U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven National Laboratory

Overview of Heavy Flavor and Quarkonia Results From STAR

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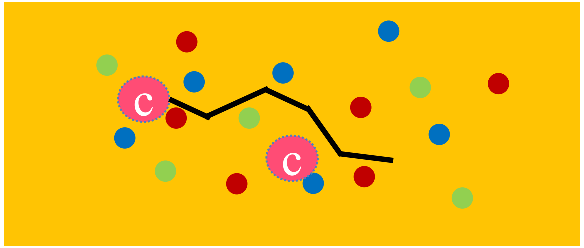
11/06/2023

2nd workshop on advancing the understanding of non-perturbative QCD using energy flow

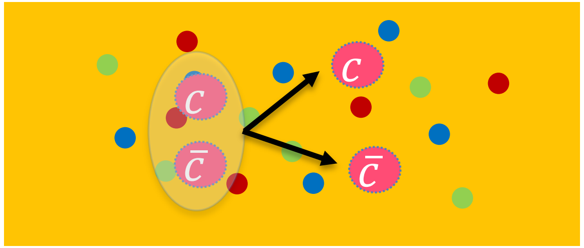
Motivation

- **Ideal probe to QGP**: form early; interact strongly
- **Ideal testing ground** of perturbative and non-perturbative physics
  - *Perturbative*: production cross section, modification in the QGP
  - *Non-perturbative*: hadronization, modification in the QGP

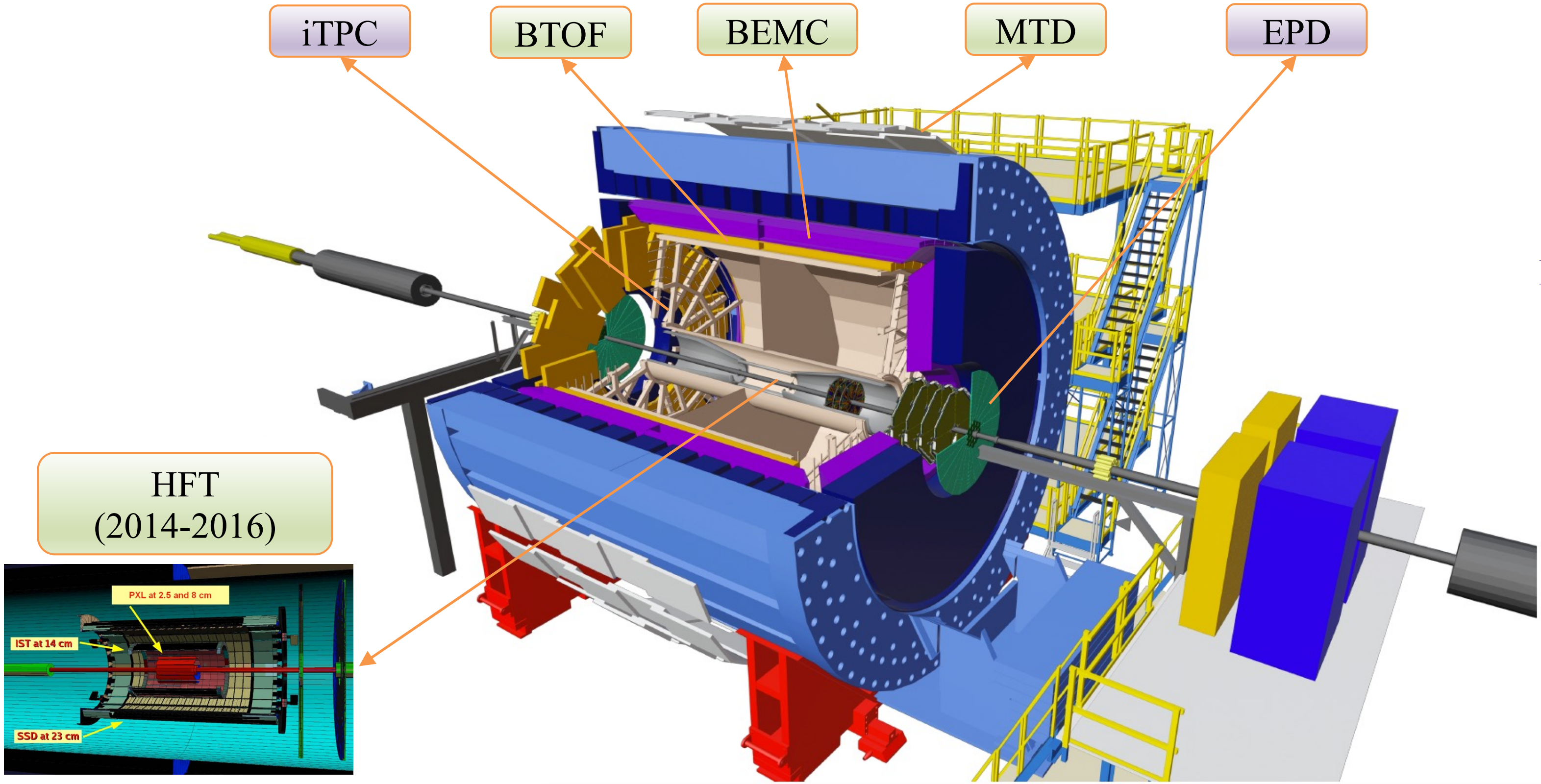
Open Heavy Flavor



Heavy Quarkonia



The STAR Detector

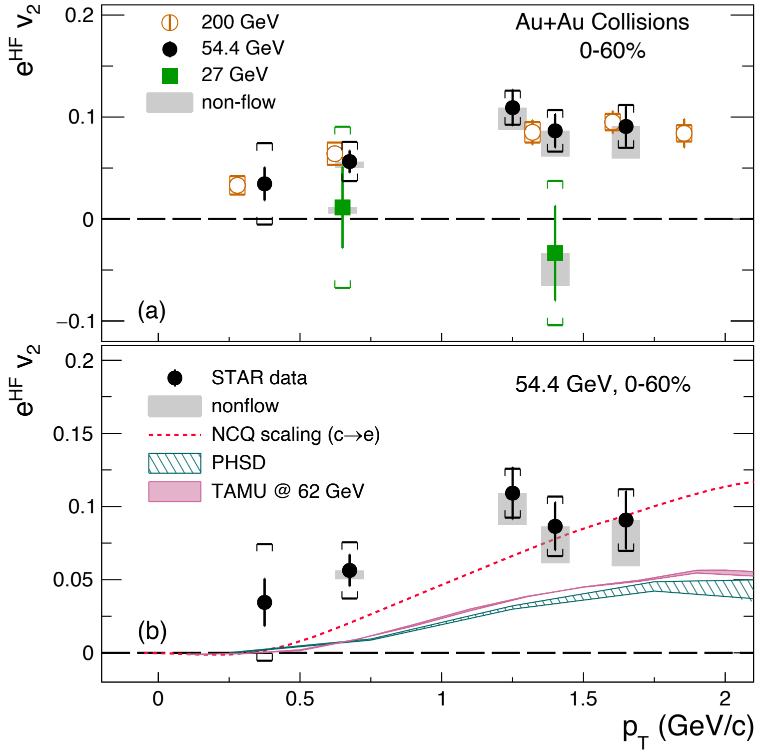


BES-II Upgrade

Open Heavy Flavor

HF electron v_2 at 54.4 and 27 GeV

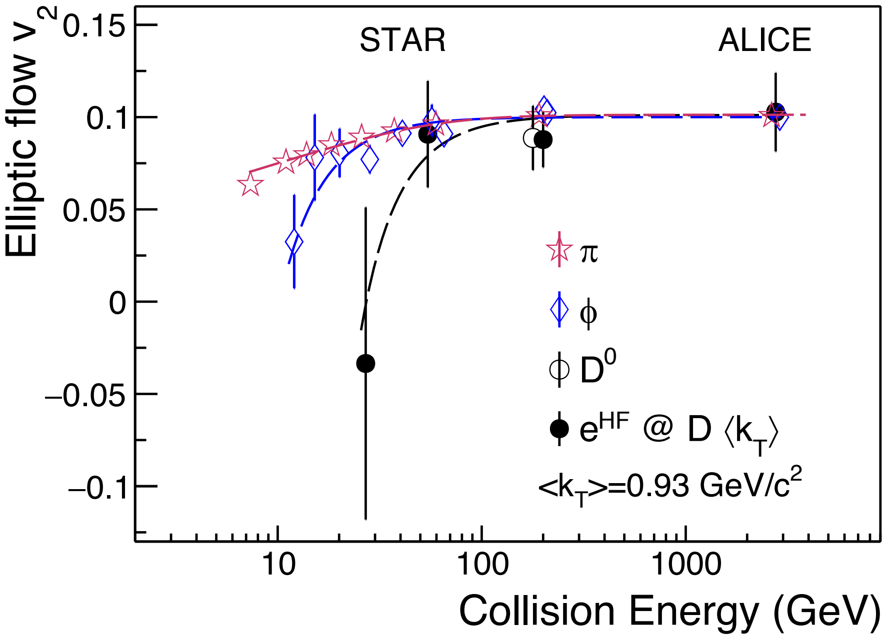
STAR, PLB 844 (2023) 138071



- 27 GeV: consistent with zero within uncertainties
- 54.4 GeV:
  - Significant v_2 comparable to that at 200 GeV
  - **Charm quarks gain v_2 close to T_{pc}**
  - Transport models seem to underpredict v_2 (1-2σ for $p_T > 0.5$ GeV/c)
  - Consistent with NCQ scaling → may reach local thermal equilibrium with the QGP

