The Charm and Beauty of RHIC

Ralf Averbeck, GSI

International School of Nuclear Physics, 30thCourse

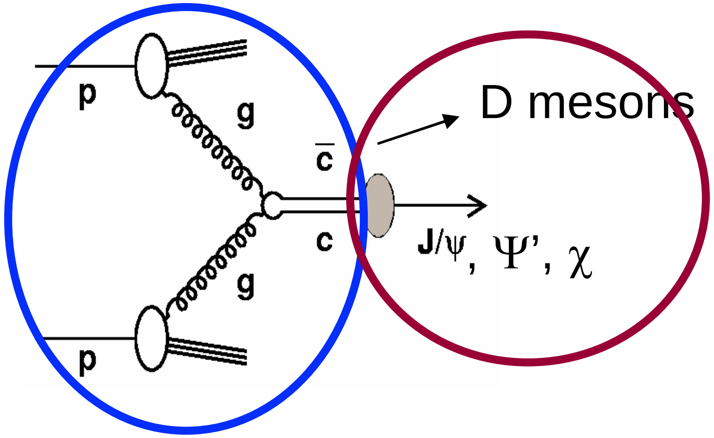
Heavy-Ion Collisions from the Coulomb Barrier to the Quark-Gluon Plasma

Erice - Sicily

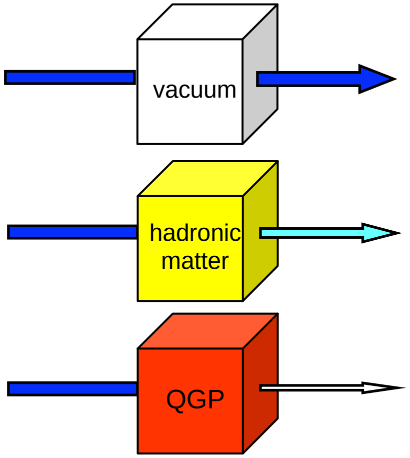
September 16-24, 2008

Introduction

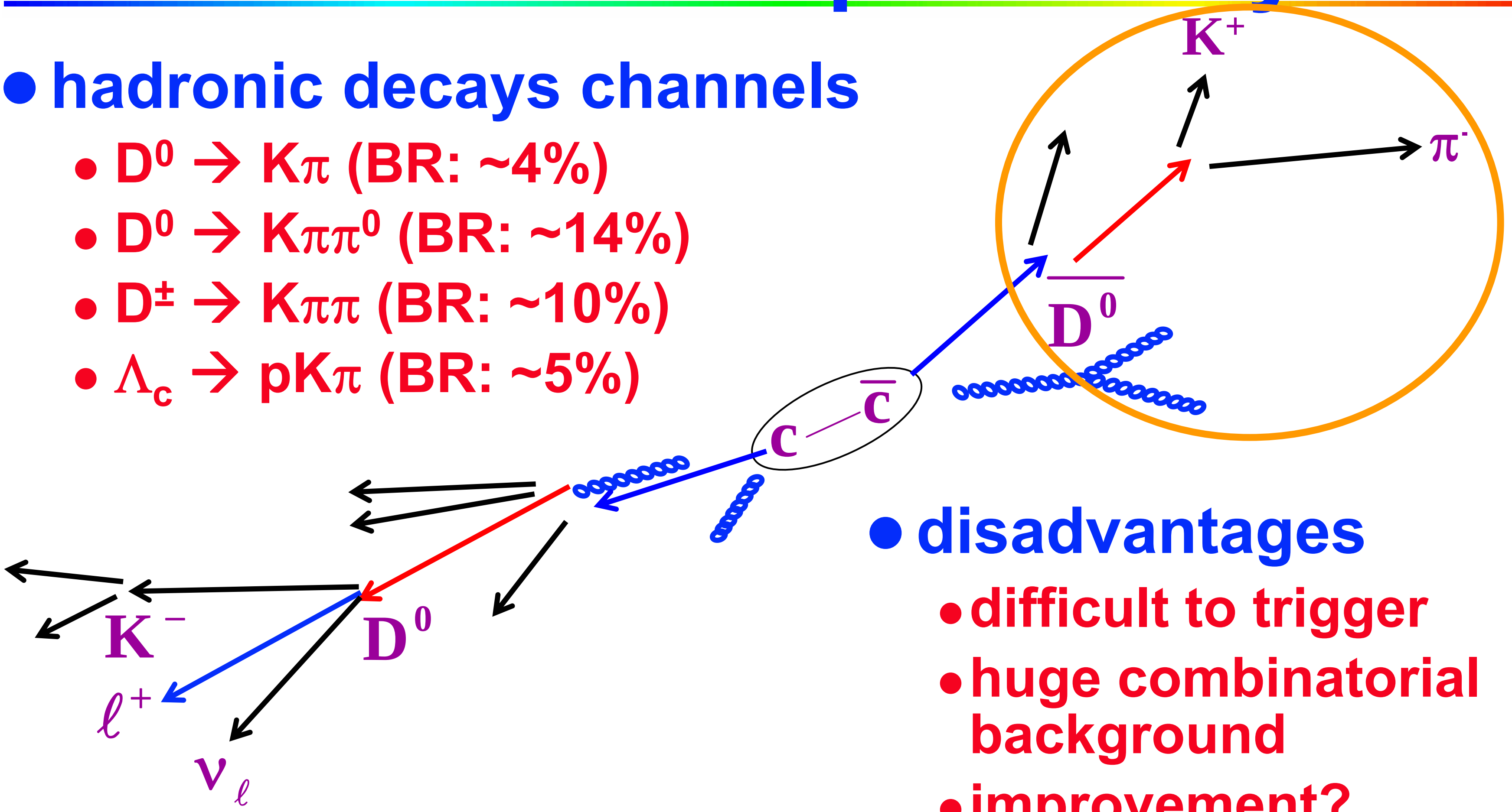
- charm and bottom from hadronic collisions
  - m_c~1.25 GeV, m_b~4.5 GeV
  - hard process ($m_q \gg \Lambda_{QCD}$), even at low p_T
  - open heavy flavor: D, Λ_c, B, Λ_b
  - (quarkonia: J/ψ, Υ)



- heavy-ion collisions
  - heavy-quark production before a medium is formed!
- heavy flavor as a hard probe
  - well calibrated in pp collisions
  - slightly affected and well understood in hadronic matter
  - strongly affected in a partonic medium
  - first systematic studies at RHIC



How to measure open heavy flavor

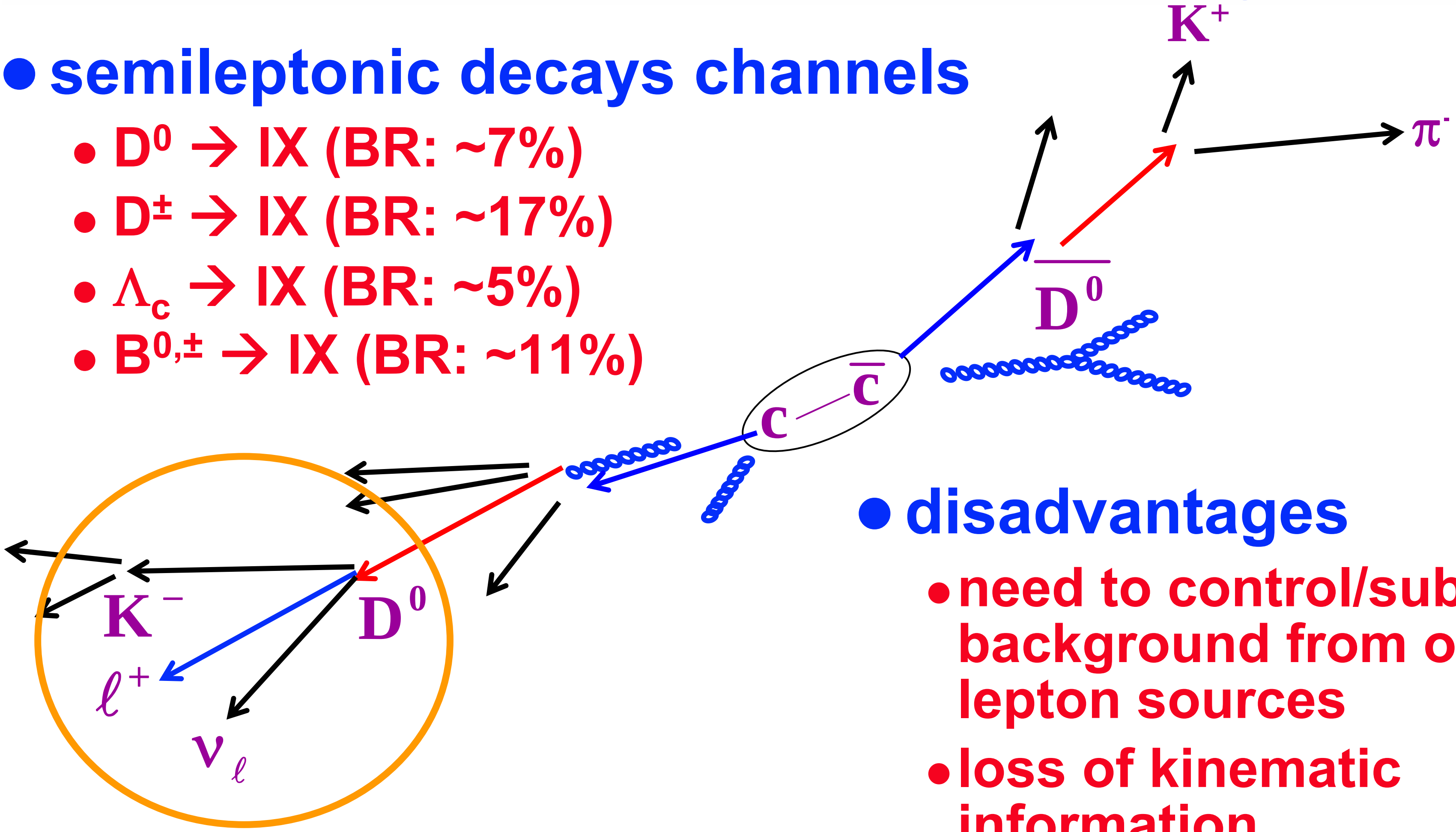


- hadronic decays channels
  - $D^0 \rightarrow K\pi$ (BR: ~4%)
  - $D^0 \rightarrow K\pi\pi^0$ (BR: ~14%)
  - $D^\pm \rightarrow K\pi\pi$ (BR: ~10%)
  - $\Lambda_c \rightarrow pK\pi$ (BR: ~5%)
- advantage
  - unambiguous identification, i.e. a peak in invariant mass
- disadvantages
  - difficult to trigger
  - huge combinatorial background
  - improvement?
    - resolve decay vertices
      - charm: $c\tau$ ~ 100-200 μm
      - bottom: $c\tau$ ~ 400-500 μm

