Measurement of single electrons from semileptonic charm and bottom hadron decays in Au+Au collisions at RHIC-PHENIX experiment

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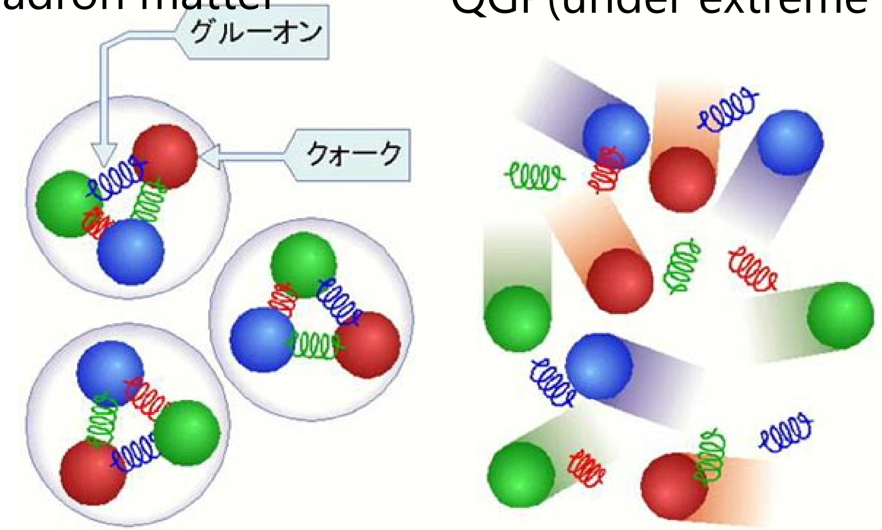
Result from Phys. Rev. C **93**.034904 (2016)

Quark Gluon Plasma (QGP)

- QGP:
  - Quarks & gluons are deconfined with hot & dense environment (Tc : ~170MeV)
  - Confirmed experimentally by High energy heavy-Ion collisions

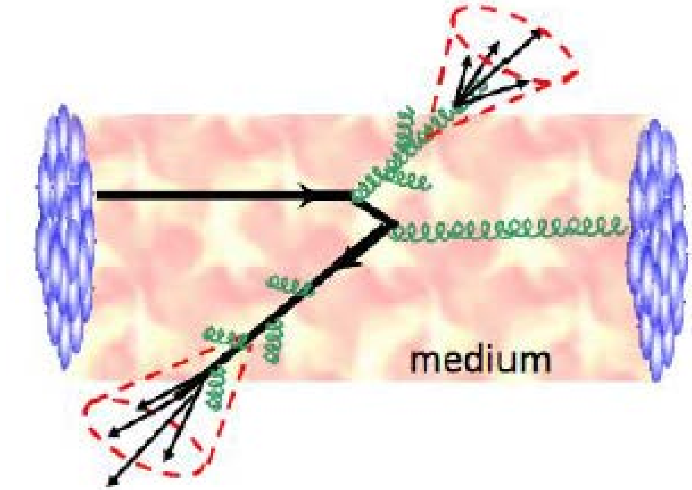
Hadron matter QGP(under extreme high temperature)



- Study characteristics of QGP

QGP Observables

Nuclear modification factor



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

1 with no suppression

Sensitive to parton energy loss at high p

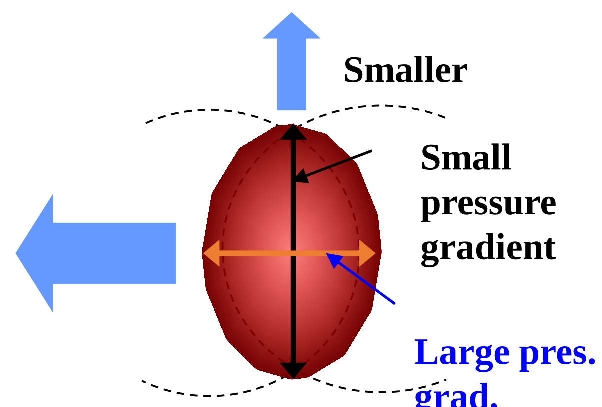
v_2 : Azimuthal anisotropy

Pressure gradient pushes particles and make corrective motion

-> Collective flow of particles

-> Azimuthal distribution can be anisotropic

v2 : 2nd Fourier coefficient

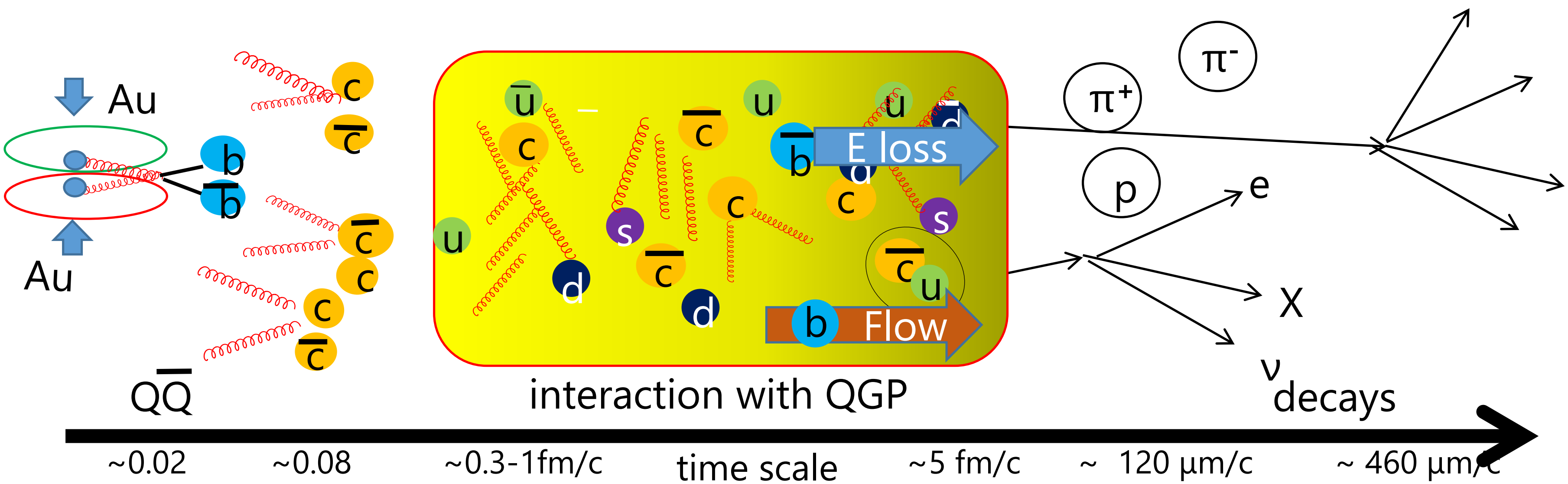


Sensitive to collective motion and medium coupling

Why heavy flavor, bottom & charm ?

- Mainly created at early stage of the collision
  - Production can be calculated by pQCD
- Passing through QGP
  - Suffer the energy loss and flow effect – HQ could be modified

Mc~1.3GeV   Tqgp ~400MeV
>>
Mb~4.5GeV Λ_{QCD} ~200MeV

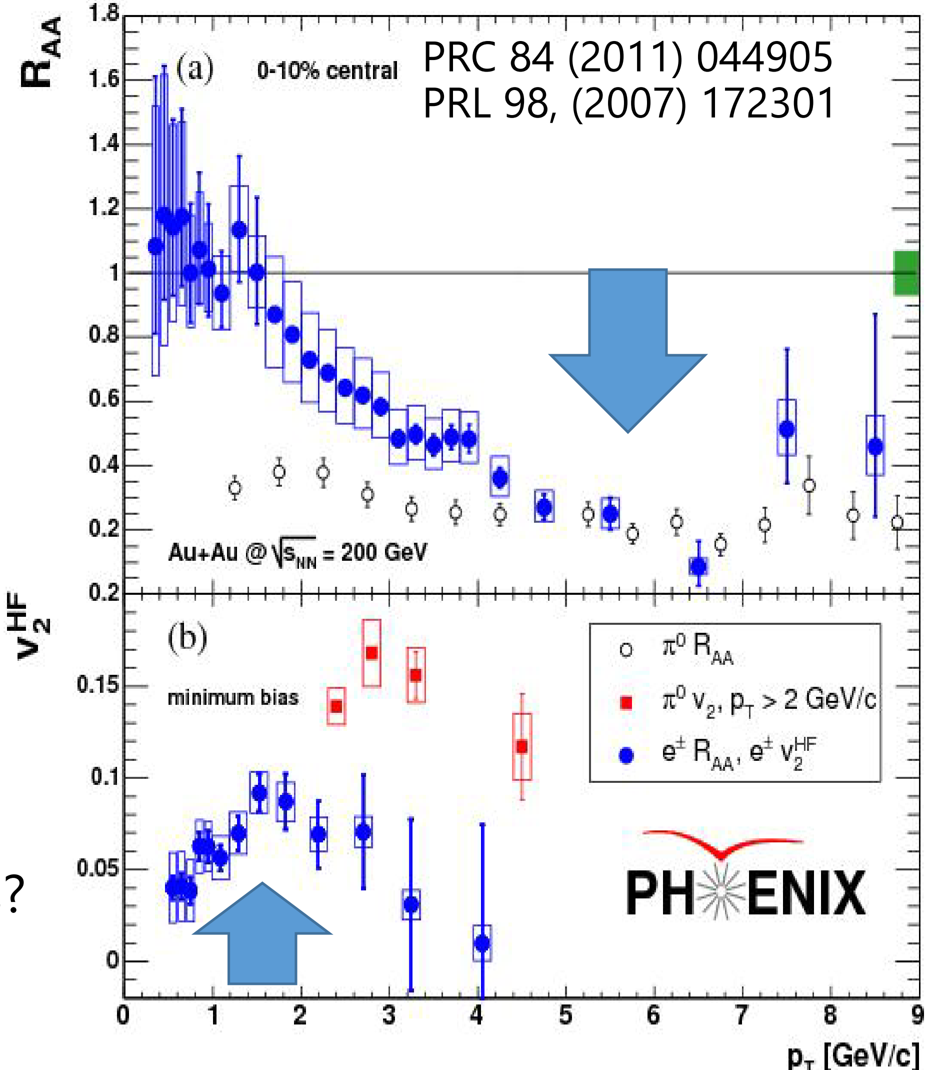


Modification of Heavy flavor is a good tool to study property of QGP

Previous inclusive (charm & bottom) result

HF→e in Au+Au 200GeV

- R_{AA}: strong suppression @ high pT
  - R_{AA}=1@ low pT
- v_2 : significant flow



Surprising results

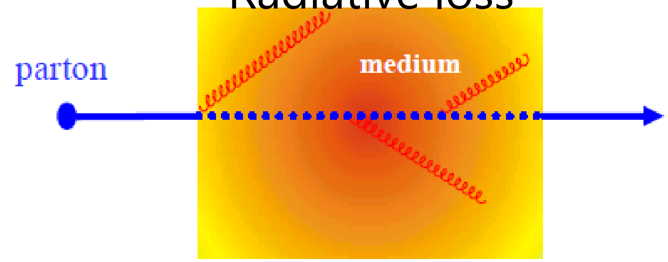
HQ expected to be less energy loss and smaller (zero) flow due to heavy mass

- Questions
  - What is the energy loss mechanism for heavy flavors?
  - Mass dependence of energy loss?

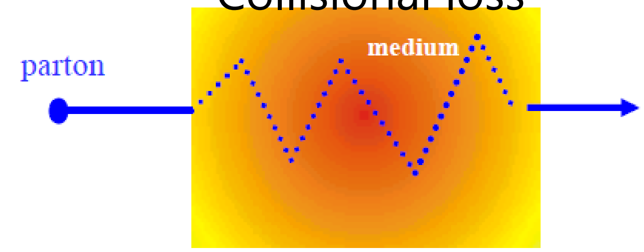
Energy loss mechanism

- Radiative loss (~ high pT)
  - Gluon radiation
  - Dead cone effect (PLB519:199,2001): $\Delta E_g > \Delta E_{LQ} > \Delta E_{HQ}$
  - Sensitive to gluon density
- Collisional loss (~ low pT)
  - Multiple scattering
  - Brownian motion in the medium
  - Sensitive to diffusion constant (D)

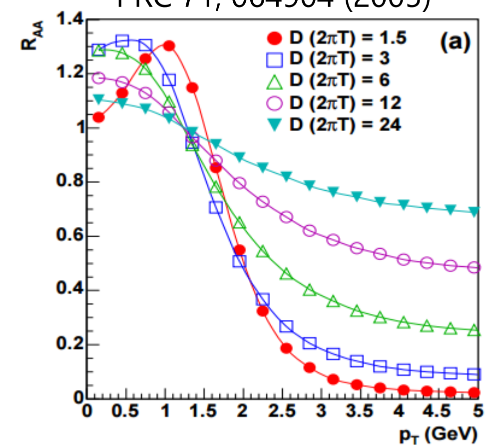
Radiative loss



Collisional loss



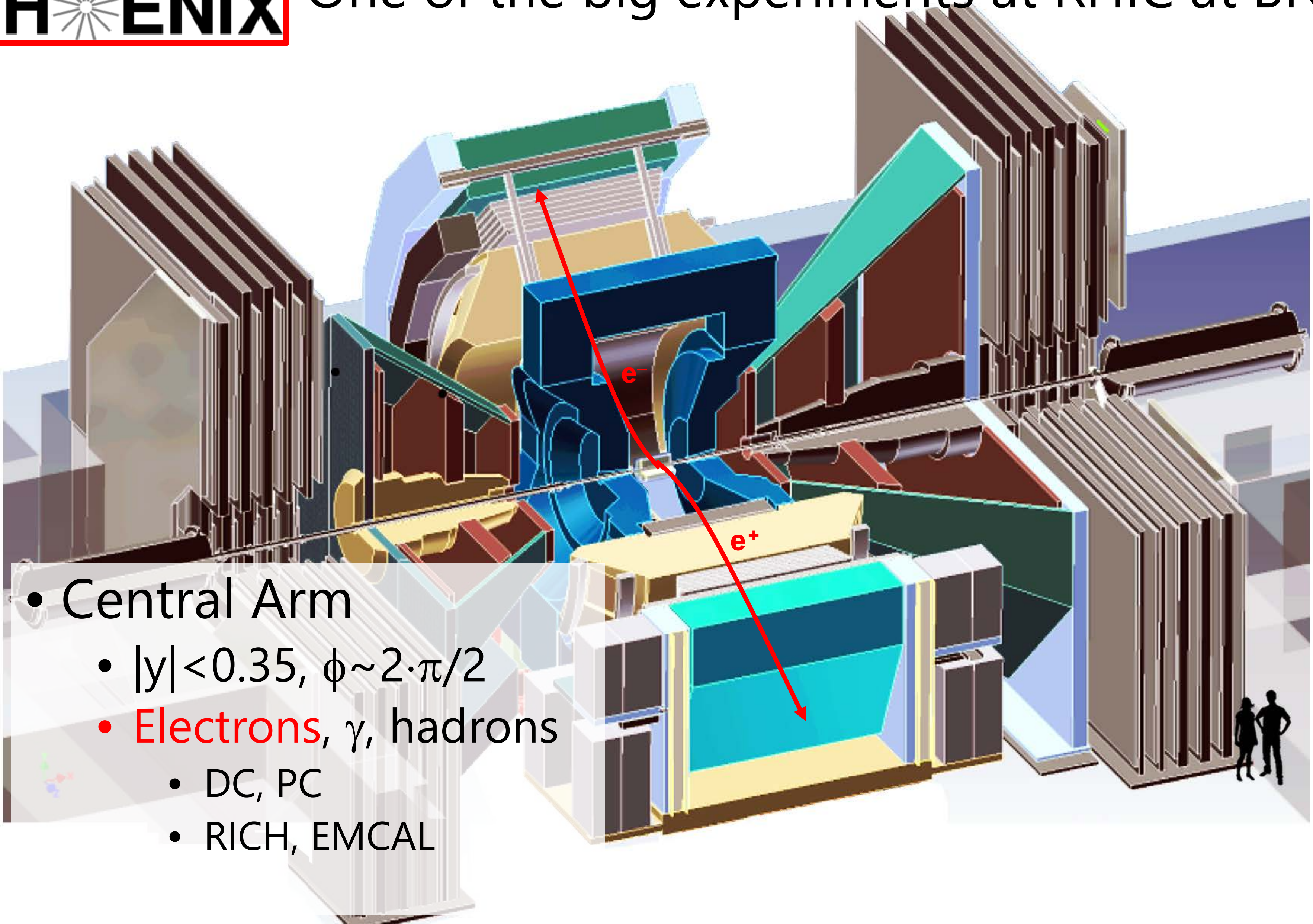
Collisional loss of charm quarks
PRC 71, 064904 (2005)



need to measure bottom & charm separately

Measurement

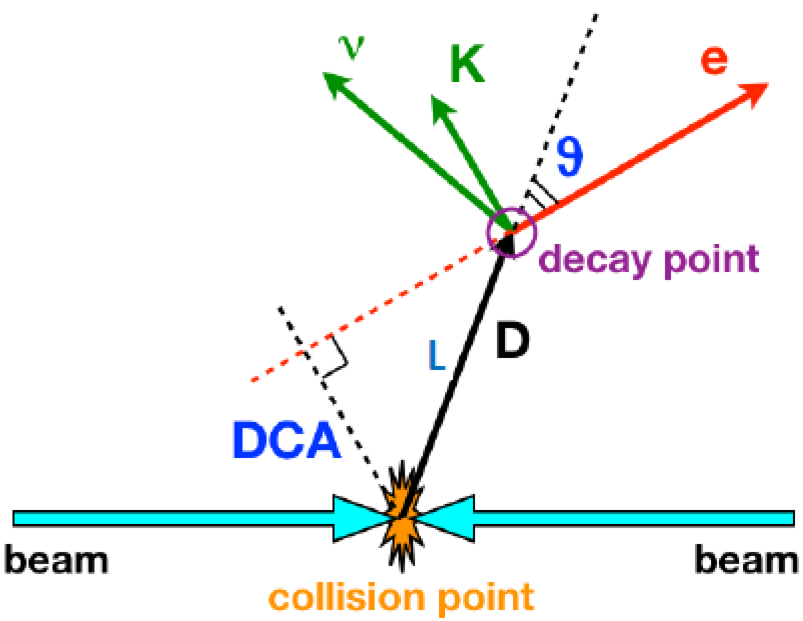
PHENIX One of the big experiments at RHIC at BNL



- Central Arm
  - $|y|<0.35$, $\phi\sim 2\cdot\pi/2$
  - Electrons, γ, hadrons
    - DC, PC
    - RICH, EMCAL

Challenge to separate b and c origin

- Utilize their different lifetimes and decay kinematics



decay length (cτ)

