PHENIX

Latest results of Heavy Flavor measurements from the PHENIX Experiment at RHIC

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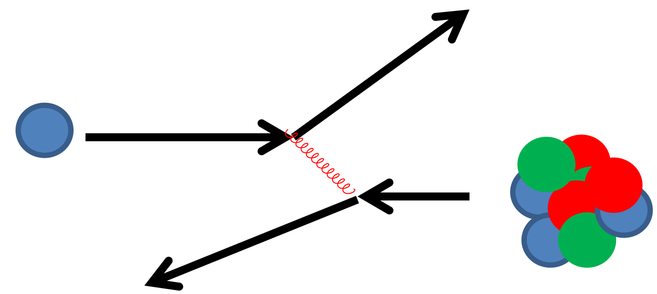
Heavy flavor in Heavy Ion collisions

Because of their large masses, charm ($m_c \approx 1.3$ GeV) and bottom ($m_b \approx 5$ GeV) quarks are produced at the early stages of the collisions.

-> suitable probes to study the evolution of the matter.

Cold nuclear matter effect

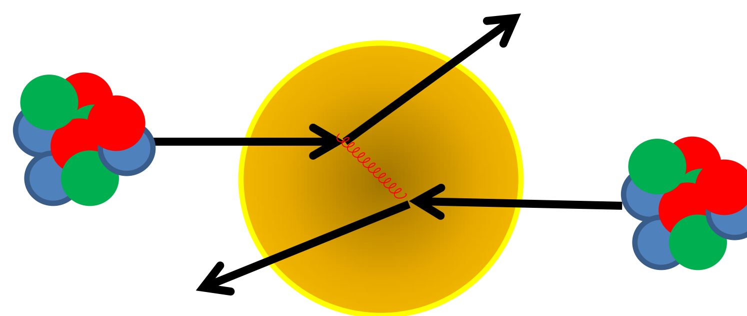
- Nuclear modification of parton distribution functions
- Energy loss of partons traversing nucleus
- Cronin effect
- Nuclear break up of quarknonia



Probing in p (d) + A collisions

Hot nuclear matter effect

- Energy loss of partons traversing QGP
- Screening and recombination of quarkonia in QGP

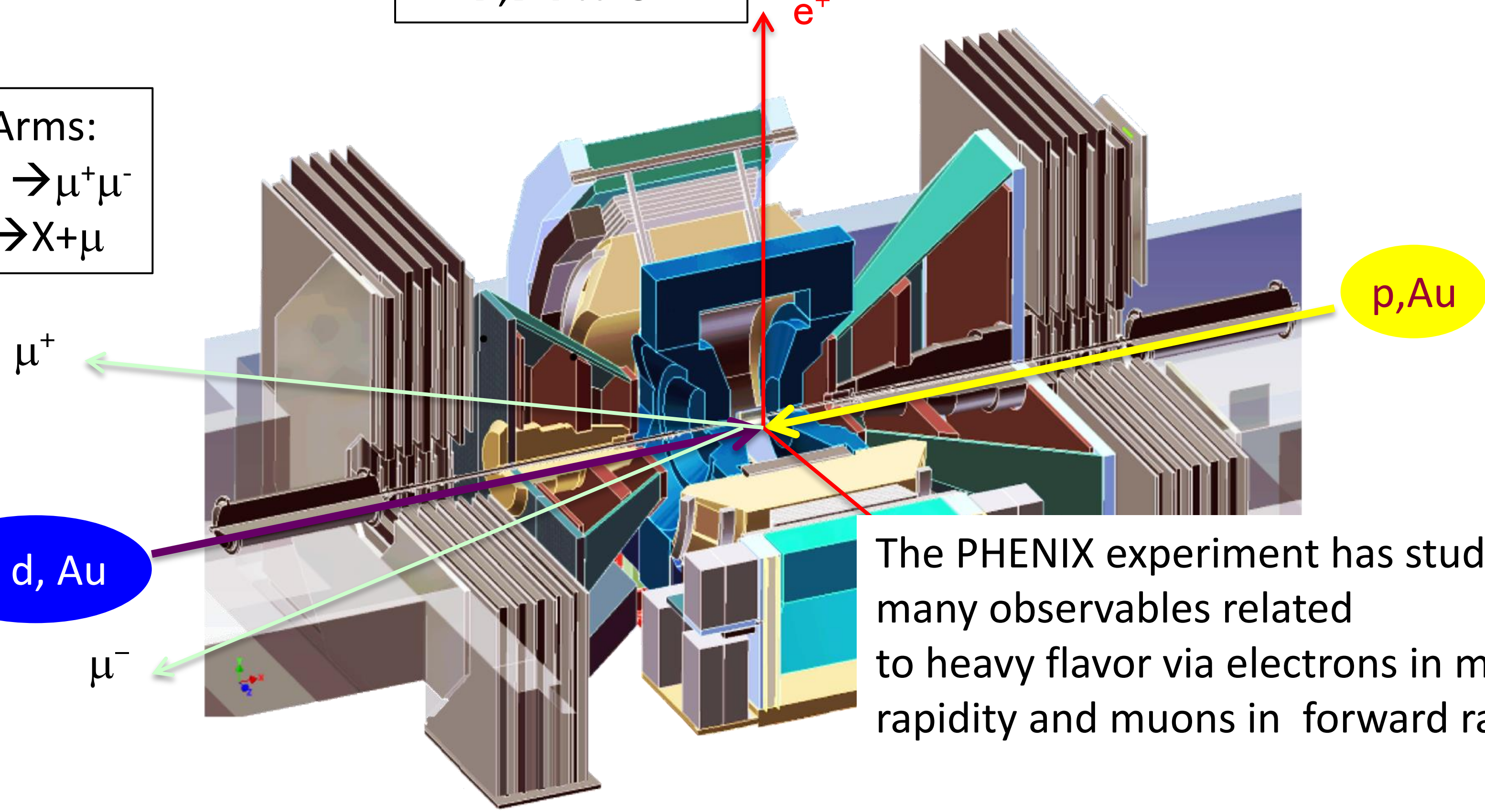


Probing in A + A collisions

Overview of the PHENIX Detector

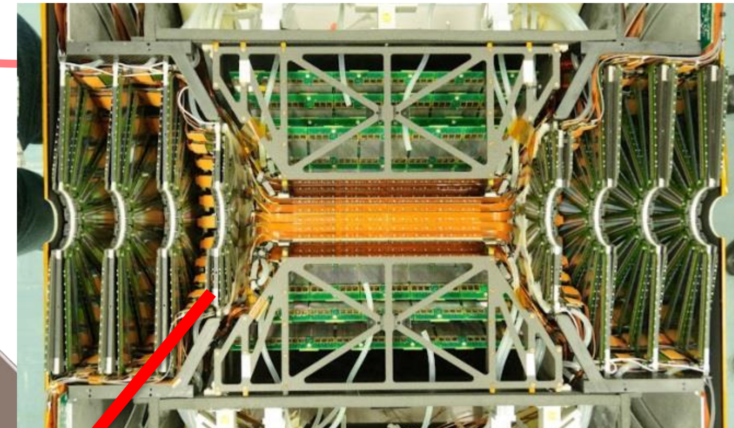
Central Arms:
- J/ψ, $\psi' \rightarrow e^+e^-$
- D,B→X+e

Muon Arms:
- $J/\psi \rightarrow \mu^+\mu^-$
- D,B→X+μ



The PHENIX experiment has studied many observables related to heavy flavor via electrons in mid-rapidity and muons in forward rapidity

Overview of the PHENIX Detector



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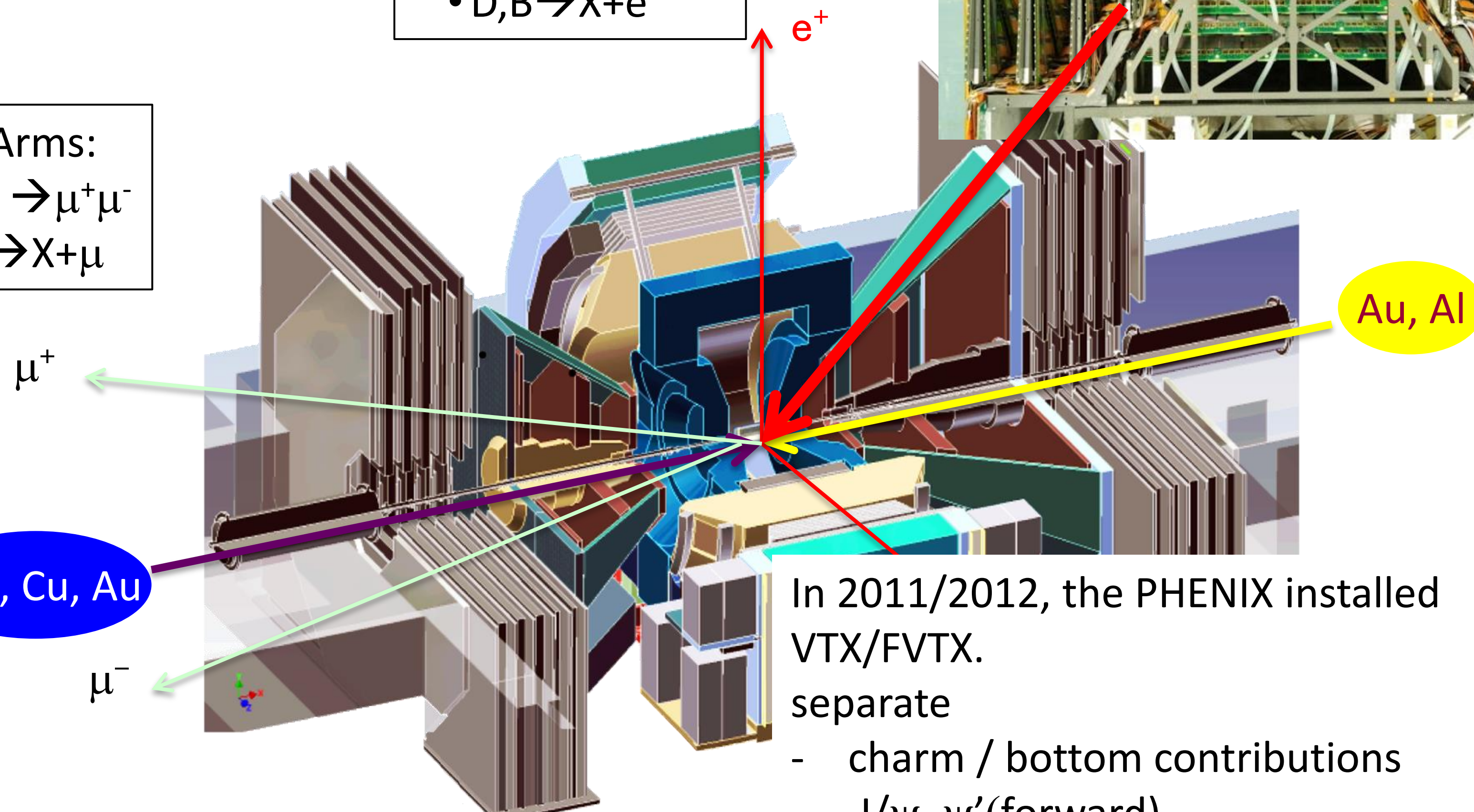


In 2011/2012, the PHENIX installed VTX/FVTX.
separate

- charm / bottom contributions
- J/ψ, ψ'(forward)

In this talk....

- New result with VTX (mid-rapidity)

Single Electrons from Charm and Bottom hadron Decays in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV

PHENIX: arXiv:1509.04662 (2015) PRC accepted !

