Recent heavy flavor measurements from PHENIX at RHIC

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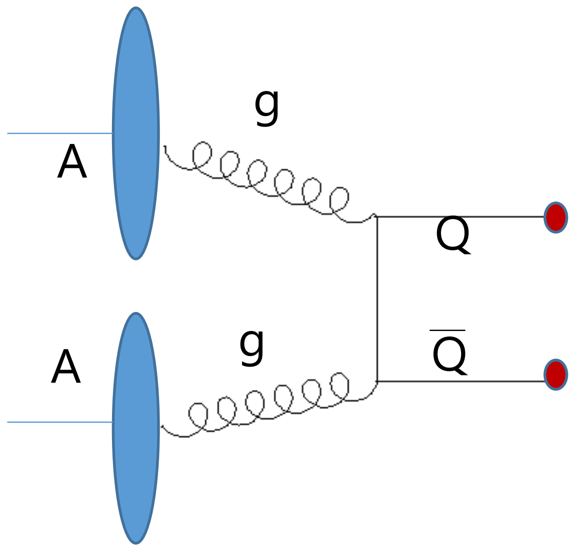
Introduction - why heavy flavor?

- Heavy Flavors (charm and bottom) in HI collisions
  - HF is created at the early stage of the collisions
    - Mainly initial hard scattering due to large mass (Mc~1.2, Mb~4.5GeV >> Λ_{QCD})
    - Production can be calculated by pQCD



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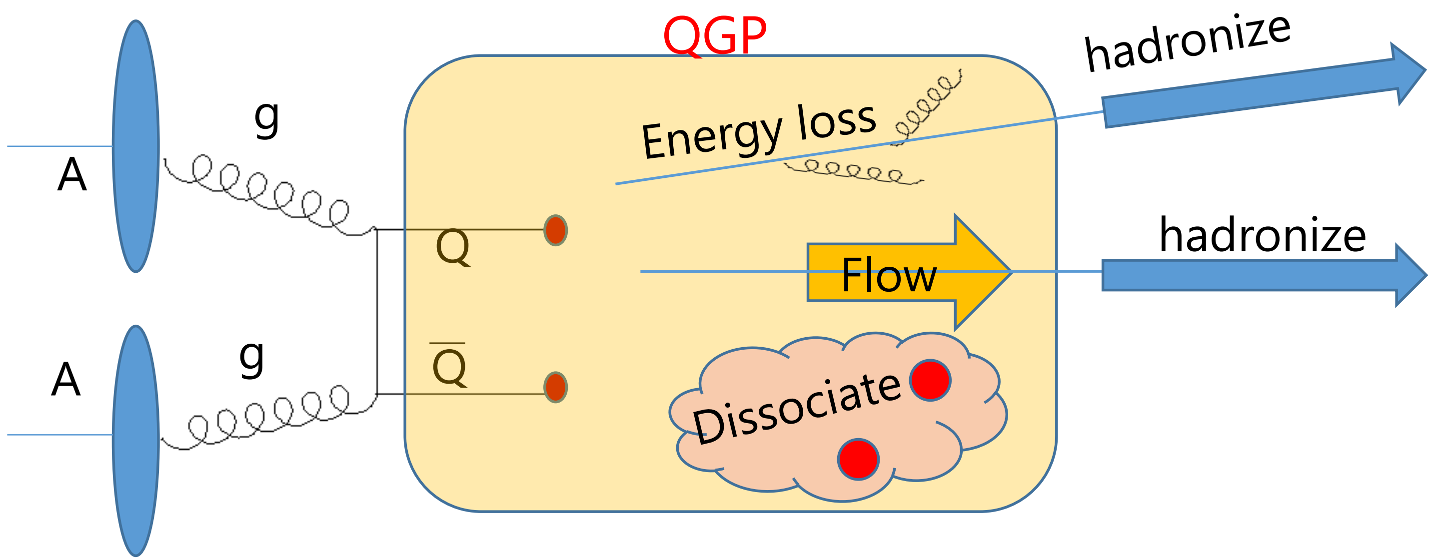
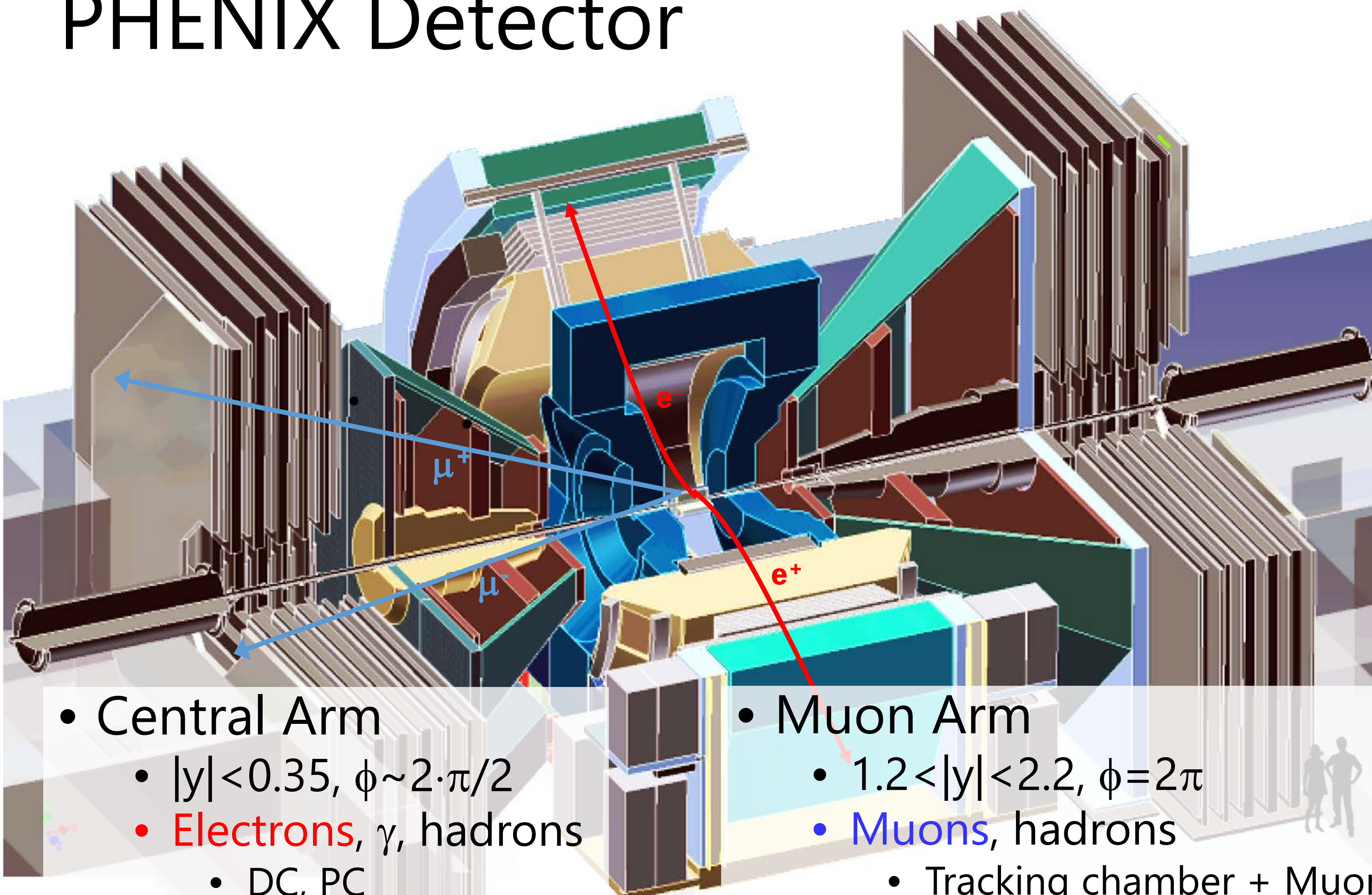
    - Mainly initial hard scattering due to large mass (Mc~1.2, Mb~4.5GeV >> Λ_{QCD})
    - Production can be calculated by pQCD
  - Passing through the hot and dense medium (QGP)
    - Suffer energy loss, flow effect, and dissociation of pairs
    - Sensitive to the medium properties



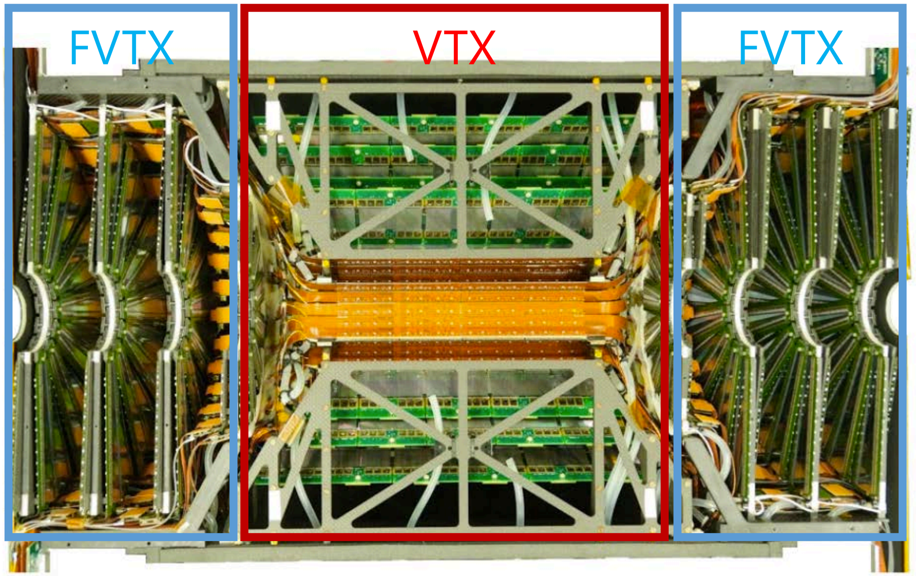
Heavy flavor is a clean probe to study QGP properties

PHENIX Detector



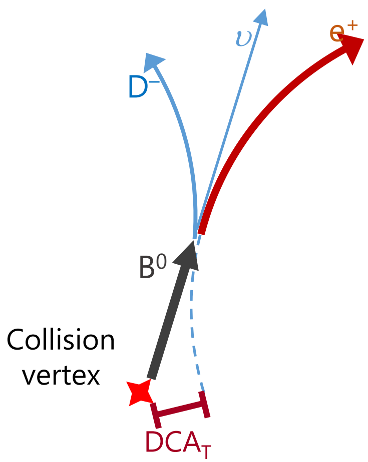
- Central Arm
  - $|y|<0.35$, $\phi\sim2\cdot\pi/2$
  - Electrons, γ, hadrons
    - DC, PC
    - RICH, EMCAL
- Muon Arm
  - $1.2<|y|<2.2$, $\phi=2\pi$
  - Muons, hadrons
    - Tracking chamber + Muon ID (absorber)

PHENIX Silicon Vertex Detector (VTX &FVTX)

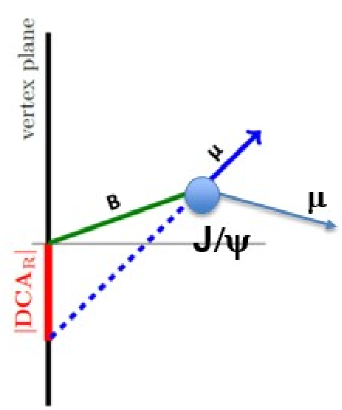


- **VTX** in 2011
  - |y|<1.2, ϕ~2π
  - 4 layers (2 pixels + 2 strips)
  - 50um pixel
- **FVTX** in 2012
  - 1.2<|y|<2.2, ϕ=2π
  - 4 layers (mini-strips)
  - 75um strips

VTX



FVTX



- To measure bottom & charm
  - Measure DCA by VTX and FVTX
  - Utilize difference of decay lengths
  - B^0 : 455 μm, D^0 : 123 μm

Topics :

1. VTX result : Separated bottom and charm electrons at **mid-rapidity** in Au+Au 200GeV

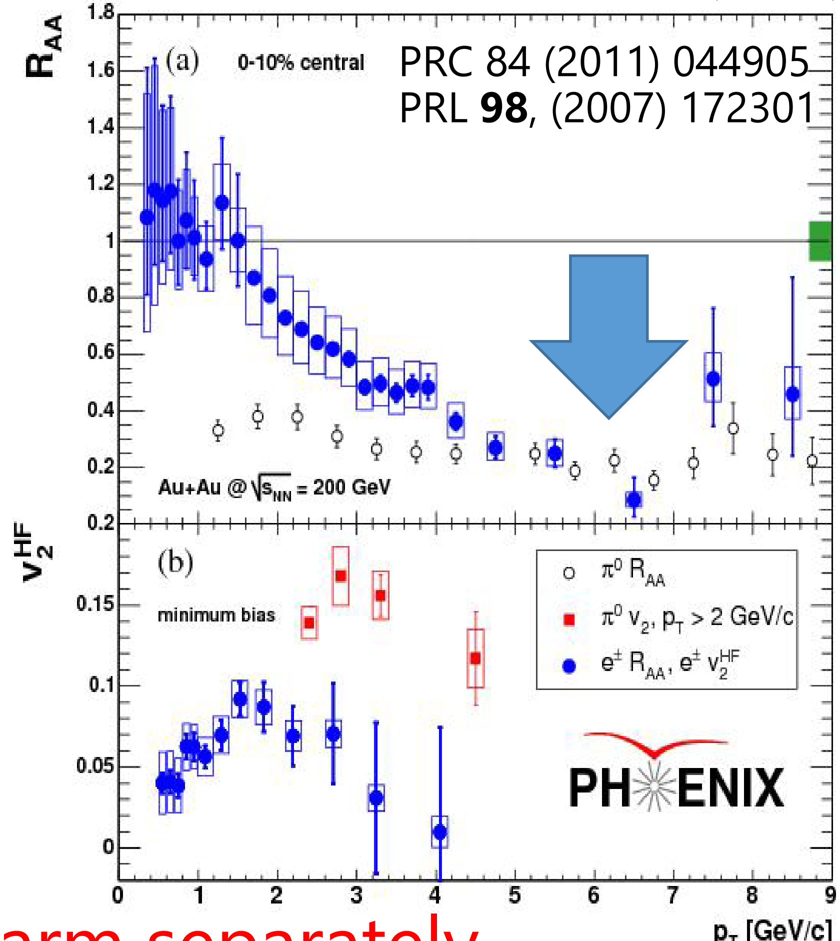
2. FVTX result : Open bottom production via $B \rightarrow J/\psi$ at **forward rapidity** in Cu+Au 200GeV

3. FVTX result : ψ' and J/ψ in p/d + A for CNM effect

Inclusive (charm & bottom) Heavy Flavor Electrons in Au+Au 200GeV

$$R_{AA} = \frac{Yield(Au+Au)}{Ncoll \; * Yield(p+p)}$$

- R_{AA}: strong suppression
  (Ncoll scaling @ low pT)
- v_2 : significant flow



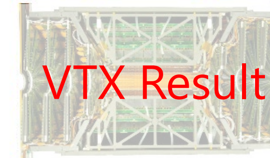
Surprising results

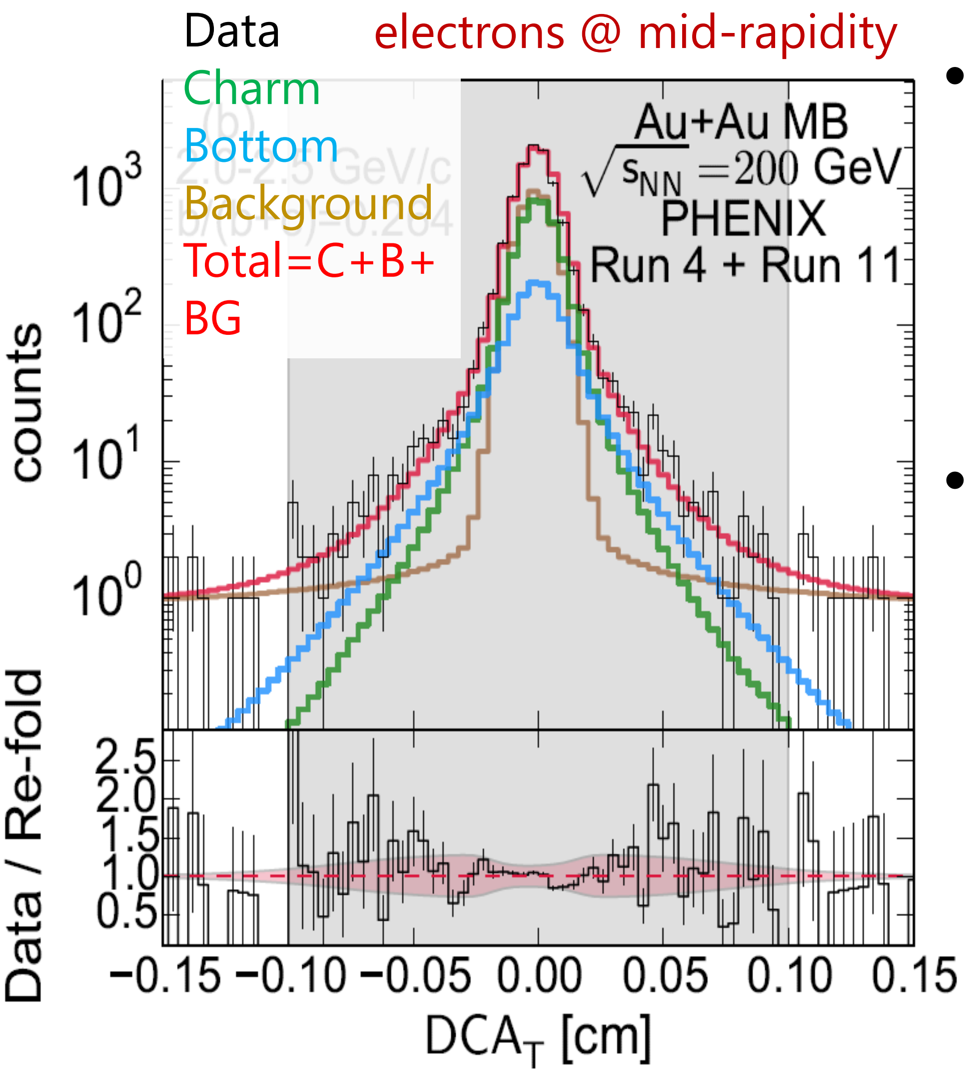
HQ expected to be less energy loss and smaller (zero) flow due to heavy mass

