Open Heavy Quarks from PHENIX

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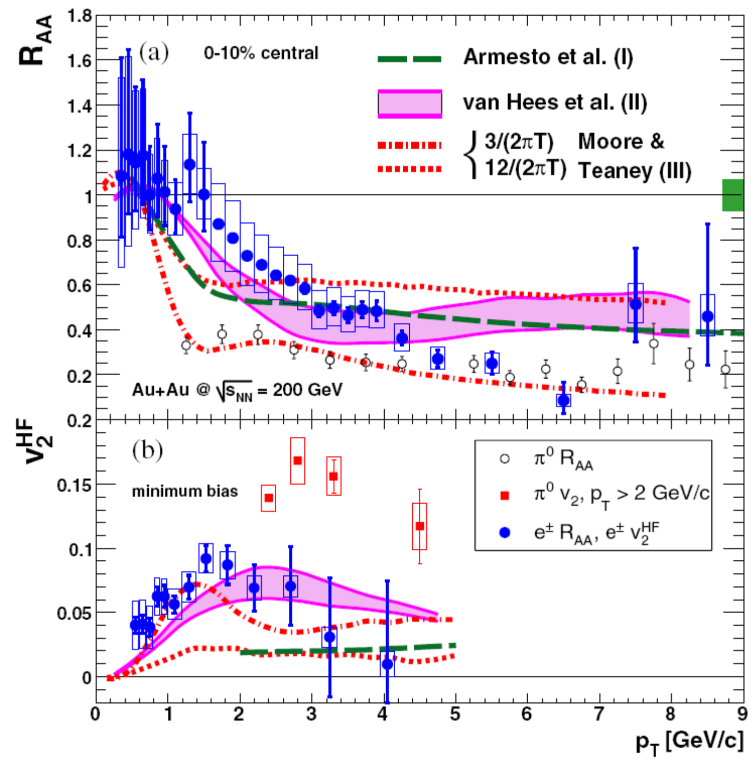
UCLA Heavy-Quark Workshop – 22 Jan 2009

- Charm & Beauty production in p+p
  - multiple measurement techniques
  - forward rapidity
  - separation of beauty & charm
  - dielectrons
- CNM (cold nuclear matter) effects in d+Au
- Effects of the QGP on heavy quarks
  - energy loss, flow
  - dielectrons

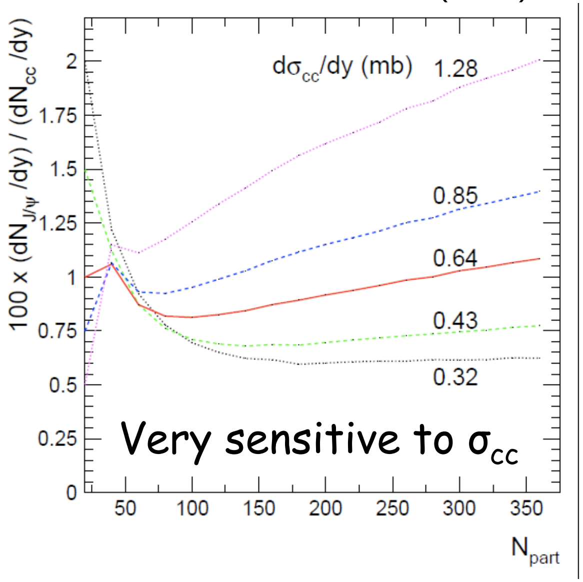


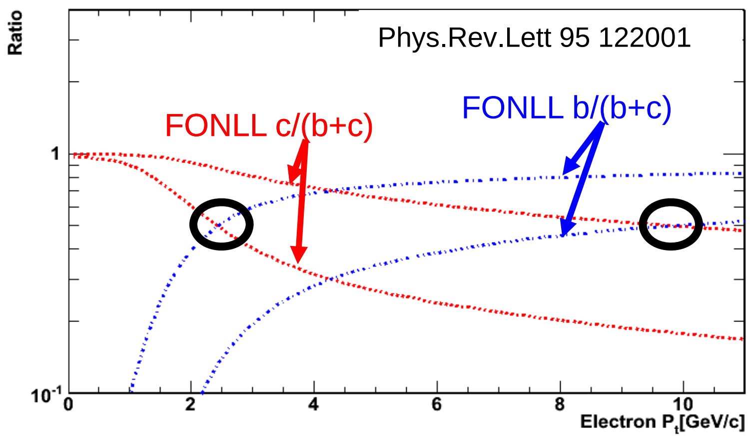
Physics Questions for p+p measurements to address

What is the charm cross section?
• are cross sections really somewhat larger than pQCD?
• important input for regeneration models in charmonia production

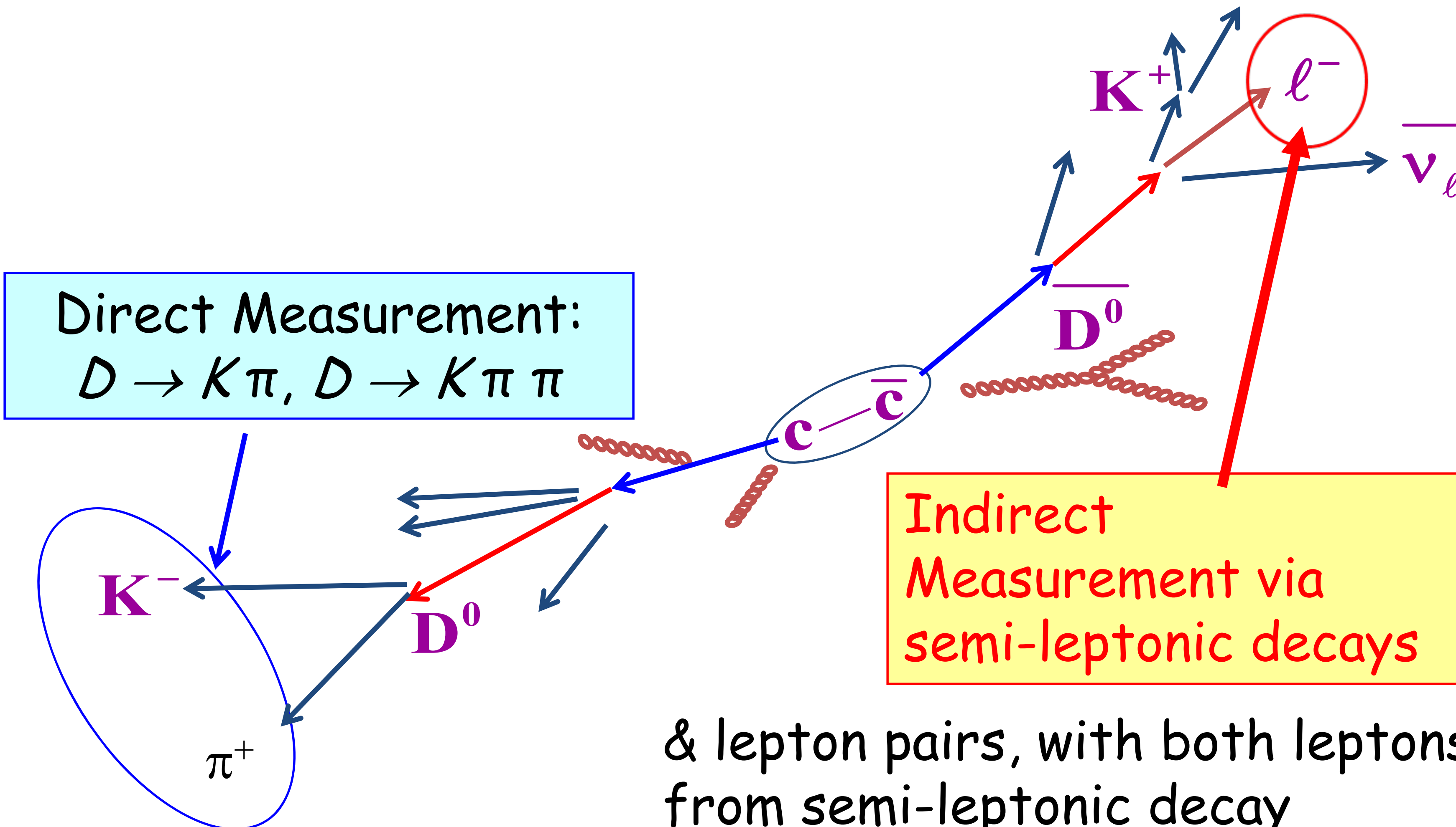
What is the balance between beauty and charm production & at what p_T does beauty start to dominate?
• important for studies of QGP effects, since charm & beauty behave differently (dE/dx & flow)

A. Andronic et al. NPA 789 (2007) 334





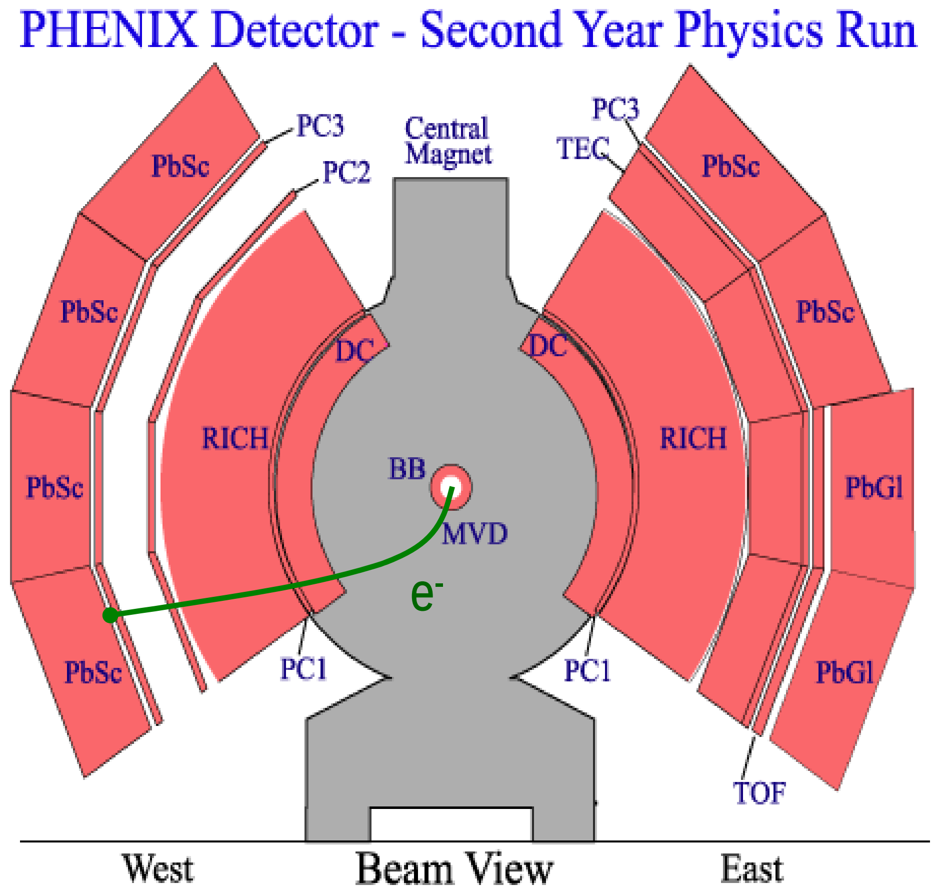
Heavy Quark Measurement



& lepton pairs, with both leptons from semi-leptonic decay

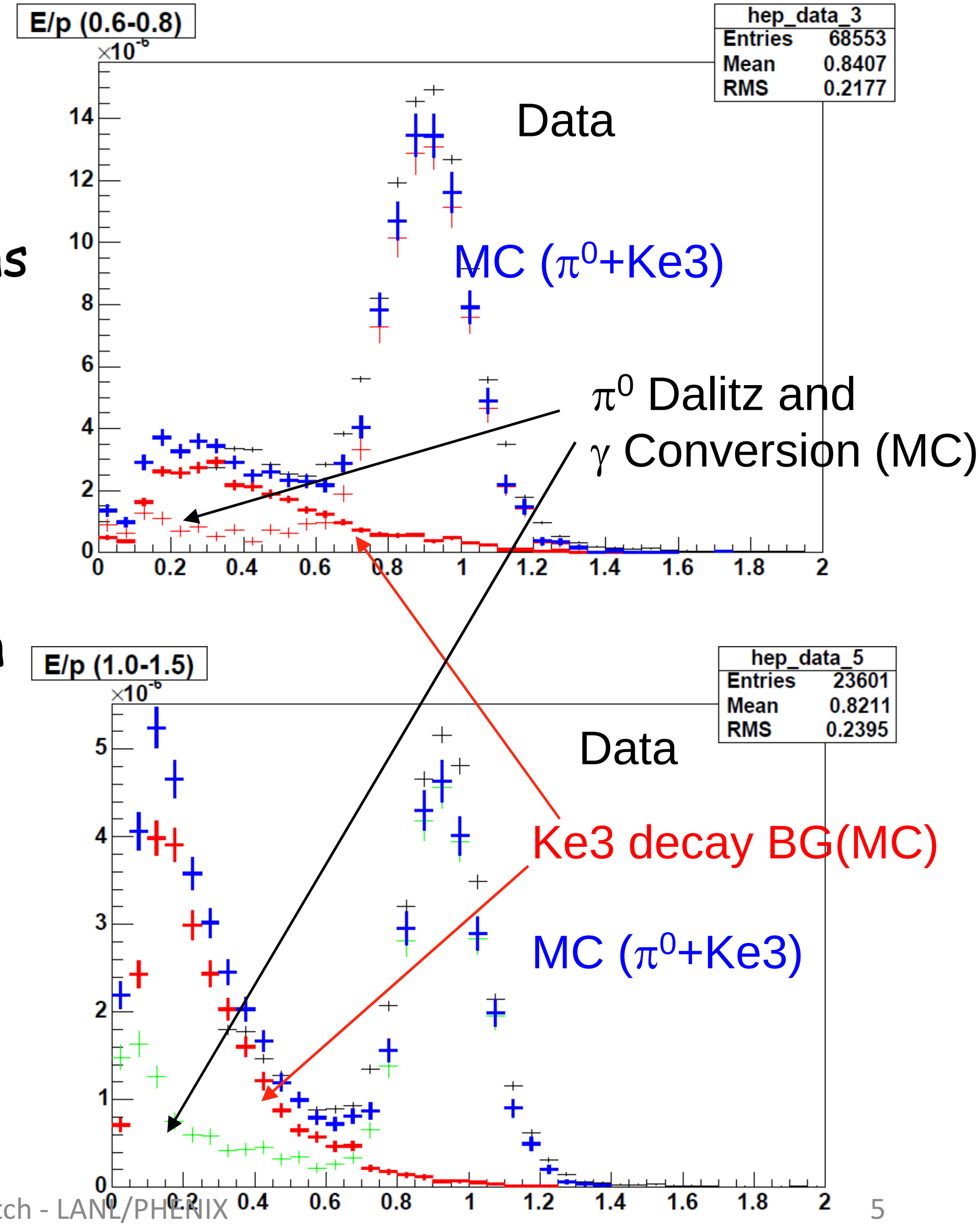
Inclusive $e^{\pm}$ measurement: roadmap

- PHENIX central arm coverage:
  - $|\eta| < 0.35$
  - $\Delta\phi = 2 \times \pi/2$
  - $p > 0.2$ GeV/c
  - typical vertex selection: $|z_{vtx}| < 20$ cm
- charged particle tracking analysis using DC and PC1
- electron identification based on
  - Ring Imaging Cherenkov detector (RICH)
  - Electro-Magnetic Calorimeter (EMC)



Electron identification

- Electron identificaition is very easy for $p_T < 5$ GeV/c
- After RICH hit is required, basically all tracks are electrons
- Electron signal is clearly visible in E/p ratio distribution (the peak ~ 1 is the electron)
- The tail part is due to off vertex conversion and Ke3 decay.
- MC reproduces the distribution very well.
- In the plots, the data and the MC are absolutely normalized



Electron Signal and Background

Photonic electron

- **Photon conversions**

  $\pi^0, \eta \rightarrow \gamma\,\gamma,$

  $\gamma \rightarrow e^+ e^-$ in material

  Main background
- **Dalitz decays**

  $\pi^0, \eta \rightarrow \gamma\, e^+ e^-$
- **Direct Photon**

  Small but significant at high p_T

  Measured by PHENIX

Non-photonic electron

- **Heavy flavor electrons**

  $D \rightarrow e^{\pm} + X$
- **Weak Kaon decays**

  K_{e3}: $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu_e$

  < 3% of non-photonic in p_T > 1.0 GeV/c
- **Vector Meson Decays**

  $\omega, \rho, \phi, J/\psi, \Upsilon \rightarrow e^+ e^-$

  < 2-3% of non-photonic in all p_T

Background is subtracted by two independent techniques:

