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Strangeness in Quark Matter
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Utrecht 2017

Measurements of charm hadron production and anisotropic flow in Au+Au collisions at 200 GeV with the STAR experiment at RHIC

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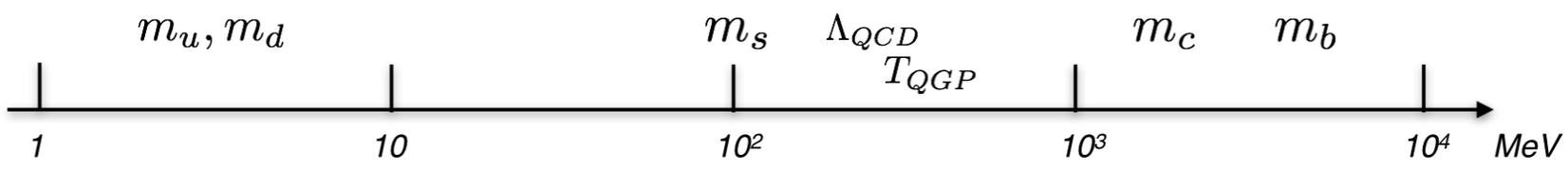
Lawrence Berkeley National Laboratory

BERKELEY LAB
U.S. DEPARTMENT OF ENERGY | Office of Science
STAR

Heavy flavor quarks as probes of QGP and initial conditions

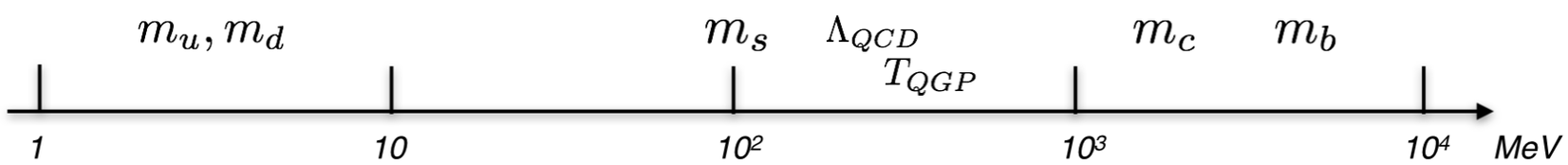


$m_{c,b} \gg T_{QGP}$ —> Produced predominantly from initial hard scatterings

$m_{c,b} \gg \Lambda_{QCD}$ —> Production cross sections amenable to pQCD calculations

==> Ideal probes to study medium effects!!

Heavy flavor quarks as probes of QGP and initial conditions



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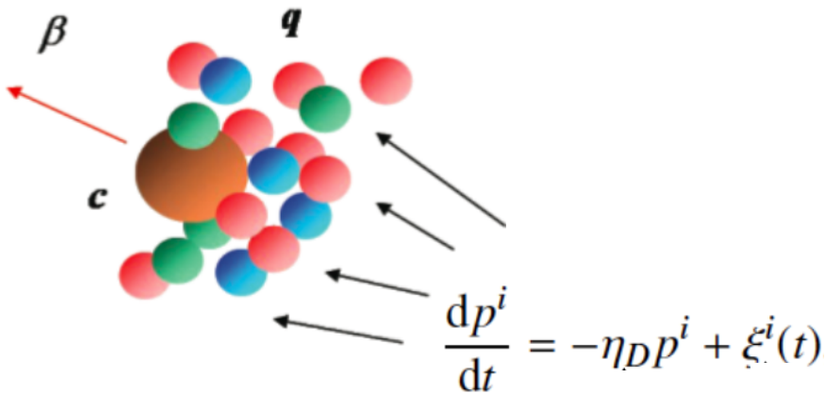
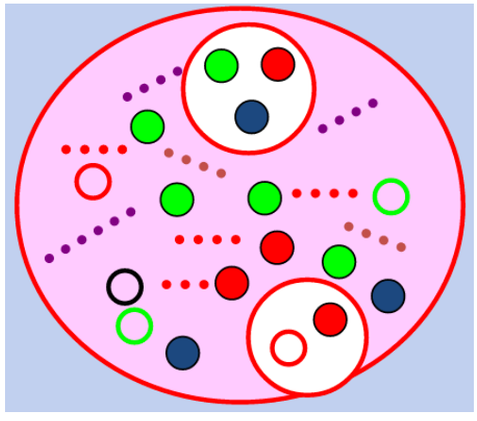
Anisotropic flow



- Elliptic and triangular flow: heavy quark diffusion through medium —> medium properties
- Directed flow: impact of early time magnetic field

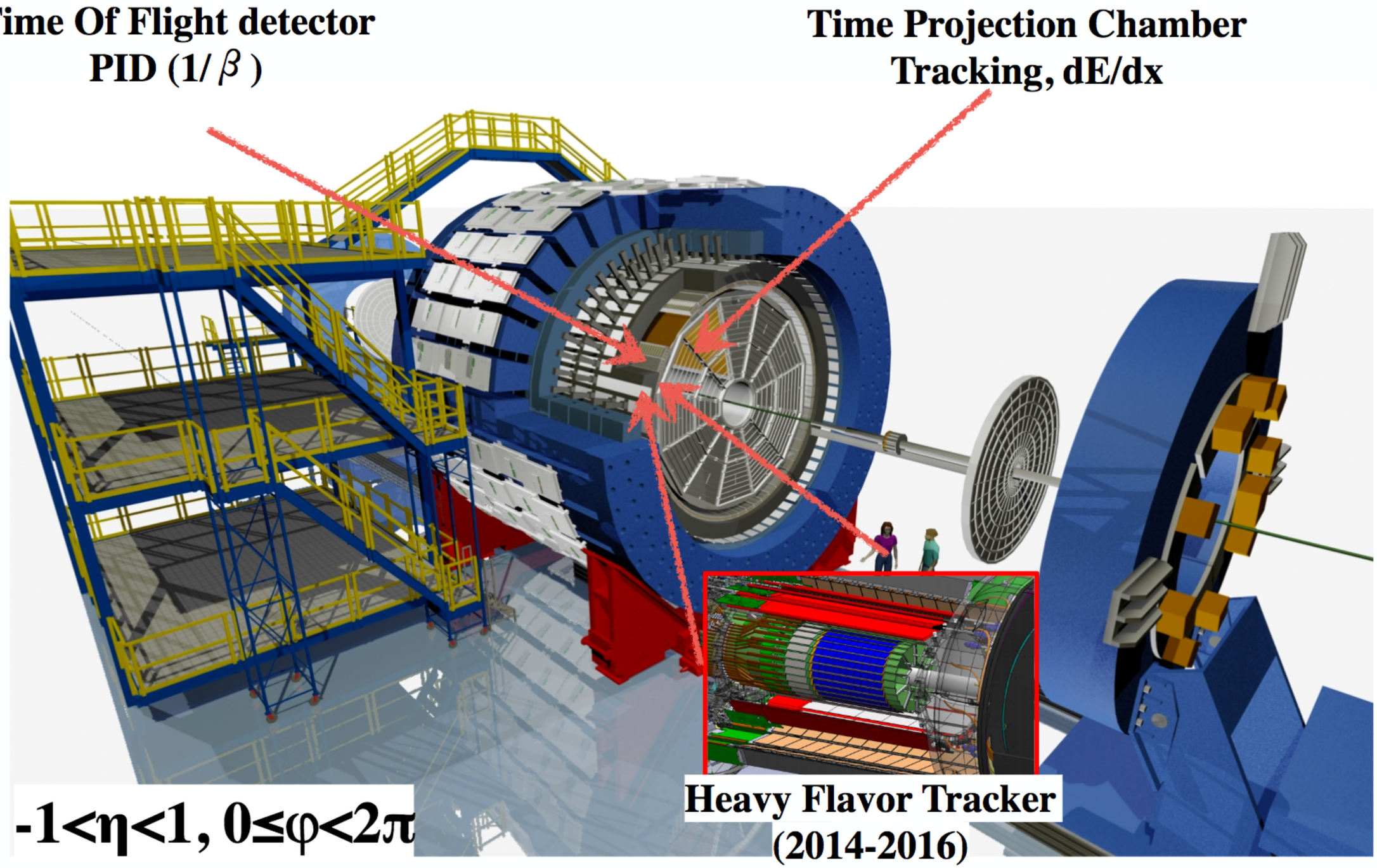
Production and hadrochemistry



?

