Open Heavy-Flavor Physics at STAR

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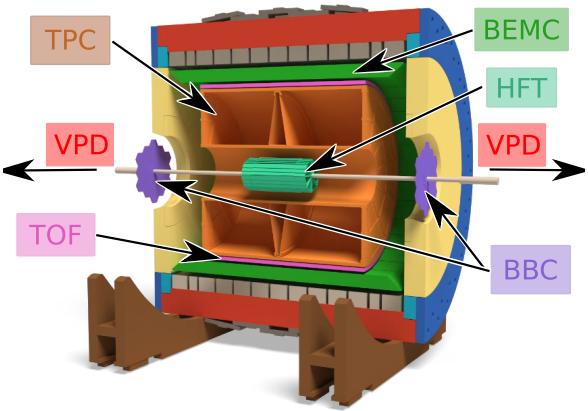
Office of Science

Outline

- STAR detector
- Heavy quarks
- Heavy-flavor electrons
- Recent results:
  - Inclusive $e^{\pm}$ from open HF hadron decays in p+p @ 200 GeV Phys. Rev. D 105, 032007 (2022)
  - $e^{\pm}$ from open HF hadron decays in Au+Au @ 200 GeV JHEP 06, 176 (2023)
  - Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV Phys. Lett. B 844, 138071 (2023)
  - Mass ordering of c and b quark energy loss Eur. Phys. J. C 82, 1150 (2022)
  - D^0 R_{AA} in isobar collisions @ 200 GeV
  - D^0-hadron femtoscopic correlations in Au+Au @ 200 GeV
  - D^0-jet fragmentation function and radial profile in Au+Au @ 200 GeV
  - D^0-jet angularity modification in central Au+Au @ 200 GeV
- STAR Heavy Flavor program for Runs 23-25
- Summary

The Solenoidal Tracker At RHIC (STAR)

Credit: https://nsww.org/



- Time Projection Chamber (**TPC**)
  - Tracking and PID ($\mathrm{d}E/\mathrm{d}x$, $\vec{p}$)
  - Acceptance $|\eta| < 1$
- Barrel Electromagnetic Calorimeter (**BEMC**)
  - High p_{T} electron identification and triggering
  - Acceptance $|\eta| < 1$
- Time-of-Flight Detector (**TOF**)
  - PID ($1/\beta$)
  - Acceptance $|\eta| < 1$
- Beam-Beam Counter (**BBC**)
  - Minimum bias trigger
  - Acceptance $3.4 < |\eta| < 5$
- Vertex Position Detector (**VPD**)
  - Minimum bias trigger
  - Acceptance $4.21 < |\eta| < 5.1$
- Heavy Flavor Tracker (**HFT**)
  - Topological reconstruction of heavy-flavor hadrons
  - Acceptance $|\eta| < 1$

Heavy quarks (c and b) as probes of QGP

- Heavy quarks: $m_Q \gg \Lambda_{\mathrm{QCD}}$, $m_Q \gg T_{\mathrm{QGP}}$
- Dominantly produced in initial hard scatterings
- Participate in the whole medium evolution
- Production cross-sections can be calculated in perturbative QCD

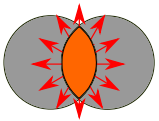
$\rightarrow$ **Ideal probes of QGP**

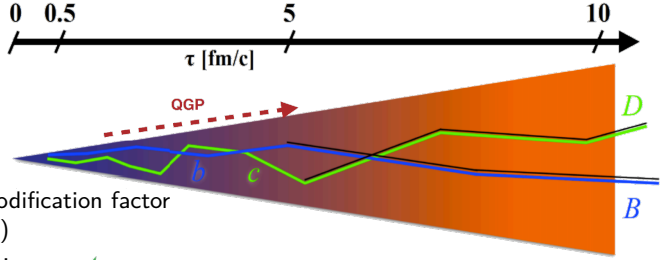
Heavy-flavor (HF)

- Open heavy-flavor - carry one **c** or **b** quark
- Quarkonia - $\mathbf{c\bar{c}}$ or $\mathbf{b\bar{b}}$

Heavy quark diffusion

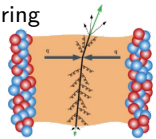
- Thermalization, diffusion
- Elliptic flow (v_2)





