Charm and beauty isolation in heavy flavor electron measurements at RHIC

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The 13th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics (QPT 2019)

Aug. 16-20, 2019, Enshi, Hubei, China

Outline

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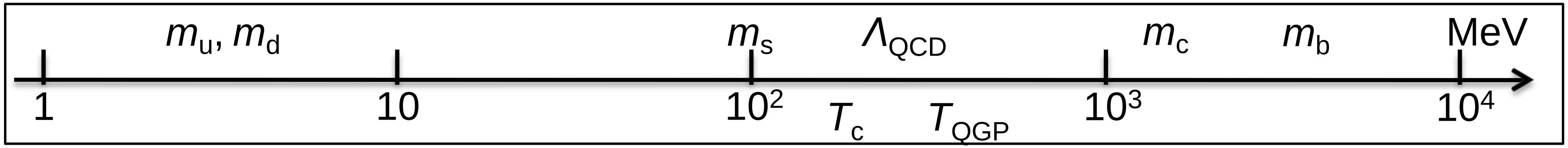
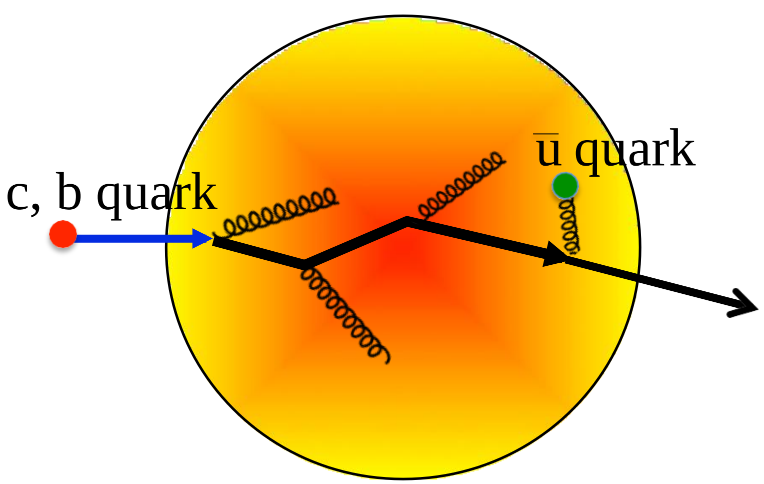
  - Beauty contribution extraction
  - c→e and b→e R_{AA}
  - c→e and b→e v_2
- **Summary and conclusion**

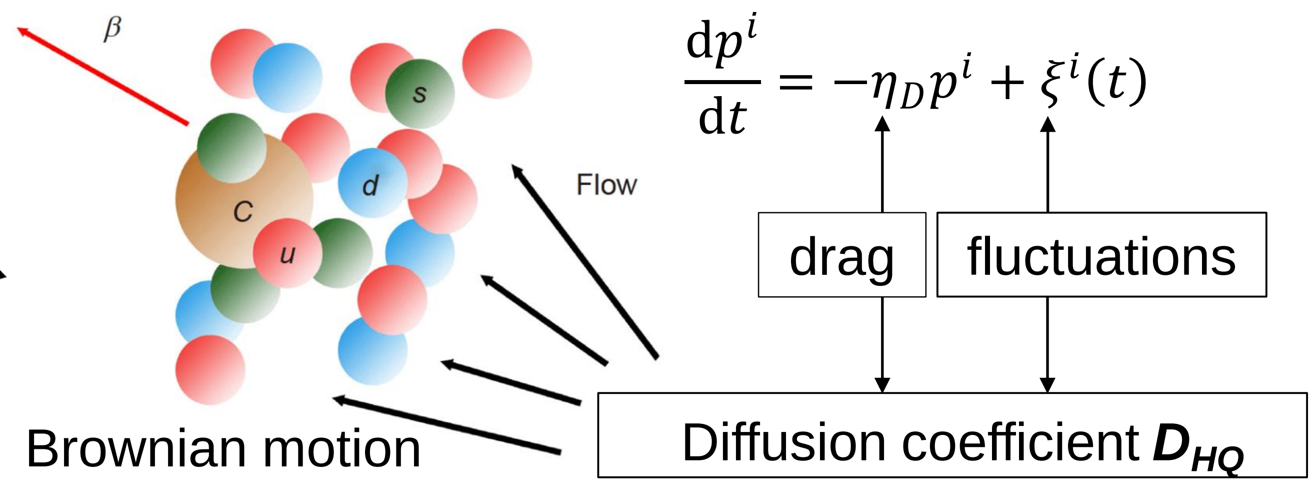
Introduction



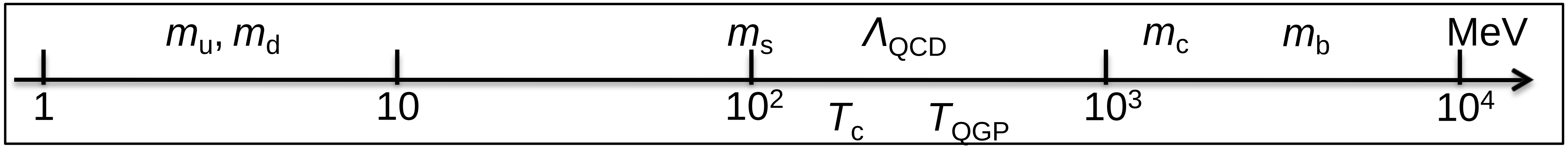
Heavy quarks (charm and beauty):

- Produced mostly before QGP and pass through it completely.
- Production yields can be evaluated by pQCD.
- Ideal probes for medium properties, diffusion coefficient, etc.
- Theoretical mass dependent energy loss: $\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$.





Introduction



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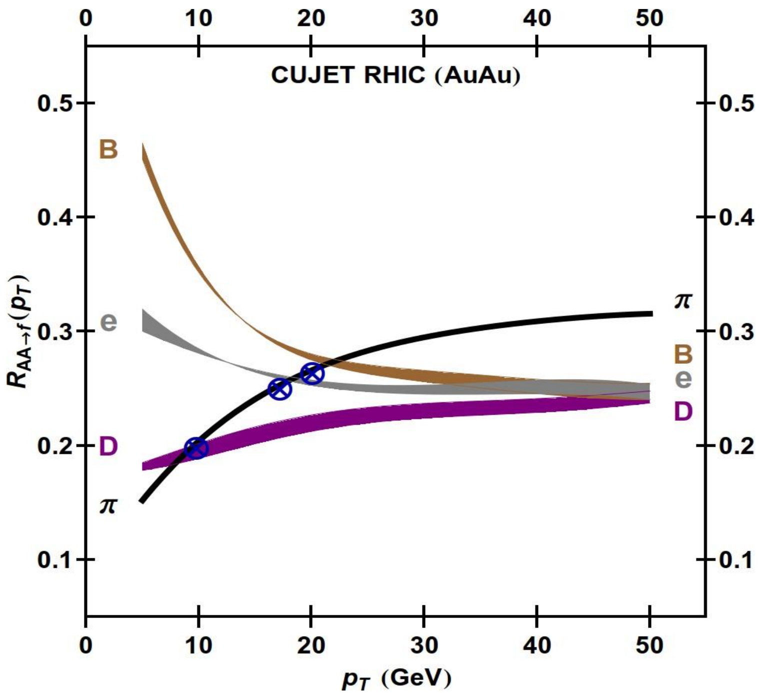
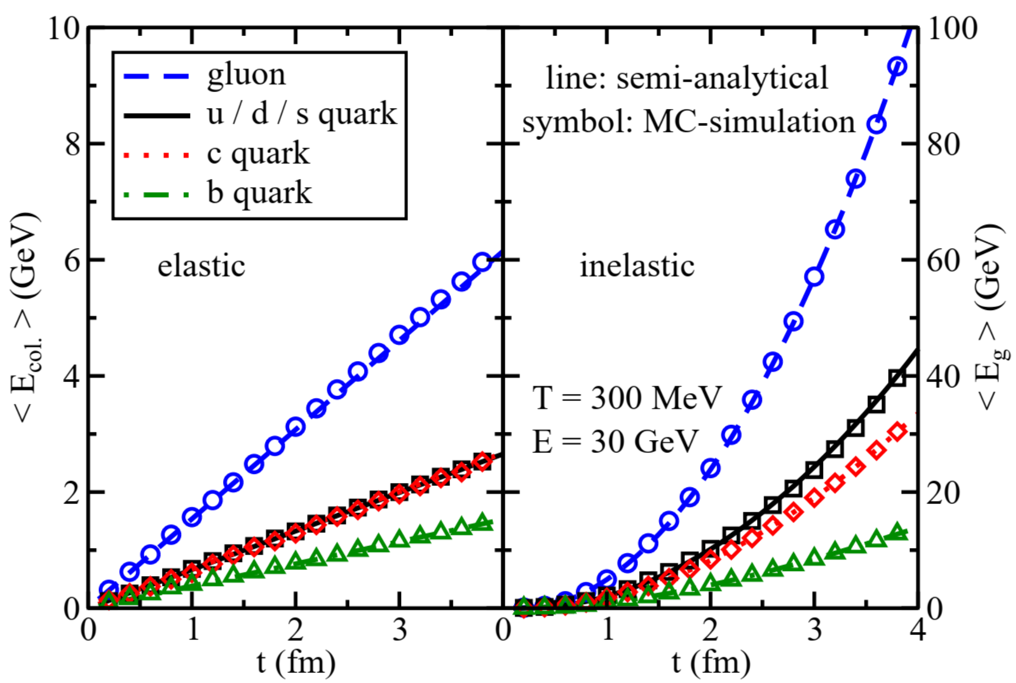


Phys. Rev. Lett. **108**, 022301 (2012)



