Quark Physics Laboratory
Hiroshima University, Japan

RIKEN

Heavy flavor measurements in p+p, d+Au, and Au+Au collisions at PHENIX

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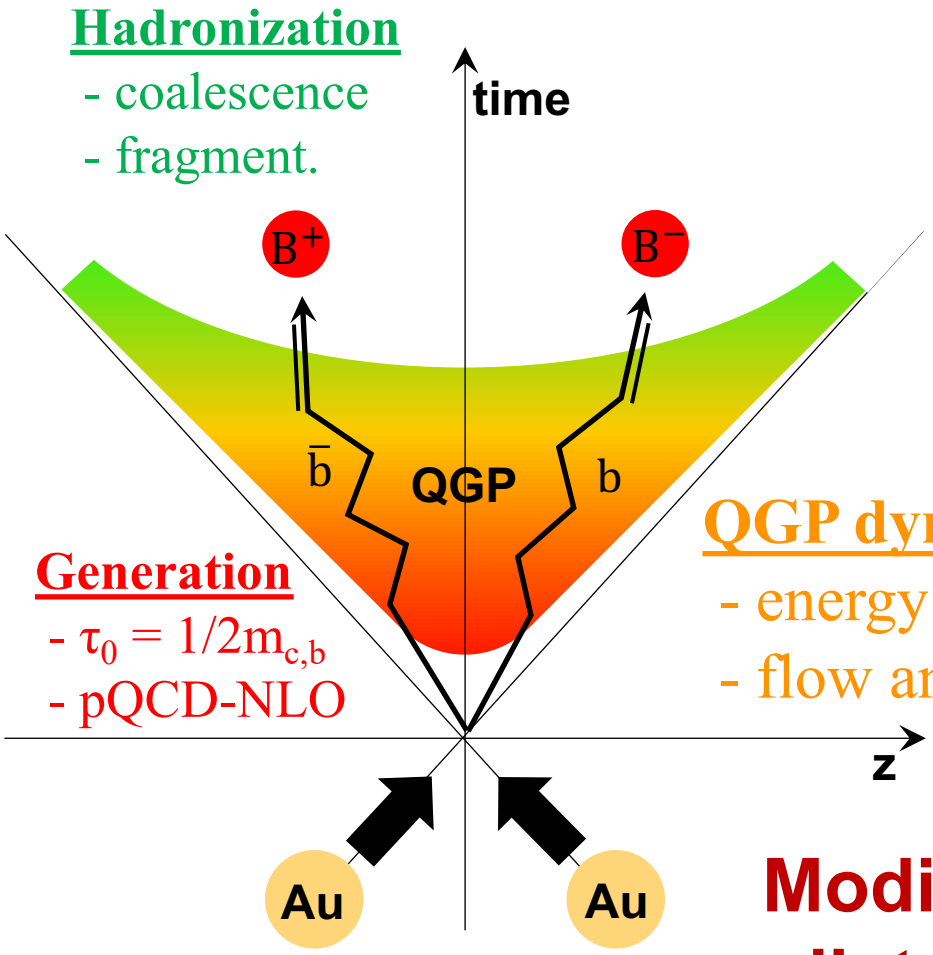
(Hiroshima Univ. / RIKEN)

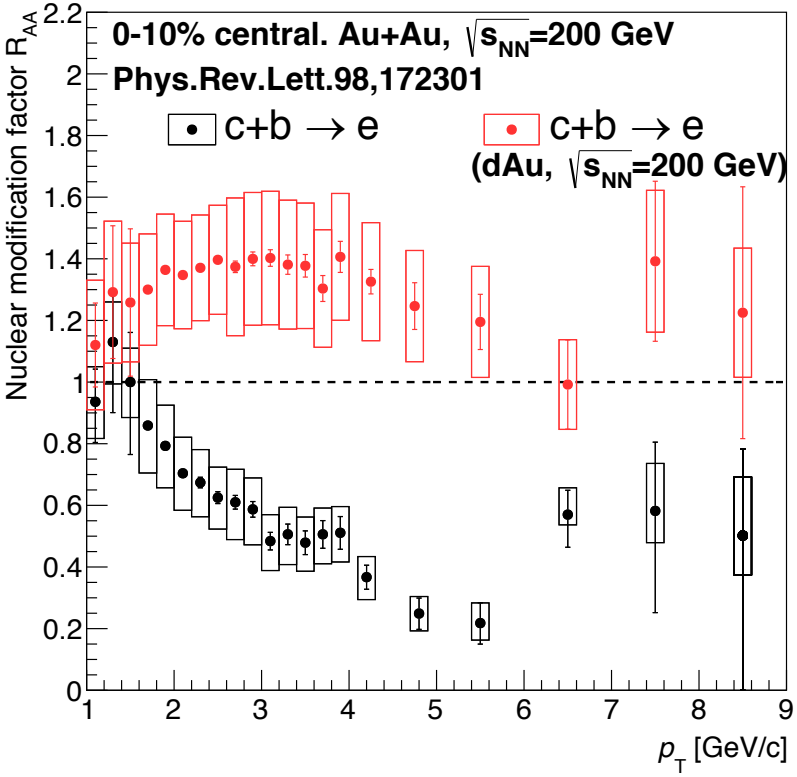
✓ Introduction of Heavy Flavor Probe

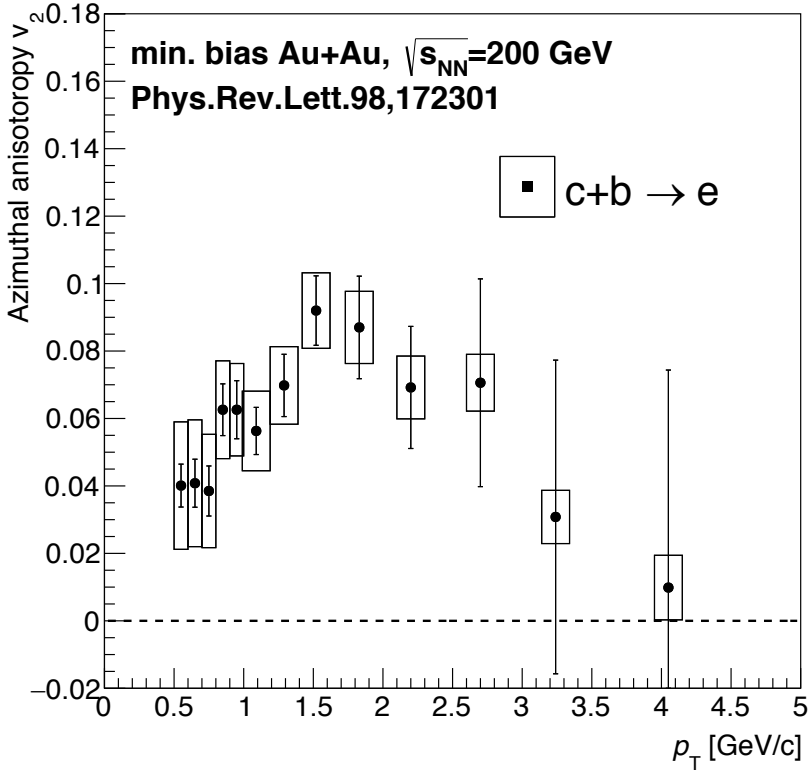


- produced in initial stage ($\tau_0 = 1/2m_{c,b}$)
- probe full time evolution
- conserved HF number

Modification of phase space dist. reflects QGP dynamics!

✓ Previous Heavy Flavor Measurement

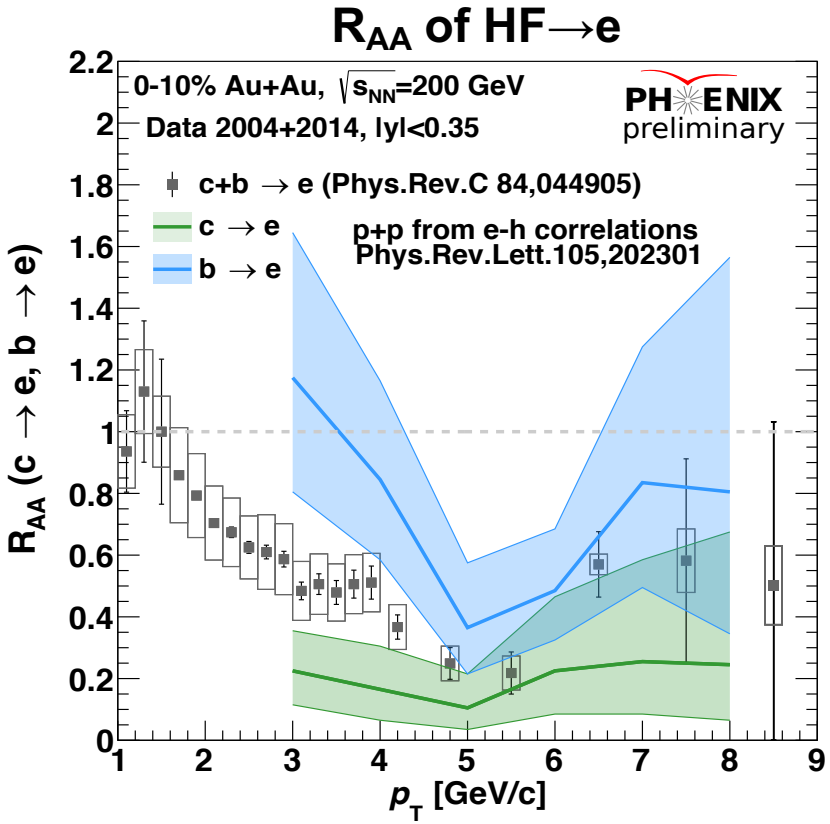


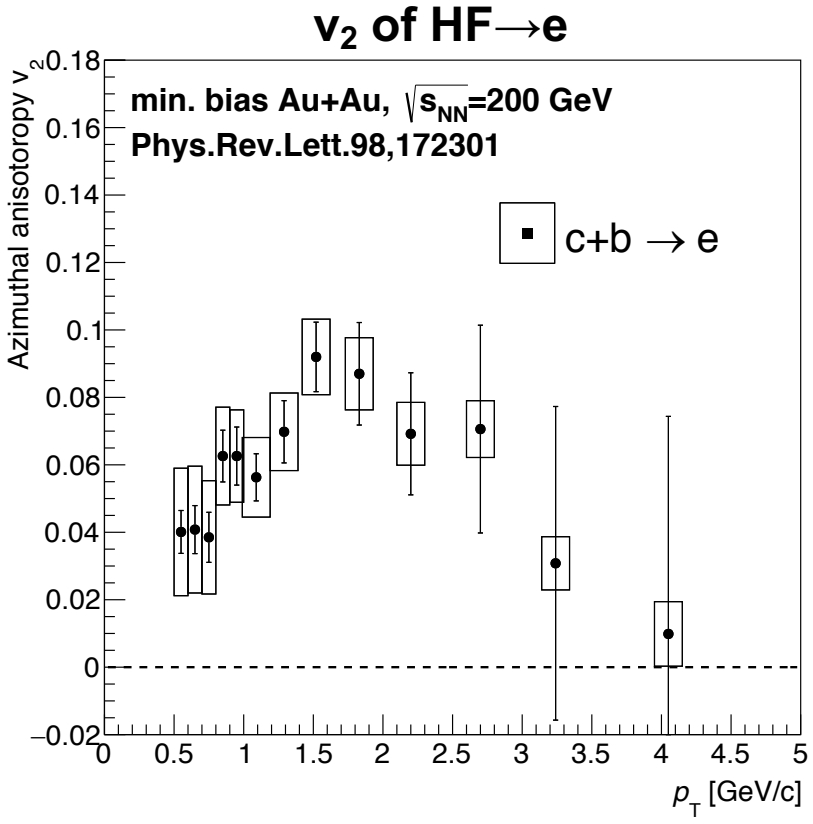


- Strong suppression in Au+Au
- Large CNM in d+Au
- Quark mass dependence?

- Large v_2 in Au+Au
- v_2 of HF→e in d+Au?
- Quark mass dependence?

✓ Previous Heavy Flavor Measurement





- Strong suppression in Au+Au
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- Quark mass dependence?

- Large v_2 in Au+Au
- v_2 of HF→e in d+Au?
- Quark mass dependence?