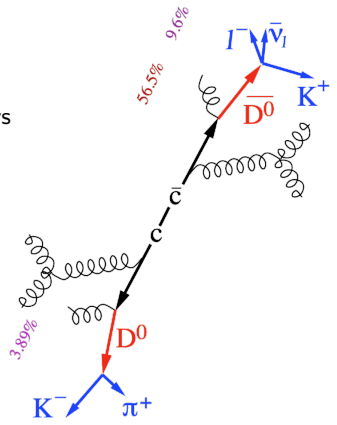
Energy loss

- Nuclear modification factor (R_{AA}, R_{CP})
- Mass ordering

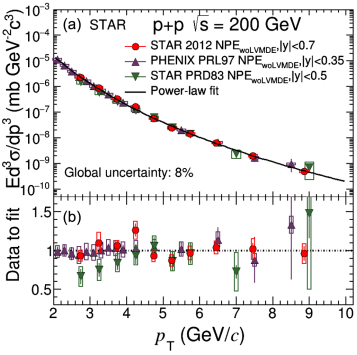


Heavy-Flavor Electrons (HFE)

- Electrons from semi-leptonic decays of heavy-flavor hadrons
- A p_{T}-dependent mixture of electrons from both **D** and **B** hadron decays
- HFE branching ratio (BR) $>$ hadronic decays of open HF hadrons BR
  - $\mathrm{D}^0 \rightarrow \mathrm{K}^- + \pi^+$; BR = (3.93 $\pm$ 0.04) %
  - $\mathrm{D}^0 \rightarrow \mathrm{e}^+ +$ anything; BR = (6.49 $\pm$ 0.11) %
  - Widely used to study heavy quark production



Inclusive $e^{\pm}$ from open HF hadron decays in p+p @ 200 GeV

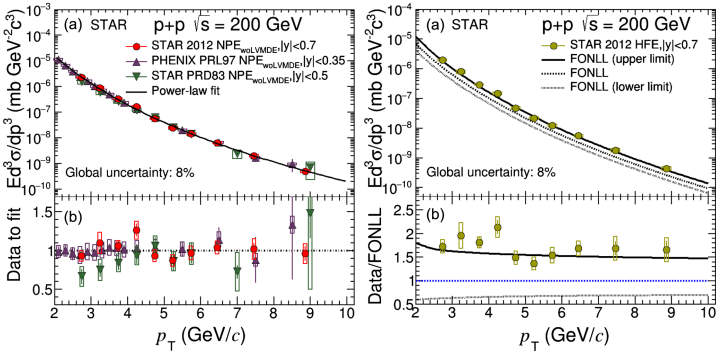


- Good agreement among the different STAR and PHENIX results
- Precision improved at $p_T > 6$ GeV/c

STAR: Phys. Rev. D 105, 032007 (2022)
STAR: Phys. Rev. D 83, 052006 (2011)
PHENIX: Phys. Rev. Lett. 97, 252002 (2006)

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = \frac{1}{2}\frac{1}{L}\frac{N_{\mathrm{NPE}}}{2\pi p_T \Delta p_T \Delta y} - \left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{\mathrm{LVMDE\ or\ HDE}}$$

Inclusive $e^{\pm}$ from open HF hadron decays in p+p @ 200 GeV



- Good agreement among the different STAR and PHENIX results
- Precision improved at $p_T > 6$ GeV/c
- Consistency with the upper limit of the FONLL uncertainty

- Further constraints on theoretical calculations
- Precise reference for R_{AA} measurements for heavy-flavor decayed electrons

STAR: Phys. Rev. D 105, 032007 (2022)
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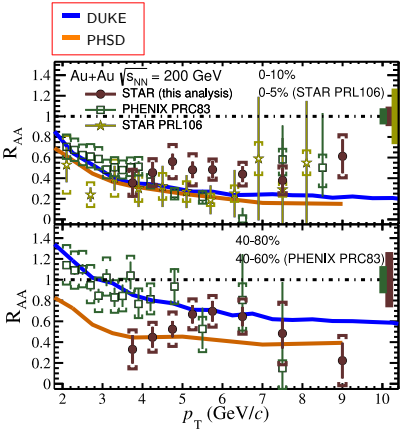
$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = \frac{1}{2}\frac{1}{L}\frac{N_{\mathrm{NPE}}}{2\pi p_T \Delta p_T \Delta y} - \left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{\mathrm{LVMDE\ or\ HDE}}$$

