Single electrons from semi-leptonic charm and bottom hadron decays in Au+Au collisions at PHENIX

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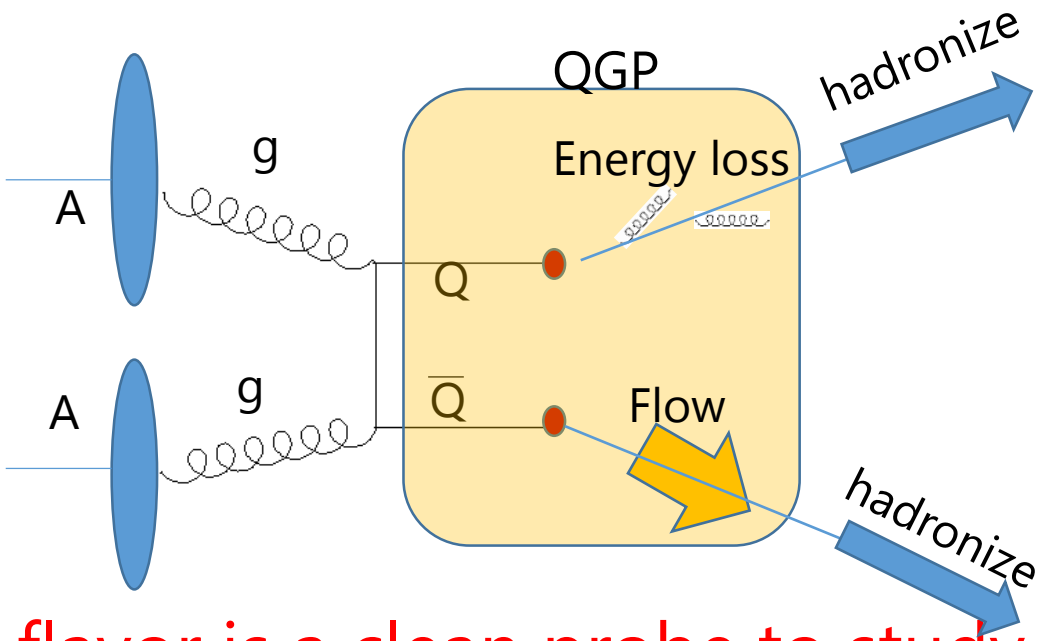
32nd Winter Workshop on Nuclear Dynamics

Introduction - why heavy flavor?

- Heavy Flavors (charms and bottoms) 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)
    - Production can be calculated by pQCD
  - Passing through the hot and dense medium (QGP)
    - Suffer the energy loss and flow effect
    - Sensitive to the medium property

Calibrated probe



Heavy flavor is a clean probe to study property of QGP

Heavy Flavor Electrons in Au+Au 200GeV

Single electrons from inclusive heavy flavor decays shows :

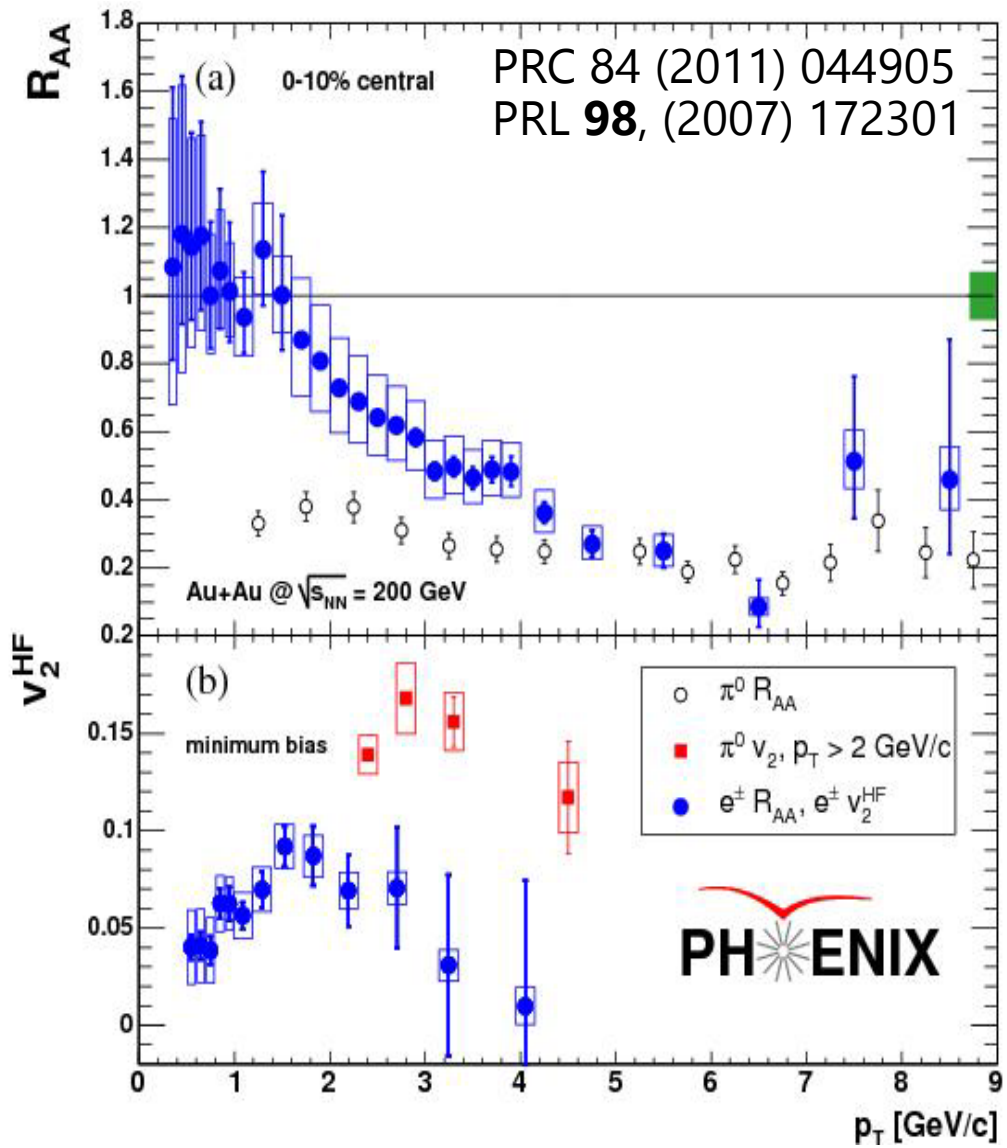
R_{AA}: strong suppression

v_2 : non-zero flow

Surprising results

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

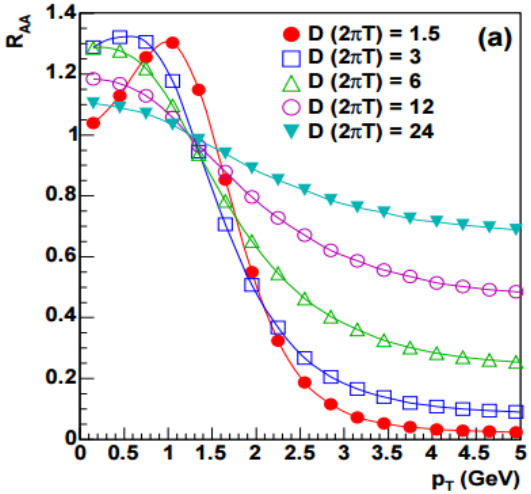
- This was mixture of charm & bottom



To Energy loss mechanism

- Radiative loss (gluon radiation)
  - Dead cone effect (PLB519:199,2001):
    - Energy loss: $\Delta E_g > \Delta E_{LQ} > \Delta E_{HQ}$
  - ~ high pT

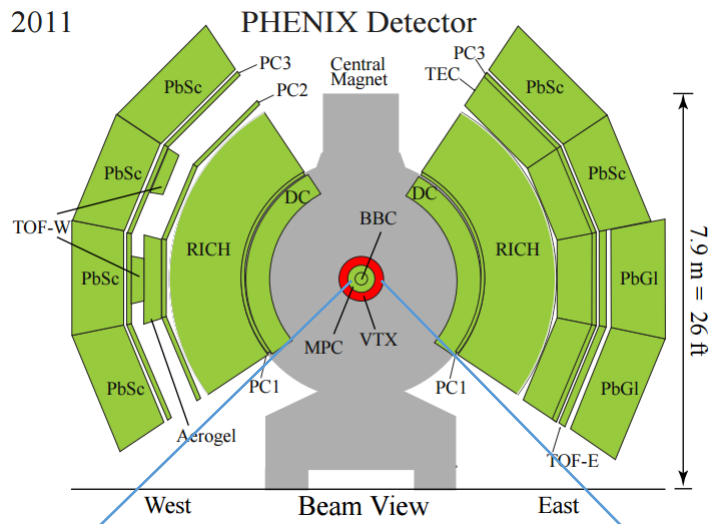
Collisional loss of charm quarks
PRC 71, 064904 (2005)

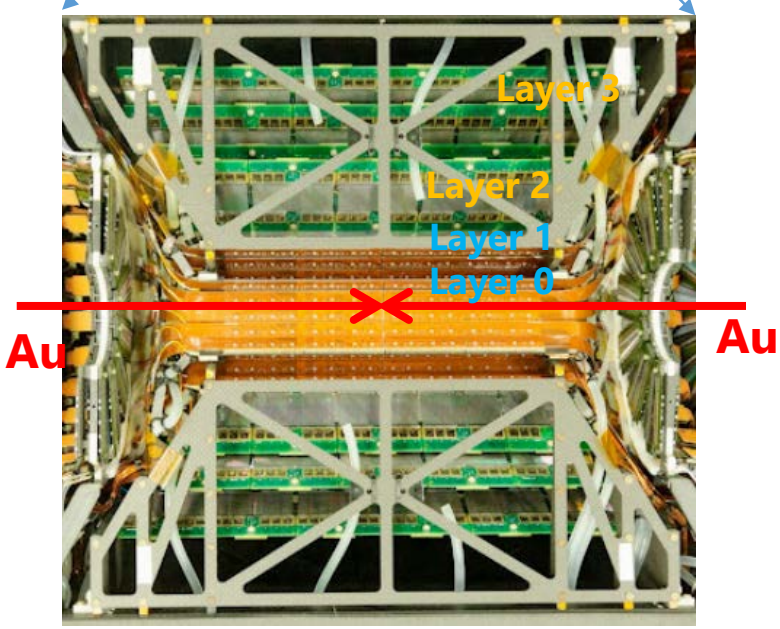


- Collisional loss (multiple scattering)
  - Brownian motion in the medium
  - ~ low pT
  - Sensitive to D (diffusion constant) : coupling strength
    - Mass dependence

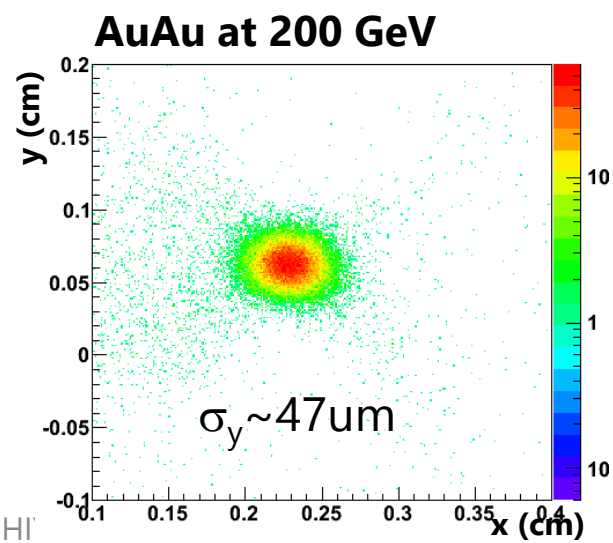
We need to measure bottom & charm separately

PHENIX Silicon Vertex Detector(VTX)





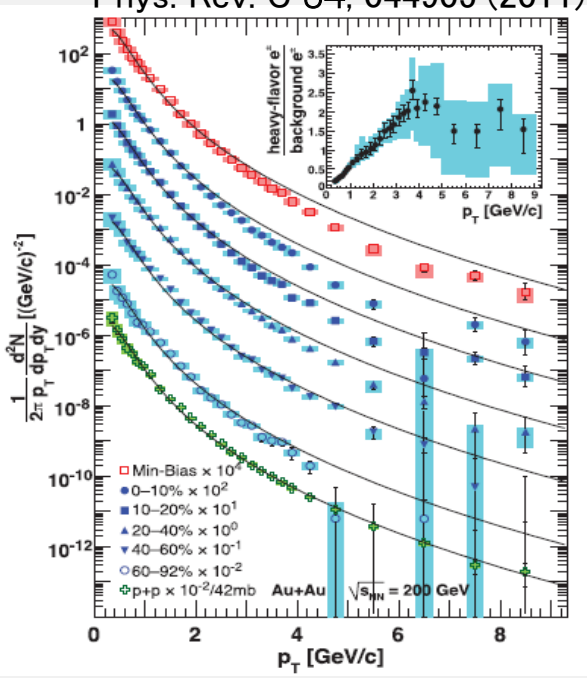
- VTX installed in Run2011
  - Large coverage
    - $|\eta|<1.2$, $\phi \sim 2\pi$
  - 4 layer silicon detectors
    - 2 inner pixel detector
    - 2 outer stripixel detector
- Measure
  - Precise displaced tracking
  - Precise 3D primary vertex



Strategy to bottom & charm separation

1. Use published invariant yield of single electrons from open heavy flavor decays with $1 < p_T < 9$(GeV/c)
   - Wide p_T coverage
   - Full efficiency corrected

Phys. Rev. C 84, 044905 (2011)

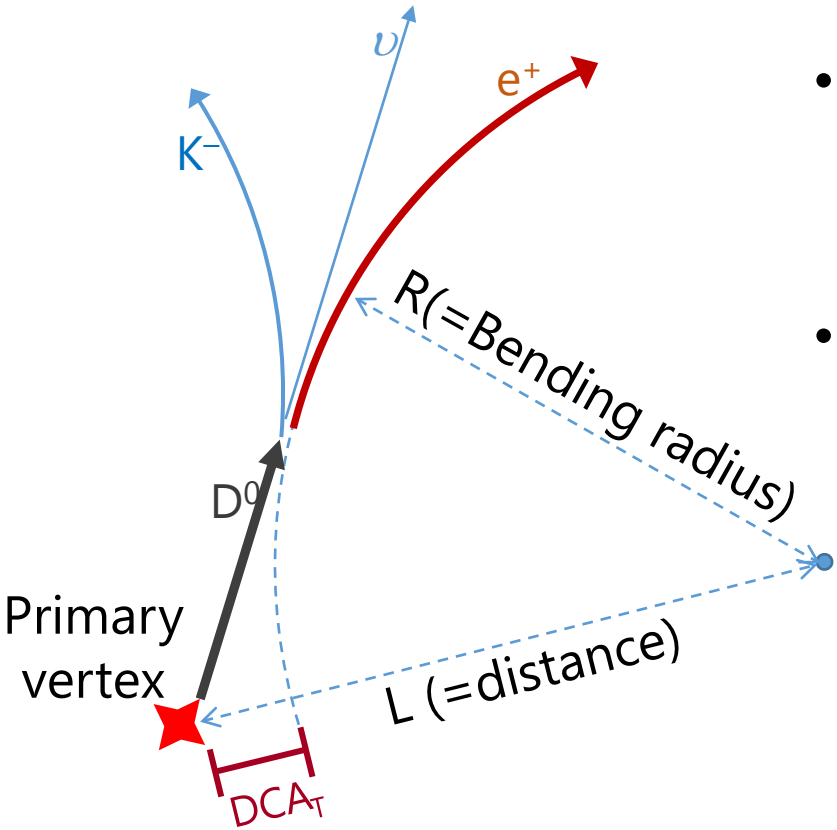


2. Measure displaced tracking of electrons in $1.5 < p_T < 5$ (GeV/c)
   - Utilize difference of decay length ($c\tau$)
   - B^+ : 491.1 μm, D^+ : 311.8 μm,

