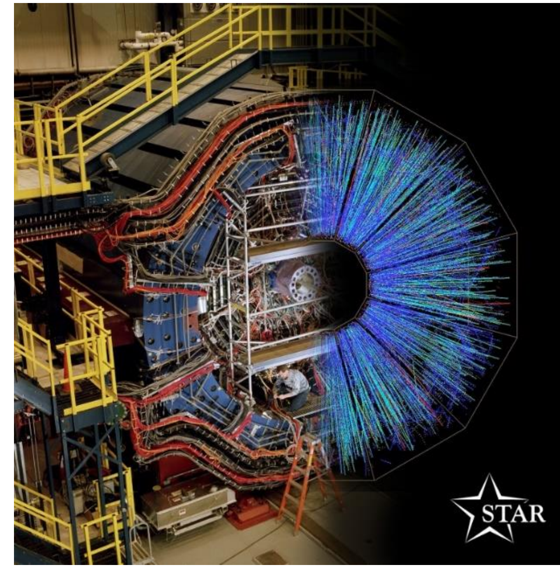
Recent hard probes measurements from STAR experiment



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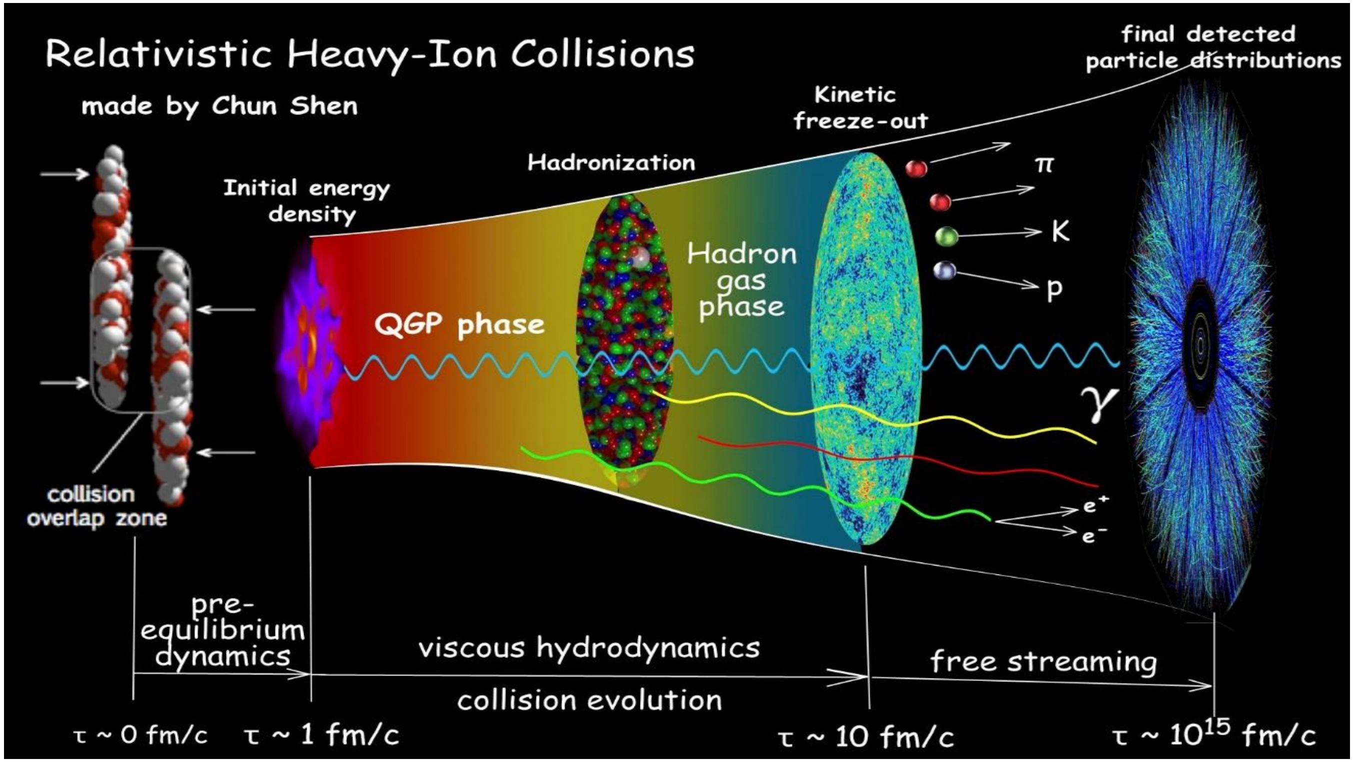
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

XII International Conference on New Frontiers in Physics, 10-22.7. 2023, Kolymbari, Crete

Outline

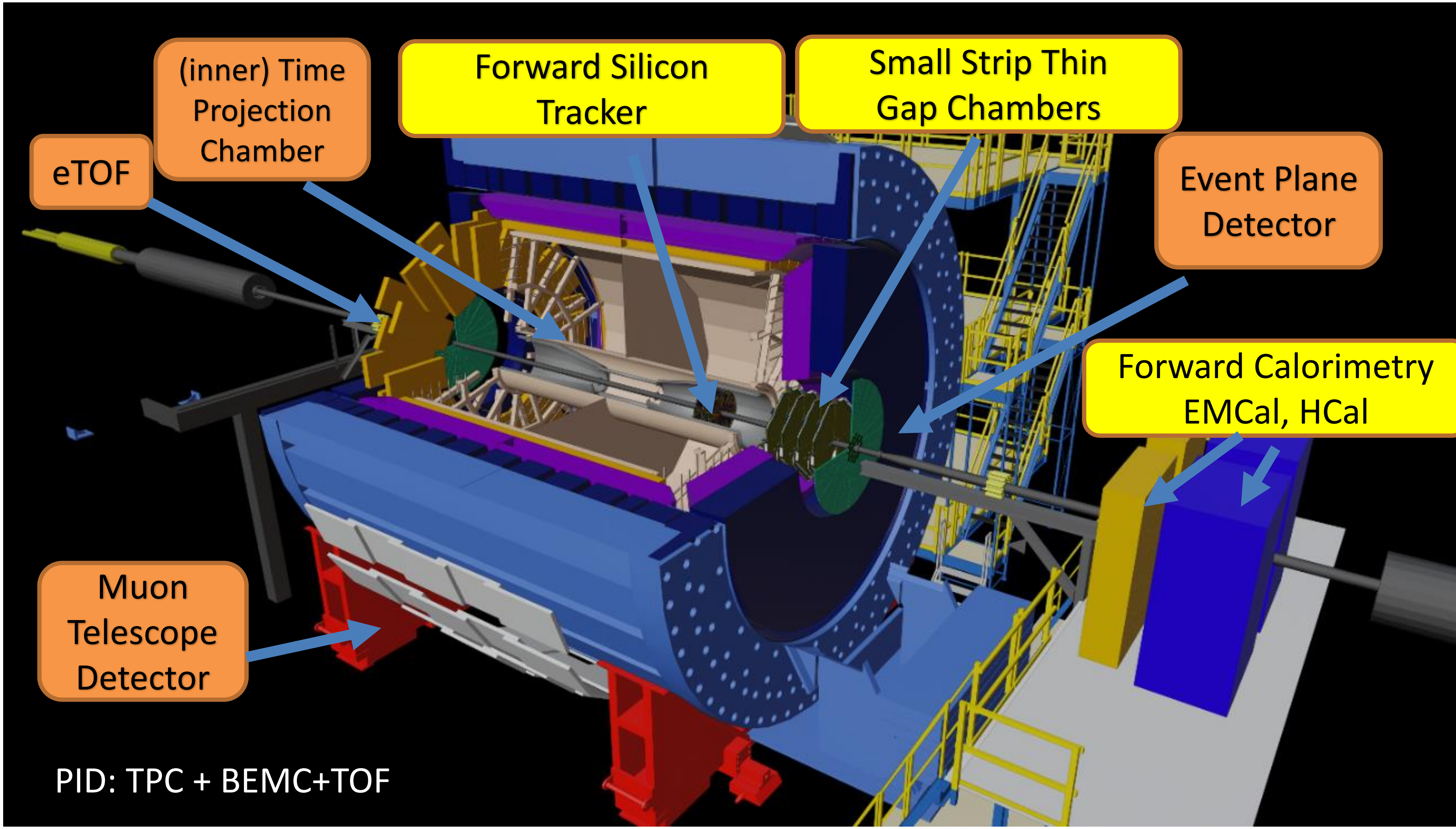


- Open heavy flavor measurements
- Quarkonium measurements
- Jet measurements

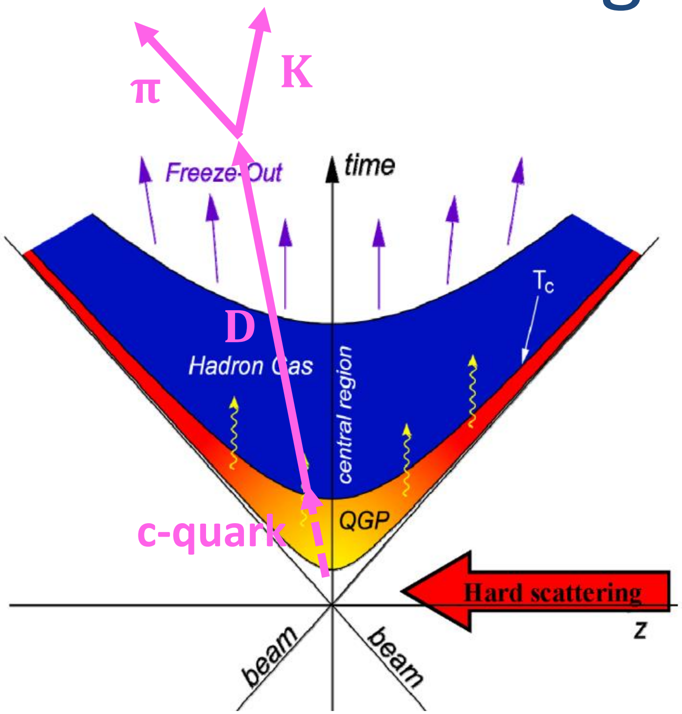
STAR experiment

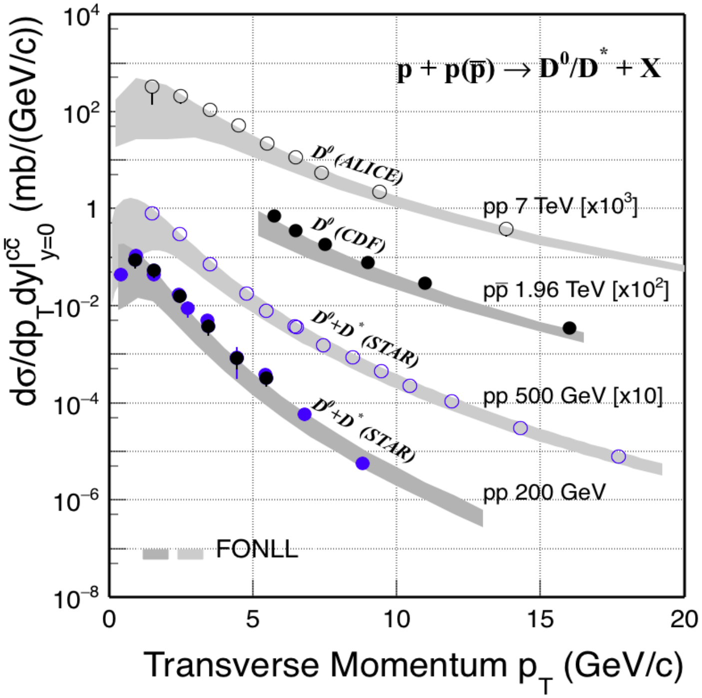
Forward upgrade: 2.5 < η < 4

Heavy flavor tracker: 2014-2016



Probing QGP with charm quark





STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

- **Charm quark: $m_c \gg T_{QGP}, \Lambda_{QCD}$**
- Produced in hard scatterings at the early stage of nuclear collisions → experience the entire evolution of medium
- We aim to understand charm quark energy loss in the medium, charm quark transport and hadronization