    → silicon vertex detectors

How to measure open heavy flavor

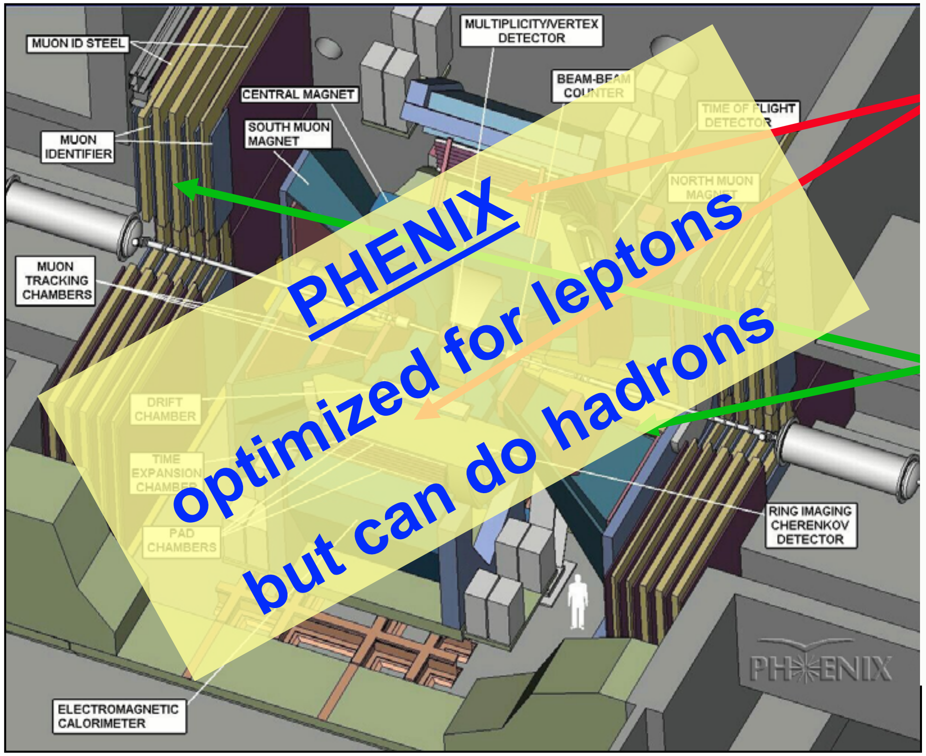
- semileptonic decays channels
  - $D^0 \rightarrow lX$ (BR: ~7%)
  - $D^{\pm} \rightarrow lX$ (BR: ~17%)
  - $\Lambda_c \rightarrow lX$ (BR: ~5%)
  - $B^{0,\pm} \rightarrow lX$ (BR: ~11%)



- advantages
  - 'straight forward' trigger
  - no combinatorial BG

- disadvantages
  - need to control/subtract background from other lepton sources
  - loss of kinematic information
  - continuum → can NOT disentangle c & b with single leptons only

PHENIX & STAR at RHIC

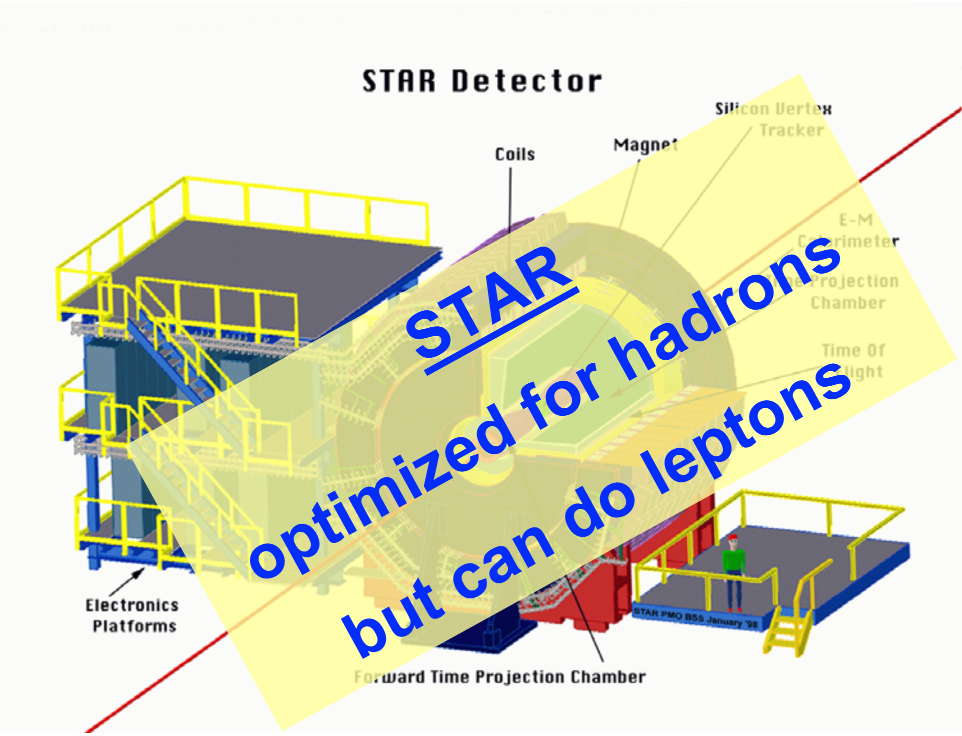


PHENIX

optimized for leptons

but can do hadrons

- electrons in central arms
  - tracking
  - electron ID:
    - RICH + EMC
- muons in forward arms
  - tracking
  - muon ID:
    - “absorber”



STAR

optimized for hadrons

but can do leptons

- large acceptance ($|\eta| < 1$) tracking detector: TPC
  - hadrons:
    - TPC (dE/dx)
    - Time-of-Flight detector
  - electron ID:
    - EMC in addition

e± from heavy flavor: difficulties

- electrons are rare: $e^{\pm}/\pi^{\pm} \sim 10^{-2}$

→ need excellent PID!

- MANY electrons sources
  - Dalitz decay of light neutral mesons
    - most important $\pi^0 \rightarrow \gamma\, e^+e^-$
    - but also: η, ω, η', ϕ
  - conversion of photons
    - main photon source: $\pi^0 \rightarrow \gamma\gamma$
    - in material: $\gamma \rightarrow e^+e^-$
  - weak kaon decays
    - K_{e3}, e.g.: $K^{\pm} \rightarrow \pi^0\, e^{\pm}\, \nu_e$
  - dielectron decays of vector mesons
    - $\rho, \omega, \phi \rightarrow e^+e^-$
  - direct/thermal radiation
    - conversion of direct photons in material
    - virtual photons: $\gamma^* \rightarrow e^+e^-$
  - heavy flavor decays

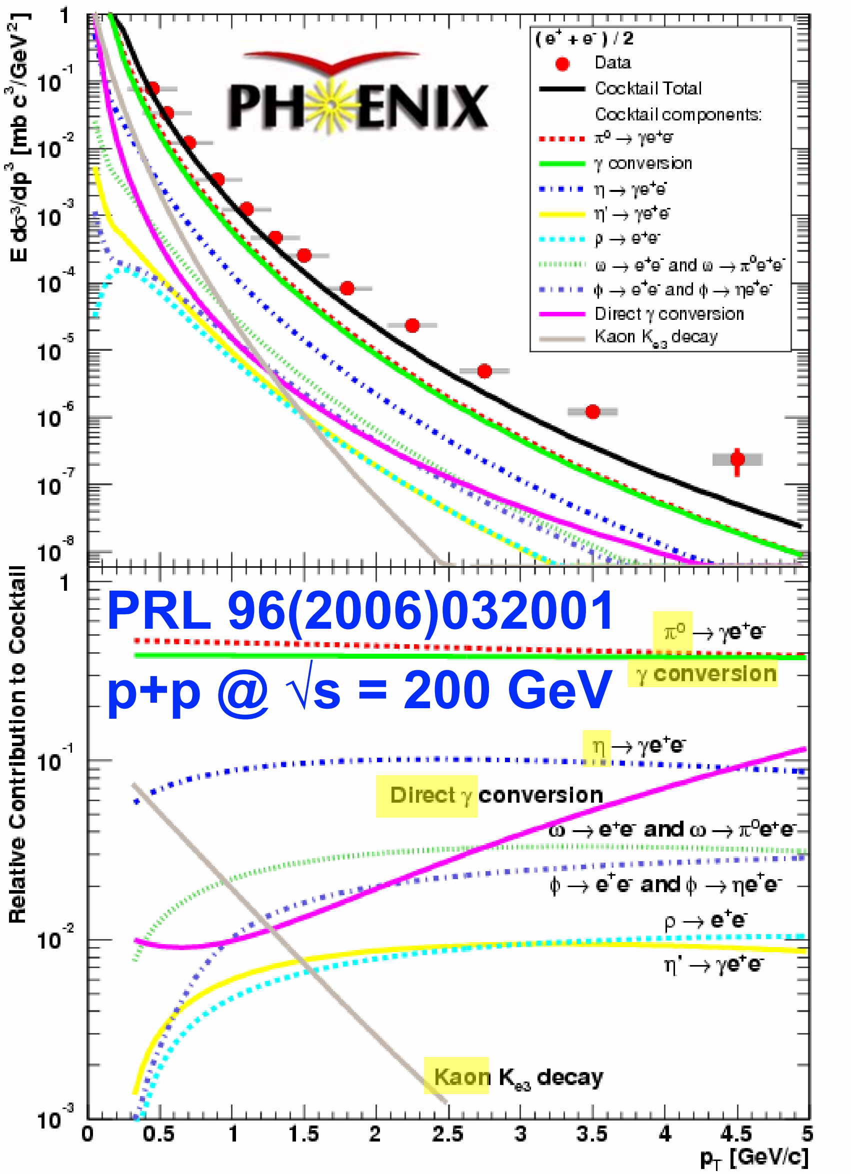
PHOTONIC e±

NON-PHOTONIC e±

→ need excellent BG subtraction!

