Recent open heavy flavor measurements at PHENIX

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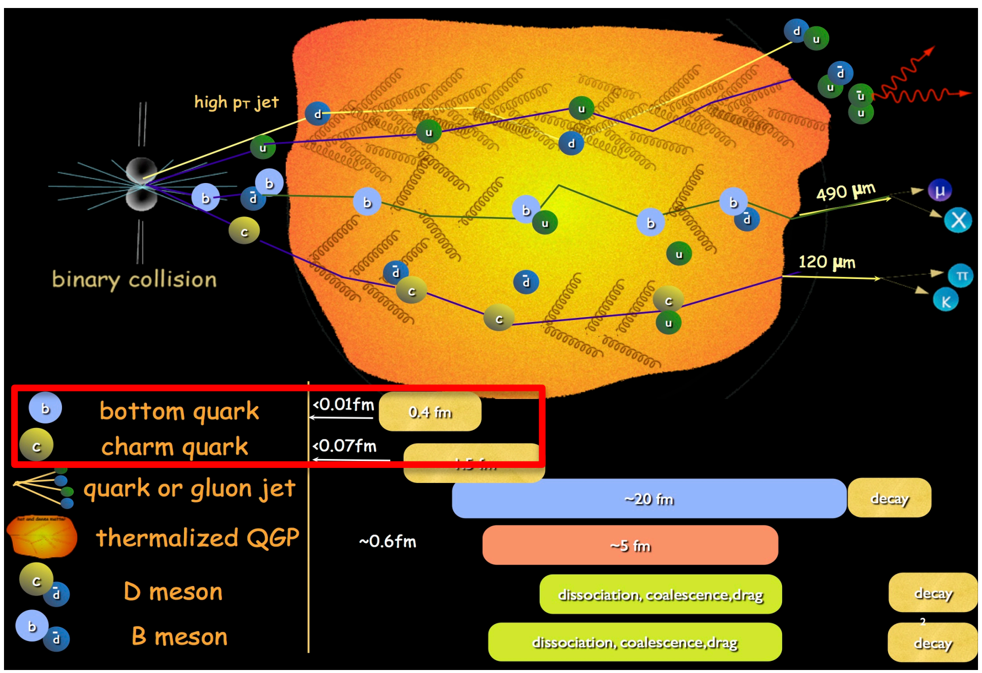
For the PHENIX Collaboration

Outline

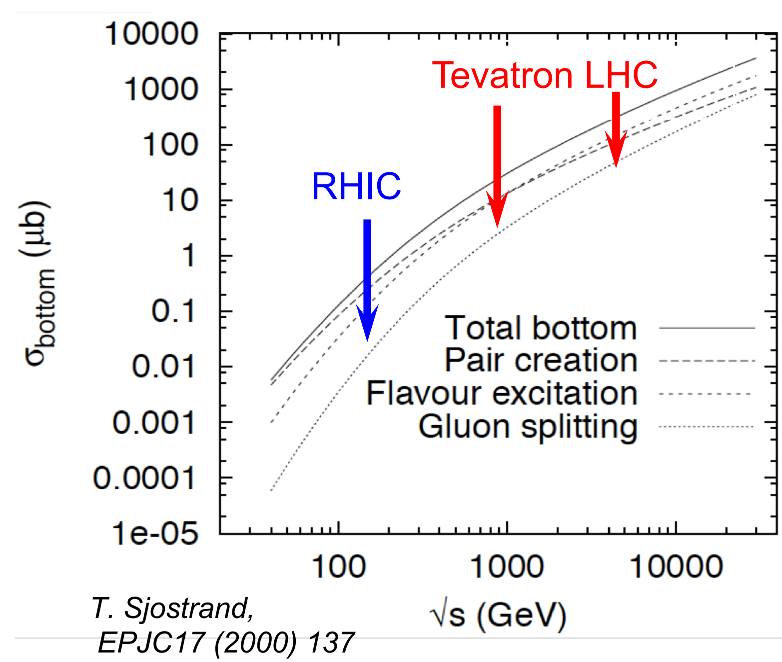
- Motivation
- Overview of RHIC and PHENIX
- Recent PHENIX open heavy flavor measurements
  - Inclusive heavy flavor measurements
    - Single muon v_2 from heavy flavor decays in 200 GeV d+Au collisions.
  - Charm/bottom separated measurements
    - Charm/bottom decay single electron measurements in 200 GeV p+p collisions.
    - Charm/bottom decay single electron R_{AA} and v_2 in 200 GeV Au+Au collisions.
    - Ongoing analysis of charm/bottom decay single muon and B to J/ψ measurements in 200 GeV p+p and 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 ($m_c/m_b >> \Lambda_{QCD}$).
- The number of heavy flavor quarks is conserved.
- Disentangle different heavy flavor production mechanisms at RHIC energies.

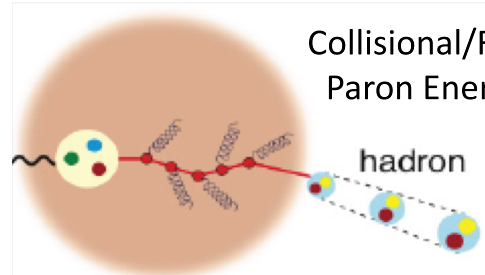


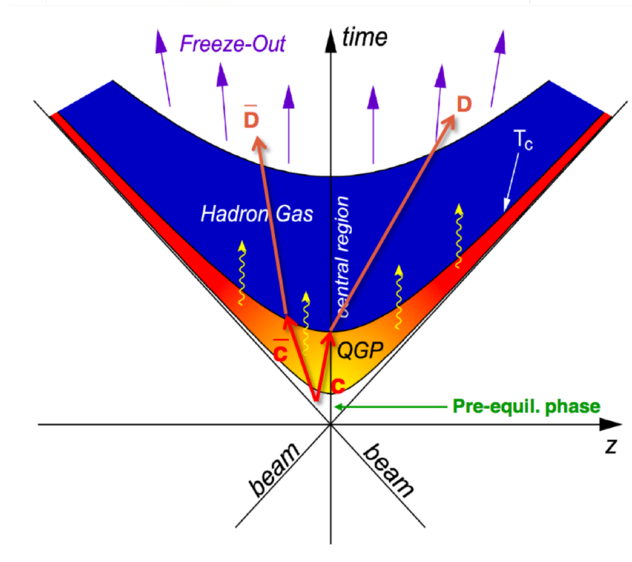
Bottom cross section in PYTHIA 6



Heavy Flavor Production in Heavy Ion Collisions

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

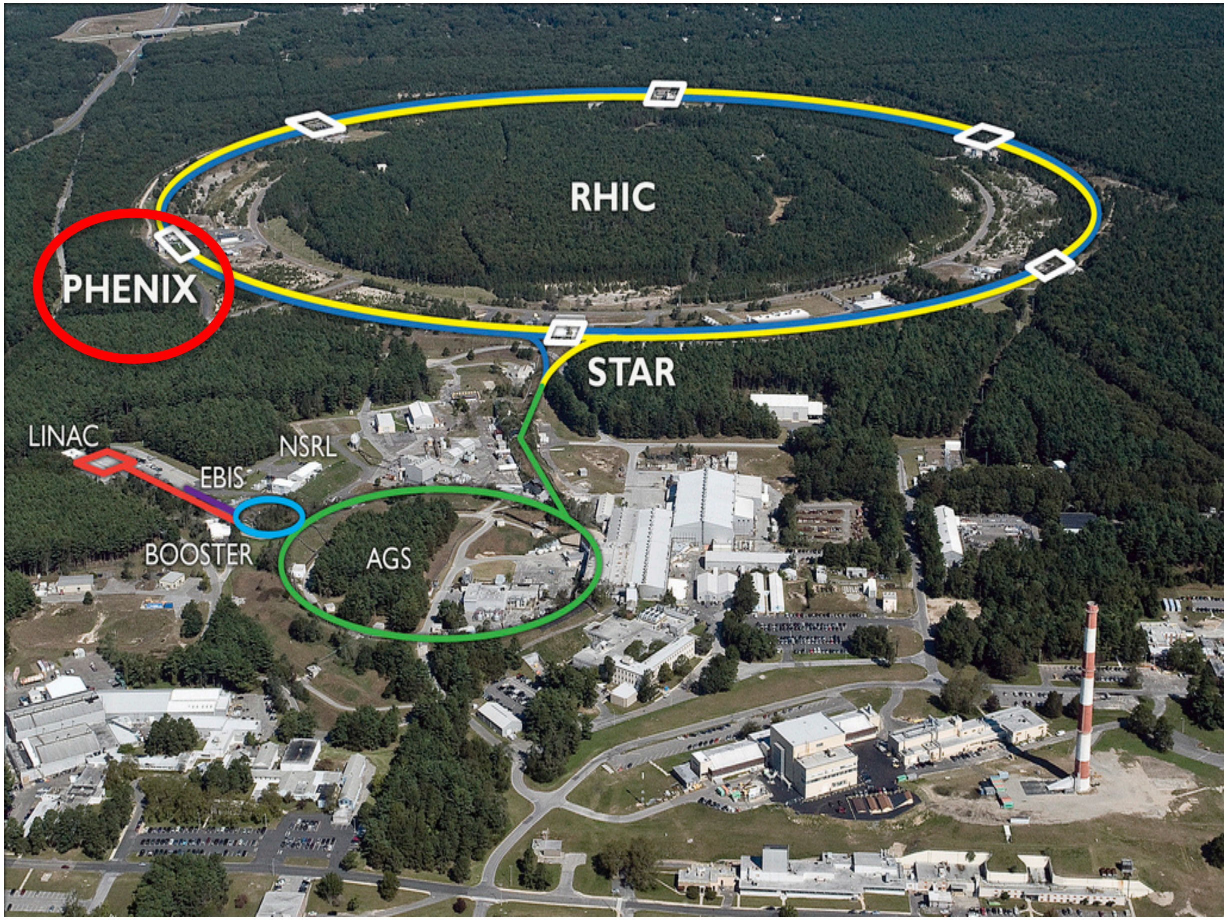


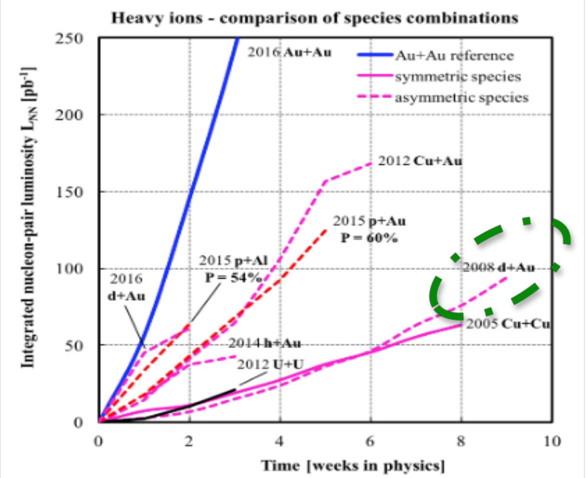


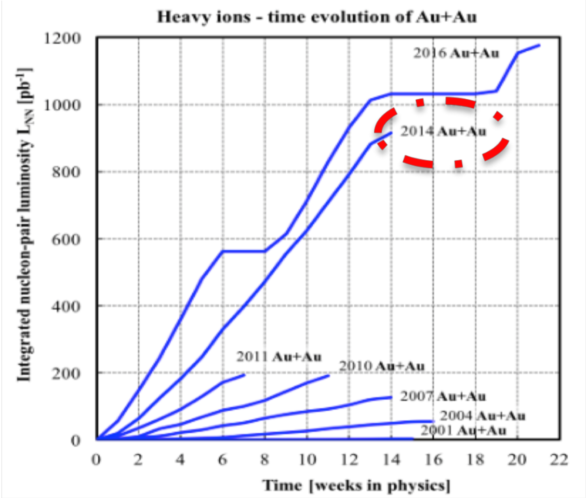
- Need to measure multiple observables in different processes to isolate the initial/final state and cold/hot nuclear matter effects.

Overview of RHIC

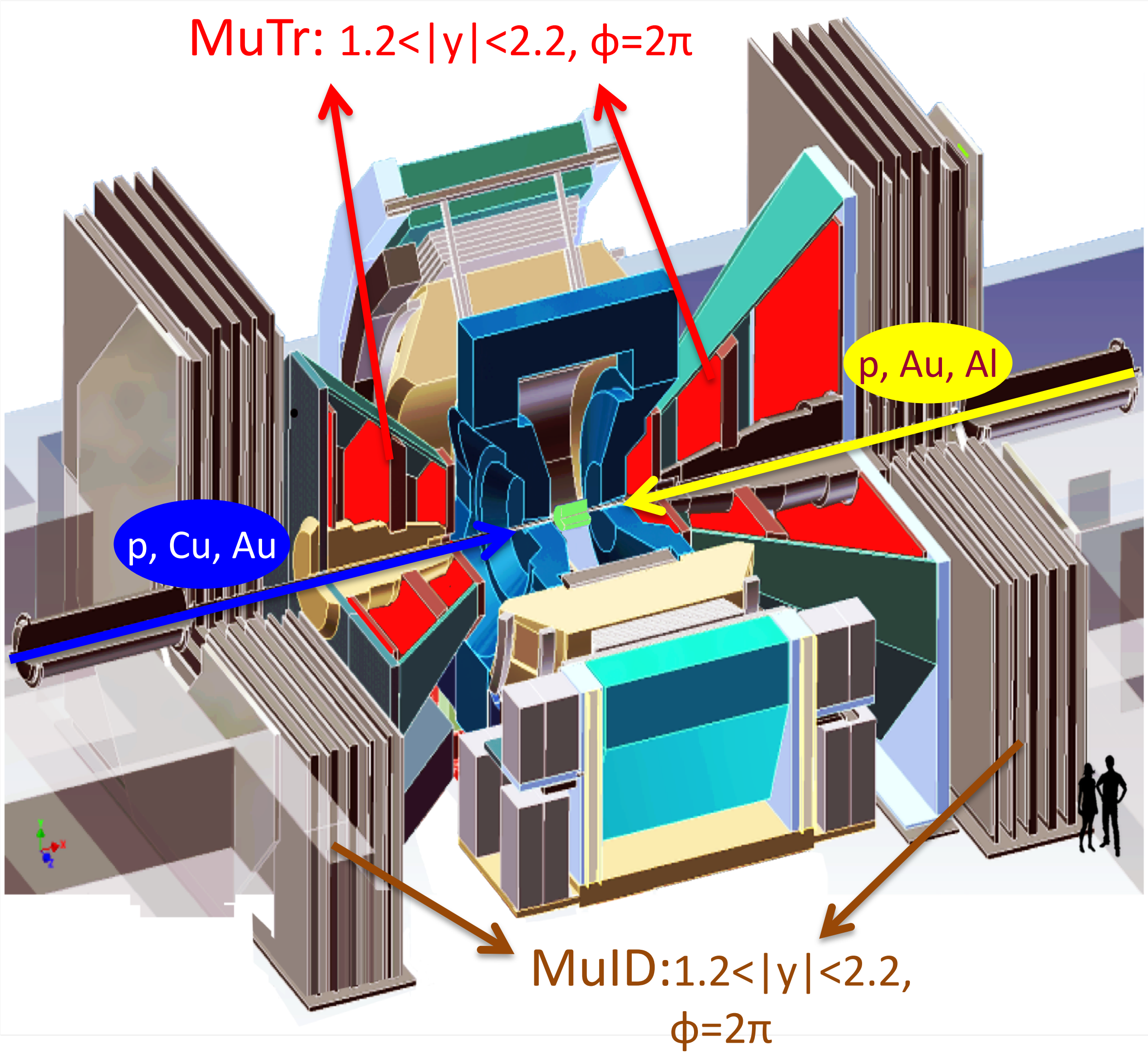
- The versatility of RHIC operation allowed us to collect data in various collision systems: p+p, p+Al, p+Au, d+Au, He^3+Au, Cu+Cu, Cu+Au, U+U, Au+Au.







