B→J/ψ measurements in p+p and Cu+Au collisions by the PHENIX Experiment

Xuan Li (LANL)

For the PHENIX Collaboration

Outline

- Motivation.
- PHENIX and the Forward Silicon Vertex Detector (FVTX).
- PHENIX Forward B→J/ψ measurements:
  - in 510 (arXiv:1701.01342) and 200 GeV p+p (arXiv:1702.01085) collisions to study the energy dependent B hadron production.
  - in 200 GeV Cu+Au collisions (arXiv:1702.01085) to explore heavy flavor production interaction with the medium (Cold Nuclear Matter/ Hot Nuclear Matter).

Measurements of $B \to J/\psi$ at forward rapidity in p+p collisions at $\sqrt{s} = 510$ GeV

C. Aidala,[39,43] N.N. Ajitanand,[61] Y. Akiba,[56,57,*] R. Akimoto,[12] J. Alexander,[61] M. Alfred,[23] K. Aoki,[32,56] N. Apadula,[28,62] H. Asano,[35,56] E.T. Atomssa,[62] A. Attila,[17] T.C. Awes,[52] C. Ayuso,[43] B. Azmoun,[7] V. Babintsev,[24] M. Bai,[6] X. Bai,[11] B. Bannier,[62] K.N. Barish,[8] S. Bathe,[5,57] V. Baublis,[55] C. Baumann,[7] S. Baumgart,[56] A. Bazilevsky,[7] M. Beaumier,[8] R. Belmont,[13,67] A. Berdnikov,[59] Y. Berdnikov,[59] D. Black,[8] D.S. Blau,[34] M. Boer,[39] J.S. Bok,[50] K. Boyle,[57] M.L. Brooks,[39] J. Bryslawskyj,[5,8] H. Buesching,[7] V. Bumazhnov,[24] C. Butler,[20] S. Butsyk,[49] S. Campbell,[14,28] C. CanoaRoman,[62] C.-H. Chen,[57] C.Y. Chi,[14] M. Chiu,[7] I.J. Choi,[25] J.B. Choi,[10,†] S. Choi,[60] P. Christiansen,[40] T. Chujo,[66] V. Cianciolo,[52] B.A. Cole,[14] M. Connors,[20,57] N. Cronin,[44,62] N. Crosswhite,[44]

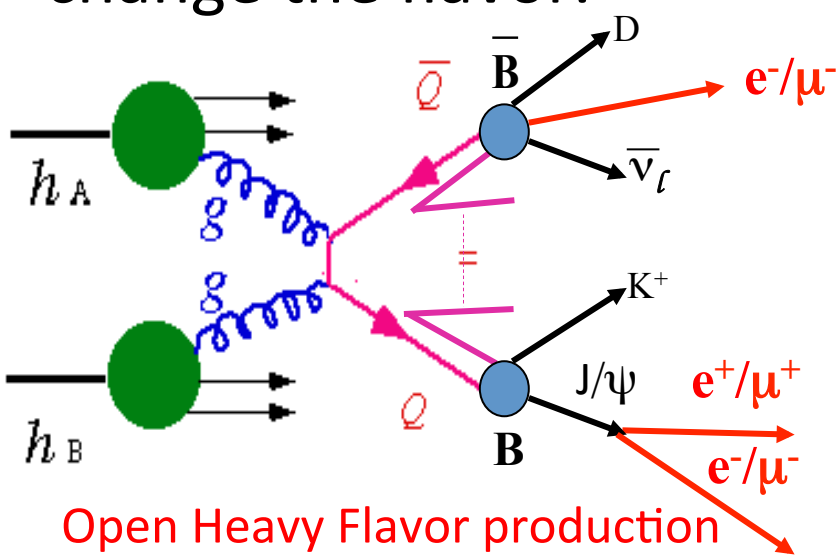
B-meson production at forward and backward rapidity in p+p and Cu+Au collisions at $\sqrt{s_{NN}}$=200 GeV

C. Aidala,[39,43] N.N. Ajitanand,[61] Y. Akiba,[56,57,*] R. Akimoto,[12] J. Alexander,[61] M. Alfred,[24] V. Andrieux,[43] K. Aoki,[32,56] N. Apadula,[29,62] H. Asano,[35,56] E.T. Atomssa,[62] T.C. Awes,[52] C. Ayuso,[43] B. Azmoun,[7] V. Babintsev,[25] A. Bagoly,[17] M. Bai,[6] X. Bai,[11] N.S. Bandara,[42] B. Bannier,[62] K.N. Barish,[8] S. Bathe,[5,57] V. Baublis,[55] C. Baumann,[7] S. Baumgart,[56] A. Bazilevsky,[7] M. Beaumier,[8] R. Belmont,[13,67] A. Berdnikov,[59] Y. Berdnikov,[59] D. Black,[8] D.S. Blau,[34] M. Boer,[39] J.S. Bok,[50] K. Boyle,[57] M.L. Brooks,[39] J. Bryslawskyj,[5,8] H. Buesching,[7] V. Bumazhnov,[25] C. Butler,[21] S. Butsyk,[49] S. Campbell,[14,29] V. Canoa Roman,[62] R. Cervantes,[62]

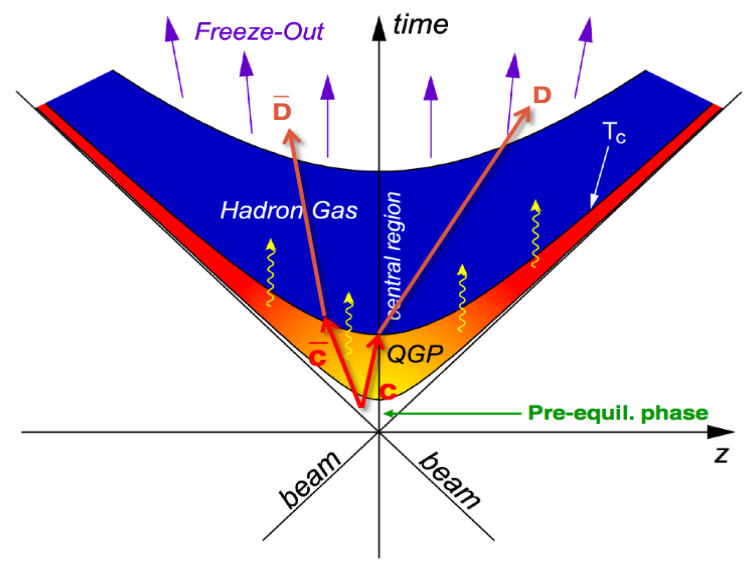
- Summary and Outlook

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 ($m_{c,b} >> \Lambda_{QCD}$).
- The heavy quark can traverse the whole evolution of the system as interactions with the medium do not change the flavor.

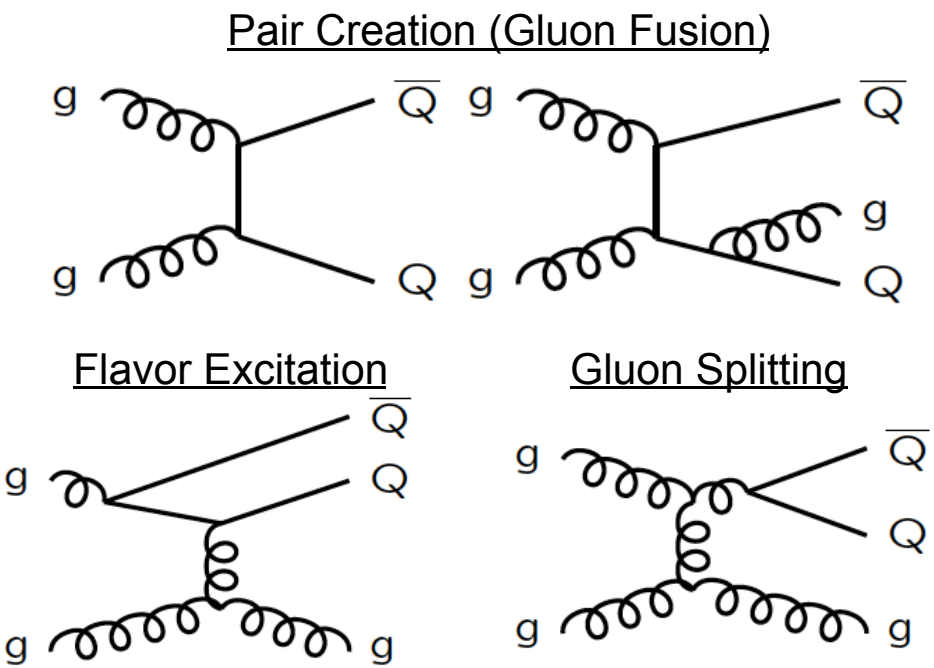


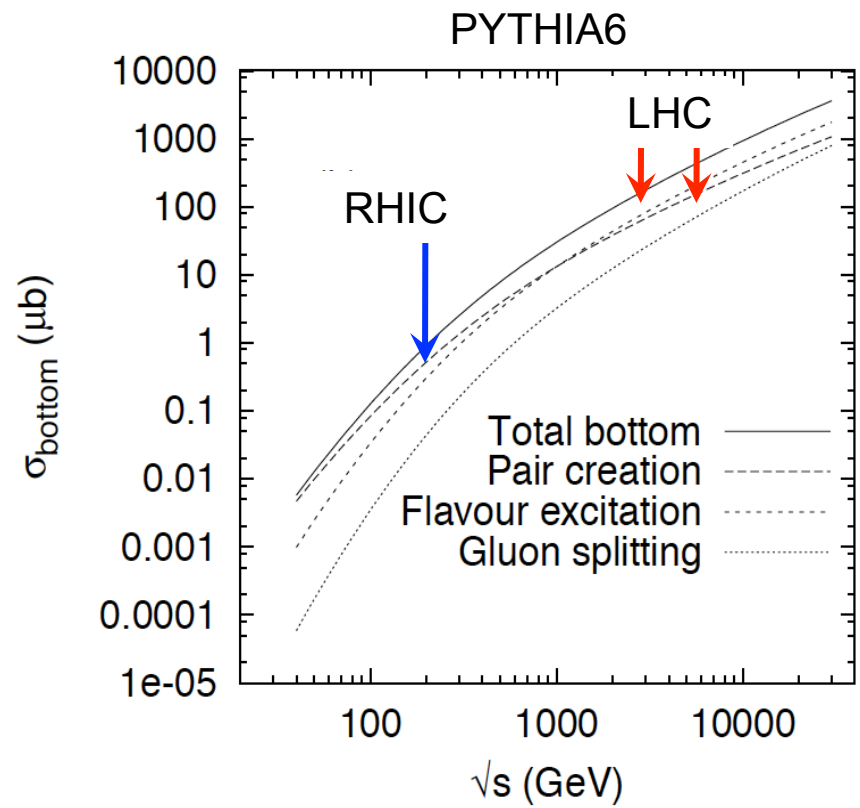
Open Heavy Flavor production



Uniqueness at RHIC

- Uniqueness at RHIC
  - Bottom production is dominated by pair creation (gluon fusion), clean interpretation for experimental results.



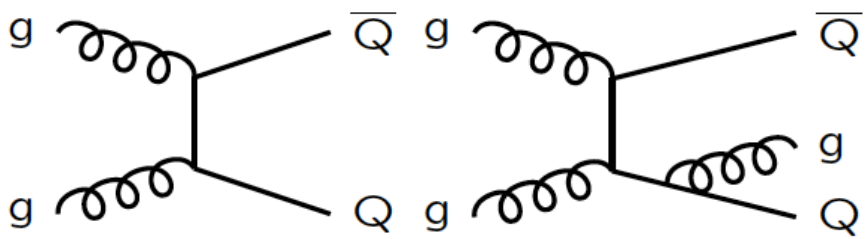


T. Sjostrand, EPJC17 (2000) 137

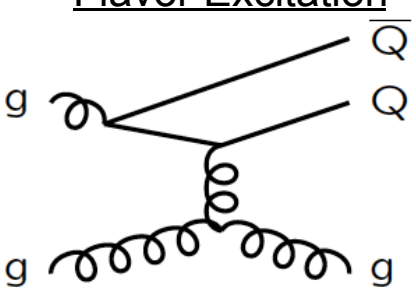
Uniqueness at RHIC

- Uniqueness at RHIC
  - Bottom production is dominated by pair creation (gluon fusion), clean interpretation for experimental results.
  - accesses complementary kinematics region compared to LHC measurements.

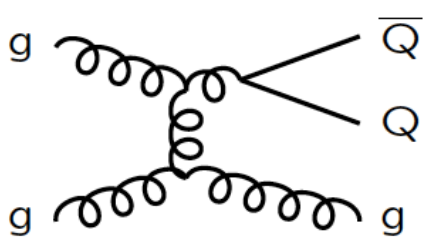
Pair Creation (Gluon Fusion)



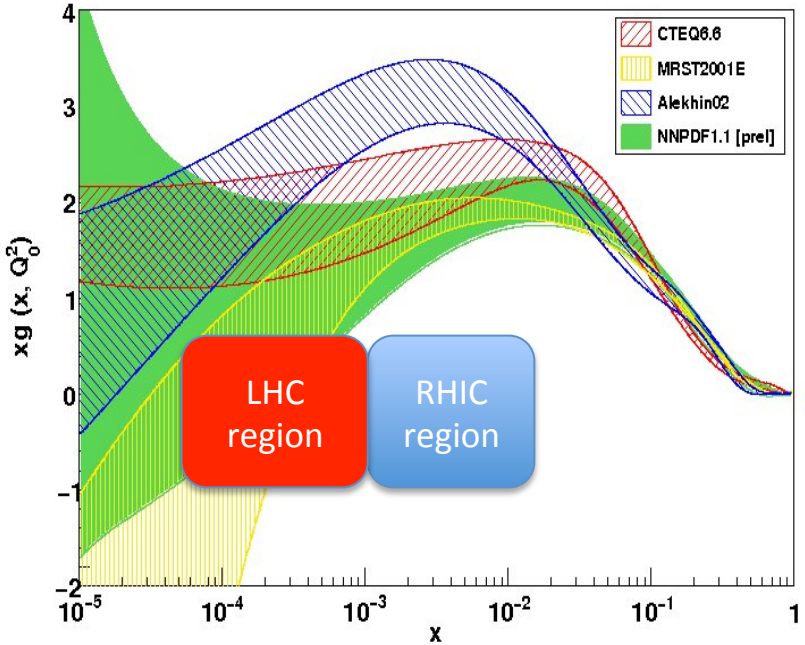
Flavor Excitation



Gluon Splitting

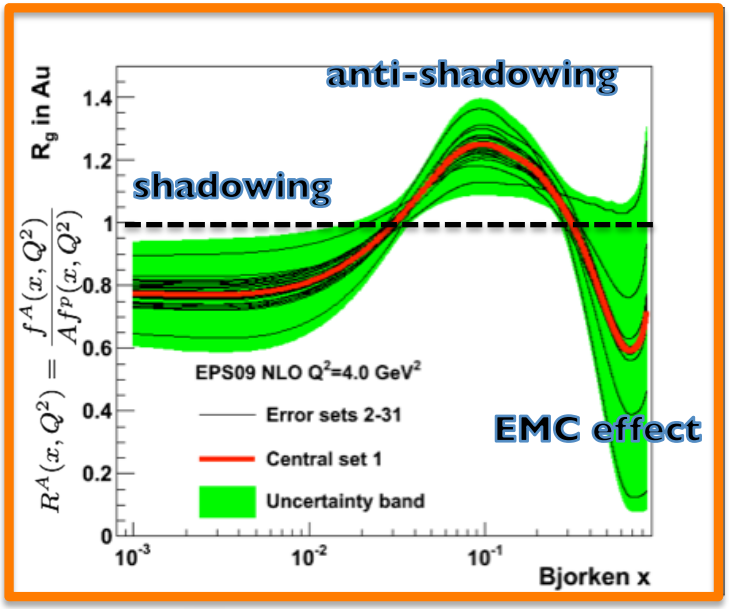


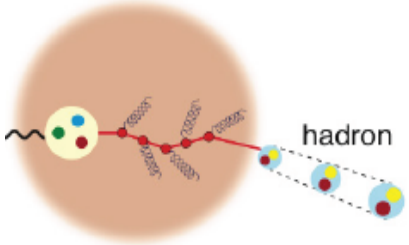
Nucleon Gluon PDF



Heavy flavor production in Heavy Ion Collisions

- Not well understood about interaction with the medium.
- Cold Nuclear Matter (CNM) effect:
  - Nuclear modification of PDFs.
  - Energy loss of partons traversing nucleus (Initial state).
  - Breakup of charmonium before exiting nucleus.
  - Co-mover absorption.





Parton E_{loss}

Heavy flavor production in Heavy Ion Collisions

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- Cold Nuclear Matter (CNM) effect:
  - Nuclear modification of PDFs.
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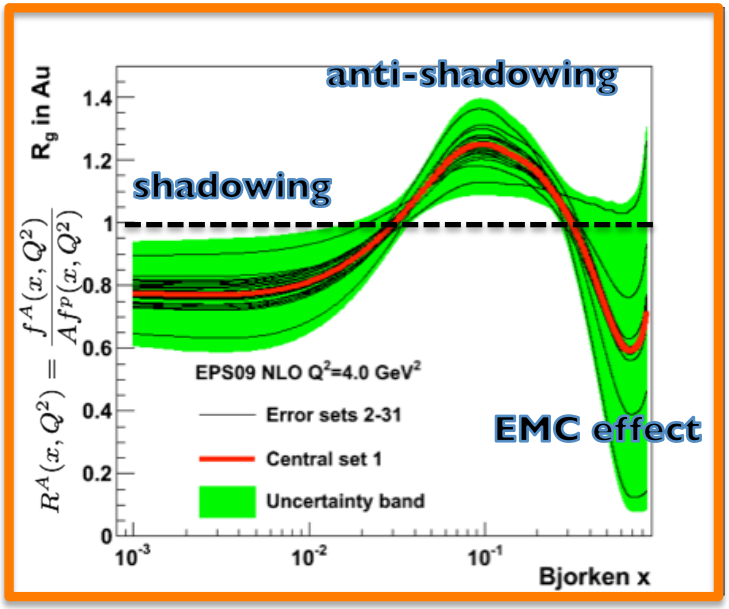
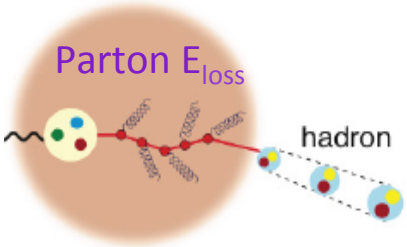
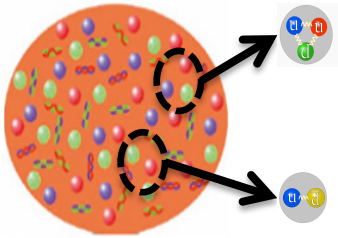
  - Breakup of charmonium before exiting nucleus.
  - Co-mover absorption.
- Hot nuclear matter effect:
  - Energy loss of partons traversing QGP.
  - Color screening.
  - Coalescence of quarkonia in QGP.





