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Heavy flavor measurements at the STAR experiment

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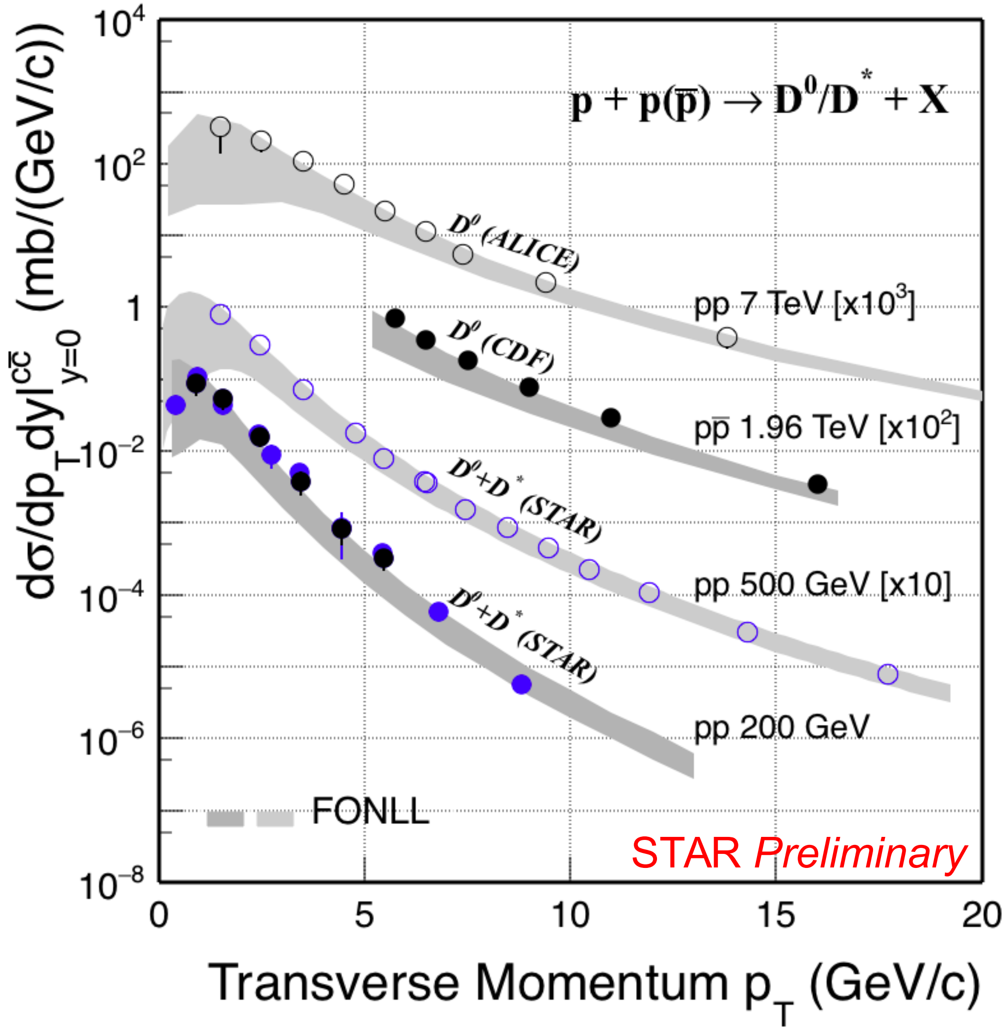
Outline

- Physics motivation
- STAR with Heavy Flavor Tracker and Muon Telescope Detector
- Open heavy flavor measurements
- Quarkonium measurements
- Outlook
- Summary

Open heavy flavor in the QGP

Heavy quarks (c, b):

- Produced early in heavy-ion collisions at RHIC in initial hard scattering → exposed to the entire evolution of the hot nuclear matter → used as a probe to study properties of the QGP medium
- Compare with light hadrons to disentangle energy loss mechanisms: radiative vs. collisional
- Compare yields of different charm hadrons to study the hadronization process



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

Quarkonia in the QGP

- Compare A+A with p+p collisions:
  study dissociation due to color screening, regeneration from uncorrelated quarks and cold nuclear matter (CNM) effects

- Charmonia:
  J/ψ, ψ', χ_C
- Bottomonia:
  $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B

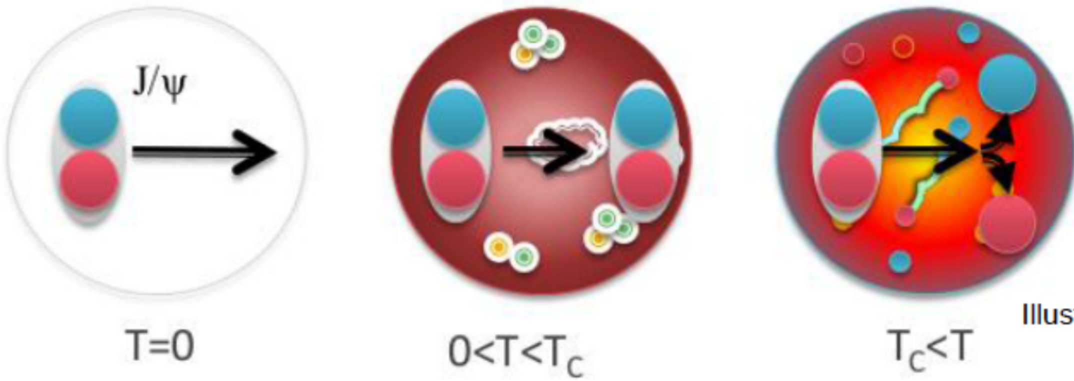


Illustration: A.Rothkopf

- Sequential melting:
  different states dissociate at different temperatures – QGP thermometer

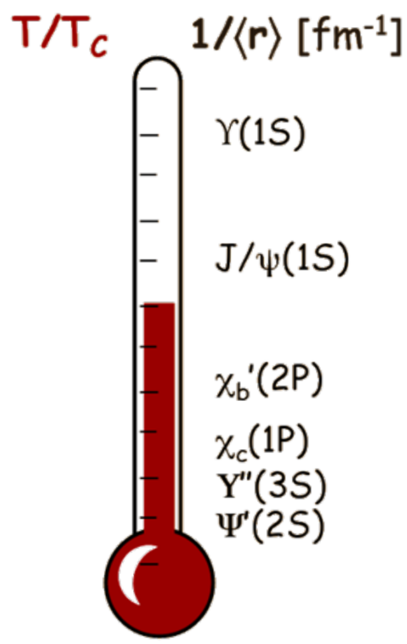
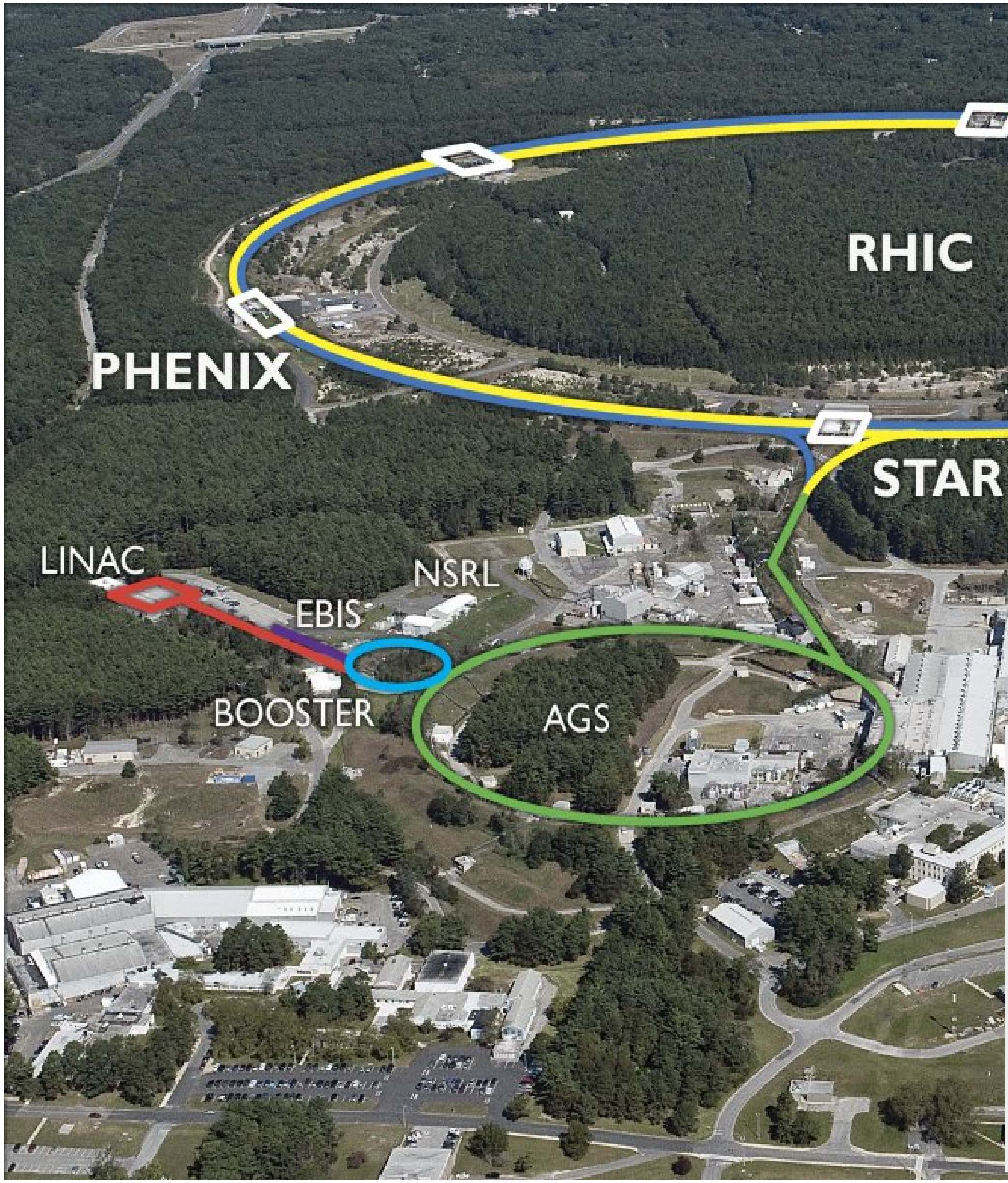