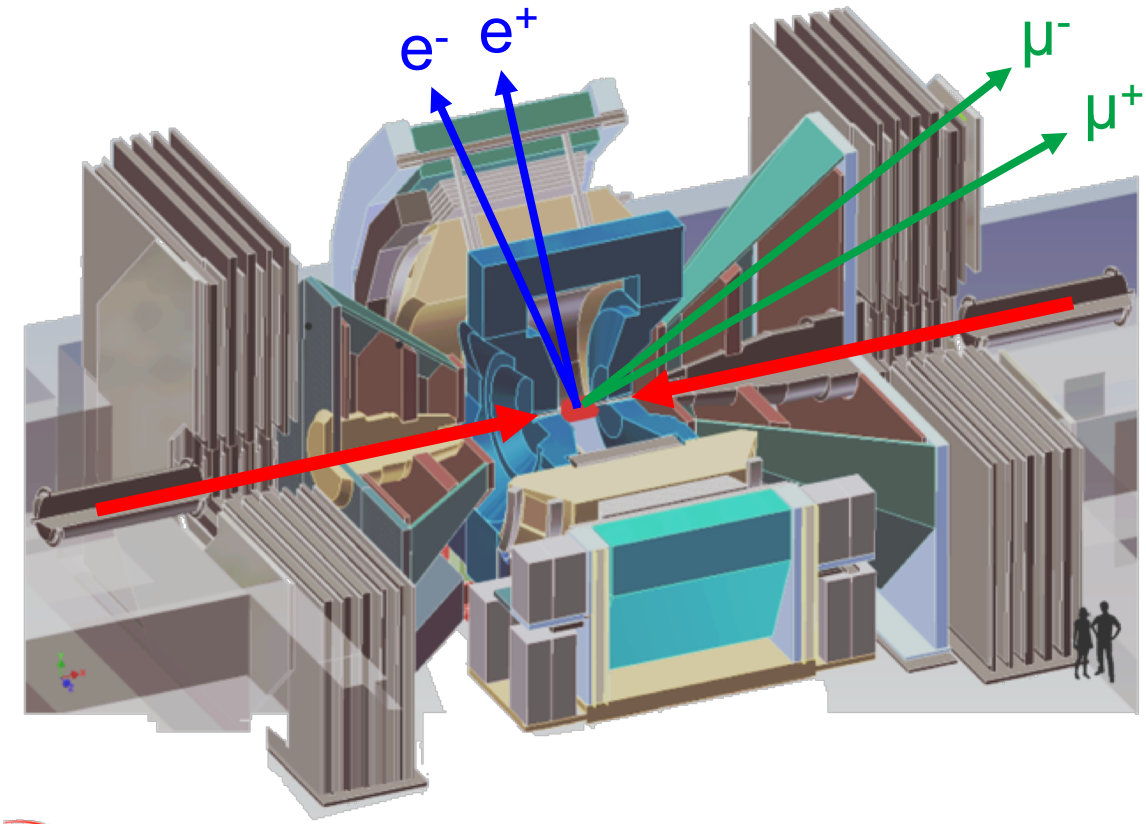
✓ Heavy Flavor Measurement at PHENIX

Mid-rapidity

electrons at Central arm
(with RICH and EMCal)
$\varphi = \pi$, $|\eta| = 0.35$

Forward-rapidity

muons at Muon arm
absorber: 7.2 X_{int}
$\varphi = 2\pi$, $1.2 < |\eta| < 2.2$



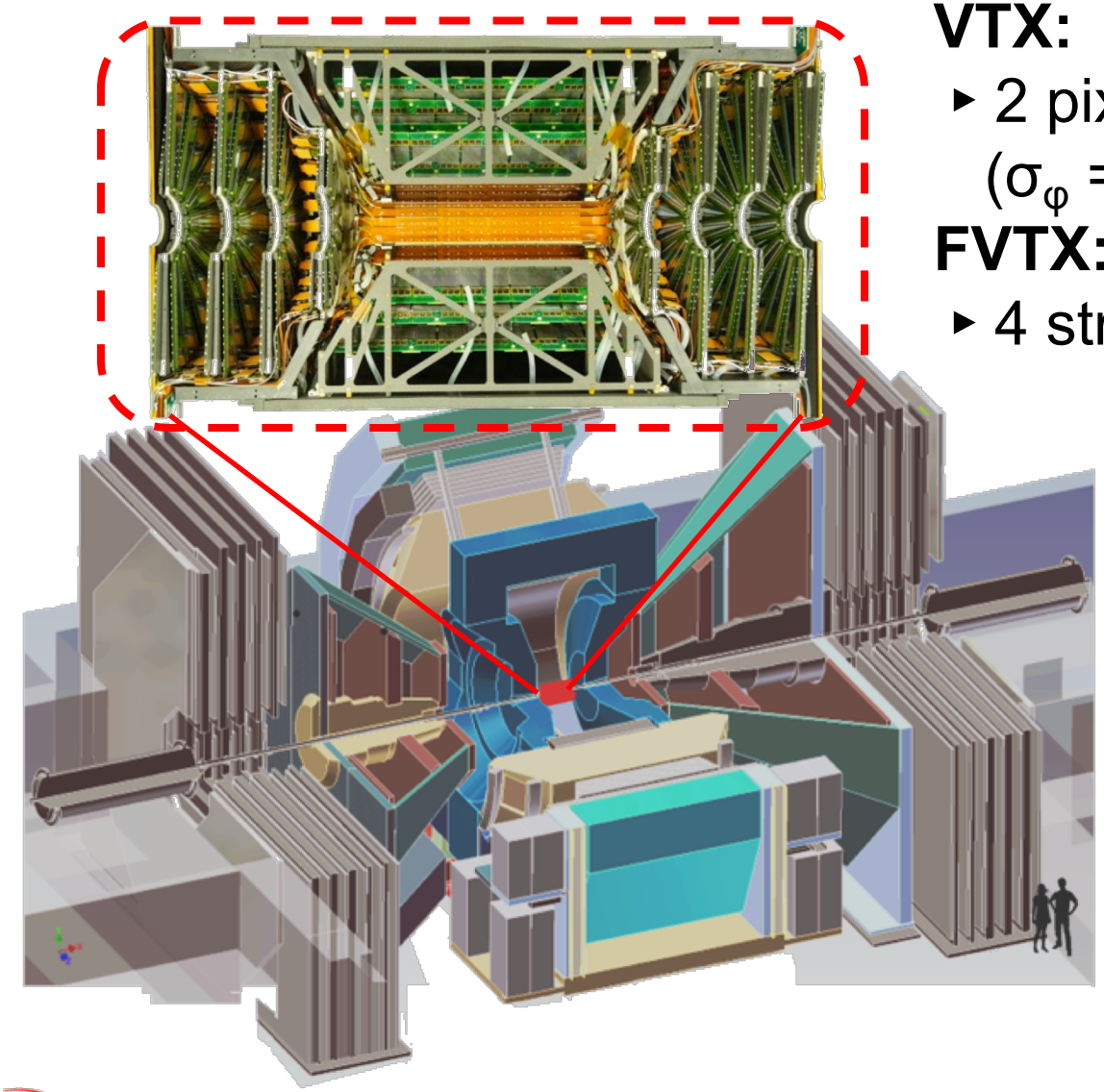
Collision systems

p+p, p+Al, p+Au, d+Au,
^{3}He+Au, AuAu, CuAu

Collision energies

20 ~ 200 ~ 510 GeV/c

✓ Silicon Vertex Detector at PHENIX



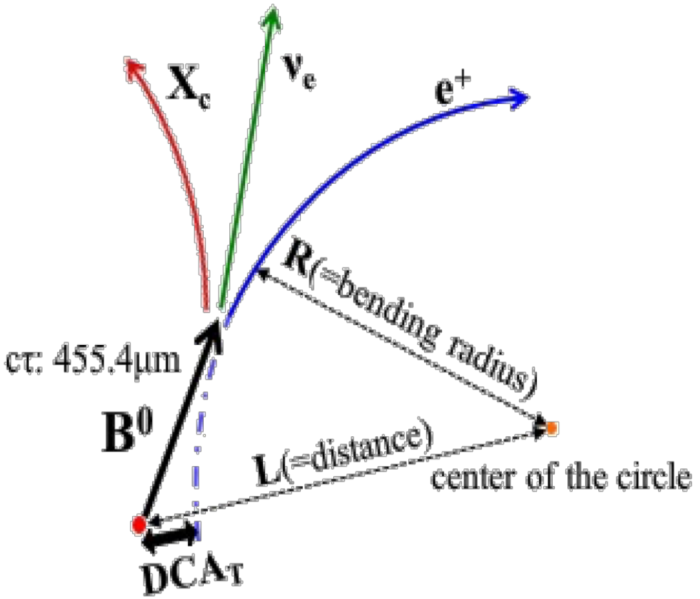
VTX:

- 2 pixel layers + 2 strip layers
  (σ_φ = 14.4 μm) (σ_φ = 23 μm)

FVTX:

- 4 strip layers (σ_φ = 75 μm)

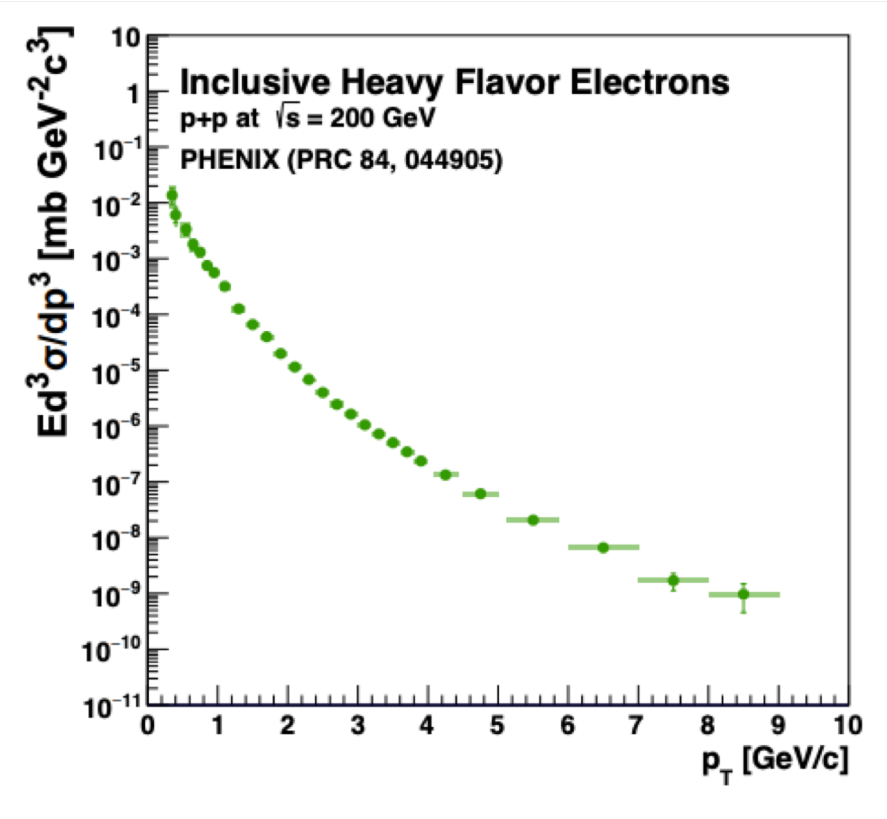
Displaced vertex analysis

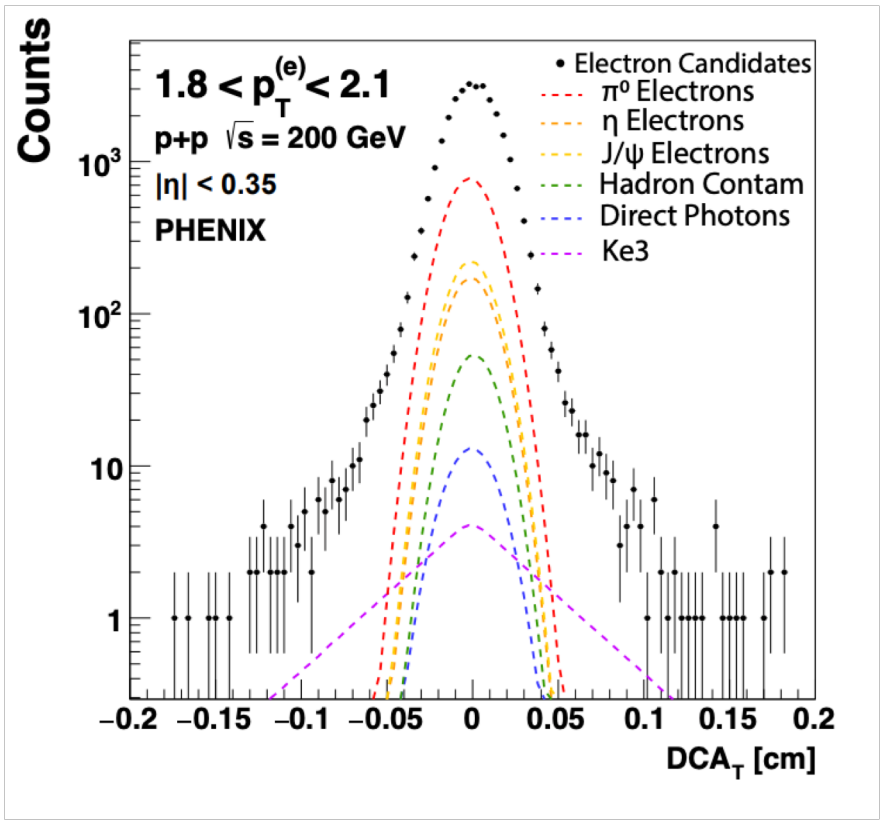


Heavy Flavor Results in Small System (p+p)

→ baseline and production mechanism

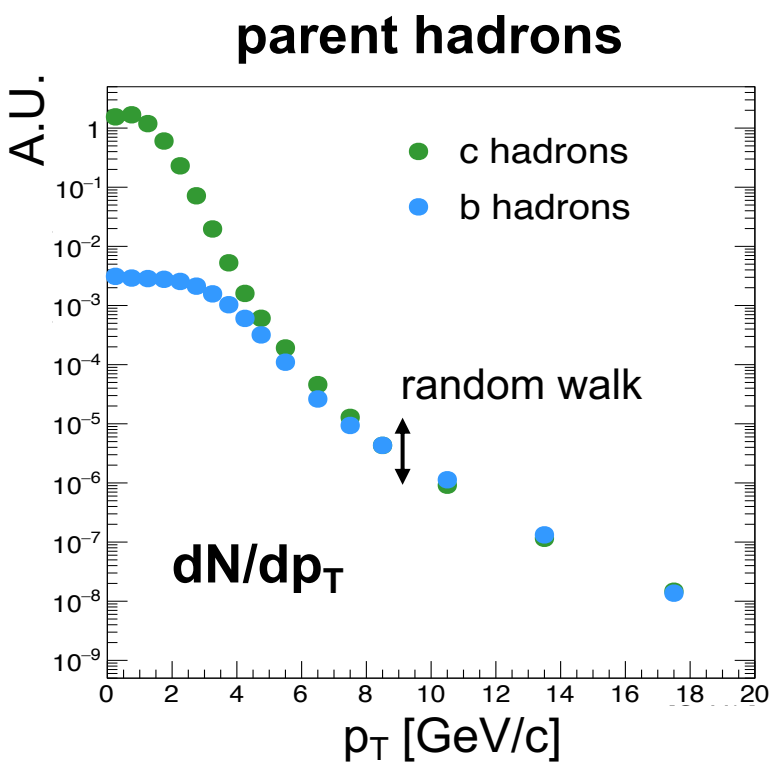
✓ Single electron analysis in p+p



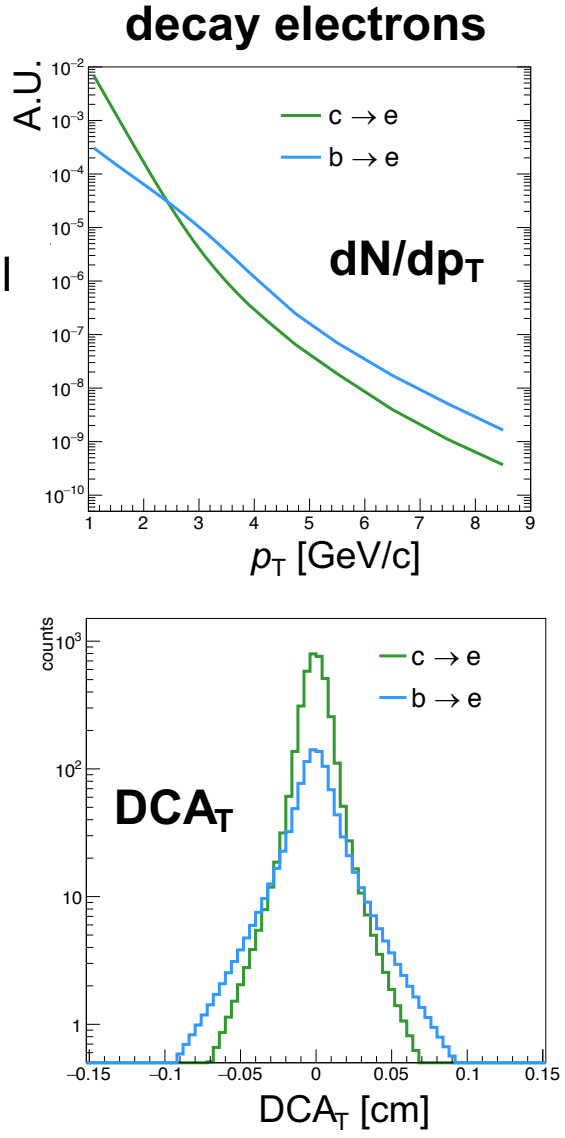


- Displaced vertex analysis at mid-rapidity
  - provides charm/bottom separation
- Unfolding problem on DCA template fit...

