Nuclear modification factor and **Flow** of charm and bottom quarks in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by the PHENIX Experiment.

Takashi HACHIYA

Nara Women's University & RIKEN BNL Research Center

for the PHENIX collaboration

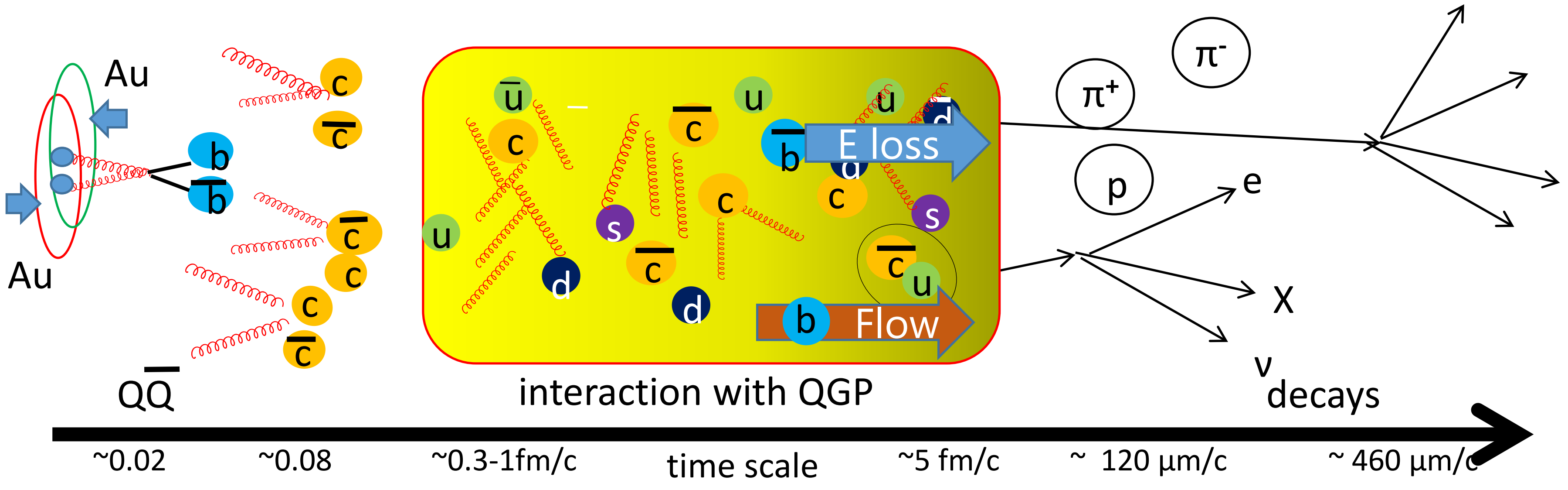
hachiya@cc.nara-wu.ac.jp

Why heavy flavor, bottom & charm ?

- Mainly created at early stage of the collision
  - Production can be calculated by pQCD
- Passing through QGP
  - Suffer energy loss and flow effects – p_T and angular distributions can be modified in QGP

Mc~1.3GeV >> T_{QGP} ~400MeV

Mb~4.5GeV Λ_{QCD} ~200MeV



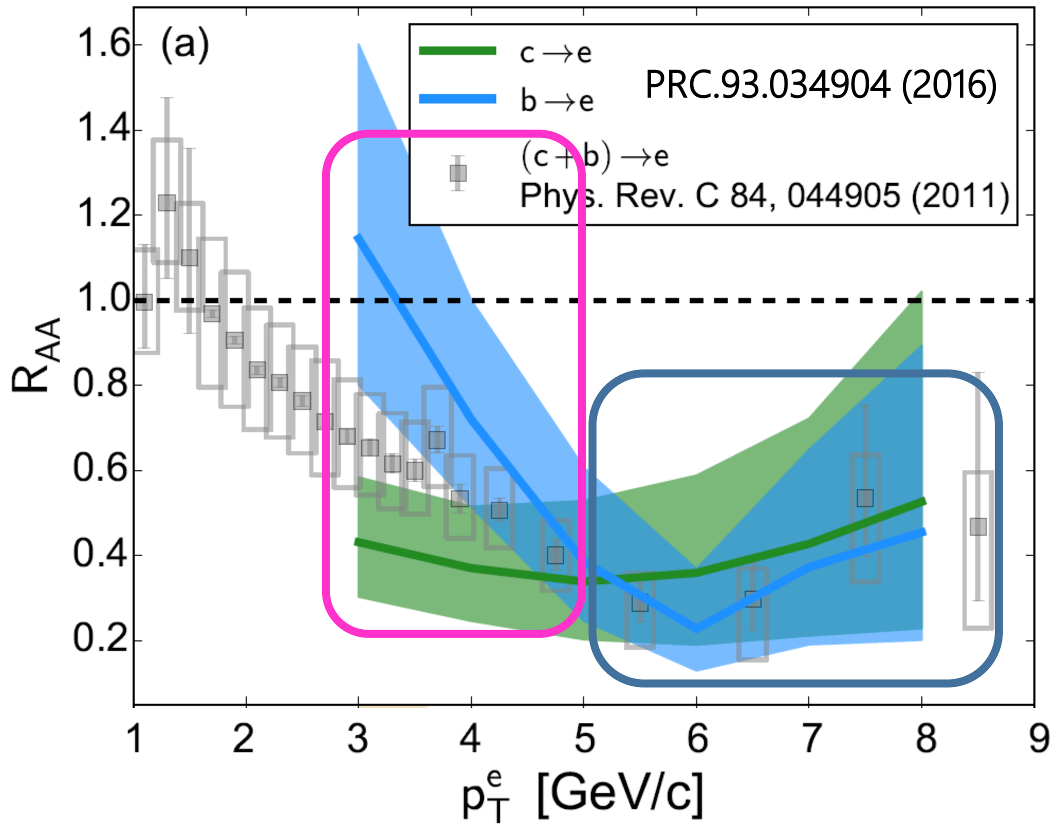
Modification of Heavy flavor is good tool to study property of QGP

Heavy flavor suppression in HI Collisions

- PHENIX observed in electron measurements
  - $R_{AA}(b) \sim R_{AA}(c) < 1$ at high p_T
  - $R_{AA}(b) > R_{AA}(c)$ at low p_T
- Consistent with the expected mass ordering
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

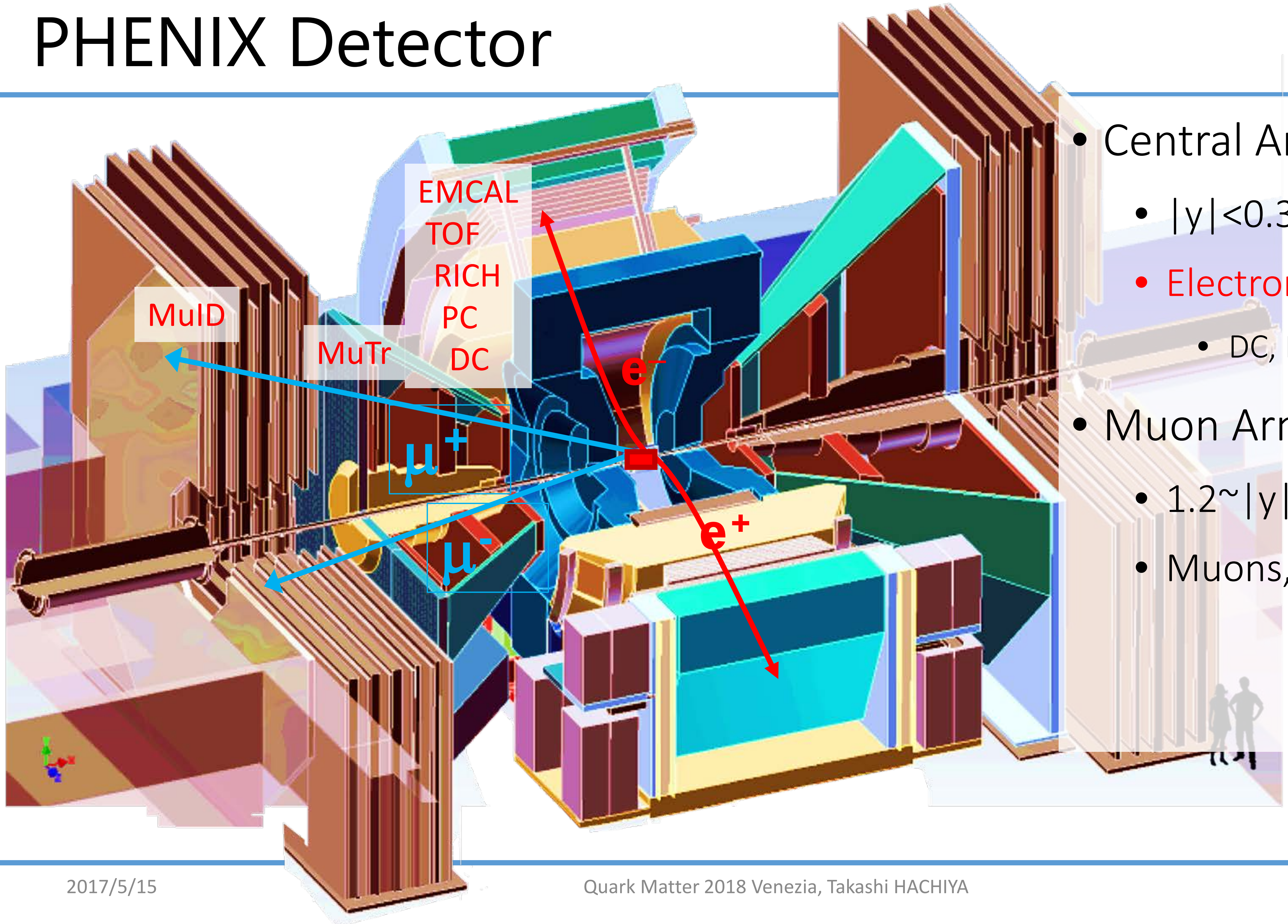
  - Radiative loss @ high p_T
  - Collisional loss @ low p_T
- To understand the suppressions of bottom and charm, need systematic study
  - Centrality dependence
  - Azimuthal anisotropy

$$R_{AA} = \frac{Yield(Au+Au)}{Ncoll * Yield(p+p)}$$



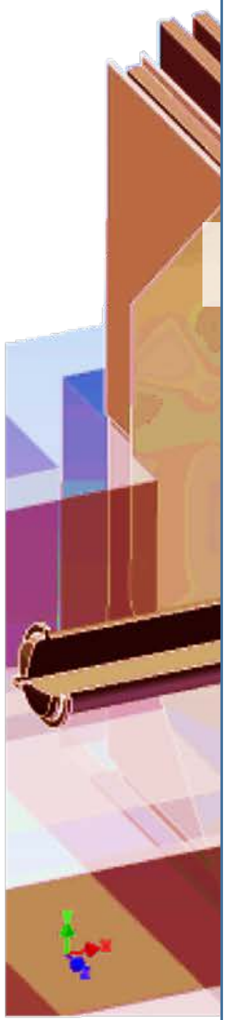
Bottom measurement is key to understand the QGP properties