Illustration: A. Mocsy, EPJC61 (2009) 705

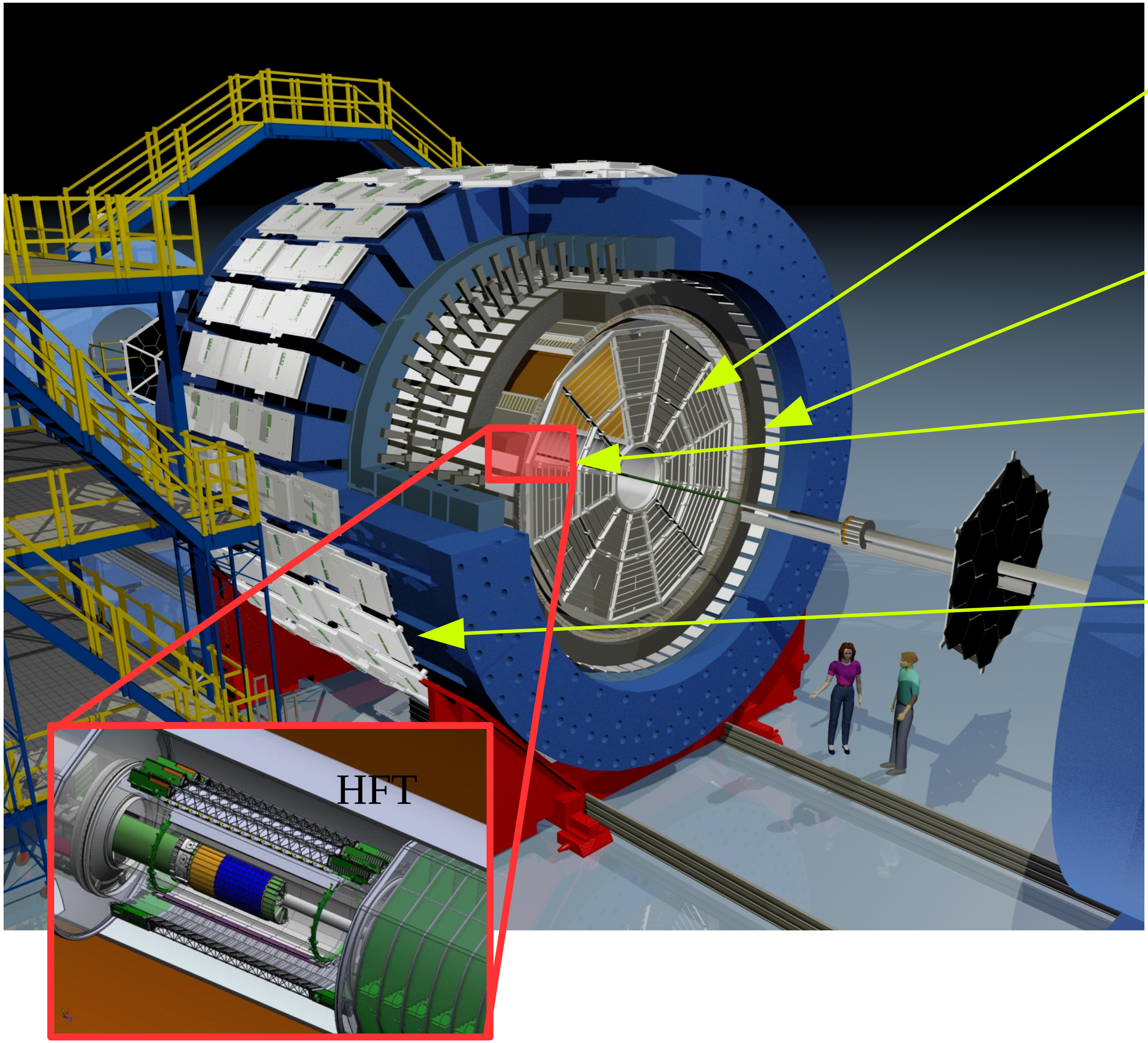
RHIC



Collsions at RHIC:

- polarized proton+proton up to $\sqrt{s}$ = 510 GeV
- A+A (Al, Cu, Au, U) up to $\sqrt{s_{NN}}$ = 200 GeV
- asymmetric: p+Au, p+Al, d+Au, Cu+Au
- fixed target

The Solenoidal Tracker At RHIC (STAR) detector



Time Projection Chamber (TPC):
- tracking
- particle identification via dE/dx

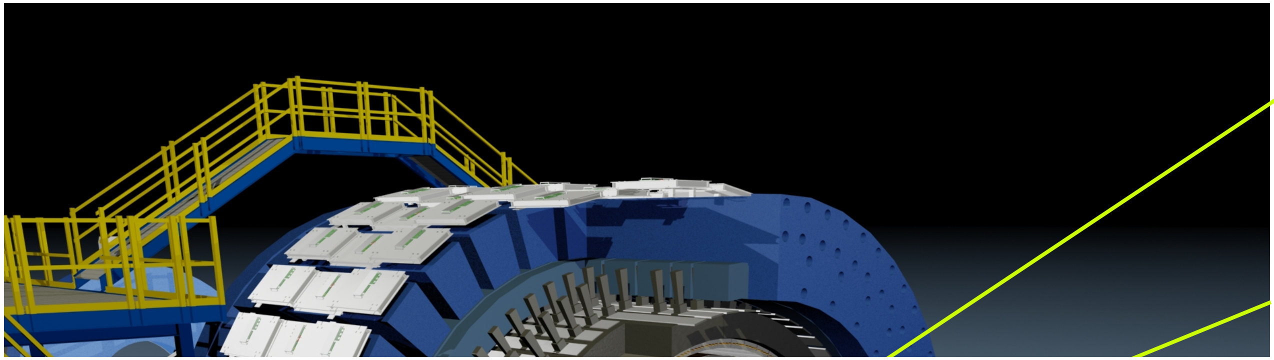
Time Of Flight (TOF):
- particle identification via $1/\beta$

Heavy Flavor Tracker (HFT):
- tracking
- secondary vertex

Muon Telescope Detector (MTD):
- triggering
- muon identification

TPC/TOF/HFT: full azimuthal coverage at mid-rapidity ($|\eta|<1$)

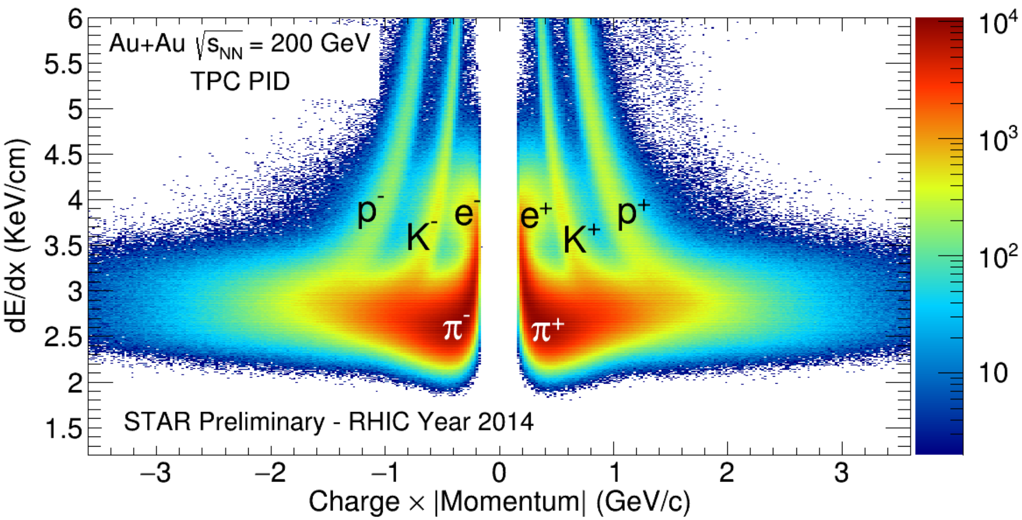
The Solenoidal Tracker At RHIC (STAR) detector