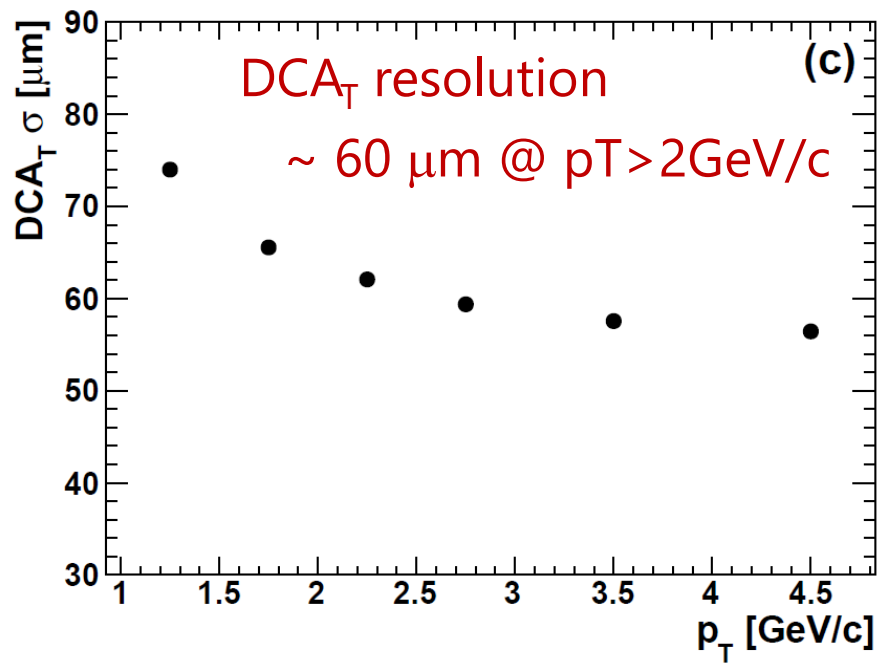
3. Apply the unfolding method to separate bottoms and charm components
   - Take into account the both information simultaneously
   - Displaced tracking can constrain the unfolding result strongly

Precise displaced tracking

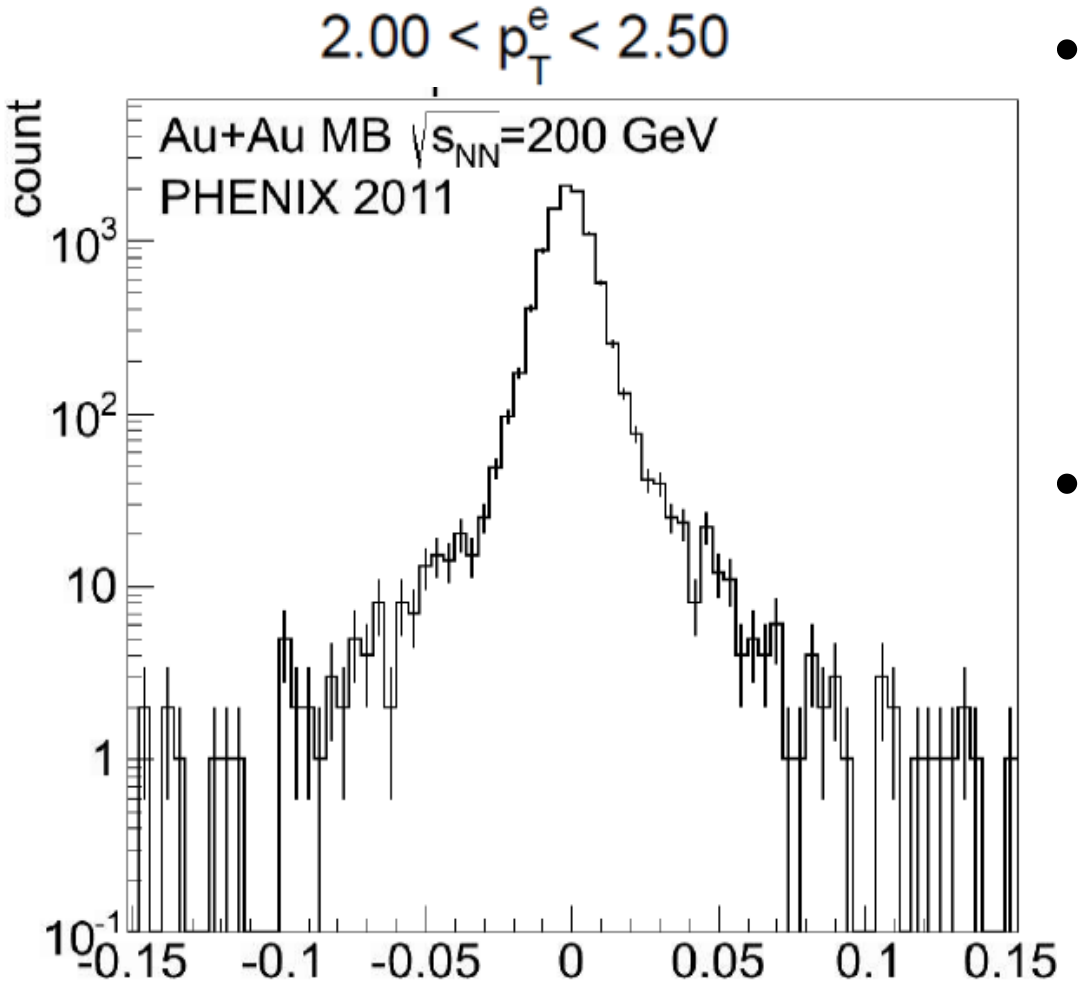
$DCA_T \equiv L - R$



- 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

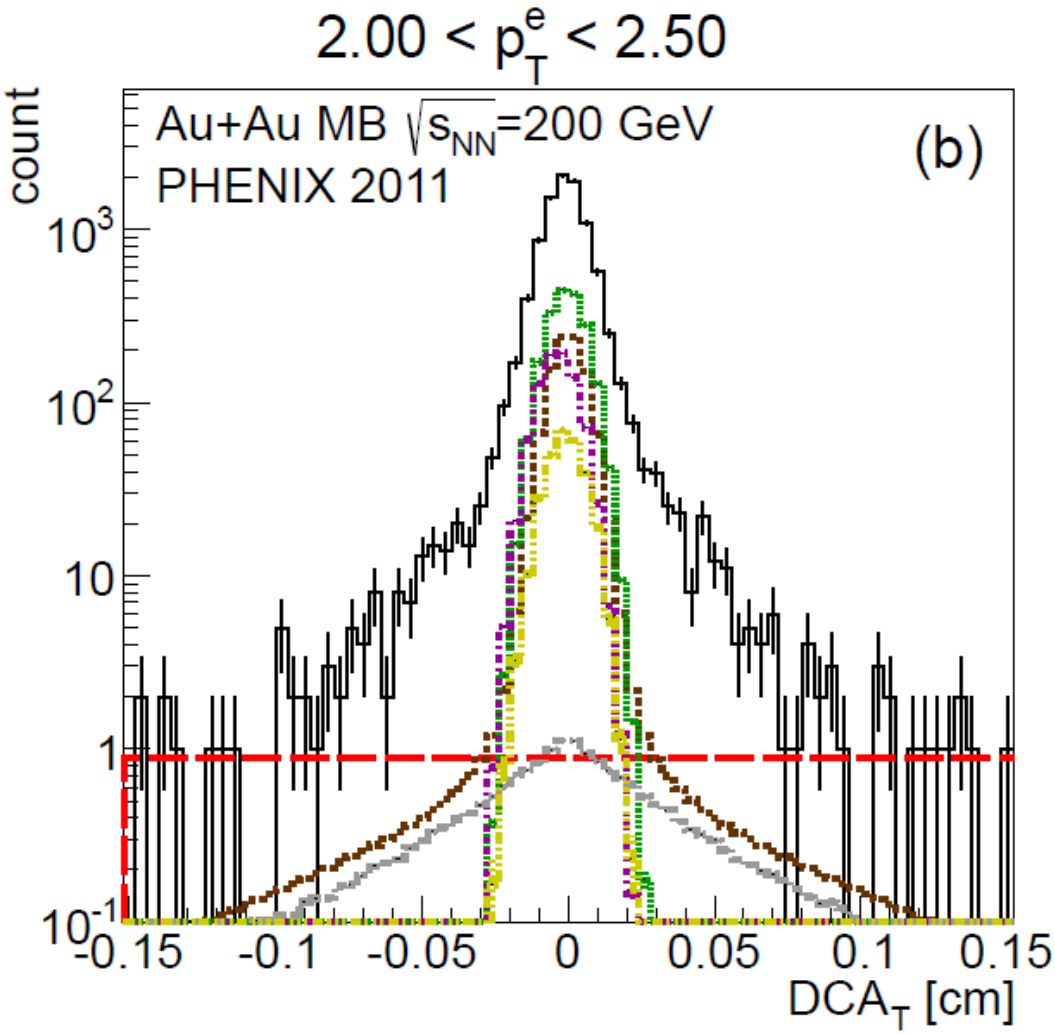


Electron DCA_T distribution



- Measure DCA_T in Run2011 dataset
  - 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
- Mis-associated with VTX

DCA_T shape and normalization determined by data driven (mixed)

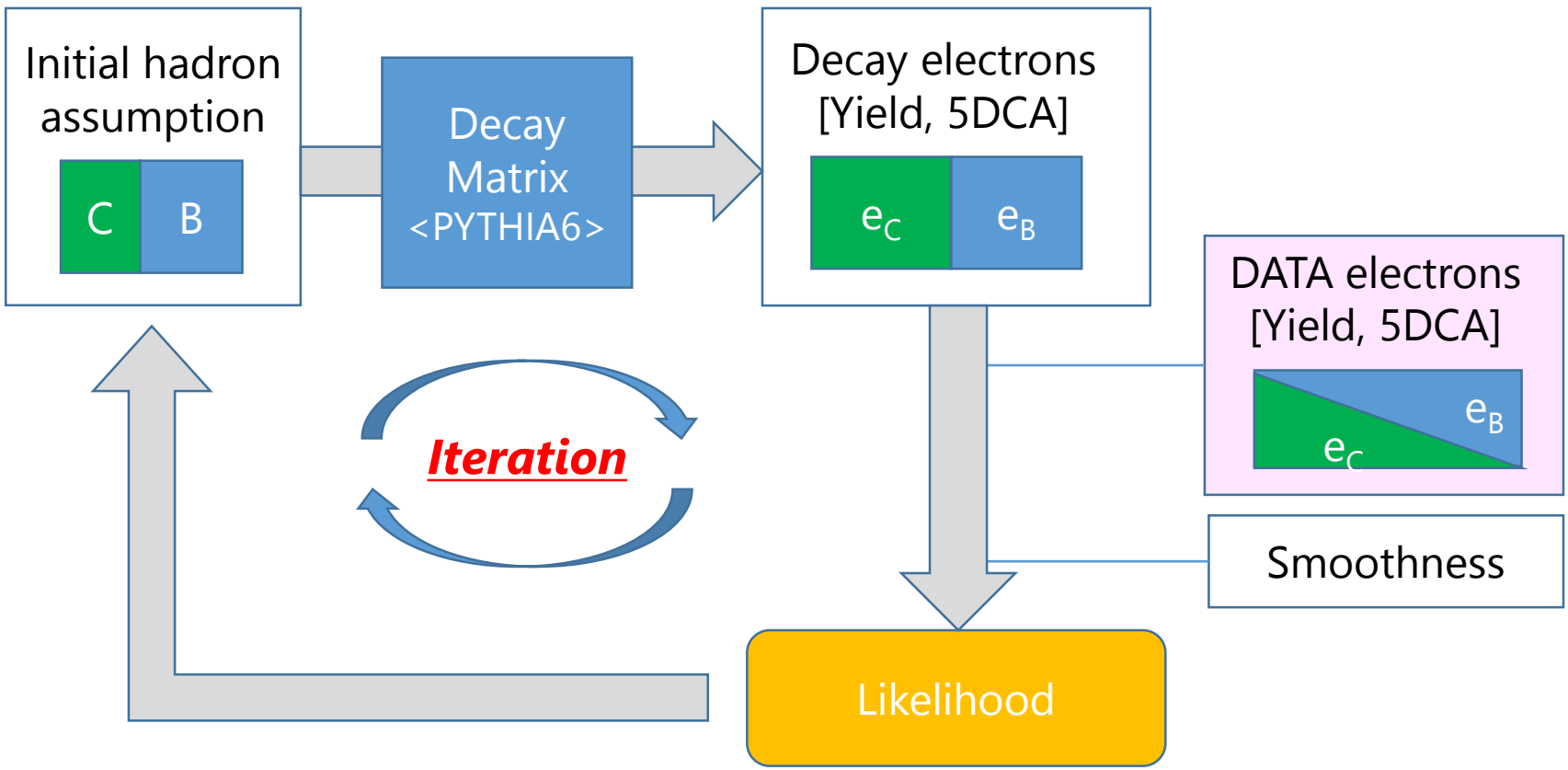
Physics origin backgrounds

- 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

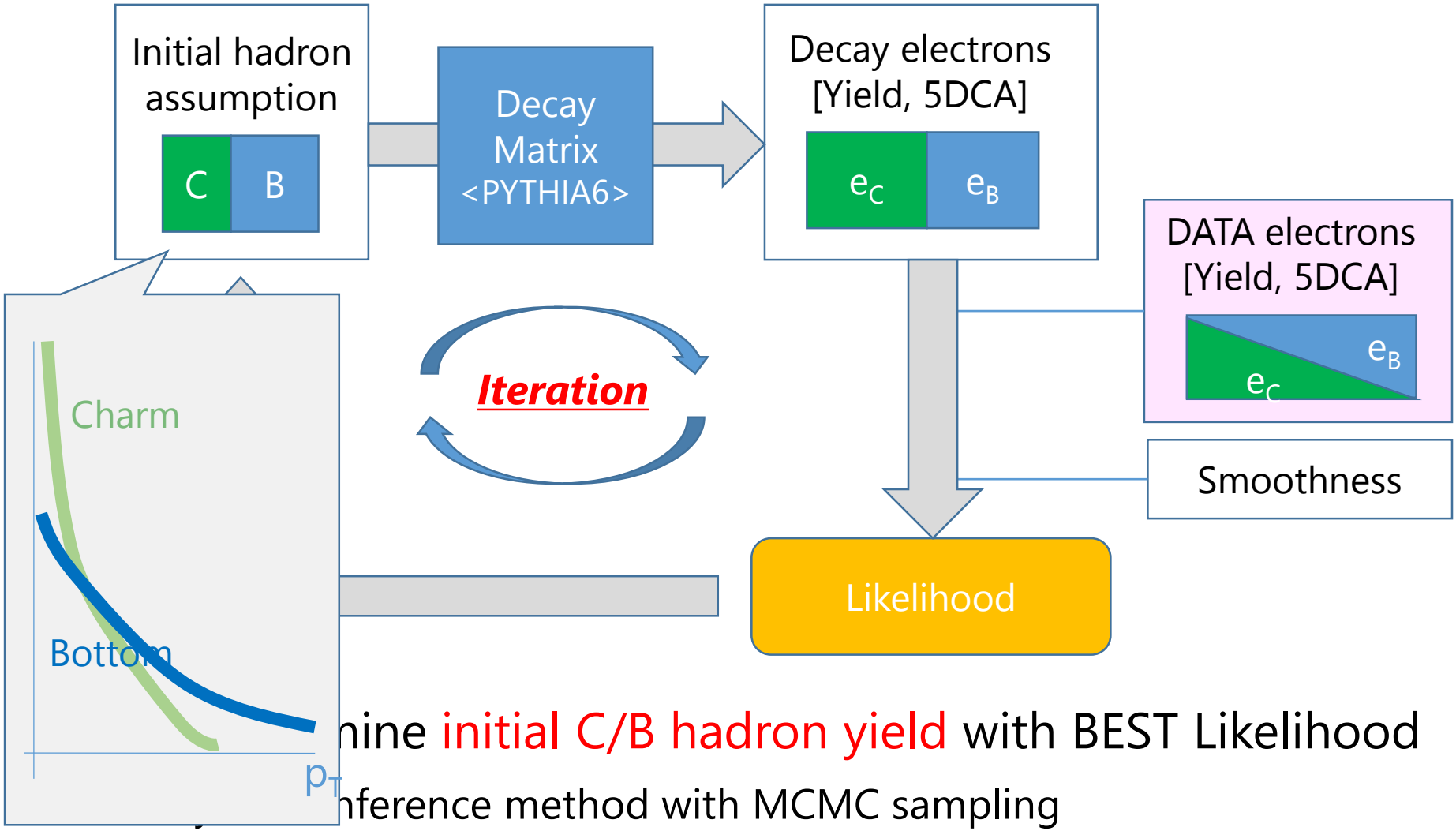
Normalization from measured yield

Unfolding : Flowchart



- Goal: determine initial C/B hadron yield with BEST Likelihood
  - Bayesian inference method with MCMC sampling
  - Probability distribution for b and c yields and correlation