- Questions
  - What is the energy loss mechanism for heavy flavor?
    - Radiative vs Collisional losses
  - Mass dependence of energy loss?

measure bottom & charm separately

DCA for Bottom/Charm separation

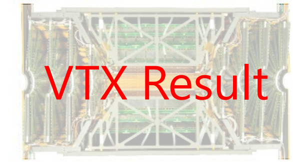




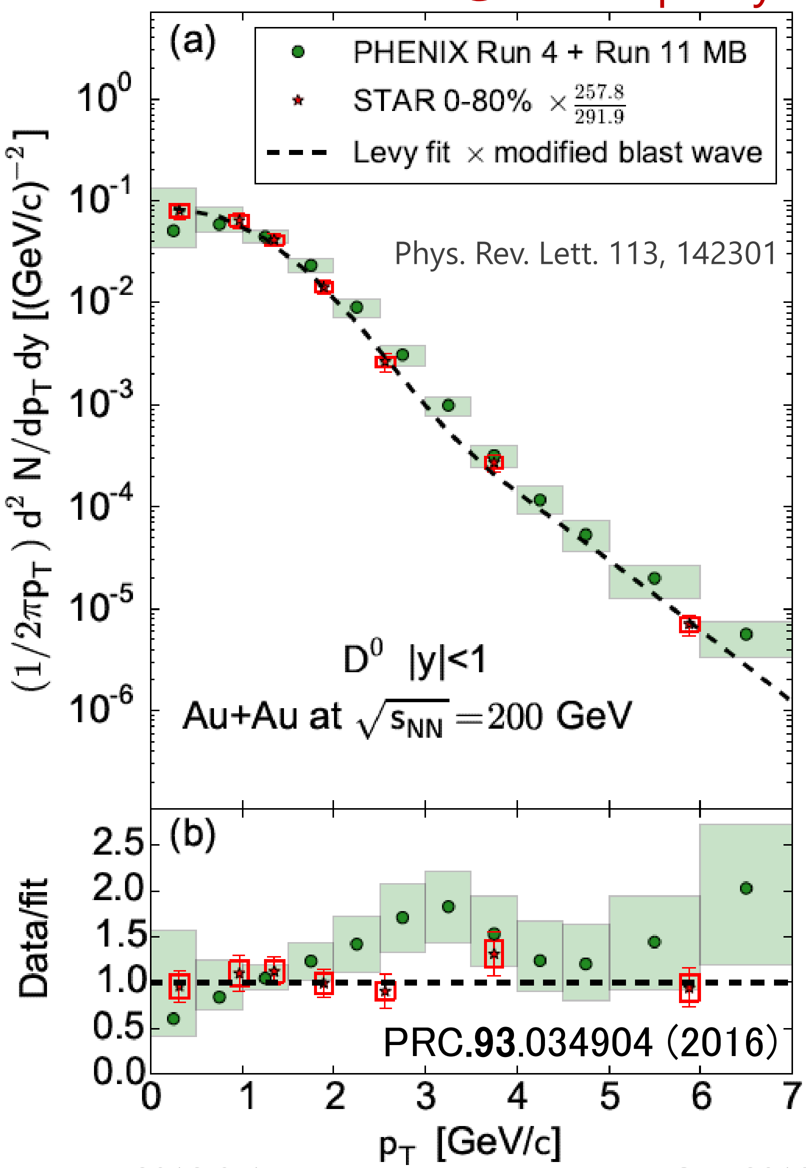
PRC.**93**.034904 (2016)

- First VTX results : Au+Au200
- DCA distributions :
  - Several backgrounds:
    - Conversions, Dalitz decays, J/psi & Ke3 decays, mis-ID hadrons, random association
  - **Bottom & Charm signal**
- Unfolding for B/C separation
  - DCA_T in 2011 & yield in 2004
  - Bayesian inference technique
  - Parameters = yield of charm/bottom hadrons

Charm hadrons from unfolding



electrons @ mid-rapidity



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- Unfolding for B/C separation
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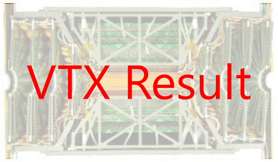
  - Bayesian inference technique
  - Parameters = yield of charm/bottom hadrons
- Unfolded charm hadrons are in good agreement with STAR D^0 measurement

Bottom electron fraction $^{b\rightarrow e}/_{b\rightarrow e+c\rightarrow e}$



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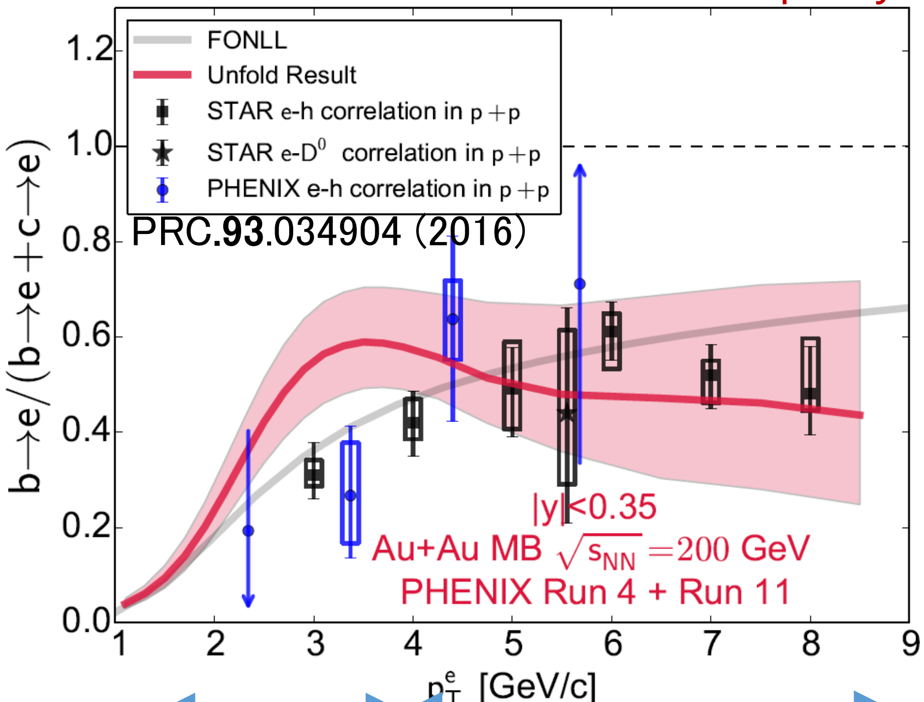
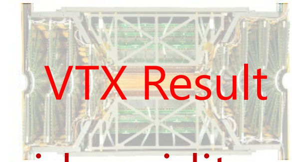
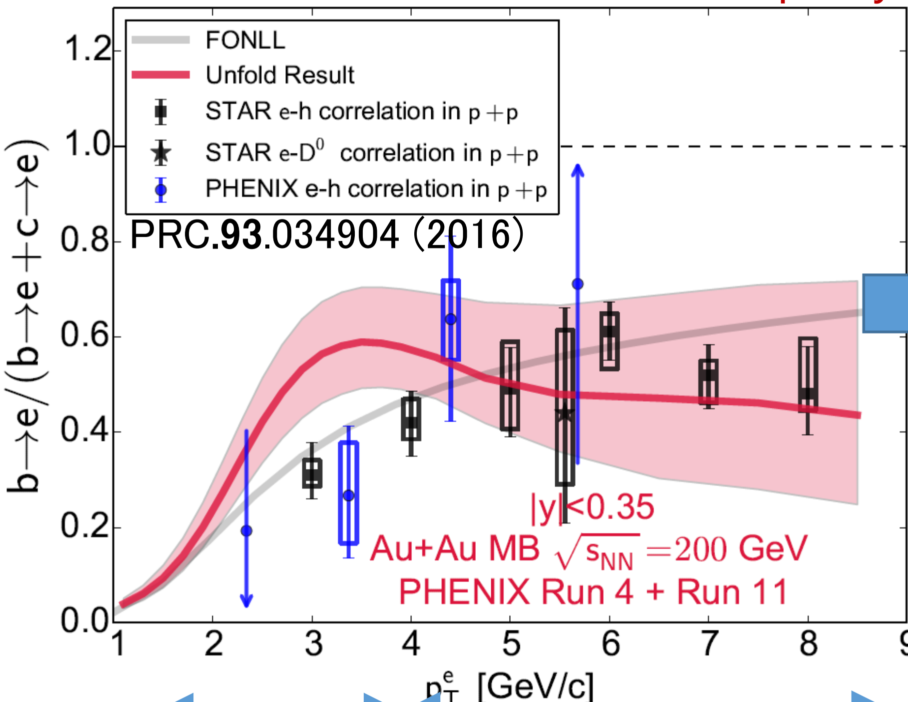


$F_{AuAu} > F_{pp}$ $F_{AuAu} \sim F_{pp}$

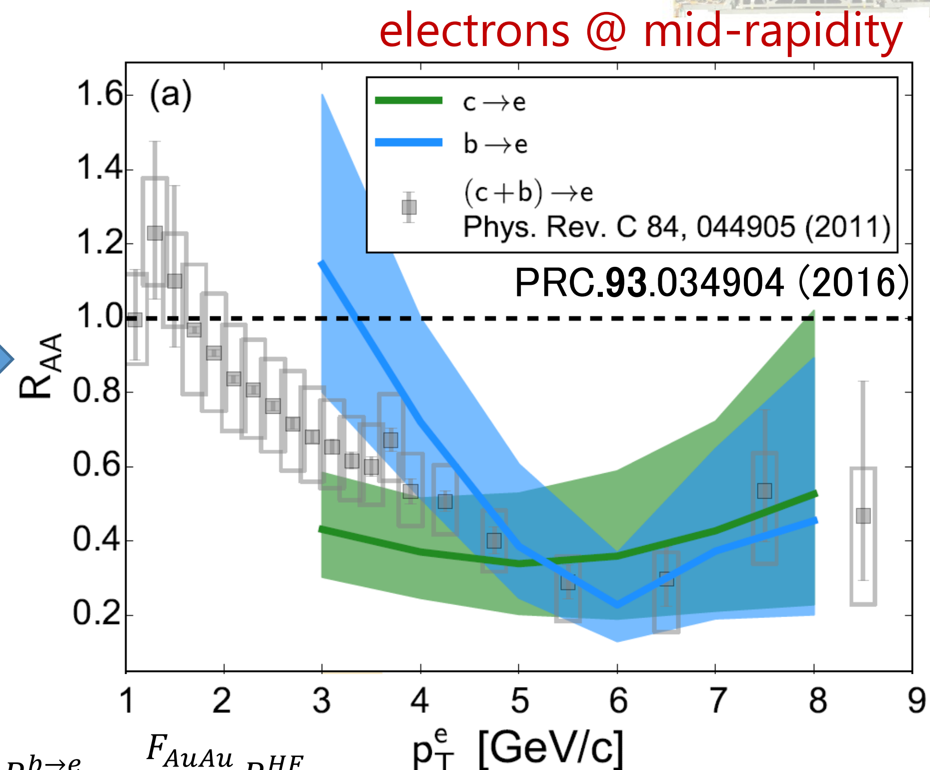
- FONLL is consistent with p+p data
  - Two particle correlation in p+p
- Au+Au shows difference with p+p

First result : Bottom and Charm R_{AA}





$F_{AuAu} > F_{pp}$ $F_{AuAu} \sim F_{pp}$



$$R^{b\to e}_{AuAu} = \frac{F_{AuAu}}{F_{pp}} R^{HF}_{AA}$$

$$R^{c\to e}_{AuAu} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R^{HF}_{AA}$$

- Bottom and charm are similarly suppressed at high p_T
- Bottom is less suppressed than charm at p_T=3-4 GeV/c
- First measurement at RHIC energy

Topics :

1. VTX result : Separated bottom and charm electrons at **mid-rapidity** in Au+Au200GeV

2. FVTX result : Open bottom production via B→J/ψ at **forward rapidity** in Cu+Au 200GeV

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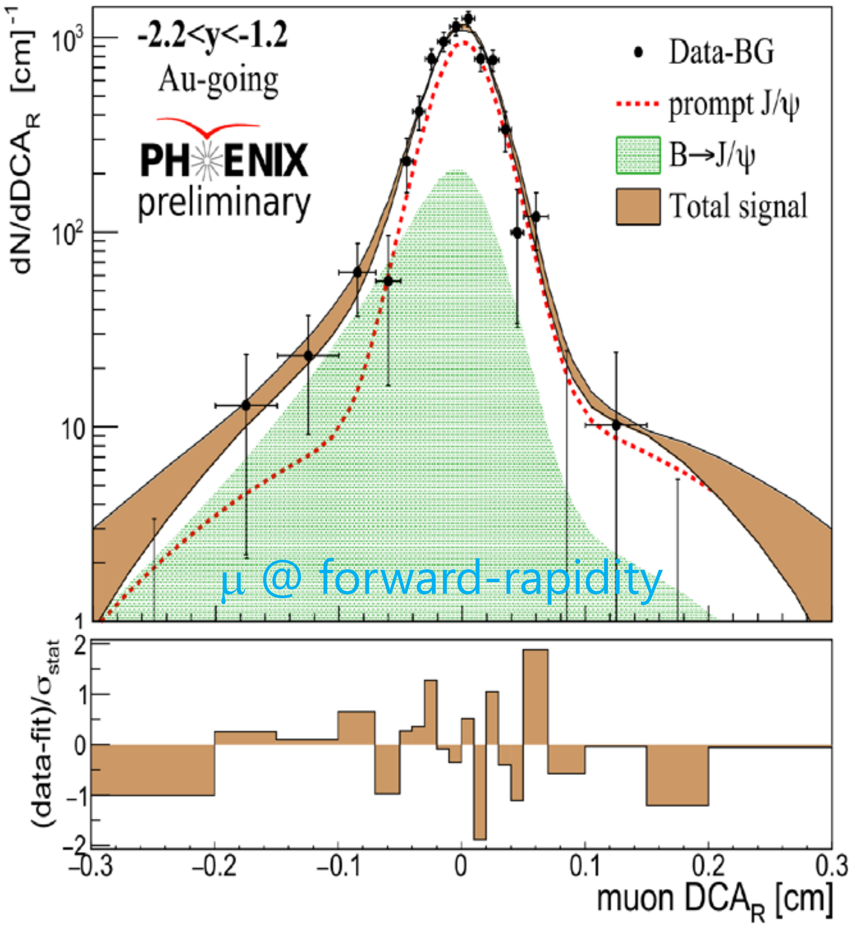
First results : B→J/ψ in Cu+Au