- Cockail Method
- Converter method

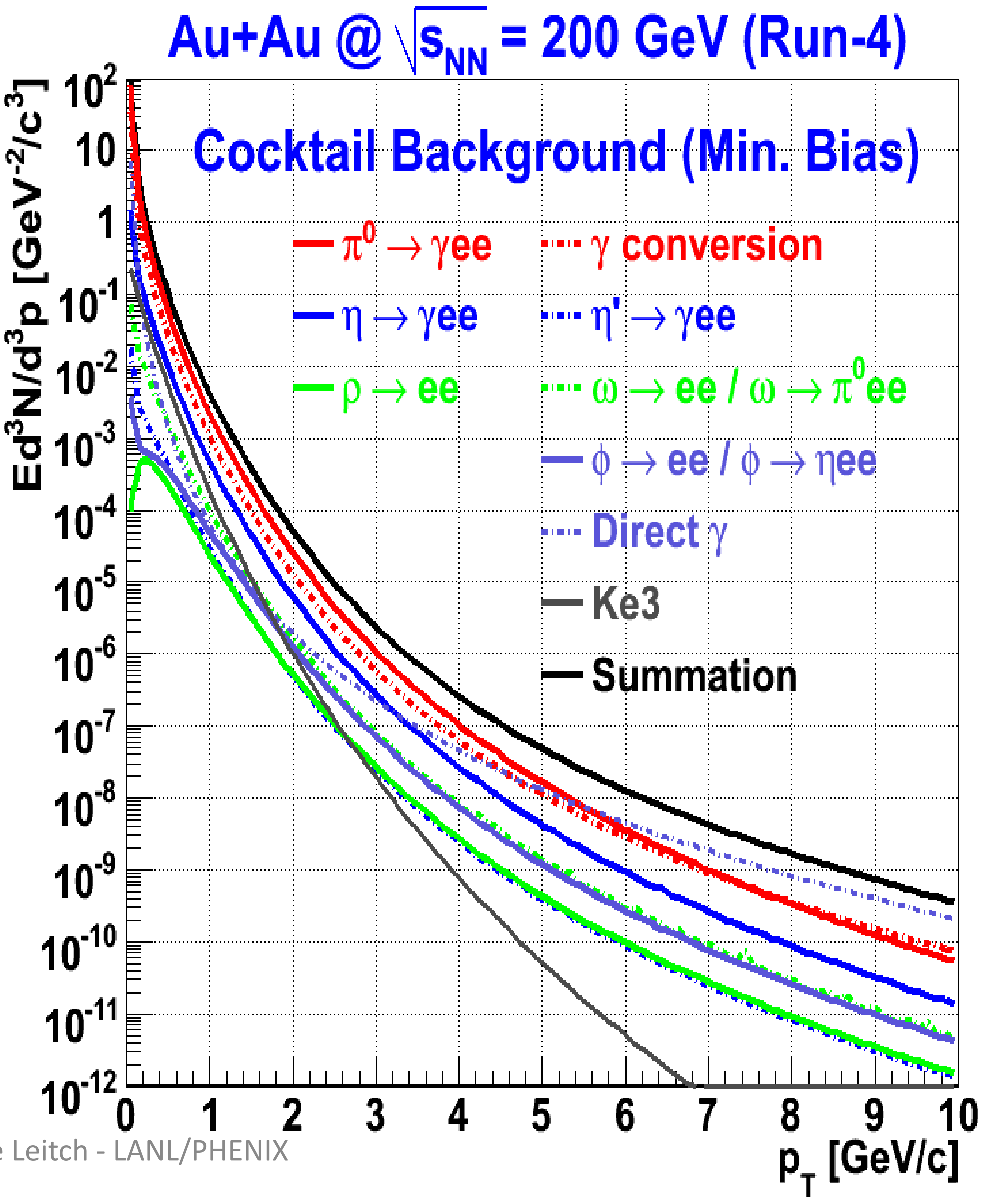
Background Subtraction: Cocktail Method

Most sources of background have been measured in PHENIX

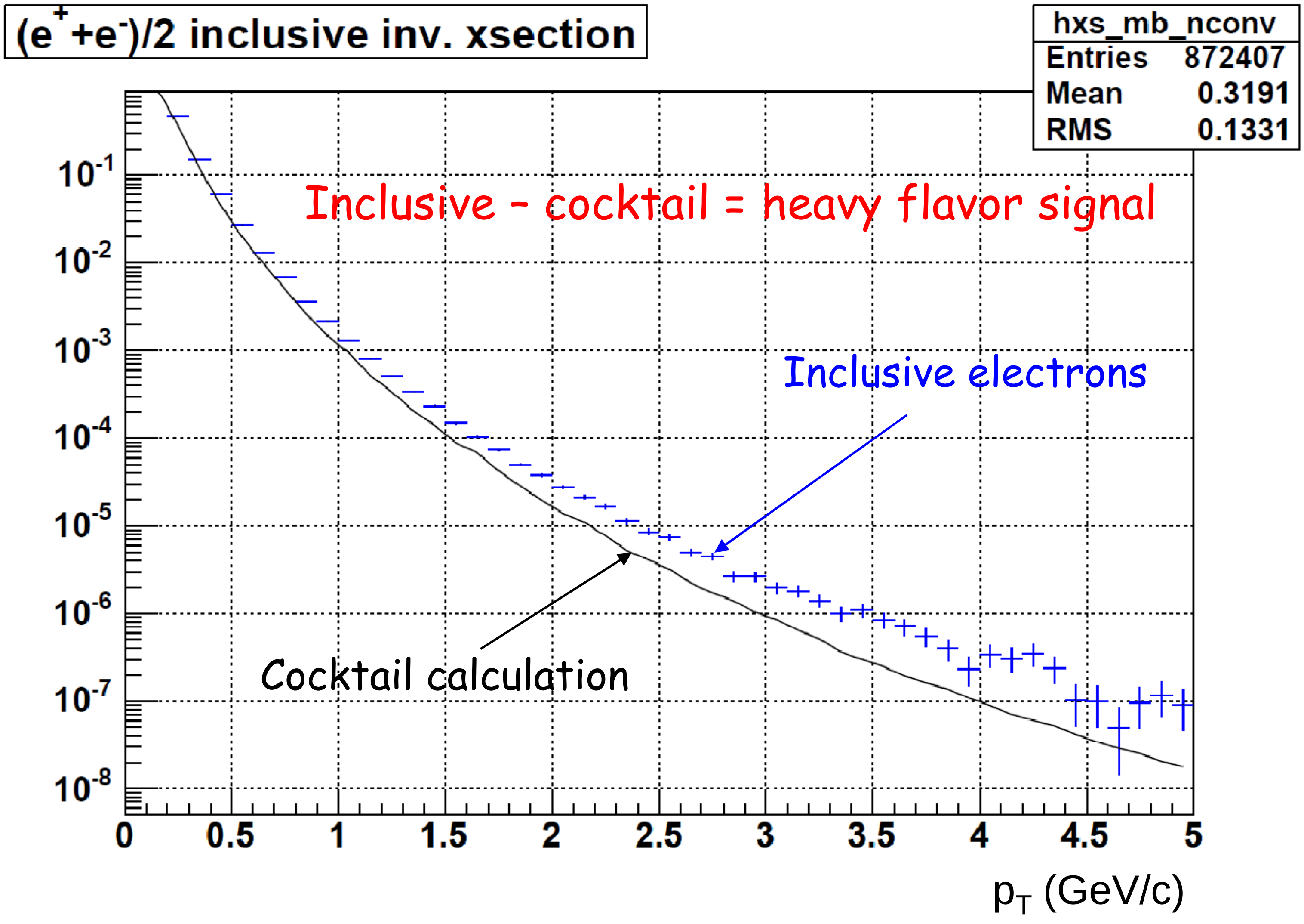
Decay kinematics and photon conversions can be reconstructed by detector simulation

Then, subtract "cocktail" of all background electrons from the inclusive spectrum

Advantage is small statistical error.

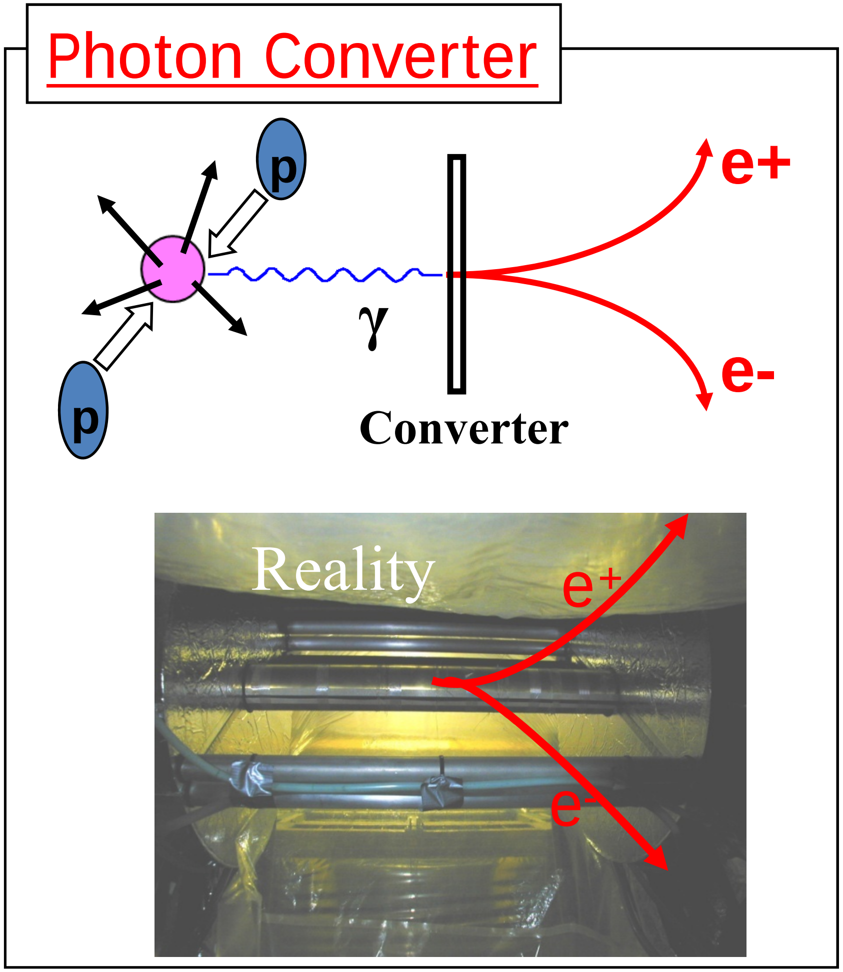


Inclusive vs cocktail



Converter subtraction method

- introduce additional converter in PHENIX acceptance for a limited time
  - 1.68 % X_0 brass foil close to beam pipe
  - increases yield of photonic electrons by a fixed factor
  - comparison of spectra with and without converter installed allows separation of electrons from photonic and non-photonic sources



Converter subtraction: the calculation

- electron yields:

$$N_e^{Conv-out} = N_e^{\gamma} + N_e^{non-\gamma}$$

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

- useful definitions:

$$R_{CN} = N_e^{Conv-in} / N_e^{Conv-out}$$

$$R_{NP} = N_e^{non-\gamma} / N_e^{\gamma}$$

- then:

$$R_{CN} = \frac{R_\gamma + (1-\varepsilon) R_{NP}}{1 + R_{NP}}$$

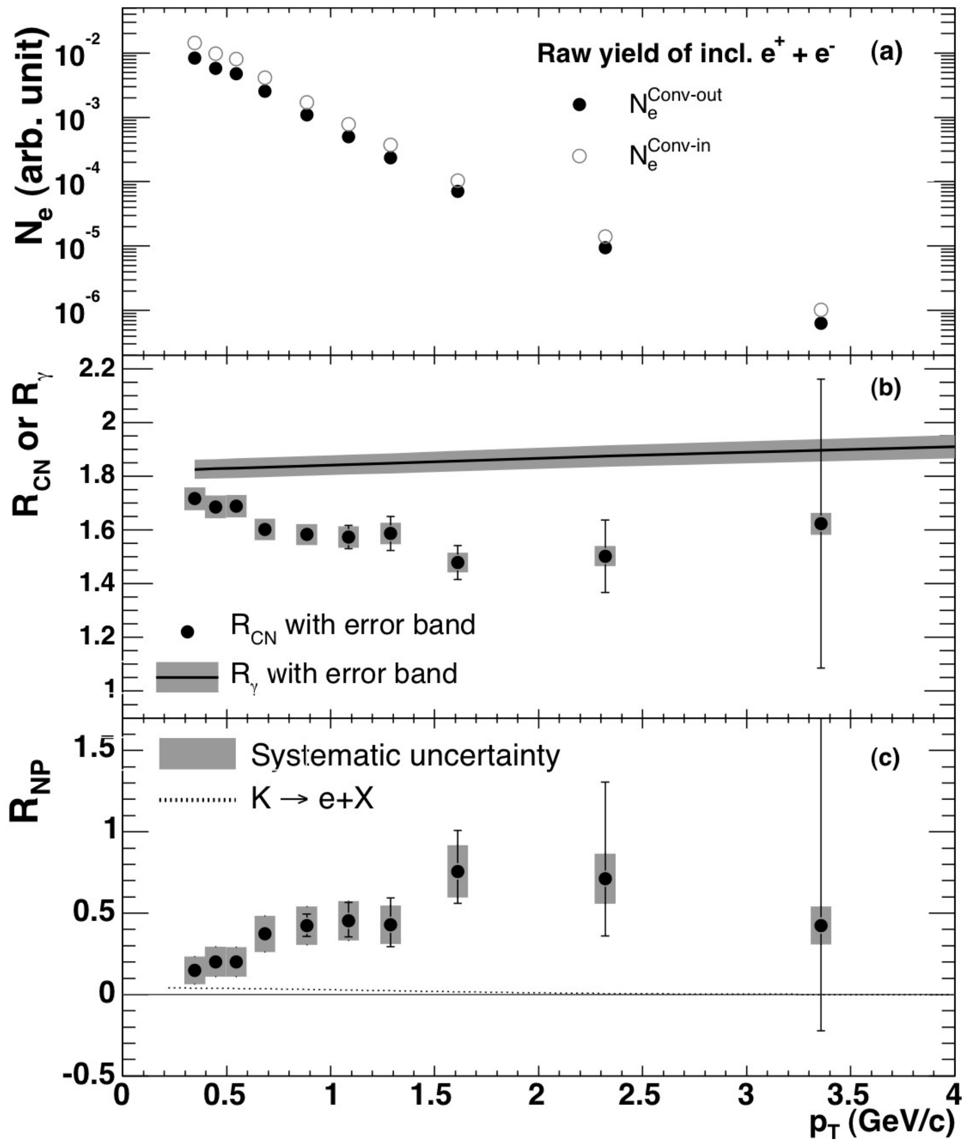
electron loss in converter (ε)

simulated (R_γ)

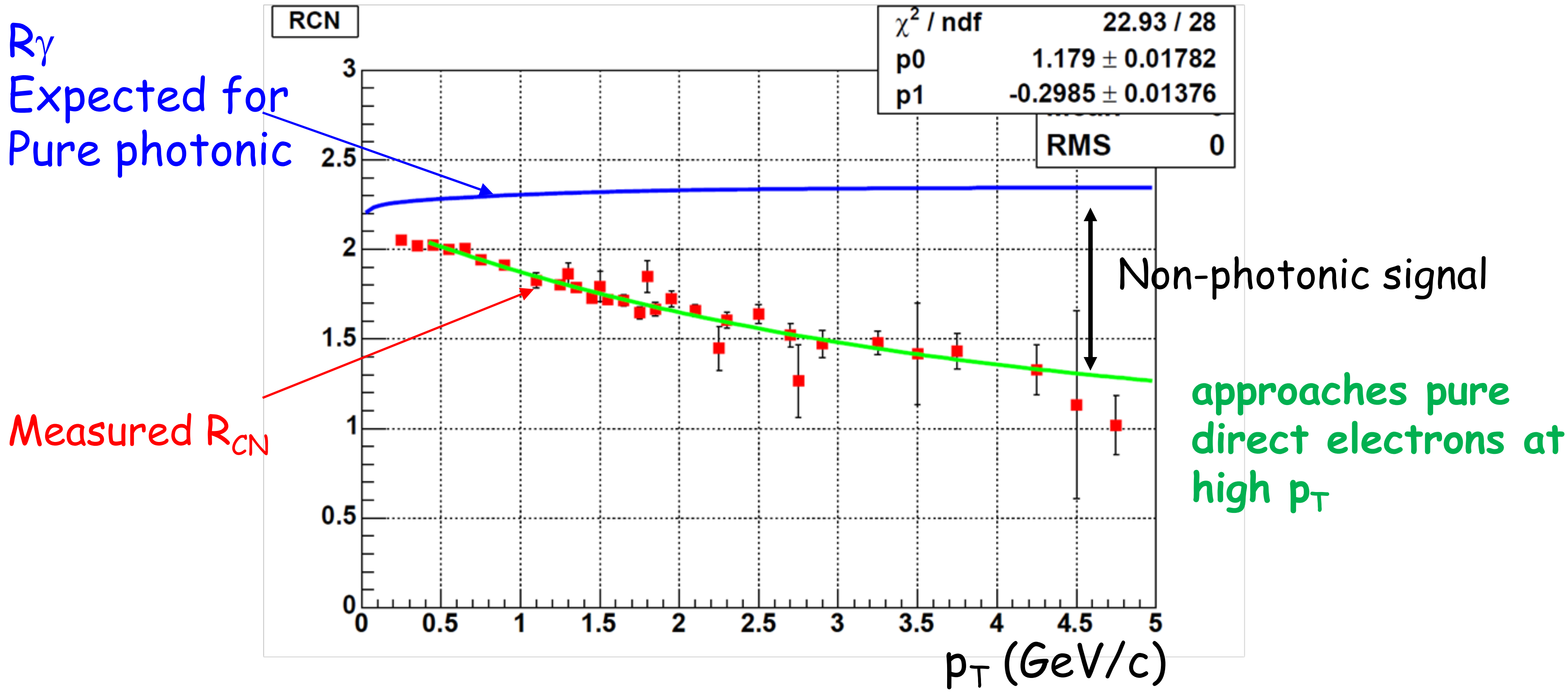
measured (R_{CN})

calculated from this equation! (R_{NP})

PRL 94(2005)082301 (run2 AuAu)

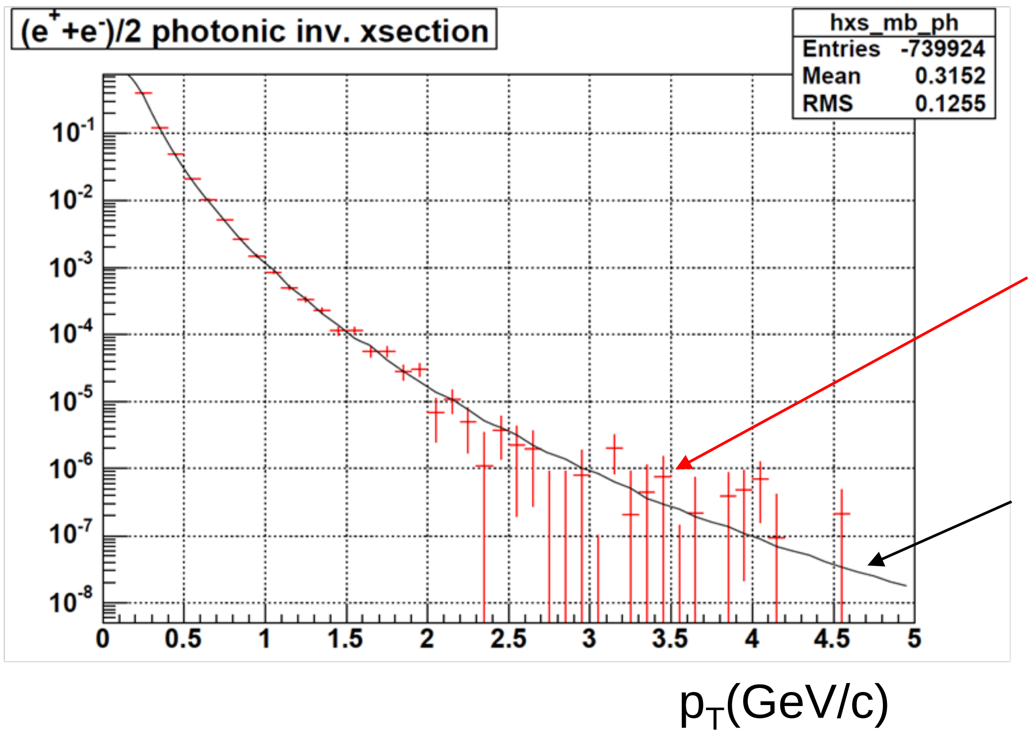


Converter/(no converter), R_{CN}, in p+p Run-5



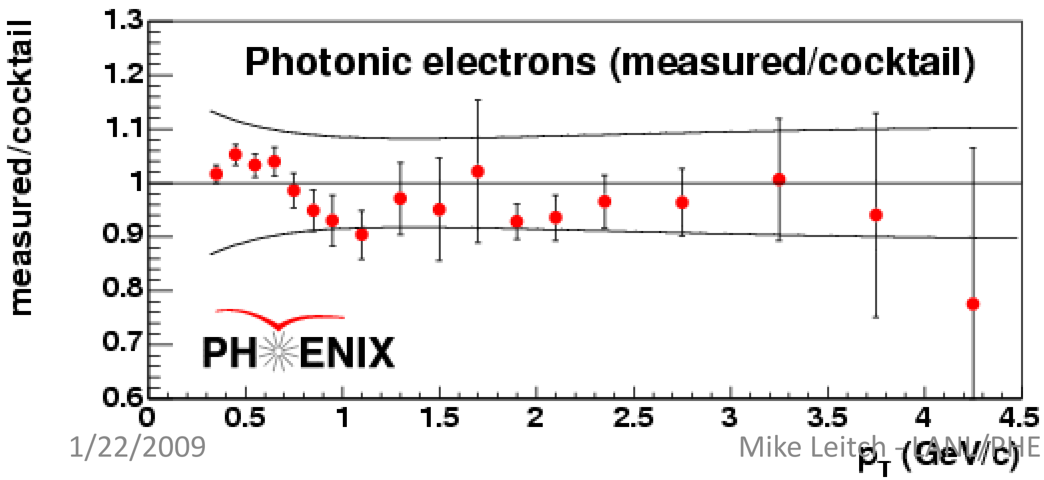
- R_{CN} is ratio of "raw" electron spectra!
- signal/background is LARGE (see next slide) and increases as function of p_T!