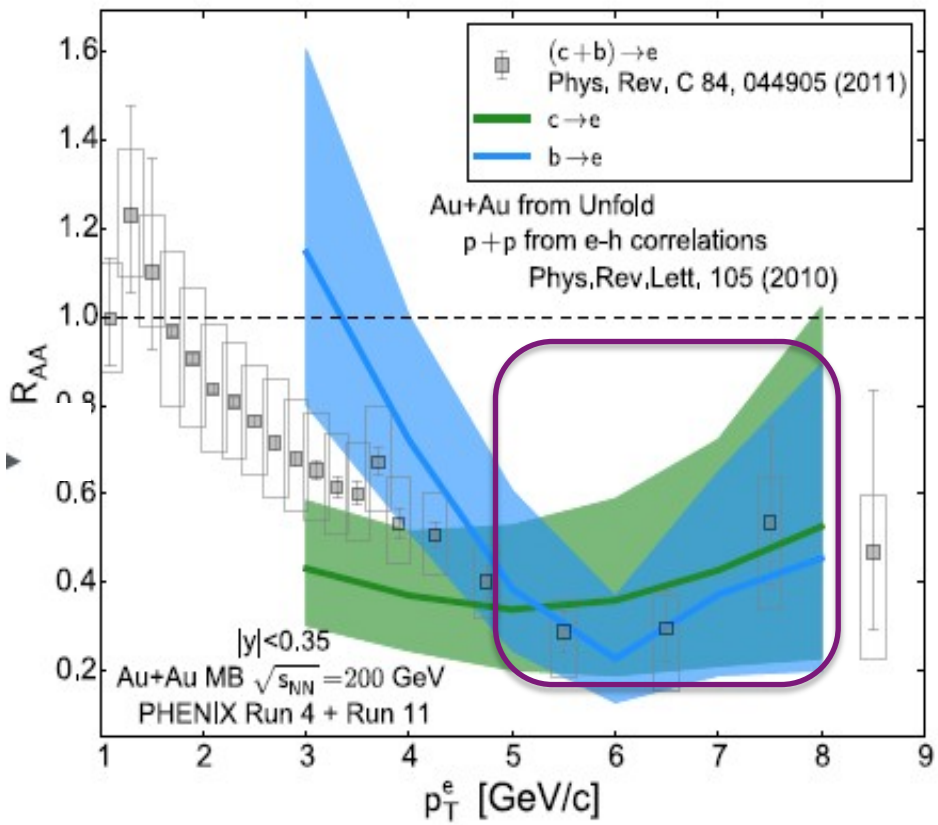


Color Coalescence

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

Indication of flavor dependent energy loss

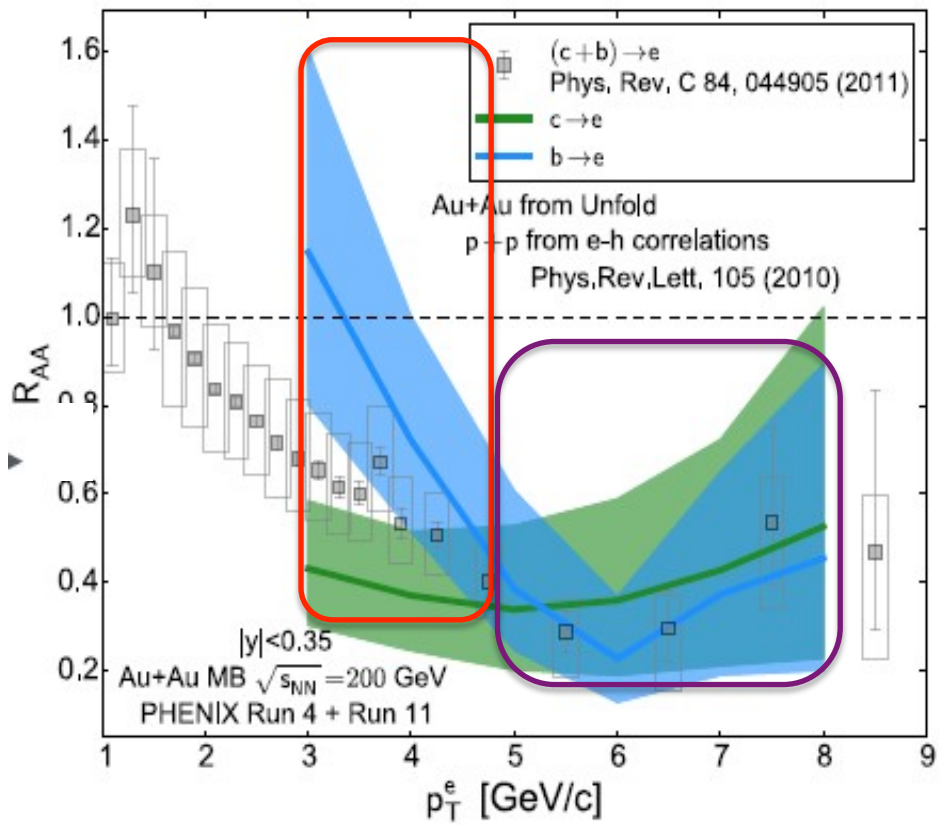
PRC 93, 034904 (2016)



- From the PHENIX charm and bottom separated single electron R_{AA} results,
  - Bottom has similar suppression as charm for high p_T region.

Indication of flavor dependent energy loss

PRC 93, 034904 (2016)



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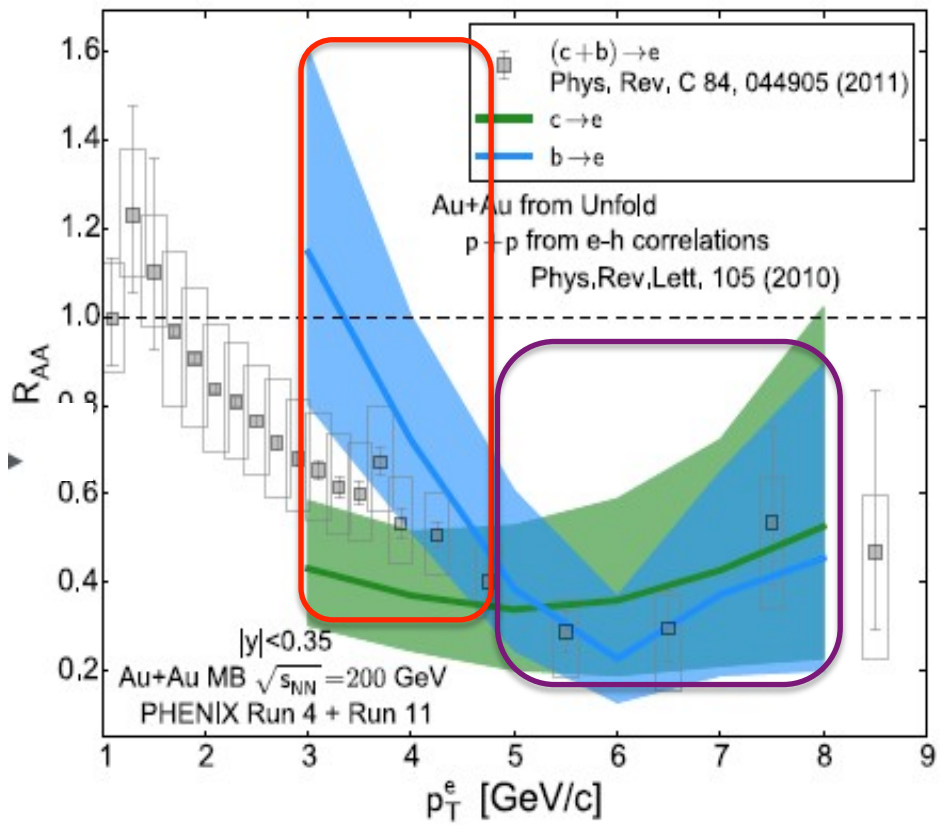

- From the PHENIX charm and bottom separated single electron R_{AA} results,
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  - Bottom may be less suppressed in the low p_T region.
- Consistent with Energy Loss mechanism:

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Indication of flavor dependent energy loss

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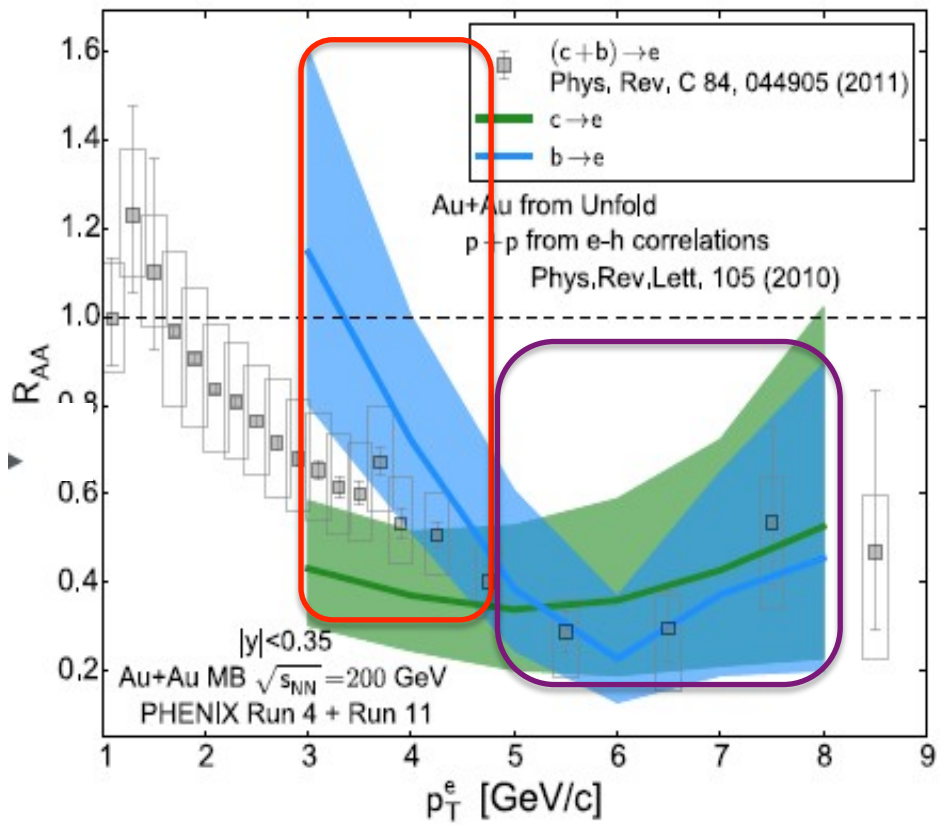

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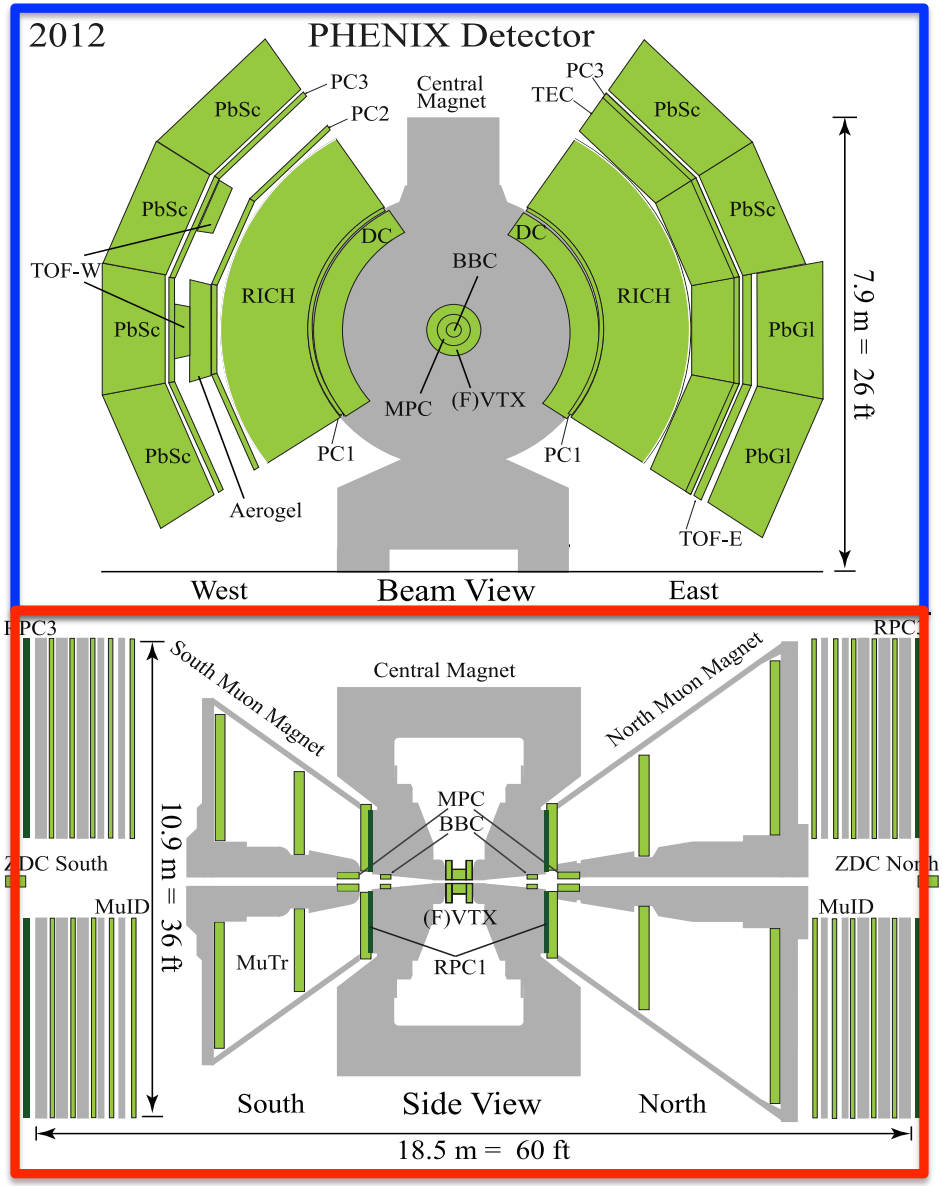
- Consistent with Energy Loss mechanism:

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

- Is bottom production less suppressed than the charm production at forward rapidity in the low p_T region?
- Need to first understand the B hadron production

→ in p+p, Cu+Au collisions.

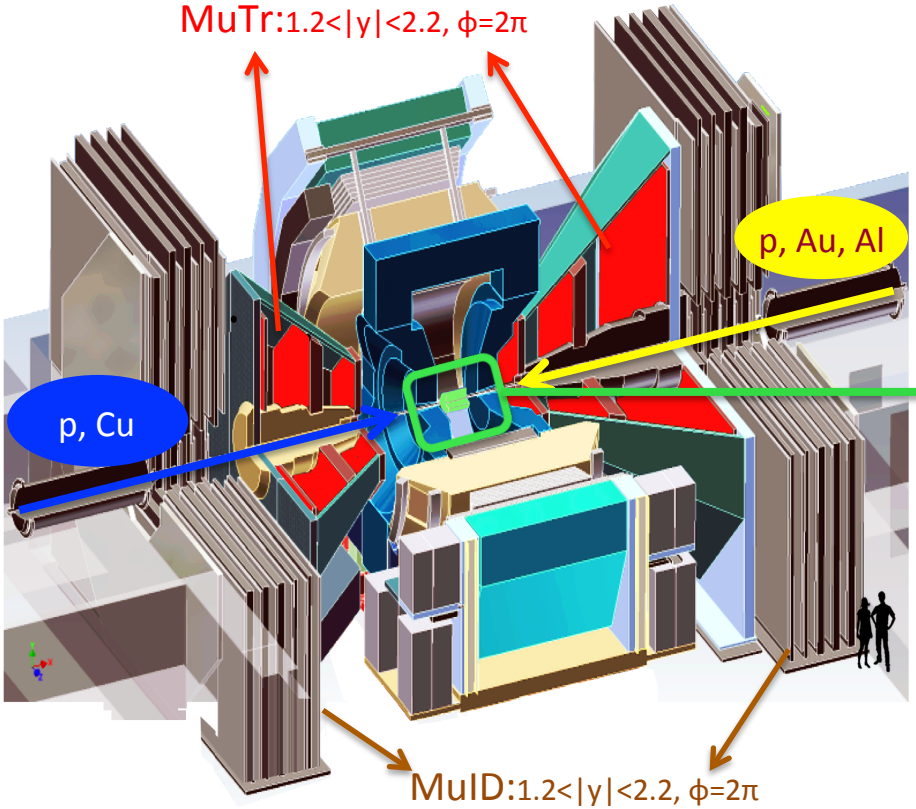
PHENIX detector



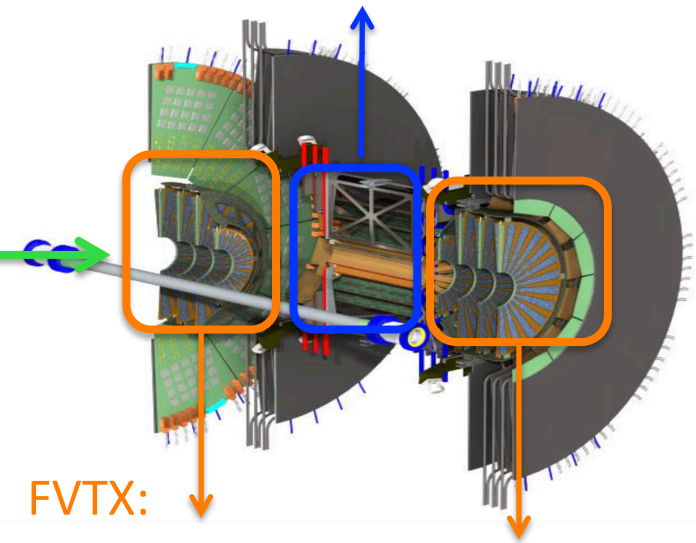
- **Central Arm (Electrons)**
  - $|\eta| < 0.35$
  - $\Delta\varphi = \pi$
  - Tracking: DC, PC, VTX
  - eID: RICH, EMcal
- **Forward Arms (Muons)**
  - $1.2 < |\eta| < 2.2$
  - $\Delta\varphi = 2\pi$
  - ~10 interaction length absorber
  - Tracking: wire chamber, FVTX
  - MuID: muon identification detector

Silicon Vertex Detectors of PHENIX

- The silicon vertex detectors: VTX(installed since 2011) and FVTX(installed 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.