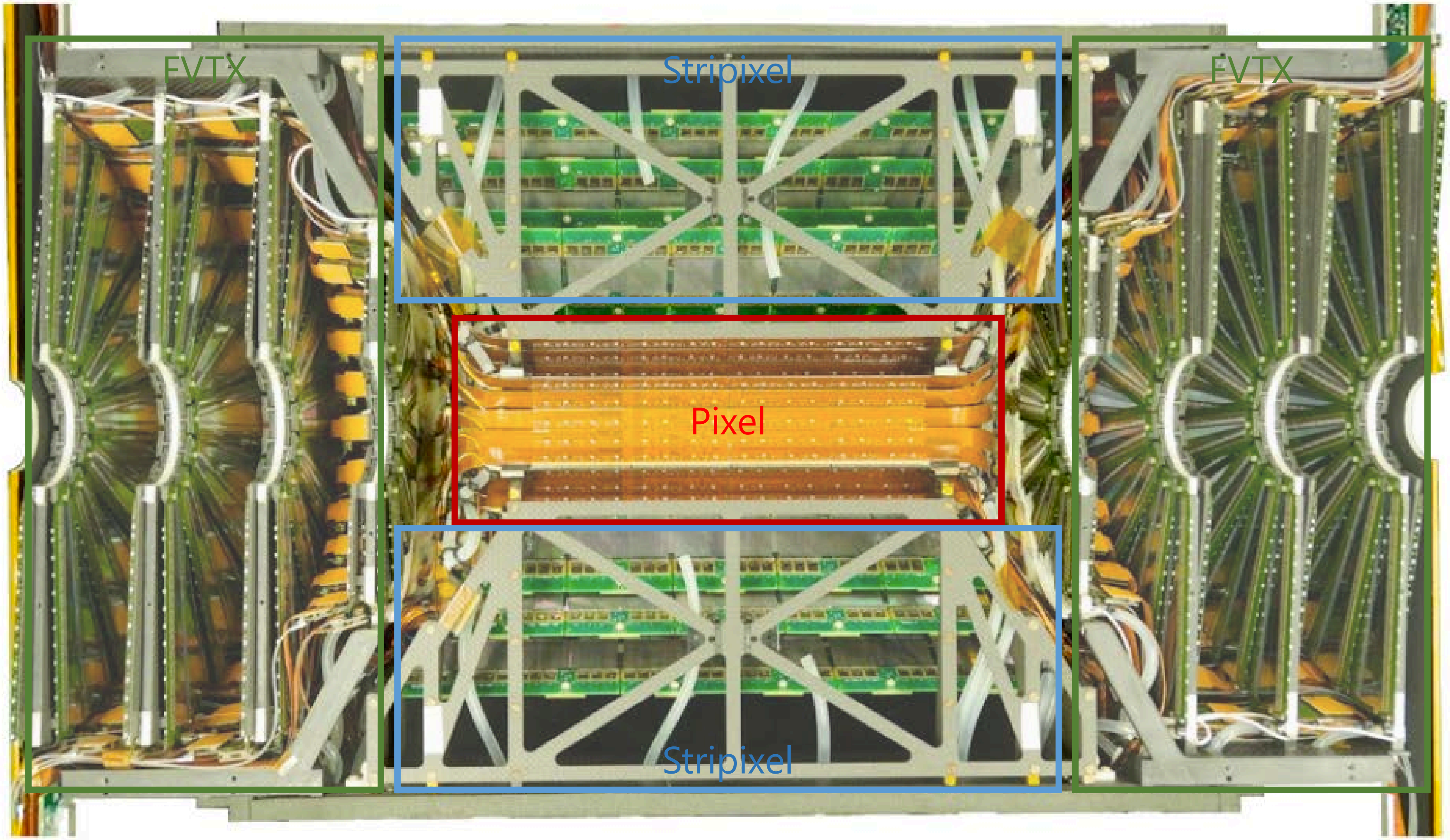
B^+ : 491.1 μm, D^+ : 311.8 μm,

if we measure
- Precise displaced tracking
- Precise primary vertex

⇩

We can separate between c-origin electrons and b-origin electrons experimentally!

PHENIX Silicion VerTeX Detector (VTX)



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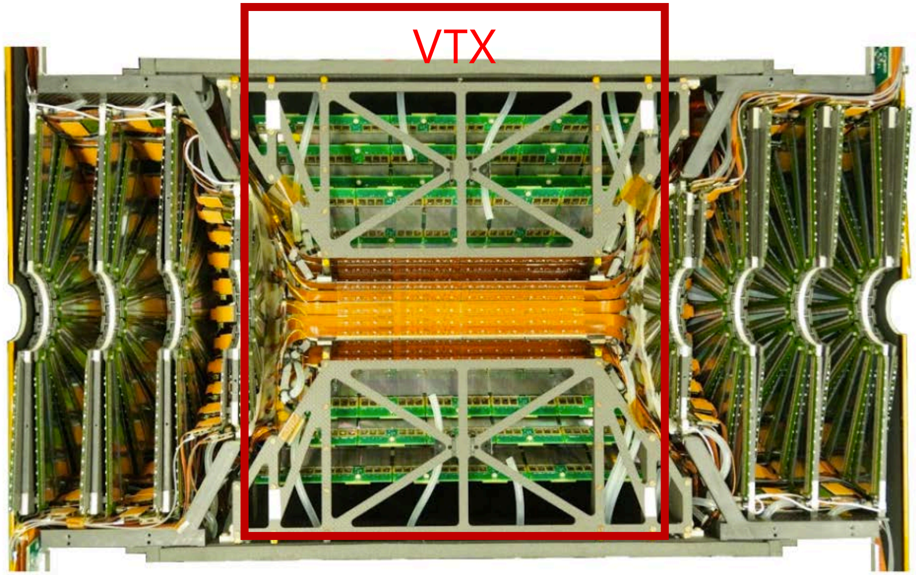
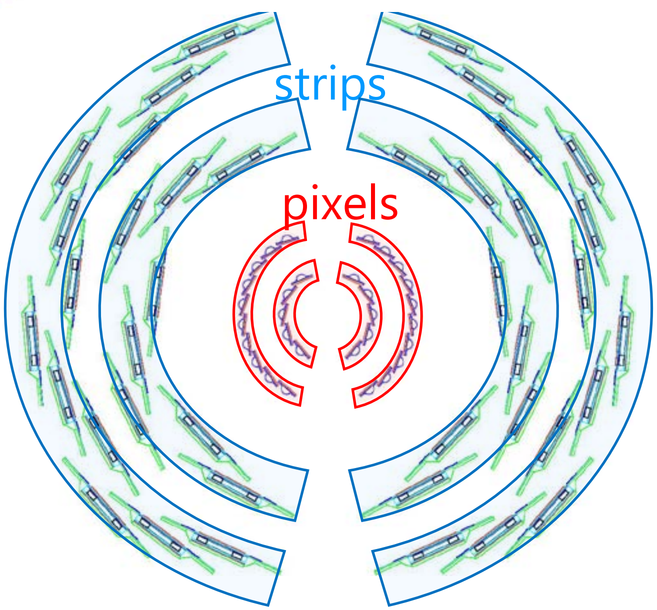
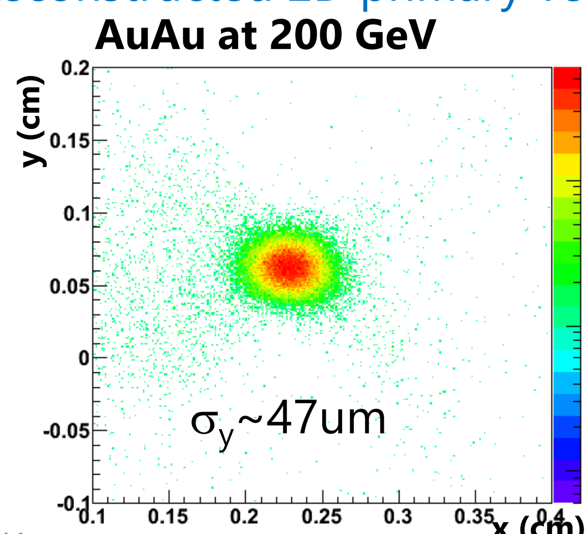




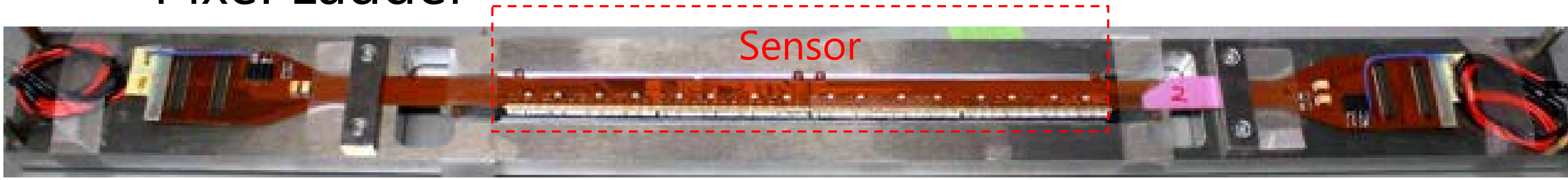
- VTX installed in Run2011
  - Large coverage
    - $|\eta|<1.2$, $\phi \sim 2\pi$
  - 4 layer silicon detectors
    - 2 inner pixel
    - 2 outer strip

Reconstructed 2D primary vertex



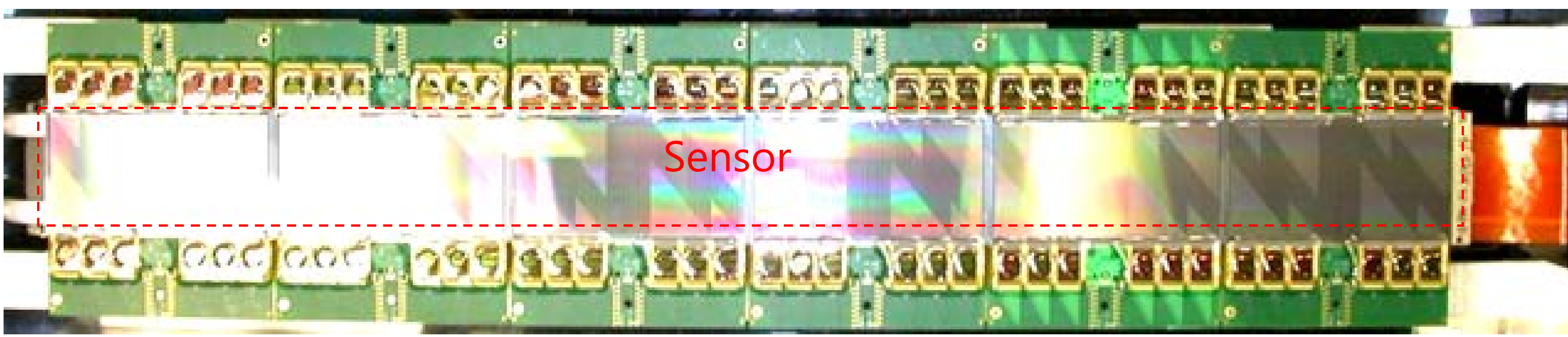
Pixel & Strip(ixel) Ladders

- Pixel Ladder



  - 50 x 425 um (ϕ x z) → 14.4 um in ϕ, 1.5% X_0
  - RIKEN radiation lab group is responsible

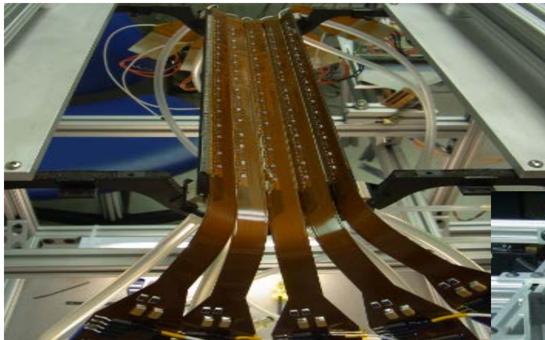
- Strip(ixel) ladder 2D



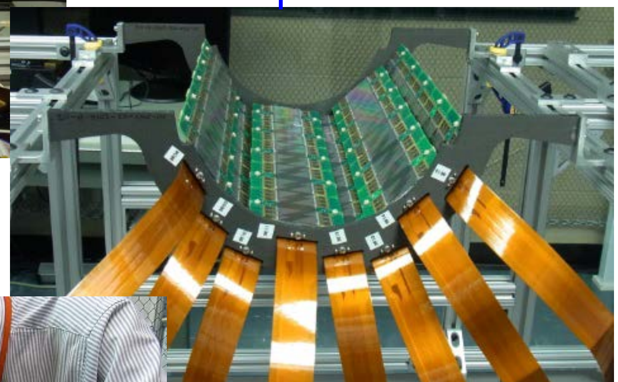
  - 80 x 1000 um (ϕ x z) → 23.0 um in ϕ, 5% X_0 8bit ADC
  - Newly designed at BNL for PHENIX

VTX construction are completed!!

Pixel

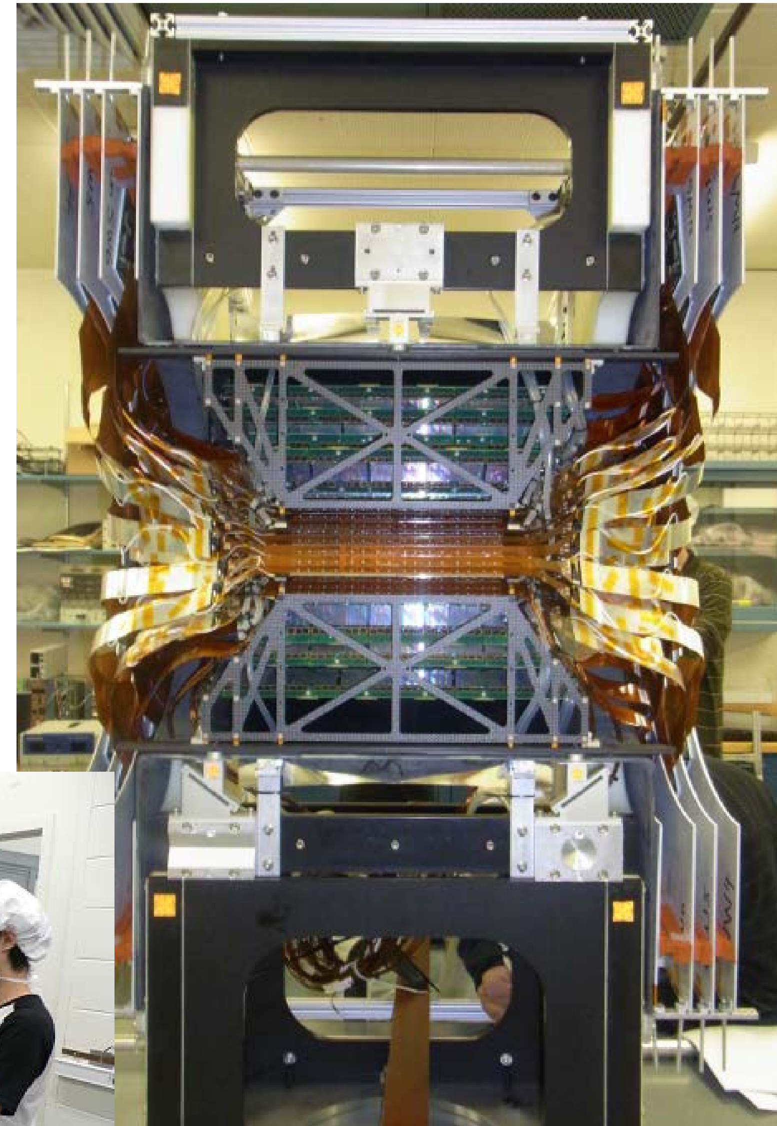


Stripixel



Takashi &Mike

Atsushi, Mike
Ryohji, Hidemitsu



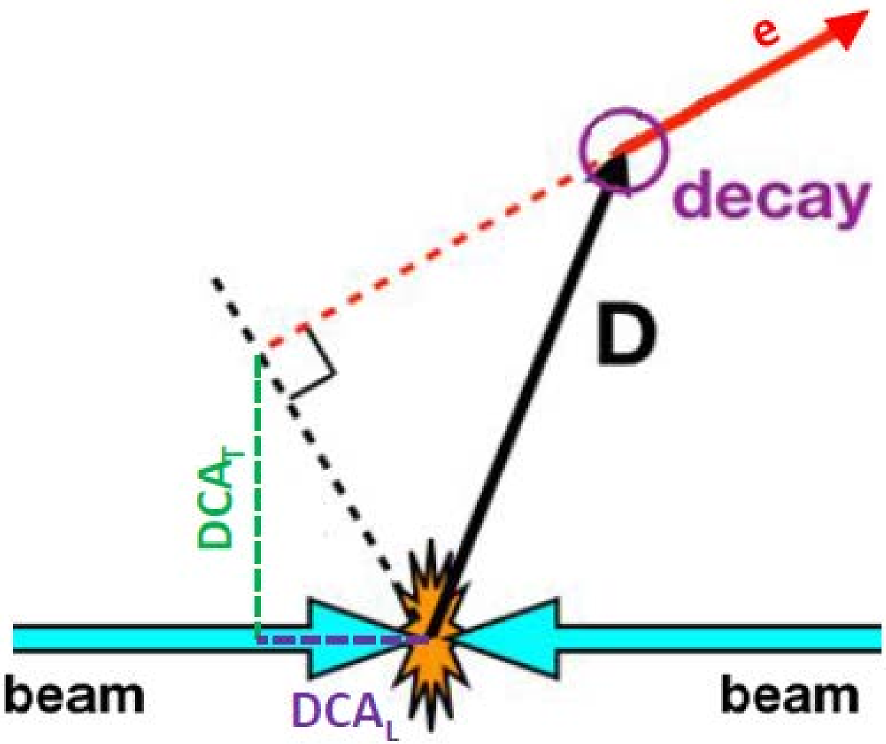
Analysis

Analysis procedure

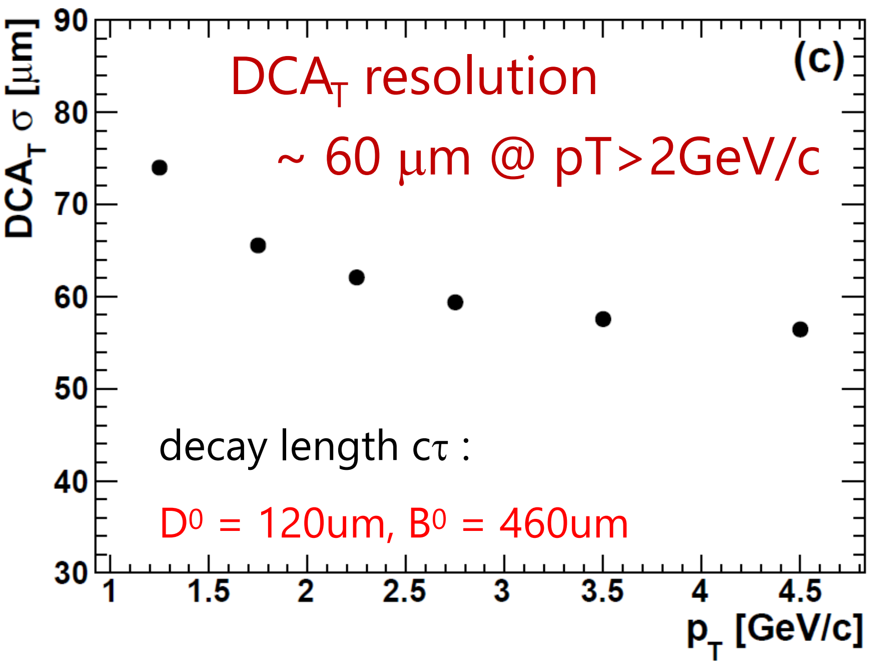
1. Measure displaced tracking of electrons using VTX
   - DCA of the electrons
   - Backgrounds estimation