Cross-check: Cocktail vs Photonic (measured)



Red:
Measured photonic electron spectrum using the converter method

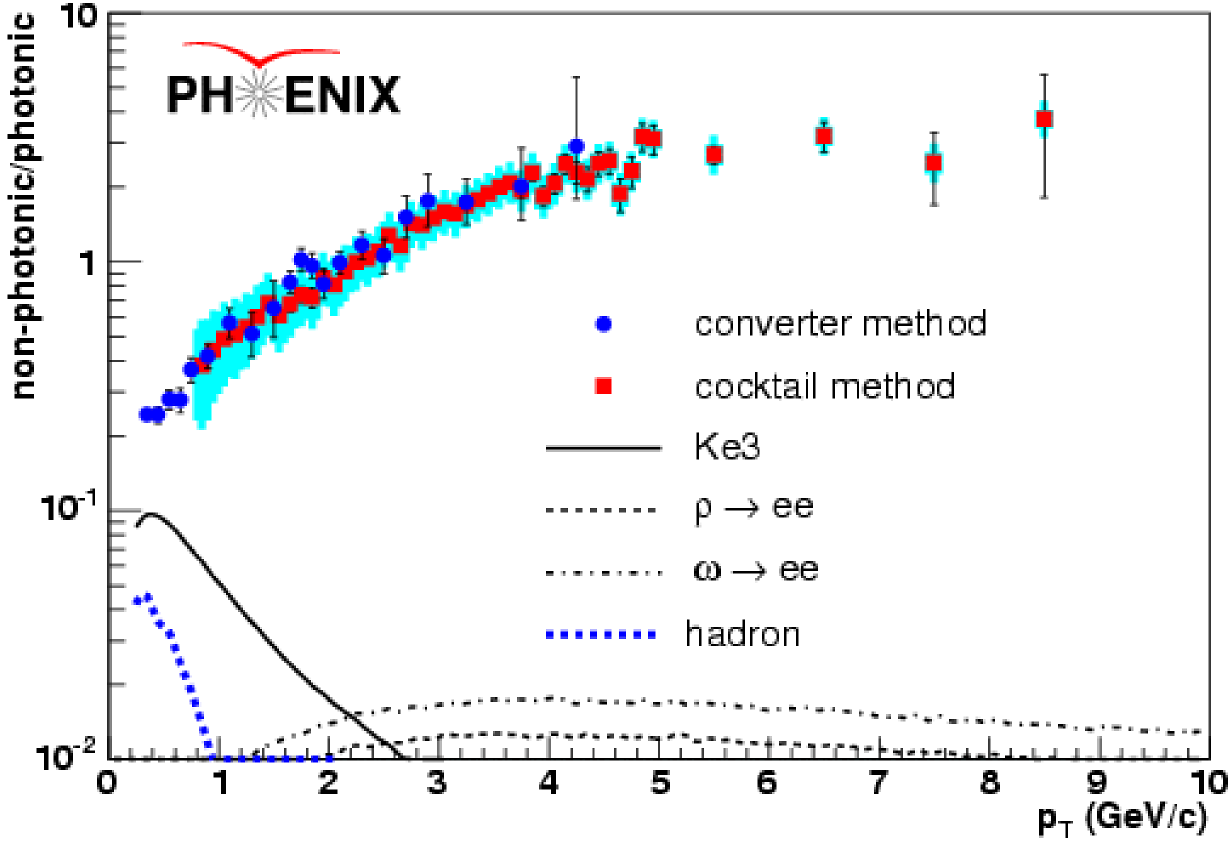
Curve:
Cocktail calculation



Photonic electron Measured/Cocktail=0.94±0.04

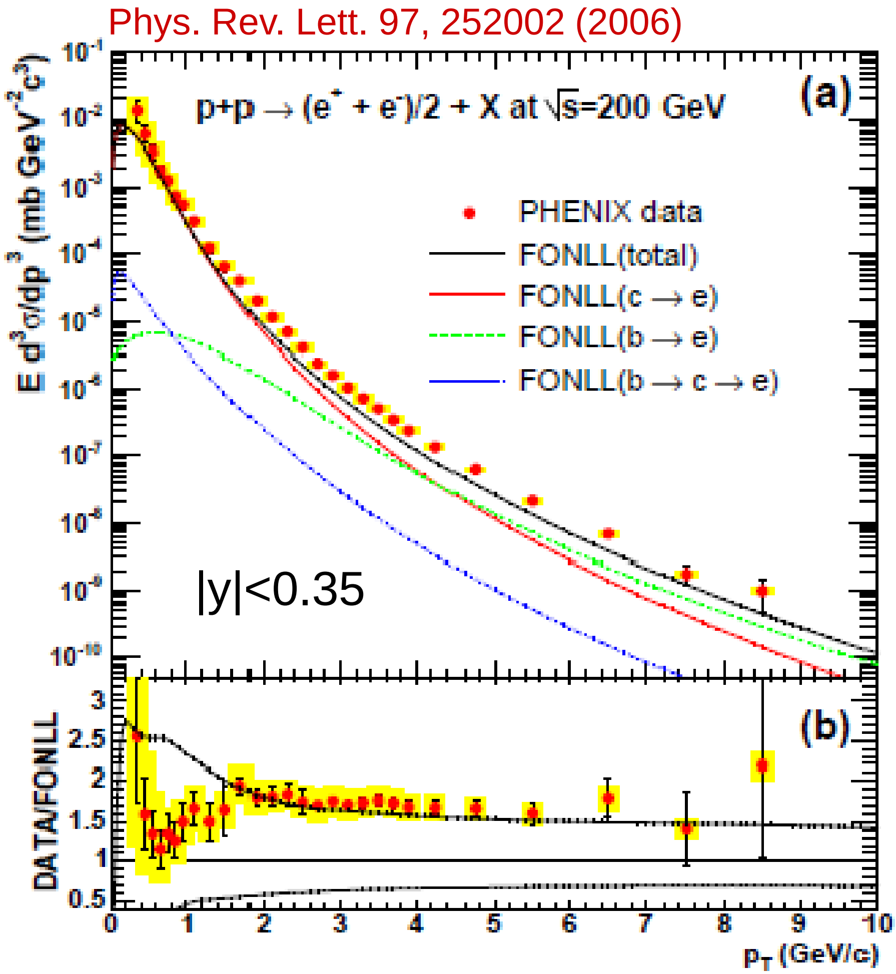
Consistent within cocktail systematic error
→ Used to re-normalize cocktail

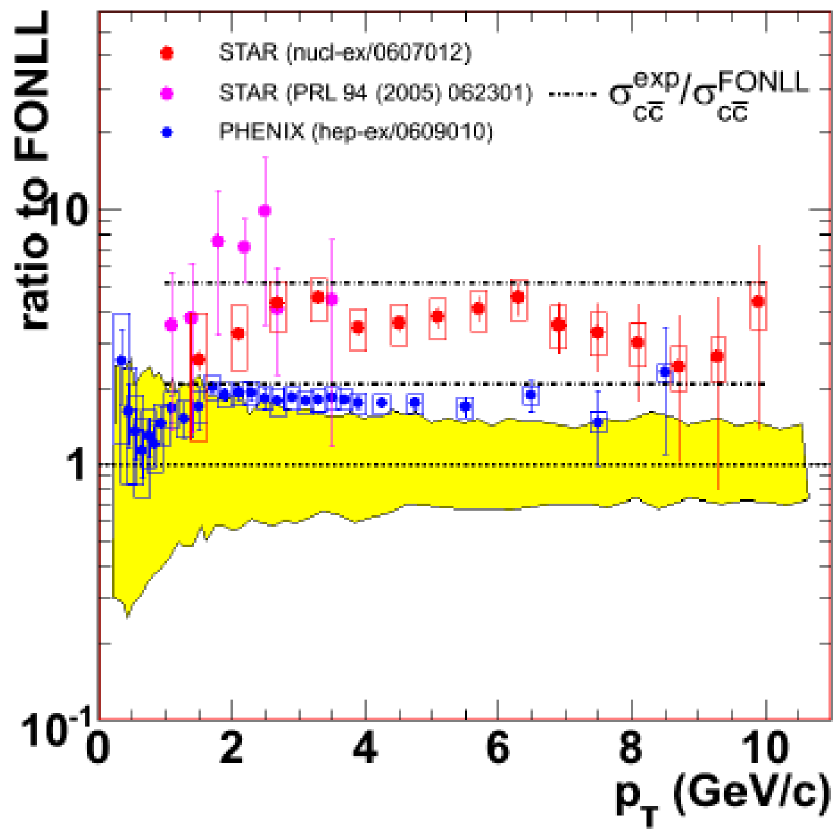
Signal/Background of Heavy Flavor electrons



- S/B = 0.1 to ~3
- Large S/B is due to small conversion material in PHENIX acceptance

Heavy flavor measurement at mid-rapidity

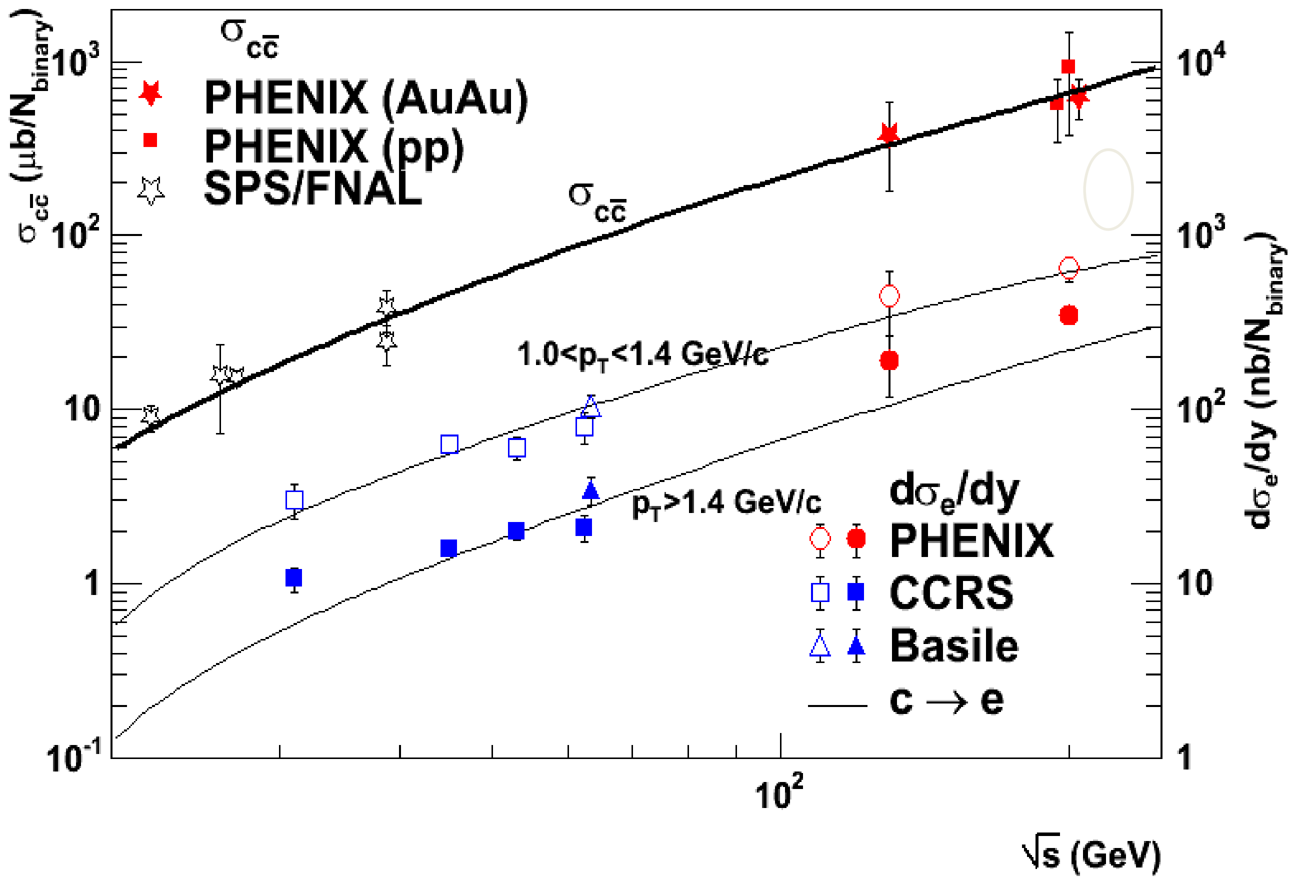




Ratio to FONLL calculations are on the high side of theoretical uncertainties.

About a factor 2 discrepancy with STAR measurement (being worked on)

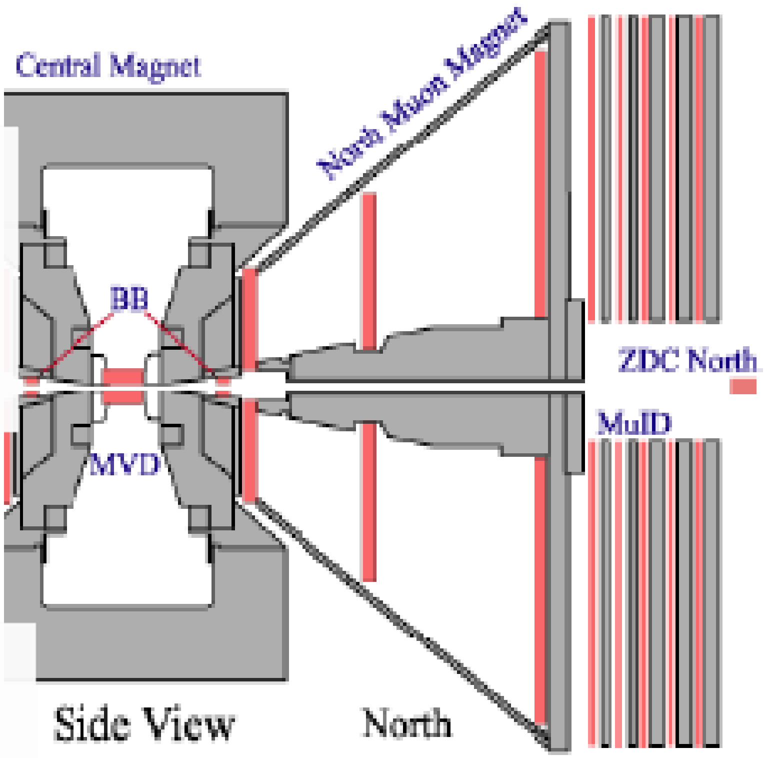
Total Charm Cross Section



$$\sigma_{C\overline{C}} = 567 \pm 57(stat) \pm 224(syst)\,\mu b$$

Phys. Rev. Lett. 97, 252002 (2006)

Heavy flavor measurement at forward rapidity



Measure inclusive single muon spectrum

- Front absorber to reject hadrons
- Cathode strip chambers to track muons
- Iarocci tubes + absorbers for identification and trigger

Subtract background sources using simulated hadron cocktail

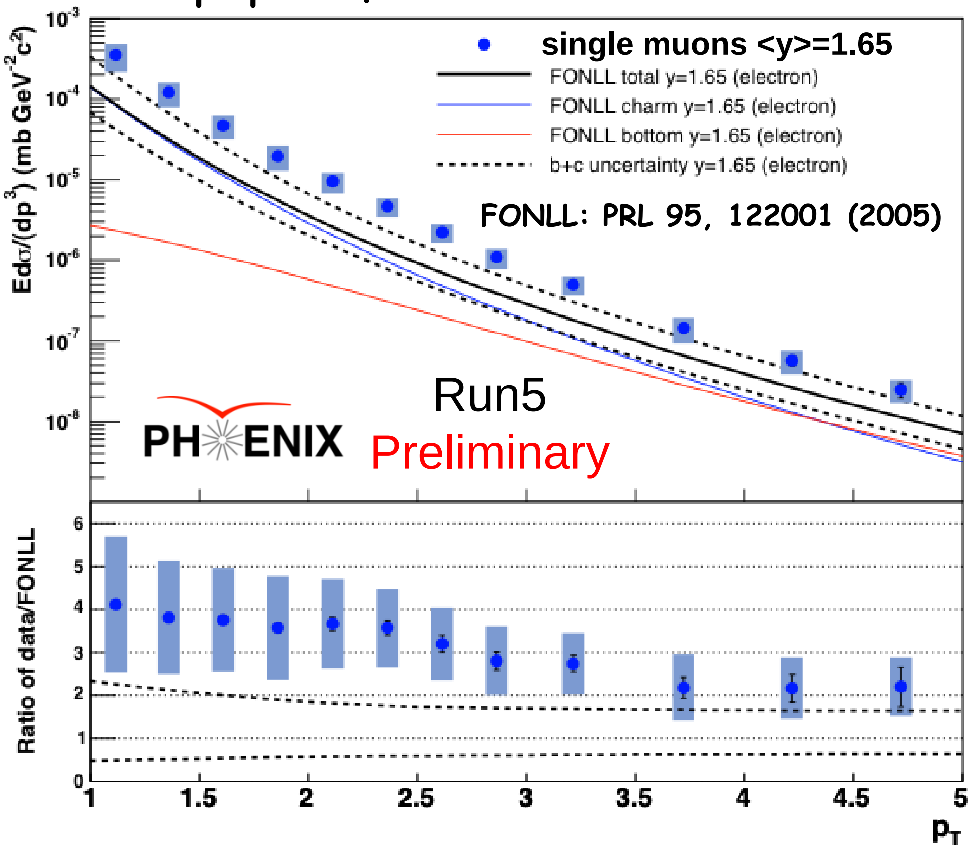
- Muons from hadron decay
- punch-through hadrons

Tune the cocktail on real data to reproduce :

- Stopped hadrons distributions in MuID gap 2 and 3
- Decay muons stopping at gap 3, (estimated using vertex z distribution)

Heavy flavors in p+p collisions at forward rapidity
p+p single muon spectra

p+p → μ+X at √s=200 GeV



Ratio to FONLL is 3.75 ±0.07 (stat.) ±1.35 (sys.)