PHENIX Detector

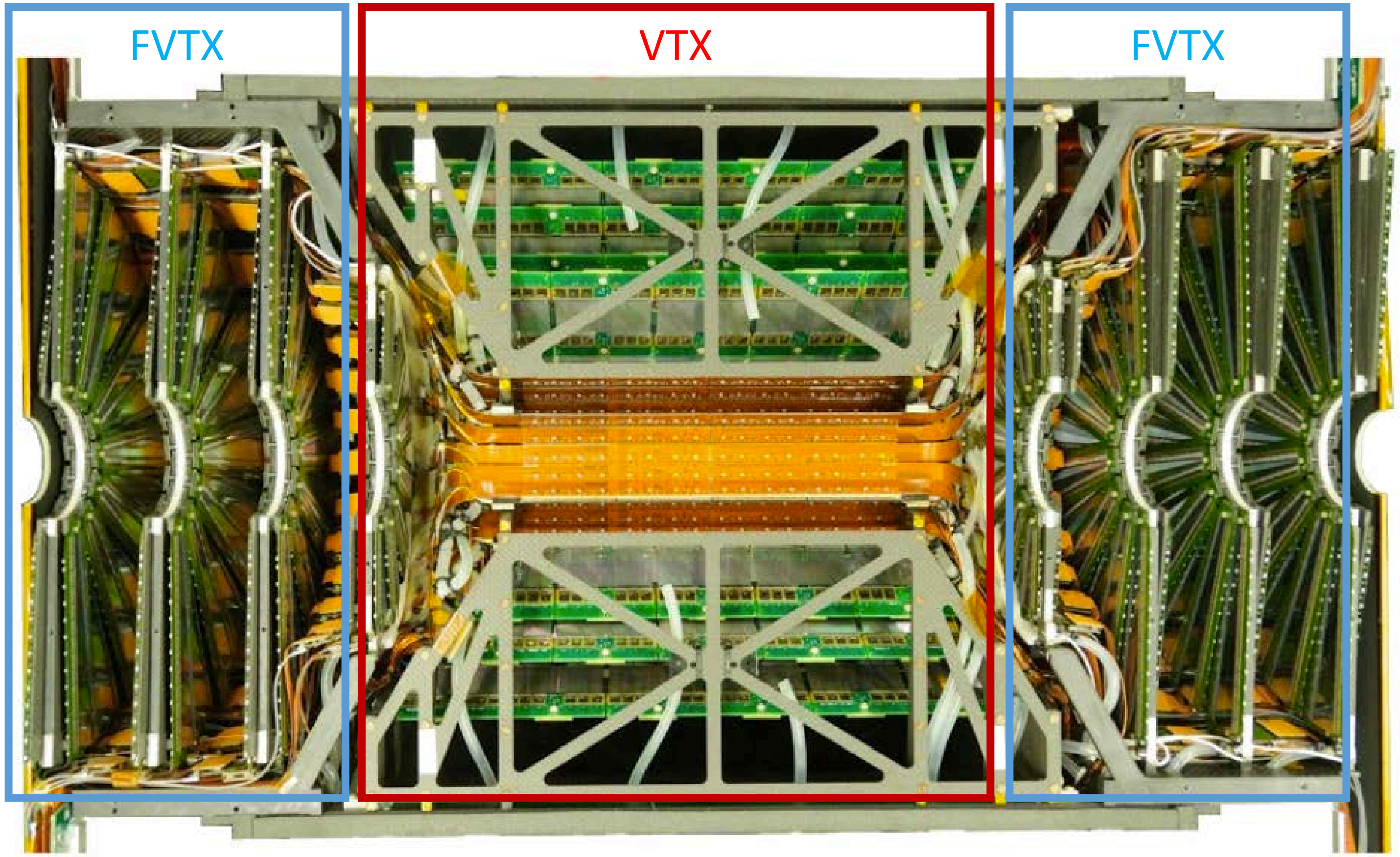


- Central Arms
  - $|y|<0.35$, $\phi\sim2\cdot\pi/2$
  - Electrons, γ, hadrons
    - DC, PC, RICH, EMCAL,TOF
- Muon Arms
  - $1.2\sim|y|<2.2$, $\phi\sim2\cdot\pi/2$
  - Muons, Hadrons