FVTX Result

μ DCA_R from J/ψ decays

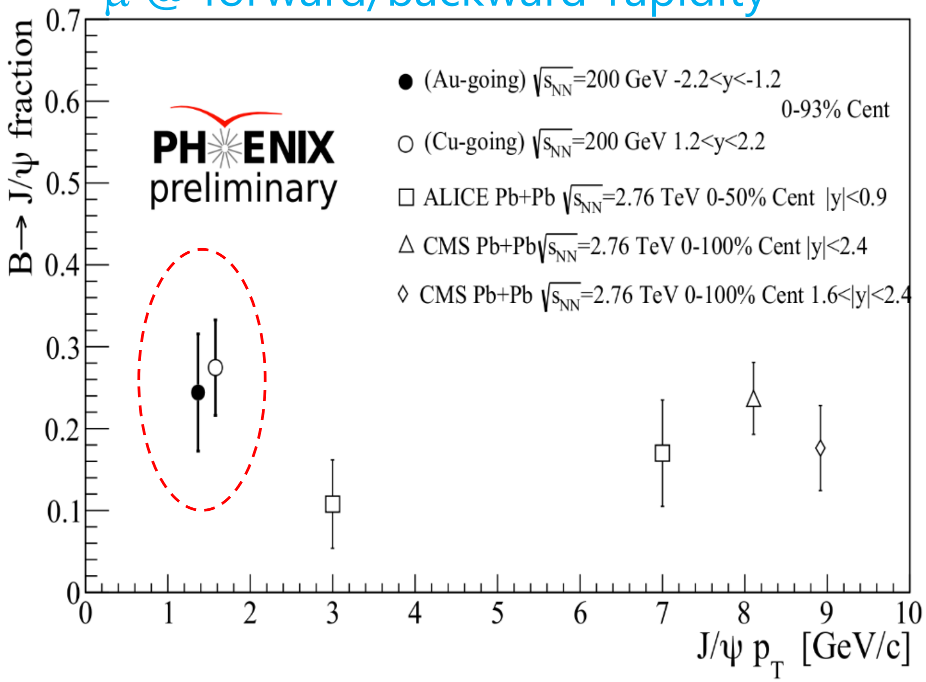


- Cu+Au 200GeV in 2012
  - Forward/Backward J/psi → μμ
- Measure μ DCA_R from J/ψ decays
  - separate B→J/ψ and prompt J/ψ
  - Utilize difference of decay lengths
  - B→J/ψ: 455 μm, Prompt J/ψ: 0μm
- DCA_R fits with template shapes of B→J/ψ & prompt J/ψ
- The sum of DCA_R contributions agrees well with the data

First results : B→J/ψ in Cu+Au

FVTX Result

μ @ forward/backward-rapidity



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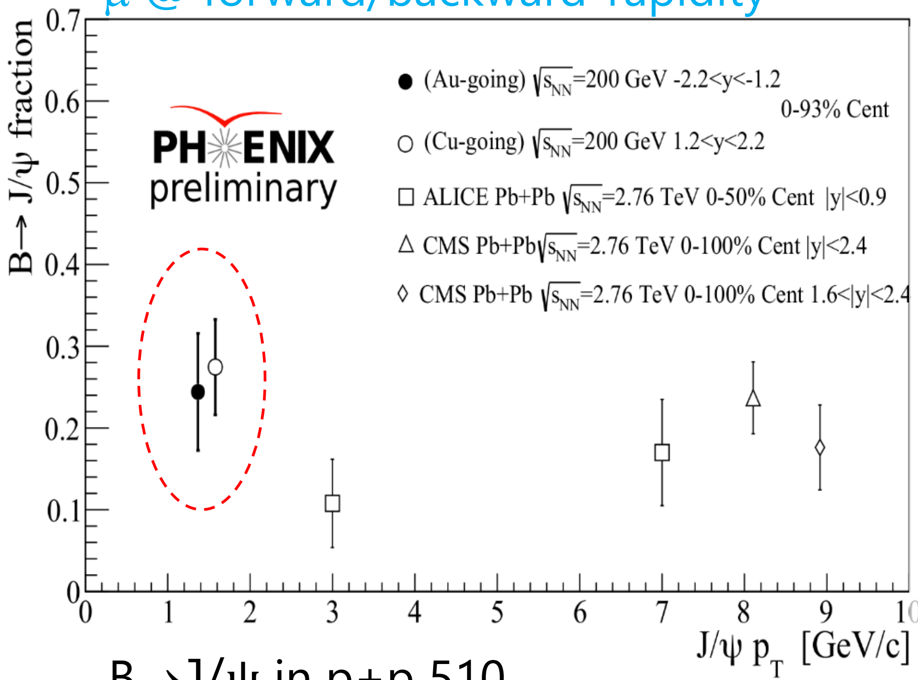
- DCA_R fits with template shapes of B→J/ψ & prompt J/ψ
- The sum of DCA_R contributions agrees well with the data
- B fraction was determined for both Cu-& Au-going directions
- B fraction is larger than that at LHC because prompt J/ψ is more suppressed at RHIC

First results : B→J/ψ in Cu+Au

FVTX Result

μ @ forward/backward-rapidity



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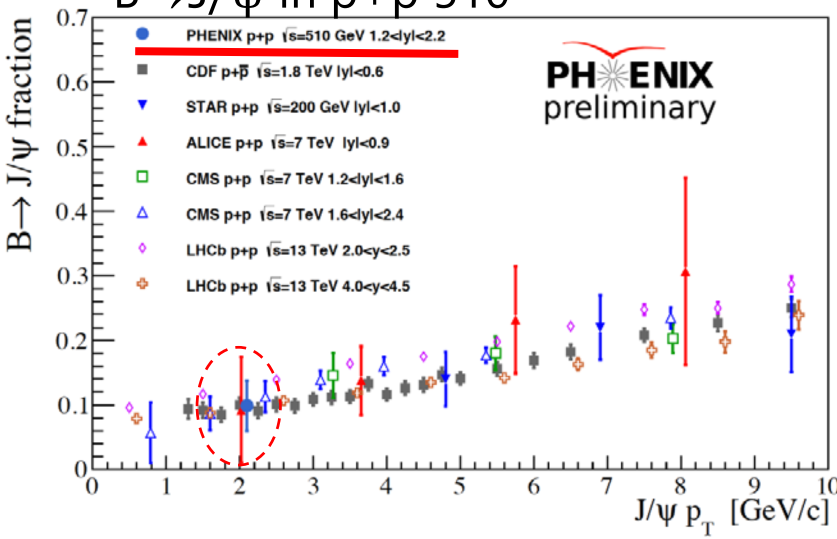
B→J/ψ in p+p 510

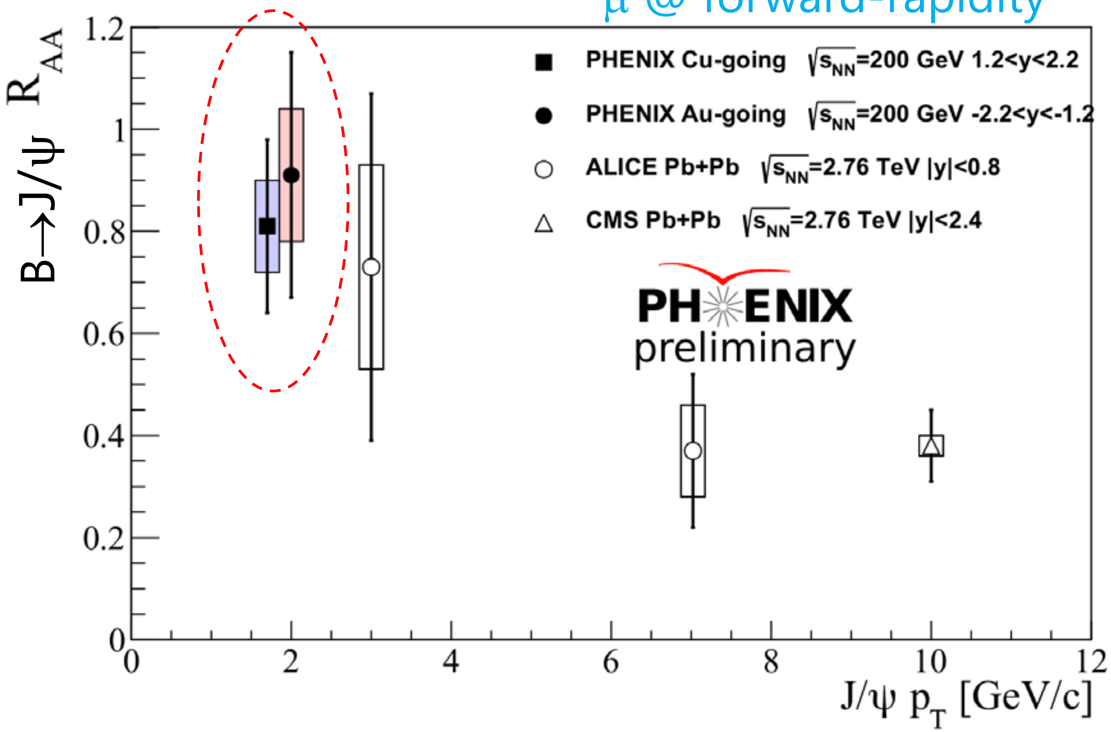


- B→J/ψ measured in p+p 510GeV.
- F(B→J/ψ) is independent with collision energy.
- Assume F(B→J/ψ) = 0.1 for R_{AA}

First results : B→J/ψ R_{AA} in Cu+Au

FVTX Result

μ @ forward-rapidity



$$R_{CuAu}^{B\to J/\psi} = \frac{F_{B\to J/\psi}^{CuAu}}{F_{B\to J/\psi}^{pp} = 0.1} R_{CuAu}^{inc.J/\psi}$$

Assume F(B) in pp =0.1

- B→J/ψ R_{AA} is consistent with little/no suppression in Cu & Au going directions
  - Consistent qualitatively with bottom electrons at RHIC
  - Same trend with the suppression at LHC
    - less at low pT and more at high pT

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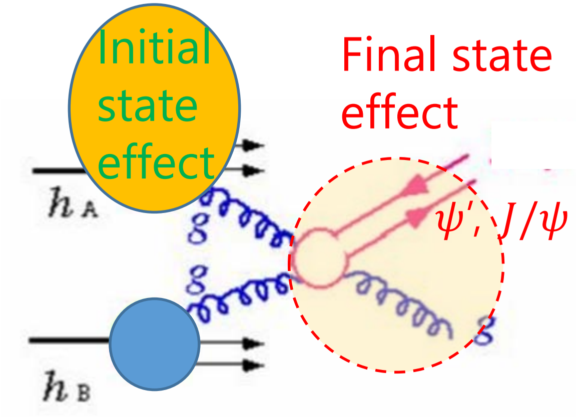
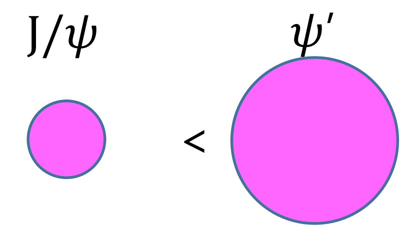
CNM in ψ' production

CNM is key to understanding charmonia suppression in QGP



- Charmonia can be dissociated in QGP due to color screening but many other effects modify charmonia yield as well
- ψ' and J/ψ is good tool to study CNM
  - **Initial state effects** (shadowing, Cronin) should be similar for J/ψ and ψ'
  - **Final state effect** (breakup) can be different since their different binding energies (=radii)



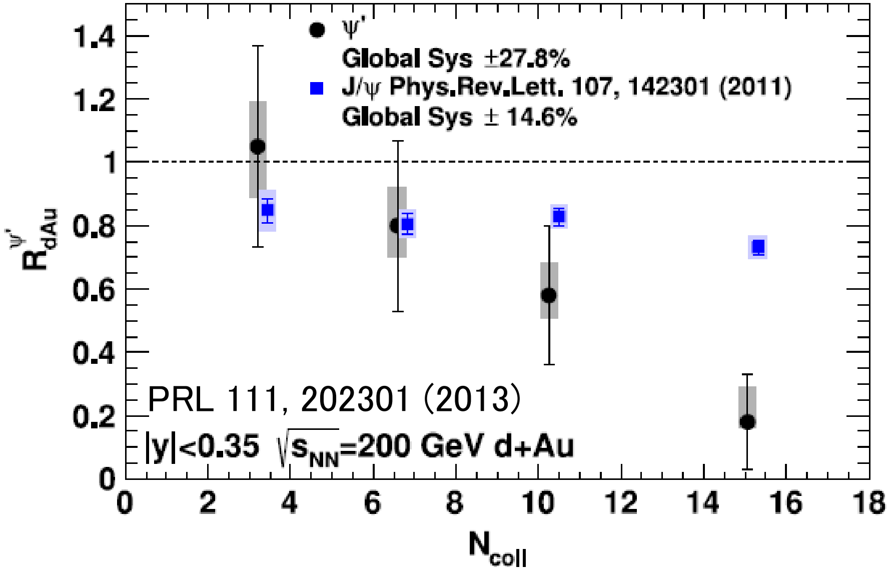
	J/ψ	ψ'
ΔE	= 0.64	0.05 (GeV)
R	= 0.25	0.45 (fm)

Measure ψ' and J/ψ in different p/d + A

ψ' suppression in d+Au 200GeV

ψ' in CNM

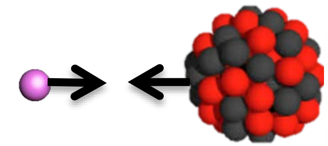
ψ', $J/\psi \rightarrow ee$ at mid. rapidity in d+Au



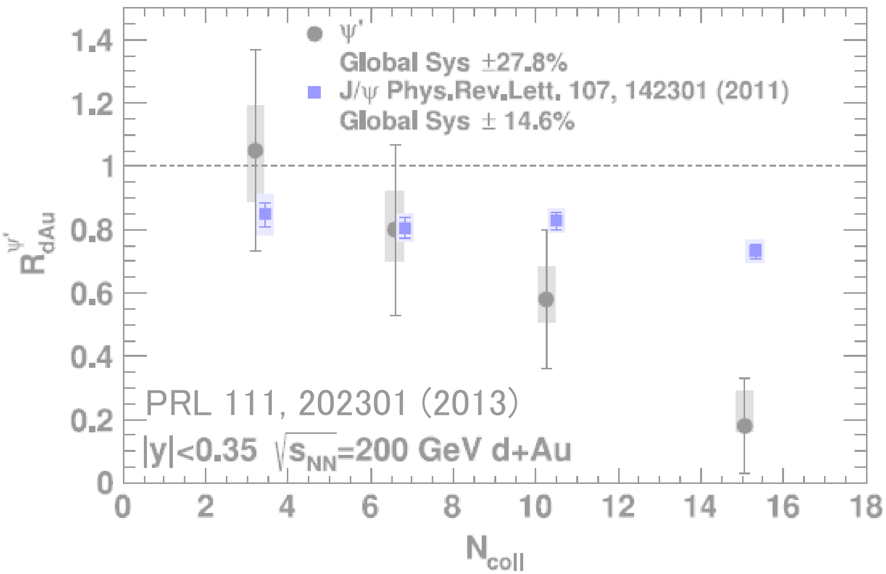
- Large suppression of ψ' is observed in central d+Au
  - Sequential suppression of J/ψ and ψ' is seen
  - nPDF & nuclear break up cannot explain