Forward and backward (<y>=1.65) measurements are in good agreement and statistically combined

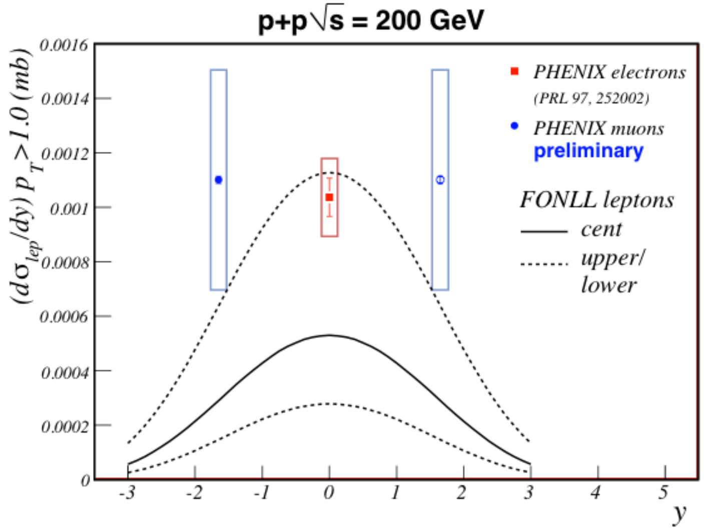
Consistent with the previous PHENIX single muon measurement (*PRD 76, 092992 (2007)*)

Compare to FONLL c+b:

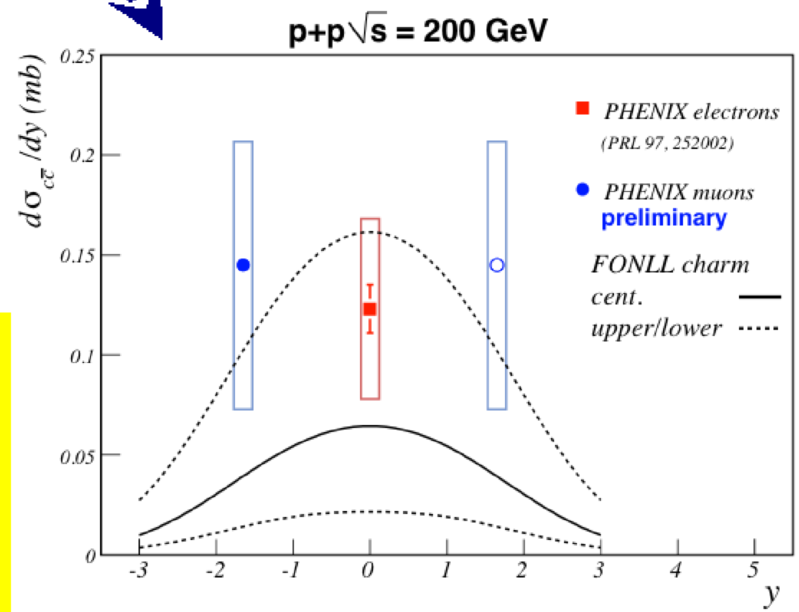
Ratio to FONLL calculations varies from 4 at low p_T to 2 at high p_T, very similar to case at mid-rapidity.

Integrated spectra: $d\sigma_{ccbar}/dy$ y=0 and y=1.65

leptons $p_T > 1.0$ GeV/c



Integrate the single muon spectra, extrapolate to p_T=0 and convert to $d\sigma_{ccbar}/dy$ using FONLL.

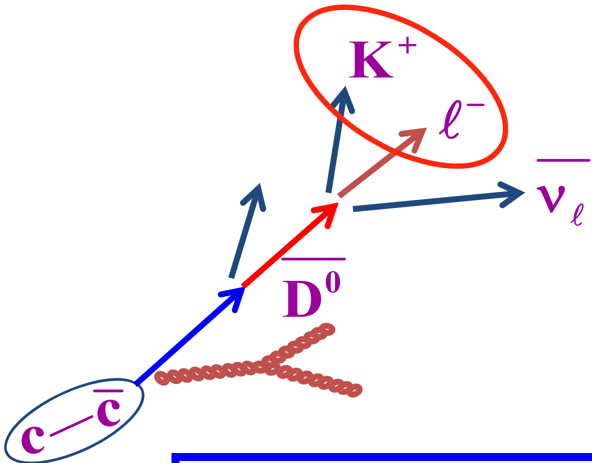


Forward muon result in good agreement with the existing mid-rapidity single electron point.

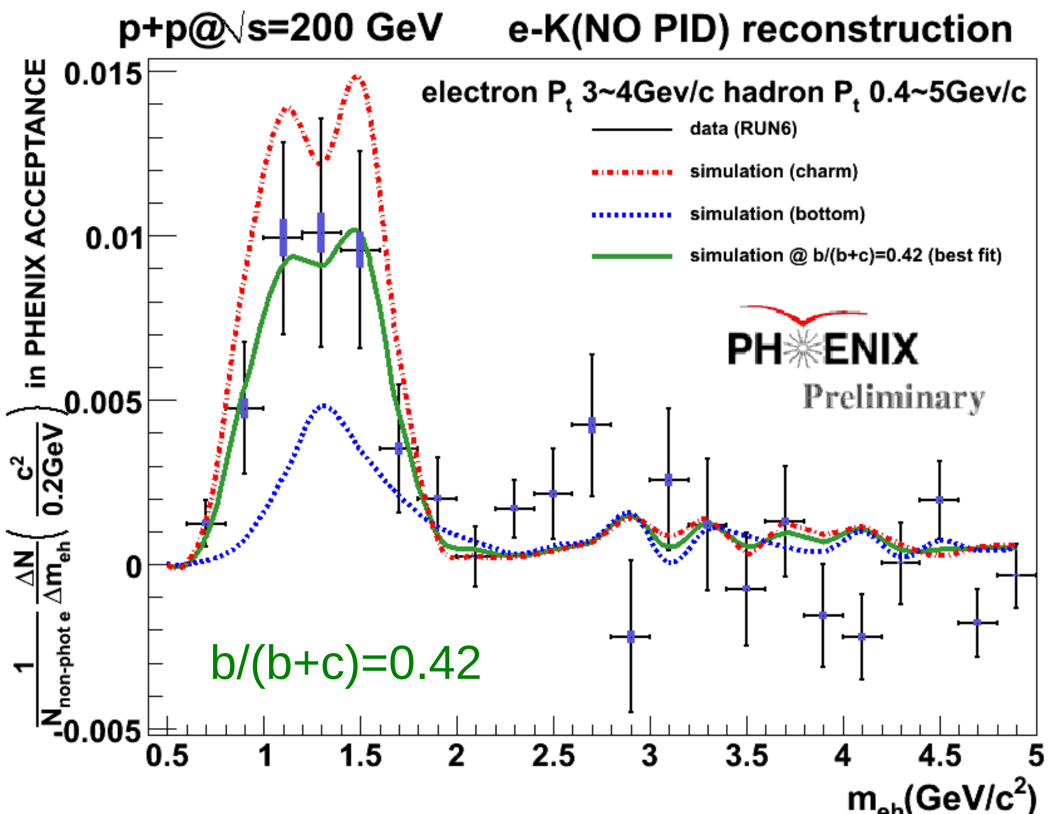
$$d\sigma_{c\bar{c}}/dy|_{y=0}$$
$$= 0.123 \pm 9.8\%\,(\text{stat}) \pm 36.5\%\,(\text{sys})$$
$$d\sigma_{c\bar{c}}/dy|_{y=1.65}$$
$$= 0.145 \pm 1.1\%\,(\text{stat}) + 42.7\% / -49.8\%\,(\text{sys})$$

Charm and bottom separation (mid-rapidity)

D/B semi-leptonic decay



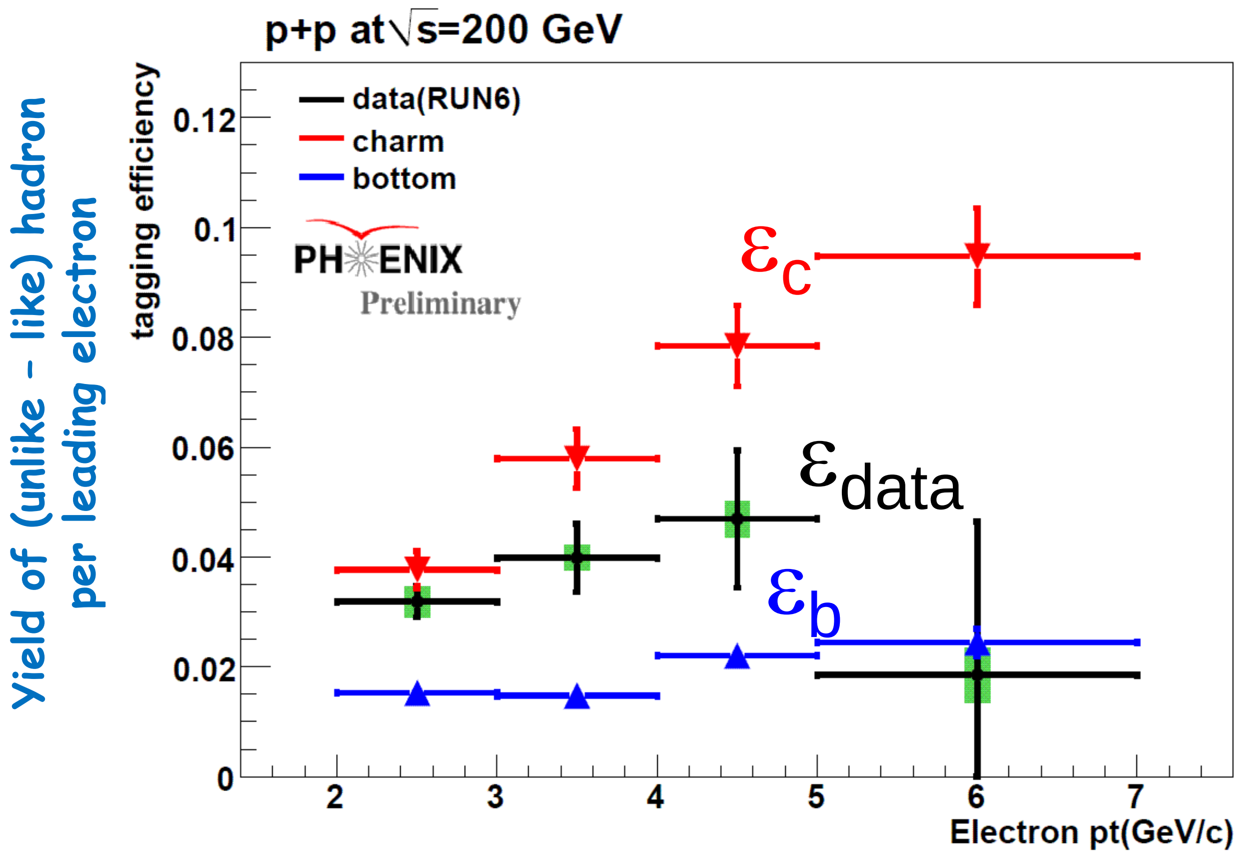
$$\frac{N_{b\to e}}{N_{c\to e}+N_{b\to e}} = \frac{\epsilon_c - \epsilon_{data}}{\epsilon_c - \epsilon_b}$$



Study the b,c → e-h decay unlike-sign pair correlations (m_{eh})

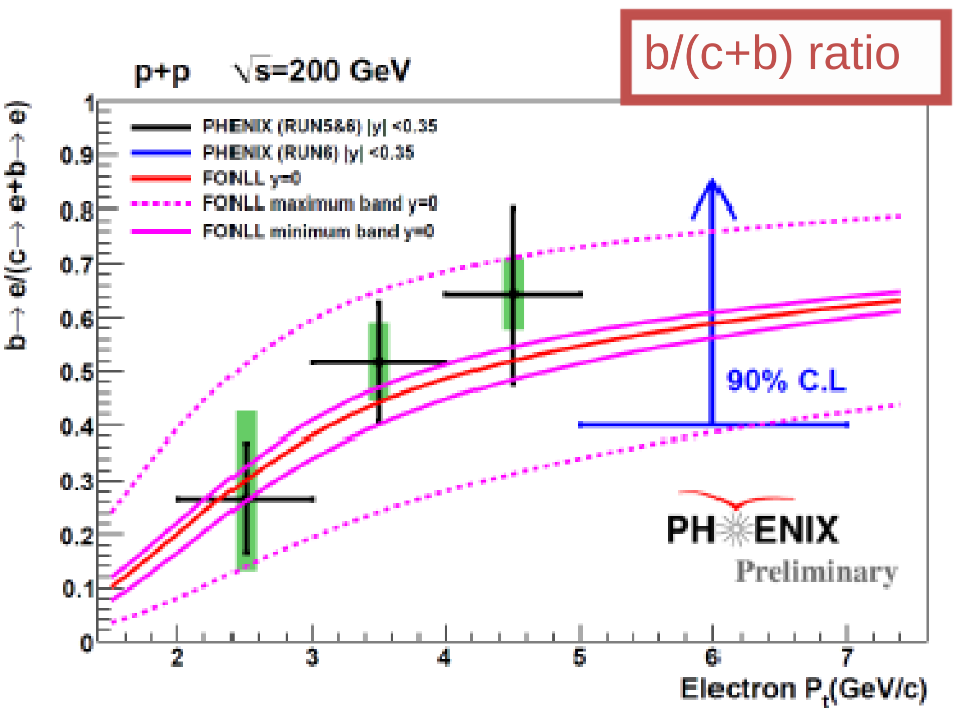
- subtract like-sign to remove (photonic) backgrounds
- efficiency for correlation larger for charm (smaller mass) than beauty
- data lies in between Pythia c and b efficiency, fit to determine fractions

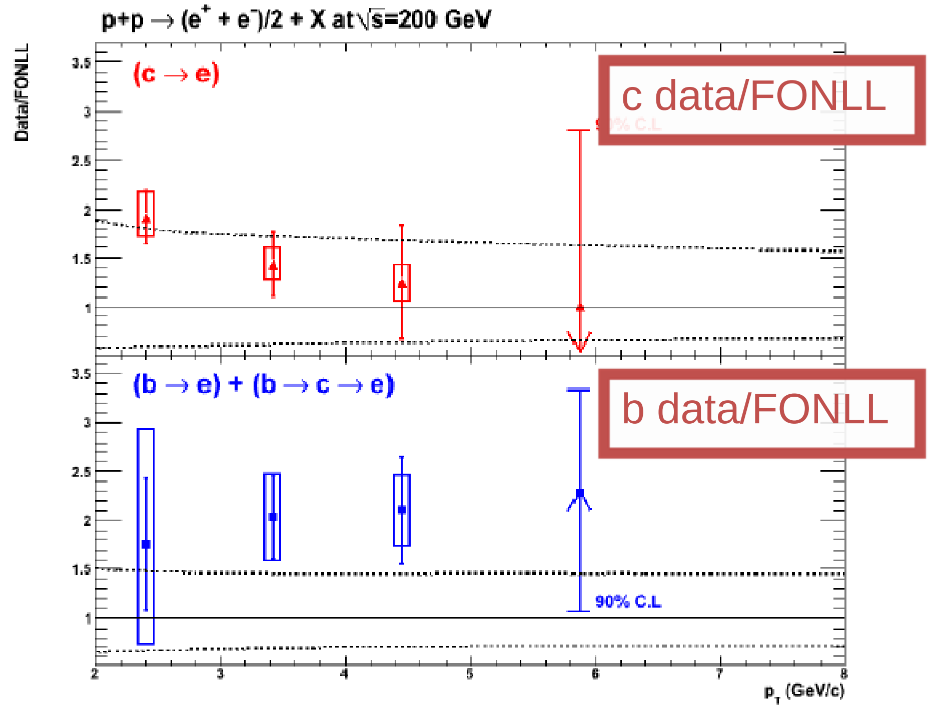
Tagging efficiency as function of p_T



- If electrons are purely from charm decay, tagging efficiency should increase with increasing electron p_T
- The tagging efficiency of pure b-decay is small and almost constant. The data is in between, indicating that the b fraction increases with p_T

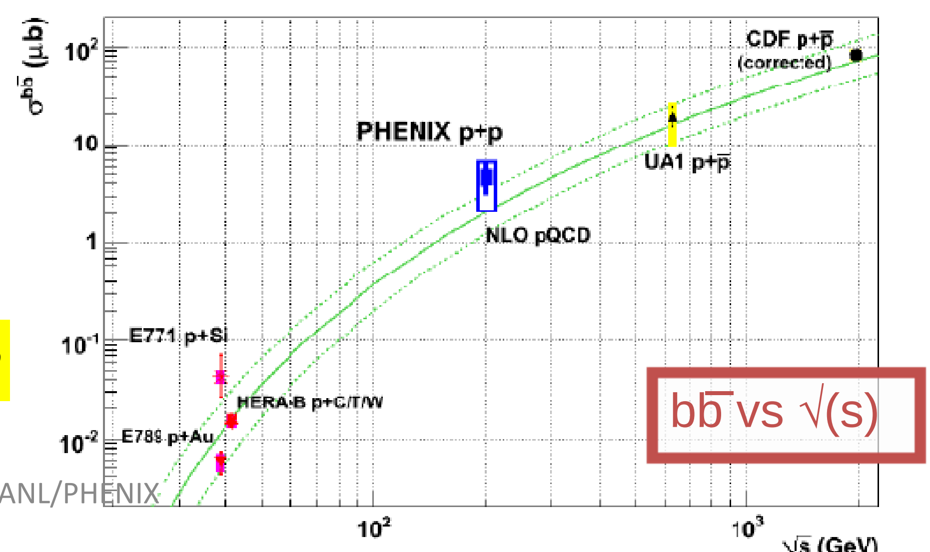
Charm and bottom separation (mid-rapidity)