PHENIX detector



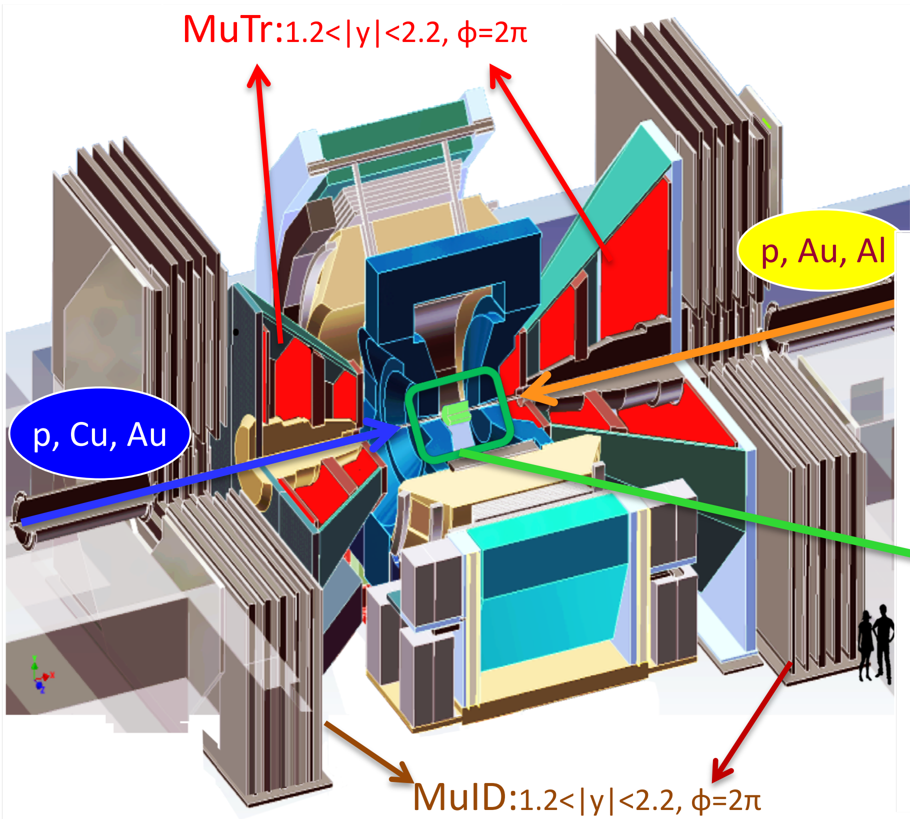
- **Central Arm (Electrons)**
  - $|\eta| < 0.35$
  - $\Delta\varphi = 2\pi$
  - Tracking: DC, PC, VTX
  - eID: RICH, EMcal

Forward Arms (Muons)

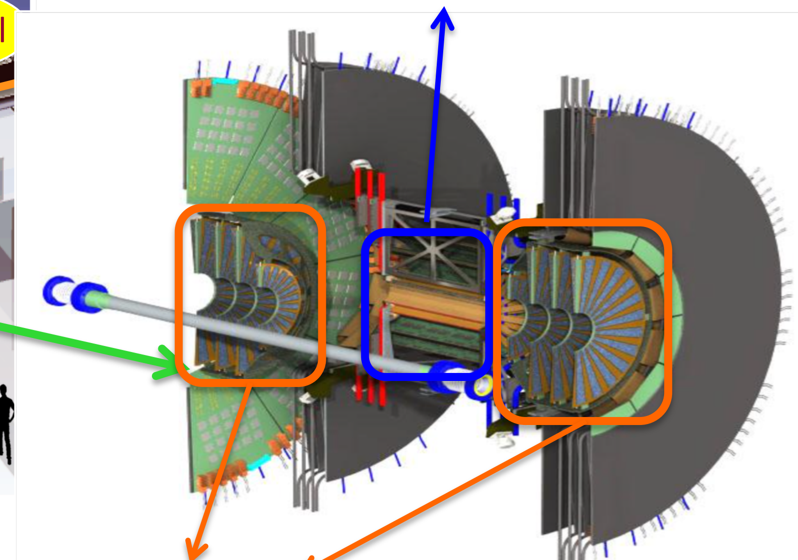
- $1.2 < |\eta| < 2.2$
- $\Delta\varphi = 2\pi$
- ~10 interaction length absorbers
- MuTr (Tracking: cathode strip chambers), FVTX
- MuID: muon identification detector

Overview of the PHENIX detector

- The silicon vertex detectors: VTX and FVTX made new heavy flavor measurements 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.



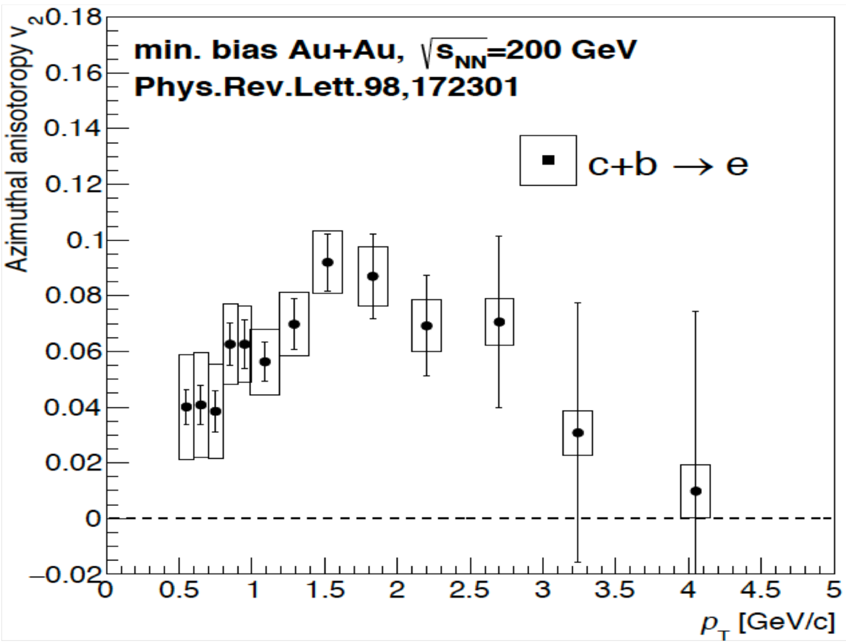
- FVTX:
  - With 1.2<|y|<2.2 and ϕ=2π coverage.
  - provide precise tracking and improved mass resolution for J/ψ, B→J/ψ and D, B separation measurements.

Inclusive open heavy flavor measurements in small asymmetric systems

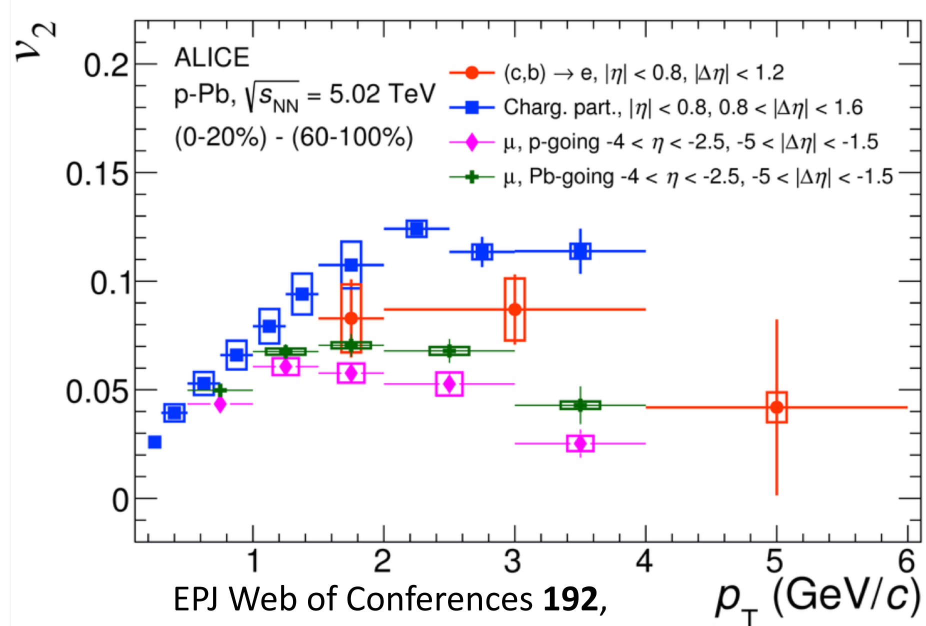
- To study the cold nuclear matter (CNM) effects
- To explore the formation of QGP droplet? Flow?

Previous open heavy flavor v_2 measurement at PHENIX

- Heavy flavor decay single electron v_2 measured in MB Au+Au collisions at PHENIX.



- Heavy flavor decay single electron/muon v_2 measured in central p+Pb collisions at ALICE.



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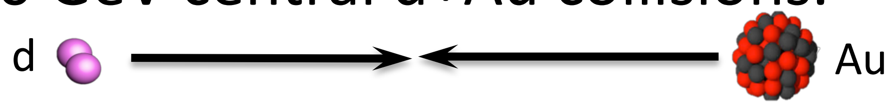
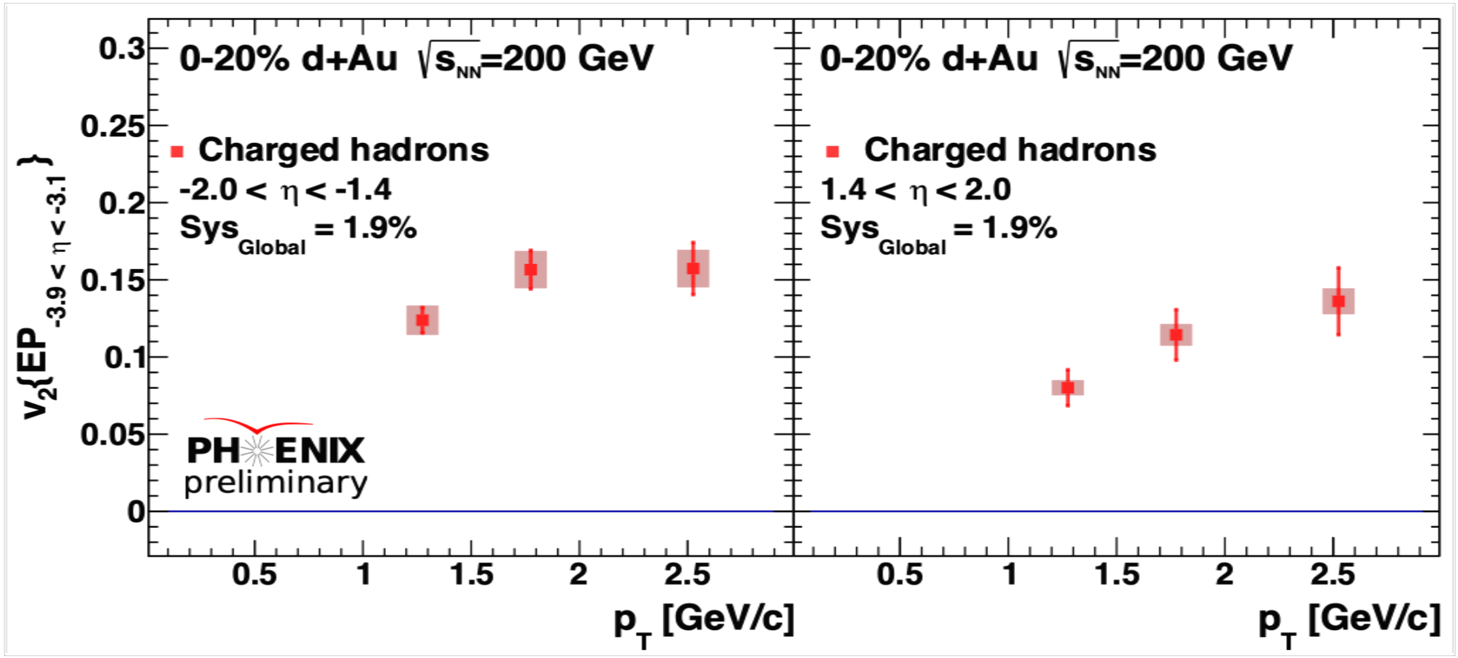
- How about open heavy flavor measurements in small systems such as p/d+Au collisions at $\sqrt{s} = 200$ GeV? At forward/backward rapidity?

Do heavy quarks flow in small system?

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

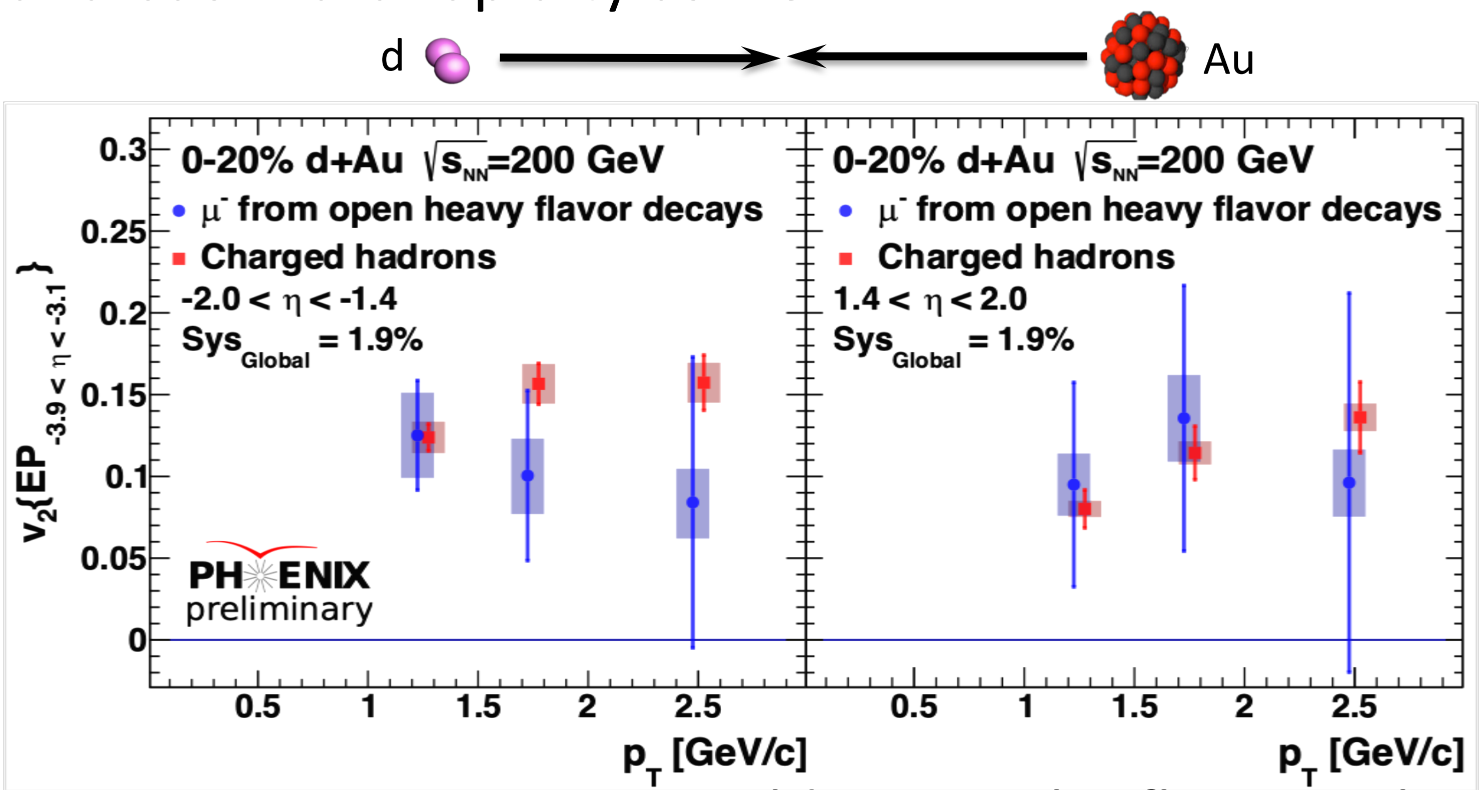




- Clear v_2 of charged hadrons measured in both forward and backward rapidity.
- How about heavy flavor?