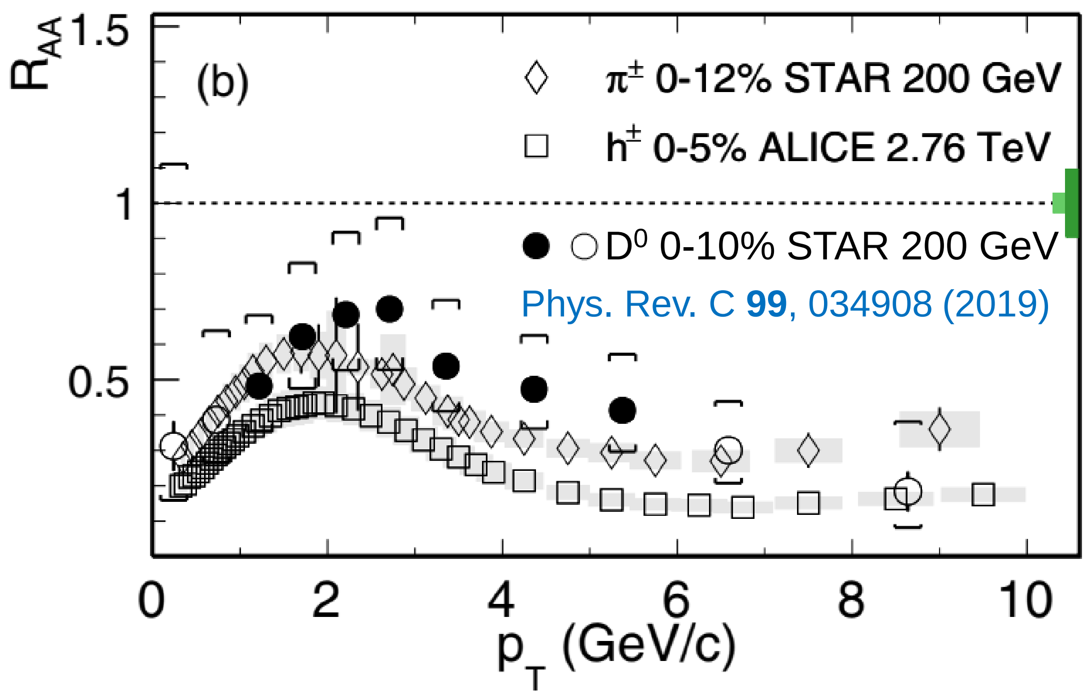
Phys. Lett. B **777,** 255-259 (2018)

Introduction

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

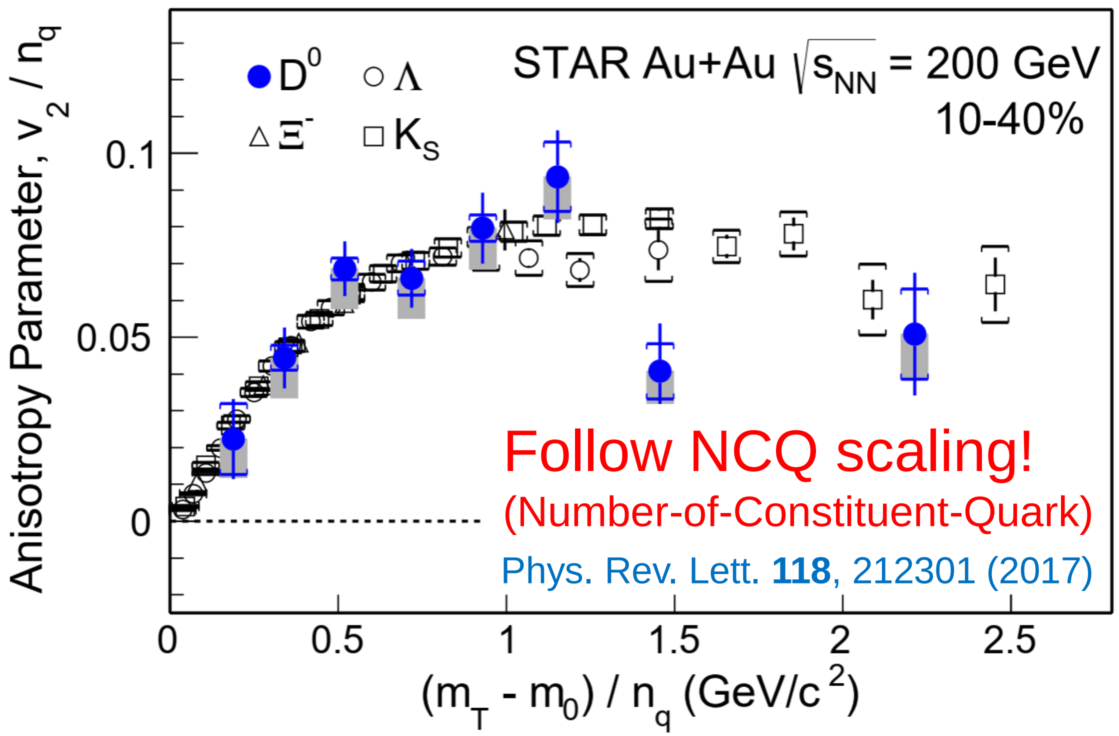
$$R_{AA}(p_T) \equiv \frac{1}{\langle N_{bin}\rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

parton energy loss by medium effect



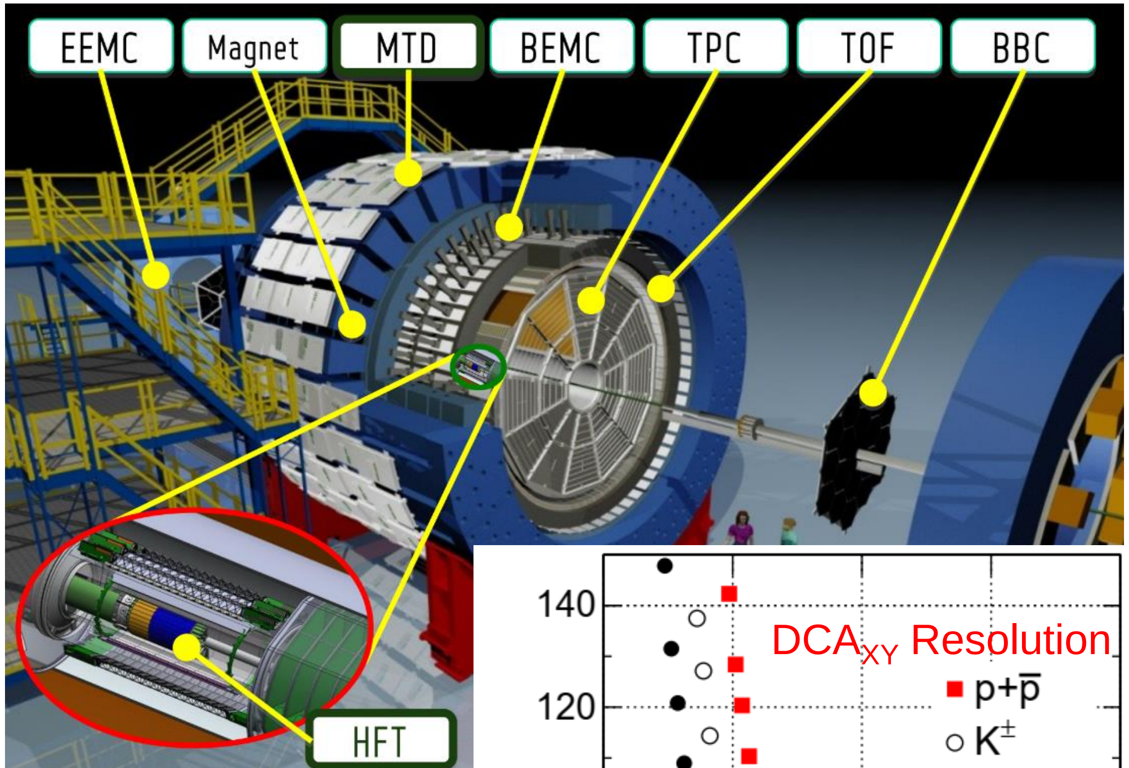
$$v_2 \equiv \langle \cos[2(\phi - \psi_r)] \rangle$$

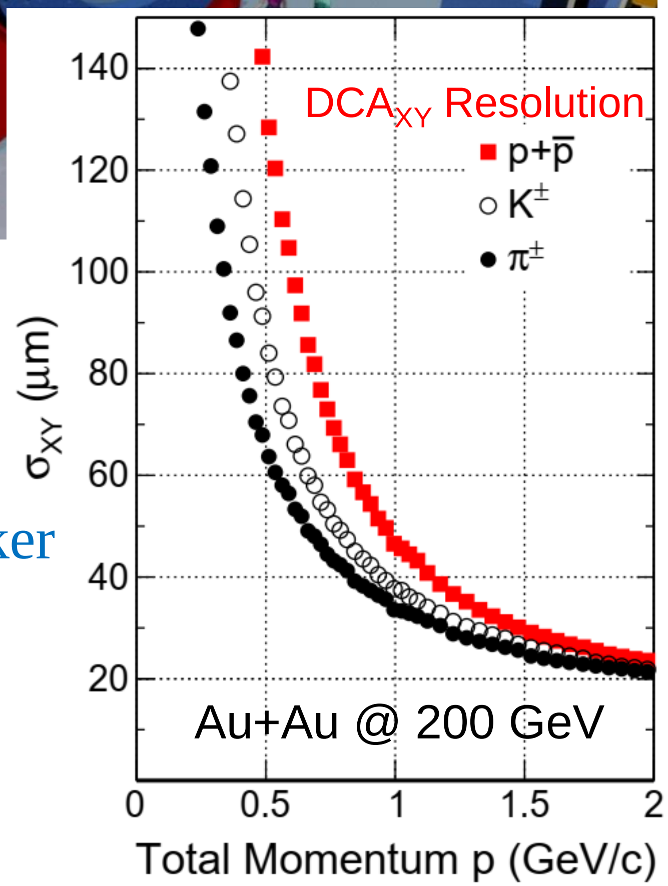
parton thermalization and other properties

