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Charm and beauty isolation in heavy flavor electron measurements at RHIC

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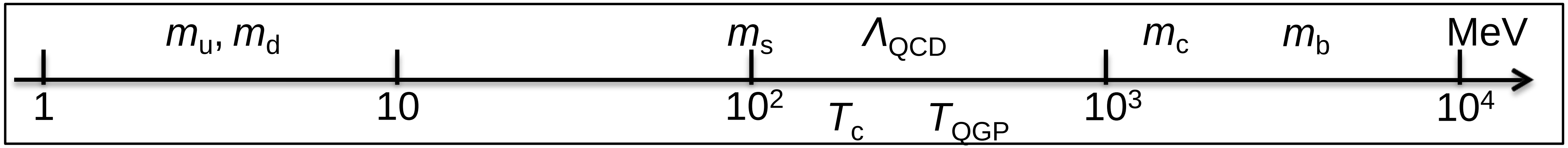
Outline

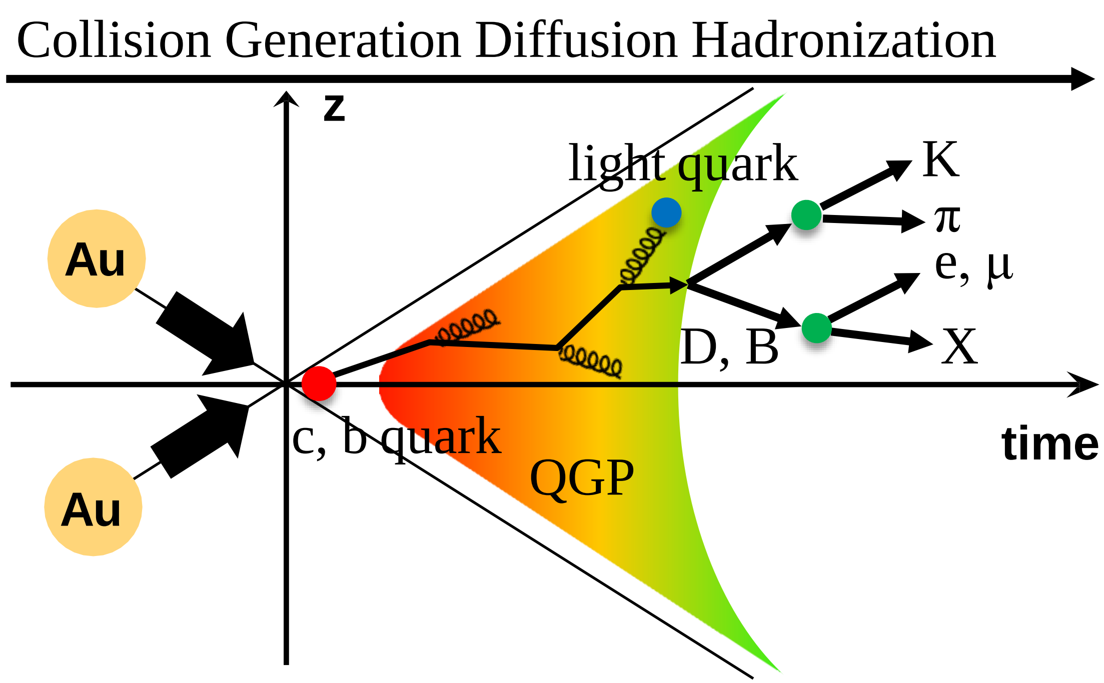
- **Introduction**
- **Method and results**
  - Semileptonic decay simulation
  - Beauty contribution extraction
  - c→e and b→e R_{AA}
  - c→e and b→e v_2
- **Summary and conclusion**

Introduction

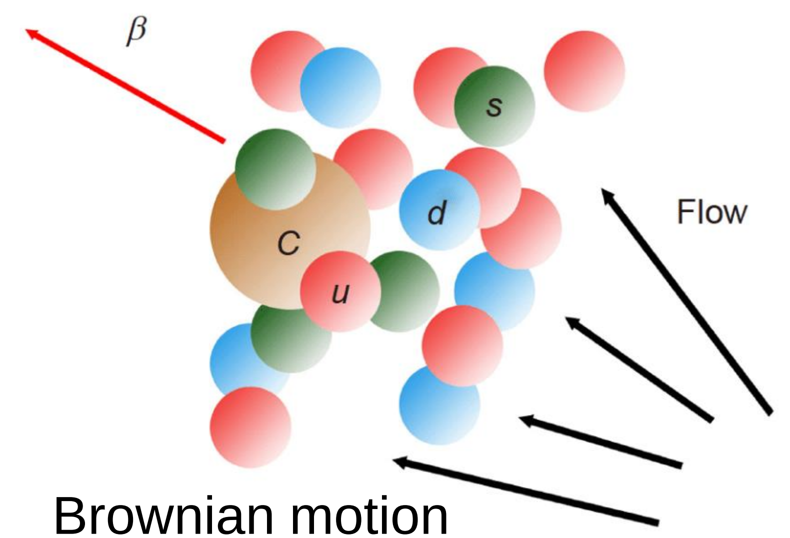


Heavy quarks (charm and beauty):

- Mainly produced in hard scatterings at the early stage of HIC.
- Experience the full time evolution of QGP.
- Production yields can be evaluated by pQCD ($m_{c,\,b} >> \Lambda_{QCD}$).
- Ideal probes for medium properties, diffusion coefficient, etc..

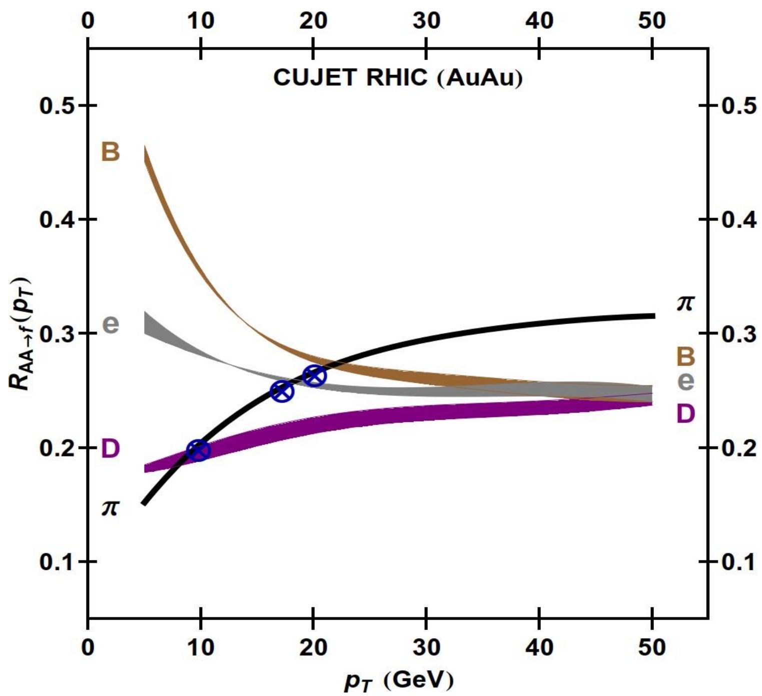


$\frac{\partial \rho}{\partial t} = D\frac{\partial^2 \rho}{\partial x^2}$, D – Diffusion coefficient

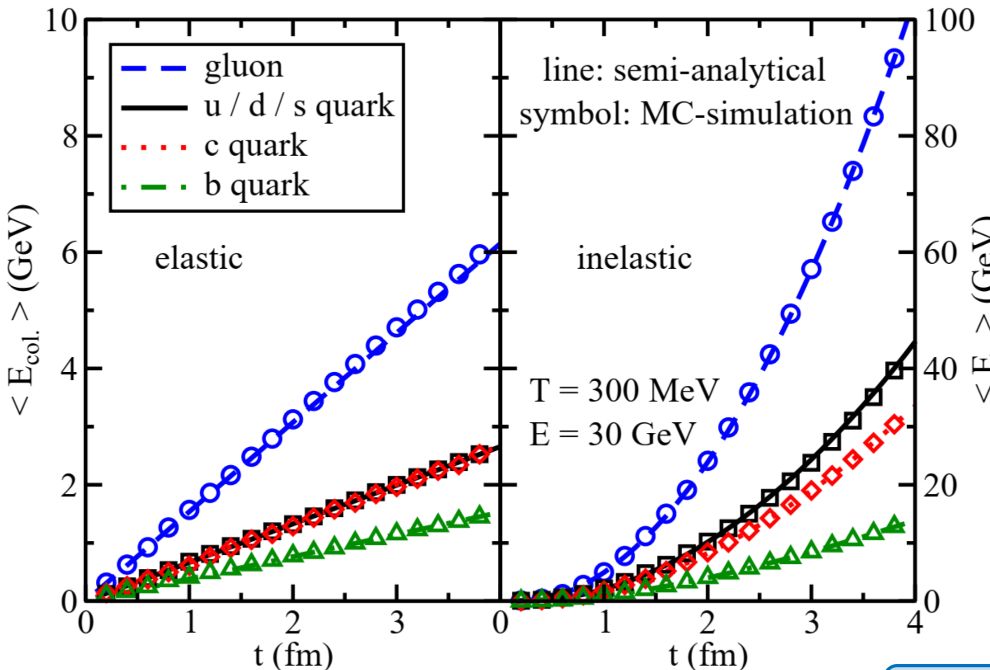


QGP dynamics

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



PRL **108**, 022301 (2012)



PLB **777,** 255-259 (2018)

- Nuclear modification factor $R_{\mathrm{AA}}(p_{\mathrm{T}}) \equiv \dfrac{1}{\langle N_{\mathrm{bin}} \rangle} \dfrac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$

