Recent results on heavy flavor production at RHIC-PHENIX

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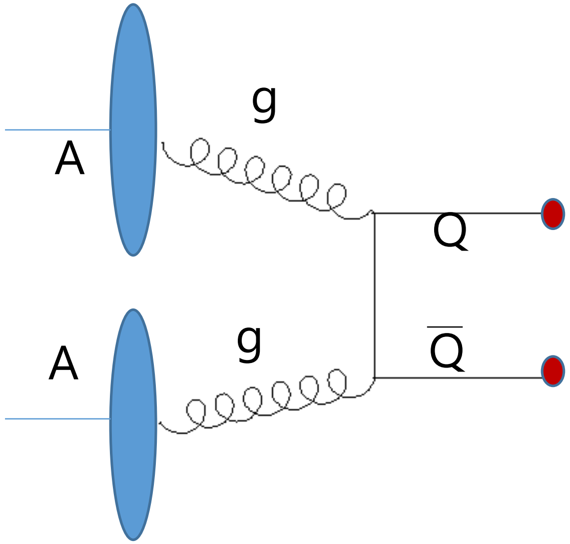
Introduction - why heavy flavor?

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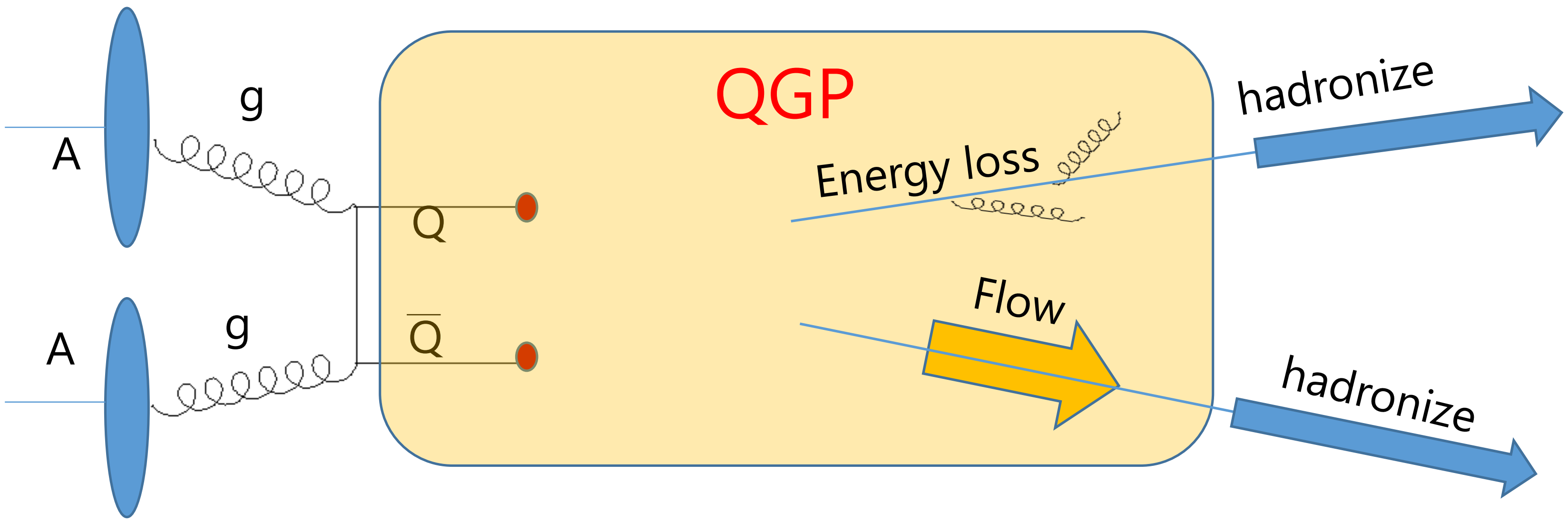
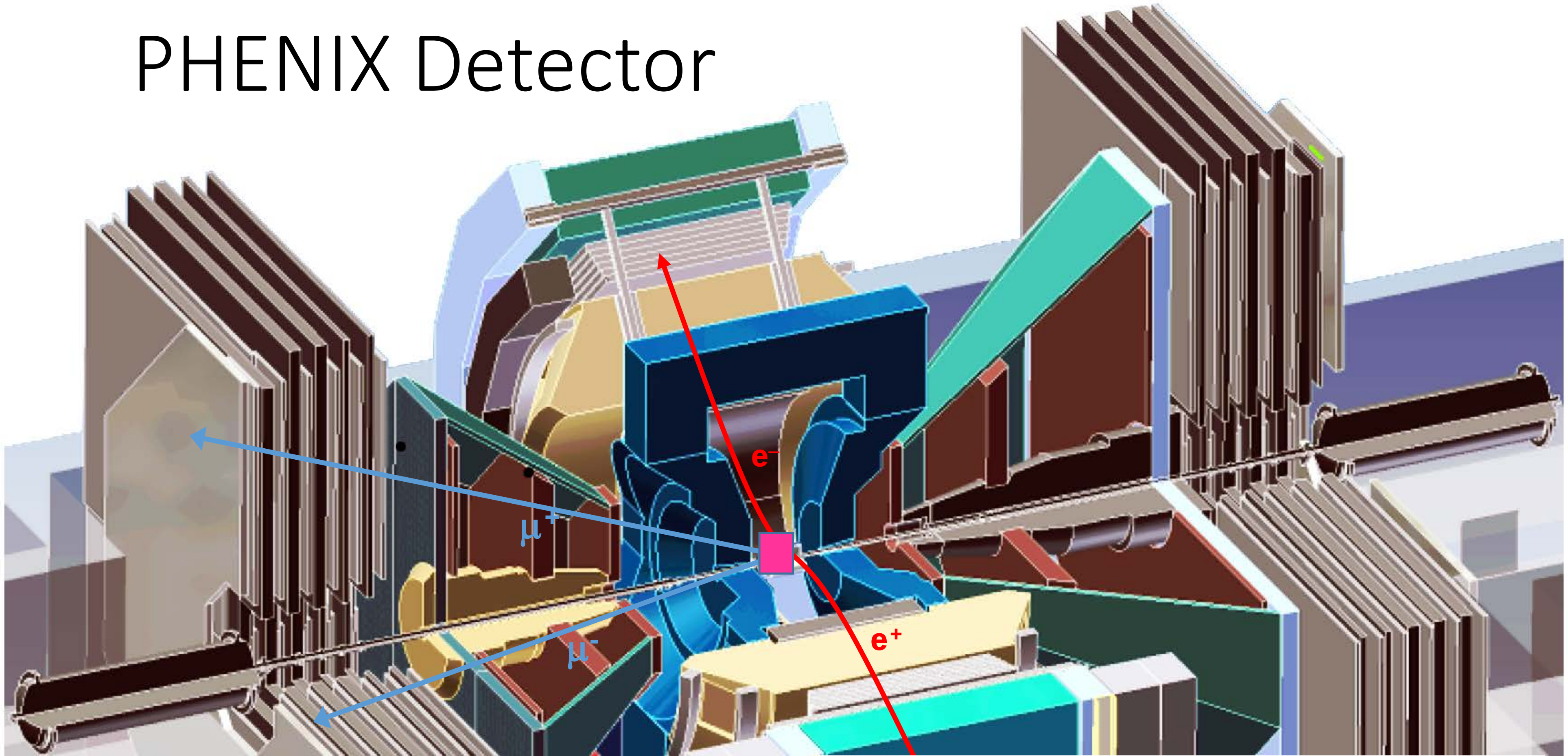
    - Mainly initial hard scattering due to large mass (Mc~1.2, Mb~4.5GeV >> Λ_{QCD}, T)
    - Production can be calculated by pQCD
  - Passing through the hot and dense medium (QGP)
    - Suffer energy loss, flow effect
    - Sensitive to the medium properties



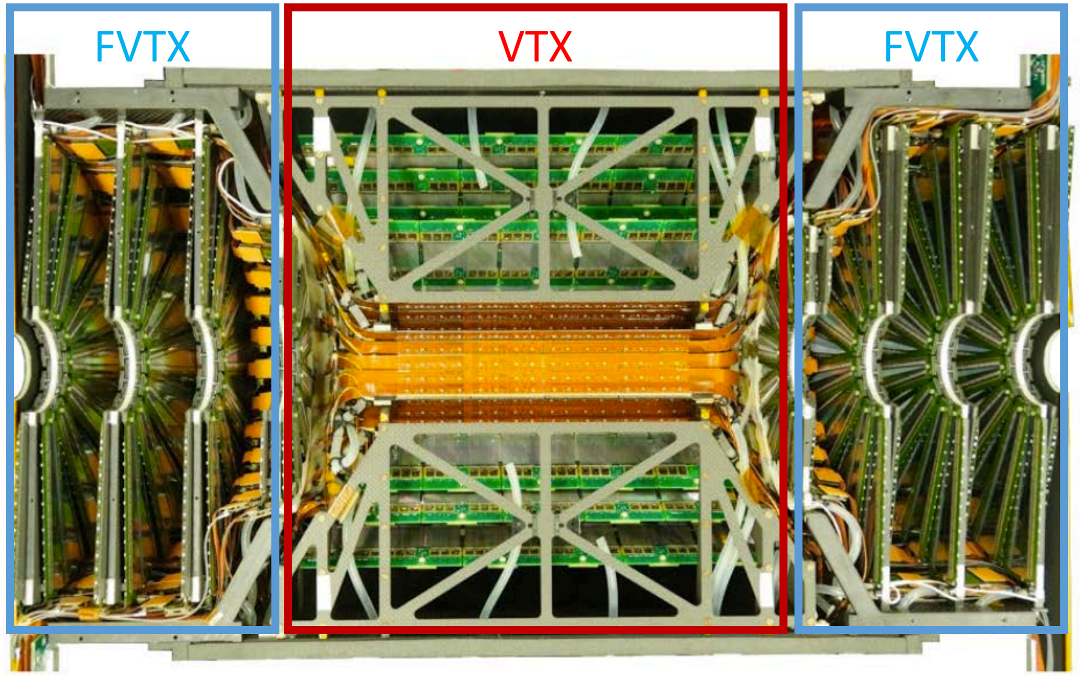
Heavy flavor is a clean probe to study QGP properties

PHENIX Detector

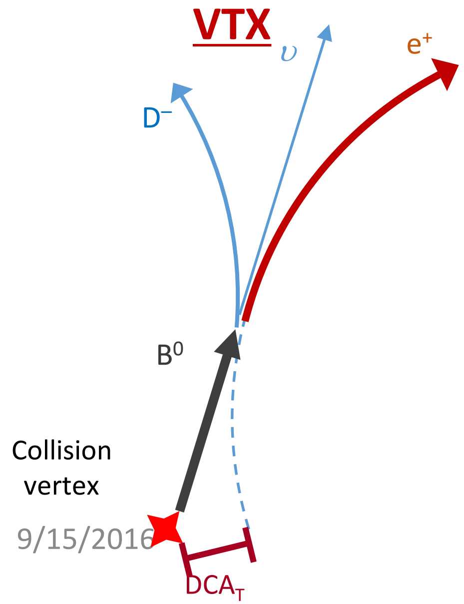


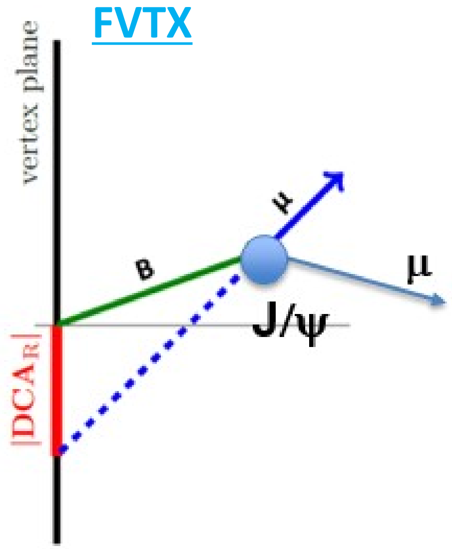
- Central Arm
  - $|y|<0.35$, $\phi \sim 2 \cdot \pi/2$
  - Electrons, γ, hadrons
    - DC, PC
    - RICH, EMCAL
- Muon Arm
  - $1.2<|y|<2.2$, $\phi=2\pi$
  - Muons, hadrons
    - Tracking chamber + Muon ID (absorber)

