Review of recent heavy flavor measurements from the STAR experiment

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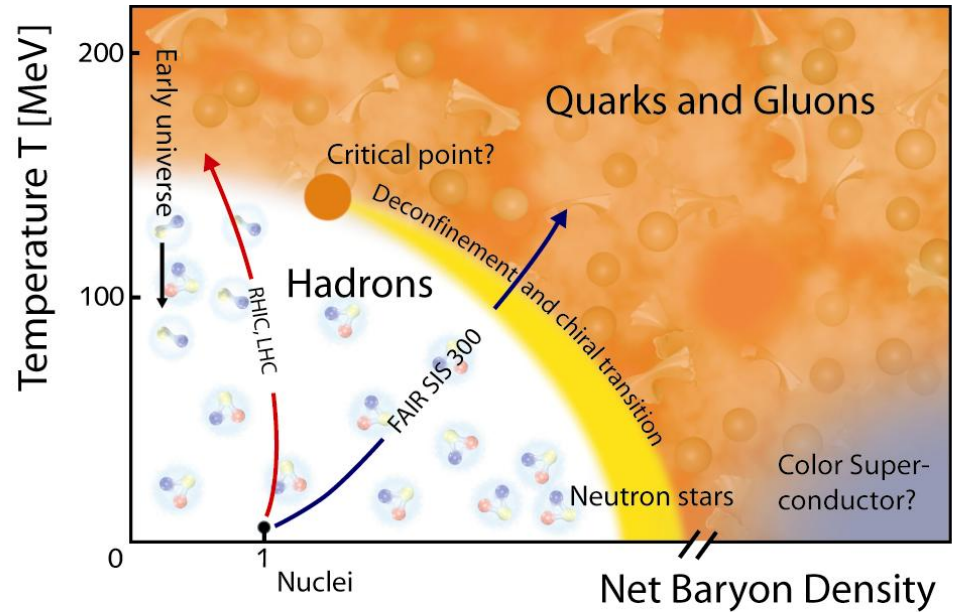
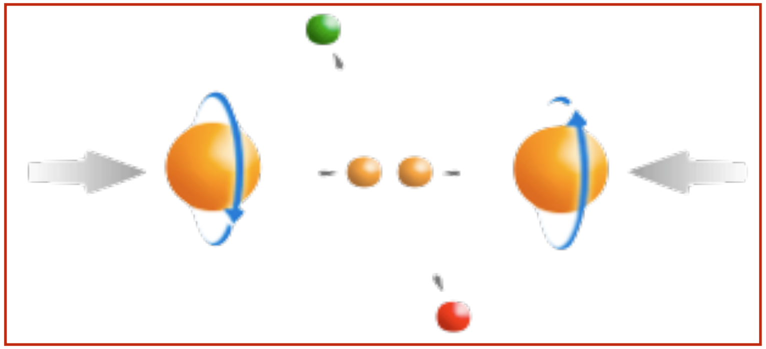
Outline

- Motivation
- Open heavy flavor measurements
  - Heavy Flavor Tracker
  - D-meson nuclear modification factor and elliptic flow
- Quarkonium measurements
  - Muon Telescope Detector
  - J/ψ nuclear modification factor
  - Υ suppression
- Outlook
- Summary

STAR physics focus

- At 200 GeV top energy
  - Collective flow and jet quenching -> novel state of matter (QGP) discovered at RHIC
  - Study QGP properties, EoS
  - QCD in hot and dense medium
- RHIC beam energy scan
  - Search for the QCD critical point
  - Chiral symmetry restoration
- Spin program
  - Shed light on proton spin puzzle

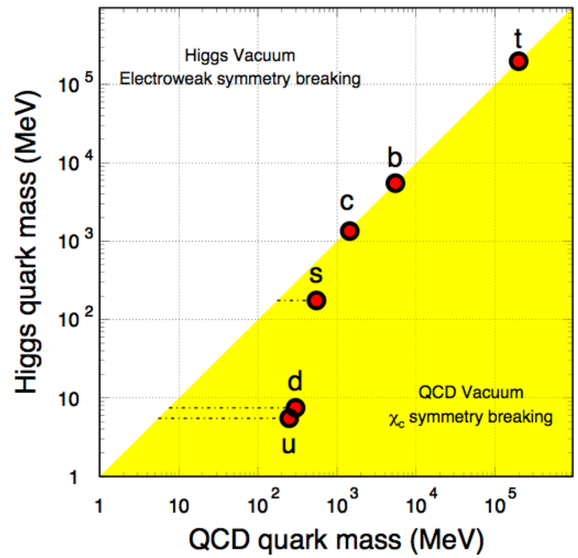




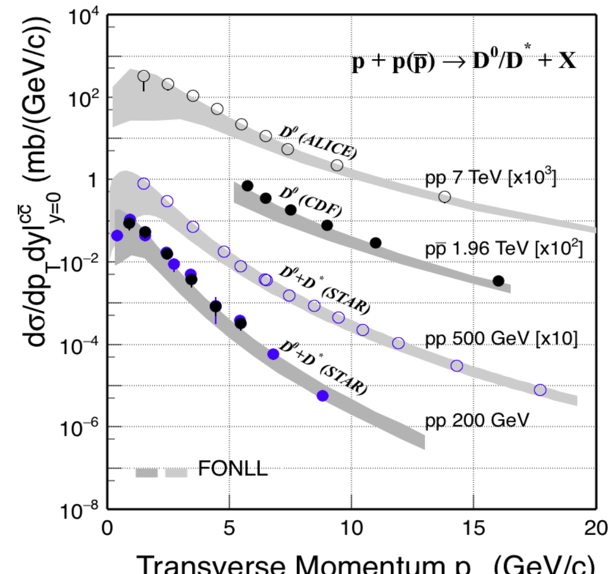
Study the QGP with open heavy flavor

Charm quarks $m_c > T_{QGP}, \Lambda_{QCD}$:

- Produced early in heavy-ion collisions at RHIC, through hard scattering -> experience the entire evolution of the system
- Compare with light hadrons to disentangle energy loss mechanisms: radiative vs. collisional
- Compare different charm hadron yields to study hadronization
- Extract properties of the QGP medium from heavy quark motion in the medium



X. Zhu, *et al*, Phys. Lett. **B647**, 366(2007).



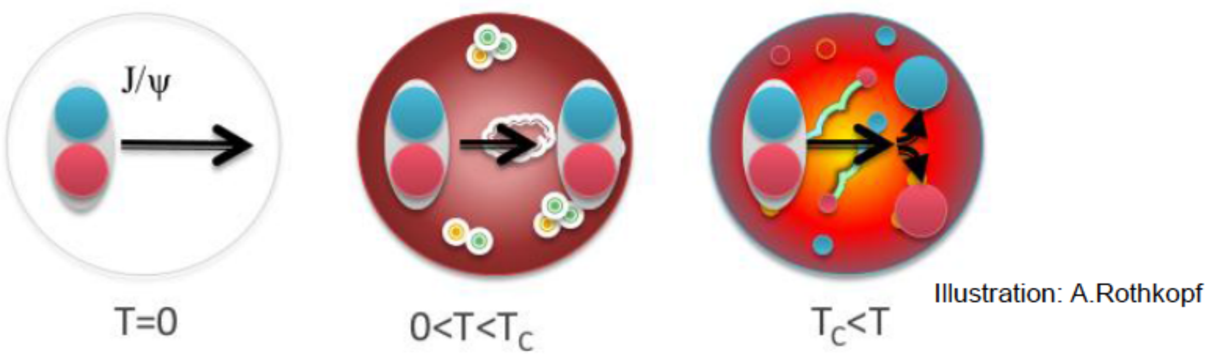
STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

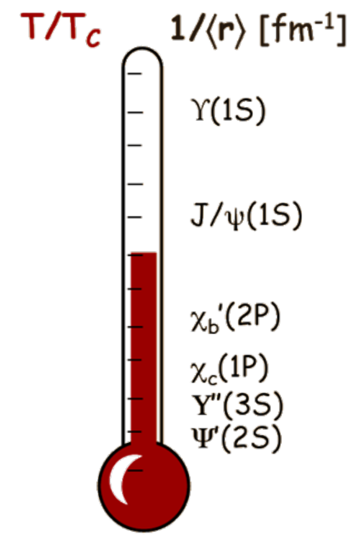
Study the QGP with quarkonia

- Compare AA with pp: study dissociation due to color screening, regeneration from uncorrelated quarks and cold nuclear matter (CNM) effects

J/ψ suppression was proposed as a direct proof of QGP formation

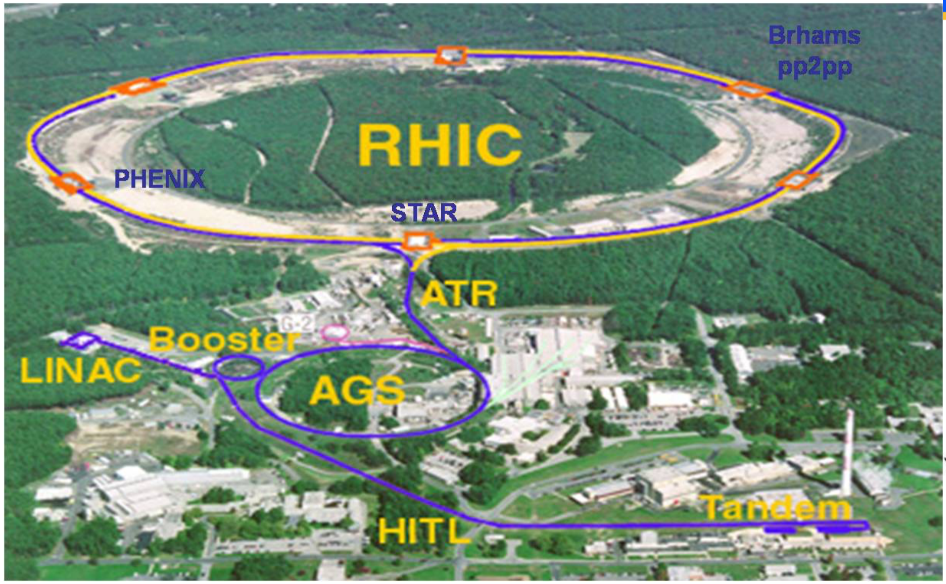
T. Matsui and H. Satz PLB 178 (1986) 416

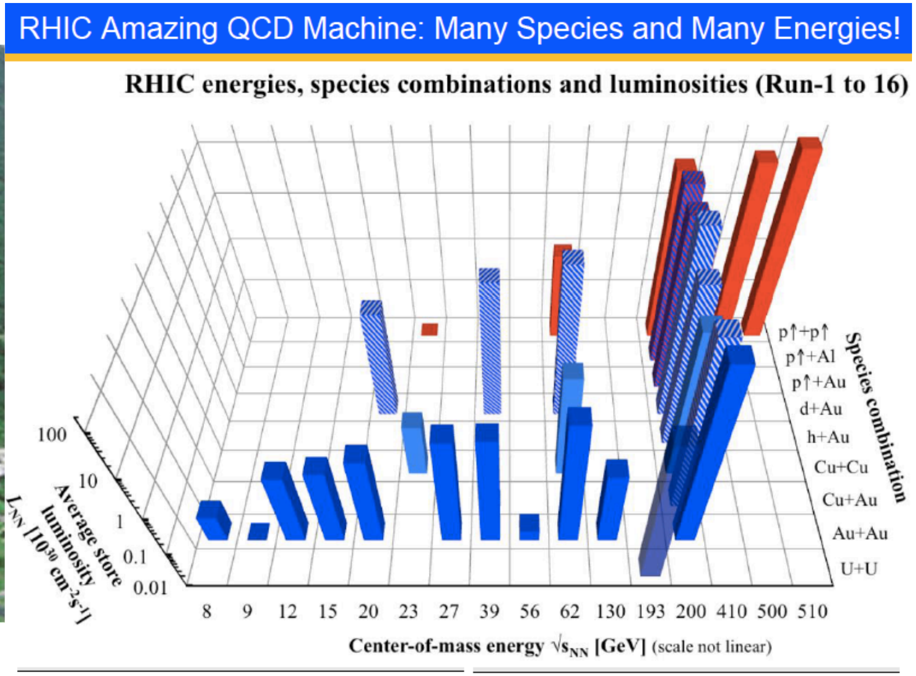




- Compare different quarkonium states: sequential melting as a thermometer for the QGP