PHENIX Detector



PHENIX Silicon Vertex Detector, VTX & FVTX



Precise tracking for charm and bottom separation

'2

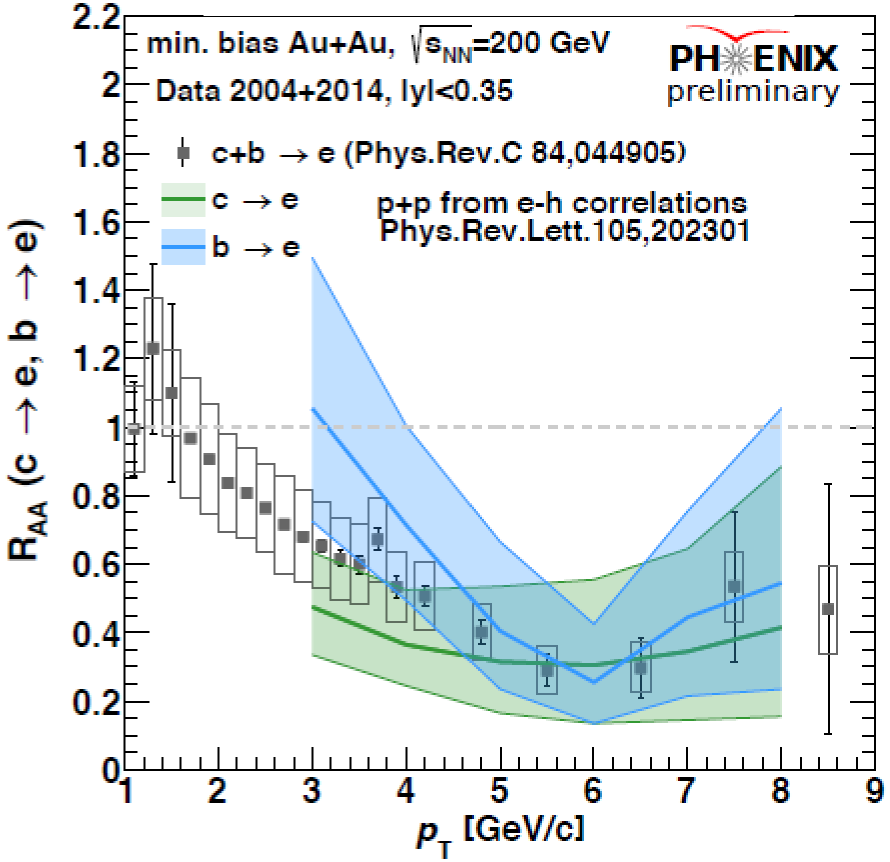
rons

MCAL,TOF

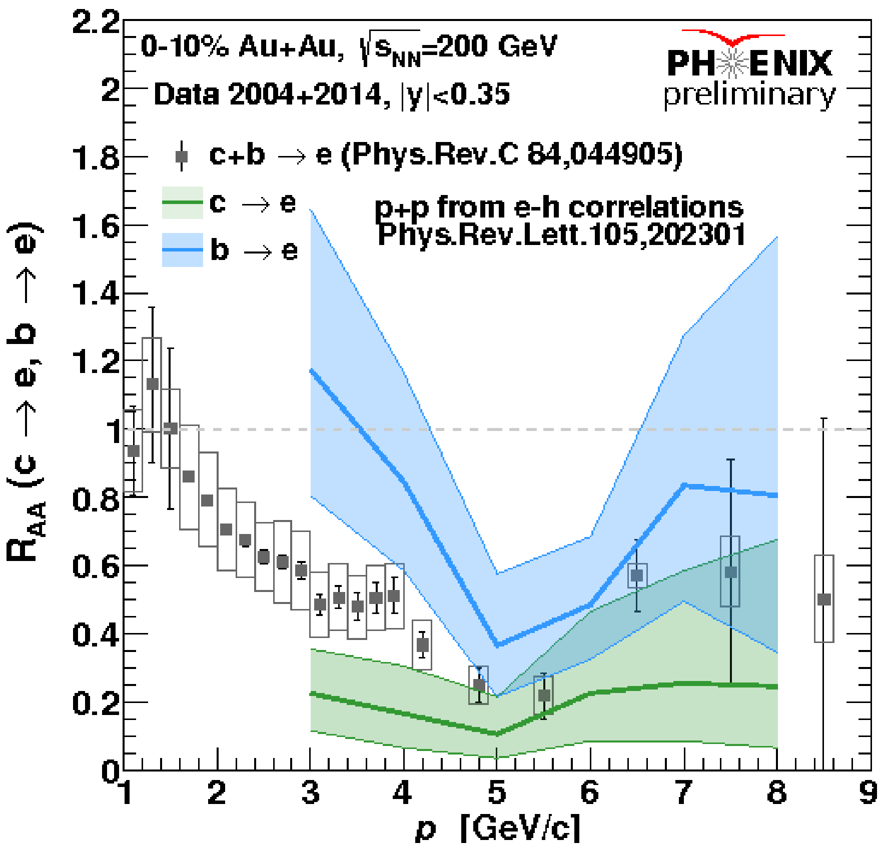
·π/2

R_{AA}(b→e) & R_{AA}(c→e) in Au+Au 200GeV

Min. Bias in Run2014

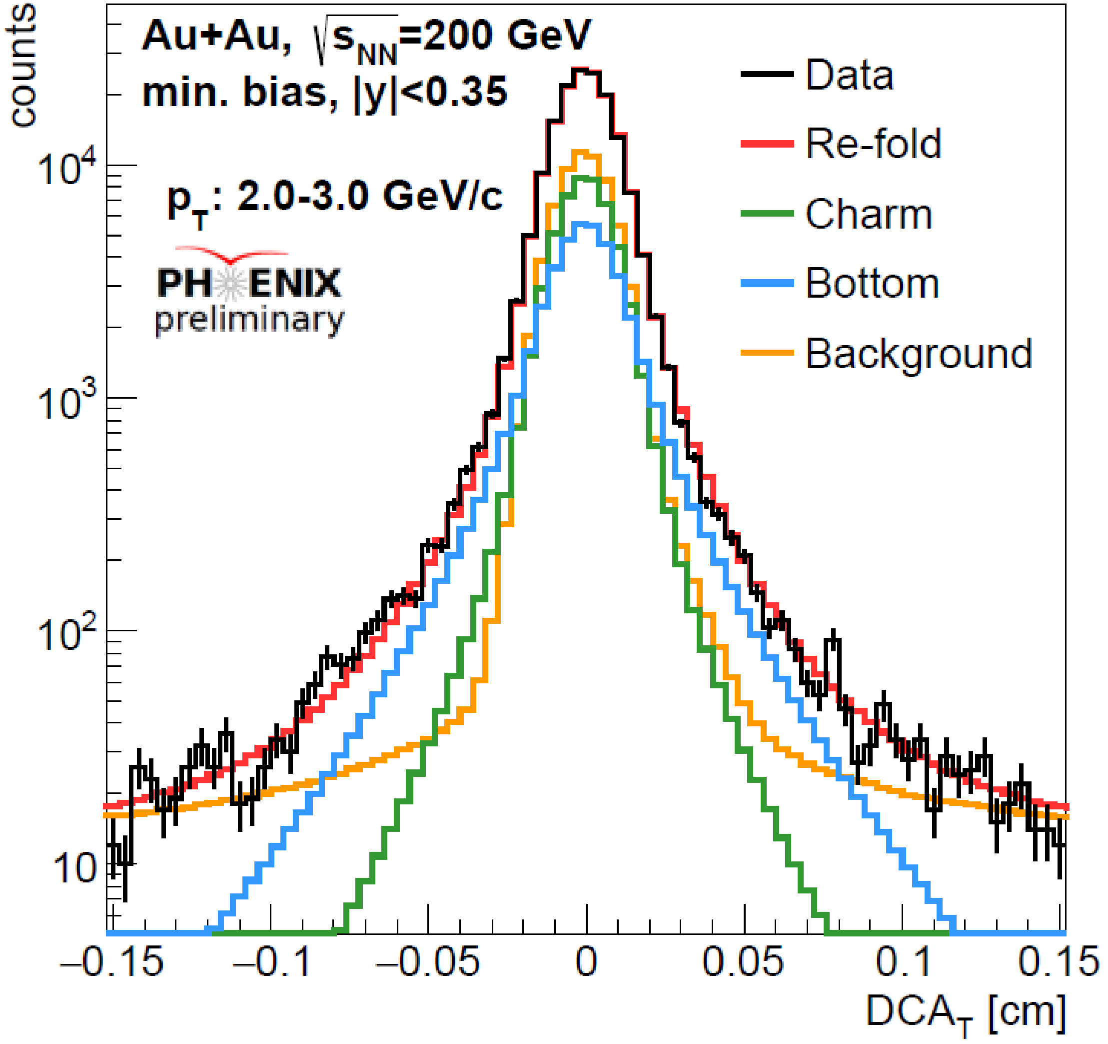


0-10% in Run2014



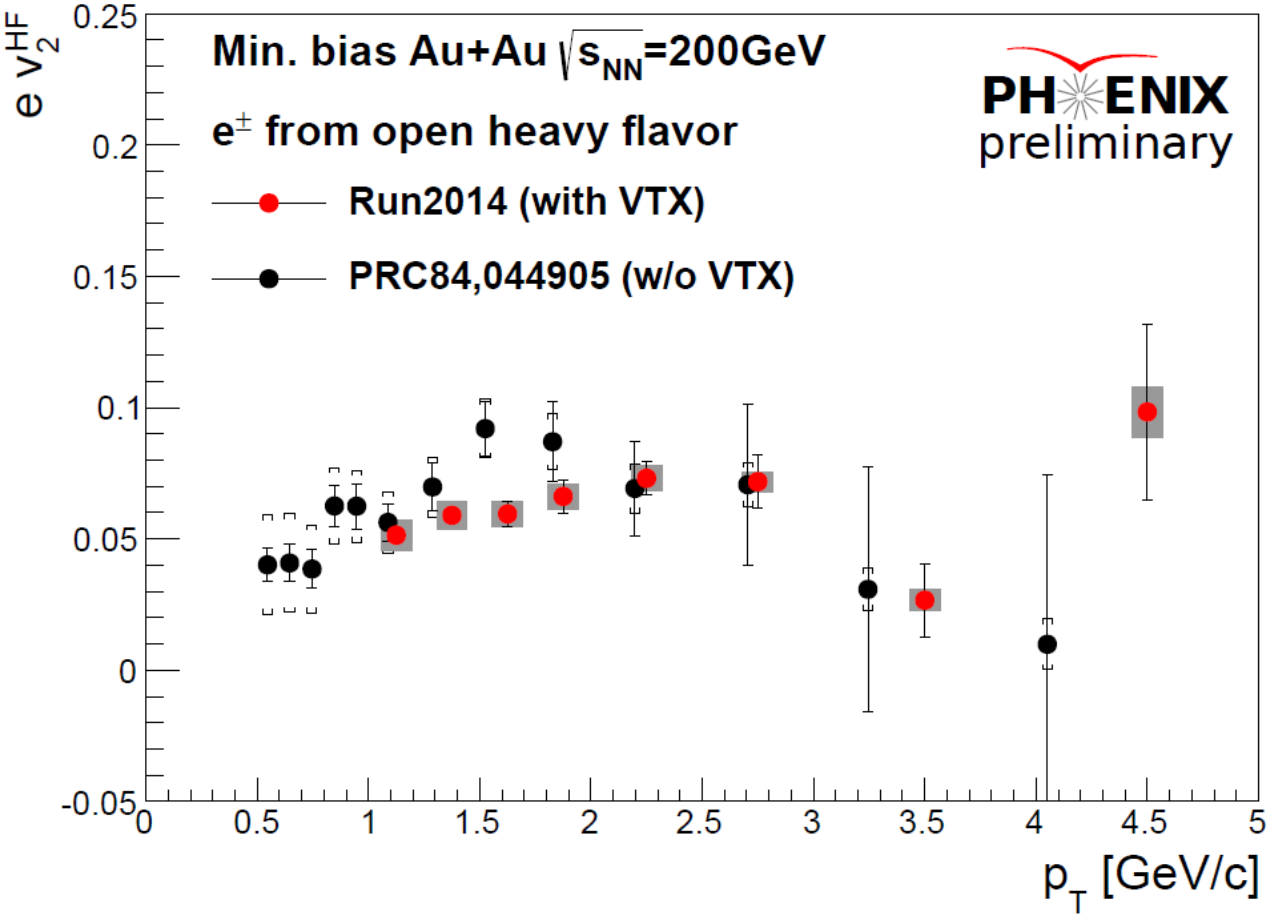
- In 0-10%, bottom and charm are more clearly separated
- Charm is more suppressed than MB
- Bottom is similar

Bottom and charm with large statistics



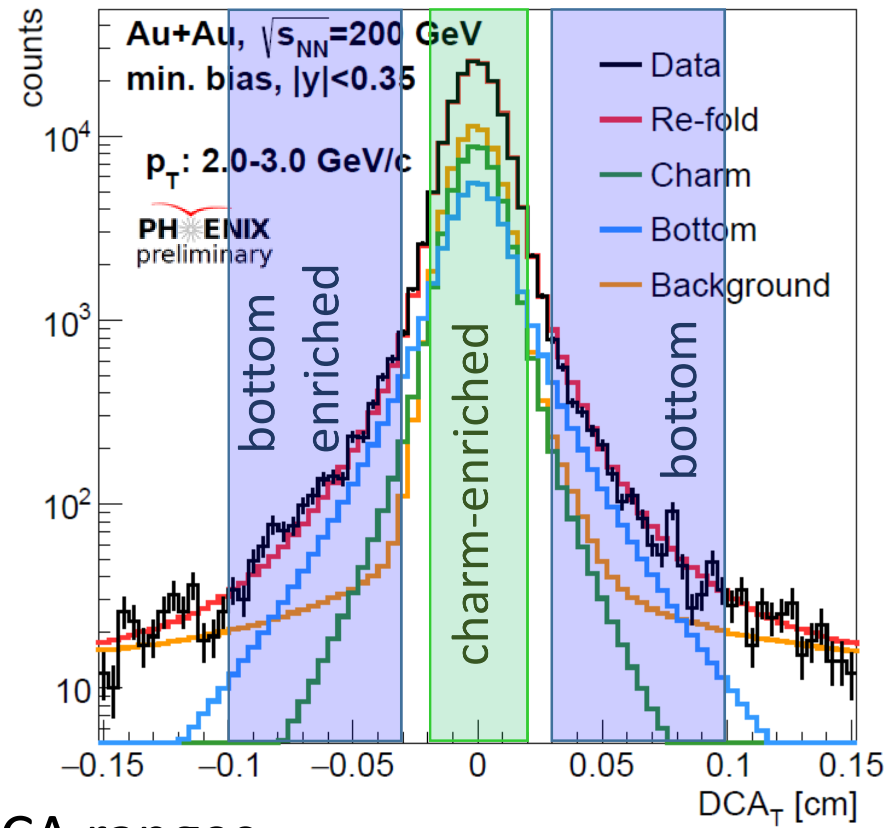
- Recorded large statistics of Au+Au 200 GeV in 2014
  - 17 B events = 4 times larger
- The dataset is available for the analysis.
- Charm and bottom separation using the DCA decomposition in progress
- Dataset enables heavy flavor v_2^{HF} measurement

Heavy Flavor electron v_2^{HF}

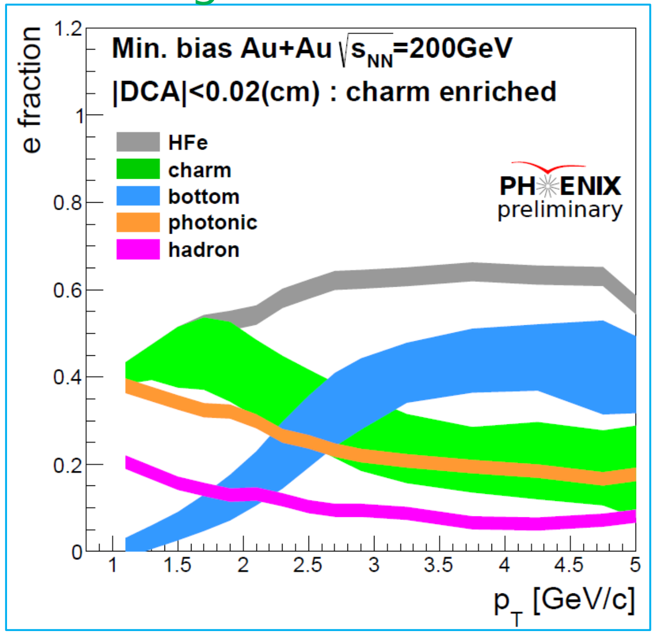


- Heavy flavor electron v_2^{HF} with (F)VTX is consistent with published measurement
  - Smaller statistical and systematic uncertainty
  - VTX and FVTX improve the v_2 measurement significantly
    - VTX reduces the photonic BG
    - FVTX provides twice higher RP resolution

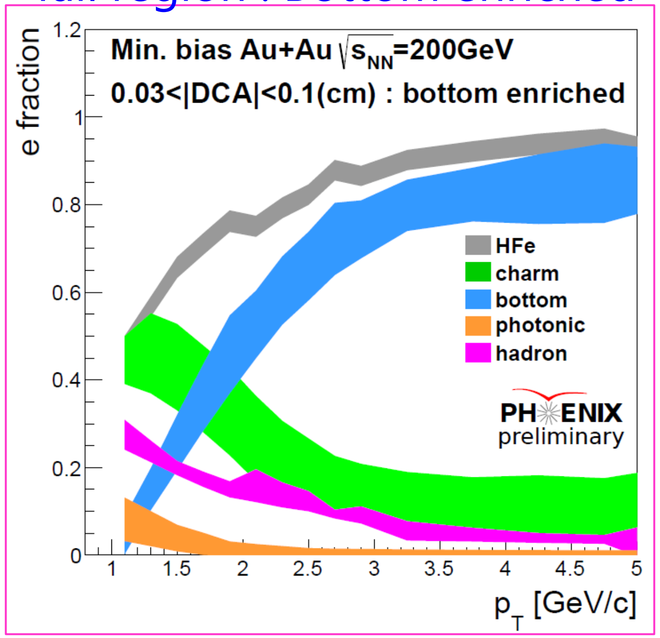
v_2 for c- and b- enriched DCA range



Peak region : Charm enriched



Tail region : Bottom enriched



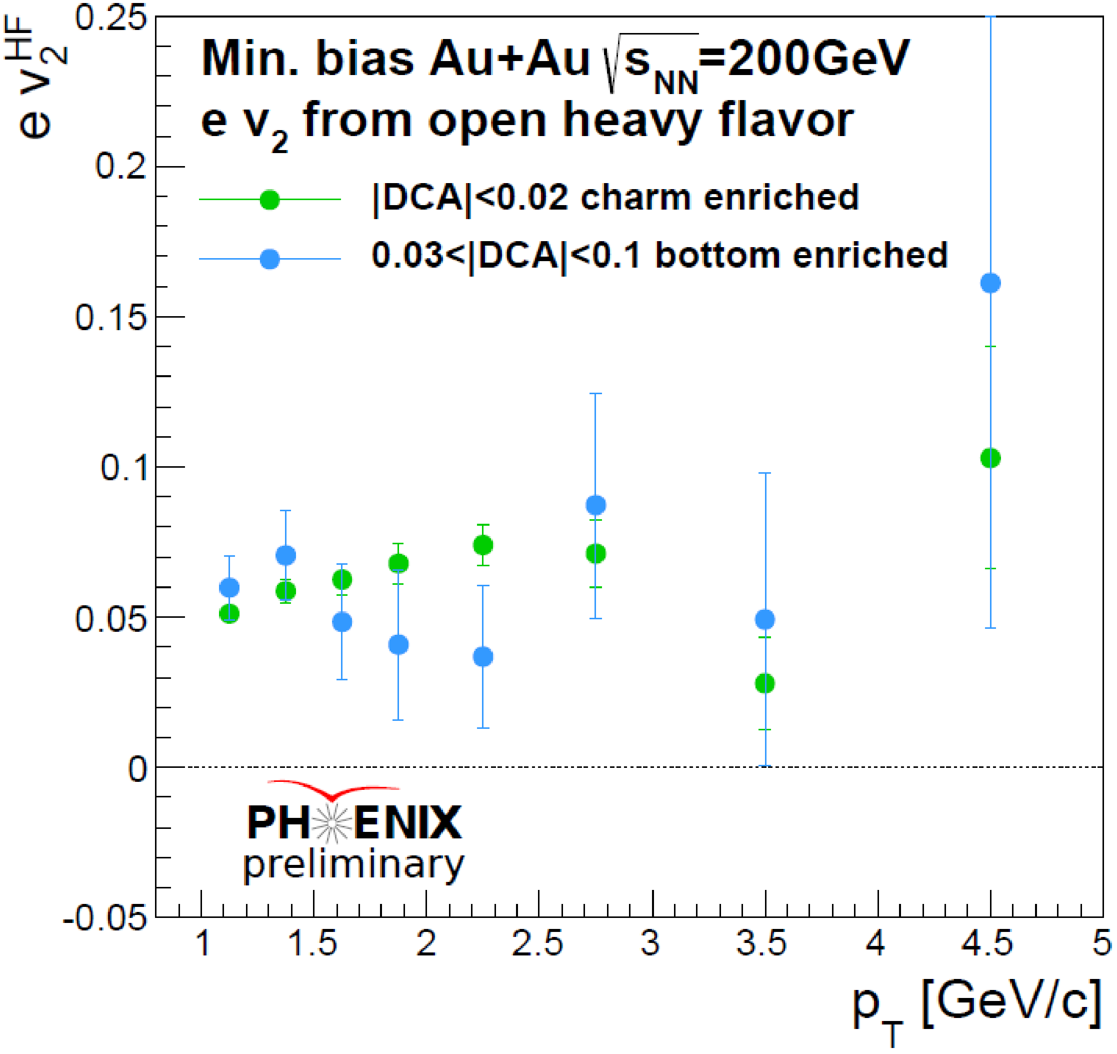
DCA ranges:

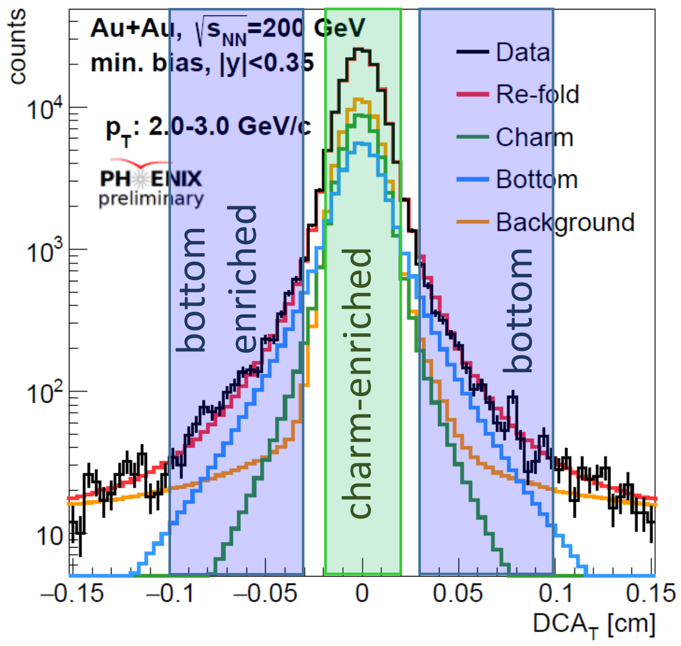
Peak : c-enriched : |DCA|<200um

Tail : b-enriched : 300|DCA|<1000um

- $v_2^{inc} = \underbrace{b \cdot v_2^b(b \to e) + c \cdot v_2^c(c \to e)}_{\mathrm{HFe} \cdot v_2^{HF}} + \mathrm{bg}_0 \cdot v_2^{\mathrm{bg}}$
- Look at v_2 from these DCA range
  - If v_2^b is small, v_2(b-enriched) < v_2(c-enriched)