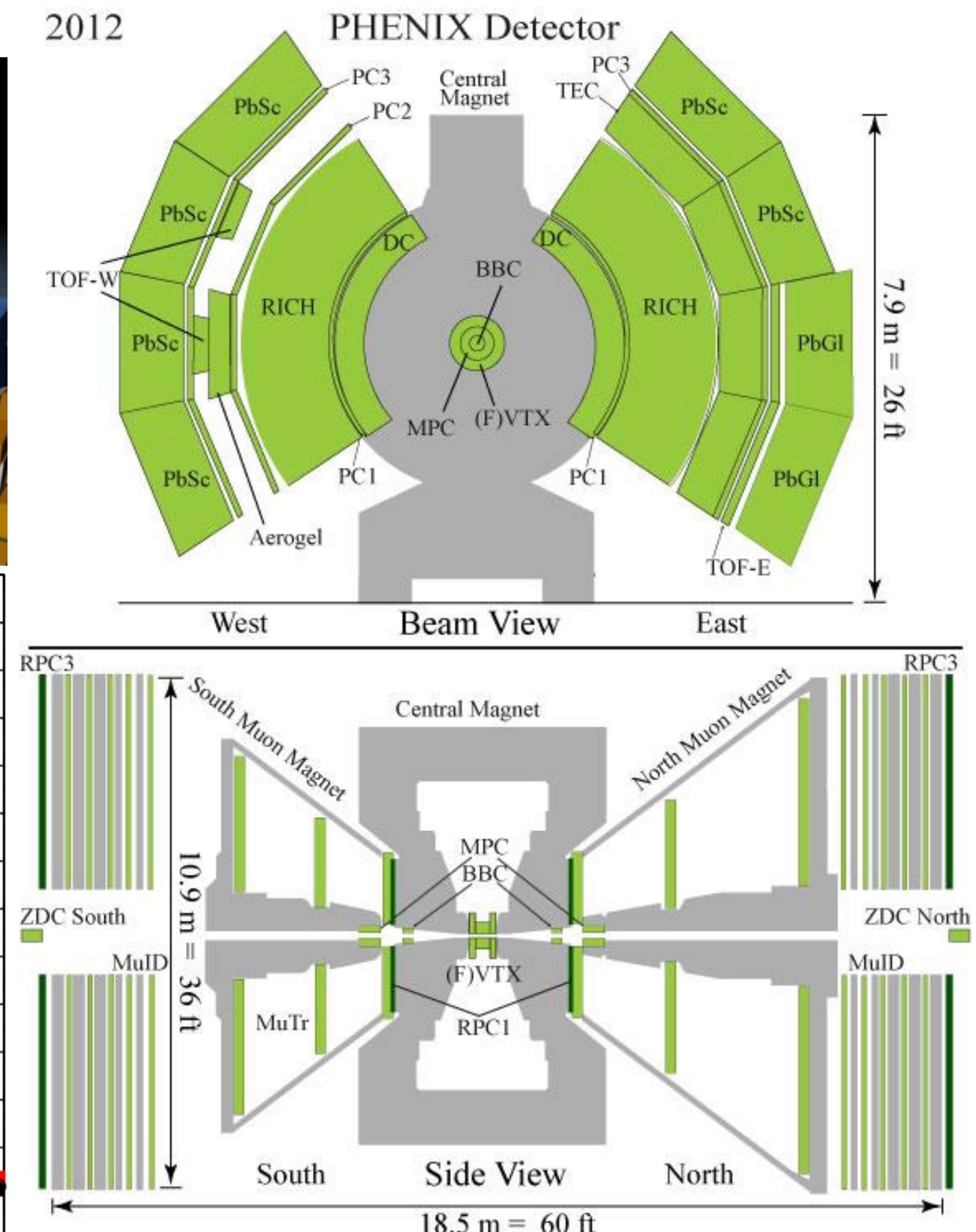


RHIC detectors

STAR Detector







Heavy Flavor Tracker

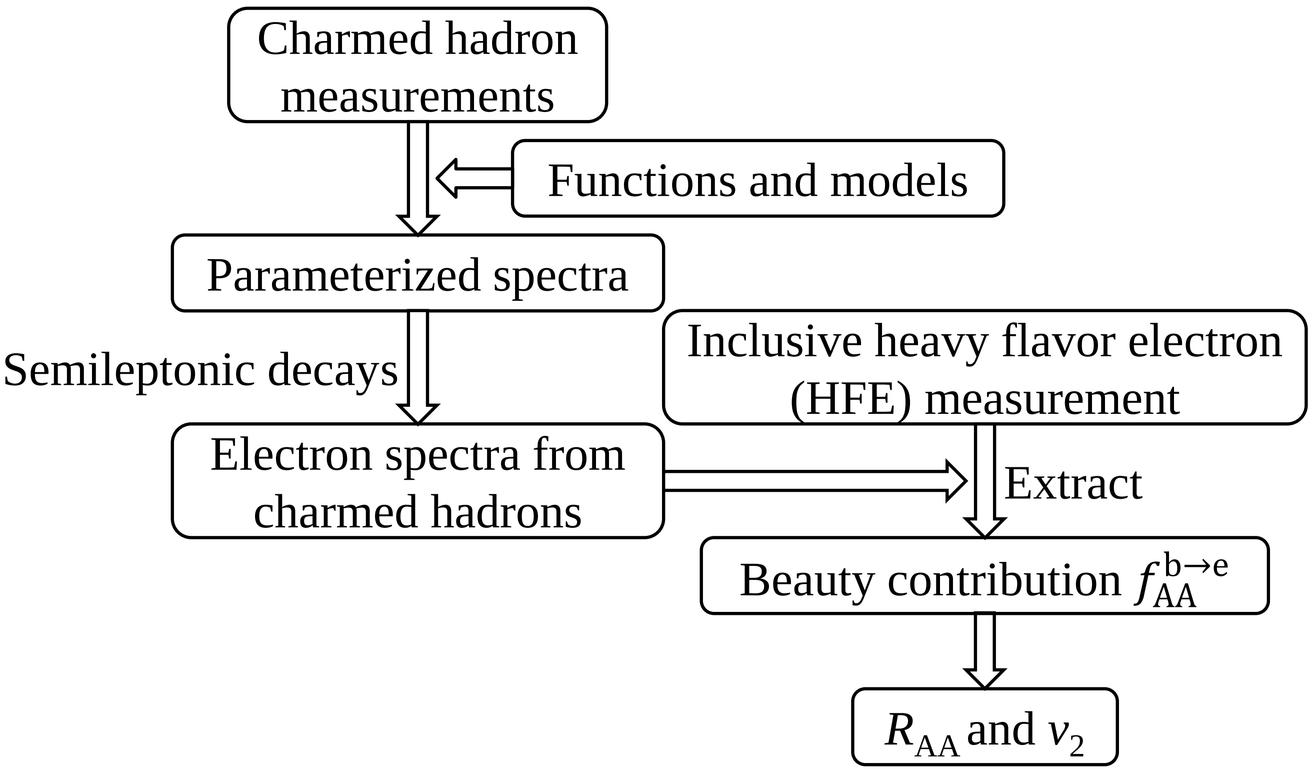
$|\eta| < 1, 0 < \varphi < 2\pi$

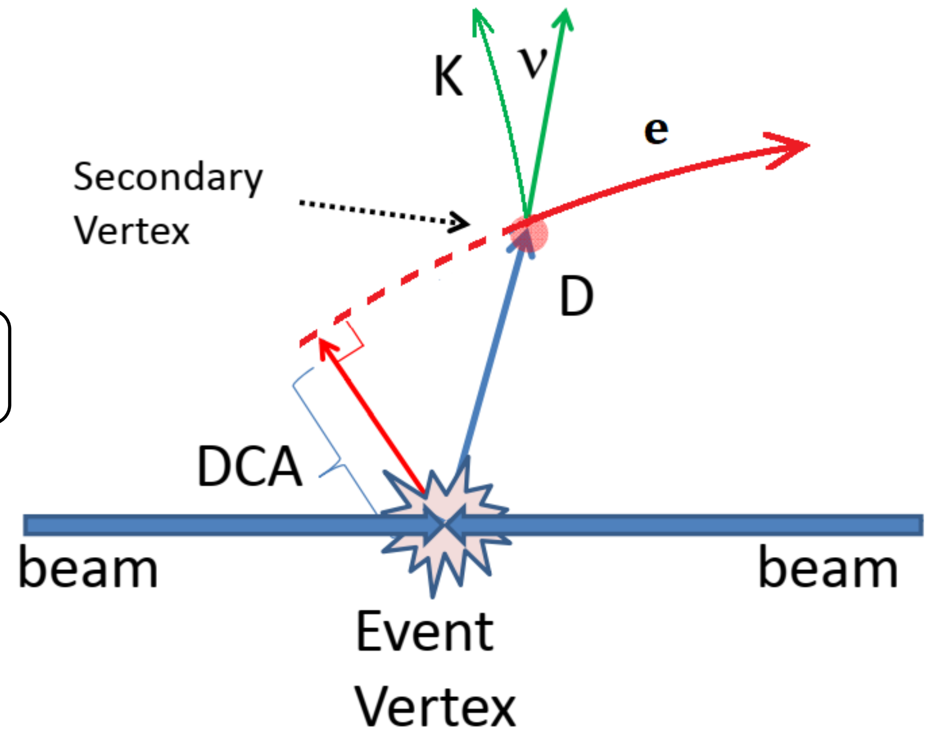
DCA: distance of closest approach

Silicon Vertex Tracker (VTX)

