Open Heavy Flavor Measurements at RHIC with STAR

Santa Fe Jets and Heavy Flavor Workshop, January 11-13, 2016

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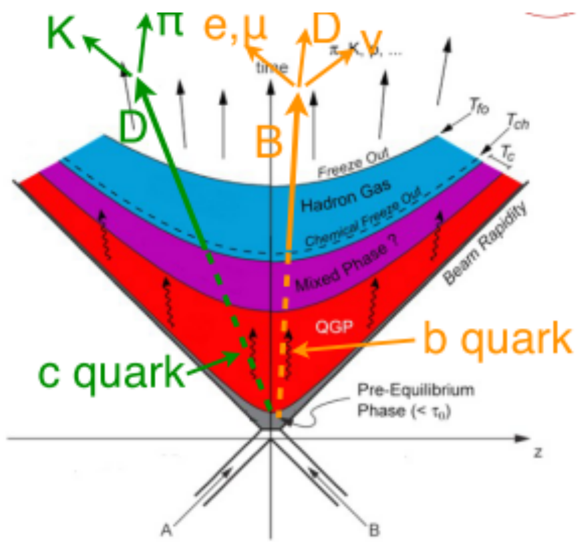
Office of Science
U.S. DEPARTMENT OF ENERGY

HuaZhong Normal University

Heavy Flavor Quarks

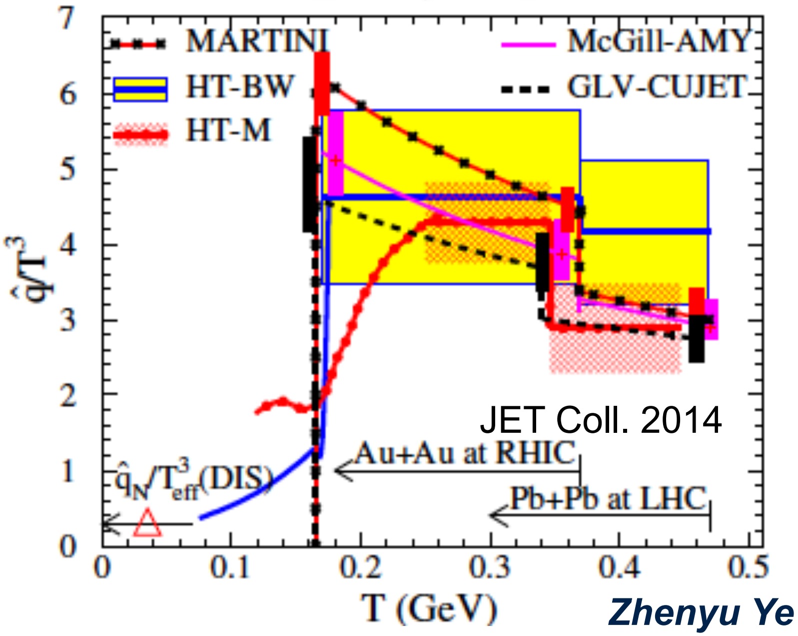
Heavy quark tomography

- produced mostly from initial hard parton scatterings at RHIC energies; exposed to the whole evolution of the QGP
- total yield or mass not (significantly) altered within the QGP



Sensitive to parton-medium interactions and medium properties

- Comparing light, charm and bottom to disentangle radiative vs collisional energy losses
- Extraction of temperature-dependent parton transport properties needs precise experimental data on heavy flavor production from RHIC



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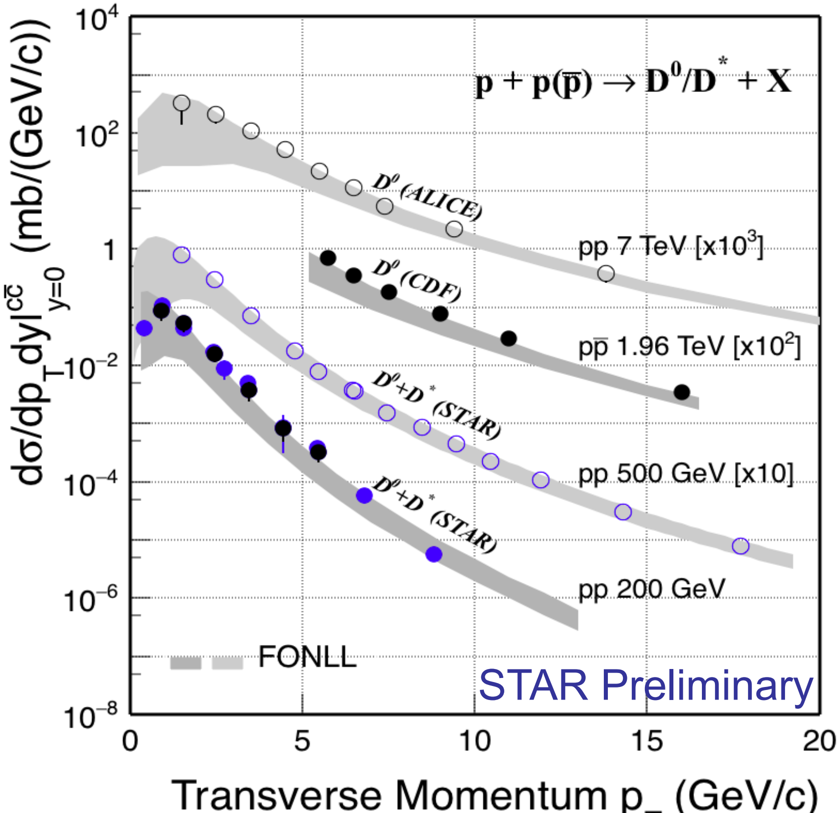
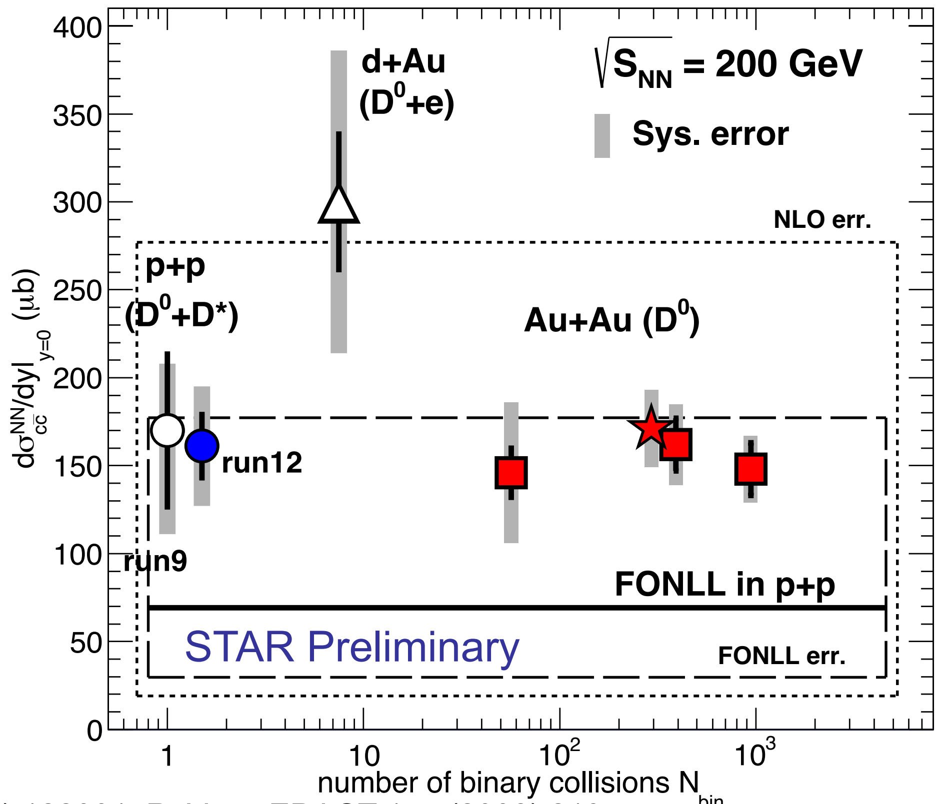
Open Charm Production at RHIC

Heavy flavor quarks can serve as calibrated probes for the QGP at RHIC:

- production in p+p collisions are described by pQCD calculations
- produced mostly in the initial hard scatterings at RHIC energies





Theory: M. Cacciari et al., PRL 95 (2005) 122001, R. Vogt, EPJ ST 155 (2008) 213

Talk on Bottom production by Zach Miller tomorrow

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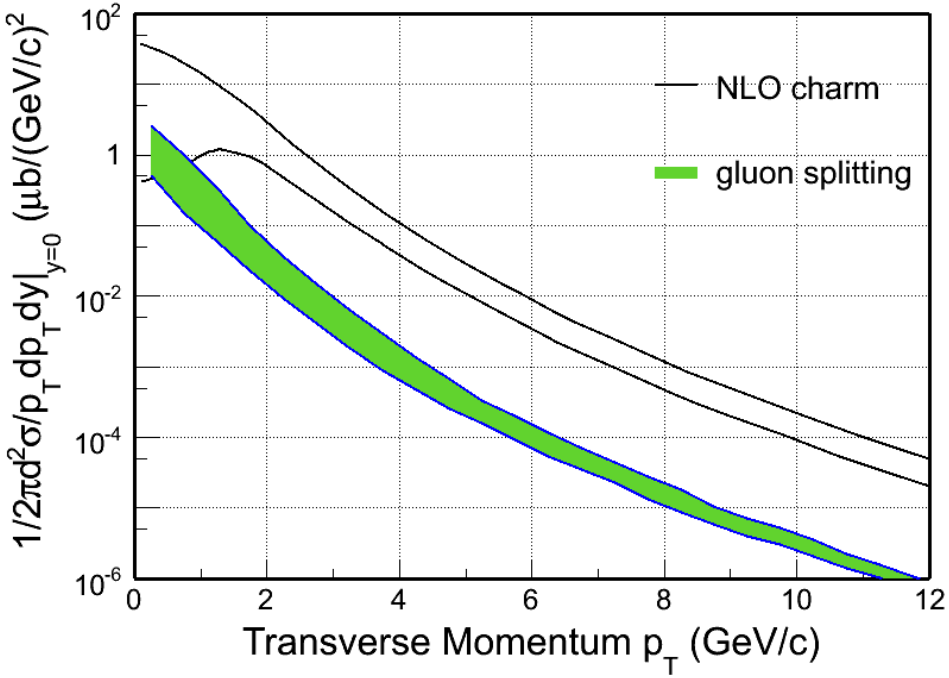
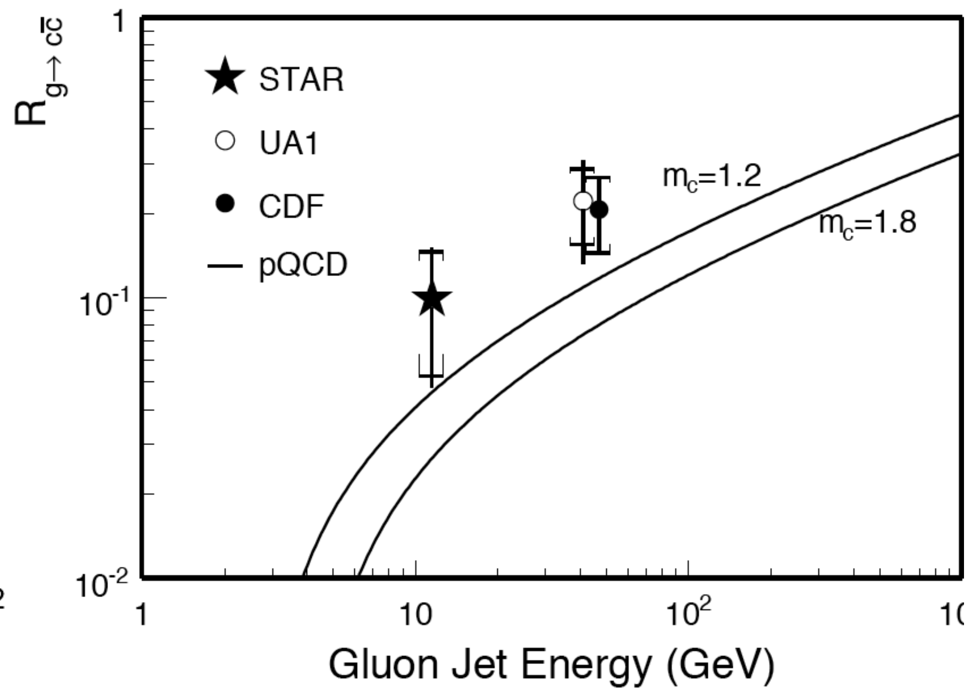
Open Charm Production at RHIC

Heavy flavor quarks can serve as calibrated probes for the QGP at RHIC:

- production in p+p collisions are described by pQCD calculations
- produced mostly in the initial hard scatterings at RHIC energies
- has only a small contribution from gluon splitting





NLO charn: M. Cacciari et al, PRL 95 (2005) 122001
gluon splitting charm: STAR Jet*pQCD R(g->ccbar)
STAR R(g->ccbar): PRD79 (2009) 112006
pQCD R(g->ccbar): Mueller & Nason PLB 157 (1985) 226; Mangano & Nason PLB 285 (1992) 160