Cocktail subtraction

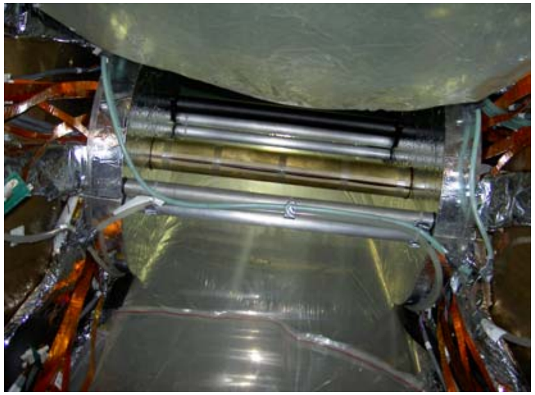
- ALL relevant background sources are measured
- calculate e± BG
- BG subtraction → e± from heavy-flavor decays
- performance limited by signal/background ratio
  - works well towards high p_T
    - good for measurement of e± spectra
  - difficult towards low p_T
    - limited use for measurement of total cross sections

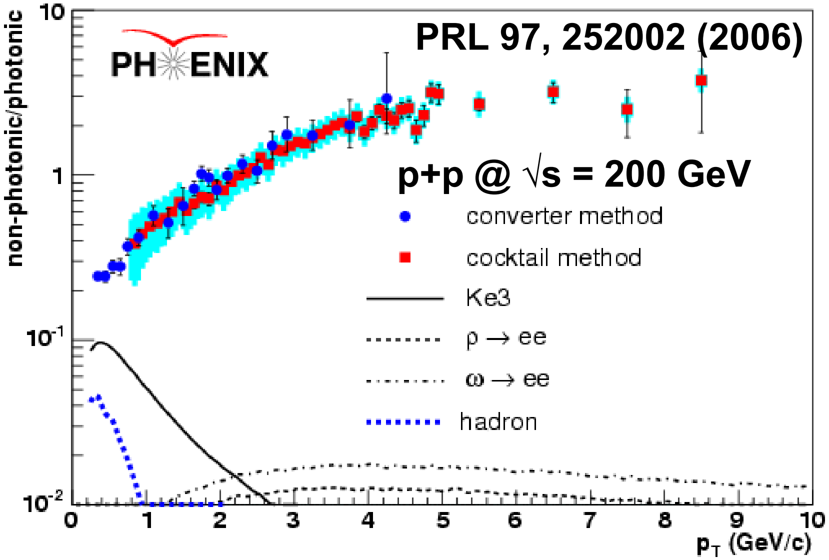

PRL 96(2006)032001

p+p @ $\sqrt{s}$ = 200 GeV

Converter subtraction

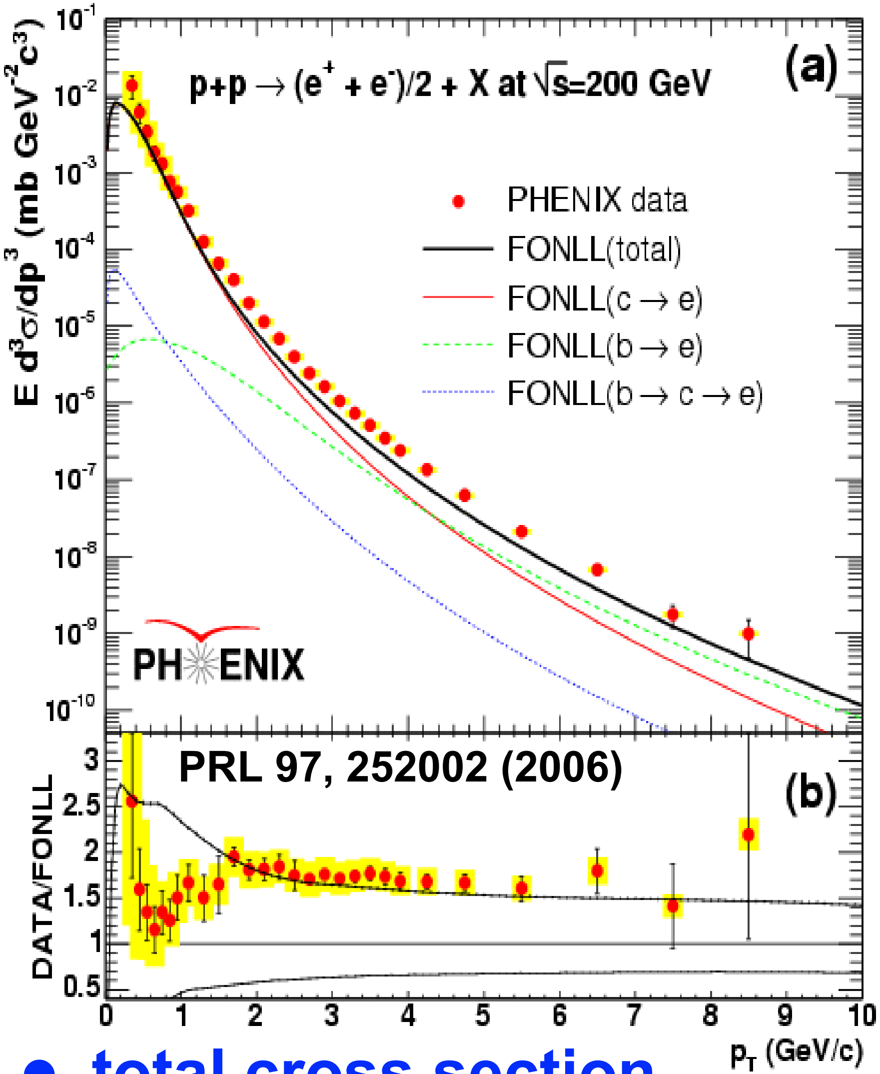
- converter (known X/X^0) added for part of the run
- converter multiplies photonic BG by KNOWN factor
  → difference between converter in & out runs MEASURES photonic BG
- performance limited by statistics in converter run
  - works well towards low p_T
    - good for total cross section measurement
  - difficult towards high p_T





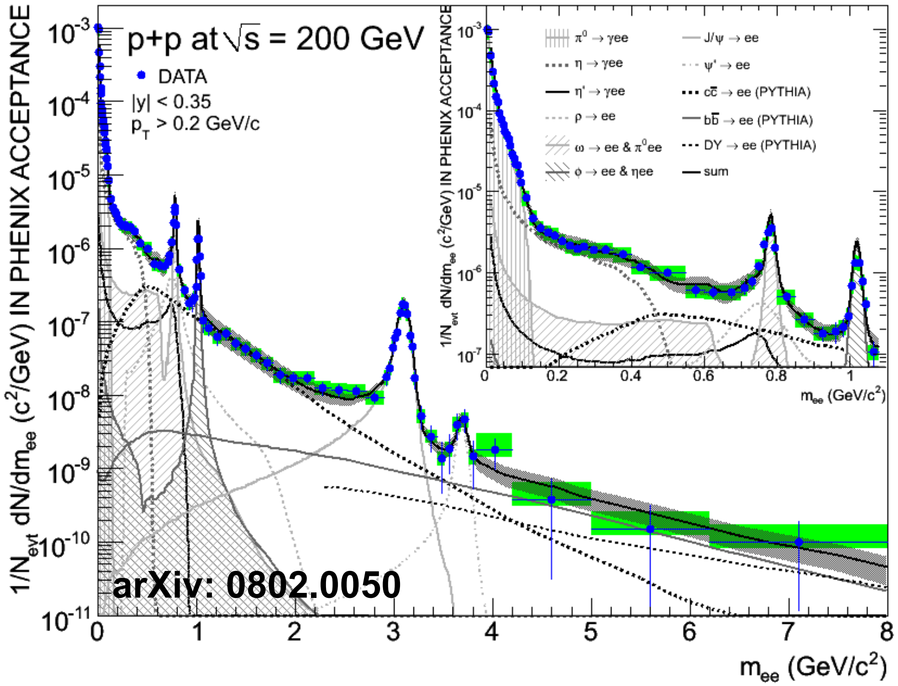
- excellent agreement between methods!