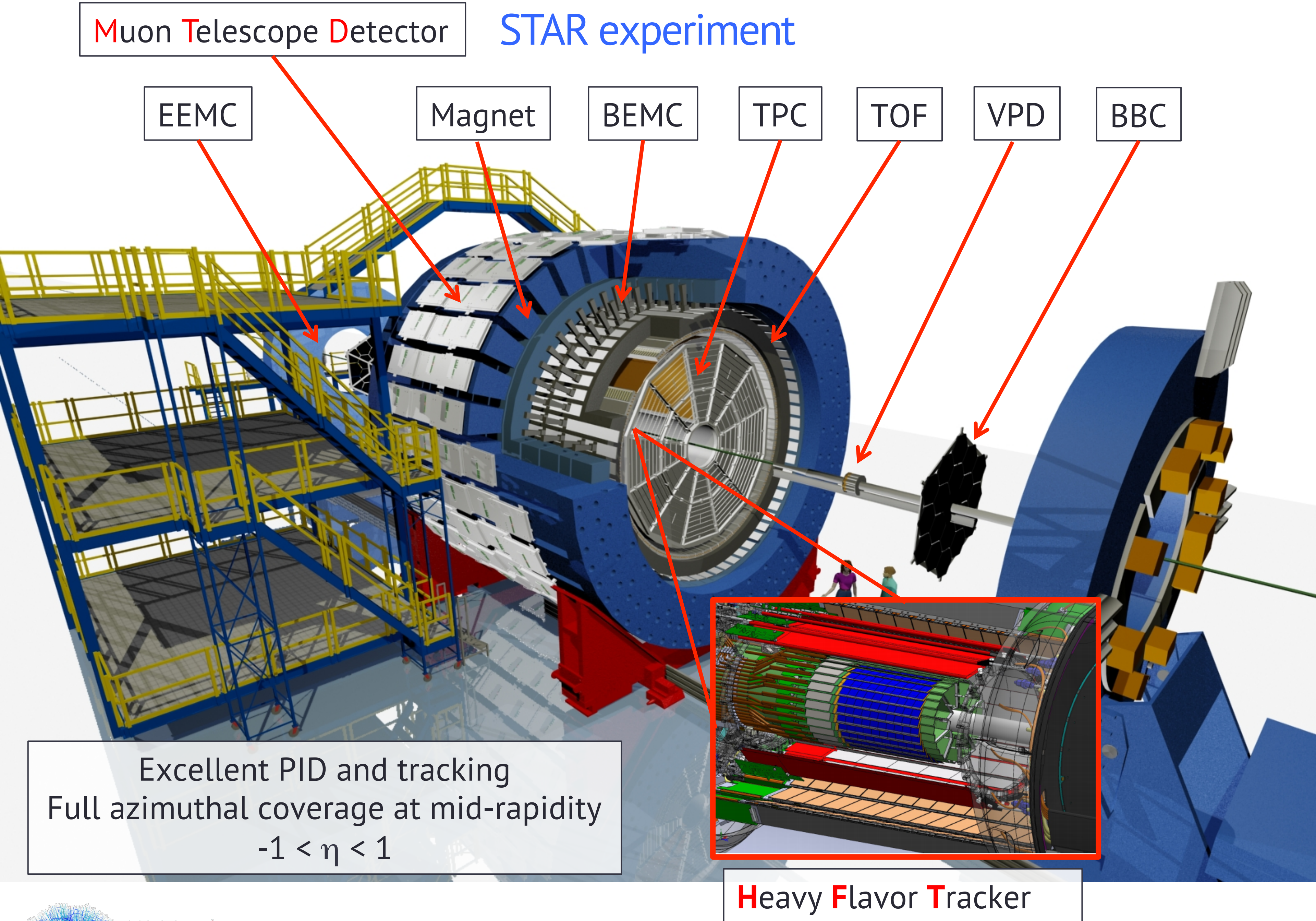
Relativistic Heavy-Ion Collider





- Extremely versatile: has collected data colliding a large array of different heavy ions
- Only polarized proton collider in the world

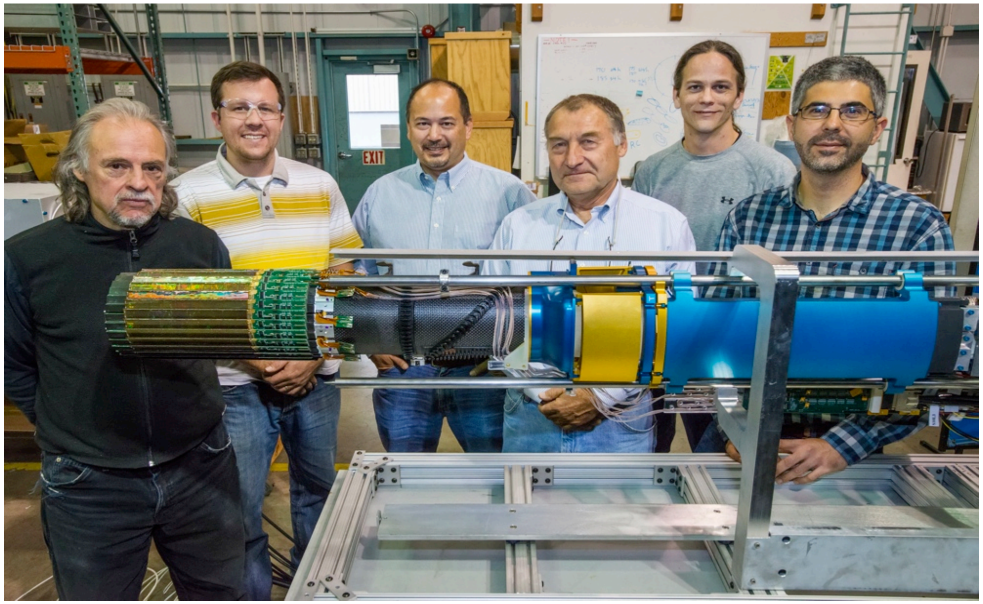
STAR experiment



Excellent PID and tracking
Full azimuthal coverage at mid-rapidity
$-1 < \eta < 1$

STAR Heavy Flavor Tracker (HFT)

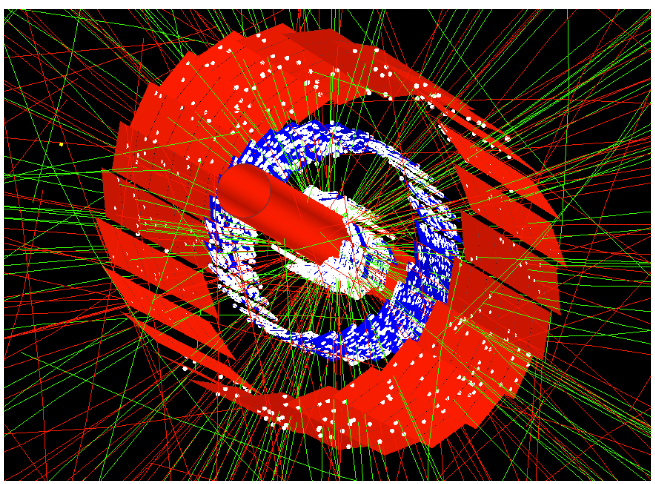
TPC – Time Projection Chamber
(main tracking detector in STAR)



HFT – Heavy Flavor Tracker

- SSD – Silicon Strip Detector
- IST – Intermediate Silicon Tracker
- PXL – Pixel Detector (356M pixels on ~0.16 m^2 of silicon)