Do heavy quarks flow in small system?

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



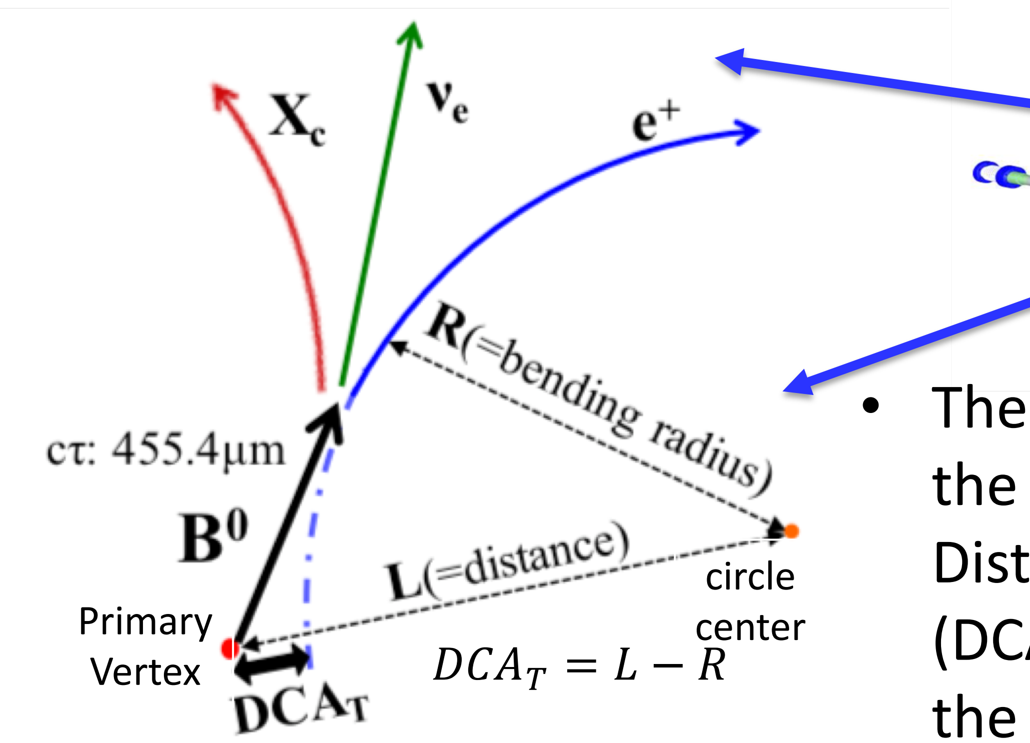
- Fragmentation process could smear the flow results.
- Initial state effects? Small QGP droplet formation?
- Need theoretical calculations.

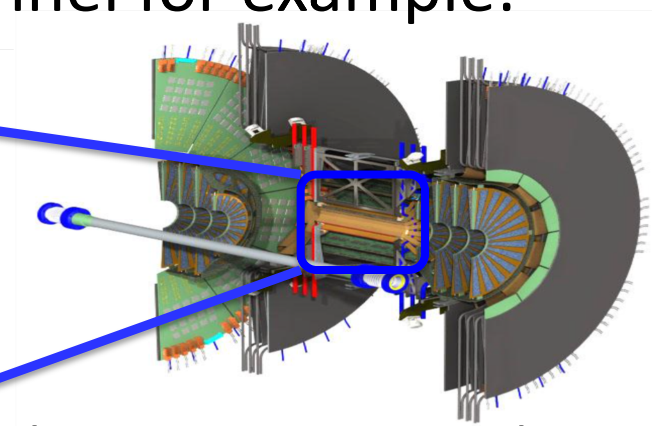
Charm/bottom measurements in p+p and heavy ion collisions with the VTX/FVTX

- **To understand the production mechanism.**
- **To study the Hot Nuclear Medium effects**
  - Flavor/mass dependent energy loss?
  - Do charm and bottom quarks flow?
  - Extend the kinematics to forward/backward rapidity and low p_T region.

Distinguish charm and bottom production

- B/D meson will decay into other particles ($e^{\pm}/\mu^{\pm}$) with the decay length ($c\tau$):
  - Charm hadron: $c\tau(D^0)$=123μm, $c\tau(D^{\pm})$=312μm.
  - Bottom hadron: $c\tau(B^0)$=455μm, $c\tau(B^{\pm})$=491μm.
- Take the semi-leptonic channel for example:

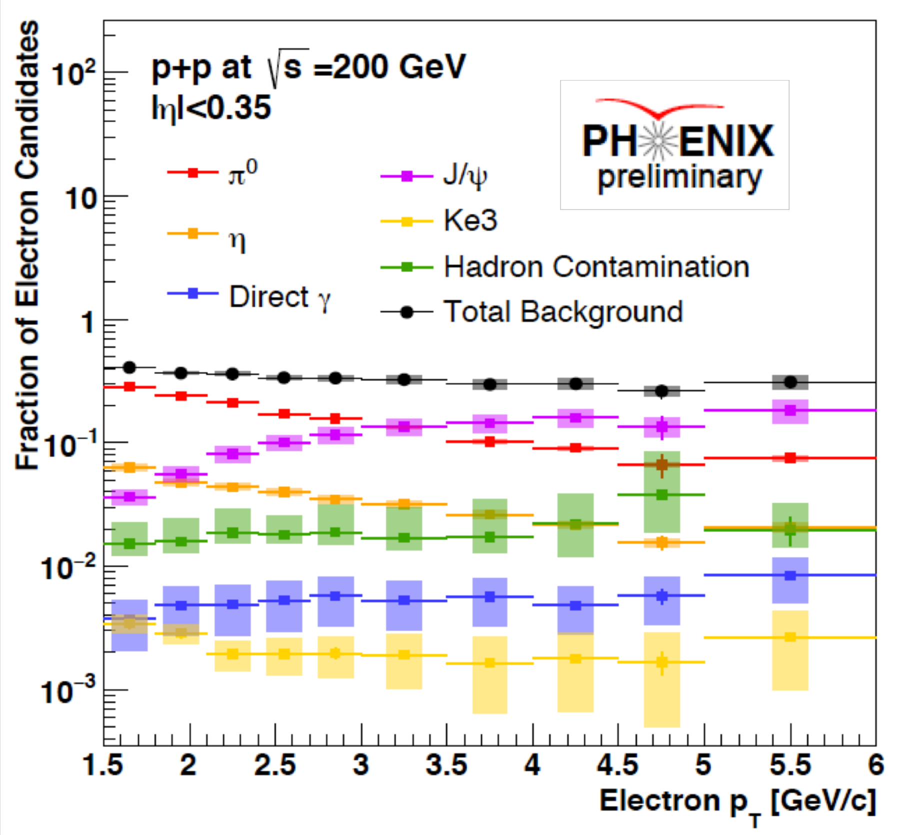


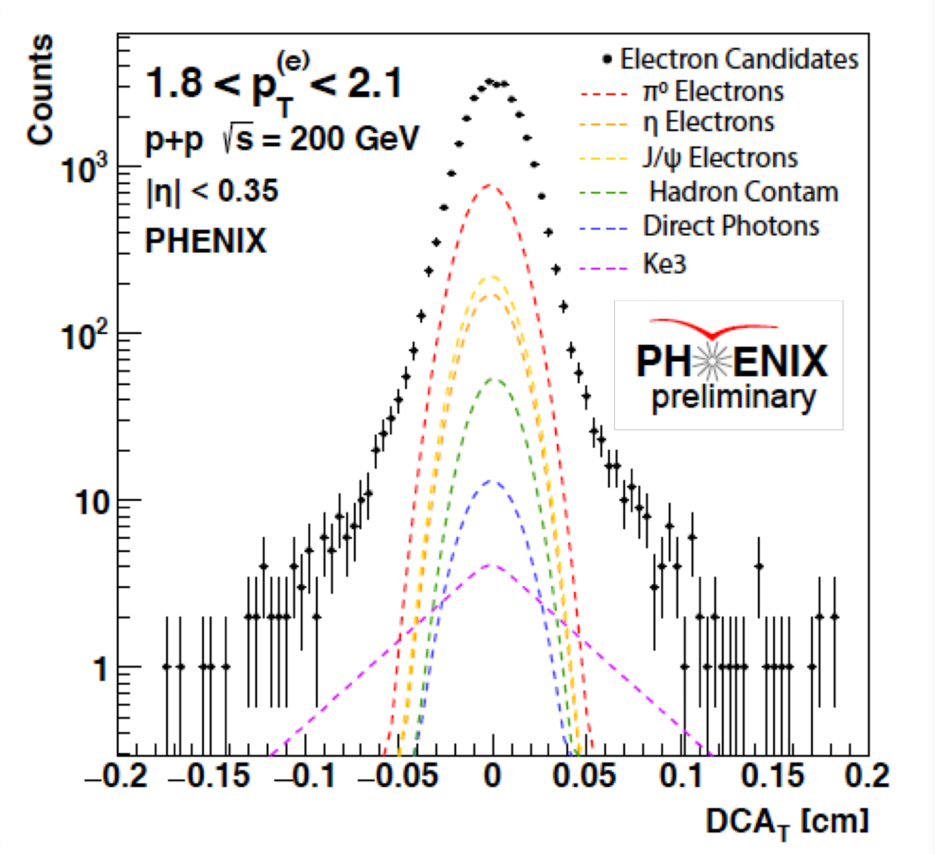


- The VTX can precisely measure the transverse projection of the Distance of Closest Approach (DCA_T), which is proportional to the decay length.

Charm/bottom decay single electrons at mid-rapidity in 2015 200 GeV p+p data

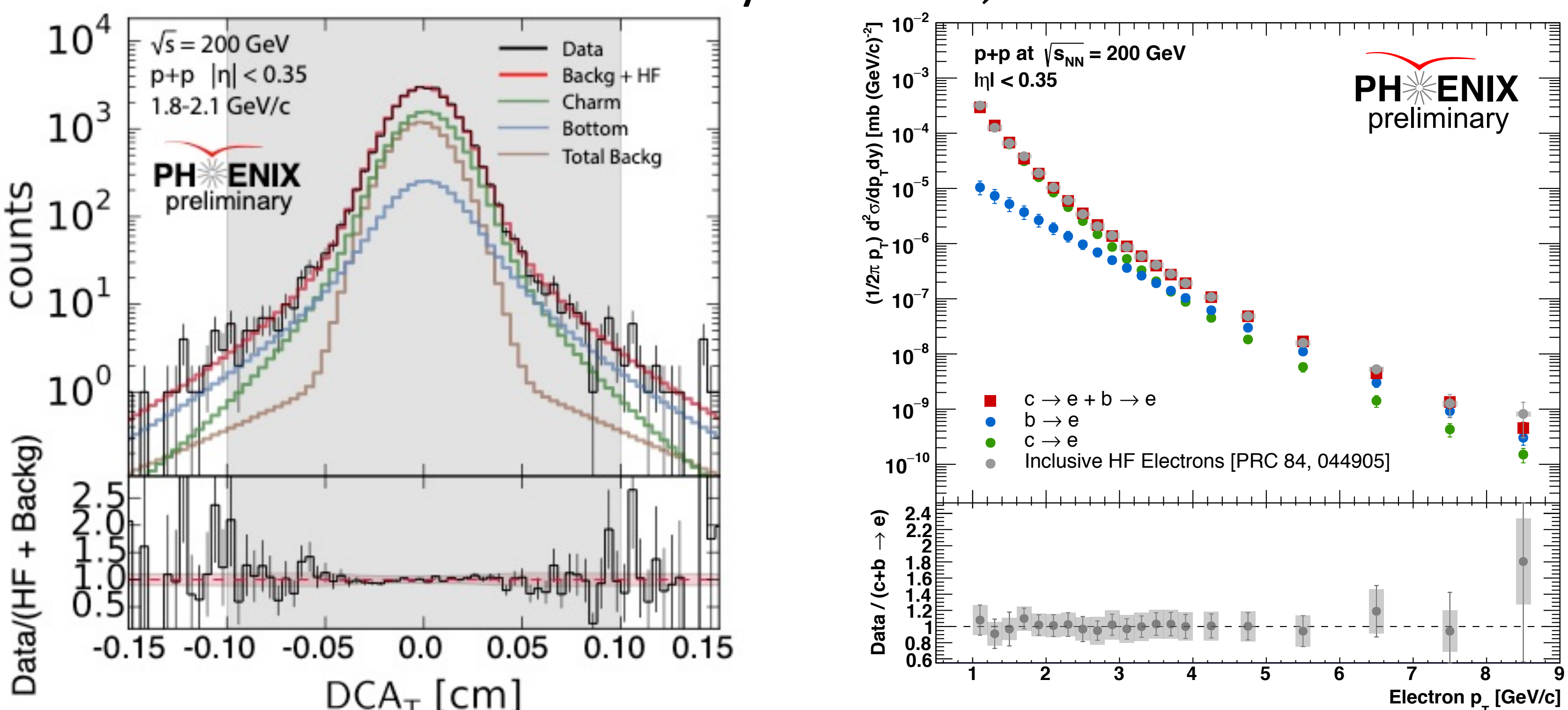
- Analysis procedure (I):
  - Determine various background contributions.
  - Measure the electron DCA_T in data and backgrounds.





