Recent Open Heavy Flavor and Quarkonia Measurements from STAR

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BERKELEY LAB

Supported by
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

Open heavy flavor measurements

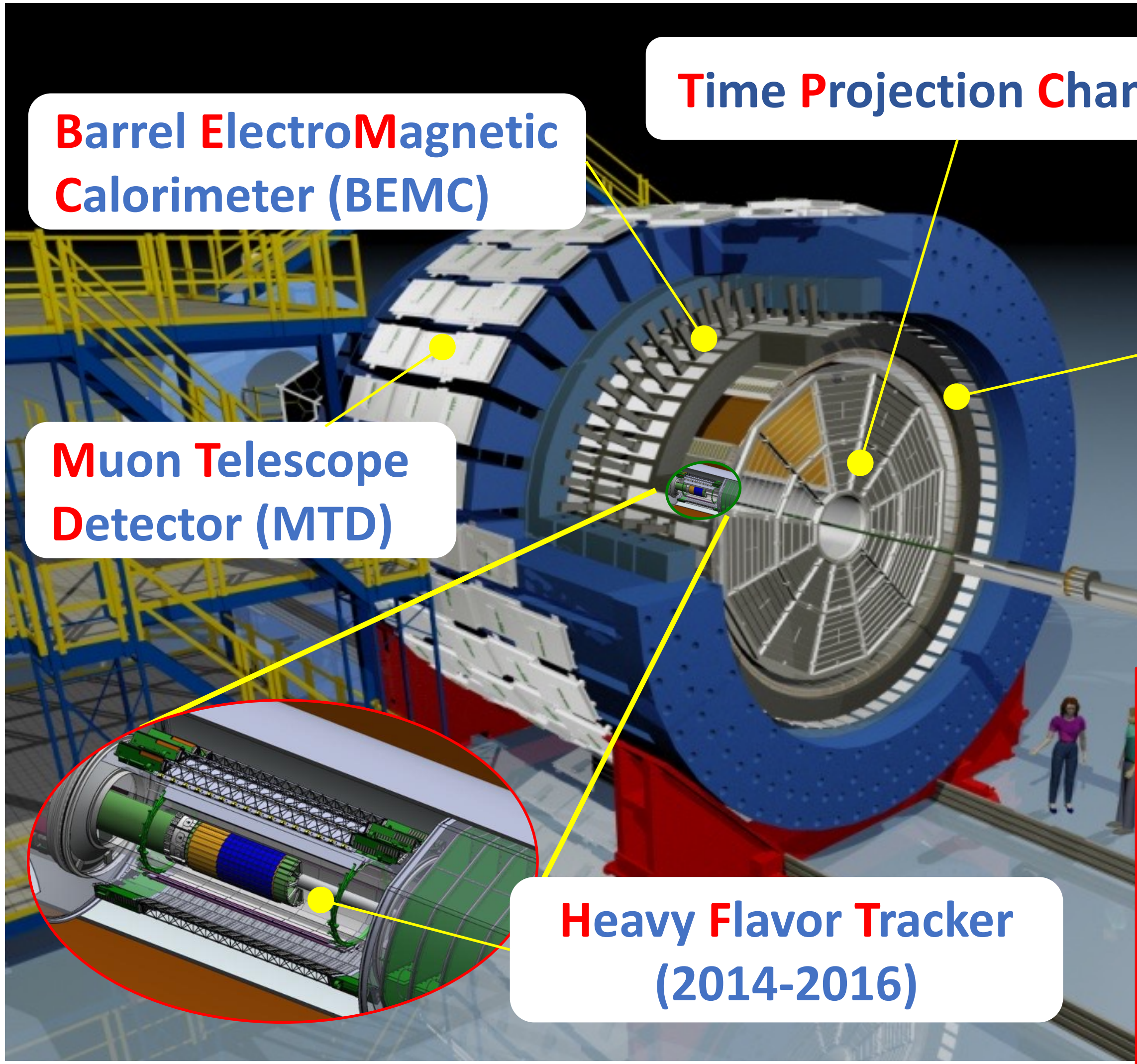
- $D_s^{\pm}$ and $D^{\pm}$ production in Au+Au @ 200 GeV
- $c, b \rightarrow e$ R_{AA} and v_2 in Au+Au @ 200 GeV
- e^{HF} v_2 in Au+Au @ 27 and 54.4 GeV

Quarkonium measurements

- J/ψ production in Au+Au @ 54.4 GeV
- J/ψ and Υ production in p+Au @ 200 GeV
- J/ψ production in jets in p+p @ 500 GeV

Outlook for Run 2023-2025

The Solenoid Tracker At RHIC (STAR)



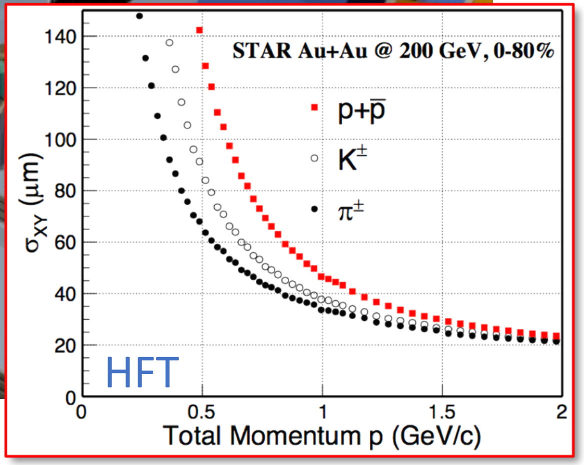
TPC - momentum and PID (dE/dx)

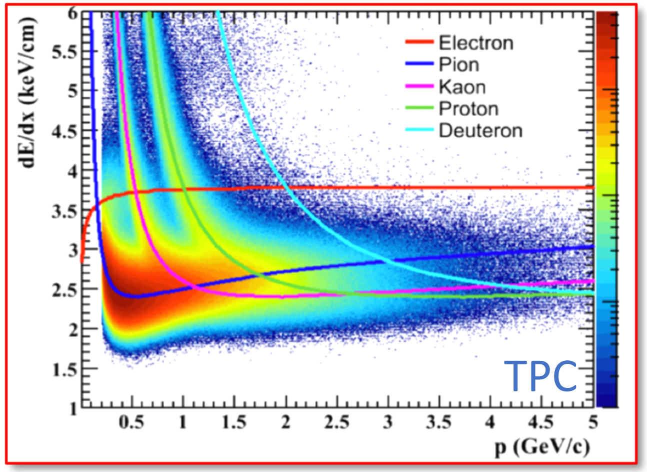
TOF - PID ($1/\beta$)

BEMC - trigger on and identify high p_T electron

HFT - excellent pointing resolution for secondary vertex reconstruction

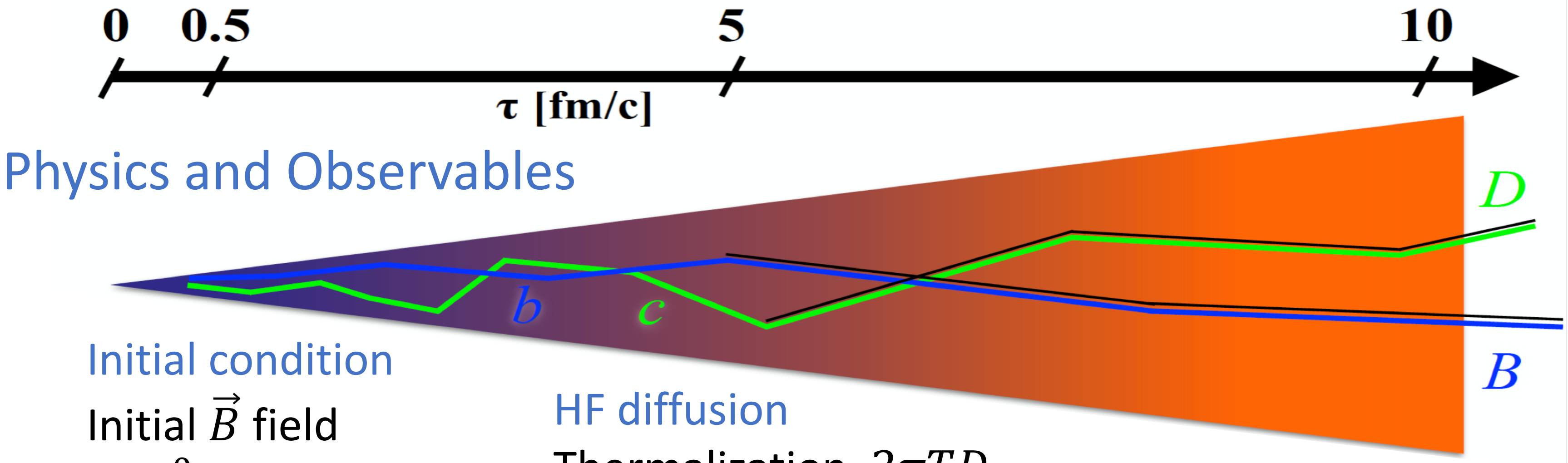
MTD - trigger on and identify muons





Why Heavy Quarks?

- $m_{c,b} \gg T_{QGP}, m_{c,b} \gg \Lambda_{QCD}$
  - Dominantly produced during initial hard scatterings
  - Cross section is calculable in pQCD



Initial condition

Initial $\vec{B}$ field

-> D^0 directed flow

HF diffusion

Thermalization, $2\pi T D_s$

-> Elliptic flow

Energy loss

Collisional vs radiative

-> R_{AA}, R_{CP}

Hadronization

Coalescence vs fragmentation

-> HF baryon, strange HF meson production

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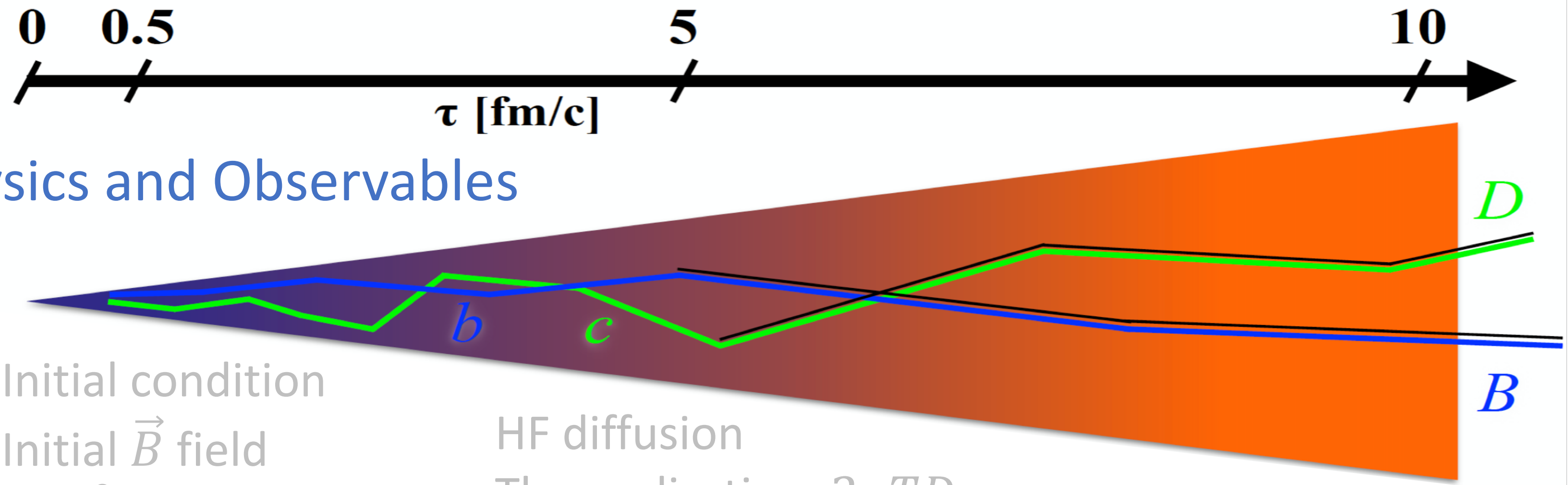
Physics and Observables



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Enhanced Λ_c^+/D^0 -> Coalescence

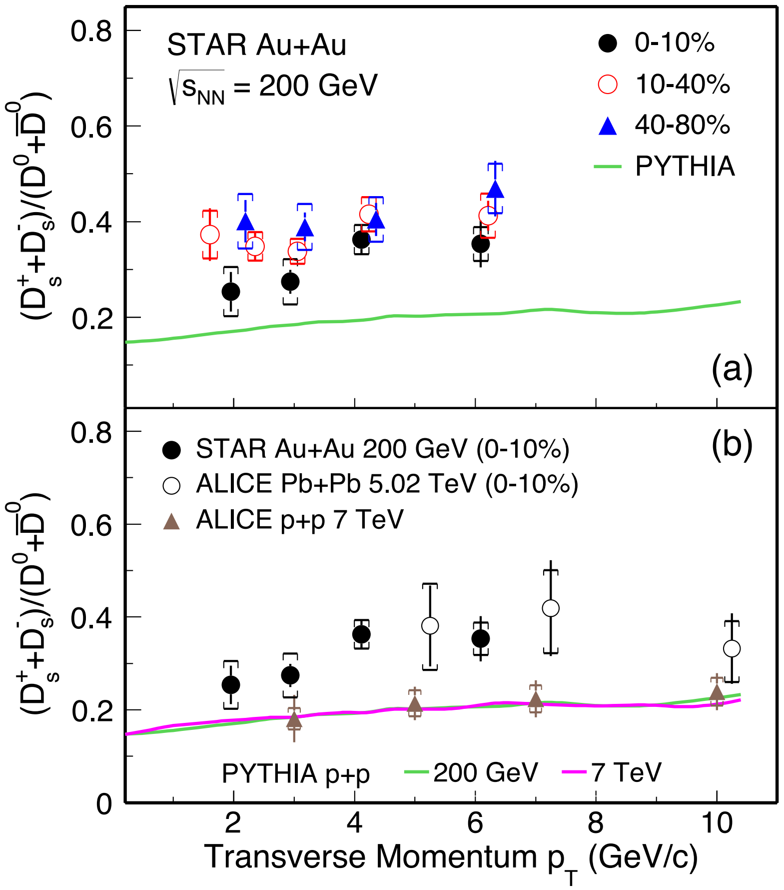
STAR PRL 124,172301 (2020)

