Supported in part by U.S. DEPARTMENT OF ENERGY

Overview of recent heavy flavor measurements from the STAR experiment

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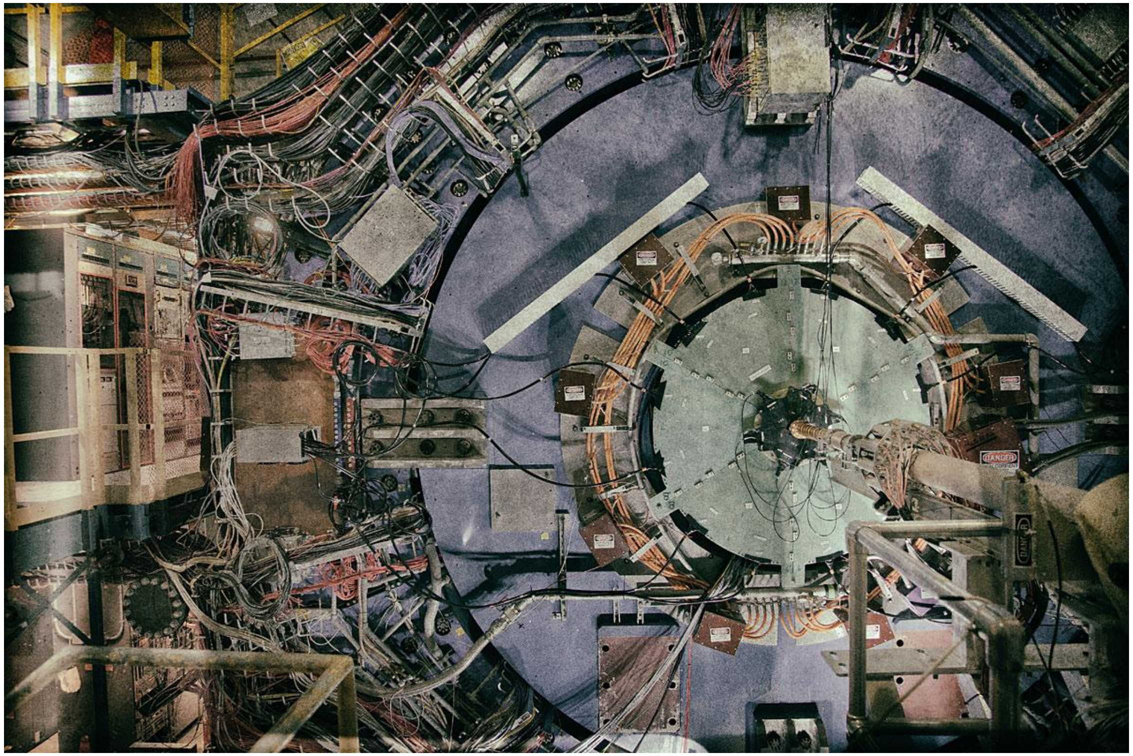
10th International Conference on New Frontiers in Physics (ICNFP 2021)

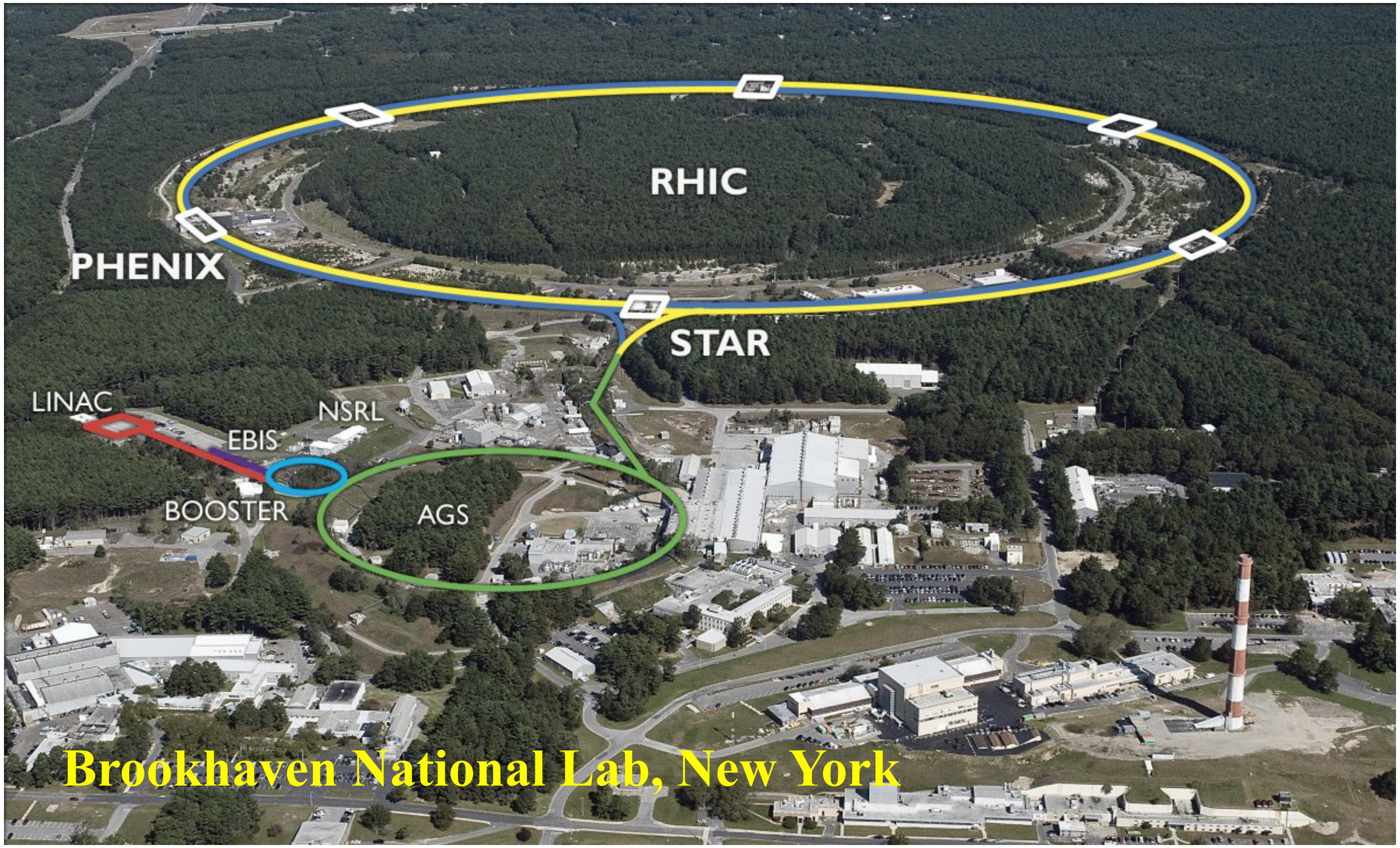
Outline

- Relativistic Heavy Ion Collider (RHIC)
- The STAR detector
- Open heavy flavor measurements
- Quarkonium measurements



Relativistic Heavy Ion Collider (RHIC)

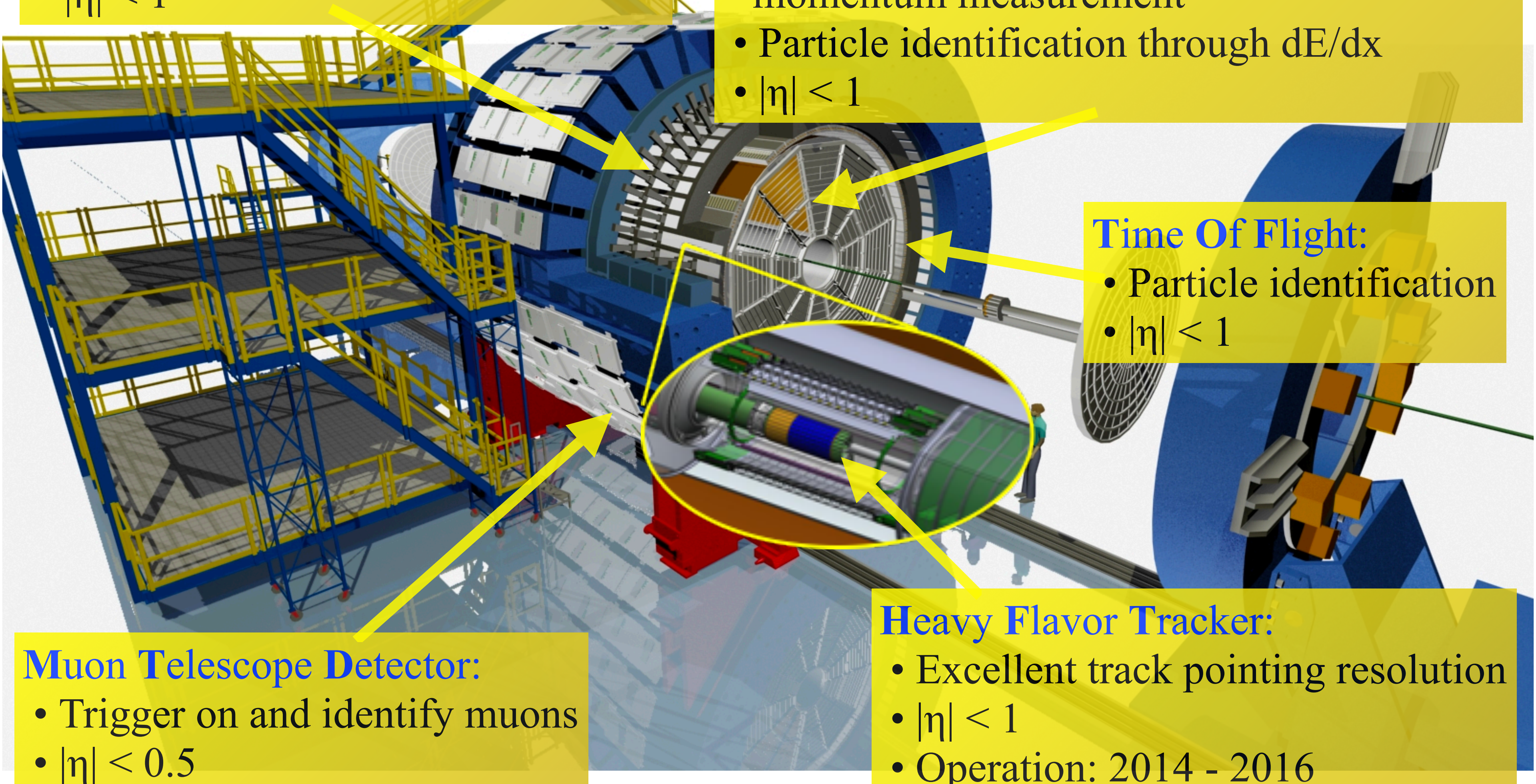
- One of the most versatile particle colliders in the world!
  - The only collider with polarized proton beam
  - Different collision systems: p+p, Au+Au, p+Au, d+Au, U+U, …
  - Wide collision energy range: 3.0 (fixed-target mode) – 200 GeV for Au+Au, and up to 510 GeV for p+p



