Studies of B to J/ψ decay with the Forward Silicon Vertex Detector (FVTX) at PHENIX Experiment

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For the PHENIX Collaboration

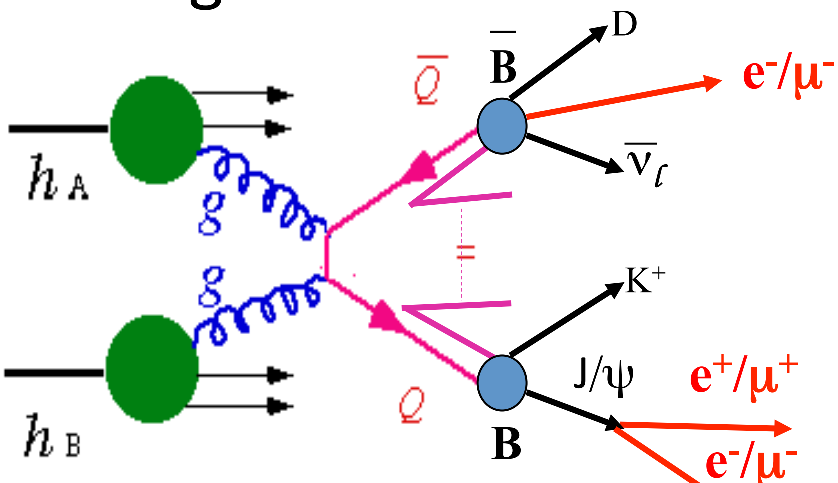
The 33rd Winter Workshop on Nuclear Dynamics

Outline

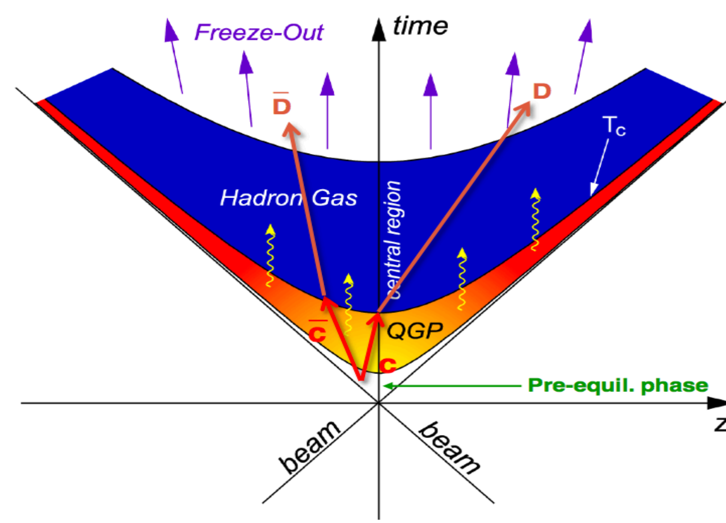
- Motivation.
- PHENIX and the Forward Silicon Vertex Detector (FVTX).
- PHENIX Forward B to J/ψ measurements
  - in 510 (arXiv:1701.01342) and 200 GeV p+p collisions to study the energy dependent B hadron production.
  - in 200 GeV Cu+Au collisions to explore heavy flavor production interaction with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

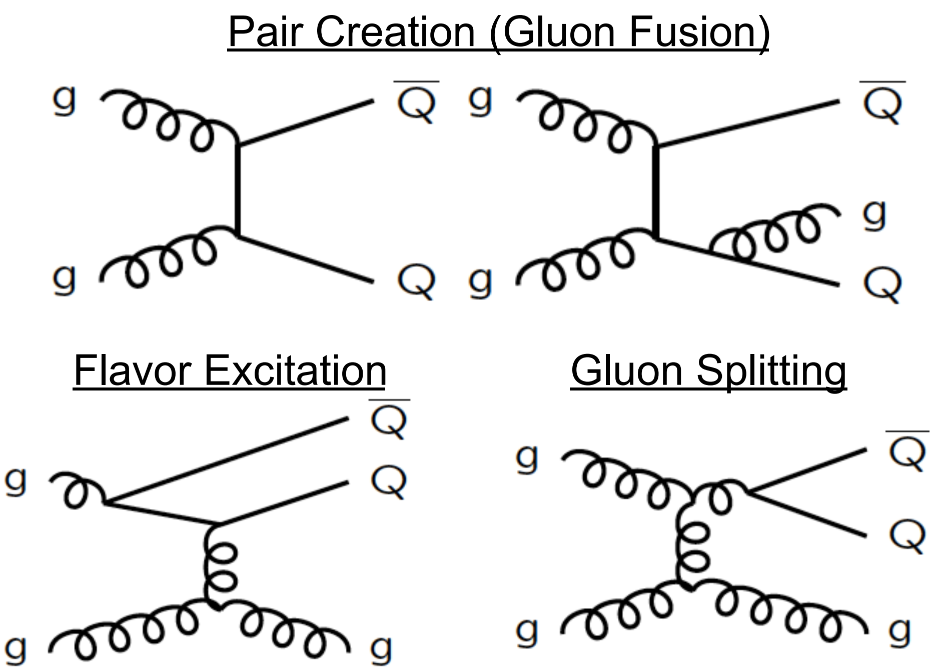


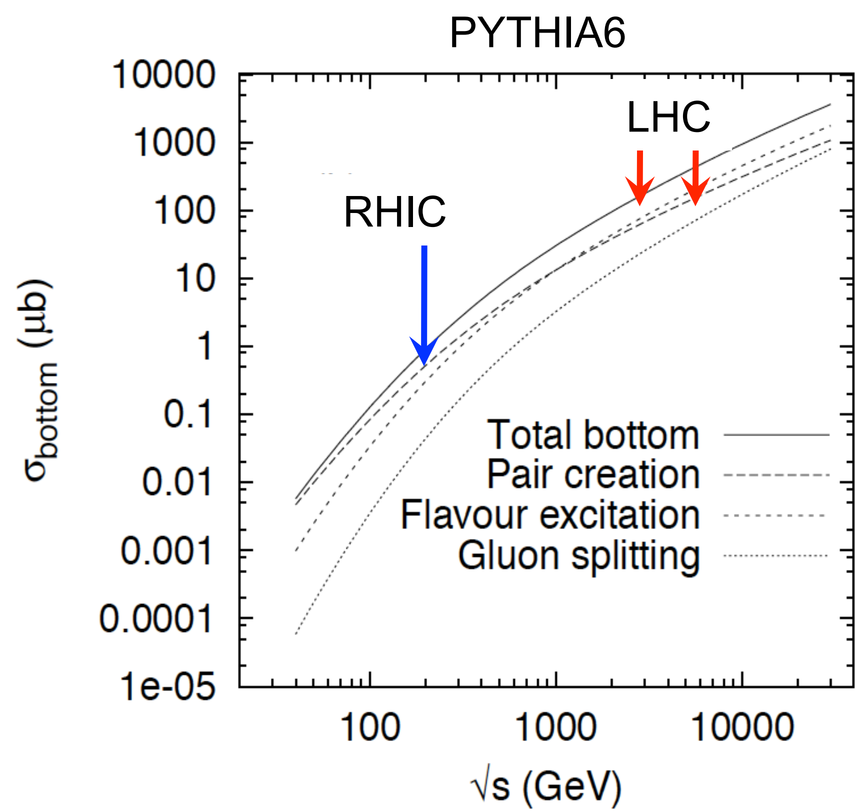
Open Heavy Flavor production



Uniqueness at RHIC

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

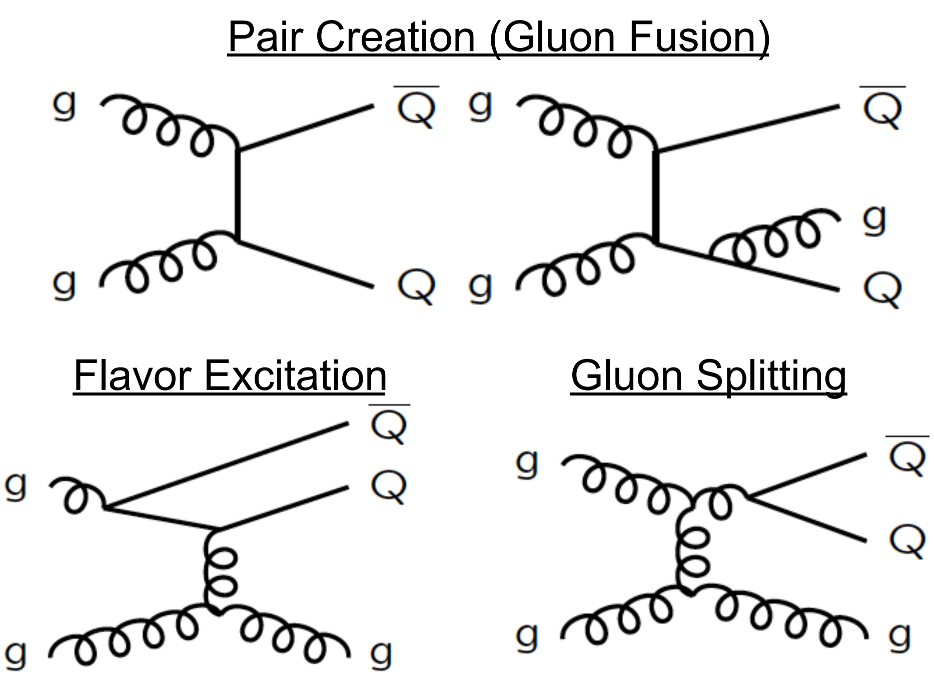


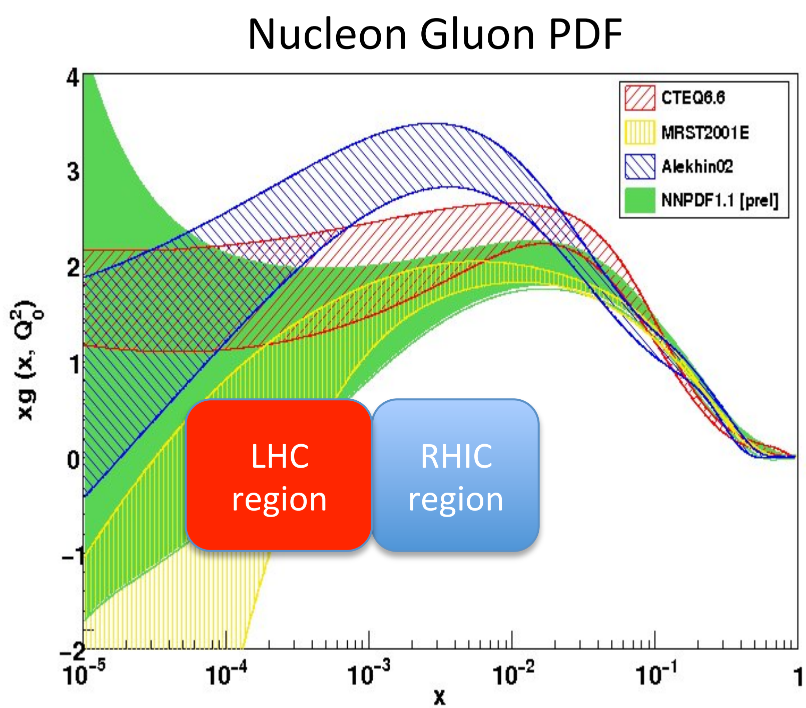


T. Sjostrand, EPJC17 (2000) 137

Uniqueness at RHIC

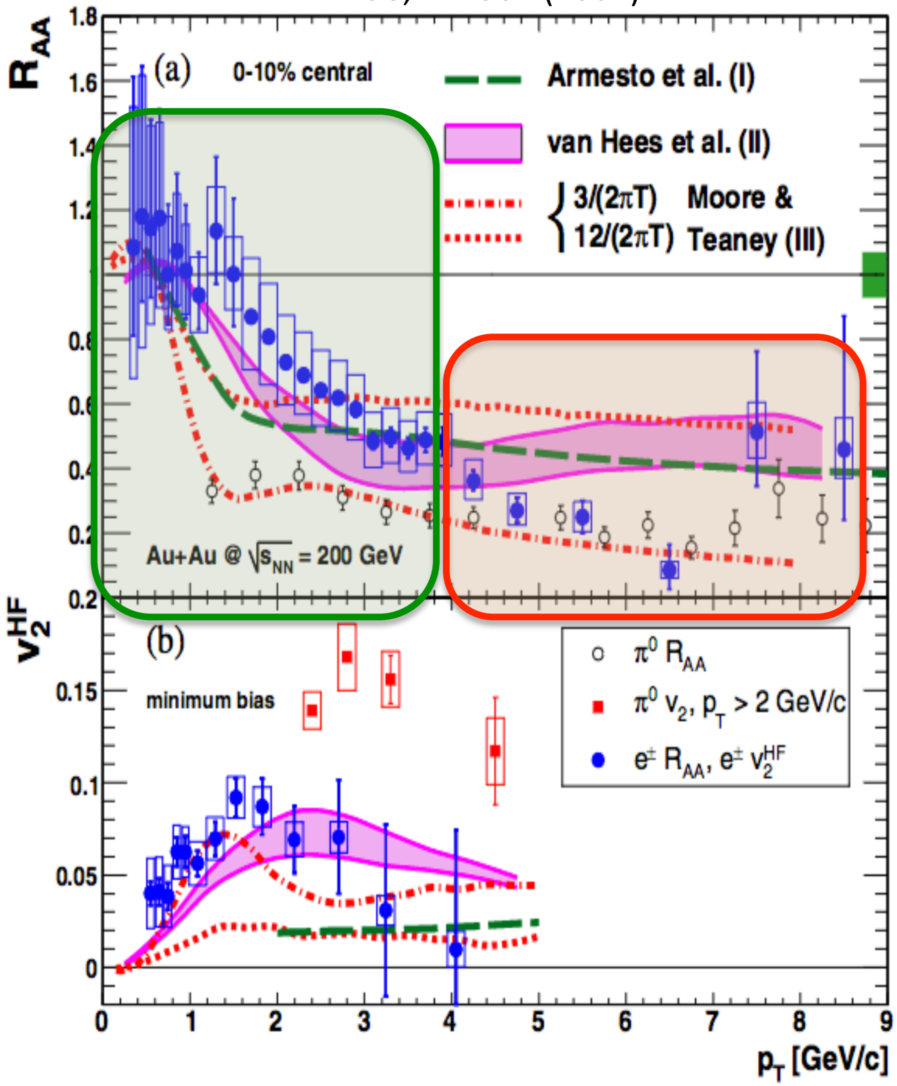
- Uniqueness at RHIC
  - dominated by pair creation (gluon fusion), clean interpretation for experimental results.
  - accesses complementary kinematics region compared to LHC measurements.





Surprise in Au+Au heavy flavor measurements (QGP formed)

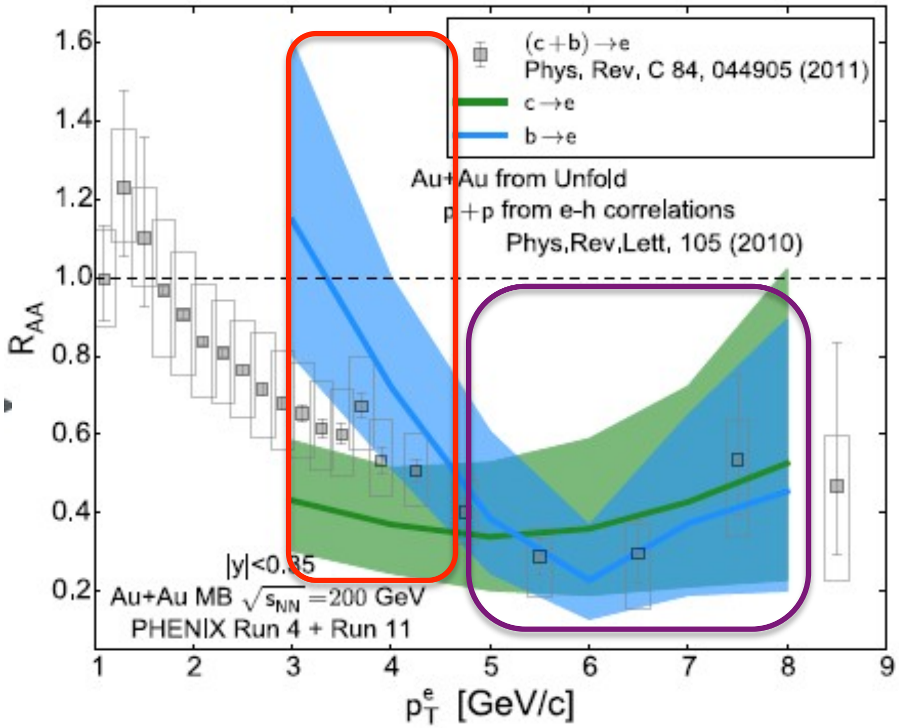
PRL 98, 172301 (2007)



- Suppression of the inclusive Heavy flavor R_{AA} and non-zero v_2 provide evidence of strong coupling between the heavy flavor and medium.
- Similar suppression of R_{AA} between the inclusive heavy flavor decayed electrons and light hadrons in high p_T region.
- Different suppression of R_{AA} in the low p_T region.
- Mass/Flavor dependent E_{loss}?

