Heavy Flavor Highlights

Open Heavy Flavor & Quarkonia

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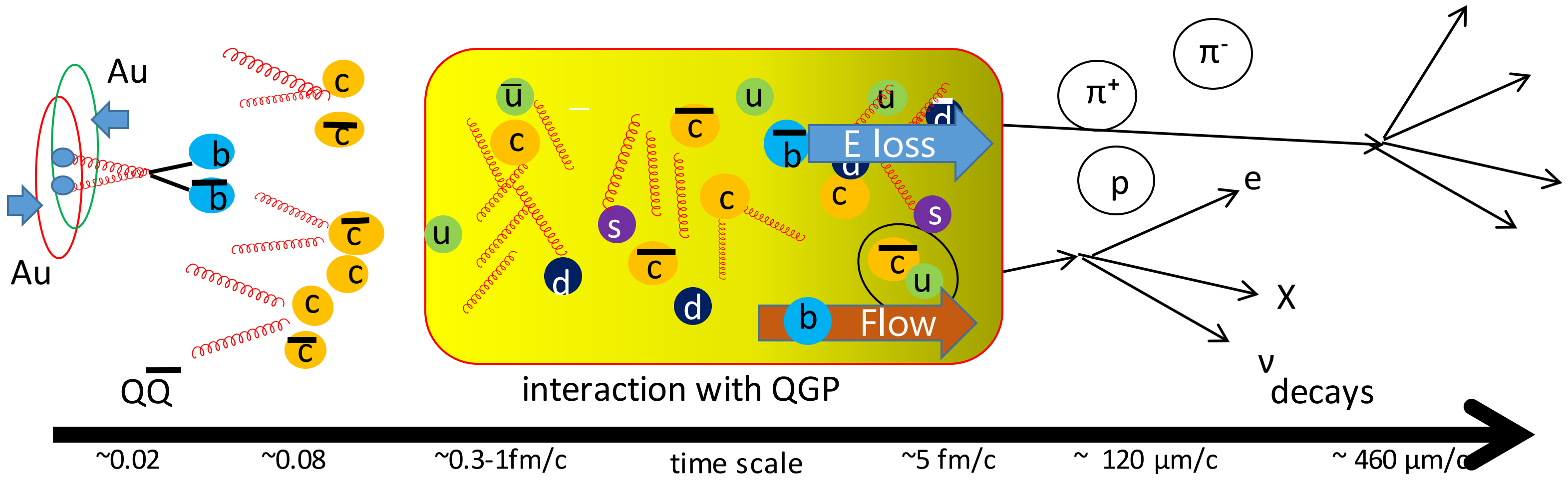
for the PHENIX collaboration

Introduction

- Quark Gluon plasma is strongly coupled QCD medium under high temperature
- Difficult to measure QGP directly
  - Space-time evolution & hadronization smears out the QGP information



- Heavy quark is a good probe to study properties of QGP
  - Created mainly by initial hard scattering (early stage of the collision)
  - Carry the QGP information when passing through QGP
    - Suffer energy loss and flow effects – p_T and angular distributions can be modified in QGP
    - Quarkonia would be melted

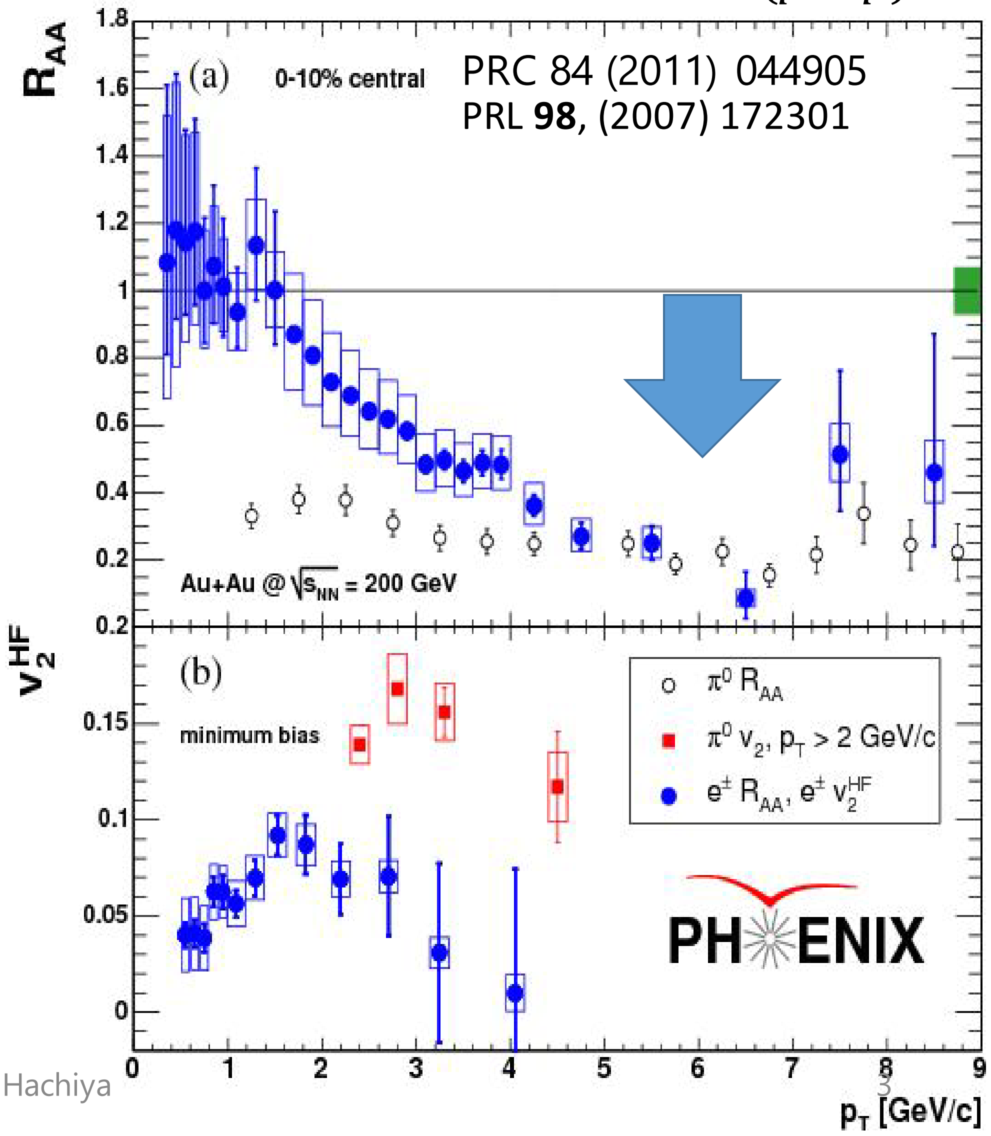
Open bottom and charm, and quarkonia provide valuable information on QGP

Previous Open HF measurement in Au+Au 200GeV

Inclusive HF decays R_{AA}:

- Strong suppression and similar w/ light quarks
  - Ncoll scaling @ low pT
- Significant flow (v2) and smaller than light quarks

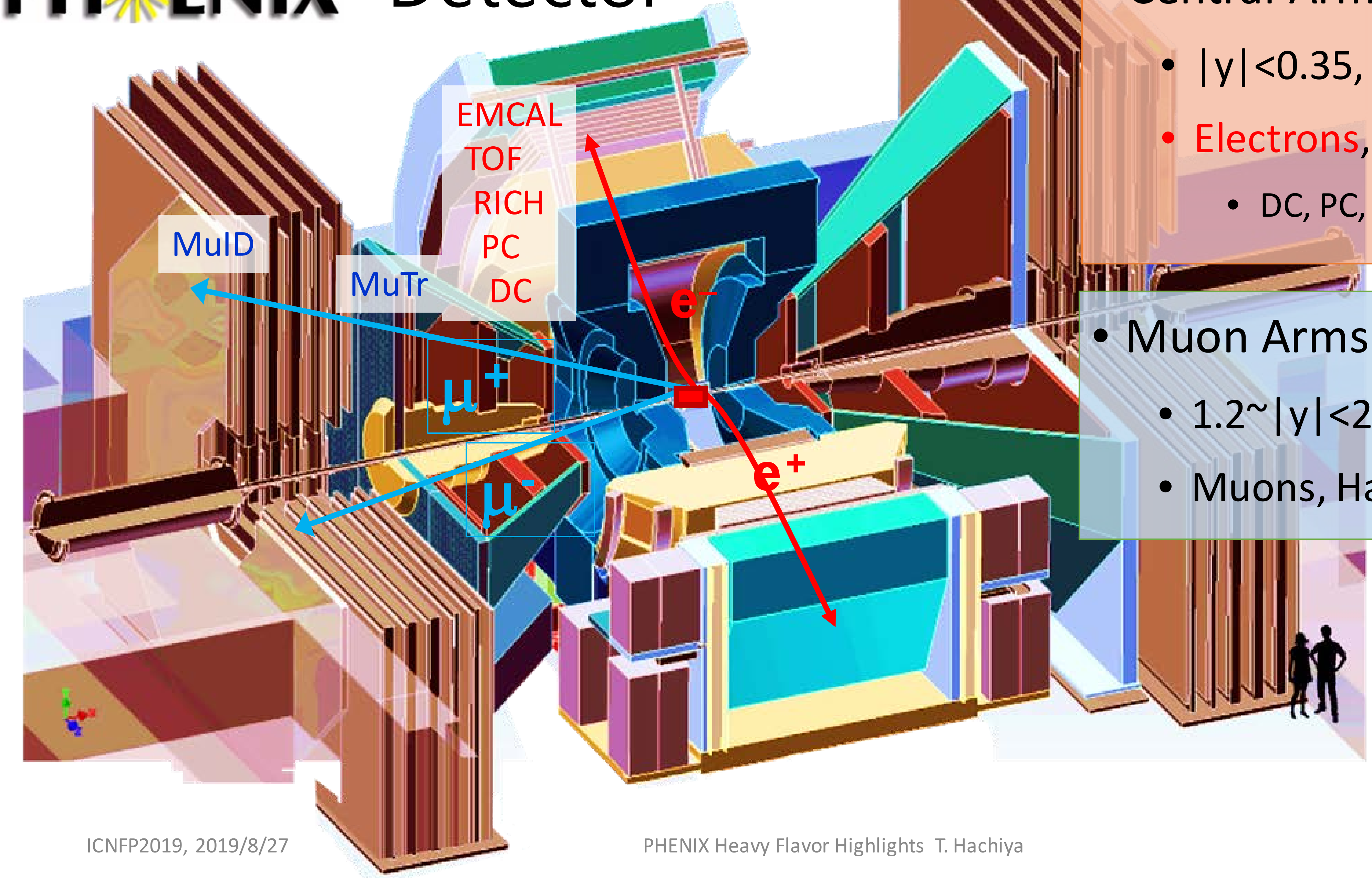
$$R_{AA} = \frac{Yield(Au + Au)}{Ncoll \ * Yield(p + p)}$$



- Surprising results
  - HQ expected to be less energy loss and smaller (zero) flow due to heavy mass
  - Radiative and collisional process play important roles for heavy flavor energy loss at high and low p_T
  - Radiative and collisional process contribute charm and bottom differently

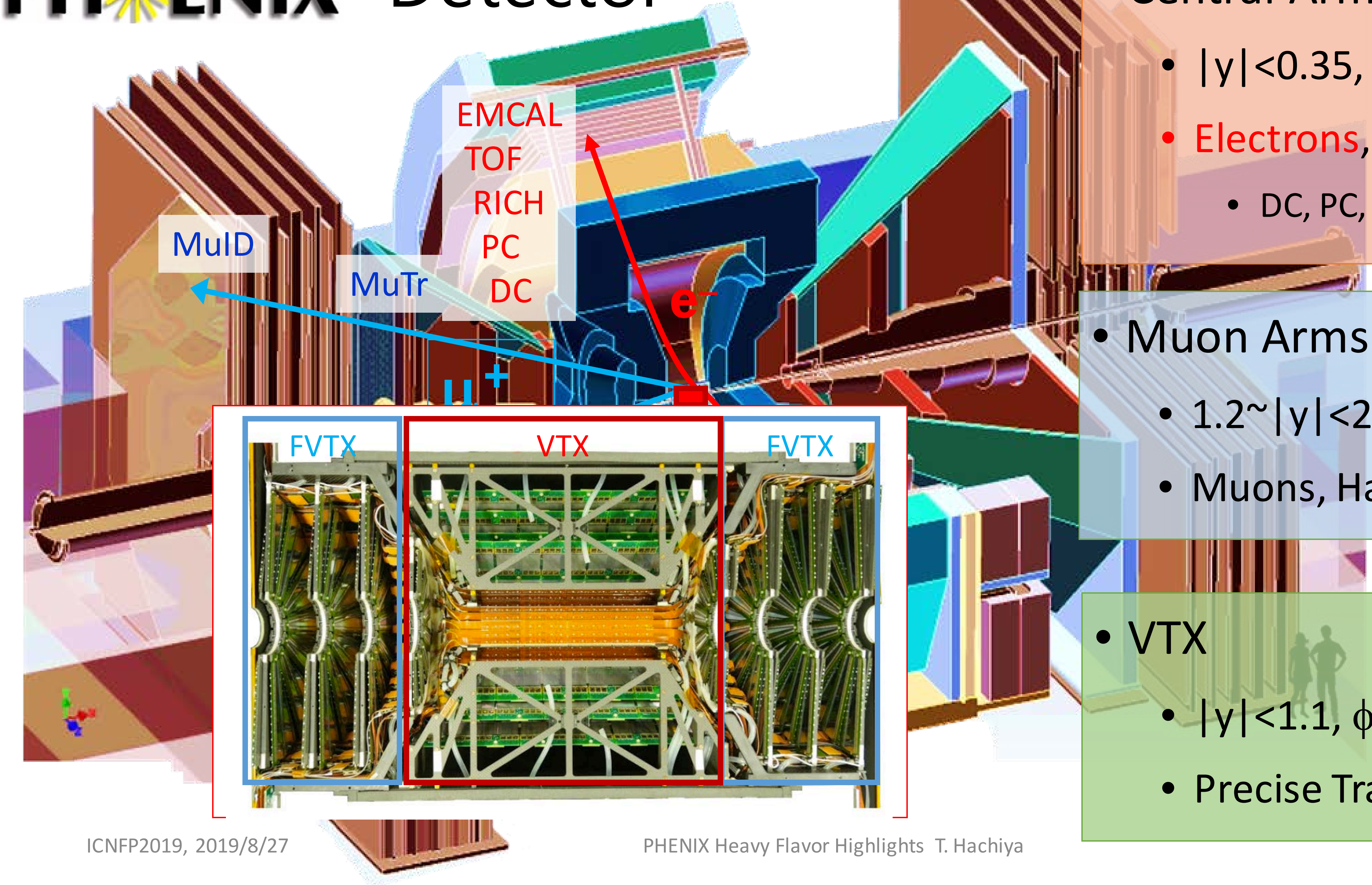
Need to separate bottoms & charms

PHENIX Detector



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

PHENIX Detector



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- Muon Arms
  - $1.2\sim|y|<2.2$, $\phi\sim 2\cdot\pi/2$
  - Muons, Hadrons
- VTX
  - $|y|<1.1$, $\phi\sim 2\pi$
  - Precise Tracking

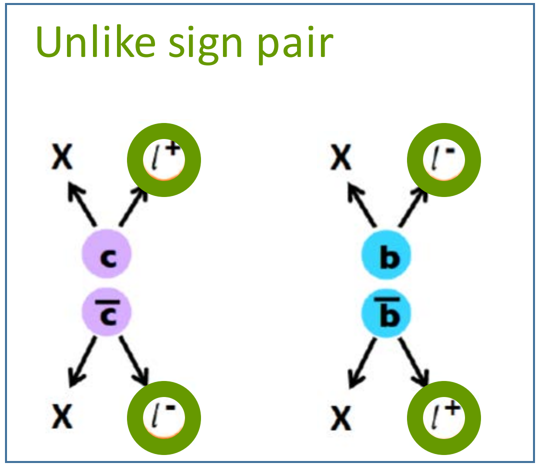
p+p Baseline measurement

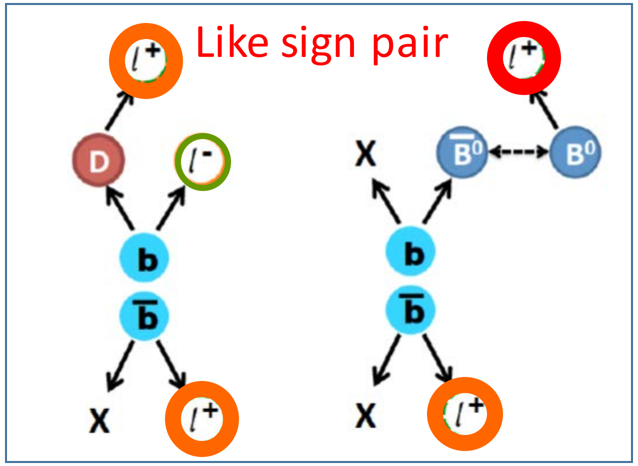
- QCD test and baseline for A+A collisions