- Its production rates are well described by pQCD in elementary collisions

Open charm hadron reconstruction

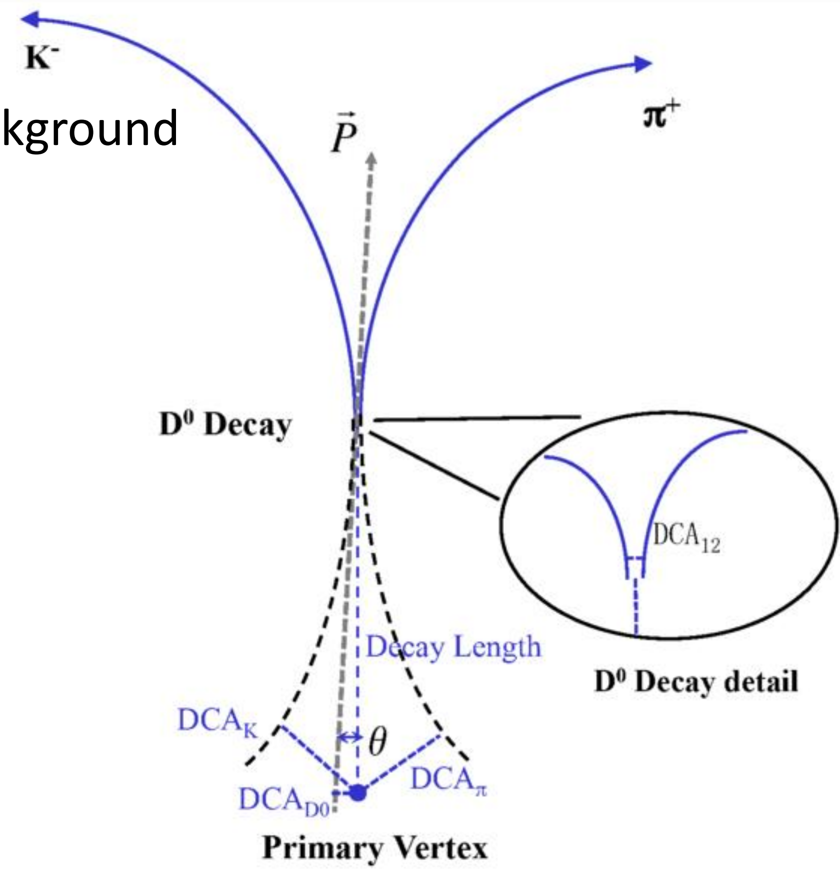
- Data from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV collected with Heavy flavor tracker in years 2014 and 2016
- HFT allows direct **topological reconstruction** of open-charm hadrons via their hadronic decays
- Significant suppression of combinatorial background
- Decay channels used:
  - $D^+ \rightarrow K^-\pi^+\pi^+$, $c\tau$ = (311.8 ± 2.1) μm

    BR = (8.98 ± 0.28) %
  - $D^0 \rightarrow K^-\pi^+$, $c\tau$ = (122.9 ± 0.4) μm

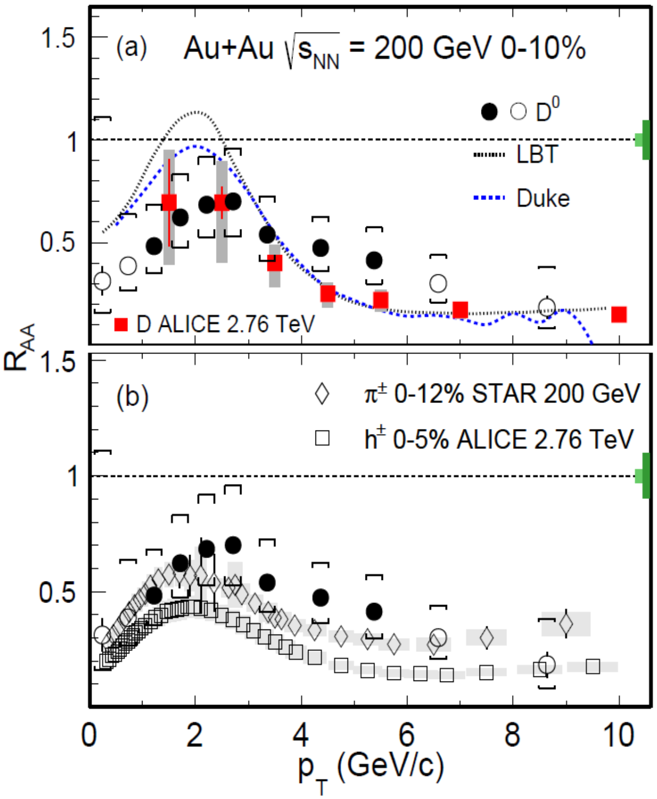
    BR = (3.93 ± 0.04) %
  - $D_s \rightarrow \pi^+\phi$, $\phi \rightarrow K^-K^+$, $c\tau$ = (149.9 ± 2.1) μm

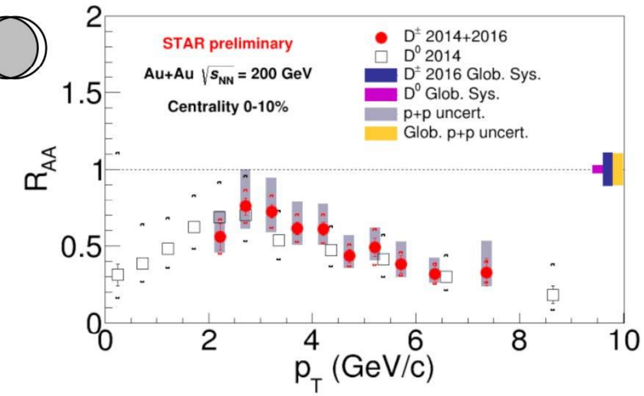
    BR = (2.27 ± 0.08) %
  - $\Lambda_c \rightarrow K^-\pi^+p$, $c\tau$ = (59.9 ± 1.8) μm

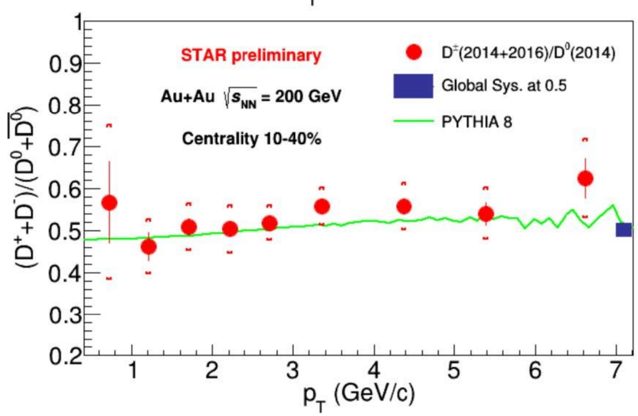
    BR = (6.35 ± 0.33) %



Nuclear modification factor R_{AA} of D^0 and $D^{\pm}$







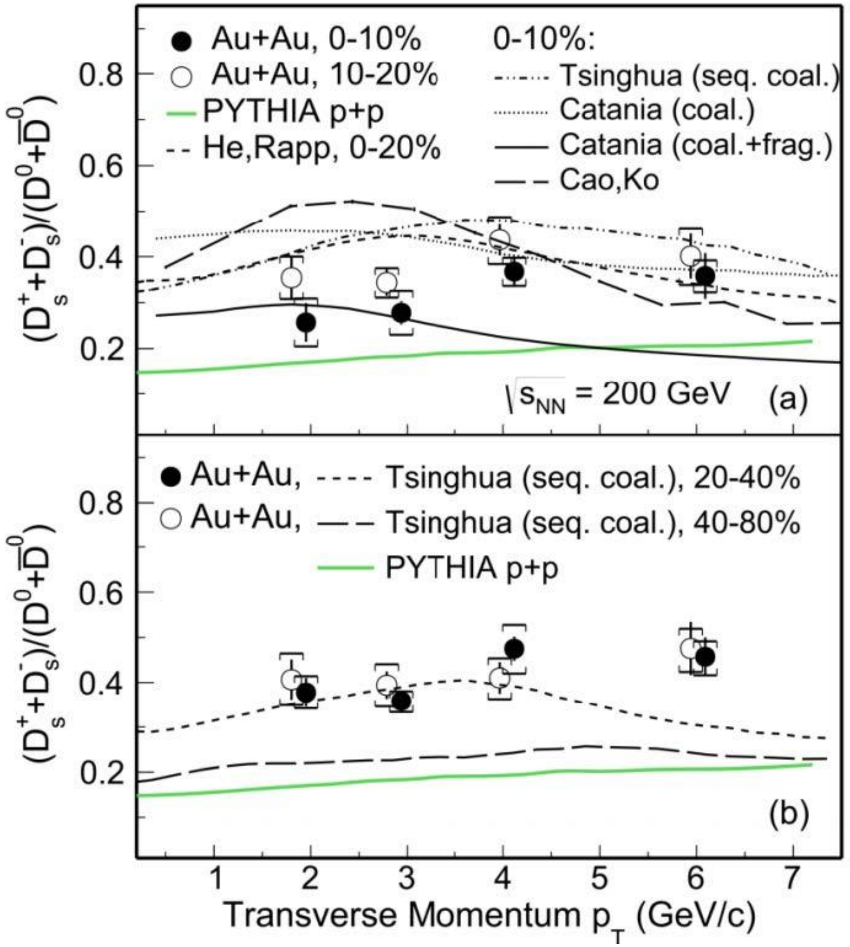
$$R_{AA}(p_T) = \frac{dN_D^{AA}/dp_T}{\langle N_{coll}\rangle \, dN_D^{pp}/dp_T}$$

D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
$\pi^{\pm}$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
$h^{\pm}$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

Strong interaction between charm quarks and medium

- Suppression of D^0 and $D^{\pm}$ mesons at high p_T comparable to light-flavor hadrons at RHIC and D mesons at LHC
- Models incorporating both **radiative** and **collisional energy** loss explain the data
- $D^{+/-}/D^0$ yield ratio in Au+Au is consistent with PYTHIA8.