$|\eta| < 1.2, \Delta\varphi \sim 2\pi$

Data-driven method





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

Charmed hadron	Mass/MeV	Branching ratio
D^0	1864.83 $\pm$0.05	e^+ anything (6.49 $\pm$0.11) %
$D^{\pm}$	1869.65 $\pm$0.05	e^+ semileptonic (16.07$\pm$0.30) %
D_s	1968.34 $\pm$0.07	e^+ semileptonic (6.5 $\pm$0.4) %
Λ_c	2286.46 $\pm$0.14	e^+ anything (4.5 $\pm$1.7) %
J/ψ	3096.900$\pm$0.006	$e^+ e^-$ (5.971$\pm$0.032) %

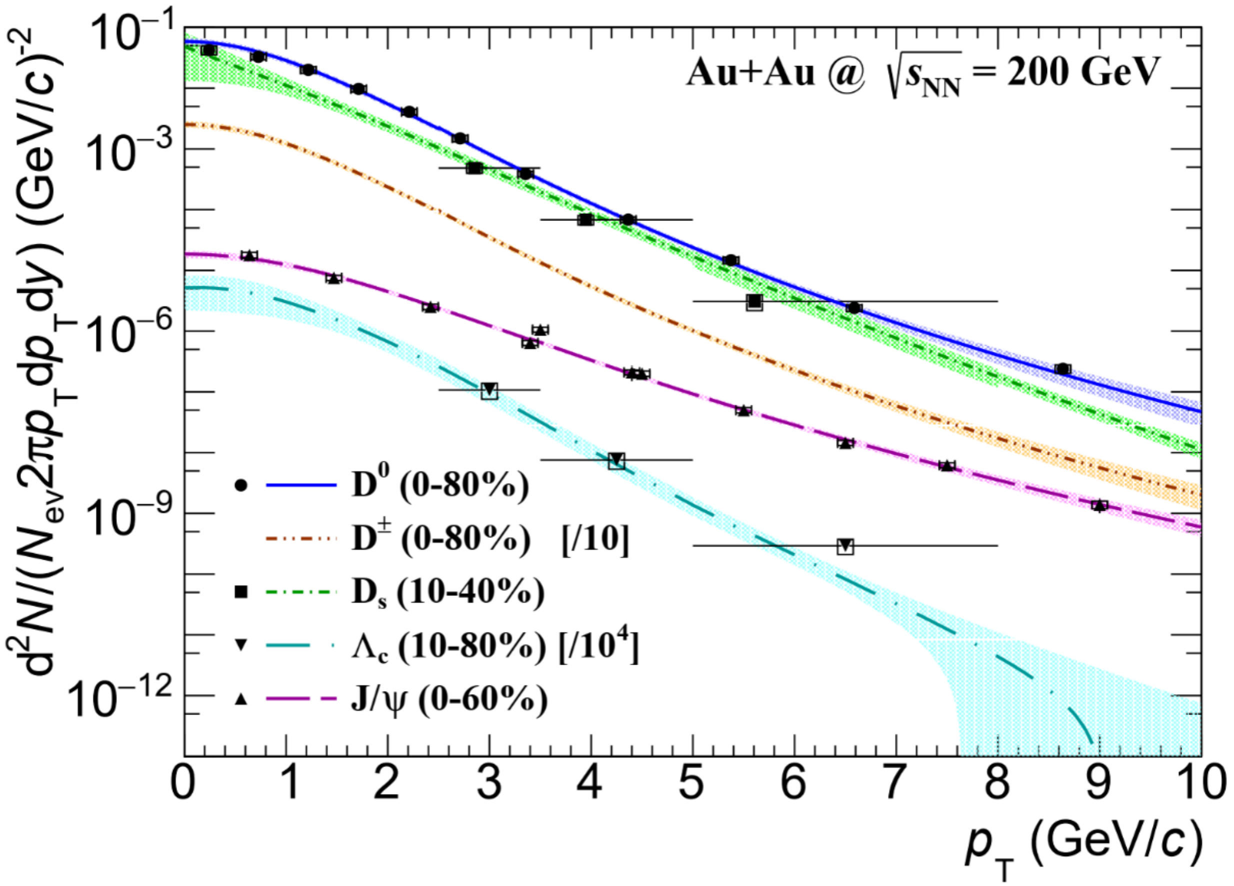
Phys. Rev. D **98**, 030001 (2018)

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.

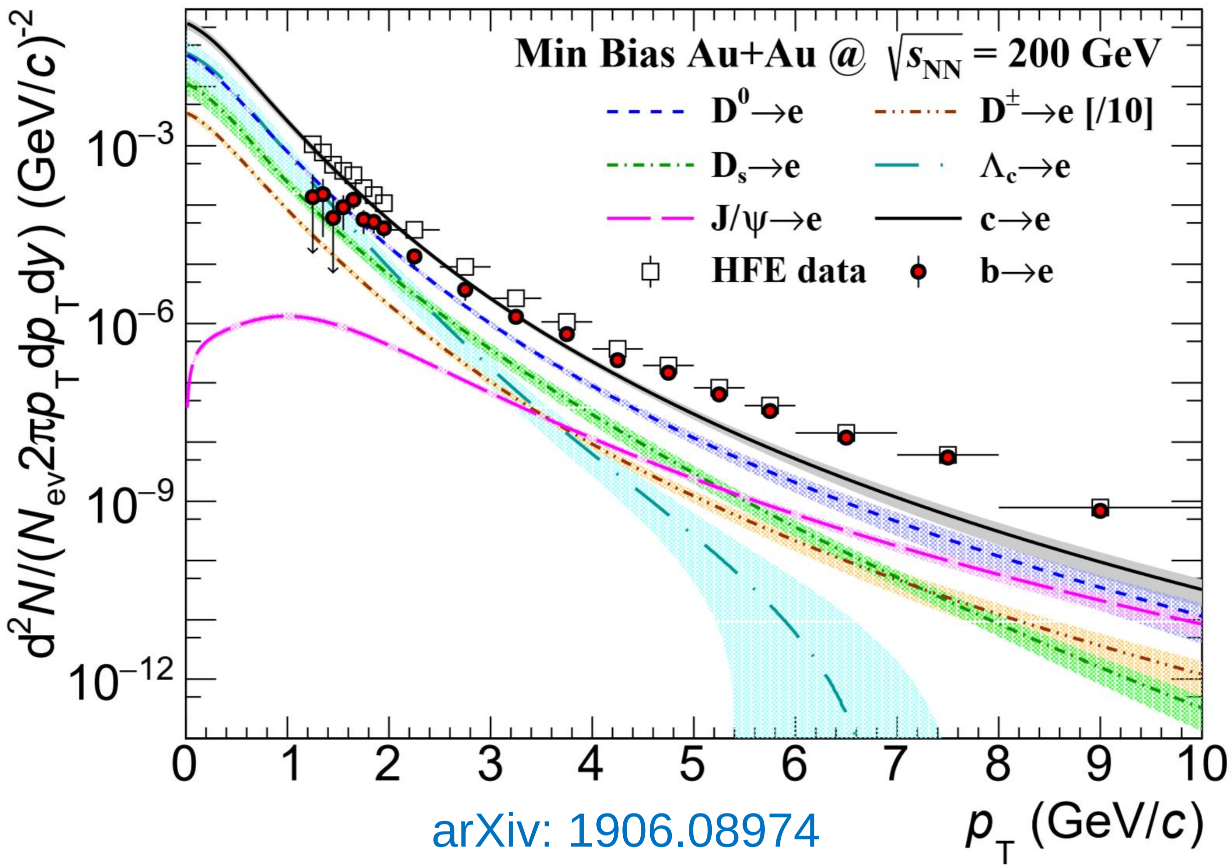
Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

Measurements	Centrality	Reference
D^0	0-80%	PRC **99**, 034908 (2019)
$D^{\pm}$	0-10%	NPA **967**, 620-623 (2017)
D_s	10-40%	
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 and branching ratios.
- Electron spectra from D_s, Λ_c and J/ψ are scaled by N_{bin} ratios to 0-80% centrality.
- c⟶e spectrum: summed contribution of charmed hadrons.
- b⟶e spectrum: extracted from inclusive HFE.