Unfolding : Flowchart



nine initial C/B hadron yield with BEST Likelihood

nference method with MCMC sampling

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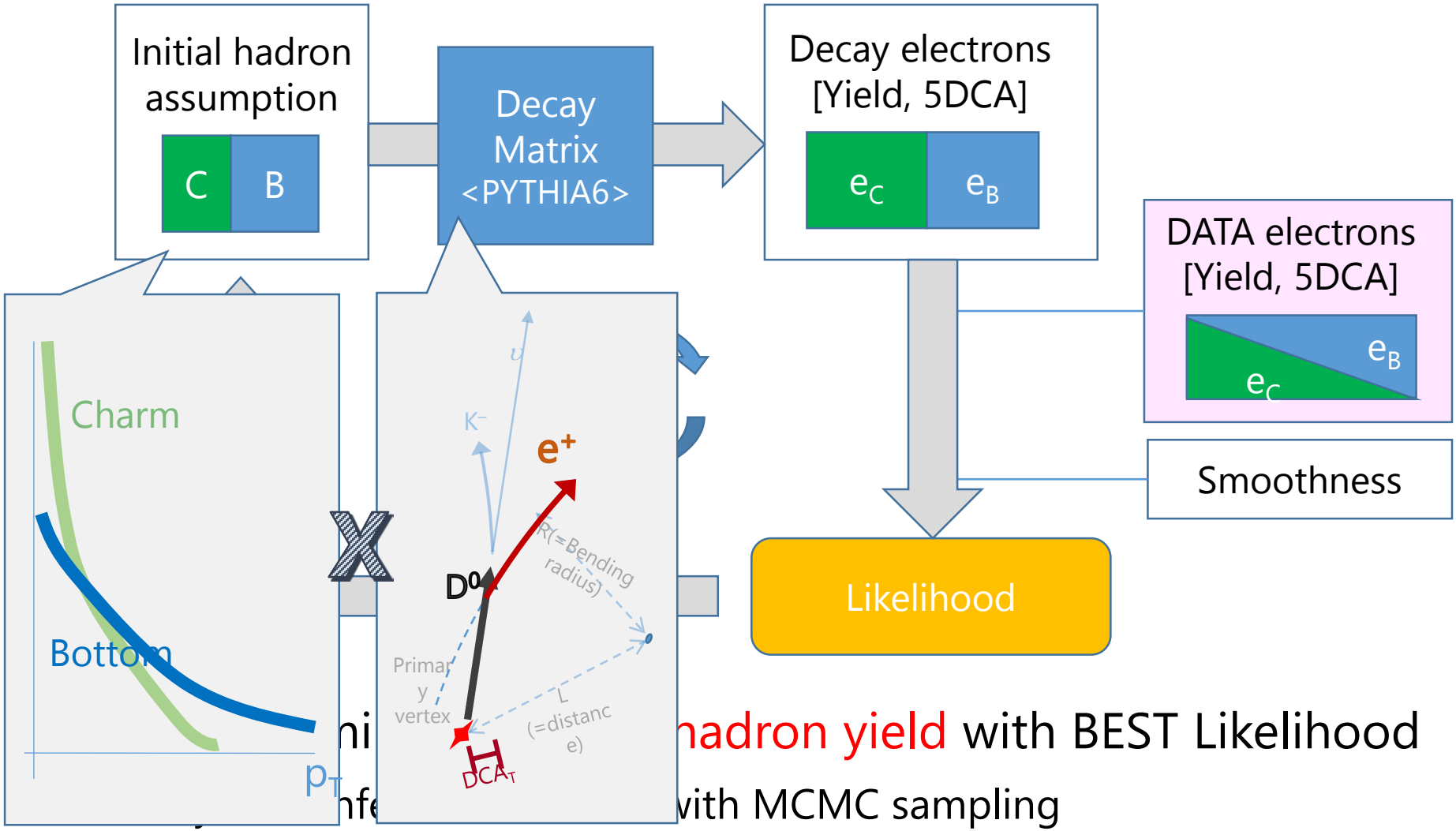
Unfolding : Flowchart



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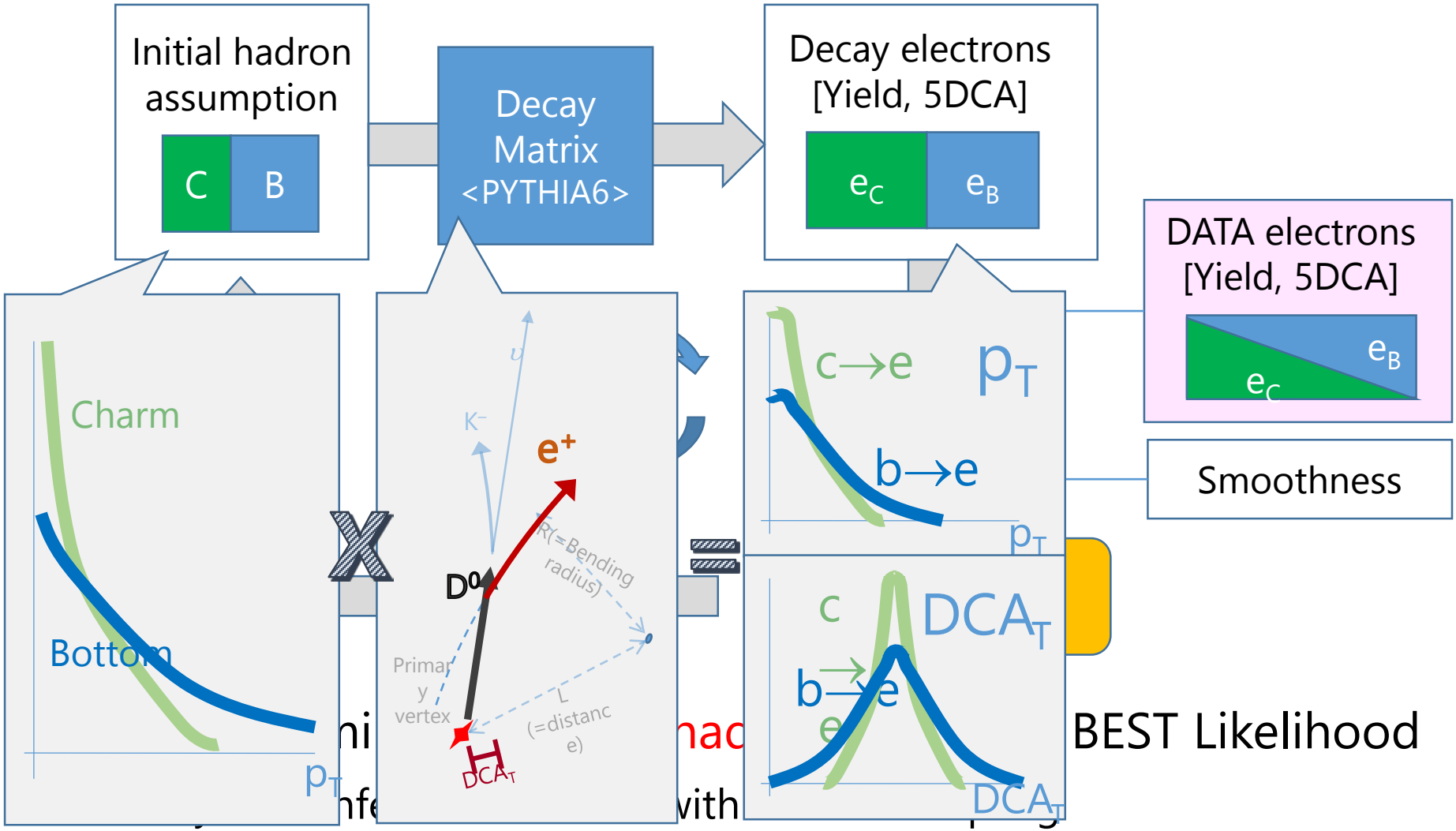

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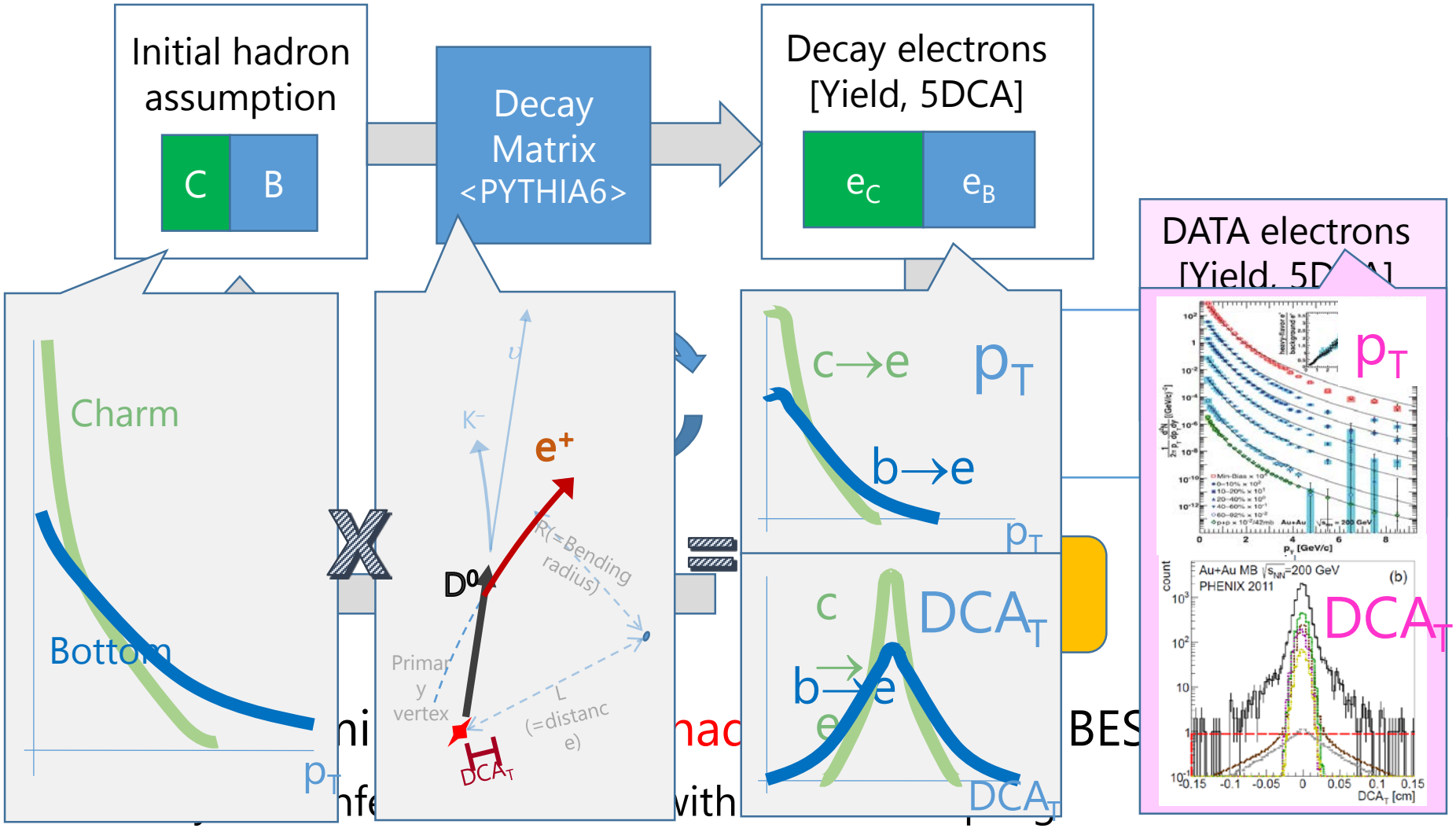

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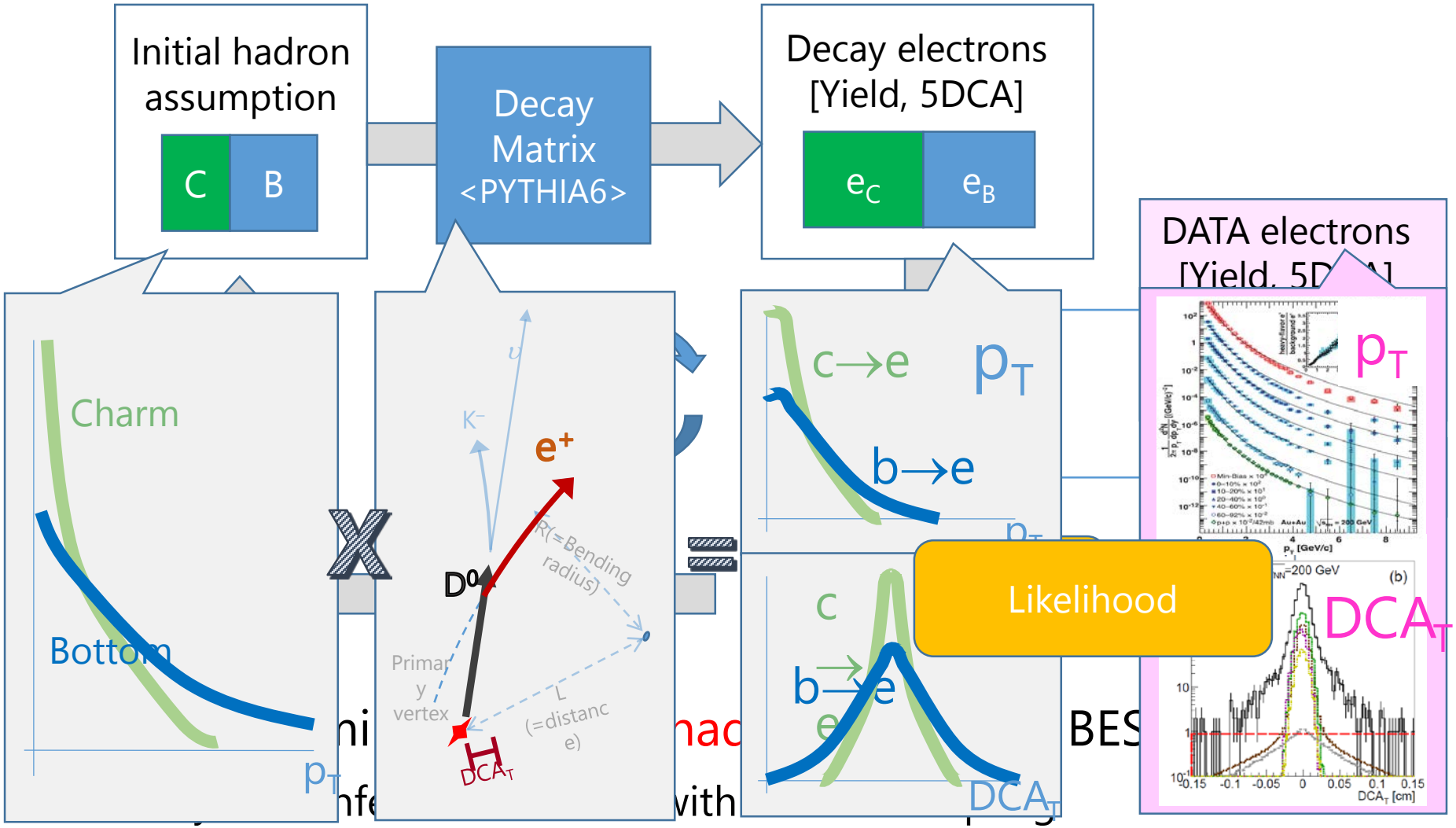

