

**Quark flavor dependence of particle  
*production* & flow in nucleus-nucleus  
collisions measured by PHENIX**

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**for the PHENIX Collaboration**

**Quark Matter 2019**

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**Wanda Reign Wuhan**

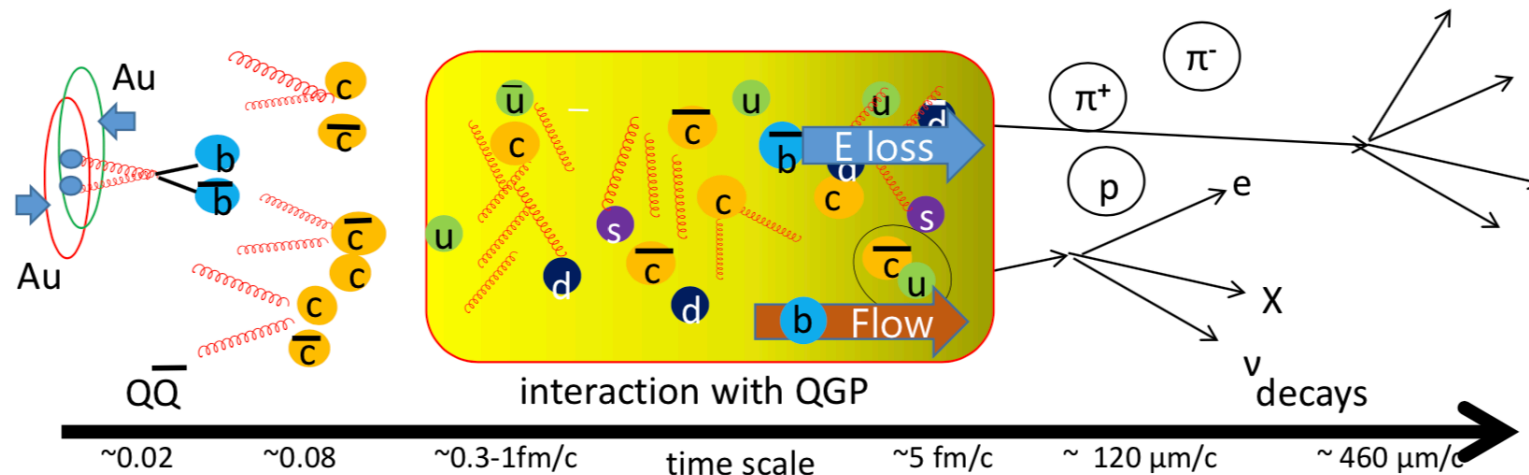


# Probe QGP with Heavy Flavor

- HF (**charm** & **bottom**) is predominantly produced at initial collision
  - Production calculable by pQCD because of the heavy mass

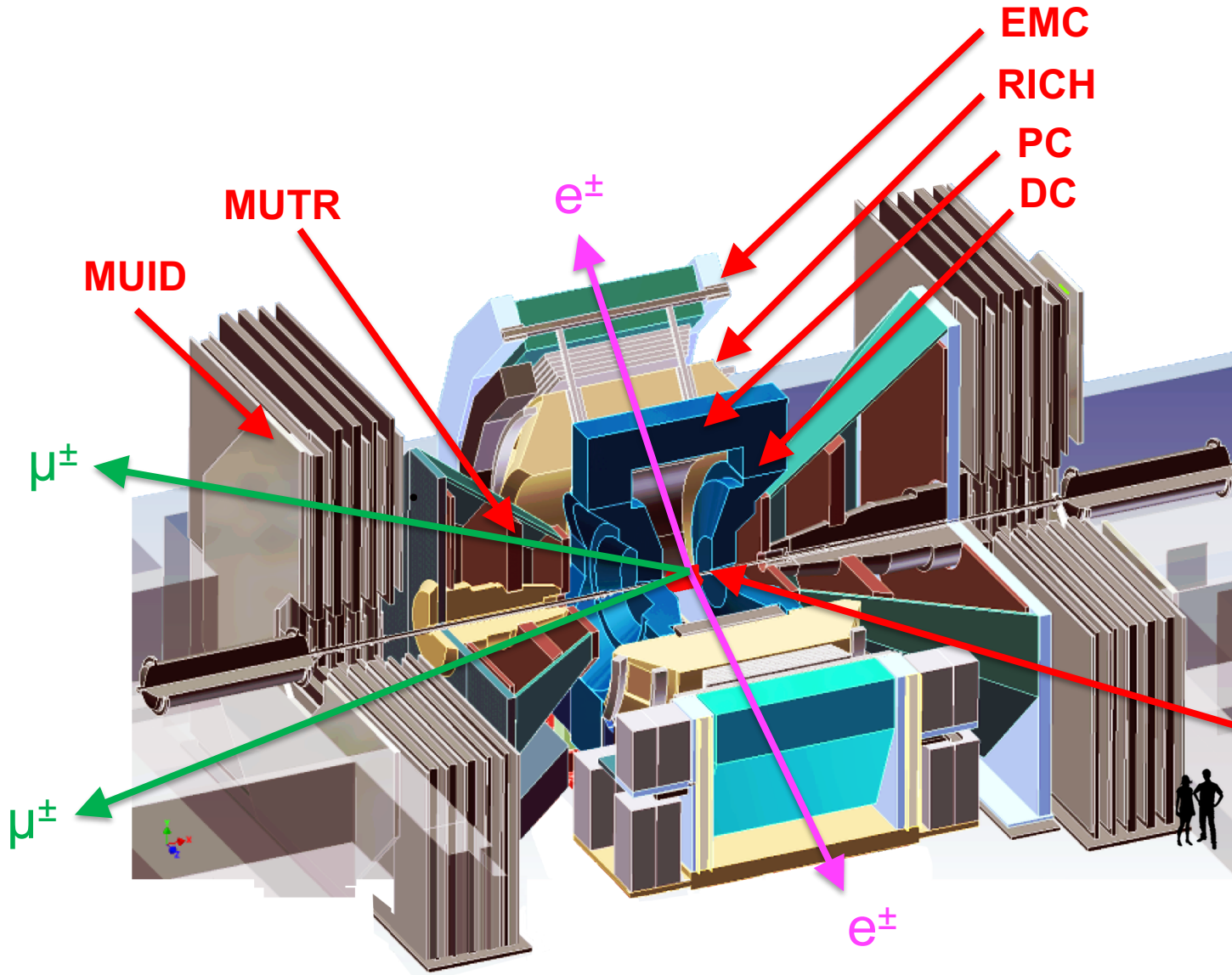
$$\begin{array}{l}
 M_{\text{charm}} \sim 1.3 \text{ GeV}/c^2 \\
 M_{\text{bottom}} \sim 4.5 \text{ GeV}/c^2
 \end{array}
 \gg
 \begin{array}{l}
 \Lambda_{\text{QCD}} \sim 200 \text{ MeV} \\
 T_{\text{QGP}} \sim 400 \text{ MeV}
 \end{array}$$

- HF experiences in-medium energy loss and flow-like expansion



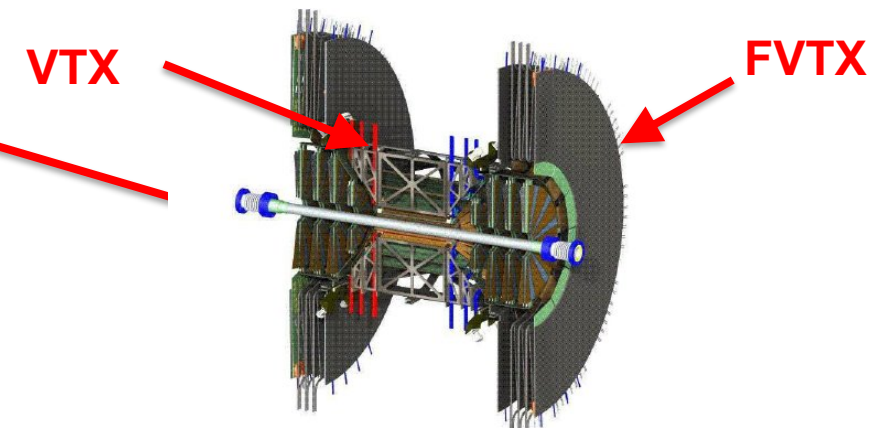
***→ HF production & flow are important probes to QGP***

# PHENIX Detector



## HF measurements over wide kinematic range

- Central Arms + VTX
  - HF  $e^\pm$ ,  $J/\psi \rightarrow e^+ + e^-$
  - $|\eta| < 0.35$ ,  $\phi = 2 \times \pi/2$
- Muon Arms + FVTX
  - $J/\psi \rightarrow \mu^+ + \mu^-$
  - $1.2 < |\eta| < 2.2$ ,  $\phi = 2\pi$



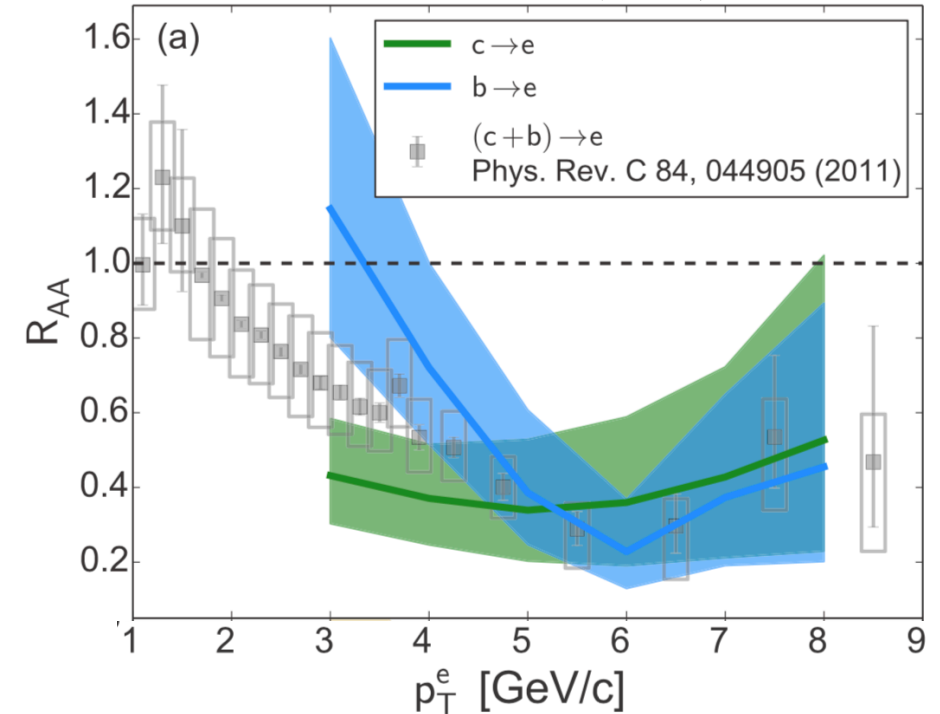
# Quark Mass Dependent Energy Loss

$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dydp_T}{d^2 \sigma_{pp}/dydp_T}$$