Indication of flavor dependent energy loss

PRC 93, 034904 (2016)



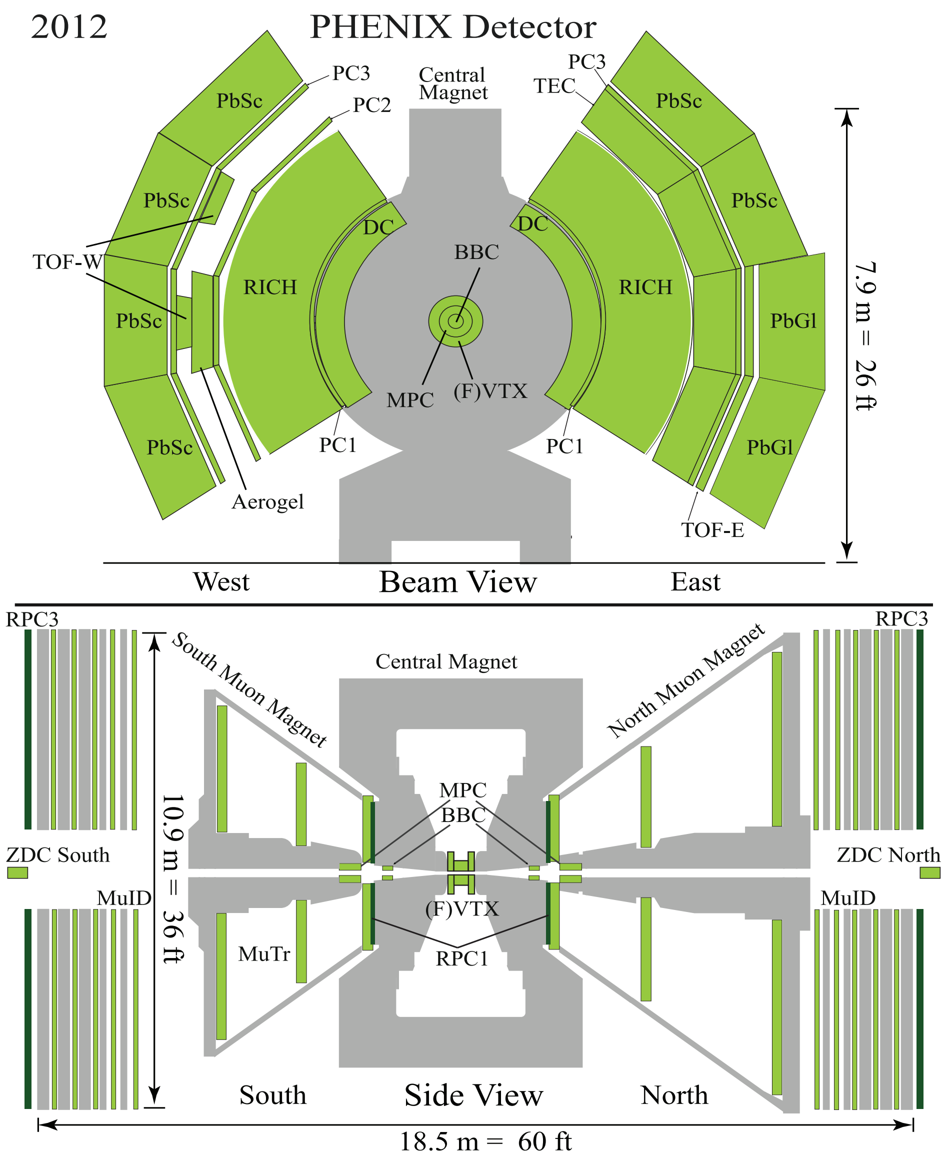
- From the PHENIX charm and bottom separated single electron R_{AA} results,
  - Bottom has similar suppression as charm for high p_T region.
  - Bottom may be less suppressed in the low p_T region.
- Consistent with Energy Loss mechanism:

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

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

→ in p+p collisions.

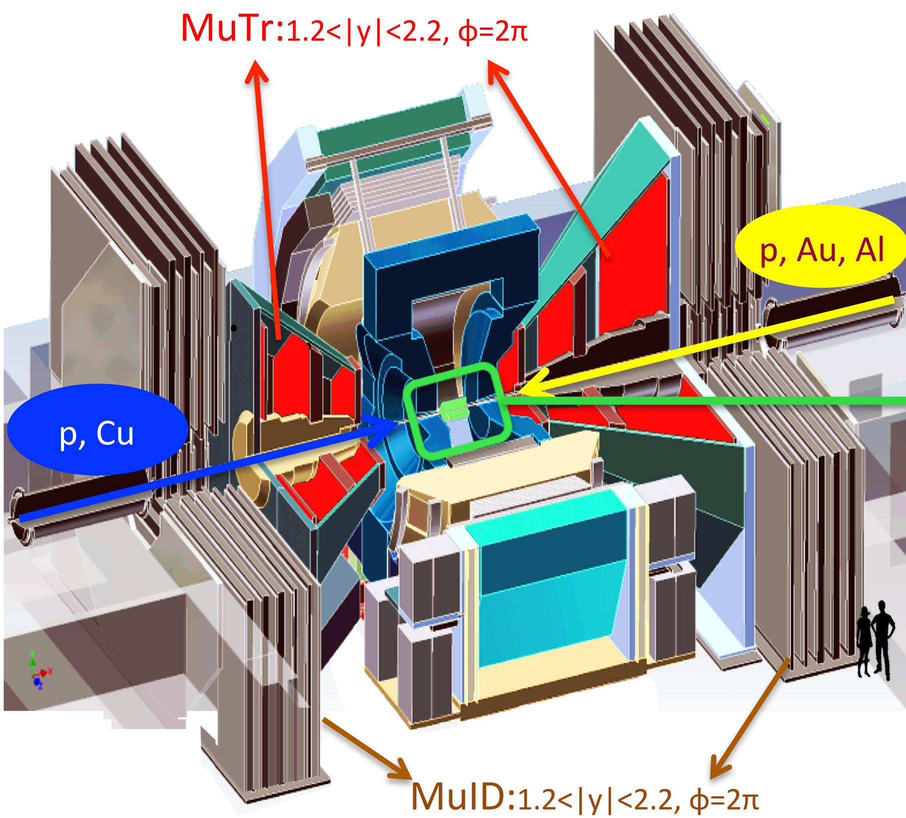
PHENIX detector



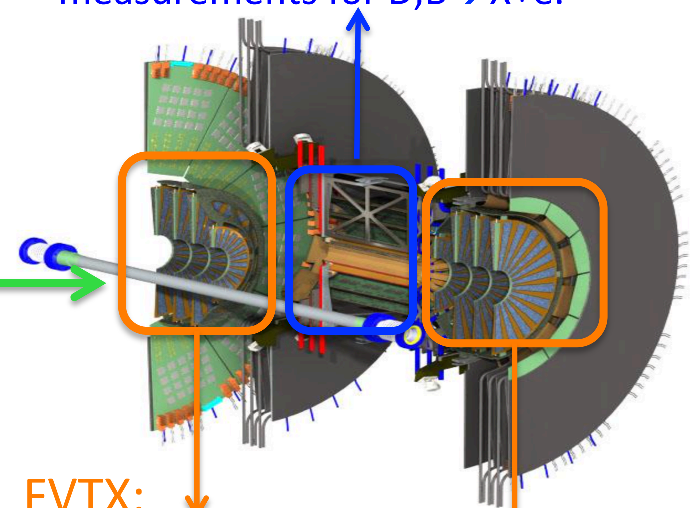
- **Central Arm (Electrons)**
  - $|\eta| < 0.35$
  - $\Delta\varphi = \pi$
  - Tracking: DC, PC, VTX
  - eID: RICH, EMcal
- **Forward Arms (Muons)**
  - $1.2 < |\eta| < 2.2$
  - $\Delta\varphi = 2\pi$
  - ~10 interaction length absorber
  - Tracking: wire chamber, FVTX
  - MuID: muon identification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

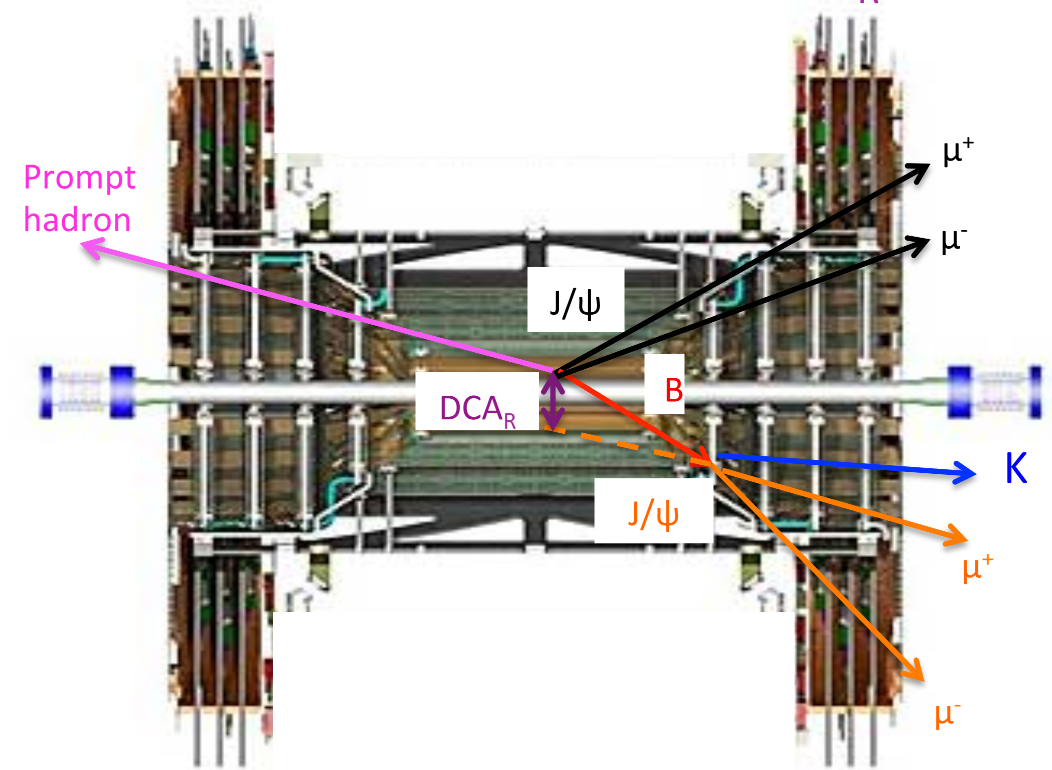


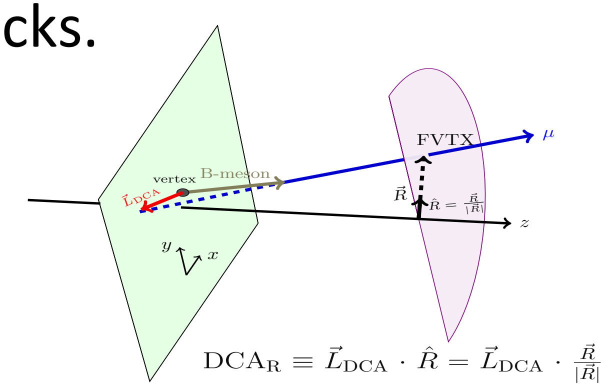
- FVTX:
  - With 1.2<|y|<2.2 and ϕ=2π coverage.
  - provide precise tracking and DCA measurements for B→J/ψ and D, B separation.

Can we measure B meson in forward rapidity?

B->J/ψ->$\mu^+\mu^-$

- B hadron decay length (cτ), about the size of hair diameter:
  - cτ(B^0)=455μm, cτ($B^\pm$)=491μm.
- 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.



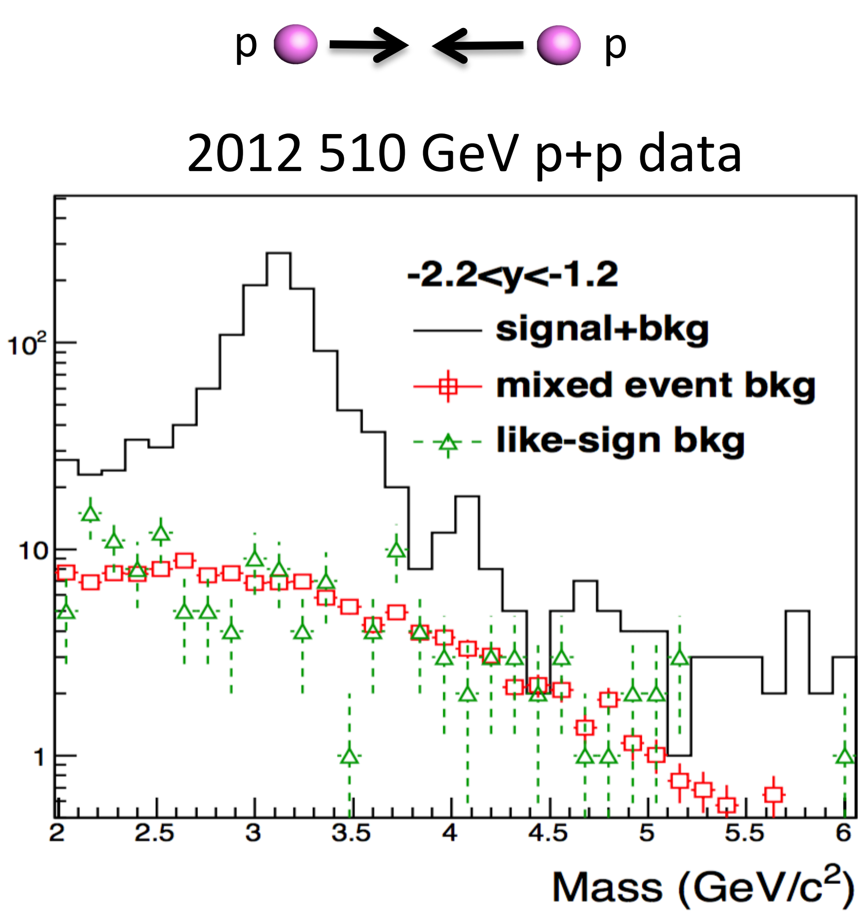


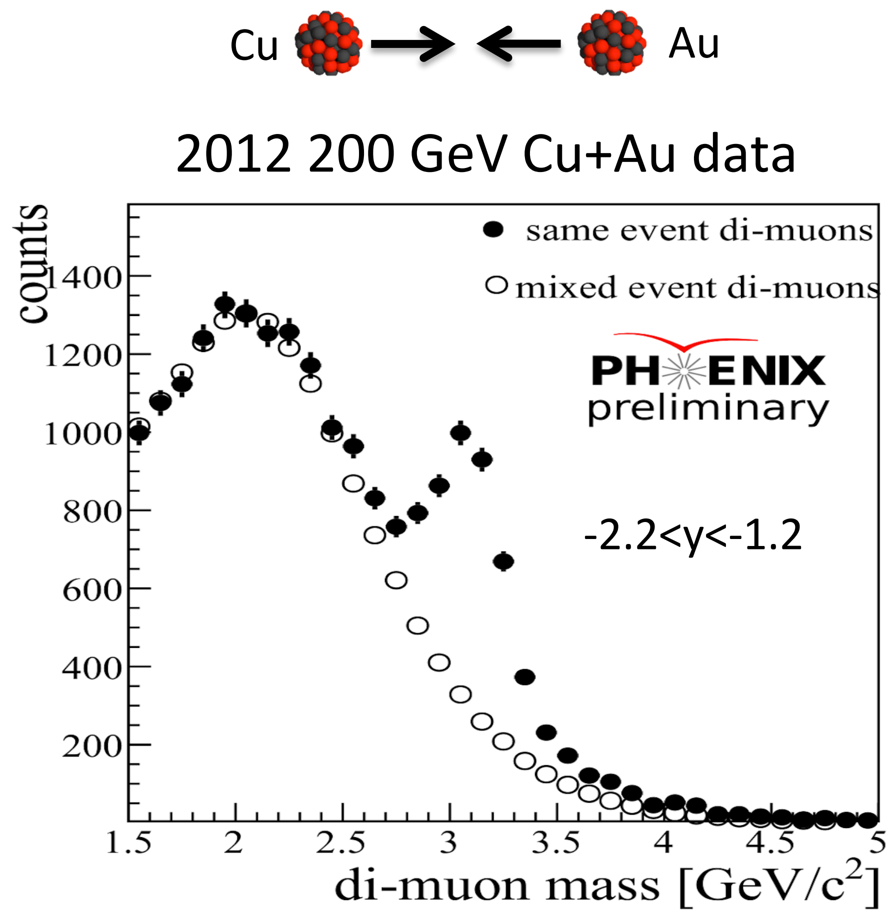
- Different shapes of DCA_R of prompt particles and decayed particles make the separation of B decayed J/ψ and prompt J/ψ feasible.

