Measurements of heavy quark production via single leptons in p+p and Au+Au collisions at $\sqrt{s}$=200 GeV

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Heavy flavor at RHIC

200 GeV p+p

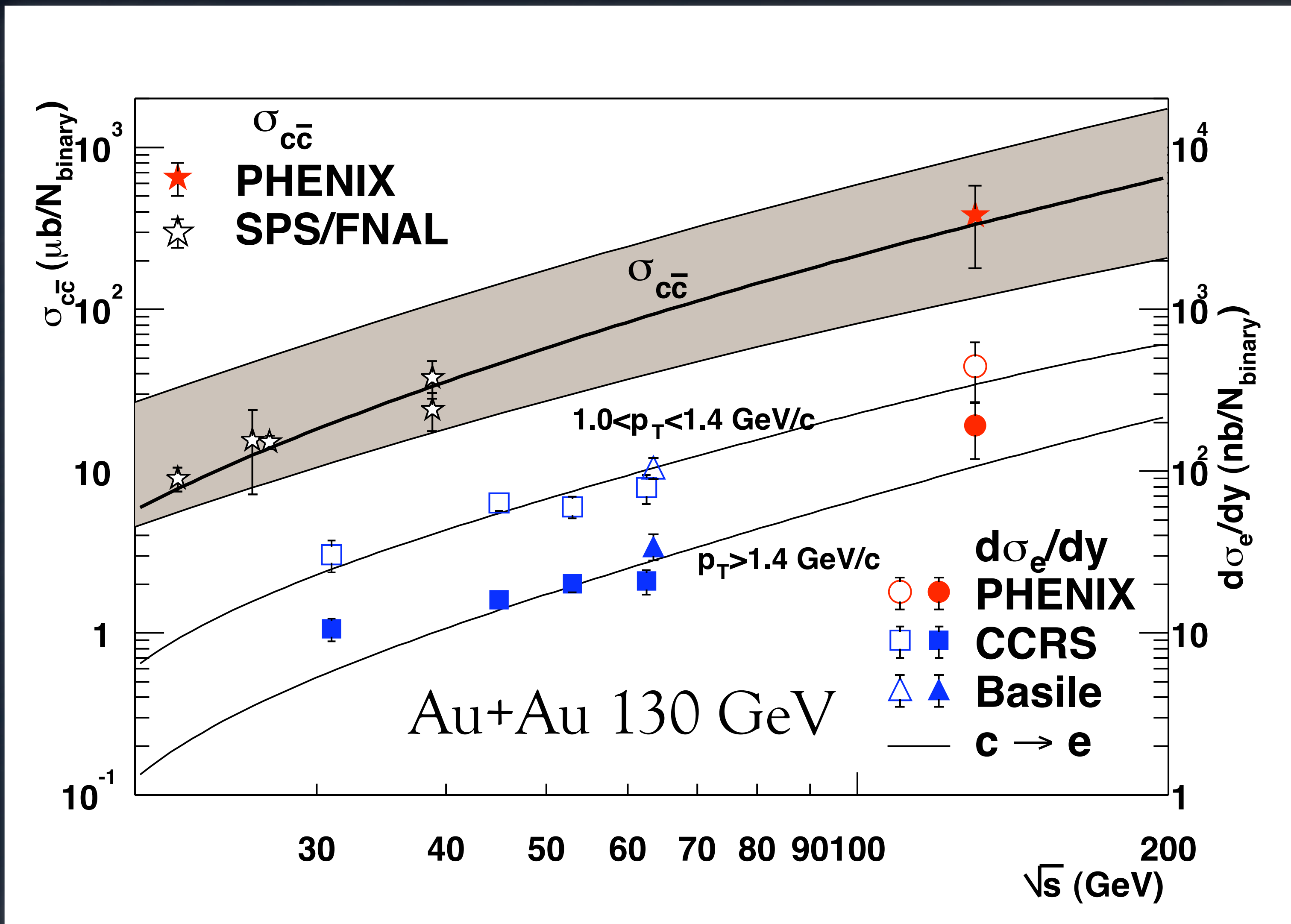
- Test pQCD predictions (FONLL)
- Measurement of total heavy flavor production cross sections (charm)
- Provide baseline reference for heavy-ion measurements

200 GeV Au+Au

- Measurement of medium effects:
  - Charm quark energy loss (Nuclear modification factor R_{AA})
  - Azimuthal anisotropy and collective motion of heavy flavor
  - Medium transport properties (viscosity/entropy ratio)

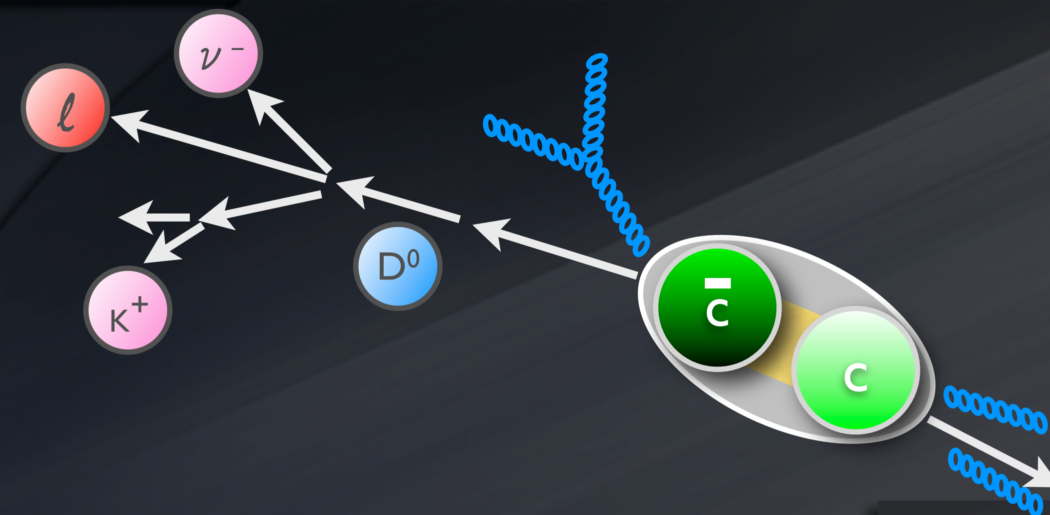
Measuring heavy flavor with single electrons

Single electrons were first used to extract charm cross sections at ISR.



Phys. Rev. Lett. 88, 192303 (2002)

PHENIX measures single electrons at y=0



After background subtraction, electron excess is attributed to heavy flavor production, assuming that heavy flavor scales with the number of binary nucleon-nucleon collisions.

single electron sources

Photonic electrons:

