Heavy Quark Measurement in High-Energy Heavy-Ion Collisions

高エネルギー原子核衝突における重いクォークの測定

Takashi HACHIYA
RIKEN

Outline

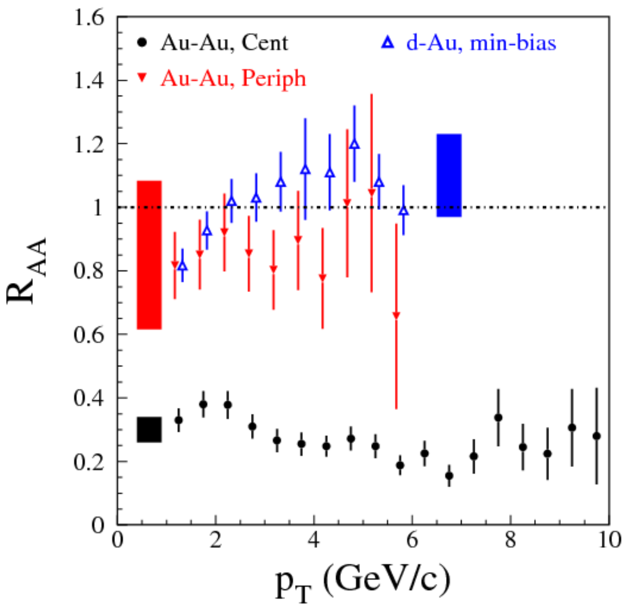
- Introduction
- Method
  - Heavy Quark Measurement
- Result
  - p+p 200GeV
  - d+Au 200GeV
  - Cu+Cu 200GeV
  - Au+Au 200GeV
- Charm / bottom separation in Au+Au200GeV
  - PHENIX Silicon Vertex Detector (VTX)
- Summary

Introduction

- Quark Gluon Plasma (QGP)
  - deconfined quarks and gluons in the hot and dense environment
  - HI collision is only way to create QGP in the laboratory

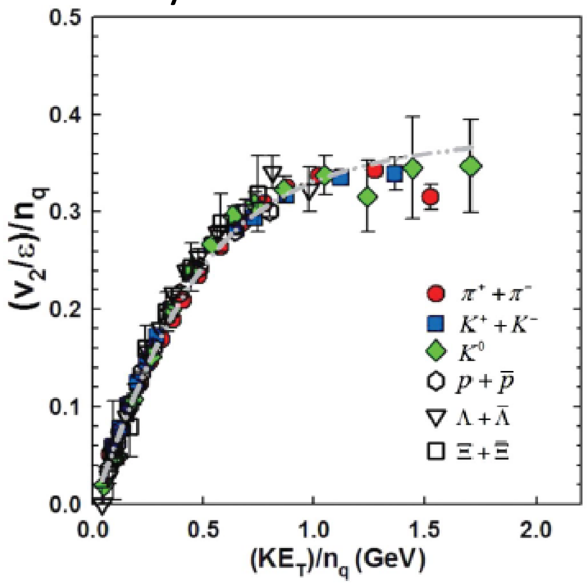
- QGP was formed at RHIC
  - Parton energy loss in the medium
  - Strong v2 described by hydro picture

Parton Energy Loss
in the medium



NPA757, 184 (2005)

Early thermalisation time



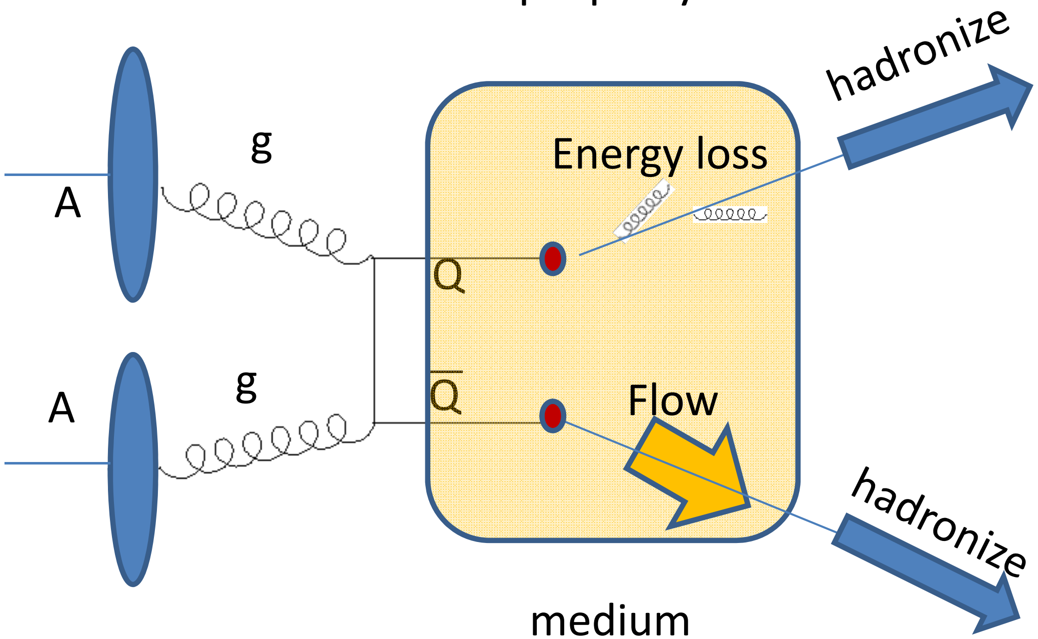
PRL98, 092301 (2007)

Our focus is moved from "observation of QGP"
to the detailed investigation of QGP property

Introduction- why heavy flavor?

- Charm and bottom (Heavy Flavors, HF or HQ) in HI collisions
  - HF is created at the early stage of the collisions
    - Mainly initial hard scattering due to large mass
    - the production can be calculated by pQCD
    - Secondary and thermal production may happen

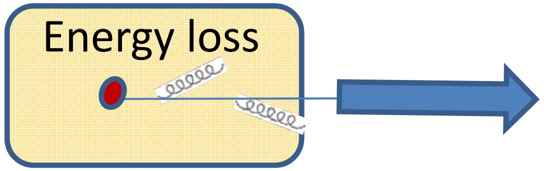
    } Calibrated probe
  - Pass through the hot and dense medium
    - Sensitive to the medium property



Heavy flavor is clean probe to study property of QGP

Observables from QGP

- Modification of p_T spectrum at high p_T
  - Sensitive to parton energy loss in the medium

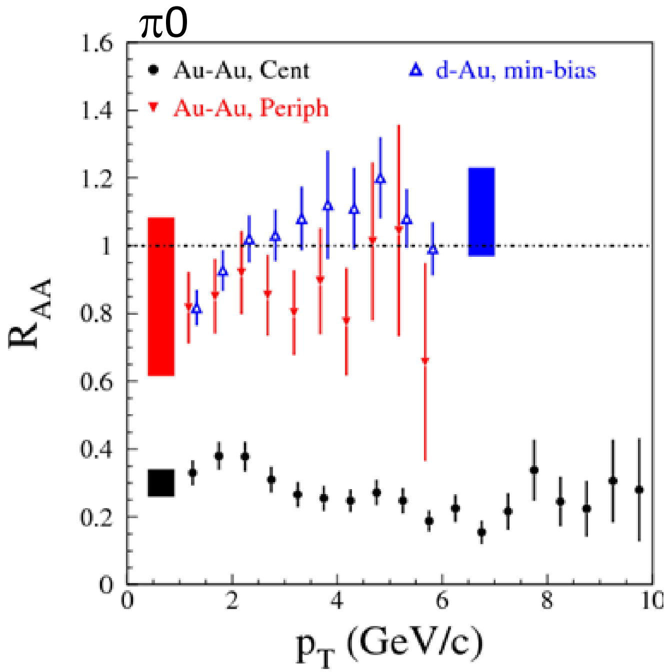


Nuclear Modification Factor

$$R_{AA} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}(p_t)/dp_t dy}{d^2N_{pp}(p_t)/dp_t dy}$$

$R_{AA} = 1$: Ncoll (binary) scaling

$R_{AA} < 1$: Suppression



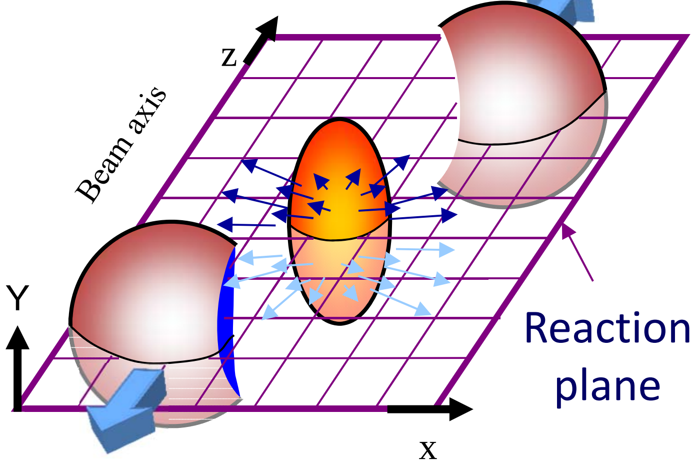
Expected that HF suffers less energy loss than light quarks.

"Dead cone effect" : Energy loss: $\Delta E_g > \Delta E_{LQ} > \Delta E_{HQ}$

Similer with energy loss in the matter, $\Delta E_e > \Delta E_\mu$

Observables from QGP

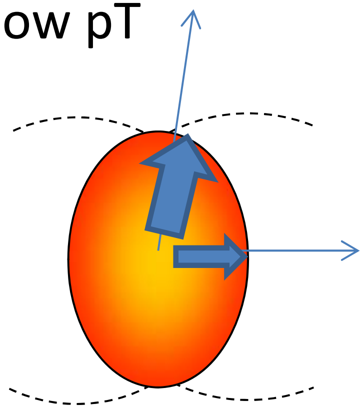
- Azimuthal anisotropy v_2
  - Different pressure gradient in non-central collision causes anisotropy in particle emission



Fourier Transform

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_r)])$$

  - Sensitive to the collective motion and thermalization at low pT
    - less (or no) flow for HQ was expected.

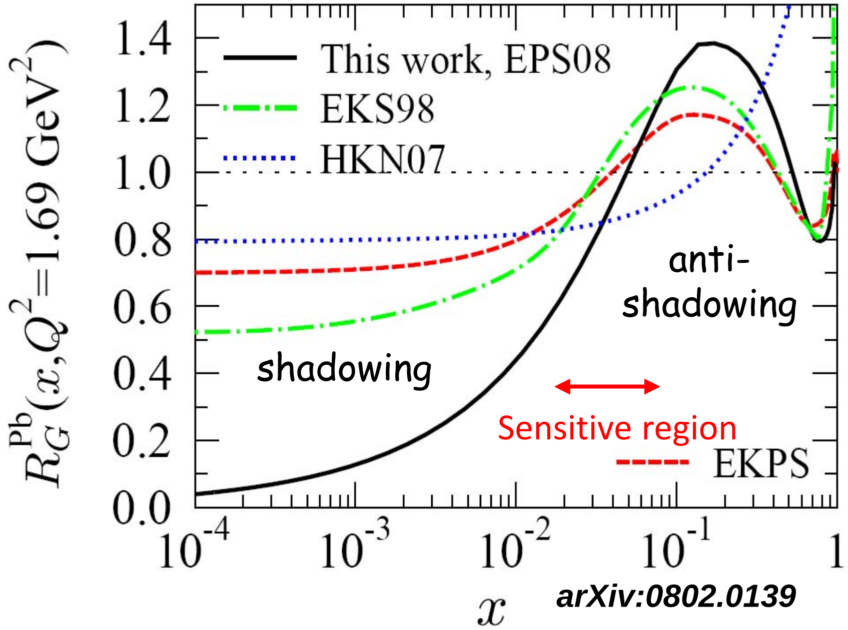


  - Path length dependence of energy loss at high pT

Cold Nuclear Matter Effect

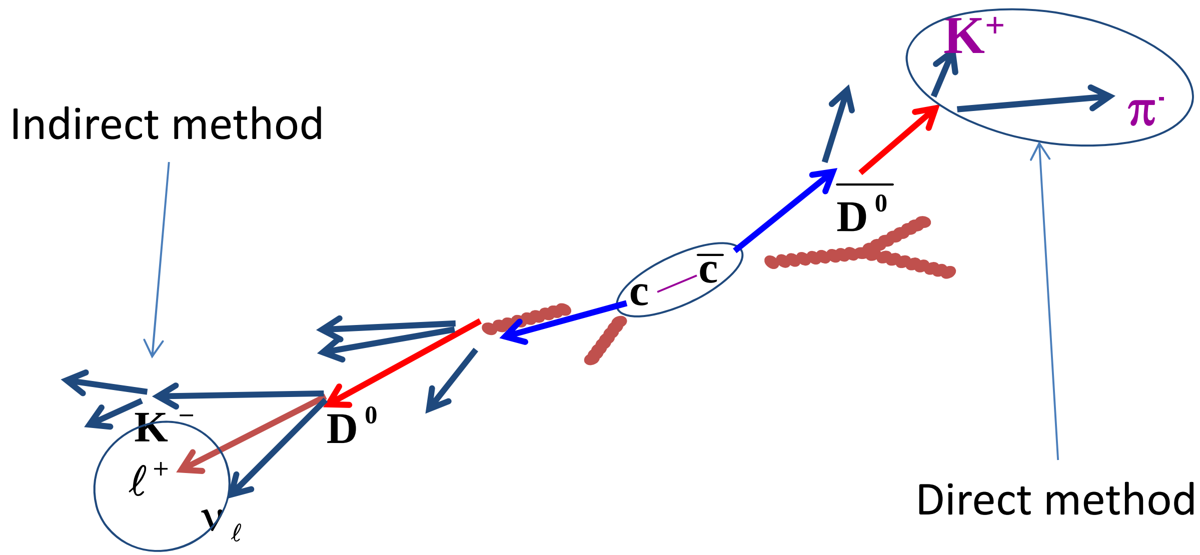
- Shadowing effect
  - nPDF is different with PDF in pp
  - Heavy Quark yield might be small
- Cronin effect
  - initial parton scattering causes the kT modification
- This effect must be in the HIC
- This effect can be studied using p(d)+A collision where the QGP doesn't form

