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Data-driven isolation for charm and beauty decay electrons at RHIC and LHC

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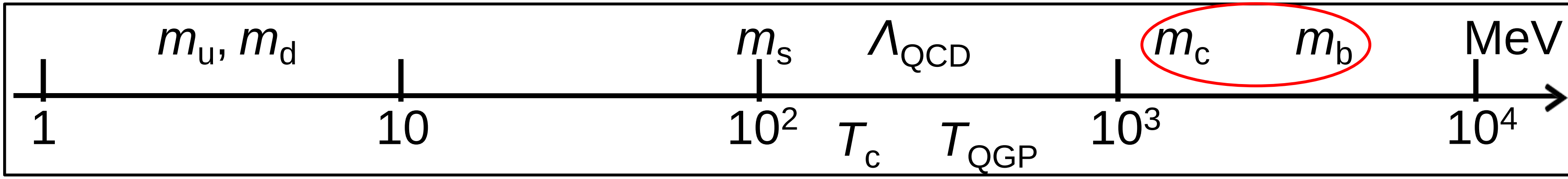
Results: *Phys.Lett.B* 805, 135465

arXiv 2110.08769v2

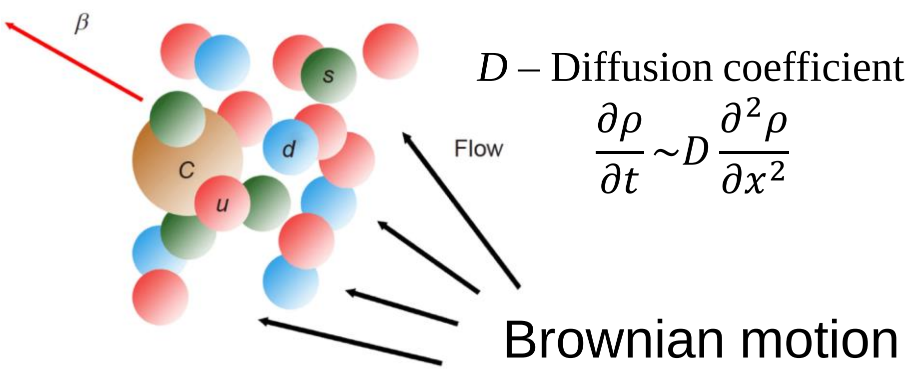
Outline

- Introduction
- Data-driven method
  - Semileptonic decay simulation
  - Beauty contribution extraction
- Results of c/b→e
  - Nuclear modification factor R_{AA}
  - Elliptic flow v_2
- Summary

Heavy quarks: charm & beauty

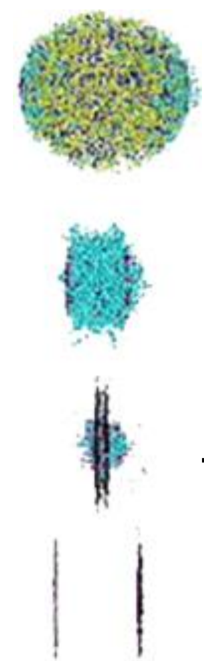


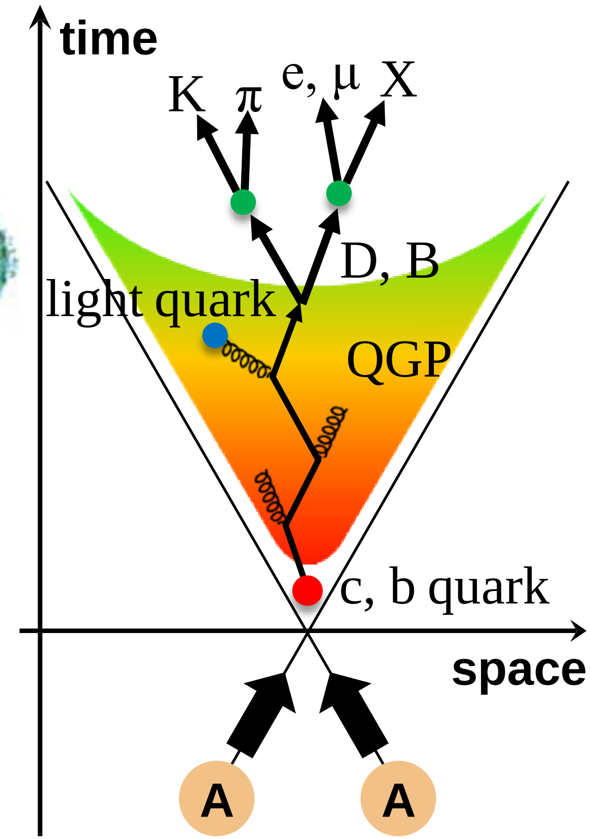
- Produced early in HIC
  - Calculable by pQCD
  - Numbers are conserved
- Experience full time evolution
  - Sensitive to properties of QGP
  - Energy loss, transport …



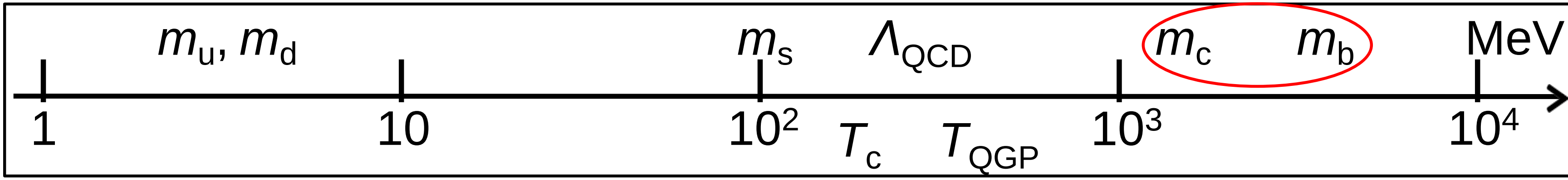
D – Diffusion coefficient

$$\frac{\partial \rho}{\partial t} \sim D \frac{\partial^2 \rho}{\partial x^2}$$





Heavy quarks: charm & beauty



- Produced early in HIC
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  - Numbers are conserved
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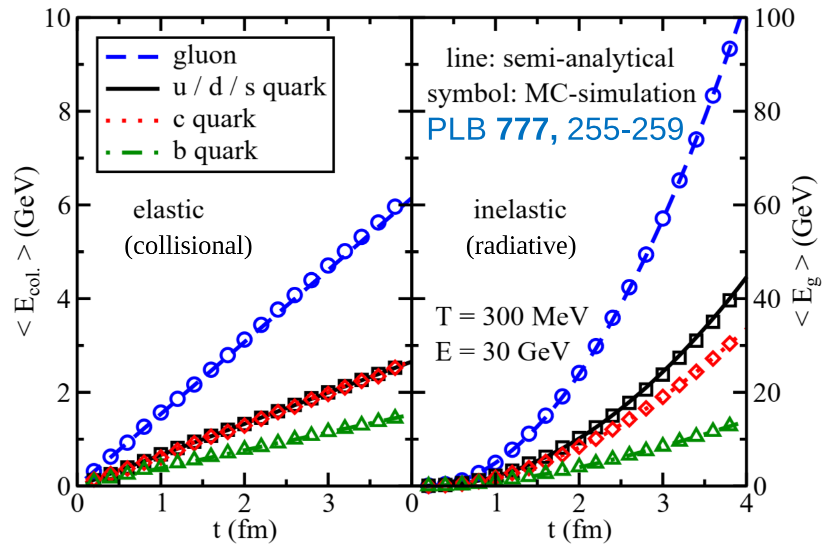
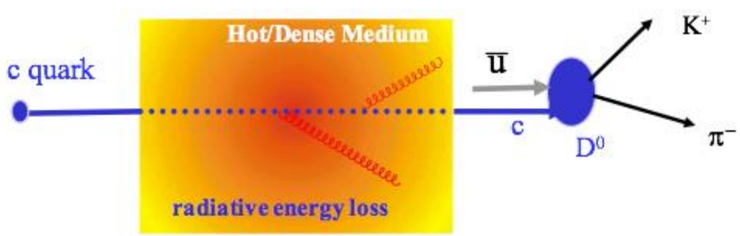
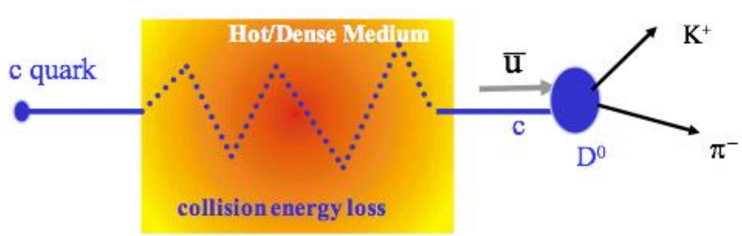
  - Energy loss, transport …
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$