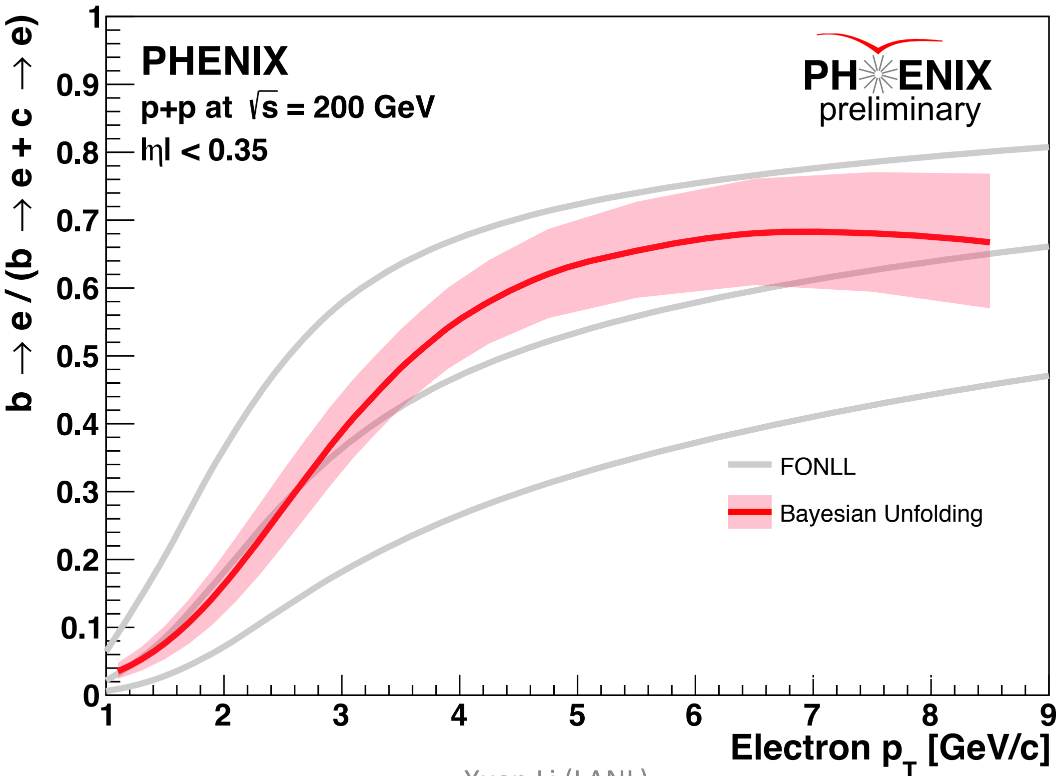
Charm/bottom decay single electrons at mid-rapidity in 2015 200 GeV p+p data

- Analysis procedure (II):
  - Simultaneous fit of the DCA_T distribution and the invariant yield and extract the charm/bottom hadron invariant yields based on Bayesian unfolding.
  - Refold back to invariant yields of $c, b \rightarrow e$.



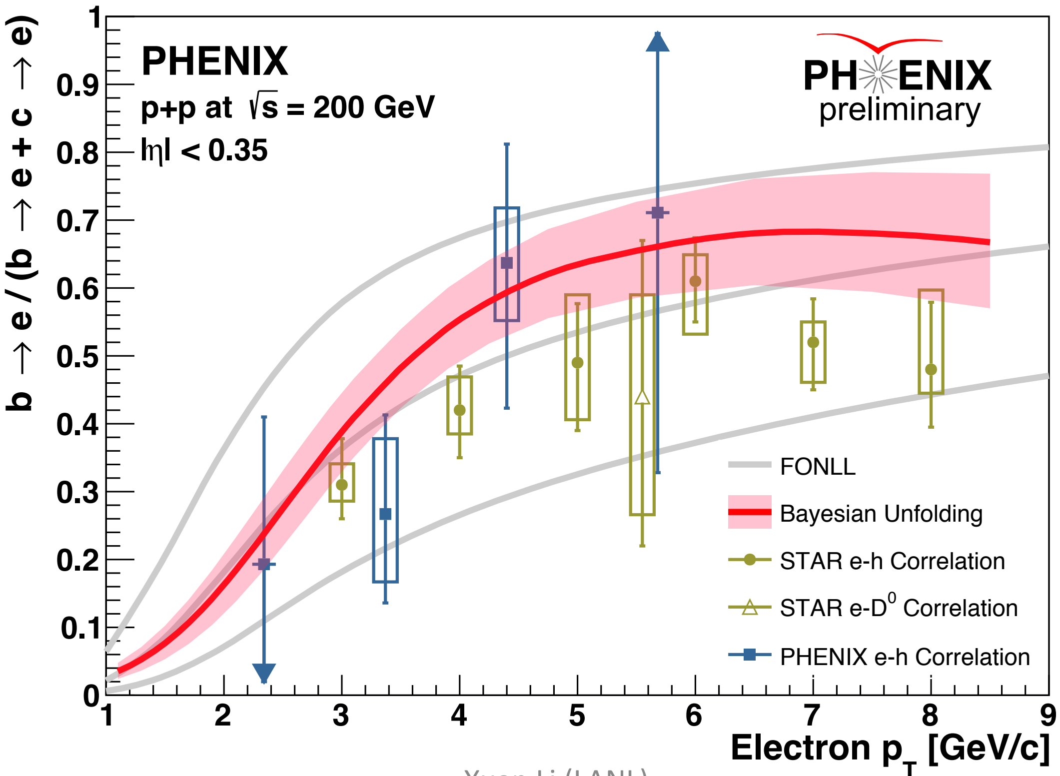
Charm/bottom decay single electrons at mid-rapidity in 2015 200 GeV p+p data

- The unfolded bottom fraction within $|\eta|<0.35$ is consistent with the FONLL calculations with significantly smaller uncertainties.



Charm/bottom decay single electrons at mid-rapidity in 2015 200 GeV p+p data

- The unfolded bottom fraction within $|\eta|<0.35$ is consistent with the FONLL calculations with significantly smaller uncertainties.
- Also consistent with previous RHIC results.



Study the Hot Nuclear Matter effect via D/B production

- To explore the mass/flavor dependent energy loss in the Quark Gluon Plasma (QGP):
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- From the PHENIX charm and bottom separated electron R_{AA} results at mid-rapidity,
  - Bottom has similar suppression as charm in the high p_T region.
  - Need to improve the uncertainty in the low p_T region to separate the charm R_{AA} from bottom R_{AA}.

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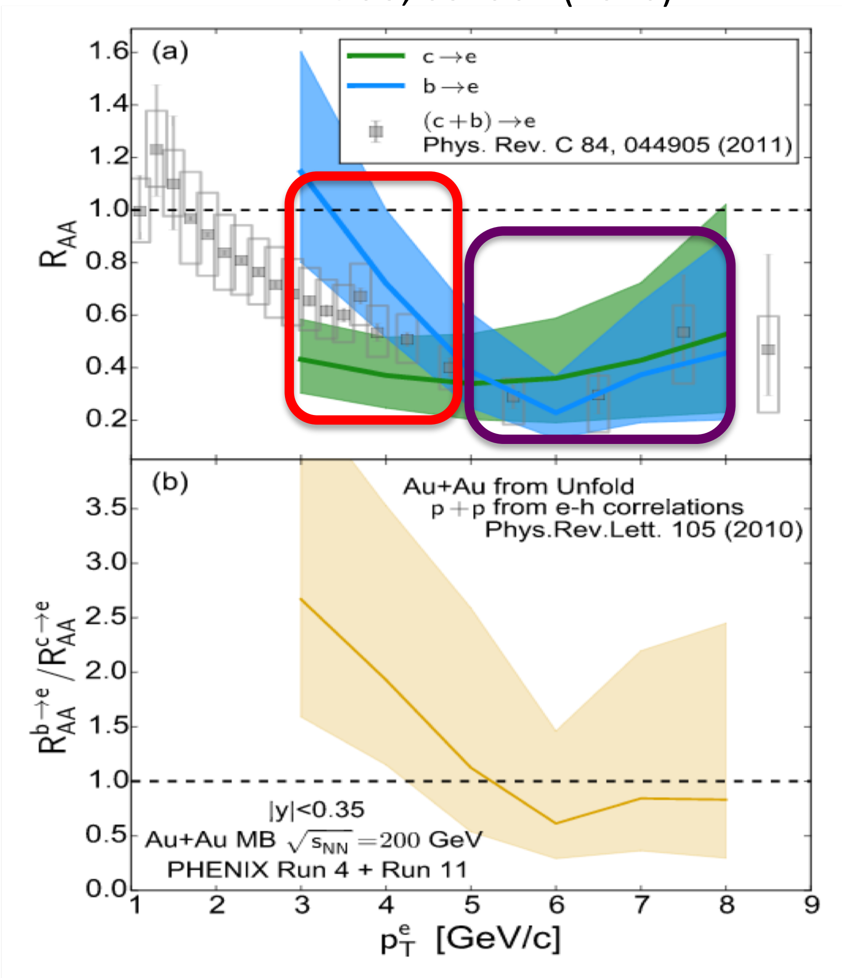
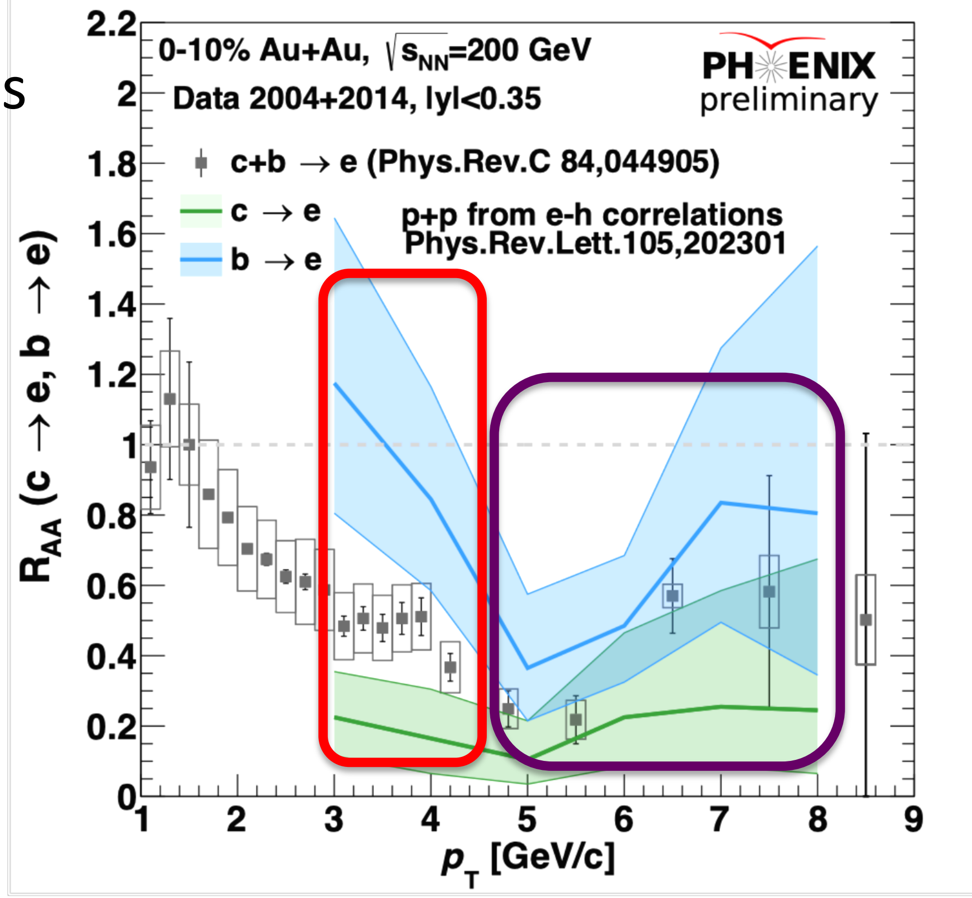


Study the Hot Nuclear Matter effect via D/B production

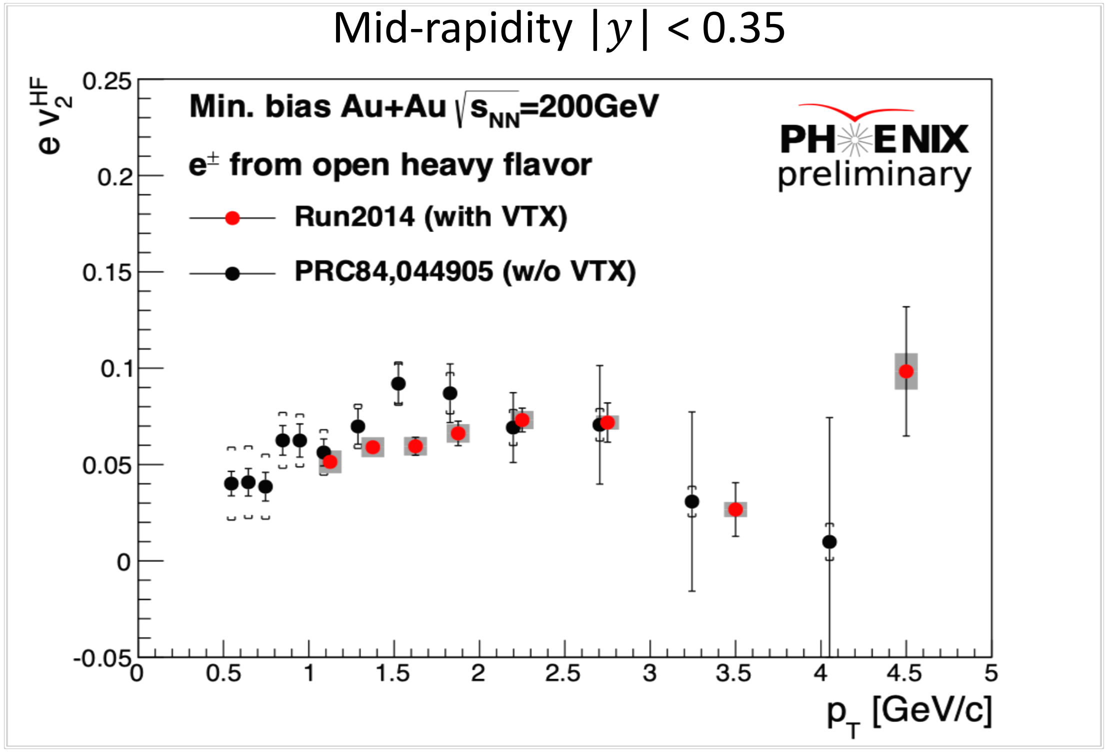
- Preliminary results of $c, b \rightarrow e$ R_{AA} in 0-10% Au+Au collisions used the p+p baseline from STAR's e-h correlation results.
- Precision will get improved with the new PHENIX p+p measurements.
- Bottom decay electrons with $p_T > 4$ GeV/c are suppressed.
- Need to improve the uncertainties in the low p_T region as well.



- 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.