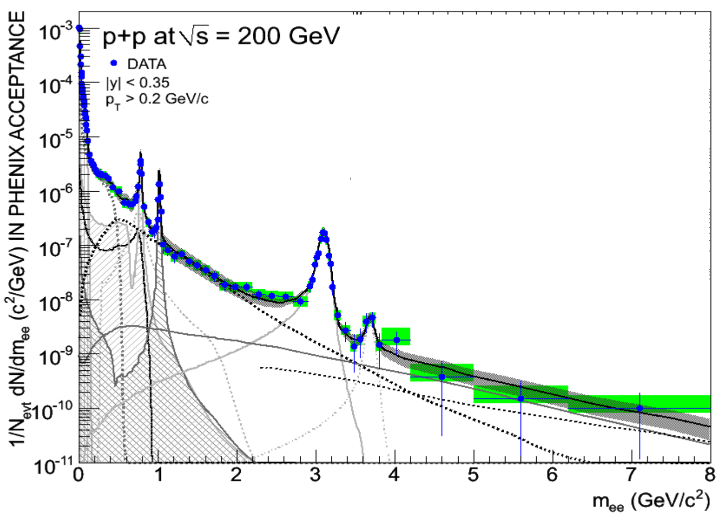


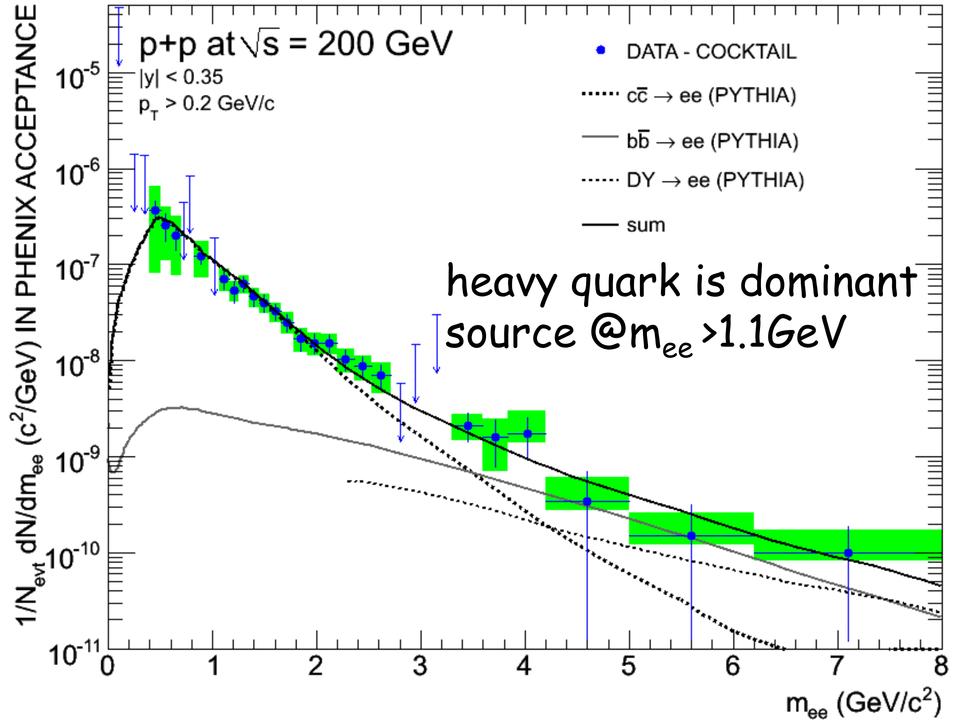
Measured ratios are in good agreement with FONLL calculations, but both experimental and theoretical uncertainties are large.

$$\sigma_{b\bar{b}} = 4.61 \pm 1.31(\text{stat}) + 2.57/-2.22(\text{sys})\,\mu b$$



Heavy quark measurement via di-electrons





- e^+e^- mass spectrum with cocktail subtraction
- high-mass is composed of $c\bar{c}$, $b\bar{b}$, Drell-Yan (& J/ψ, ψ′ peaks)
- uncertainties due to - correlations (20%), charm particle mix & BR's (33%), PDF's (11%), bbar+DY (7%)

PHENIX - PLB 670, 313 (2009)

$$\sigma_{c\bar{c}} = 544 \pm 39(\text{stat}) \pm 142(\text{sys}) \pm 200(\text{model})\,\mu b$$

or with simultaneous charm & bottom fit :

$$\sigma_{c\bar{c}} = 518 \pm 47(\text{stat}) \pm 135(\text{sys}) \pm 190(\text{model})\,\mu b$$

$$\sigma_{b\bar{b}} = 3.9 \pm 2.4(\text{stat}) + 3/-2(\text{sys}) \pm 1.6(\text{model})\,\mu b$$

Charm and bottom cross sections at RHIC

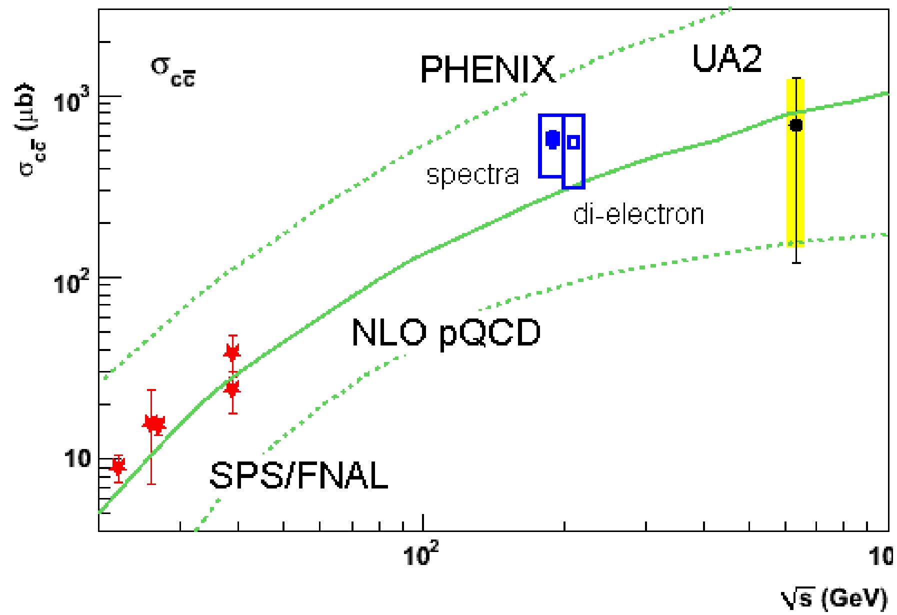
First measurements of bottom cross section at RHIC energies!!!

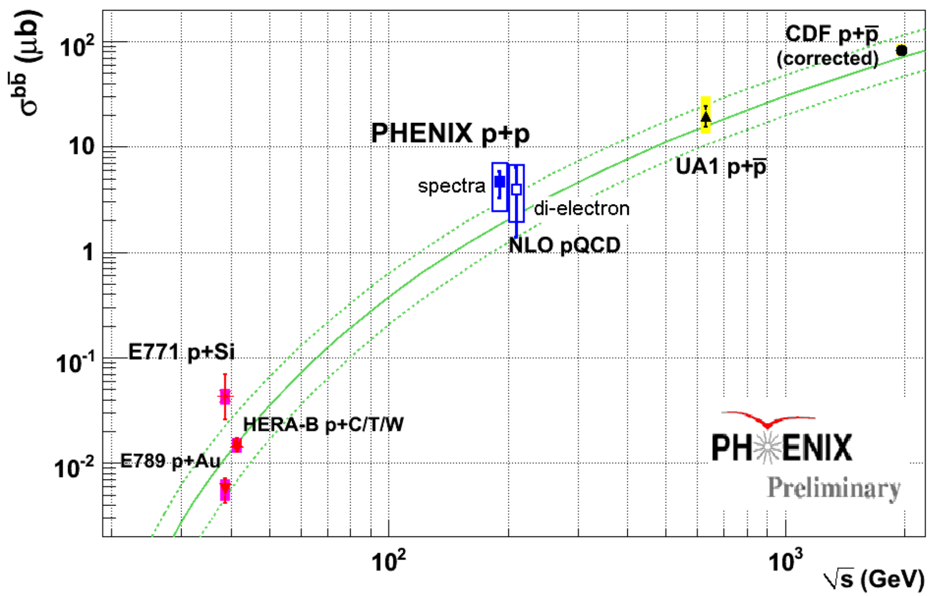
CHARM

Dilepton measurement in agreement with single electron, single muon, and with FONLL (upper end)

BOTTOM

Dilepton measurement in agreement with measurement from e-h correlation and with FONLL (upper end)

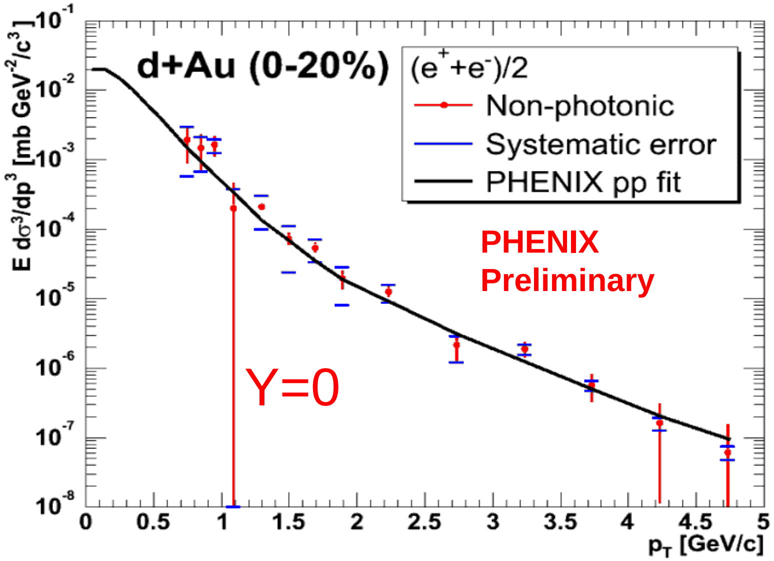




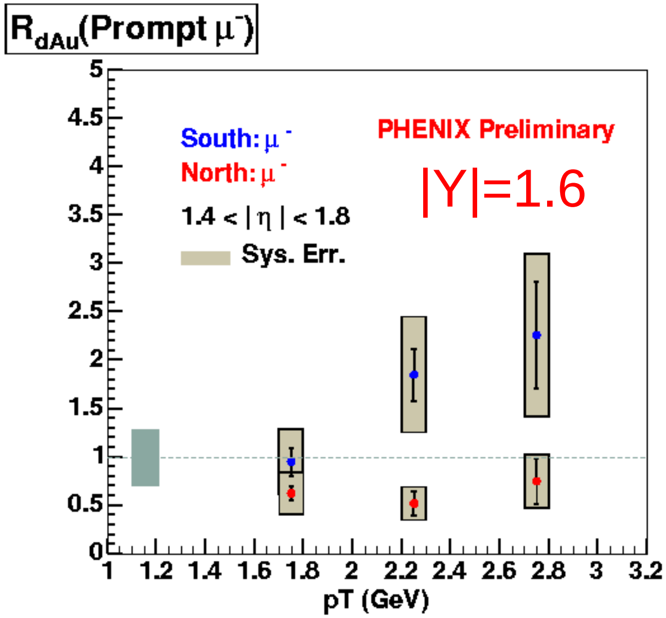
$$\text{single-electron msmt: } \sigma_{c\bar{c}} = 567 \pm 57 \pm 224\,\mu b \quad \text{PRL 97, 252002 (2006)}$$

$$\text{di-electron msmt: } \sigma_{c\bar{c}} = 544 \pm 39 \pm 142\,\mu b \quad \text{PLB 670, 313 (2009)}$$

Open charm in Cold Nuclear matter?



d+Au is consistent with p+p scaled by #binary collisions



But at forward rapidity (deuteron direction) suppression is observed. And enhancement at backward rapidity

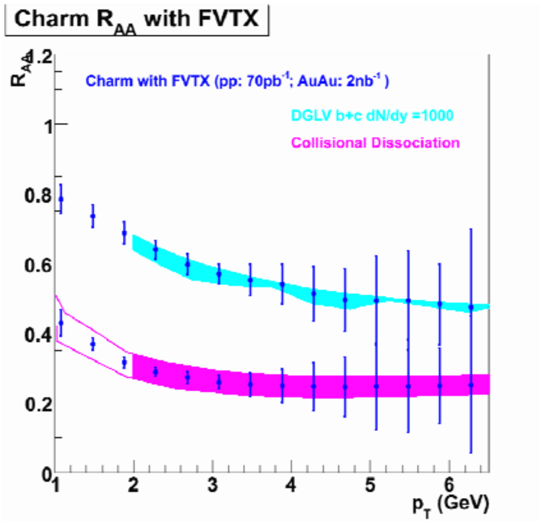
Physics from Heavy Quarks in the Hot-dense matter?

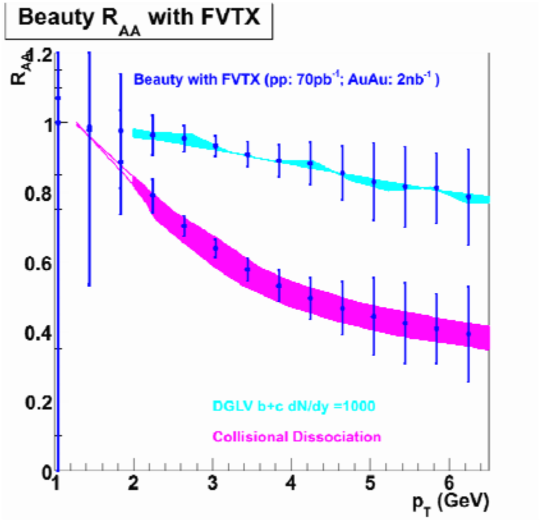
Do heavy quarks lose energy like light quarks?

What is the balance between beauty and charm production & how is it altered in A+A collisions
- important for studies of QGP effects, since charm & beauty behave differently (dE/dx & flow)
- these modifications need to be theoretically described in a self consistent way

Are they thermalized in the medium & do they exhibit flow like light quarks?

Knowing the charm production cross section <u>in A+A collisions</u> is critical in regeneration models for charmonia production





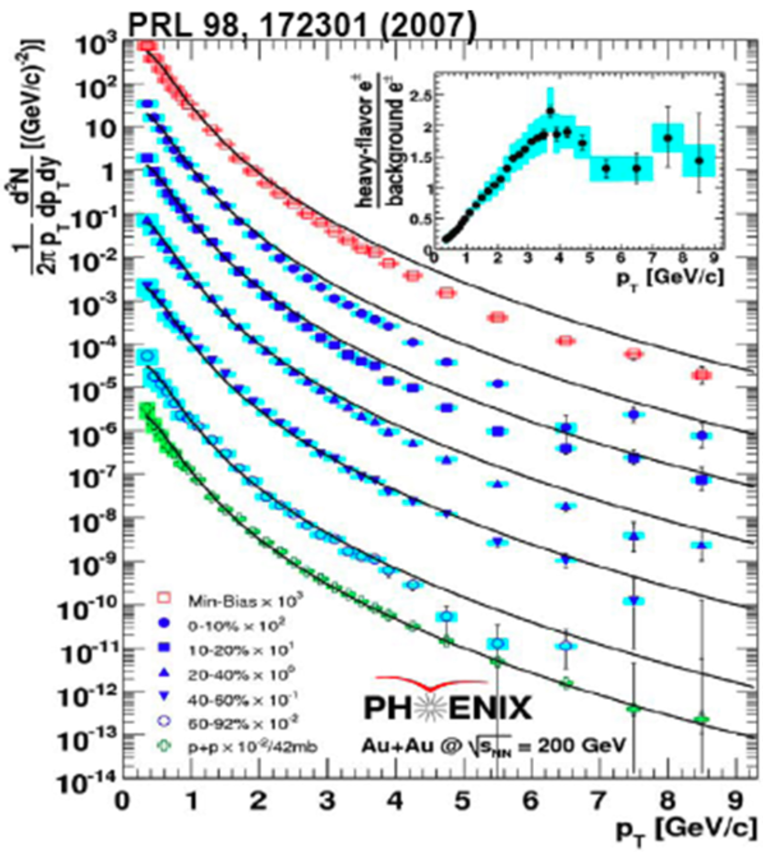
Run-4 Au+Au Result at $\sqrt{s_{NN}}$ = 200 GeV

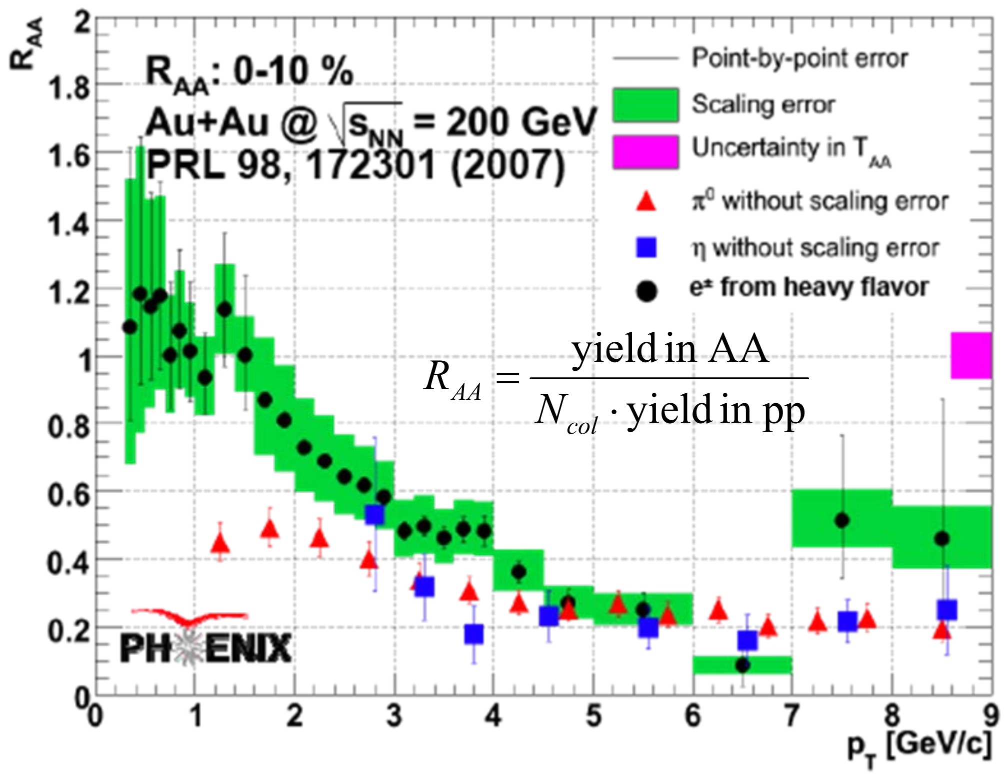
Same methods as for p+p

S/B > 1 for p_T > 2 GeV/c

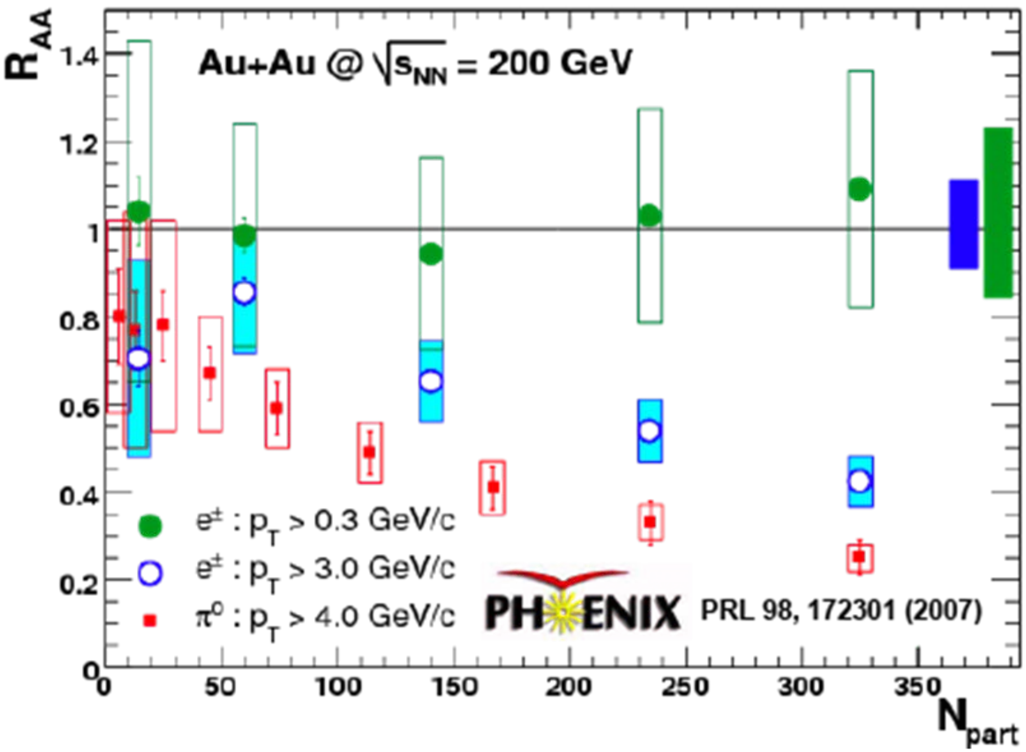
Heavy flavor electron compared to binary scaled p+p data (FONLL*1.71)

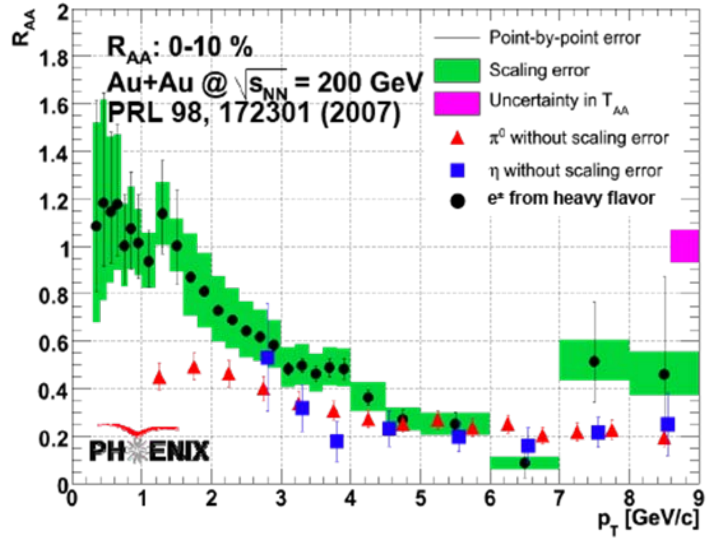
Suppression level is the almost the same as π^0 and η in high p_T region





Run-4 Au+Au Result at $\sqrt{s_{NN}}$ = 200 GeV





- Binary scaling works well for p_T > 0.3 GeV/c (total charm yield is not changed)
- but large suppression for high p_T (> 4 GeV/c)

High p_T suppression is similar to light mesons measurements.