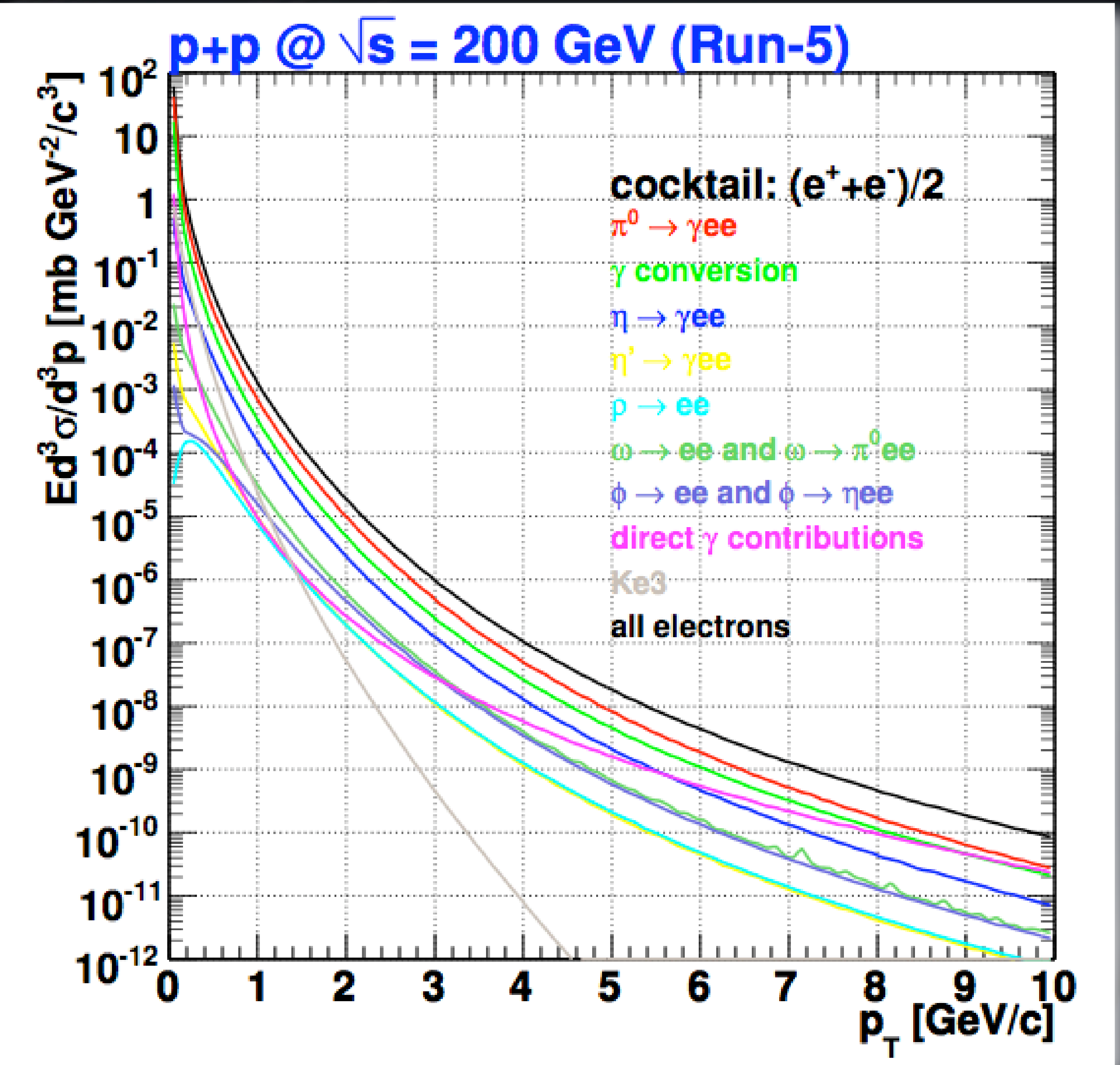
- Photon conversion in material
  $\pi^0, \eta \rightarrow \gamma\gamma$
- Dalitz decay of light neutral mesons
  $\pi^0, \eta \rightarrow \gamma e^+e^-$
- Direct photons - created in initial hard processes and parton fragmentation

Non-photonic electrons:

- **Heavy flavor electrons**, dominant non-photonic component, primarily from $D \rightarrow e^\pm + X$
- Weak kaon decay
  (relevant below $p_T = 1.0$ GeV/c)
  K_{e3}: $K^\pm \rightarrow \pi^0, e^\pm, \nu_e$
- Vector meson decay
  $\omega, \rho, \phi, J/\Psi \rightarrow e^+e^-$

Backgrounds are estimated using two independent techniques.

Single electron cocktail method



Cocktail uses combined backgrounds with decay kinematics and photon conversions in full detector simulation.

Modified Hagedorn parameterization of the **measured** PHENIX π^0 spectra.

$$E\frac{d^3\sigma}{dp^3} = \frac{c}{(exp(-ap_T - bp_T^2) + p_T/p_0)^n}$$

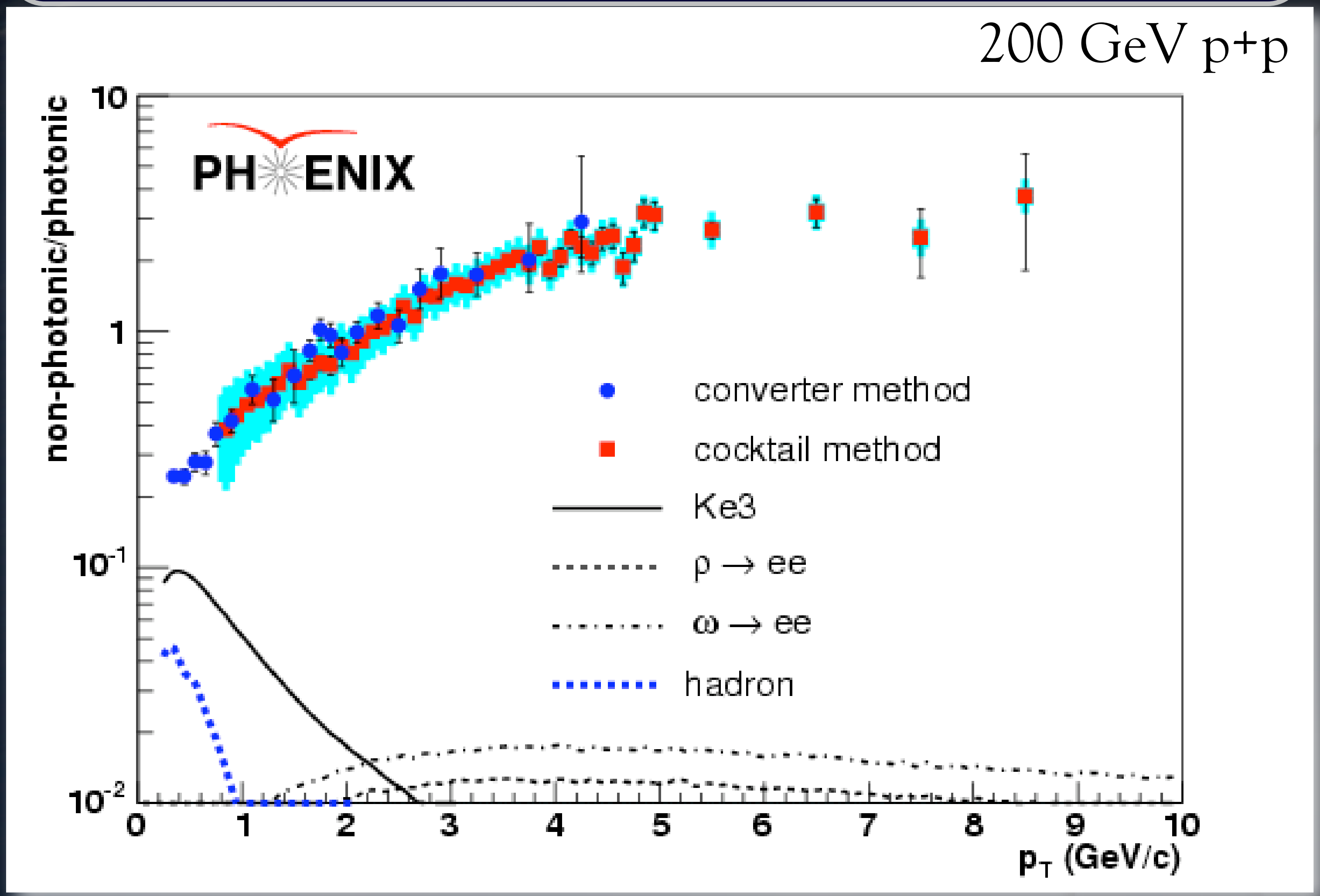
Remaining hadrons scale the π^0 fit using measured hadron ratios and use m_T scaling:

$$p_T \rightarrow \sqrt{p_T^2 + m_{hadron}^2 - m_{\pi^0}^2}$$

Cocktail method used for higher p_T

Single electron converter method

non-photonic signal to photonic background



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

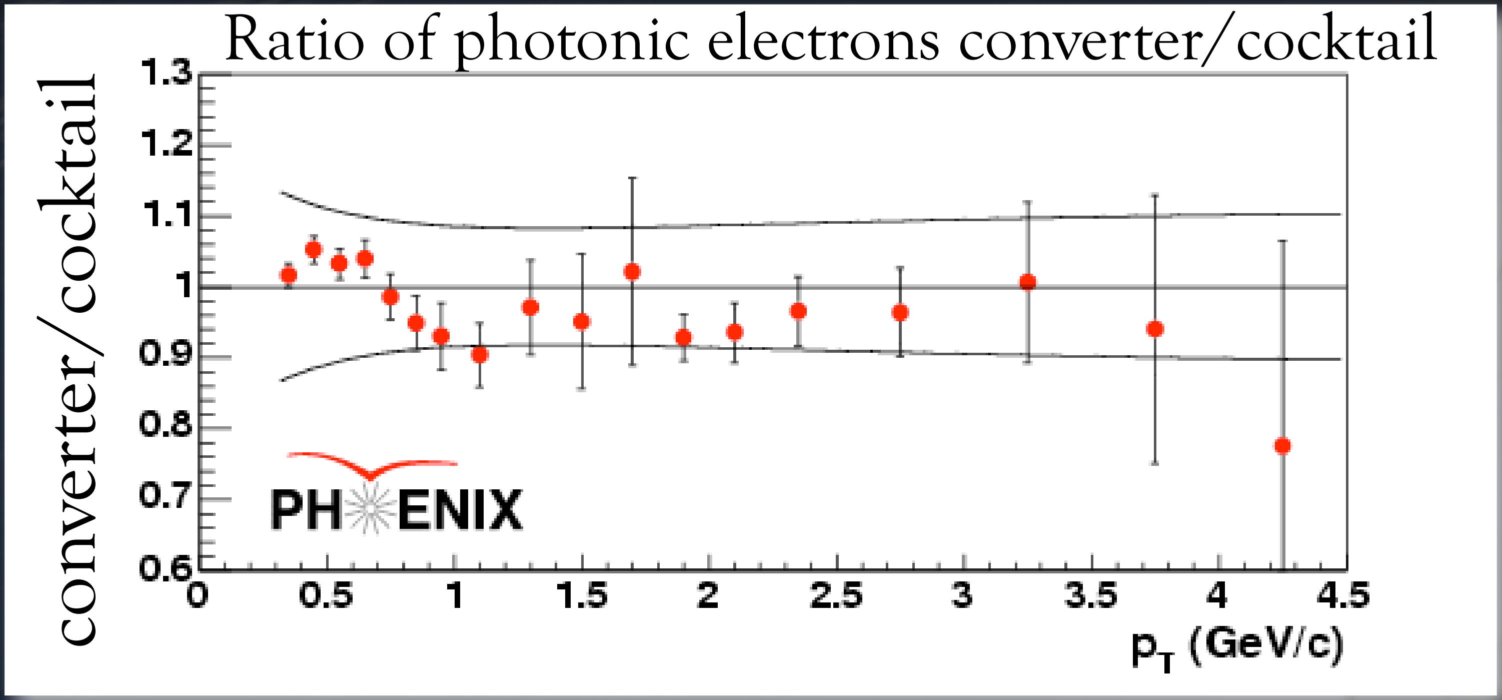
For fraction of the run, material added around the beam pipe (1.67 % X_0) increases photonic electrons by fixed amount

Converter method precisely measures photonic electron background.

Converter method has smaller systematic uncertainties than cocktail method at low p_T

Converter method used for low p_T

Cross check of the two methods



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

$p_T < 4.0$ GeV/c both methods in strong agreement

Subtract photonic electron estimate from inclusive yield:

$$E\frac{d^3\sigma^{non-\gamma}}{dp^3} = E\frac{d^3\sigma^{incl}}{dp^3} - E\frac{d^3\sigma^{\gamma}}{dp^3}$$

Non-photonic electron cross section is extracted by:

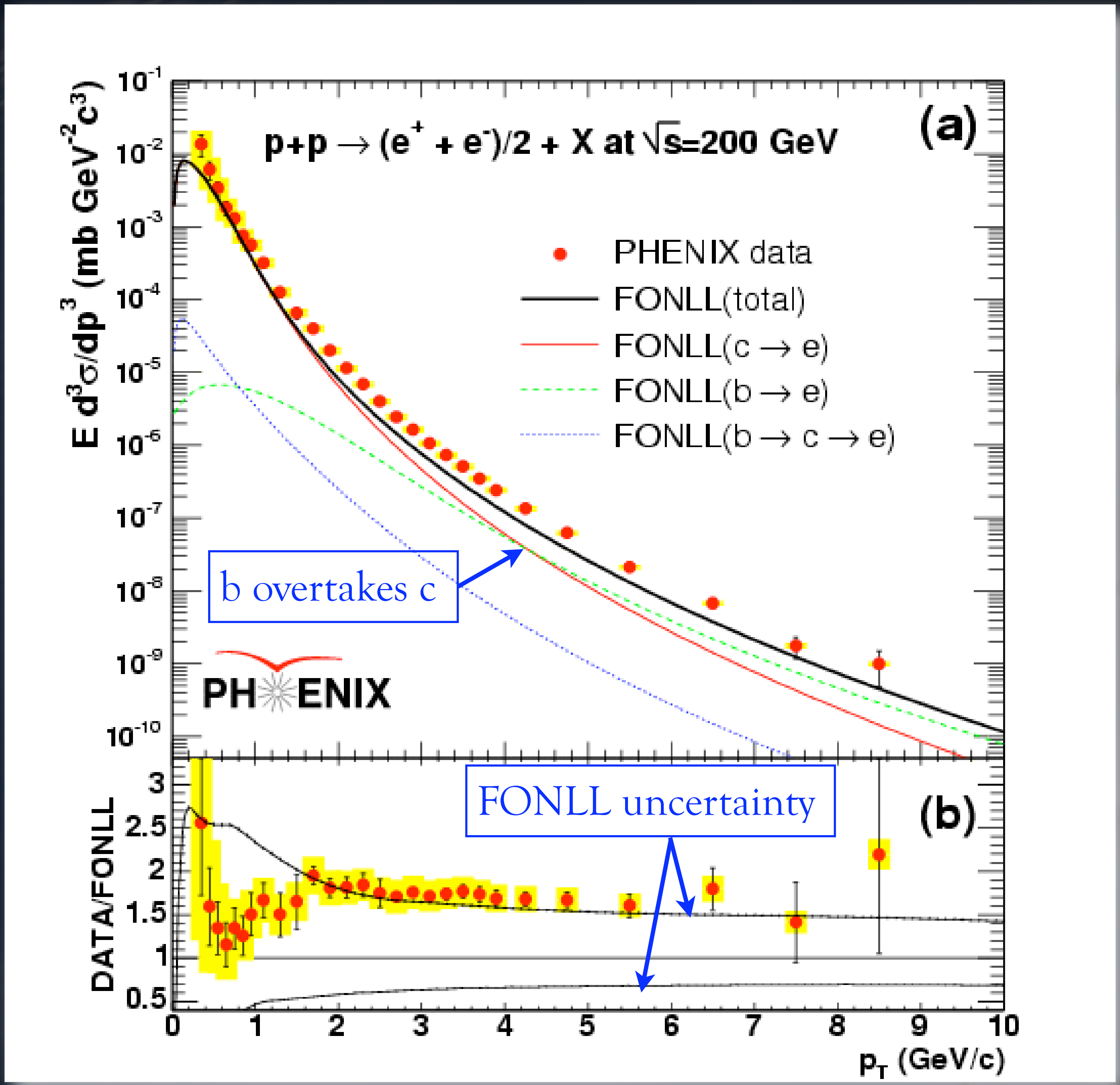
$$E\frac{d^3\sigma^{HQ}}{dp^3} = E\frac{d^3\sigma^{non-\gamma}}{dp^3} - E\frac{d^3\sigma^{K_{e3}}}{dp^3} - E\frac{d^3\sigma^{\rho\to ee}}{dp^3} - E\frac{d^3\sigma^{\omega\to ee}}{dp^3}$$

