Universiteit Utrecht

Recent heavy flavor results from RHIC

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Outline

- High energy heavy-ion physics
- In-medium production of heavy flavor (charm and bottom)
- Detectors at RHIC
- A selection of recent results
  - Charm production cross-section in heavy-ion collisions
  - Heavy-quark energy loss in the medium
  - Flow of non-photonic electrons
  - Experimental access to charm and bottom contributions
  - Quarkonia

Matter in extremes: Quark-Gluon Plasma

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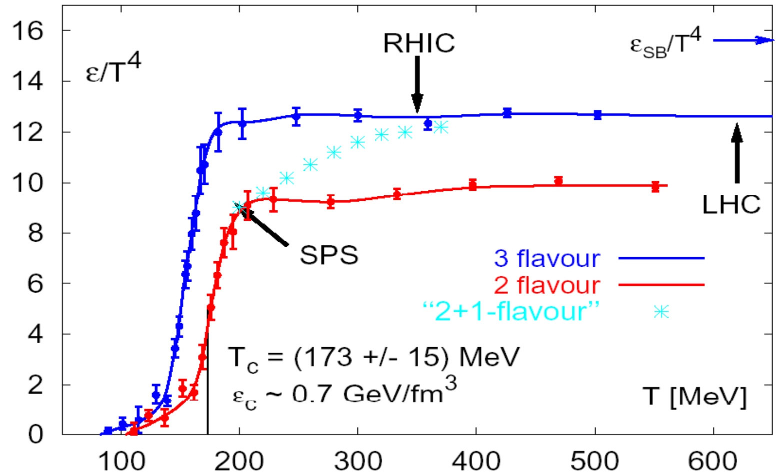
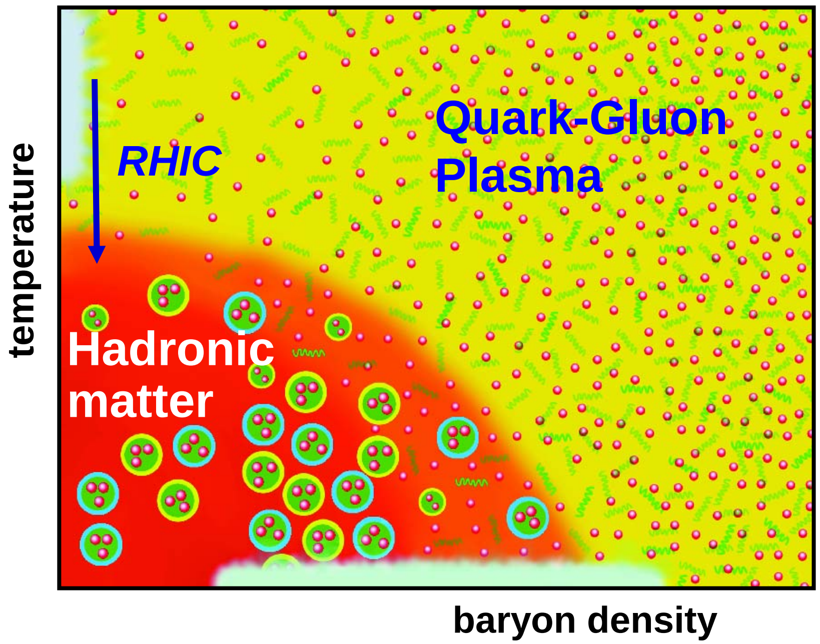
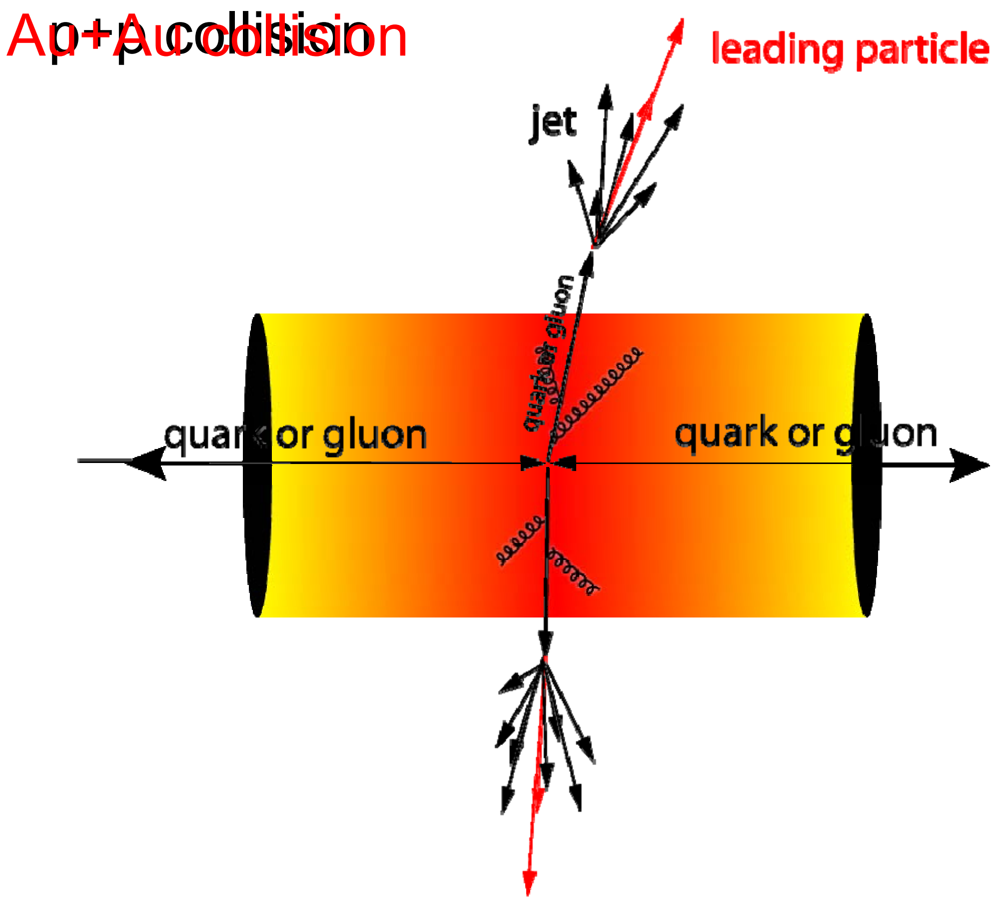




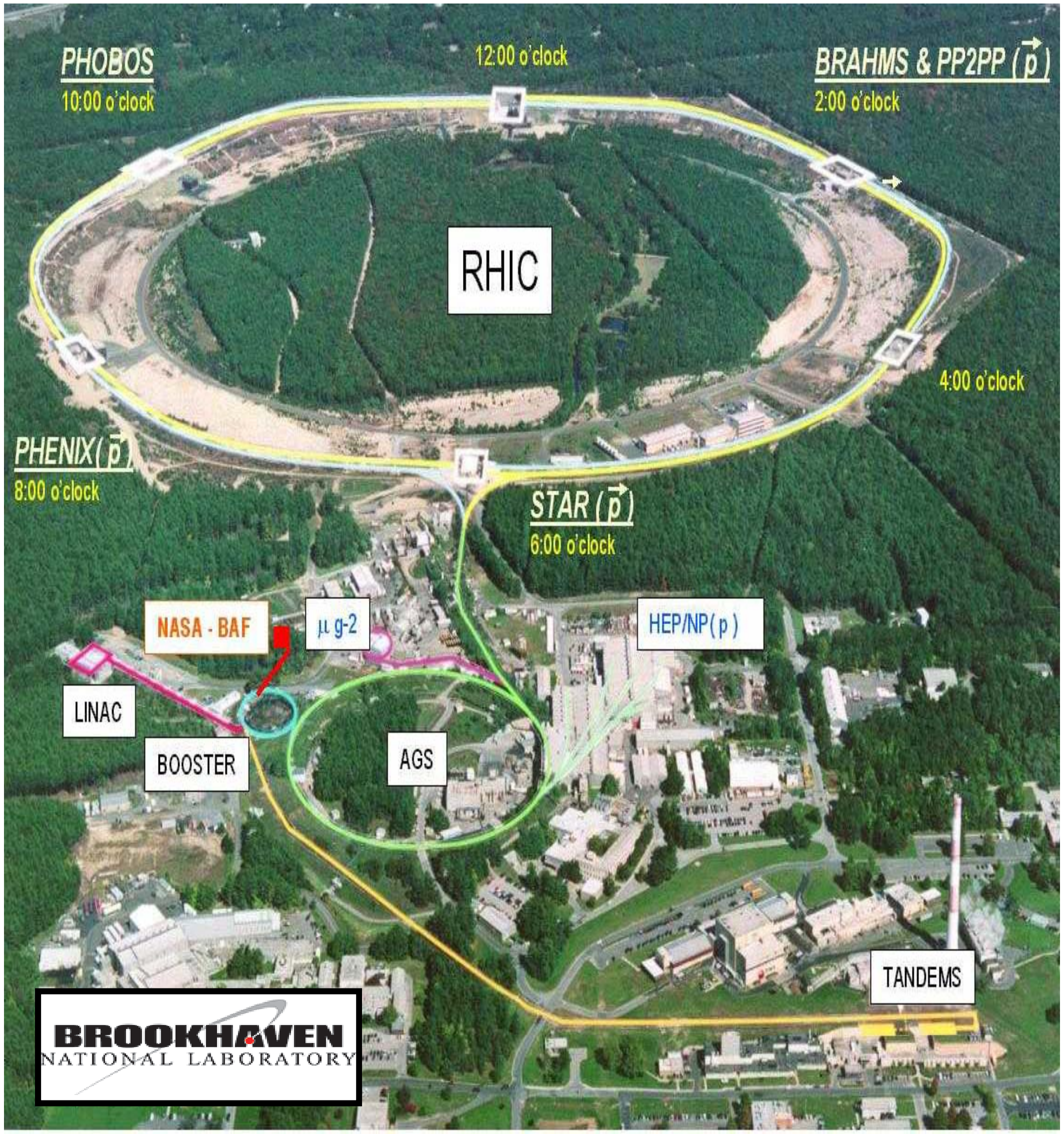
- Study strongly interacting matter under extreme conditions
  - high temperature
  - high density
- Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the Quark-Gluon Plasma
- QCD phase diagram of nuclear matter
- Experimental access via high energy heavy-ion collisions