Compared to light flavor

STAR, PLB 844 (2023) 138071

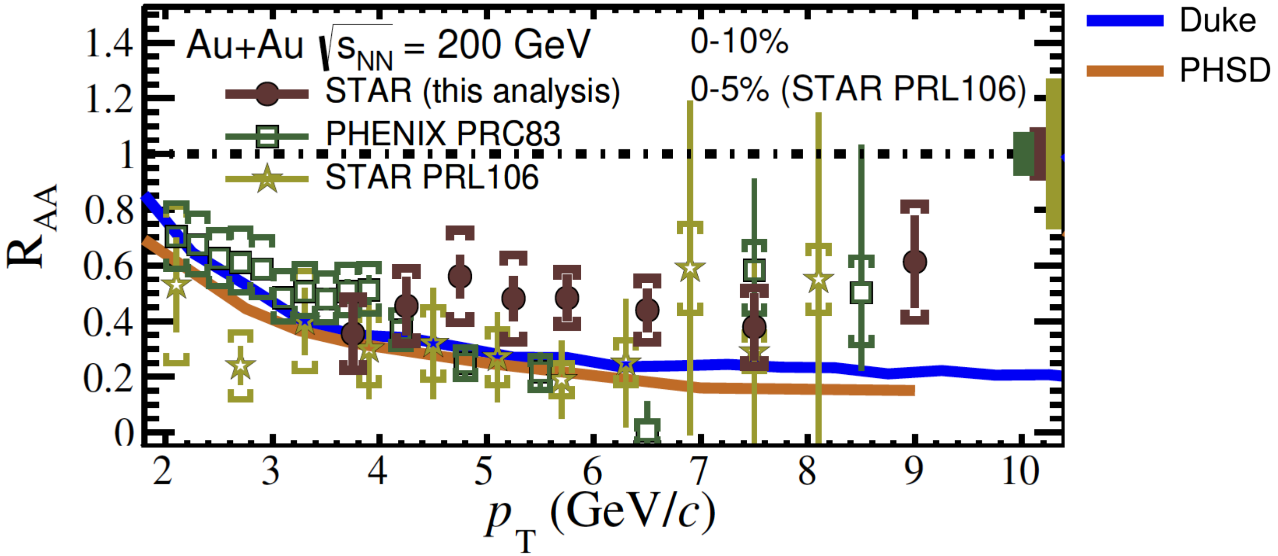


$$\langle k_T \rangle = \langle m_T - m_0 \rangle$$

- v_2 comparison: π vs. ϕ vs. D^0 vs. e^{HF}
- Above 54.4 GeV: similar v_2 for all particles
- Below 54.4 GeV: hint of heavier particles dropping faster than light particles with deceasing collision energy

Au+Au: HF electron R_{AA}

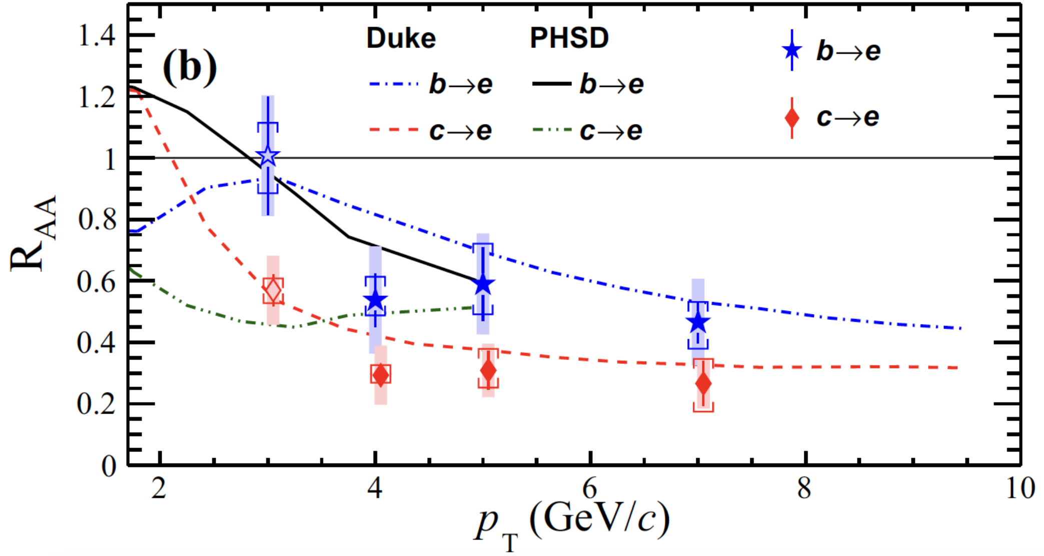
STAR, JHEP 06 (2023) 176



- ✓ About a factor of 2 suppression in 0-10% central Au+Au collisions compared to p+p
  - Improved precision at high p_T upon previous results
- Provide baseline for separate measurements of $b \rightarrow e$ and $c \rightarrow e$

Au+Au: ordered HF suppression

STAR, EPJC 82 (2022) 1150

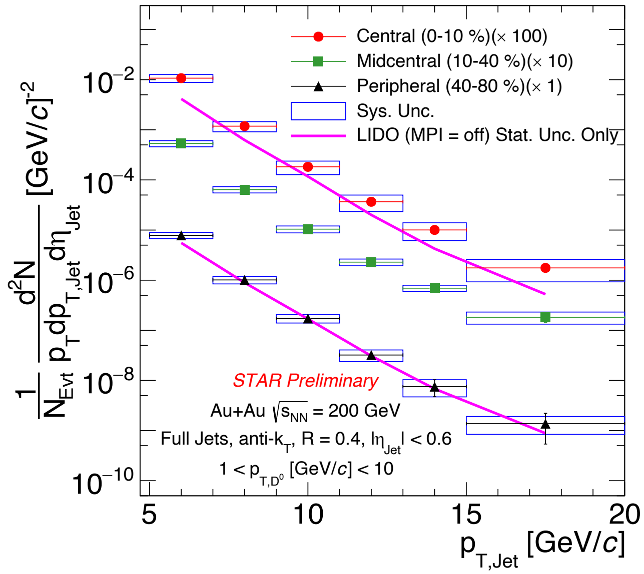


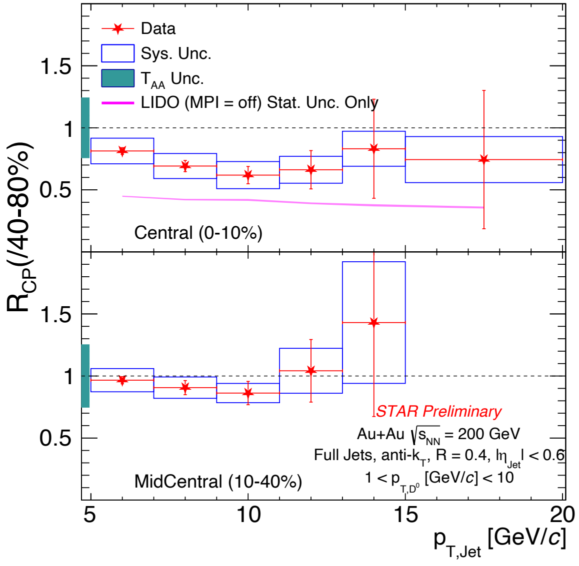
- Charm quarks are systematically more suppressed than bottom quarks

✓ Parton mass dependence of energy loss in the QGP

Au+Au collisions: D^0-jet R_{CP}

Per event





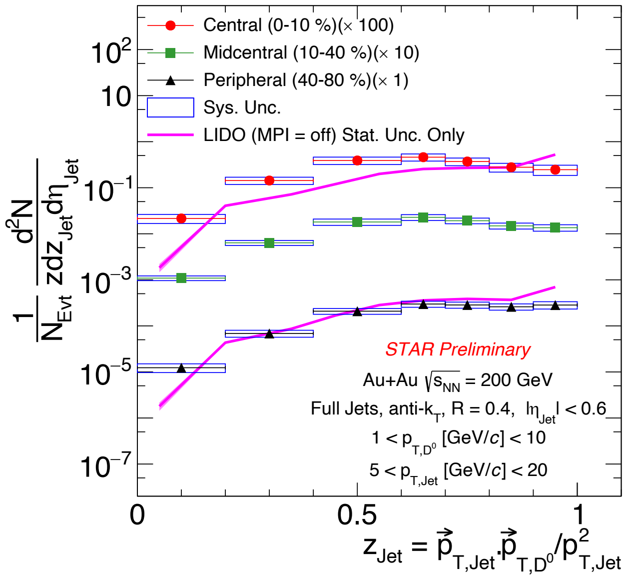
✓ Hint of ~ 20-30% suppression in 0-10% central compared to peripheral collisions

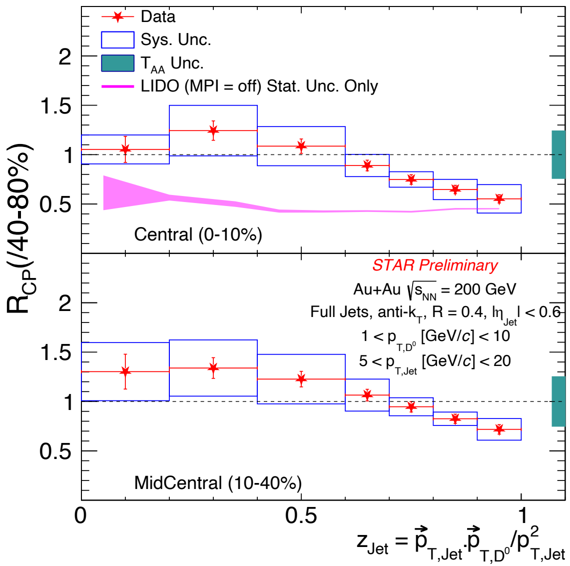
- LIDO calculation overshoots suppression