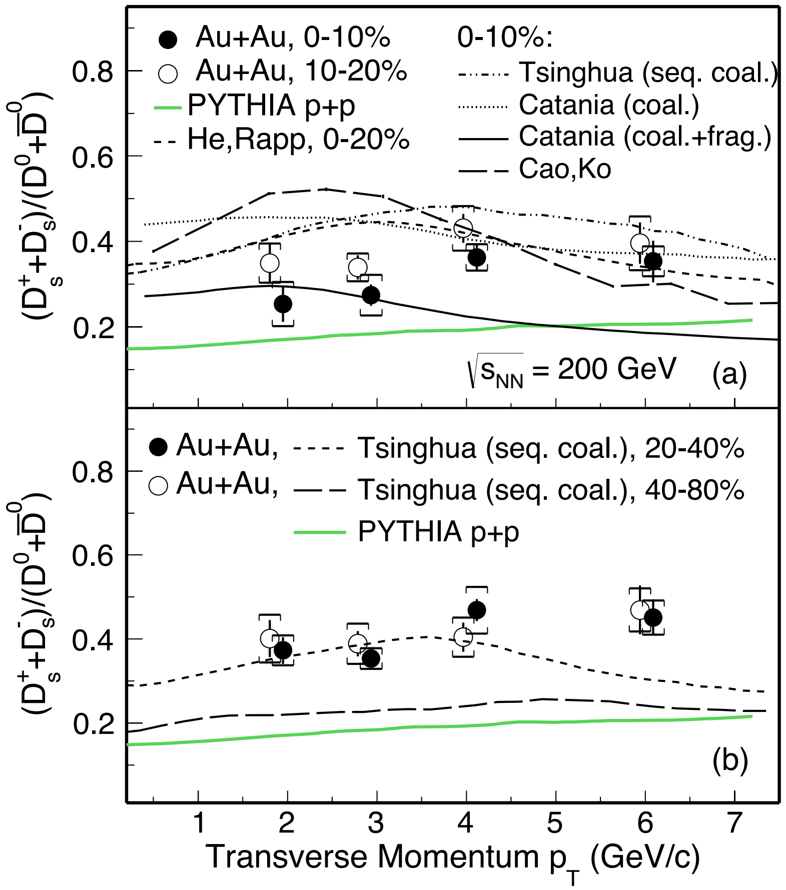
$D_s^{\pm}$ Production in Au+Au @ 200 GeV

Submitted to PRL

arxiv:2101.11793

ALICE: EPJC 77, 550 (2017)
ALICE: JHEP 2018, 174 (2018)





Tsinghua: arXiv:1805.10858 (2018)
Catania: EPJC 78, 348 (2018)
He/Rapp :PRL 124, 042301 (2020)
Cao,Ko: PLB 807, 135561 (2020)

- Significant enhancement of D_s^+/D^0 yield ratio compared to PYTHIA and p+p @ 7 TeV
  - No strong centrality dependence
  - Comparable to Pb+Pb @ 5.02 TeV

- Models incorporating coalescence with enhanced strangeness production qualitatively describe data

Why Heavy Quarks?

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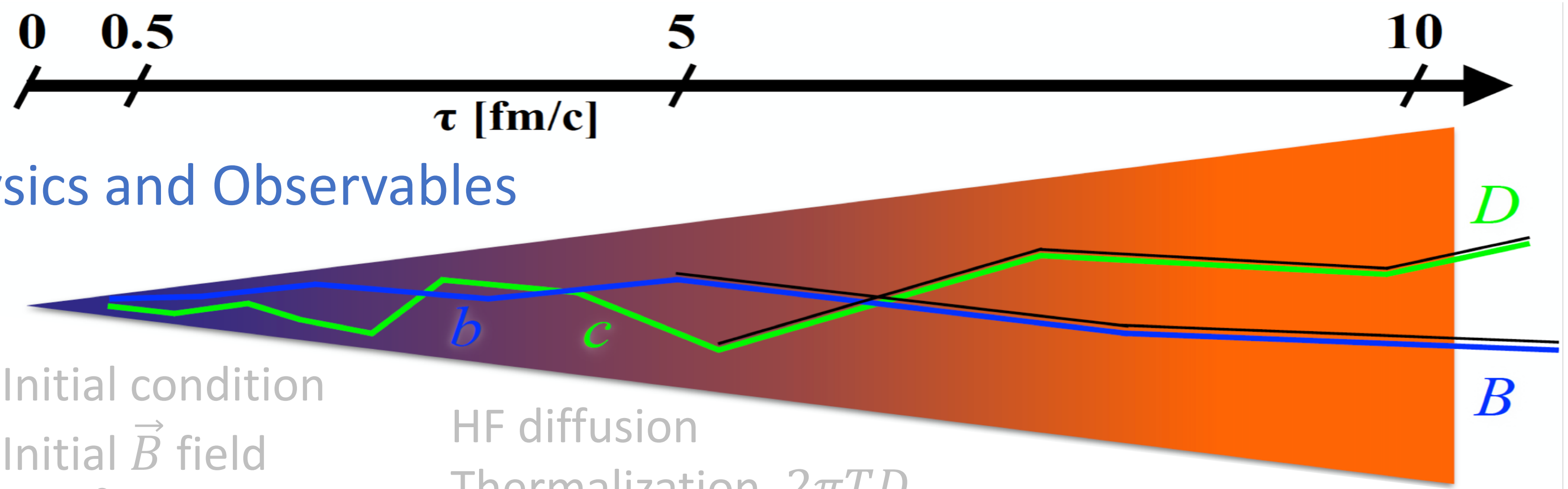

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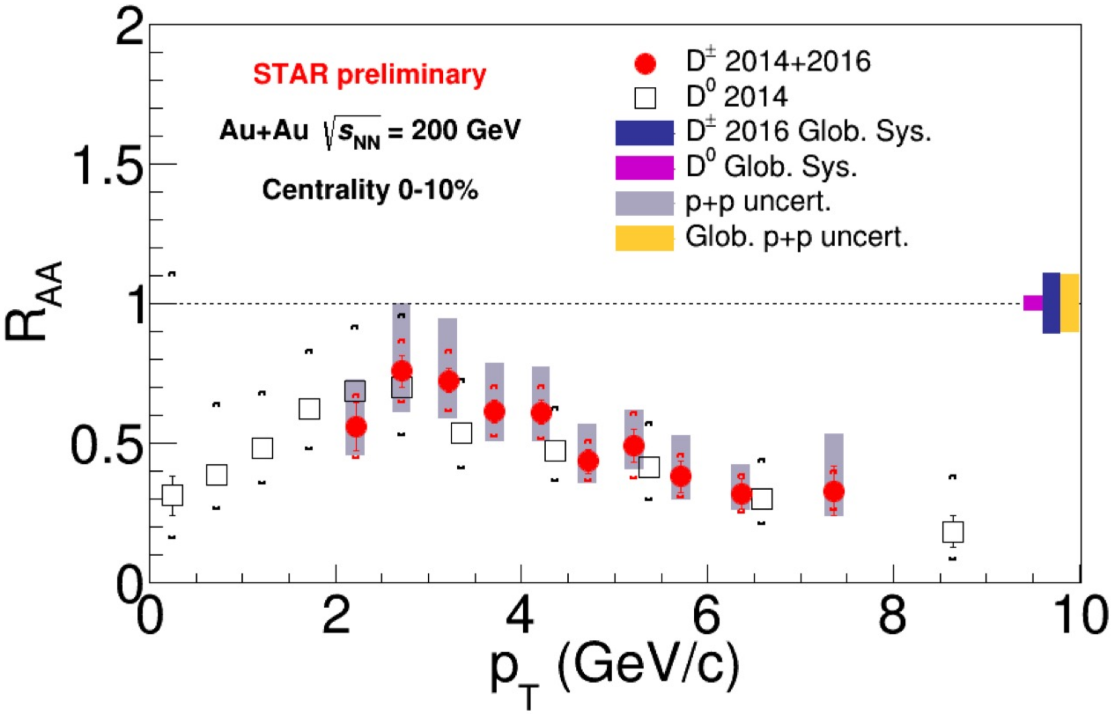
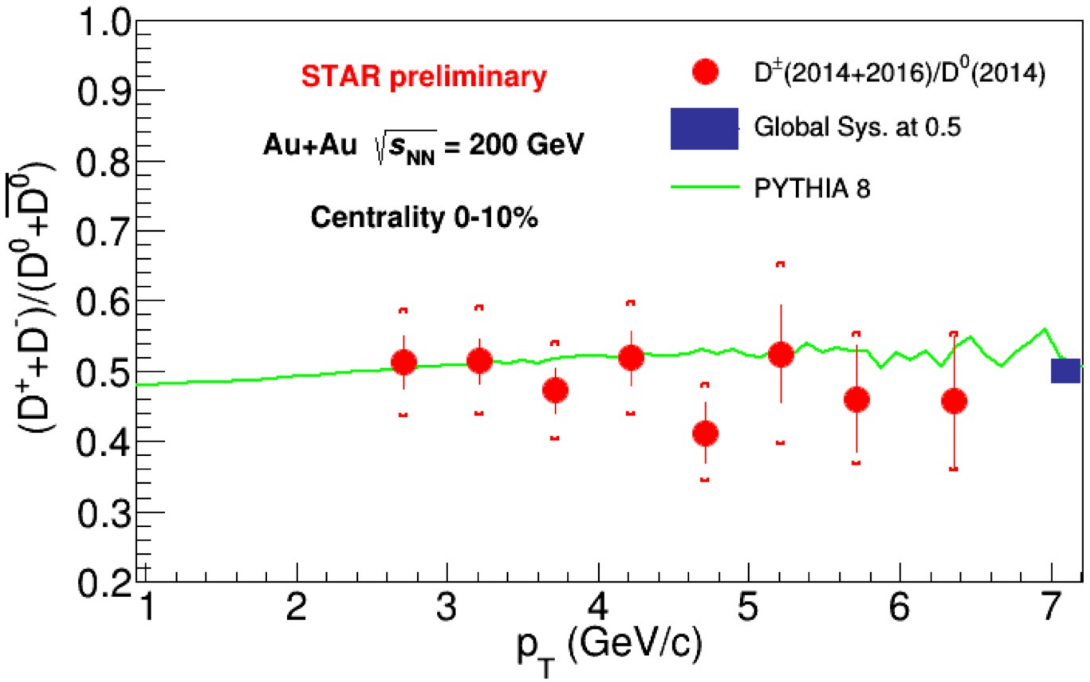
$D^{\pm}$ Production in Au+Au @ 200 GeV

p+p reference (STAR): PRD 86, 072013 (2012)
D^0 (STAR): PRC 99, 034908, (2019)

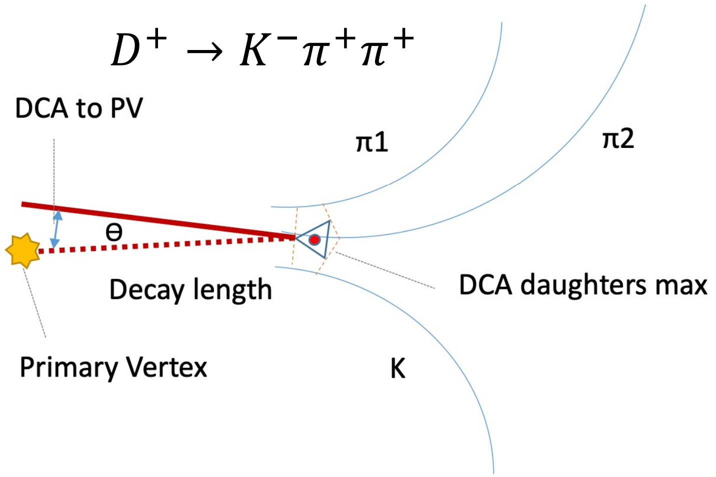




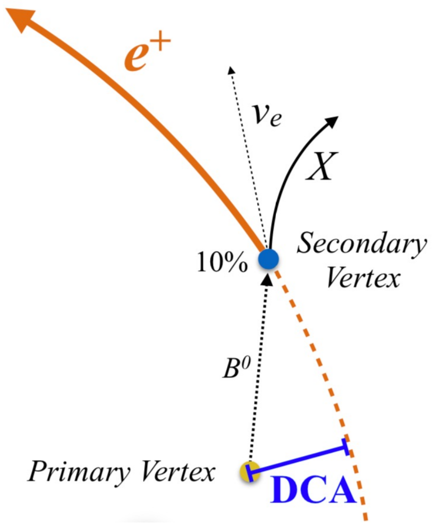
$$R_{AA} = \frac{1}{N_{coll}} \frac{d^2N_{AA}/(dp_T dy)}{d^2N_{pp}/(dp_T dy)} \quad \frac{\text{QGP Medium}}{\text{QCD Vacuum}}$$

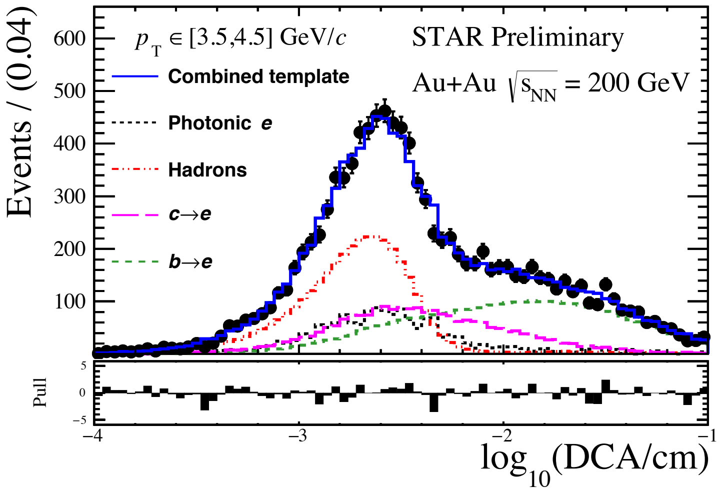
- D^+ R_{AA} consistent with D^0 R_{AA} within uncertainties
  - Significant suppression in central Au+Au collisions at high p_T
- No significant p_T dependence in D^+/D^0 yield ratio and PYTHIA8 predictions are consistent with data

