aligned relative to a reference sector by iteratively minimizing residual distributions
- IST and SST then aligned relative to the pixel detector
- Global alignment to the STAR TPC by minimizing residuals to full field cosmic ray tracks
- Global alignment residuals $\sim 25\mu\text{m}$
Comparable to the PXL sensor size



Accounting for *uncertainties* in the HFT alignment will be important in understanding the ultimate detector performance.

Towards Physics Results

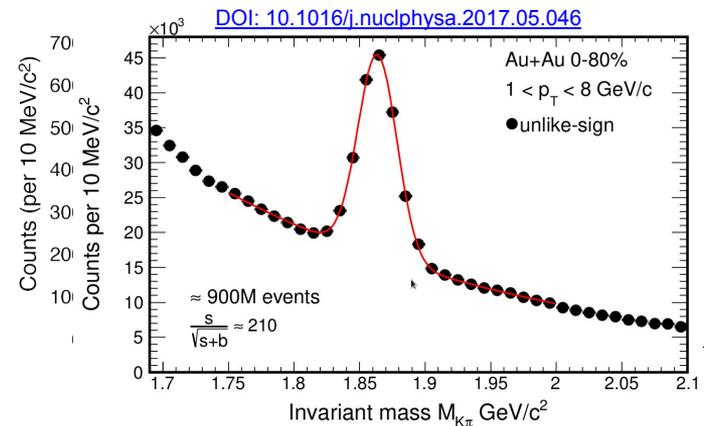
As analyses advance and mature, the HFT program has addressed even more challenging physics topics. The ultimate efficiency and resolution will be driven by the quality of the simulation in heavy ion collisions. Need to address several questions:

- How (& how well) do we understand the efficiency of the tracker for finding the daughters of heavy flavor decays?
 - ... and our topological cuts?
- How do we understand our backgrounds?
- And what role do the uncertainties in calibrations play?

Quark Matter 2017

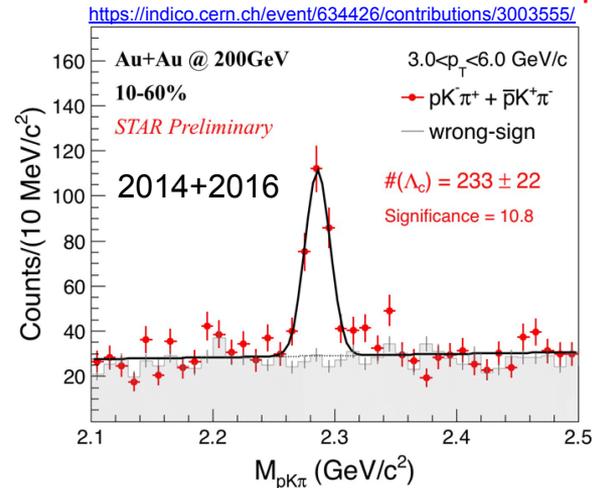
$\sigma_T \sim 120 \mu\text{m}$

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Hard Probes 2018

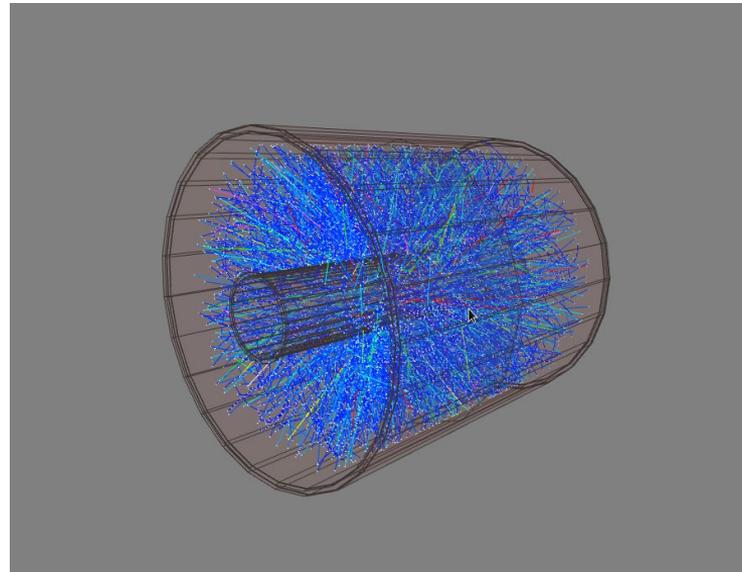
$\sigma_T \sim 60 \mu\text{m}$



Towards Physics

Typical *interaction rates* of 50-60 kHz during HFT operation.

- TPC integration time of 40 μs
 - ~ 2 minbias events drifting through the TPC during collision of interest
- PXL continuous readout over 185.6 μs
 - 8-9 minbias events in PXL during collision of interest
 - Comparable flux of low-energy (~ 70 MeV) electrons from UPC
- IST and SST are both “fast” detectors, helps mitigate pileup.