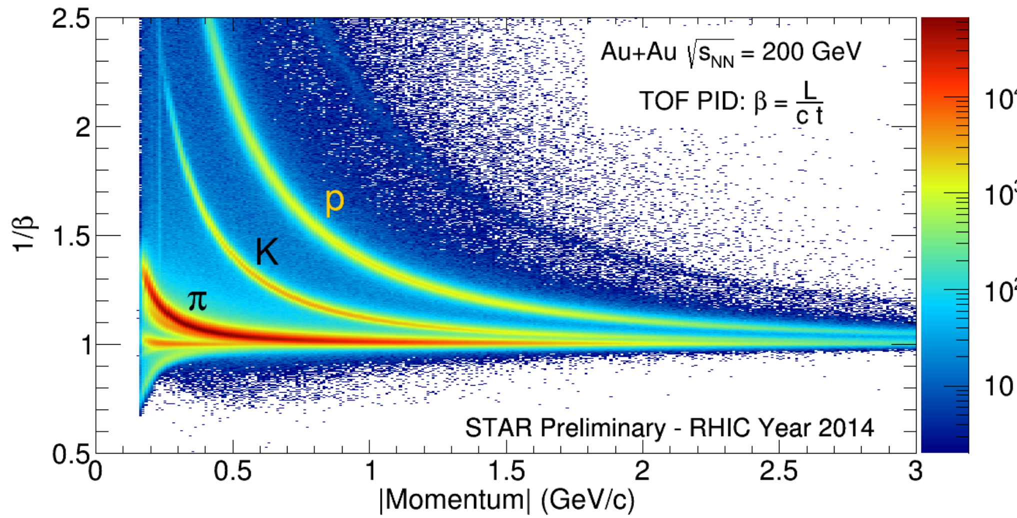


Time Projection Chamber (TPC):
- tracking
- particle identification via dE/dx

Time Of Flight (TOF):
- particle identification via 1/β

Excellent identification of long-lived hadrons and electrons in TPC and TOF

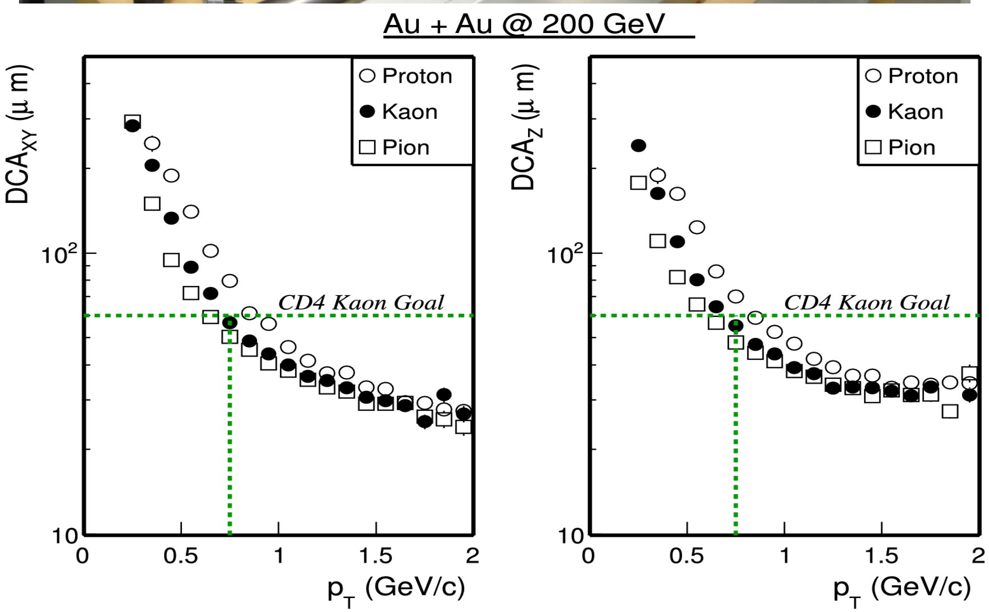


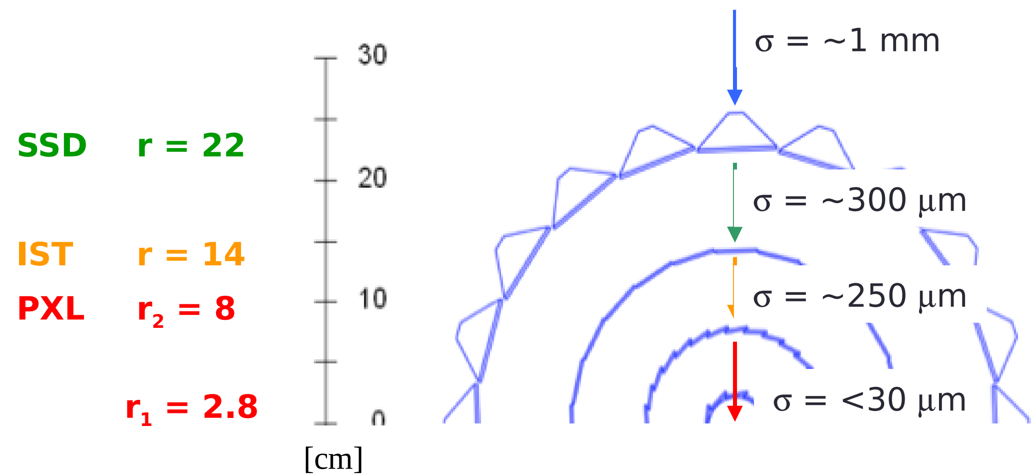


STAR with Heavy Flavor Tracker

Heavy Flavor Tracker (HFT):

- SSD – Silicon Strip Detector
- IST – Intermediate Silicon Tracker
- PXL – Pixel Detector (MAPS, 356M pixels of silicon, 20x20 μm^2, 0.4% X_0, air-cooled)





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

Kaon track pointing resolution exceeds the requirement < 55 μm at $p_T = 750$ MeV/c

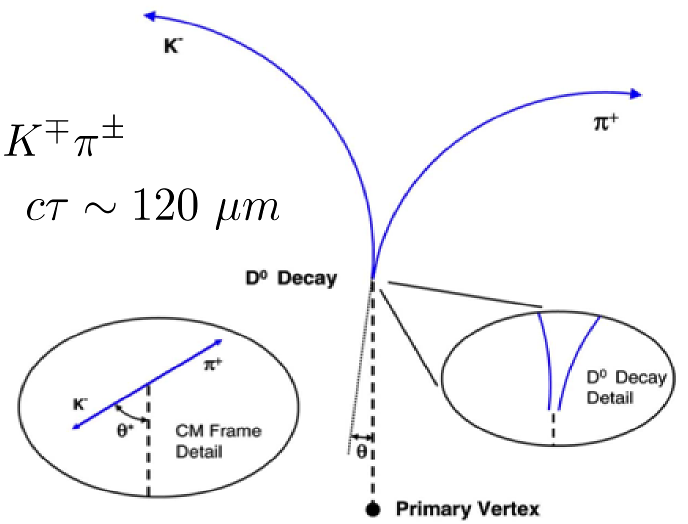
Pointing resolution with Al-cables ~ 45 μm