- In medium energy loss
- D_s, Λ_c yields: hadronization mechanism

STAR Heavy Flavor Tracker (HFT)



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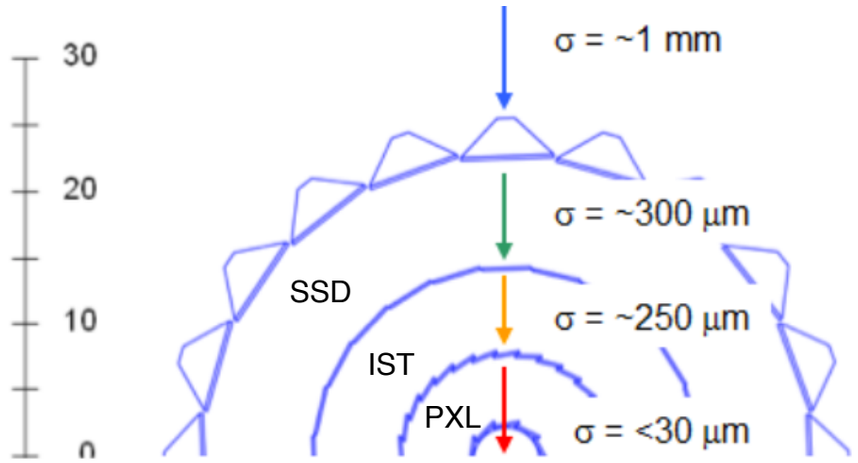
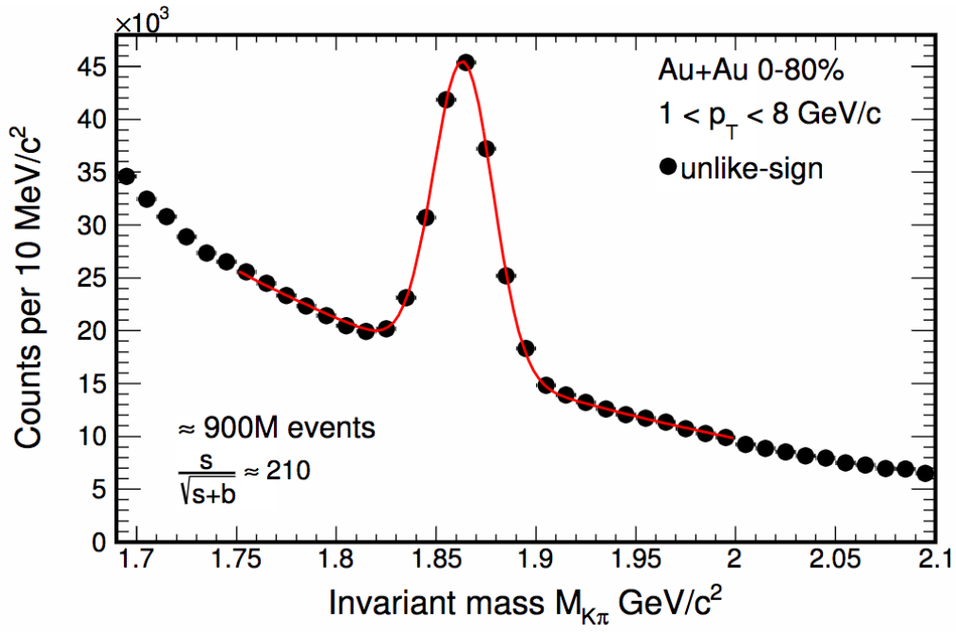
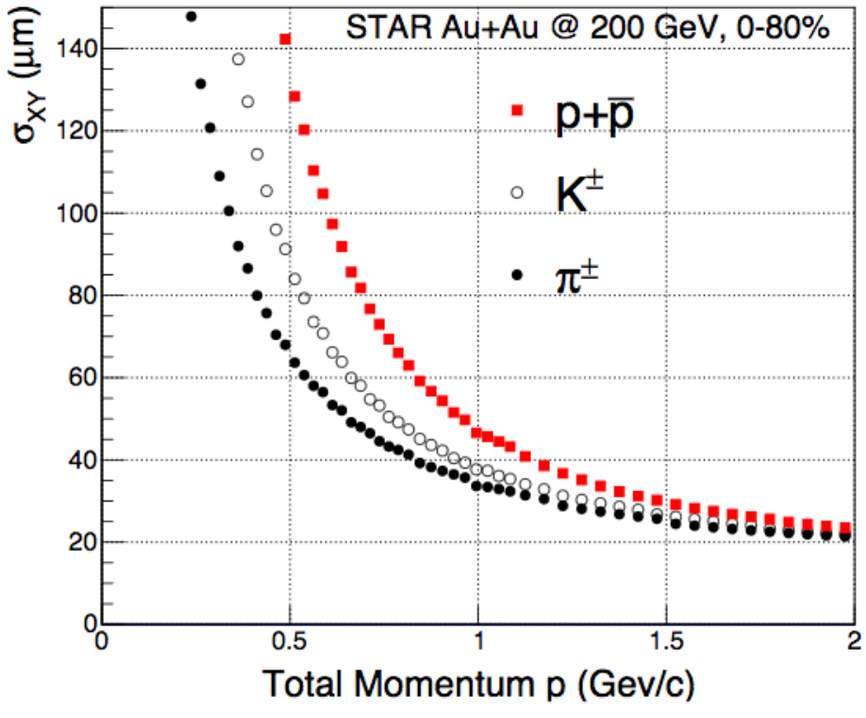


- Excellent track pointing resolution
- Enables topological reconstruction of heavy flavor hadrons.



STAR: Phys. Rev. Lett. 118, 212301 (2017)

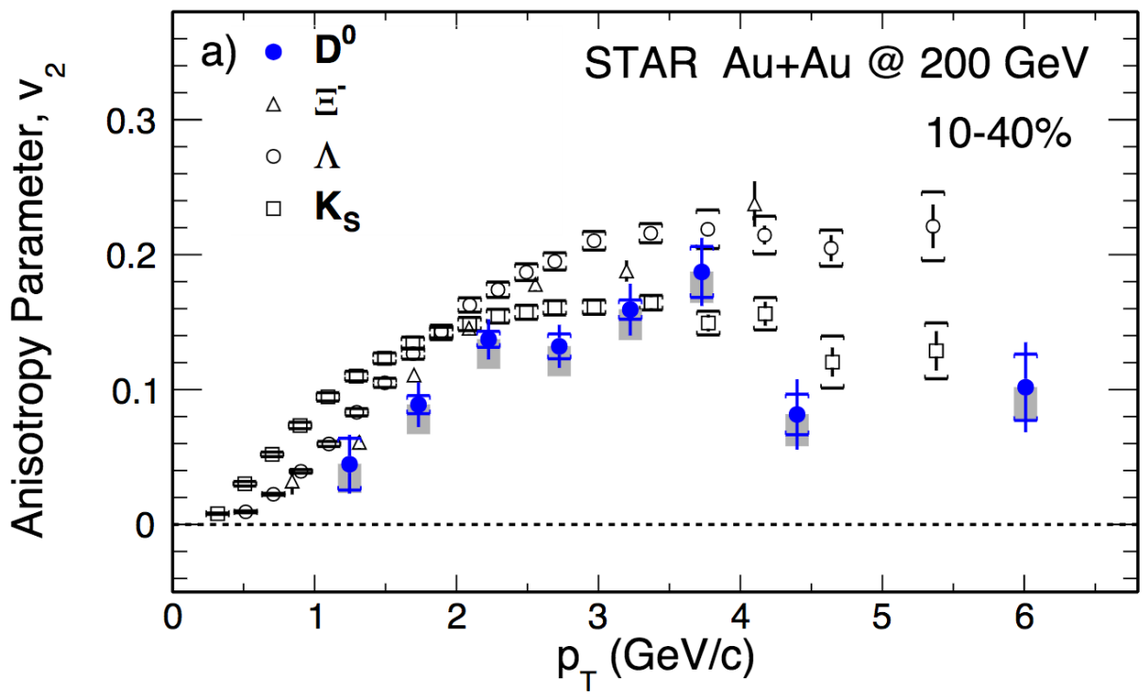


	w/o HFT	w/ HFT
	2010+2011	2014
#events(MB) analyzed	1.1 billion	~900 million
sig. per billion events	13	220

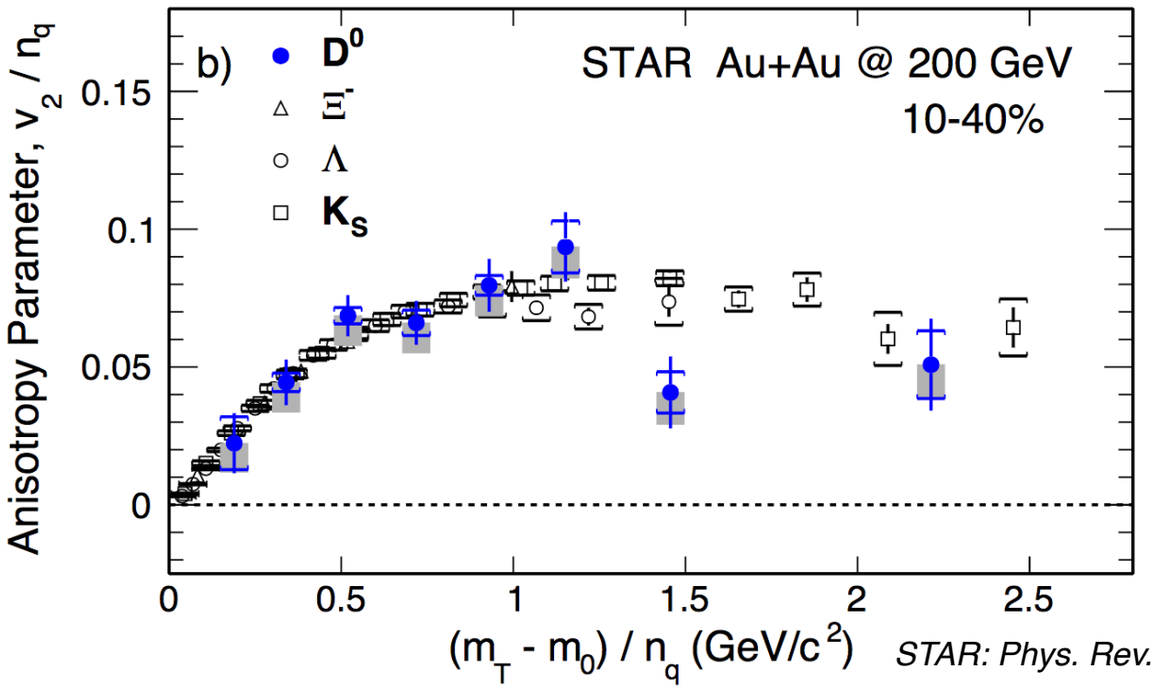
STAR: Phys. Rev. Lett. 113, 142301 (2014)

