Recent Heavy flavor measurements at PHENIX at RHIC

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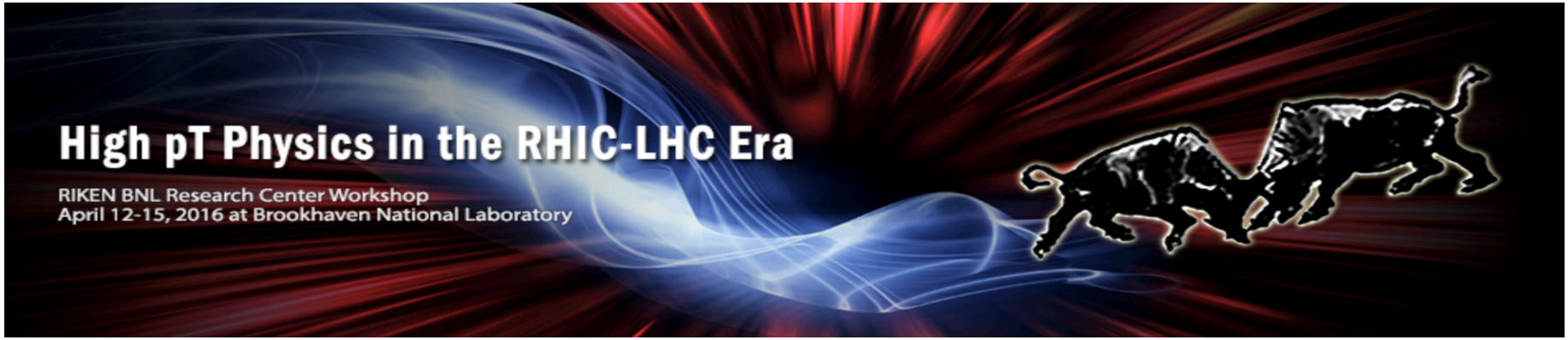
For the PHENIX Collaboration

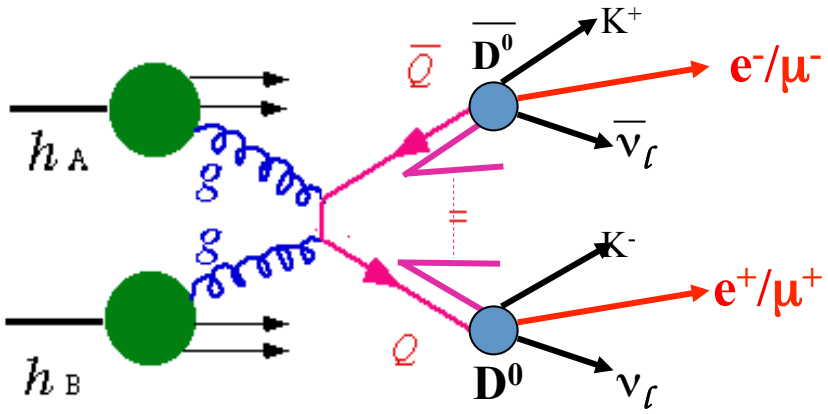


Outline

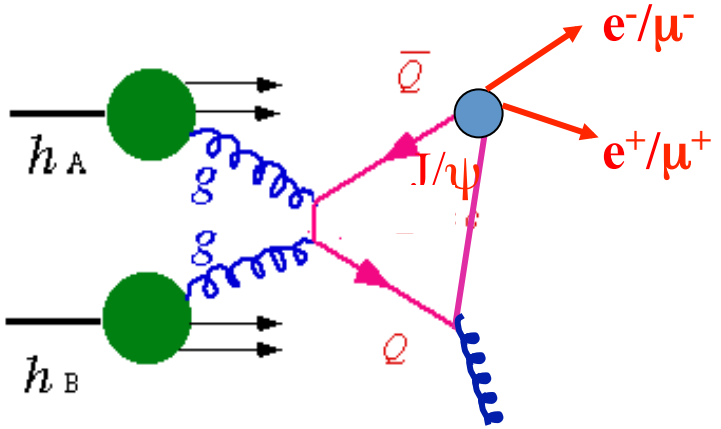
- Motivation
- Overview of RHIC and PHENIX
- Selected PHENIX measurements
  - Forward J/ψ and ψ' ratio via di-muon channel in p+p, p+Al and p+Au collisions.
  - Mid-rapidity B/D R_{AA} via single electron channel in Au+Au collisions.
  - Forward B to J/ψ ratio via di-muon channel in p+p and Cu +Au collisions.
- Summary and Outlook

Motivation

- Heavy flavor production is a good 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>>Λ_{QCD}).
- Quarkonia are expected to dissociate in QGP due to color screening and sequentially melt in later stage. Therefore, quarkonia can be treated as thermometer to probe the QGP temperature.



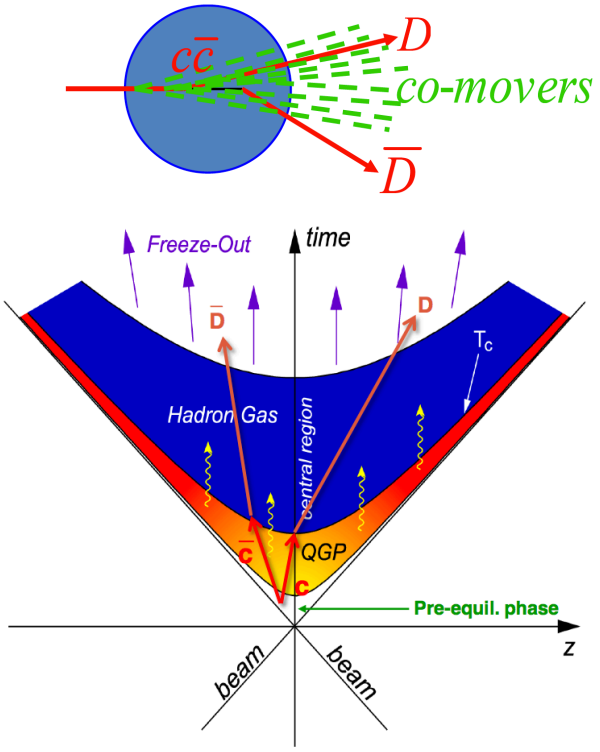
Open Heavy Flavor production



Heavy Flavor quarkonia production

Heavy flavor production in Heavy Ion Collisions

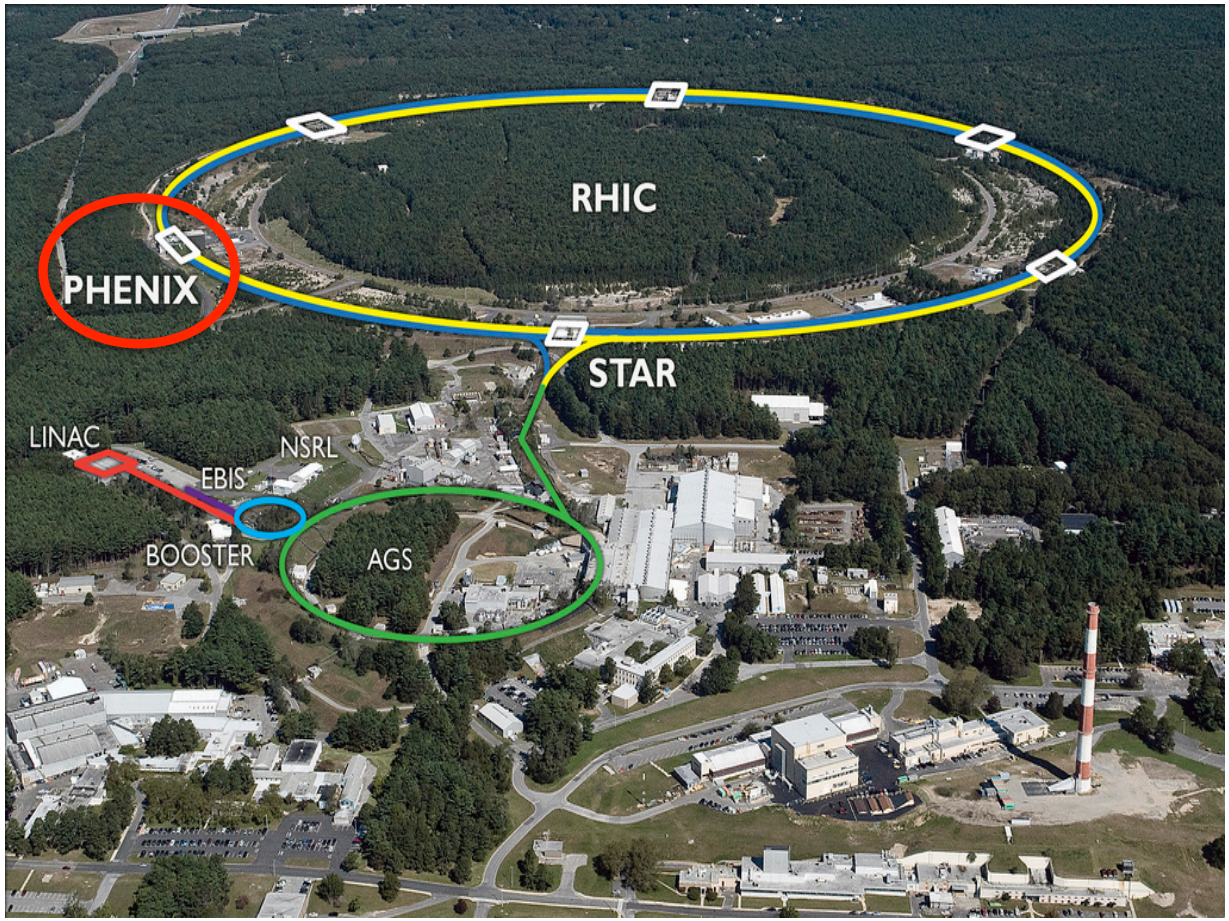
- Not well understood about interaction with the medium.
  - Cold Nuclear Matter (CNM) effect:
    - Nuclear modification of PDFs.
    - Cronin/EMC effect.
    - Energy loss of partons traversing nucleus (Initial state).
    - Breakup of charmonium before exiting nucleus.
    - Co-mover absorption.
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

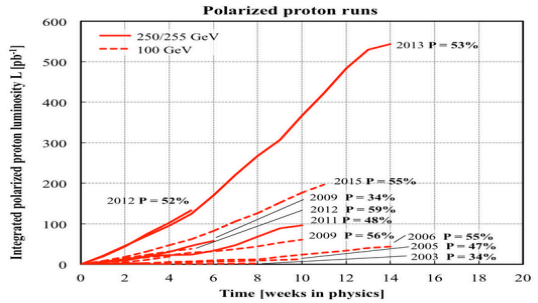


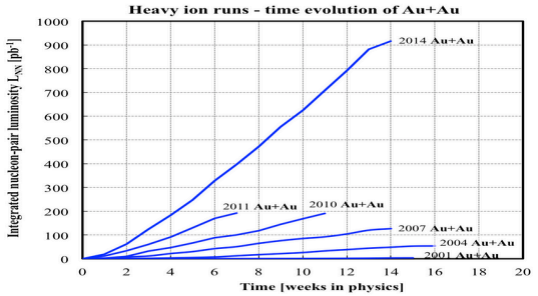
- Need to measure multiple observables in different processes to isolate the initial/final state and cold/hot nuclear matter effects.

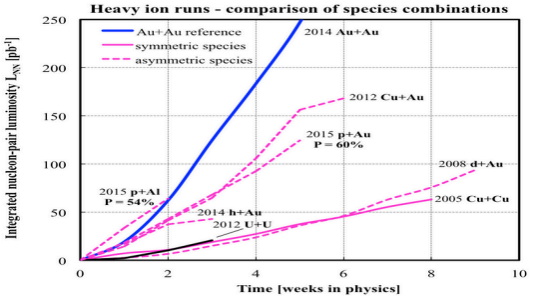
Overview of RHIC

- RHIC collects high luminosity data in various nuclear-nuclear collisions: p+p, p+Al, p+Au, d+Au, He^3+Au, Cu +Cu, Cu+Au, U+U, Au+Au.



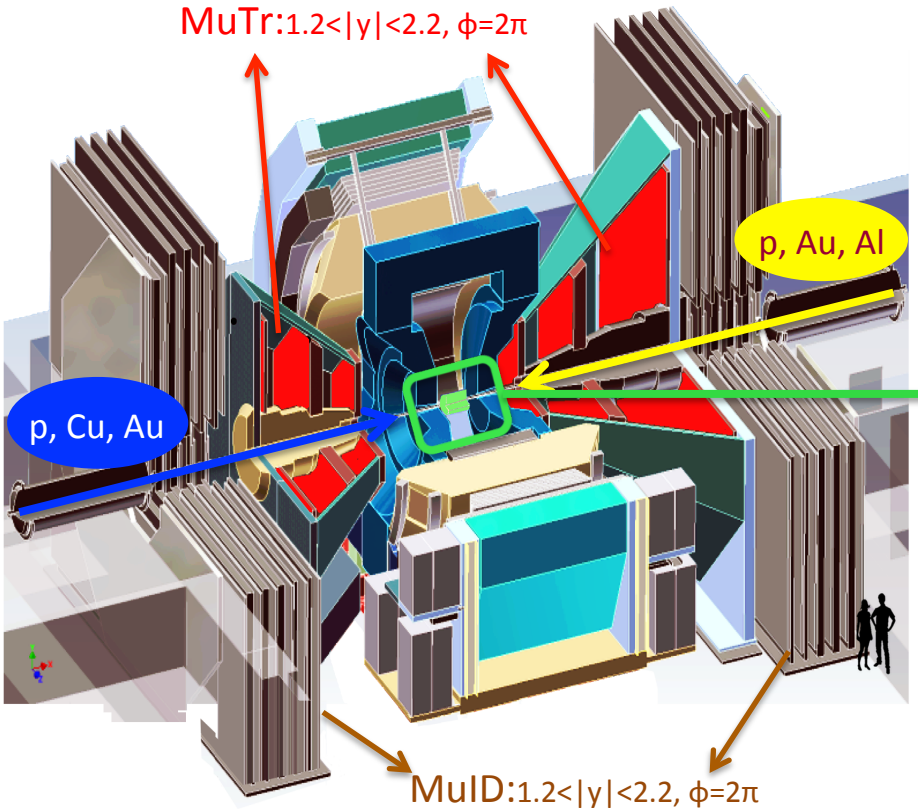




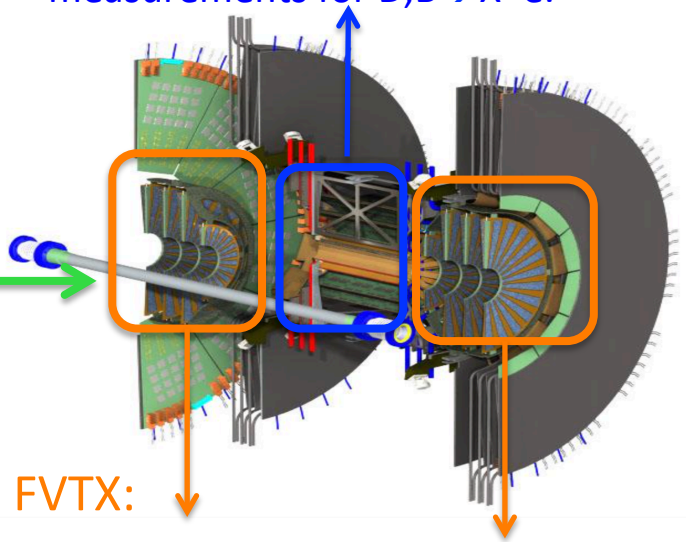


Overview of the PHENIX detector

- The newly installed silicon vertex detectors: VTX(since 2011) and FVTX(since 2012) make the new heavy flavor measurement possible in p+p, p+Al, p+Au, Cu+Au and Au+Au collisions.