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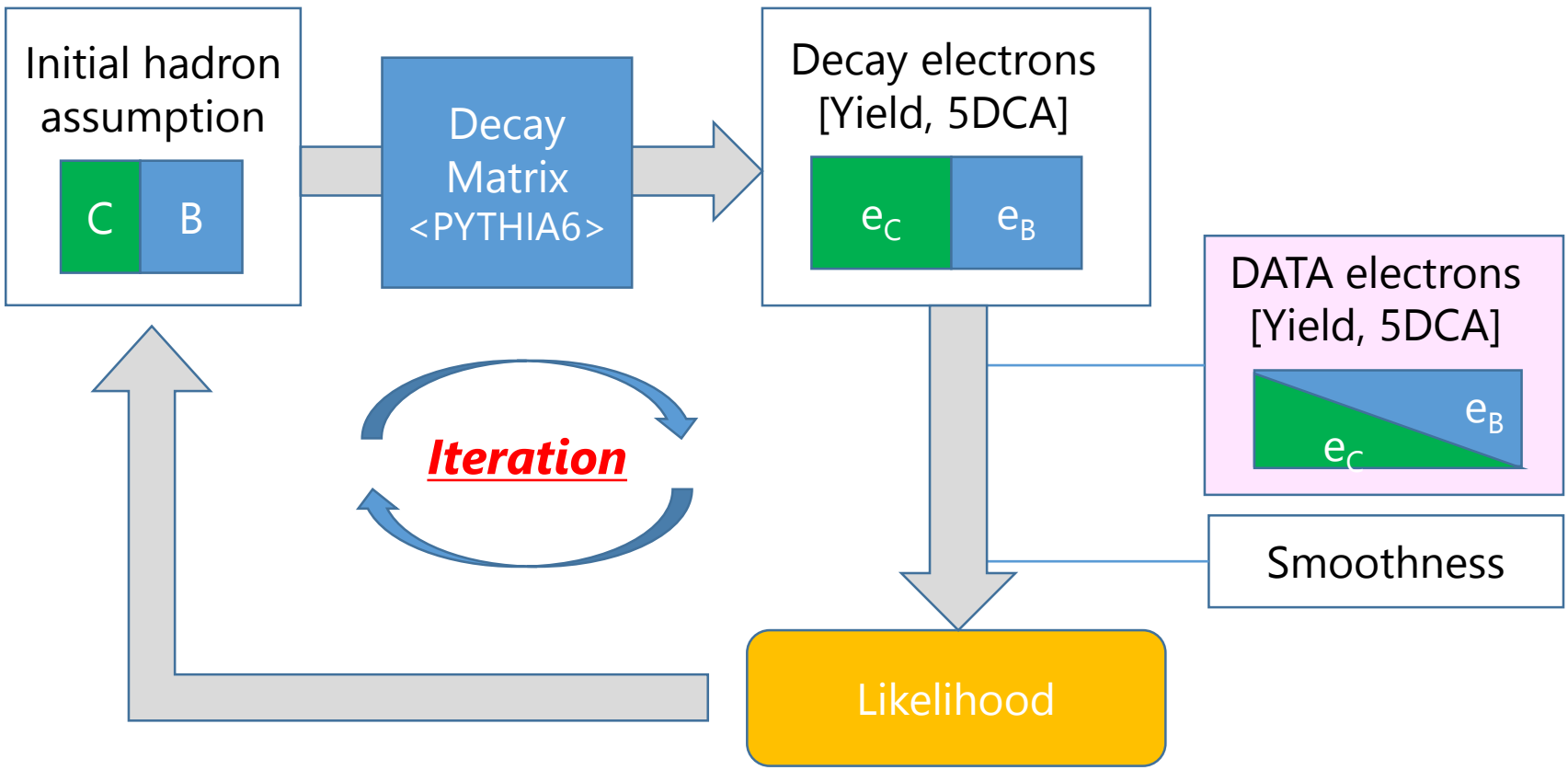
Unfolding : Flowchart



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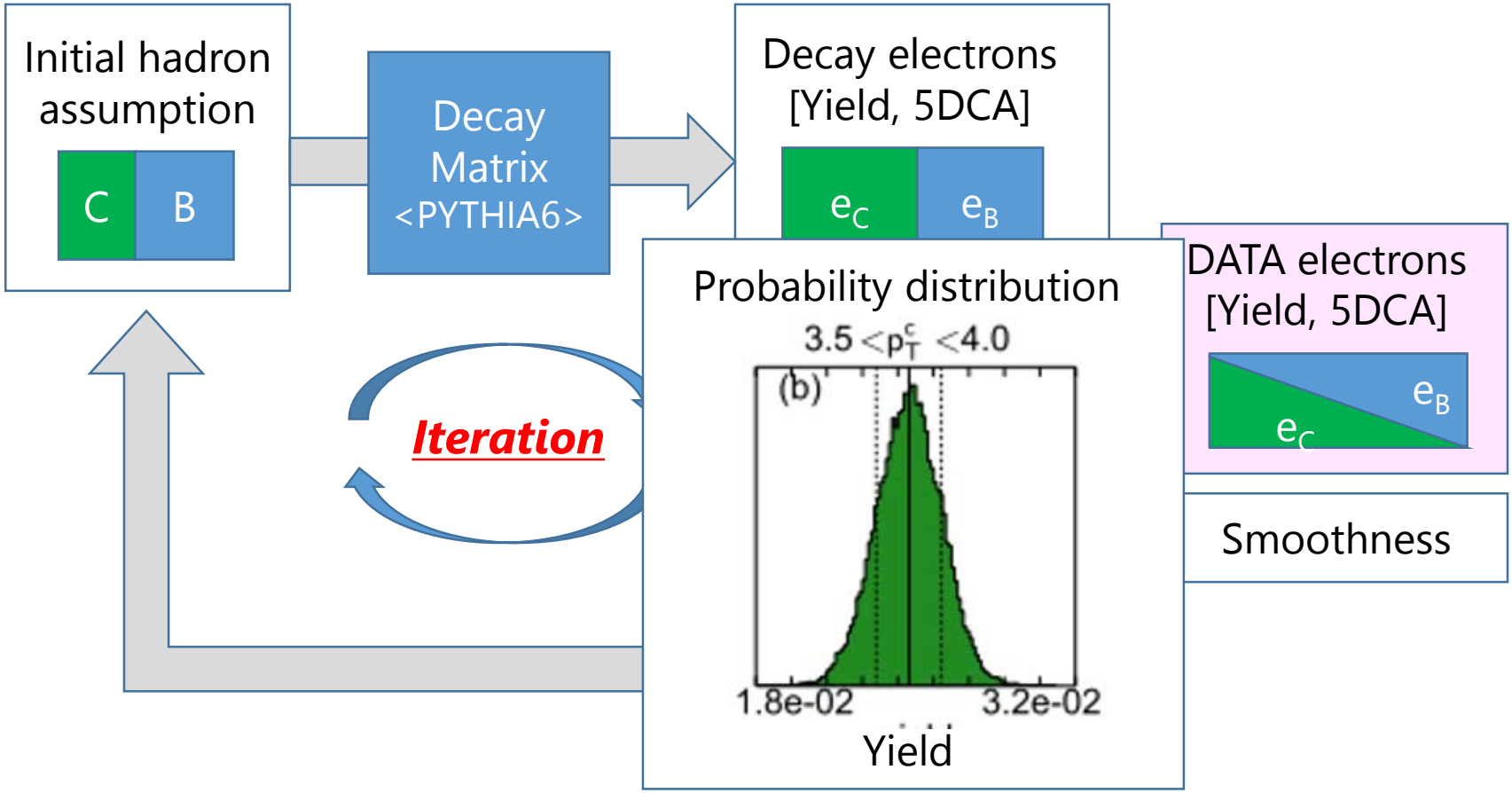
Unfolding : Flowchart



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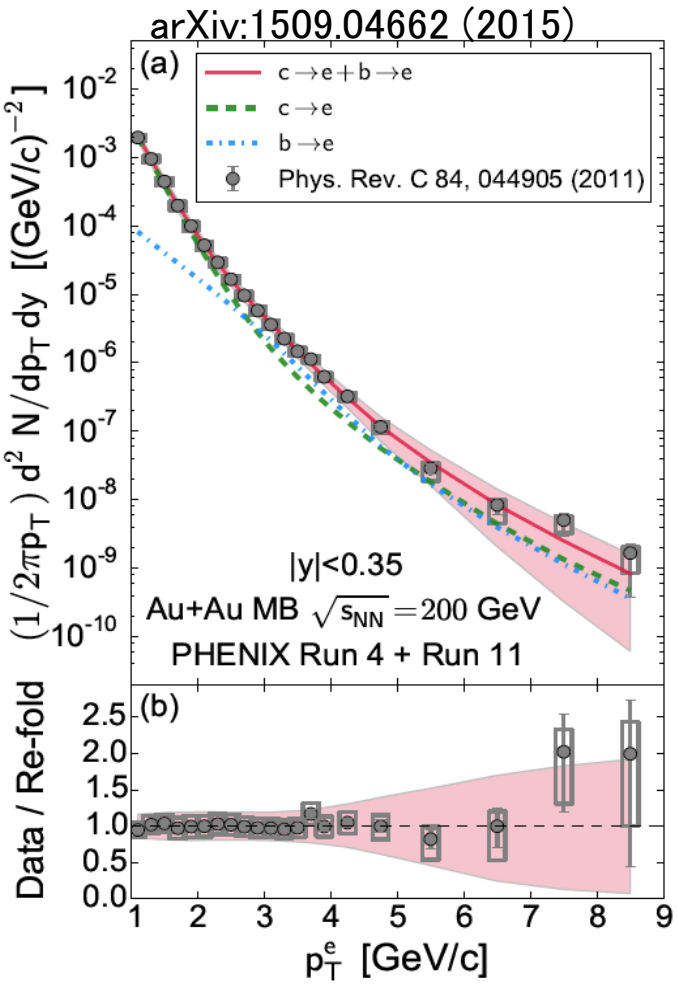
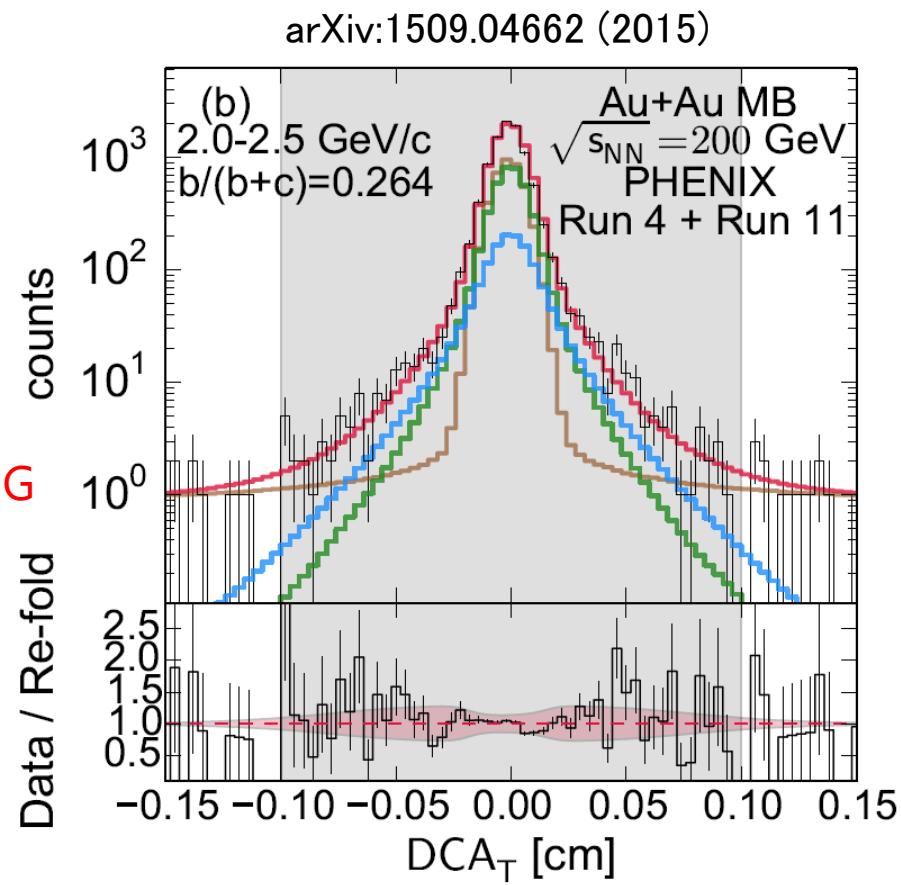
Comparison : Unfolding & Data



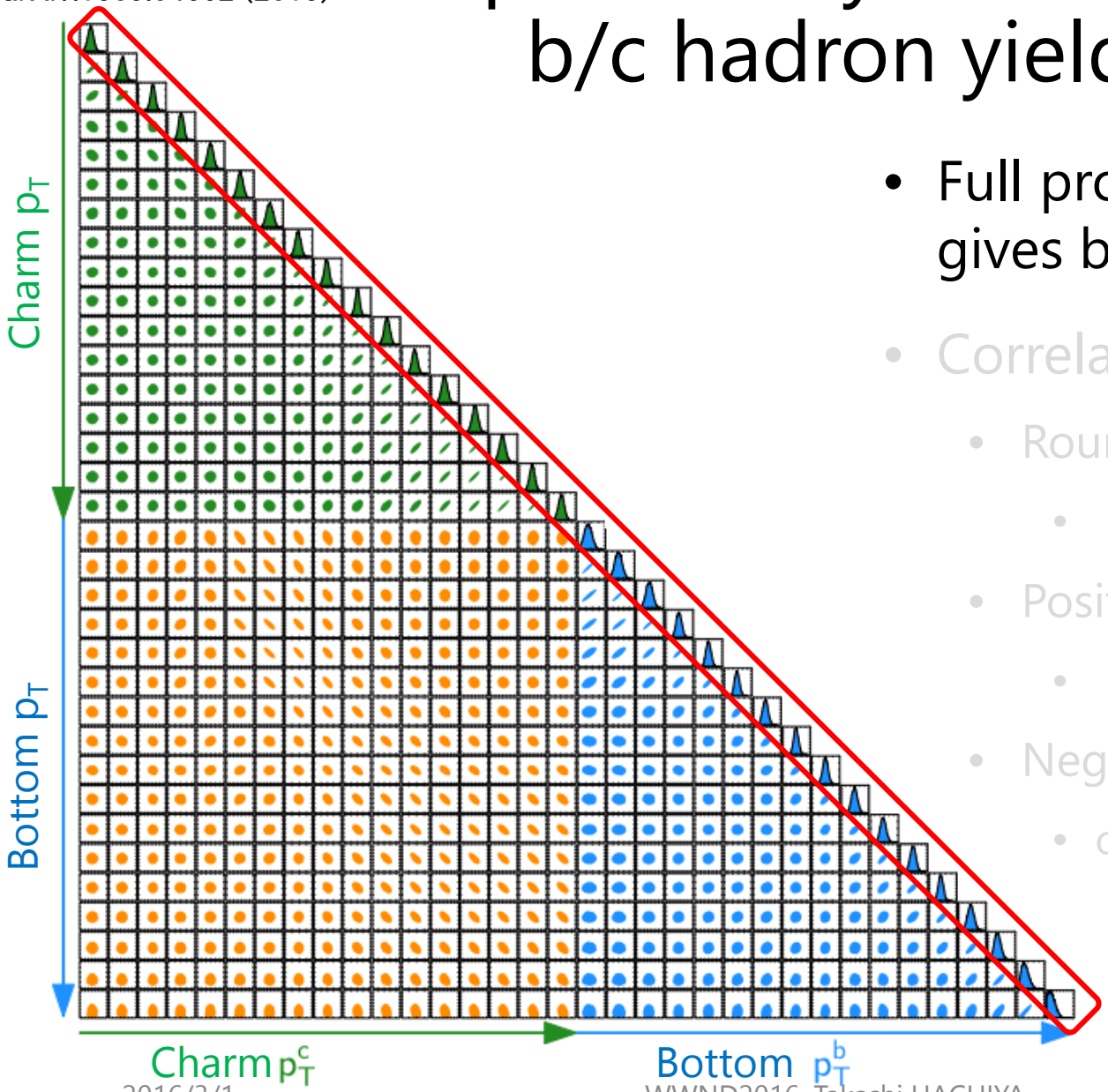
Data
Charm
Bottom
Background
Total=C+B+BG