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

- In p+p and heavy ion (eg. Cu+Au) data:
  - Identify the J/ψ candidates from di-muon mass spectrum after applying quality cuts.
  - Use the FVTX to determine the DCA_R of muons from di-muon pairs in data.
  - Use simulation (embedding) with realistic detector condition and collision environment to determine the muon DCA_R shape from prompt J/ψ and J/ψ from B-meson decay in p+p (Cu+Au) collisions.
  - Determine various background components.
  - Simultaneously extract the prompt J/ψ and B-meson decay J/ψ through fitting on data.
  - Apply the acceptance*efficiency corrections.
  - Calculate the systematic errors.

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

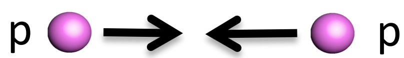




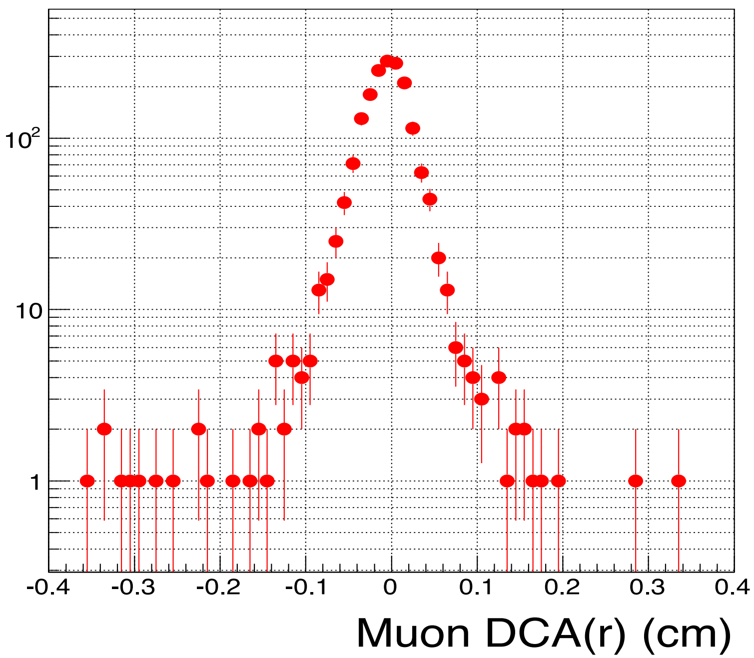
- Clear J/ψ peaks are found in both p+p and Cu+Au data.

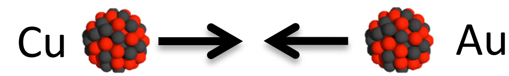
Analysis strategy for the B to J/ψ ratio measurement (II)

- After select good J/ψs, require the muon track of di-muon pairs matching to the FVTX and measure the DCA_R.
- Muon DCA_R measurement in data with $-2.2<y<-1.2$:

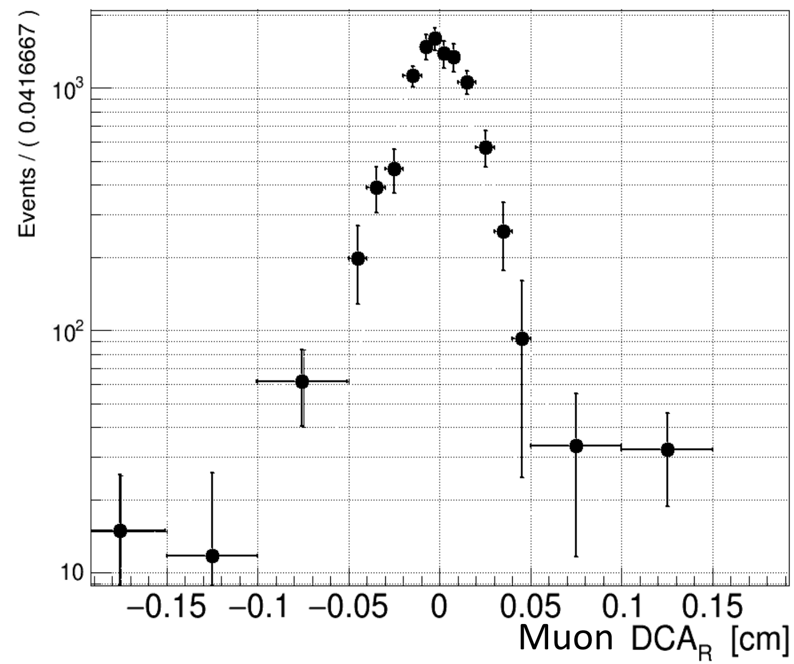


2012 510 GeV p+p



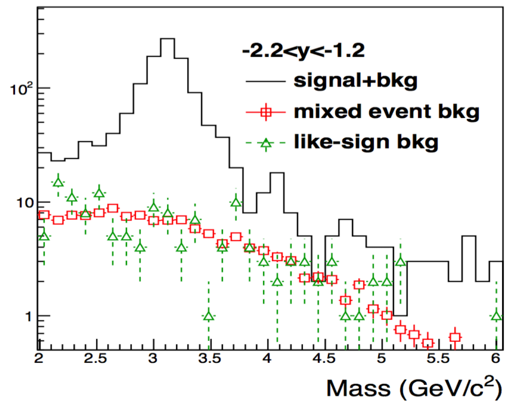


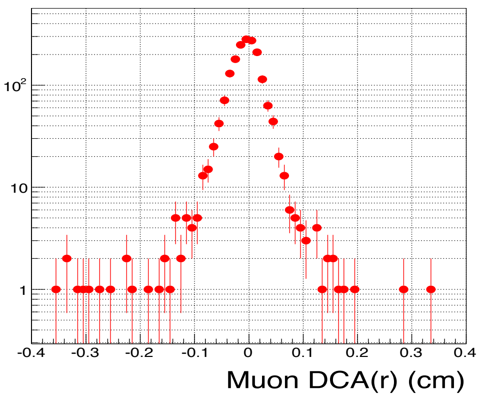
2012 200 GeV Cu+Au



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

2012 510 GeV p+p data

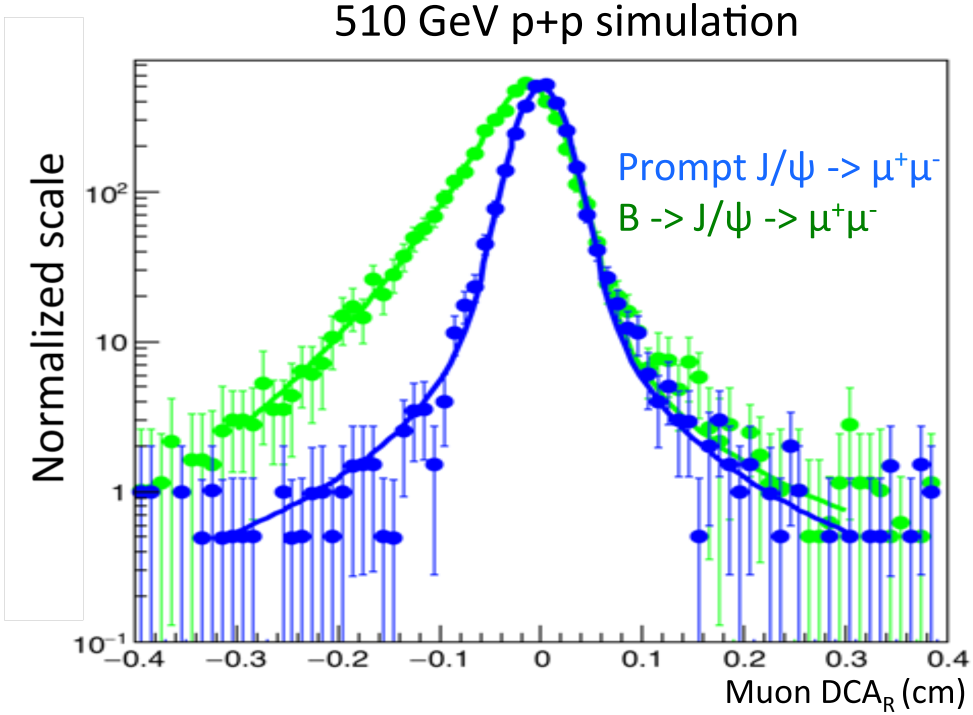




- Clear J/ψ peaks are found in both p+p and Cu+Au data.
- Muon DCA_R determined in data.

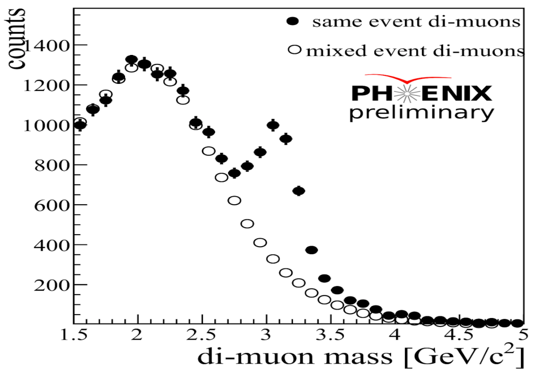
- Signal determination
  - Generate prompt J/ψ and B to J/ψ events in full simulation (PYTHIA +GEANT+RECO) for p+p with realistic vertex and dead maps etc.
- Obvious DCA_R shape difference between prompt J/ψ and B to J/ψ.

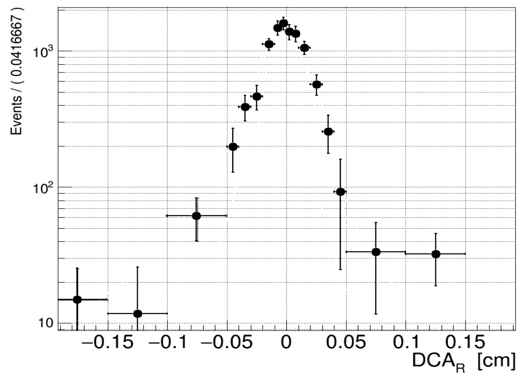
510 GeV p+p simulation



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

2012 200 GeV Cu+Au data

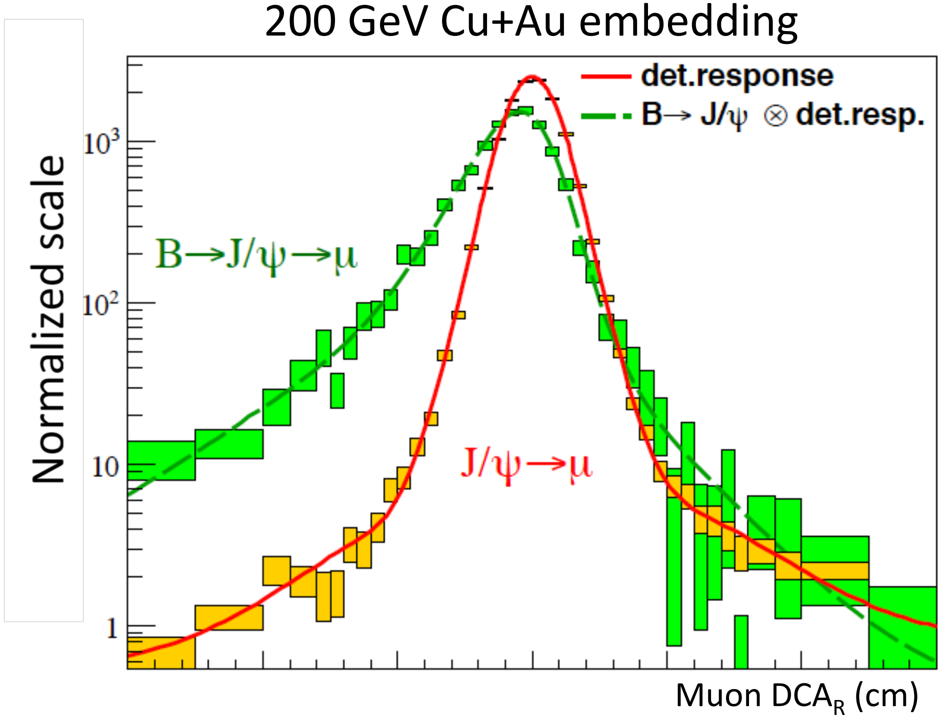




- Clear J/ψ peaks are found in both p+p and Cu+Au data.
- Muon DCA_R determined in data.

- Signal determination
  - Generate prompt J/ψ and B to J/ψ events in embedding for Cu+Au with realistic vertex and dead maps etc.
- Obvious DCA_R shape difference between prompt J/ψ and B to J/ψ.

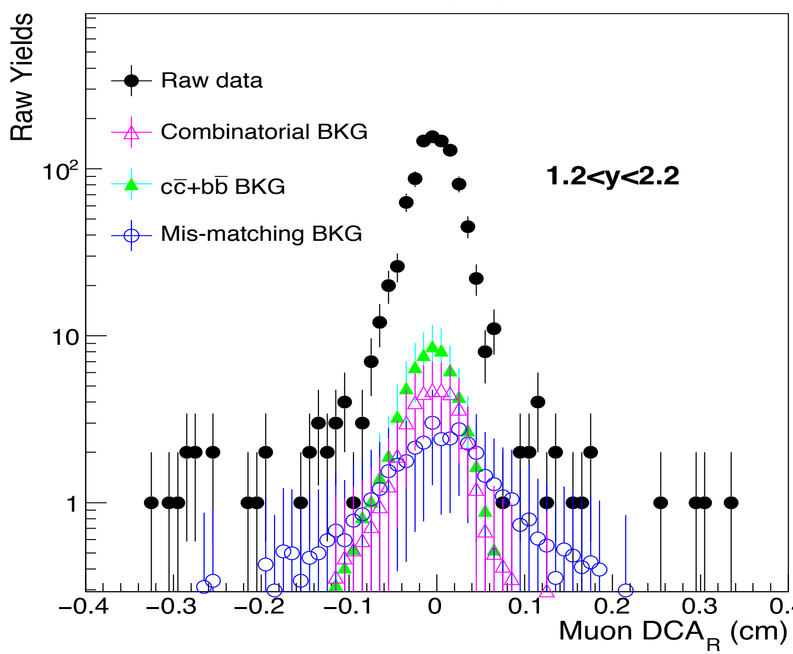
200 GeV Cu+Au embedding



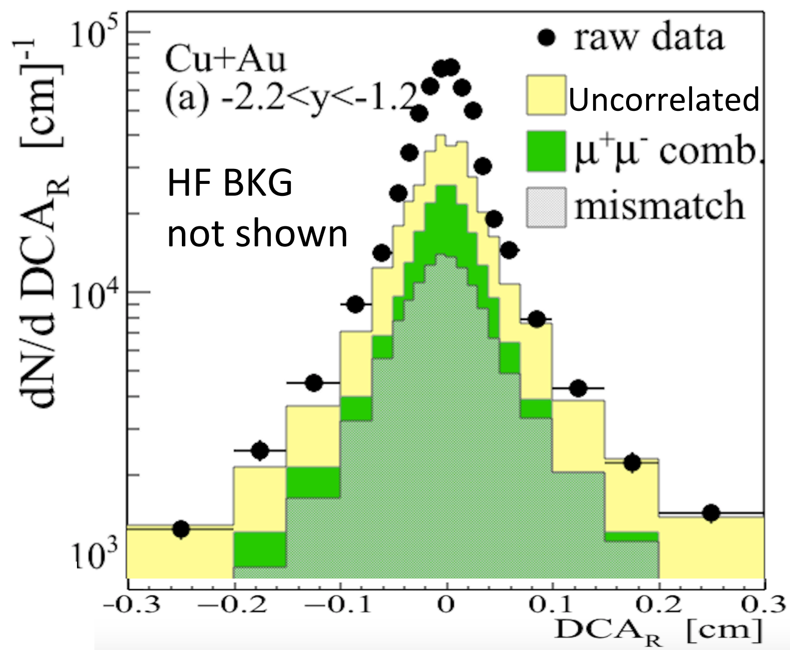
Analysis strategy for the B to J/ψ ratio measurement (IV)

- Background determination
  - Dimuon combinatorial background using mixed events.
  - FVTX-Mutr track mis-matching using topological detector event mixing technique.
  - Heavy flavor continuum (dominated by ccbar), generated in simulation with fraction determined in data.