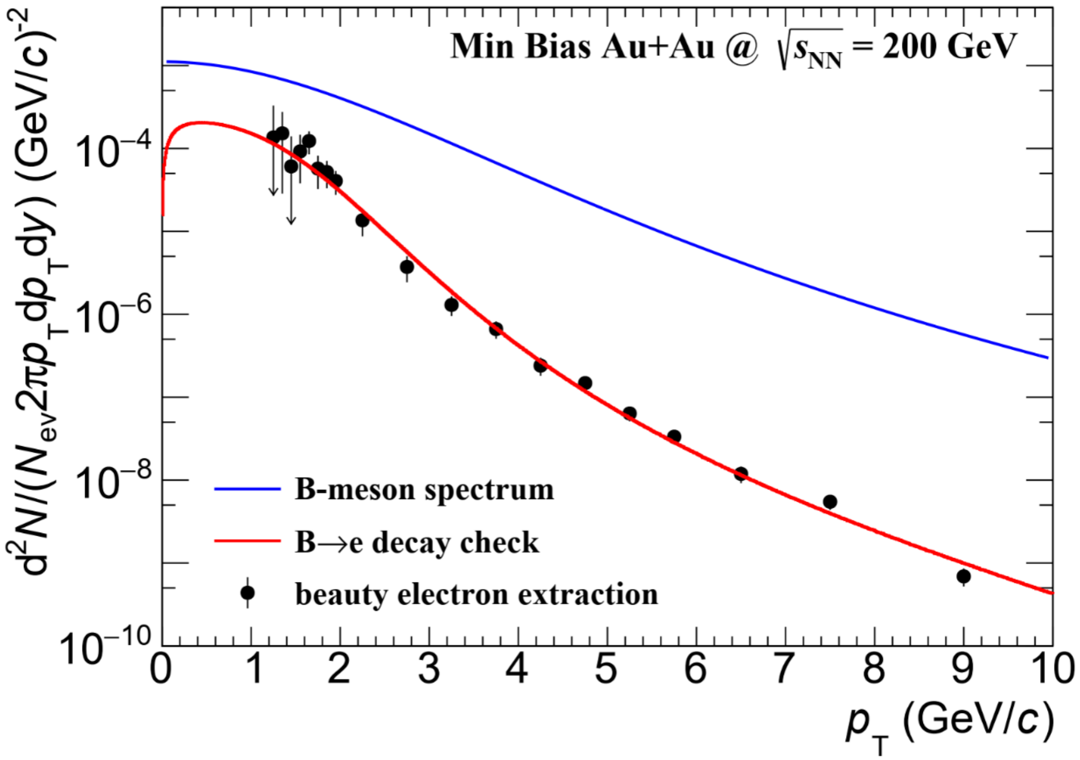


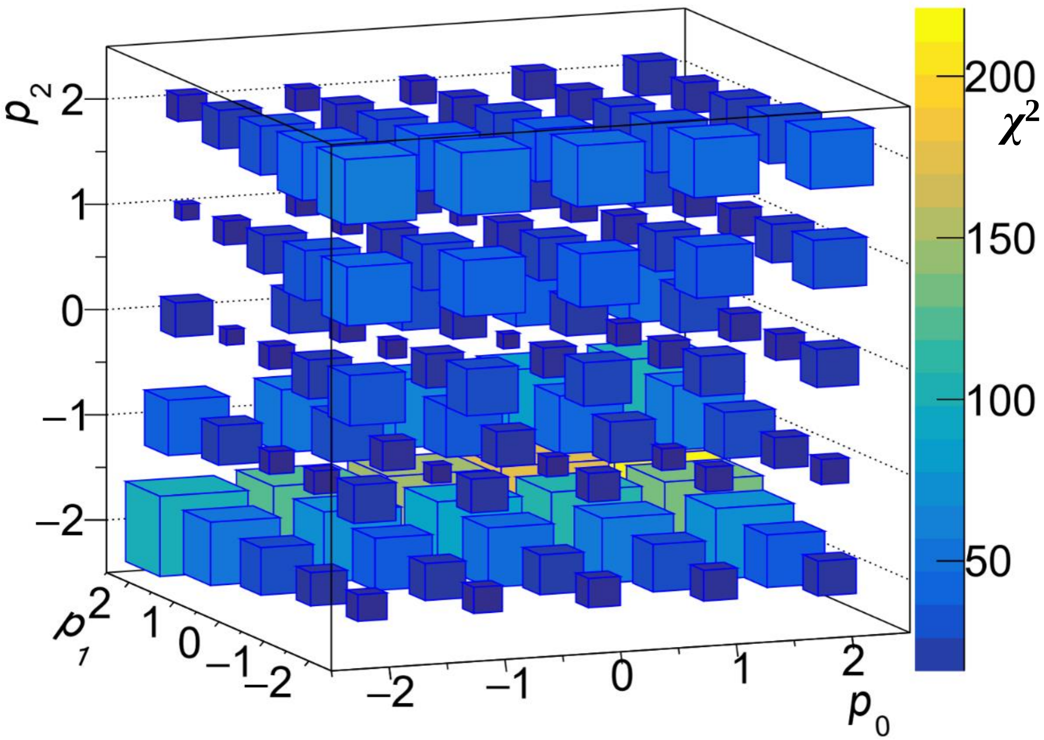
arXiv: 1906.08974

B-meson spectrum unfolding

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

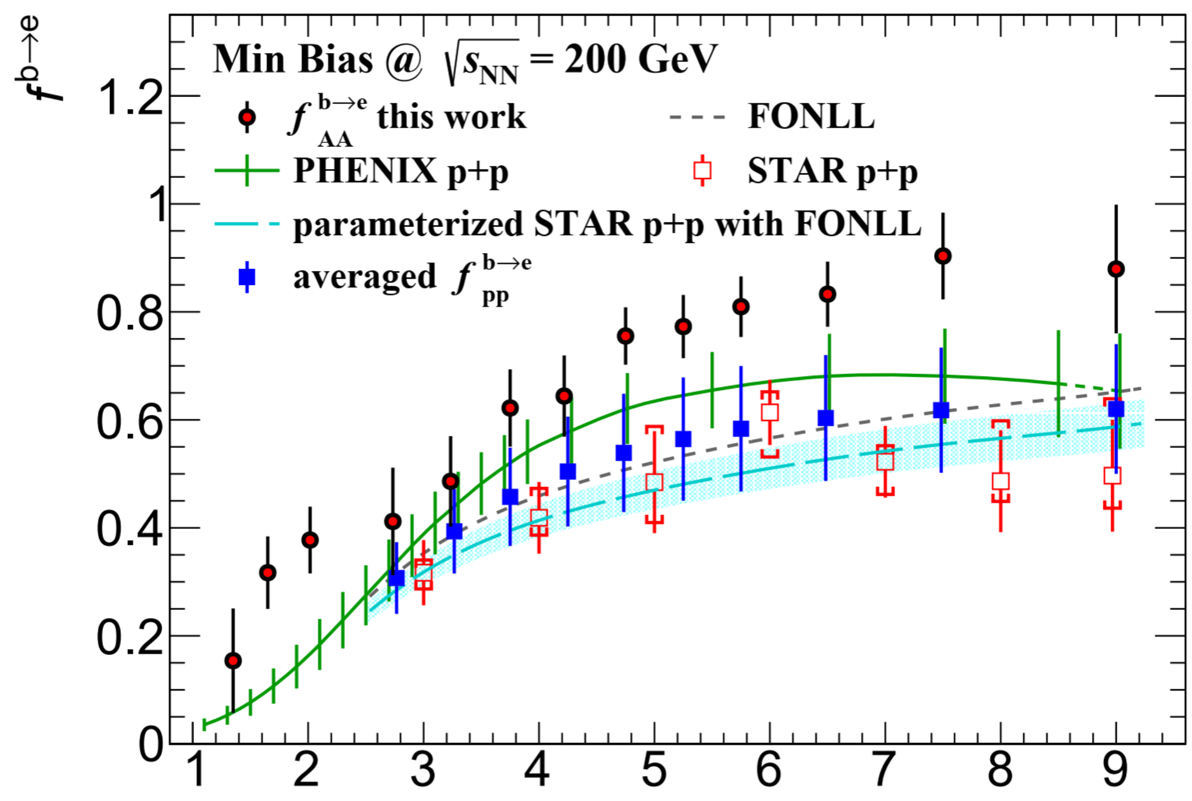
- Assume B-meson spectrum follows Levy function.
- Apply iteration until its electron spectrum fits the extraction. (χ^2/ndf =16.55/19)
- Decay check: change each parameter (step: 5%) of the B-meson spectrum function and calculate χ^2.





Beauty Contribution

- $f^{\mathrm{b\to e}} = \frac{\mathrm{b\to e}}{\mathrm{HFE}} = 1 - f^{\mathrm{c\to e}}$
- At $p_{\mathrm{T}} \sim 3.5$ GeV/c, $f^{\mathrm{b\to e}} \sim 50\% \sim f^{\mathrm{c\to e}}$.
- $f_{\mathrm{AA}}^{\mathrm{b\to e}}$ 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

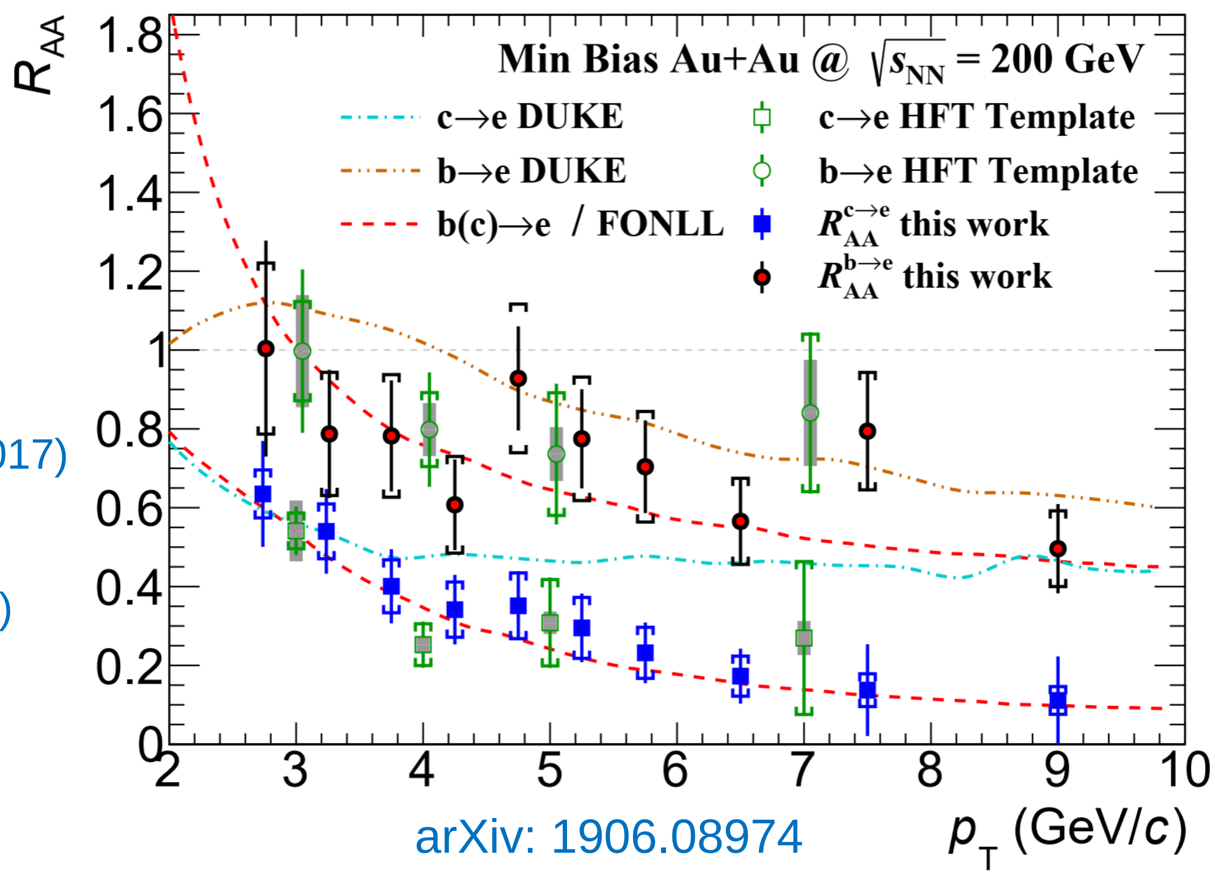
- $R_{AA}^{b\to e} = \frac{f_{AA}^{b\to e}}{f_{pp}^{b\to e}} R_{AA}^{HFE}$