Acceptance coverage:
$-1 < \eta < 1$
$0 < \phi < 2\pi$

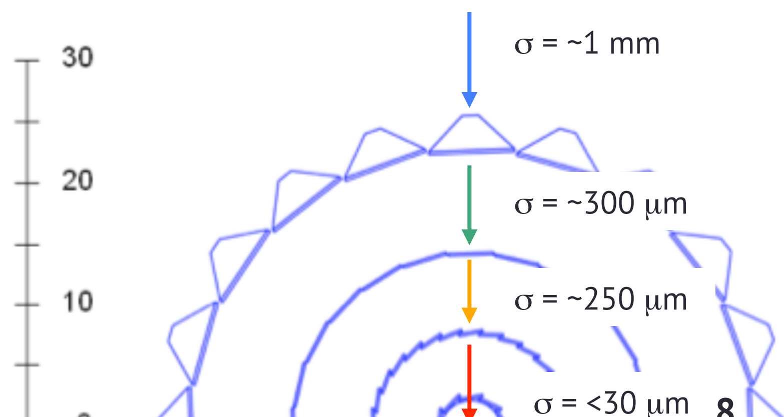


SSD **r = 22**

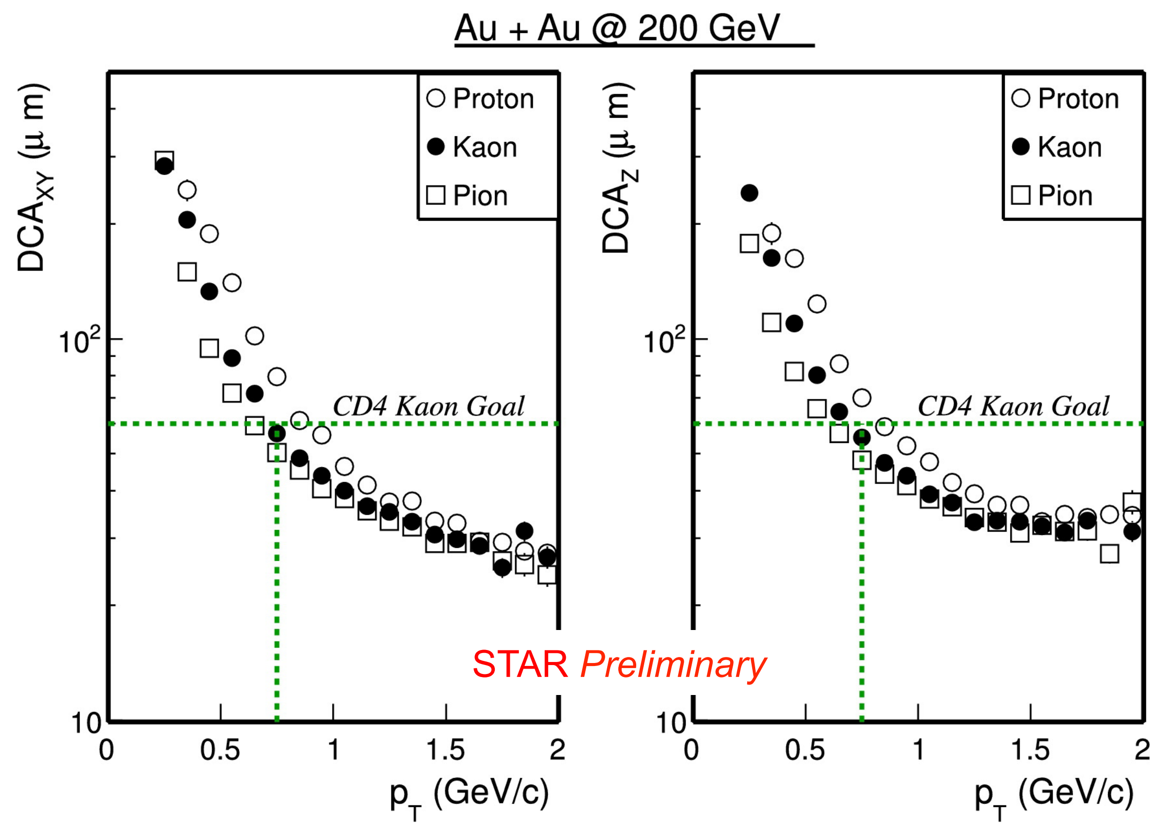
IST **r = 14**

PXL **r_2 = 8**

r_1 = 2.8

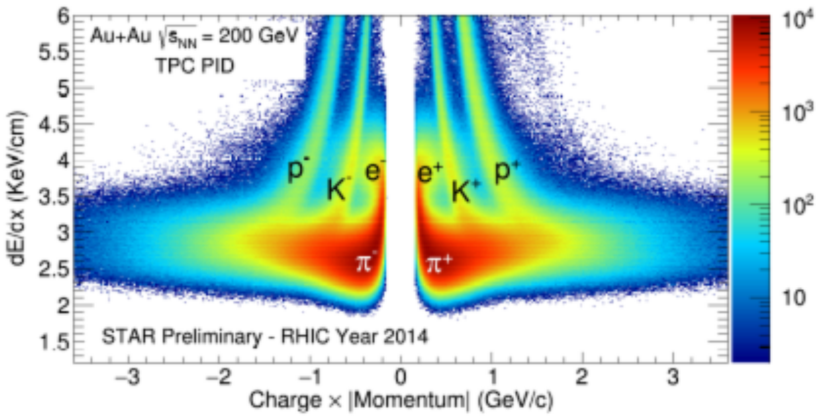


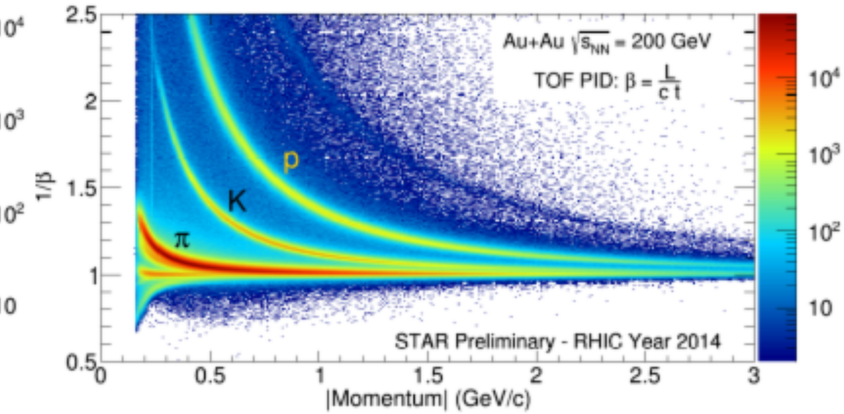
HFT Performance vs. design goals

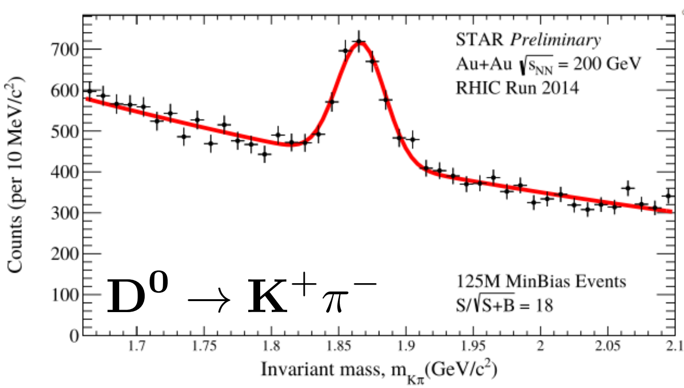


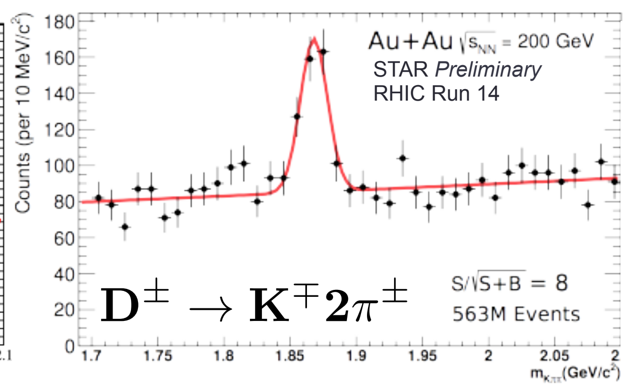
- Kaon track pointing resolution exceeds the requirement < 55 μm at p_T=750 MeV/c
- Pointing resolution in the region with Al-cables ~ 45 μm

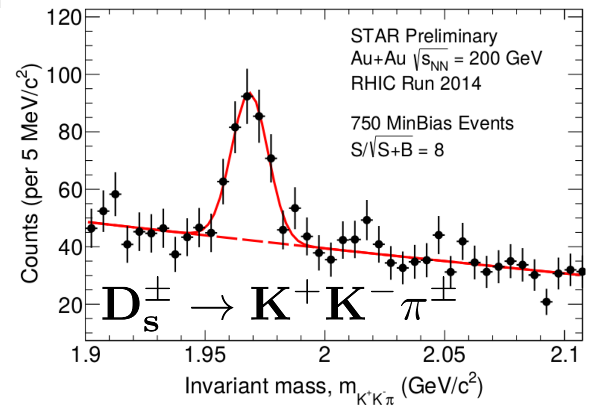
Particle Identification







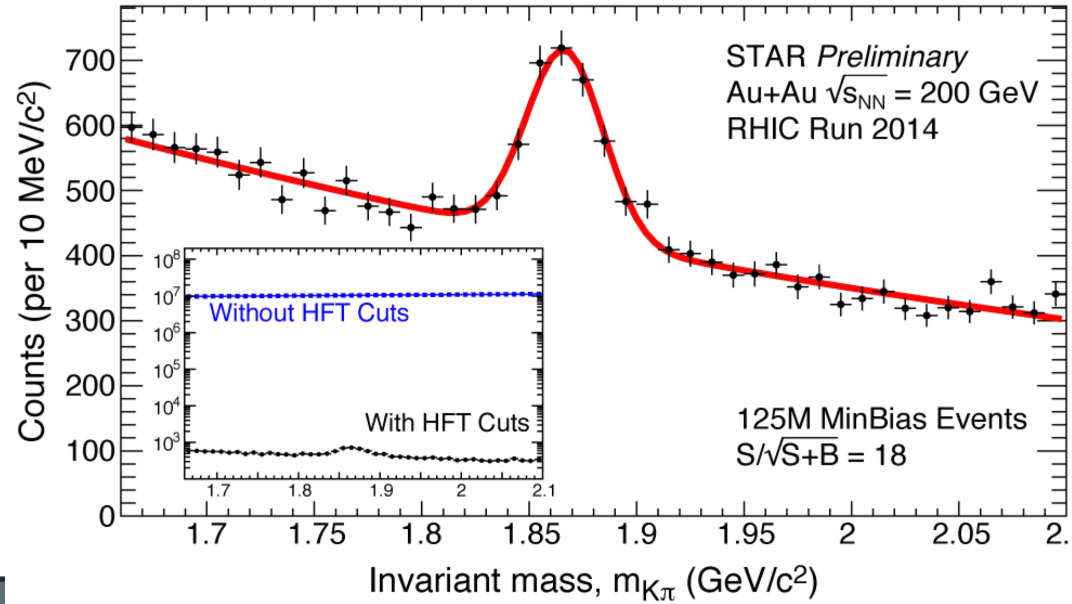




- Excellent long-lived hadron and electron identification
- Secondary vertex reconstruction with HFT → full kinematic reconstruction of charmed hadron

Topological reconstruction with HFT

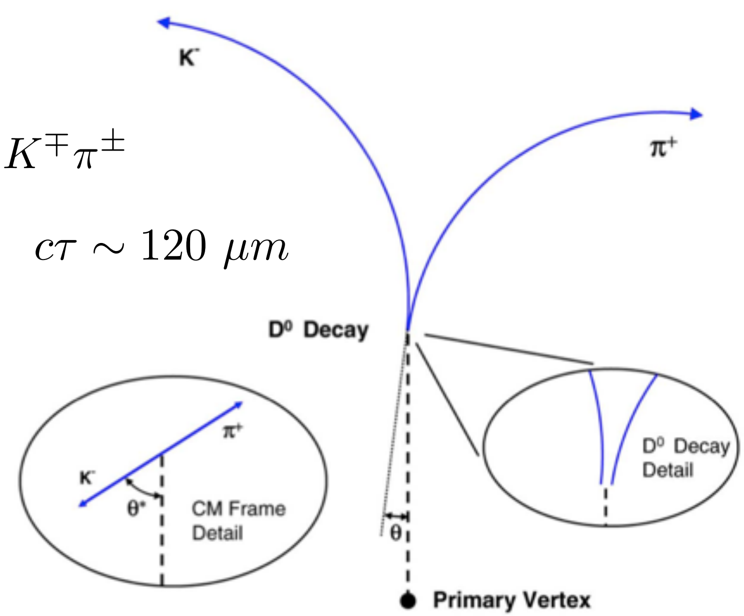
- Greatly reduced combinatorial background (4 orders of magnitude)
- Highly improved S/B



	w/o HFT	w HFT
	2010 + 2011	2014
# events(MB) analyzed	1.1 B	780 M
significance per billion events	13	51

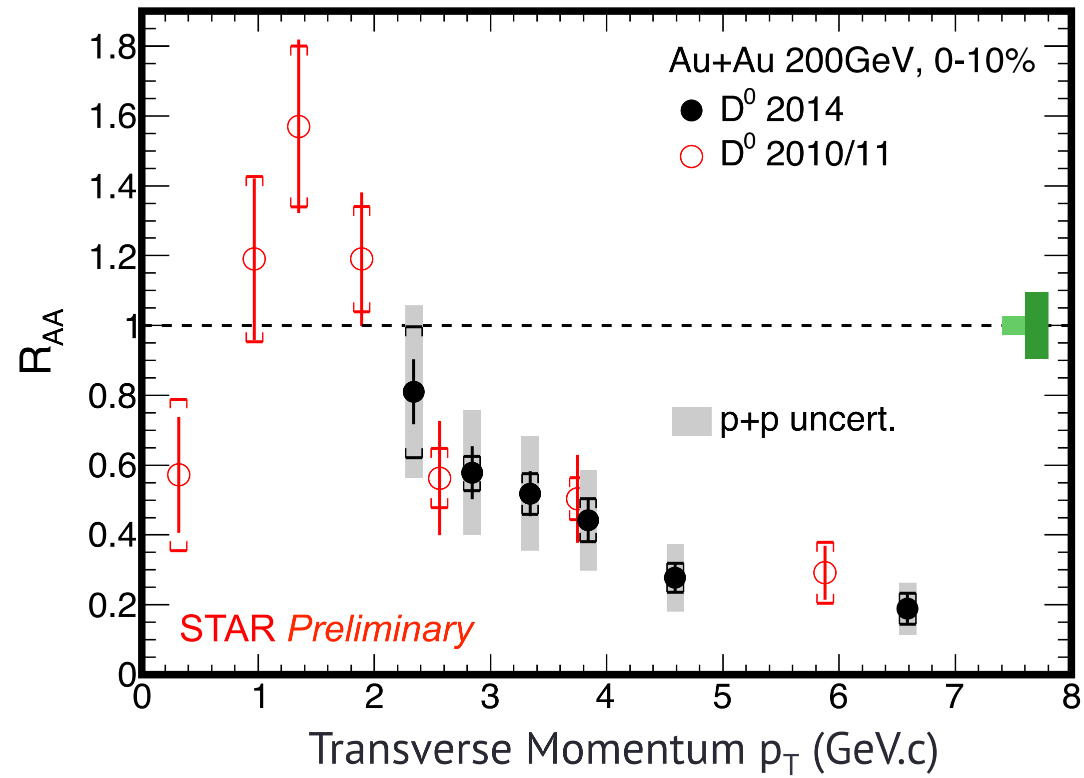
$$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$$

$$\text{B.R. } 3.9\% \quad c\tau \sim 120\ \mu m$$



D^0 vs. π R_{AA}

- High p_T: significant suppression in central Au+Au collisions.
  - New results have improved precision
  - Strong charm-medium interaction
- R_{AA}(D) > 1 p_T ~ 1.5 GeV/c
  - Indication of charm coalescence with bulk