Probe hot and dense QCD matter



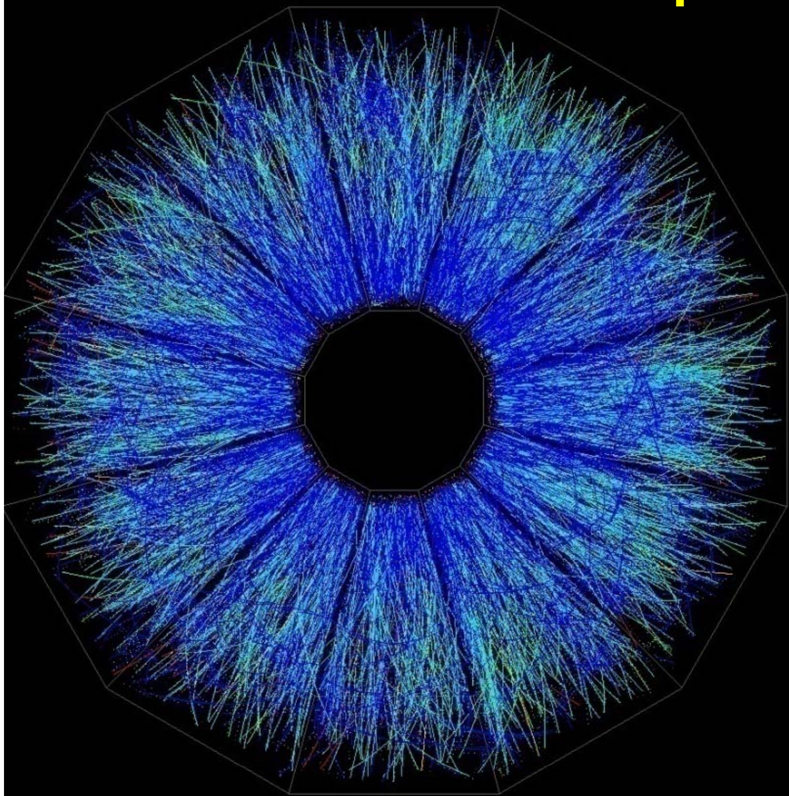
- Hard processes occur in the early stage of the collision
- High momentum transfer → perturbative QCD
- Hard scattered partons traverse through the medium and interact strongly
- Energy loss via medium induced gluon radiation (Bremsstrahlung)

The RHIC accelerator at BNL



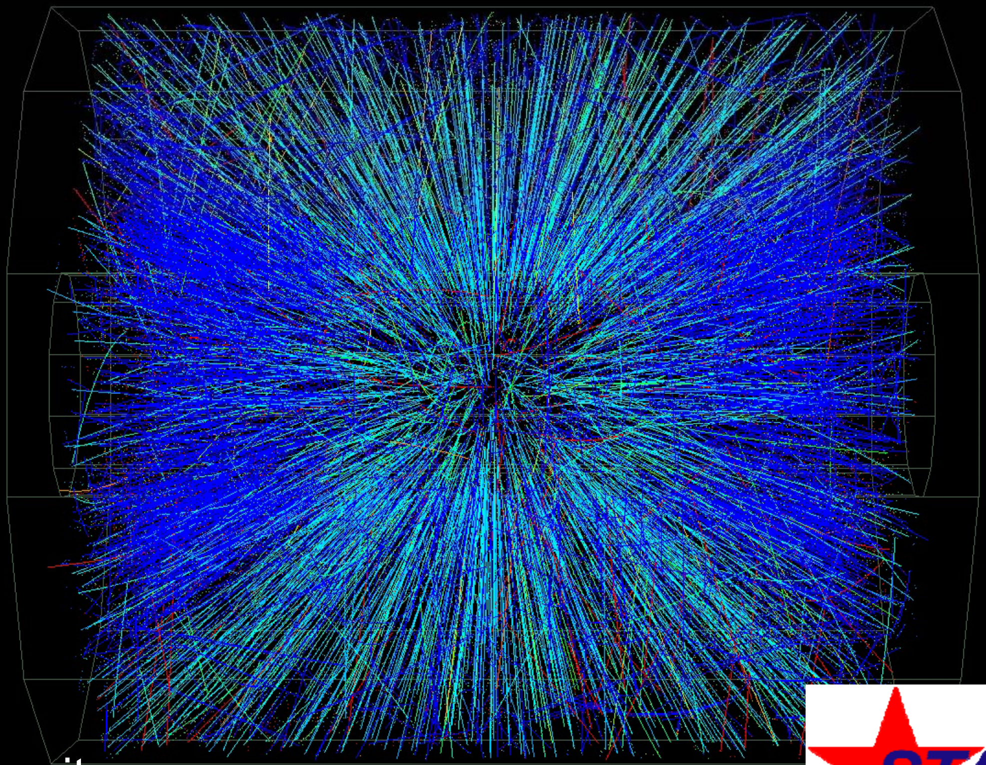
- Relativistic Heavy Ion Collider at Brookhaven National Laboratory
- Two concentric superconducting magnet rings, 3.8 km circumference
- Counter-rotating ion beams
- First collisions in June 2000
- Ion species and energies
  - Au+Au, $\sqrt{s_{NN}}$ = 22, 62, 130, 200 GeV
  - Cu+Cu, $\sqrt{s_{NN}}$ = 200 GeV
  - d+Au, $\sqrt{s_{NN}}$ = 200 GeV
  - polarized p+p, $\sqrt{s}$ = 200, 500 GeV

Gold-gold collision at a cms energy 130 GeV per nucleon-nucleon pair



Central event obtained with the STAR TPC -

typically 1,000 to 2,000 tracks per event



Energy density at RHIC (Bjørken estimate)

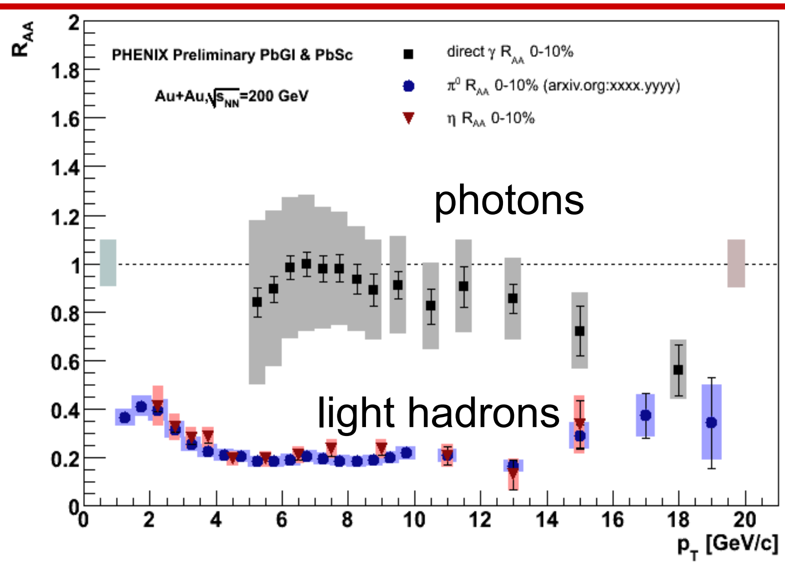
$$\varepsilon = \frac{1}{\pi R^2 \tau_0} \frac{dN}{dy} = 5 - 15\,\mathrm{GeV/fm^3}$$

more than 30× normal nuclear matter density

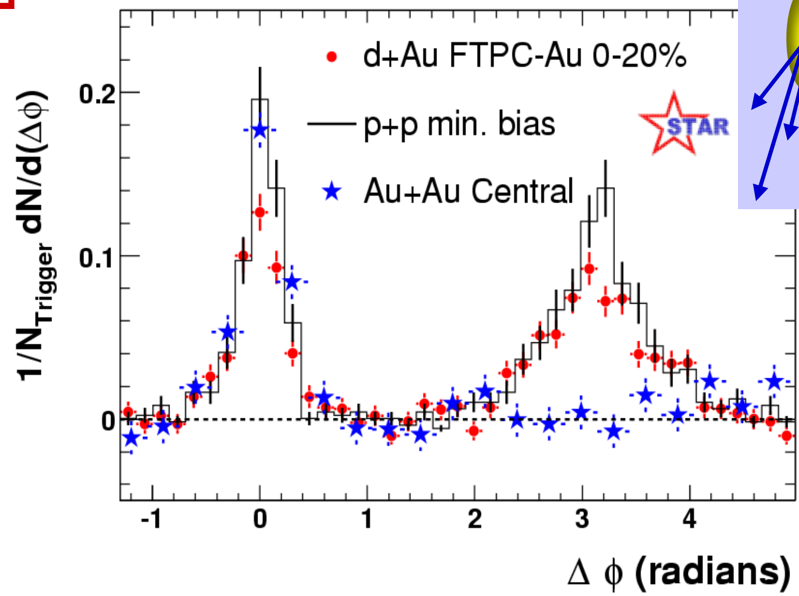
STAR

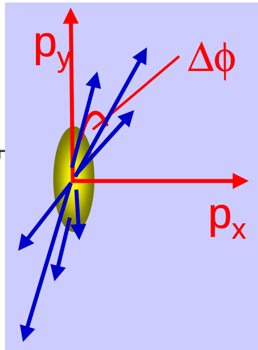
Exciting results from light quarks

Nuclear modification factor: $R_{AA} = \dfrac{\text{yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{yield}_{pp}}$