LIDO, PRC 98 (2018) 064901

Au+Au collisions: D^0-jet FF

Per event





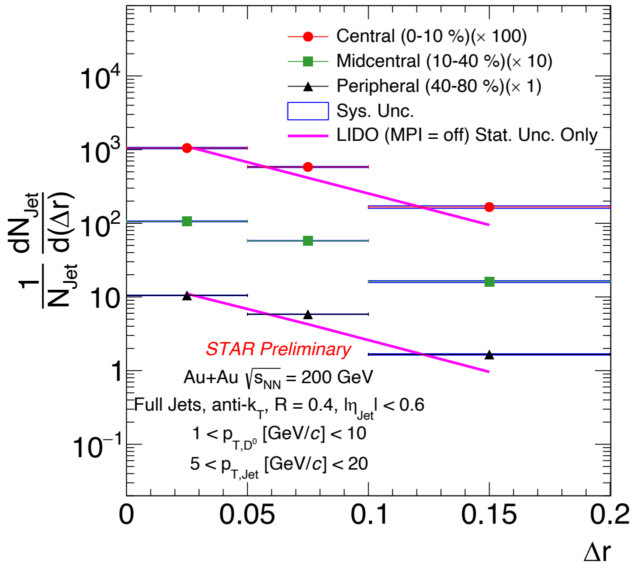
- ✓ Increasing suppression for harder-fragmented charm jets, while low-z jets are consistent with no suppression

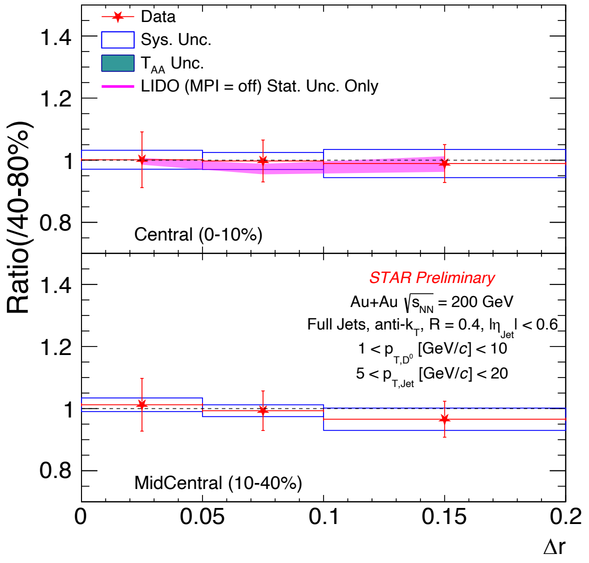
LIDO, PRC 98 (2018) 064901

Au+Au collisions: D^0-jet radial profile

$$\Delta r = \sqrt{(\eta_{Jet}^2 - \eta_{D^0}^2) + (\phi_{Jet}^2 - \phi_{D^0}^2)}$$

Per jet





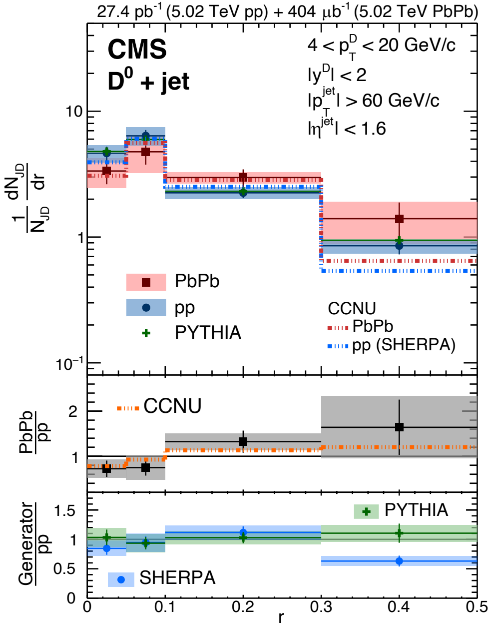
- ✓ D^0-jet radial profile consistent between central and peripheral events
- LIDO model describes results quite well

LIDO, PRC 98 (2018) 064901

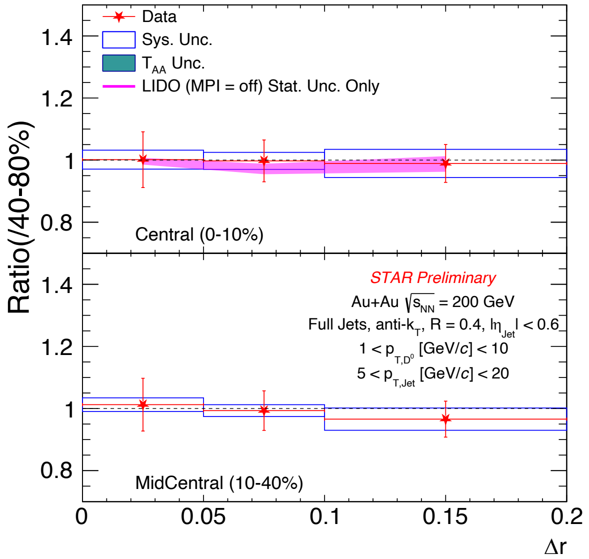
D^0-jet radial profile: RHIC vs. LHC

LHC

CMS, PRL 125 (2020) 102001

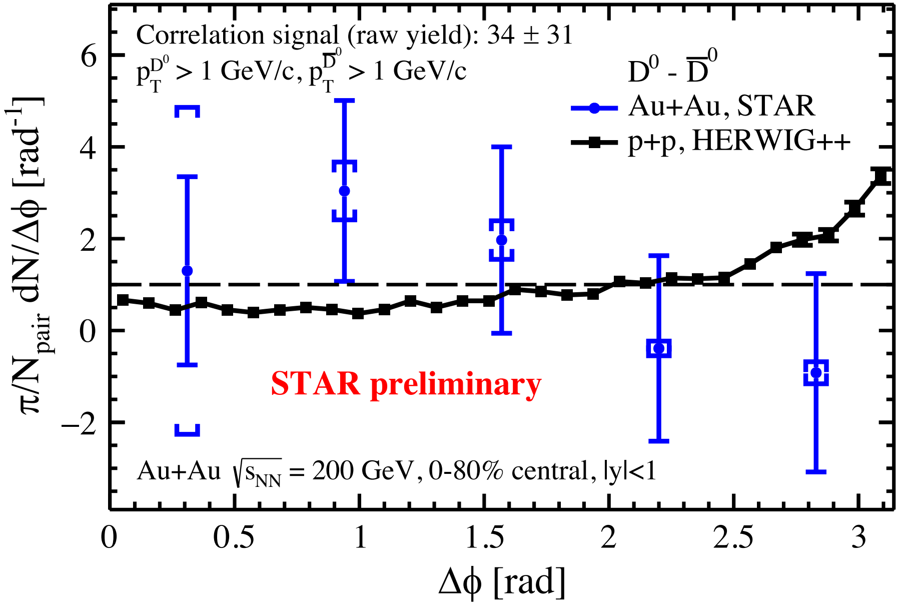


RHIC



- Hint of different behaviors: **energy dependence? Uncertainty limited?**

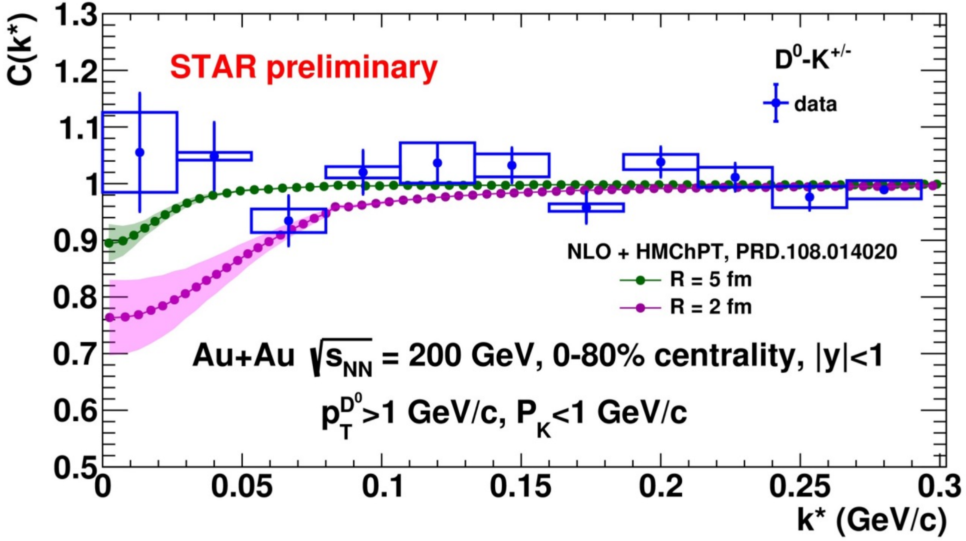
Au+Au: D^0-$\overline{D^0}$ correlation



✓ No appreciable correlation observed in 200 GeV Au+Au collisions, but statistics is limited

Au+Au: D^0-K femtoscopy correlation

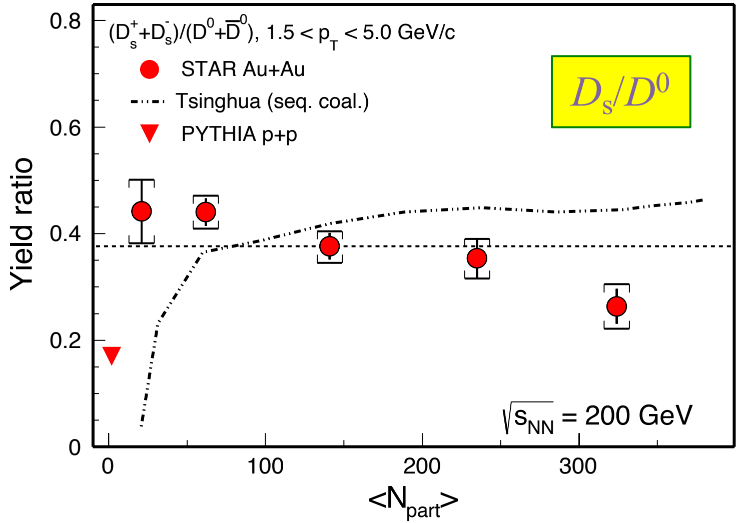
➢ Probe emission source size and possible final-state interactions