*2011 Au+Au Data*

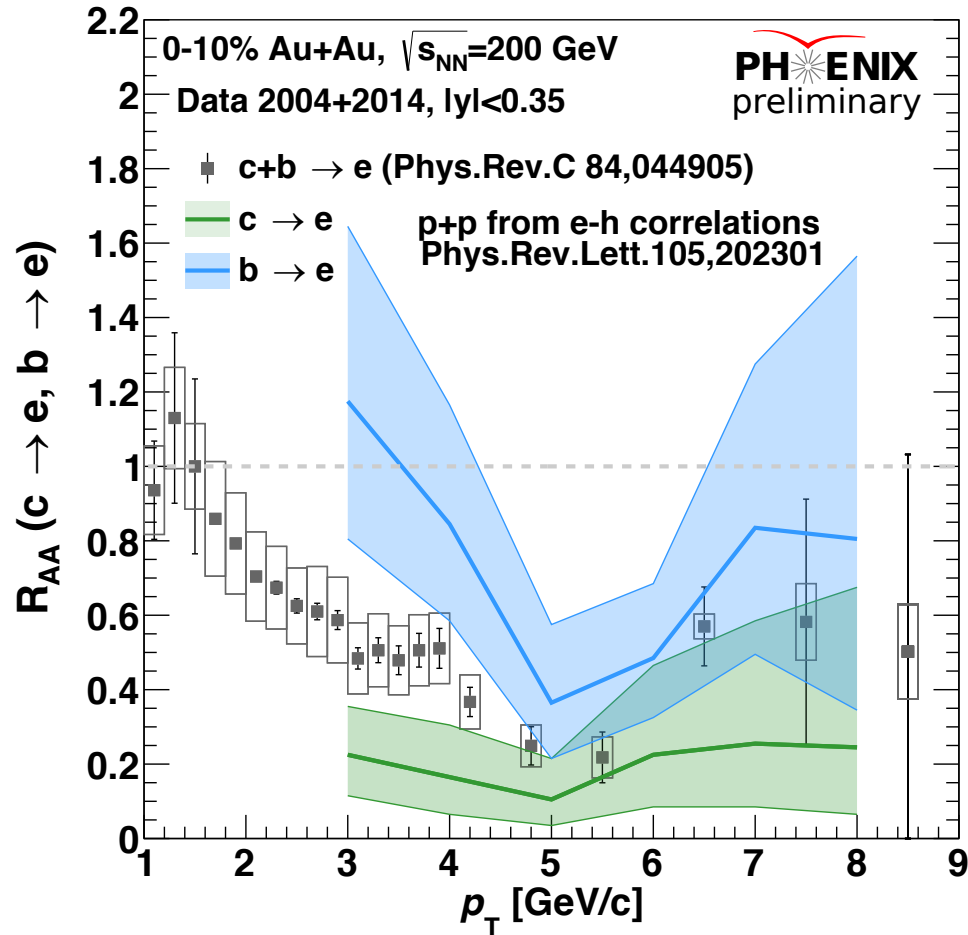
*PHENIX : PRC93.(2016).034904*

- Suppression of HF decay  $e^\pm$  observed
  - High- $p_T$  : **charm**  $R_{AA} \sim$  **bottom**  $R_{AA}$ 
    - Radiative energy loss
  - Low- $p_T$  : **charm**  $R_{AA} <$  **bottom**  $R_{AA}$ 
    - Collisional energy loss
- The predicted mass dependence consistent with data
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Next Step : *Coherent understanding of energy loss, transport property & coalescence effect*
  - *Measurements of  $R_{AA}$  &  $v_2$  for charm & bottom electrons, and  $J/\psi$*



# Charm & bottom $R_{AA}$ in Au+Au 200GeV

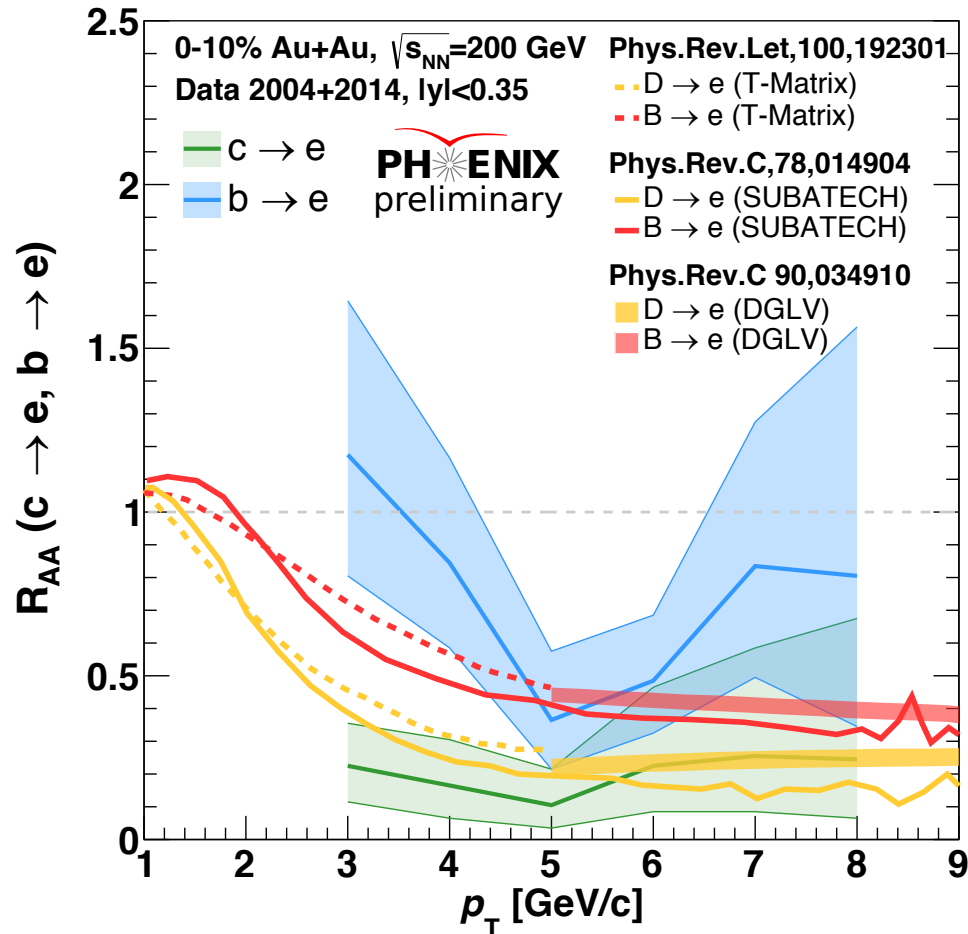
2014 Au+Au Data



- Charm & bottom  $R_{AA}$  using 2014 data
  - 3 times more data than 2011 data
  - Clearer separation in 0-10% central collisions

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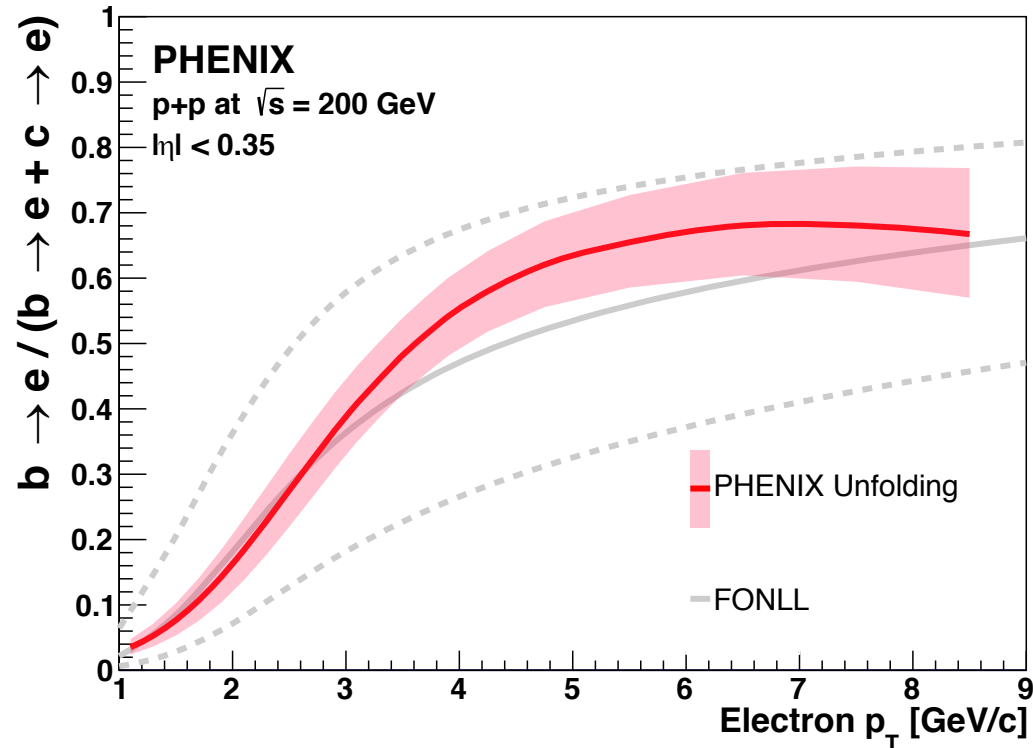


- **Charm & bottom**  $R_{AA}$  using 2014 data
  - 3 times more data than 2011 data
  - Clearer separation in 0-10% central collisions
- 3 models consistent with data
  - T-Matrix + small diffusion const ( $2\pi TD=4$ )
    - **Strong coupling QGP**
  - SUBATECH : Energy loss + running coupling const.
  - DGLV : Energy loss + plasma w/ static & dynamic potentials
- Need better precision in data to distinguish these models

# Bottom electron fraction in p+p 200GeV

*2015 Data published*

*PHENIX : PRD.99.(2019)092003*

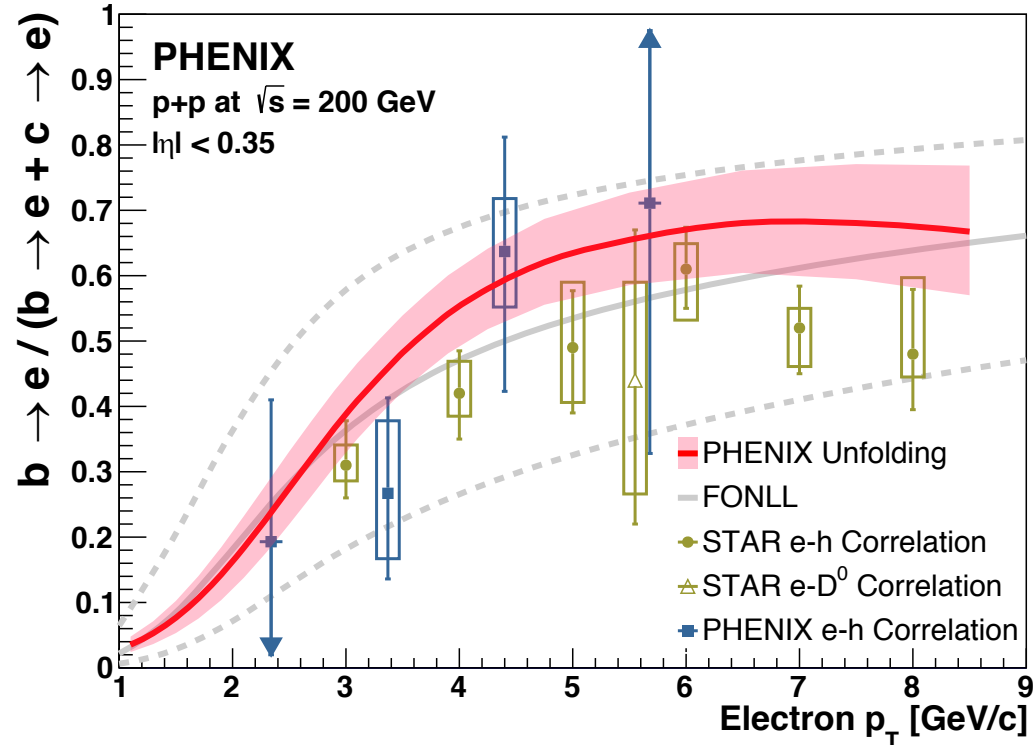


- FONLL calculation consistent with data

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*PHENIX : PRD.99.(2019)092003*