ψ' & J/ψ Suppression in p+A 200GeV

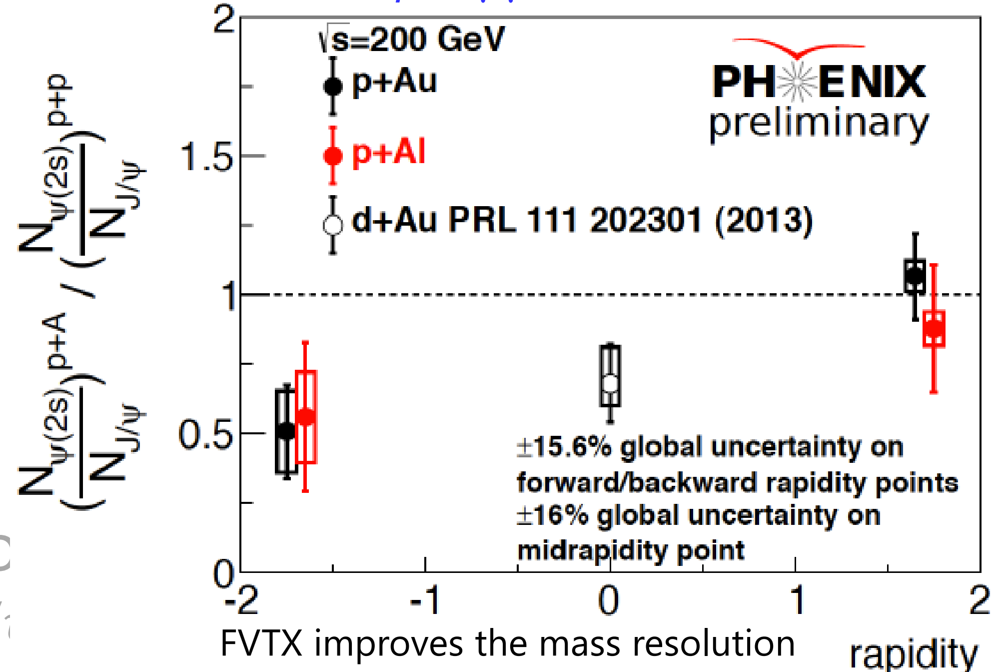
ψ' in CNM



ψ', $J/\psi \rightarrow ee$ at mid. rapidity in d+Au



New result : $\psi' \rightarrow \mu\mu$ at forward/backward

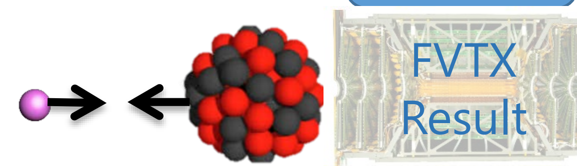


FVTX improves the mass resolution

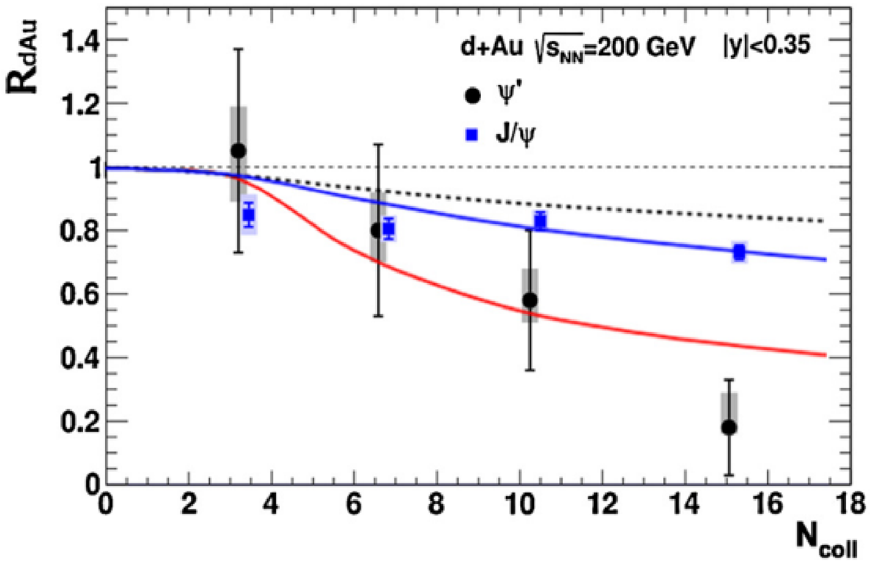
- Large suppression of ψ' is c
  - Sequential suppression of J/
  - nPDF & nuclear break up cannot explain
- Larger suppression on ψ' for A-going and equivalent suppression on both states for p-going direction
  - No collision system dependence is seen

ψ' & J/ψ comparison with Model

ψ' in CNM



ψ', $J/\psi \rightarrow ee$ at mid. rapidity



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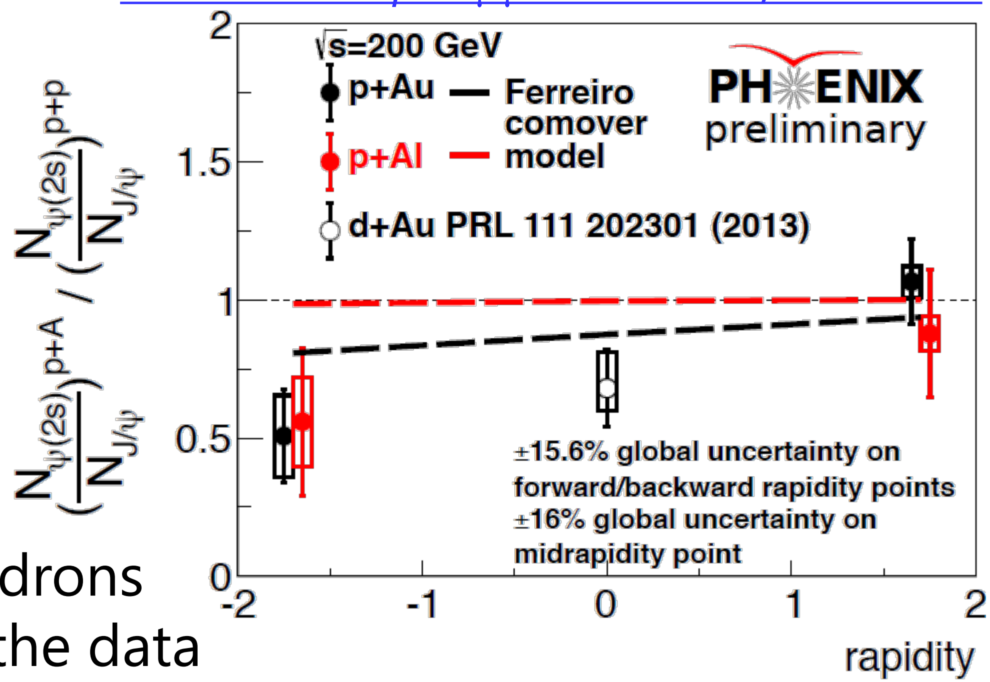
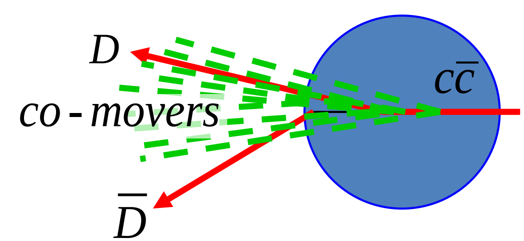


- Model including co-moving hadrons is qualitatively consistent with the data
  - Sequential suppressions of J/ψ and ψ'
  - Rapidity dependence of the suppressions



Co-moving hadrons should contributes to J/ψ suppression in A+A collisions

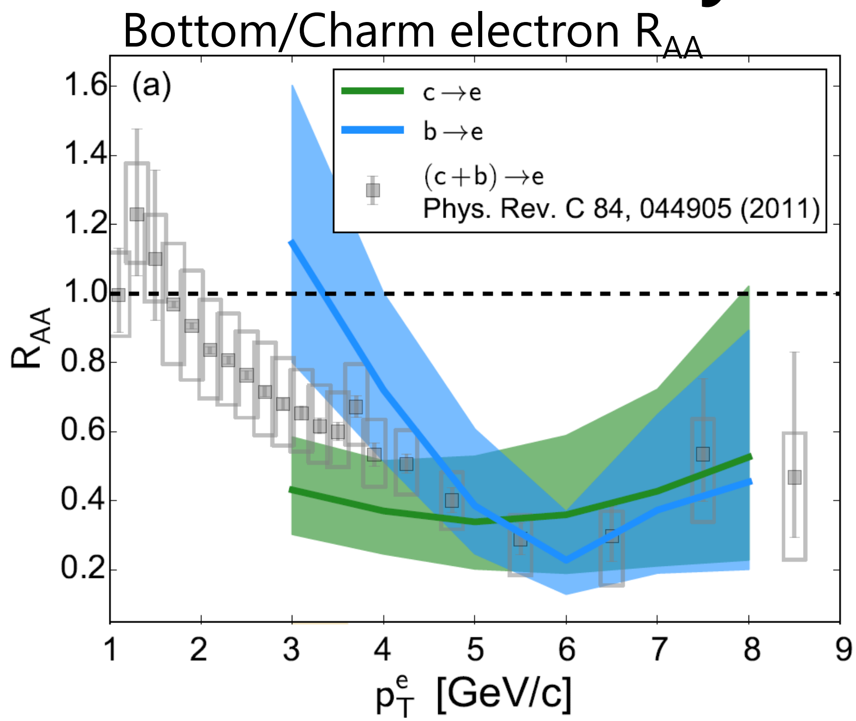
Summary

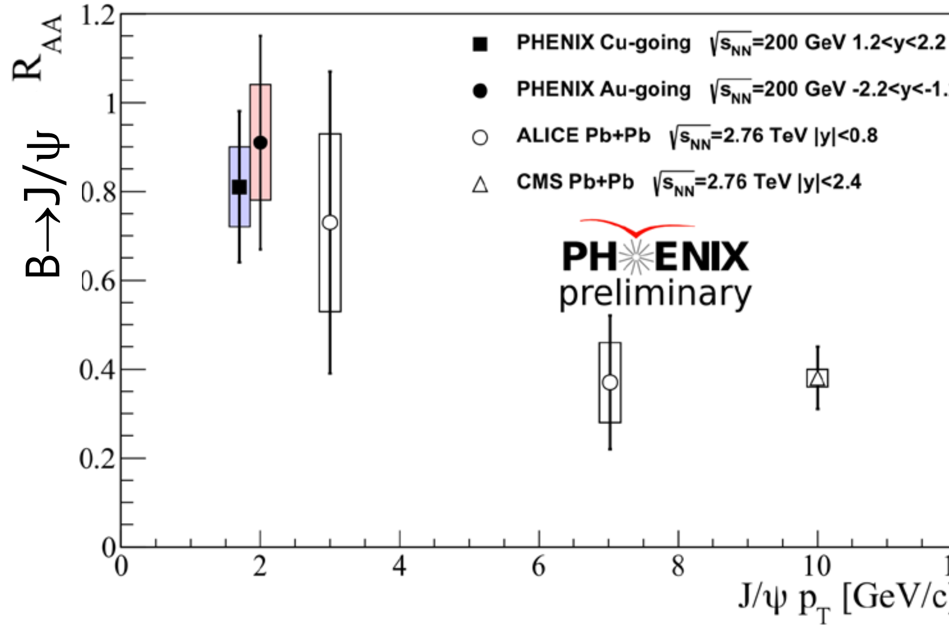
VTX Result
FVTX Result
ψ' in CNM

- New bottom results
  - First result of bottom suppression from both VTX and FVTX
  - Bottom in Au+Au 200 GeV
    - similarly suppressed as charms at high p_T
    - less suppressed at low pT
  - Little suppression for $B \to J/\psi$ at low p_T in Cu+Au 200 GeV
- ψ' suppression in CNM
  - Sequential suppressions of ψ' and J/ψ is observed at mid. and backward rapidity in 200 GeV p/d + A collisions
  - Co-moving hadrons are important to understand quarkonia suppression
- Outlook
  - VTX / FVTX silicon detector enables precise open/closed heavy flavor measurements
  - 10x Larger statistics Au + Au and good p+p/p+A dataset in 2014-2016. New results will come soon. Stay tuned!

Backup

Outlook : Heavy Flavor

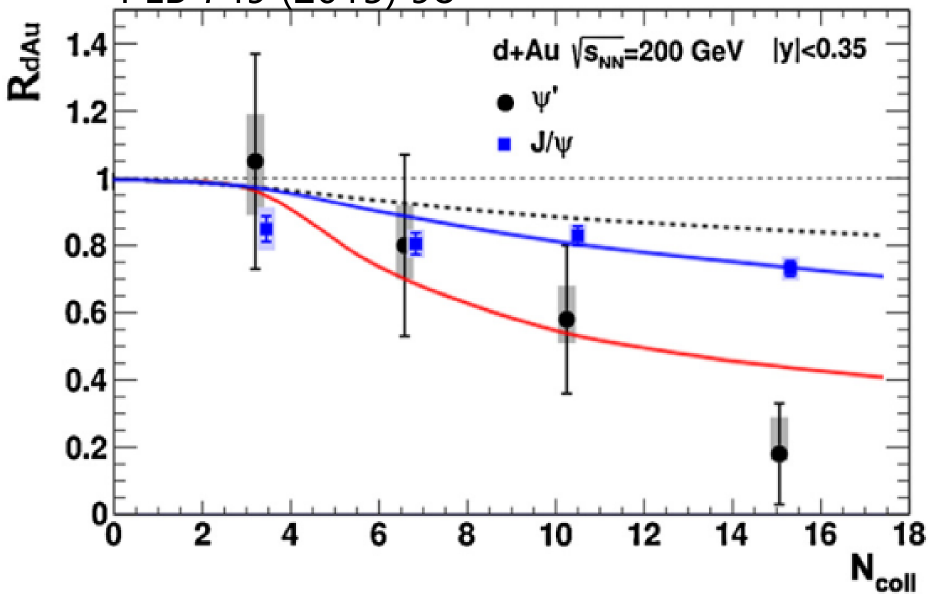


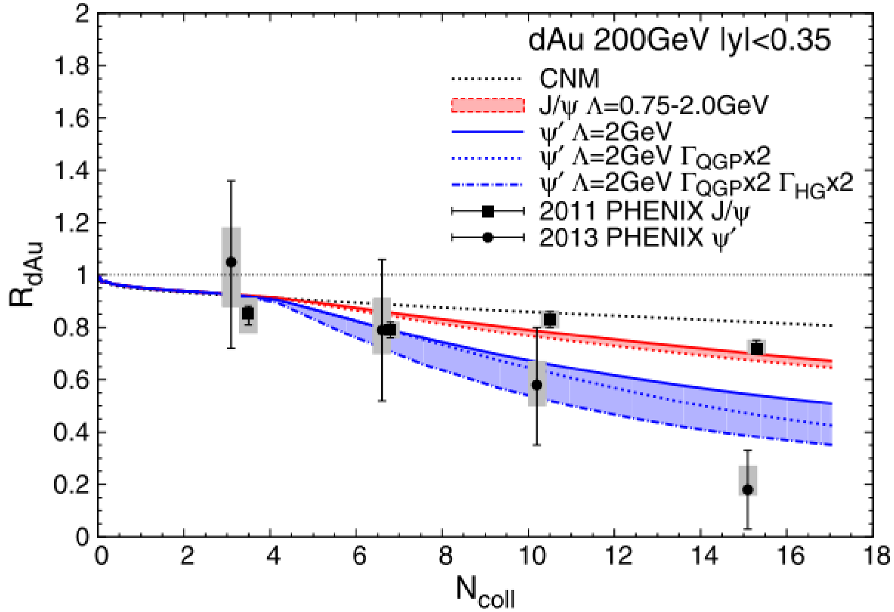


- Large statistics in 2014 + 2016 Au+Au datasets
  - 10 ~ 20 times enables to study with separated bottom/charm
    - Higher pT,
    - centrality dependence
    - Vn
- Good 2015 p+p and p+Au datasets for baseline