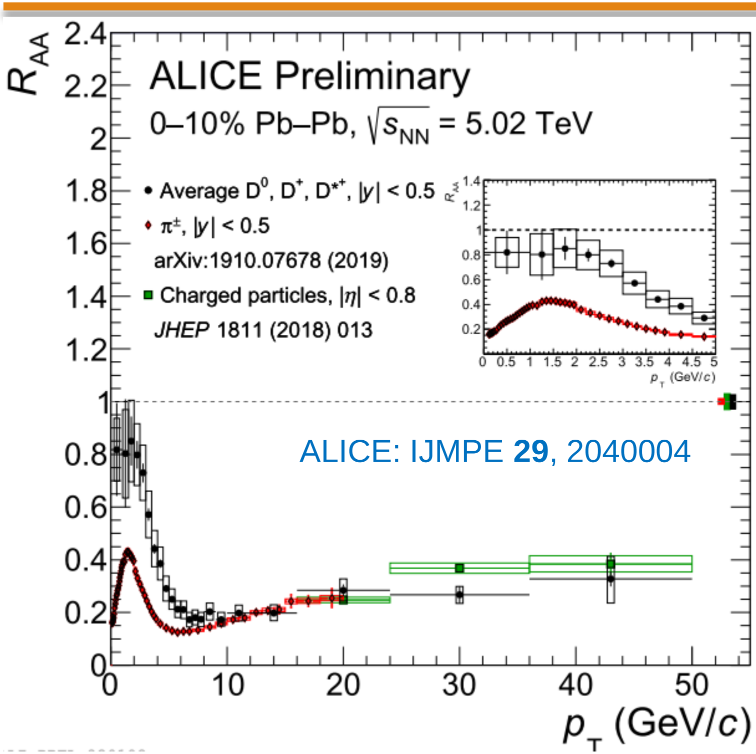


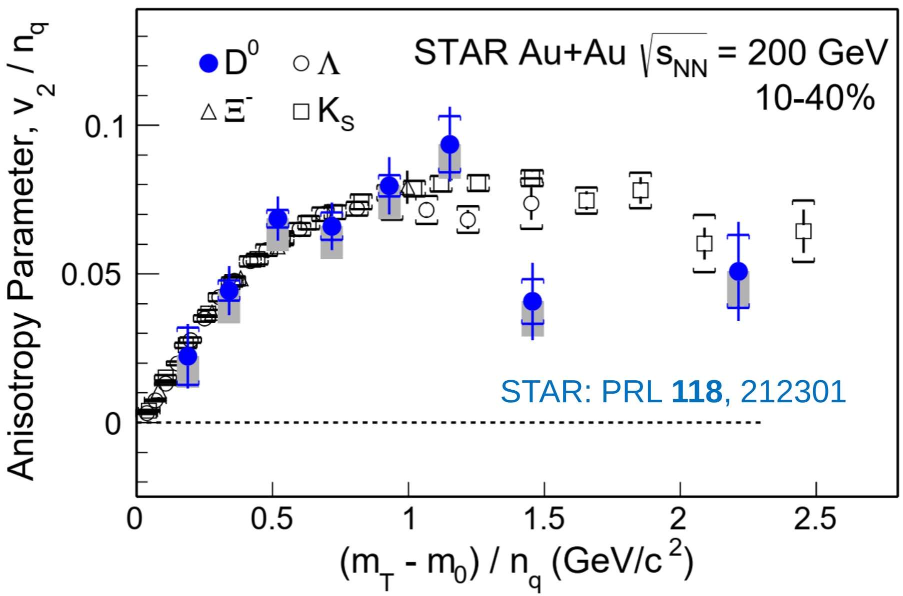
(Baier *et al*, Kharzeev *et al*, Djordjevic *et al*, Wiedemann *et al.*)



(Teaney *et al*, Rapp *et al*, Molnar *et al*, Gossiaux *et al.*)

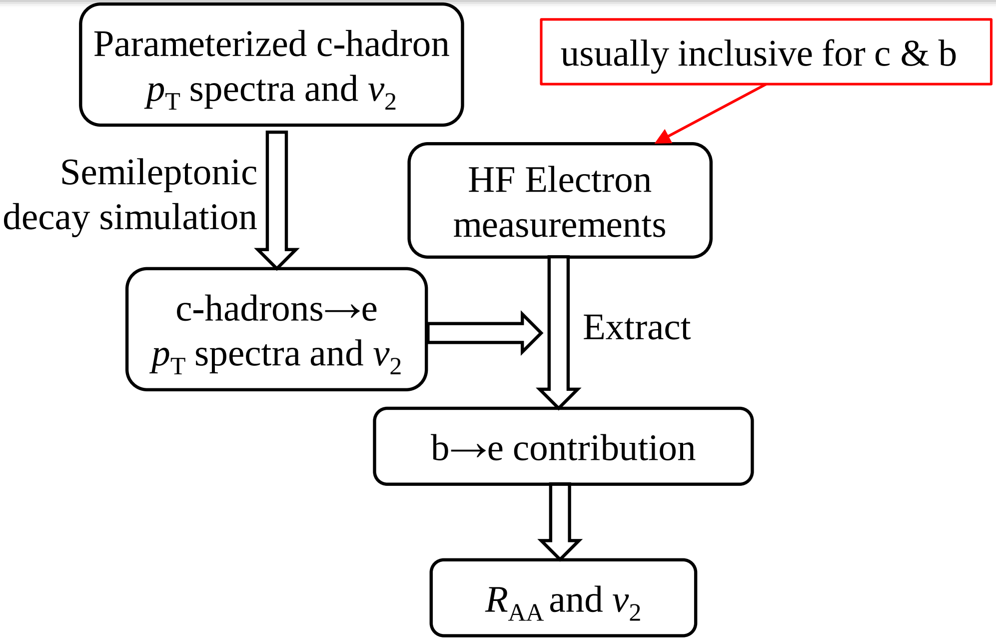
Heavy flavor in sQGP

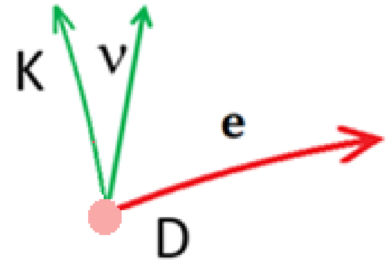




- Charm is as ordinary as light quarks!
  - Similar suppression of R_{AA}
  - Number-of-constituent-quark (NCQ) scaling v_2
- $m_b > 3m_c$: Different properties of beauty in the medium?
  - Lower production of b → more difficult to reconstruct b-hadrons
  - Smaller B.R. of hadron decay channel ↑