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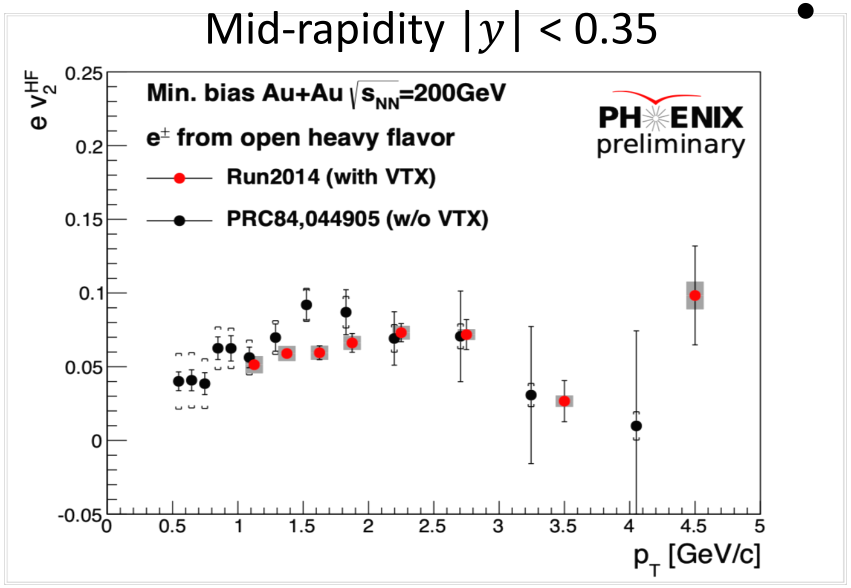
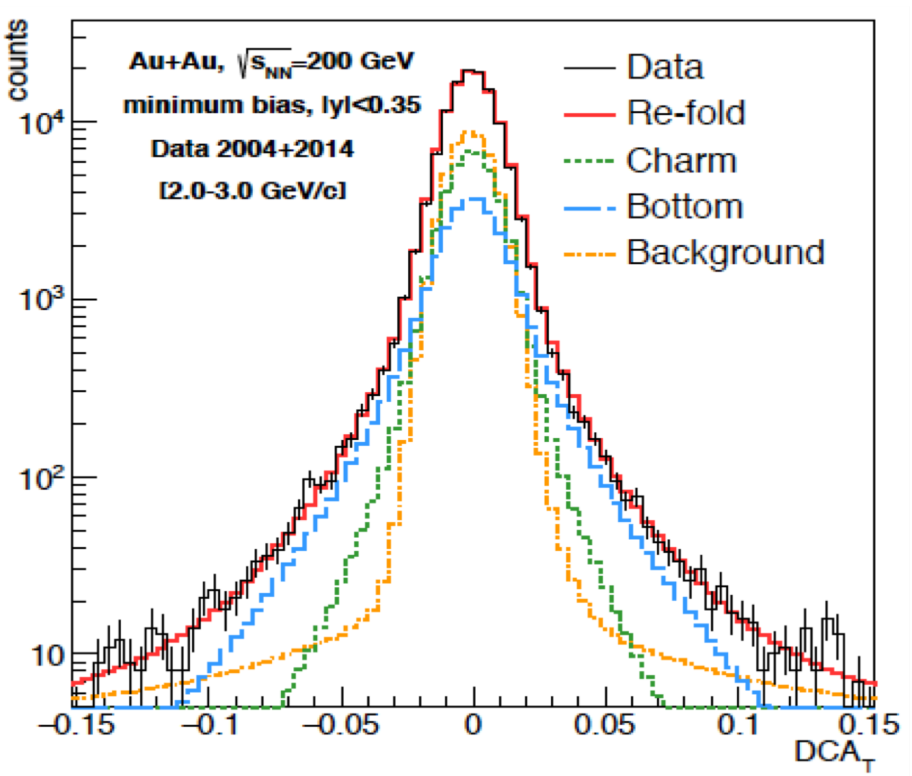


- Measure the electron DCA_T with the VTX and determine the charm and bottom electron through unfolding.



Heavy flavor electron v_2 in Au+Au collisions

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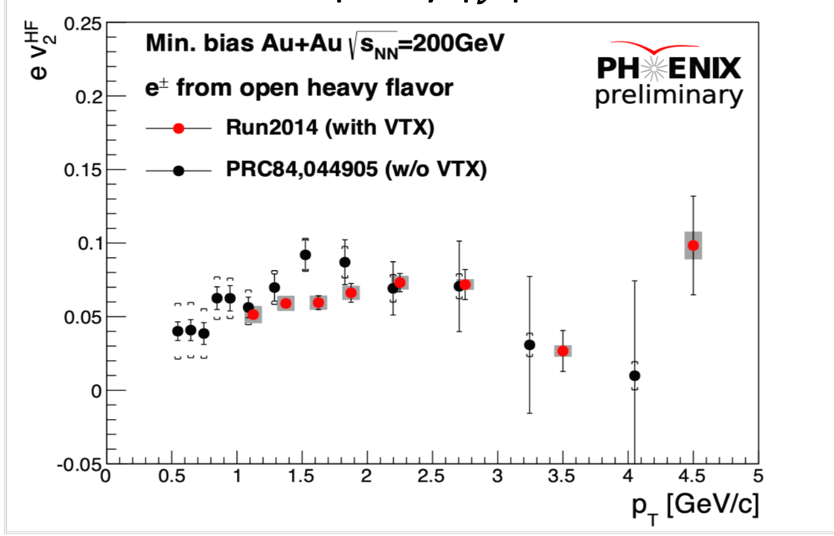
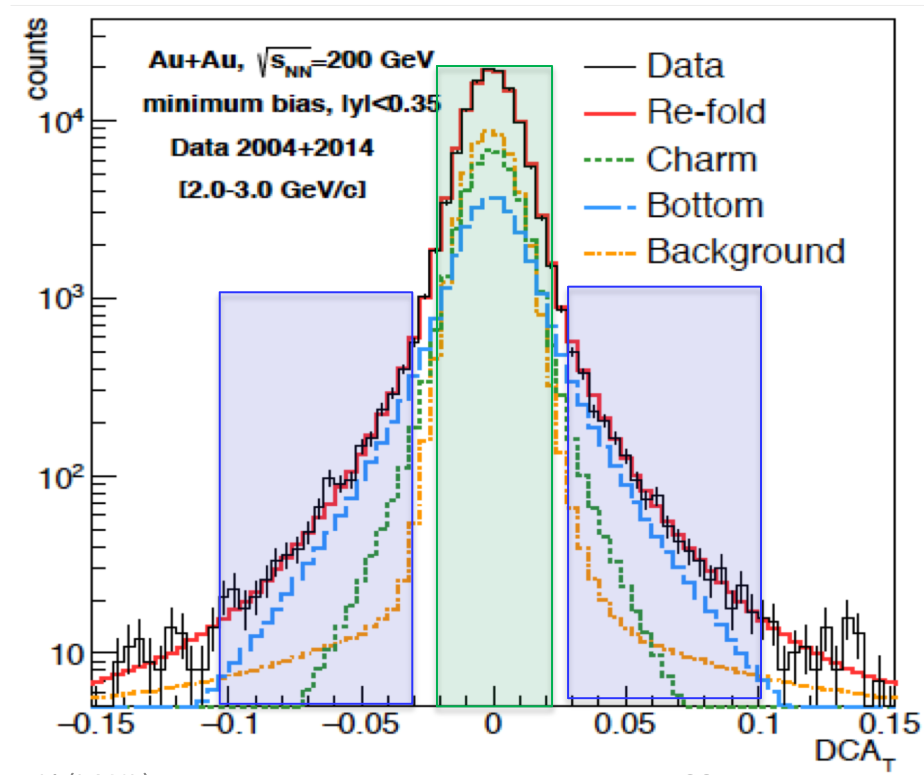
Mid-rapidity $|y| < 0.35$

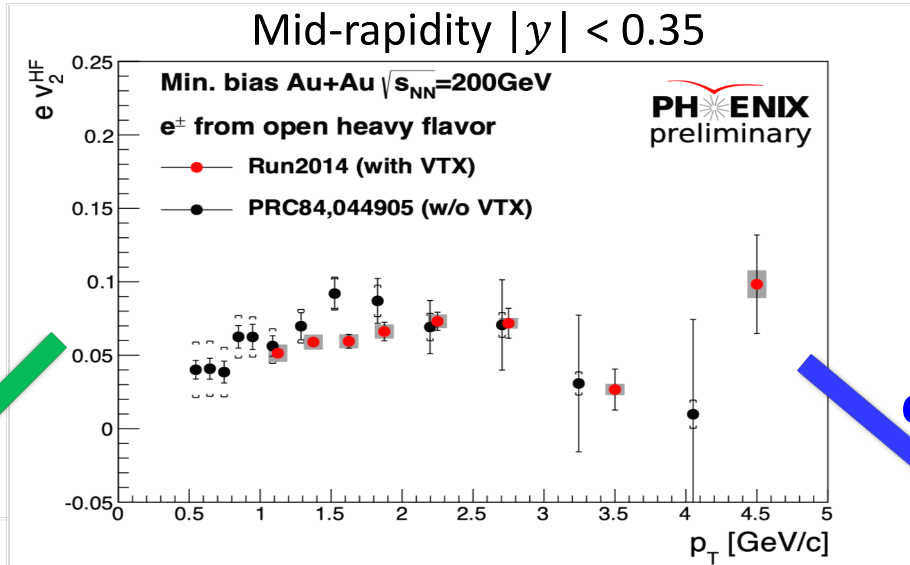


- Measure the electron DCA_T with the VTX and determine the charm and bottom electron through unfolding.



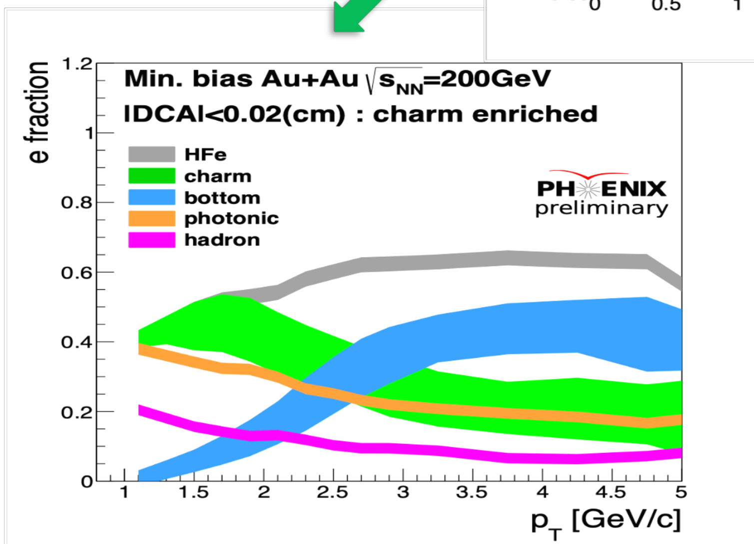
- Charm enriched region: $|DCA_T| < 200\ \mu m$
- Bottom enriched region: $300\ \mu m < |DCA_T| < 1000\ \mu m$

Heavy flavor electron v_2 in Au+Au collisions



Charm enriched sample

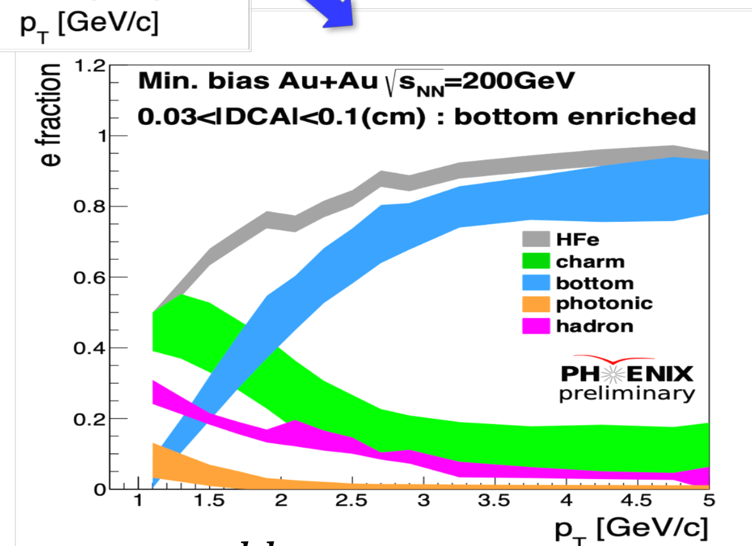
Bottom enriched sample



Simultaneously extract

$v_2(c \rightarrow e)$

$v_2(b \rightarrow e)$

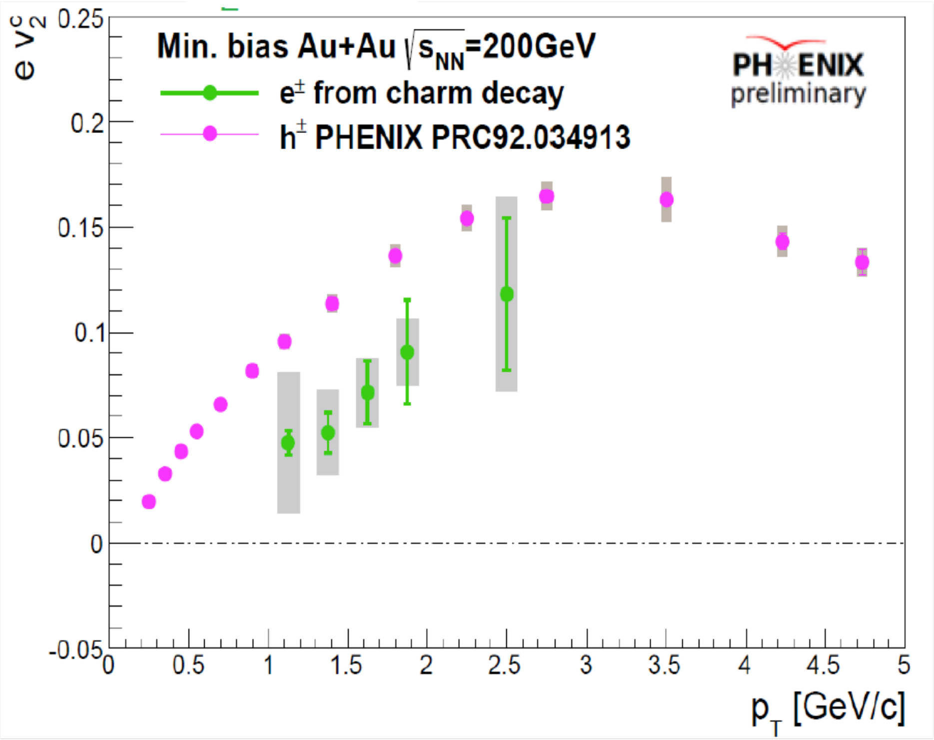


$$v_2^{c\ enrich} = F_c \times v_2^c + F_b \times v_2^b + F_{bkg} \times v_2^{bkg}$$