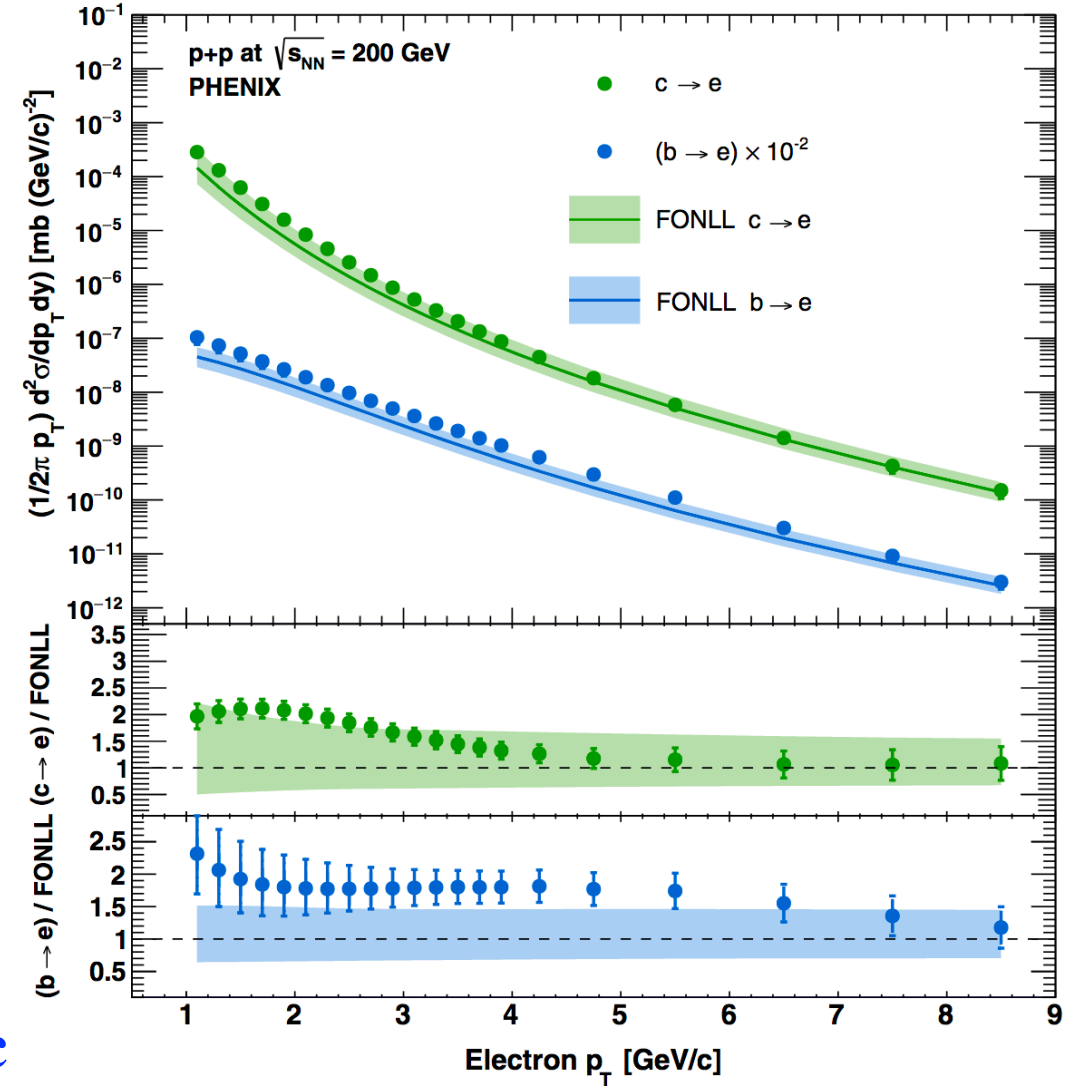
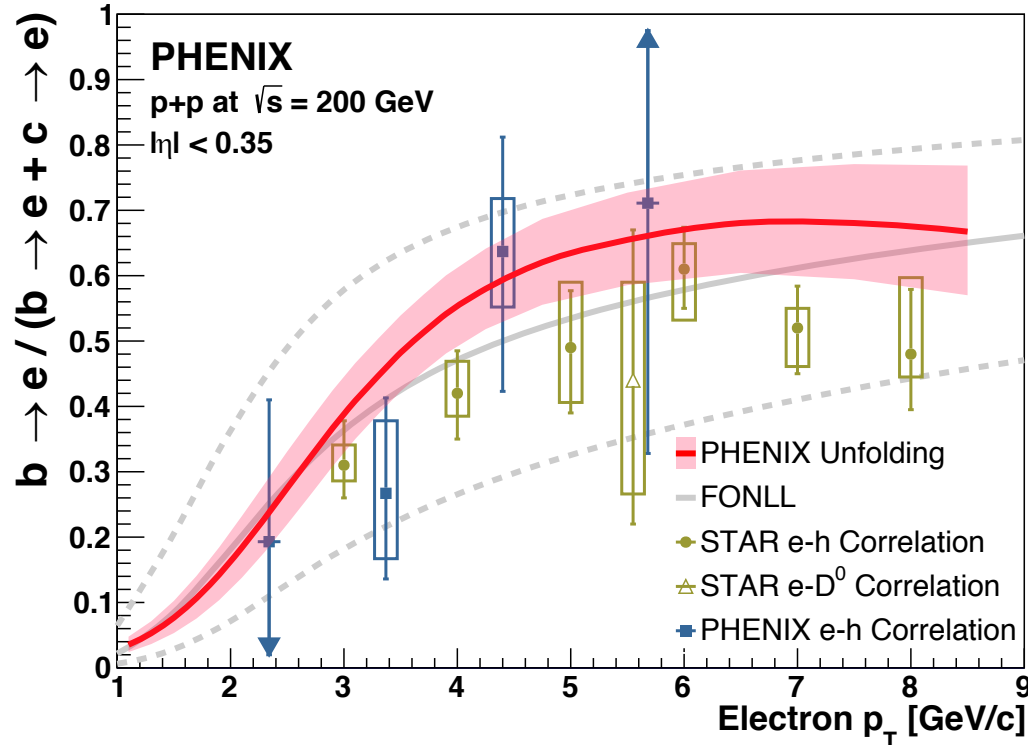


- FONLL calculation consistent with data
- *Significant reduction of uncertainty*

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2015 Data published

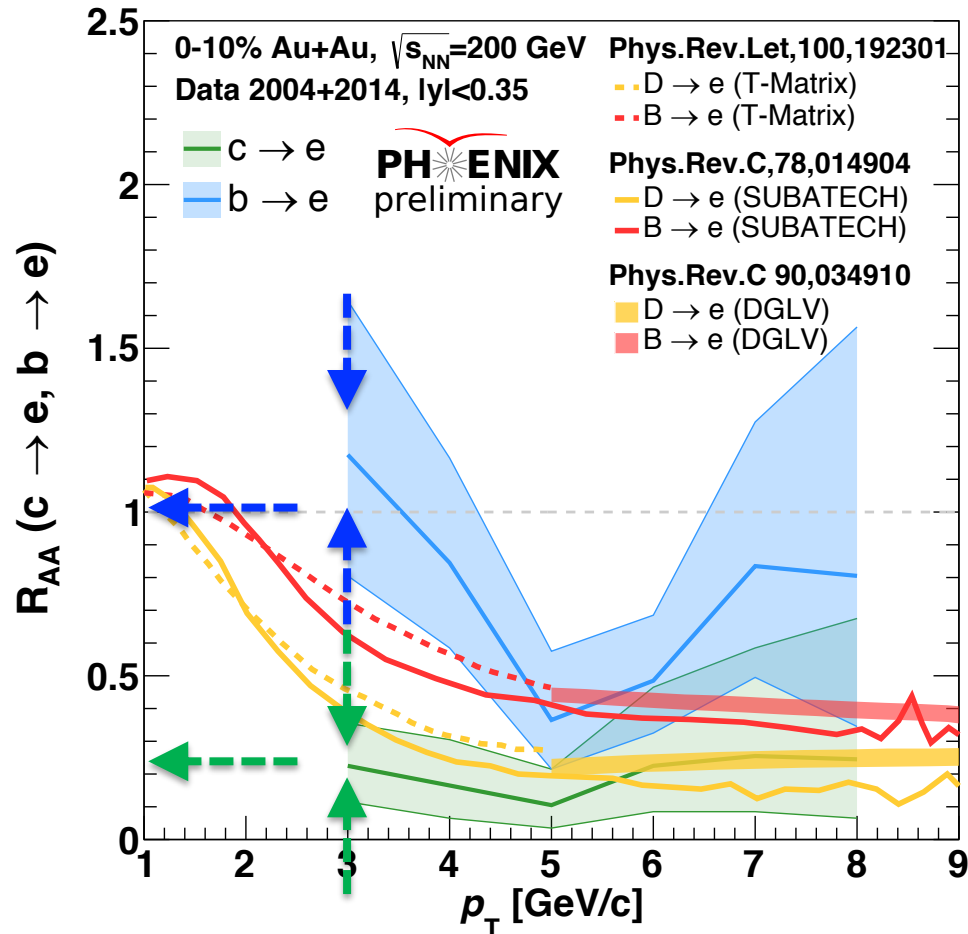
PHENIX : PRD.99.(2019)092003



- FONLL calculation consistent with data
- **Significant reduction of uncertainty**
- **New reference for  $R_{AA}$  down to  $p_T=1\text{GeV}/c$**

# Towards final **charm** & **bottom** $R_{AA}$

## 2014 Au+Au Data



- Use the published precise p+p reference
- Analyze **8 times more Au+Au events** from 2014 & 2016 combined data
  - Shrink uncertainties
  - Extend the measurement down to  $p_T=1$  GeV/c
- Final result will add more constraints to the model calculations

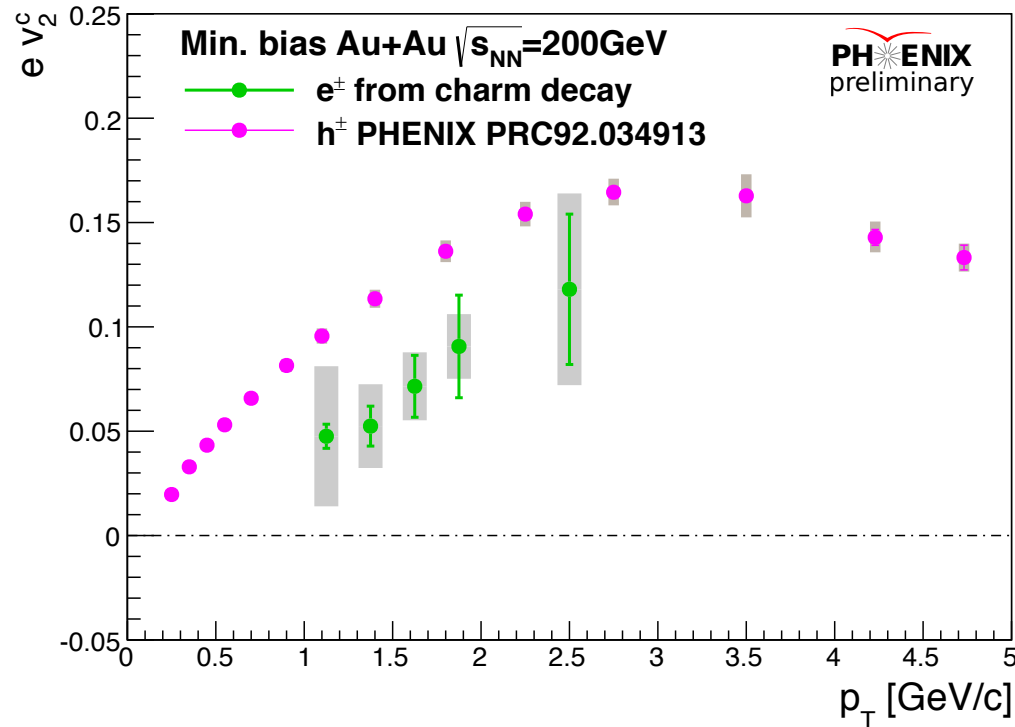
*Publication coming soon!*

# Recap for open HF productions

- **Charm** & **bottom**  $R_{AA}$  can be described by models based on strong coupling QGP as well as those based on quark mass dependent energy loss
- New high statistics p+p measurement has been just published
- Final **charm** & **bottom**  $R_{AA}$  results with **8 times more Au+Au data** & the published precise p+p reference will
  - Shrink uncertainties
  - Extend the measurement down to  $p_T=1\text{GeV}/c$
  - Provide more constraints to the model calculations
- **Next : Further tests of models with flow measurement**