$D^+ \to K^-\pi^+\pi^+$

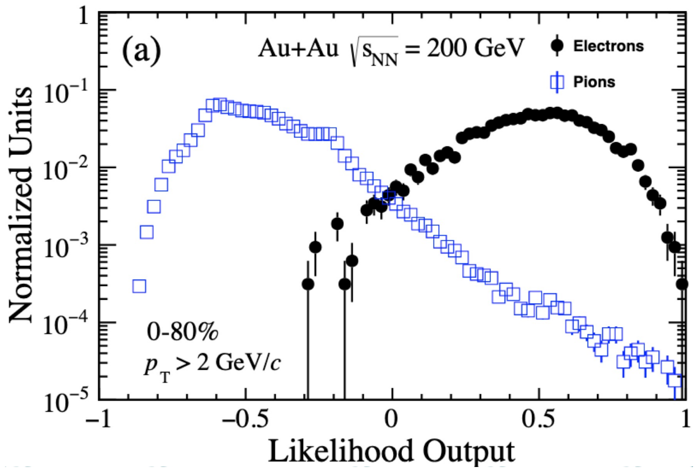


$c, b \to e$ in Au+Au @ 200 GeV

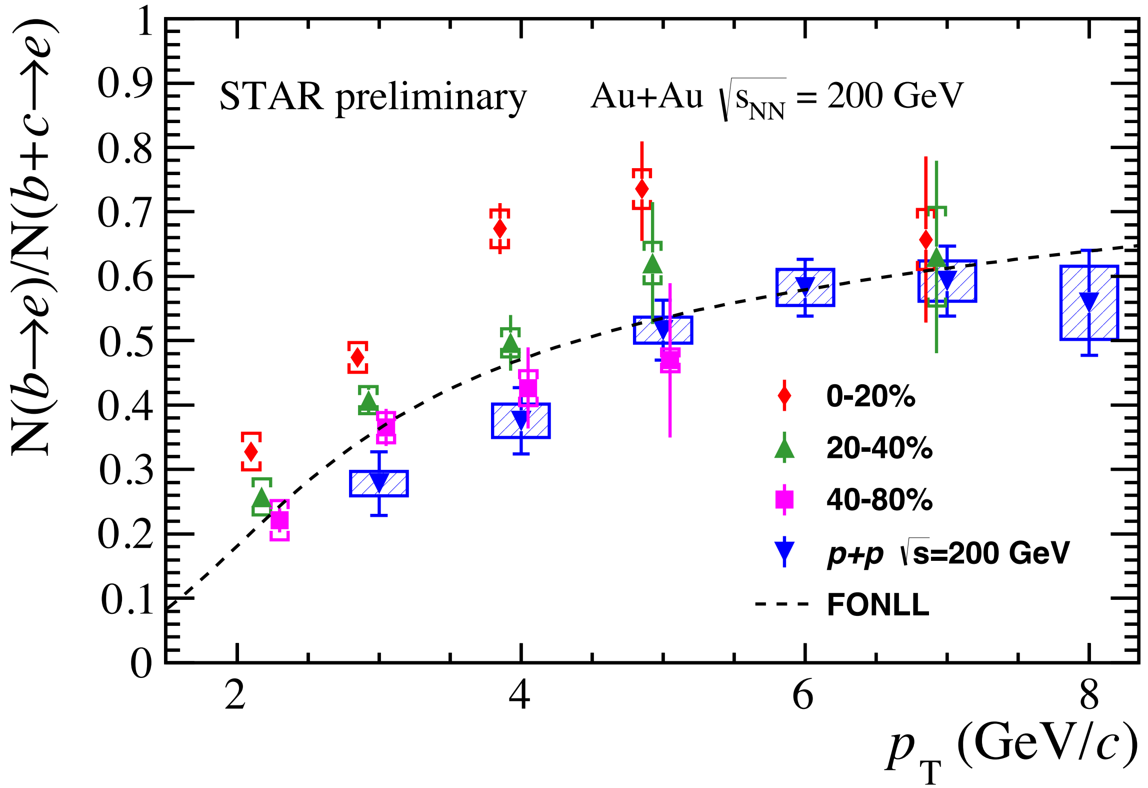




- Extraction of $c, b \to e$ with template fit to log of 3D DCA distribution



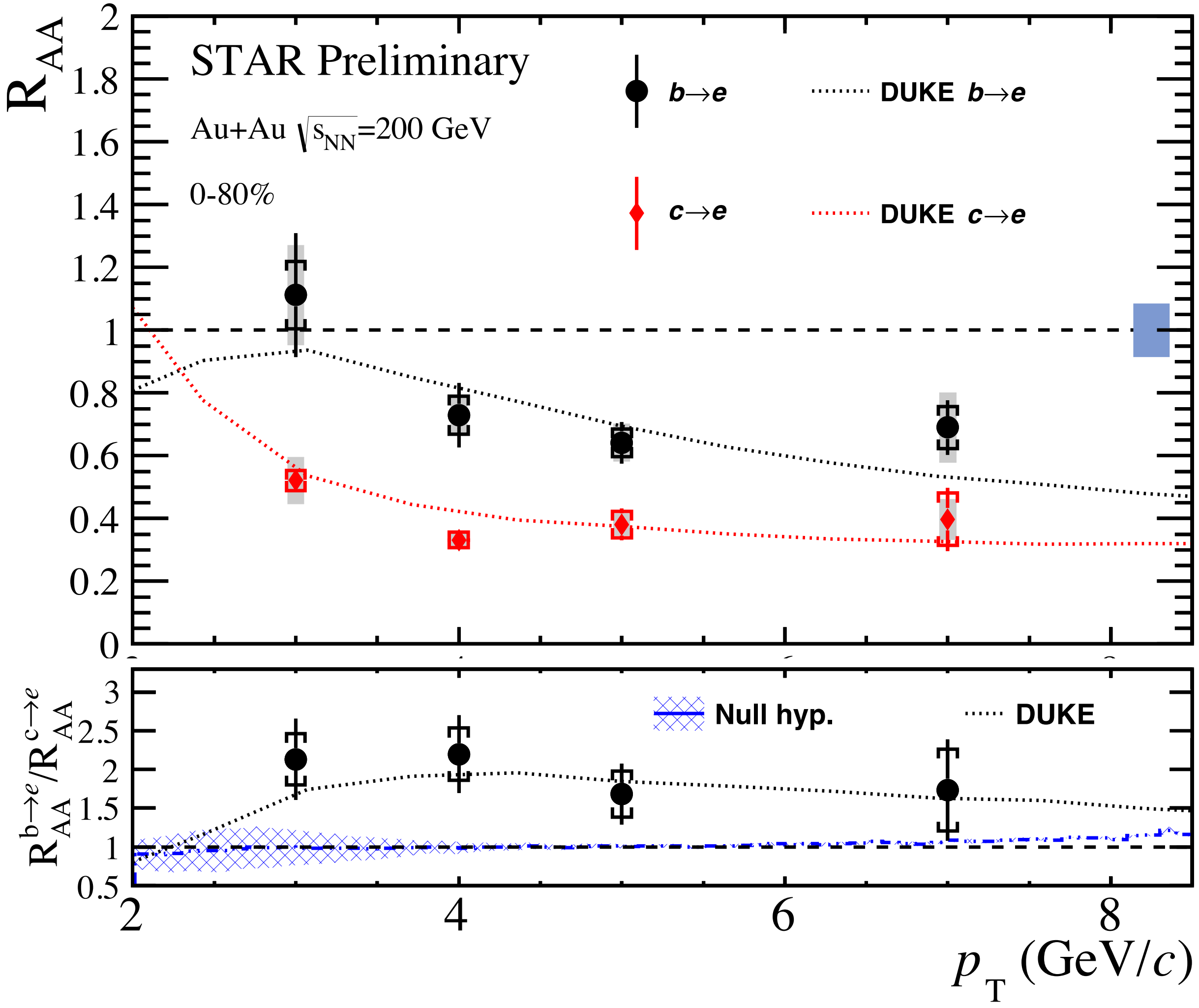
- Electron PID improved with likelihood MVA classifier



- Bottom fraction significantly enhanced in central Au+Au collisions at 200 GeV
- Consistent with p+p and FONLL in peripheral collisions.

$c, b \rightarrow e\ R_{AA}$ in Au+Au @ 200 GeV

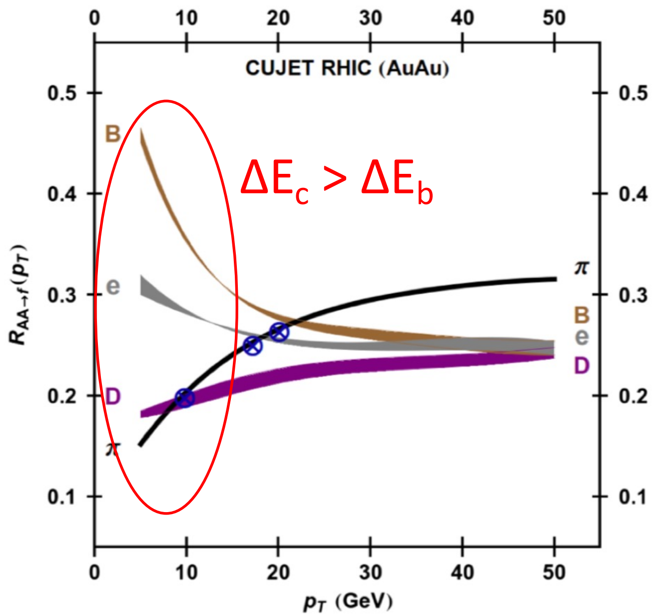
STAR



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

$R_{AA}(c \rightarrow e) < R_{AA}(b \rightarrow e)$ (~3σ at 3 - 7 GeV/c).

- Consistent with mass hierarchy of parton energy loss
- Duke calculations are consistent with data



A. Buzzatti et al., PRL 108, 022301 (2012)

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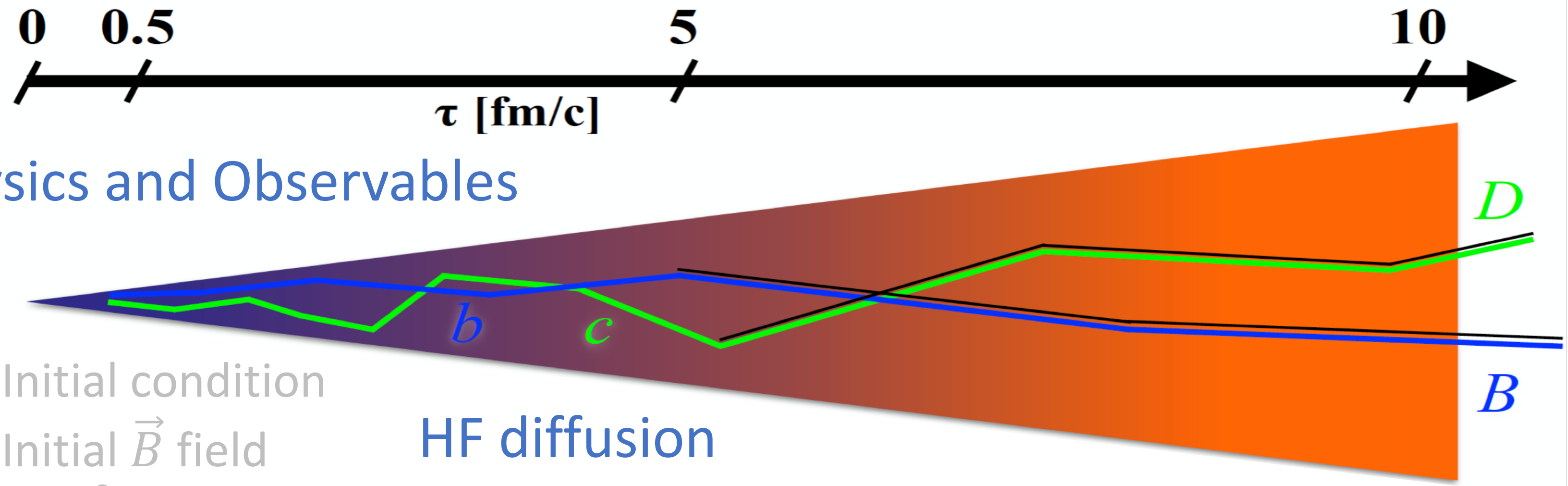