HF v_2 for c- and b-enriched DCA ranges

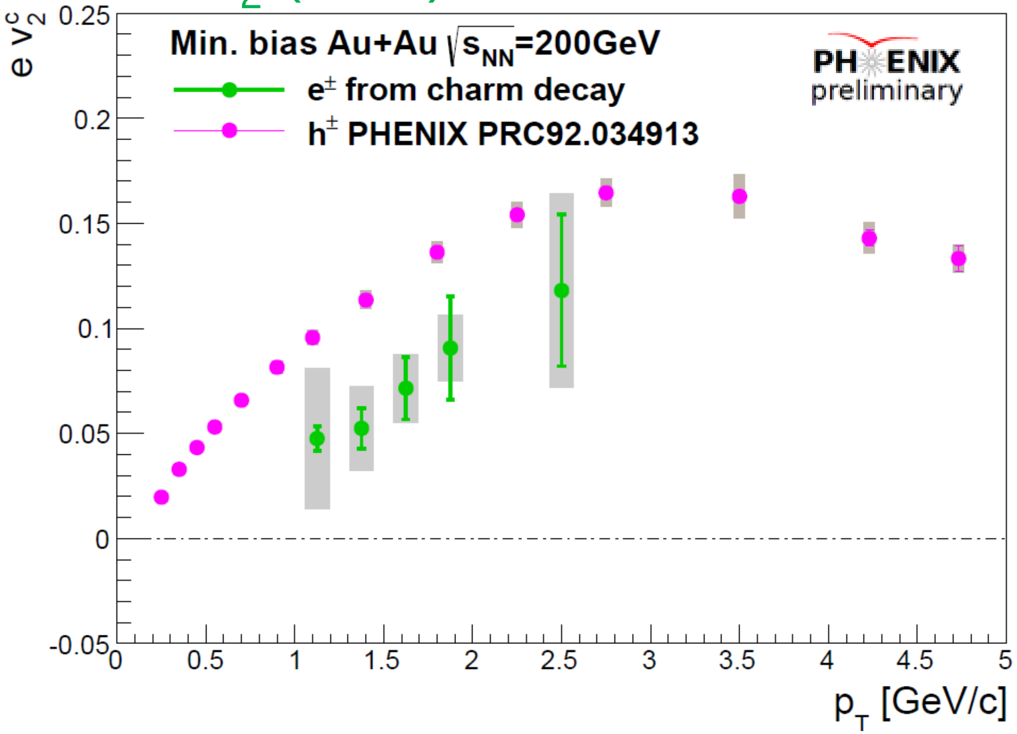




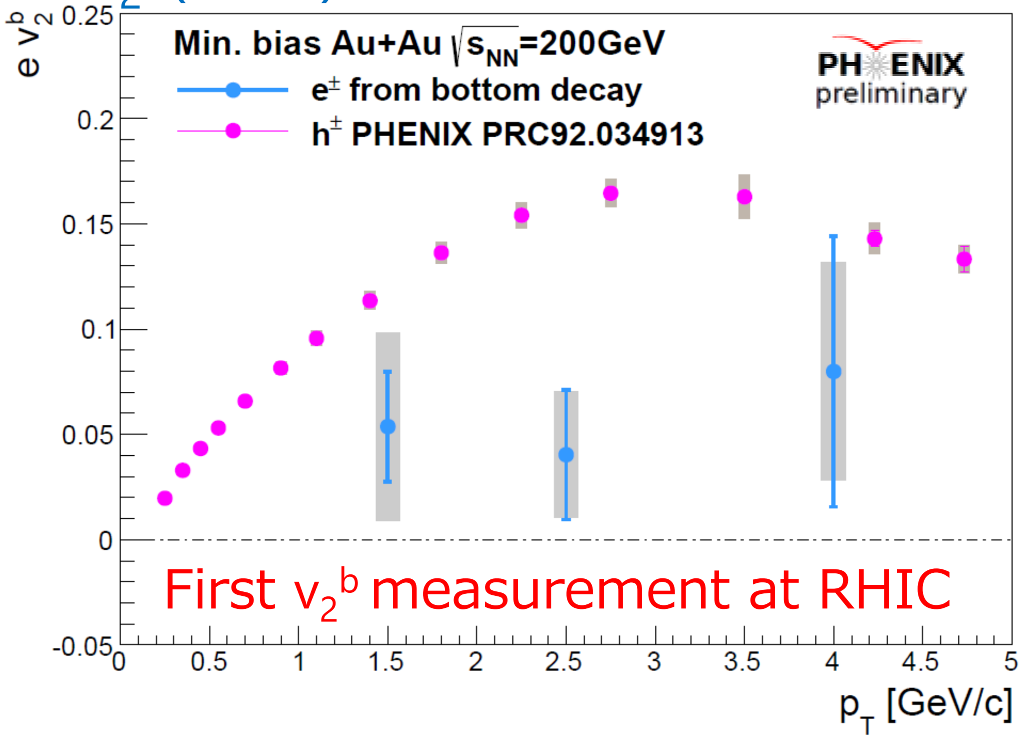
- Clear difference for c- and b- enriched DCA ranges
  - Photonic and hadron background subtracted
  - No b-fraction information is used
- Suggests $v_2^b(b\rightarrow e) < v_2^c(c\rightarrow e)$ at low p_T

$v_2^c(c\to e)$ and $v_2^b(b\to e)$ in Au+Au 200GeV

$v_2^c(c\to e)$



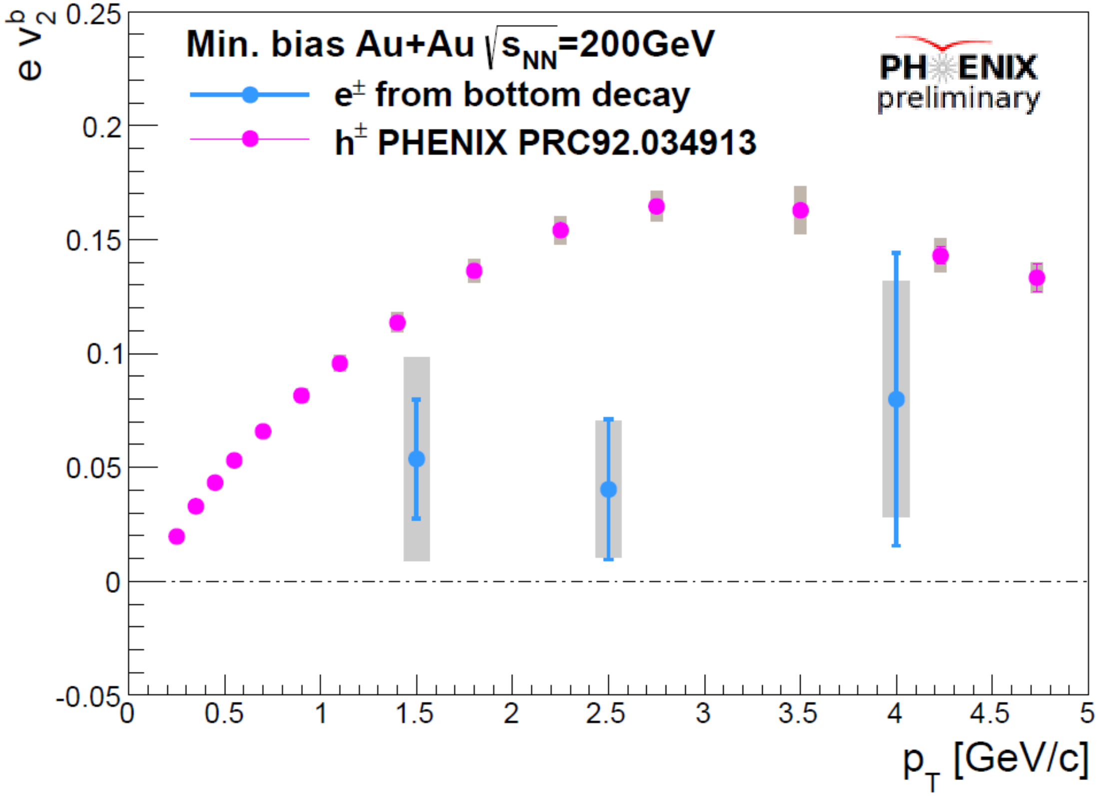
$v_2^b(b\to e)$

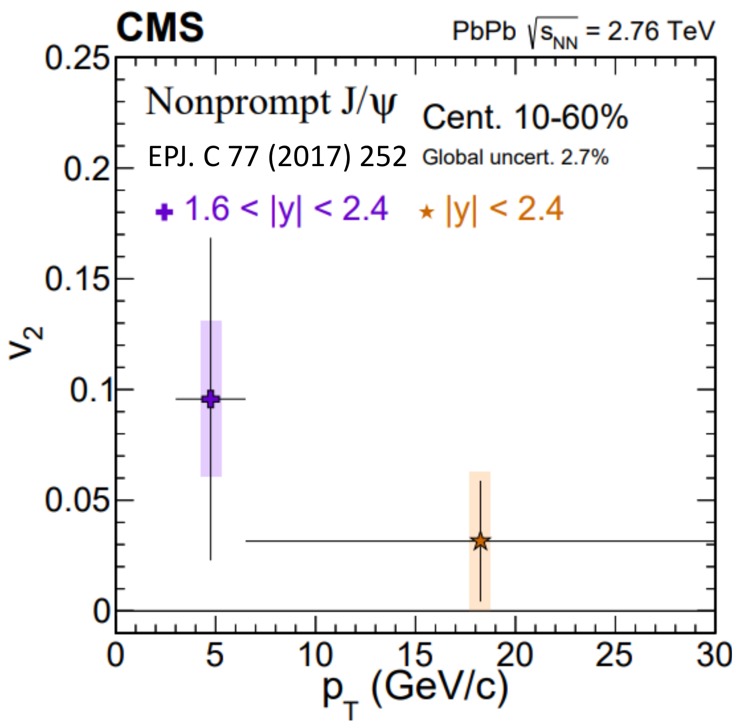


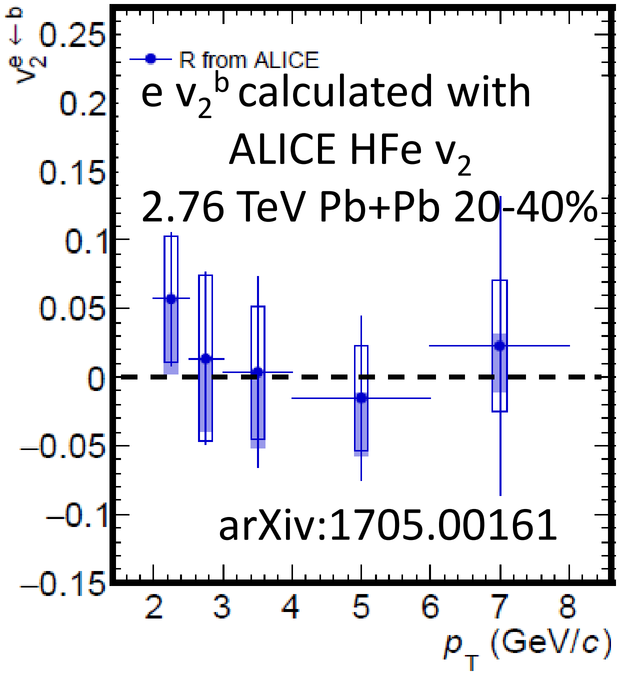
- $v_2(c \to e)$ is positive and smaller than charged hadron v_2
- First $b \to e$ $v_2(b \to e)$ measurement at RHIC
  - consistent with zero within large uncertainty
  - Likely smaller than $v_2(c\to e)$