$e^{\pm}$ from open HF hadron decays in Au+Au @ 200 GeV



$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{coll}}} \times \frac{\mathrm{d}N^2_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}N^2_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

- Suppression by factor of 2 in central collisions within $3.5 < p_{\mathrm{T}} < 8$ GeV/c
- Significant energy loss of heavy quarks in QGP

STAR: JHEP 06, 176 (2023)
PHENIX: Phys. Rev. C 84, 044905 (2011)
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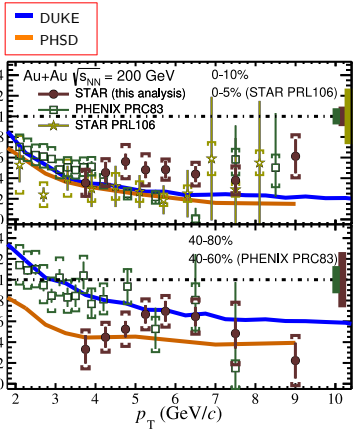
$e^{\pm}$ from open HF hadron decays in Au+Au @ 200 GeV



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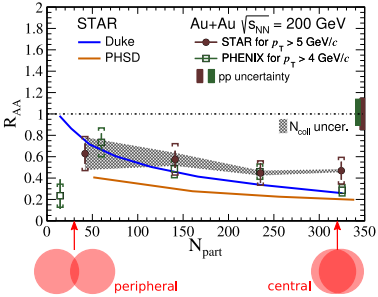
- Suppression by factor of 2 in central collisions within $3.5 < p_{\mathrm{T}} < 8$ GeV/c
- Significant energy loss of heavy quarks in QGP
- A hint of HFE R_{AA} decreasing from peripheral to central collisions
- Stronger parton energy loss in central collisions



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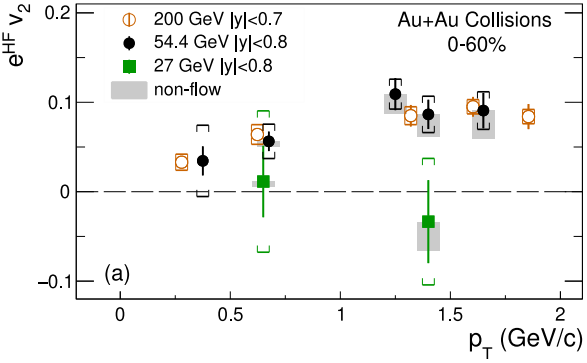
- Consistency with PHENIX results
- Qualitative description of data by Duke and PHSD models

Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV

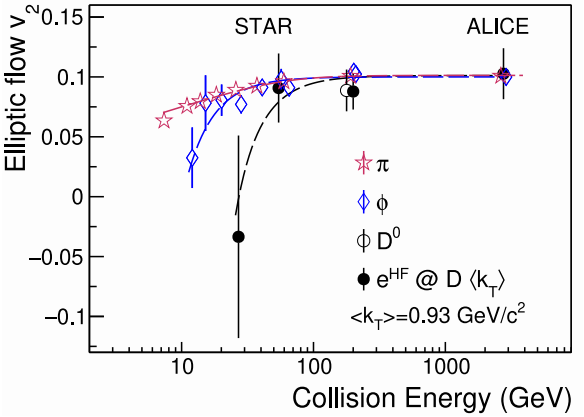


$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\phi - \psi_n)]$$

- 54.4 GeV - significant v_2 of e^{HF}
  - Strong interaction of c quarks with QGP
  - Hints of close to thermal equilibrium with the medium
- 27 GeV - v_2 is consistent with 0 within uncertainties
  - Hints of deviation of c quarks from local thermal equilibrium?