- Unfolding is consistent with data for electron invariant yield and DCA_T data

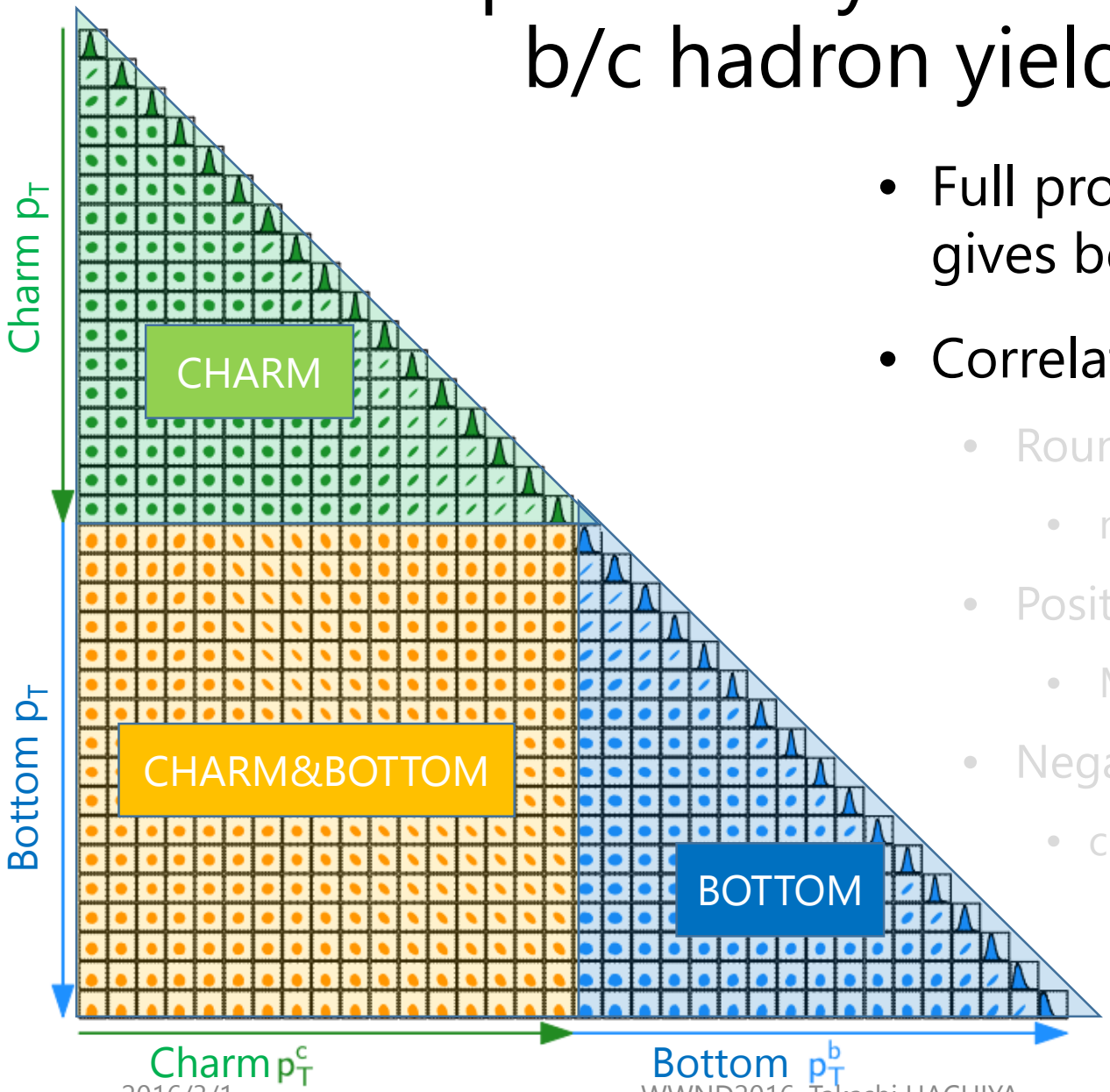
Full probability distribution b/c hadron yield

arXiv:1509.04662 (2015)



- 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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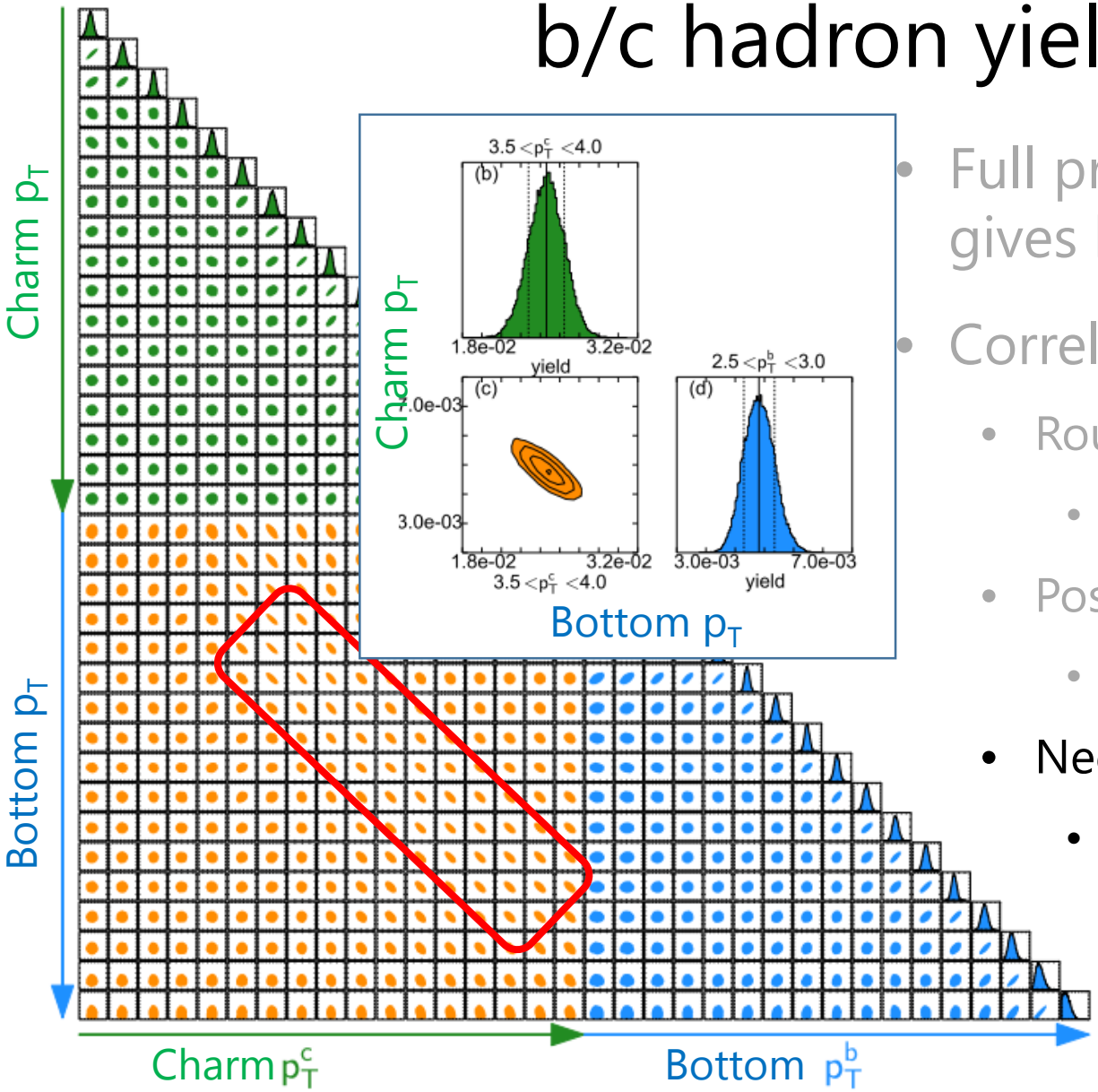
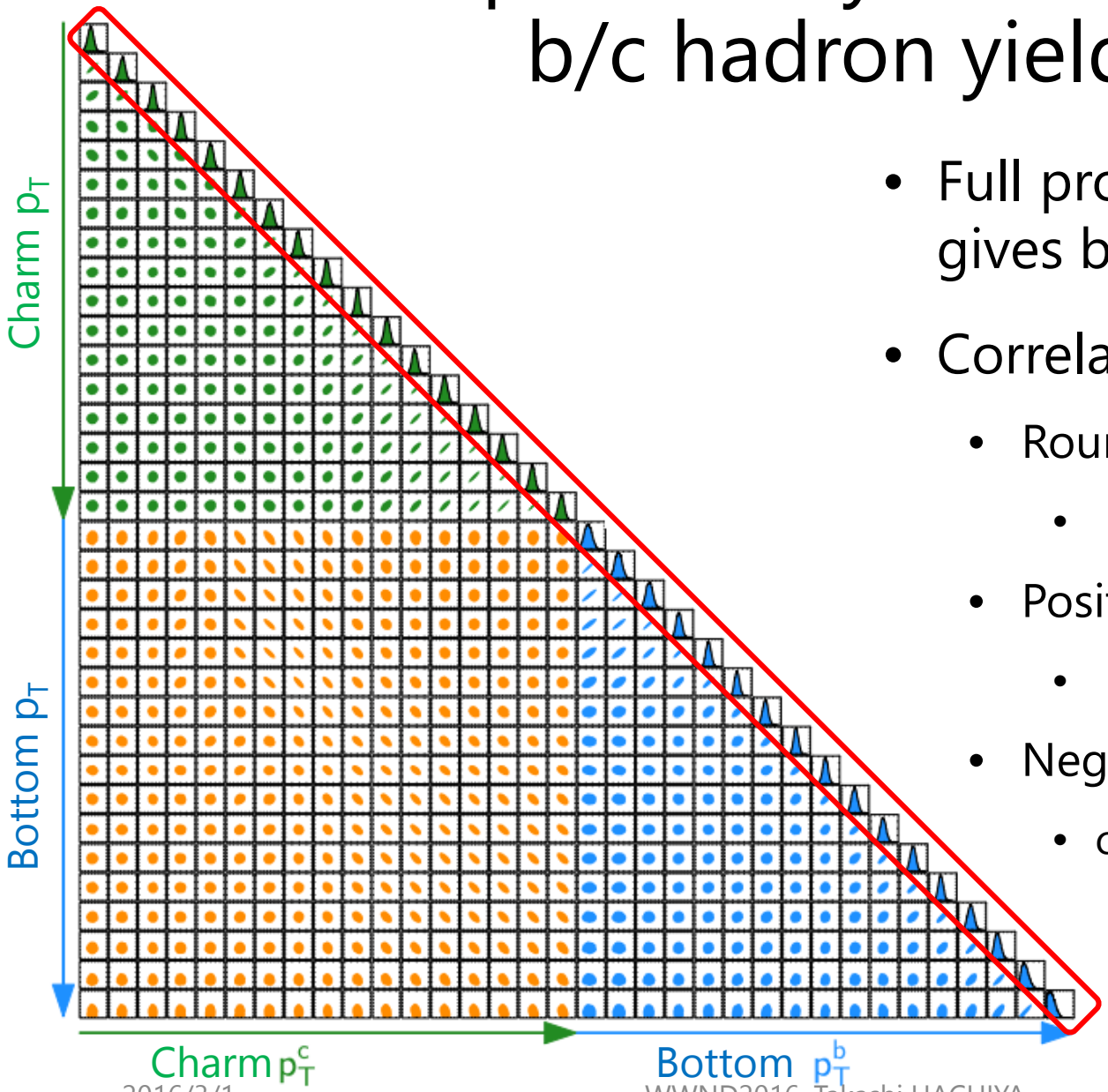


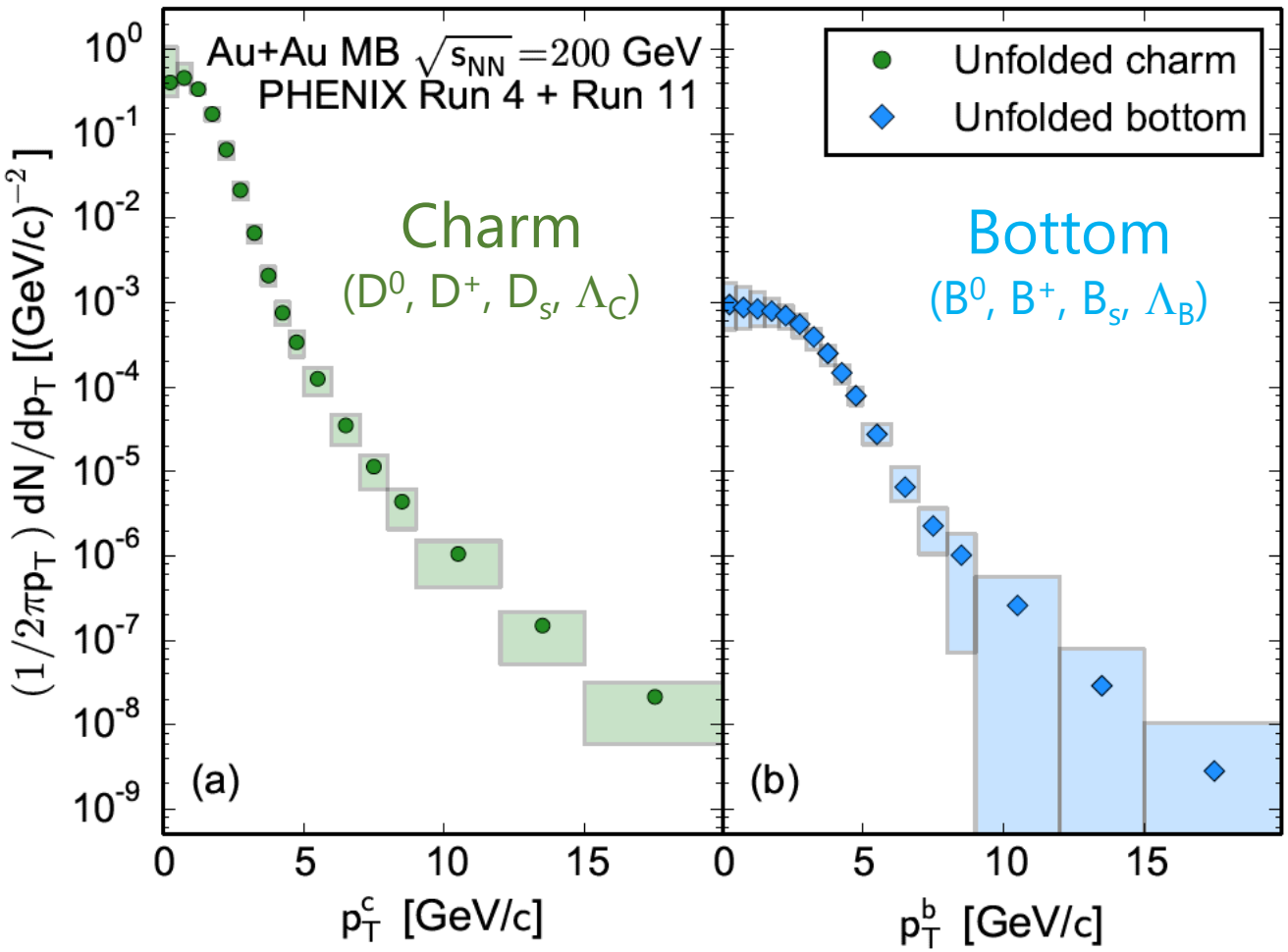
- Full probability distribution gives bottom & charm yield
- Correlation in yield
  - Round
    - no correlation
  - Positive in charm near pT
    - increase simultaneously
- Negative
  - charm ↑ + bottom ↓