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





- 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

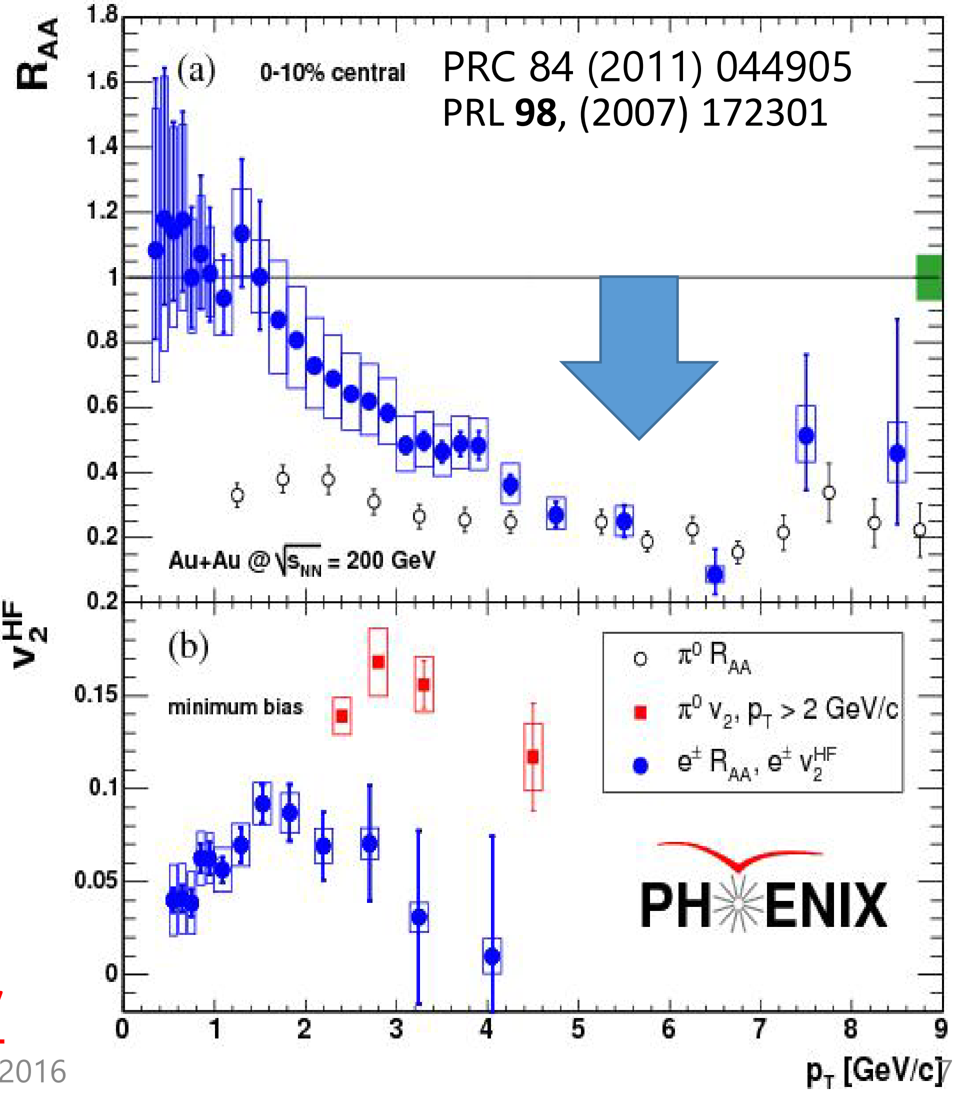
Inclusive Heavy Flavor Electrons in Au+Au 200GeV

Inclusive = charm & bottom

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

Surprising results

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



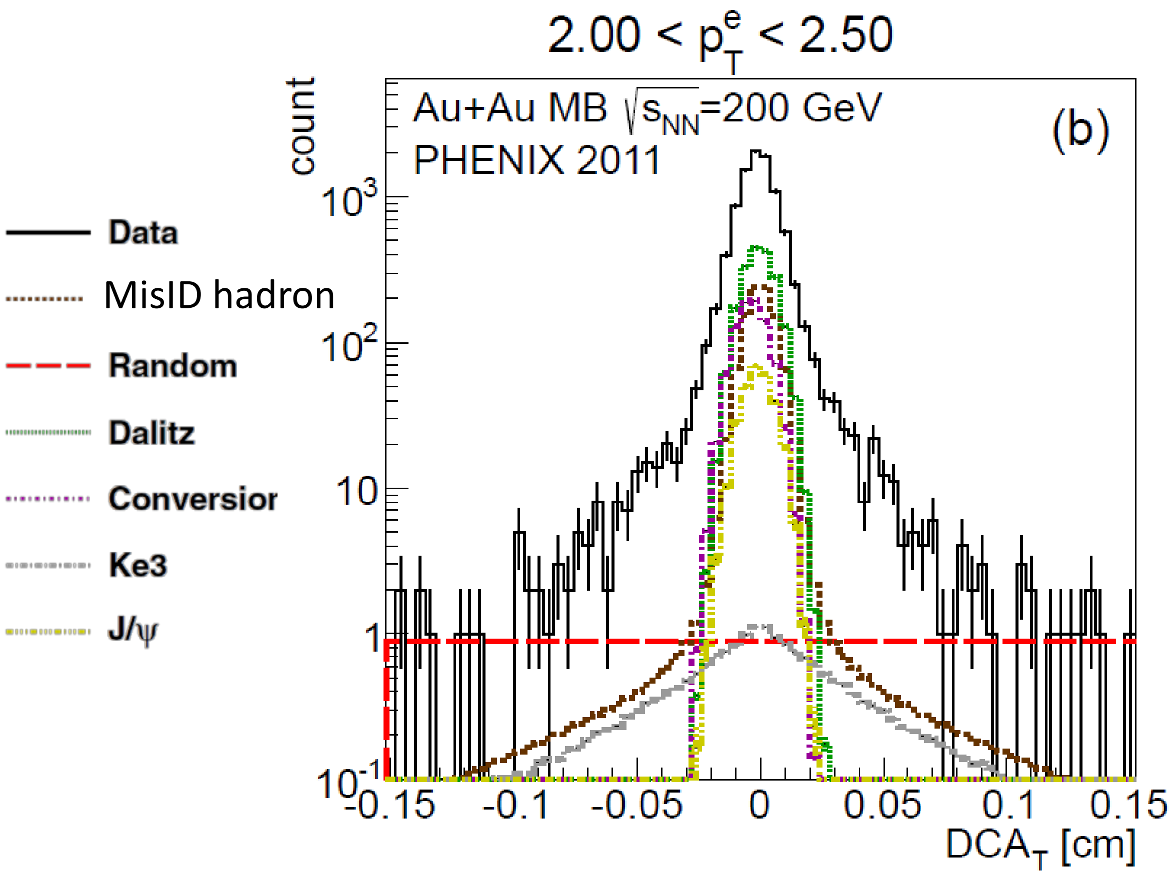
Heavy flavor expected to be less energy loss and smaller (zero) flow due to heavy mass

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

measure bottom & charm separately

Electron DCA_T distribution

VTX Result



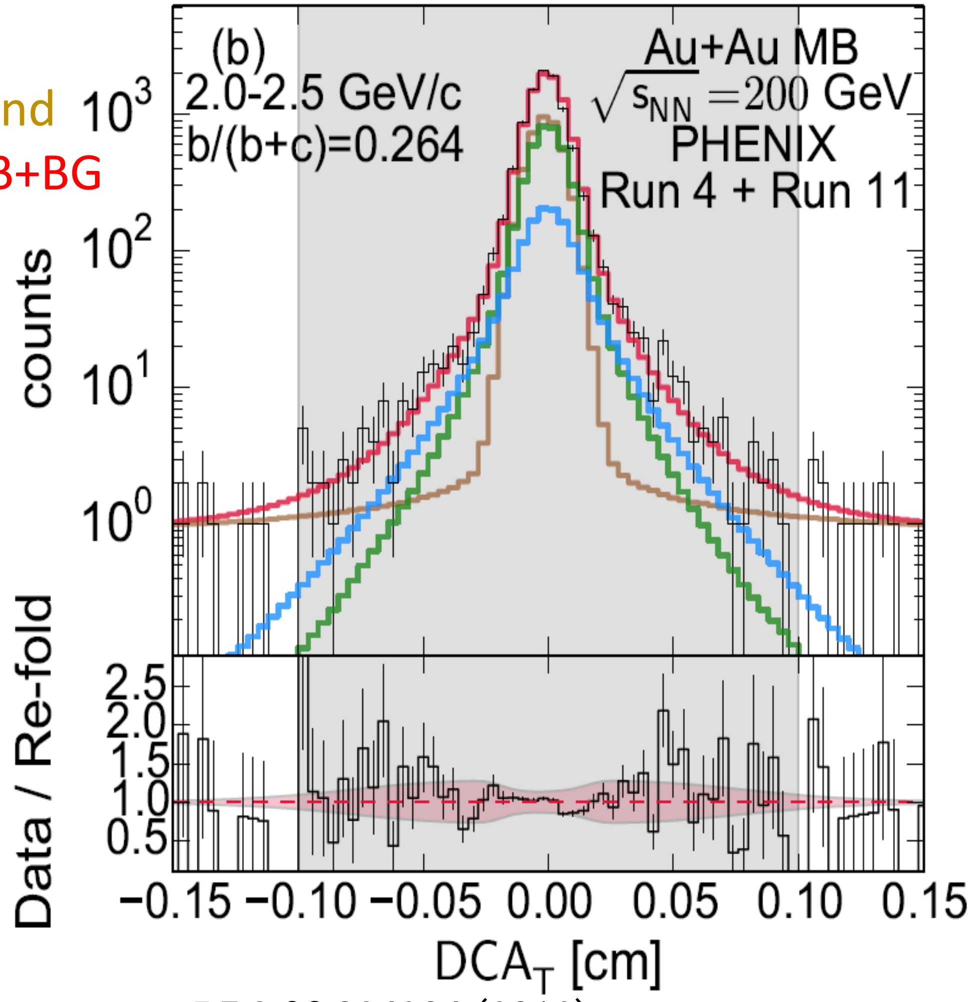
- First VTX results : Au+Au200
- DCA distributions :
  - Several backgrounds:
    - Conversions, Dalitz decays, J/psi & Ke3 decays, mis-ID hadrons, random association
  - **Bottom & Charm signal**

DCA for Bottom/Charm separation

VTX Result

Data
Charm
Bottom
Background
Total=C+B+BG

electrons @ mid-rapidity



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

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  - Several backgrounds:
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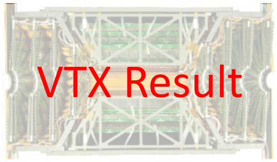
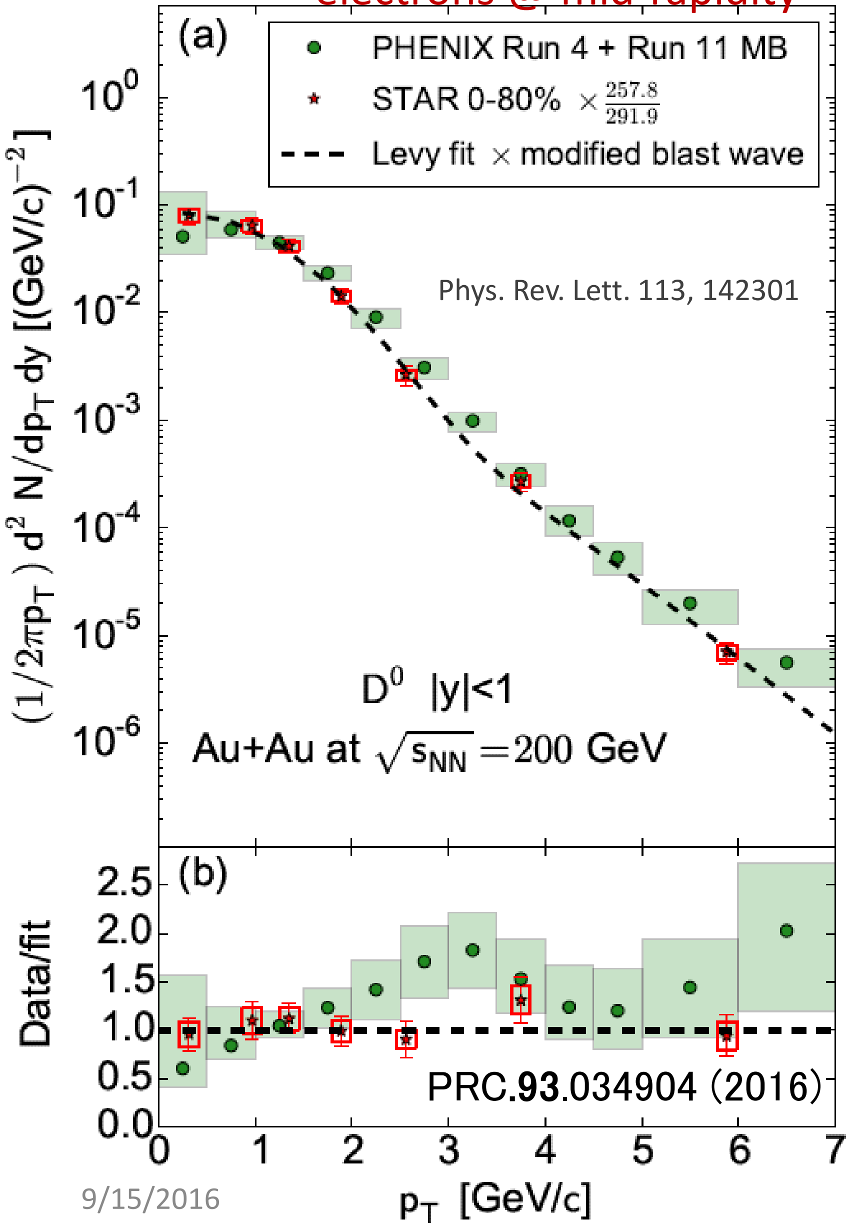
  - **Bottom & Charm signal**
- Unfolding for B/C separation
  - DCA_T in 2011 & yield in 2004
  - Bayesian inference technique
  - Parameters = yield of charm/bottom hadrons