Shadowing Effect



arXiv:0802.0139

Open Heavy Flavor Measurements



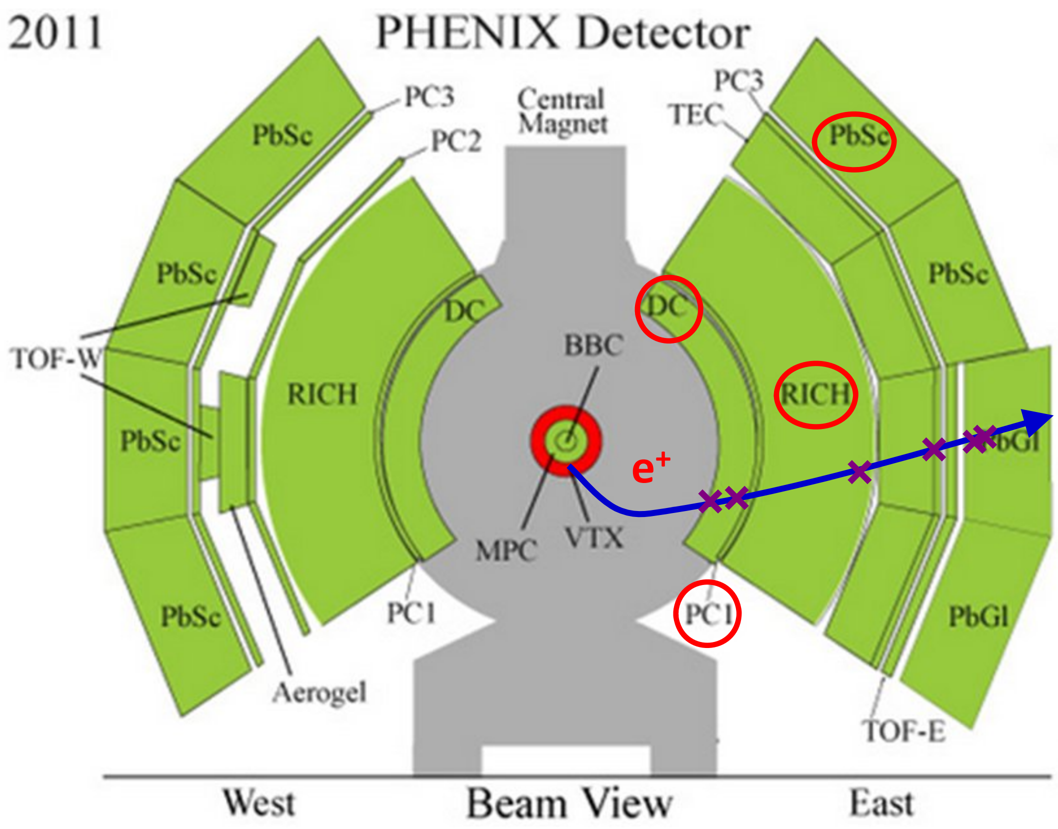
- Direct method
  - Reconstruct parent HF hadron using decay products.
  - Clear signal, but branting ratio is too small (large BG)

B -> J/psi +X (BR: 1%)
D0 → Kπ (BR : 4%)
D+ → Kππ (BR : 9.4%)
but small acc.

- Indirect method
  - Measure electrons from semi-leptonic decays of heavy-flavors
  - (relatively) Large branching ratio.
  - PHENIX relies on this method

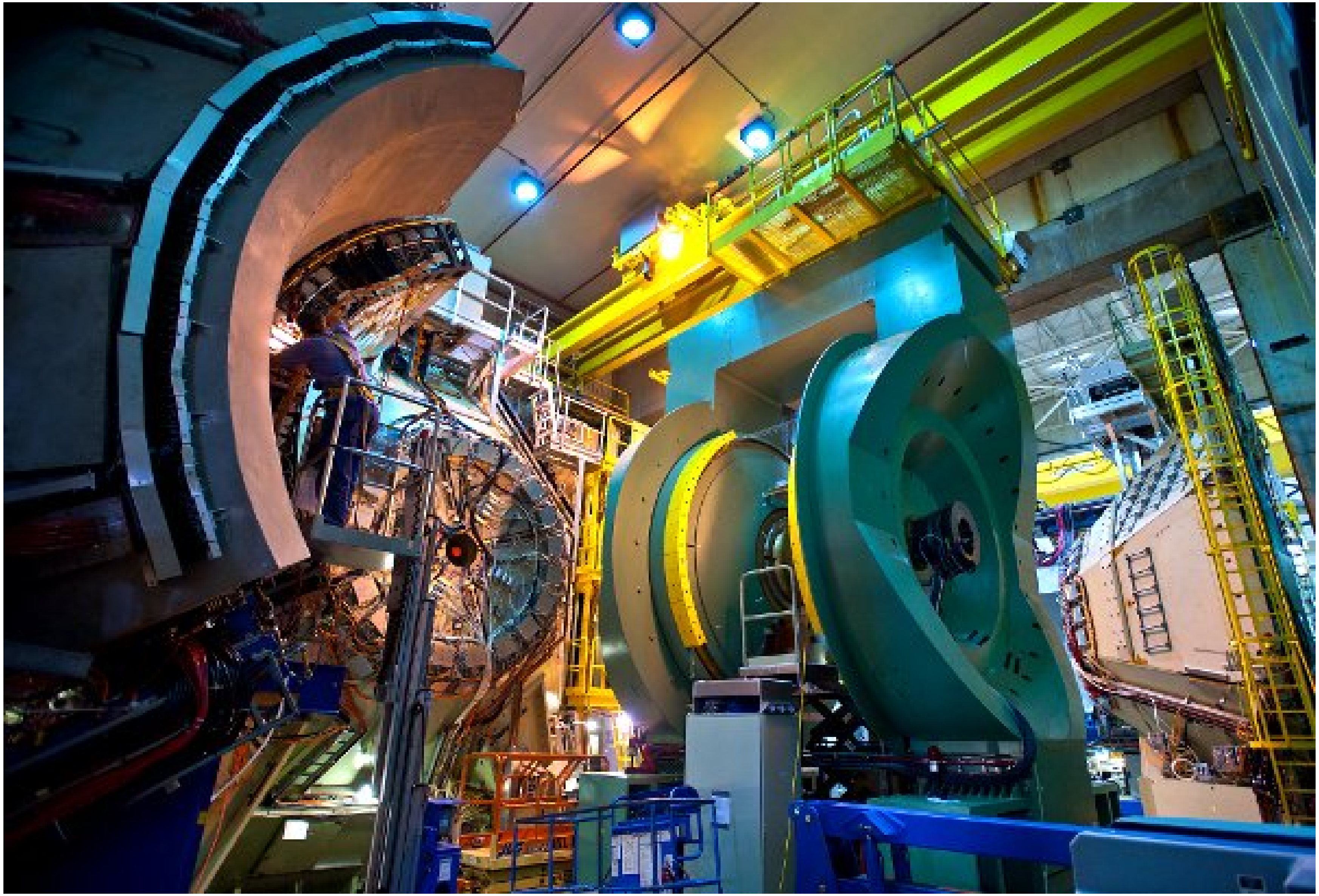
Branching ratio
c → e + X (BR : 9.6%)
b → e + X (BR : 11%)

PHENIX Detector and electron ID

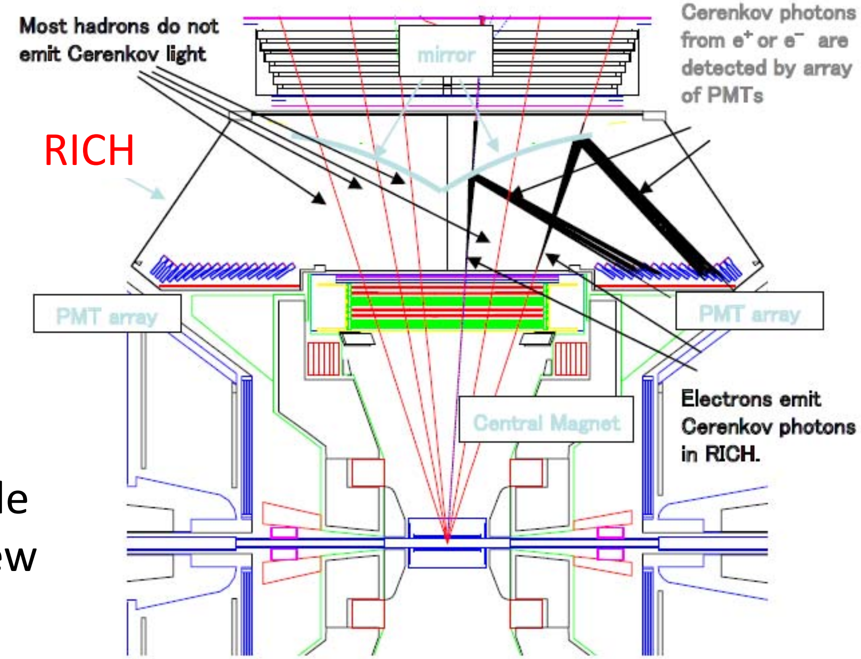


- PHENIX Central Arm
  - 2 arm structure
  - $|\eta|<0.35$
  - $\Delta\phi=\pi/2 \times 2$,
- Charged particle tracking and momentum
  - Drift chamber
  - Pad chamber
- Electron Identification
  - RICH is primary eID device.
  - EMCal measures energy :

PHENIX detector

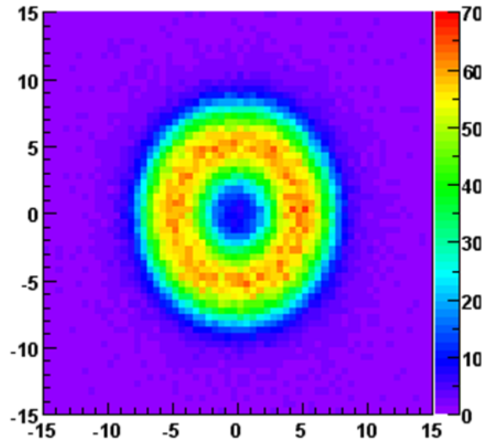


Electron ID with RICH + EMCAL

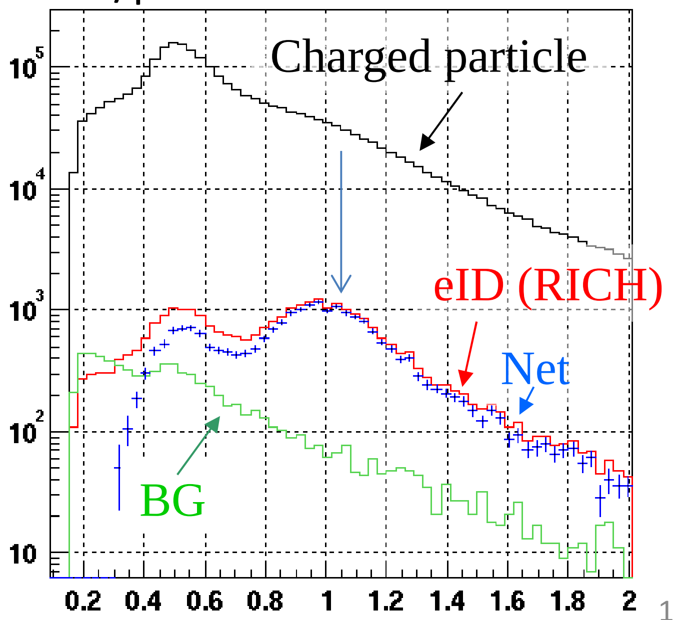


Side view

Measured Ring Image in RICH



E/p distribution



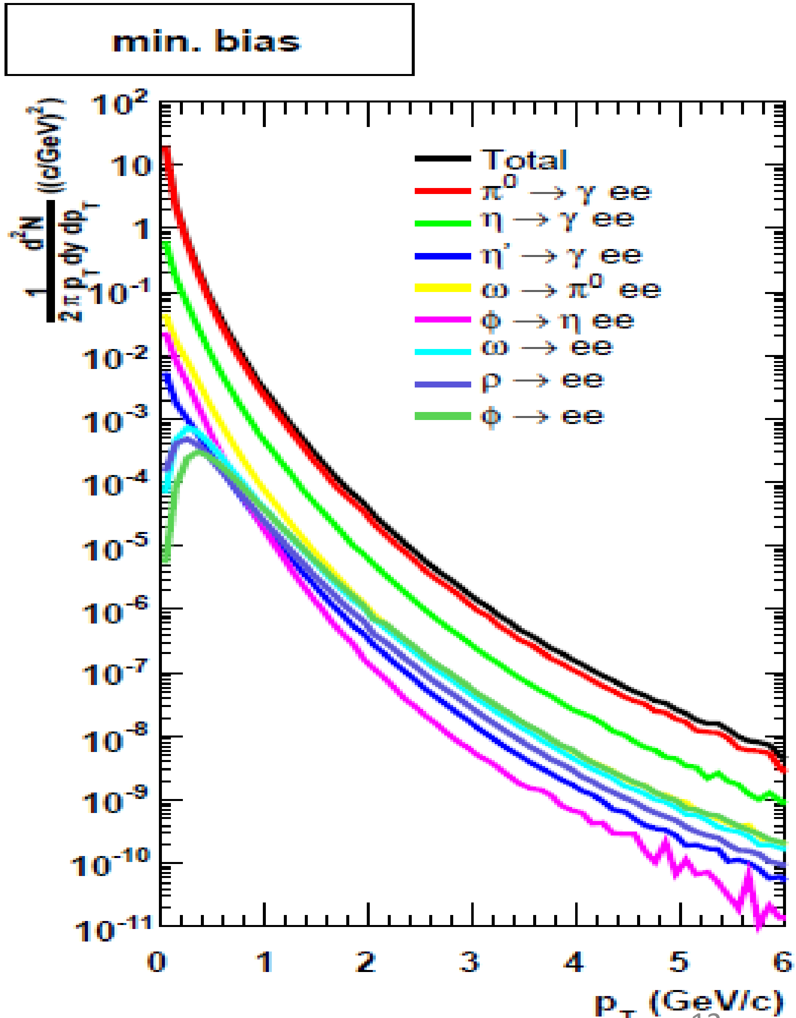
- RICH
  - Ring Imaging Cherenkov Detector
    - C02 : ~4.8GeV/c π+ threshold
    - $\cos\theta_c = (\beta n)^{-1}$: $\beta > 1/n$
  - Hadron rejection ~ 50~100x
  - nHit and RING shape cut
- E/p matching using EMCAL and momentum
  - E/p ~ 1 for electrons,
  - E/p << 1 for hadrons
  - ~ 5~10x rejection
- In total, ~300 rejection achieved