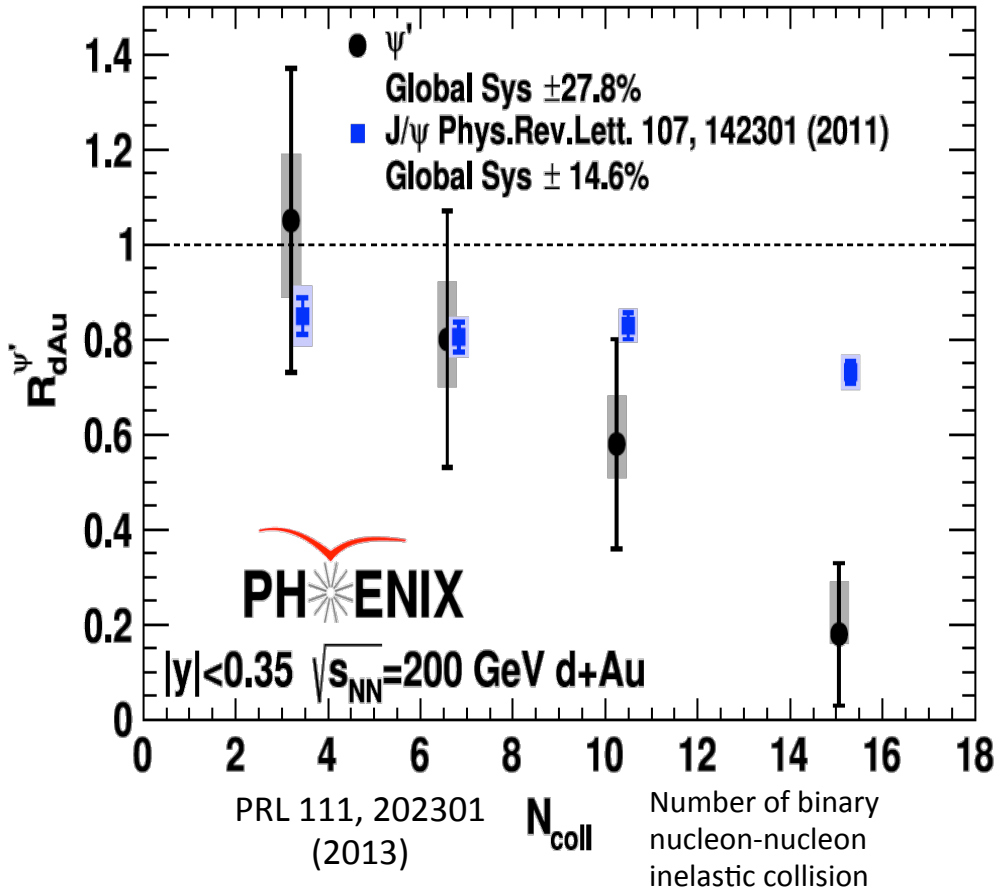
- VTX:
  - With |y|<1.2 and ϕ≈2π coverage.
  - provide precise vertex and tracking measurements for D,B→X+e.



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

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.



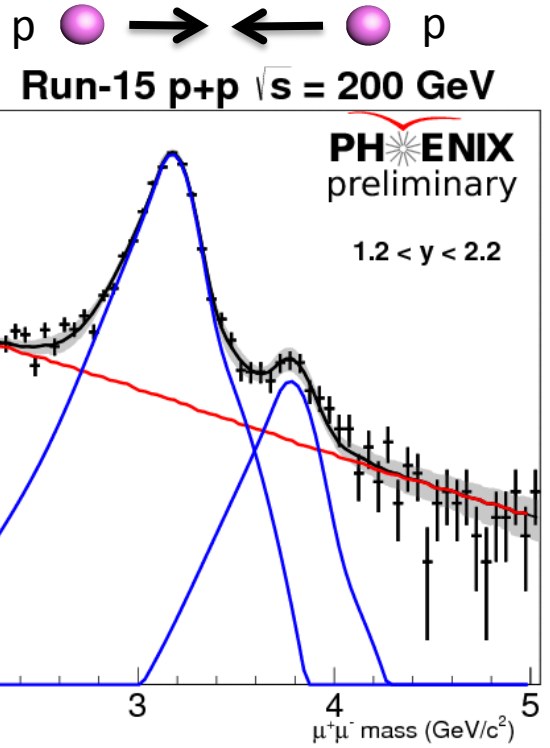
PRL 111, 202301 (2013)

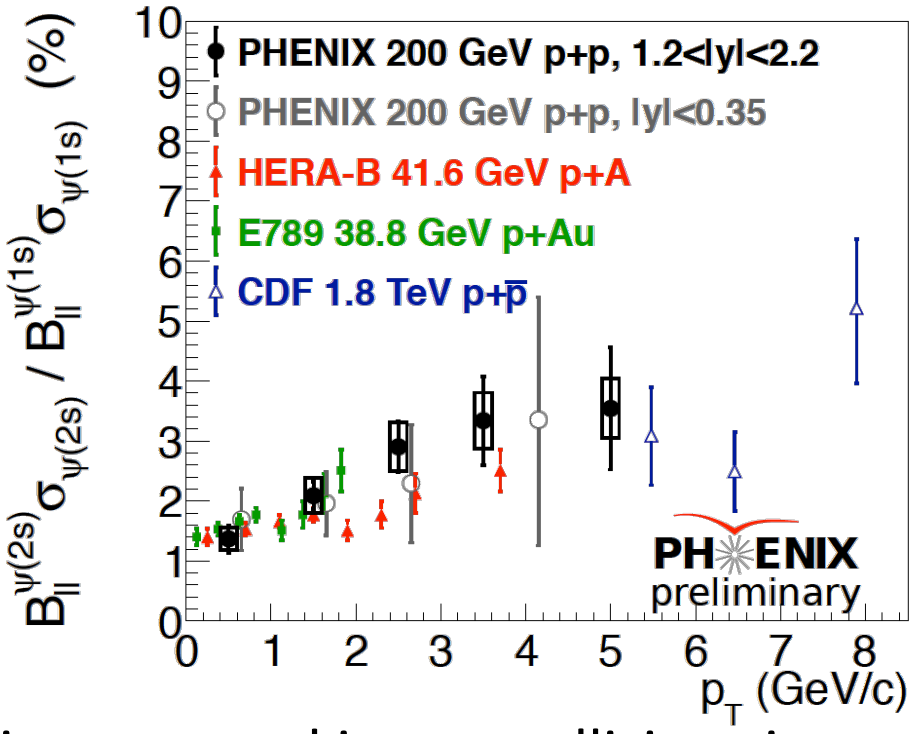
Number of binary nucleon-nucleon inelastic collision

- 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 system?

Forward J/ψ and ψ' measurement in p+p collision

- With improved mass resolution provided by FVTX, clear J/ψ and ψ' identification via di-muon channel (1.2<|y|<2.2) in run15 200 GeV p+p data.

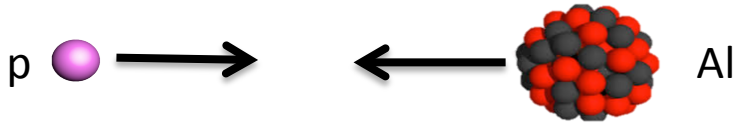


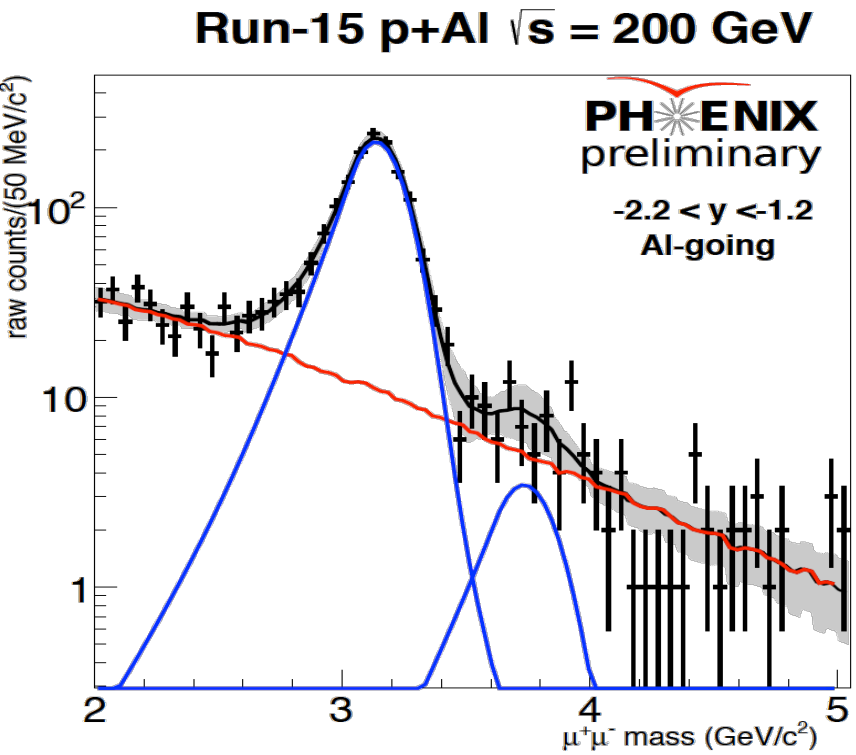


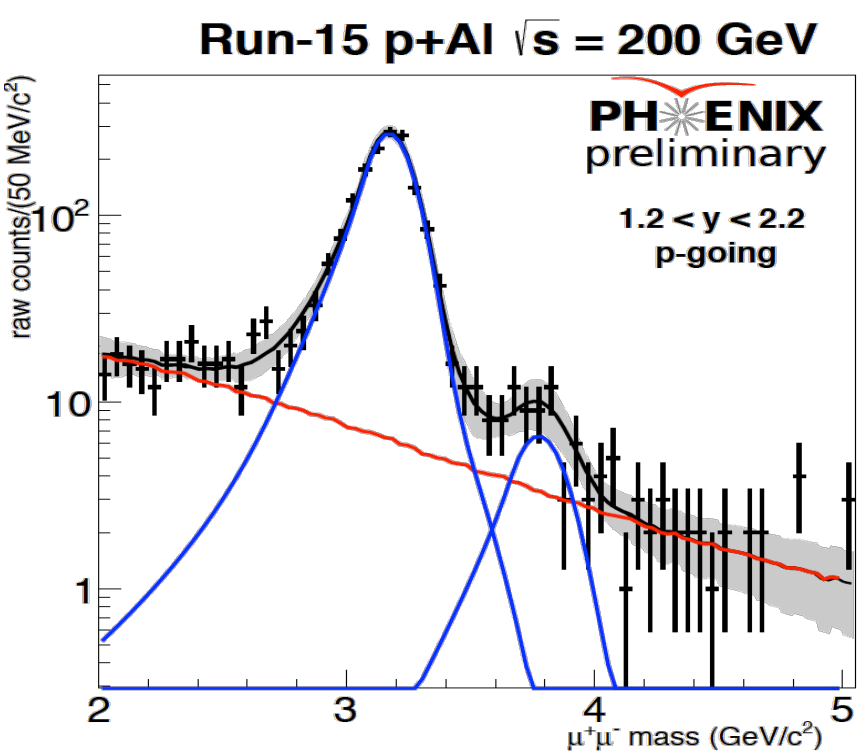
- The forward ψ' to J/ψ ratio measured in p+p collisions is consistent with the global data.

How about asymmetric nuclear collisions?

- In 200 GeV p+Al collisions.



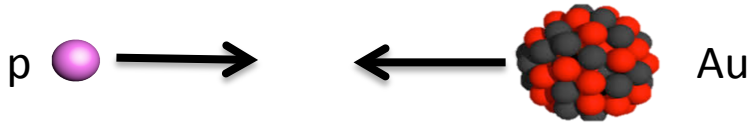


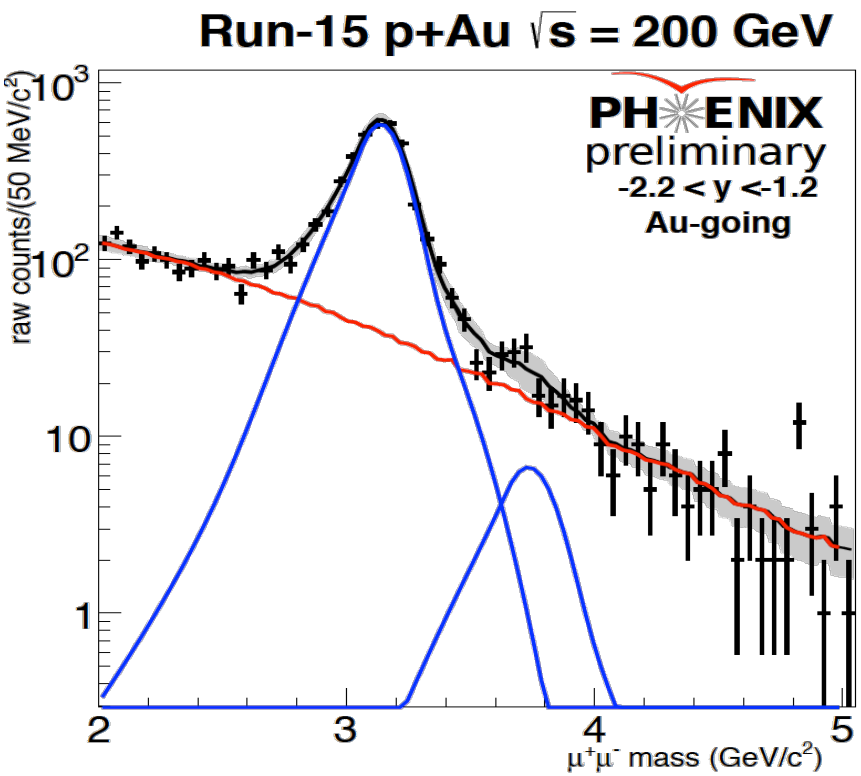


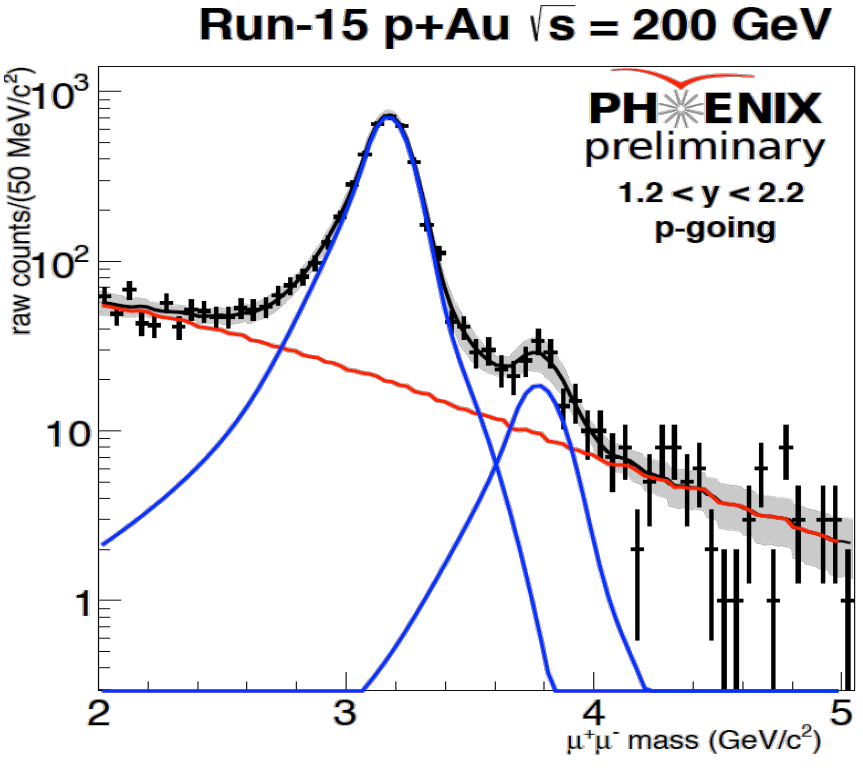
- Even with raw data, clearly the ψ' yield is suppressed relative to J/ψ in the Al going direction.