The STAR detector

Barrel ElectroMagnetic Calorimeter:
- Trigger on and identify electrons
- $|\eta| < 1$

Time Projection Chamber:
- Charged particle tracking and precise momentum measurement
- Particle identification through dE/dx
- $|\eta| < 1$



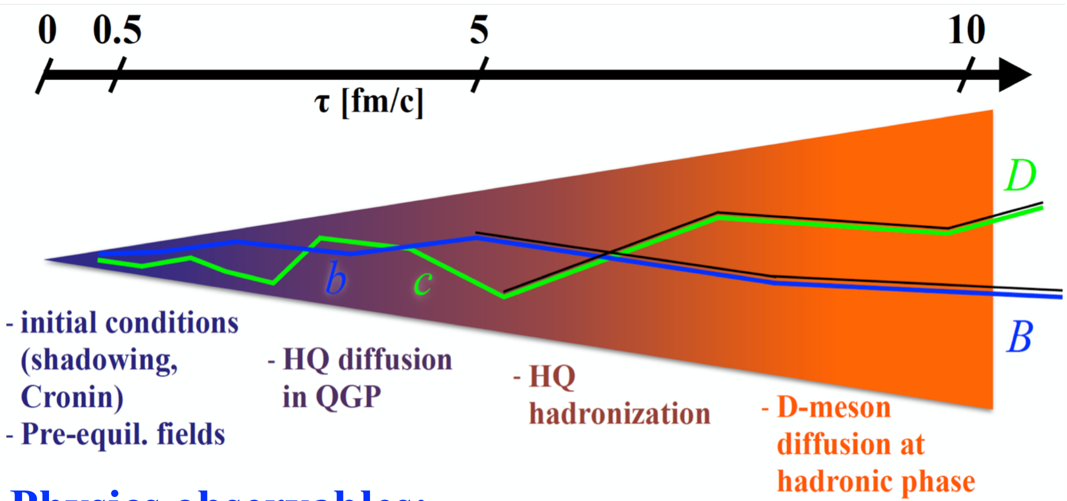
Time Of Flight:
- Particle identification
- $|\eta| < 1$

Muon Telescope Detector:
- Trigger on and identify muons
- $|\eta| < 0.5$

Heavy Flavor Tracker:
- Excellent track pointing resolution
- $|\eta| < 1$
- Operation: 2014 - 2016

Motivation - Open heavy flavor in A+A collisions

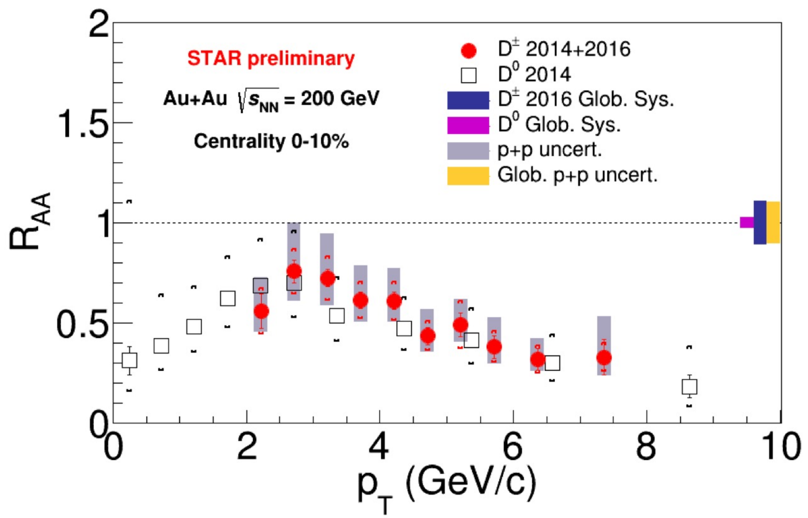
- The production cross section can be calculated by perturbative QCD (pQCD)
- Dominantly produced during initial hard scatterings at early stage of A+A collisions
- Experience the entire evolution of the QGP medium

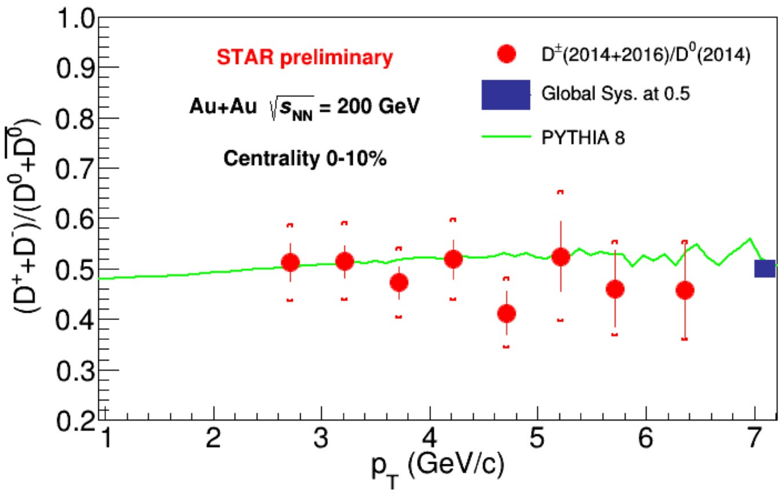


Physics observables:

- Diffusion:
  - elliptic flow (v_2)
- Energy loss:
  - nuclear modification factor (R_{AA}, R_{CP})
- Hadronization:
  - relative yields of various hadrons

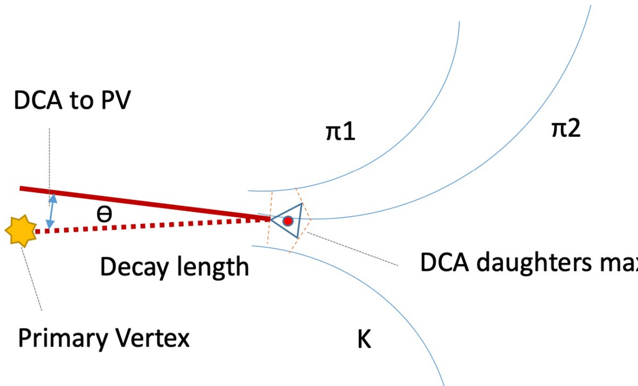
$D^{\pm}$ production in Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV





$$R_{AA} = \frac{1}{N_{coll}} \frac{d^2N_{AA}/(dp_T dy)}{d^2N_{pp}/(dp_T dy)}$$

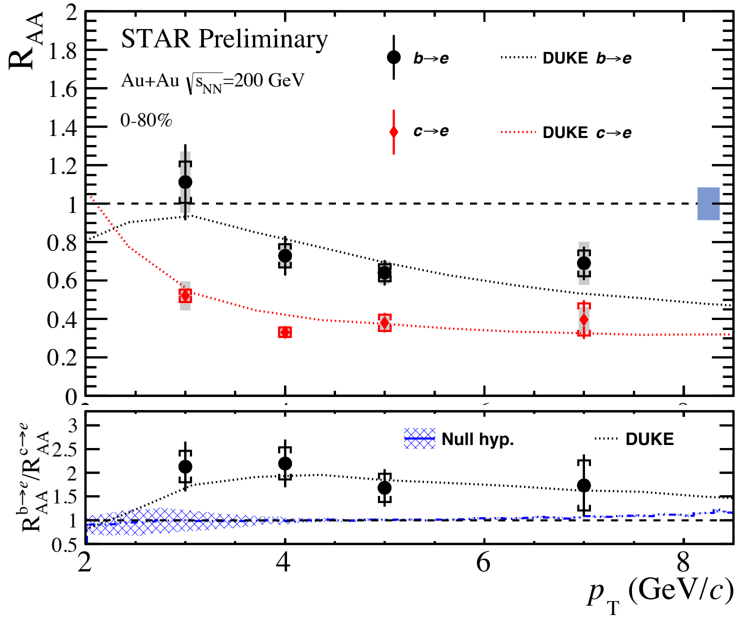
- $D^{\pm}$ R_{AA} is consistent with D^0 R_{AA} within uncertainties
  - Significant suppression at high-p_T in central Au+Au collisions
- $D^{\pm}/D^0$ yield ratio is consistent with PYTHIA8 predictions and has no significant p_T dependence

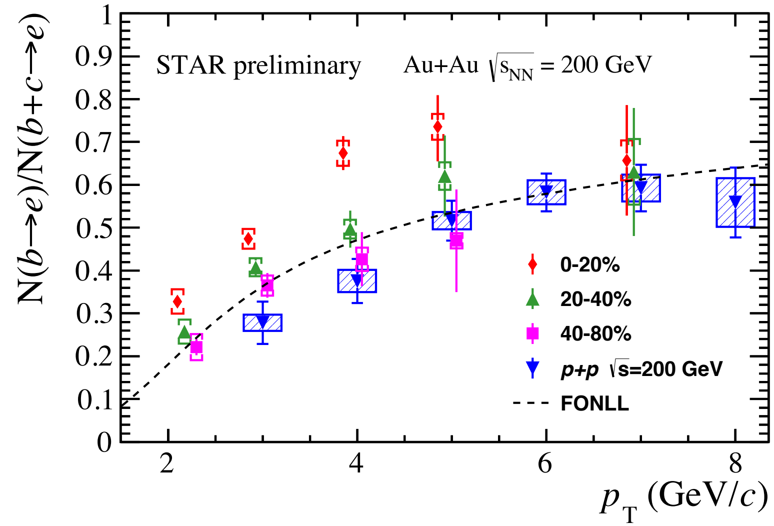


More details about open charm hadrons in Jan Vanek's talk at 11:00 AM tomorrow at Room 2