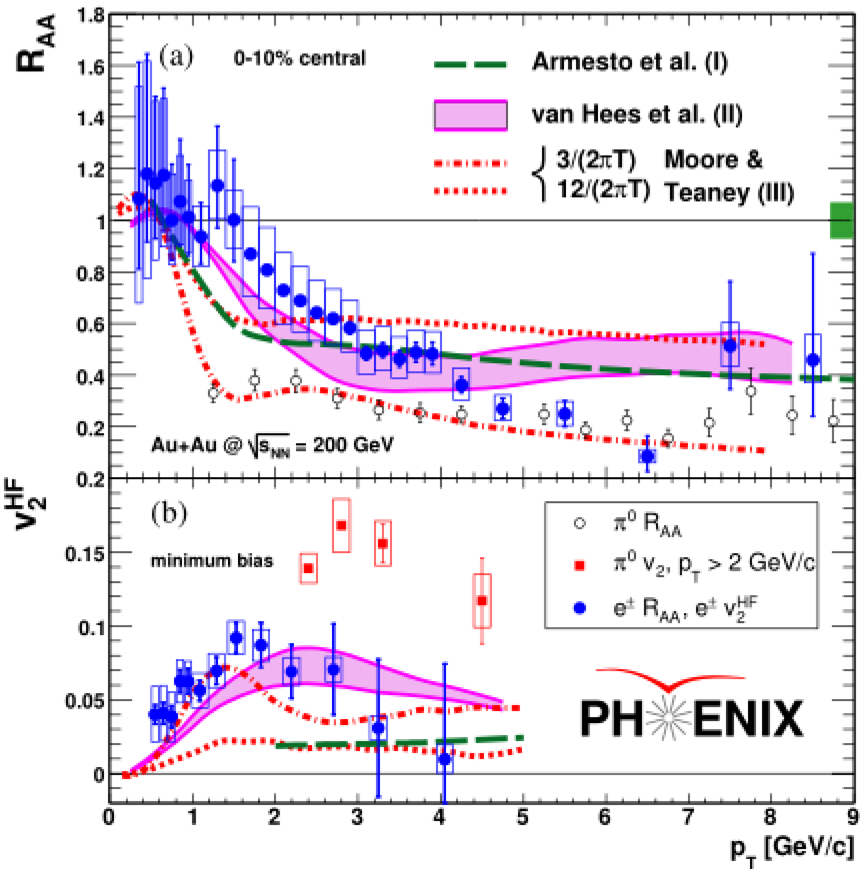
- New result with FVTX (forward/backward-rapidity)

preliminary results of J/ψ/ ψ' ratio in p+Al and p+Au collisions at $\sqrt{s_{NN}}$= 200 GeV

Single electrons from Charm and Bottom

previous PHENIX measurement (2004 data)

PRL 98, 172301 (2007)



-Single electrons from combined charm and bottom hadron decays are strongly suppressed in Au+Au compared to p+p

Nuclear Modification factor:

$$R_{AA}(p_T, y; b) = \frac{d^2N_{AA}/dydp_T}{N_{\rm coll} \times d^2N_{pp}/dydp_T}.$$

Number of binary nucleon-nucleon inelastic collision in A+A

- Results are challenging for theoretical models
- bottom is suppressed ??
- want to separate charm and bottom to understand mass dependence of energy loss!

Analysis strategy to separate c->e / b->e

Utilize their different lifetimes and decay kinematics

-Measure displaced tracking of electron with VTX + Central arms
1.5 < pT < 5.0 [GeV/c] in 2011 Au+Audata.

charm hadron

$$c\tau_{D^0} = 123\ \mu m,\ c\tau_{D^\pm} = 312\ \mu m$$

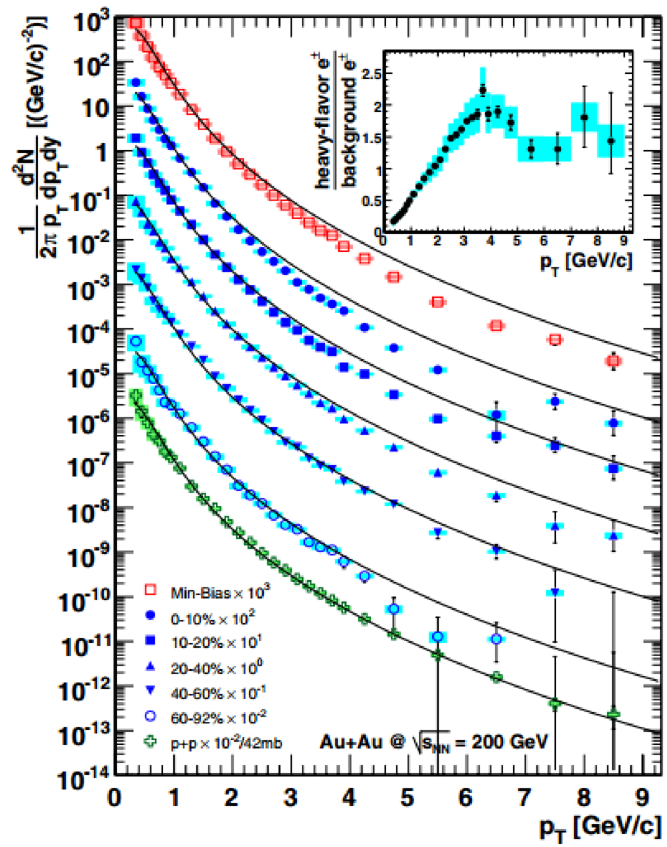
bottom hadron

$$c\tau_{B^0} = 455\ \mu m,\ c\tau_{B^\pm} = 491\ \mu m$$

-Use published invariant yield of single electrons from combined charm and bottom decays in 2004 data.
1.0 < pT < 9.0 [GeV/c]

--Higher pT reach
--Efficiency corrected (absolute normalization)

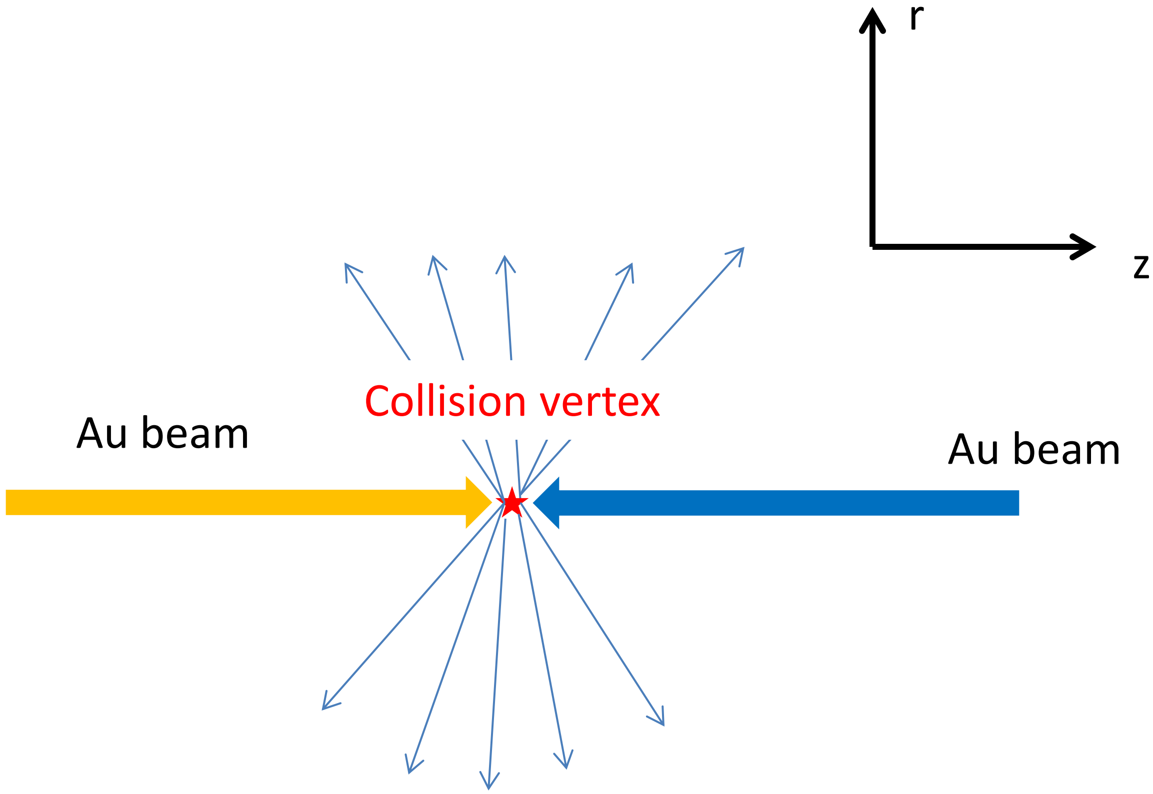
PRL 98, 172301 (2007)



Use unfolding techniques to simultaneously take into account both pieces and statistically separate charm and bottom.

Precise displaced tracking with VTX

- Reconstruct collision vertex position in three dimensions, with the VTX hit information alone



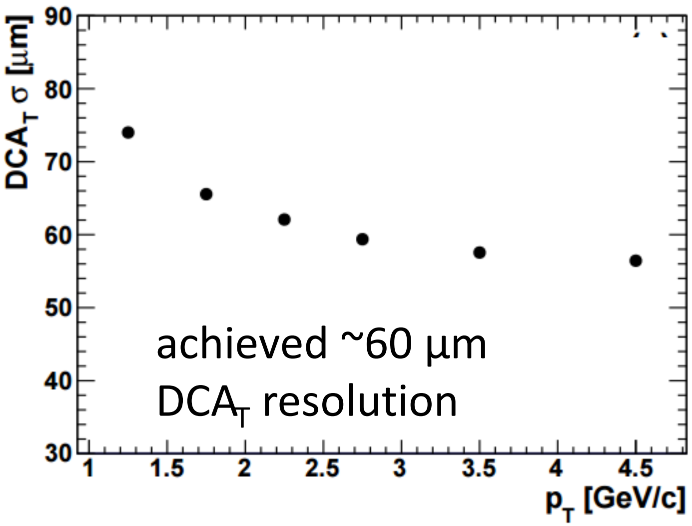
Precise displaced tracking with VTX

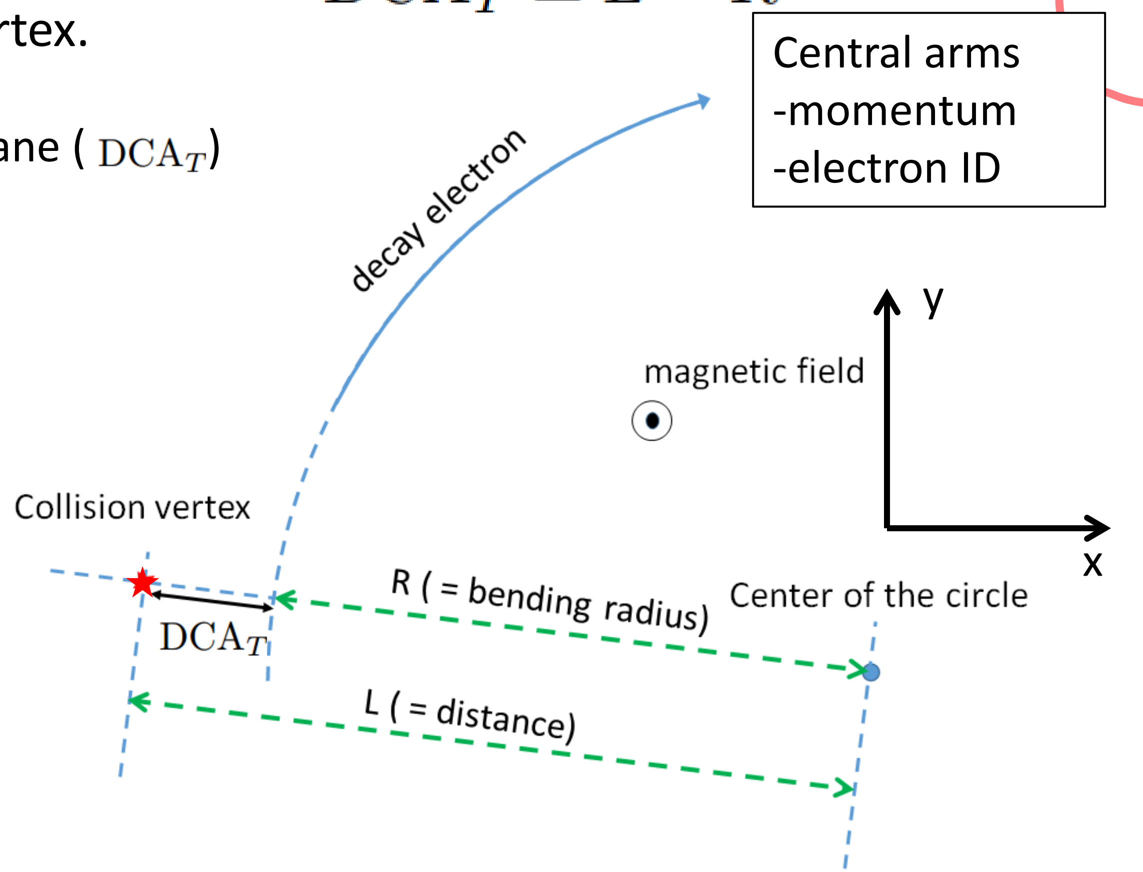
Calculate the Distance of Closest Approach (DCA) of a track to the collision vertex.