✓ c/b separation with Bayesian inference

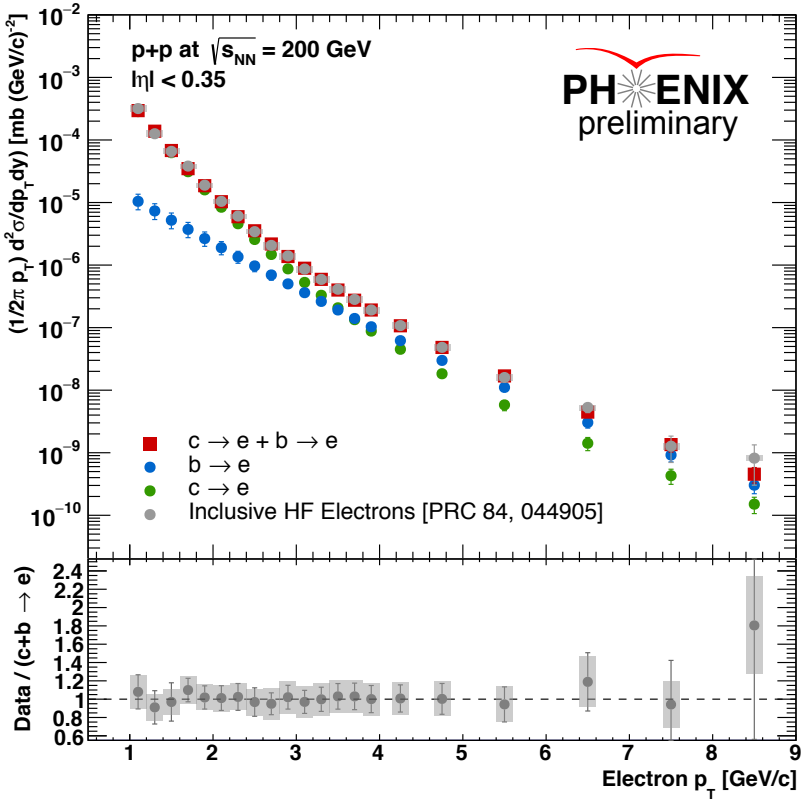


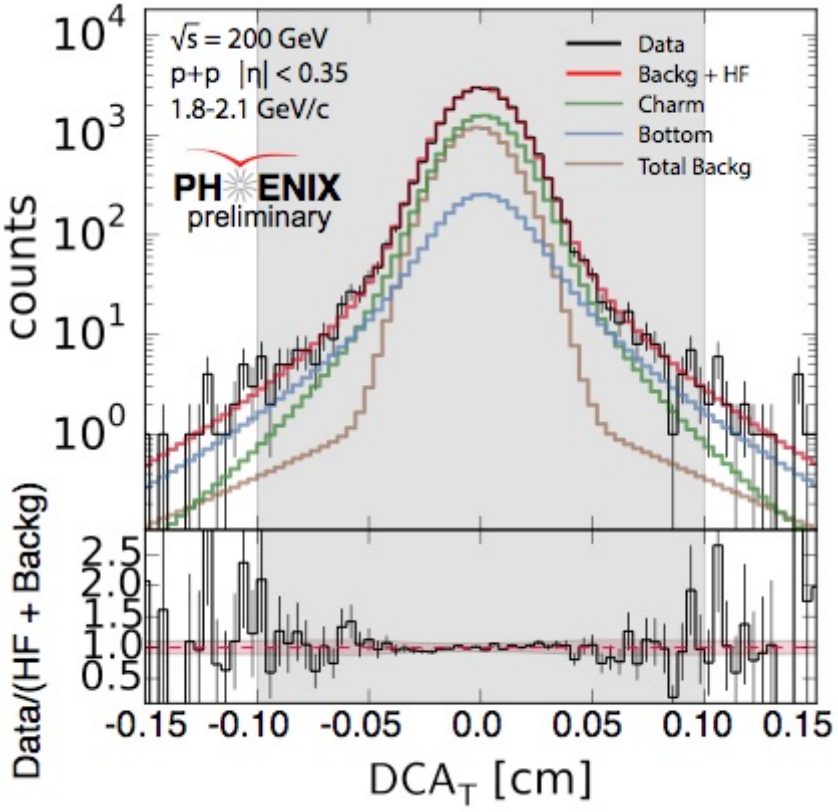
decay model (PYTHIA6)



1. predict parent hadron dN/dp$_T$
2. convert to decay e space
3. fit to data in decay e space
4. require spectrum smoothness

✓ Invariant Yield of c→e and b→e in p+p



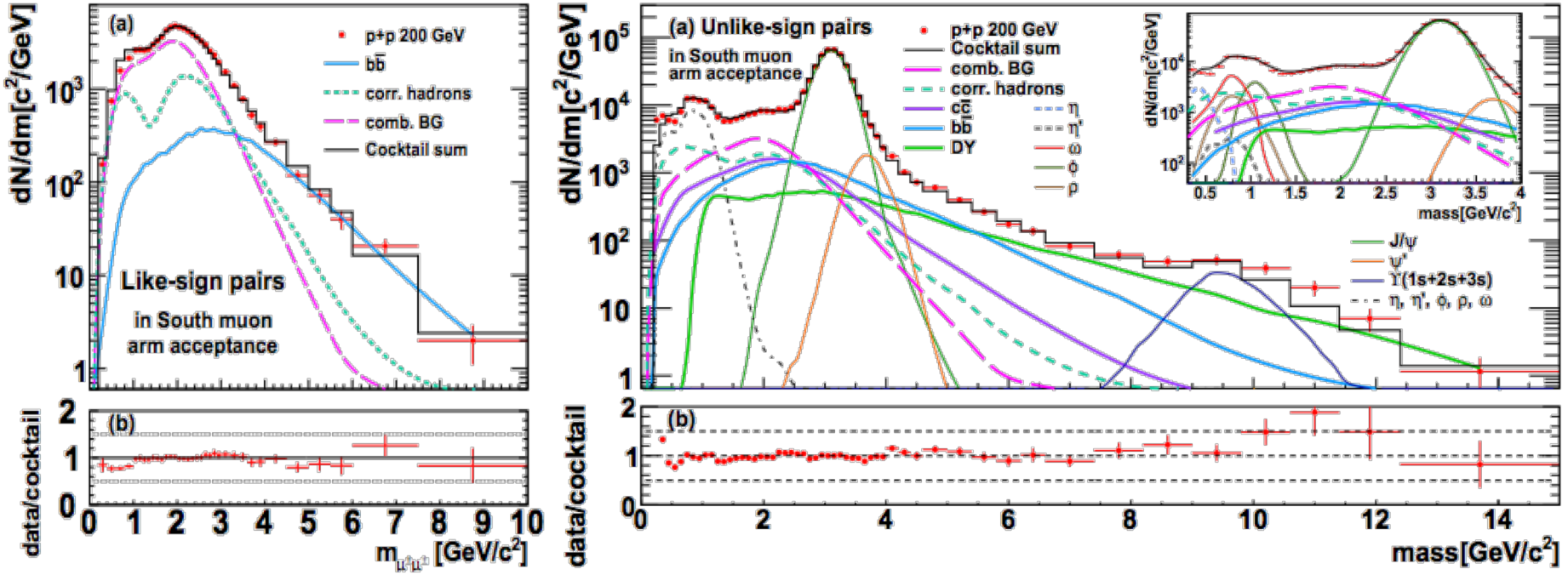


- Unfold x-section of parent c,b hadron
  - refold simultaneous invariant yield and DCA_T distribution
- Precision baseline measurement for Au+Au collisions

✓ Di-muon mass spectrums in p+p

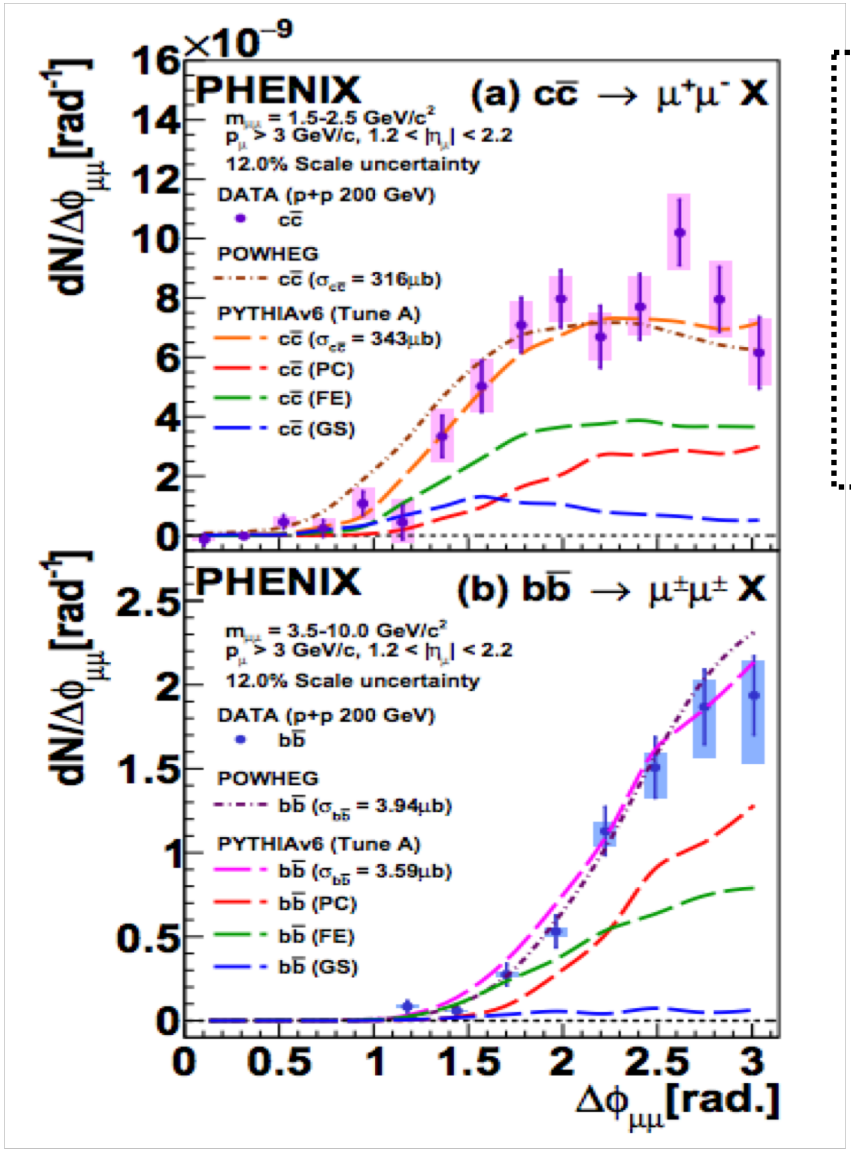
Like sign pairs

Un-like sign pairs

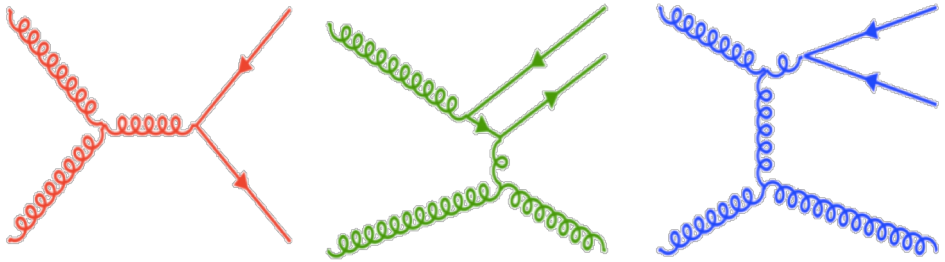


- high mass spectrum provides high S/B for $c\bar{c}$, $b\bar{b}$
  - $b\bar{b}$ dominates in like sign pairs
- Extraction of x-section of $c\bar{c}$ and $b\bar{b}$ with cocktail

✓ Production Mechanism of $c\bar{c}$ and $b\bar{b}$



Fit with 3 templates (from PYTHIA)



Pair creation Flavor excitation Gluon splitting

$c\bar{c}$ production:

- Flavor excitation dominates
- Wider distribution than $b\bar{b}$
  - NLO process dominates

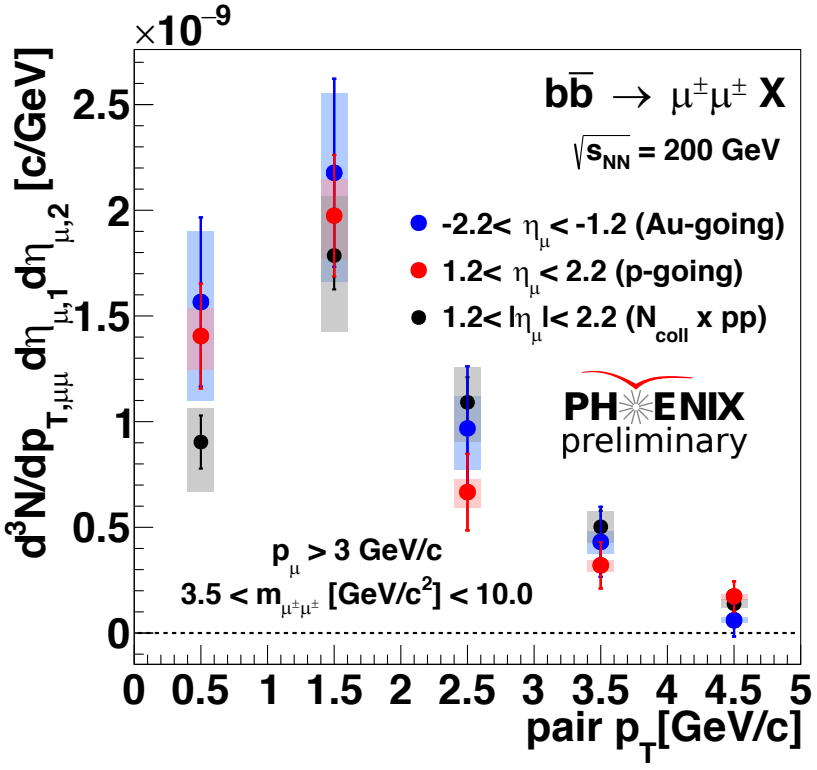
$b\bar{b}$ production:

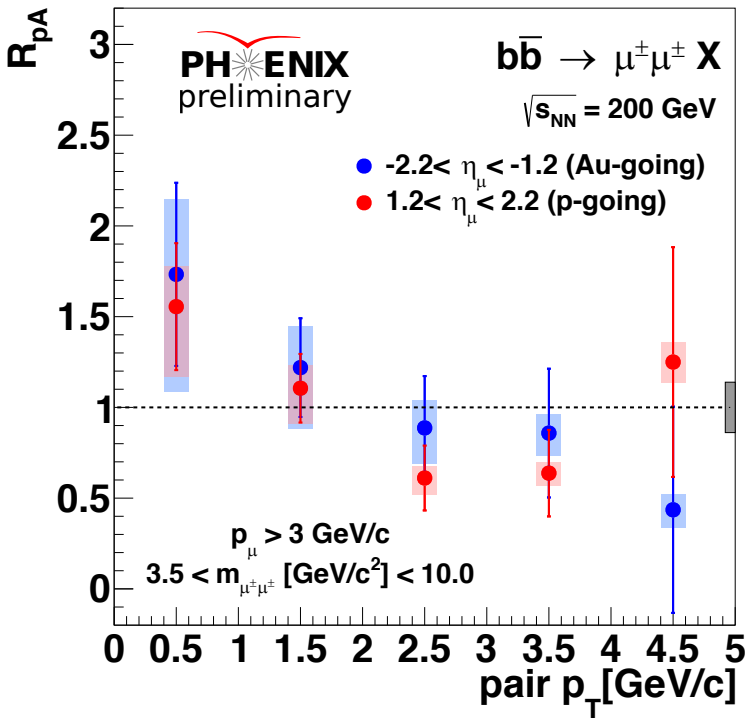
- Pair creation dominates

Heavy Flavor Results in Small System (p,d+Au)

→ CNM effect and Flow

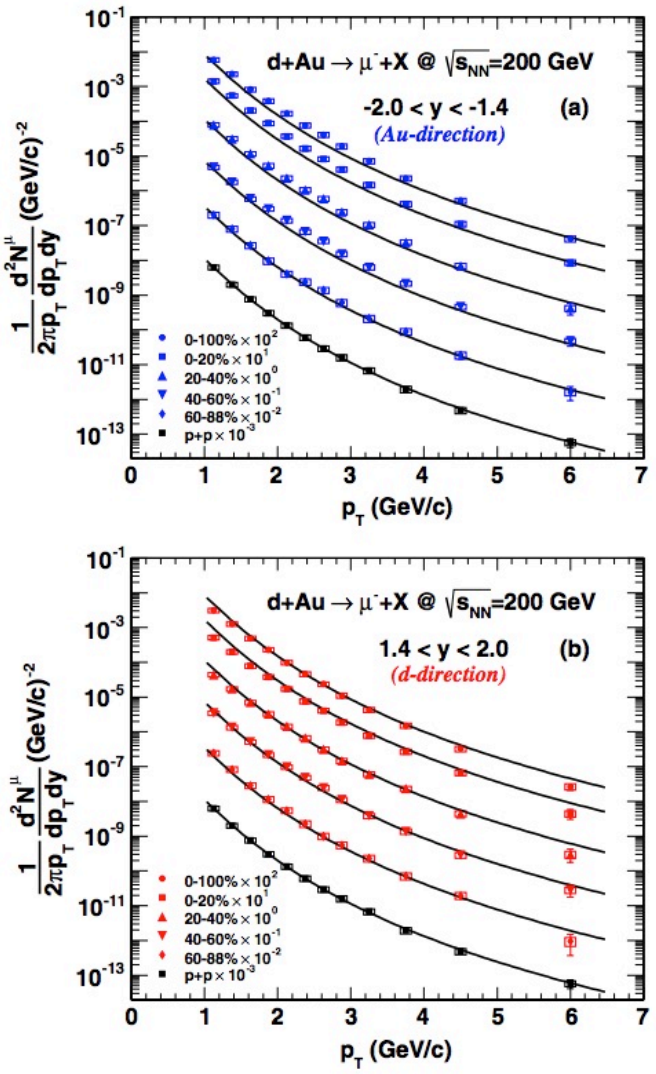
✓ Nuclear Modification of $b\bar{b}$ in p+Au





- Extraction of $b\bar{b}$ x-section from dimuon mass dist.
- R_{pA} shows no modification of $b\bar{b}$
  - high-multiplicity event?

