Brookhaven National Laboratory
20 years of RHIC
October 22-23, 2020 | Virtual RHIC/AGS Annual Users' Meeting
Topical workshops: October 22 | Plenary sessions: October 23

PHENIX
Heavy Flavor Overview

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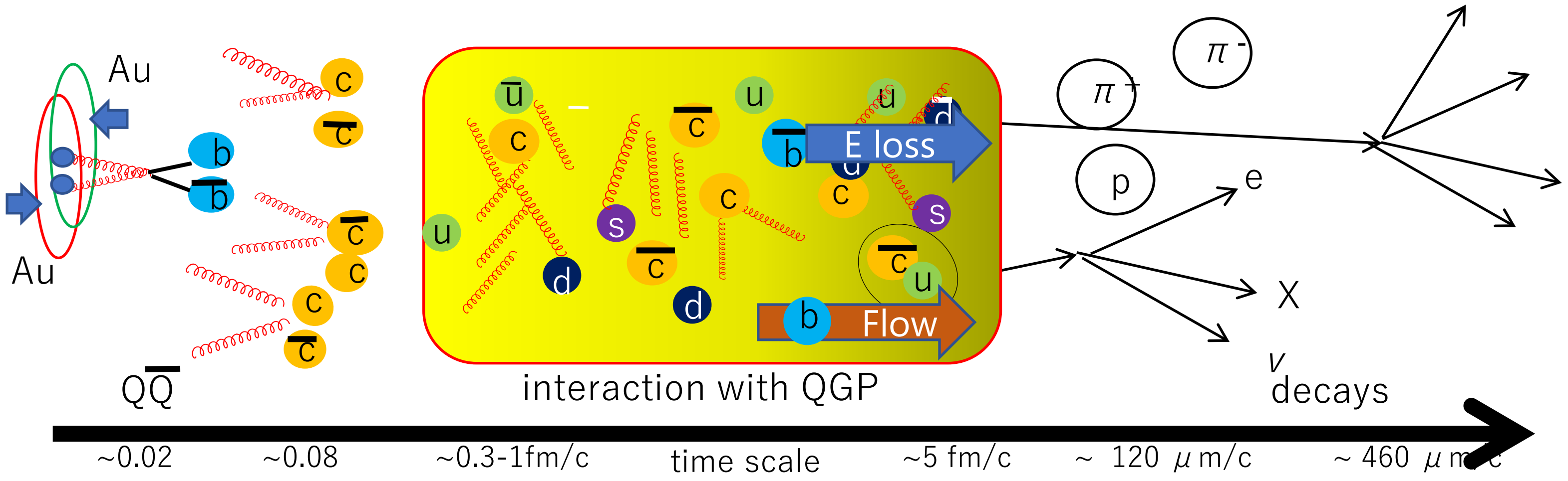
for the PHENIX collaboration

Heavy Flavor as a QGP probe

- Heavy quark is mainly produced via initial hard scattering
  - $m_b > m_c > \Lambda_{QCD}, T_{QGP}$
    4.5GeV 1.2GeV 0.2 GeV

Production can be calculated by pQCD



- Heavy quark carries the QGP information when passing through QGP
  - Energy loss and flow effects
  - Quarkonia would be melted

p_T and angular distributions can be modified in QGP

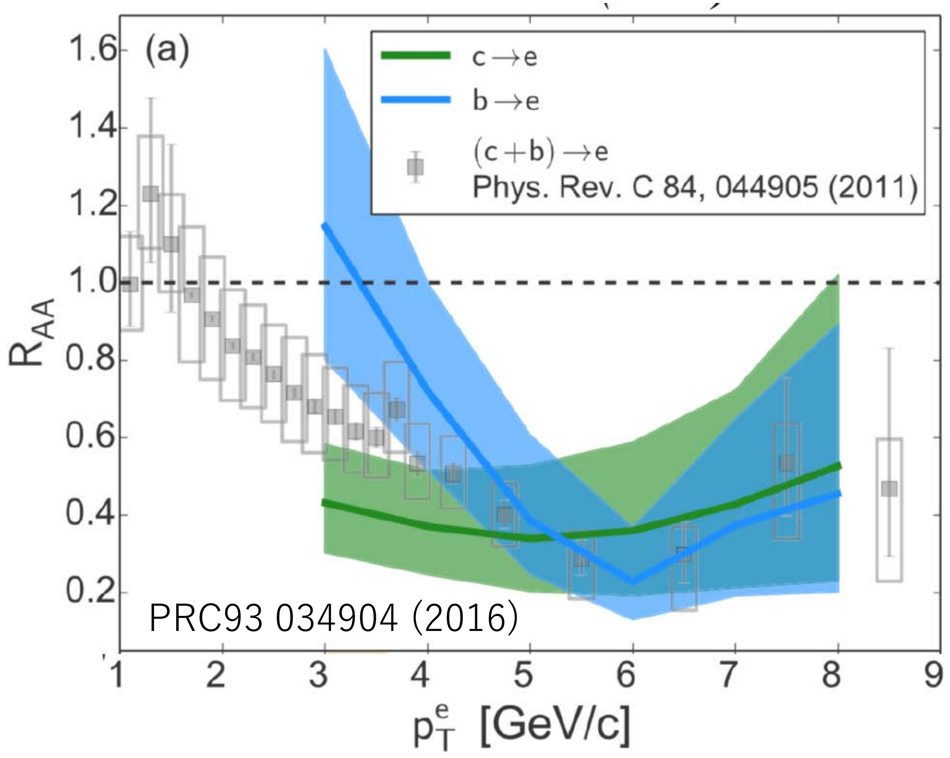
Open bottom and charm, and quarkonia are important probes to QGP

Bottom and Charm suppression in Au+Au

- Electrons from bottom and charm decays
- High pT
  - R_{AA} : Bottom ~ Charm (p_T>5GeV/c)
  - Radiative loss dominant
- Low~Mid pT
  - R_{AA} : Bottom > Charm (p_T<5GeV/c)
  - Collisional loss dominant
- Expected quark mass dependence
  - $\Delta E_b < \Delta E_c < \Delta E_q < \Delta E_g$

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

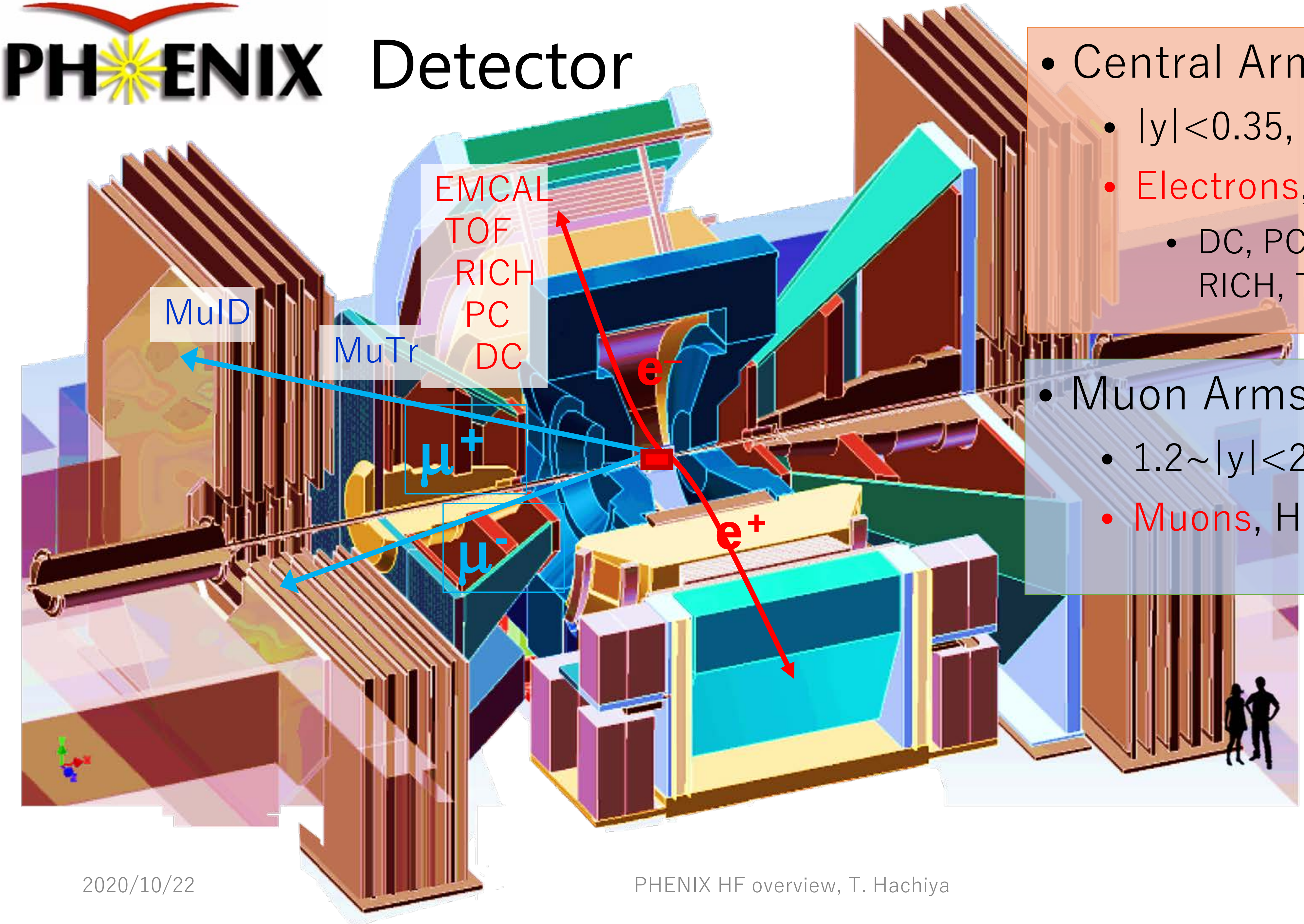
Au+Au in 2011



Further investigation to extract transport properties of QGP

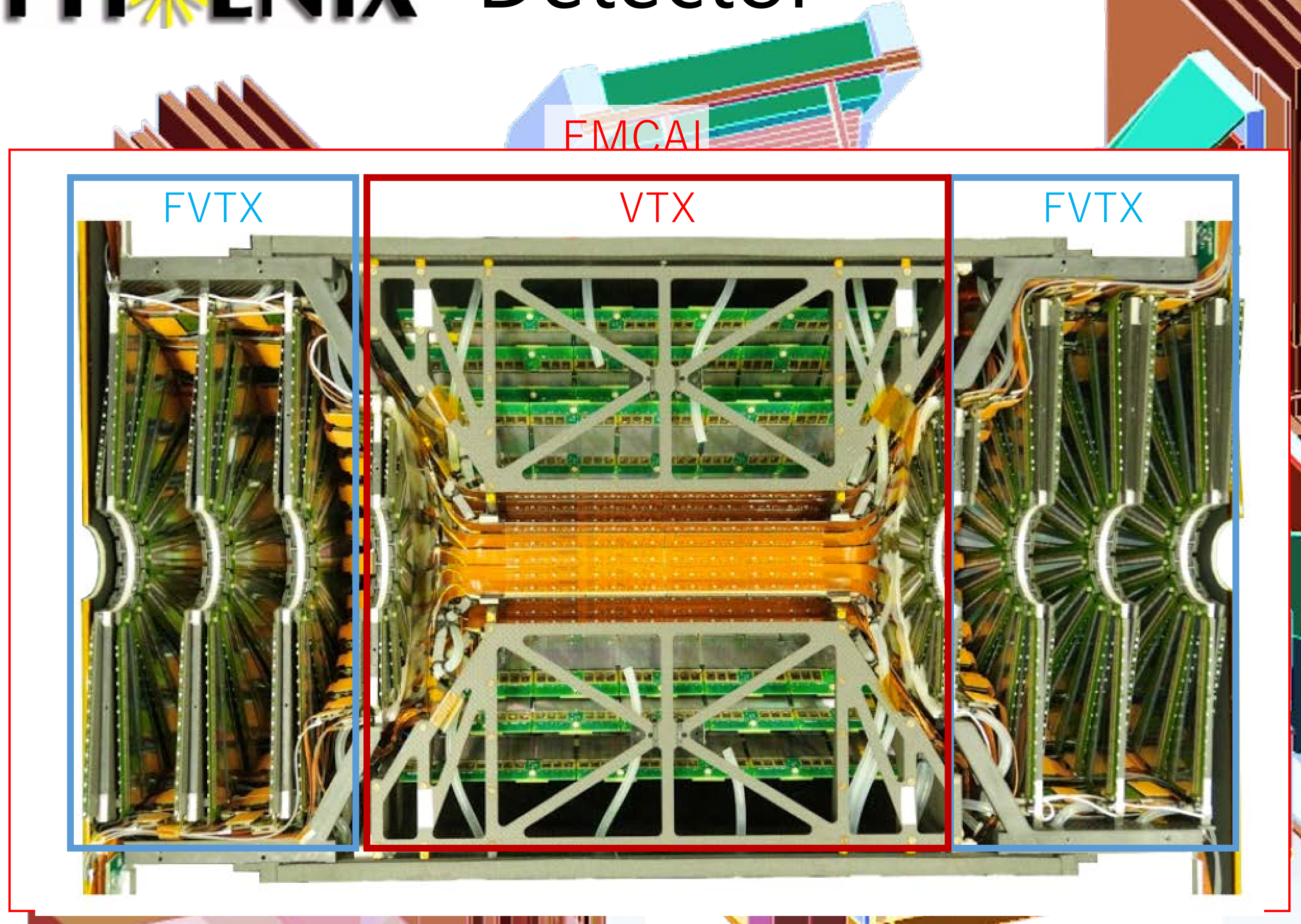
R_{AA} and v_2 of bottom and charm precisely

PHENIX Detector



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

PHENIX Detector



- Central Arms
  - |y|<0.35, ϕ~2·π/2
  - Electrons, γ, hadrons
    - DC, PC, RICH, TOF, EMCAL
- Muon Arms
  - 1.2~|y|<2.2, ϕ~2·π/2
  - Muons, Hadrons
- VTX + FVTX
  - |y|<1.1, ϕ~2π
  - Precise displaced tracking
  - Primary vertex

Open heavy flavor in p+p

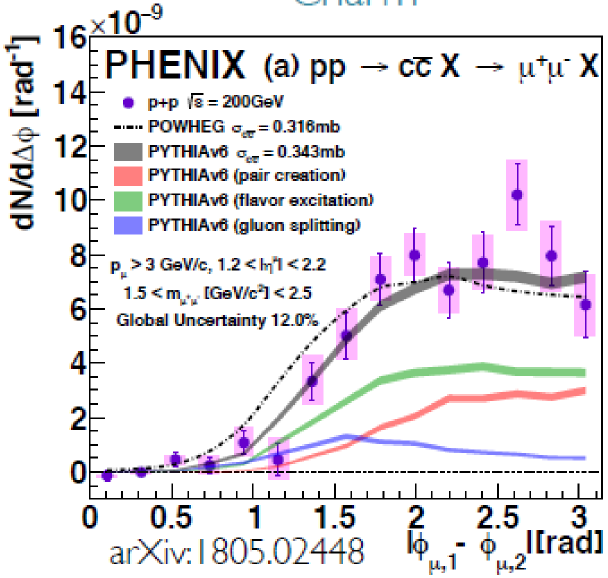
Baseline measurement

Understanding the production mechanism

p+p 200GeV

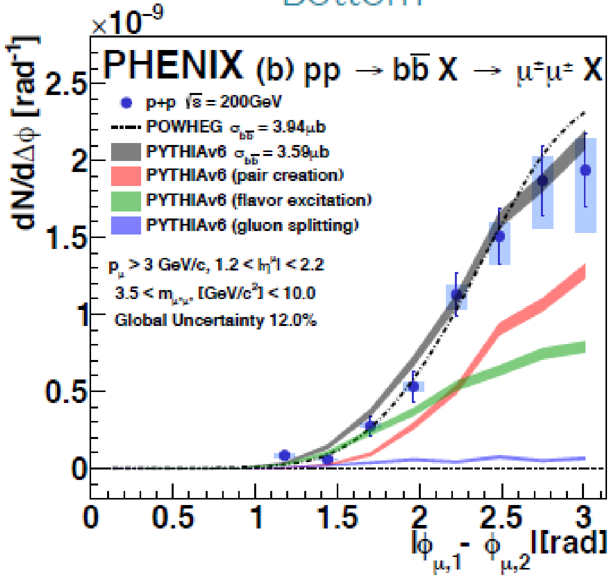
PRD 99, 072003 (2019)