STAR (27 & 54.4 GeV): Phys. Lett. B 844, 138071 (2023)
STAR (200 GeV): Phys. Rev. C 95, 034907 (2017)

Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV



STAR: Phys. Lett. B 844, 138071 (2023)
STAR: Phys. Rev. C 95, 034907 (2017)

- Indication of v_2 of heavier particles drops faster with decreasing collision energy

⇓

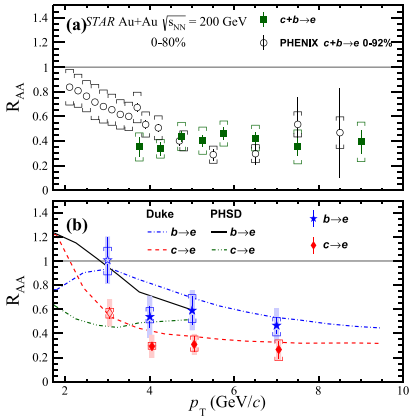
Mass hierarchy

- PHSD model: The QGP volume and the fraction of energy in the medium to the total collision energy deposited are smaller at low $\sqrt{s_{\mathrm{NN}}}$

⇓

- The influence of QGP medium on final-state particle dynamics is reduced as the collision energies decrease

Mass ordering of c and b quark energy loss



STAR: Eur. Phys. J. C 82, 1150 (2022)
PHENIX: Phys. Rev. C 84, 044905 (2011)

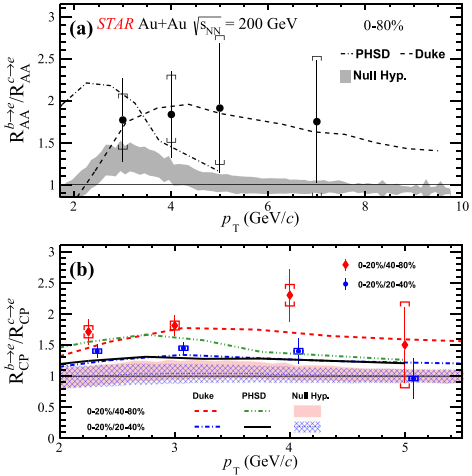
$$\blacksquare\ R_{AA}^{incl} = \frac{1}{N_{coll}} \times \frac{dN_{AA}^2/dp_T dy}{dN_{pp}^2/dp_T dy}$$

$$\bigstar\ R_{AA}^{b\to e} = f_b^{AA}/f_b^{pp} \times R_{AA}^{incl}$$
$$\blacklozenge\ R_{AA}^{c\to e} = (1 - f_b^{AA})/(1 - f_b^{pp}) \times R_{AA}^{incl}$$

f_b^{AA} - fraction measured in Au+Au

- Compatibility with PHENIX measurement
- Larger suppression of c-decay $e^{\pm}$ than b-decay $e^{\pm}$
- Improved precision
- Good agreement with both Duke and PHSD models

Mass ordering of c and b quark energy loss



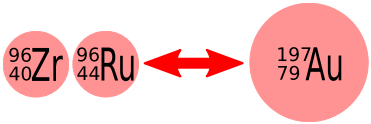
STAR: Eur. Phys. J. C 82, 1150 (2022)

$$R_{AA}^{b\to c} = f_b^{AA}/f_b^{pp} \times R_{AA}^{incl}$$
$$R_{AA}^{c\to e} = (1 - f_b^{AA})/(1 - f_b^{pp}) \times R_{AA}^{incl}$$

- $R_{AA}^{b\to e} > R_{AA}^{c\to e}$
- Significant deviation of both R_{CP} from unity
  $\Rightarrow$ Evidence of mass ordering at RHIC
- Good agreement with both Duke and PHSD models

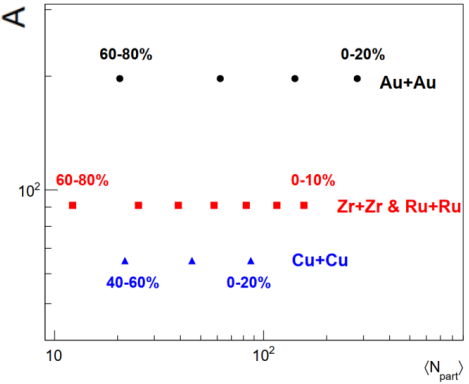
D^0 R_{AA} in isobar collisions @ 200 GeV