$$R_{AA} = \frac{dN_{AA}/dy}{N_{binary} \times dN_{pp}/dy}$$

STAR: PRL 113 (2014) 142301
PLB 655 (2007) 104

D^0 vs. π R_{AA}

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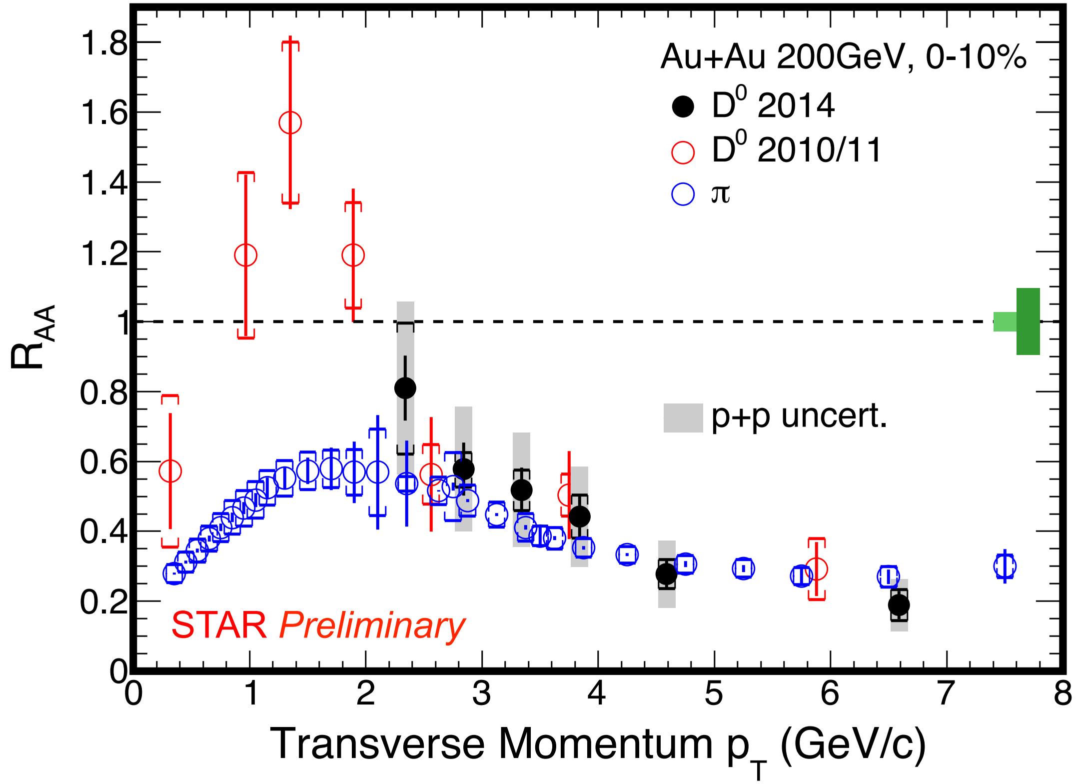
- $R_{AA}(D) > 1$ $p_T \sim 1.5$ GeV/c
  - Indication of charm coalescence with bulk
- Similar suppression for light partons and charm quarks at high p_T (>4 GeV/c)



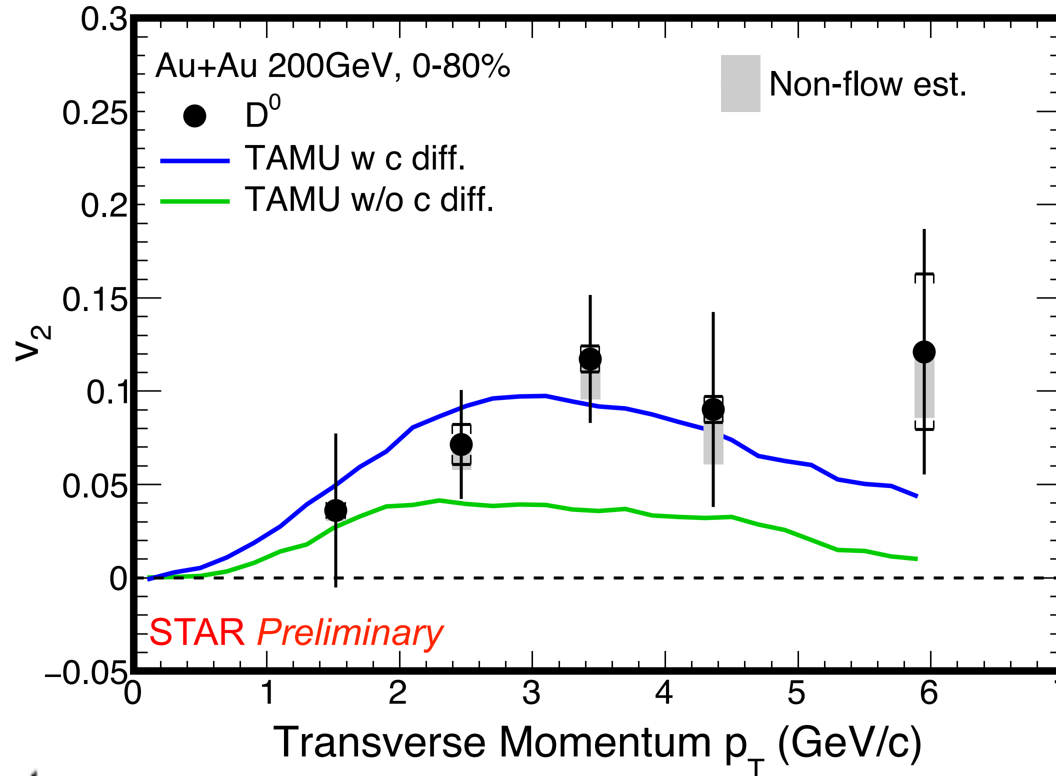
$$R_{AA} = \frac{dN_{AA}/dy}{N_{binary} \times dN_{pp}/dy}$$

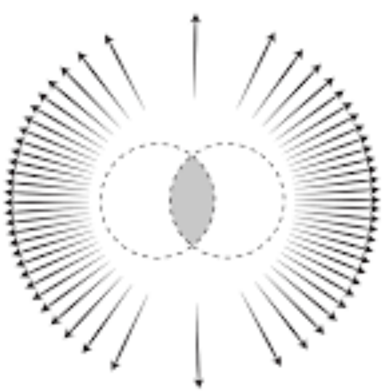
STAR: PRL 113 (2014) 142301
PLB 655 (2007) 104

D^0 v_2

- D^0 azimuthal anisotropy significantly above zero for p_T > 2 GeV/c

- Data favor the model including charm quark diffusion in the medium



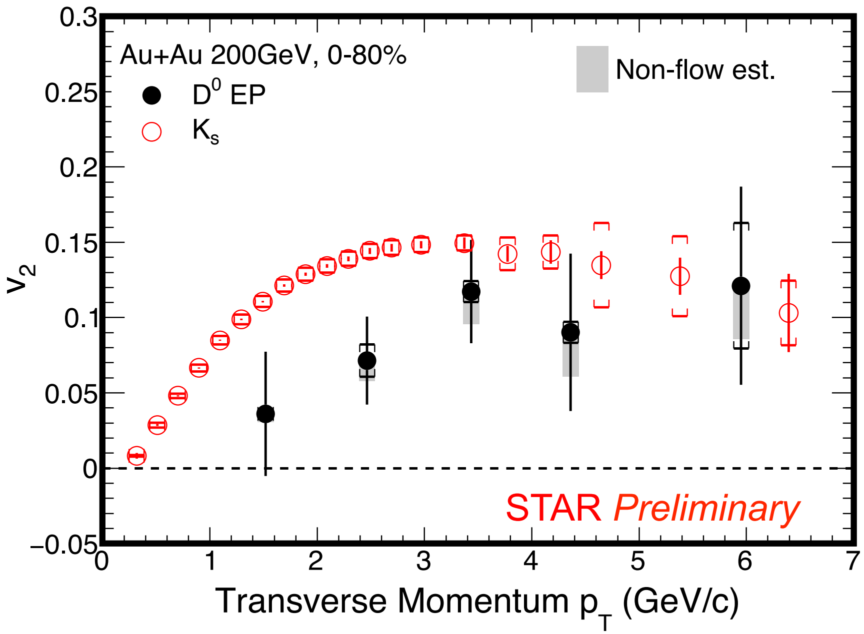


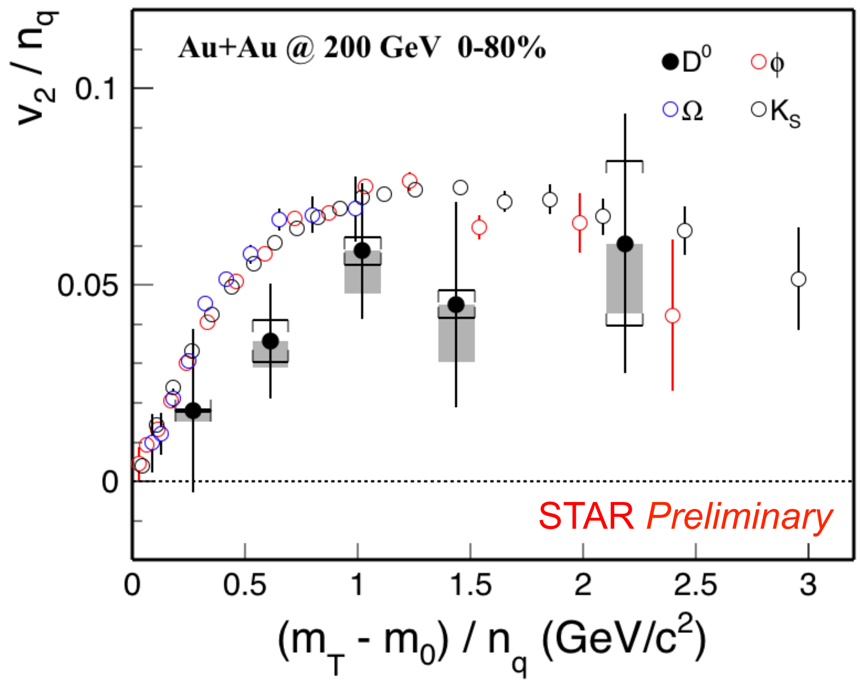
$$\frac{dN}{d\phi} = N_0 \left[1 + \sum_N 2 v_N cos(n\phi) \right]$$

Theory: arXiv:1506.03981 (2015) & private comm.

Mass effect

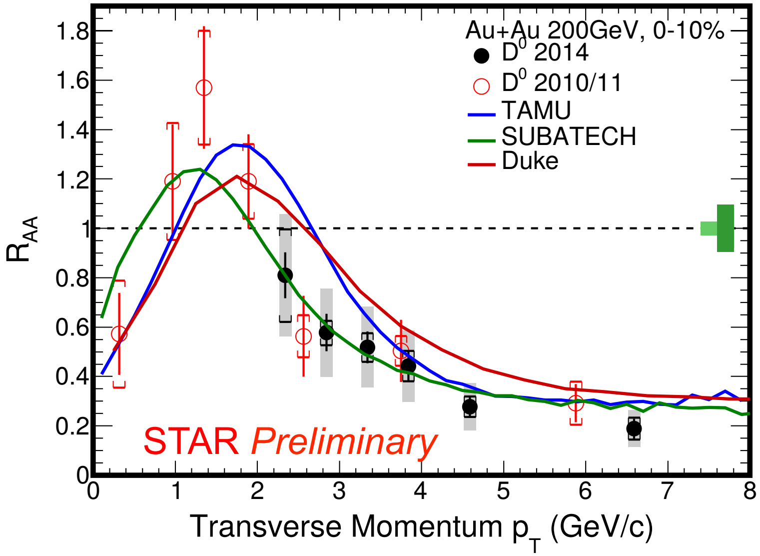
STAR:PRC 77 (2008) 54901
PRL 116 (2016) 62301

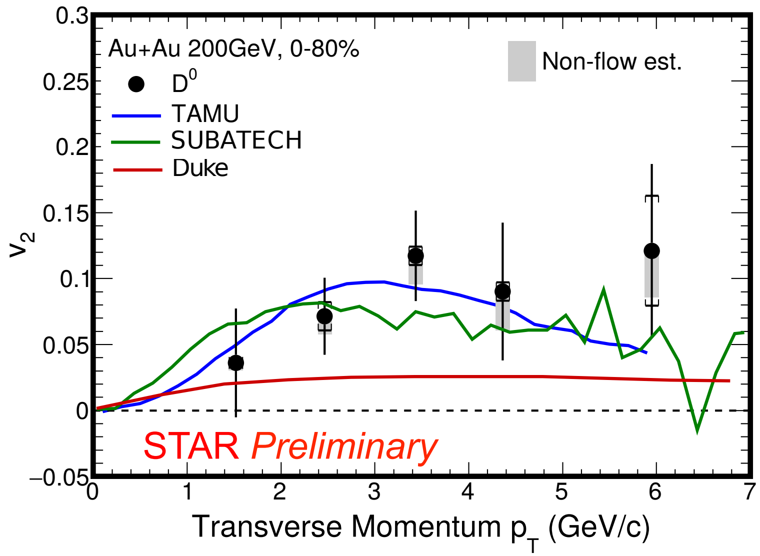




- Systematically below results obtained for light hadrons. Need better statistics for a firm conclusion
  - Suggests charm quarks may not be fully thermalized with the medium