Electrons Source
(HF decays and Backgrounds)

- Non-photonic Electrons
  - Heavy Flavor Electrons (HFe)
    - Semi-leptonic decays of heavy flavor

      c → e, b → e
  - Background Electrons :
    - Ke3 (K → eνπ) <6% @ p_T>1GeV/c
    - φ,ρ,ω → ee <3%@p_T>1GeV/c
    - J/ψ → ee, Drell-Yan
      - Small contribution at low pT
- Photonic Electrons
  - Dalitz decays : $\pi^0,\eta \to \gamma ee$, $\omega \to \pi^0 ee$
  - Photon conversions : $\pi^0,\eta \to \gamma\gamma$, $\gamma \to ee$
  - Major background in experiment, needs to subtract

Relative yield of BG e (calculation)



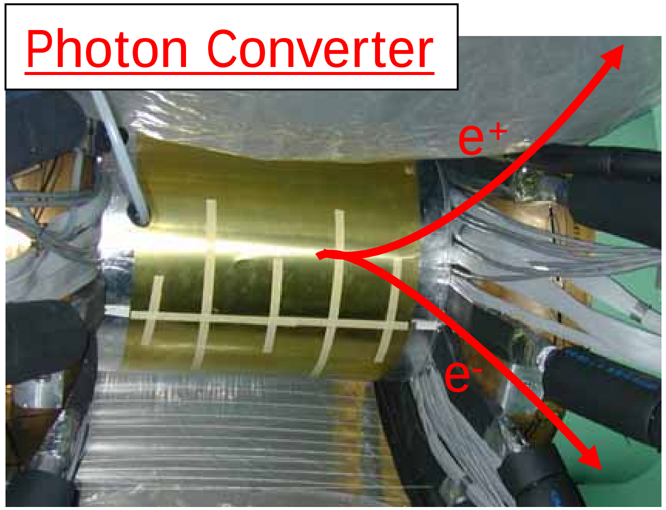
Heavy Flavor Electron Extraction

- Converter method

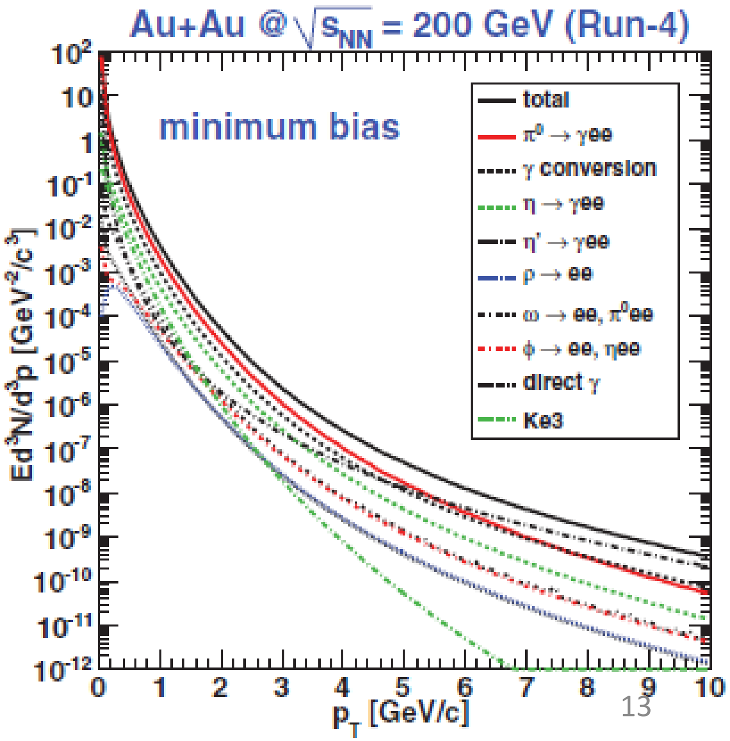
$$N^{conv-out} = N^{\gamma} + N^{non-\gamma}$$

$$N^{conv-in} = R_{\gamma} N^{\gamma} + (1-\varepsilon) N^{non-\gamma}$$

  - The converter increases photonic e with fixed factor.
    - Photonic e calibration
  - Advantage: small sys. error
  - Dis: Small statistics, low pT

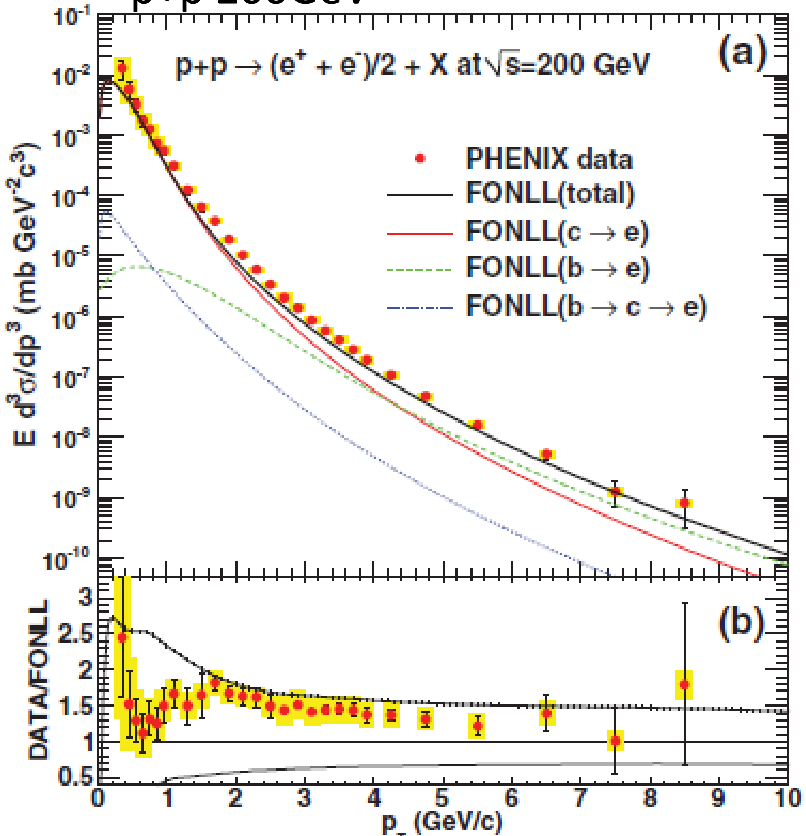


- Cocktail method
  - Based on measured pion yield (and others)
    - mT scaling
  - Calculated by the decay generator
  - Advantage: reach to high pT
  - Dis : sys error limited by pion measurement

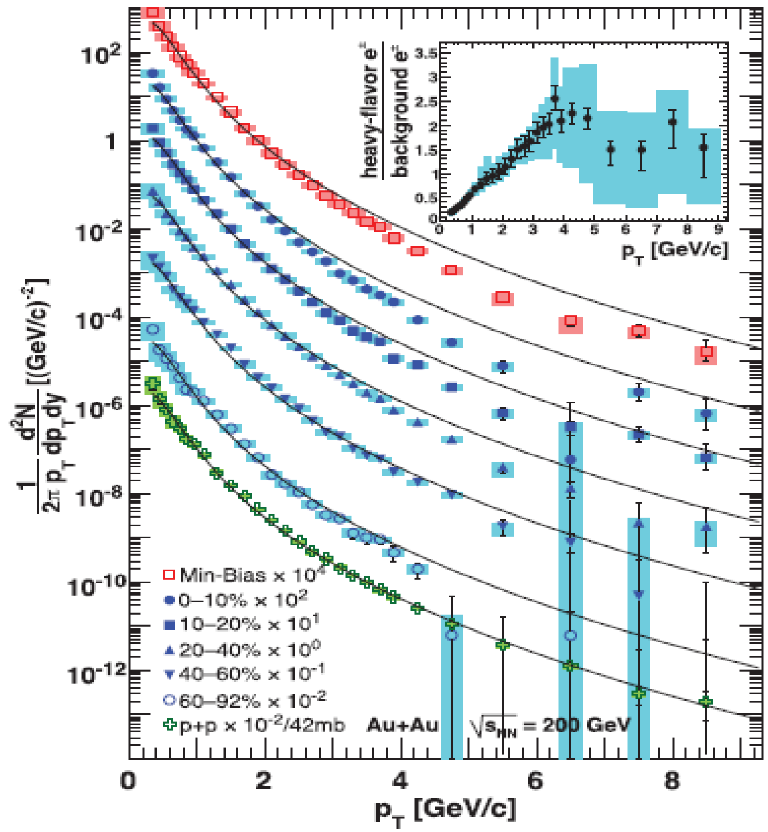


HF electrons in p+p and Au+Au 200GeV

p+p 200GeV



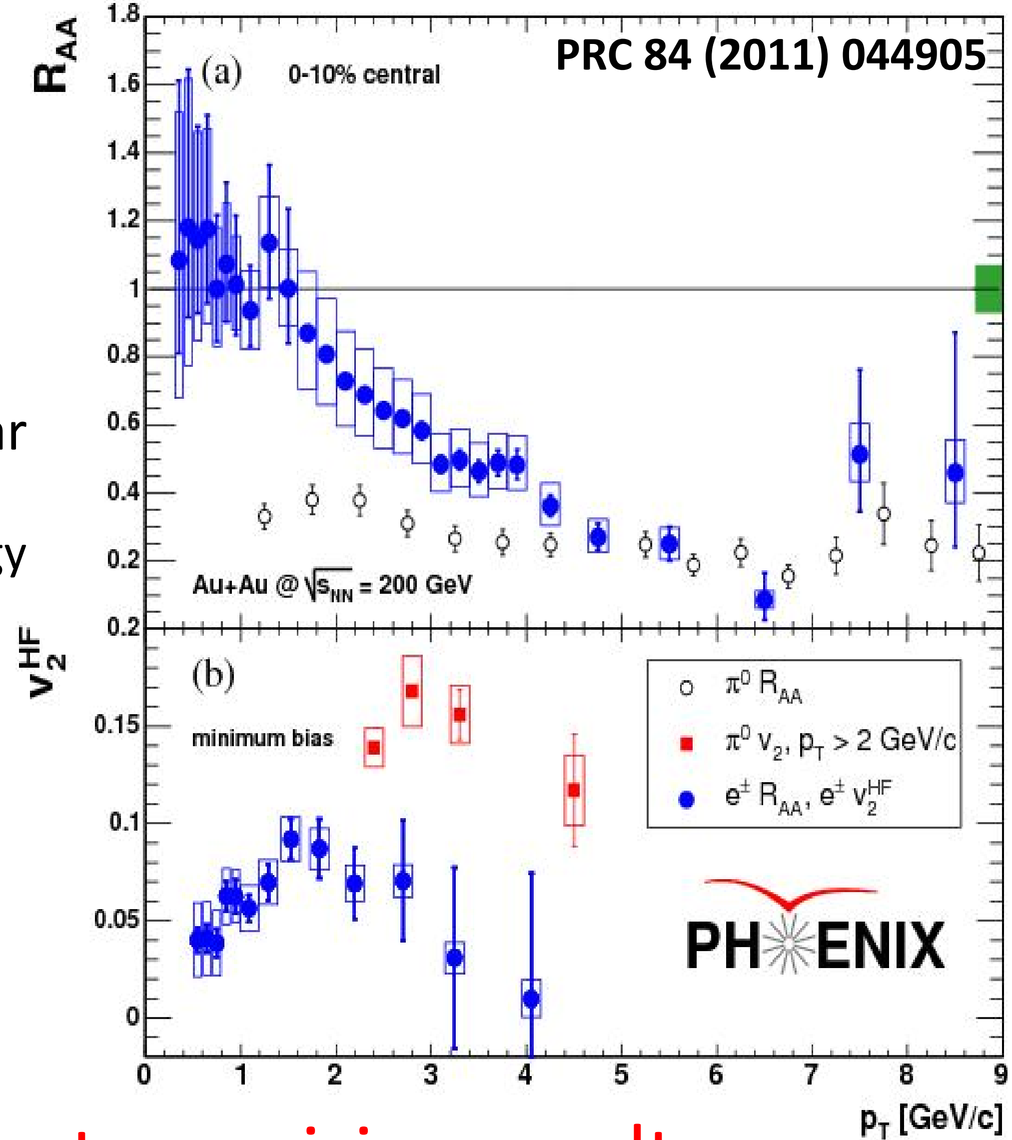
Au+Au 200GeV



- Heavy Flavor electrons was measured with wide pT range in both pp and Au+Au
- Heavy Flavor electrons in p+p200GeV
  - FONNL is consistent w/ data .
  - FONNL : Charm < bottom around 4GeV/c in pT
- Heavy Flavor electrons in Au+Au 200GeV
  - Binary scaling at low pT
  - Suppression compared with p+p. → R_{AA} measurement