Suppression in d+Au 200GeV

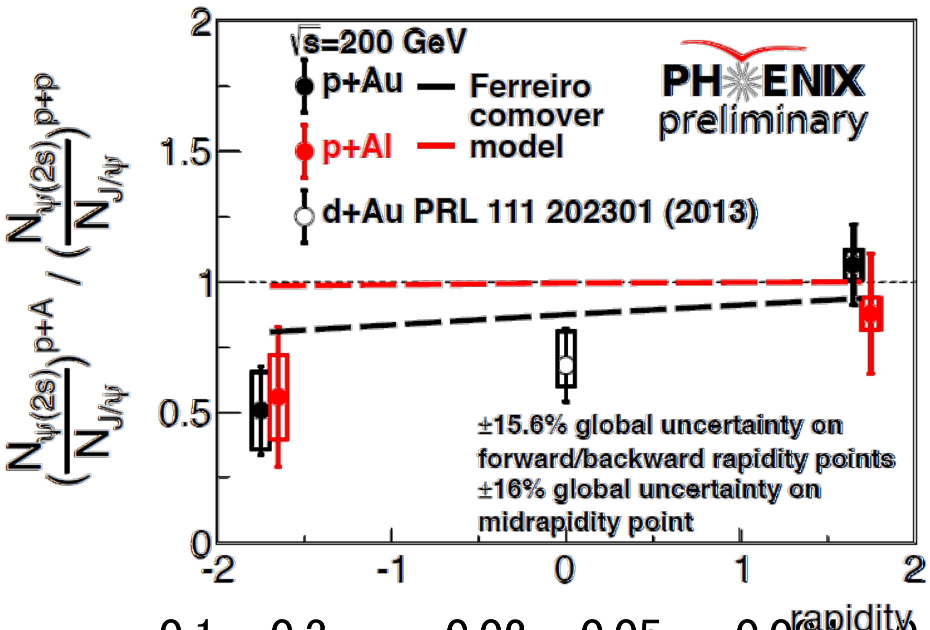
PLB 749 (2015) 98

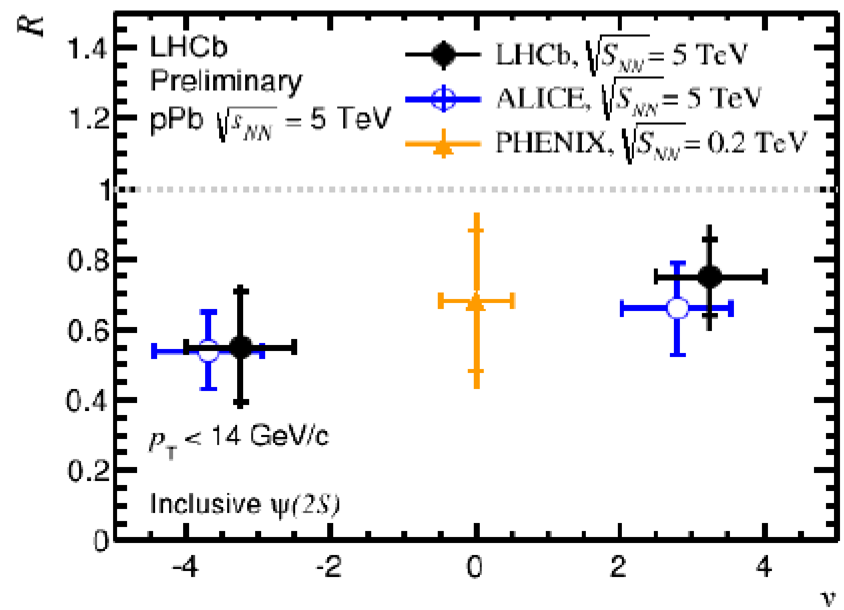




- Large suppression of Psi’ is observed in central d+Au
  - Break up in nucleus or co-moving hadrons?
- Model including co-moving hadrons is in good agreement with sequential dissociation of J/psi and Psi’ in d+Au collisions
- A model including QGP in d+Au + hadron gas is also in good agreement

Comparison with LHC





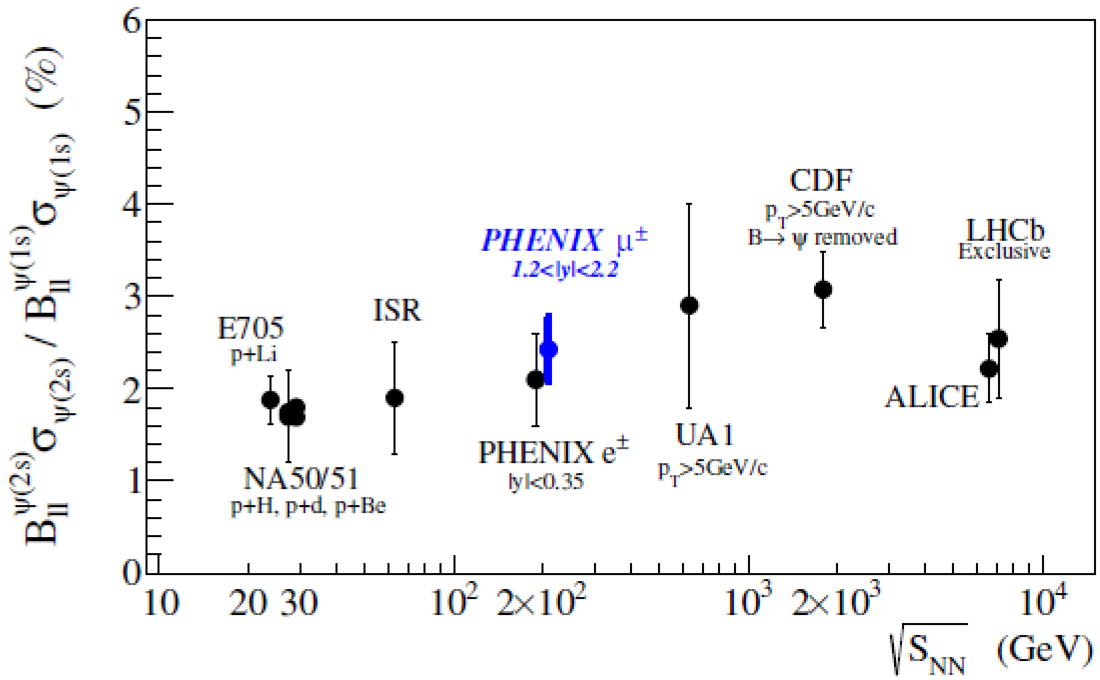
0.1 – 0.3 0.02 – 0.05 0.004 – 0.01

nuclear crossing time τ (fm/c)

J/psi formation time: ~ 0.15

- Similar suppression of Psi' and J/psi at LHC
- But large suppression even at forward y
  - Breaking up by comover may be significant due to larger particle multiplicity

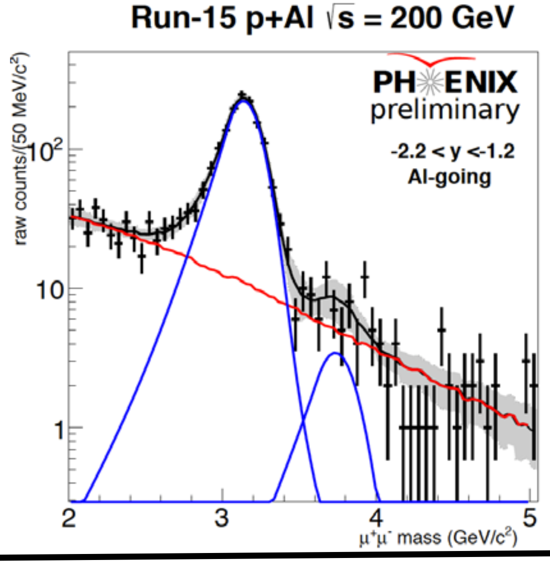
Psi' / J/psi ratio in pp



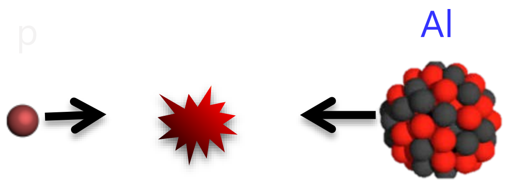
- The ratio is independent of collision energy
  - Even cc cross section changes with collision energy

Quarkonia:

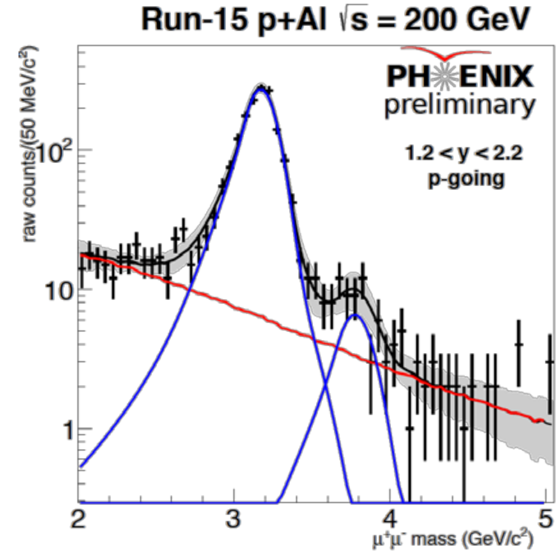
Backward: Al-going direction



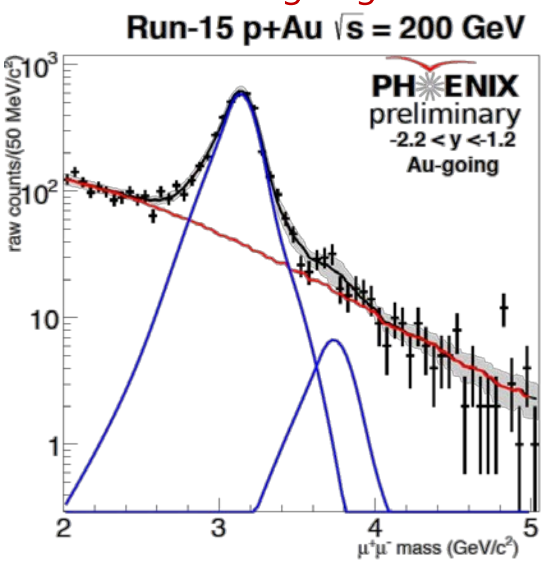
central collision



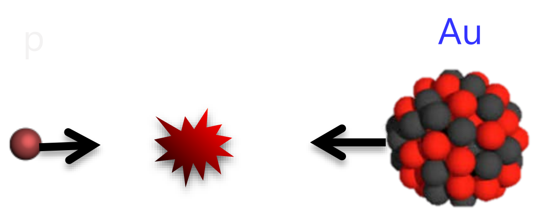
Forward: p-going direction



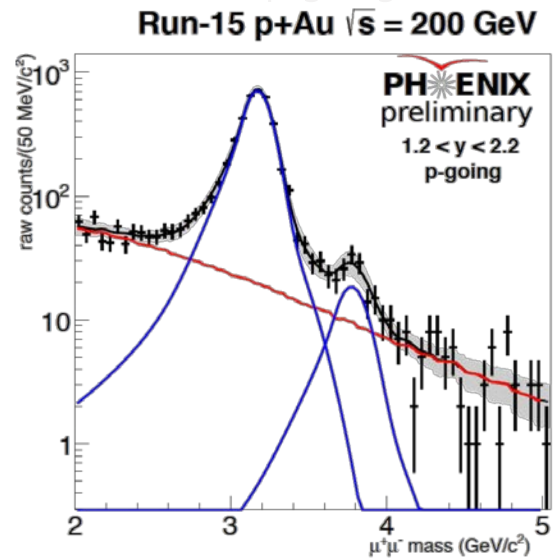
Backward: Au-going direction



central collision

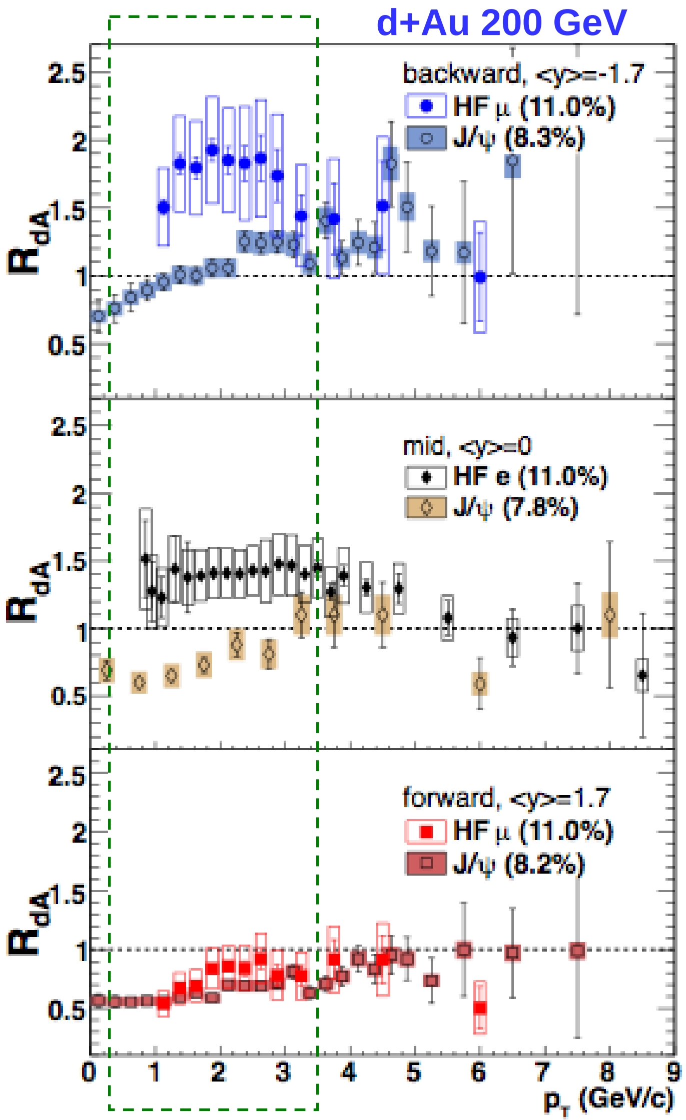


Forward: p-going direction



RAA for open and closed heavy flavor

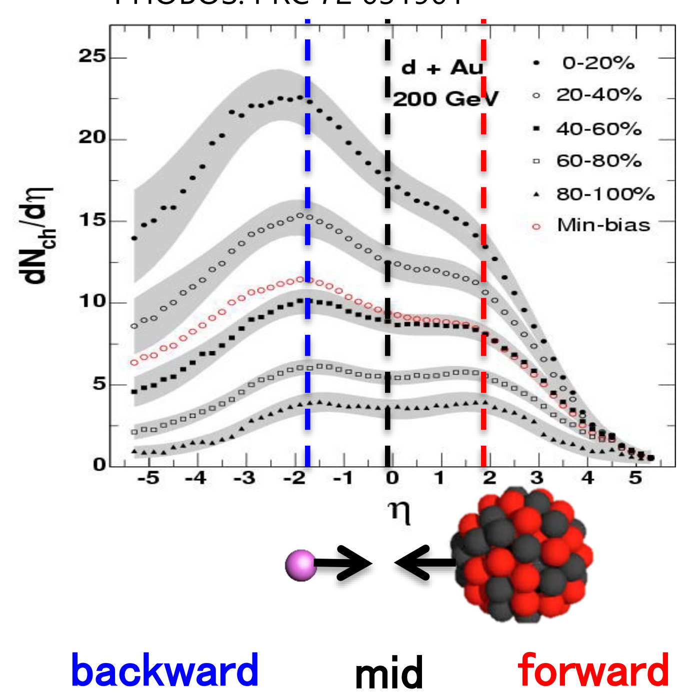
PEHNIX: PRC 87 034904
PHENIX: PRL 112 252301



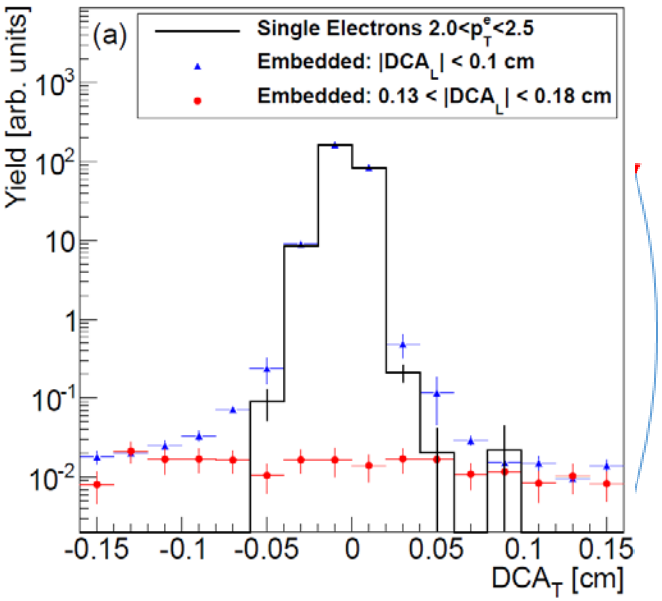
- **In the most central collision:**

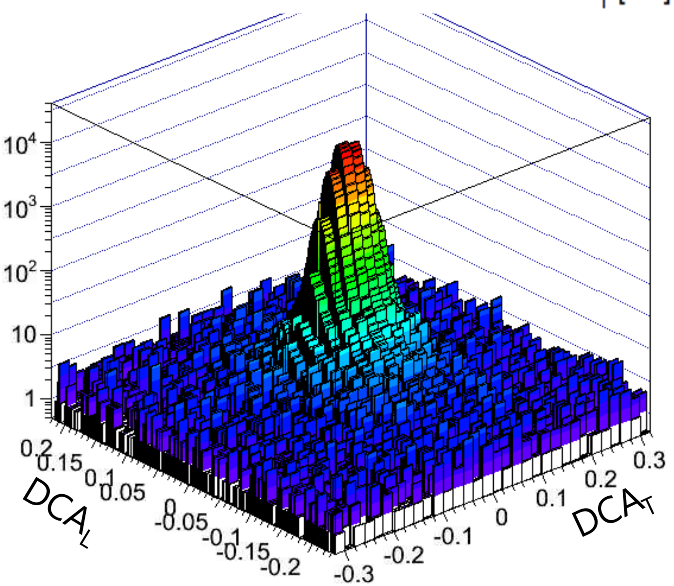
1. R_{dA} of HF muon and J/ψ are consistent at forward rapidity
2. however, clearly different at backward rapidity
3. charm production is enhanced but J/ψ production is significantly suppressed due to nuclear breakup inside dense comovers at backward rapidity
    - Shadowing (nPDF) should be similar for single and J/psi
    - Final state effect is related with multiplicity