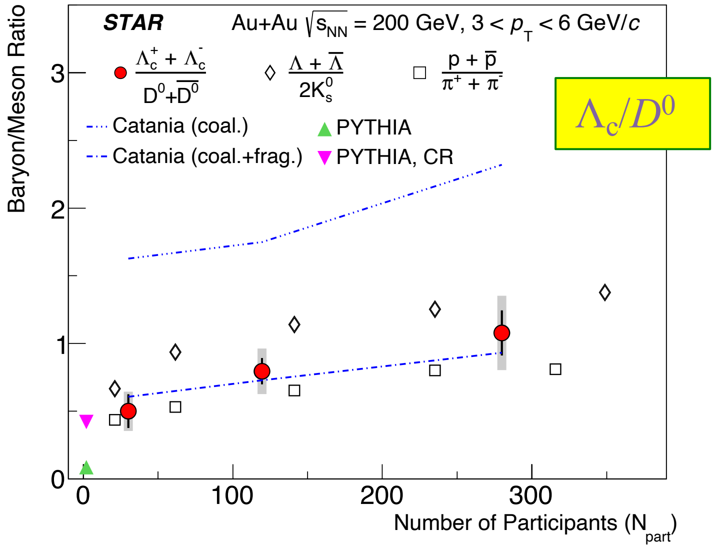
✓ Within uncertainties, results are consistent with no correlation or a large source size

Charm Hadrochemistry

STAR, PRL 127 (2021) 092301



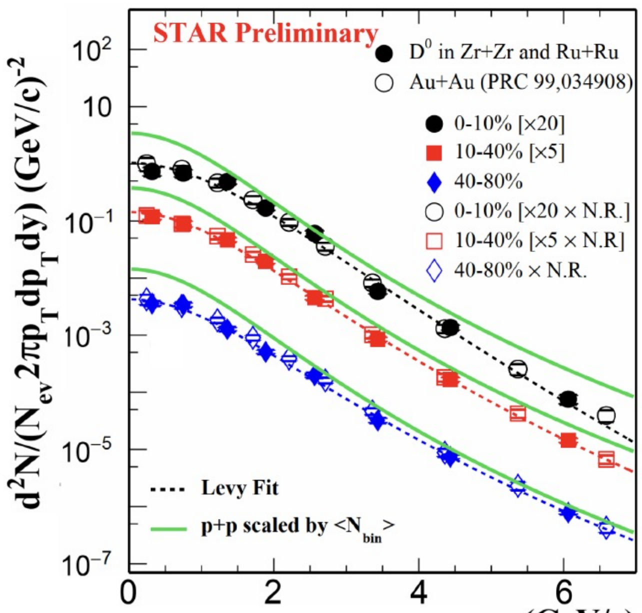
STAR, PRL 124 (2020) 172301



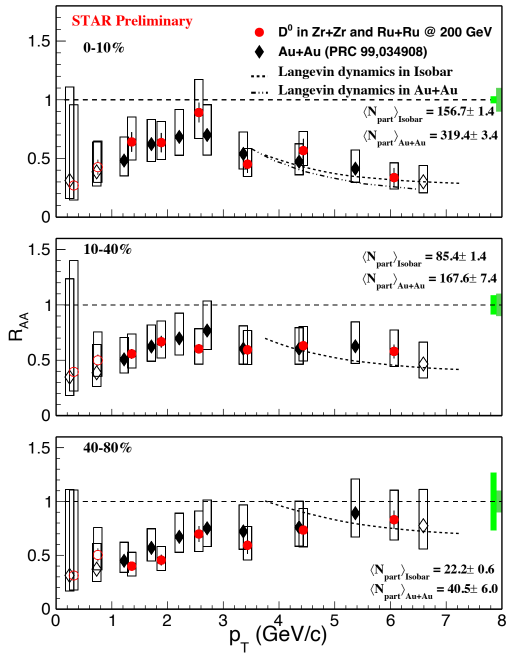
✓ Clear enhancements of D_s/D^0 and Λ_c/D^0 ratios compared to PYTHIA → coalescence is important

- Need to extend measurements down to zero p_T (total charm cross section)

Ru+Ru/Zr+Zr: D^0 suppression



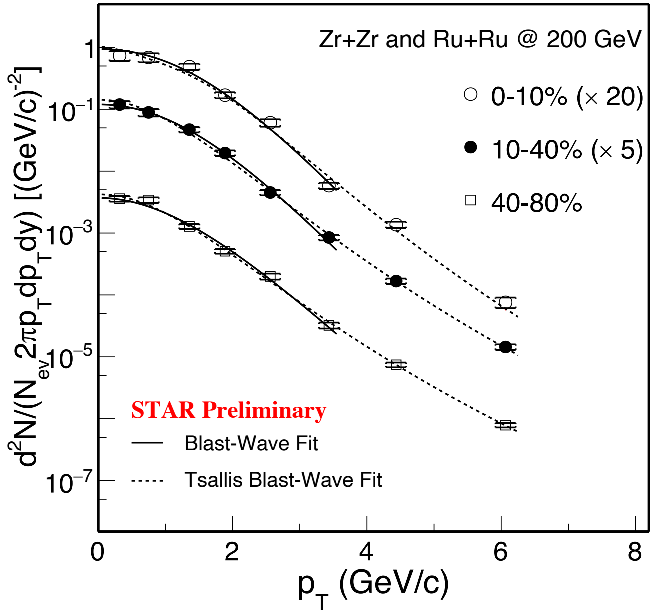
$N.R. = N_{coll}^{Isobar}/N_{coll}^{Au+Au}$

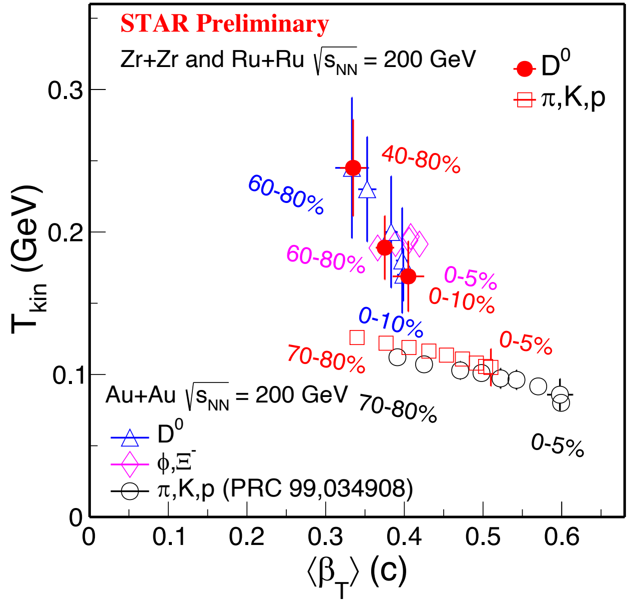


- ✓ Similar level of suppression in Isobar and Au+Au at the same centrality class
- Qualitatively reproduced by energy loss model calculations

Model: G. Qin, private communication

Ru+Ru/Zr+Zr: D^0 kinetic freeze-out





- D^0 behaves differently from light hadrons
  - Earlier freeze-out
  - Hint of different system-size dependence

Summary

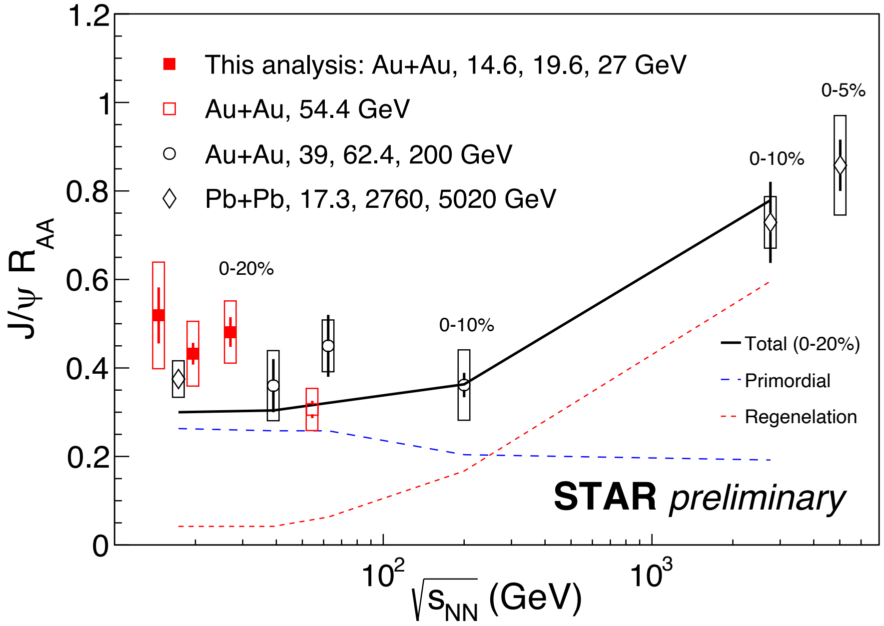
STAR continues to make strong impacts in studying interactions between heavy flavor and QGP in finer and finer details

Open Heavy Flavor

- Strong QGP effect at 200 GeV: mass-dependent energy loss; modified hadrochemistry; strong D^0 suppression and z-dependent modification to D^0 jets
- Hint of QGP effect decreasing at lower energy