$$\mathrm{DCA}_T \equiv L - R$$

Calculated separately in transverse plane (DCA_T)
and longitudinal plane (DCA_L)

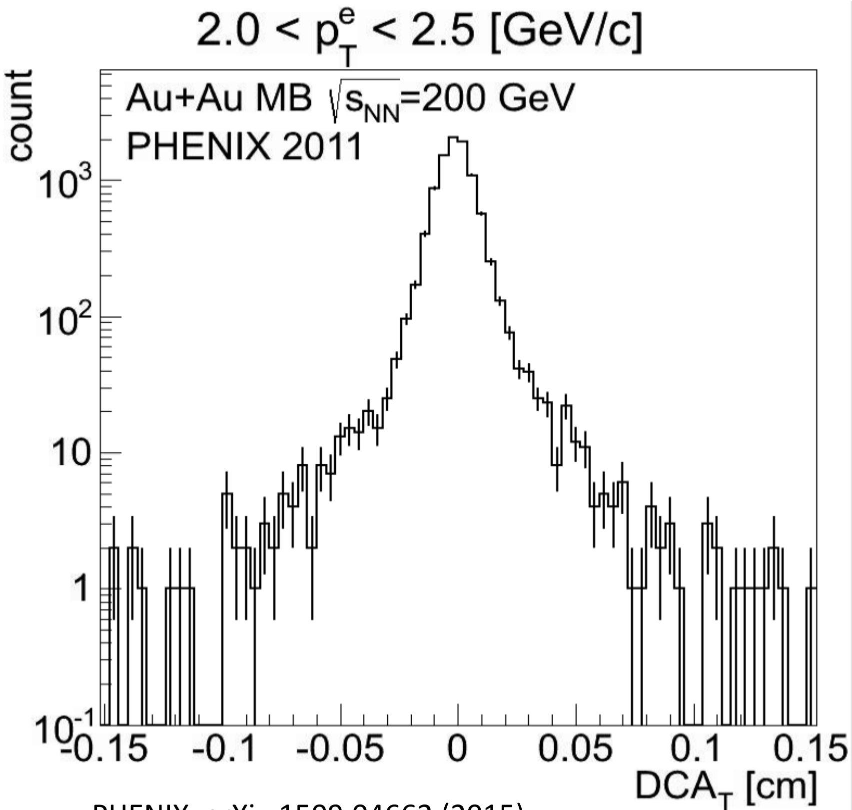
PHENIX: arXiv:1509.04662 (2015)





electron DCA_T distribution

Measured DCA_T distribution of electrons from 2011 (Run 11) Au + Au MB data , (|η|<0.35)



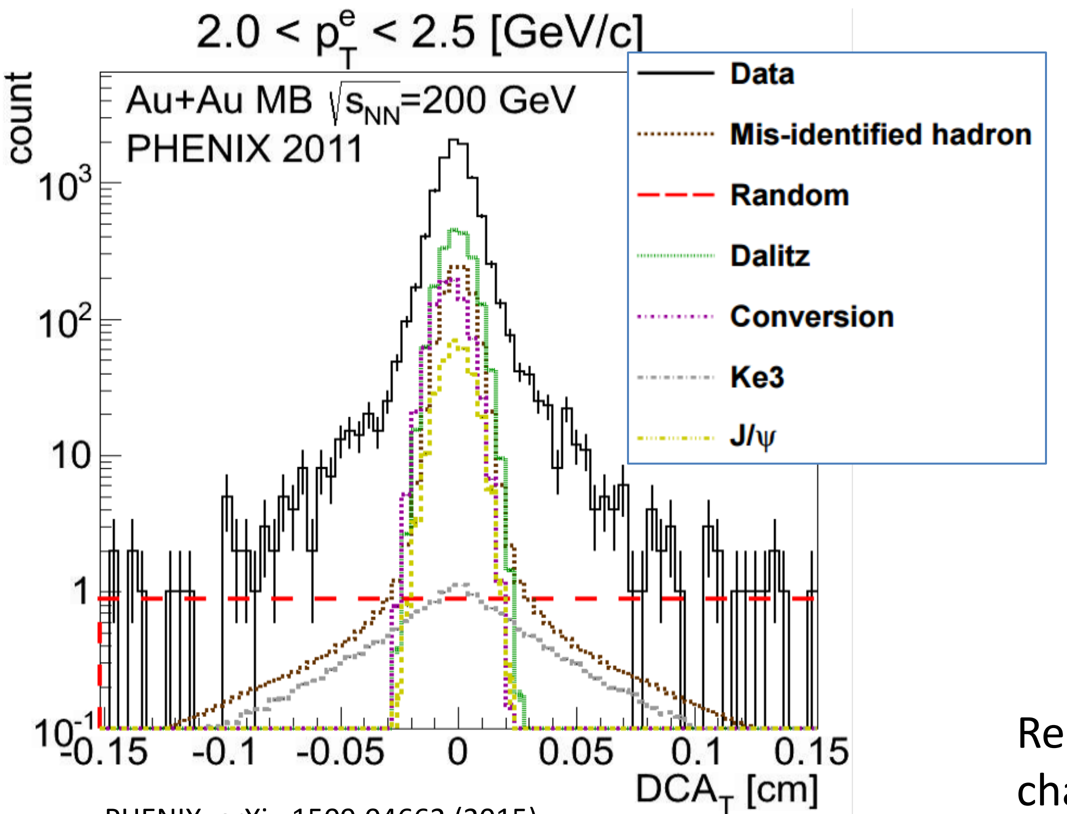
PHENIX: arXiv:1509.04662 (2015)

- 5 electron pT bins $1.5 < pT < 5.0$ [GeV/c]
- no efficiency correction

- At first, determine normalized background contributions and then subtract.

electron DCA_T distribution

Measured DCA_T distribution of electrons from 2011 (Run 11) Au + Au MB data , (|η|<0.35)



PHENIX: arXiv:1509.04662 (2015)

Mis-reconstructed components
- Hadrons identified as electrons
- Wrong VTX hit association

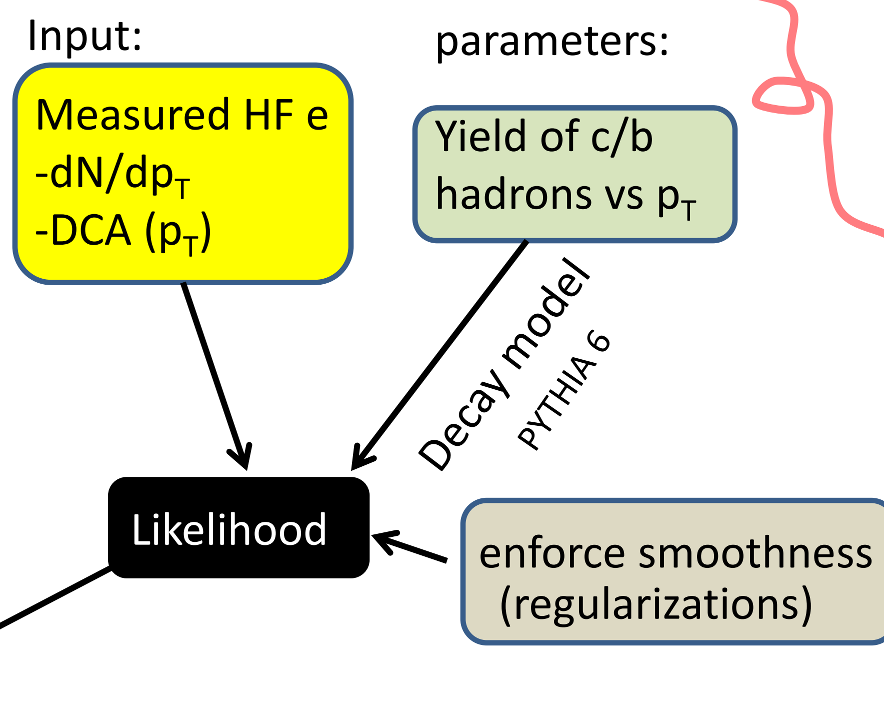
Prompt components
- Dalitz decay (π, η -> $e^+e^-\gamma$)
- J/ψ -> e^+e^-

Non-prompt components
- Conversions γ -> e^+e^-
- Ke3

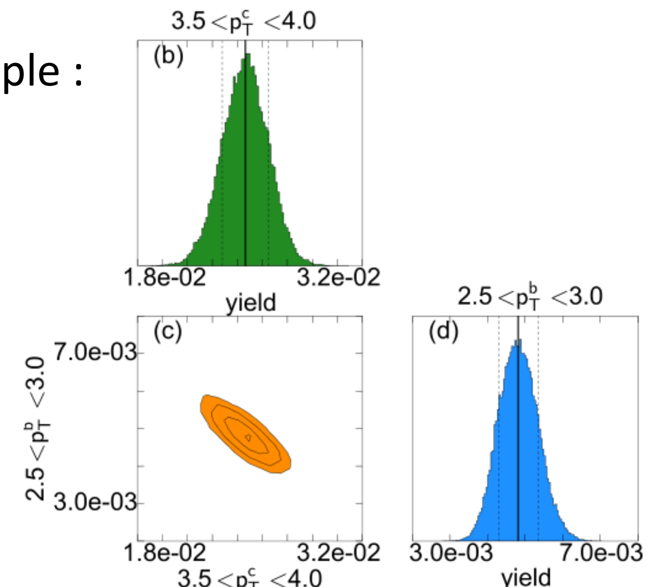
Remaining components come from charm + bottom

Unfolding

Use Bayesian inference methods to determine parent charm and bottom hadron p_T^h distributions.
- use PYTHIA 6 to make model of yield of c/b vs pT, as well as electron's pT and DCA_T
- sample model parameters many times and compared with data using likelihood function.



Example :



Probability distribution of Invariant yield of charm and bottom hadrons
and
their correlations

