

$B \rightarrow J/\psi$ measurements in p+p and Cu+Au collisions by the PHENIX Experiment

Xuan Li (LANL)

For the PHENIX Collaboration

Santa Fe Jets and Heavy Flavor workshop 2017



Outline

- Motivation.
- PHENIX and the Forward Silicon Vertex Detector (FVTX).
- PHENIX Forward $B \rightarrow J/\psi$ 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 $B \rightarrow J/\psi$ 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. Canoa Roman,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. Chiu,⁶⁶ V. Ciencialo,⁵² R.A. Cole,¹⁴ M. Connors,^{20,57} N. Cronin,^{44,62} N. Cussetta,⁴⁴

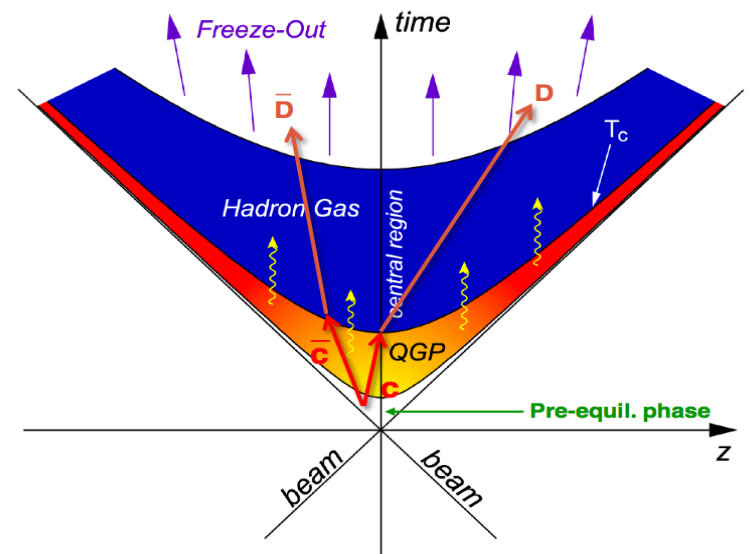
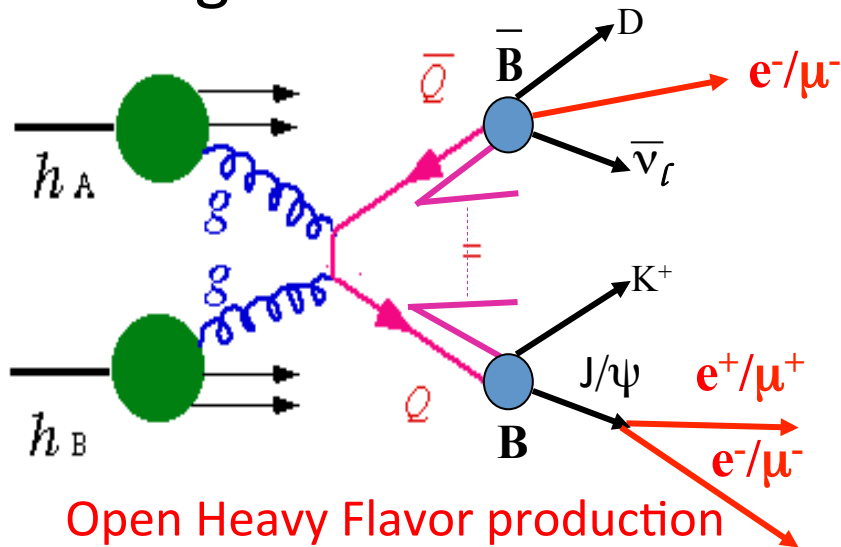
B-meson production at forward and backward rapidity in p+p and Cu+Au collisions at $\sqrt{s_{NN}}=200$ GeV

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

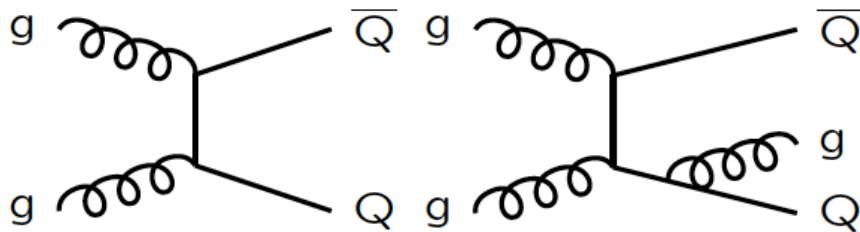


Uniqueness at RHIC

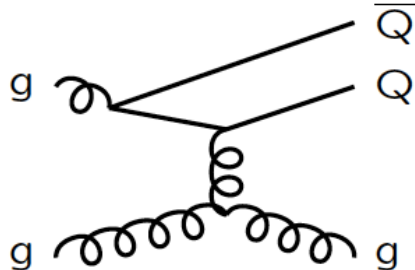
- Uniqueness at RHIC

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

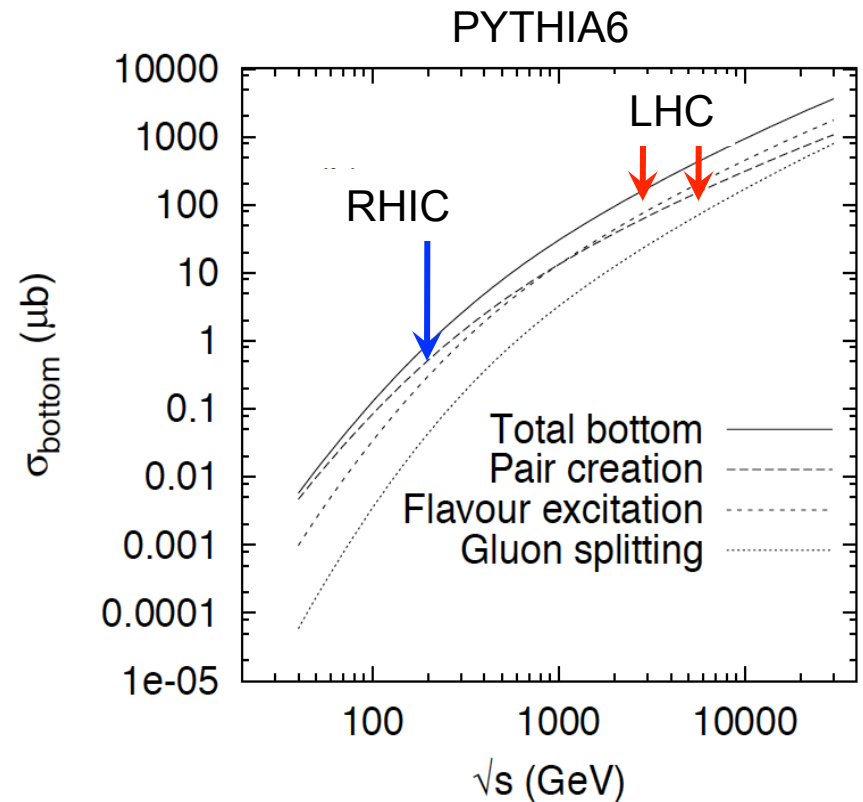
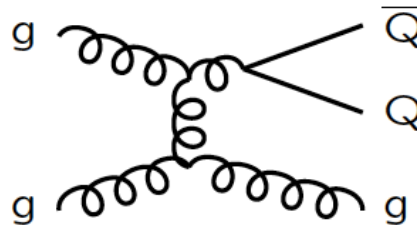
Pair Creation (Gluon Fusion)



Flavor Excitation



Gluon Splitting

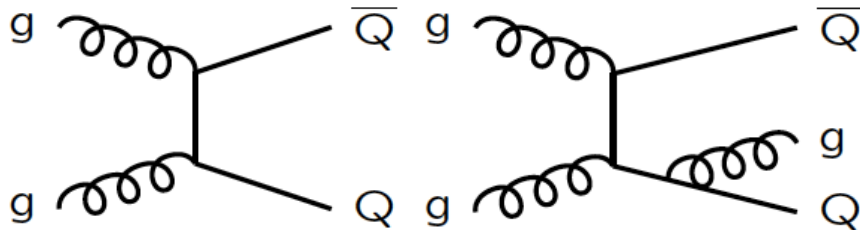


T. Sjostrand, EPJC17 (2000) 137

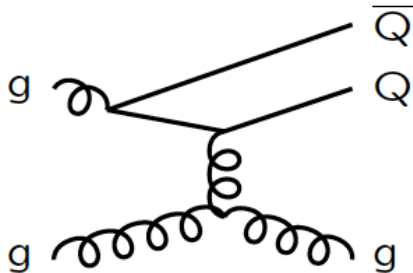
Uniqueness at RHIC

- 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.

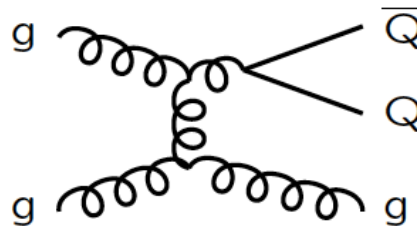
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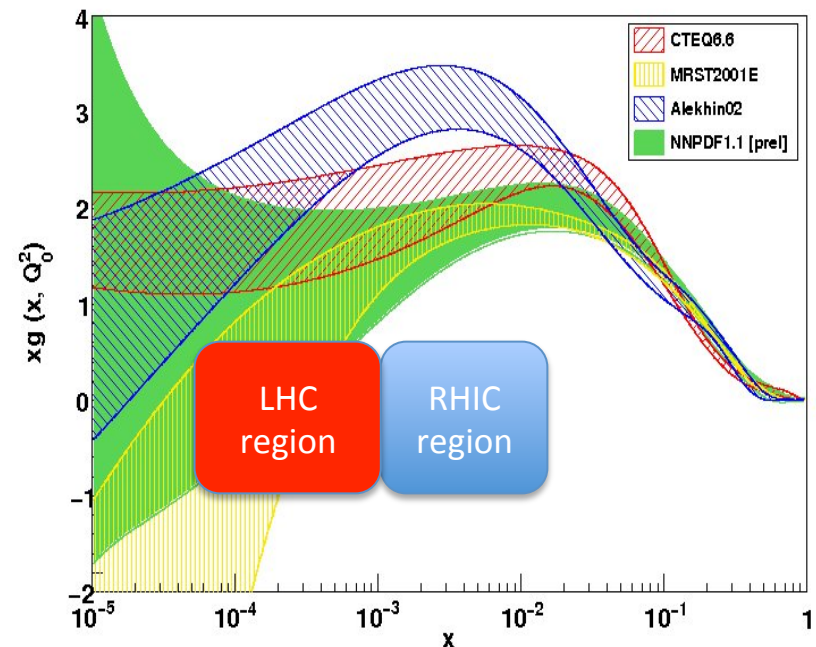
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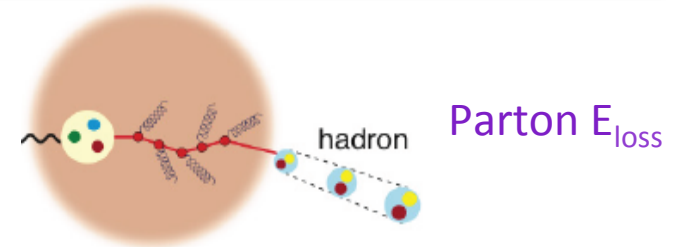
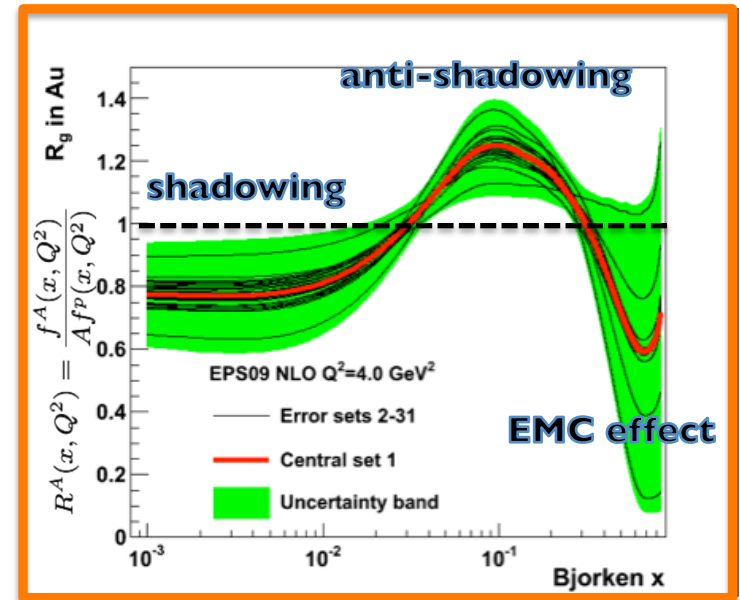


Nucleon Gluon PDF



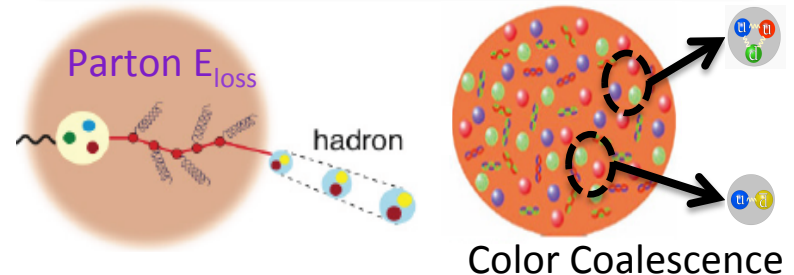
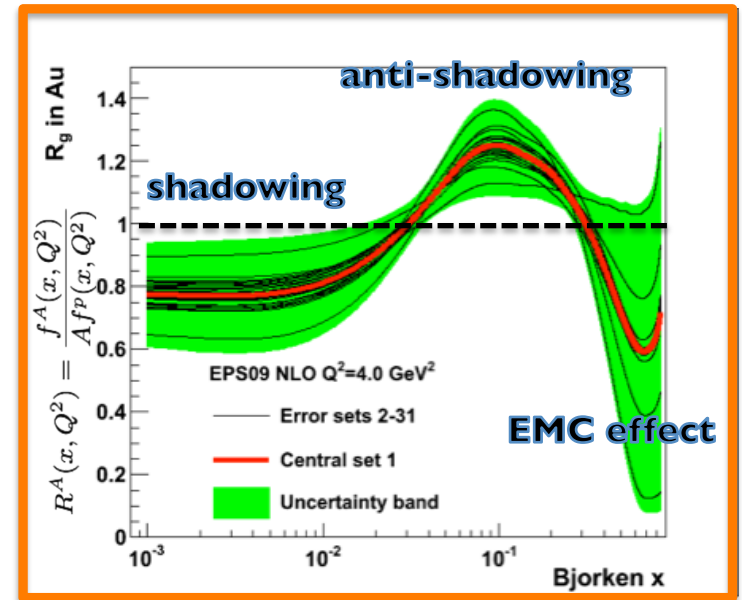
Heavy flavor production in Heavy Ion Collisions

- 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.



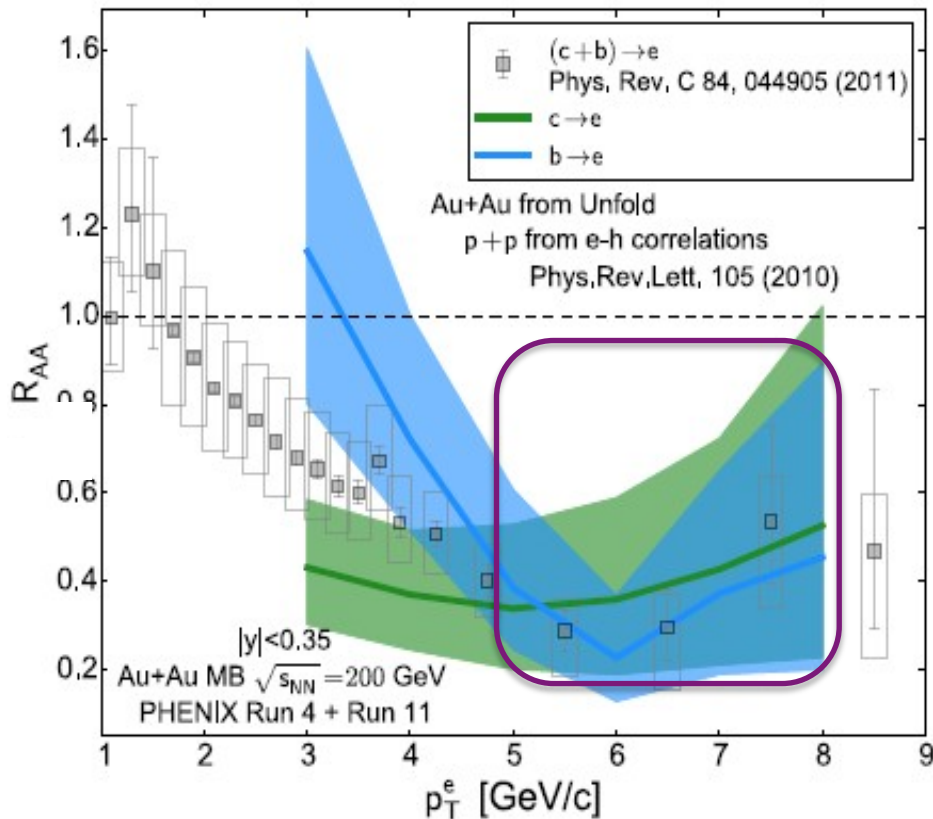
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 - Breakup of charmonium before exiting nucleus.
 - Co-mover absorption.
- Hot nuclear matter effect:
 - Energy loss of partons traversing QGP.
 - Color screening.
 - Coalescence of quarkonia in QGP.
- Need to measure multiple observables in different processes to isolate the initial/final state and cold/hot nuclear matter effects.