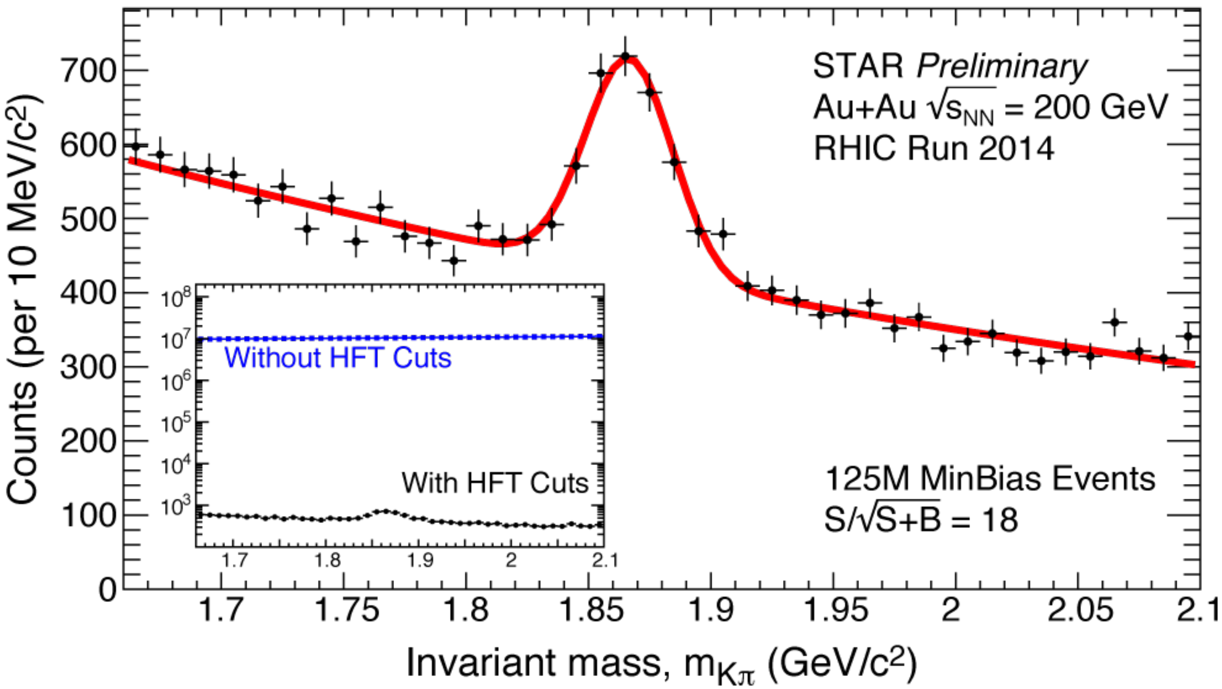
Topological reconstruction with HFT

- Secondary vertex reconstruction with HFT → full kinematic reconstruction of charmed hadron
- Combinatorial background suppressed by 4 orders of magnitude
- Highly improved signal-to-background ratio

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

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



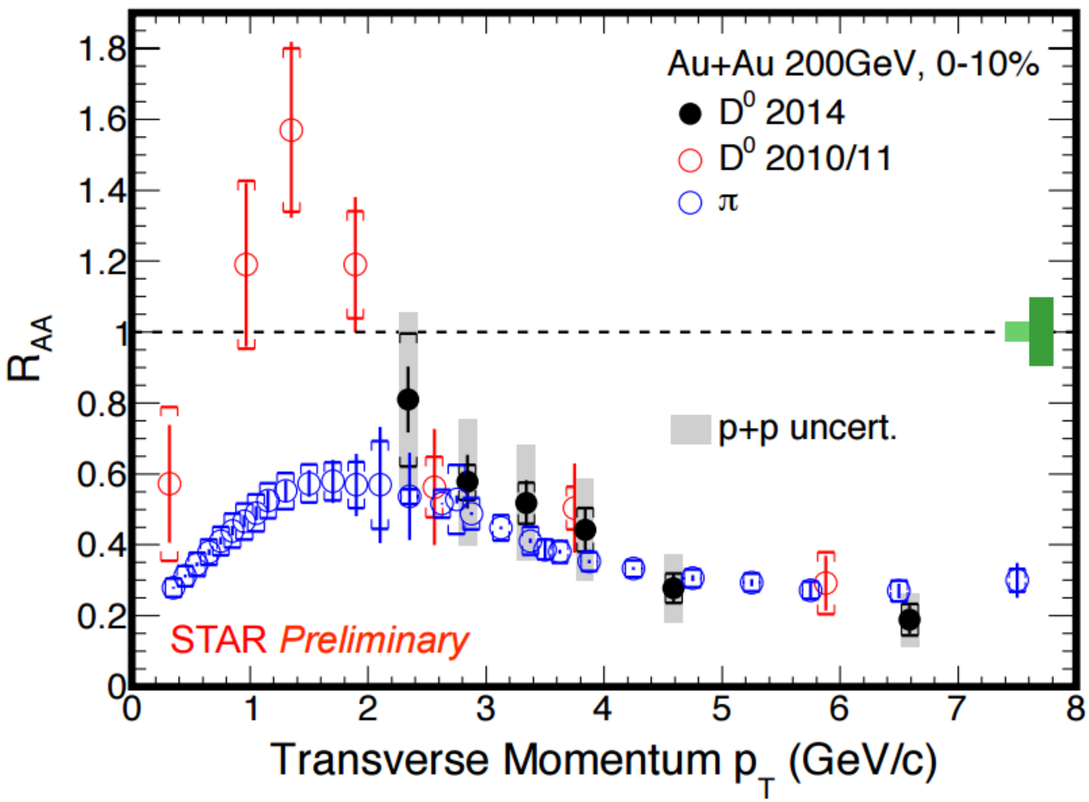


	w/o HFT	with HFT
year	2010+2011	2014
Number of events analyzed	1.1G	780M
significance per billion events	13	51

D^0 R_{AA}

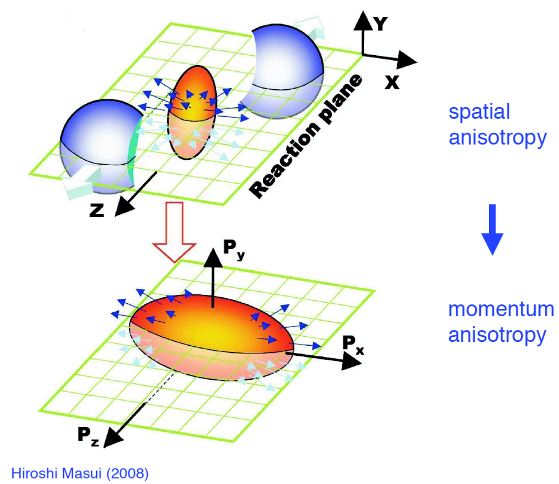
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}$$

- High p_T: significant suppression in central Au+Au collisions → strong charm-medium interaction
- $R_{AA}(D^0) > 1$ at $p_T \sim 1.5$ GeV/c → indication of charm coalescence with bulk
- Similar suppression for light partons and charm quarks at high p_T



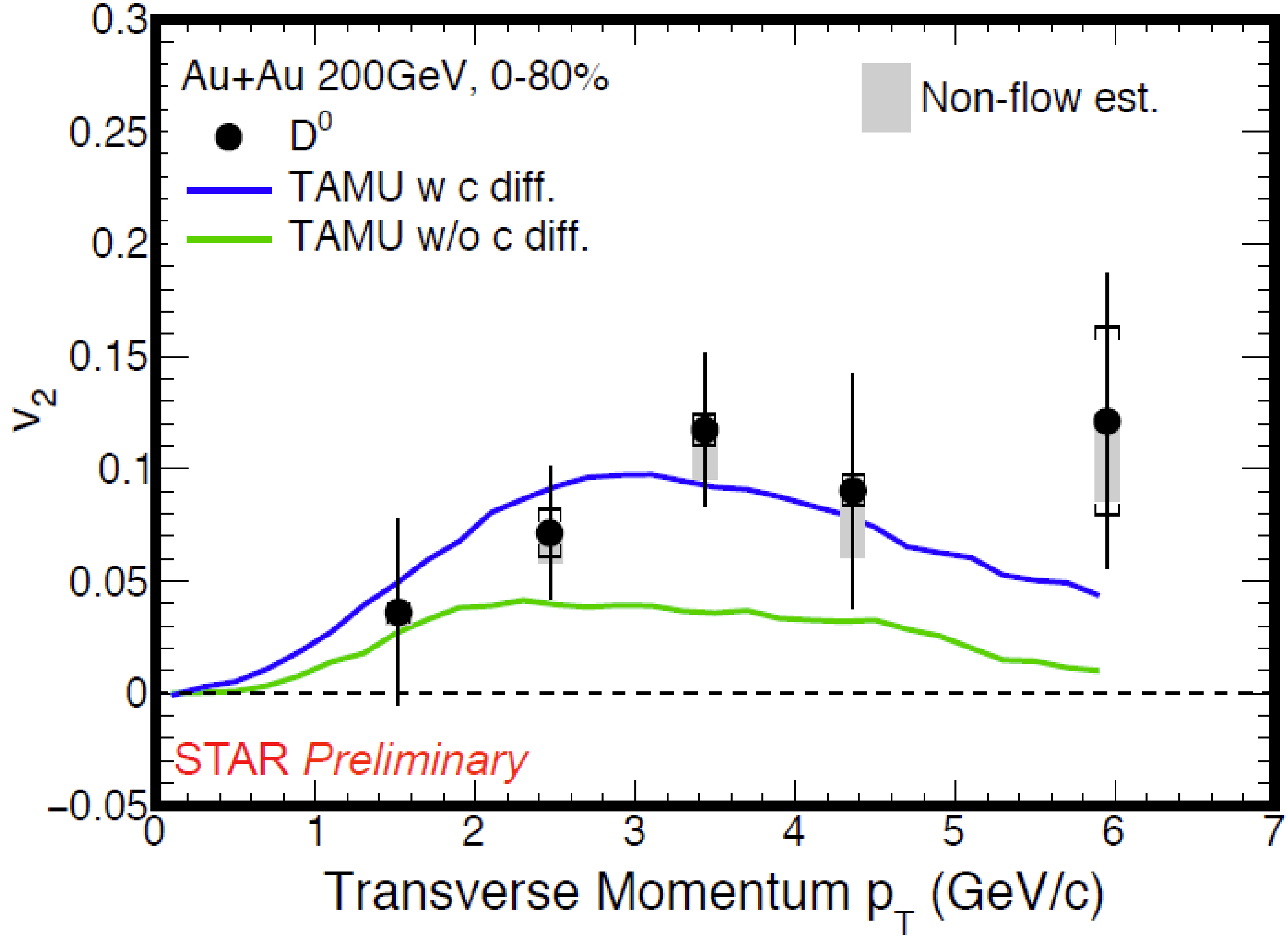
STAR: PRL 113 (2014) 142301
PLB 655 (2007) 104