Heavy Quarkonia

Quarkonia: energy dependence



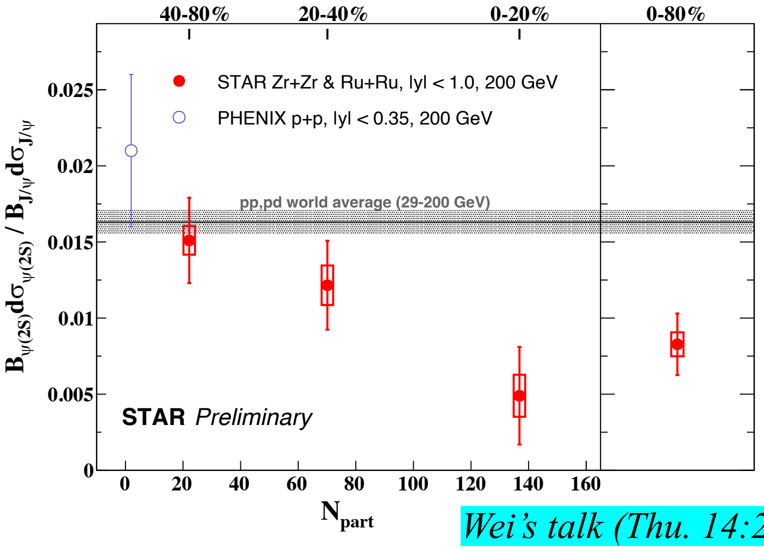
✓ No significant energy dependence of $J/\psi\ R_{AA}$ below 200 GeV

- Can be qualitatively explained by model calculation including CNM, dissociation and regeneration
  - Regeneration starts to dominate above 200 GeV

Wei's talk (Thu. 14:20)

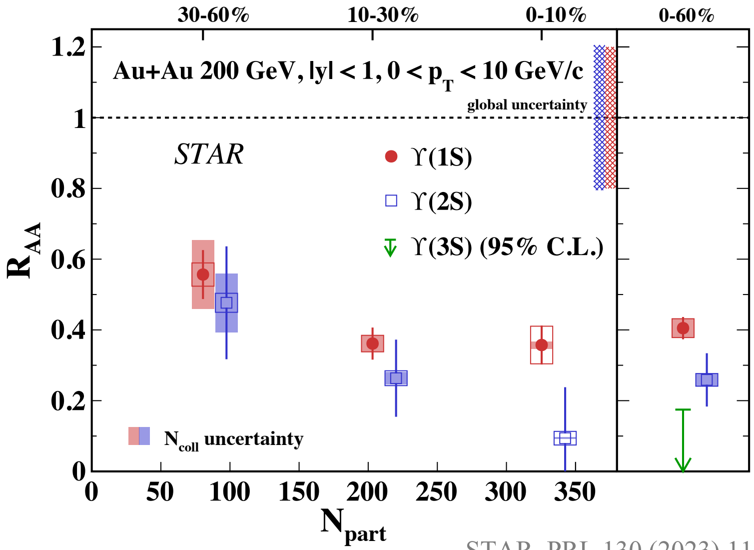
Quarkonia: binding energy dependence

Charmonia in Ru+Ru/Zr+Zr



Wei's talk (Thu. 14:20)

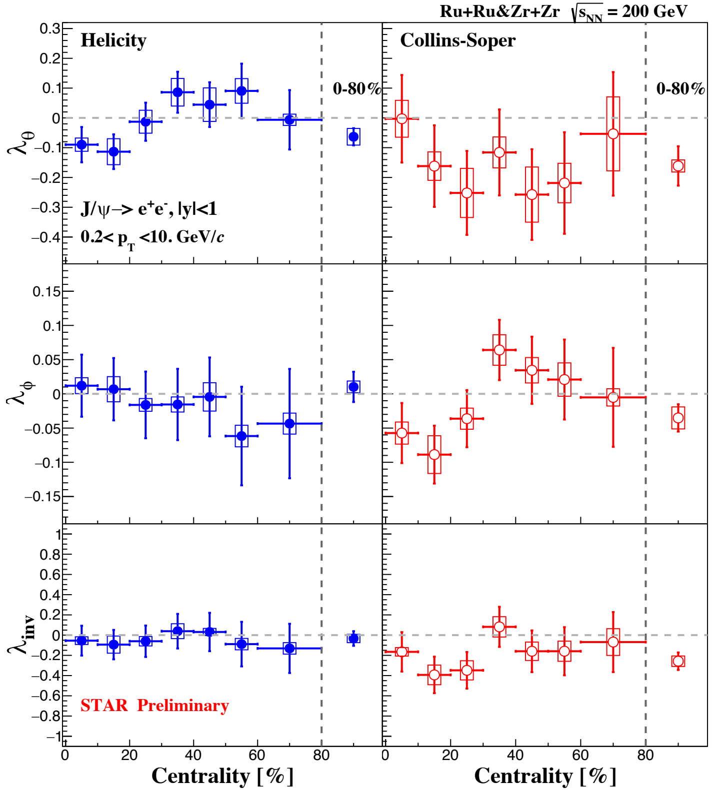
Bottomonia in Au+Au



STAR, PRL 130 (2023) 112301

✓ Sequential suppression at RHIC → QGP thermal properties

J/ψ polarization in Ru+Ru/Zr+Zr



B.L. Ioffe, D.E. Kharzeev, PRC 68 (2003) 061902(R)

- Theory predicts $\lambda_\theta \sim 0.35 - 0.4$ in HX frame for low-p_T J/ψ if npQCD effects are screened by the QGP
  - A hint of positive λ_θ is observed at the LHC

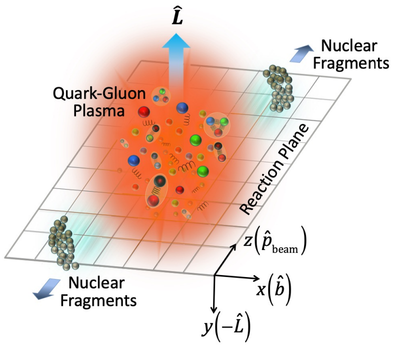
ALICE, PLB 815 (2021) 136146

- ✓ λ_θ and λ_ϕ in both HX and CS frames are consistent with 0
  - Similar to that observed in p+p collisions

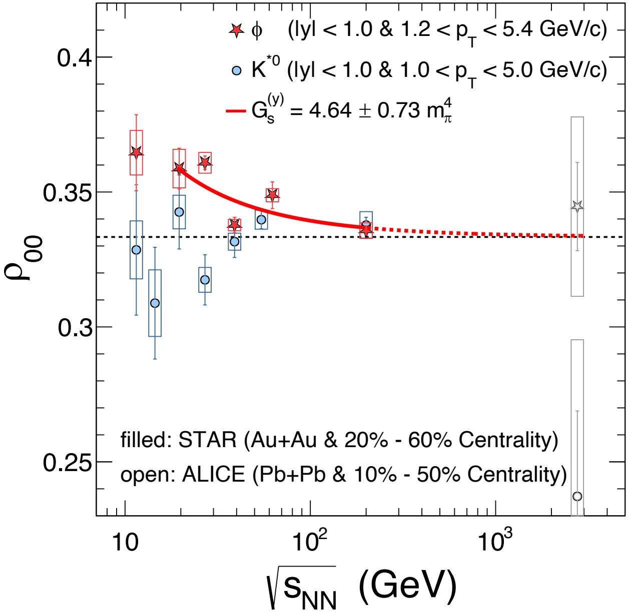
STAR, PRD 102 (2020) 092009

- ✓ No clear centrality dependence
- Consistent λ_{inv} for the two frames, as expected

Vector meson spin alignment

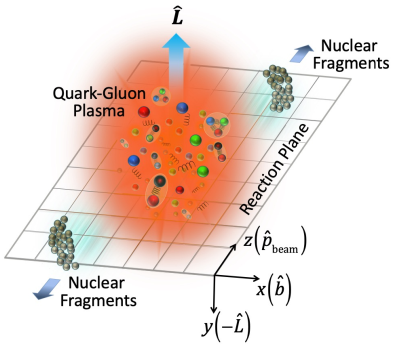


STAR, Nature 614 (2023) 244

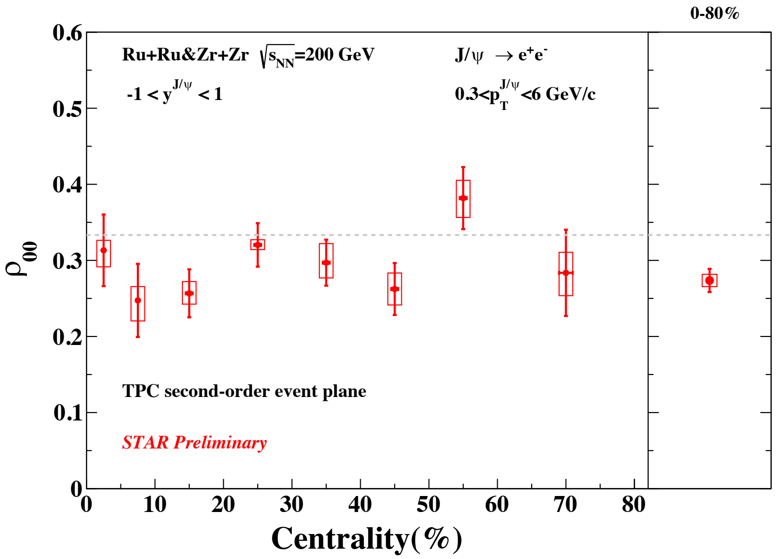


- ➢ Significant spin alignment for ϕ → could originate from strong force field of strange quarks
- ➢ **How about *J/ψ*?**