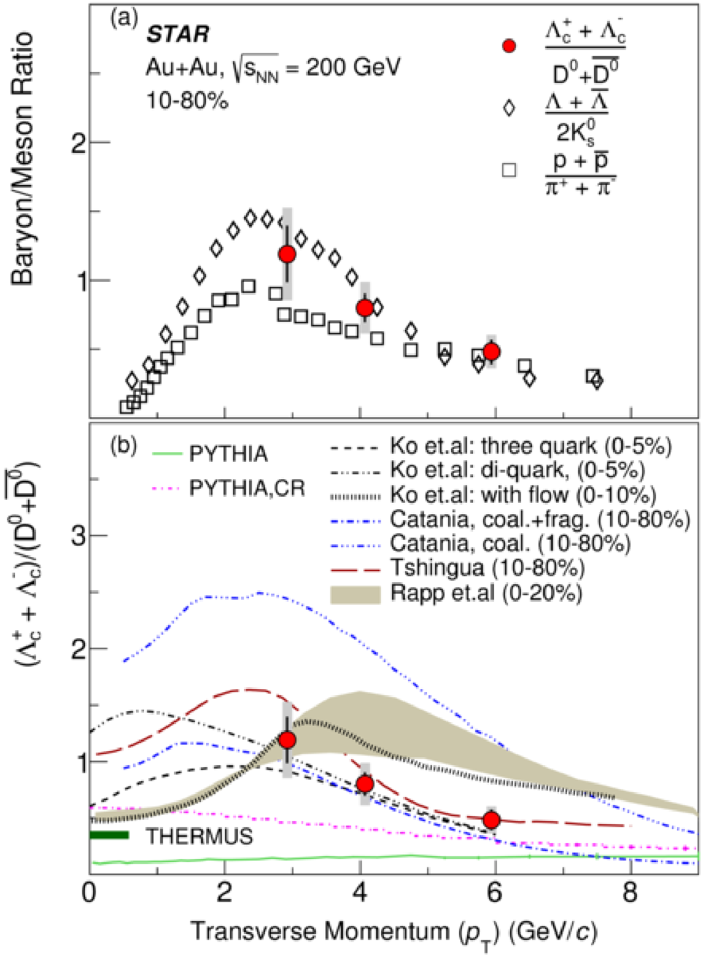
D_s/D^0 yield ratio enhancement



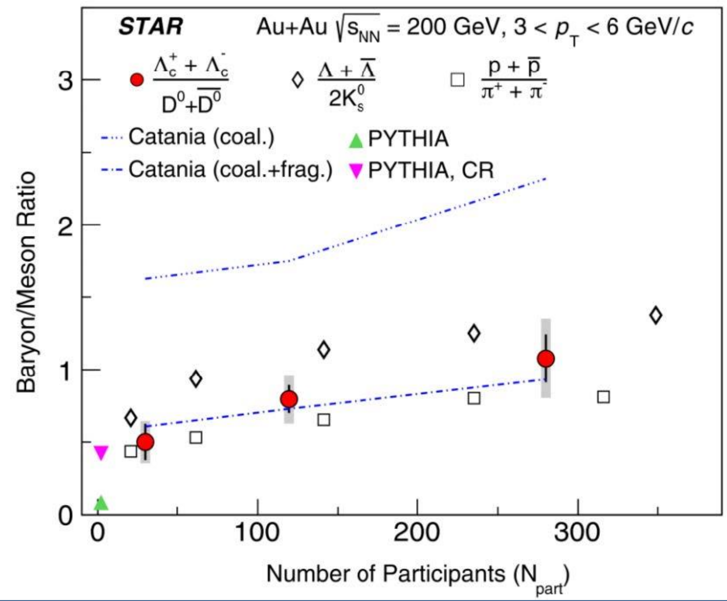
- **Observed strong enhancement of the D_s/D^0 yield ratio** compared to PYTHIA 6.4 p+p baseline
- The enhancement can be qualitatively described by model calculations incorporating thermal abundance of strange quarks in the QGP and coalescence hadronization
- None of the models can decribe the data in measured p_T range
- **Recombination** of charm quarks with strange quarks in the QGP plays an important role

STAR, Phys. Rev. Lett. 127 (2021) 092301

Λ_c/D^0 yield ratio



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



- Λ_c/D^0 ratio is comparable to baryon-to-meson ratios of light-flavor hadrons
- Clear enhancement observed compared to PYTHIA 8.24
- Most of the models incorporating charm quark hadronization via coalescence are consistent with data
- Enhancement of ratio increases in central collision

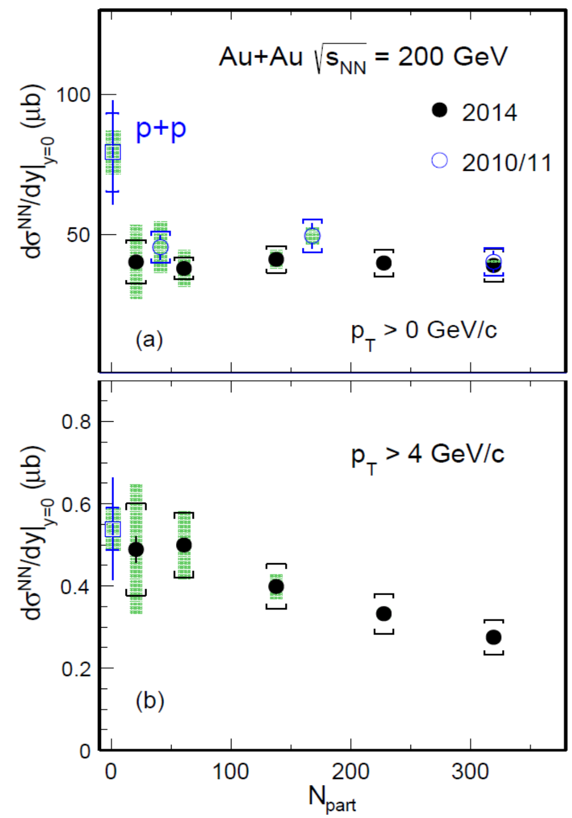
Importance of coalescence of charm quarks

Charm production cross section

Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3*
	D_s [2]	15 ± 2 ± 4
	Λ_c [3]	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV [4]	**Total**	130 ± 30 ± 26

* Preliminary $D^{+/-}$ results ** Λ_c cross-section using Λ_c/D^0 yield ratio

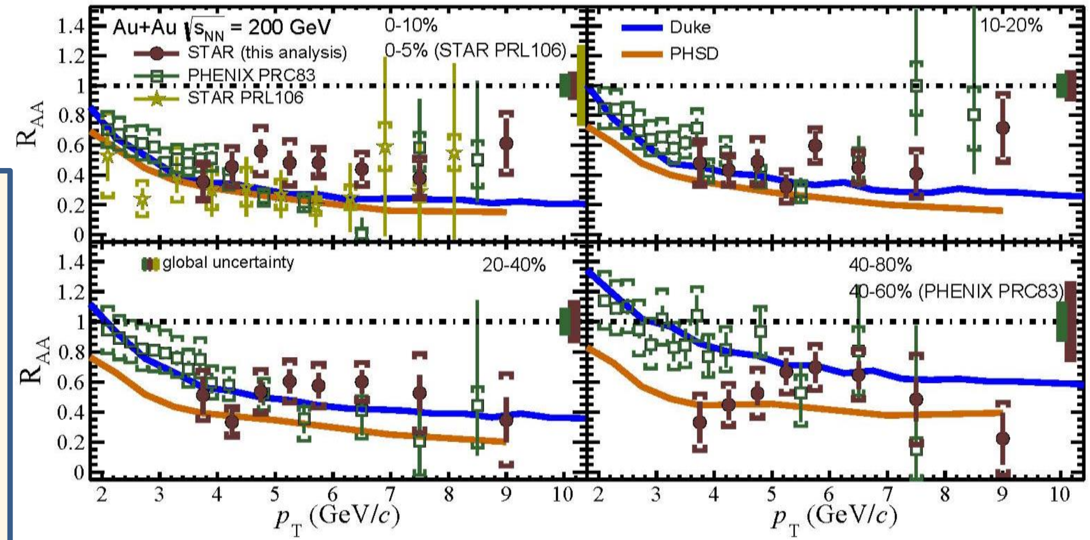
[1] D^0 (STAR): Phys. Rev. C 99, 034908, (2019)
[2] D_s (STAR): Phys. Rev. Lett. 127 (2021) 092301
[3] Λ_c (STAR): Phys. Rev. Lett. 124 (2020) 172301
[4] p+p (STAR): Phys. Rev. D 86 072013, (2012)

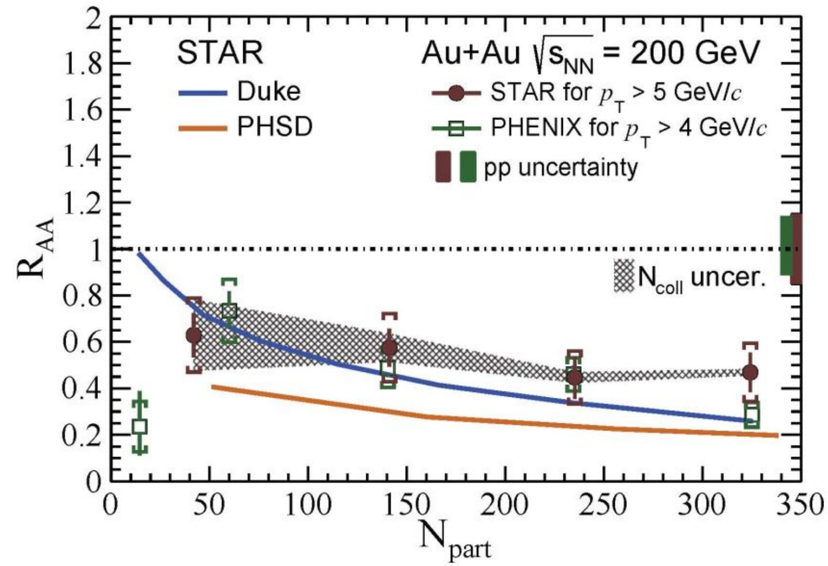


- Total charm production **cross-section per binary collision** in Au+Au
  - Au+Au result is consistent with that measured in p+p collisions within uncertainties

Electrons from HF hadron decays

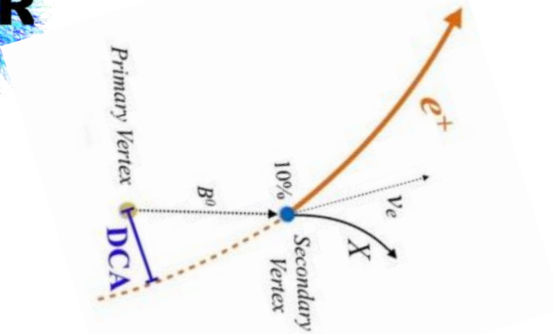
- Precise high-p_T measurement $3.5 < p_T < 9$ GeV/c
- A suppression by about a factor of 2 is observed in central and semi-central collisions
- No p_T dependence observed
- A hint of R_{AA} decreasing from peripheral to central collisions
- Models describe the data well
- Indication of substantial energy loss of heavy quarks in the QGP