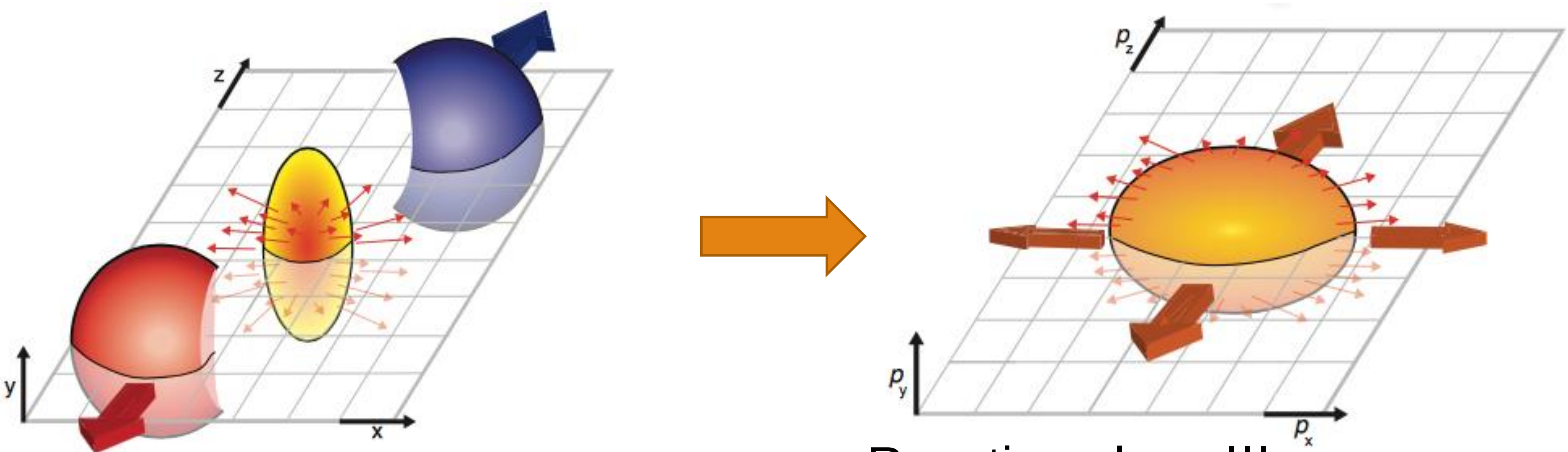
QCD medium

QCD vacuum

  - Signal for the medium existence and parton energy loss.
  - In-medium energy loss suppresses $R_{\mathrm{AA}} < 1$ at moderate-to-high p_{T}.

QGP dynamics

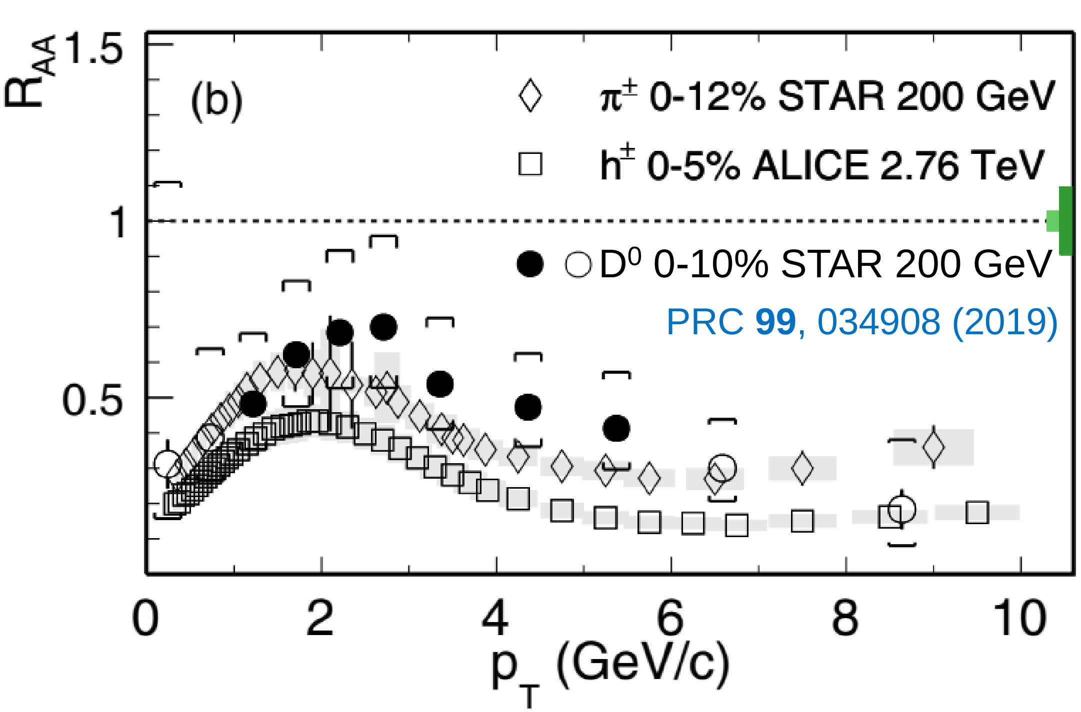
- Flow and thermalization
  - Following collectivity.
  - Azimuthal anisotropy.

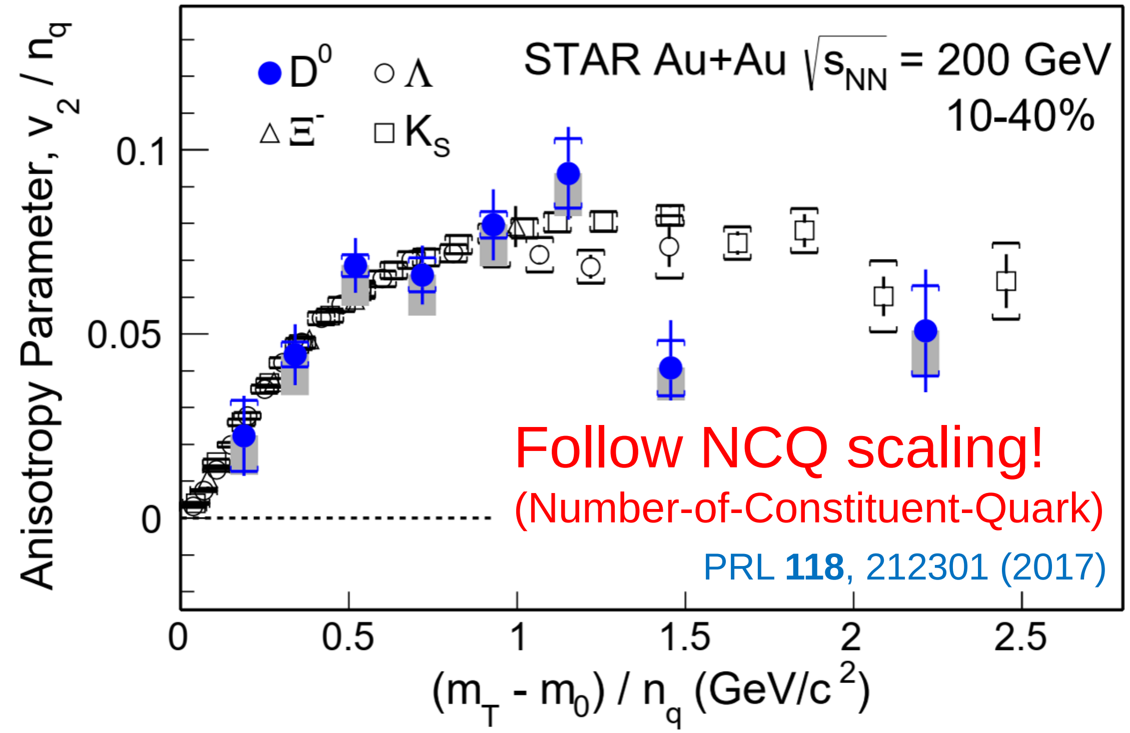


Reaction plane Ψ_R

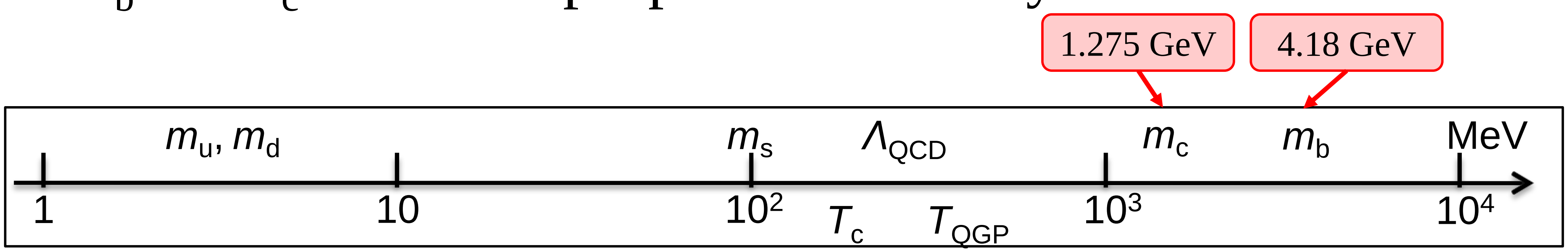
- Elliptic flow $v_2 \equiv \langle \cos[2(\phi - \Psi_\mathrm{R})] \rangle$ (2nd Fourier coefficient)
  - $E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}\{1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_\mathrm{R})]\}$
  - Description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

What about beauty?



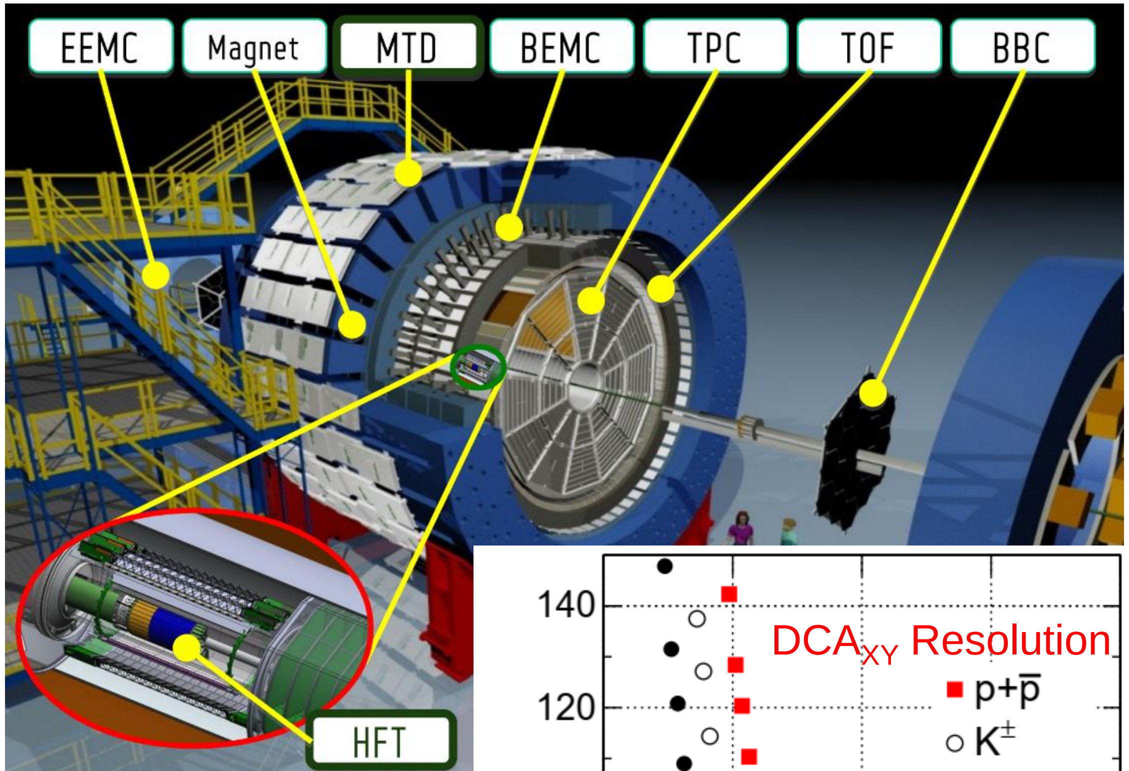


- Comparable R_{AA} and v_2 of light flavor and charmed hadrons.
  - Similar energy loss and thermalization: Charm seems like light quarks.
- $m_b \gtrsim 3m_c$: Different properties of beauty in the medium?