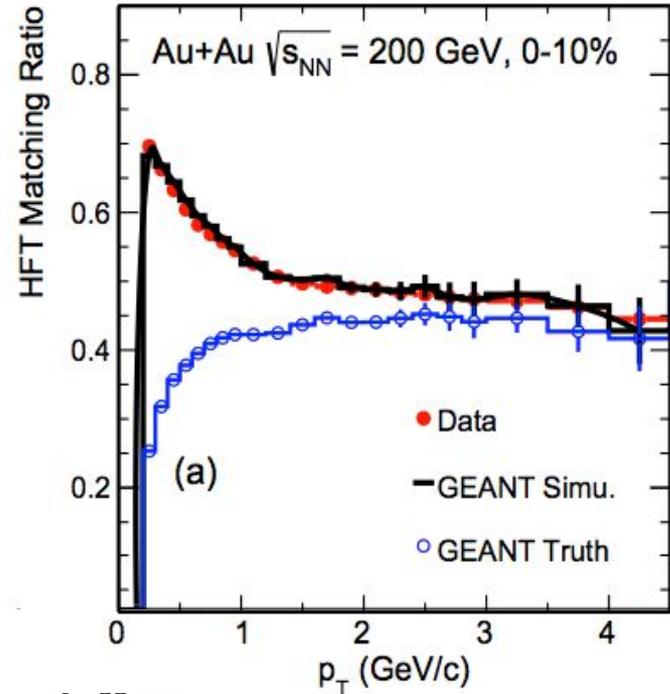
Pileup Challenges

Significant numbers of out-of-time tracks in the TPC and significant numbers of “random” hits in the PXL...

- Introduces inefficiencies from picking up the wrong hit on a good track from the event
- Provides a source of background tracks from out-of-time TPC tracks finding hits in the HFT

Effects are illustrated at right.

- The ratio of tracks with HFT hits to the total number of tracks found is plotted versus p_T .
- Simulations are performed with mocked PXL backgrounds tuned to match the data



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

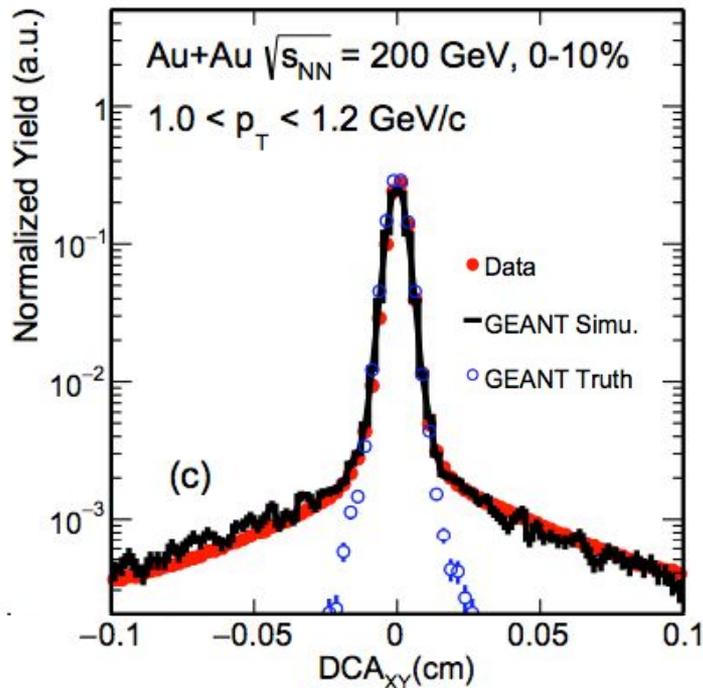
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Effects are illustrated at right.

- The DCA distribution of the tracks is shown
- Simulations are performed with mocked PXL backgrounds tuned to match the data



Pileup Strategies: Pure Simulation

Run a GEANT simulation of the STAR detector, accounting for the out-of-time and UPC pileup contributions in the TPC and PXL detectors.

Requirements:

- Full understanding of TPC and HFT detector response (digitization)
 - Modeling of detector noise (e.g. pedestals)
- Tuned simulation of the UPC contribution

Pros:

- Works (to sufficient precision) with ideal geometry model
- Contains full tracking and vertexing MC truth information

Cons:

- Only as good as the underlying event generators
- Requires tuning to match data
 - Background contributions (out-of-time and UPC pileup)
 - Detector response
 - Calibration uncertainties
- CPU intensive (TPC simulation)

Pileup Strategies: Data Driven Simulation

Efficiency of the TPC tracking can be obtained from standard or embedding simulations (next slide). *Relative* performance of the HFT taken from data.

Requirements:

- Input distributions representing the relative efficiency of the HFT tracking and its DCA resolution

Pros:

- Captures the detector acceptance and real background environment
- Realistic model of the tracking performance
- FAST (7000 times faster than standard simulation chain)

Cons:

- No MC truth information
- Secondary contributions are not modeled
- Vertex resolution effect
- Does not work for single tracks

Pileup Strategies: Embedding

Measure pileup in-situ during the run, and merge channel-by-channel with simulation.