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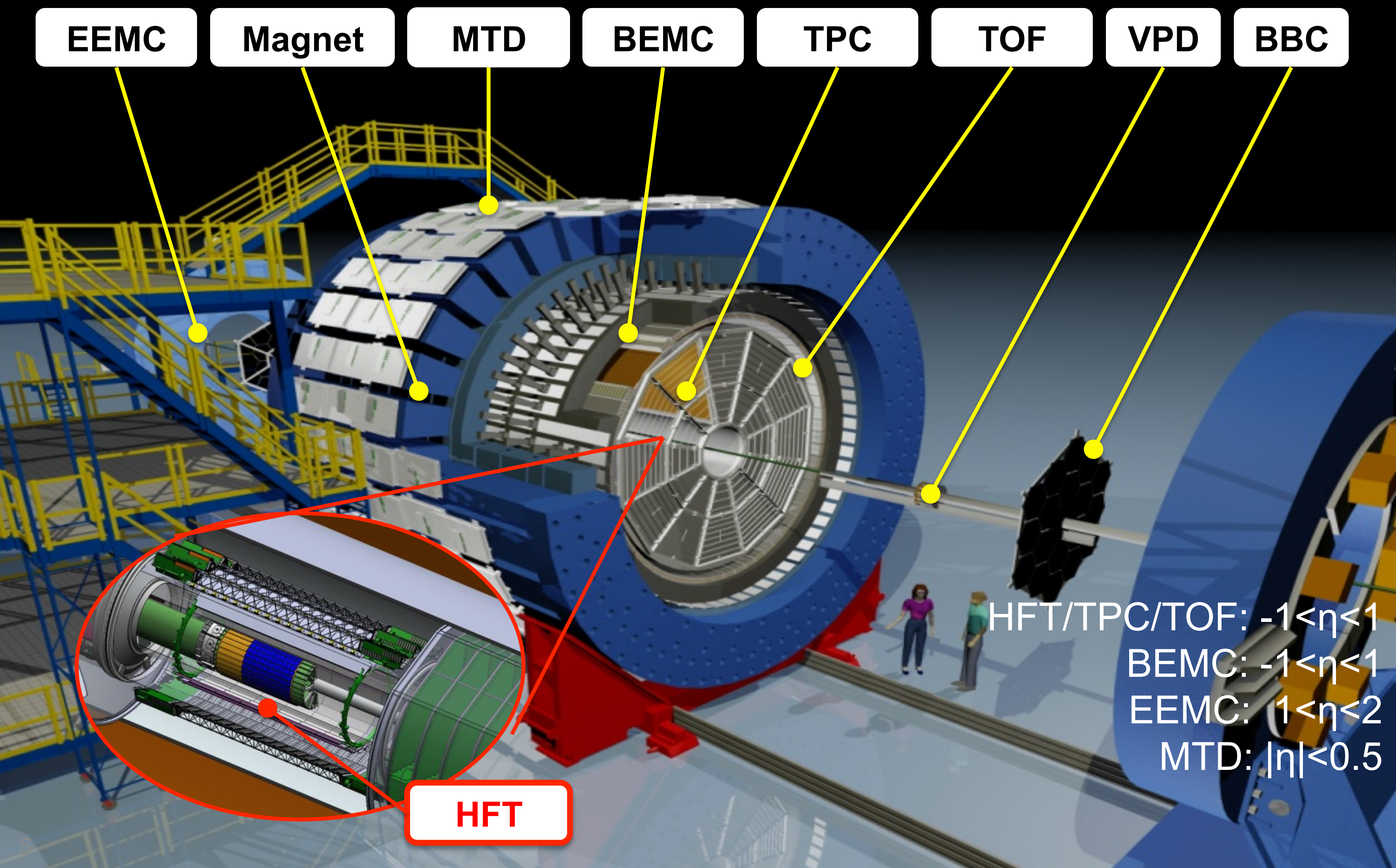
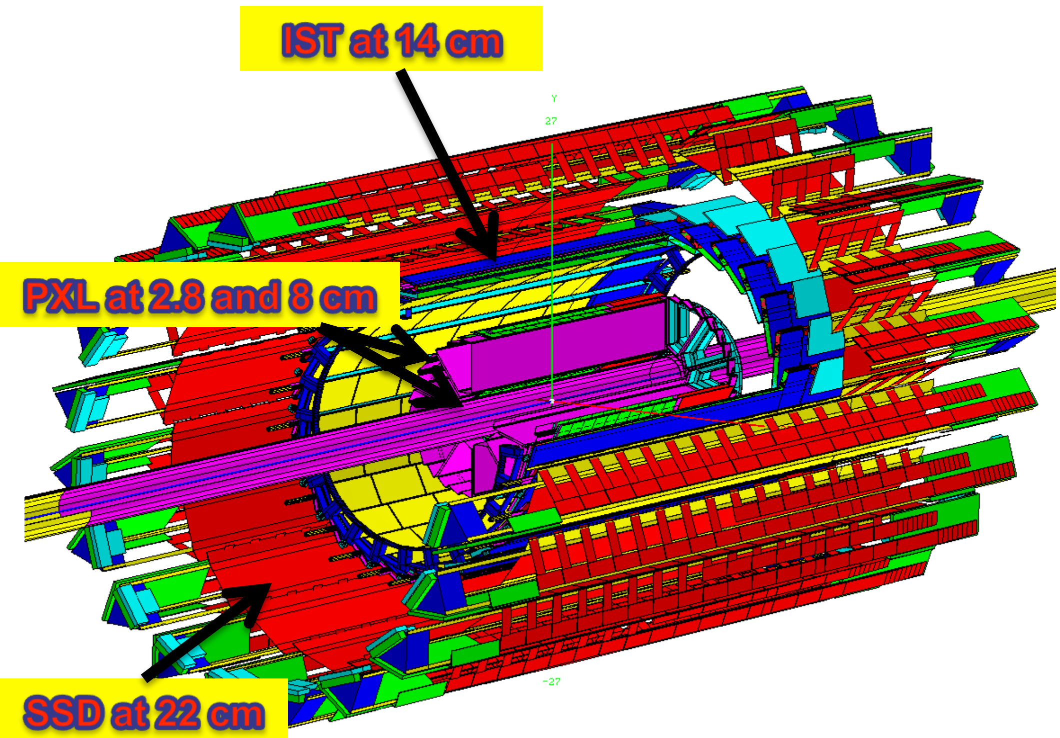
STAR Experiment at RHIC



STAR Heavy Flavor Tracker



<u>PiXeL detector (PXL)</u>

- two layers of thin Monolithic Active Pixel Sensors with 356M 20.7x20.7 μm pixels
- excellent DCA resolution for HF studies

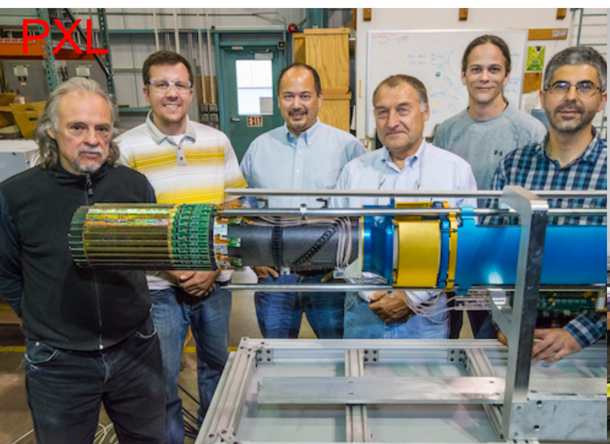
<u>Intermediate Silicon Tracker (IST)</u>

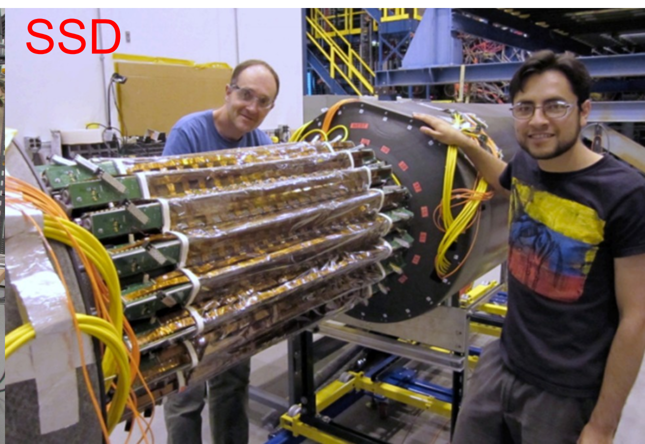
- one layer of fast readout single-sided double-metal silicon strip detector

<u>Silicon Strip Detector (SSD)</u>

- existing one layer of double-sided silicon strip detector with electronic upgrade

Detector	Radius (cm)	Hit Resolution R/φ - Z (μm)	Radiation length
SSD	22	20 / 740	1% X_0
IST	14	170 / 1800	<1.5 %X_0
PXL	2.8/8	6 / 6	~0.4 %X_0





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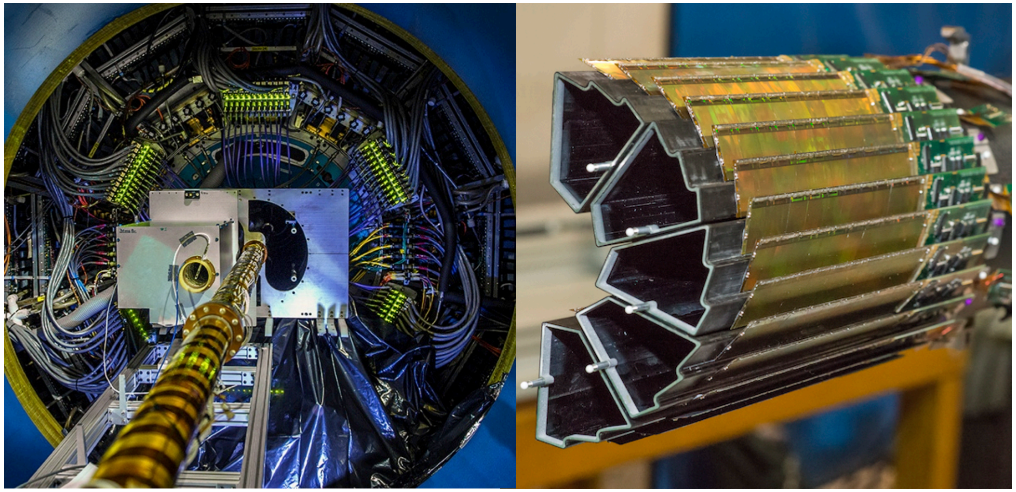
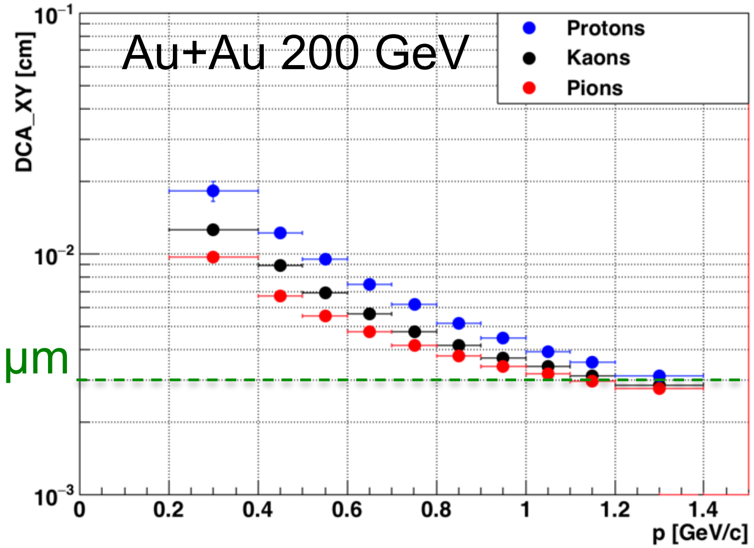
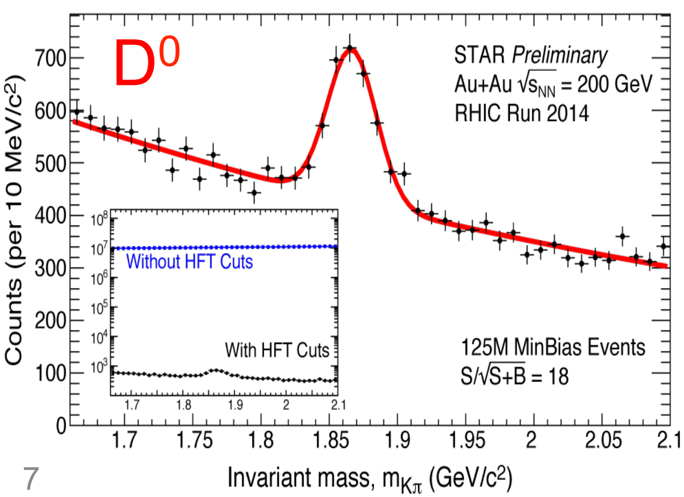
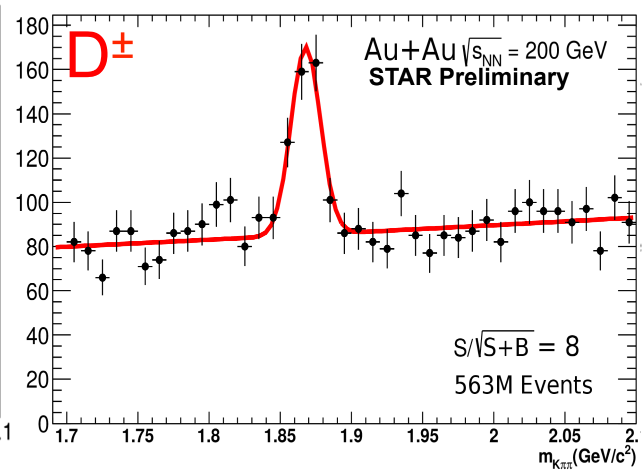
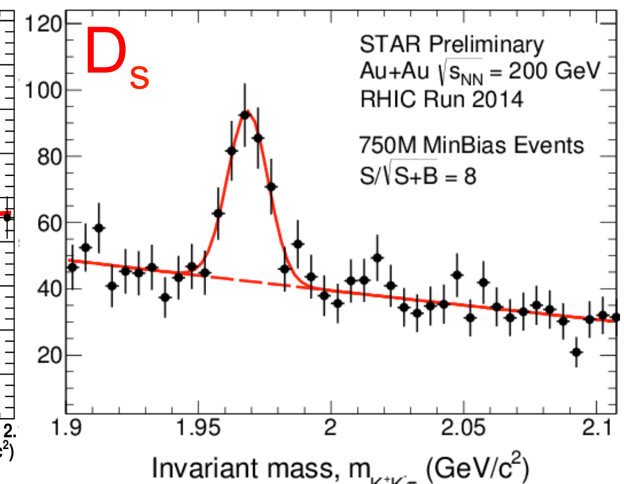