Physics and Observables

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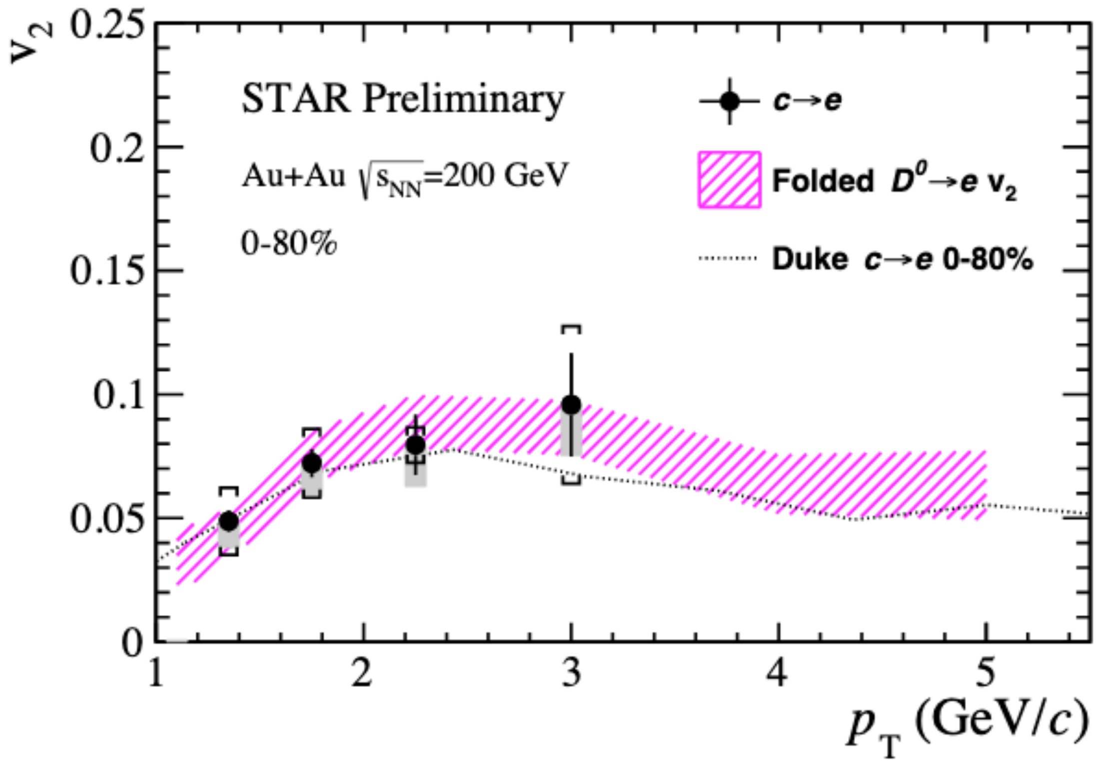
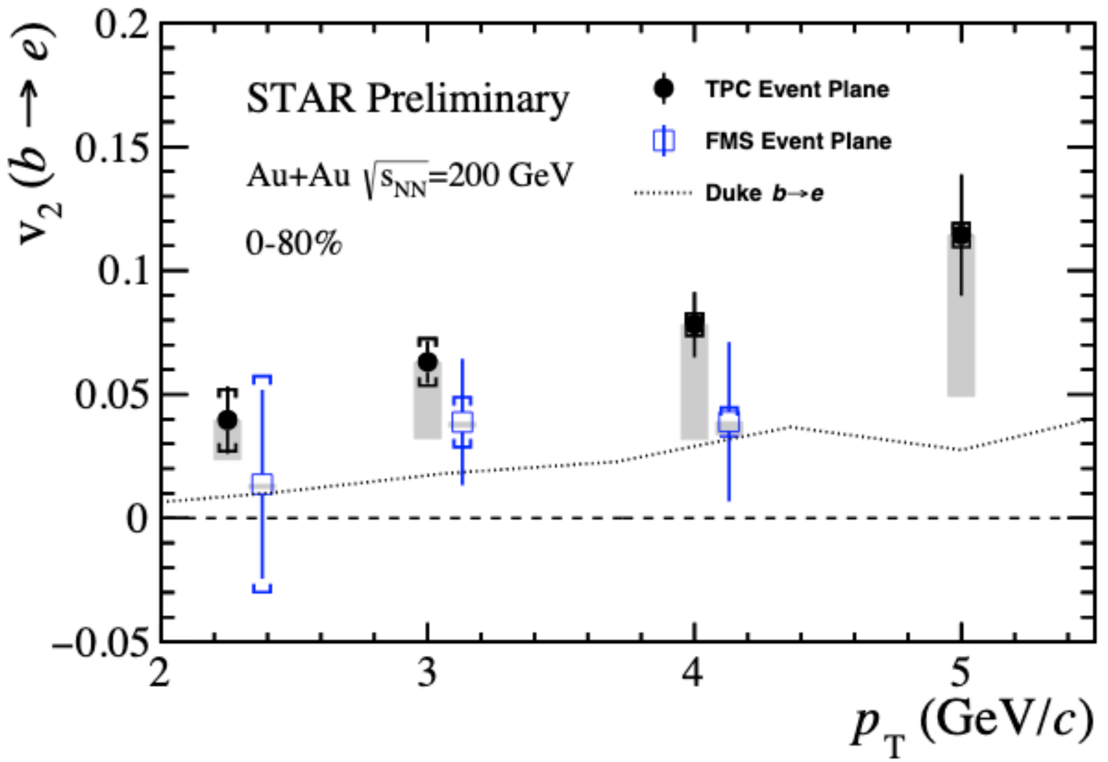
$c, b \rightarrow e$ Elliptic Flow in Au+Au @ 200 GeV

STAR D0: PRL 118, 212301 (2017)

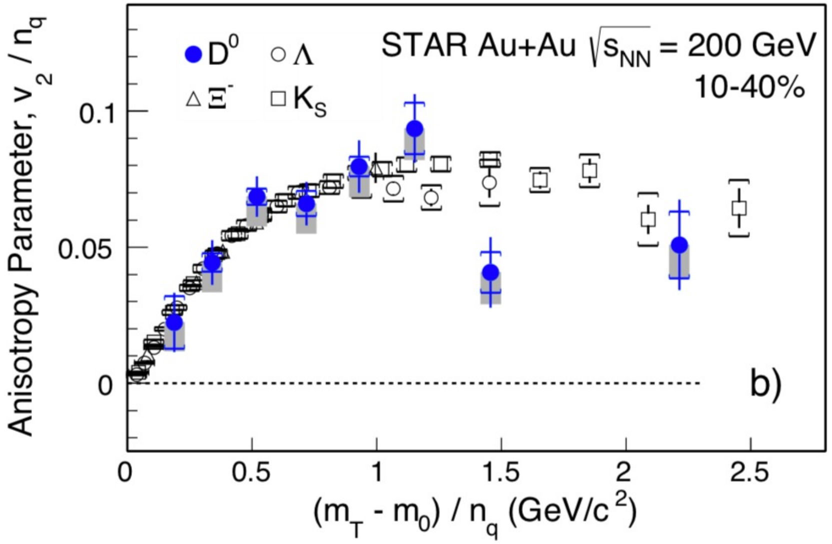


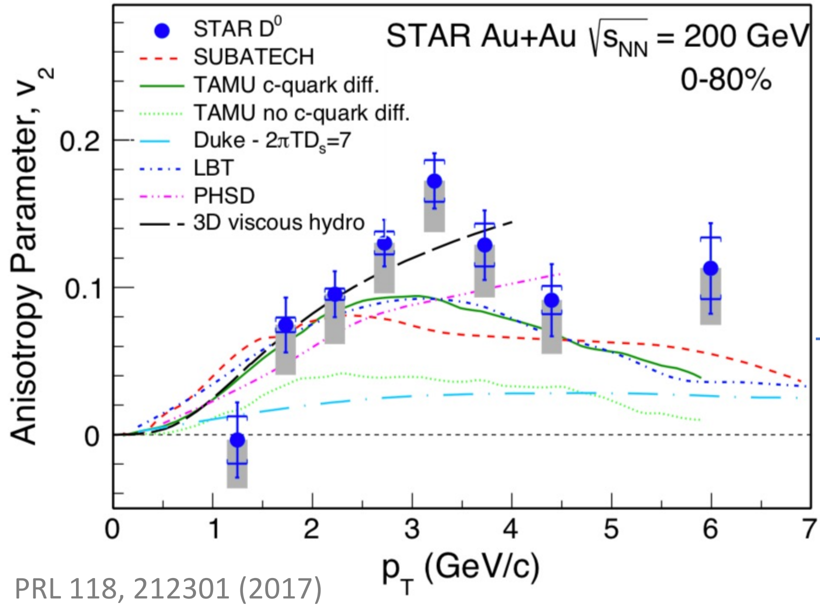
DUKE: PRC 92:024907 (2015)



- $c \rightarrow e$ v_2 consistent with STAR D^0 measurement folded to decayed electrons
- Non-zero $b \rightarrow e$ v_2 with significance >3σ
- Duke calculations are consistent with data considering non-flow

e^{HF} Elliptic Flow at Low Energies





PRL 118, 212301 (2017)

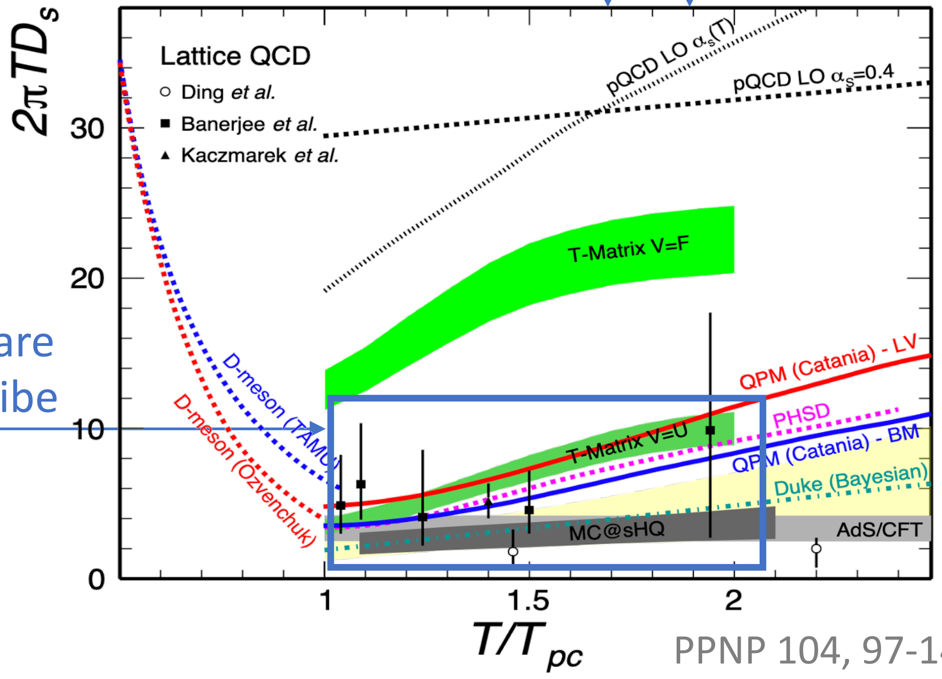
- D⁰ v_2 similar to the light hadrons @ 200 GeV
  - How about charm quarks flow at lower energies?
- Provide new insights into temperature dependence of charm quark $2\pi T D_s$ from HF electrons v_2 measurements at low energies

Initial temperature in TAMU calculation

Au+Au 62.4 200 GeV 0-20% centrality

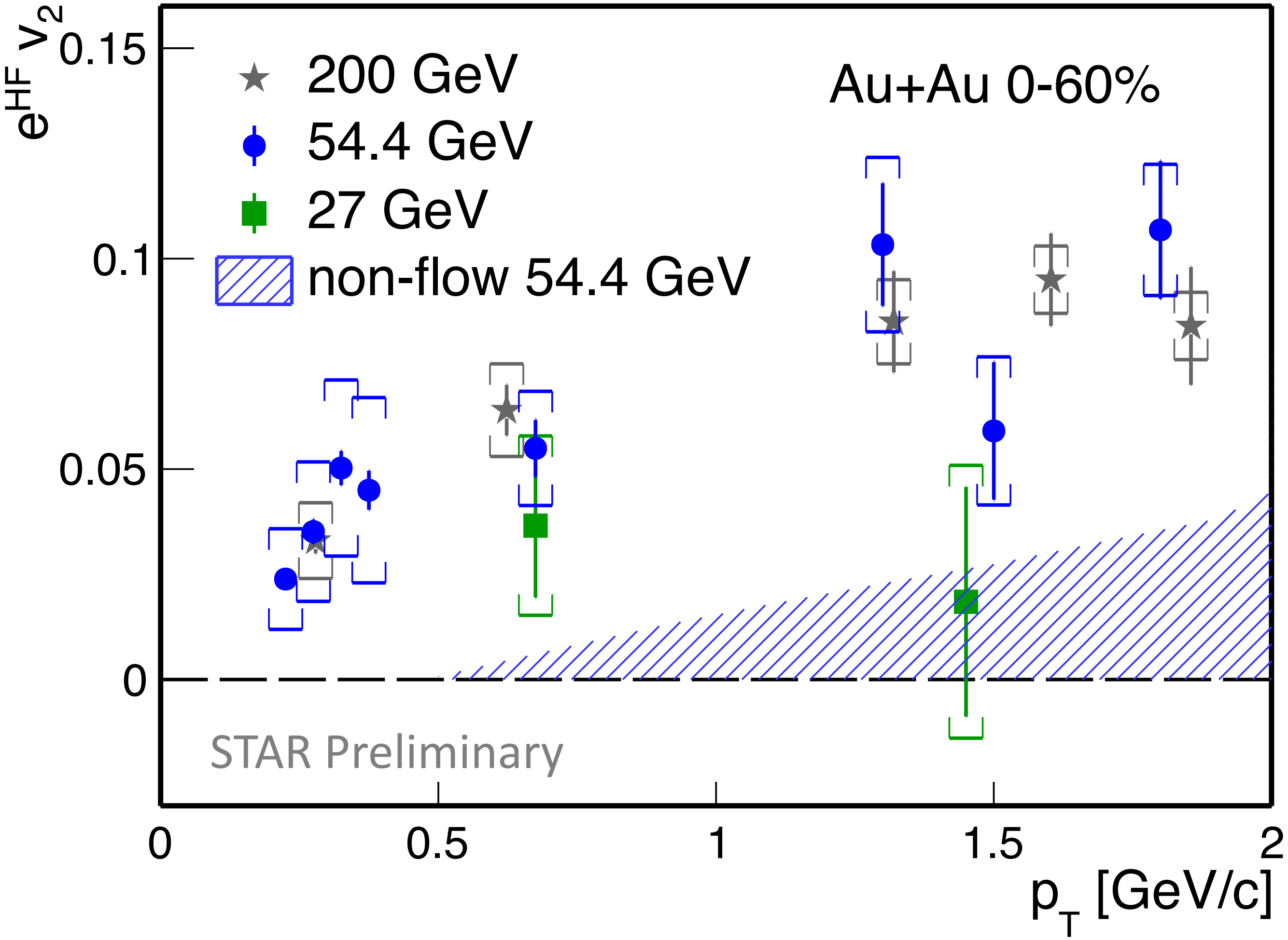
M. He et al. PRC 91,024904 (2015) and private communication

models that are able to describe D⁰ v_2

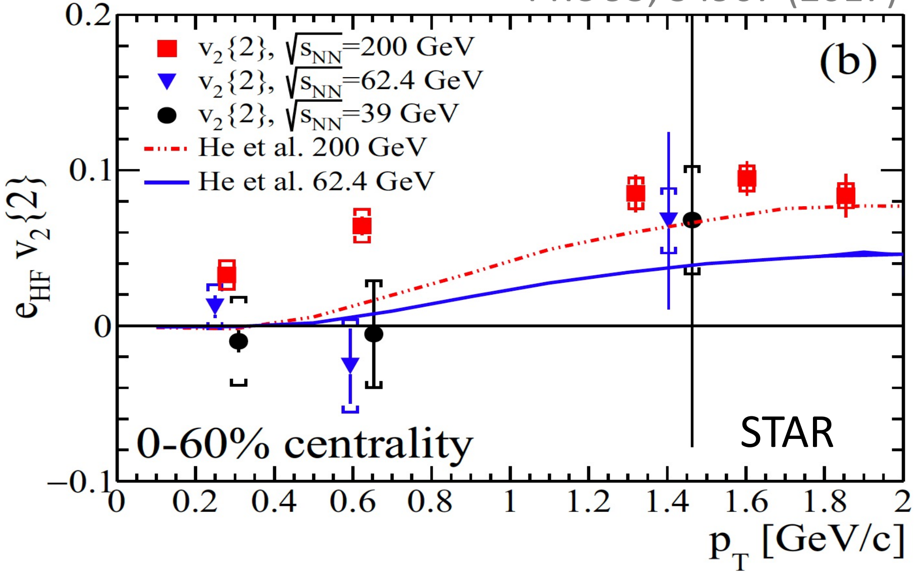


PPNP 104, 97-141 (2019)