RHIC detectors

STAR Detector

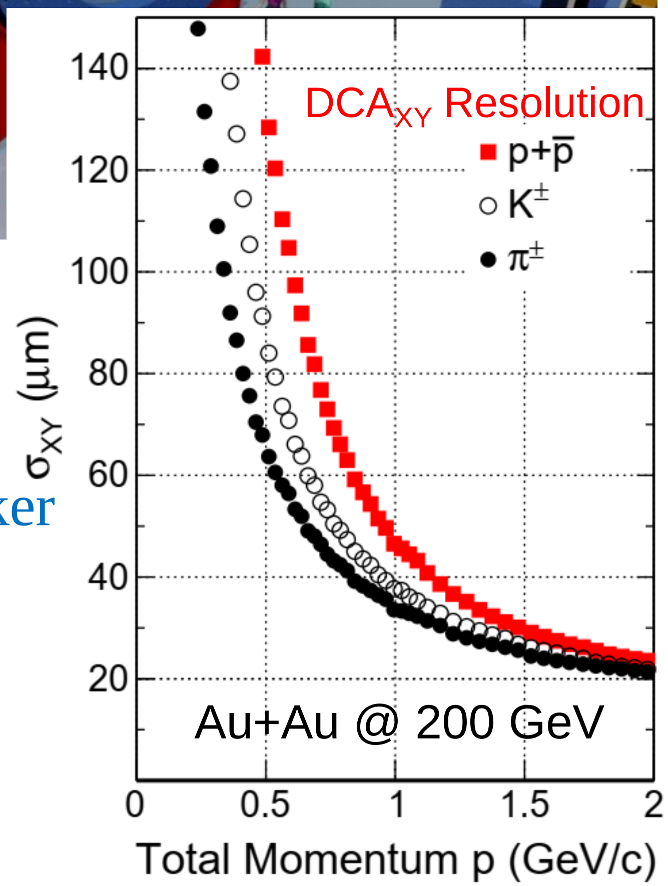


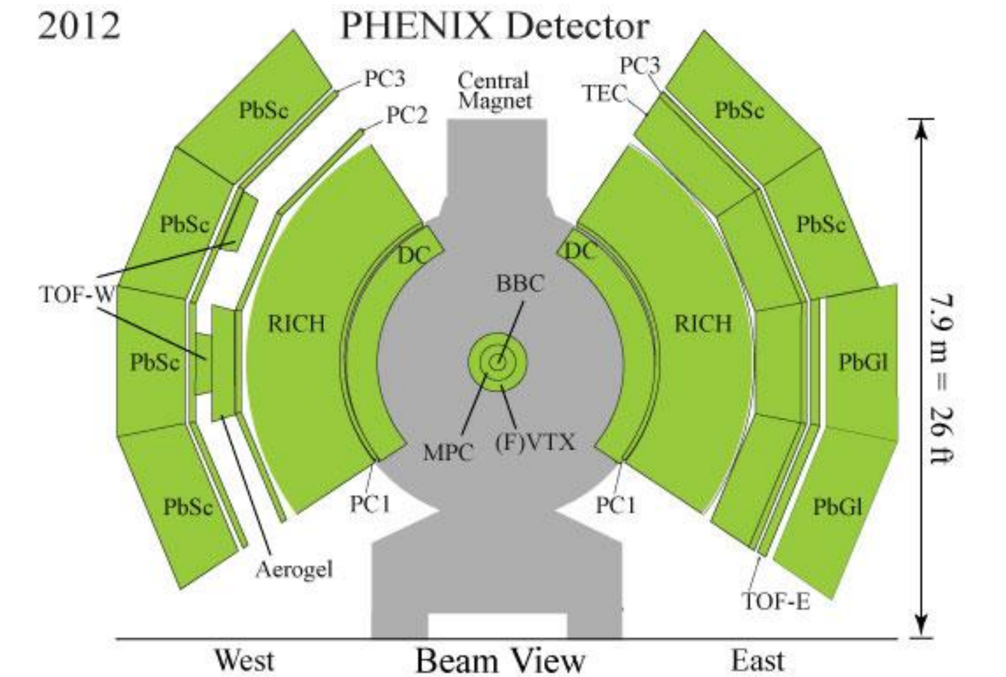
Heavy Flavor Tracker

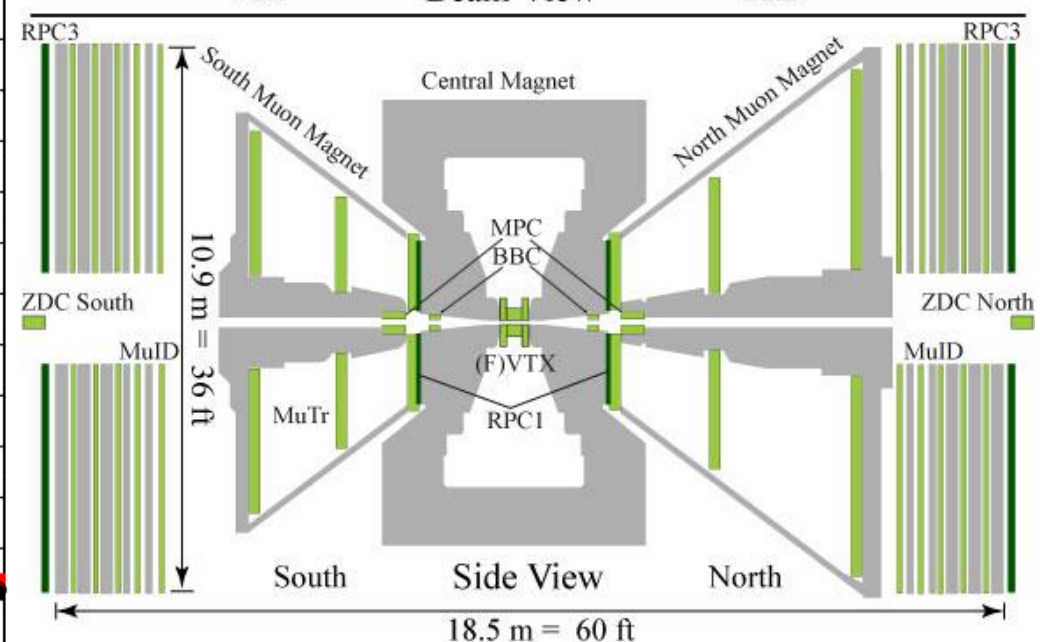
$|\eta| < 1,\ 0 < \varphi < 2\pi$

reconstruct HF

DCA: distance of closest approach



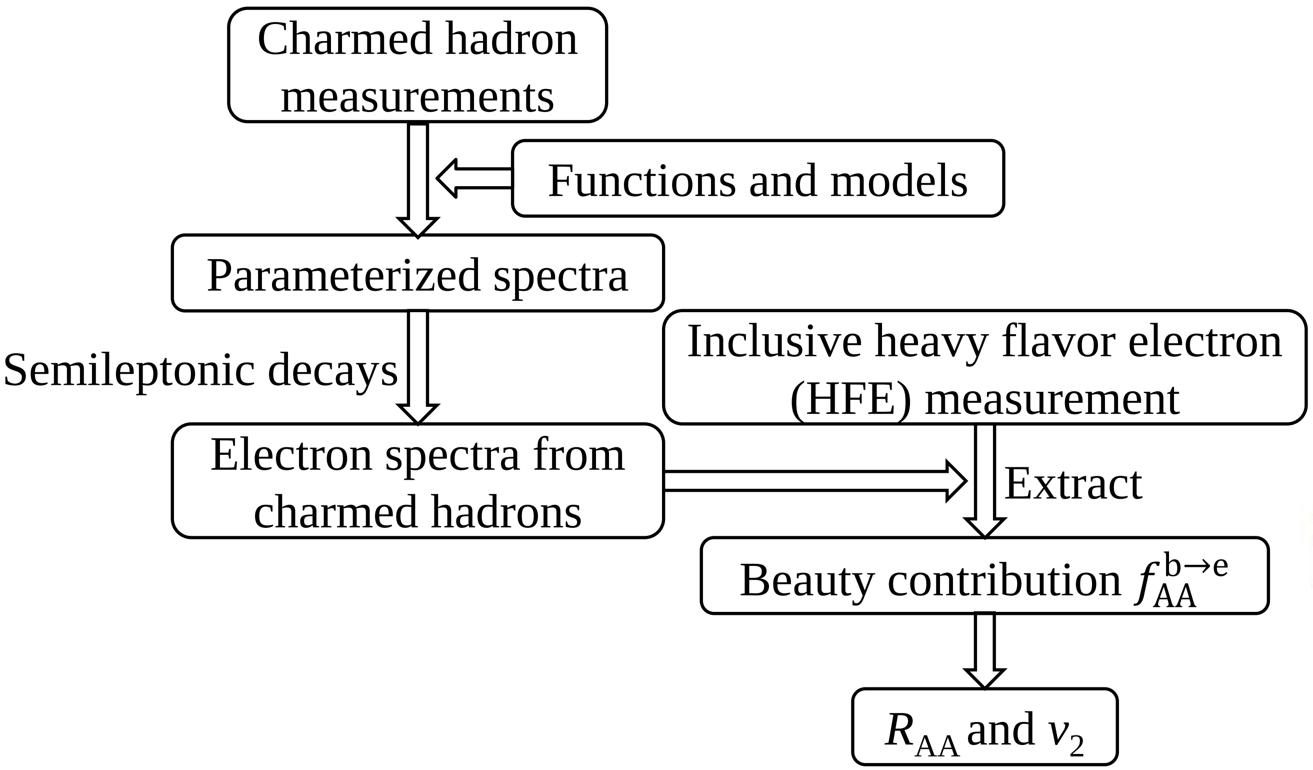


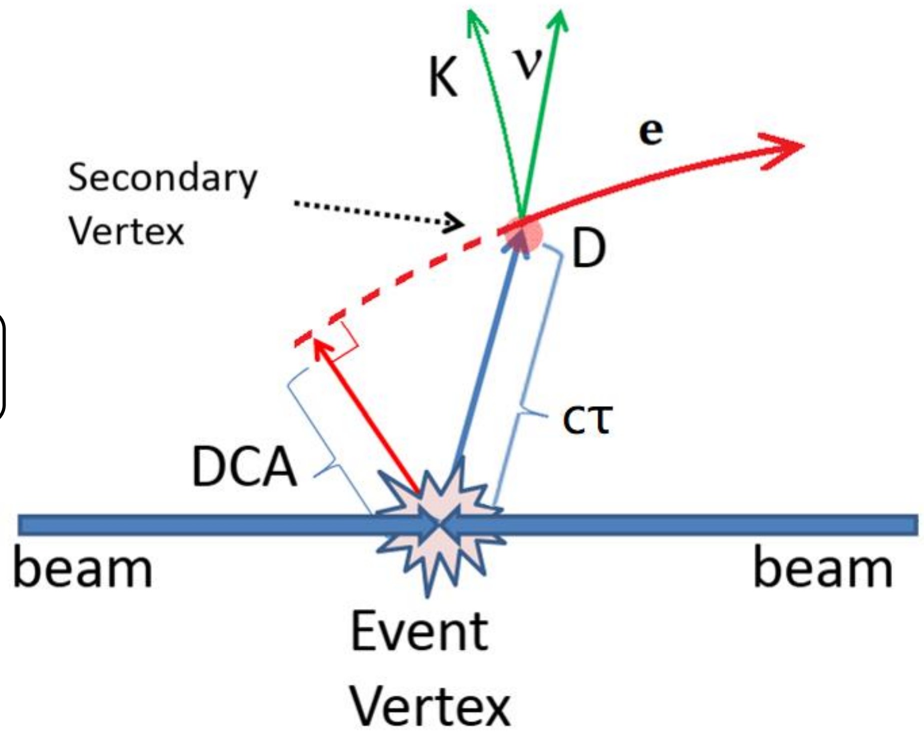


Silicon Vertex Tracker (VTX)

$|\eta| < 1.2,\ \Delta\varphi \sim 2\pi$, DCA of HFE and unfold

Data-driven method





- Electrons are able to show the properties of quarks kept by hadrons.

PRD **98**, 030001 (2018)

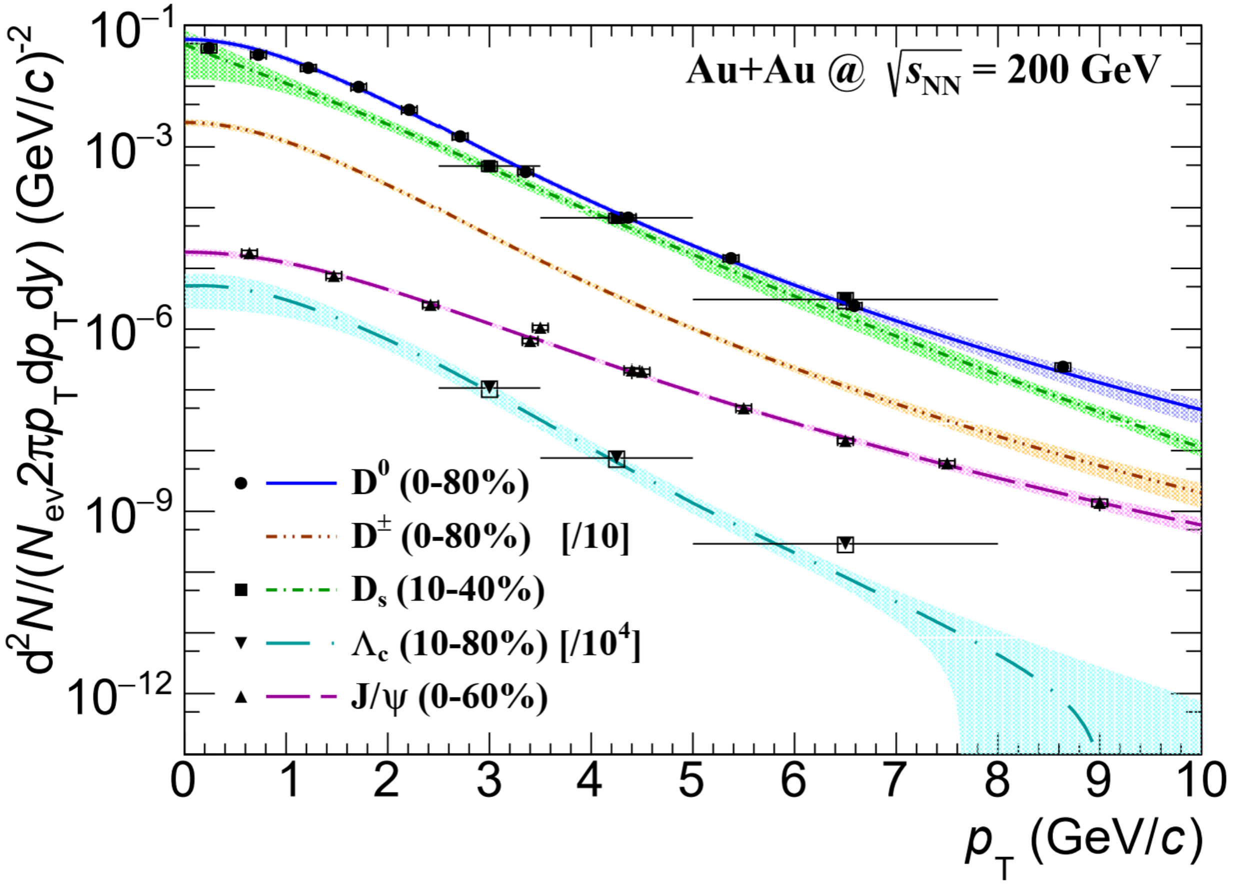
Charmed hadron	$c\tau$ (μm)	Mass (MeV/c^2)	Branching ratio (→eX)