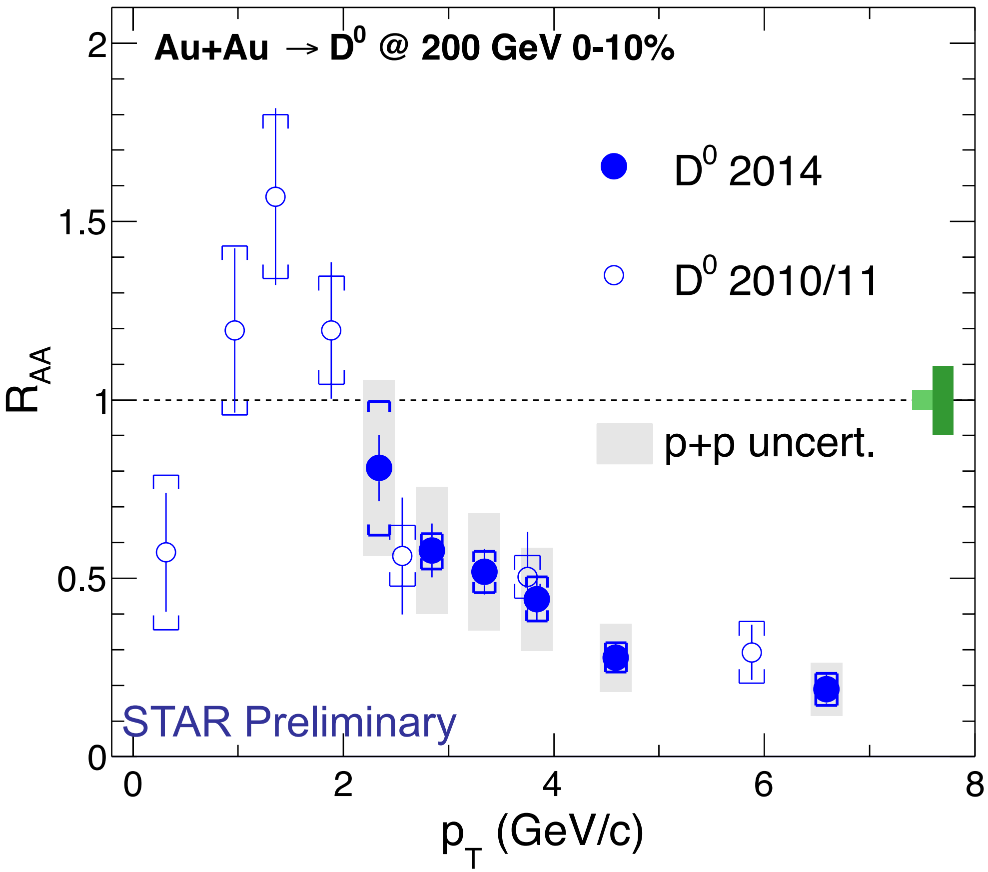
A factor of ~4 improvement in D^0 significance by the HFT. First results on $D^{\pm}$ and D_s.







New Results from the HFT – D^0 R_{AA}



- $R_{AA}(D)>1$ for p_T~1.5 GeV/c

Charm coalescence with a radially flowing bulk medium

- High p_T: significant suppression in central Au+Au collisions.

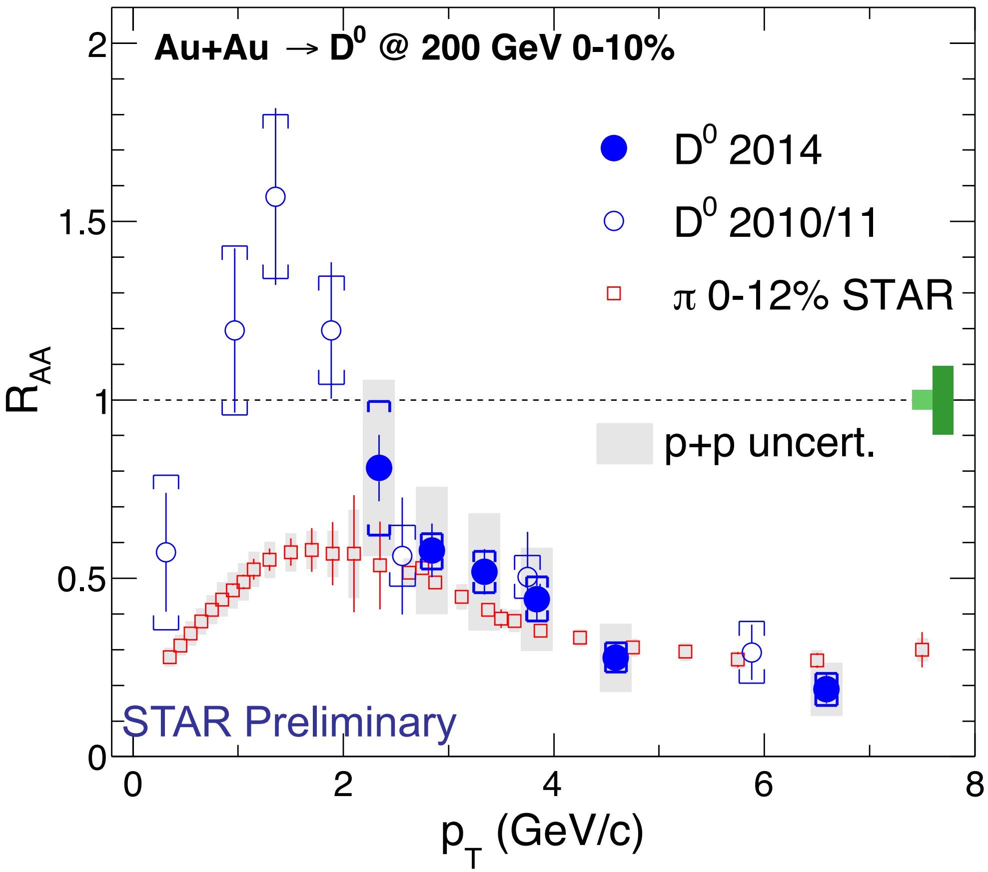
Strong charm-medium interaction

- Improved Au+Au precision at high p_T thanks to the HFT. R_{AA} at low p_T with Run14 Au+Au and Run15 p+p HFT data are underway.

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

STAR D^0 2010/11: PRL 113 (2014) 142301

New Results from the HFT – D^0 R_{AA}



- R_{AA}(D)>1 for p_T~1.5 GeV/c

  Charm coalescence with a radially flowing bulk medium

- High p_T: significant suppression in central Au+Au collisions.

  Strong charm-medium interaction

- R_{AA}(D) ~ R_{AA}(π) at p_T>4 GeV/c

  Similar suppression for light partons and charm quarks at high p_T

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

STAR D^0 2010/11: PRL 113 (2014) 142301
STAR π 0-12%: PLB 655 (2007) 104

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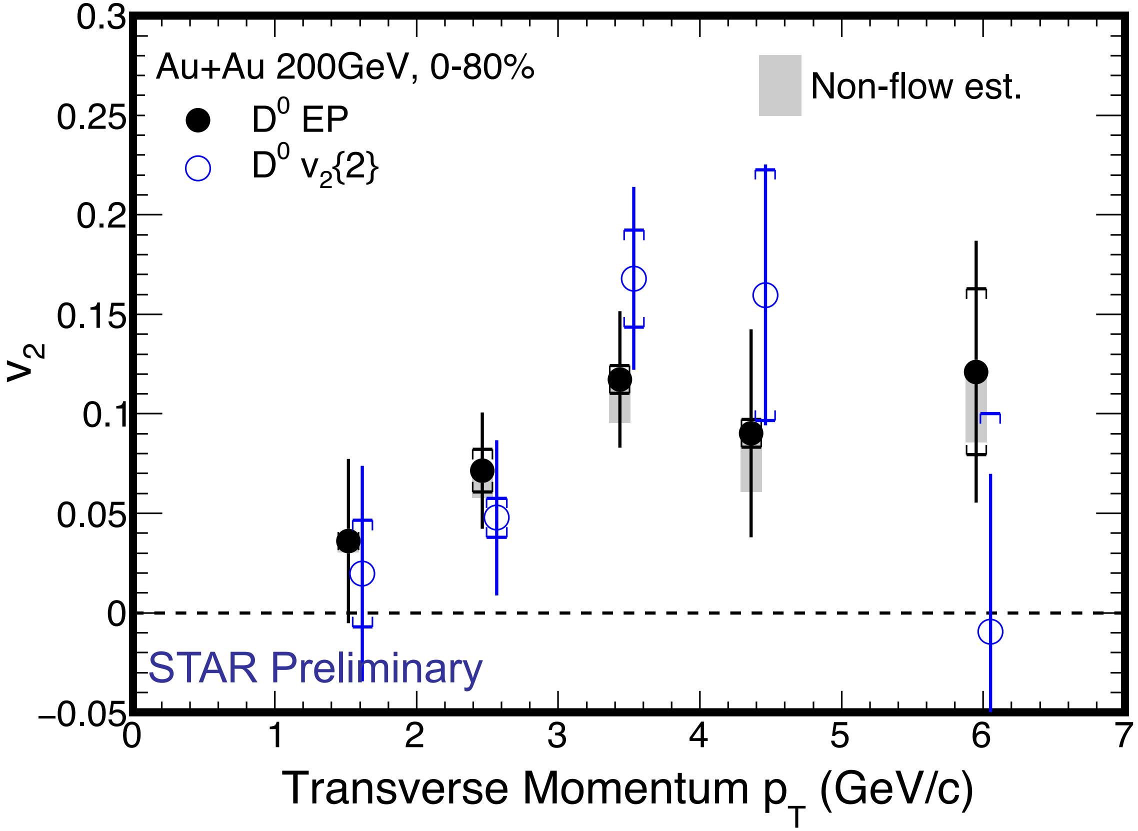
New Results from the HFT – D^0 v_2



- Finite D^0 v_2 for p_T>1 GeV/c

$$\frac{dN}{d\phi} = N_0\left[1 + \sum_n 2v_n \cos n\phi\right]$$

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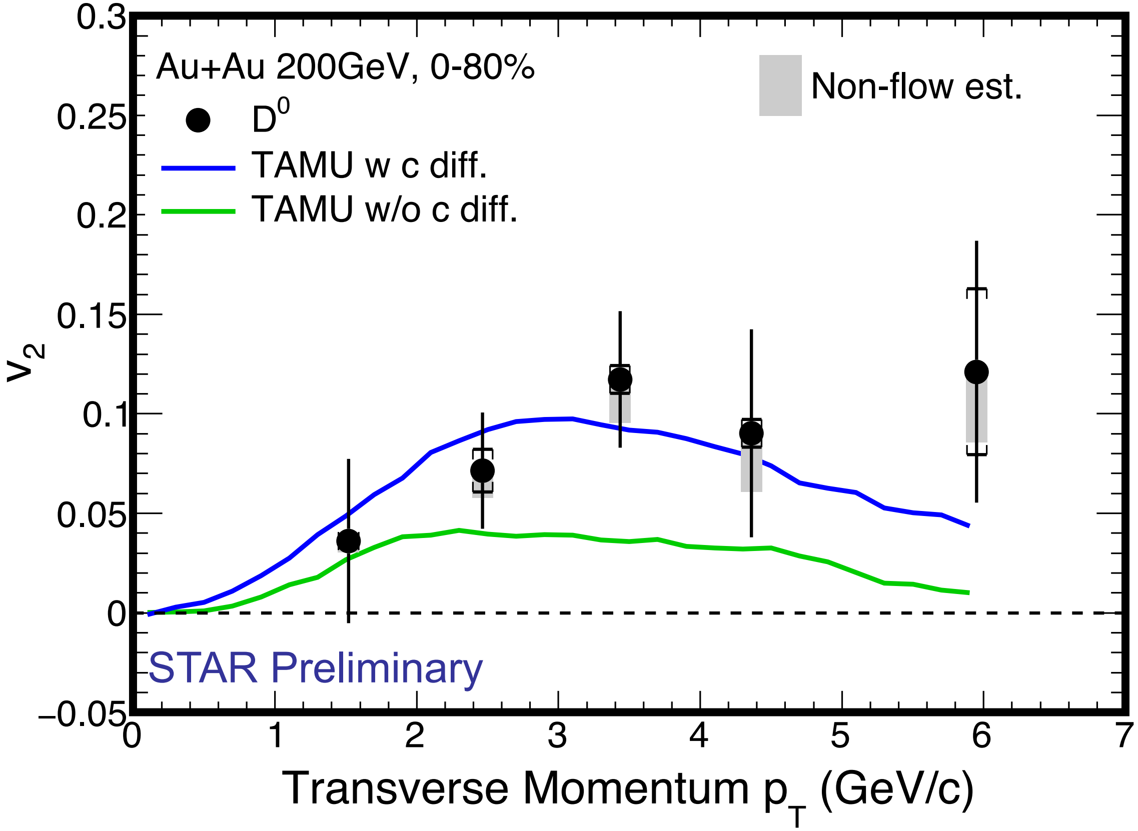
New Results from the HFT – D^0 v_2