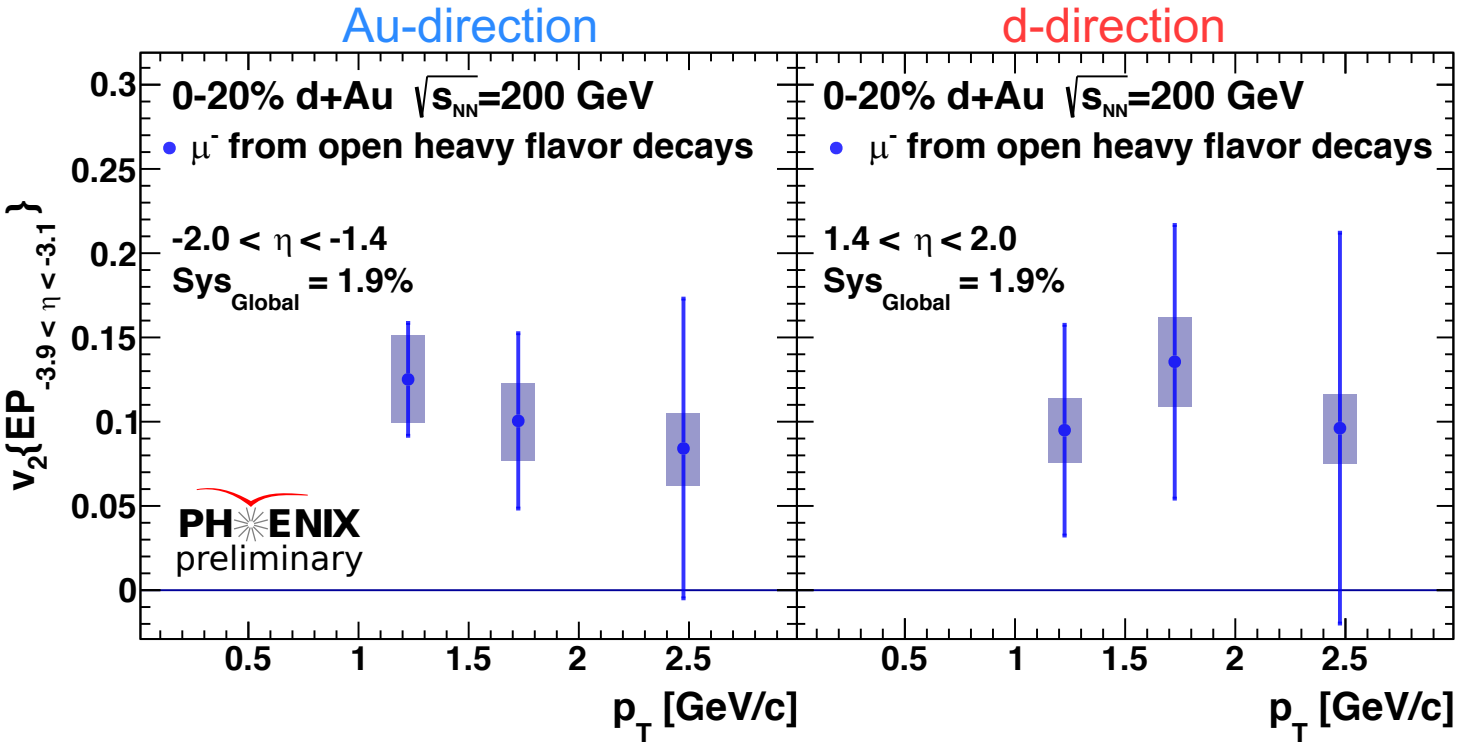
✓ Single muon measurement in d+Au



- Single muons are measured at both Au-direction and d-direction.
- 0-20% high-multiplicity events are used for v_2^{HF} analysis.
- Main background sources:
  - + hadron decay μ
  - + punch thorough hadrons
  - + J/ψ decay μ
- v_2^{HF} is calculated by

$$v_2^{HF} = \frac{1}{F_{HF}}(v_2^{\text{incl.}} - (1 - F_{\text{HF}}) \times v_2^{\text{bg}})$$

✓ Heavy Flavor Anisotropic Flow in d+Au

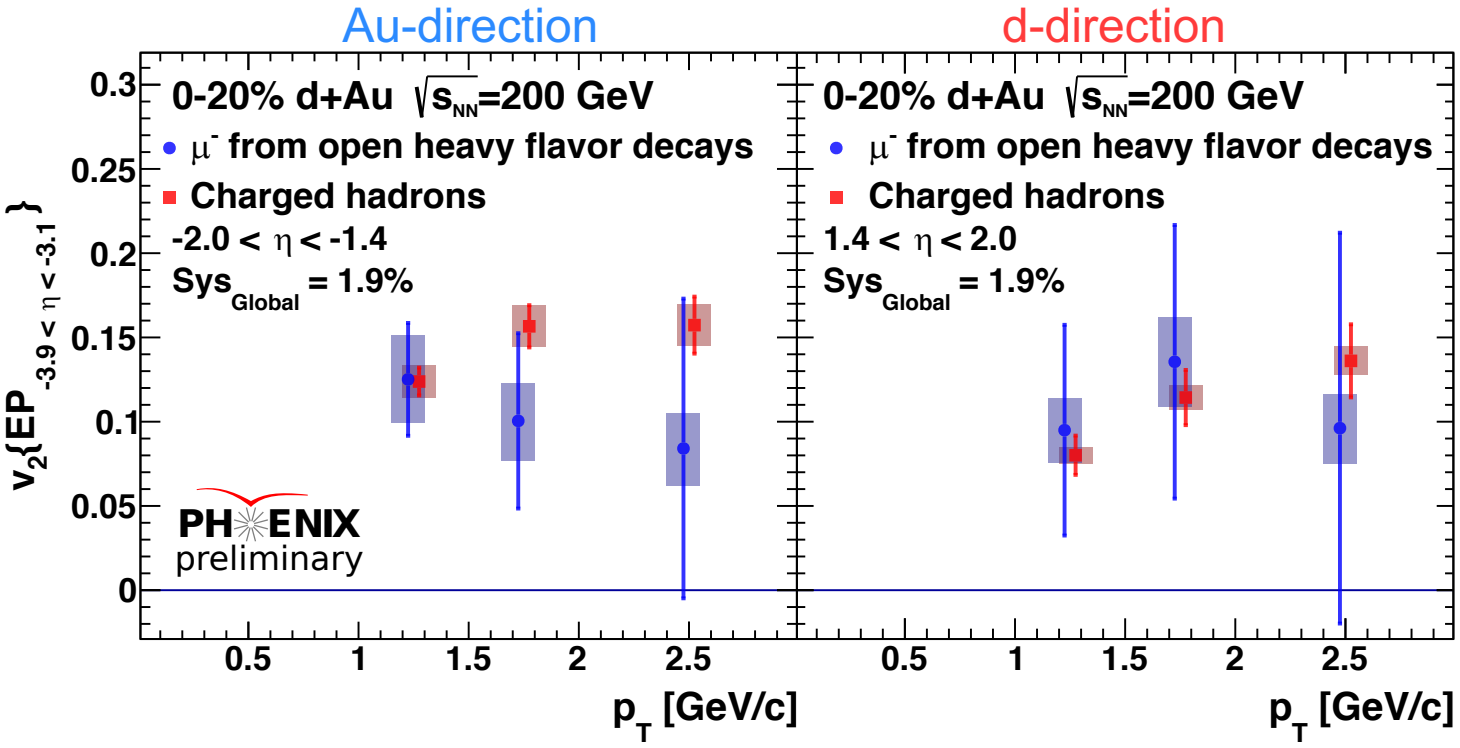


Measured non-zero $v_2^{c+b\to\mu}$ in small collision system

- heavy flavor flows in small collision system?
- similar order of magnitude, $v_2^{c+b\to\mu} \sim v_2^{h}$

→ key to understand flow in small system

✓ Heavy Flavor Anisotropic Flow in d+Au



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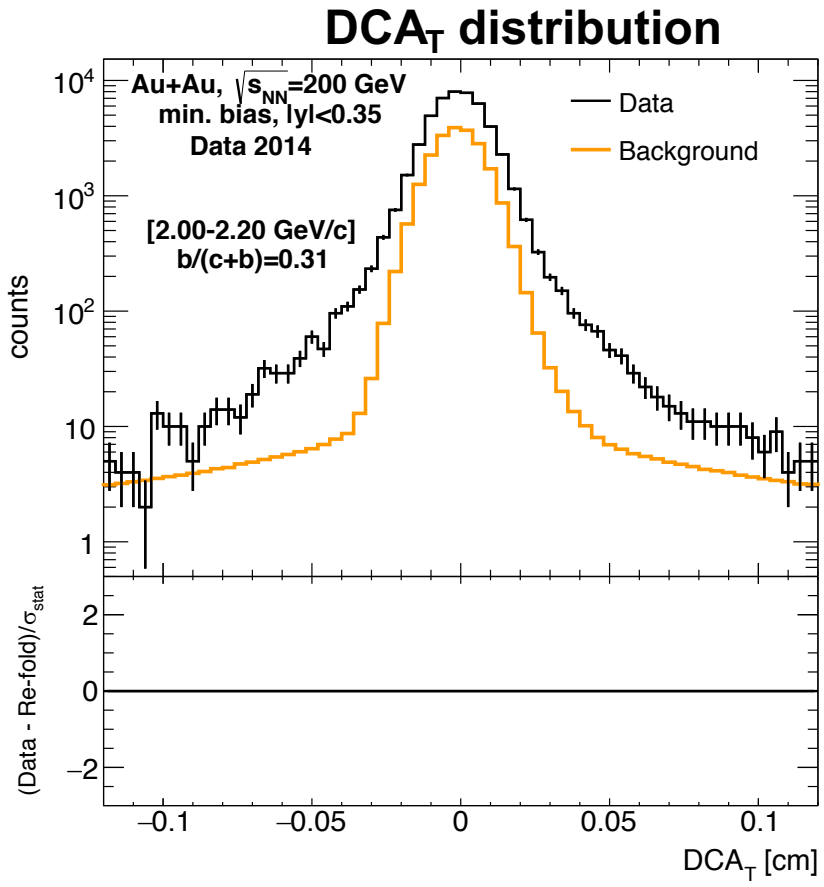
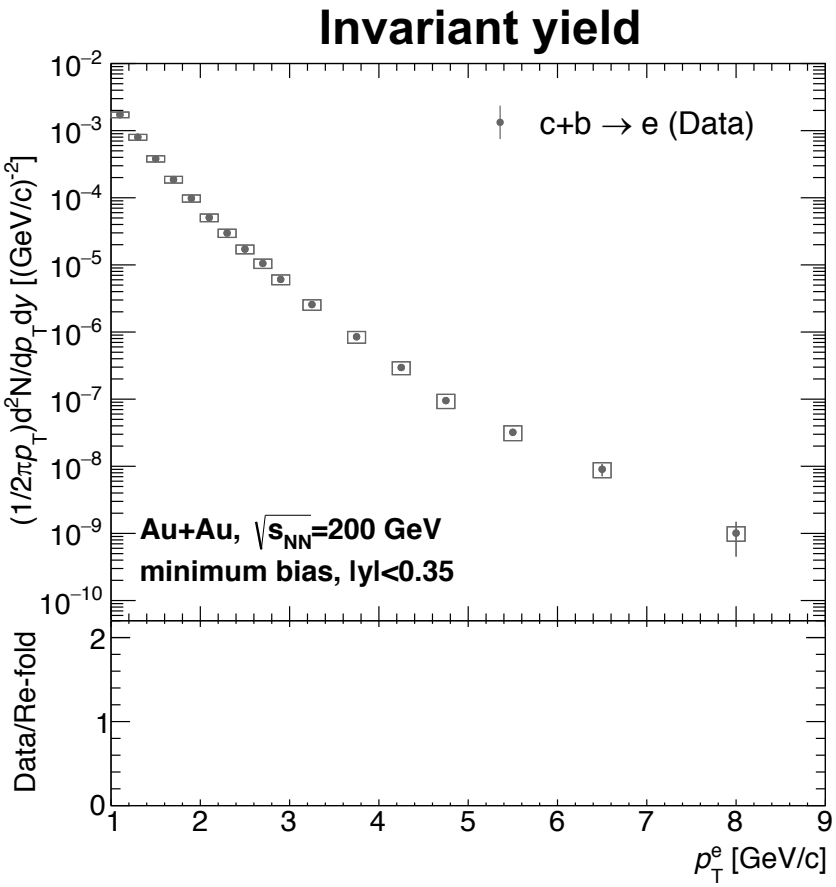
Heavy Flavor Results in Large System (Au+Au)

→ HF dynamics in QGP

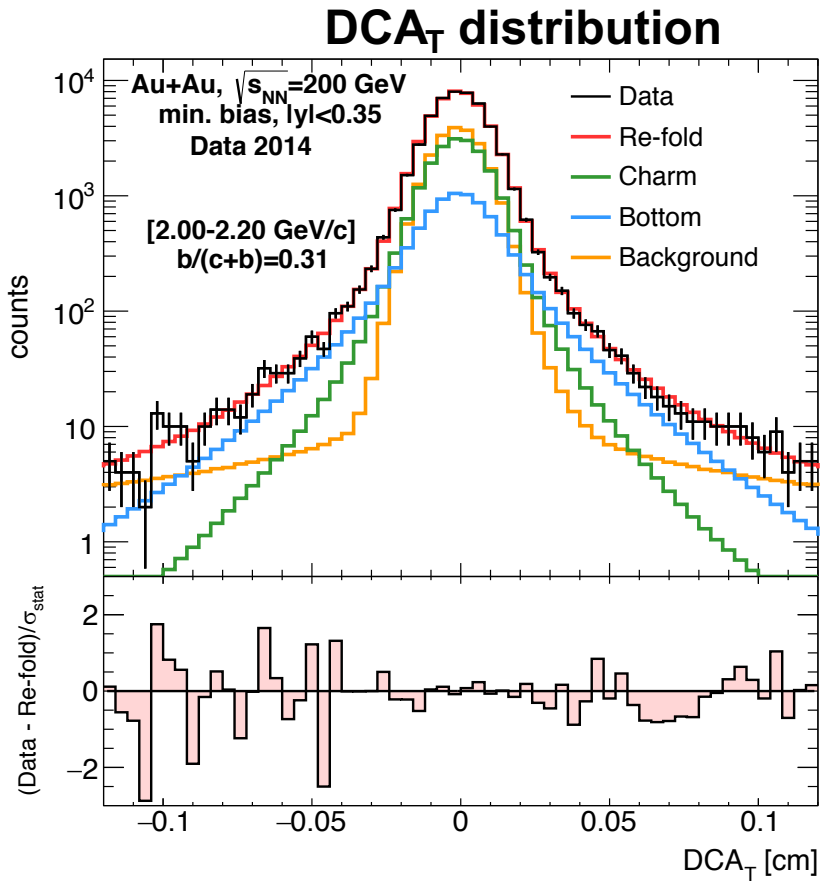
✓ Invariant Yield of c, b→e in Au+Au

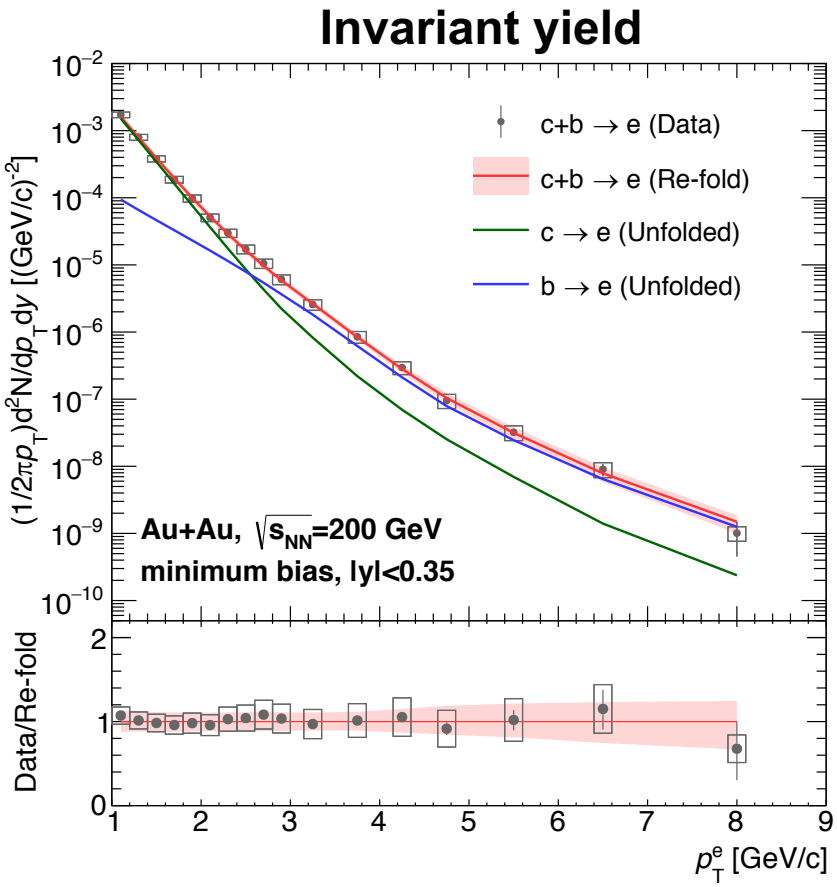




- Displaced vertex analysis at mid-rapidity
- Simultaneous fit to DCA$_T$ distribution and invariant yield