Requirements:

- Non-zero-suppressed data acquired with a random or minbias trigger during the runs
- Detailed geometry in simulation accounting for the misalignments of the detector
- Fine tuned detector response simulations (digitization)

Pros:

- Less CPU intensive than full simulation
- Captures the detector acceptance
- Detector noise provided for free
- **Background environment is directly measured simultaneous to the data**

Cons:

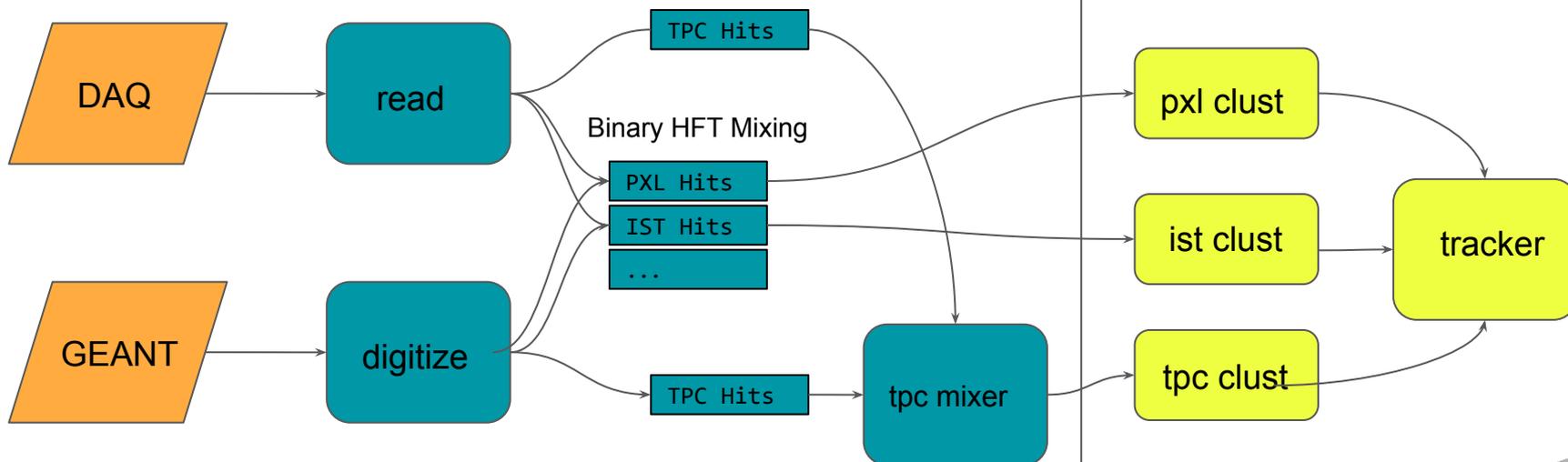
- Requires detailed matching of the geometry model to the real detector
- Requires detailed tuning of the detector response

Embedding Workflow

Input *measured* backgrounds and *simulated* events

Merge real data with simulation channel-by-channel

Reconstruction software is identical to standard data production



HFT Response Simulation (Digitization)

PXL response simulator implemented based on DIGMAPS for MAPS sensor simulations. Generates the cluster profile based on the track trajectory using parameterized function forms.

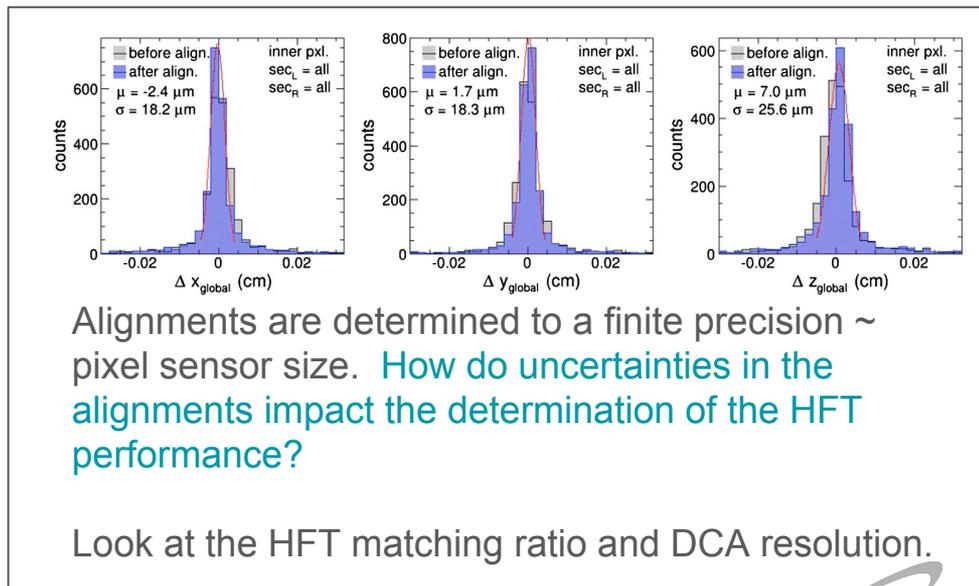
- Highly constrained from
 - Bench test results
 - Cosmic ray data
 - Low luminosity AuAu collisions
- Single hit efficiencies measured w/ cosmic rays
 - PXL efficiency 97%
 - IST efficiency 98%