STAR: Phys. Rev. Lett. 118, 212301 (2017)

Elliptic flow of D^0 mesons



- Large v_2 values, comparable to light hadrons, is seen for D^0 mesons
- Clear mass ordering seen below 2 GeV/c

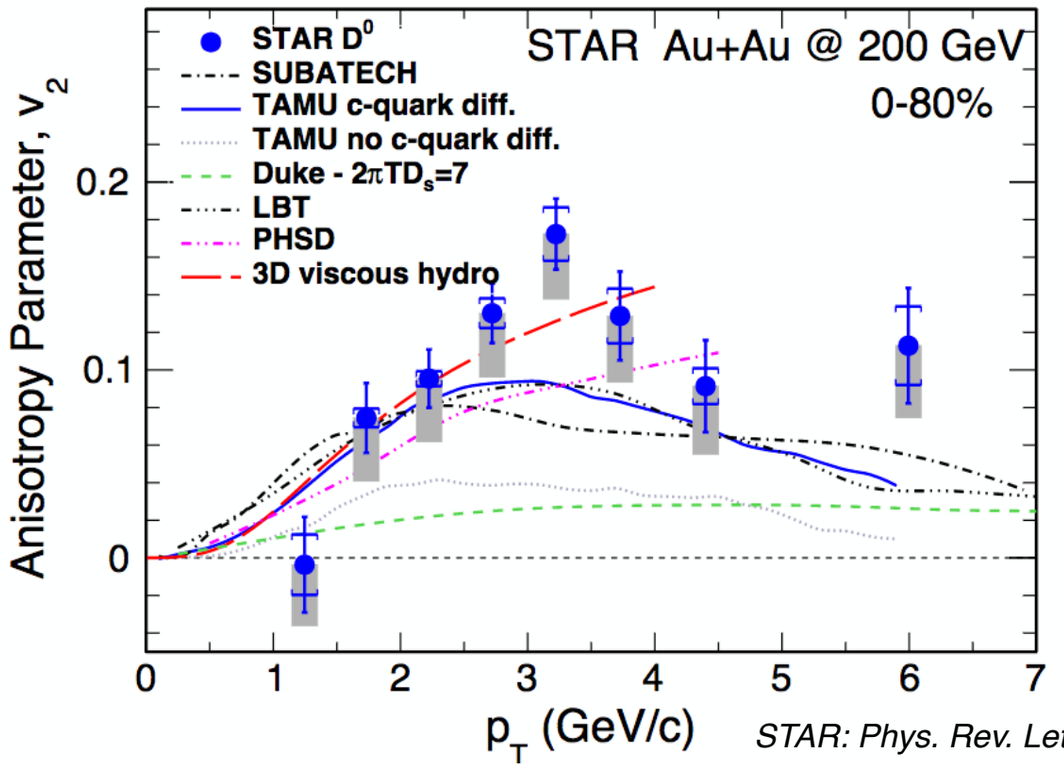


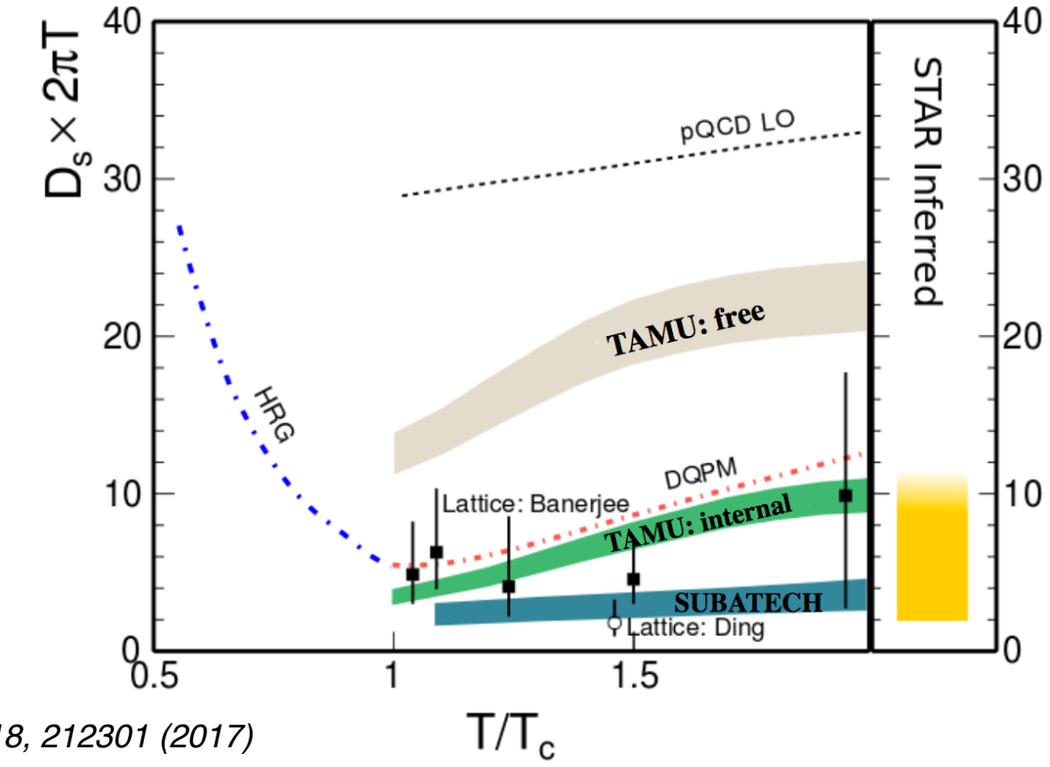
- v_2 values of D^0 scaled with number of constituent quarks (NCQ) follow the same trend as light hadrons
- Suggest charm quarks flow with the QGP

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

STAR: Phys. Rev. Lett. 118, 212301 (2017)