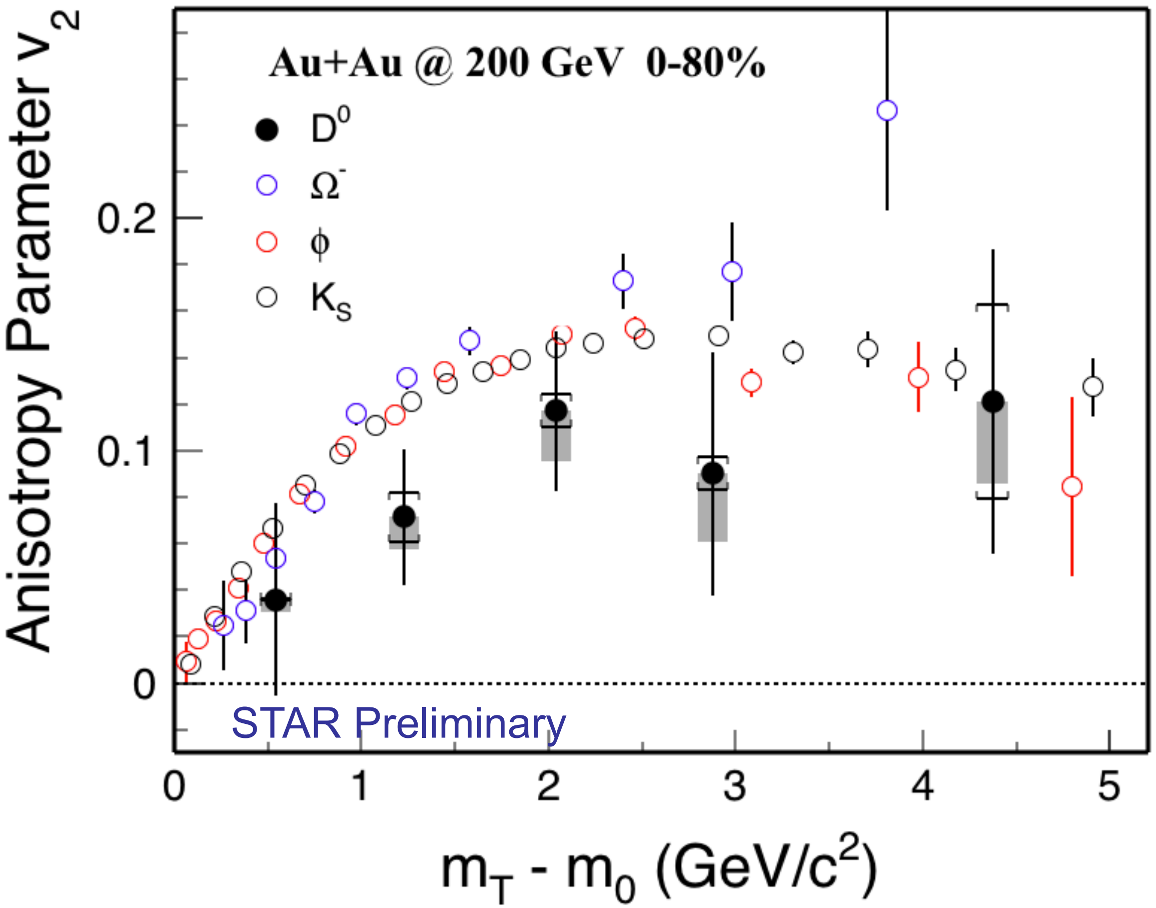
$$\frac{dN}{d\phi} = N_0\left[1 + \sum_n 2v_n \cos n\phi\right]$$

- Finite D^0 v_2 for p_T>1 GeV/c

Favors charm quark diffusion

Theory curves: latest calculations from private communications
TAMU: PRC 86 (2012) 014903, PRL 110 (2013) 112301

New Results from the HFT – D^0 v_2



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

- Finite D^0 v_2 for p_T>1 GeV/c

Favors charm quark diffusion

- Lower than light hadron v_2

Indicates that charm quarks are not fully thermalized with the medium

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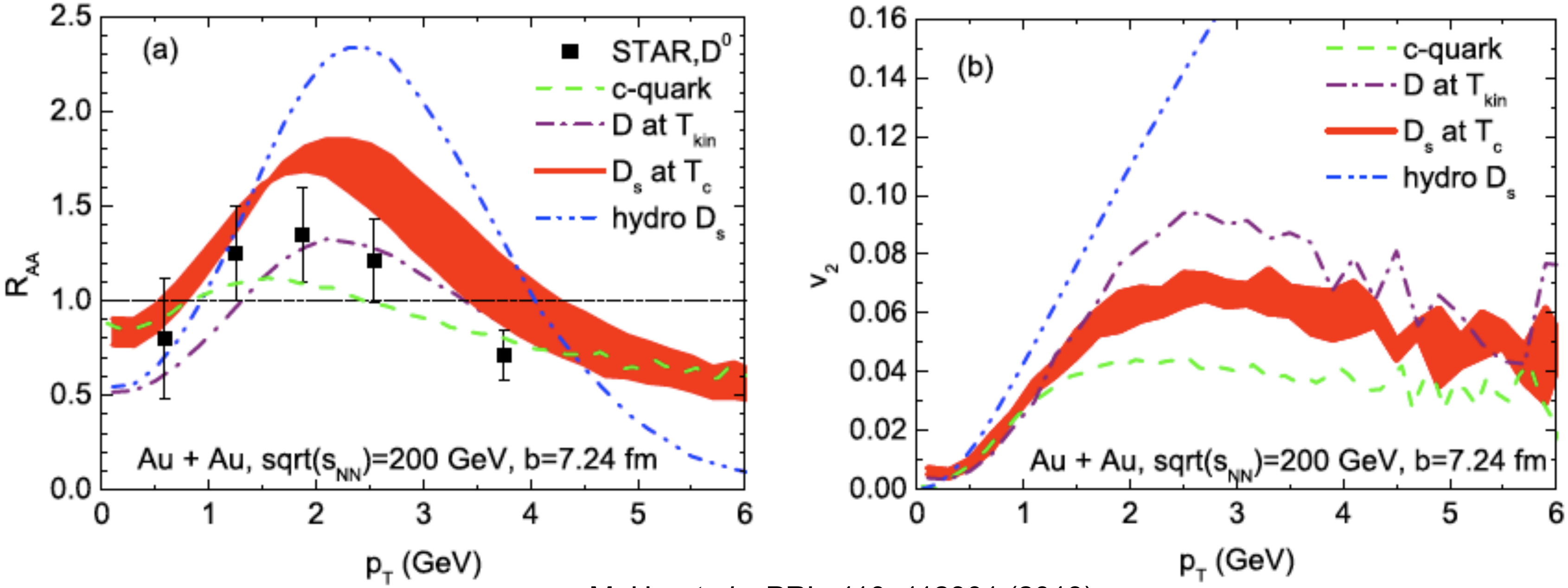
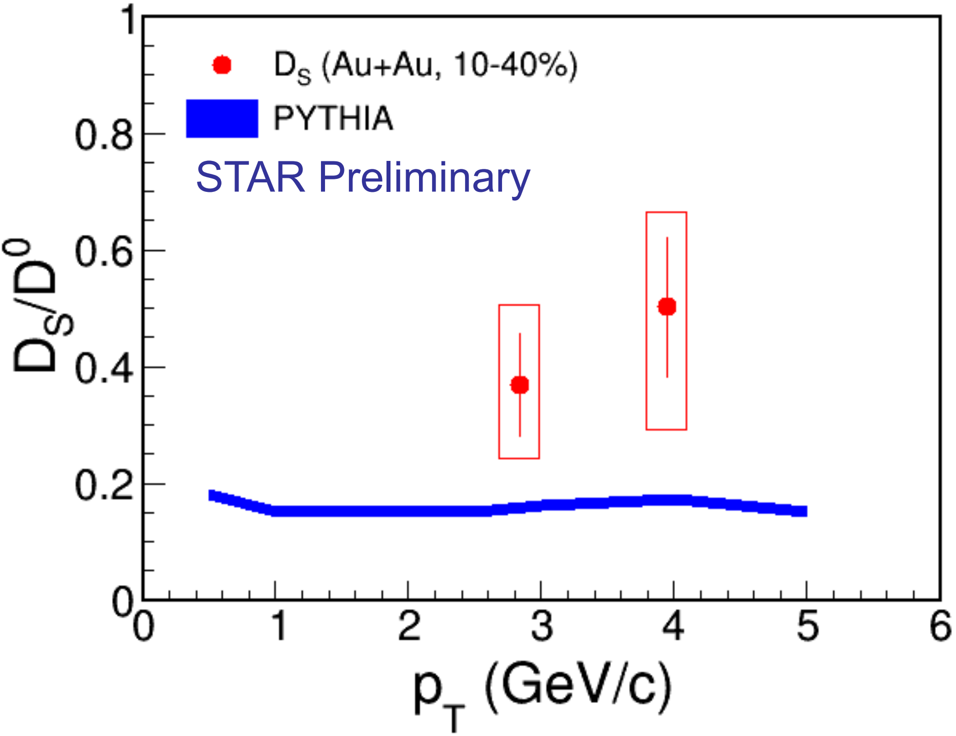
New Results from the HFT - D_s

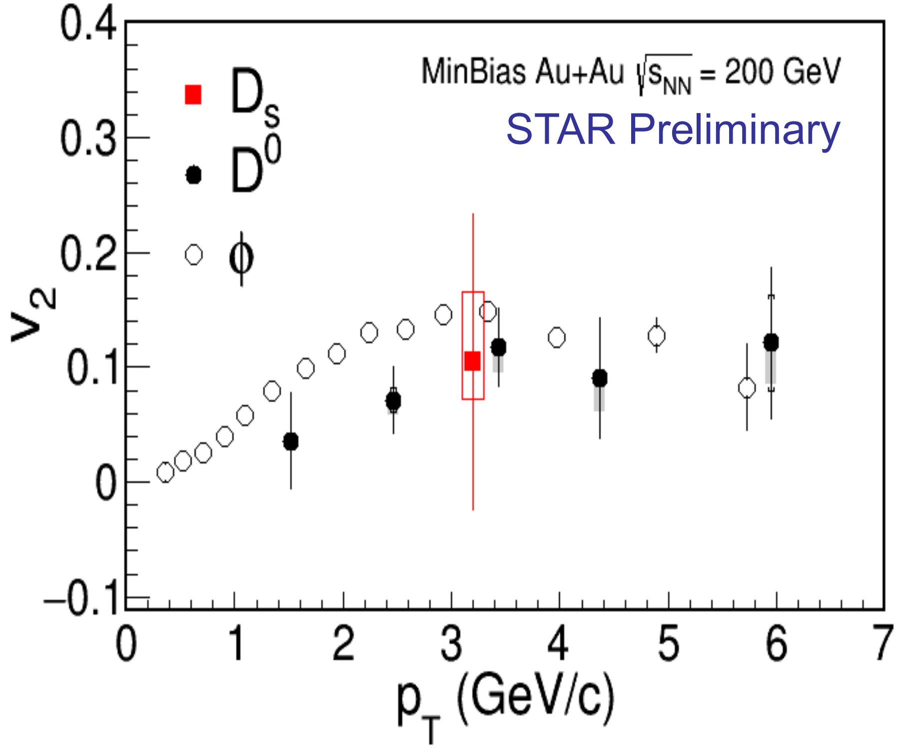


M. He *et al.*, PRL 110, 112301 (2013)

- Strangeness enhancement in heavy-ion collisions is expected to affect the yield of D_{S}: relative increase of D_S yield than D^0 predicted.
- Elliptic flow of $D_S < D^0$ is expected due to earlier freeze out of D_S.