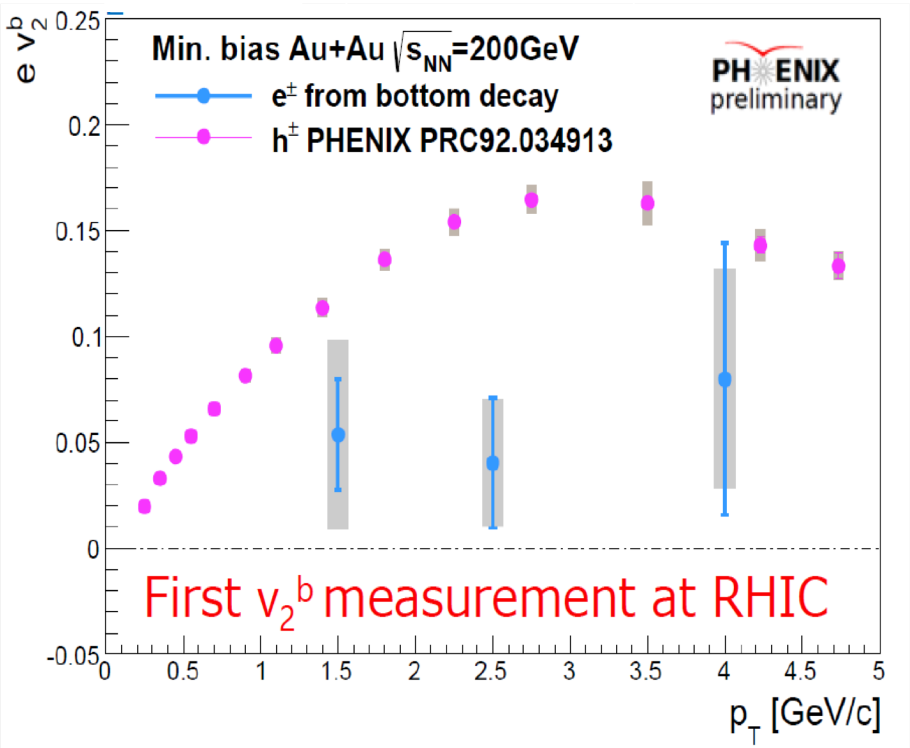
$$v_2^{b\ enrich} = F_c' \times v_2^c + F_b' \times v_2^b + F_{bkg}' \times v_2^{bkg}$$

Charm electron v_2 and Bottom electron v_2

$v_2(c \rightarrow e)$



$v_2(b \rightarrow e)$

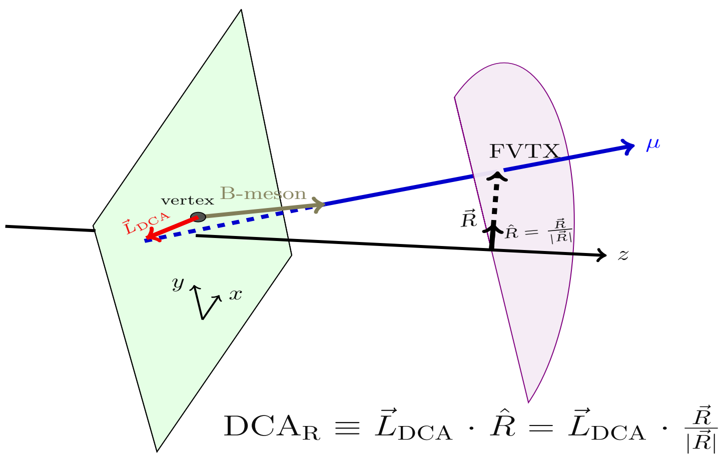


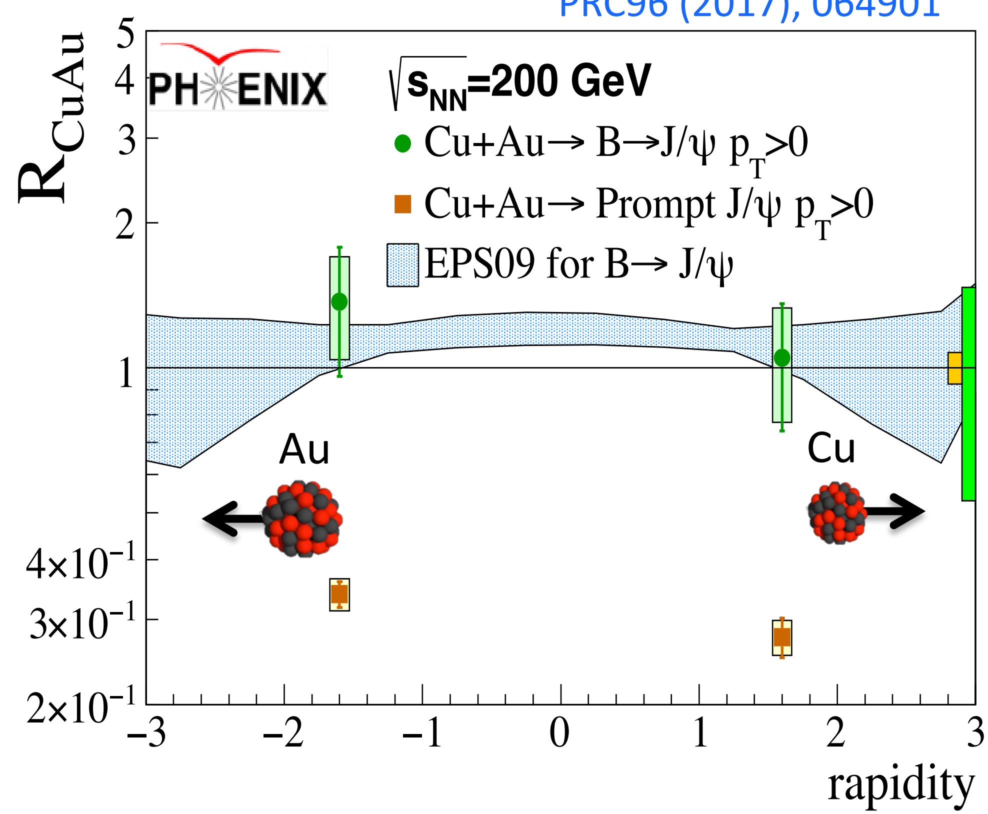
- Significant charm electron v_2, smaller magnitude than charged hadron v_2 might be due to charm decay kinematics.
- Indication of non-zero bottom v_2.
- $v_2(b \rightarrow e)$ might be equal to or smaller than $v_2(c \rightarrow e)$.

How about the forward/backward rapidity?

- B/D hadron is further boosted at forward rapidity.
- The FVTX can precisely determine the Distance of Closest Approach along the radial projection (DCA_R) of tracks.
- No significant modifications on the $B \rightarrow J/\psi$ R_{CuAu} which suggests a small initial state modification.

PRC96 (2017), 064901

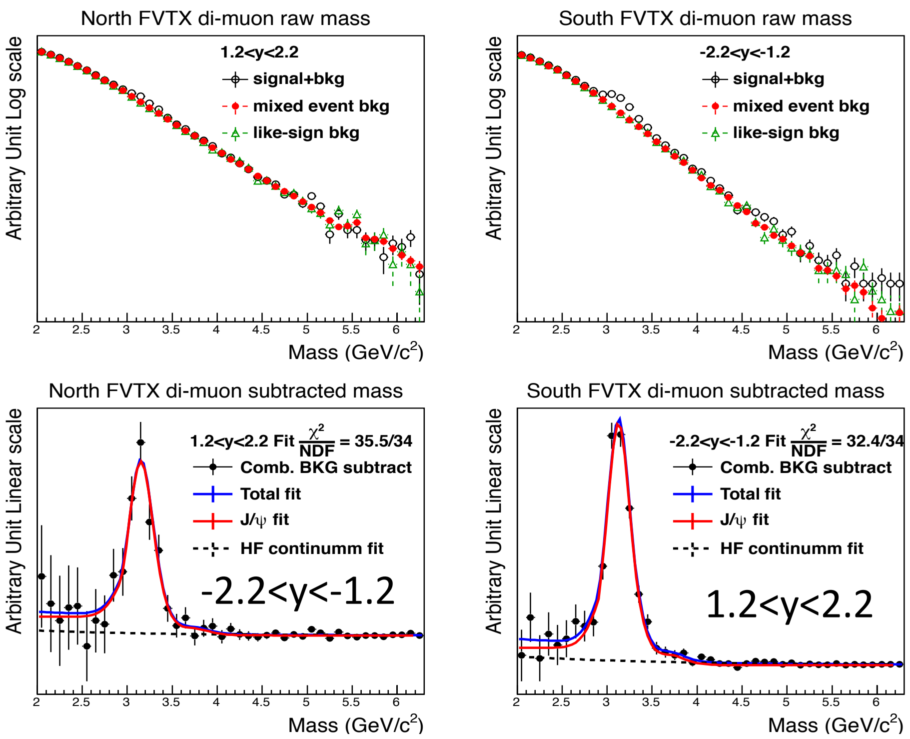




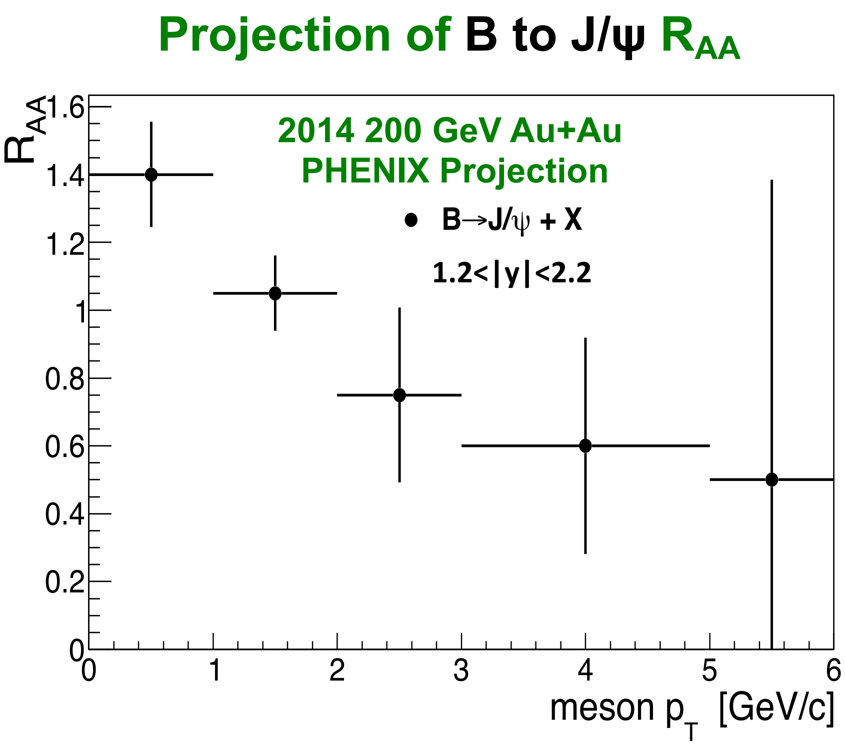
- How about the Au+Au measurements?
- How about charm/bottom muon channel?

Forward/backward 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.
- Clear J/ψ signal has been observed in partial Au+Au data.
- Analysis procedure has been updated and data analysis is underway.



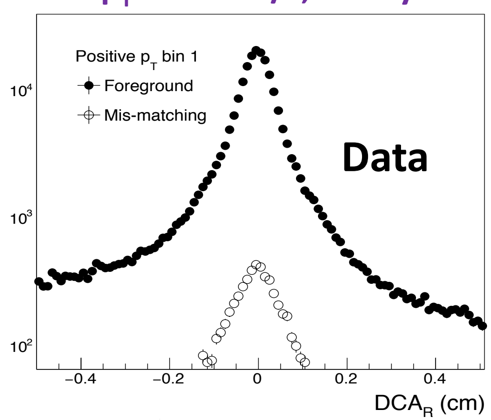
Di-muon mass in partial 2014 Au+Au data.

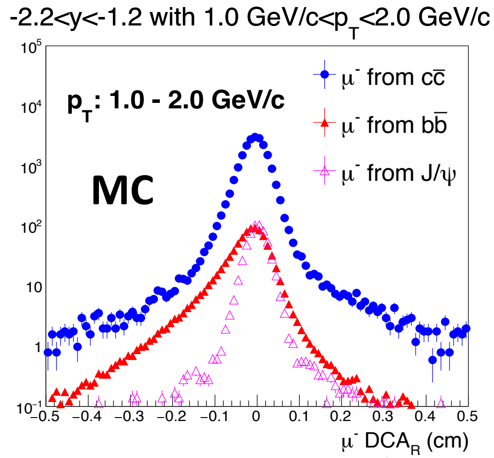


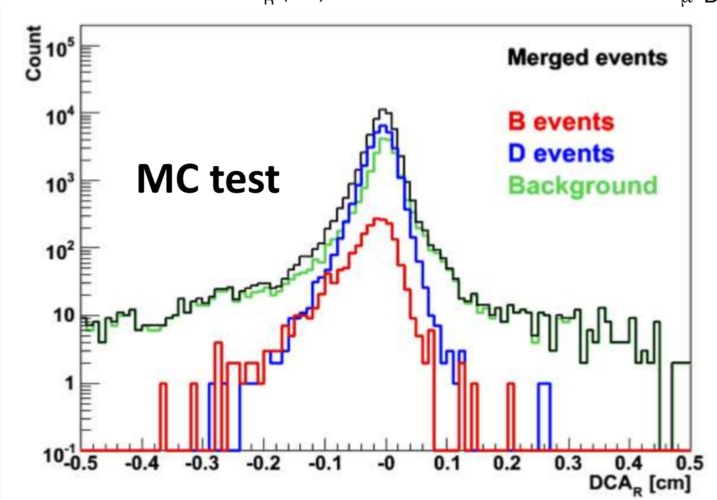
Forward/backward charm/bottom muon analysis

- Analysis with 2015 200 GeV p+p and 2014 200 GeV Au+Au data is ongoing.
- Take the p+p analysis for example:

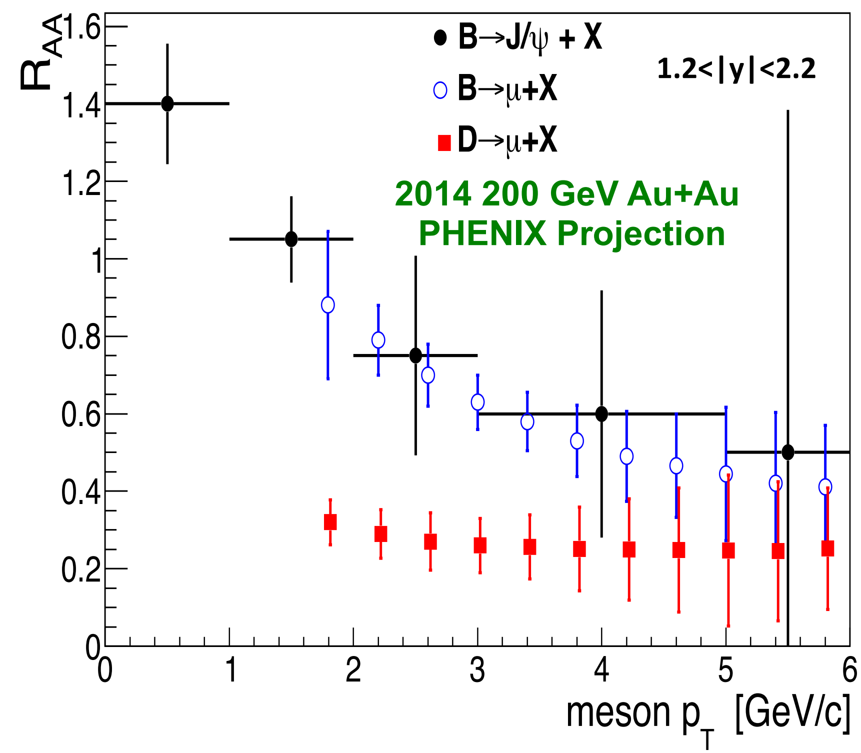
muon p_T: 1-2 GeV/c, $-2.2<y<-1.2$







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



Summary

- Evidence of non-zero heavy flavor v_2 in small system provide new path to understanding the heavy quark interactions with the cold nuclear medium.
- The charm/bottom production ratio in p+p collisions is consistent with the FONLL calculations.
- Charm/bottom decay single electrons are suppressed within $p_T > 4$ GeV/c region in central Au+Au collisions, the precision of nuclear modification factor will get improved with better statistics and the new p+p baseline.
- First bottom decay electron v_2 at RHIC has been measured in the mid-rapidity region.