Indication of flavor dependent energy loss

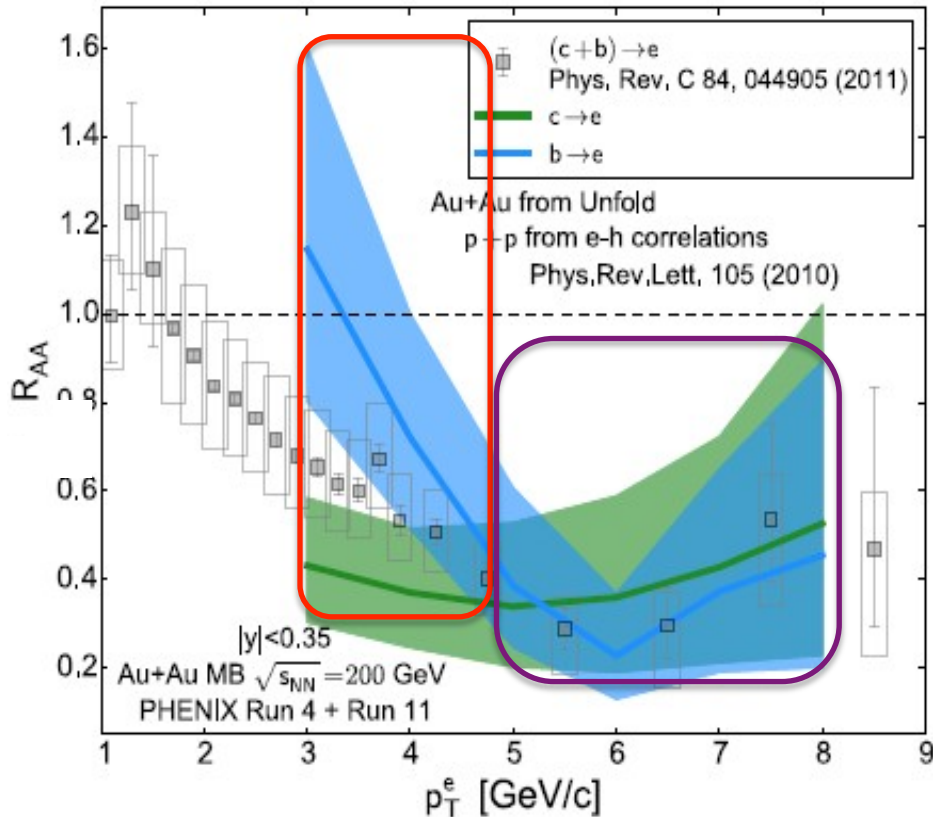
PRC 93, 034904 (2016)



- 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

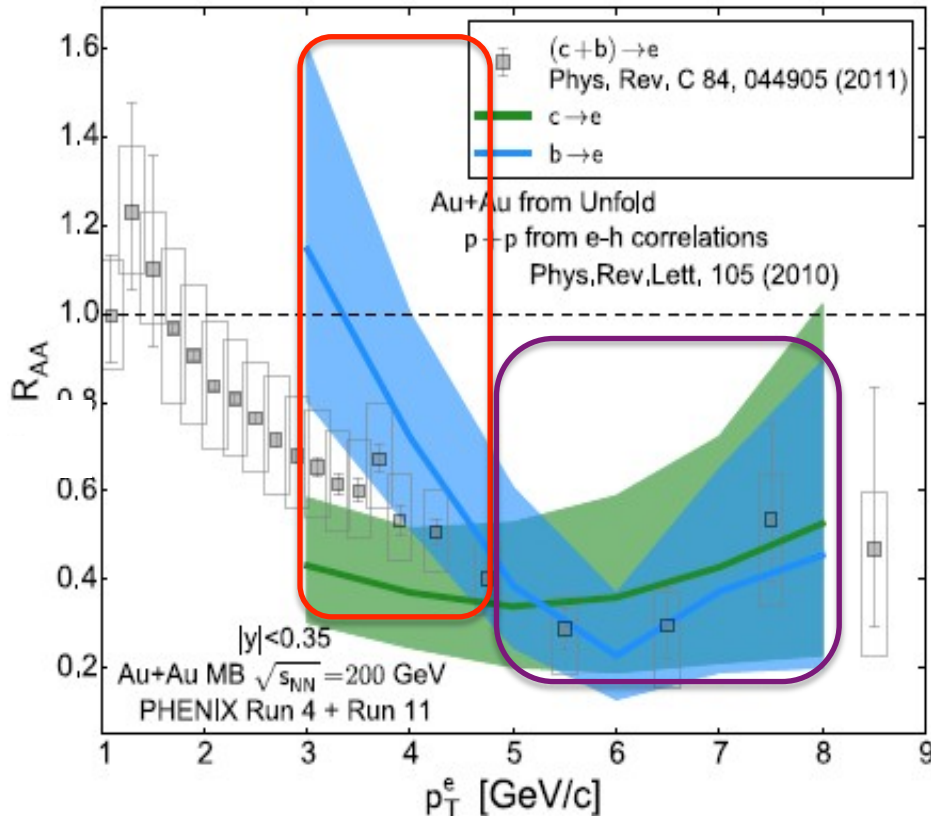
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Indication of flavor dependent energy loss

PRC 93, 034904 (2016)



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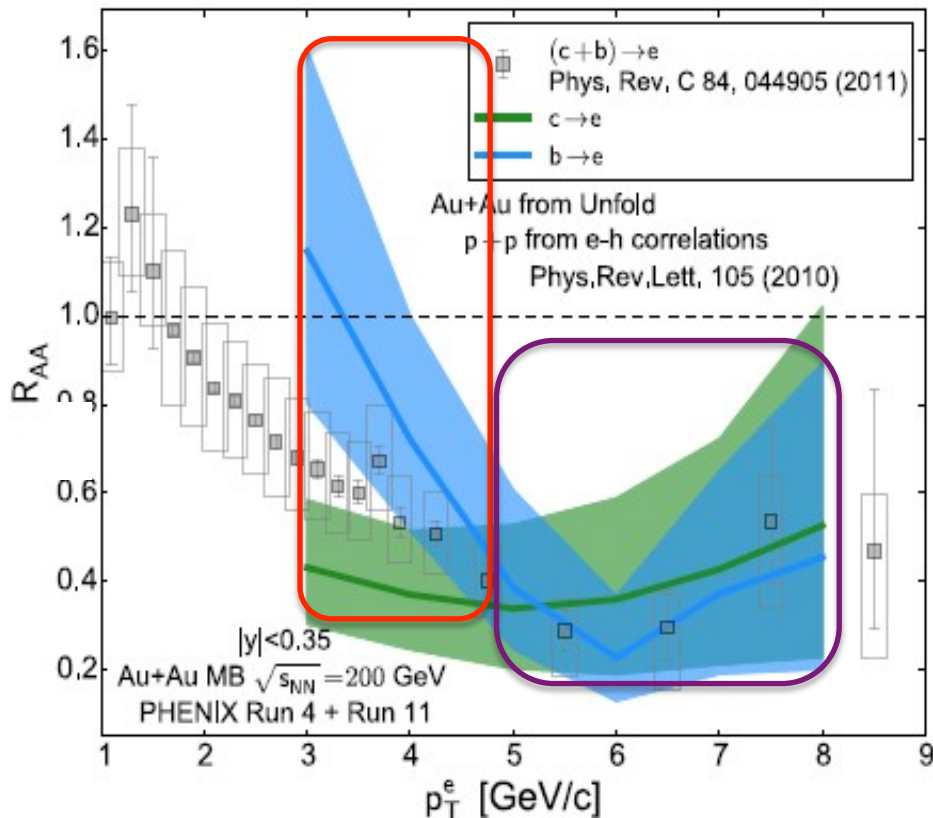
- Bottom has similar suppression as charm for high p_T region.
- Bottom may be less suppressed in the low p_T region.

- 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

PRC 93, 034904 (2016)

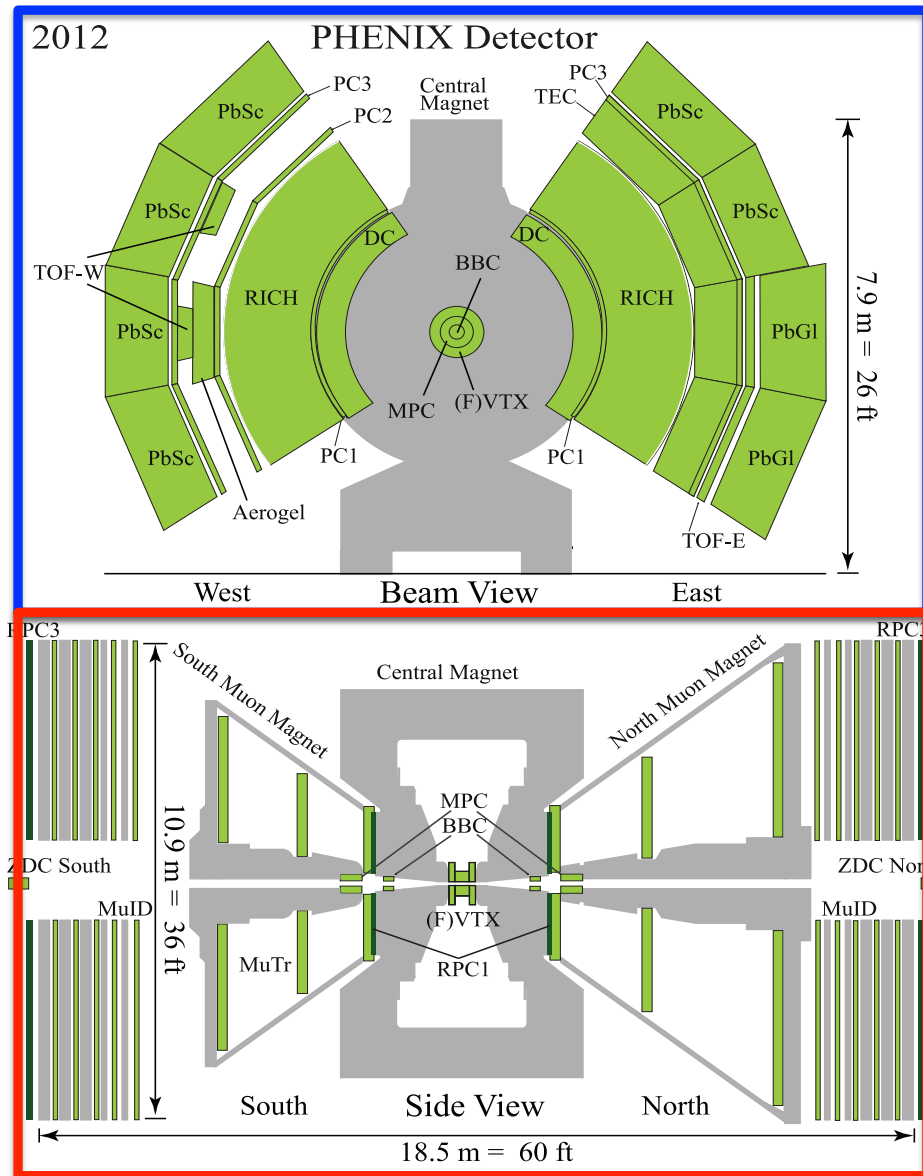


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 - Bottom has similar suppression as charm for high p_T region.
 - Bottom may be less suppressed in the low p_T region.
- Consistent with Energy Loss mechanism:

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

- 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)**

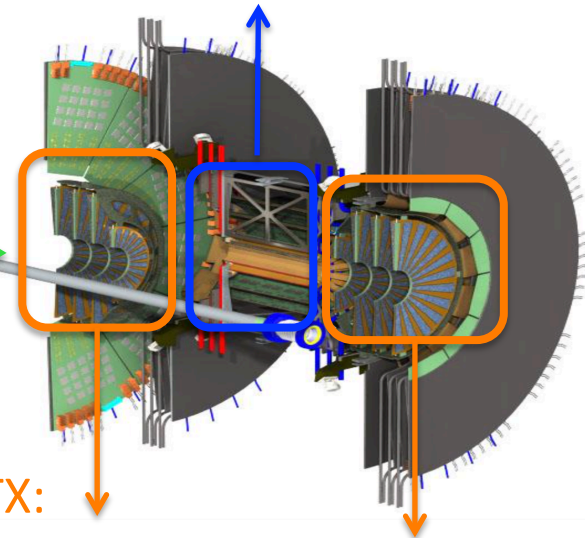
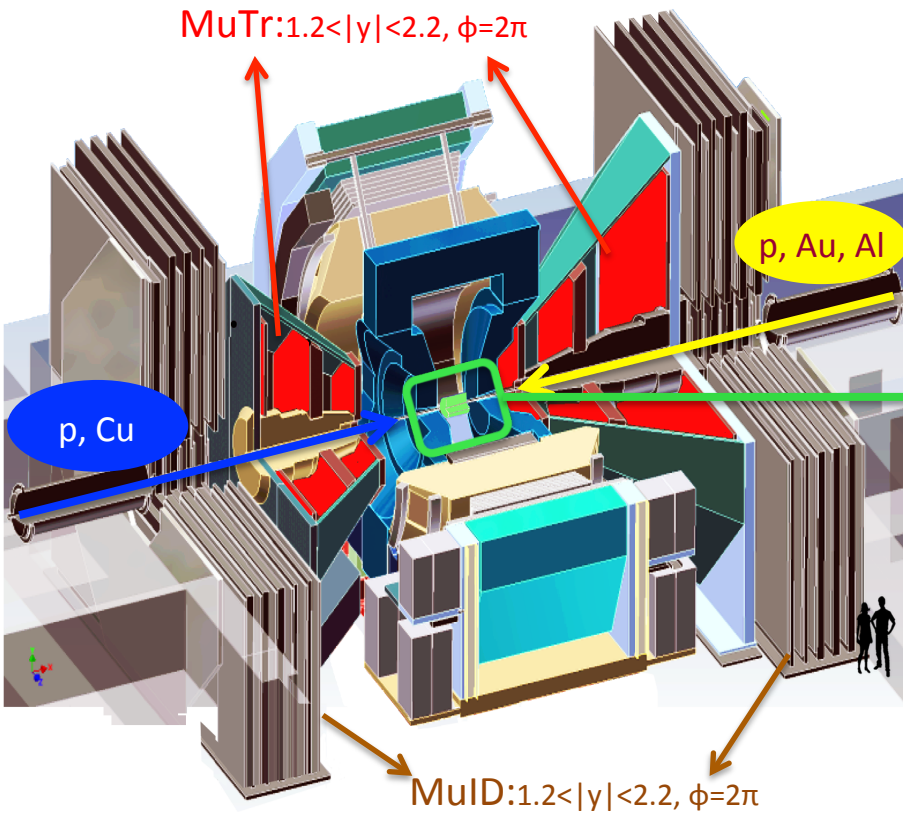
- $1.2 < |\eta| < 2.2$
- $\Delta\varphi = 2\pi$
- ~ 10 interaction length absorber
- Tracking: wire chamber, **FVTX**
- MuID: muon identification detector

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 $\phi \approx 2\pi$ coverage.
- provide precise vertex and tracking measurements for $D, B \rightarrow X + e$.



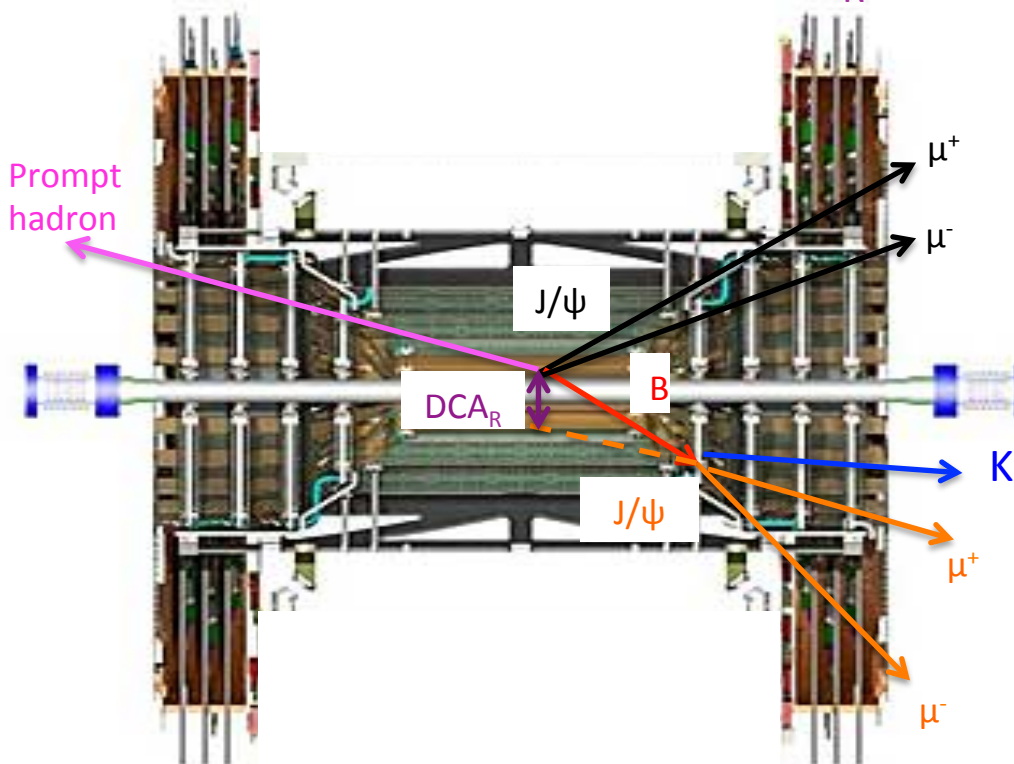
- FVTX:**

- With $1.2 < |y| < 2.2$ and $\phi = 2\pi$ coverage.
- provide precise tracking and DCA measurements for $B \rightarrow J/\psi$ and D, B separation.