D^0	122.9	1864.83 ±0.05	(6.49 ±0.11) %
$D^{\pm}$	311.8	1869.65 ±0.05	(16.07±0.30) %
D_s	151.2	1968.34 ±0.07	(6.5 ±0.4) %
Λ_c	59.9	2286.46 ±0.14	(4.5 ±1.7) %
J/ψ	2.13×10^{-6}	3096.900±0.006	(5.971±0.032) %

Spectra of charmed hadrons

- D^0, D_s and J/ψ: parameterized and extrapolated by Levy and power-law functions
- $D^{\pm}$: scaling D^0 spectrum by $D^{\pm}/D^0$ ratio (from 0-10%)
- Λ_c: mean of 4 models (Ko: di-&three-quark, Greco, Tshingua)
- Uncertainty bands from parameterization and different models are also input.

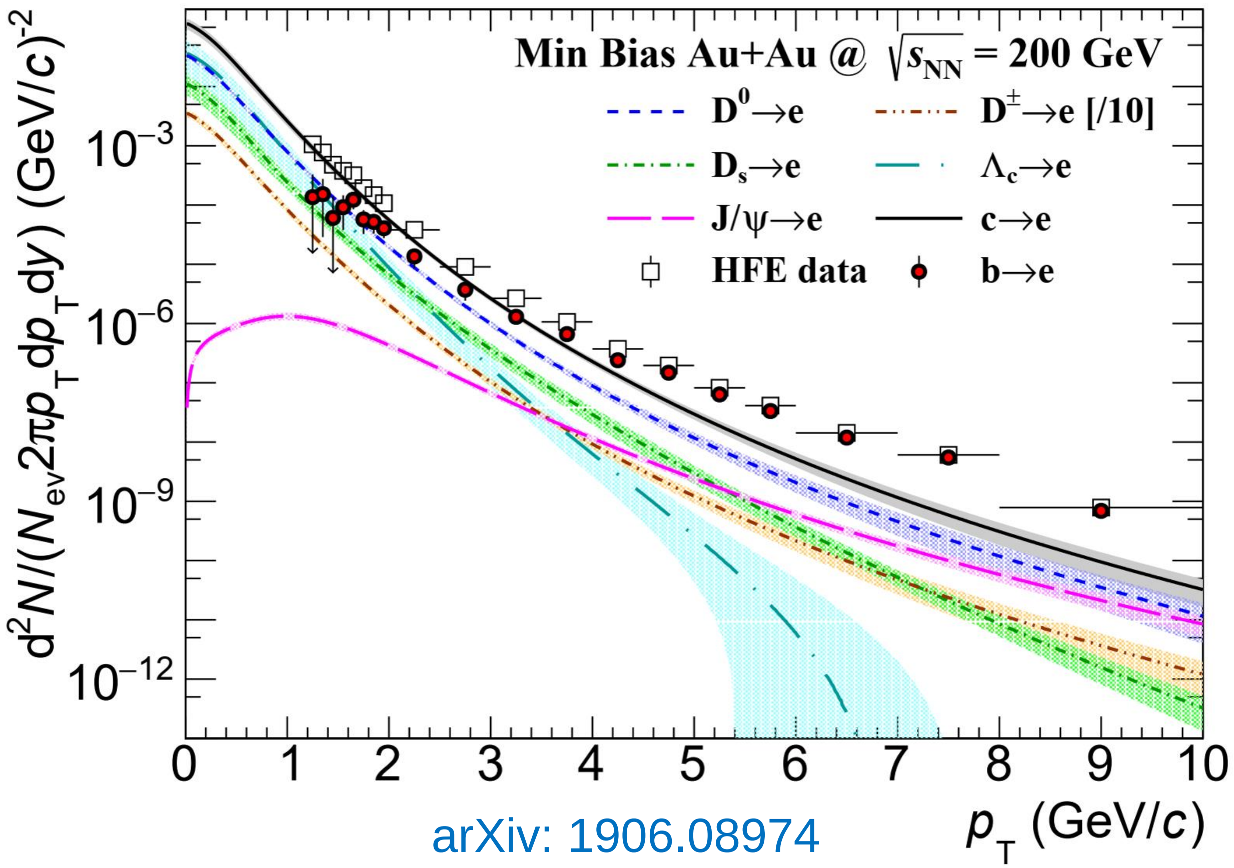
Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