RHIC white papers, Nucl. Phys. A757 (2005)

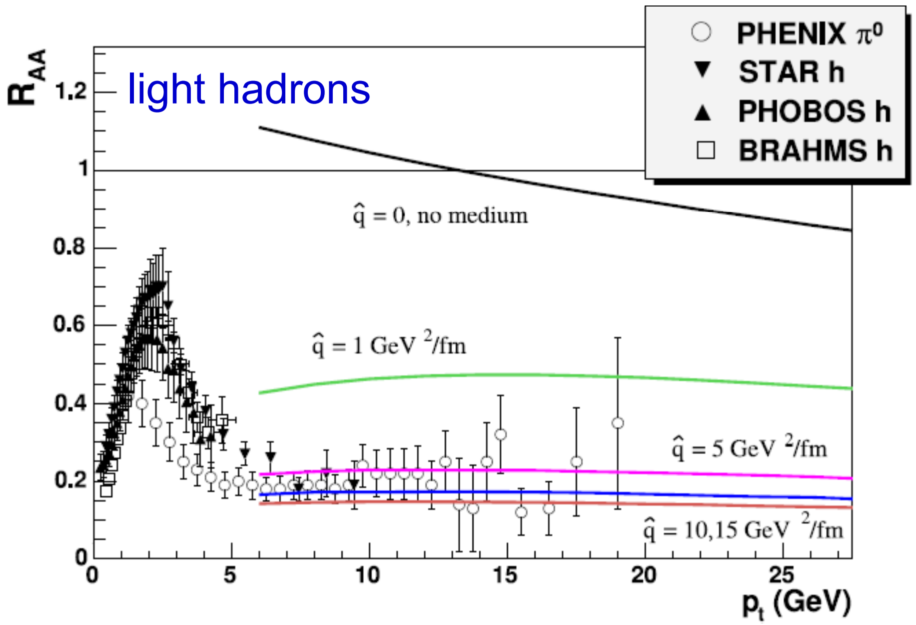


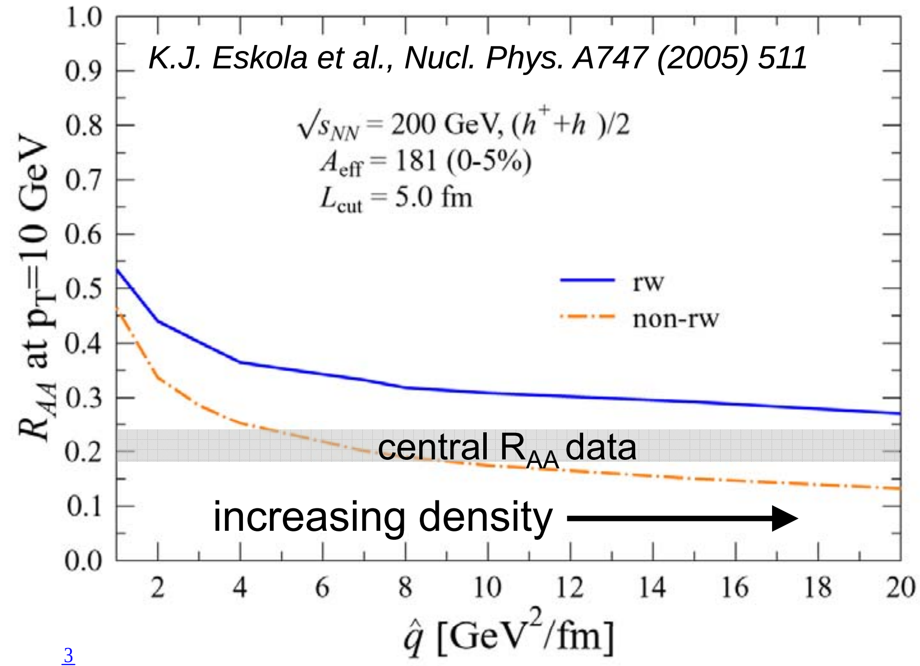


What have we learnt so far?

- Central Au+Au collisions produce dense, rapidly thermalizing matter
- Jet quenching in opaque medium → strongly interacting plasma (sQGP)
- Produced matter shows collective behavior; well described by ideal hydrodynamics (no viscosity) → “Perfect Liquid”
- Relevant degrees of freedom seem to be partonic (constituent quark scaling)

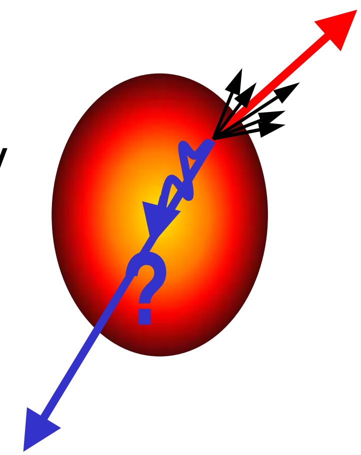
Limitations of R_{AA}





time averaged transport coefficient: $\hat{q} \sim \rho_{medium} \sim \varepsilon^{\frac{3}{4}}$

- Jet quenching well described by energy loss models
- Surface bias effectively leads to saturation of R_{AA} with density
- Limited sensitivity to the region of highest energy density
- Needed: - insensitive trigger particles: Prompt photons
  - more penetrating probes: Heavy quarks



In-medium energy loss of heavy quark

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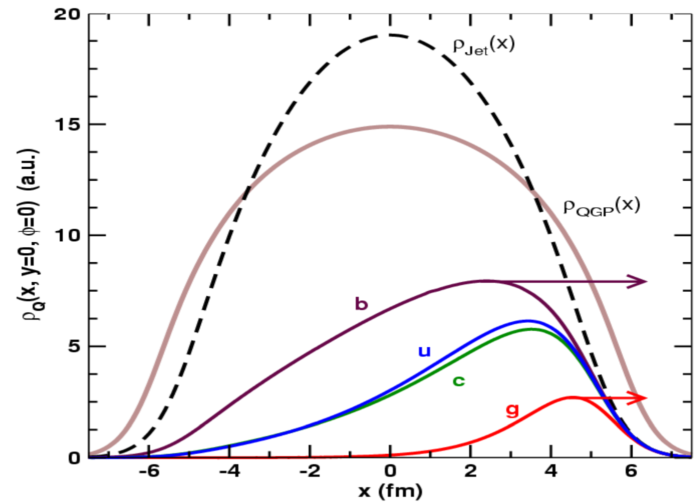
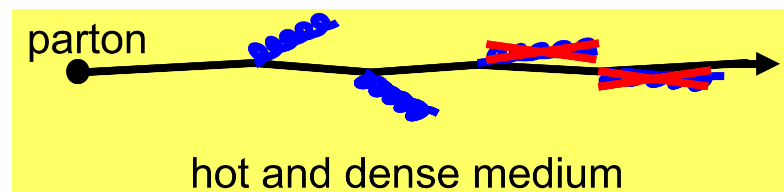
- Due to their large mass, heavy quarks
  - primarily *gg* → QQ
  - production rates calculated in pQCD
  - sensitivity to initial state gluon distribution

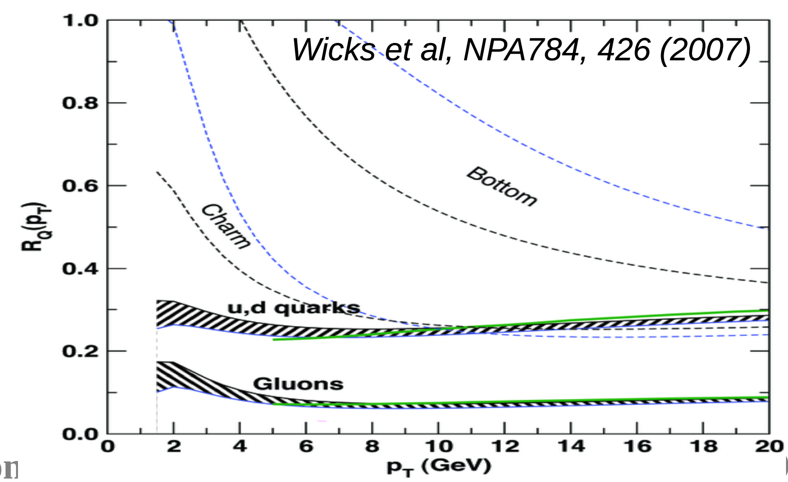
→ Does it hold for heavy-ion collisions? – Measure production cross sections



- Heavy quarks
  - are "grey probes"
  - lose less energy due to suppression of small angle gluon radiation (dead-cone effect) *Dokshitzer & Kharzeev, PLB 519, 199 (2001)*



- Which questions can be addressed?
  - Open charm/bottom: Energy loss mechanism, degree of thermalization
  - Quarkonia: Deconfinement (dissociation in QGP), degree of thermalization