Can we measure B meson at forward rapidity?

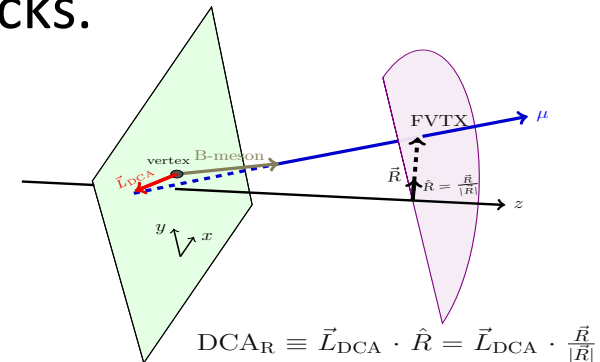
$$B \rightarrow J/\psi \rightarrow \mu^+ \mu^-$$

- **B hadron** decay length ($c\tau$), about the size of hair diameter:
 - $c\tau(B^0)=455\mu\text{m}$, $c\tau(B^\pm)=491\mu\text{m}$.
- **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.



SHARU RE JETS and HP 2017

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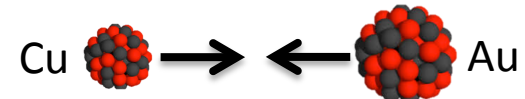
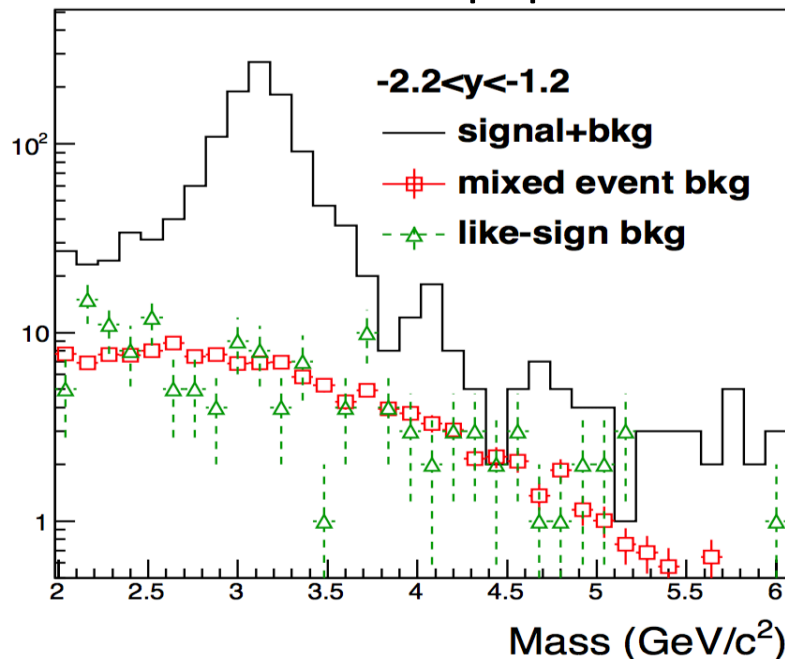
- Different shapes of DCA_R of **prompt particles** and **decayed particles** make the separation of **B decayed J/psi** and prompt J/psi feasible.

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

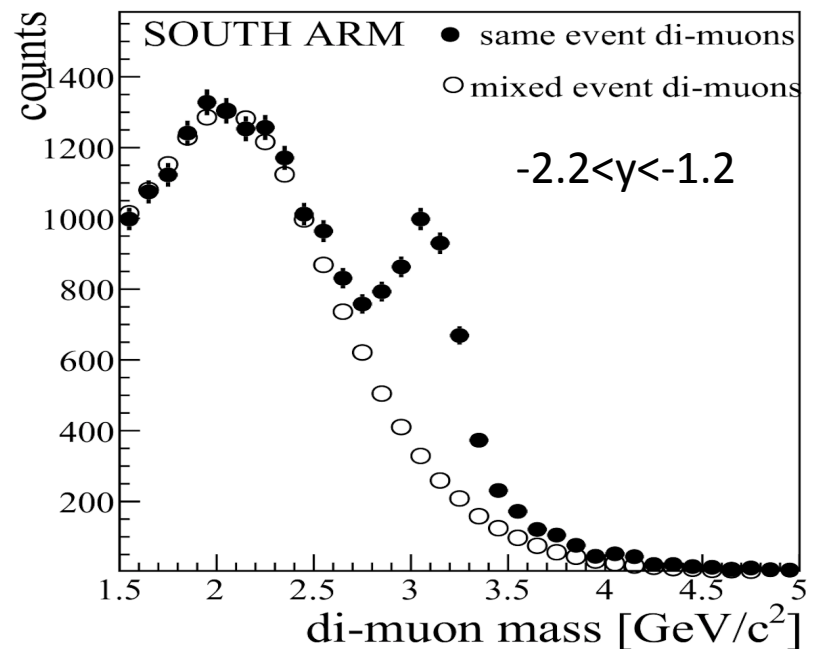
- In p+p and heavy ion (eg. Cu+Au) collisions:
 - 1) Identify the J/ψ candidates from di-muon mass spectrum after applying quality cuts.



2012 510 GeV p+p data



2012 200 GeV Cu+Au data



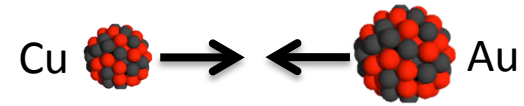
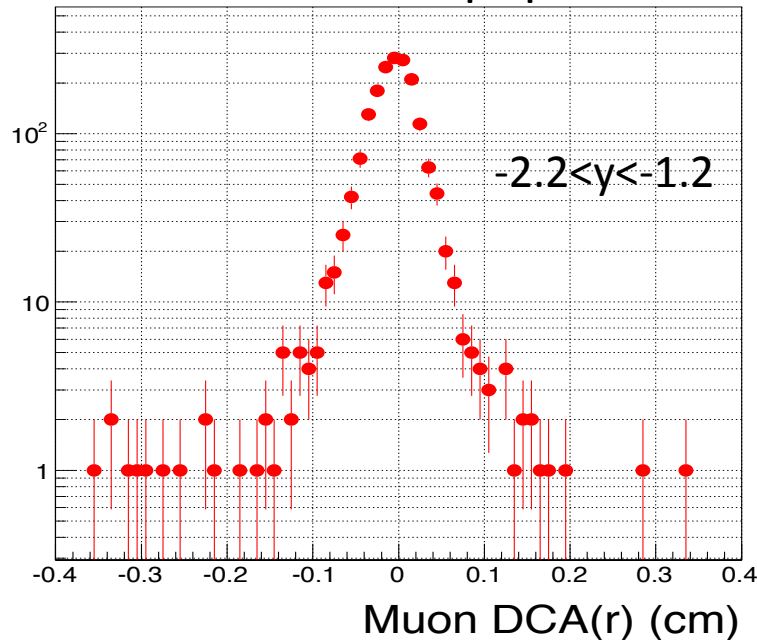
- Clear J/ψ peaks are found in both p+p and Cu+Au data.

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

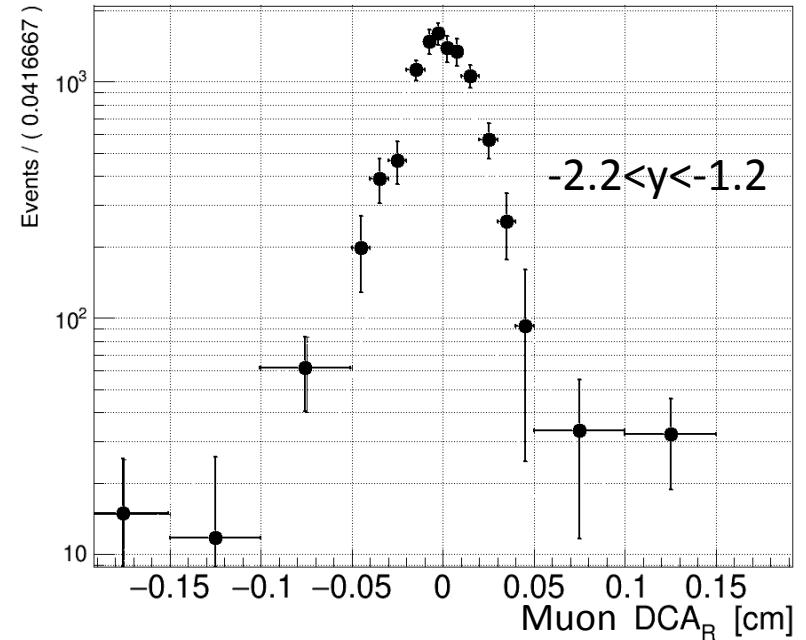
- In p+p and heavy ion (eg. Cu+Au) collisions:
 - 2) After select good J/ψ s, require the muon track of di-muon pairs matching to the FVTX and measure the DCA_R .



2012 510 GeV p+p data



2012 200 GeV Cu+Au data

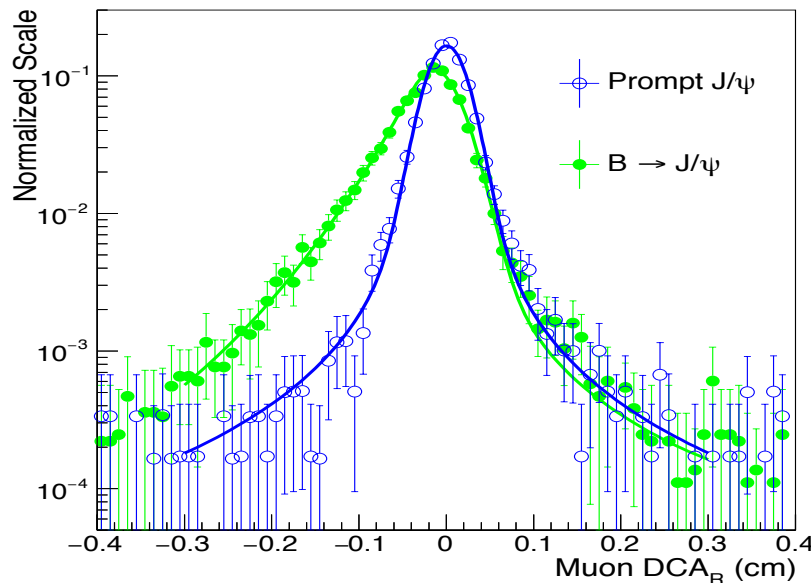


- Hints of asymmetric in muon DCA_R shapes.

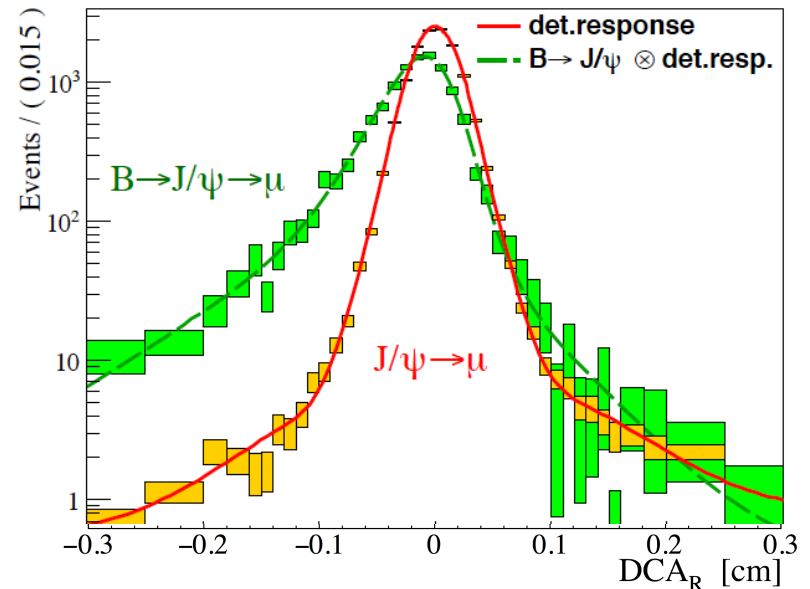
How to determine the J/ψ from B-meson decay?

- 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

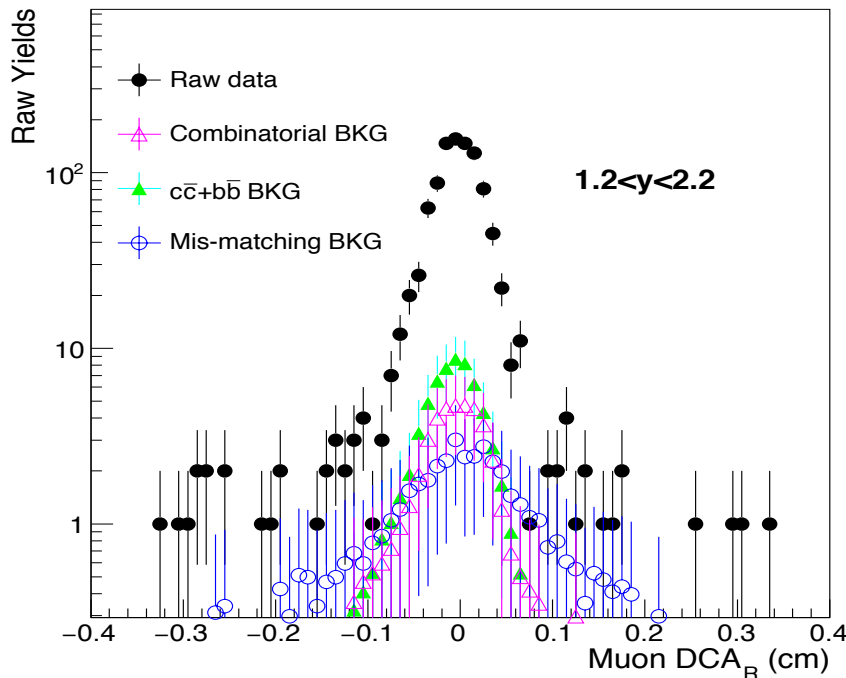


- Obvious muon DCA_R shape difference between **prompt J/ψ** and **B to J/ψ** .

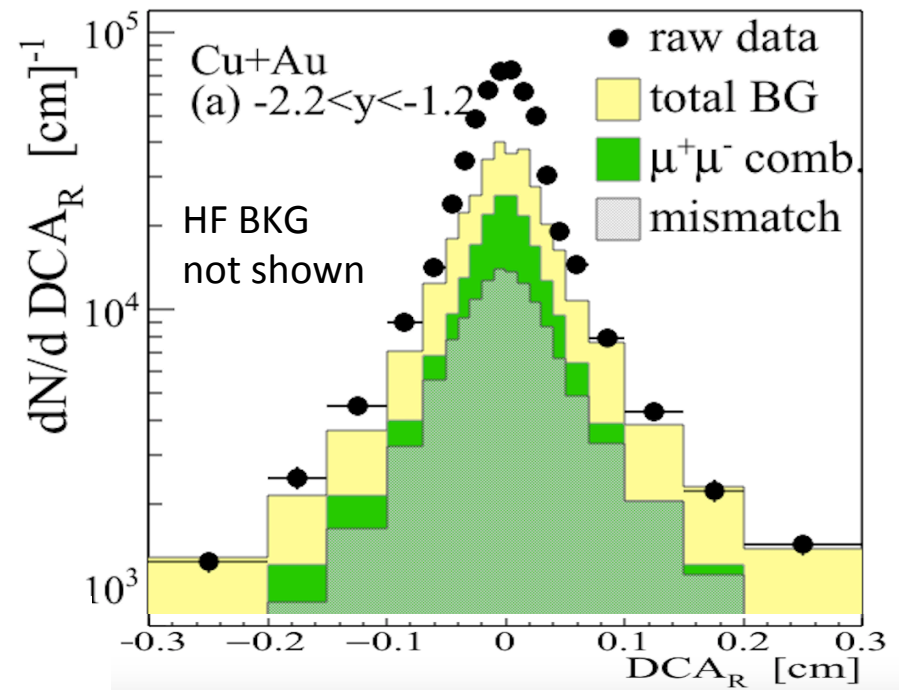
How to determine the J/ψ from B-meson decay?