2. Separate b→ e and c → e component
   - Unfold the b and c components

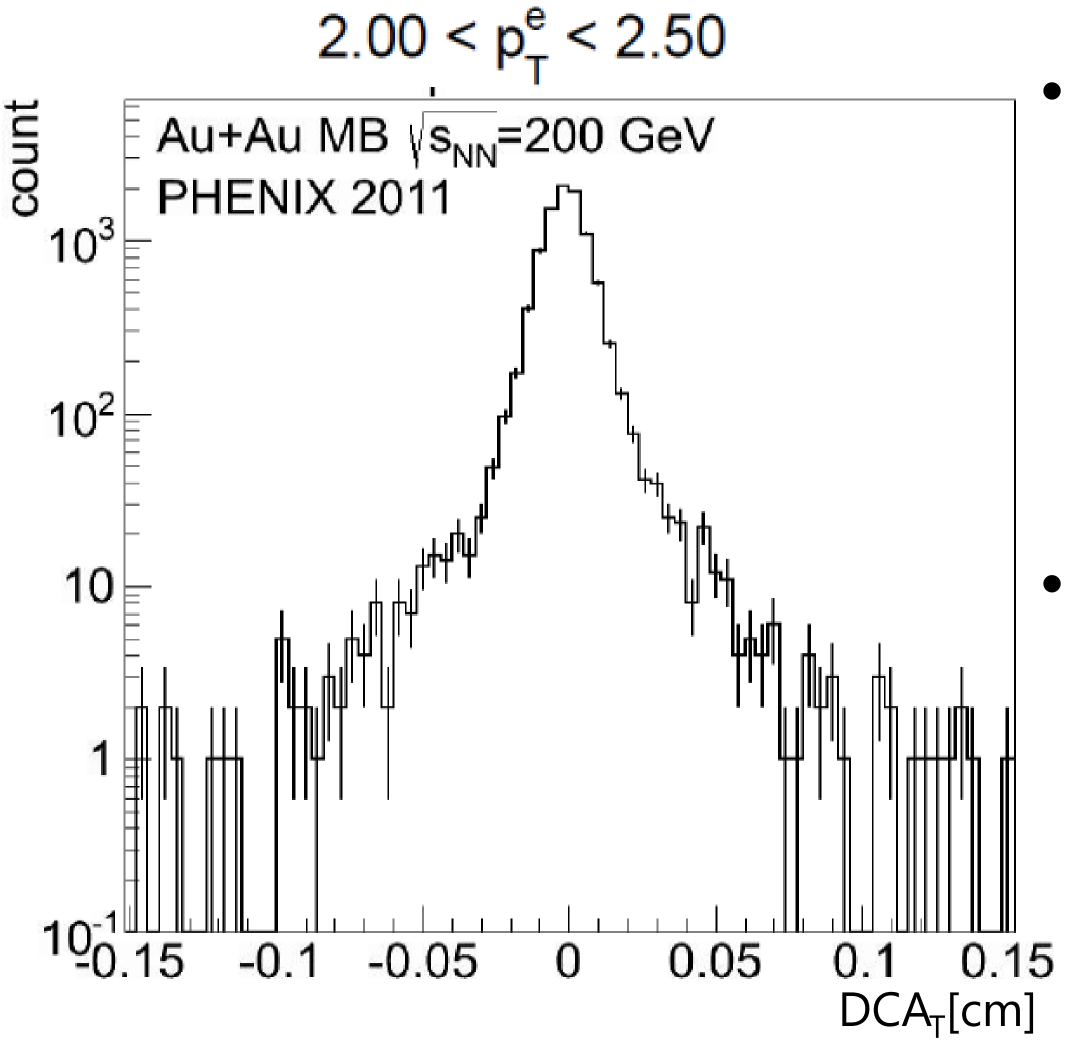
Precise displaced tracking



- Calculate Distance of Closest Approach (DCA) of electrons to primary vertex
  - Proxy for decay length
- Calculate separately
  - DCA_T = in transverse plane
  - DCA_L = in longitudinal plane
- DCA_T is better by detector design

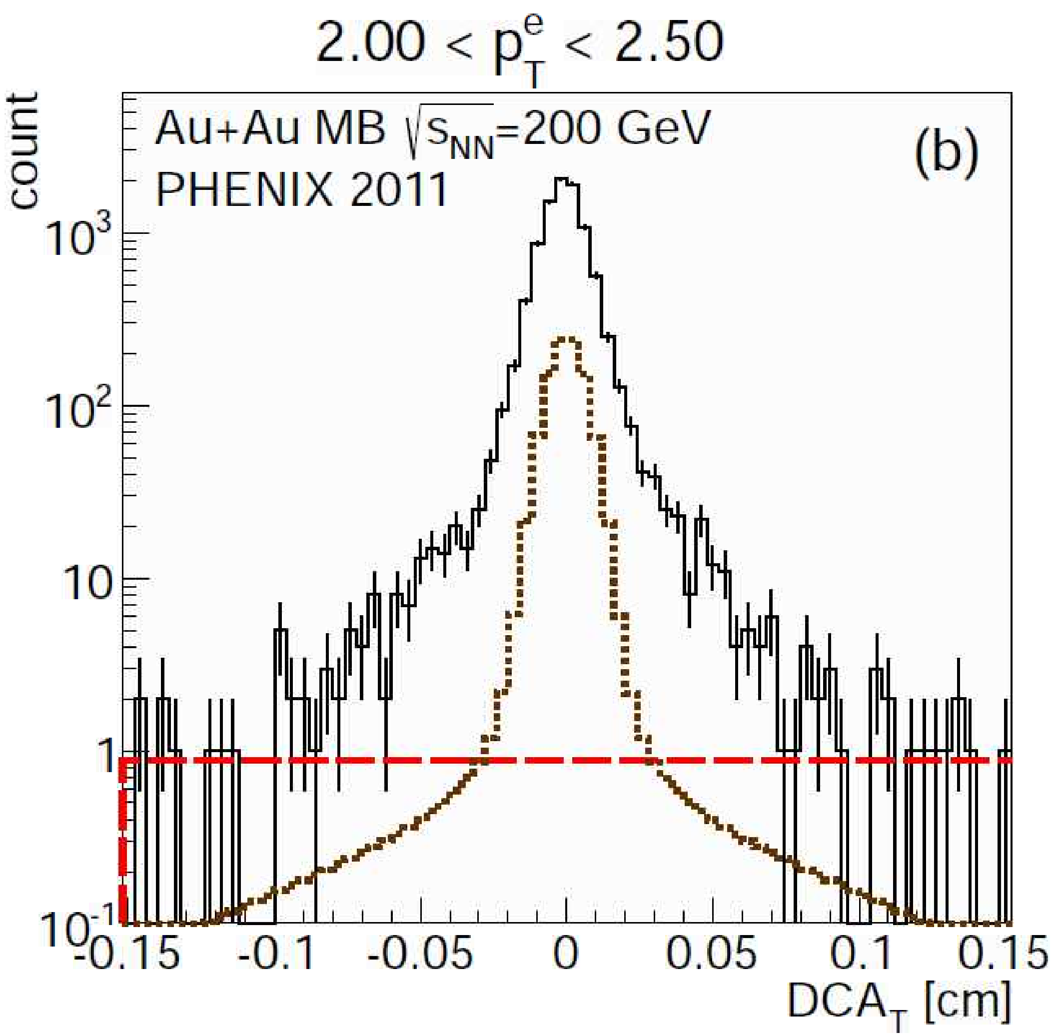


Electron DCA_T distribution



- DCA_T in Run2011 dataset
  - 2.5B min. bias events
  - 5 p_T bins in 1.5-5GeV/c
  - No efficiency correction
- Contain various BG components
  - Determine the normalization and DCA_T shape

Electron DCA_T distribution



- Various backgrounds

Detector origin backgrounds

- Mis-identified hadrons
- ***Random association with VTX***

DCA_T shape and normalization determined by data driven (mixed)

Physics origin backgrounds

- ***Photon Conversions***

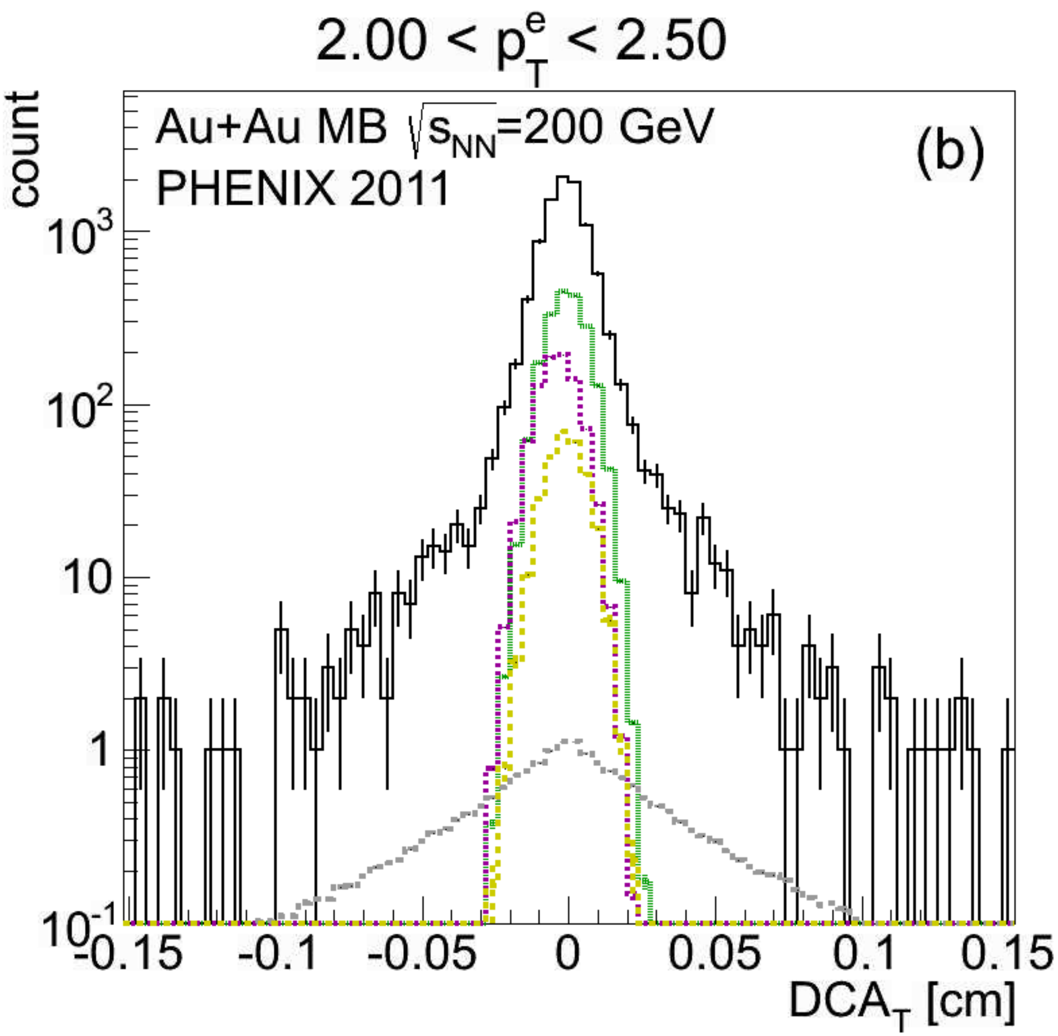
  ~ 75% rejected by analysis cut

- ***Dalitz decays of π^0 & η***
- $J/\psi \rightarrow e+e$
- Ke3 ($K \rightarrow e+X$)

DCA_T shape from MC

Normalization from measured yield

Electron DCA_T distribution



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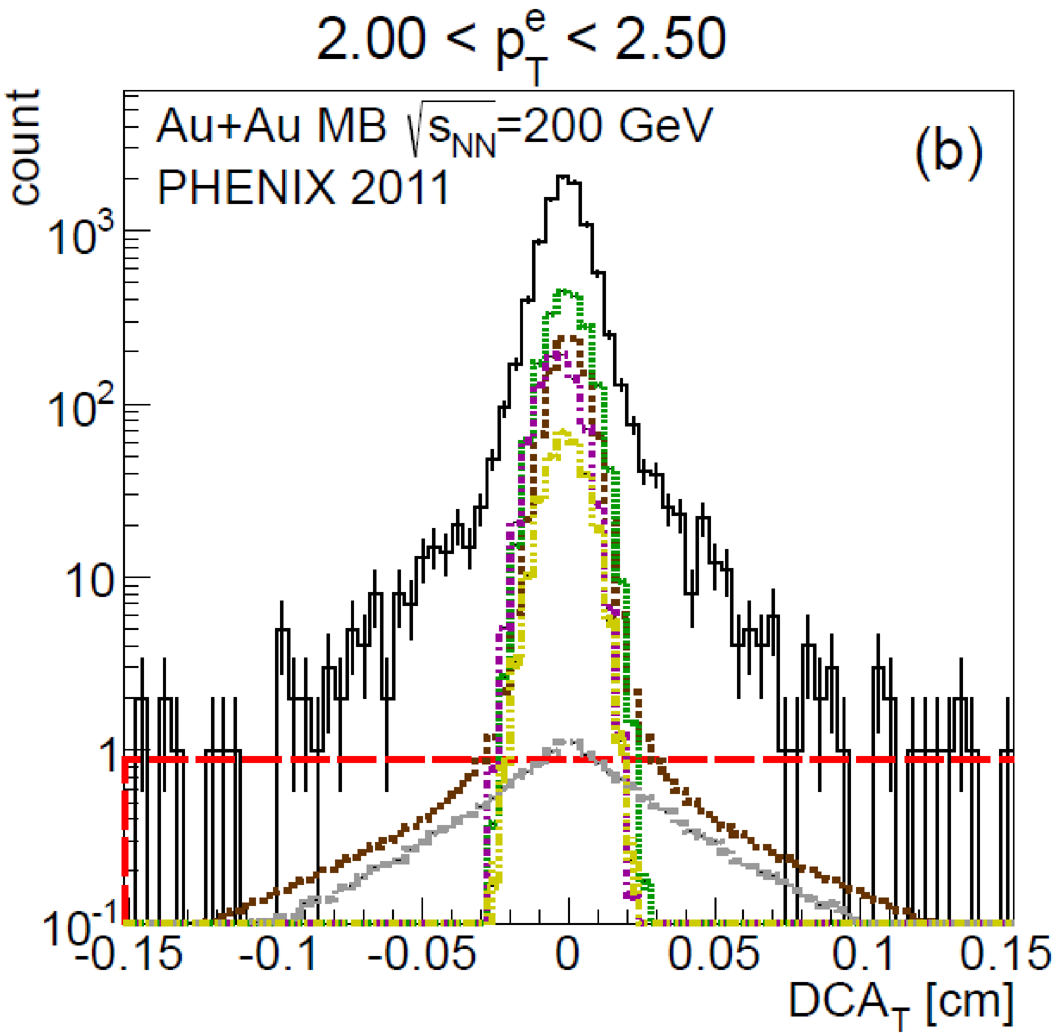

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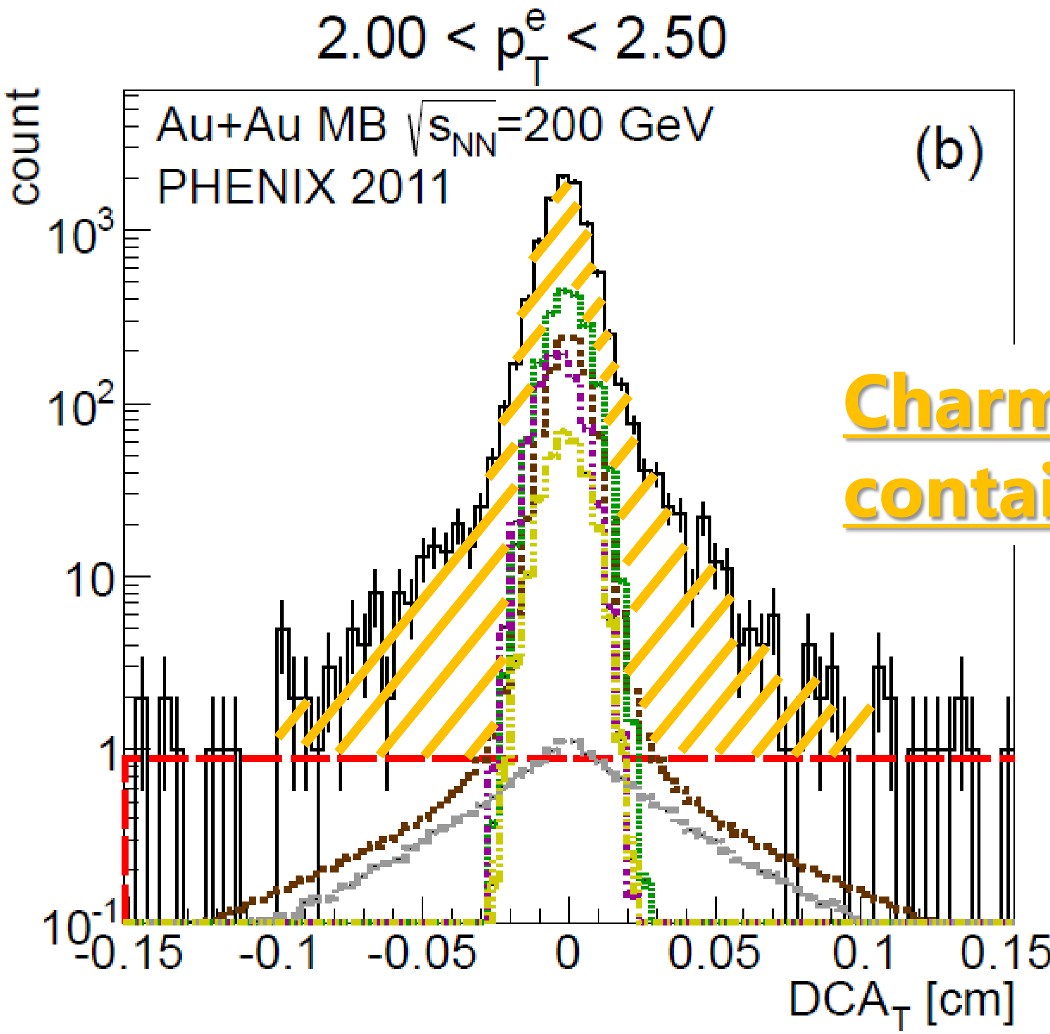
Electron DCA$_T$ distribution