New Results from the HFT - D_s





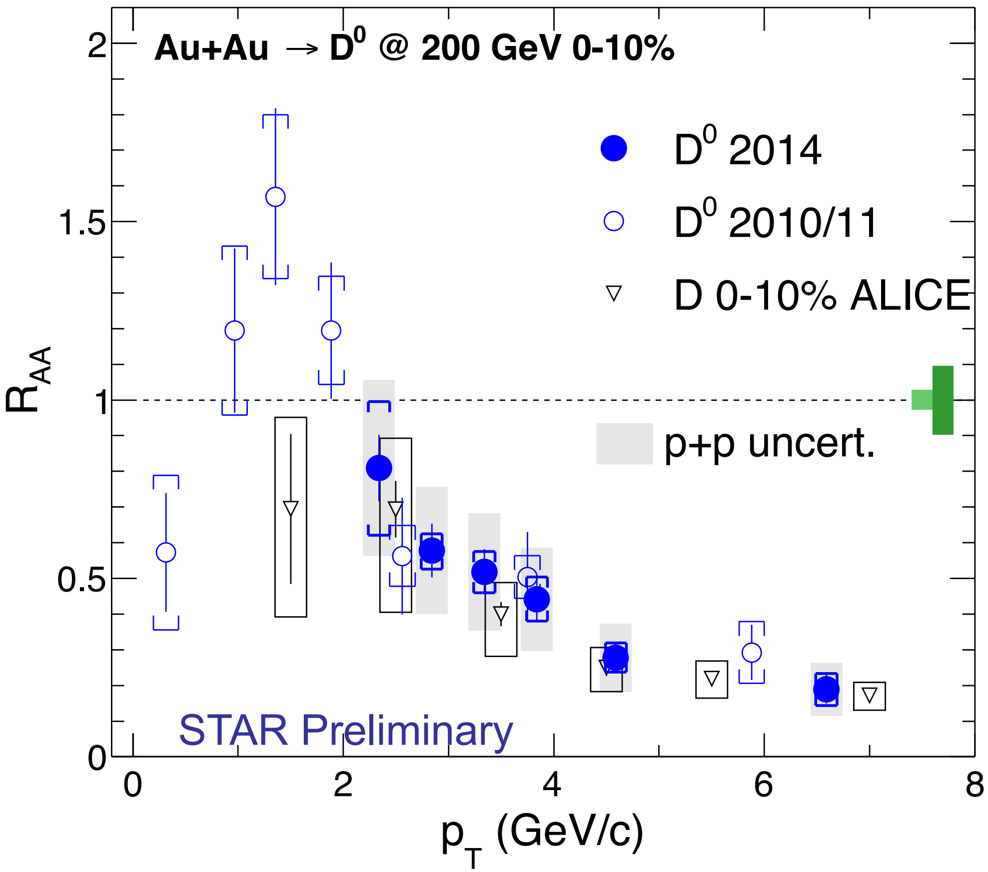
- Strangeness enhancement in heavy-ion collisions is expected to affect the yield of $D_{S:}$ relative increase of D_S yield than D^0 predicted:

The ratio of D_S/D^0 yield measured in Au+Au collisions is found to be higher than that in p+p collisions from PYTHIA

- Elliptic flow of D_S < D^0 is expected due to earlier freeze out of D_S:

First measurement of D_S v_2 in heavy-ion experiment. More data are needed to draw conclusion.

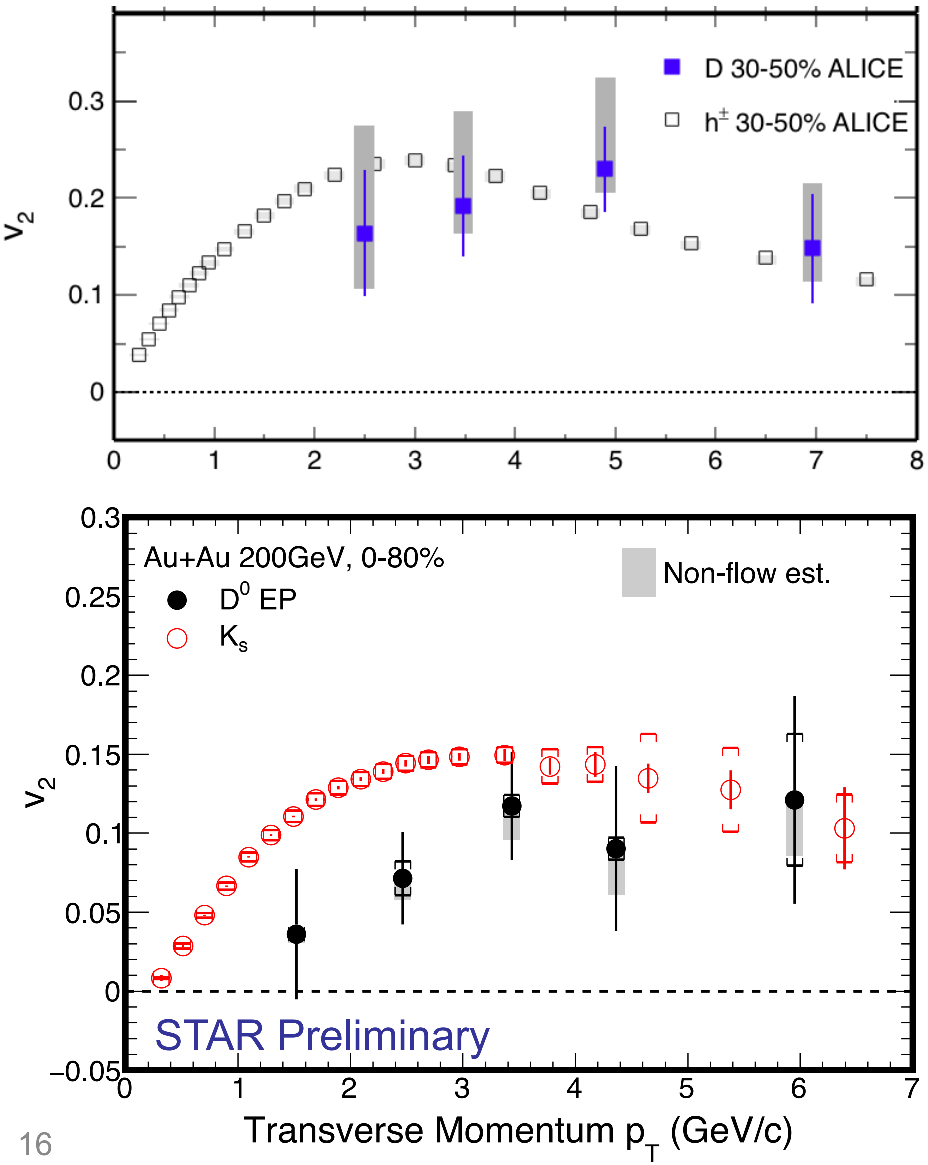
Comparison with LHC Results



- D meson R_{AA}@ RHIC ~ R_{AA}@LHC at p_T>4 GeV/c

Strong charm-medium interaction at RHIC and LHC

Comparison with LHC Results



- D meson R_{AA}@ RHIC ~ R_{AA}@LHC at p_T>4 GeV/c

Strong charm-medium interaction at RHIC and LHC

- D^0 v_2 LHC results are compatible with light flavor v_2
- D^0 v_2 STAR results are lower than light flavor v_2

Charm thermalized at LHC energy but not fully thermalized at RHIC?

- More precise data and systematic theoretical studies of heavy flavor production at RHIC and LHC will be very helpful.

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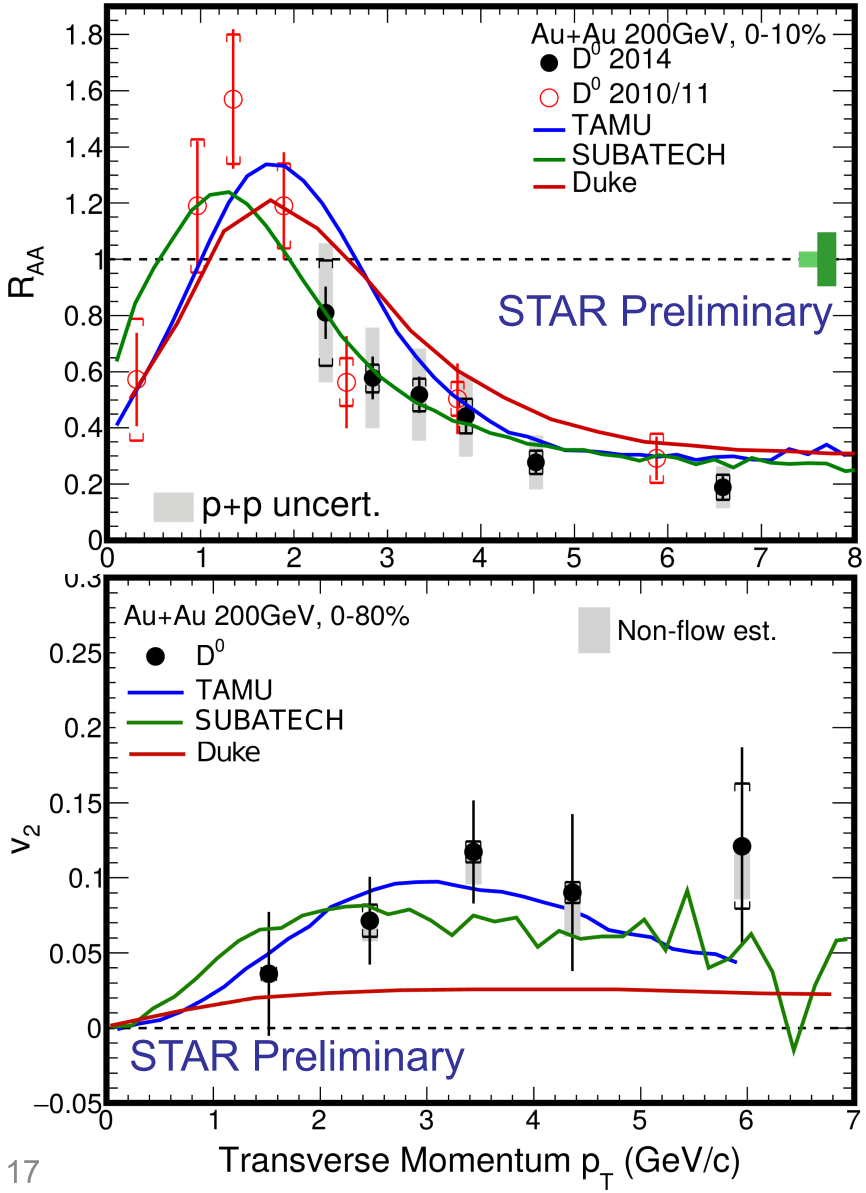
Comparison with Theory



TAMU: non-perturb. T-matrix
$(2\pi T)D$ = 2-11

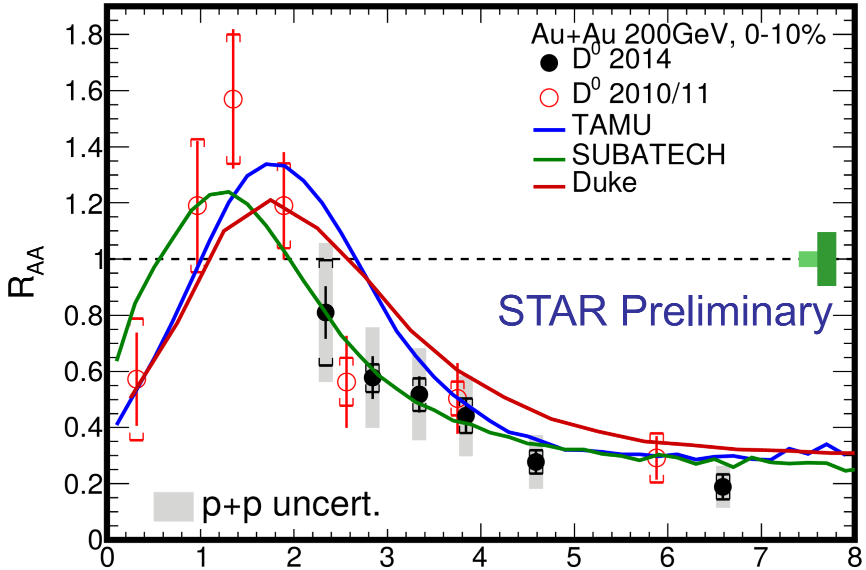
SUBATECH: perturb.+resummation
$(2\pi T)D$ = 2-4

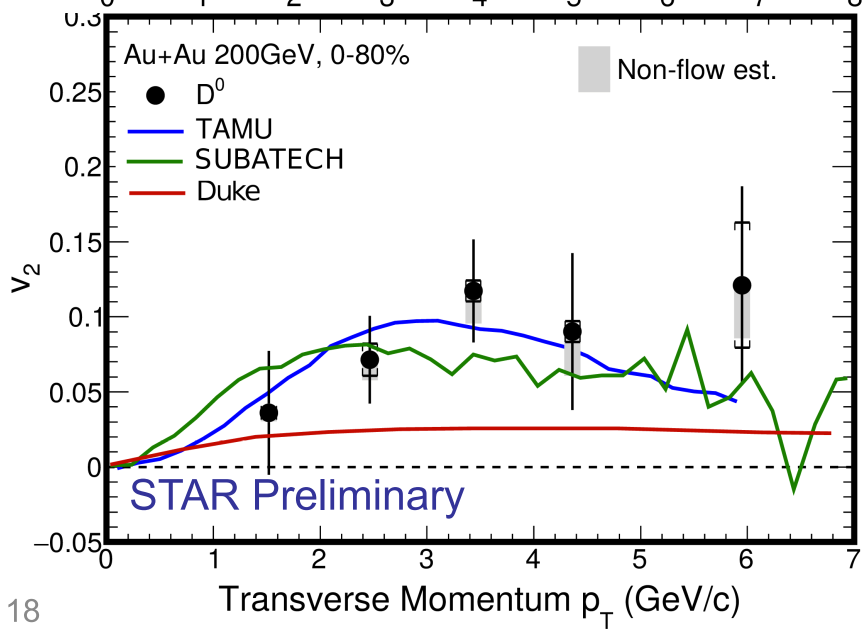
DUKE: Langevin simulation with input parameter tuned to the LHC data
$(2\pi T)D$ = 7

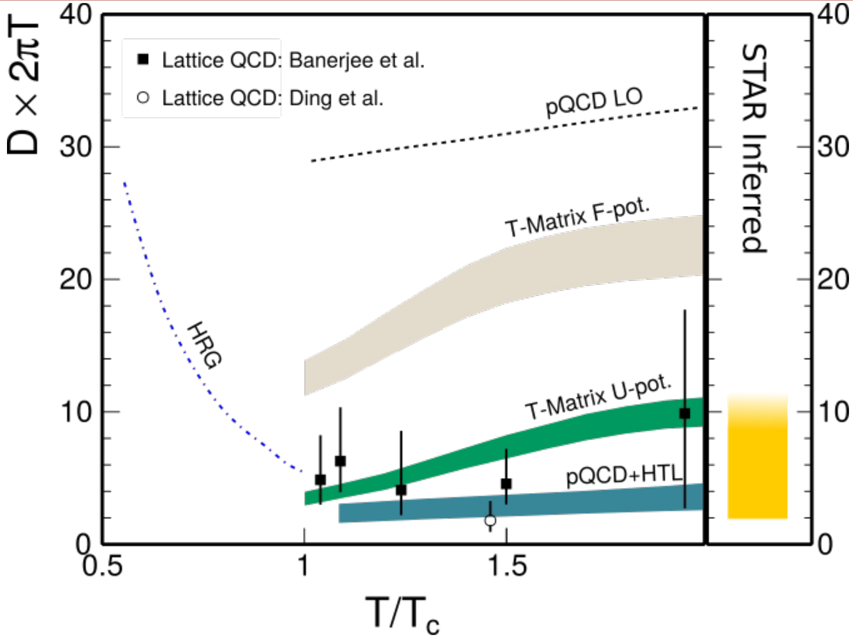
	$D \times 2\pi T$	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

STAR D^0 2010/11: PRL 113 (2014) 142301
Theory curves: latest calculations from private communications
DUKE: PRC 92 (2015) 024907
A.Andronic arXiv:1506.03981(2015)

Comparison with Theory







Models with charm diffusion coefficient of 2-~10 describe STAR D^0 R_{AA} and v_2 results. Lattice calculations are consistent with values inferred from data.