Charm hadrons from unfolding



electrons @ mid-rapidity



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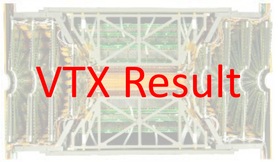
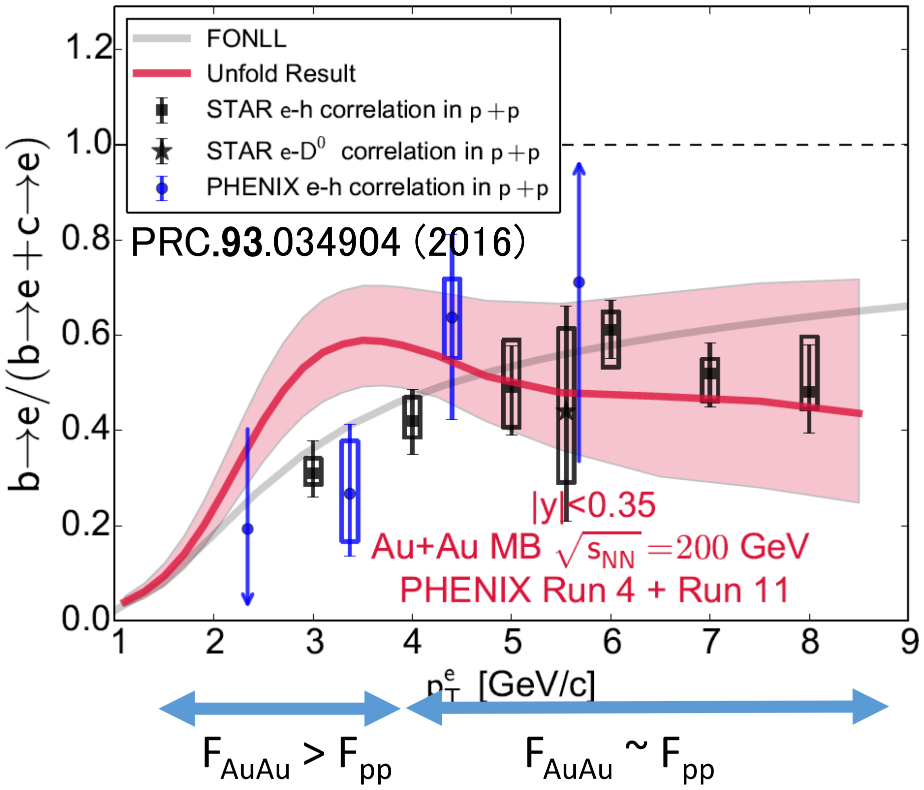
  - **Bottom & Charm signal**
- Unfolding for B/C separation
  - DCA_T in 2011 & yield in 2004
  - Bayesian inference technique
  - Parameters = yield of charm/bottom hadrons
- Unfolded charm hadrons are in good agreement with STAR D^0 measurement

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

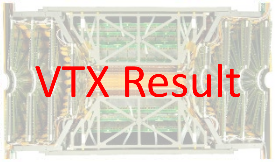


electrons @ mid-rapidity

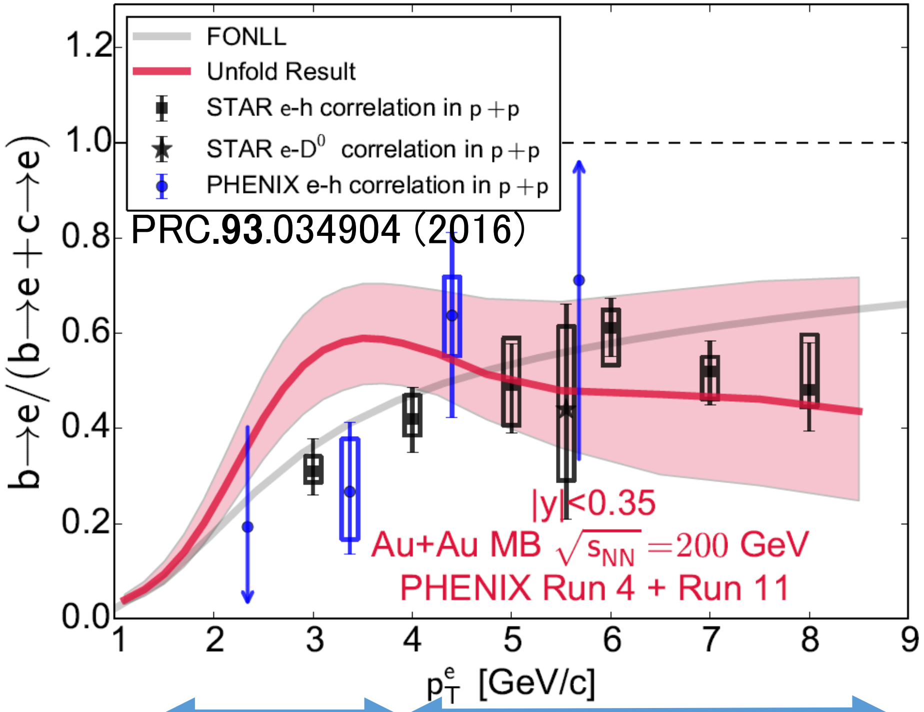


- FONLL is consistent with p+p data
  - Two particle correlation in p+p
- Au+Au shows difference with p+p

First result : Bottom and Charm R_{AA}

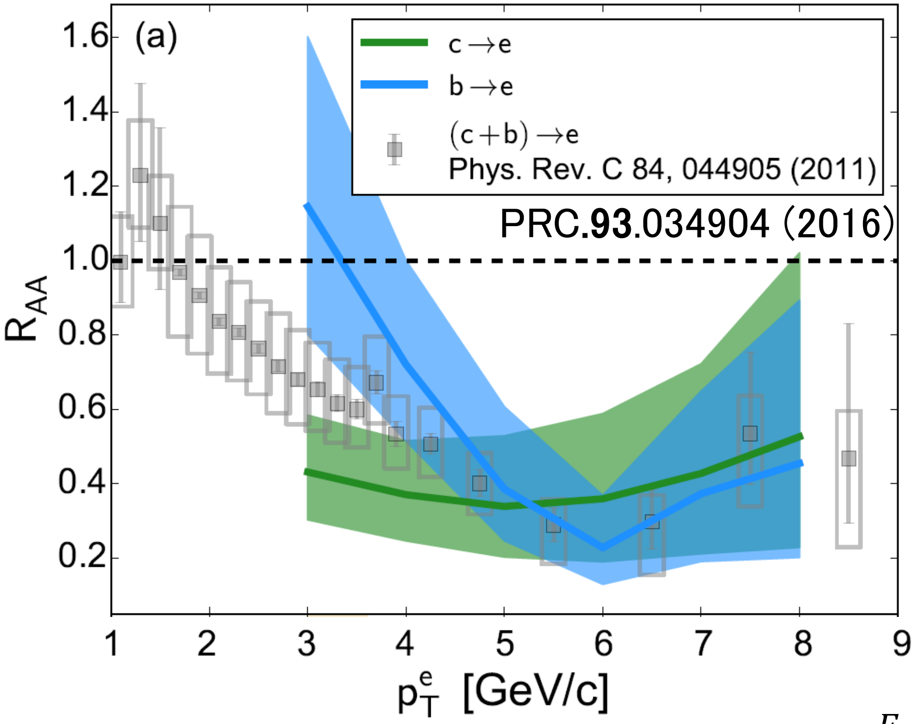


electrons @ mid-rapidity



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

electrons @ mid-rapidity



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

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

- 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

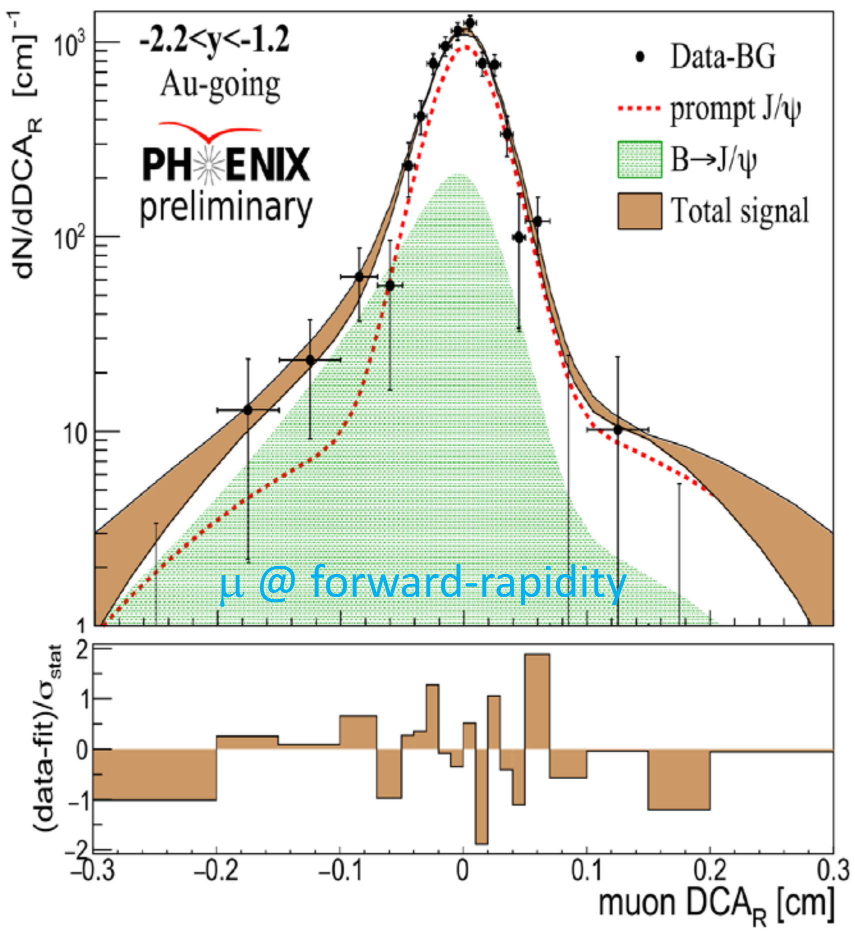
Topics :

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

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

First results : B→J/ψ in Cu+Au

μ DCA_R from J/ψ decays

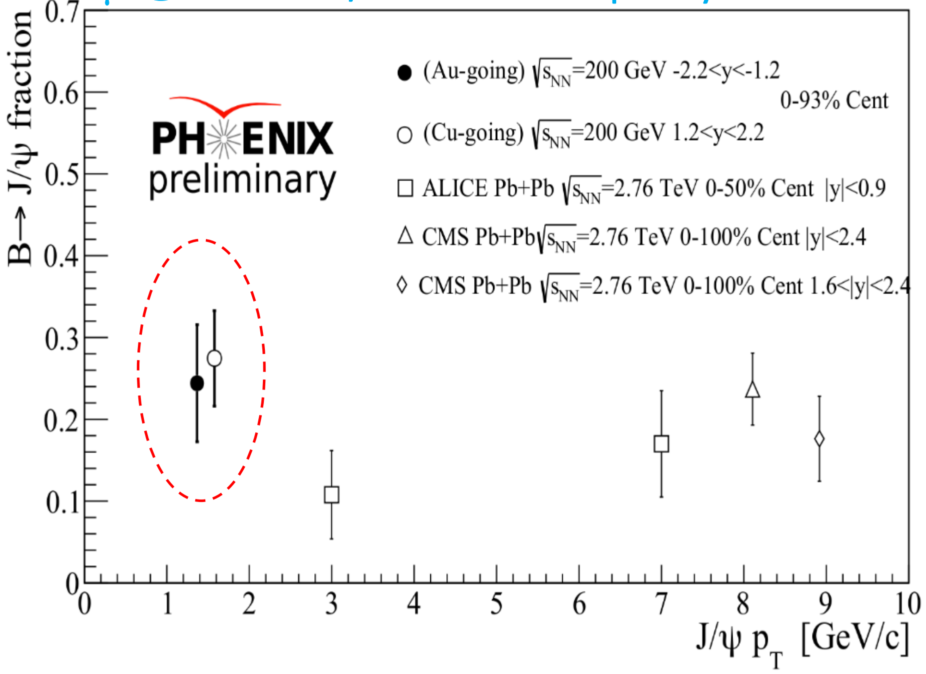


- Cu+Au 200GeV in 2012
  - Forward/Backward J/psi → μμ
- Measure μ DCA_R from J/ψ decays
  - separate B→J/ψ and prompt J/ψ
  - Utilize difference of decay lengths
  - B→J/ψ: 455 μm, Prompt J/ψ: 0μm
- DCA_R fits with template shapes of B→J/ψ & prompt J/ψ
- The sum of DCA_R contributions agrees well with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