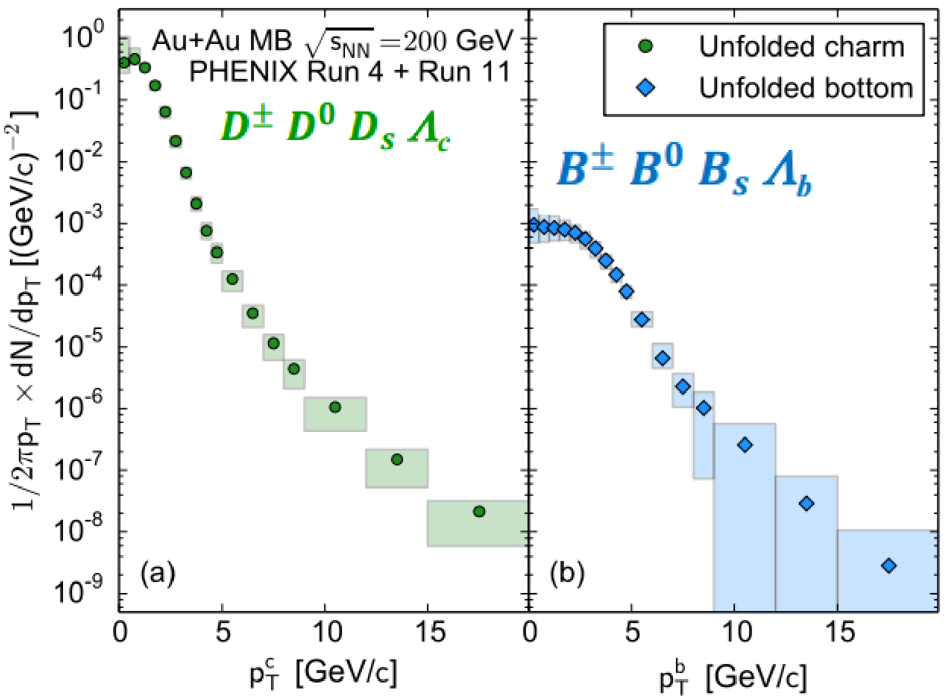
Charm and Bottom Hadrons Yield

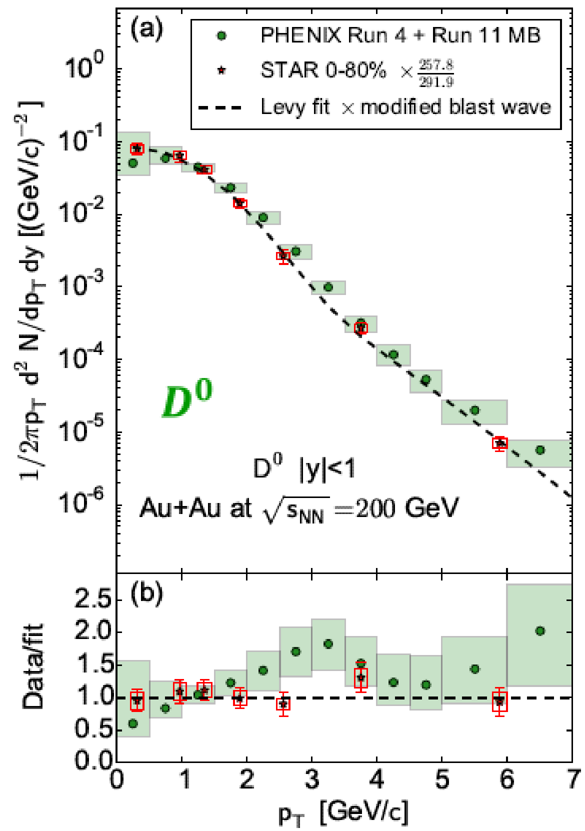
Yields for Min. bias Au+Au at 200 GeV

, integrated over all rapidities.

- Using PYTHIA + Charm hadron yield
  Calculate D ^{0} yield within |y|<1
- Compare with D ^{0} measurement from STAR

(Phys. Rev. Lett. 113, 142301)





PHENIX: arXiv:1509.04662 (2015)

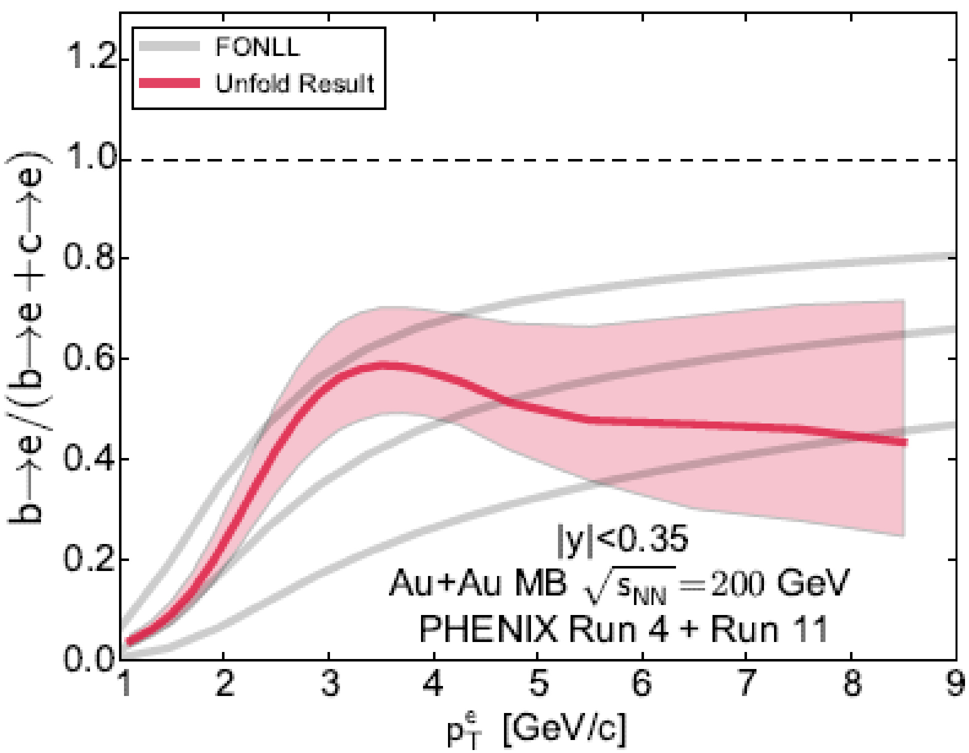
Very good agreement !

electrons from bottom fraction

back to electron's pT space....

Fraction of electrons from bottom

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



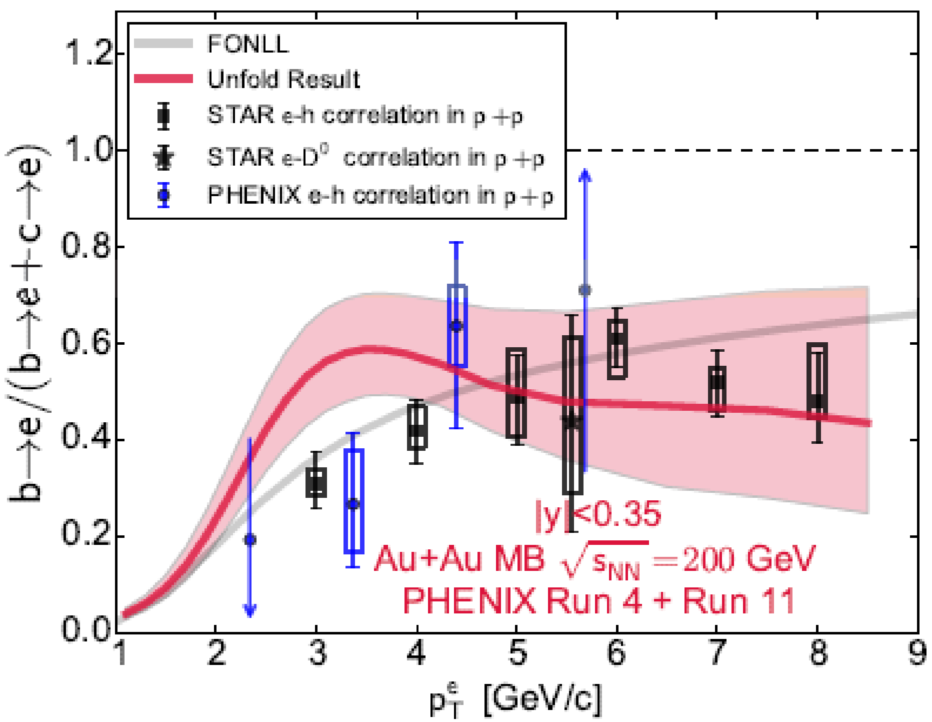
Apparent shape difference when compared to FONLL

electrons from bottom fraction

back to electron's pT space....

Fraction of electrons from bottom

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



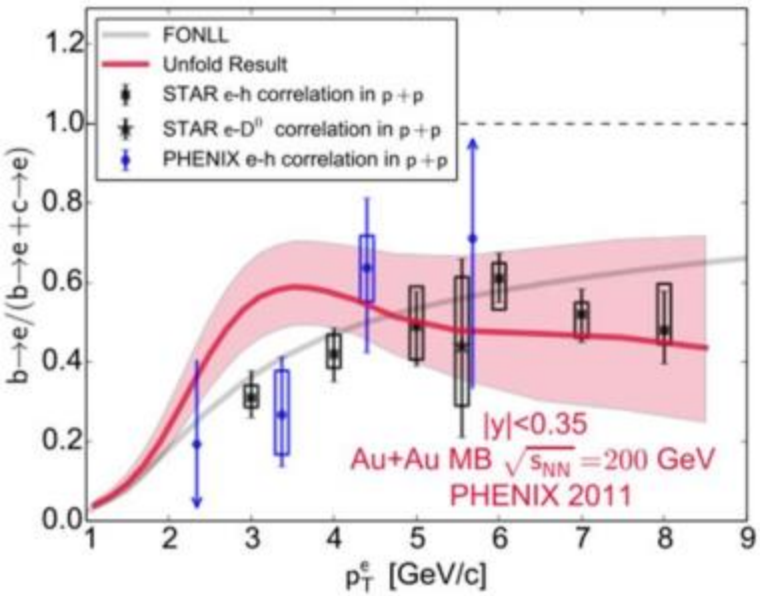
Apparent shape difference when compared to p+p data from e-h correlation measurements.

Charm electron and Bottom electron R_{AA}

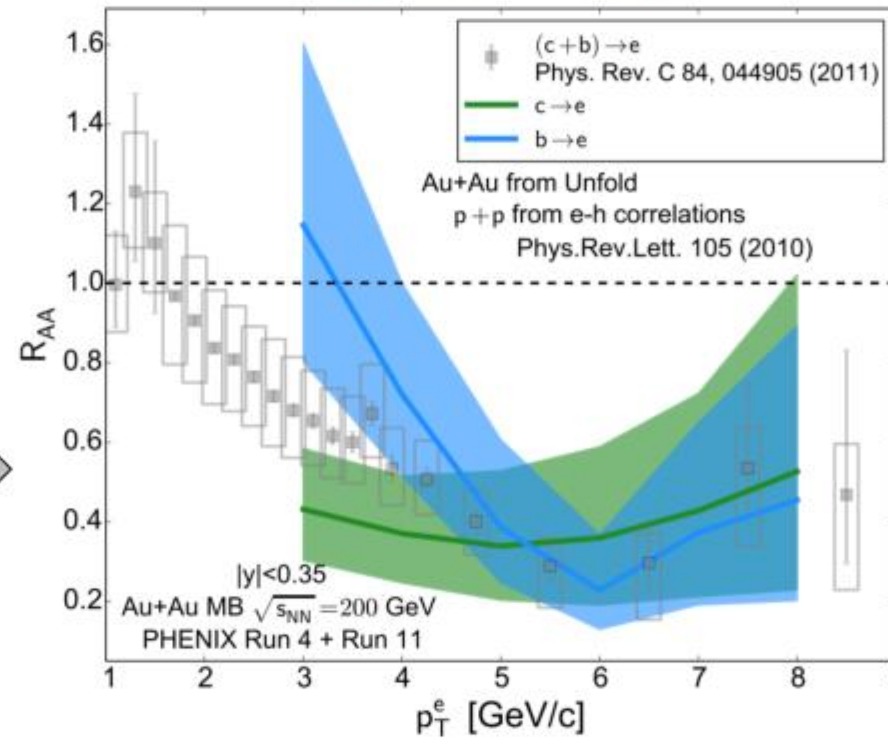
Fraction of electrons from bottom

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

PHENIX: arXiv:1509.04662 (2015)



Single electron R_{AA} for bottom and charm



red line (uncertainty band) is the VTX result in Au+Au collisions.

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

previous PHENIX result (c->e + b->e) in Au+Au
Phys. Rev. C 84, 044905 (2011).

STAR b->e fraction in p+p
Phys. Rev. Lett. 105, 202301 (2010).

$R_{AA}^{c\to e} < R_{AA}^{b\to e}$ at 3 < pT < 4 GeV/c
$R_{AA}^{c\to e} \sim R_{AA}^{b\to e}$ above 4 GeV/c

First measurement that b->e are suppressed in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV !

future:

- VTX : high statistic data (~x10) in Au+Au (2014)
  -> significantly improve uncertainties in c->e , b->e
  : p+p data (2015)
  -> provide baseline with same method.

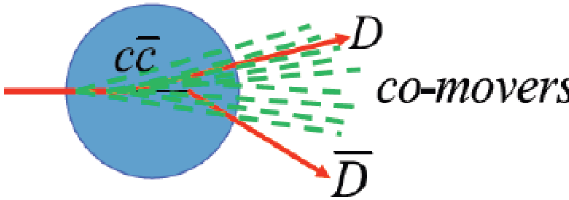
Those data should provide new constraints on theoretical description of charm and bottom energy loss.

next topic ...