DIGMAPS Presentation,
<https://indico.cern.ch/event/144152/contributions/1379141/>

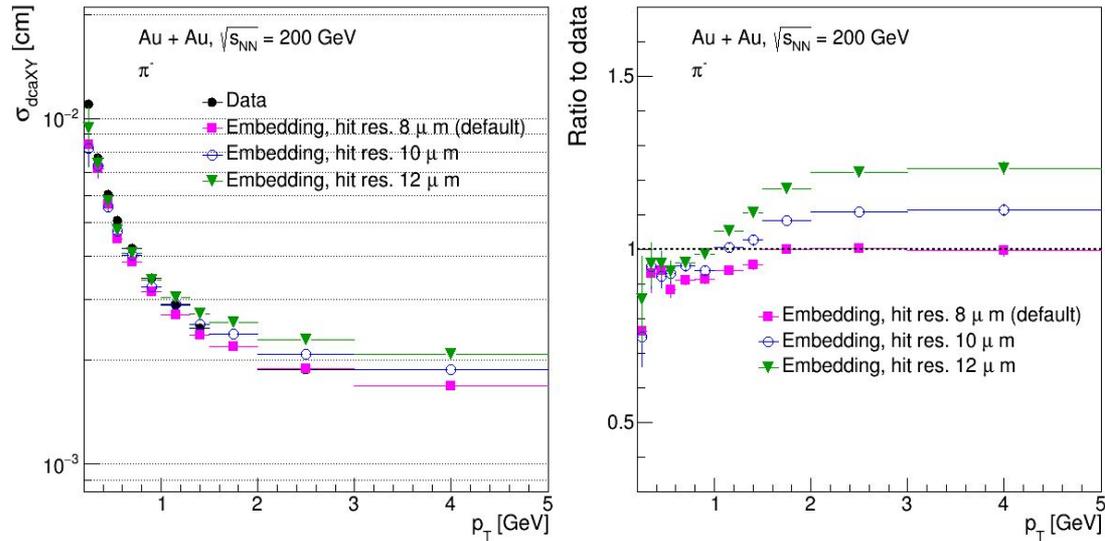
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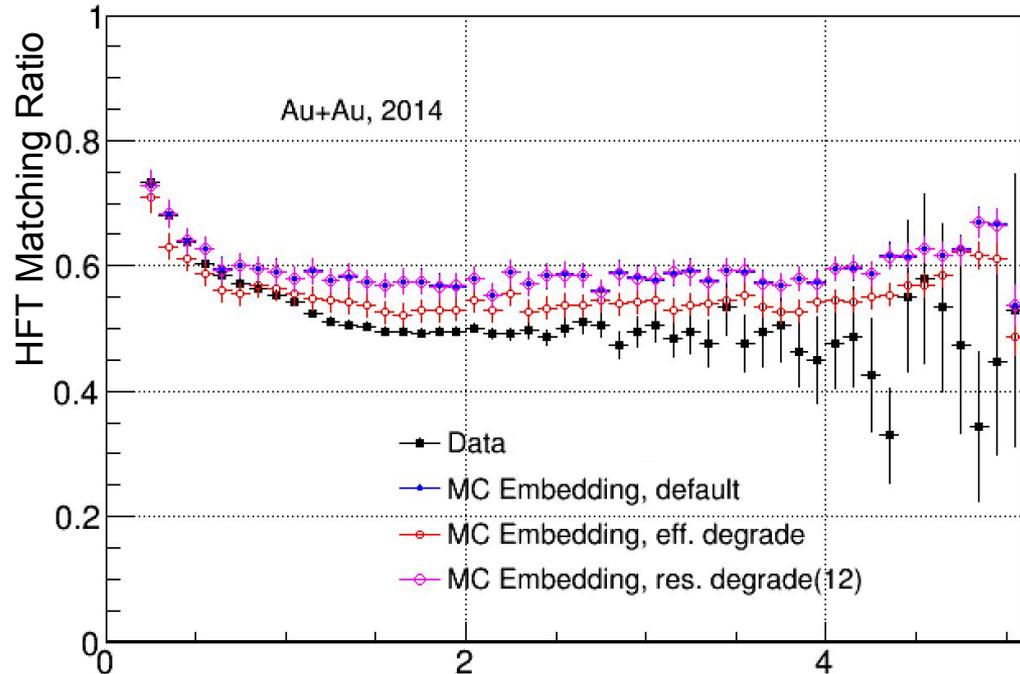


Applying Alignment Uncertainties



- Single pions embedded into minbias triggered data
- Alignment uncertainties treated as an additional smearing of the hit position
- DCA peak broadens with degraded hit resolution
- No perfect solution. 8 microns chosen as optimum. (Differences considered in estimating systematic errors).