Data-driven method

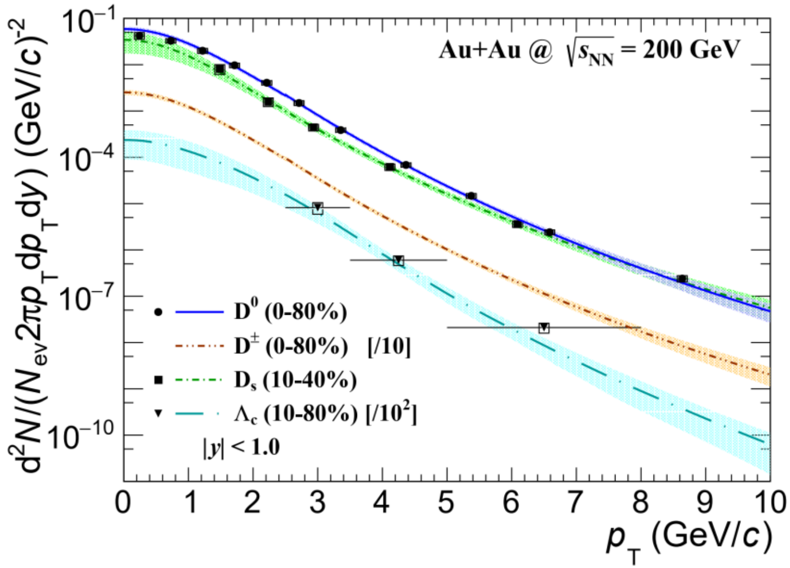


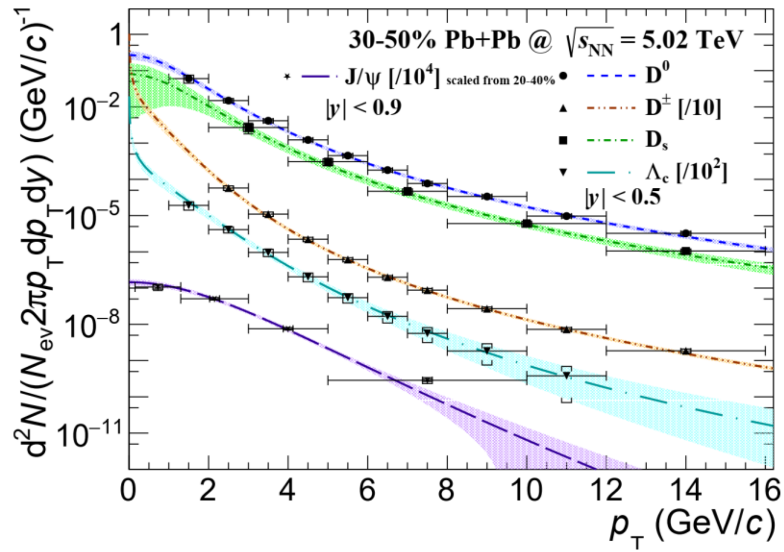


PTEP **2020**, 083C01

Open charm hadron	$c\tau$ (μm)	Mass (MeV/c^2)	Branching ratio (→eX)
$D^0(\overline{D}^0)$ ($c\bar{u}$, $\bar{c}u$)	122.9	1864.83 ±0.05	(6.49 ±0.11) %
$D^\pm$ ($c\bar{d}$, $\bar{c}d$)	311.8	1869.65 ±0.05	(16.07 ±0.30) %
$D_s^\pm$ ($c\bar{s}$, $\bar{c}s$)	151.2	1968.34 ±0.07	(6.5 ±0.4) %
$\Lambda_c^\pm$ (udc, $\bar{u}\bar{d}\bar{c}$)	60.7	2286.46 ±0.14	(3.95 ±0.35) %

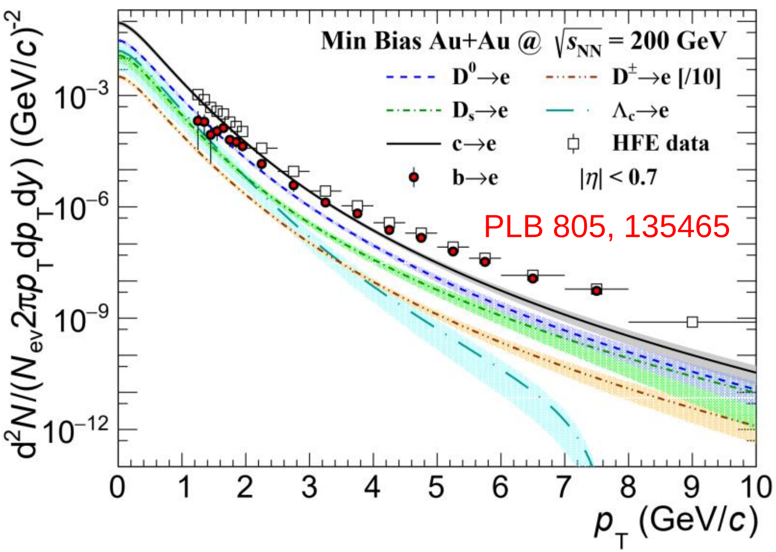
c-hadron spectra

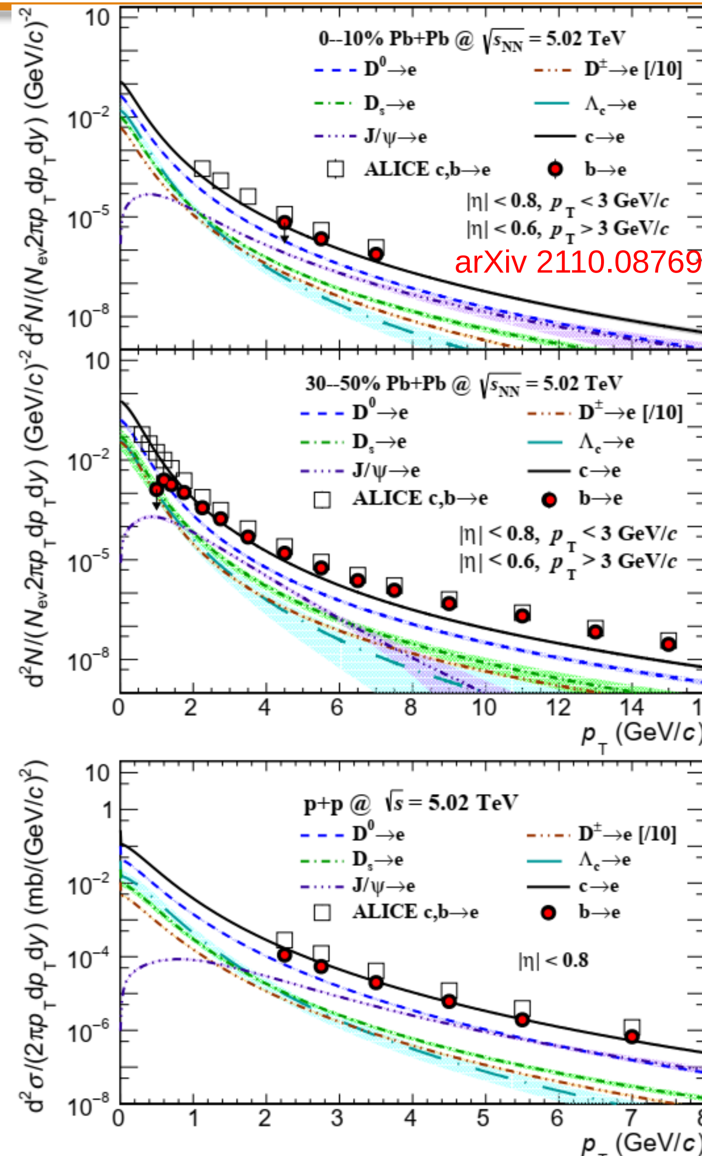




Measurement	200 GeV Au+Au		5.02 TeV Pb+Pb		5.02 TeV p+p
	Centrality	Reference (STAR)	Centrality	Reference (ALICE)	Reference (ALICE)
D^0	0-80%	PRC 99, 034908	0-10% & 30-50%	JHEP 2018, 174	JHEP 05, 220
$D^\pm$	0-10%	NPA 967, 620-623			
D_s	10-40%				
Λ_c/D^0	10-80%	PRL 124, 172301		JPCS 1602, 012031	arXiv:2011.06078
J/ψ	/	/	0-20% & 20-40%	PLB 805, 135434	JHEP 05 (2021) 220