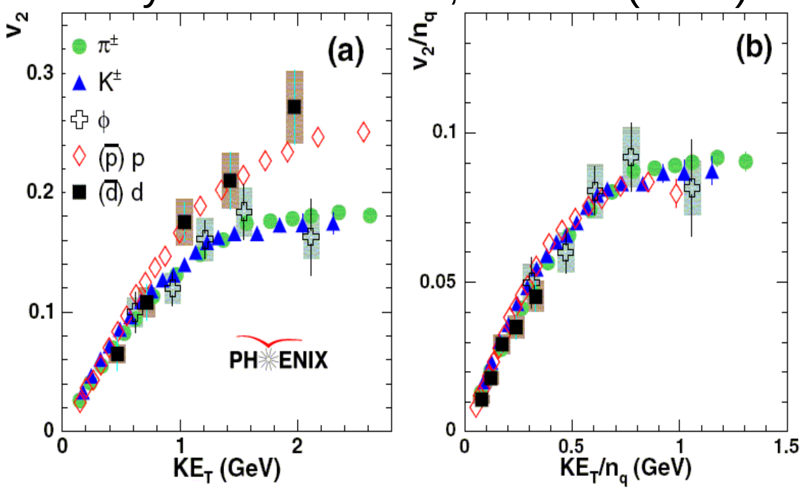
Unexpected in terms of radiative energy loss, due to dead-cone effect

Possible explanations include:

- Elastic (collisional) energy loss
- QGP effect
- in-medium D and B dissociation

Elliptic Flow for light and heavy quarks

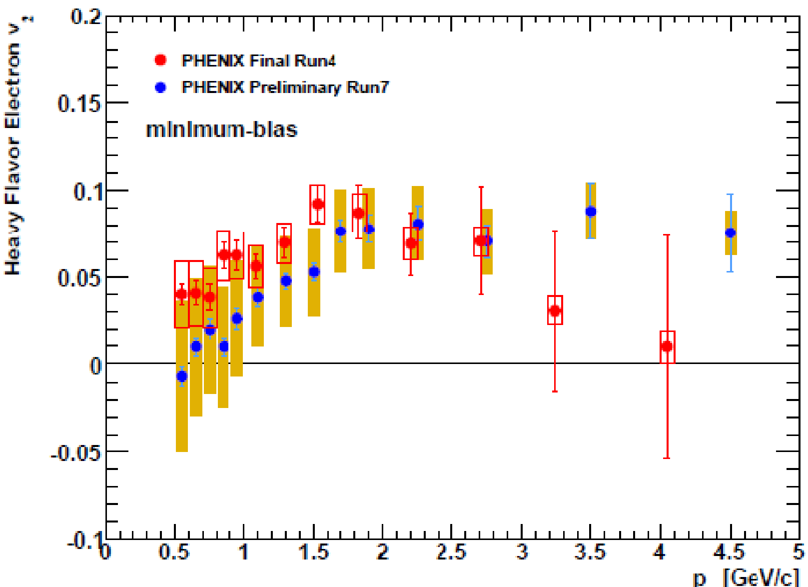
Phys. Rev. Lett. 99, 052301 (2007)



Large positive elliptic flow observed for light particles.

This requires an early thermalization of the medium.

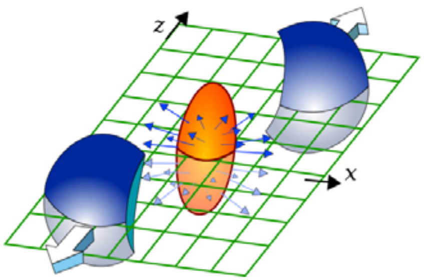
Scaling properties suggest pre-hadronic degrees of freedom.

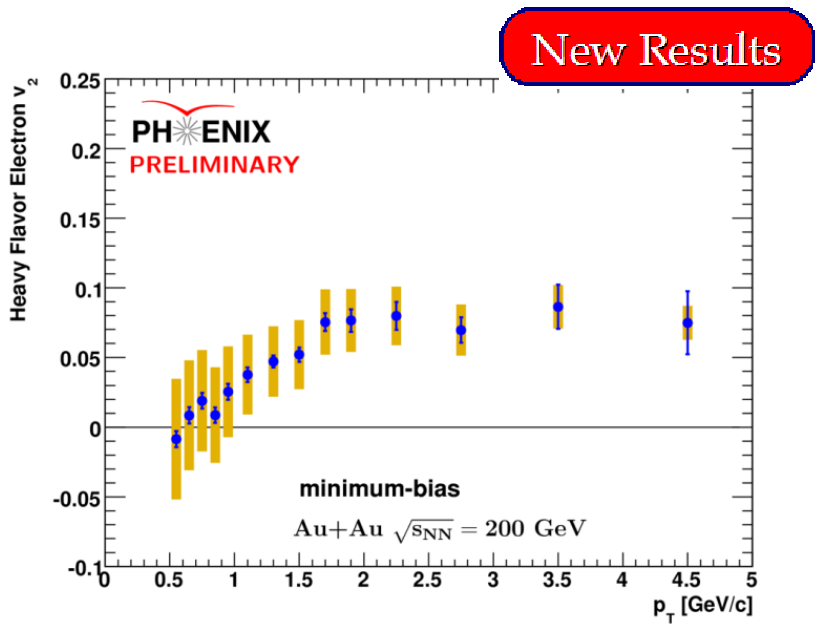


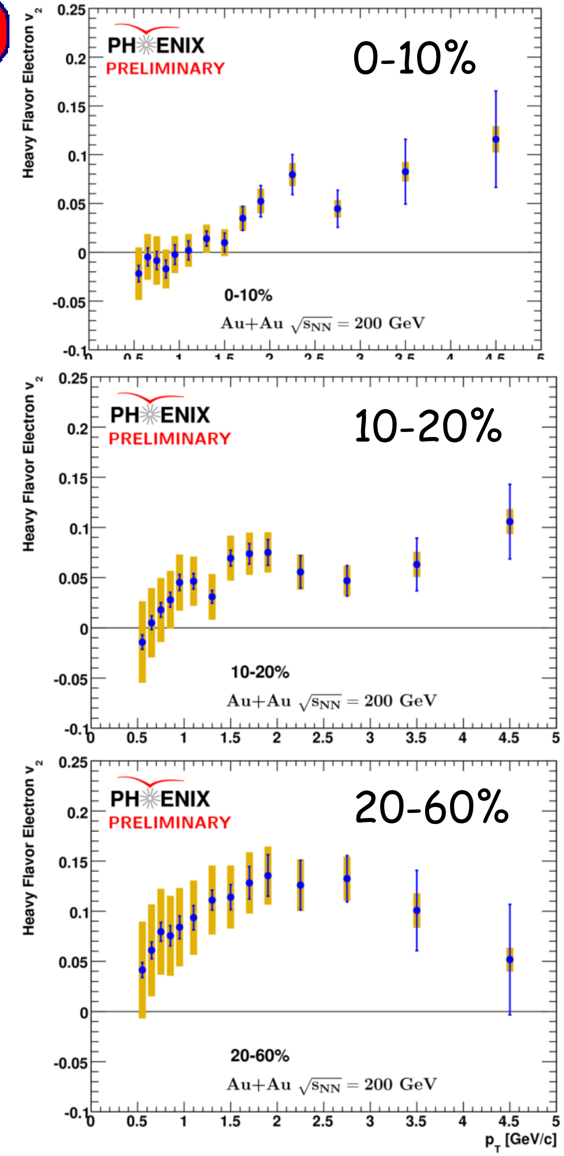
Large positive elliptic flow also observed for D and B.

Heavy quarks are also thermalized.

Collective motion in Au+Au: single electron v_2





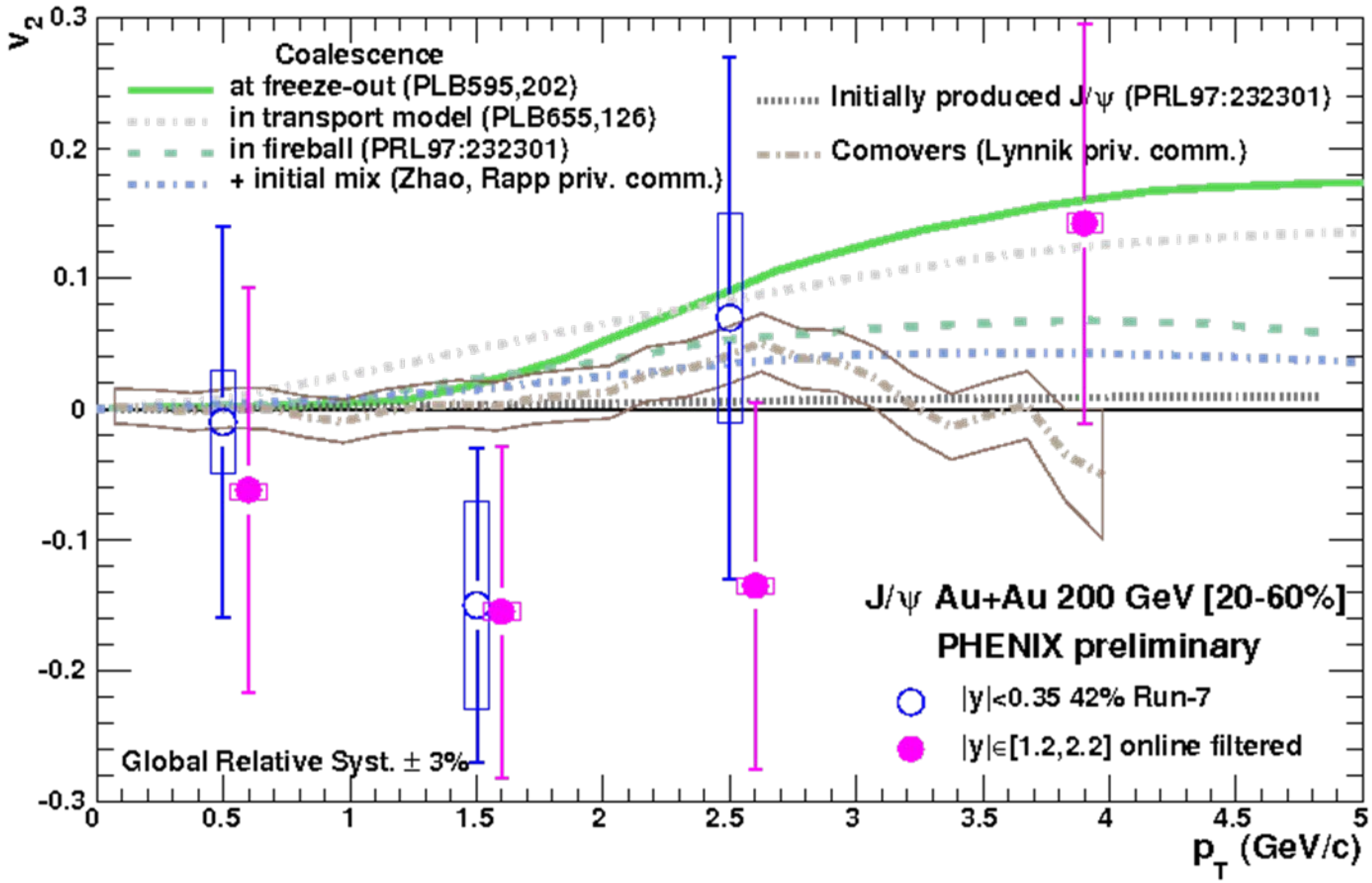


Reduced errors at high p_T due to new reaction plane detector.

v_2 centrality dependence for heavy flavor $e^{\pm}$

- Non-zero v_2 at higher p_T. Bottom contributes meaningfully above p_T ~ 3.0 GeV/c

J/ψ elliptic flow



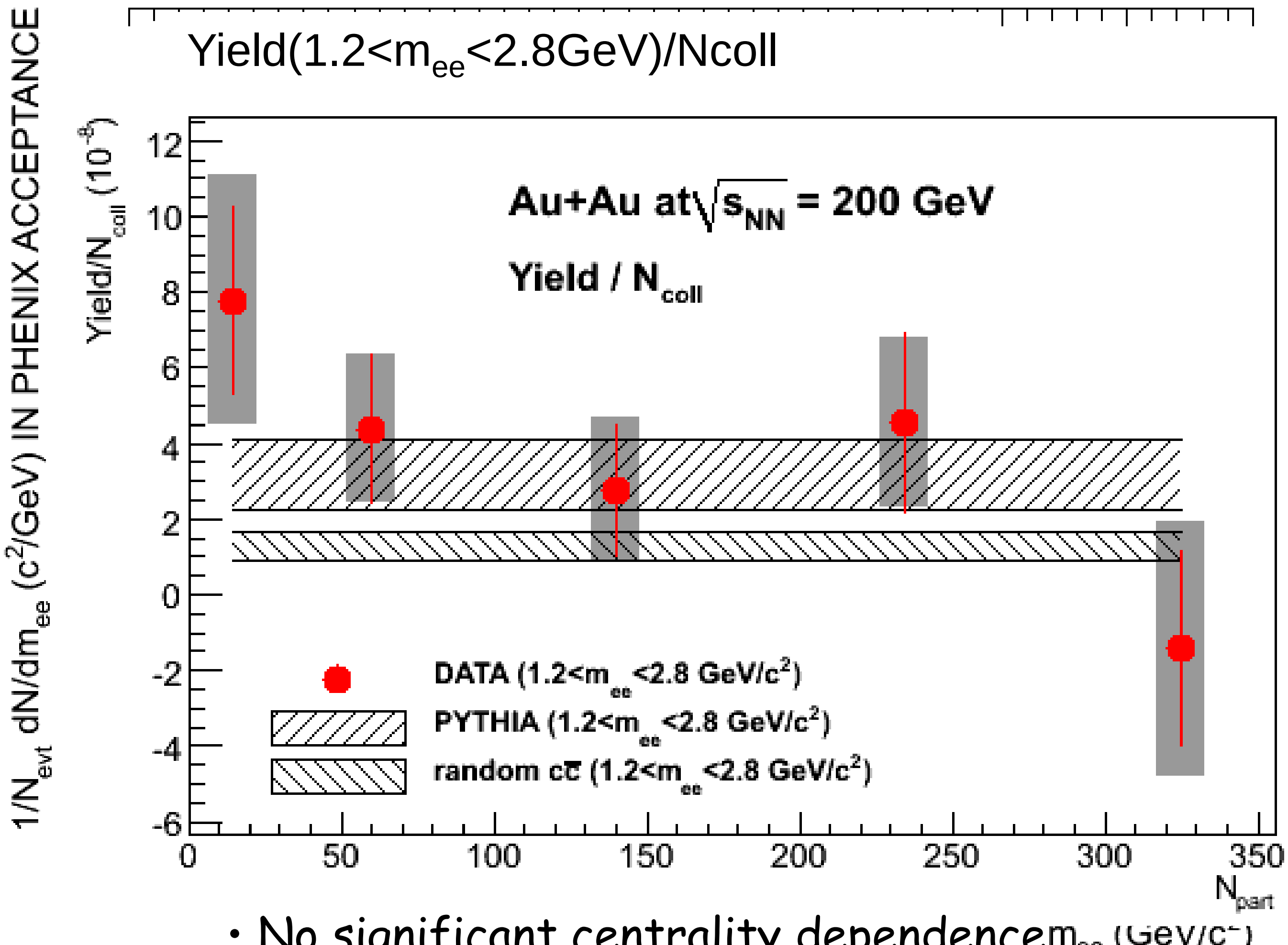
This is a first measurement, at both mid and forward rapidity

