Energy and System Dependent Heavy Flavor Measurements at PHENIX at RHIC

Xuan Li (LANL)

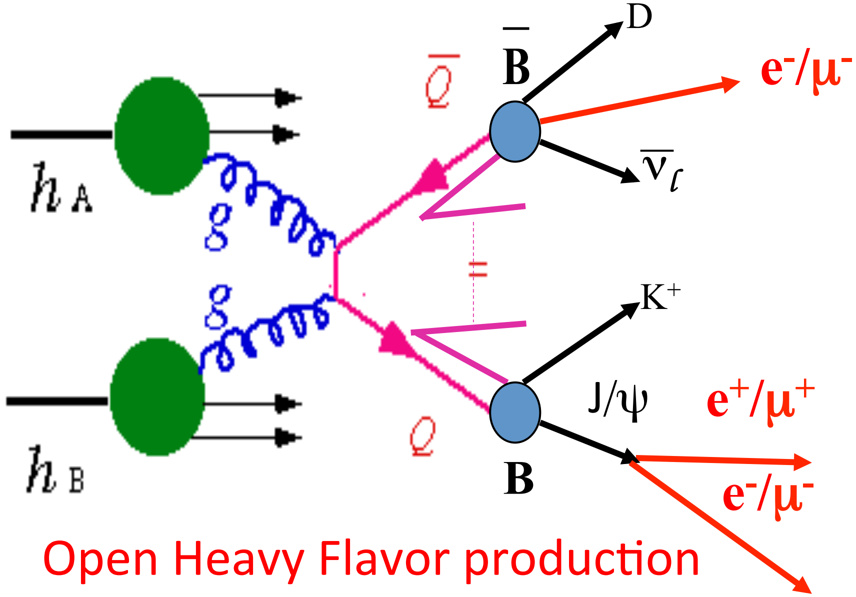
For the PHENIX Collaboration

Outline

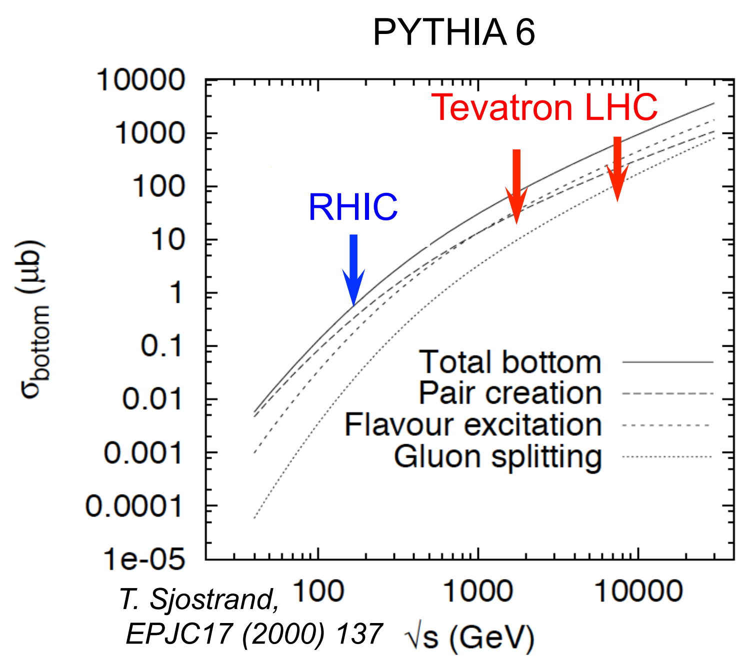
- Motivation
- Overview of RHIC and PHENIX
- Selected PHENIX heavy flavor measurements
  - In small systems
    - Measurement of charm and bottom via di-muon channel in p+p and p+Au collisions.
    - Forward and backward J/ψ R_{AB} via di-muon channel in p+Al, p+Au and He^3+Au collisions.
    - Single muon v_2 from heavy flavor decays in d+Au collisions.
  - In heavy ion collisions
    - Mid-rapidity B/D R_{AA} and v_2 via single electron channel in Au+Au collisions.
- Summary and Outlook

Motivation

- Heavy flavor production is an ideal probe to study the full evolution of the medium as it is produced in the early stage of nuclear collisions due to its high mass ($m_c/m_b >> \Lambda_{QCD}$).
- Disentangle different heavy flavor production mechanisms at RHIC energies.

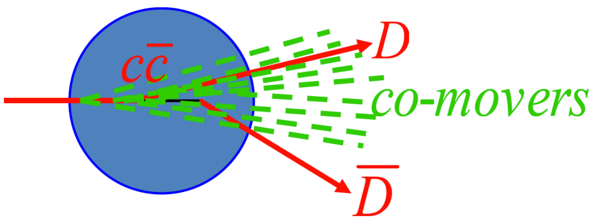


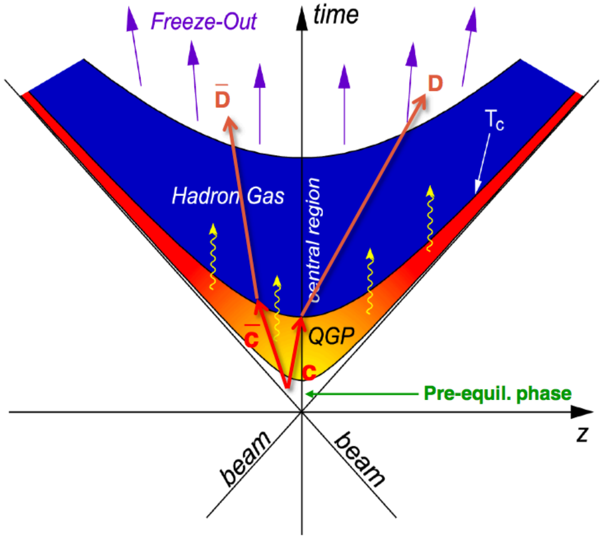
Open Heavy Flavor production



Heavy Flavor Production in Heavy Ion Collisions

- Not well understood about interaction with the medium.
  - Cold Nuclear Matter (CNM) effect:
    - Nuclear modification of PDFs.
    - Cronin/EMC effect.
    - Energy loss of partons traversing nucleus (Initial state).
    - Breakup of charmonium before exiting nucleus.
    - Co-mover absorption for quarkonia.
  - Hot nuclear matter effect:
    - Energy loss of partons traversing QGP.
    - Color screening.
    - Coalescence of quarkonia in QGP.

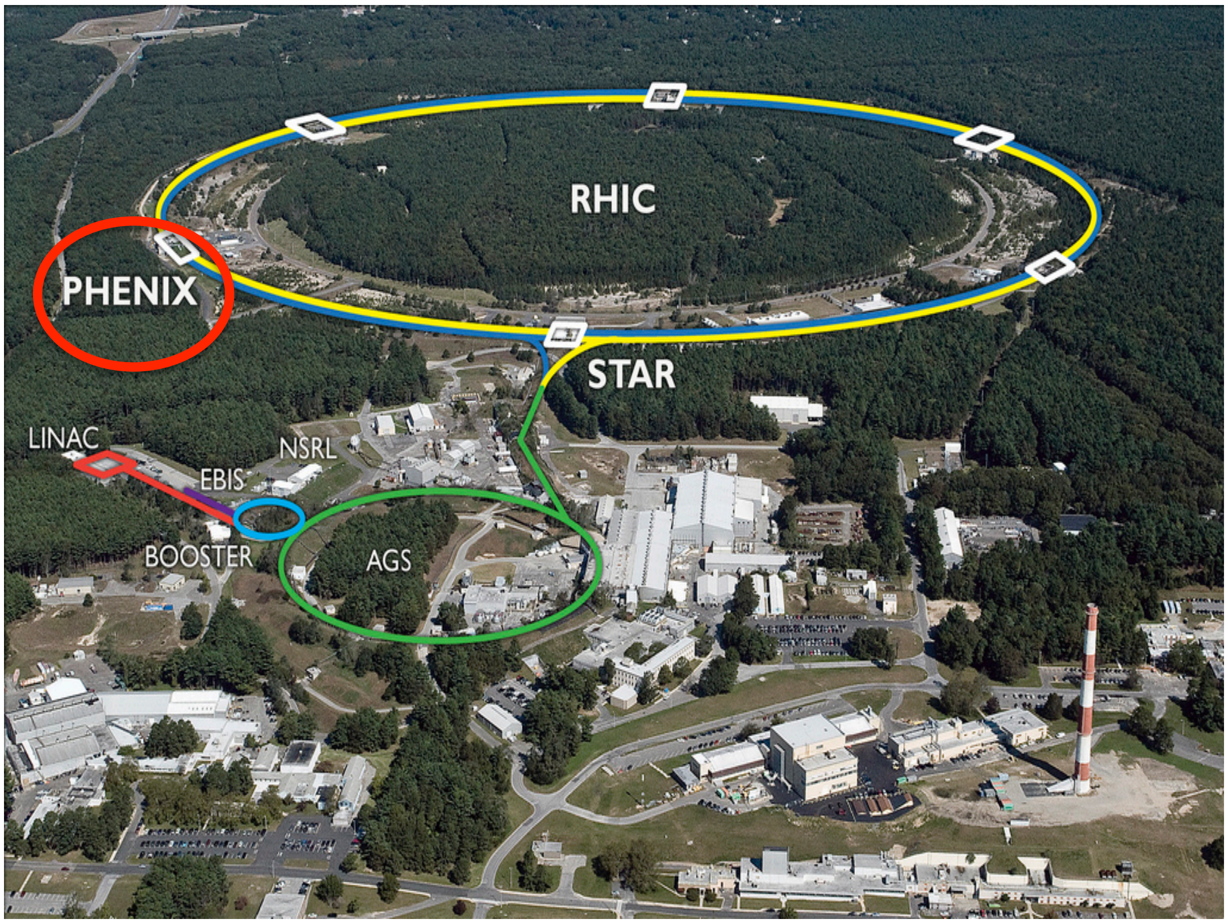


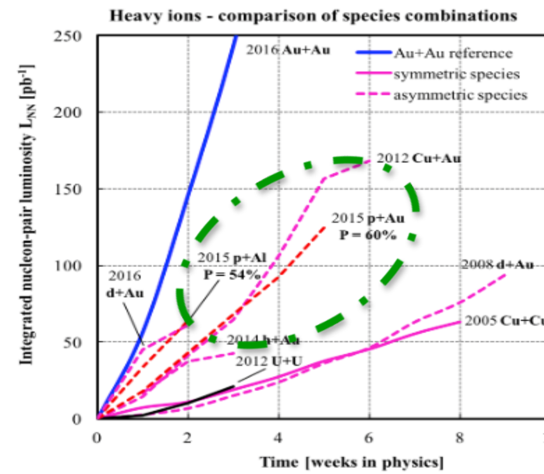


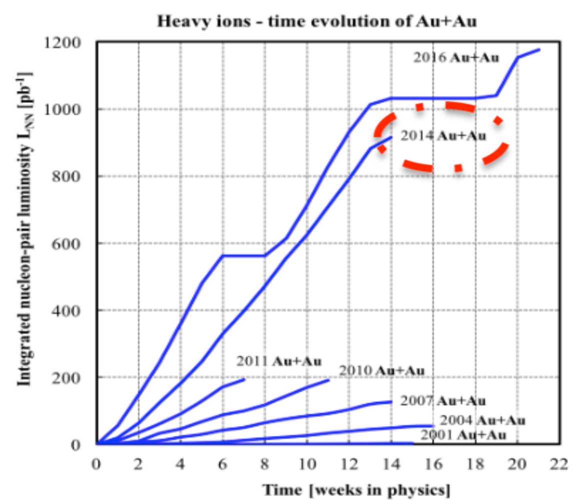
- Need to measure multiple observables in different processes to isolate the initial/final state and cold/hot nuclear matter effects.

Overview of RHIC

- The versatility of RHIC operation allowed us to collect data in various collision systems: p+p, p+Al, p+Au, d+Au, He^3+Au, Cu+Cu, Cu+Au, U+U, Au+Au.

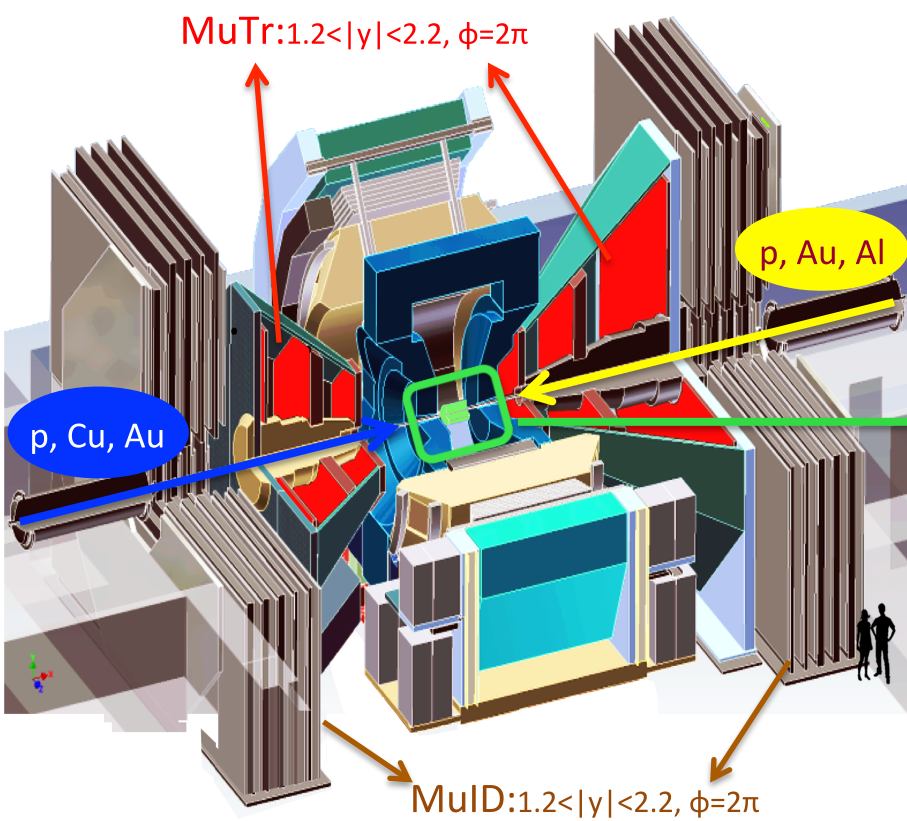




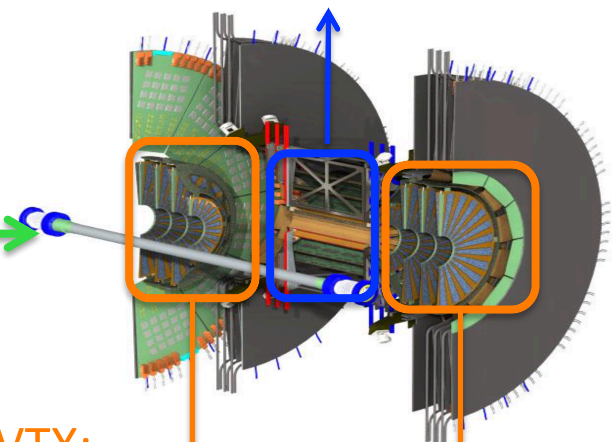


Overview of the PHENIX detector

- PHENIX had electron ID detectors at mid-rapidity and muon ID detectors at forward/backward rapidity.
- The silicon vertex detectors: VTX and FVTX made new heavy flavor measurement possible in small systems and Au+Au collisions.