- converter low p_T & cocktail high p_T
- separate GEANT simulation
- cocktail
- cocktail

contributions small in converter p_T range

Excess of non-photonic electrons attributed to heavy flavor

p+p single electron spectra



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

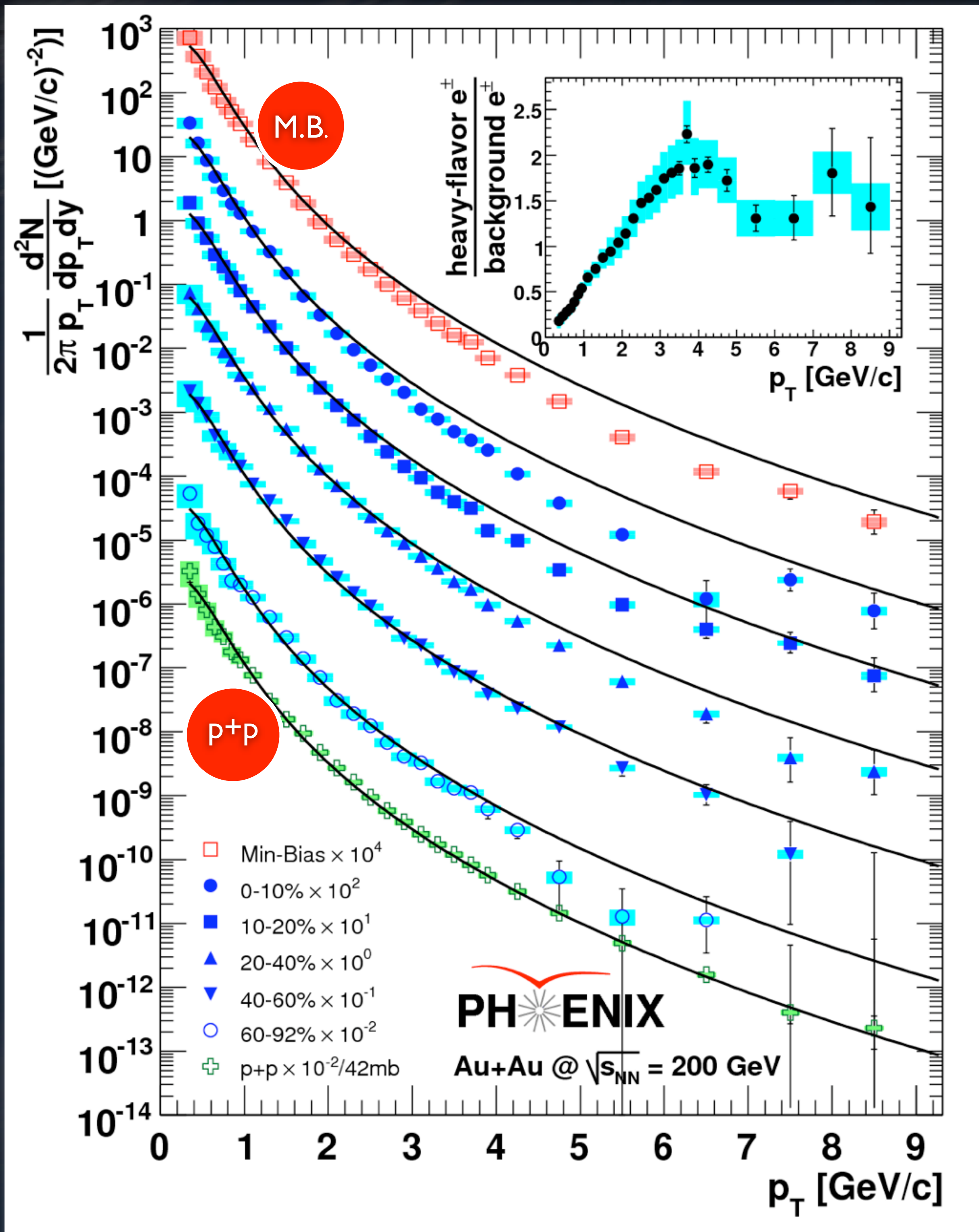
Extension of measurement from 5.0 to 9.0 GeV/c, using cocktail and tighter eID cuts

FONLL - Fixed Order Next to Leading Log hep-ph/0502203

Data/Theory ratio:
1.71 ± 0.02 (stat) ± 0.19 (sys)
compatible within uncertainties

Crucial baseline for heavy quark production in Au+Au collisions

Au+Au single electron spectra



nucl-ex/0611018

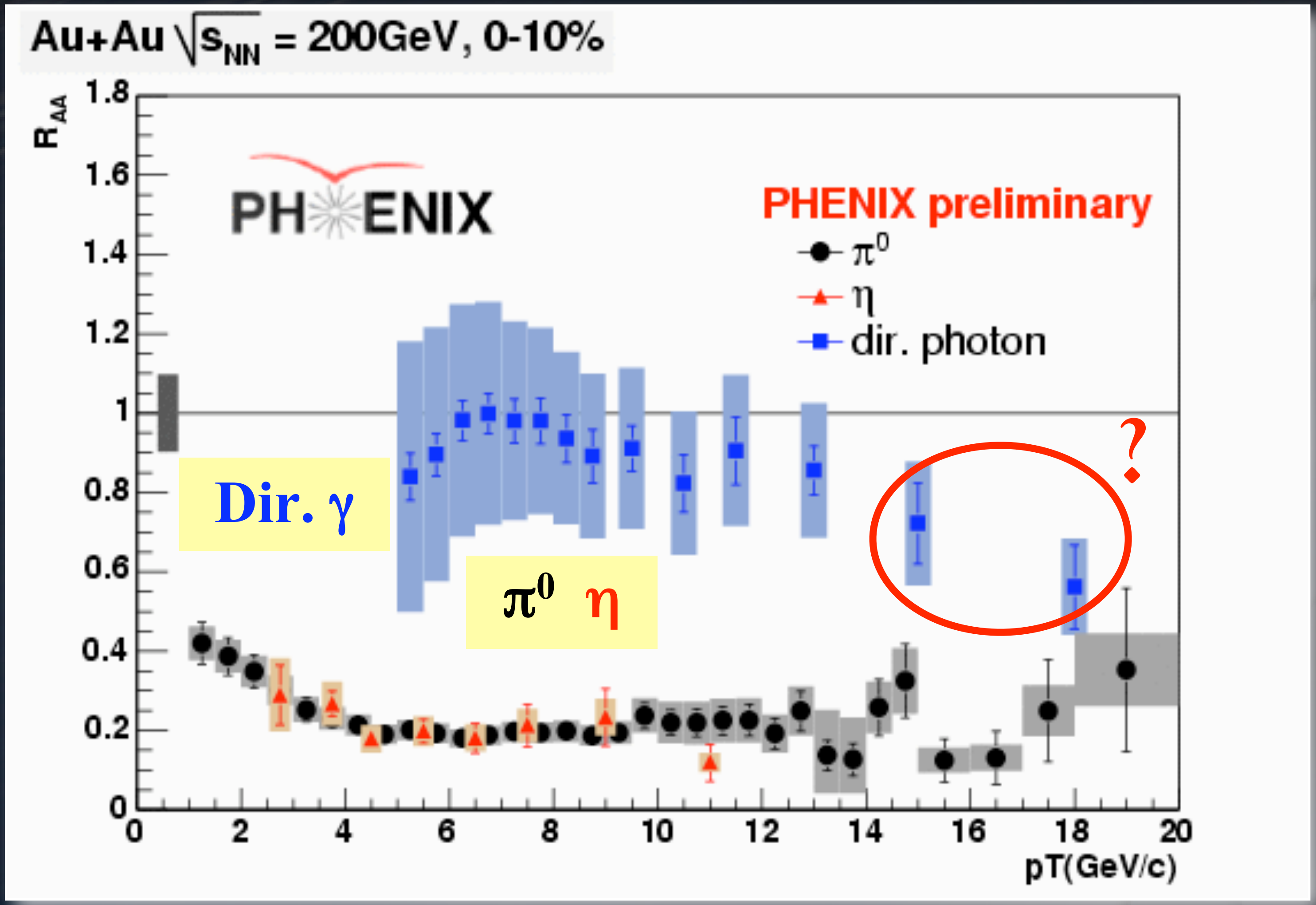
Solid lines: FONLL normalized to p+p data and scaled by number of binary NN collisions.

For all centralities, the Au+Au spectra agree well with the p+p reference at low p_T

Suppression is apparent at high p_T relative to scaled p+p results.