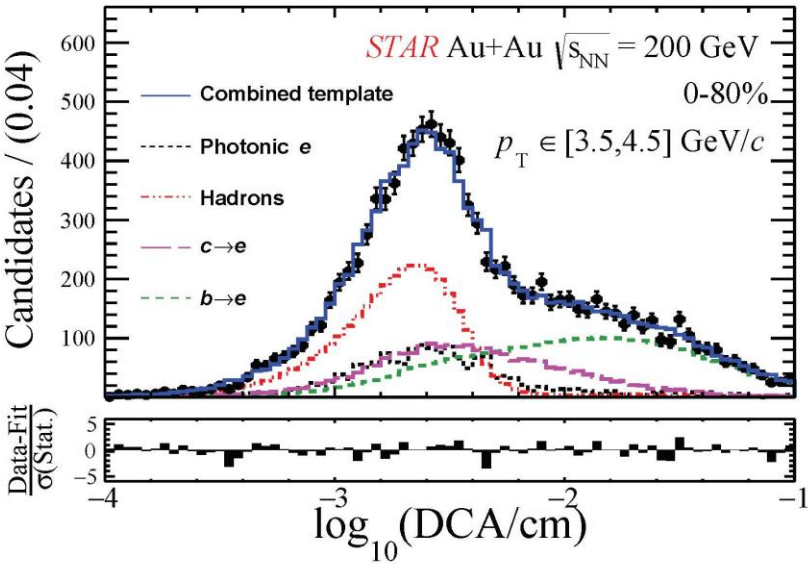


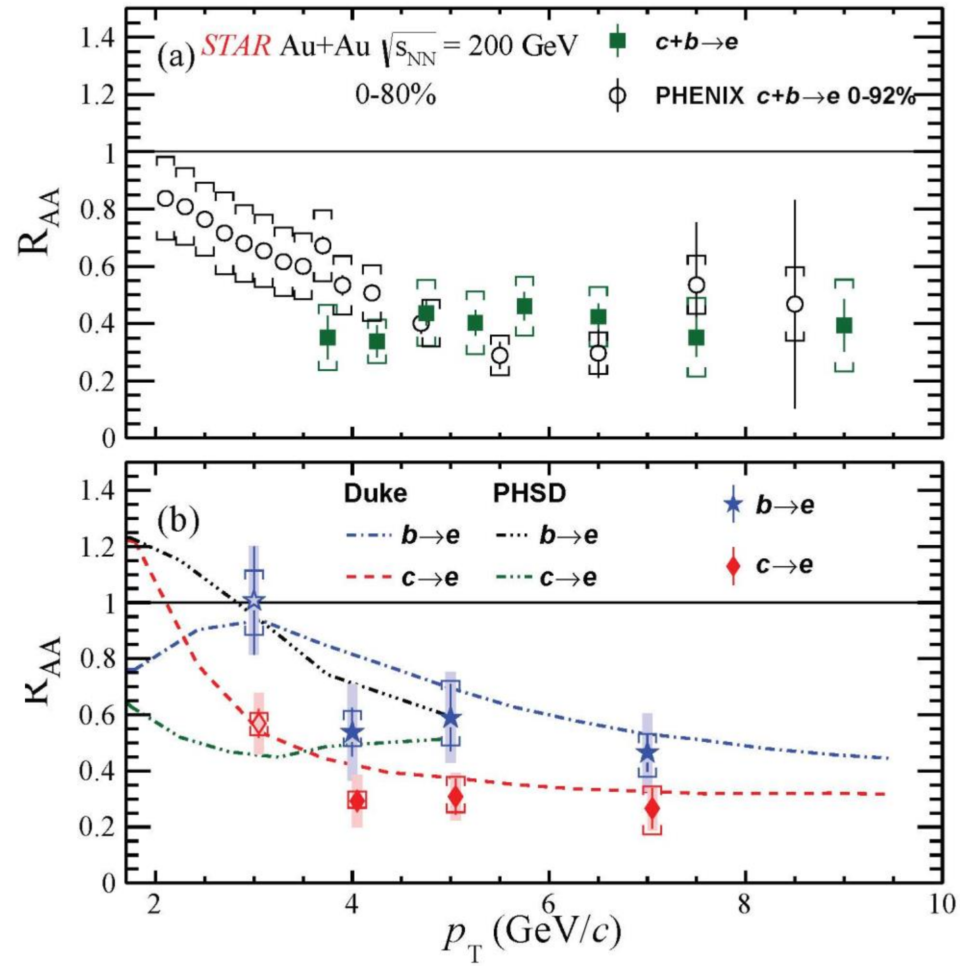


STAR: JHEP 06 (2023) 176

Mass ordering of heavy quarks energy loss







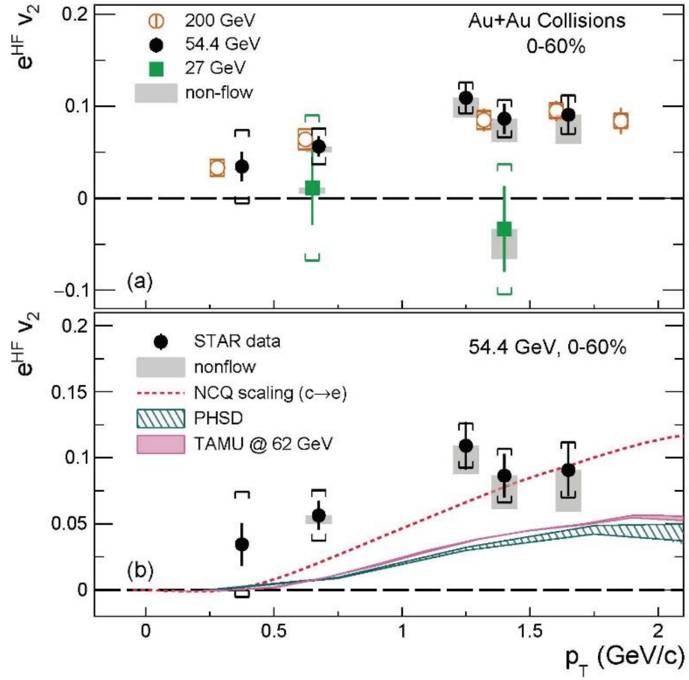
STAR Eur. Phys. J. C 82, 1150 (2022)

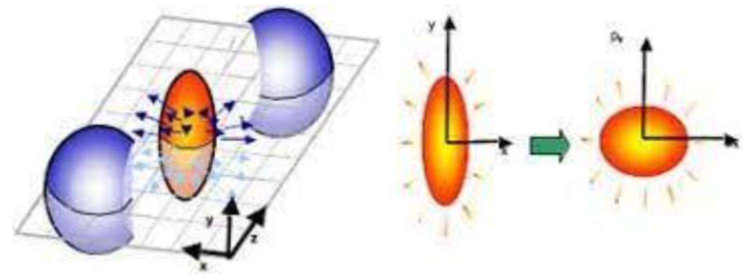
Heavy-flavor hadron decayed electrons: c → e and b → e **separation** in 200 GeV Au+Au collisions thanks to HFT

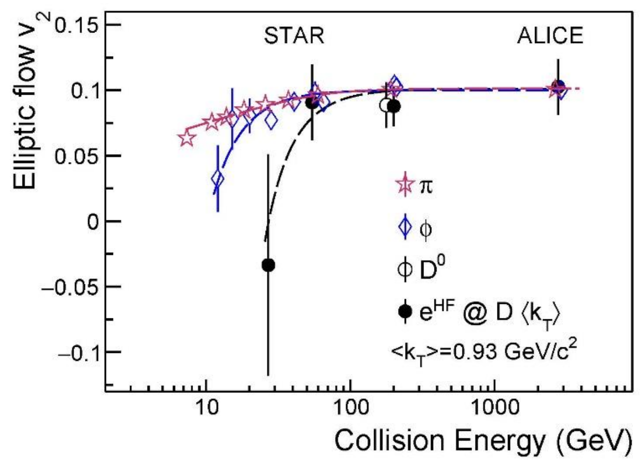
- Observation of less suppression for *B→e* than *D→e*
- Consistent with expected mass hierarchy for parton energy loss **$\Delta E_c > \Delta E_b$**

Energy dependence of HFE elliptic flow

$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$







STAR: arXiv:2303.03546 (PLB accepted)

- v_2 vs coll. energy → temperature dependence of charm quark diffusion coefficient
- At 27 GeV v_2 of c,b → e consistent with zero
- Significant non-zero v_2 of c,b → e at 54.4 – 200 GeV
- At low p_T models underestimate data
- **HF quarks interact strongly with the medium at 54.4 – 200 GeV**
- A hint of mass hierarchy is observed where the v_2 of heavier particles drops faster than lighter ones with decreasing collision energy

Quarkonium states in A+A

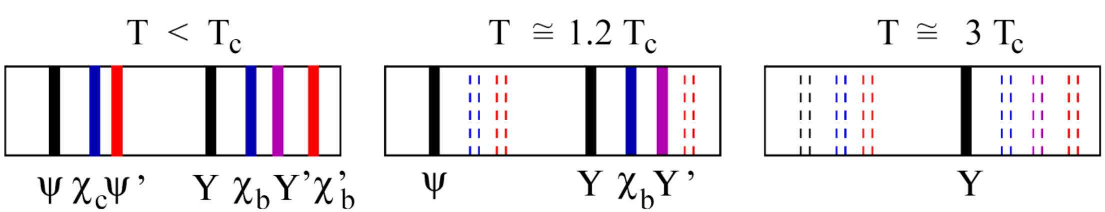
Charmonia: J/ψ, ψ', χ_c Bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

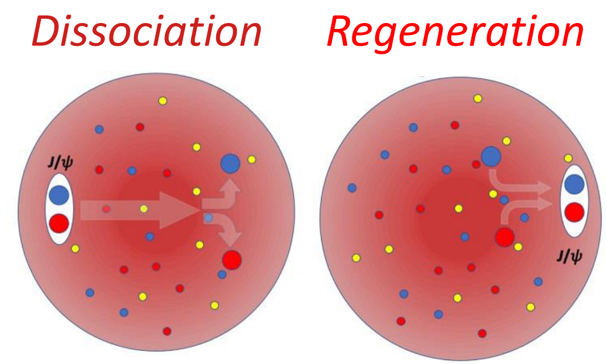
<u>Hot nuclear matter:</u>

QQbar potential and spectral function modified in the QCD medium w.r.t. vacuum

- **Dissociation** due to color screening and **regeneration**

$T_{diss}(\psi') \approx T_{diss}(\chi_c) < T_{diss}(\Upsilon(3S)) < T_{diss}(J/\psi) \approx T_{diss}(\Upsilon(2S)) < T_{diss}(\Upsilon(1S))$





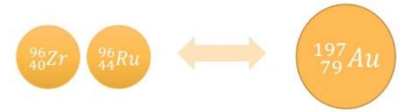
- Sequential suppression of states is determined by T_C and their binding energy