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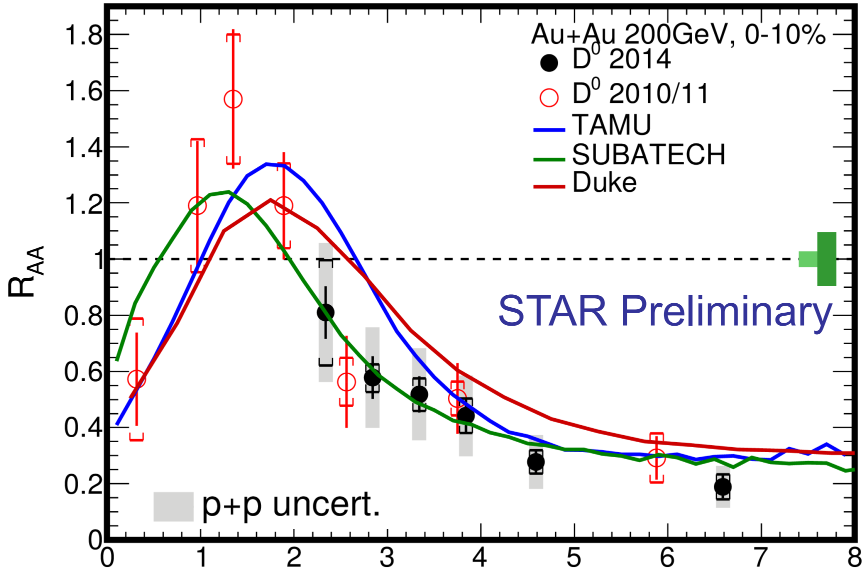
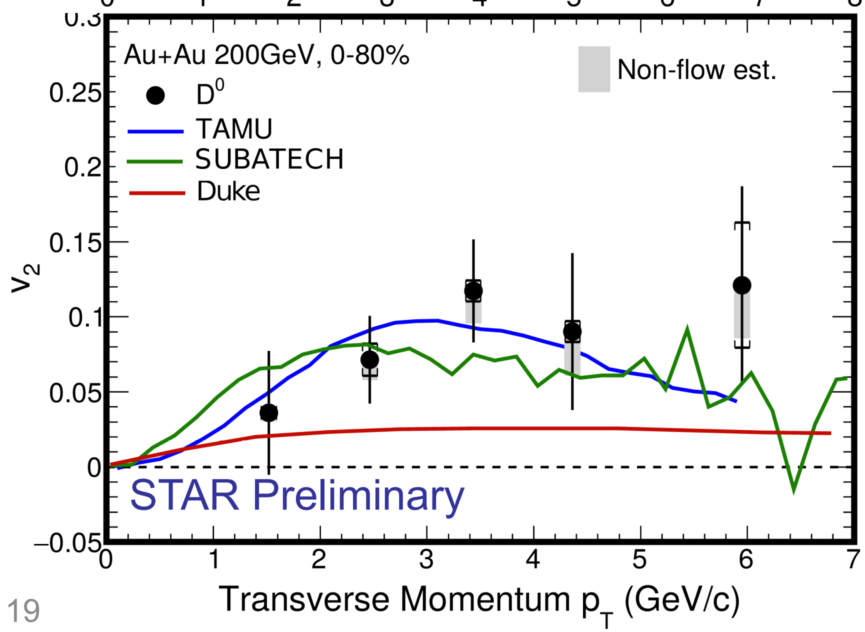
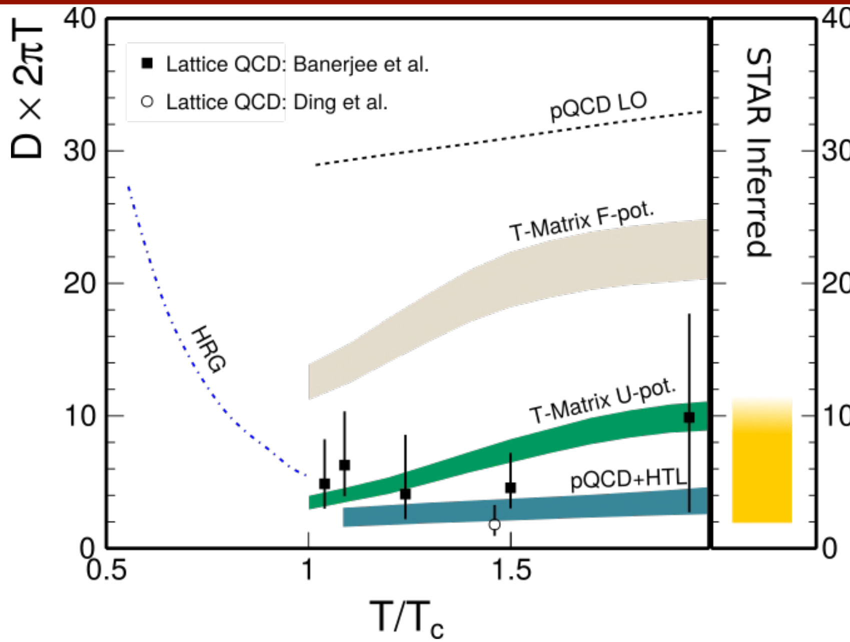


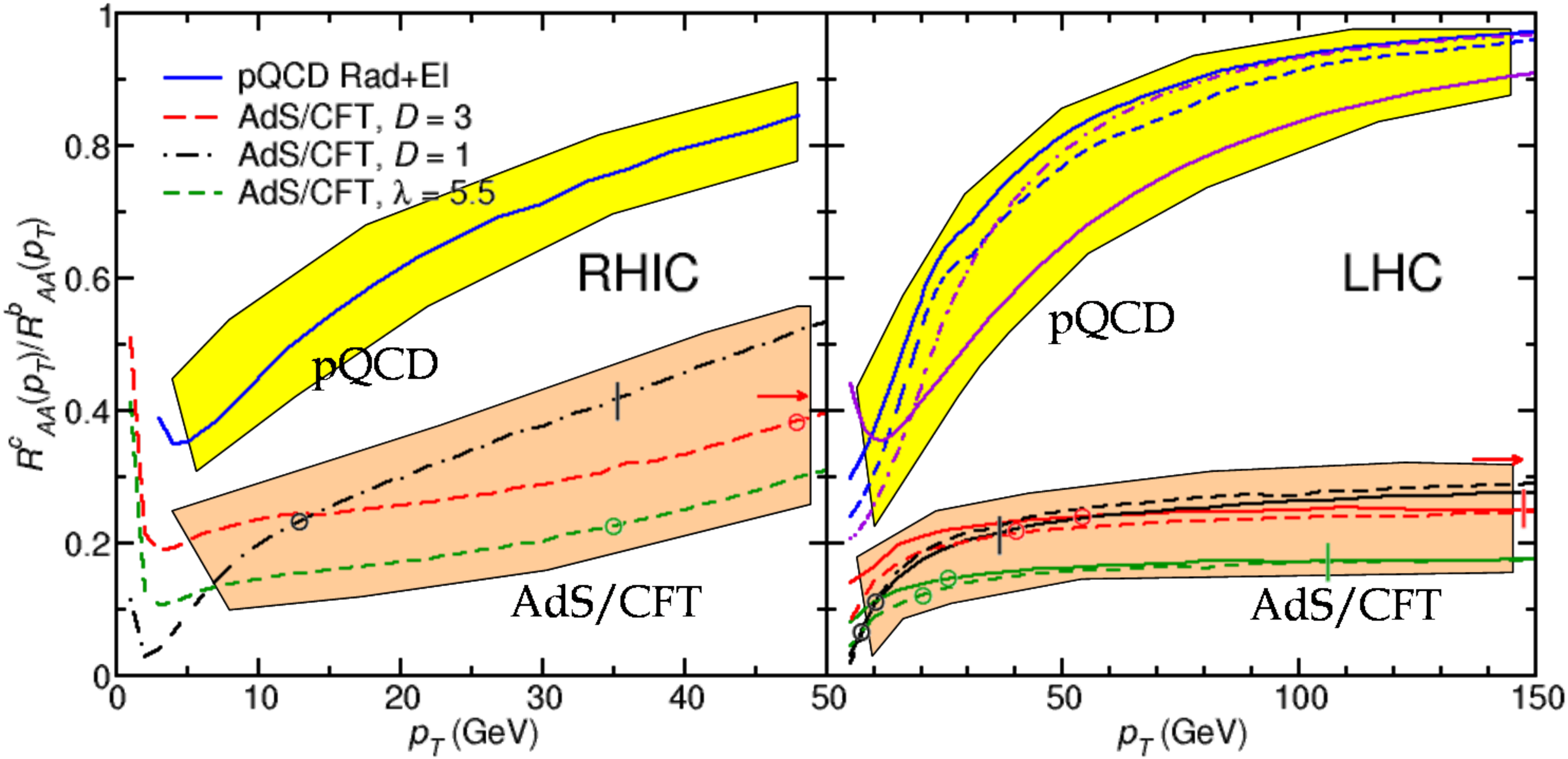




Models with charm diffusion coefficient of 2-~10 describe STAR D^0 R_{AA} and v_2 results. Lattice calculations are consistent with values inferred from data.

More precise results expected from STAR Run15 (pp, pAu) and Run16 (AuAu) data: improved p+p baseline, CNM, a factor of ~3 increase in Au+Au data size, improved DCA resolution at low p_T with Al cables for PXL

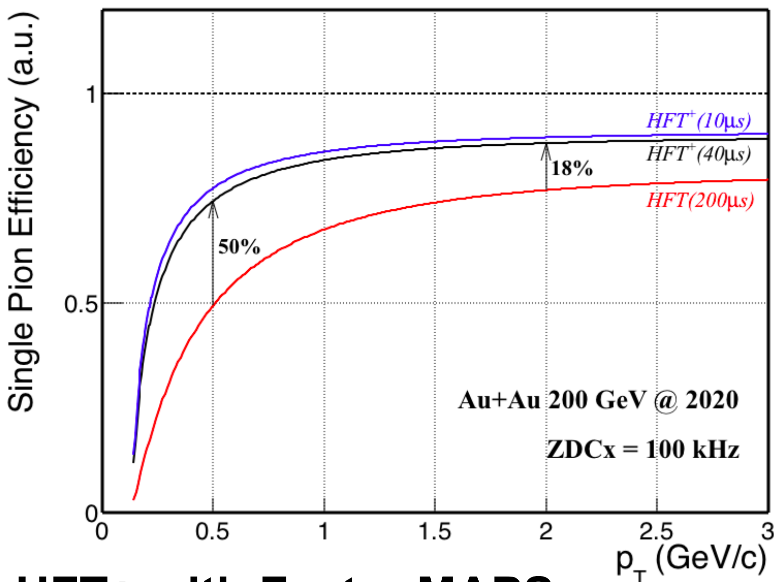
STAR Heavy Flavor II (2021-2022)