Charm



arXiv:1805.02448

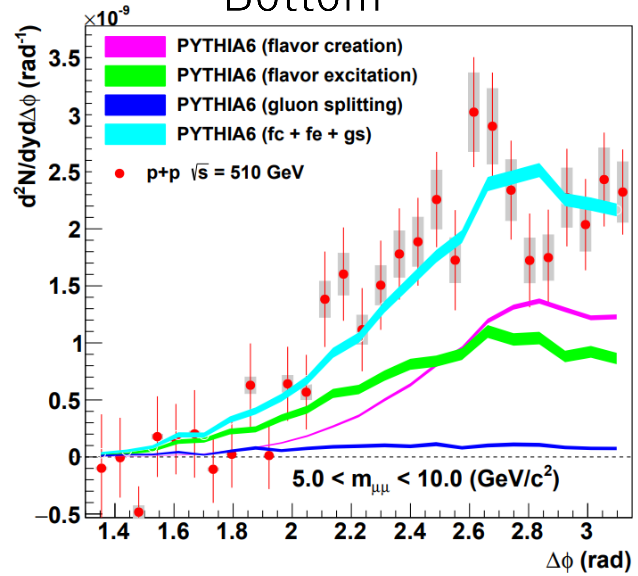
Bottom

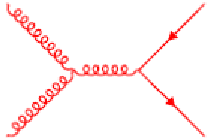


p+p 510GeV

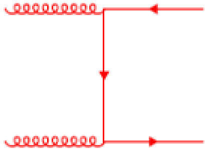
arXiv:2005.14276

Bottom



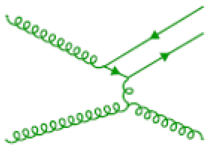


(a) s-channel Flavor Creation



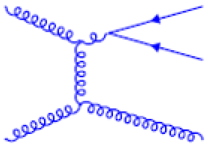
(b) t-channel Flavor Creation

back to back



(c) Flavor Excitation

intermediate



(d) Gluon Splitting

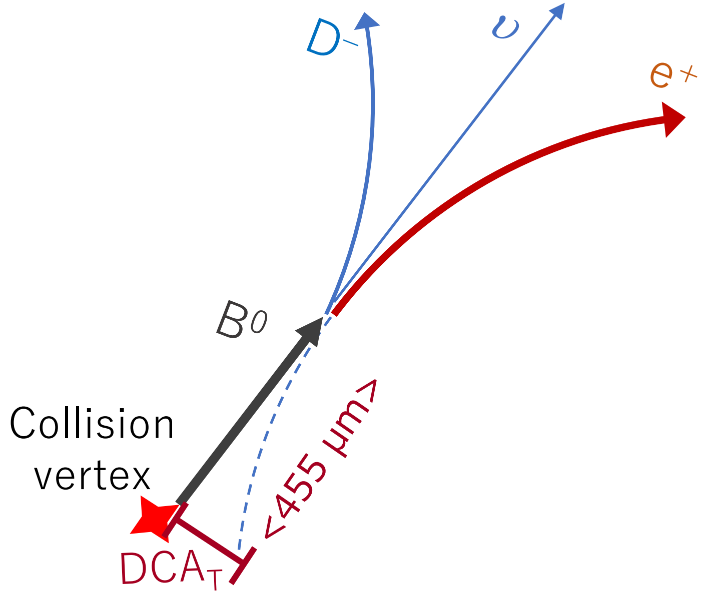
Round shape

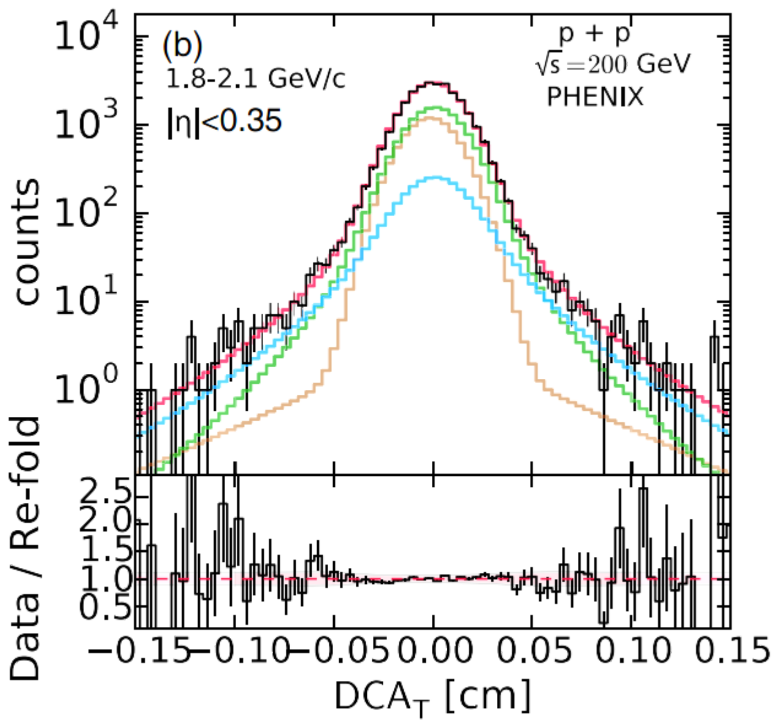
Production mechanism

- Charm : Flavor excitation
- Bottom : Pair creation
  - + flavor excitation @ 510 GeV

- Bottom is simple and sensitive to initial gluon dynamics at RHIC
- Gluon splitting is expected to be dominant at LHC

Electrons from bottom and charm decays



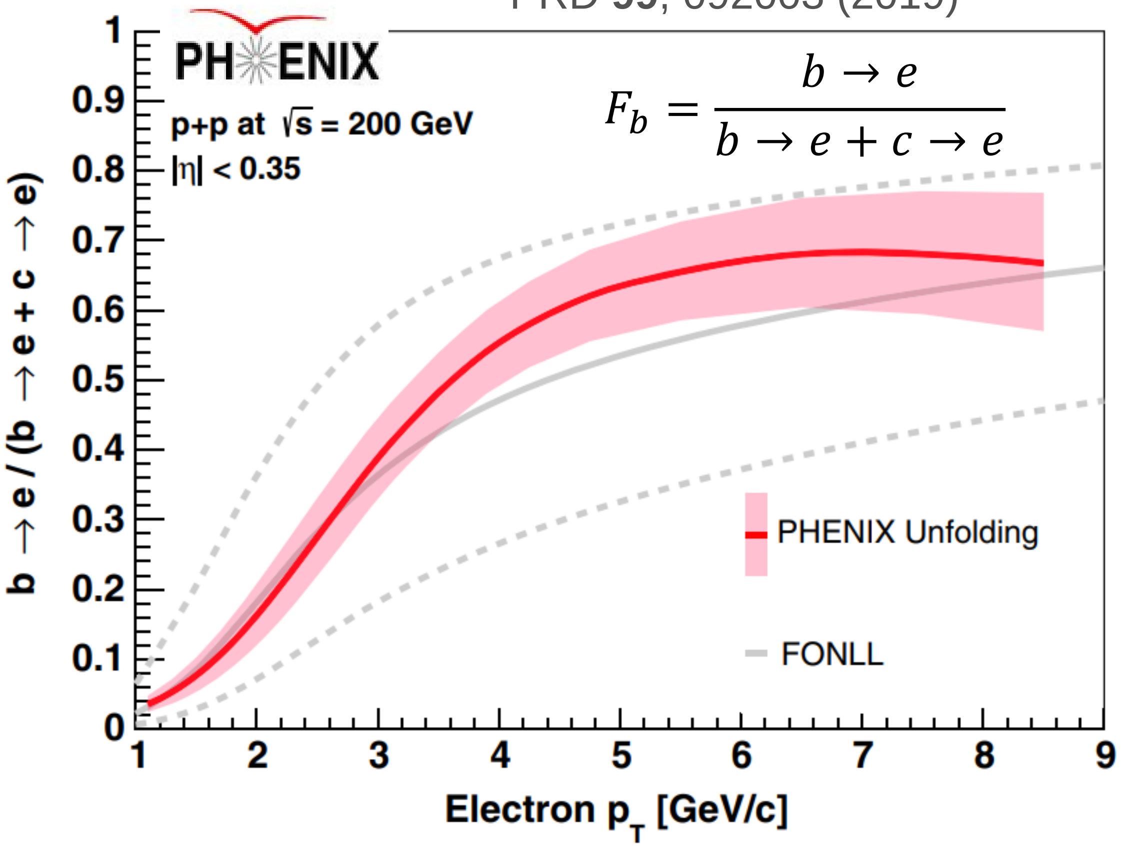


- Electrons from semi-leptonic decay of bottom and charm hadrons
- Utilize decay length to separate b and c
  - B^0 : 455 μm, D^0 : 123 μm
- VTX enables distance of closest approach, DCA,
  - DCA resolution ~ 60μm

- b→e and c→e is separated using DCA and yield distributions with the unfolding method
  - Bayesian inference technique
- b→e and c→e DCA shape reproduce data well

p+p Baseline : Bottom Electron Fraction

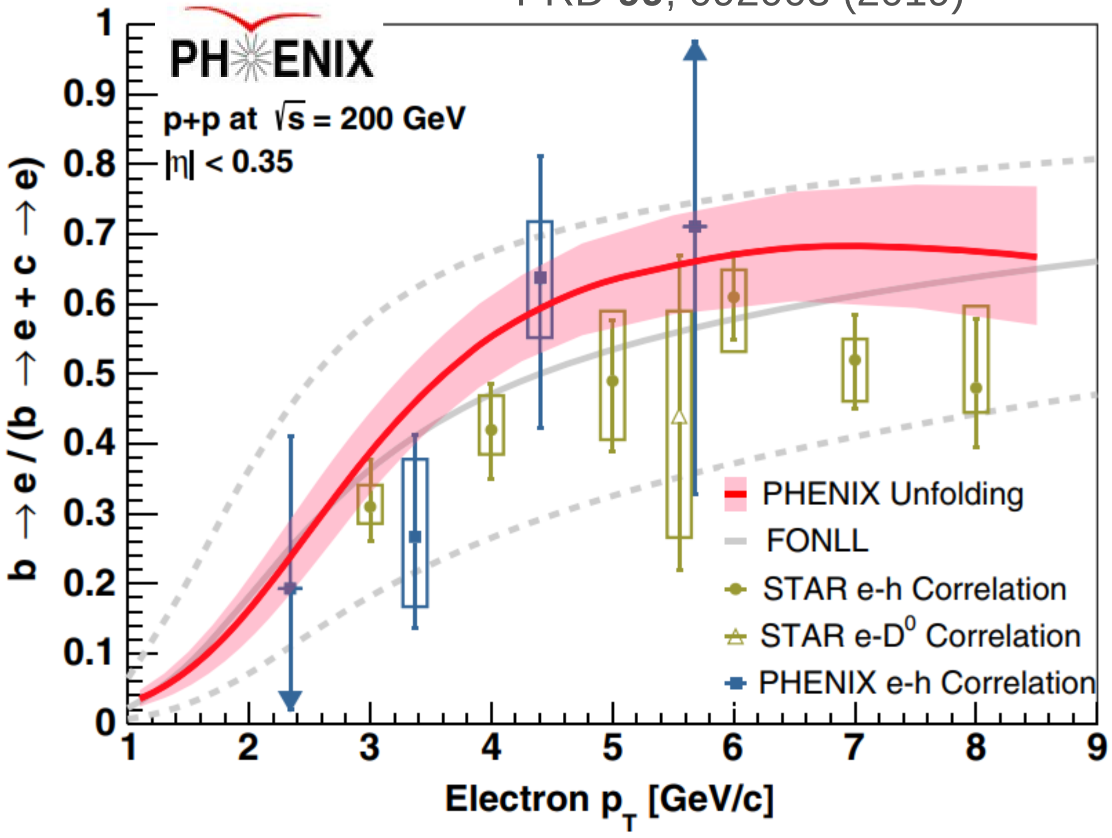
PRD **99**, 092003 (2019)