✓ Invariant Yield of c, b→e in Au+Au

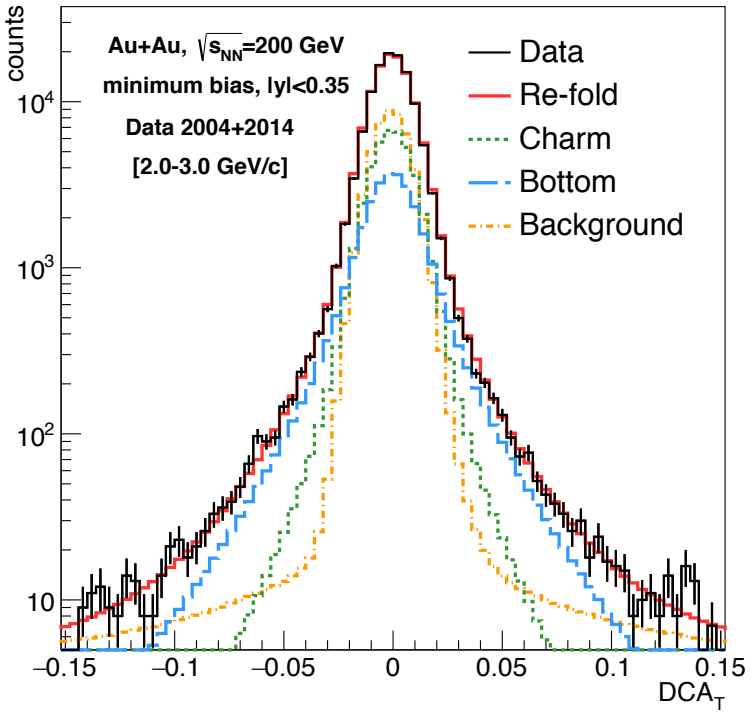




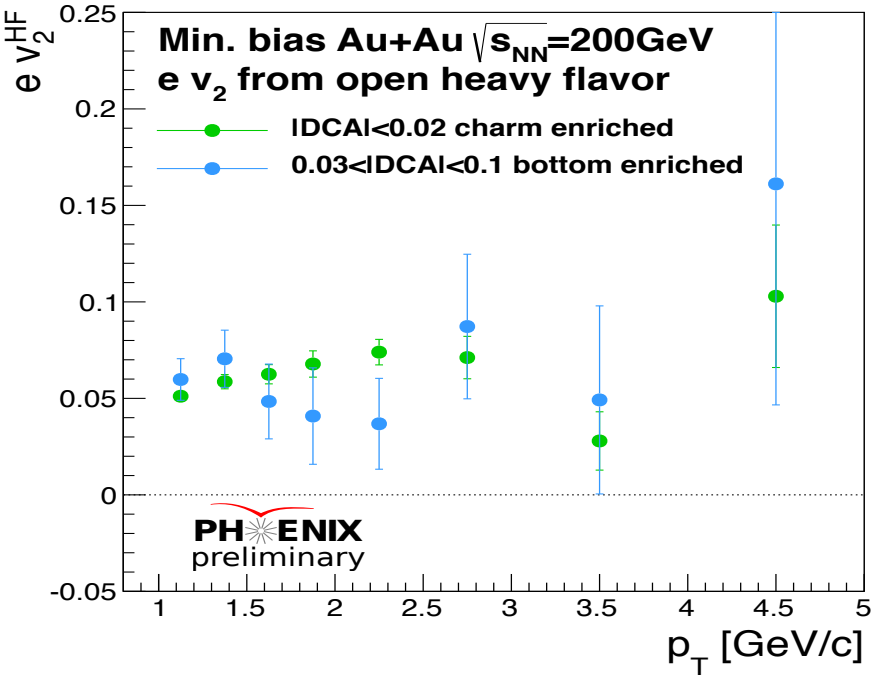
- Displaced vertex analysis at mid-rapidity
- Simultaneous fit to DCA$_T$ distribution and invariant yield
  → Extraction of $v_2^{c\to e}$ and $v_2^{b\to e}$ with DCA distributions

✓ Extraction of $v_2^{c\to e}$ and $v_2^{b\to e}$ with DCA

DCA distribution



c rich and b rich v_2



c rich region:

|DCA| < 200μm

b rich region:

300 < |DCA| < 1000μm

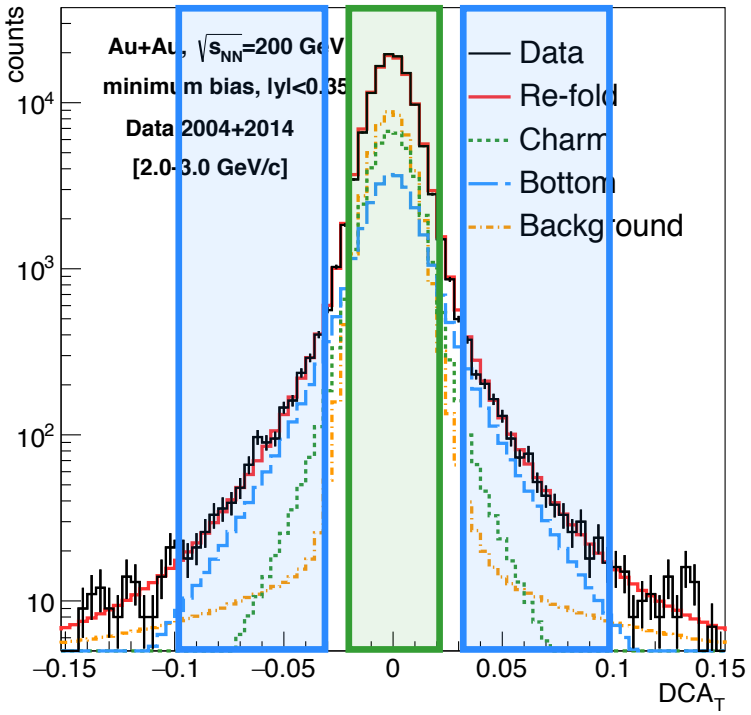
Extraction of c→e and b→e v_2

$$v_2^{\text{c rich}} = F_c \times v_2^c + F_b \times v_2^b$$
$$v_2^{\text{b rich}} = F_c \times v_2^c + F_b \times v_2^b$$

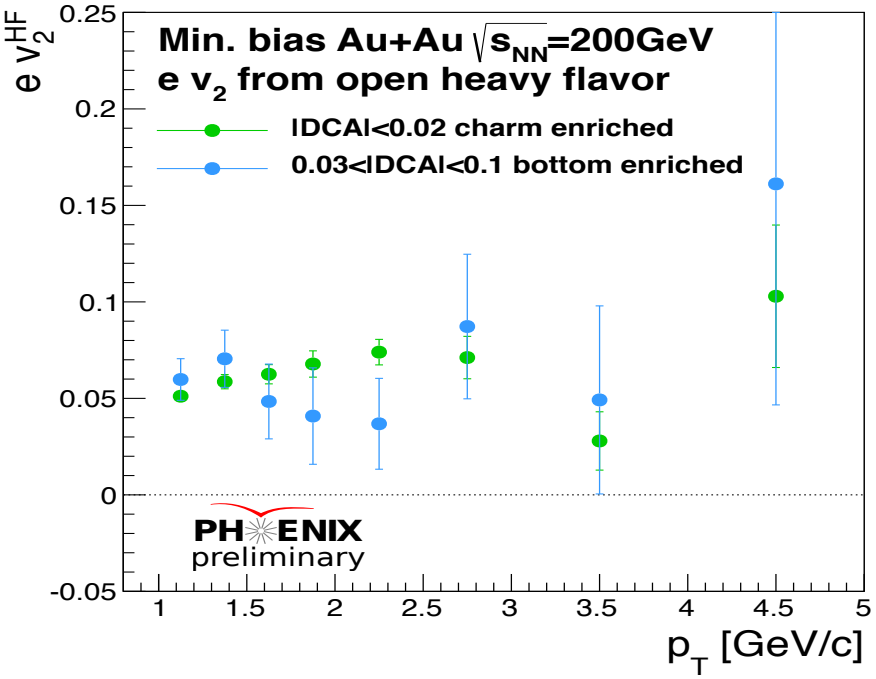
>> Solve simultaneous equations!

✓ Extraction of $v_2^{c\to e}$ and $v_2^{b\to e}$ with DCA

DCA distribution



c rich and b rich v_2



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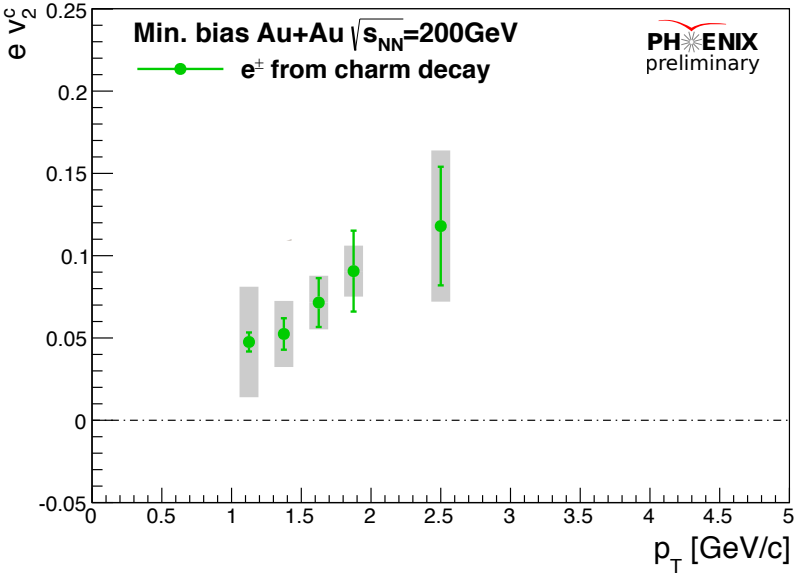
$$v_2^{\text{b rich}} = F_c \times v_2^c + F_b \times v_2^b$$

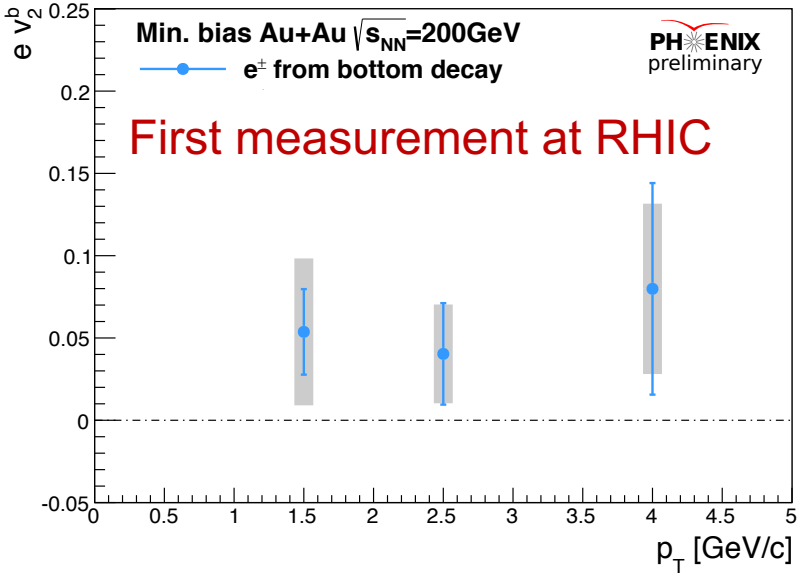
>> Solve simultaneous equations!

✓ Anisotropic Flow of c, b→e in Au+Au

c→e



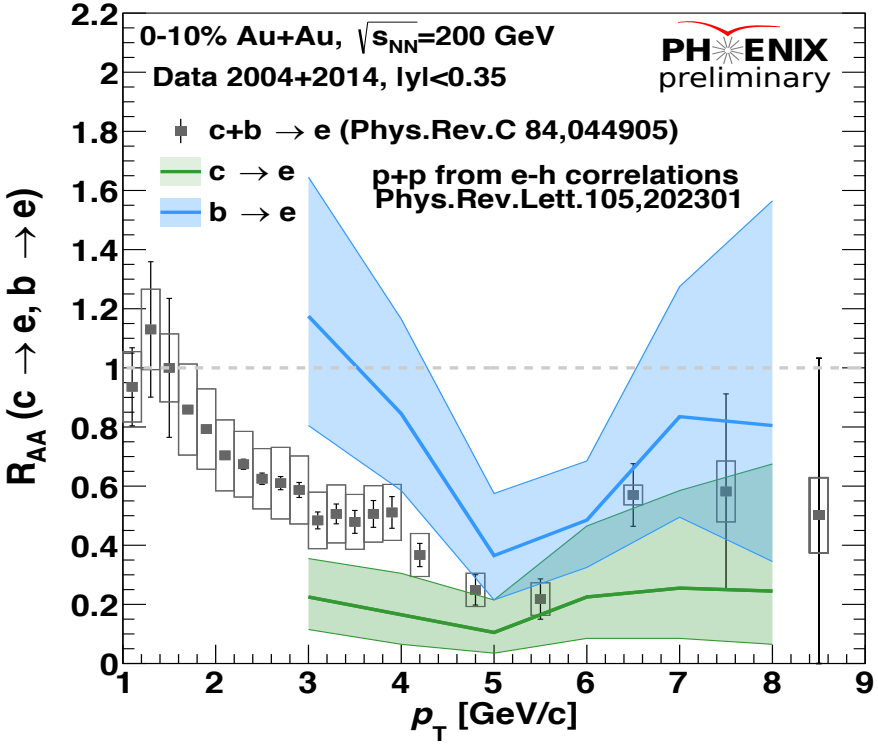
b→e



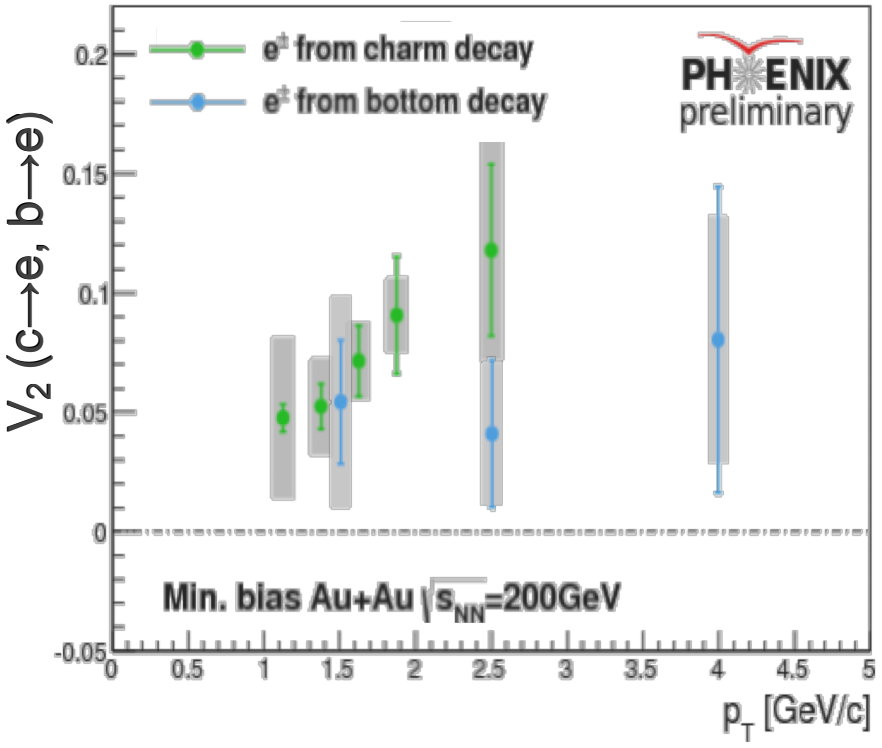
- Extraction of $v_2^{c\to e}$ and $v_2^{b\to e}$ with DCA
- Large v_2 of c→e, 0 < $v_2^{c\to e}$
  - c-quark is strongly coupled in QGP
- Likely non-zero v_2 of b→e?, 0 < (?) $v_2^{b\to e}$ < (?) $v_2^{c\to e}$
  - will be improved with higher statistics data

✓ Quark Mass Dependent Dynamics in QGP

Nuclear modification factor R_{AA}



Azimuthal anisotropy v_2



PHENIX has measured R_{AA} and v_2 of c, b→e

- quark mass dependent suppression and flow?