c-hadron decay electrons

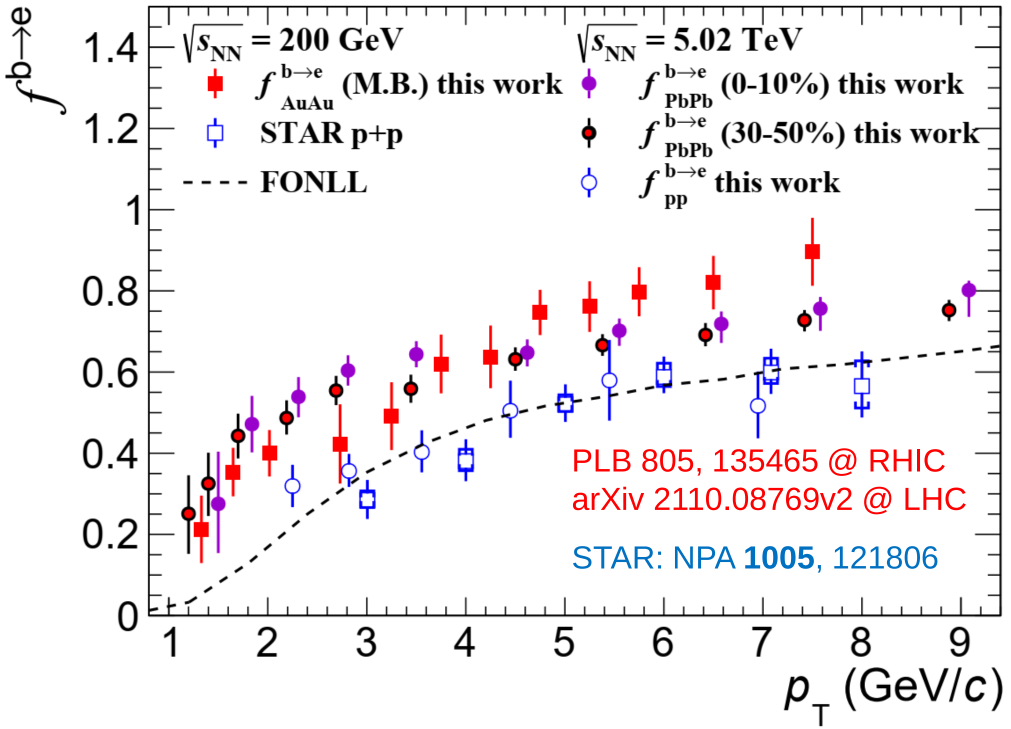




- Semileptonic decay simulations
  ↳output electron spectra
  - Norm. by cross sect., B.R. & N_{bin}

- $b \to e$ = HFE − $c \to e$
- $c \to e = D^0 \to e + D^\pm \to e + D_s \to e$
- $+ \Lambda_c \to e$ (+ $J/\psi \to e$ @ LHC)

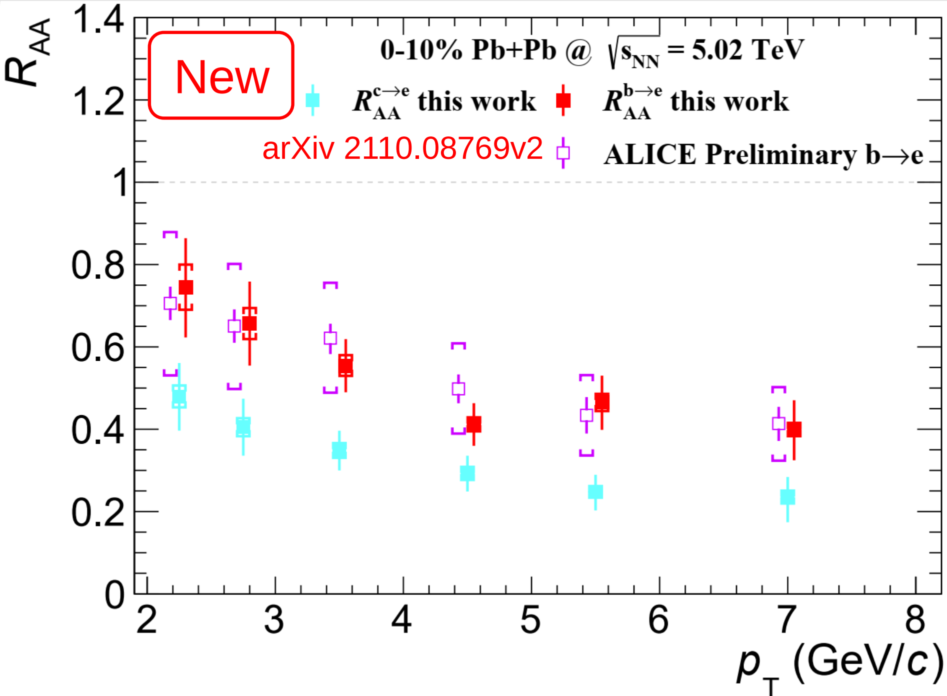
Beauty contribution



- $f^{\,b\to e}$ = b→e/HFE
- J/ψ→e in ALICE HFE

- Consistent $f_{pp}^{b\to e}$ at LHC and RHIC energies
  - Reference for HIC
- Slightly higher $f_{PbPb}^{b\to e}$ in 0-10% than in 30-50%
- Clearly higher $f_{AA}^{b\to e}$ than $f_{pp}^{b\to e}$

R_{AA} isolation



ALICE Preliminary:
D. Thomas's Talk @ QM2019

- $R_{AA}^{b\to e} = \frac{f_{AA}^{b\to e}}{f_{pp}^{b\to e}} R_{AA}^{HFE}$
- $R_{AA}^{c\to e} = \frac{1-f_{AA}^{b\to e}}{1-f_{pp}^{b\to e}} R_{AA}^{HFE}$

- Both $R_{AA}^{b\to e}$ in 0-10% & 30-50% consistent with ALICE
- Stronger suppression of charm than beauty
  - Agreement with mass-dependent energy loss: $\Delta E_c > \Delta E_b$
- Centrality dependence is not very clear

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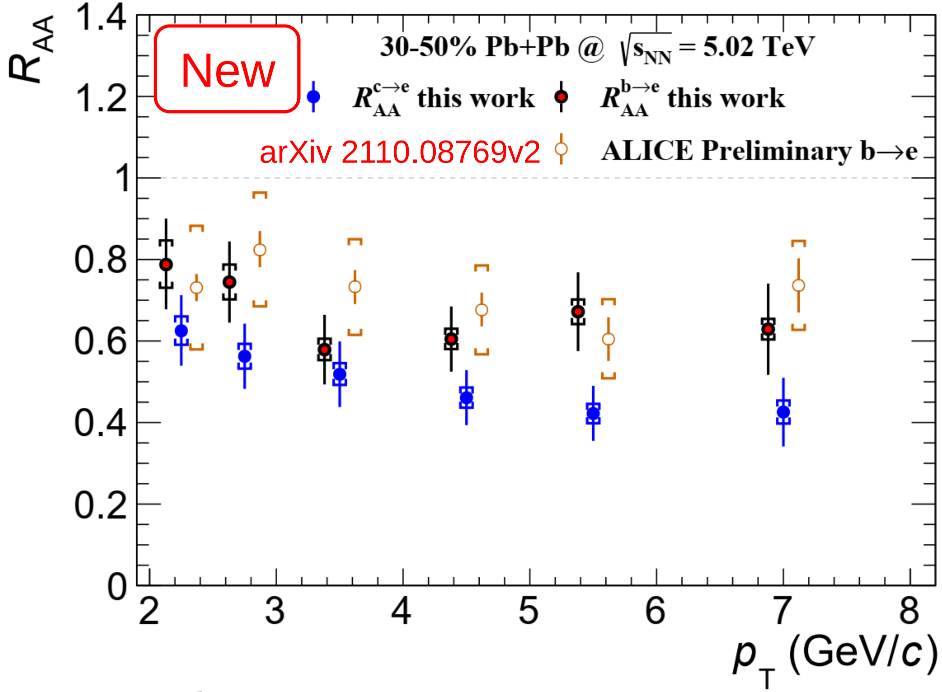