- 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



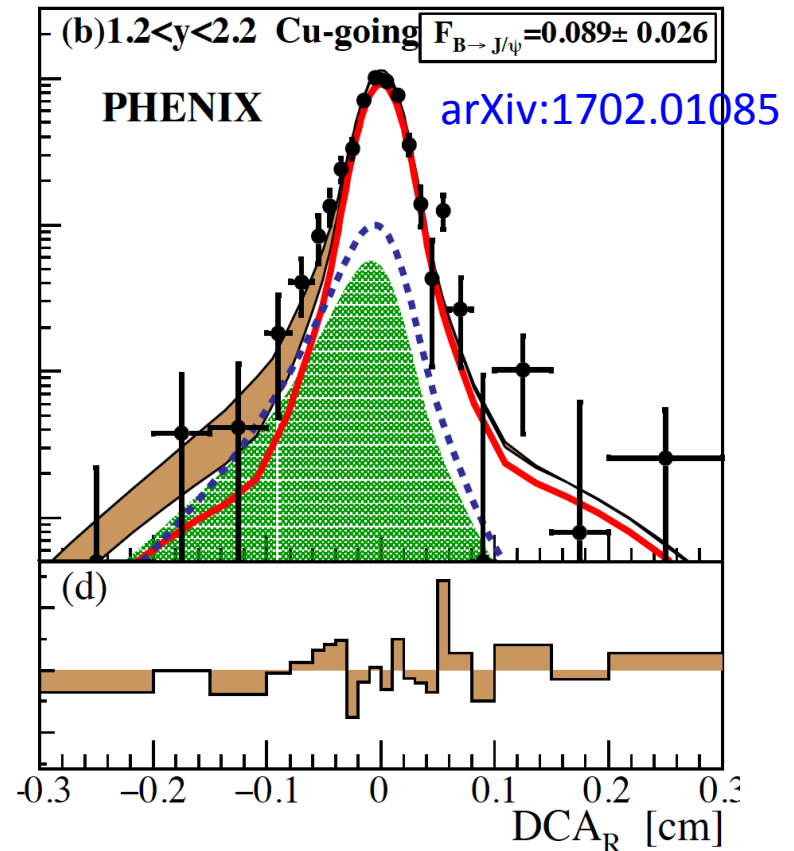
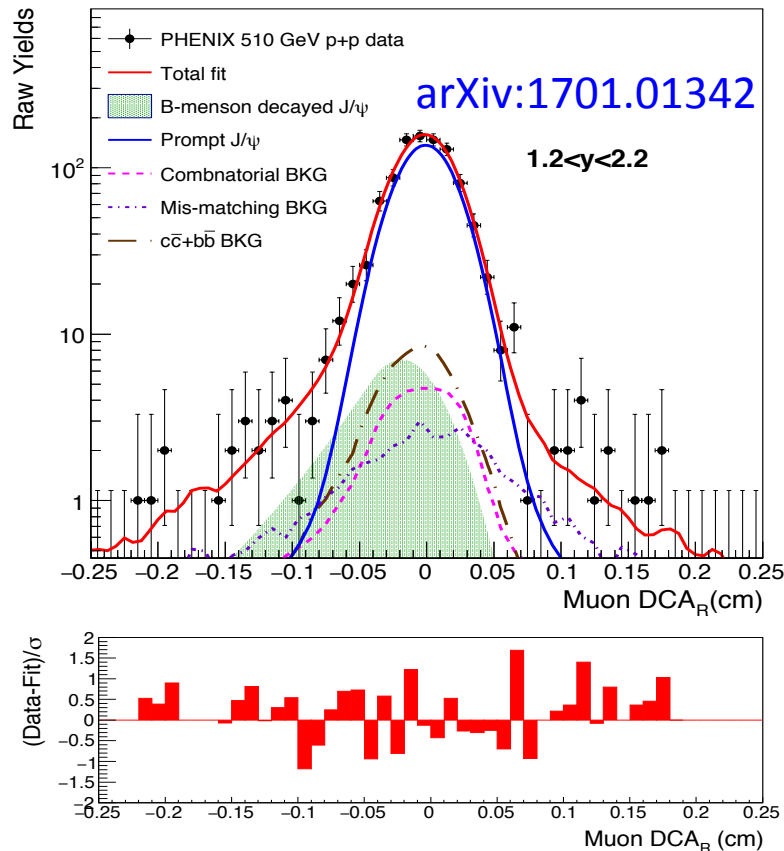
2012 200 GeV Cu+Au collisions



- Backgrounds are well determined.

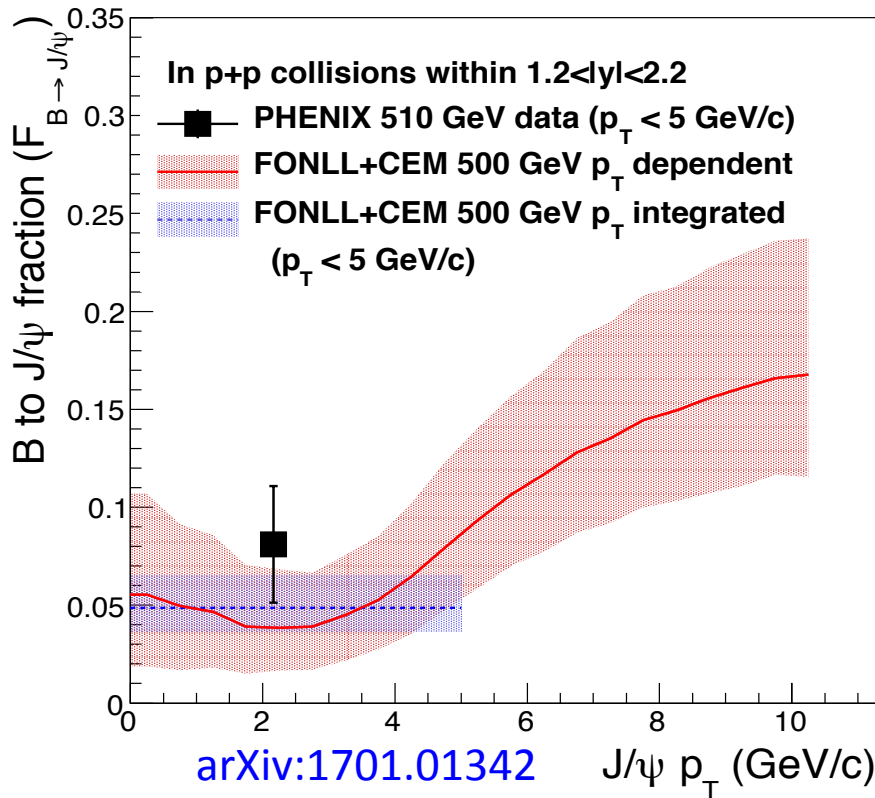
How to determine the J/ψ from B-meson decay?

- 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.



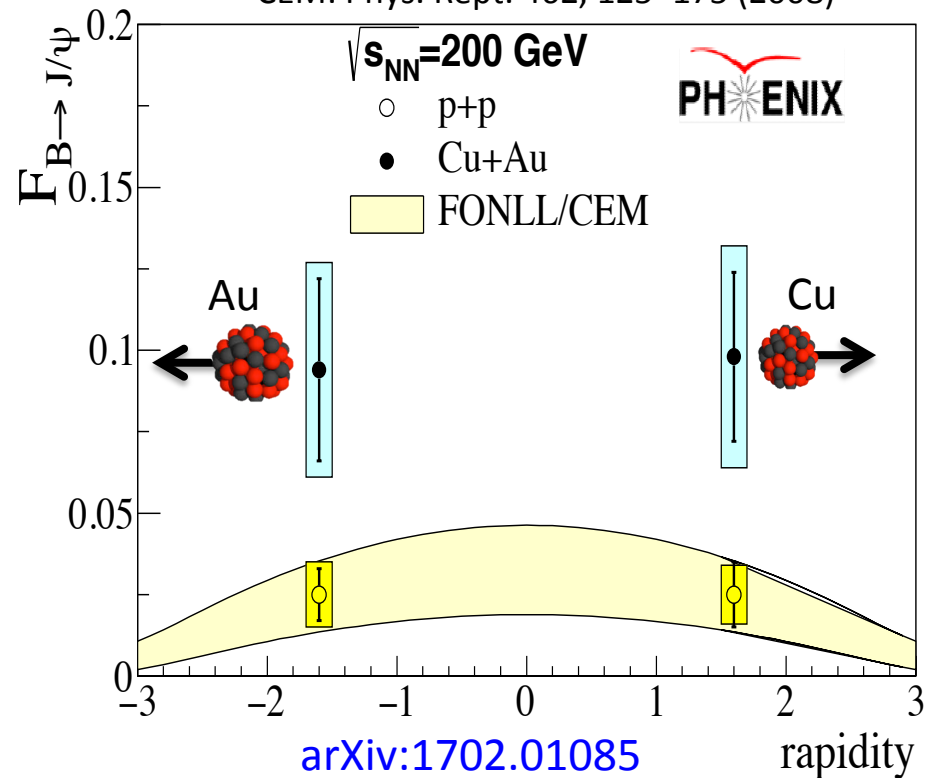
B \rightarrow J/ ψ fraction in p+p and Cu+Au collisions

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



FONLL: JHEP 05, 007 (1998)

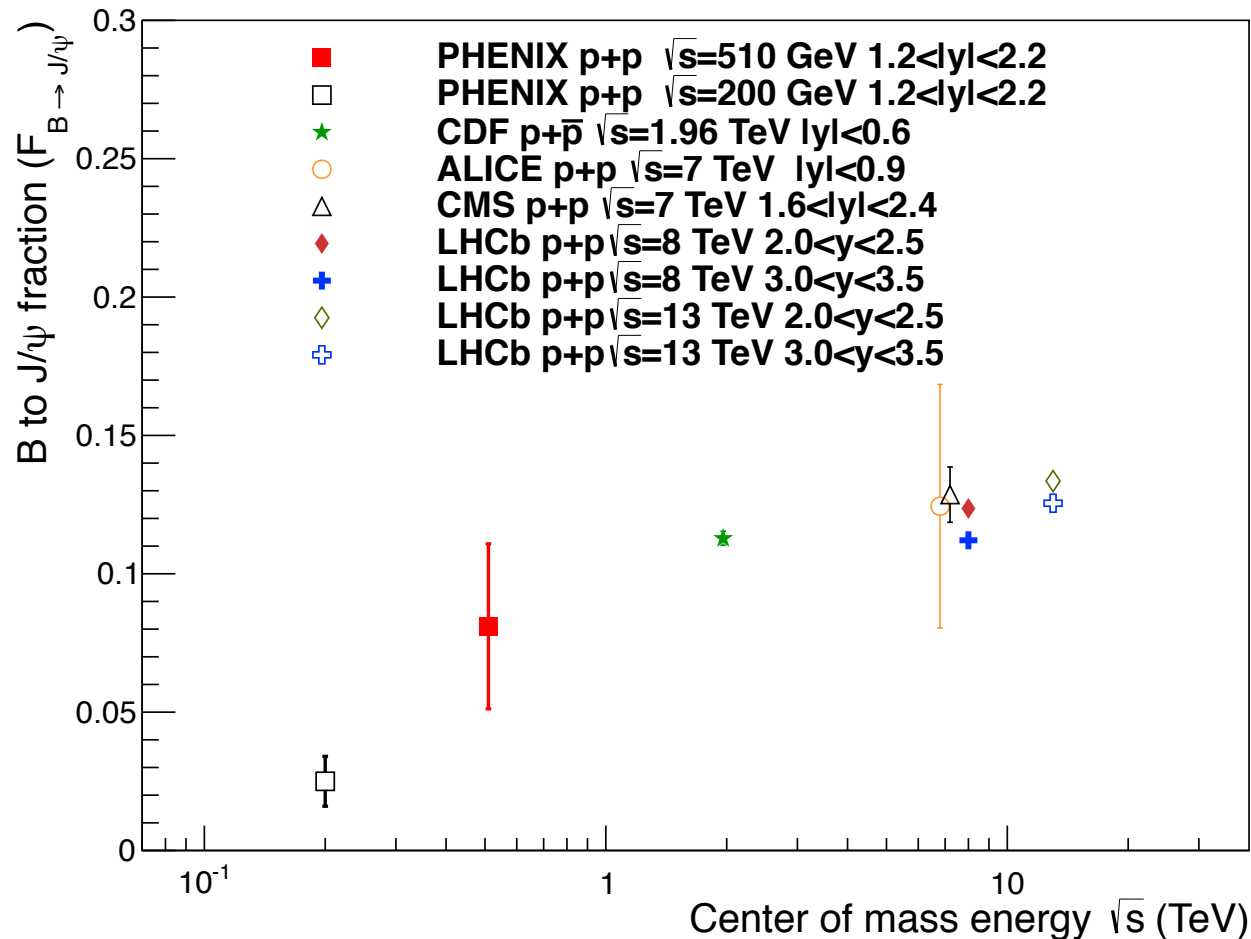
CEM: Phys. Rept. 462, 125–175 (2008)



- The forward B \rightarrow 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 $B \rightarrow J/\psi$ fraction

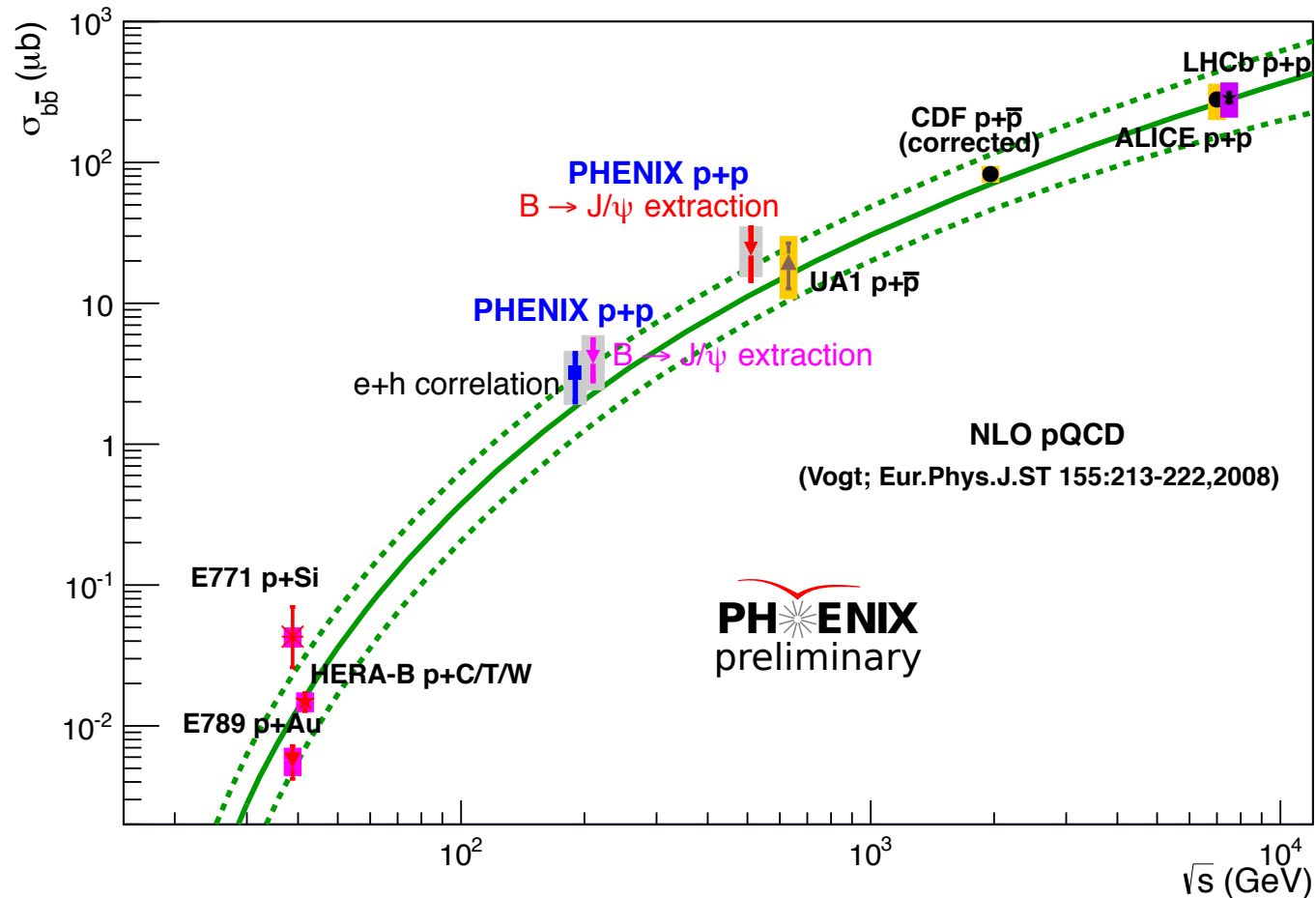
- A smooth energy dependence is found from 0.2 to 13 TeV p+p (p+pbar) collisions for $B \rightarrow J/\psi$ fraction measured with integrated J/ψ p_T .



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 $B \rightarrow J/\psi$ fractions measured in 200 and 510 GeV p+p collisions are in reasonable agreements with the NLO pQCD predictions.