→ will be improved with high stat. data and new baseline

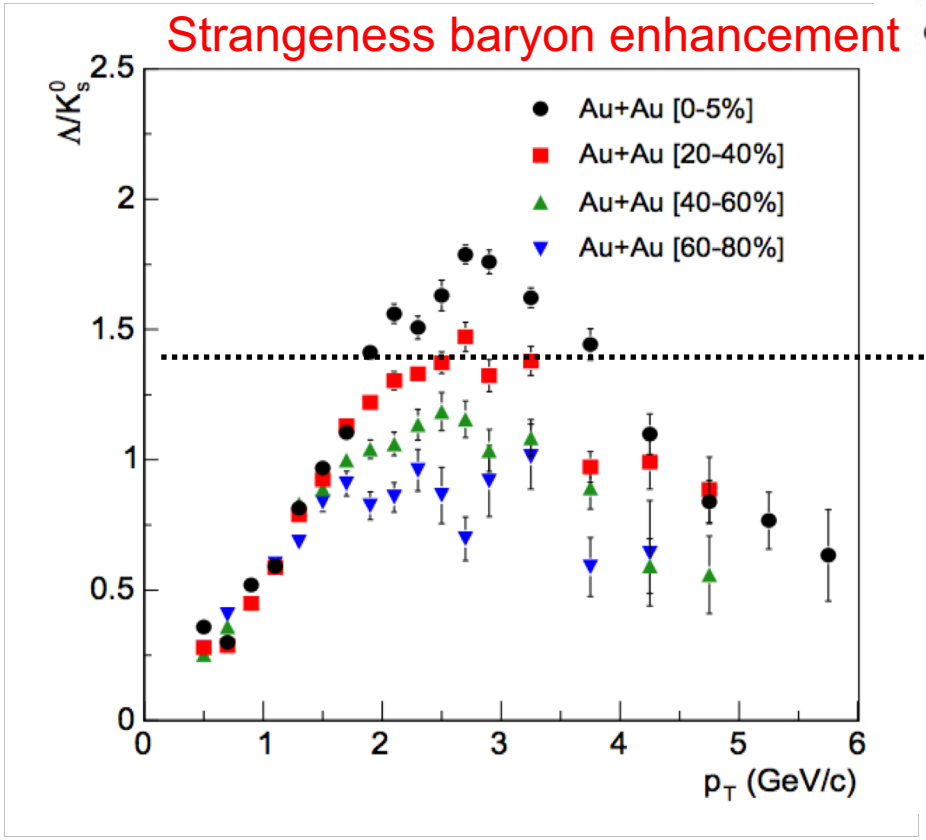
✓ Summary

- PHENIX has measured heavy flavors in small and large collision systems at $\sqrt{s_{NN}}$ = 200 GeV
- Heavy flavor measurements in p+p collisions
  - obtained new baseline measurement for Au+Au
  - understood production mechanism from pair angle dist.
- Heavy flavor measurements in p+ and d+Au collisions
  - R_{pA} of $b\bar{b}$ shows no modification in p+Au
  - found non-zero v_2 of c+b→μ in 0-20% d+Au
- Heavy flavor measurements in Au+Au collisions
  - measured R_{AA} and v_2 of separated c→e and b→e
    → Quark mass dependence ?
  - will be improved with high stat. data and new baseline

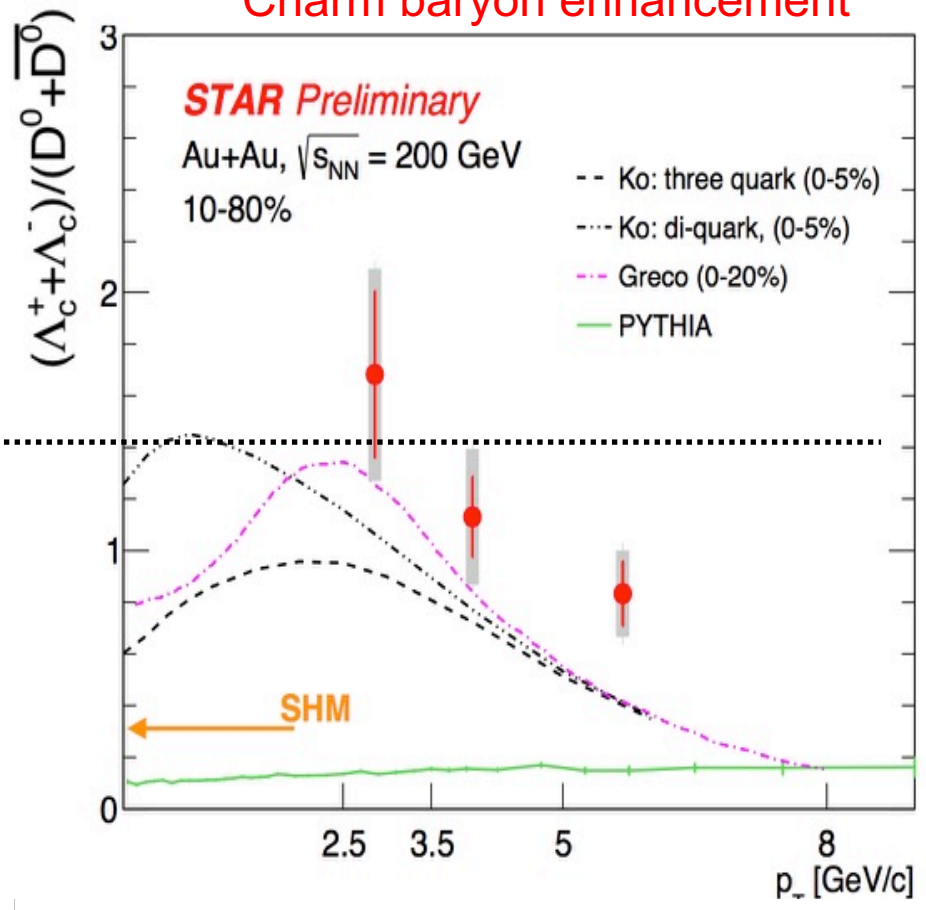
✓ Backup

✓ Baryon Enhancement

Strangeness baryon enhancement



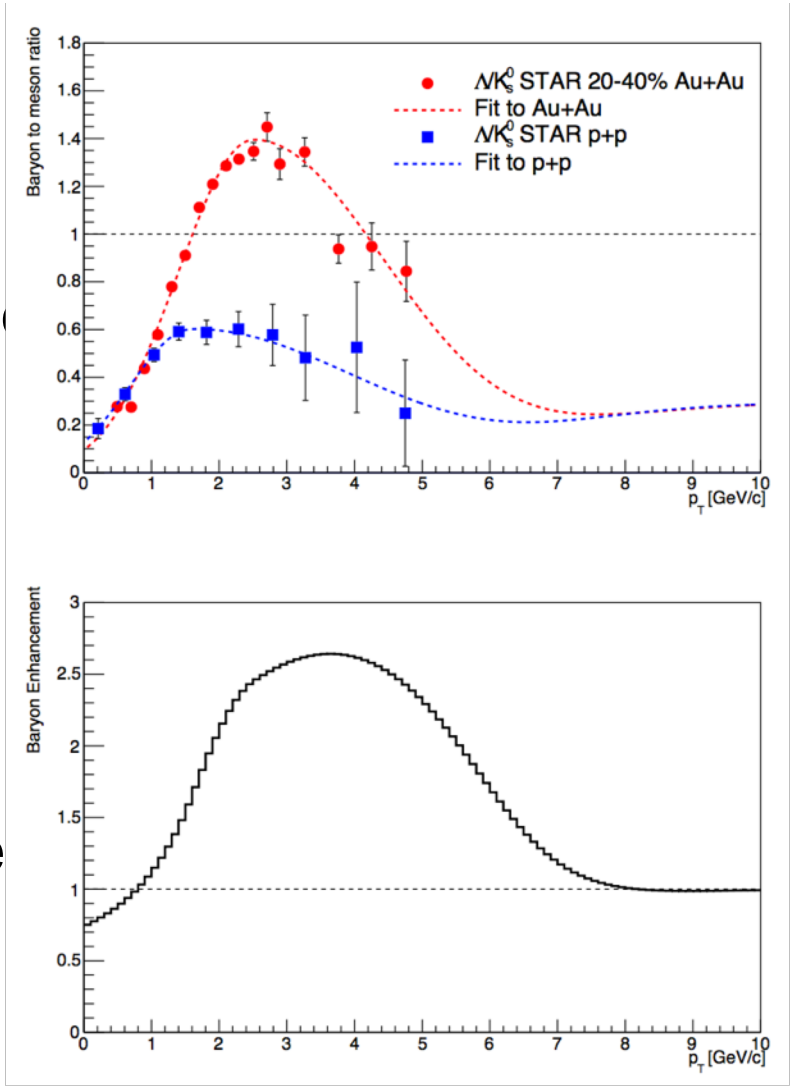
Charm baryon enhancement



Charm baryon enhancement is similar order of magnitude as Strangeness baryon enhancement

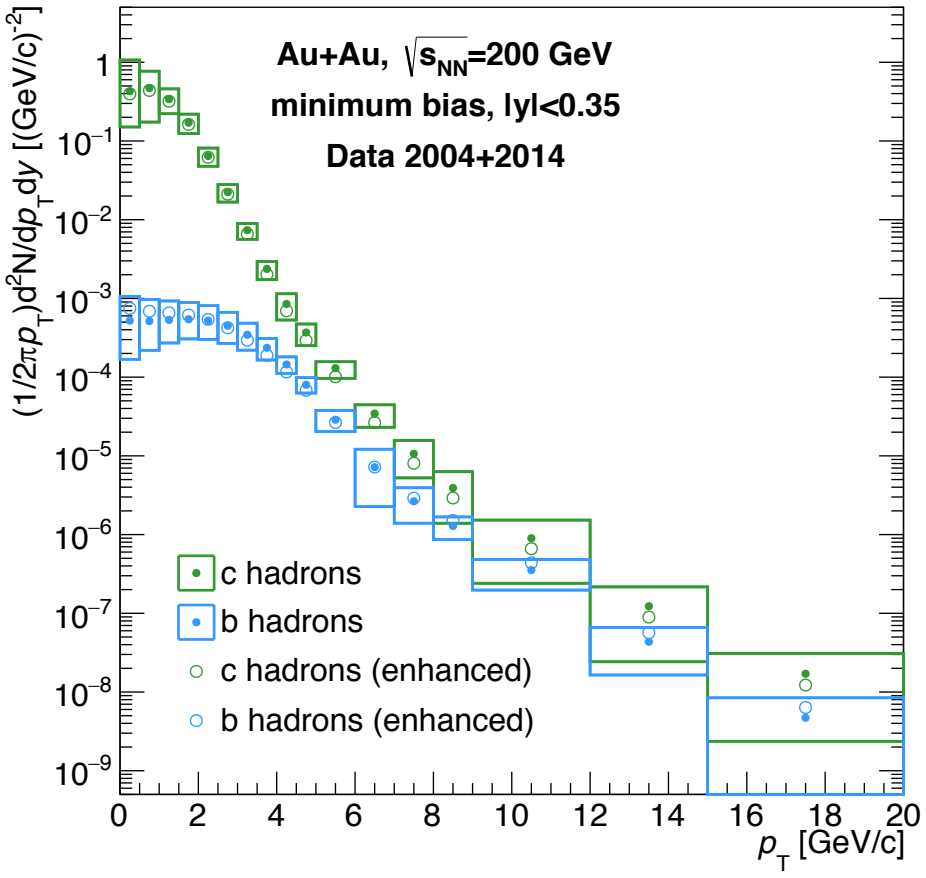
✓ Testing Possible Baryon Enhancement

- Follow P. Sorensen and X. Dong
  (Phys Rev C 74, 024902 (2006))
- Λ/Ks ratio measured
  in STAR 20-40% Au+Au at 200 G
  and STAR in p+p at 200 GeV
  (arXiv:nucl-ex/0601042)
- Fit both data
- Fix asymptotic value to 0.3
  in both Au +Au and p+p
- Apply enhanced the ratio of
  Λ_c/D and Λ_b/B to the decay matrice



✓ Testing Possible Baryon Enhancement

c and b hadron yields



Default decay matrix is obtained from PYTHIA model.

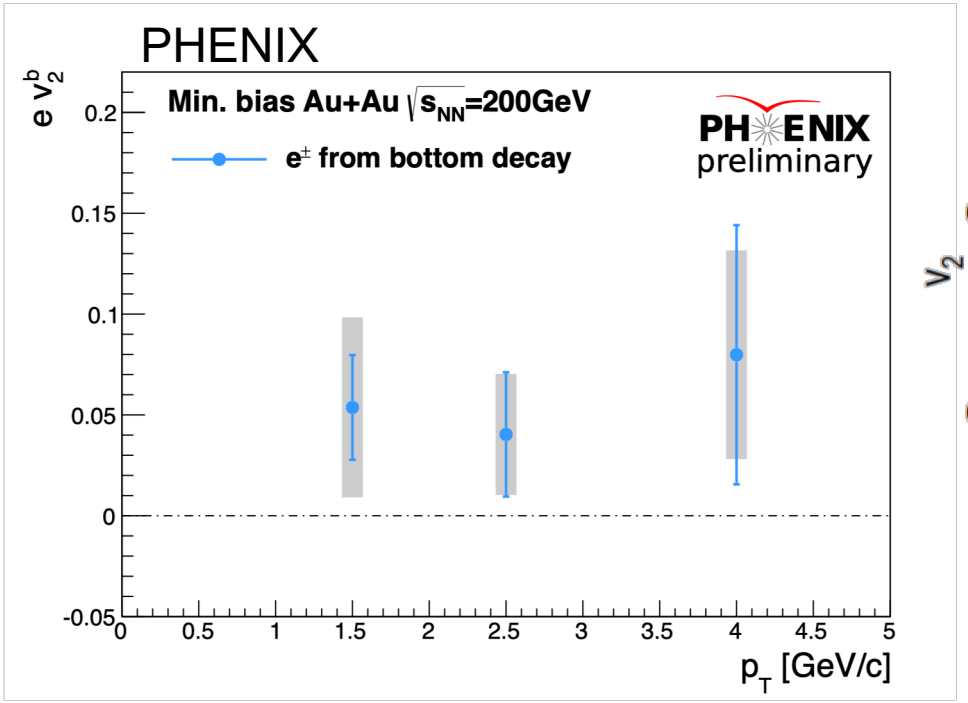
Decay matrix is modified
- include baryon enhancement