First results : B→J/ψ in Cu+Au

FVTX Result

μ @ forward/backward-rapidity



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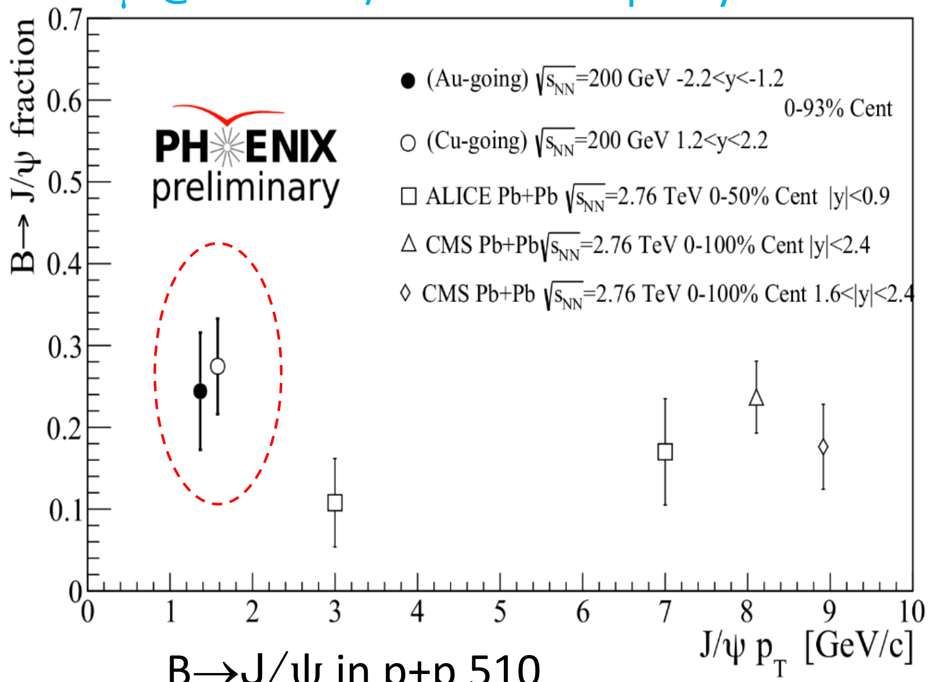
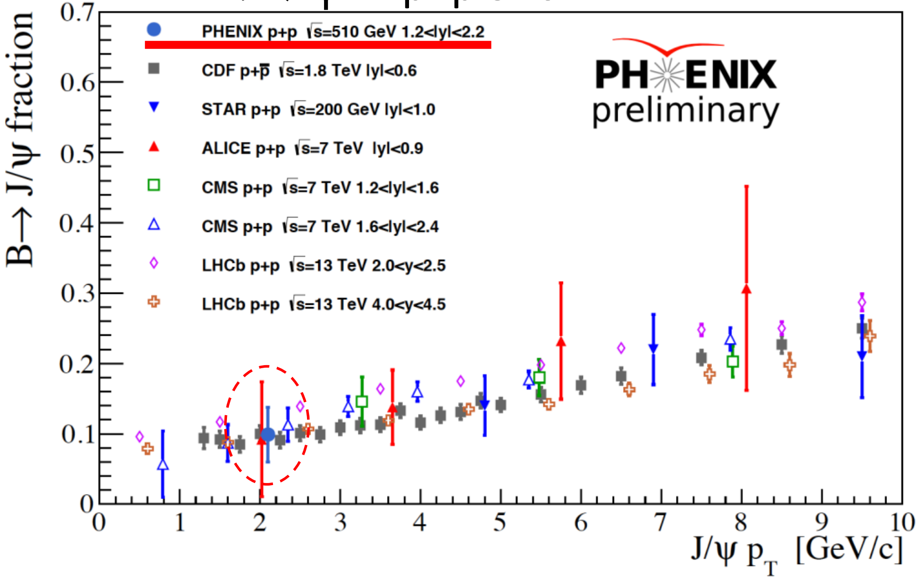
  - Utilize difference of decay lengths
  - B→J/ψ: 455 μm, Prompt J/ψ: 0μm
- DCA_R fits with template shapes of B→J/ψ & prompt J/ψ
- The sum of DCA_R contributions agrees well with the data
- B fraction was determined for both Cu-& Au-going directions
- B fraction is larger than that at LHC because prompt J/ψ is more suppressed at RHIC

First results : B→J/ψ in Cu+Au

μ @ forward/backward-rapidity



B→J/ψ in p+p 510

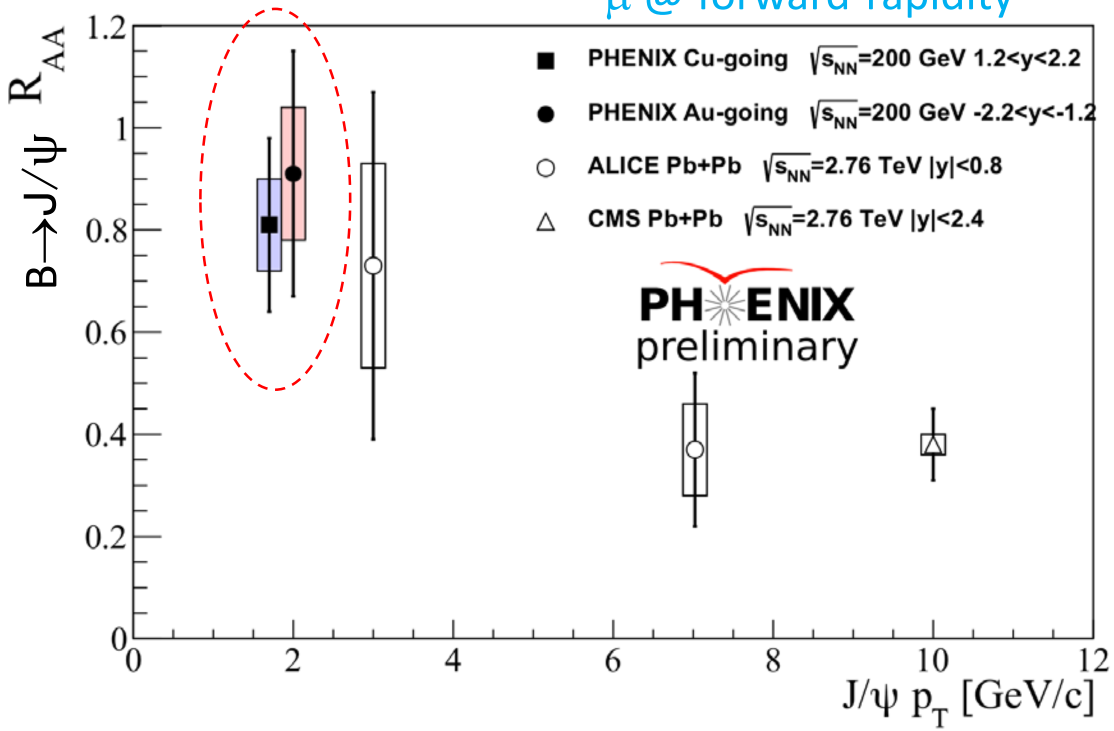


- Cu+Au 200GeV in 2012
  - Forward J/psi → μμ
- Measure μ DCA_R from J/ψ decays
  - separate B→J/ψ and prompt J/ψ
  - Utilize difference of decay lengths
  - B→J/ψ: 455 μm, Prompt J/ψ: 0μm
- DCA_R fits with template shapes of B→J/ψ & prompt J/ψ
- The sum of DCA_R contributions agrees well with the data

- 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}
- pQCD F(B → J/ψ) is smaller within large uncertainty

First results : B→J/ψ R_{AA} in Cu+Au

μ @ forward-rapidity

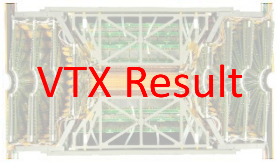


$$R_{CuAu}^{B\to J/\psi} = \frac{F_{B\to J/\psi}^{CuAu}}{F_{B\to J/\psi}^{pp} = 0.1} R_{CuAu}^{inc.J/\psi}$$

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 p_T and more at high p_T
  - New pp200 baseline measurement will be coming soon

Summary



- New bottom results at RHIC energy
  - First results of bottom suppression from both VTX and FVTX
  - Bottom in Au+Au 200 GeV

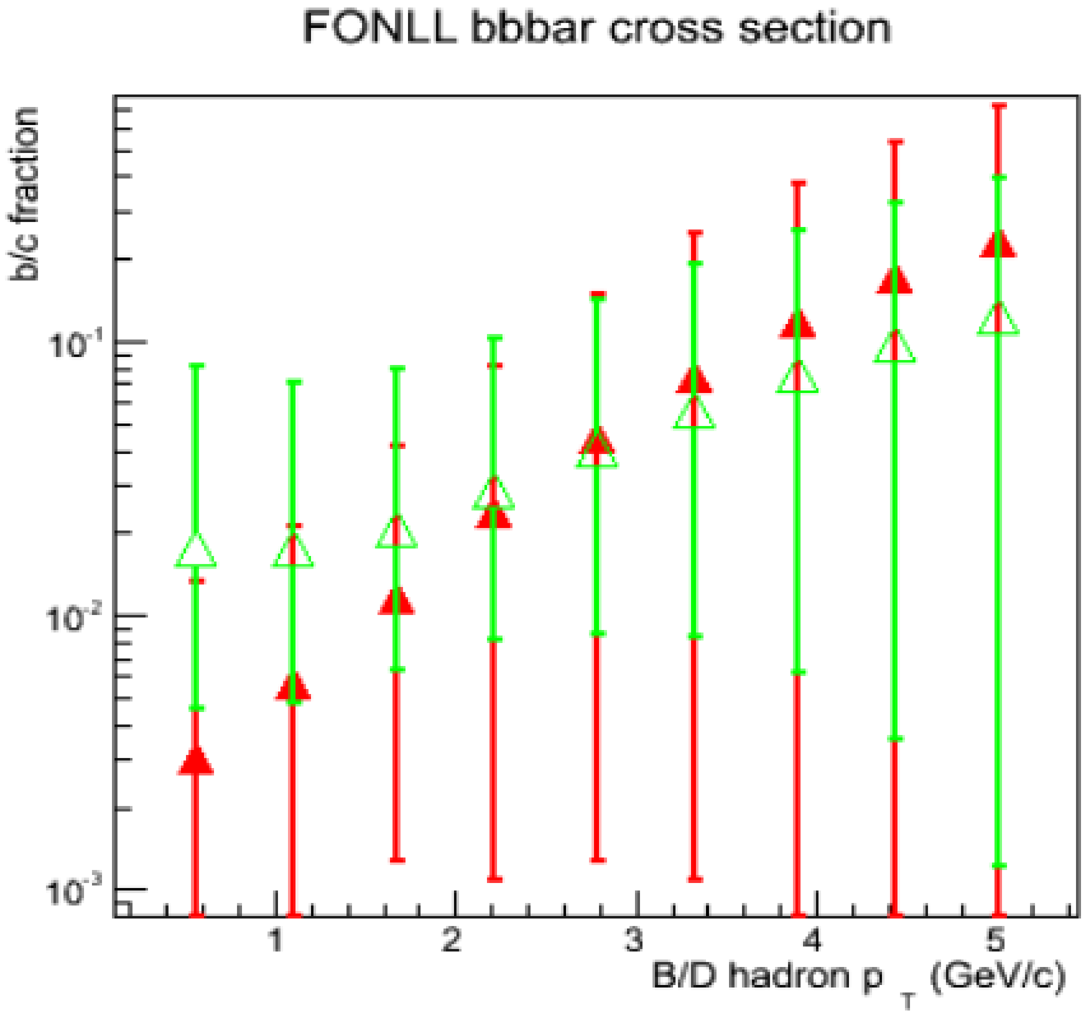
    similarly suppressed as charm at high p_T

    less suppressed at low p_T
  - Almost no suppression for $B \to J/\psi$ at low p_T in Cu+Au 200 GeV

- Outlook
  - VTX / FVTX silicon detector enables precise open 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