- FONLL is consistent with data

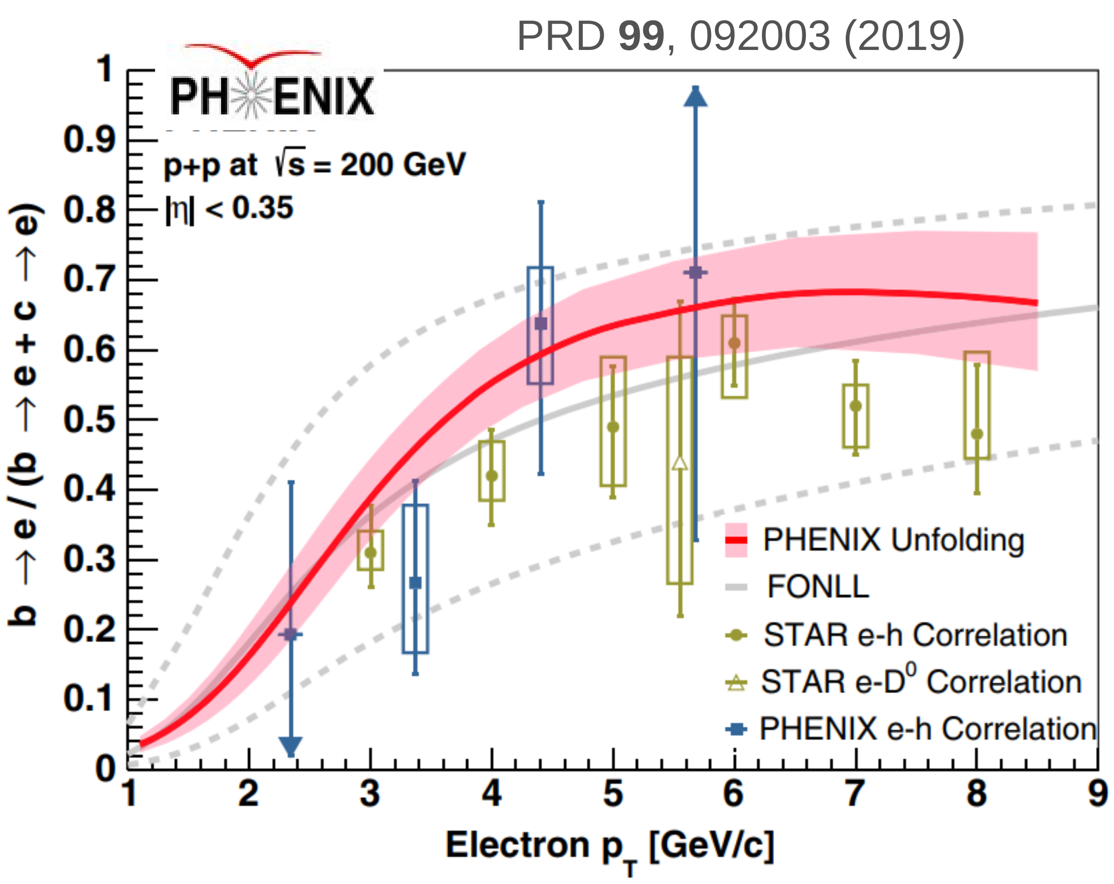
p+p Baseline : Bottom Electron Fraction

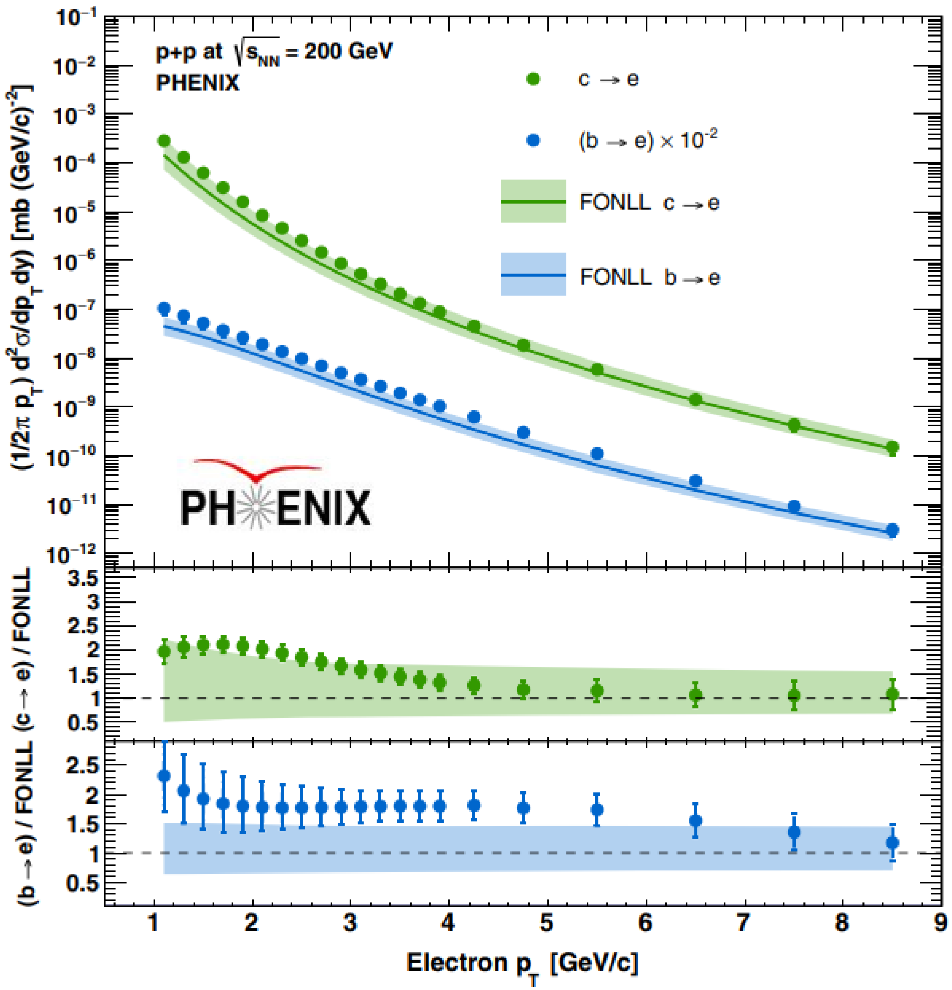
PRD **99**, 092003 (2019)



- FONLL is consistent with data
- New data shows significantly small uncertainty
  - consistent with previous results

p+p Baseline : Bottom Electron Fraction





- New P+P Baseline of bottoms and charms available w/ 1~9GeV/c in p_T
  - HF electrons, μ for mid- & forward rapidity

Open heavy flavor in Au+Au

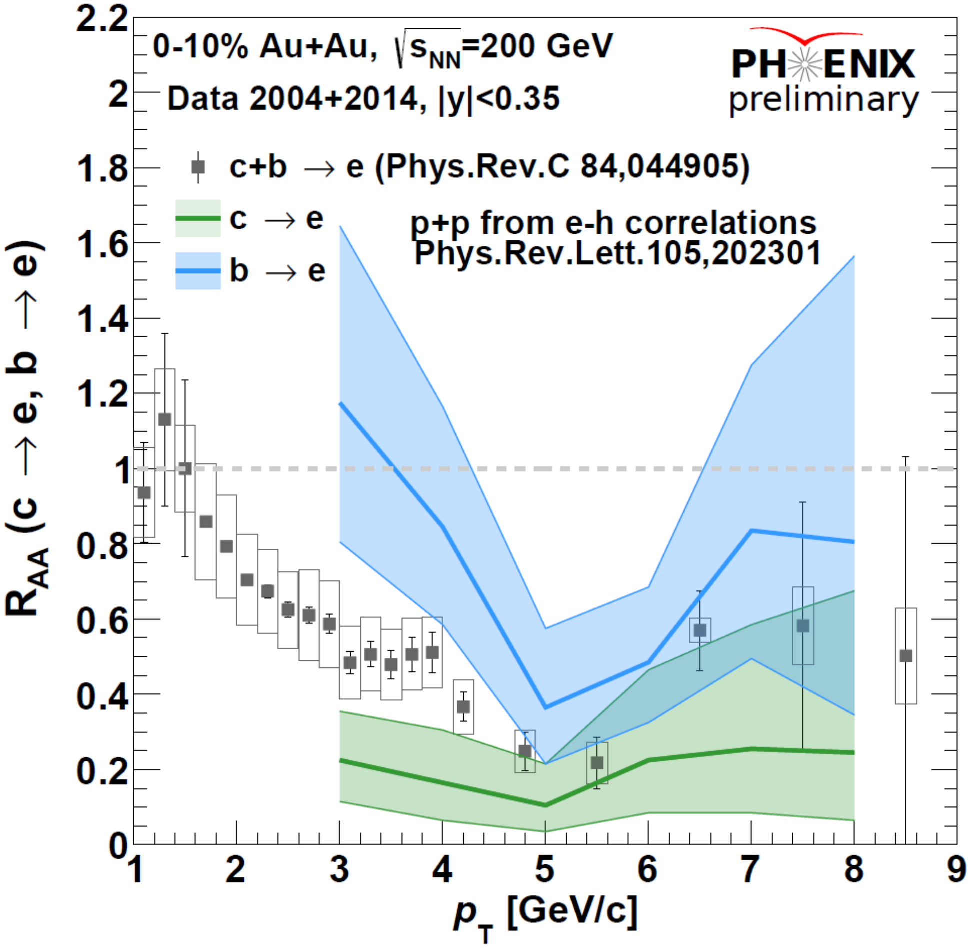
Suppressions & Flows

Centrality Dependence

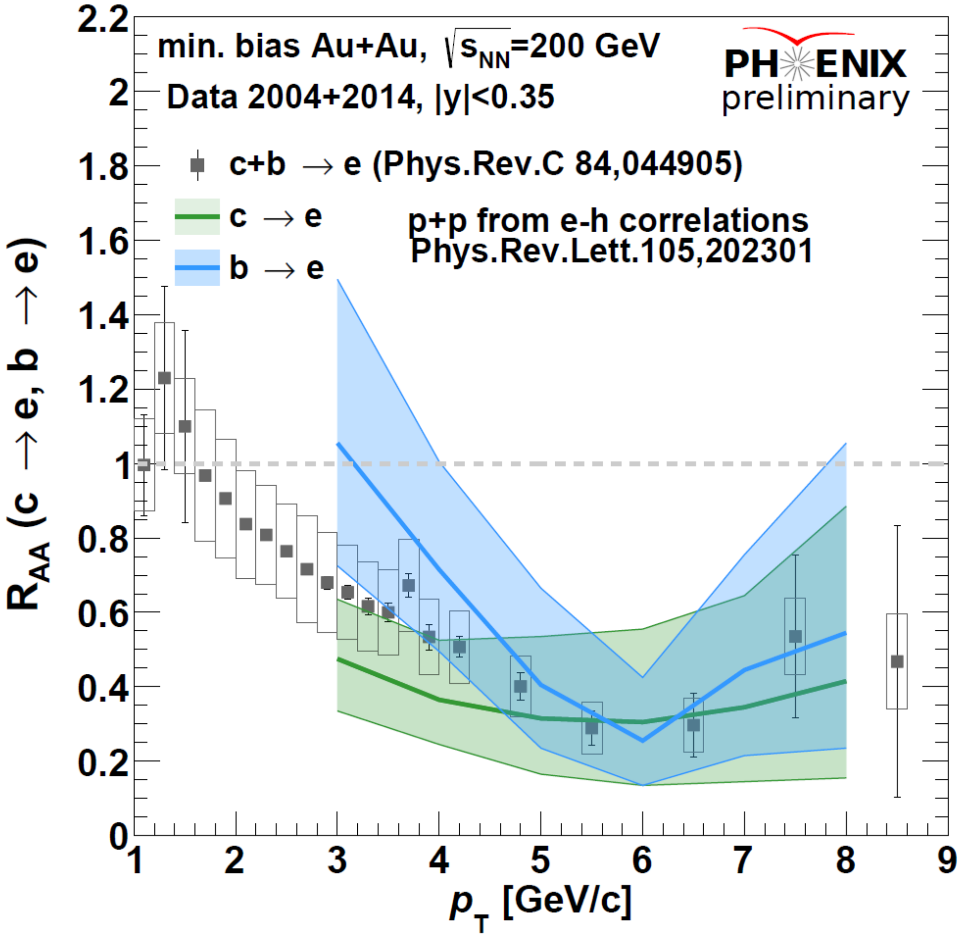
3 times more data in Run14 than in Run11

New p+p baseline is not used

0-10% Au+Au



Min. Bias

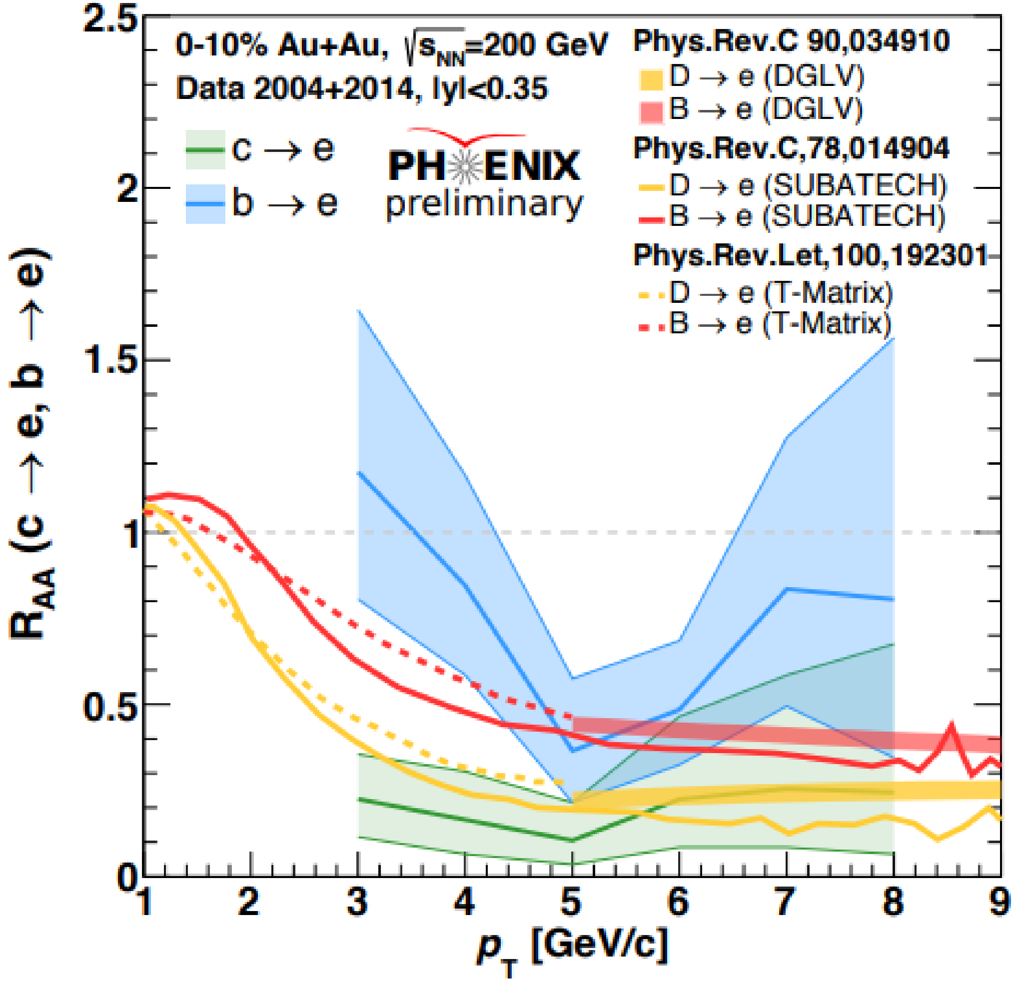


- R_{AA}(b→e) ~ R_{AA}(c→e) at high p_T
- R_{AA}(b→e) > R_{AA}(c→e) at low p_T

R_{AA}(c→e) 0-10% < Min. Bias

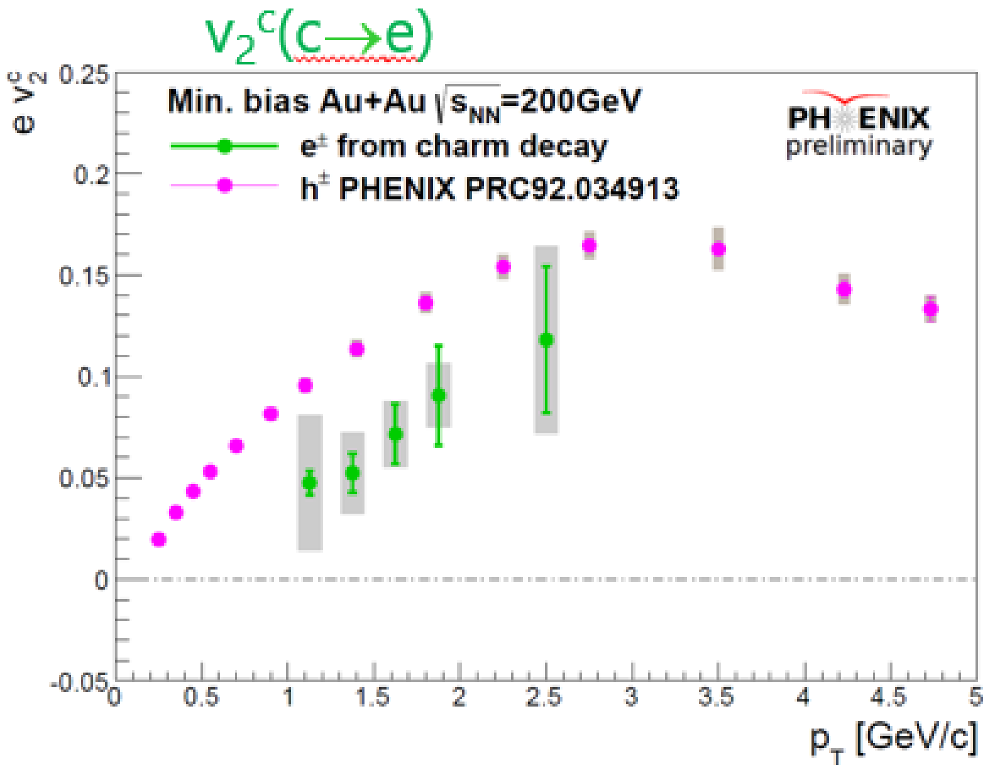
Model comparisons

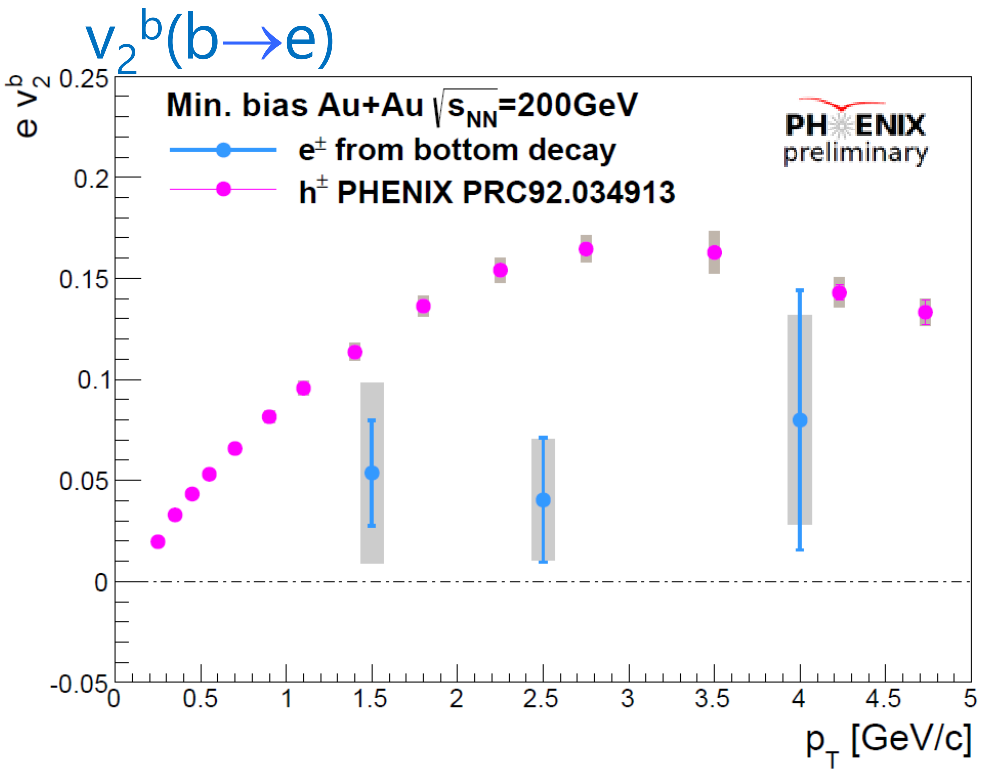
b→e & c→e in 0-10%



- Compared with 3 models
  - T-Matrix + diffusion (2πTD=4)
    → Strongly coupled QGP
  - SUBATECH: E-loss + running coupling
  - DGLV: E-loss + plasma w/ static potentials
- Precise measurement is necessary to distinguish these models
- The result will be updated using new p+p baseline and full 2014 + 2016 Au+Au dataset (36 billion)
  - Extend to low p_T
  - Centrality dependence