- VTX:
  - With |y|<1.2 and ϕ≈2π coverage.
  - provide precise vertex and tracking for D,B→X+e measurements.



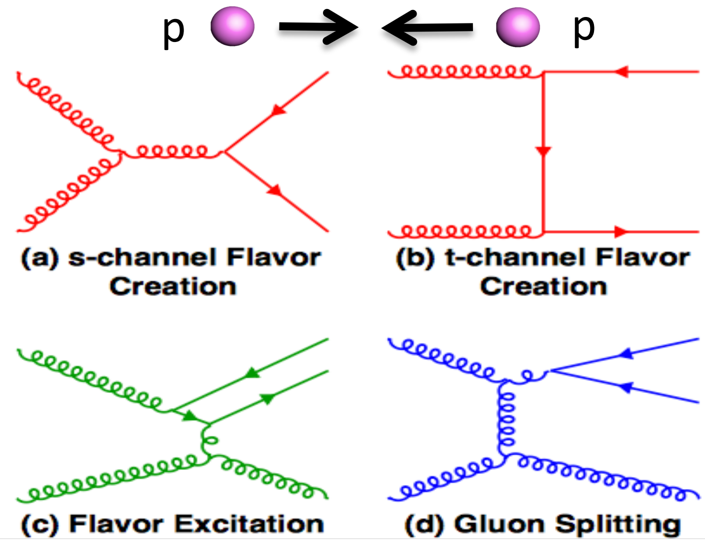
- FVTX:
  - With 1.2<|y|<2.2 and ϕ=2π coverage.
  - provide precise tracking and improved mass resolution for J/ψ, B→J/ψ and D, B separation measurements.

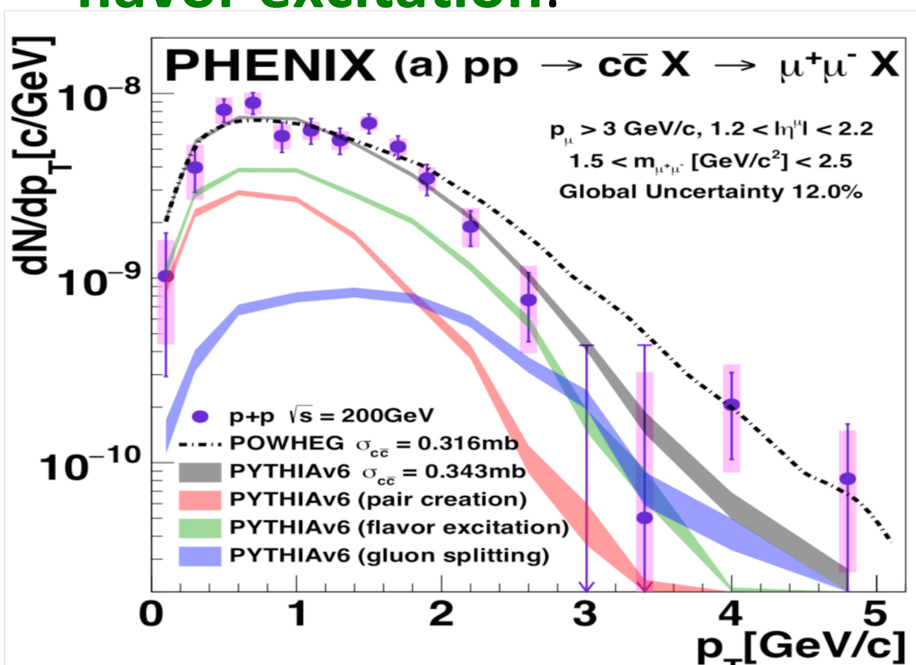
Heavy flavor measurements in small systems

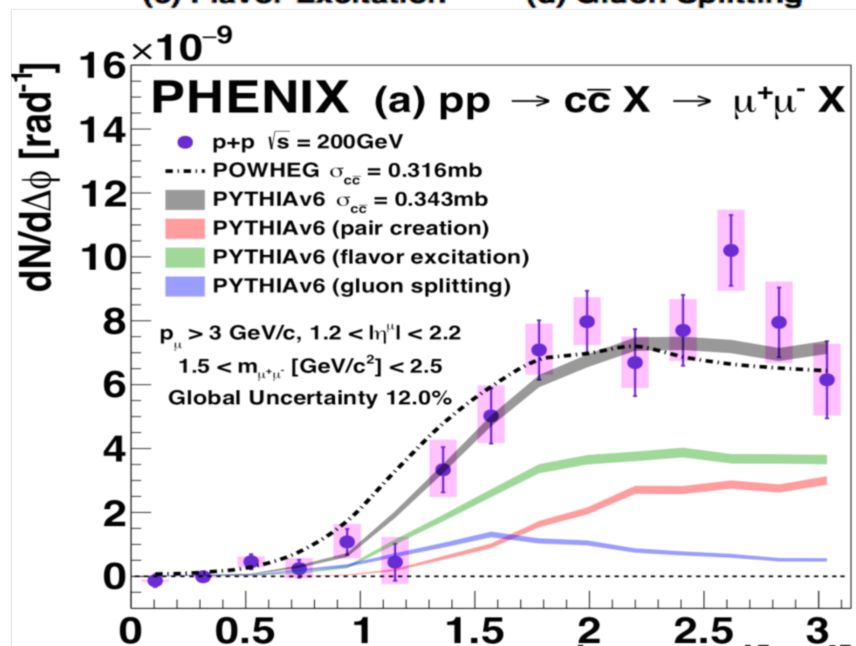
- to understand the production mechanism
- to study the cold nuclear matter (CNM) effects
- to explore the formation of QGP droplet? Flow?

Di-muon correlations (1.2<|y|<2.2) in 200 GeV p+p collisions

- Unlike-sign and like-sign di-muon correlations with template fit and comparison with PYTHIA Tune A (POWHEG) models suggests the **charm production** in 200 GeV p +p collisions is dominated by **flavor excitation**.



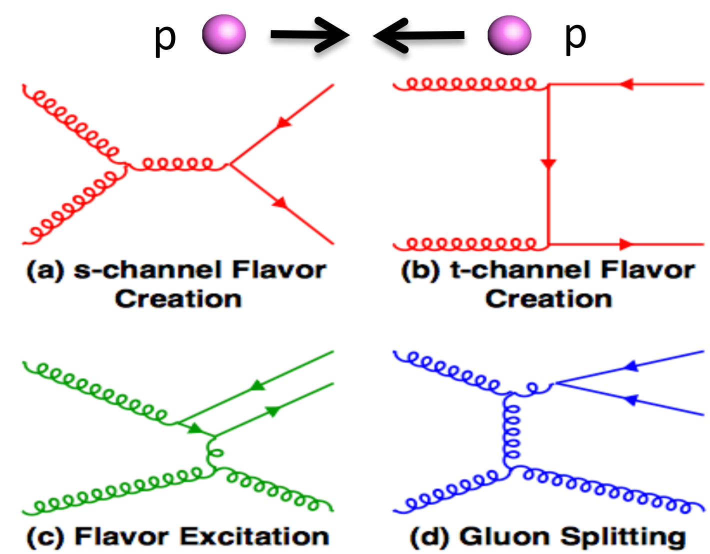


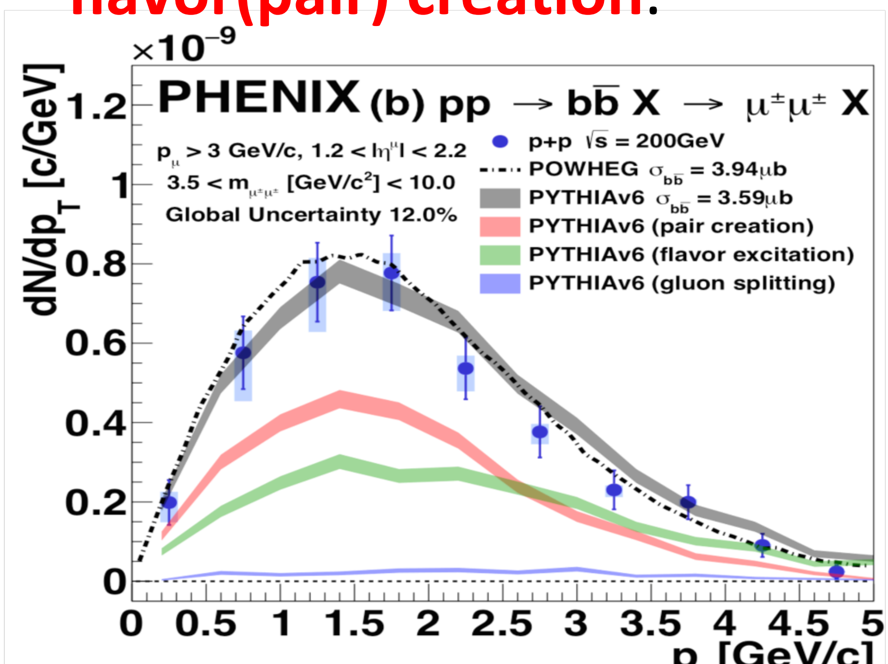


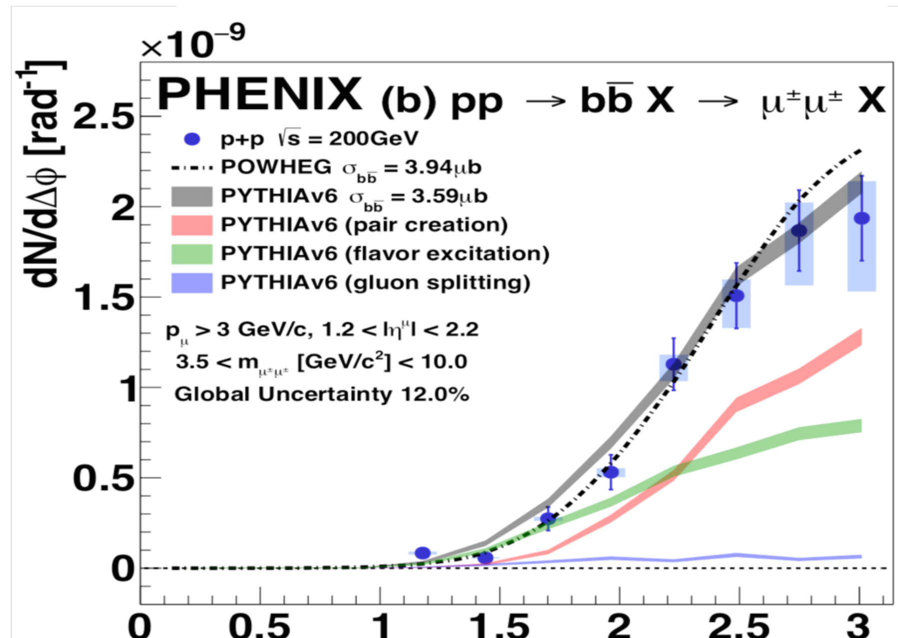
arXiv:1805.02448

Di-muon correlations (1.2<|y|<2.2) in 200 GeV p+p collisions

- Unlike-sign and like-sign di-muon correlations with template fit and comparison with PYTHIA Tune A (POWHEG) models suggests the **bottom production** in 200 GeV p +p collisions is dominated by **flavor(pair) creation**.



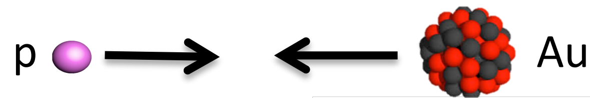


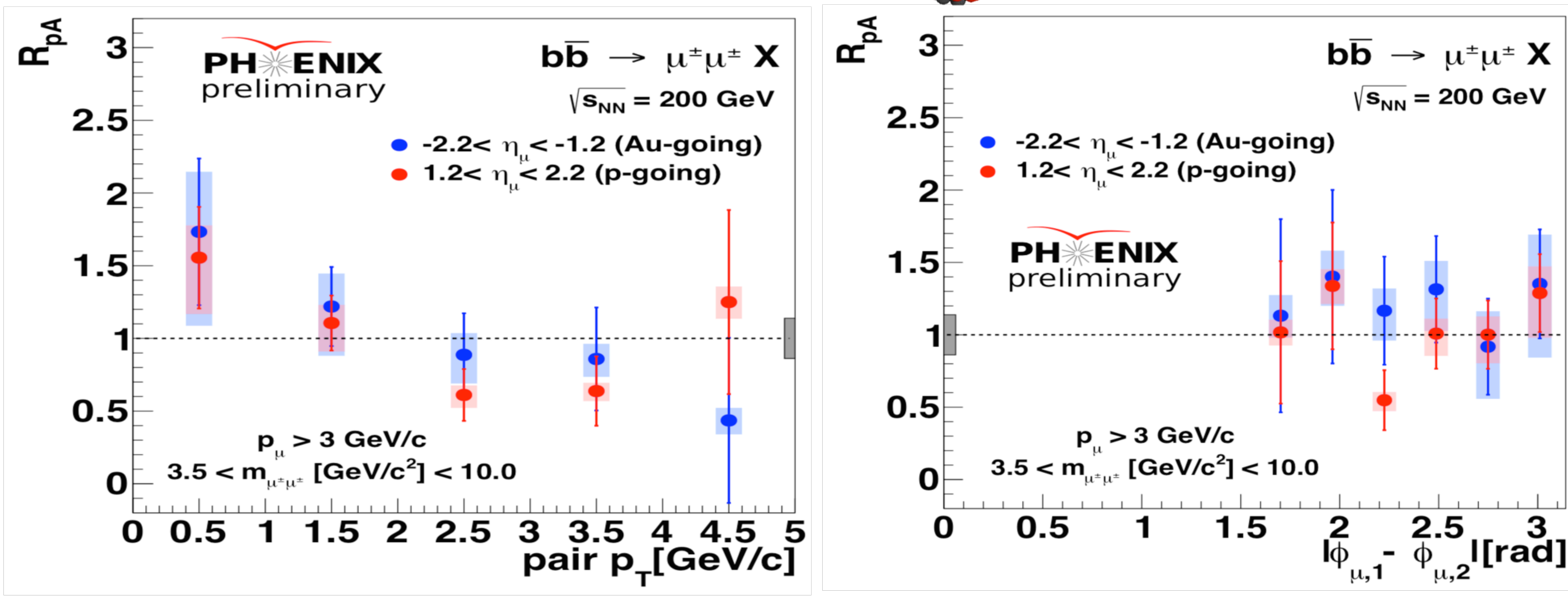


arXiv:1805.02448

Di-muon correlations (1.2<|y|<2.2) in 200 GeV p+Au collisions

- Use like-sign di-muon correlations with template fit to extract bottom contribution at forward/backward rapidity.