Applying Alignment Uncertainties



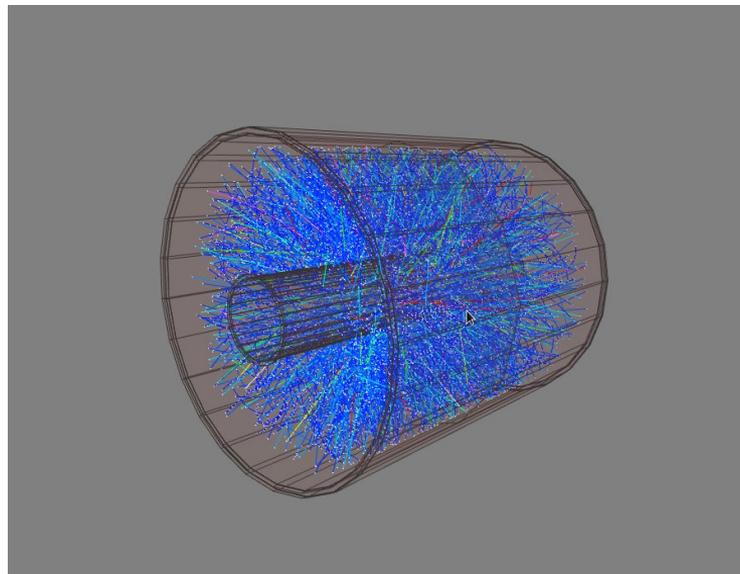
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- Alignment uncertainties treated as an additional smearing of the hit position
- DCA peak broadens with degraded hit resolution
- No perfect solution. 8 microns chosen as optimum. (Differences considered in estimating systematic errors).
- HFT Matching Ratio is not sufficiently affected by the alignment uncertainty
- Degrading the single hit resolution insufficient as well, ... so we must turn to the other possible culprit....

Applying TPC Calibration Uncertainties

Understanding the production of primary ionization, and the drifting of the resulting charge distributions in the TPC gas volume is central to reconstructing tracks in STAR. Involves accounting for several effects, but principally the distortions due to

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

To understand the uncertainties in these corrections requires a second, high precision tracking detector, such as... the HFT.