$B \rightarrow J/\psi$ fraction in Cu+Au collisions

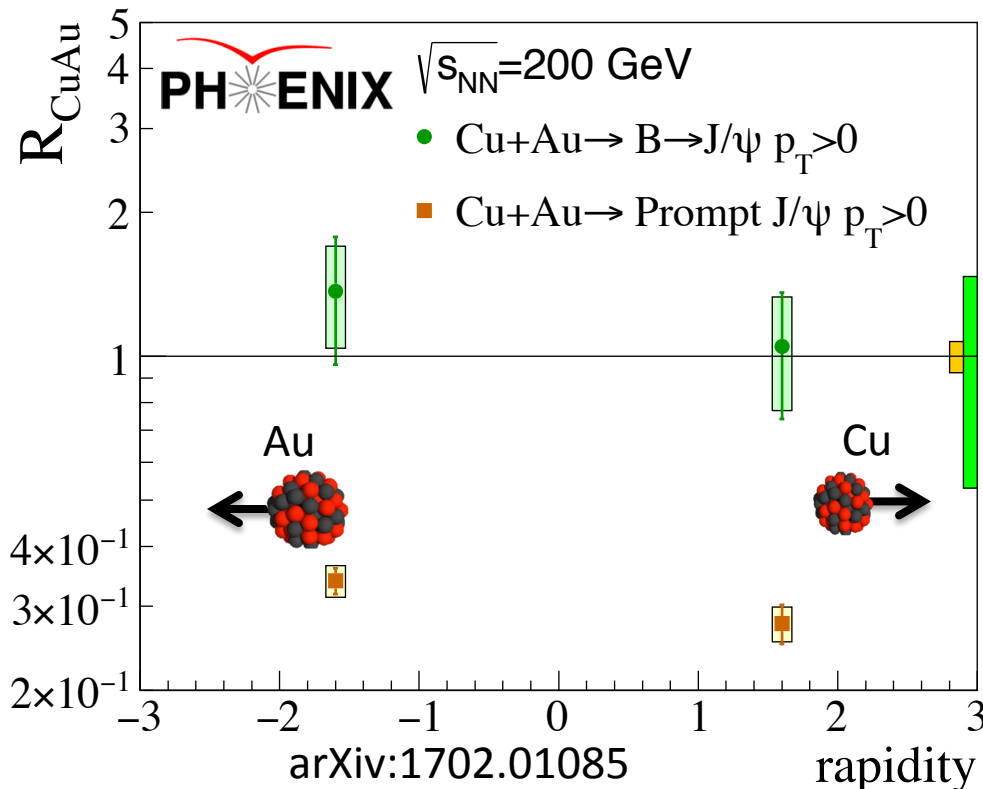
- The nuclear modification factor R_{CuAu} can be derived from the $B \rightarrow J/\psi$ fractions in p+p and Cu+Au collisions and the inclusive J/ψ R_{CuAu} according to this formula:

$$R_{\text{CuAu}}^{B \rightarrow J/\psi} = \frac{F_{B \rightarrow J/\psi}^{\text{CuAu}}}{F_{B \rightarrow J/\psi}^{\text{pp}}} R_{\text{CuAu}}^{\text{inc. } J/\psi}$$

B→J/ψ fraction in Cu+Au collisions

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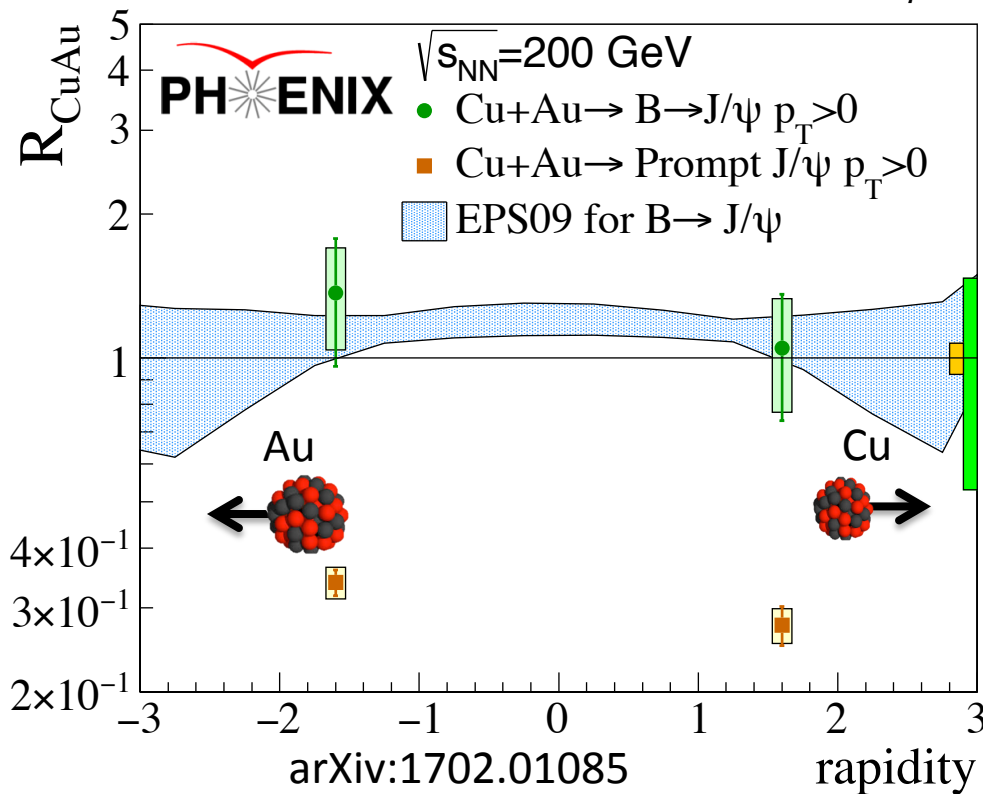


- No significant modifications on the B→J/ψ R_{CuAu} which suggests a small initial state modification.
- Significant modifications on the prompt J/ψ R_{CuAu} which indicates prompt J/ψ breaks up in final states.

B → J/ψ fraction in Cu+Au collisions

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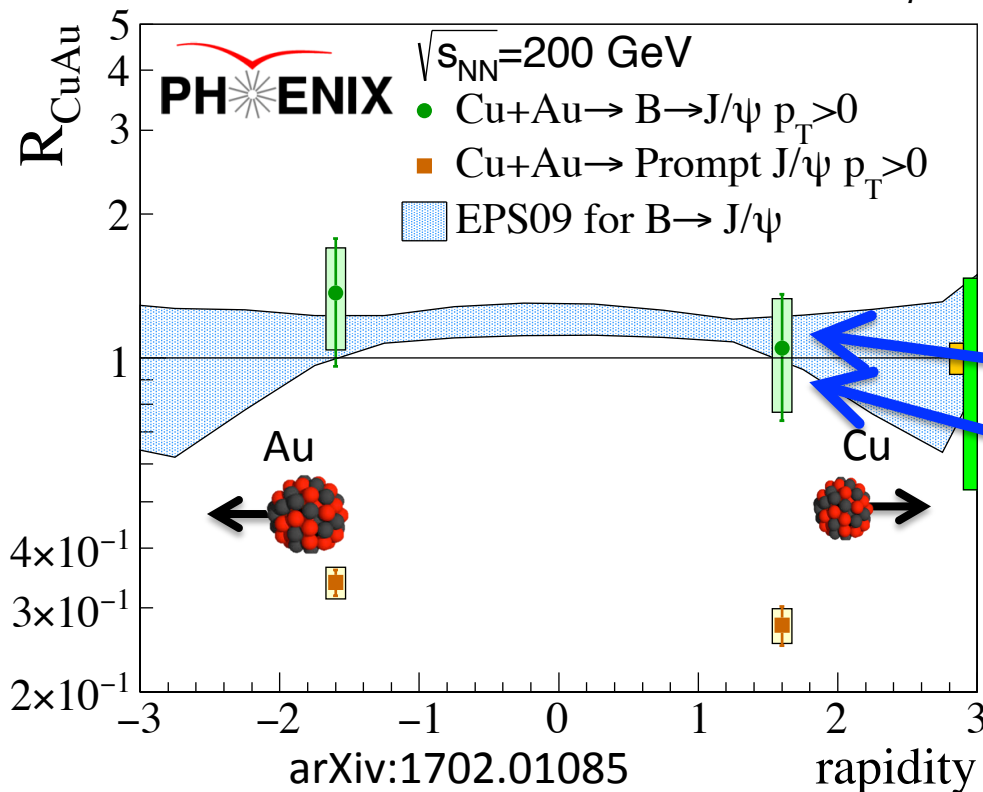


- B → J/ψ R_{CuAu} is consistent with expectations from nPDF modifications in initial states (EPS09).

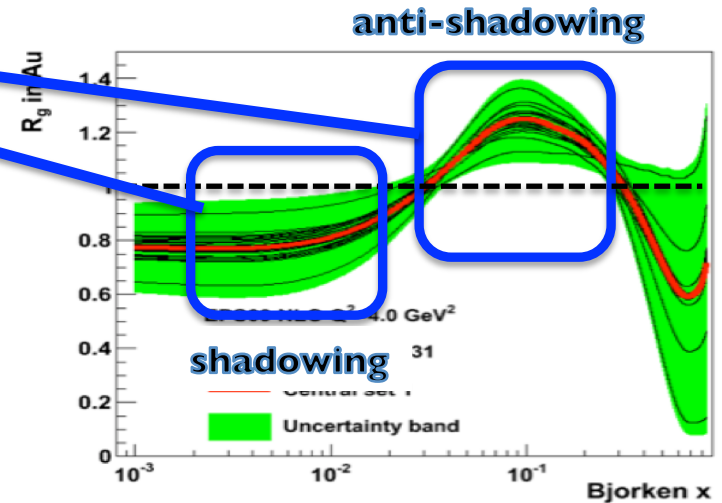
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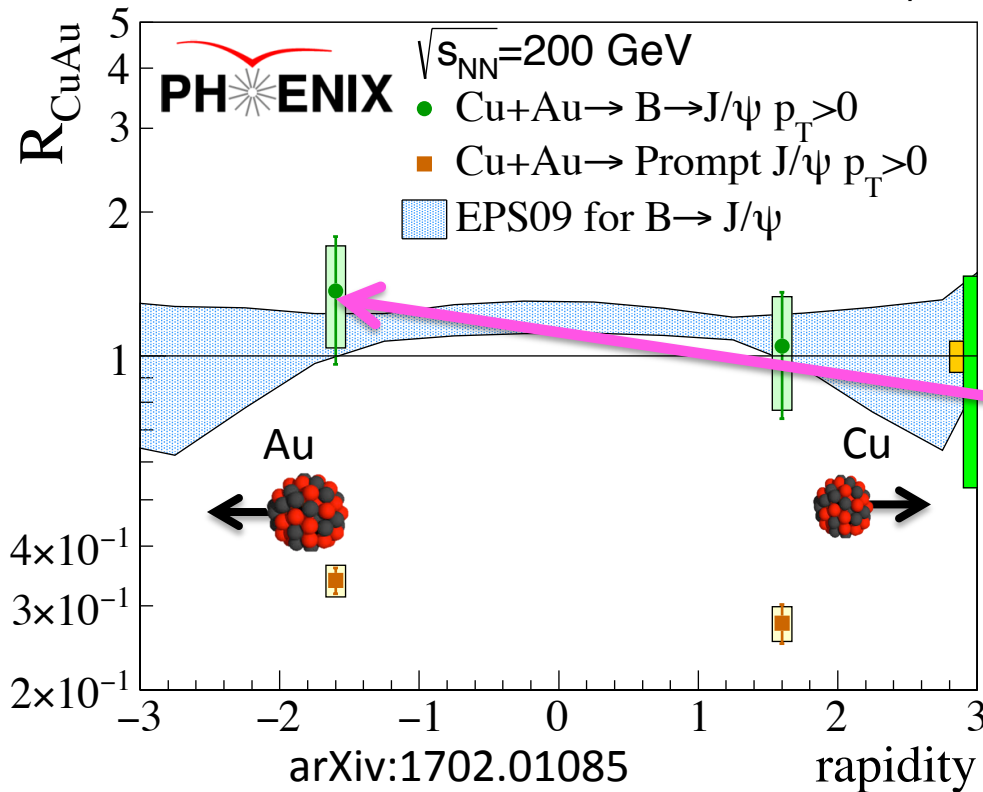
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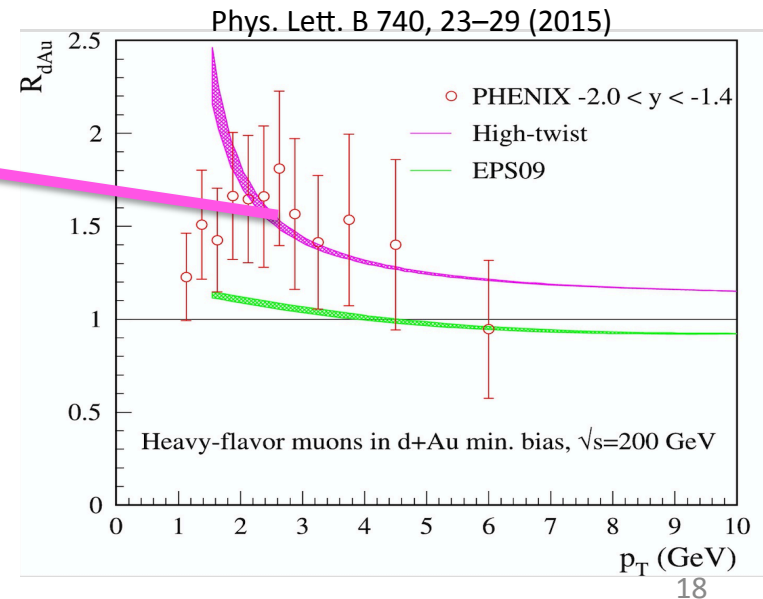
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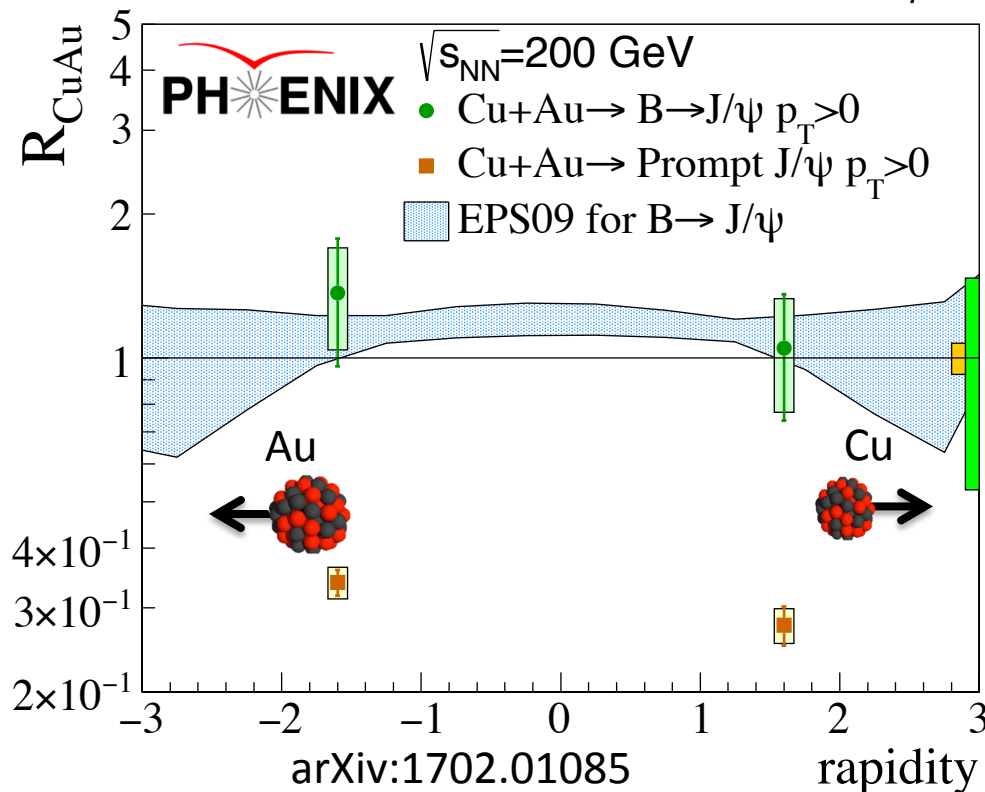
- Backward enhancement
Incoherent multiple scattering?



B → J/ψ fraction in Cu+Au collisions

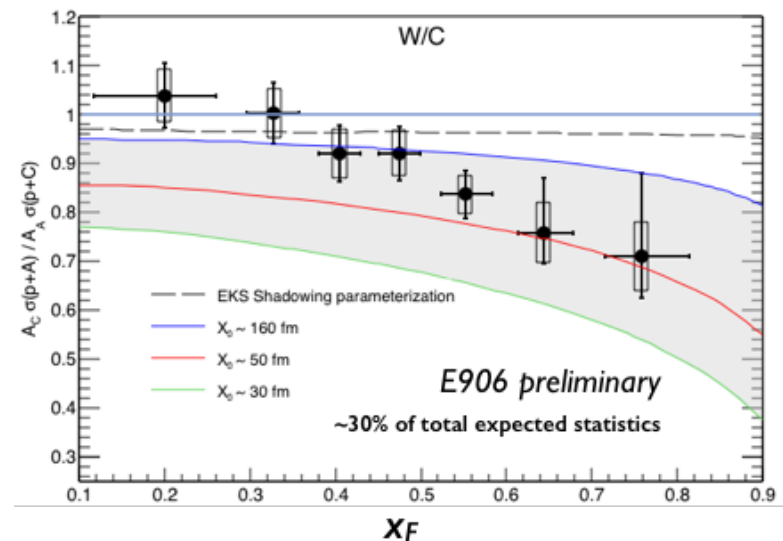
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- Initial state parton energy loss?