PRELIMINARY



Motivation

- Moderate size collision system between Au+Au and Cu+Cu
- Good for studying hot nuclear medium effects dependence on colliding system size

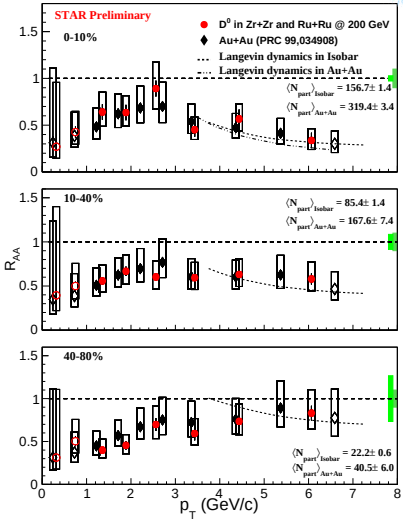


D^0 R_{AA} in isobar collisions @ 200 GeV

PRELIMINARY

- No obvious centrality dependence for the low p_T suppression
  - ⇒ Interplay of radial flow, the cold nuclear matter effects, and the charm hadrochemistry
- Suppression in central collisions at $p_T > 3$ GeV/c
  - ⇒ Significant energy loss of c quarks in the bulk QCD medium
  - ⇒ Centrality dependence of the high p_T suppression
- Good description by a Langevin model from 3 GeV/c
- Similar suppression in isobar and Au+Au collisions despite different $\langle N_{\text{part}} \rangle$ at a given energy

STAR: Phys. Rev. C 99, 034908 (2019)



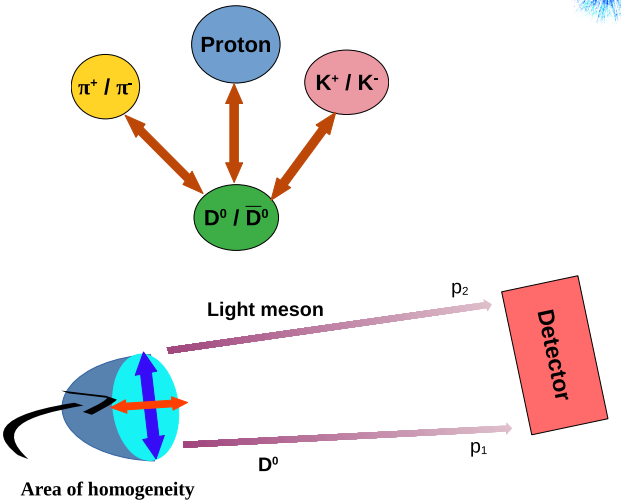
D^0-hadron femtoscopic correlations in Au+Au @ 200 GeV

PRELIMINARY

- Freeze-out dynamics and final state interaction of charmed mesons
- Only strong interaction contributes to $D^0/\overline{D}^0$-$h^{\pm}$ femtoscopy
- Correlation function

$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 \mathrm{d}^3 r^*$$

  - $\vec{k}^*$ - reduced momentum difference of pair in rest frame
  - $S(\vec{r}^*)$ - source emission function
  - $\Psi(\vec{k}^*, \vec{r}^*)$ - pair wave function
- $C(k^*)$ measured for D^0-K, D^0-π, and D^0-p



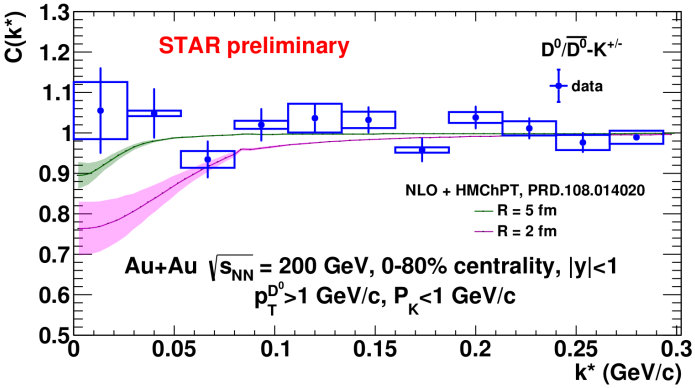
D^0-K femtoscopic correlations in Au+Au @ 200 GeV