Measurements	Centrality	Reference
D^0	0-80%	PRC **99**, 034908 (2019)
$D^{\pm}$	0-10%	NPA **967**, 620-623 (2017)
D_s	10-40%	NPA **967**, 620-623 (2017)
Λ_c	10-80%	NPA **982**, 659-662 (2019)
J/ψ	0-60%	PLB **722**, 55-62 (2013) PRC **90**, 024906 (2014)



Semileptonic decay simulation

- Output spectra are normalized by measured cross sections of respective charmed hadrons and branching ratios.
- Electron spectra from D_s, Λ_c and J/ψ are scaled by N_{bin} ratios to 0-80% centrality.
- $c \rightarrow e$ spectrum: summed contribution of charmed hadrons.
- $b \rightarrow e$ spectrum: extracted from inclusive HFE.

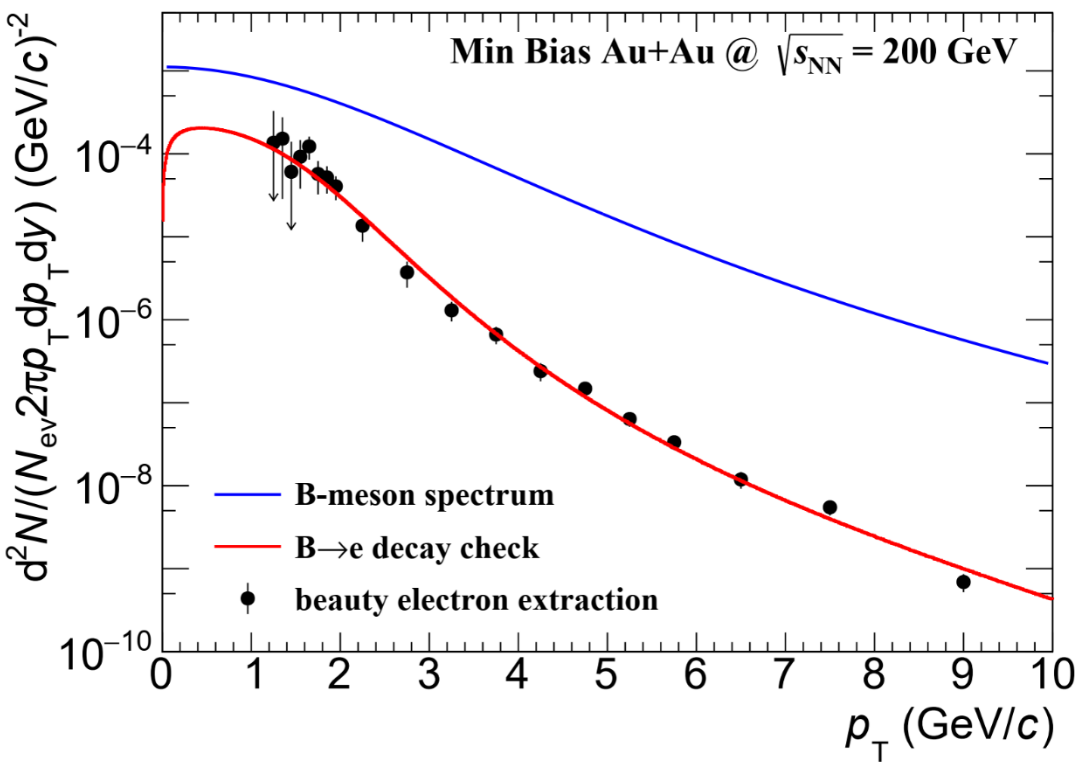


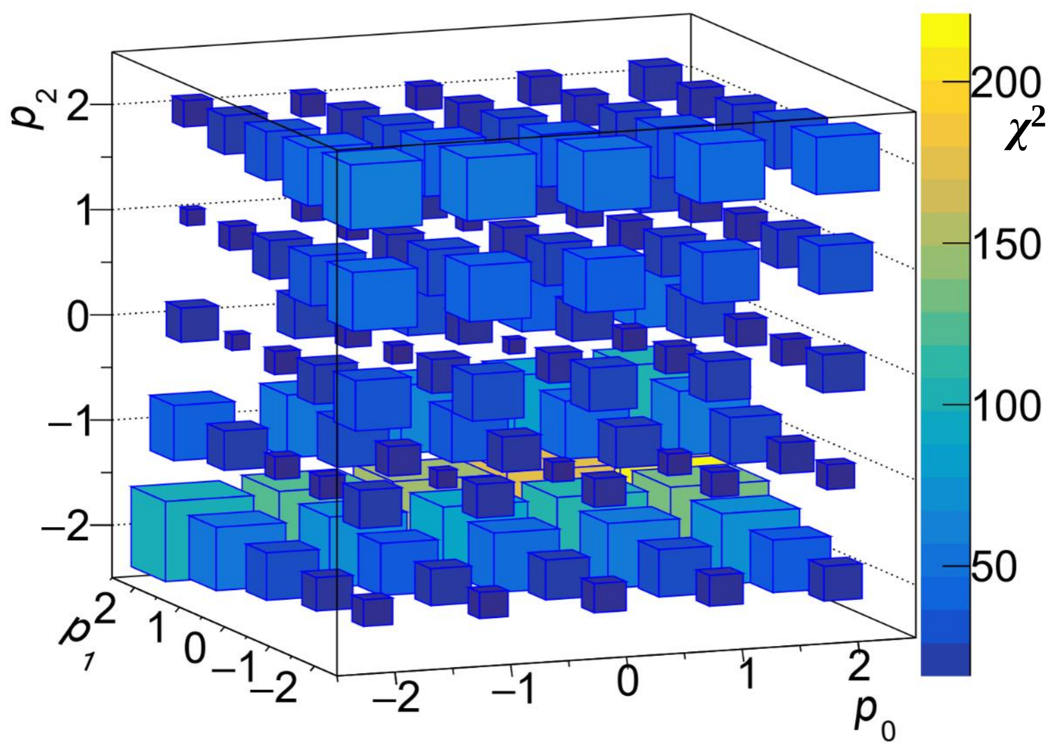
arXiv: 1906.08974

B-meson spectrum unfolding

Attempt to obtain B-meson spectrum from b→e extraction.

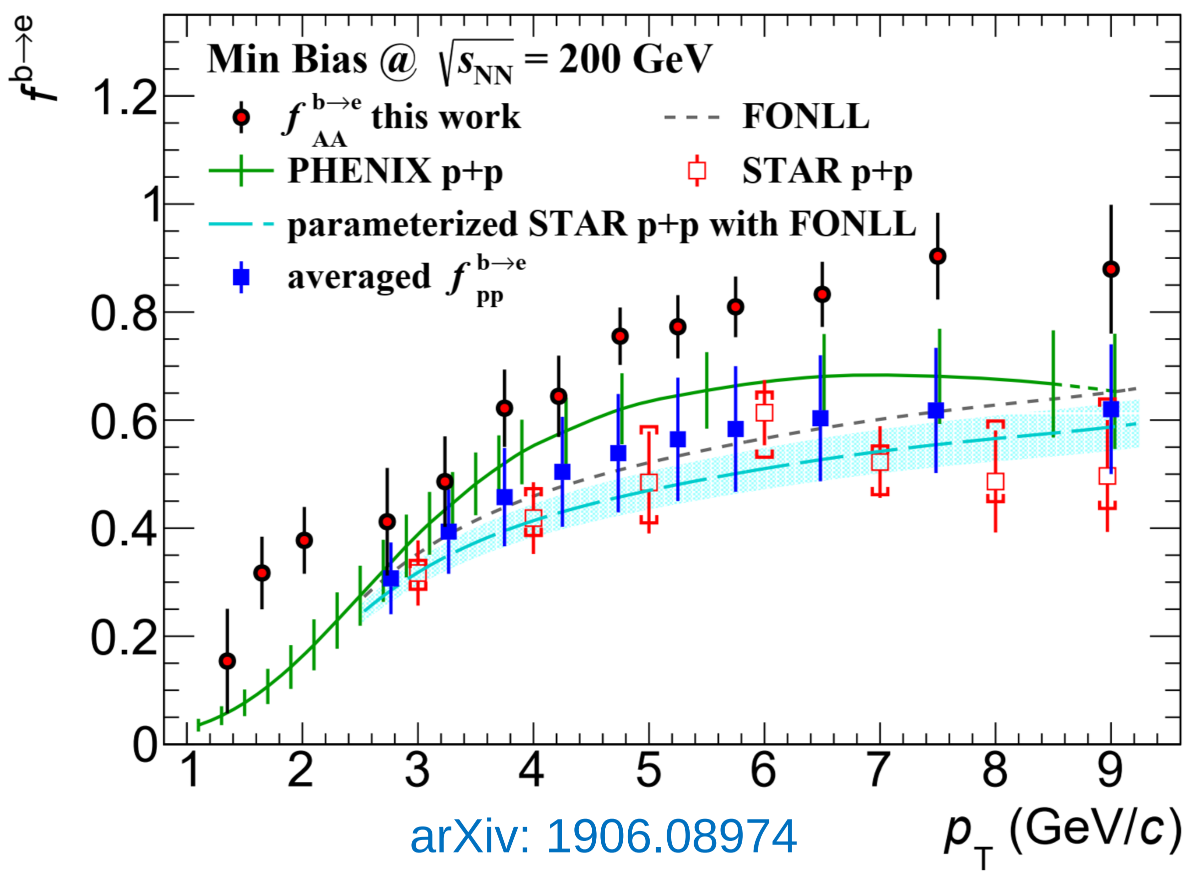
- Assume B-meson spectrum follows Levy function.
- Apply iteration until its electron spectrum fits the b→e data points. (χ^2/ndf =16.55/19)
- Decay check: change each parameter (step: 5%) of the B-meson spectrum function and calculate χ^2.