Full probability distribution b/c hadron yield



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

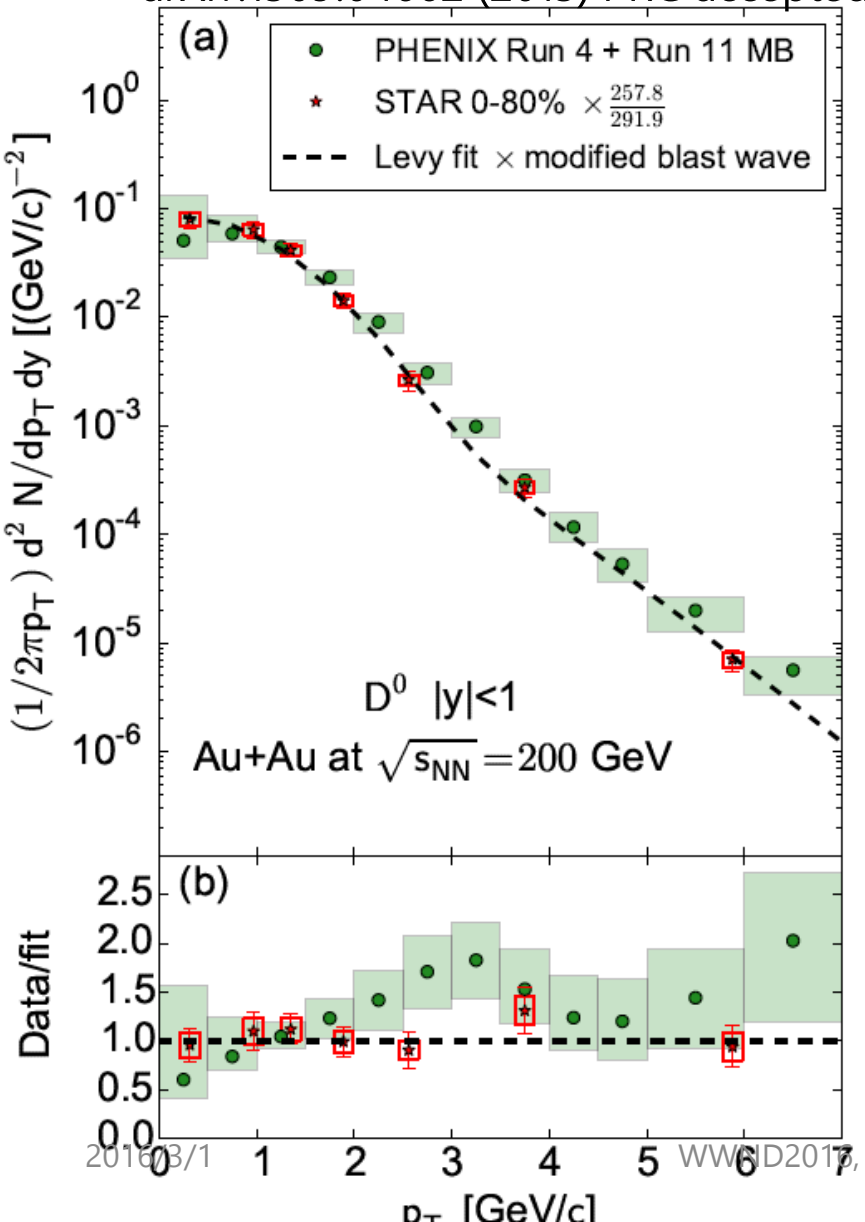
Unfold Charm and Bottom hadron spectra



- Bottom & Charm hadron yield is obtained

Unfolding agrees with data

arXiv:1509.04662 (2015) PRC accepted

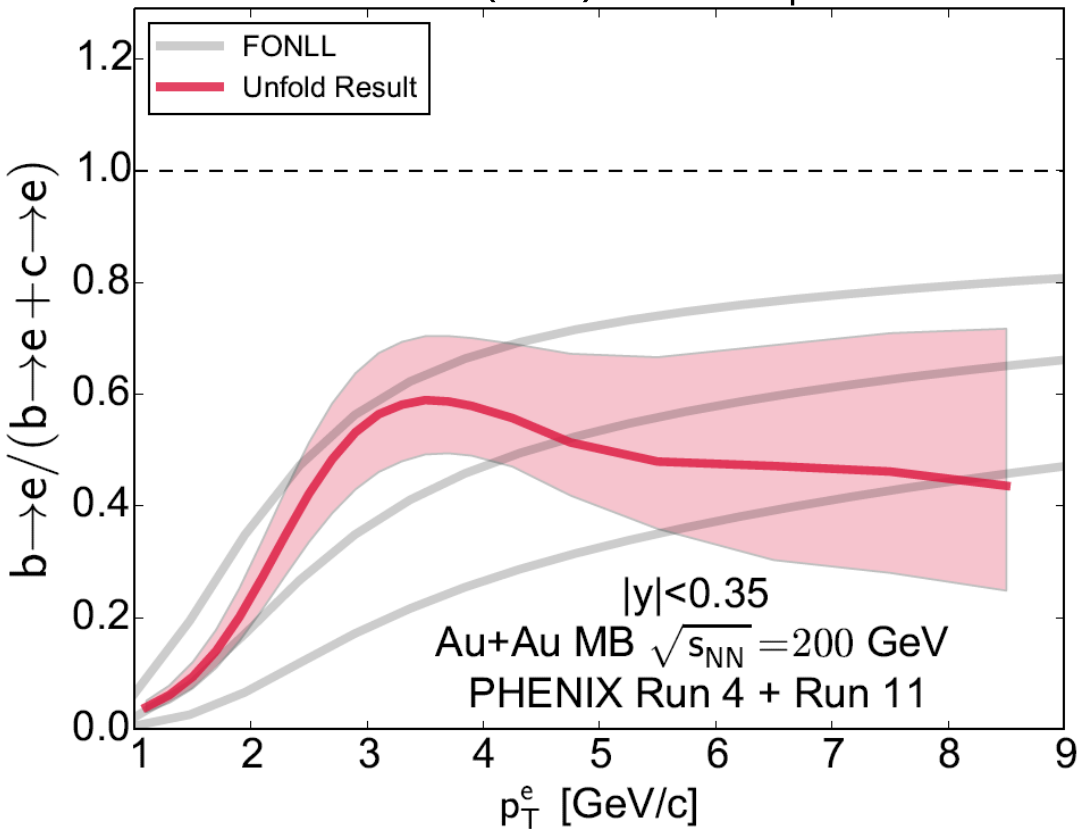


- Unfold charm hadron yield is converted to D^0
  - Scale to |y|<1 by PYTHIA model
- Unfold charm hadron yield is in agreement with STAR D^0 measurement

  Phys. Rev. Lett. 113, 142301
- The unfolding method successfully extracted charm. thus, bottom yield should be reliable

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

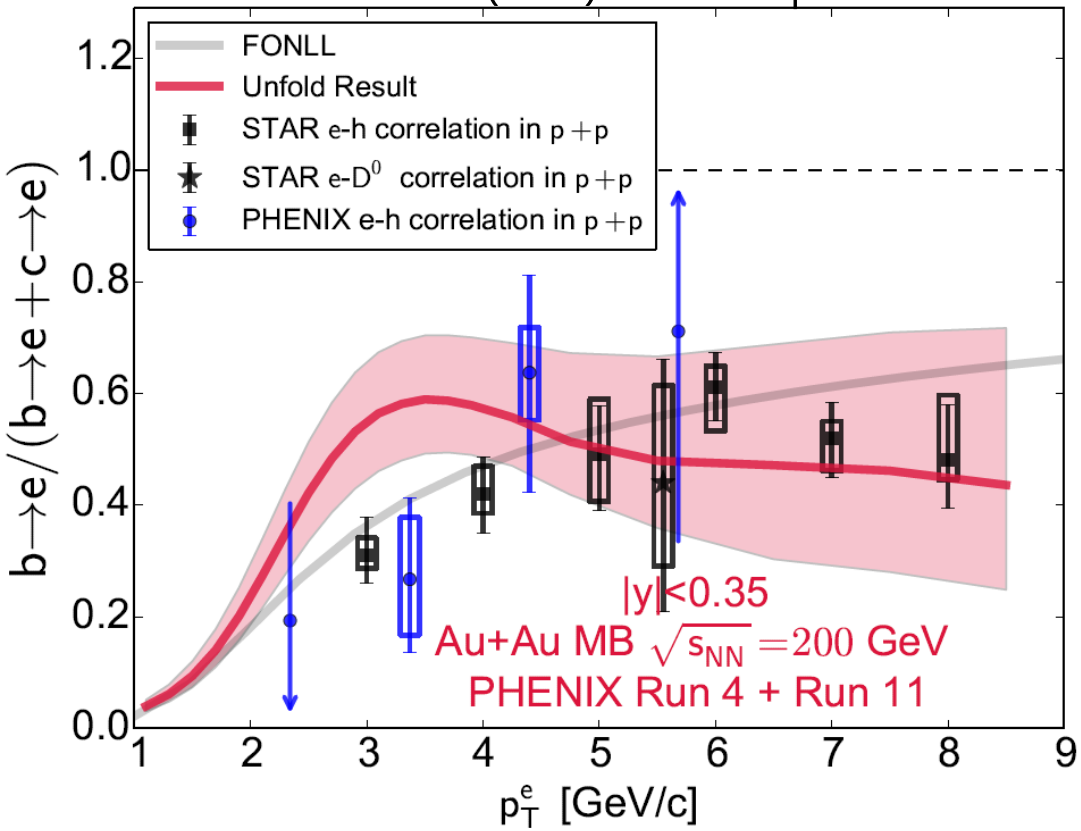
arXiv:1509.04662 (2015) PRC accepted



- Consistent with FONLL within error
- Shape is different with FONLL
  - A peak at p_T=3GeV/c and decreasing w/ higher p_T

Comparison with p+p data

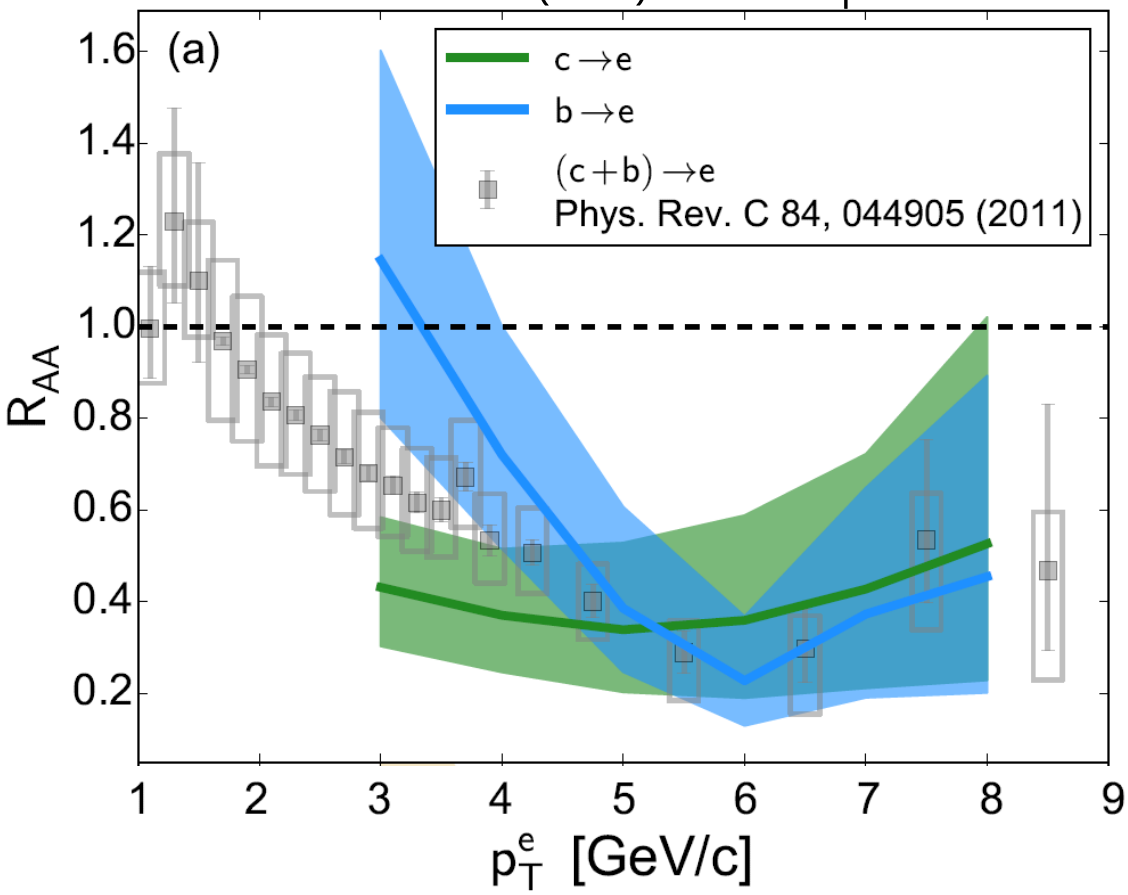
arXiv:1509.04662 (2015) PRC accepted



- p+p data is consistent with FONLL
  - b fraction in p+p by 2 particle correlation
- Au+Au has clear peak at p_T=3GeV/c
  - This implies the suppression is different with p_T

Bottom and Charm R_{AA}

arXiv:1509.04662 (2015) PRC accepted



Using

F_{AuAu}: bottom fraction in Au+Au

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

R_{AA}^{HF} : Open HF R_{AA}^{HF} in Au+Au

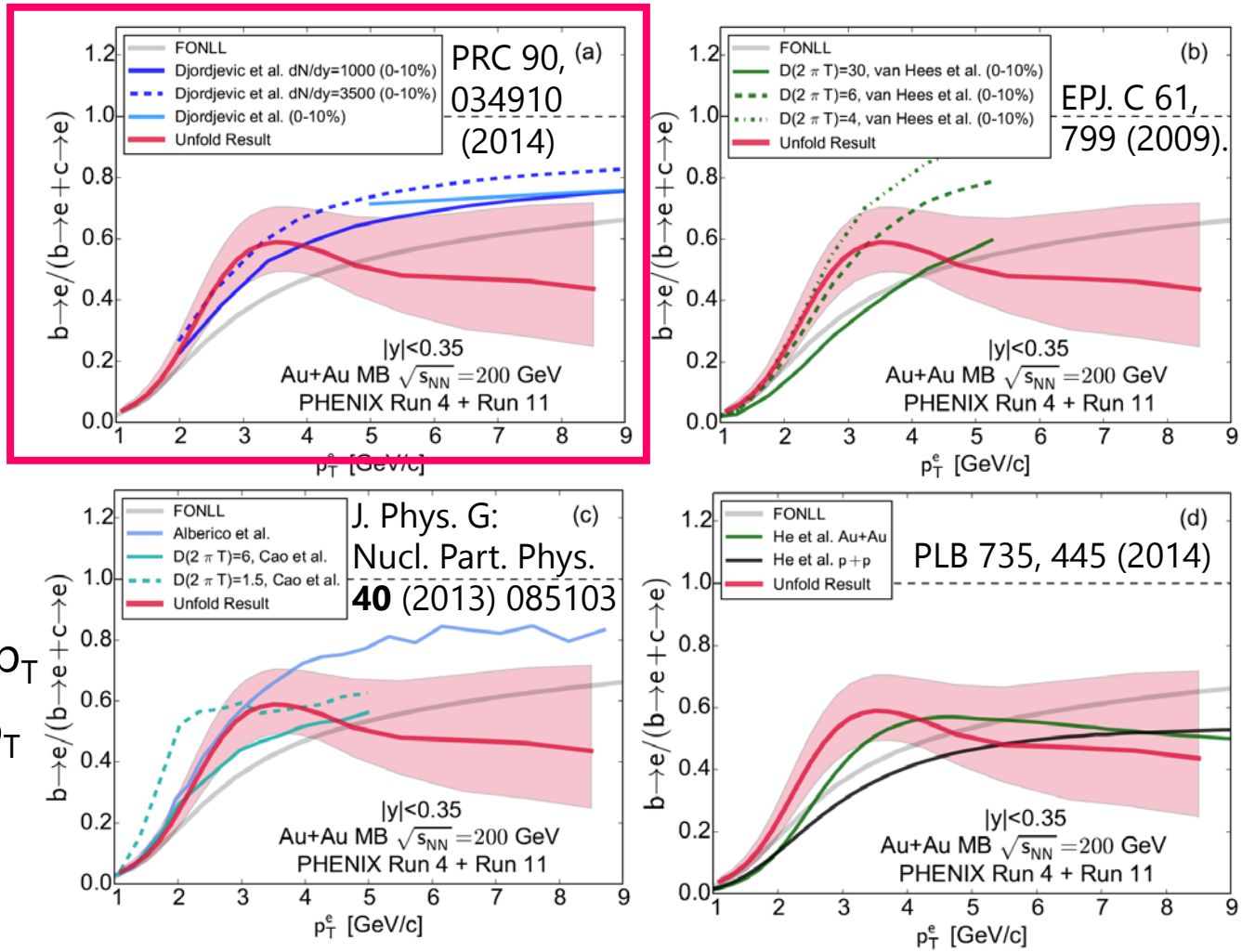
$$R_{AuAu}^{c\to e} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R_{AA}^{HF}$$

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

- Bottom and charm are suppressed at high p_T
- Charm is more suppressed than bottom at p_T=3-4 GeV/c

Comparison with Models

There are many models describing heavy flavor energy loss collisional (+radiative)