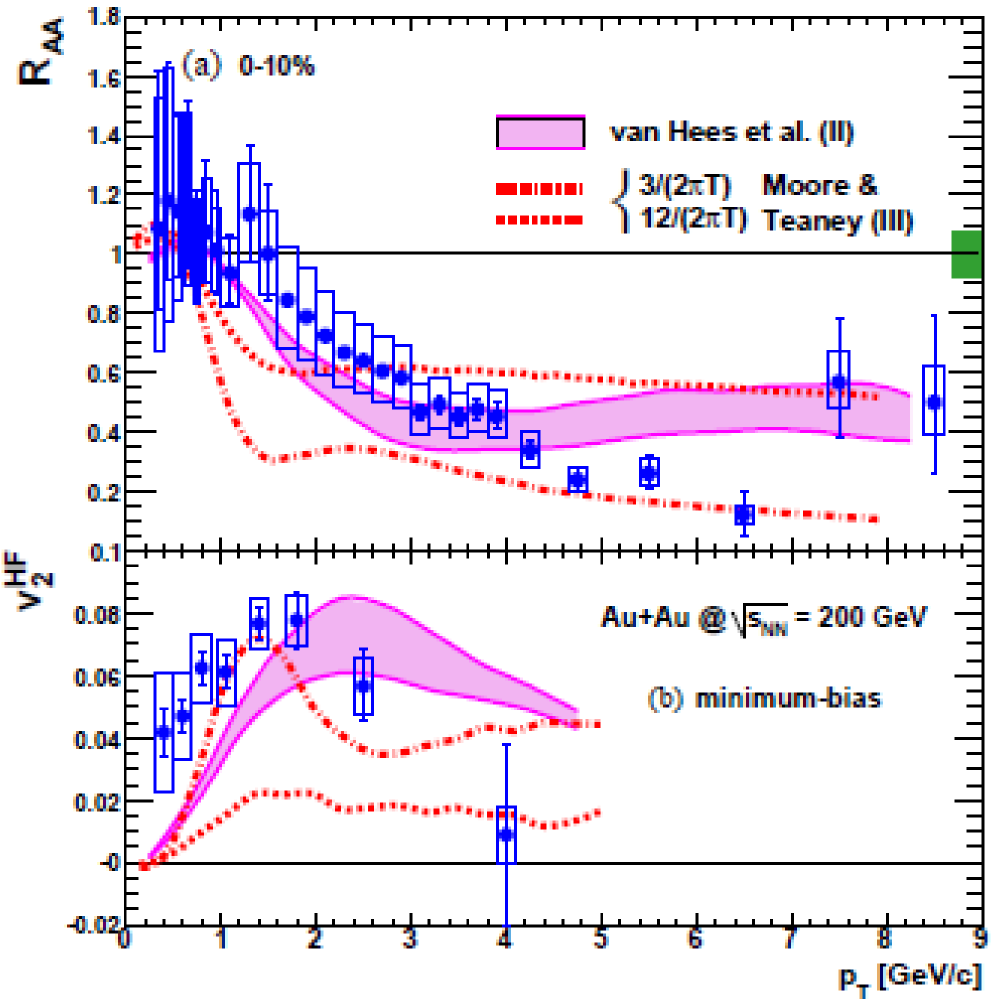
Heavy Flavor Electrons in Au+Au 200GeV

- R_{AA}: large suppression
  - $R_{AA} = \frac{1}{N_{coll}} \cdot \frac{Ne(Au+Au)}{Ne(p+p)}$
  - R_{AA} (HFe) shows
    - Large suppression similar with pion at high pT
      - Indicating similar energy loss with pion
    - Consistent with Ncoll scaling at low pT
- v_2 : non-zero flow
  - HF is also affected by flow



One of the most surprising results

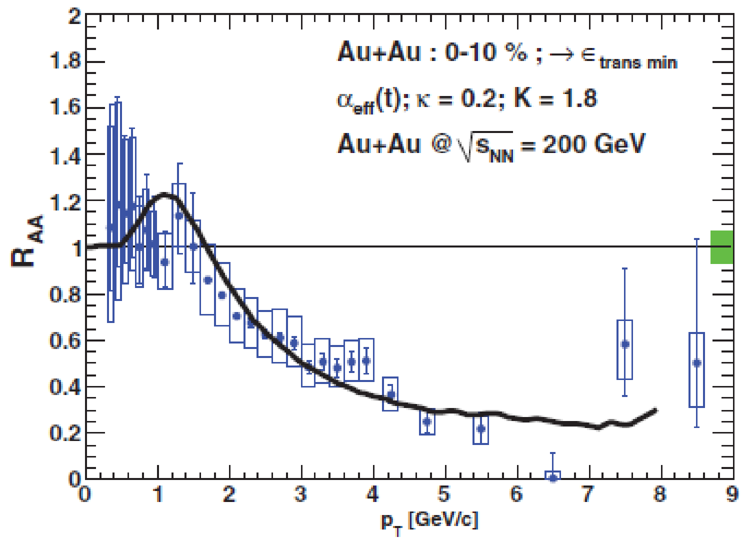
Model comparison & η/s evaluation

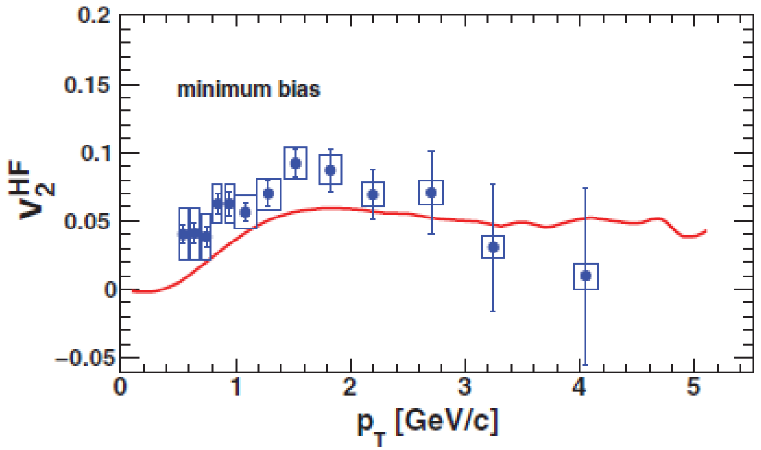


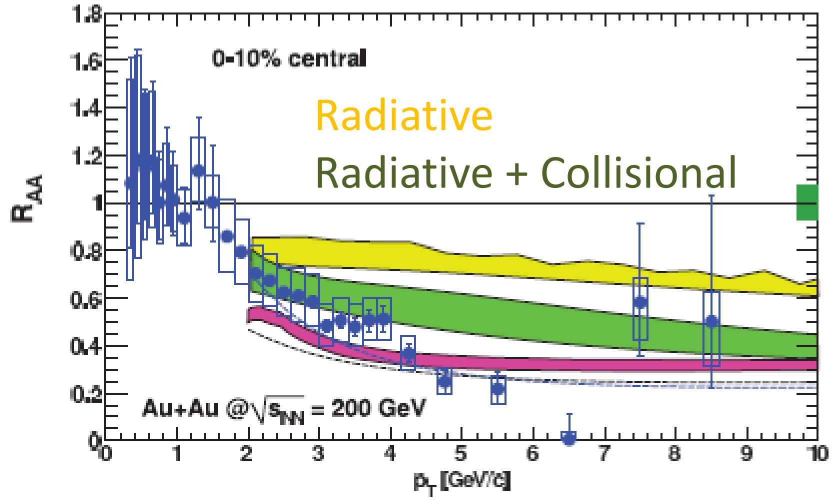
- Collisional energy loss models with common D failed to reproduce R_{AA} and v2.
- R_{AA} and v2 is compared with langevin based model
  - $D_{HQ} = 4\sim6/(2\pi T)$ reproduces the data
    - D ~ 6 × η/Ts at mu_B =0
  - $\eta/s \sim (4/3\text{-}2)/4\pi$

More comparisons

pQCD based model







- Some models reproduces our data
  - Which one ?
- Separated B and D measurement gives more constraint to the models.
  - Is it possible to separate radiative and collisional energy loss?

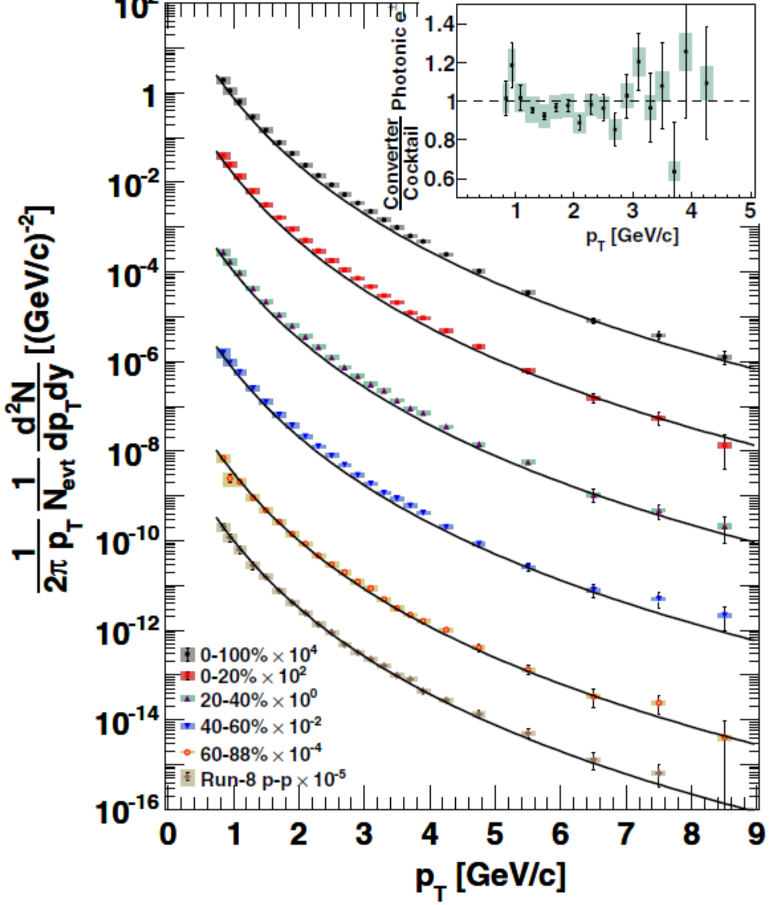
Heavy Flavor Electrons in d+Au and Cu+Cu

- d+Au
  - study the CNM effect since no QGP is created in p(d)+Au

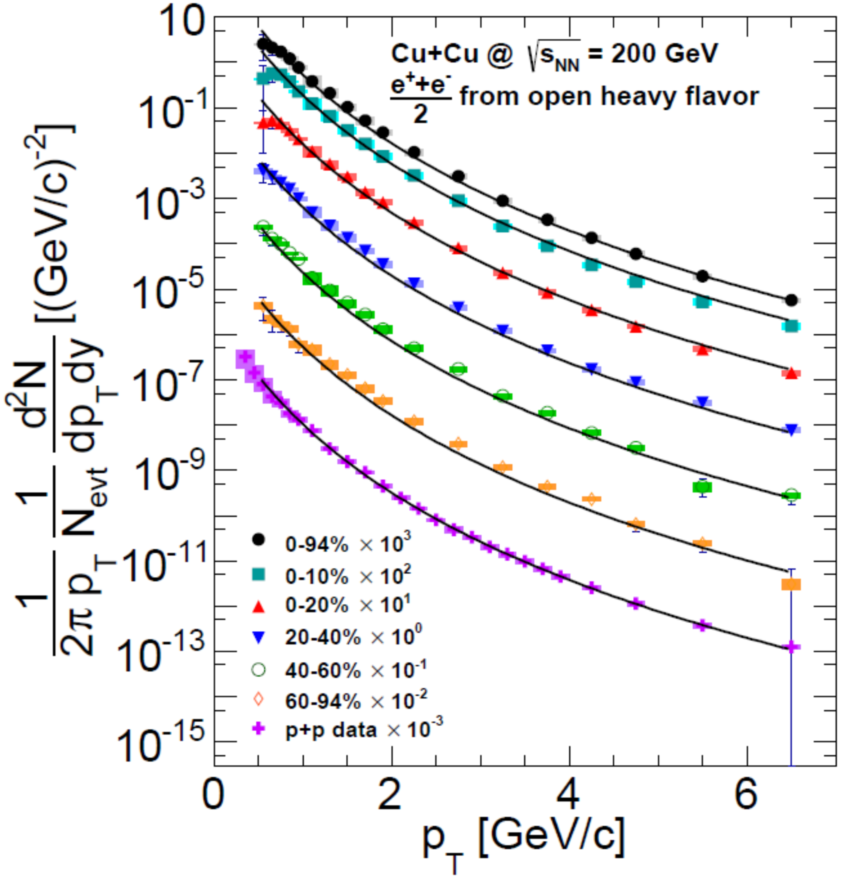
- Cu+Cu
  - study the energy loss effect in smaller system

Heavy Flavor Electrons in d+Au and Cu+Cu 200GeV

d+Au (2008) PRL 109, 242301 (2012)



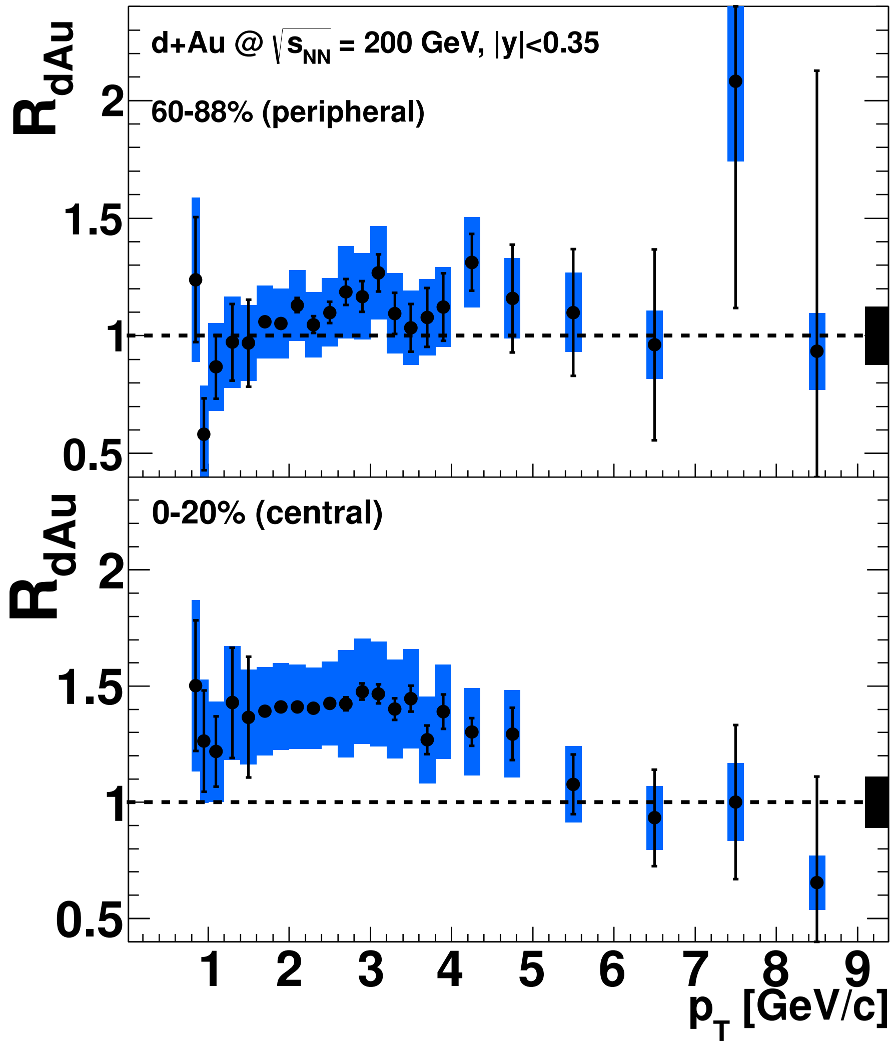
Cu+Cu arXiv:1310.8286v1



- Heavy flavor electrons were measured in both d+Au and Cu+Cu 200GeV with wide pT range

Heavy Flavor Electron R_{AA} in d+Au 200GeV

PRL 109, 242301 (2012)



In peripheral,

- R_{AA} =1 for all pT range:
  - Consistent with p+p within uncertainty.