D^0 v_2



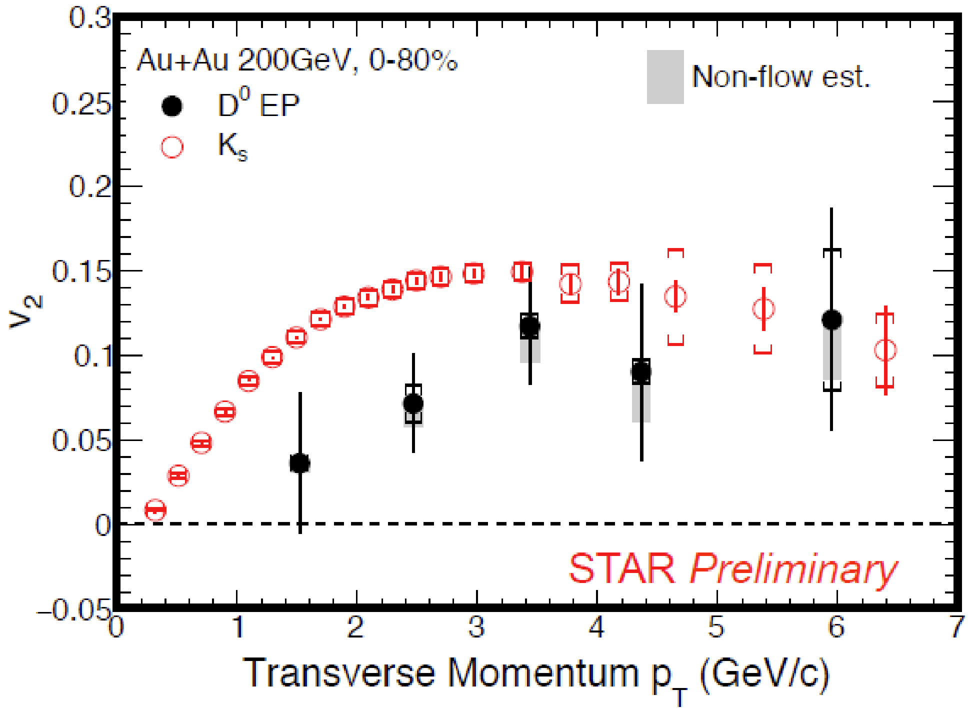
- D^0 azimuthal anisotropy significantly above zero for p_T > 2 GeV/c
- Data favor the model with charm quark diffusion in the medium

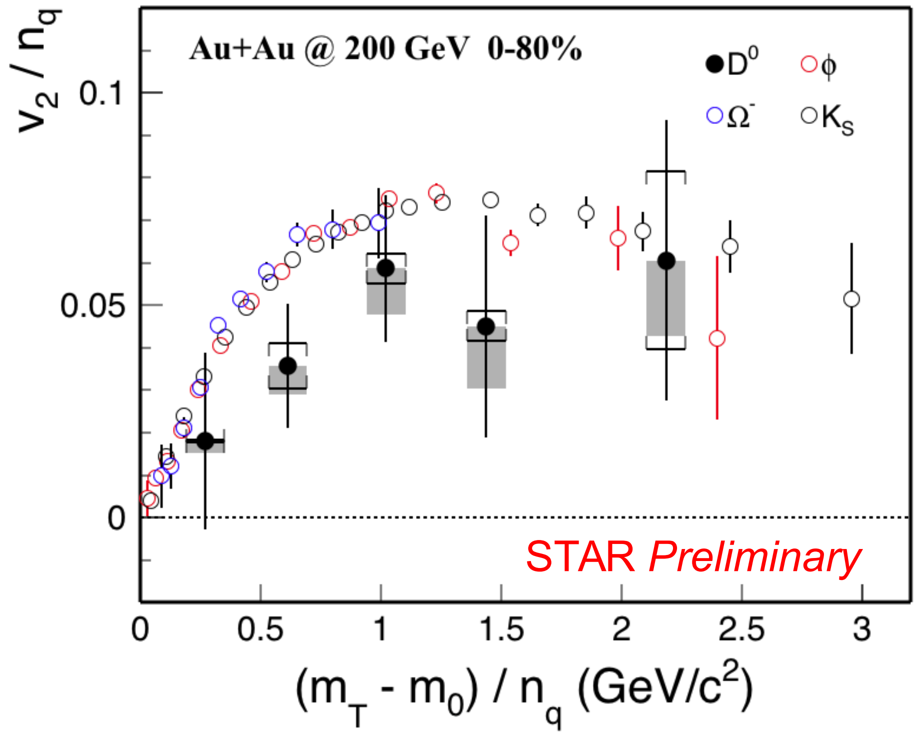
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\psi_r\right)\right)\right)$$



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

D^0 v_2



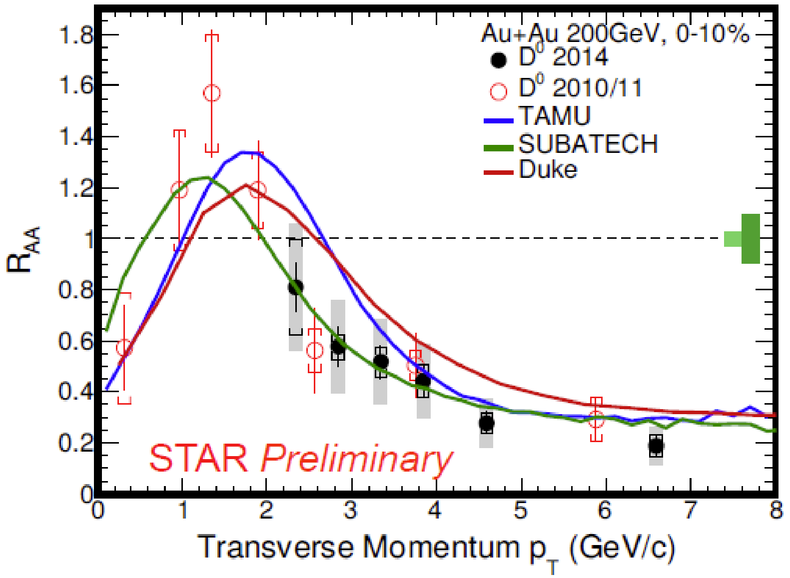


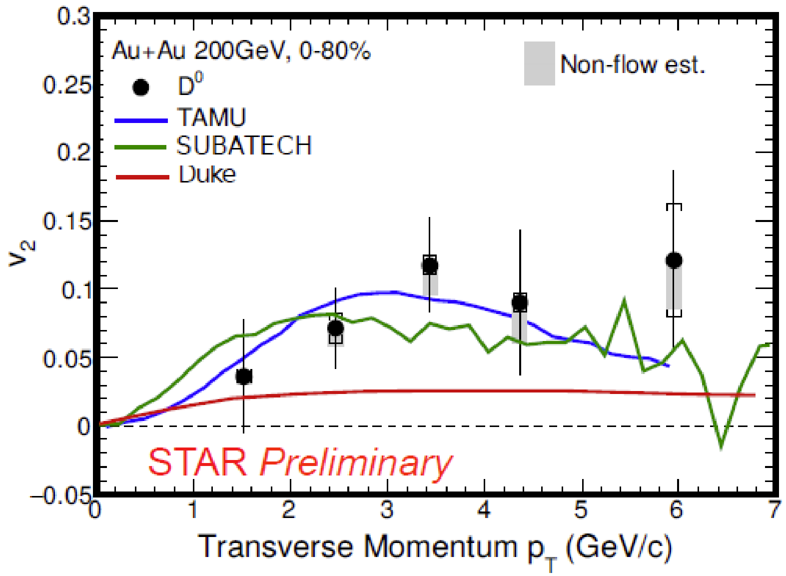
$$m_T = \sqrt{p_T^2 + m_0^2}$$

- Systematically lower than results for light hadrons in 0-80% centrality bin.
- Suggests charm quarks are not fully thermalized with the medium?
  - More statistics will enable a comparison in finer centrality bins.