FONLL b/b+c cross section ratio

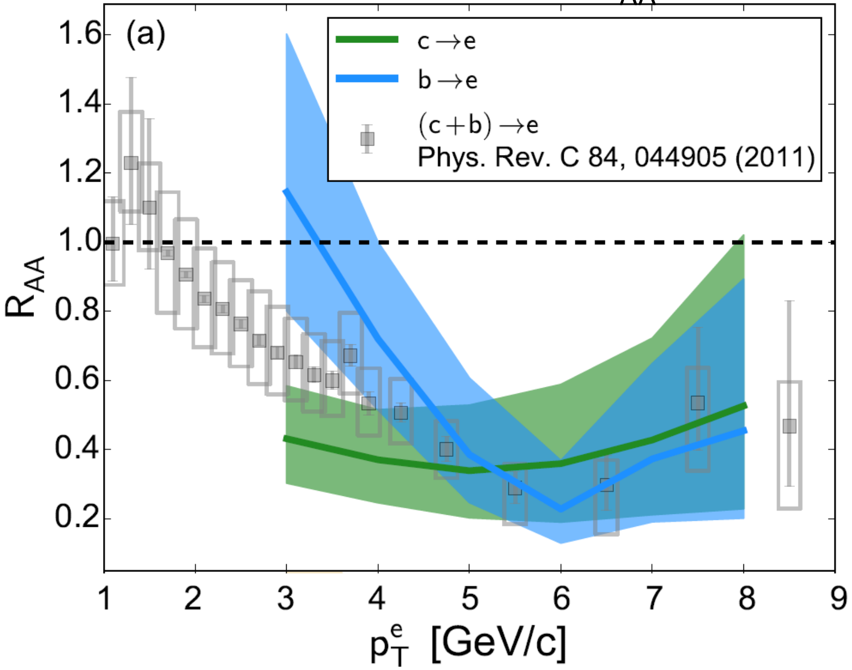


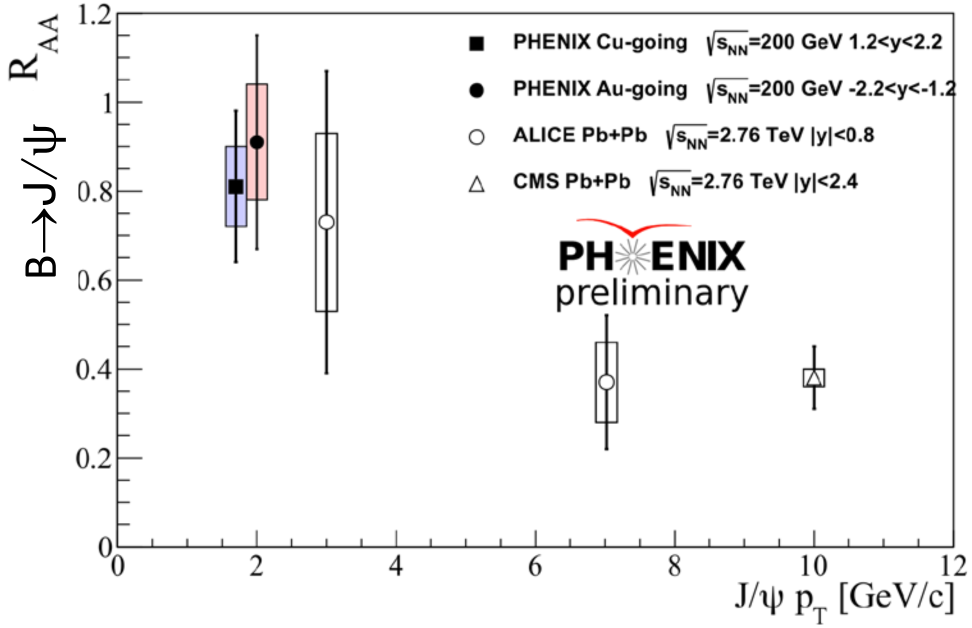
- pp510 1.2<y<2.2 (PHENIX forward)
- ppb 1.96TeV |y|<0.6 (CDF)

- Center value is factor 5 smaller at low pT
- Different pT dependence may smear the energy dependence

Outlook : Heavy Flavor

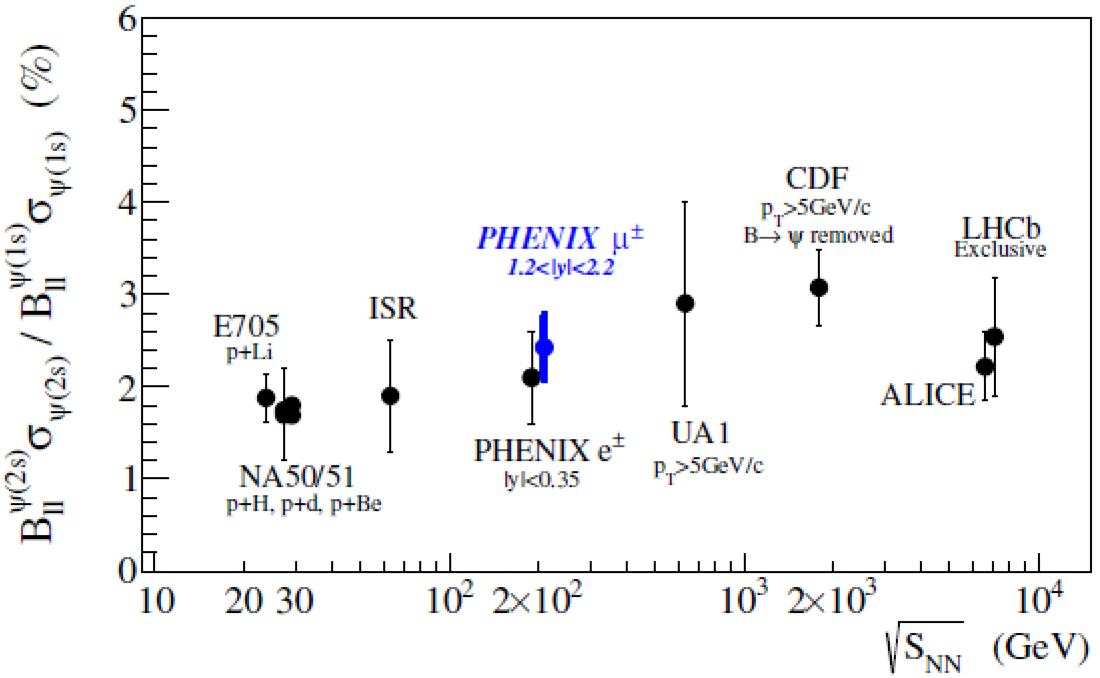
Bottom/Charm electron R_{AA}





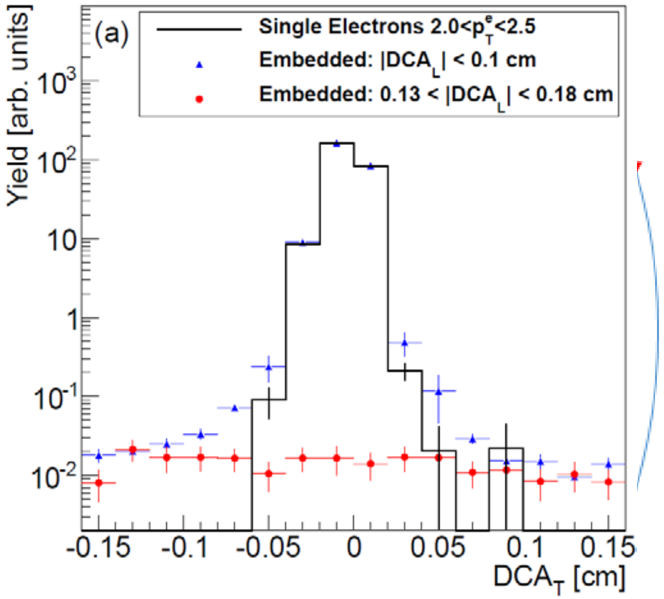
- Large statistics in 2014 + 2016 Au+Au datasets
  - 10 ~ 20 times enables to study with separated bottom/charm
    - Higher pT,
    - centrality dependence
    - Vn
- Good 2015 p+p and p+Au datasets for baseline

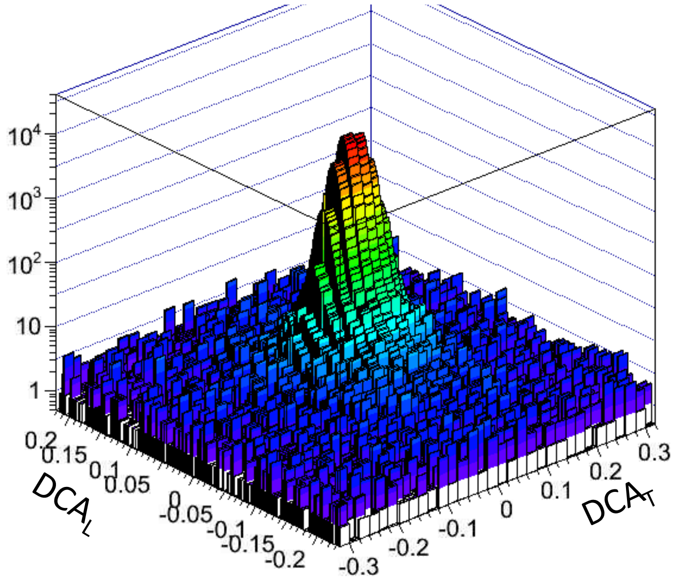
Psi' / J/psi ratio in pp



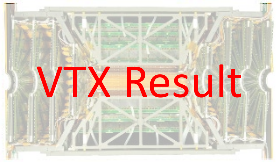
- The ratio is independent of collision energy
  - Even cc cross section changes with collision energy

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

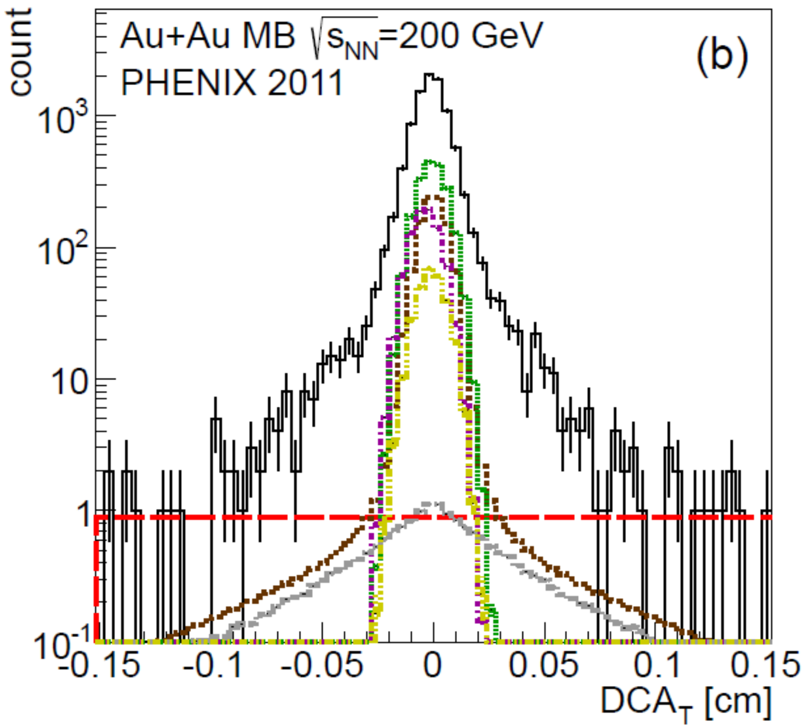


Unfolding: Bayesian inference

- Purpose: extract parent B/C hadron yield
  - Input : electron DCA & invariant yield
  - B/C hadron based on Bayesian inference
  - MCMC(Markov chain Monte Carlo) sampling

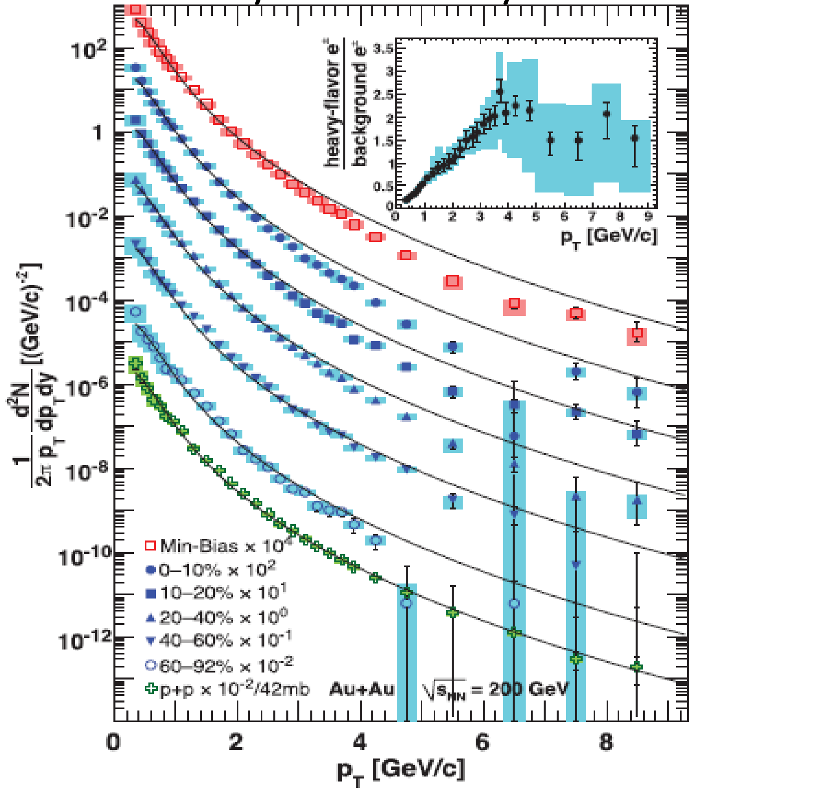
$$P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$$

DCA of single electrons



Phys. Rev. C 84, 044905 (2011)