$e^{\pm}$ from heavy flavor in p+p ($\sqrt{s}$=200 GeV)



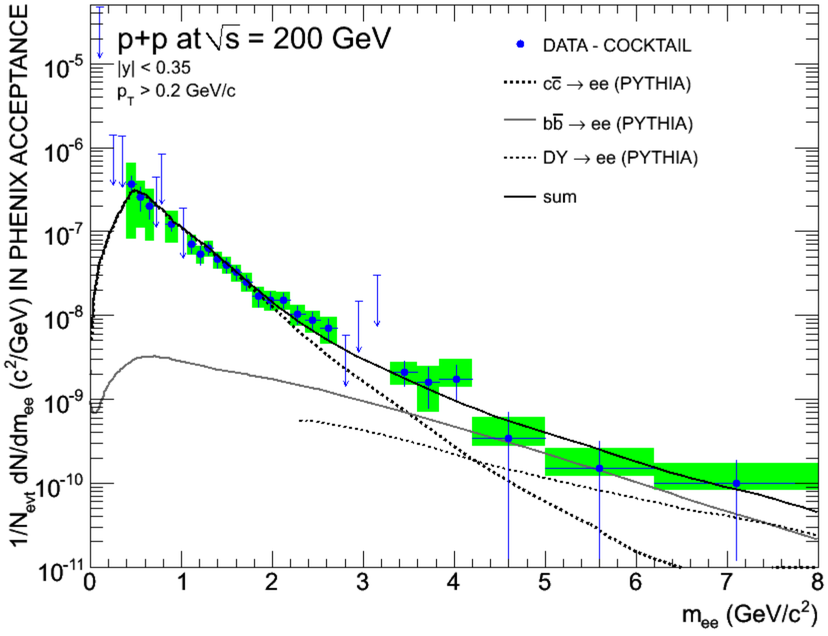
- **non-photonic $e^{\pm}$ from $c \rightarrow e^{\pm}$ and $b \rightarrow e^{\pm}$**
  - **compare with FONLL**
    - **Fixed Order Next-to-Leading Log pQCD**
      (M. Cacciari, P. Nason, R. Vogt PRL95,122001 (2005))
    - **data ~ 2 x FONLL**
      - **seen also in charm yields at**
        - **DESY (photoproduction)**
        - **FNAL (hadroproduction)**
    - **consistent within large uncertainties**
  - **bottom becomes important at high p_T!**
- **total cross section**
  - **σ_{cc}= 567 ± 57(stat) ± 224(sys) μb**

Charm and bottom from e^+e^- pairs



arXiv: 0802.0050

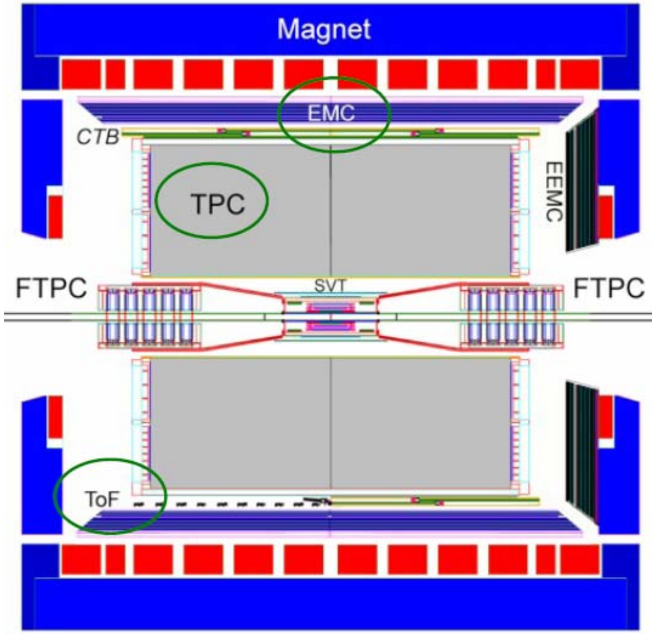
- **e^+e^- inv. mass after background subtraction compared to cocktail**
- **excellent agreement**
- **charm & bottom accessible after cocktail subtraction**

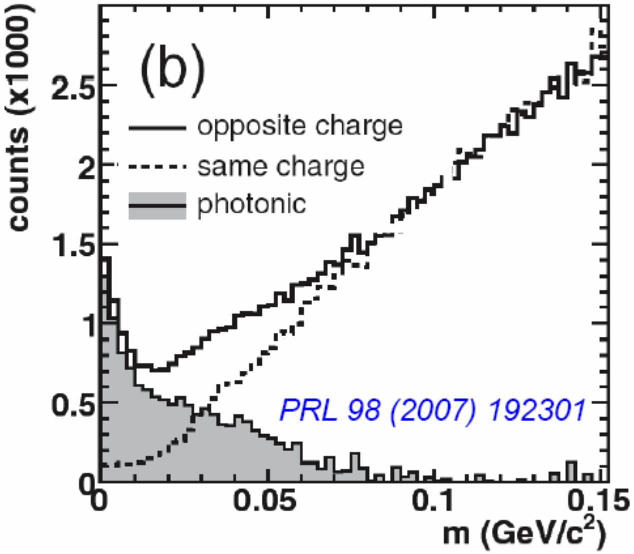


- **simultaneous fit of charm & bottom**
  - **σ_{cc}= 518 ±47(stat)±135(sys)±190(model) μb**
  - **σ_{bb}= 3.9 ±2.4(stat)+3/-2(sys) μb**
- **bottom irrelevant for total $e^\pm$ yield, but crucial at high p_T!**

Background subtraction in STAR

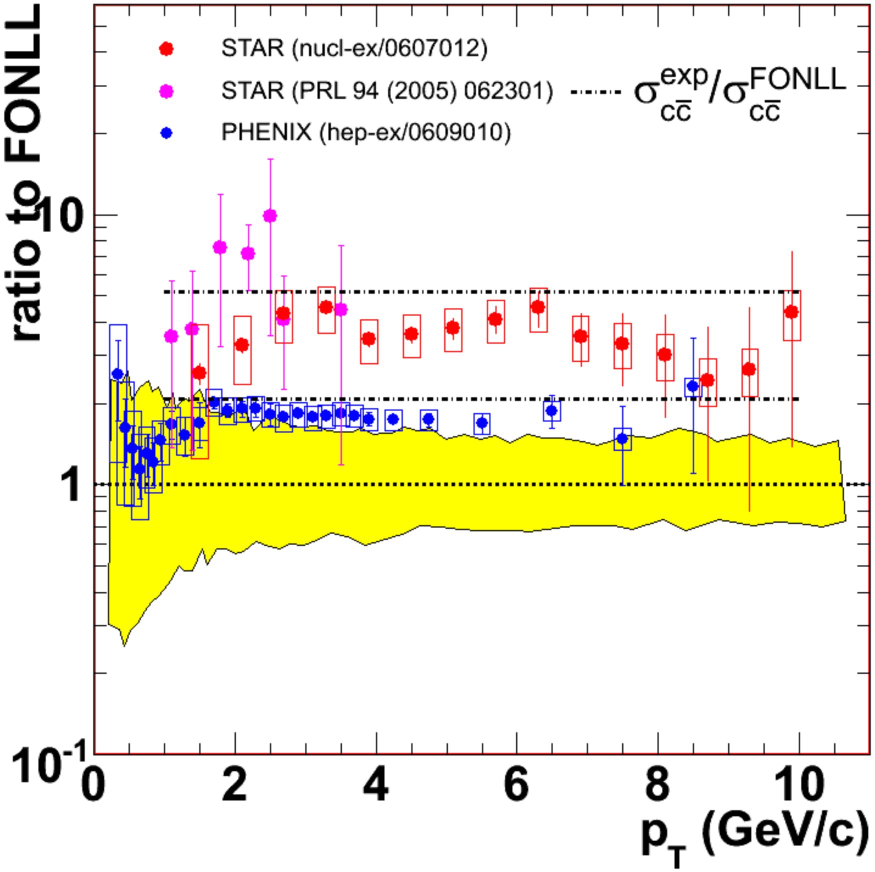
- photonic $e^{\pm}$ BG in STAR
  - dominant source
    - photon conversions
      - mainly in Si detectors near vertex
      - conv. / Dalitz ~ 5
  - subtraction
    - large acceptance TPC
    - reconstruction and subtraction of conversion and Dalitz pairs
      - efficiency: ~ 70-80% for $p_T > 4$ GeV/c
    - remaining BG: cocktail





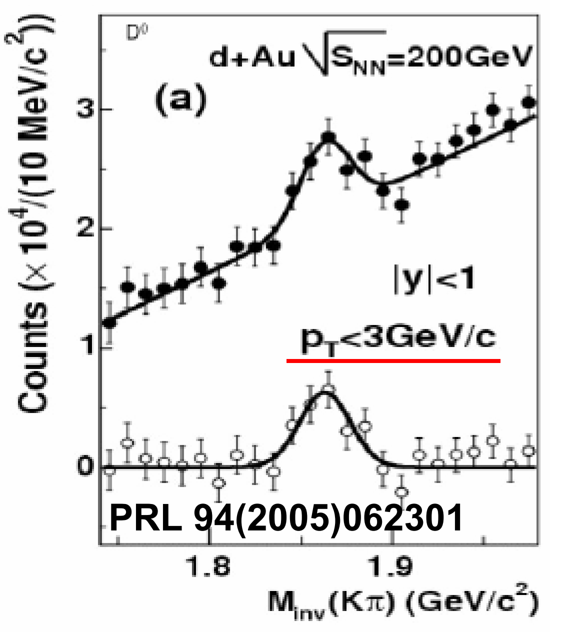
PHENIX vs. STAR vs. FONLL

- ratio of heavy-flavor $e^{\pm}$ spectra to FONLL
  - PHENIX
    - spectral shape of $e^{\pm}$ agrees with FONLL
    - total cross section above FONLL by a factor ~2
  - STAR
    - shape consistent with PHENIX and FONLL
    - total cross section above FONLL by a factor ~4
  - systematic uncertainties in pQCD are large