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

Comparison to models





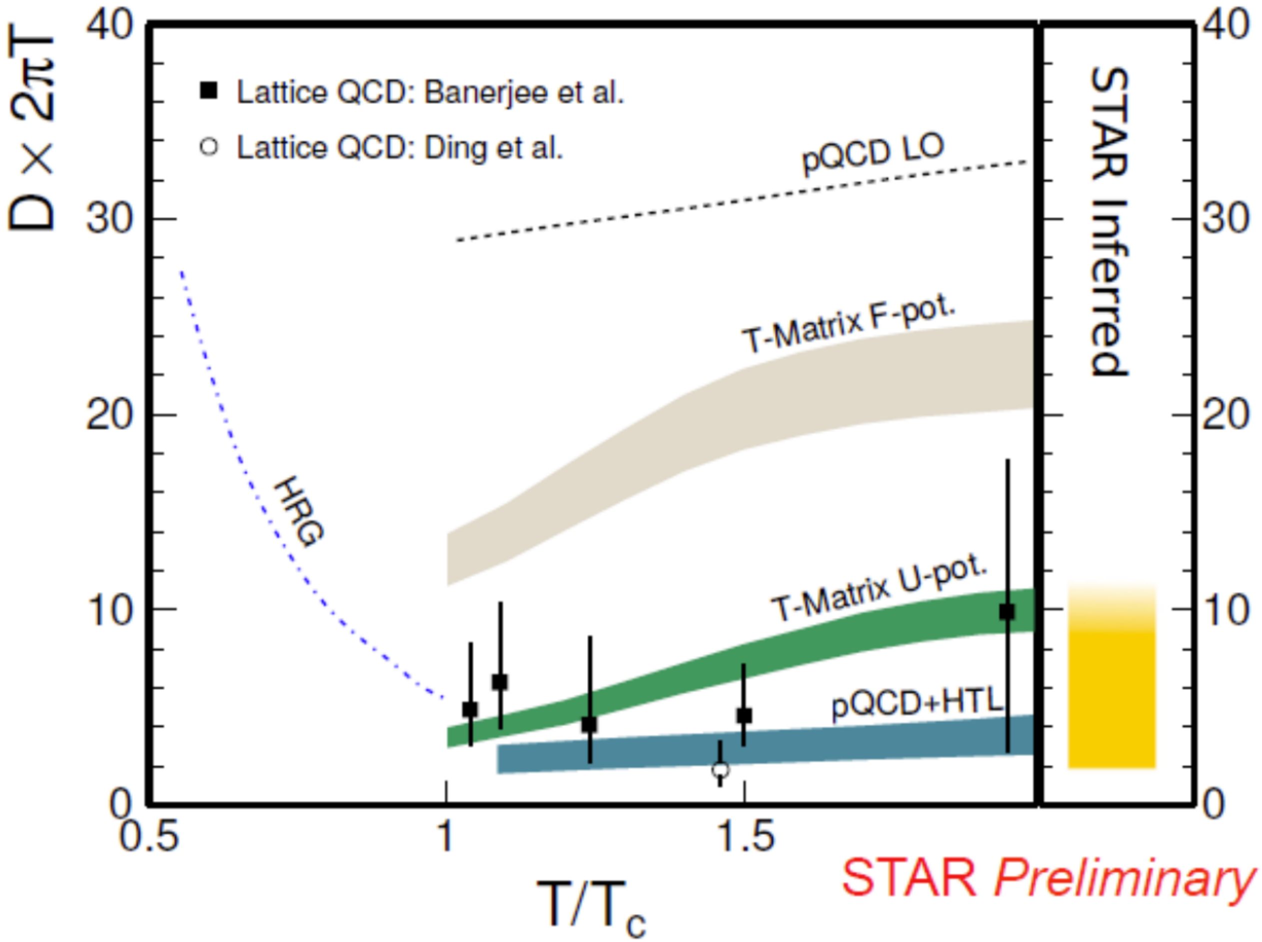
- Models can describe both R_{AA} and v_2
- **TAMU**: non-perturbative T-Matrix approach: $(2\pi T)D = 2$ - ~10
- **SUBATECH**: pQCD + Hard Thermal Loops for resummation: $(2\pi T)D = 2 – 4$
- **DUKE**: Langevin simulation with transport properties tuned to LHC data: $(2\pi T)D = 7$

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

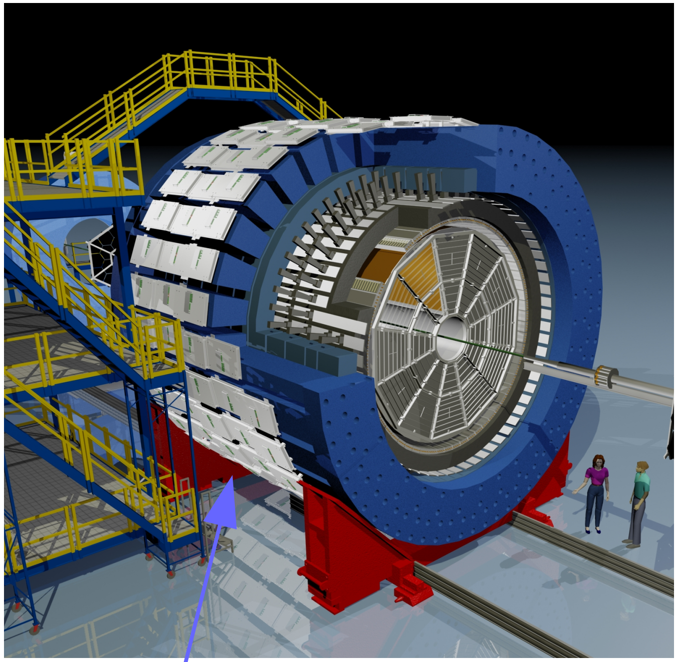
Diffusion coefficient (2πT)D

- The diffusion coefficient extracted from models as a function of T/T_C and the inferred range $(2\pi T)D = 2$ - ~10 from the STAR data

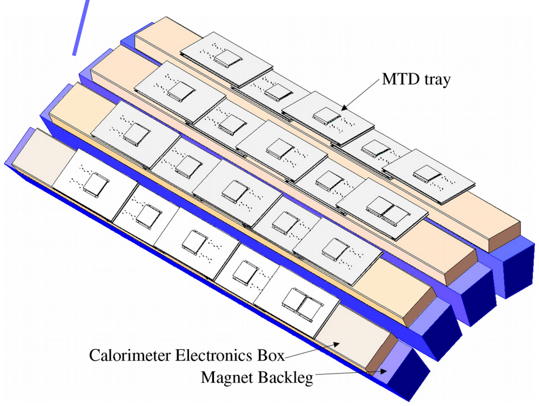
- The extracted values are consistent with the lattice QCD calculation

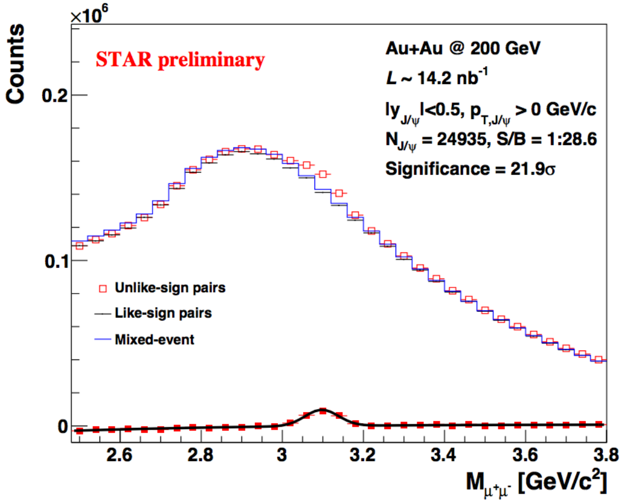


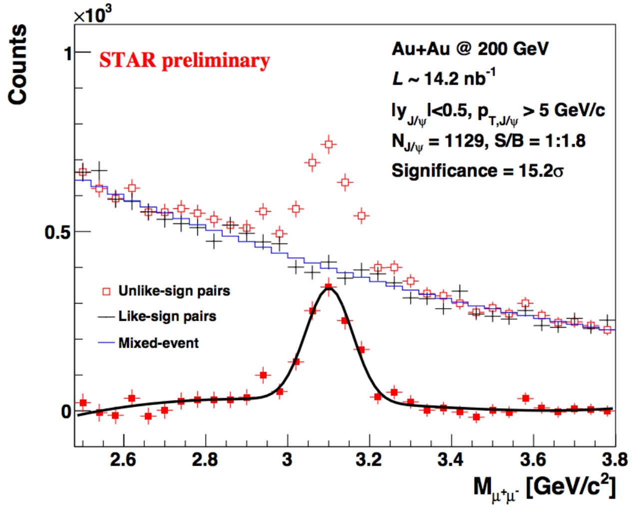
STAR Muon Telescope Detector (MTD)