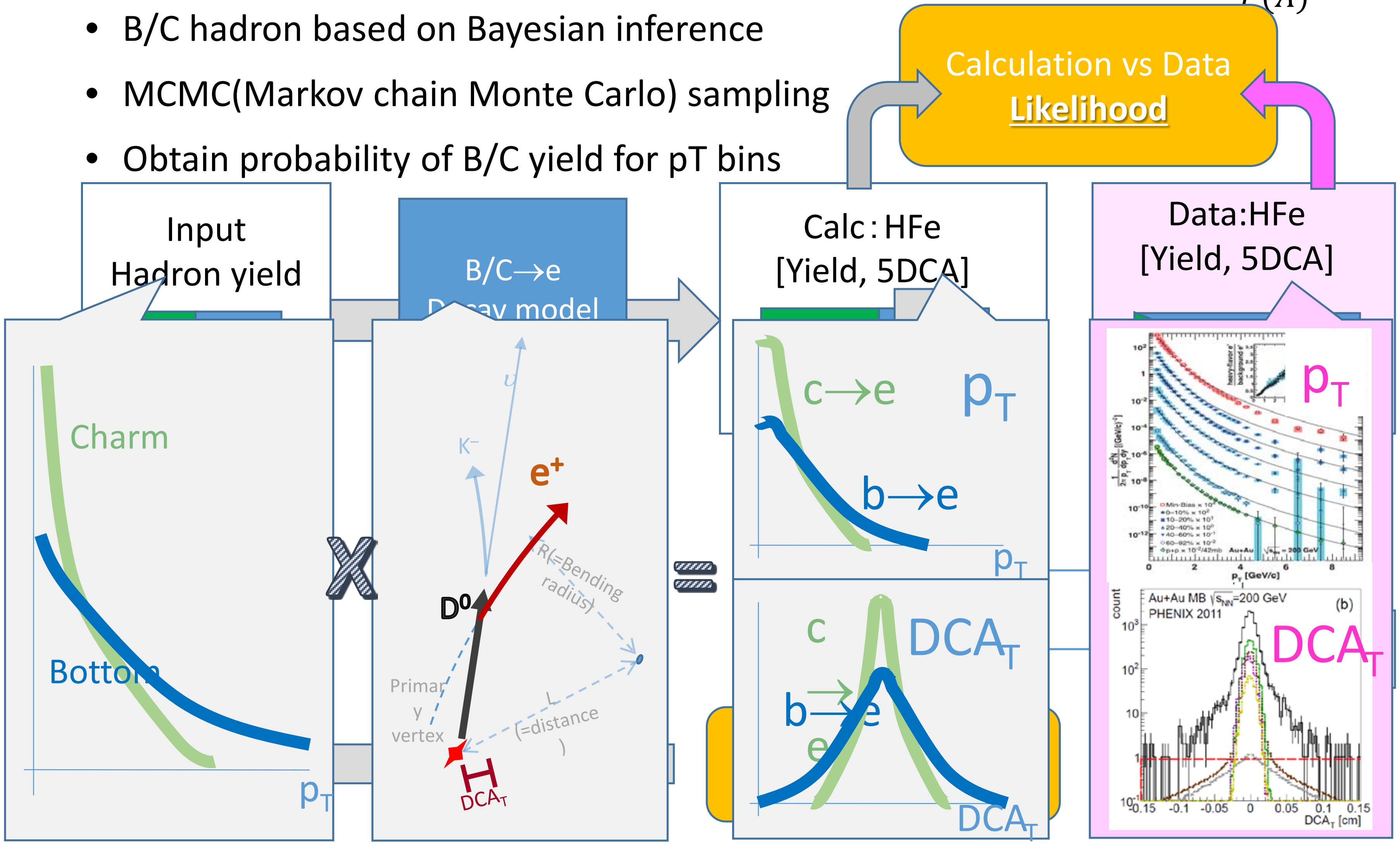
Invariant yield of heavy flavor electrons



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

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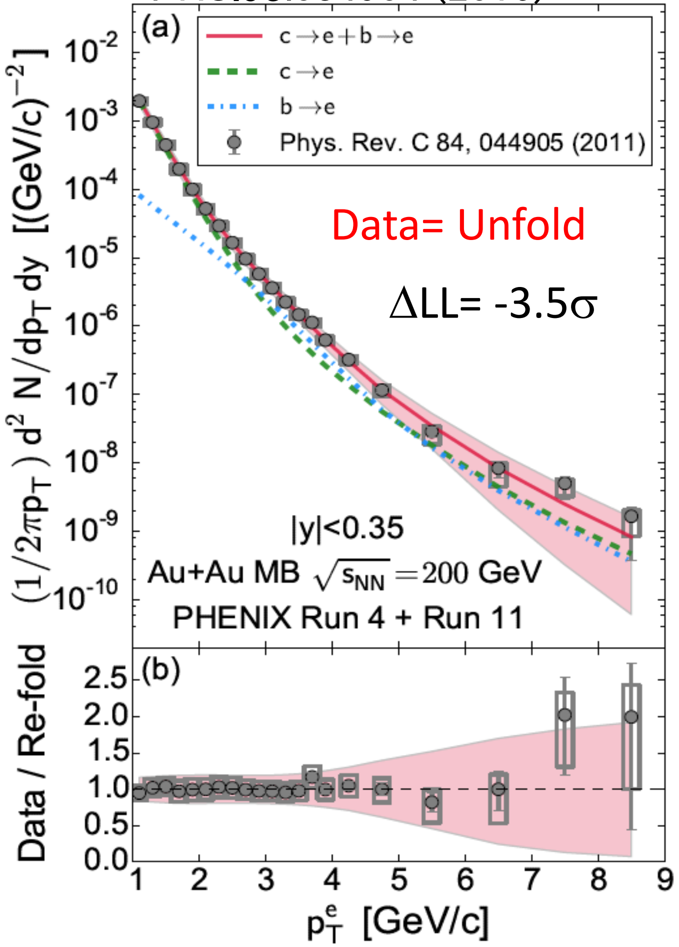

Data
Charm
Bottom
Background
Total=C+B+BG

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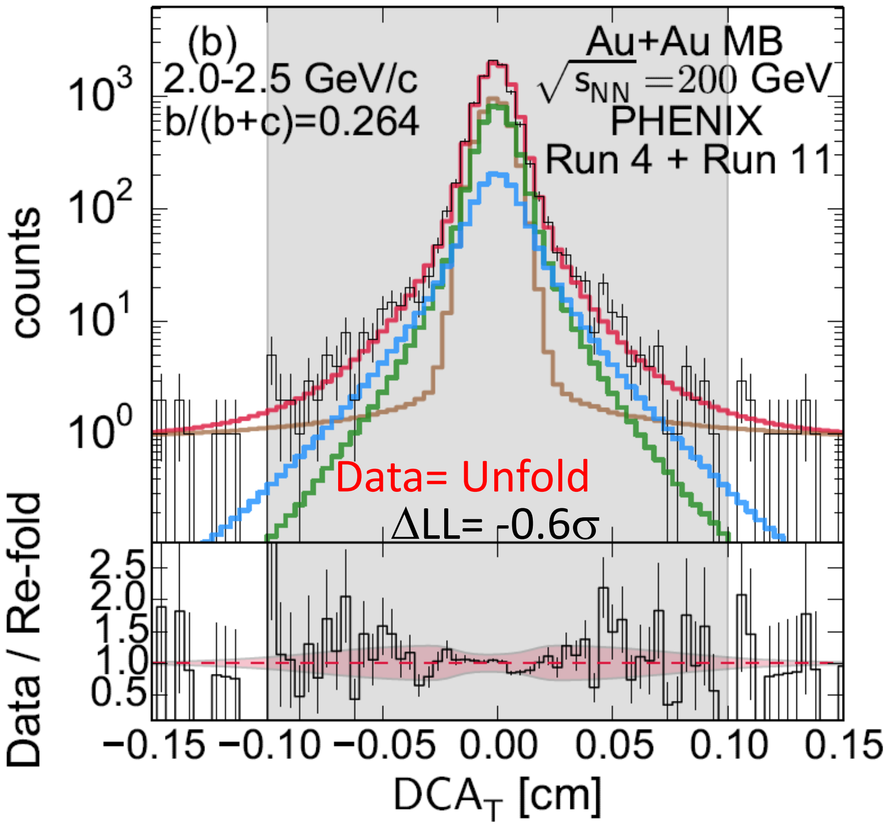
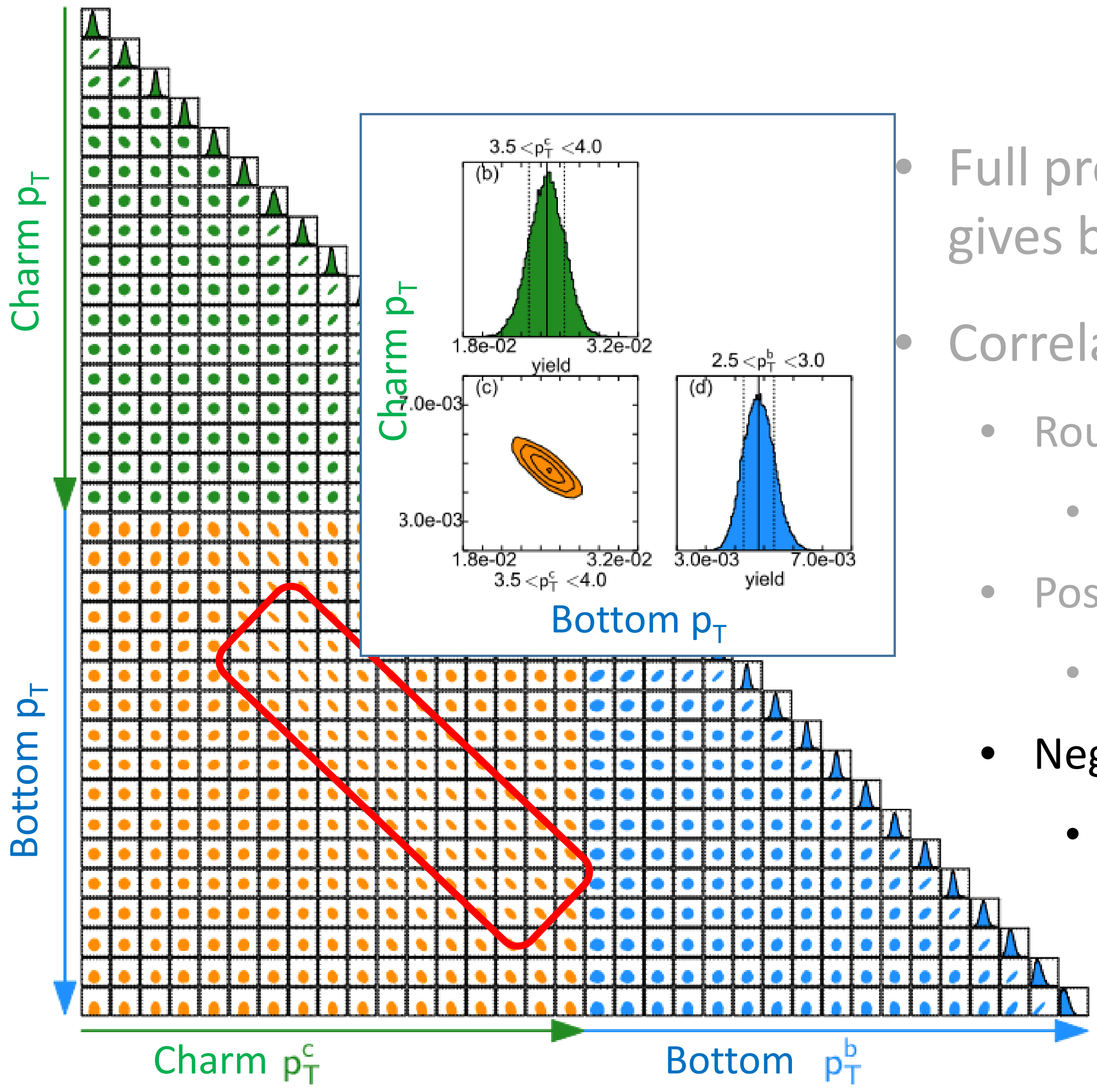


- Unfolding is consistent with electron data for yield and DCA_T
  - Diff likelihood: ΔLL= -0.6 ~ 3.8 σ