Charm and Bottom Elliptic Flow

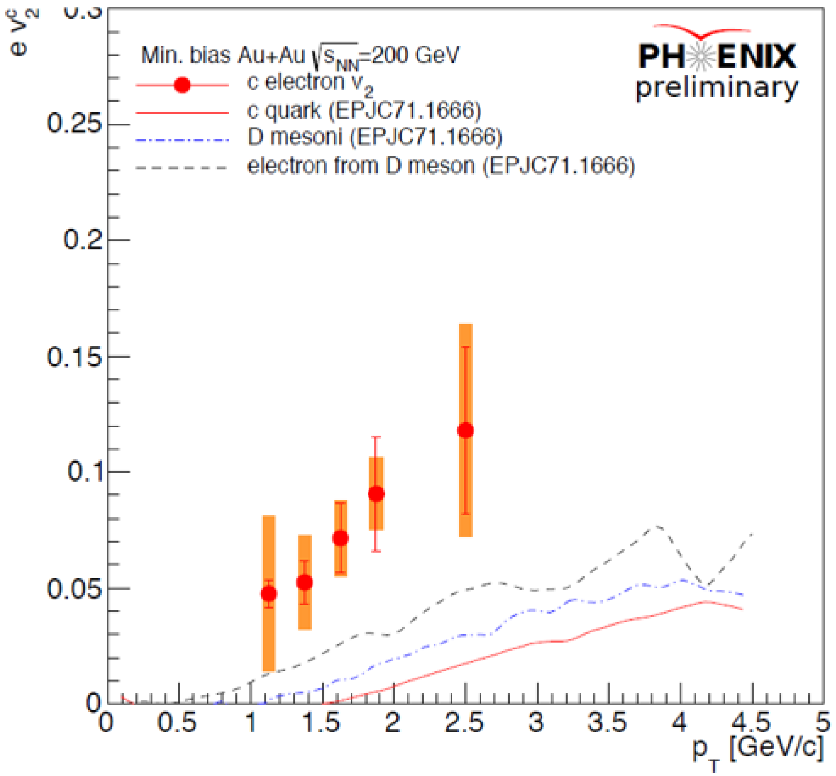


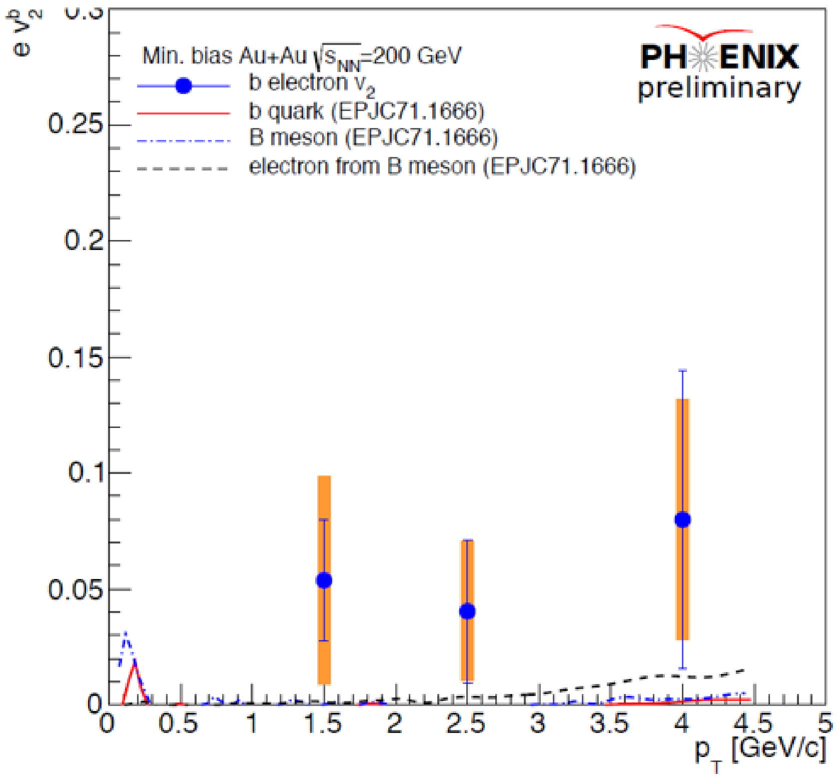


- Bottom and charm v_2 successfully extracted at low p_T
- Positive charm $v_2^c(c \to e)$
- Hint for finite bottom $v_2^b(b \to e)$
    - also consistent w/ zero

Likely to be $v_2(b\to e) < v_2(c\to e)$

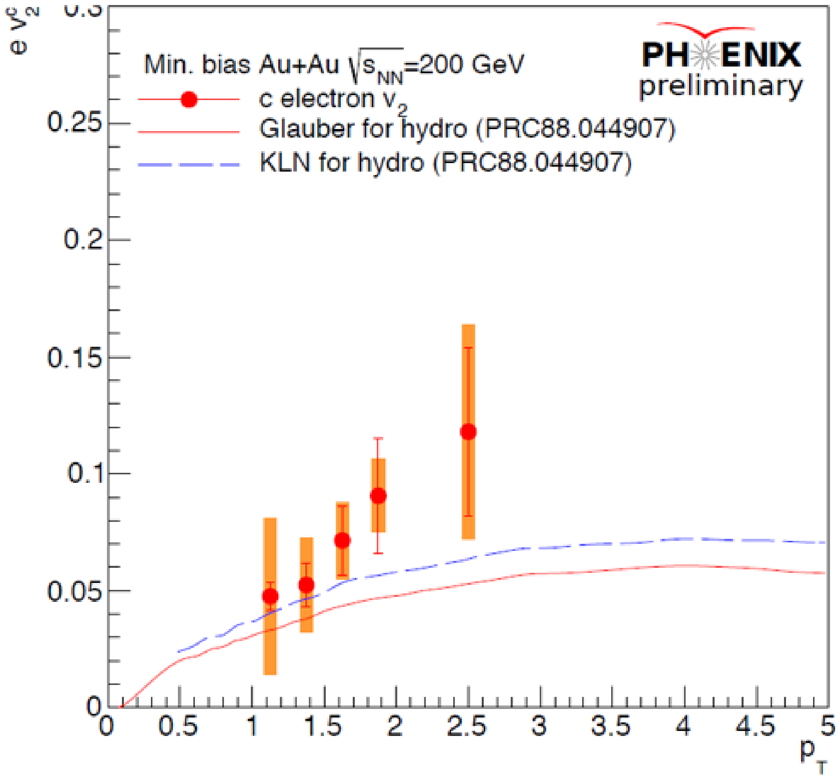
Model comparisons

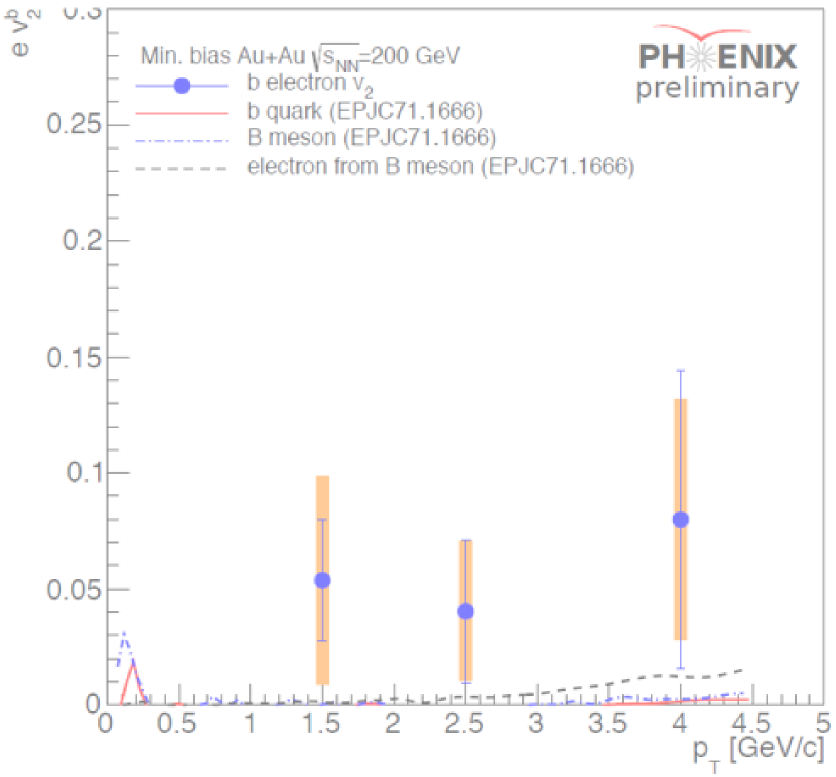




- Hydro without coalescence underestimate charm and bottom v_2
  - Langevin + viscous hydro

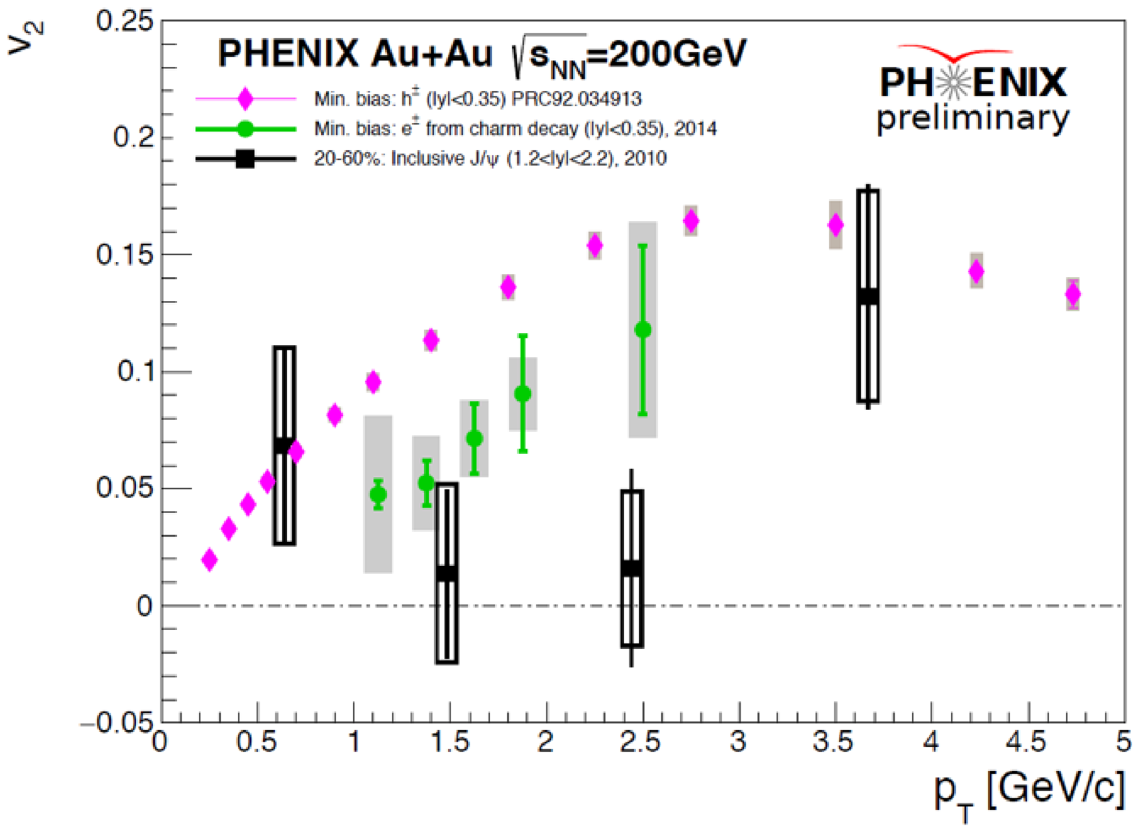
Model comparison





- Hydro without coalescence underestimate charm and bottom v_2
- Hydro with coalescence shows similar trend of charm v_2
  - Light quarks drags charms in coalescence

Charm vs J/ψ v_2



J/ψ : 1.2<|y|<2.2 ($\mu\mu$)

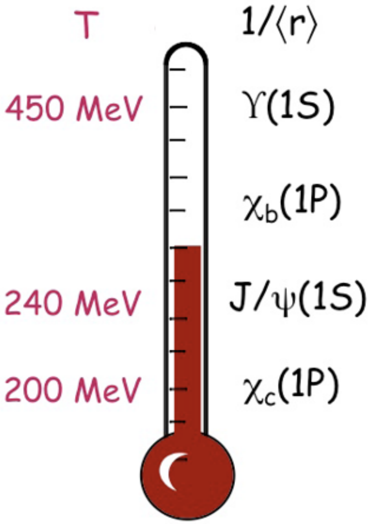
Charm : |y| < 0.35

- J/ψ v_2: non-zero with 1.1 σ
- Charm v_2 (c->e) > J/ψ v_2 with 0.7 σ at mid-p_T
- Consistent with the scenario
    - Light quarks drags charms in coalescence

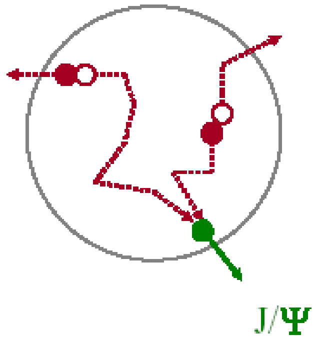
Quarkonia in small system

Quarkonia as QGP probe

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



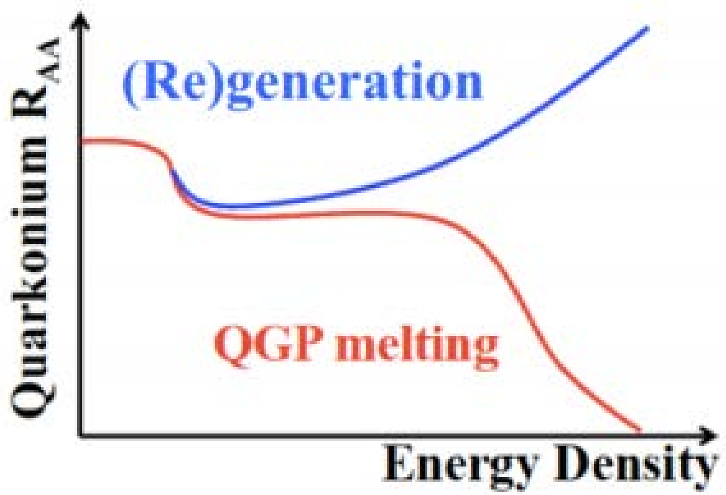
- Quarkonia can be melted in QGP due to Debye color screening
- Sequential melting of bound states should be seen
  - QGP thermometer!