- Di-muon measurement at forward rapidity
- Single electrons at mid-rapidity

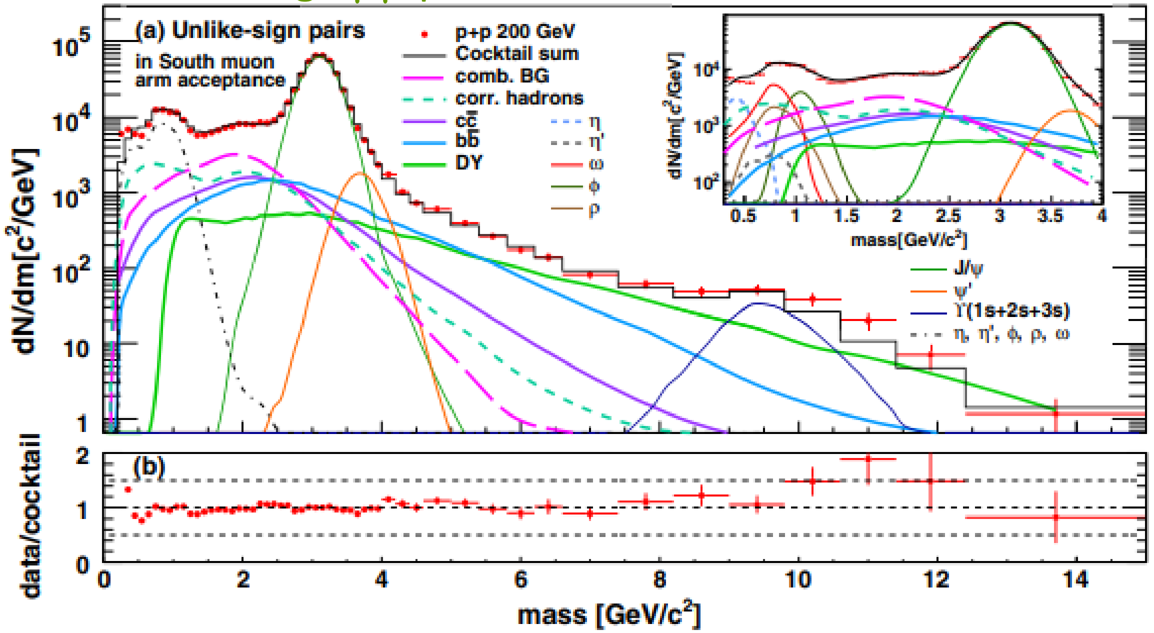
p+p Baseline measurements via μμ pairs

- Semi-leptonic decays of charm and bottom produce lepton pairs

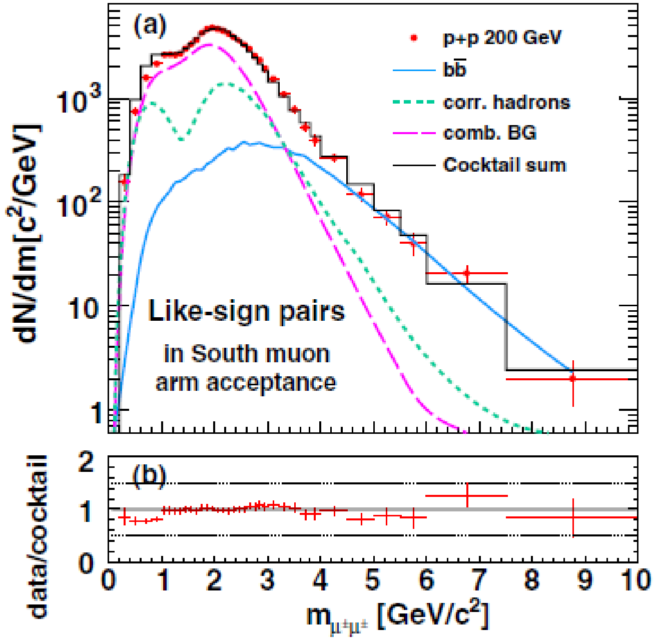




Unlike sign μμ pairs



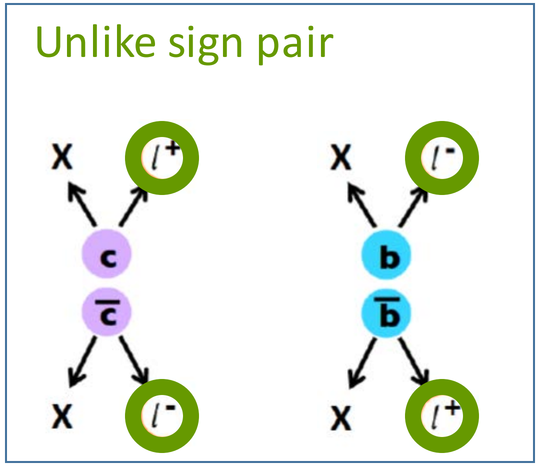
Like sign μμ pairs

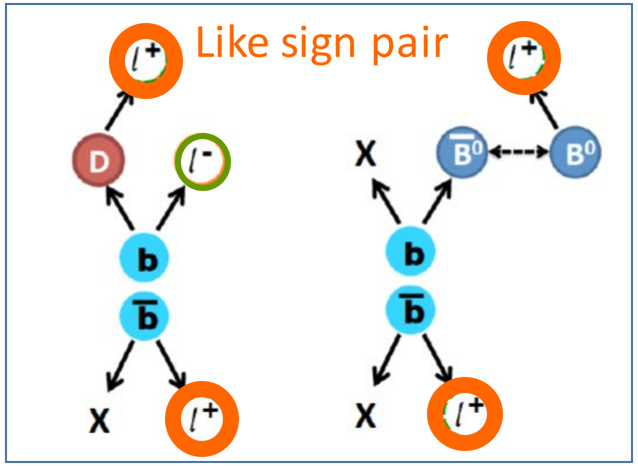


or Hi

p+p Baseline measurements via μμ pairs

- Semi-leptonic decays of charm and bottom produce lepton pairs



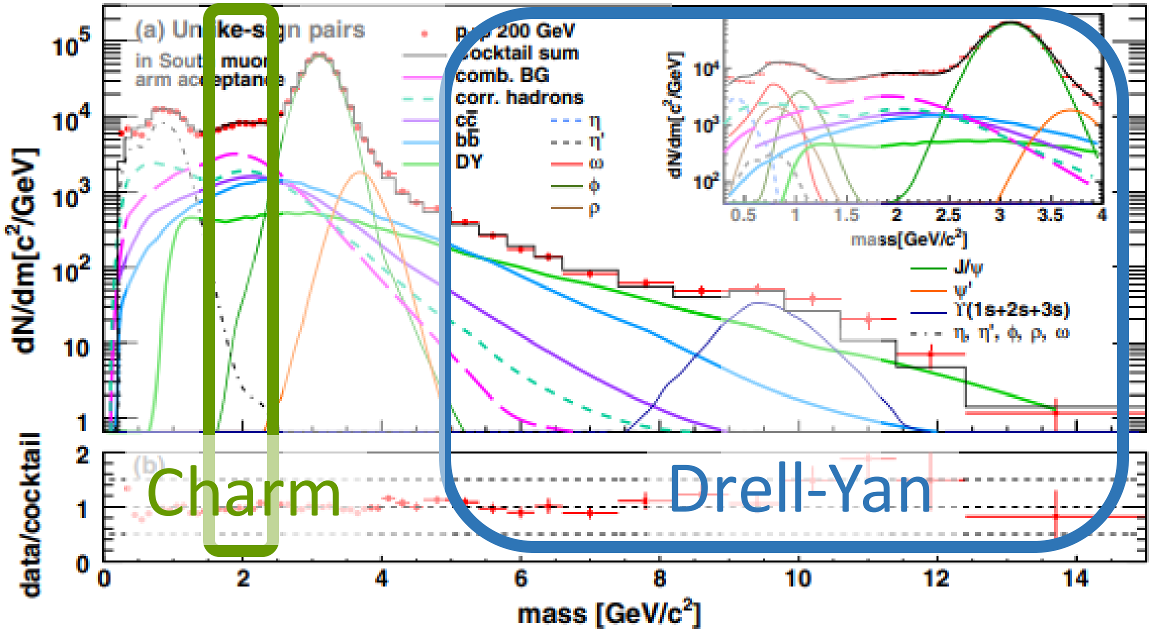


Bottom : hi-mass Like sign
(3.5 – 10.0 GeV/c^2)

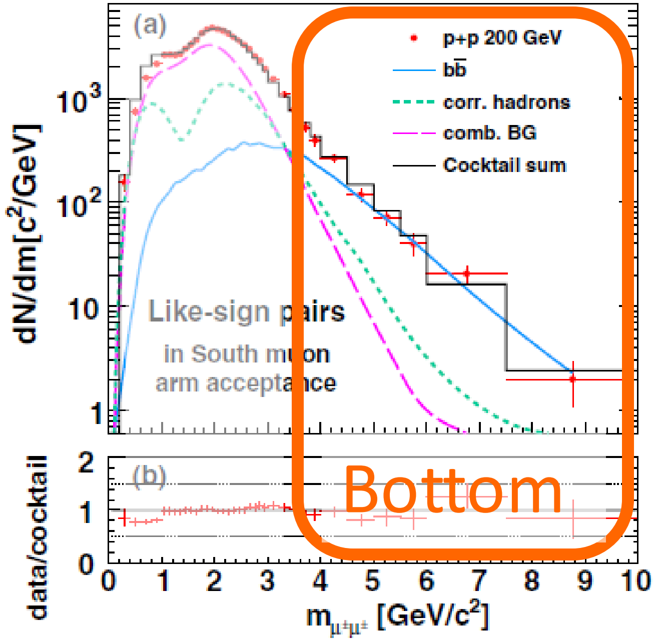
Charm : Lo-mass unlike sign
(1.5 – 2.5 GeV/c^2)

Drell-Yan : Hi-mass unlike sign
(4.8 – 8.2, 11.2-15.0 GeV/c^2)

Unlike sign μμ pairs

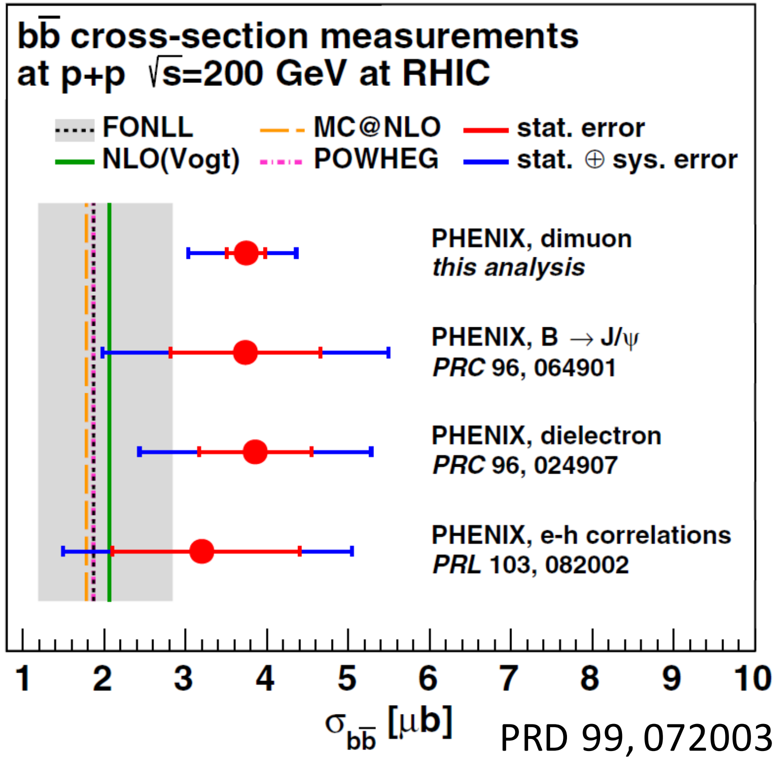


Like sign μμ pairs



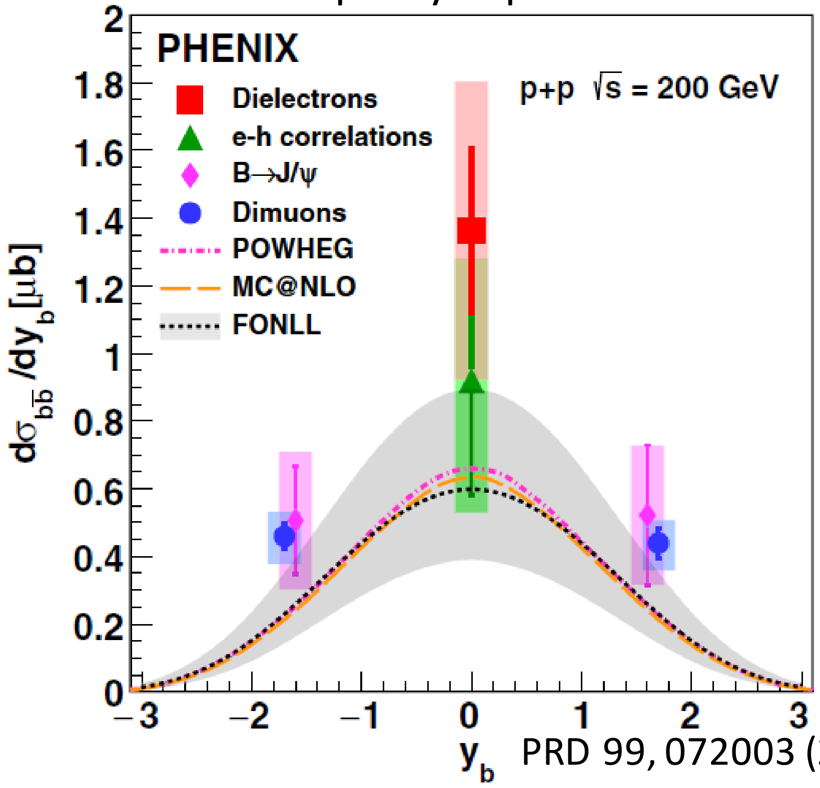
p+p Baseline measurements via μμ pairs in p+p 200GeV

bottom production



PRD 99, 072003 (2019)

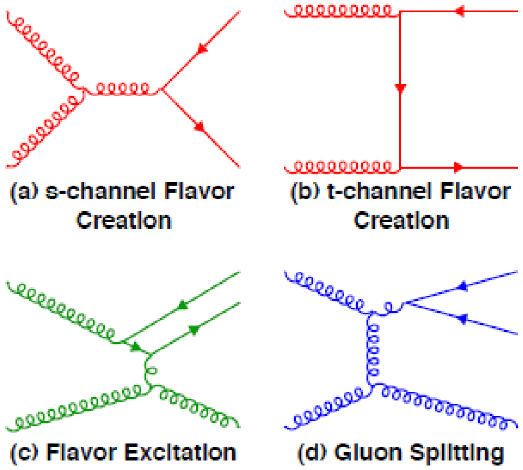
Rapidity dependence



PRD 99, 072003 (2019)

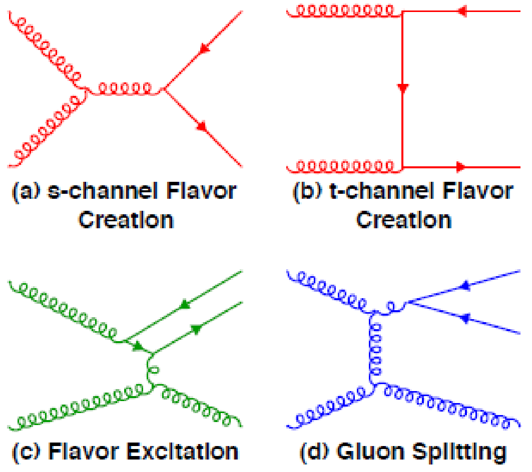
- New bb cross section is consistent w/ previous PHENIX measurements
- Bottom production is 2 times higher than FONLL

Understanding the production mechanism



- Angular correlations are different for the production mechanism
  - Pair creation : back to back
  - Flavor excitation : intermediate
  - Gluon splitting : round shape (narrower)

Understanding the production mechanism



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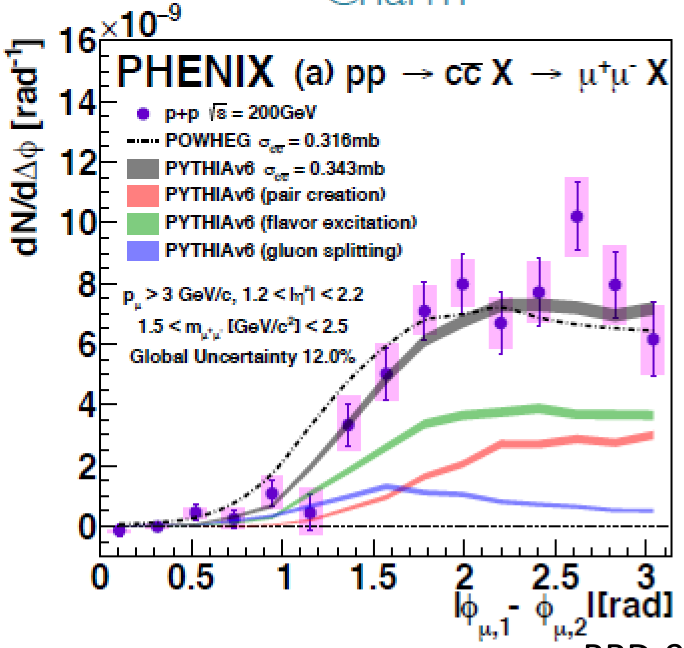
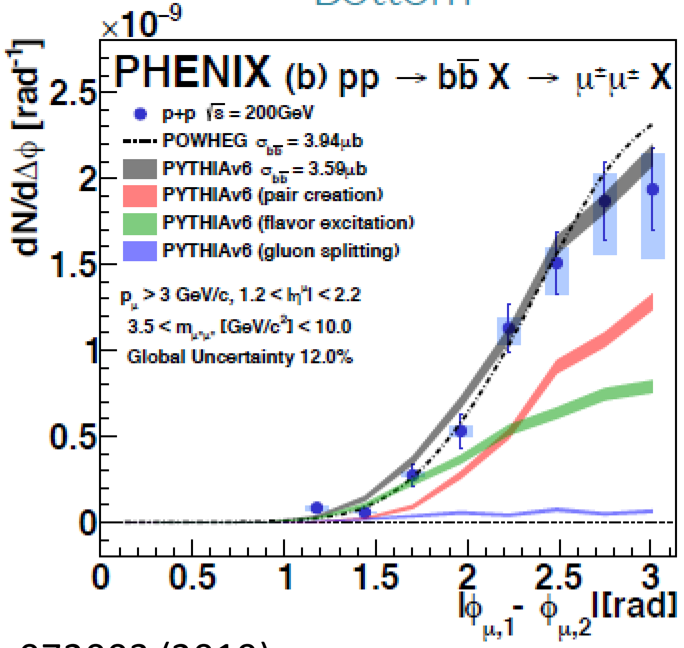
Charm



Bottom



In p+p 200GeV

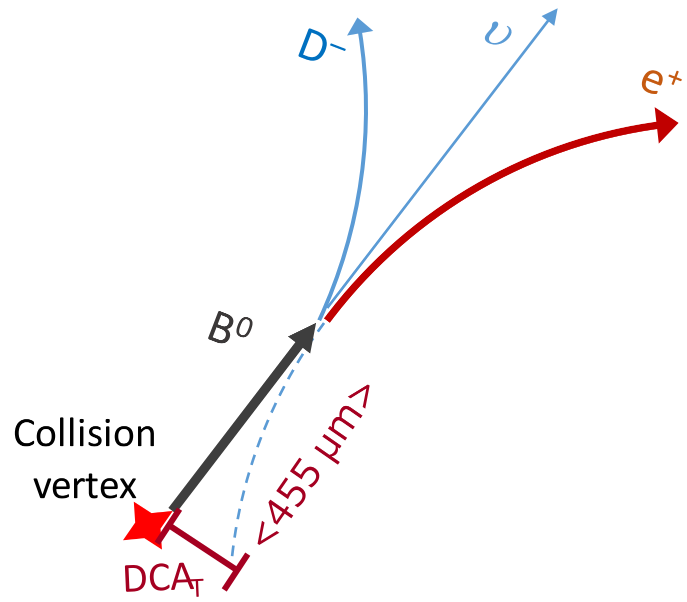
- Charm : Flavor excitation
- Bottom : LO pair creation

- Bottom is simple and sensitive to initial gluon dynamics at RHIC
  - Small gluon splitting contribution

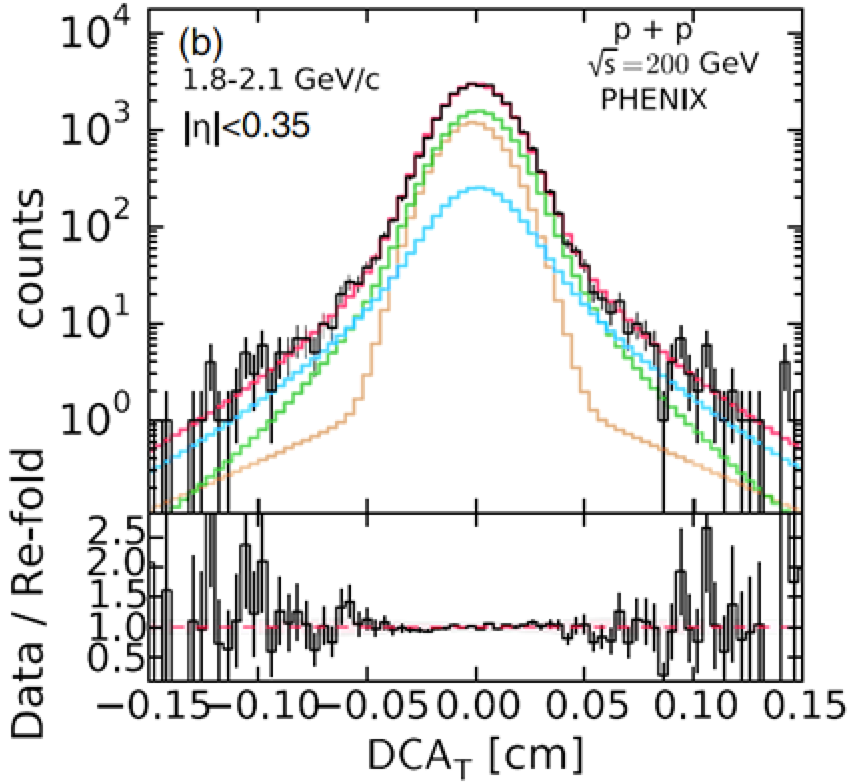
- Gluon splitting is expected to be dominant at LHC

PRD 99, 072003 (2019)