e^{HF} Elliptic Flow at Low Energies



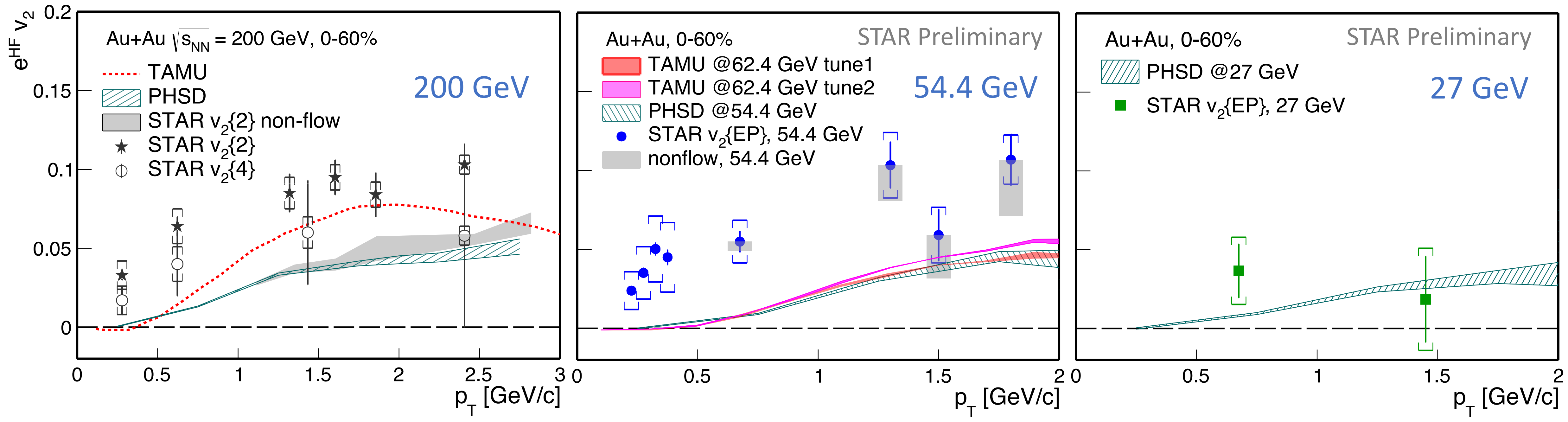
PRC 95, 34907 (2017)



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

e^{HF} v_2 : Compare to Models

M. He et al. PRC 91,024904 (2015)
T. Song et al. PRC 92, 014910 (2015)
T. Song et al. PRC 96, 014905 (2017)



- 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

Summary - Open Heavy Flavor

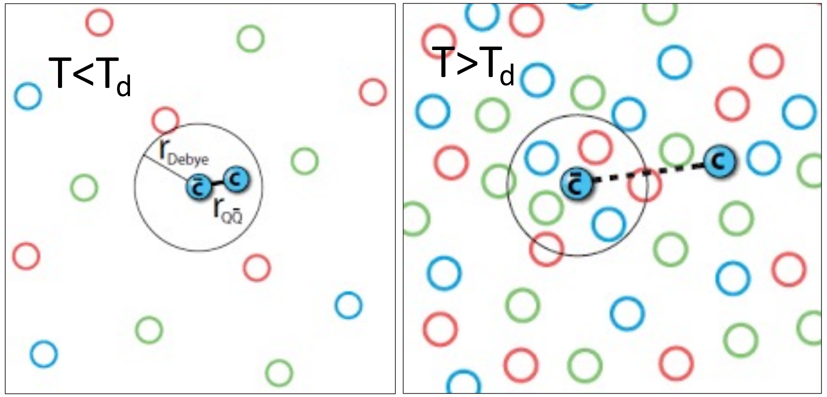
- Significant enhancements of D_s^+/D^0 and Λ_c^+/D^0 ratios in Au+Au w.r.t. *p+p*
  - Important role of coalescence in charm hadronization
- Significant R_{AA} suppression for both D^+ and D^0 in 200 GeV central Au+Au collisions;
  Non-zero NPE v_2 in Au+Au 54.4 GeV collisions comparable to that of 200 GeV
  - Charm quarks interact with QGP medium strongly from 54.4 to 200 GeV
- Hierarchy of *b/c*→*e* R_{AA} in Au+Au 200 GeV
  - Mass dependence of parton energy loss ($\Delta E_b < \Delta E_c$) in the QGP
- Non-zero *b*→*e* v_2 (3.4σ) in Au+Au 200 GeV

Provide additional constraints on QGP transport properties!

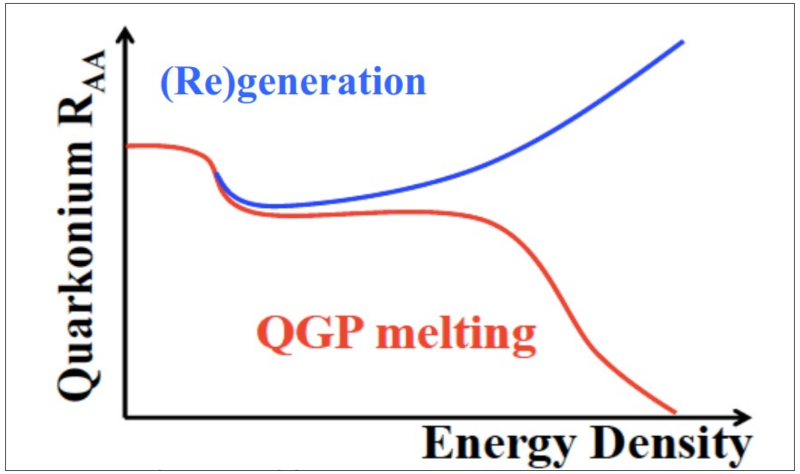
Why Quarkonium?

- Production in A+A
  - Dissociation in QGP
    - e.g. static and dynamic screening
  - Other effects
    - e.g. regeneration, cold nuclear matter effects, final state effects

T_d: dissociation temperature



Dissociation in QGP

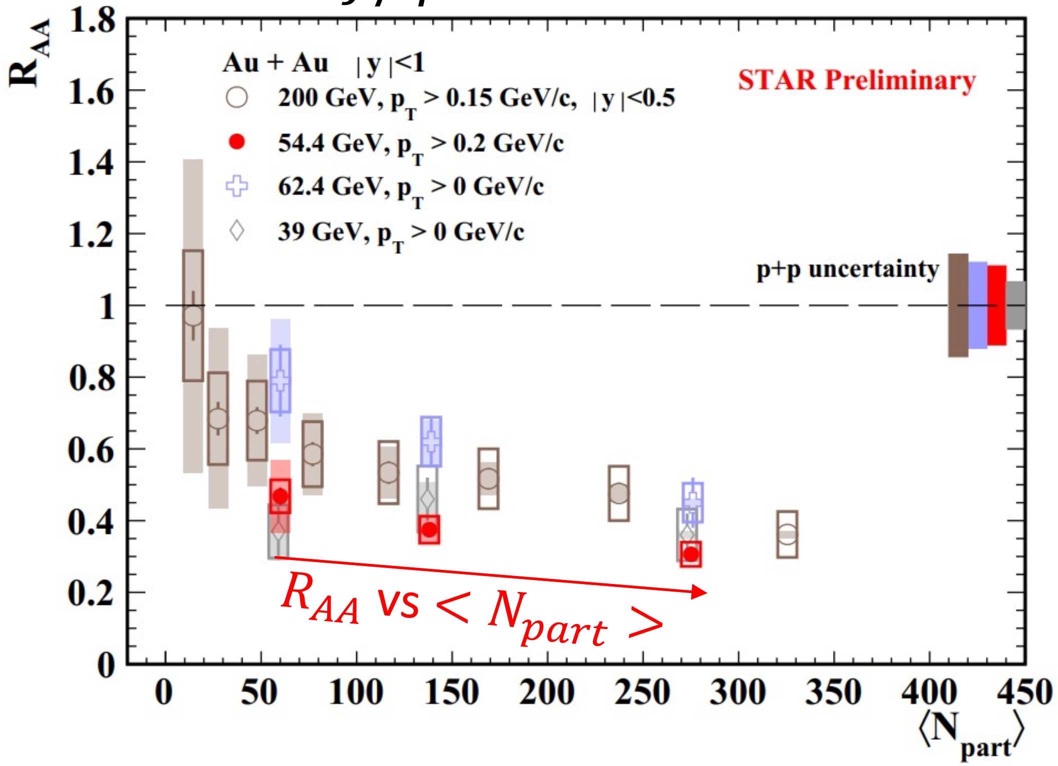


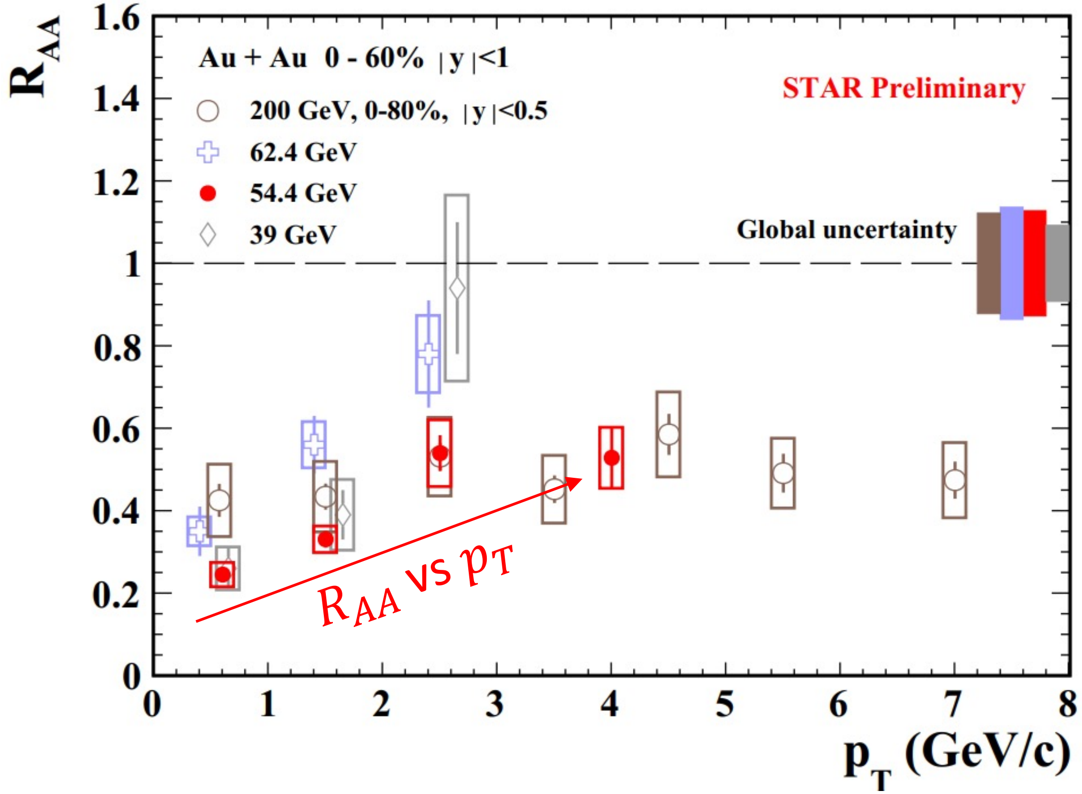
$J/\psi\ R_{AA}$ in Au+Au @ 54.4 GeV

New!

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

39,62.4 and 200 GeV data: STAR PLB 771, 13-20 (2017), PLB 797, 134917 (2019)

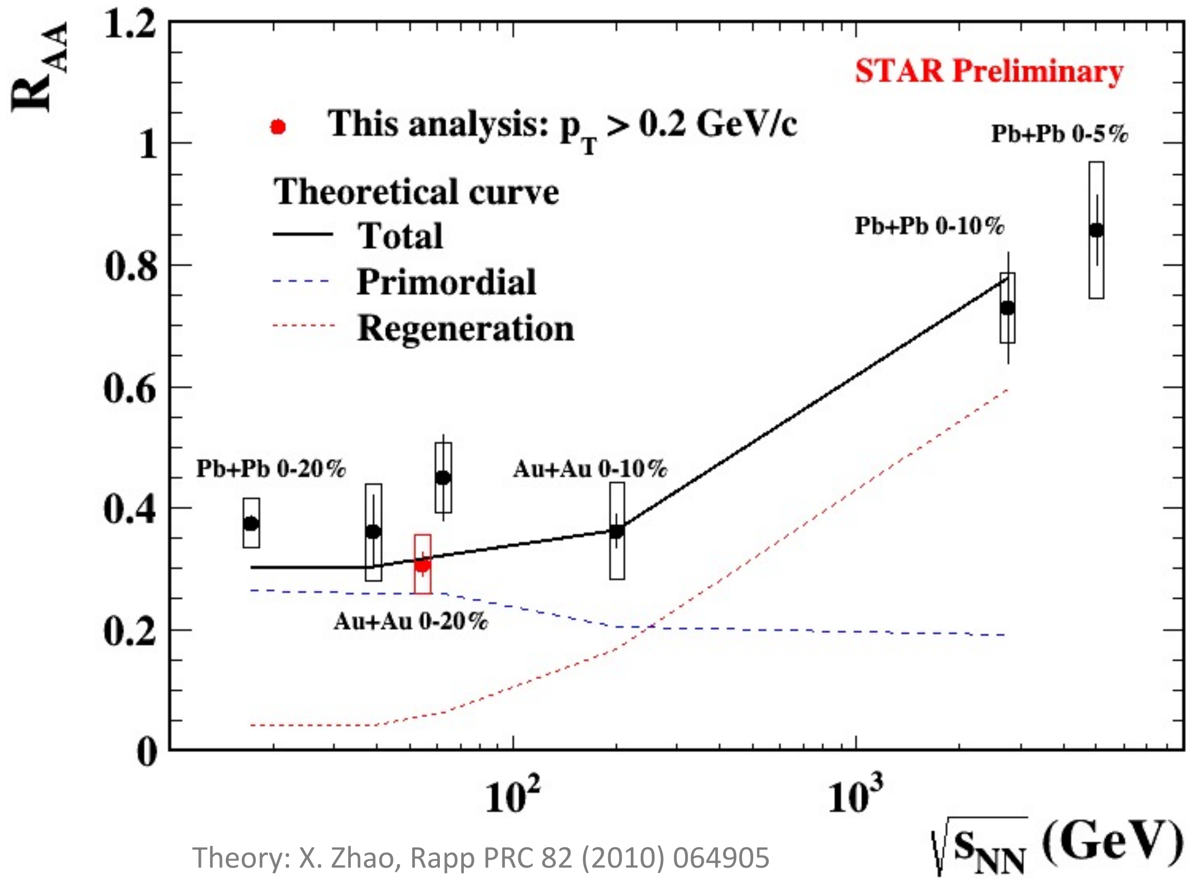




- Better precision with 54.4 GeV data compared to previous measurements at STAR
- More suppression towards central collisions, with no significant energy dependence
- R_{AA} increases with increasing p_T for 39, 54.4 and 62.4 GeV

Collision Energy Dependence of J/ψ R_{AA}

New!