J/ψ global spin alignment in Isobar

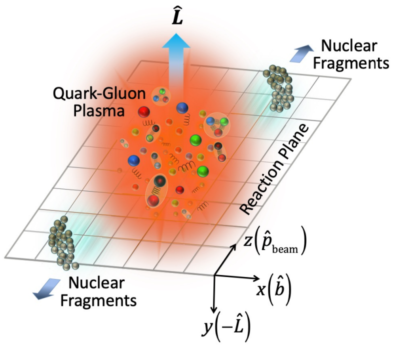


STAR, Nature 614 (2023) 244

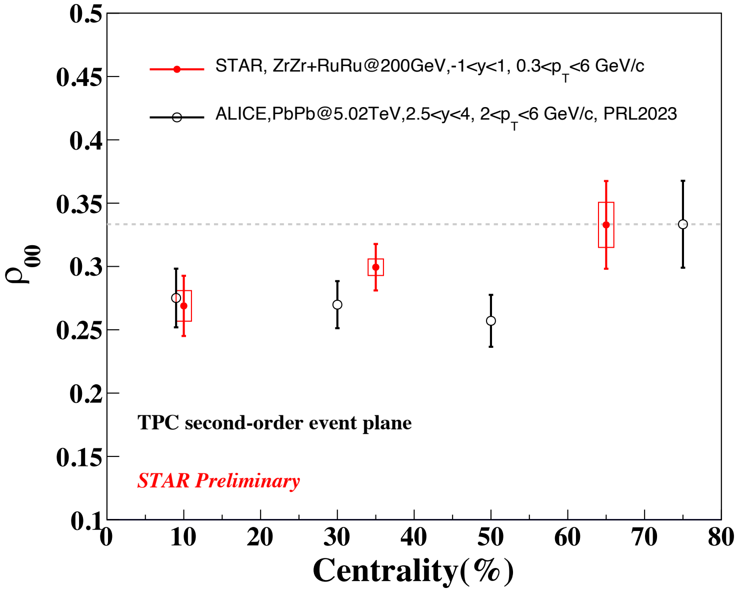


- First measurement of J/ψ ρ_{00} at RHIC
- ✓ Lower than 1/3 (3.5σ) in 0-80%
- No significant centrality dependence observed

J/ψ global spin alignment: RHIC vs. LHC



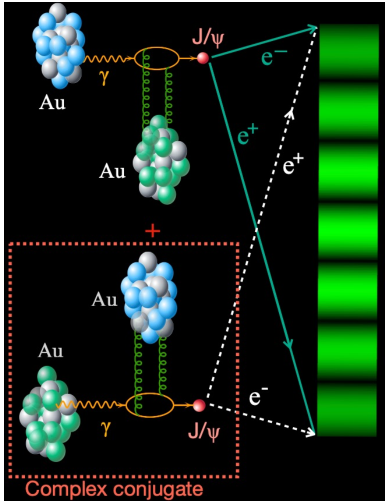
STAR, Nature 614 (2023) 244

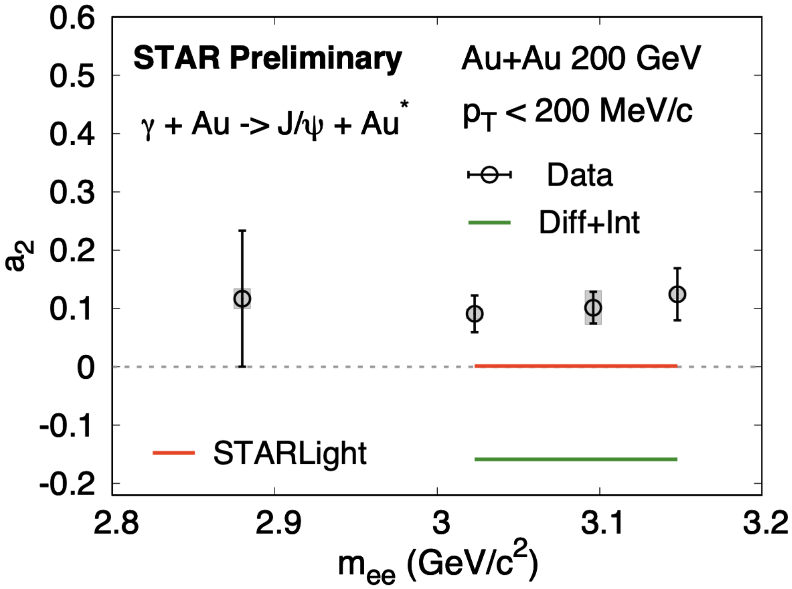


- Similar magnitude and centrality dependence at RHIC and LHC, despite of very different collision energy, collision system, rapidity, etc

J/ψ interference in UPC

Credit: Ashik Ikbal Sheikh





a_2: cos(2ϕ) modulation

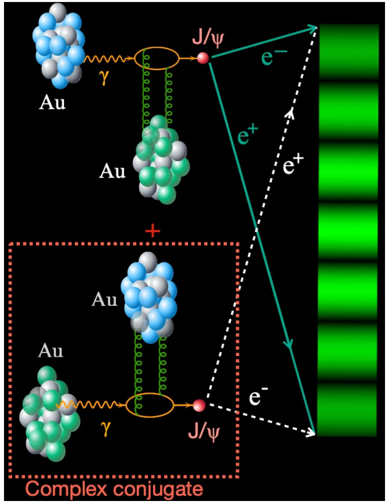
✓ ~10% spin interference signal (~3σ) in *J/ψ* production

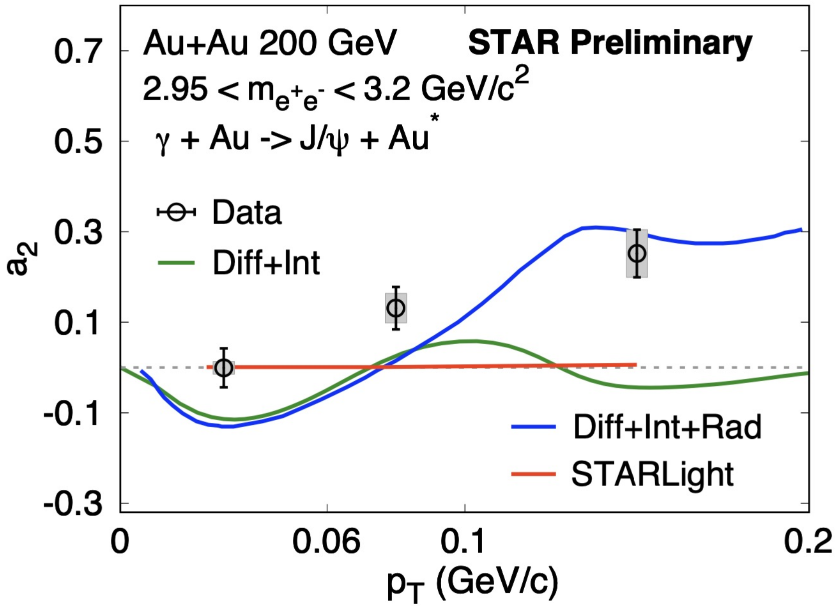
- Theories could not describe data

Diff+Int: W. Zhao, et. al., private communication & arXiv:2207.03712

J/ψ interference in UPC

Credit: Ashik Ikbal Sheikh





a_2: cos(2ϕ) modulation

Diff+Int: W. Zhao, et. al., private communication & arXiv:2207.03712
Diff+Int+Rad: Brandenburg et. al, PRD 106 (2022) 074008

- ✓ Clear rising trend with p_T
- Adding soft-photon radiation can qualitatively describe the rising trend

Summary

STAR continues to make strong impacts in studying interactions between heavy flavor and QGP in finer and finer details

Open Heavy Flavor

- Strong QGP effect at 200 GeV: mass-dependent energy loss; modified hadrochemistry; strong D^0 suppression and z-dependent modification to D^0 jets
- Hint of QGP effect decreasing at lower energy

Heavy Quarkonia

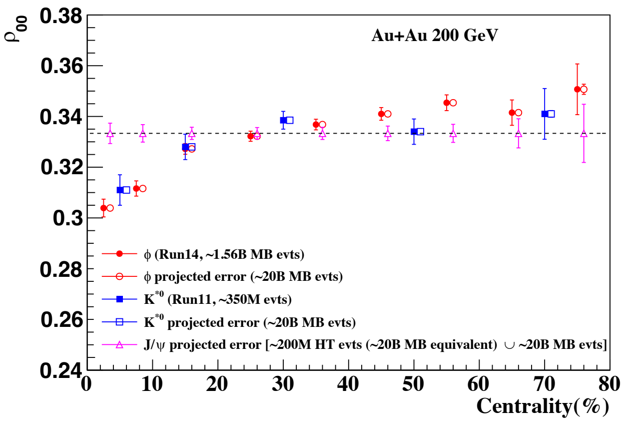
- Comprehensive measurements of suppression vs. p_T, binding energy, centrality, collision energy, collision system, etc
- First signs of J/ψ spin alignment in heavy-ion collisions and entanglement-enabled interference in UPC at RHIC

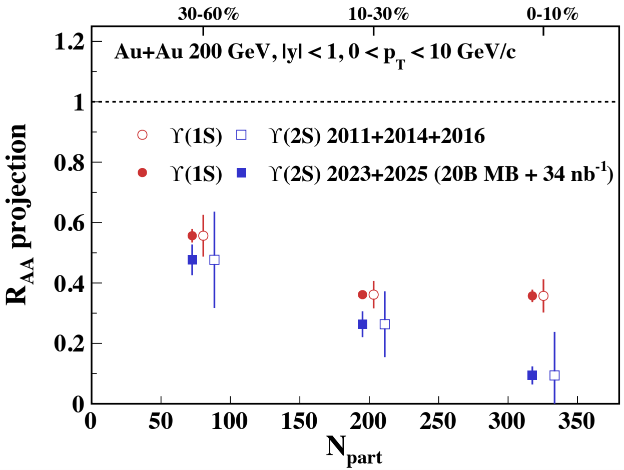
Outlook

✓ Run23-25: entering the precision era

- Unprecedented statistics for *p*+*p*, *p*+Au, Au+Au collisions
- Low material budget
- STAR detector with enhanced capabilities
  - Particle identification; tracking; extended coverage