In central,

- R_{AA} > 1 at mid pT:

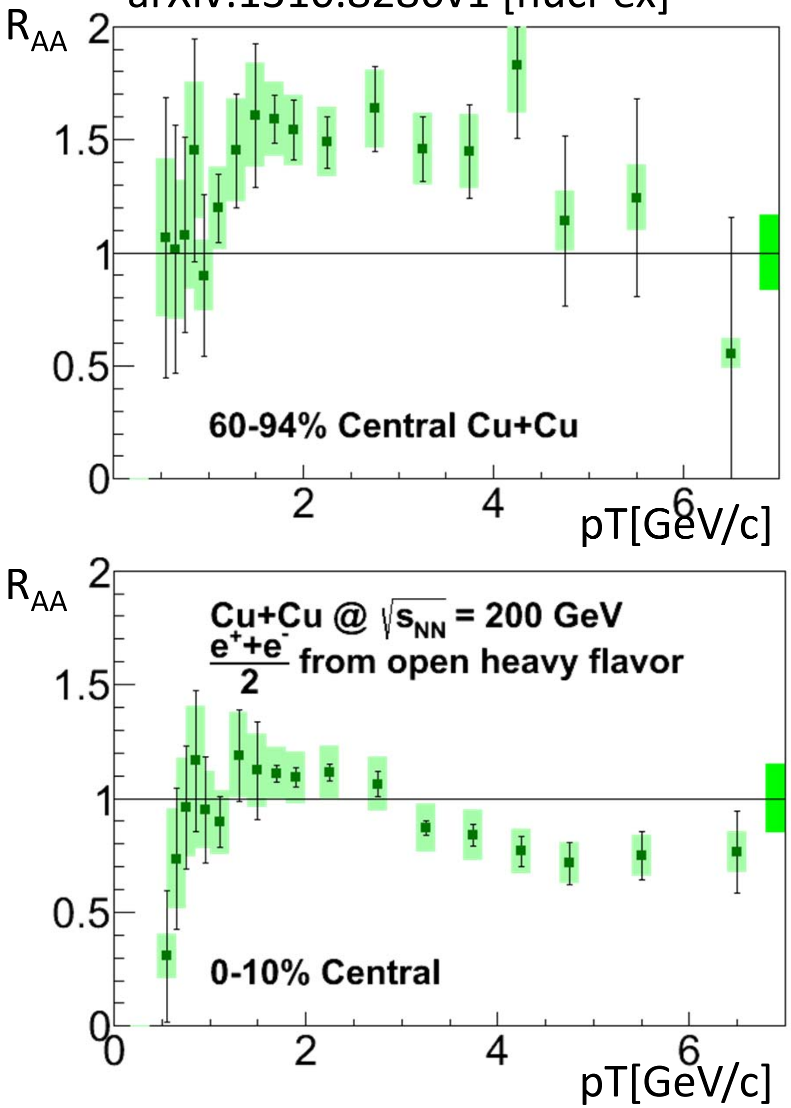
  → Cronin-like *initial* scattering?

  similar trend is seen in pion

- No suppression from CNM
  - Large suppression in Au+Au can be attributed to the hot and dense matter effect
- Enhancement may also be apparent in Au+Au

Heavy Flavor Electrons in Cu+Cu 200GeV

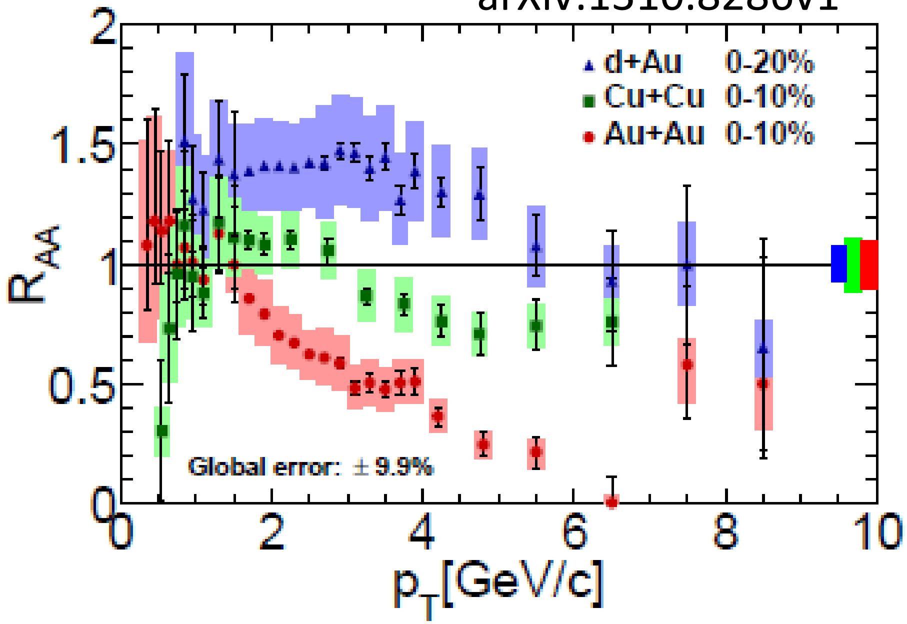
arXiv:1310.8286v1 [nucl-ex]



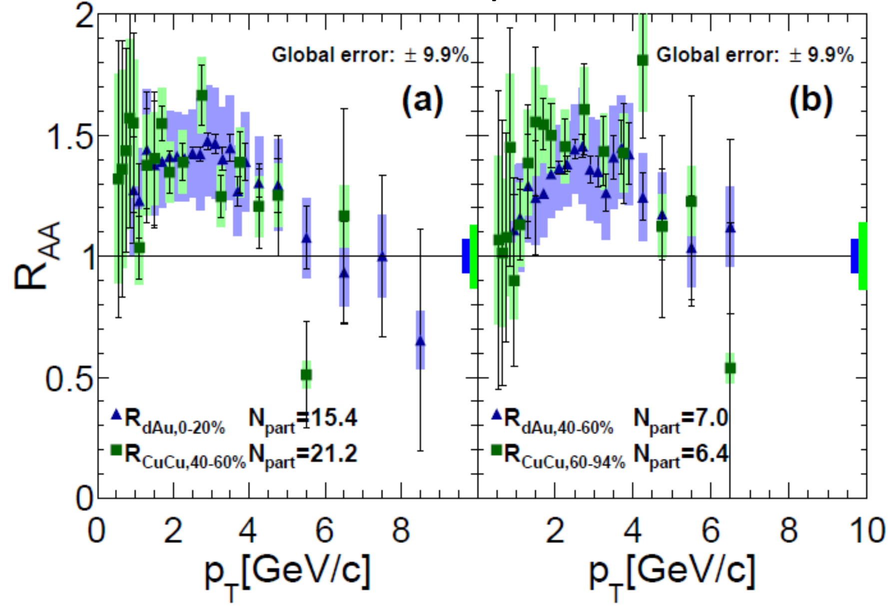
- In peripheral,
  - Significant enhancement
  - Similar with d+Au.
- In central,
  - Slight suppression at high pT

System Size Dependence

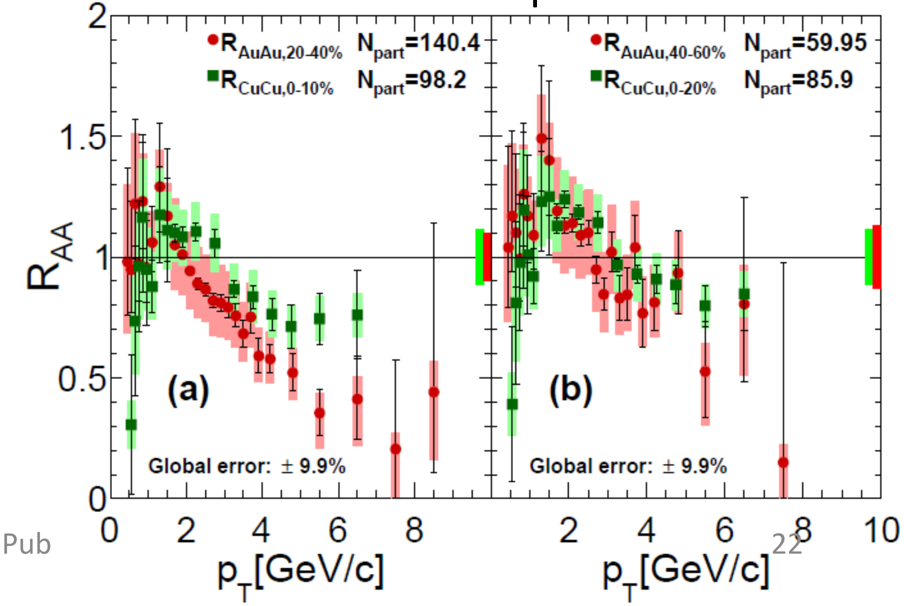
HFe in 200GeV arXiv:1310.8286v1



Central RdAu ~ Peripheral RCuCu



Central RCuCu ~ Peripheral RAuAu



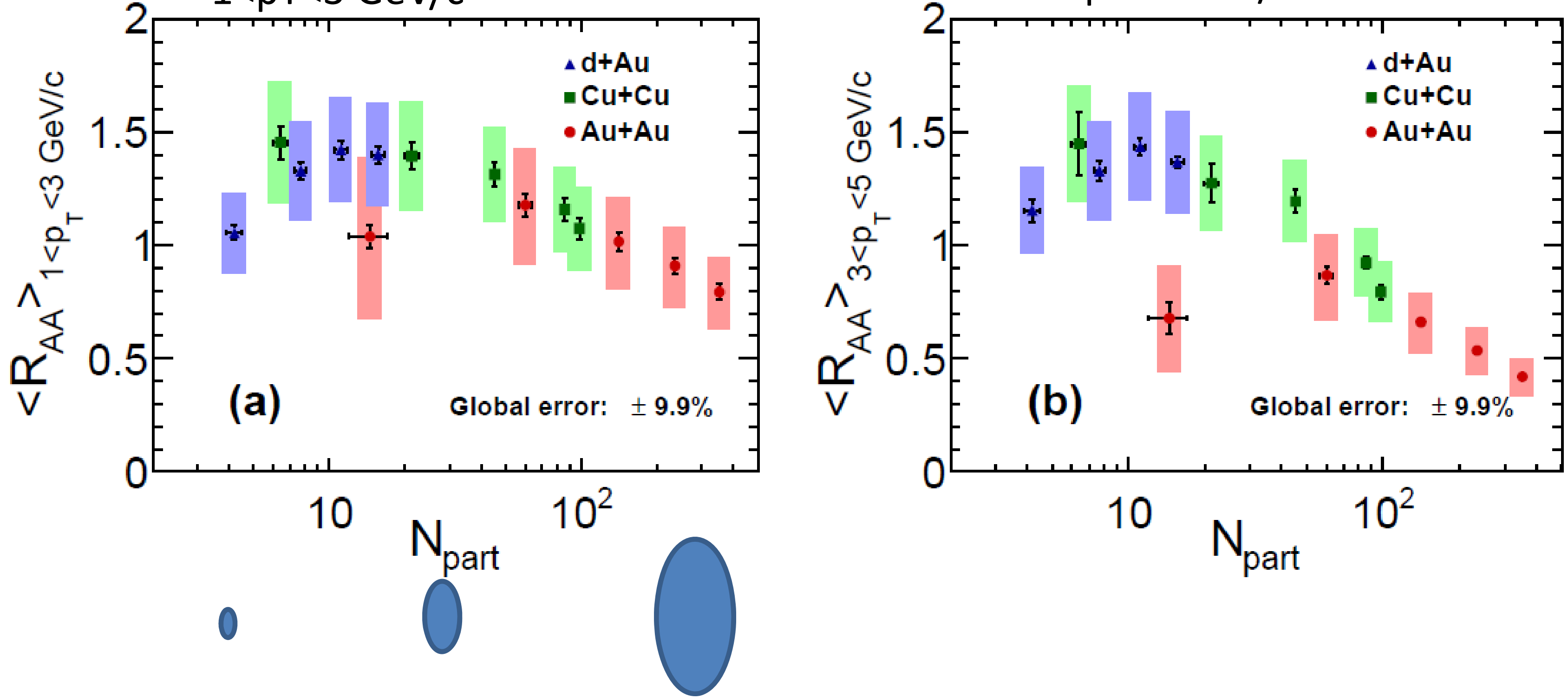
- RdAu > RCuCu > RAuAu

Npart(5.4±1.0) (98.2±2.4) (352.2±3.3)