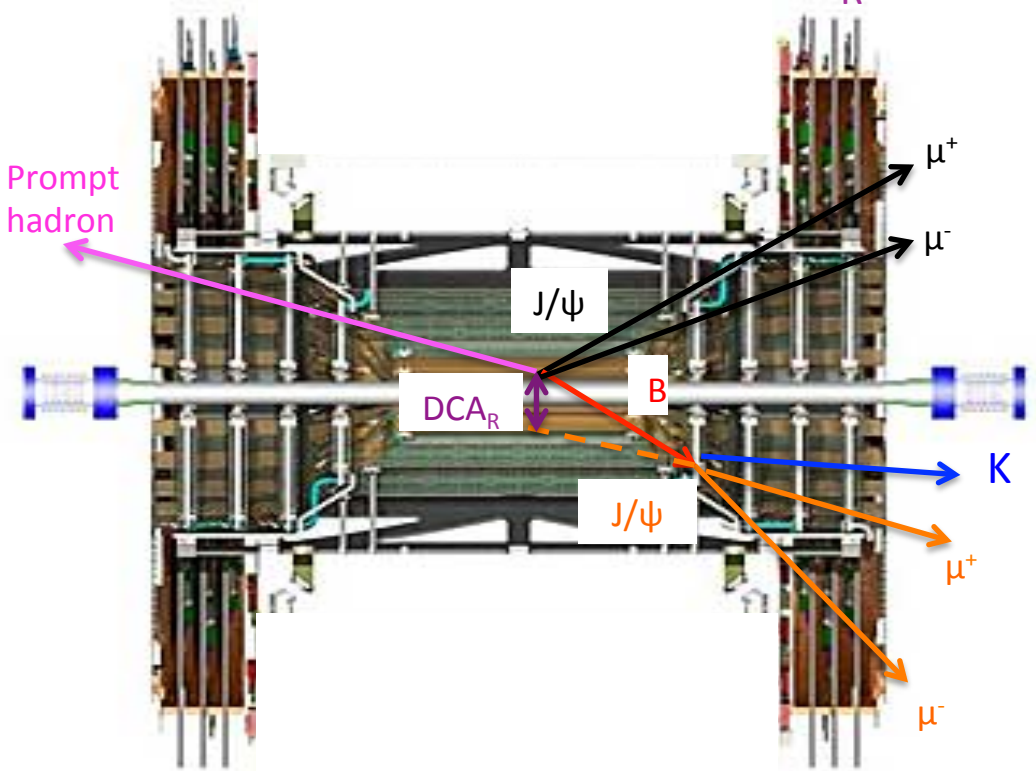


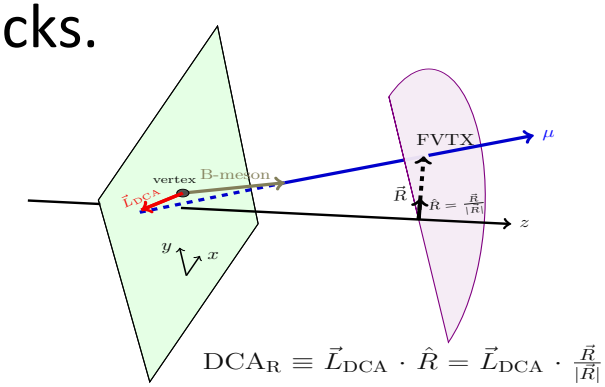
- FVTX:
  - With 1.2<|y|<2.2 and ϕ=2π coverage.
  - provide precise tracking and DCA measurements for B→J/ψ and D, B separation.

Can we measure B meson at forward rapidity?

$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$

- B hadron decay length (cτ), about the size of hair diameter:
  - $c\tau(B^0)=455\mu m$, $c\tau(B^{\pm})=491\mu m$.
- B hadron is further boosted at forward rapidity.
- FVTX can precisely determine the Distance of Closest Approach along the radial projection (DCA_R) of tracks.



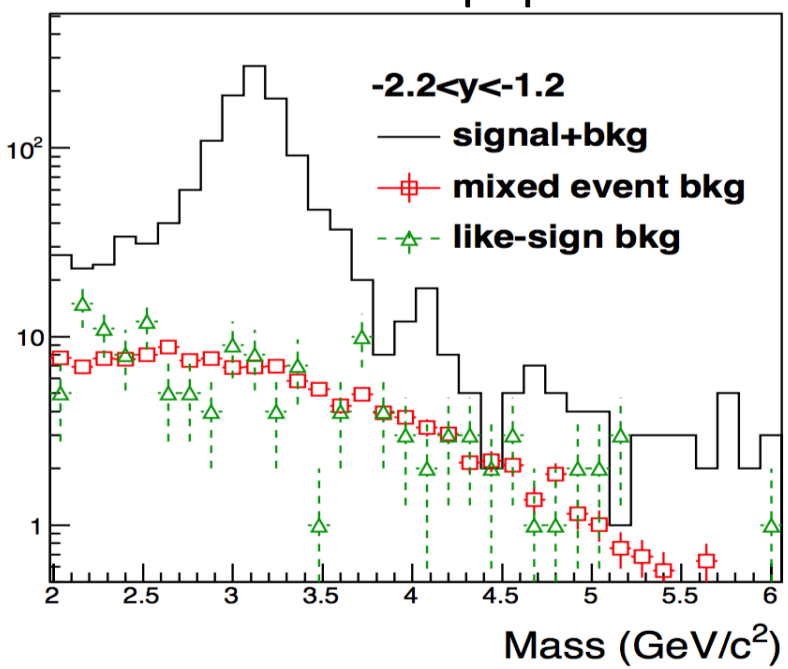


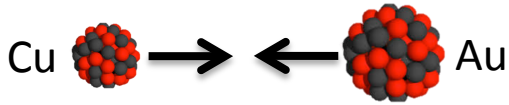
- Different shapes of DCA_R of prompt particles and decayed particles make the separation of B decayed J/ψ and prompt J/ψ feasible.

How to determine the J/ψ from B-meson decay?

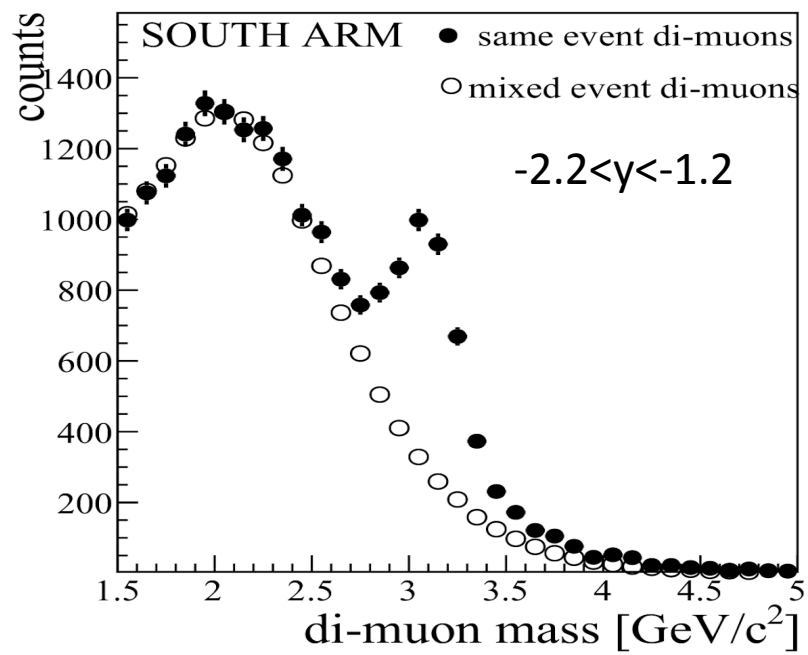
- In p+p and heavy ion (eg. Cu+Au) collisions:
  1) Identify the J/ψ candidates from di-muon mass spectrum after applying quality cuts.

2012 510 GeV p+p data





2012 200 GeV Cu+Au data

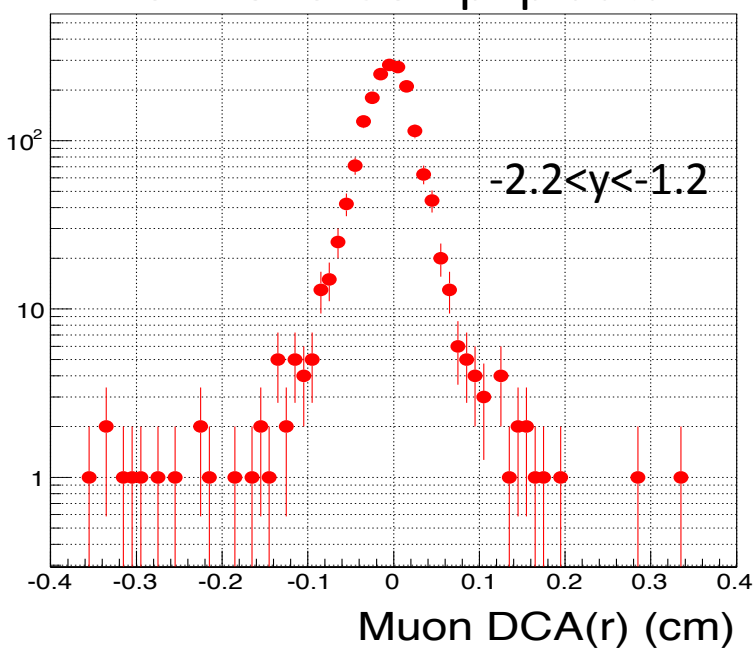


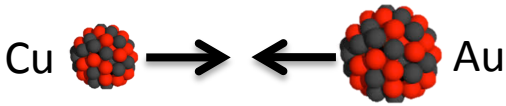
- Clear J/ψ peaks are found in both p+p and Cu+Au data.

How to determine the J/ψ from B-meson decay?

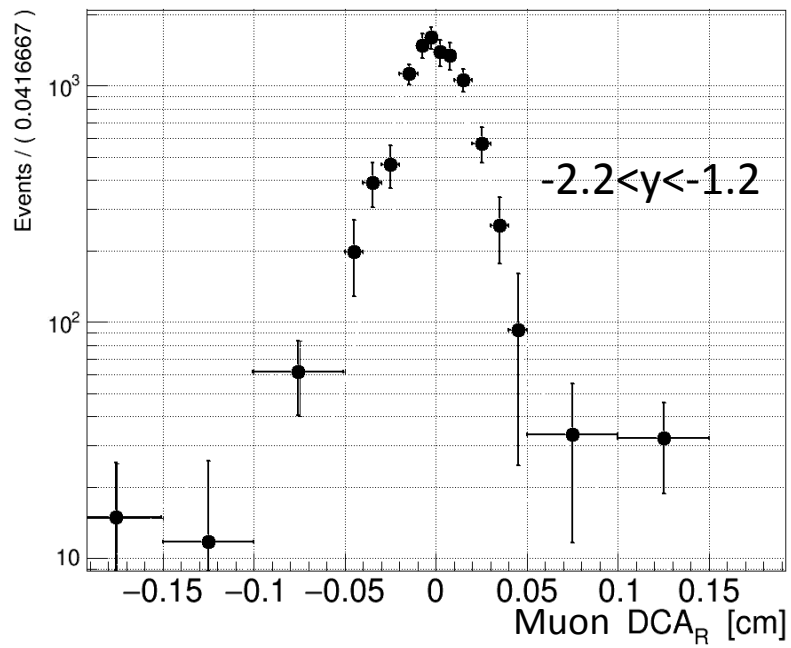
- In p+p and heavy ion (eg. Cu+Au) collisions:
  2) After select good J/ψs, require the muon track of di-muon pairs matching to the FVTX and measure the DCA_R.

2012 510 GeV p+p data





2012 200 GeV Cu+Au data

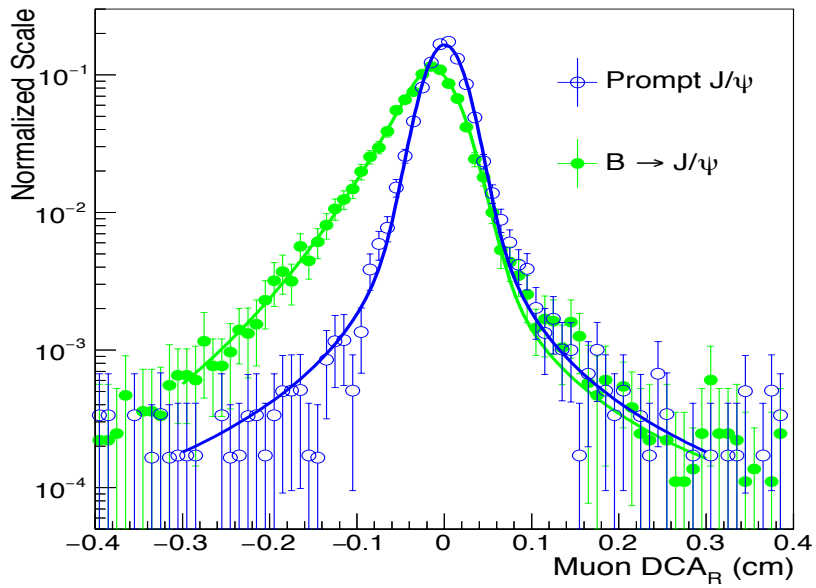


- Hints of asymmetric in muon DCA_R shapes.

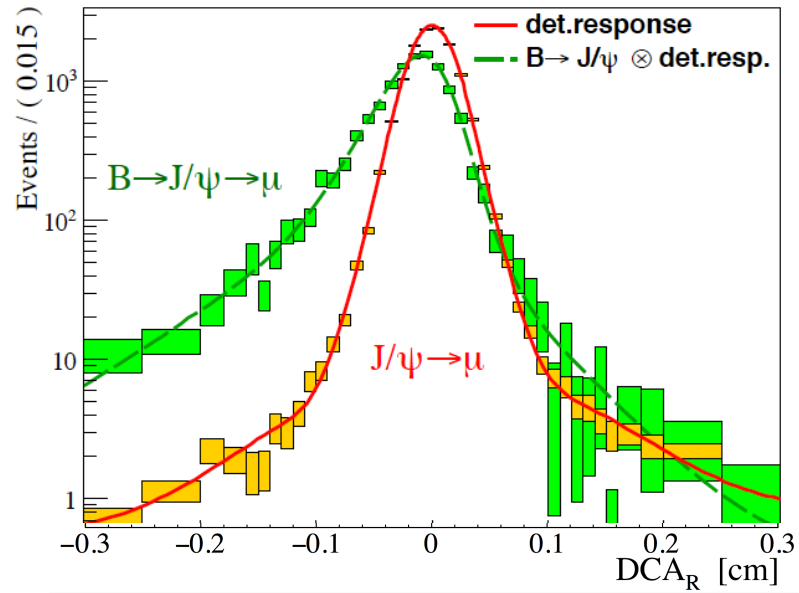
How to determine the J/ψ from B-meson decay?

- In p+p and heavy ion (eg. Cu+Au) collisions:
  3) Signal determination: generate prompt J/ψ and B to J/ψ events in full simulation (PYTHIA+GEANT+RECO) or embedding for p+p or Cu+Au with realistic vertex and dead maps etc.

510 GeV p+p simulation



200 GeV Cu+Au embedding

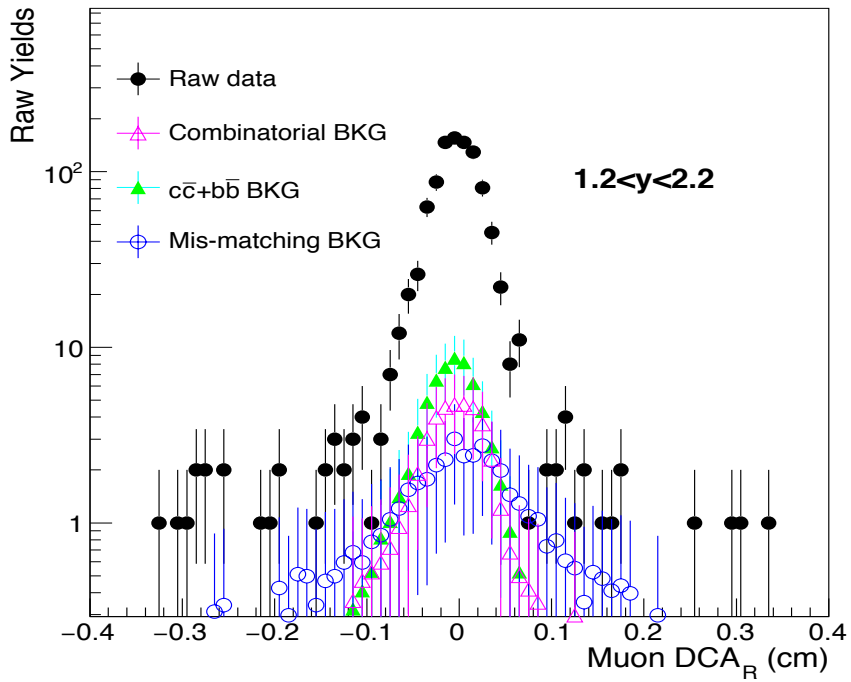


- Obvious muon DCA$_R$ shape difference between prompt J/ψ and B to J/ψ.

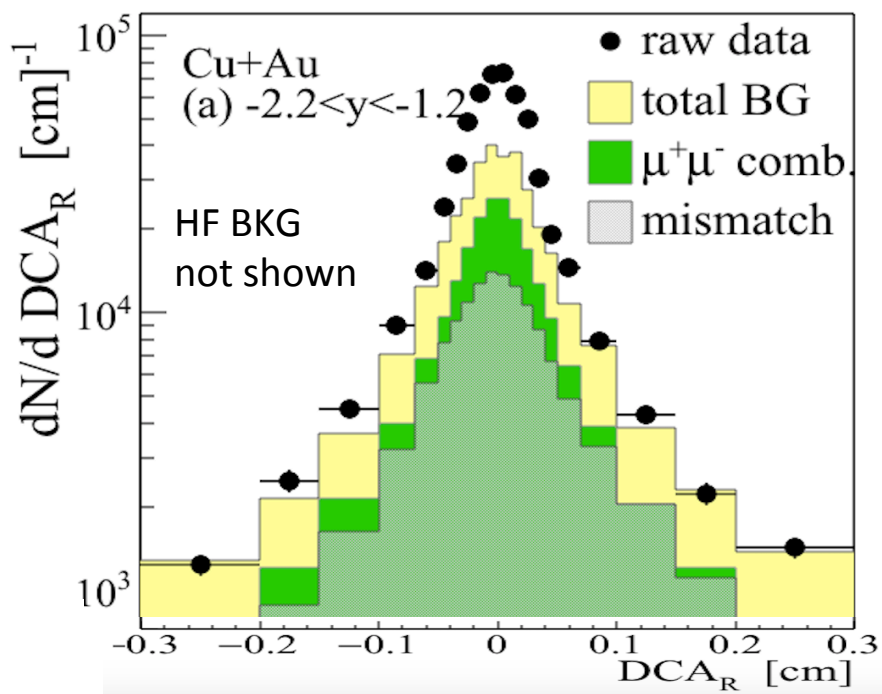
How to determine the J/ψ from B-meson decay?