Heavy flavor measurements

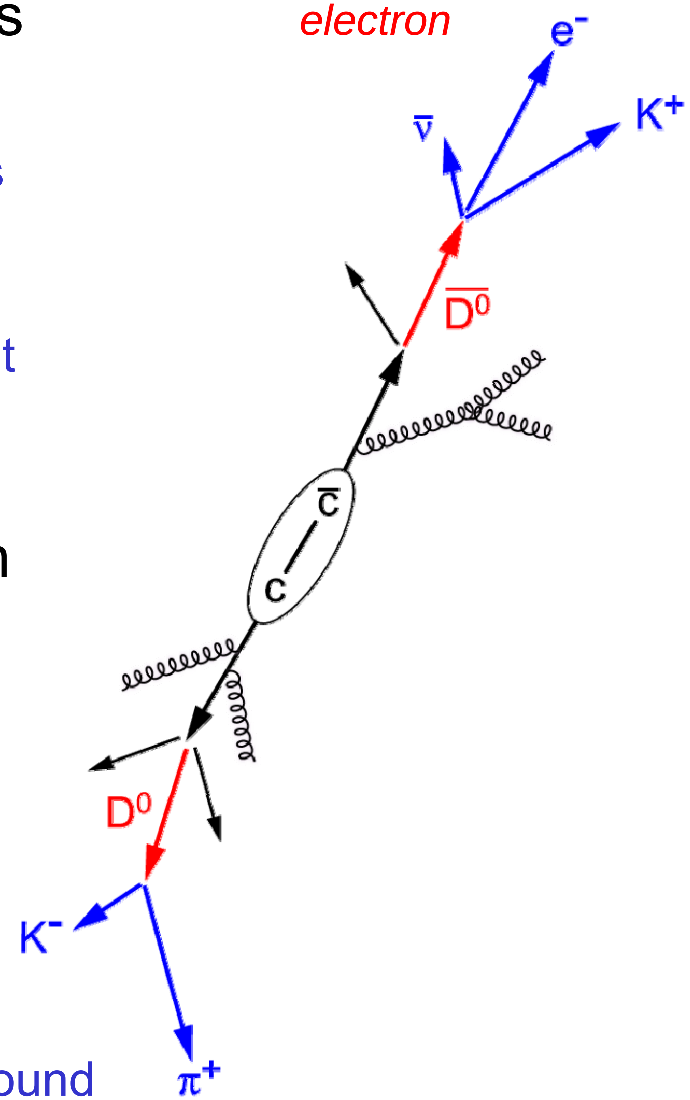
- Full reconstruction of open charm mesons
  - $D^0 \rightarrow K + \pi$ (BR = 3.83%)
  - direct clean probe: signal in invariant mass distribution
  - difficulty: large combinatorial background; especially in a high multiplicity environment
  - event-mixing and/or vertex tracker needed

- Semi leptonic decay of charm and bottom mesons
  - $c \rightarrow$ lepton + X (BR = 9.6%)

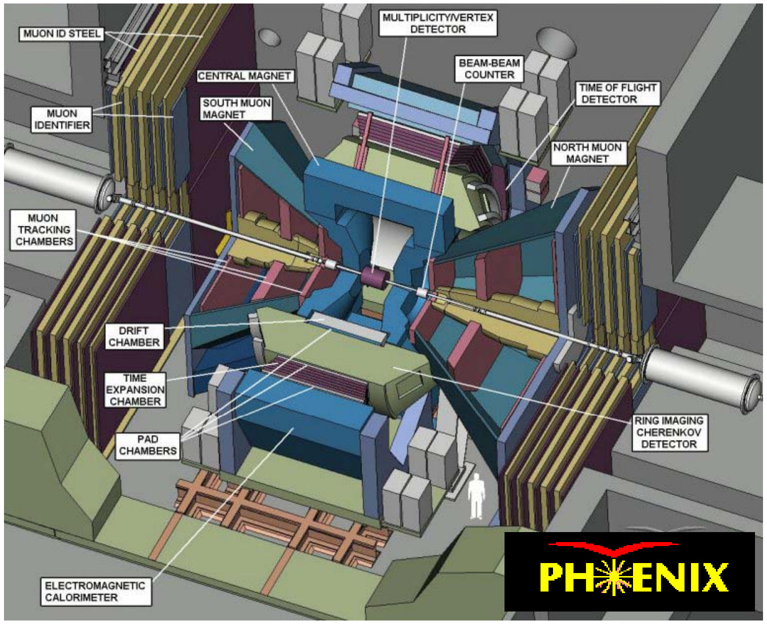
    $D^0 \rightarrow e^+ + X$ (BR = 6.87%)

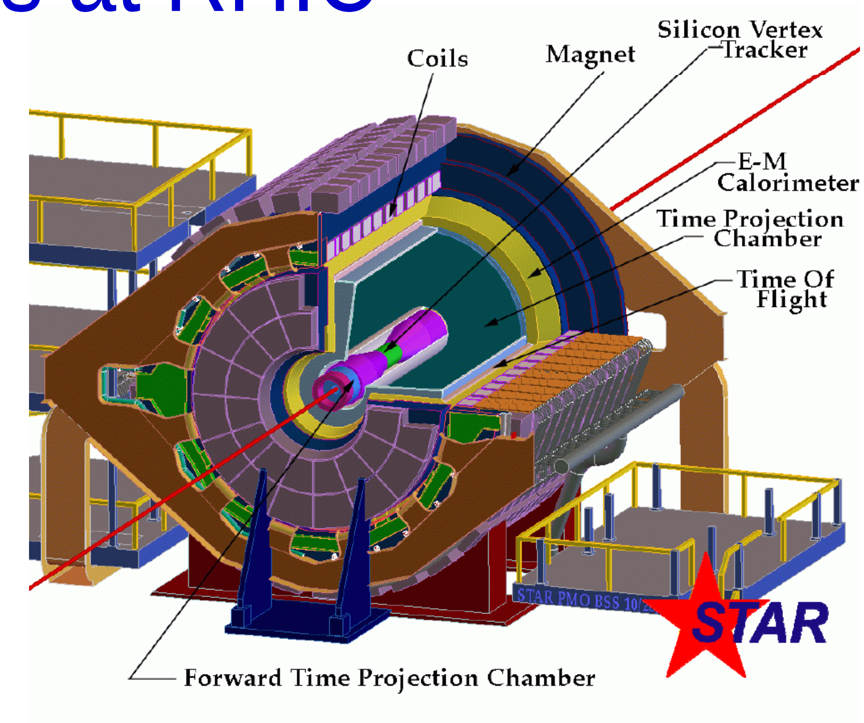
    $D^0 \rightarrow \mu^+ + X$ (BR = 6.5%)
  - $b \rightarrow$ lepton + X (BR = 10.9%)
  - robust electron trigger
  - needs handle on photonic electron background

called non-photonic electron



Experiments at RHIC





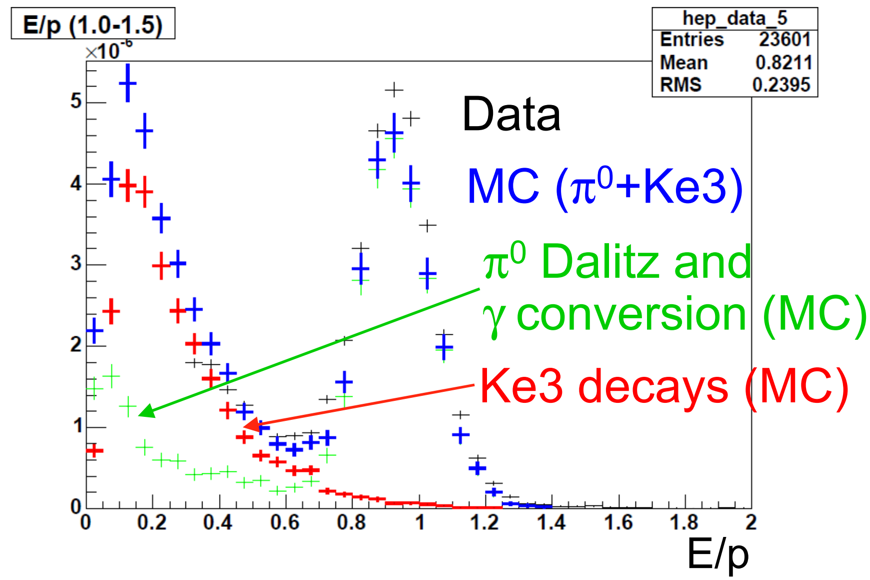
- Designed for leptonic measurements
- DC, PC, TEC, RICH, EMC and Muon tracking - low radiation length
- Open heavy flavors
  - muons (Muon arms at forward rapidities)
  - electrons
- Quarkonia states

- Large acceptance magnetic spectrometer
- High resolution TPC, ToF, CTB and EMC
- Open heavy flavors
  - hadronic reconstruction of D mesons: TPC + ToF
  - muon identification with TPC + ToF
  - electrons
- Quarkonia states using special triggers