Separation of b → e and c → e



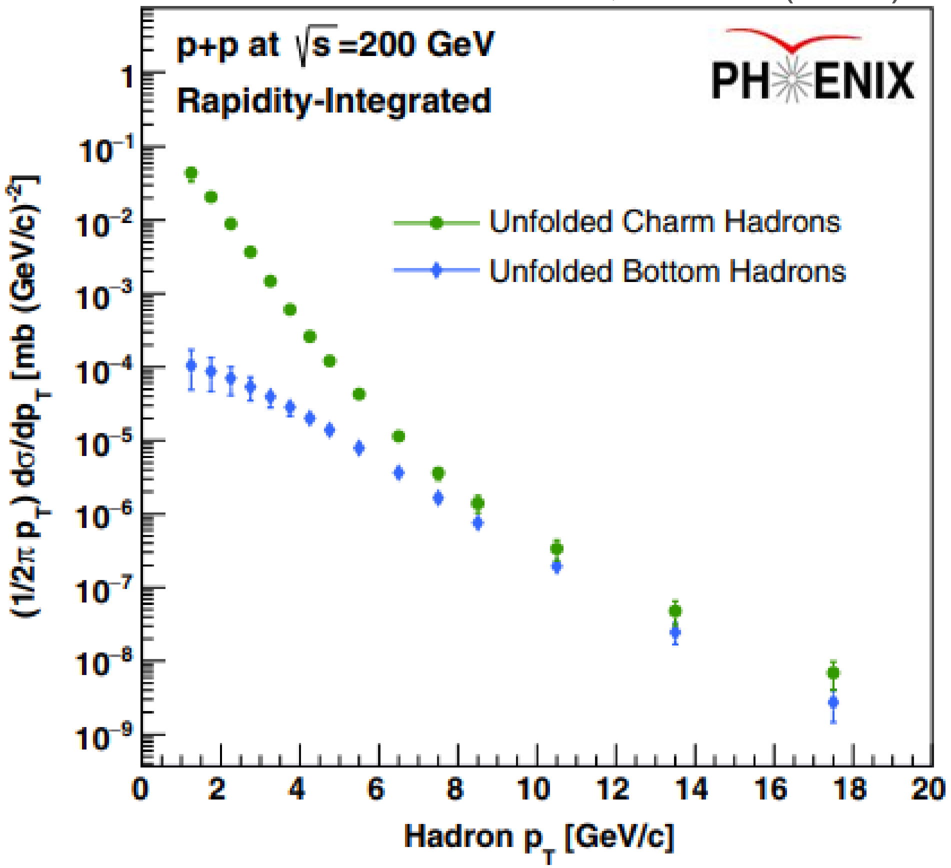
- Electrons from semi-leptonic decay of bottom and charm hadrons
- VTX enables distance of closest approach, DCA,
  - DCA Resolution ~ 60μm
- Utilize decay length to separate b and c
  - B^0 : 455 μm, D^0 : 123 μm



- b→e and c→e is separated using DCA and yield distributions with Bayesian unfolding method
  - b→e and c→e DCA shape reproduce data well
  - B and D hadron yields are extracted

p+p Baseline : B and D hadron from b → e and c→e

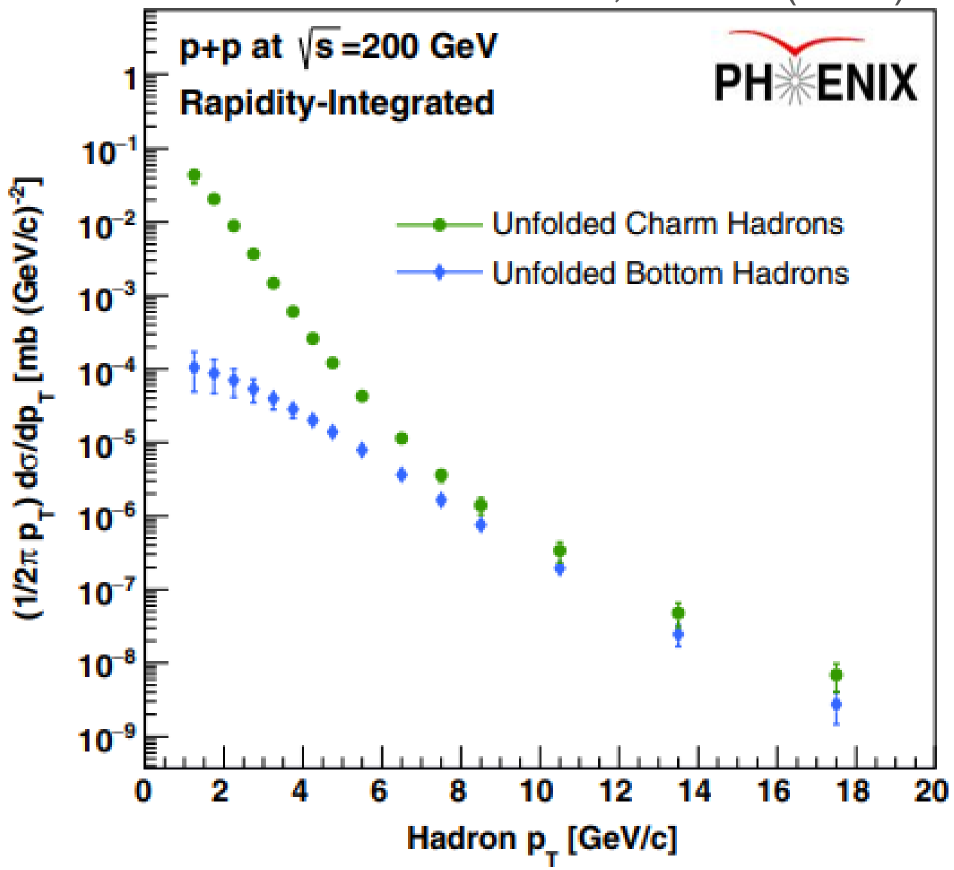
PRD **99**, 092003 (2019)



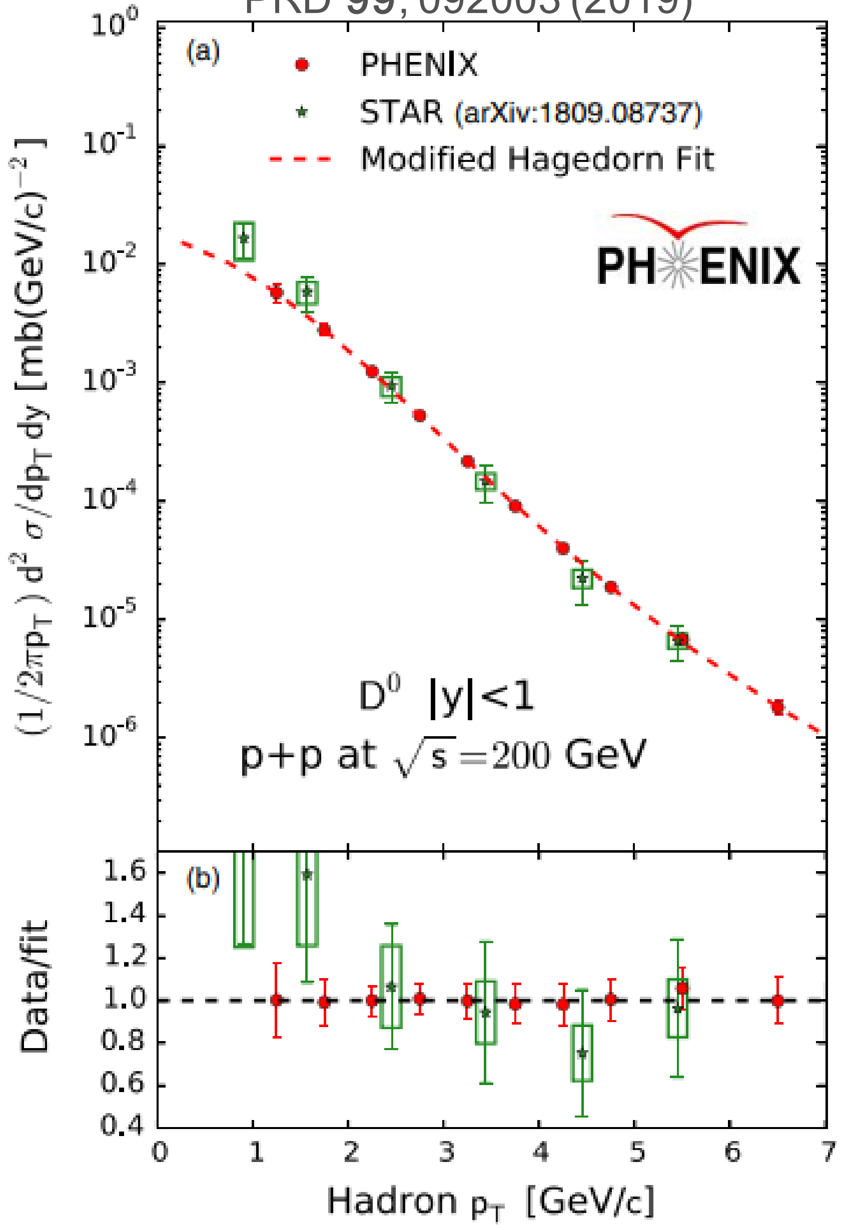
- B & D hadron yield is extracted from the electron measurement
  - Cover broad p_T range

p+p Baseline : B and D hadron from b → e and c→e

PRD **99**, 092003 (2019)



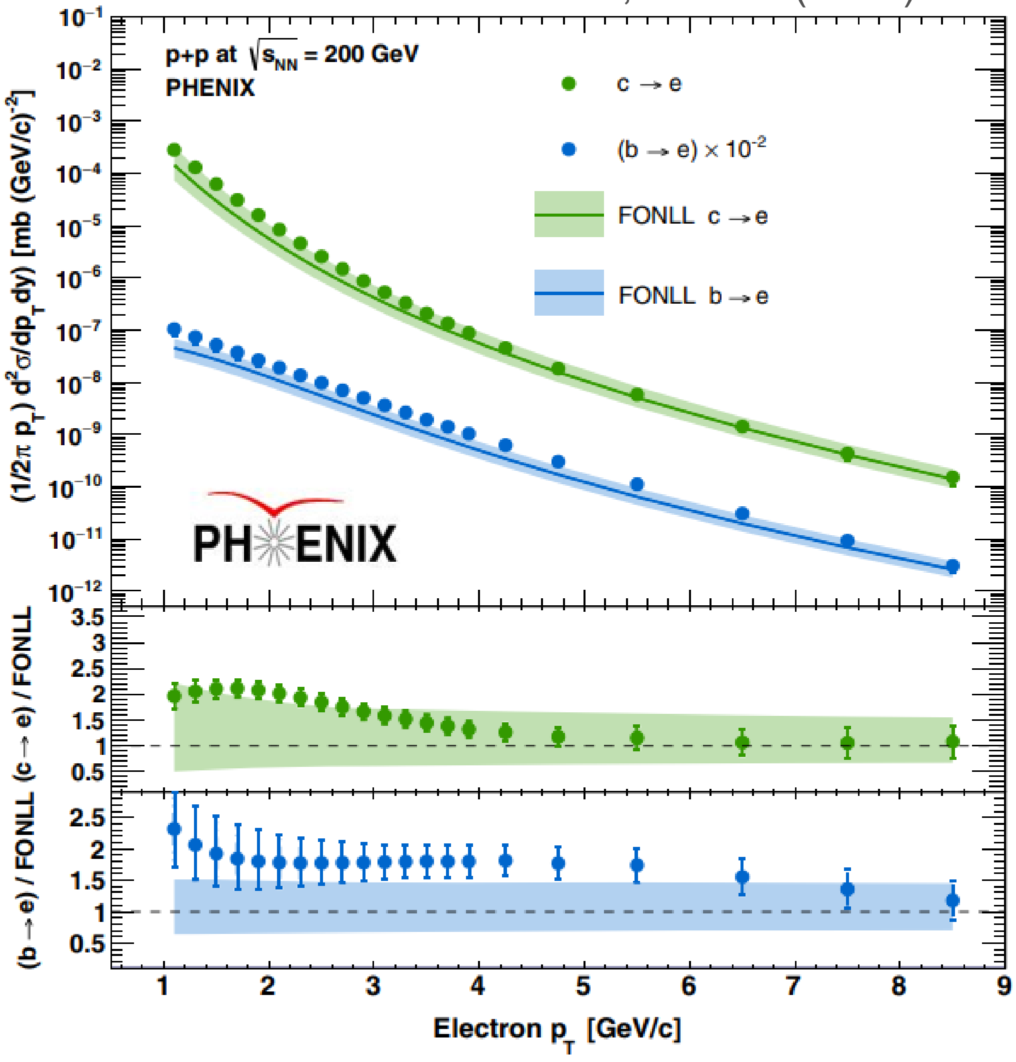
PRD **99**, 092003 (2019)



- B & D hadron yield is extracted from the electron measurement
  - Cover broad p_T range
- Good agreement with STAR D^0 in comparable p_T range

p+p Baseline measurements via single electrons

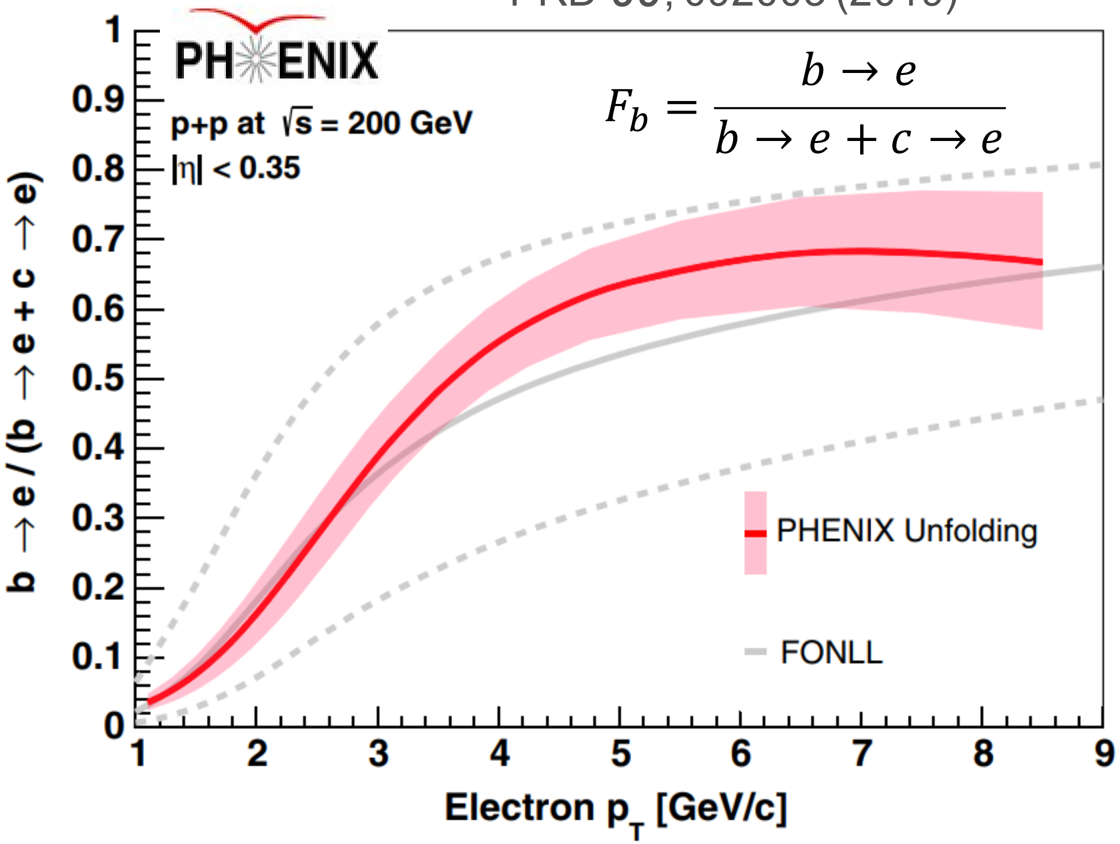
PRD **99**, 092003 (2019)



- b→e and c→e is successfully separated via Bayesian unfolding
- b→e and c→e is 2x higher than FONLL
  - consistent with the μμ pair result

p+p Baseline : Bottom Electron Fraction, F_b

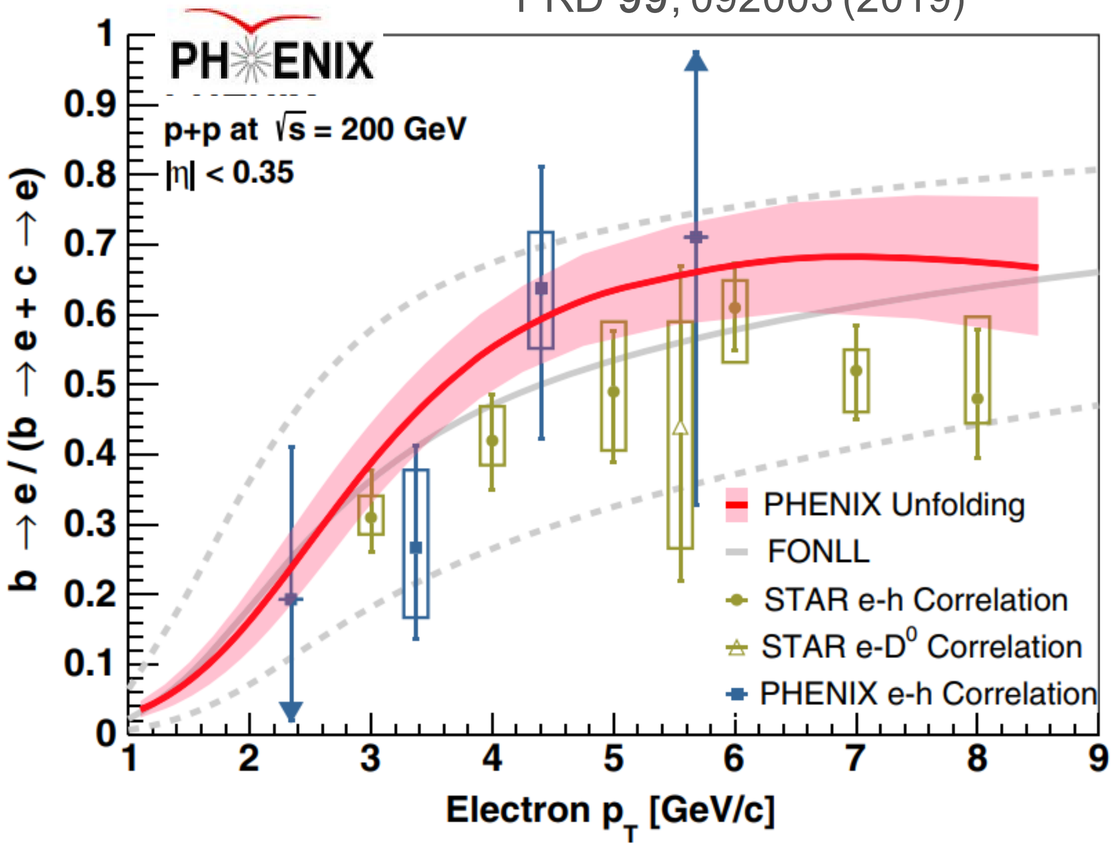
PRD **99**, 092003 (2019)



- FONLL is consistent with F_b data

p+p Baseline : Bottom Electron Fraction

PRD **99**, 092003 (2019)



- FONLL is consistent with F_b data
- New data is consistent with previous measurements

P+P Baseline of bottoms and charms available

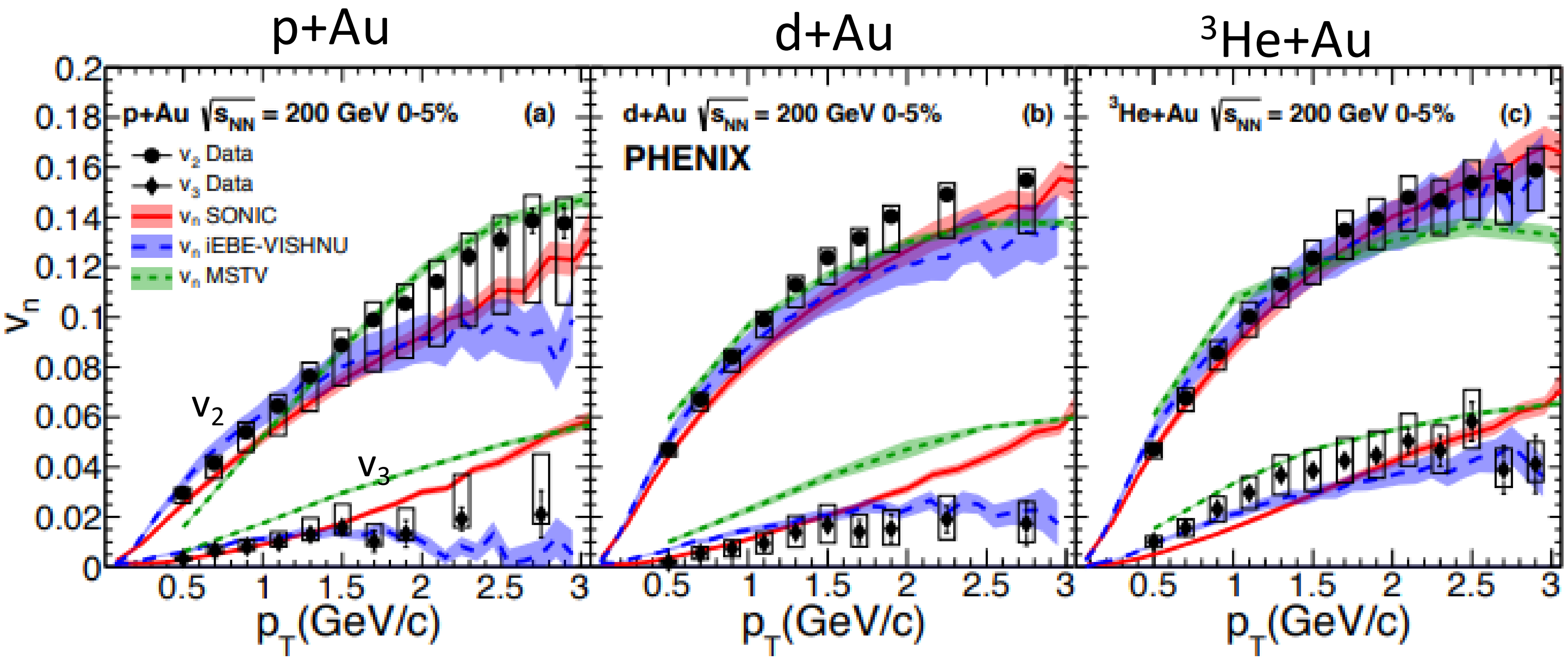
D/B hadrons, electrons, μ for mid- & forward rapidity

Open heavy flavor in d + A

PHENIX measured v_2 and v_3 in small system.