c,b→e R_{AA} in Au+Au collisions at 200 GeV

- b→e and c→e are identified using DCA from HFT





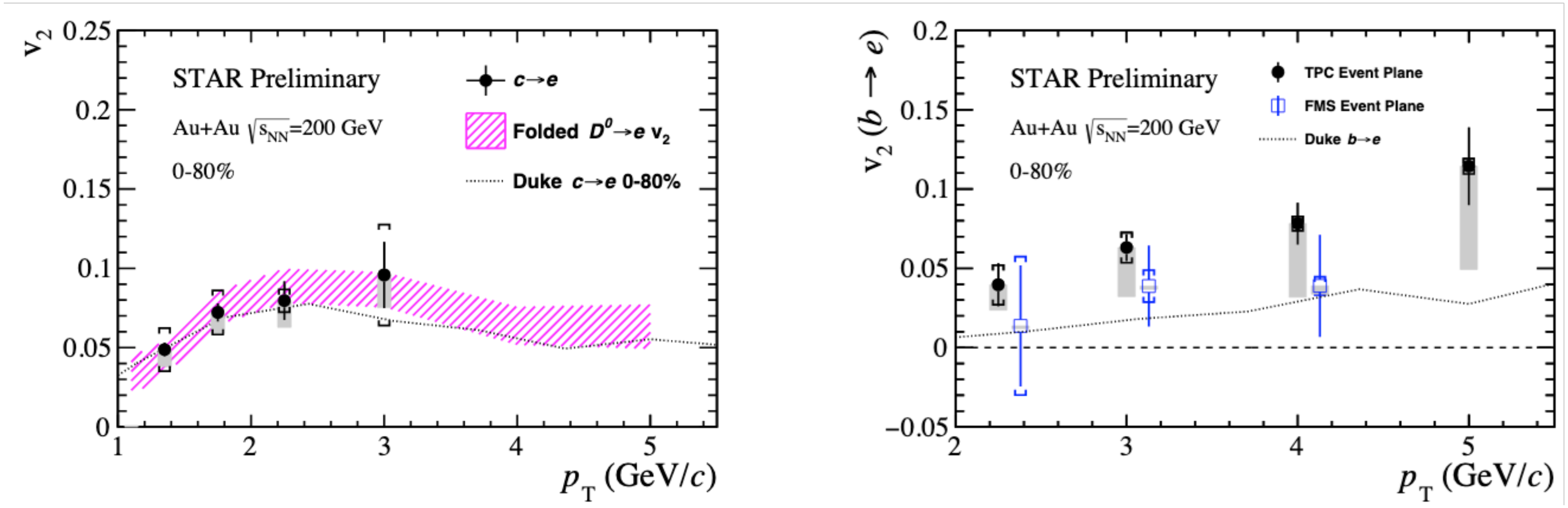
STAR: Phys. Rev. C 92 (2015) 024907

$$R_{AA}^{b/c\rightarrow e} = \frac{f_{Au+Au}^{b/c\rightarrow e}}{f_{p+p}^{b/c\rightarrow e}} R_{AA}^{HFe}$$

- $R_{AA}^{c\rightarrow e} < R_{AA}^{b\rightarrow e}$ or $\Delta E_c > \Delta E_b$ is consistent with mass hierarchy of parton energy loss
- Model with mass hierarchy for parton energy loss (Duke model) can reasonably describe the data

c,b→e elliptic flow in Au+Au collisions at 200 GeV

STAR D0: PRL 118, 212301 (2017)
DUKE: PRC 92:024907 (2015)

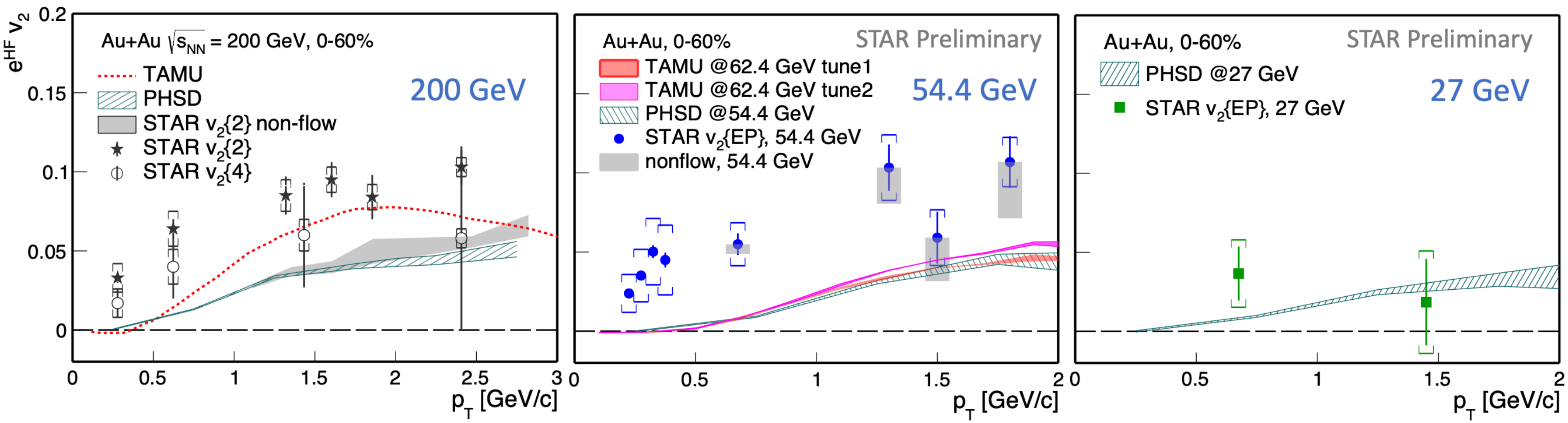


- c→e v_2 is consistent with STAR D^0 measurement folded to decayed electrons
- Non-zero b→e v_2 with significance > 3σ
- Model with b-quark diffusion in the QGP reasonably describes the data considering non-flow

e^{HF} elliptic flow at low energies

- e^{HF}: electrons from decays of bottom or charm hadrons ($e^{HF} = e^{inc.} - e^{pho.}$)
- e^{HF} measurements at lower energies can help probe T dependence of charm quark transport in QGP

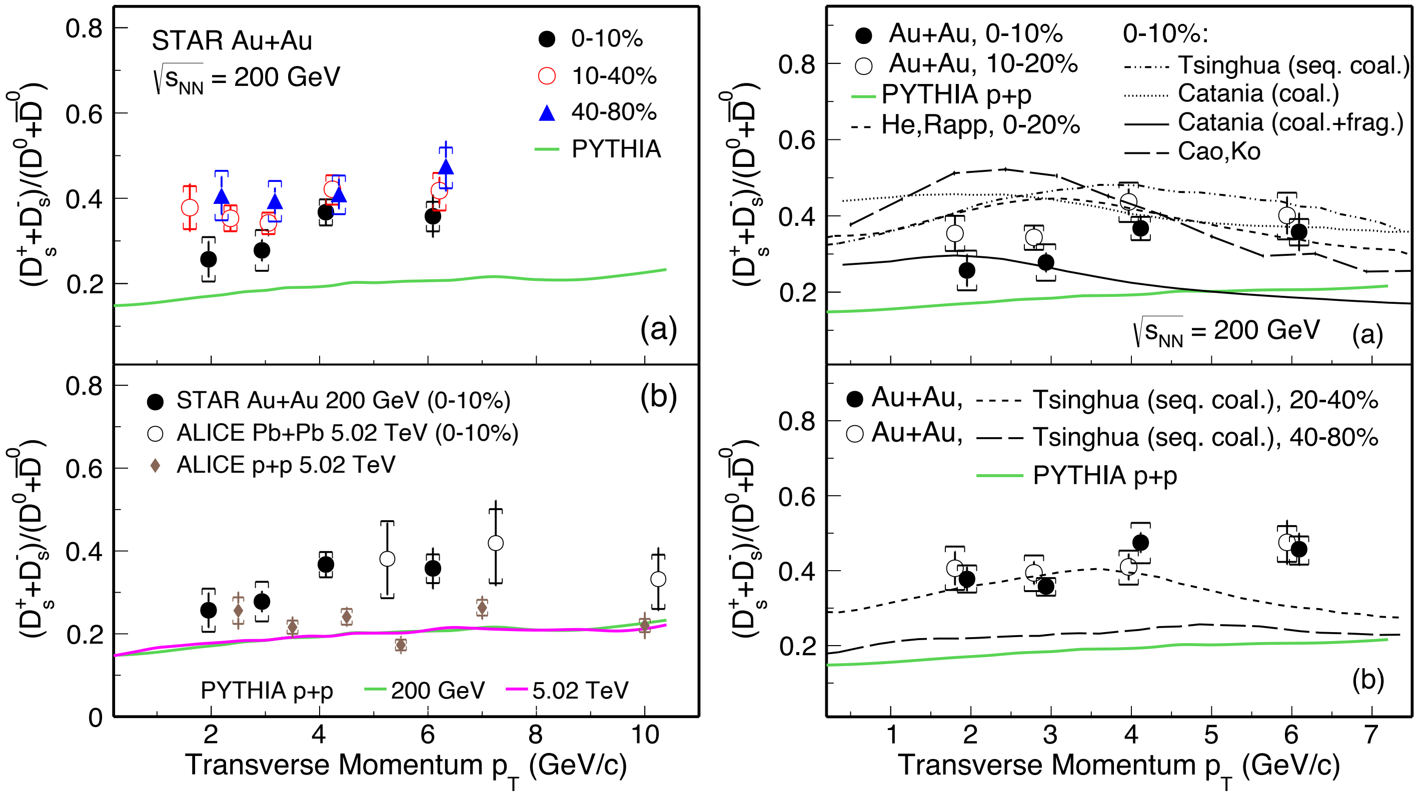
TAMU: M. He et al. PRC 91,024904 (2015)
PHSD at 200 GeV: T. Song et al. PRC 92, 014910 (2015)
PHSD at 27 and 54.4 GeV: T. Song et al. PRC 96, 014905 (2017)



- Non-zero e^{HF} v_2 at 54.4 GeV is comparable to that at 200 GeV
  - Charm quarks interact with hot medium strongly at 54.4 GeV Au+Au collisions
- TAMU and PHSD calculations are lower than $v_2\{EP\}$ at 54.4 GeV below 1.4 GeV/c
- Data and model calculations are comparable at p_T>1.4 GeV/c considering the upper limit of estimated non-flow contribution and uncertainties

$D_s^{\pm}$ production in Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV

Phys. Rev. Lett. 127, 092301 – Published 26 August 2021



Catania: Eur. Phys. J. C 78, 348, (2018).
Tsinghua: arXiv1805.10858, (2018).
He, Rapp, Phys. Rev. Lett. 124, 042301 (2020)
Cao, Ko et al.: Phys. Lett. B 807, 135561 (2020).