Comparison to models





- Models can successfully describe both R_{AA} and v_2

TAMU: non-perturbative T-Matrix approach:

$(2\pi T)D = 2 - \sim 10$

SUBATECH: pQCD + Hard Thermal Loops for resummation:

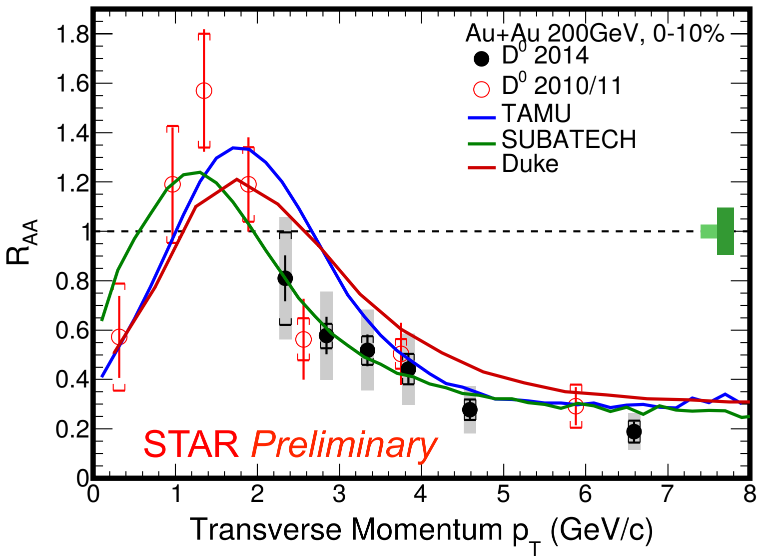
$(2\pi T)D = 2 - 4$

DUKE: Langevin simulation with transport properties tuned to LHC data:

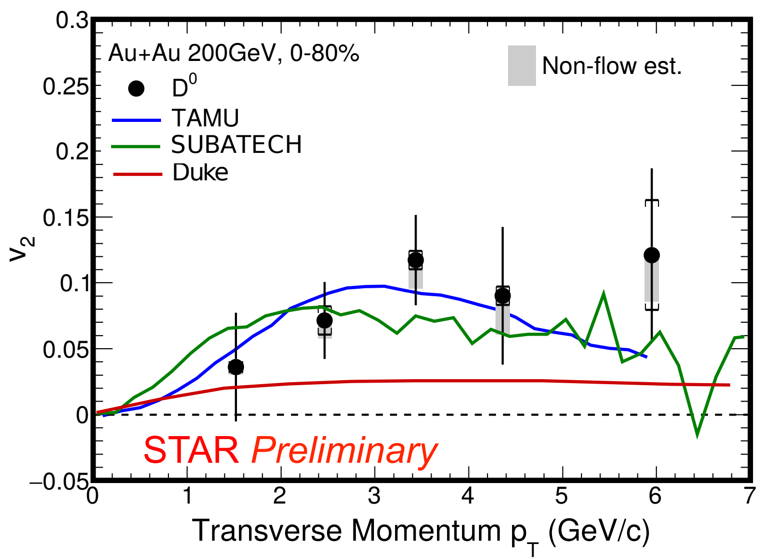
$(2\pi T)D = 7$

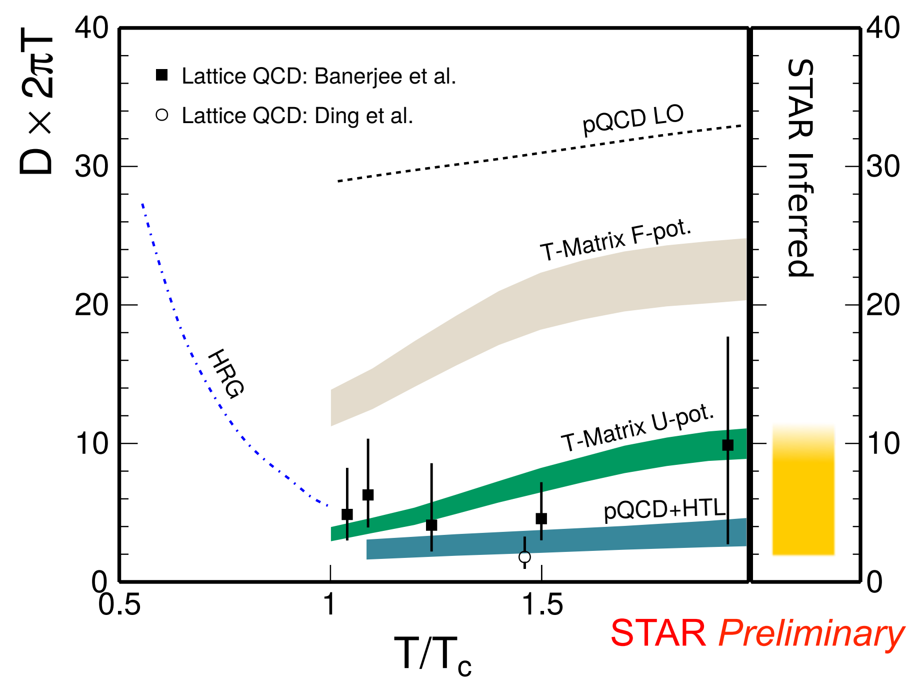
Theory: PRC 92(2015) 024907
arXiv:1506.03981 (2015)
& private comm.
STAR 2010/11: PRL 113 (2014) 142301

Extracting the diffusion coefficient (2πT)D

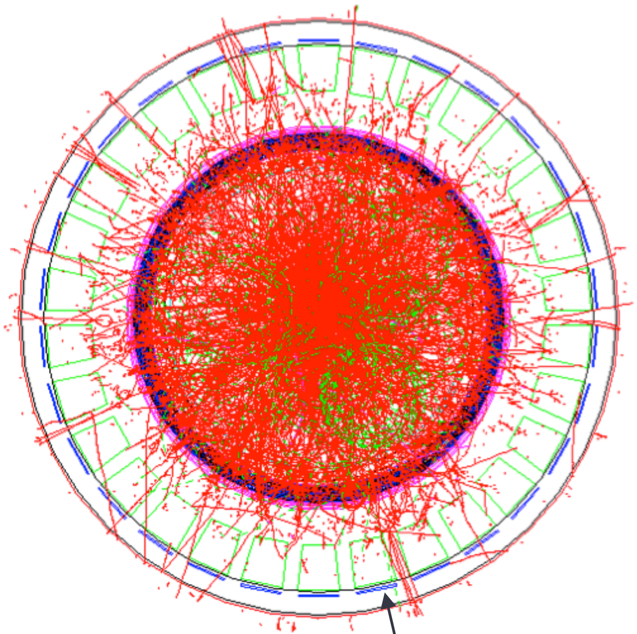


- Values for the diffusion coefficient extracted from models as a function of T/T_c and inferred range (2 to ~ 10) from STAR data.
- Lattice calculations, although with large uncertainties, are consistent with values inferred from data





Muon Telescope Detector (MTD)



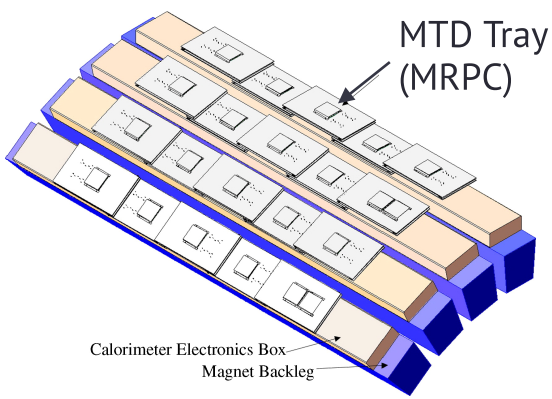
- Designed for muon triggering and identification based on precise timing information: ~100 ps for p_T >1.2 GeV/c muons

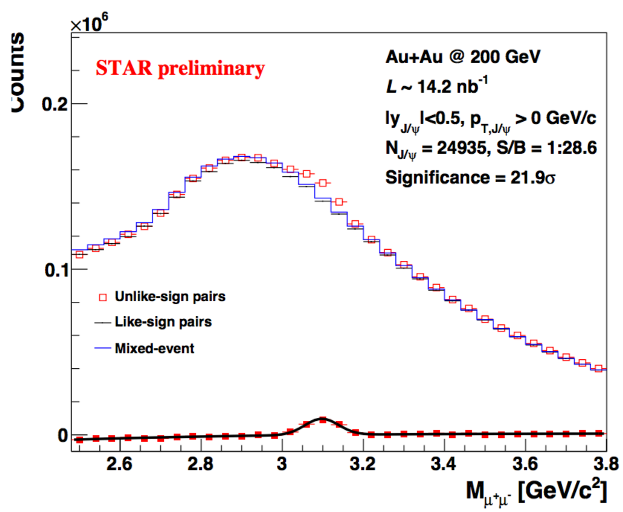
- Multi-gap resistive plate chambers (MRPC): similar technology as used for Time of Flight (TOF) detector

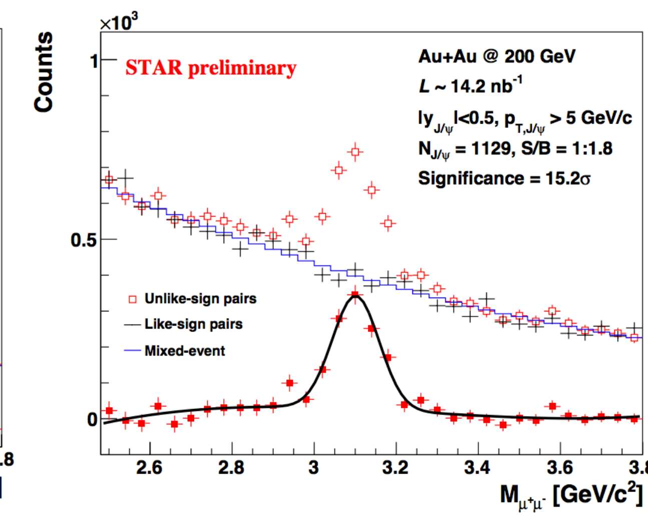
- 45% geometrical acceptance within | η |< 0.5

- Placed behind magnet to absorb hadrons (5 nuclear interaction lengths)

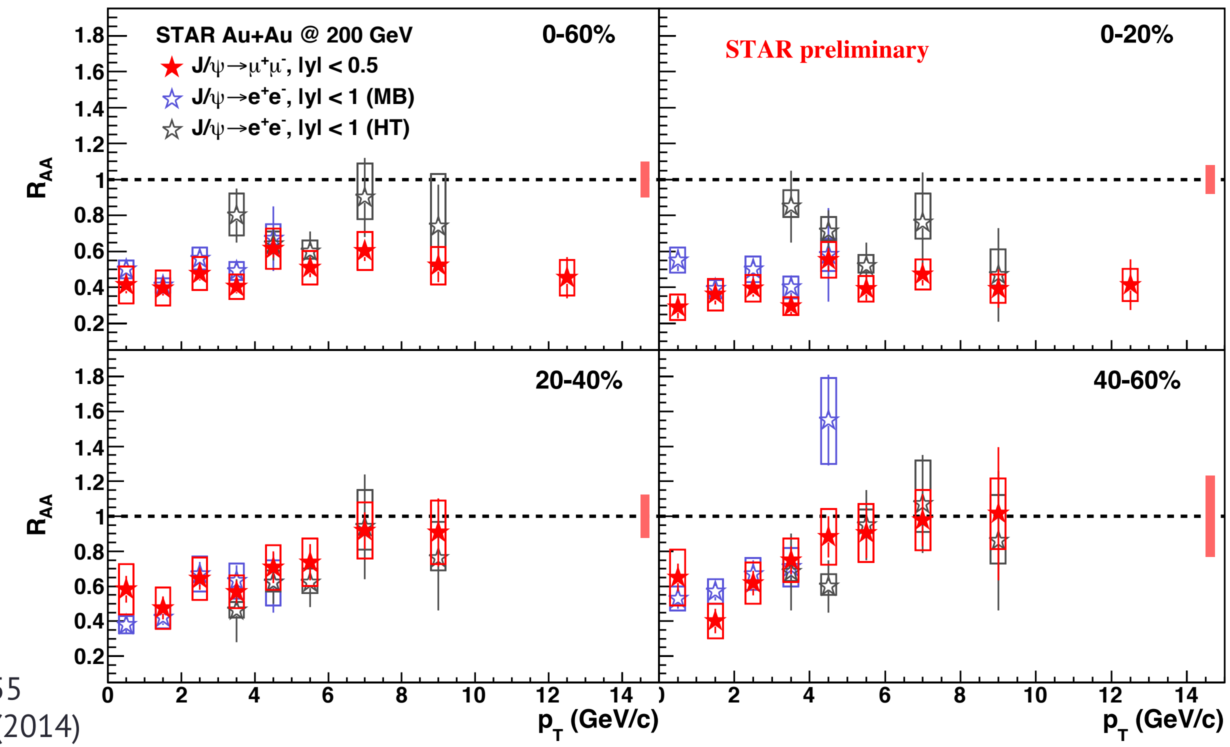
MTD Tray (MRPC)