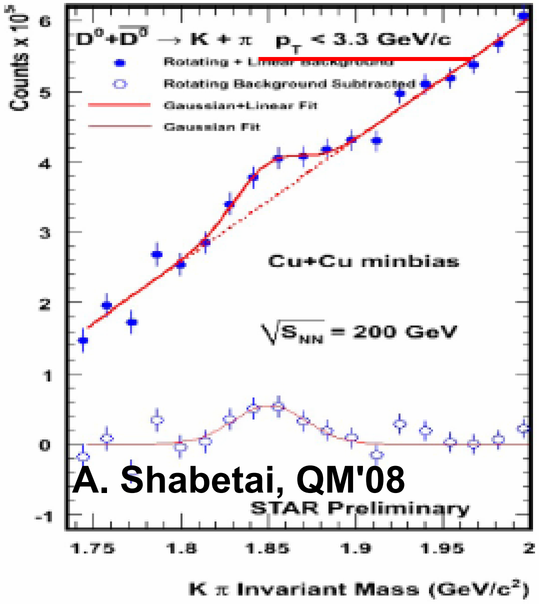


D-meson reconstruction in STAR

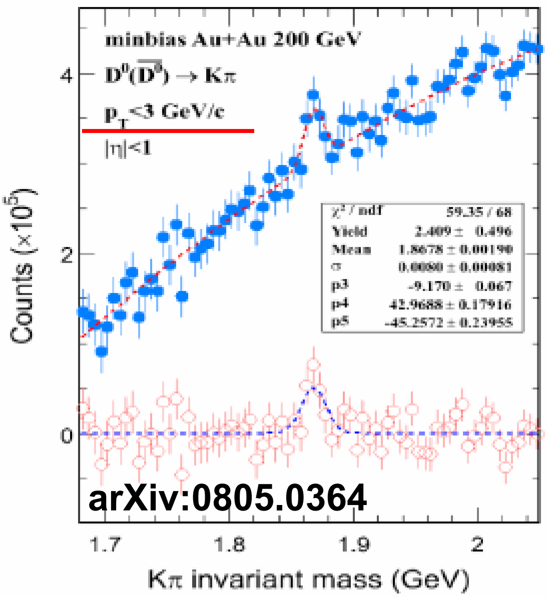
- $D^0 \rightarrow K\pi$ invariant mass analysis
  - main problem: S/B ratio << 1/100
    → need huge stat. (yield uncertainty ~ 40-50%)
  - currently limited to $p_T \lesssim$ ~3 GeV/c
    - reasonable for total cross section
    - insufficient to address flow & high p_T suppression



PRL 94(2005)062301



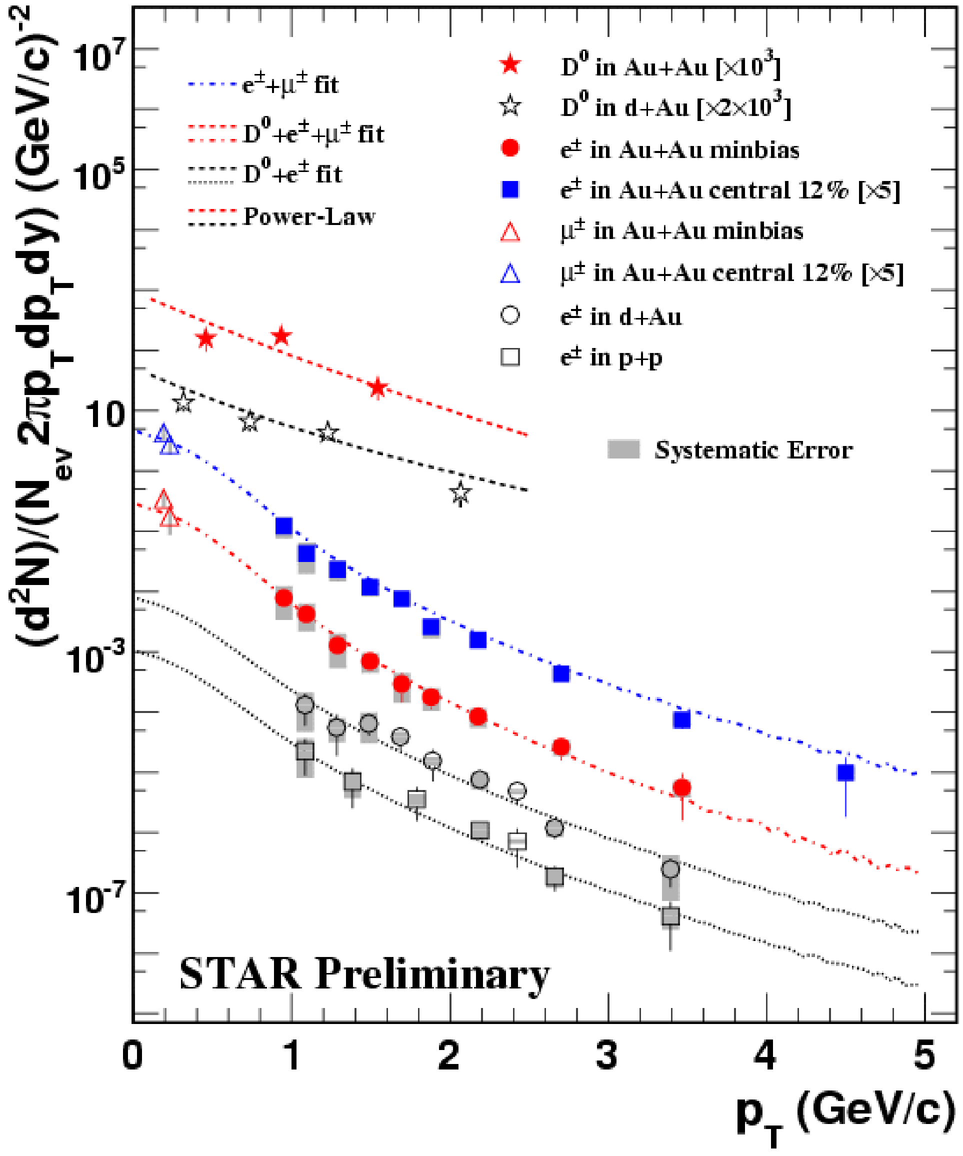
A. Shabetai, QM'08



arXiv:0805.0364

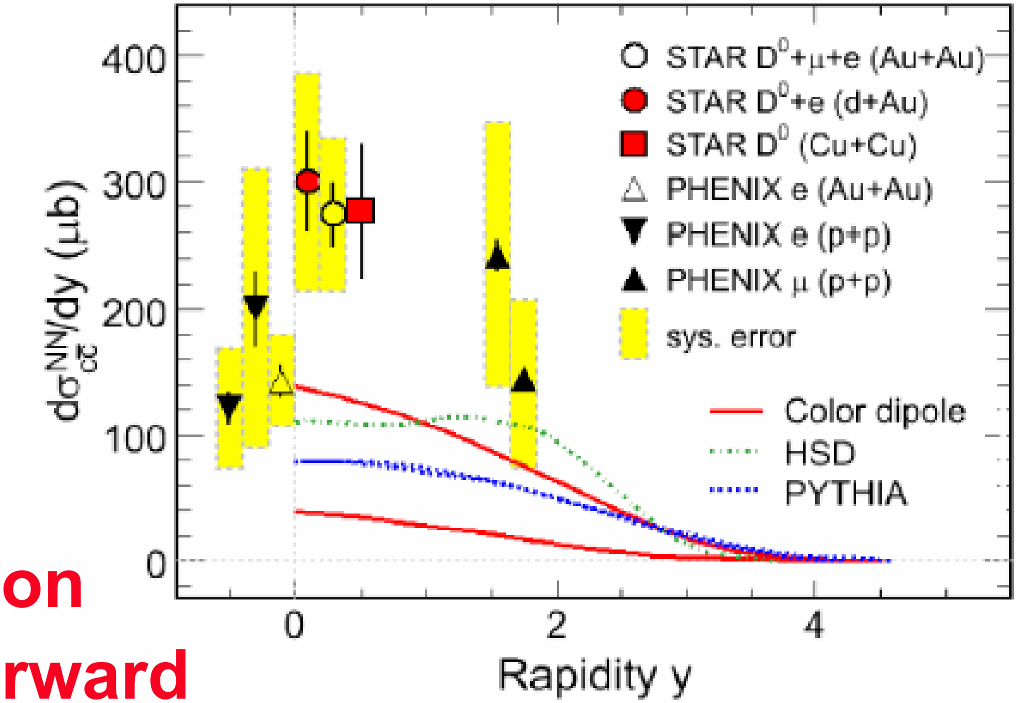
Charm cross section in STAR

- combined fit to
  - non-photonic $e^{\pm}$
  - reconstructed D^0
  - very low p_T $\mu^{\pm}$
    - sensitive to σ_{cc}
    - insensitive to spectral shape of charm
- different channels
  - consistent within uncertainties
  - various systems
    - p+p
    - d+Au
    - Au+Au
    - (Cu+Cu)



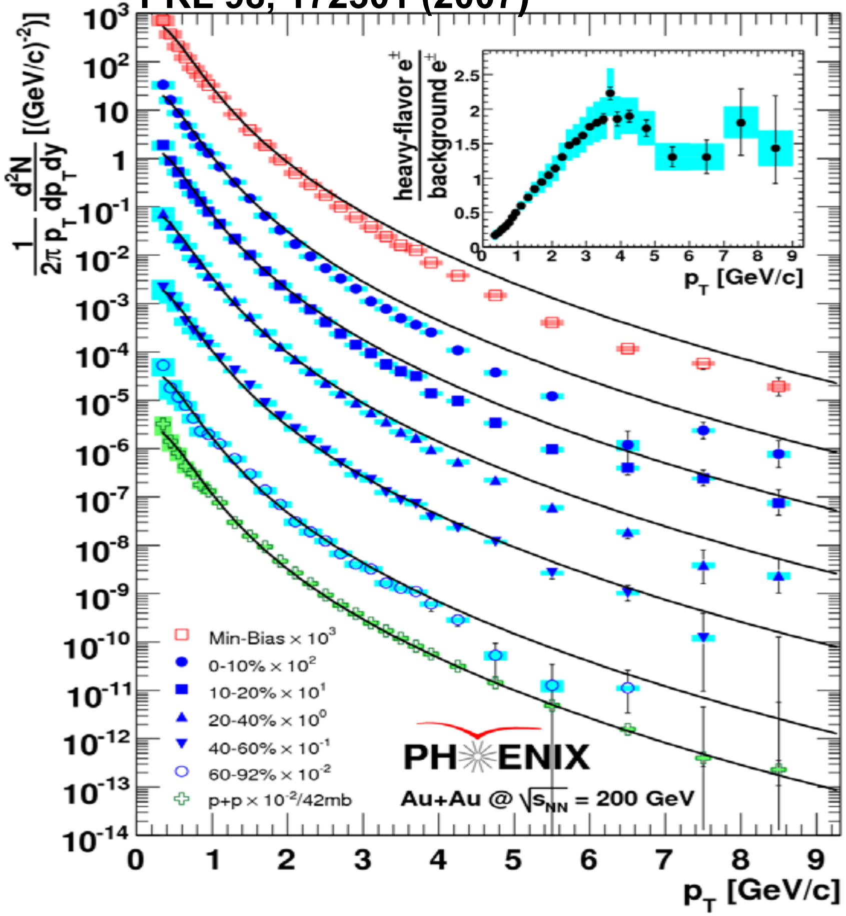
Summary: charm cross section at RHIC

- charm cross section measured at $\sqrt{s}$ = 200 GeV
- experiments
  - self consistent
  - not consistent with each other
- charm yield
  - large and consistent with pQCD expectation
  - similar at mid and forward rapidity (PHENIX μ data)
- substantial uncertainties in data & calculations
- better data are needed → measurement of displaced vertices