Very limited statistics so that no strong conclusion can be drawn

Need more data, and detector upgrades

Measurement of di-electron(Au+Au@200GeV)

arXiv:0706.3034



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happens to
as π^0 due to
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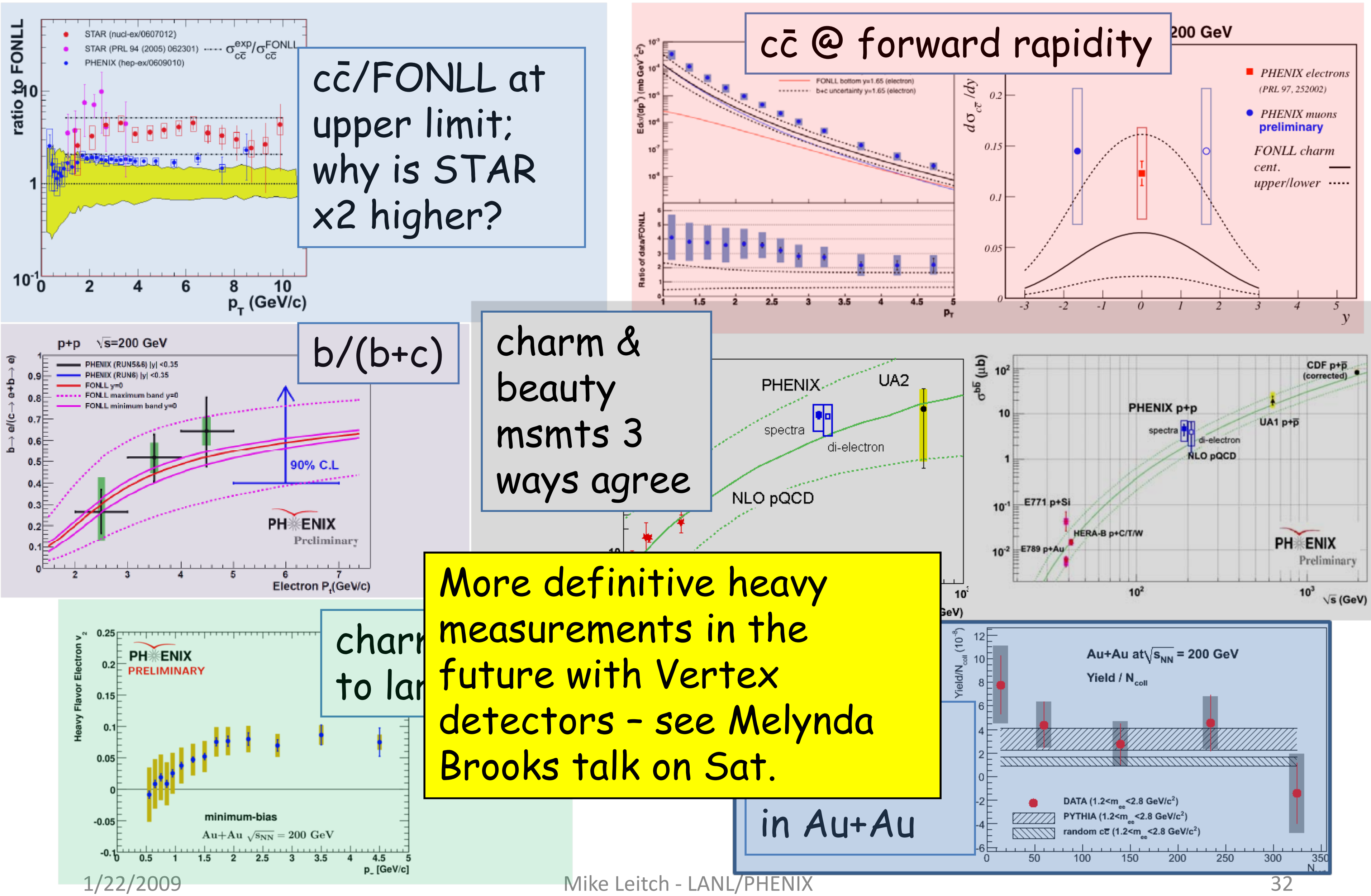
+ suppression)

- No significant centrality dependence
- consistent with PYTHIA & random $c\bar{c}$ scenarios

Summary – with Newest Results



$c\bar{c}$/FONLL at upper limit; why is STAR x2 higher?

$c\bar{c}$ @ forward rapidity

b/(b+c)

charm & beauty msmts 3 ways agree

char... to lar...

in Au+Au

More definitive heavy measurements in the future with Vertex detectors – see Melynda Brooks talk on Sat.

Backup Slides

The PHENIX Collaboration

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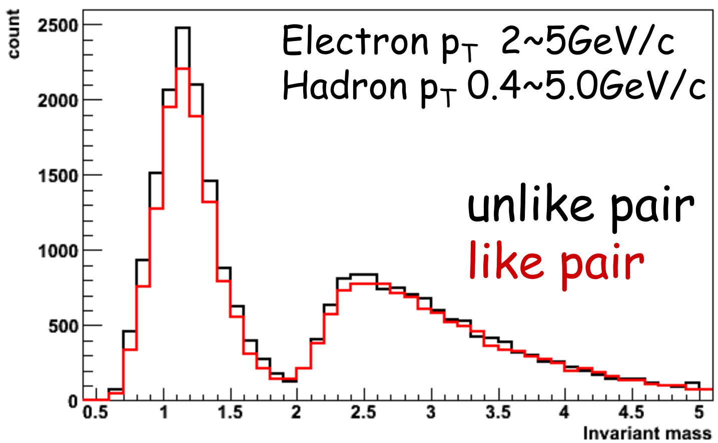
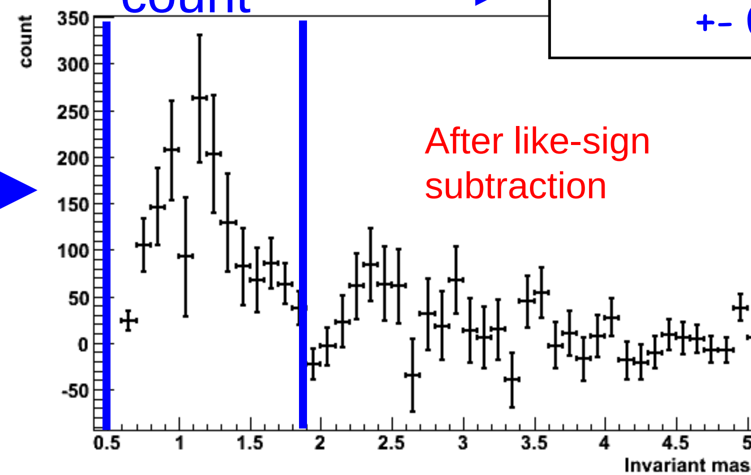
Details of the Analysis

From real data



count

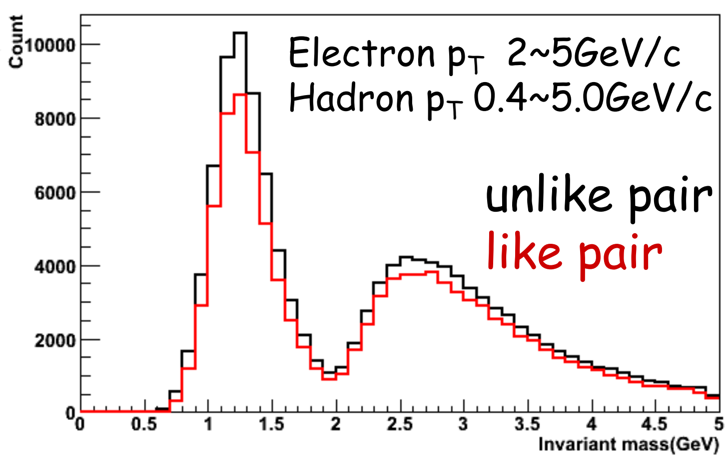
X $1/N_{non\text{-}phot\ e}$



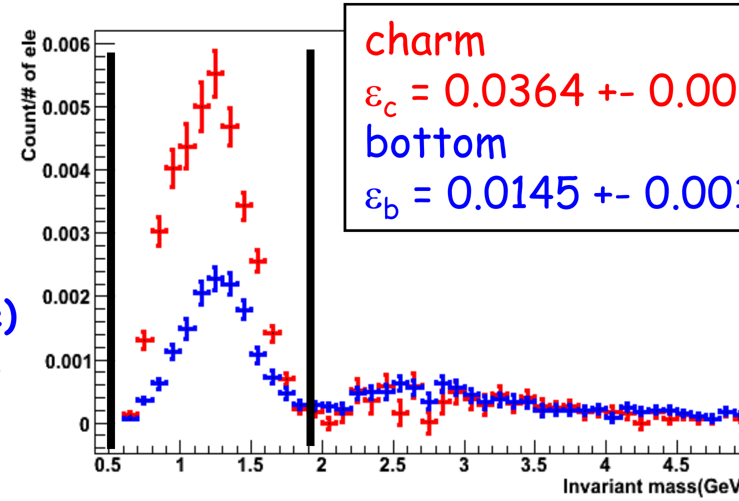
ε_{data}
= 0.029 +- 0.003(stat)
+- 0.002(sys)

From simulation (PYTHIA and EvtGen (B decay MC))

bottom production



(unlike-like) /#electron



charm
ε_c = 0.0364 +- 0.0034(sys)
bottom
ε_b = 0.0145 +- 0.0014(sys)

Charge correlation in b-decay and/or for high mass are due to charge conservation

Dominant sources of tracks in the muon arm

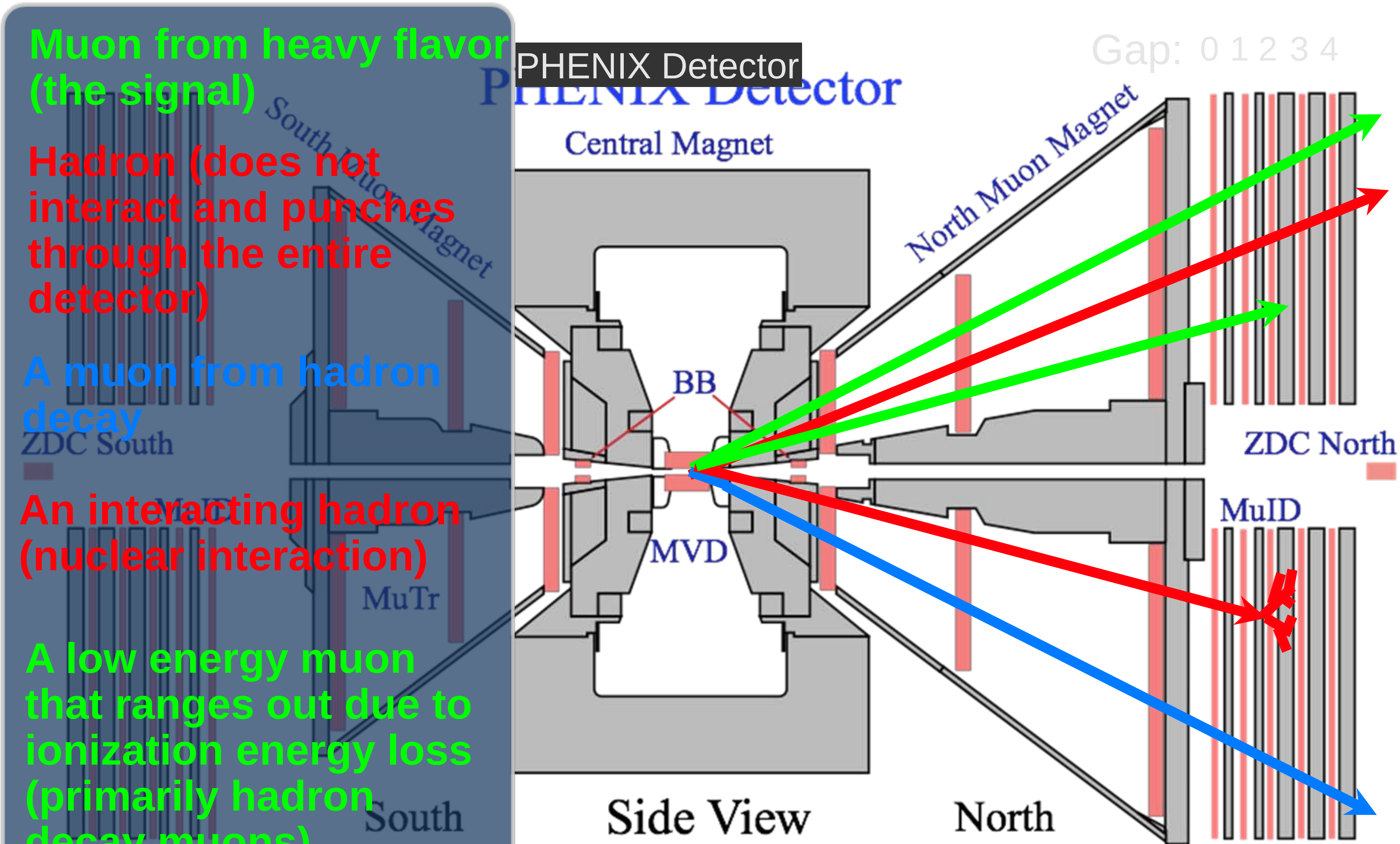
Muon from heavy flavor (the signal)

Hadron (does not interact and punches through the entire detector)

A muon from hadron decay

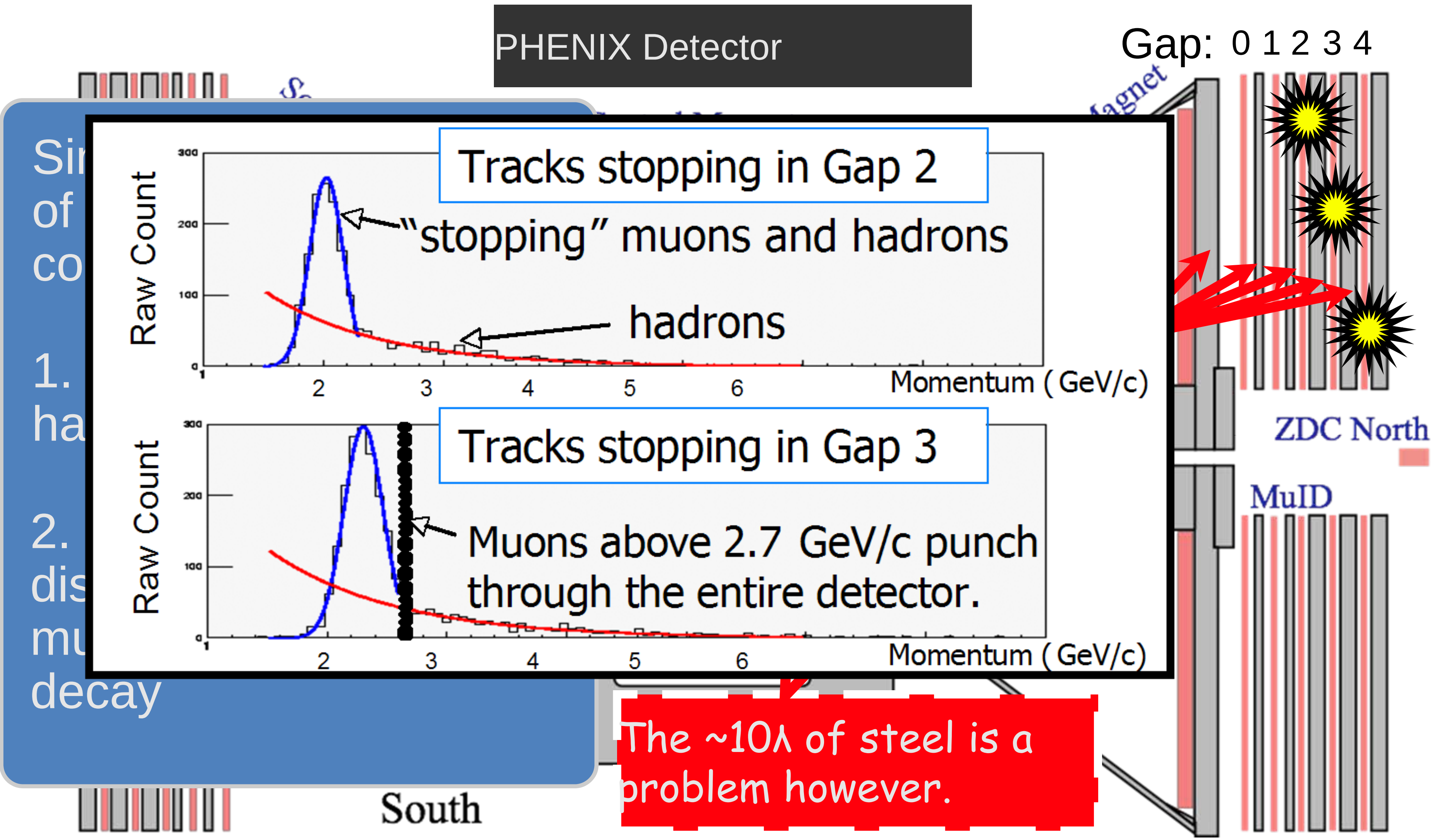
An interacting hadron (nuclear interaction)

A low energy muon that ranges out due to ionization energy loss (primarily hadron decay muons)



Analysis by D. Hornback (U. Tennessee)