Recombine non-initial pair of HQ

Not simple…

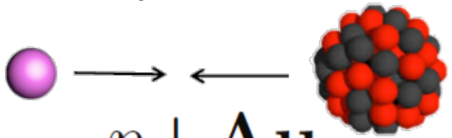
- Cold nuclear matter effects (CNM)
  - Initial state: shadowing(nPDF), k_T broadening
  - Final state : absorption, co-movers
- Regeneration/Recombination (not negligible)
  - Significant at LHC



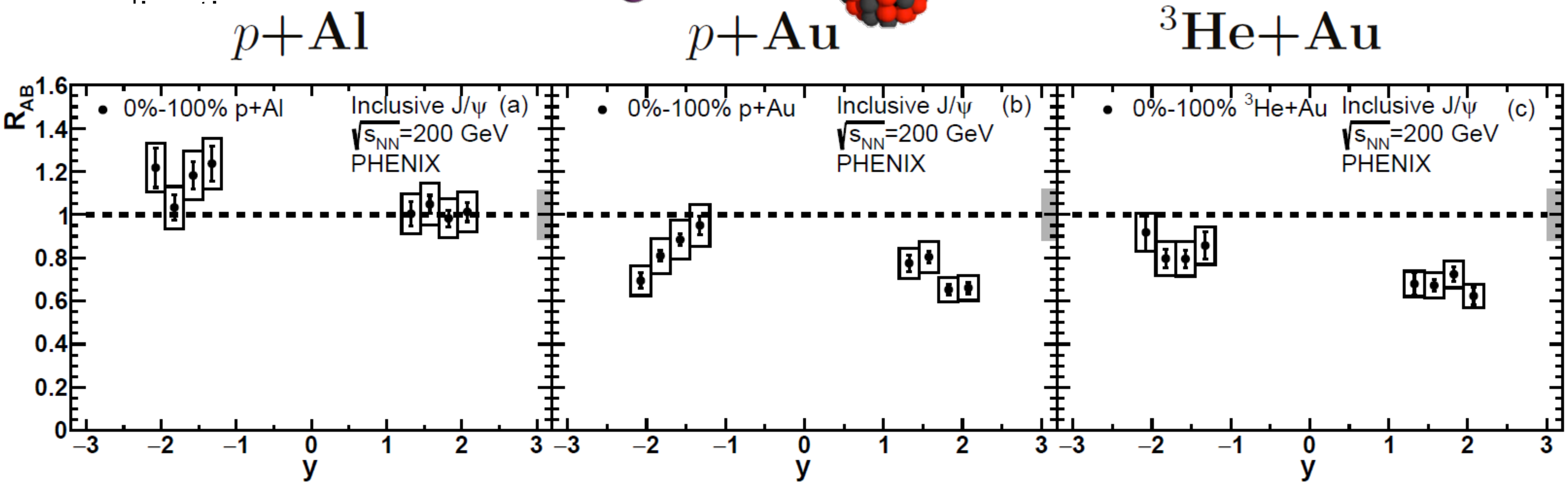
- CNM effect is key to quantify quarkonia melting in A+A
  - Systematic study of CNM effect by changing nuclear thickness with p+Al, and p/d/^{3}He+Au

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

Al/Au-going



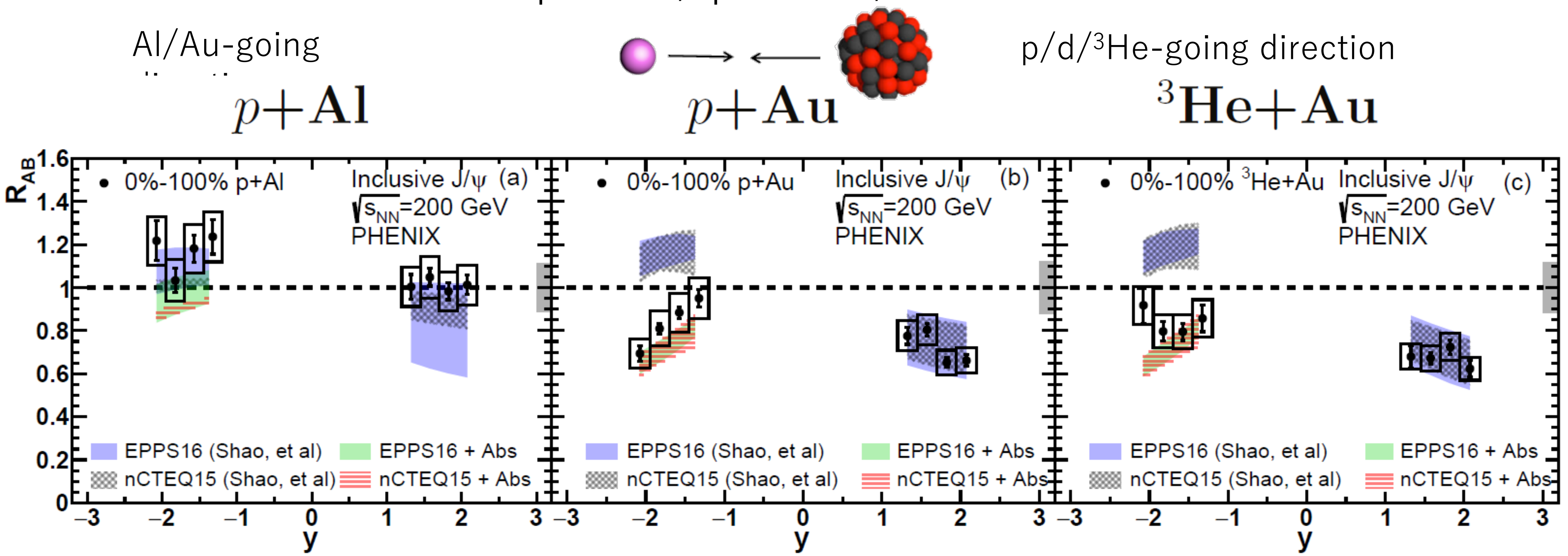
p/d/^{3}He-going direction



Phys. Rev. C **102**, 014902

- Systematic study of CNM effects
  - Suppression at forward rapidity for Au. pAl ~1 , pAl < pAu, ^{3}HeAu

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

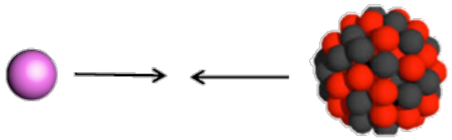


Phys. Rev. C **102**, 014902

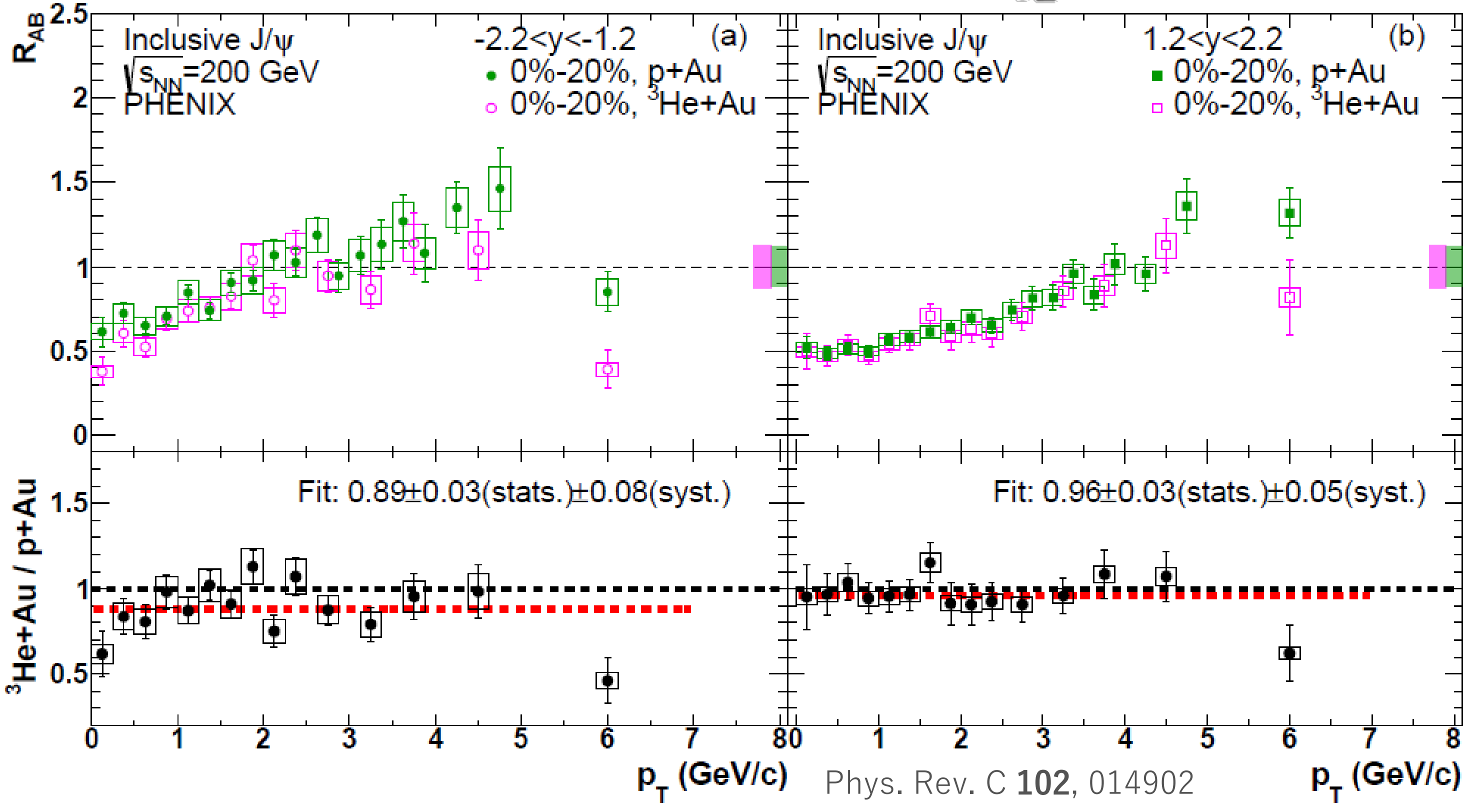
- Systematic study of CNM effects
  - pAl ~1 , pAl < pAu, ^{3}HeAu
- Forward :described by shadowing (ISE, EPPS16, nCTEQ15)
- Backward : adding nuclear absorption (FSE) reasonably reproduce data

J/ψ : R_{AA} ratio in p+Au, ^{3}He+Au 200GeV

Al/Au-going direction
(Backward)

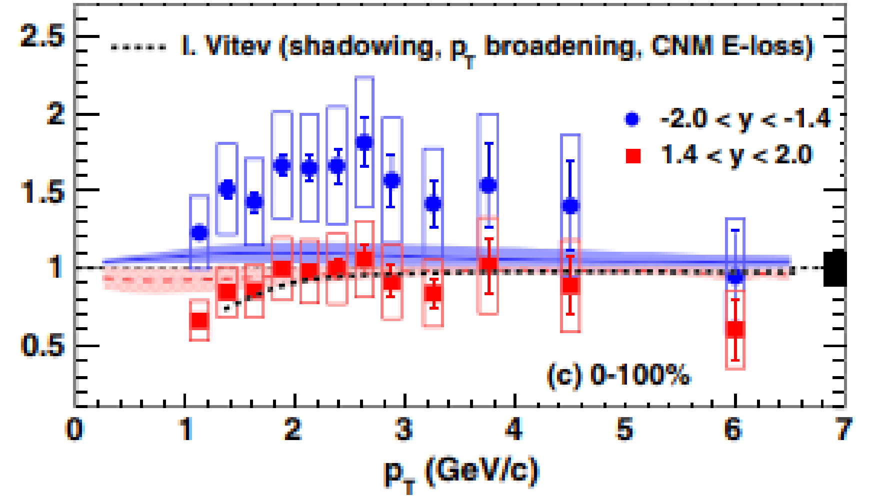


p/^{3}He-going direction
(Forward)



Phys. Rev. C **102**, 014902

Open HF in d+Au



Suppression at forward
Enhancement at backward

- Suppression at both forward and backward rapidity
  - Forward : shadowing effect (ISE)
  - Backward: absorption (FSE)
- Stronger suppression in He+Au than in p+Au with 1.3 σ : small final state effect at backward

Summary and Outlook

- P+P baseline updated
  - Pair creation and flavor excitation is dominant for bottom and charm
  - $b \rightarrow e$ and $c \rightarrow e$ spectra with broad p_T range (1-9 GeV/c) and small uncertainty
- Au+Au
  - Suppression : $R_{AA}(b \rightarrow e) > R_{AA}(c \rightarrow e)$ at mid-p_T
  - v_2 : $v_2(b \rightarrow e) < v_2(c \rightarrow e)$
    - Coalescence model describe $v_2(c \rightarrow e)$,
      - charm quark is dragged by light quarks
    - $v_2(c \rightarrow e) > v_2(J/\psi)$ suggests this scenario
- Quarkonia in small system
  - J/ψ suppressed with absorption (FSE) at backward rapidity
    - Shadowing (ISE) at forward rapidity
- Outlook
  - Analysis with Au+Au full statistics (36 billion events) from 2014 and 2016 is going
    - New heavy flavor results, bottom R_{AA} and v_2 will come soon.