How about asymmetric nuclear collisions?

- In 200 GeV p+Au collisions.



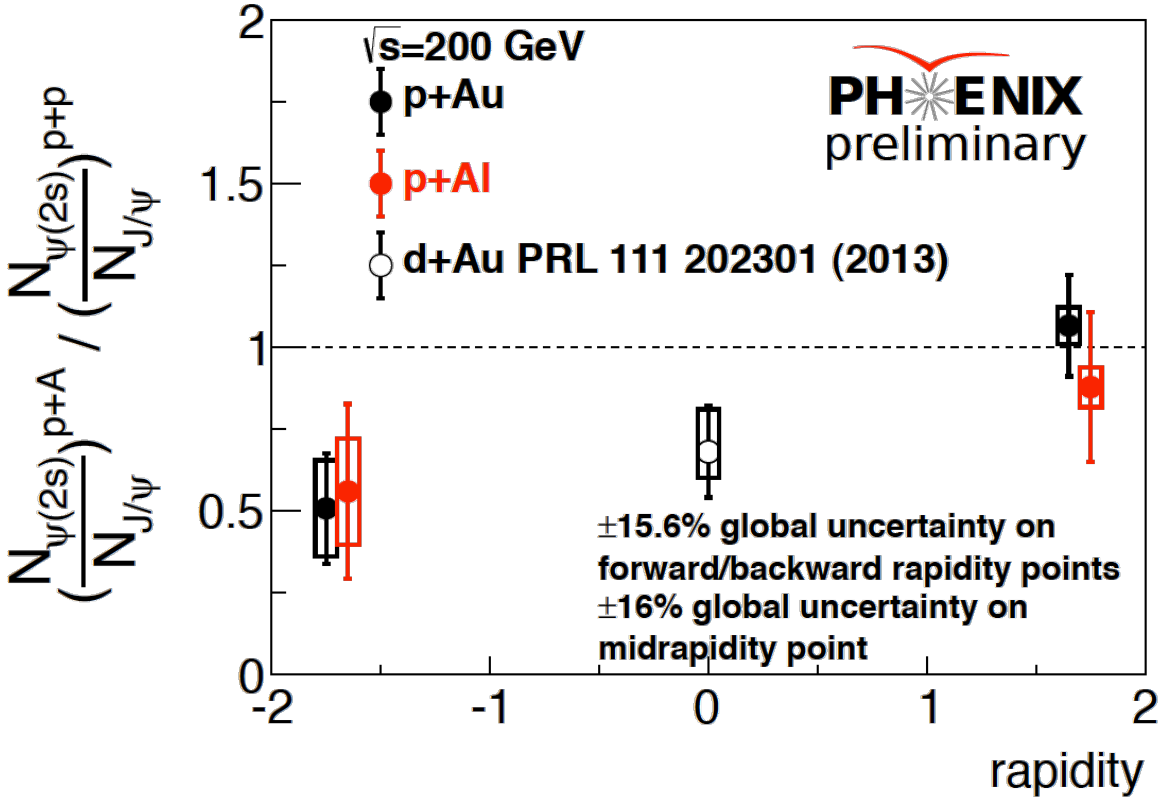




- Even with raw data, clearly the ψ' yield is suppressed relative to J/ψ in the Au going direction as well.

Relative ratio of ψ' to J/ψ VS rapidity

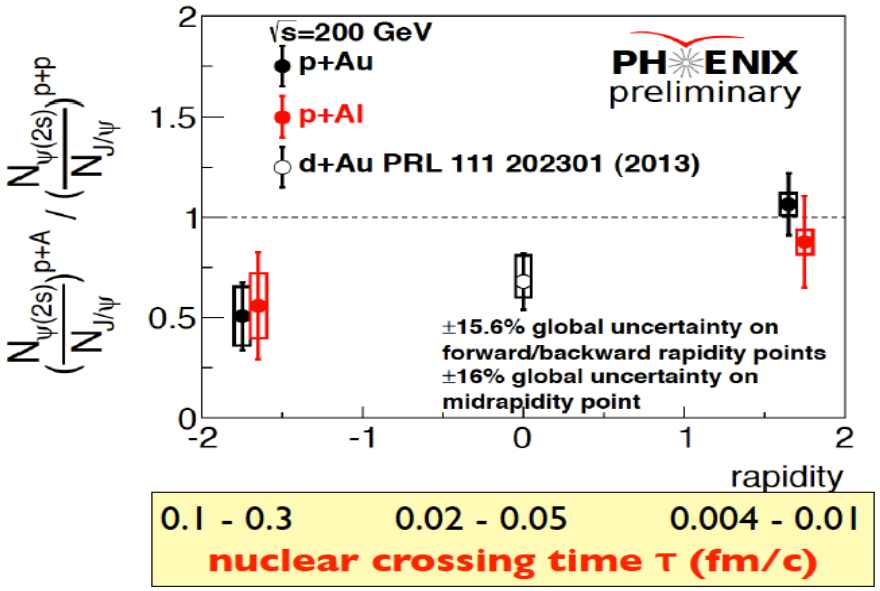
- Centrality integrated relative ratio of ψ' to J/ψ VS rapidity for p+Au, p+Al and d+Au (mid-rapidity).



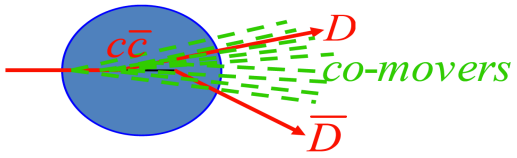
- The J/ψ and ψ' have similar suppression at forward rapidity.
- Strong relative suppression is observed at back rapidity.

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.



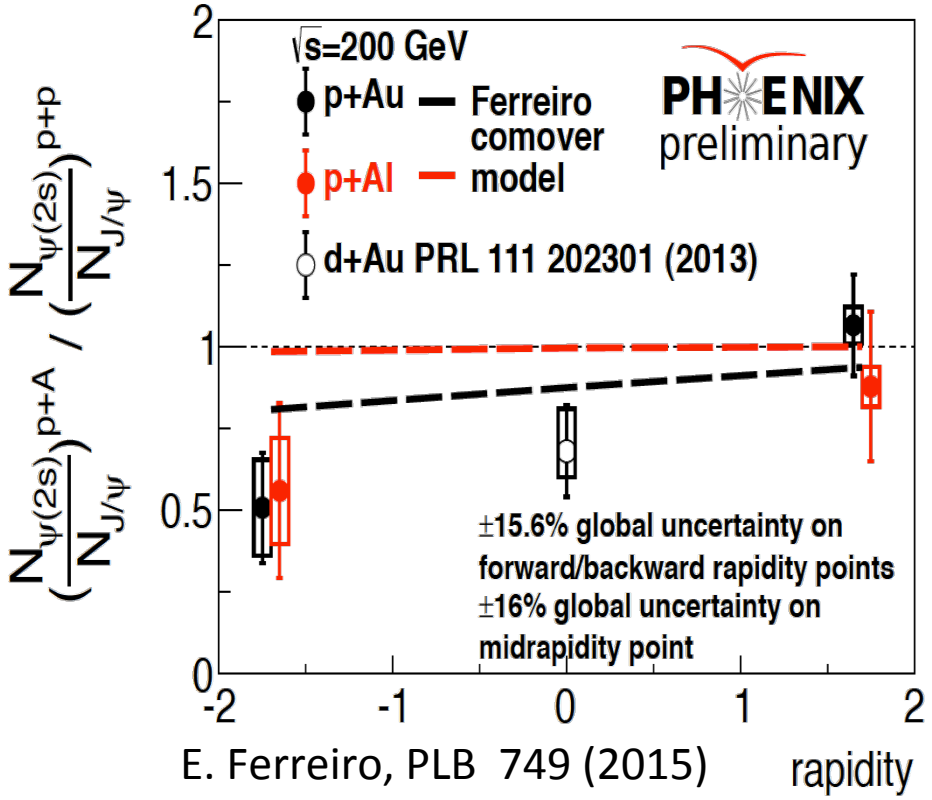
  - According to the crossing time τ dependent model fit on world wide data (PRC 87 (2013) 054910), very small contributions.
  - This effect can not explain the backward rapidity suppression.



- 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.

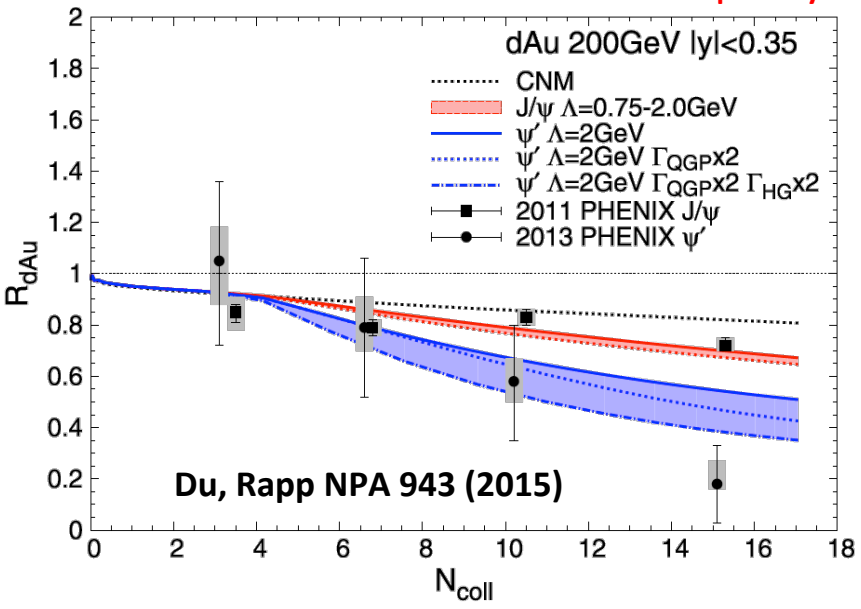
Relative ratio of ψ' to J/ψ VS rapidity

- 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

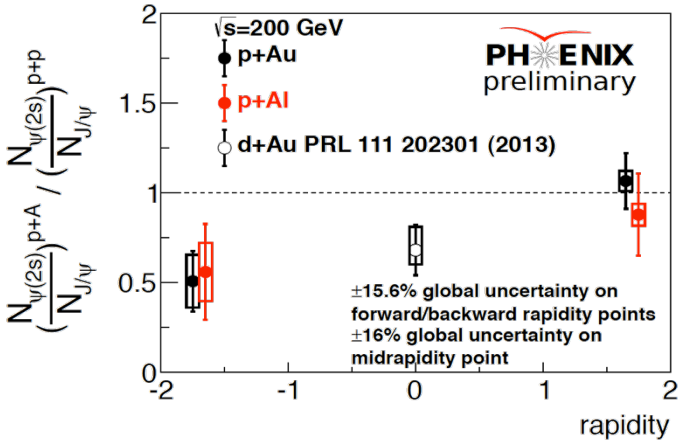


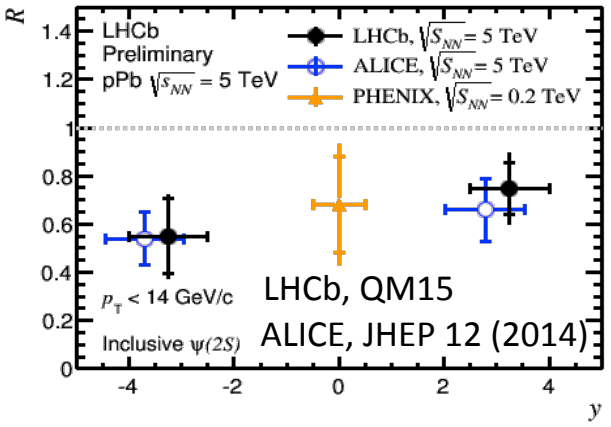
New calculation allows for short QGP phase in central collisions + hadron resonance gas.

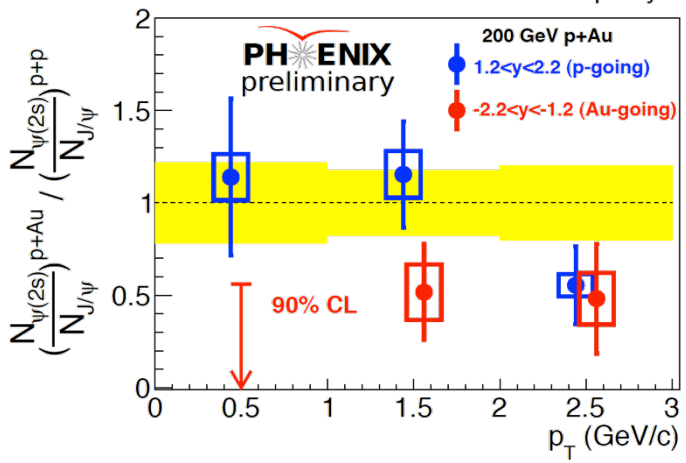
- Result is generally consistent within significant statistical uncertainties with co-mover dissociation model.
- New model calculations? Plasma effect in central collisions?