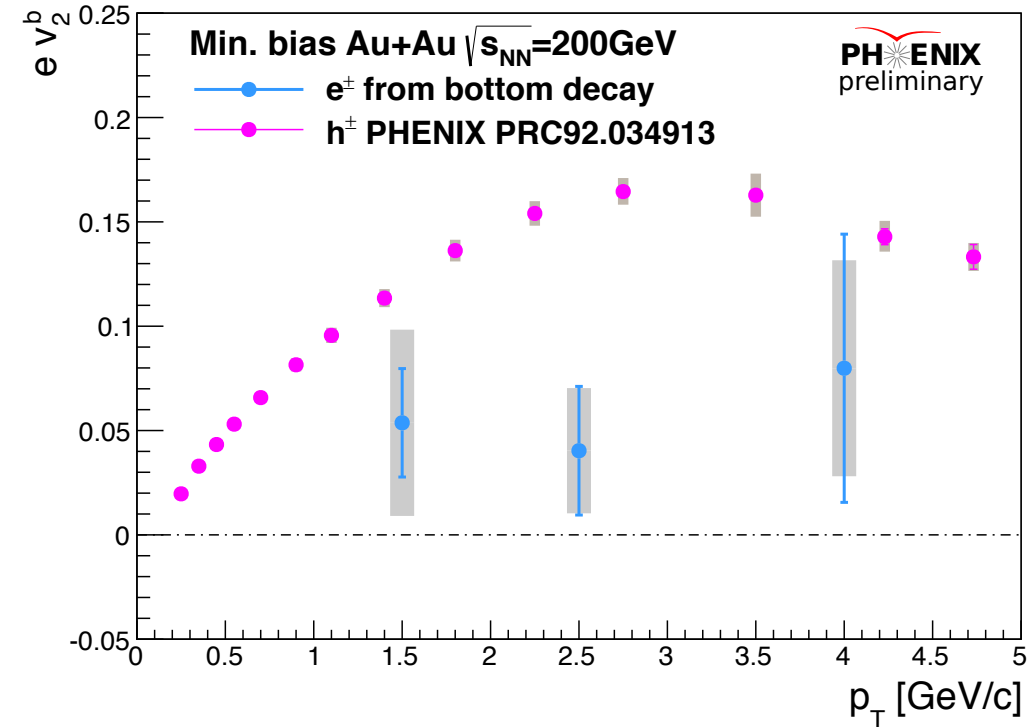
# Charm & bottom $v_2$ in Au+Au 200GeV

Charm



Bottom

2014 Au+Au Data



- Finite **charm**  $v_2$  is observed with a significance of  $\sim 3.5\sigma$
- A hint of finite **bottom**  $v_2$  is observed at  $1.1\sigma$  significance
- **Charm**  $v_2$  is larger than **bottom**  $v_2$  at  $\sim 0.6\sigma$  significance

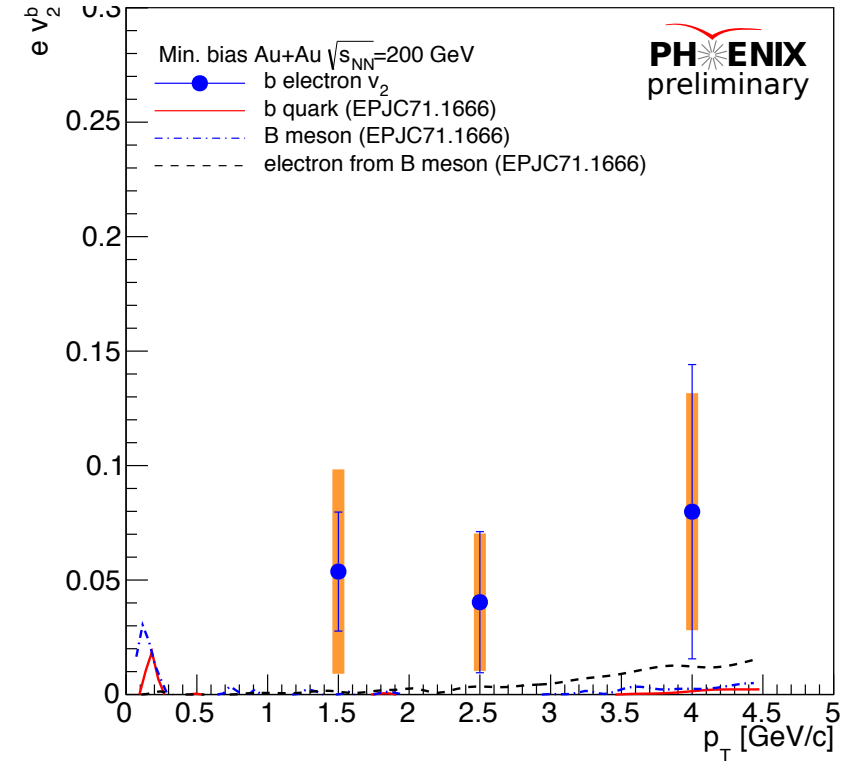
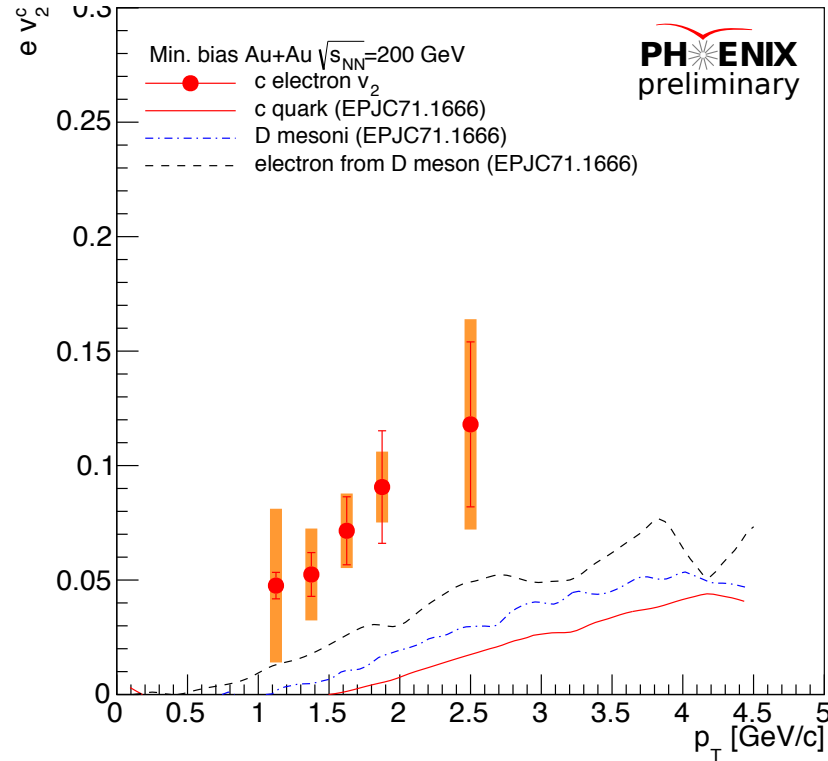
# Charm & bottom $v_2$ models

Charm

Bottom

2014 Au+Au Data

Alberico et. al. : EPJC.71.(2011) 1666



- Langevin + viscous hydro **without coalescence**
  - Underestimate both **charm** & **bottom**  $v_2$

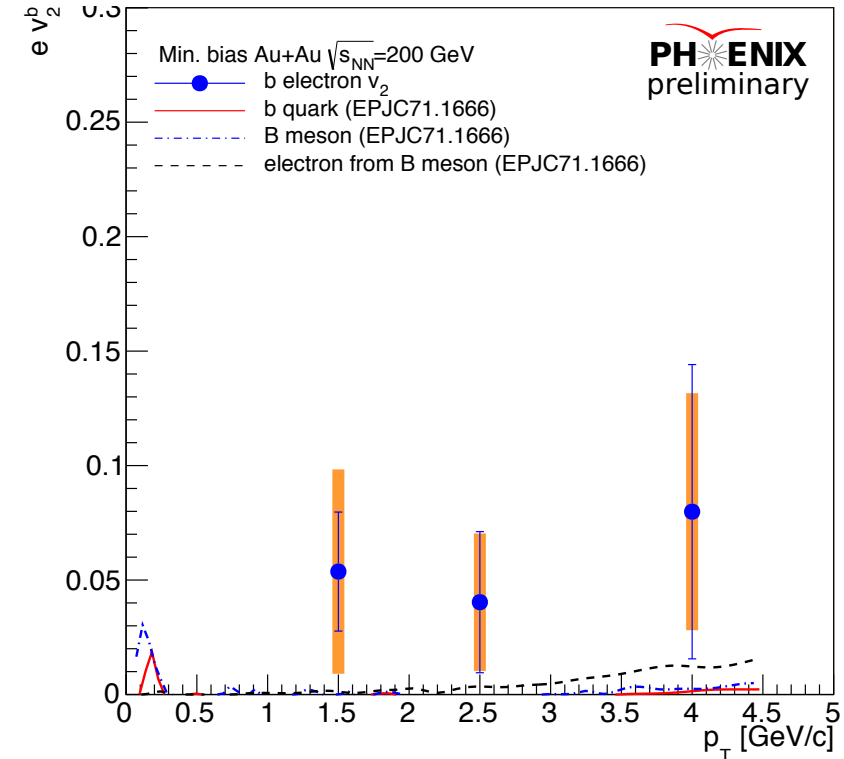
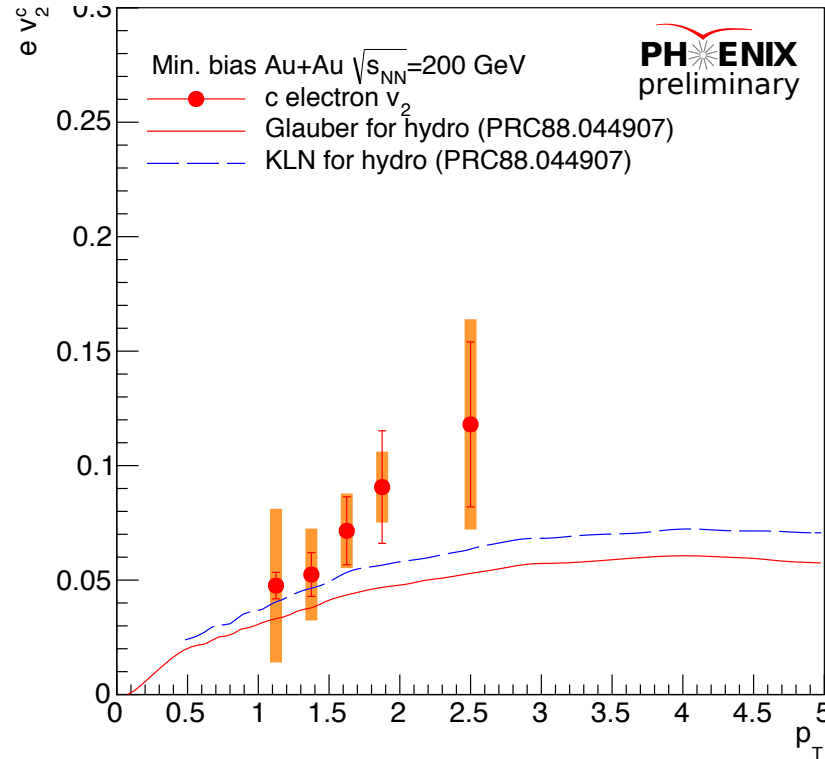
# Charm & bottom $v_2$ models

Charm

Bottom

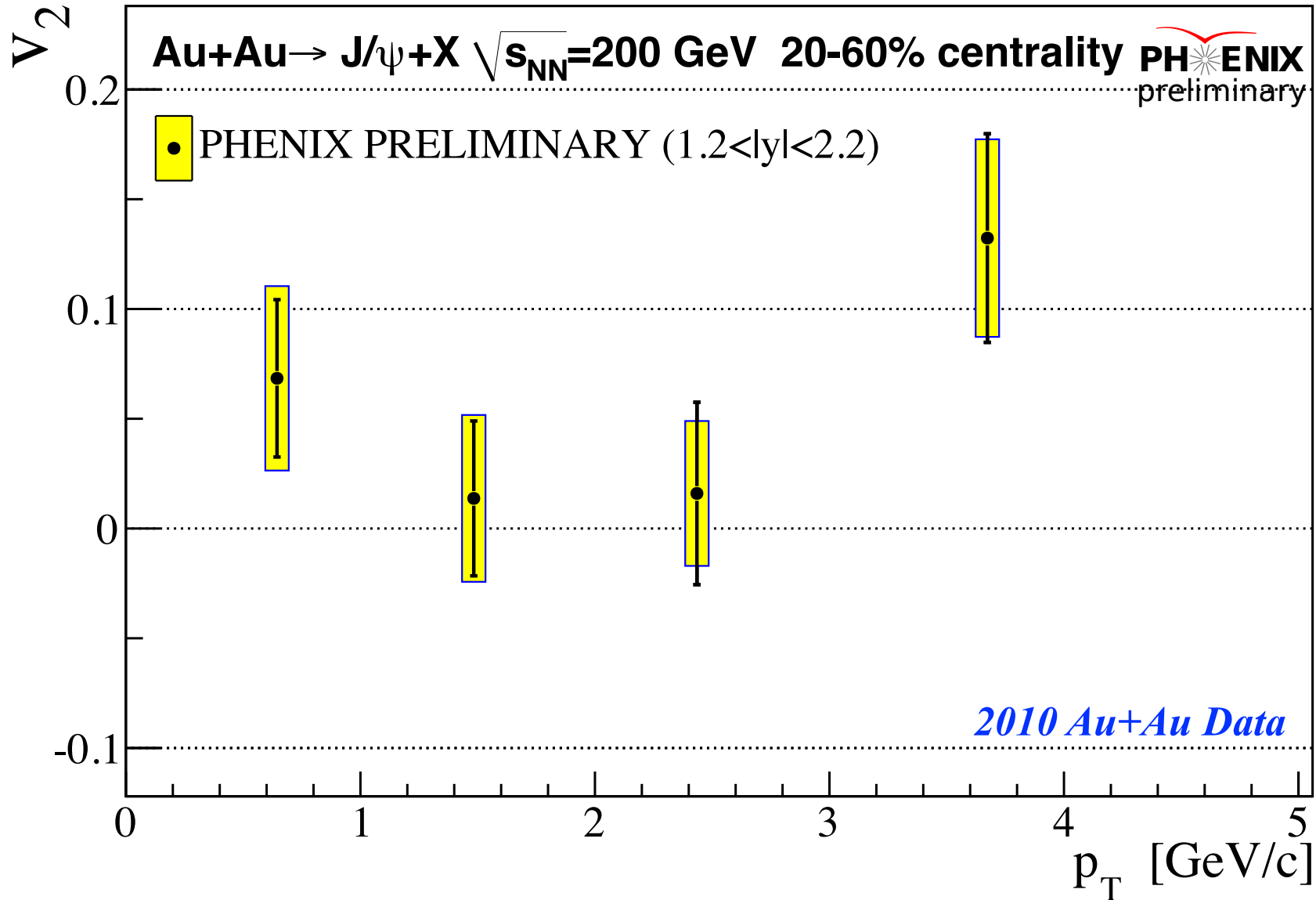
2014 Au+Au Data

Cao et. al.: PRC.88.(2013) 044907



- Langevin + viscous hydro **with coalescence**
  - Better describes **charm**  $v_2$
  - **Charm** quarks dragged by light-flavor quarks with coalescence