Theory: X. Zhao, Rapp PRC 82 (2010) 064905

ALICE: PLB 734, 314 (2014), NPA 1005, 121769 (2021)
STAR: PLB 771, 13-20 (2017), PLB 797, 134917 (2019)
NA50: PLB 477, 28 (2000)
EPJC 43, 145 (2005)

- 54.4 GeV data follow the trend with improved precision
- No significant energy dependence observed within uncertainties up to 200 GeV
  - Interplay of dissociation, regeneration and cold nuclear matter effects
- Model calculations are consistent with data

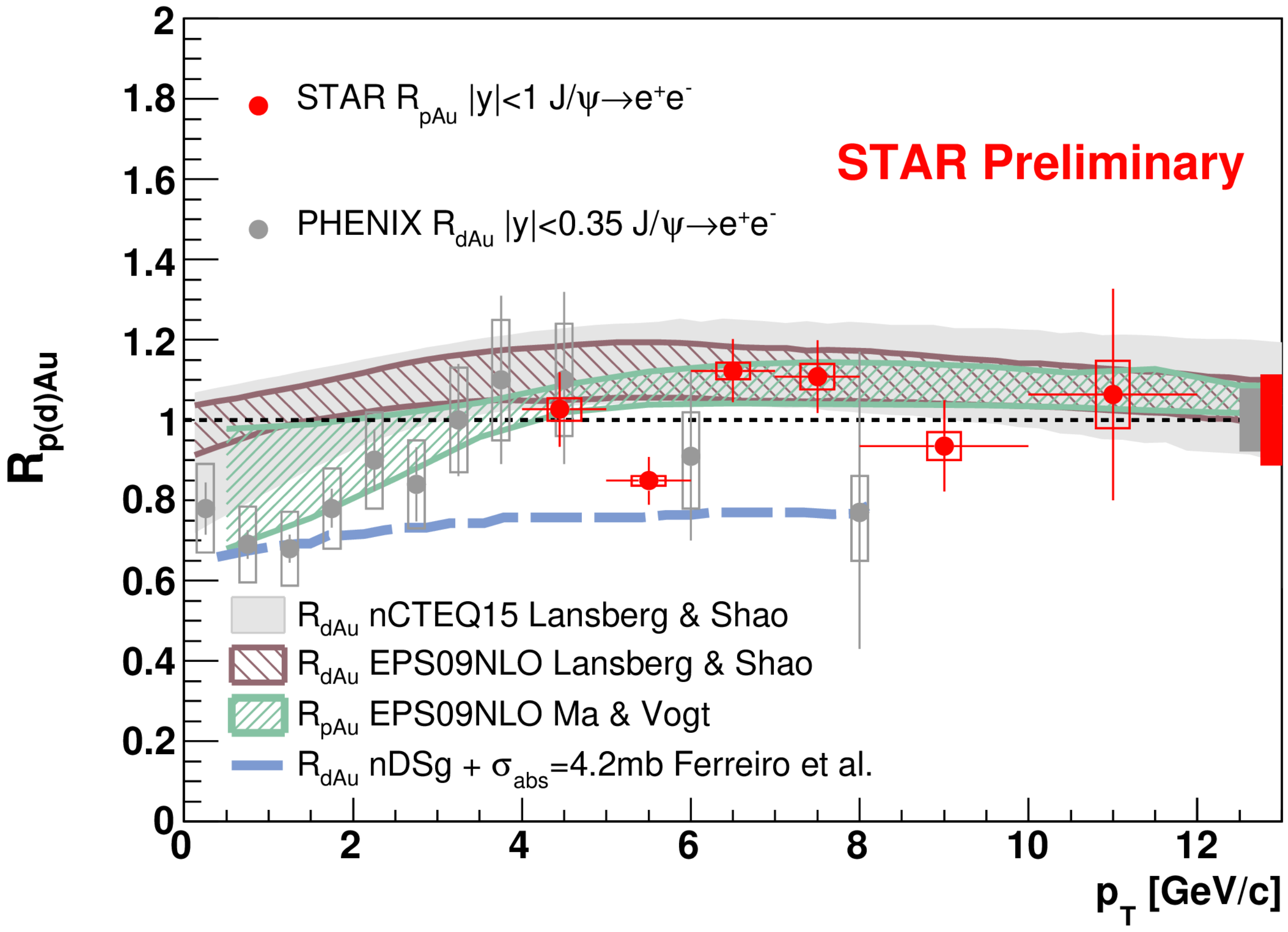
Theory calculations are for the same system as data points in 0-20% centrality

Why Quarkonium?

- Production in A+A
  - Dissociation in QGP
    - e.g. static and dynamic screening
  - Other effects
    - e.g. regeneration, cold nuclear matter effects, final state effects

- Production in p+A
  - Cold nuclear matter effects (CNM)
    - e.g. nuclear Parton Distribution Functions (nPDFs), nuclear absorption, coherent energy loss
  - Final state effects
    - e.g. co-mover interactions

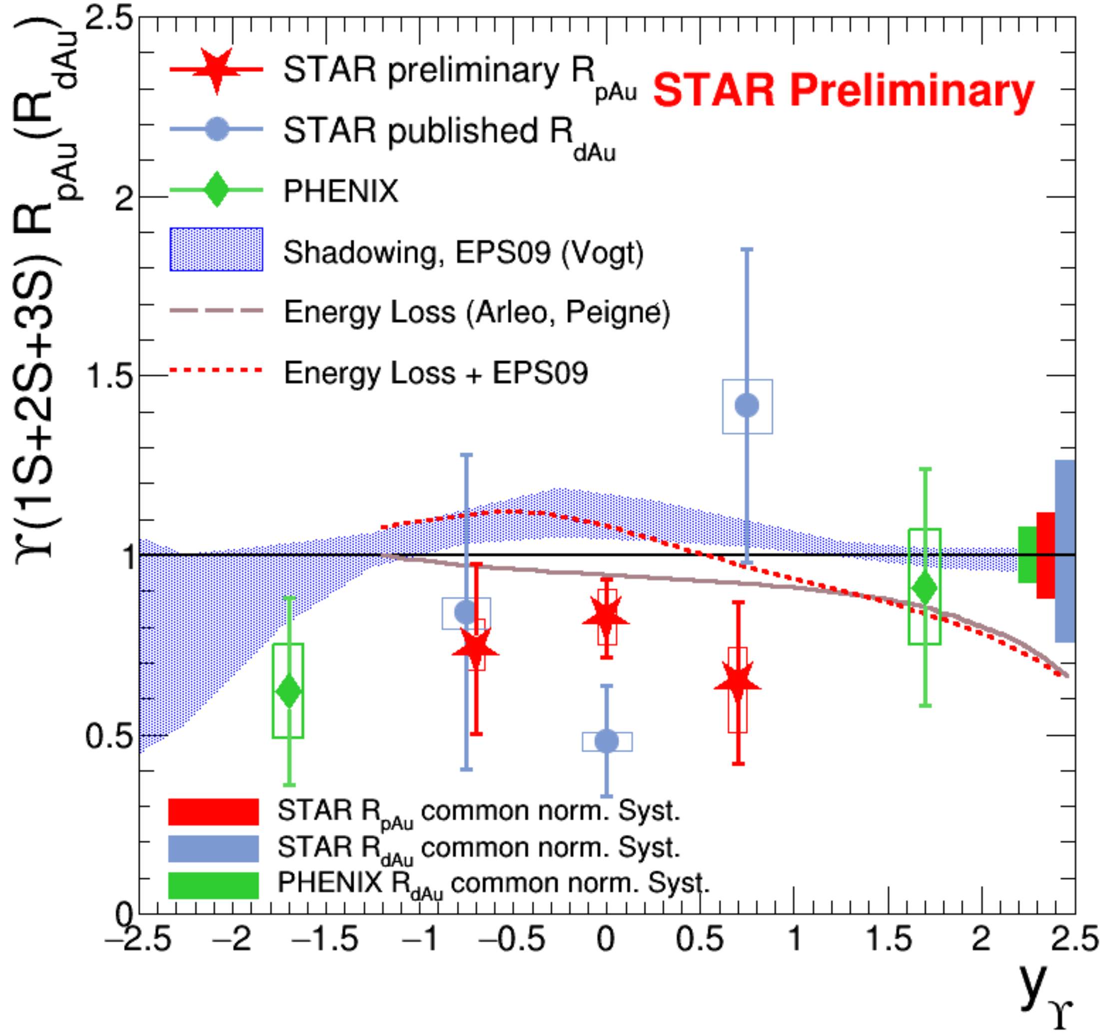
J/ψ Production in p+Au @ 200 GeV



- R_{pAu} consistent with unity at high p_T
  - Suggesting no modifications due to the CNM effects
  - Models with nPDF effects consistent with data

- Consistent with PHENIX R_{dAu}
  - Indicating similar CNM effects in p+Au and d+Au collisions

ϒ Production in p+Au @ 200 GeV



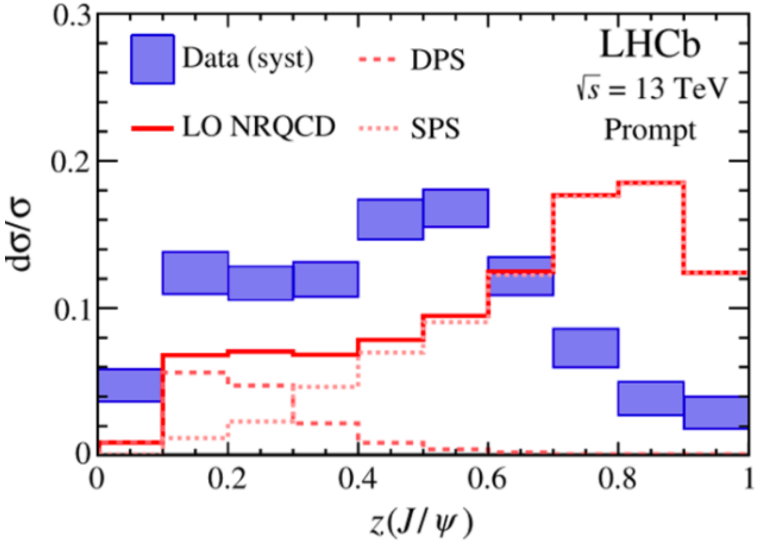
- Improved precision over previous d+Au results (~50% smaller statistical uncertainty)
- Indication of more suppression than that in models with nPDF effects and energy loss in cold nuclear matter

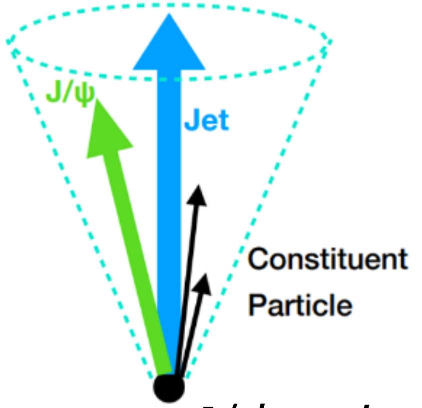
PHENIX, PRC 87, 034904 (2013)
EPS09+NLO, Ma & Vogt, Private Common
nCTEQ, EPS09+NLO, Lansberg & Shao: EPJ.C77, no.1, 1 (2017)
Comp. Phys. Comm. 198, 238-259 (2016)
Comp. Phys. Comm. 184 , 2562-2570 (2013)
Ferreriro et al., Few Body Syst. 53 (2012) 27

J/ψ Production in Jets in p+p @ 500 GeV

- Understand production mechanism of J/ψ
- Produced directly or in parton shower (associated with jets)?

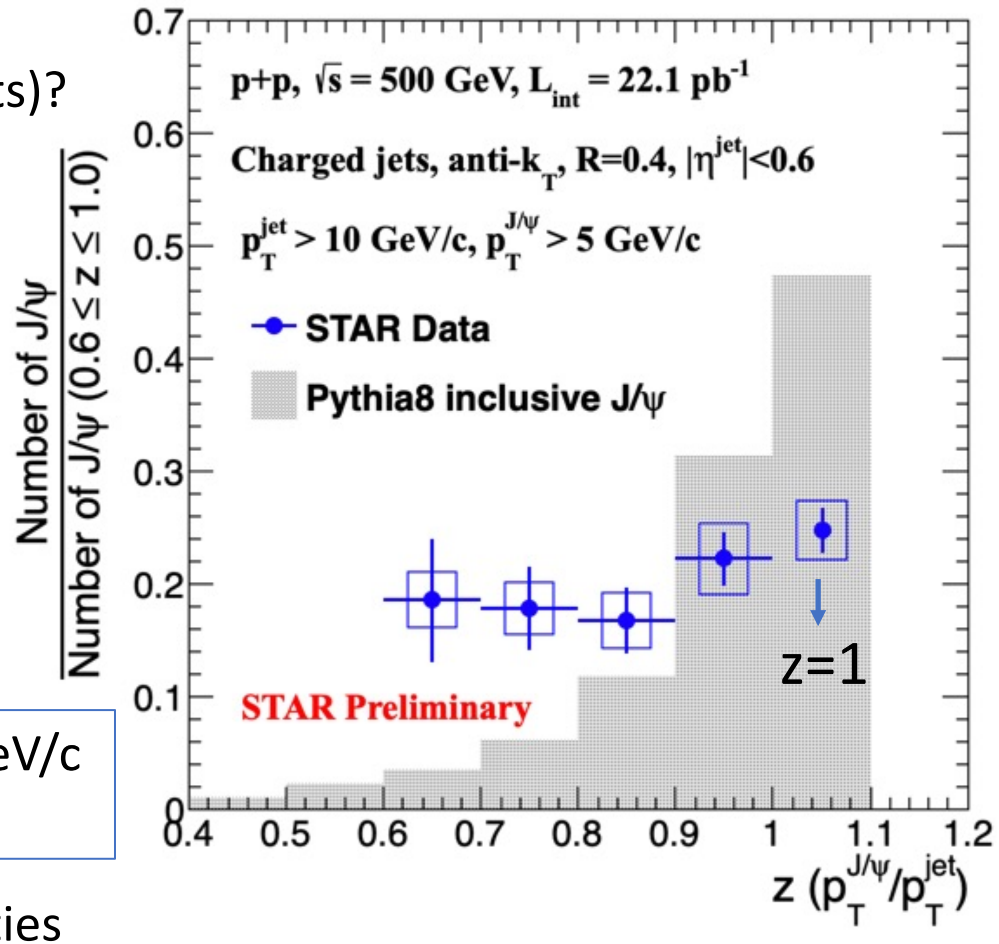
LHCb, PRL 118, 192001 (2017)





$$z = p_T^{J/\psi} / p_T^{jet}$$

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



- No significant z dependence observed within uncertainties
  - Different trends compared to Pythia8
- Help to constrain LDMEs in NRQCD calculations