- Significant enhancement of $D_s^{\pm}/D^0$ yield ratio compared to PYTHIA and p+p at 5.02 TeV
    - No strong centrality dependence
    - Comparable to Pb+Pb at 5.02 TeV
- Models incorporating coalescence with enhanced strangeness production can qualitatively describe data

Summary for open heavy flavor

$D^{\pm}$ and D^0 in Au+Au collisions at 200 GeV:

- Significant suppression for both $D^{\pm}$ and D^0 in central collisions indicates significant energy loss of charm quarks in the QGP

$b/c \rightarrow e$ in Au+Au collisions at 200 GeV:

- $b/c \rightarrow e$ R_{AA} follows the mass hierarchy of parton energy loss ($\Delta E_c > \Delta E_b$)
- Non-zero $b \rightarrow e$ v_2 observed with significance > 3σ

e^{HF} v_2 at low energies:

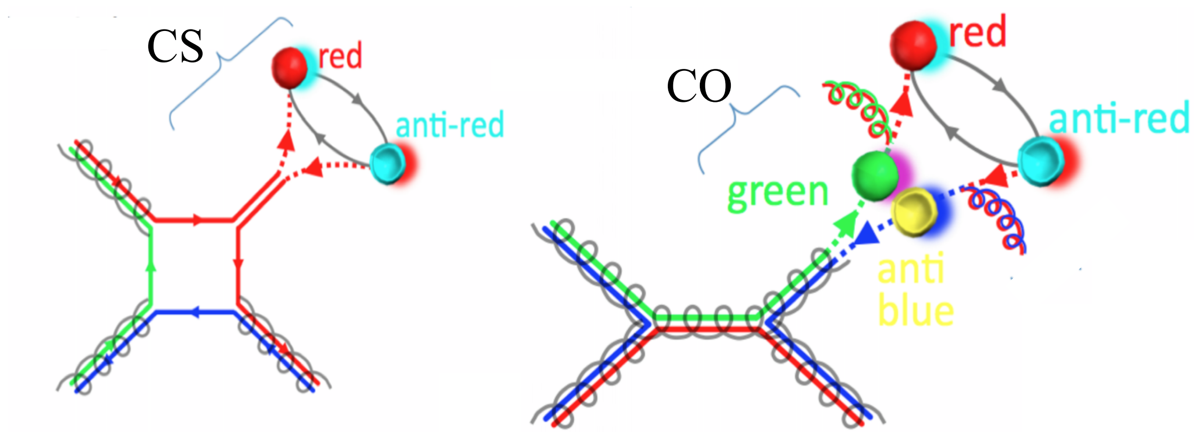
- Non-zero e^{HF} v_2 at 54.4 GeV is comparable to that at 200 GeV
  - Charm quarks interact strongly with the hot medium produced in 54.4 GeV Au+Au collisions

$D_s^{\pm}$ in Au+Au collisions at 200 GeV:

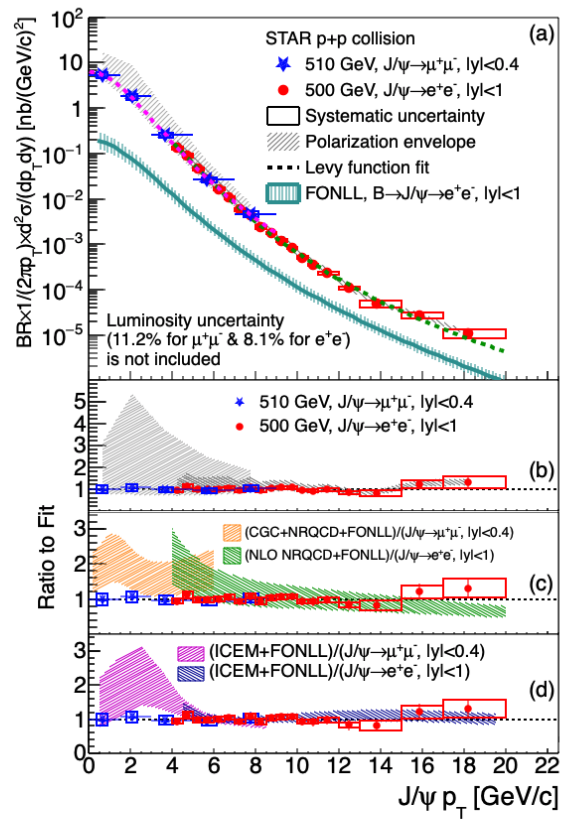
- Significant enhancement of $D_s^{\pm}/D^0$ yield ratio compared to PYTHIA predictions. It is qualitatively described by coalescence models

Motivation - Quarkonium in p+p collisions

- The production mechanism of heavy quarkonium is not fully understood in vacuum
- Some popular models on the market:
  - Color Singlet Model (CSM)
  - Color Octet Mechanism (COM)
  - Non-relativistic QCD (NRQCD)
    - + Color Glass Condensate effective theory (CGC)
  - Color Evaporation Model (CEM) / Improved CEM



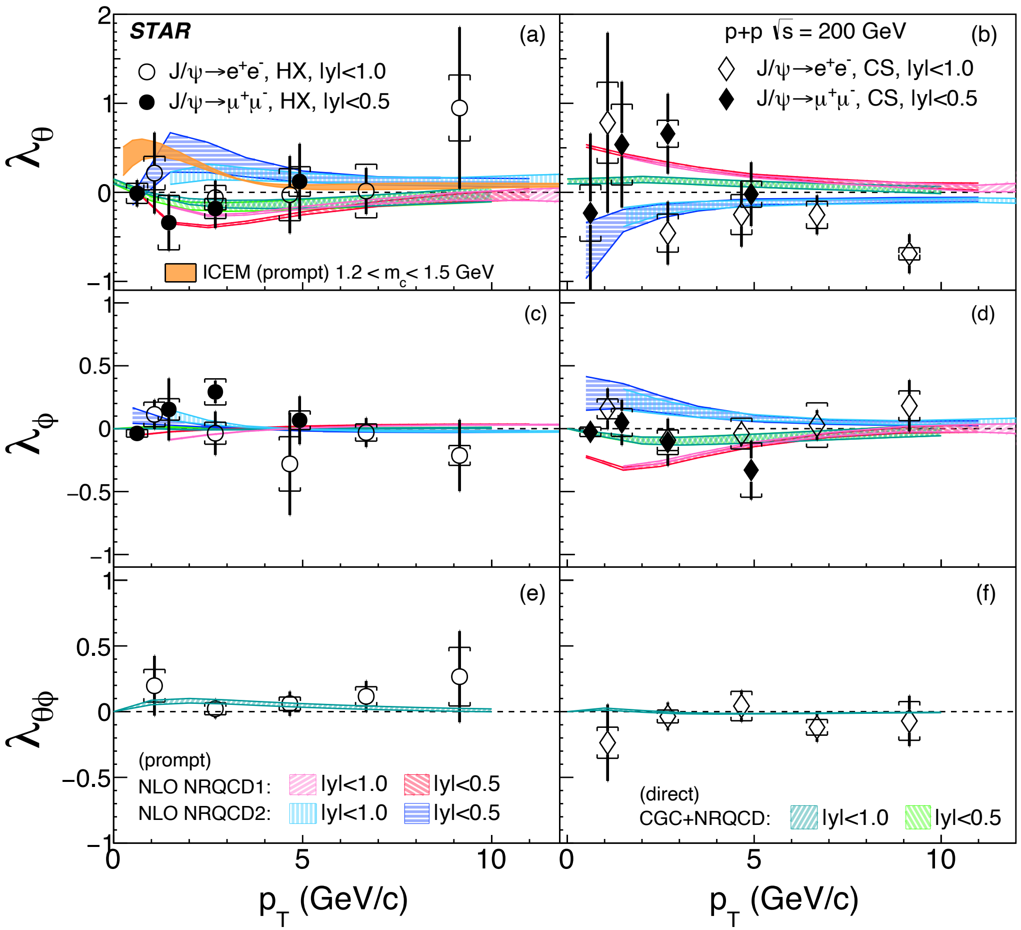
From Cristina Biino's Talk (FPCP2013)

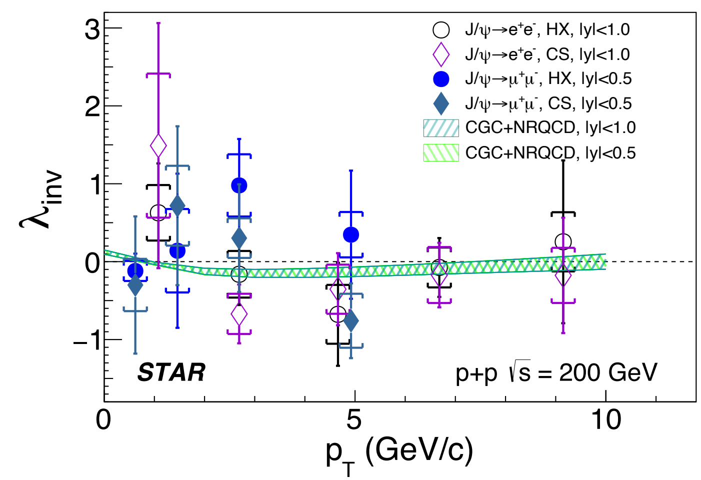


STAR: Phys. Rev. D 100, 052009 (2019)

J/ψ polarization measurements

- First measurement of J/ψ polarization in both Helicity (HX) and Collins-Soper (CS) frames from STAR via dimuon decay channel in p+p collisions at 200 GeV

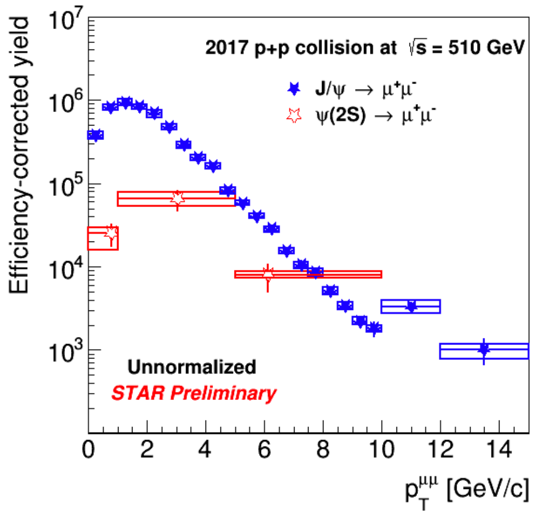


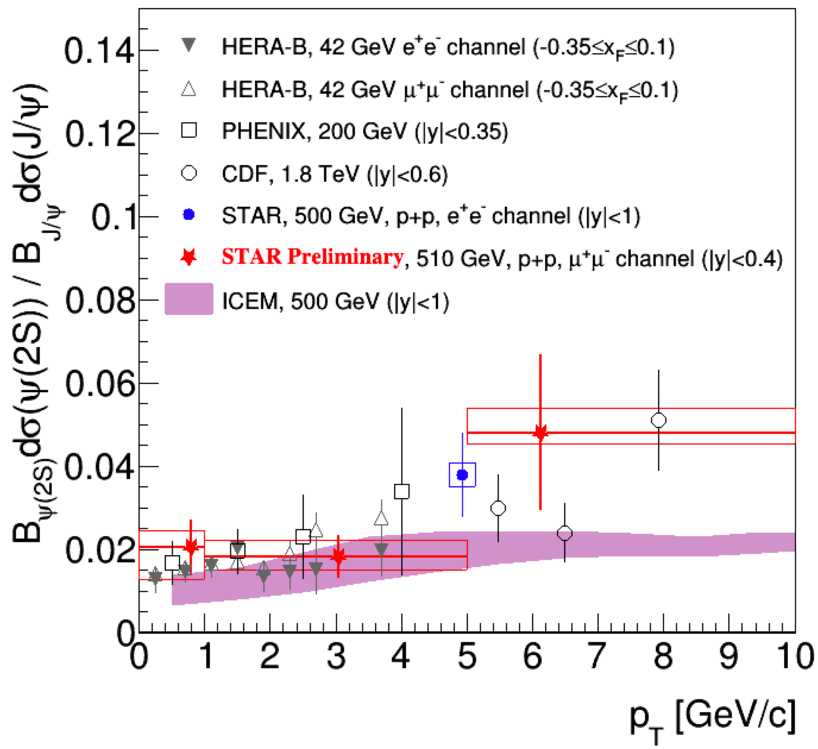


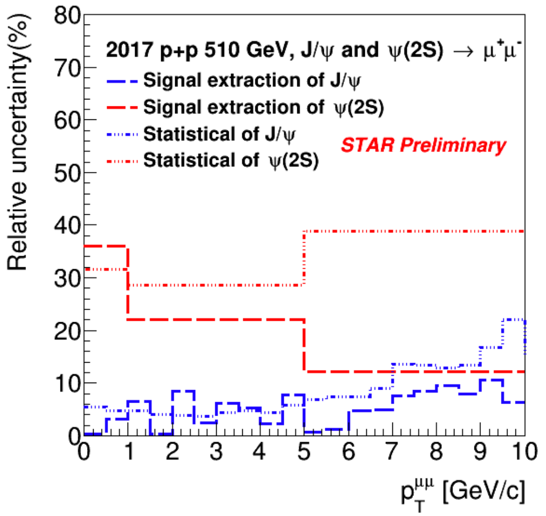
- λ_θ, λ_φ and $\lambda_{\theta\varphi}$ are consistent with zero within uncertainty
- Theory calculations are consistent with data within uncertainties