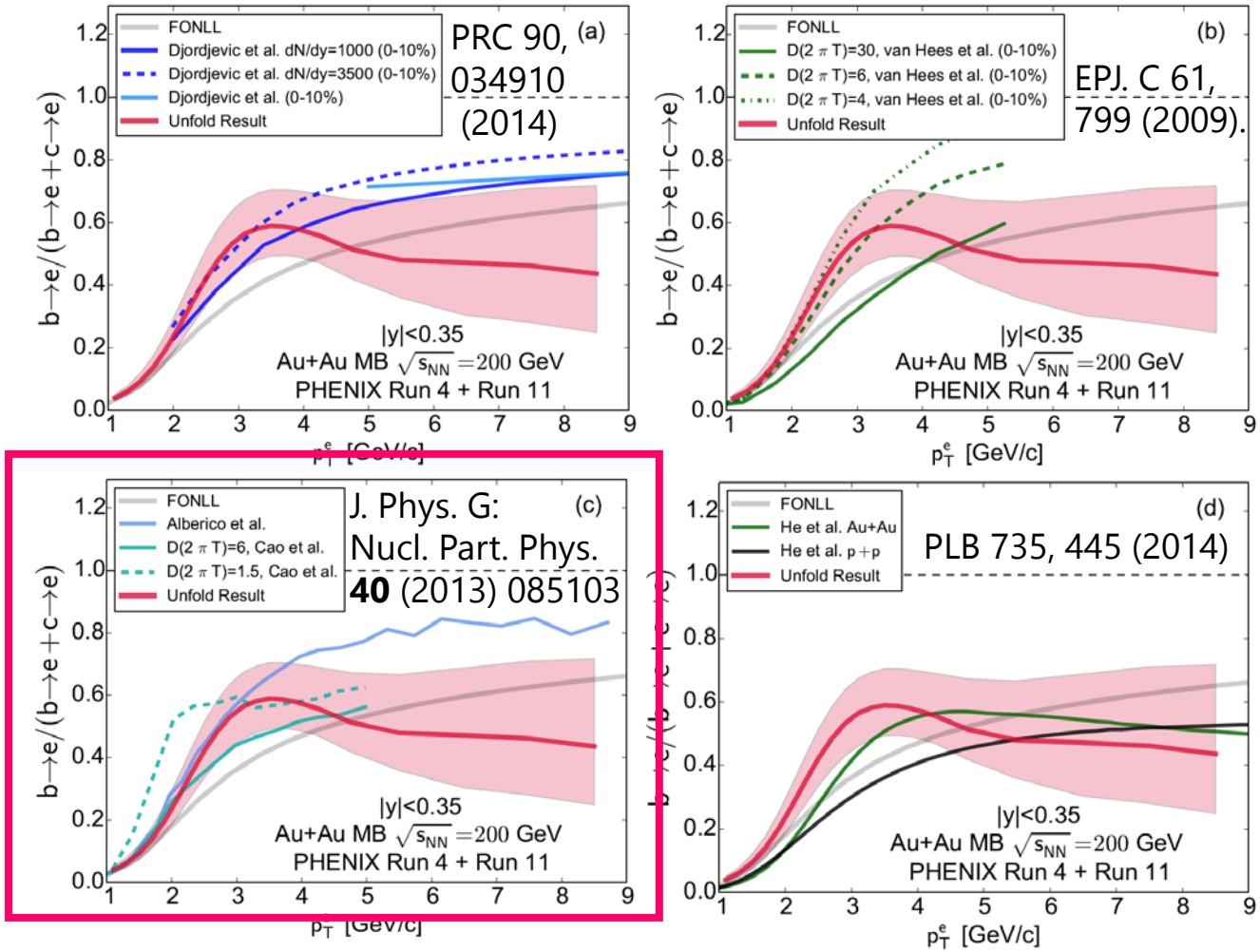


- Radiative loss by DGLV model
- Consistent at low p_T
- Different at high p_T

Comparison with Models

There are many models describing heavy flavor energy loss collisional (+radiative)

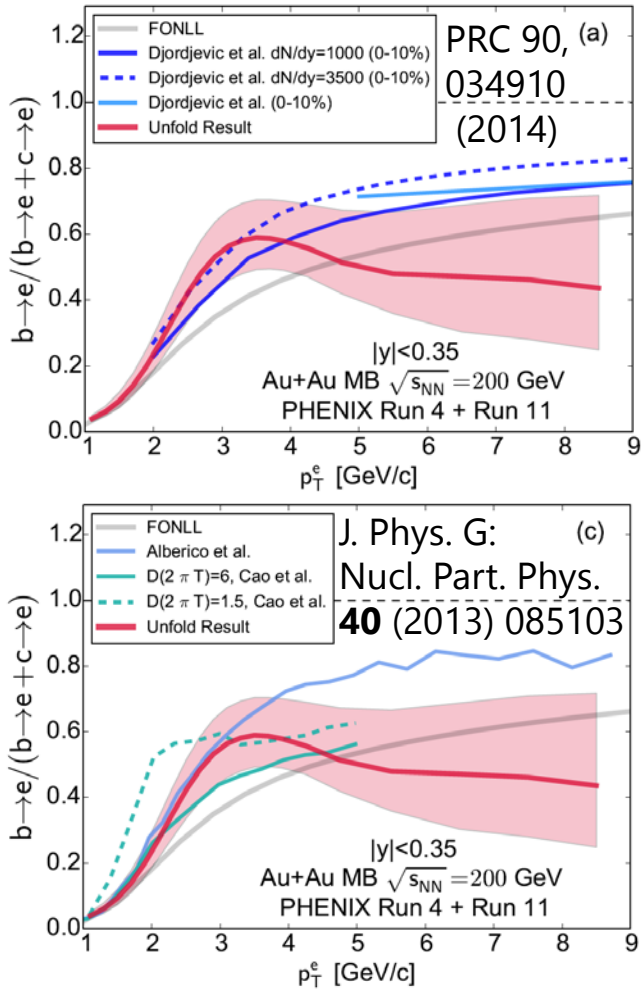
- Collisional loss by Langevin approach
- Agree with D=6 at low p_T
- increasing monotonically

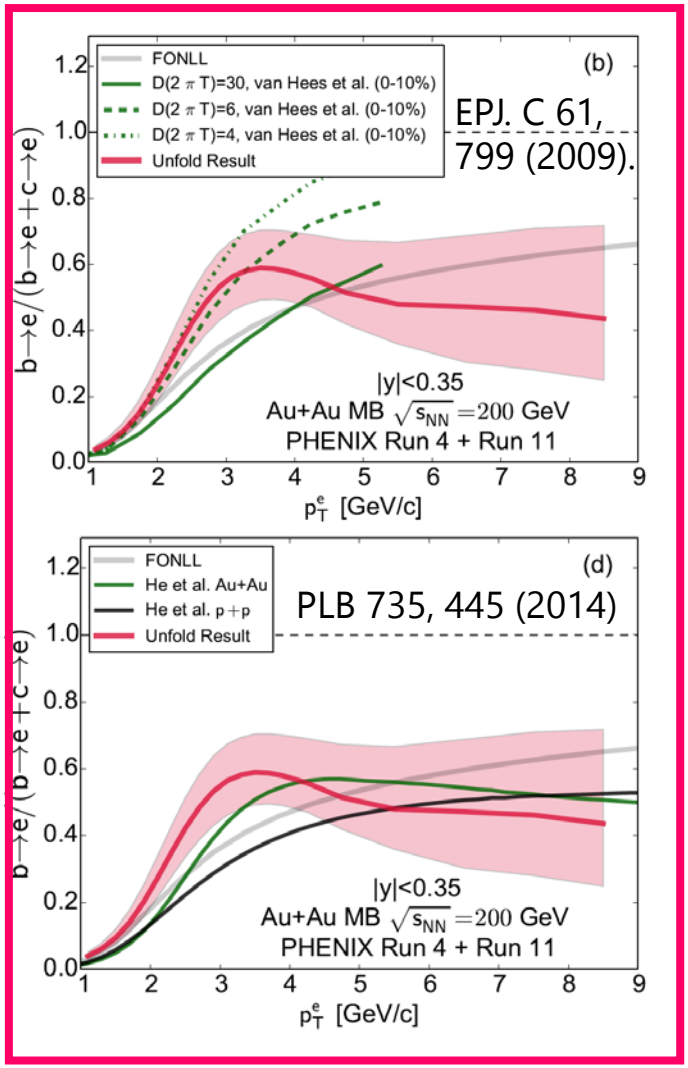


Comparison with Models

There are many models describing heavy flavor energy loss collisional (+radiative)

- Collisional loss by T-matrix approach
- Agree with D=4-6 at low p_T
- Similar trend with data





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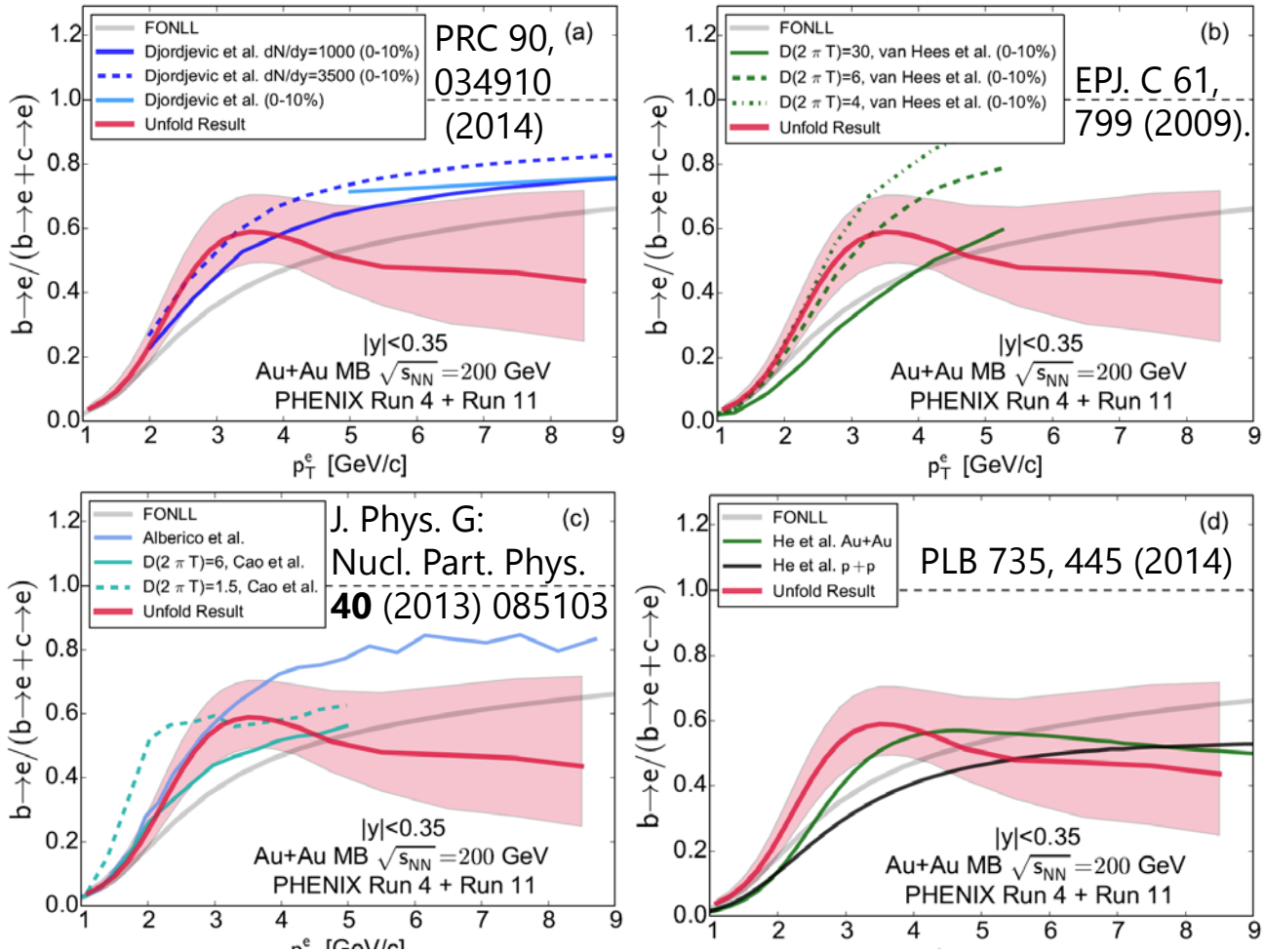


- Models not well described the data
  - Data gives an additional constraint with models
- Our data has large uncertainty for high p_T. Need higher statistics

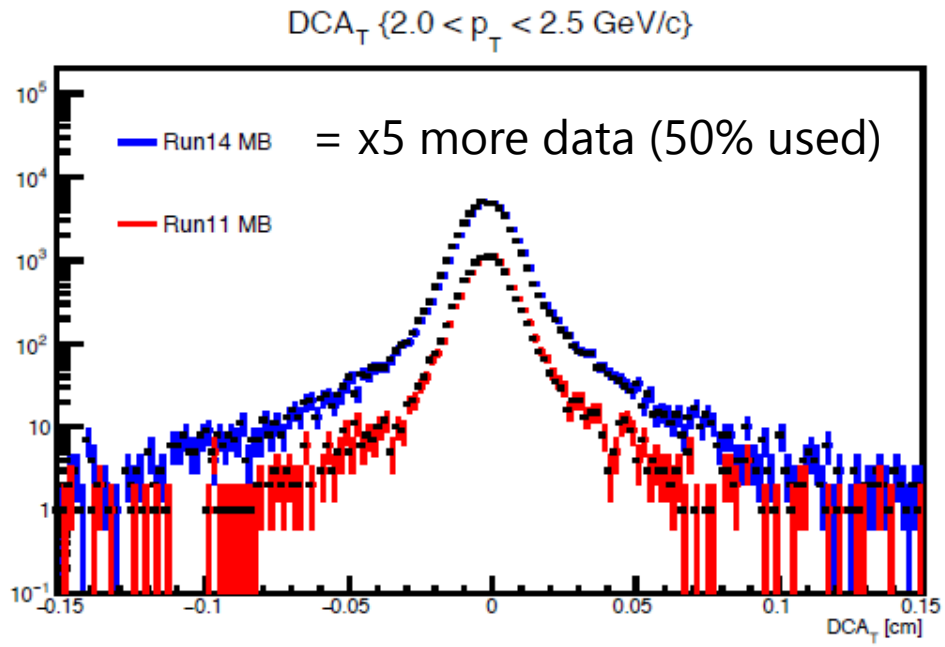
Future prospects

- High quality data in run2014 – 2016 Au+Au & p+p
  - 10 time larger statistics in run2014 Au+Au 200GeV
    - Run2016 is running to make the statistics twice.
  - Detector performance improved

High p_T extension
Centrality dependence

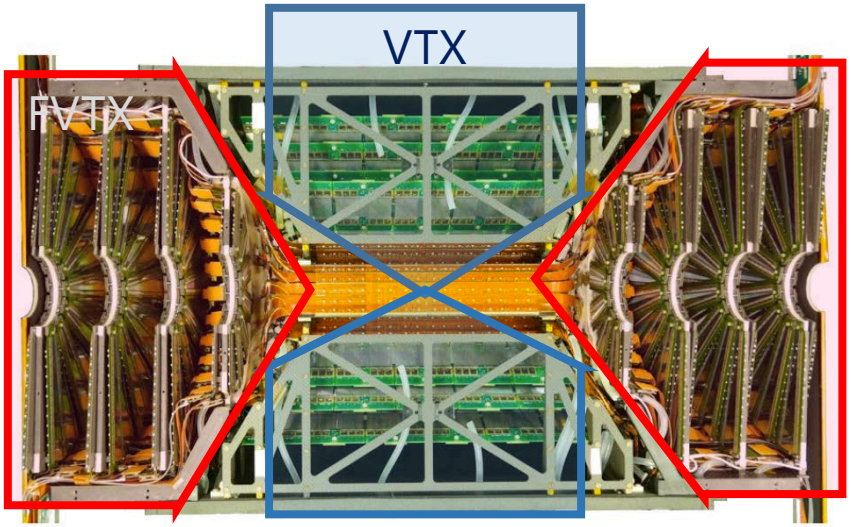
- Apply the analysis technique to run2014 – 2016 data