PRELIMINARY

- Correlation function

$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 \mathrm{d}^3 r^*$$

  - $\vec{k}^*$ - reduced momentum difference of pair in rest frame
  - $S(\vec{r}^*)$ - source emission function
  - $\Psi(\vec{k}^*, \vec{r}^*)$ - pair wave function
- $C(k^*)$ for $\mathbf{D^0}$-**K**
  - ⇒ No significant correlations
  - ⇒ Consistent with theoretical model predictions ($R \geq 5$ fm)



NLO+HMChPT: Phys. Rev. D 108, 014020 (2023)

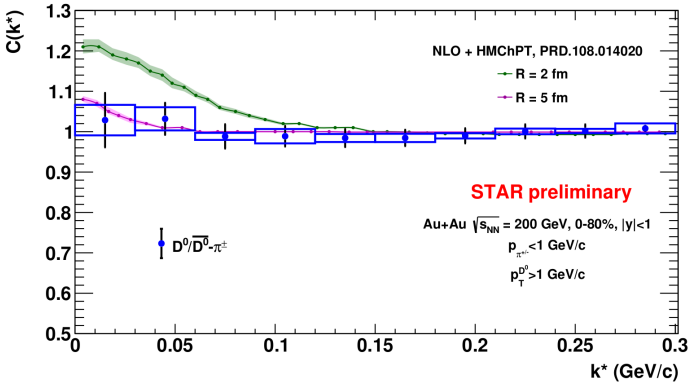
D^0-π femtoscopic correlations in Au+Au @ 200 GeV

PRELIMINARY

- Correlation function

$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 \mathrm{d}^3 r^*$$

  - $\vec{k}^*$ - reduced momentum difference of pair in rest frame
  - $S(\vec{r}^*)$ - source emission function
  - $\Psi(\vec{k}^*, \vec{r}^*)$ - pair wave function
- $C(k^*)$ for $\mathbf{D^0}$-$\boldsymbol{\pi}$
  - ⇒ No significant correlations
  - ⇒ Consistent with theoretical model predictions ($R \geq 5$ fm)



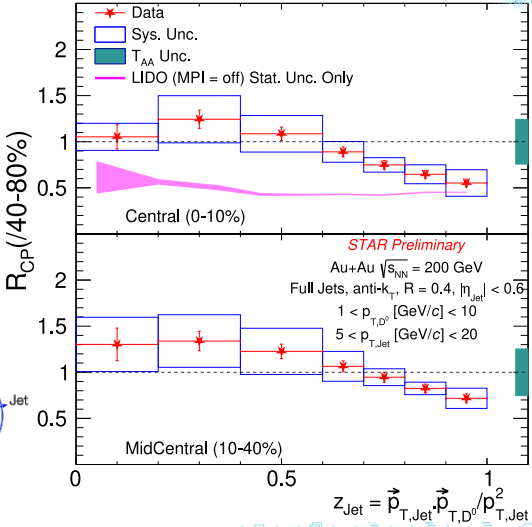
NLO+HMChPT: Phys. Rev. D 108, 014020 (2023)

D^0-jet fragmentation function in Au+Au @ 200 GeV

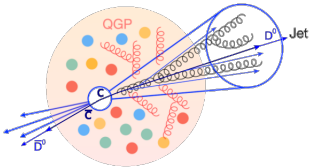
PRELIMINARY

$$z_{\text{Jet}} = \frac{\vec{p}_{\text{T,Jet}} \cdot \vec{p}_{\text{T,D}^0}}{|\vec{p}_{\text{T,Jet}}|^2}$$

- z_{Jet} related to fragmentation function in DGLAP equation
- Hard fragmented D^0-jet yield suppressed in central/midcentral events
- Soft fragmented D^0-jet yield ratio consistent with 1 in central/midcentral events
- LIDO agrees well with yield in peripheral events, slightly underpredicts yield in central events