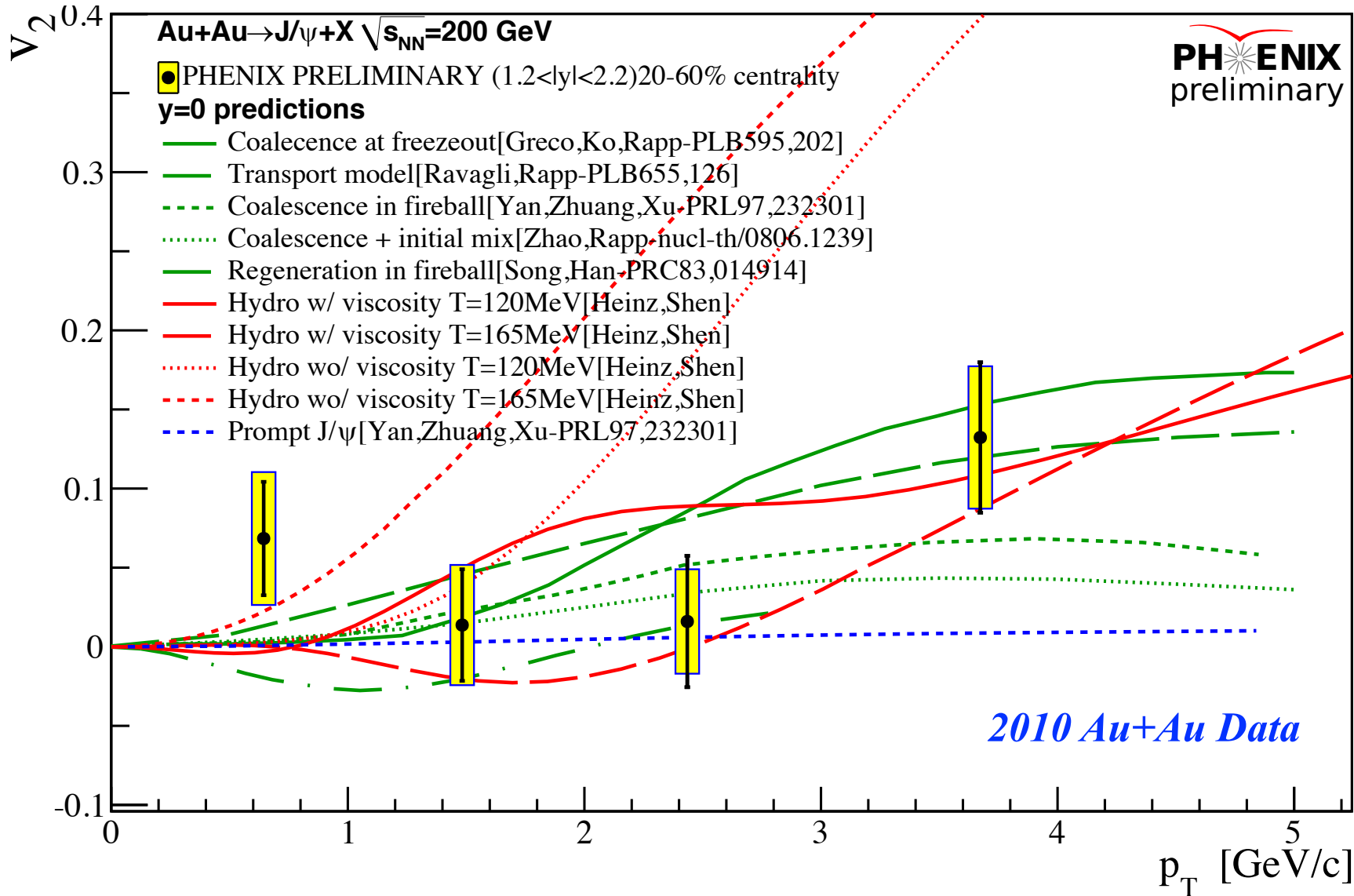
# $J/\psi$ $v_2$ measurement



$J/\psi : 1.2 < |y| < 2.2$

- Finite  $J/\psi$   $v_2$  with a significance of  $1.1\sigma$

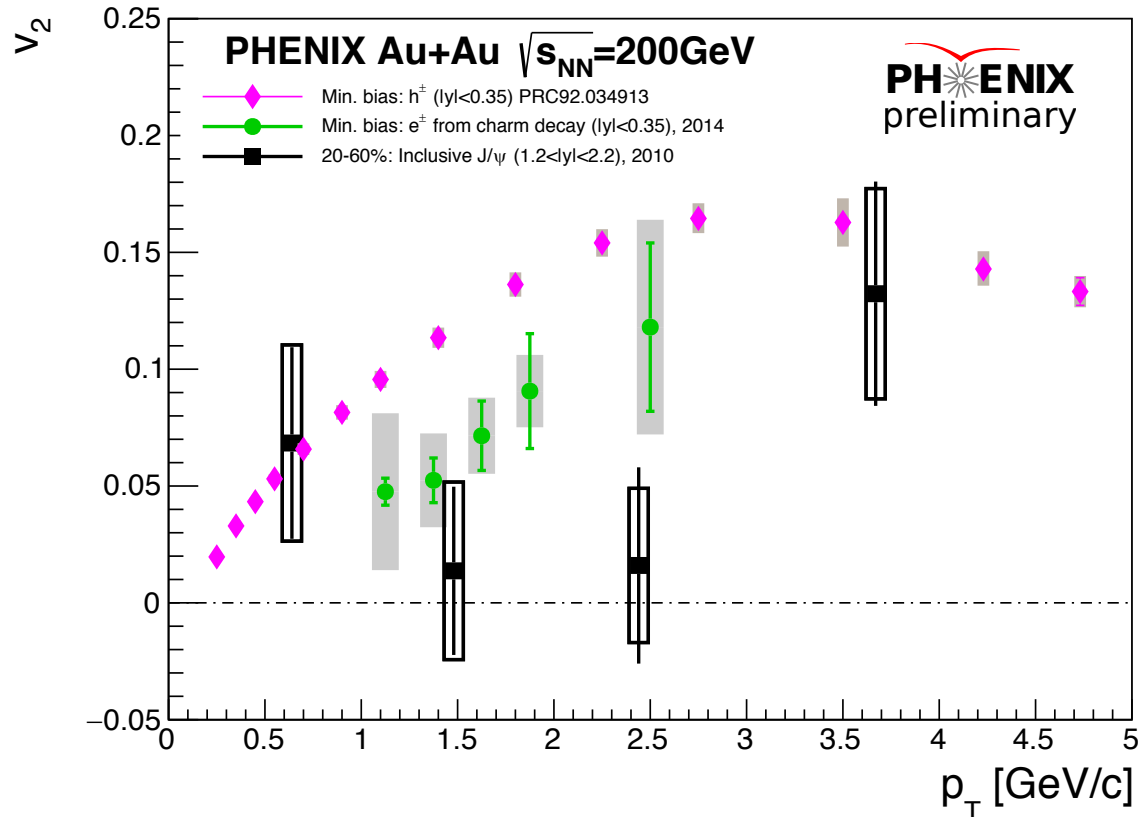
# $J/\psi$ $v_2$ model calculations



$J/\psi$  :  $1.2 < |y| < 2.2$   
 Models :  $y=0$

- Need better precision in data to distinguish these models
- 5 times more data available from 2014 & 2016
  - Potential to constrain models

# Charm & $J/\psi$ $v_2$ in Au+Au 200GeV



$J/\psi$  : 2010 data,  $1.2 < |y| < 2.2$

Charm  $\rightarrow e^{\pm}$  : 2014 data,  $|y| < 0.35$

- **Charm**  $v_2$  is larger than  $J/\psi$   $v_2$  at  $0.7\sigma$  significance at intermediate  $p_T$  range
  - A hint that charm quarks dragged by light-flavor quarks with coalescence

# Recap for open HF & $J/\psi$ $v_2$

- Finite **charm** (**bottom**)  $v_2$  is observed with significances of  $3.5(1.1)\sigma$
- Langevin + viscous hydro **with coalescence** better describes **charm**  $v_2$
- **Charm**  $v_2$  is larger than  $J/\psi$   $v_2$  with a significance of  $0.7\sigma$ 
  - **A hint that charm quarks dragged by light-flavor quarks with coalescence**

# Future prospects

- New analyses are underway using **36 billion** Au+Au 200 GeV collision events from 2014 & 2016 data sets
  - **Charm** & **bottom**  $R_{AA}$  : 8 times more data
  - **Charm** & **bottom**  $v_2$  : 2 times more data
  - $J/\psi$   $v_2$  : 5 times more data
- New p+p result using high statistics 2015 data has been just published
  - Shrink uncertainties of **charm** & **bottom**  $R_{AA}$
  - Extend the **charm** & **bottom**  $R_{AA}$  measurement down to  $p_T=1\text{ GeV}/c$
- A new Bayesian inference method to separate **charm** & **bottom**  $v_2$  is being developed
  - Expect to reduce both systematic and statistical uncertainties

# Summary

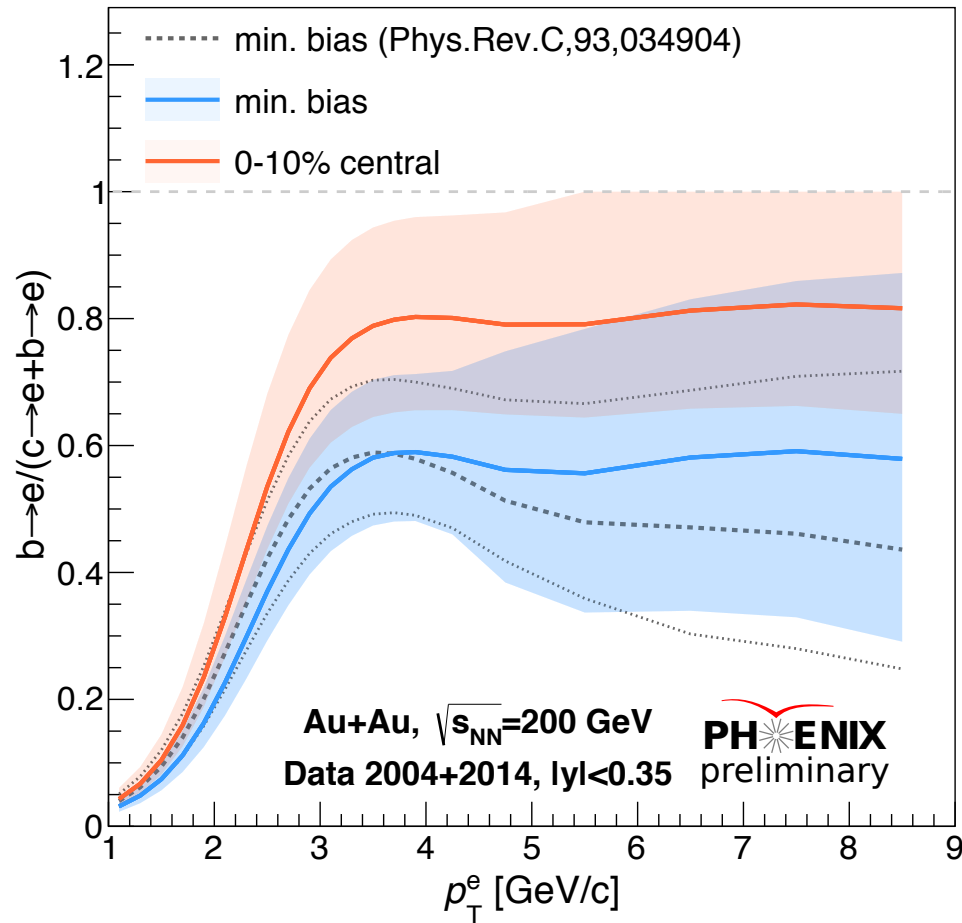
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- **Charm**  $v_2$  is larger than  $J/\psi$   $v_2$  with a significance of  $0.7\sigma$ 
  - **A hint that charm quarks dragged by light-flavor quarks with coalescence**