Au + Au -> small system : p+Au, p+Al

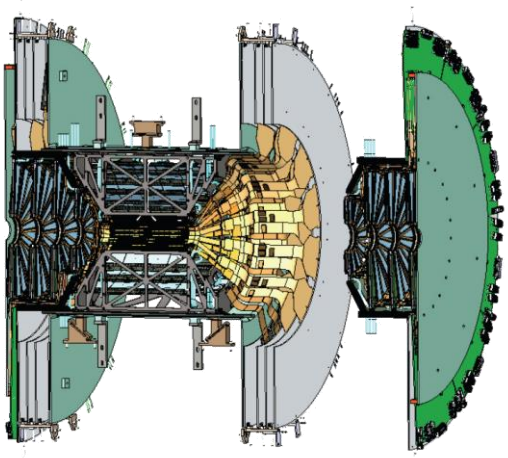
Open Heavy flavor -> charmonia

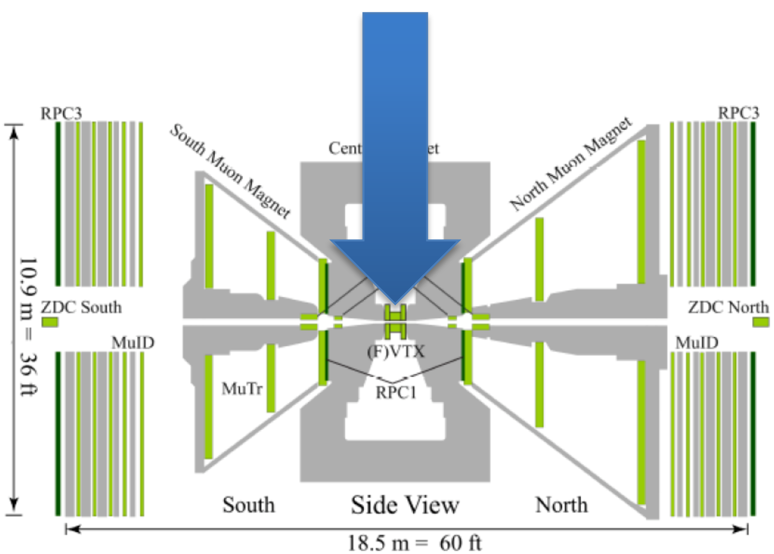
- Same : sensitive to same initial state effect
  -- gluon shadowing, kT broadening, partonic energy loss in nucleus
- Difference : charmonia can be broken up by nuclear medium or co-movers

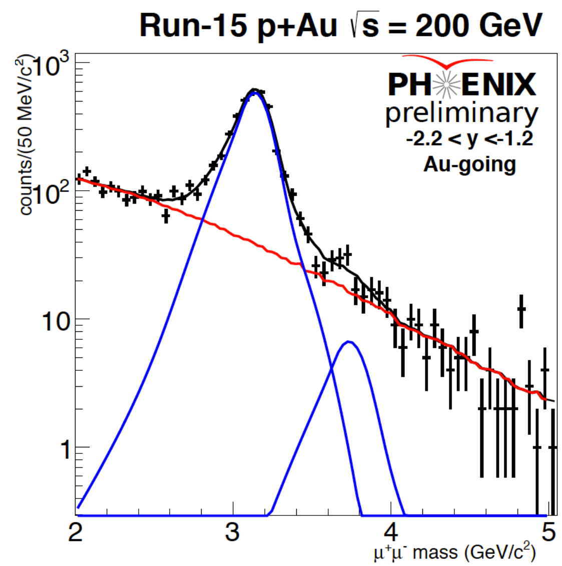


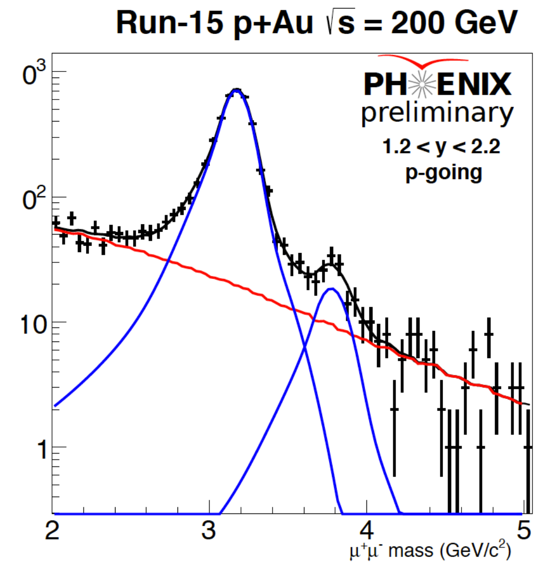
- want to separate the J/ψ and the ψ' !
- The ψ' is more weakly bound than the J/ψ
- The ψ' is an interesting probe to have further insight on the charmonium behaviour in pA.
-

FVTX allows clean separation of J/ψ, ψ’









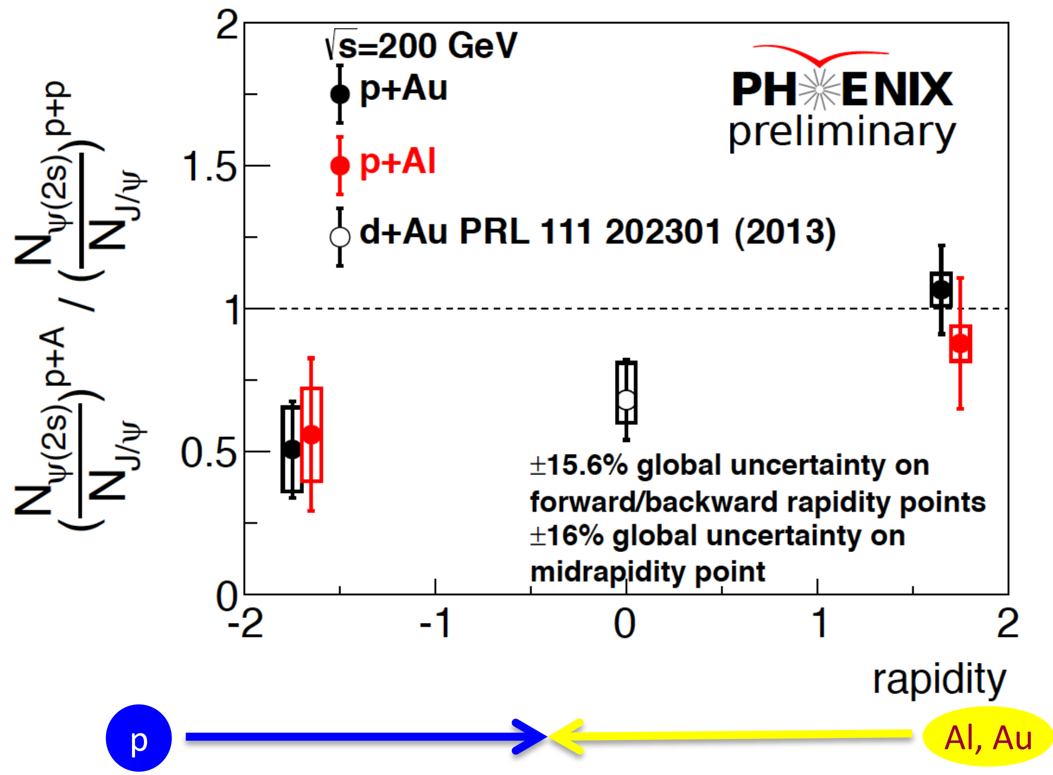
Opening angle in front of absorber:
Greatly improved mass resolution
and background rejection

Forward Rapidity ψ’ :J/ψ in p+Al, p+Au

- Year 2015 (RUN15) p+Al and p+Au 200 GeV analyzed at forward and backward rapidity
- strong suppression of ψ’ in the A-going direction (backward rapidity), but not p-going (forward rapidity)

- breakup in collisions with nucleons does not explain such a large suppression (PRC 87 (2013)54910)
- no initial states effect can explain this strong suppression.

- interaction with co-movers ? i.e. suppression is caused by interactions with produced particles ?



Summary & outlook

- PHENIX Silicon Vertex Trackers (VTX & FVTX) allows to access heavy flavor precisely.

future:

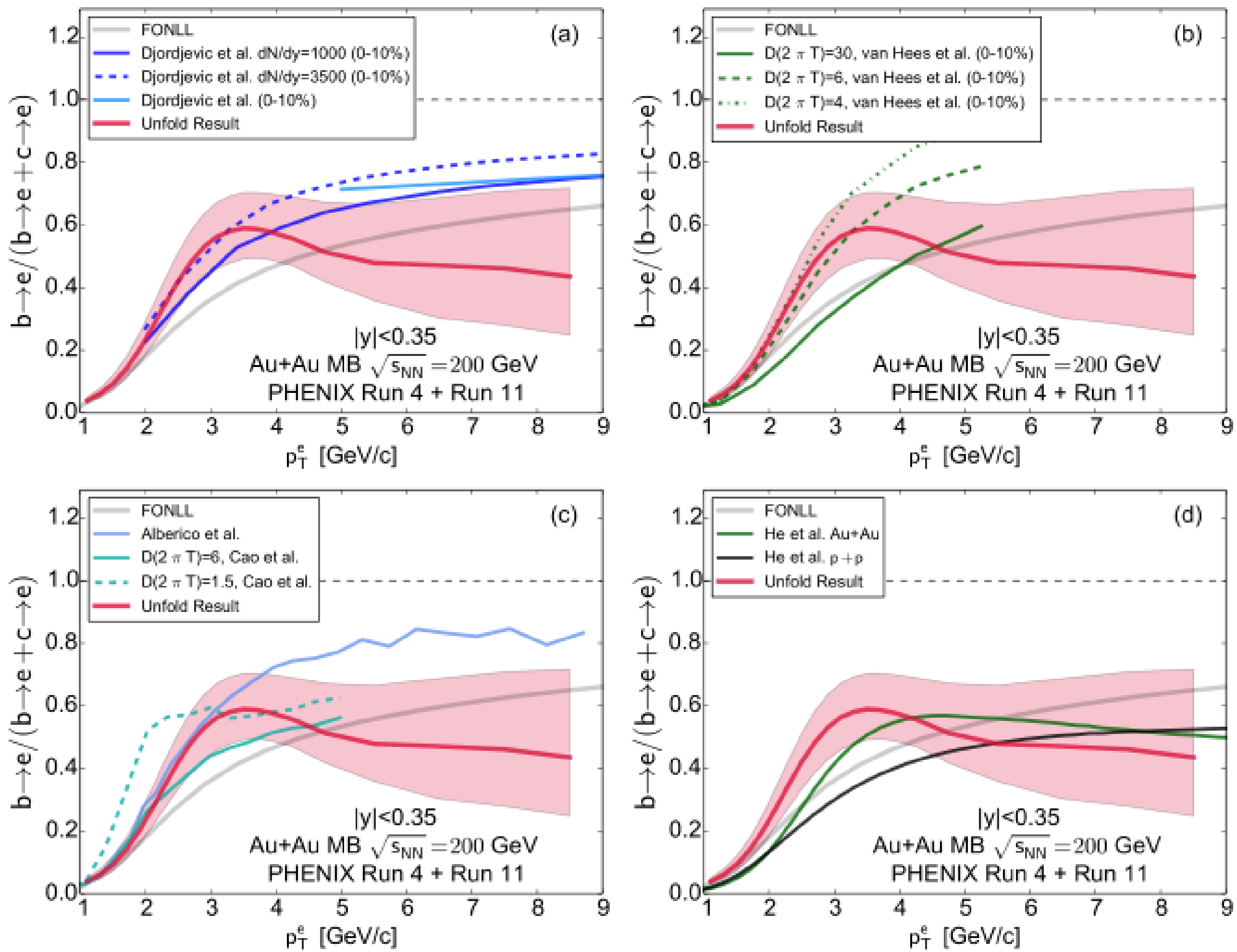
- VTX : high statistic data in Au+Au (2014)
  -> significantly improve uncertainties in c->e , b->e
  : p+p data (2015)
  -> provide baseline with same method.
- FVTX
  Forward/backward $B \rightarrow J/\psi$ and separation of $D/B \rightarrow \mu$+X for p+p, p+A, Cu+Au, Au+Au

backups

Theoretical Model Comparisons

PHENIX: arXiv:1509.04662 (2015)