Z. Kang et .al, PRL 119, 032001 (2017)

Summary - Quarkonium

- Au+Au – J/ψ R_{AA} @ 54.4 GeV
  - Suppression of J/ψ R_{AA} observed at 54.4 GeV
  - No significant energy dependence of J/ψ R_{AA} suppression observed in central collisions up to 200 GeV

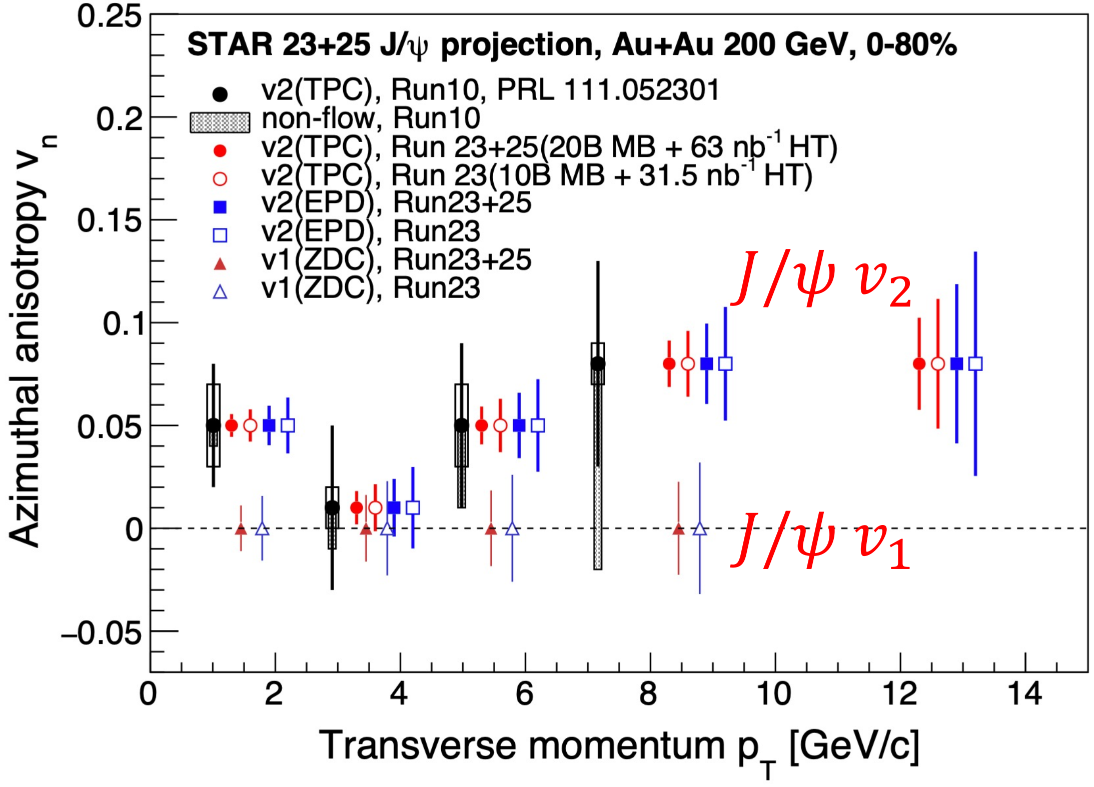
    - Interplay of dissociation, regeneration and cold nuclear matter effects

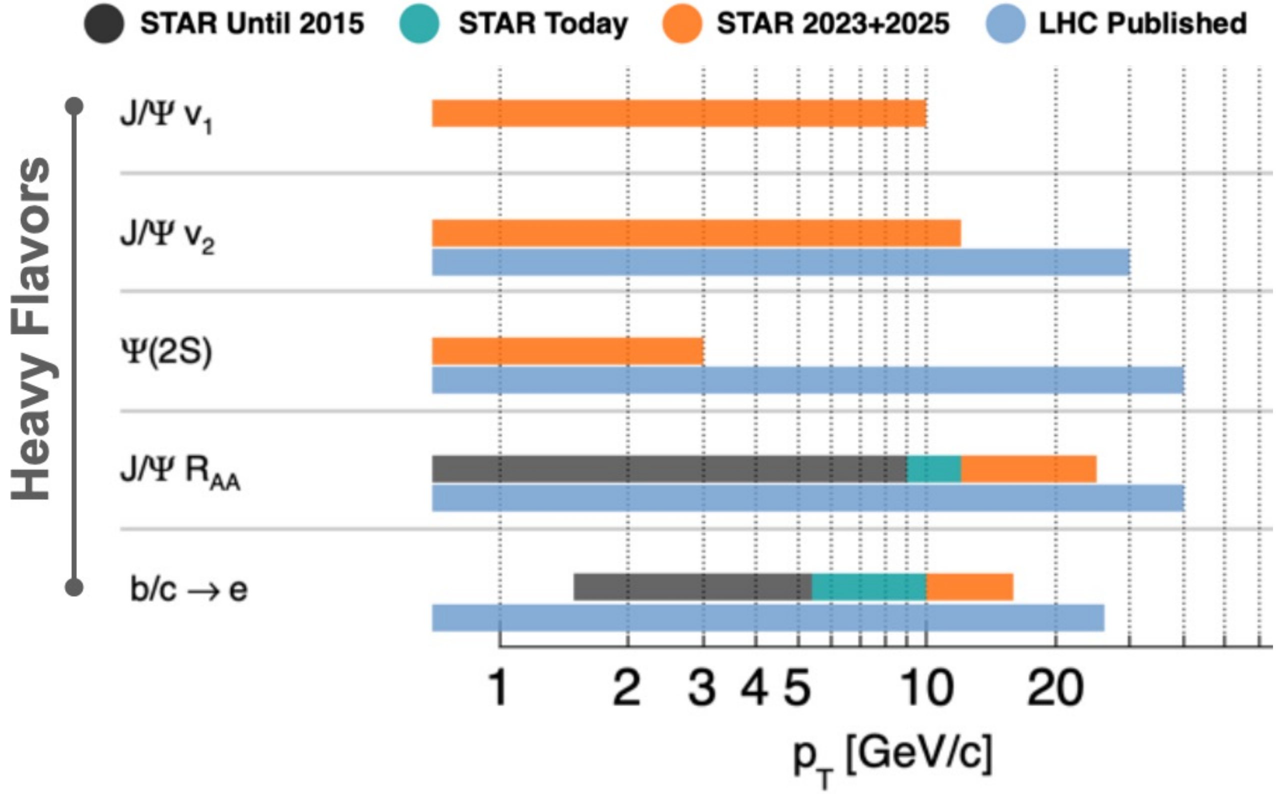
- p+Au - J/ψ and Υ R_{pAu} @200 GeV
  - The CNM effects are negligible for high-p_T J/ψ (p_T > 4 GeV/c), but not for low-p_T Υ

- p+p - J/ψ in jets @ 500 GeV
  - No significant z dependence of J/ψ production in jets observed for J/ψ p_T > 5 GeV/c and jet p_T > 10 GeV/c
    - Different trends compared to Pythia8

Outlook – HF at STAR 2023-2025

- Run 23+25: expect 20×10^9 MB events for Au+Au 200 GeV (10 times of Run 14+16)
- Utilize detector upgrades (iTPC, EPD, etc)



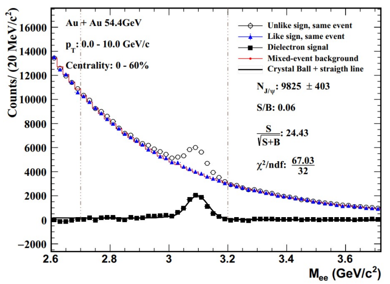


- $J/\psi\ v_1$ - initial tilt of bulk medium
- $J/\psi\ v_2$ - regeneration mechanism

- Broader momentum coverage at RHIC
- Complementary between RHIC and LHC

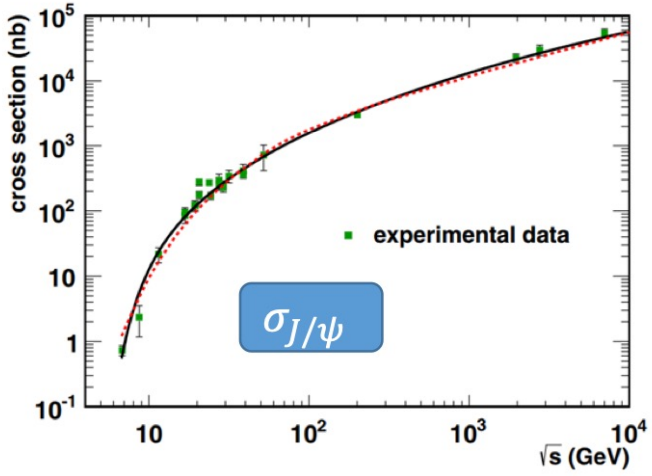
- Back ups

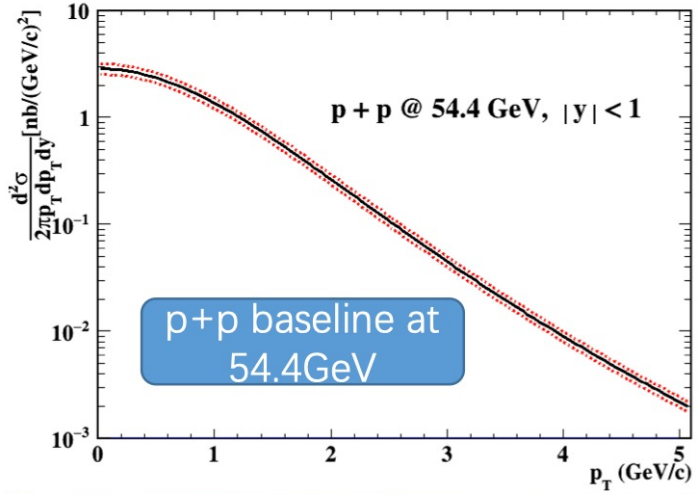
J/ψ Production in Au+Au @ 54.4 GeV



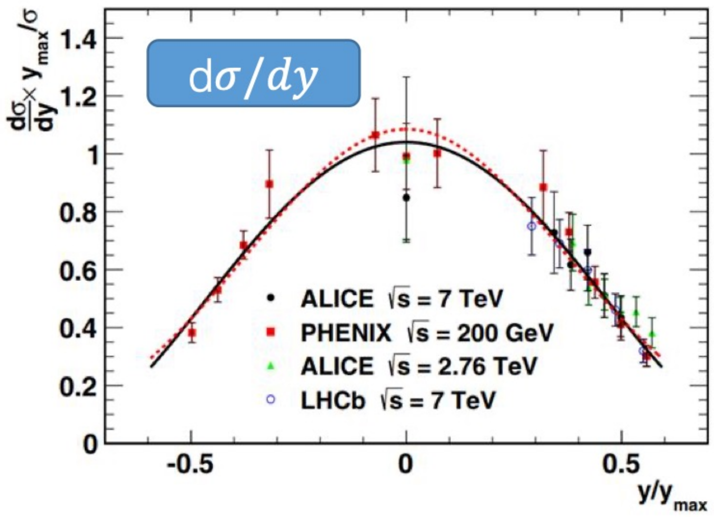
- **For p+p baseline at 39, 54.4, and 62.4 GeV, they are extracted from phenomenological calculations**

W. Zha, et al., Phys. Rev. C 93 (2016) 024919.



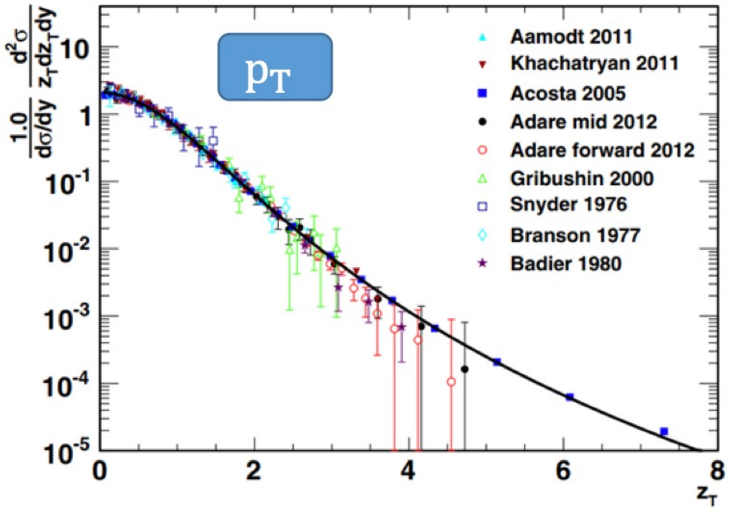


- ➢ Energy interpolation from the existing total J/ψ cross section measurements
- ➢ Energy evolution of the rapidity distribution
- ➢ Energy evolution of J/ψ transverse momentum distribution



$$\frac{1}{\sigma}\frac{d\sigma}{d(y/y_{max})} = a e^{-\frac{1}{2}\left(\frac{y/y_{max}}{b}\right)^2}$$