Electron identification

Phenix

- Electromagnetic calorimeter and RICH at mid rapidity
  - $p_T < 5$ GeV/c



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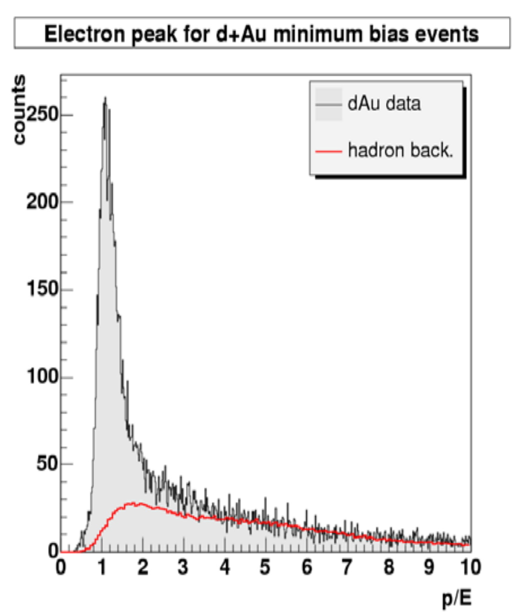
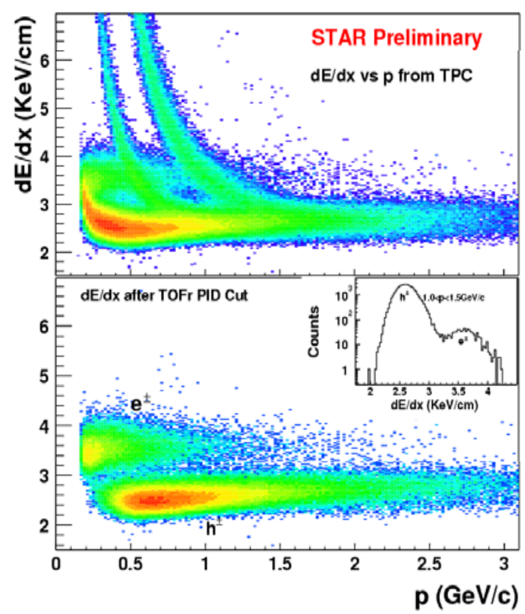
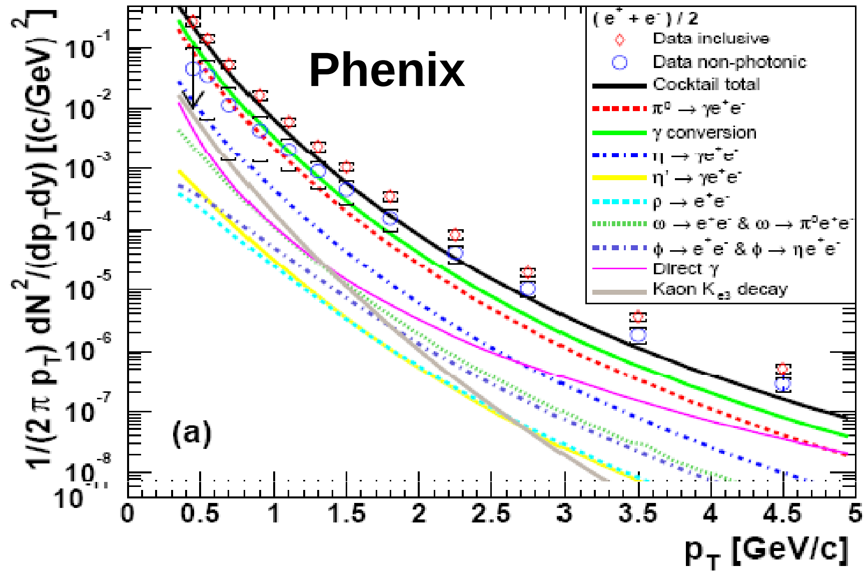
- ToF + TPC
  - $p_T < 4$ GeV/c
- EMCal + TPC
  - $p_T > 1.5$ GeV/c

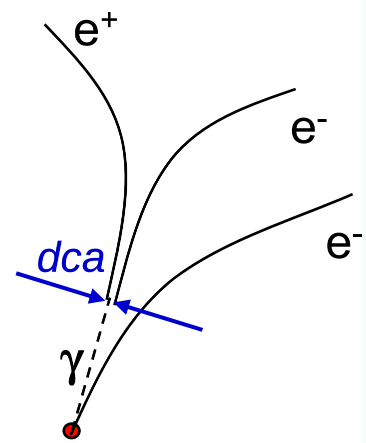


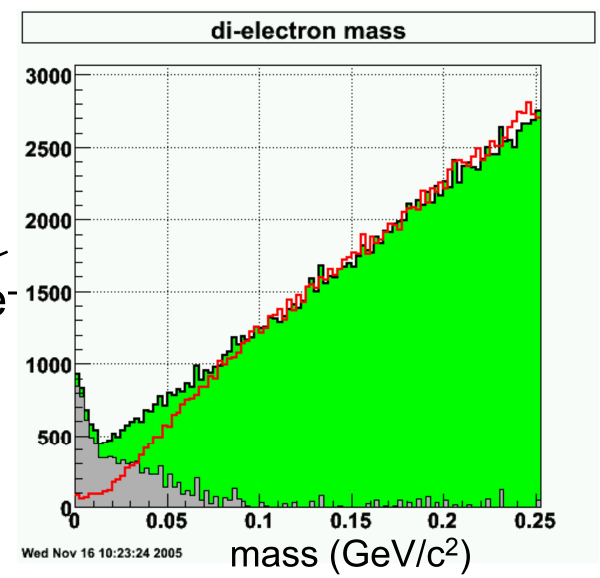


Electron background sources

- Most of electrons in the final state are originating from other sources than heavy-flavor decays
  - $\gamma \rightarrow e^+ + e^-$ (small for Phenix)
  - $\pi^0 \rightarrow \gamma + e^+ + e^-$
  - η, ω, ϕ, etc.
- Phenix is almost material free $\rightarrow$ their background is highly reduced compared to STAR
- Background is subtracted by two independent techniques - very good consistency between them
  - converter method (1.68 % X_0)
  - cocktail method
- STAR measures the background using invariant mass







Charm production cross-section in heavy-ion collisions

- Identified particle spectra

Charm cross section from STAR

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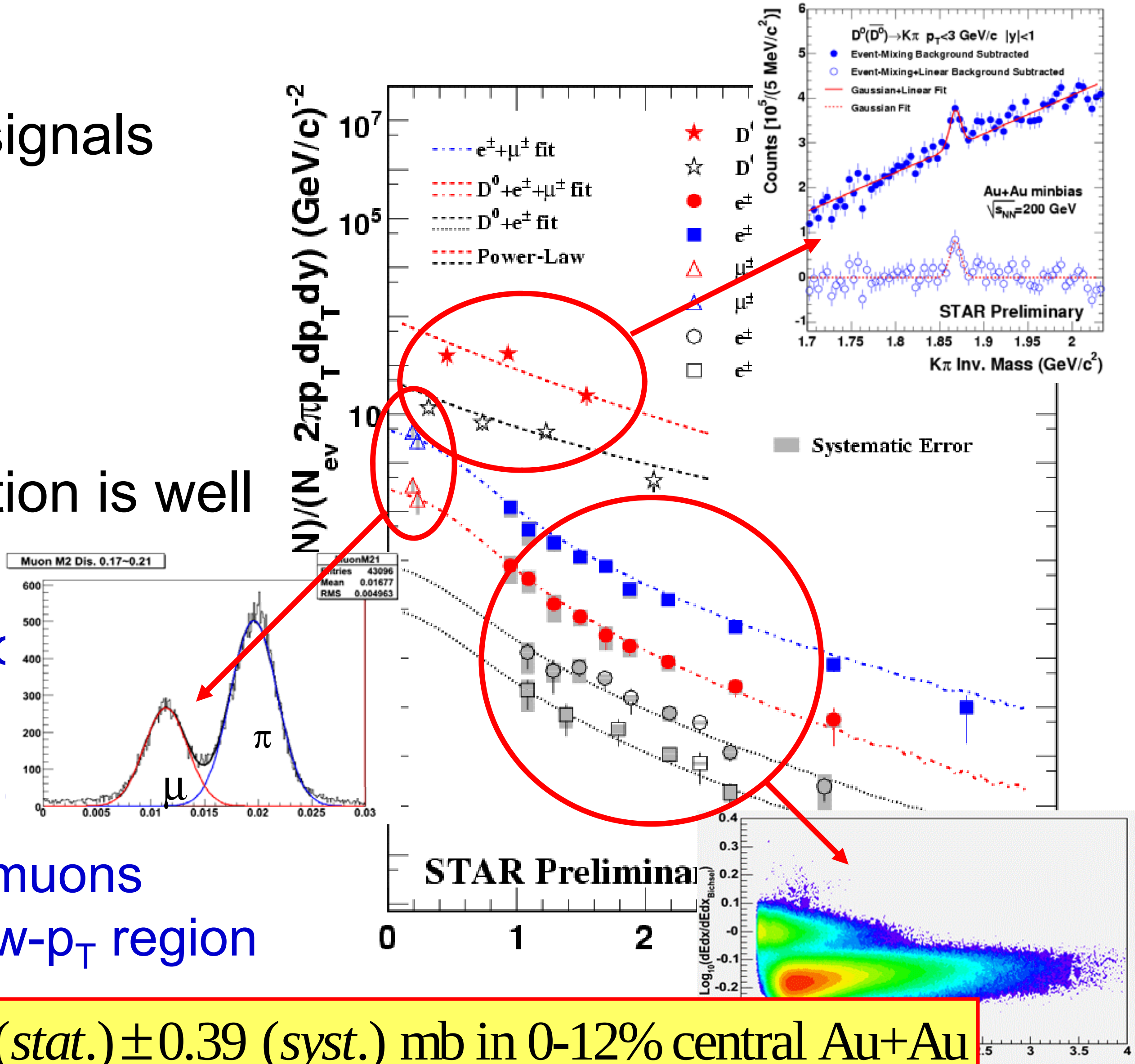
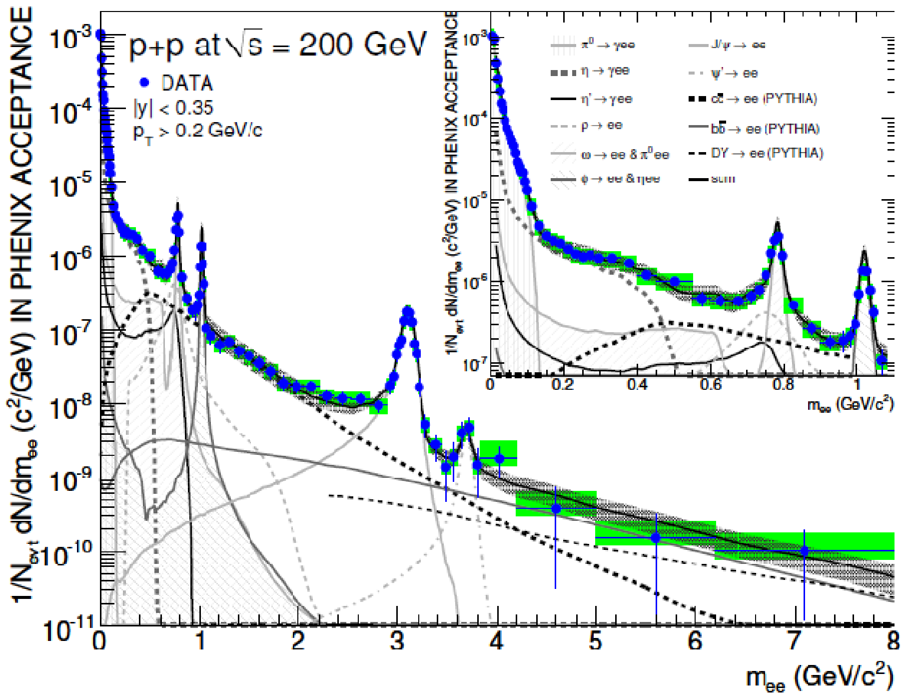
- Use all possible signals
  - D^0 mesons
  - electrons
  - muons