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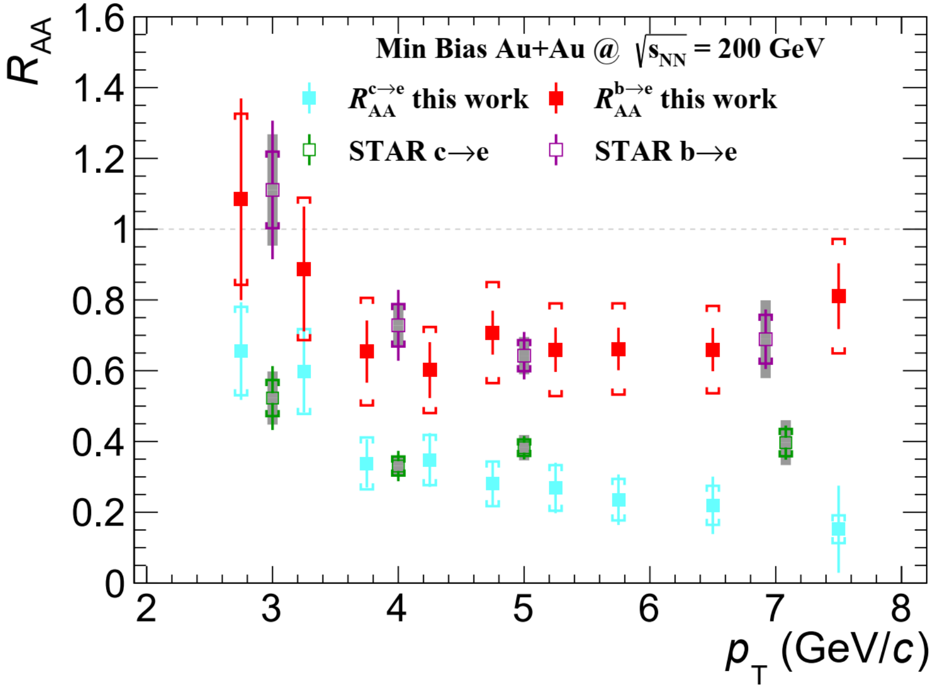

STAR: NPA **1005**, 121806

PLB 805, 135465 @ RHIC

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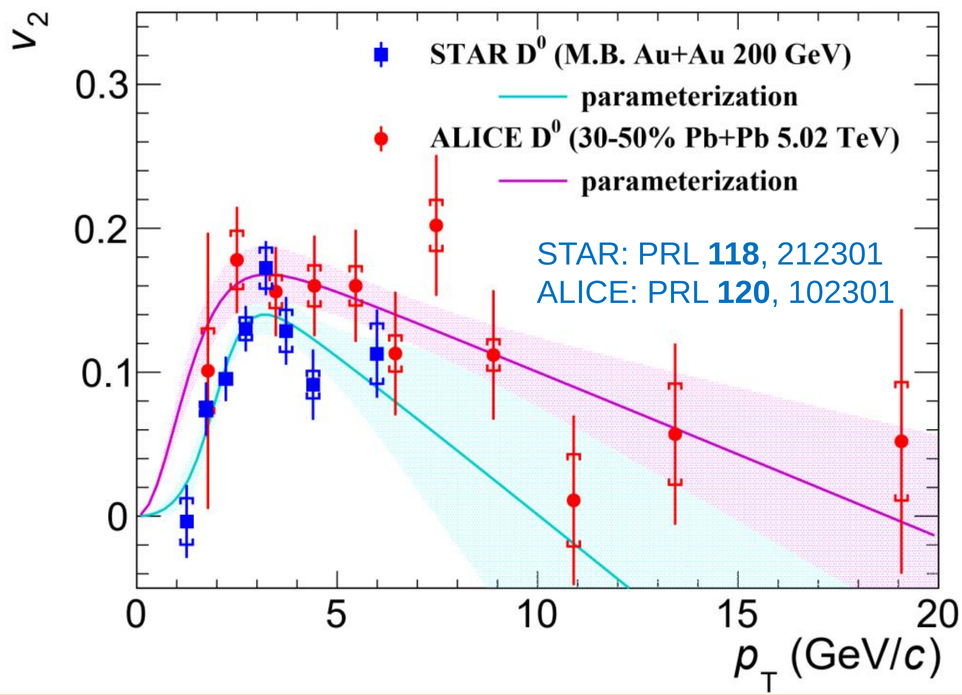
- $R_{AA}^{b\to e}$ is consistent with STAR and ALICE
  - Similar beauty energy loss at RHIC and LHC energies

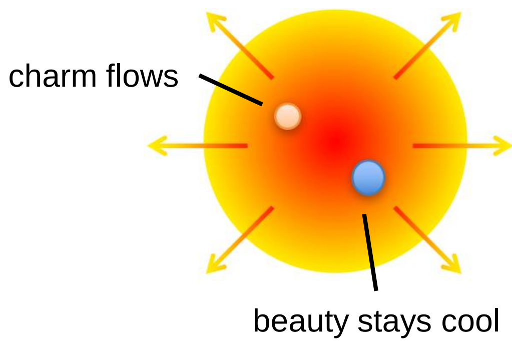
c-hadron and c/b→e v_2

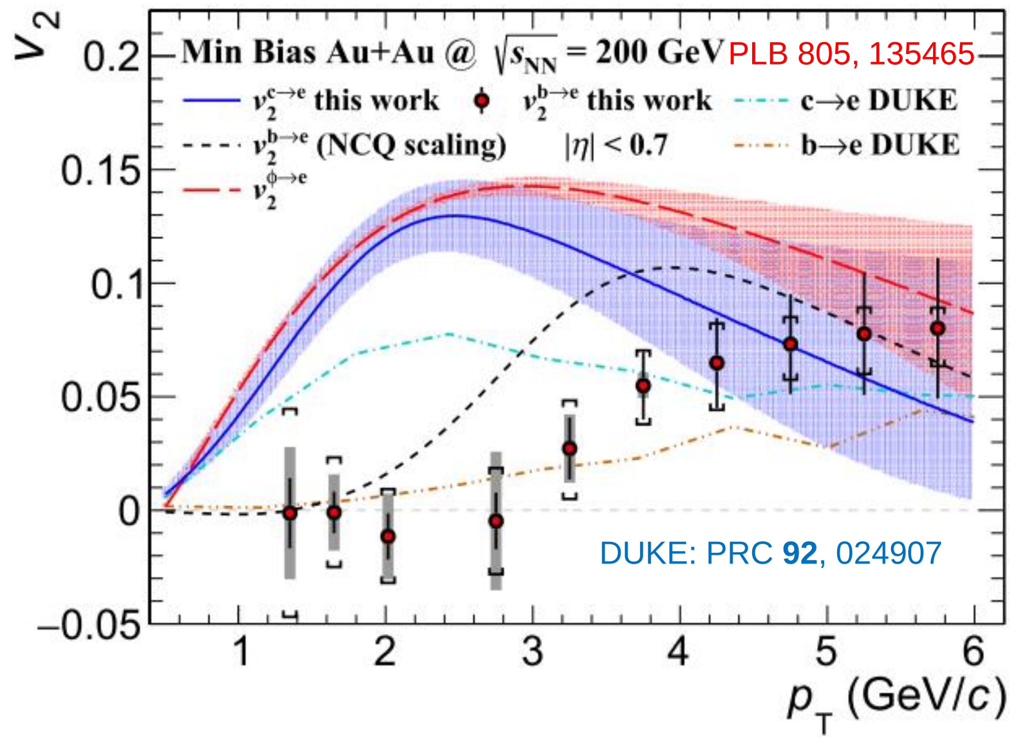
- $\frac{v_2}{n} = \frac{p_0}{1+\exp\left(\left(p_1 - \frac{m_T - m_0}{n}\right)/p_2\right)} - \frac{p_0}{1+\exp\left(\frac{p_1}{p_2}\right)} + p_3 \frac{m_T - m_0}{n}$
  - $m_T = \sqrt{p_T^2 + m_0^2}$, n = # constituent quarks
  - Invariance of v_2/n as a function of $(m_T - m_0)/n$ (NCQ scaling)
- D meson v_2
- Λ_c v_2: assumed following NCQ scaling