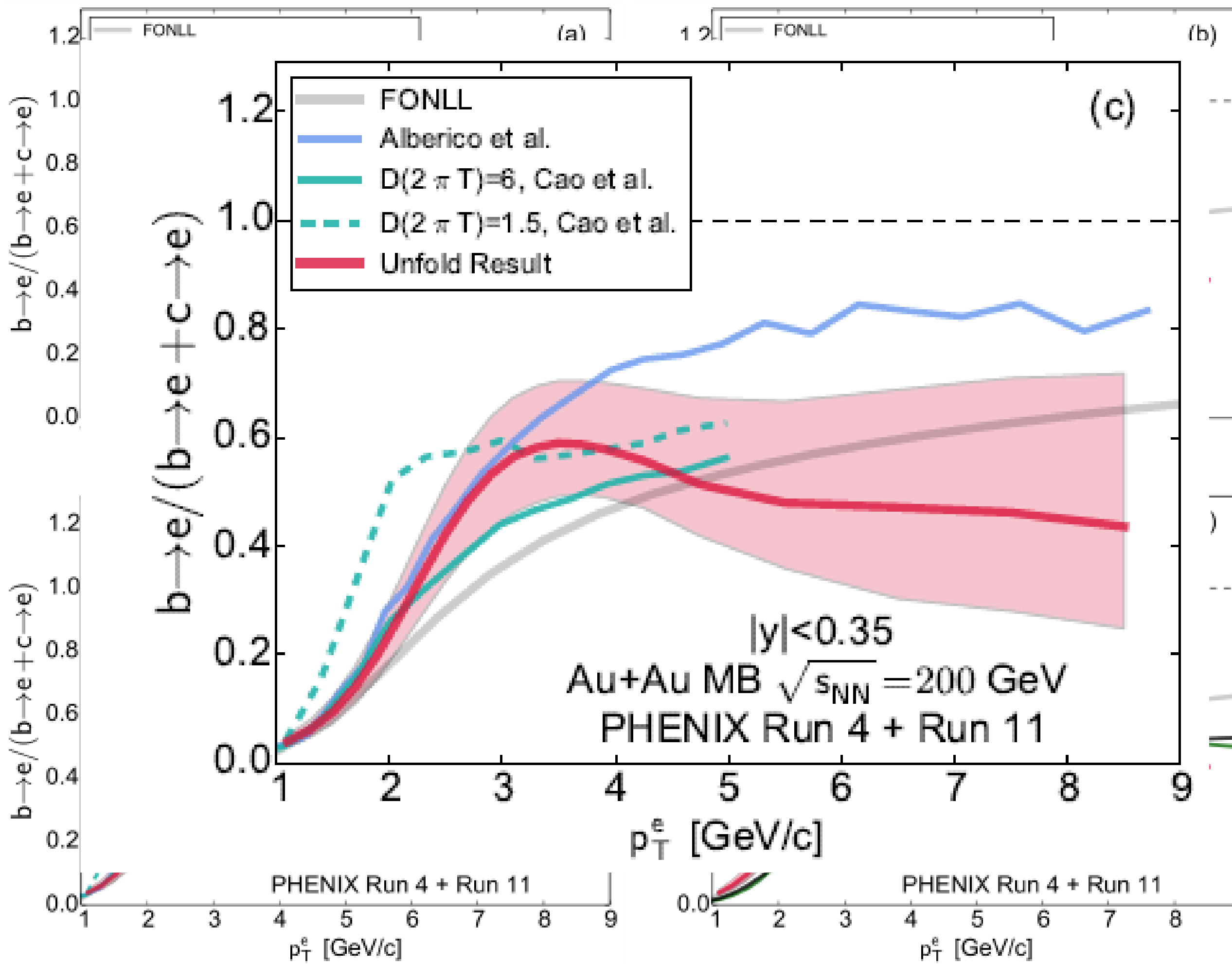
Theoretical models which take into account radiative energy loss and collisional energy loss.



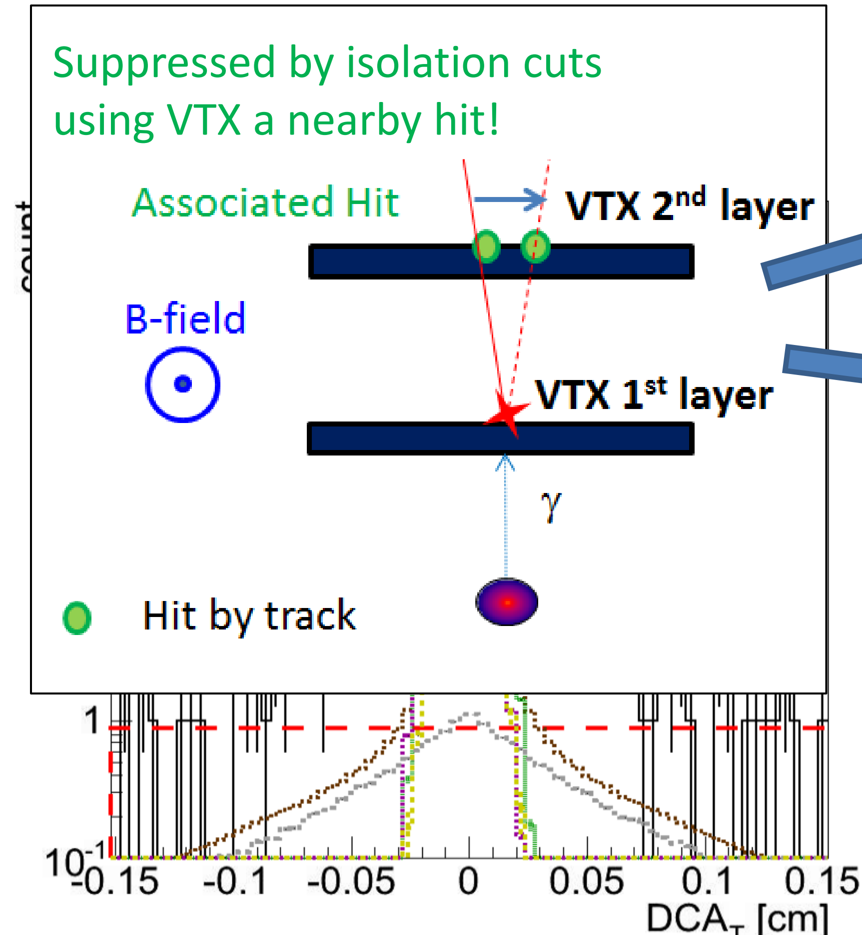
Theoretical Model Comparisons

PHENIX: arXiv:1509.04662 (2015)

Collisional energy loss via Langevin approach
J. Phys. G: Nucl. Part. Phys. ***40*** *(2013) 085103*
& Eur.
Phys. J. C 71, 1666 (2011)



electron DCA_T distribution



PHENIX: arXiv:1509.04662 (2015)

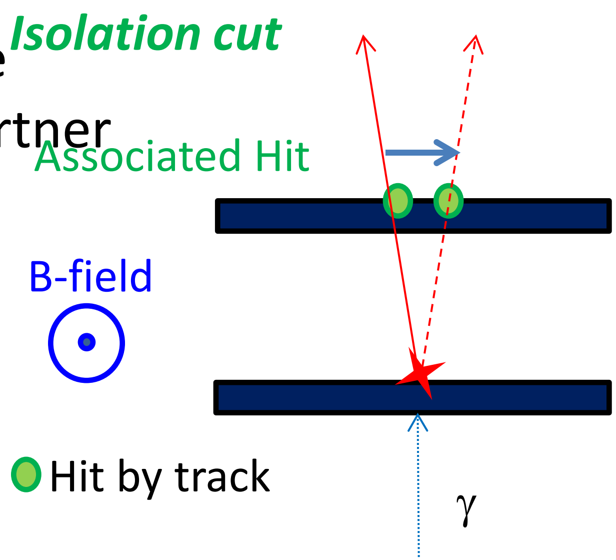
Prompt components
- Dalitz decay (π, η -> $e^+e^-\gamma$)
- J/ψ -> e^+e^-

Non-prompt components
- Conversions γ -> e^+e^-
- Ke3

Mis-reconstructed components
- Hadrons identified as electrons
- Wrong VTX hit association

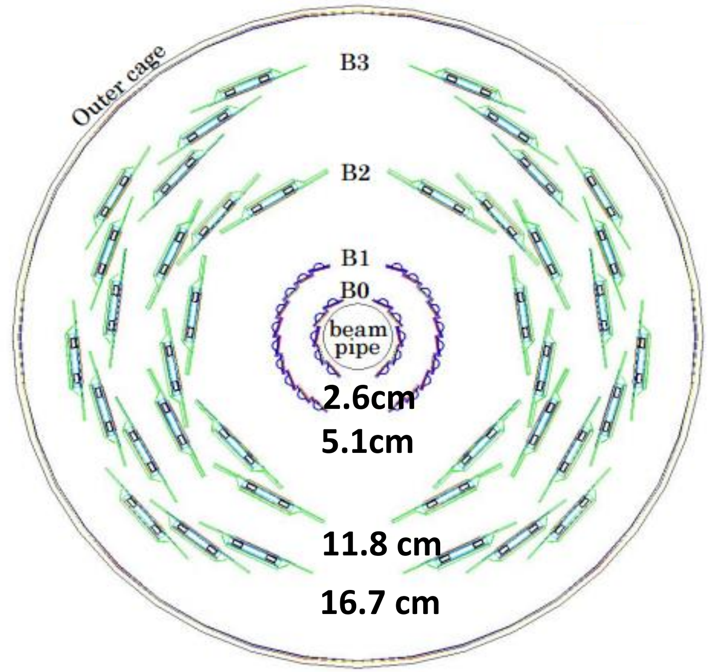
Photonic Electron Veto with VTX

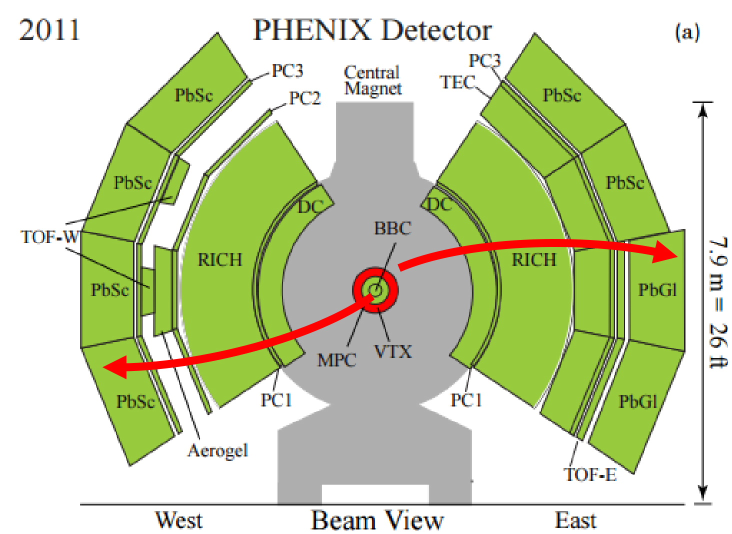
- Main background in HF electron measurement is photonic electrons.
  - Most conversions happen in the outer layers
    - (total X0: 12 % (B0: 1.3%, B1: 1.3%, B2:4.7% and B3: 4.7%). They are suppressed by requiring a hit in inner silicon layer B0.
- Isolation cut
  - Photonic electrons:
    - Created by pair with small opening angle
    - Additional hit made by its conversion partner
  - Non-photonic electrons:
    - Single track without any near-by hit
  - We can veto photonic electrons using the isolation cut