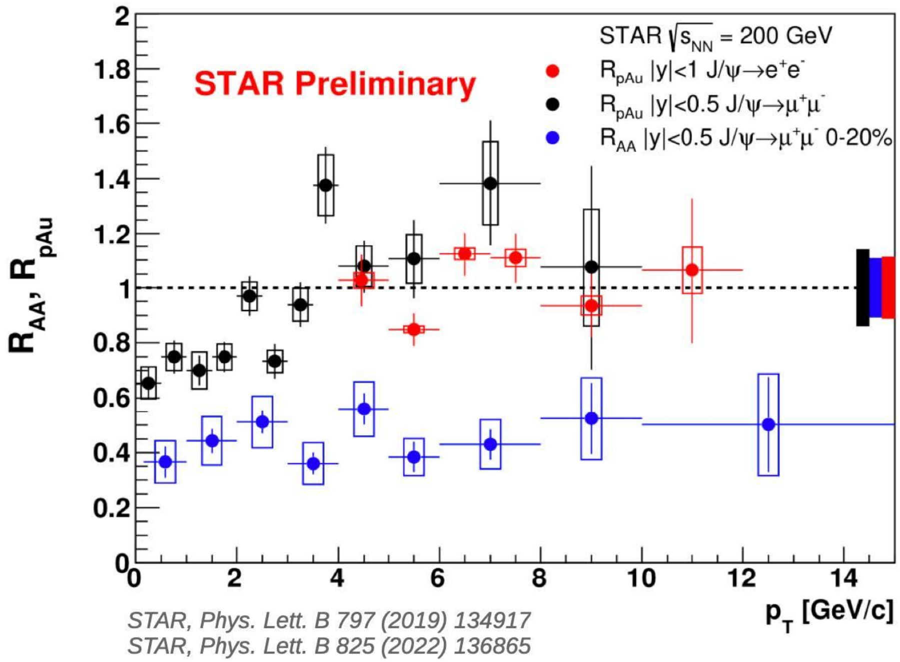
<u>Cold nuclear matter (p+Au):</u>

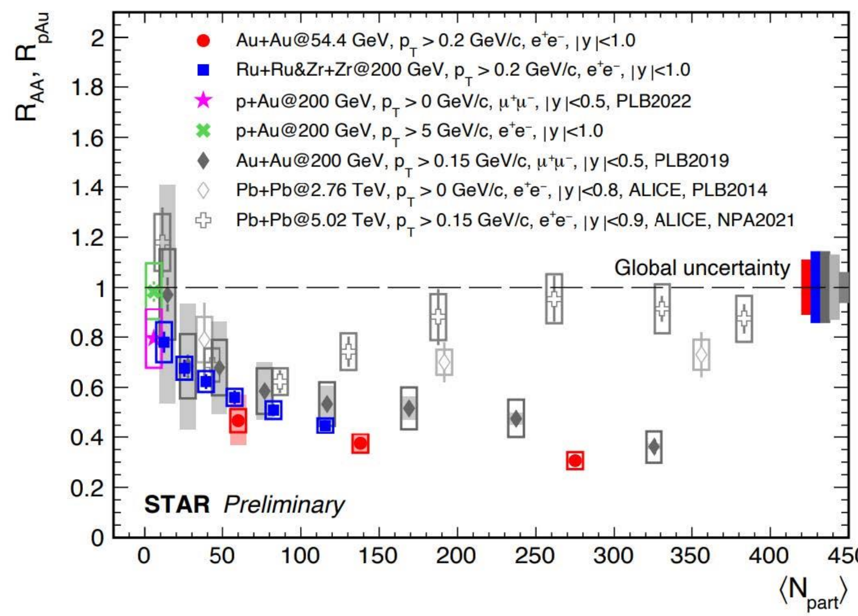
- Modification of PDFs, nuclear absorption, coherent energy loss, co-mover absorption…

<u>Production mechanism (p+p)</u>

J/ψ production in heavy-ion collisions



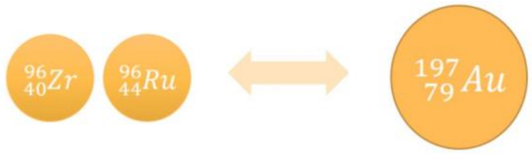




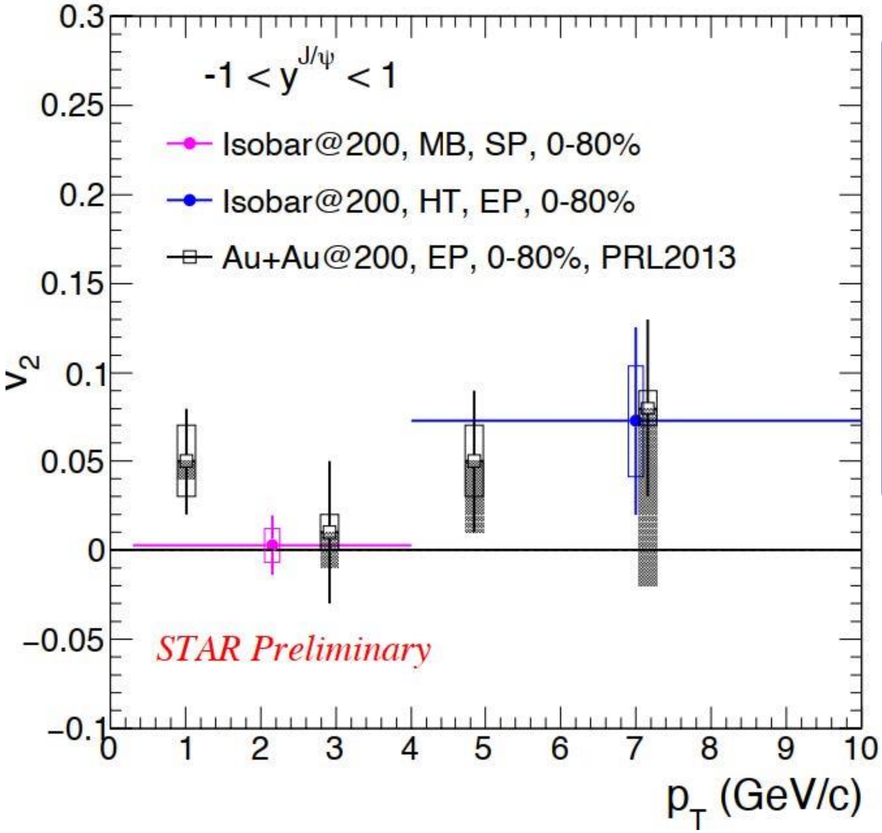
- Low p_T < 2 GeV/c: Cold nuclear matter effect are **not negligible**
- High p_T: **suppression in Au+Au** due to QGP

- No significant collision system dependence of the J/ψ suppression at similar <N_{part}>
- Suppression driven by system energy density
- At high p_T: Strong suppression at RHIC and regeneration at LHC

J/ψ elliptic flow



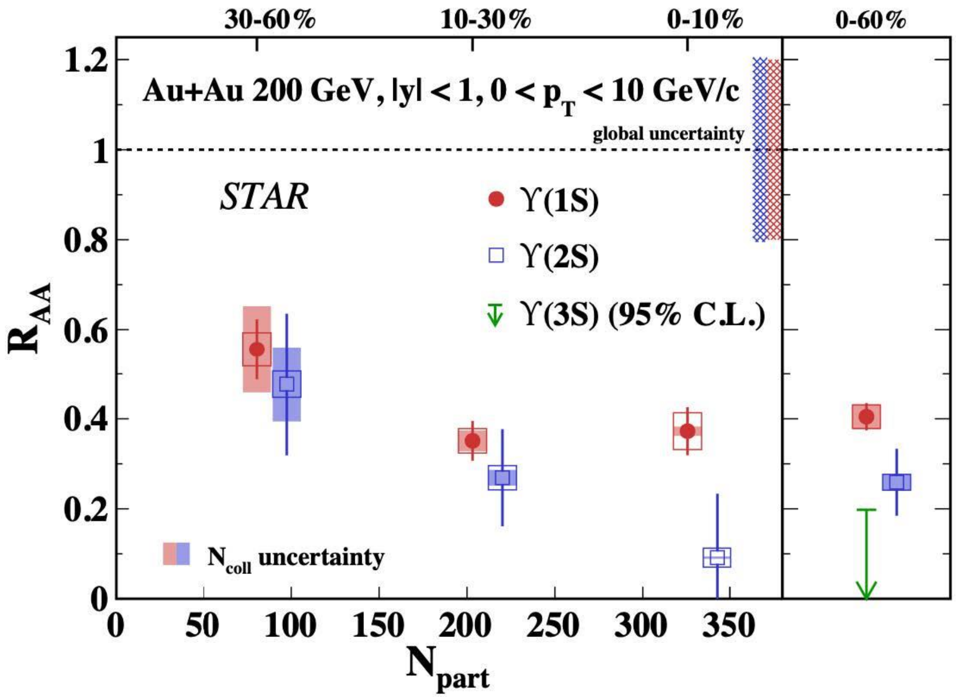
Isobar: Ru+Ru&Zr+Zr@200 GeV

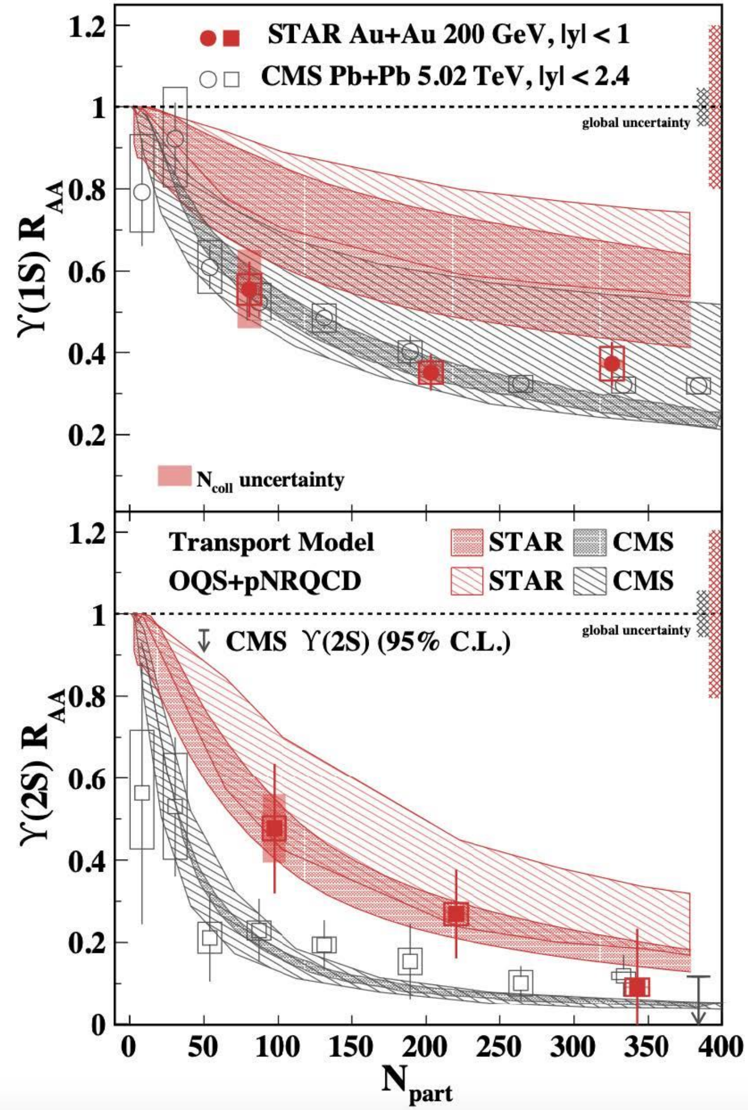


- More precise v_2 measurement at $p_T < 4$ GeV/c than in previous Au+Au 200 GeV
- v_2=0.003 ± 0.017($stat.$) ± 0.010($sys.$)
- Indication of **little regeneration** and/or small charm quark flow