PHENIX for 16 years of data taking

√s [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

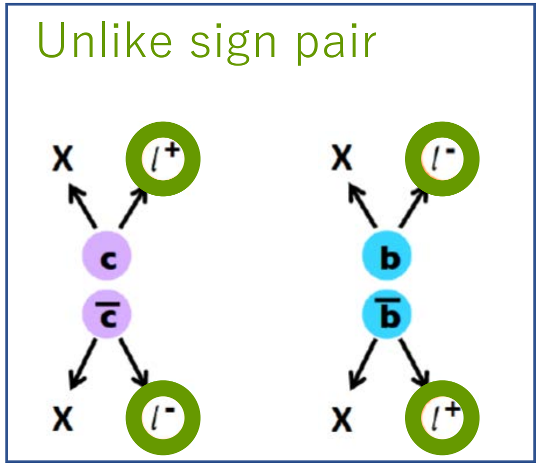
- PHENIX recorded data for 16 years and completed the data taking in 2016.
  - Moving to the next generation

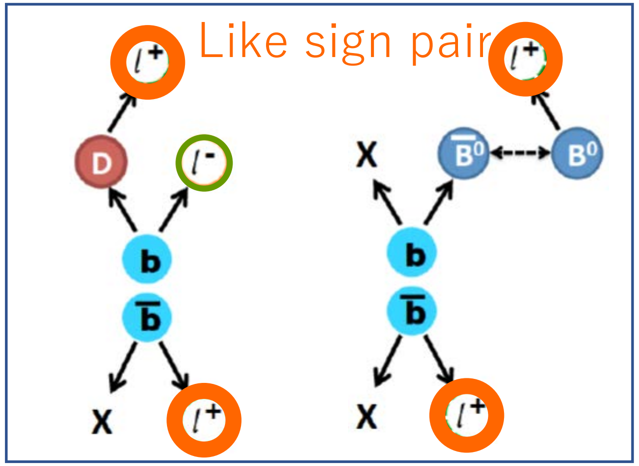
- PHENIX collected wide range of different collision system in the last three years with VTX+FVTX
  - Run14: Au+Au, ^{3}He+Au
  - Run15: p+p, p+Al, p+Au
  - Run16: d+Au BES, Au+Au

  - Data analyses continues with these dataset

p+p Baseline measurements via μμ pairs

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



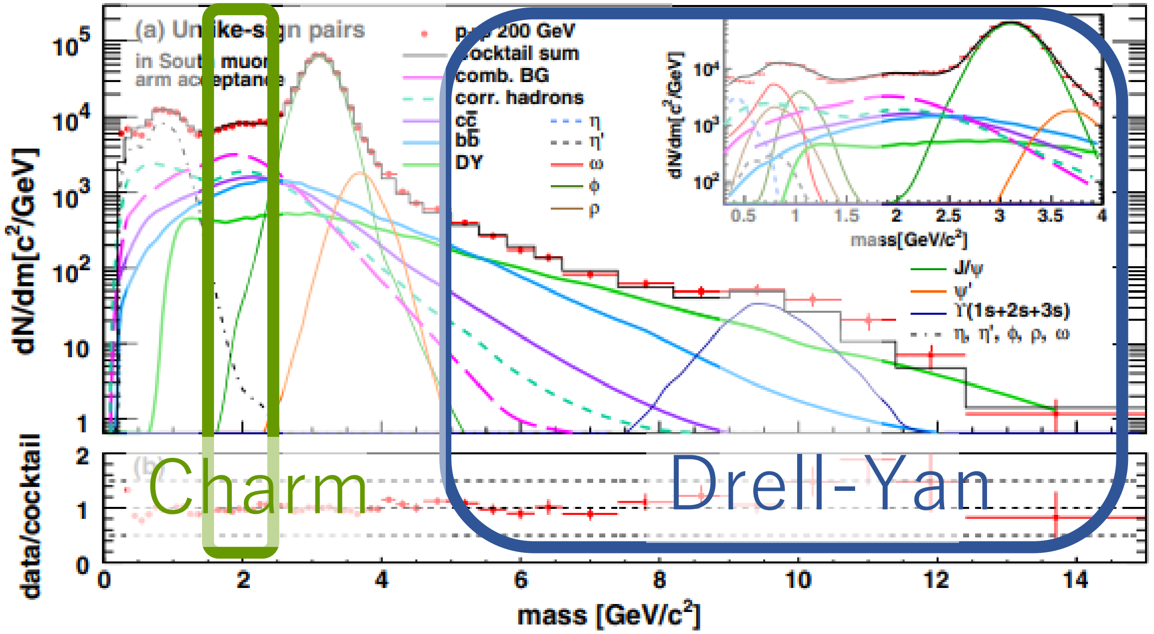


Bottom : hi-mass Like sign
(3.5 – 10.0 GeV/c^2)

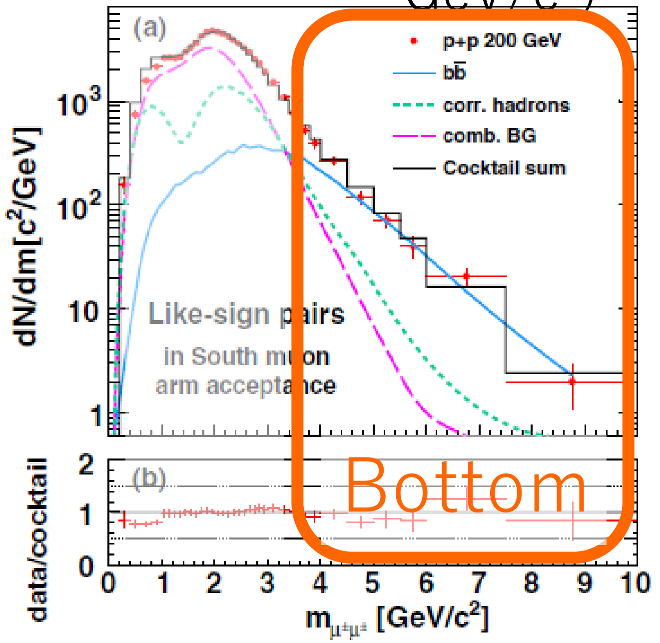
Charm : Lo-mass unlike sign
(1.5 – 2.5 GeV/c^2)

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

Unlike sign μμ pairs

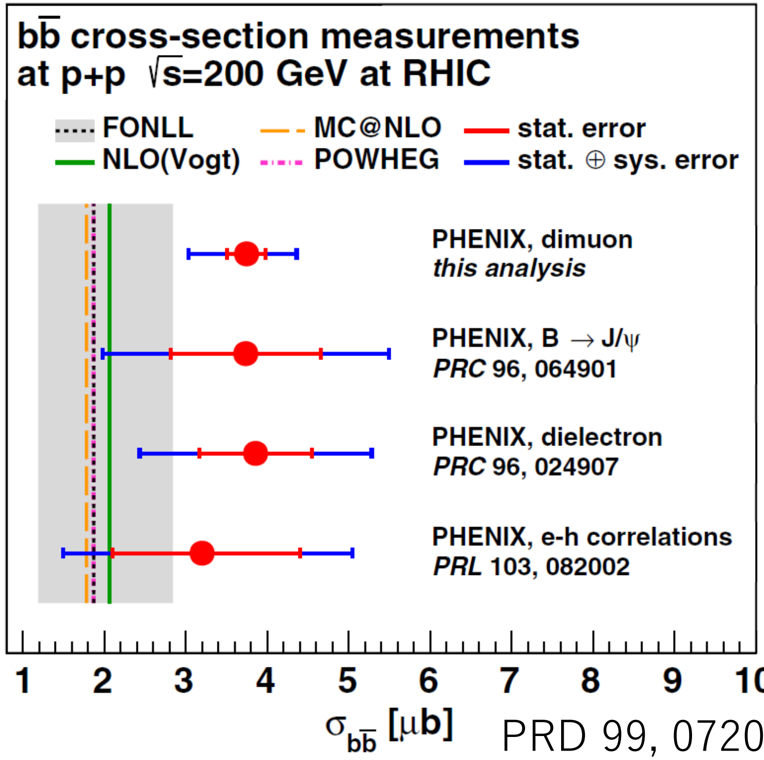


Like sign μμ pairs

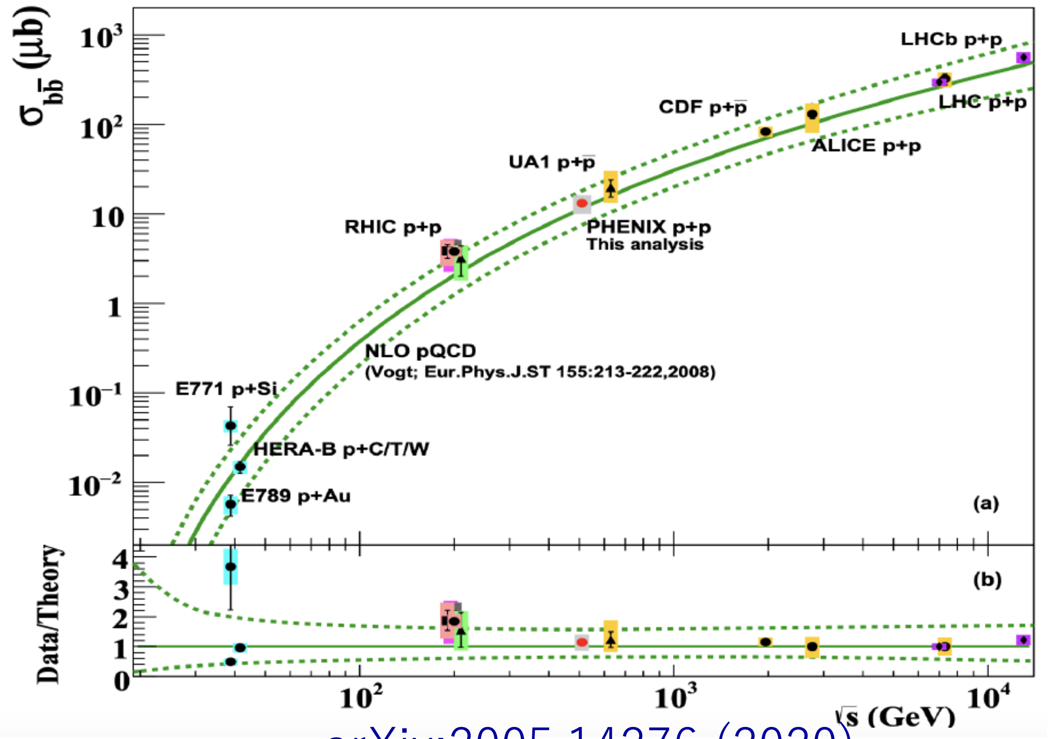


p+p Baseline measurements via μμ pairs in p+p 200GeV

Bottom production



PRD 99, 072003 (2019)

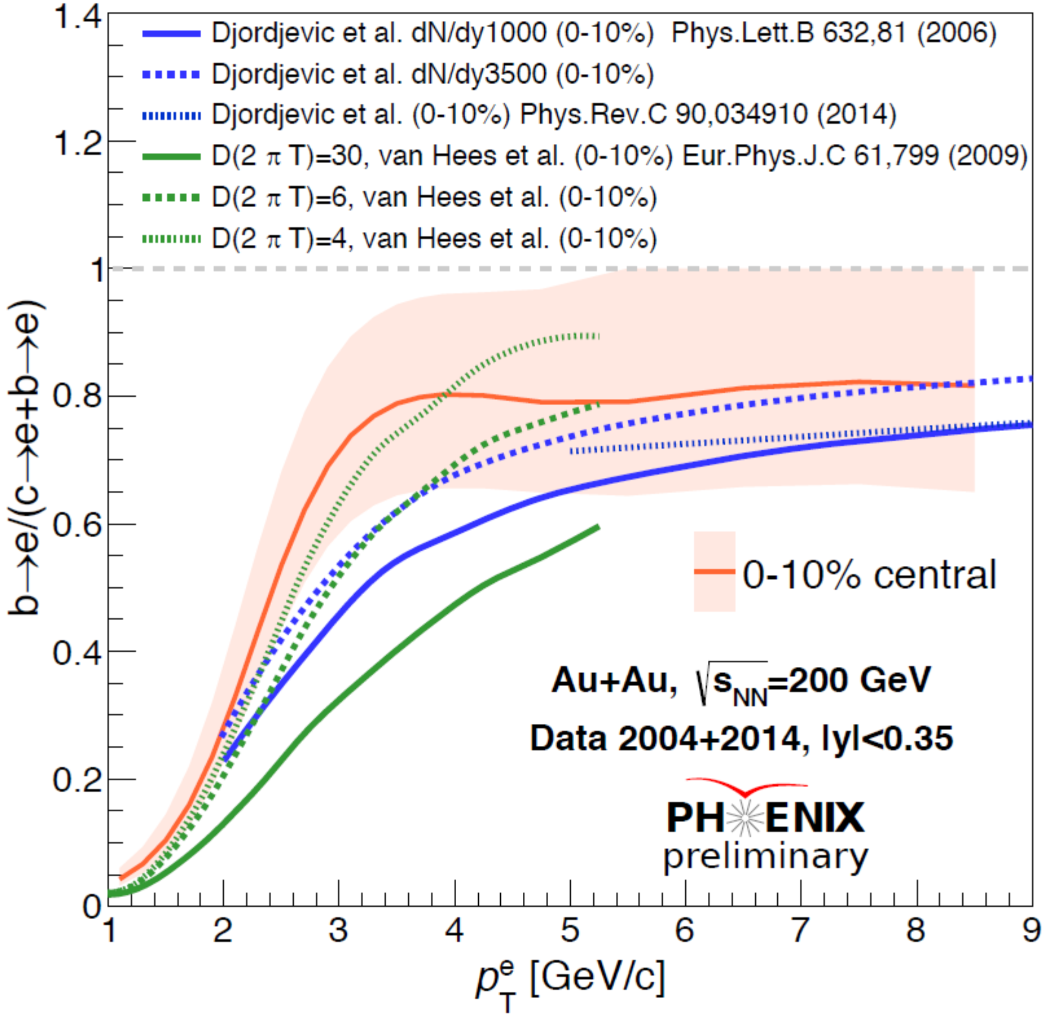


arXiv:2005.14276 (2020)