PHOBOS: PRC 72 031901



Background : Mis-associated with VTX



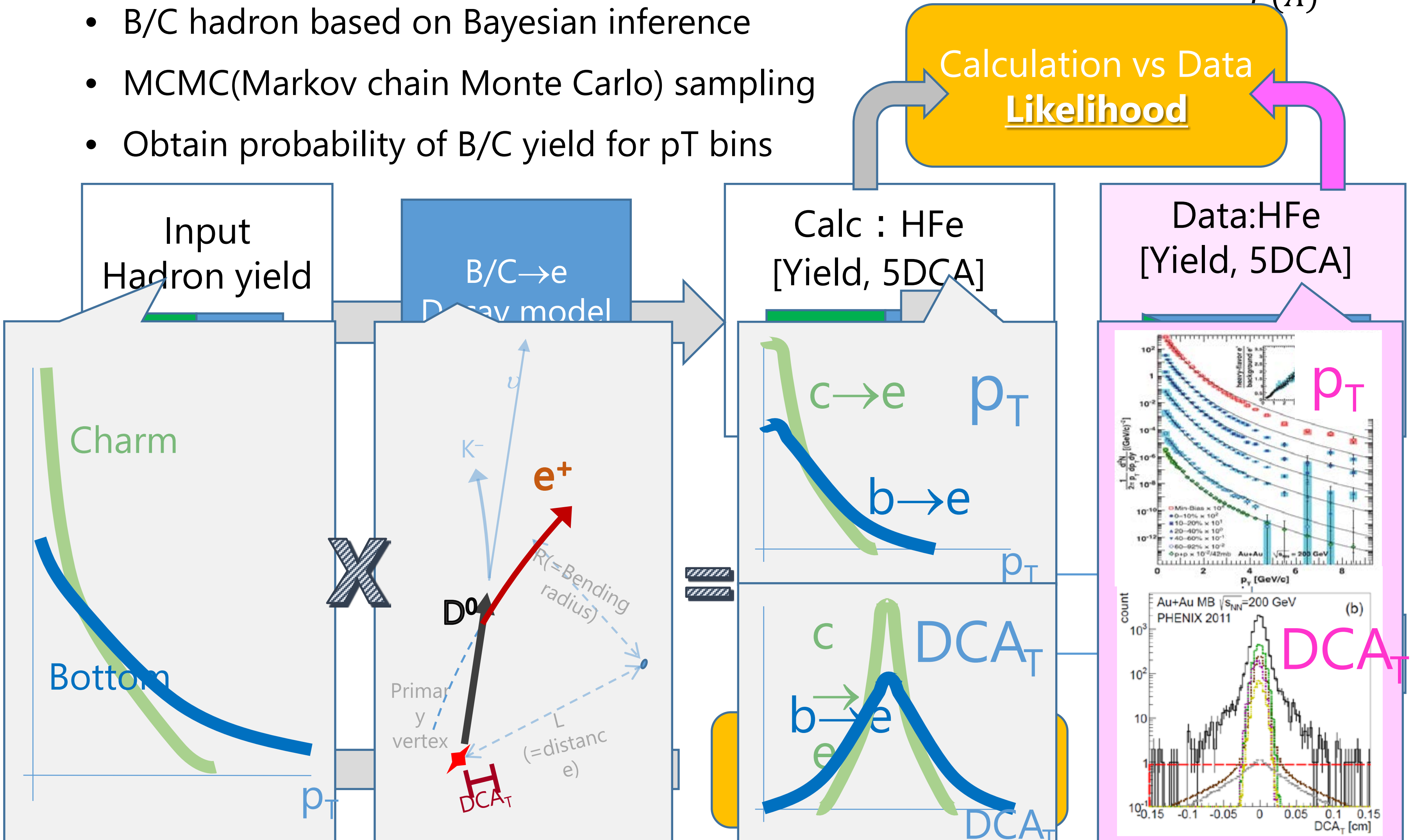


- The BG widely spreads with flat shape
  - Large DCA_L has mostly the BG.
- The BG is studied by embedding e into data
  - Embedding reproduces the BG nicely
- Use DCA_T distribution with $0.13<|DCA_L|<0.18$cm

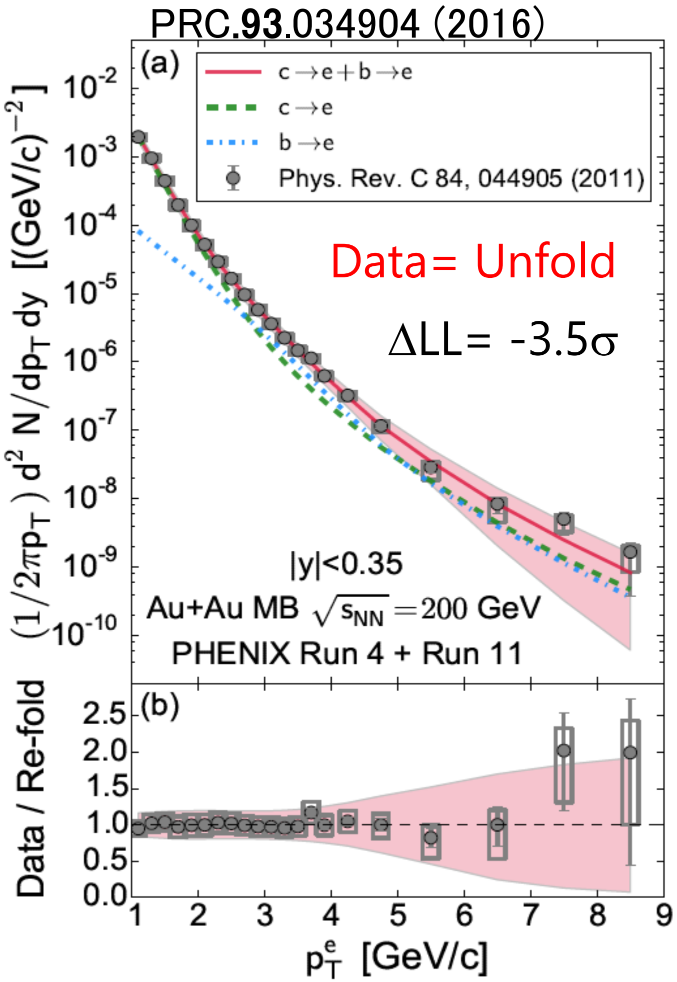
Unfolding: Bayesian inference

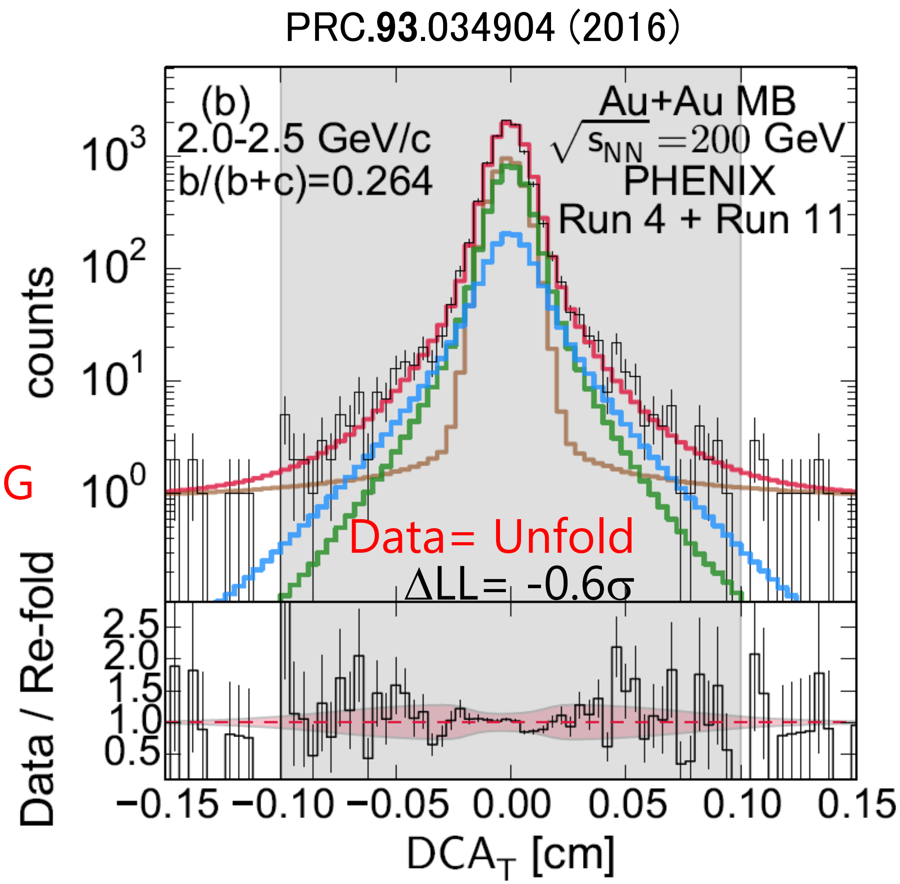
- Purpose: extract parent B/C hadron yield
  - B/C hadron based on Bayesian inference
  - MCMC(Markov chain Monte Carlo) sampling
  - Obtain probability of B/C yield for pT bins

$$P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$$



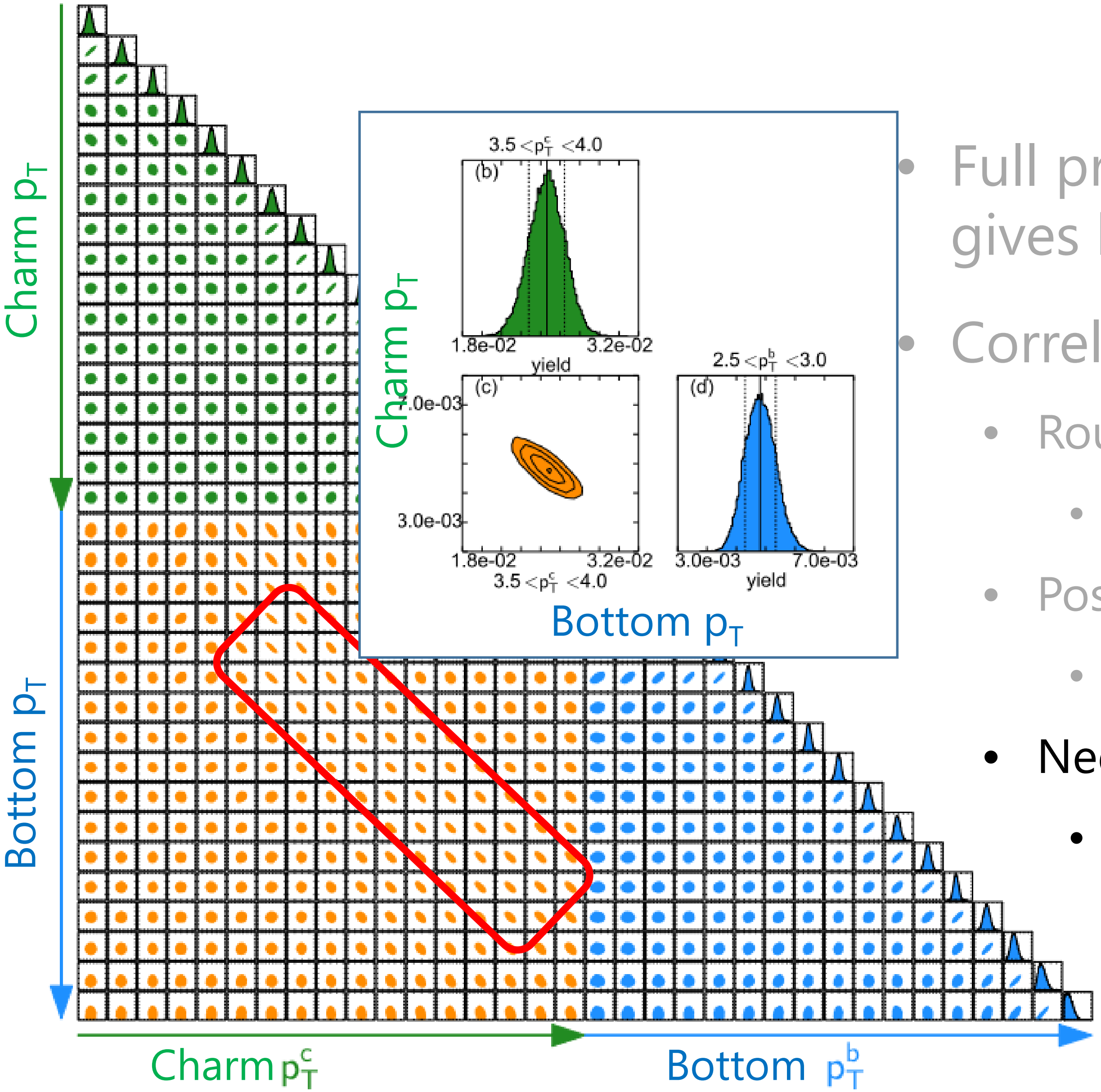
Validation: Unfolding & Data





- Unfolding is consistent with electron data for yield and DCA_T
  - Diff likelihood: ΔLL= -0.6 ~ 3.8 σ

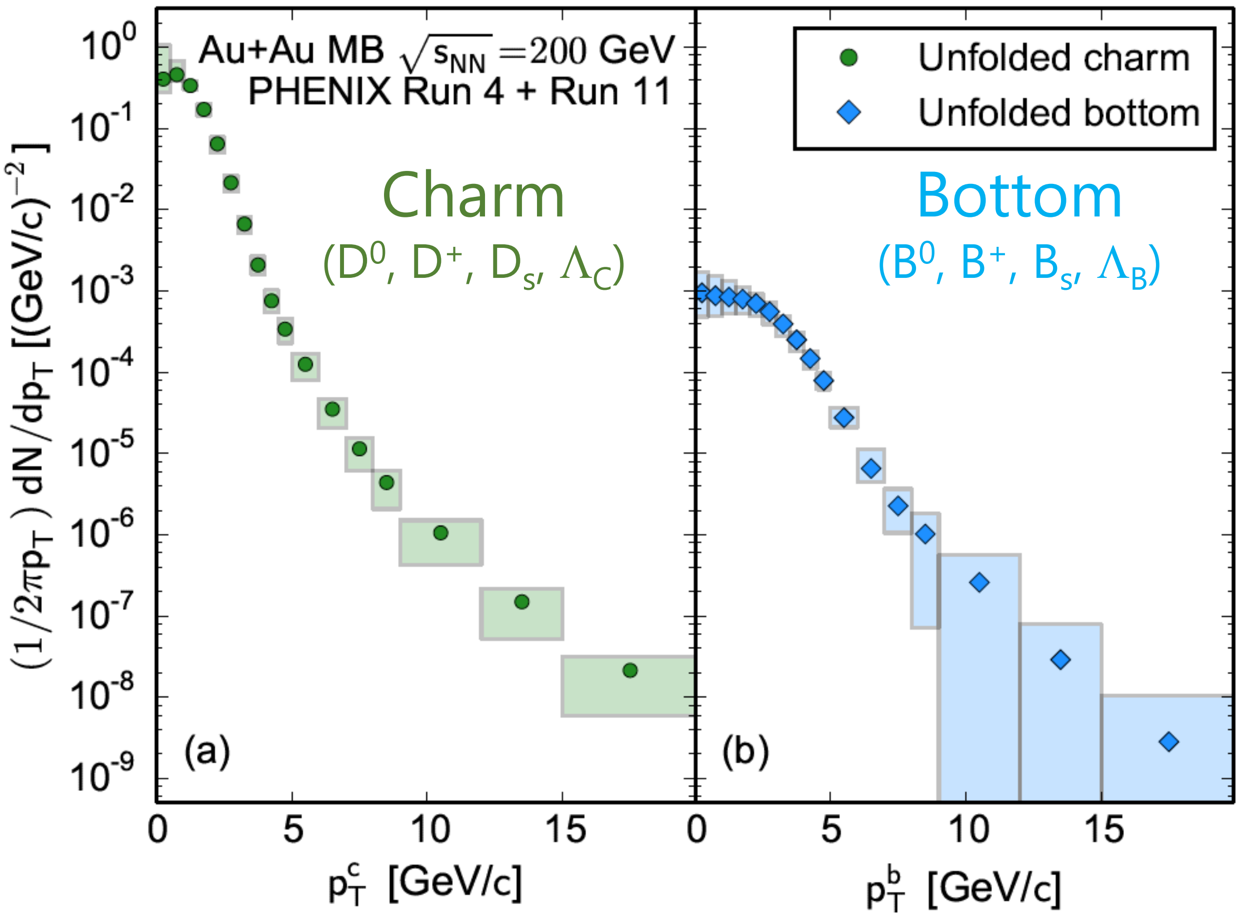
Full probability distribution
d



- Full probability distribution gives bottom & charm yield
- Correlation in yield
  - Round
    - no correlation
  - Positive in charm near pT
    - increase simultaneously
  - Negative
    - charm ↑ + bottom ↓