- Various backgrounds

Detector origin backgrounds

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DCA$_T$ shape and normalization determined by data driven (mixed)

Charm & Bottom signal contains

- ~ 75% rejected by analysis cut

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- J/ψ → e+e
- Ke3 (K → e+X)

DCA$_T$ shape from MC

Normalization from measured yield

Analysis procedure

1. Measure displaced tracking of electrons using VTX
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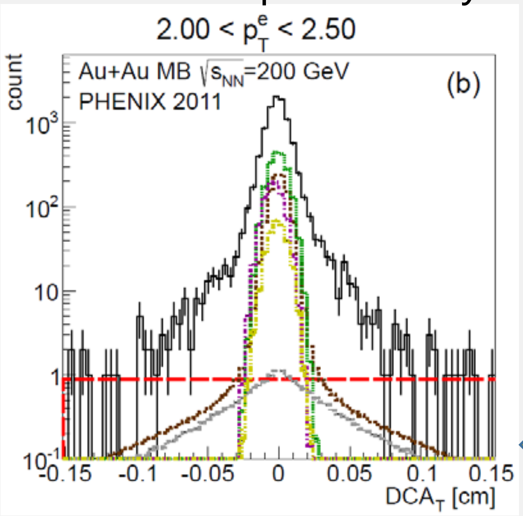
2. Separate b→ e and c → e component
   - Unfold the b and c components

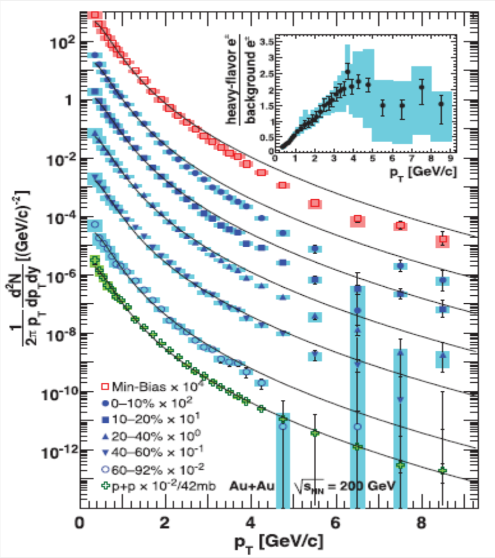
Strategy of bottom & charm separation

1. DCA distributions $1.5<p_T<5$
   - Utilize decay length ($c\tau$) of b & c
   - B^+ : 491.1 μm, D^+ : 311.8 μm,
   - DCA shape ～ decay length



2. Previous HF electron yield $1< p_T < 9$(GeV/c)
   - Broad p_T range
   - Efficiency fully corrected
   - Constrain b & c yield

Phys. Rev. C 84, 044905 (2011)



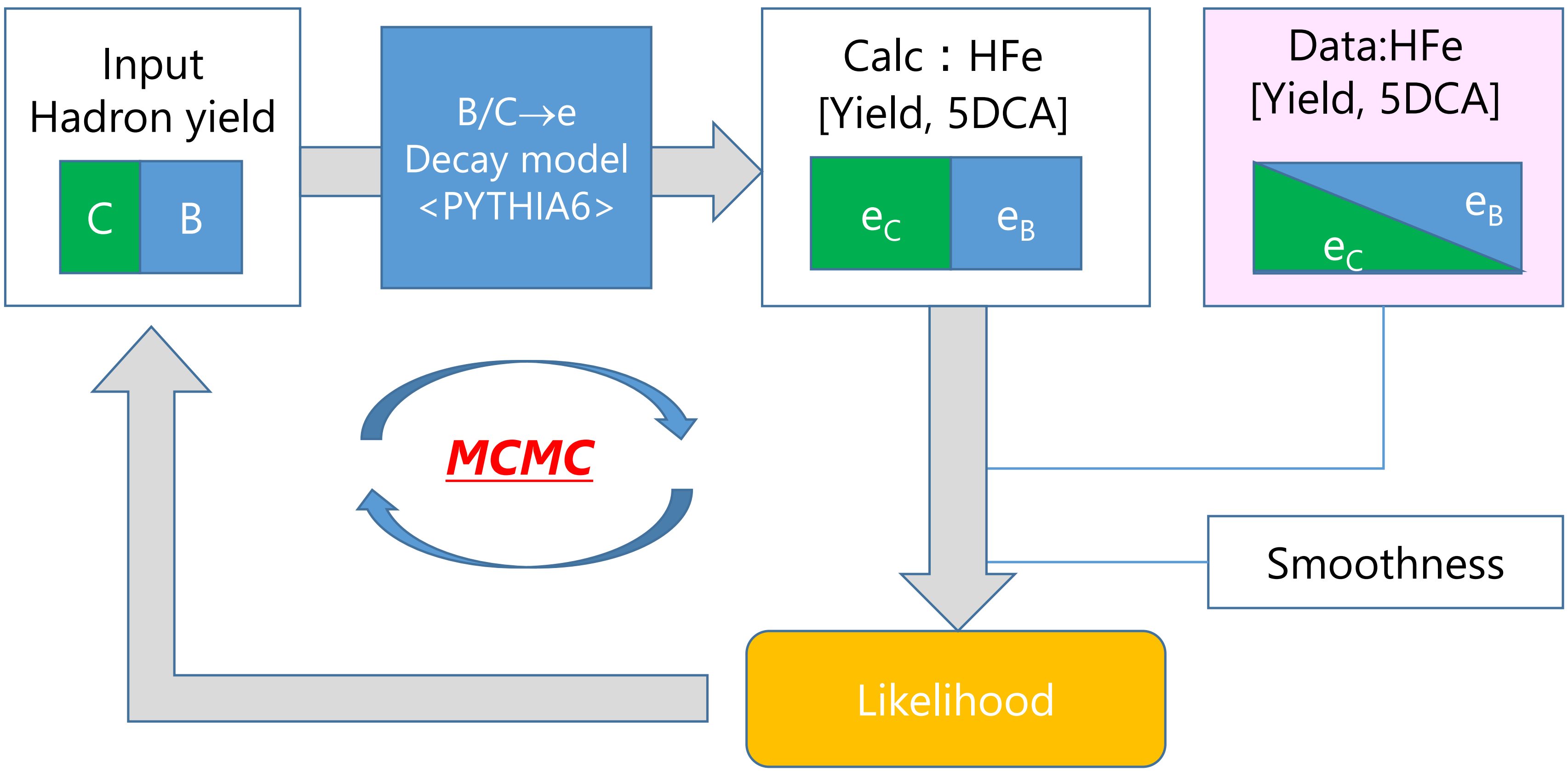
More constrain

- Unfold method employs to separate bottom & charm
  - Fit with DCA and yield simultaneously

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

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



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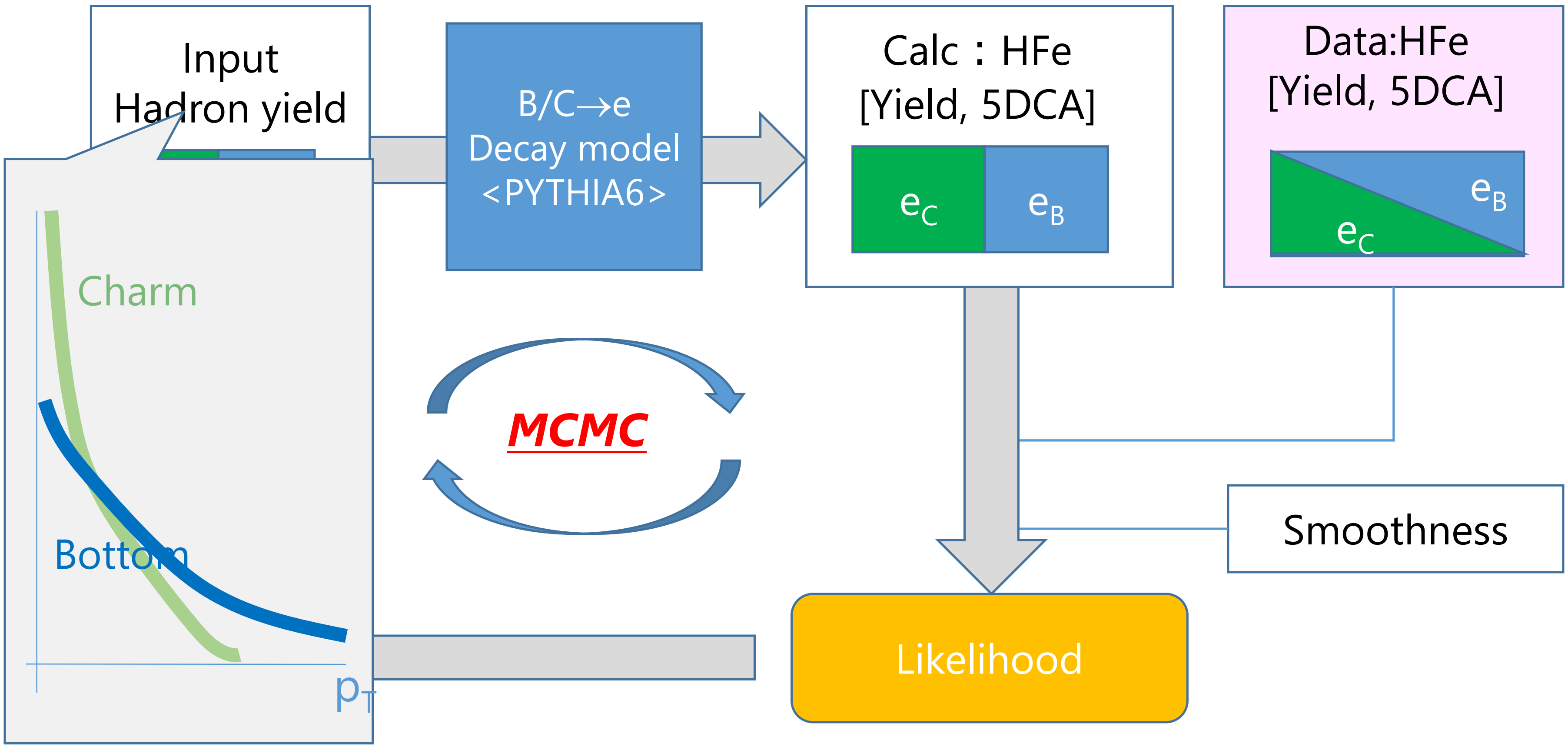

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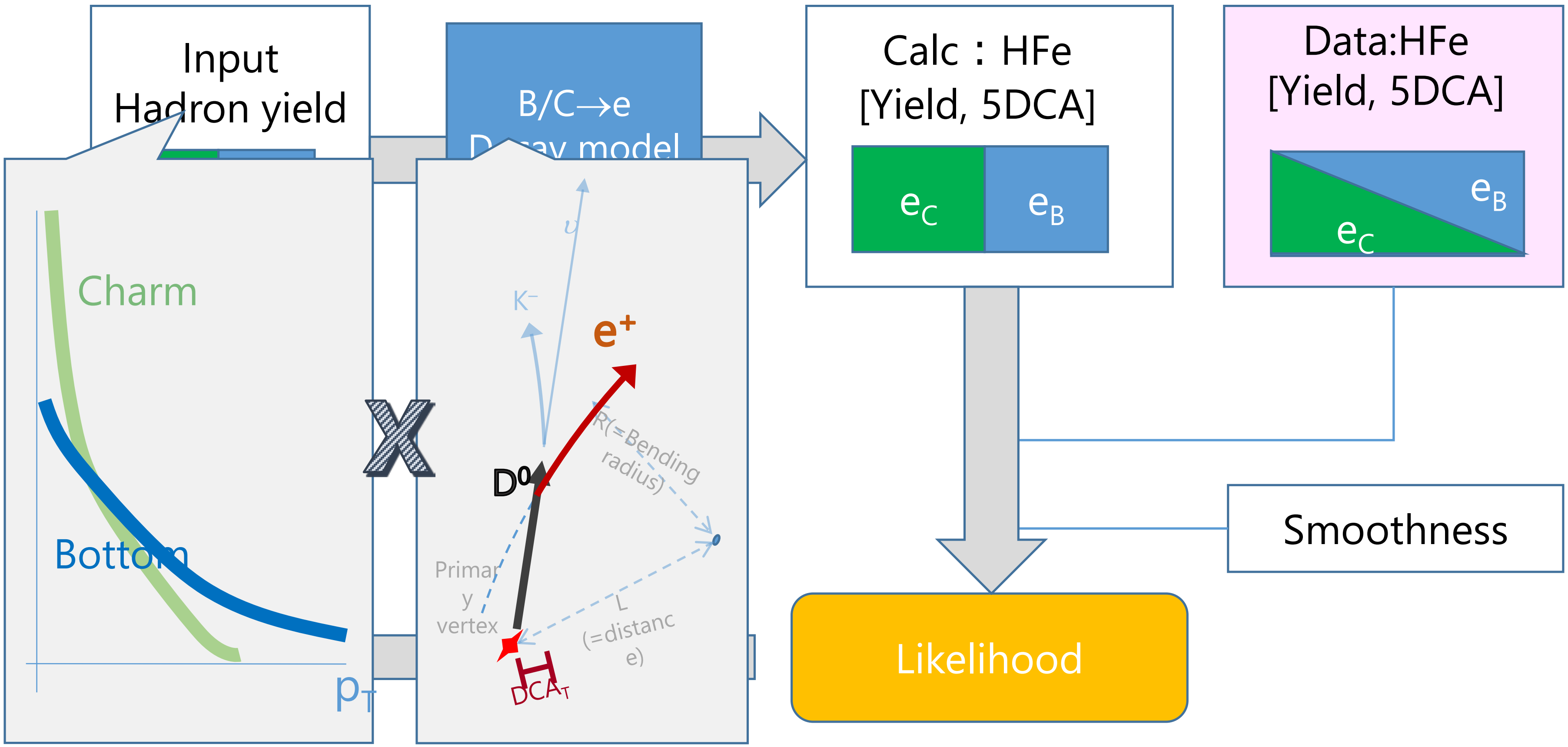

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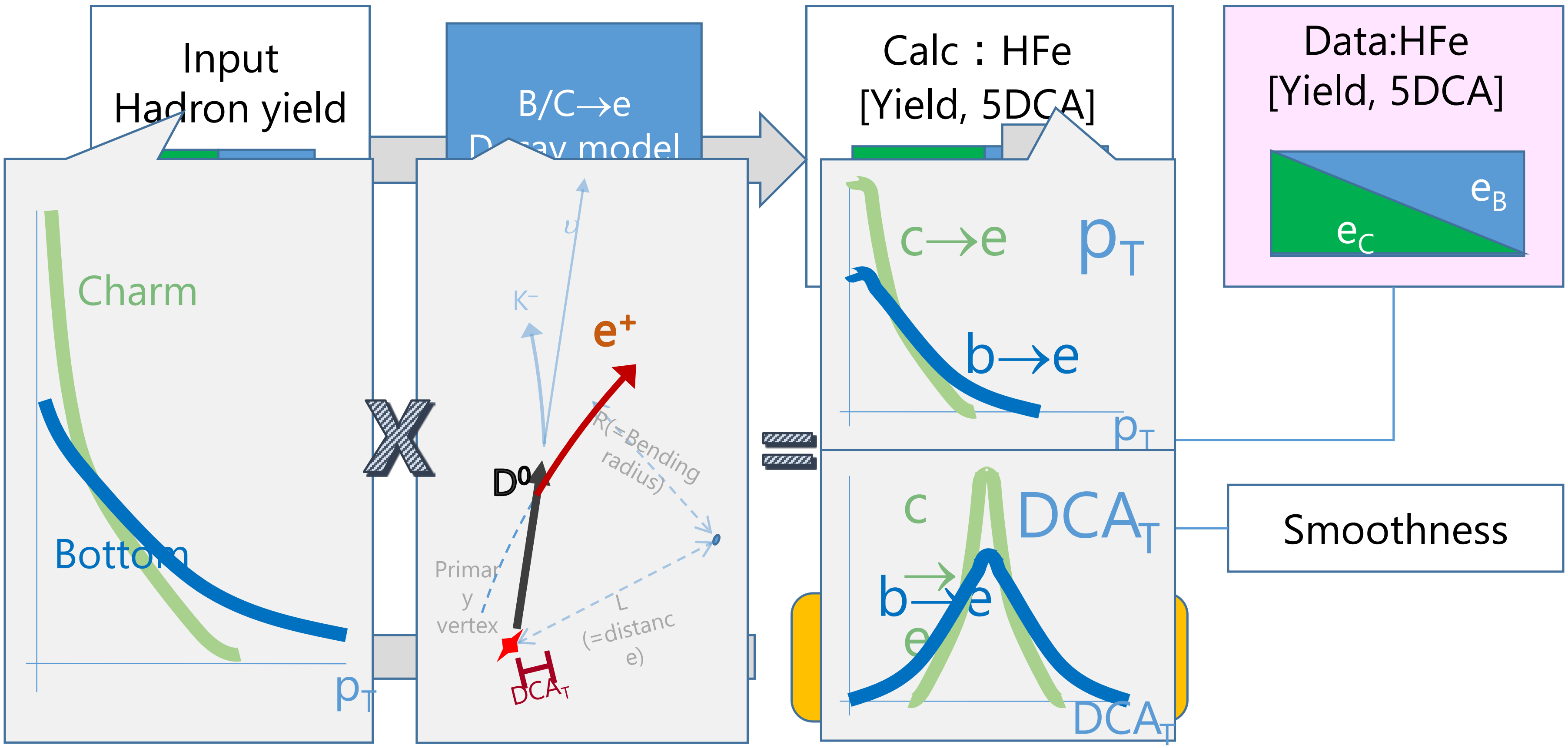