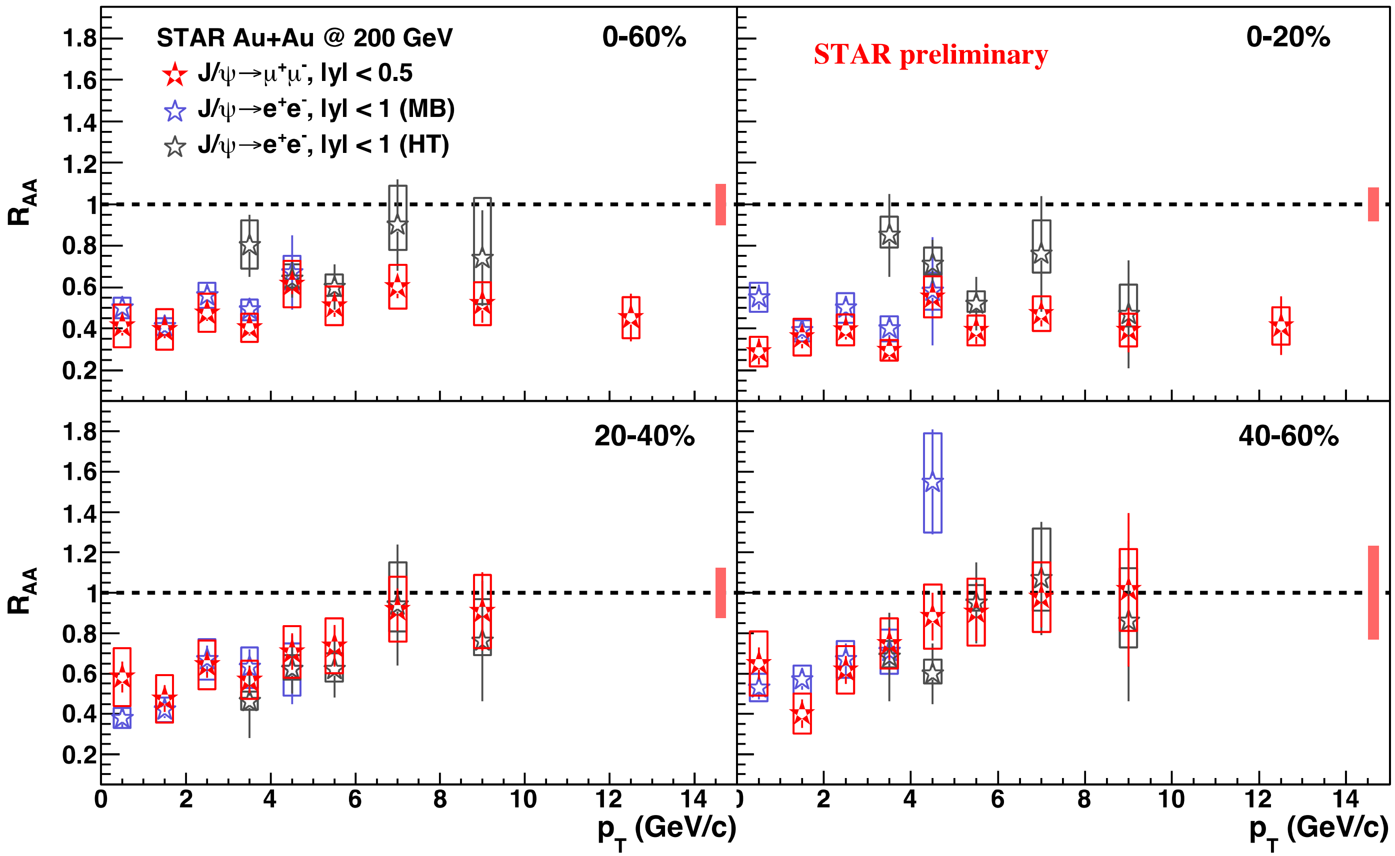
- Designed for muon triggering and identification with precise timing: σ ~ 100 ps for p_T>1.2 GeV/c
- Multi-gap resistive plate chambers (MRPC), similar technology as used for Time of Flight (TOF) detector
- Placed behind magnet, which is used as a hadron absorber
- Geometrical acceptance: 45% in azimuth within |η| < 0.5







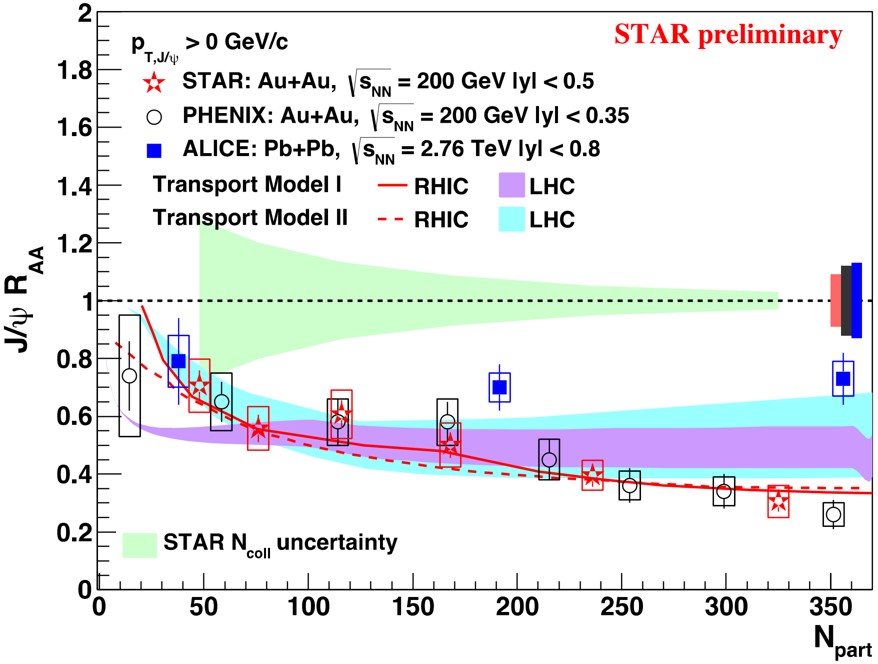
J/ψ R_{AA} in Au+Au collisons

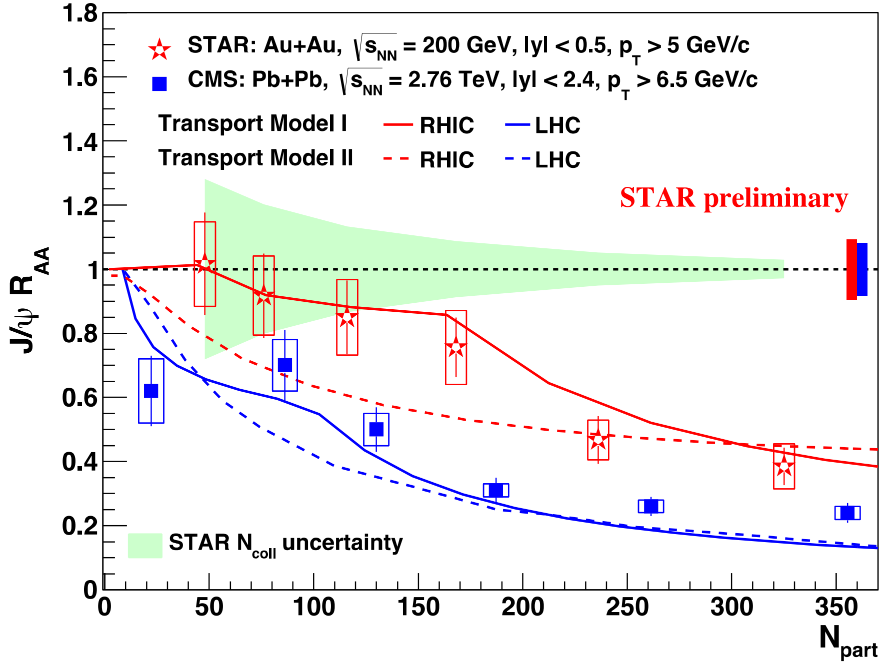


- Consistent with di-electron channel results over entire p_T for all centralities
- Distinct rising R_{AA} with p_T for 20-40% and 40-60% centrality bins