Beauty Contribution

- $f^{\mathrm{b \to e}} = \frac{\mathrm{b \to e}}{\mathrm{HFE}} = 1 - f^{\mathrm{c \to e}}$
- At $p_T \sim 3.5$ GeV/c, $f^{\mathrm{b \to e}} \sim f^{\mathrm{c \to e}} \sim 50\%$.
- $f_{\mathrm{AA}}^{\mathrm{b \to e}}$ is systematically higher than $f_{\mathrm{pp}}^{\mathrm{b \to e}}$.
- Charm is more strongly suppressed than beauty due to the medium effect in Au+Au collisions.



arXiv: 1906.08974

R_{AA} isolation

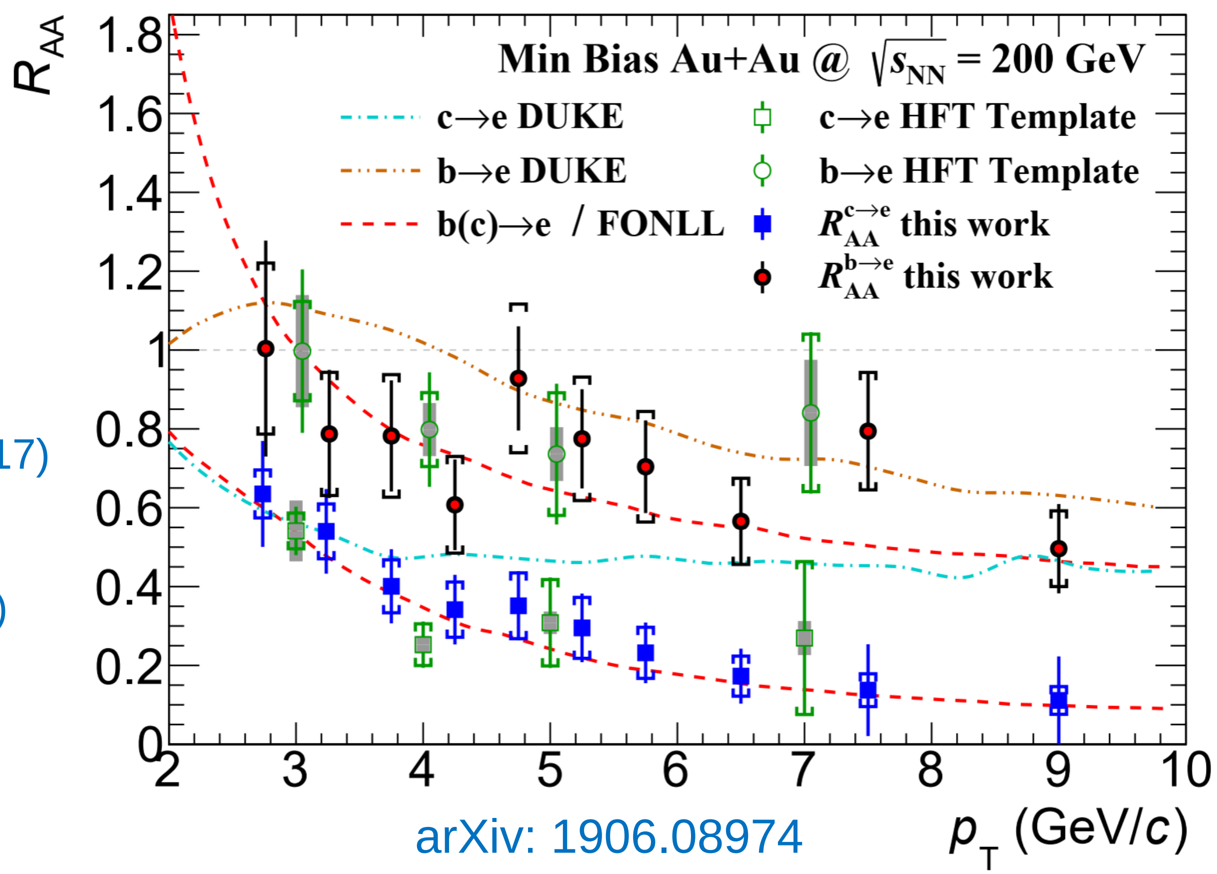
- $R_{AA}^{b\to e} = \frac{f_{AA}^{b\to e}}{f_{pp}^{b\to e}} R_{AA}^{HFE}$

  $R_{AA}^{c\to e} = \frac{1-f_{AA}^{b\to e}}{1-f_{pp}^{b\to e}} R_{AA}^{HFE}$
- Cross-check: b(c)→e/FONLL obtained by the definition.

Our work
arXiv: 1906.08974

HFT Template
NPA **967**, 632-635 (2017)

DUKE
PRC **92**,024907 (2015)



arXiv: 1906.08974

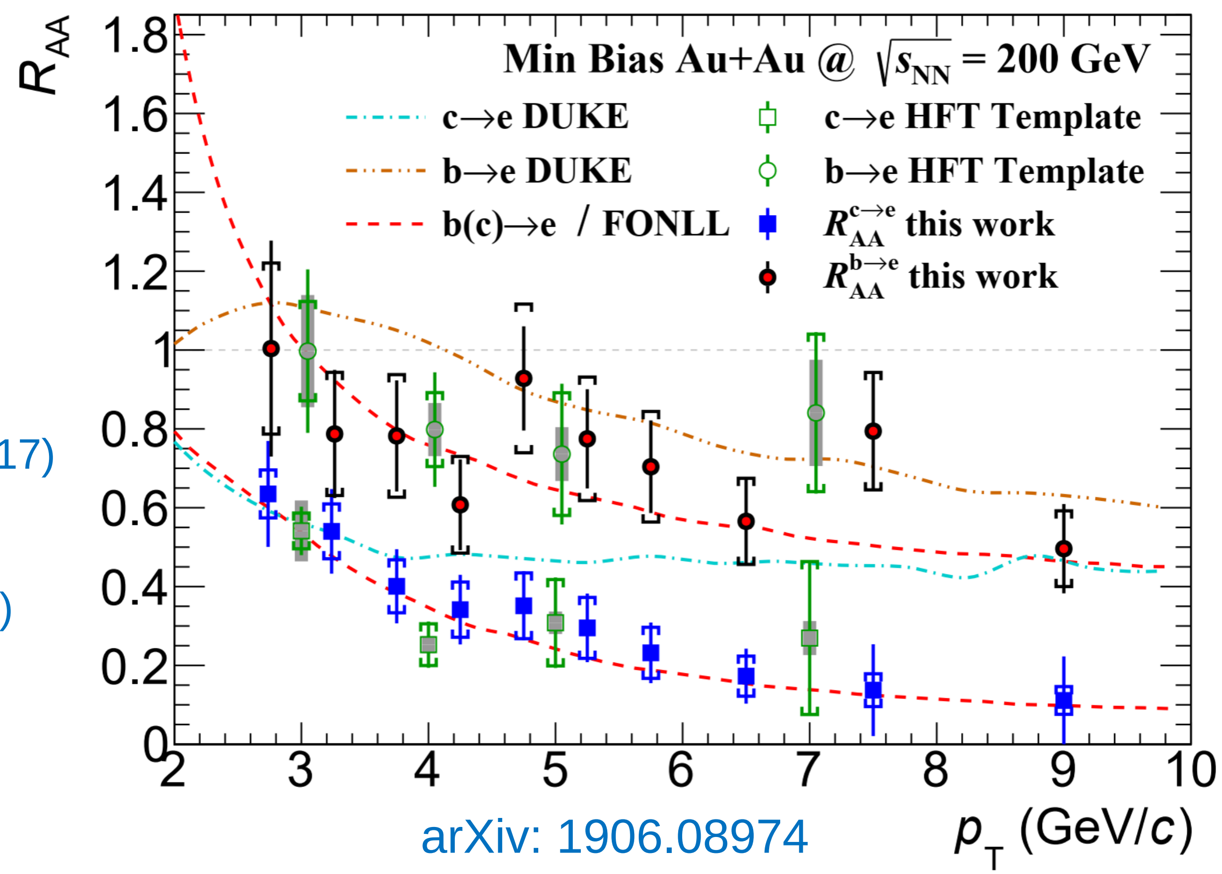
R_{AA} isolation

- Consistent with the template analysis with STAR HFT and show an improved precision.
- b→e: roughly consistent with DUKE model prediction
  c→e: a stronger suppression at $p_T > 4$ GeV/c.
- An agreement with mass dependent energy loss: $\Delta E_c > \Delta E_b$.

Our work
arXiv: 1906.08974

HFT Template
NPA **967**, 632-635 (2017)

DUKE
PRC **92**,024907 (2015)