Theory comparisons

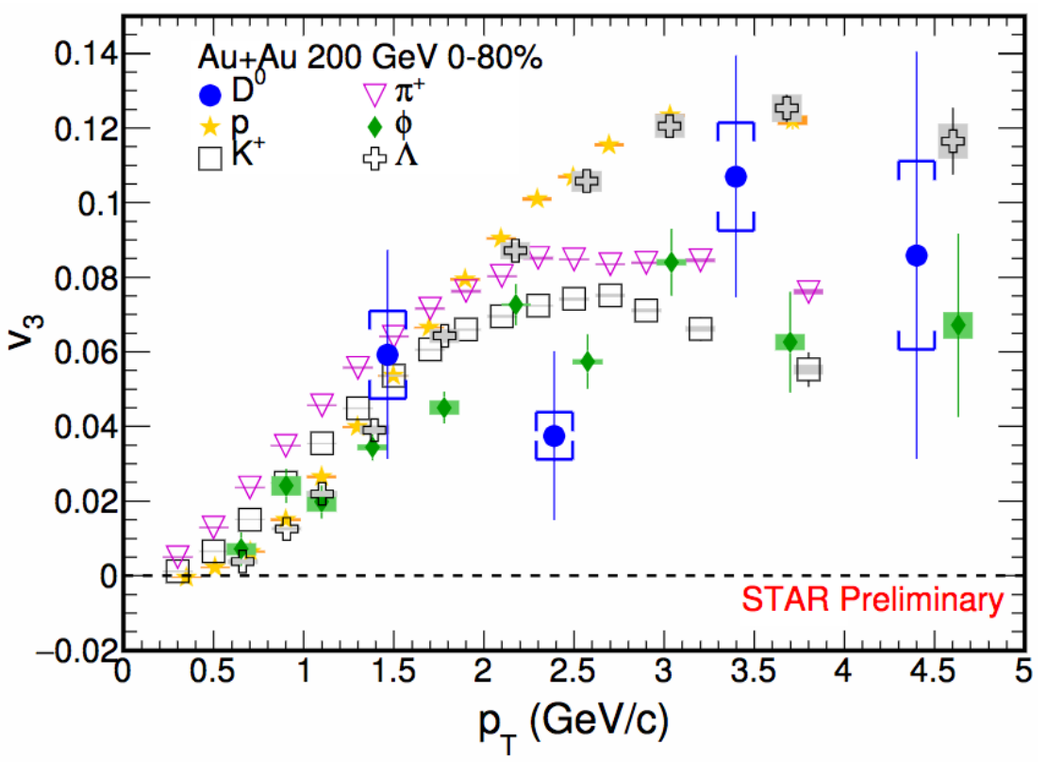


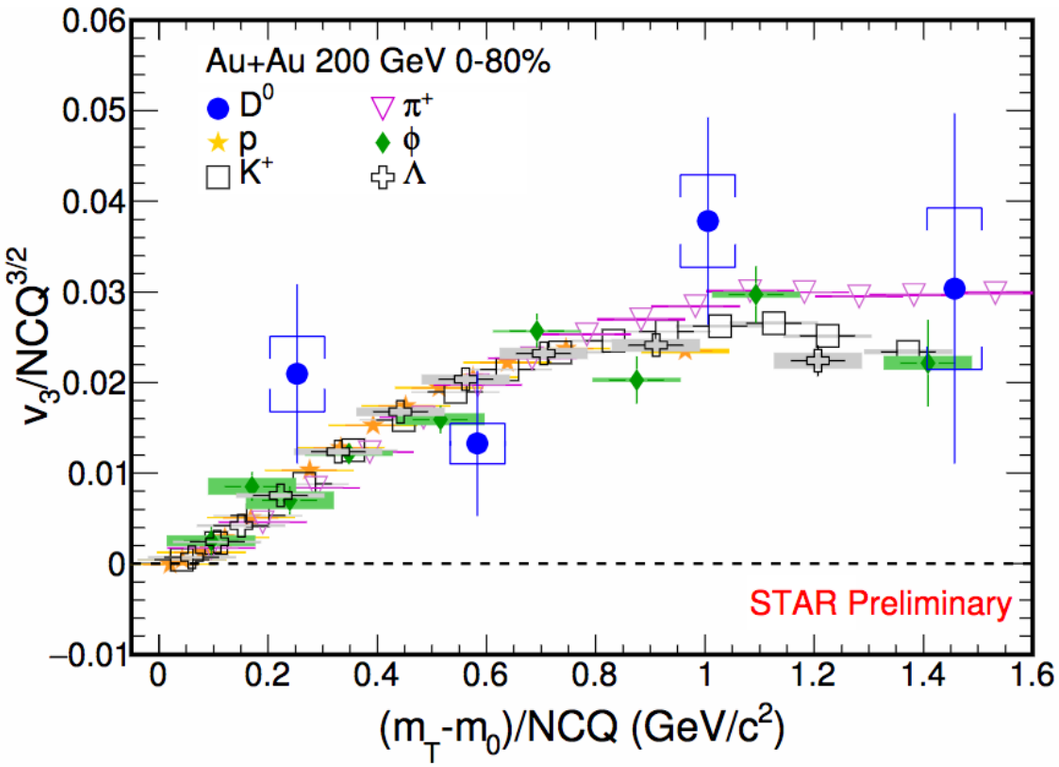


- 3D viscous hydro describes the data well below 4 GeV/c
  - suggest thermalized charm quarks in the medium
- Dynamic models with temperature dependent $2\pi TD_s$ in the range 2 – 12 (in the range T_c — $2T_c$), also describe the data well

	$2\pi TD_{HQ}$	χ^2/N.D.F.	p value
SUBATECH	2-4	15.2/8	0.06
TAMU c diff.	5-12	10.0/8	0.26
TAMU no c diff.	…	29.5/8	$2x10^{-4}$
Duke	7	35.7/8	$2x10^{-5}$
LBT	3-6	11.1/8	0.19
PHSD	5-12	8.7/7	0.28
3D viscous hydro	…	3.6/6	0.73

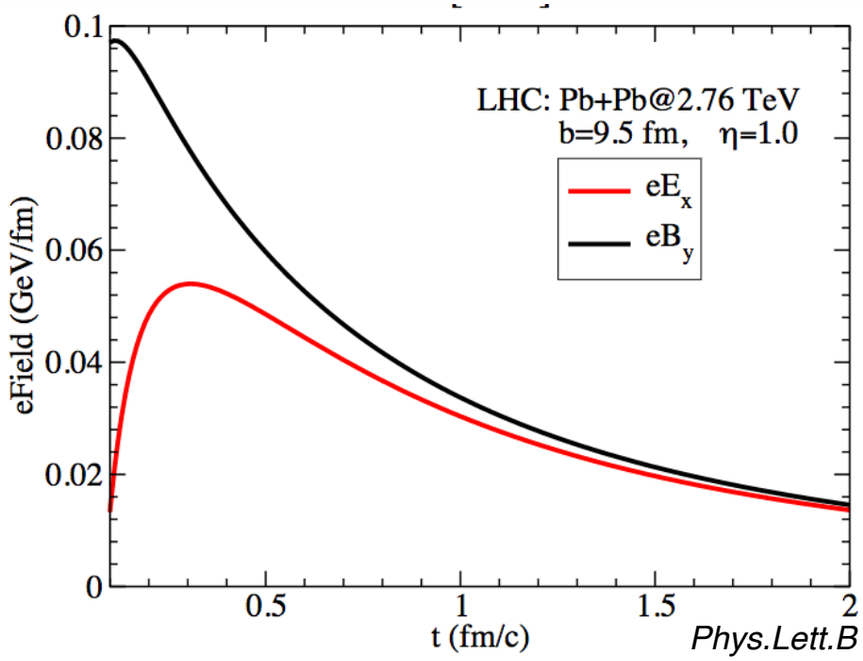
Triangular flow



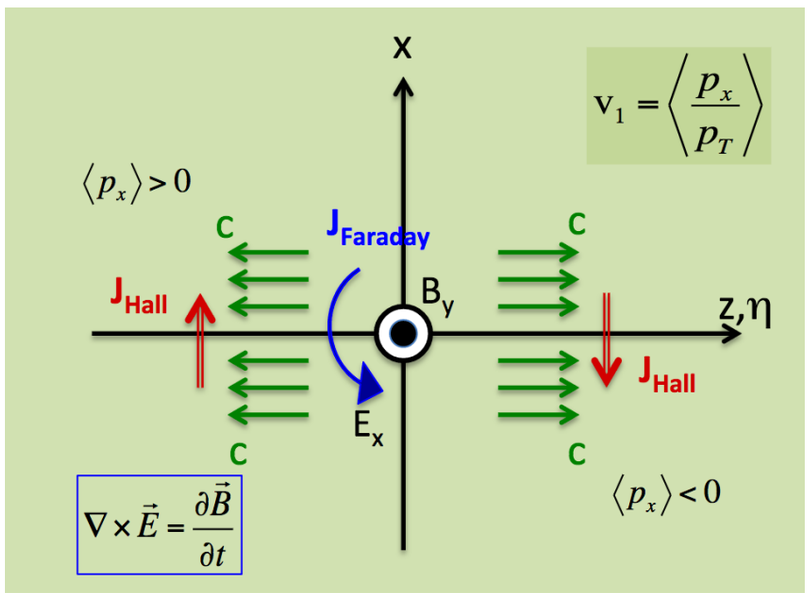


- Non-zero D^0 v_3 values; comparable to light hadron v_3
- Consistent with NCQ scaling within large error bars
- Also points to strong interactions between charm quarks and the QGP medium

Directed flow, probe for early magnetic field?