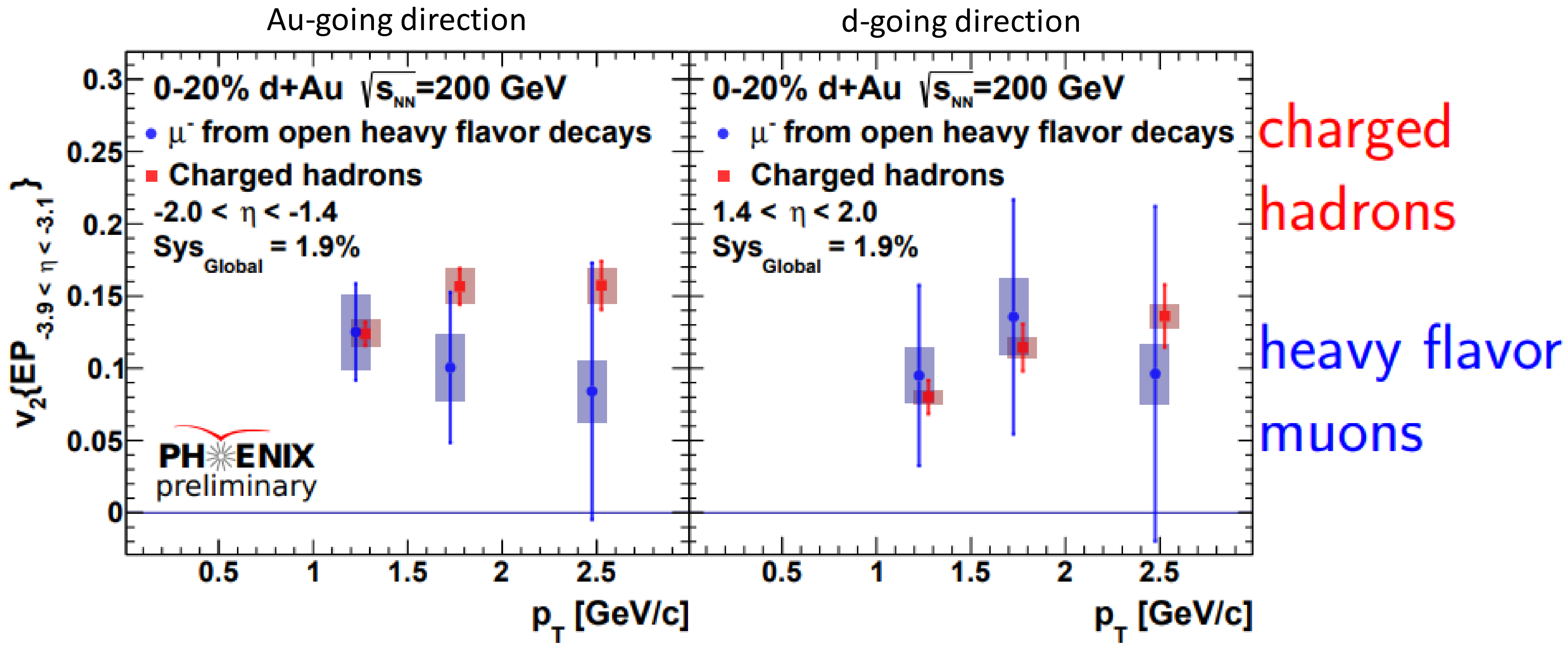
Data are well described by hydro models including the QGP formation

Nature Physics 15, 214 (2019)



Heavy flavor is also flows in small system?

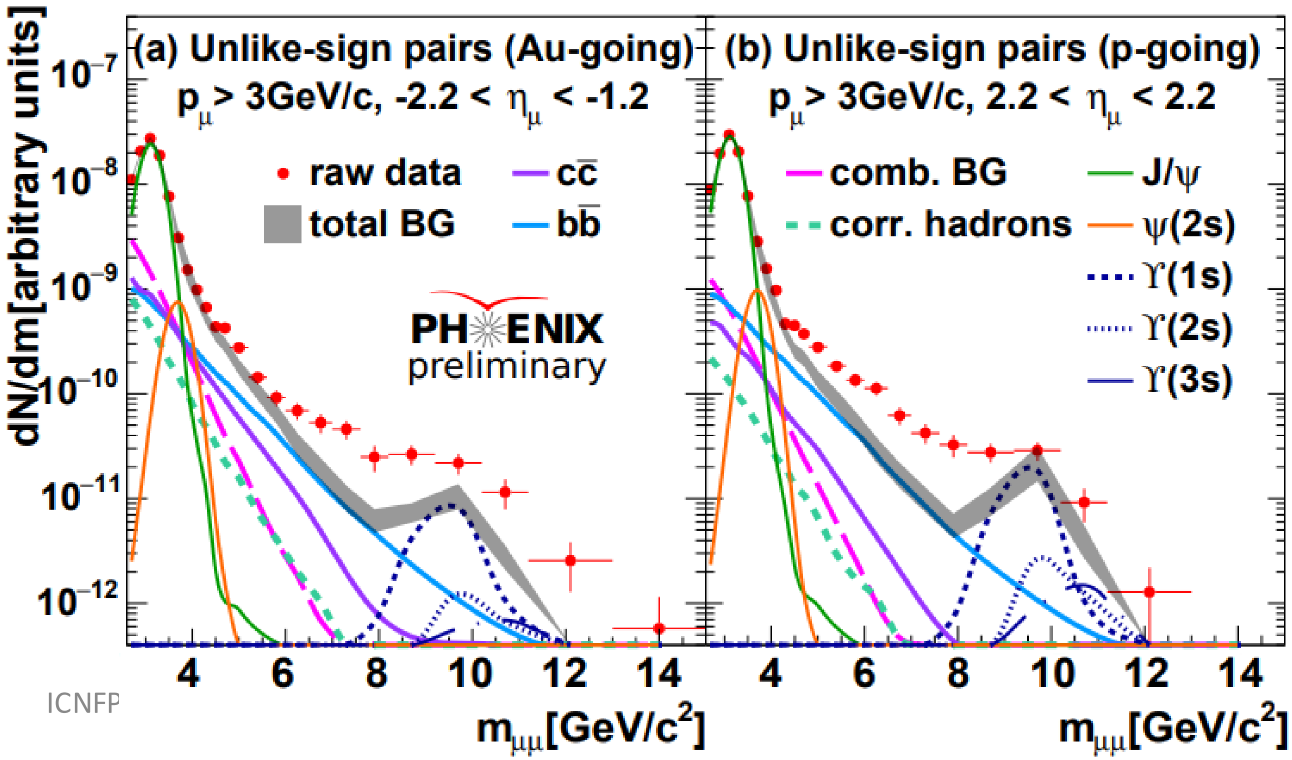
Heavy flavor muon v_2^{HF} in d+Au 200GeV

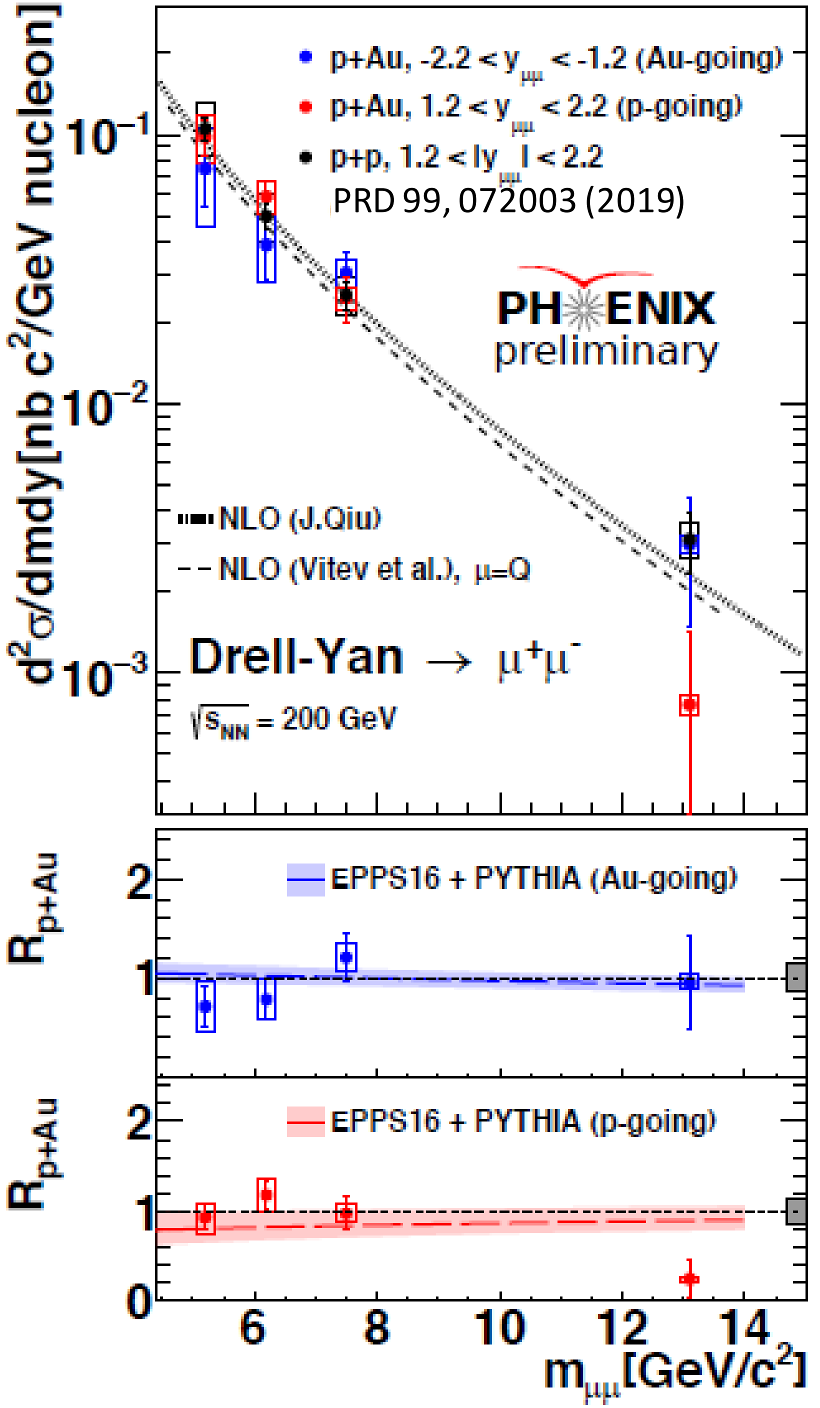


- Re-analyzed run8 dataset
- Significant non-zero v_2 in d+Au collisions !!
  - both Au-going and d-going direction

Drell-Yan in p+A 200GeV

- High di-muon mass region
- Sensitive to initial state nuclear effect
- First measurement at RHIC
- R_{pAu} is consistent with EPPS16 + PYTHIA



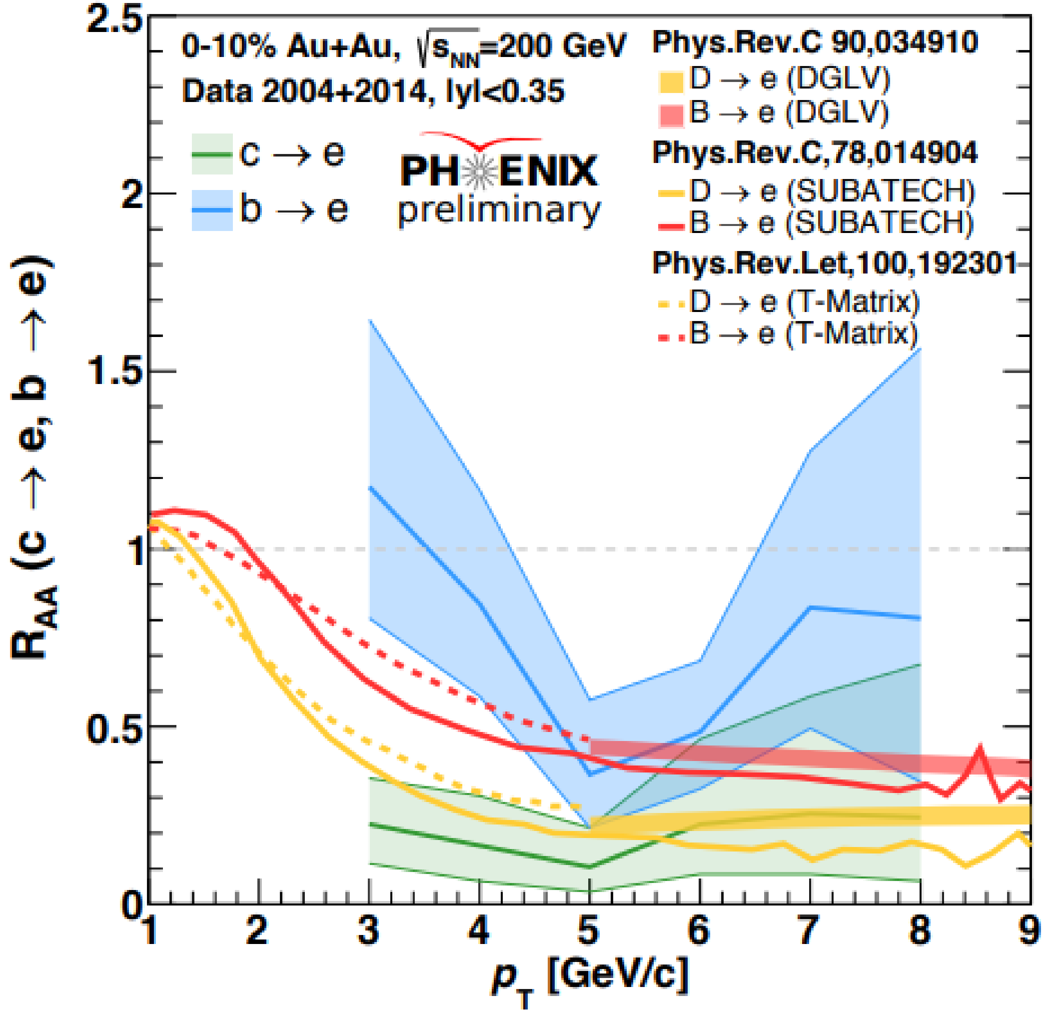


Open heavy flavor in Au+Au

Suppressions & Flows

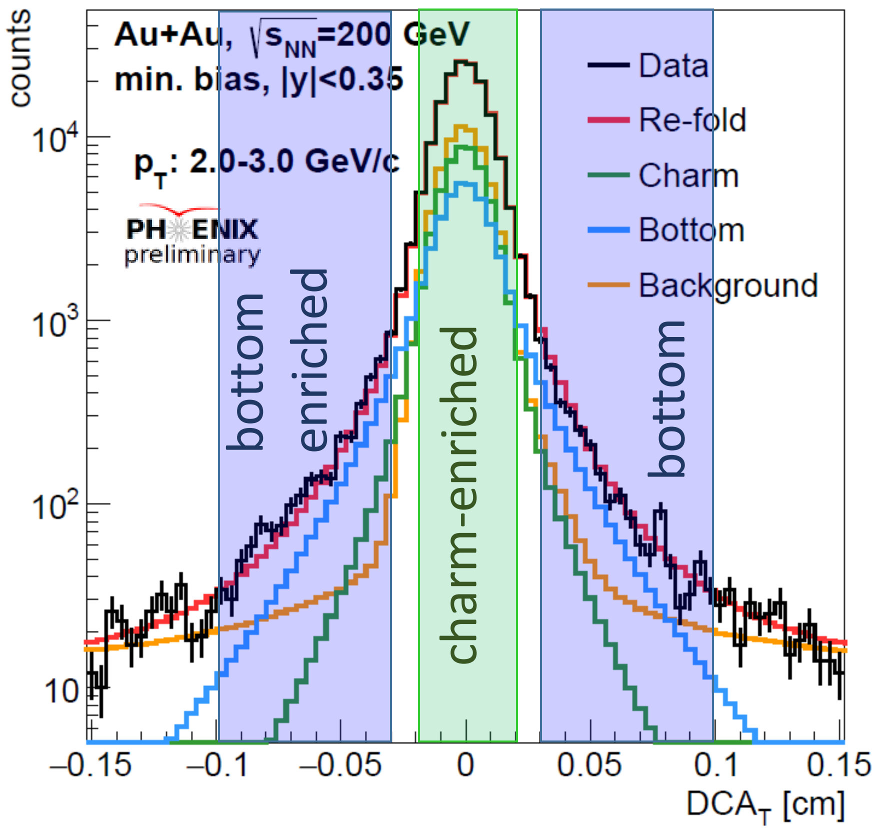
Bottom and Charm R_{AA} in Au+Au 200

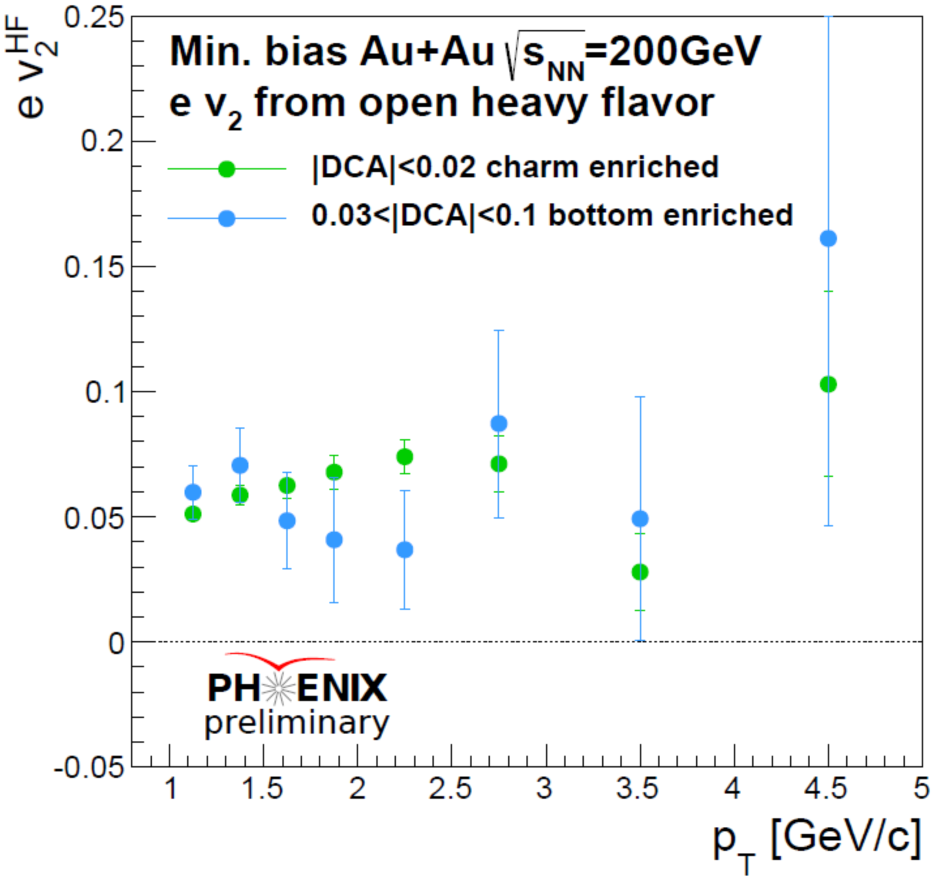
b→e & c→e in 0-10% Au+Au



- 10% of 2014 Au+Au dataset analyzed
- Most central Au+Au (0-10%),
  - R_{AA}(b→e) ~ R_{AA}(c→e) in high p_T
  - R_{AA}(b→e) < R_{AA}(c→e) in low p_T
- The result will be updated using new p+p baseline and full 2014 Au+Au dataset (x10)
  - Extend to low p_T.
  - Preliminary was calculated using STAR e-h in p+p.