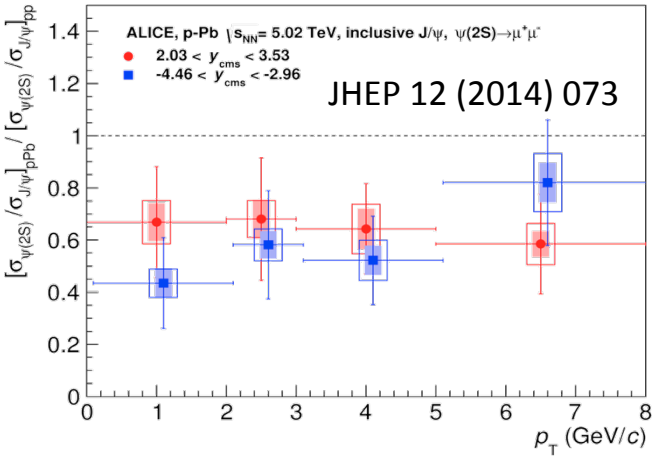
Comparison with the LHC results

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







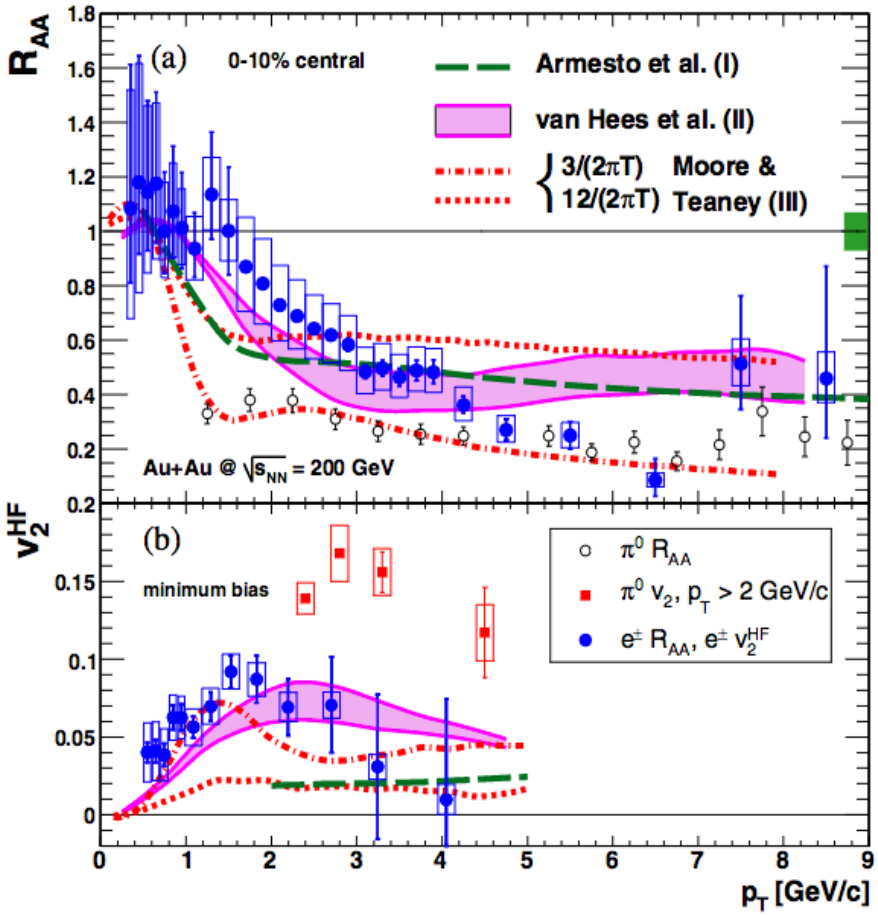


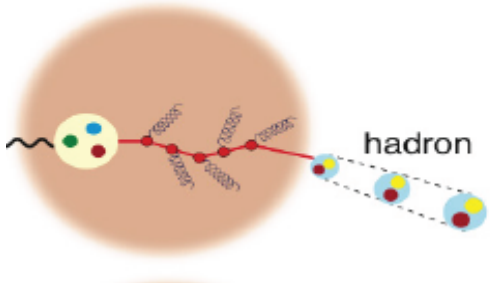
- Larger co-mover contribution in the LHC era? Gluon saturation change spectroscopic charmonium states ?

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)

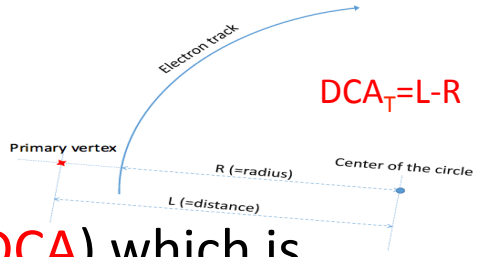




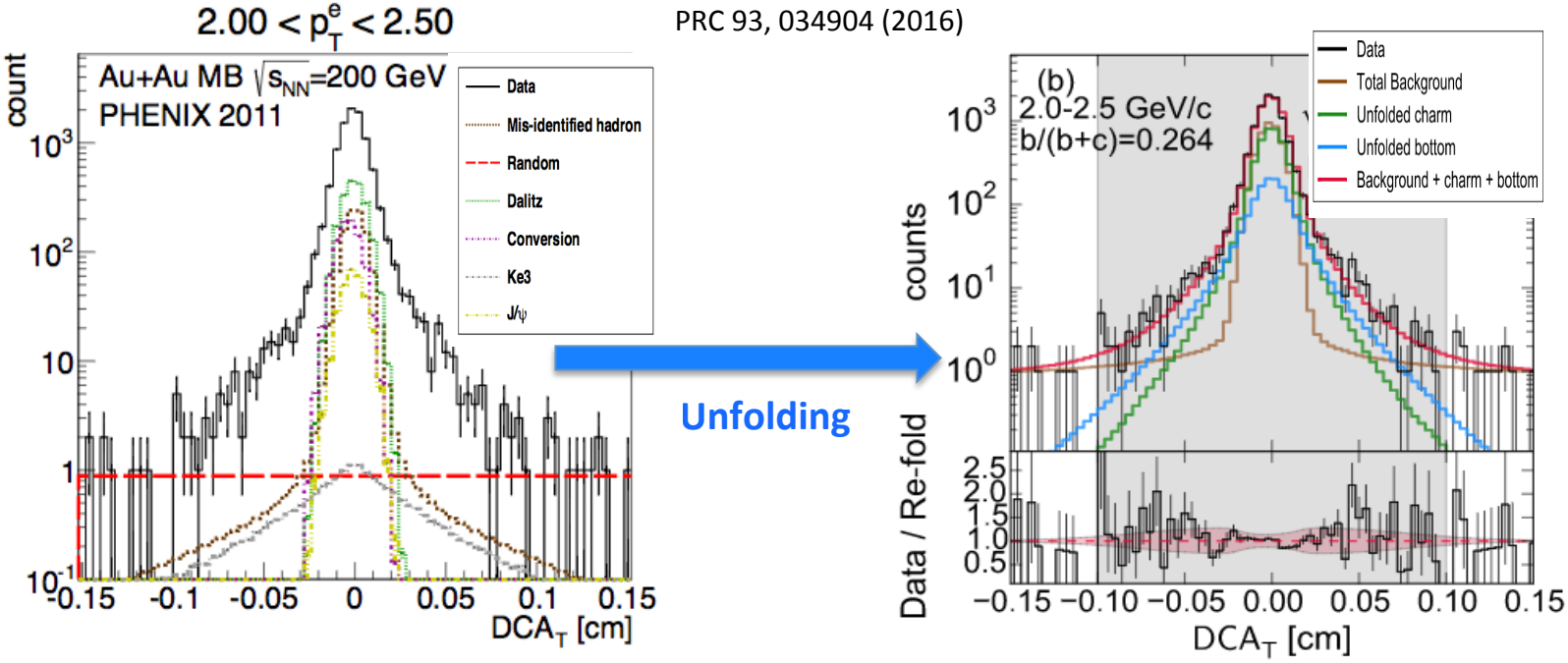
- Light hadron and heavy flavor production have different suppression, flavor dependent coupling?
- Need to separate charm and bottom and study the mass dependent quark energy loss.

Analysis strategy to separate charm and bottom

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



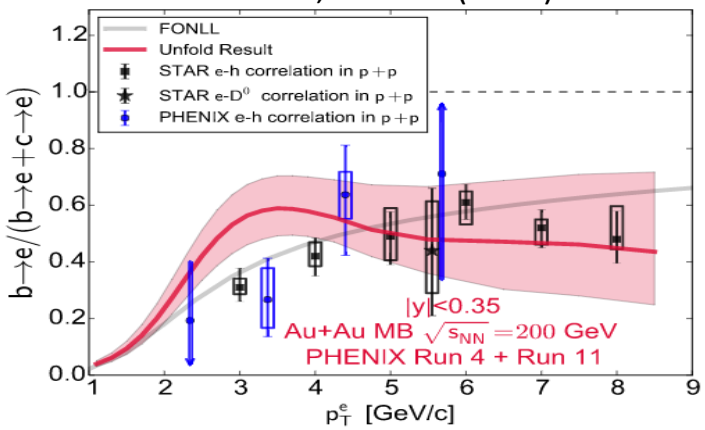
PRC 93, 034904 (2016)



Study the Hot Nuclear Matter effect via D/B production

- The bottom fraction has different p_T dependence between p +p collisions and Au+Au collisions.

PRC 93, 034904 (2016)



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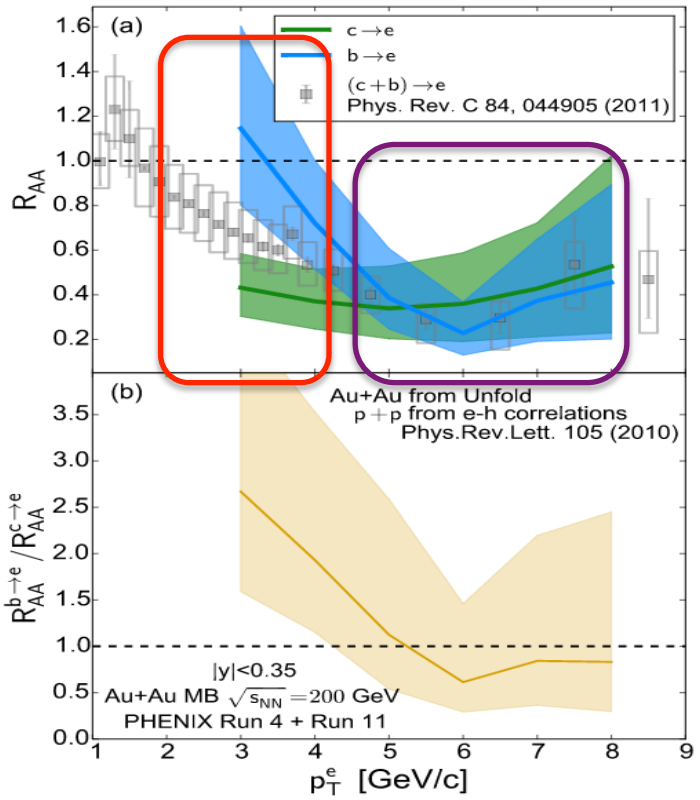


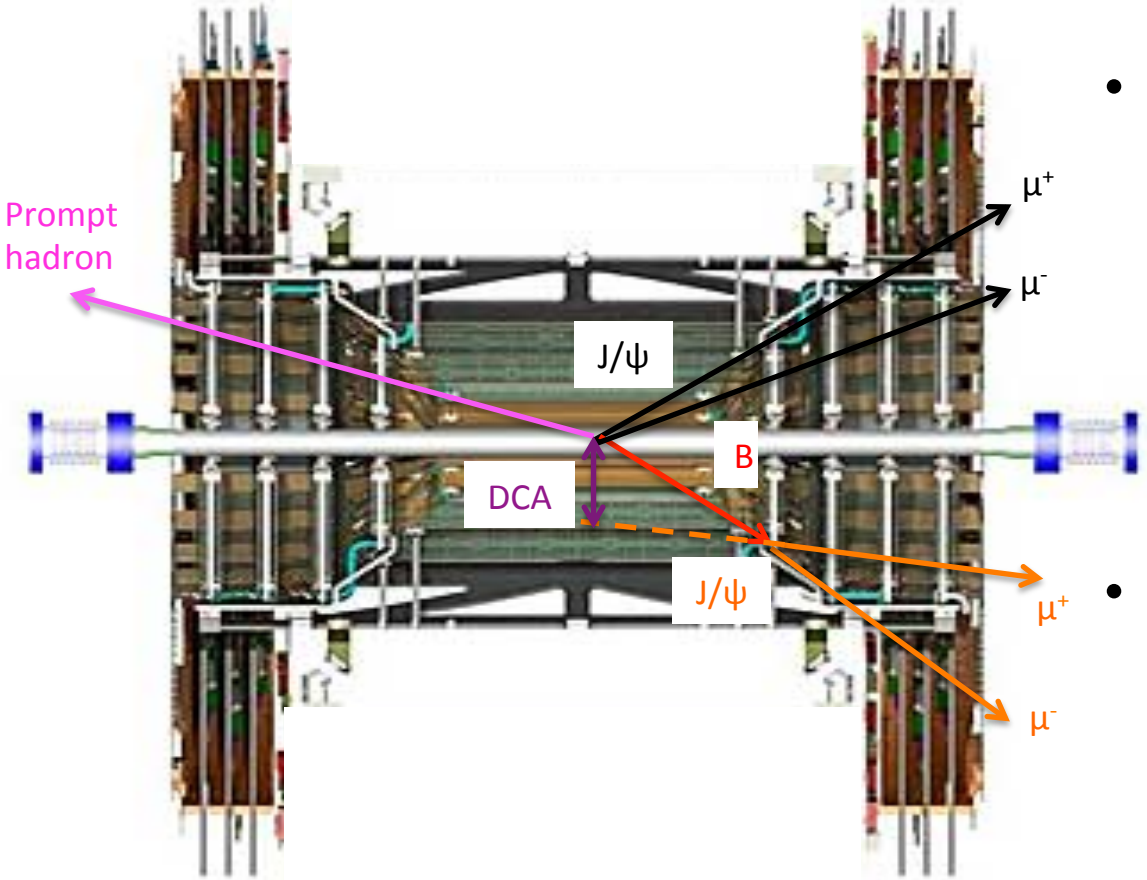
- From the R_{AA} results,
  - Bottom has similar suppression as charm for high p_T region.
  - Bottom may be less suppressed in the low p_T region.

- New analysis with the high statistics run14 Au+Au data is ongoing.

Can we measure B meson in forward rapidity?

B->J/ψ->$\mu^+\mu^-$

- B mesons measured in the forward/backward rapidity with longer decay length may probe different QGP evolution stage in heavy ion collisions from the mid-rapidity region.



- Different DCA_R shapes of prompt particles and decayed particles make the separation of B decayed J/ψ and prompt J/ψ feasible.
- Heavy quark decay populate to the negative DCA region.