2012 510 GeV p+p collisions

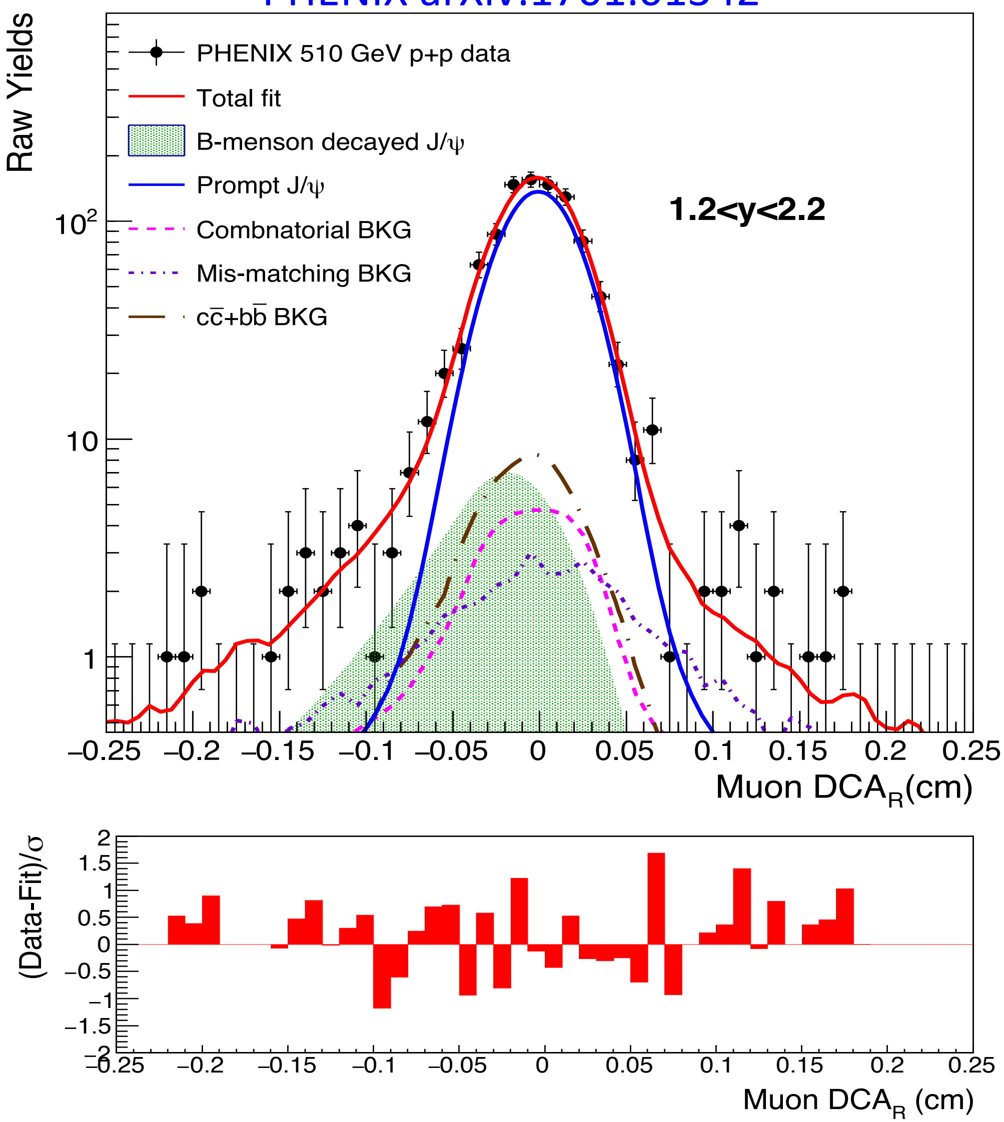


2012 200 GeV Cu+Au collisions



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

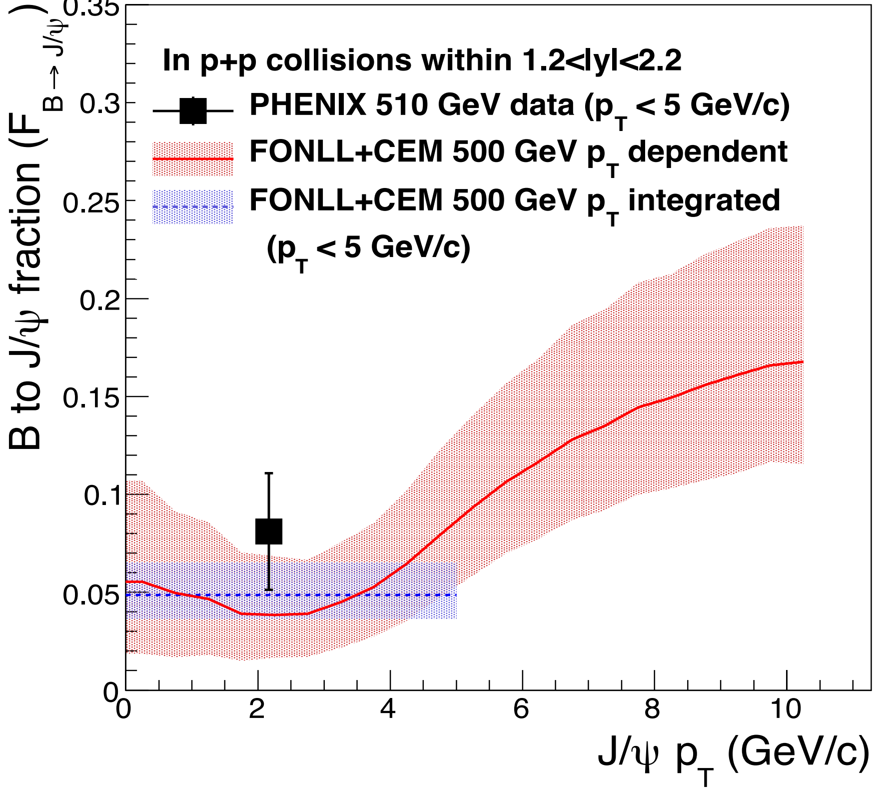
PHENIX arXiv:1701.01342



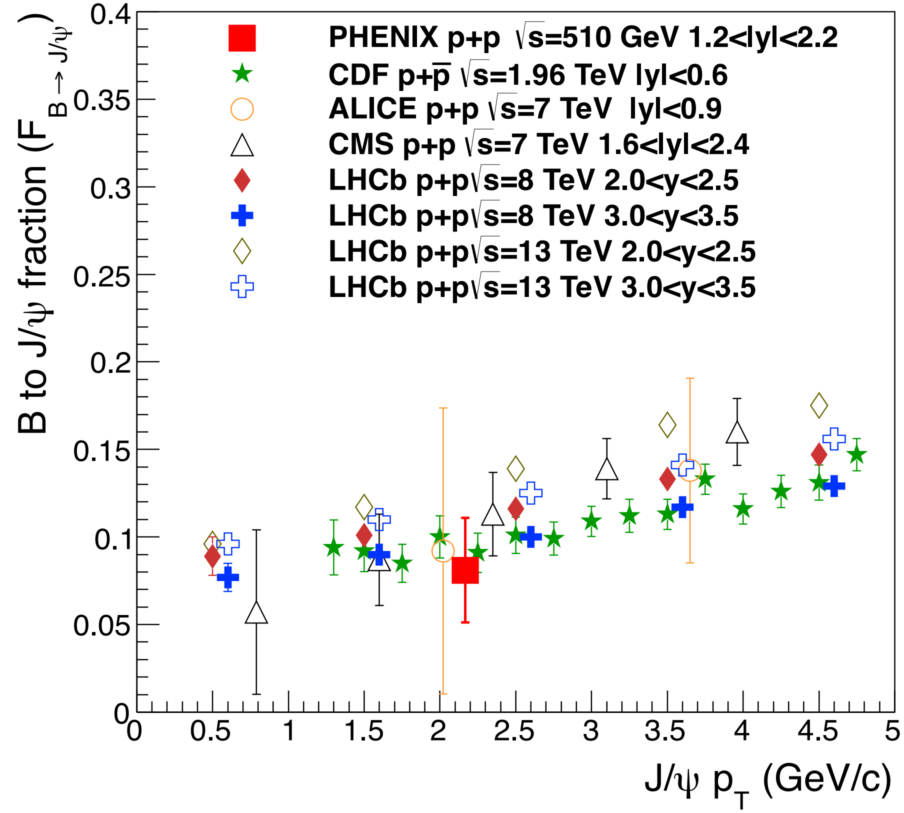
- Fit on DCA_R in data to simultaneously determine the prompt J/ψ and J/ψ from B-meson decay yields and extract the B to J/ψ fraction.
- Apply the relative acceptance*efficiency correction to B to J/ψ fraction result.

B->J/ψ fraction in 510 GeV p+p data

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

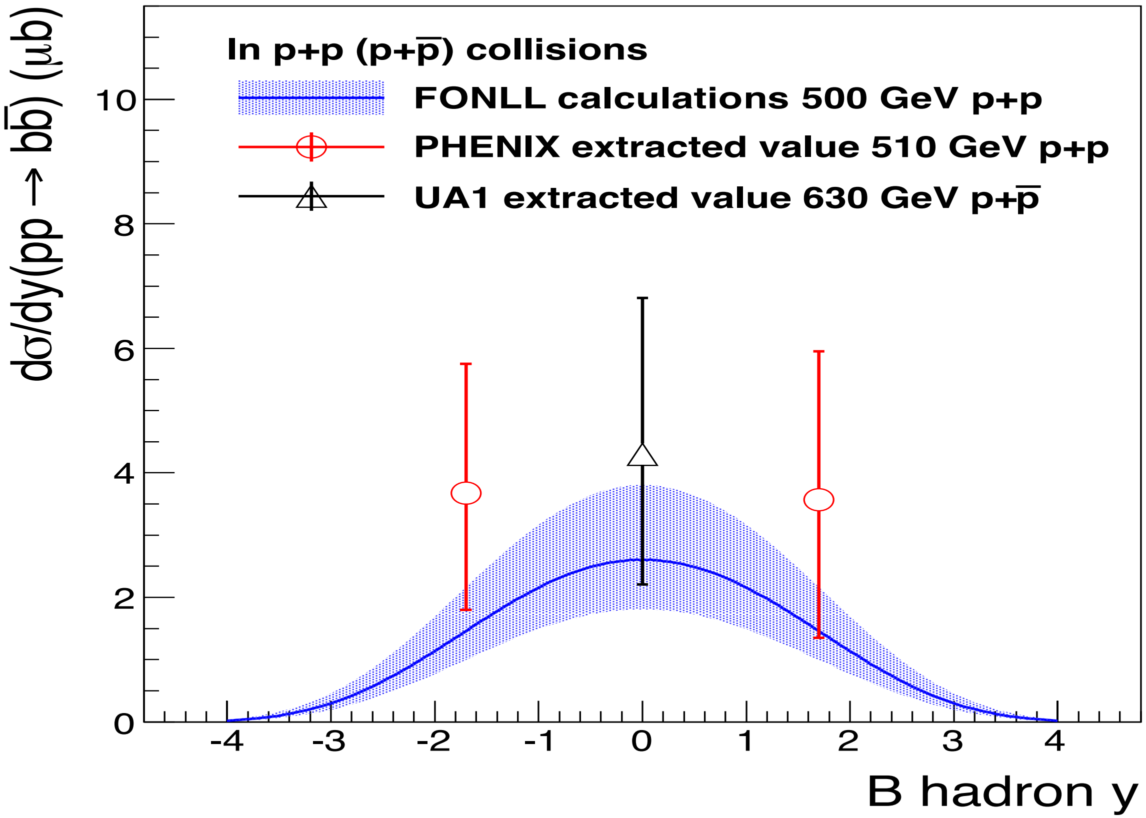


PHENIX arXiv:1701.01342



- The forward B->J/ψ fraction measured at PHENIX in 510 GeV p+p collisions is in reasonable agreements with the FONLL+CEM model calculation.
- The PHENIX result in 510 GeV p+p collisions is comparable with higher energy measurements.

$b\bar{b}$ cross section in 510 GeV p+p data



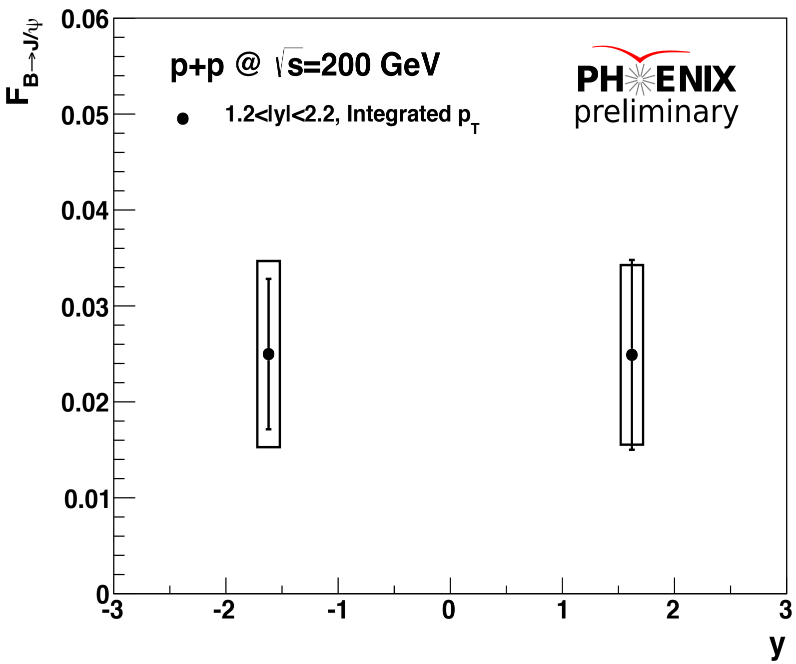
PHENIX arXiv:1701.01342

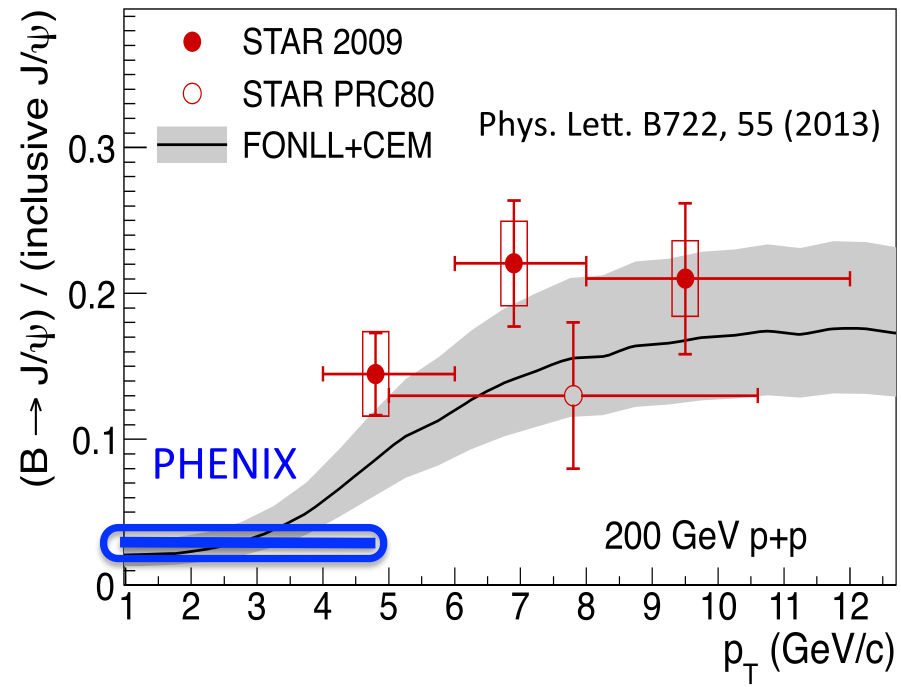
FONLL:
M. Bedjidian et al. (2004), hep-ph/0311048

- The $b\bar{b}$ cross section is determined by the measured B->J/ψ fraction ($p_T > 0$ GeV/c) at PHENIX and extrapolated inclusive J/ψ cross section in 510 GeV p+p collisions.
- Good agreements with the FONLL model calculations, and comparable with UA1 results.

B->J/ψ fraction in 200 GeV p+p data

- Using the same method, PHENIX just achieves the preliminary result of the B->J/ψ fraction in 200 GeV p+p collisions within the kinematic regions of J/ψ p_T < 5GeV/c and 1.2<|y|<2.2 rapidity.