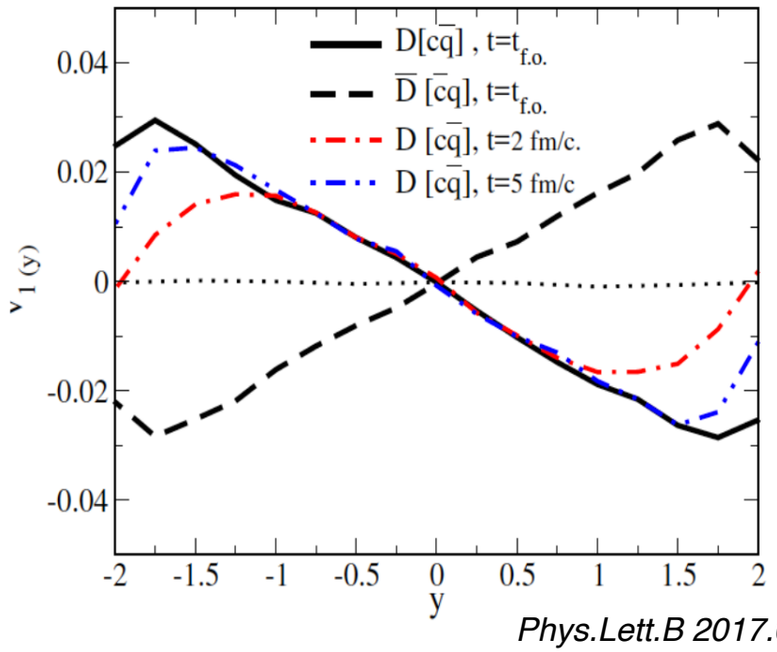


Phys.Lett.B 2017.02.046



V.Greco QM 2017

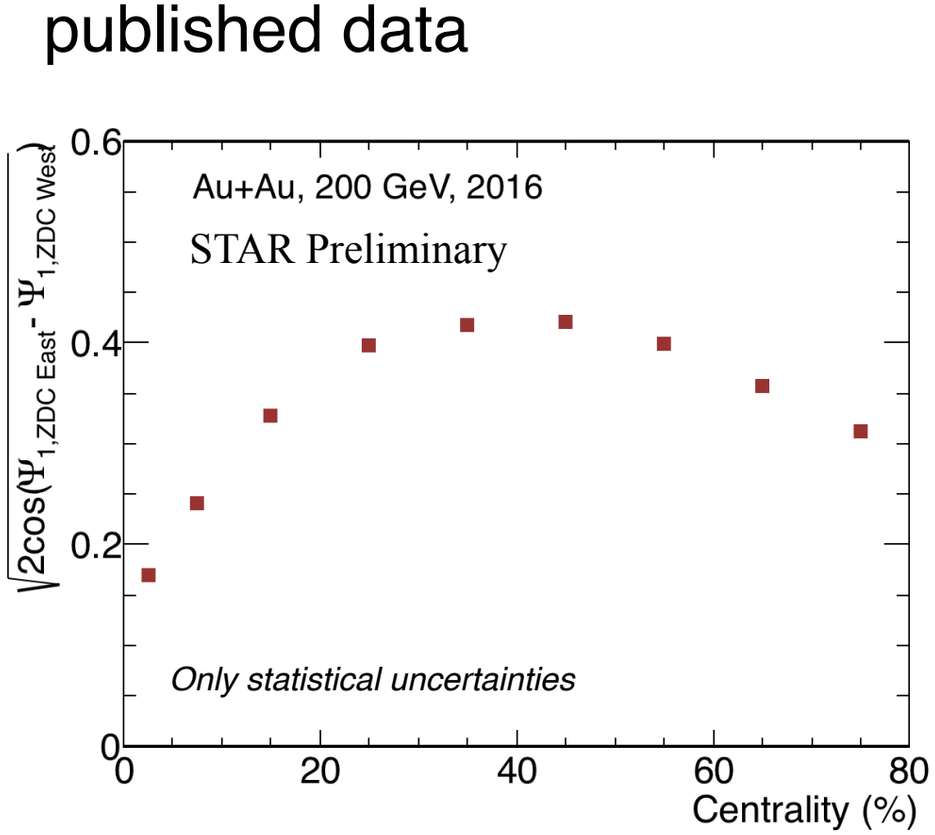
- Large magnetic field (~10^{19} Gauss) produced in early stages of heavy-ion collisions
- Heavy quarks predominantly produced during initial hard scatterings
  - Experience Lorentz deflection transverse to the direction of motion
  - Transient magnetic field ==> gives rise to a Faraday current; opposite to Lorentz deflection
  - Significant directed flow (v_1) is predicted for D^0 mesons



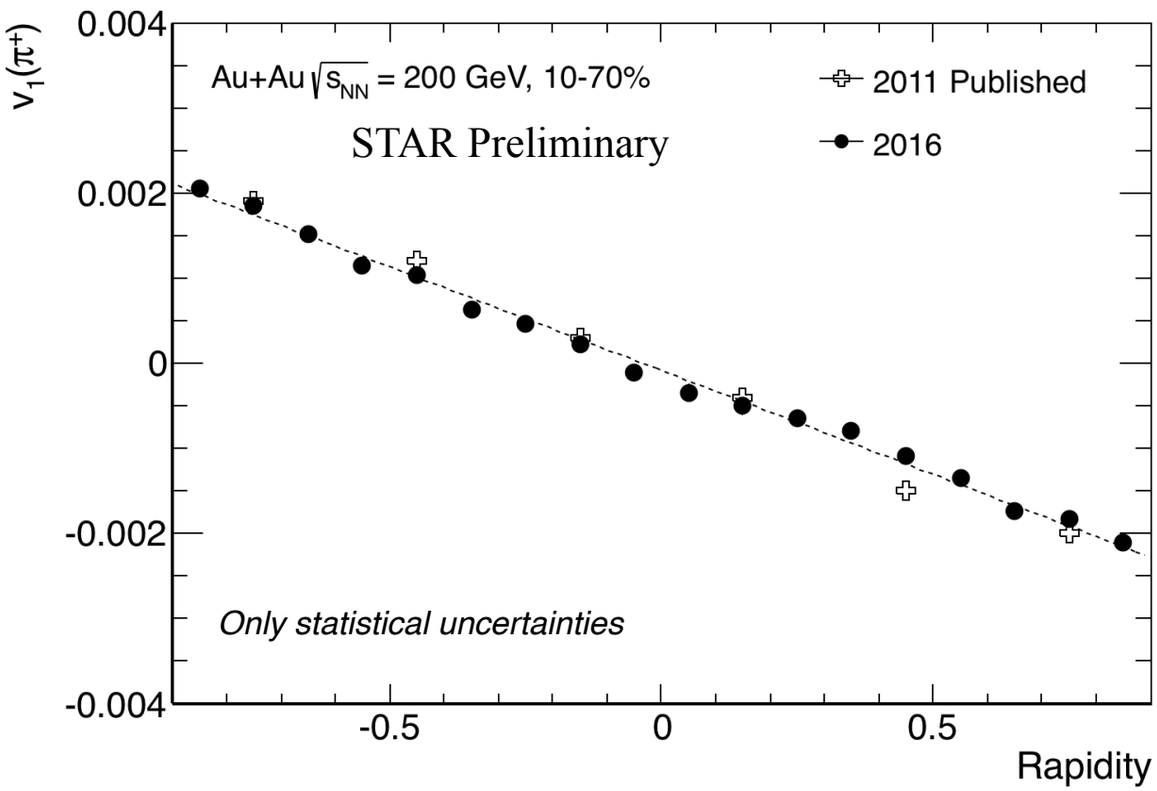
Phys.Lett.B 2017.02.046

D^0 meson directed flow measurement

- Study of D^0 azimuthal distribution w.r.t. event plane that is determined from spectator neutrons detected by ZDC-SMD ($\eta > 6.4$)
- Pion v_1 values (with HFT used in tracking) are consistent with the published data



STAR 2011 Published: Phys. Rev. Lett. 108, 202301 (2012)



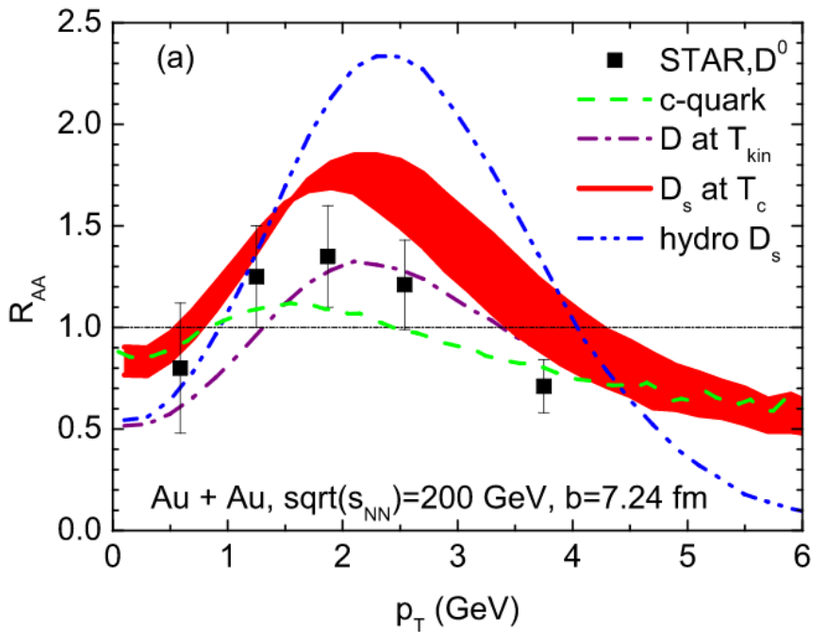
- Measurement of D^0 v_1 is ongoing using data (with HFT) from 2014+2016