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

Bottom electron fraction in Au+Au 200GeV

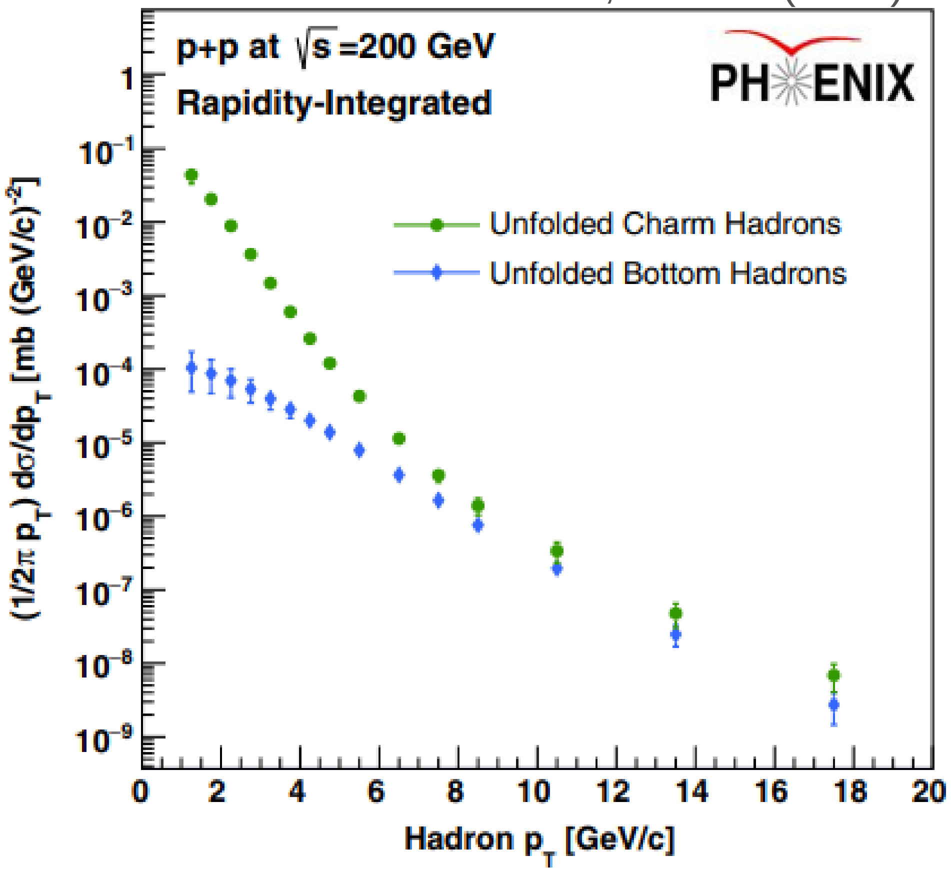
2014 Au+Au Data



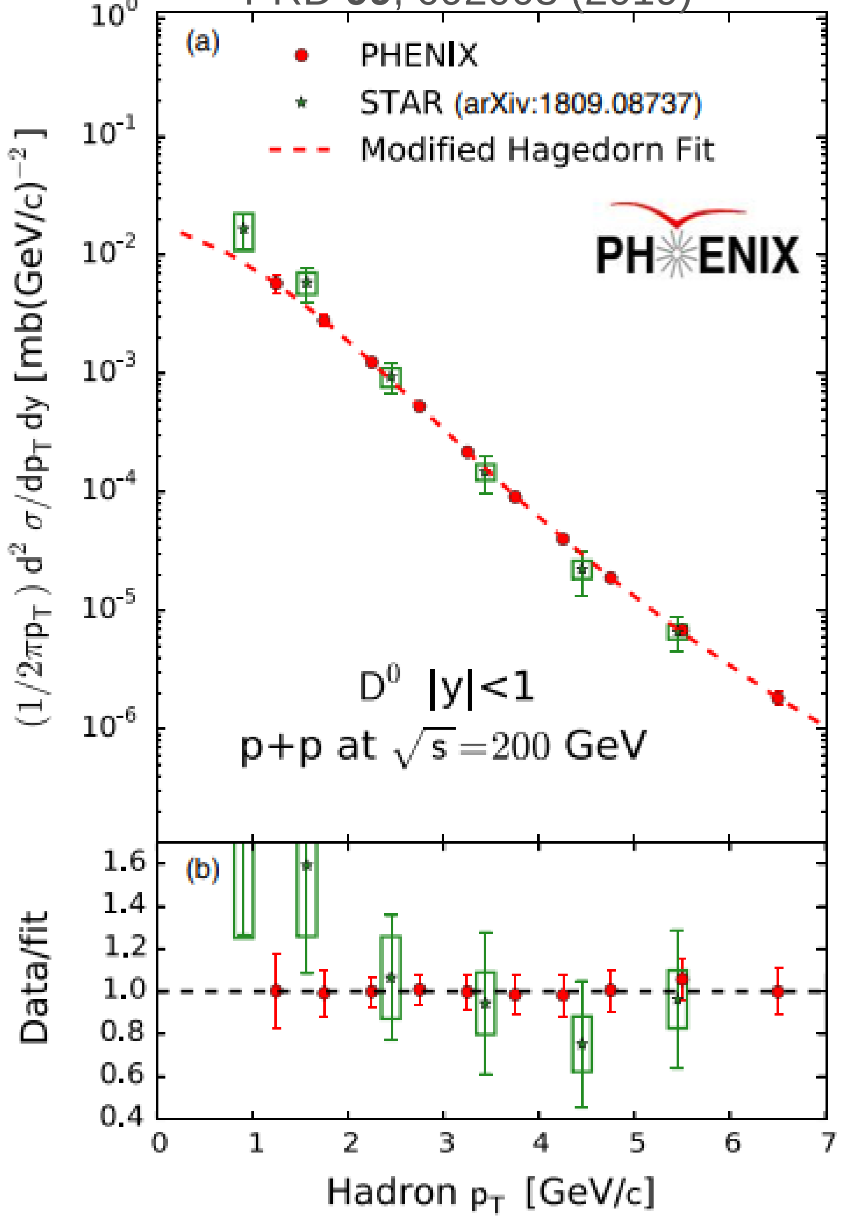
- 2014 result with 3 time more data consistent with 2011 published result
- T-Matrix+ small diffusion scenarios (2πTD=4-6) are consistent with data
  - Large diffusion scenario (2πTD=30) rejected by data
  - **Strongly coupling QGP**
- DGLV models with different gluon densities also consistent with data

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

PRD **99**, 092003 (2019)



PRD **99**, 092003 (2019)



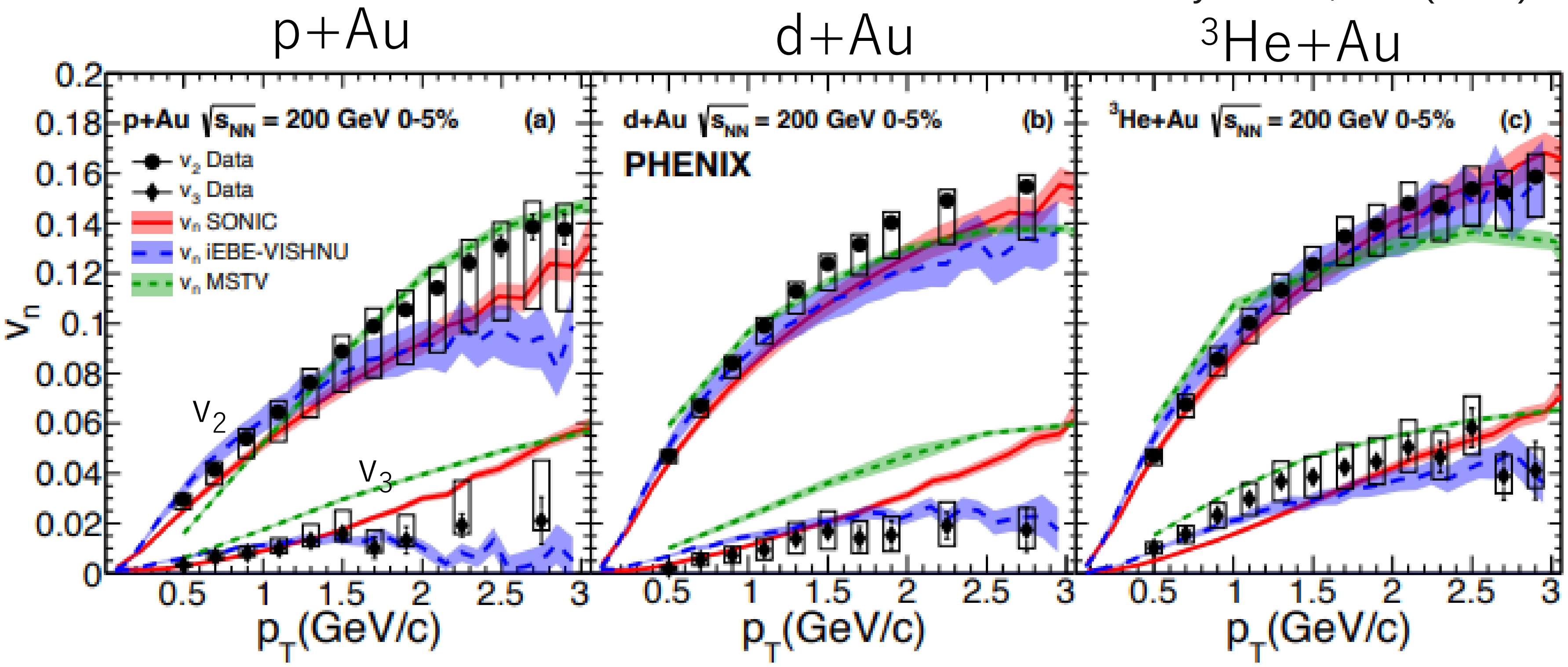
- B & D hadron yield is extracted from the electron measurement
  - Cover broad p_T range
- Good agreement with STAR D^0 in comparable p_T range

Open heavy flavor in d + A

PHENIX measured v_2 and v_3 in small system.

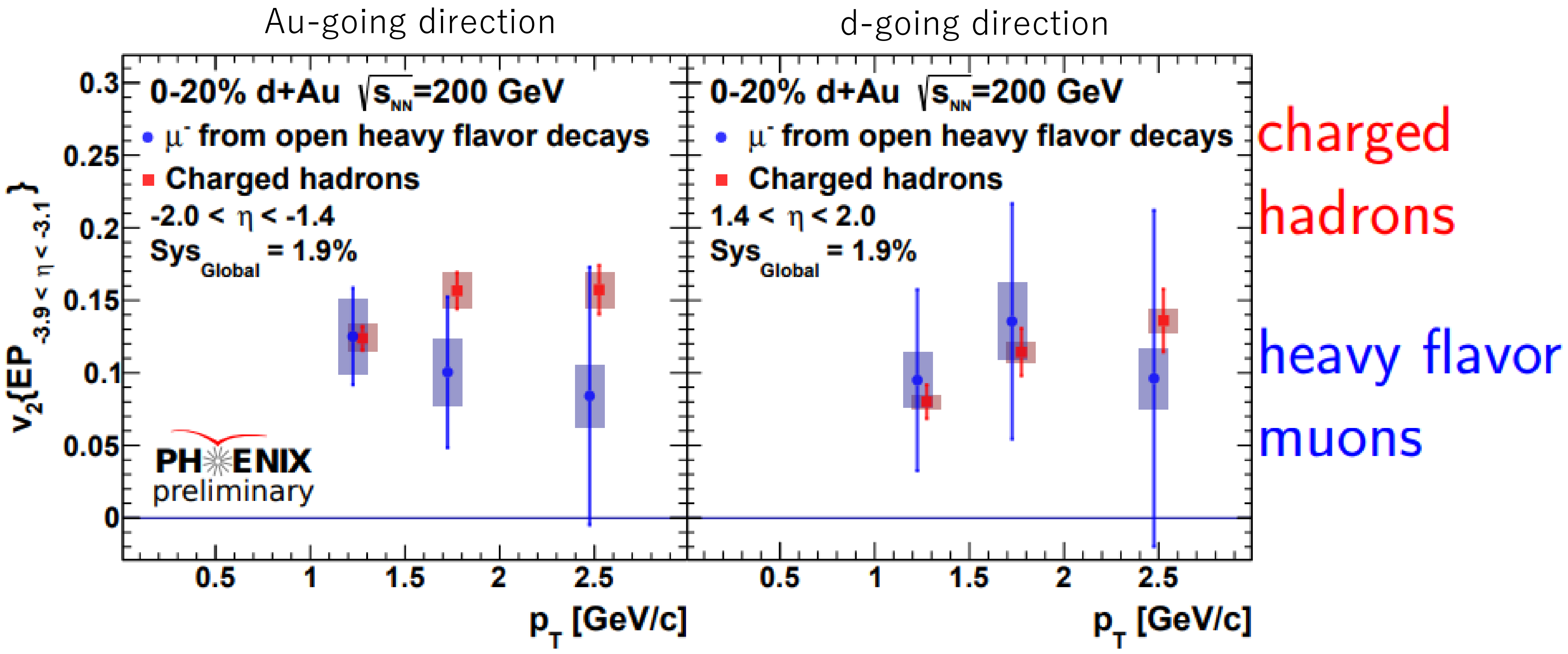
Data are well described by hydro models including the QGP formation

Nature Physics 15, 214 (2019)



Heavy flavor is also flows in small system?

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

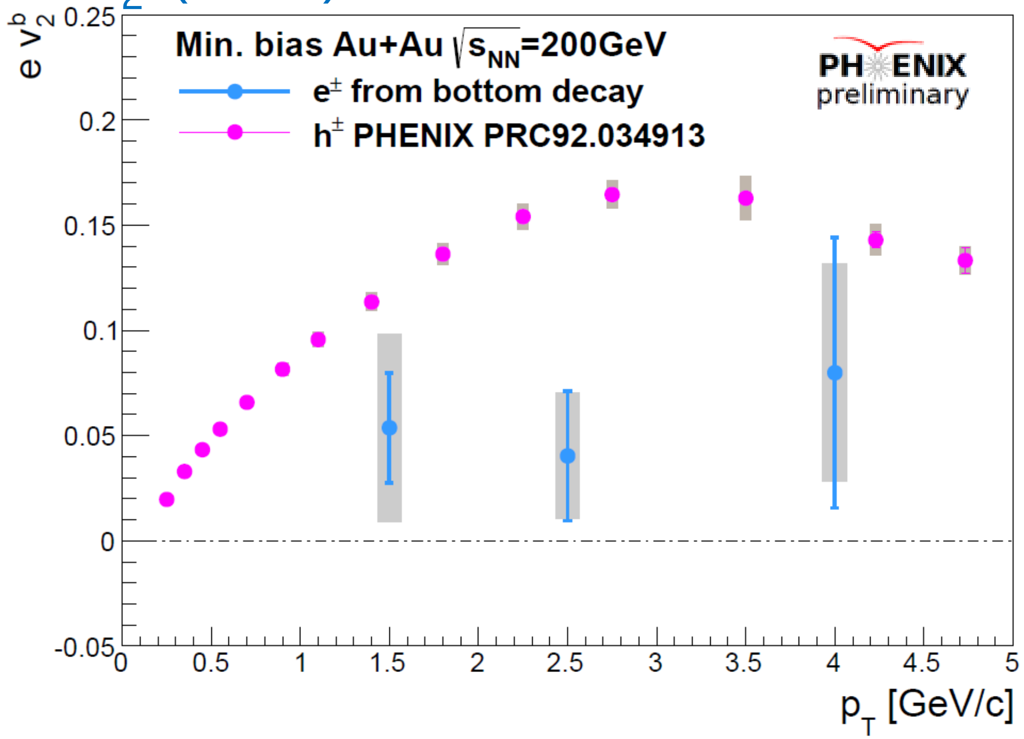


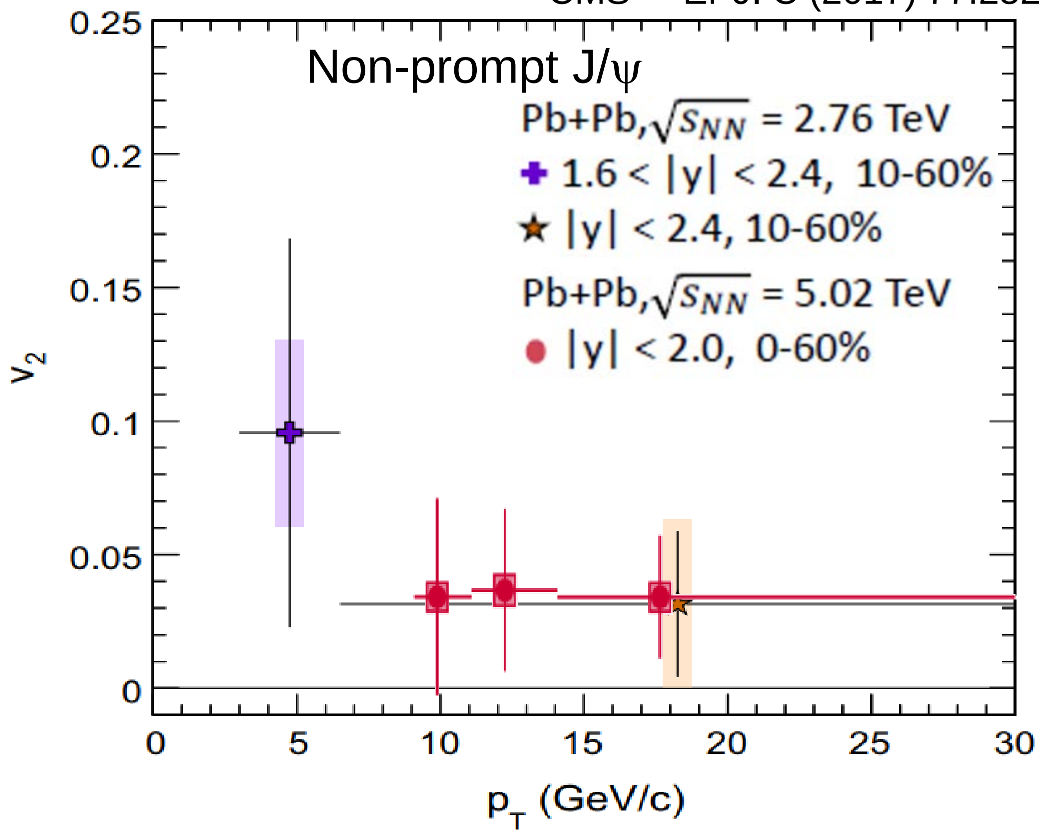
- Re-analyzed run8 dataset
- Significant non-zero v_2 in d+Au collisions !!
  - both Au-going and d-going direction

Bottom v_2 : comparison to LHC

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

$v_2^b(b \rightarrow e)$



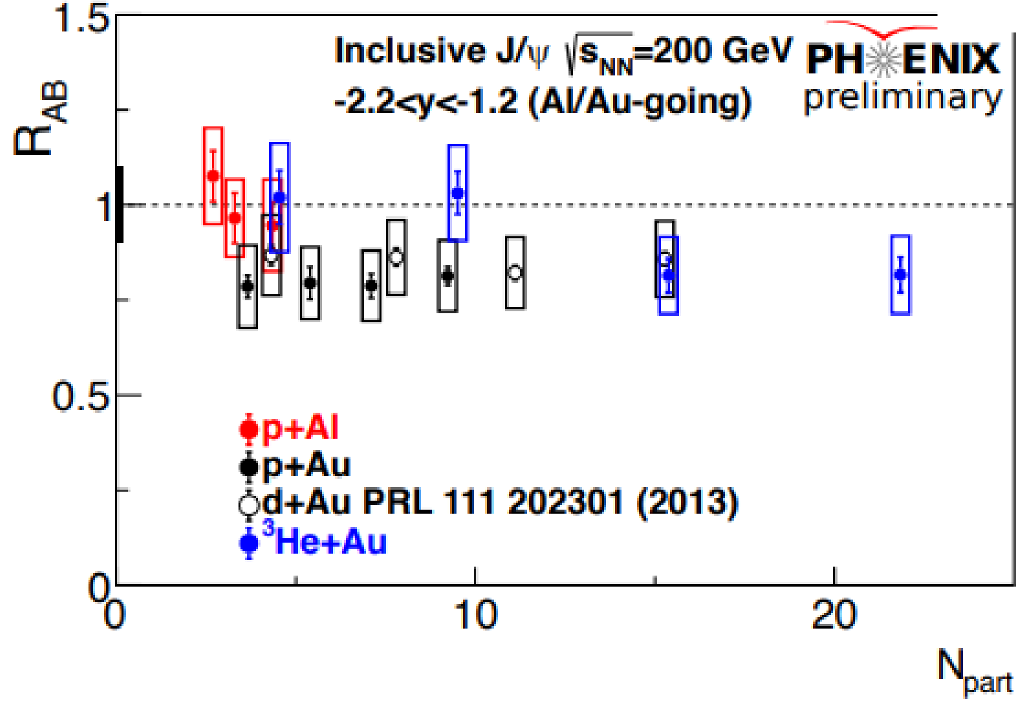


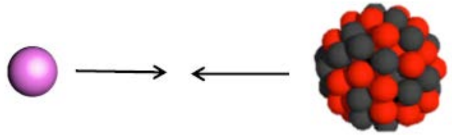
- ATLAS and CMS also measured positive bottom v2 for p_T > 3GeV/c
  - Low p_T is sensitive to flow, and high p_T is good for energy loss?
- consistent with these results
- b-quark suffer flow?