$v_2^b(b \rightarrow e)$ comparison with LHC

$v_2^b(b \rightarrow e)$

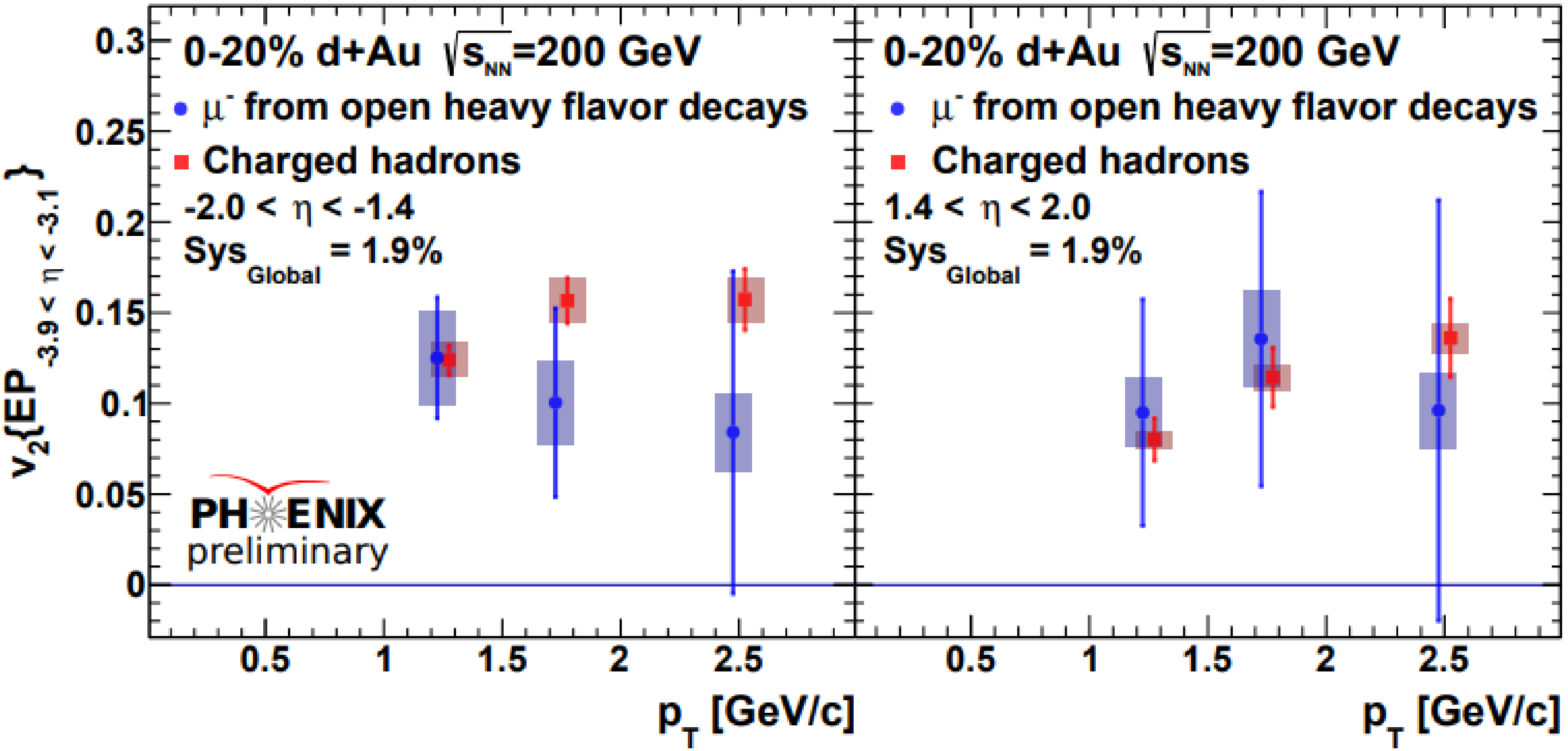






Consistent with LHC results

Heavy flavor muon v_2^{HF} in small system

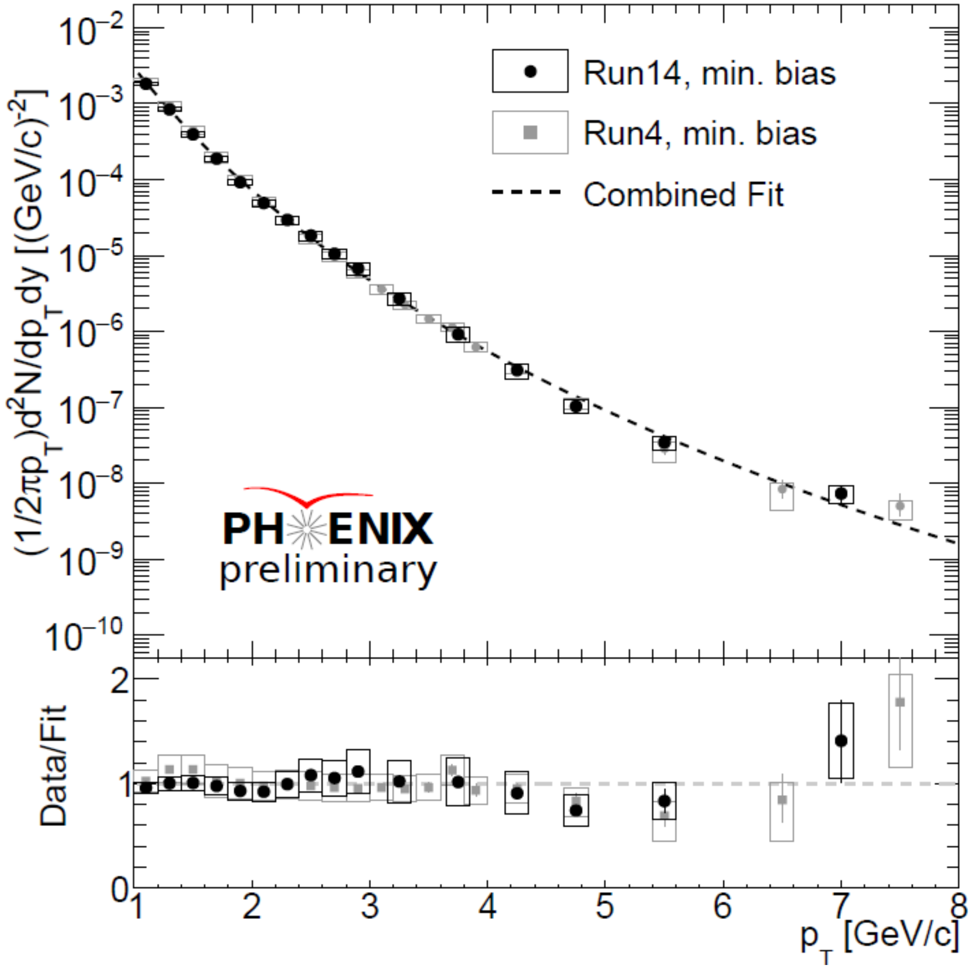


charged hadrons

heavy flavor muons

- First measurement at RHIC
- Significant non-zero v_2 in d+Au collisions !!
  - 99.93% (98.61%) confidence level at backward (forward)

Future prospects



- b->e and c->e separation in progress for Au+Au 200GeV with full statistics
  - 20 B events in Run2014 = 4 times larger than the preliminary
  - HF yields are consistent w/ published result
  - 16 B events more from run2016
- New p+p reference in run2015 coming soon
- p+A in 2015 to study CNM effect
- New b-fraction in Au+Au improves v_2 (b→e) and v_2(c→e)
- B→ J/ψ in Au+Au with 16x more statistics than in Cu+Au
- Heavy flavor in small system

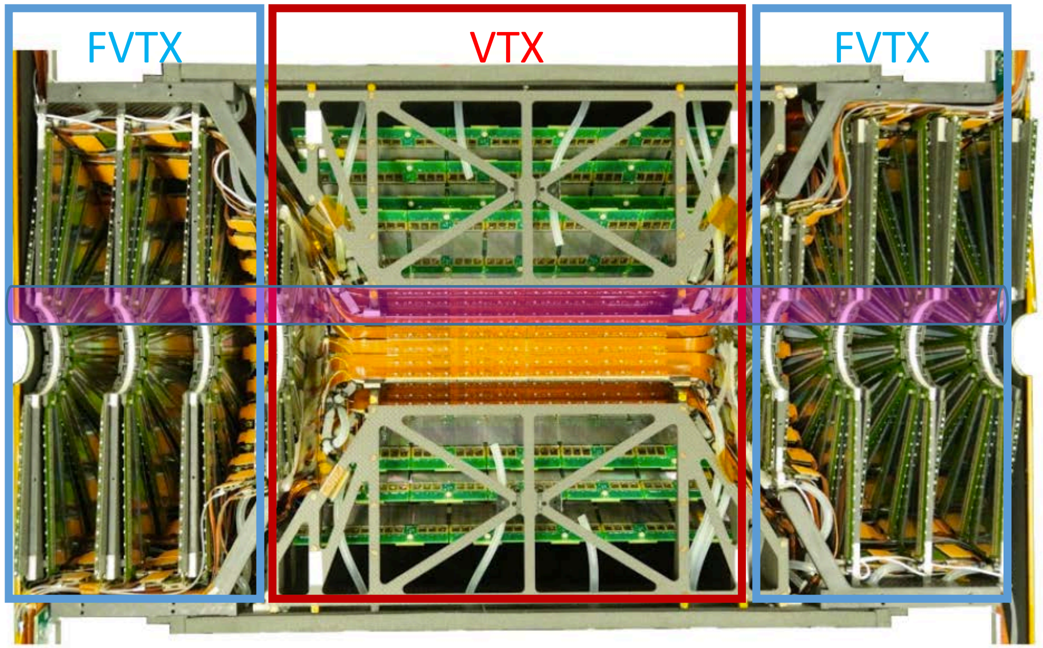
Detailed bottom and charm measurements in progress to study mass dependence of QGP effects

Summary

- Open heavy flavor yield and v_2 measurements in progress
- PHENIX measures heavy flavor e v_2, charm and bottom electron v_2 in min.bias Au+Au collisions at 200 GeV
- HF v_2^{HF} for charm- & bottom- enriched DCA range shows
  - $v_2(b \rightarrow e)$ is smaller than $v_2(c \rightarrow e)$ at low p_T
- Separated charm and bottom electron $v_2(c \rightarrow e)$
  - $v_2^c(c \rightarrow e)$ increase smoothly with p_T
  - $v_2^b(b \rightarrow e)$ is consistent with zero within statistical and systematic uncertainty
    - Likely smaller than $v_2^c(c \rightarrow e)$
- Outlook
  - New bottom and charm results are coming soon for both Mid- and FW rapidity in Au+Au and p+p 200GeV, others
    - Not only charm & bottom yield but flow with large statistics

Backup

PHENIX Silicon Vertex Detector, VTX & FVTX

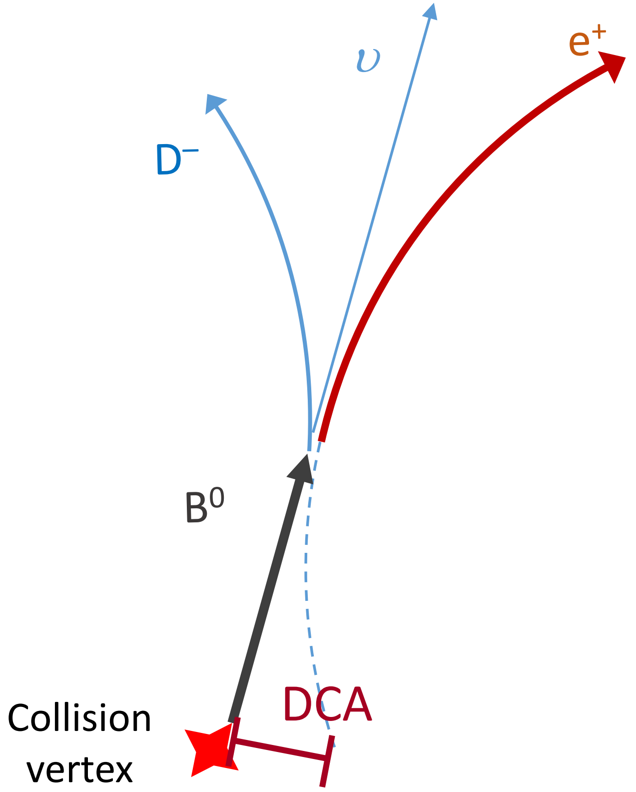


VTX installed in 2011

$|y|<1.2$, $\phi\sim2\pi$: 4 layers (2 pixels + 2 strips)