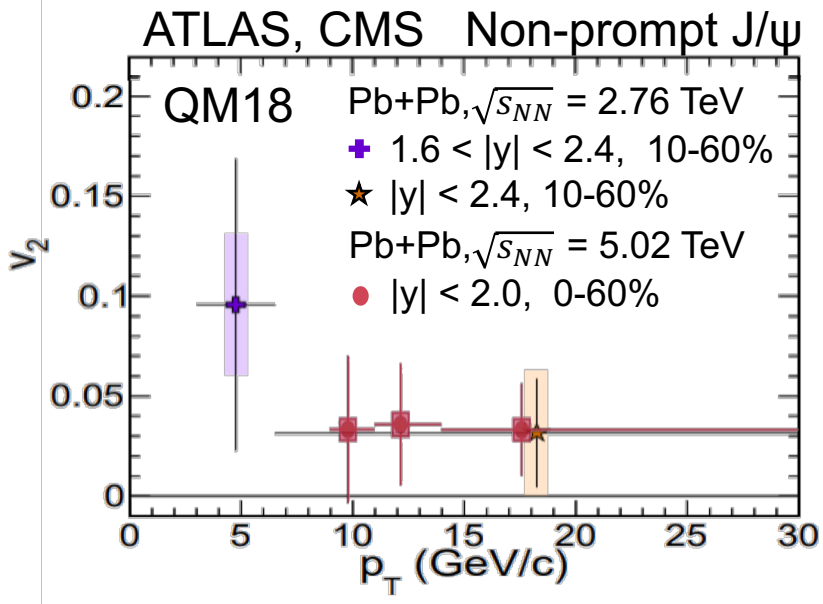
Filled marker
- use default decay matrix

Open marker
- use modified decay matrix

Baryon enhancement effect is covered by current uncertainty

✓ Comparison of bottom anisotropic flow

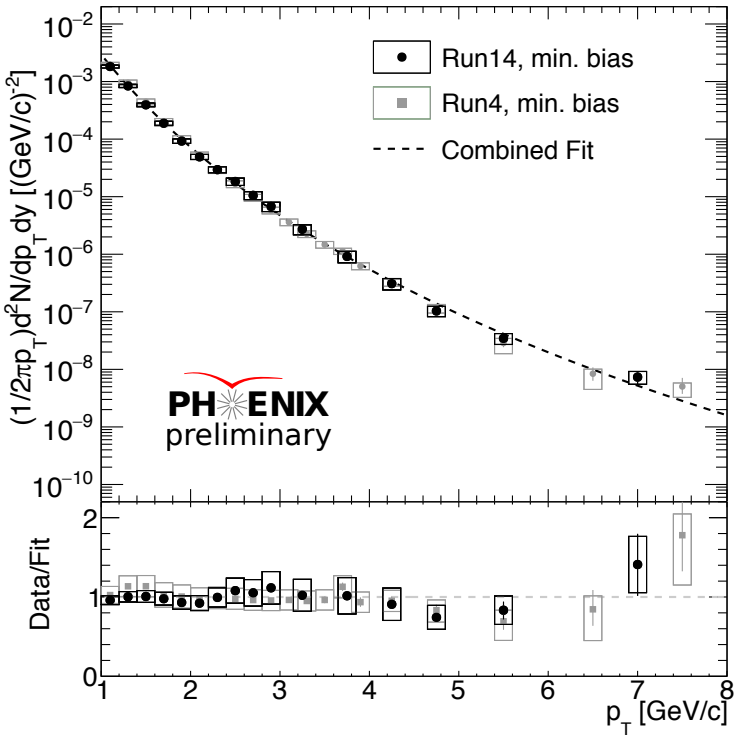




- ATLAS and CMS reported positive b-quark v_2
- PHENIX measure low p_T b-quark v_2
  - sensitive region of flow in QGP
- b-quark v_2 indicates non-zero positive value
  → b-quark slightly flows and loses energy in QGP?

✓ Heavy flavor measurement in Au+Au

Invariant yield



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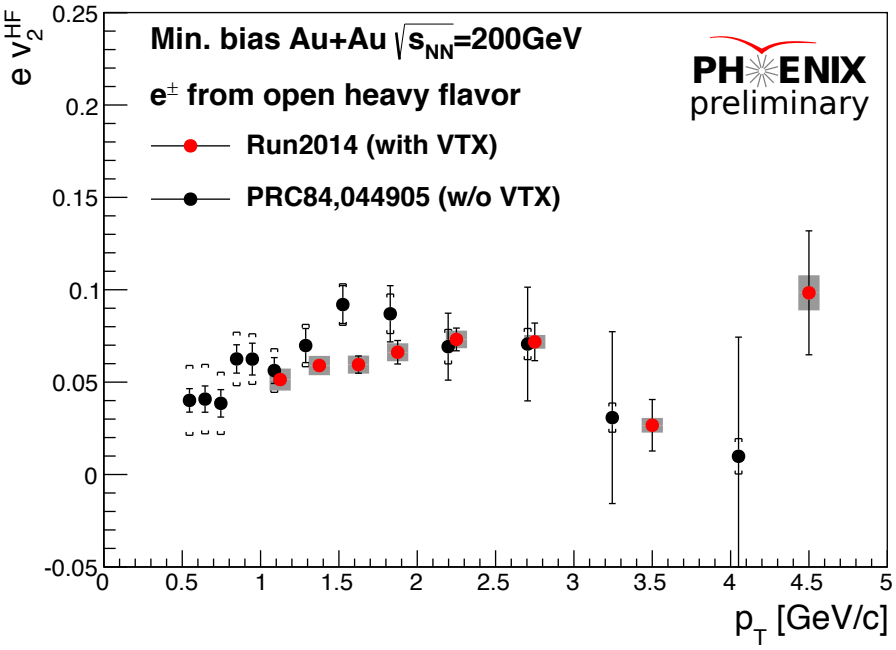


- Recode high statistics (Run14) AuAu data ~ 17 B events.
- PHENIX VTX allow precise measurement of c+b→e.
  > provides smaller photonic BG and higher RP resolution
- Measurement of inclusive HF v_2 is significantly improved.

✓ Bayesian Inference Techniques

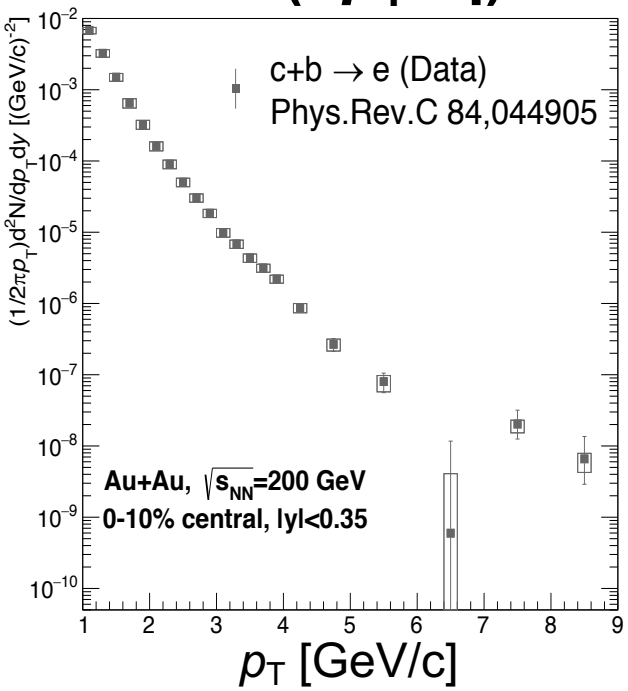
- Bayes' theorem $\boldsymbol{P(\theta|x) \propto P(x|\theta)\pi(\theta)}$
- Simultaneous fit to dN/dp_T and $DCA_T(p_T)$

Measured data
dN/dp_T, $DCA_T(p_T)$

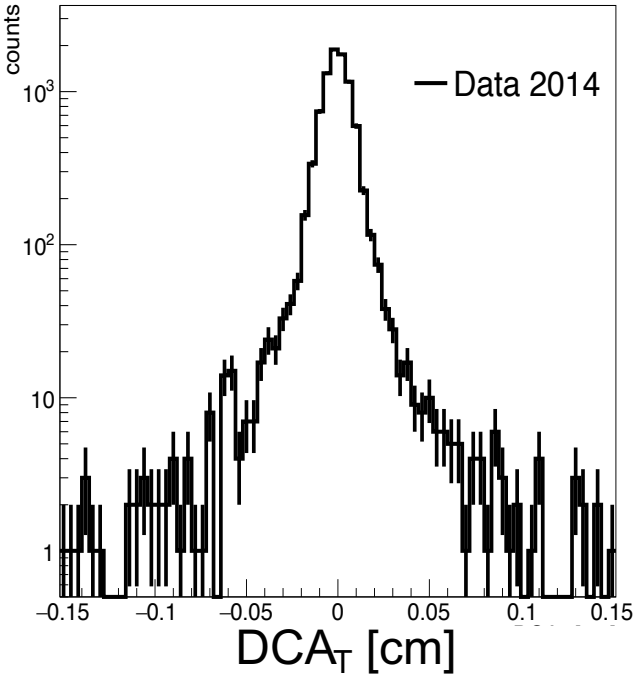
↓

$\boldsymbol{P(x|\theta)\pi(\theta)}$
Likelihood

$dN/(dp_T d\eta)$

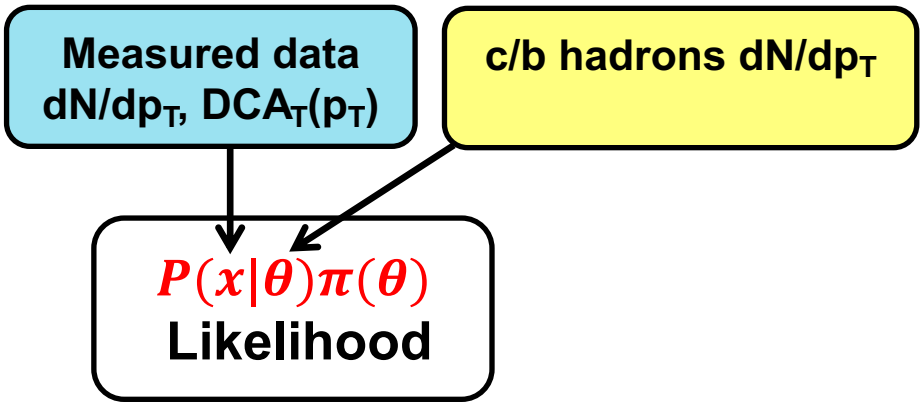


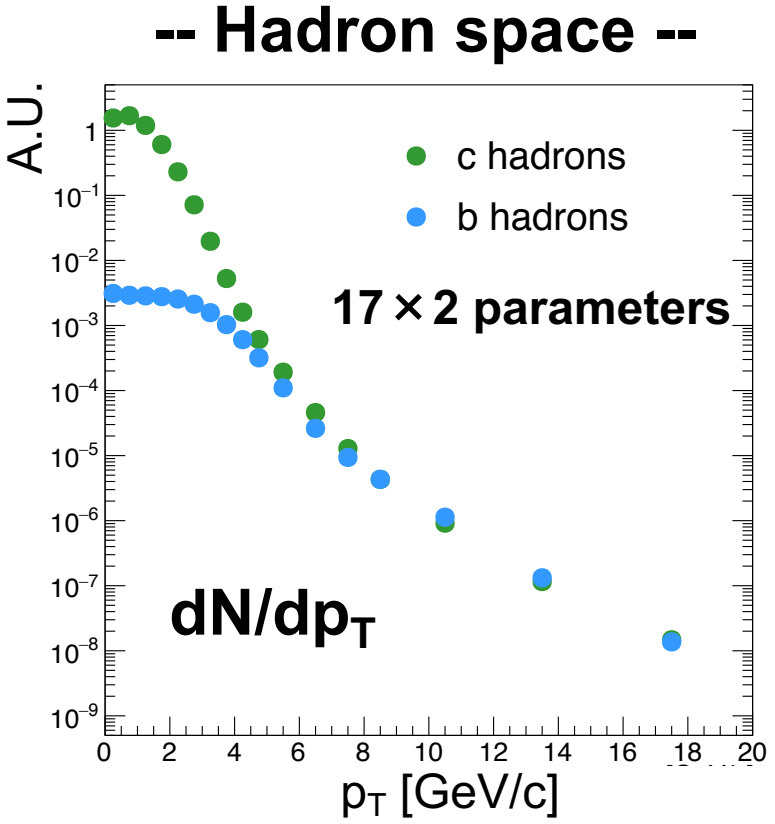
DCA_T



✓ Bayesian Inference Techniques

- Bayes' theorem $\boldsymbol{P(\theta|x) \propto P(x|\theta)\pi(\theta)}$
- Simultaneous fit to dN/dp_T and $DCA_T(p_T)$





✓ Bayesian Inference Techniques

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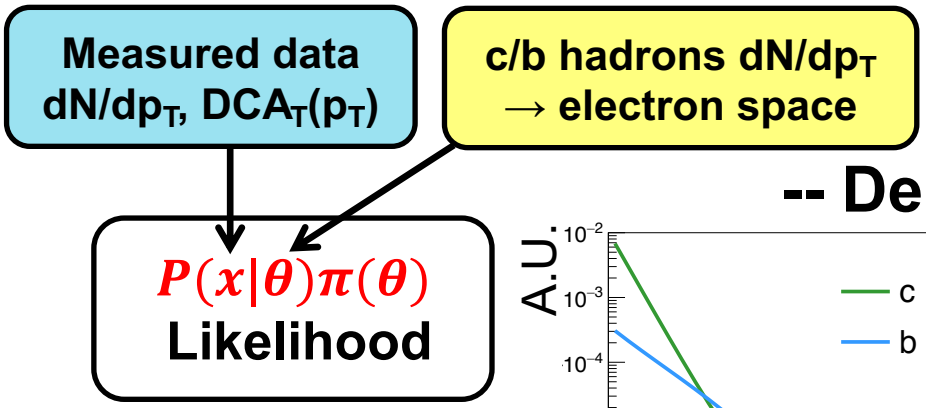
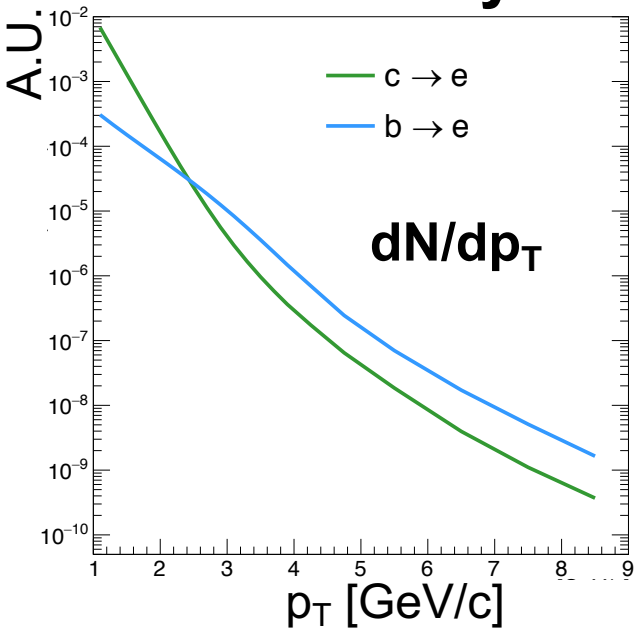
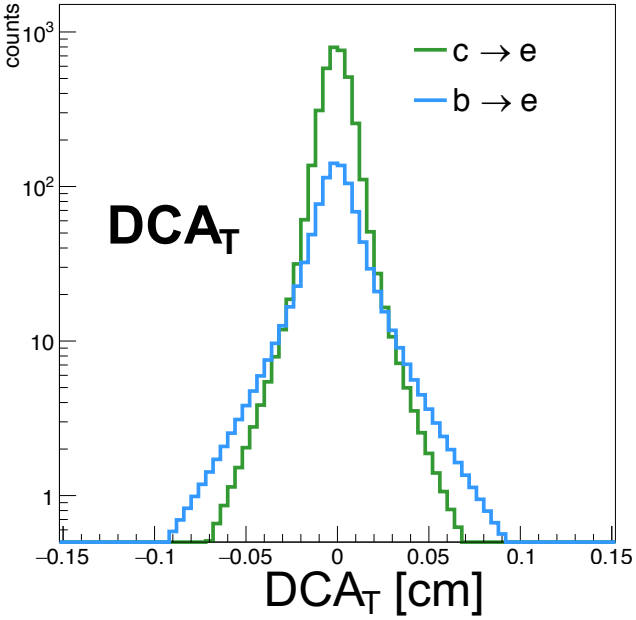