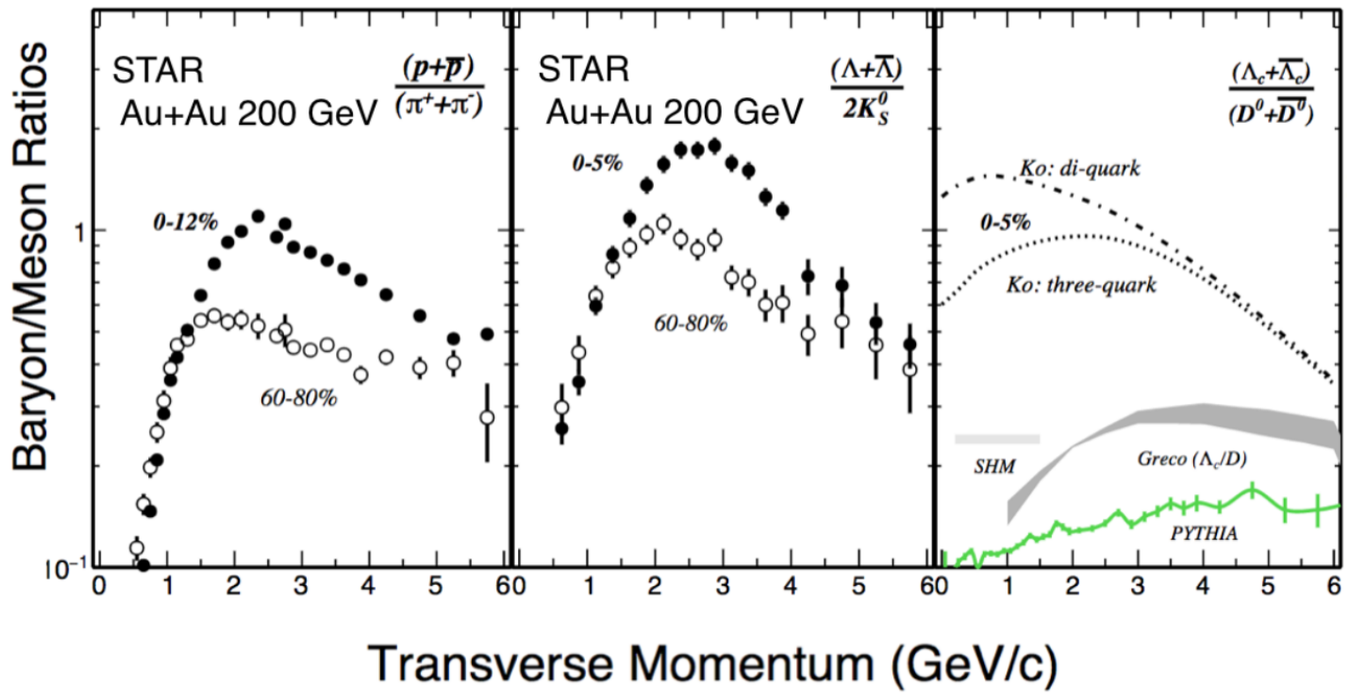
Strangeness and baryon enhancements

- How do charm quarks hadronize in QGP?
- In case of coalescence hadronization of charm, one expects for intermediate p_T (2-6 GeV/c):
  - enhancement of strange relative to non-strange charmed mesons
  - enhancement of charmed baryon/meson ratio

Ko: Phys.Rev.C 79 (2009) 044905
Greco: Phys.Rev.D 90 (2014) 054018
SHM: Phys.Rev.C 79 (2009) 044905

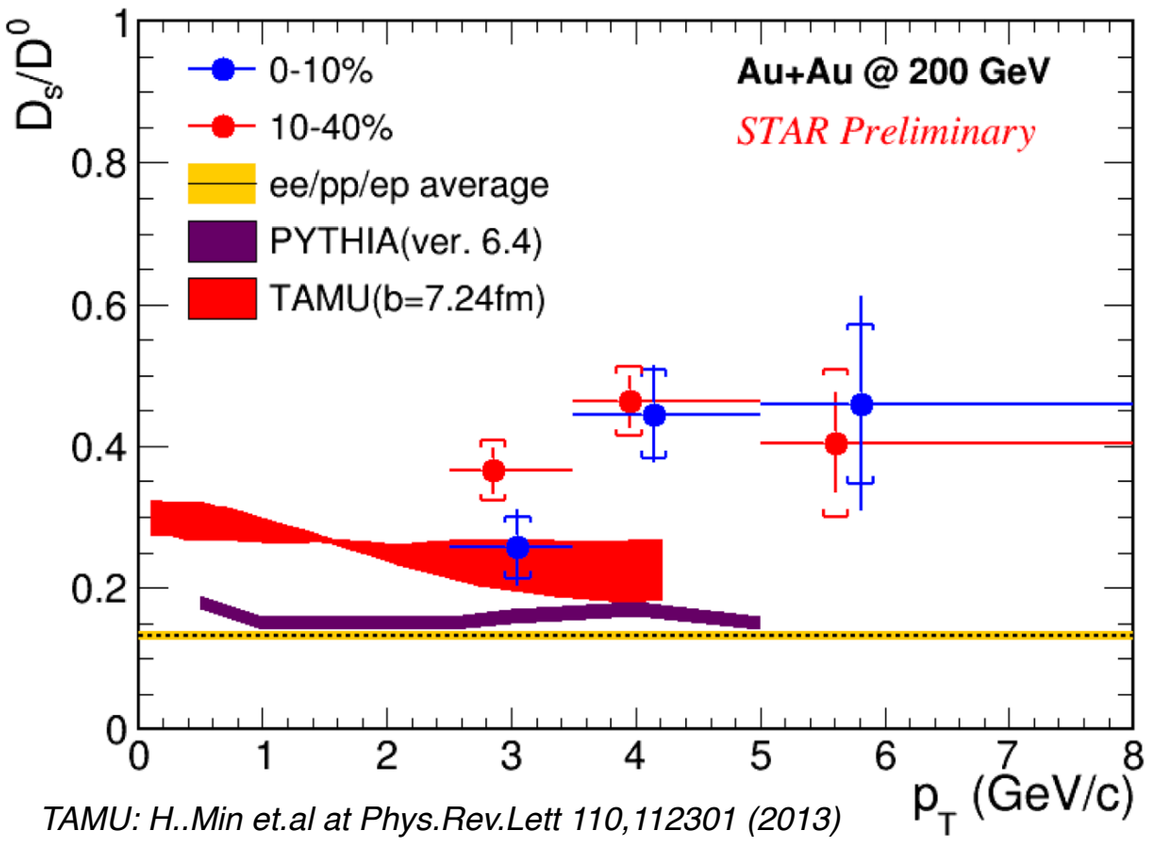
H. Min et al. Phys.Rev.Lett 110,112301 (2013)



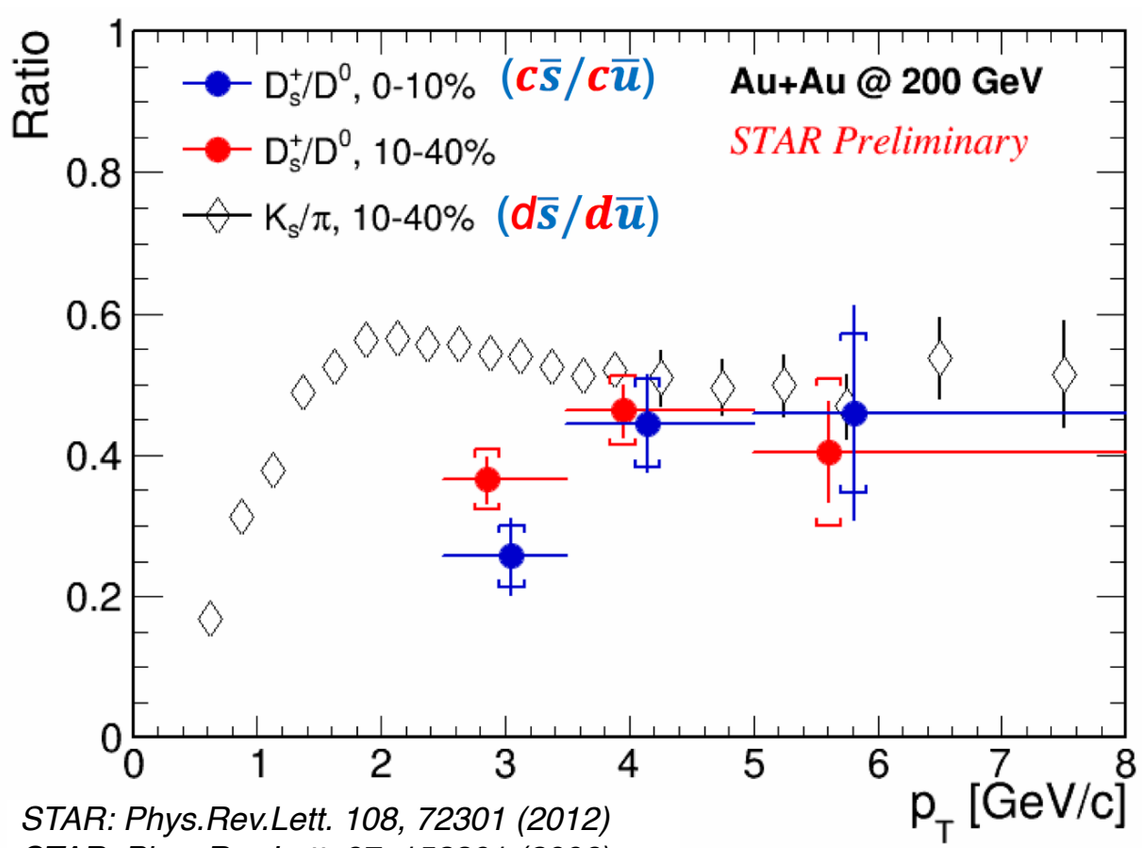


- Magnitudes of enhancement also depend on degree of charm quark thermalization, extent of strangeness enhancement, presence of diquarks