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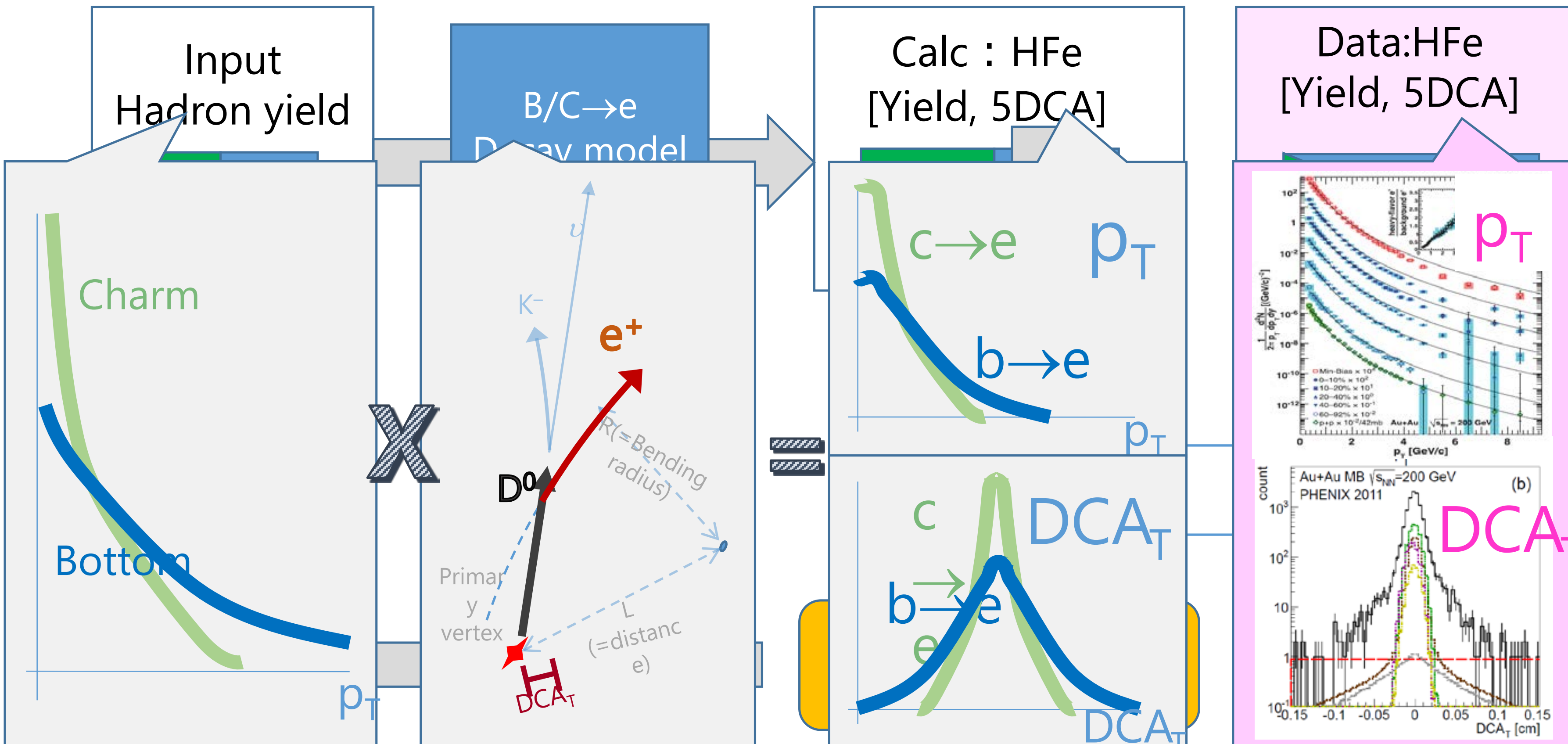

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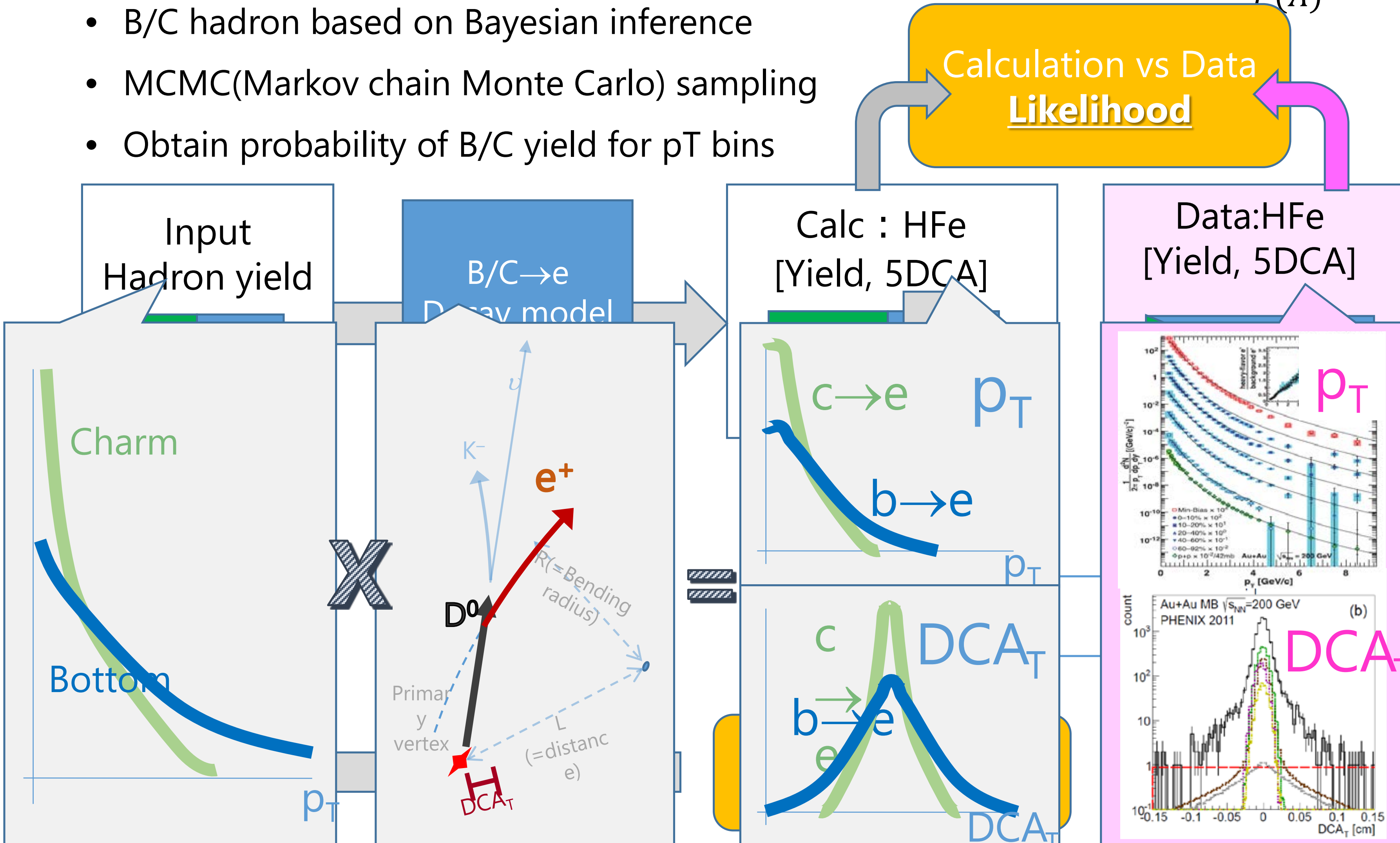

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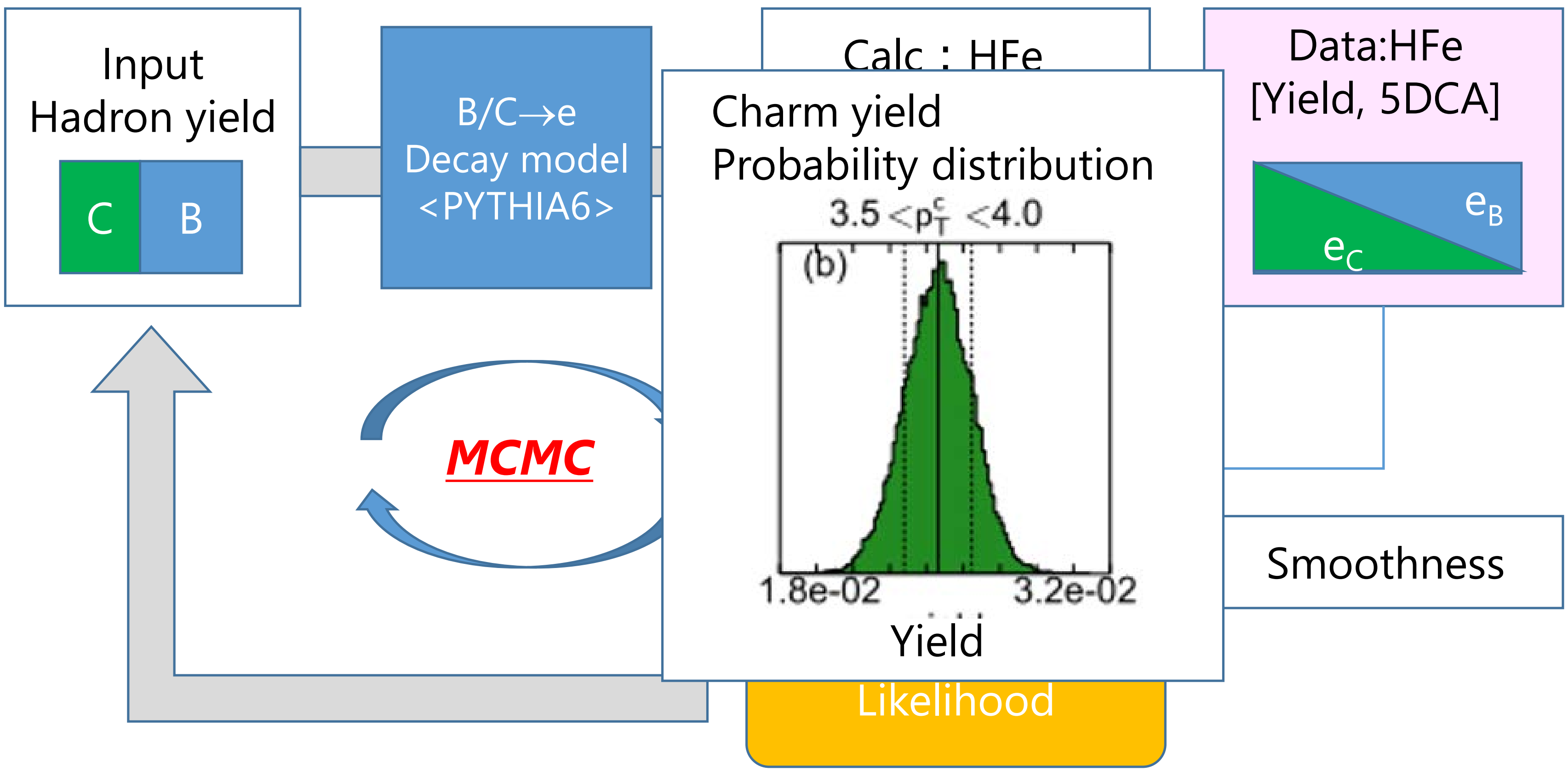
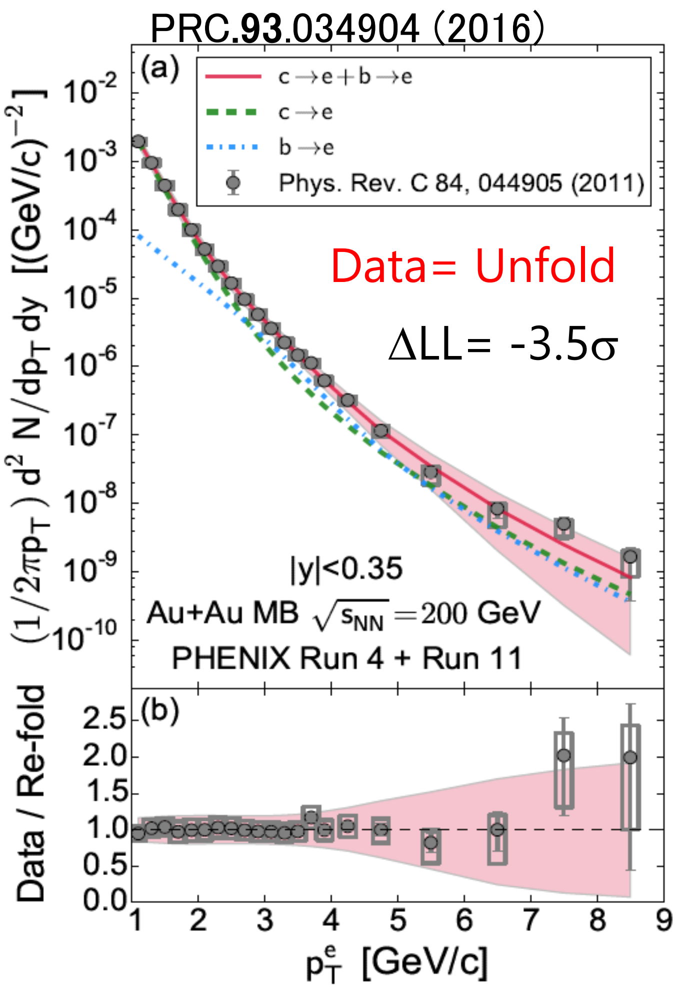
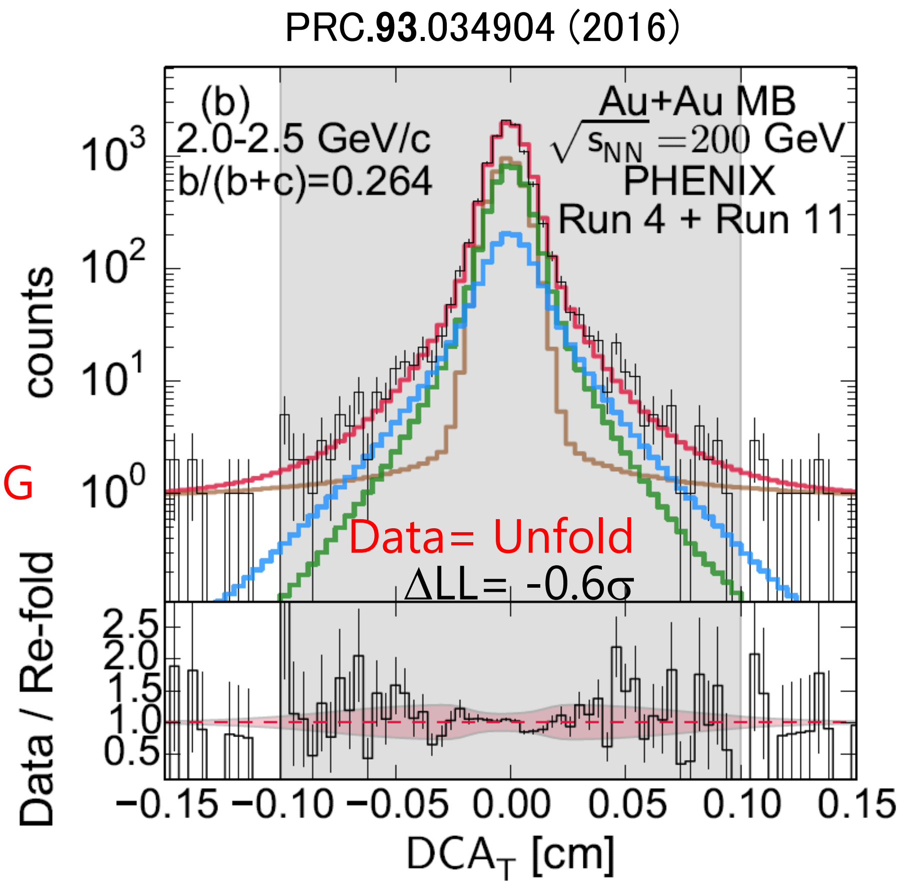


Validation: Unfolding & Data



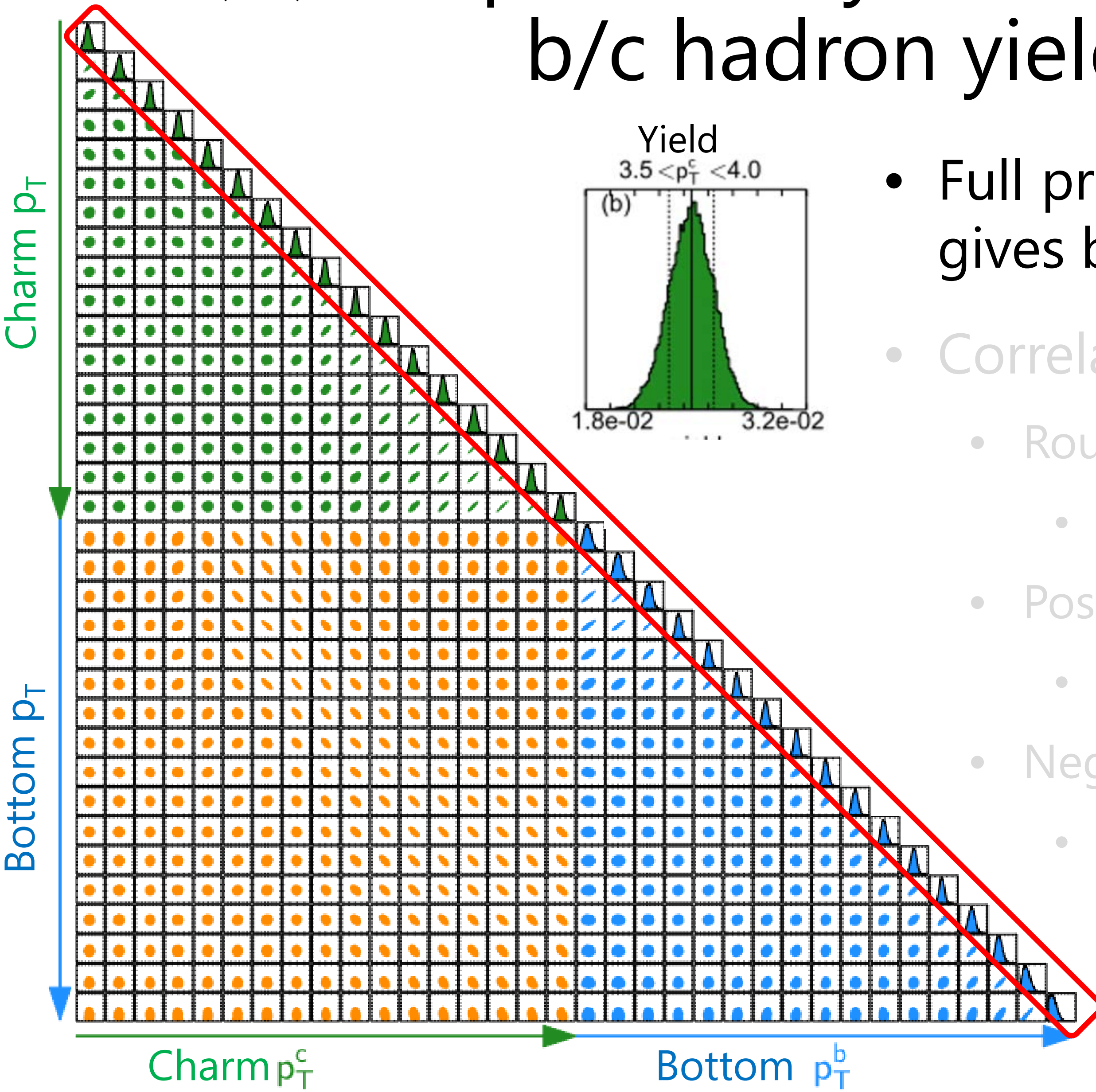
Data
Charm
Bottom
Background
Total=C+B+BG