Unfold Charm and Bottom hadron spectra

PRC.**93**.034904 (2016)

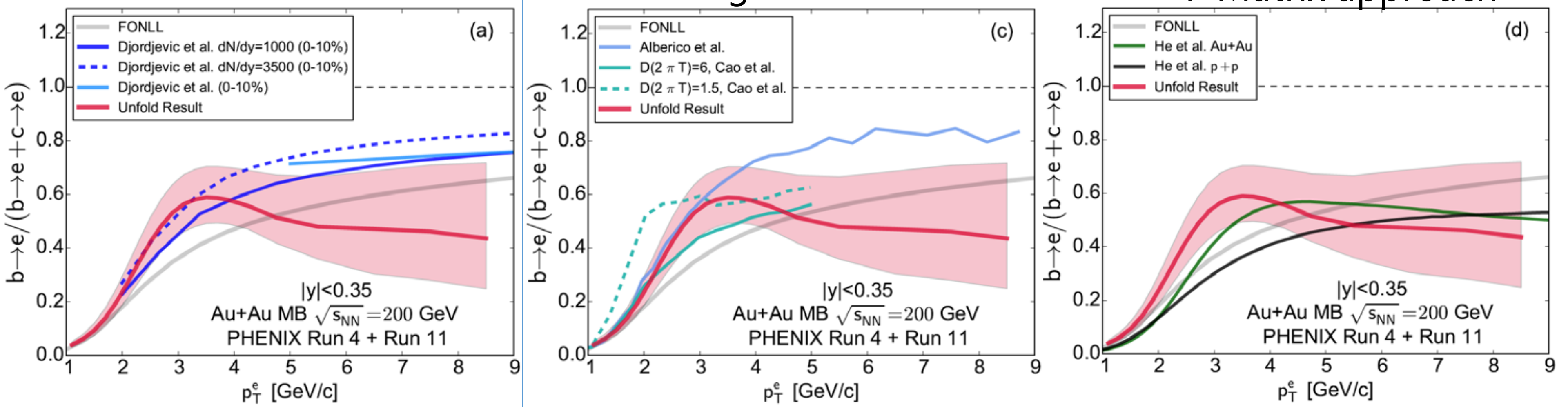


New method is successfully developed.

- Bottom & Charm hadron yield are successfully extracted
  - Whole rapidity
- First bottom hadron measurement

Comparison with Model

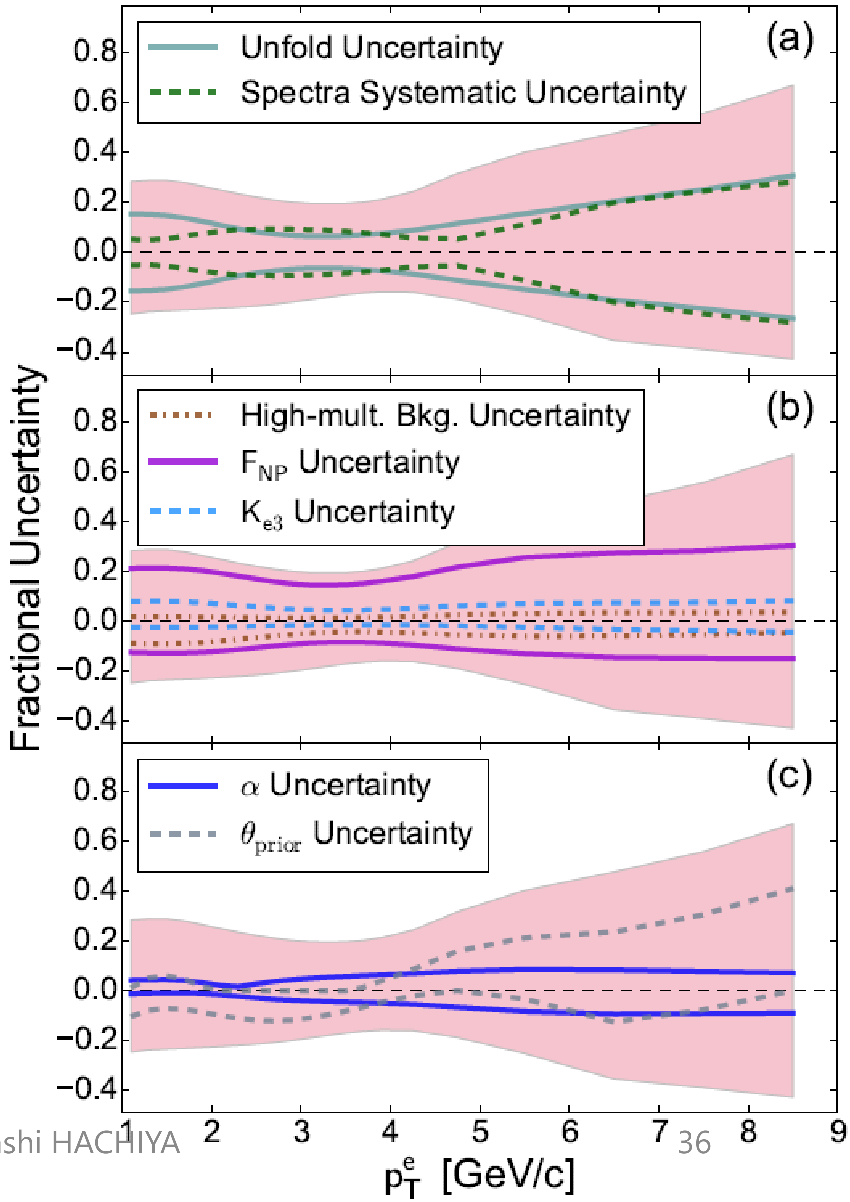
Radiative DGLV | Collisional Langevin based | Collisional T-Matrix approach



- Models are not consistent with data
  - Models shows monotonic and non-monotonic behavior
  - Data can constrain the models
- Need higher statistics to improve error at high p_T
  - Available from 2014-2016 : 10x more stat & good detector condition
  - New data will show the centrality dependence and VN measurement as well

Systematic uncertainty on unfolding

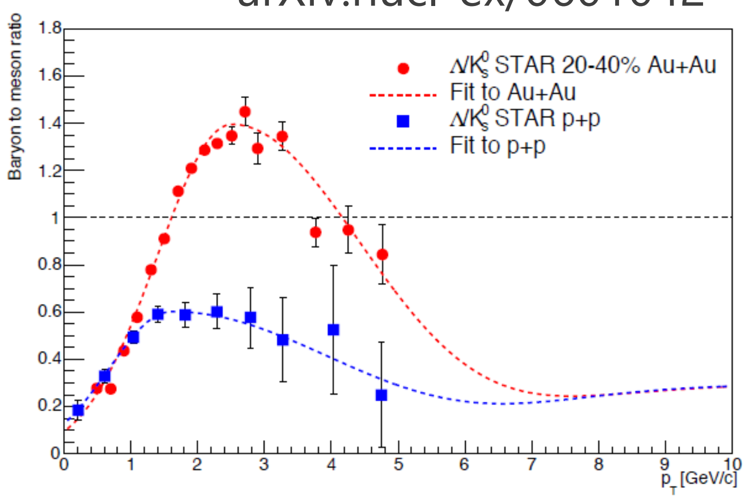
- Systematic uncertainty is obtained by changing the inputs within systematic uncertainty for each component.
- Type of uncertainties
  1. Unfold uncertainty : Due to data statistics
  2. Spectra uncertainty : Invariant HF spectrum
  3. High-mult Bkg : Mis-associated bg
  4. FNP : normalization on photonic BG
  5. Ke3 : Ke3 normalization
  6. α : Strength of smoothness
  7. θ_{prior} : Reference hadron shape for smoothness

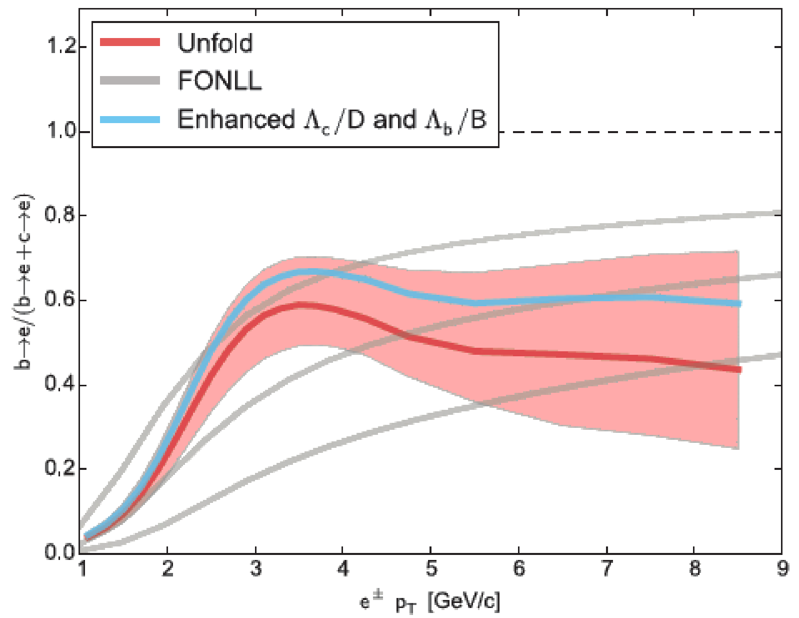


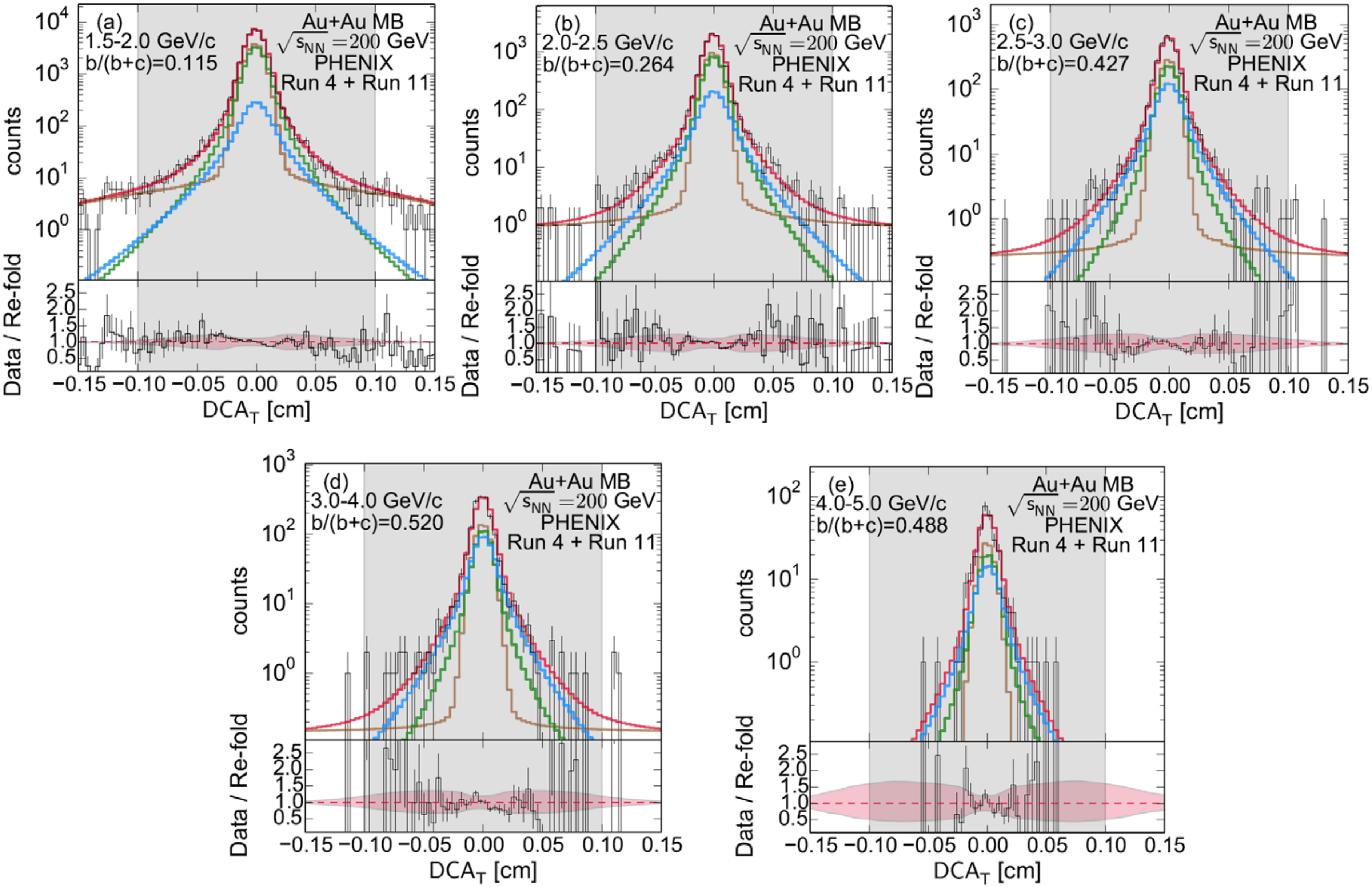
Effect on Baryon enhancement

- A baryon enhancement was observed in strange and non-strange hadrons. Same (or similar) enhancement may happen in heavy quarks.
- We tested how the enhancement change the bottom electron fraction
  - Input : STAR Λ/Ks in AuAu & pp
- Result
  - Bottom fraction was changed but within systematic uncertainty
  - We did not include this difference as an additional systematic uncertainty

arXiv:nucl-ex/0601042

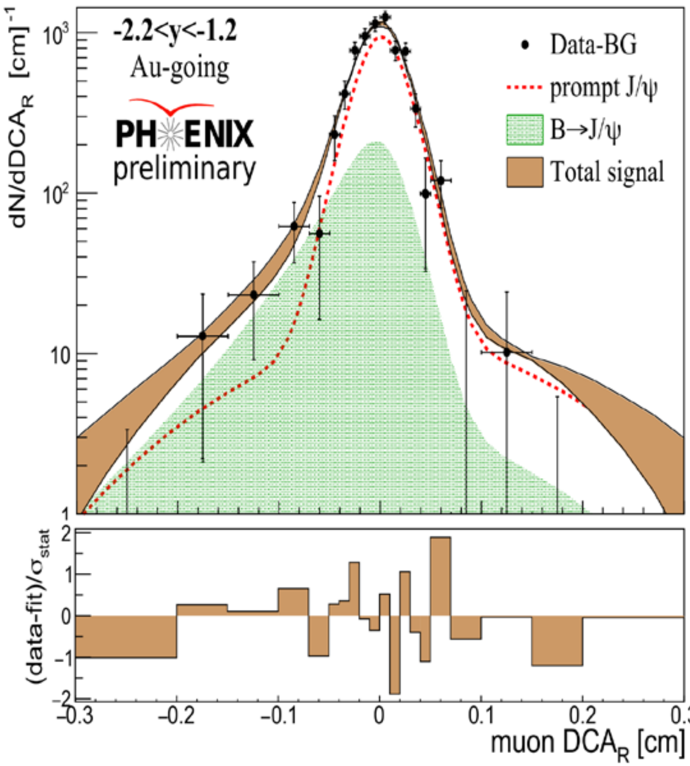




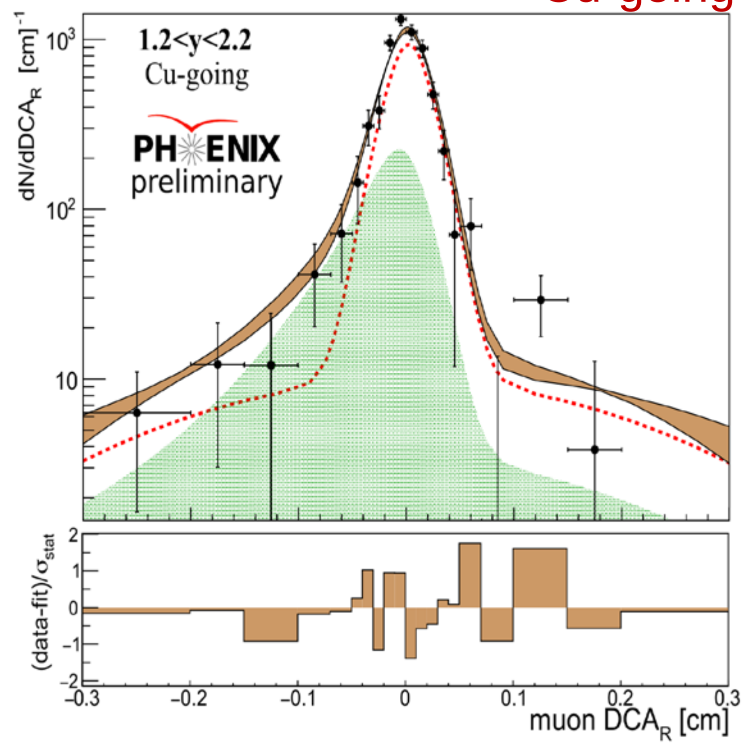

(a)
1.5-2.0 GeV/c
b/(b+c)=0.115
(b)
2.0-2.5 GeV/c
b/(b+c)=0.264
(c)
2.5-3.0 GeV/c
b/(b+c)=0.427
(d)
3.0-4.0 GeV/c
b/(b+c)=0.520
(e)
4.0-5.0 GeV/c
b/(b+c)=0.488
Au+Au MB
$\sqrt{s_{NN}} = 200$ GeV
PHENIX
Run 4 + Run 11
counts
Data / Re-fold
DCA_T [cm]