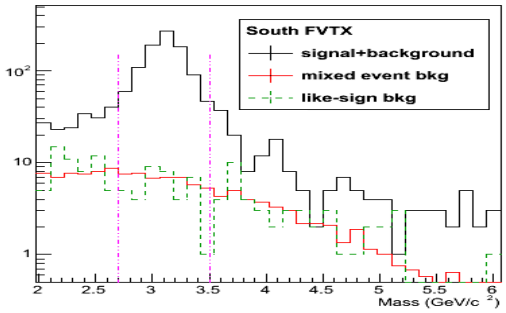
Analysis strategy for the B to J/ψ ratio measurement (I)

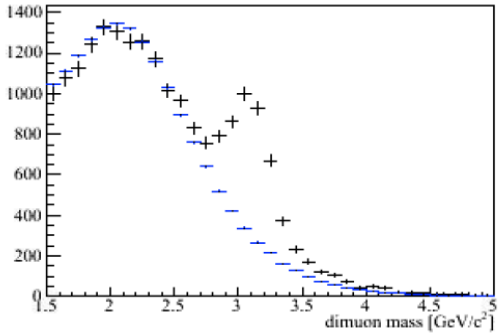
- J/ψ candidate selection in data after QA check and mis-alignment correction.
  - Di-muons passing quality cuts (tracking, vertex, detector matching etc.)
  - Combinatorial background is comparable between mixed events and like-sign candidates.

510 GeV p+p data

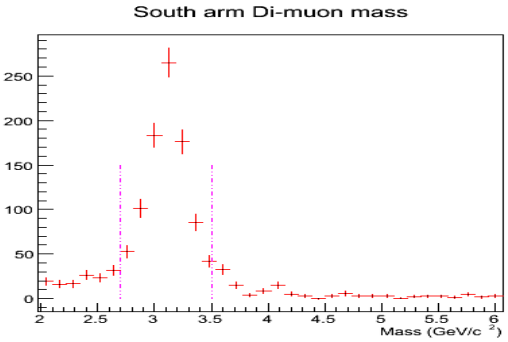
200 GeV Cu+Au data

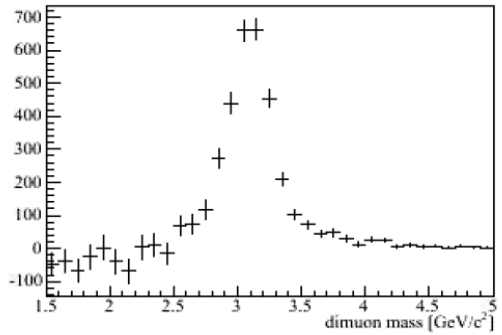
Foreground and combinatorial BKG





Combinatorial BKG subtracted yields



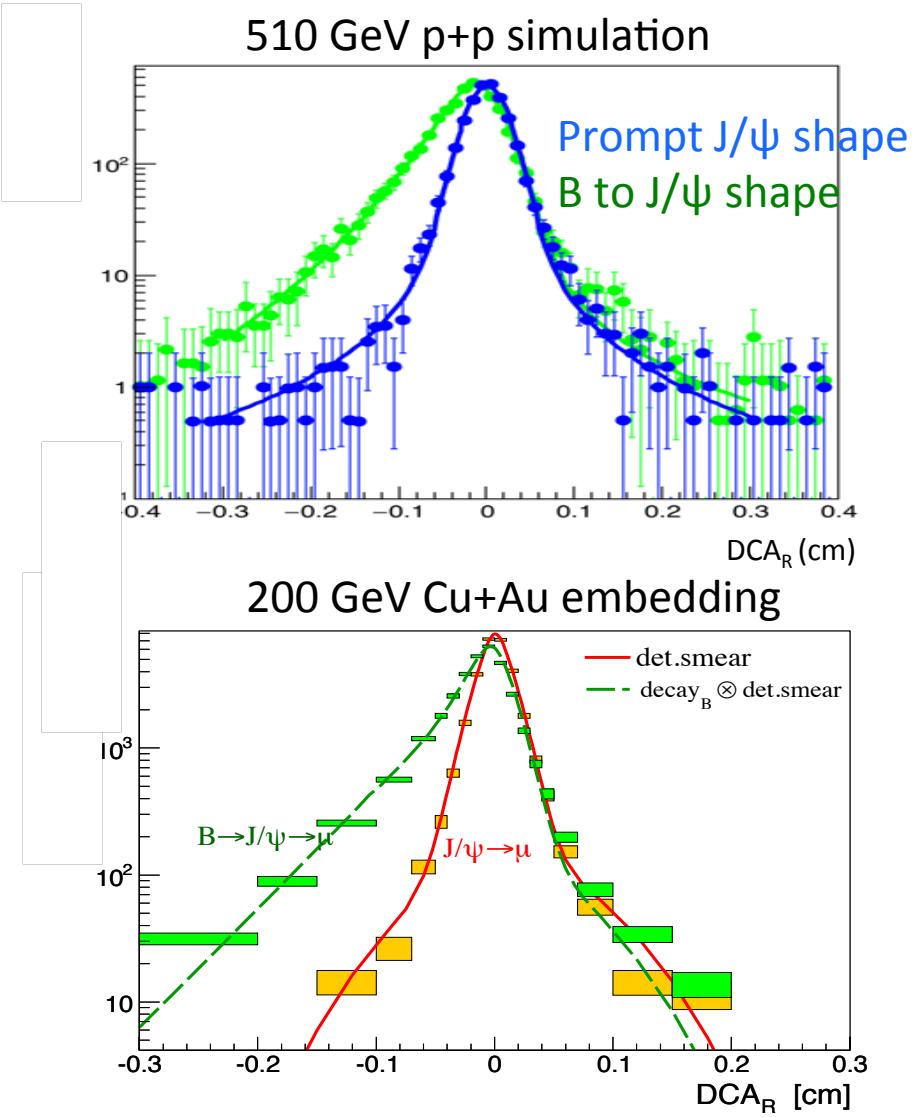


- Clear J/ψ peak is found in both p+p and Cu+Au data.

Analysis strategy for the B to J/ψ ratio measurement (II)

- J/ψ candidate selection
  - Di-muons passing quality cuts (tracking, vertex, detector matching etc.)
- Clear J/ψ peak is found in both p+p and Cu +Au data.

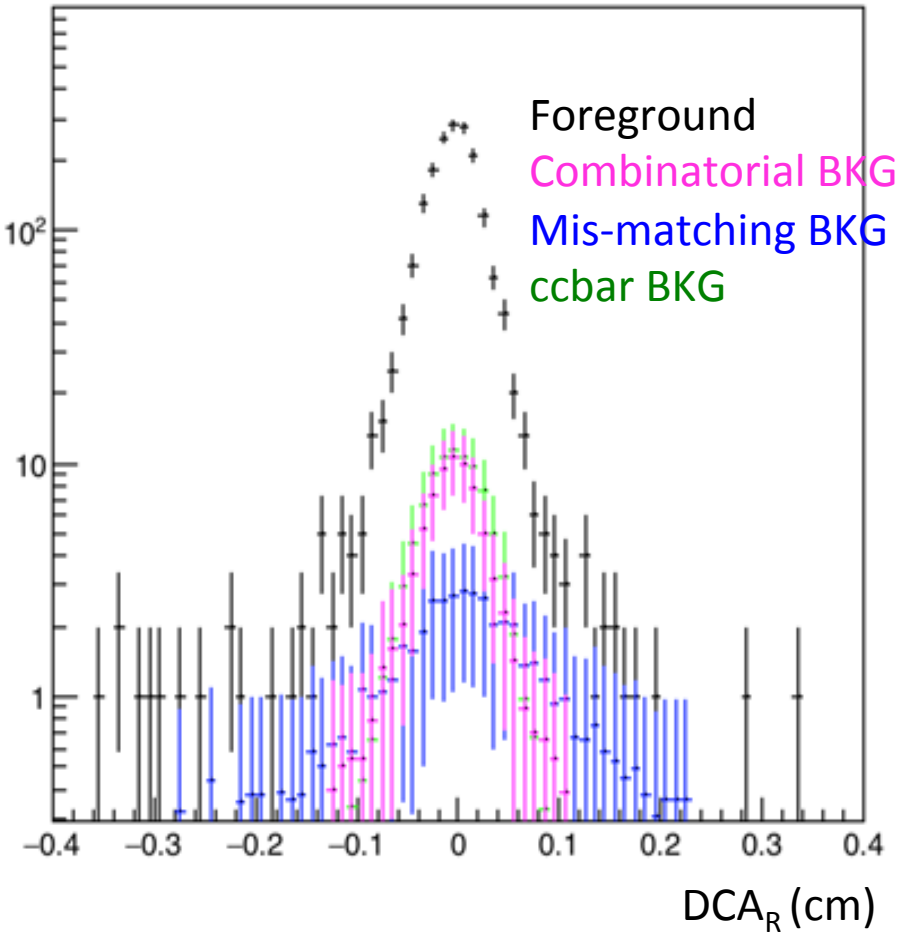
- Signal determination
  - Set up full simulation (PYTHIA +GEANT+RECO) for p+p and embedding for Cu+Au with realistic tracking, vertex and dead maps etc.
  - Generate prompt J/ψ and B to J/ψ events in simulation.
  - Same cuts applied as in data.
- Obvious DCA_R shape difference between prompt J/ψ and B to J/ψ.



Analysis strategy for the B to J/ψ ratio measurement (III)

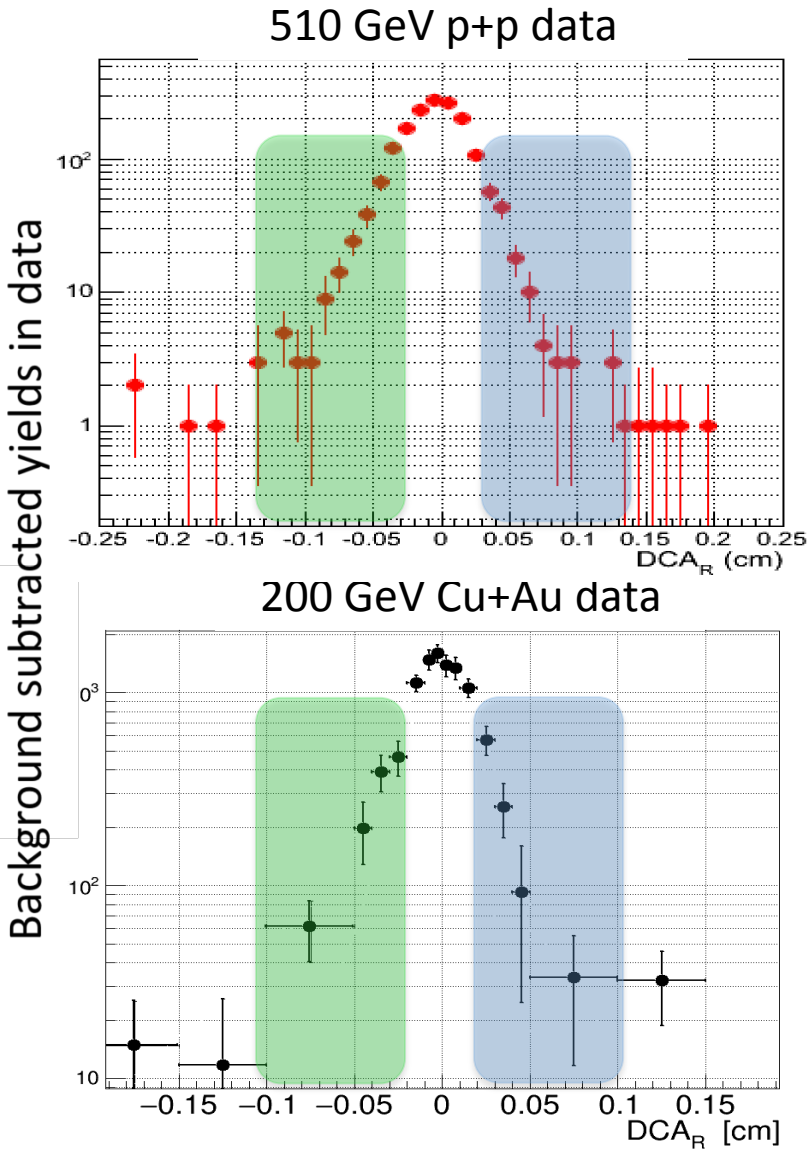
- J/ψ candidate selection
  - Di-muons passing quality cuts (tracking, vertex, detector matching etc.)
- Clear J/ψ peak is found in both p+p and Cu +Au data.
- Signal determination
  - Set up full simulation (PYTHIA+GEANT+RECO) for p+p and embedding for Cu+Au with realistic tracking, vertex and dead maps etc.
  - Generate prompt J/ψ and B to J/ψ events in simulation.
  - Same cuts applied as in data.
- Obvious DCA_R shape difference between prompt J/ψ and B to J/ψ.
- Background determination
  - Combinatorial background using mixed events.
  - Detector mis-matching using topological detector event mixing technique.
  - Heavy flavor continuum (dominanted by ccbar), generated in simulation with fraction determined in data.