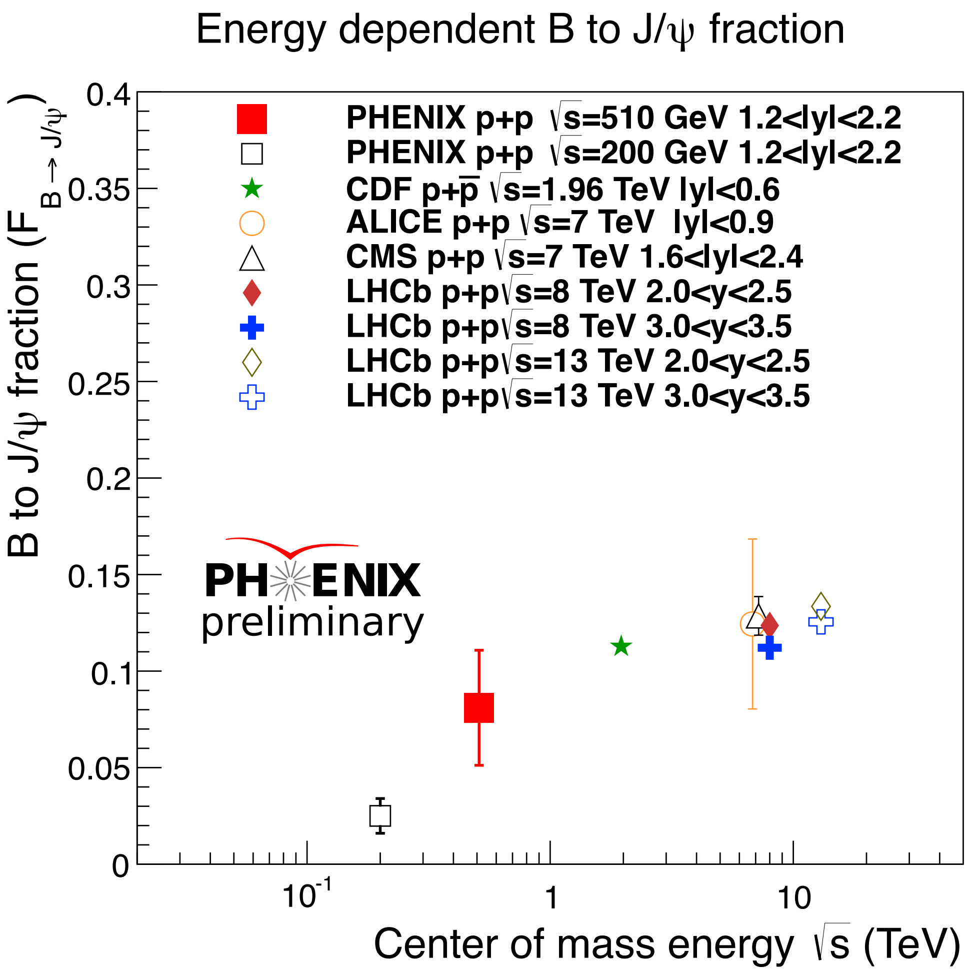




- Both STAR and PHENIX measured B->J/ψ fractions are in reasonable agreements with the FONLL+CEM calculation.

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 J/ψ p_T < 5 GeV/c.



PHENIX arXiv:1701.01342

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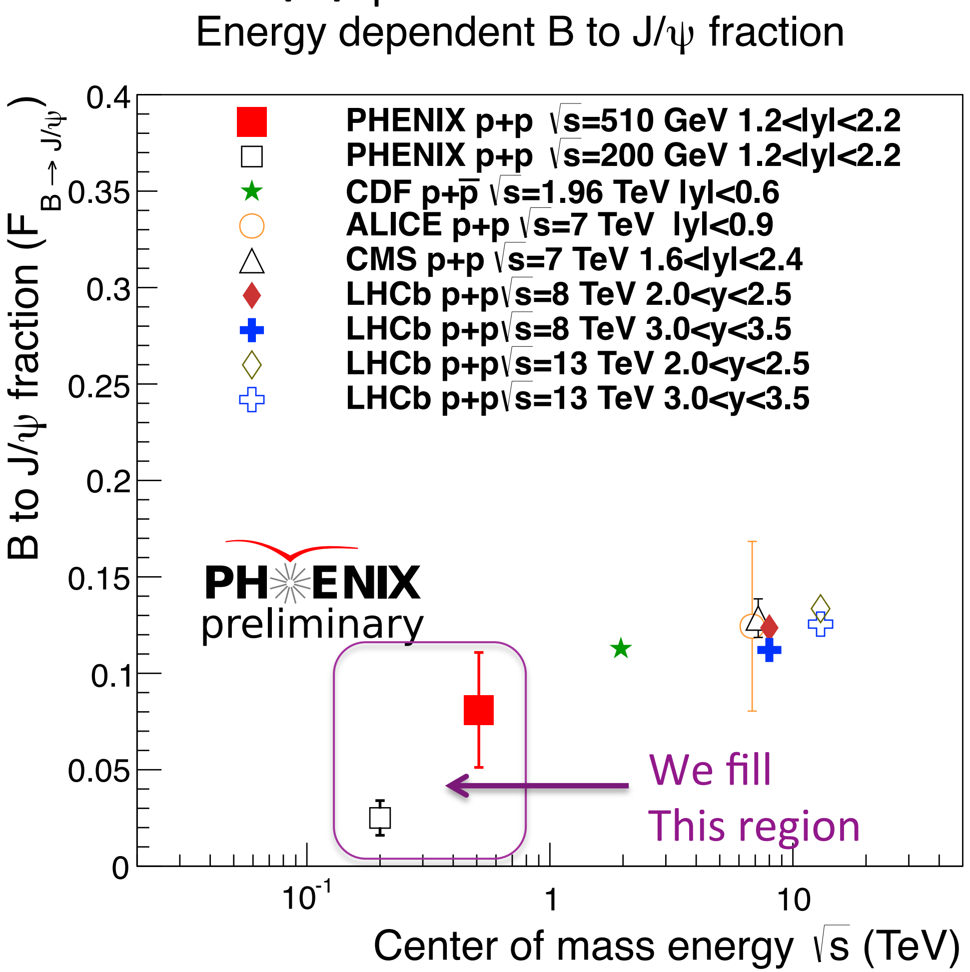
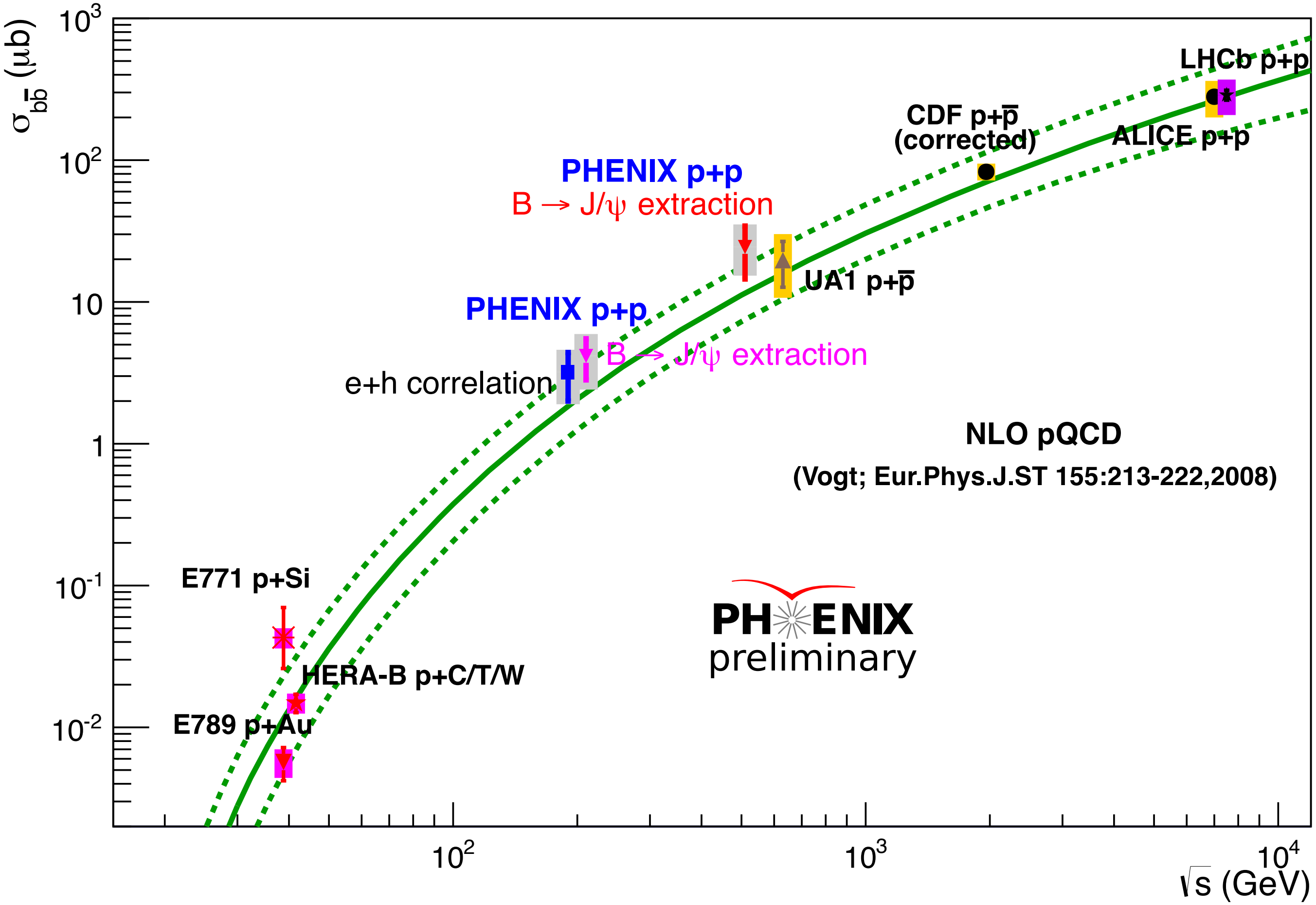


PHENIX arXiv:1701.01342

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

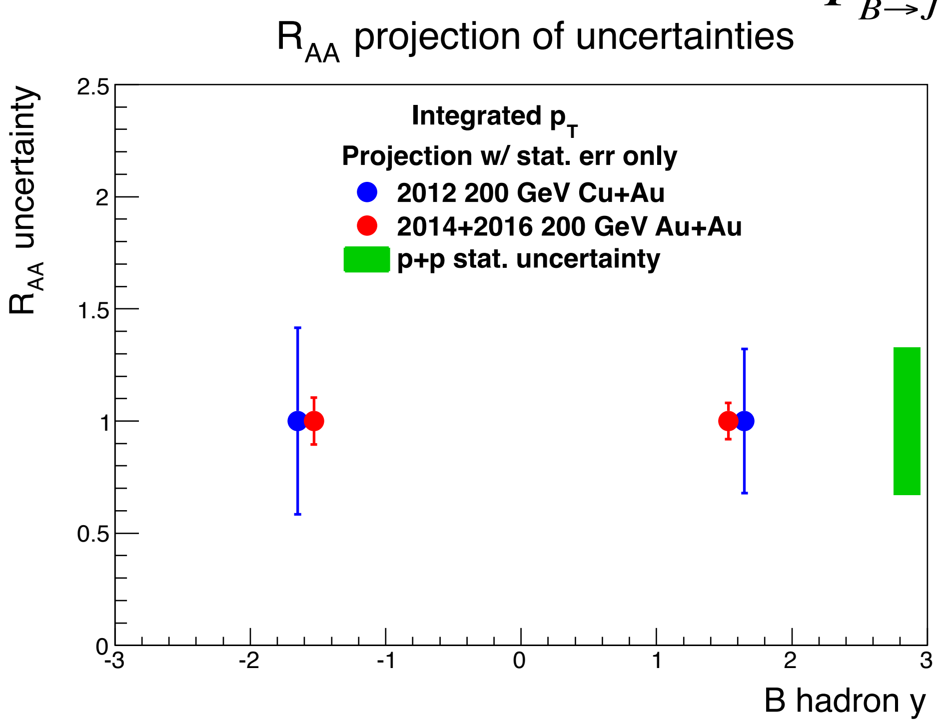
- The extracted $b\bar{b}$ cross section results based on the B->J/ψ fractions measured in 200 and 510 GeV p+p collisions are in reasonable agreements with the NLO pQCD predications.



B->J/ψ fraction in Cu+Au and Au+Au collisions

- The 2012 200 GeV Cu+Au analysis is being finalized. The 2014/2016 200 GeV Au+Au data production is ongoing.
- The nuclear modification factor R_{AA} can be derived from the B->J/ψ fraction and the inclusive J/ψ R_{AA} according to this formula:

$$R^{B\to J/\psi}_{CuAu/AuAu} = \frac{F^{CuAu/AuAu}_{B\to J/\psi}}{F^{pp}_{B\to J/\psi}} R^{inc.J/\psi}_{CuAu/AuAu}$$



- The B hadron R_{AA} through the B->J/ψ measurements will improve the knowledge of bottom quark energy loss in QGP.

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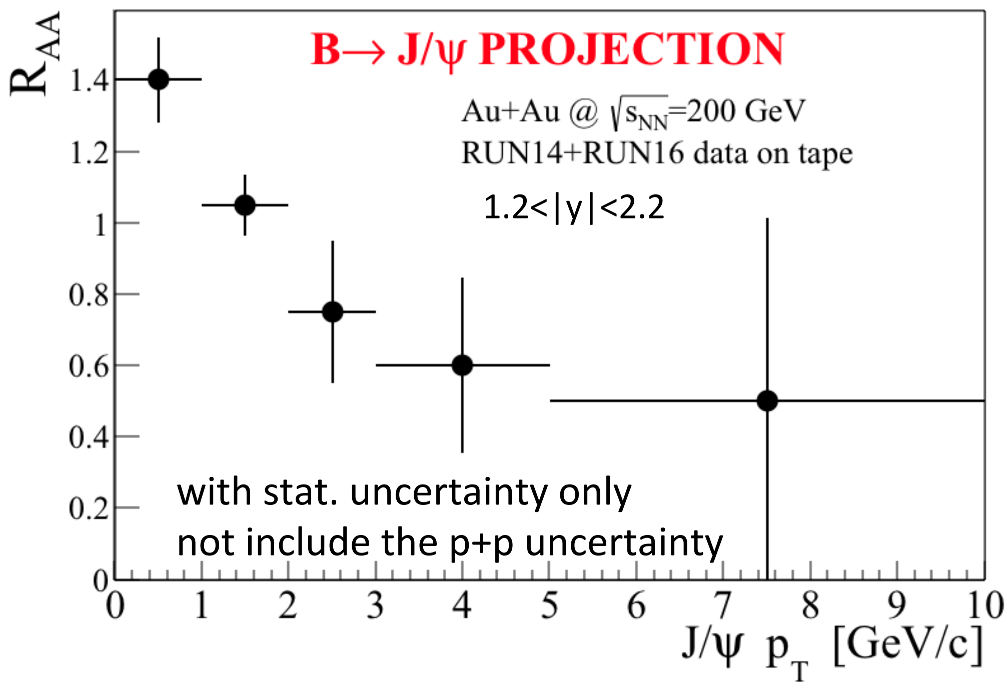

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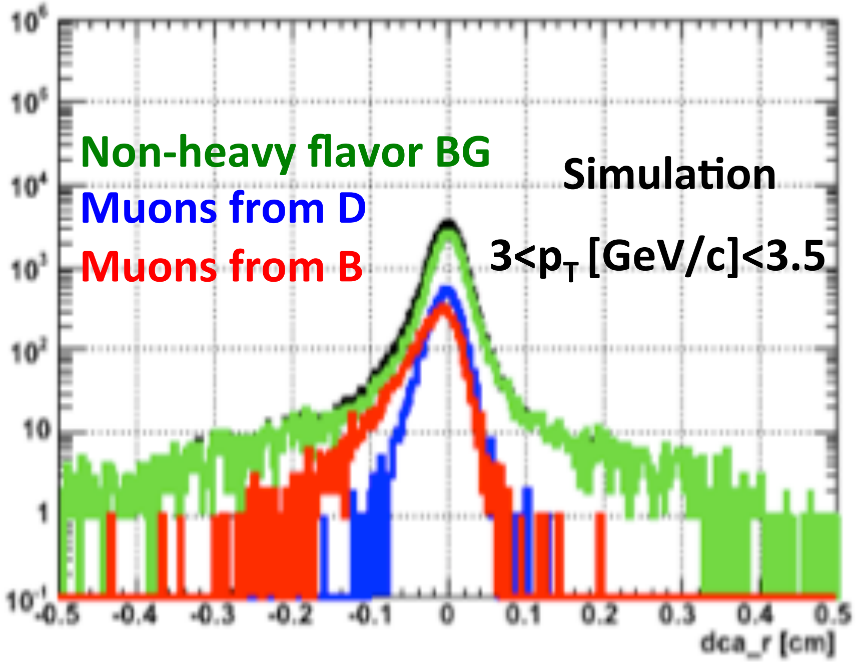
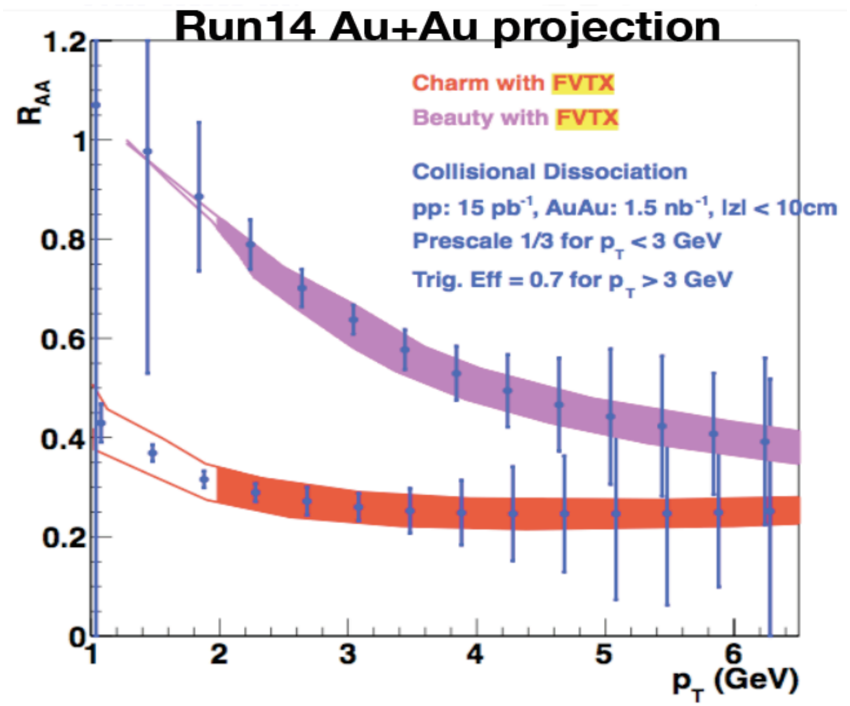
Charm and Bottom decayed inclusive single muons

- 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

- First measurement of J/ψ from B decays in forward/backward rapidity with integrated p_T are achieved in both 510 GeV (arXiv:1701.01342) and 200 GeV p+p collisions.
  - A smooth center of mass energy dependence is found for integrated p_T J/ψ from B-meson decay in p+p (p+pbar) collisions from 0.2 to 13 TeV.
  - Indication of a smooth transition from LO process to NLO process for bottom production is found through the B to J/ψ measurements.