LIDO, Phys. Rev. C 98, 064901

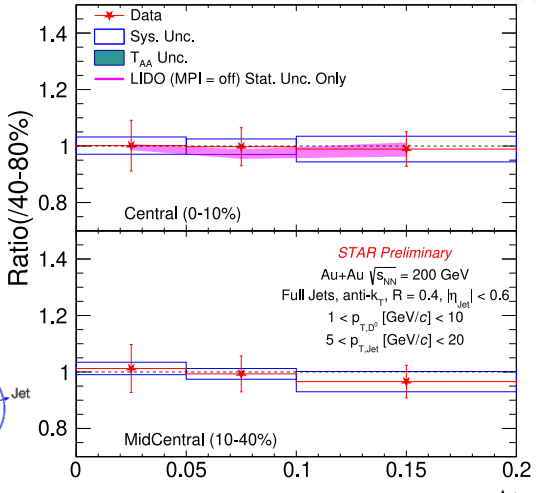


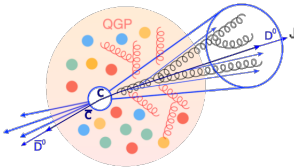
D^0-jet radial profile in Au+Au @ 200 GeV

PRELIMINARY

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

- Ratio of radial profiles consistent with 1 → No hint of D^0 radial profile modification at RHIC energies
- LIDO qualitatively explains radial profile trends, along with ratio of radial profile for central and peripheral events

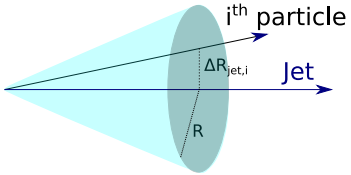




LIDO, Phys. Rev. C 98, 064901

Outlook: D^0-jet angularity modification in central Au+Au @ 200 GeV

- D^0 meson tagged jets (anti-k_T, $R = 0.4$)



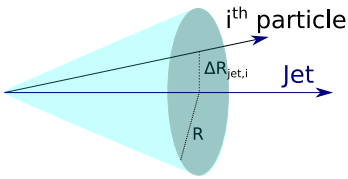
- Generalized angularities

$$\lambda_\alpha^\kappa = \sum_{i \in \text{Jet}} \overbrace{\left(\frac{p_{T,i}}{p_{T,\text{Jet}}}\right)^\kappa}^{\text{soft/hard}} \overbrace{\left(\frac{\Delta R_{\text{Jet},i}}{R}\right)^\alpha}^{\text{collinearity sensitive}}$$

- IRC safe observable for parameters $\kappa = 1$, $\alpha > 0$.
  It is calculable from pQCD
- Study of **modification generalized angularities in HI collisions**

Outlook: D^0-jet angularity modification in central Au+Au @ 200 GeV

- D^0 meson tagged jets (anti-k_T, $R = 0.4$)



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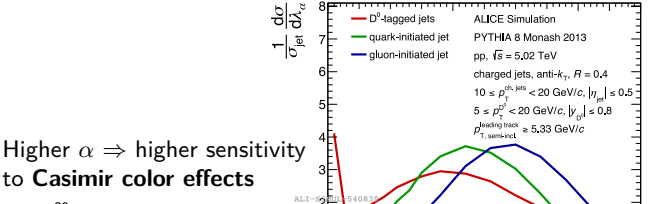
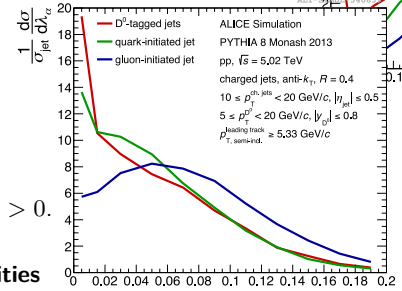


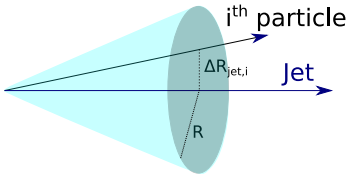
- Higher $\alpha \Rightarrow$ higher sensitivity to **Casimir color effects**