Raw yields of foreground and background in 510 GeV p+p collisions



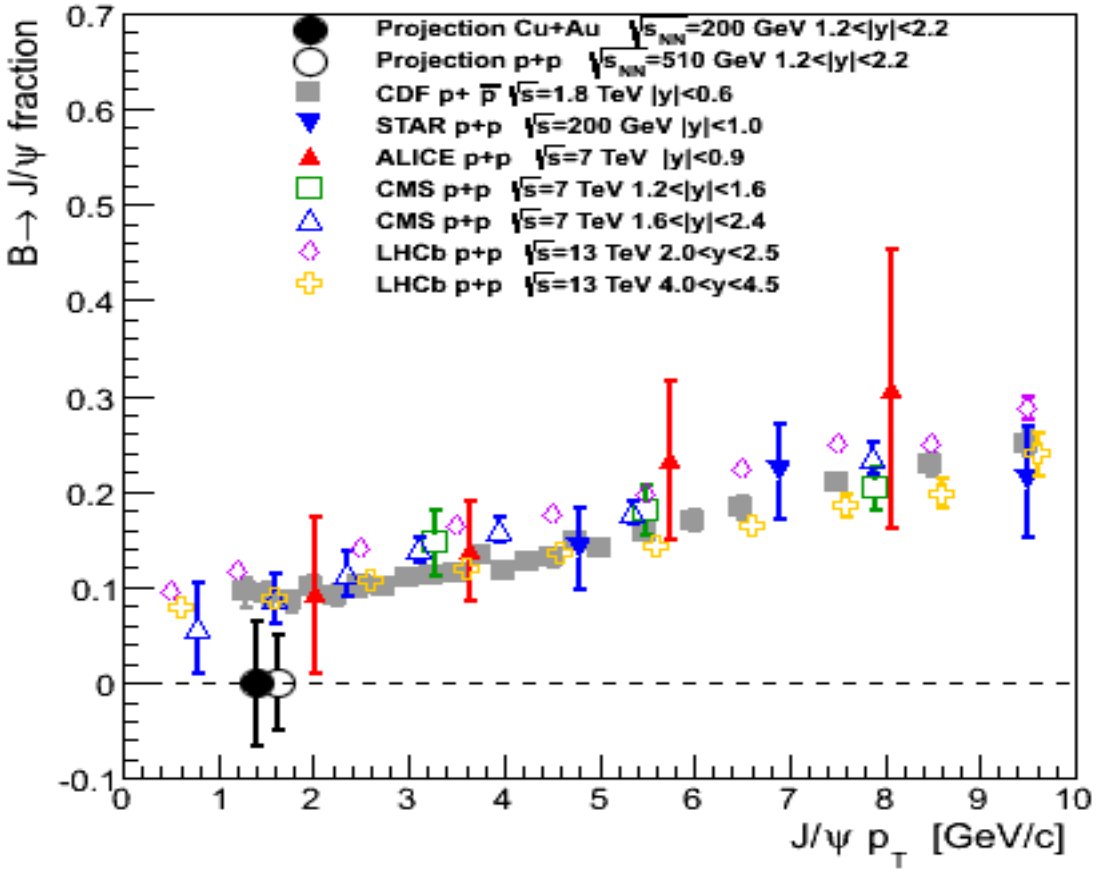
Analysis strategy for the B to J/ψ ratio measurement

- J/ψ candidate selection
  - Di-muons passing quality cuts (tracking, vertex, detector matching etc.)
- Clear J/ψ peak is found in both p+p and Cu +Au data.
- Signal determination
  - Set up full simulation (PYTHIA+GEANT+RECO) for p+p and embedding for Cu+Au with realistic tracking, vertex and dead maps etc.
  - Generate prompt J/ψ and B to J/ψ events in simulation.
  - Same cuts applied as in data.
- Obvious DCA_R shape difference between prompt J/ψ and B to J/ψ.
- Background determination
  - Combinatorial background using mixed events.
  - Detector mis-matching using topological detector event mixing technique.
  - Heavy flavor continuum (dominanted by ccbar), generated in simulation with fraction determined in data.
- Asymmetric DCA_R shapes in both p+p and Cu+Au data indicates clear B contribution.



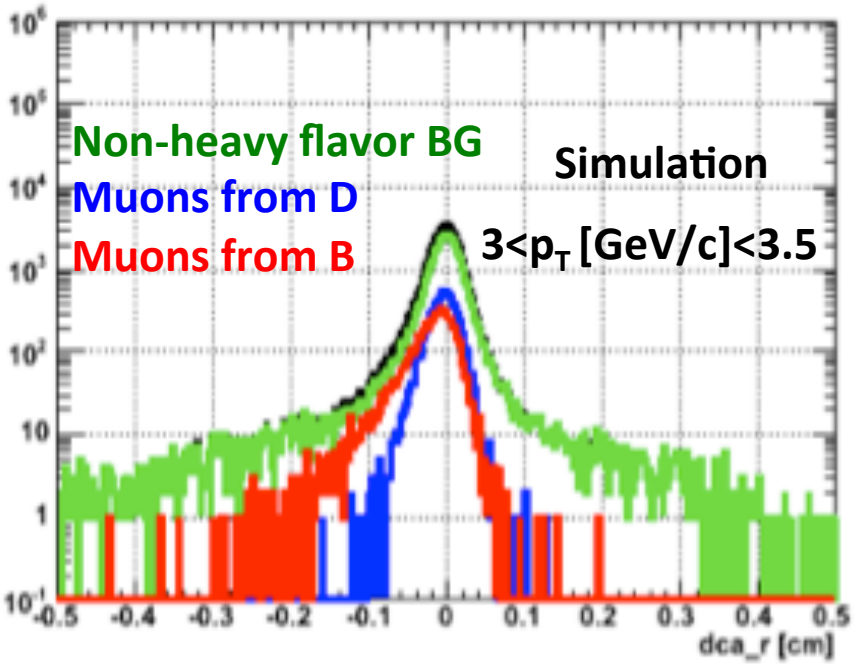
Projection of the B to J/ψ ratio

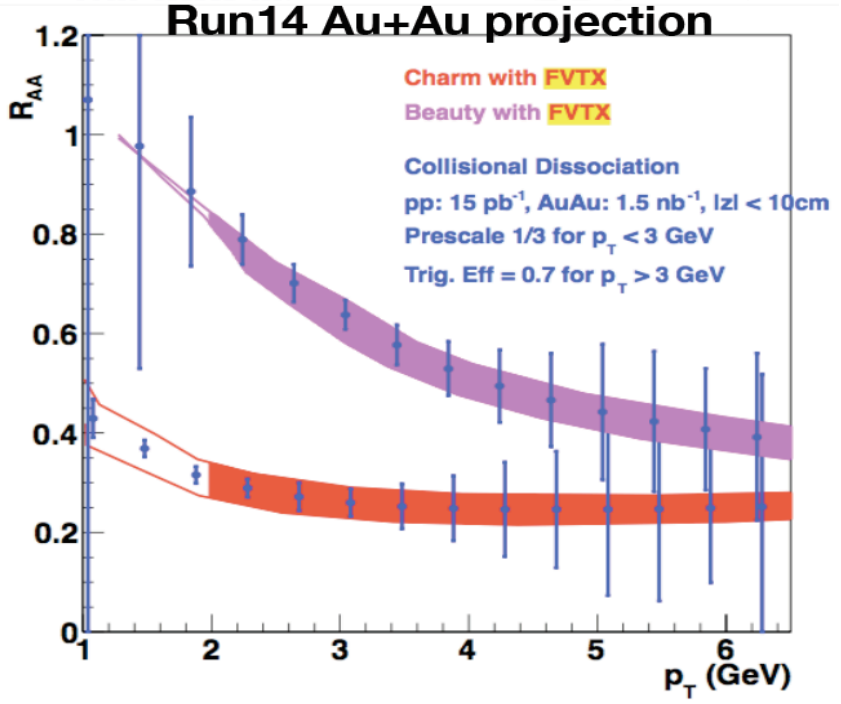
- Here is the projected statistical uncertainties of the B to J/ψ ratio in 510 GeV p+p collisions (open circle) and in 200 GeV Cu+Au collisions(closed circle).
- Final results are under collaboration review.



Charm and Bottom from inclusive single muons

- High statistics measurement with similar method developed in the B to J/ψ analysis.
- Analysis is underway.
- The challenge is to minimize systematics.





Summary

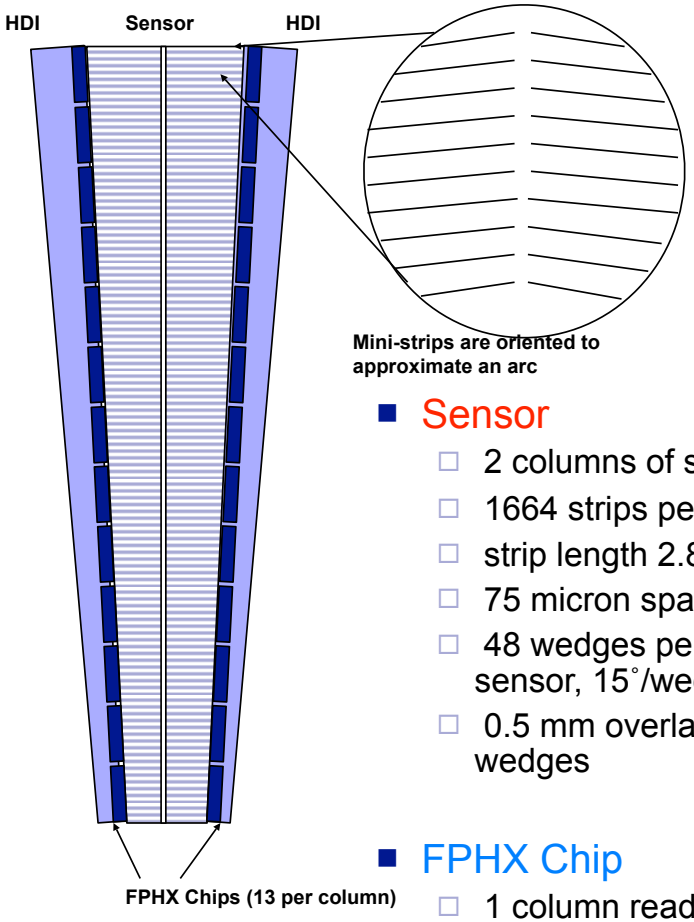
- Differential suppression of ψ′ to J/ψ relative ratio in p+Al and p+Au data shows strong evidence of final state effects.
  - The co-mover model provides a reasonable description.
  - Other theory calculations?
- First D/B separated single electron measurement.
- First forward/backward B to J/ψ measurements at low p_T are achieved in both p+p and Cu+Au collisions. Results to be released soon.

Outlook

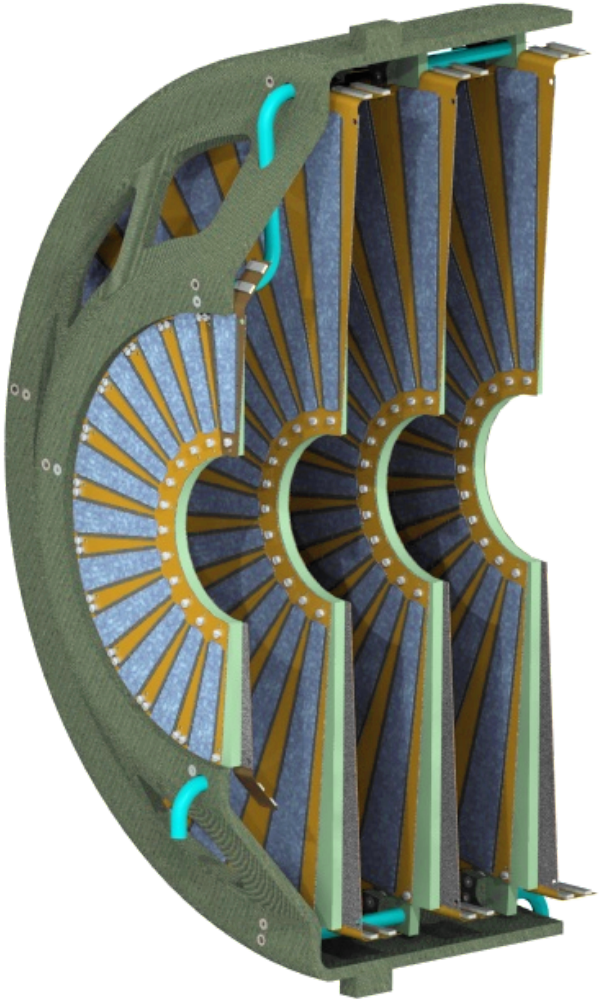
- Large data set in various types of heavy ion collisions collected at PHENIX provide opportunities to study
  - ψ' to J/ψ ratio in run14/16 Au+Au collisions to demonstrate hot nuclear matter effect like color screening in QGP.
  - D/B separate single elections/muons in run14/16 Au +Au collisions with higher statistics.
  - Forward/backward B to J/ψ via di-muon channel in run15 p+p, p+Au, run14/16 Au+Au collisions to understand CNM and hot nuclear matter effect.
  - …
- More to come.

Backup

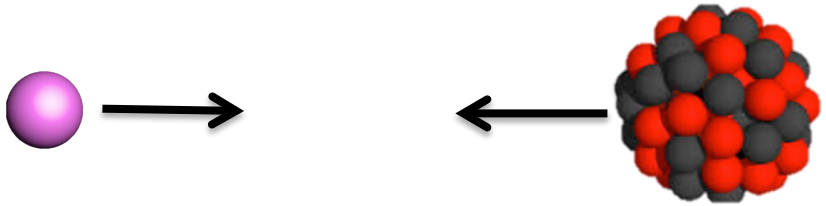
The Forward Vertex Detector (FVTX)

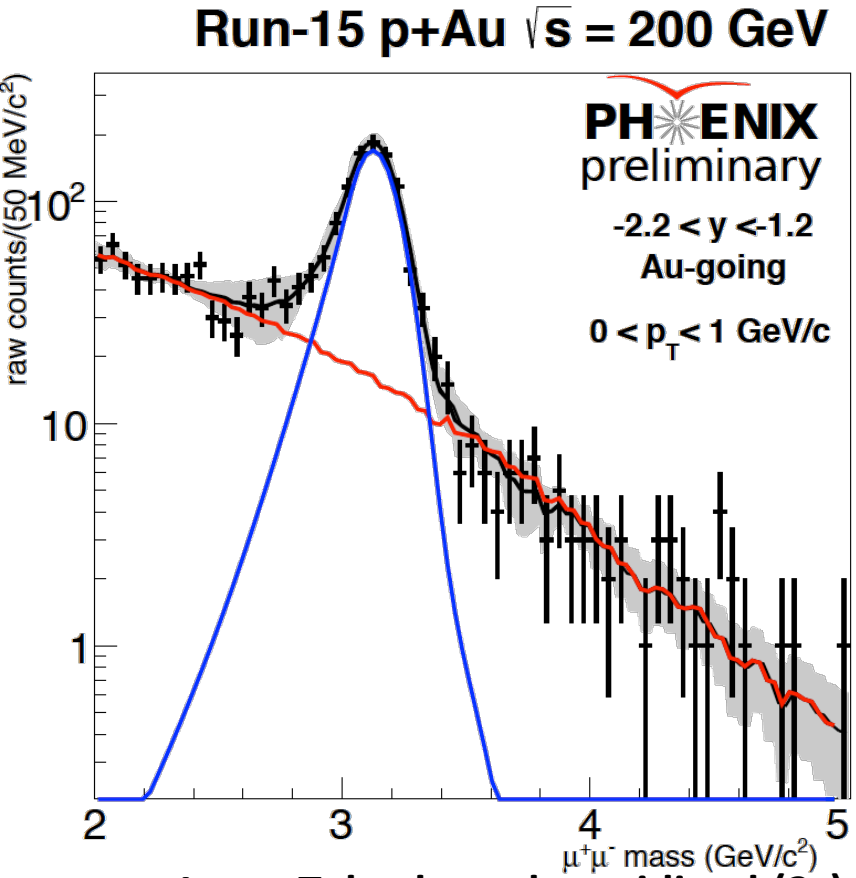


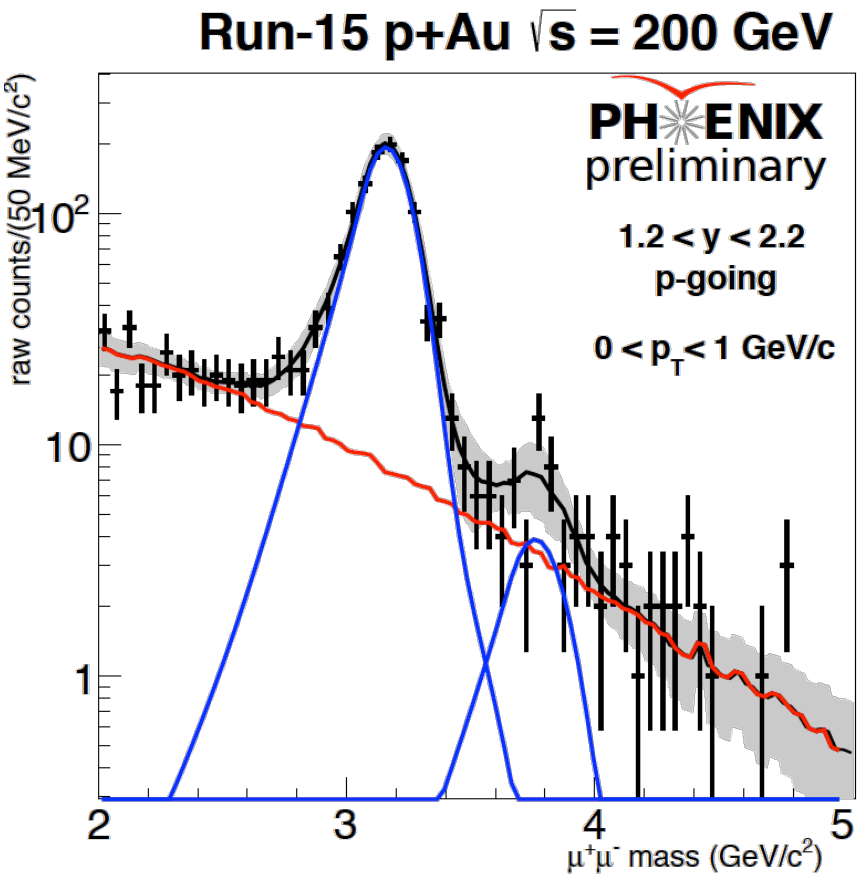
- Sensor
  - 2 columns of strips
  - 1664 strips per column
  - strip length 2.8 to 11.2 mm
  - 75 micron spacing
  - 48 wedges per disk (7.5˚/ sensor, 15˚/wedge)
  - 0.5 mm overlap with adjacent wedges
- FPHX Chip
  - 1 column readout
  - 128 channels
  - ~ 70 microns channel spacing
  - Dimensions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