STAR: Phys. Rev. D 102 (2020) 92009
NRQCD1: Phys. Rev. Lett 114 (2015) 092006
NRQCD2: Phys. Rev. Lett 110 (2013) 042002
CGC+NRQCD: JHEP 12 (2018) 057
ICEM: Phys. Rev. D 98 (2018) 114029

ψ(2S) to J/ψ ratio @ pp 510 GeV with 2017 data



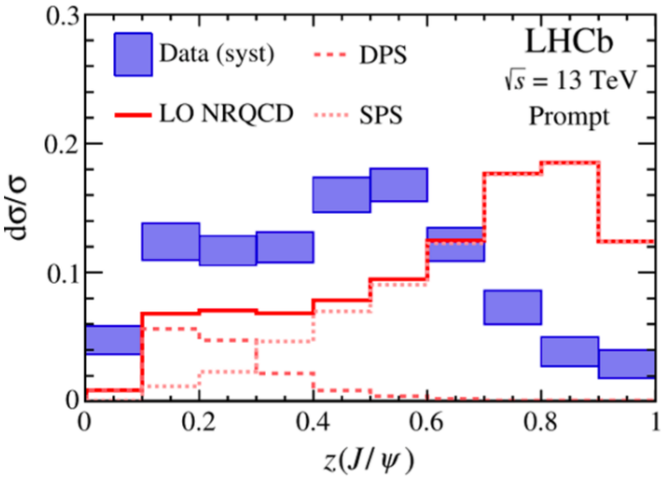


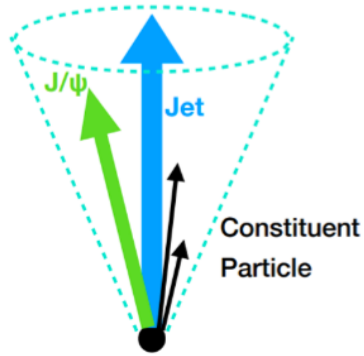


- Measurements of ψ(2S) to J/ψ production ratio help understand the quarkonium production mechanism
- For the first time, we can measure p_T differential cross section of ψ(2S) at STAR
- p_T differential ψ(2S) to J/ψ ratio follows world-data trend

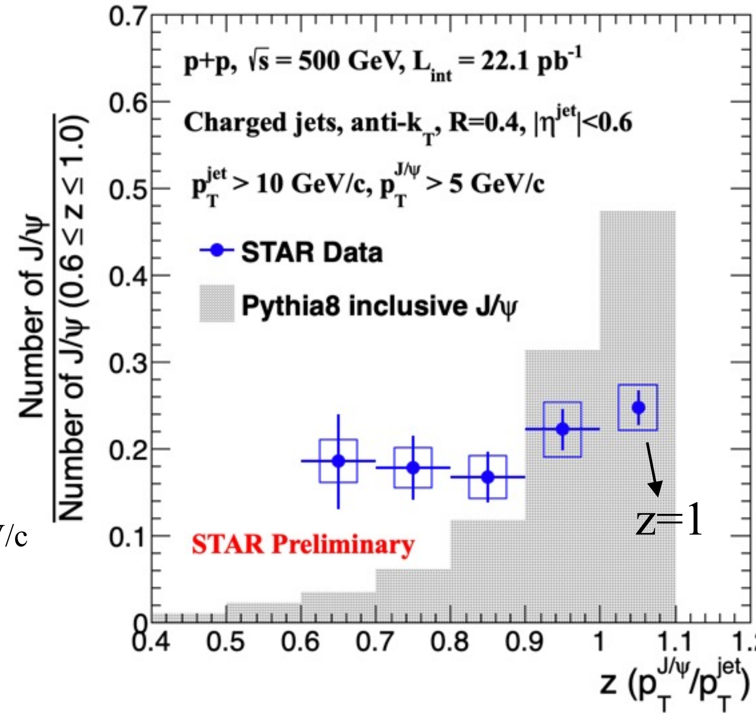
J/ψ production in jets in p+p collisions at 500 GeV

LHCb, PRL 118, 192001 (2017)





STAR: charged jet, p_T^{jet}>10 GeV/c
LHCb: full jet, p_T^{jet}>20 GeV/c



- Help understand J/ψ production mechanism
  - Produced directly or in parton showers?
- No significant z dependence observed within uncertainties
- Less isolated production in data compared to PYTHIA
- Could help to constrain LDMEs in NRQCD

Motivation - Quarkonium in A+A collisions

- Quarkonium suppression is one of smoking guns of the QGP formation (by T. Matsui and H. Satz PLB 178 (1986) 416)
- Color-screening: quarkonium dissociates in the medium
- Sequential melting: different states dissociate at different temperatures

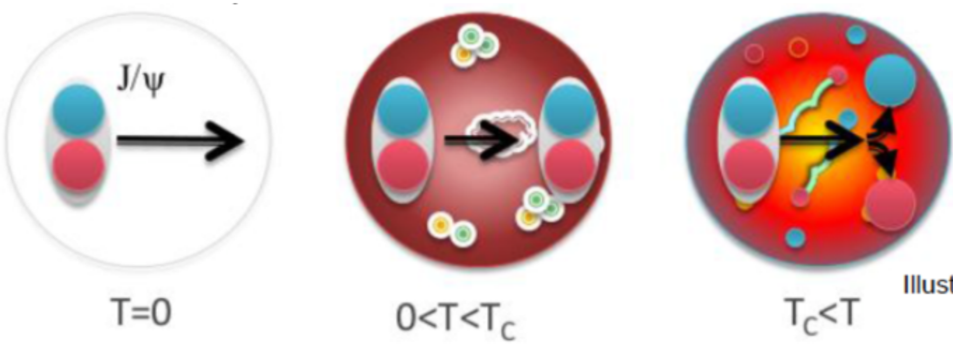
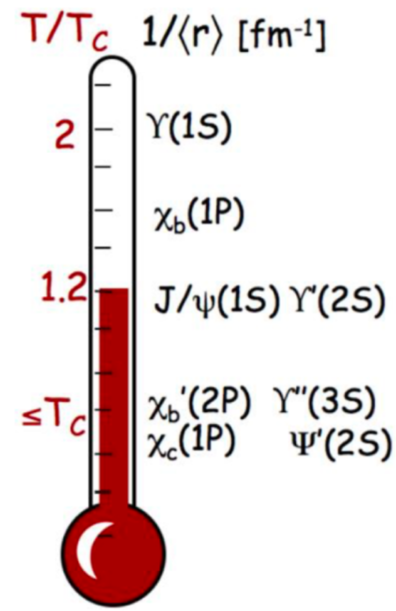


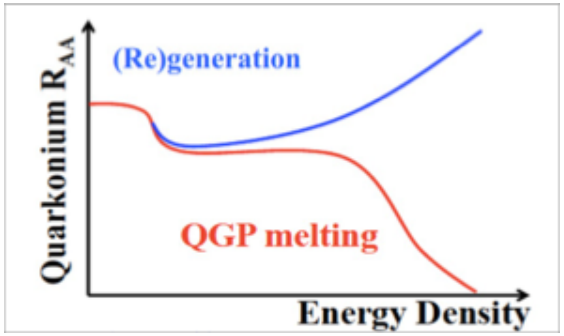
Illustration: A.Rothkopf



A. Mocsy, EPJ C61 (2009) 705

Interpretation of quarkonium suppression is complicated:

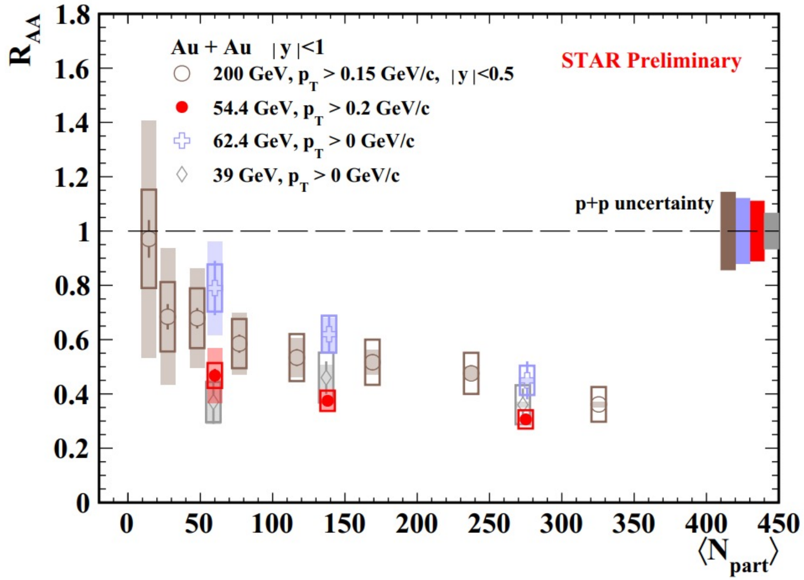
- Hot nuclear matter effects
  - Dissociation
  - Regeneration from deconfined quarks in the medium
  - Energy loss in the medium
  - Formation time effect
- Cold nuclear matter (CNM) effects
- Feed-down from excited states and B-hadrons