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

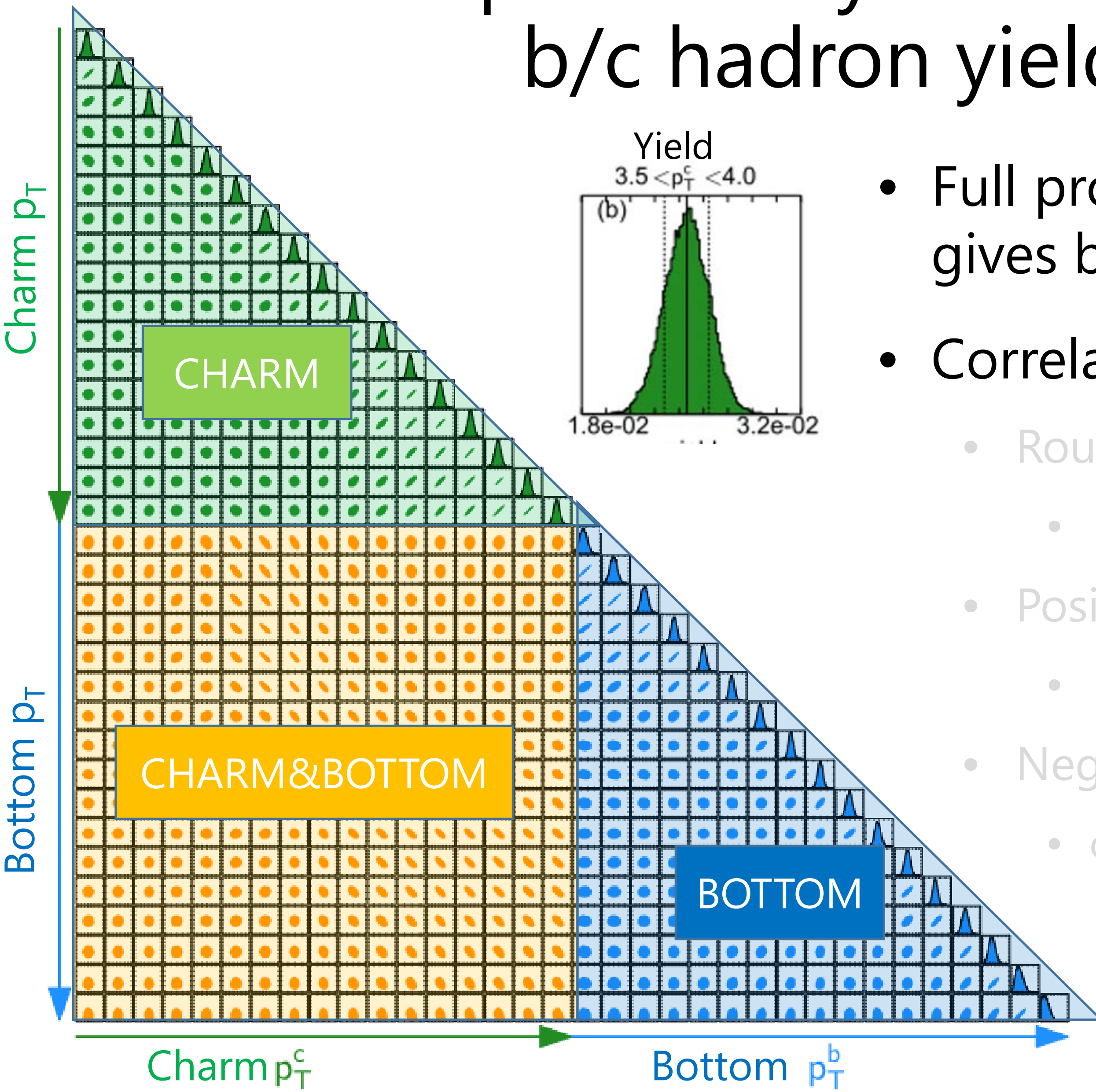
Full probability distribution b/c hadron yield

PRC.93.034904 (2016)



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

Full probability distribution b/c hadron yield



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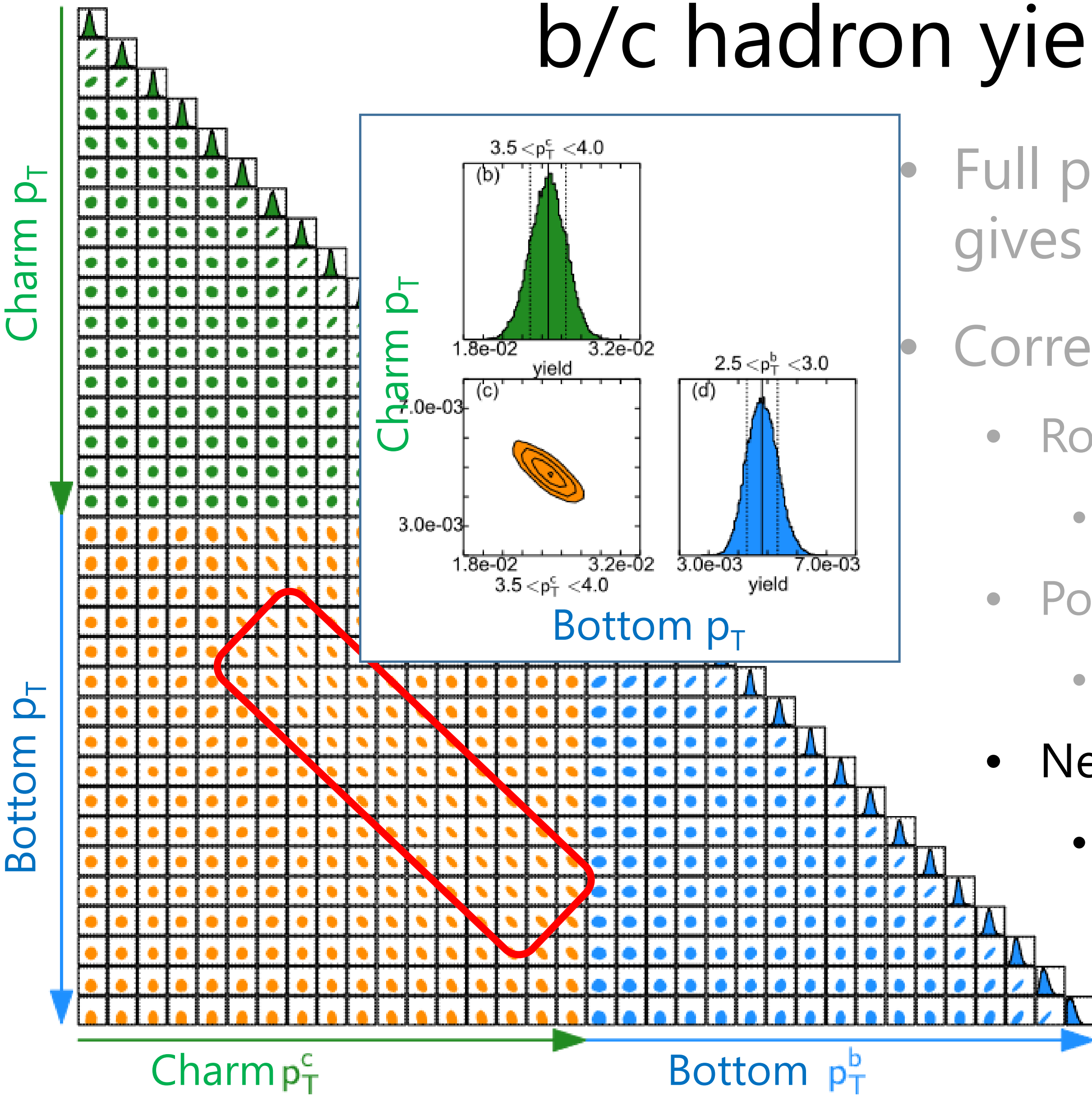


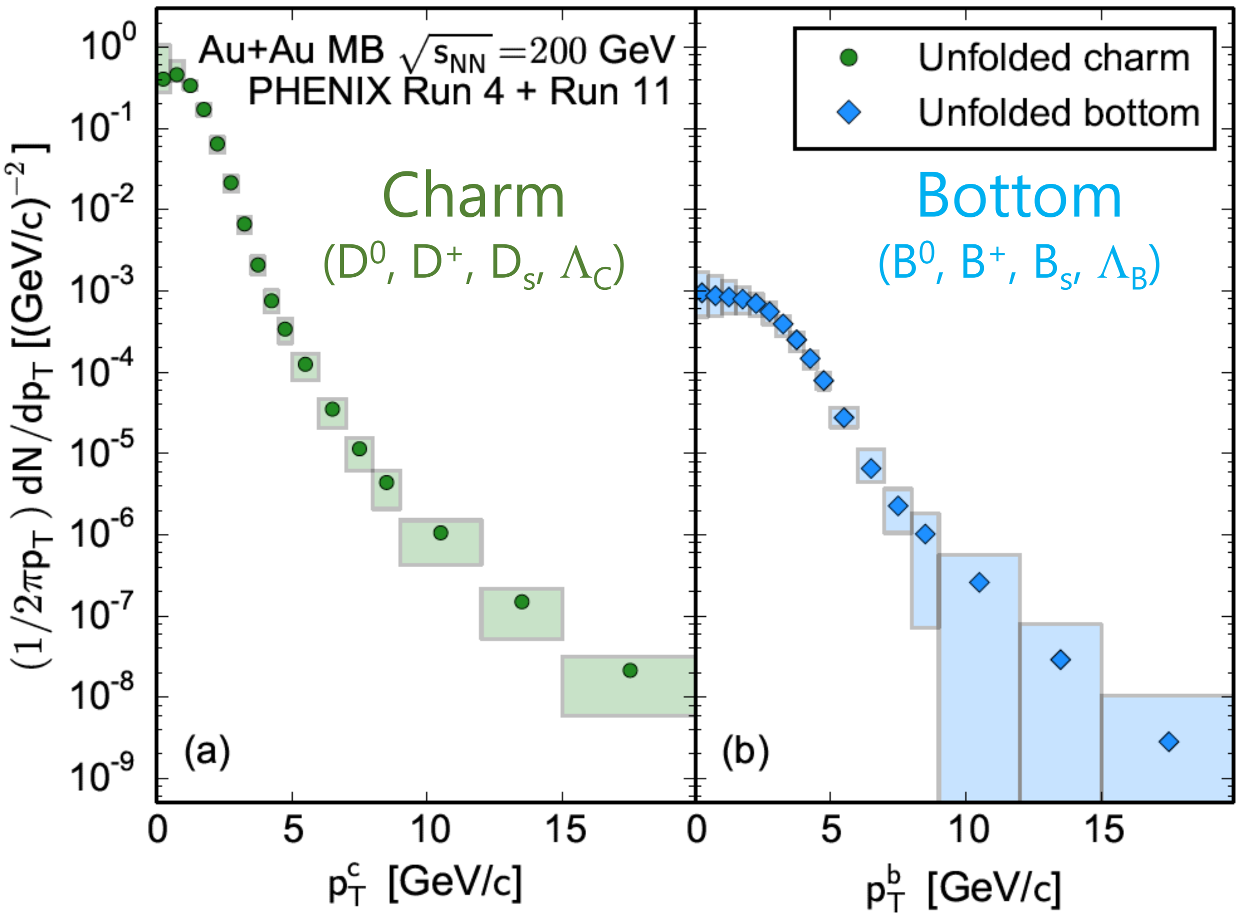
- Full probability distribution gives bottom & charm yield
- Correlation in yield
  - Round
    - no correlation
  - Positive in charm near pT
    - increase simultaneously
  - Negative
    - charm ↑ + bottom ↓

Results

Unfolded Charm and Bottom hadron

VTX Result

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



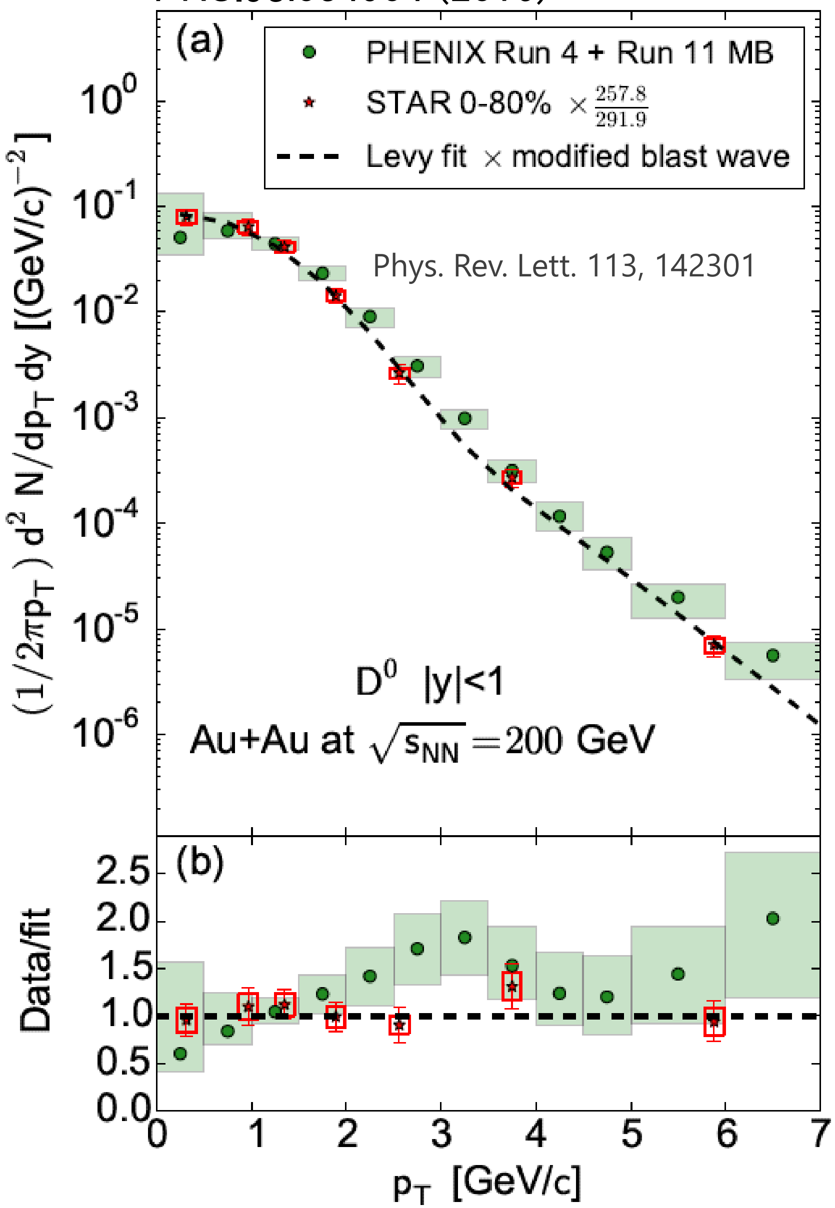
New unfolding method is successfully developed.

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

Unfolded vs STAR Charm Hadron

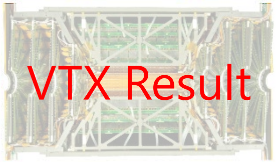
VTX Result

PRC.93.034904 (2016)



- Unfold charm hadron yield is compared with to STAR D^0
  - Convert D^0 by PYTHIA model
    - Scale to |y|<1
  - Fit STAR D^0 with Levy function
- Unfolded charm hadron yield is in agreement with STAR D^0

Bottom Electron Fraction $F = \frac{b \to e}{b \to e + c \to e}$



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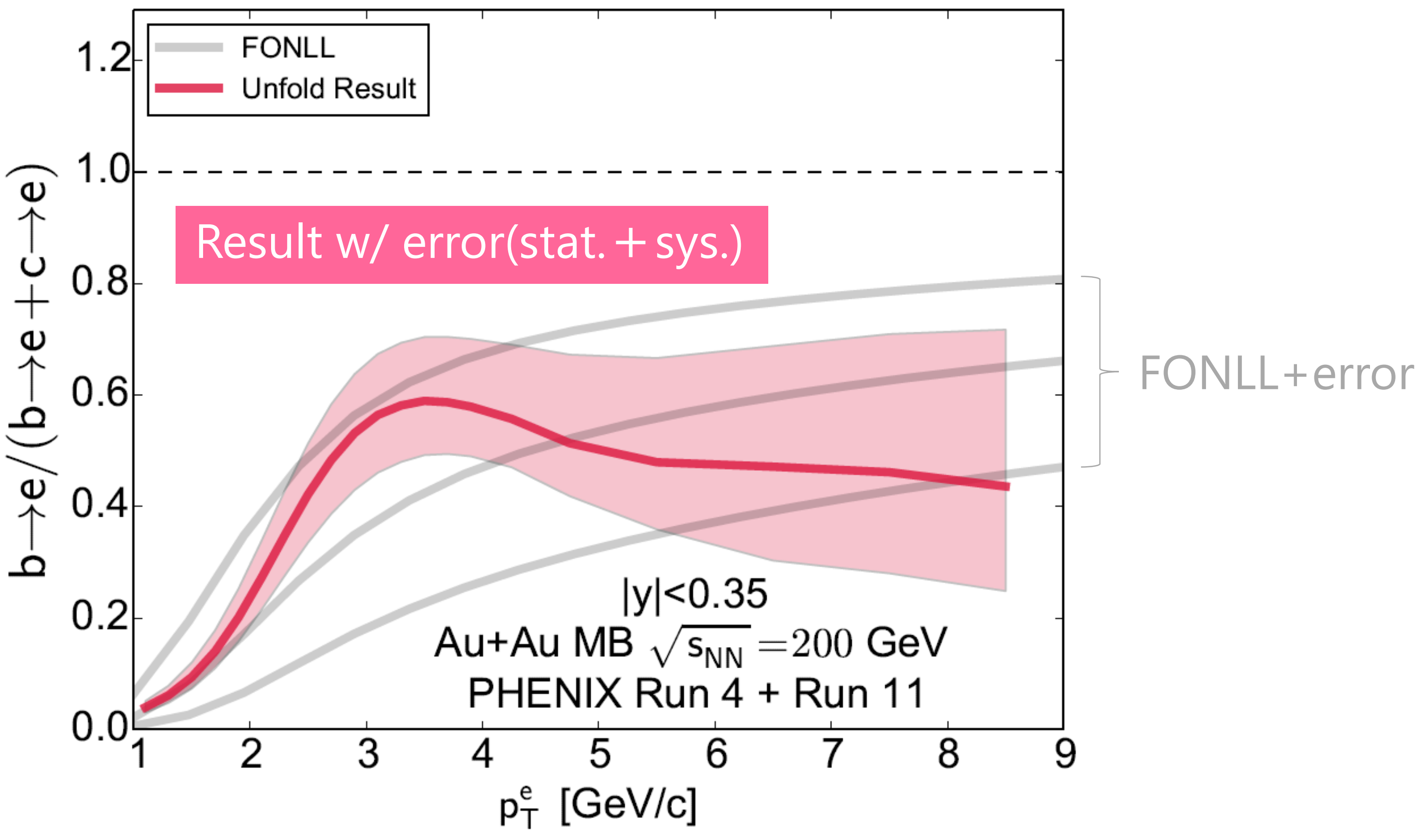
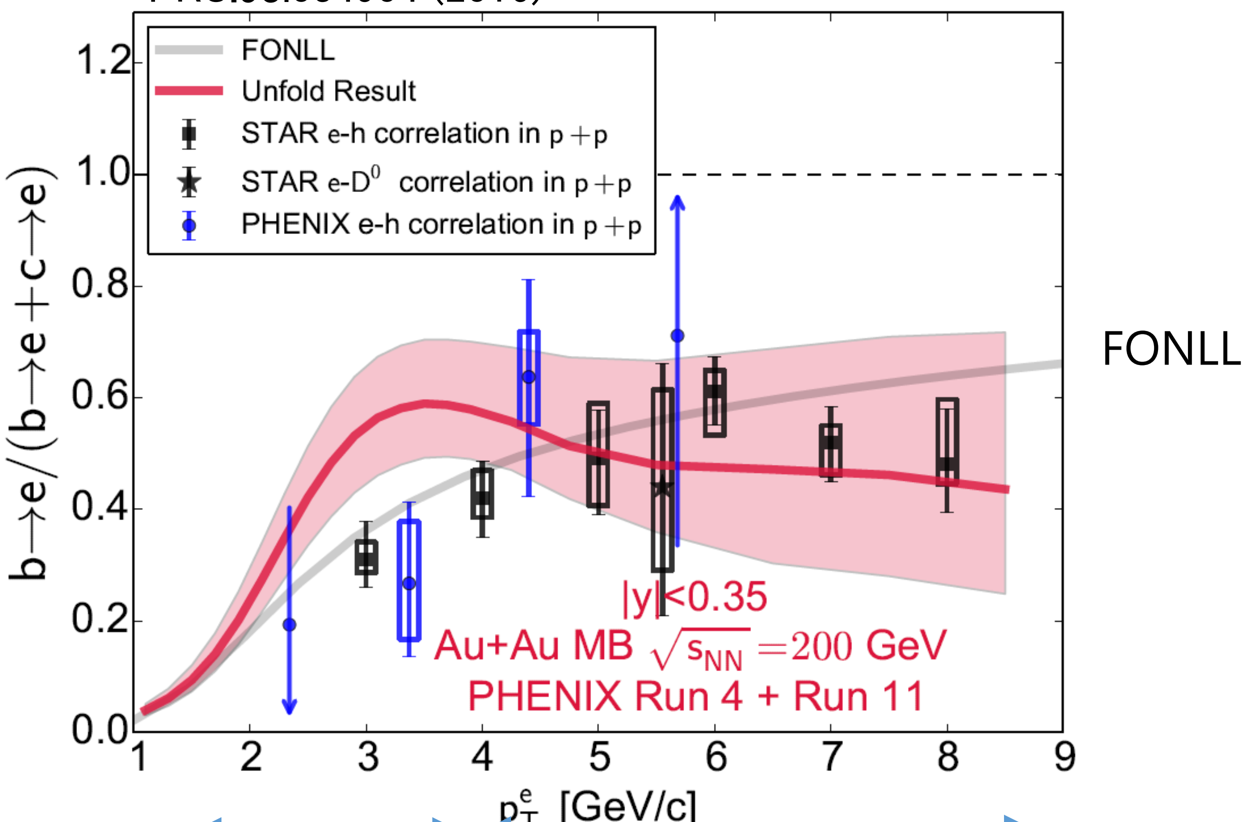