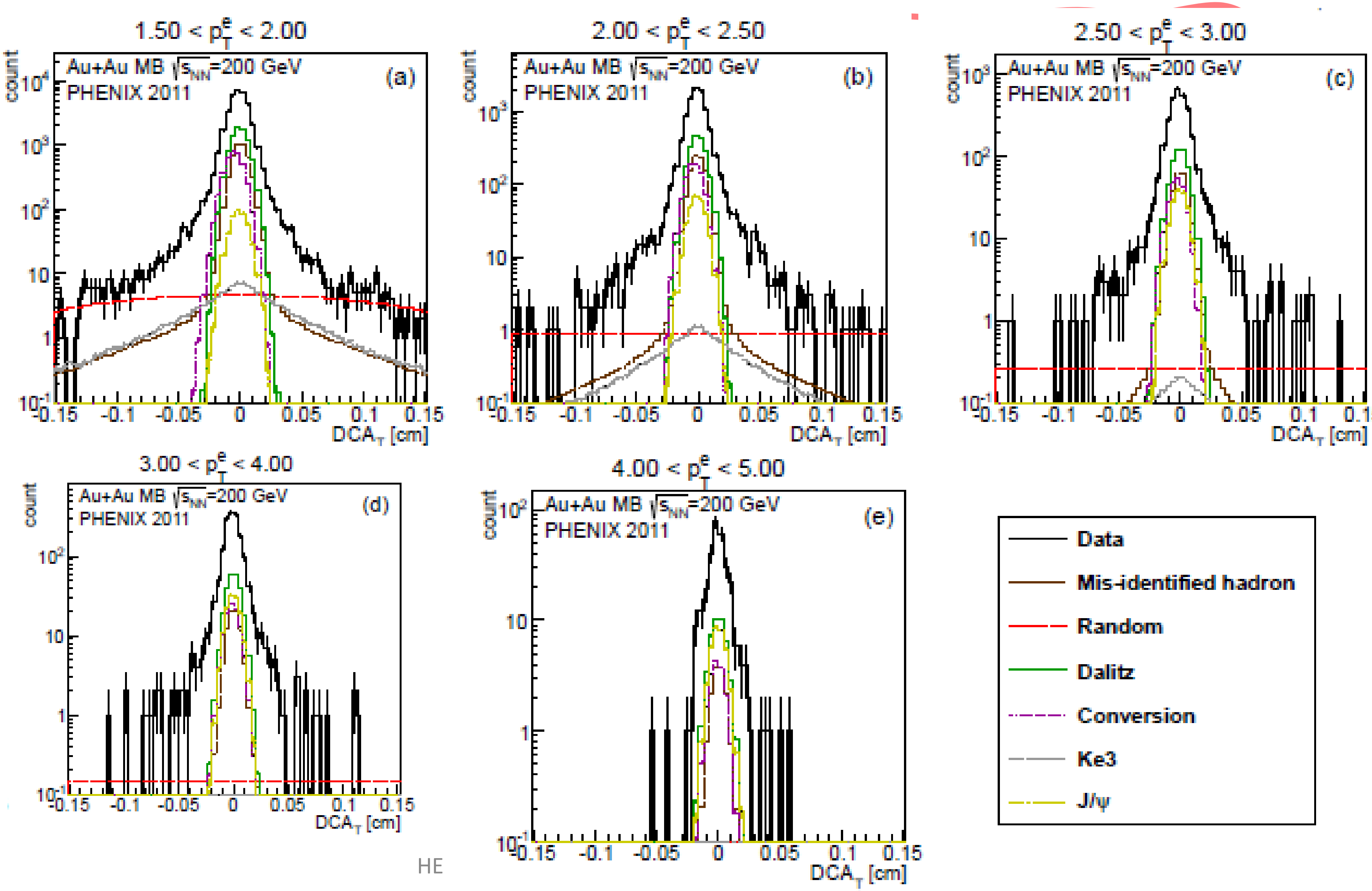
PHENIX Silicon Vertex Tracker (VTX)

- Barrel vertex detector installed in 2011
  - Inner 2 layers composed of Pixel (B0/B1)
  - Outer 2 layers composed of Stripixel (B2/B3)





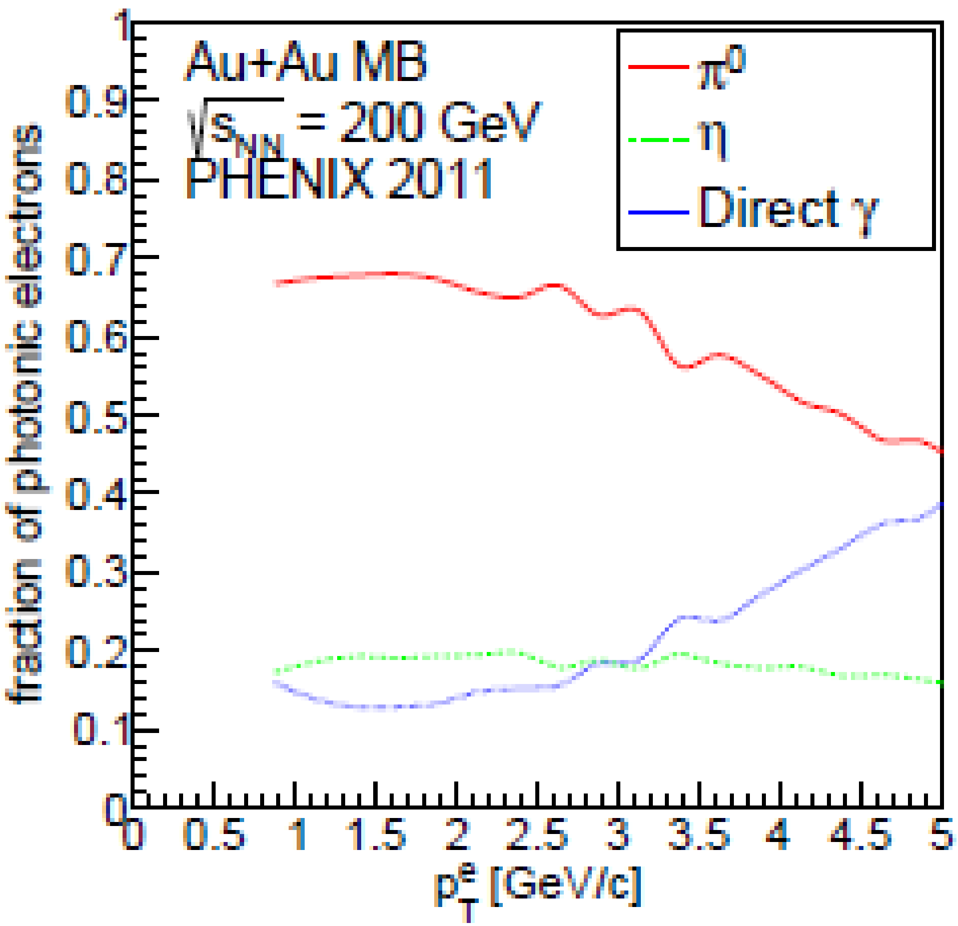
Reconstruct precise tracking as well as precise collision vertex



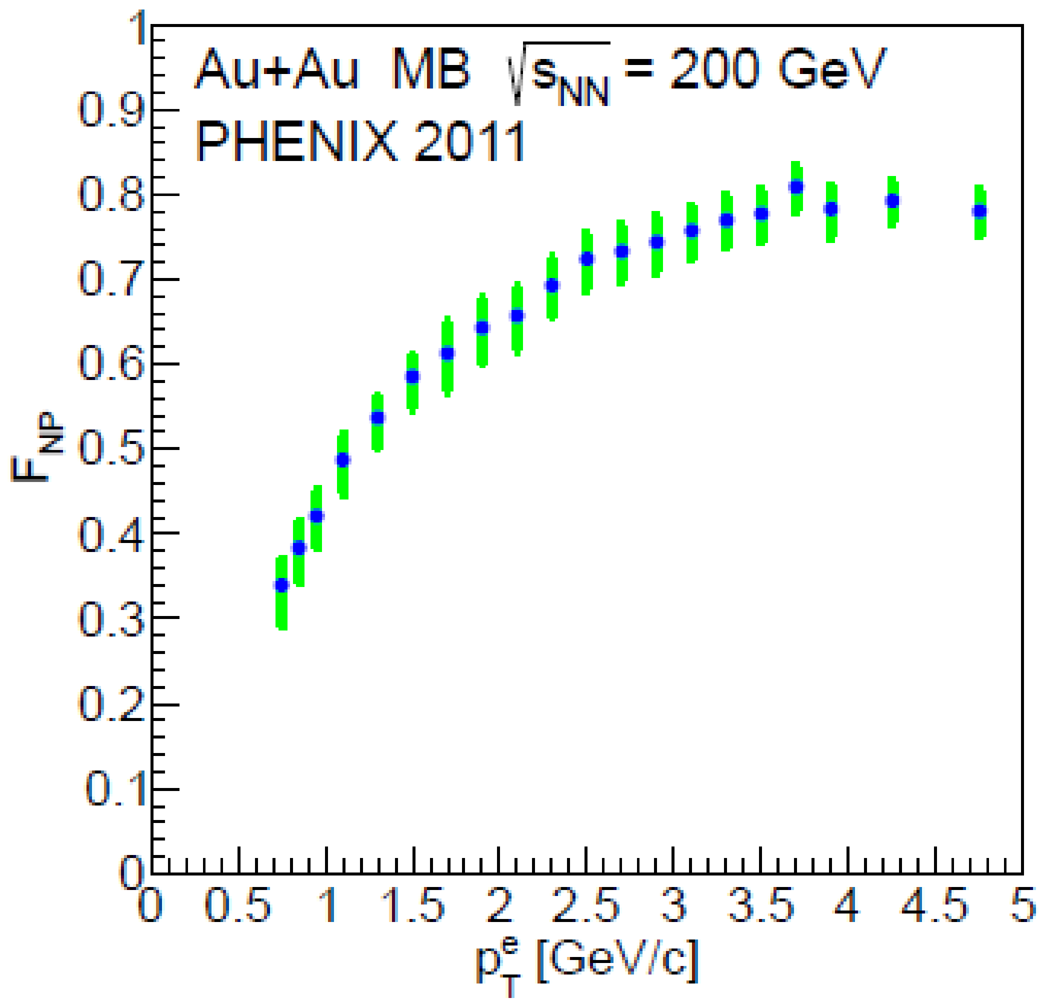
$1.50 < p_T^e < 2.00$
Au+Au MB $\sqrt{s_{NN}}$=200 GeV
PHENIX 2011
(a)
$2.00 < p_T^e < 2.50$
Au+Au MB $\sqrt{s_{NN}}$=200 GeV
PHENIX 2011
(b)
$2.50 < p_T^e < 3.00$
Au+Au MB $\sqrt{s_{NN}}$=200 GeV
PHENIX 2011
(c)
$3.00 < p_T^e < 4.00$
Au+Au MB $\sqrt{s_{NN}}$=200 GeV
PHENIX 2011
(d)
$4.00 < p_T^e < 5.00$
Au+Au MB $\sqrt{s_{NN}}$=200 GeV
PHENIX 2011
(e)
count
DCA_T [cm]
Data
Mis-identified hadron
Random
Dalitz
Conversion
Ke3
J/ψ

HE

fraction of photonic electrons



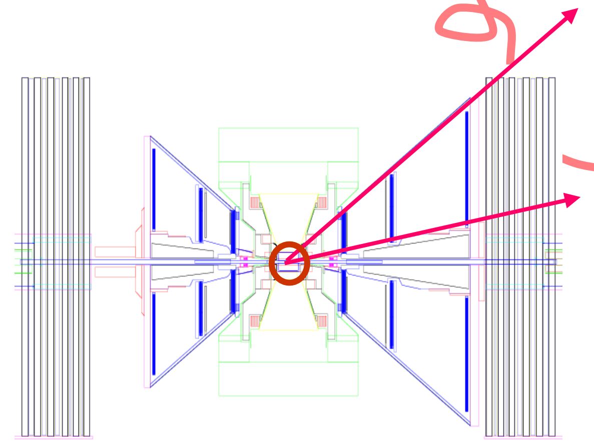
The fraction of nonphotonic electrons to inclusive electrons



Heavy Flavor Measurements With FVTX

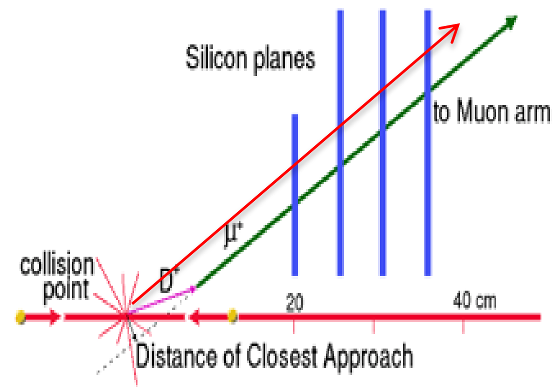
Two Methods for Measuring D/B:

- Direct measurement of B→J/ψ
- Separation of D/B components in single muon spectra

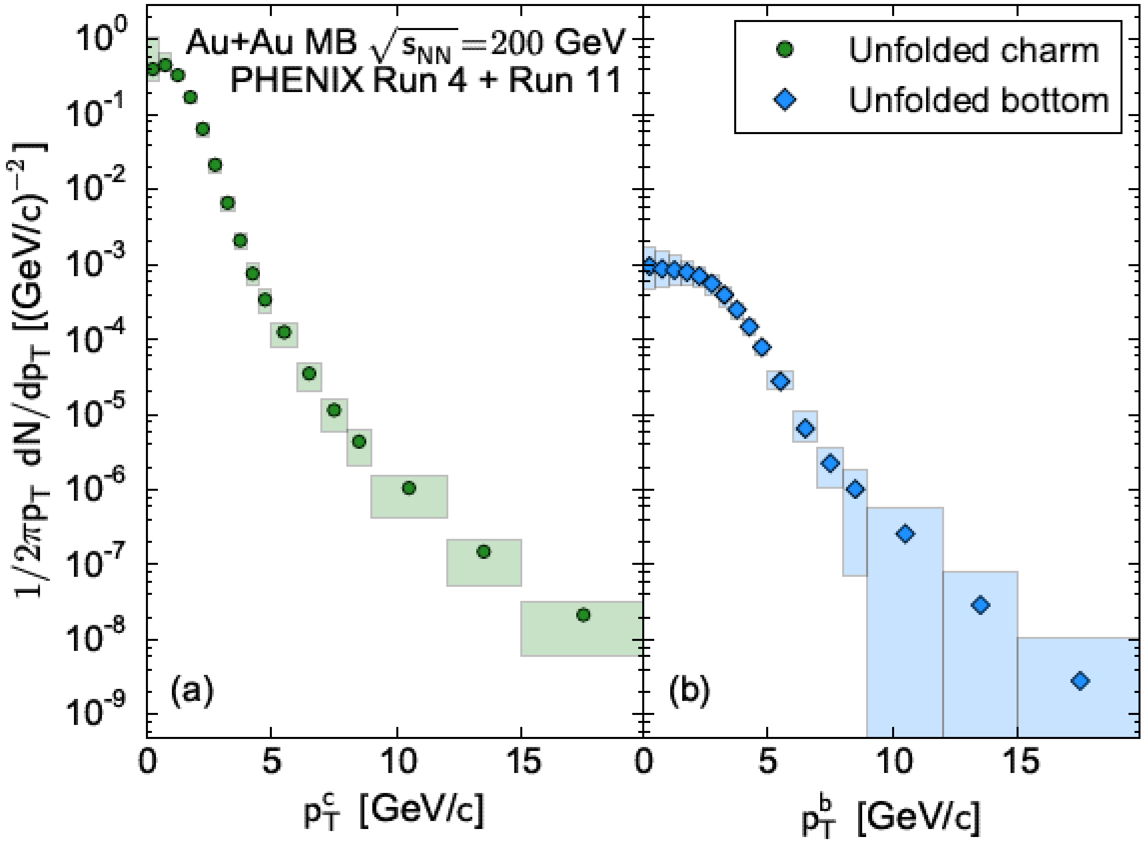


Heavy Flavor Extraction Method:

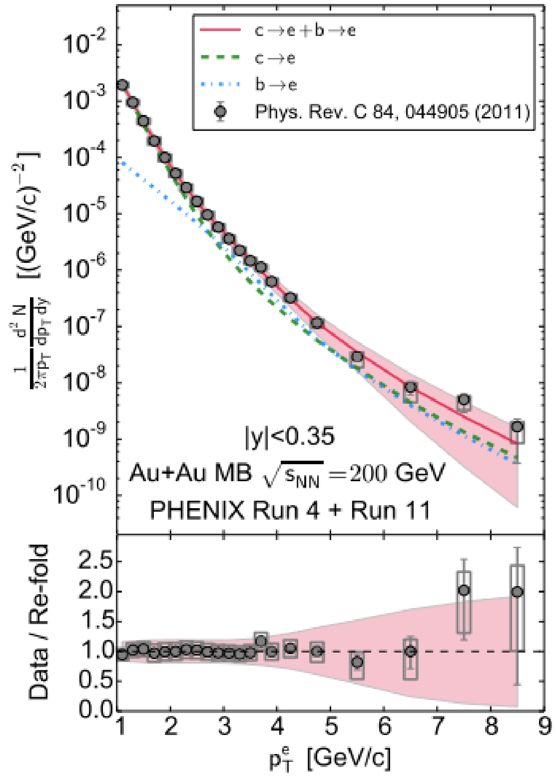
- Precision vertex determined with combination of FVTX+VTX detectors
- Muon system tracks projected to FVTX, select best candidate track within a search window
- Perform combined fit of MuTr + FVTX hits and project to vertex
- Dca_r distributions different for prompt, short- and long-lived decays



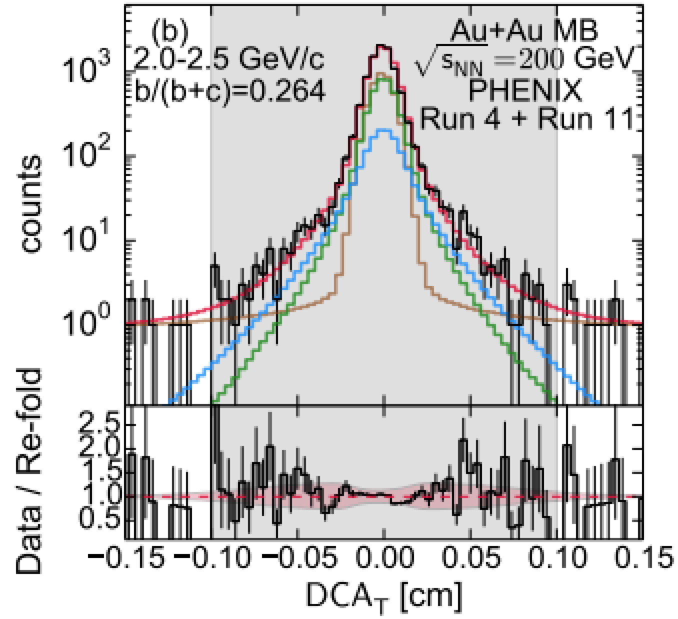
slide from M. Brooks,


Au+Au MB $\sqrt{s_{NN}}$=200 GeV
PHENIX Run 4 + Run 11
Unfolded charm
Unfolded bottom
(a)
(b)
$1/2\pi p_T\ dN/dp_T\ [(GeV/c)^{-2}]$
p_T^c [GeV/c]
p_T^b [GeV/c]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
5
10
15

Comparison to Data



Data
c->e
b->e
Total
Background
Components



Unfold gives good consistency with electron invariant yield and DCAT distribution

- new c->e , b->e yield with VTX
- new Charmonia states in dimuon spectrum with FVTX

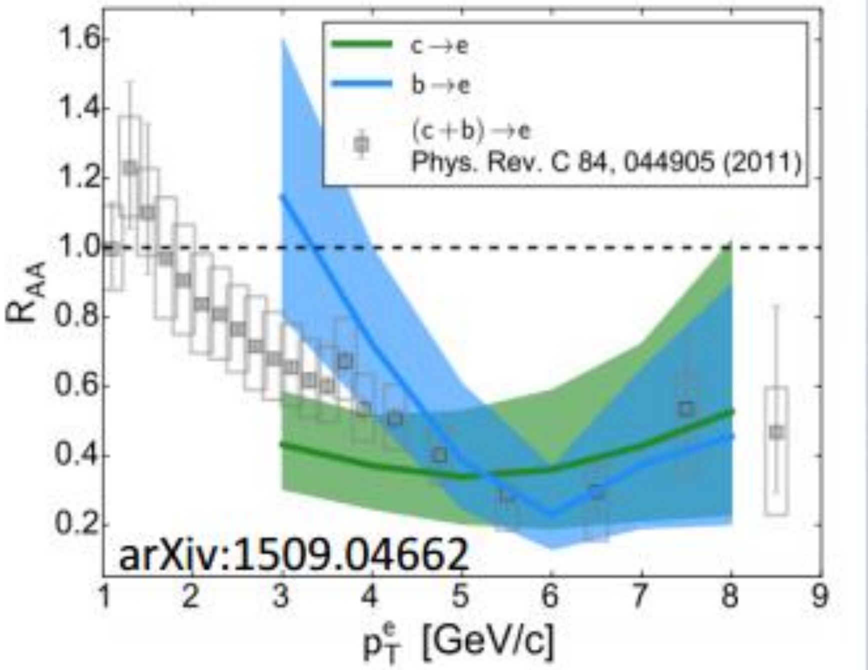
- (future prospect ? RUN14/15 VTX , B->Jpsi FVTX)

-not cover

- Nuclear matter effects on J/psi production in asymmetric Cu+Au collisions
- Cross Section of b¥bar{b} Production in p+p Collisions at sqrt(s) = 500 GeV
- Heavy Quark Production and Elliptic Flow in Au+Au Collisions at sqrt(s_NN)=62.4GeV

Central arms (mid-rapidity , $|\eta| < 0.35$)

PHENIX: arXiv:1509.04662 (2015) PRC accepted !



Summary of the VTX results

First measurement of electrons from separated charm and bottom by PHENIX.

Extracted charm and bottom hadron yields.

Compares well to STAR measurements of D 0 yield in Au+Au.?

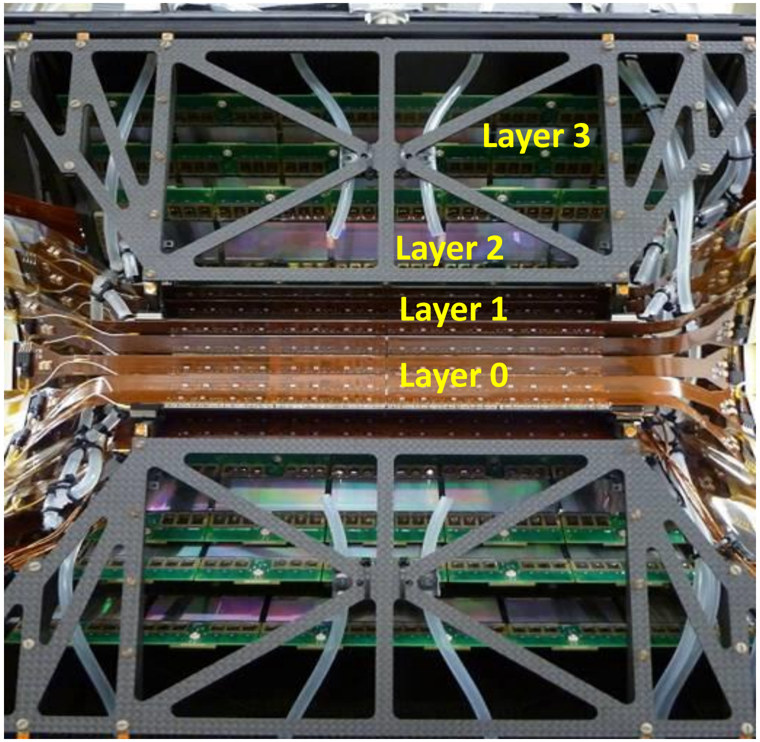
Electrons from bottom decays are less suppressed than those from charm for 3 < p T < 4 GeV/c, similarly suppressed for p T > 4 GeV/c.

Separated charm/bottom adds a new dimension for disentangling medium effects at RHIC.

Expect high precision Au+Au as well as p+p baseline from 2014 & 2015 data sets

- Challenge in the DCA measurement of single electrons is the Conversion Electron Background (CEB).

- Most conversions happen in the outer layers (total radiation length = 12 % (B0: 1.3%, B1: 1.3%, B2:4.7% and B3: 4.7%). They are suppressed by requiring a hit in inner silicon layer B0.



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- Conversions in the beam pipe and B0, and Dalitz are suppressed by rejecting electron tracks with a nearby hit : Conversion Veto. (isolation cut)