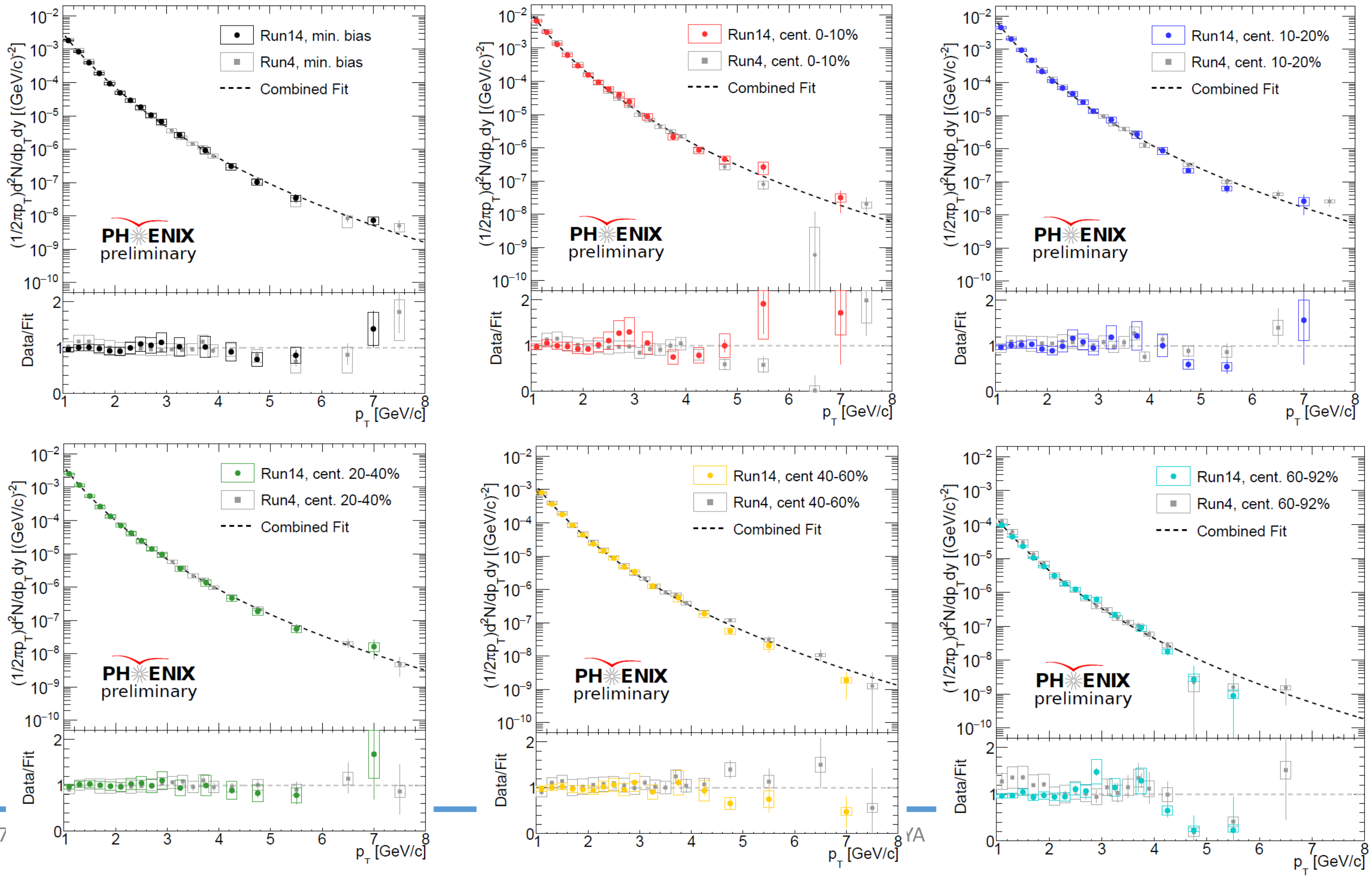
FVTX installed in 2012

$1.2<|y|<2.2$, $\phi=2\pi$: 4 layers

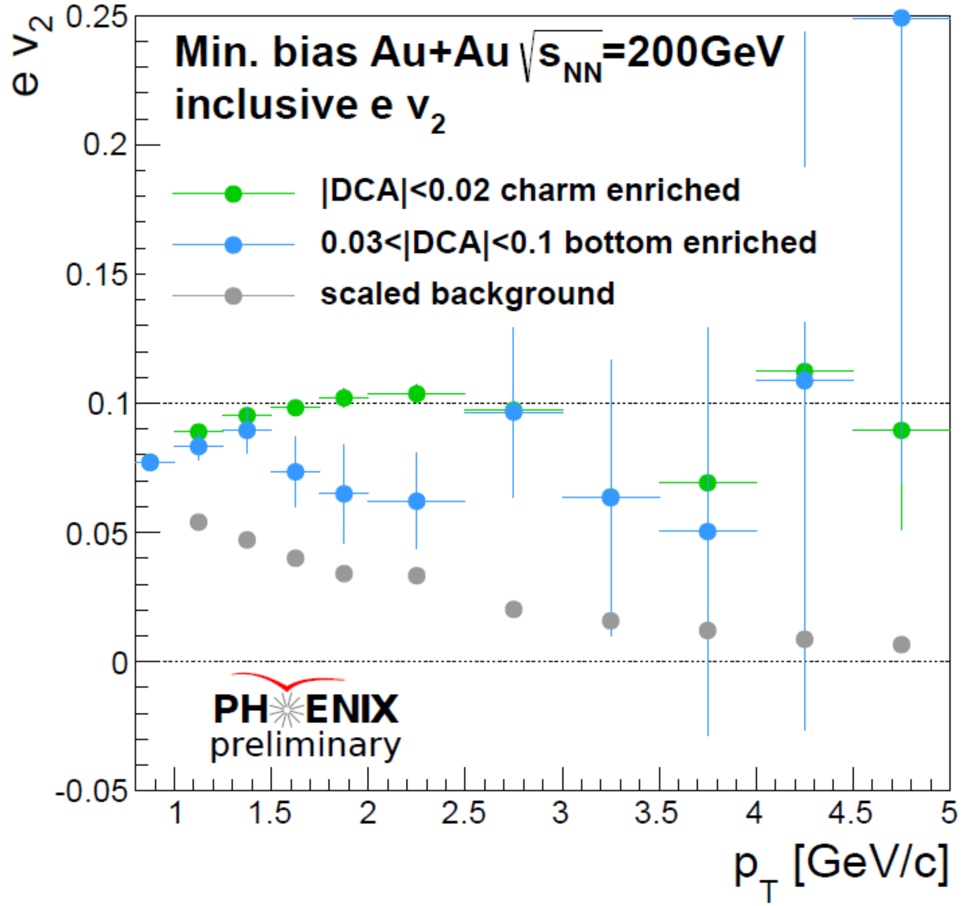


- Purpose
  - Measure DCA for charm-bottom separation
    - Proportional to decay length
    - B^0 : 455 μm, D^0 : 123 μm
  - VTX : Collision vertex determination
  - FVTX: Event plane :twice higher resolution

Heavy flavor e yield at Au+Au 200GeV



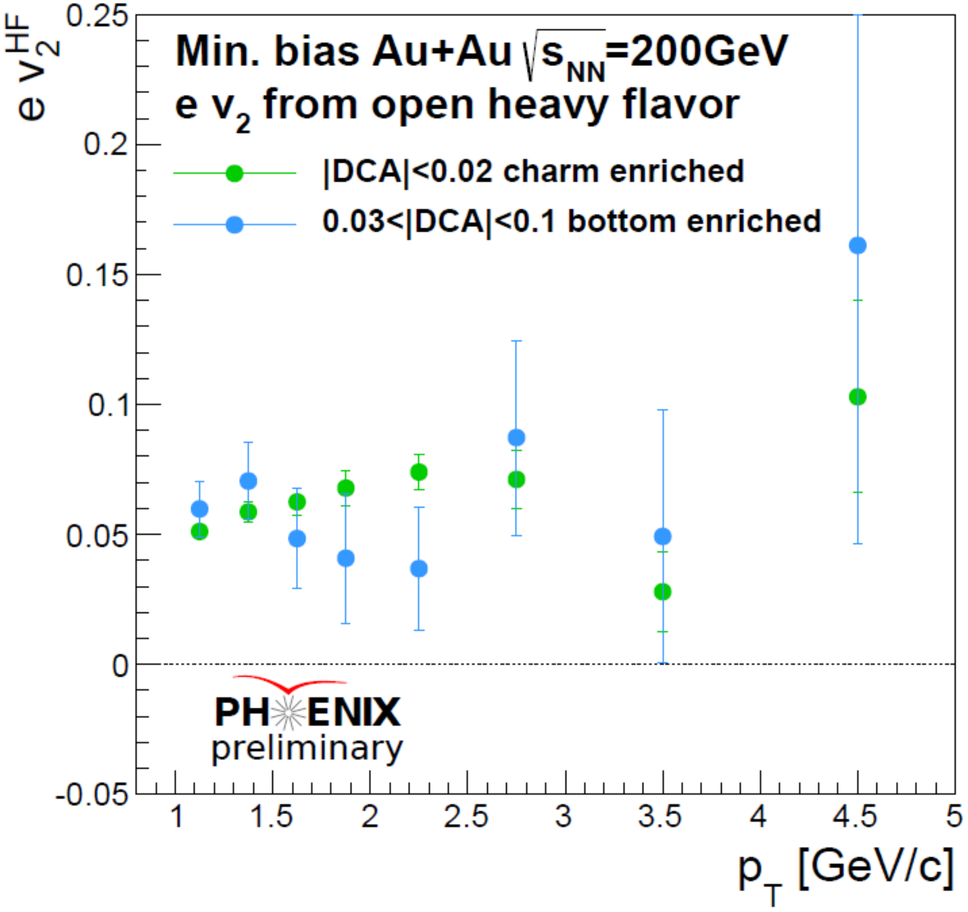
Inclusive e v_2^{inc} for the c- and b-enriched DCA ranges



- Clear difference for c- and b- enriched DCA ranges
- Backgrounds contribute it:
  - Need to be subtracted :

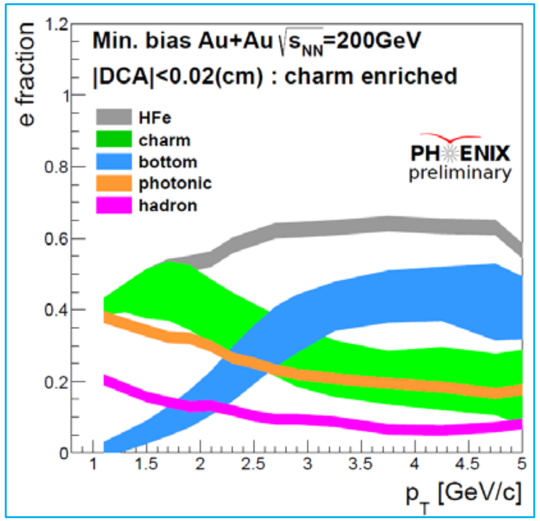
$$v_2^{inc} = b \cdot v_2^b(b \rightarrow \mathrm{e}) + c \cdot v_2^c(c \rightarrow \mathrm{e}) + \mathrm{bg}_0 \cdot v_2^{\mathrm{bg}}$$

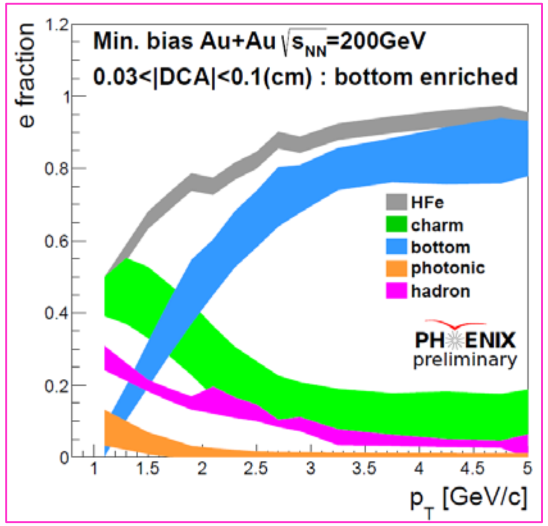
Extract v_2^c (c → e) and v_2^b (b → e)



$$v_2^{HF} = b \cdot v_2^b + c \cdot v_2^c$$

- 2 HFe v_2^{HF} from c- and b-enriched
- b->e and c->e fractions are determined by the DCA analysis with VTX
  - Unfolding provides yields and DCA shape of b->e and c->e