Methodology of this single muon analysis

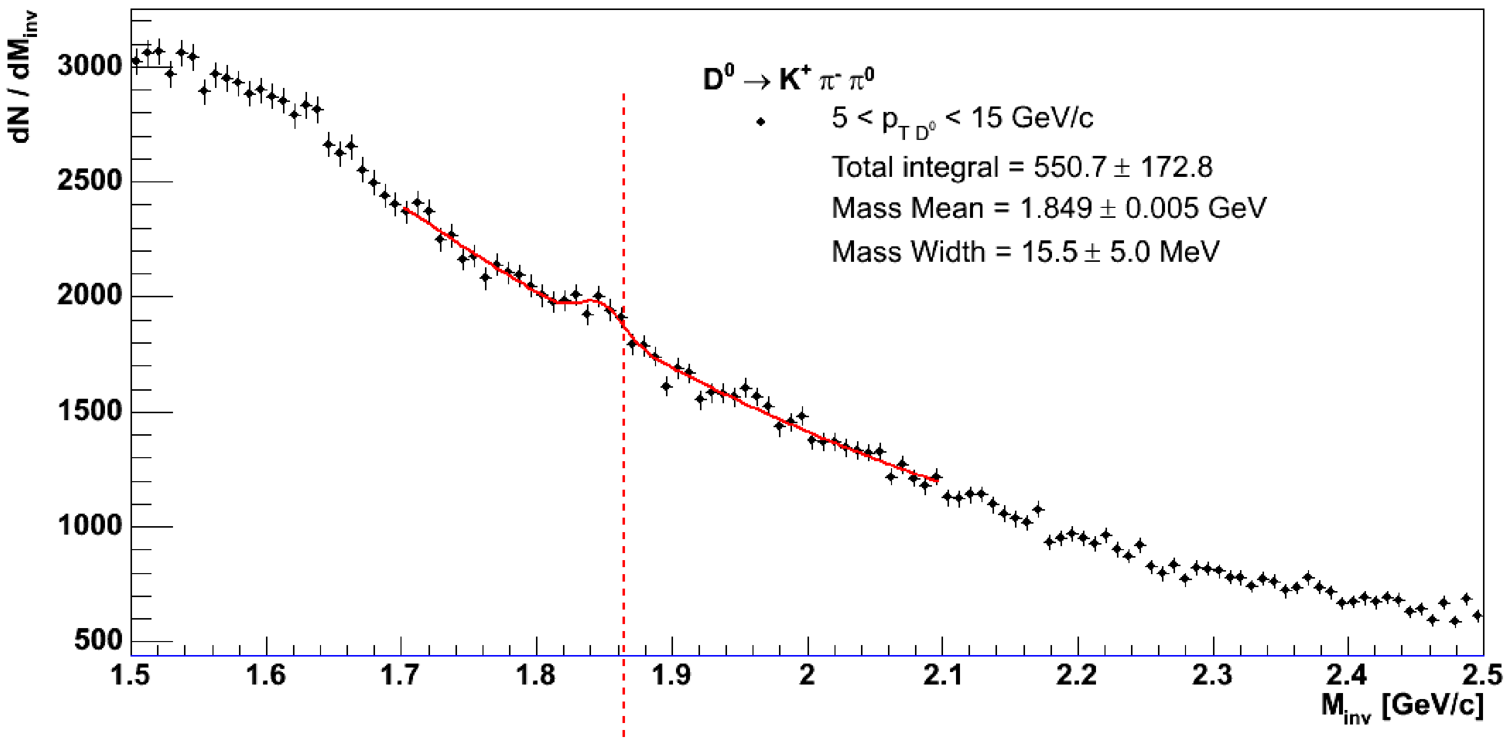


$D^0 \rightarrow K^- \pi^+ \pi^0$ reconstruction

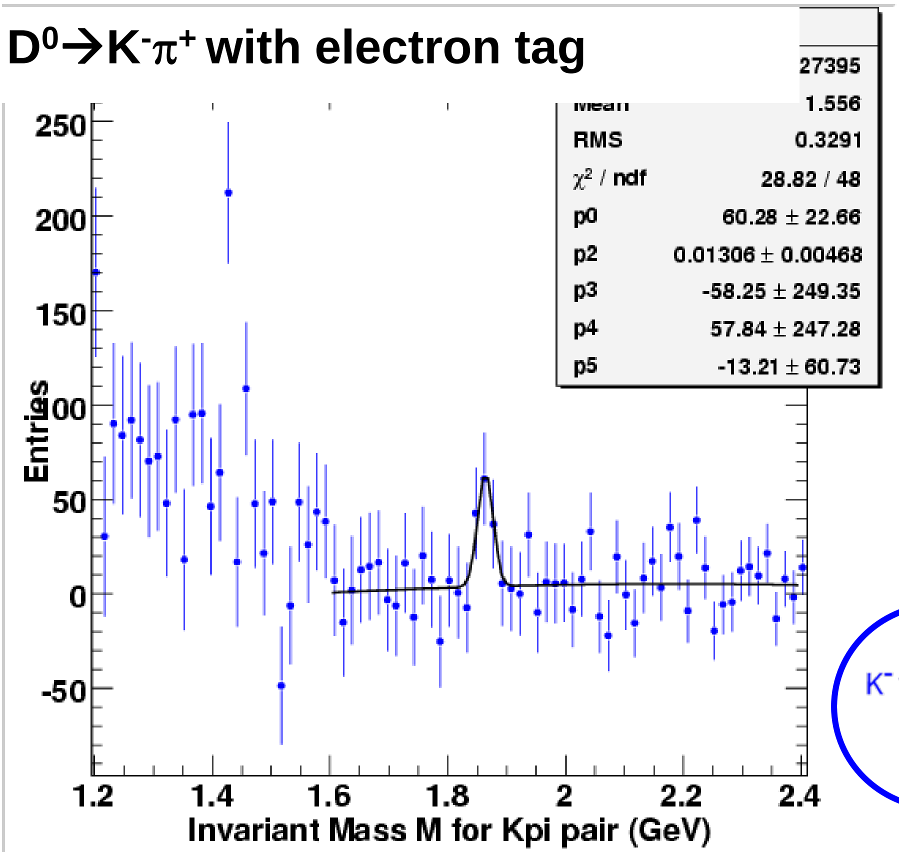
large branching ratio(14.1%)

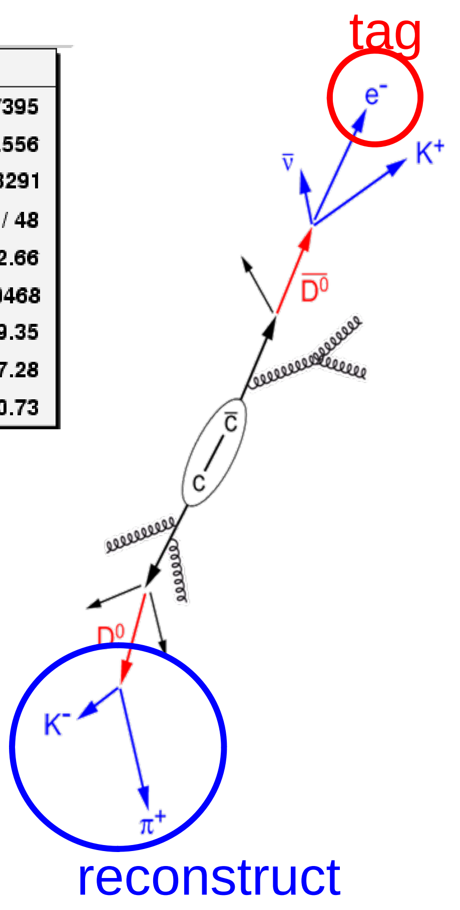
S.Butsyk[poster]

$D^0 \rightarrow K^- \pi^+ \pi^0$ decay channel



electron tag reduce combinatorial background

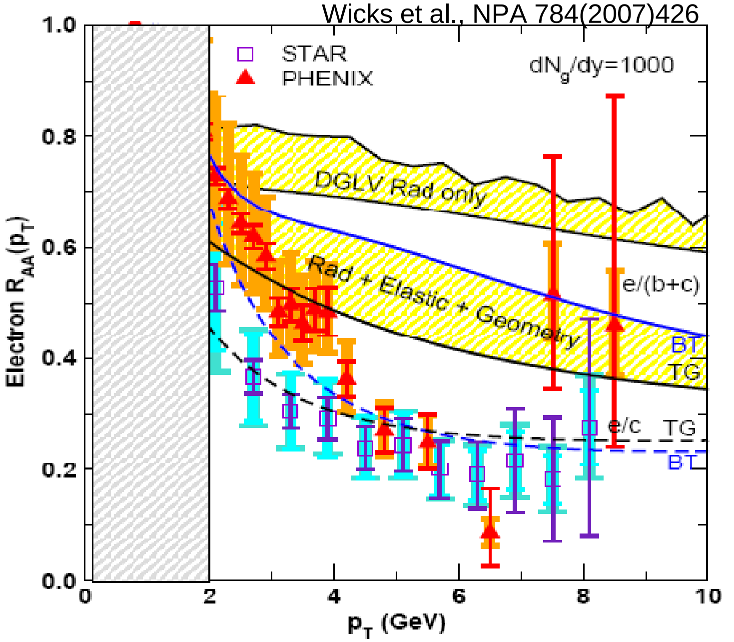




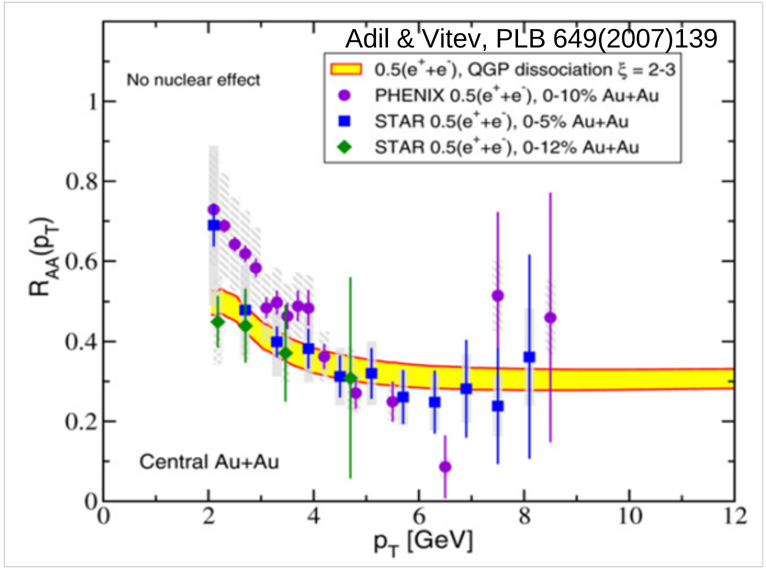
- observe D^0 peak
- cross section of D is coming up

$e^{\pm}$ R_{AA}: a Challenge for Models

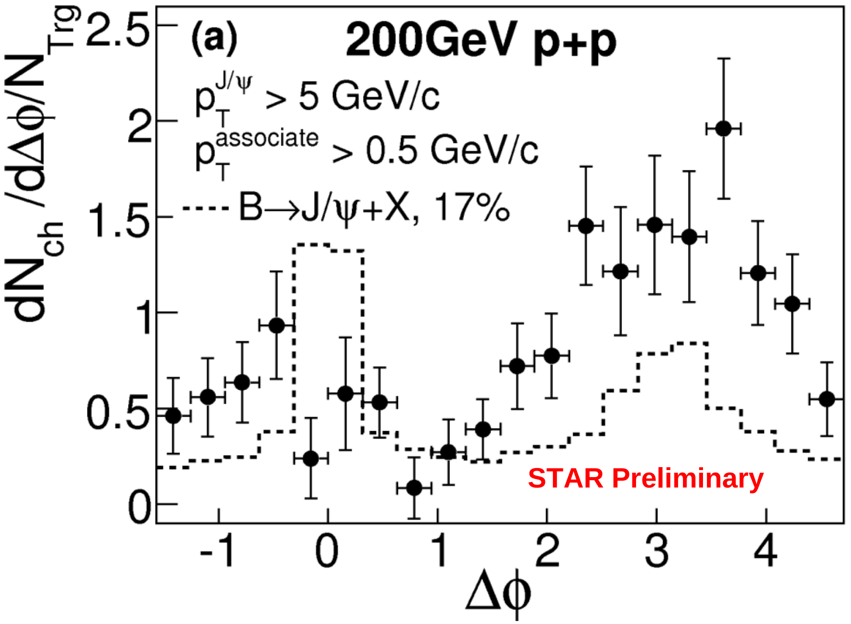
- testing ground for various parton energy loss (ΔE) models
  - radiative ΔE only
    - Djordjevic et al., PLB 632(2006)81
    - Armesto et al., PLB 637(2006)362)
  - collisional ΔE included
    - Wicks et al., NPA 784(2007)426
    - van Hees & Rapp, PRC 73(2006)034913)

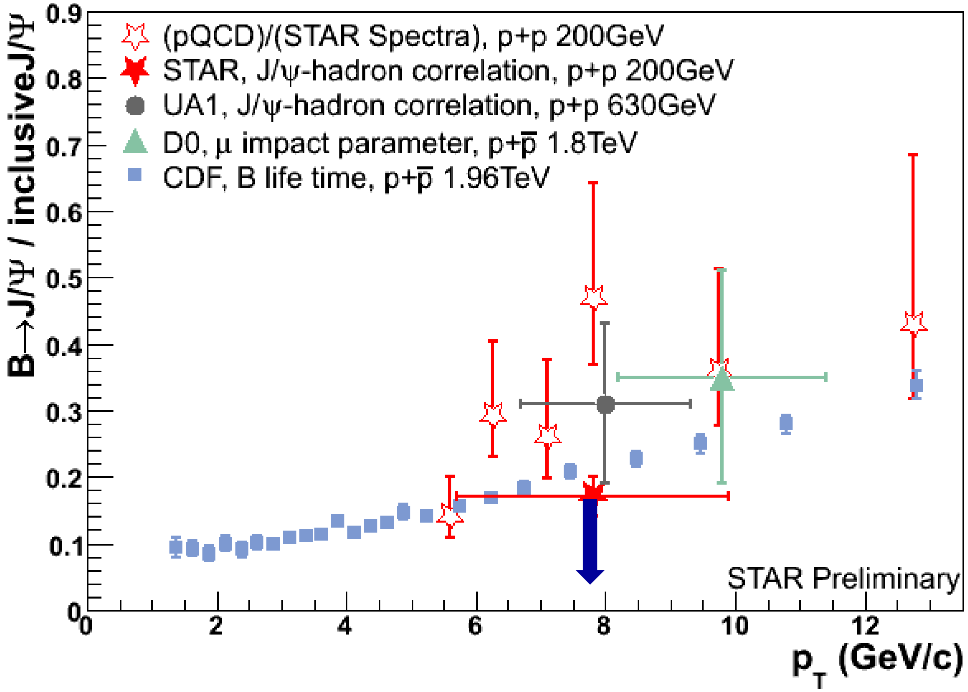


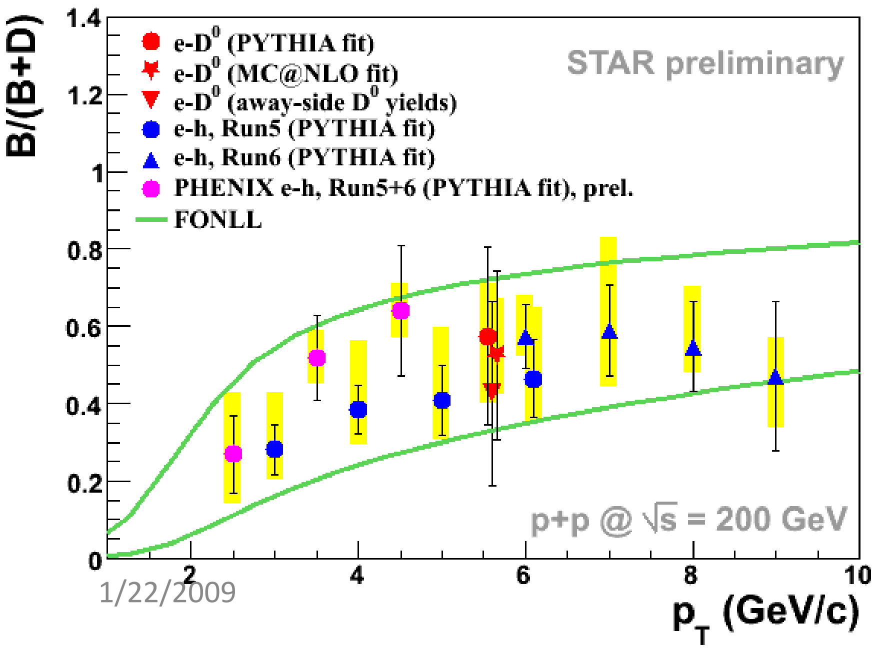
- or alternative approaches to interpret the suppression
  - collisional dissociation of heavy mesons (charm and bottom!)
    - Adil & Vitev, PLB 649(2007)139
  - contribution from baryon enhancement
    - Sorensen & Dong, PRC 74(2006)024902



Constrain Bottom yields





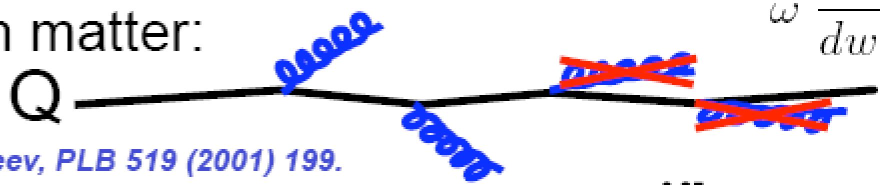


- pQCD predicts significant B➔J/Ψ
- Correlations shows low B contribution
- can used to further constrain B yields
- PYTHIA productions all show strong near-side correlation ➔ higher order production mechanism?
- constrain Correlation from jet fragmentation

Unexpected: Heavy Quarks Suppressed and Flow

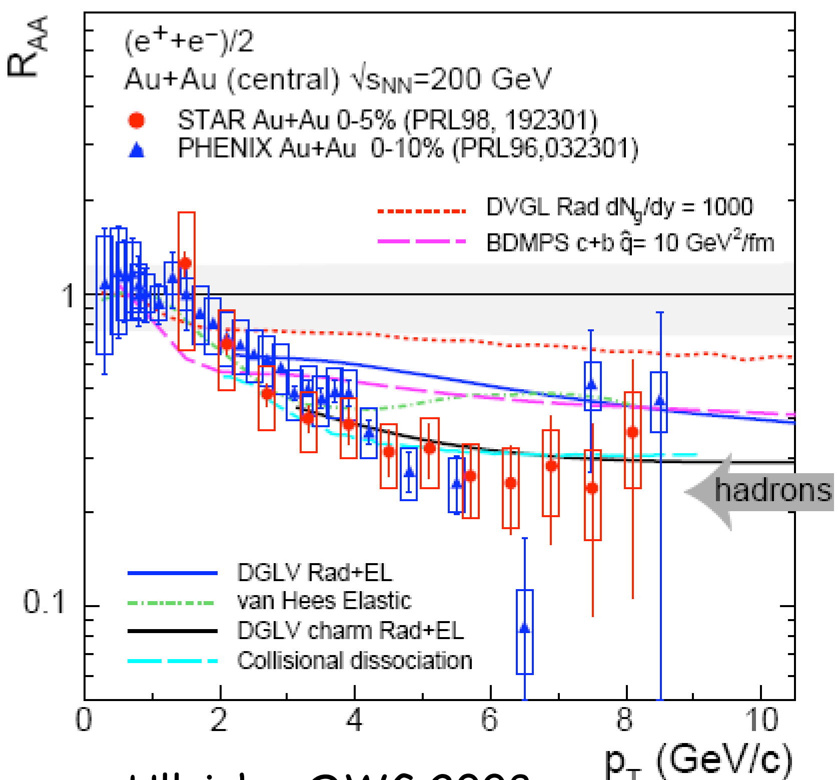
Dead cone effect implies lower heavy quark energy loss in matter:

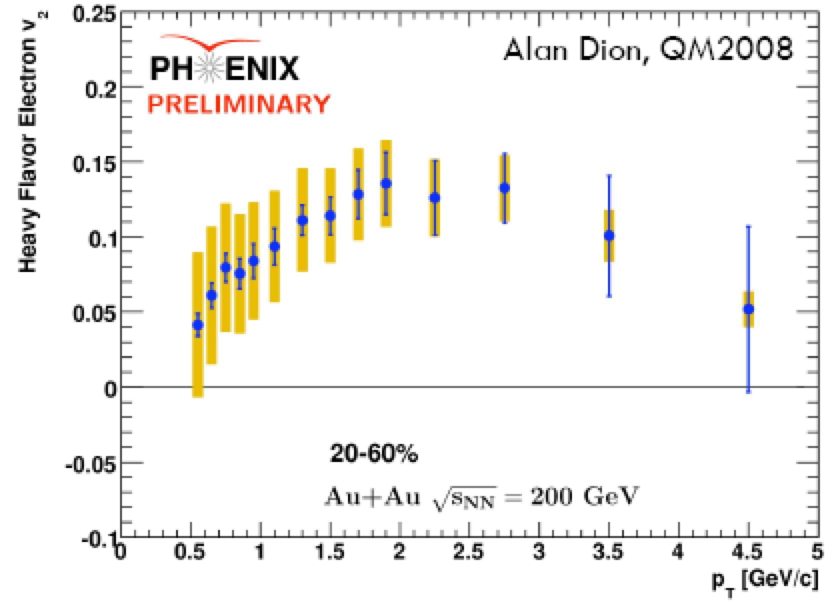
$$\omega \frac{dI}{dw}\bigg|_{\mathrm{HEAVY}} = \frac{\omega \frac{dI}{dw}\Big|_{\mathrm{LIGHT}}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$



Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Semileptonic decays: c,b→e X





- Substantial suppression on same level to that of light mesons
- Charm flows !
- Describing suppression and flow is difficult for models