D_s enhancement at RHIC



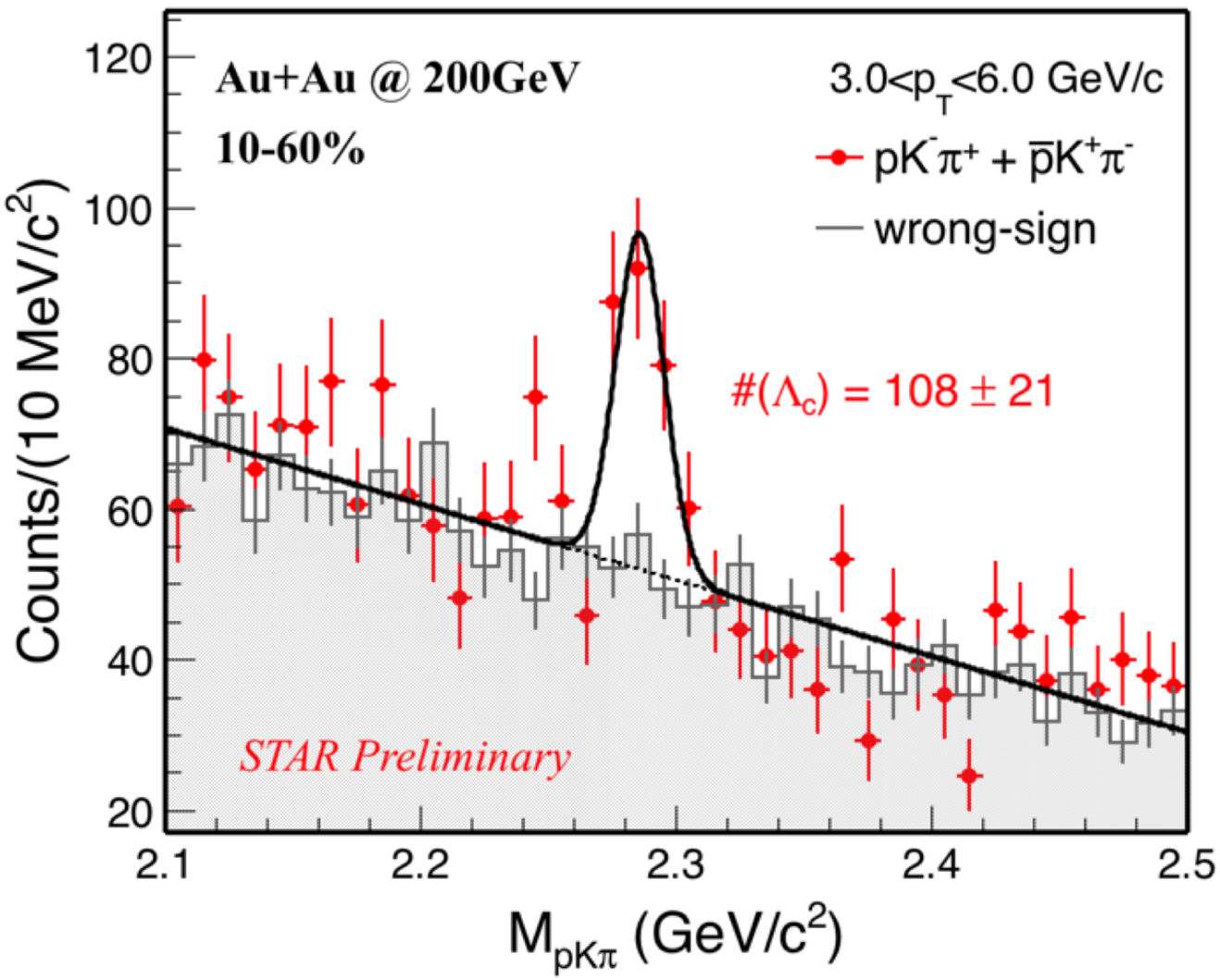
TAMU: H..Min et.al at Phys.Rev.Lett 110,112301 (2013)



STAR: Phys.Rev.Lett. 108, 72301 (2012)
STAR: Phys.Rev.Lett. 97, 152301 (2006)

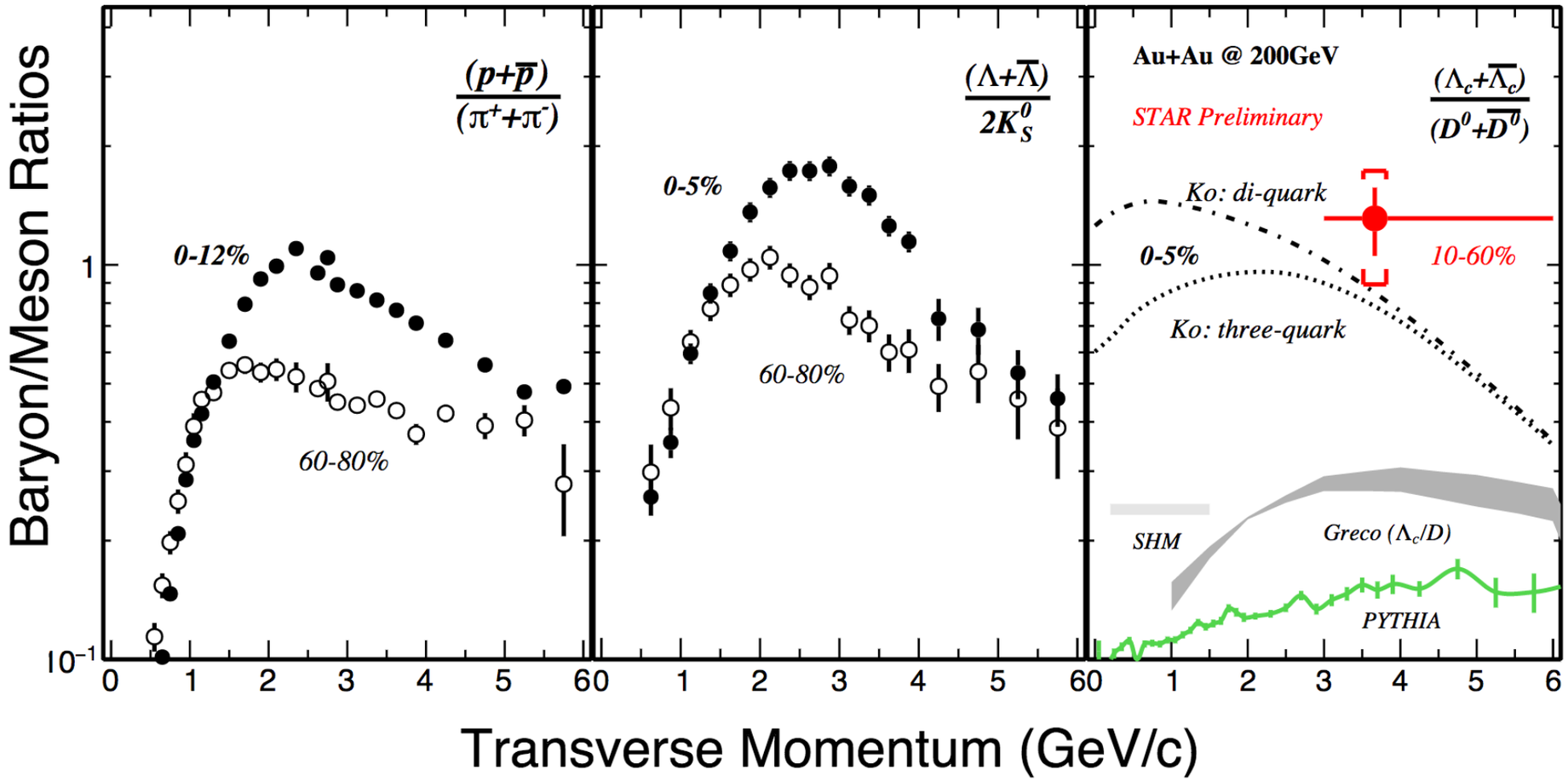
- Strong enhancement is seen for the D_s/D^0 yields ratio relative to PYTHIA
  ==> charm quarks in QGP hadronize very differently than in vacuum
- Enhancement is larger than in the TAMU model (uses coalesence mechanism) prediction.
- Similar enhancement as for the light hadrons for $p_T > 3.5$ GeV/c. Smaller values in 2.5 - 3.5 GeV/c

Λ_c production in heavy-ion collisions



- Λ_c ($c\tau \sim 60\mu m$) reconstructed in $\pi K p$ channel
- First measurement in heavy-ion collisions!