Extent of suppression quantified using nuclear modification factor.

a quick detour: light quark p_T suppresion



Phys. Rev. Lett. 91, 072301 (2003)

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{\frac{dN^{AA}}{dp_T}}{\frac{T_{AA}d\sigma^{pp}_{inel}}{dp_T}}$$

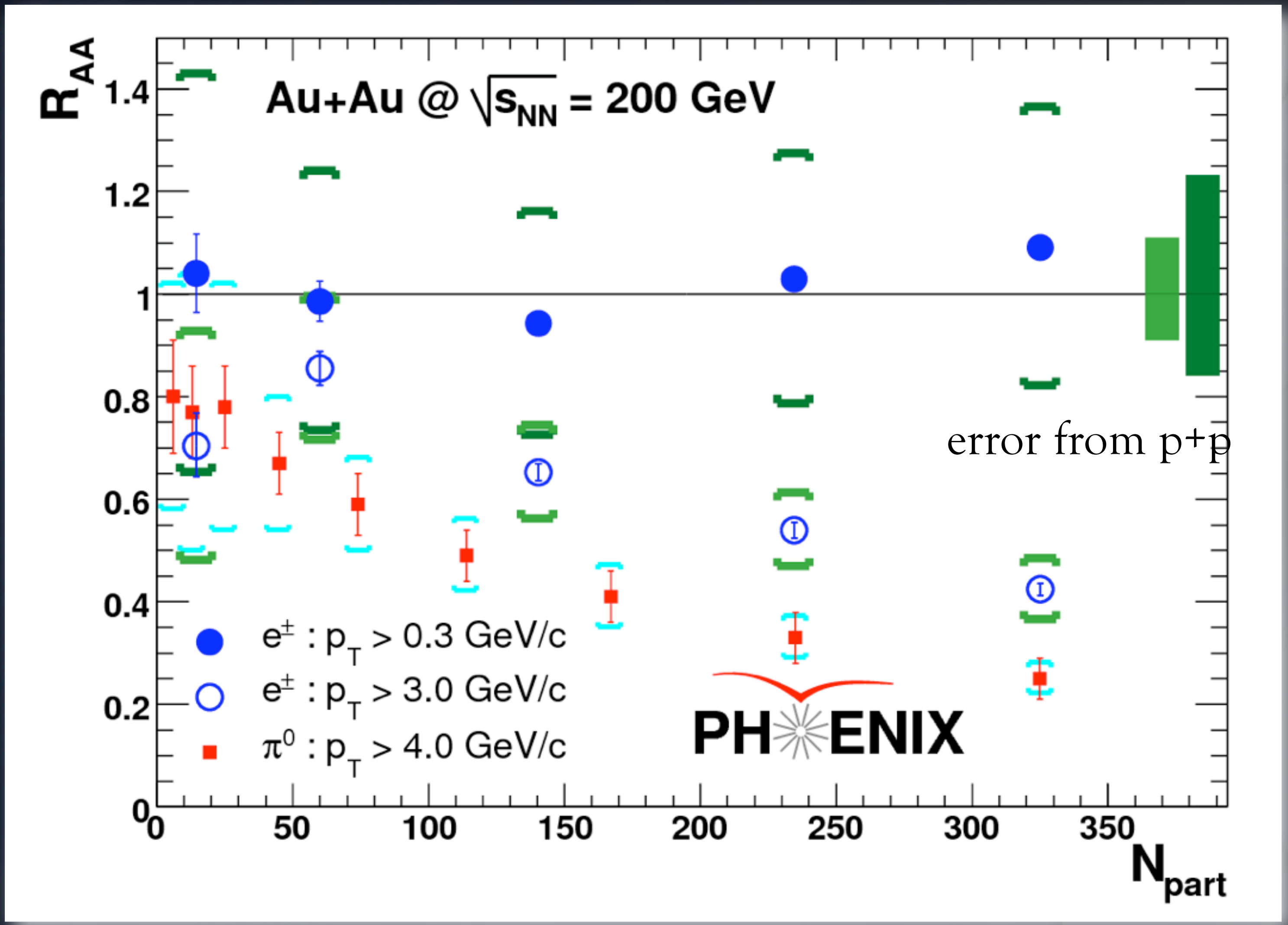
p_T Suppression (R_{AA} below 1) indicates strong coupling of quarks to the produced medium.

Photons not suppressed by the medium

Mesons suppressed by medium by factor of ~5

Heavy flavor R_{AA} vs. N_{part}

Heavy flavor was not expected to show strong suppression



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However, high p_T single electrons do show strong suppression (charm coming from D's).

Heavy flavor suppression better accommodated by theory with addition of elastic energy loss and geometrical path length fluctuations

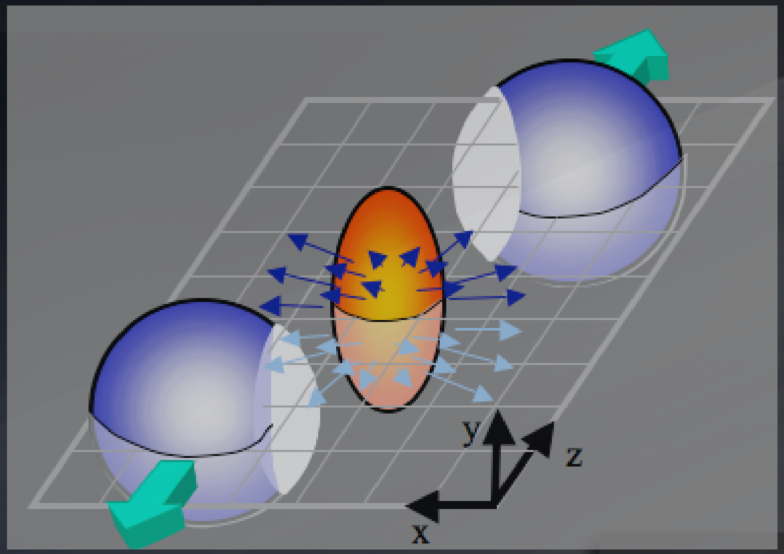
Wicks, et al. nucl-th/0512076

Integrated heavy flavor electrons exhibit binary scaling.

Elliptic Flow

Initial state spatial anisotropy leads to final state momentum anisotropy.

Azimuthal anisotropy "strength" indicated by v_2



$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$

$$v_2 = \left\langle \cos 2\left(\varphi - \Psi_R\right)\right\rangle$$

v_2 provides evidence of collective motion in the medium

non-photonic electron v_2 obtained by subtraction of photonic v_2

$$v_2^{non-\gamma} = \frac{((1+R_{NP})v_2^{inc} - v_2^{\gamma})}{R_{NP}}$$

R_{NP} - ratio of non-photonic to photonic electrons

- v_2^{γ} taken from cocktail using measured v_2 of background hadrons as input
- v_2^{γ} measured directly with converter method confirms cocktail result