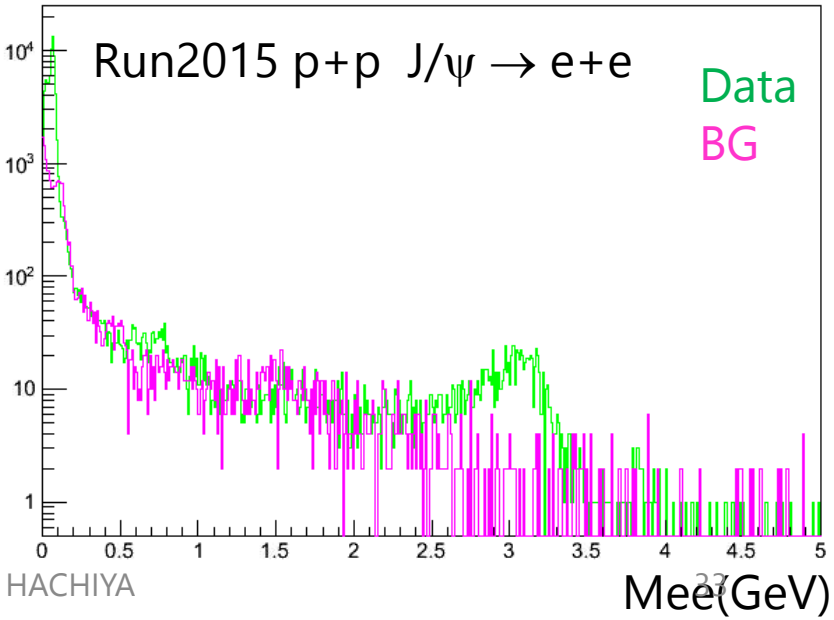
Example : DCA_T in run2014



Future prospect

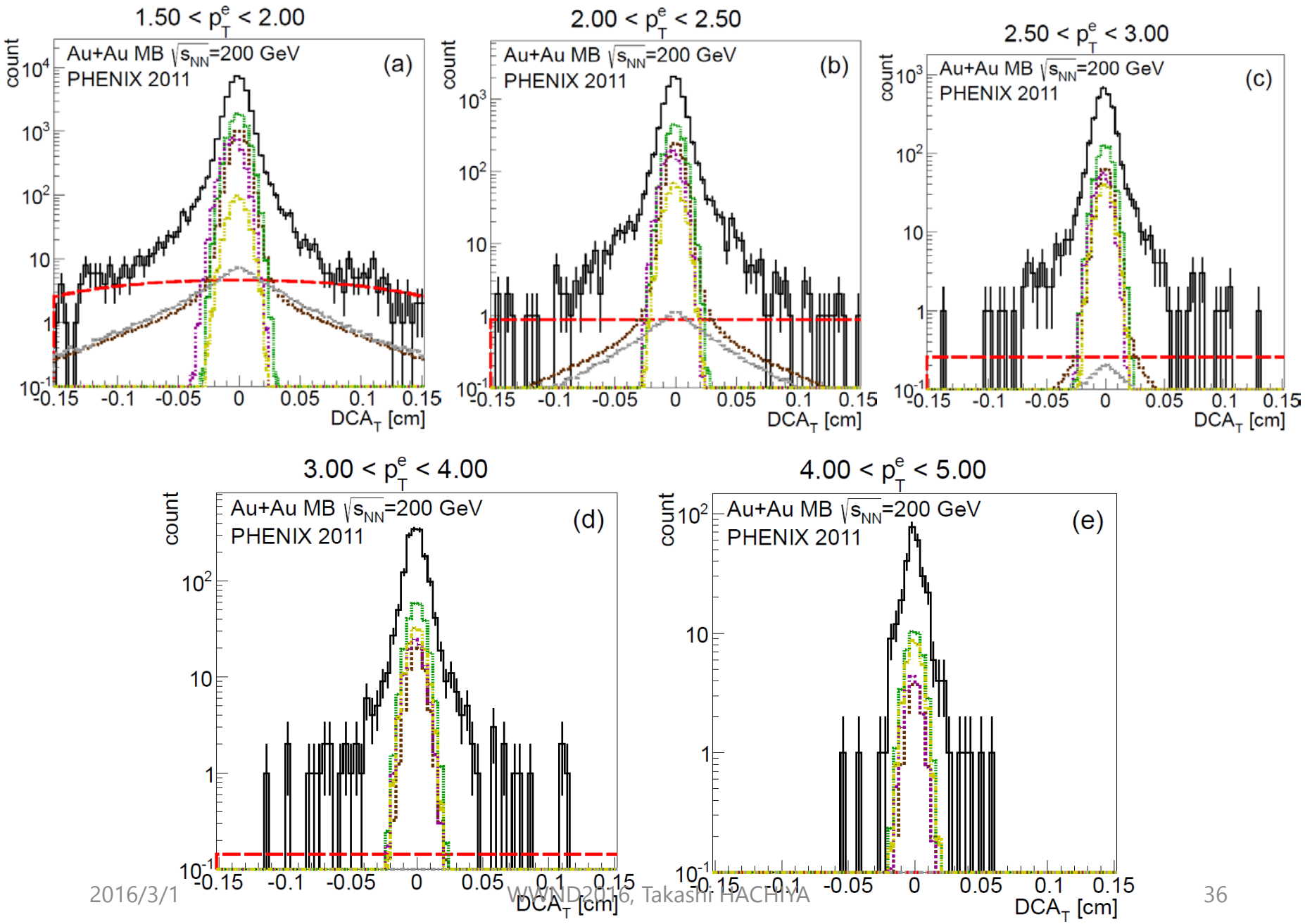
- Direct heavy flavor measurement
  - $D \rightarrow K + \pi$
  - Non-prompt J/ψ ($B \rightarrow J/\psi$)
- VTX ($|\eta|<1.2$)
  - $J/\psi \rightarrow e+e$ @ mid rapidity
  - Secondary vertex reconstruction
    - Separate prompt & non-prompt J/ψ
- FVTX ($1.2<|\eta|<2.2$)
  - $J/\psi \rightarrow \mu+\mu$ @ forward rapidity

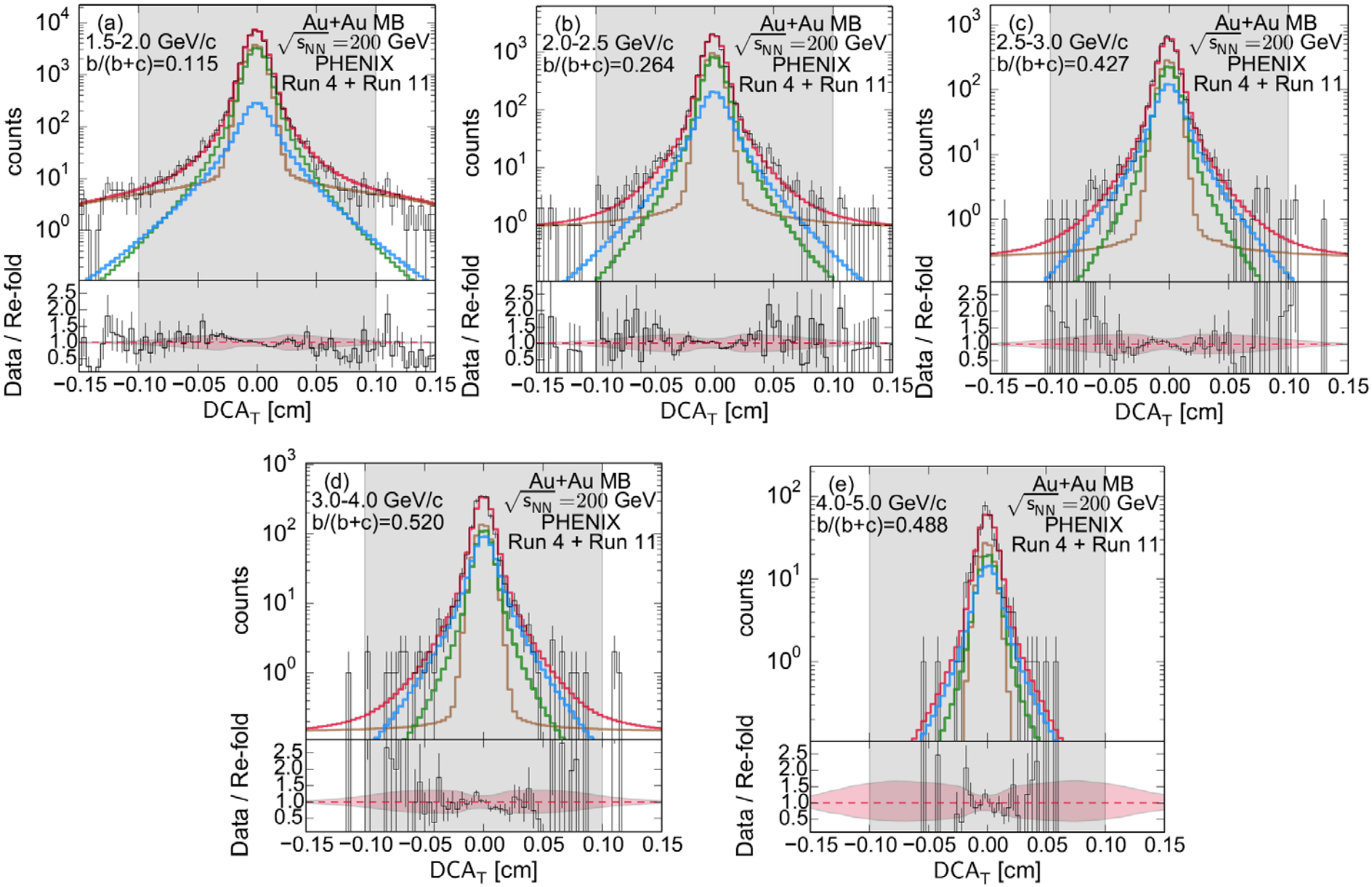




Summary

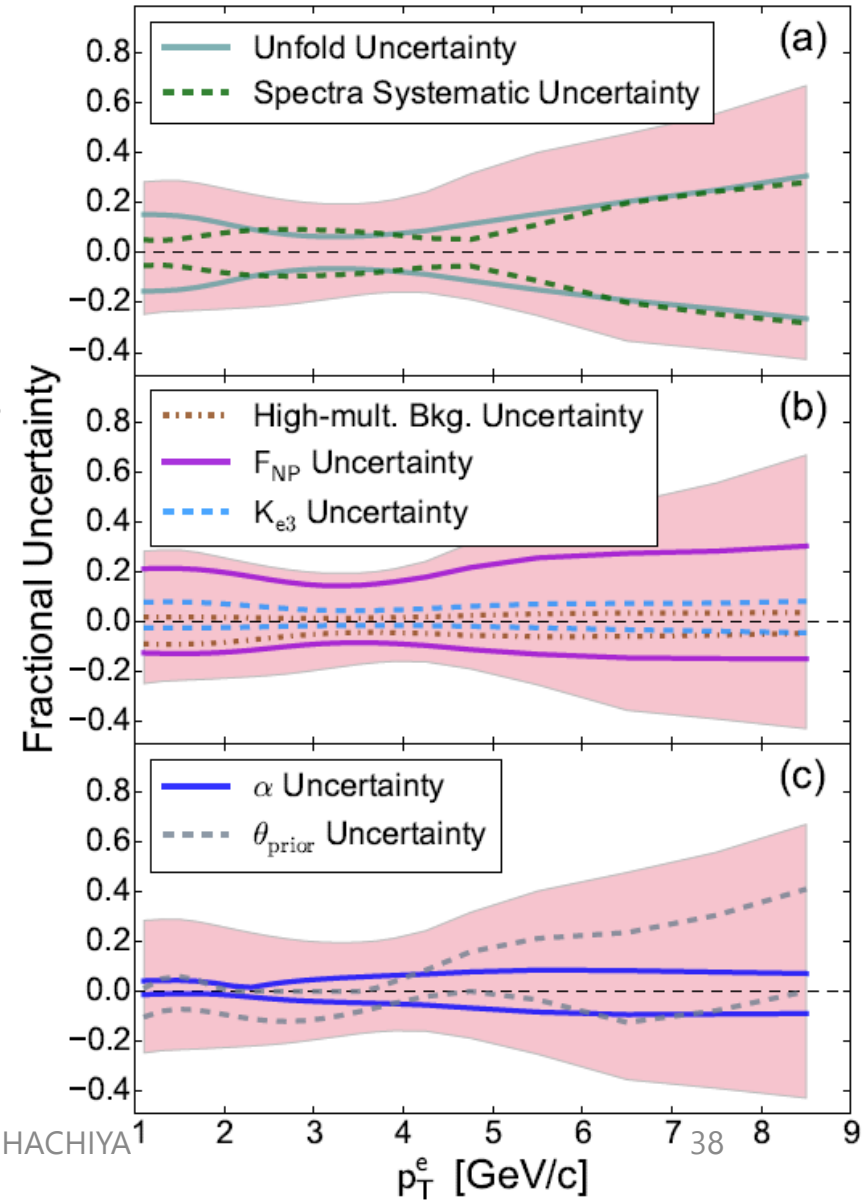
- First measurement of separated bottom and charm electrons at RHIC energy
  - VTX measures displaced tracking with σ_{DCAT}=60μm
  - Unfolding method successfully separates the bottom & charm contributions
- Bottom and charm are similarly strongly suppressed at p_T > 4 GeV/c
  - Bottom electrons are less suppressed at p_T<4GeV/c
- Bottom electron fraction shows peak structure at p_T~3 GeV/c
  - Additional constraint to models.
  - Data prefers smaller diffusion constant
- 10x statistics in run2014-2016 enables more precise measurement


1.50 < p_T^e < 2.00
2.00 < p_T^e < 2.50
2.50 < p_T^e < 3.00
3.00 < p_T^e < 4.00
4.00 < p_T^e < 5.00
Au+Au MB $\sqrt{s_{NN}}$=200 GeV
PHENIX 2011
(a)
(b)
(c)
(d)
(e)
count
DCA_T [cm]

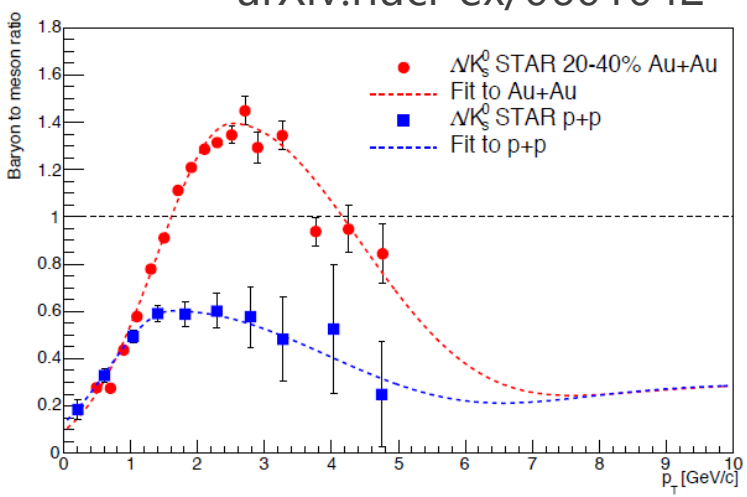
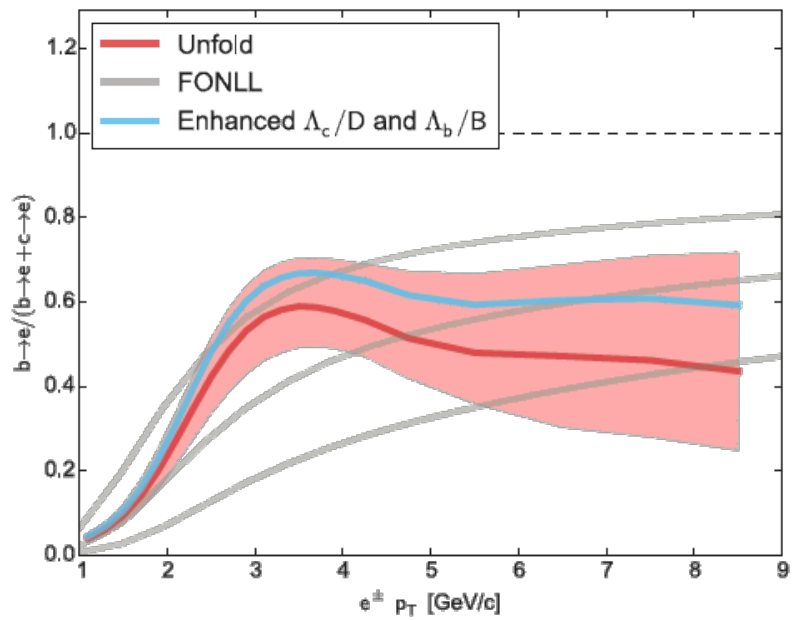

(a)
1.5-2.0 GeV/c
b/(b+c)=0.115
Au+Au MB
$\sqrt{s_{NN}}$ =200 GeV
PHENIX
Run 4 + Run 11
(b)
2.0-2.5 GeV/c
b/(b+c)=0.264
(c)
2.5-3.0 GeV/c
b/(b+c)=0.427
(d)
3.0-4.0 GeV/c
b/(b+c)=0.520
(e)
4.0-5.0 GeV/c
b/(b+c)=0.488
counts
Data / Re-fold
DCA$_T$ [cm]

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