- Simileptonic decay simulation
  - φ sample: $\frac{dN}{d\varphi} = 1+2v_2\cos(2\varphi)$
- $v_2^{c\to e}$: average of $v_2^{D\to e}$ and $v_2^{\Lambda_c\to e}$ weighted by relative yields
- $v_2^{b\to e} = \frac{v_2^{HFE} - \left(1 - f_{AA}^{b\to e}\right) v_2^{c\to e}}{f_{AA}^{b\to e}}$

v_2 isolation @ RHIC

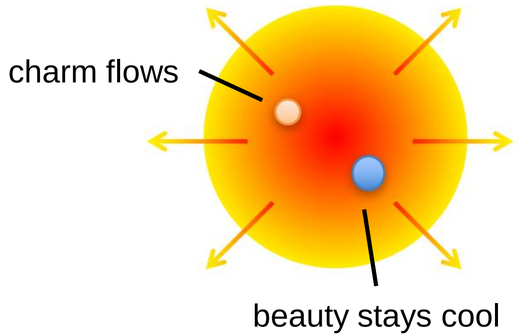


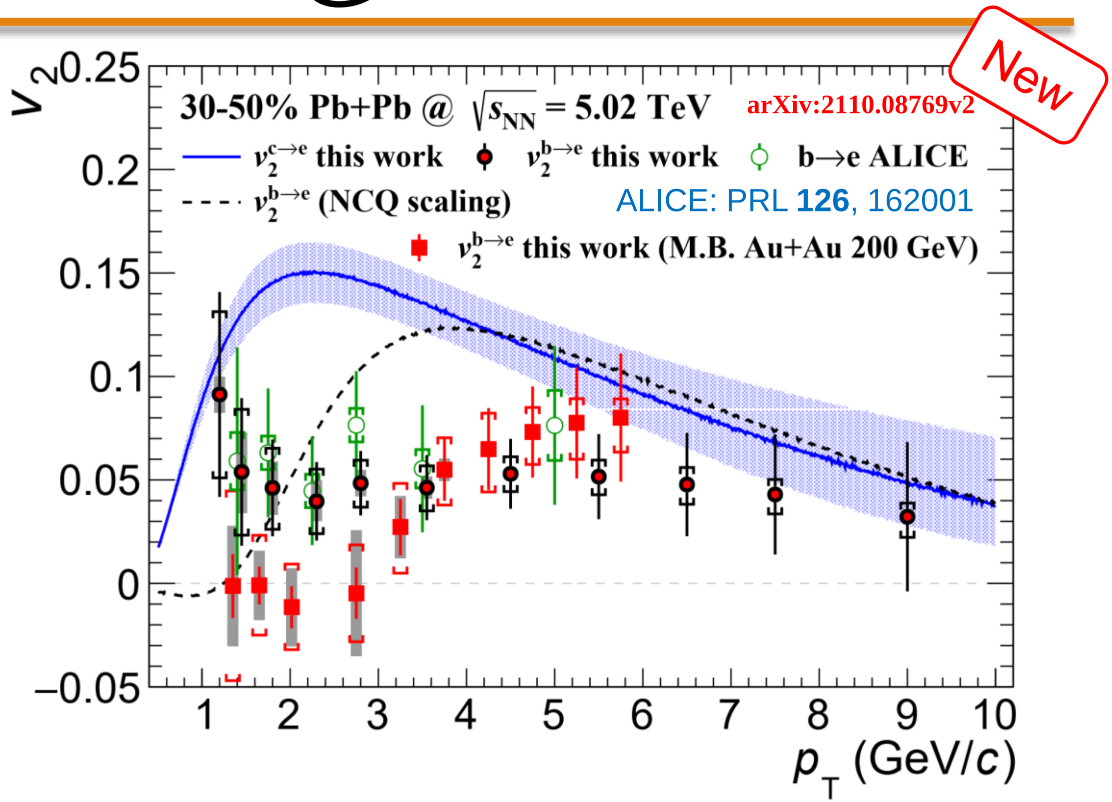


- Charm flows as light quarks at RHIC energy

- First observation of non-zero $v_2^{b\to e}$ @ $p_T > 3$ GeV/c (4-σ, χ^2/ndf =29.7/6)
- Beauty is unlikely thermalized at RHIC (too heavy to be moved)
  - Smaller $v_2^{b\to e}$ than NCQ scaling hypothesis @ $2.5 < p_T < 4.5$ GeV/c (χ^2/ndf =14.3/4)

v_2 isolation @ LHC





- Non-zero $v_2^{b\to e}$ observed
  - Consistent with ALICE
  - Higher than $v_2^{b\to e}$ at RHIC @ $p_T < 3$ GeV/c

- Beauty is still not thermalized at LHC energy
  - Smaller than NCQ scaling @ $2 < p_T < 8$ GeV/c (5.04-σ, χ^2/ndf =37.60/5)

Summary

- Centrality dependence of R_{AA} is not clear at LHC
- Stronger suppression of charm than beauty in HIC
  - Similar at RHIC and LHC energies
  - Consistent with mass-dependent energy loss

- Observation of non-zero $v_2^{b\to e}$ at RHIC ($p_T > 3$ GeV/c) and LHC
- Clear deviation of $v_2^{b\to e}$ from NCQ scaling
  - Beauty is unlikely thermalized at RHIC and LHC

Thank you!