  - Npart ~ system size

- Similar enhancement in RdAu@cent ~ RCuCu@peri
- Similar suppression in RCuCu@cent ~ RAuAu@peri

System size : $\langle R_{AA} \rangle$ vs <Npart>



- Smoothly changing in dAu -> CuCu -> AuAu
  - Enhancement at small size (small Npart)
  - Suppression at large size (large Npart)
  - Consistent behavior in 2 different pT bins
- This trend is dependent on the system size (Npart)
- Overall description is necessary to understand HF energy loss seen in Au+Au

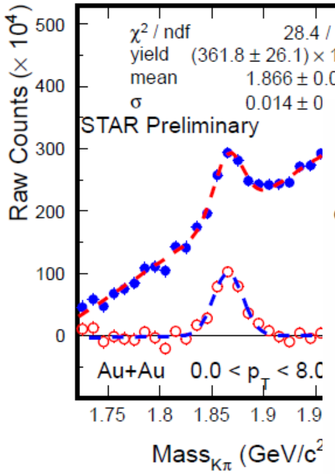
Bottom / Charm Separation

- Direct Measurement
  - D meson reconstruction at RHIC
  - D meson reconstruction at ALICE
  - Non-prompt J/psi at CMS (B from Jpsi)

- Bottom and Charm separation using HFe

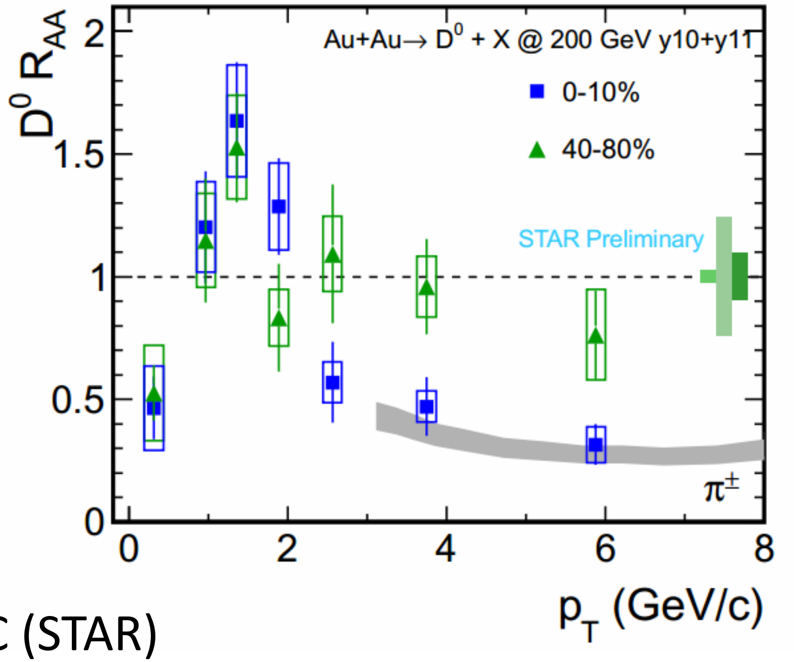
Direct Measurement of D/B

D → K + π



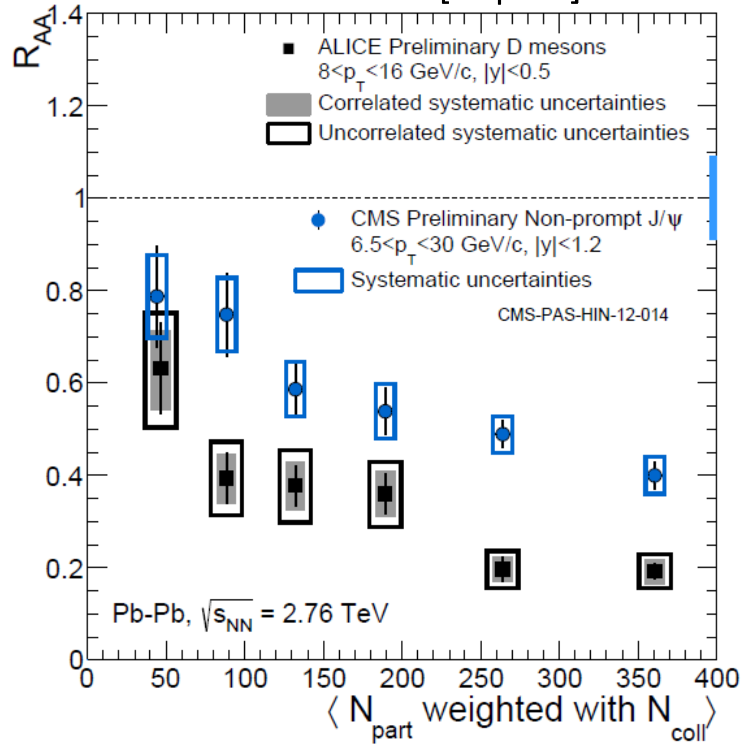
STAR measurement @ QM12

NPA 904–905 (2013) 170c–177c



LHC measurement

arXiv:1310.7366v1 [hep-ex]



- At RHIC (STAR)
  - Suppression is comparable with pi (consistent with HFe)
  - The maximum at 2GeV/c is consistent with transverse flow models
- At LHC (ALICE and CMS)
  - First measurement of non-prompt Jpsi
  - Clear mass ordering of HF suppression (RAA(D)< RAA(np Jpsi))

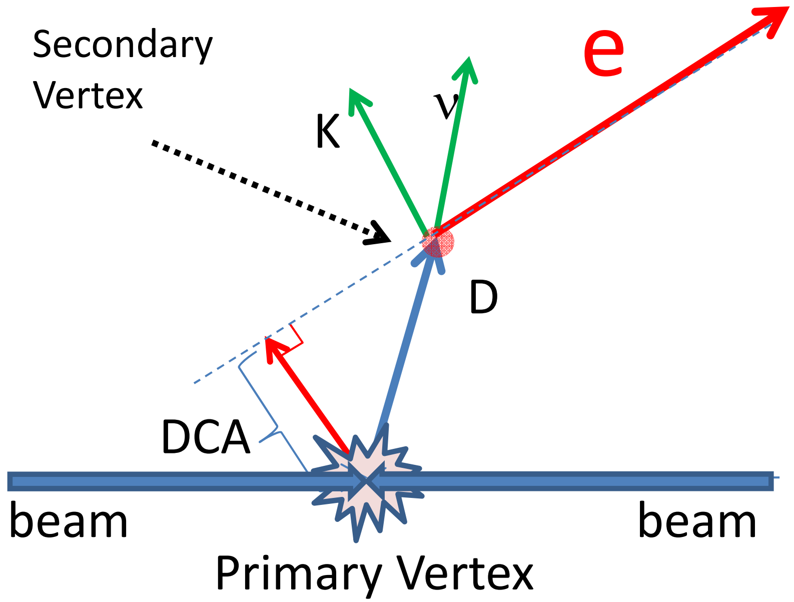
- What happen in RHIC?

Bottom / Charm Separation

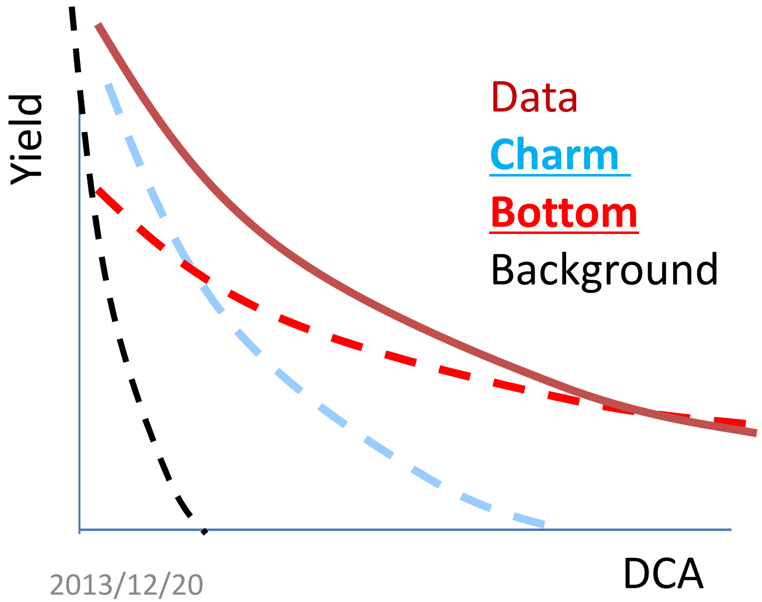
- Direct Measurement
  - D meson reconstruction at RHIC
  - D meson reconstruction at ALICE
  - Non-prompt J/psi at CMS

- Bottom and Charm separation using HFe

Charm/bottom separation using DCA



- Distance of Closest Approach
  - DCA of electron track from primary vertex
  - DCA corresponds to the life time(cτ)

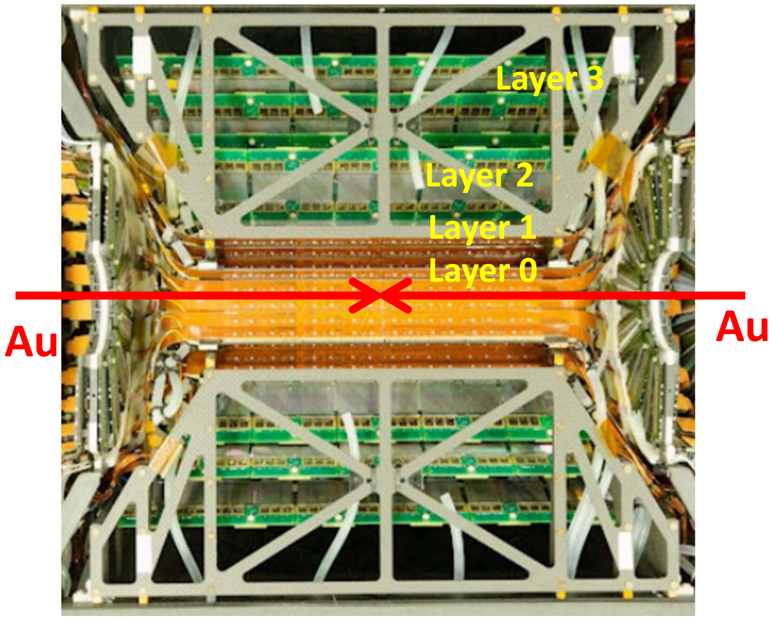


Unique lifetime of c and b

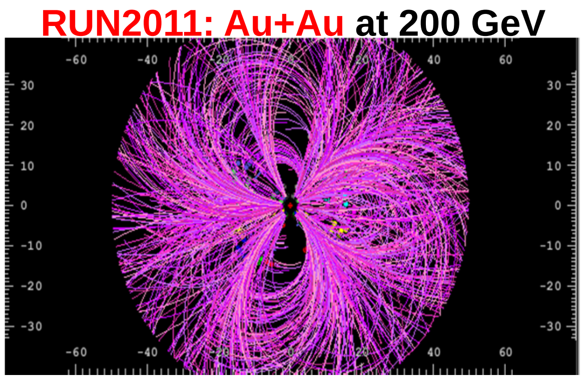
D0	122.9 μm	Charm
D+	311.8 μm	
B0	457.2 μm	Bottom
B+	491.1 μm	

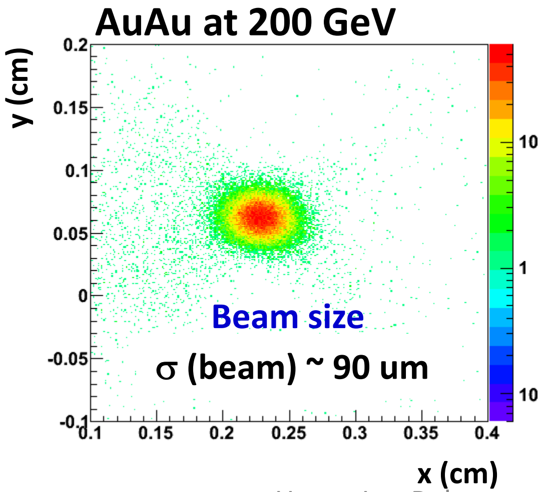
Precise DCA measurement allows clear separation of charms and bottoms

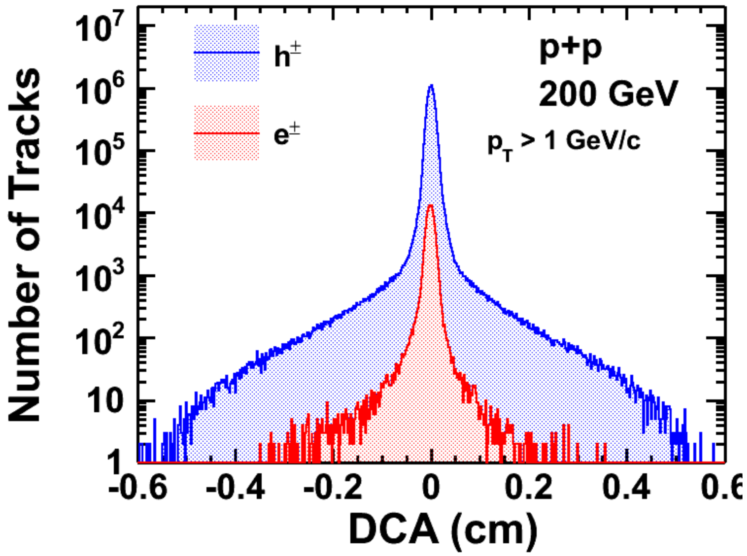
PHENIX Silicon Vertex Detector(VTX)



- VTX was installed from Run2011
  - Large coverage
    - $|\eta|<1.2, \phi \sim 2\pi$
  - 4 layer silicon detectors
    - 2 inner pixel detector
    - 2 outer stripixel detector
  - Placed near collision (R~2.5cm)
  - DCA & Primary vertex
- DCA resolution of 77um is archived