W. Horowitz and M. Gyulassy, arXiv:0710.0703

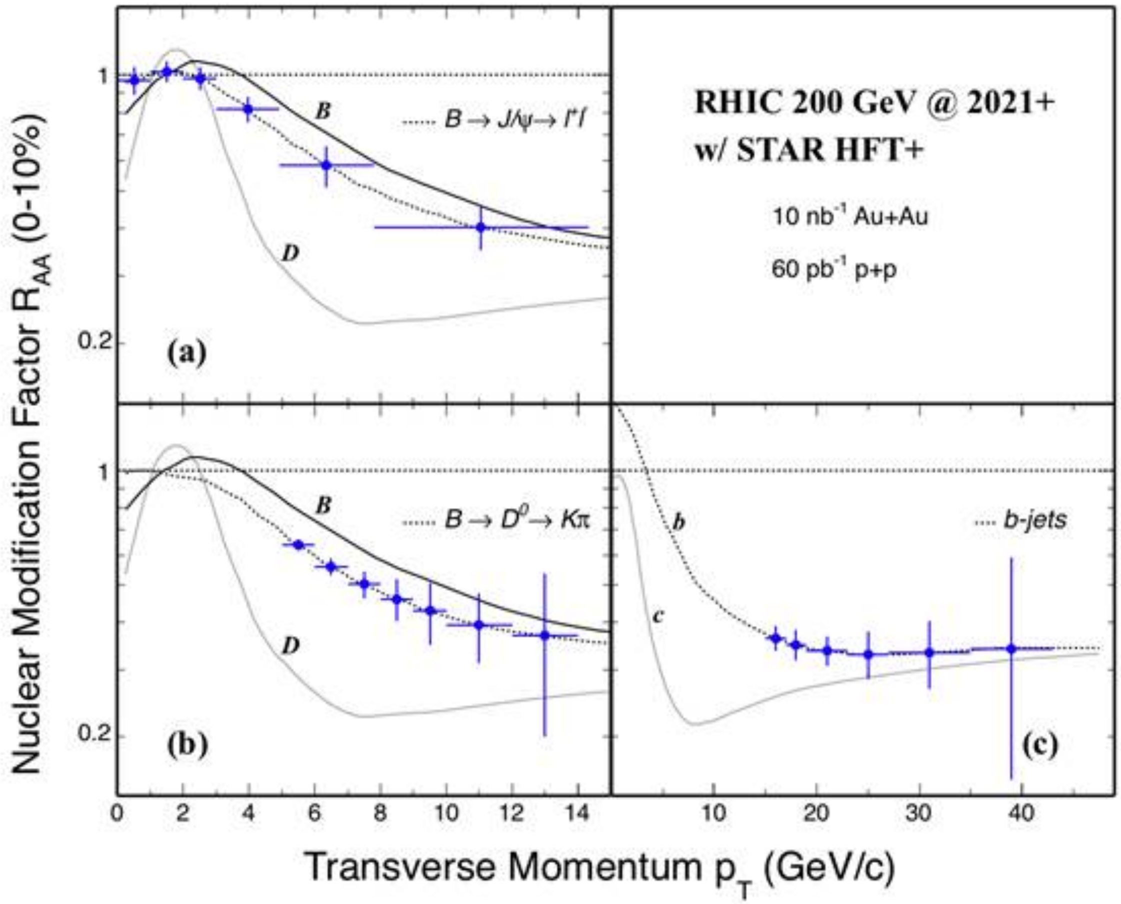
Without Bottom from RHIC, can we claim that we fully understand the energy loss mechanisms, or mass- and temperature-dependent parton transport coefficients of the QGP? Does b quark diffuse in the QGP at RHIC energies and if so how much?

STAR Heavy Flavor II (2021-2022)



HFT+ with Faster MAPS sensors

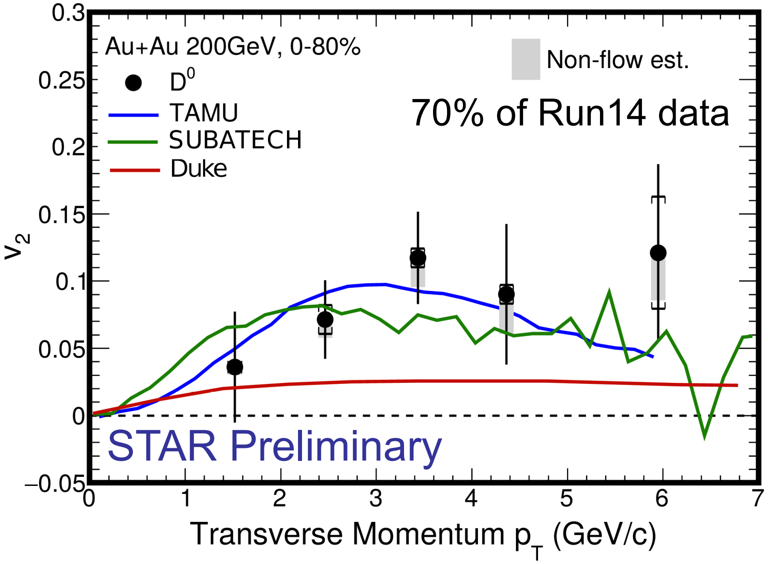
- integration time from ~185 μs to below 40 μs – less pile-up hits and thus better tracking efficiency
- use chips developed for ALICE ITS upgrade and existing HFT infrastructure – cost effective
- experienced team worked on HFT



Projected R_{AA}(0-10%) stat. uncertainty
for RHIC pp and AuAu running in 2021-22

Precise bottom measurements with the HFT+ to complete the heavy flavor physics at RHIC. Complementary to ALICE HF and sPHENIX Jet and Upsilon programs.

Summary and Outlook



STAR HFT in Run14-16

Run14: Au+Au, results based on ~70% stat.
Run15: p+p baseline, p+Au for CNM effects
Run16(+14): x4 Au+Au data size than QM15, inner PXL 0.5->0.4%X_0 with Al cables

- **Precise charm results**
- First bottom results

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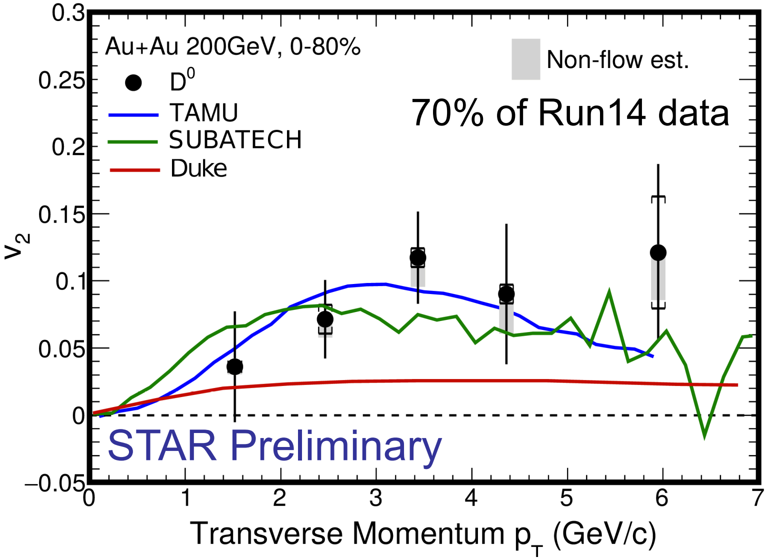
Summary and Outlook



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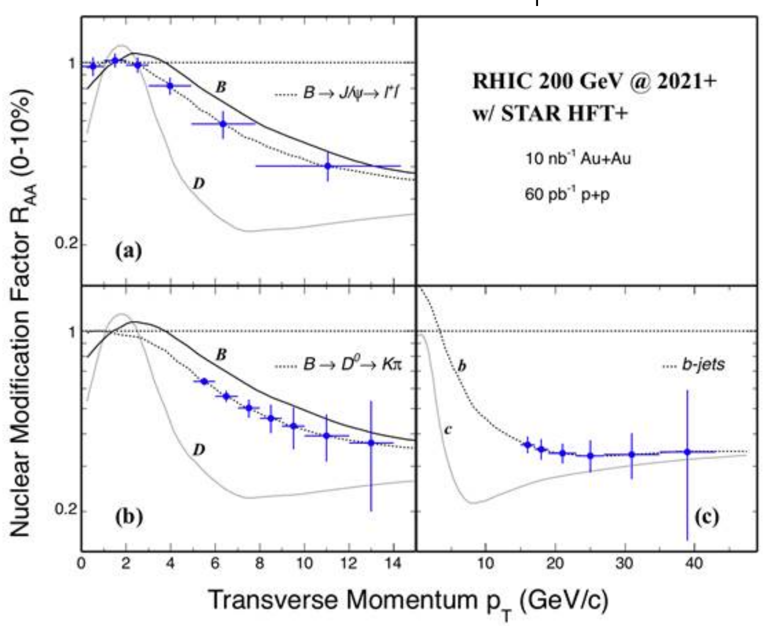

Upgraded HFT+ in 2020+

HFT+ with faster MAPS sensors will allow precise measurements of bottom quark production at RHIC through B->J/ψ, B->D and b-tagged jets

- **Precise bottom results**

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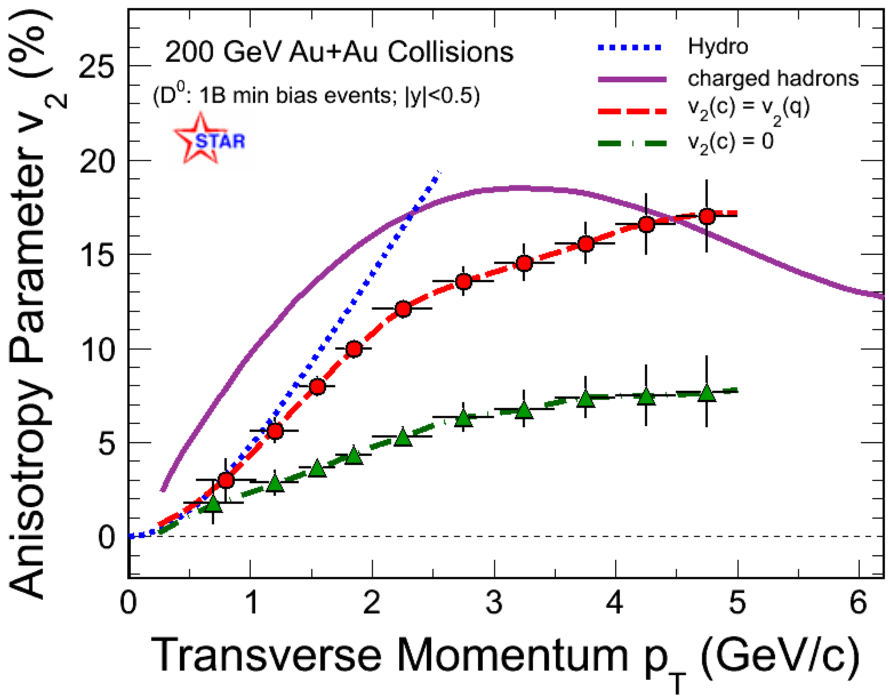
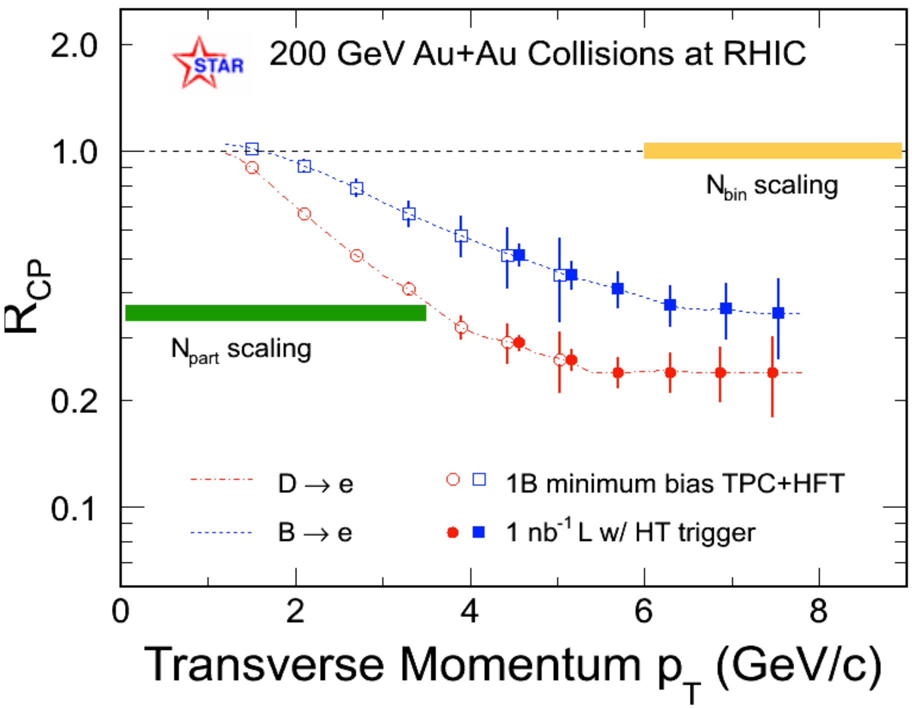
Backup