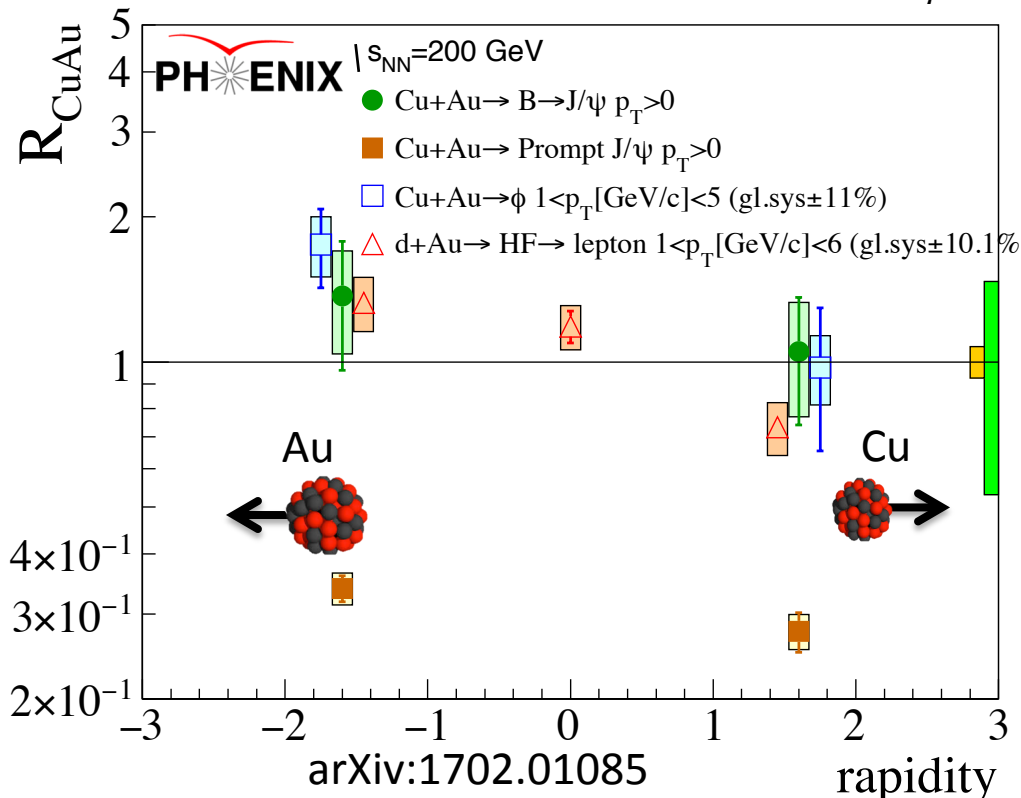
Clear initial state E_{loss} observed at E906



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:

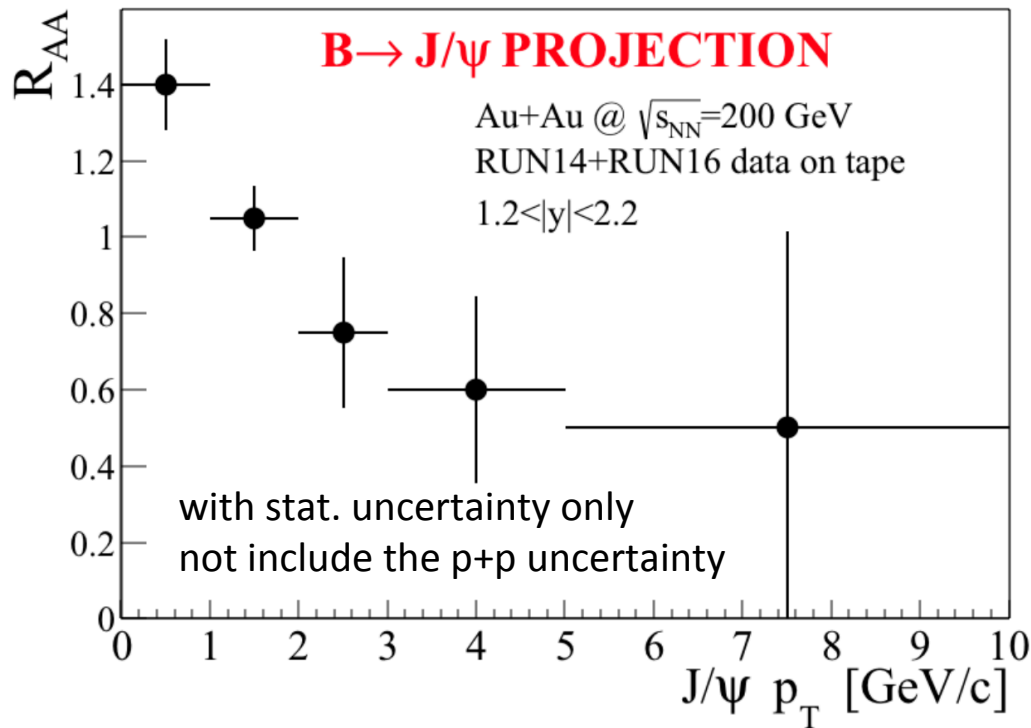
$$R_{\text{CuAu}}^{B \rightarrow J/\psi} = \frac{F_{B \rightarrow J/\psi}^{\text{CuAu}}}{F_{B \rightarrow J/\psi}^{\text{pp}}} R_{\text{CuAu}}^{\text{inc. J}/\psi}$$



- Similar trends have 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.

$B \rightarrow J/\psi$ fraction in Au+Au collisions

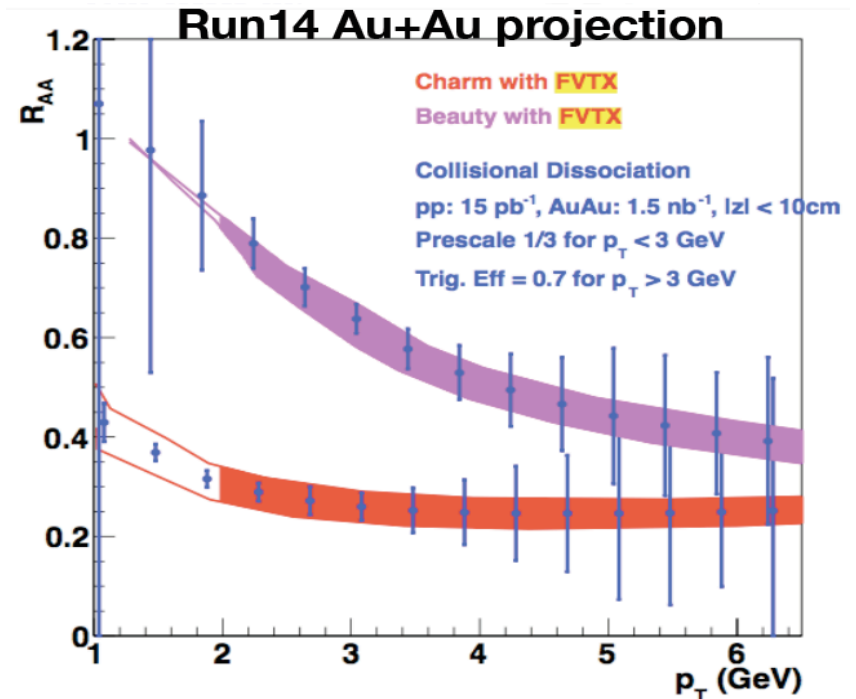
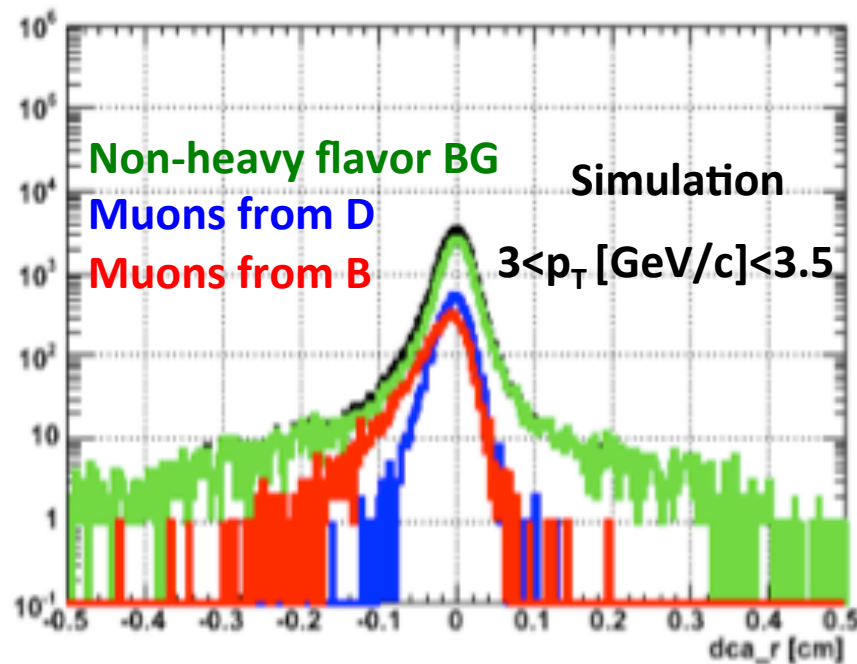
- Similarly, the nuclear modification factor R_{AuAu} can be derived from the $B \rightarrow J/\psi$ fractions in p+p and Au+Au collisions.
- The Au+Au data production in RHIC 2014+2016 is ongoing.



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

Charm and Bottom decayed inclusive single muons

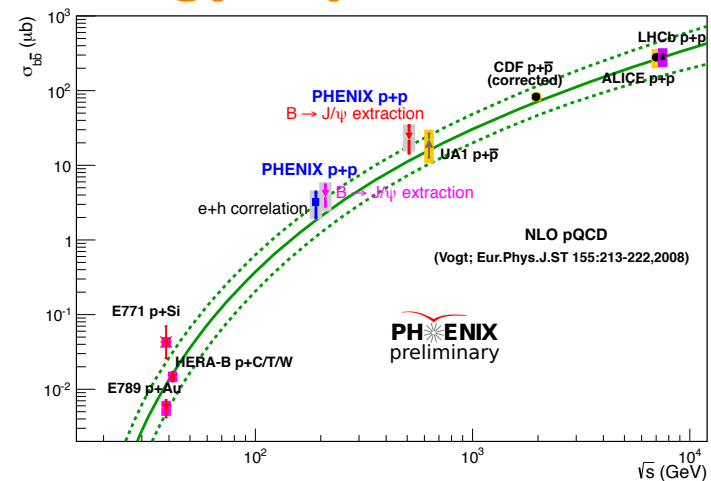
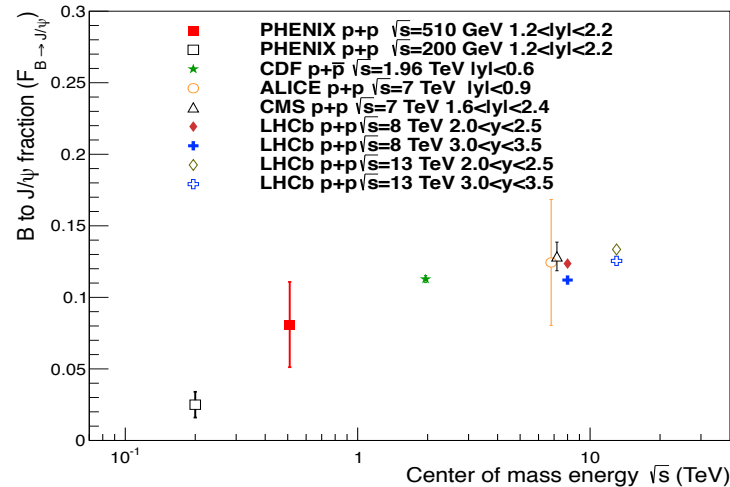
- High statistics measurement with similar method developed in the B to J/ψ analysis.
- Extend to high p_T region to determine the p_T dependence for **charm** and **bottom** production.
- Analysis is underway.
- The challenge is to minimize systematics.



Summary

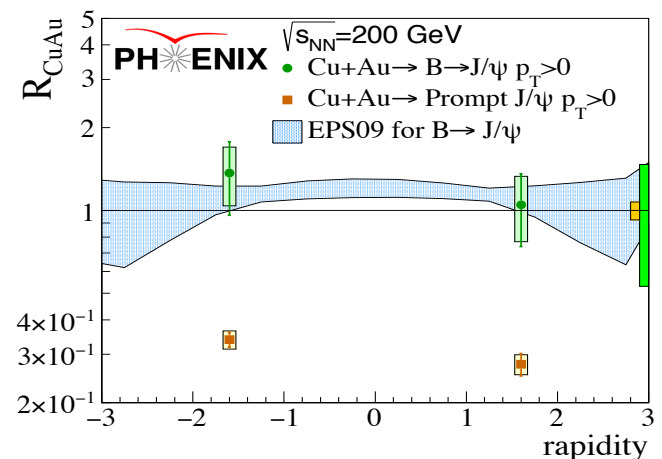
- $B \rightarrow J/\psi$ production (arXiv:1701.01342,1702.01085):

A smooth center of mass energy dependence



- First measured $B \rightarrow J/\psi$ 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 $B \rightarrow J/\psi$ 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.

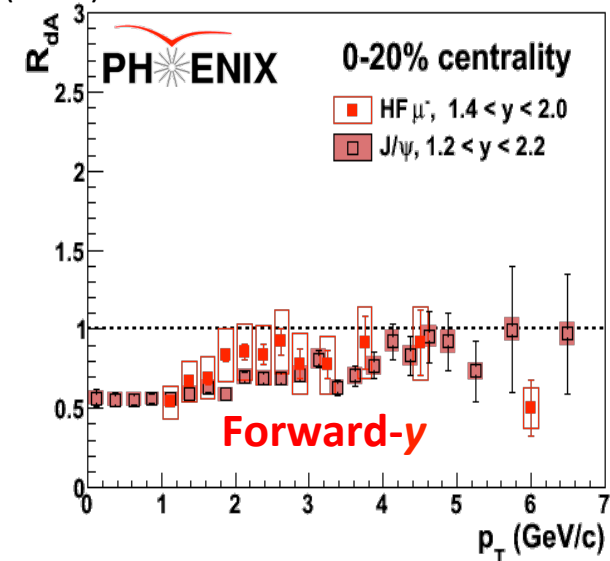
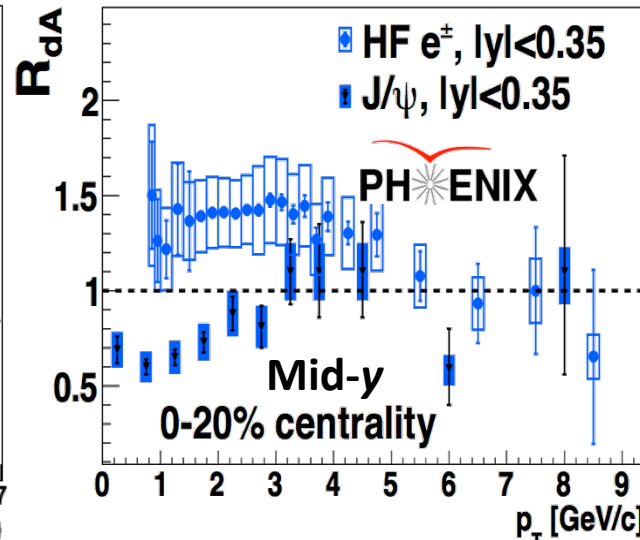
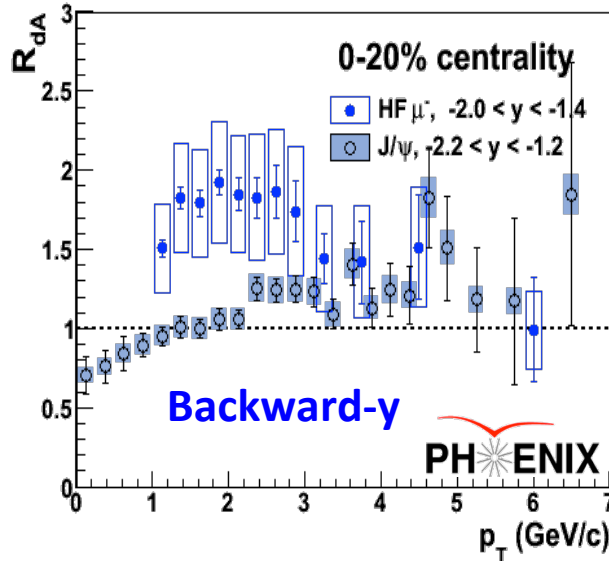
More to explore!