STAR Beam Use Request

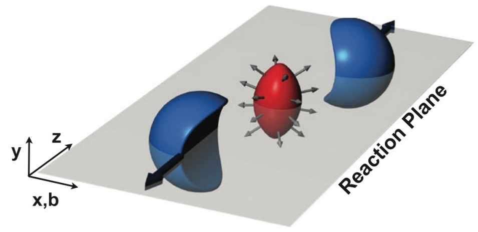




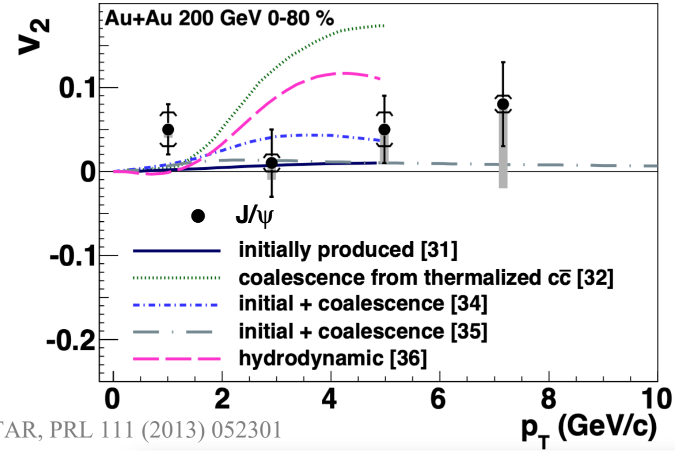
Backup

RHIC: Does J/ψ Flow?

✓ Elliptic flow (v_2): a different angle to probe regeneration
- – Primordial: little or zero v_2
- – Regenerated: inherit v_2 of constituent charm quarks
  - Strong evidence of charm quark v_2 from D^0 measurements STAR, PRL 118 (2017) 212301



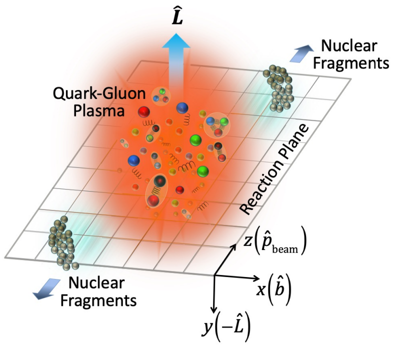
R. Snellings, New J. Phys. 13 (2011) 055008



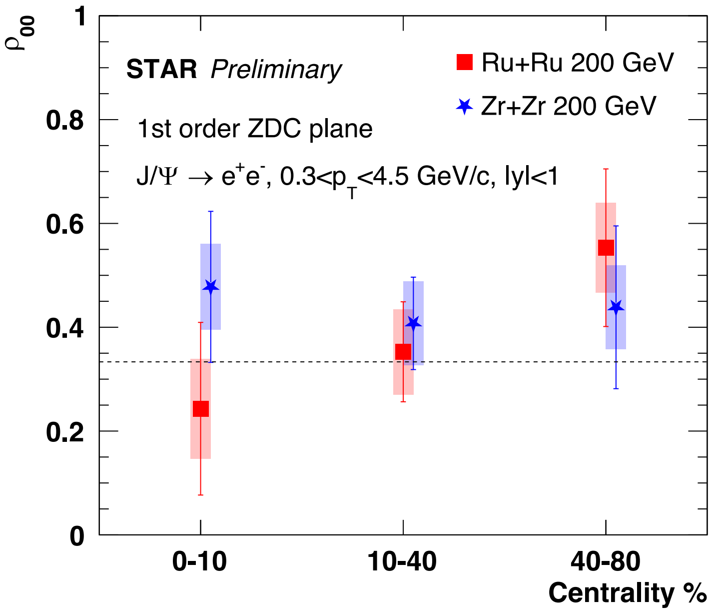
STAR, PRL 111 (2013) 052301

At $p_T > 2$ GeV/c
- Consistent with zero within large uncertainties
- Disfavor the scenario of dominate regeneration from thermalized charm quarks
- *Need better precision*

J/ψ global spin alignment in Isobar



STAR, Nature 614 (2023) 244

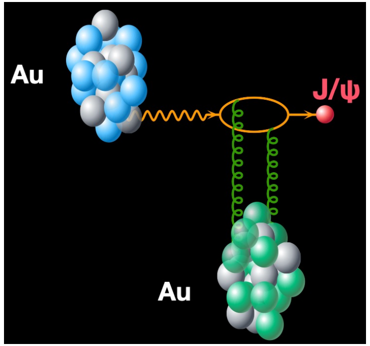


First-order event plane

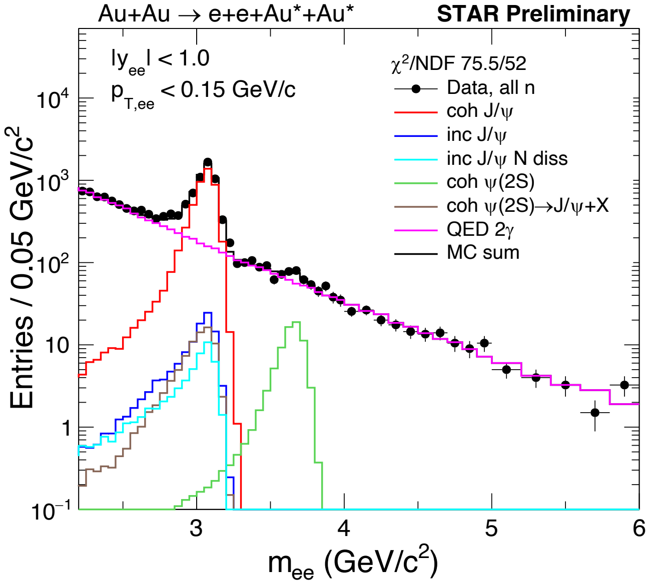
- First measurement of J/ψ ρ_{00} at RHIC

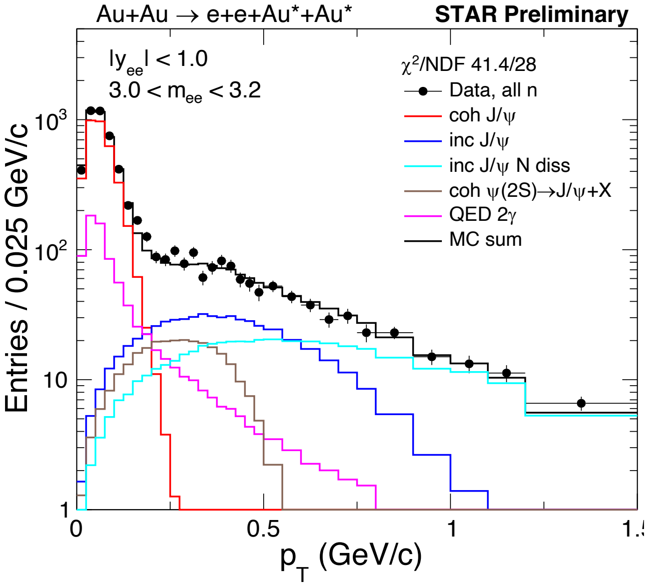
✓ Consistent with 1/3 within large uncertainties

J/ψ production in UPC



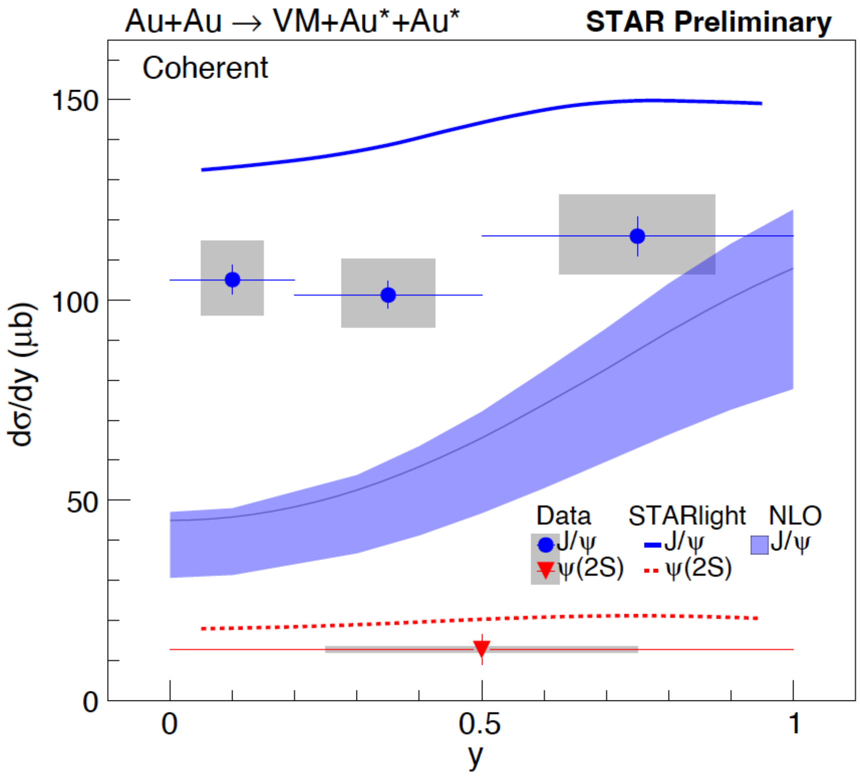
Credit: Ashik Ikbal Sheikh





- Coherent vs. incoherent production
- Sensitive to gluon structure and fluctuations