Outlook

- The 200 GeV Cu+Au B to J/ψ paper preparation is ongoing, the final result is expected to be released soon.
- Large data sets in various types of collision systems collected at PHENIX provide opportunities to study
  - Forward/backward B to 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.

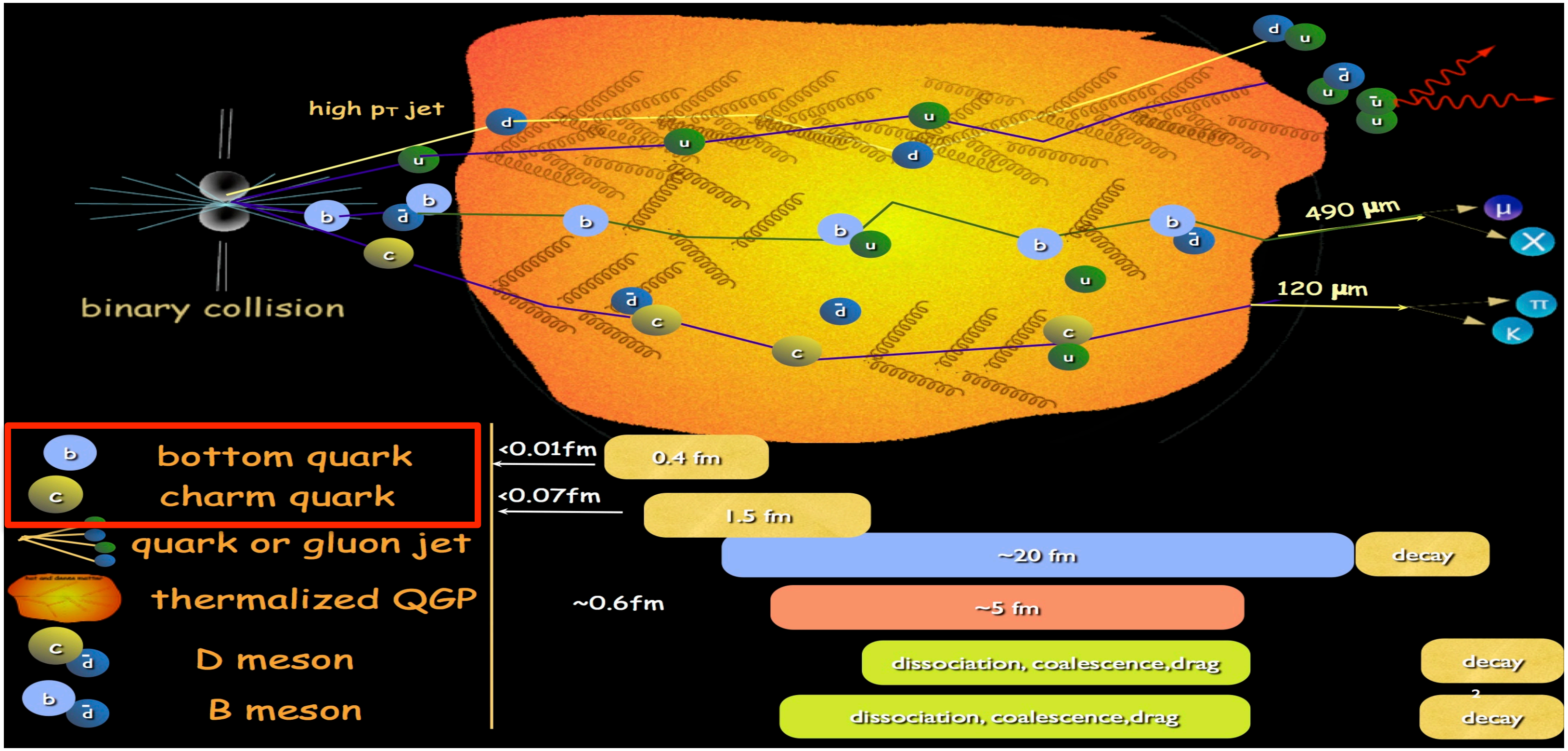
Backup

Advantages to use heavy quarks to scan the QGP

– Short wavelength which can probe the small scale volume (<5fm). Uncertainty principle: $m_c \approx 1.3$ GeV and $m_b \approx 4.6$ GeV.

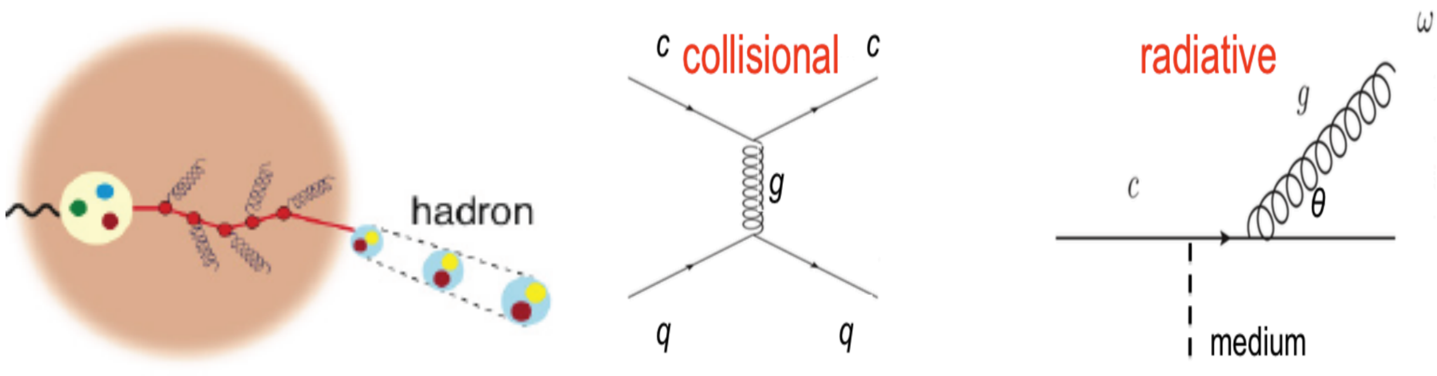
– Formed before the QGP creation (<1fm/c after the Big-Bang) to study the full evolution.

– Probes that can cross the plasma and don't vanish.



Energy loss in the QGP

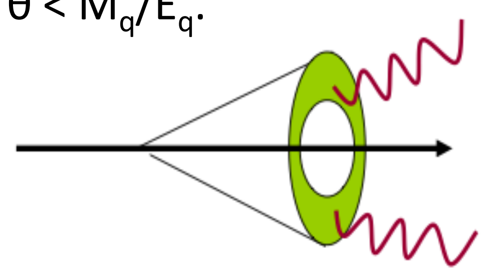
- Energy loss Mechanism:
- (I) Heavy quarks lose energy when crossing the medium (indicated by the R_{AA} suppression).



- 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 $\theta < M_q/E_q$.

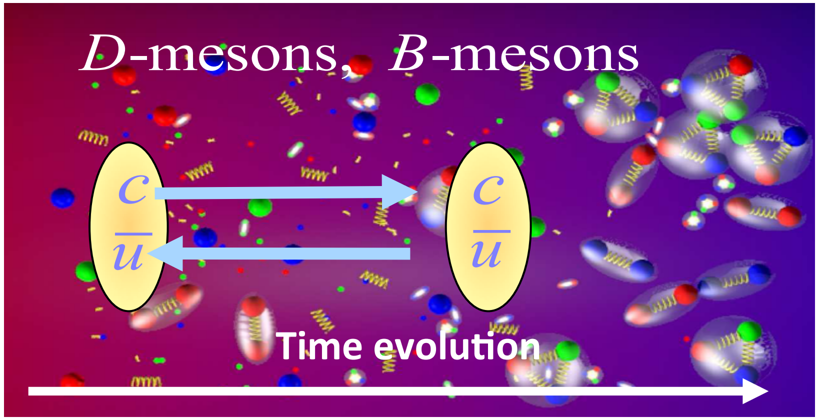


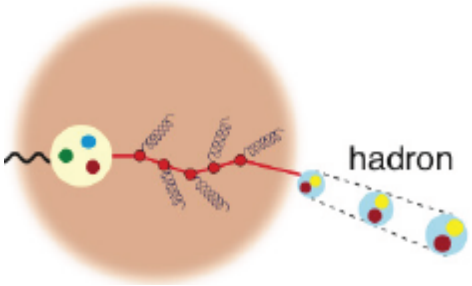
Energy loss in the QGP

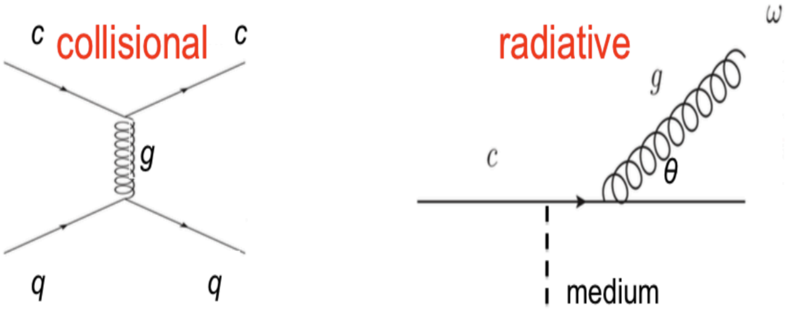
- Energy loss Mechanism:
- (II) Shorter formation and dissociation time of b(c) quark to B(D) from light quark hadrons.

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

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

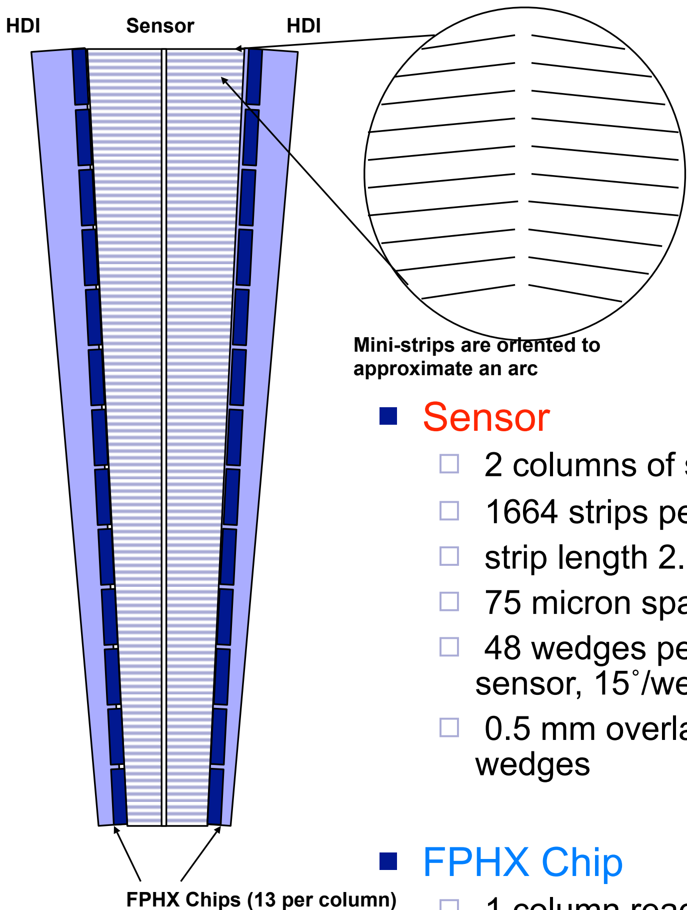




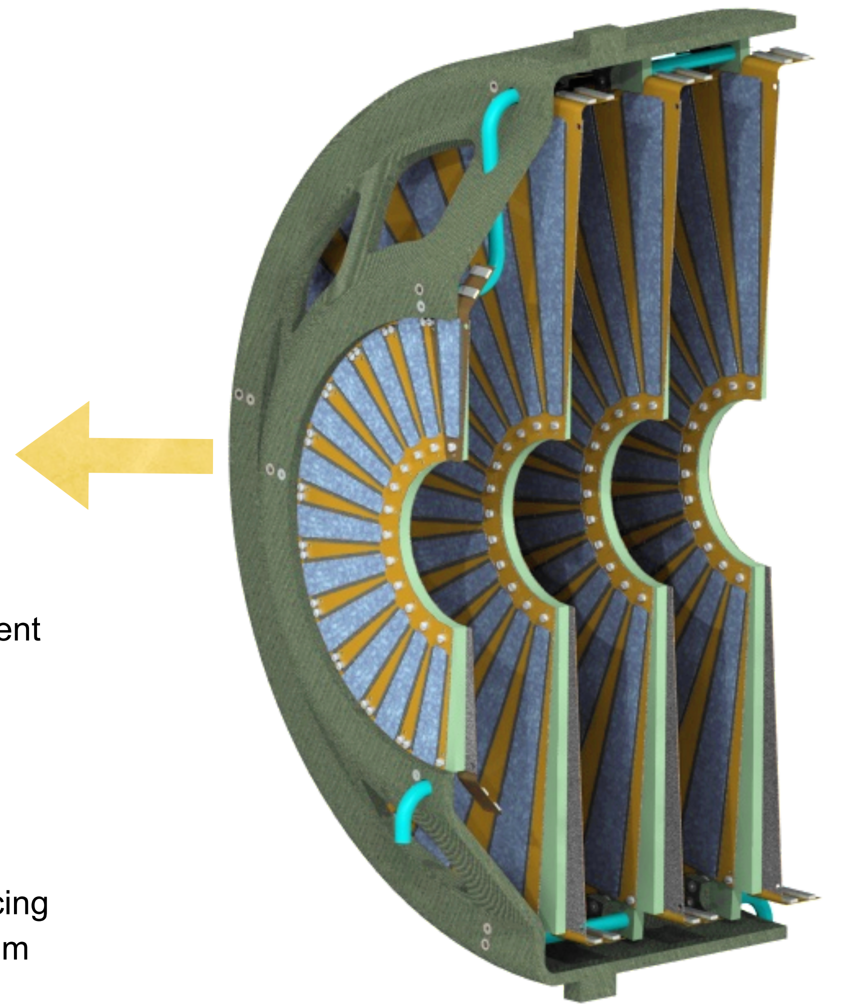


- Mass effect is negligible at high p_T but not in low p_T region.
- Low p_T heavy flavor production is dominated by charm, need to separate charm and bottom and study the mass/flavor dependence.