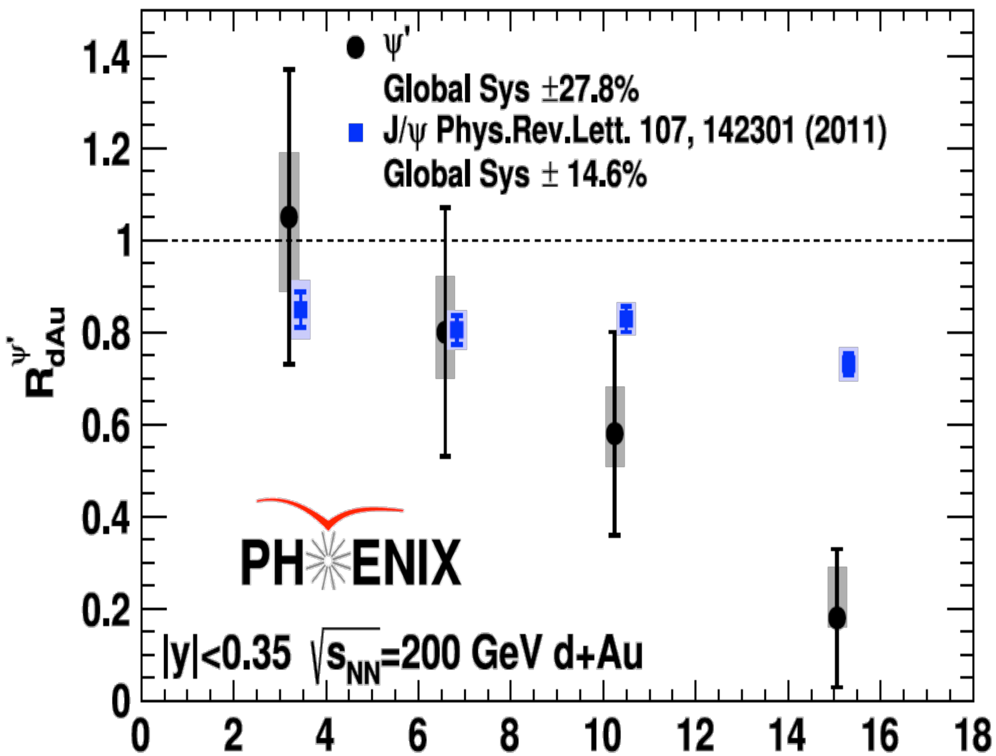




- No significant nuclear modification on the **bottom production** in 200 GeV p+Au collisions.
- Analysis of charm/DY di-muons in p+Au data is underway.

Explore the CNM effect via J/ψ and ψ’

- Mid-rapidity ψ’ R_{dAu} measured at PHENIX in d+Au collisions has different trend and magnitude of suppression versus N_{coll} from the J/ψ results.



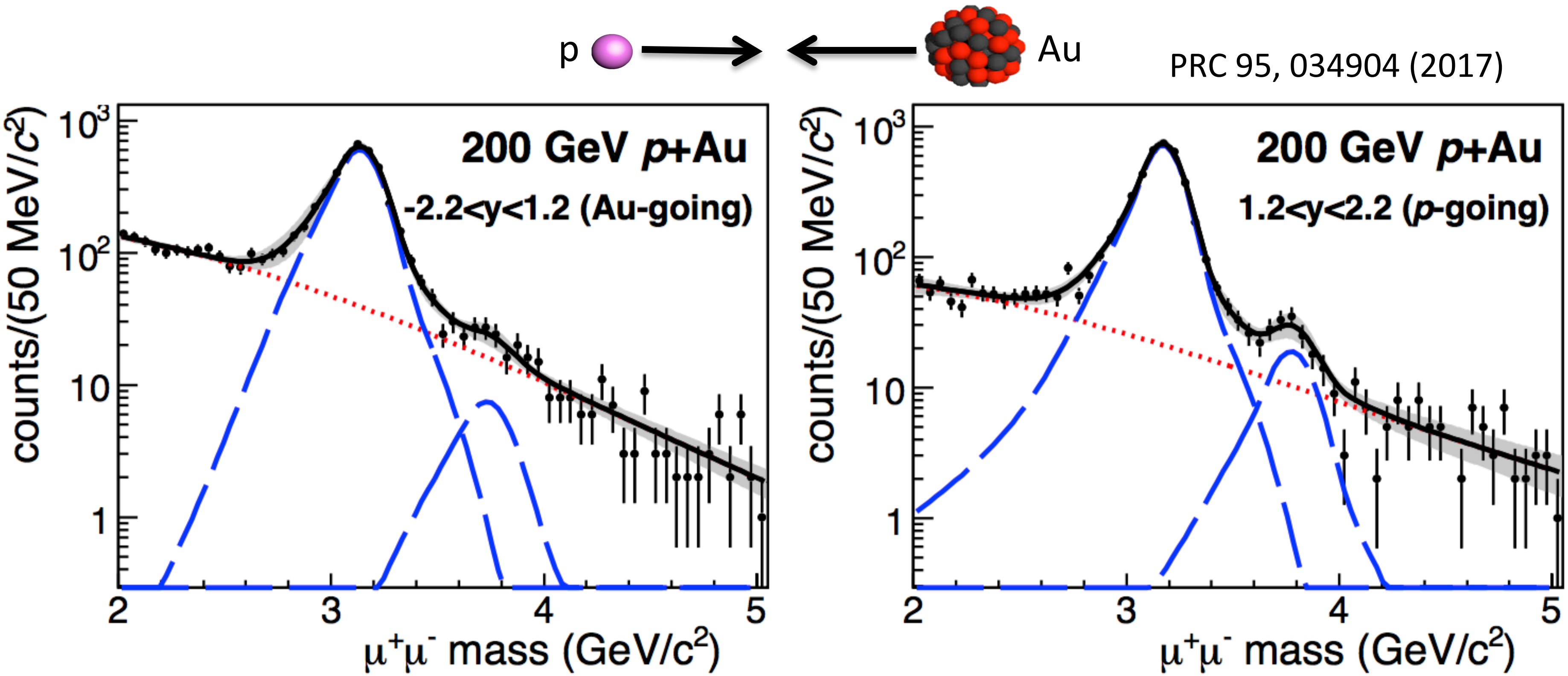
PRL 111, 202301 (2013) N_{coll} Number of binary nucleon-nucleon inelastic collision

- Similar initial state effect (shadowing, energy loss etc.) on J/ψ and ψ’.
- Indications of impacts from final state effects cause the difference.
- Can we study this in forward/backward rapidity and different collision systems?

J/ψ and ψ' measurement in p+Au collisions

- With improved mass resolution provided by FVTX, clear J/ψ and ψ' identification via di-muon channel (1.2<|y|<2.2) in 200 GeV p+Al, p+Au and ^{3}He+Au data.

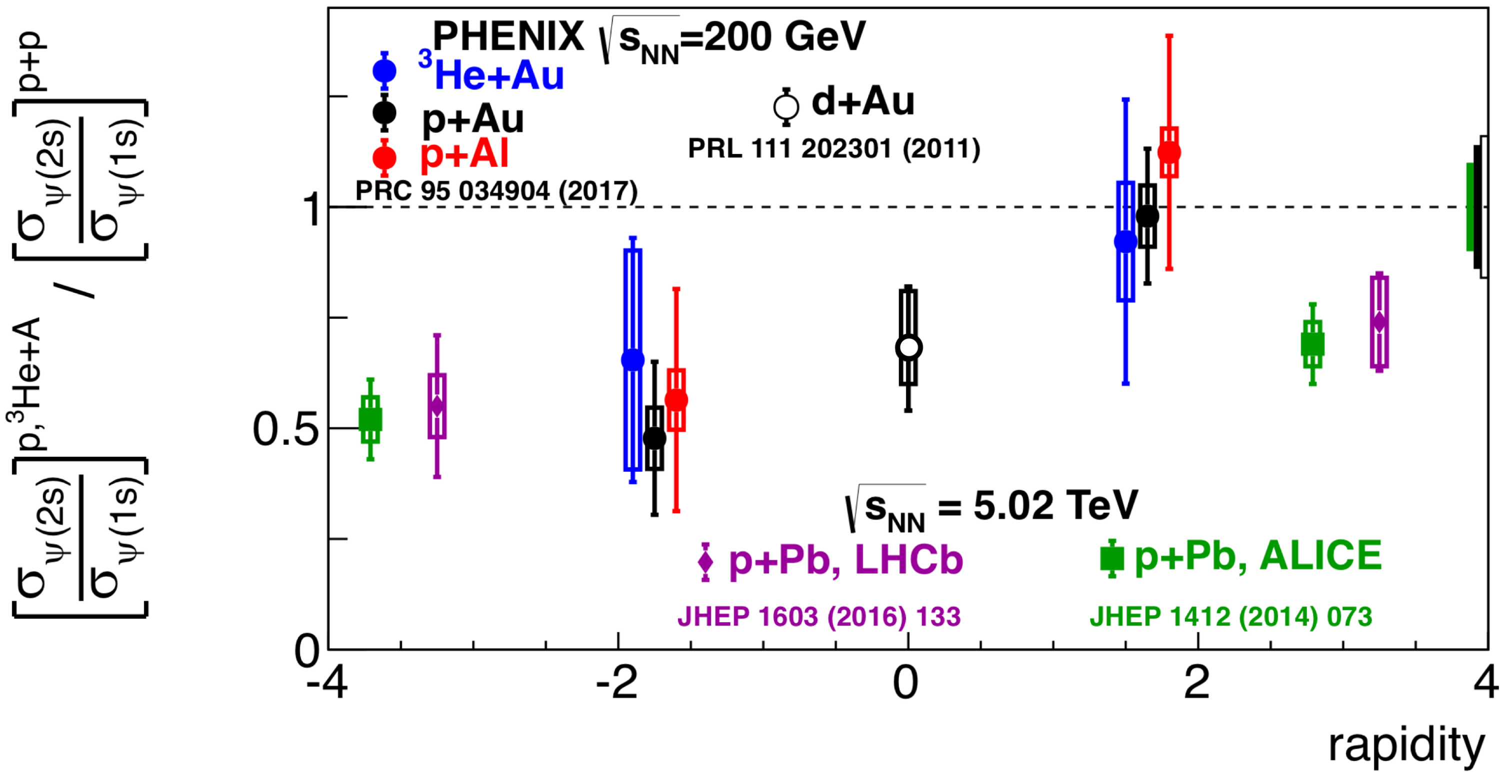
PRC 95, 034904 (2017)



- Clear J/ψ signal in both directions.
- Ψ' is relatively suppressed in Au going direction.

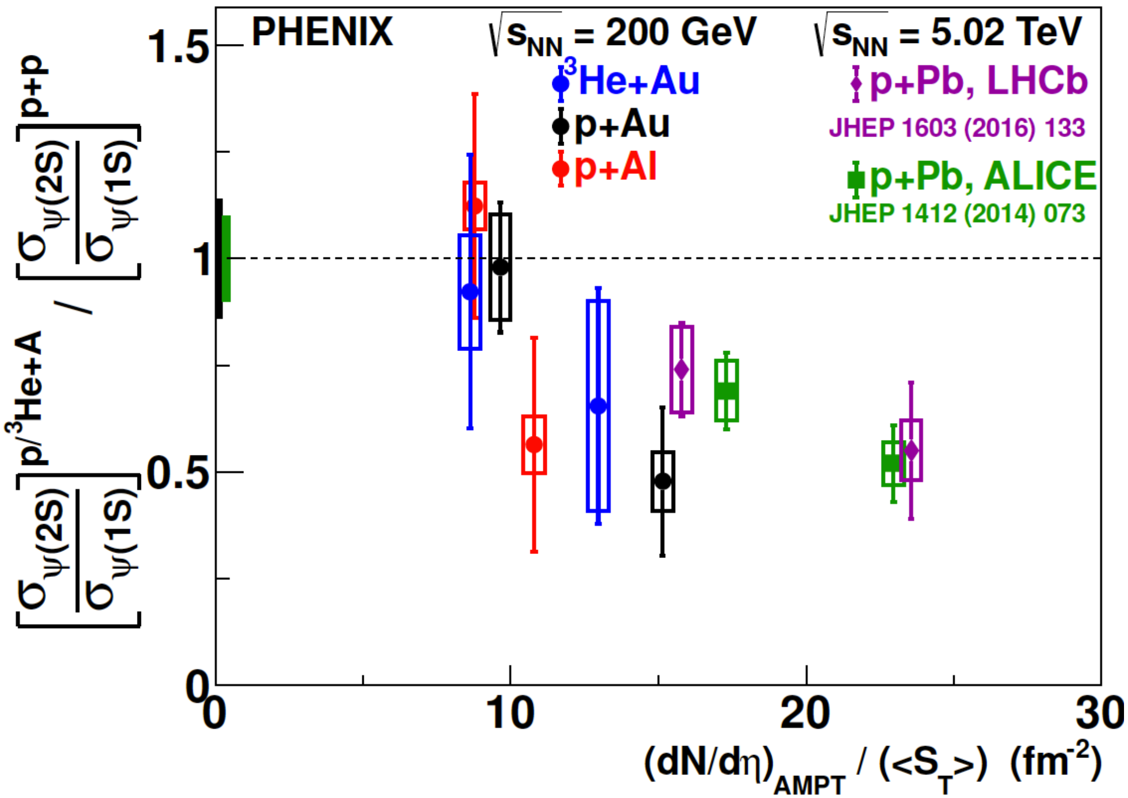
Relative ratio of ψ' to J/ψ vs rapidity

- Centrality integrated relative ratio of ψ' to J/ψ VS rapidity.



- Forward rapidity: J/ψ and ψ' have similar suppression at PHENIX.
- Backward rapidity: strong relative suppression and comparable with LHC results.