Extract v_2 for b → e and c → e





Measure heavy flavor electron v_2 from 2 DCA ranges

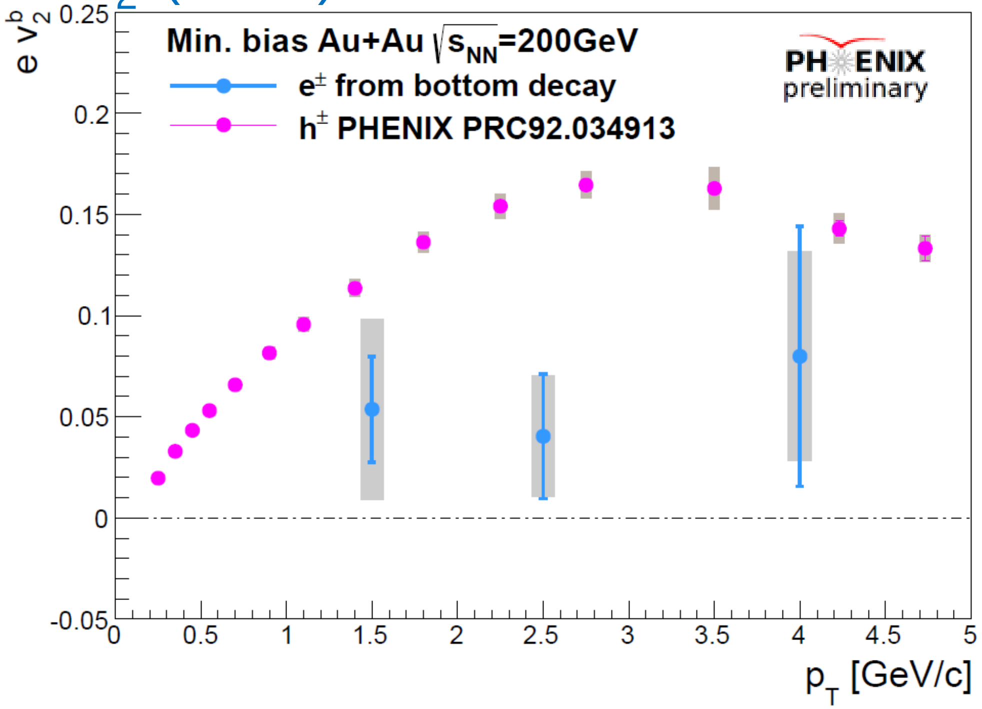
Peak : c-enriched : |DCA|<200um

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

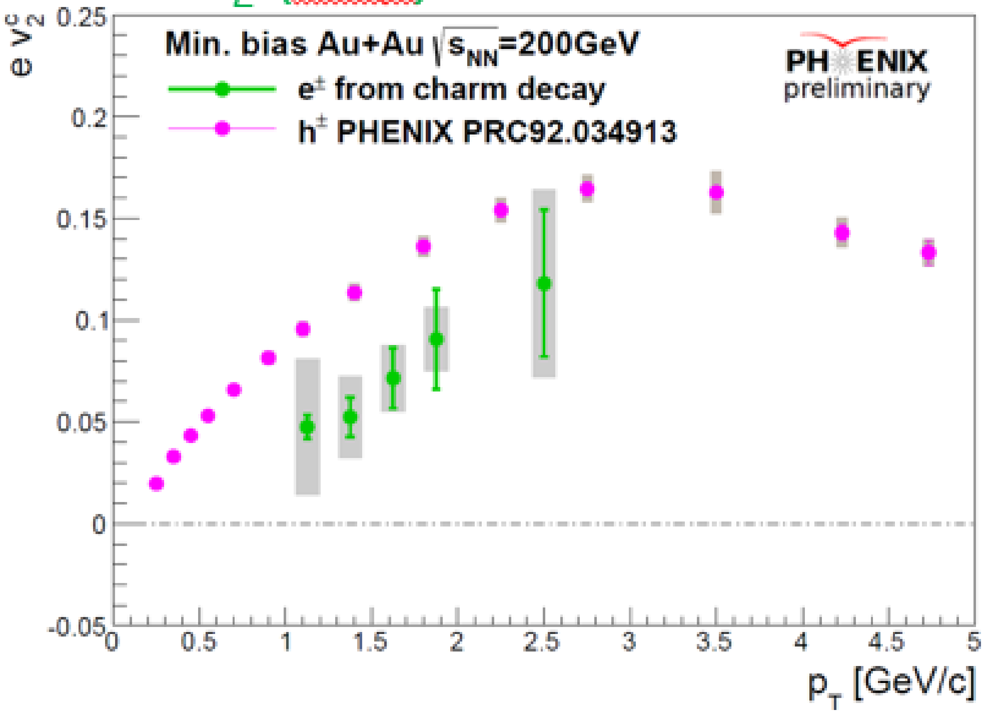
- Solve the v_2 equations to extract separated v_2(b → e) and v_2(c → e)

Charm and Bottom Elliptic flow in Au+Au 200GeV

$v_2^b(b \to e)$



$v_2^c(c \to e)$



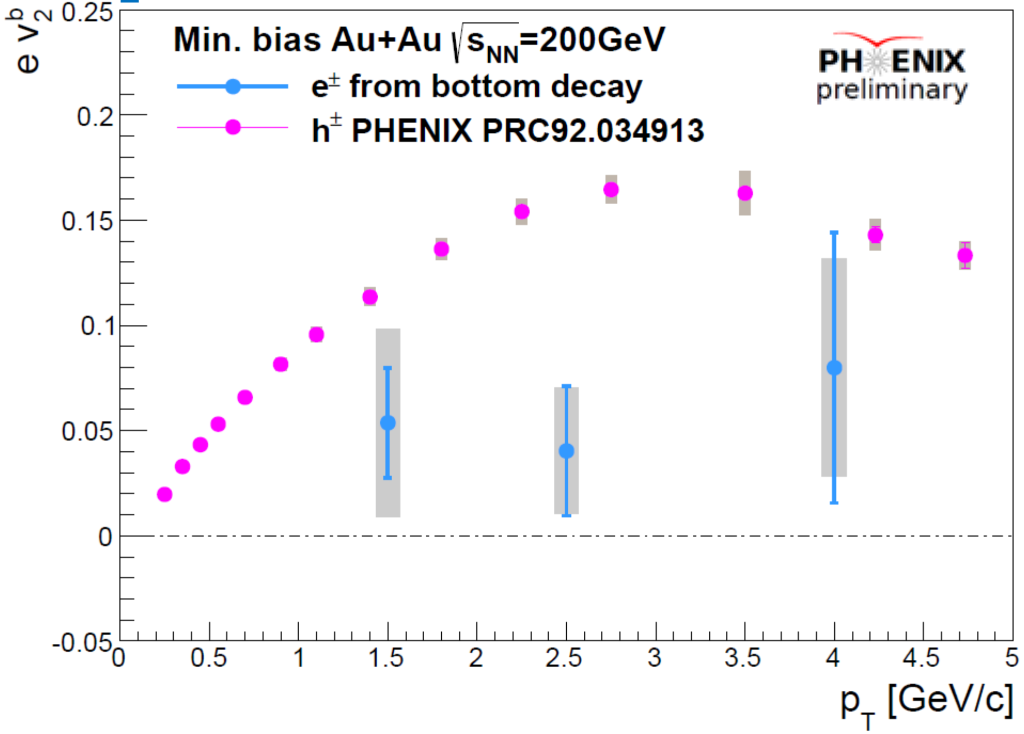
- Bottom and charm v2 successfully extracted at low pT
- Hint for possible bottom flow
  - also consistent w/ zero
- Positive charm v2c(c->e) and smaller than v2h

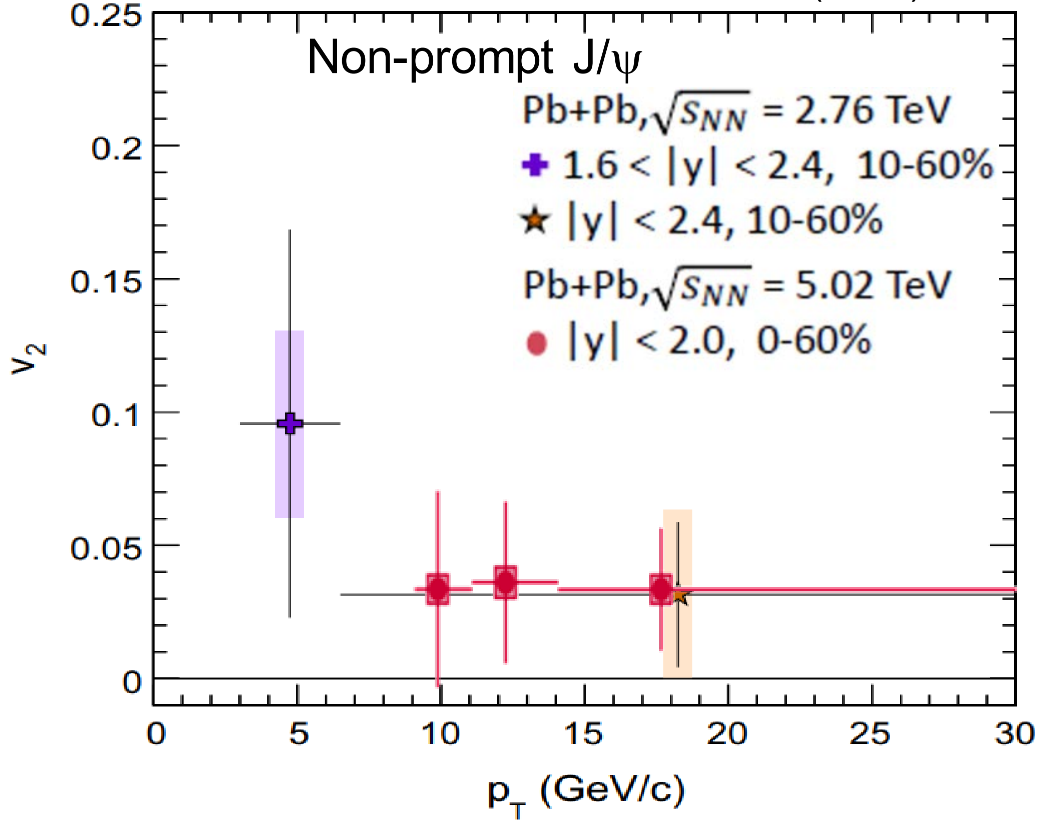
Likely to be $v2(b \to e) < v2(c \to e)$

Bottom v_2 : comparison to LHC

ATLAS EPJ. C (2018) 78:784
CMS EPJ. C (2017) 77:252

$v_2^b(b \rightarrow e)$





- ATLAS and CMS also measured positive bottom v2 for p_T > 3GeV/c
  - Low p_T is sensitive to flow, and high p_T is good for energy loss?
- consistent with these results
- b-quark suffer flow?

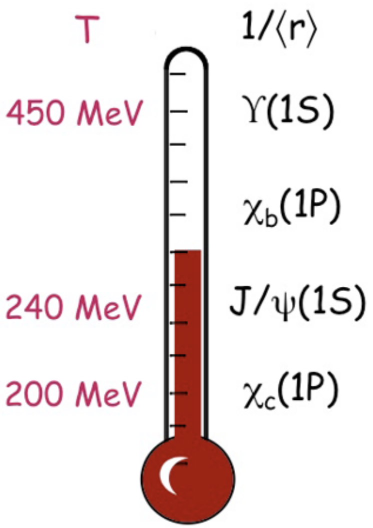
Bottom v2 became available. Need precise measurement

Quarkonia in small system

Quarkonia as QGP probe

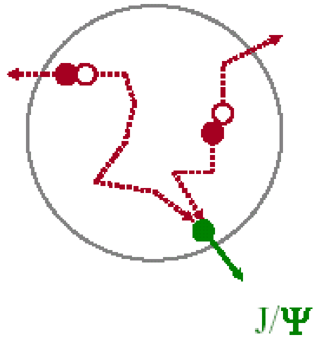
T. Matsui and H. Satz
PLB 178 (1986) 416

- Quarkonia can be melted in QGP due to Debye color screening
- Sequential melting of bound states should be seen
  - QGP thermometer!

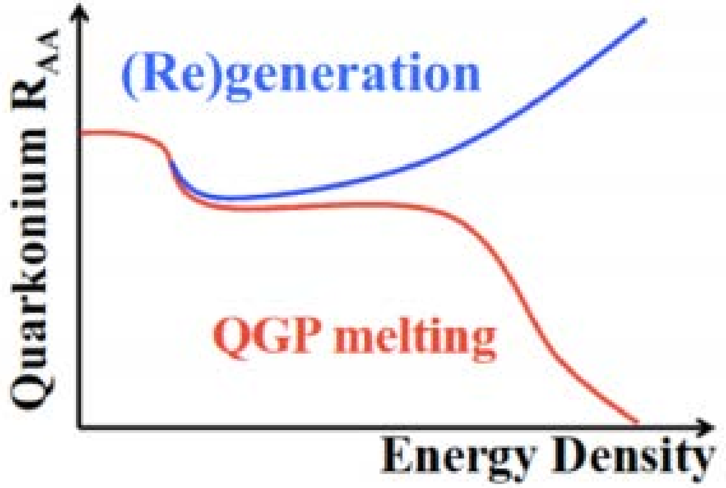


Not simple…

- Cold nuclear matter effects (CNM)
  - Initial state: shadowing(nPDF), k_T broadening
  - Final state : cc breakup , co-movers
- Regeneration/Recombination (not negligible)
  - Significant at LHC

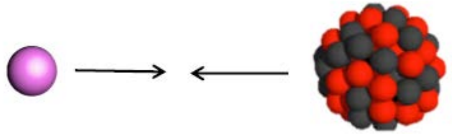


Recombine non-initial pair of HQ

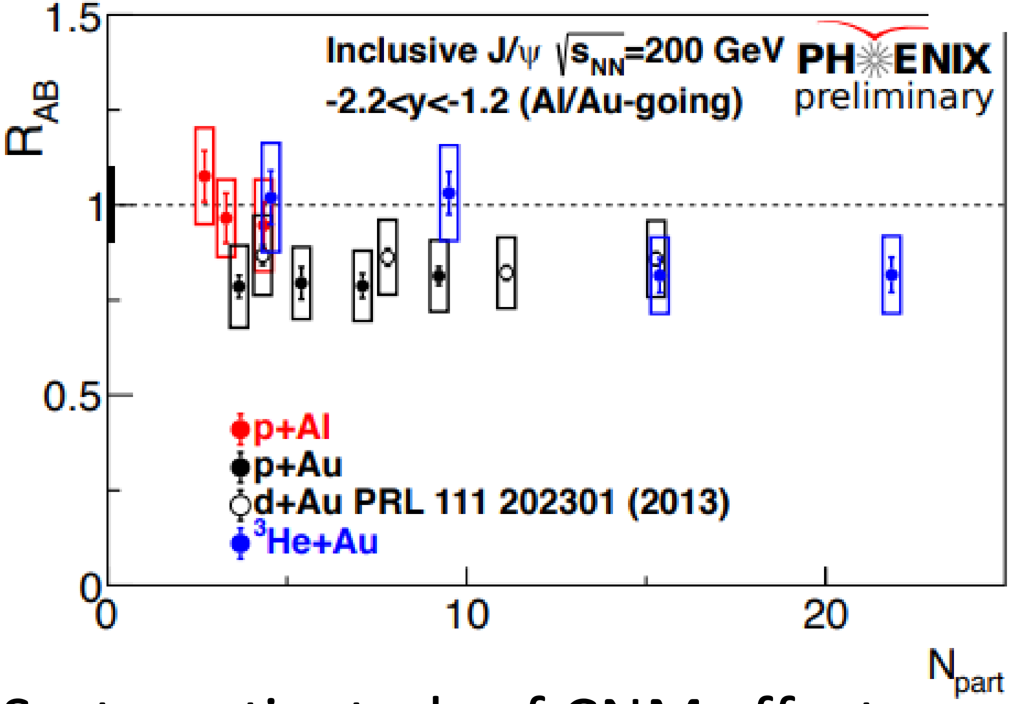


- CNM effect is key to quantify quarkonia melting in A+A
  - Systematic study of CNM effect by changing nuclear thickness with p+Al, and p/d/^{3}He+Au

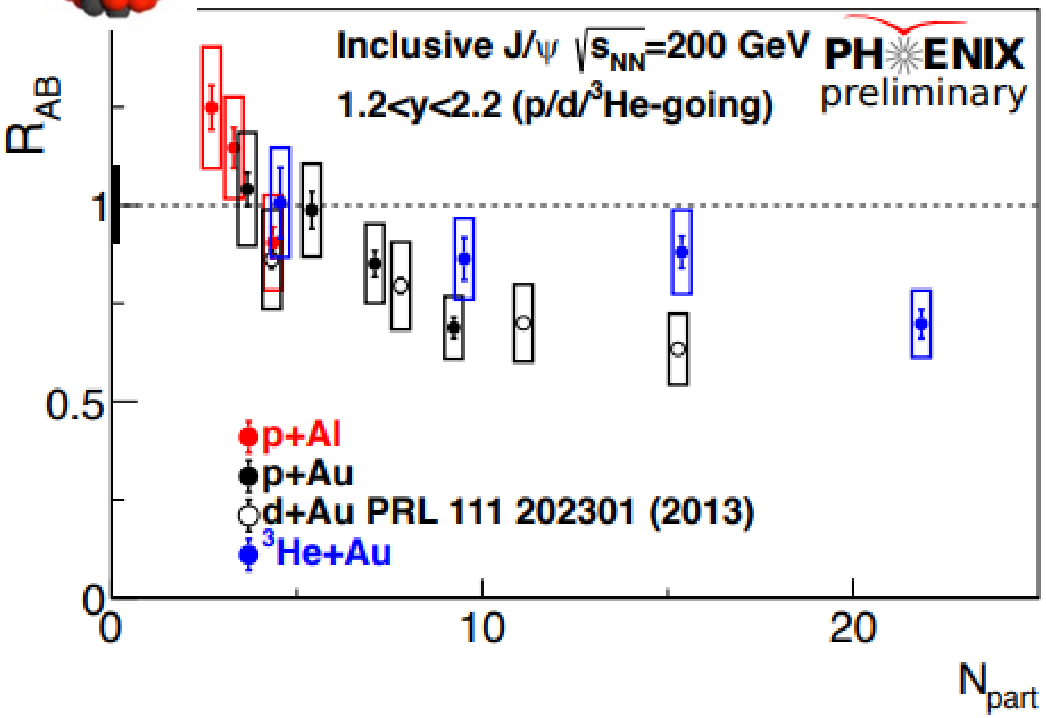
J/ψ : CNM effects in p+Al, p+Au, d+Au, ^{3}He+Au 200GeV