- In p+p and heavy ion (eg. Cu+Au) collisions:
  4) Determine various background components: combinatorial, FVTX-MuTr mis-matching and HF continuum backgrounds.

2012 510 GeV p+p collisions



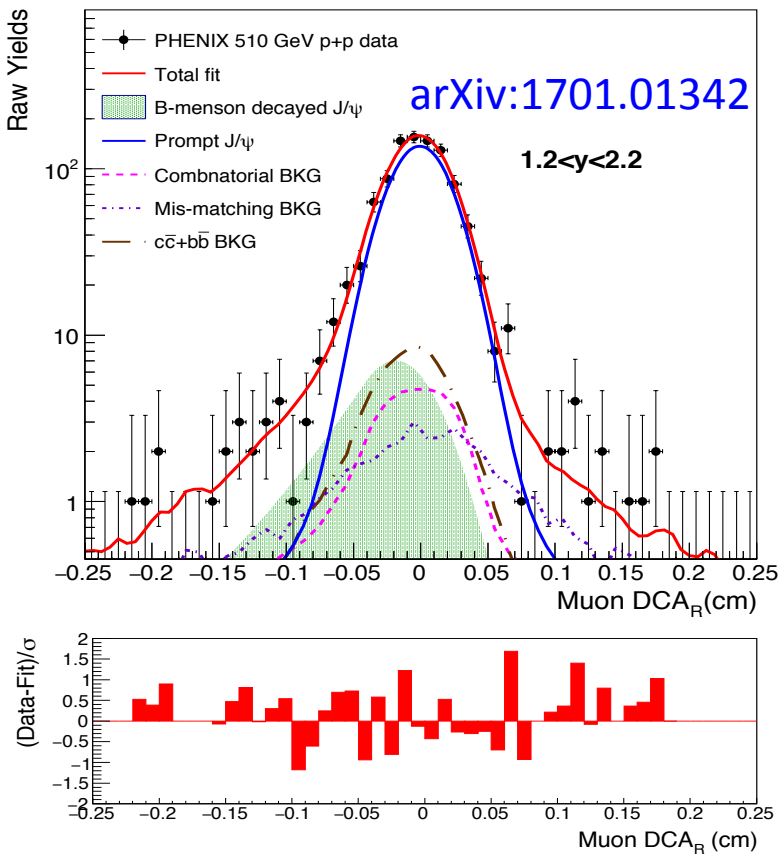
2012 200 GeV Cu+Au collisions

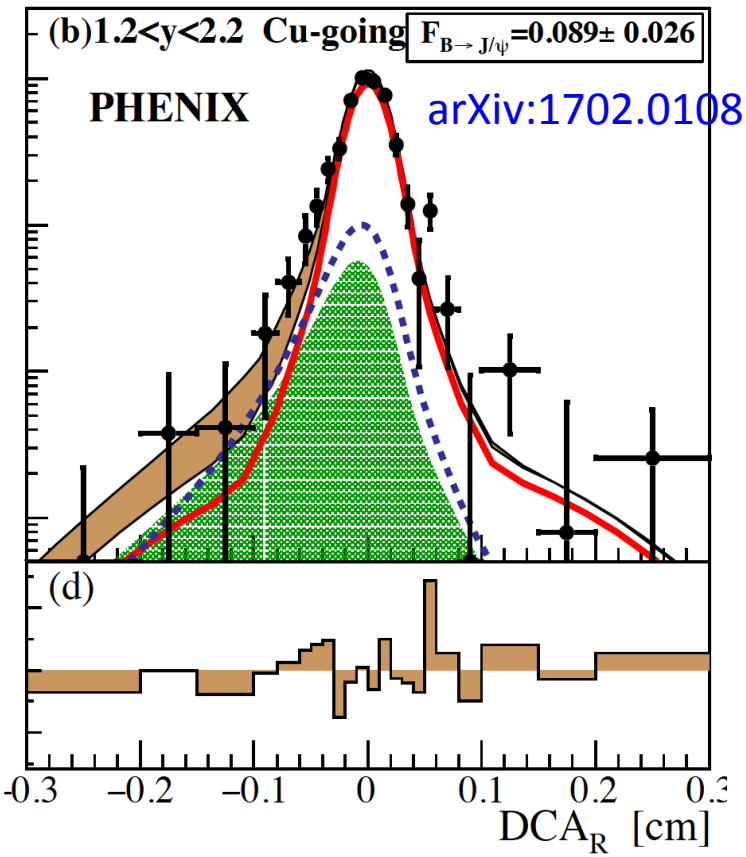


- Backgrounds are well determined.

How to determine the J/ψ from B-meson decay?

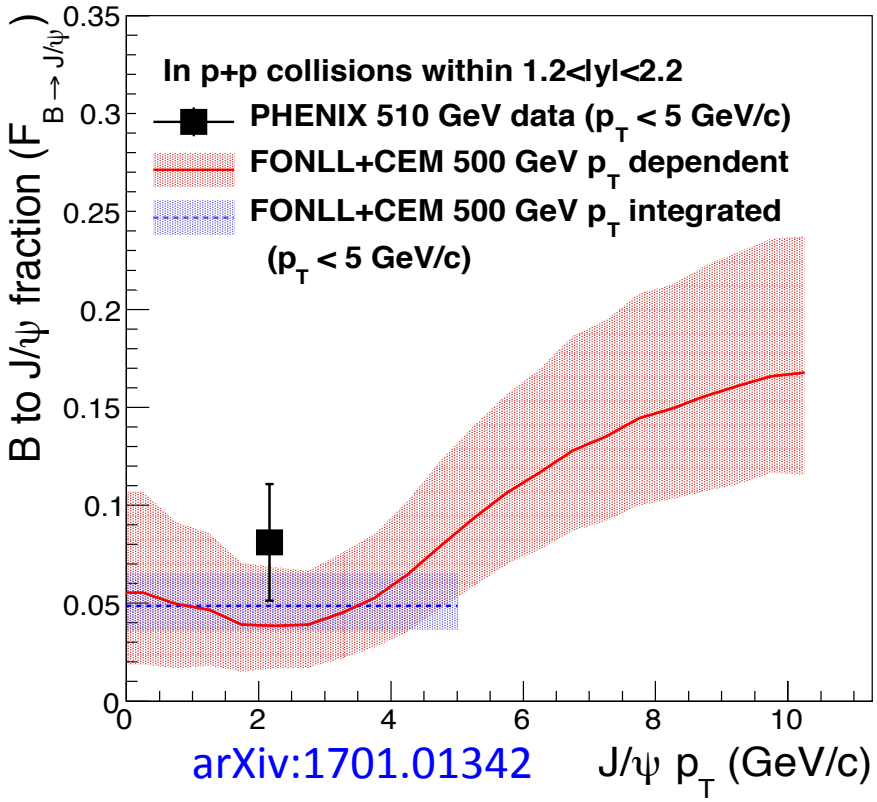
- In p+p and heavy ion (eg. Cu+Au) collisions:
  4) Fit on DCA_R in data to simultaneously determine the prompt J/ψ and J/ψ from B-meson decay yields and extract the B to J/ψ fraction.





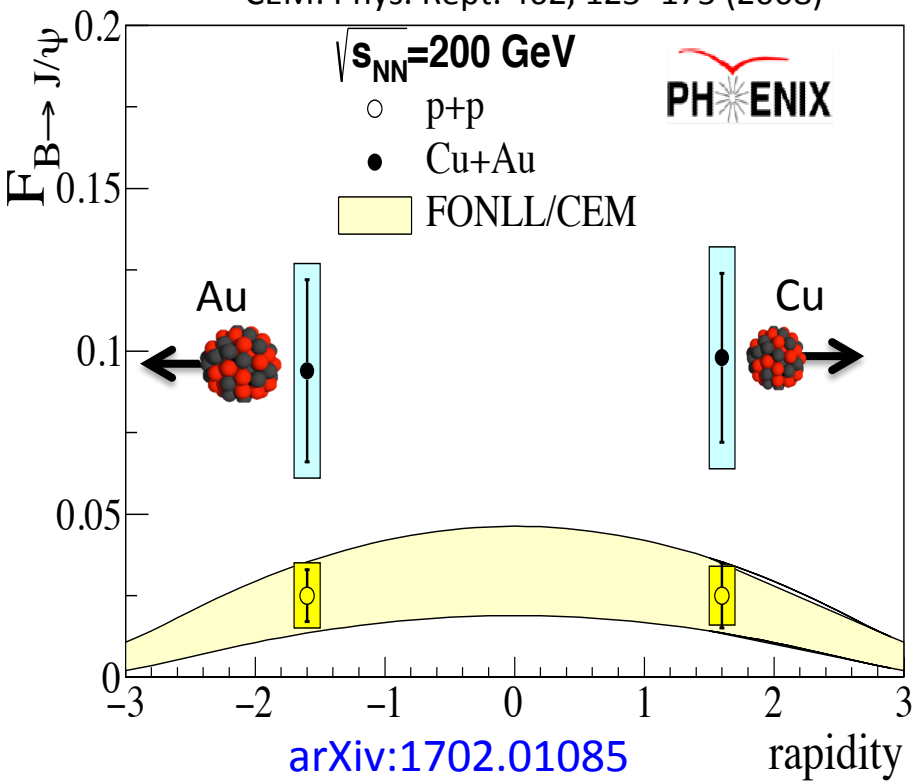
B→J/ψ fraction in p+p and Cu+Au collisions

FONLL+CEM: Phys. Rev. C 87, 014908 (2012)
Private communication with Ramona



arXiv:1701.01342

FONLL: JHEP 05, 007 (1998)
CEM: Phys. Rept. 462, 125–175 (2008)

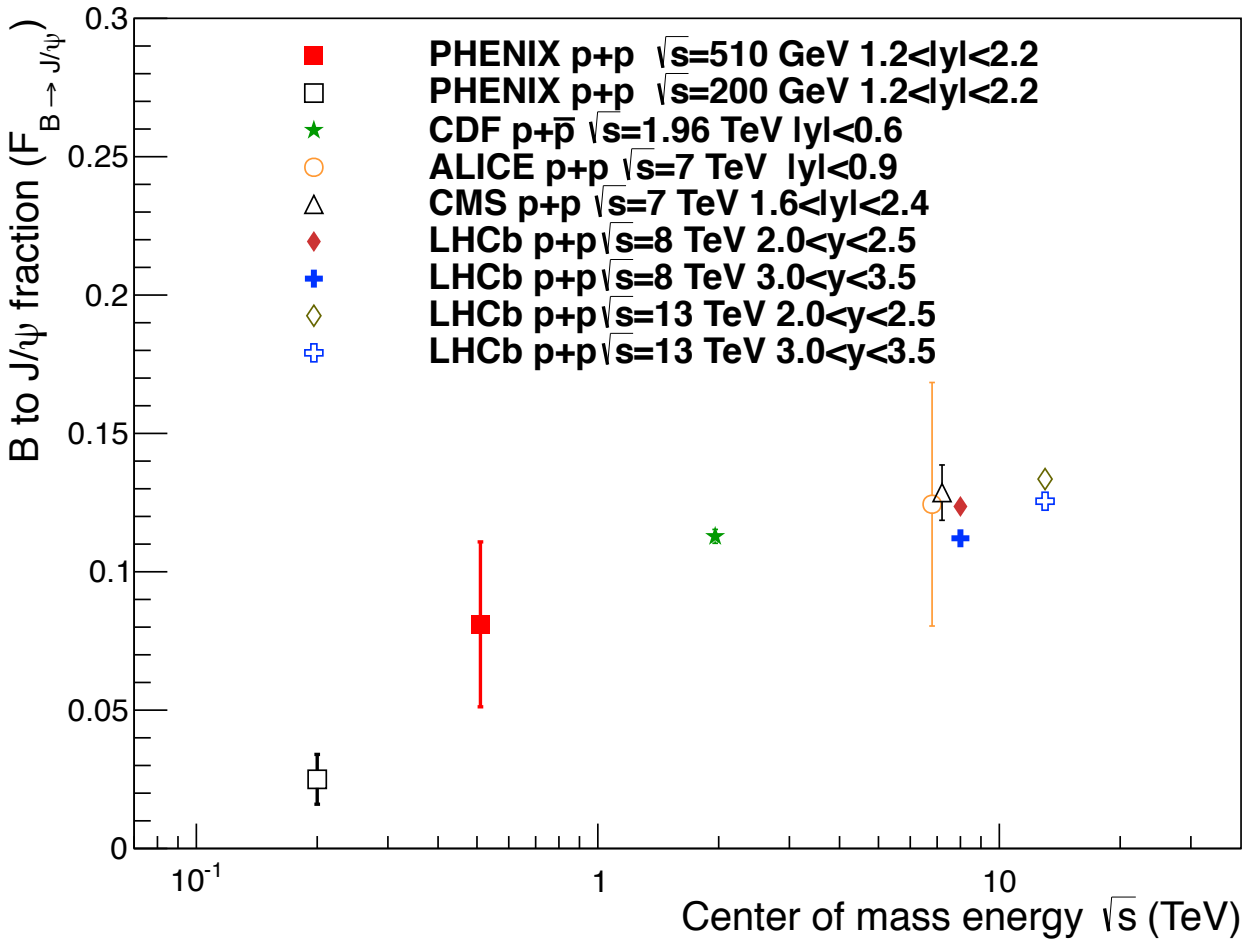


arXiv:1702.01085

- The forward B→J/ψ fraction measured at PHENIX in 510 (200) GeV p+p collisions is in reasonable agreements with the FONLL +CEM (FONLL/CEM) model calculation.
- The fraction measured in Cu+Au is higher than in p+p collisions.

Center of mass energy dependent B→J/ψ fraction

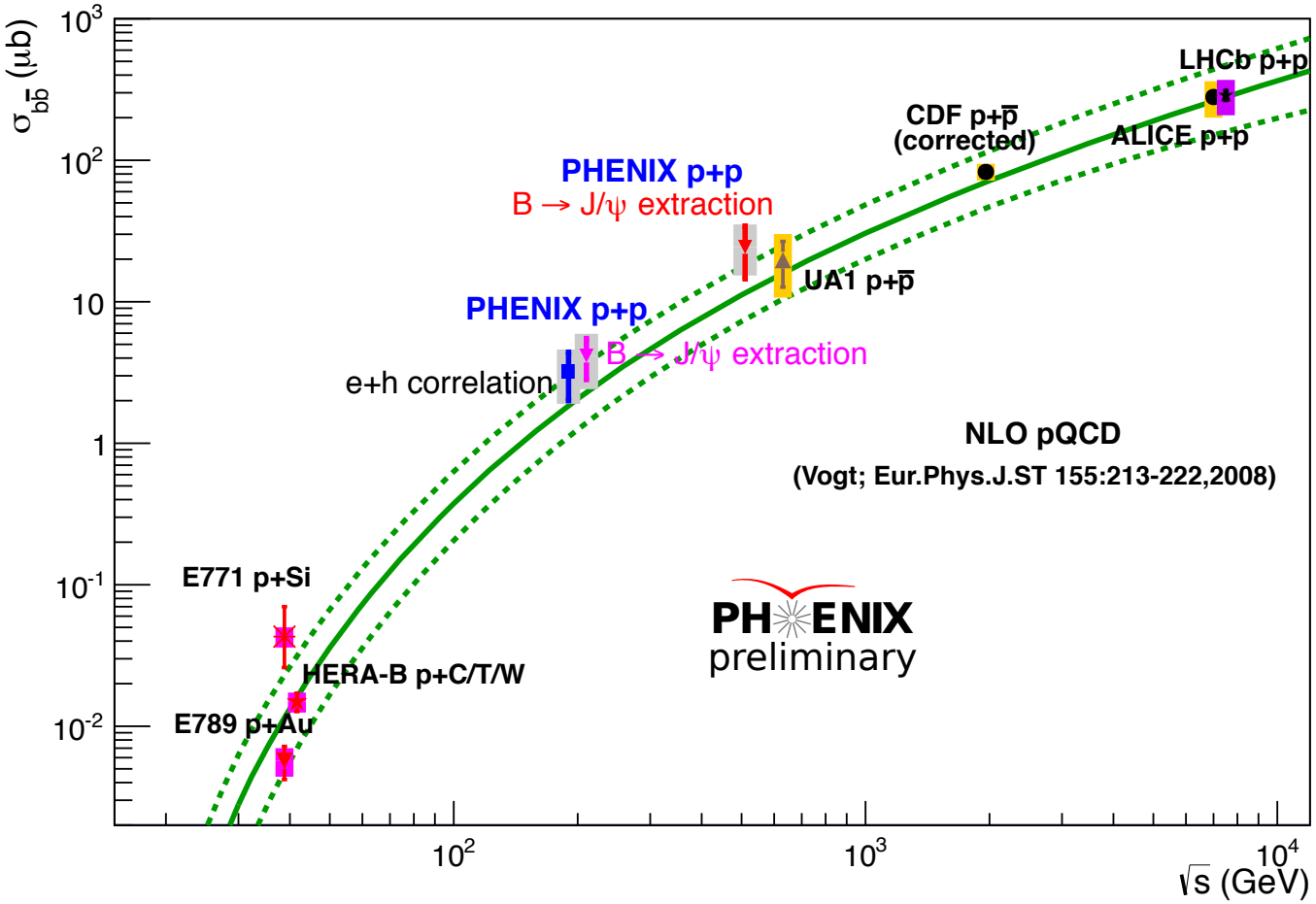
- A smooth energy dependence is found from 0.2 to 13 TeV p+p (p+pbar) collisions for B→J/ψ fraction measured with integrated J/ψ p_T.



arXiv:1701.01342
arXiv:1702.01085

Center of mass energy dependent $b\bar{b}$ cross section

- The extracted $b\bar{b}$ cross section results based on the B→J/ψ fractions measured in 200 and 510 GeV p+p collisions are in reasonable agreements with the NLO pQCD predictions.