Relative ratio of ψ' to J/ψ vs co-moving particle density



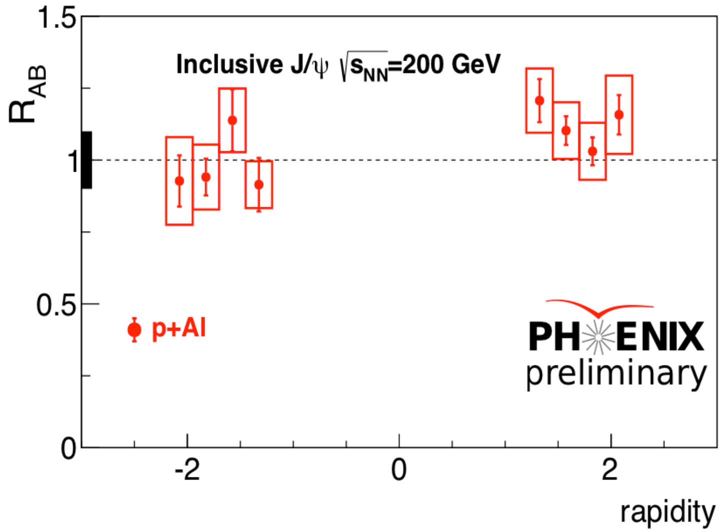
PRC 95, 034904 (2017)

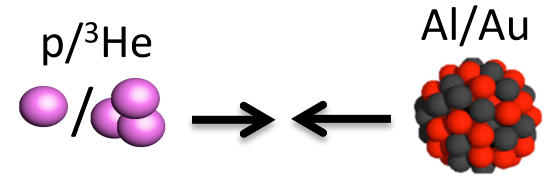
$$< S_T >= 4\pi\sqrt{< x^2 >< y^2 > - < xy >^2}$$

from Glauber model

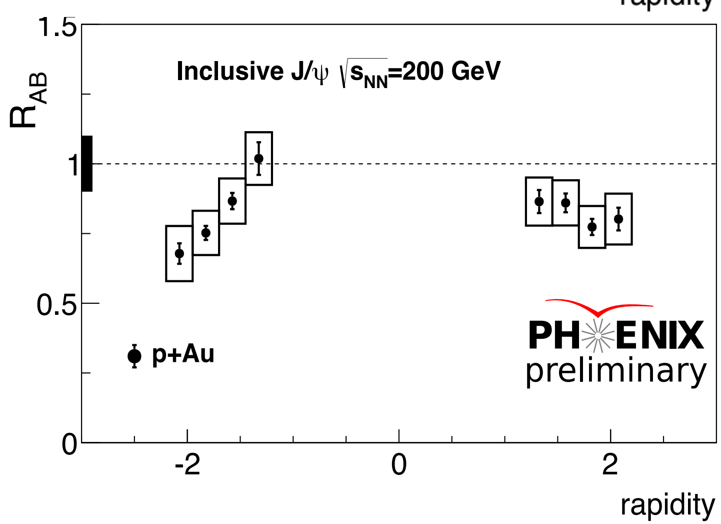
- The suppression of ψ' to J/ψ relative ratio at both RHIC and LHC scales with co-moving particle density.

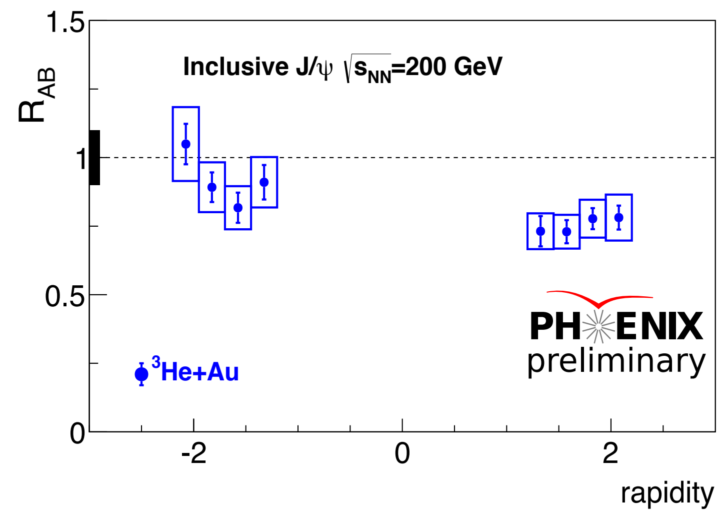
Rapidity dependent J/ψ R_{AB} in p+Al/Au, ^{3}He+Au collisions





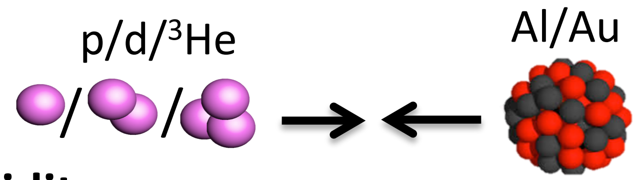
Initial or final state effects causing the difference?



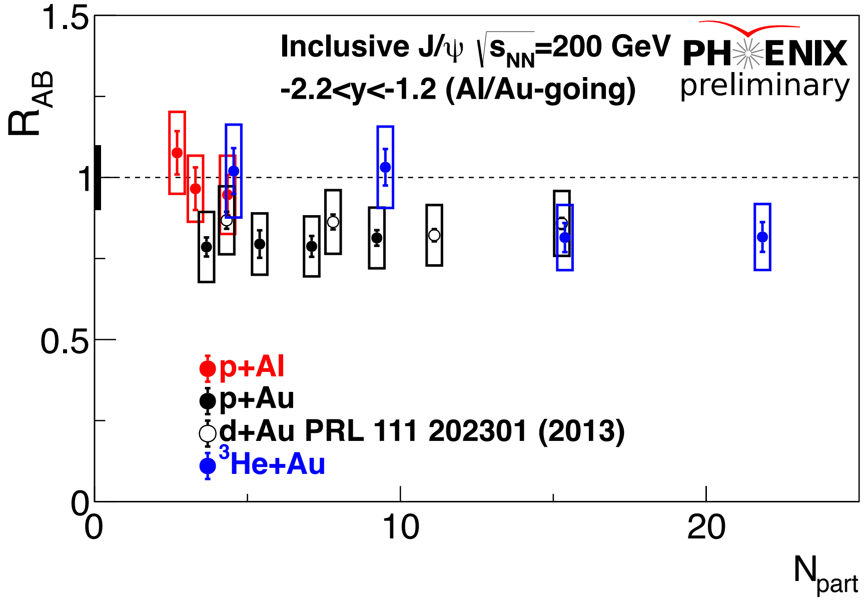


- Indication of A dependent suppression of J/ψ R_{AB} at forward rapidity and smaller nuclear modification at backward rapidity.

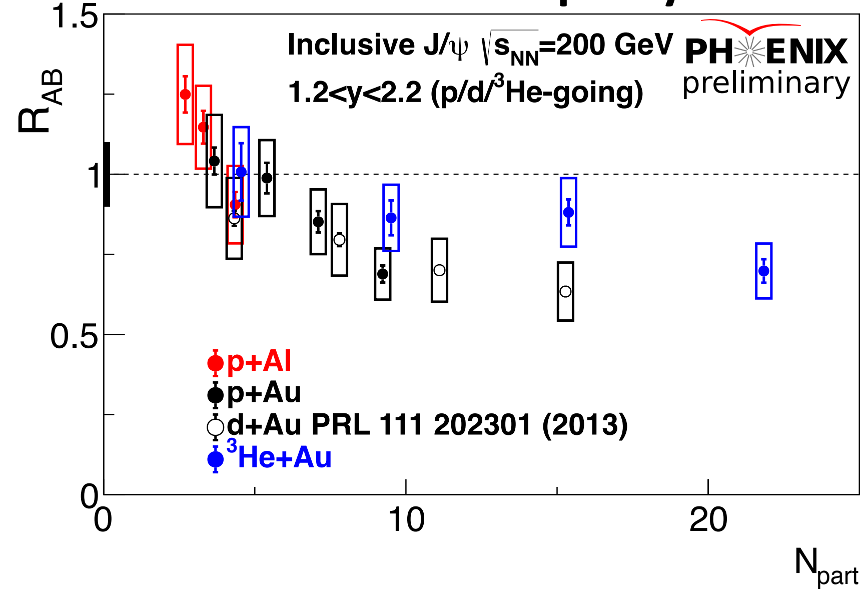
N_{part} dependent J/ψ R_{AB} in small systems



Backward rapidity

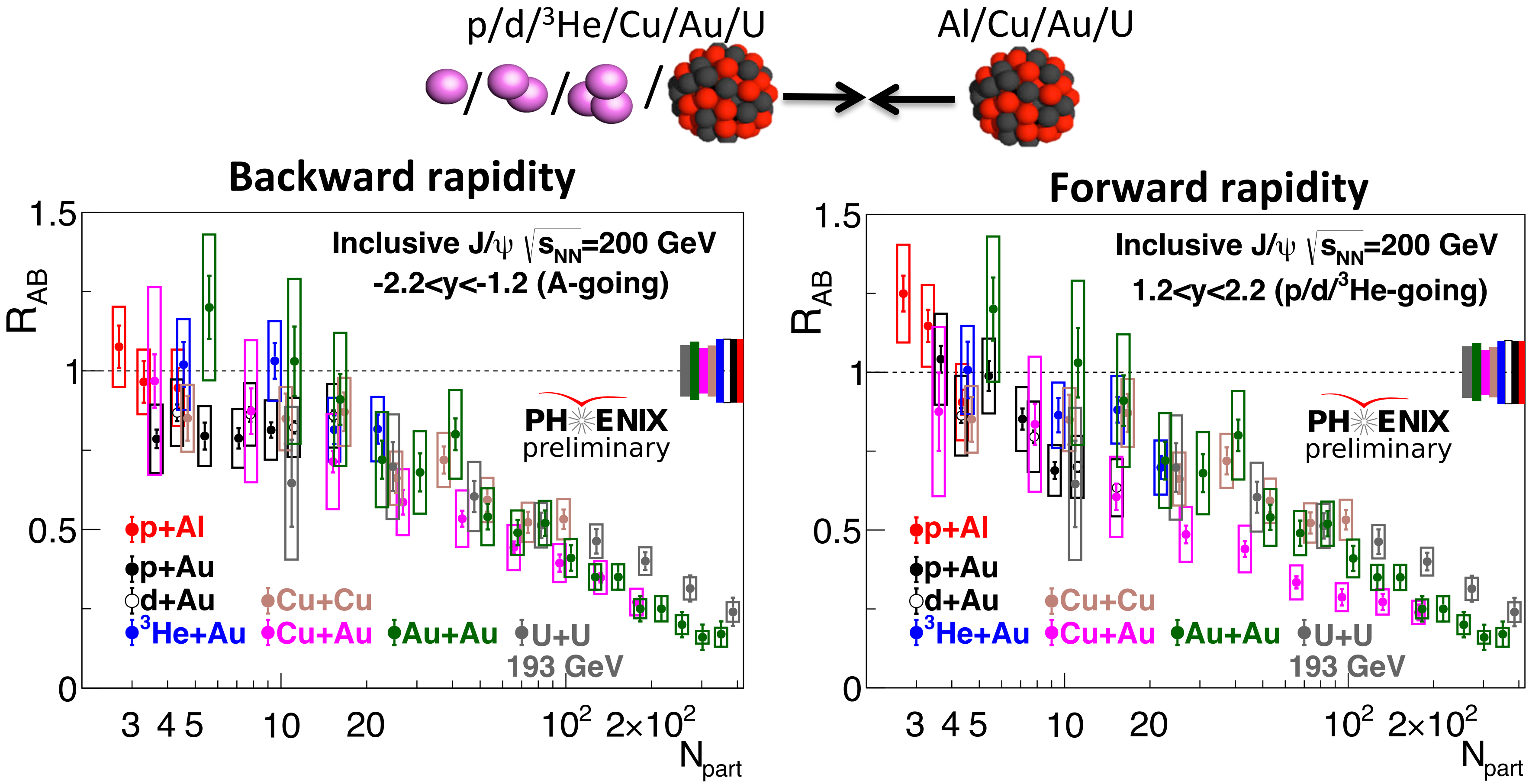


Forward rapidity



- Forward rapidity: indication of shadowing and energy loss may be the dominant effects of the suppression with relatively low hadron density.
- Backward rapidity: suggests “breakup” or co-mover may be the dominate effects with relatively high hadron density.

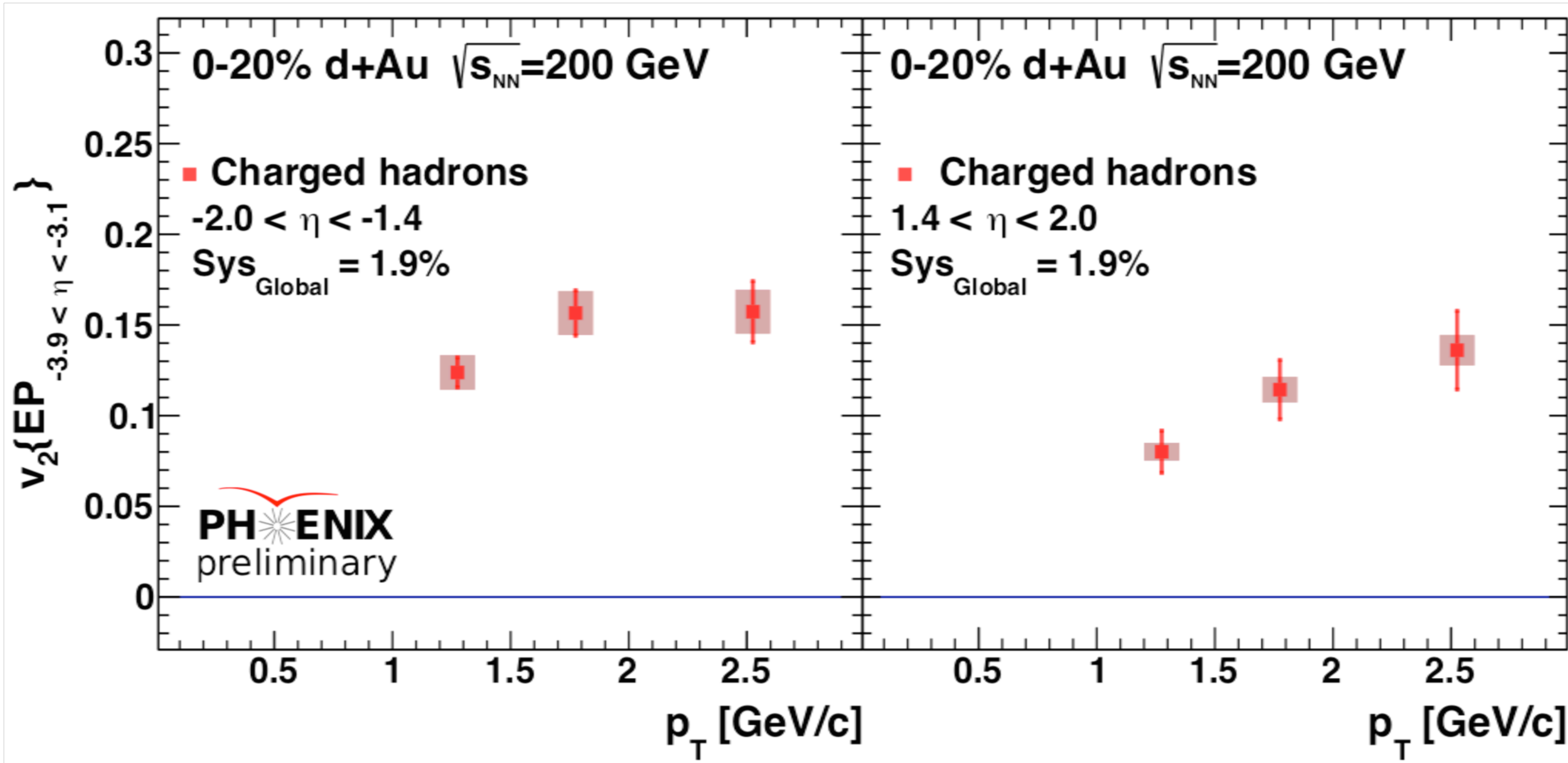
N_{part} dependent J/ψ R_{AB} in all systems



- Consistent N_{part} dependent J/ψ R_{AB} results at forward and backward rapidity in both small and large system.
- Final state effects such as color screening can not be ignored for the J/ψ measurements.