- Charm cross section is well constrained
  - 90% of the total c section
  - direct measurem
  - D^0 mesons and muons constrain the low-p_T region

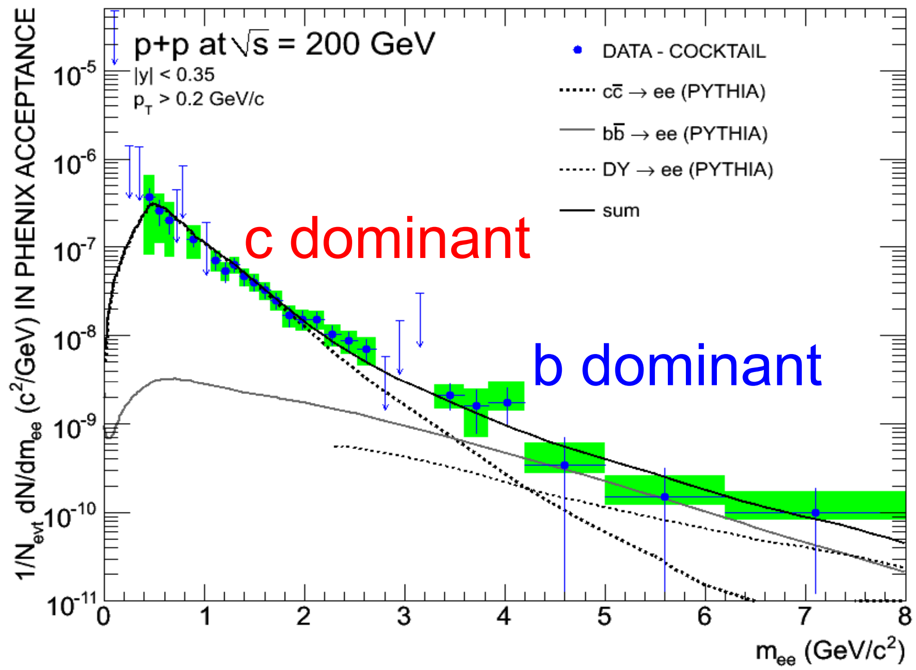


$$\sigma_{c\bar{c}}^{NN} = 1.40 \pm 0.11\,(stat.) \pm 0.39\,(syst.)\text{ mb in 0-12\% central Au+Au}$$

Charm cross section from Phenix



after subtraction of cocktail



<u>Signals:</u>

- Electrons
- Di-electrons

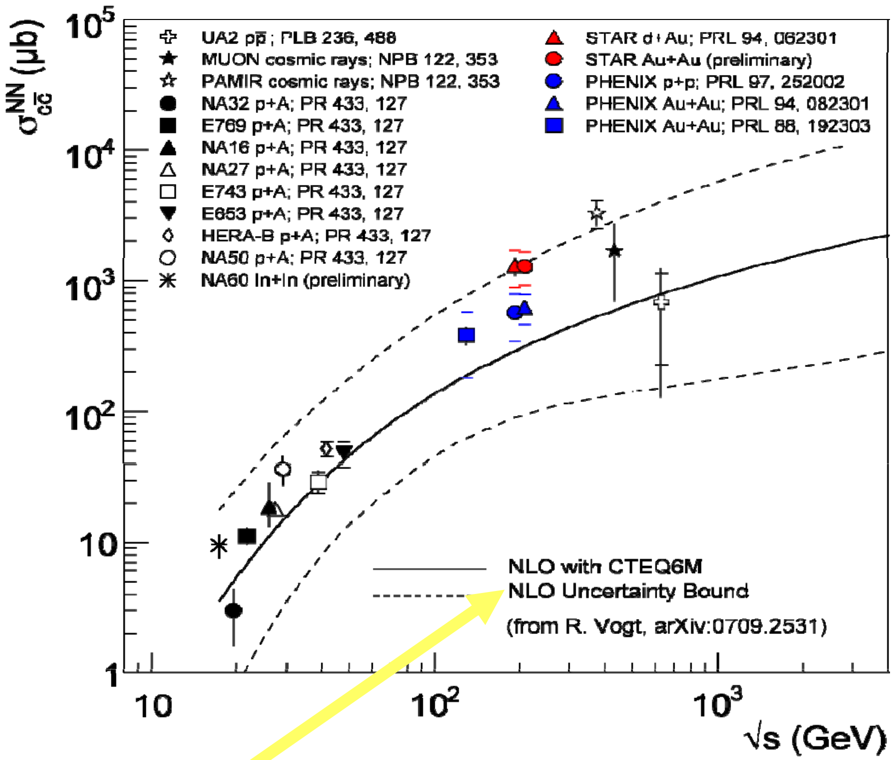
- Fit to *a*charm* + *b*bottom* (with PYTHIA shape)

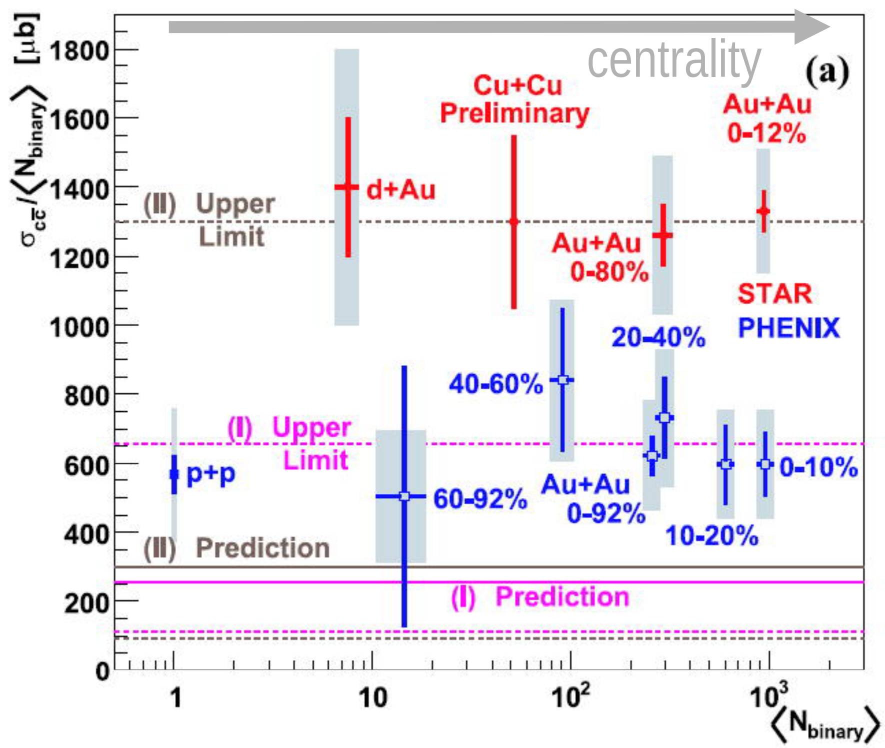
$$\sigma_{c\bar{c}} = 518 \pm 47(stat) \pm 135(sys) \pm 190(model)\ \mu b$$
$$\sigma_{b\bar{b}} = 3.9 \pm 2.5(stat)^{+3}_{-2}(sys)\mu b$$

- Good agreement with single electron result

- Open charm: $D^0 \rightarrow K^+\pi^-\pi^0$ where $\pi^0 \rightarrow \gamma\gamma$

Total charm cross section





- Progress in determining theoretical uncertainties, R. Vogt et al., hep/ph: 0709.2531
- More data points needed to constraint model