p+A pT dependence



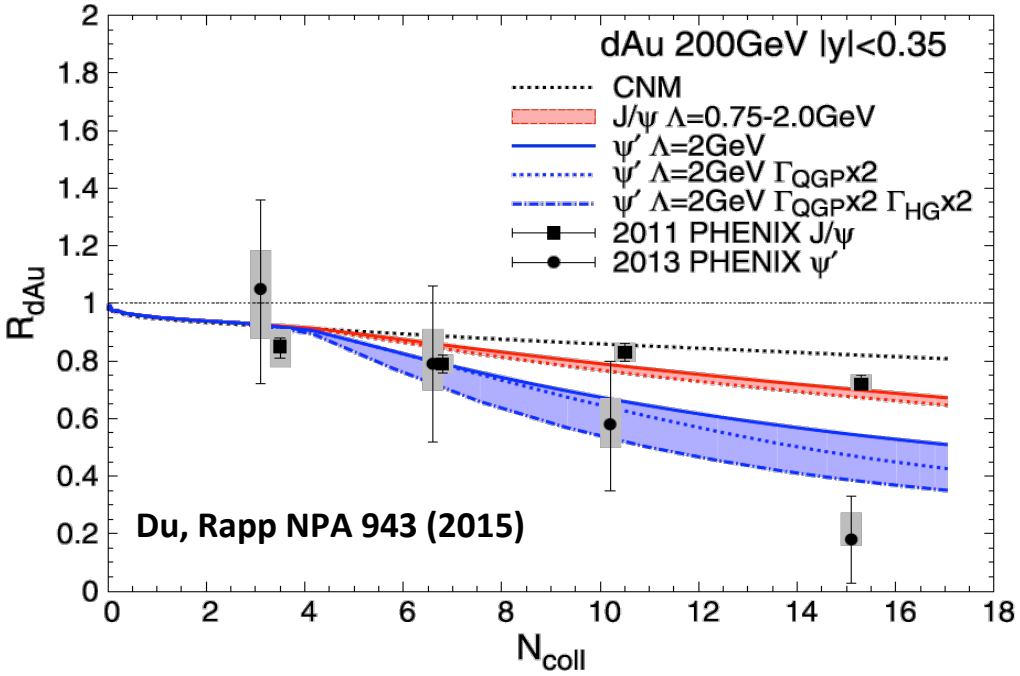




Low pT, backwards rapidity ψ(2s) yields *consistent with ZERO.*

Model comparison for J/ψ and ψ' measurements

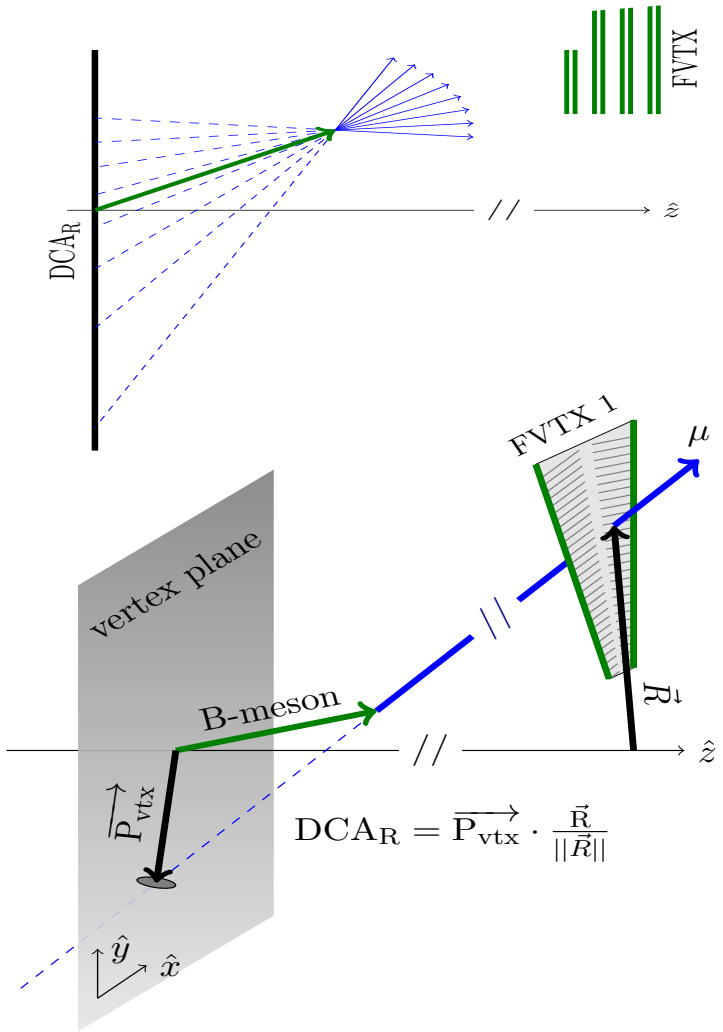
- New model



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

Distance of Closest Approach (DCA) definition

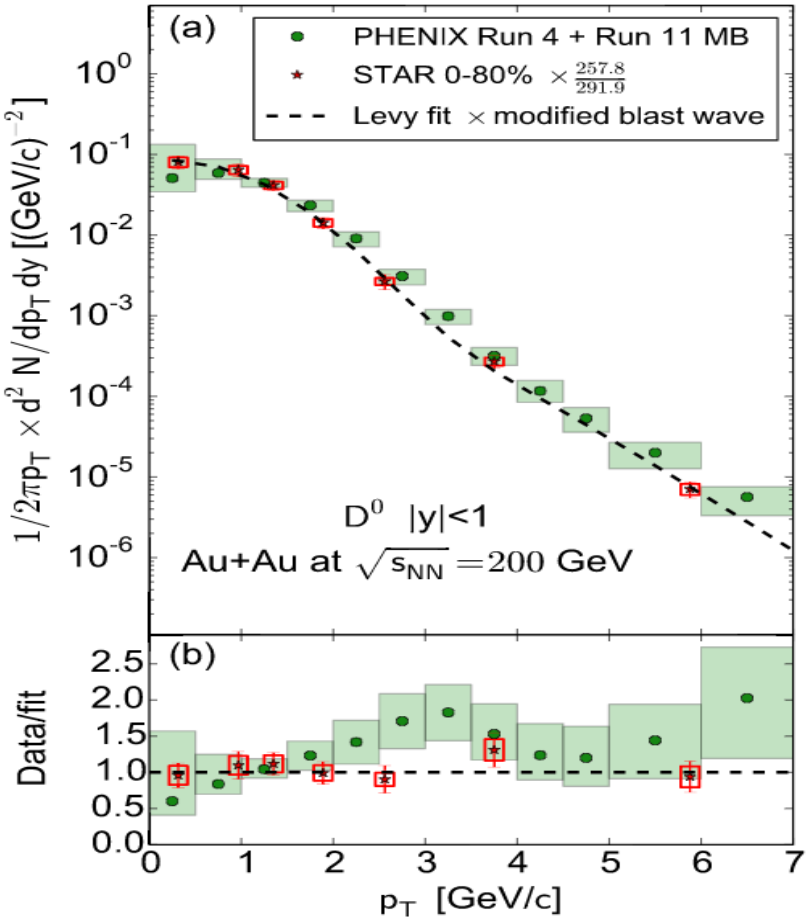
- Definition of the DCA_R.



- Track projection to the primary vertex xy plane. The projection (x_{proj}, y_{proj}) and the primary vertex (x_0,y_0) forms the DCA vector (x_{proj}-x_0, y_{proj}-y_0).
- For p+p data, we use the beam average x_0, y_0 values.
- We define DCA_R is along the direction of the detector radial direction.

Cross check for single electron analysis

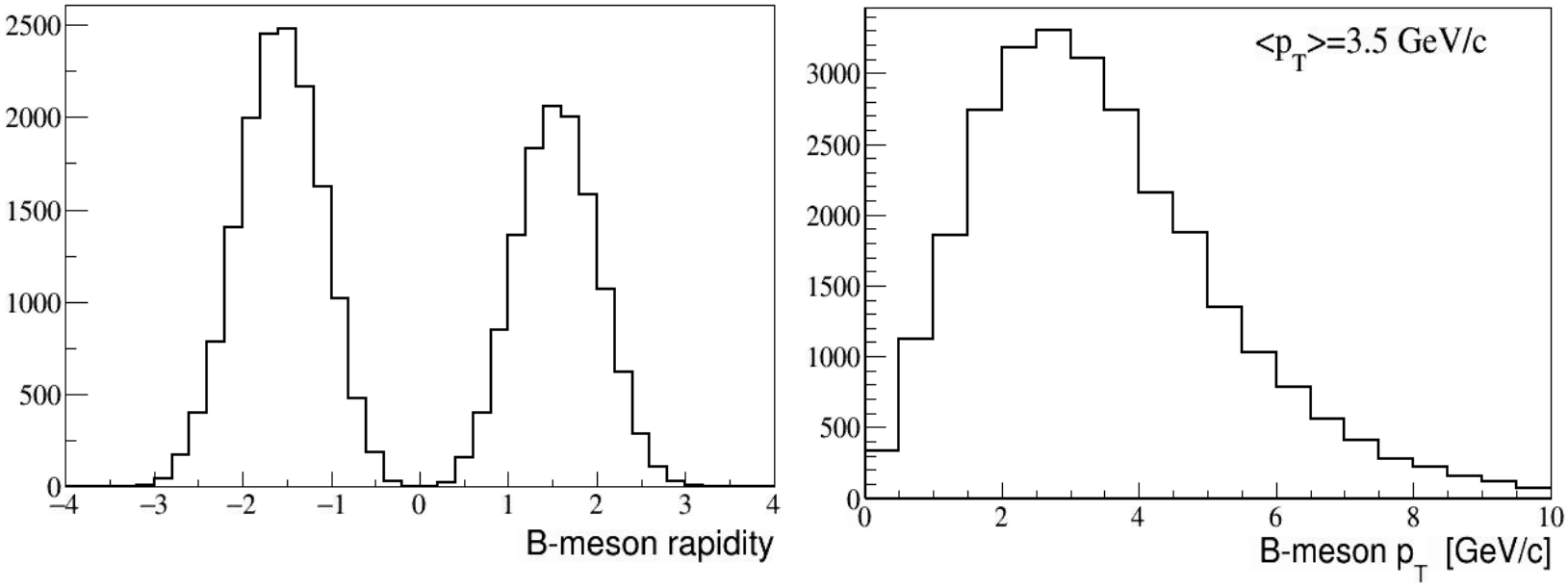
- Comparison with STAR measurements.



Can we measure B meson in forward rapidity?

- PHENIX provides good access to low p_T B mesons via B to J/ψ decay channel in the forward and backward rapidity in both p+p and heavy ion collisions.

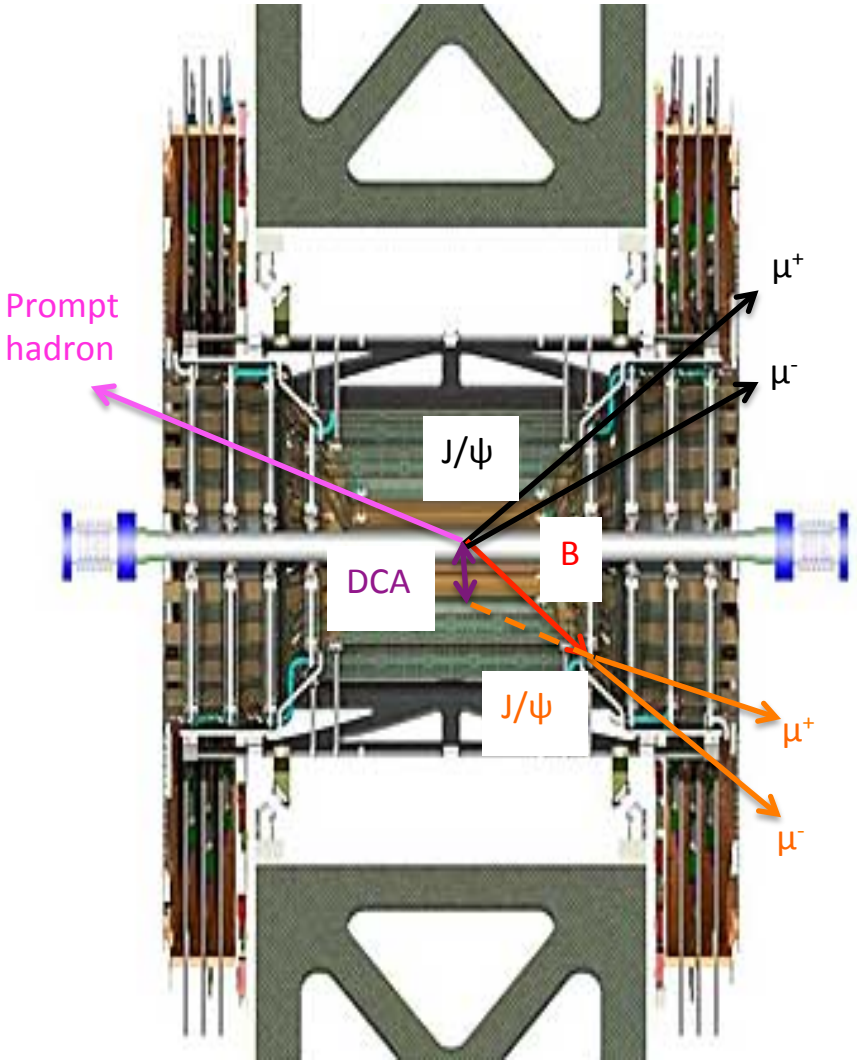
Kinematics of B mesons probed by PHENIX FVTX in PYTHIA simulation

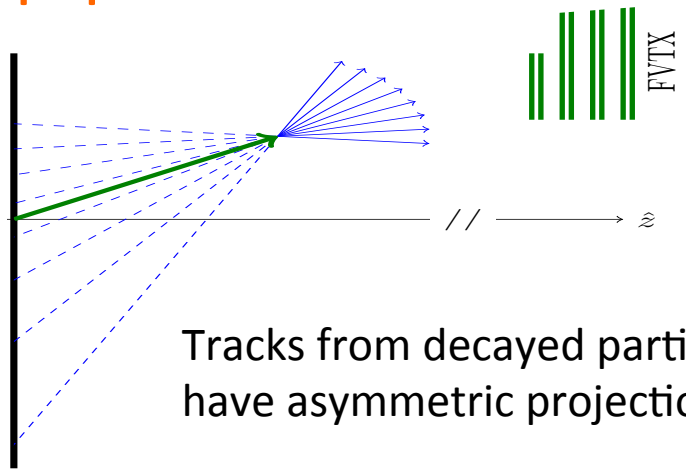


- B mesons measured in the forward/backward rapidity with longer decay length may probe different QGP evolution stage in heavy ion collisions from the mid-rapidity region.