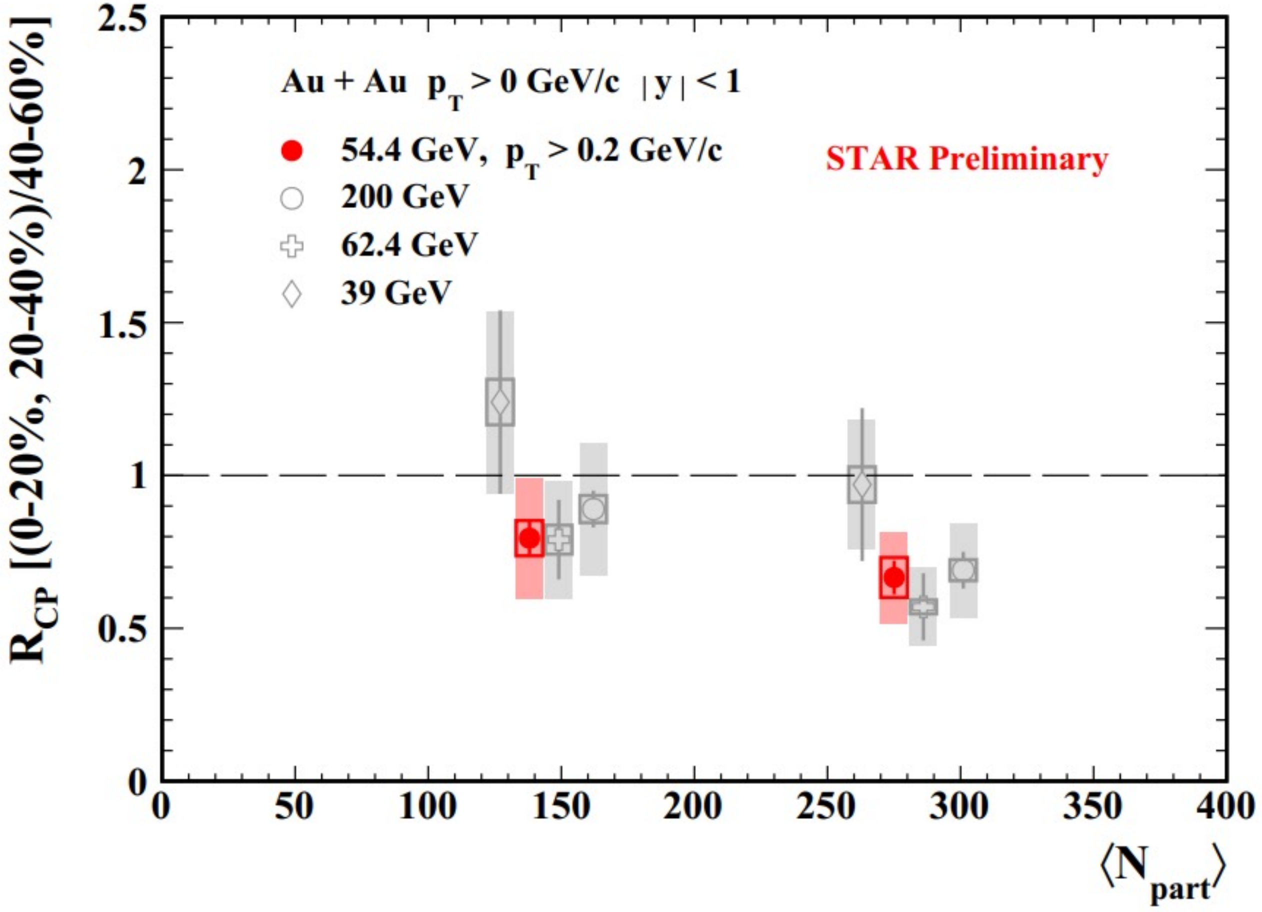
where $y_{max} = \ln\left(\frac{\sqrt{s}}{m_{J/\psi}}\right)$



$$\frac{1}{d\sigma/dy}\frac{d^2\sigma}{z_T dz_T dy} = a \times \frac{1}{(1+b^2 z_T^2)^n}$$

where $z_T = p_T/\langle p_T \rangle$

$\langle N_{part} \rangle$ dependence of J/ψ R_{CP} in Au+Au

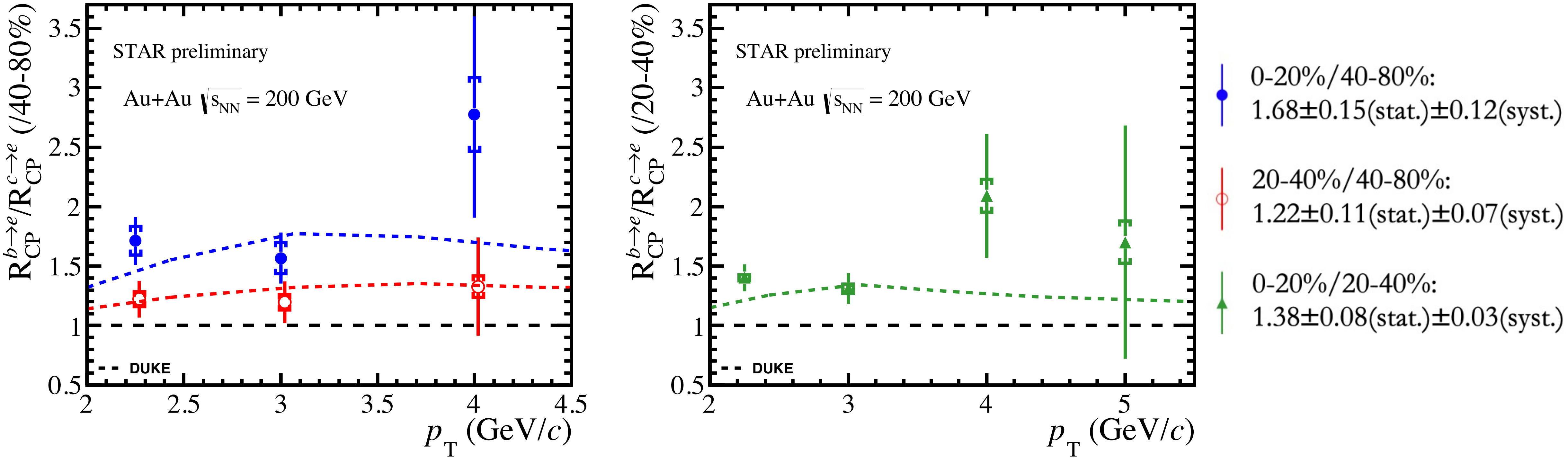


$$R_{CP} = \frac{\frac{dN/dy}{\langle N_{coll} \rangle}(\text{central})}{\frac{dN/dy}{\langle N_{coll} \rangle}(\text{peripheral})}$$

- Suppression observed in central Au+Au collisions at 54.4 GeV, similar to that at 62.4 and 200 GeV.

Double ratio of R_{CP}

$$\frac{R_{CP}^{b\to e}}{R_{CP}^{c\to e}} = \frac{f_b^{central}}{1 - f_b^{central}} \frac{1 - f_b^{peripheral}}{f_b^{peripheral}}$$



- Calculated from centrality dependent bottom fraction
- Large cancelation of correlated systematic uncertainties
- Constant fit to double ratio >1, significant at 3.5σ and 4.4σ for R_{CP}(0-20%/40-80%) and R_{CP}(0-20%/20-40%)

Quarkonium Physics at STAR

Production in p+p

- Production mechanism of J/ψ still not fully understood
- Difficult for models to account for the hadronization:
    - Color Singlet Model
    - NRQCD approach(CGC+NRQCD)
      - Long distance matrix elements(LDMEs)
    - Improved Color Evaporation Model
    - …

Quarkonium Physics at STAR

Production in p+p

- Production mechanism of J/ψ still not fully understood
  - NRQCD approach (factorization formalism)

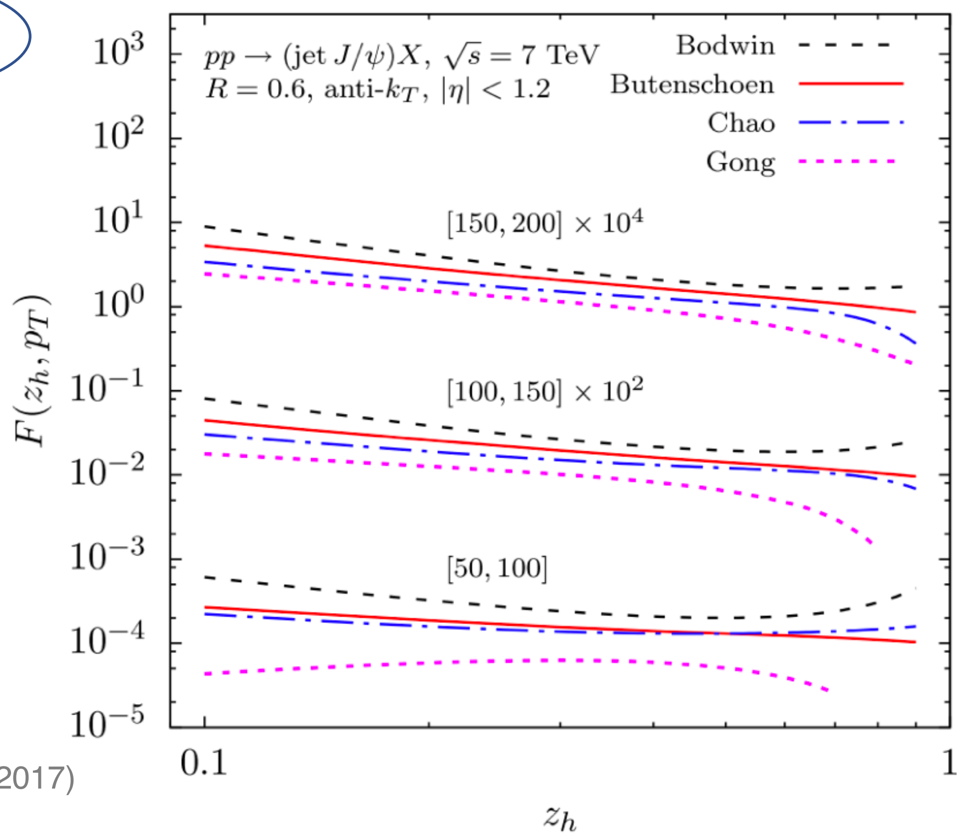
$$d\sigma[pp \to J/\psi X] = \sum_n d\sigma[pp \to c\bar{c}(n)X]\langle \mathcal{O}^{J/\psi}(n)\rangle$$

Production of $c\bar{c}$ (pQCD)

Evolution of $c\bar{c}$ into J/ψ (non-pQCD)

long-distance matrix elements (LDMEs)

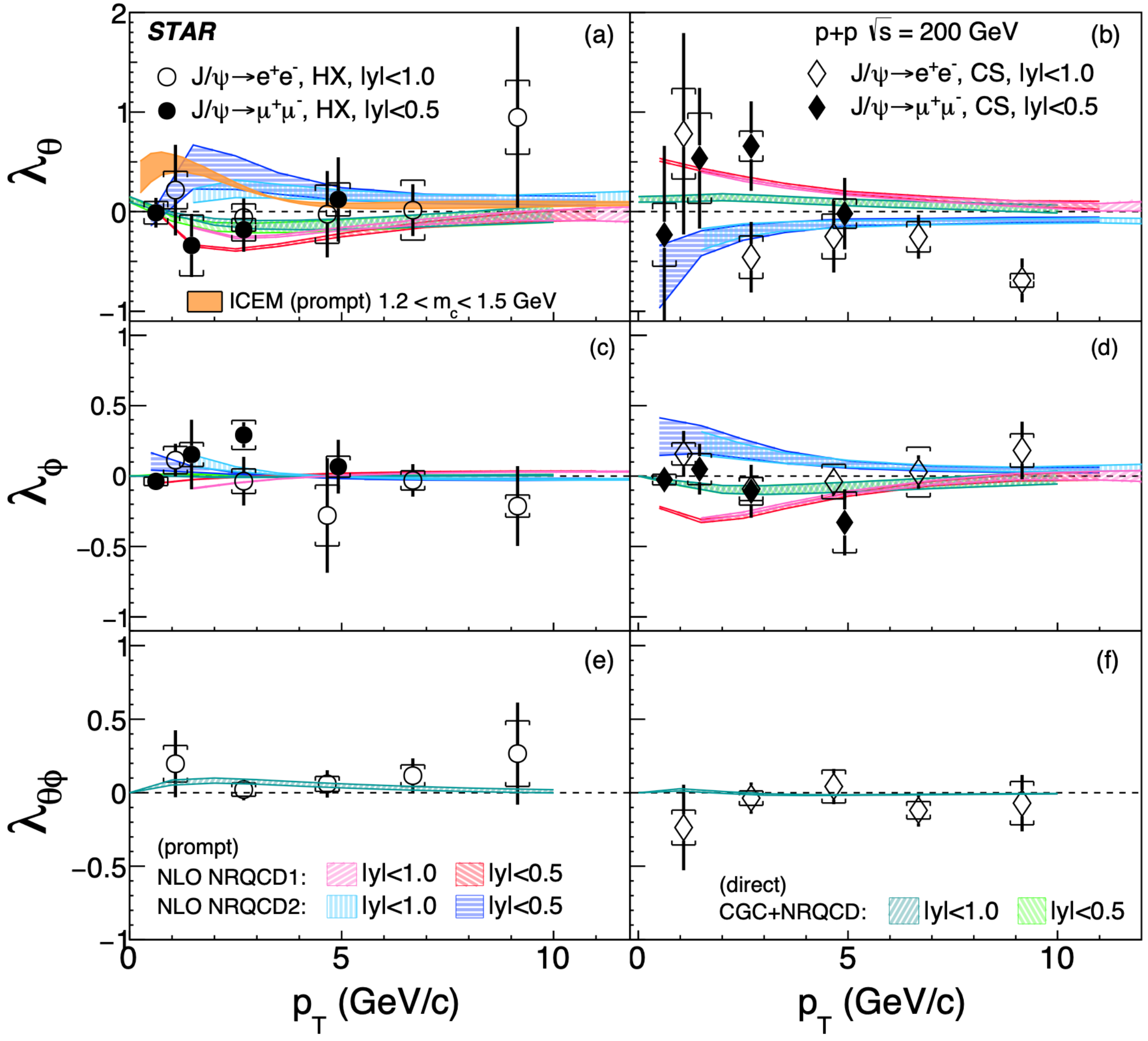
- J/ψ distrbition in jet is predicted to constrain the LDMEs



Z. Kang et .al, PRL 119, 032001 (2017)

J/ψ polarization in p+p @ 200 GeV

Final!



$$\frac{d^2N}{dcos\theta d\phi} \sim 1 + \lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi$$
$$+\lambda_{\theta\phi} sin2\theta cos\phi$$

- λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ are consistent with 0 in both HX and CS frames
- NRQCD calculations with two different sets of LDMEs and CGC+NRQCD calculation are all consistent with data within uncertainties

NRQCD1: PRL 114 (2015) 092006
NRQCD2: PRL 110 (2013) 042002
CGC+NRQCD: JHEP 12 (2018) 057