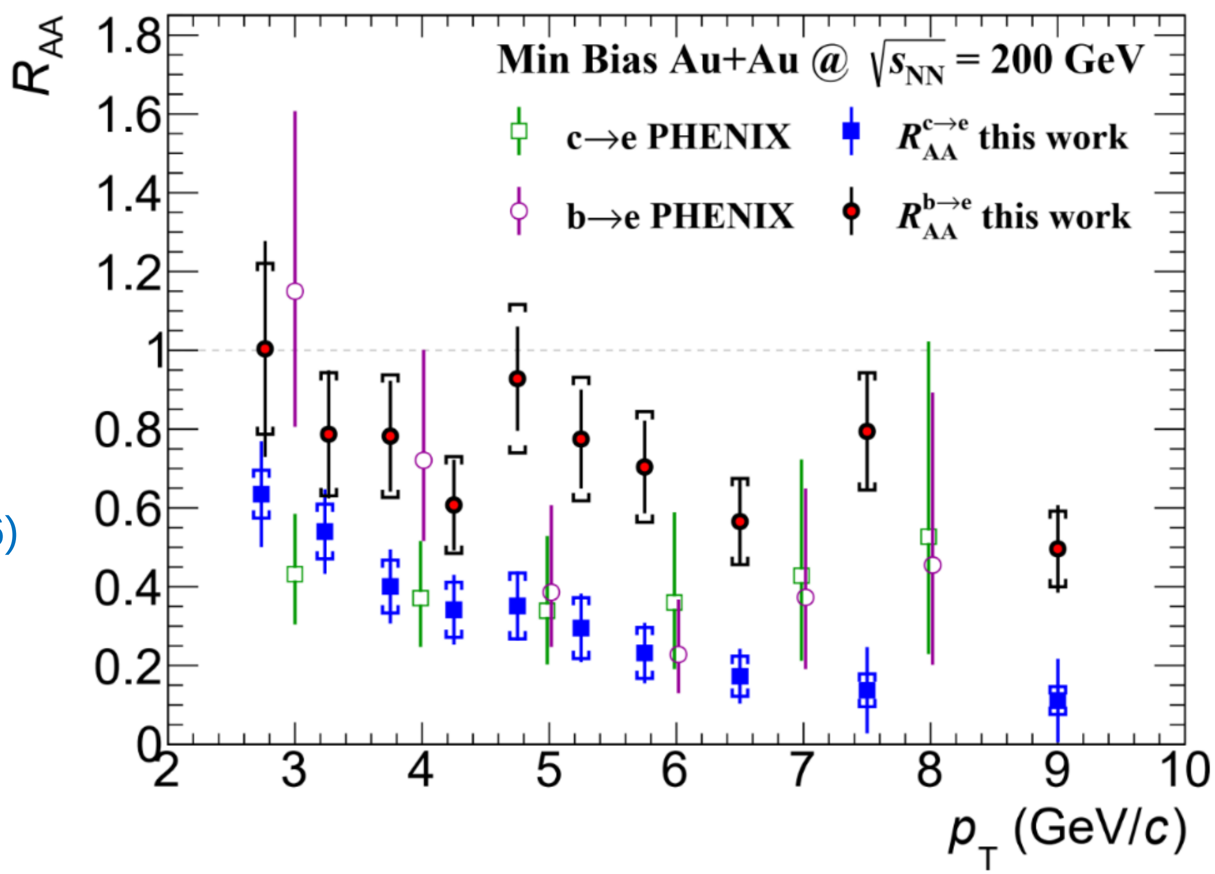
arXiv: 1906.08974

R_{AA} isolation

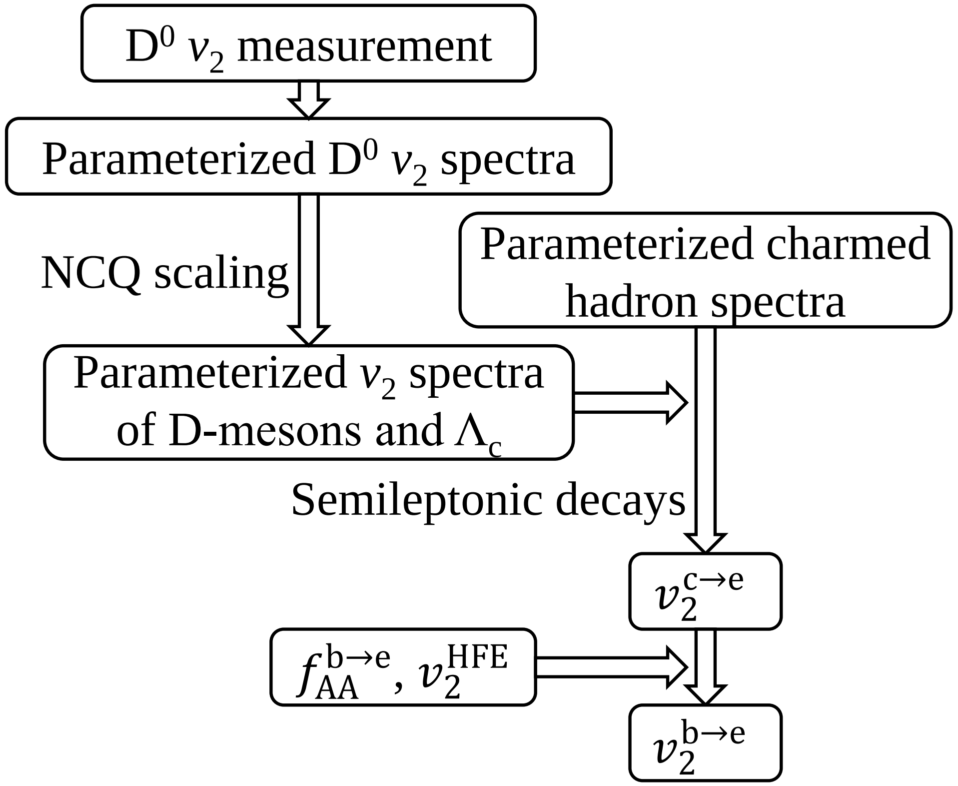
- An agreement with PHENIX ones within uncertainties.
- Improve the precision.
- Isolate charm and beauty.
- Show clear mass dependence of energy loss.

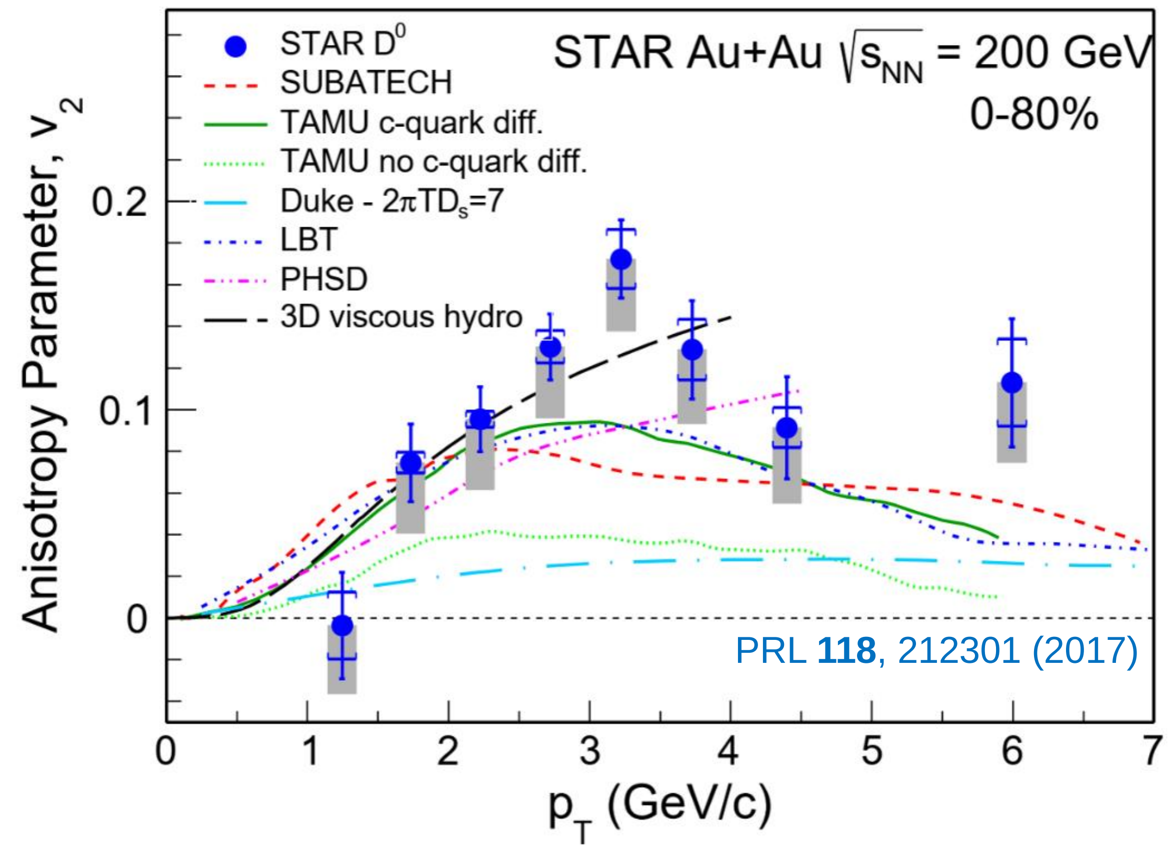
Our work
arXiv: 1906.08974

PHENIX
PRC **93**, 034904 (2016)



v_2 isolation method





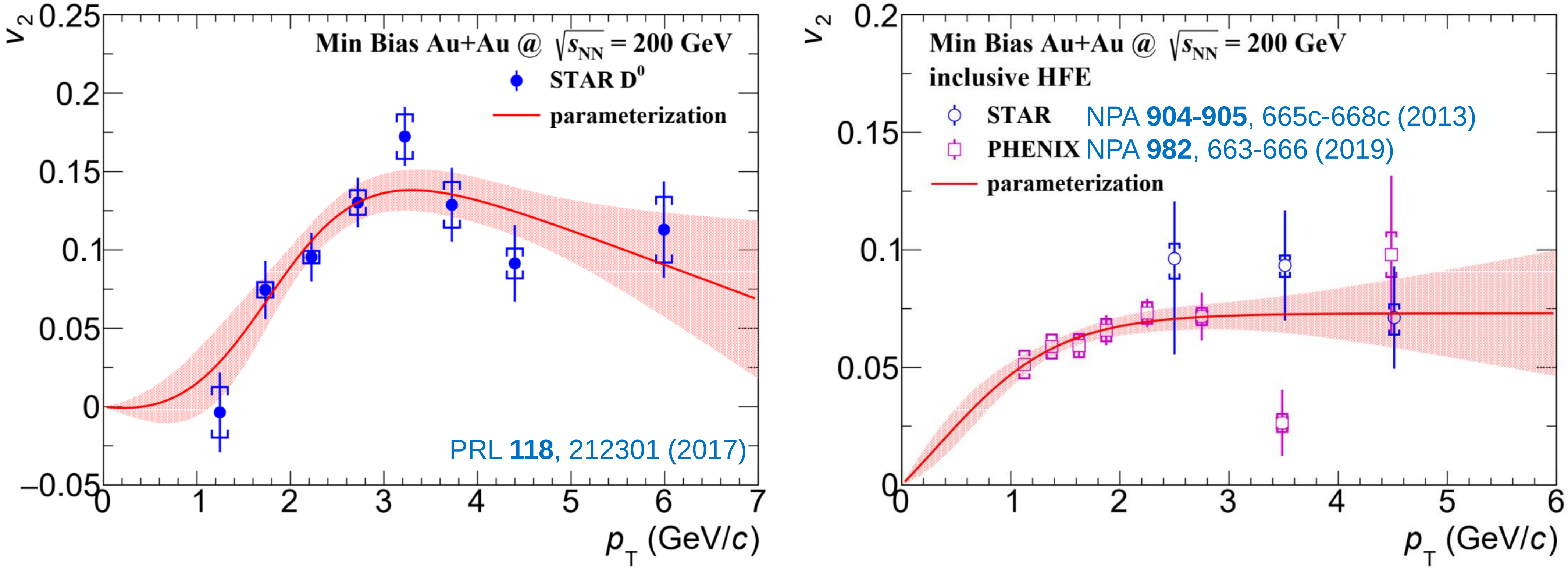
- Azimuthal angle (ϕ) distribution: $\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + 2v_2\cos(2\phi)$.
- $v_2^{c\to e}$: average of $v_2^{D\to e}$ and $v_2^{\Lambda_c\to e}$ weighted by relative yields.
- Same as $v_2^{HFE} \Rightarrow v_2^{b\to e} = \frac{v_2^{HFE} - (1-f_{AA}^{b\to e})v_2^{c\to e}}{f_{AA}^{b\to e}}$

v_2 parameterization

- Parameterization function:

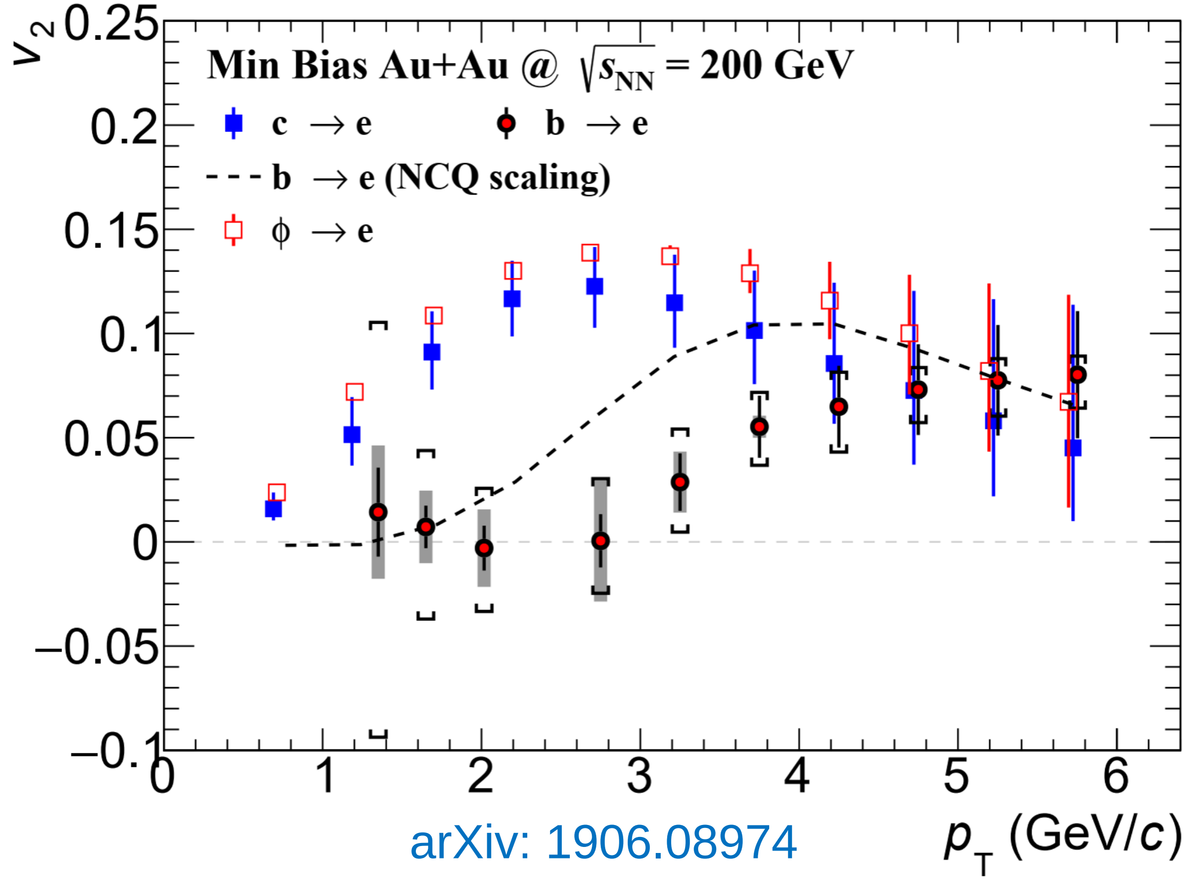
$$v_2(p_T) = \frac{p_0 n}{1+\exp\left(\frac{p_1 - \frac{p_T}{n}}{p_2}\right)} - \frac{p_0 n}{1+\exp\left(\frac{p_1}{p_2}\right)} - p_3 n p_T$$

- The uncertainty band of D^0 v_2 from parameterization is input and propagated to the electron v_2 spectra.



v_2 isolation

- Charm seems like light quarks (c⟶e and ϕ⟶e).
- At $p_T < 4$ GeV/c, $v_2^{b\to e}$ is dramatically smaller than $v_2^{c\to e}$.
- At $2.5 < p_T < 4.5$ GeV/c, $v_2^{b\to e}$ deviates the curve assuming B-meson v_2 follows NCQ scaling (98.2%, χ^2/ndf =11.92/4).
- Beauty is unlikely thermalized and seems too heavy to be moved to follow the collectivity at RHIC.



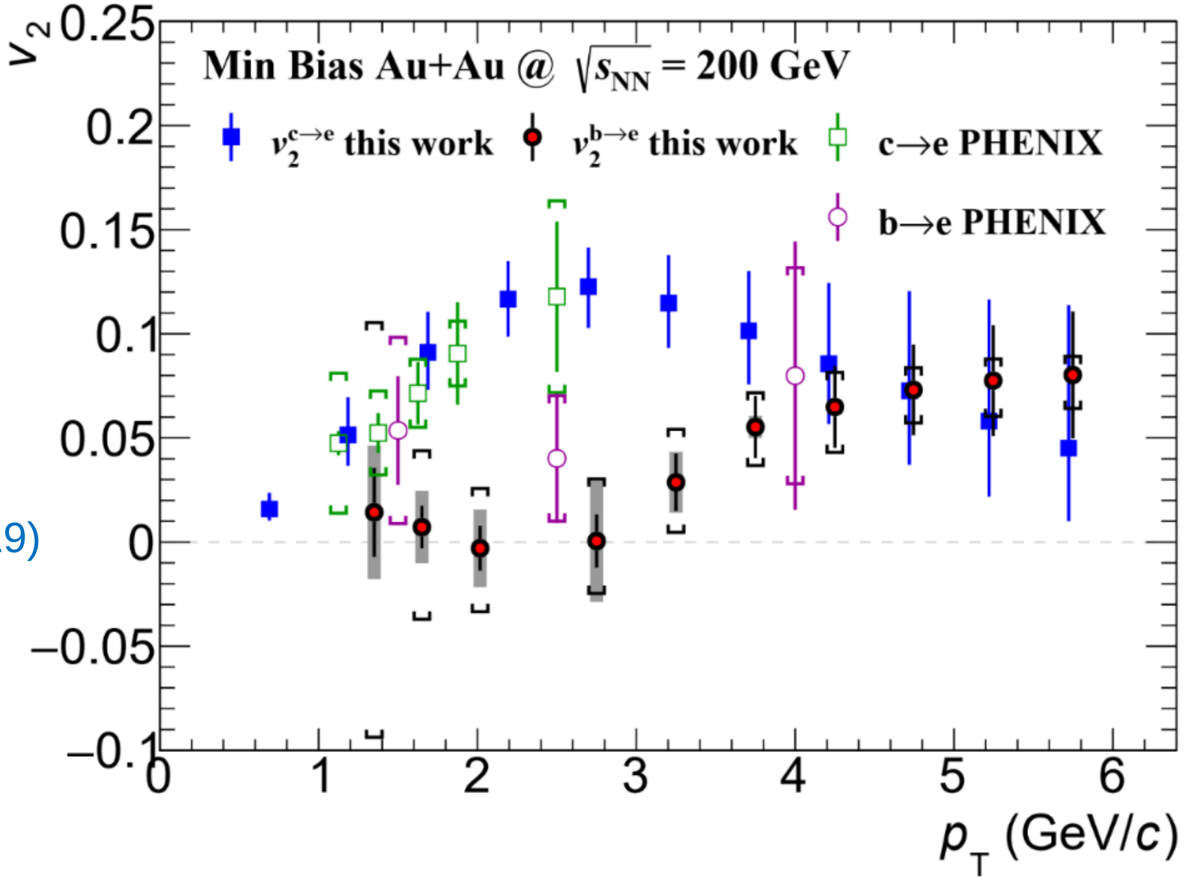
arXiv: 1906.08974

v_2 isolation

- An agreement with PHENIX results.
- Improve the precision.
- Show clear difference between charm and beauty.

Our work
arXiv: 1906.08974

PHENIX
NPA **982**, 663-666 (2019)



Summary

- Improved electron R_{AA} and v_2 are obtained from $f^{\,b\to e}$ via the data-driven method taking advantage of the largest statistics and best precision of open charm measurements.
- Stronger suppression of charm than beauty predicted by mass dependent energy loss is supported by our R_{AA} results.
- Charm follows the collective motion like light quarks, which is shown by the agreement between $v_2^{c\to e}$ and $v_2^{\phi\to e}$.
- Non-zero $v_2^{b\to e}$ is observed at $p_T > 3$ GeV/c at RHIC.
- Less flow of b→e is observed than $v_2^{c\to e}$ at $p_T < 4$ GeV/c and $v_2^{b\to e}$ NCQ hypothesis at $2.5 < p_T < 4.5$ GeV/c, which indicates that beauty is unlikely thermalized in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Thank you!

Effect of extrapolation

- The proportion of the electrons decaying from D^0 at $p_T > 10$ GeV/c (unmeasured region) in each electron p_T bin.
- 100% electrons at $p_T = 9.5$ GeV/c and 16.8% at $p_T = 6$ GeV/c.
- Limited effect of D^0 $p_T > 10$ GeV/c on electrons $p_T < 6$ GeV/c.
- The total proportion of electrons at $p_T < 10$ GeV/c decaying from D^0 at $p_T > 10$ GeV/c is only 1.2×10^{-5}.