J/ψ suppression in Au+Au collisions

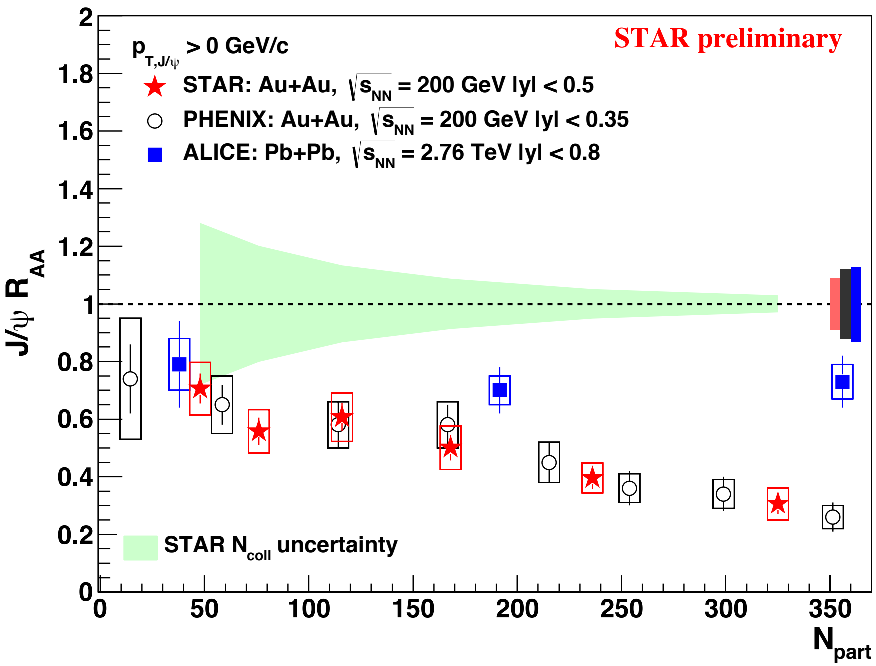


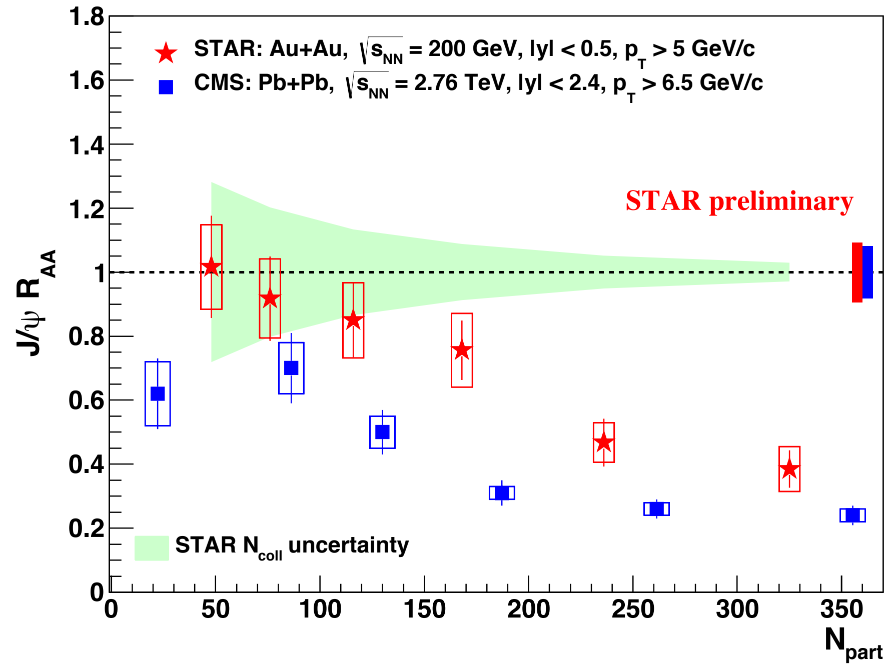
Di-electron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

- Consistent with di-electron channel results over entire p_T for all centralities
- Distinct rising R_{AA} with p_T for 20-40% and 40-60% centrality bins

ALICE: PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

J/ψ R_{AA}



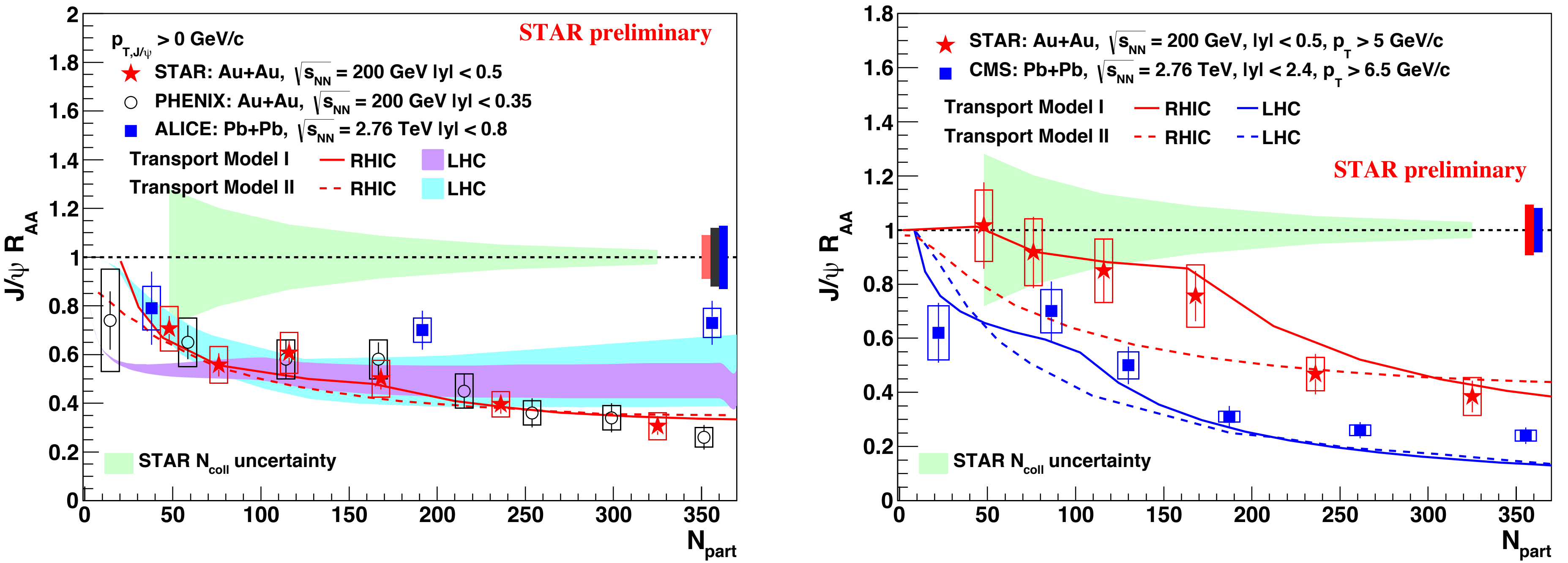


- J/ψ R_{AA} for p_T > 0 GeV/c: Smaller at RHIC than LHC -> more recombination at LHC
- J/ψ R_{AA} for p_T > 5 GeV/c: Larger at RHIC than LHC -> stronger dissociation at LHC

ALICE: PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

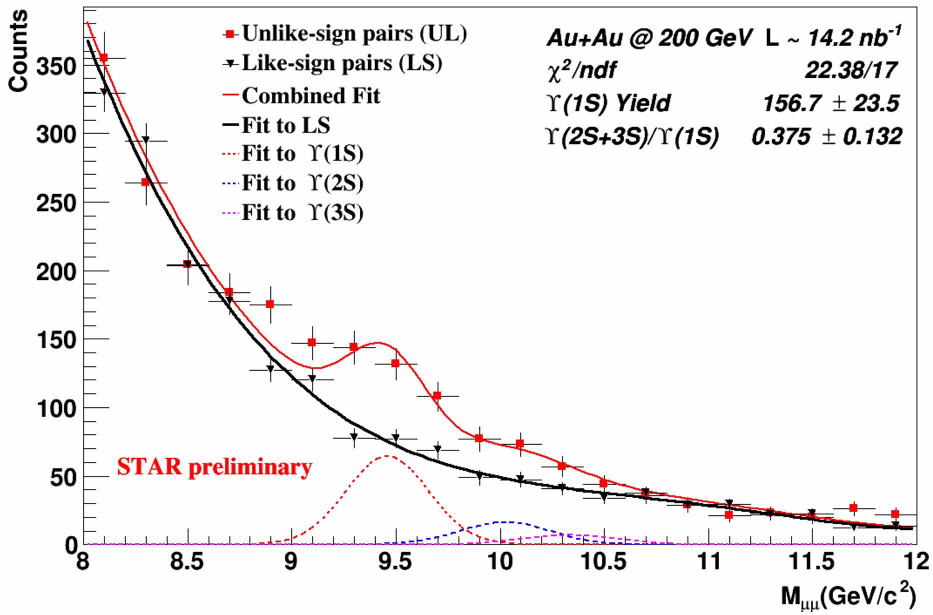
J/ψ R_{AA}

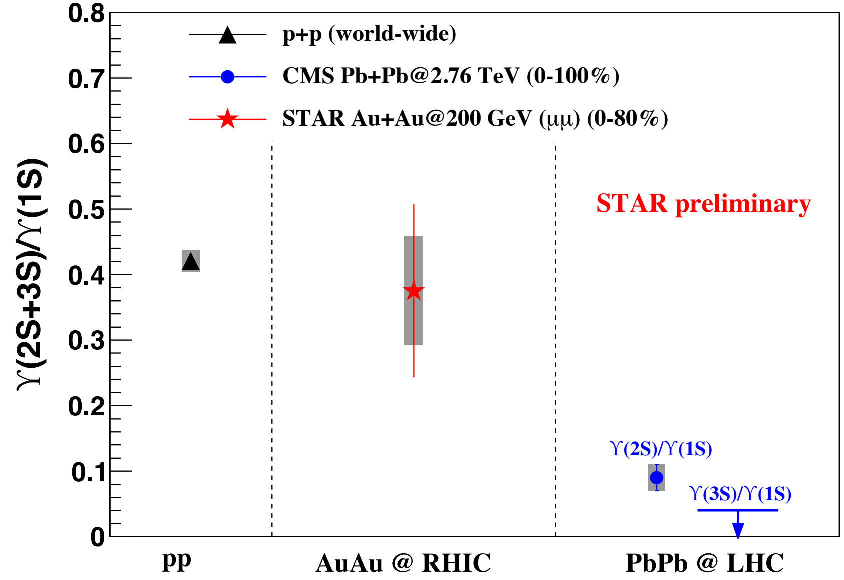
Transport models:
Model I at RHIC: PLB 678 (2009) 27
Model I at LHC: PRC89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114



- J/ψ R_{AA} for $p_T > 0$ GeV/c: Smaller at RHIC than LHC -> more recombination at LHC
- J/ψ R_{AA} for $p_T > 5$ GeV/c: Larger at RHIC than LHC -> stronger dissociation at LHC
- Transport models with both regeneration and dissociation can qualitatively describe the data