The Forward Vertex Detector (FVTX)

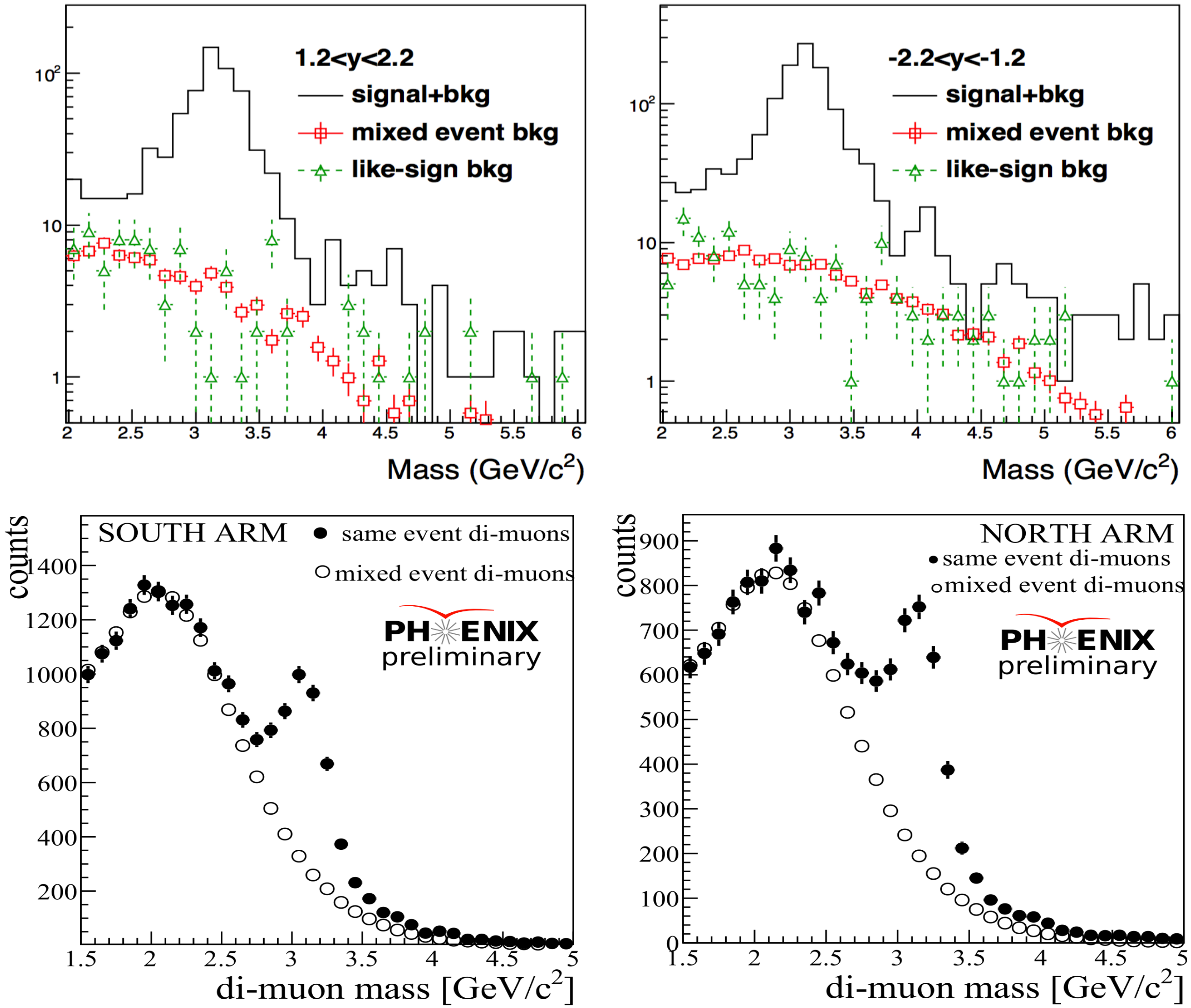


- Sensor
  - 2 columns of strips
  - 1664 strips per column
  - strip length 2.8 to 11.2 mm
  - 75 micron spacing
  - 48 wedges per disk (7.5˚/ sensor, 15˚/wedge)
  - 0.5 mm overlap with adjacent wedges
- FPHX Chip
  - 1 column readout
  - 128 channels
  - ~ 70 microns channel spacing
  - Dimensions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



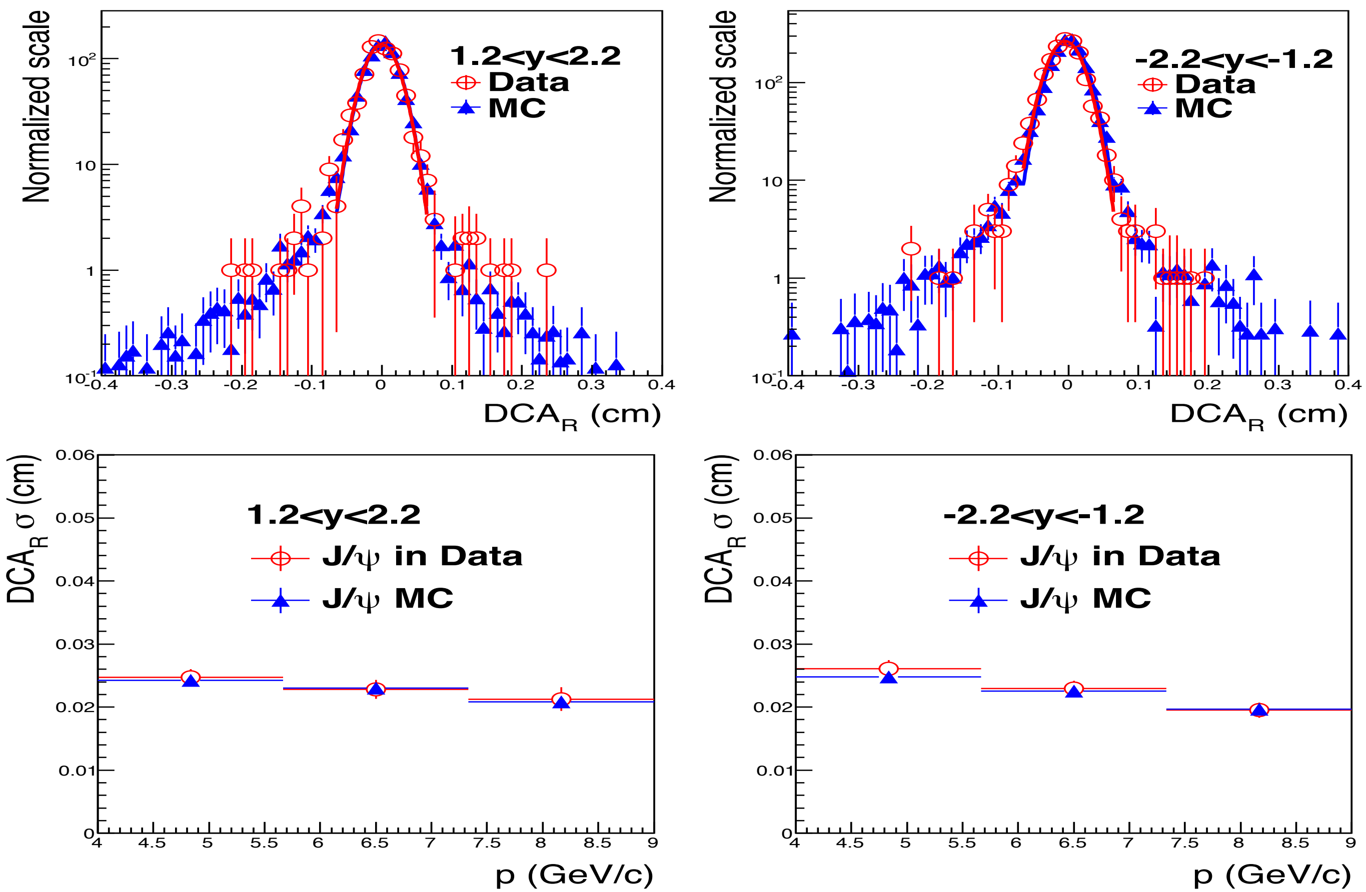
Invariant mass of di-muons

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



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

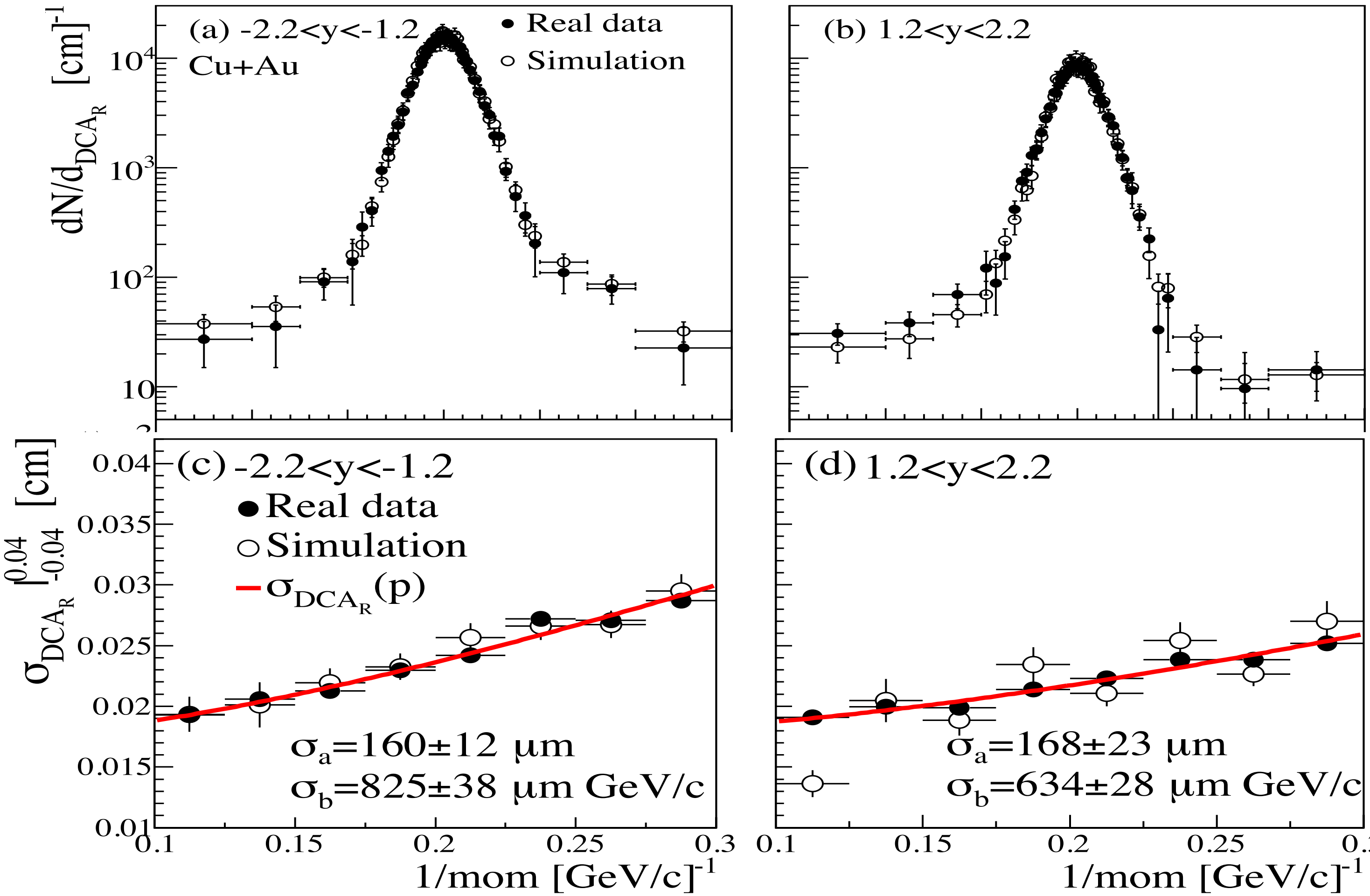
- DCA(r) of J/ψ decayed muons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.



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

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

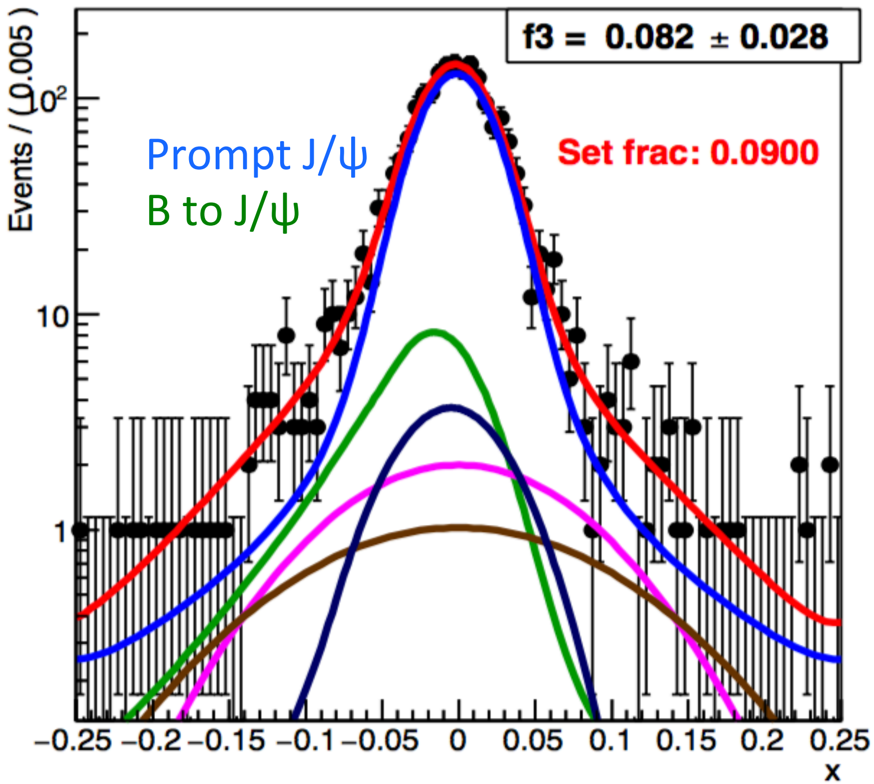
- DCA(r) of stopped hadrons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.

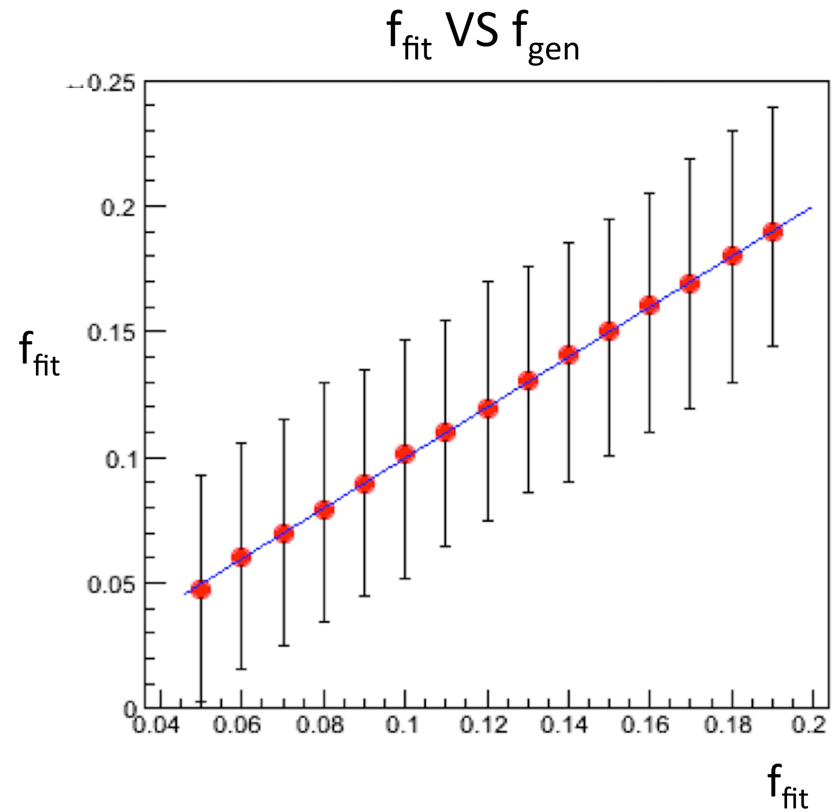


- Good agreement between data and simulation for DCA(r) resolution.

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.



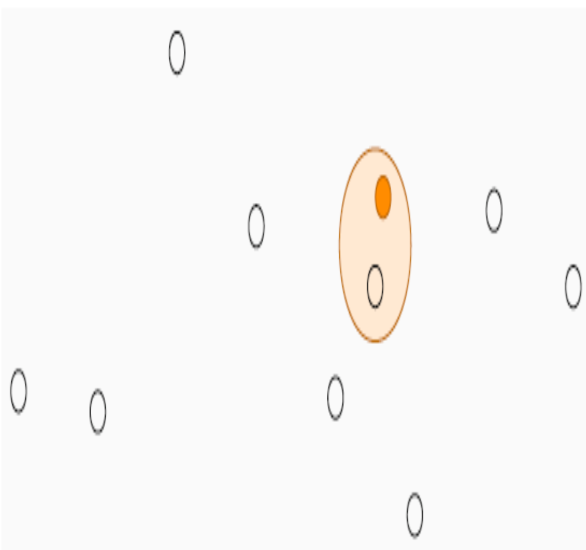


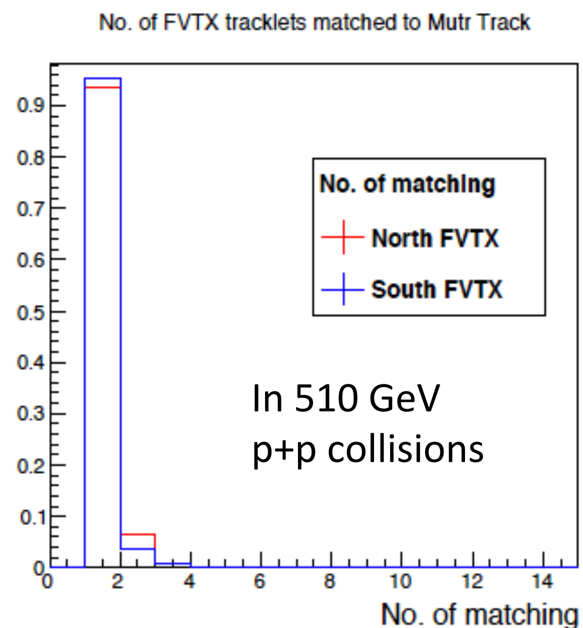
- Good linearity between generated and B to J/ψ ratio.
- Final results from data are under collaboration review.