Λ_c production in heavy ion collisions



Greco: is for Λ_c/D

- Significant baryon/meson enhancement in the charm sector
- Magnitude is consistent with that of light hadrons
- Coalescence models with thermalized charm quarks in medium agree with the measurement

Summary

- Elliptic and triangular flow of D^0:
  - Follow mass ordering; NCQ scaled values agree with those for light hadrons
  - Model calculations with the temperature dependent charm quark diffusion coefficient describe v_2 data
  - Can be described by 3D viscous hydro at low p_T (< 4 GeV/c)
  - Suggest near thermalized charm quarks flowing with the QGP

- Significant enhancement of D_s/D^0 and Λ_c/D^0 ratios
  - Similar enhancements with those for light hadrons
  - For Λ_c the coalescence model with thermalized charm quarks agrees with data

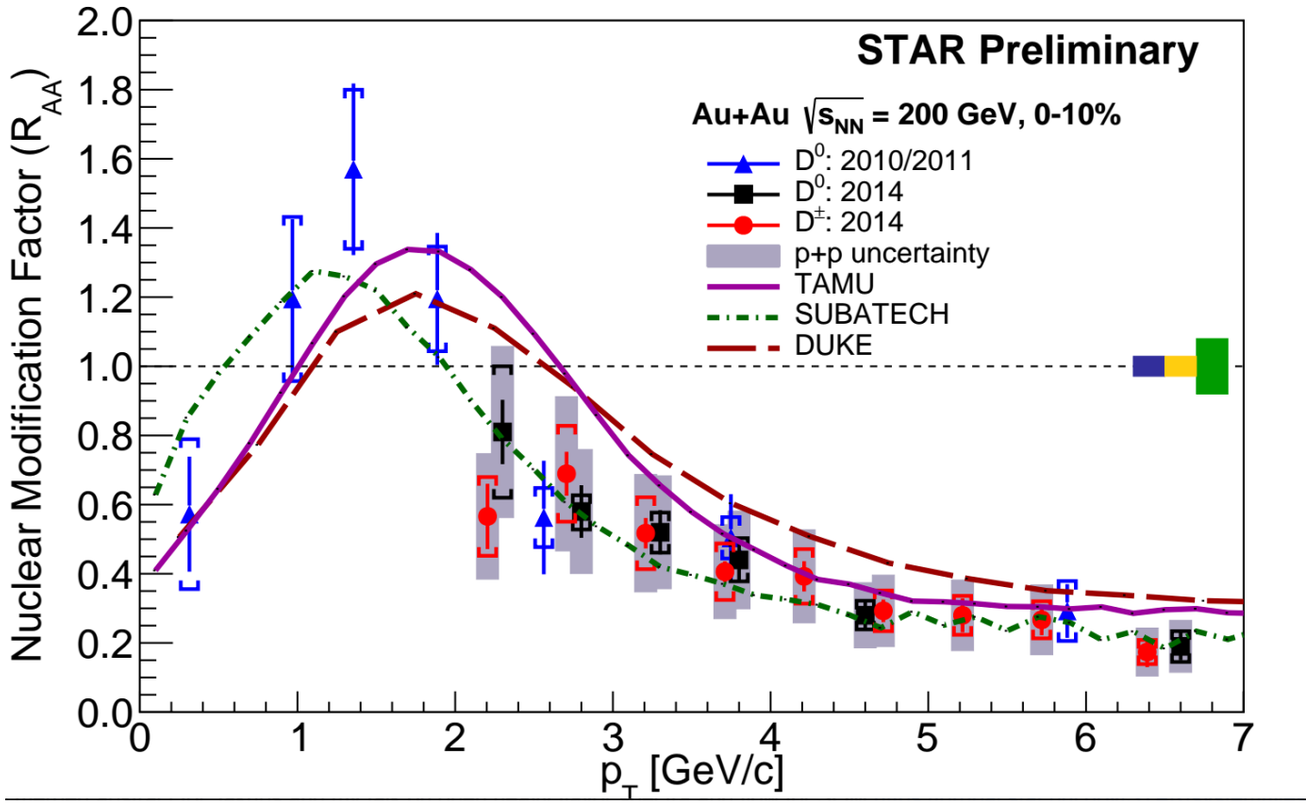
- Measurements suggest strongly interacting and thermalized charm quarks in QGP medium

- Results are from 2014 data. New results are coming soon with the improved precision from 2014+2016 data combined

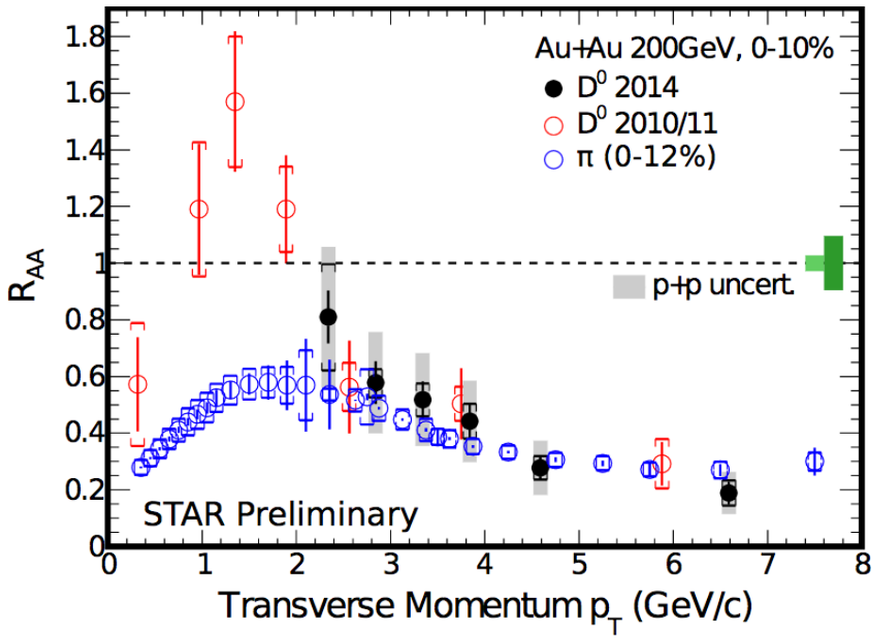
Back Up

Heavy flavor suppression at RHIC

- Energy loss of color charged partons through medium: radiative and collisional energy loss
- Expect $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

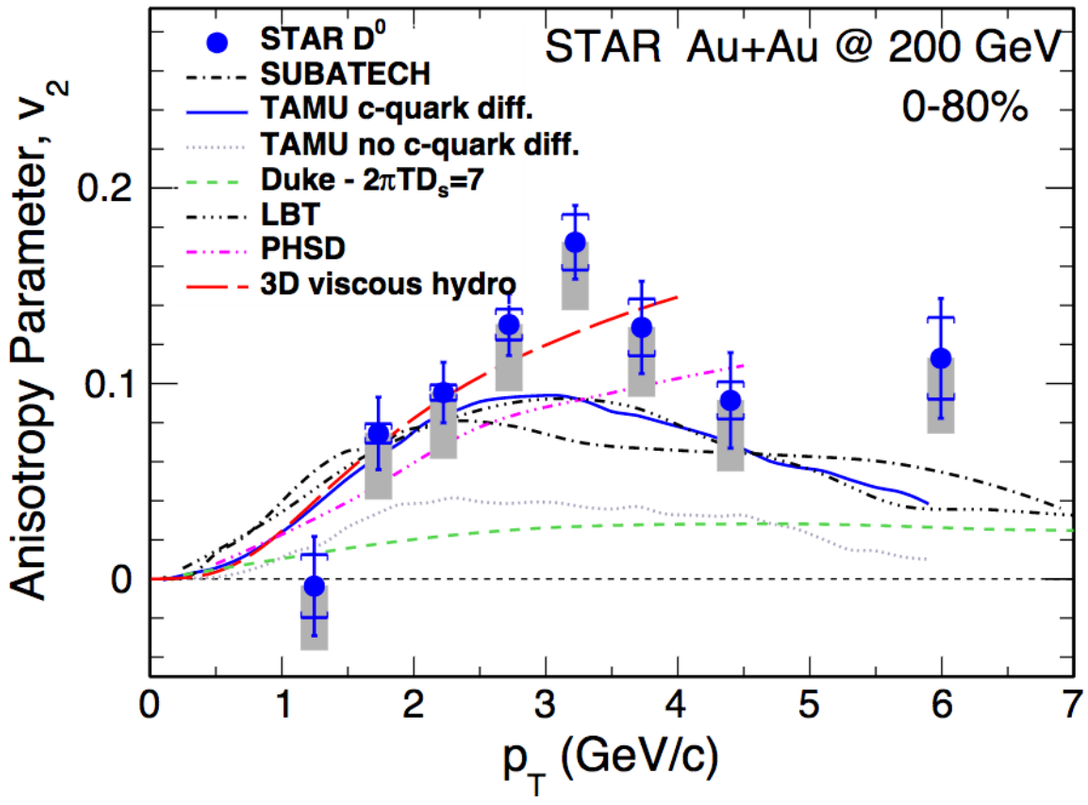


$$R_{\mathrm{AA}} = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}} \rangle \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$



- Strong suppression of D^0 and $D^{+/-}$ at high p_T
- R_{AA} values for D^0 are consistent with those for pions (for $p_T > 4$ GeV)
  - values depend on the spectrum shape
  - not R_{AA} of charm quarks (hadronization)
- Models with strong charm medium interaction describe the data.

Elliptic flow and charm quark diffusion



SUBATECH: pQCD + hard thermal loop
P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, Strangeness in quark matter

TAMU: T-matrix, non-perturbative, internal energy potential
M. He, R. J. Fries, and R. Rapp, PRC86, 014903 (2012)

Duke: free constant Ds, fit to LHC high p_T R_{AA}
S. Cao, G.-Y. Qin, and S. A. Bass, PRC88, 044907 (2013)

hydro: A 3D viscous hydrodynamic model
L.-G. Pang, Y. Hatta, X.-N. Wang, and B.-W. Xiao,PRD91, 074027 (2015)

PHSD: Parton-Hadron-String Dynamics, a transport model
H. Berrehrah et al. PRC90 (2014) 051901

LBT: A Linearized Boltzmann Transport model
S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, PRC94, 014909 (2016)