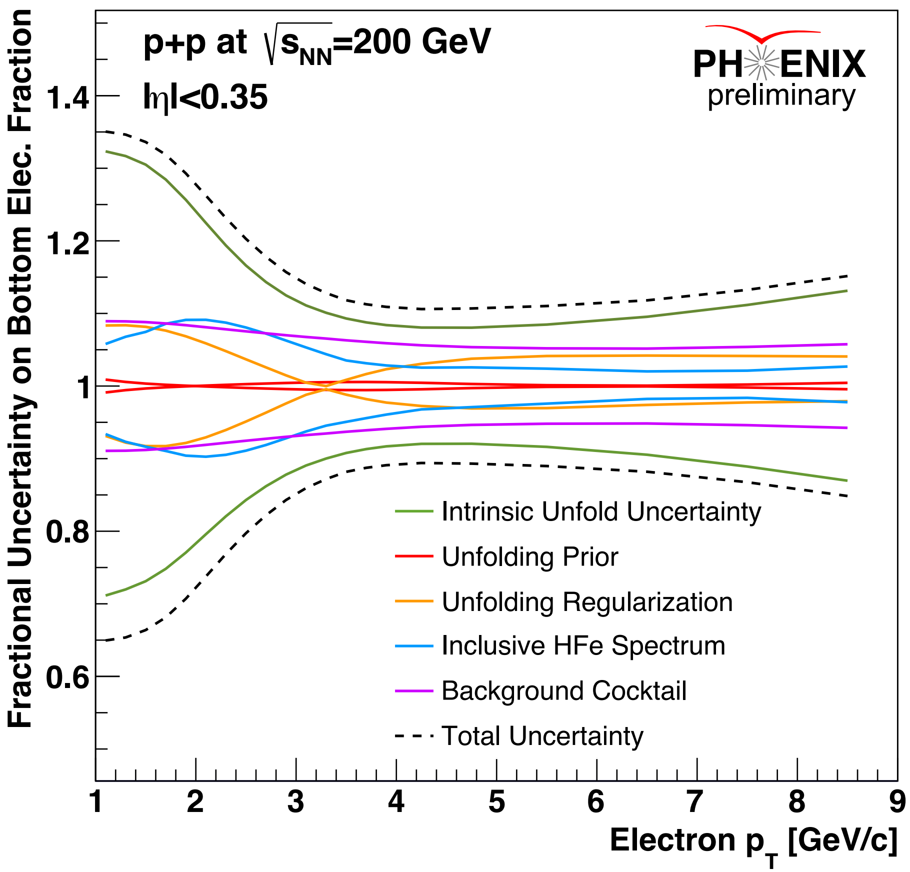
Outlook

- Large data sets in various types of heavy ion collisions collected at PHENIX provide opportunities to study
  - Nuclear modification and thermalization properties of D/B separate single electrons/muons in 2014/2016 Au+Au collisions with higher statistics.
  - Forward/backward B to J/ψ via di-muon channel in 2014/2016 Au+Au collisions to understand the hot nuclear matter effects.
  - …
- More results to come soon.

Backup

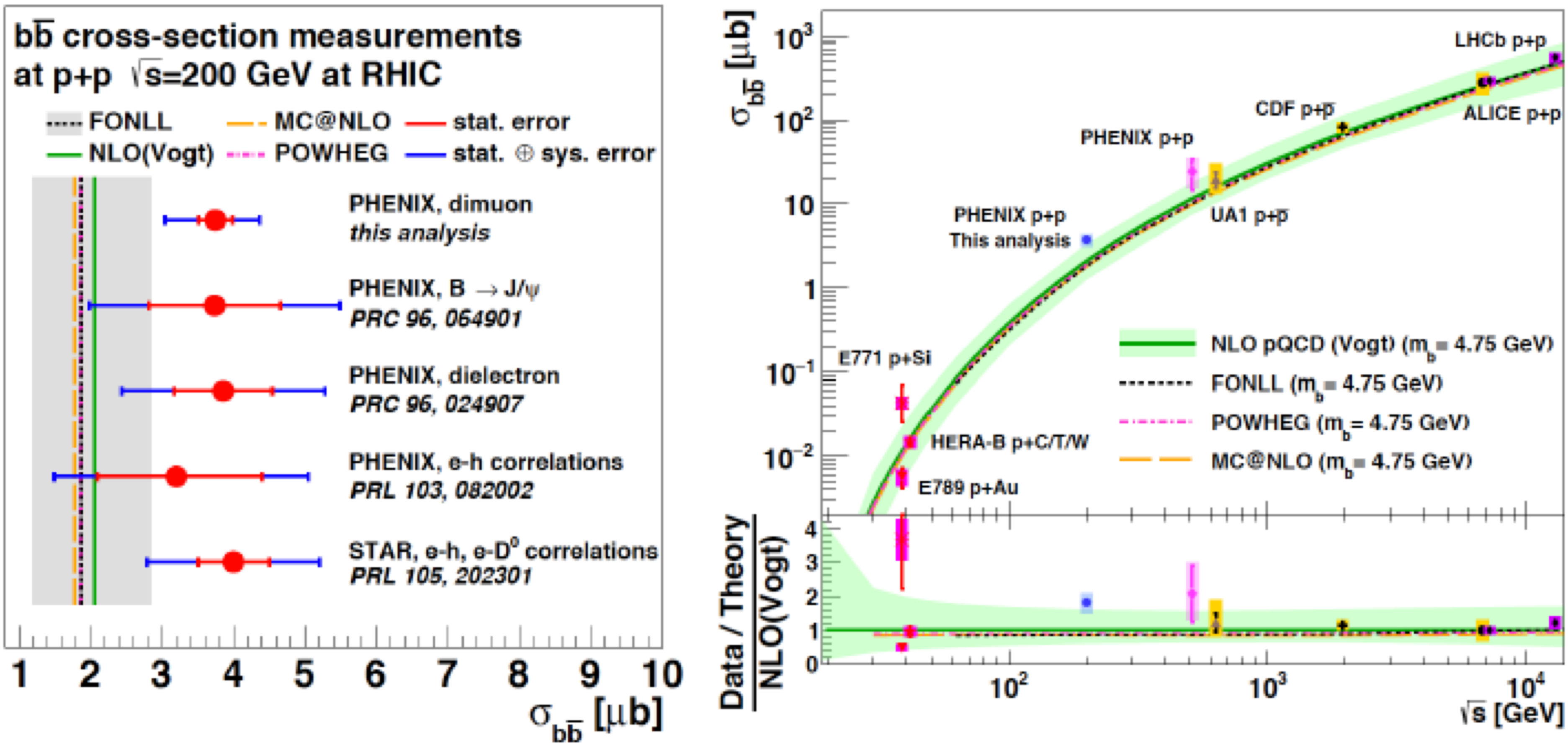
Charm/bottom decay electron in p+p collisions systematic uncertainties

- Summary of the systematic uncertainties.



Bottom cross section in p+p at PHENIX

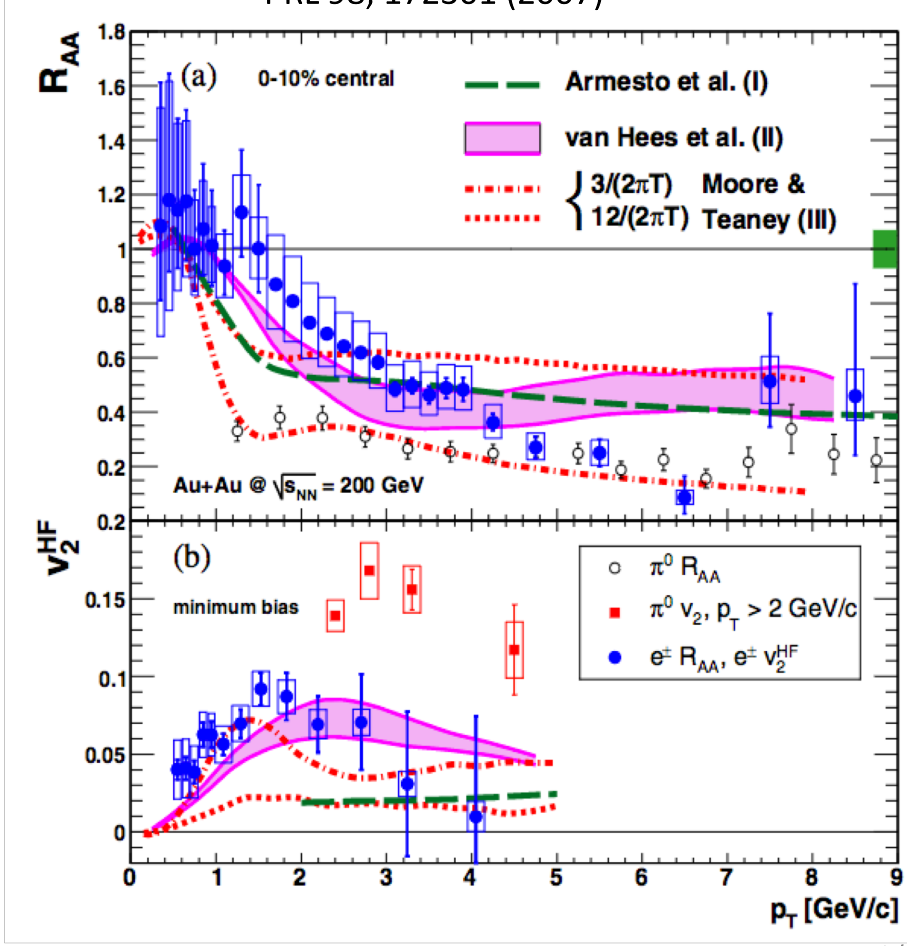
- Consistent with NLO pQCD calcutions

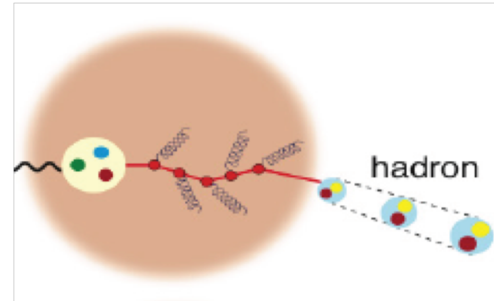


Study the Hot Nuclear Matter effect via D/B production

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

PRL 98, 172301 (2007)

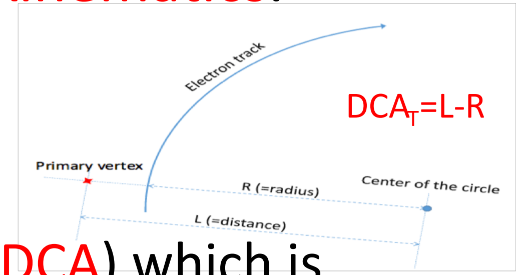




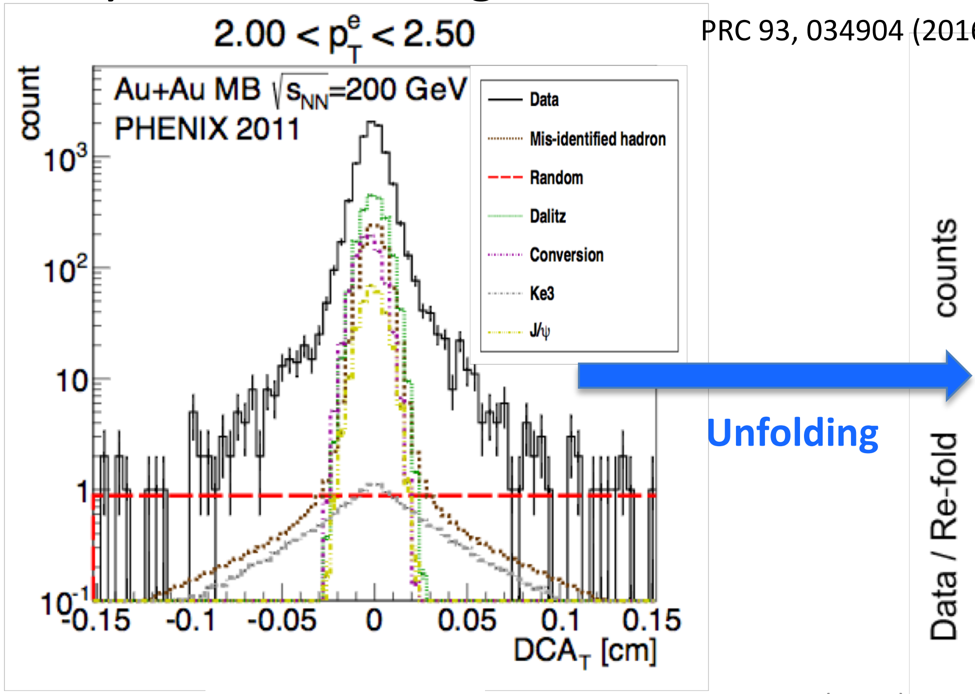
- Light hadron and heavy flavor production have different suppression, flavor dependent coupling?
- Need to separate charm and bottom and study the mass dependent quark energy loss.

Analysis strategy to separate charm and bottom

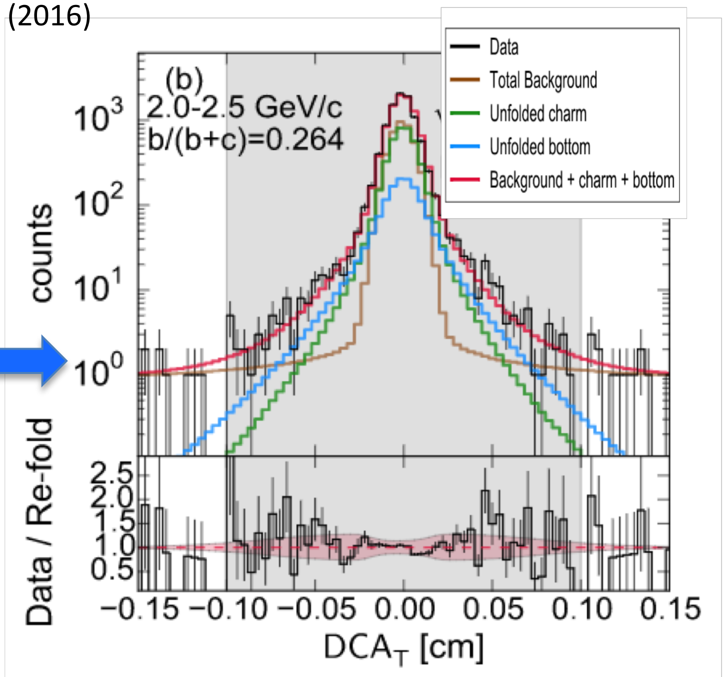
- Based on different lifetimes and decay kinematics.
- Decay length (cτ):
  - Charm hadron: cτ(D^0)=123μm, cτ($D^\pm$)=312μm.
  - Bottom hadron: cτ(B^0)=455μm, cτ($B^\pm$)=491μm.