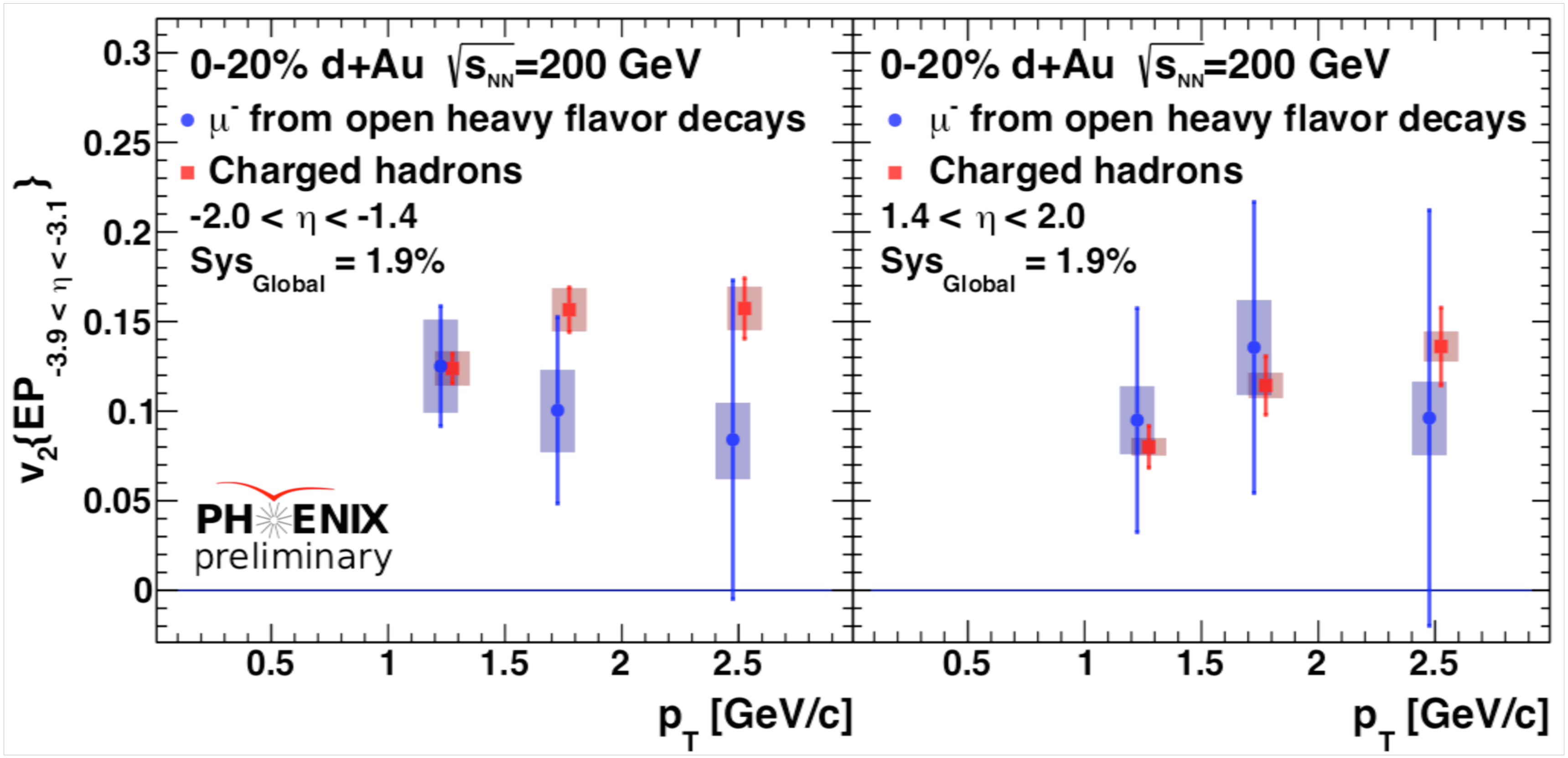
Do heavy quarks flow in small system?

- Charged hadrons flow at low p_T in forward and backward rapidity in 200 GeV d+Au collisions.



Do heavy quarks flow in small system?

- Charged hadrons flow at low p_T in forward and backward rapidity in 200 GeV d+Au collisions.



- Indication of heavy flavor muons may flow in forward and backward rapidity as well.

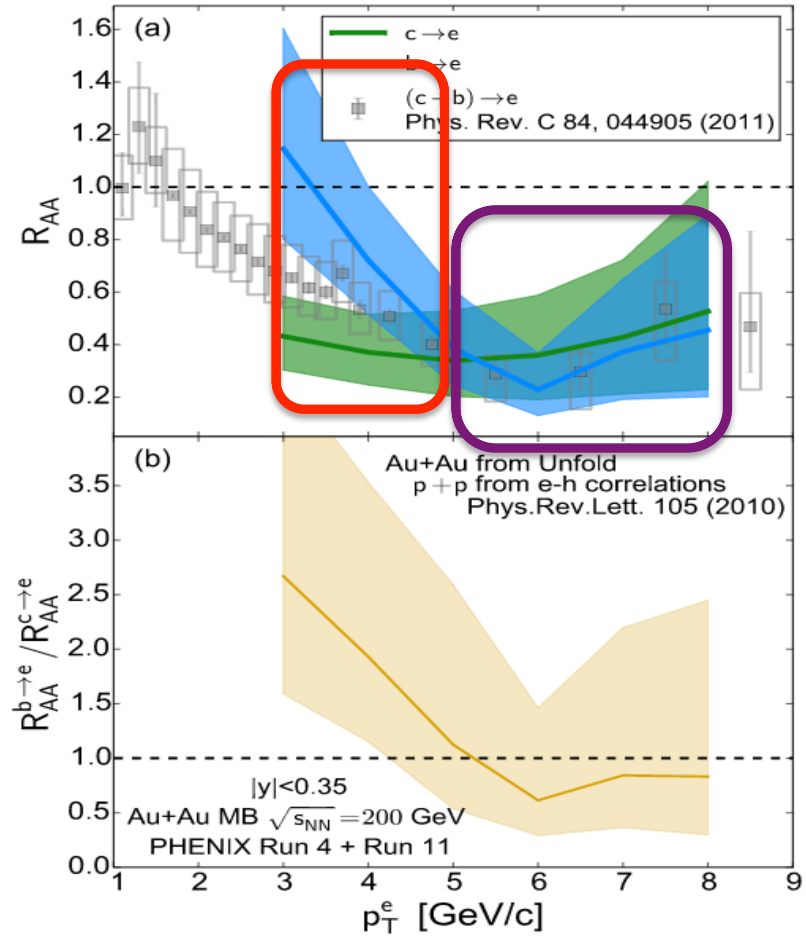
Heavy flavor measurements in Heavy Ion Collisions

- to study the Hot Nuclear Medium effects
  - Do charm and bottom quarks flow?
  - Forward and backward B to J/ψ R_{AA}

Study the Hot Nuclear Matter effect via D/B production

- From the PHENIX charm and bottom separated electron R_{AA} results at mid-rapidity,
  - Bottom has similar suppression as charm for high p_T region.
  - Bottom may be less suppressed than charm in the low p_T region.
- Consistent with the mass/ flavor dependent energy loss in the Quark Gluon Plasma (QGP):
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

PRC 93, 034904 (2016)

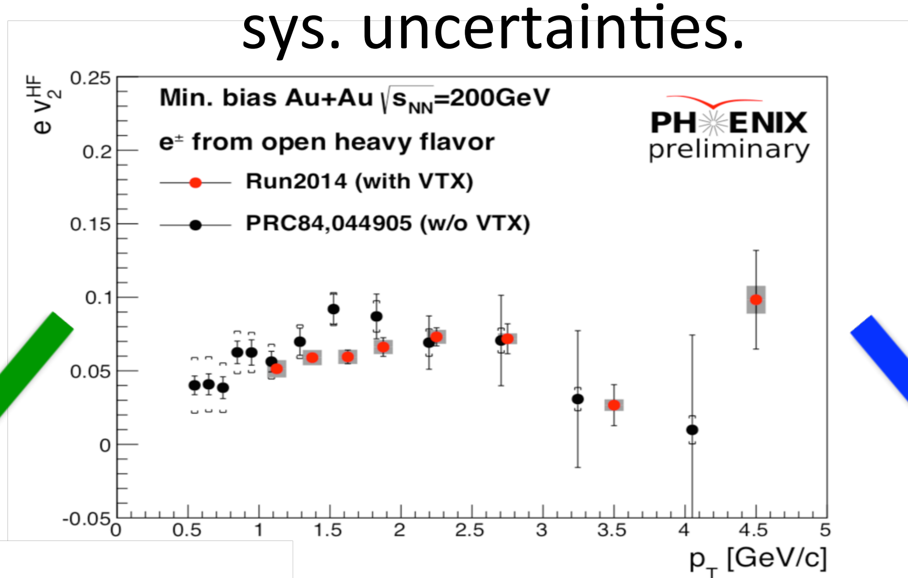


- Do heavy quarks flow in Au+Au collisions?
- Do bottom quarks and charm quarks have the same flow?

Heavy flavor electron v_2 in Au+Au collisions

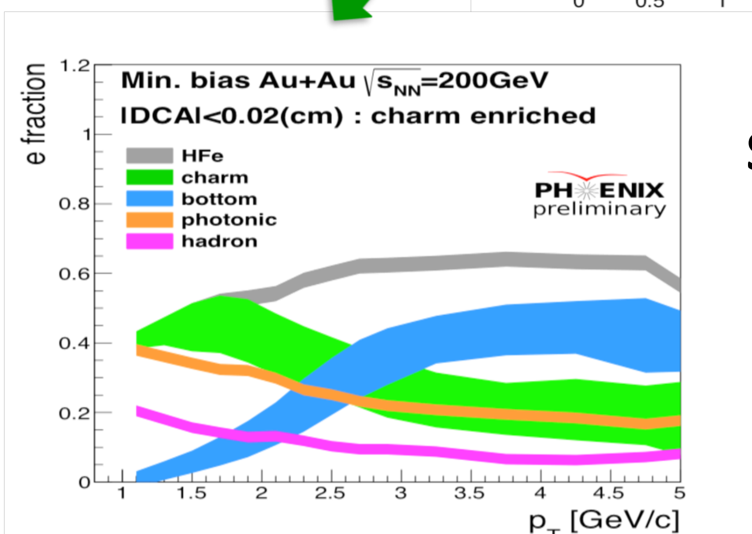
- New heavy flavor electron v_2 with (F)VTX is consistent with published results but with significantly improved stat. and sys. uncertainties.