B→J/ψ fraction in Cu+Au collisions

- The nuclear modification factor R_{CuAu} can be derived from the B→J/ψ fractions in p+p and Cu+Au collisions and the inclusive J/ψ R_{CuAu} according to this formula:

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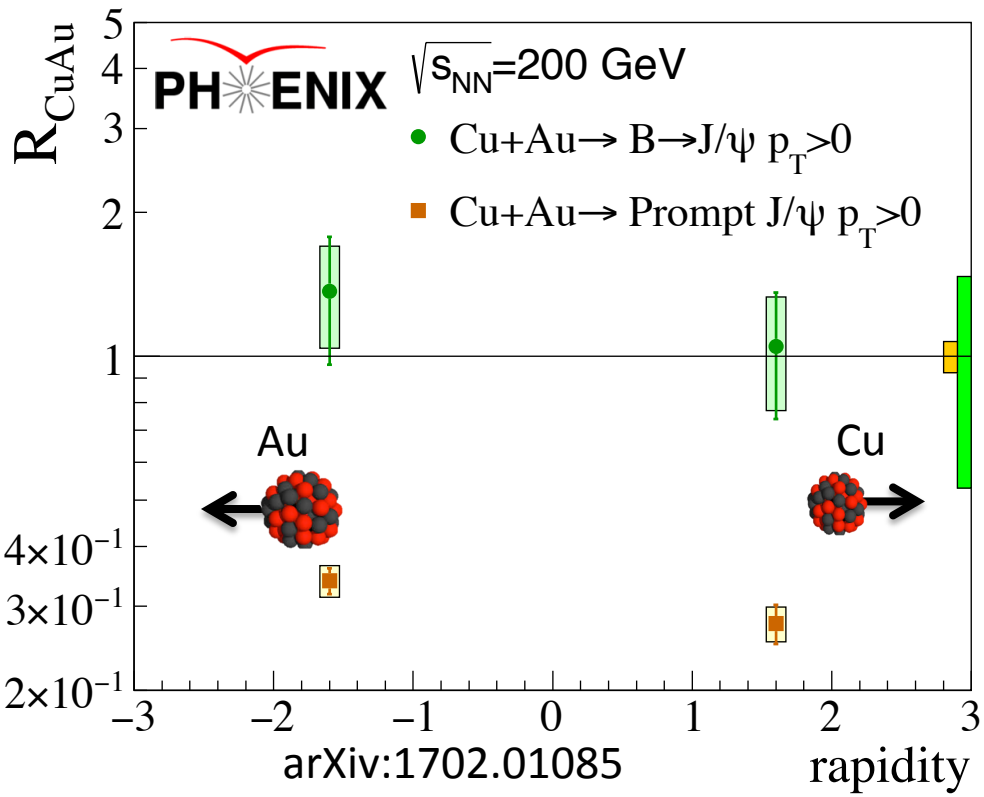

- No significant modifications on the B→J/ψ R_{CuAu} which suggests a small initial state modification.
- Significant modifications on the prompt J/ψ R_{CuAu} which indicates prompt J/ψ breaks up in final states.

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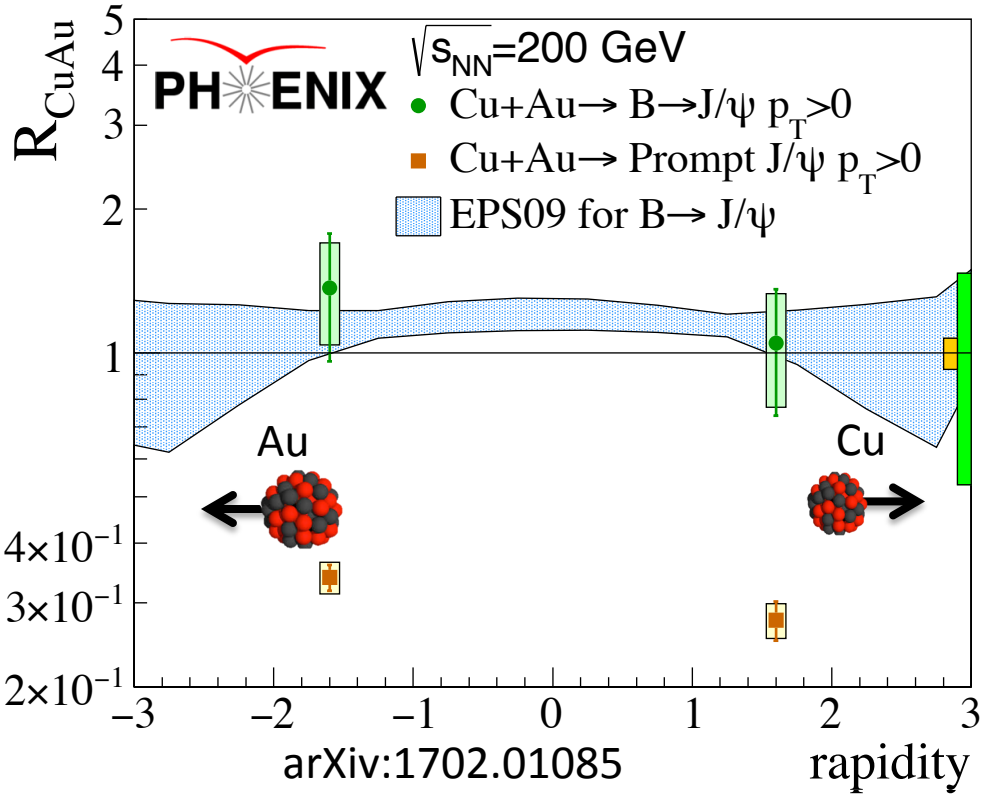

arXiv:1702.01085

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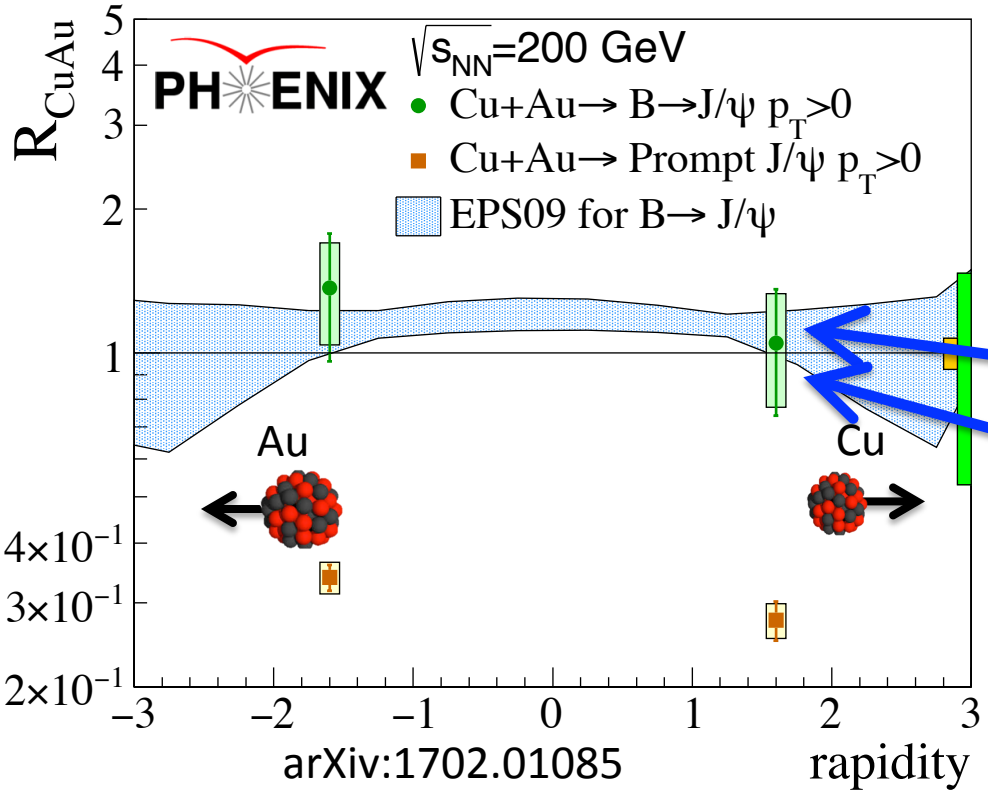

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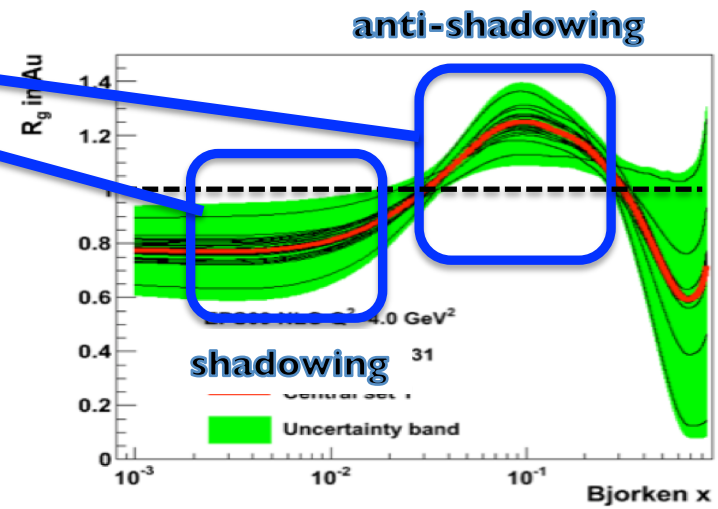

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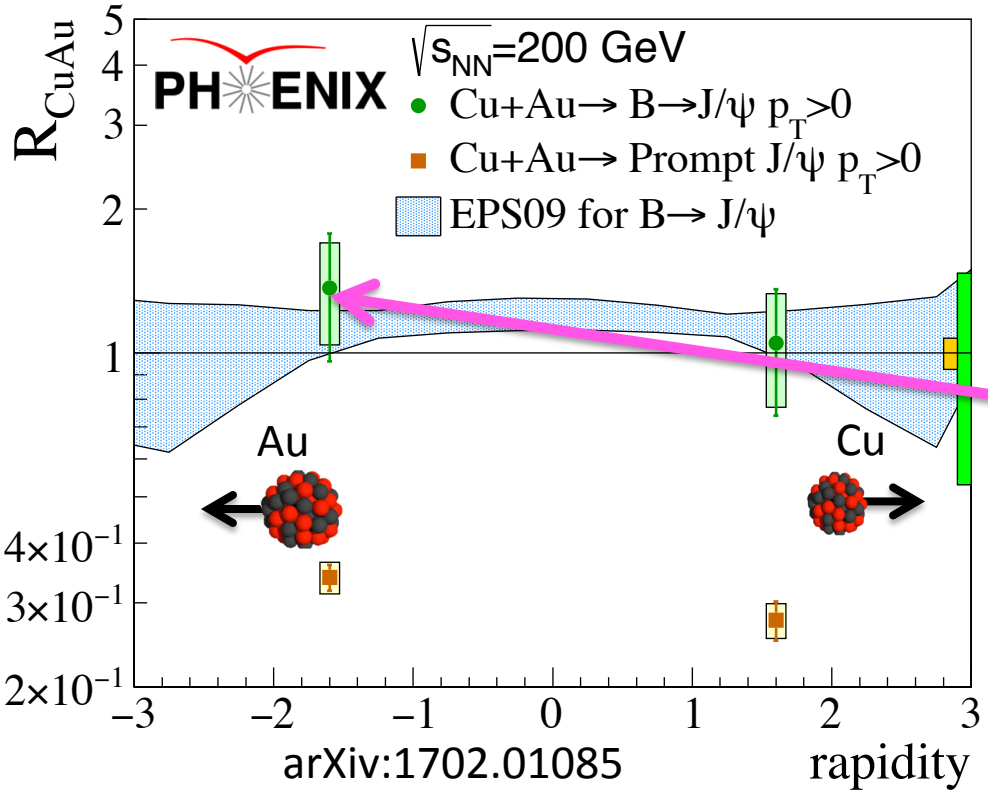
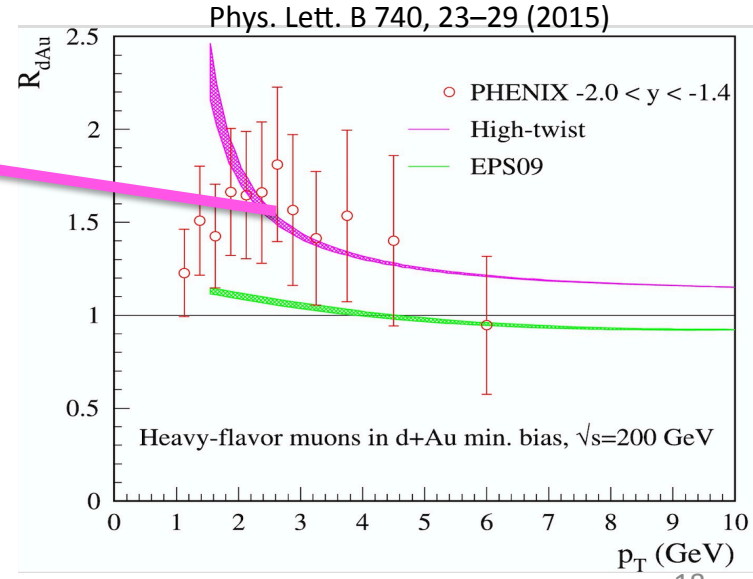


arXiv:1702.01085

- Backward enhancement
  Incoherent multiple scattering?

Phys. Lett. B 740, 23–29 (2015)



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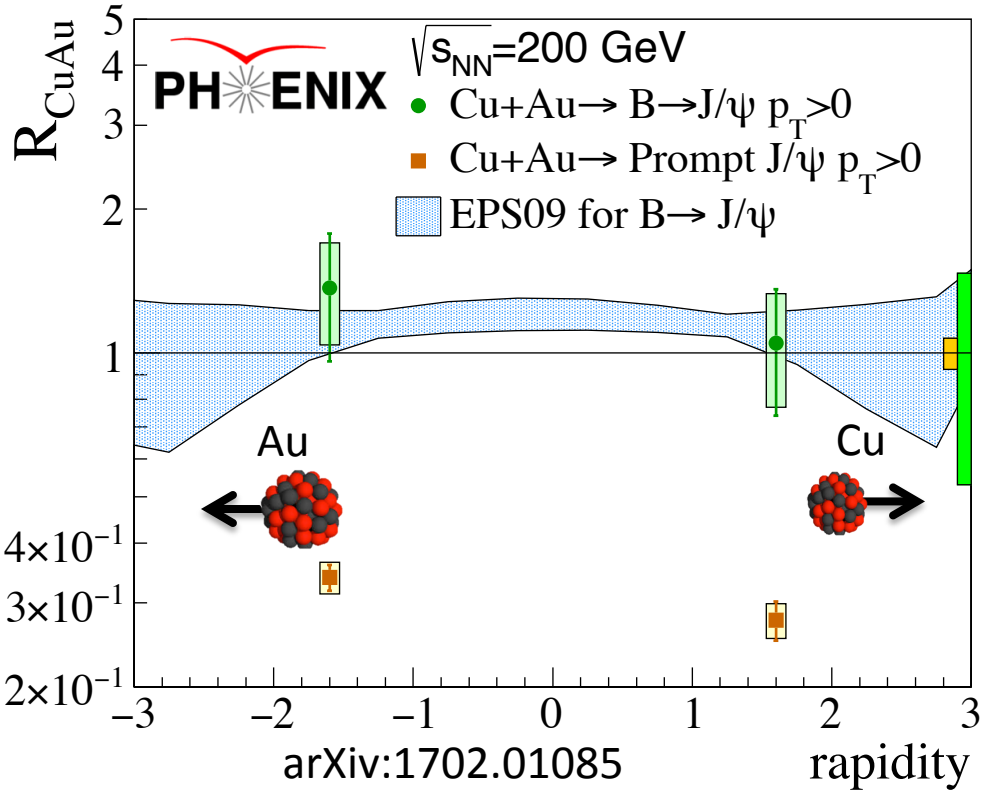
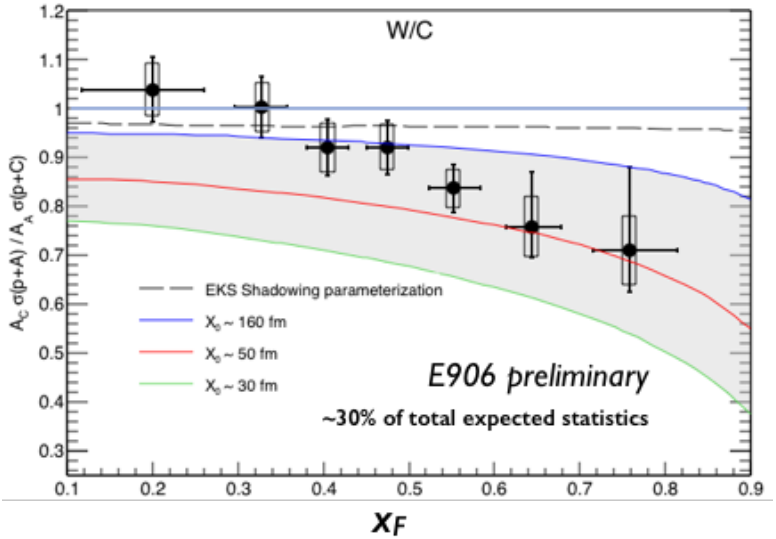


arXiv:1702.01085

- Initial state parton energy loss?