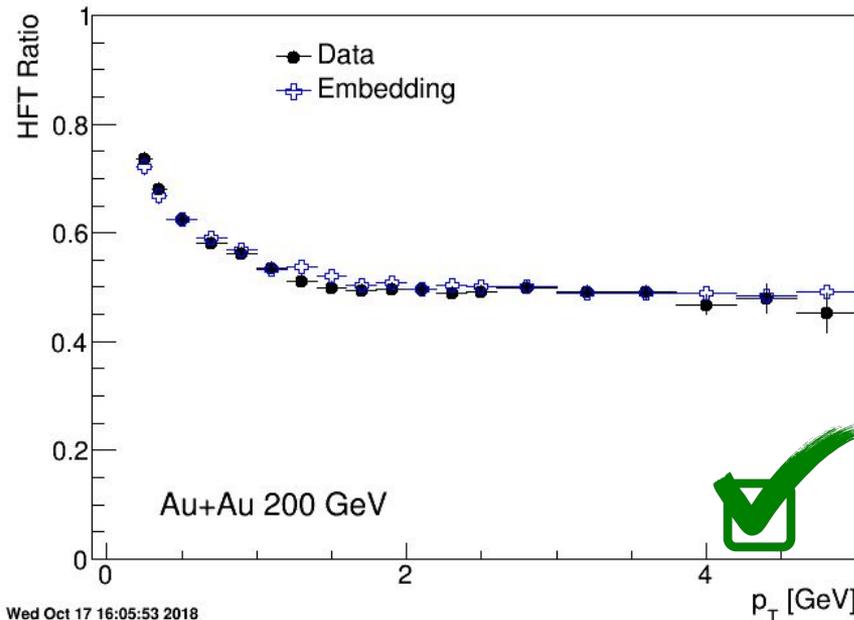


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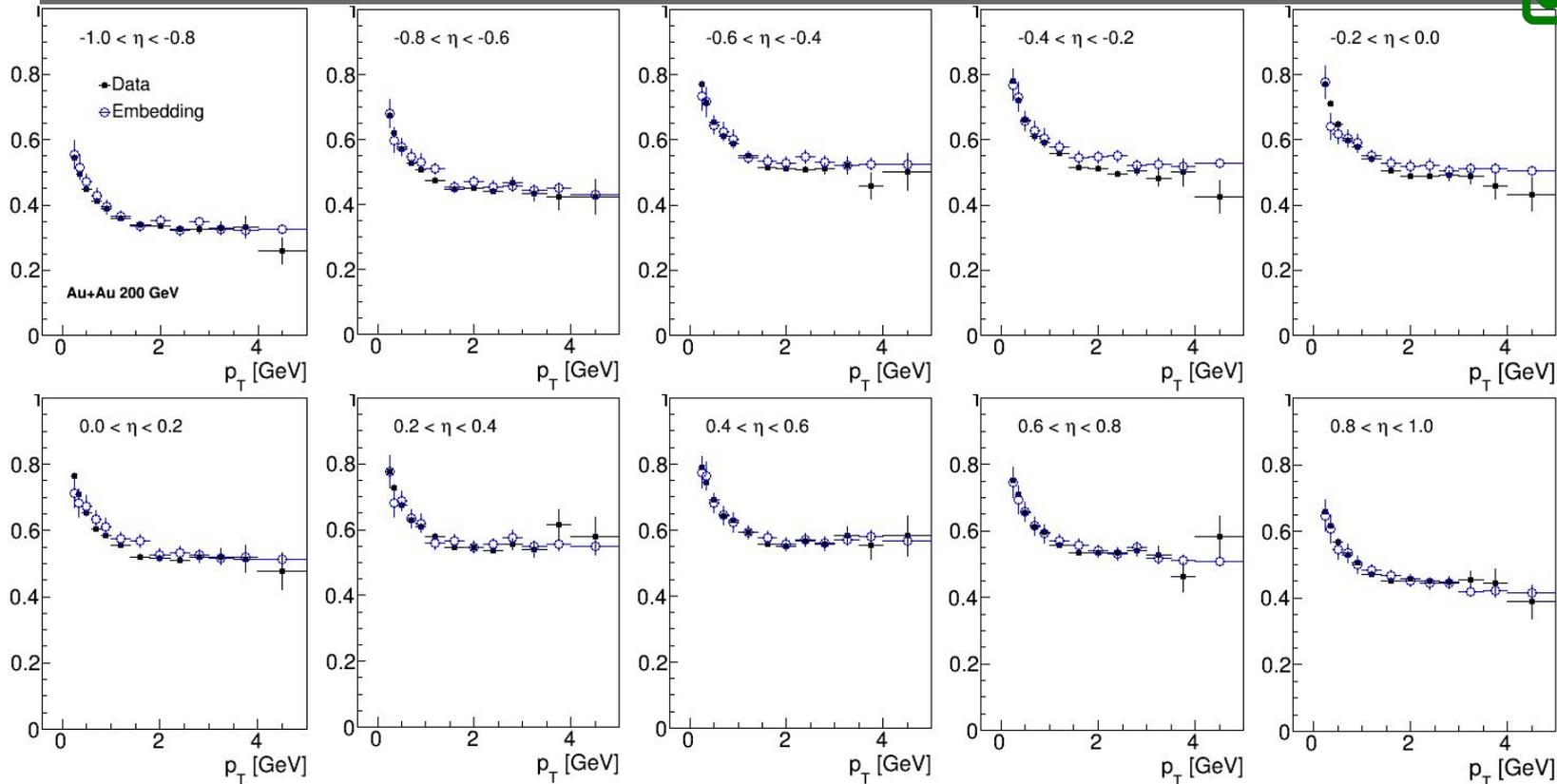
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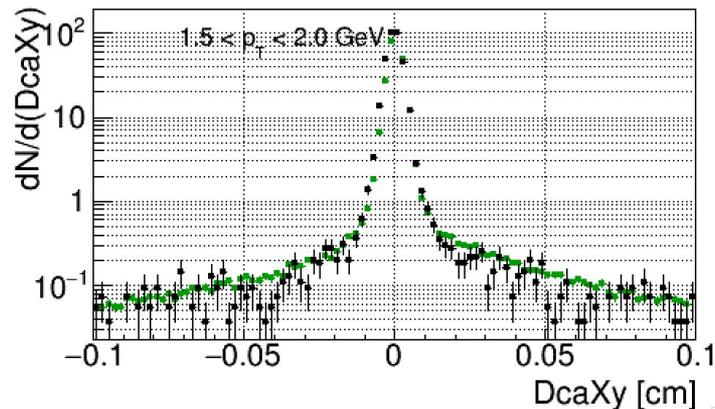
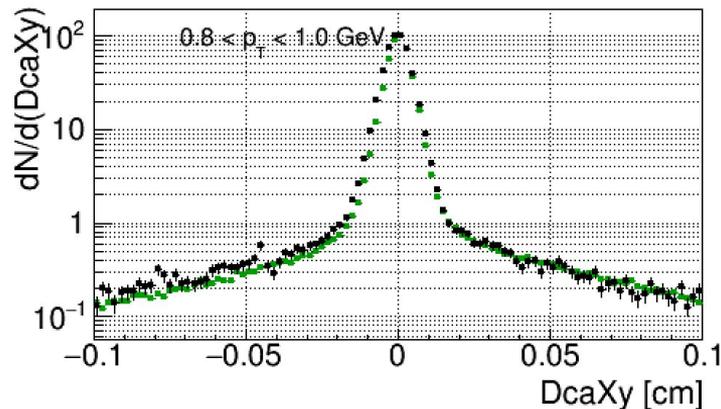
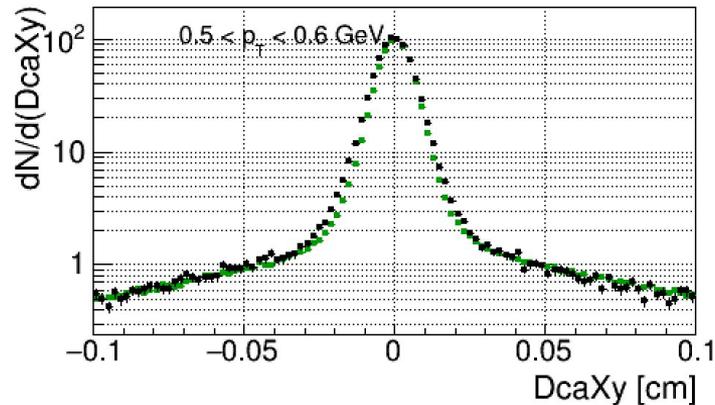
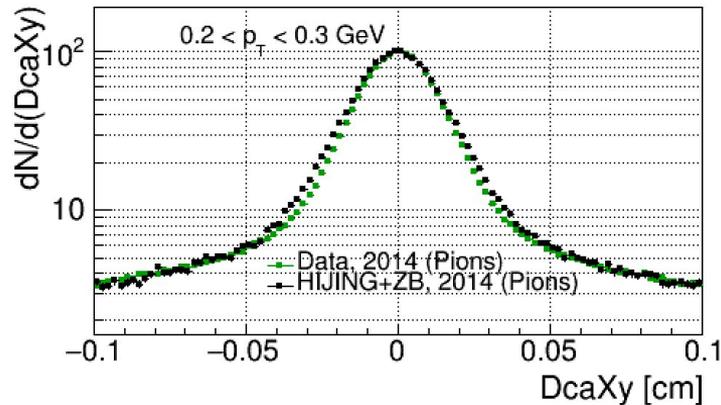