Au+Au: Phys. Rev. Lett. 111 (2013) 52301

Υ(nS) suppression in heavy-ion collisions



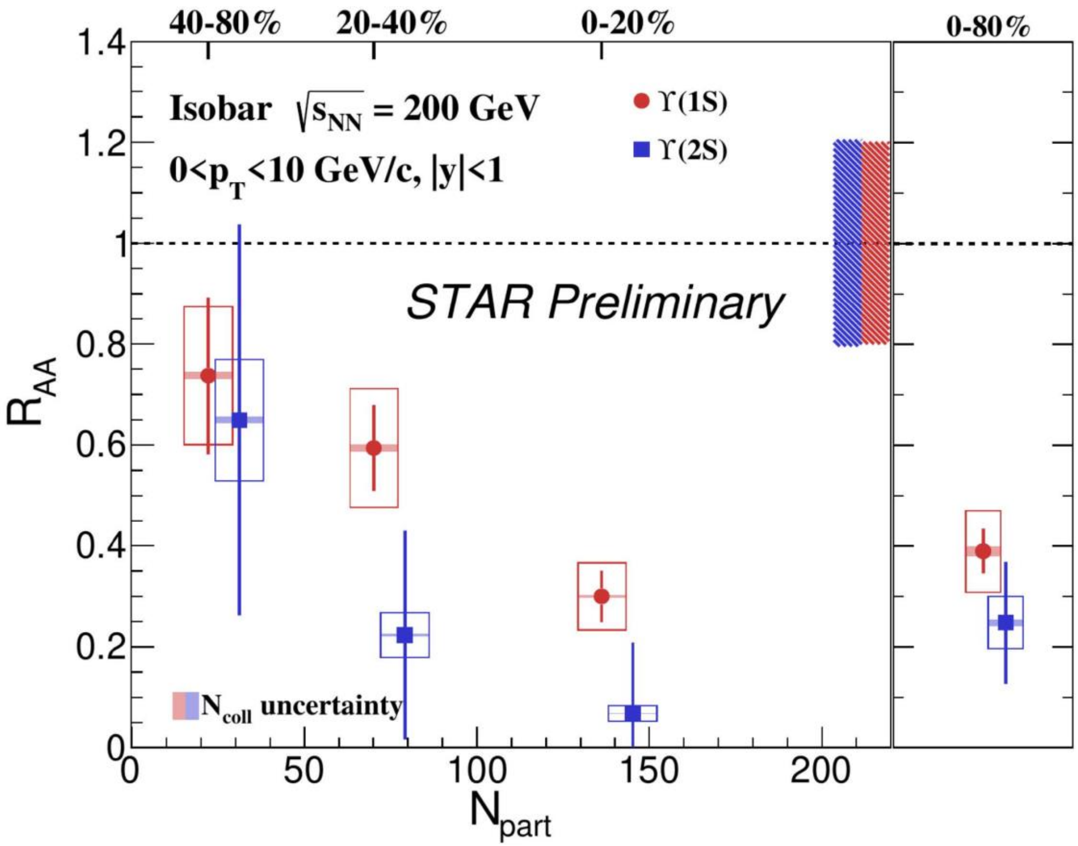


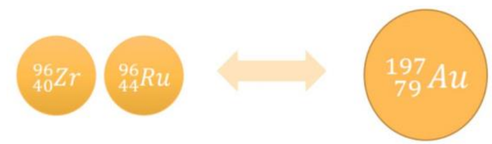
Transport, PRC 96 (2017) 054901   OQS+pQCD, arXiv:2205.10289

- Observed **sequential suppression** of different Υ(nS) states: R_{AA}[Υ(1S) > Υ(2S) > Υ(3S)]
- Υ(1S): Similar suppression at RHIC and LHC
- Υ(2S): Less suppression in peripheral collisions at RHIC

Phys. Rev. Lett. 130 (2023) 112301

Υ(1S), Υ(2S) suppression in isobaric collisions



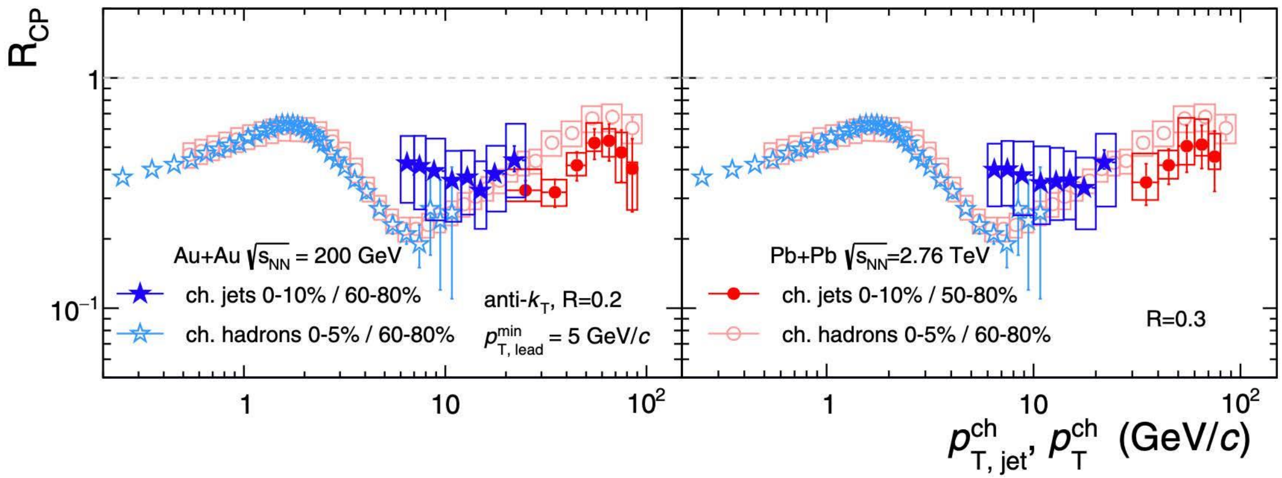


- Similar level of suppression of Υ(1S) and Υ(2S) observed in isobar collision as in Au+Au 200 GeV
- Significant suppression, increasing with collision centrality
- Hint of **sequential suppression** of Υ(nS) states: R_{AA}[Υ(1S) > Υ(2S)]

Jets

- Jets – clusters of final- state particles resulting from QCD evolution of hard scattered partons
- Jets – well established hard probe of QGP
- Modifications to the jet energy and structure in Au+Au relative to those in p + p or p+Au collisions -> due to the transport properties of the QGP

STAR: PRC 102, 054913 (2020)

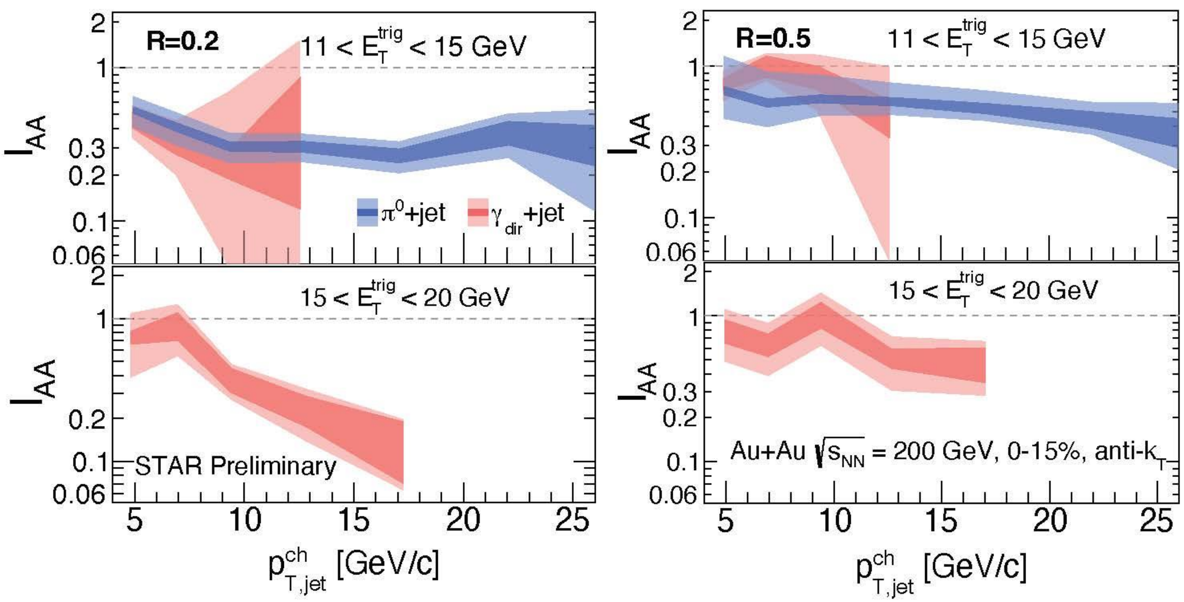


$$R_{CP}=\frac{\left(\frac{d^2N_{AA}}{dp_T d\eta}\right)^{cent}/N_{coll}^{cent}}{\left(\frac{d^2N_{AA}}{dp_T d\eta}\right)^{periph}/N_{coll}^{periph}}$$

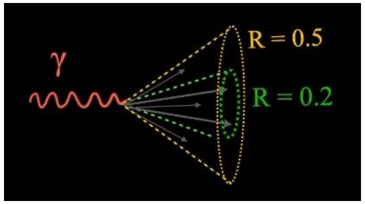
- Inclusive charged jet suppression R_{CP} at RHIC and LHC comparable
- Recent jet measurements address jet modifications using jet substructure measurements like — jet mass, jet shape, etc.

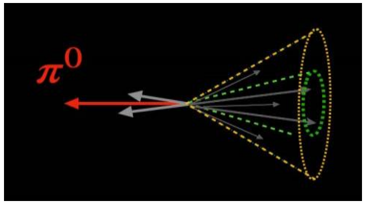
Nuclear modification factor of recoil jets

- Semi-inclusive γ+jet and π^0+jet measurement



$I_{AA} = Y_{Au+Au}/Y_{p+p}$

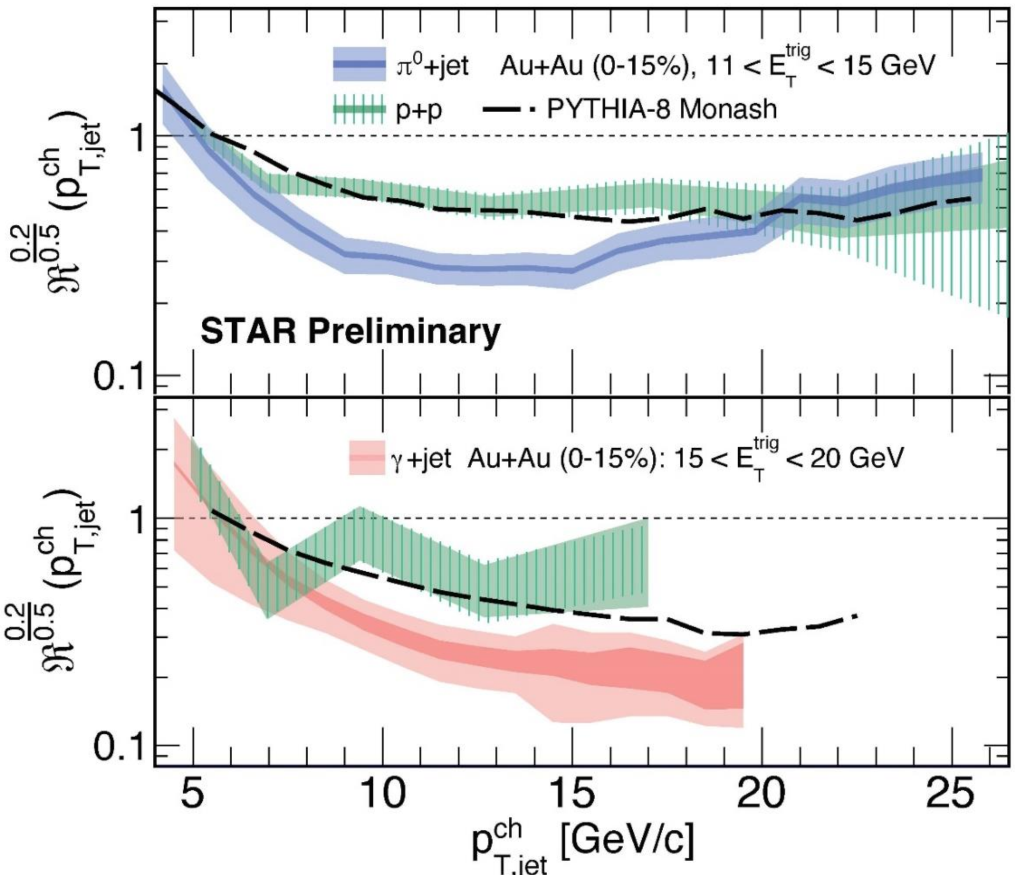




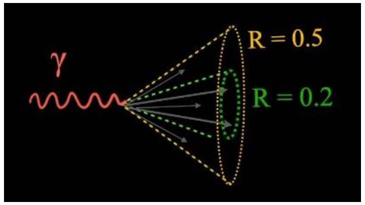
- Recoil jet yield is more suppressed for R=0.2 than R=0.5 indicating lost jet energy redistribution in the medium
- γ+jet and π^0+jet show similar level of suppression, within uncertainty