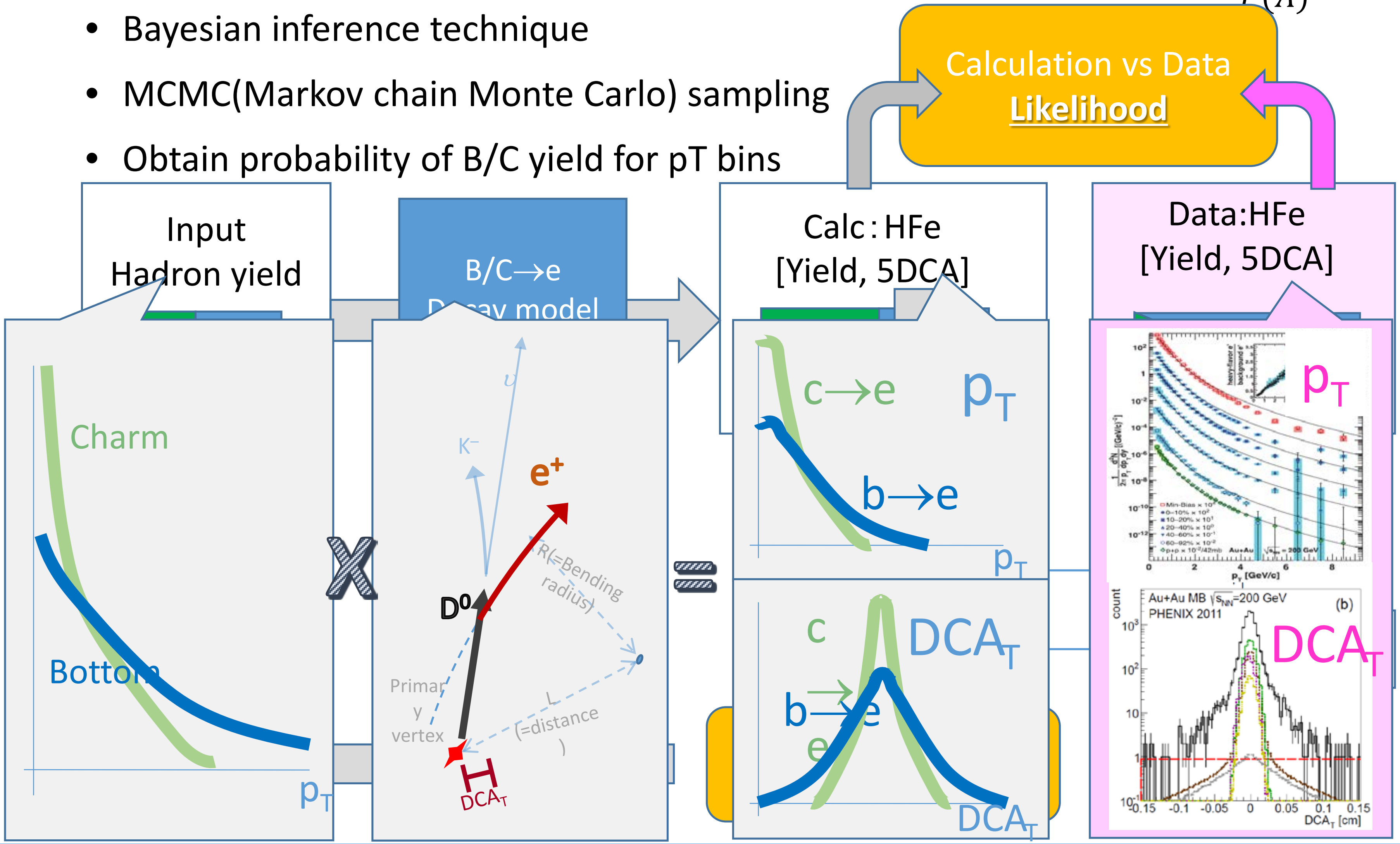




Unfolding: Bayesian inference

- Purpose: extract parent B/C hadron yield
  - Bayesian inference technique
  - MCMC(Markov chain Monte Carlo) sampling
  - Obtain probability of B/C yield for pT bins

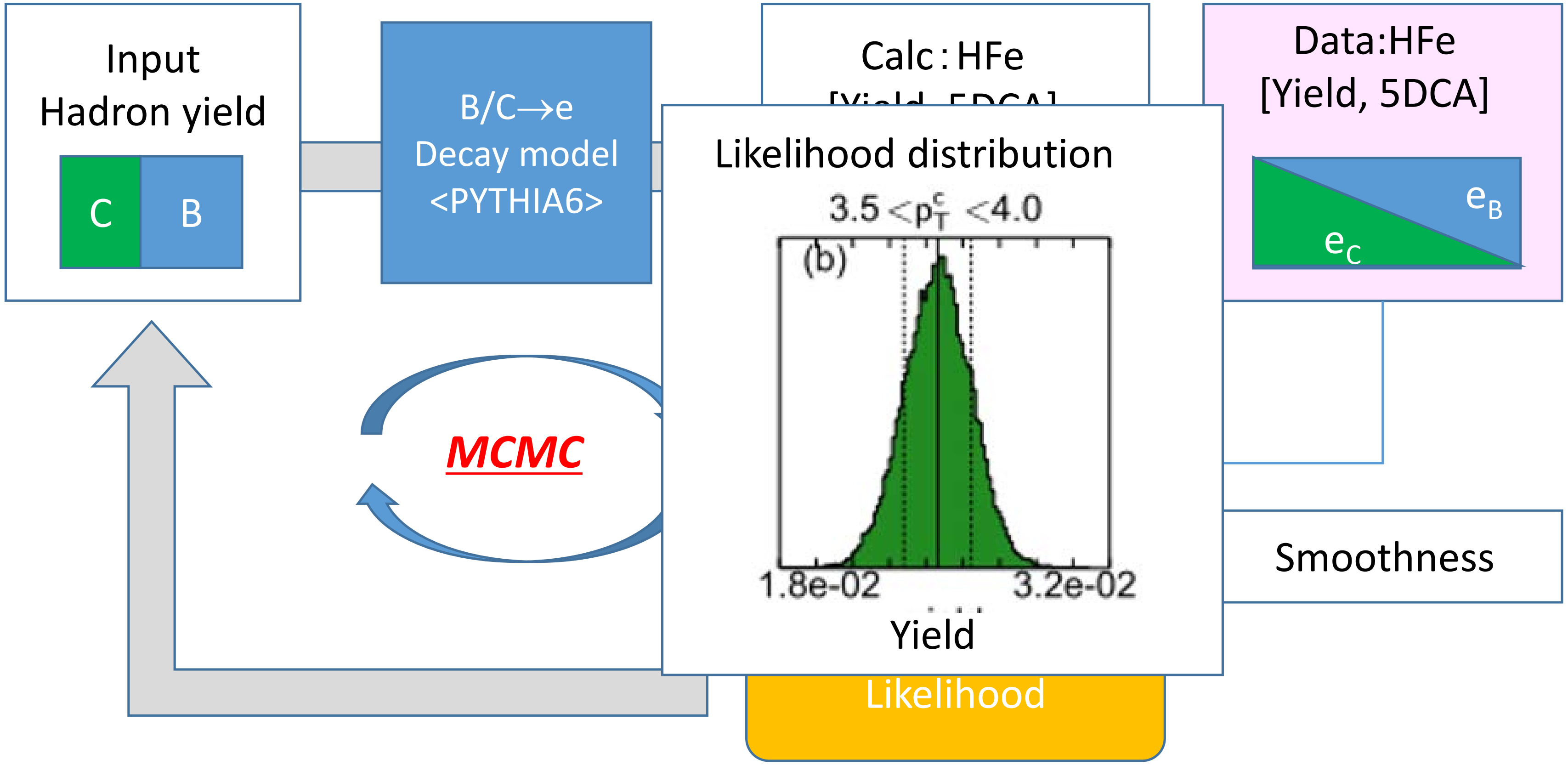
$$P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$$



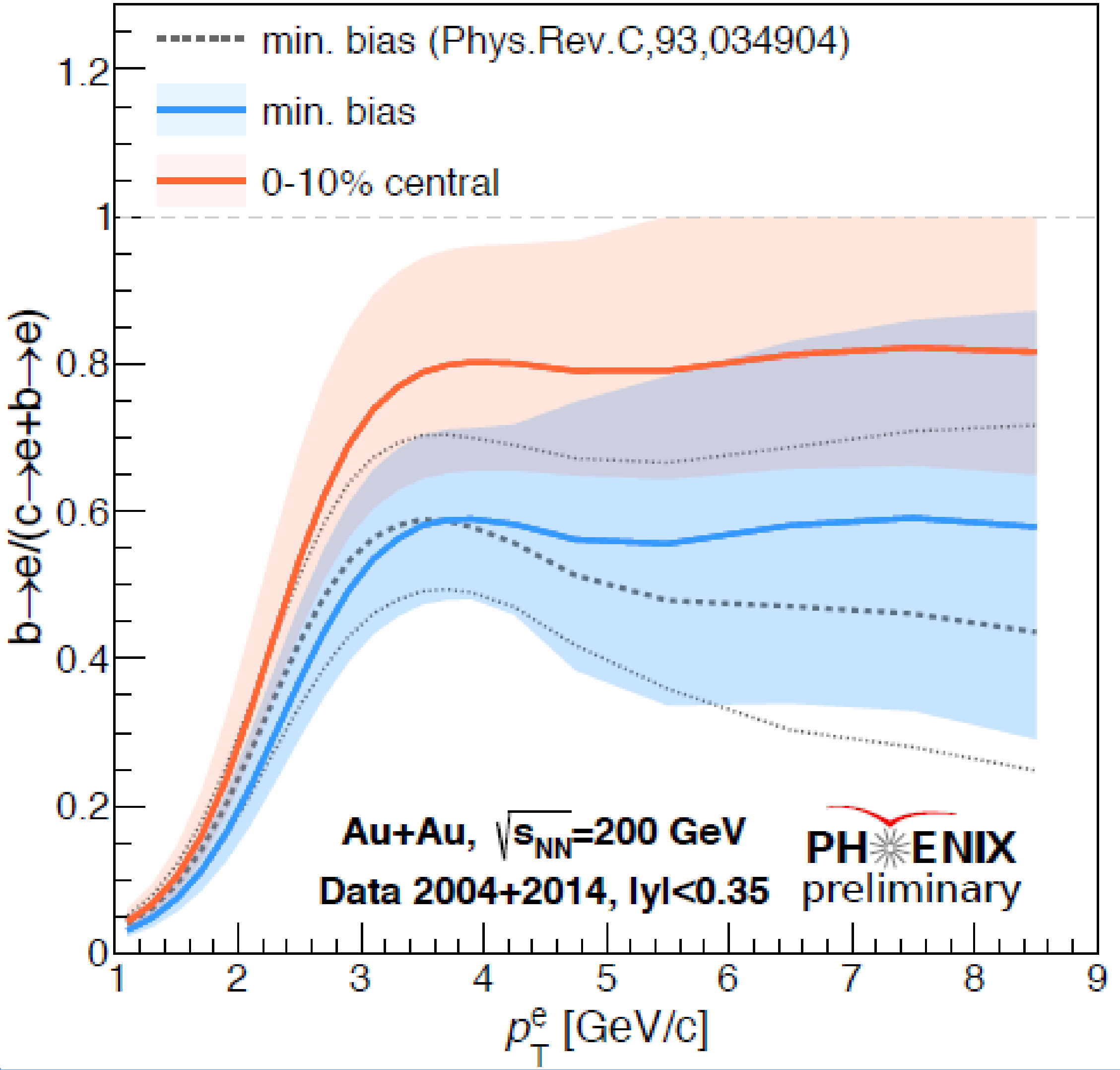
Unfolding: Bayesian inference

- Purpose: extract parent B/C hadron yield
  - Bayesian inference technique
  - MCMC(Markov chain Monte Carlo) sampling
  - Obtain probability of B/C yield for pT bins