Flow of Single electrons

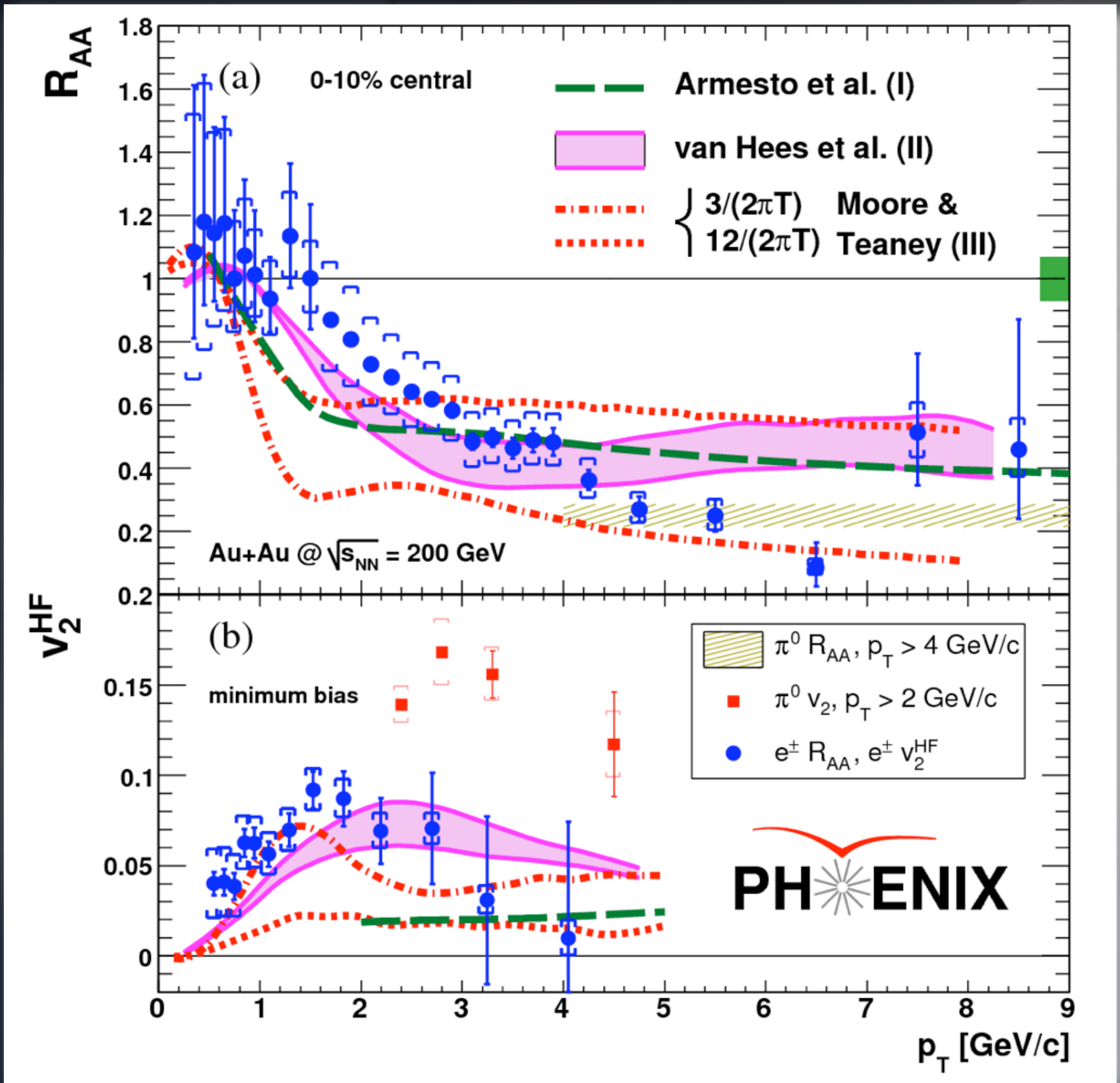
R_{AA} and v_2 comparisons with theoretical calculations

Charm flows, suggesting early thermalization of the medium

Simultaneous R_{AA} and v_2 hydro model comparisons suggest small HQ relaxation time and/or diffusion coefficient, D.

$$D \propto \eta/(sT)$$

AdS/CFT conjectures a quantum lower bound for η/s suggesting the medium is a near perfect liquid: $\frac{4\pi\eta}{s} \to 1$



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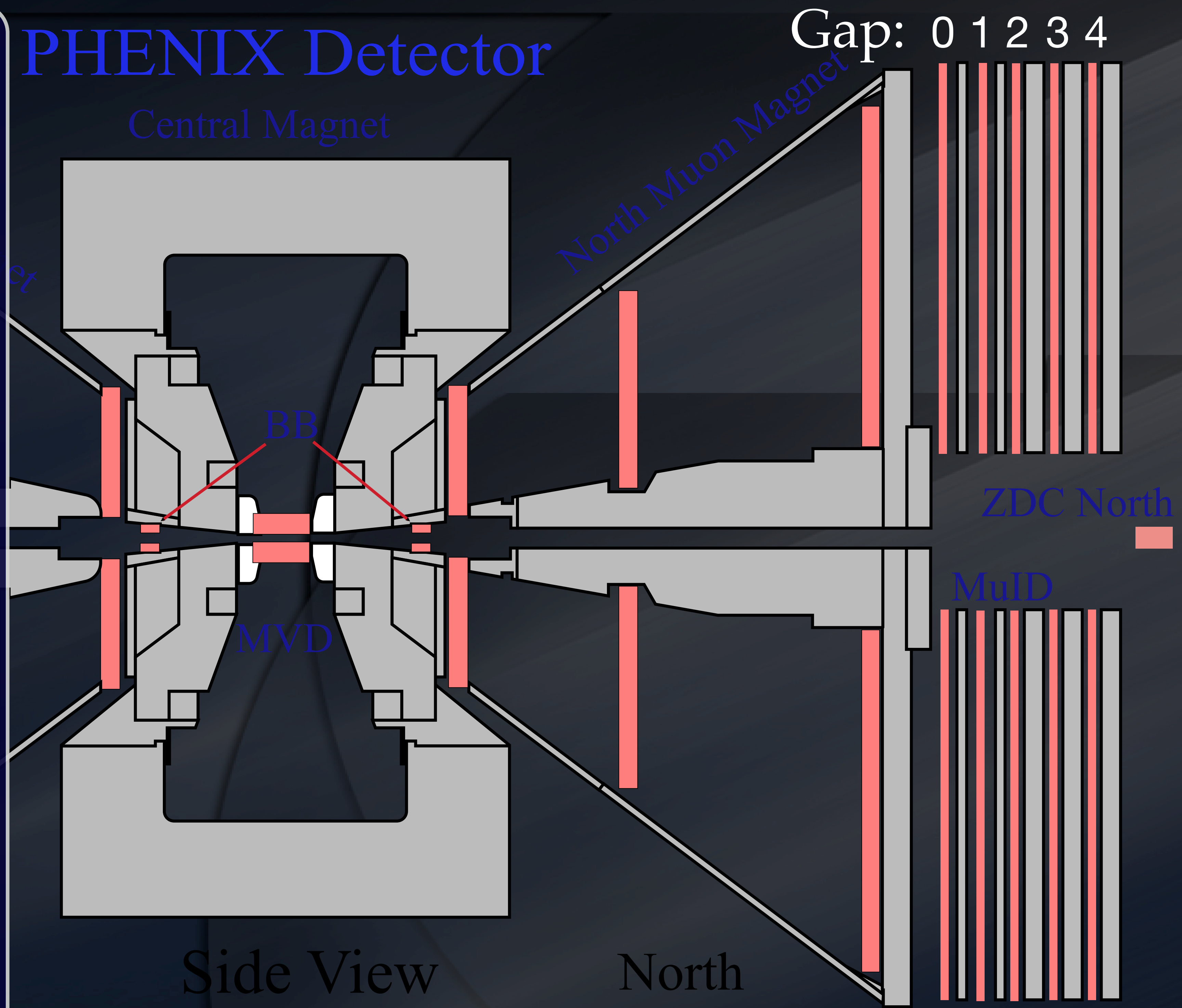
Measuring single muons at PHENIX