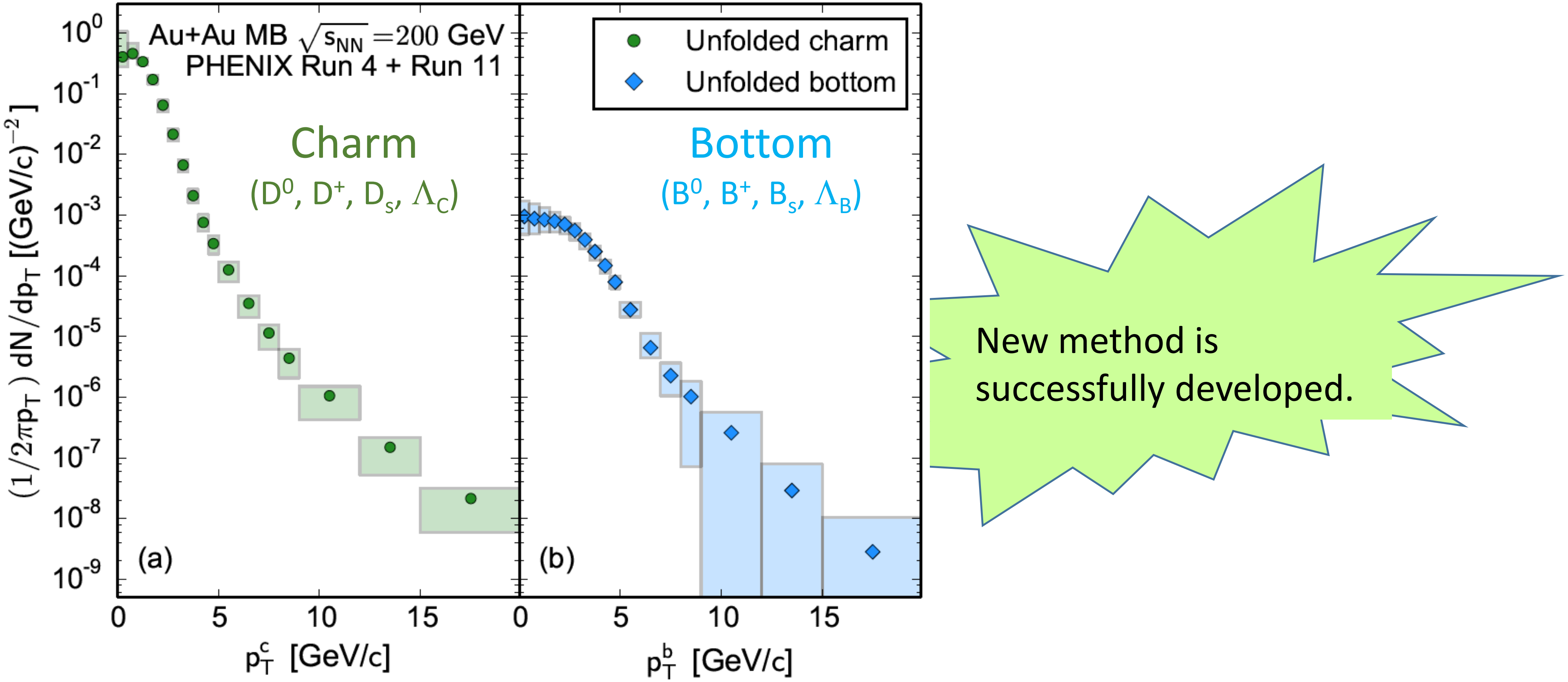
Full probability distribution



- 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

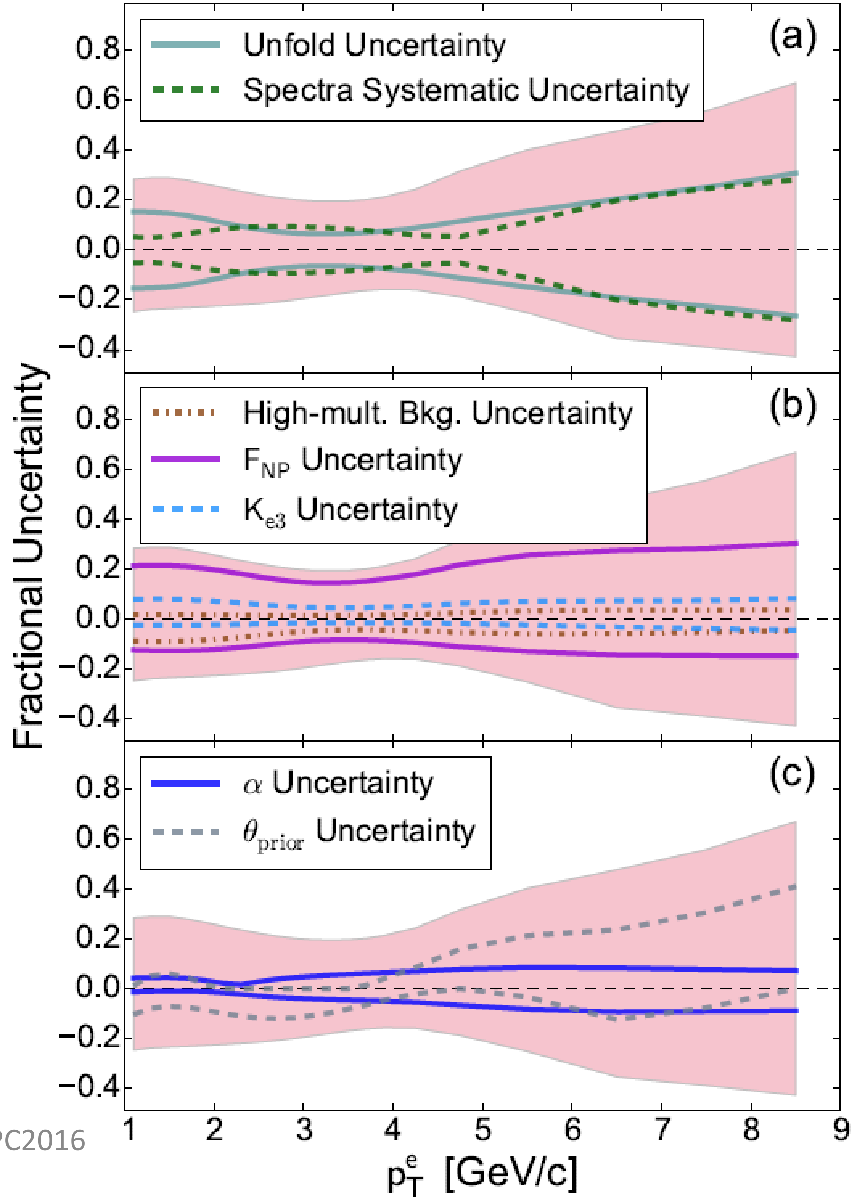
PRC.93.034904 (2016)



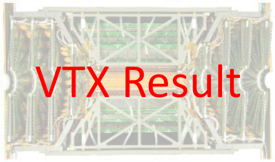
- Bottom & Charm hadron yield are successfully extracted
  - Whole rapidity
- First bottom hadron measurement

Systematic uncertainty on unfolding

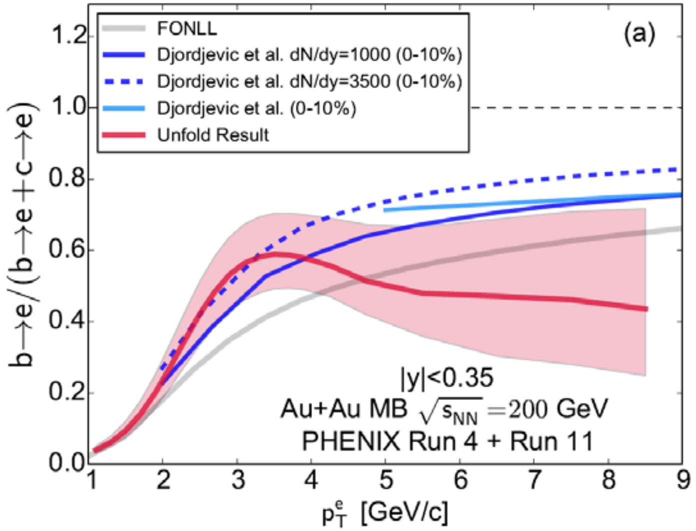
- Systematic uncertainty is obtained by changing the inputs within systematic uncertainty for each component.
- Type of uncertainties
  1. Unfold uncertainty : Due to data statistics
  2. Spectra uncertainty : Invariant HF spectrum
  3. High-mult Bkg : Mis-associated bg
  4. FNP : normalization on photonic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



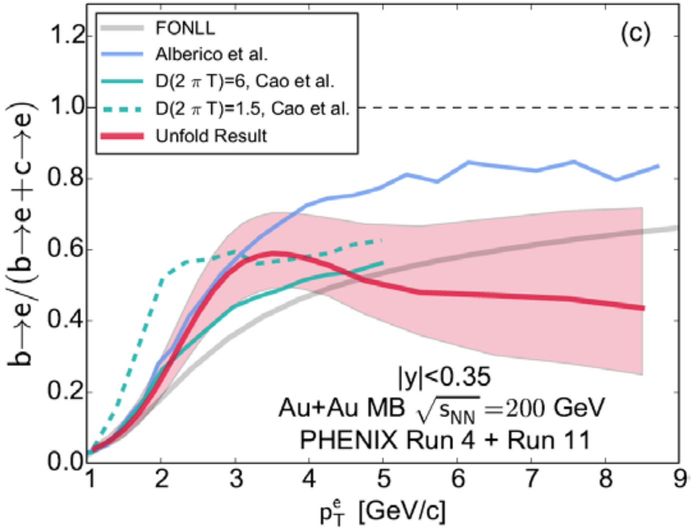
Comparison with Model



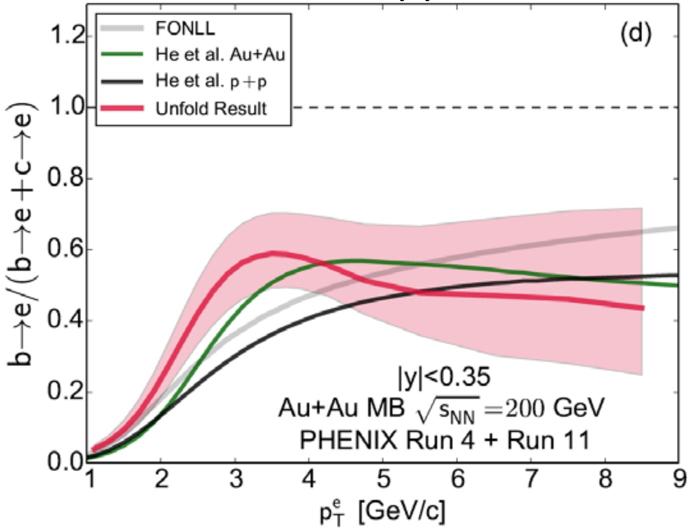
Radiative
DGLV



Collisional
Langevin based



Collisional
T-Matrix approach

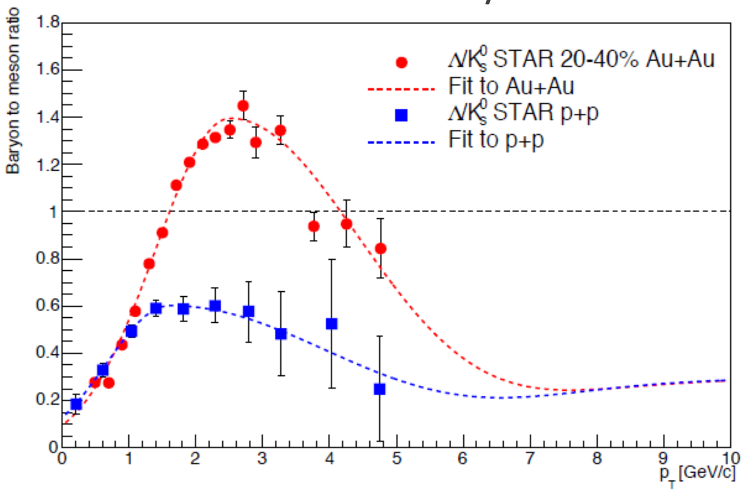


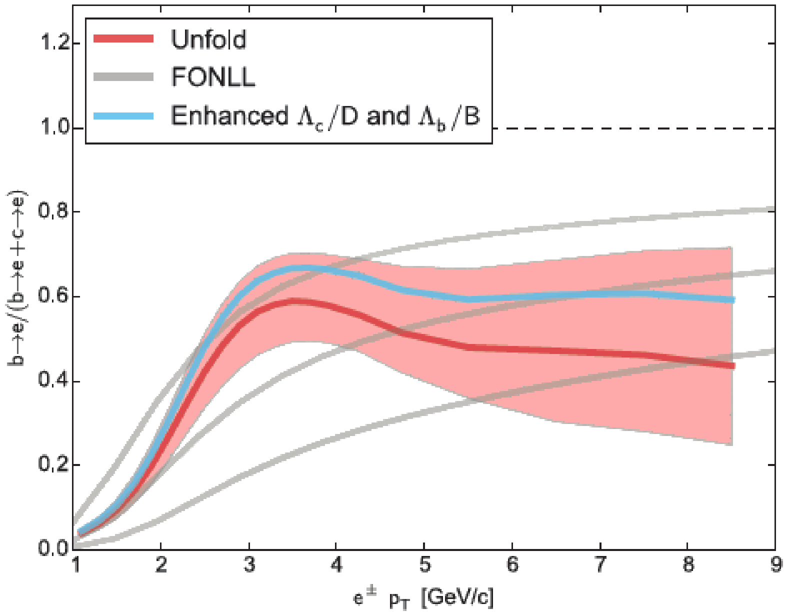
- Models are not consistent with data
  - Models show monotonic and non-monotonic behavior
  - Data cannot constrain the models quantitatively
- Need higher statistics to improve error at high p_T
  - Available from 2014-2016 : 10x more stat & good detector condition
  - New data will show the centrality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