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

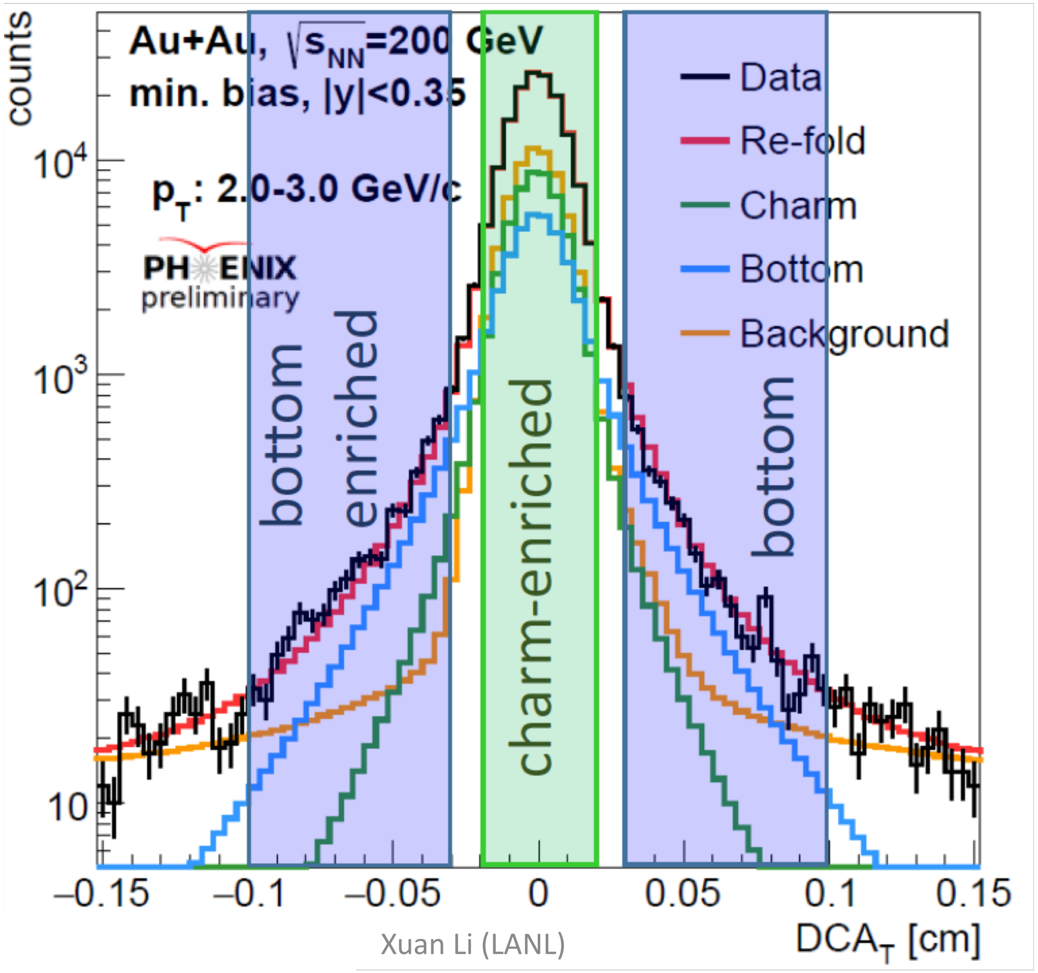


PRC 93, 034904 (2016)



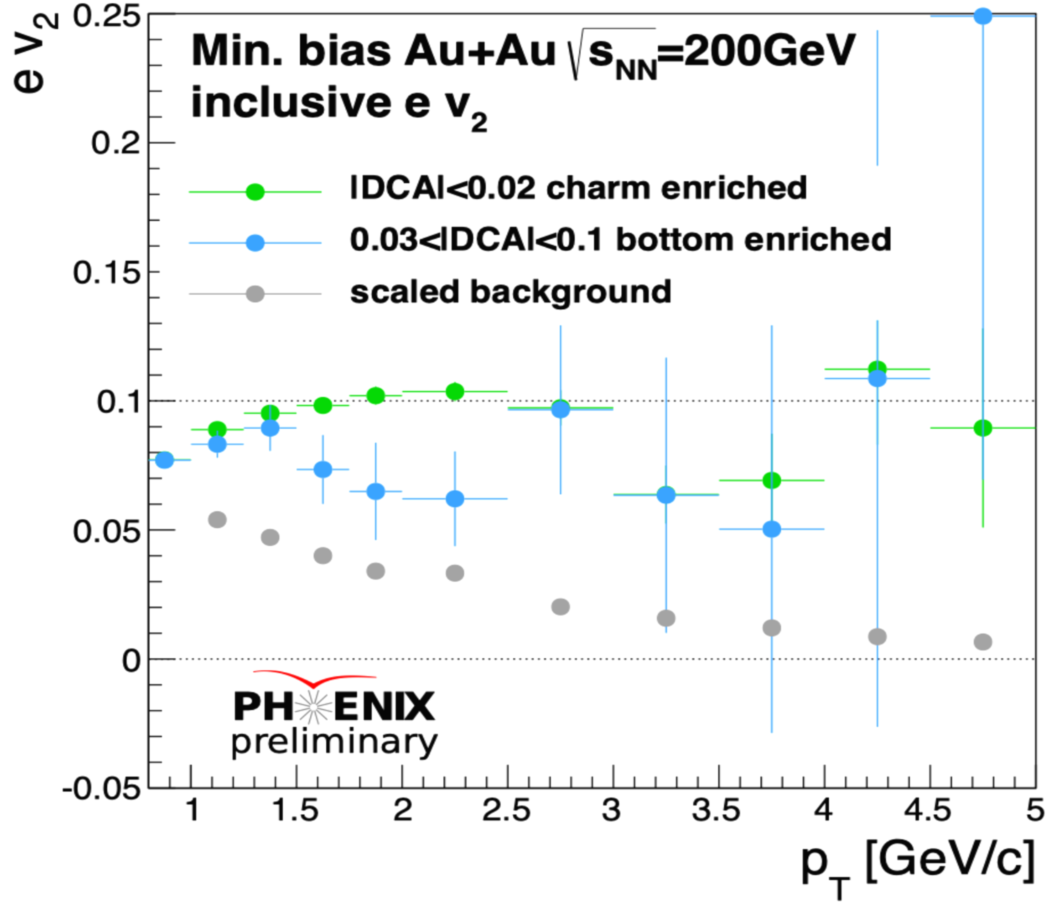
Select charm (bottom) enriched sample based on electron DCA_T

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

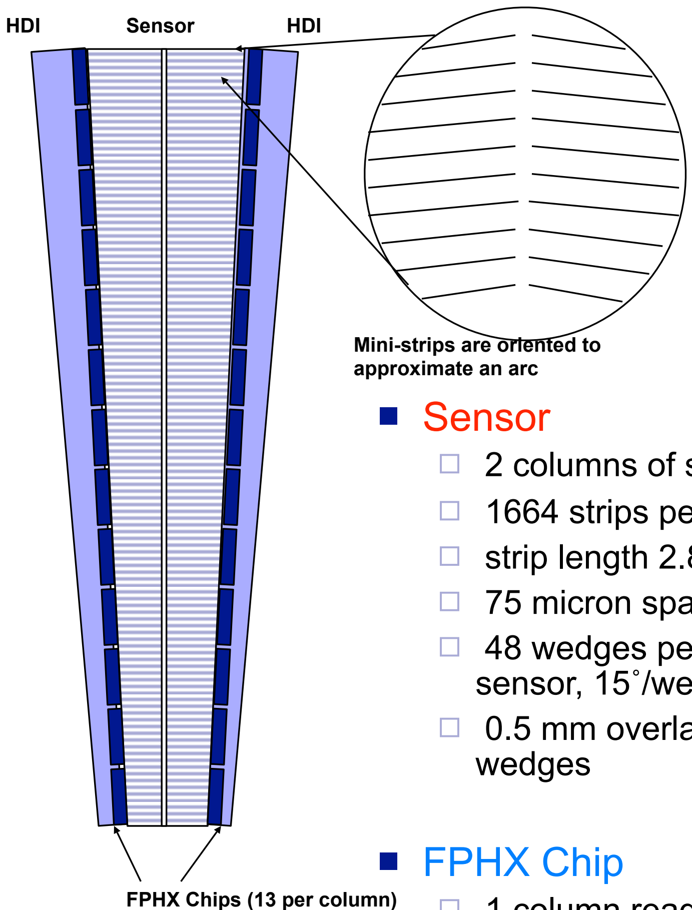


Charm and bottom enriched v_2 measurements

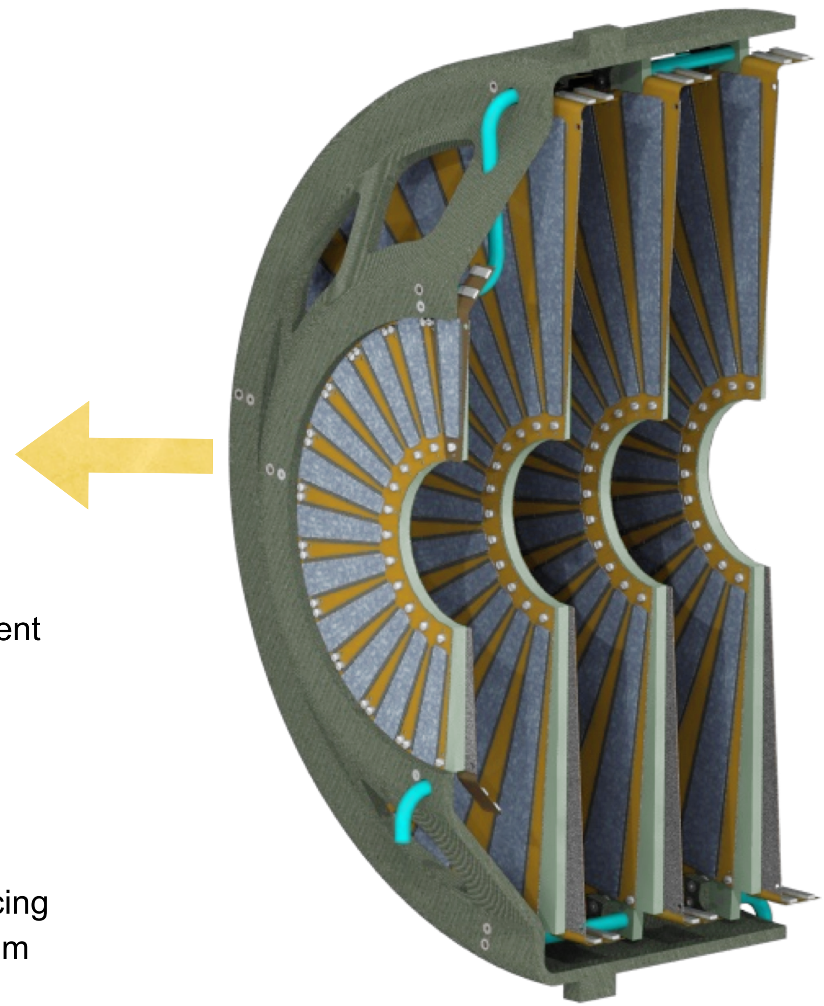
- Indication of mass/flavor dependence for p_T>1.5 GeV/c.



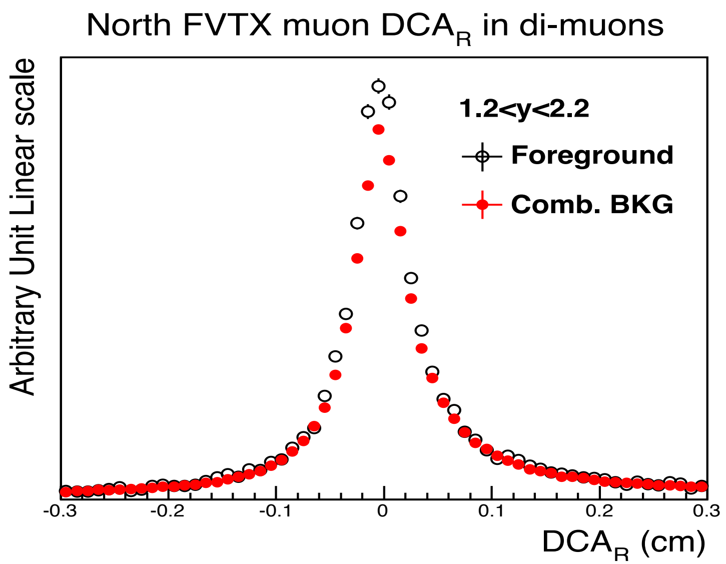
The Forward Vertex Detector (FVTX)

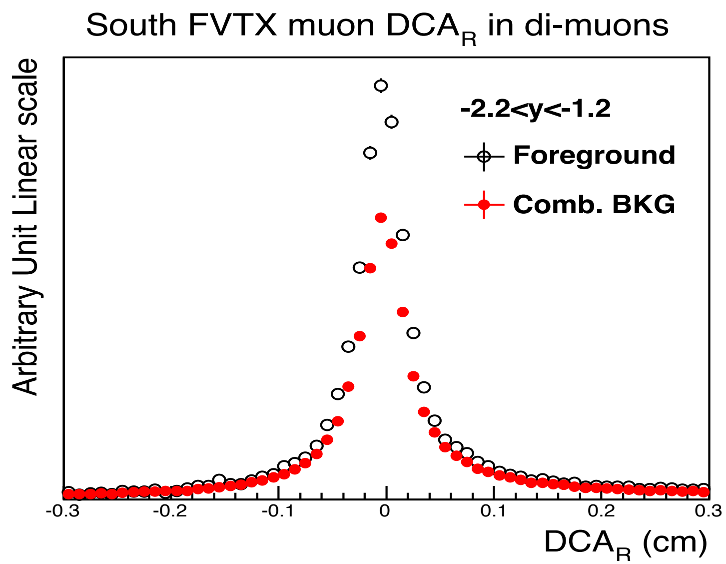


- **Sensor**
  - 2 columns of strips
  - 1664 strips per column
  - strip length 2.8 to 11.2 mm
  - 75 micron spacing
  - 48 wedges per disk (7.5˚/ sensor, 15˚/wedge)
  - 0.5 mm overlap with adjacent wedges
- **FPHX Chip**
  - 1 column readout
  - 128 channels
  - ~ 70 microns channel spacing
  - Dimensions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



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





Single muon DCA_R in Au+Au simulation