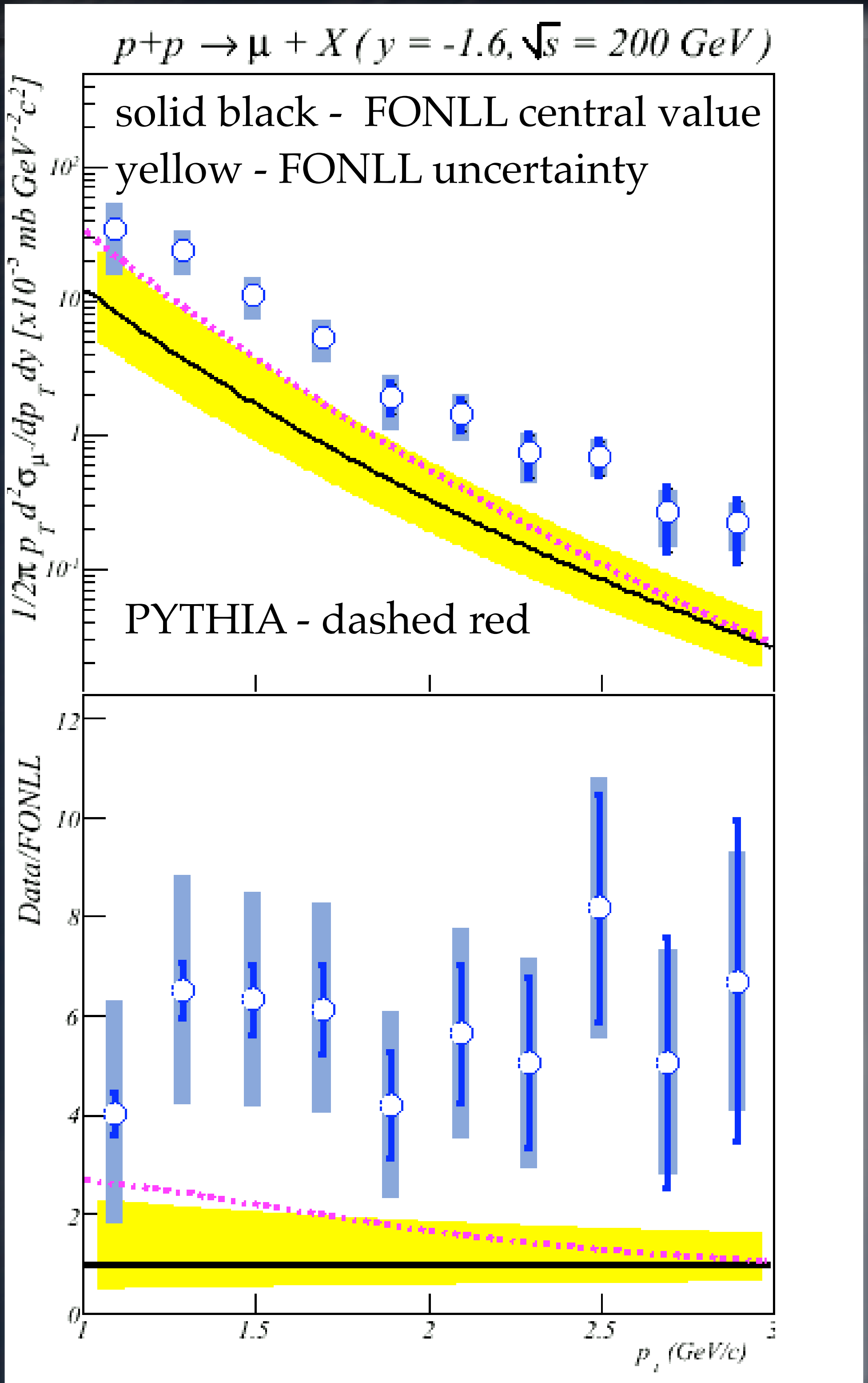
Heavy flavor single muons penetrate the entire detector.

A significant amount of steel (gray regions) in the muon arm provides pion rejection of > 250:1

Measured hadrons stopping in MuID gaps are used in conjuction with a GEANT hadron simulations to estimate inclusive backgrounds



Single muon results



nucl-ex/0609032

First forward rapidity single muon measurement in PHENIX

Data lies above FONLL (a few σ)

Substantial uncertainties exist in the measurement, which are to be reduced in future measurements.

Provides initial baseline for heavy ion study at forward rapidity Au+Au , d+Au, and Cu+Cu

Total charm cross section vs. rapidity

$$\frac{d\sigma_{\bar{c}c}}{dy}\Big|_{y=0} = 123\ \mu b \pm 12\ (stat) \pm 45\ (sys)$$

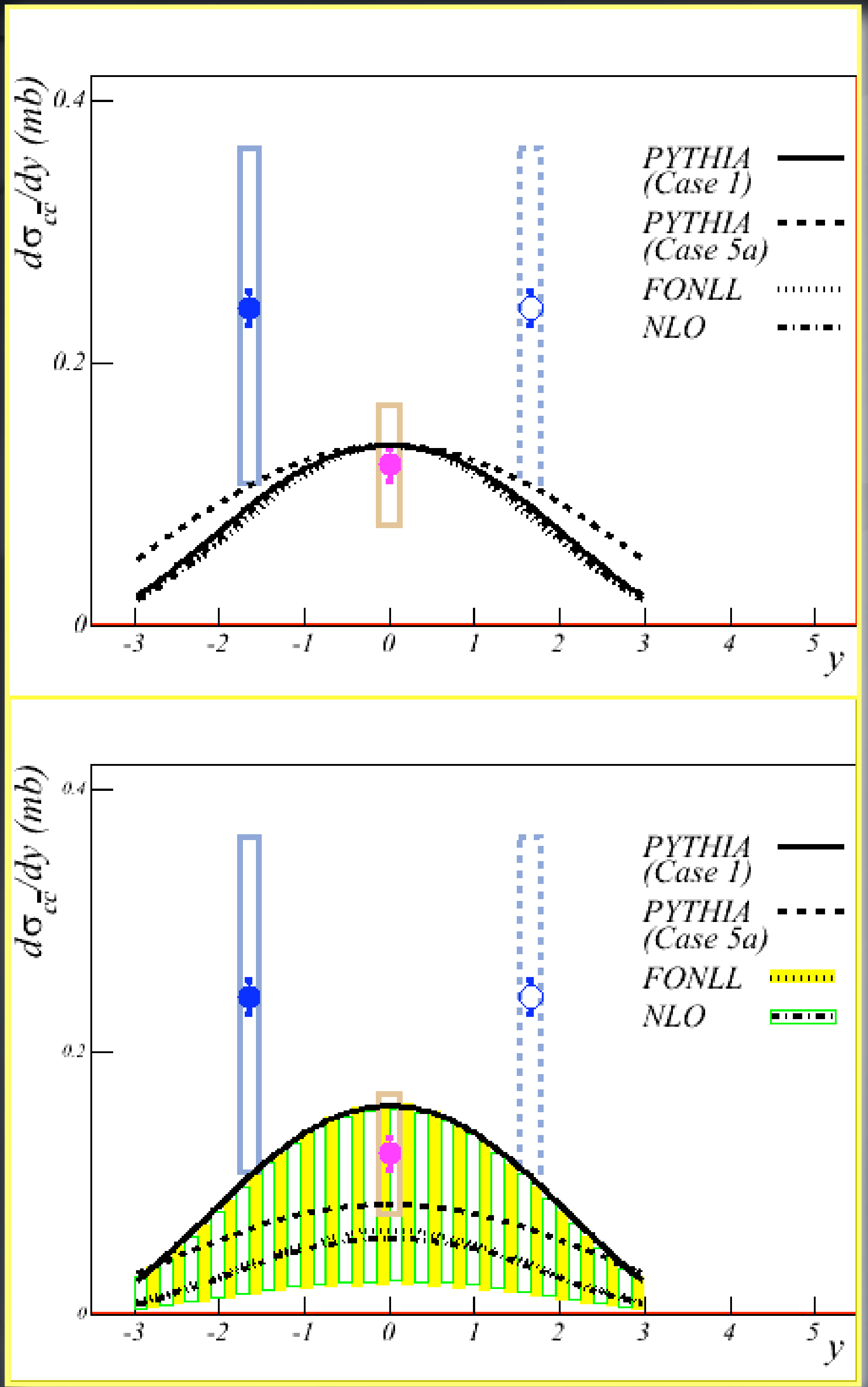
$$\frac{d\sigma_{\bar{c}c}}{dy}\Big|_{y=1.6} = 243\ \mu b \pm 13\ (stat) \pm 105\ (sys)$$

y=1.6 total cross section compatible with y=0 measurement ... within errors

Total charm cross section:

567 μb ± 57 (stat) ± 224 (sys)

derived from y=0 measurment



nucl-ex/0609032

Conclusions

Heavy flavor in p+p collisions consistently above FONLL calculation central values, but compatible within uncertainties.

Charm quark suppression in Au+Au nearly comparable to that of light quarks

Charm participate in collective flow suggesting early thermalization of the medium at RHIC.