Mid-rapidity
$|y| < 0.35$



Select charm enriched sample

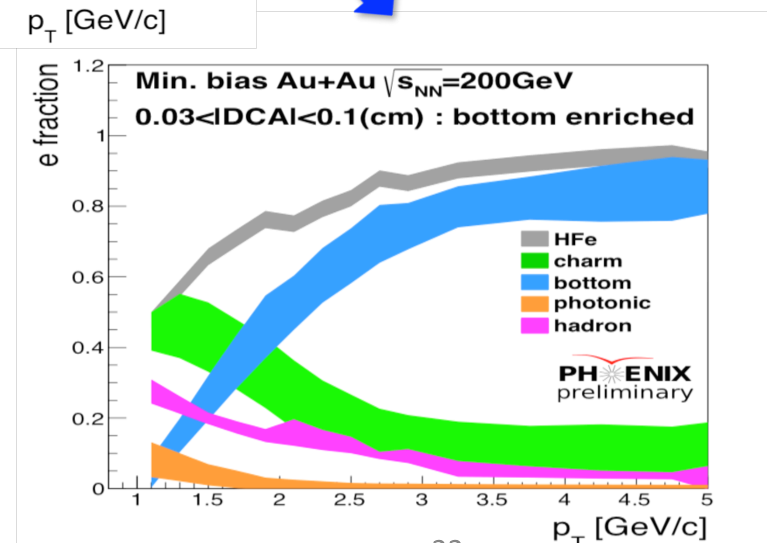
Select bottom enriched sample



Simultaneously extract

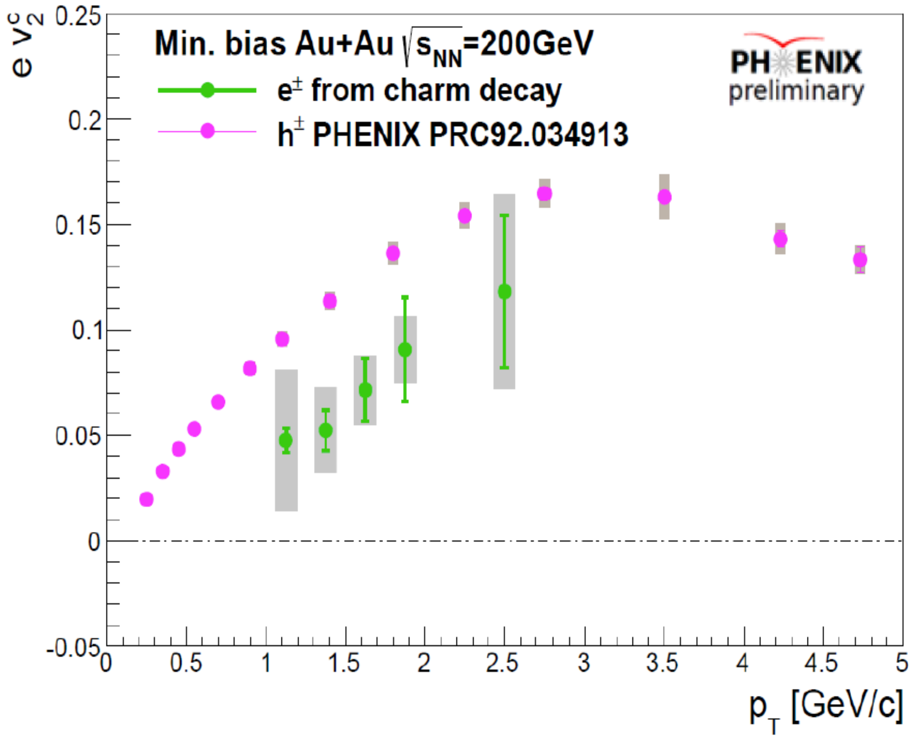
$v_2(c \rightarrow e)$

$v_2(b \rightarrow e)$

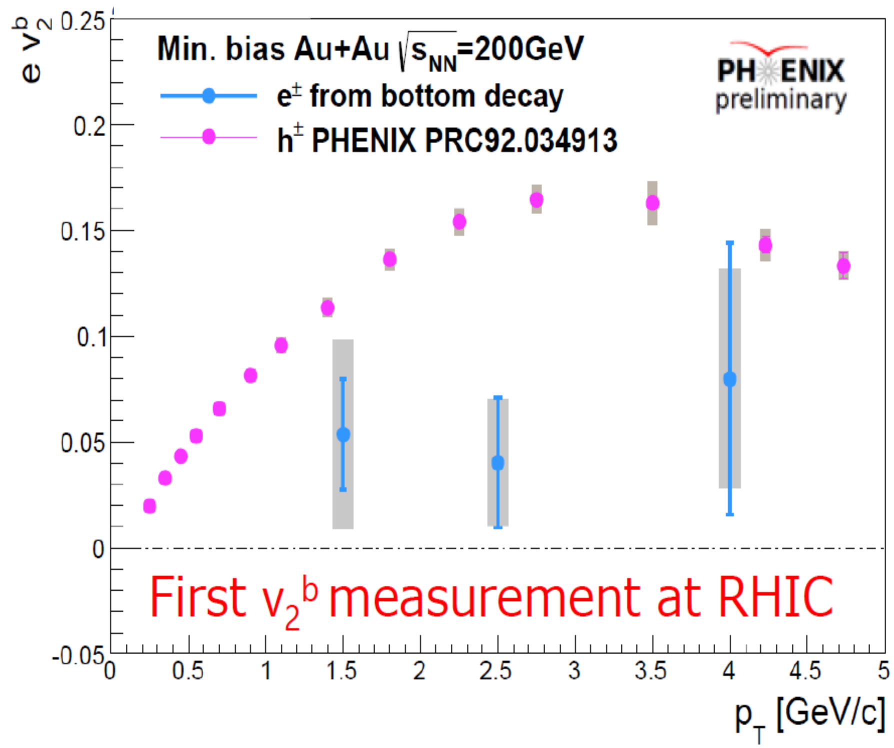


Charm electron v_2 and Bottom electron v_2

$v_2(c \rightarrow e)$



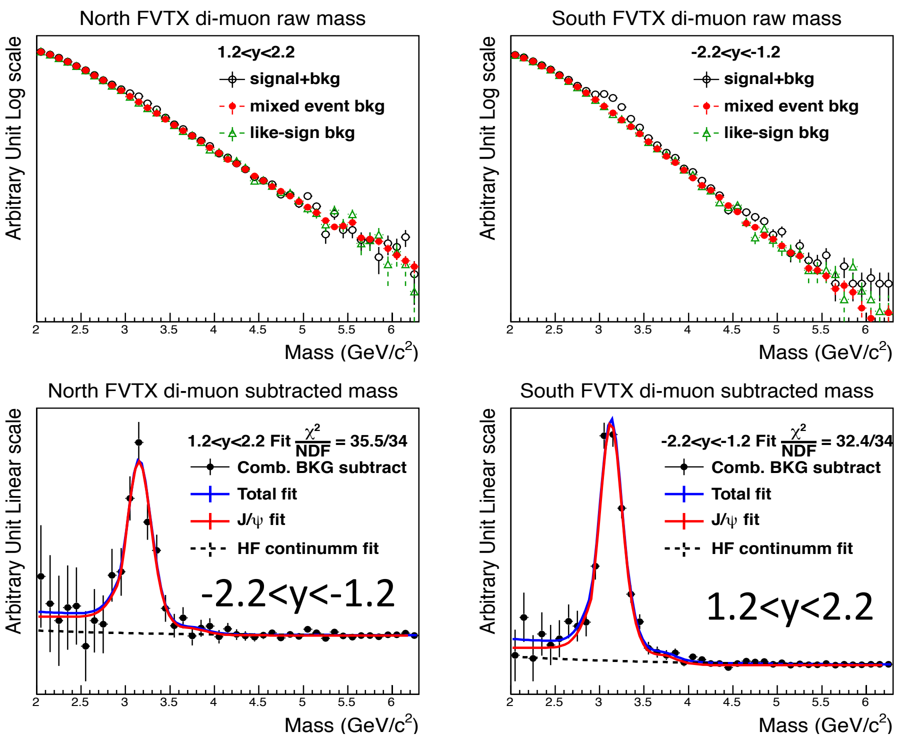
$v_2(b \rightarrow e)$



- Significant charm electron v_2, smaller magnitude than charged hadron v_2 might due to charm decay kinematics.
- Indication of non-zero bottom v_2.
- Likely $v_2(b \rightarrow e) < v_2(c \rightarrow e)$.

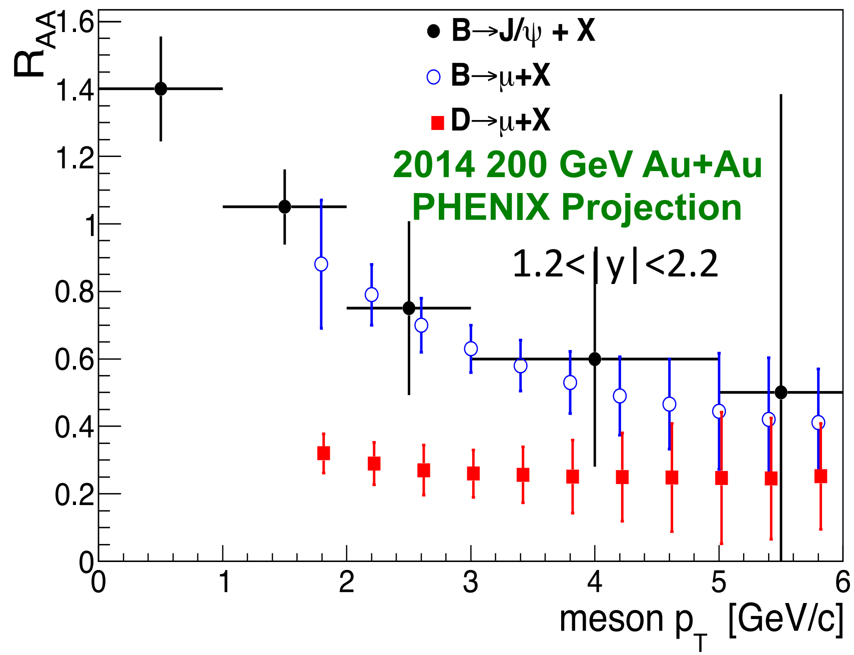
Ongoing analysis of forward B to J/ψ in Au+Au collisions

- Analysis framework has been developed for the B to J/ψ studies in p+p and Cu+Au collisions.
- Analysis procedure has been updated and data processing is underway.
- The challenge is to minimize systematics.



Clear J/ψ found in Au+Au collisions

Projection of B to J/ψ, B to $\mu^{\pm}$ and D to $\mu^{\pm}$ R_{AA}



Summary

- Forward/backward di-muon correlations provide information about the sub-process of the charm/bottom production.
- Differential suppression of ψ' to J/ψ relative ratio and J/ψ nuclear modification measurements in small system shows strong evidence of final state effects.
- Evidence of non-zero heavy flavor v_2 in small system.
- First bottom electron v_2 measurement at RHIC indicates flavor/mass dependent thermalization in the QGP.

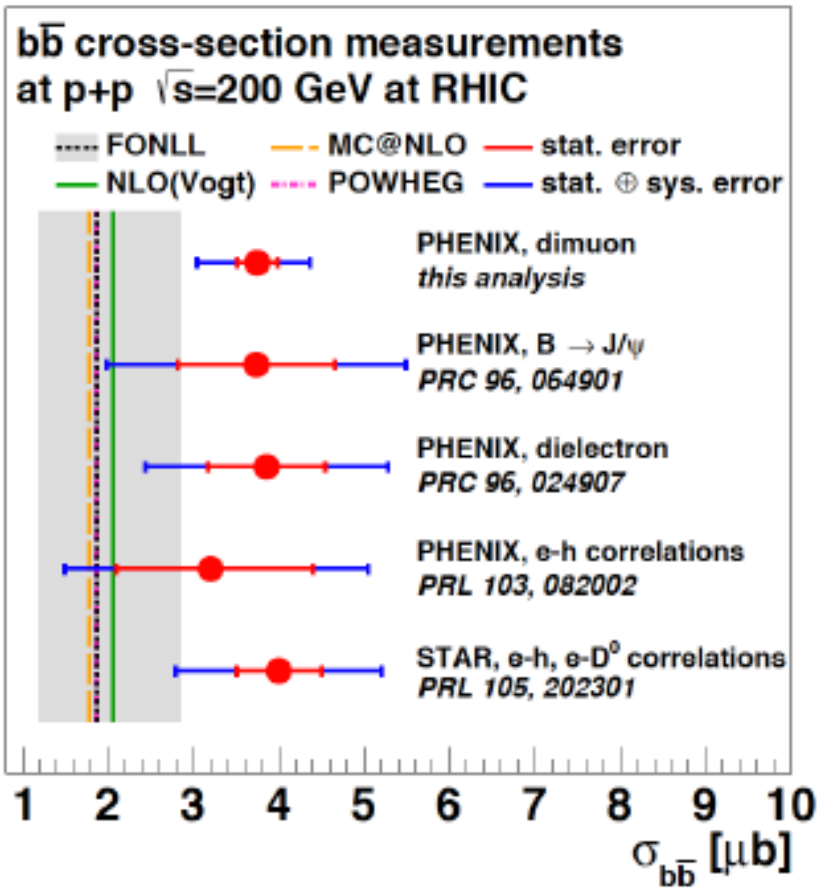
Outlook

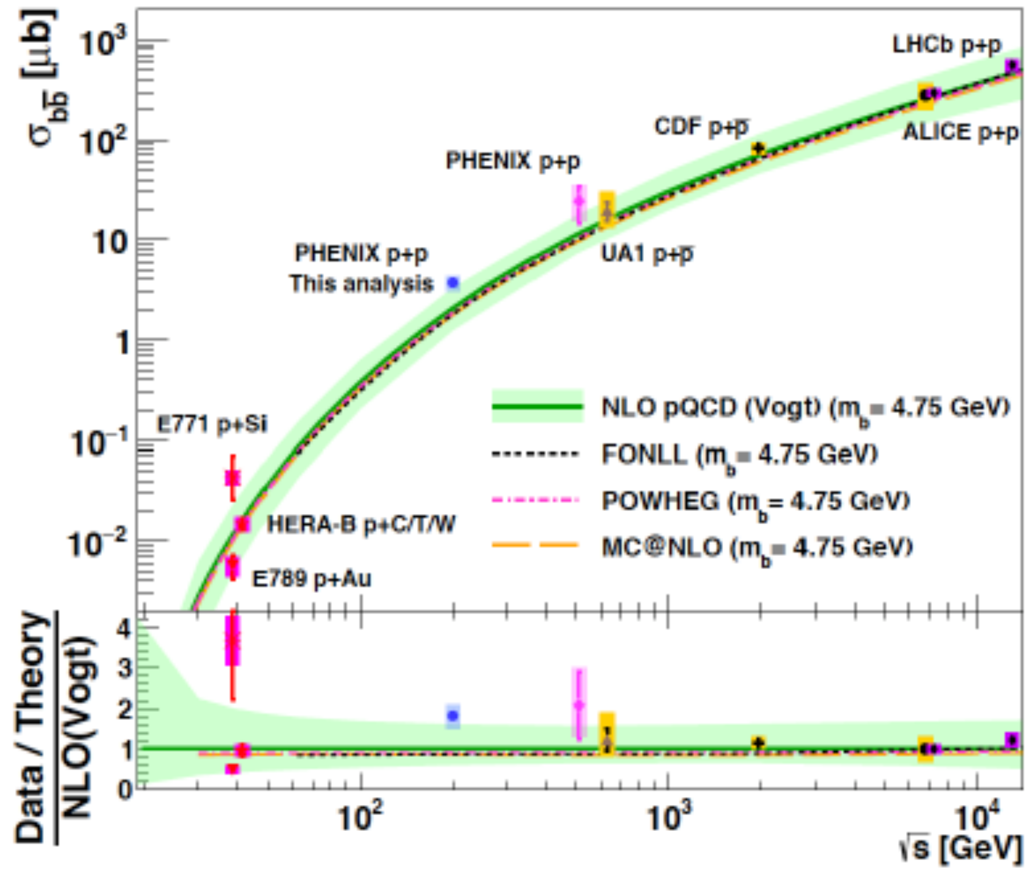
- Large data set in various types of heavy ion collisions collected at PHENIX provide opportunities to study
  - ψ' to J/ψ ratio in run14/16 Au+Au collisions to demonstrate hot nuclear matter effect like color screening in QGP.
  - Nuclear modification and thermalization properties of D/B separate single electrons/muons in run14/16 Au+Au collisions with higher statistics.
  - Forward/backward B to J/ψ via di-muon channel in run14/16 Au+Au collisions to understand hot nuclear matter effect.
  - …
- More to come soon.

Backup

Bottom cross section in p+p at PHENIX

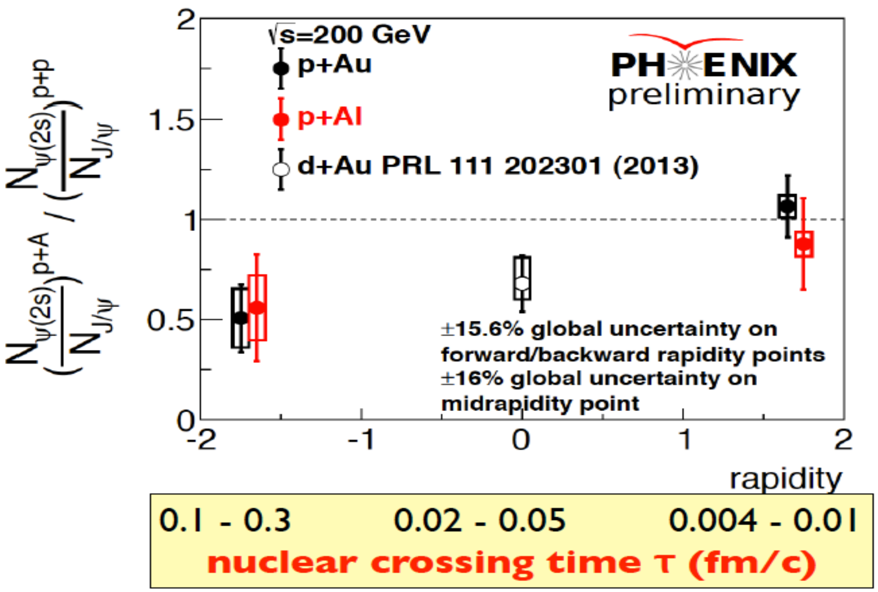
- Consistent with NLO pQCD calcutions



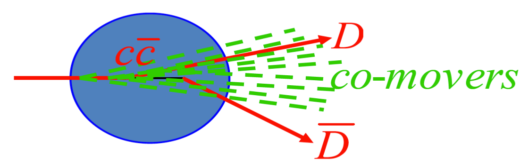


Possible contributions to the differential suppression

- Time spent inside the nucleus
  - Longer time and path length spent by the cc-bar in Au- (Al-) going direction than the p- going direction.