From PYTHIA6 decay model

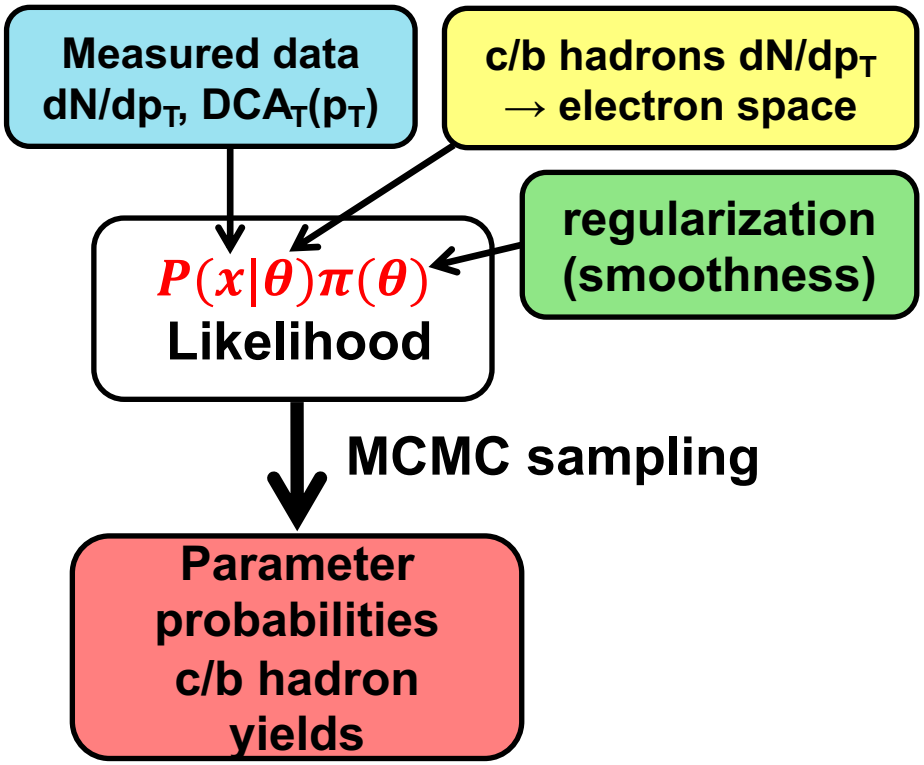
-- Decay electron space --

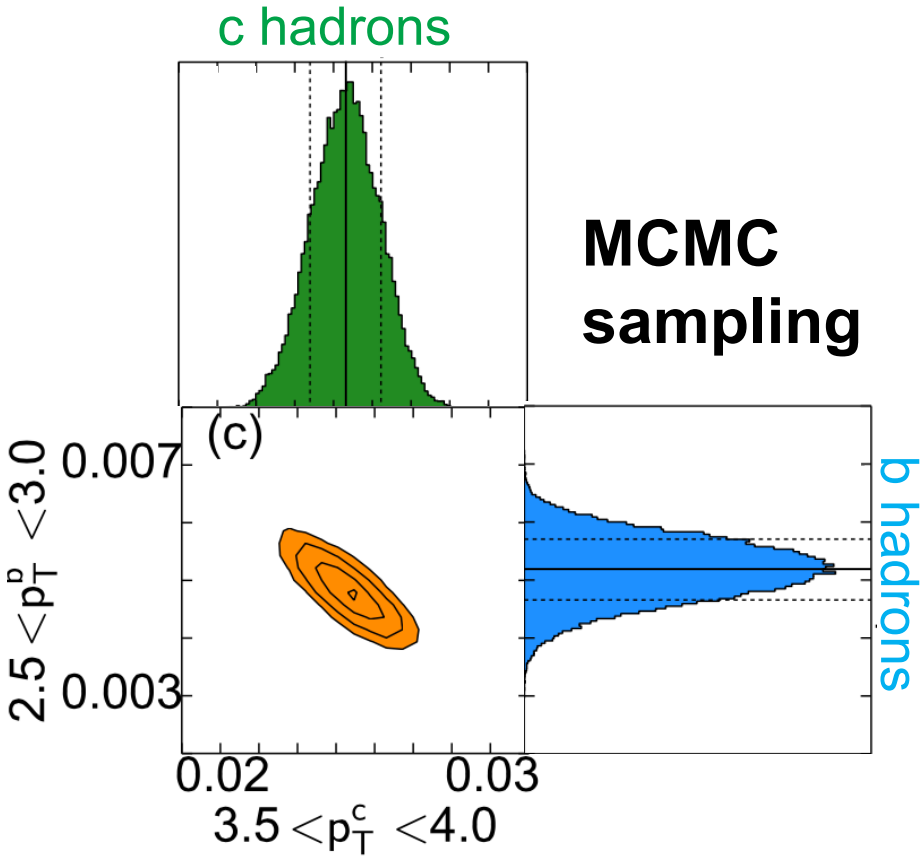




✓ Bayesian Inference Techniques

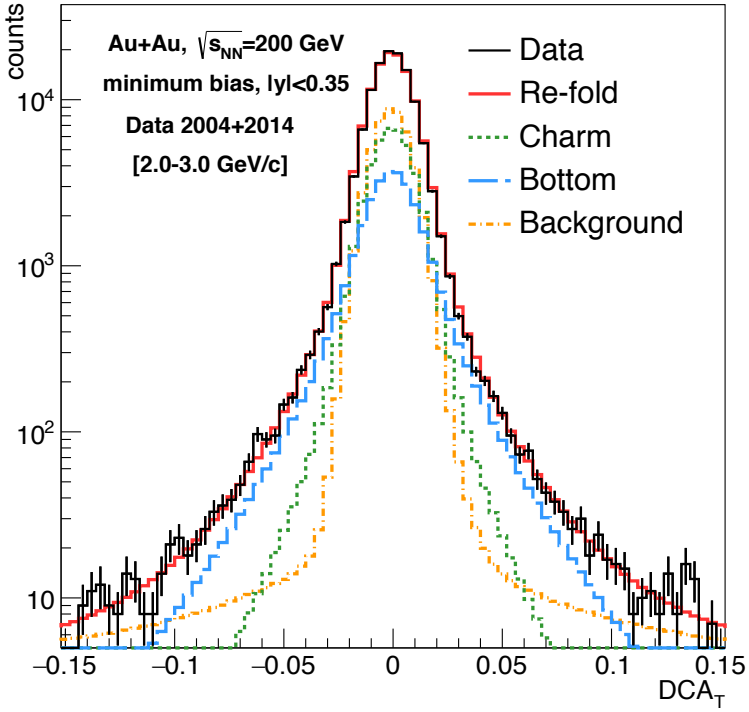
- Bayes' theorem $\boldsymbol{P(\theta|x) \propto P(x|\theta)\pi(\theta)}$
- Simultaneous fit to dN/dp_T and $DCA_T(p_T)$
- employ Markov Chain Monte Carlo (MCMC) for sampling



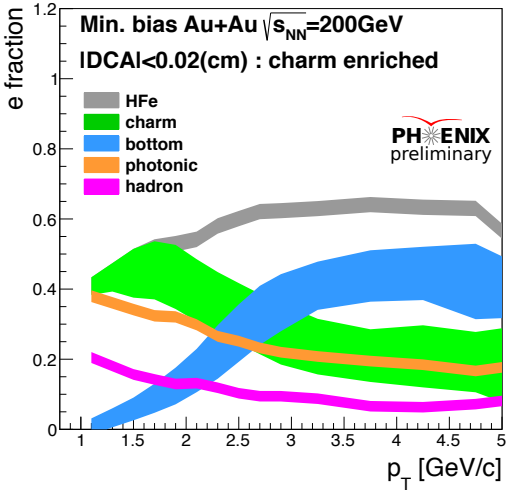


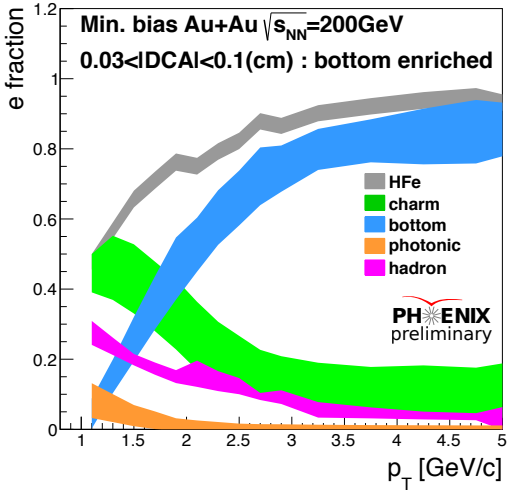
✓ Extraction of c→e and b→e with DCA

DCA distribution



Electron fraction





c rich region:
|DCA| < 200μm

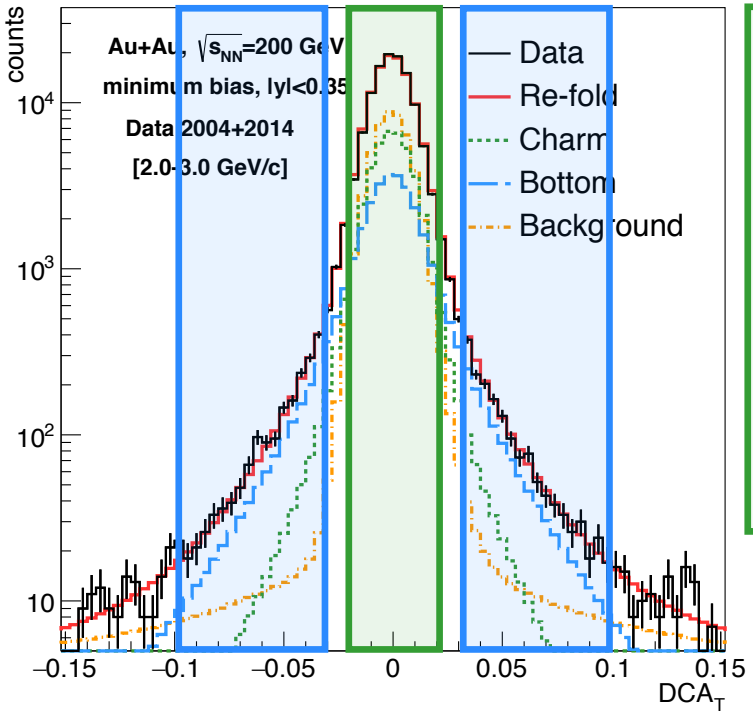
b rich region:
300 < |DCA| < 1000μm

Extraction of c→e and b→e v_2

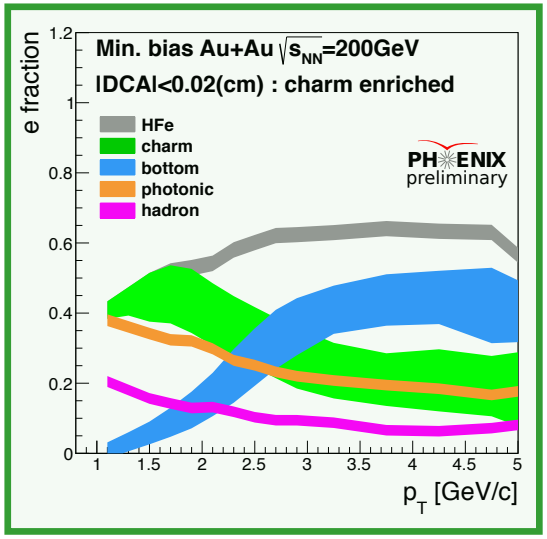
$$v_2^{\text{c rich}} = F_c \times v_2^c + F_b \times v_2^b$$
$$v_2^{\text{b rich}} = F_c \times v_2^c + F_b \times v_2^b$$

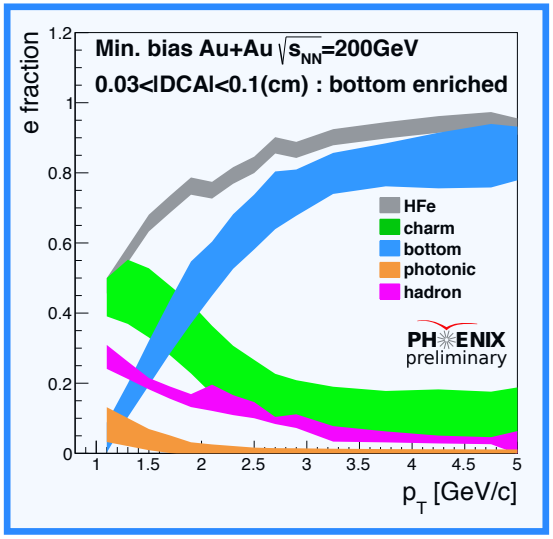
✓ Extraction of c→e and b→e with DCA

DCA distribution



Electron fraction





c rich region

b rich region

c rich region:

|DCA| < 200μm

b rich region:

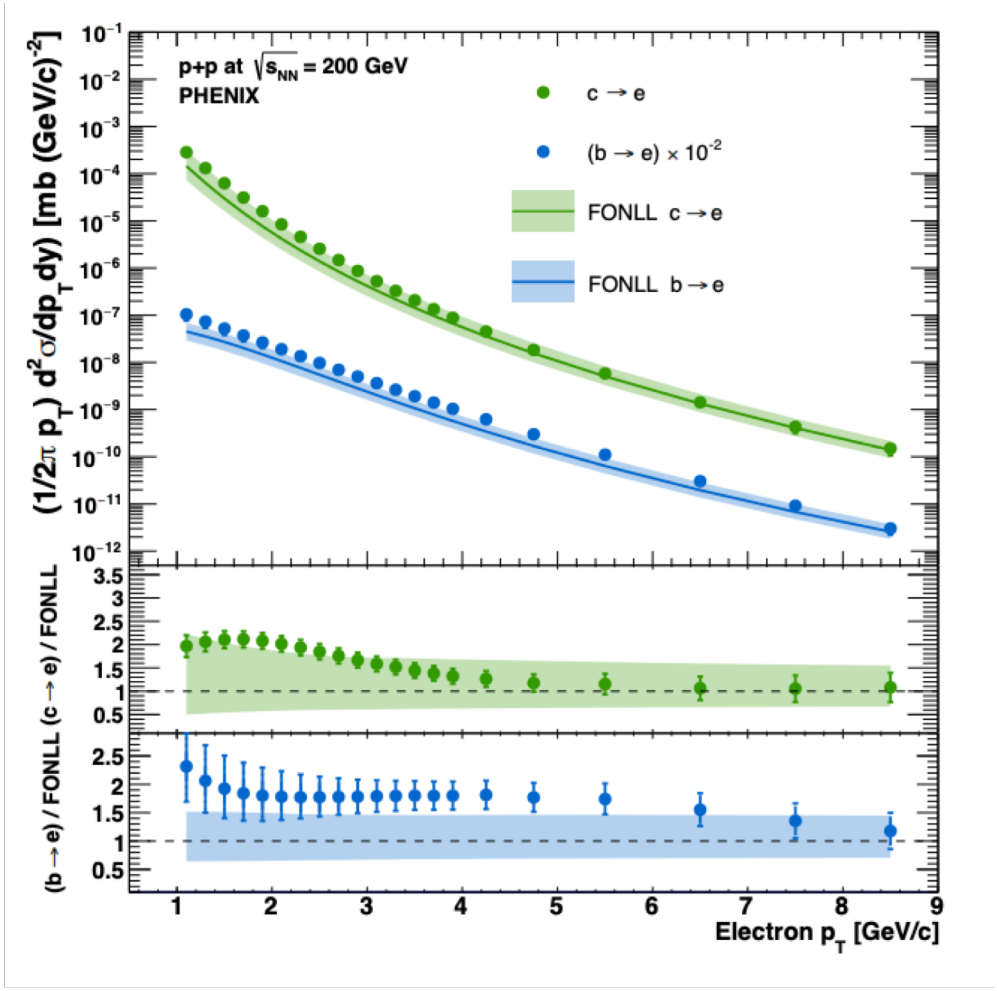
300 < |DCA| < 1000μm

Extraction of c→e and b→e v_2

$$v_2^{\text{c rich}} = F_c \times v_2^c + F_b \times v_2^b$$

$$v_2^{\text{b rich}} = F_c \times v_2^c + F_b \times v_2^b$$

✓ Comparison to FONLL



Invariant yields are compared to FONLL calculations

FONLL calculations are in reasonable agreement with data

Data is higher than FONLL by a factor of two at low p_T - total cross section