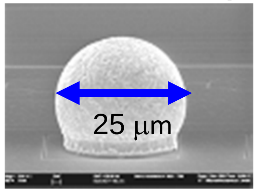


Pixel Detector in detail

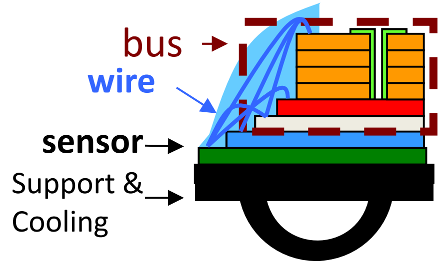
- Developed by RIKEN with ALICE
- Channels: : 3900k channels
  - PHENIX EMCAL : 25k channels

- Spec:
  - Pixel Size: 50 um (ϕ) x 425 um (z)
  - sensor module + 4 RO chips.
  - Bump bonding

Solder bump

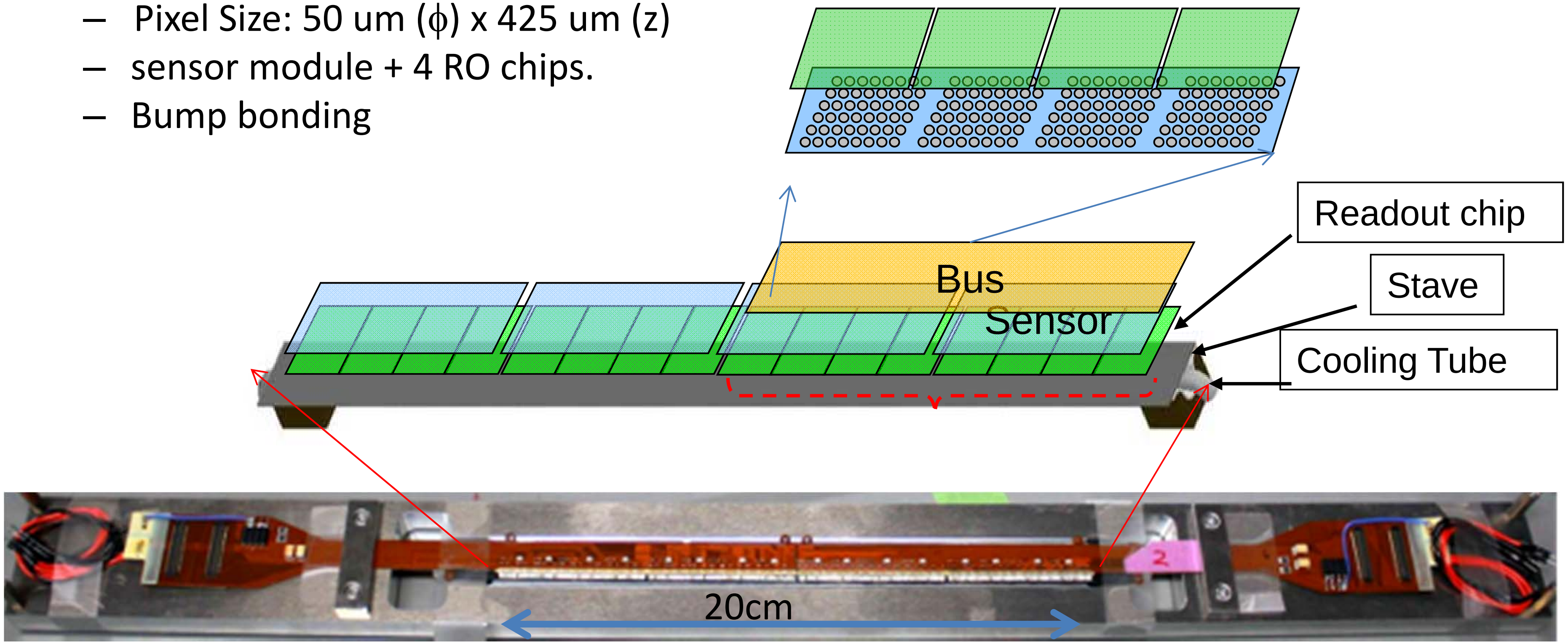


cross-section view



Wires with encap.

Sensor module
(Sensor+4ROchip)

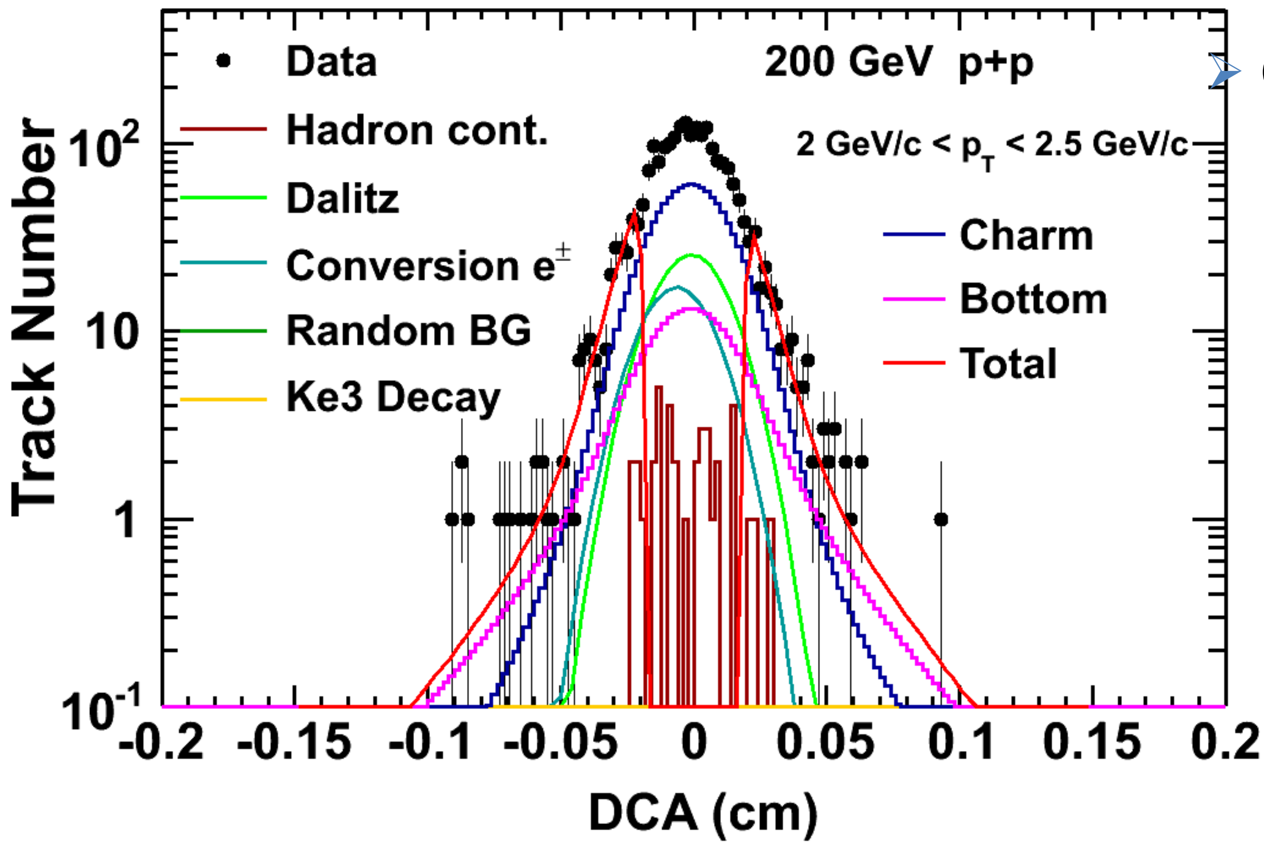


DCA decomposition

DCA Decomposition

DCA data are fit by expected DCA shapes of

- Signal components : c→e and b→e (right column)
- Background components (left column)



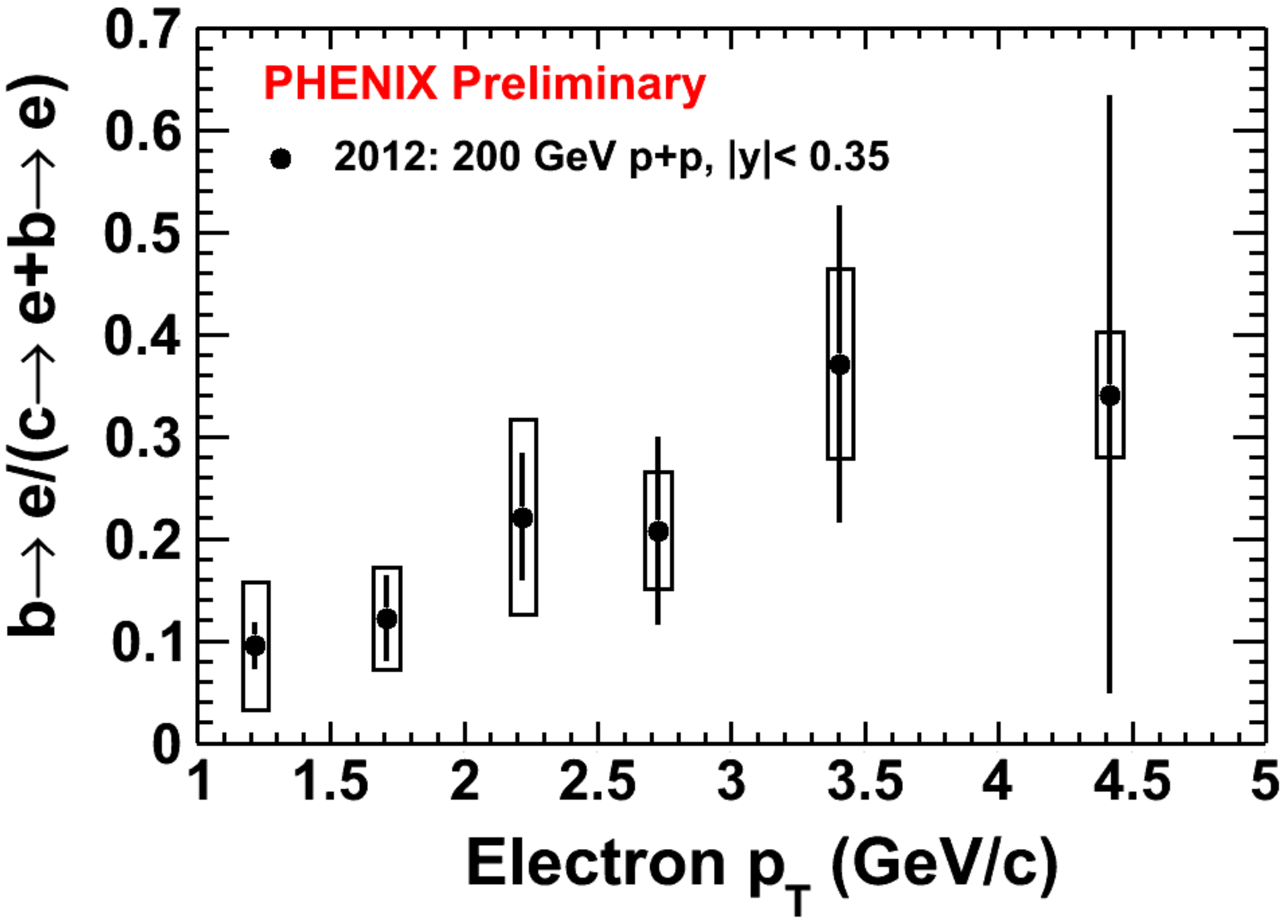
Fit range :
0.2<|DCA|<1.5(mm)

b/(b+c)=0.22+-0.06

- expected DCA shape
  - Charm/Bottom assumes PYTHIA spectra
  - Background : detector simulation with measured data input

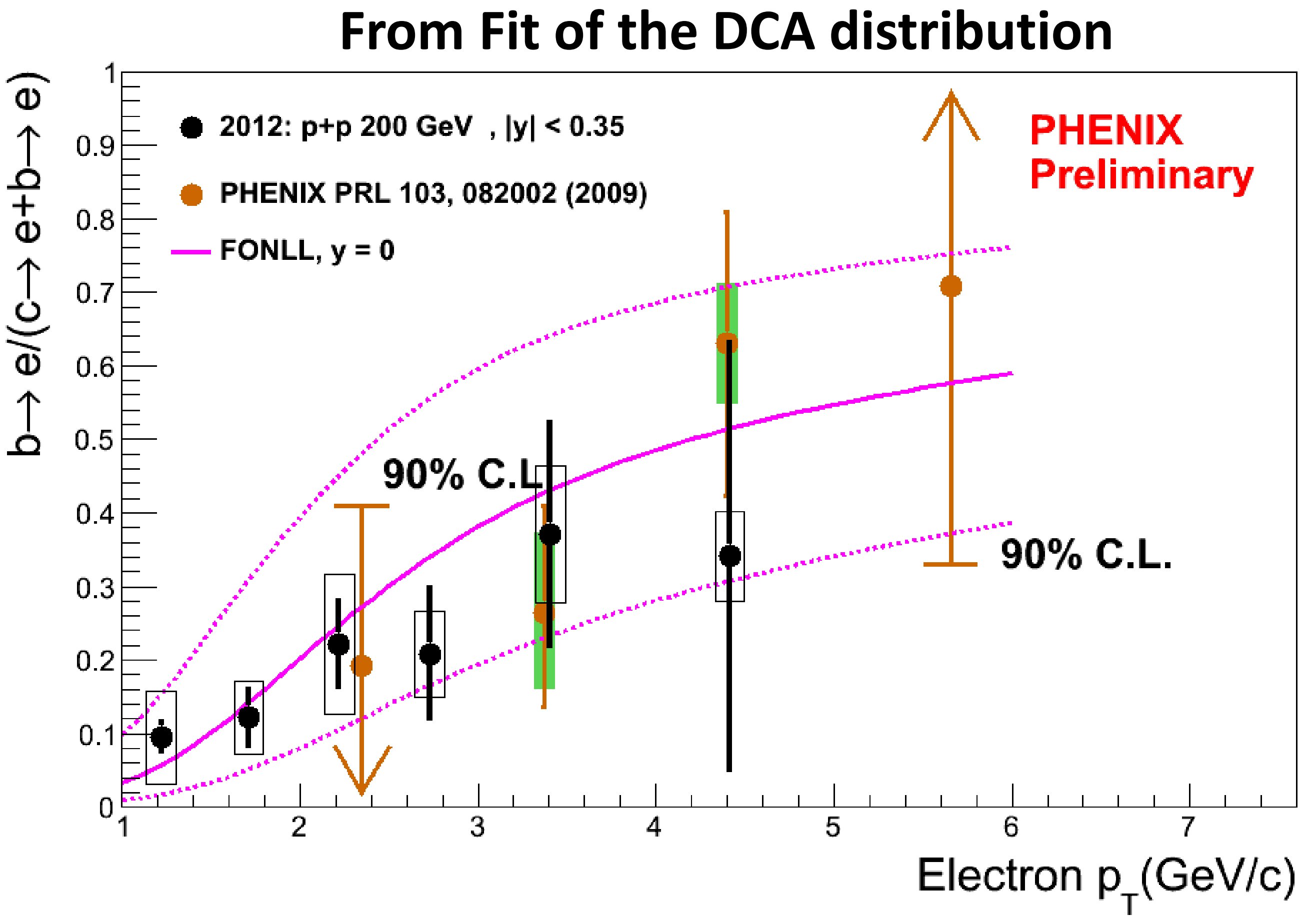
Bottom to HF(b+c) ratio in p+p

From Fit of the DCA distribution $\frac{b \rightarrow e}{c \rightarrow e + b \rightarrow e}$