Υ States



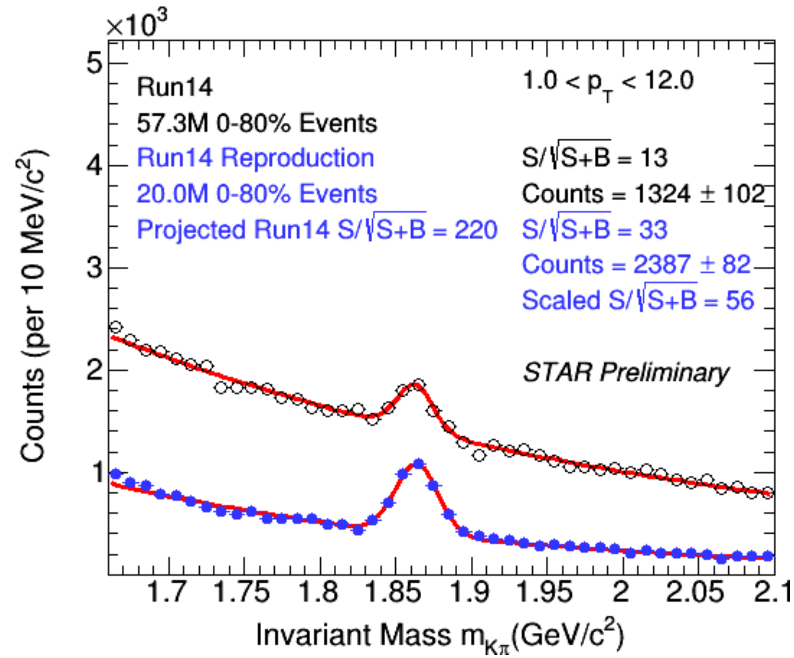


- $b\bar{b}$ production cross-section is small -> Υ is a cleaner probe for color screening
- Different states should dissociate at different temperatures
- Reconstructed signal from excited Υ (2S+3S) states
  - Challenging in di-electron channel due to Bremsstrahlung
- Hint of less Υ (2S+3S) melting at RHIC than LHC

World-wide: PRC 88 (2013) 067901
CMS: PRL 109 (2012) 222301
CMS: JHEP 04 (2014) 103

Outlook

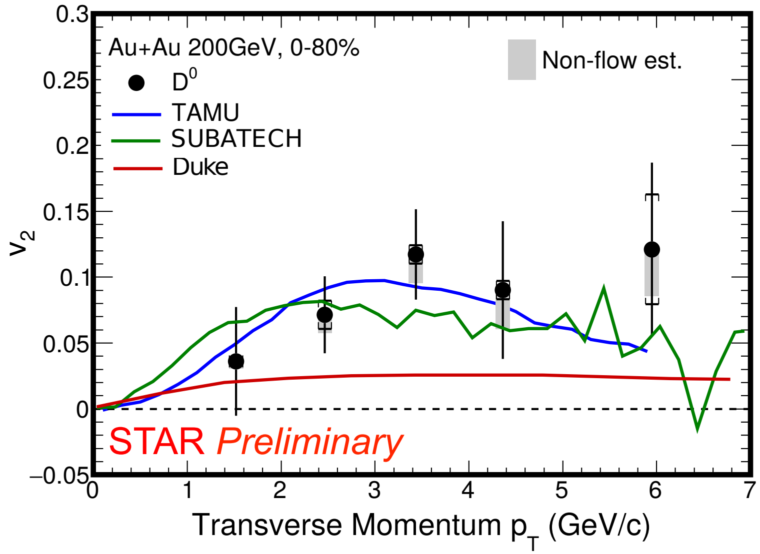
- Improved HFT tracking efficiency after PXL decoding issue has been discovered and resolved -> Factor 2-4 improvement in D^0 significance
- Preliminary results are consistent with the results obtained with the available re-processed sample
- Run 16:
  - Full aluminum cables for inner layer of PXL: Factor 2 -3 further improvement for D^0 significance @ 1 GeV/c
  - Equivalent MTD data collected
  - Precision heavy flavor measurements

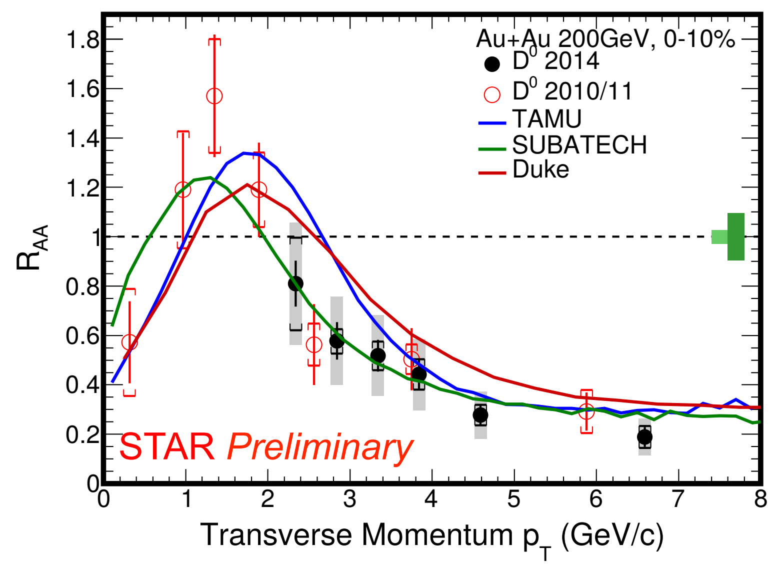


Year	System	MTD di-muon sampled luminosity	Events HFT
Run 14:			
	Au+Au	14.3 nb^{-1}	1.2 B
Run 15:			
	p+p	122.1 pb^{-1}	1 B
	p+Au	0.41 pb^{-1}	0.6 B
Run 16:			
	Au+Au	12.8 nb^{-1}	~2.0 B
	d+Au		~0.3 B

Summary

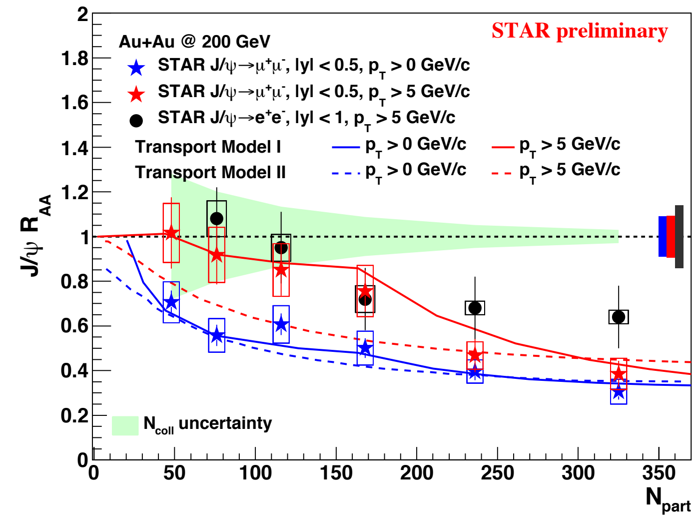
- STAR HFT and MTD deliver first set of preliminary heavy flavor results with Run14 dataset
- Open heavy flavor with HFT:
  - First implementation of MAPS vertex detector in a collider experiment
  - Charm quarks interact strongly with the QGP medium
  - Charm quarks flow with the medium, although results suggest they are not fully thermalized

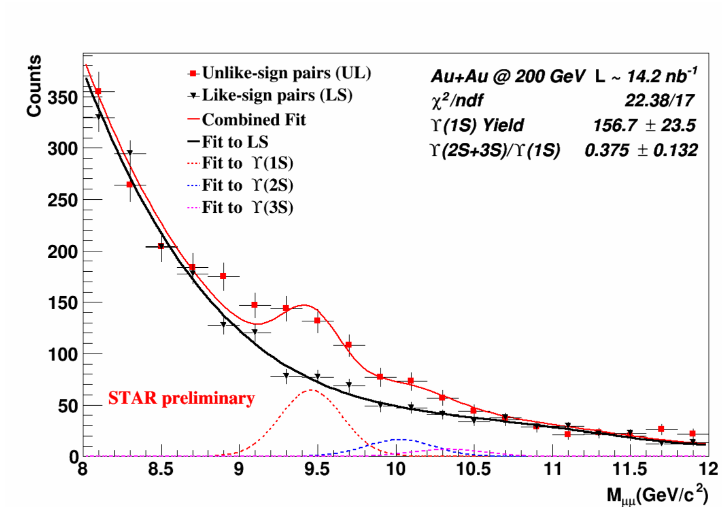




Summary

- Quarkonium measurements with MTD:
  - J/ψ R_{AA} obtained in dimuon channel consistent with di-electron results
  - Distinct rising R_{AA} with p_T for 20-60%
  - At high p_T, R_{AA} < 1 → dissociation in effect
- Outlook:
  - More exciting results to come. New HFT reconstruction software will increase D^0 significance efficiency by a factor of 2-4
  - Factor 4(2) AuAu data on tape for HFT(MTD) for open heavy flavor (D_s, Λ_c, B, …) and quarkonia (J/ψ and Υ) from Run14+16 datasets

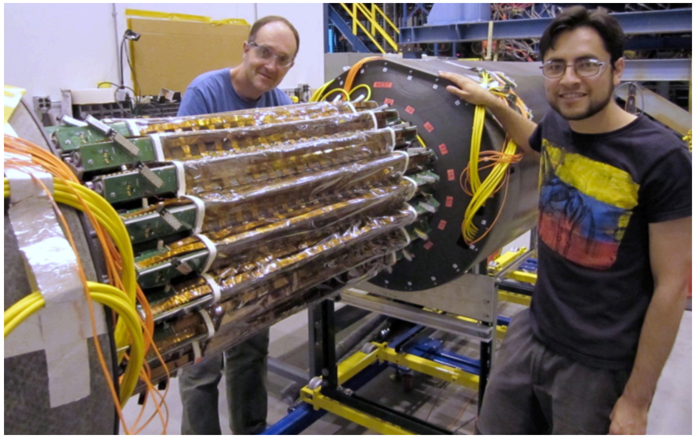




Thank you!

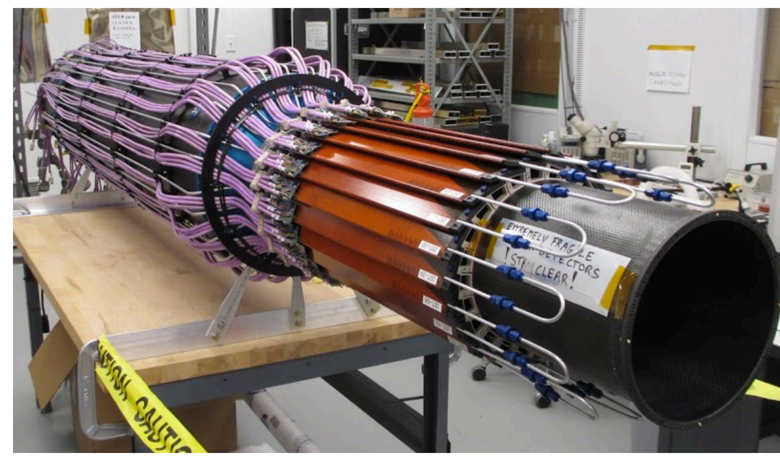
Back ups

HFT Subsystems



Silicon Strip Detector (SSD)
- Double sided silicon strip modules with 95 µm pitch
- Existing detector with new faster electronics
- Radius: 22 cm – Length: ~106 cm

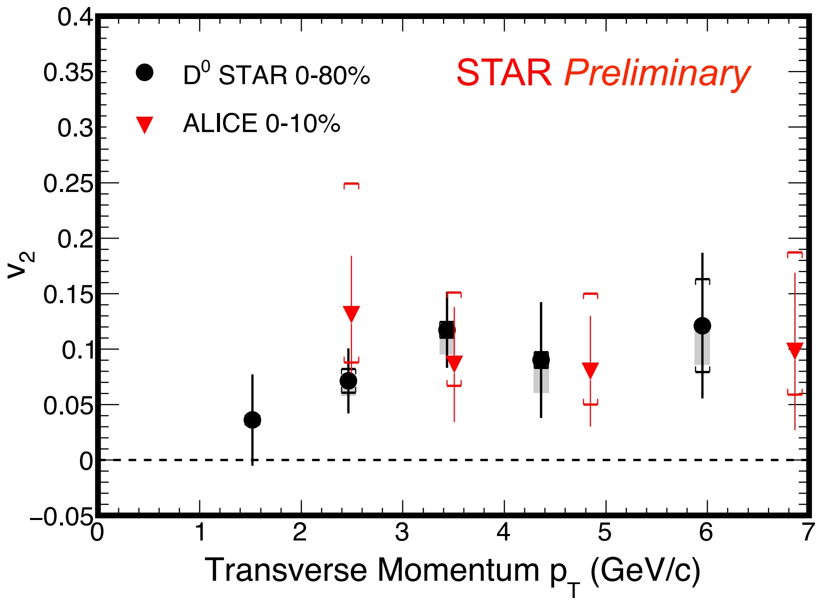
Intermediate Silicon Tracker (IST)
- Single sided double-metal silicon pad with 600 µm x 6 mm pitch
- Radius: 14 cm – Length: ~50 cm