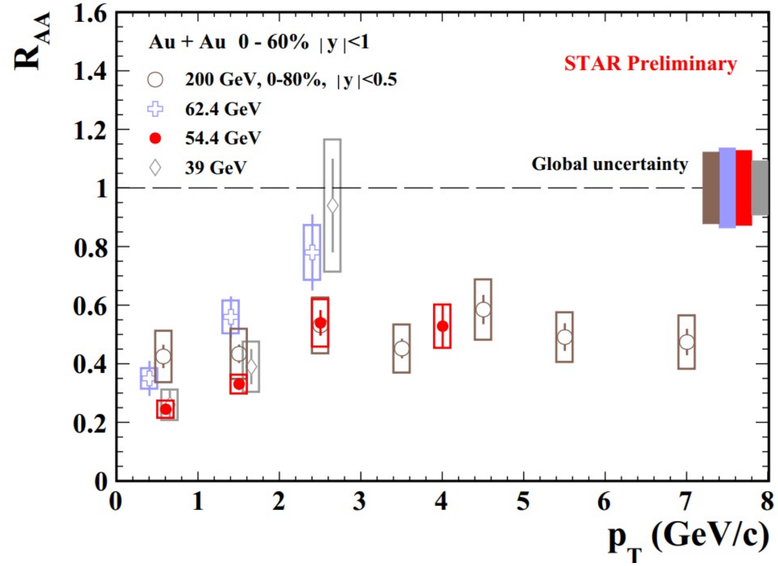


J/ψ R_{AA} in Au+Au collisions at 54.4 GeV

$J/\psi \rightarrow e^+e^-$

STAR J/ψ→e+e-: PLB 771, 13-20 (2017)
STAR J/ψ→μ+μ-: PLB 797, 134917 (2019)

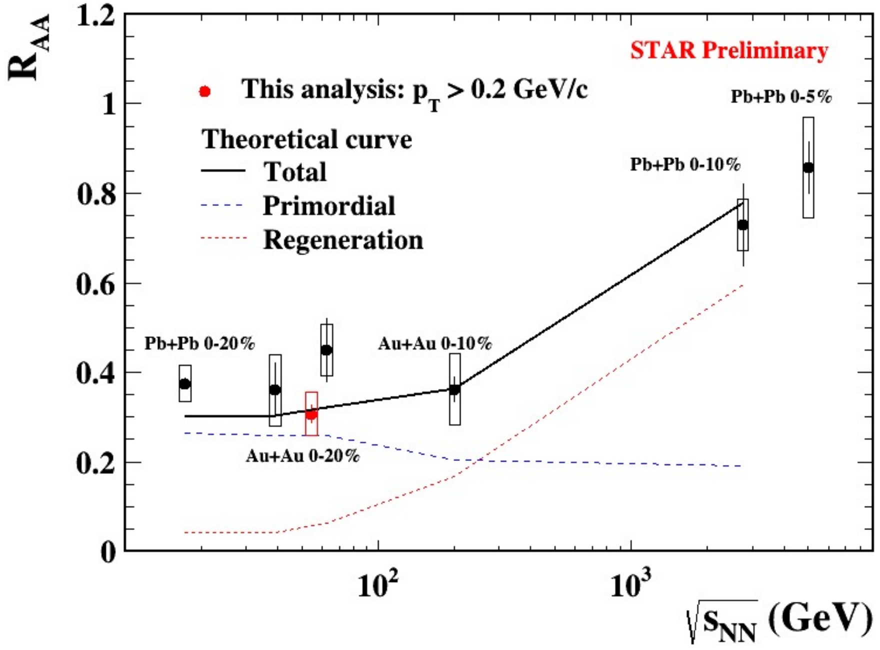




- Better precision with 54.4 GeV data compared to STAR previous measurements
- More suppression towards central collisions, no significant collision energy dependence
- For 39, 54.4, 62.4 GeV data, R_{AA} increases with increasing p_T

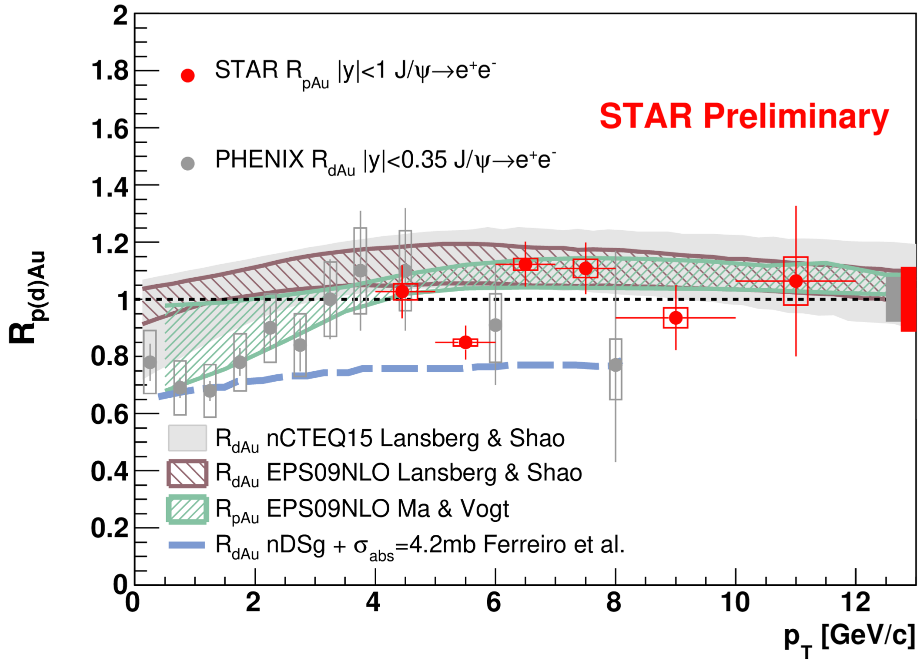
Collision energy dependence of J/ψ R_{AA}

STAR $J/\psi \to e^+e^-$: PLB 771, 13-20 (2017), PLB 797, 134917 (2019)
ALICE: PLB 734, 314 (2014), NPA 1005, 121769 (2021)
NA50: PLB 477, 28 (2000), EPJC 43, 145 (2005)
Theory: X. Zhao, Rapp PRC 82 (2010) 064905



- 54.4 GeV data follows the trend with better precision
- No significant collision energy dependence within uncertainties up to 200 GeV
- Theory calculations with dissociation and regeneration components are consistent with data in central collisions

J/ψ production in p+Au collisions at 200 GeV



- R_{pAu} is consistent with unity at high p_T
  - No modification due to CNM effects at high p_T
  - Suggesting that the high p_T suppression in Au+Au collisions is predominantly arising from hot nuclear matter effects
- Consistent with PHENIX R_{dAu} results indicating similar CNM effect in p+Au and d+Au collisions
- Models with nPDF effects are consistent with data

Summary for quarkonium

J/ψ in p+p collisions:

- J/ψ polarization is measured by STAR at 200 GeV. λ_θ, λ_φ and $\lambda_{\theta\varphi}$ are consistent with zero within uncertainties, and can be described by theory calculations
- First p_T differential measurement of $\psi(2S)$ to J/ψ ratio is measured at STAR at 510 GeV and it follows the world-data trend.
- No significant z dependence observed for J/ψ production in charged jets at 500 GeV within uncertainties and has a very different trend compared to PYTHIA8 prediction

J/ψ in Au+Au collisions at 54.4 GeV:

- More suppression towards central collisions, no significant collision energy dependence up to 200 GeV

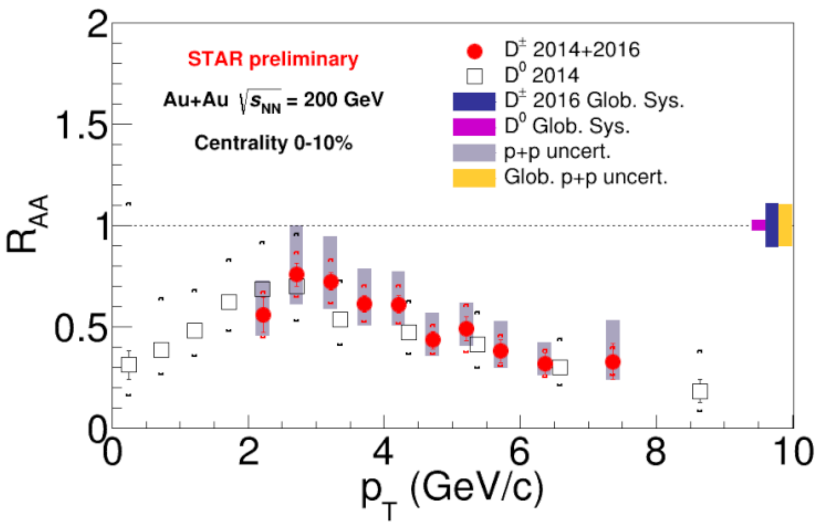
J/ψ in p+Au collisions at 200 GeV:

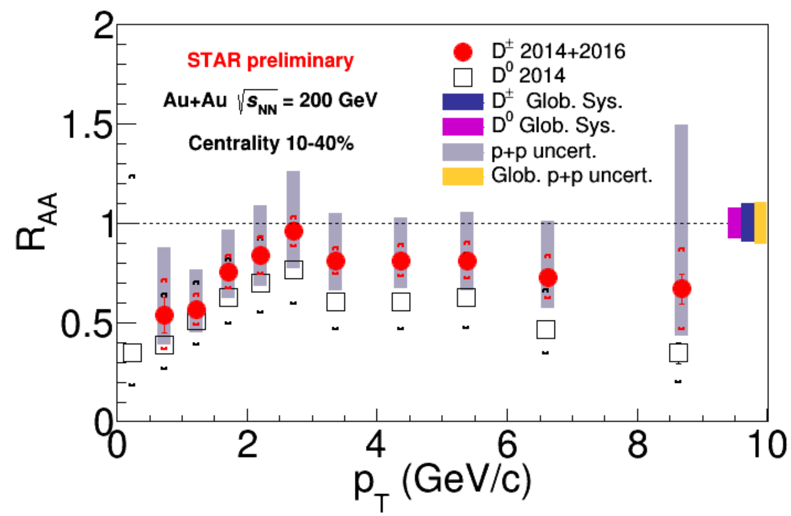
- R_{pAu} is consistent with unity at high p_T, suggesting that the high p_T suppression in Au+Au collisions is predominantly hot nuclear matter effects

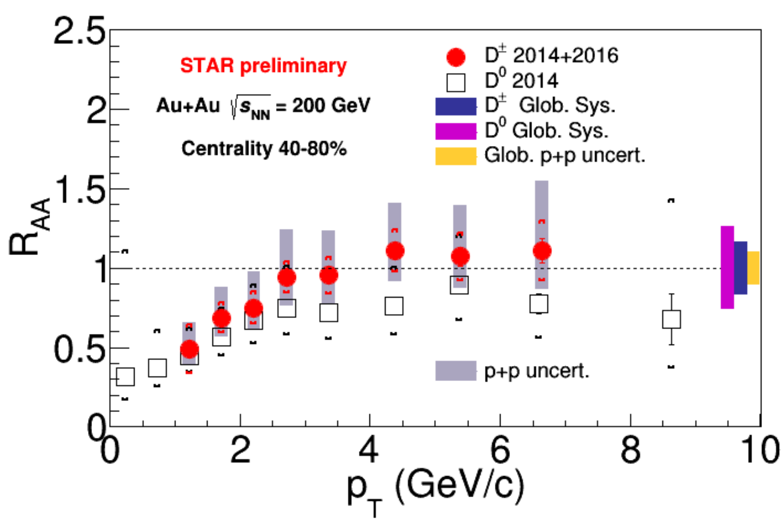
21

Backup

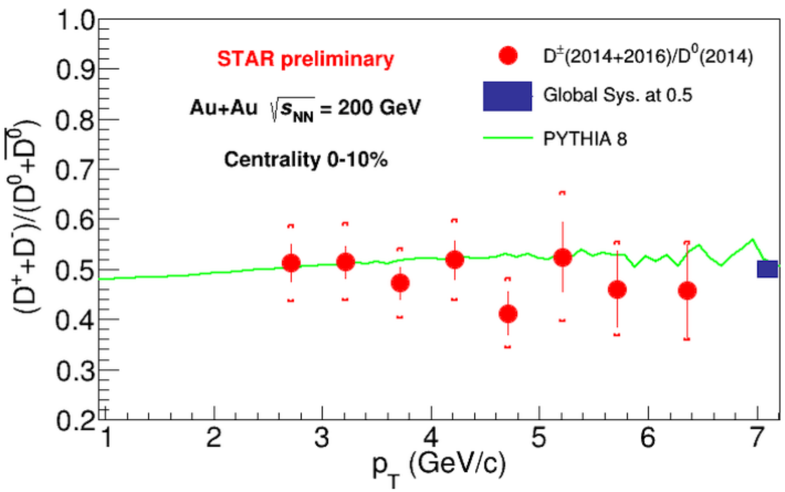
$D^{\pm}$ production in Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV

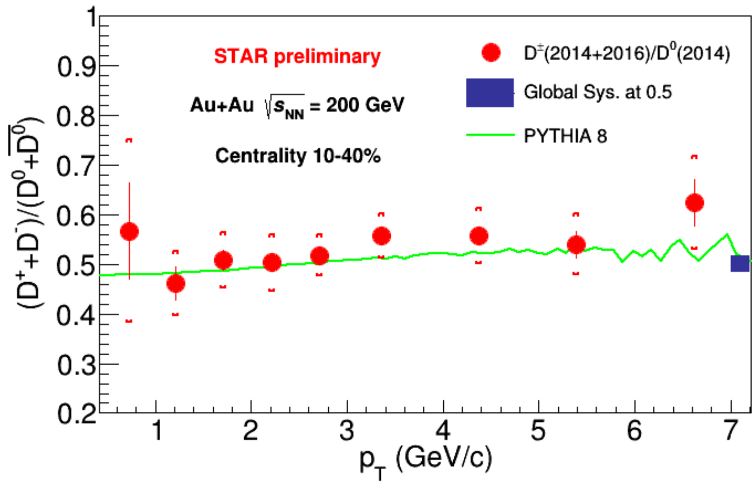


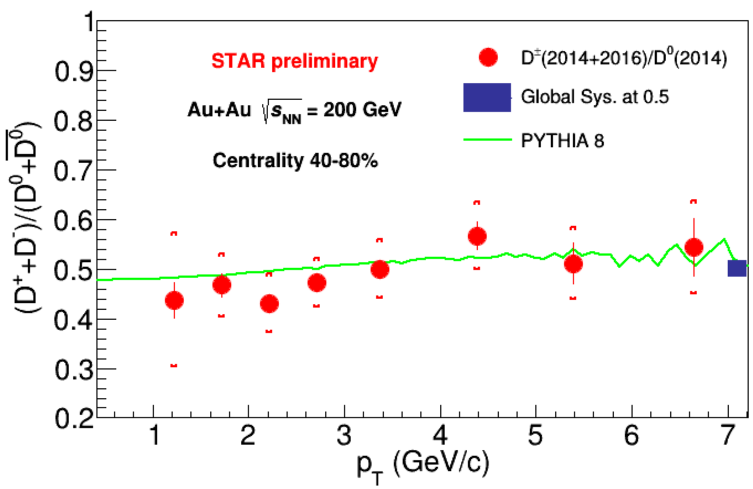




$D^{\pm}/D^0$ yield ratio

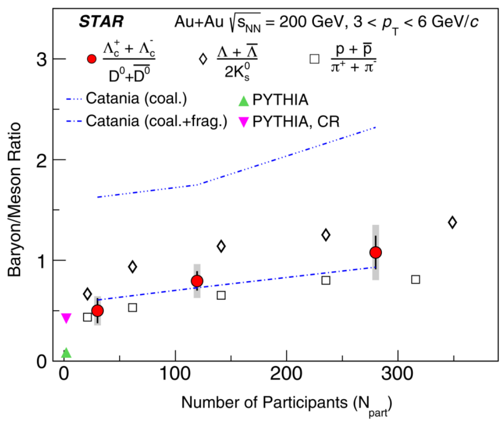






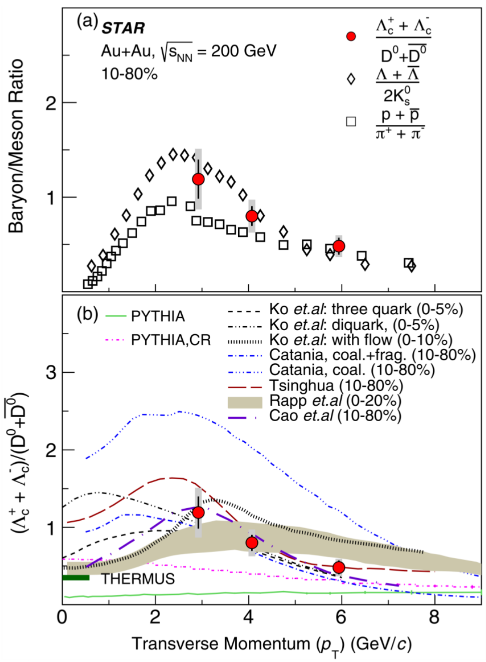
$\Lambda_c^{\pm}$/D⁰ yield ratio in Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV

Phys. Rev. Lett. 124, 172301, (2020)



Centrality dependence:

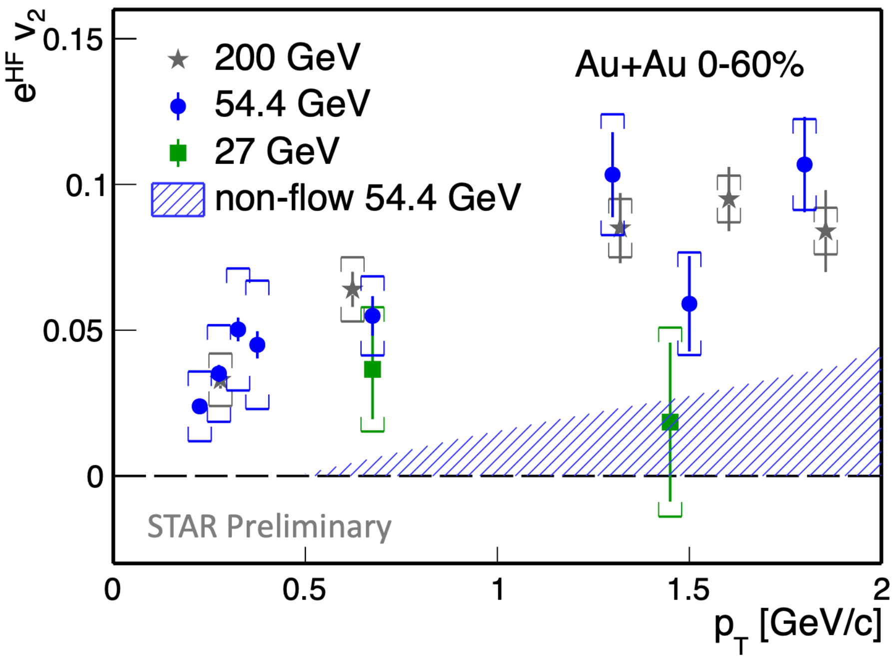
- Enhancement increases toward central collisions
- Catania model with coalescence and fragmentation can describe data reasonably.

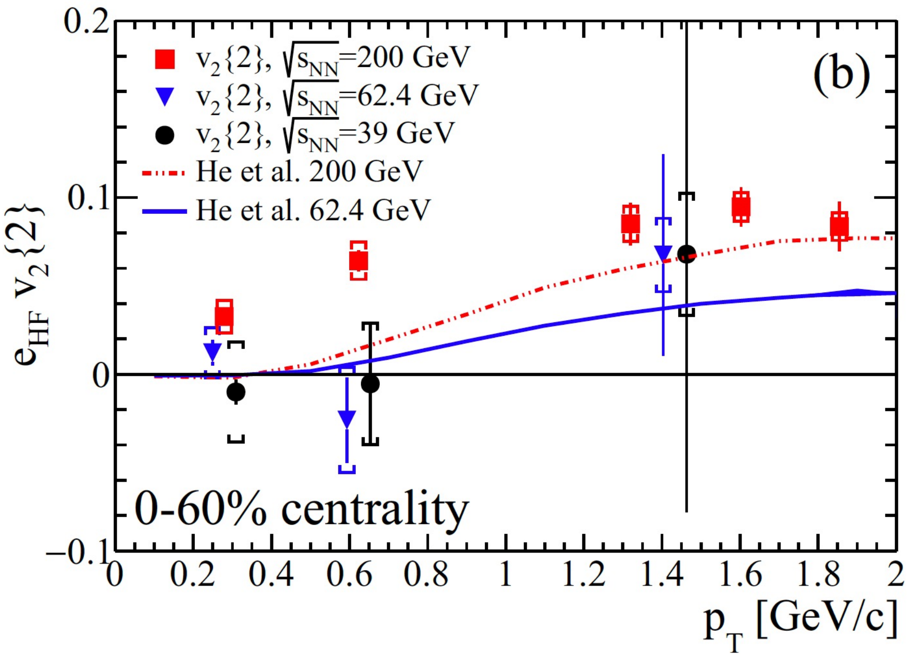


p_T dependence:

- Significant enhancement compared to PYTHIA prediction
- Models with coalescence described the data