Can we measure B meson in forward rapidity?

B->J/ψ->$\mu^+\mu^-$



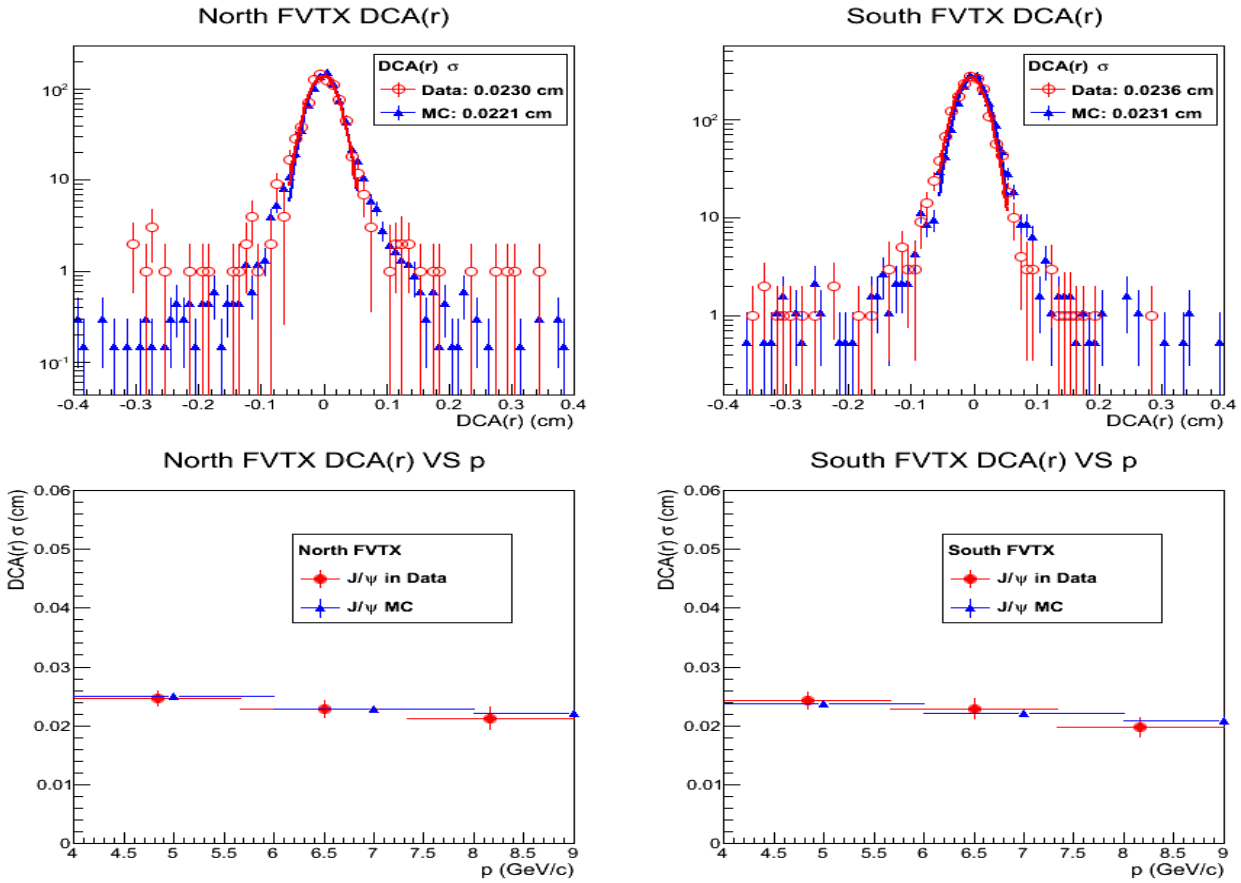


Tracks from decayed particles have asymmetric projection.

- Distance of Closest Approach (DCA) of track projection in the xy plane from the primary vertex.
- DCA has better resolution in radial (r) than azimuthal (ϕ) direction. Use DCA(r) for this analysis.
- Different DCA(r) shapes of prompt particles and decayed particles make the separation of B decayed J/ψ and prompt J/ψ feasible.

Comparison of DCA(r) between data and simulation (p+p)

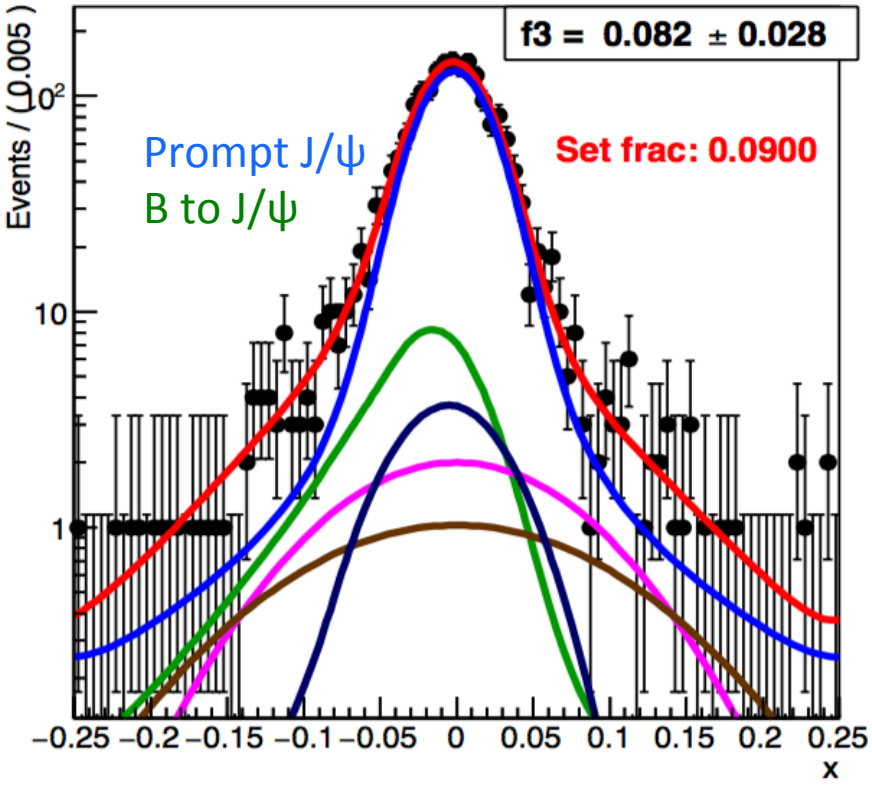
- DCA(r) of J/ψ decayed muons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.

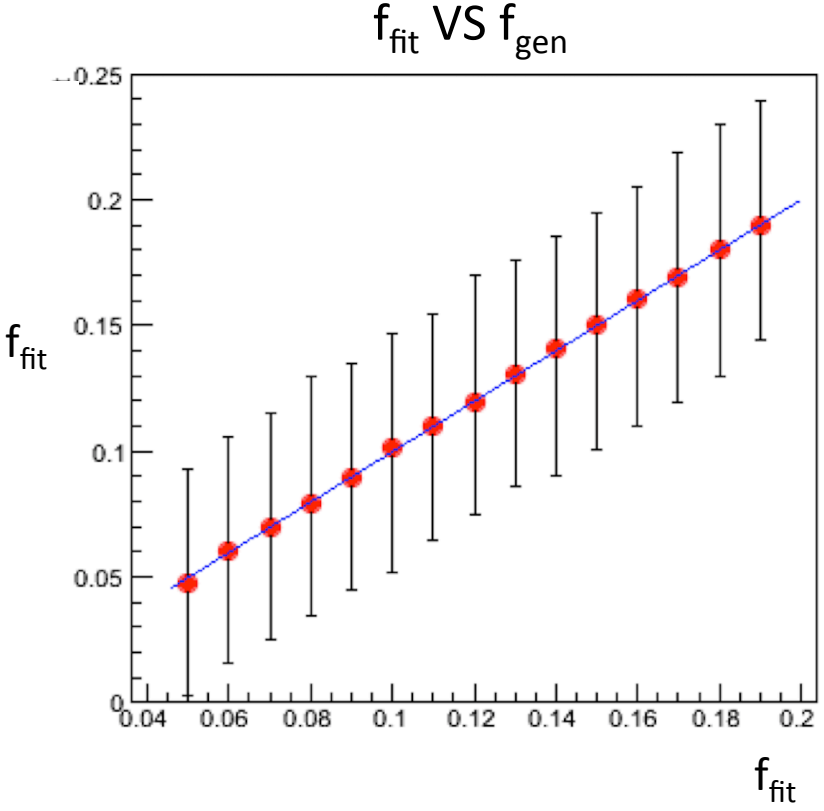


- Good agreement between data and simulation for DCA(r) resolution.

Test the fit package in Toy MC

- Generate pseudo-data according to the shape of foreground and background. Use the same fit packages applied in data.

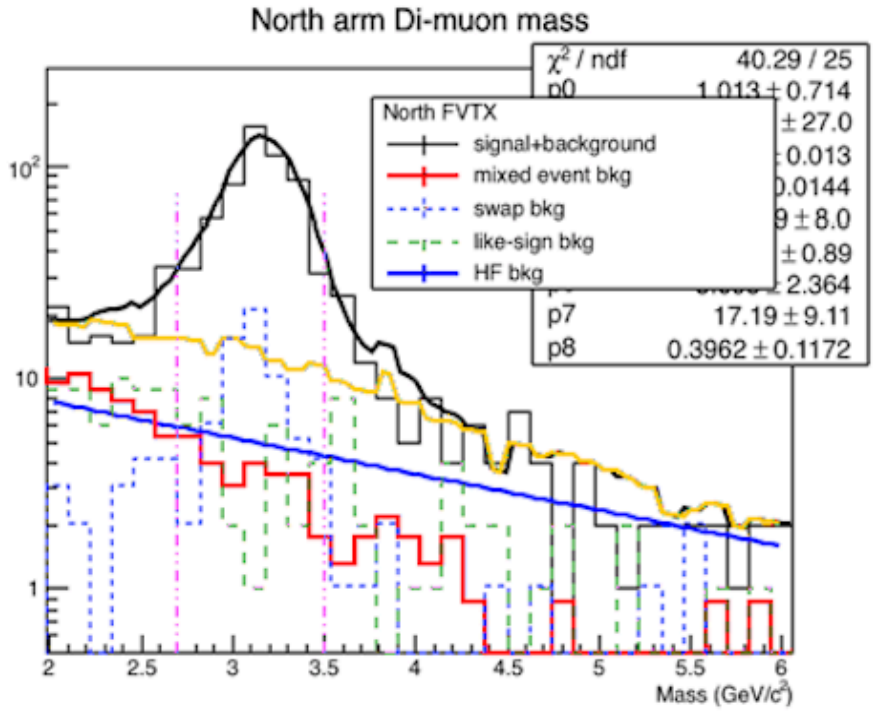


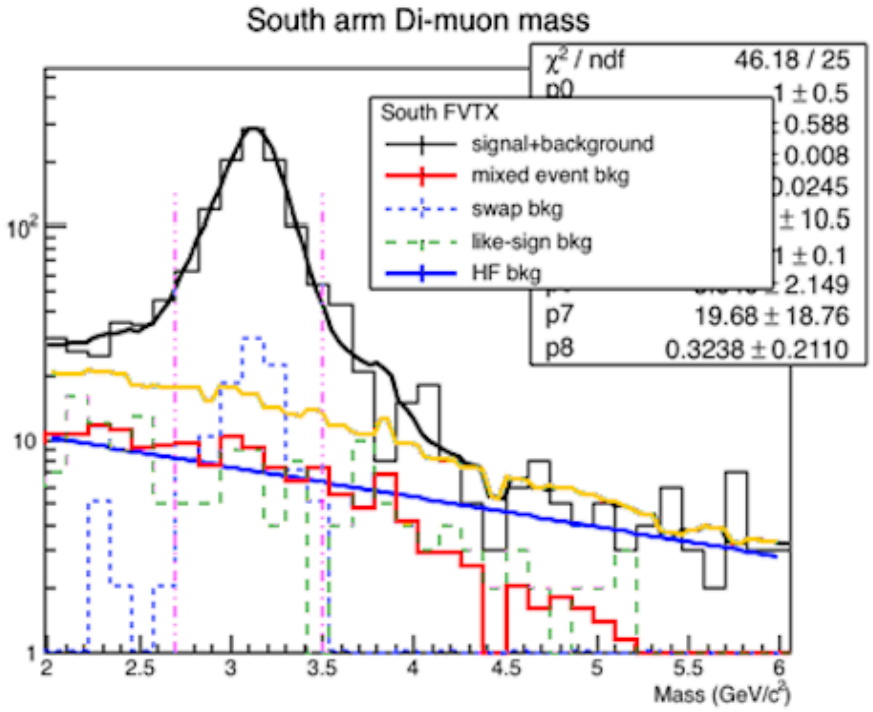


- Good linearity between generated and B to J/ψ ratio.
- Final results from data are under collaboration review.

HF continuum background fraction

- Fit the di-muon mass to extract the HF continuum background.





- Total background (10.1%) only consists of HF continuum background (4.7%) and mixed event background (5.4%).
- HF continuum background is comparable with the mixed event background within the mass cut window.