→ *Stay tuned for new results with huge amount of data from 2014+2016*

# Back Up

# Bottom electron fraction in Au+Au 200GeV

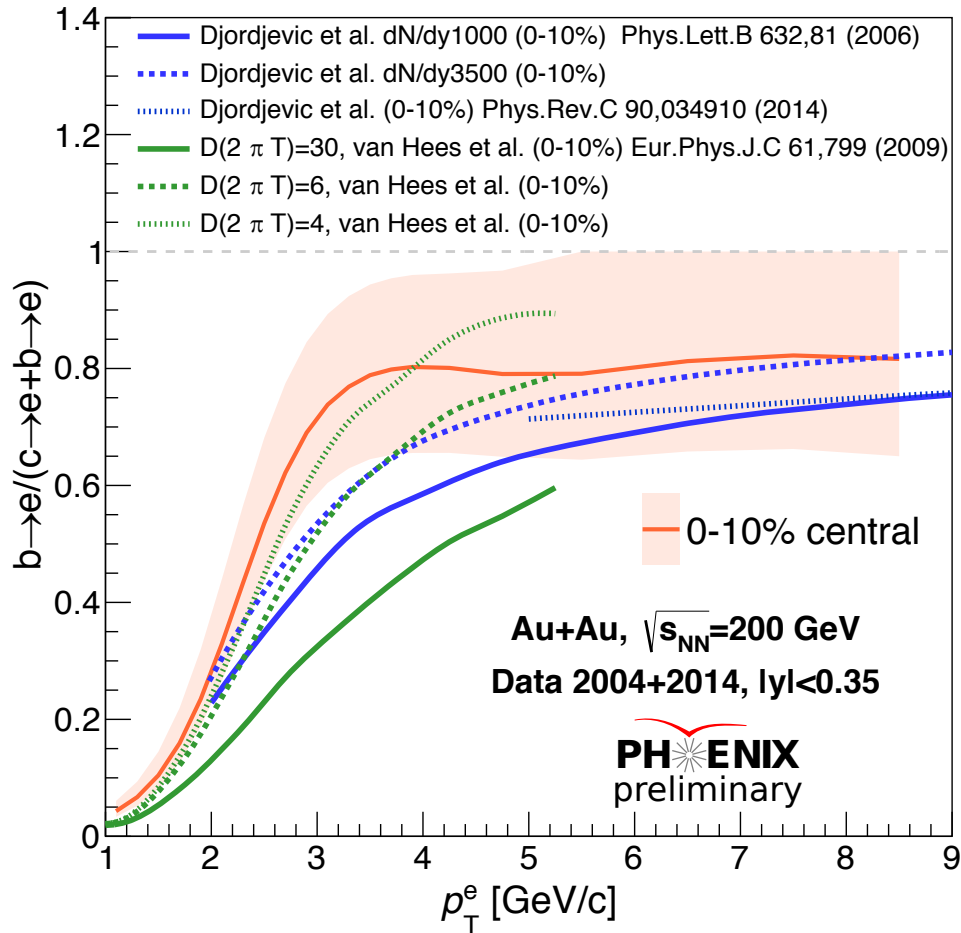
## 2014 Au+Au Data



- 2014 result with 3 time more data consistent with 2011 published result

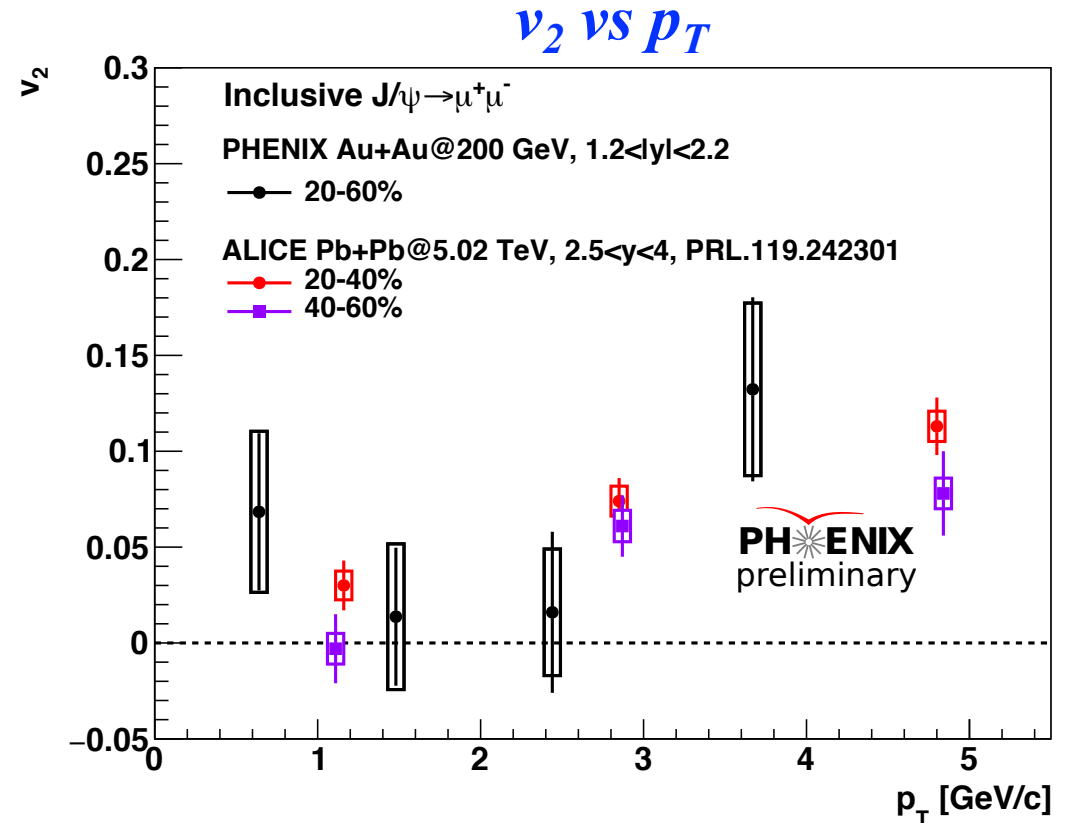
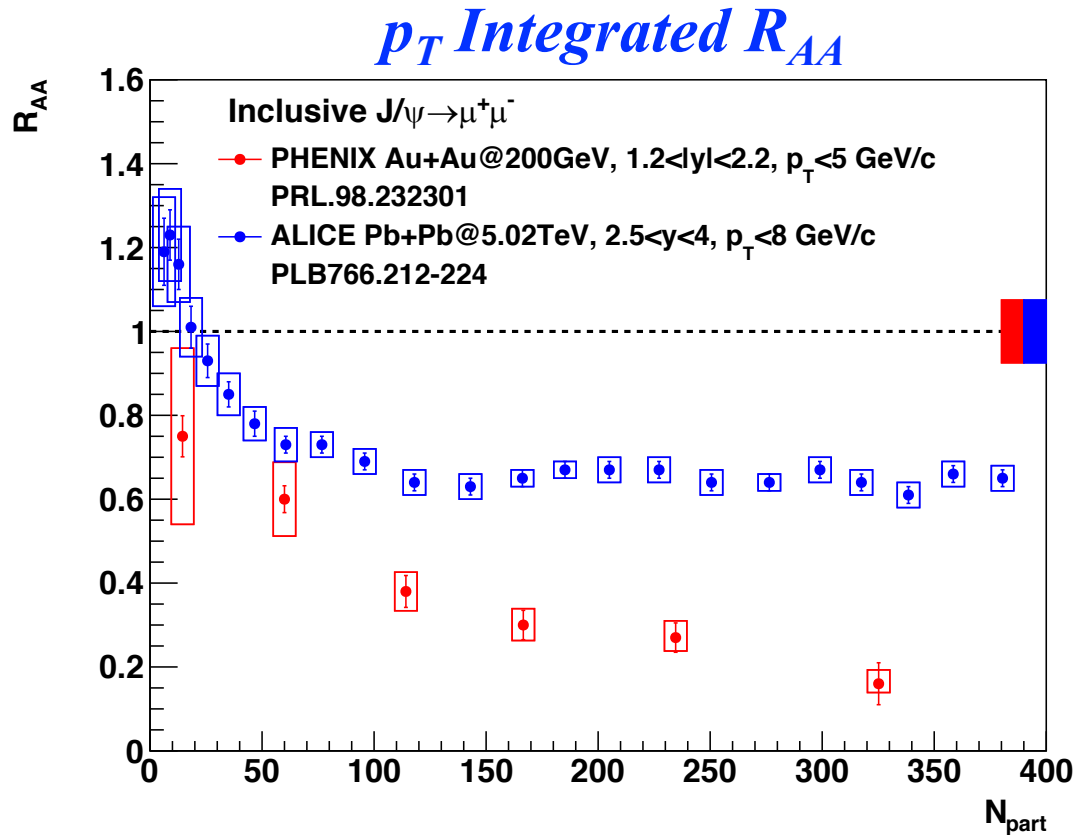
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## 2014 Au+Au Data