FVTX-MuTr mis-matching background determination

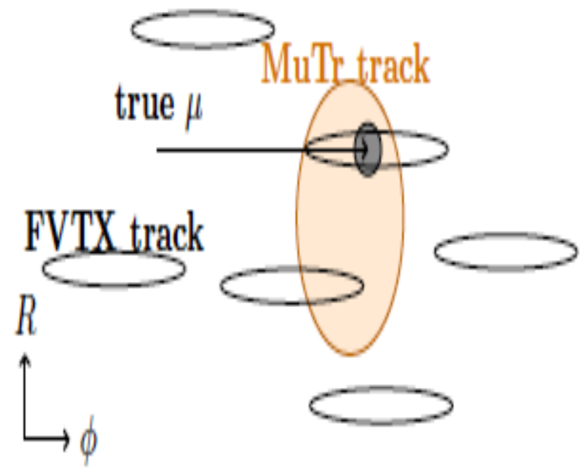
- For one MuTr track, there is a probability of finding more than one FVTX track within the matching window.

In 510 GeV p+p collisions





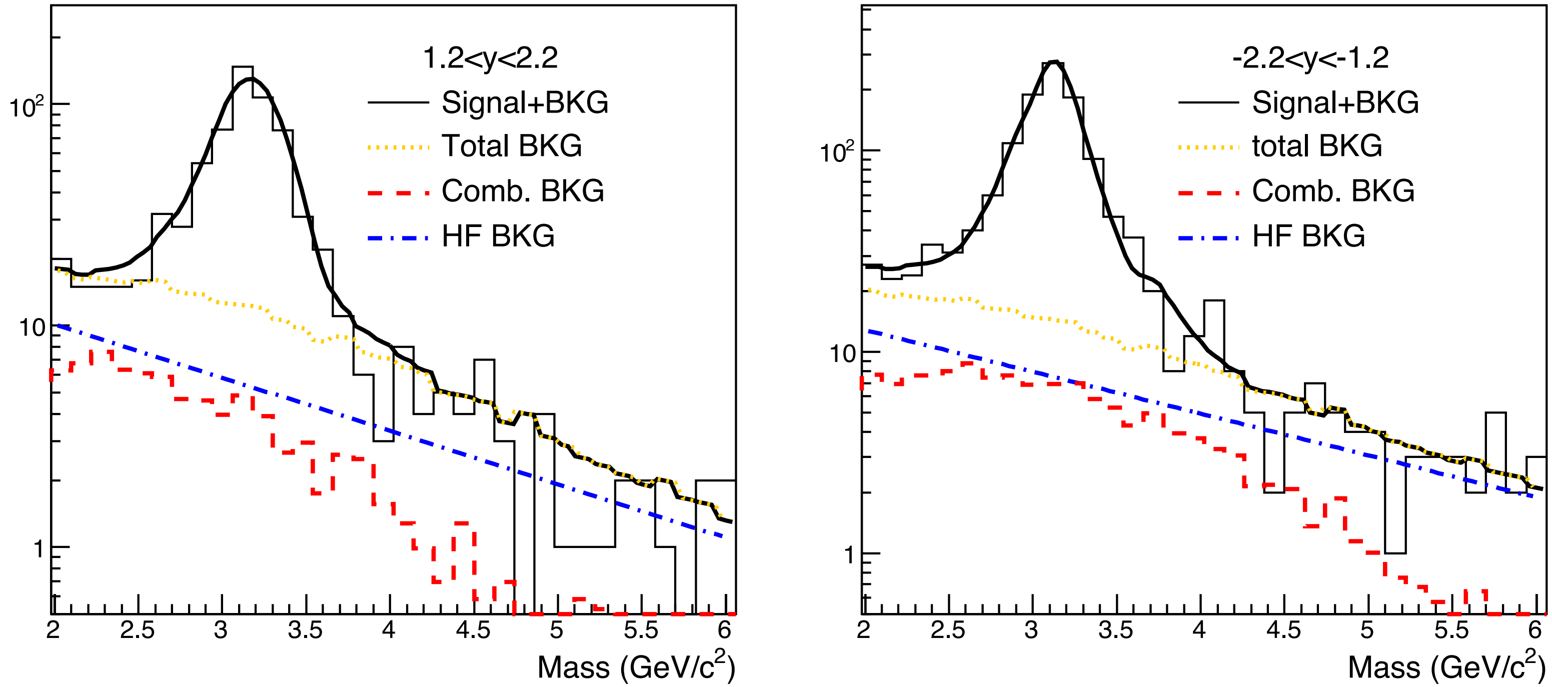
In 200 GeV Cu+Au collisions



- 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.

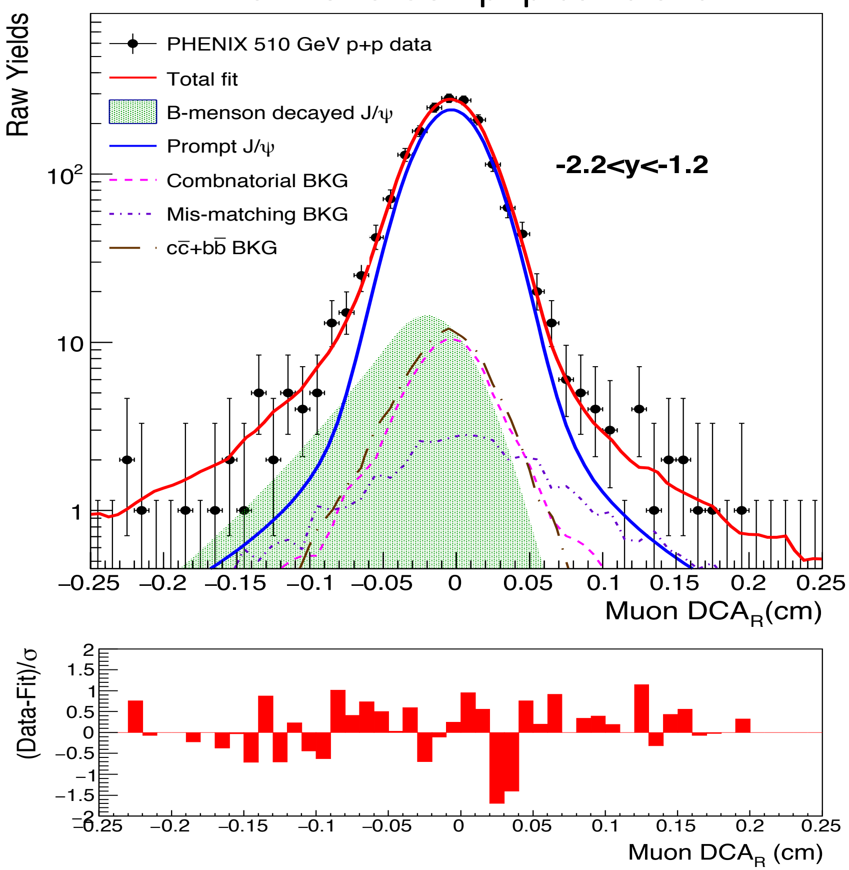


- Total background consists of HF continuum background and mixed event background.
- HF continuum background is comparable with the mixed event background within the mass cut window.

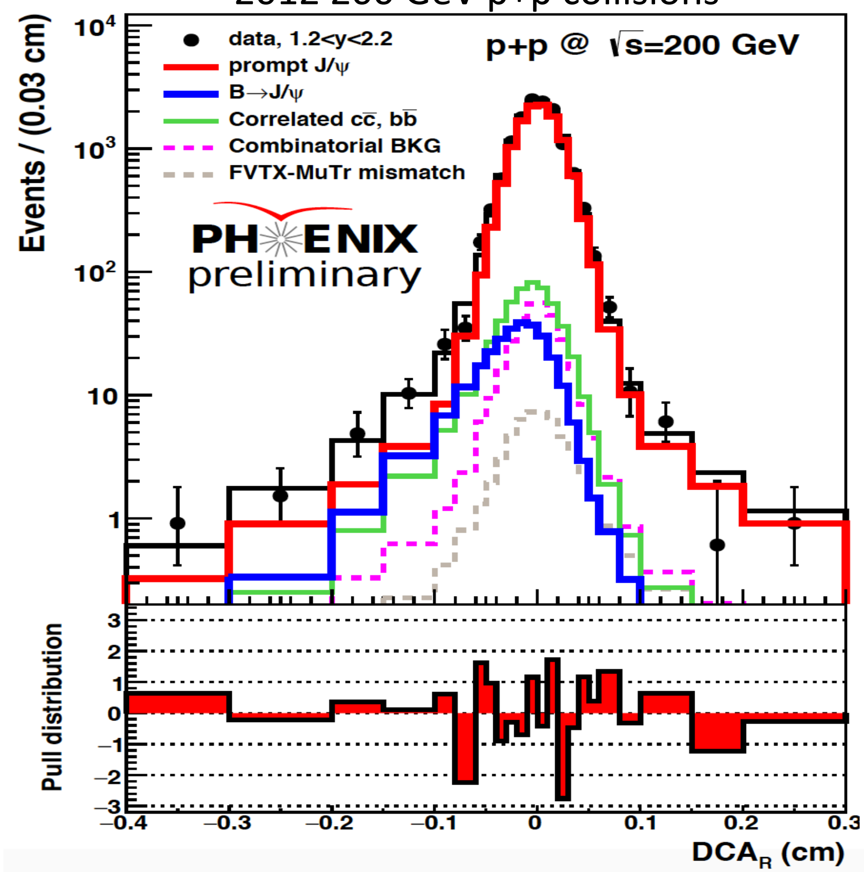
Analysis strategy for the B to J/ψ ratio measurement (III)

- 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

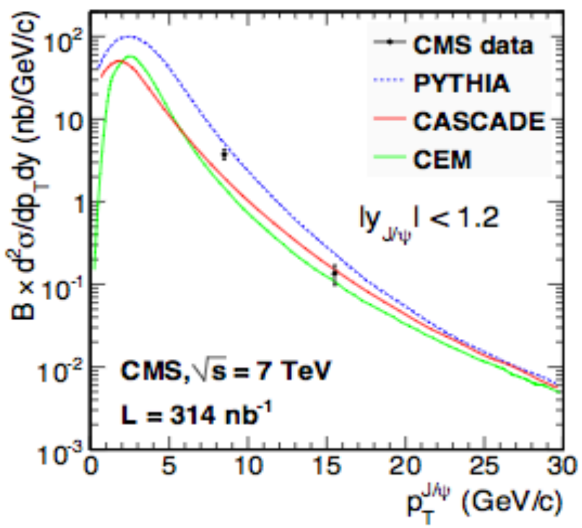


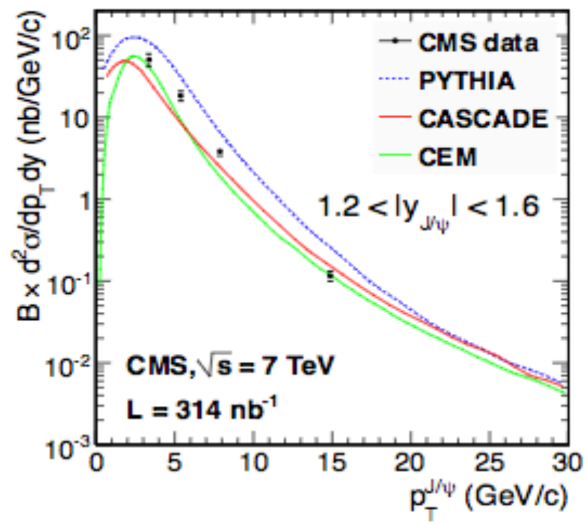
Extracted total $b\bar{b}$ cross section as a function of center of mass energy

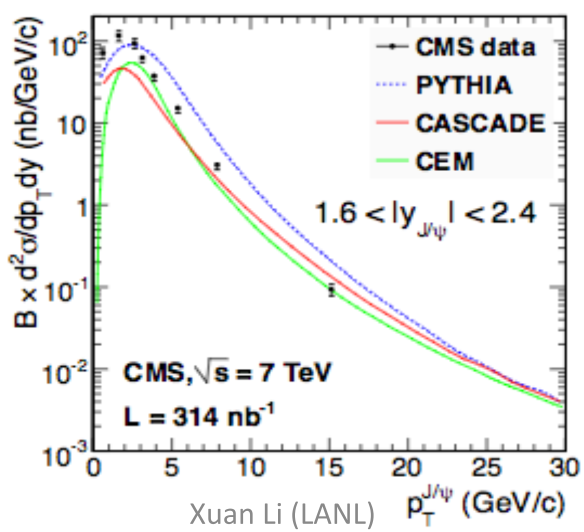
- Use the PPG104 dσ/dy to evaluated inclusive J/ψ cross section within 1.2<|y|<2.2 at 200 GeV.
- Scale from 200 GeV to 500 GeV according to CEM total inclusive J/ψ cross section calculation.
- Divide this value by the PDG b->J/ψ branching ratio 1.09±0.32%.
- Scale the cross section within 1.2<|y|<2.2 to the full rapidity range and scaling factor is calculated based FONLL calculations.

But, something beyond current theory

- CMS 7 TeV prompt J/ψ cross section.



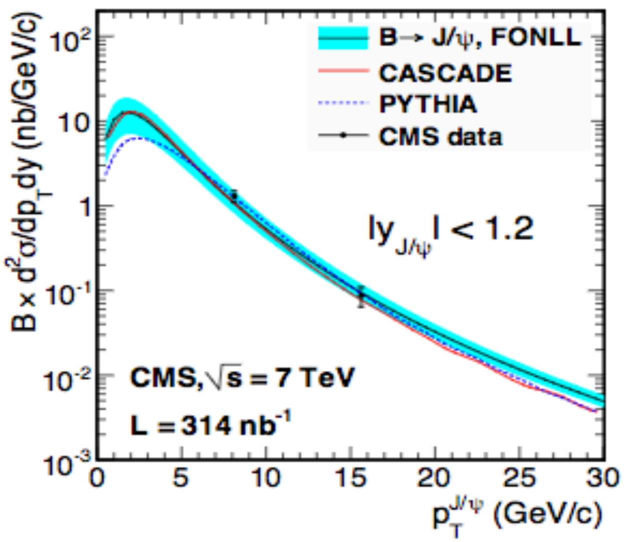


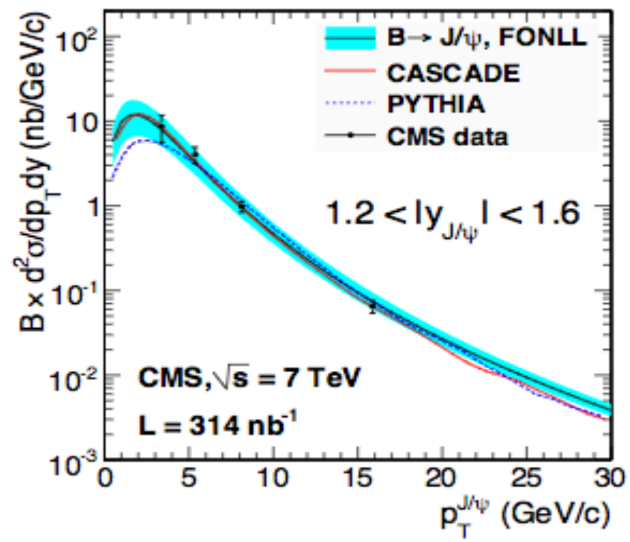


For p_T<5GeV/c, data are much higher than NLO predictions

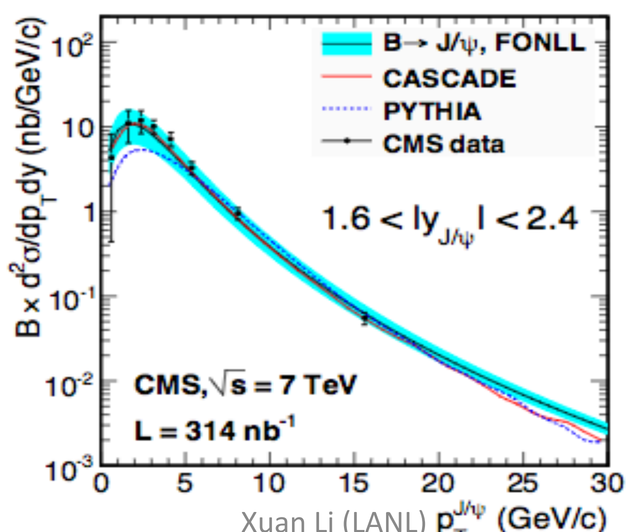
But, something beyond current theory

- CMS 7 TeV Non prompt J/ψ (from B decay) cross se





Expect to see lower B to J/ψ fraction at LHC than theory predictions.



For p_T<5GeV/c, data are on the top edge of theory predictions