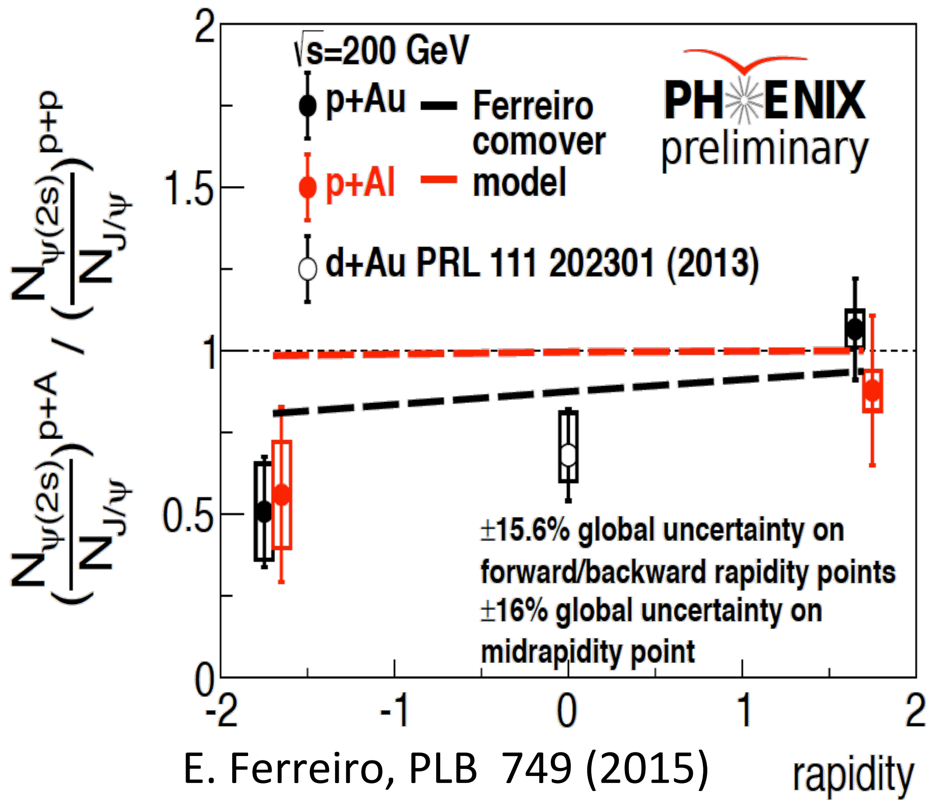
  - According to the crossing time τ dependent model fit on world wide data (PRC 87 (2013) 054910), very small contributions.
  - This effect can not explain the backward rapidity suppression.



- Co-movers absorption?
  - Charmonium can break up with the presence of co-movers.
  - Higher particle density in the Au- (Al-) going direction may cause larger suppression.

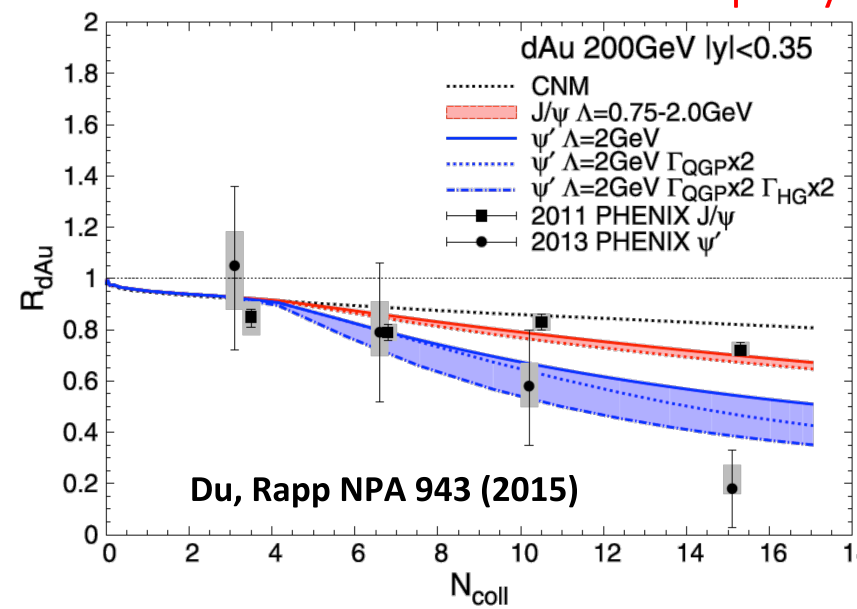
Relative ratio of ψ' to J/ψ VS rapidity

- Centrality integrated relative ratio of ψ' to J/ψ VS rapidity for p+Au, p+Al and d+Au (mid-rapidity).



E. Ferreiro, PLB 749 (2015)

Need calculations at forward rapidity

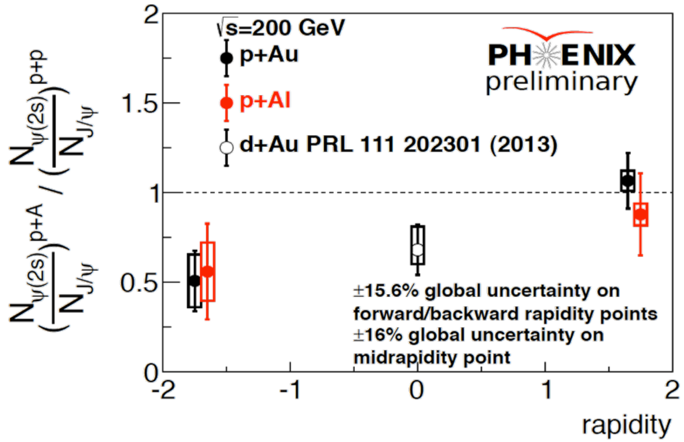


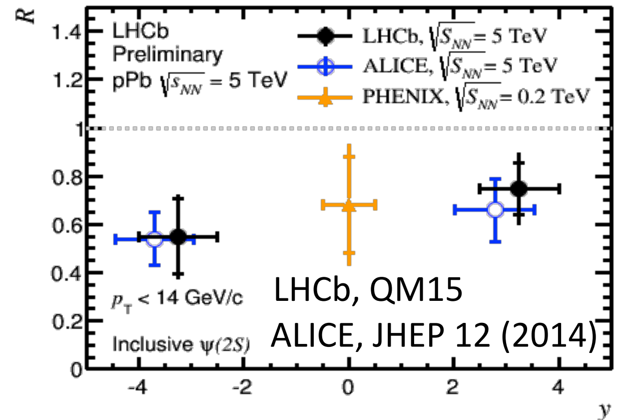
New calculation allows for short QGP phase in central collisions + hadron resonance gas.

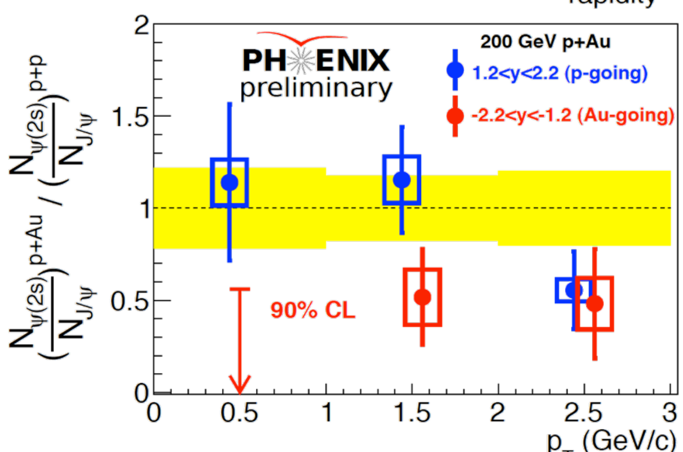
- Result is generally consistent within significant statistical uncertainties with co-mover dissociation model.
- New model calculations? Plasma effect in central collisions?

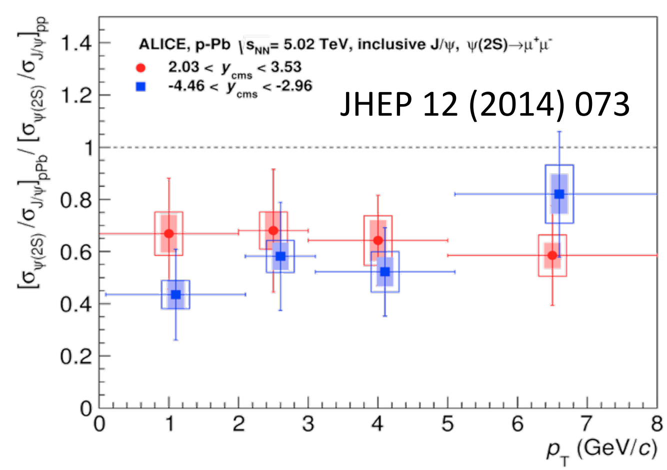
Comparison with the LHC results

- Similar suppression trend for the rapidity dependence. More suppression in LHC especially in the forward rapidity?







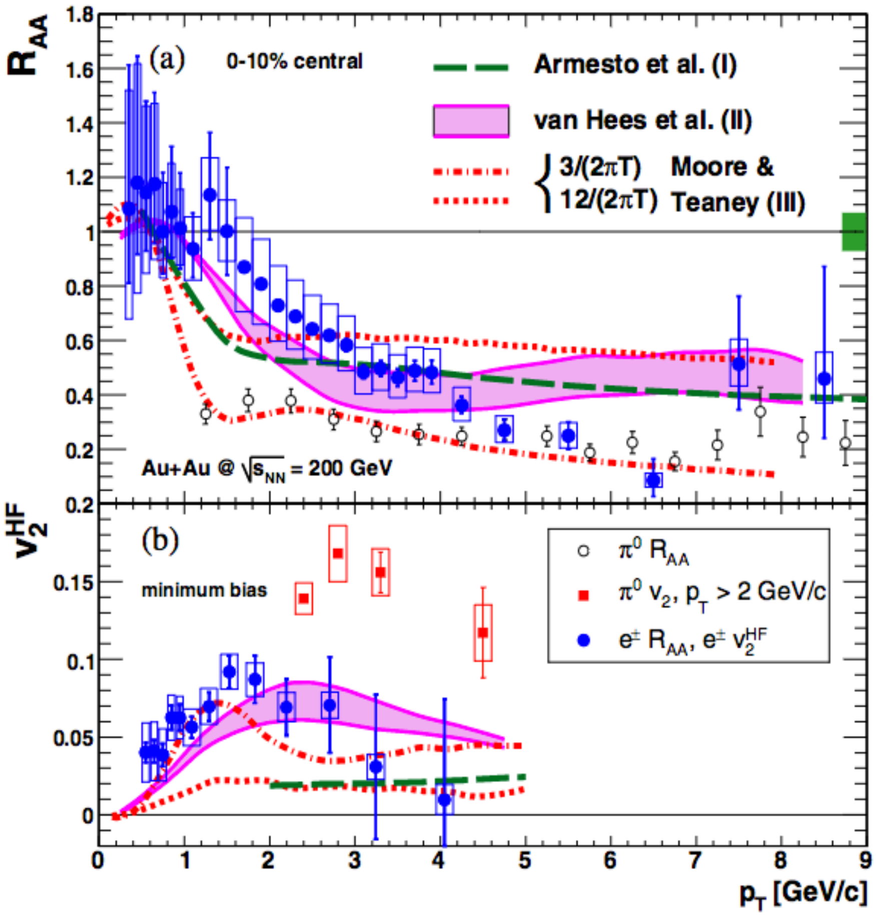


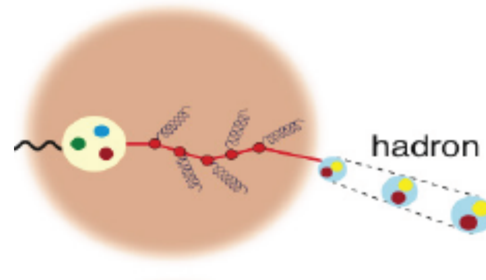
- Larger co-mover contribution in the LHC era? Gluon saturation change spectroscopic charmonium states ?

Study the Hot Nuclear Matter effect via D/B production

- Suppression of the inclusive Heavy flavor R_{AA} provides evidence of strong coupling between the heavy flavor and medium.

PRL 98, 172301 (2007)

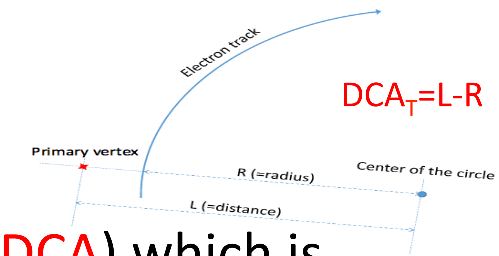




- Light hadron and heavy flavor production have different suppression, flavor dependent coupling?
- Need to separate charm and bottom and study the mass dependent quark energy loss.

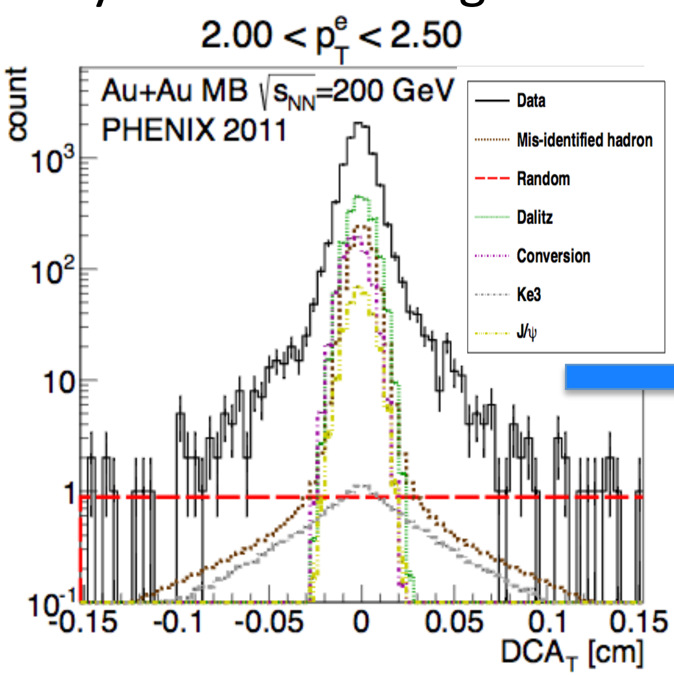
Analysis strategy to separate charm and bottom

- Based on different lifetimes and decay kinematics.
- Decay length (cτ):
  - Charm hadron: $c\tau(D^0)=123\mu m$, $c\tau(D^{\pm})=312\mu m$.
  - Bottom hadron: $c\tau(B^0)=455\mu m$, $c\tau(B^{\pm})=491\mu m$.