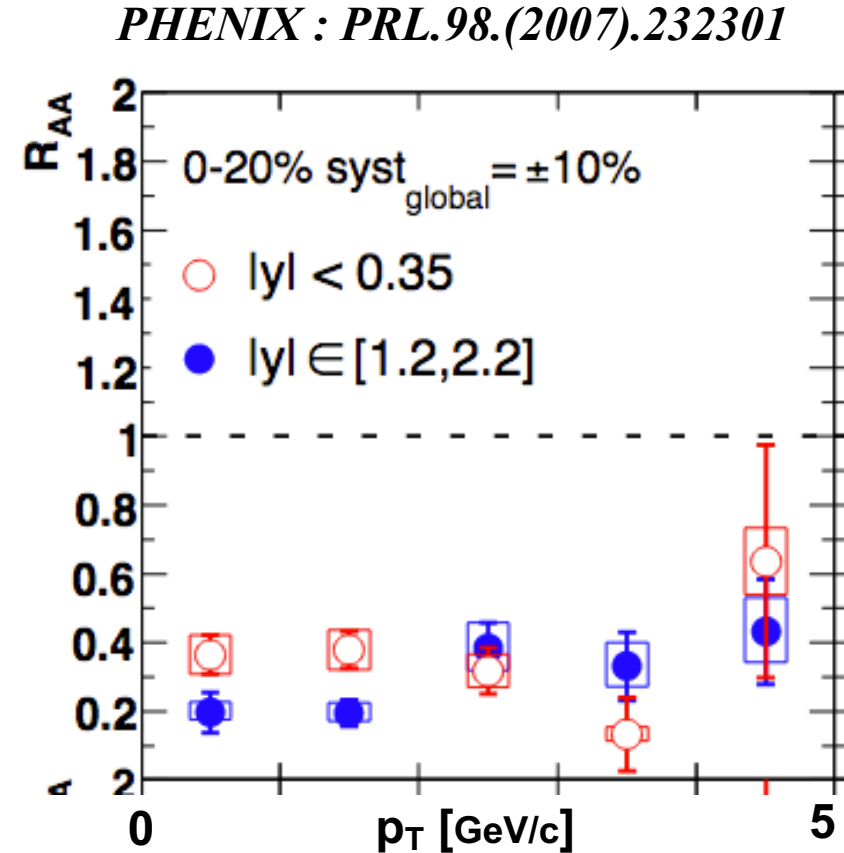
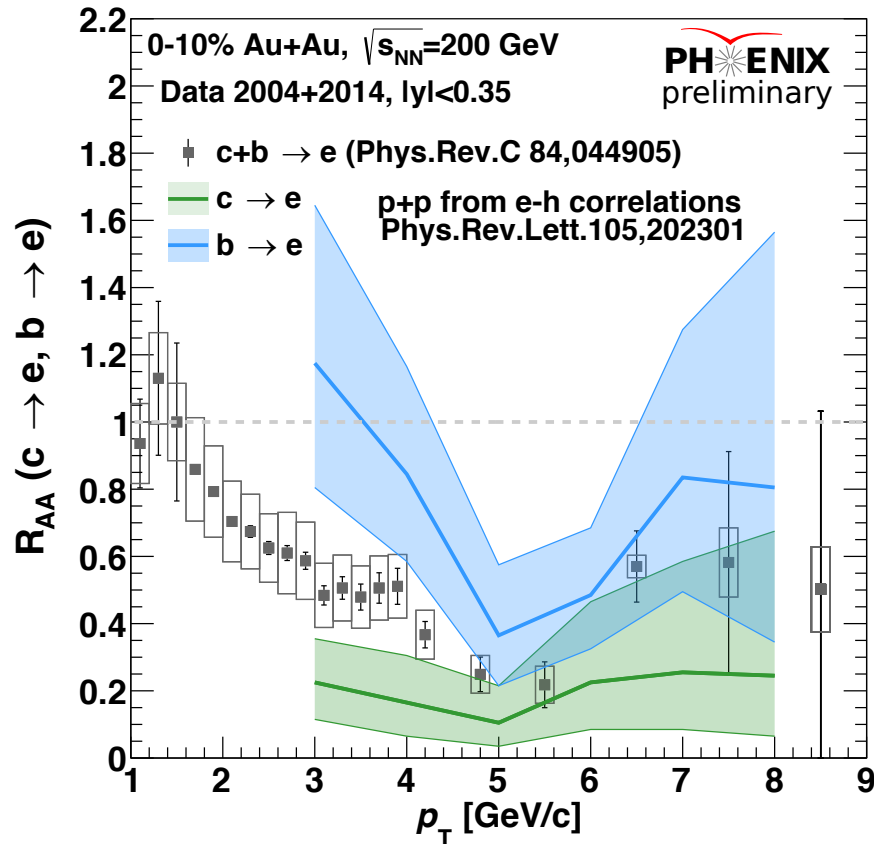
- 2014 result with 3 time more data consistent with 2011 published result
- T-Matrix+ small diffusion scenarios ( $2\pi TD=4-6$ ) are consistent with data
  - Large diffusion scenario ( $2\pi TD=30$ ) rejected by data
  - **Strongly coupling QGP**
- DGLV models with different gluon densities also consistent with data

# $J/\psi$ $R_{AA}$ & $v_2$ collision energy dependence



- Significant reduction of  $p_T$ -integrated  $R_{AA}$  from Pb+Pb 5.02TeV to Au+Au 200GeV
  - Smaller contribution from regenerated  $J/\psi$  at RHIC collision energy
- $J/\psi$   $v_2$  in Au+Au 200GeV is consistent with Pb+Pb data within huge uncertainties

# Charm & $J/\psi$ $R_{AA}$ in Au+Au 200GeV



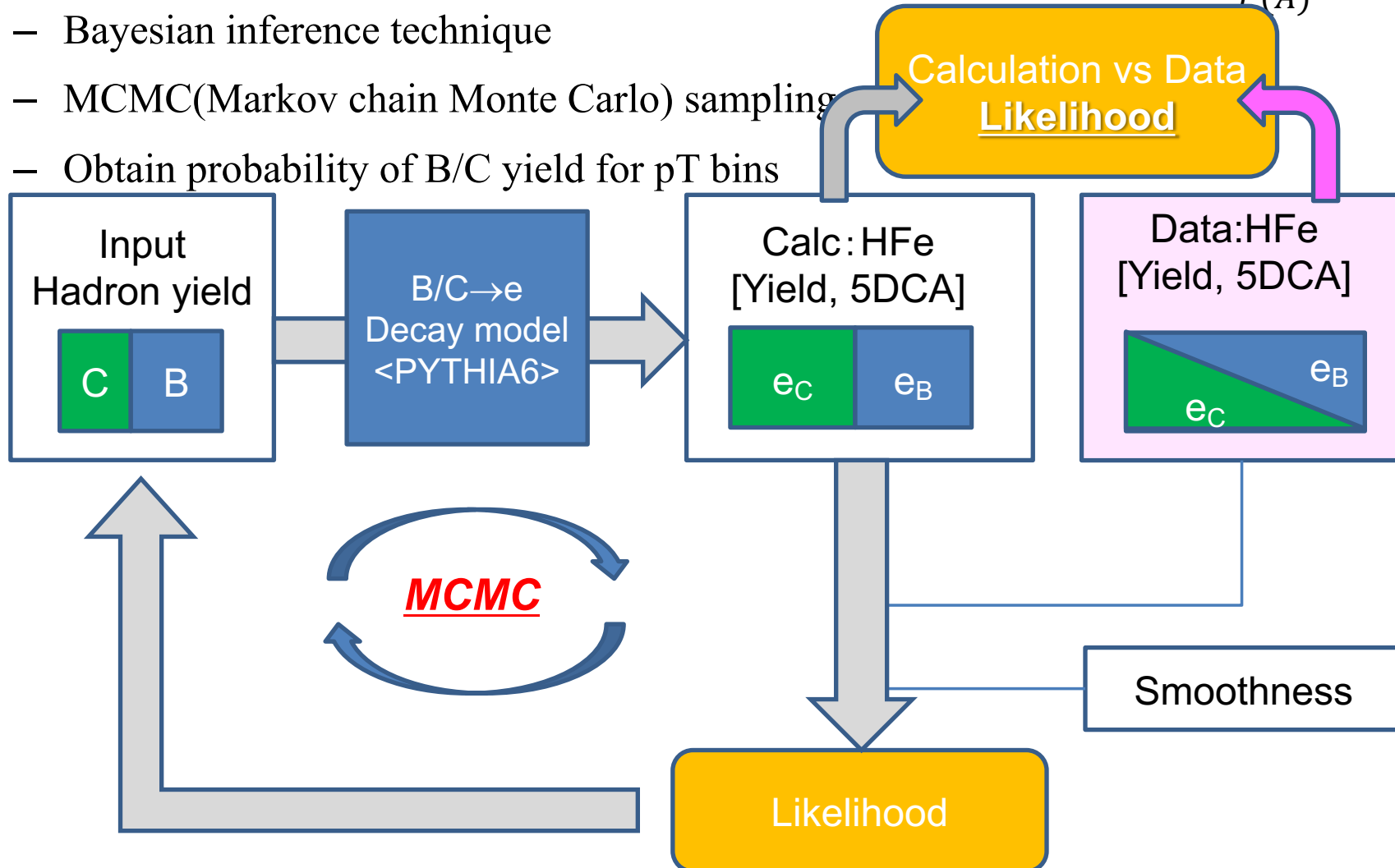
- Similar suppressions are seen between  $c \rightarrow e^\pm$  &  $J/\psi$  at mid-rapidity

# 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

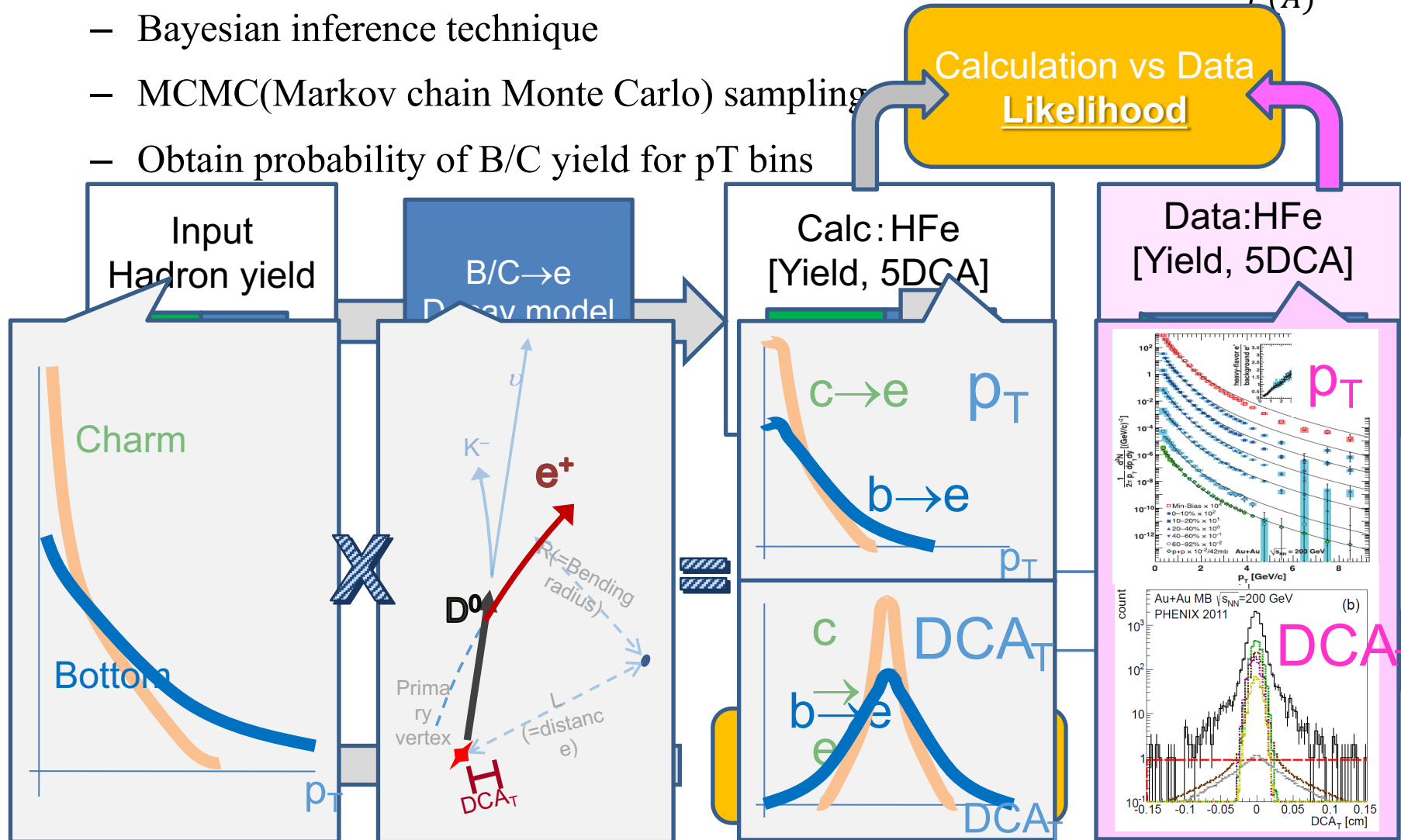
$$P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$$