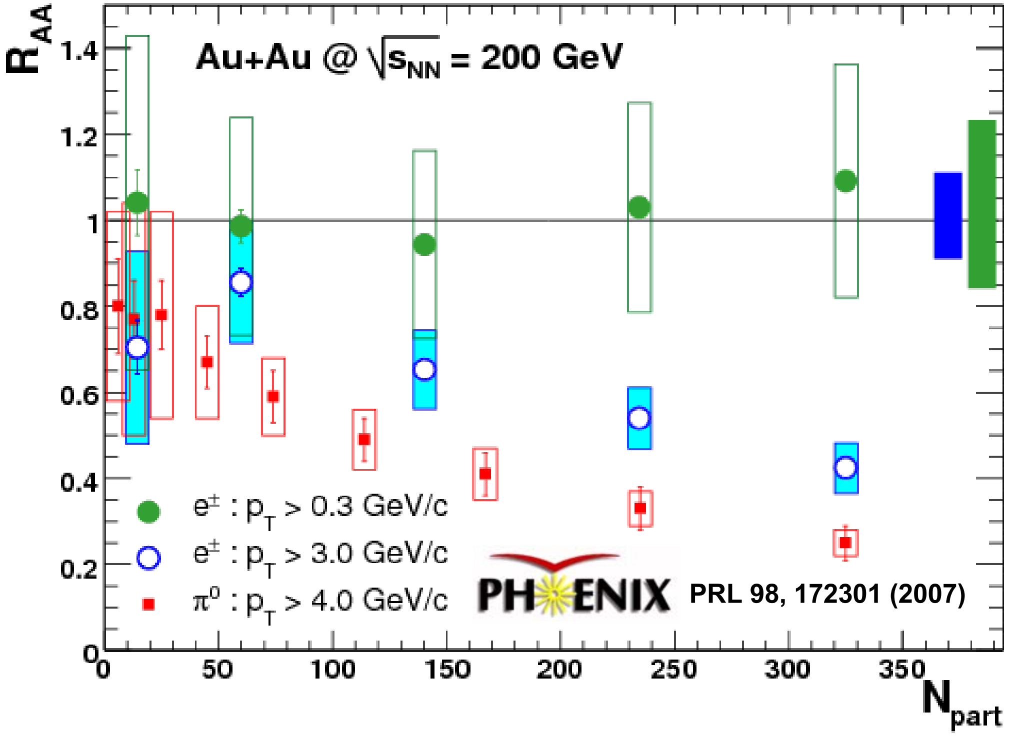


Probing the medium in Au+Au

PRL 98, 172301 (2007)



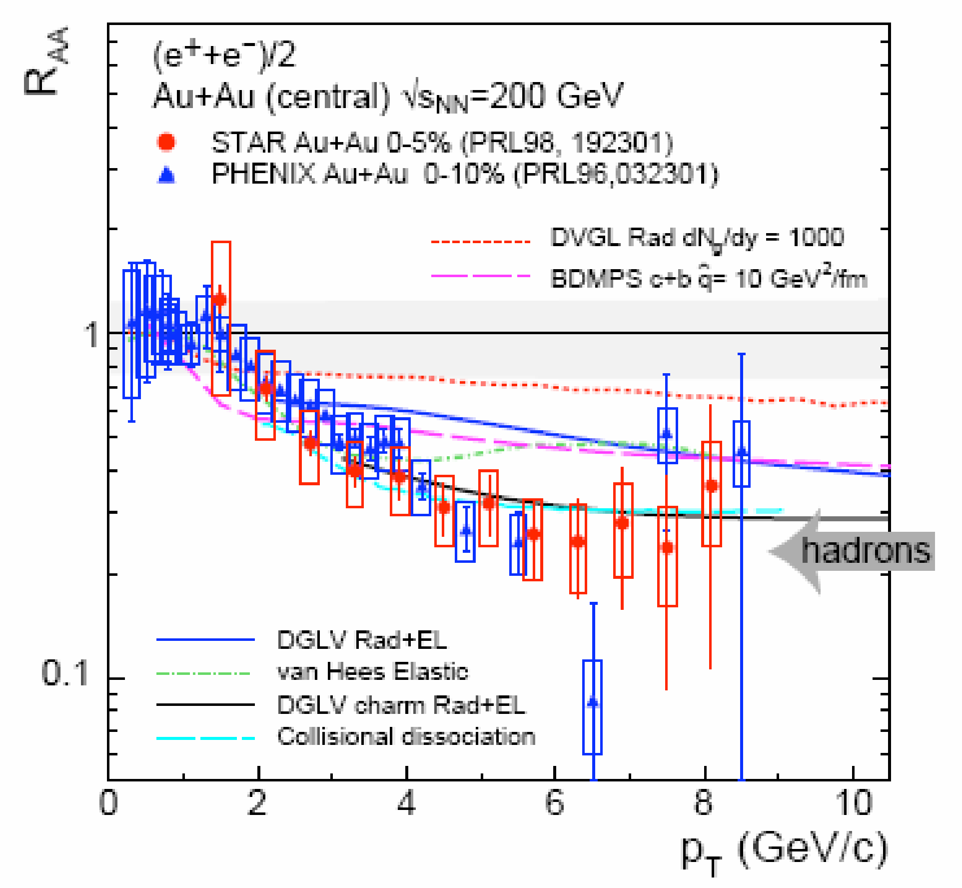
$$R_{AA} = \frac{Yield\ in\ Au+Au}{N_{binary} \times Yield\ in\ p+p}$$



- binary scaling of total $e^{\pm}$ yield from heavy-flavor decays
- high p_T $e^{\pm}$ suppression increasing with centrality
  - footprint of medium effects; similar to π^0 (a big surprise)

Nuclear modification factor R_{AA}

- **PHENIX & STAR: R_{AA} agrees**
  - normalization discrepancy "cancels"



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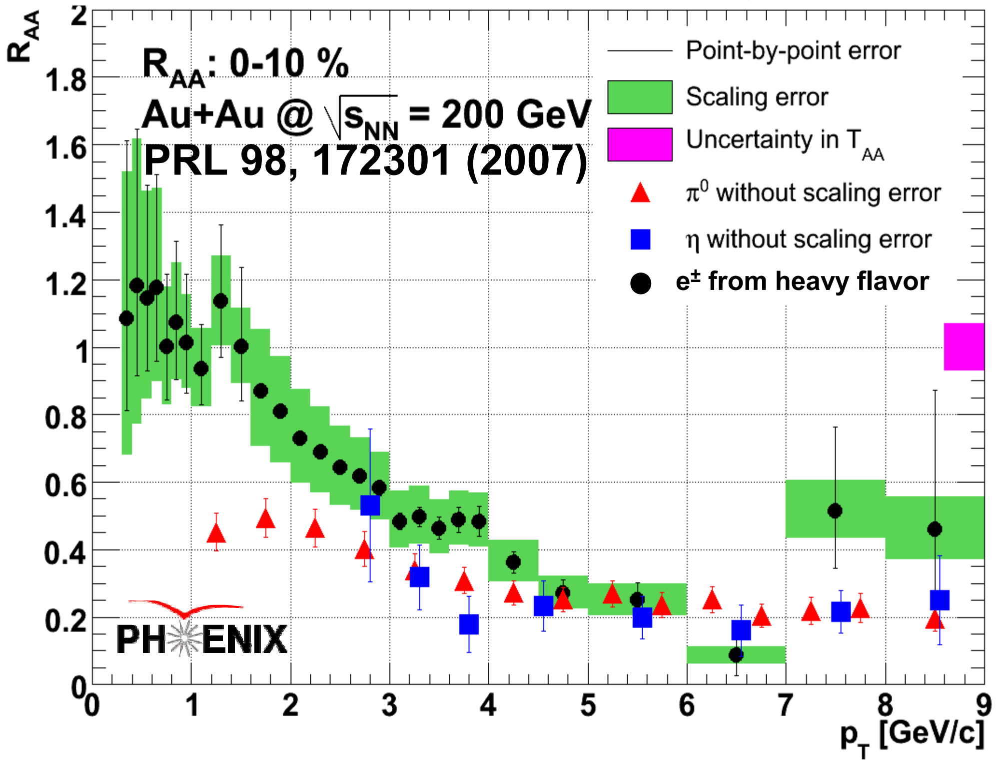
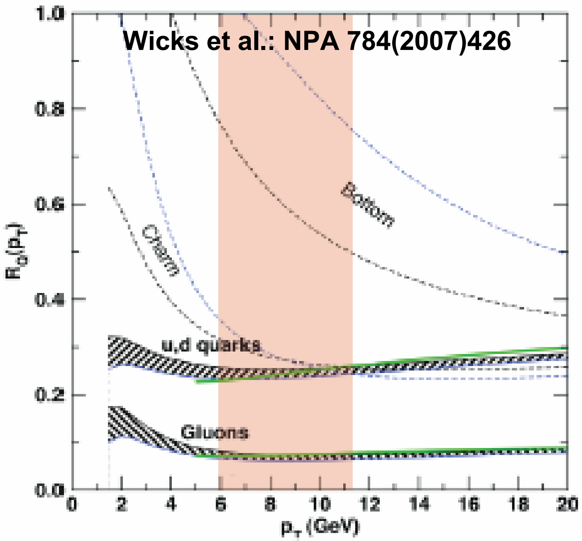