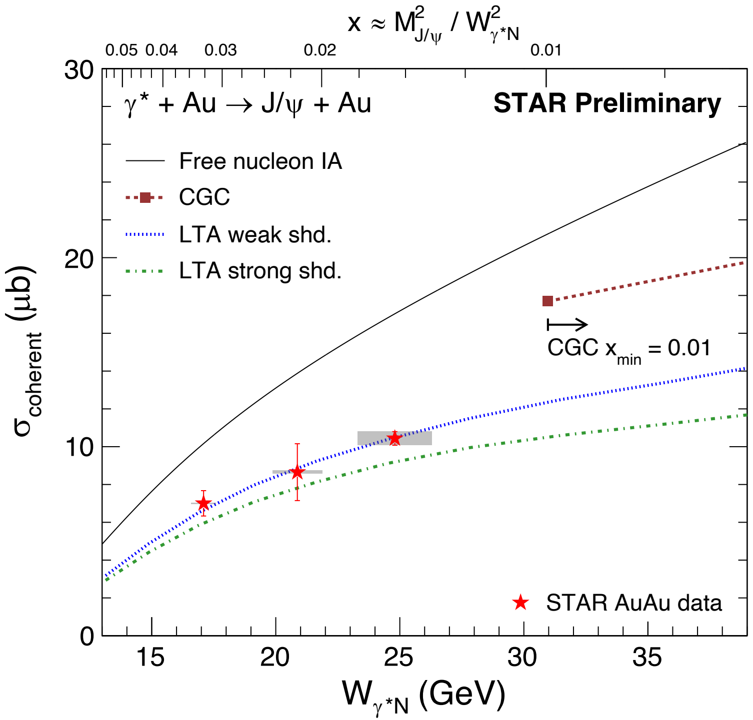
J/ψ in UPC: rapidity dependence



- Coherent production independent of rapidity
- Stringent constraints on model calculations
  - NLO calculation already constrained by LHC data

NLO: K. J. Eskola, et. al., PRC 106 (2022) 035202, PRC 107 (2023) 044912

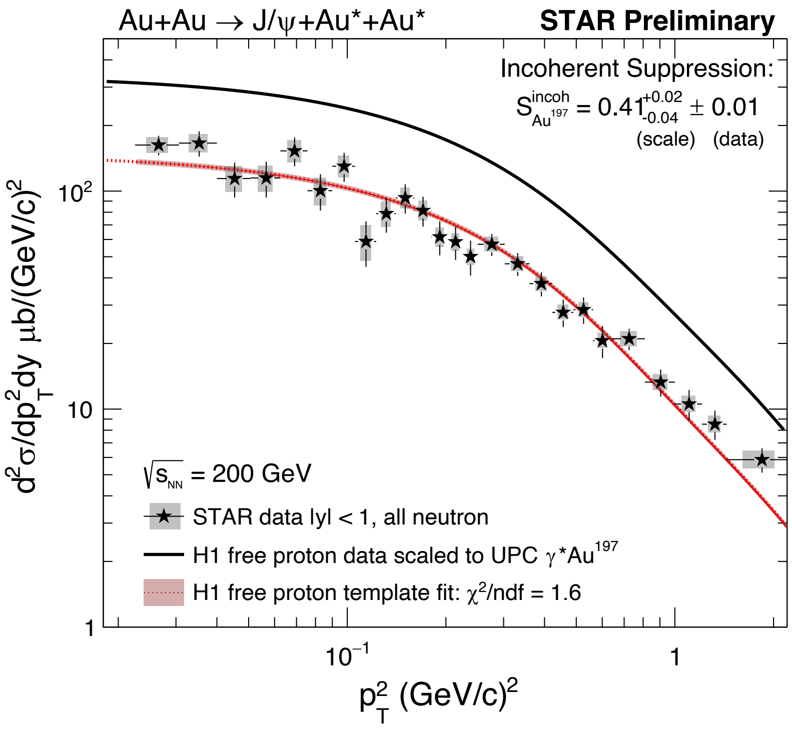
Coherent J/ψ suppression



- ✓ ~40% suppression compared to free nucleons
- LTA shadowing model describes data quite well
- STAR data sensitive to the transition region between low and high *x*

CGC: *PRD* 106 (2022) 074019
LTA: 1) Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942
2) Strikman, Tverskoy, Zhalov, PLB 626 (2005) 72-79

Incoherent J/ψ suppression



- ✓ ~60% suppression compared to free nucleons
  - Larger than tha for coherent production

- Similar shape to the H1 data, which support sub-nucleonic fluctuations, indicating similar fluctuations for bound nucleons

H. Mantysaari, B. Schenke, PRL 117 (2016) 052301
H. Mantysaari, F. Salazar, B. Schenke, PRD 106 (2022) 074019

Feed-down Contribution: J/ψ

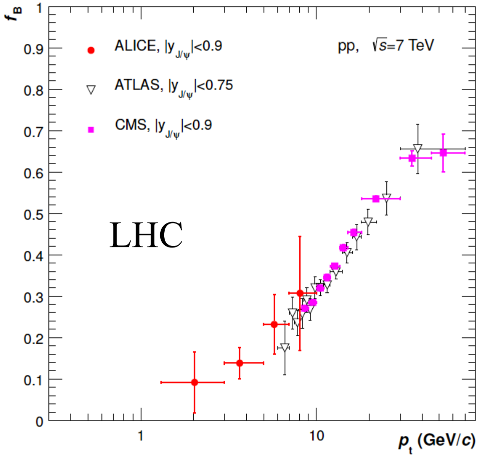
J. Lansberg, Phys. Report, 889 (2020) 1

Excited charmonia

	direct	from χ_{c1}	from χ_{c2}	from $\psi(2S)$
"low" P_T J/ψ	79.5 ± 4 %	8 ± 2 %	6 ± 1.5 %	6.5 ± 1.5 %
"high" P_T J/ψ	64.5 ± 5 %	23 ± 5 %	5 ± 2 %	7.5 ± 0.5 %

Table 2: J/ψ FD fraction in hadroproduction at Tevatron and LHC energies.

b-hadron decays



A. Andronic, et. al., RPJC 76 (2016) 107

Feed-down Contribution: J/ψ

S. Digal, P. Petreczky, H. Satz, PRD 64 (2001) 094015
L. Antoniazzi et al., PRD 46 (1992) 4828 1992; PRL 70 (1993)

TABLE I. Cross sections for direct charmonium production in $\pi^- N$ and pN collisions, normalized to the overall J/ψ production cross section in the corresponding reaction [8]; feed-down fractions and mass gap to the open charm threshold.

State	$R_i(\pi^- N)$	$R_i(pN)$	$f_i(\pi^- N)$ (%)	$f_i(pN)$ (%)	E_{dis} (MeV)
$J/\psi(1S)$	0.57±0.03	0.62±0.04	57±3	62±4	0.642
$\chi_1(1P)$	0.72±0.18	0.60±0.15	20±5	16±4	0.229
$\chi_2(1P)$	1.04±0.29	0.99±0.29	15±4	14±4	0.183
$\psi(2S)$	0.14±0.04	0.14±0.04	8±2	8±2	0.054
J/ψ	1	1	100	100	

300 GeV fixed-target collisions

Feed-down Contribution: Υ

J. Lansberg, Phys. Report, 889 (2020) 1

	$F^{\text{direct}}_{\Upsilon(1S)}$	$F^{\chi_{b1}(1P)}_{\Upsilon(1S)}$	$F^{\chi_{b2}(1P)}_{\Upsilon(1S)}$	$F^{\Upsilon(2S)}_{\Upsilon(1S)}$	$F^{\chi_b(2P)}_{\Upsilon(1S)}$	$F^{\Upsilon(3S)}_{\Upsilon(1S)}$	$F^{\chi_b(3P)}_{\Upsilon(1S)}$
"low" P_T	71 ± 5	10.5 ± 1.6	4.5 ± 0.8	7.5 ± 0.5	4 ± 1	1 ± 0.5	1.5 ± 0.5
"high" P_T	45.5 ± 8.5	21.5 ± 2.7	7.5 ± 1.2	14 ± 2	6 ± 2	2.5 ± 0.5	3 ± 1

Table 3: $\Upsilon(1S)$ FD fraction [in %] in hadroproduction at Tevatron and LHC energies.

	$F^{\text{direct}}_{\Upsilon(2S)}$	$F^{\chi_b(2P)}_{\Upsilon(2S)}$	$F^{\Upsilon(3S)}_{\Upsilon(2S)}$	$F^{\chi_b(3P)}_{\Upsilon(2S)}$
"low" P_T	65 ± 20	28 ± 16	4 ± 1	4.5 ± 3
"high" P_T	59.5 ± 11.5	28 ± 8	8 ± 2	4.5 ± 1.5

Table 4: $\Upsilon(1S)$ FD fraction [in %] in hadroproduction at Tevatron and LHC energies. We have doubled the uncertainties on $F^{\chi_b(2P)}_{\Upsilon(2S)}$ and $F^{\chi_b(2P)}_{\Upsilon(2S)}$ at low P_T since they are extrapolated.

	$F^{\text{direct}}_{\Upsilon(3S)}$	$F^{\chi_b(3P)}_{\Upsilon(3S)}$
"low" P_T	60 ± 20	40 ± 20
"high" P_T	60 ± 10	40 ± 10

Table 5: $\Upsilon(3S)$ FD fraction [in %] in hadroproduction at Tevatron and LHC energies. We have doubled the uncertainties on $F^{\chi_b(3P)}_{\Upsilon(3S)}$ at low P_T since it is extrapolated.