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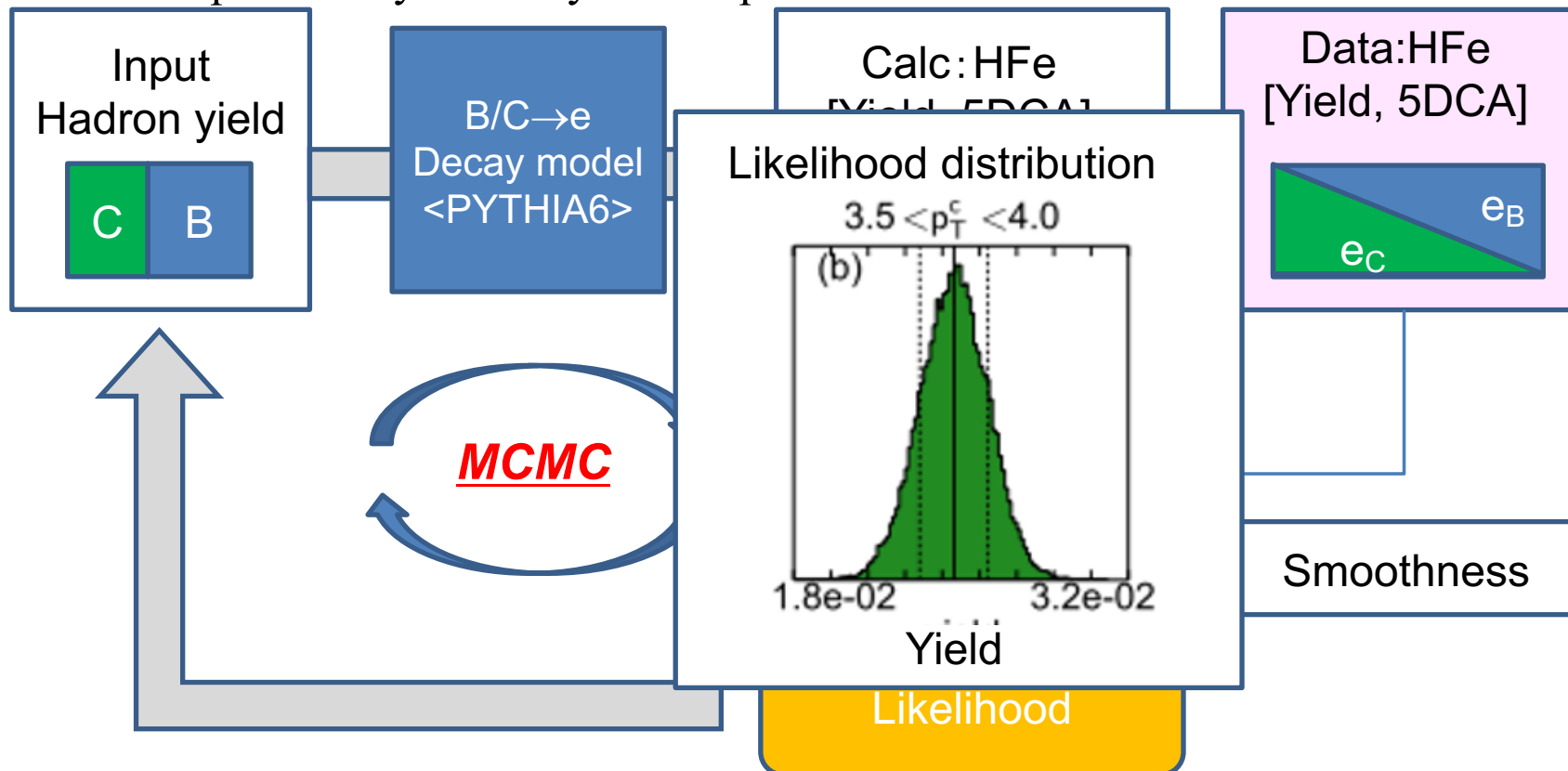
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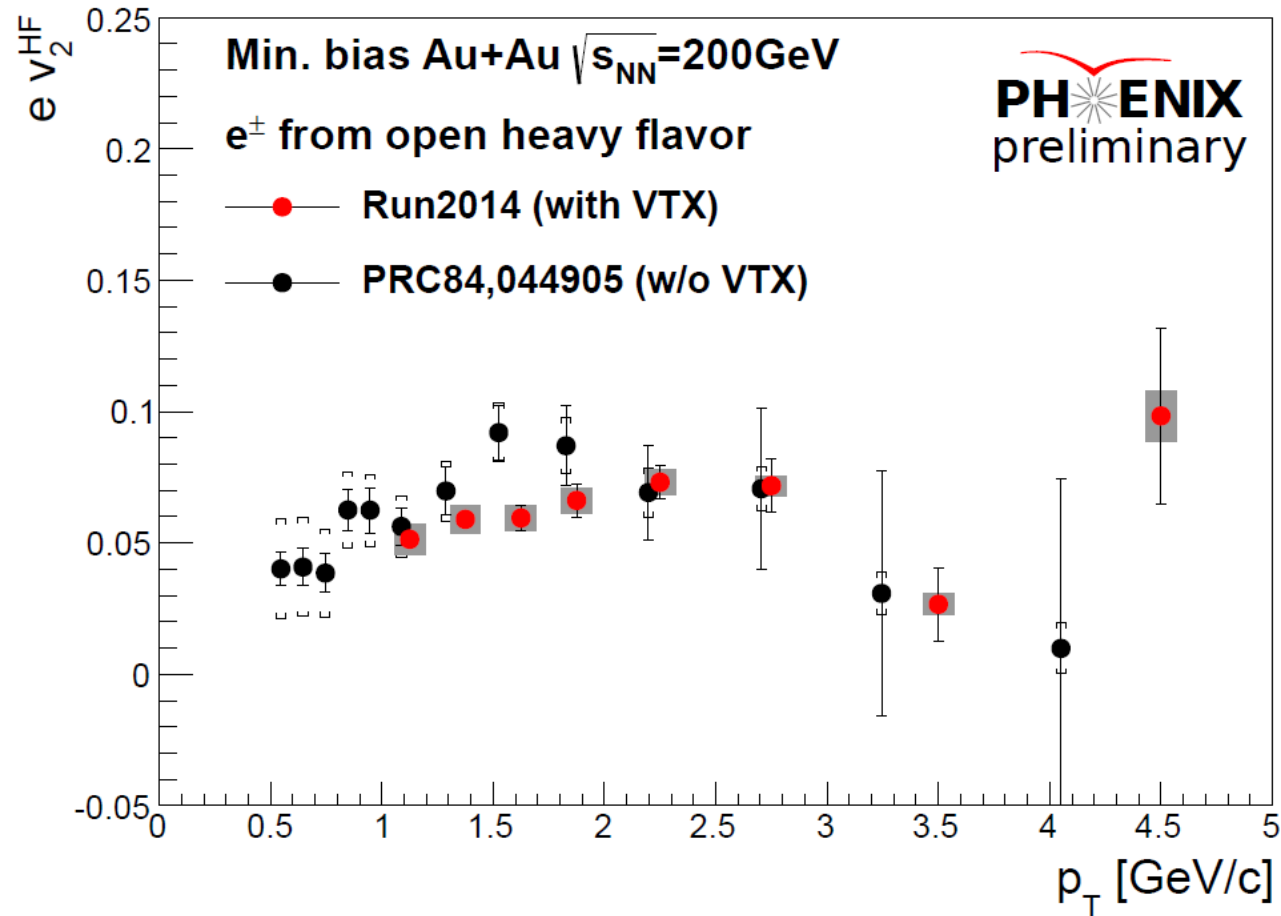
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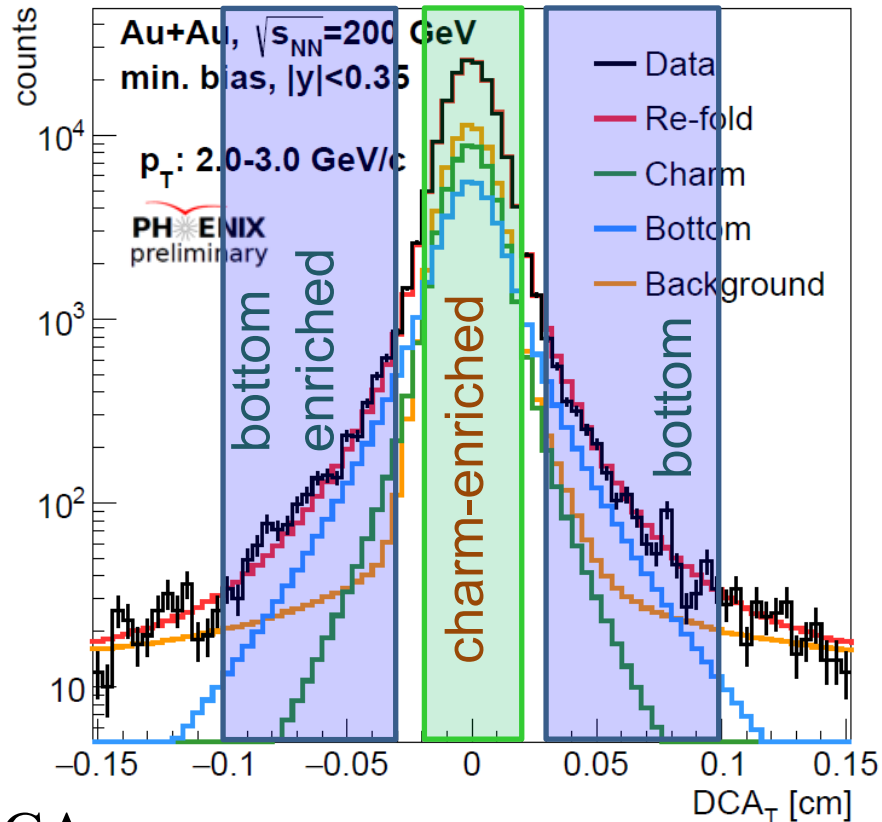


# Heavy Flavor electron $v_2^{\text{HF}}$

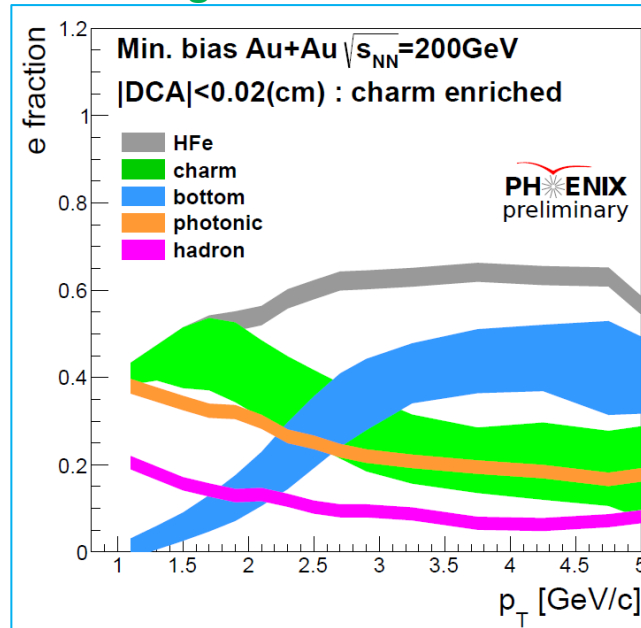


- Heavy flavor electron  $v_2^{\text{HF}}$  with (F)VTX is **consistent with published measurement**
  - Smaller statistical and systematic uncertainty
  - VTX and FVTX improve the  $v_2$  measurement significantly
    - VTX reduces the photonic BG
    - FVTX provides twice higher RP resolution

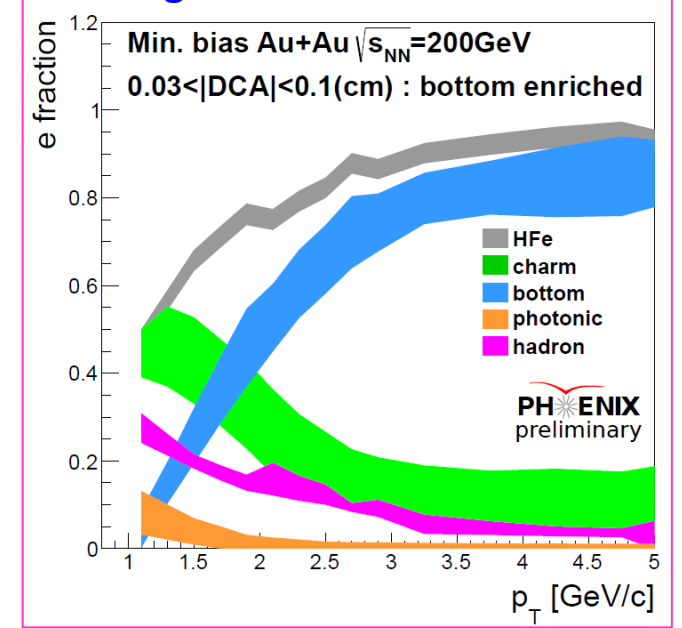
# $v_2$ for charm and bottom enriched DCA range



Peak region : Charm enriched



Tail region : Bottom enriched



$$HFe \cdot v_2^{HF}$$

- $v_2^{inc} = \overbrace{b \cdot v_2^b (b \rightarrow e) + c \cdot v_2^c (c \rightarrow e)}^{HFe \cdot v_2^{HF}} + bg_0 \cdot v_2^{bg}$
- Look at  $v_2$  from these DCA range
  - If  $v_2^b$  is small,  $v_2(\text{b-enriched}) < v_2(\text{c-enriched})$

DCA ranges:

Peak : c-enriched :  $|DCA| < 200 \mu\text{m}$

Tail : b-enriched :  $300 < |DCA| < 1000 \mu\text{m}$