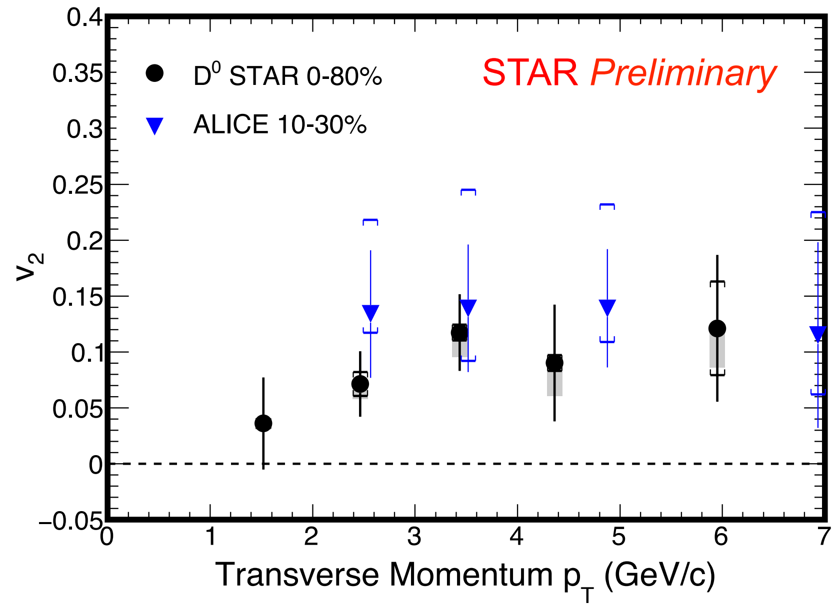


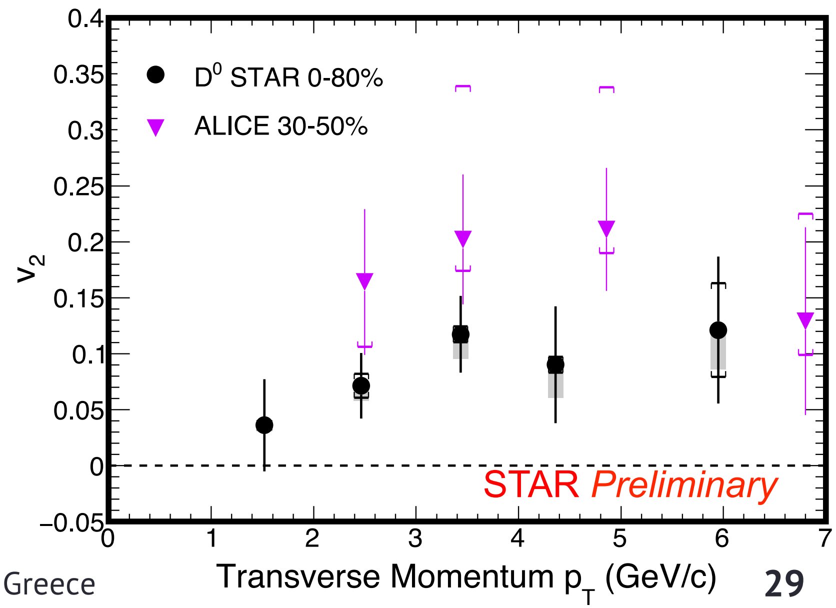
PiXeL detector (PXL)
- *Monolithic Active Pixel Sensor* technology
- 20.7 µm pitch pixels
- Radius: 2.8 and 8 cm – Length: ~20 cm

First MAPS-based vertex detector at a collider experiment

Comparison to ALICE

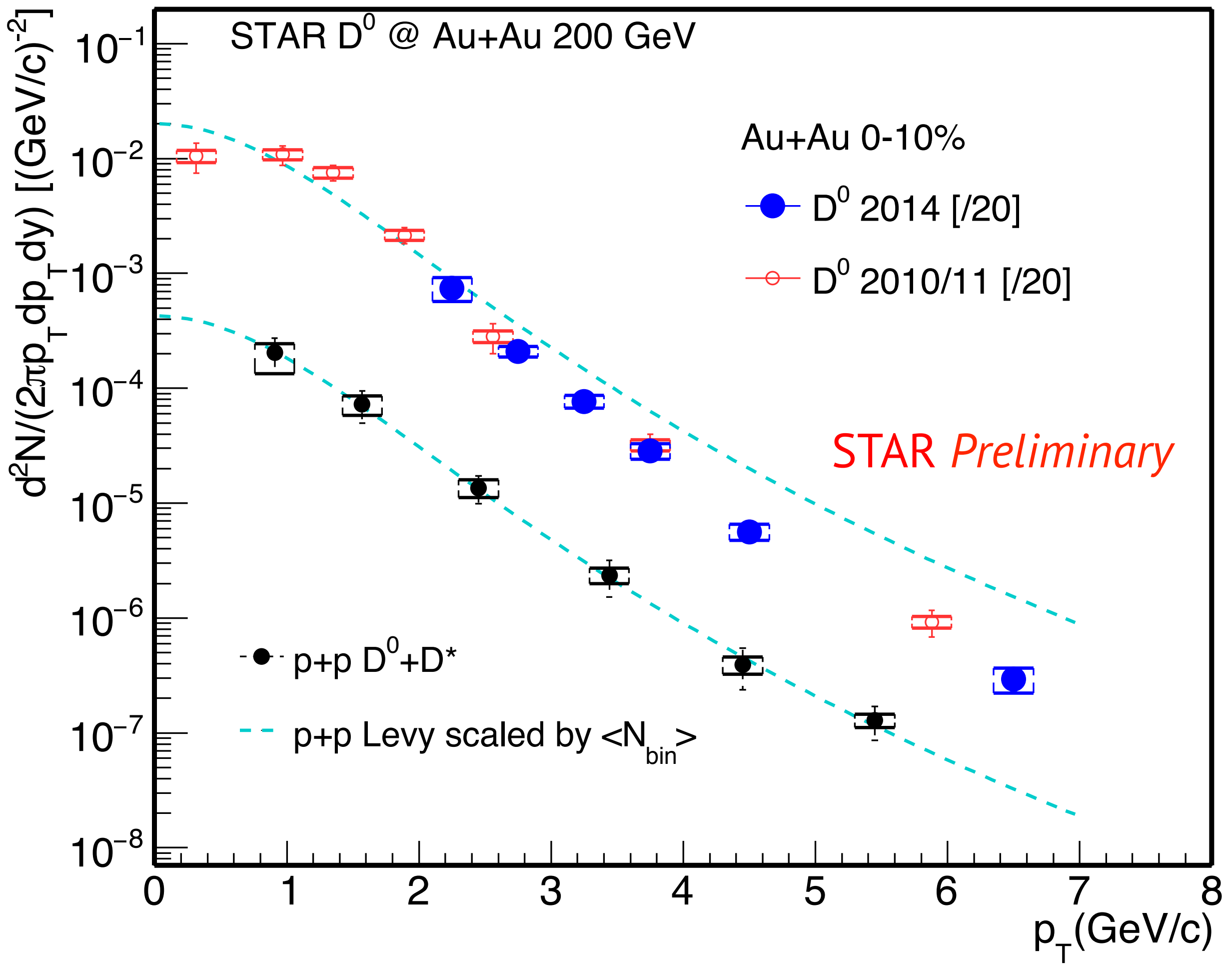






Invariant yields

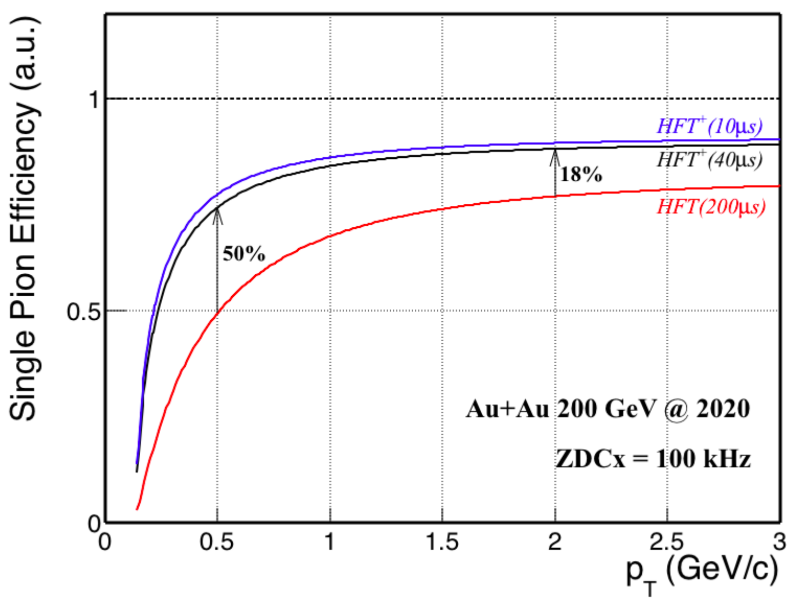
STAR: PRL 113 (2014) 142301



- [High p_T] Consistent with published result, with improved statistical precision
  - Finalizing systematic uncertainties for p_T< 2 GeV/c and in peripheral collisions

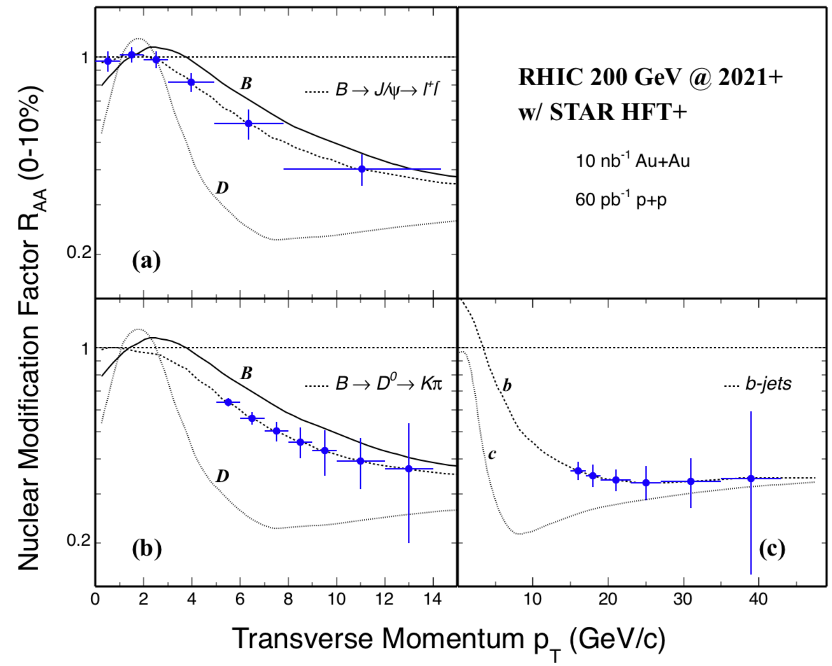
HFT+ simulation

Efficiency: fast vs. slow HFT



- HFT (~200 μs) → HFT+ (≲40 μs)

HFT+ flagship measurements



- R_{AA} for *J/ψ* and *D^0* from *B*, and *b-jets*

- The planned HFT+ program (2021-2022) is complementary to sPHENIX at RHIC and ALICE HF program at LHC

Future HFT+ Upgrade plan (2021-2022)

HFT+ upgrade motivation:

- Measure **bottom quark hadrons** at the RHIC energy
- Take data in **higher luminosity** with high efficiency

HFT+ detector requirements:

- **Faster** frame readout of 40 μs or less
- **Similar or better**: pointing resolution
  S/N ratio
  Total power consumption
  Radiation length

→ **ALICE ITS Upgrade** MAPS sensor

- **Compatible** with the existing insertion mechanism, support structure, air cooling system

→ **STAR HFT** mechanics and services

HFT+ read-out electronics requirements:

- **Compatible** with STAR DAQ system and trigger

→ **STAR + ALICE** new development