Bottom v2 became available. Need precise measurement

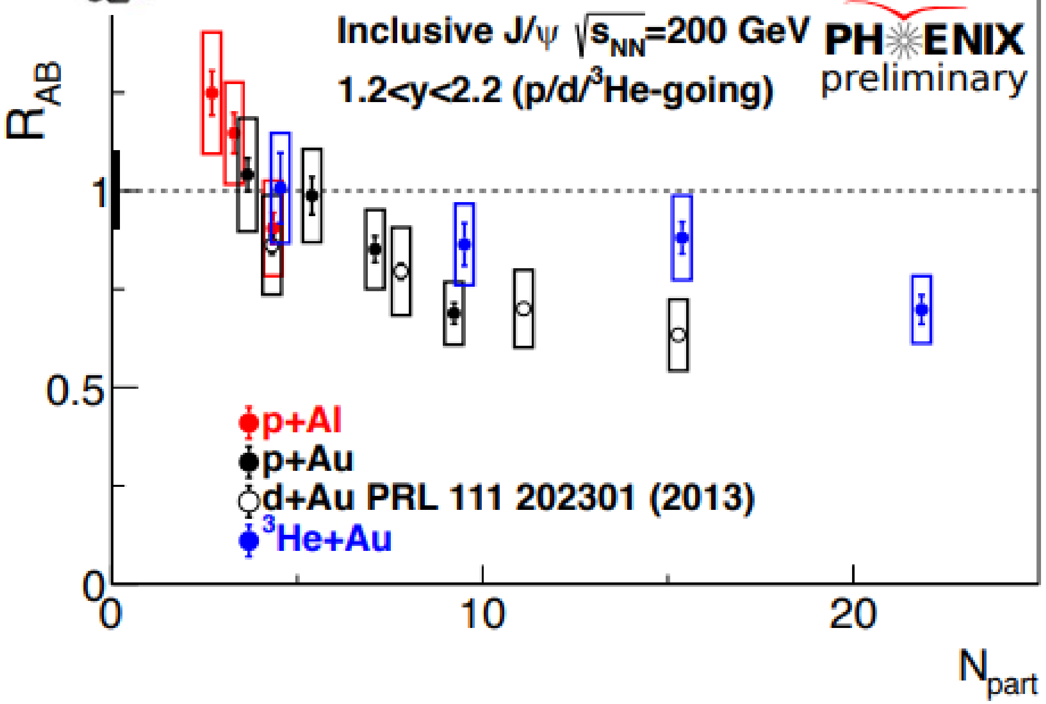
J/ψ : CNM effects in p+Al, p+Au, d+Au, ^{3}He+Au 200GeV

Al/Au-going direction



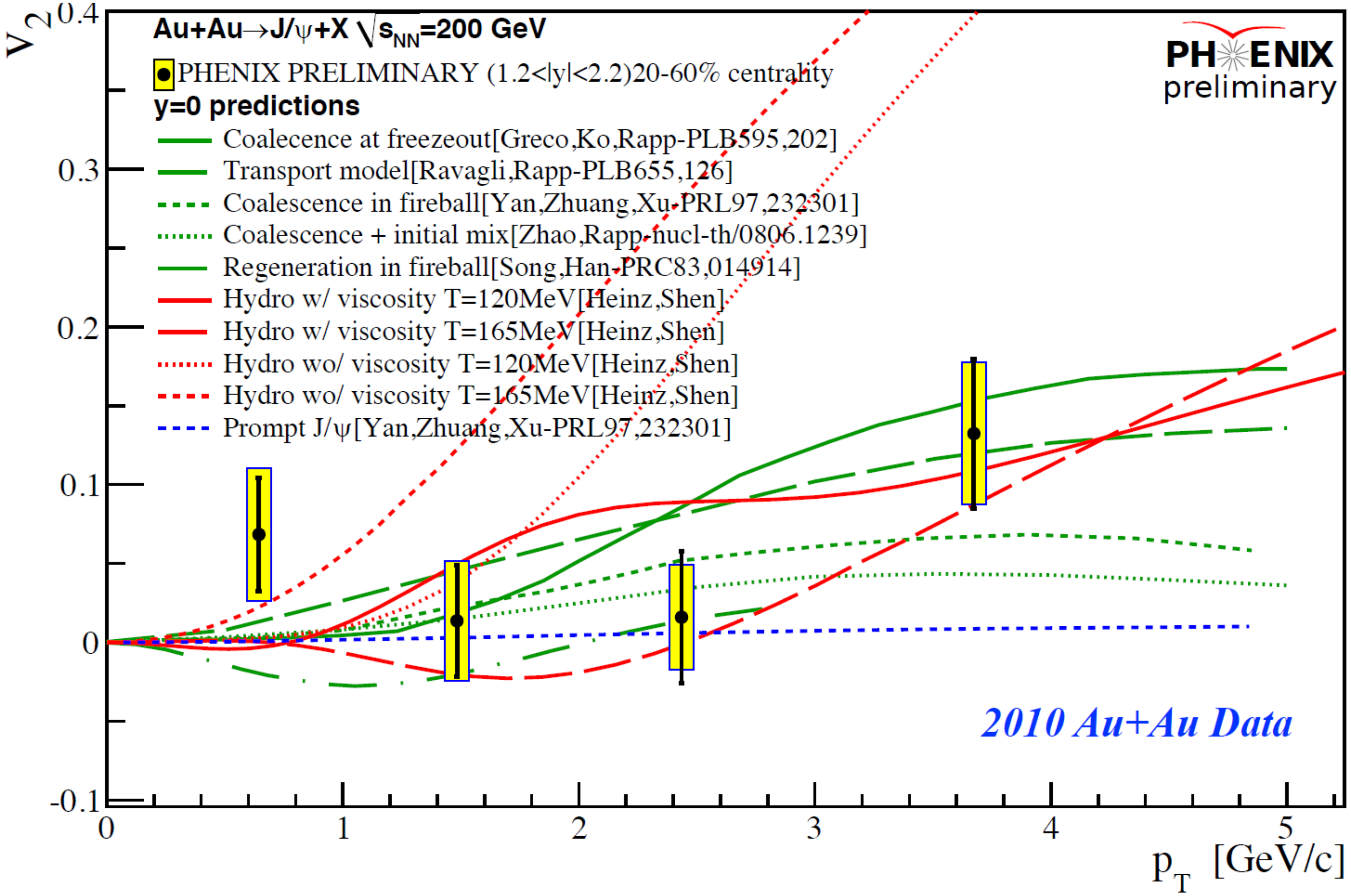


p/d/^{3}He-going direction



- 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

J/ψ v_2 model calculations

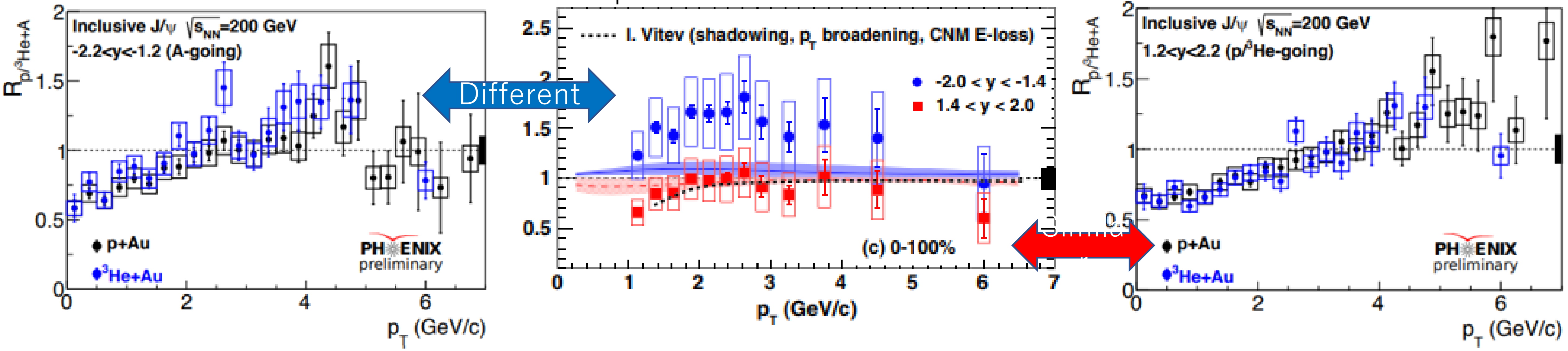


CNM effects : R_{AB} vs p_T in p/^{3}He + Au

Au going

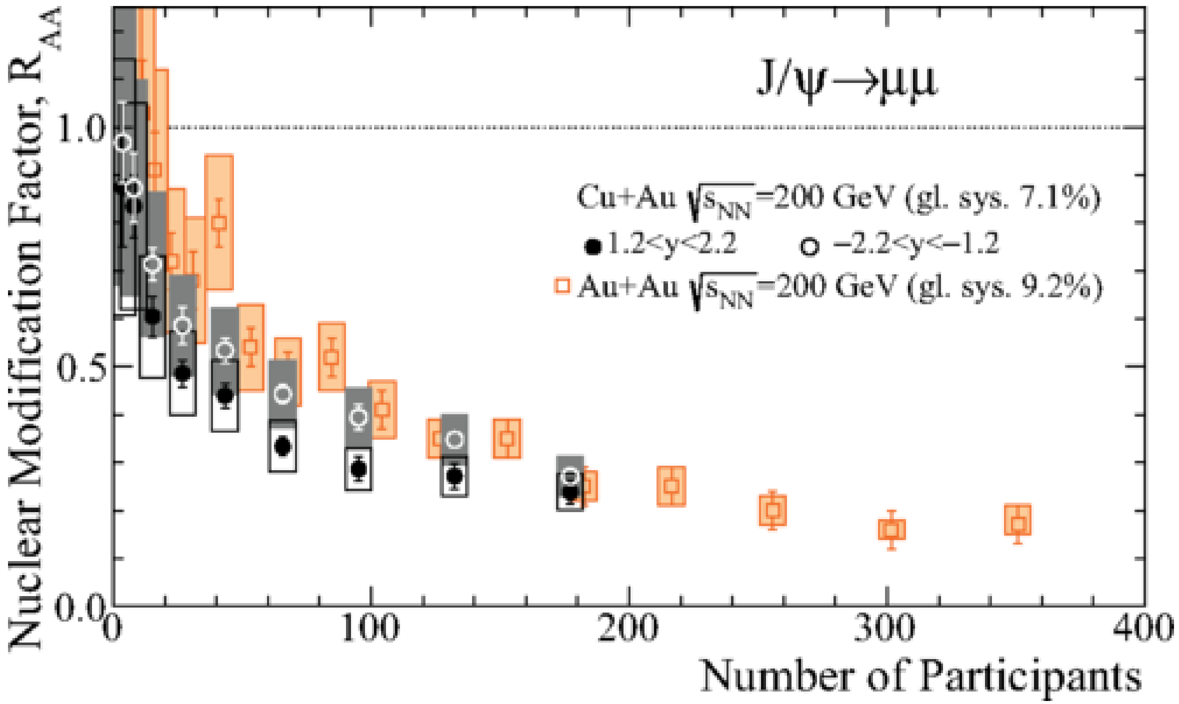
Open HF in d+Au

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

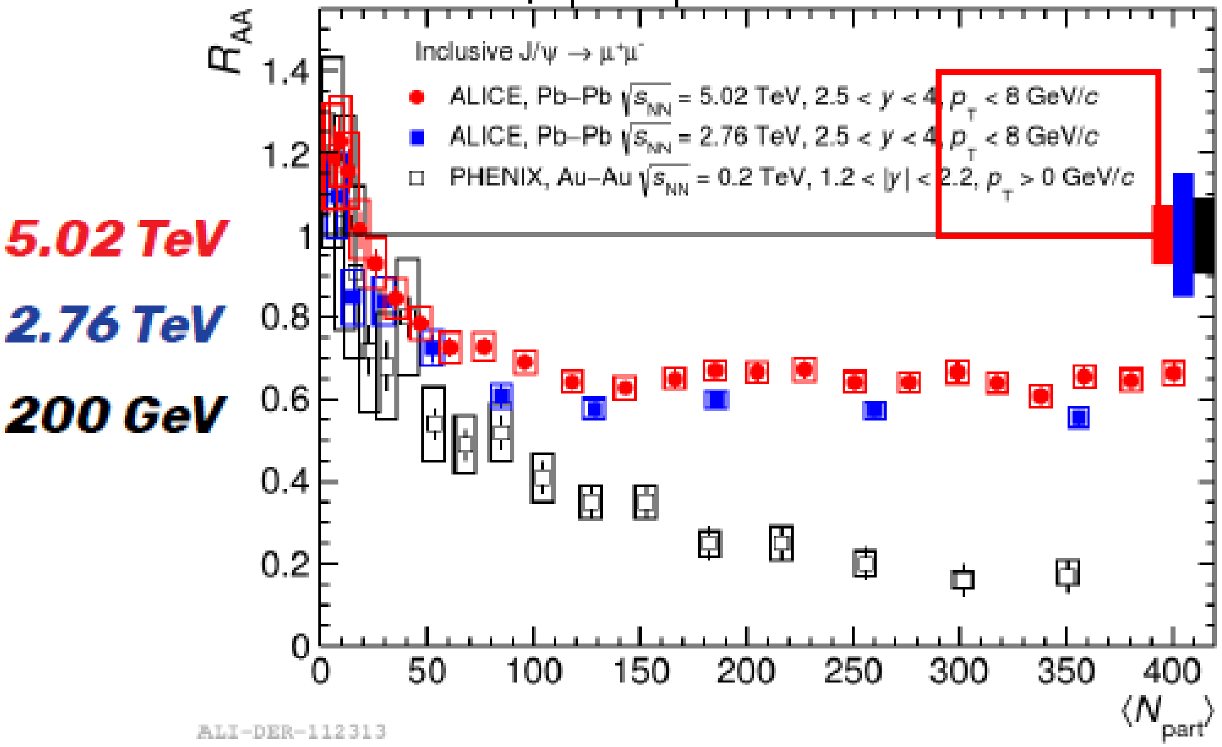
J/ψ : Regeneration at RHIC and LHC



Cu (Cu+Au) < Au (Cu+Au) < Au (Au+Au)

Debye screening failed to describe data

Low p_T J/ψ



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