First Results : B-meson → J/ψ in Cu+Au 200 GeV

Cu-going



Cu-going



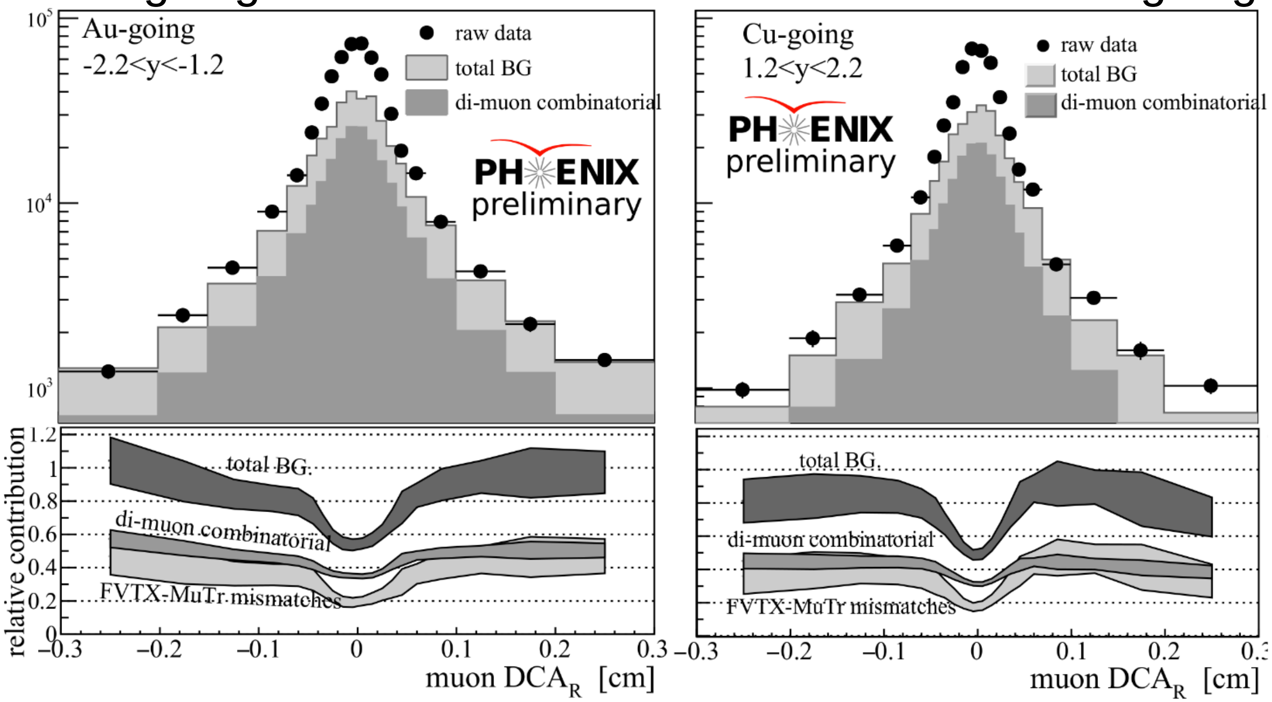
DCA_R Distributions. BG is subtracted for clarity

What NEW on Open Heavy Flavor?

Background components included

Au-going

Cu-going

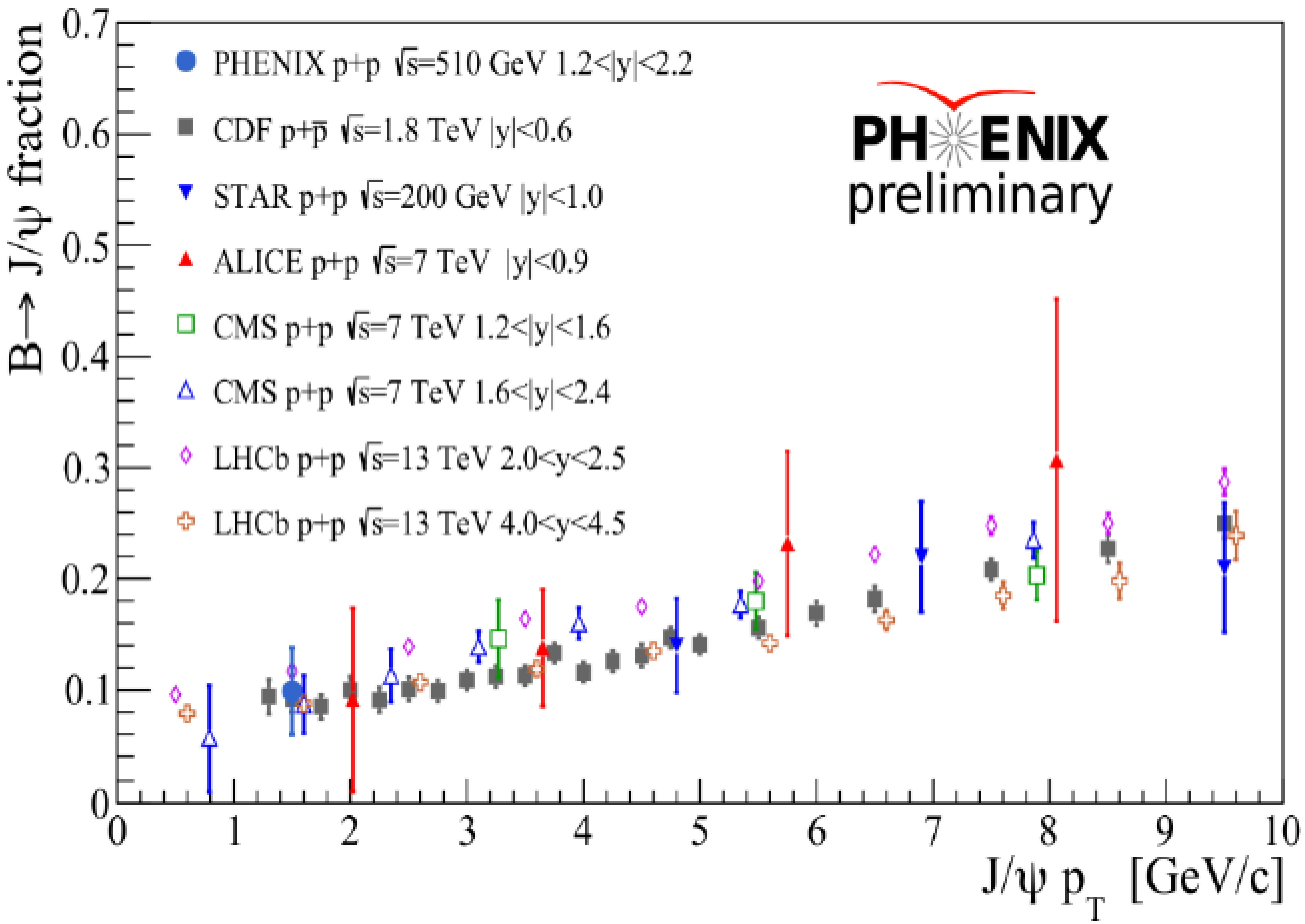


Two sources of background:

- Di-muon combinatorial
- FVTX-MuTr mismatches
  - Coming from incorrectly matching a MuTr track to the FVTX stand alone track.
- ccbar

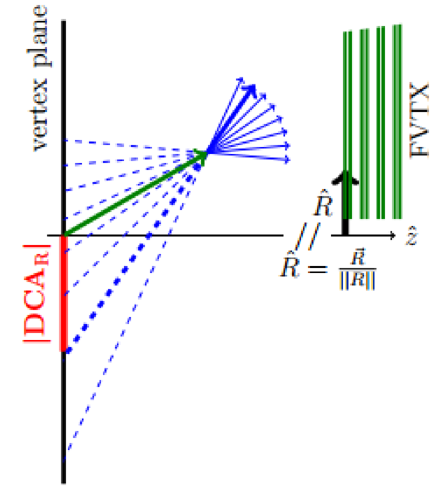
Signal templates and backgrounds are fitted together to extract the $B \rightarrow J/\psi$ fraction.

B fraction in pp : World data

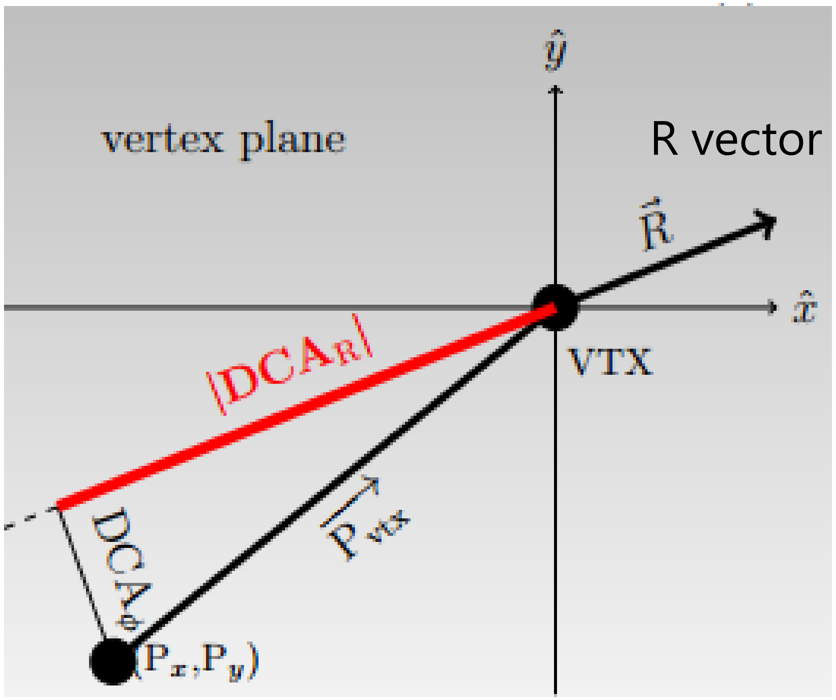


- B fraction is mostly independent of collision energy

DCA_R definition



R vector at FVTX point

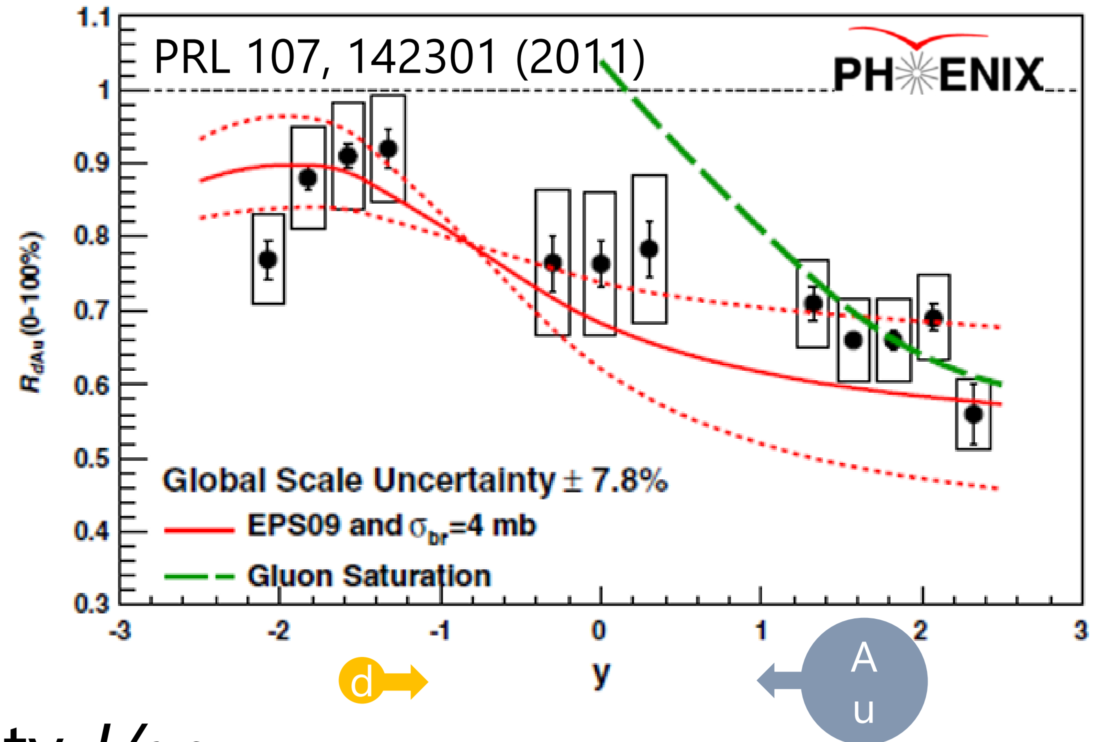


Projection to X-Y plane
at Z=collision vertex

$$DCA_R = \overrightarrow{P_{vtx}} \cdot \frac{\vec{R}}{||\vec{R}||}$$

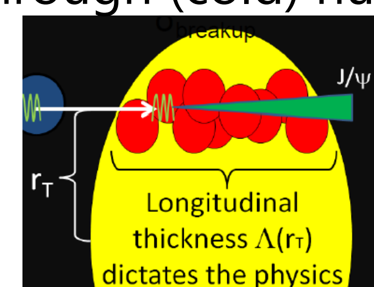
- DCA_R is the projection of DCA vector to R vector on the vertex plane.
- DCA_R can be negative if R and P vector goes opposite direction.
- For B->Jpsi which decays at far from vertex, P vector get longer due to Lorentz boost to Z direction. Therefore,

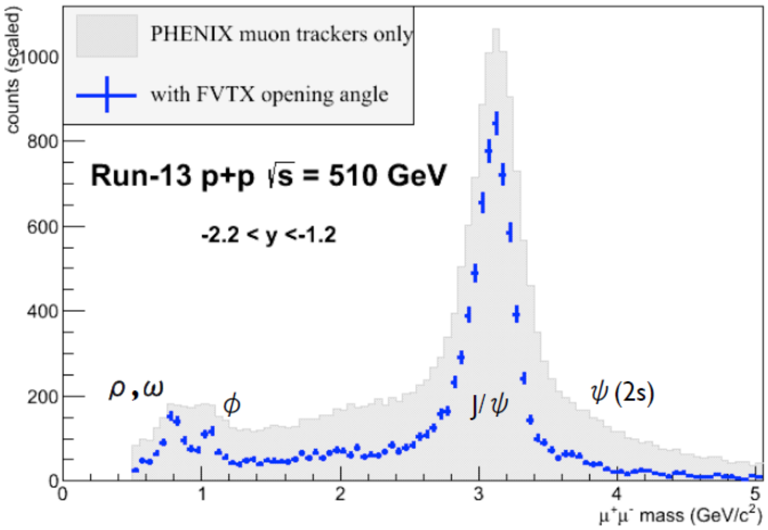
J/ψ in d+Au 200GeV: CNM effect



- Rapidity J/ψ
  - Asymmetric Suppression
    - Stronger @ forward y
  - Nuclear shadowing + cc breakup describes the data
    - favors σ_{br} = 4mb

cc breakup :
cc loses pair when passing through (cold) nuclei





PHENIX muon trackers only
with FVTX opening angle
Run-13 p+p √s = 510 GeV
-2.2 < y <-1.2
ρ , ω
ϕ
J/ψ
ψ (2s)
counts (scaled)
μ+μ- mass (GeV/c2)