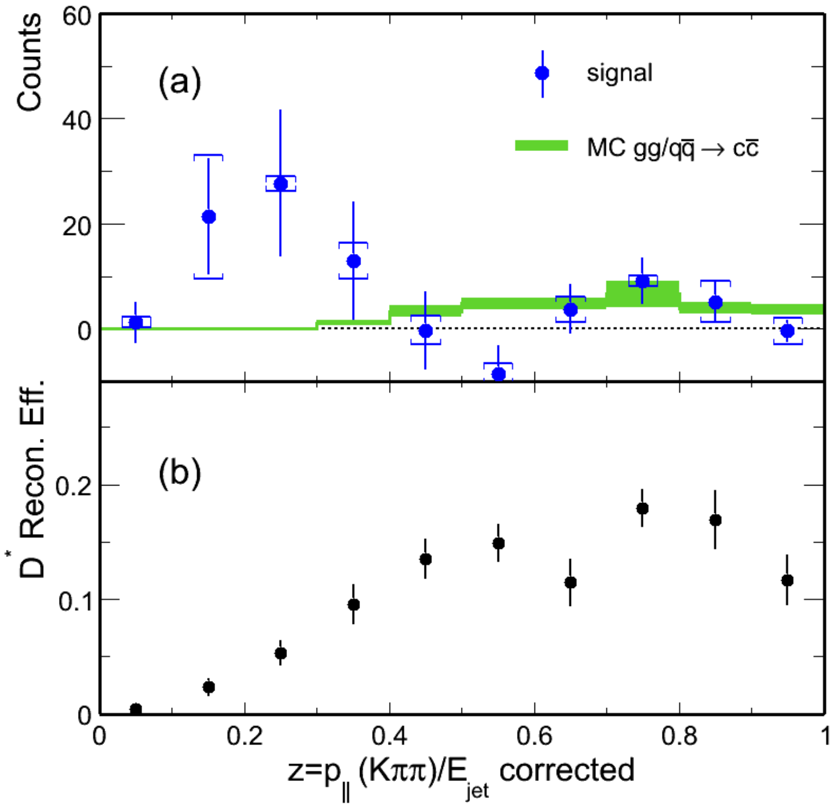
STAR Heavy Flavor Tracker





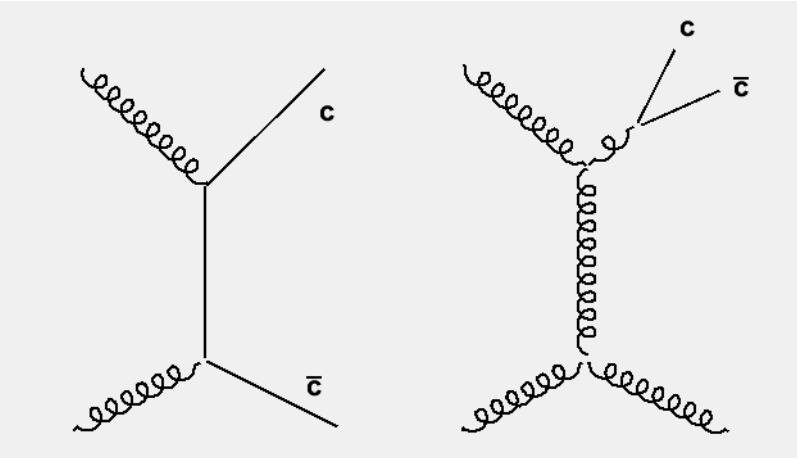
High precision R_{AA}, R_{pA}, v_2, correlations results for D mesons and HF leptons;
Unique at low p_T -> medium thermalization, total charm production

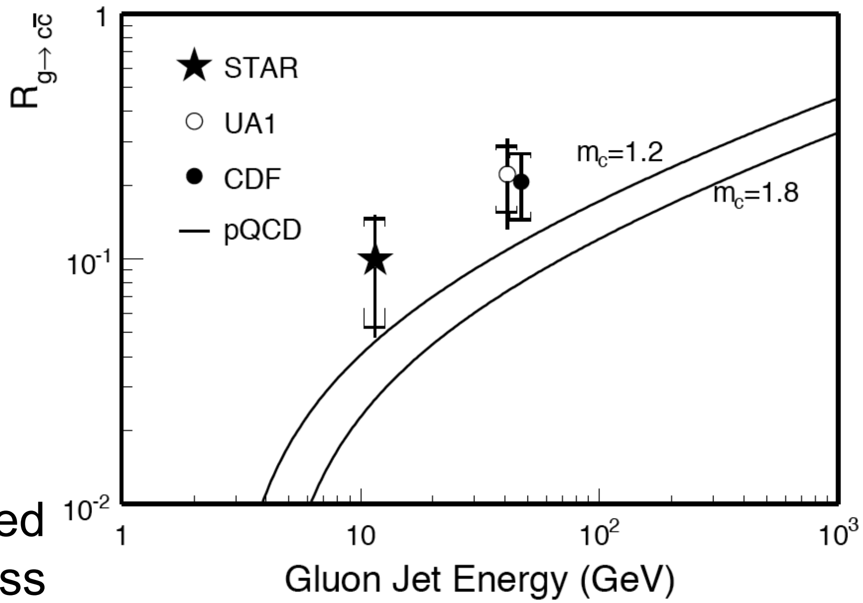
Charm Production at RHIC



$N(D^*)/N(jets) = (1.5 \pm 0.8 \pm 0.7) \times 10^{-2}$

High z production is suppressed w.r.t. low z by trigger bias. The magnitude in data is reproduced by MC with direct flavor creation process. Excess at low z is from high order processes.





STAR PRD79 (2009) 112006

Charm Production at RHIC

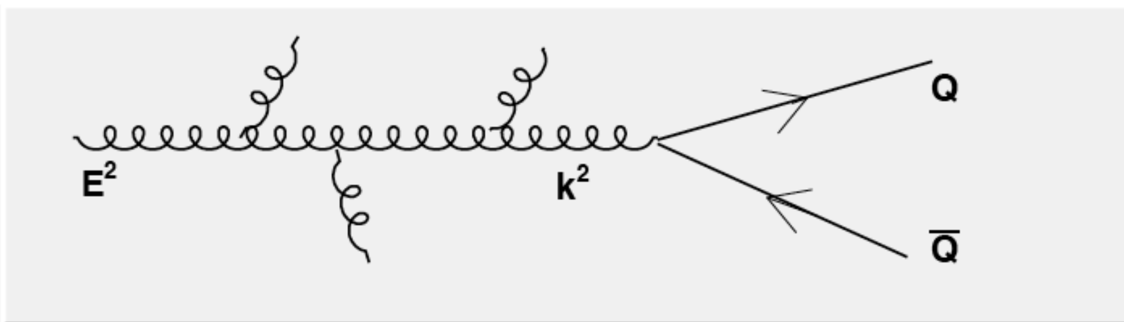


Figure 1: Gluon splitting into $Q\bar{Q}$

Gluon framentation into $Q\bar{Q}$ pairs is calculable in perturbative QCD. The process is represeted in Fig. 1. The gluon multiplicity of those having virtuality k^2 could be calculated as:

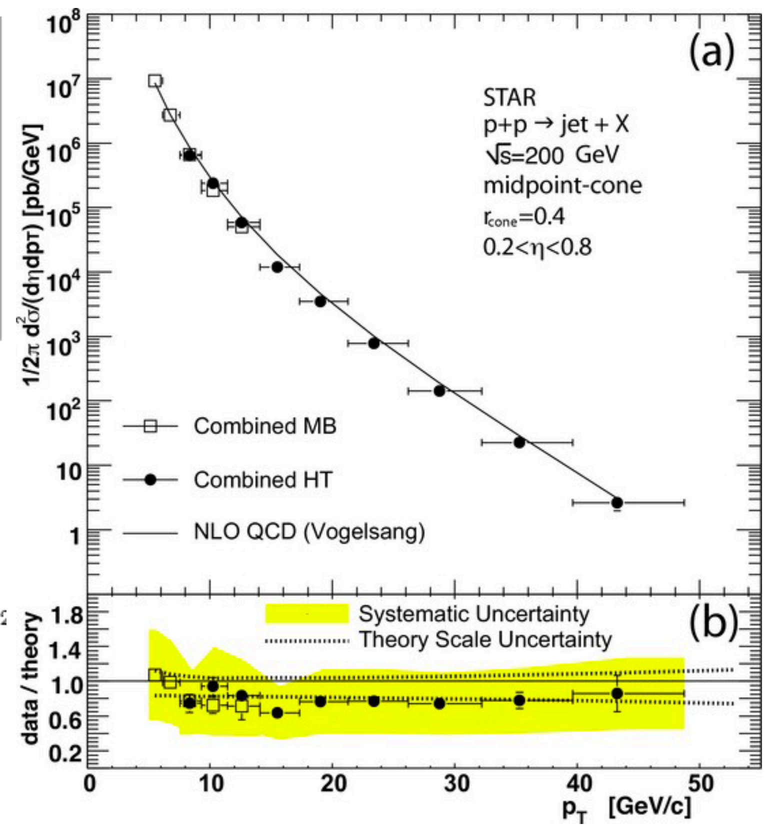
$$n_g(E^2, k^2) = \left[\frac{\ln(E^2/\Lambda^2)}{\ln(k^2/\Lambda^2)}\right]^a \times \exp\left\{[(2C_A/\pi b)\ln(E^2/\Lambda^2)]^{1/2}\right\} / \exp\left\{[(2C_A/\pi b)\ln(k^2/\Lambda^2)]^{1/2}\right.$$

where $a = -1/4 \times [1 + (2N_f/3\pi b)(1 - C_F/C_A)]$, $b = (11C_A - 2N_f)/12\pi$.
The average number of $Q\bar{Q}$ pairs in a gluon jet is:

$$R_{Q\bar{Q}}(E) = \int_{4m^2}^{E^2} \frac{dk^2}{k^2}\frac{\alpha_s(k)}{2\pi}\int_{z_-}^{z_+}\frac{1}{2}[z^2 + (1-z)^2 + \frac{2m^2}{k^2}]dz \times n_g(E^2, k^2)$$

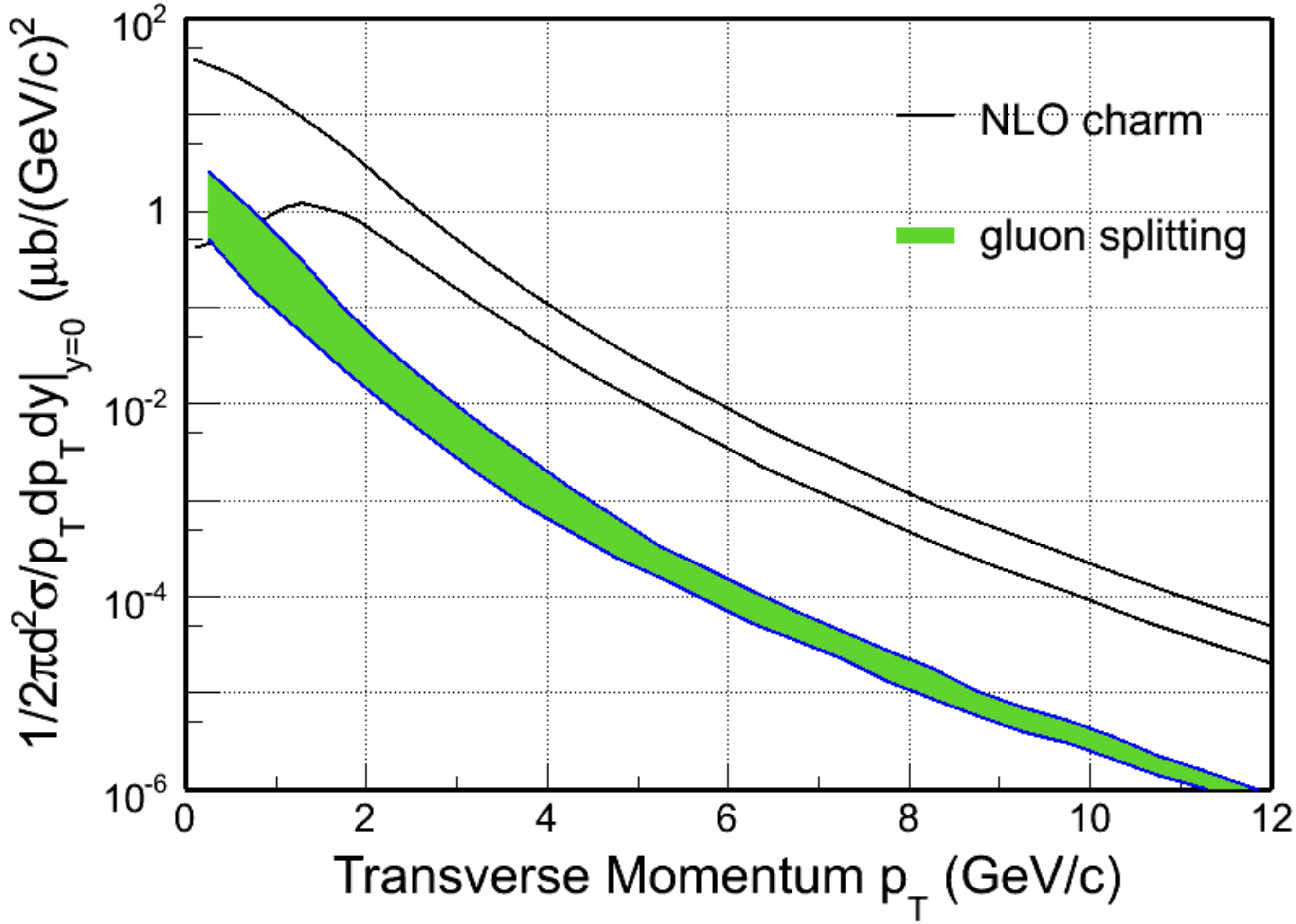
where $z_\pm = (1 \pm \beta)/2$ and $\beta = \sqrt{1 - 4m^2/k^2}$. m is the heavy quark mass.
In my calculation for z_H (charm hadron z) coverage, the charm quark fragmentation function is used as the Peterson fragmentation function:

$$D_Q^H(z) \propto \frac{1}{z}(1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z})^{-2}$$



STAR PRL 97 (2006) 252001

Charm Production at RHIC



Charm production in jets at p_T ~ 2-10 GeV/c has a small contribution from gluon splitting and is dominated by jets initiated by charm quarks

HFT+ Upgrade plan (2021+)

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

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