First direct measurements of bottom production at RHIC in p+p

Comparison

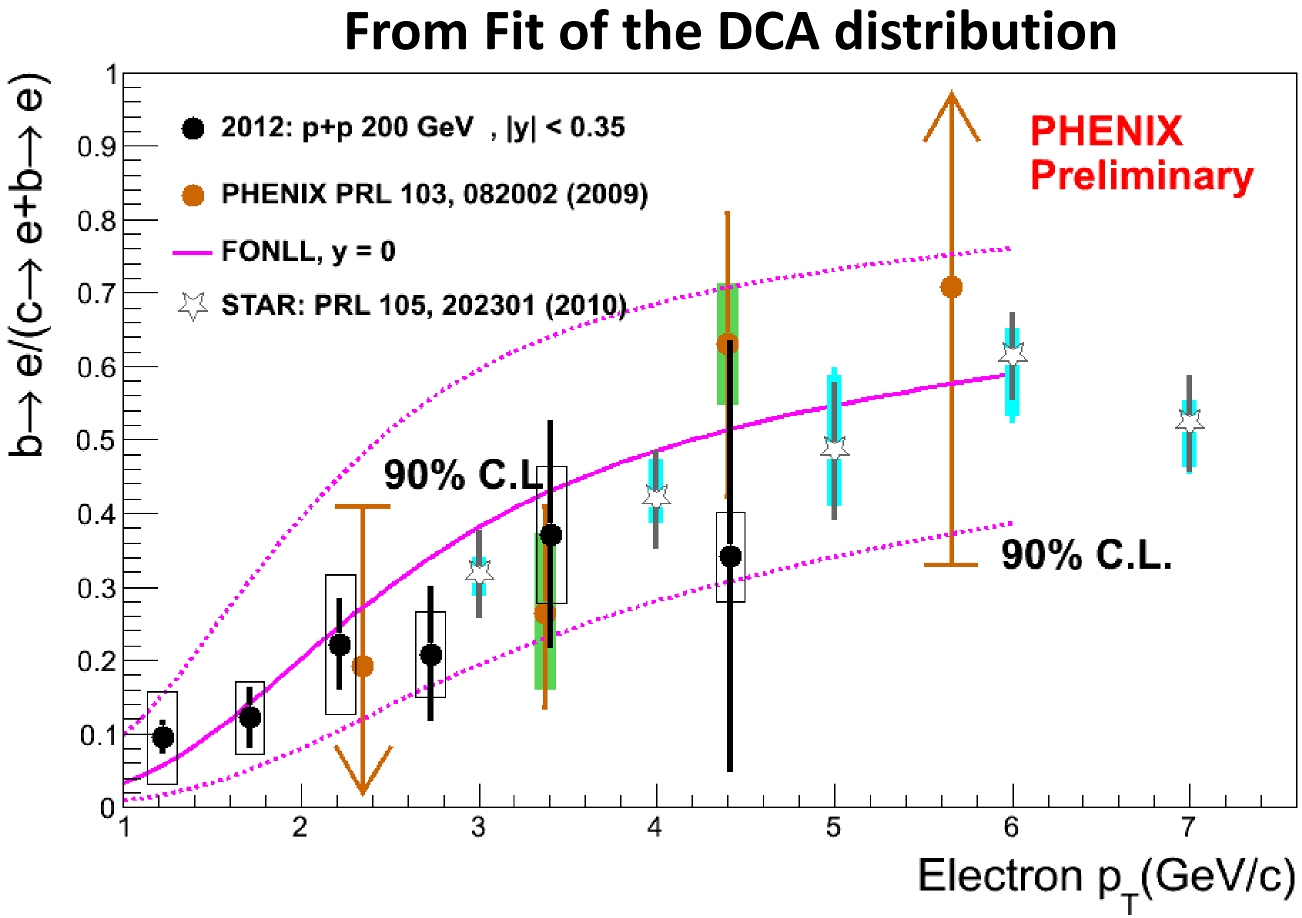


PHENIX Published data agree with new data

FONLL agree with data

VTX direct measurement of b/b+c using DCA confirms published results using e-h correlation

Comparison



PHENIX Published data agree with new data

FONLL agree with data

STAR indirect measurement is consistent with our data

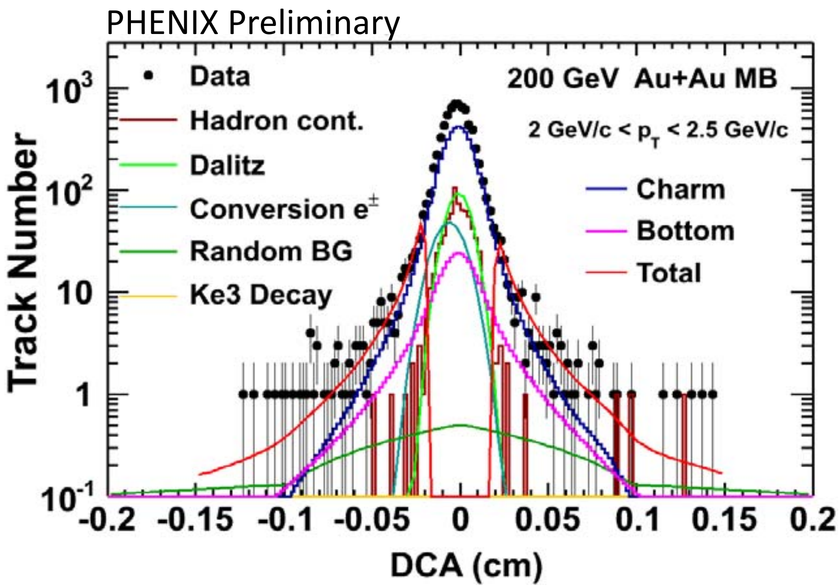
VTX direct measurement of b/b+c using DCA confirms published results using e-h correlation

DCA decomposition in Au+Au

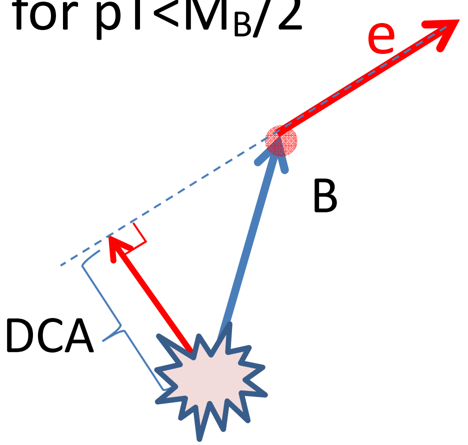
DCA distribution shows:

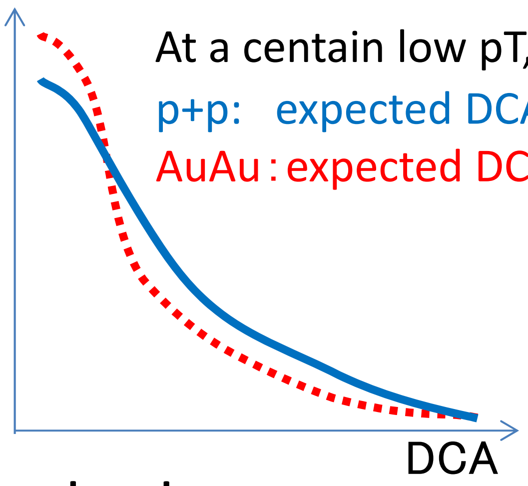
- **N(e) at large DCA is smaller than in pp**
  - **This implies b suppression**

  → B has longer decay length



- Difficulty in Au+Au
  - The expected DCA shape depends on the its parent pT shape
    - It is a convolution of parent pT spectrum and decay kinematics
    - Especially for pT<M_B/2

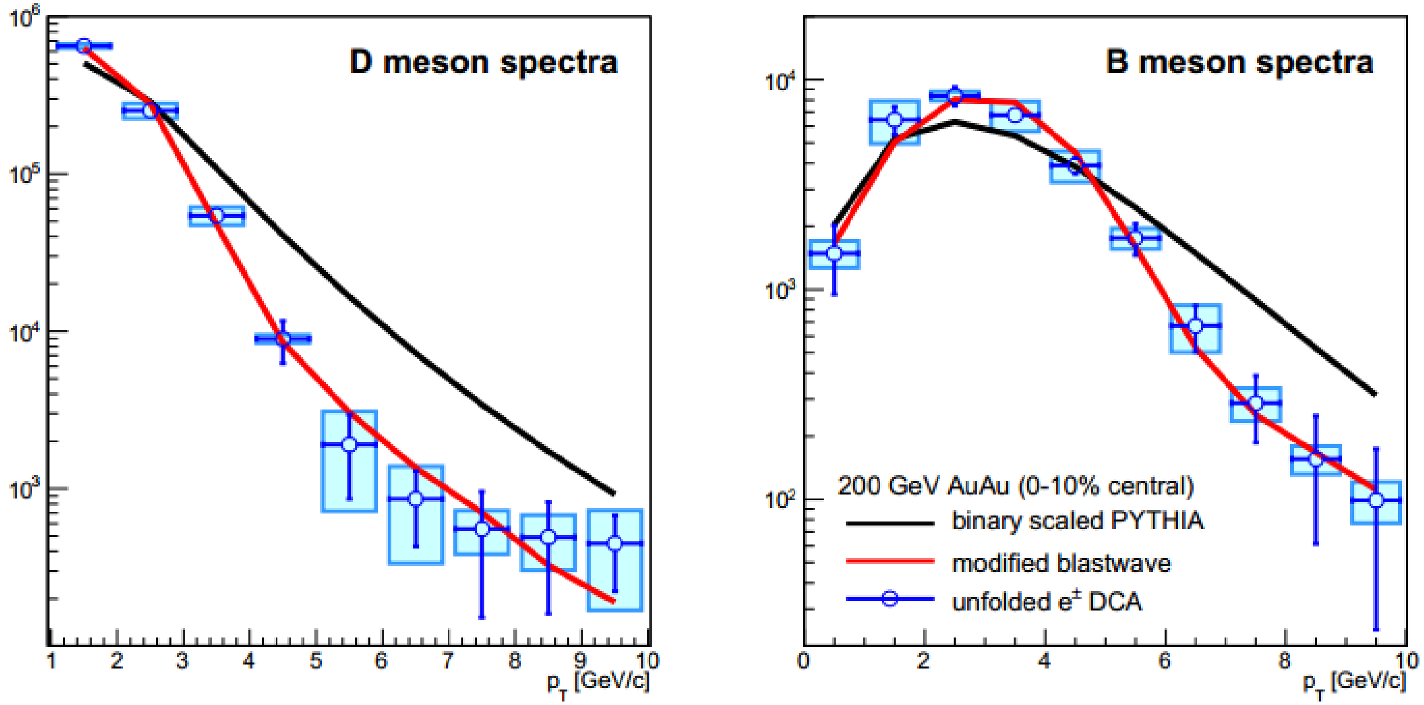




Currently, we are developing new method.

Snapshot of c/b separation

This is simulation



- Some methods are being tested if charm and bottom contribution can be separated properly using HFe DCA distribution.
  - Unfolding technique.
- This method work well to reproduce the input pT distribution of D and B meson
- We keep testing the method what is the best way to remove the bias in the method.

Summary

- Heavy Flavor electrons (from heavy flavor decay) were measured in p+p, d+Au, Au+Au, Cu+Cu 200GeV at RHIC
  - Strong suppression and v2 in Au+Au 200GeV
    - Small eta/s, consistent with other measurement
  - Enhancement in central d+Au
  - Smooth changing from enhancement to suppression in Cu+Cu
  - Some models succeeded reproduce the data.
    - It is necessary to describe overall behavior of Raa and v2 for small-large system
    - Separated measurement of bottom and charm provides further constraint

- Direct measurement
  - D is consistent with HFe suppression at RHIC and LHC
  - Non-prompt J/psi from Bdecay shows R_{AA}(np-Jpsi) > R_{AA}(D) at LHC

- Bottom / charm separation is in progress
  - New method shows better separation in simulation.

Outlook

- Cu+Au and U+U data in run12 is in hand
  - Data analysis is on-going
  - Systematic study of R_{AA} and v2 extends to other systems.

- Au+Au 200 GeV in run14 will start soon
  - We plan to take more data with run11 Au+Au
    - VTX is fully functional
  - Large statistics allows us to measure non-prompt Jpsi in PHENIX