Clear initial state E_{loss} observed at E906



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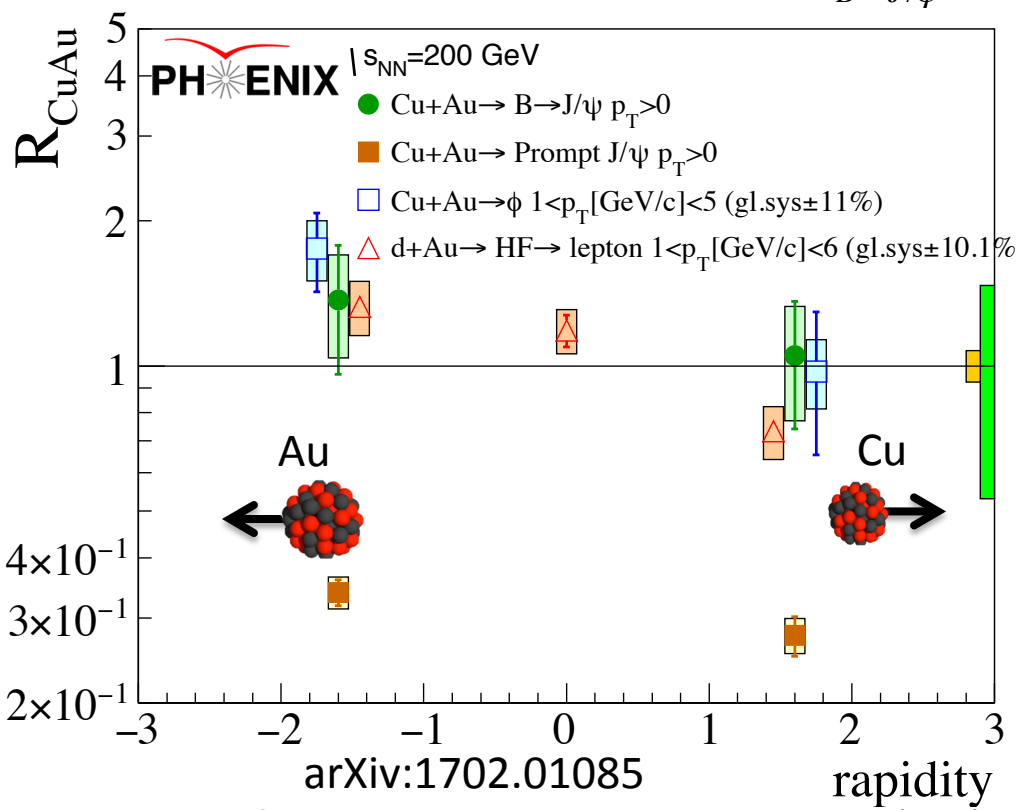
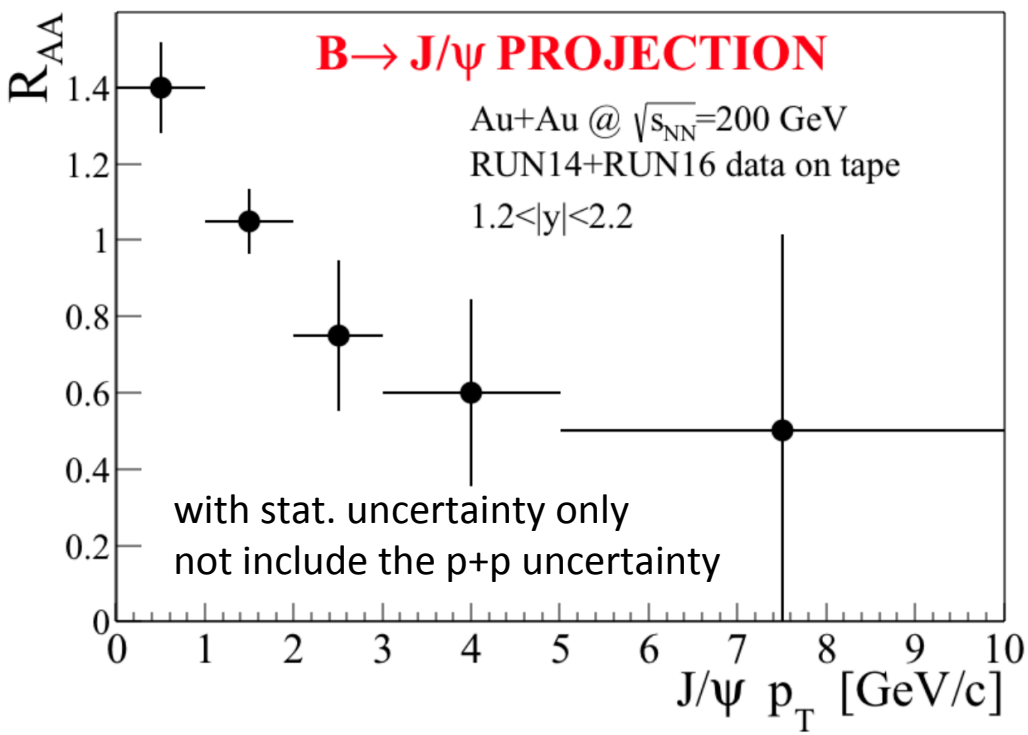


arXiv:1702.01085

- Similar trends has been found in ϕ meson R_{CuAu} and HF semi-leptonic decayed leptons R_{dAu}.
- Further verifications of final state break up of prompt J/ψ.

B→J/ψ fraction in Au+Au collisions

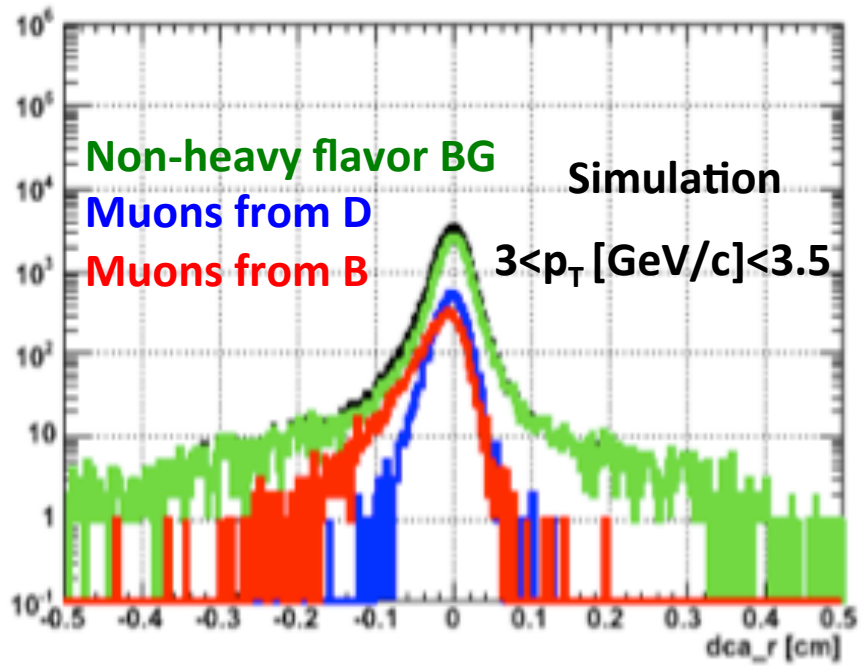
- Similarly, the nuclear modification factor R_{AuAu} can be derived from the B→J/ψ fractions in p+p and Au+Au collisions.
- The Au+Au data production in RHIC 2014+2016 is ongoing.

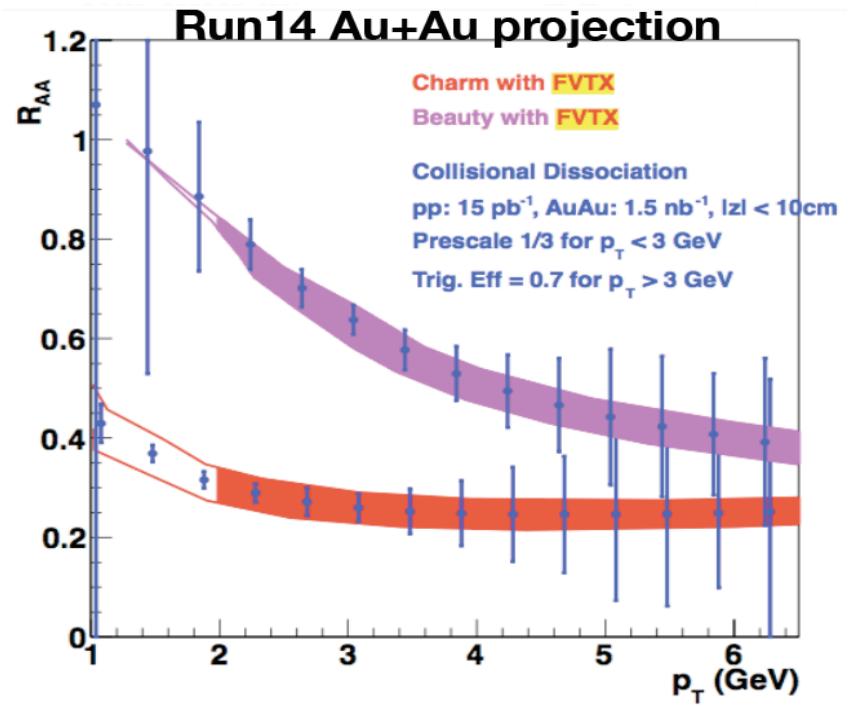


- The B hadron R_{AuAu} through the B→J/ψ measurements at low p_T will improve the knowledge of bottom quark energy loss in QGP.

Charm and Bottom decayed inclusive single muons

- High statistics measurement with similar method developed in the B to J/ψ analysis.
- Extend to high p_T region to determine the p_T dependence for charm and bottom production.
- Analysis is underway.
- The challenge is to minimize systematics.

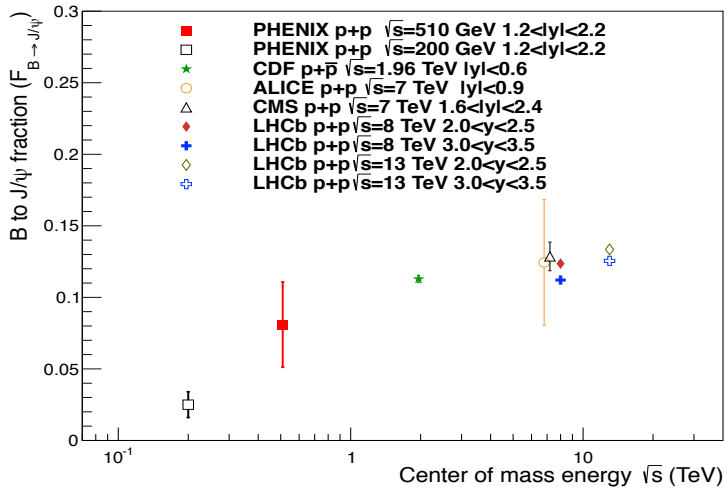


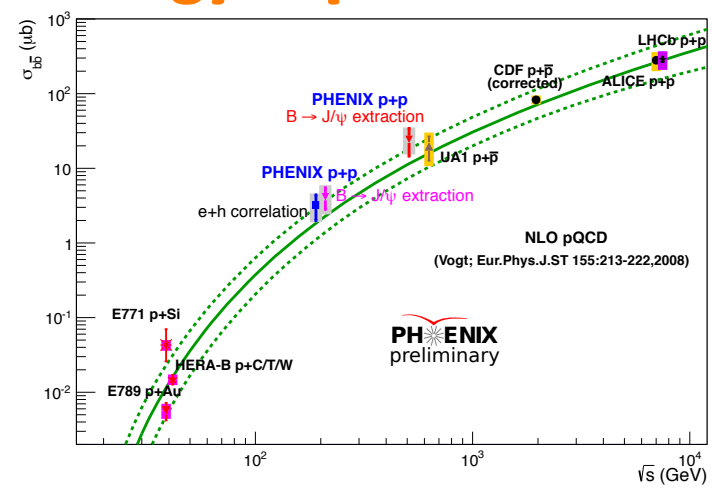


Summary

- B→J/ψ production (arXiv:1701.01342,1702.01085):

A smooth center of mass energy dependence

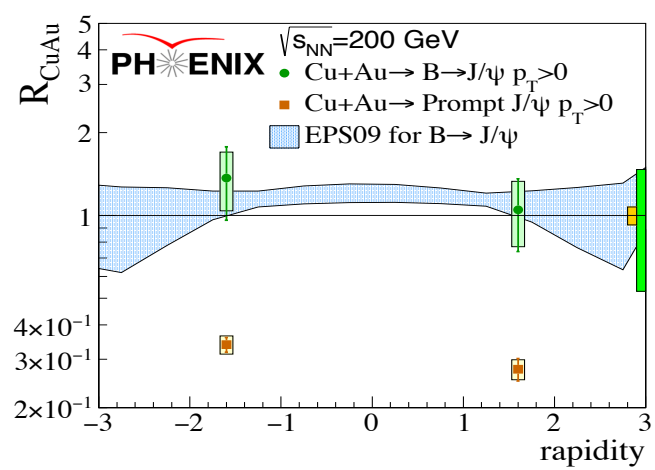




- First measured B→J/ψ R_{CuAu} (arXiv:1702.01085):

No significant nuclear modifications.

consistent with p+p binary scaling and expectations from nPDF modifications.



Outlook

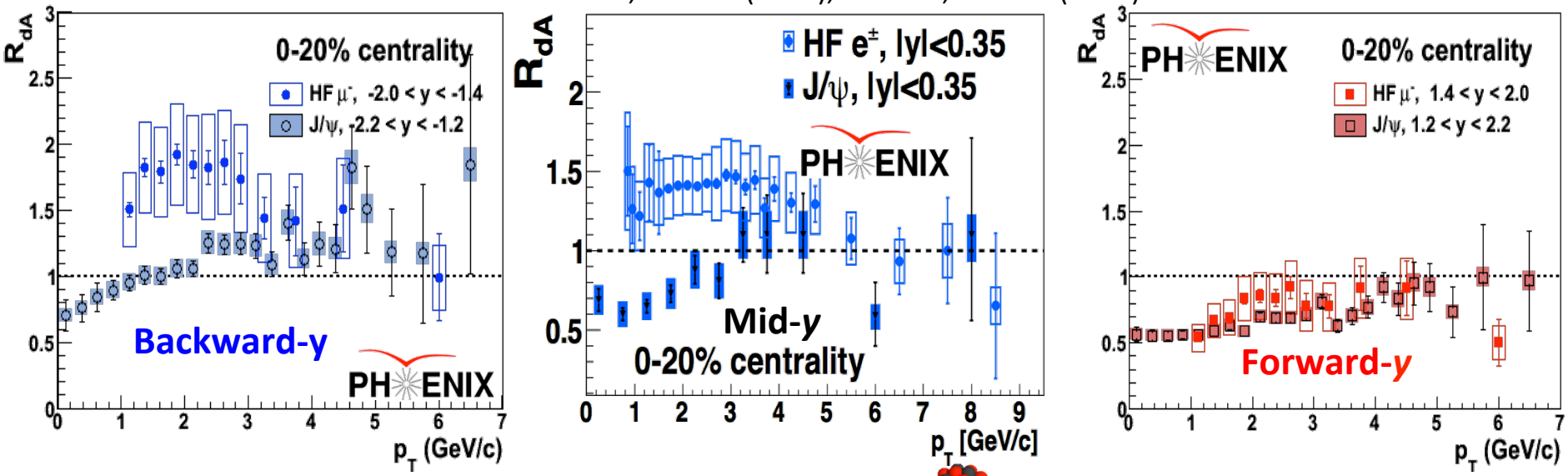
- Large data sets in various types of collision systems collected at PHENIX provide opportunities to study
  - Forward/backward B→J/ψ via di-muon channel in 2015 p+Au, 2014/2016 Au+Au collisions to understand CNM and QGP effect.
  - Study the D/B separated single muons in 2012/2015 p+p, 2015 p+Au and 2014/2016 Au+Au collisions with higher statistics will help understand the charm and bottom production and the mass dependent energy loss in QGP.

More to explore!

Backup

Open HF semi-leptonic decay in d+Au collisions at RHIC

PRL 109, 242301 (2012), PRL 112, 252301 (2014)



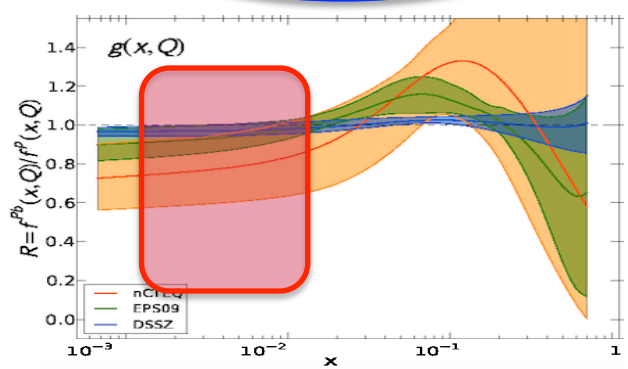
d → ← Au

- Define nuclear modification factor:

$$R_{AB} = \frac{1}{\langle N_{coll} \rangle} \times \frac{Yield(A+B)}{Yield(p+p)}$$

→ Cold Nuclear Matter effects

- Clear CNM effects are observed.
- Forward rapidity: Similar suppression indicates similar initial state effects (shadowing, energy loss) for J/ψ and open charm production.



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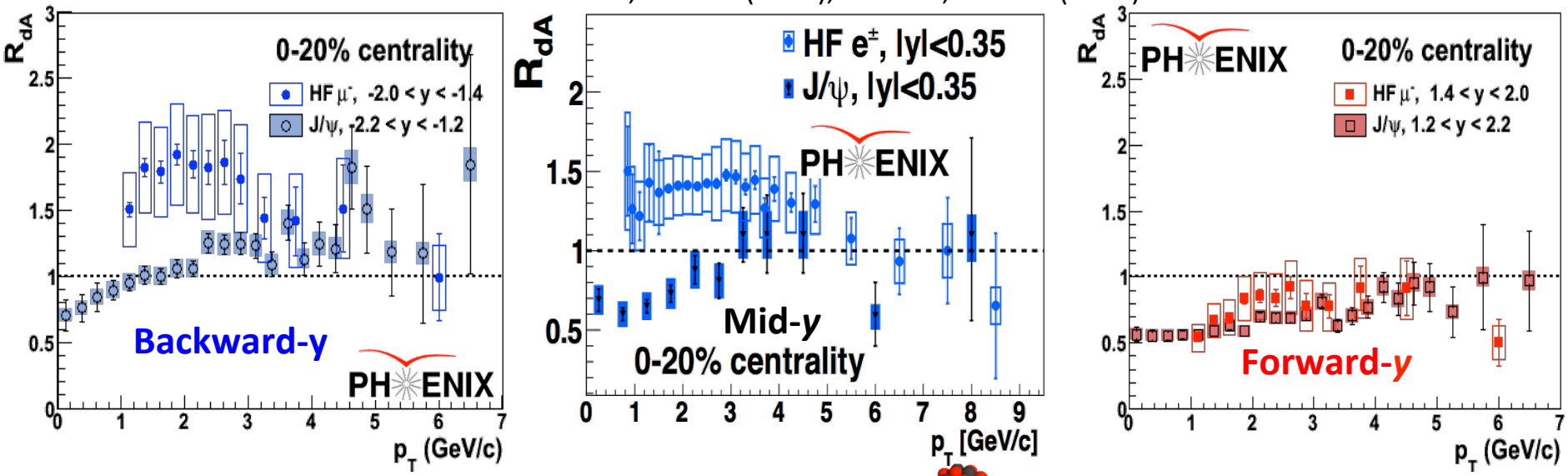
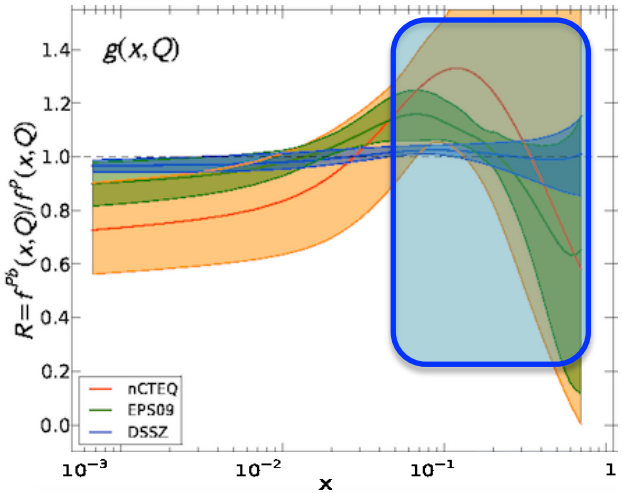


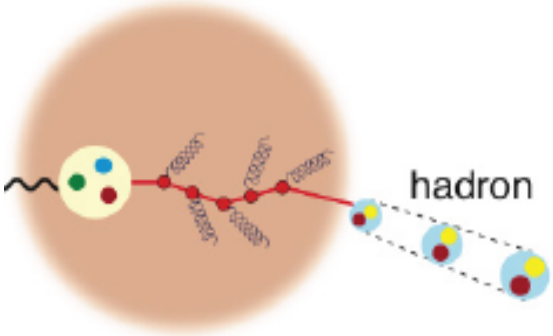
d → ← Au

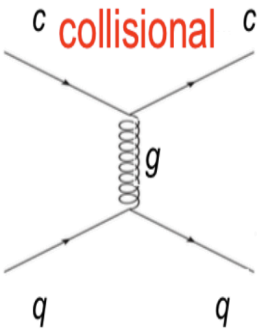
- Clear CNM effects are observed.
- Mid and Backward rapidity: Different trends between J/ψ and open heavy flavor. Final-state effects like co-mover absorption can not be neglected for J/ψ production.