- Both STAR and Phenix are self-consistent
- STAR results ~2x larger than Phenix

→ Some work to do for both experiments

- Cross section follows binary collision scaling

→ Charm is exclusively produced in initial state; as expected

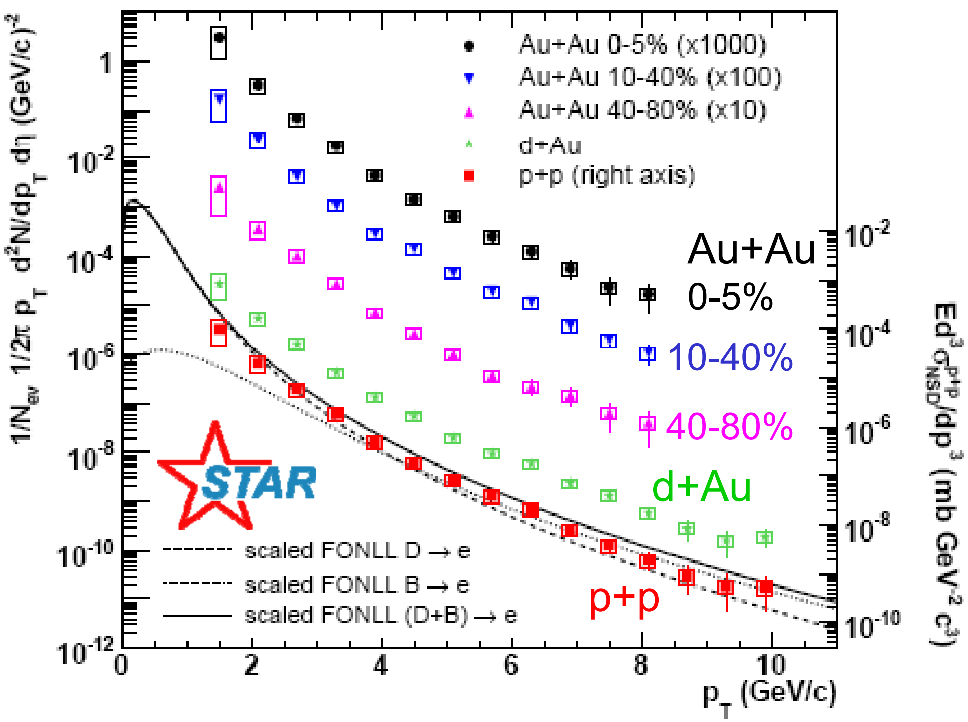
→ No room for thermal production

Heavy-quark energy loss in the medium

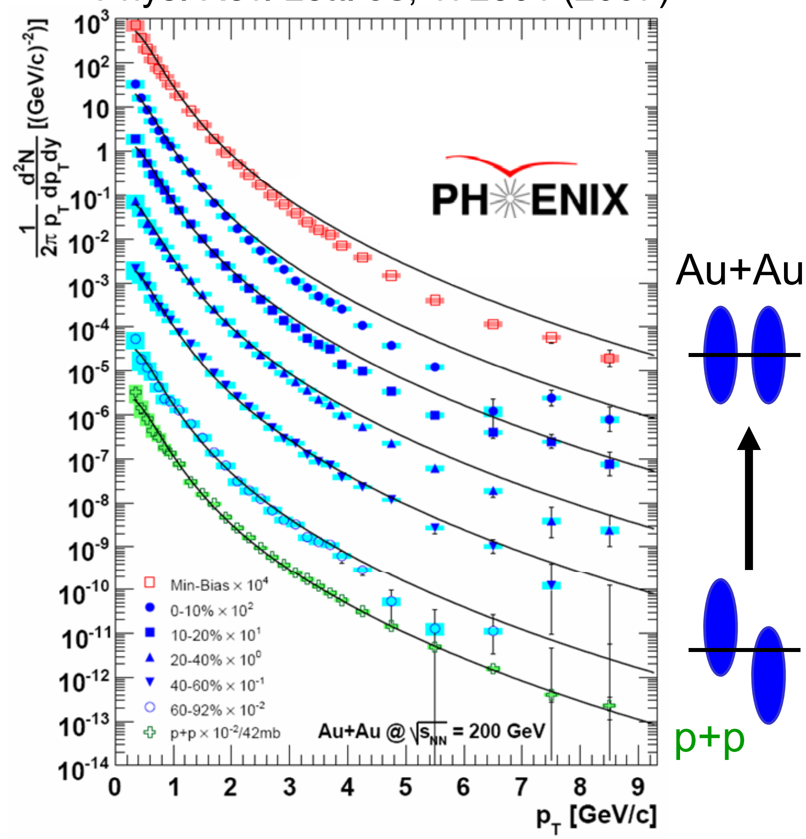
- Non-photonic electron spectra

Non-photonic electron spectra

Phys. Rev. Lett. **98** (2007) 192301



Phys. Rev. Lett. **98**, 172301 (2007)



- Spectra measured up to 10 GeV/c
- Integrated yield follows binary collision scaling
- Yield strongly suppressed at high p_T for central Au+Au

R_{AA} for non-photonic electrons

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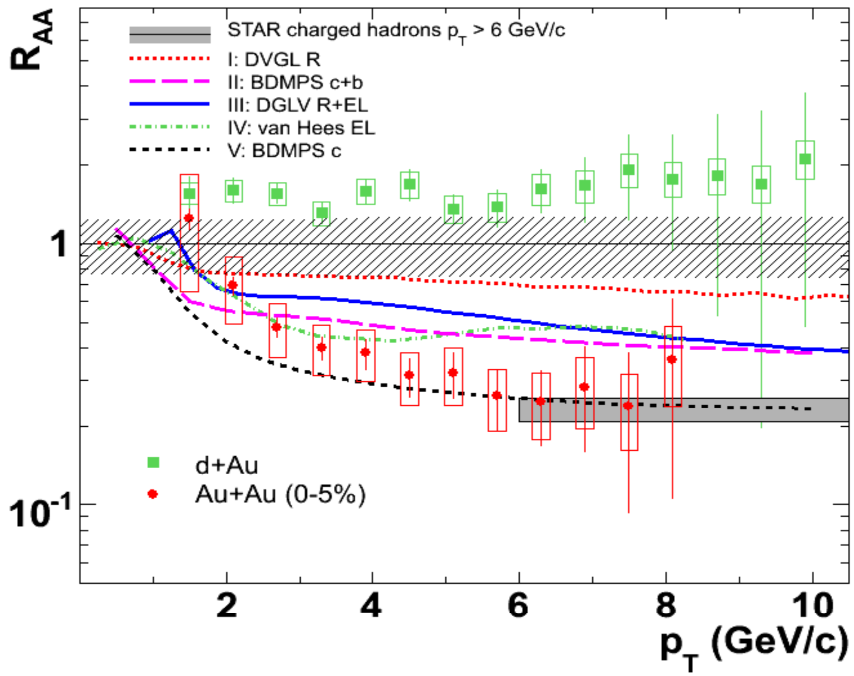

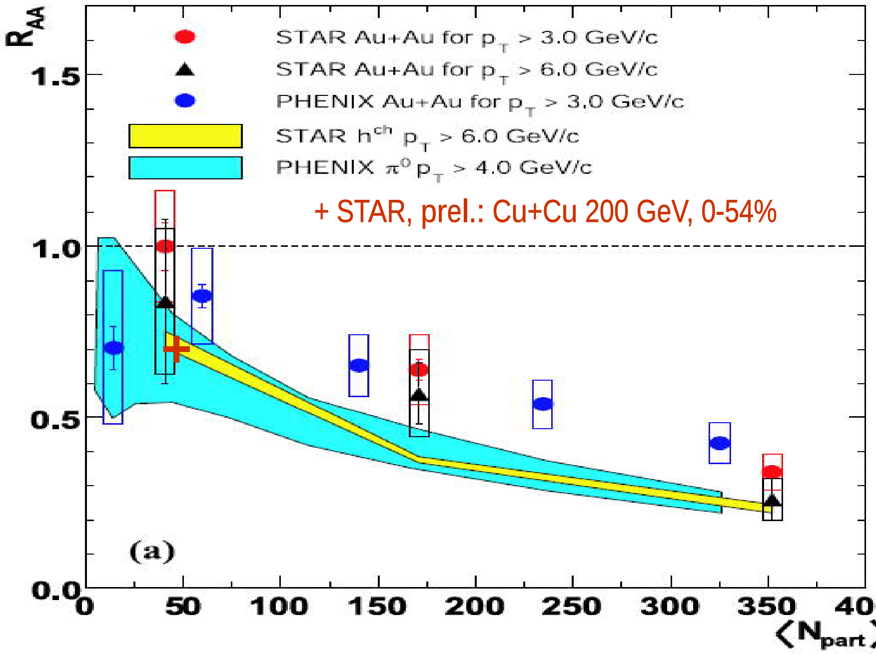

- Agreement between STAR and PHENIX
- Findings not in line with expectations from dead-cone effect
- Models implying D and B energy loss are inconclusive yet

– collisional energy loss or heavy quark fragmentation and dissociation in the medium may play a role

- Smoothly decreases from peripheral to central Au+Au

Degree of thermalization

- Flow of non-photonic electron

Phenix: Flow of non-photonic electrons

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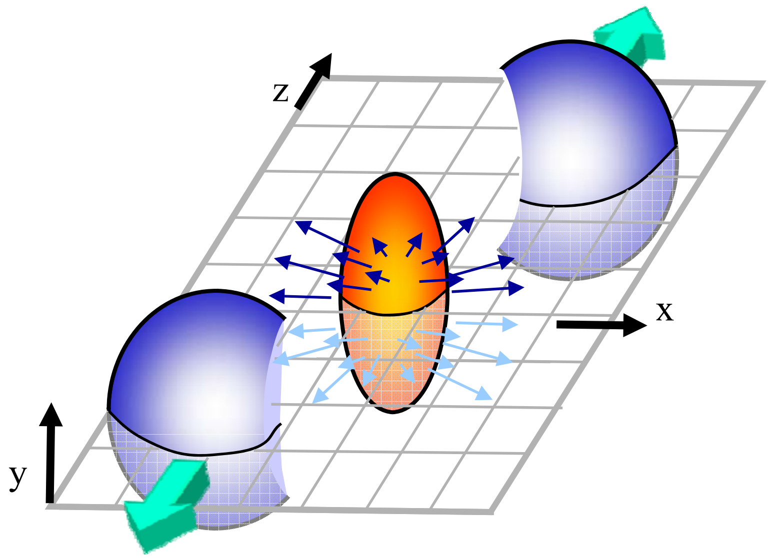

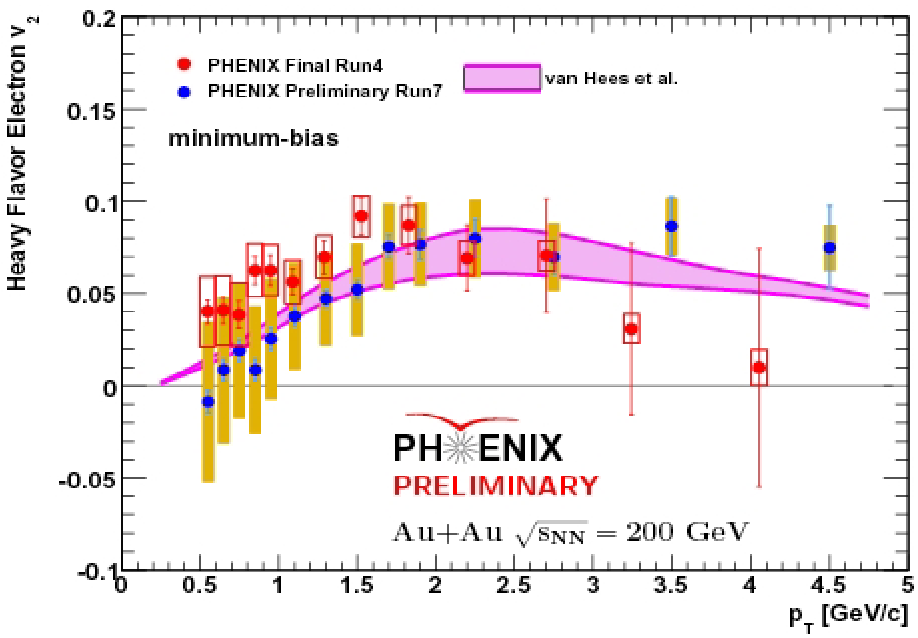

- Pressure gradient generates collective flow → anisotropy in momentum space
- $v_2 = \langle \cos 2(\varphi - \Psi_r) \rangle$
- Updated result on flow of non-photonic electrons

  - saturation at p_T > 2 GeV/c

→ Together with R_{AA}: Charm suppressed and thermalizes

→ But, since $m_{c,b}$ >> T_c much more collisions are needed

→ What fraction of this is from bottom?