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

Our work
arXiv: 1906.08974

HFT Template
Nucl. Phys. A **967**, 632-635 (2017)

DUKE
Phys. Rev. C **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

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Nucl. Phys. A **967**, 632-635 (2017)

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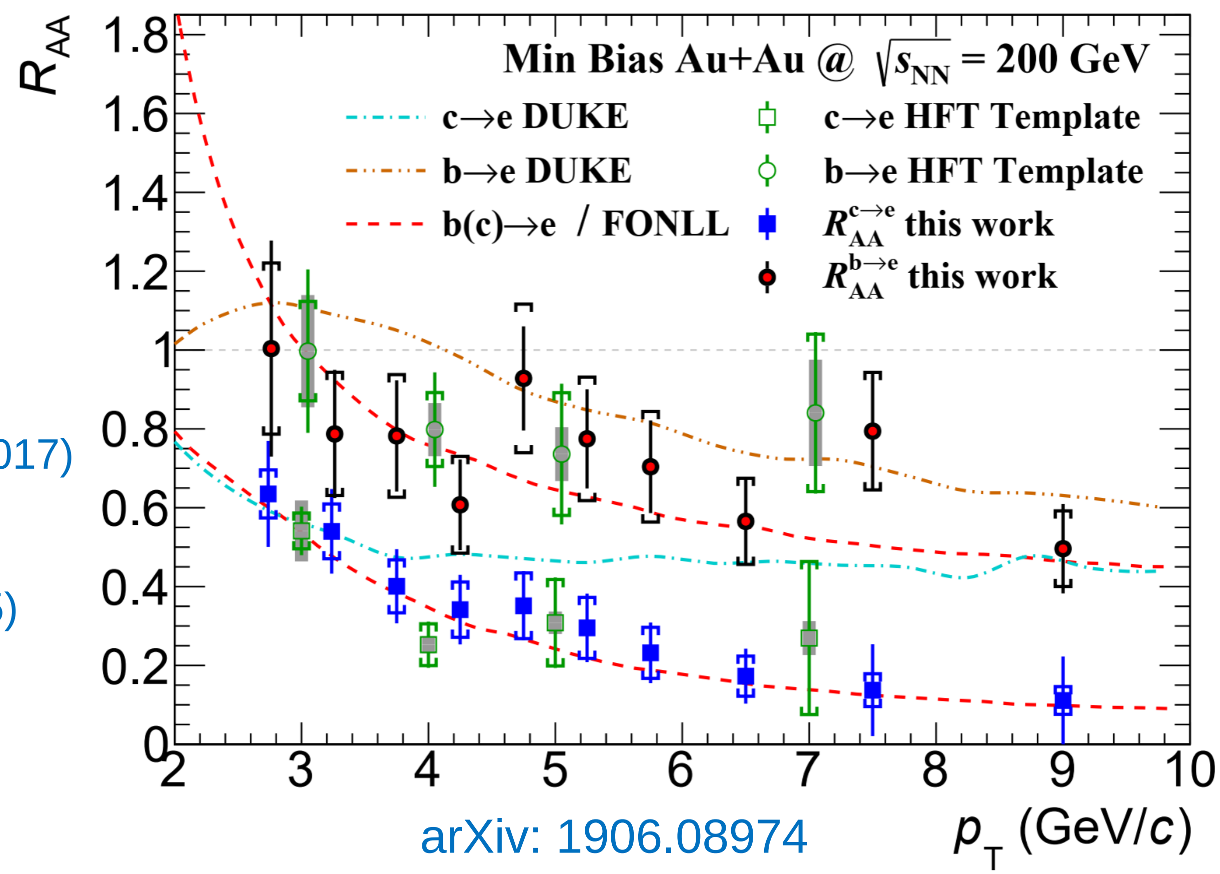


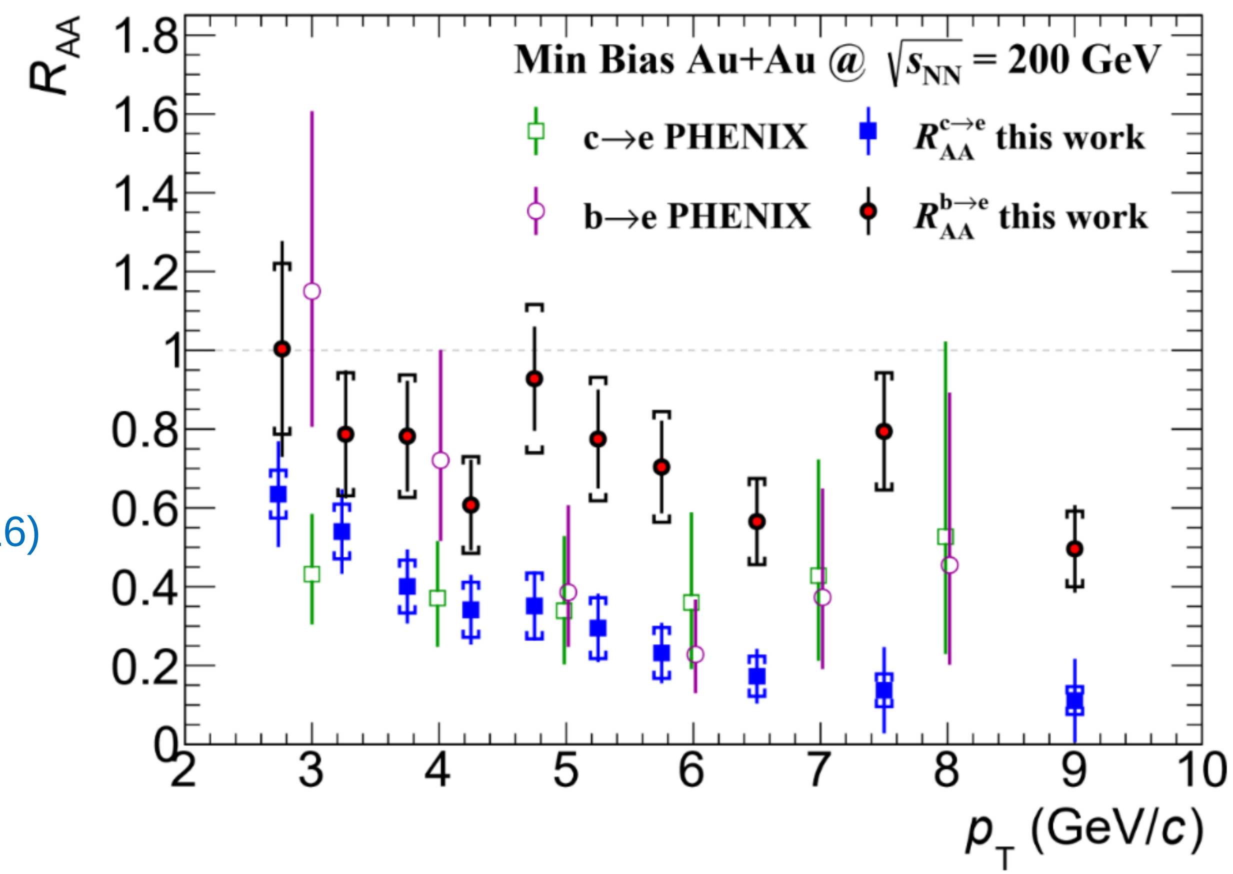
arXiv: 1906.08974

R_{AA} isolation

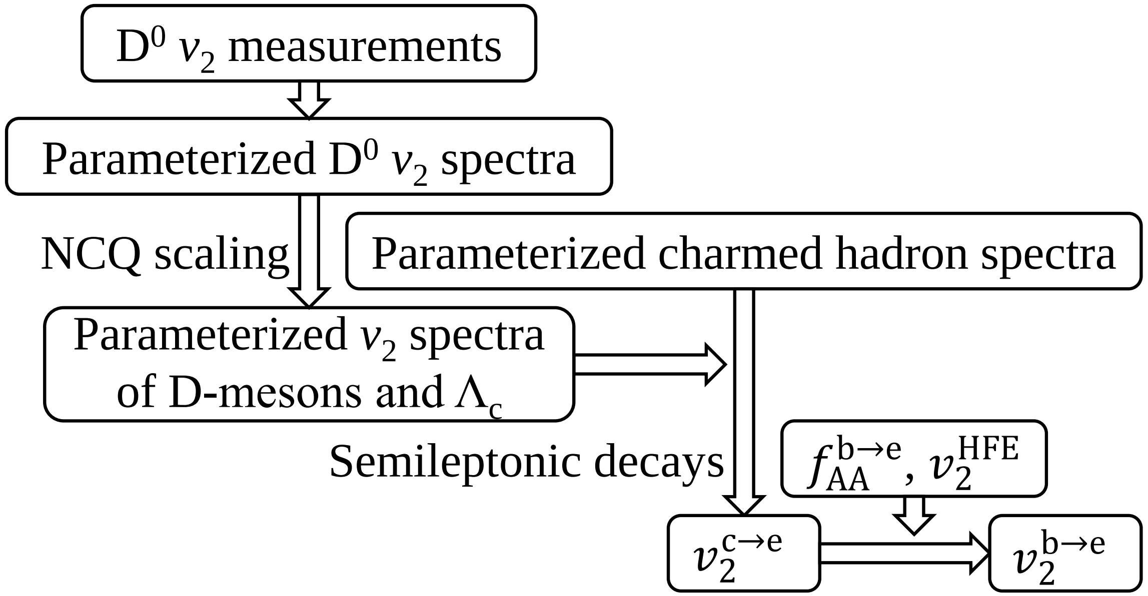
- An agreement with PHENIX ones within uncertainties.
- Improve the precision.
- Isolate charm and beauty.
- Show clear mass dependence of energy loss.