- FONLL is consistent with data within large uncertainties
- Shape is different with FONLL
  - increasing at p_T=3GeV/c and decreasing w/ higher p_T

Comparison with p+p data

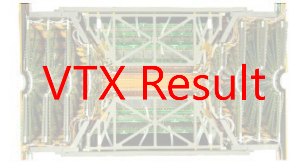
VTX Result

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



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

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



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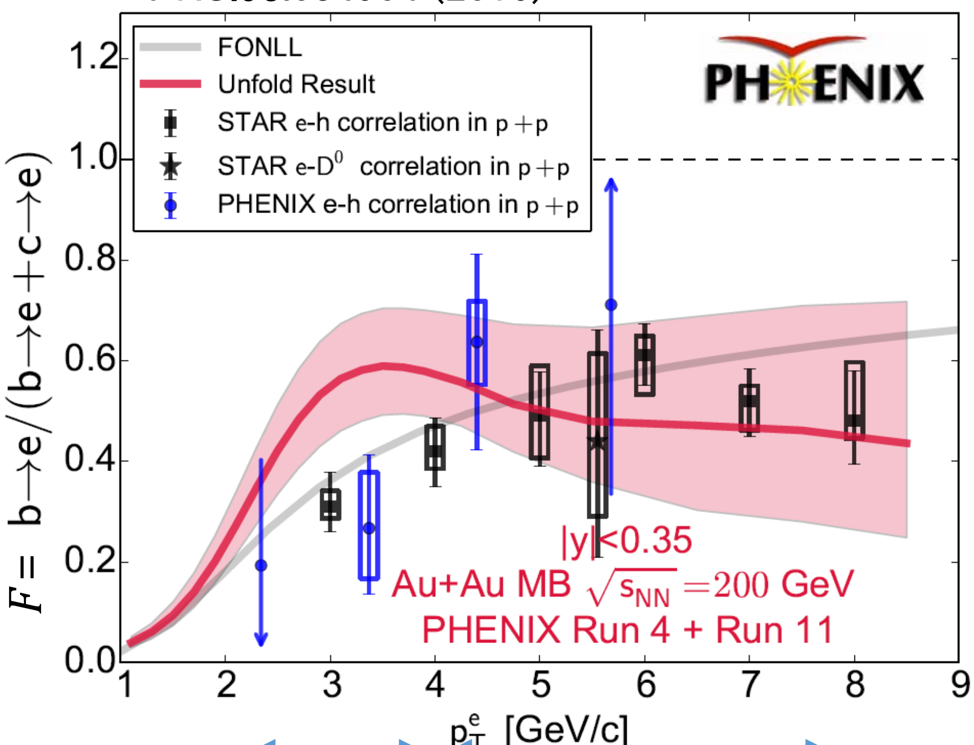
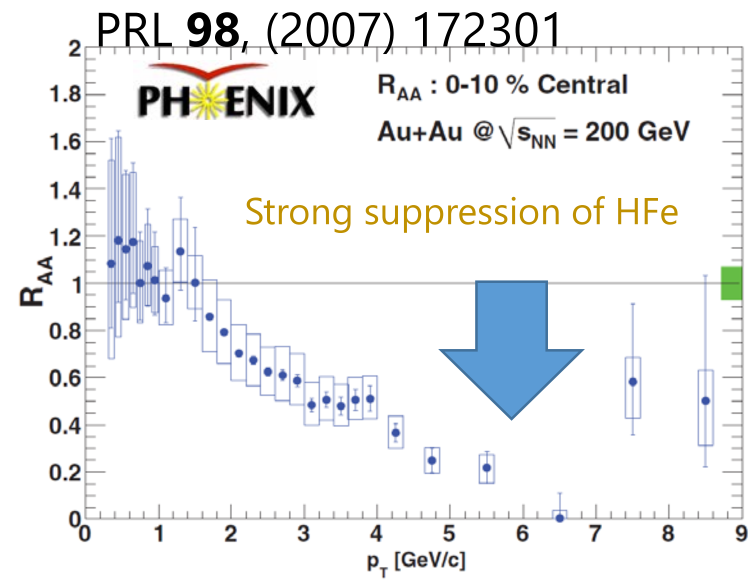
PRC.**93**.034904 (2016)



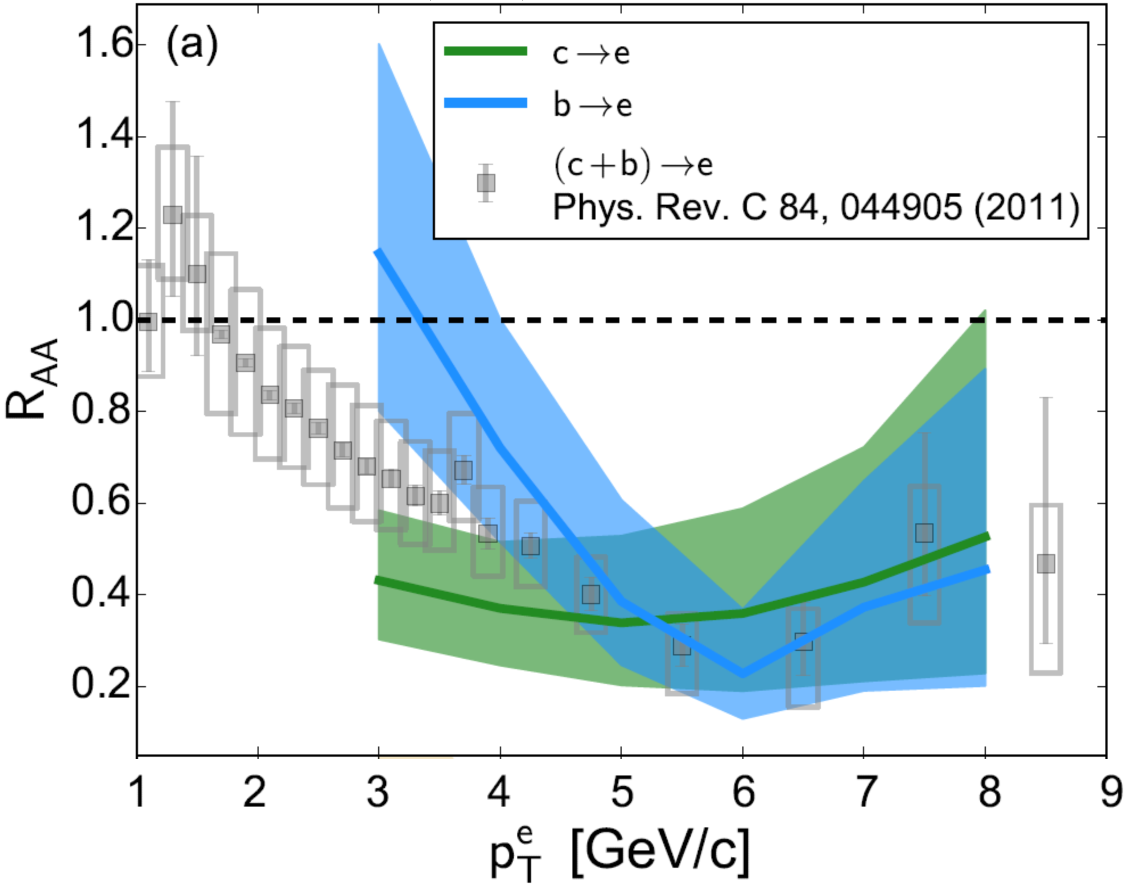


$F_{AuAu} > F_{pp}$ $F_{AuAu} \sim F_{pp}$

- Au+Au is difference with p+p
- Means bottom suppression is different with charm

Bottom and Charm R_{AA}

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



Using

F_{AuAu}: bottom fraction in Au+Au

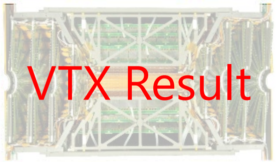
F_{pp} : STAR bottom fraction in p+p

R_{AA}^{HF} : PHENIX HFe R_{AA}^{HF} in Au+Au

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

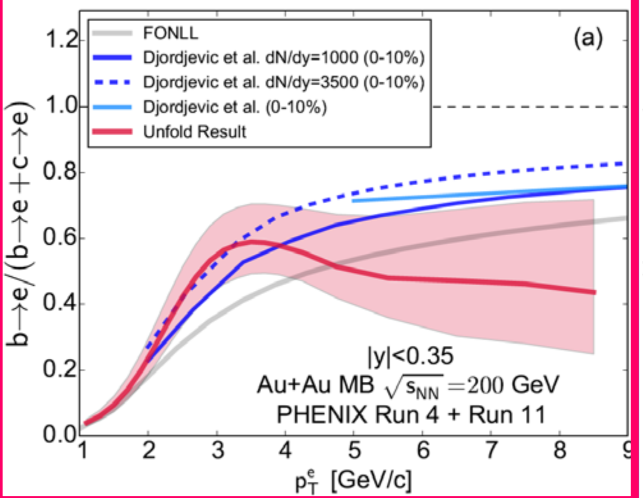
$$R_{AuAu}^{b\to e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF}$$

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

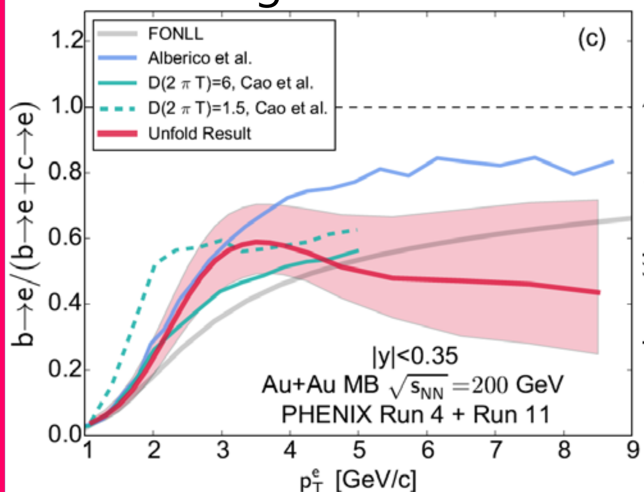


Comparison with Models

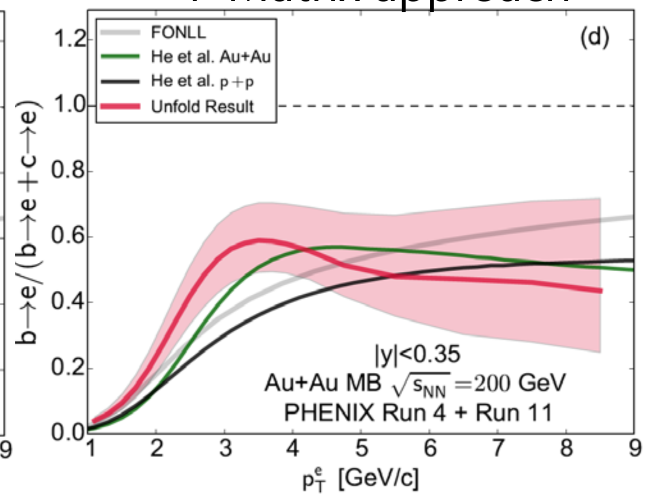
Radiative
DGLV



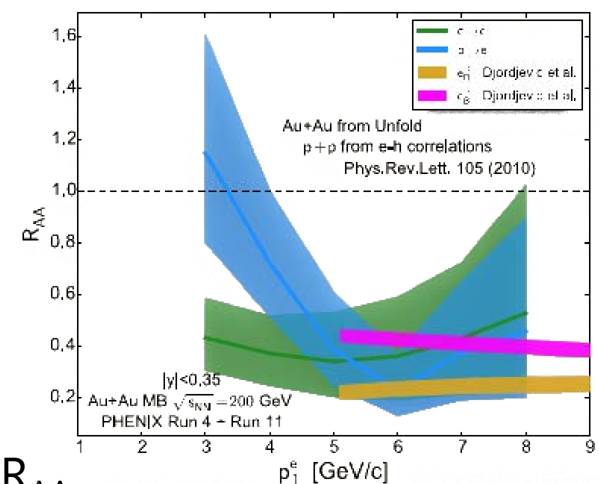
Collisional
Langevin based



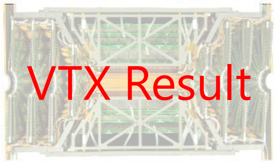
Collisional
T-Matrix approach



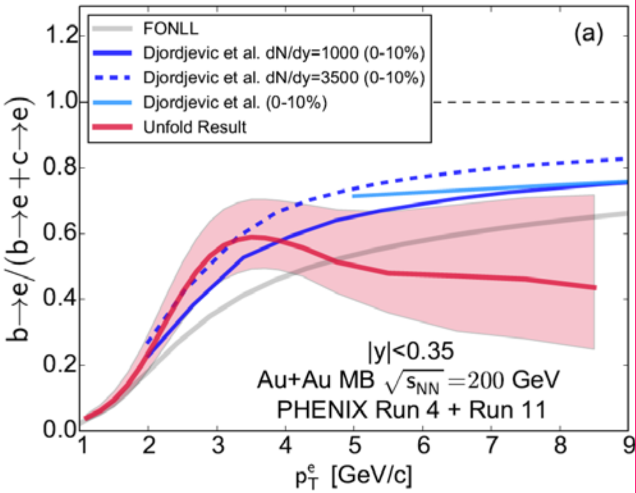
- Radiative energy loss by DGLV model (central)
  - Consistent at low $p_{T,}$ different at high p_T
  - Increasing monotonically
- Updated DGLV model w/ collisional loss
  - Slightly off (0-10%)
  - Reasonable agreement with measured electron R_{AA}