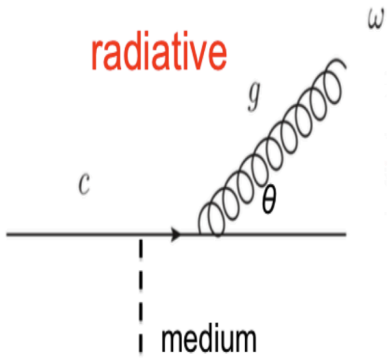


Energy loss in the QGP

- Energy loss Mechanism:
- (I) Heavy quarks lose energy when crossing the medium (indicated by the R_{AA} suppression).



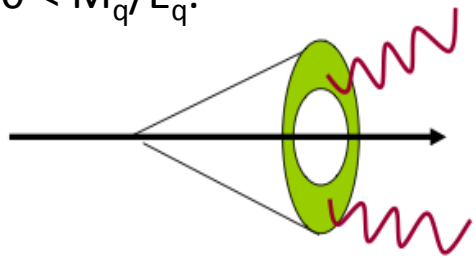




- Due to the dead cone effect, the energy loss in the medium is mass dependent:

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Dead cone effect: gluon radiation from massive quarks suppressed at angle $\theta < M_q/E_q$.

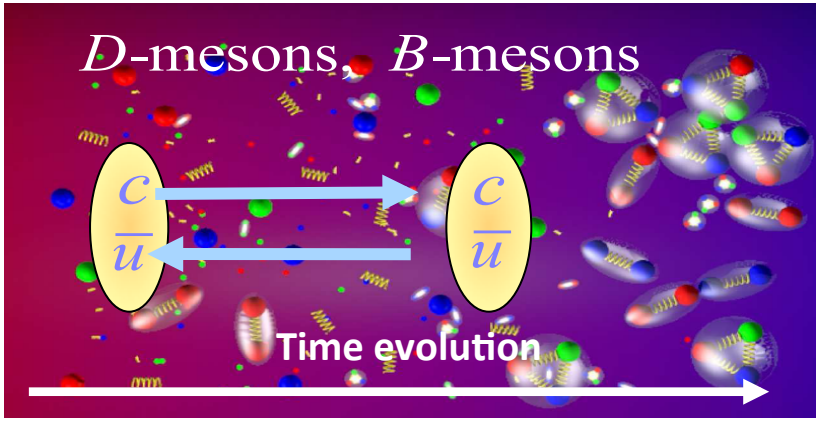


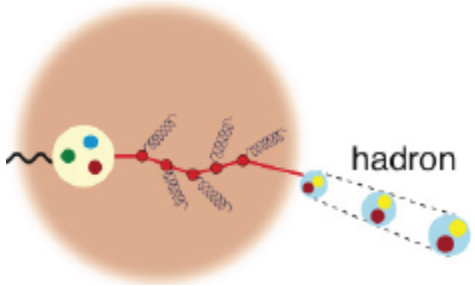
Energy loss in the QGP

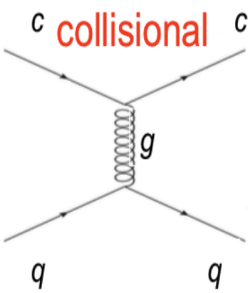
- Energy loss Mechanism:
- (II) Shorter formation and dissociation time of b(c) quark to B(D) from light quark hadrons.

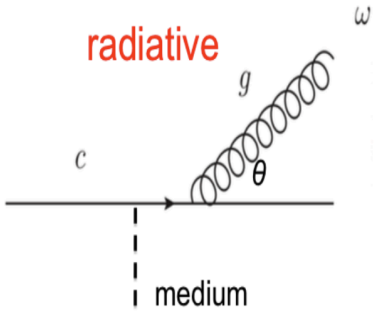
$$\Delta E_g > \Delta E_{u.d.s} > \Delta E_c > \Delta E_b$$

A.Adil, I.Vitev, Phys. Lett. B649 (2007)



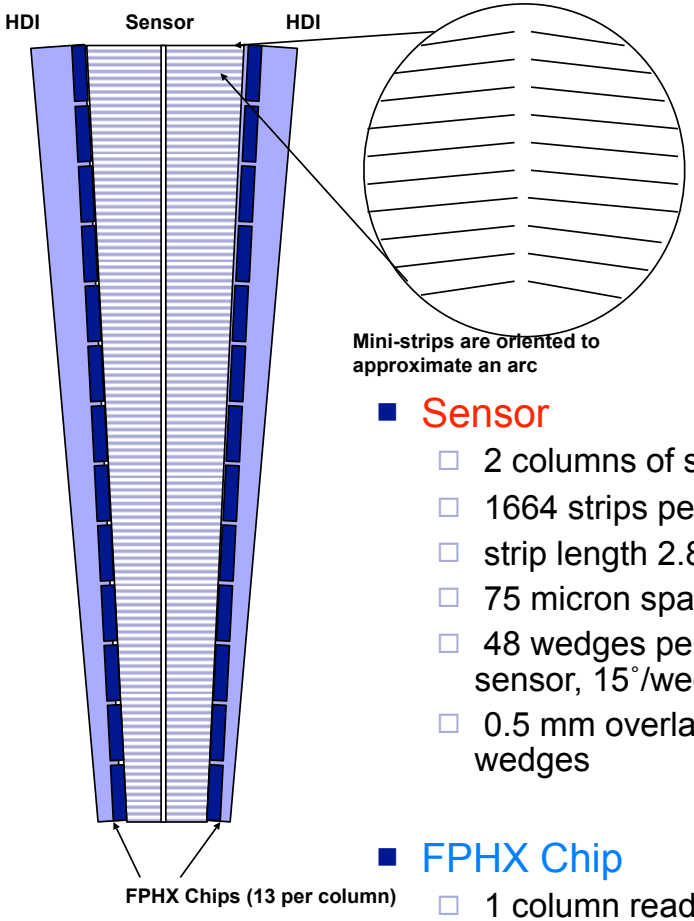




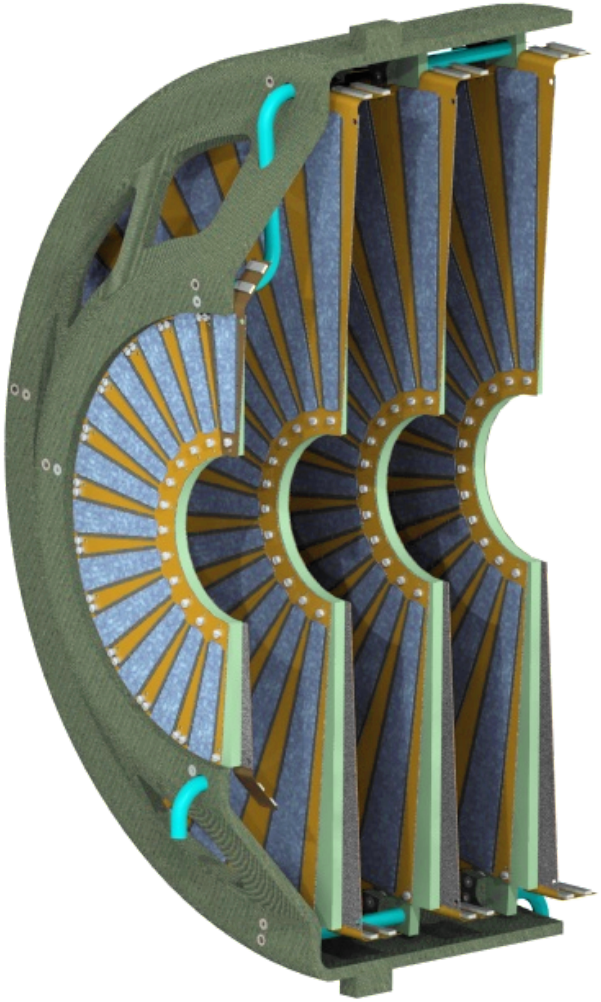


- Mass effect is negligible at high p_T but not in low p_T region.
- Low p_T heavy flavor production is dominated by charm, need to separate charm and bottom and study the mass/ flavor dependence.

The Forward Vertex Detector (FVTX)

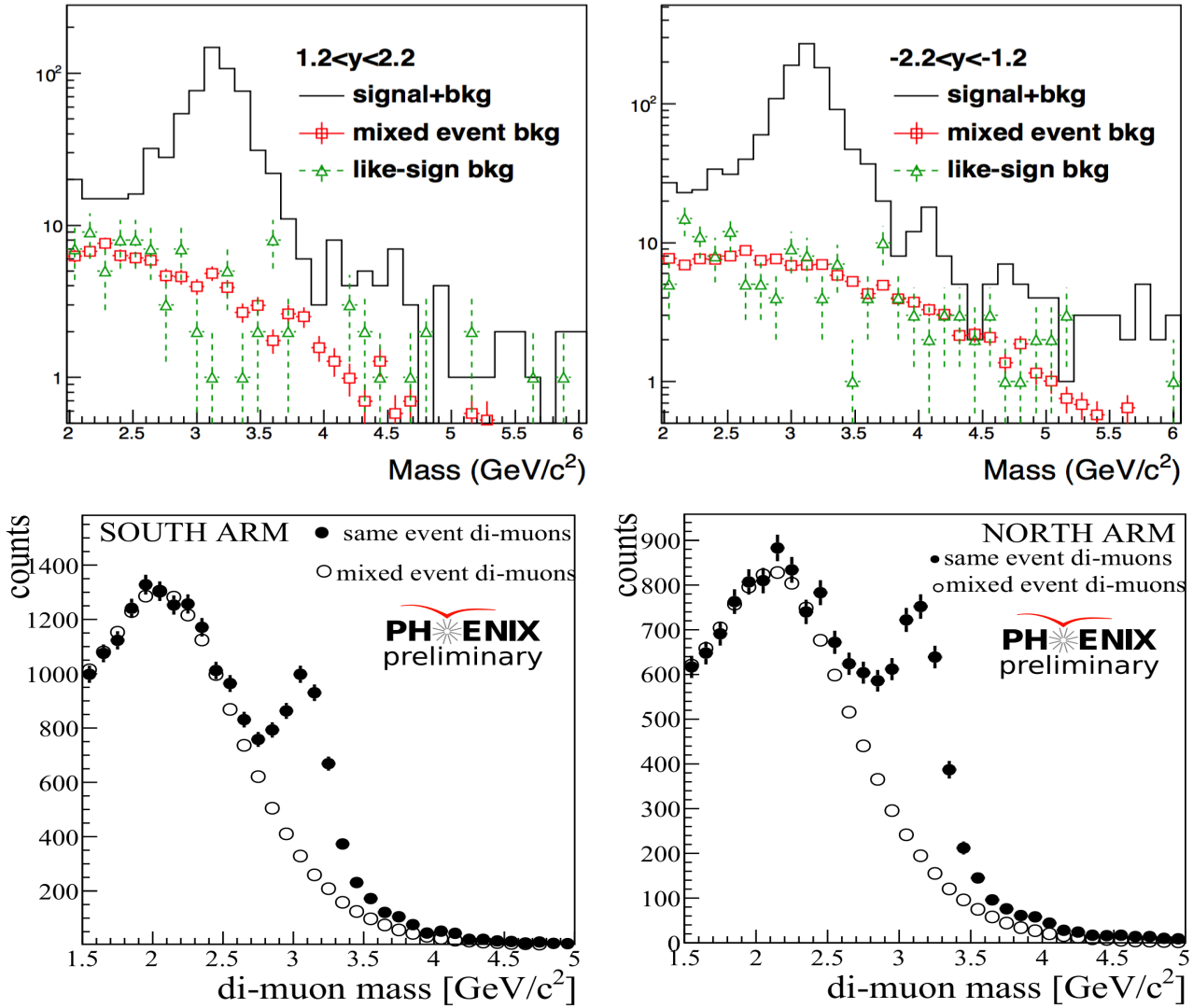


- Sensor
  - 2 columns of strips
  - 1664 strips per column
  - strip length 2.8 to 11.2 mm
  - 75 micron spacing
  - 48 wedges per disk (7.5˚/ sensor, 15˚/wedge)
  - 0.5 mm overlap with adjacent wedges
- FPHX Chip
  - 1 column readout
  - 128 channels
  - ~ 70 microns channel spacing
  - Dimensions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



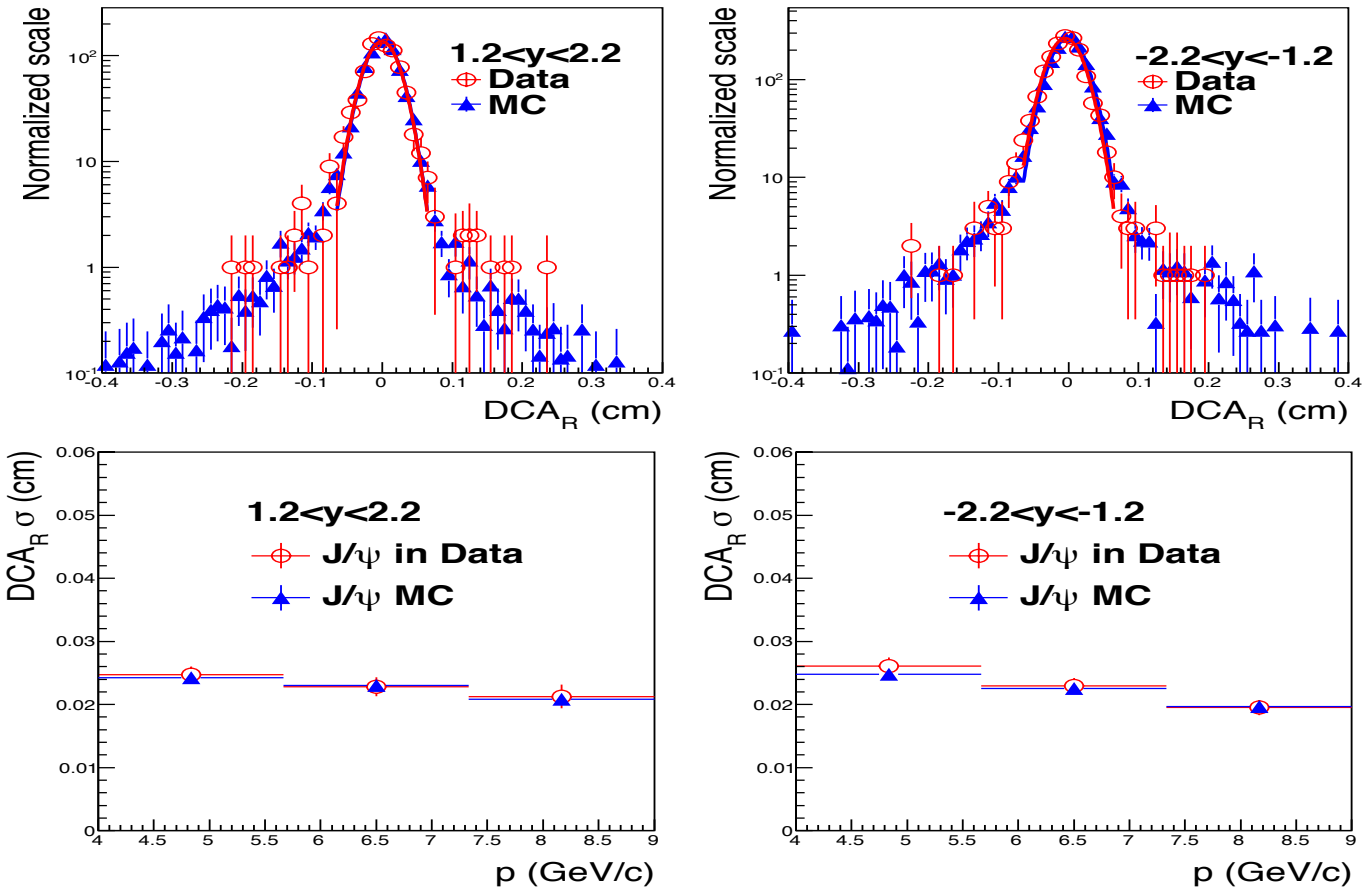
Invariant mass of di-muons

- In 2012 510 GeV p+p (top) and Cu+Au (bottom) data.