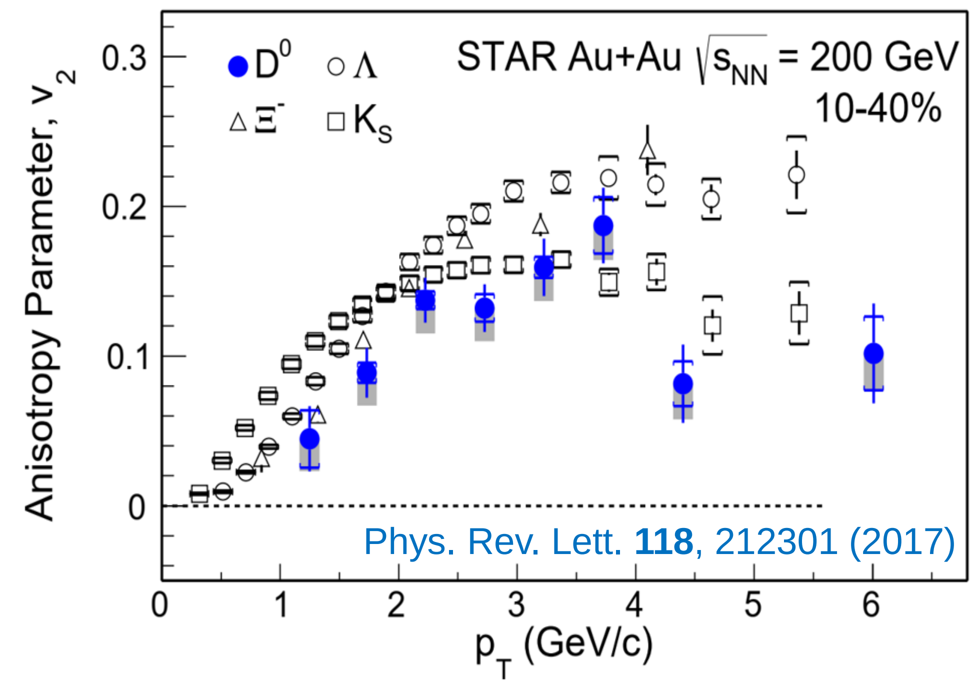
Our work
arXiv: 1906.08974

PHENIX
Phys. Rev. C **93**, 034904 (2016)



v_2 isolation method





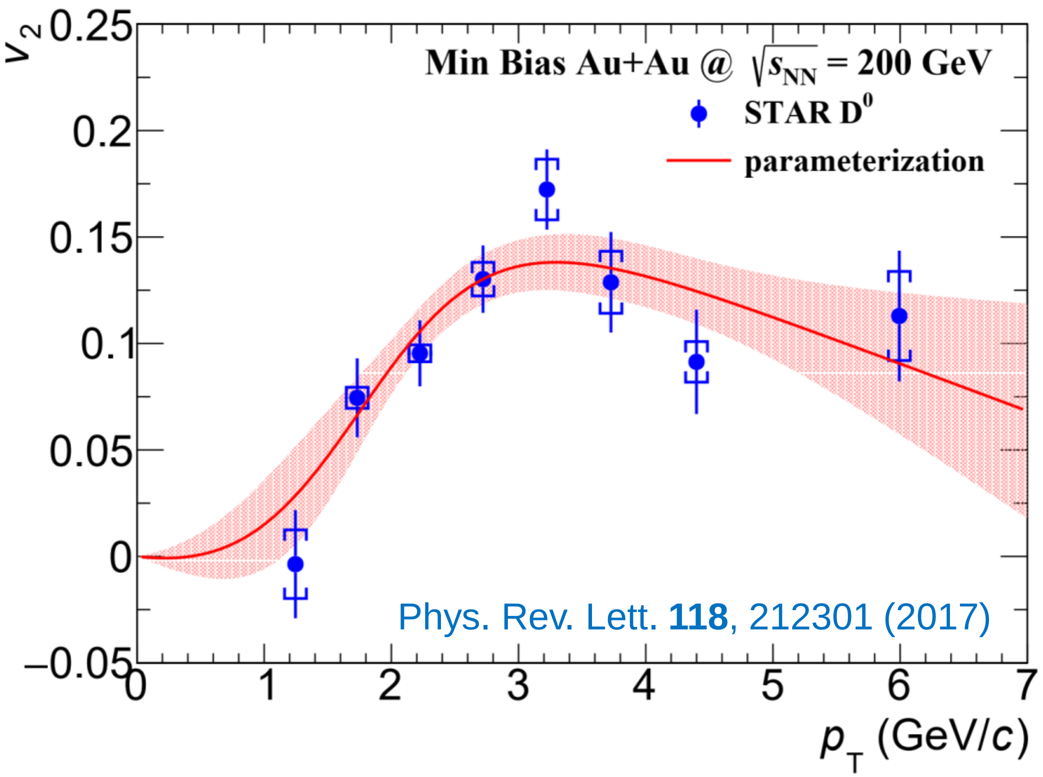
- $E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\{1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi_r)]\}$
- Elliptic flow (v_2): 2nd coefficient of Fourier expansion.
- Azimuthal angle (ϕ) distribution: $\frac{dN}{d\phi} = 1 + 2v_2\cos(2\phi)$.
- $v_2^{c\to e}$: average of $v_2^{D\to e}$ and $v_2^{\Lambda_c\to e}$ weighted by relative yields.
- Same as $v_2^{HFE} \Rightarrow v_2^{b\to e} = \frac{v_2^{HFE} - (1 - f_{AA}^{b\to e}) v_2^{c\to e}}{f_{AA}^{b\to e}}$

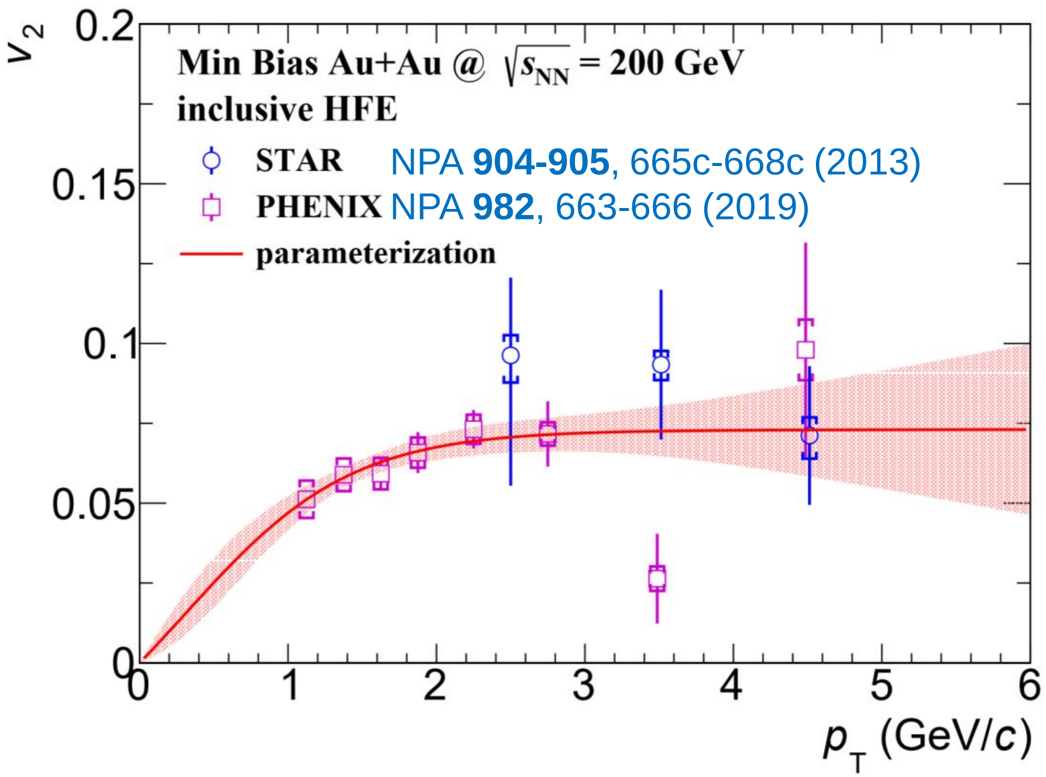
v_2 parameterization

- Parameterization function:

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

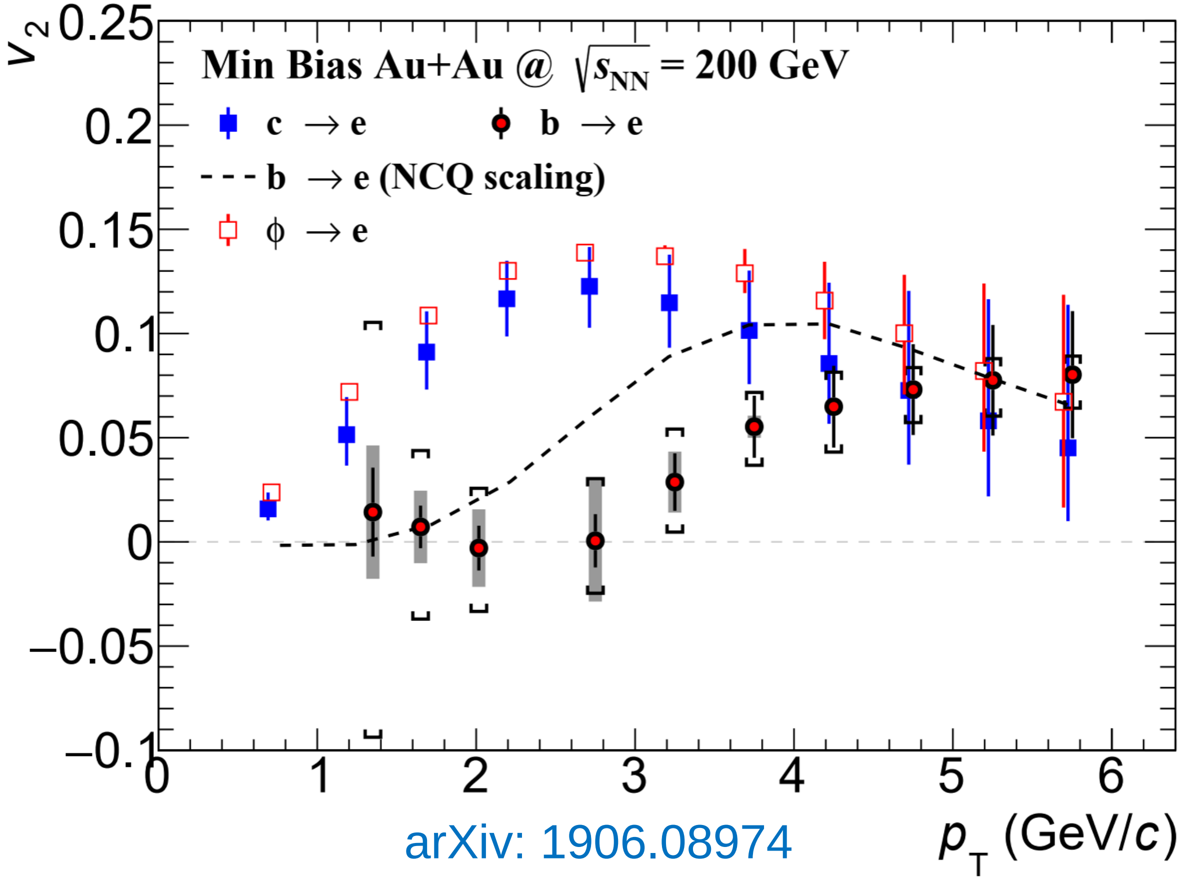
- The uncertainty band of D^0 v_2 from parameterization is input and propagated to the electron v_2 spectra.





v_2 isolation

- Charm seems like light quarks ($v_2^{c\to e}$ and $v_2^{\phi\to e}$).
- 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 too heavy to be moved at RHIC.



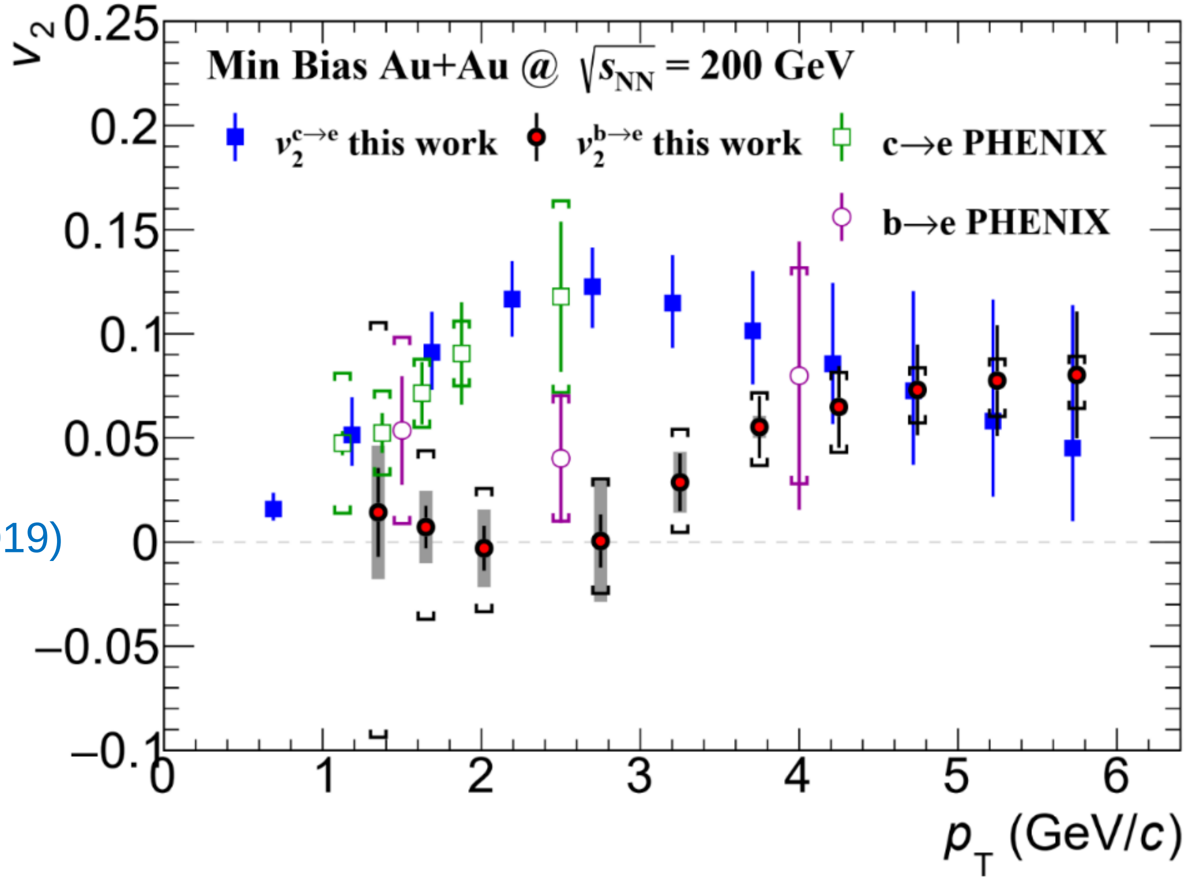
arXiv: 1906.08974

v_2 isolation

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

Our work
arXiv: 1906.08974

PHENIX
Nucl. Phys. A 982, 663-666 (2019)



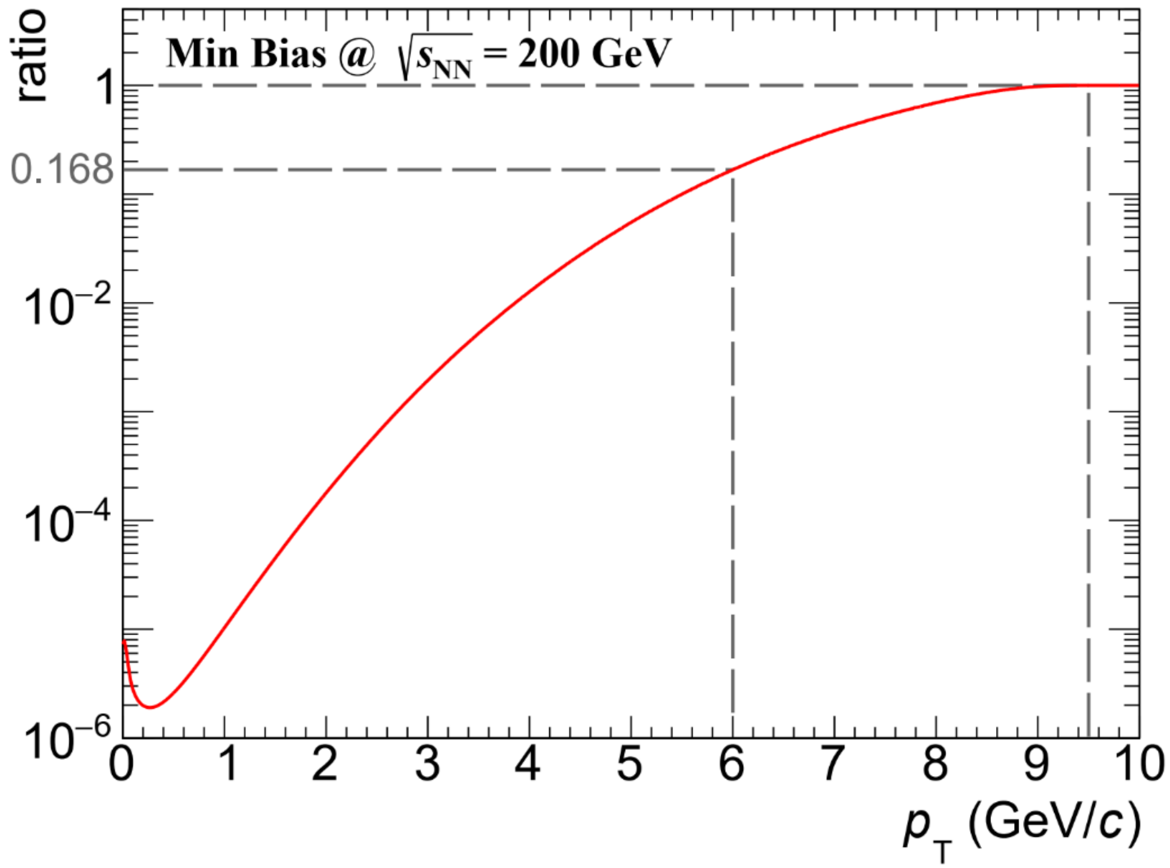
Summary

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



B-meson v_2

Attempt to obtain B-meson v_2 spectrum from b→e v_2.

- Apply iteration to search a parameterized v_2 spectrum which can decay to the b→e v_2 spectrum obtained before.
- χ^2/ndf =0.72/10