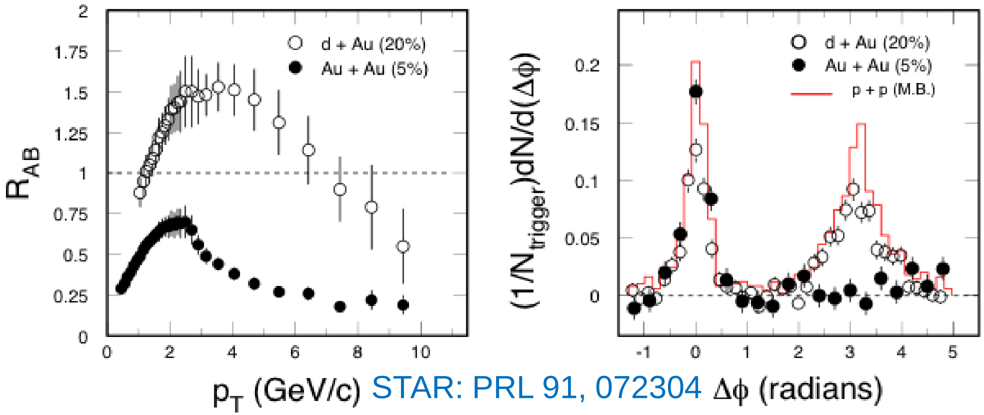
Back up

Light flavor in sQGP

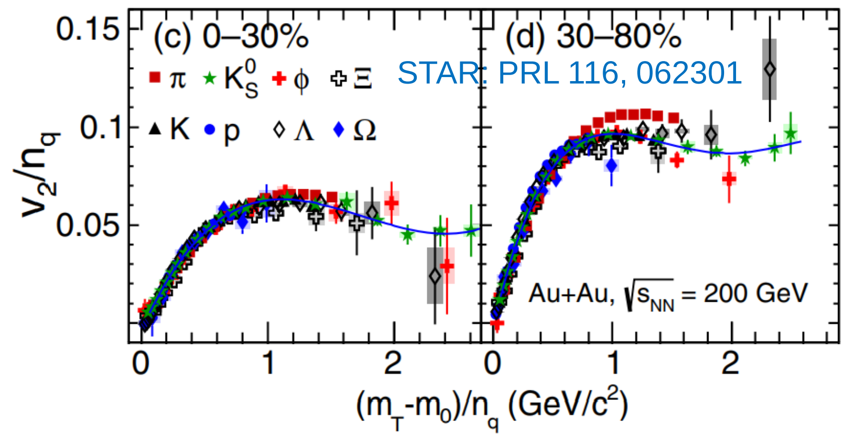
- High p_T
  - Energy loss
    - R_{AA} suppression
  - Jet quenching

$$R_{AA}(p_T) \equiv \frac{1}{\langle N_{bin} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$$v_2 \equiv \langle \cos[2(\varphi - \psi_R)] \rangle$$



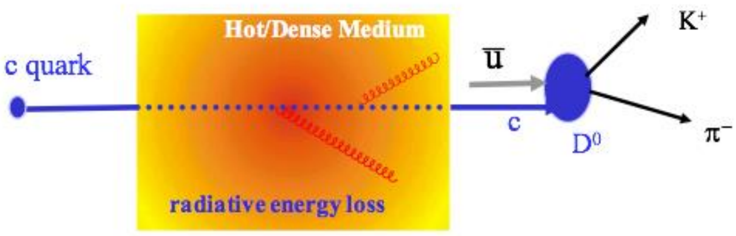
- Low-to-intermediate p_T
  - Partonic collectivity
    - Azimuthal anisotropy
    - Number-of-constituent-quark (NCQ) scaling v_2



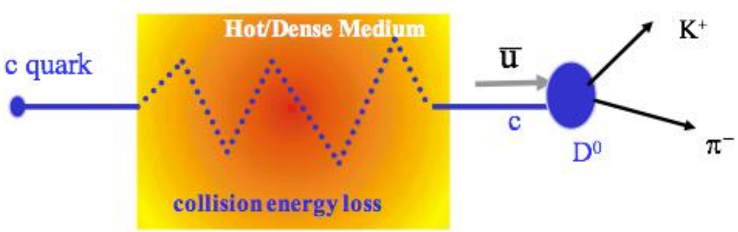
- Strong interaction: light quarks & strongly coupled QGP

QGP dynamics: Energy loss

- Elastic (collisional) and inelastic (radiative) medium effect.
- Theoretical mass-dependent energy loss: $\Delta E_{\mathrm{u,d,s}} > \Delta E_{\mathrm{c}} > \Delta E_{\mathrm{b}}$



(Baier *et al*, Kharzeev *et al*, Djordjevic *et al*, Wiedemann *et al*.)



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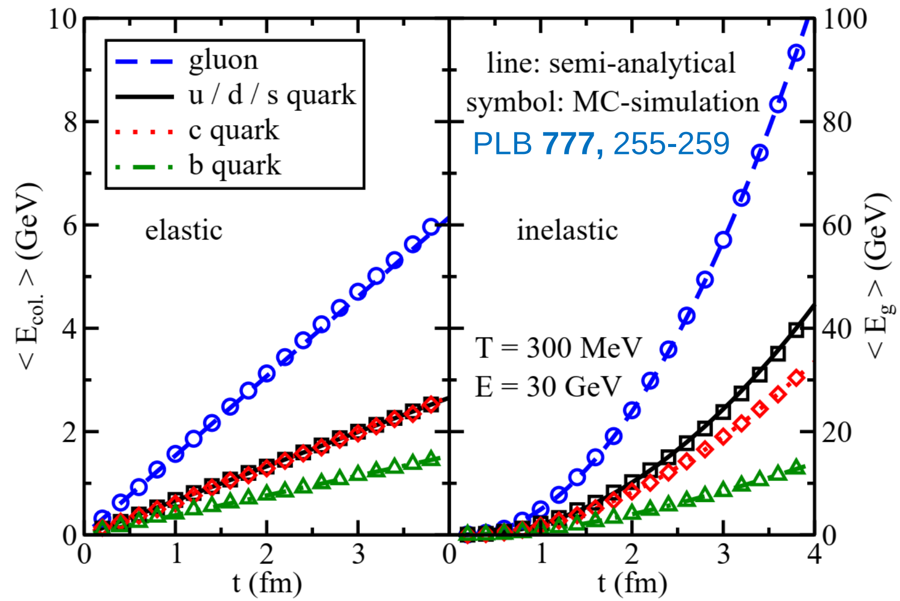
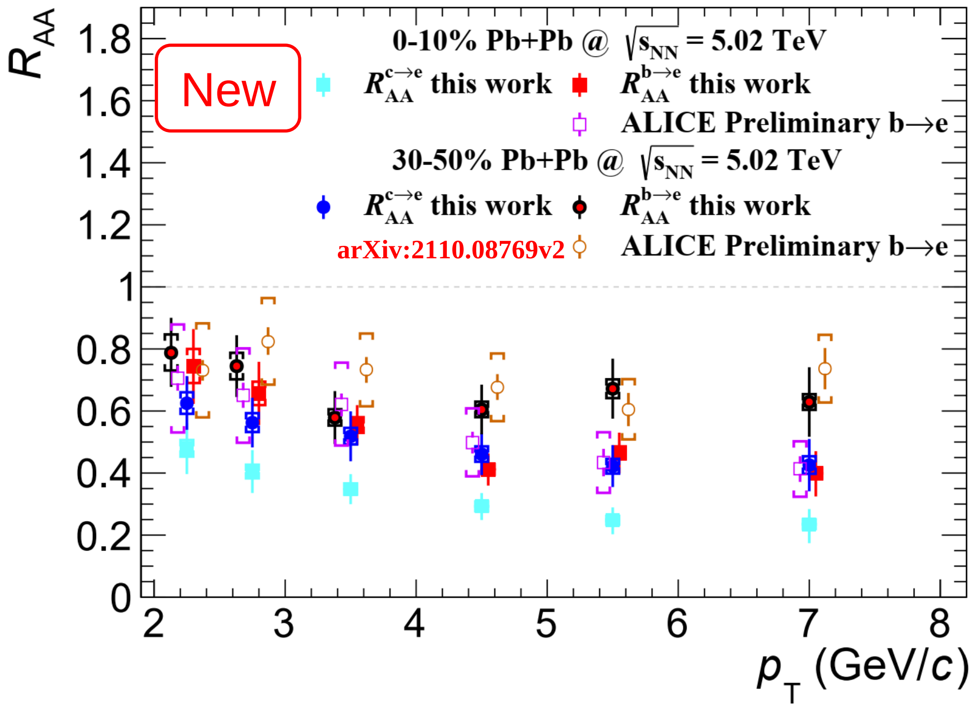


- Nuclear modification factor $R_{\mathrm{AA}}(p_{\mathrm{T}}) \equiv \frac{1}{\langle N_{\mathrm{bin}}\rangle}\frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$
  - Signal for QGP existence and parton energy loss.
  - Energy loss → $R_{\mathrm{AA}} < 1$ at intermediate-to-high p_{T}.