Simultaneous measurements of R_{AA} and v_2 suggest the medium produced in central Au+Au collisions is a near perfect fluid

Outlook

A new PHENIX single muon preliminary result (run 5) is forthcoming:

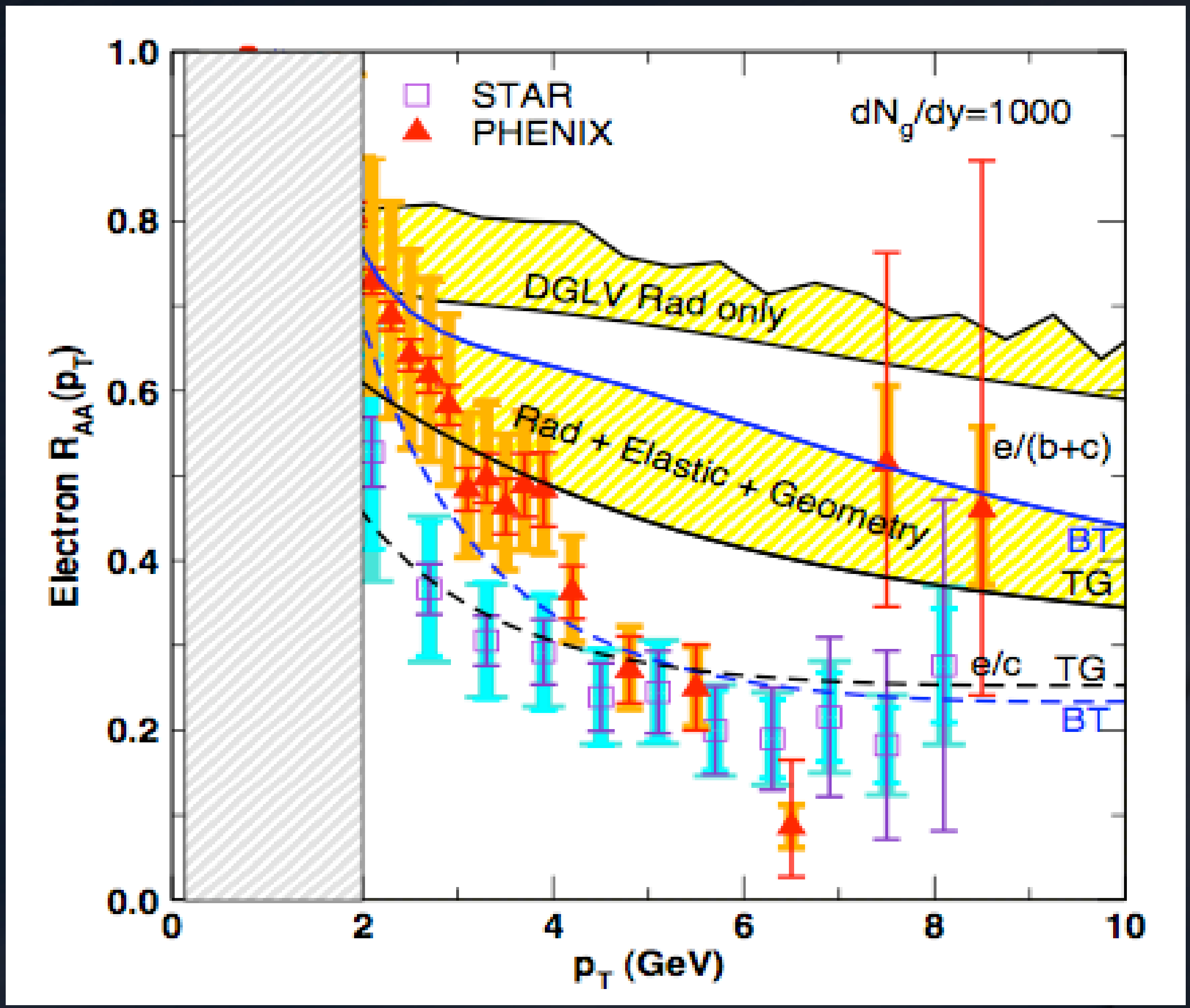
- extension in p_T to above 5.0 GeV/c
- factor of 100 more statistics than existing result
- better baseline at forward rapidity for heavy ions
- more quantitative statement of charm cross section rapidity evolution

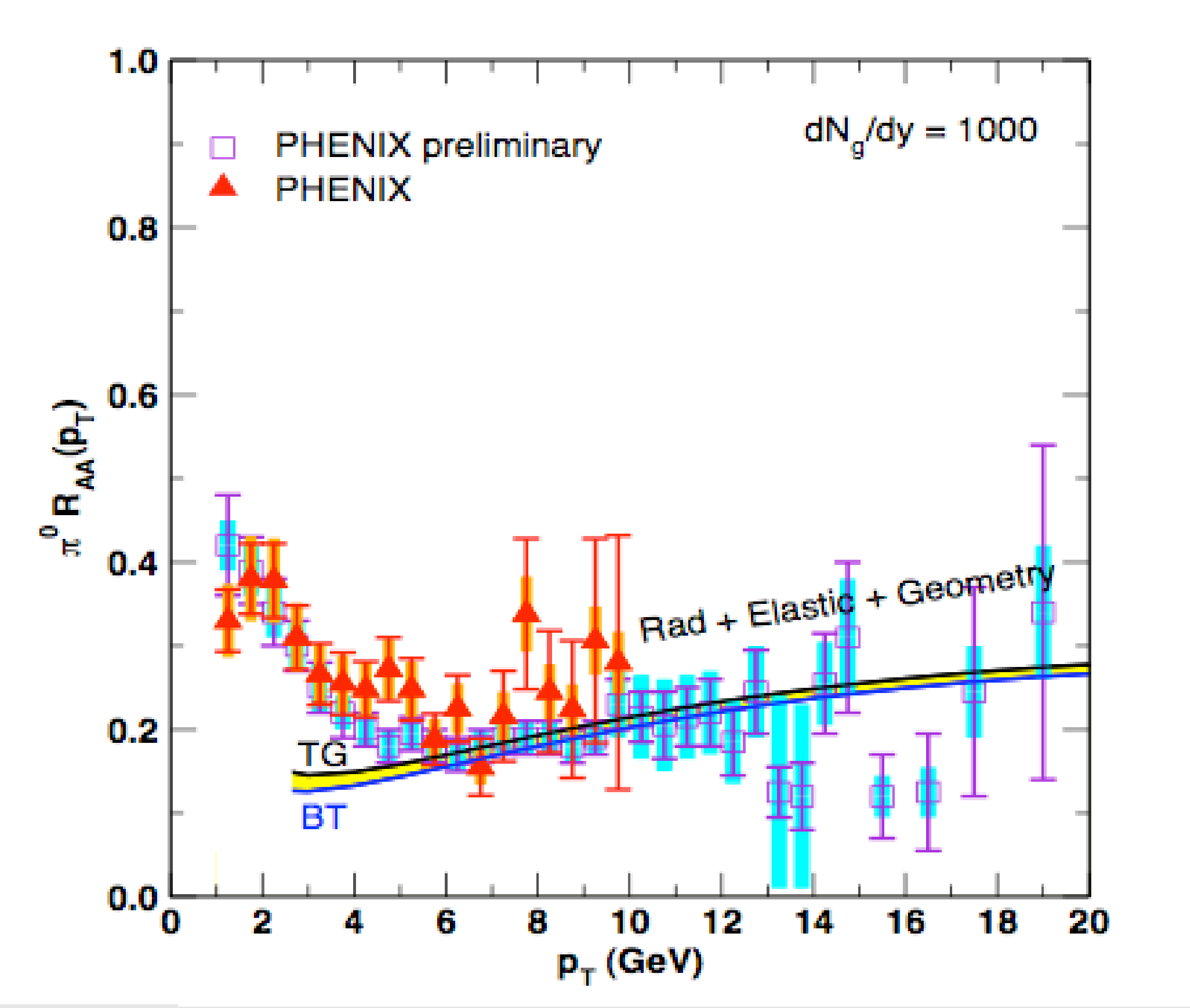
Extraction of gluon polarization from heavy-flavor single **electrons** is attainable.

Installation of a new silicon vertex detector will measure displaced vertices of electrons and muons, significantly improving PHENIX's ability to measure heavy flavor via single leptons.

R_{AA}

Calculations including both elastic and inelastic energy losses as well as jet path length fluctuations.





data: single electron central Au+Au
dashed lines have bottom neglected

data: π^0