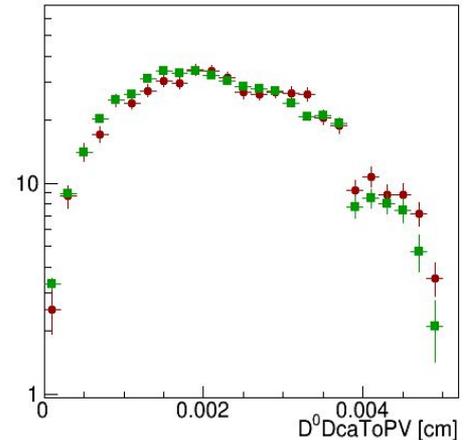
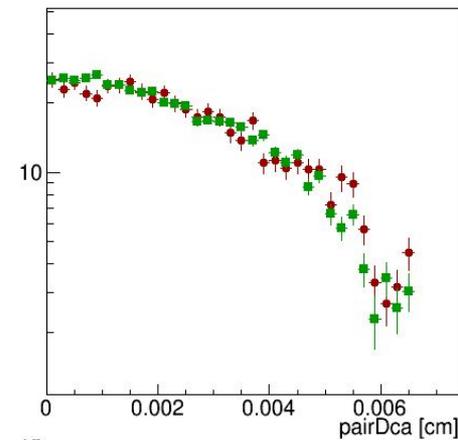
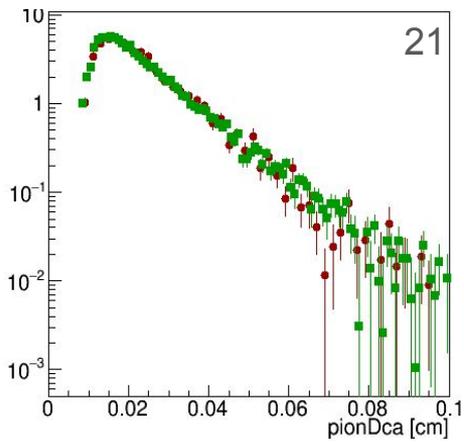
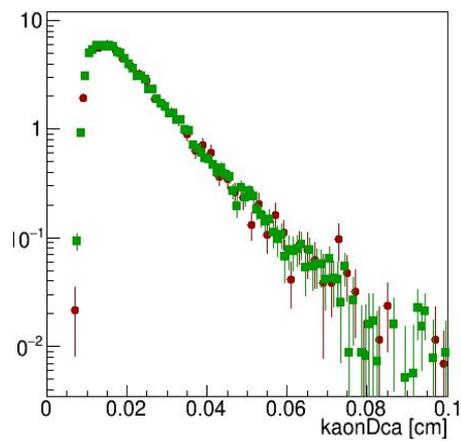
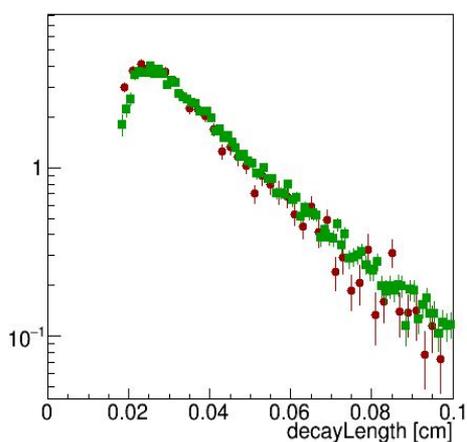
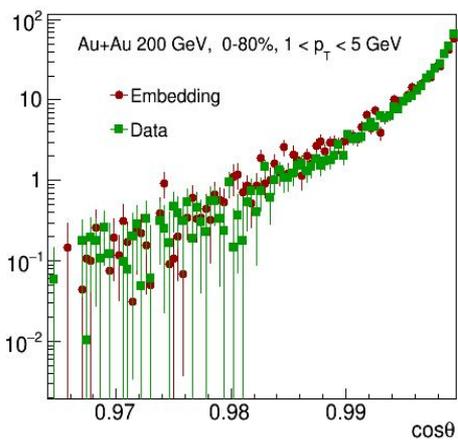
Introducing fluctuations in these quantities at the 5% level achieves good agreement in the relative performance of the HFT to the TPC.