Backup

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

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

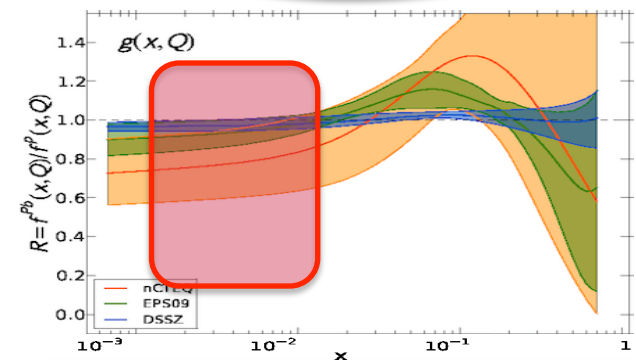


- Define nuclear modification factor:

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

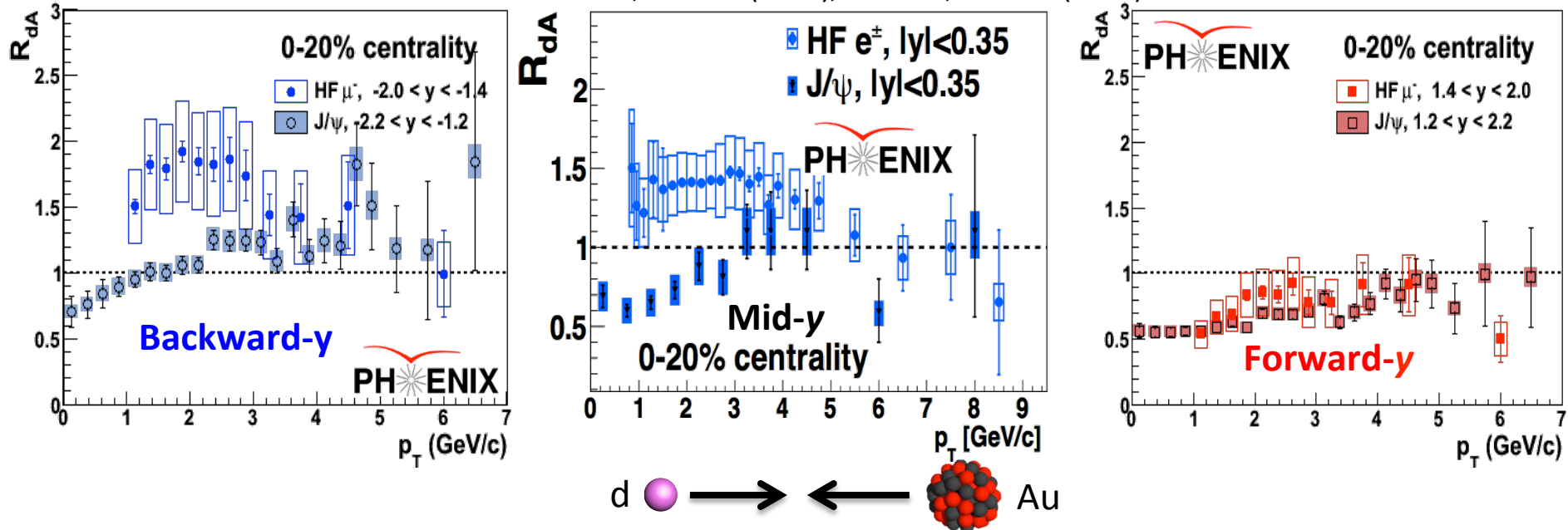
- Clear CNM effects are observed.
- Forward rapidity:** Similar suppression indicates similar initial state effects (shadowing, energy loss) for J/ ψ and open charm production.

Cold Nuclear Matter effects

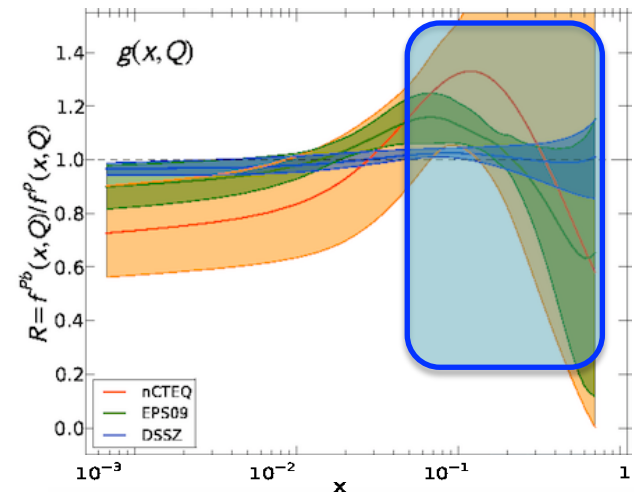


Open HF semi-leptonic decay in d+Au collisions at RHIC

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

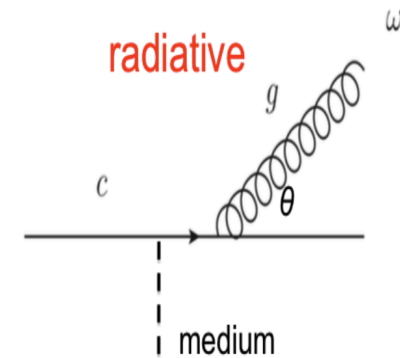
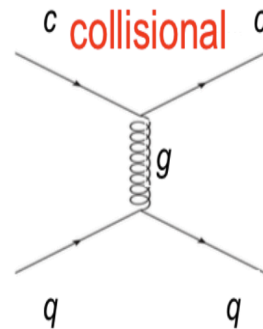
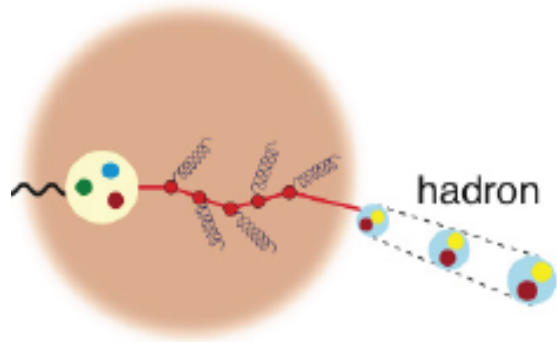


- Clear CNM effects are observed.
- Mid and **Backward rapidity**: Different trends between J/ ψ and open heavy flavor. Final-state effects like co-mover absorption can not be neglected for J/ ψ production.



Energy loss in the QGP

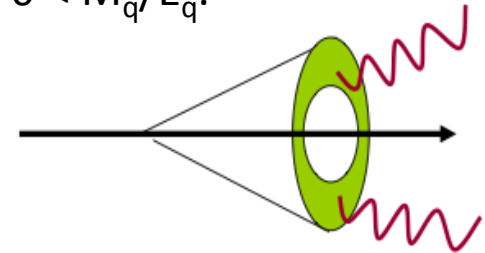
- Energy loss Mechanism:
- (I) Heavy quarks lose energy when crossing the medium (indicated by the R_{AA} suppression).



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

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

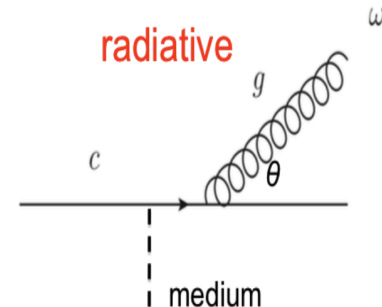
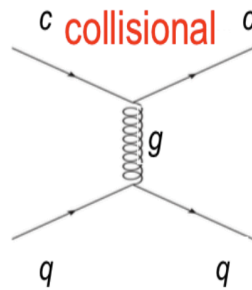
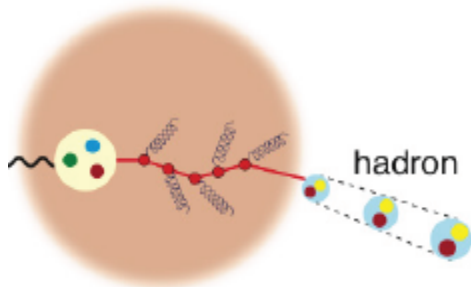
Dead cone effect: gluon radiation from massive quarks suppressed at angle $\theta < M_q/E_q$.



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.

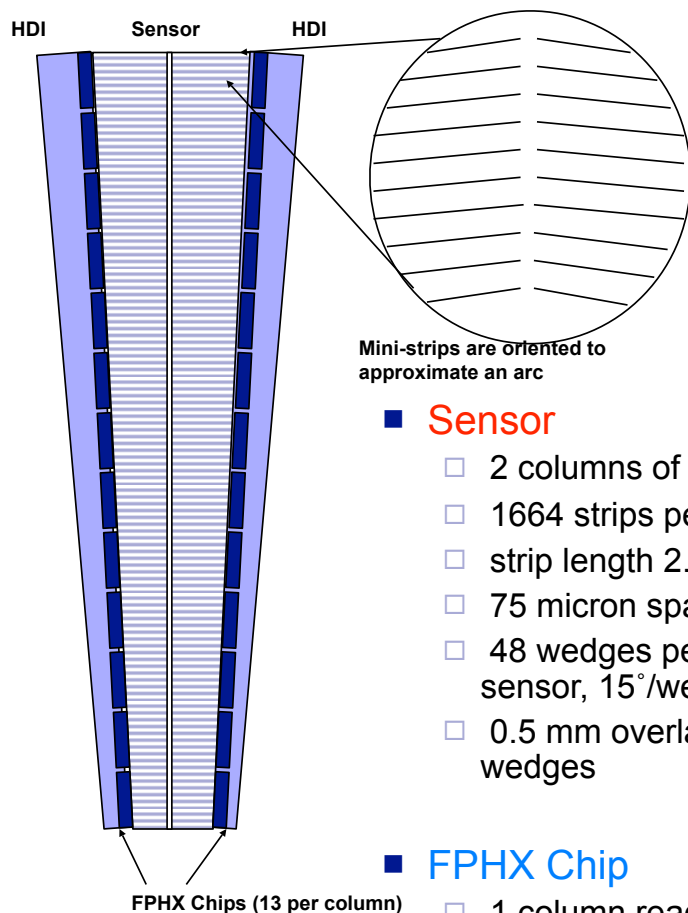
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



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)

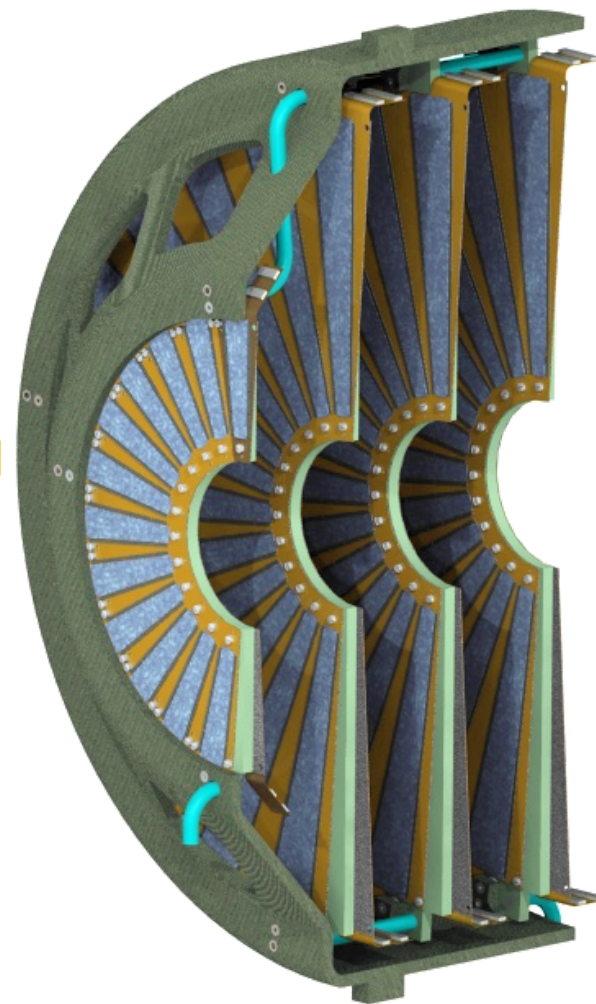


■ Sensor

- 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

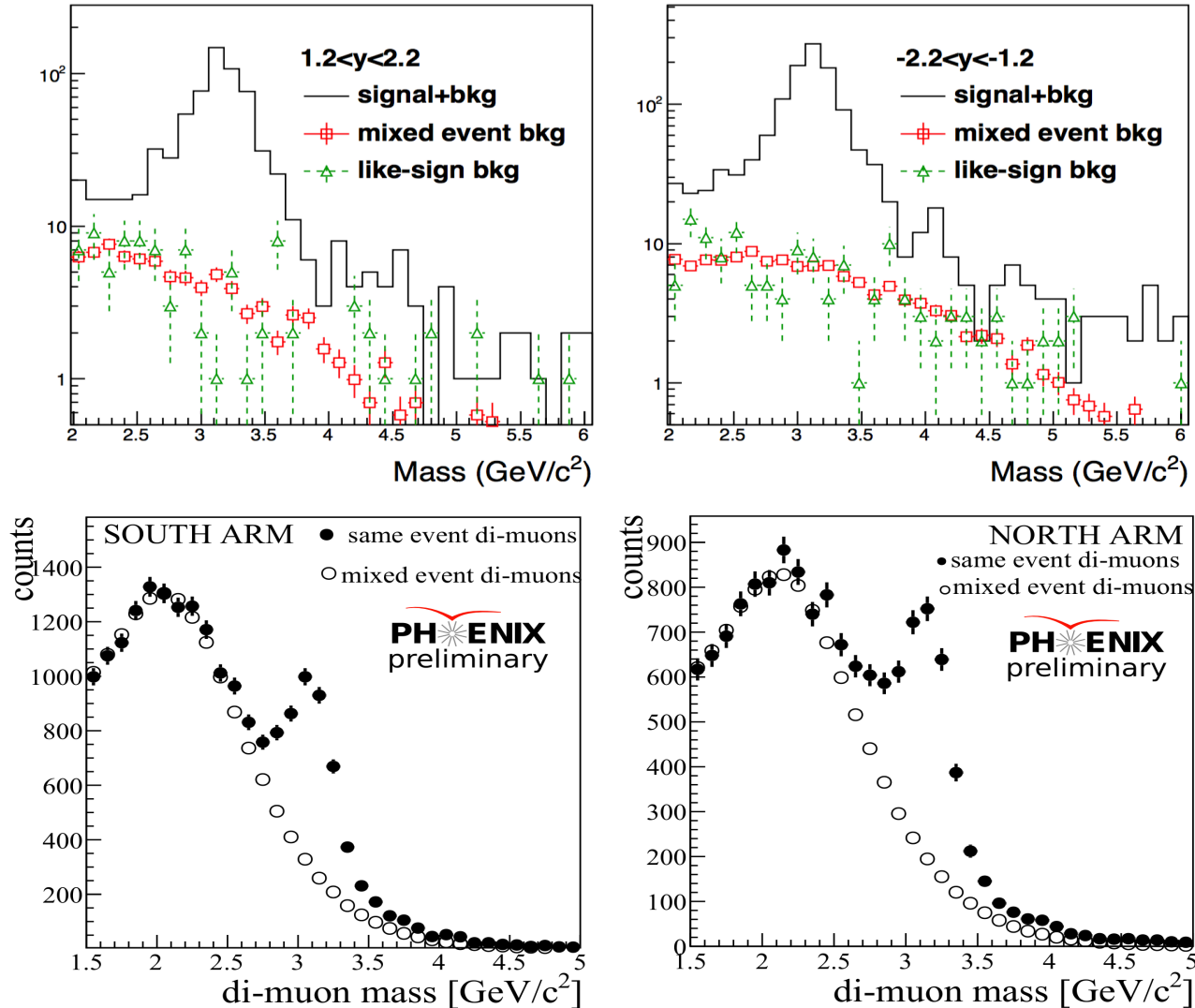
■ FPHX Chip

- 1 column readout
- 128 channels
- ~ 70 microns channel spacing
- Dimensions –9mm x 1.2 mm