$$\mathrm{P(B|A)} = \frac{P(A|B) \cdot P(B)}{P(A)}$$



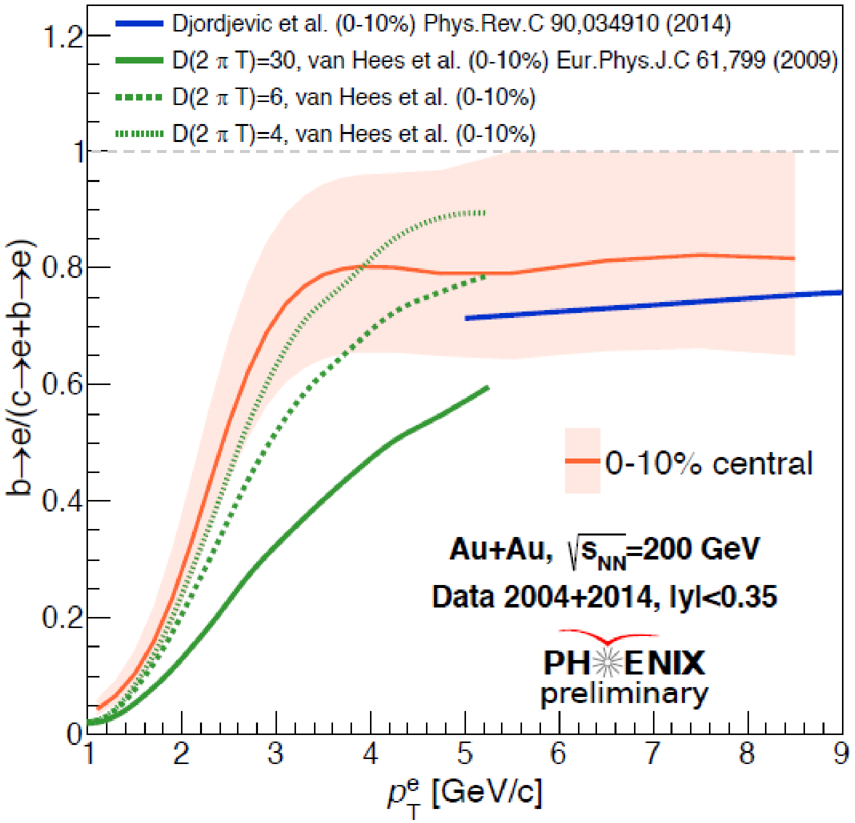
Bottom electron fraction in 0-10%



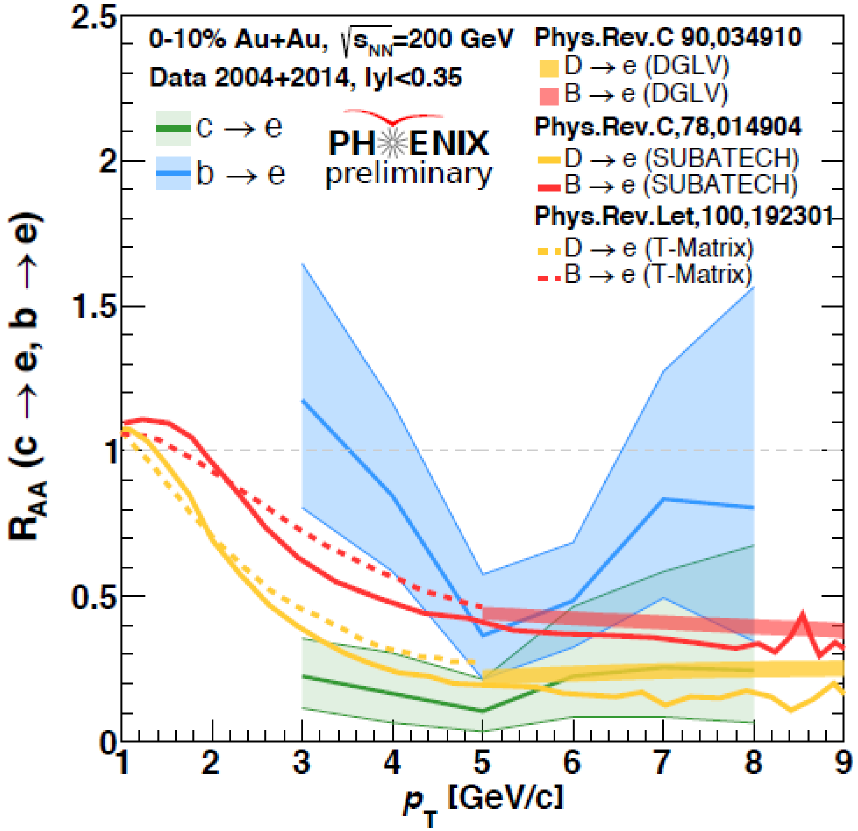
- New result in MB is consistent with published measurement
  - 3 time more statistics that the published result
- higher fraction@0-10%
  - Suppression can be different

Model comparisons in 0-10%

Sensitive to relative modification



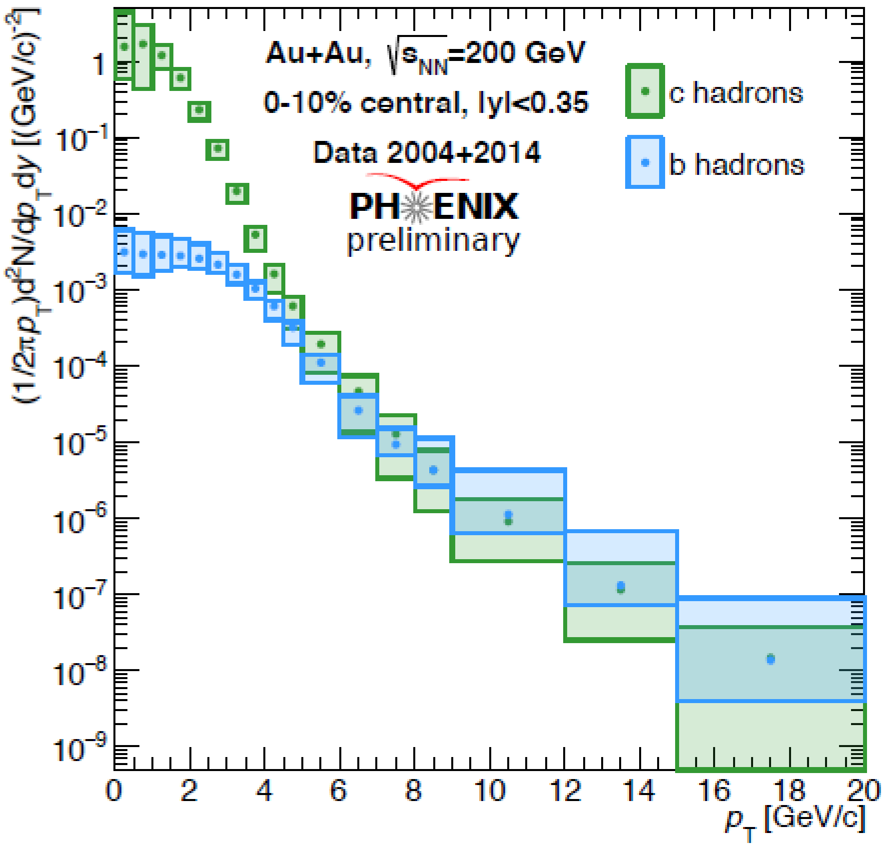
Sensitive to total modification



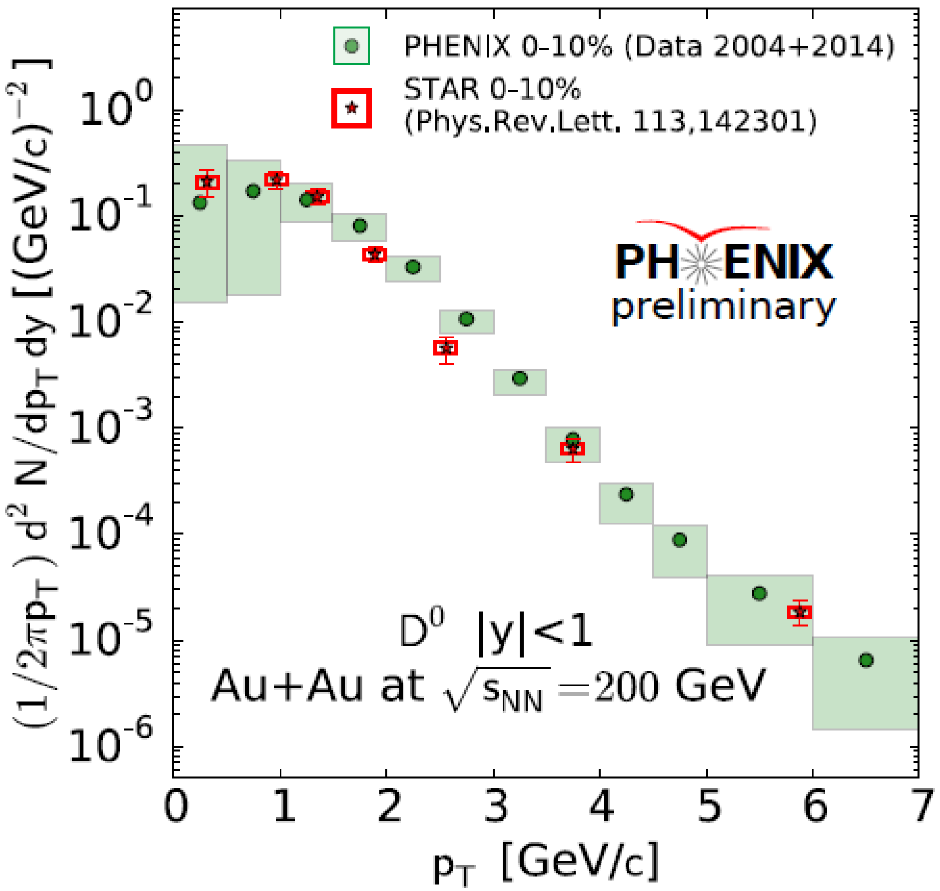
- Data prefers smaller diffusion parameter(D=4) = strong coupling
- Need smaller uncertainty to distinguish these models
  - These models are consistent with our result though slightly smaller at low pT

Unfold results for 0-10%

0-10% Au+Au 200GeV



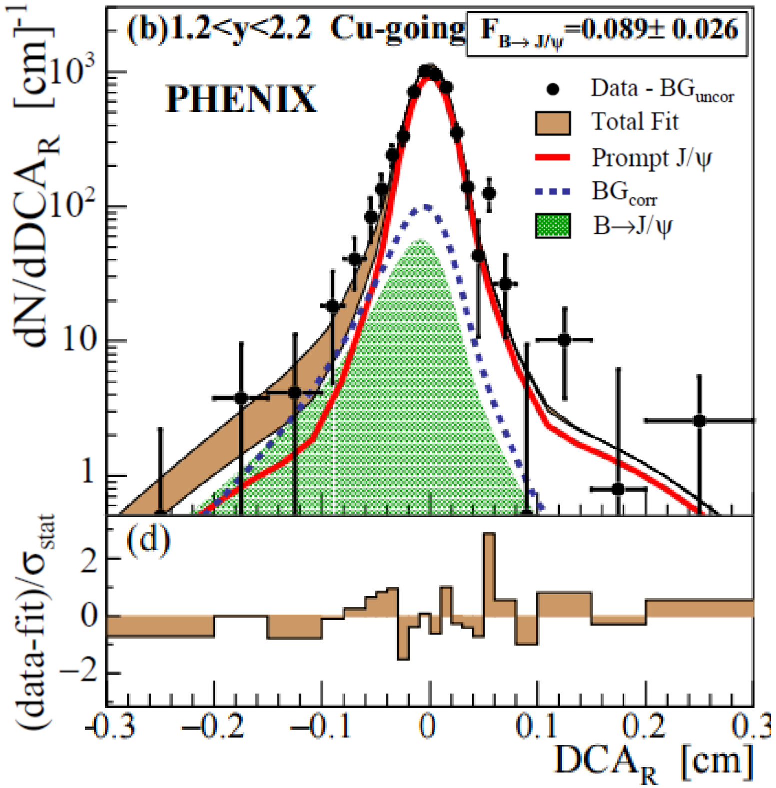
0-10% Au+Au 200GeV



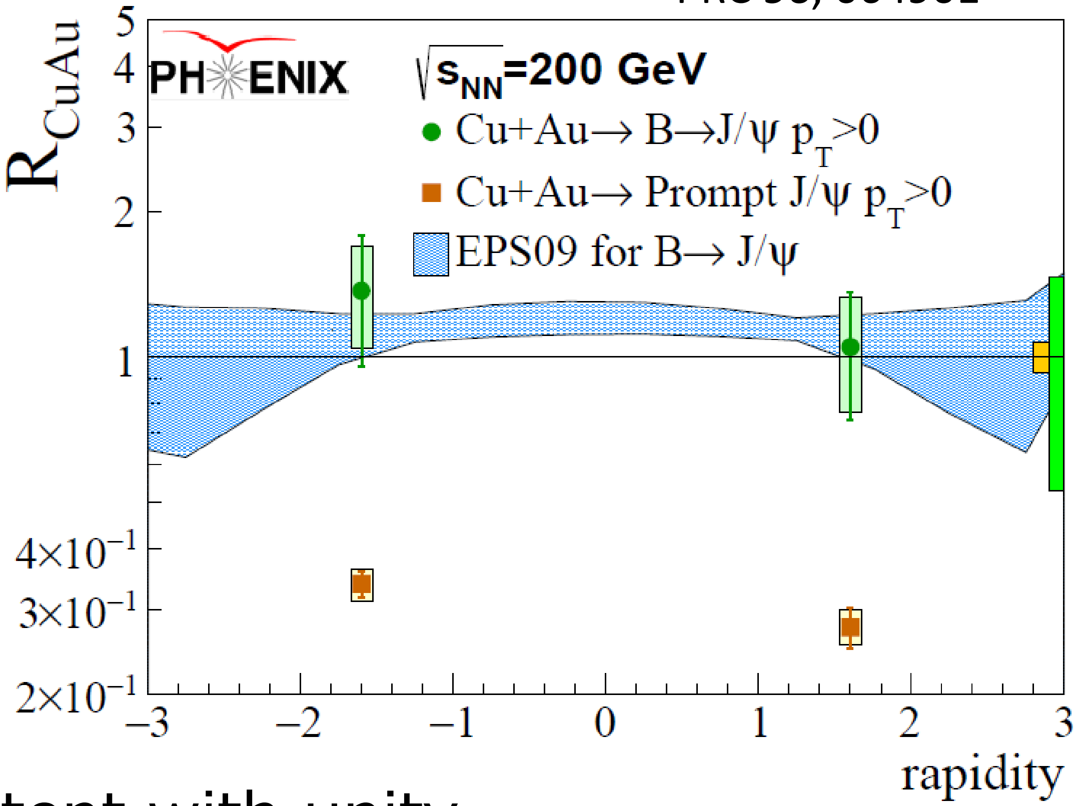
- Invariant yields of bottom and charm hadrons
- Unfold charm hadron is in good agreement with direct D measurement by STAR

$B \to J/\psi\ R_{AA}$ in Cu+Au at Forward rapidity

DCA from FVTX



PRC **96**, 064901



- $B \to J/\psi$: No suppression – consistent with unity
  - Also consistent with a modest enhancement by EPS09
- Prompt J/ψ : Large suppression
  - breaks up in final state

$$R_{CuAu}^{B\to J/\psi} = \frac{F_{B\to J/\psi}^{CuAu}}{F_{B\to J/\psi}^{pp}} R_{CuAu}^{inc.J/\psi}$$