- Lower $\alpha \Rightarrow$ higher sensitivity to **mass effects**

Outlook: D^0-jet angularity modification in central Au+Au @ 200 GeV

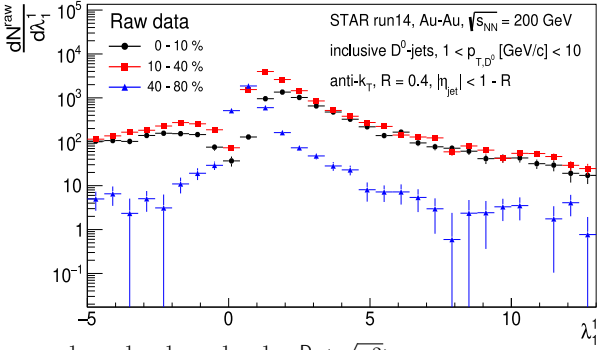
- D^0 meson tagged jets (anti-k_T, $R = 0.4$)



- Generalized angularities

$$\lambda_\alpha^\kappa = \sum_{i \in \text{Jet}} \overbrace{\left(\frac{p_{T,i}}{p_{T,\text{Jet}}}\right)^\kappa}^{\text{soft/hard}} \overbrace{\left(\frac{\Delta R_{\text{Jet},i}}{R}\right)^\alpha}^{\text{collinearity sensitive}}$$

- IRC safe observable for parameters $\kappa = 1$, $\alpha > 0$. It is calculable from pQCD
- Study of **modification generalized angularities in HI collisions**



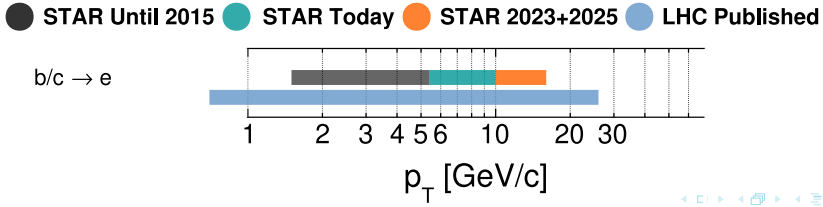
- $\lambda^1_{0.5}$, λ^1_1, $\lambda^1_{1.5}$, λ^1_2, λ^1_3, p_T^D $(\sqrt{\lambda^2_0})$
- $0 \leq \lambda^1_1 \leq 1$
- Unphysical results caused by background subtraction $\rightarrow$ **2D unfolding based on Pythia simulation needed**

STAR Heavy Flavor program for Runs 23-25

- Detector upgrades:
  - EPD: Event Plane Detector (2018)
  - iTPC: inner Time Projection Chamber (2019)
  - eTOF: endcap Time-Of-Flight (2019)
  - FTS: Forward Tracking System (2022)
  - FCS: Forward Calorimeter System (2022)
- Proposed Run-23 - Run-25:

$\sqrt{s_{\mathrm{NN}}}$ [GeV]	Species	Sampled Luminosity	Year
200	Au+Au & p+Au	AuAu 32.7 nb^{-1} pAu 0.69 pb^{-1}	2023+2025
200	p+p	142 pb^{-1}	2024

- Potential enhancement at high p_{T} for the STAR results:



Summary

HFE in p+p:

- Precision improvement at $p_{\mathrm{T}} > 6$ GeV/c
- Precise reference for R_{AA} measurements

HFE in Au+Au:

- Significant energy loss of HQ in QGP
- Improvement of precision for $p_{\mathrm{T}} > 6$ GeV/c
- Mass ordering of c and b quark energy loss

Elliptic flow:

- 54.4 GeV: significant v_2 of e^{HF}
- 27 GeV: v_2 consistent with 0

D^0-hadron femtoscopic correlations:

- No significant correlations for D-K, D-π, and D-p pairs
- Consistent with theoretical model predictions ($R \geq 5$ fm)

D^0 R_{AA} in isobar collisions:

- Suppression in central collisions at $p_{\mathrm{T}} > 3$ GeV/c
- Similar suppression in isobar and Au+Au collisions

D^0-jet fragmentation function and radial profile:

- Hard fragmented D^0-jet yield suppressed in central/midcentral events
- No hint of D^0 radial profile modification at RHIC energies

Outlook:

D^0-jet generalized angularities:

- Study of modification generalized angularities in HI collisions

High statistics p+p and Au+Au datasets from years 2023-2025

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