- bottom contribution at high p_T?
  - is bottom suppressed?!
- needed: R_{AA} of identified charm and bottom hadrons

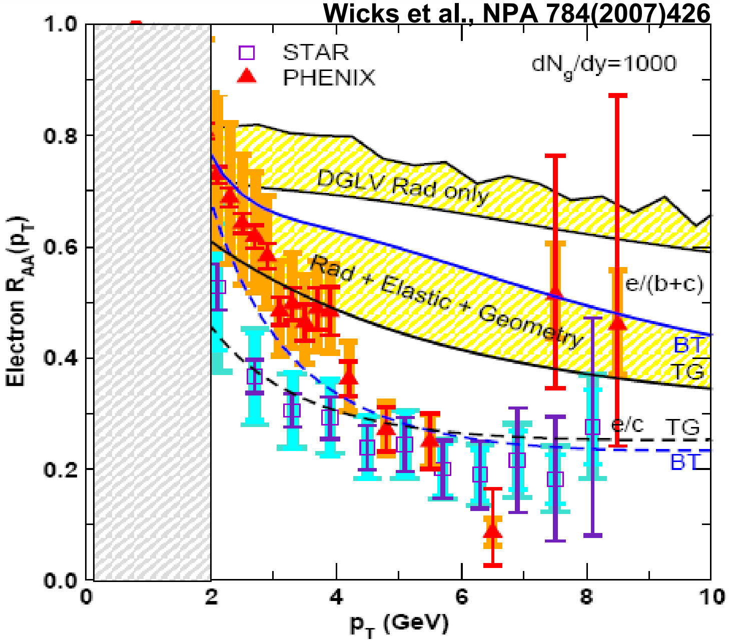
- compare to light hadrons

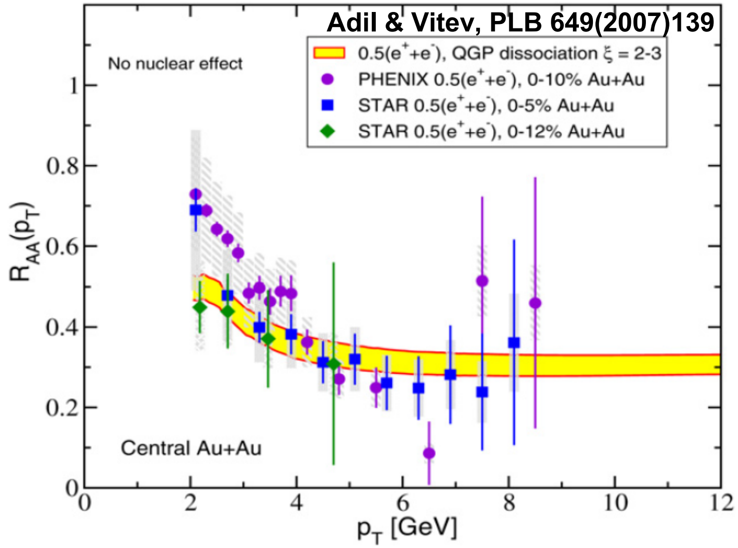


- careful:
  - kinematics: $p_T(e^\pm) < p_T(D)$
- intermediate p_T
  - indication for quark mass hierarchy as expected for radiative energy loss
    (Dokshitzer and Kharzeev, PLB 519(2001)199)
- highest p_T
  - $R_{AA}(e^\pm) \sim R_{AA}(\pi^0) \sim R_{AA}(\eta)$

Energy-loss mechanism?

- $e^{\pm}$ R_{AA}: 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)
    - →would need a very large colour opacity with static scattering centers
  - collisional ΔE included
    - Wicks et al., NPA 784(2007)426
    - van Hees & Rapp, PRC 73(2006)034913
    - →reduces R_{AA} significantly, but the challenge persists
- alternative approaches
  - collisional dissociation of heavy mesons (charm and bottom!)
    - Adil & Vitev, PLB 649(2007)139
  - contribution from baryon enhancement
    - Sorensen & Dong, PRC 74(2006)024902


Wicks et al., NPA 784(2007)426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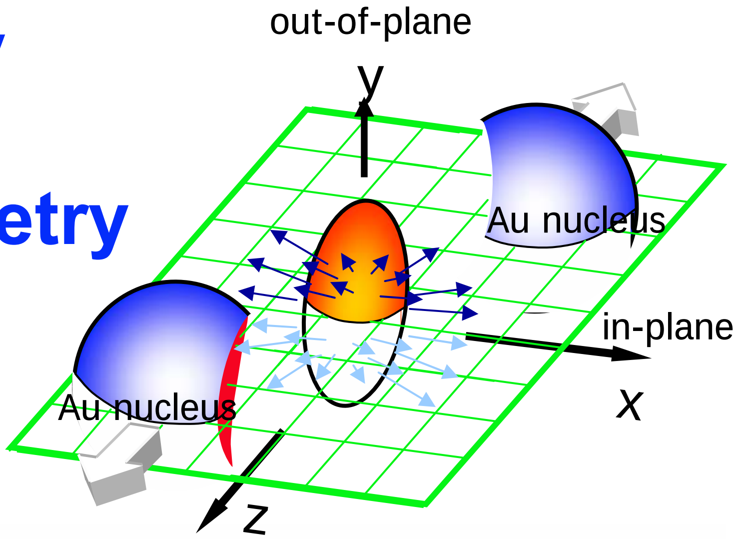
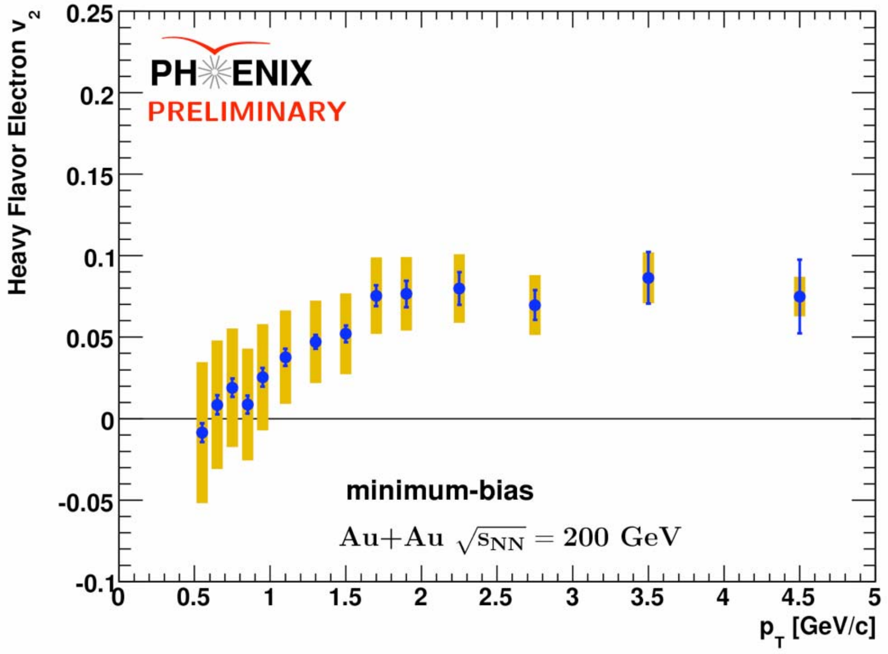
Does charm flow?



- **initial state spatial asymmetry**
  - **asymmetric pressure gradients**
- **final state momentum asymmetry**
  - **Fourier expansion**

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

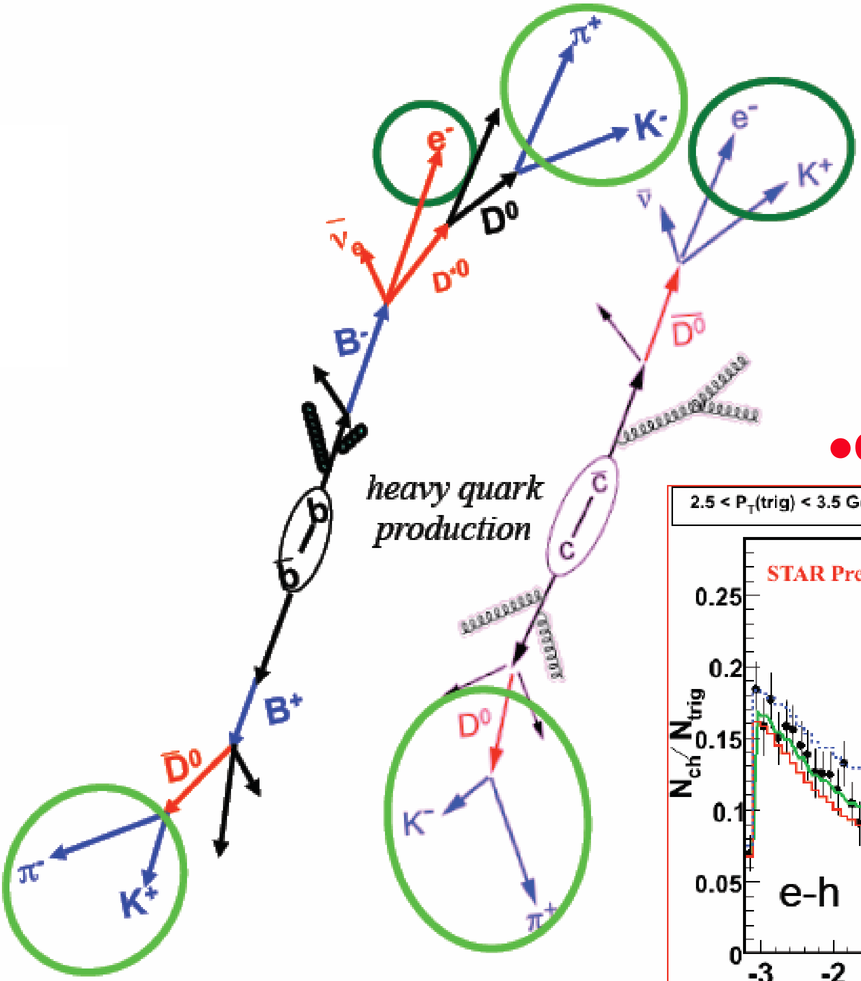
  - **elliptic flow strength v_2**
    - **self quenching**
    - **reflects early interactions**