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

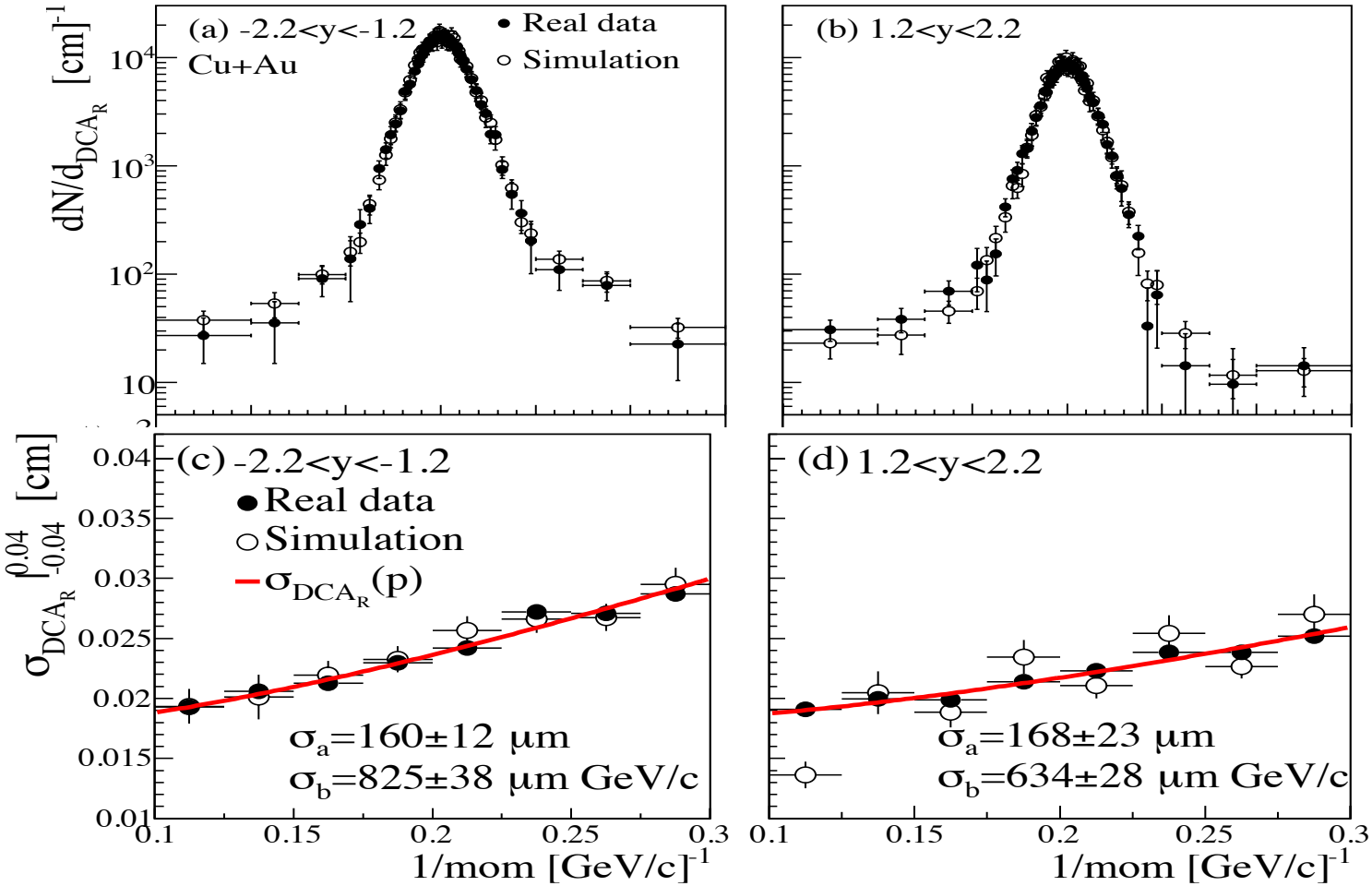
- DCA(r) of J/ψ decayed muons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.



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

Comparison of DCA(r) between data and simulation (Cu+Au)

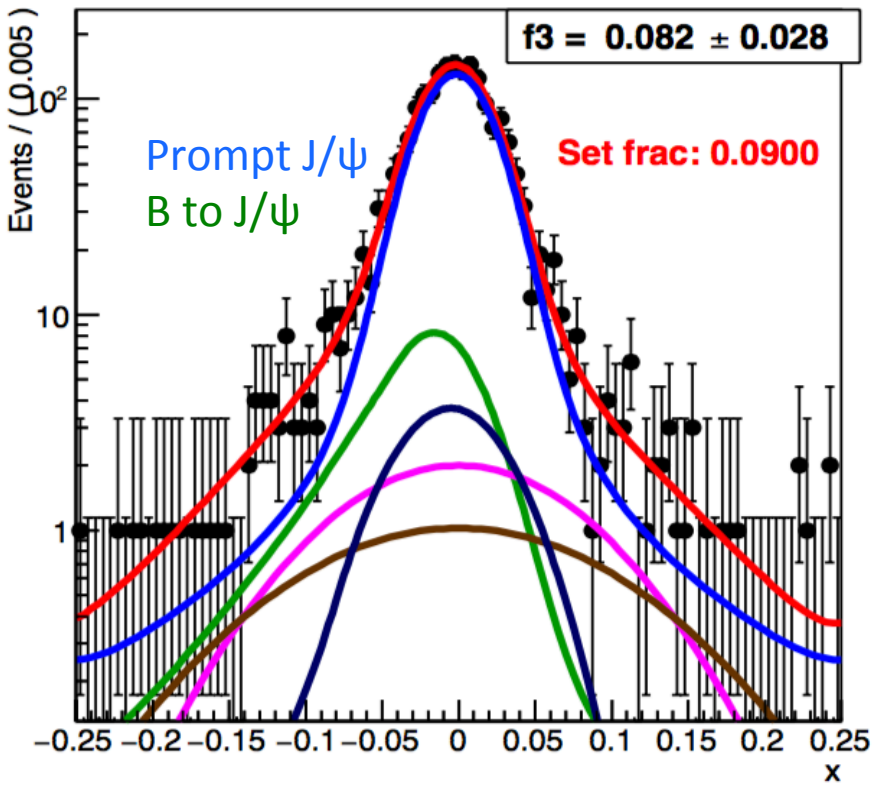
- DCA(r) of stopped hadrons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.

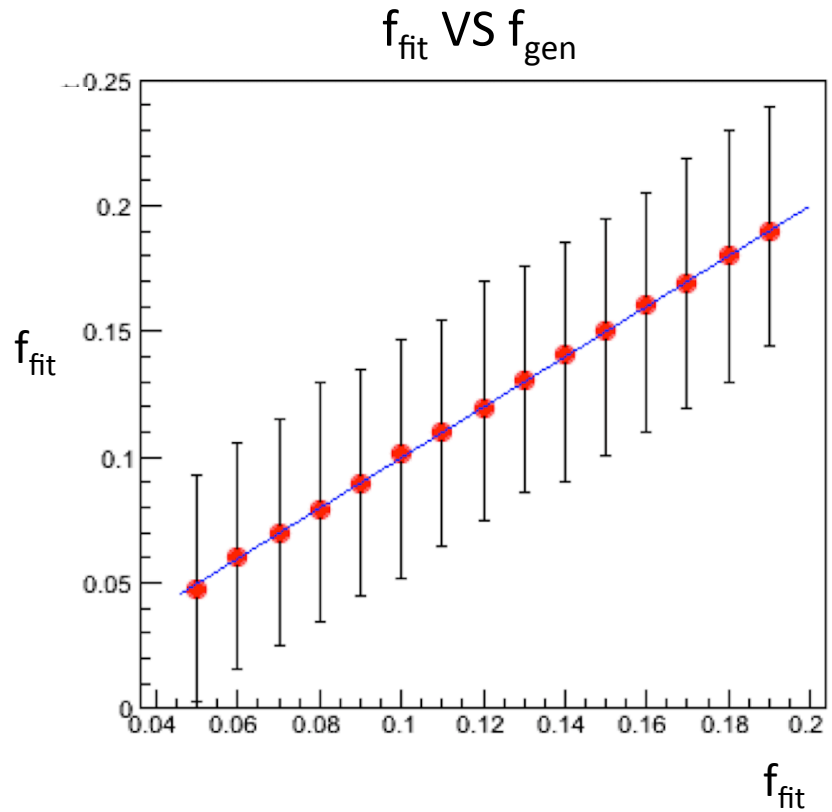


- Good agreement between data and simulation for DCA(r) resolution.

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.



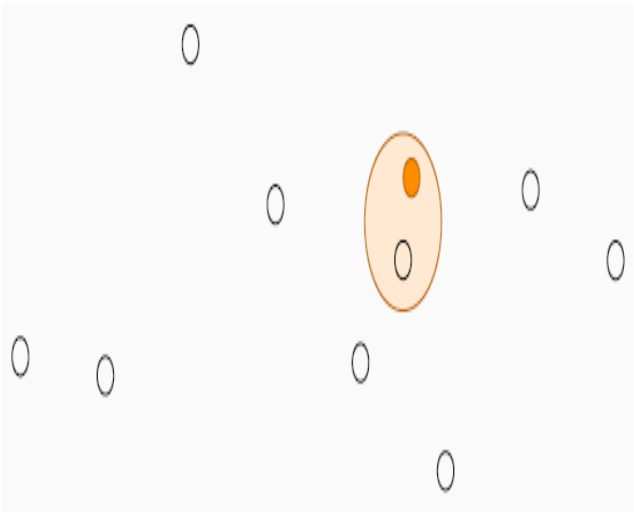


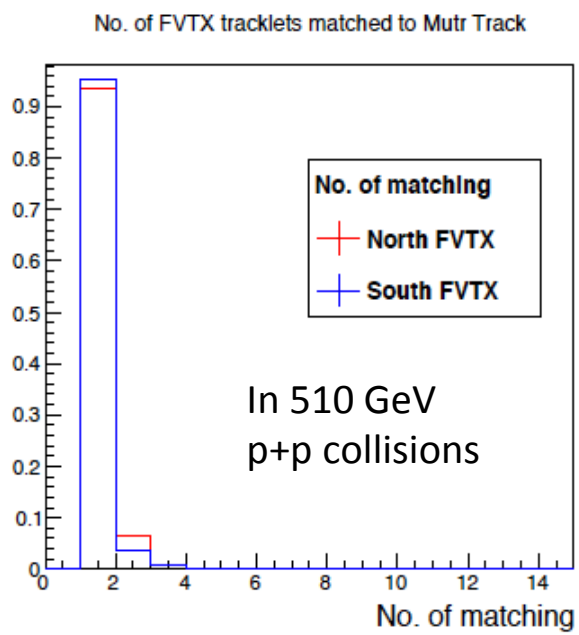
- Good linearity between generated and B to J/ψ ratio.
- Final results from data are under collaboration review.

FVTX-MuTr mis-matching background determination

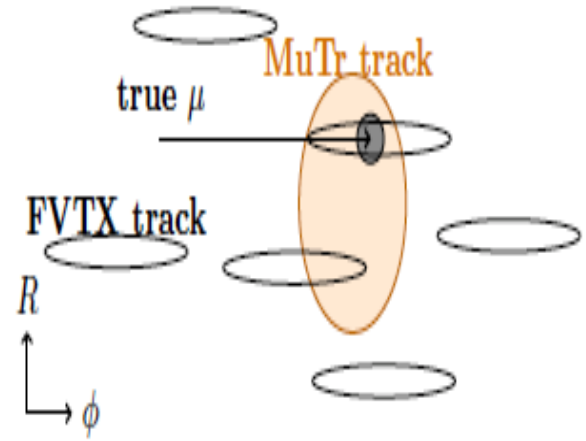
- For one MuTr track, there is a probability of finding more than one FVTX track within the matching window.

In 510 GeV p+p collisions





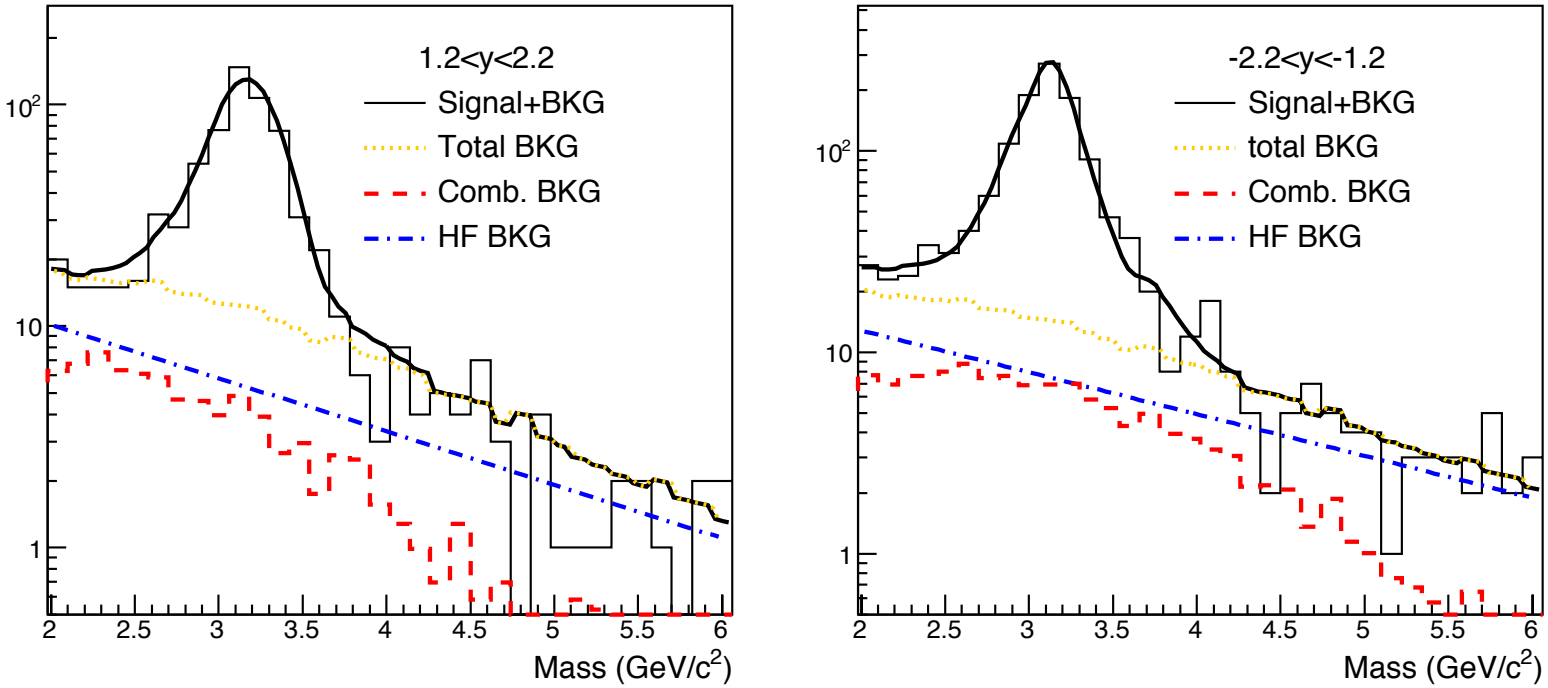
In 200 GeV Cu+Au collisions



- In p+p collsions, the probability to have more than one FVTX track matched with the MuTr track is around or less than 5%.
- In heavy ion collisions such as Cu+Au collisions, the probability is much higher.

HF continuum background determination (510 GeV p+p)

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

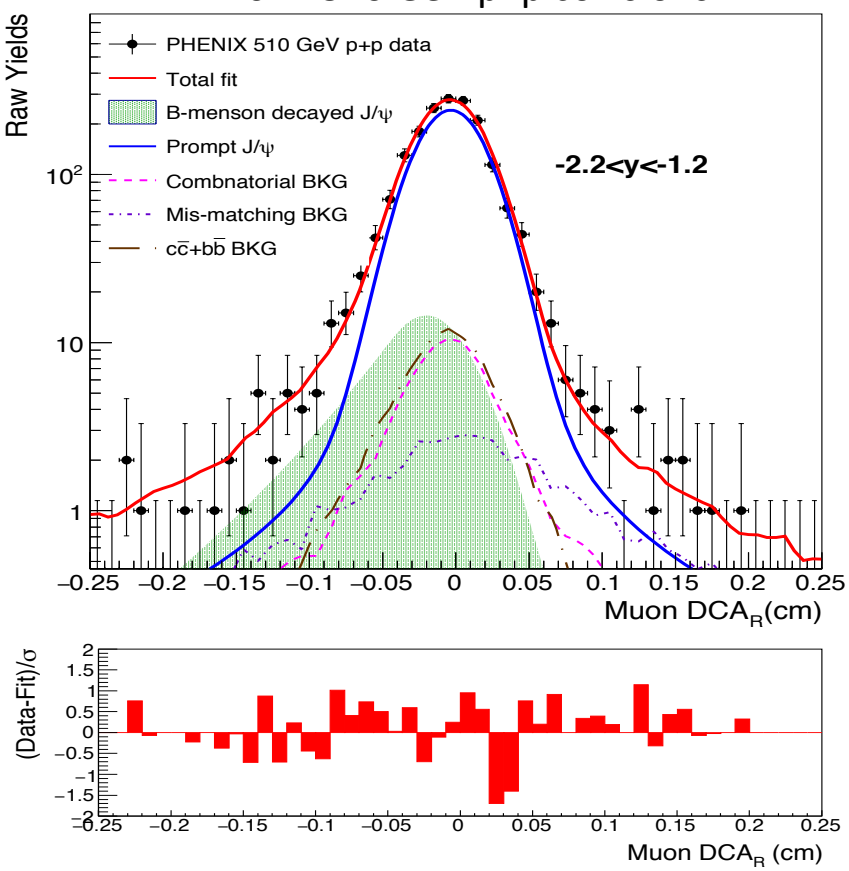
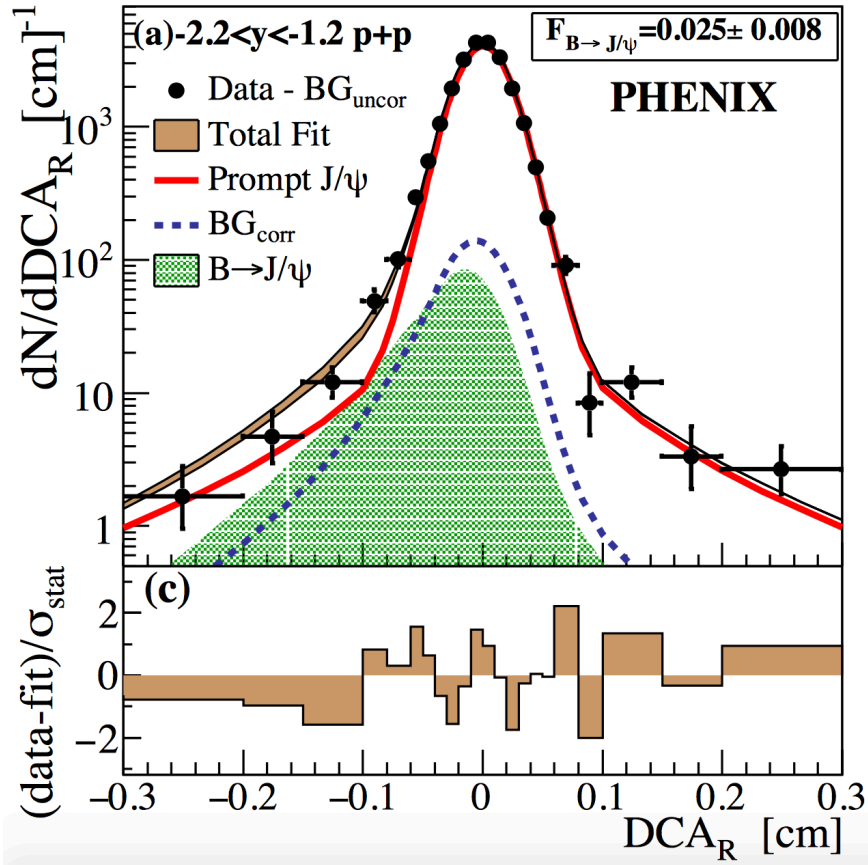


- Total background consists of HF continuum background and mixed event background.
- HF continuum background is comparable with the mixed event background within the mass cut window.

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

- Fit on DCA_R in data to simultaneously determine the prompt J/ψ and J/ψ from B-meson decay yields and extract the B to J/ψ fraction.

2012 510 GeV p+p collisions



2012 200 GeV p+p collisions