R_{AA} isolation



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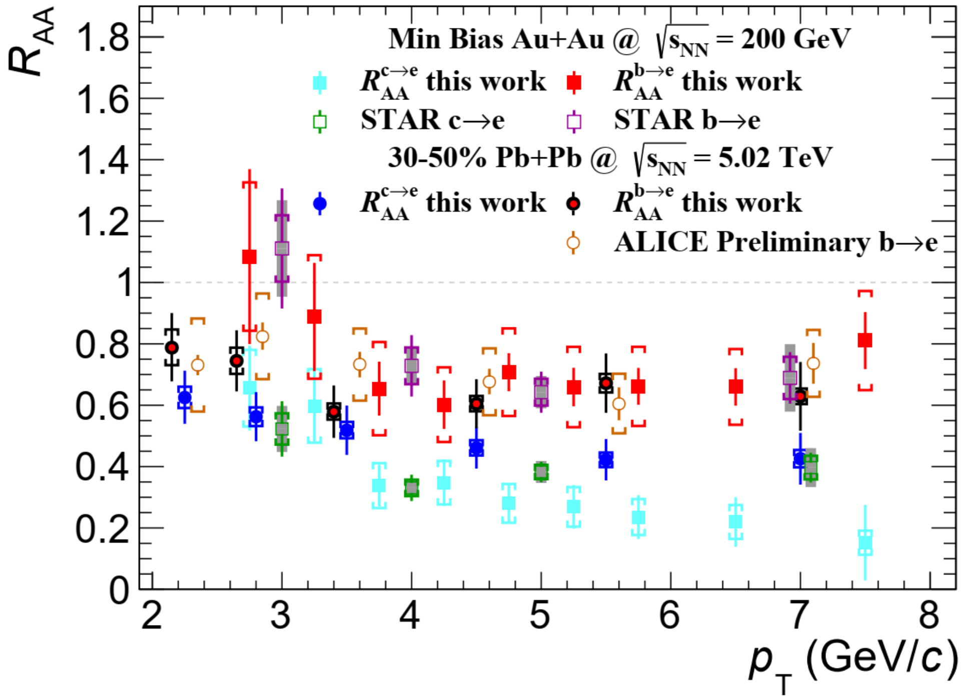

STAR: NPA **1005**, 121806

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PLB 805, 135465 @ RHIC

arXiv 2110.08769v2 @ LHC

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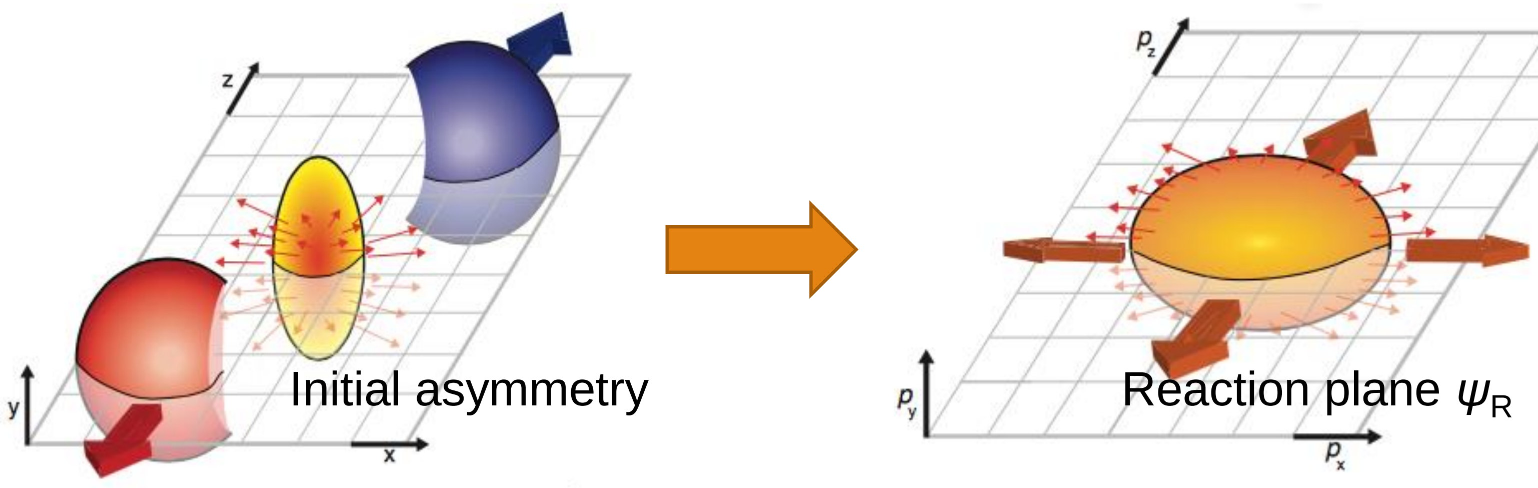
  - Similar beauty energy loss at RHIC and LHC energies

QGP dynamics: Collectivity

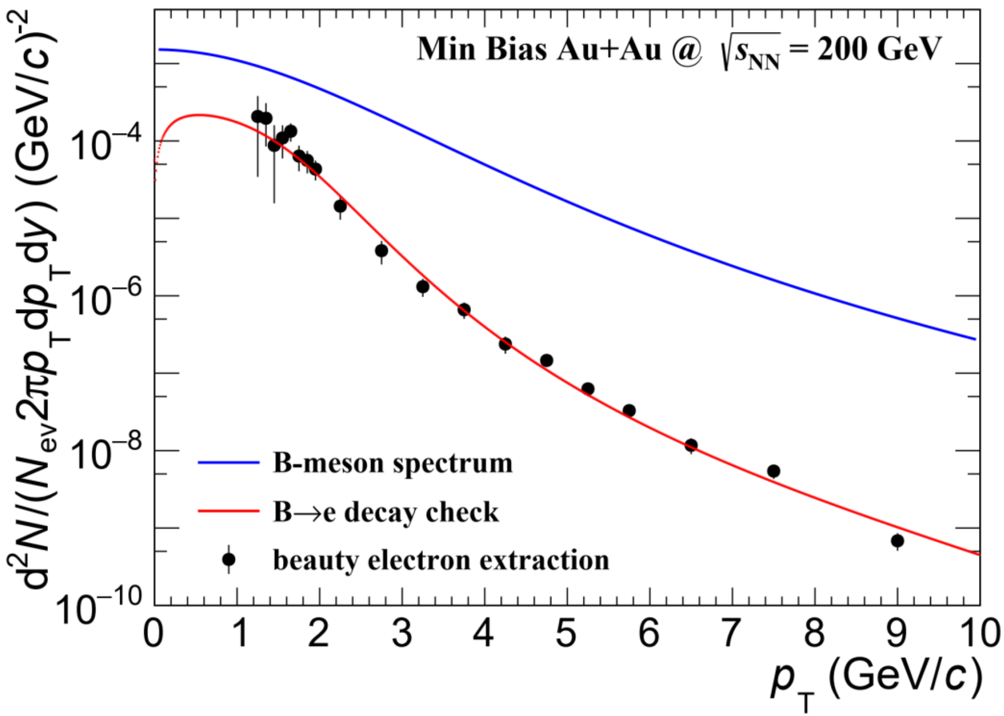
- Initial asymmetry of HIC → Azimuthal anisotropy
- Parton thermalization → Collective flow



- Fourier: $E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{\mathrm{d}^2N}{2\pi p_T \mathrm{d}p_T \mathrm{d}y}\{1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \psi_R)]\}$
- Elliptic flow $v_2 \equiv \langle\cos[2(\varphi - \psi_R)]\rangle$ (2nd coefficient)
  - Description of collective motion and thermalization of partons.
  - Azimuthal anisotropy → $v_2 > 0$ at low-to-intermediate p_T.

B-meson spectrum unfolding

- Assume B-meson spectrum follows Levy function
- Apply iteration
  - Simulate B-meson semileptonic decay and obtain B→e spectrum
  - Change Levy parameters
- Until decay electron spectrum fits b→e data points



HFE v_2 parameterization