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

J/ψ R_{AA} vs. centrality



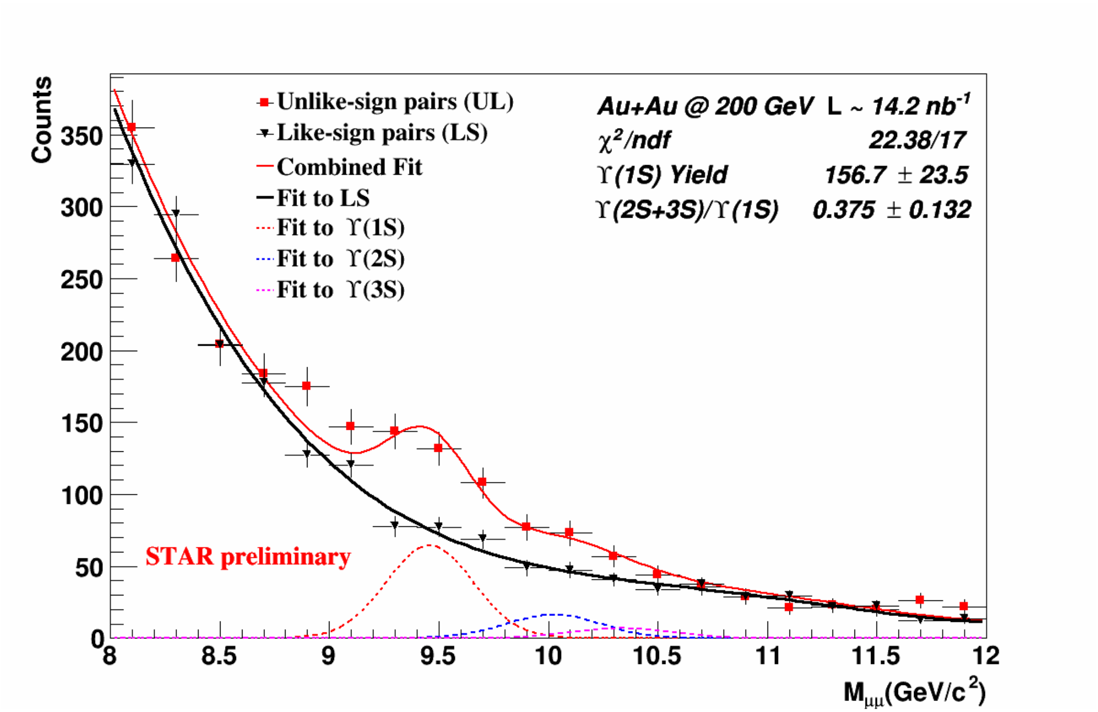


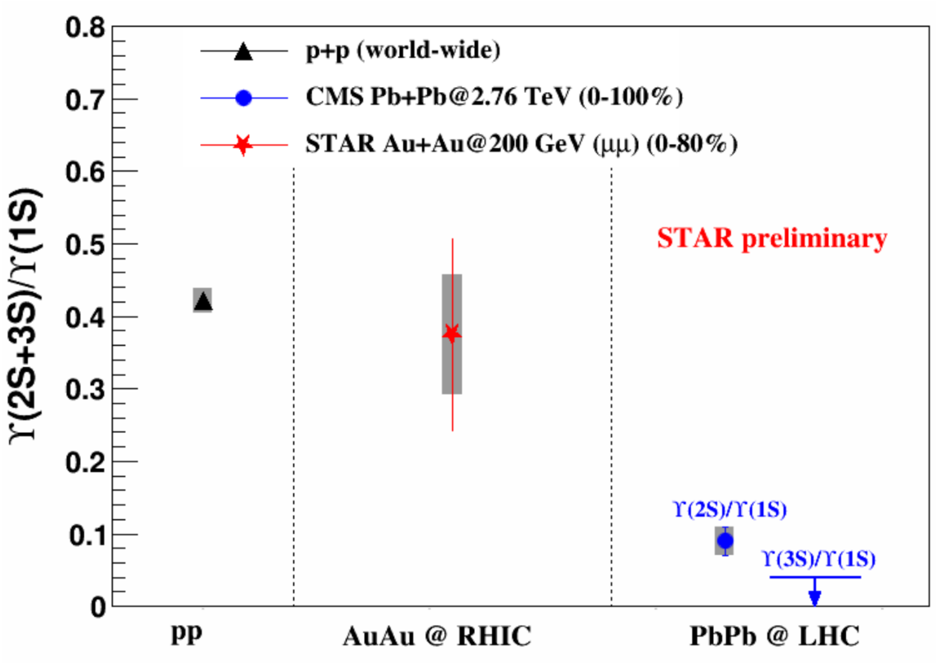
- J/ψ R_{AA} for p_T > 0 GeV/c: smaller at RHIC than LHC → more recombination at LHC
- J/ψ R_{AA} for p_T > 5 GeV/c: larger at RHIC than LHC → stronger dissociation at LHC
- Transport models with both regeneration and dissociation can qualitatively describe the data

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

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

Y analysis with MTD





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

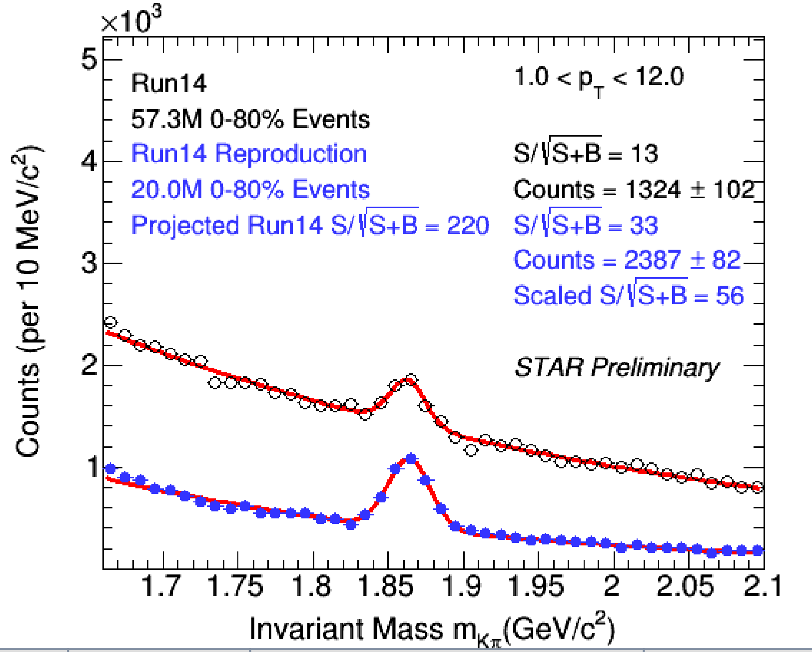
- Sign of excited Y(2S+3S) states from the di-muon channel
    - Challenging in di-electron channel due to Bremsstrahlung
- Hint of less Y(2S+3S) dissociation at RHIC than LHC

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 reprocessed sample

- Run 16:
  - Full aluminum cables for inner layer of PXL: factor 2-3 further improvement for D^0 significance at 1 GeV/c
  - Equivalent MTD data collected as in Run 14
  - Precision heavy flavor measurements



Year	System	MTD di-muon sampled luminosity	HFT MB events
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 heavy flavor results with Run14 dataset

- Open heavy flavor measurements with HFT:
  - First implementation of MAPS technology in a collider experiment
  - Charm quarks interact strongly with the QGP medium
  - Charm quarks flow with the medium

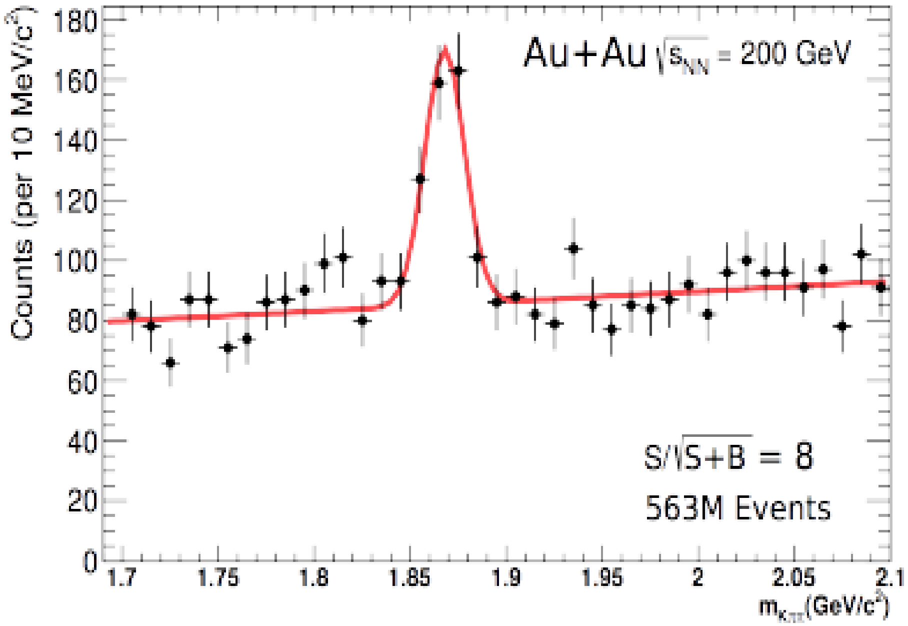
- Quarkonium measurements with MTD:
  - J/ψ R_{AA} obtained in di-muon channel consistent with di-electron results
  - Distinct rising R_{AA} with p_T for 20-60%
  - At high p_T, $R_{AA} < 1 \rightarrow$ dissociation in effect

- Outlook:
  - New HFT reconstruction software will increase D^0 significance by a factor of 2-4
  - More exciting results to come. Factor 4(2) Au+Au data on tape for HFT(MTD) for open heavy flavor (D_s, Λ_c, B, …) and quarkonia (J/ψ and Y) from Run14+16 datasets

Backup

Topological reconstruction with HFT – three body decays

$\mathbf{D^{\pm} \rightarrow K^{\mp} 2\pi^{\pm}}$



$\mathbf{D_s^{\pm} \rightarrow K^+ K^- \pi^{\pm}}$