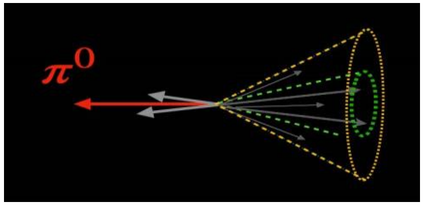
Jet-medium interaction

- Semi-inclusive γ+jet and π^0+jet measurement



$$\mathfrak{R}^{\text{small}-R}_{\text{large}-R} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-R}}{Y(p_T^{\text{jet,ch}})^{\text{large}-R}}$$



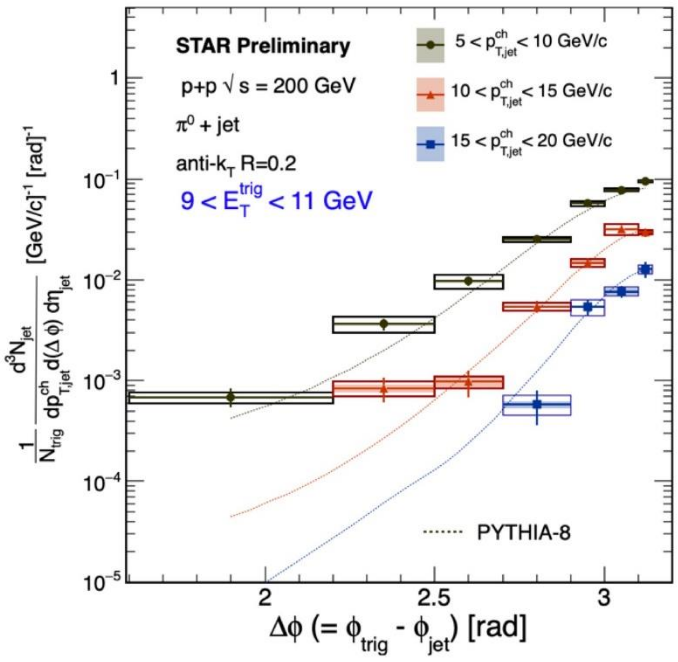


- In-medium intra-jet broadening in Au+Au w.r.t. p+p collisions
- Separating vacuum shower and in-medium radiation

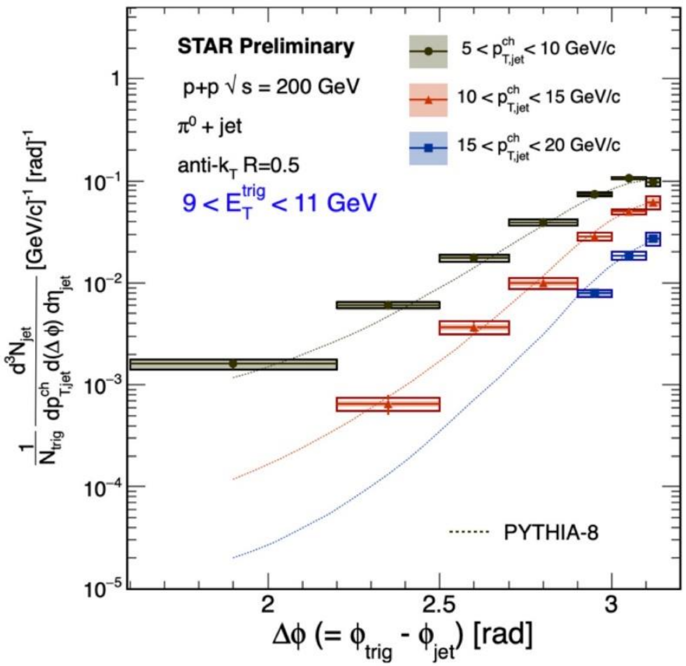
- $\mathfrak{R}^{0.2/0.5}$ < 1 in p+p collisions due to jet radial profile in vacuum
- $\mathfrak{R}^{0.2/0.5}$ is smaller in Au+Au than in p+p indicating in-medium broadening of jet shower

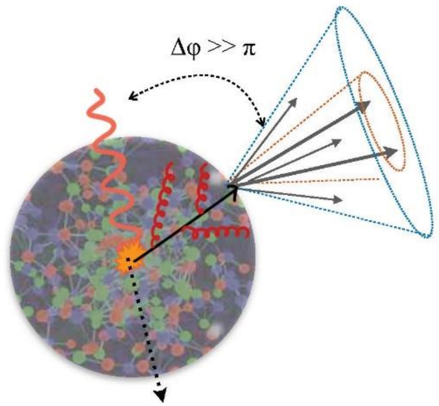
π^0 +jet azimuthal correlation in p+p collisions

R=0.2



R=0.5

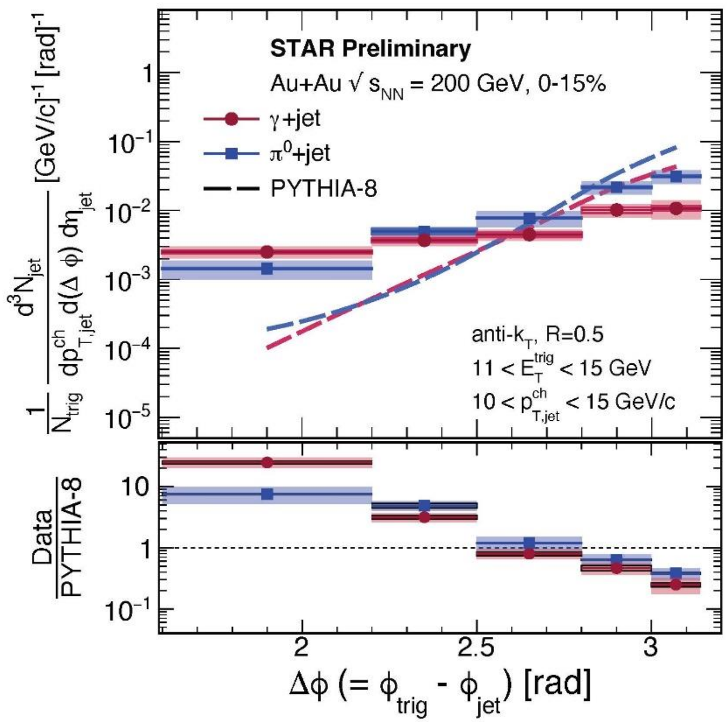


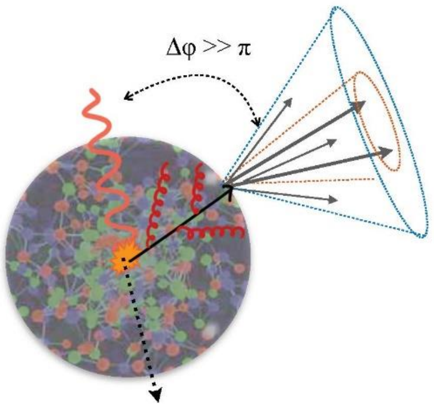


- PYTHIA-8 (MONASH tune) describes the π^0 +jet azimuthal correlation in p+p 200 GeV well

Jet acoplanarity in heavy-ion collisions

R=0.5

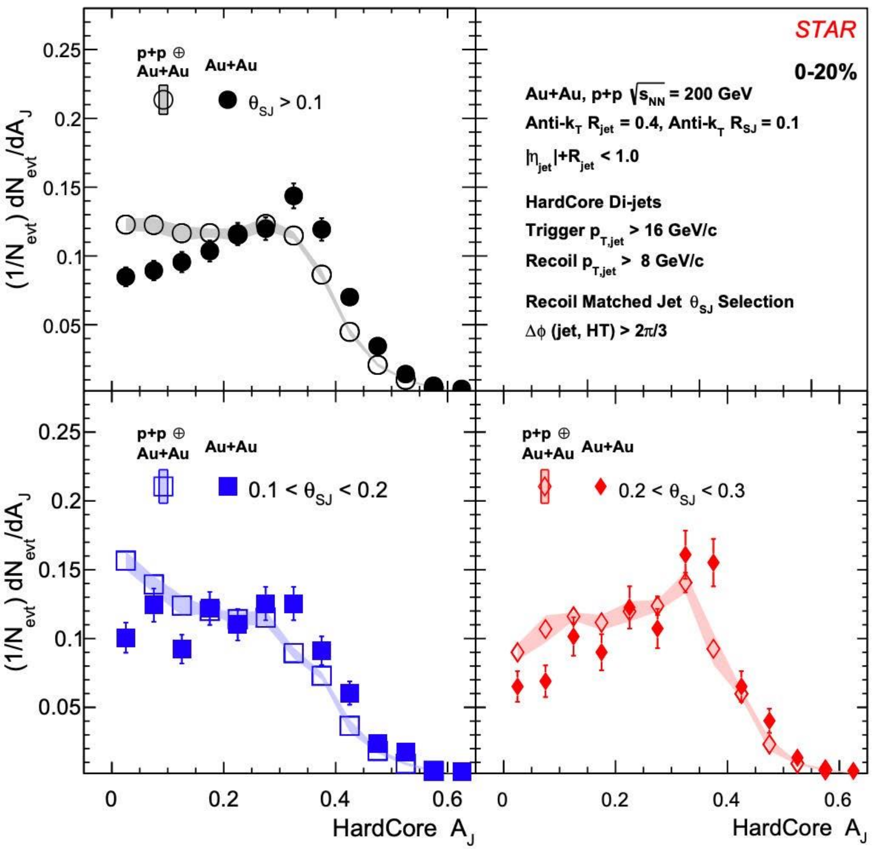


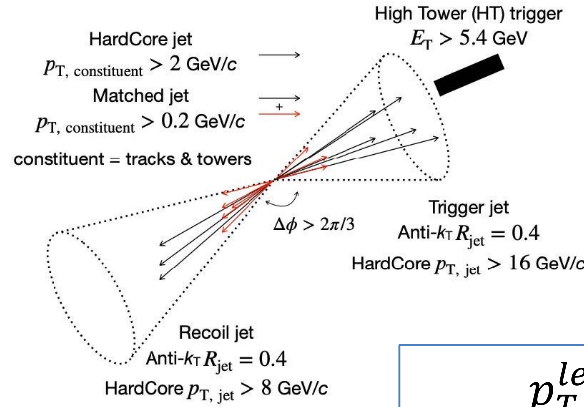


- Excess recoil jet yield around $\pi/2$ - acoplanarity observed in Au+Au collisions (jets with R=0.5)
  - In-medium jet scattering?
  - Medium response?