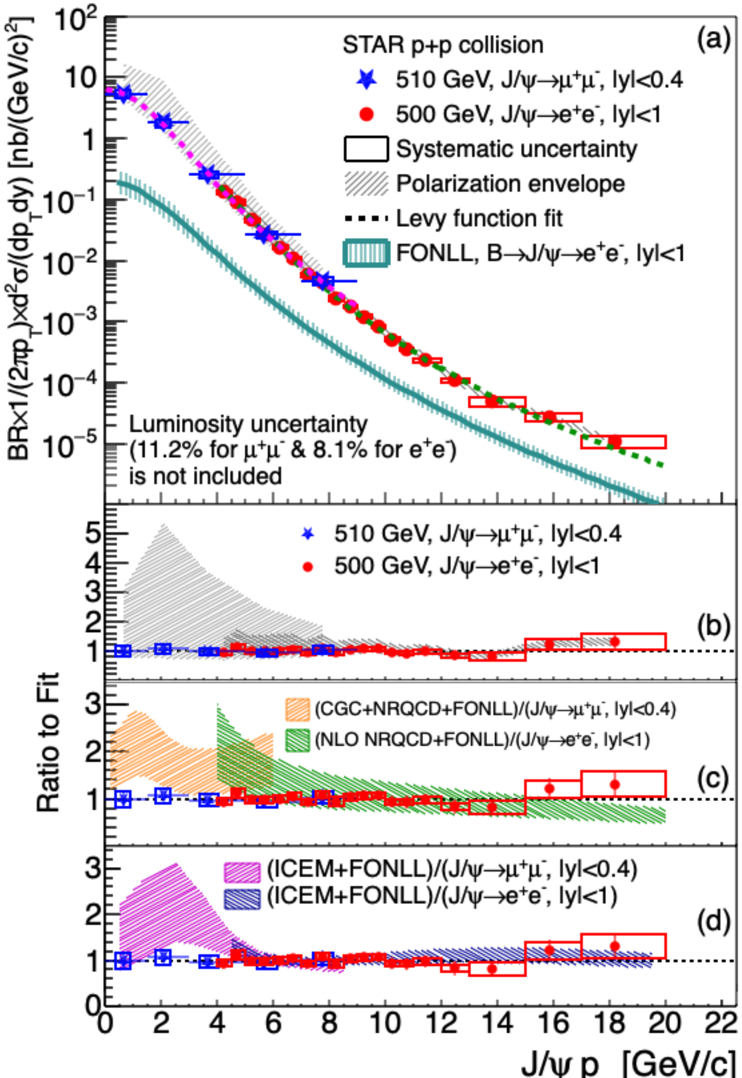
e^{HF} elliptic flow at low energies

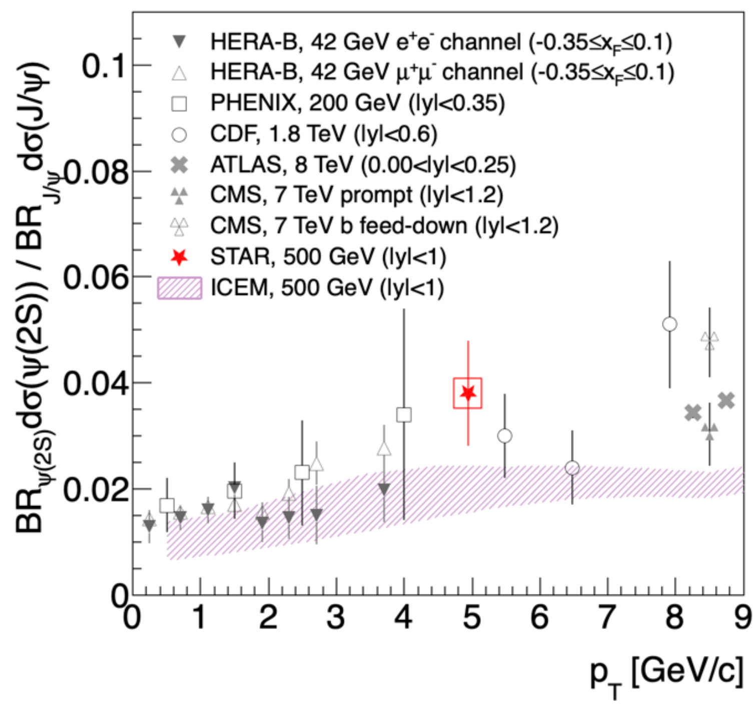




- 10x more statistics for 27 and 54.4 GeV compared to 39 and 62.4 GeV
- Non-zero e^{HF} v_2 in 54.4 GeV comparable to that in 200 GeV
  - Charm quark interact with hot medium strongly at 54.4 GeV Au+Au collisions

J/ψ cross-section in p+p collisions @ 500 GeV

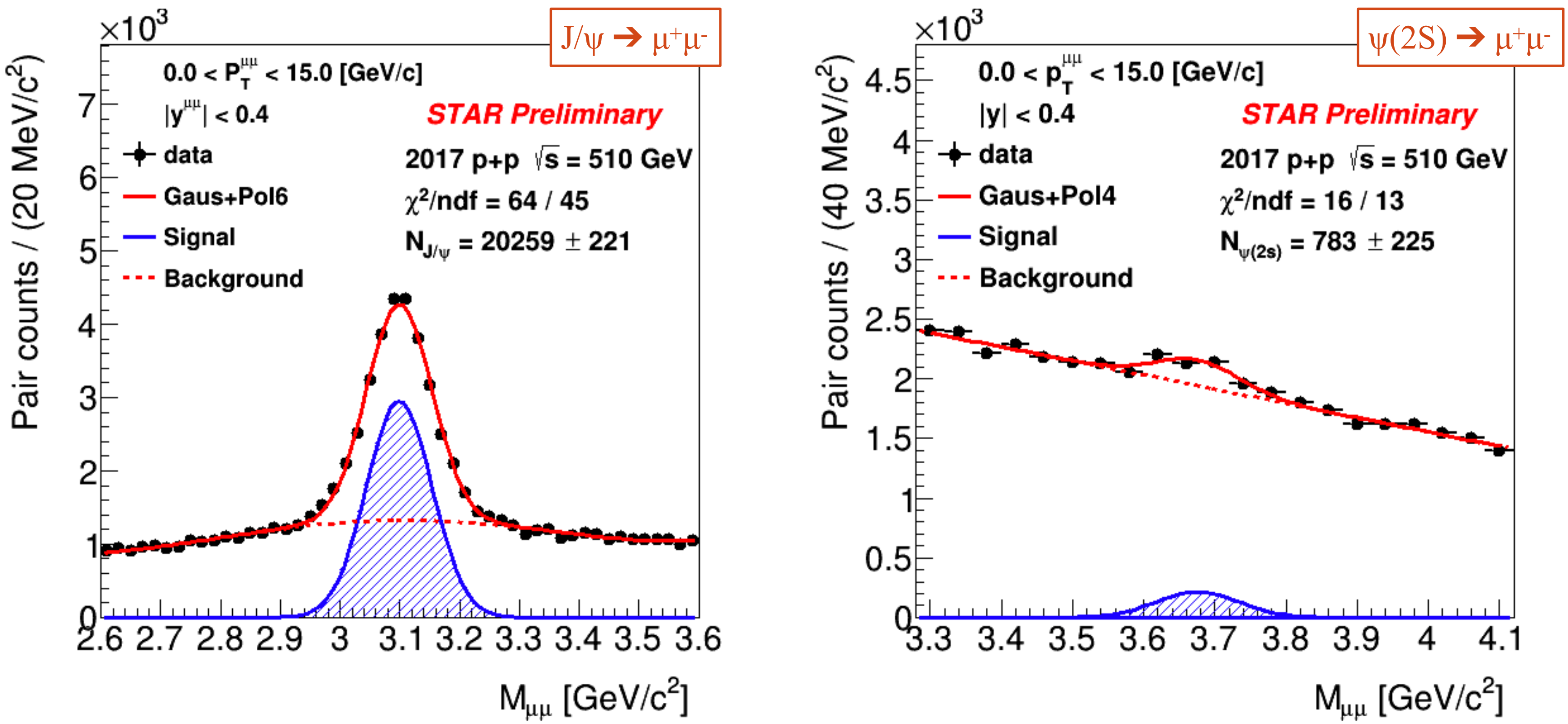




- Precise measurements of J/ψ cross-section covered J/ψ p_T from 0 to 20 GeV/c
- Consistent with CGC+NRQCD, NLO NRQCD, and ICEM calculations (B feed-down from FONLL included) with a small tension at low p_T
- ψ(2S) to J/ψ ratio follow the world trend

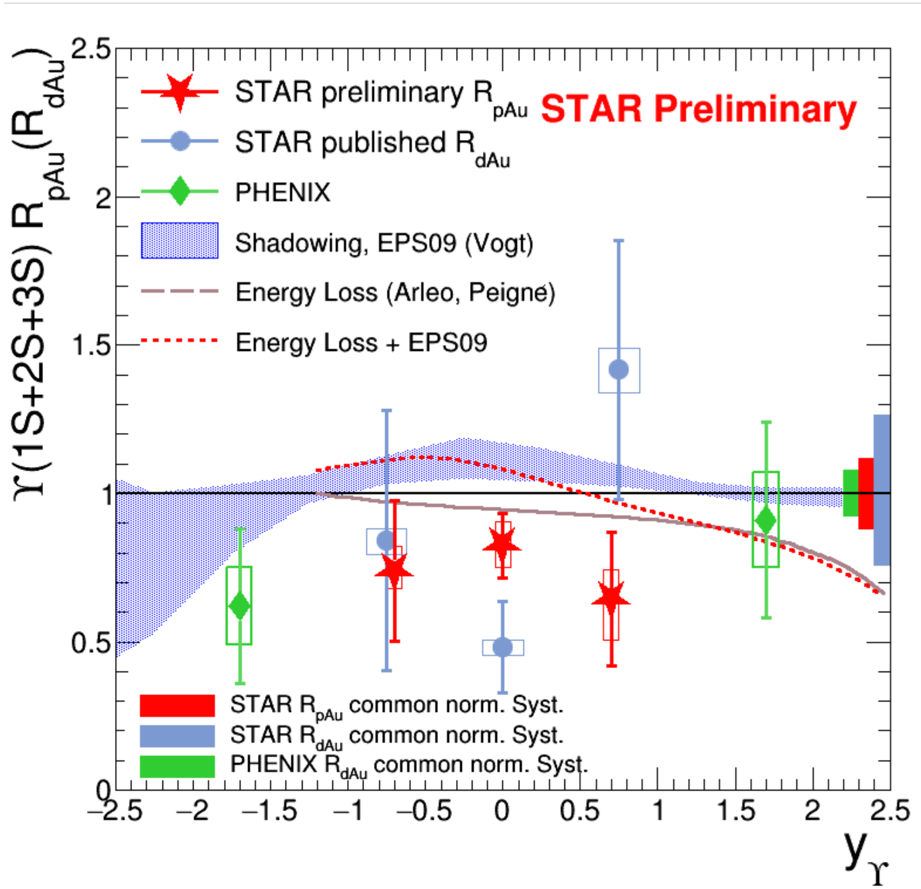
Phys. Rev. D 100, 052009 (2019)

J/ψ and ψ(2S) in p+p @ 510 GeV with 2017 data



- In 2017, STAR collected a large data set of p+p collisions at 510 GeV (integrated luminosity ~ 120 pb^{-1})
- We have more than ten times number of J/ψ with dimuon trigger compared with 2013 data and enough ψ(2S) events for detailed analysis.

Υ production in p+Au collisions at 200 GeV



PHENIX, PRC 87, 034904 (2013)
EPS09+NLO, Ma & Vogt, Private Common
nCTEQ, EPS09+NLO, Lansberg & Shao: EPJ.C77, no.1, 1 (2017)
Comp. Phys. Comm. 198, 238-259 (2016)
Comp. Phys. Comm. 184 , 2562-2570 (2013)
Ferreriro et al., Few Body Syst. 53 (2012) 27

- Improved precision compared to previous d+Au measurement
- Models systematically higher than data indicating more suppression than nPDF effect and energy loss in CNM