Al/Au-going direction



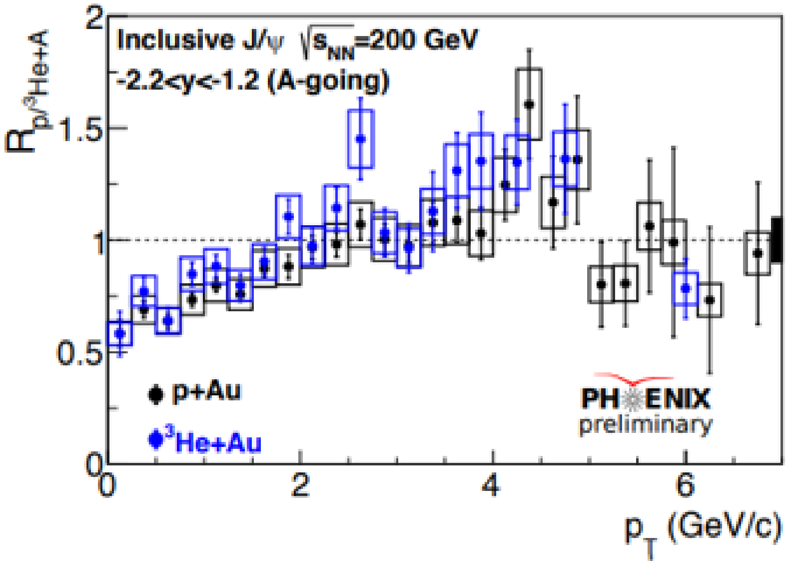
p/d/^{3}He-going direction



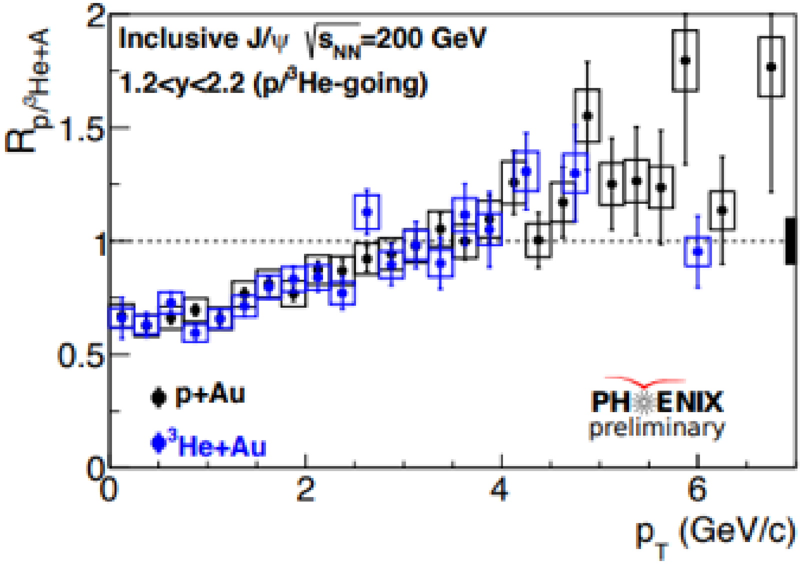
- Systematic study of CNM effects
- J/ψ R_{AA} vs Npart is on a common scaling curve in p/d/3He going and Au/Al going
  - Consistent with unity at small Npart
  - R_{AB} ~< 1 at larger Npart

CNM effects : R_{AB} vs p_T in p/^{3}He + Au

Au going



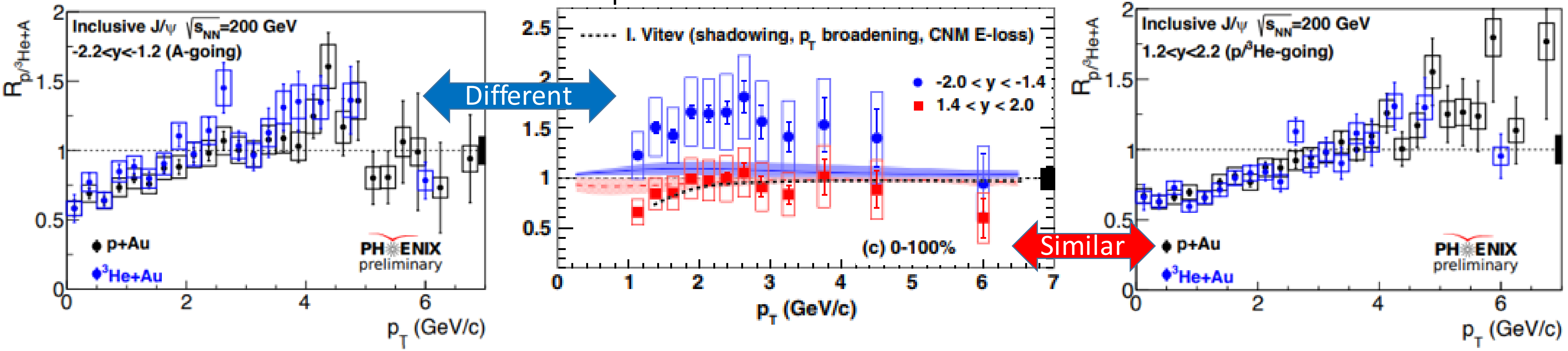
p/^{3}He going



- J/ψ is suppressed in both p-going and Au-going direction

CNM effects : R_{AB} vs p_T in p/^{3}He + Au

Au going　　Open HF in d+Au　　p/^{3}He going

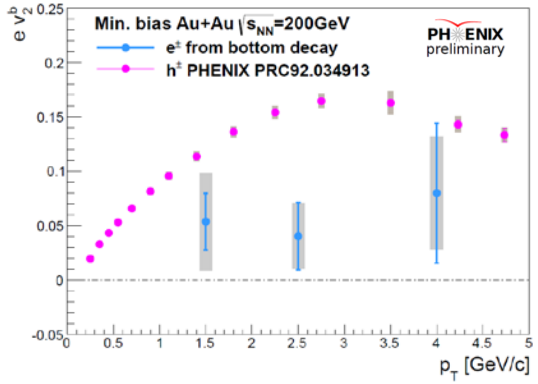


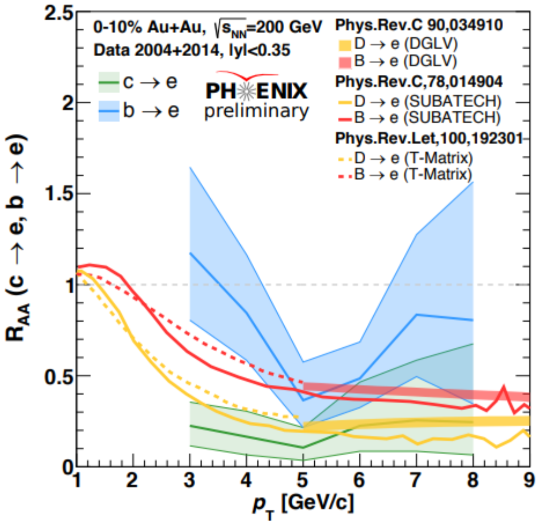
- J/ψ is suppressed in both p-going and Au-going direction
  - p/^{3}He-going : Shadowing effect (ISE) - Similar w/ HFμ
  - Au-going : Break up effect (FSE) – different w/ HFμ (enhancement)
    - Large multiplicity for Au going

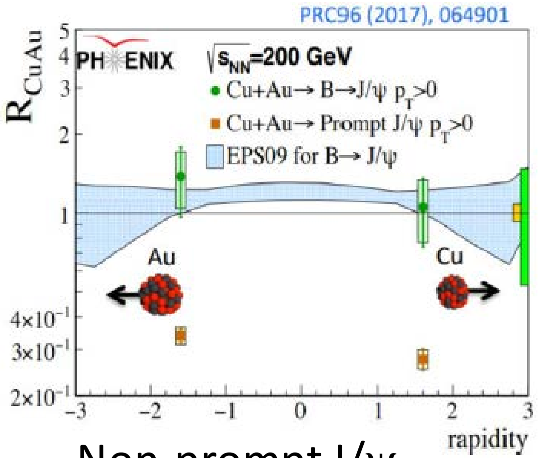
Summary and Outlook

- PHENIX measures open and closed heavy flavor in p+p, Au+Au and small systems
- P+P baseline improved by di-muon and single electron from HF decays
  - Bottom cross section is 2x higher than FONLL at mid- and forward rapidity
  - Production mechanism of bottom and charm by azimuthal correlation of di-muons
  - Bottom electron fraction is consistent with FONLL
- p/d+Au
  - HF muon show positive v_2. hint for HF flow at small system
  - First Drell-Yan measurement in p+A
- Au+Au
  - Bottom electron v_2 is likely smaller than charm electron v_2
    - PHENIX data is consistent with LHC
- Quarkonia in small system
  - J/ψ suppressed with FSE in Au going direction
- Outlook
  - Analysis with Au+Au full statistics (20x) is going
  - New bottom R_{AA} and v_2 will come soon. Stay tuned!

$v_2^b(b \to e)$

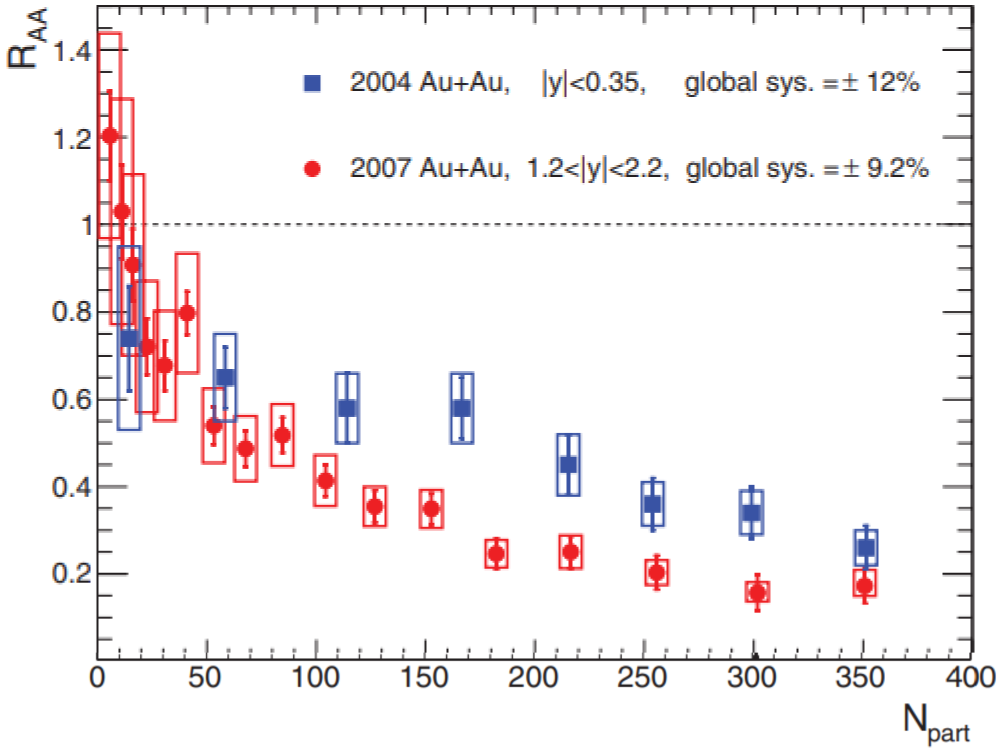






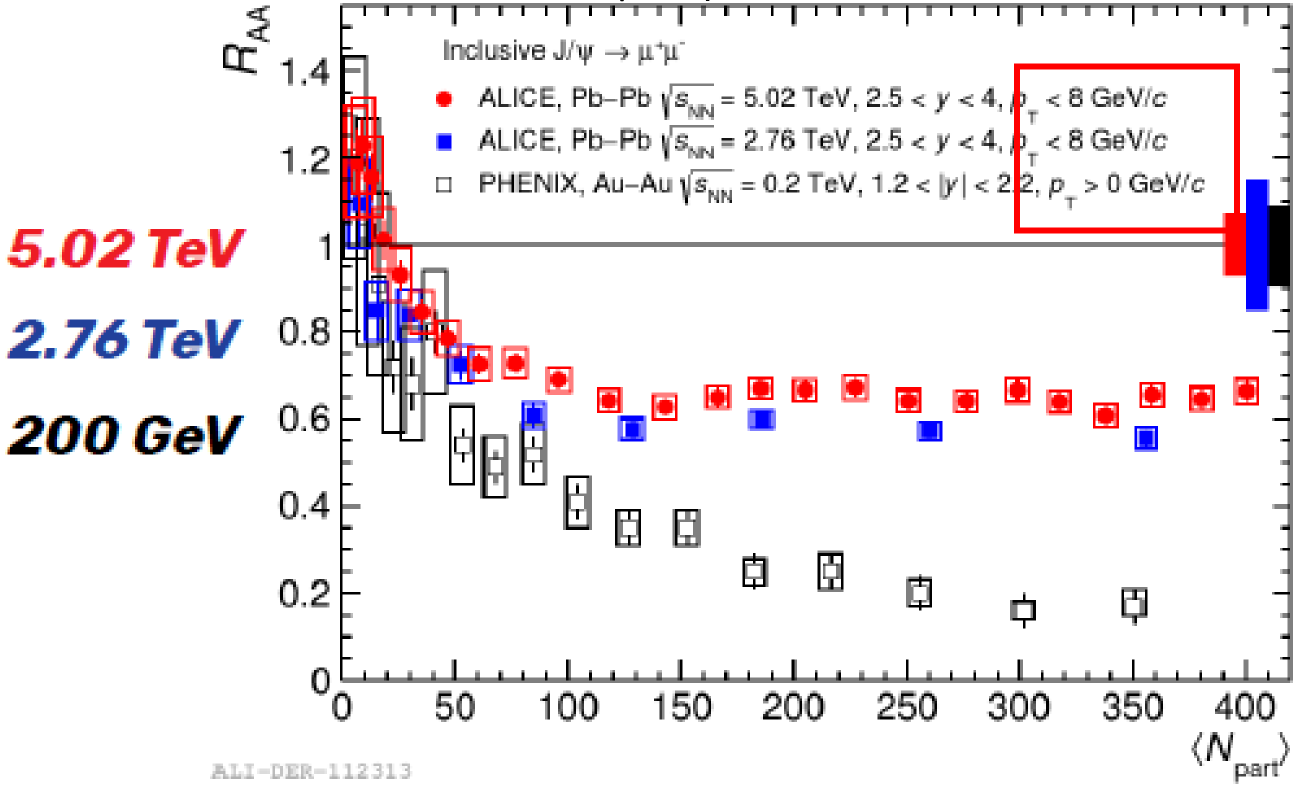
Non-prompt J/ψ

J/ψ : Regeneration at low p_T



- R_{AA}(Mid) < R_{AA}(FW)

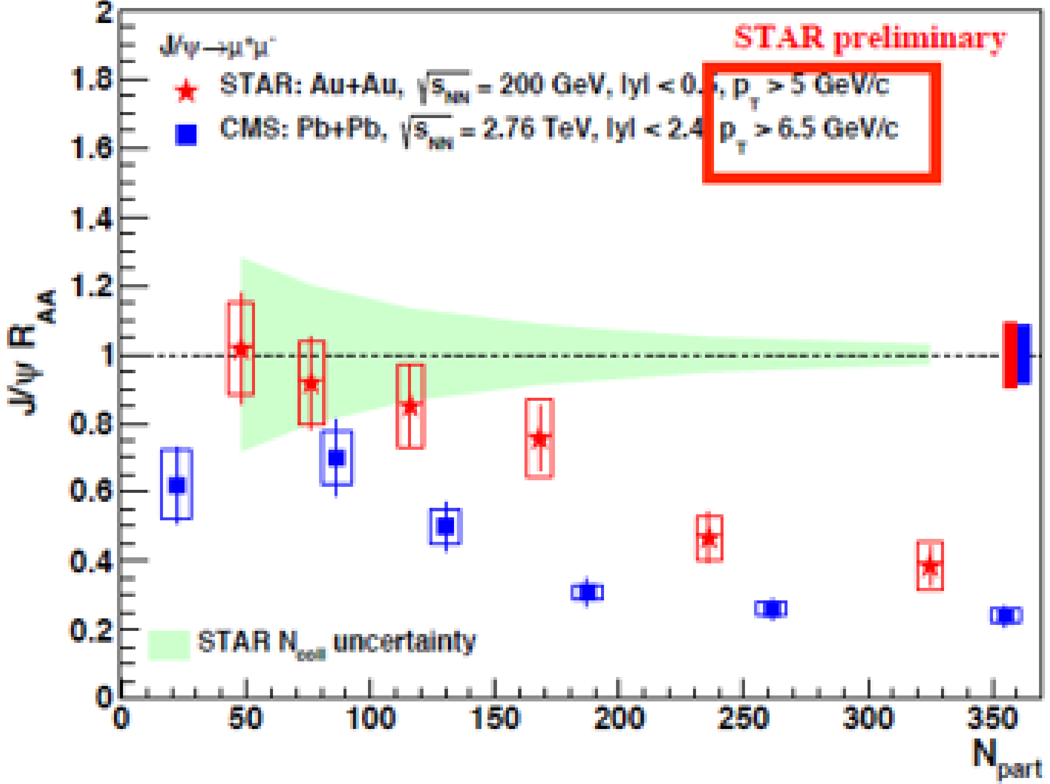
Low p_T J/ψ



- R_{AA}(RHIC) < R_{AA}(LHC) at low pT
- Regeneration (recombination)

J/ψ : Dissociation in high p_T vs Regeneration in low p_T

High p_T J/ψ



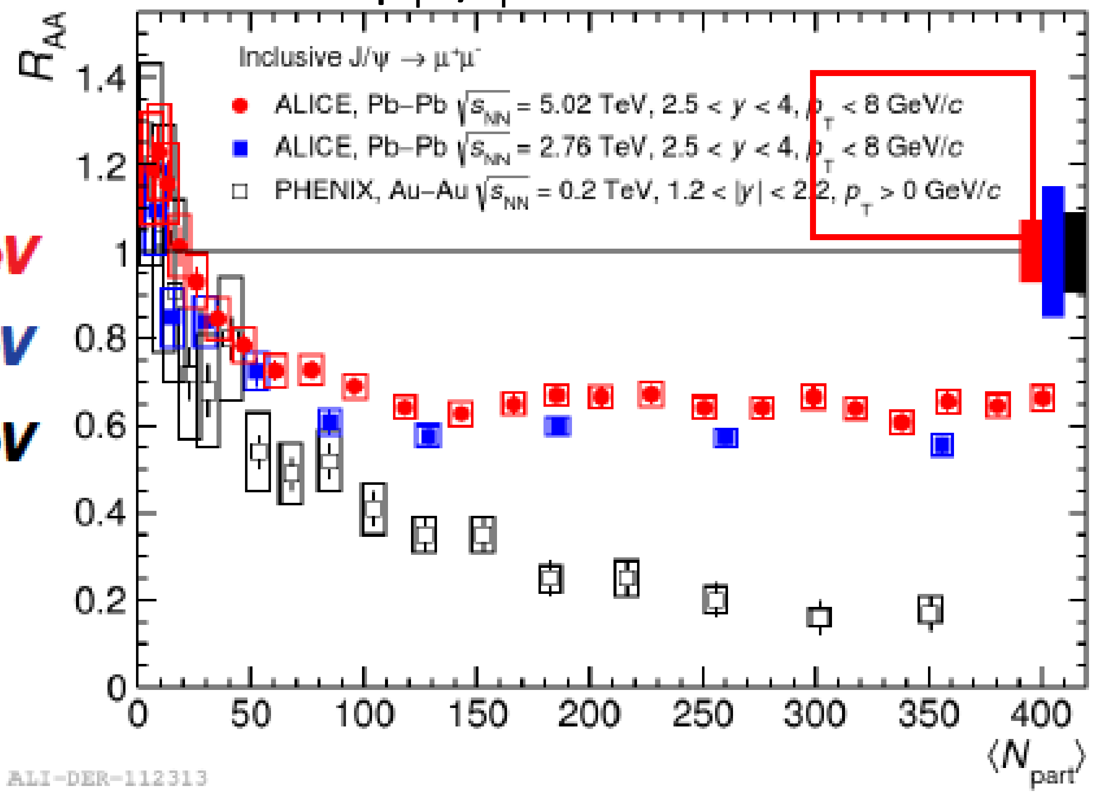
- More suppression with centrality
- R_{AA}(RHIC) > R_{AA}(LHC) at high pT
- Dissociation
  - Small regeneration and CNM.