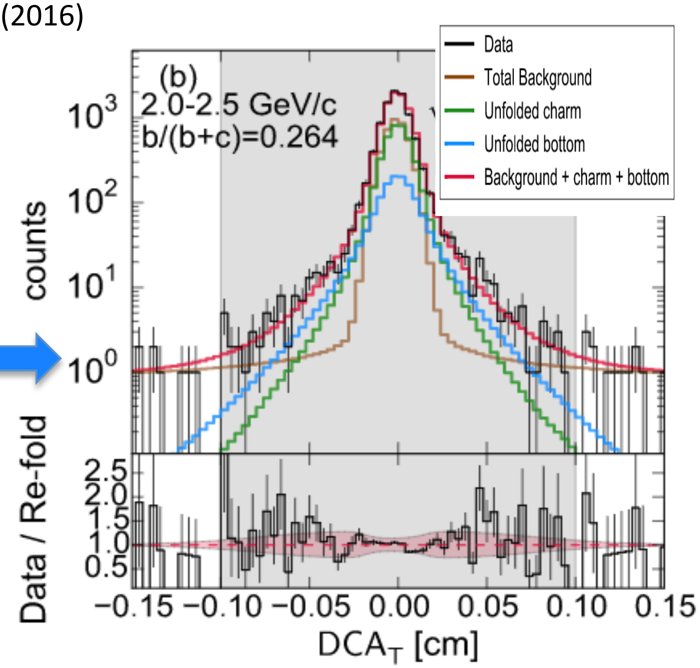


- Measure the Distance of Closet Approach (DCA) which is proportional to the decay length.
- Simultaneously extract statistically separated charm and bottom via Bayesian Unfolding.

PRC 93, 034904 (2016)

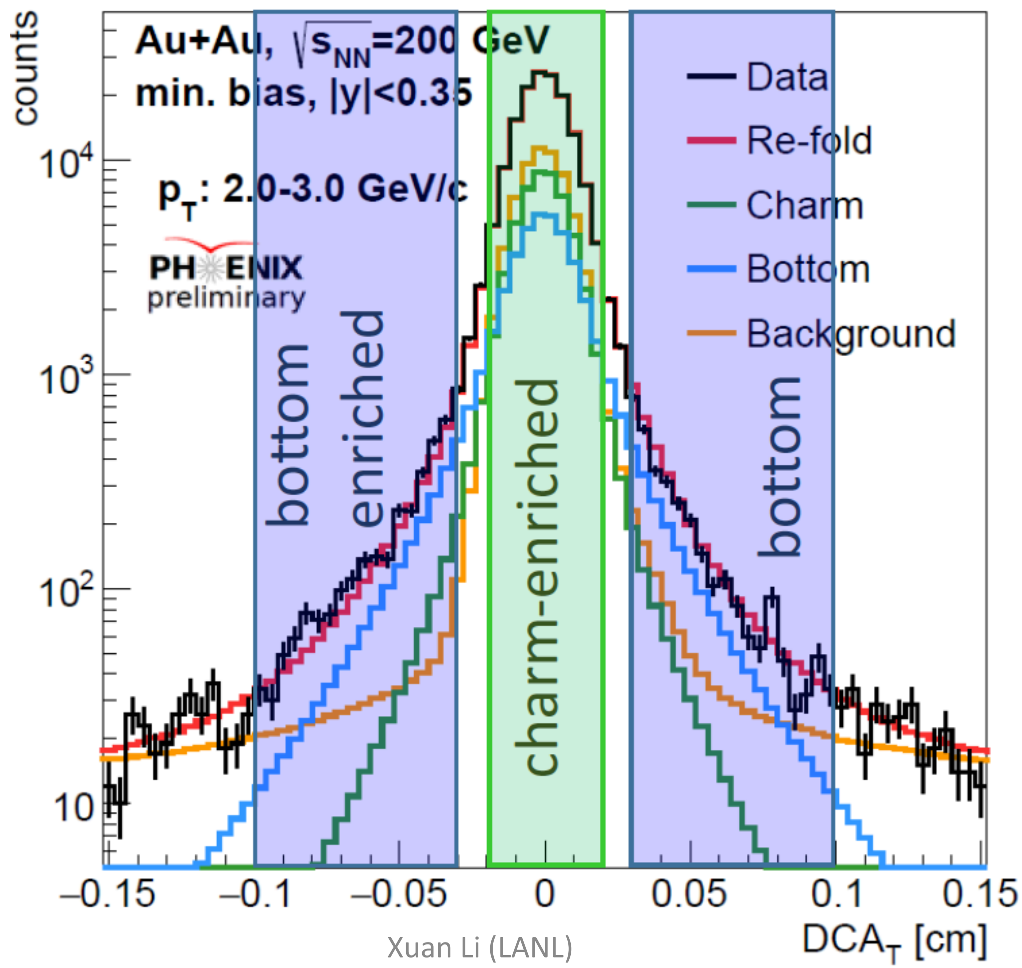


Unfolding



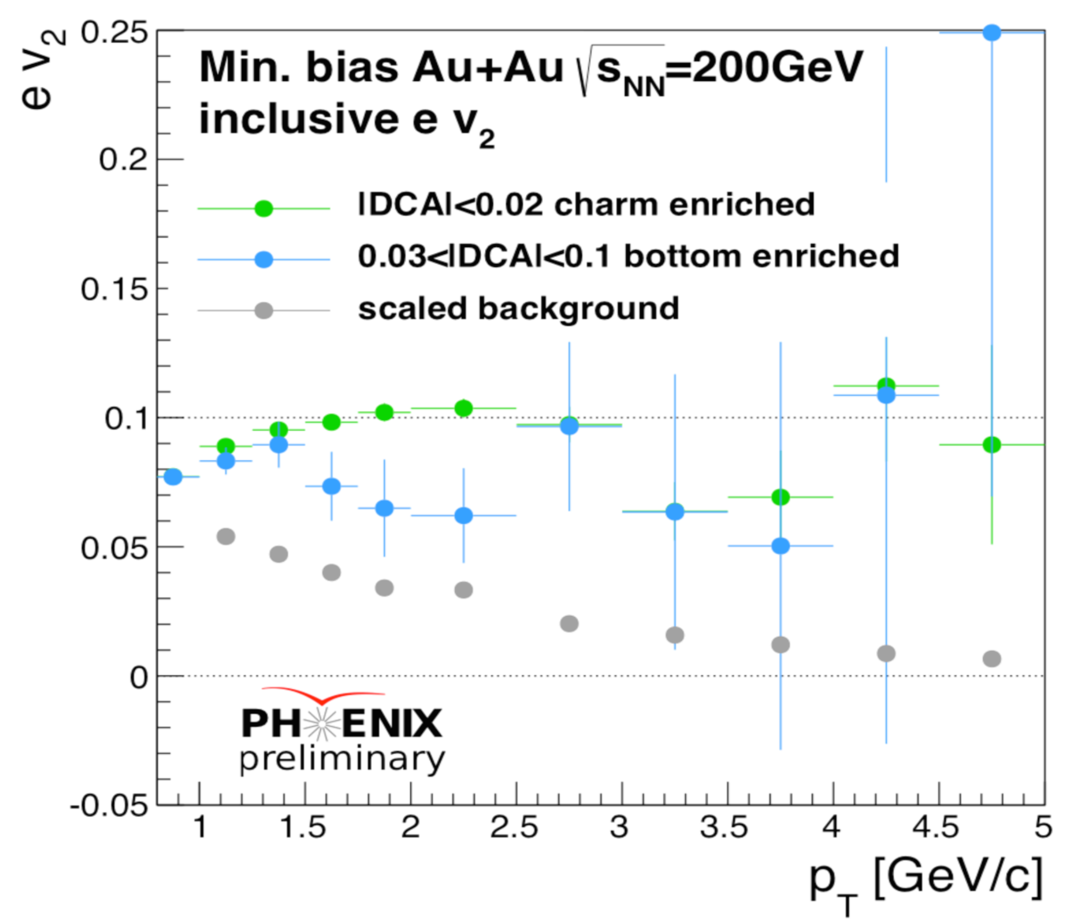
Select charm (bottom) enriched sample based on electron DCA_T

- The fraction of charm and bottom varies in different DCA_T region.

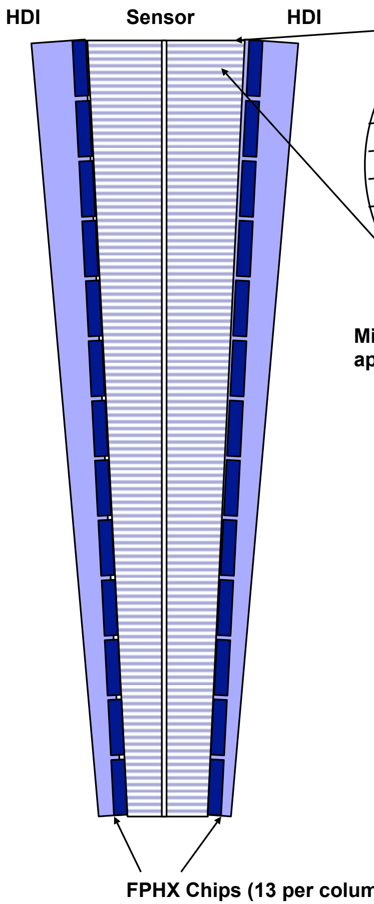


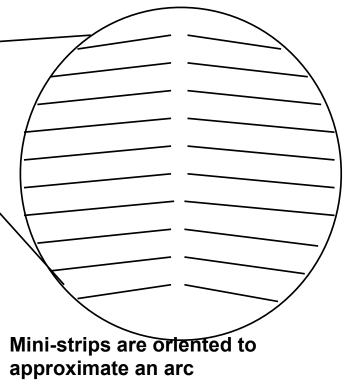
Charm and bottom enriched v_2 measurements

- Indication of mass/flavor dependence for p_T>1.5 GeV/c.

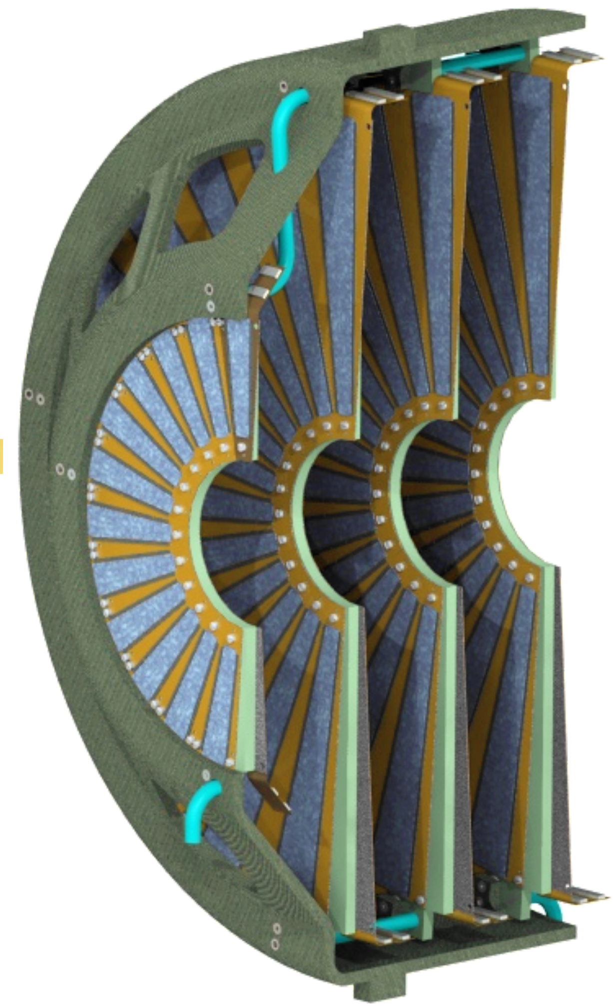


The Forward Vertex Detector (FVTX)

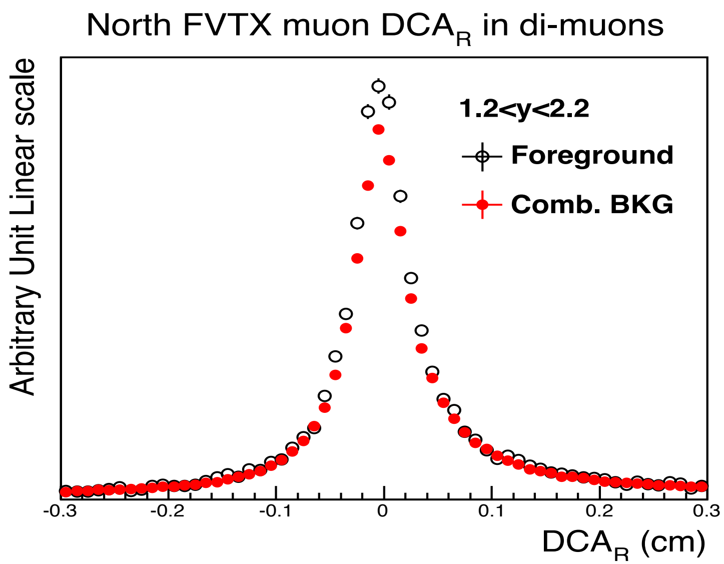


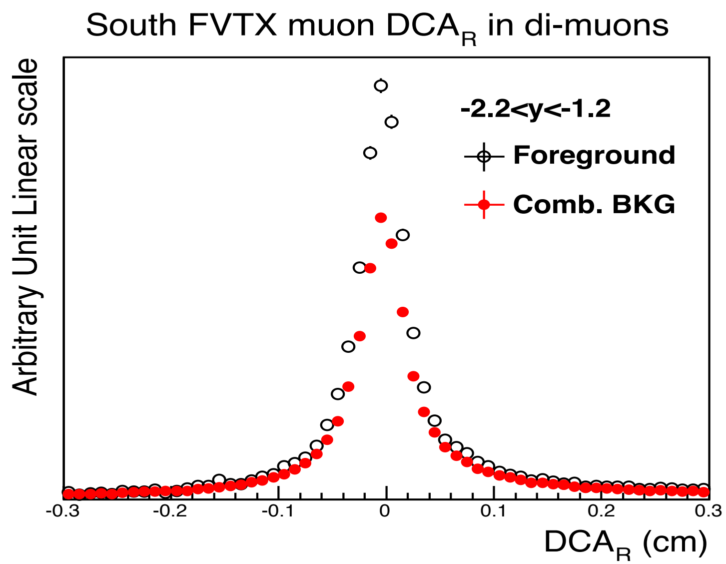


- Sensor
  - 2 columns of strips
  - 1664 strips per column
  - strip length 2.8 to 11.2 mm
  - 75 micron spacing
  - 48 wedges per disk (7.5˚/ sensor, 15˚/wedge)
  - 0.5 mm overlap with adjacent wedges
- FPHX Chip
  - 1 column readout
  - 128 channels
  - ~ 70 microns channel spacing
  - Dimensions –9mm x 1.2 mm



Muon DCA_R of good J/ψs in Au+Au collisions





Single muon DCA_R in Au +Au simulation