Detailed matching between embedding and real data



Detailed matching between embedding and real data





Detailed matching of the topological variables of the D0 decays

Proper accounting of the uncertainties in the HFT alignment and TPC distortions sufficient to describe

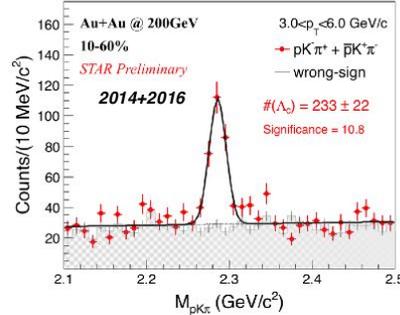
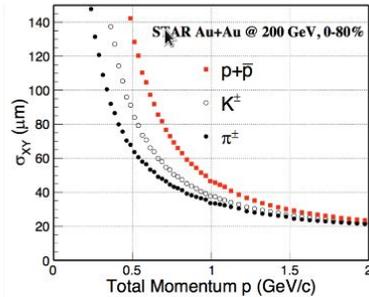
- The HFT matching ratio
- DCA distributions
- D0 topological observables



High confidence in the measured efficiencies

Λ_c production in heavy ion collisions

- Λ_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 $\Lambda_c = 60 \mu\text{m}$!
- Supervised Learning Methods (BDT) used to improve signal-background separation for Λ_c reconstruction

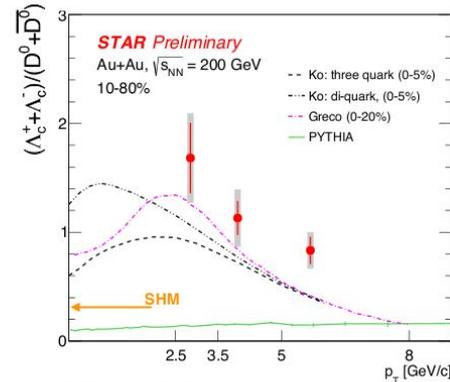
Talk by G. Xie: 04/10 Thu, 11.25 (P3)

Sooraj Radhakrishnan

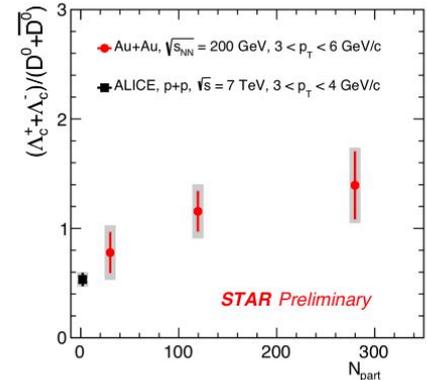
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Recent Results @ [Hard Probes 2018](#)

Λ_c production in heavy ion collisions



Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905



- Strong enhancement of Λ_c production compared to PYTHIA calculations
- Suggest coalescence hadronization of charm quarks in QGP at intermediate p_T (2-6 GeV/c)

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

Sooraj Radhakrishnan

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Summary



- The production of charmed hadrons provides important insights into the evolution of the dense medium created in heavy ion collisions
- The STAR Heavy Flavor tracker was operated from 2014 to 2016, providing the precision tracking required to topologically identify charmed hadron decays
- Understanding tracking efficiencies requires detailed simulations, accounting for the sources of pileup background, the misalignments of the detectors, and a detailed understanding of the uncertainties in our calibrations
- STAR utilizes embedding, where simulations are merged channel-by-channel with real data accumulated during data taking, enabling the direct, in-situ measurement of the background and detector environment
- **Physics analysis of the HFT data samples is progressing, and the embedding framework will allow us to realize the maximum physics impact from these data.**