Low p_T J/ψ

5.02 TeV

2.76 TeV

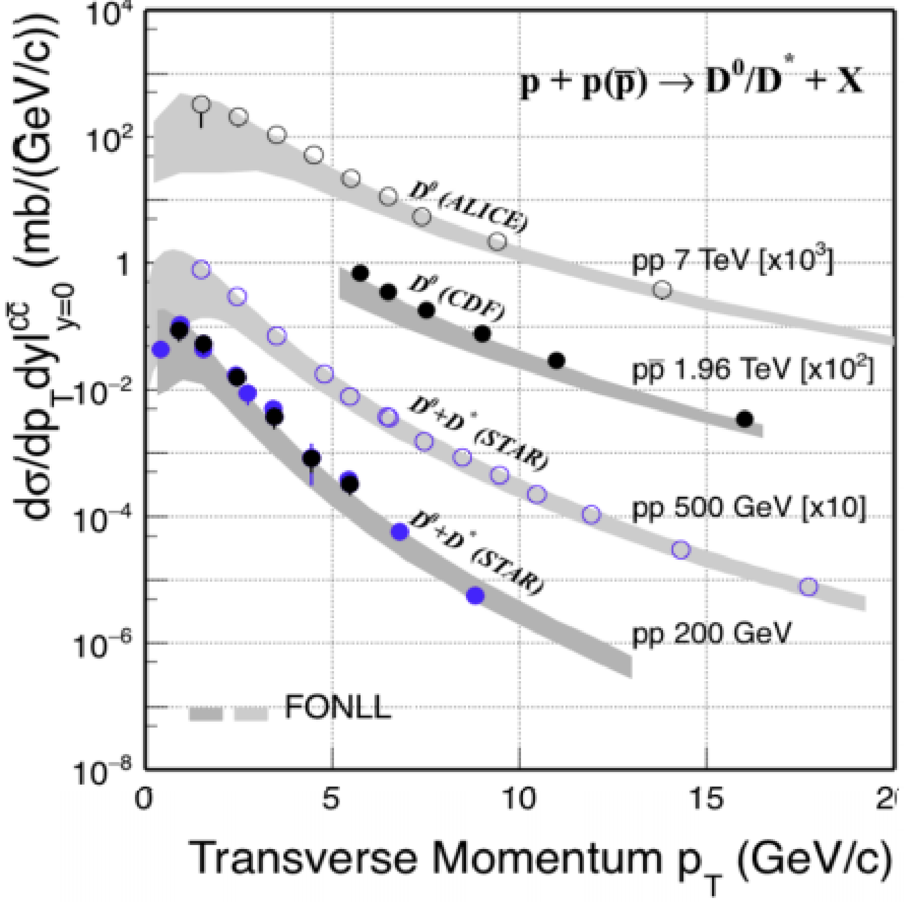
200 GeV



- R_{AA}(RHIC) < R_{AA}(LHC) at low pT
- Regeneration (recombination)

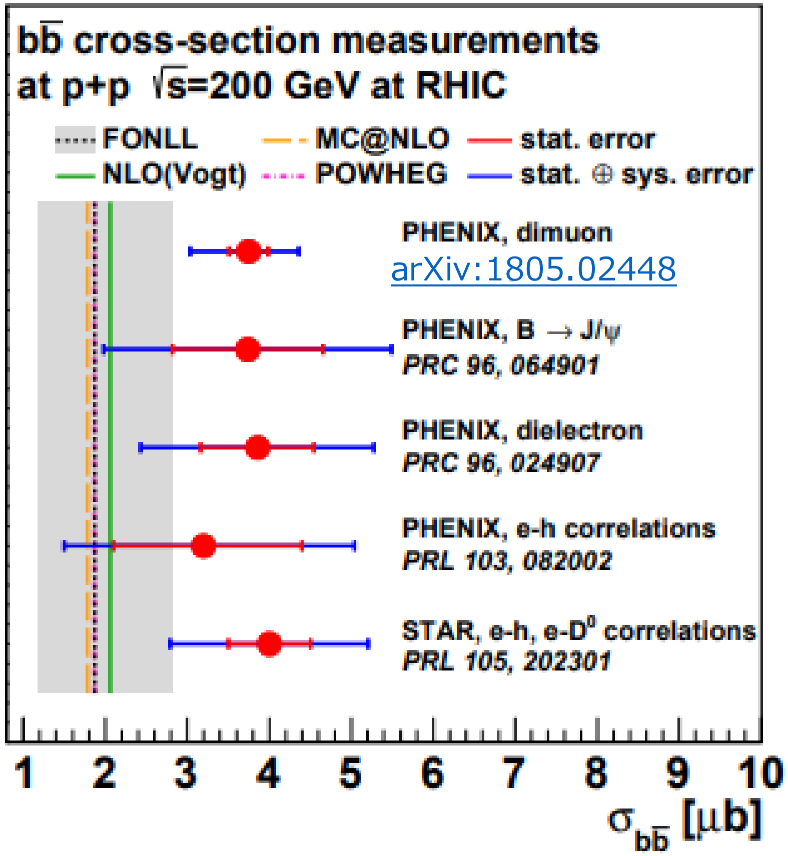
P+P Baseline measurements

D^0/D^*



- Charm production is well reproduced by FONLL

bottom production

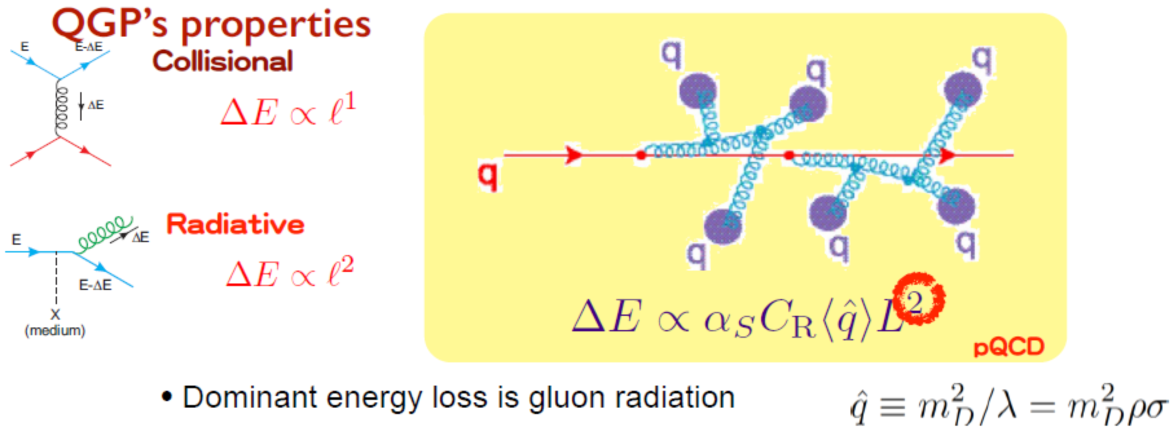


- Bottom production is higher than theories but consistent within error

Heavy flavor as a useful probe

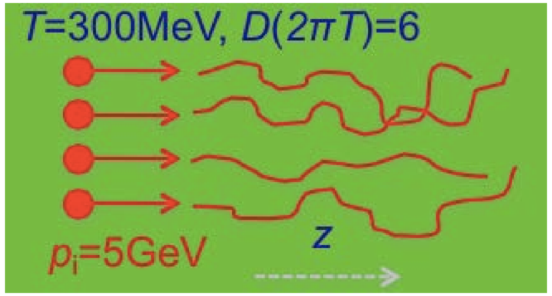
- Properties of QGP
  - R_{AA}: Energy loss, q-hat & L dependence of Eloss at high pT

    Collisional vs Radiative ?

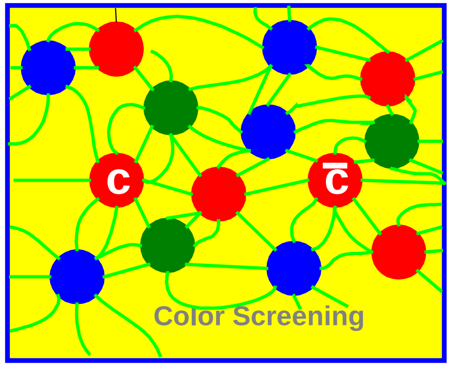


dE ~ l^3 (Ads/CFT)

- Flow (v_2) at low pT
  - Heavy quark is sensitive to an transport coefficient of QGP（～eta/s)

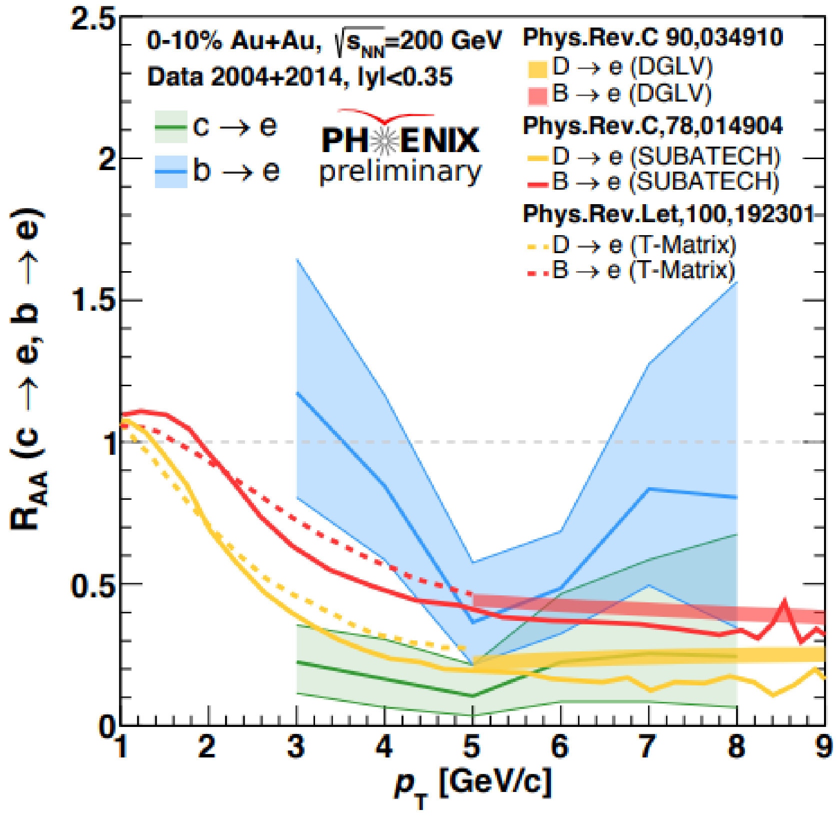


- Medium temperature
  - Quarkonia melting in QGP



Bottom R_{AA} in Au+Au and Cu+Au

b→e & c→e in 0-10% Au+Au



B → J/ψ in Cu + Au

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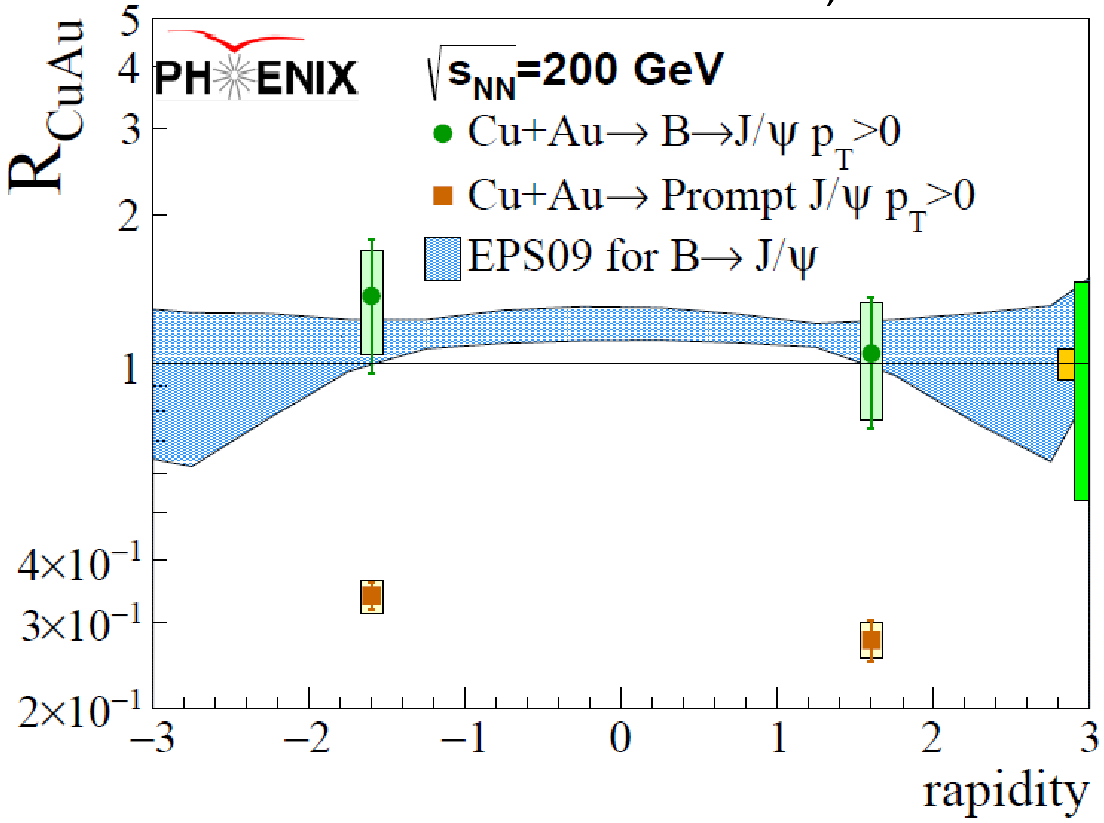
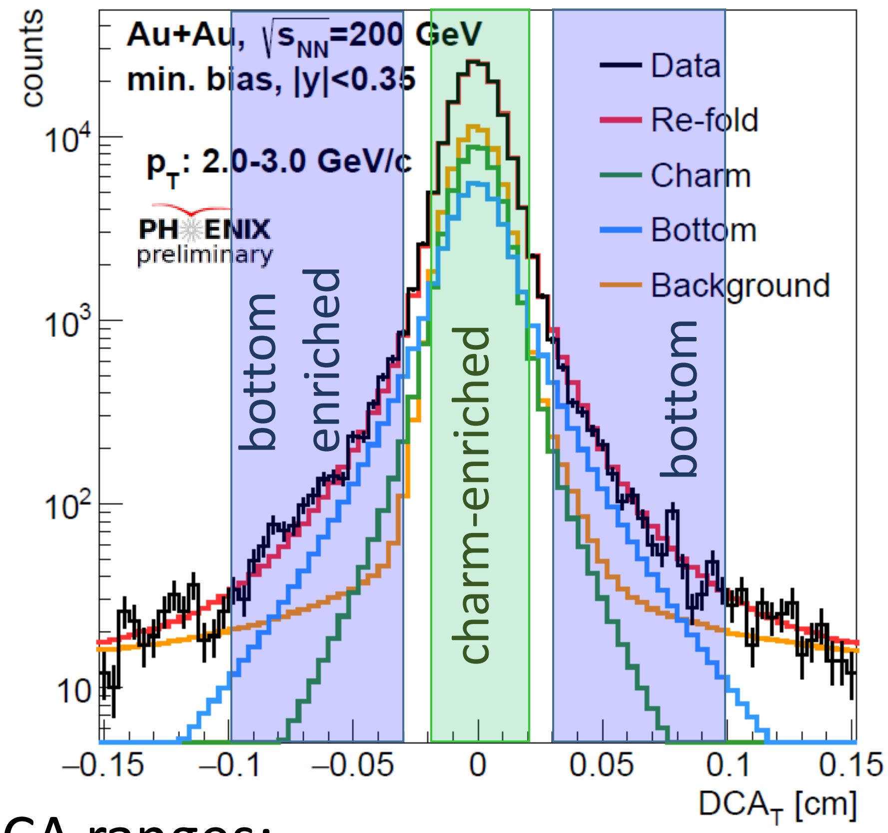
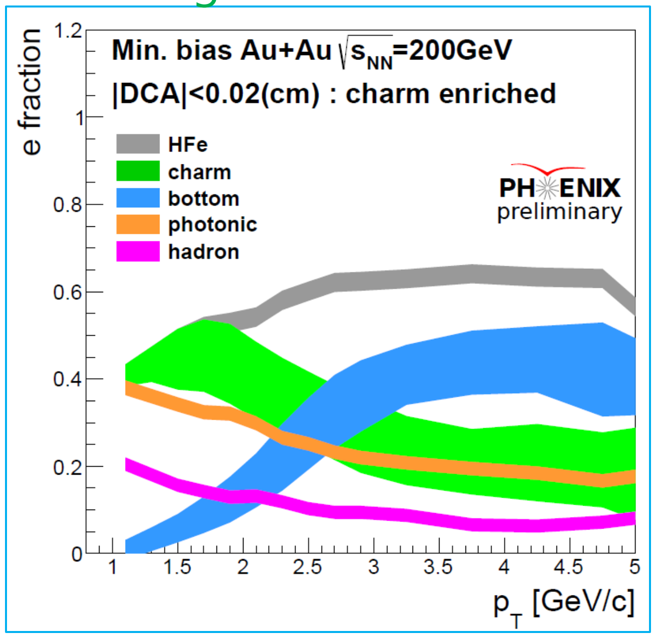


- In 0-10% Au+Au,
  - R_{AA}(b→e) ~ R_{AA}(c→e) in high pT
  - R_{AA}(b→e) < R_{AA}(c→e) in low pT
- In min. bias Cu+Au,
  - R_{AA}(B→J/ψ) ~ 1, N_{coll} scaling (& nPDF)
  - R_{AA}(J/ψ) <1

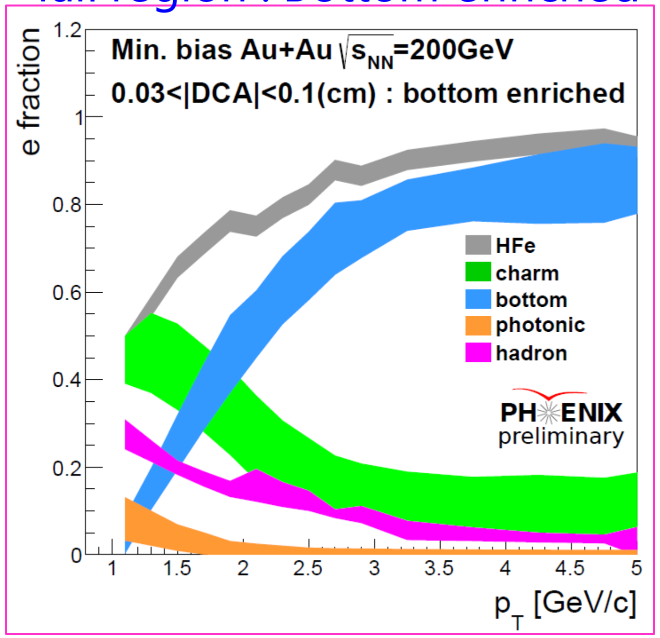
v_2 for c- and b- enriched DCA range



Peak region : Charm enriched



Tail region : Bottom enriched



DCA ranges:

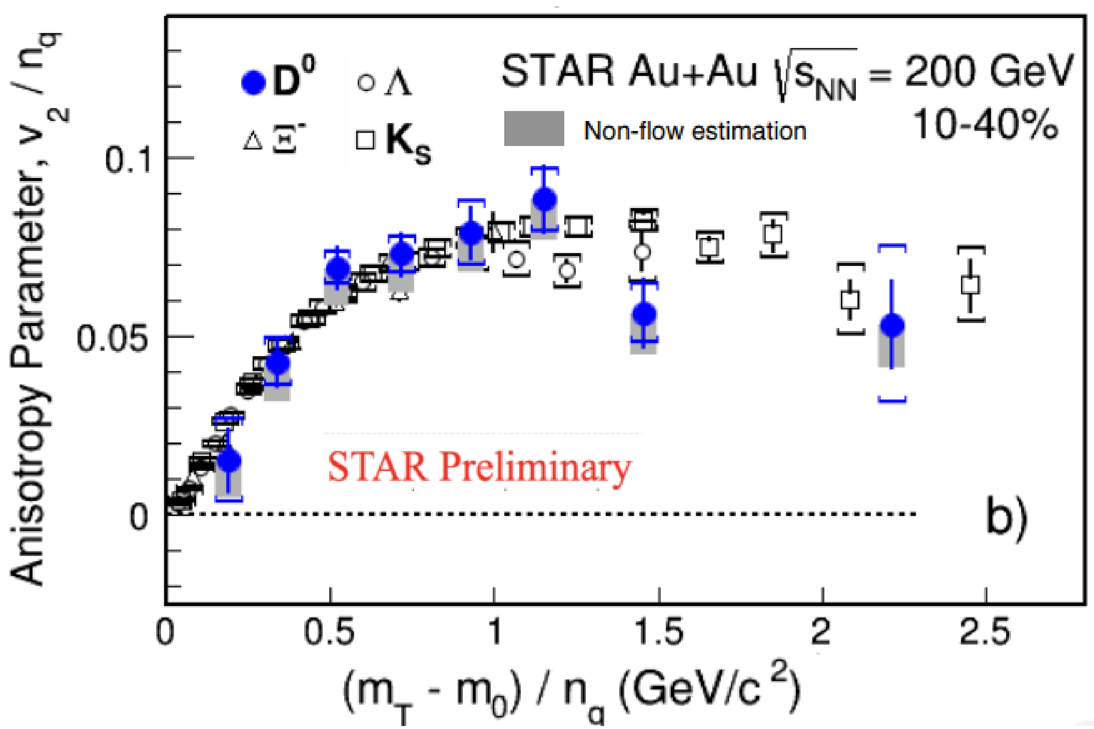
Peak : c-enriched : |DCA|<200um

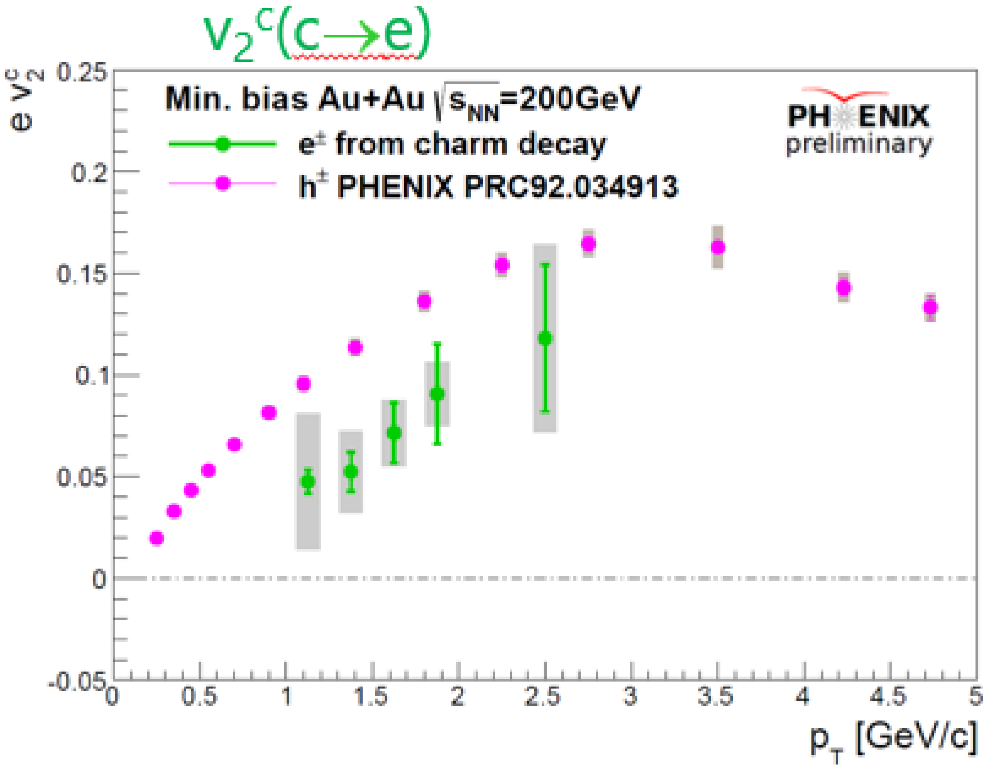
Tail : b-enriched : 300<|DCA|<1000um

$$\underbrace{\qquad\qquad\qquad}_{\mathrm{HFe}\cdot v_2^{HF}}$$

- $v_2^{inc}(0) = \mathrm{b}(0)\cdot v_2^b(b\to \mathrm{e}) + c(0)\cdot v_2^c(c\to \mathrm{e}) + \mathrm{bg}_0\cdot v_2^{\mathrm{bg}}$
- $v_2^{inc}(1) = \mathrm{b}(1)\cdot v_2^b(b\to \mathrm{e}) + c(1)\cdot v_2^c(c\to \mathrm{e}) + \mathrm{bg}_1\cdot v_2^{\mathrm{bg}}$
- Look at v_2 from these DCA range
  - If v_2^b is small, v_2(b-enriched) < v_2(c-enriched)

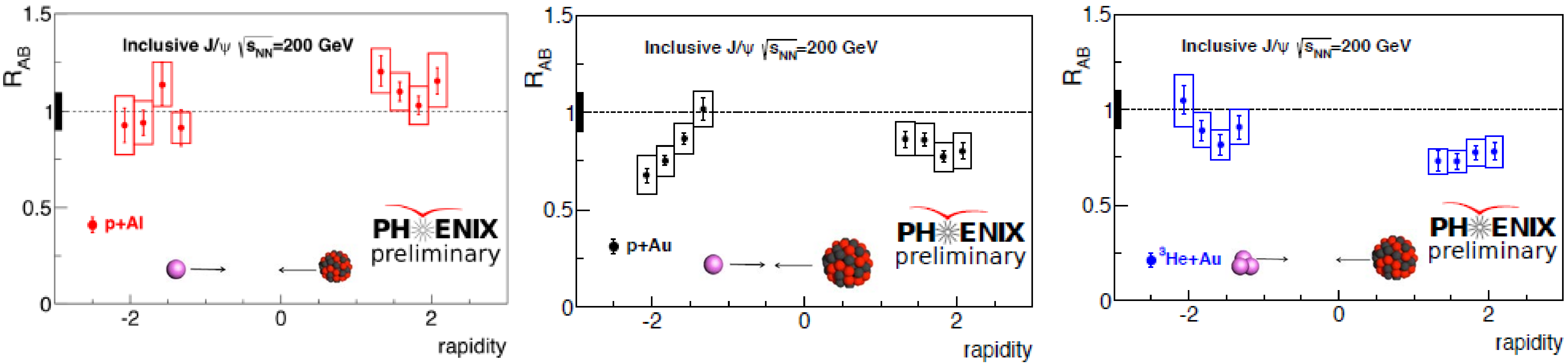
Charm Elliptic Flow in Au+Au





- Significant positive v2 for charm in D and D->e in Au+Au
- v2 (D & c->e) < v2 (light hadrons) at low pT
  - Similar at LHC
- Charm follows NCQ scaling. Suggests charm thermalization

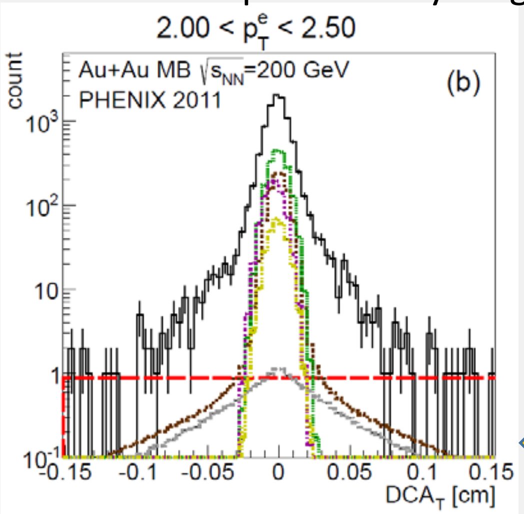
J/ψ : CNM effects in p+Al, p+Au, ^{3}He+Au



- Systematic study of CNM effects
- p/^{3}He going: consistent with nuclear shadowing
- Au going: suppression in p+Au. Final state effect?
  - Higher multiplicity for Au going

Strategy of bottom & charm separation

1. DCA distributions $1.5<p_T<5$
   - Utilize decay length ($c\tau$) of b & c
   - B^+ : 491.1 μm, D^+ : 311.8 μm,
   - DCA shape ∼ decay length



2. Previous HF electron yield $1< p_T < 9$(GeV/c)
   - Broad p_T range
   - Efficiency fully corrected
   - Constrain b & c yield

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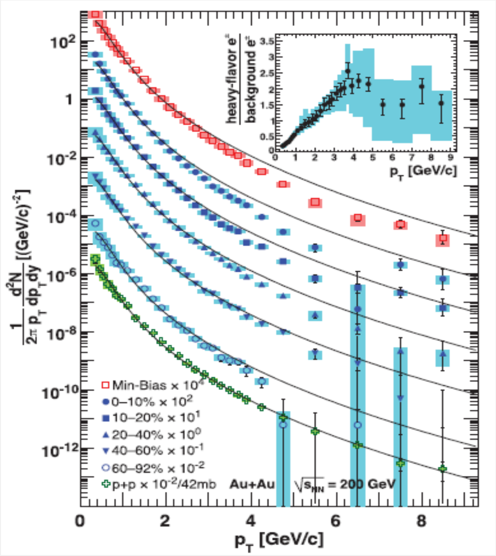


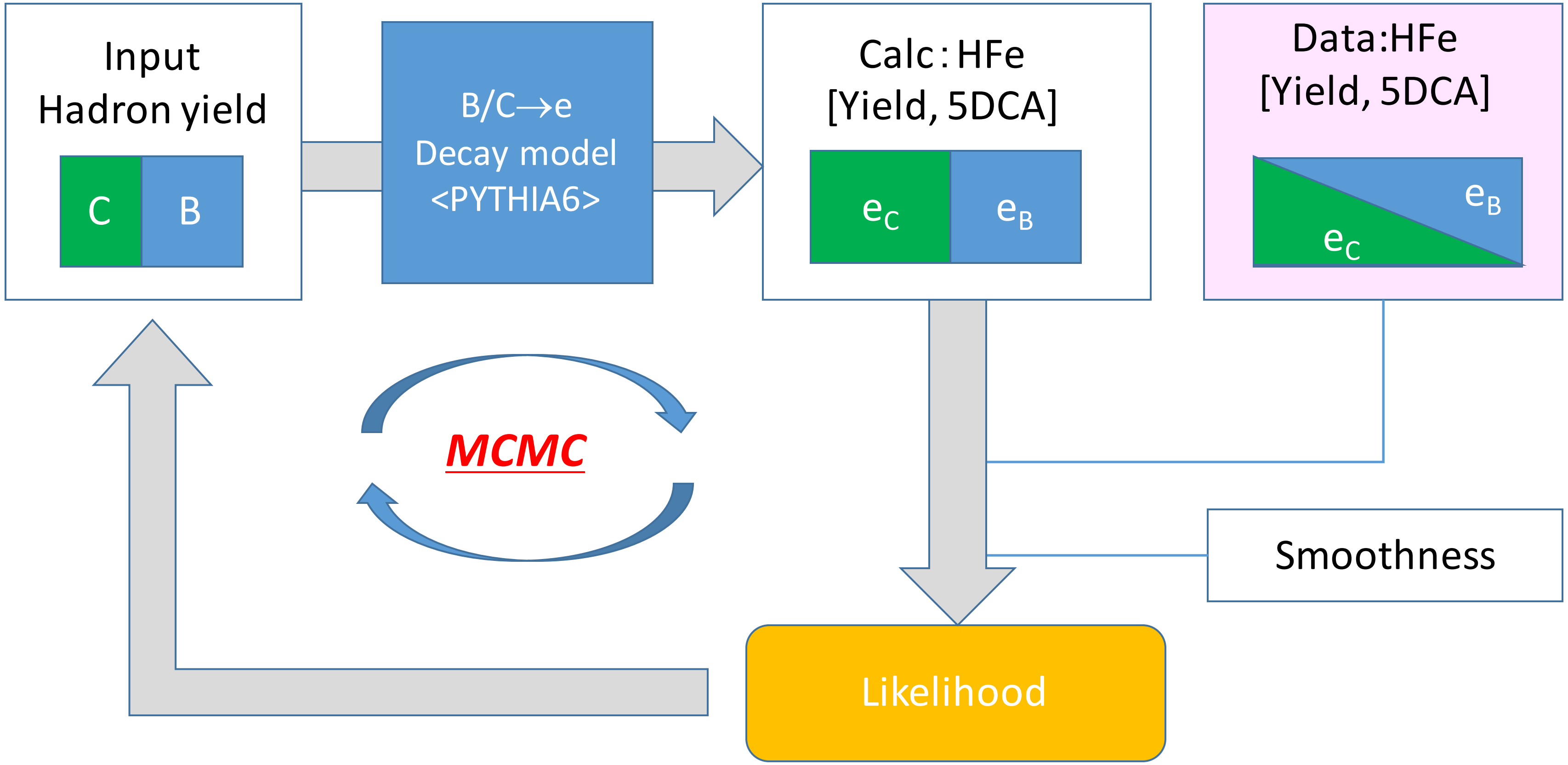
More constrain

- Unfold method performs a simultaneous fitting with electron DCA and invariant yield.

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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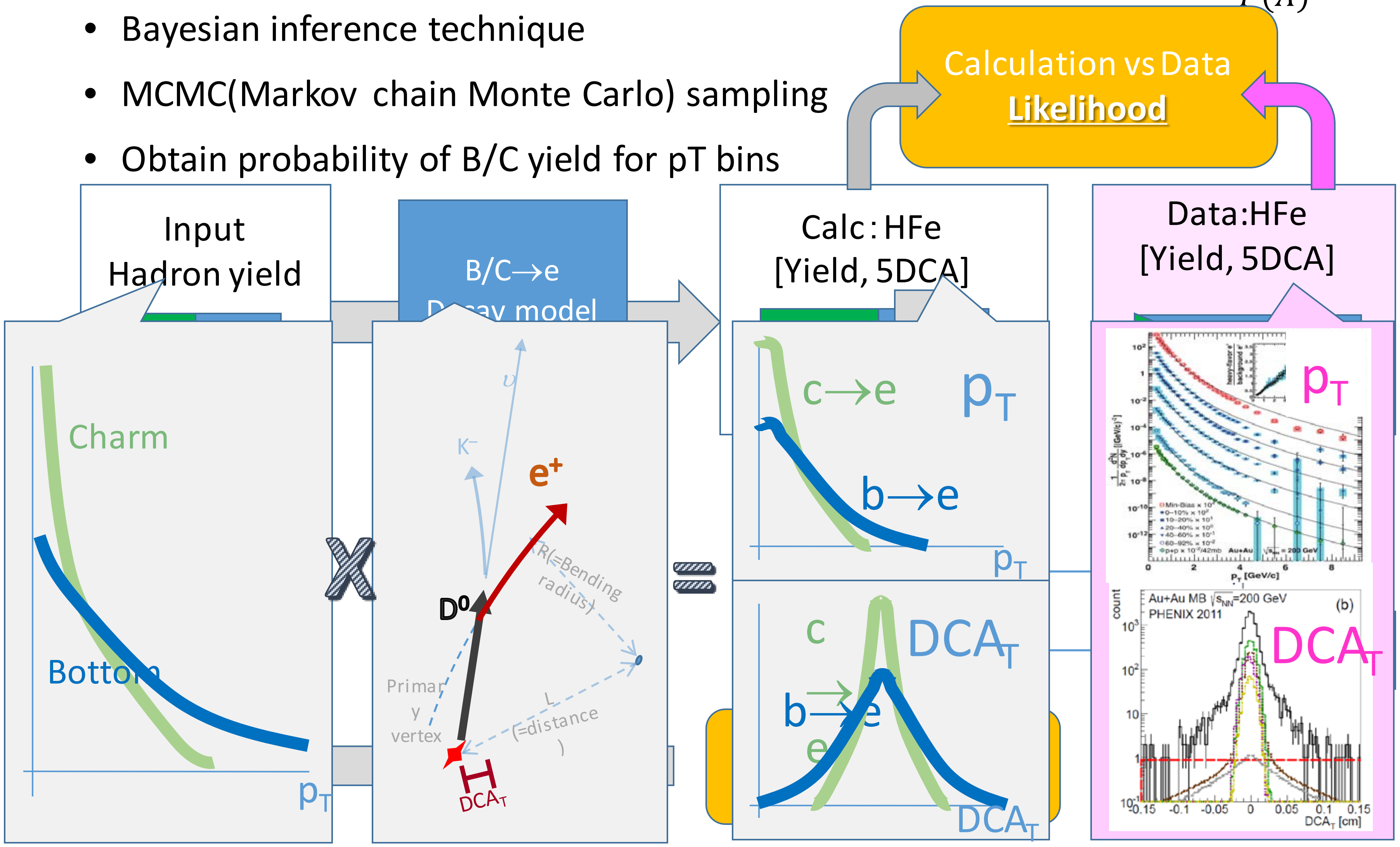
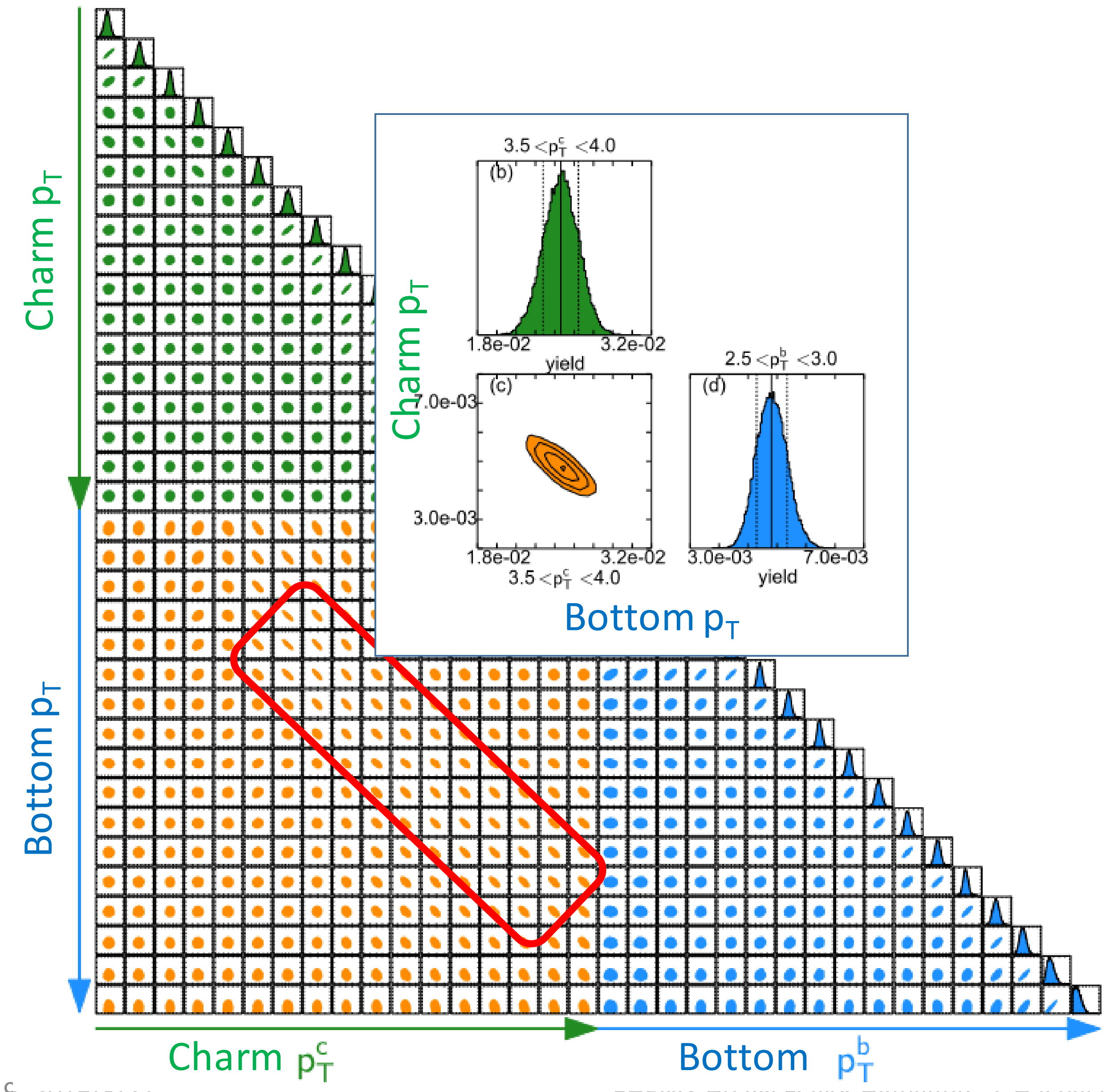


Full probability distribution



ɔbability distribution
ottom & charm yield

ıtion in yield

nd

no correlation

ıtive in charm near pT

increase simultaneously

ative

charm ↑ + bottom ↓