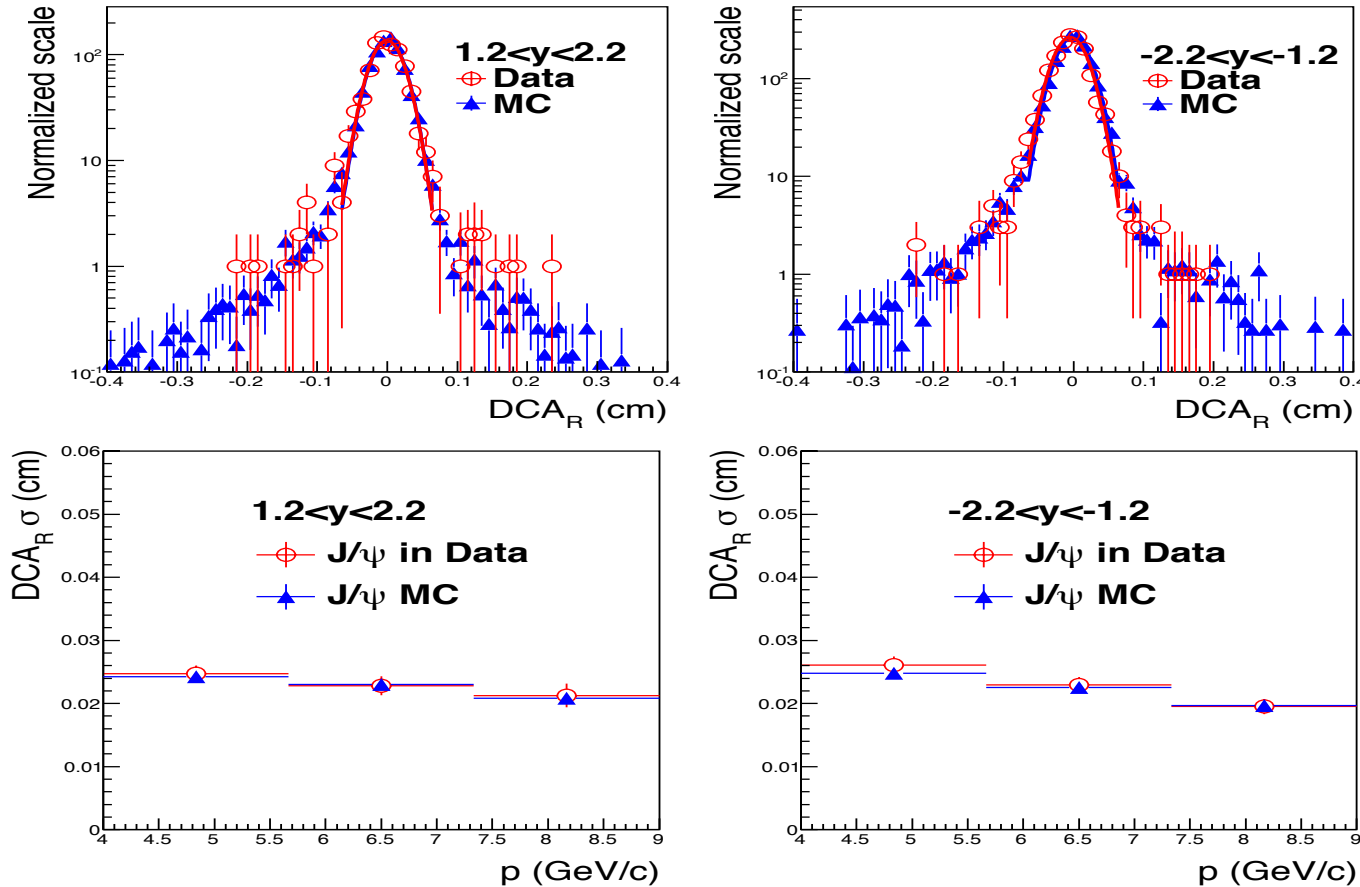
Invariant mass of di-muons

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



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

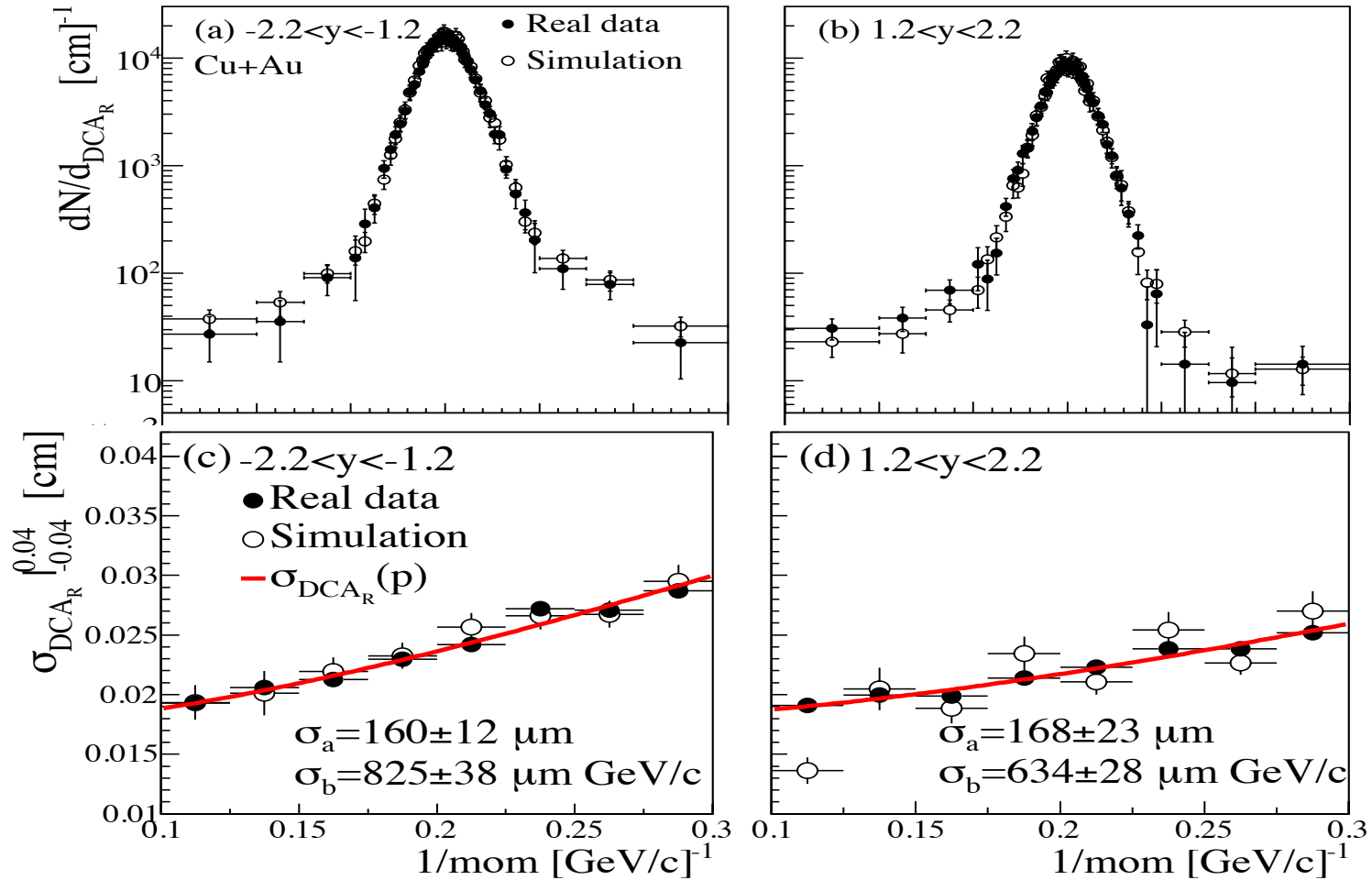
- DCA(r) of J/ ψ decayed muons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.



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

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

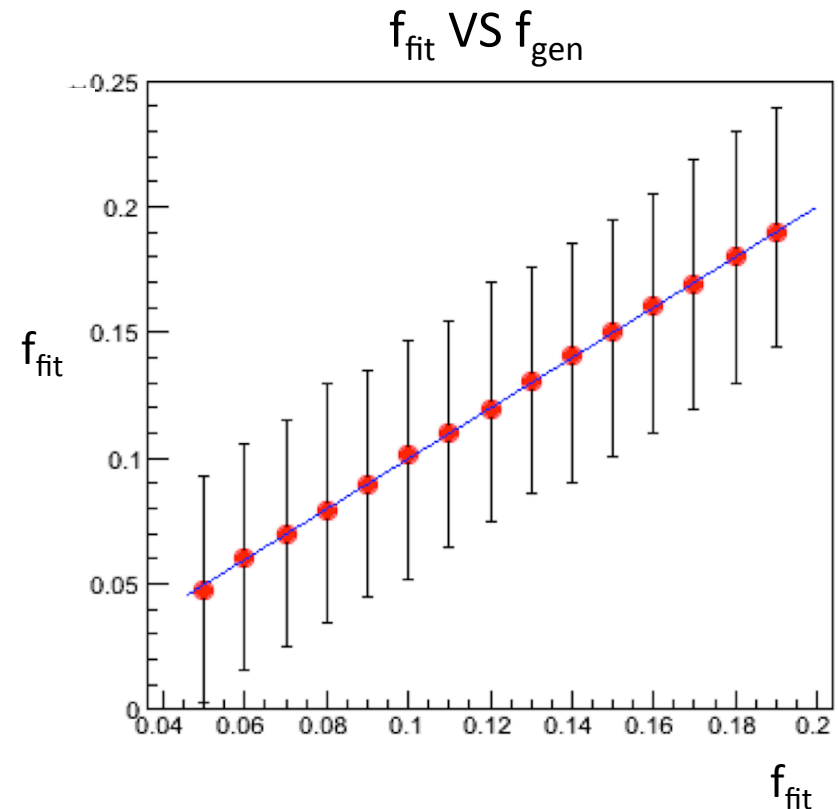
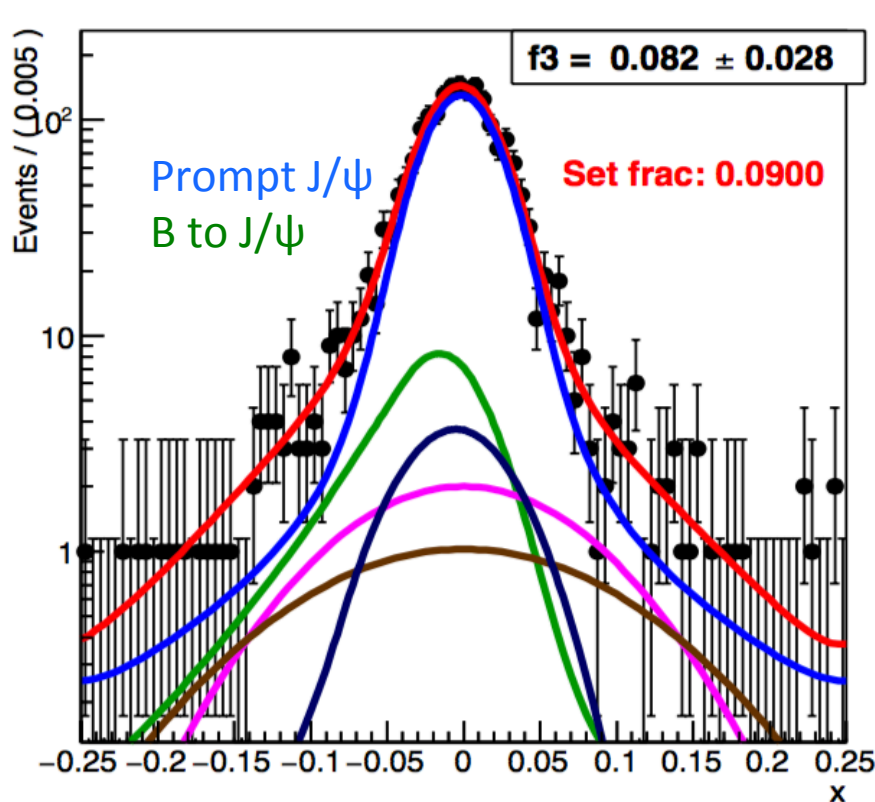
- DCA(r) of stopped hadrons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.



- 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.

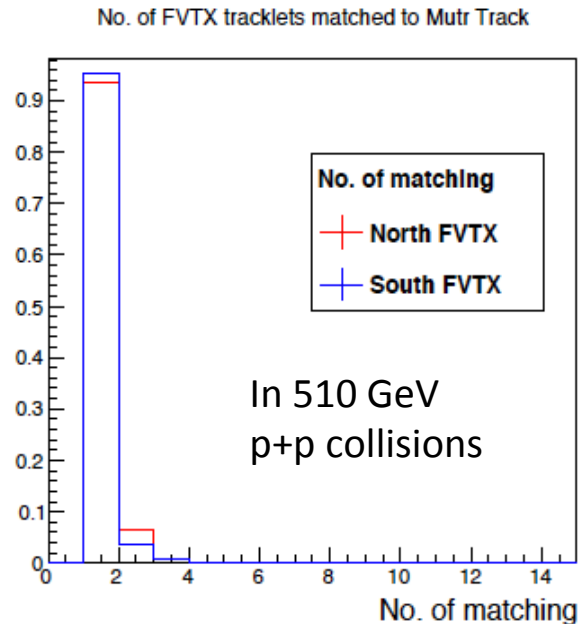
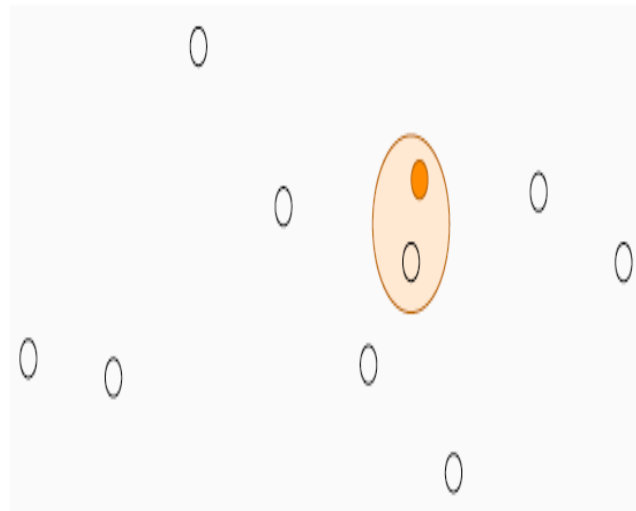


- Good linearity between generated and B to J/ψ ratio.
- Final results from data are under collaboration review.

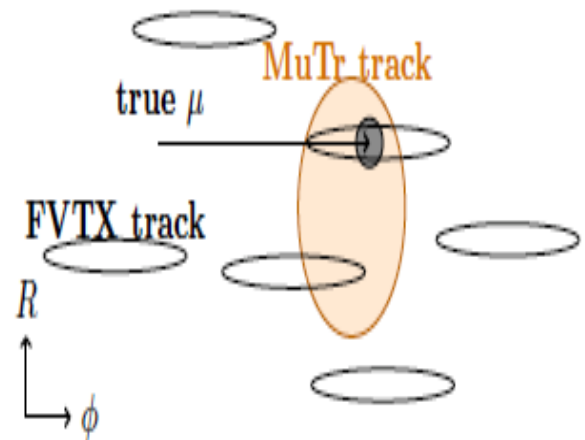
FVTX-MuTr mis-matching background determination

- 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



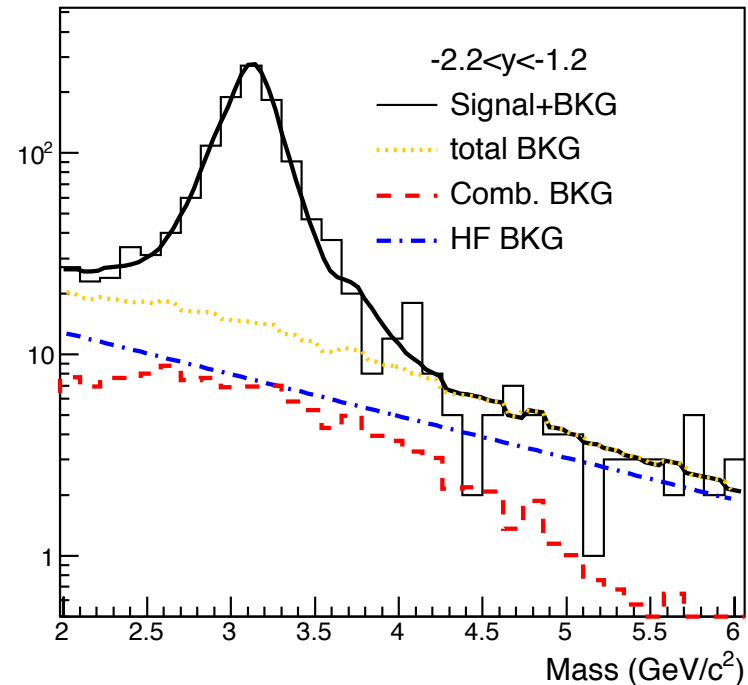
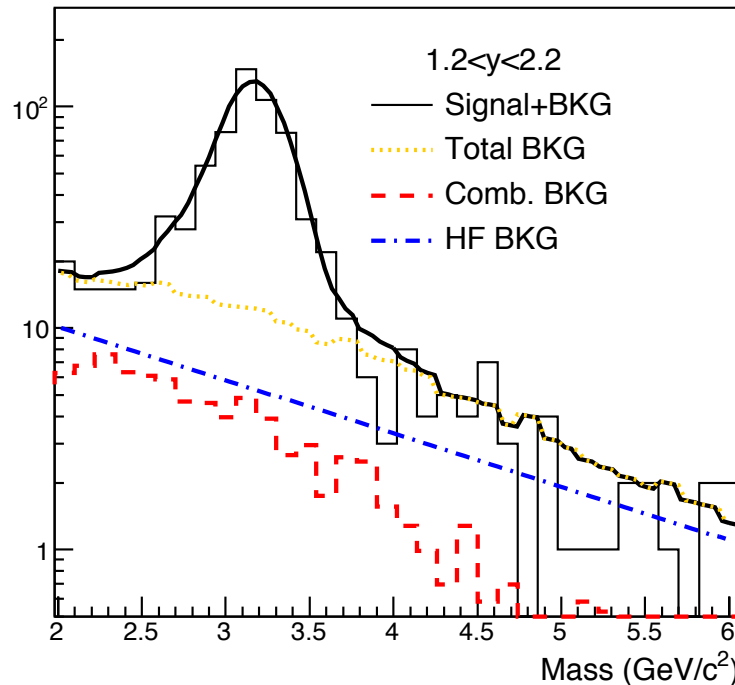
In 200 GeV Cu+Au collisions



- In p+p collisions, 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.