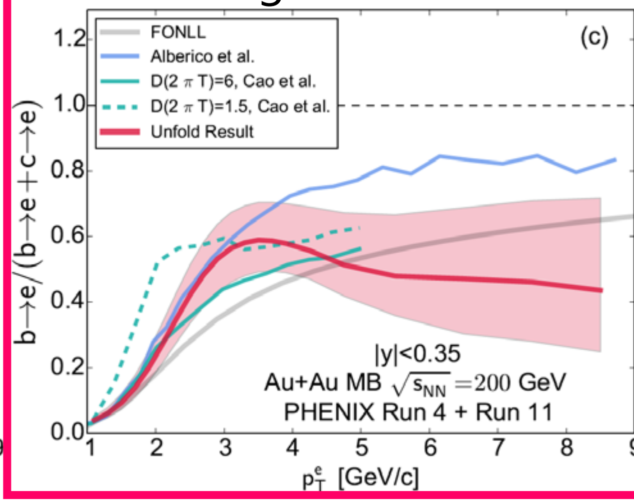
Comparison with Models



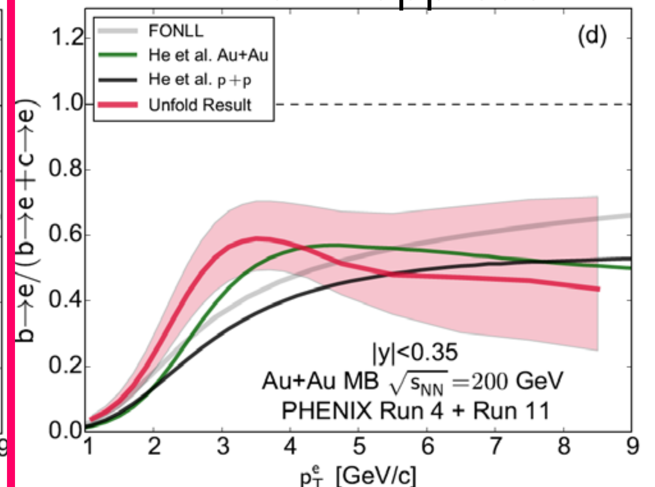
Radiative
DGLV



Collisional
Langevin based



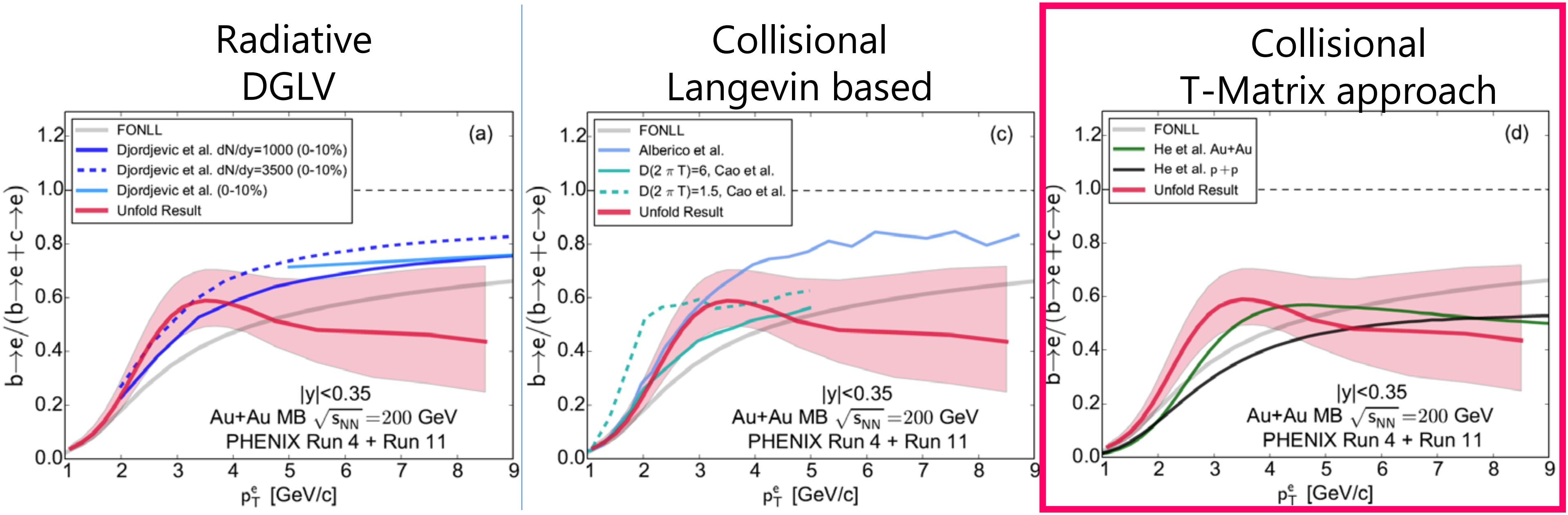
Collisional
T-Matrix approach



- Collisional loss by Langevin approach
  - Sensitive to medium coupling
  - Increasing monotonically
- Agree with D=6 at low p_T
  - Smaller D ⇔ Strong coupling
  - Disagree with D=1.5 (must be too small)

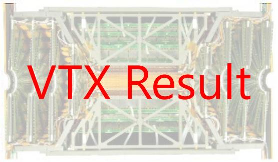
Comparison with Model

VTX Result



- Collisional loss by T-Matrix approach
  - Full non-perturbative HQ transport coefficient
  - p+p baseline differs from FONLL
  - Increasing @ low pT and decreasing @ high pT
- Qualitatively similar trend with data
  - Not well matched with data

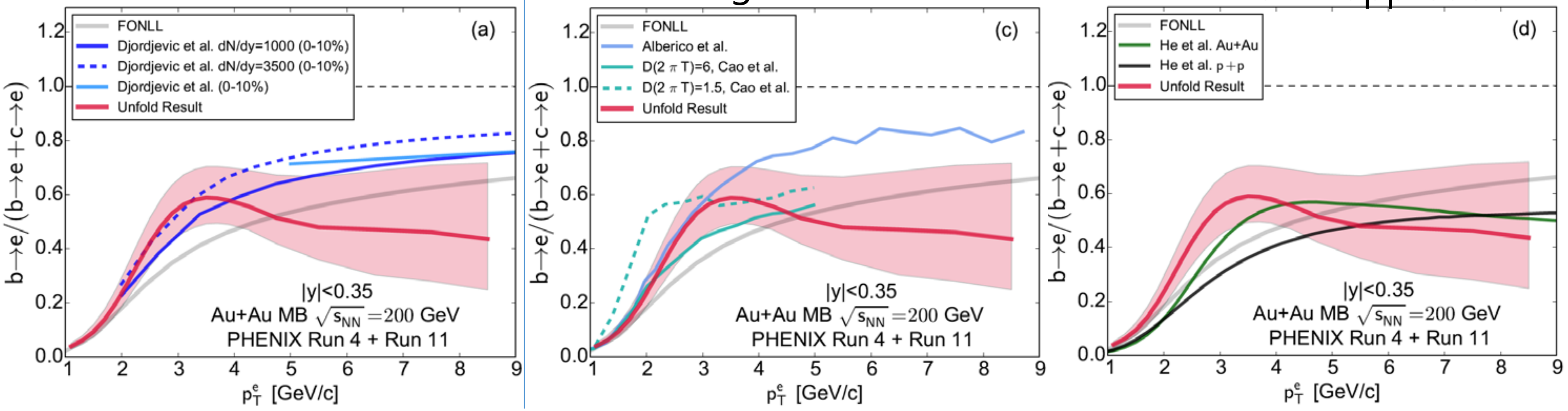
Comparison with Model



Radiative
DGLV

Collisional
Langevin based

Collisional
T-Matrix approach



- Models are not consistent with data
  - Models shows monotonic and non-monotonic behavior
  - Data w/ uncertainty is hard to constrain these models

- Need higher statistics to disentangle effects
  - Au+Au and p+p reference are available from 2014-2016

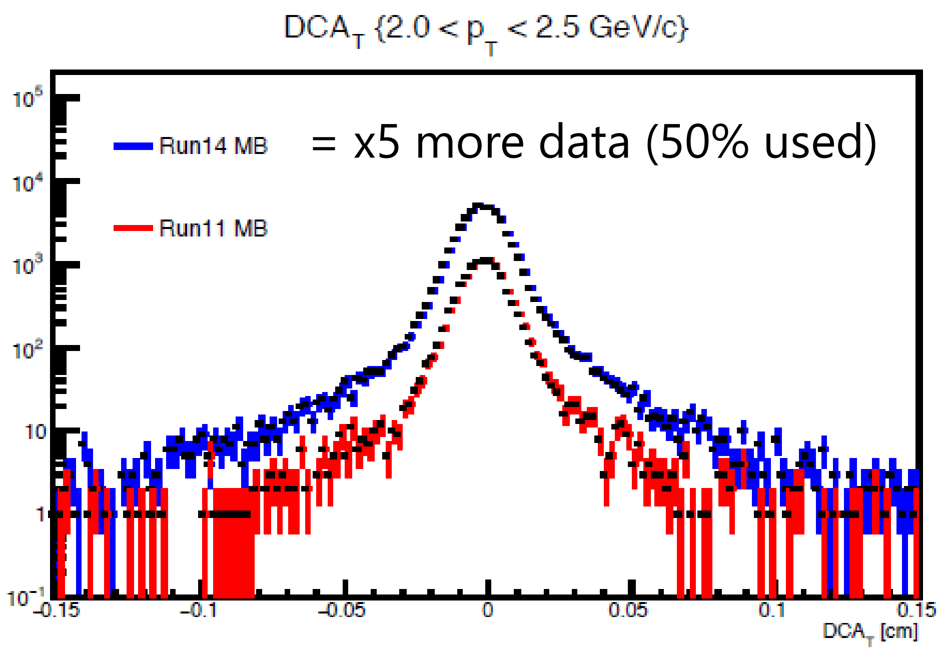
Future prospects

- High quality data in run2014 – 2016 Au+Au & p+p
  - 20 time larger statistics in run2014/2016 Au+Au 200GeV
  - Detector performance improved

B-fraction & R_{AA}
High p_T extension
Centrality dependence
HF vn measurement

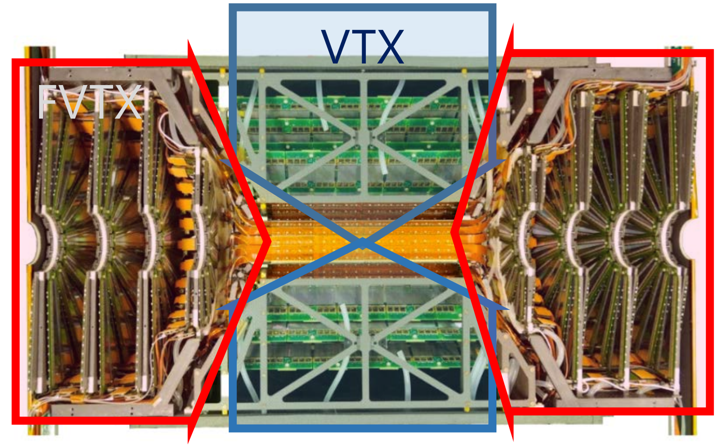
- Apply the analysis technique to run2014 – 2016 data

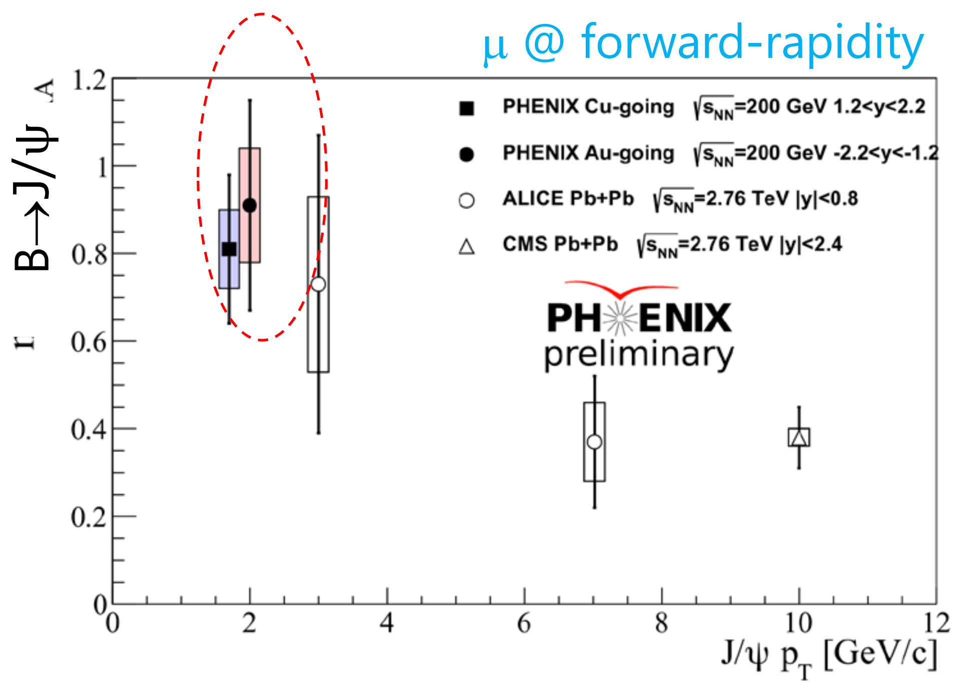
Example : DCA_T in run2014



Future prospects

- Non-prompt J/ψ (B → J/ψ)
  - Direct heavy flavor measurement
- New result in Cu+Au from FVTX (1.2<|y|<2.2)
  - Consistent with unity, no suppression at low pT





Summary

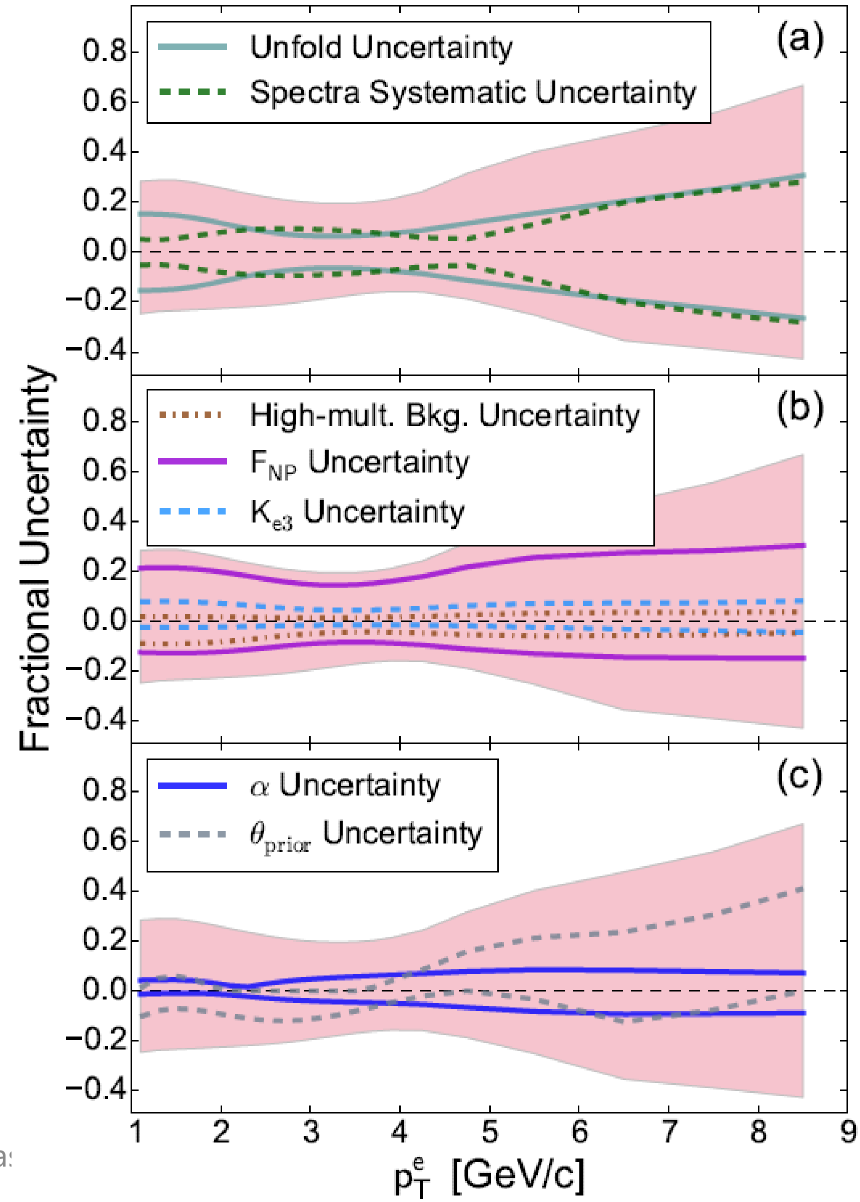
- First measurement of separated bottom and charm electrons by PHENIX VTX with the unfolding method
- Extracted Bottom and Charm hadrons
- First result of bottom suppression at RHIC energy
  - less suppressed at low p_T
  - similarly suppressed as charm at high p_T
- Separated bottom & charm provides additional information to disentangle QGP property
- 20x statistics in run2014-2016 enables more precise measurement

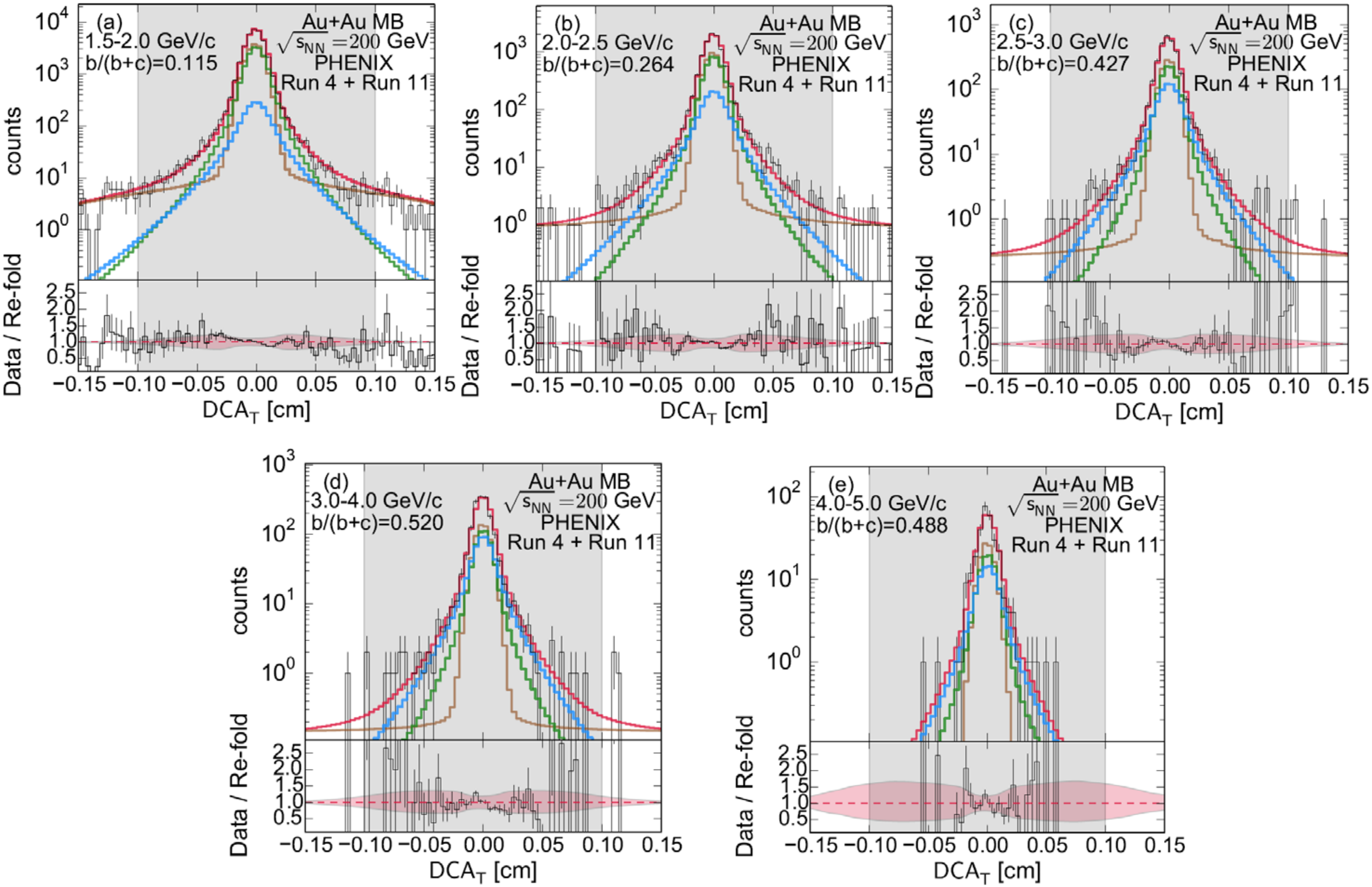
backup

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




(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]