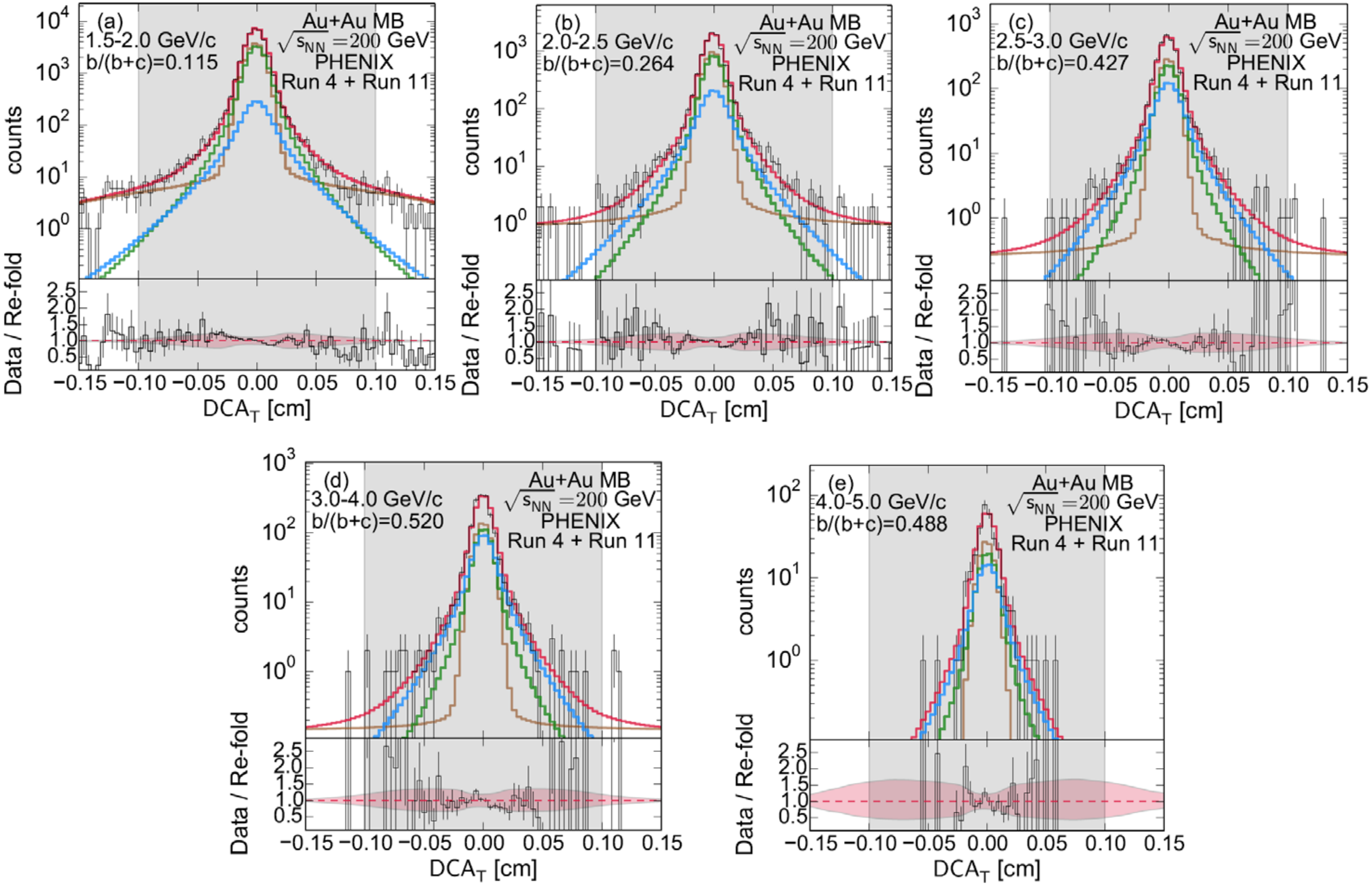
Effect on Baryon enhancement

- 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



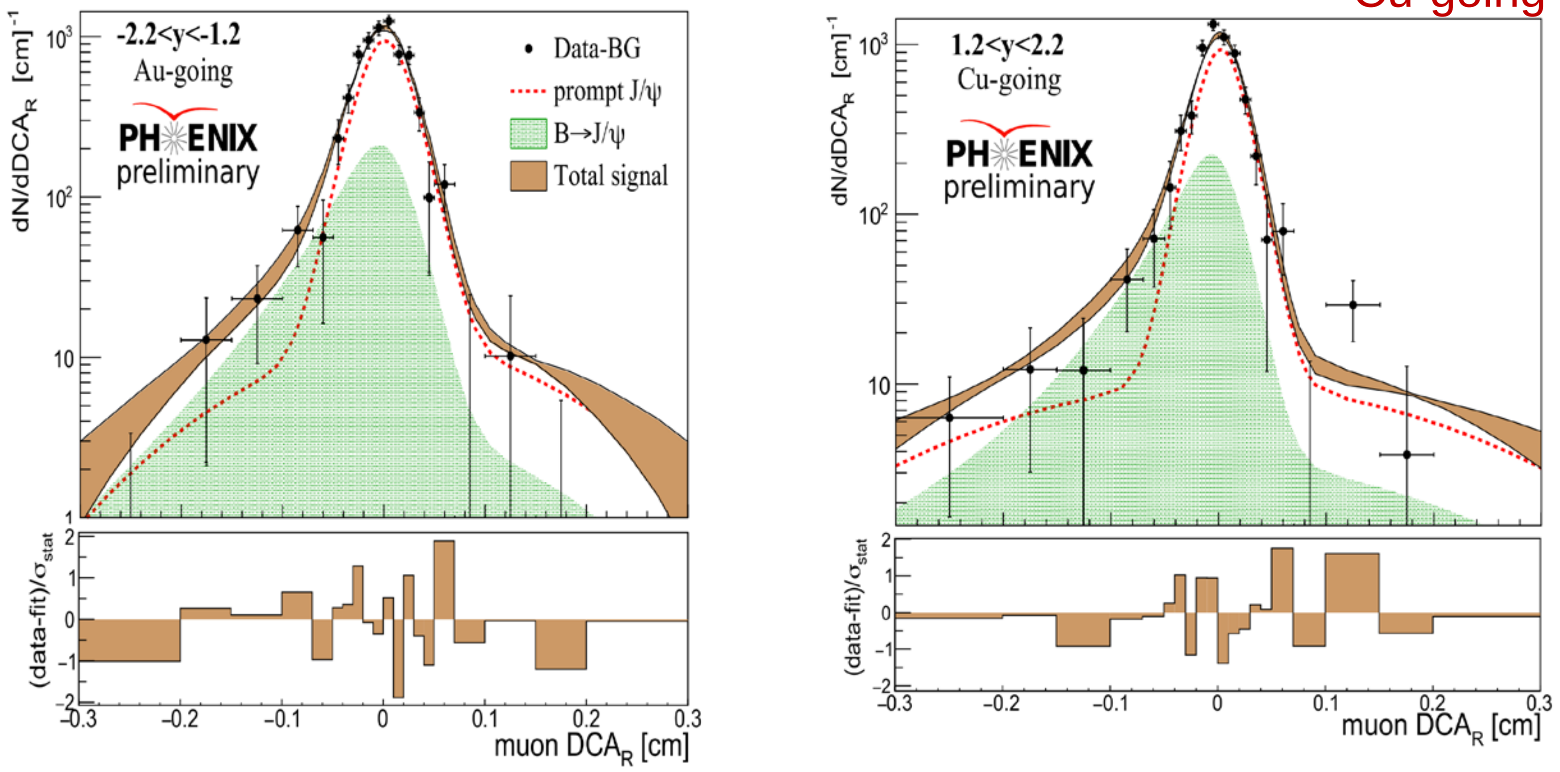



(a)
1.5-2.0 GeV/c
b/(b+c)=0.115
Au+Au MB
$\sqrt{s_{NN}}=200$ GeV
PHENIX
Run 4 + Run 11
(b)
2.0-2.5 GeV/c
b/(b+c)=0.264
(c)
2.5-3.0 GeV/c
b/(b+c)=0.427
(d)
3.0-4.0 GeV/c
b/(b+c)=0.520
(e)
4.0-5.0 GeV/c
b/(b+c)=0.488
counts
Data / Re-fold
DCA_T [cm]

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

Cu-going

Cu-going

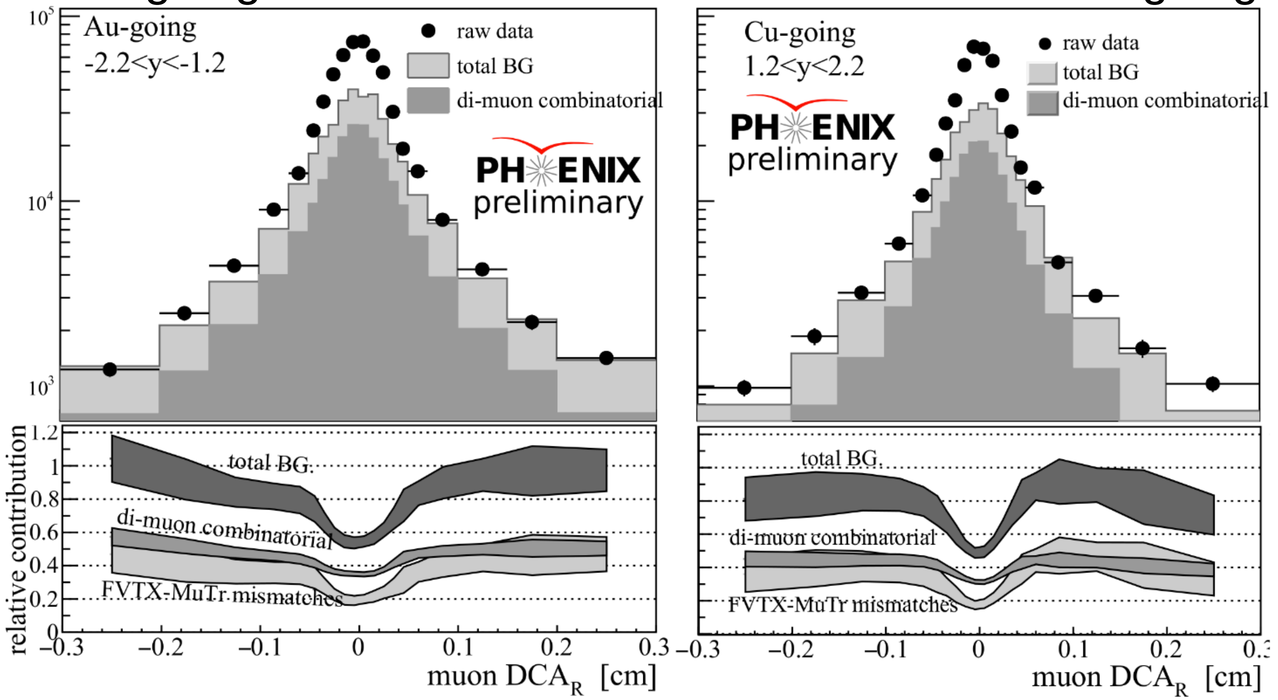


DCA_R Distributions. BG is subtracted for clarity

What NEW on Open Heavy Flavor?

Background components included

Au-going Cu-going

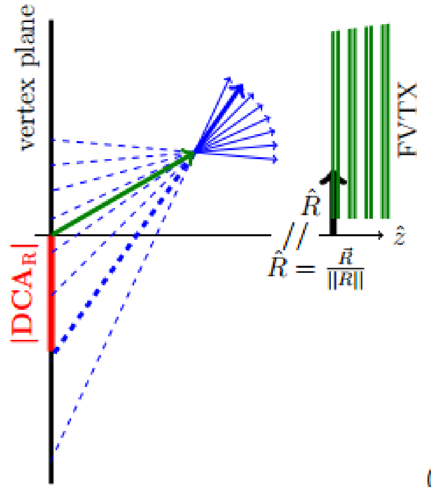


Two sources of background:

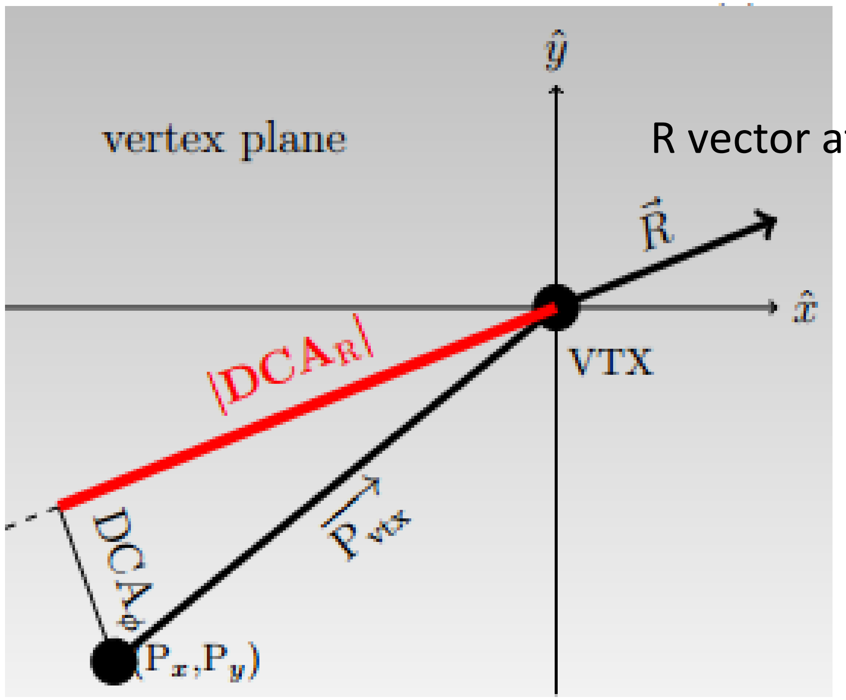
- Di-muon combinatorial
- FVTX-MuTr mismatches
  - Coming from incorrectly matching a MuTr track to the FVTX stand alone track.
- ccbar

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

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,

Charm & Bottom cross section