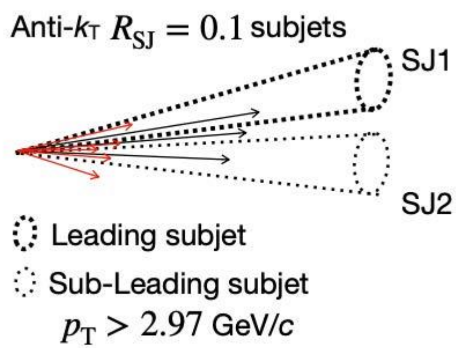
Dijet asymmetry

HARDCORE





$$A_J = \frac{p_{T,jet}^{lead} - p_{T,jet}^{sub}}{p_{T,jet}^{lead} + p_{T,jet}^{sub}}$$



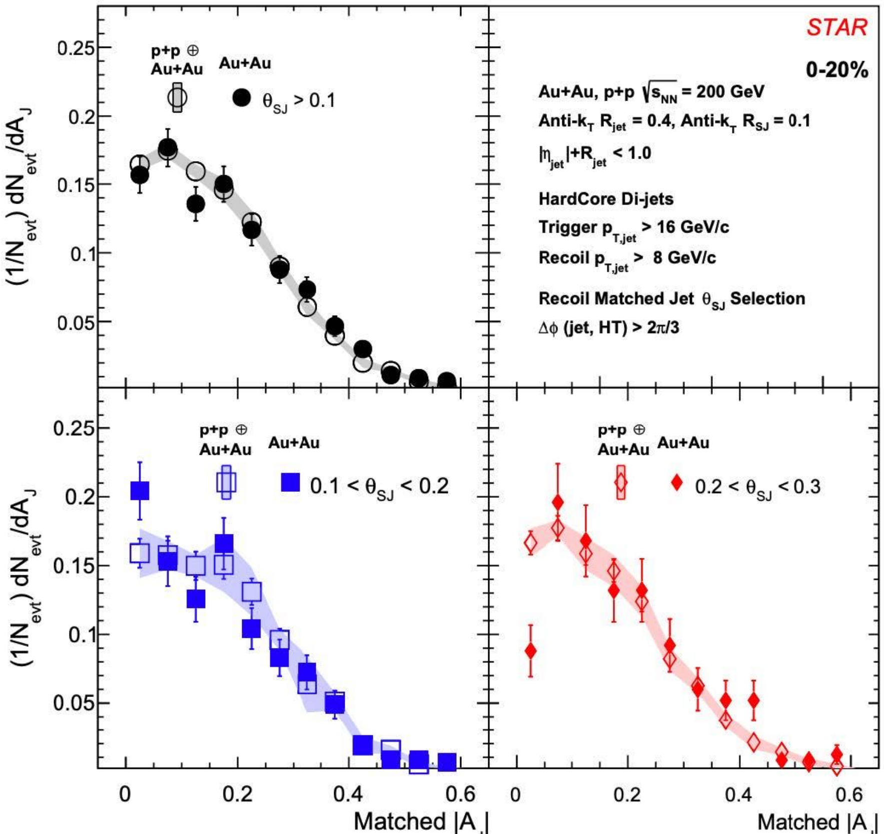
$\theta_{SJ} = \Delta R_{SJ1,SJ2}$

STAR, Phys.Rev.C 105 (2022) 044906

- Disagreement between Au+Au and p+p⨁Au+Au at all angles — jets are modified in Au+Au

Dijet asymmetry

MATCHED



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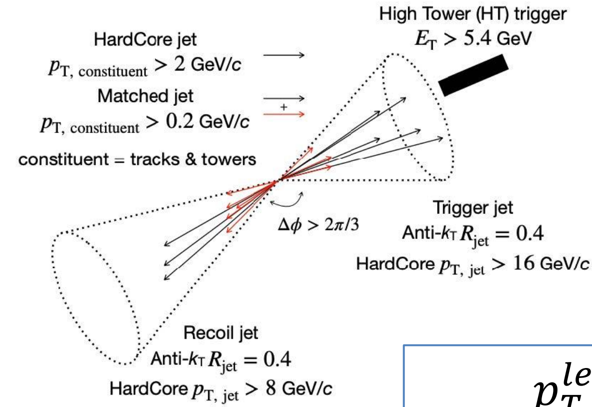
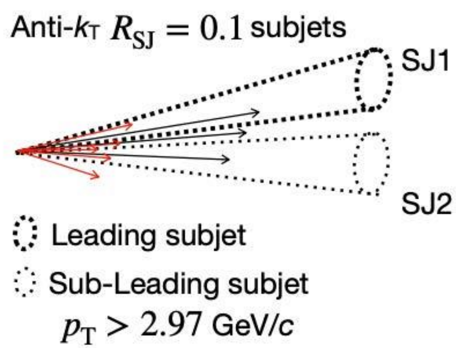


$$A_J = \frac{p_{T,jet}^{lead} - p_{T,jet}^{sub}}{p_{T,jet}^{lead} + p_{T,jet}^{sub}}$$



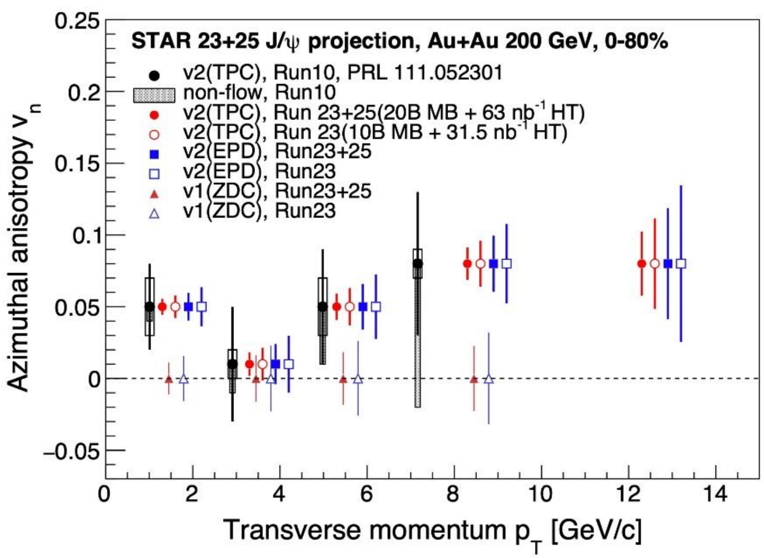
$\theta_{SJ} = \Delta R_{SJ1,SJ2}$

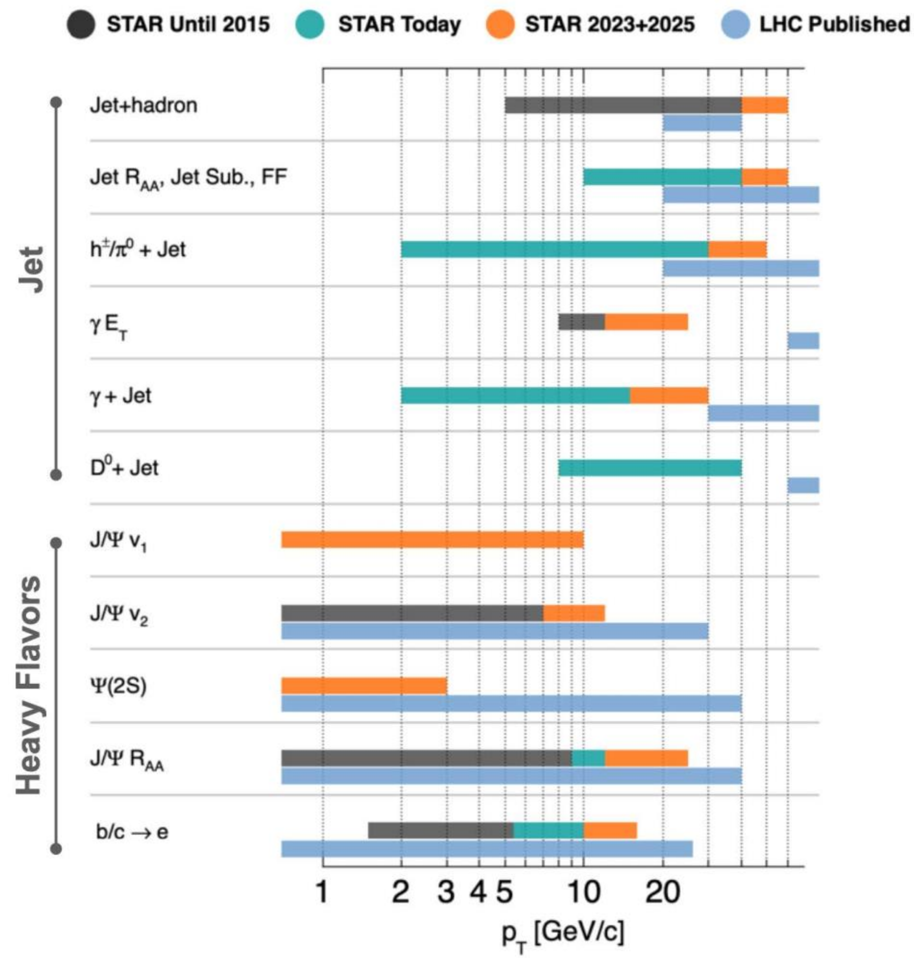
- No difference between Au+Au and p+p⊕Au+Au — for matched to HardCore jets
- Matches jets are balanced – energy recovered
- No angular dependence
- **Consistent with recoil jet loses energy as single color charge radiating in medium**

Outlook of 2023-2025

STAR BUR-2022:

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	20B / 40 nb^{-1}	2023+2025
200	p+p	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024





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

https://indico.bnl.gov/event/15148/attachments/40846/68609/STAR_BUR_Runs23_25___2022 (1).pdf

Summary

- STAR extensively studied production of open-charmed hadrons, quarkonia and jets
- **D^0, $D^{\pm}$ meson R_{AA} and HFE v_2** in Au+Au collisions:
  - Indicate strong charm-medium interactions
- **Λ_c/D^0 and D_s/D^0** yield ratios are enhanced in Au+Au collisions with respect to p+p collisions
  - Coalescence plays an important role in charm quark hadronization
- Indication of less suppression for ***B→e* than *D→e***
  - Consistent with expected mass hierarchy of parton energy loss
- **J/ψ suppression**: no significant collision system and energy dependence
  - Interplay of dissociation and regeneration effects
- **Sequential Υ** suppression at RHIC
- **Jet** suppression and accoplanarity:
  - Manifestation of jet-medium interactions
- **Dijet asymmetry**:
  - No angular dependence of jet energy loss for recoiled matched jets

Many jet substructure measurements in p+p collision….