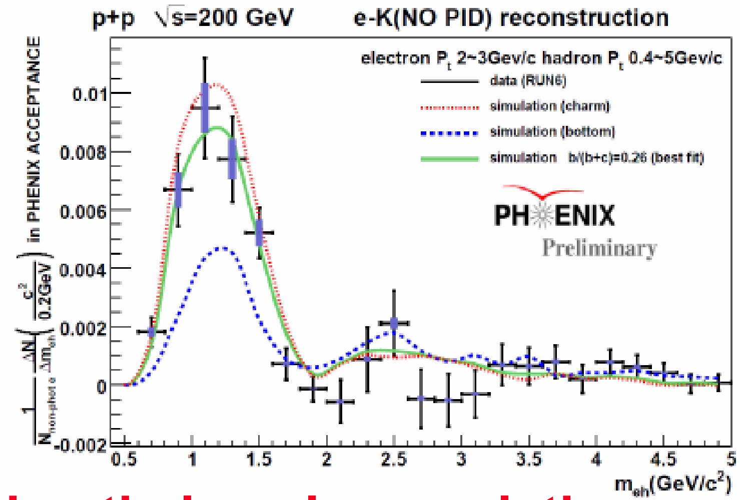
- **non-zero v_2 of $e^{\pm}$ → charm flows!**
- **does bottom flow?**

Separating c→e from b→e

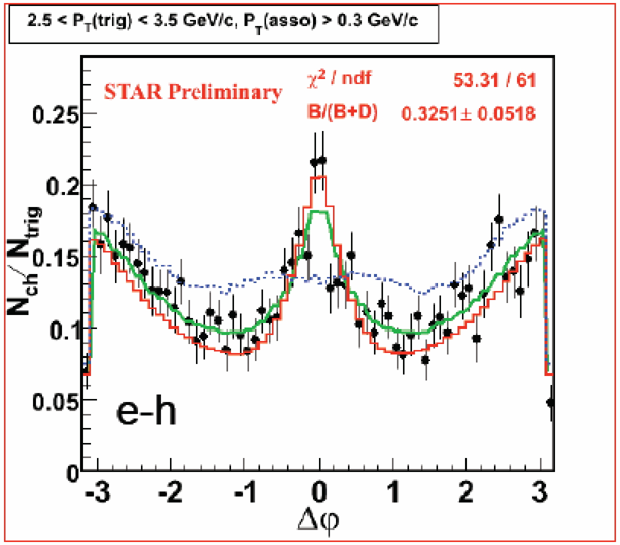
- **electron-hadron correlations**
  - **charm and bottom are different**

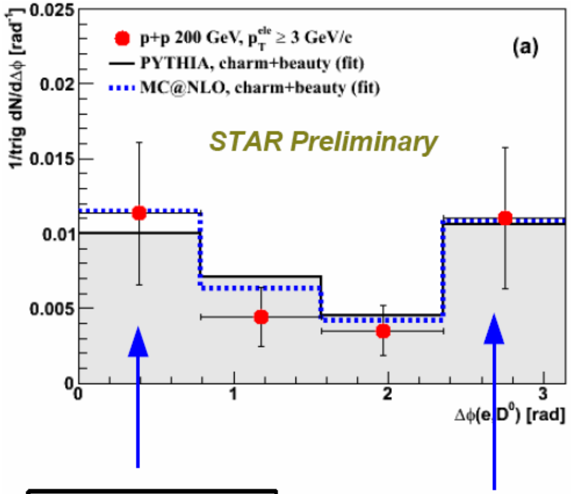


- **e-h charge correlation & m_{inv}**



- **e-h, e-D⁰ azimuthal angle correlation**





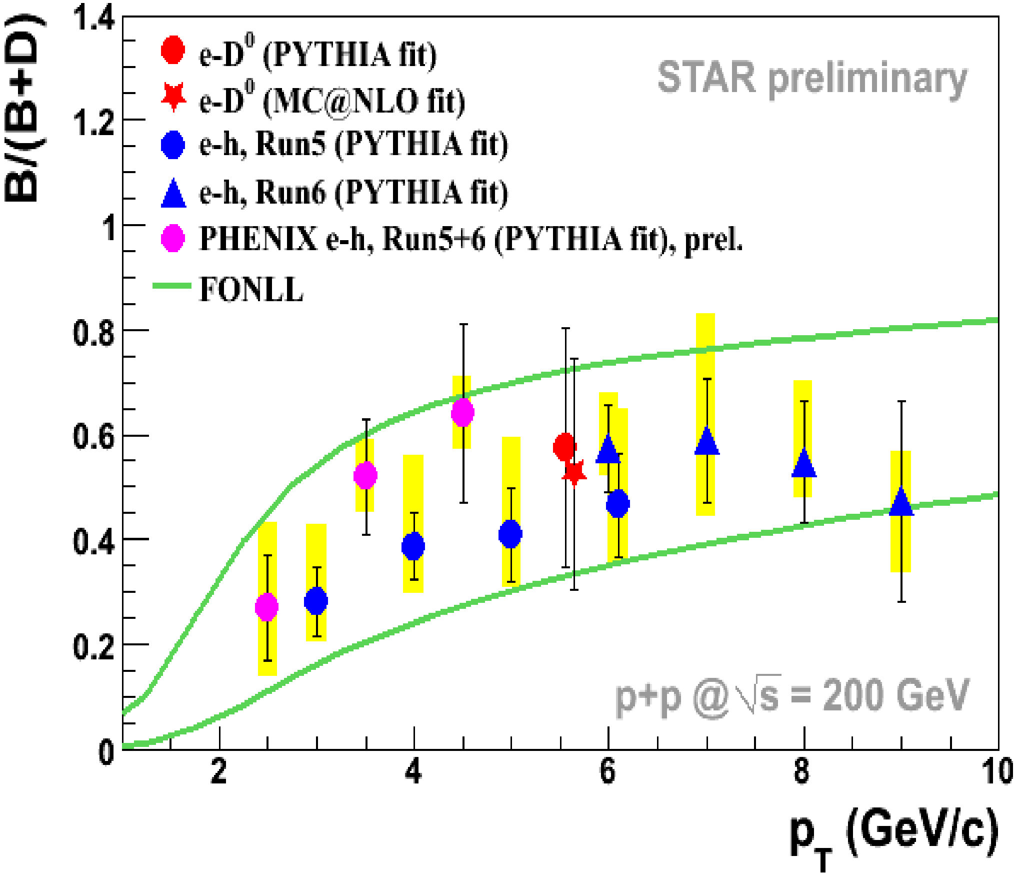
Essentially from B decay

Charm + Bottom decay

B contribution to e± spectra

- consistent with FONLL
- large uncertainties (experiment & theory)

  → need better data to disentangle contributions



Summary

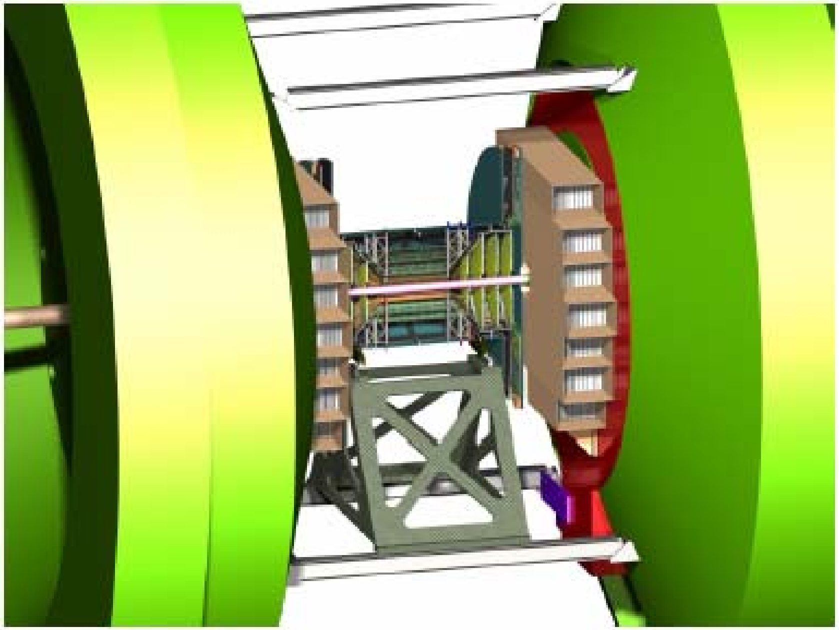
- systematic heavy flavor measurements @ RHIC
    - reference data from p+p collisions
        - experiments are sensitive to charm and bottom production
        - large charm cross section (discrepancy between PHENIX & STAR)
        - pQCD agrees with data within large uncertainties
    - (cold nuclear matter modifications in d+Au collisions)
        - no large effects observed
        - substantial new data set recorded in last RHIC run
    - hot medium effects in Au+Au collisions → many surprises
        - substantial high p_T suppression of $e^{\pm}$ from heavy-flavor decays
        - charm flows
        - even bottom is affected by the interaction with the medium
- missing
    - precision measurements
    - unambiguous separation of charm from bottom

Outlook

- silicon vertex trackers for resolution of displaced vertices

  → direct D- and B-meson measurements

PHENIX



STAR