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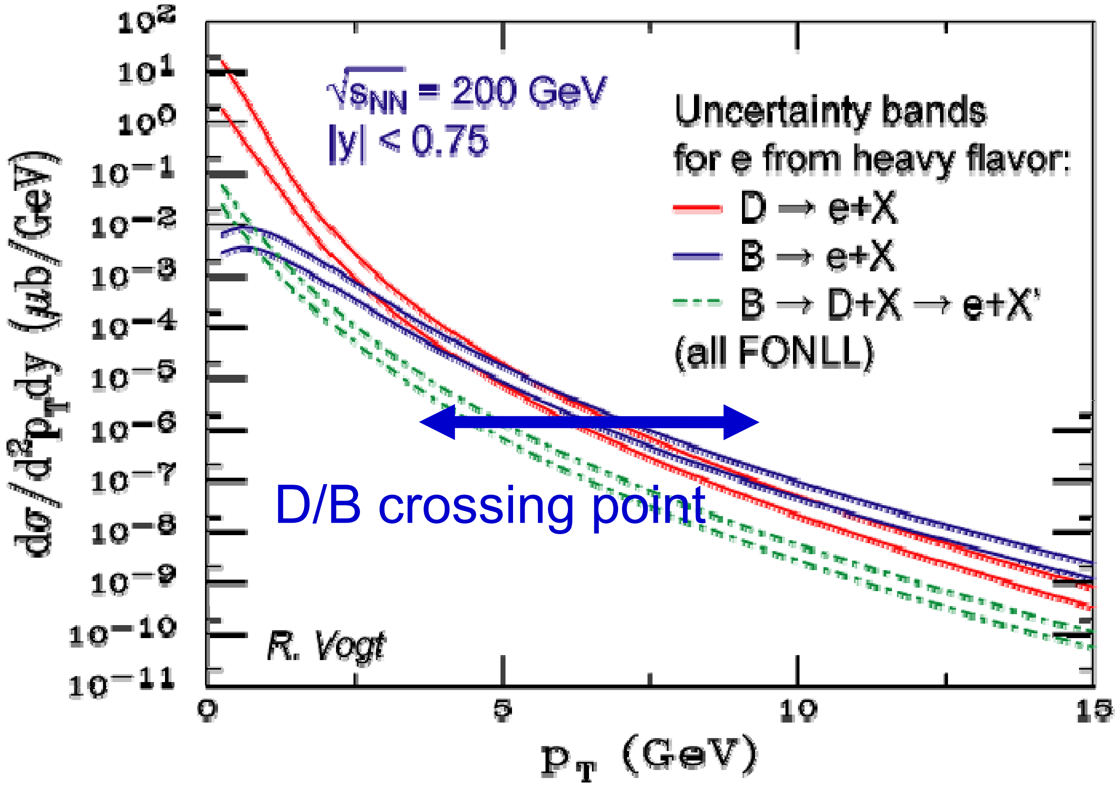
Experimental access to charm and bottom contributions

- Heavy-flavor particle correlations

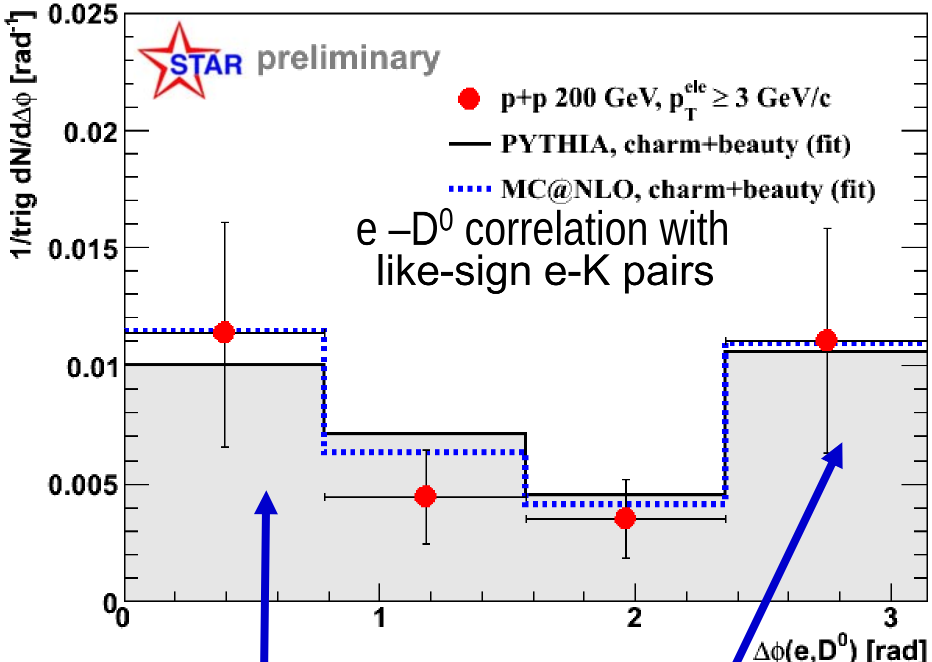
Single electrons from NLO/FONLL



- Large uncertainty in D/B crossing point: p_T = 3-10 GeV/c
- Need to separate D and B contribution experimentally
- Two heavy-flavor particle correlations

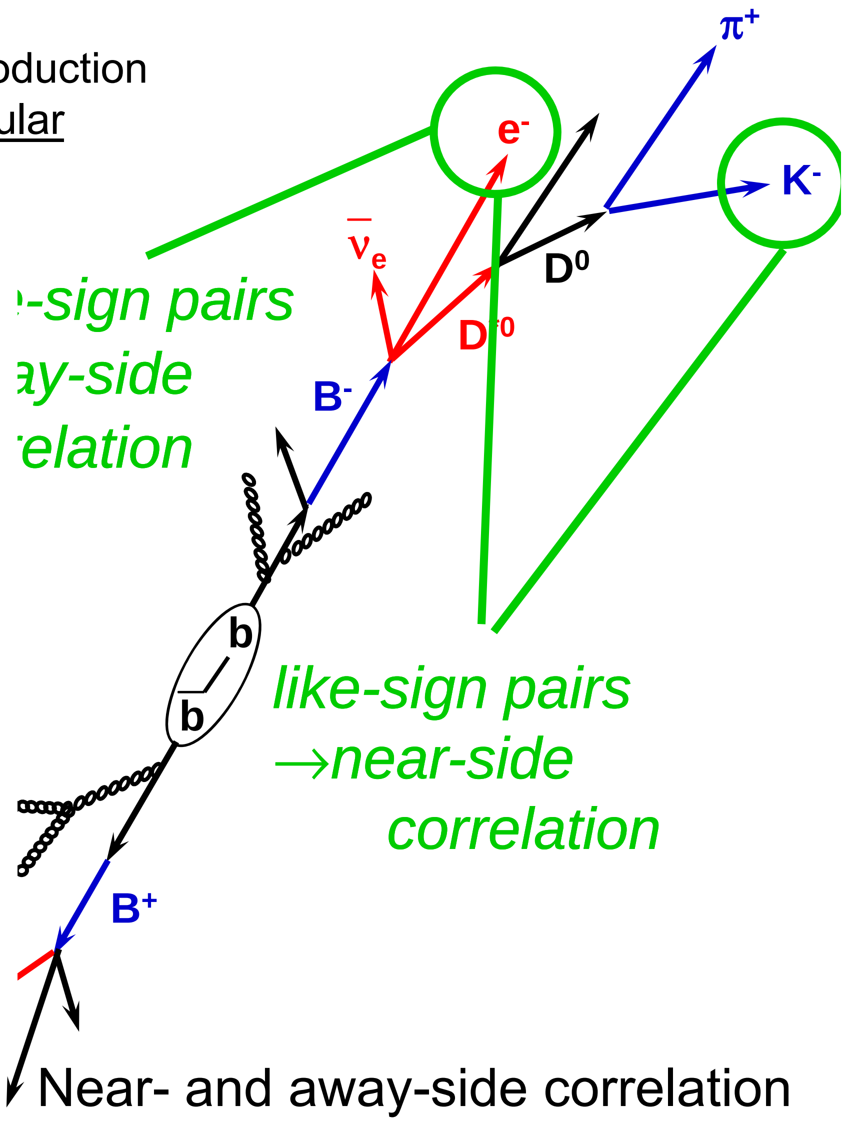
Electron tagged correlations

Identification and separation of charm and bottom production events using their <u>decay topology</u> and <u>azimuthal angular correlation</u> of their decay products



essentially from B decays only

≈75% from charm
≈25% from beauty



Near- and away-side correlation peak expected for B production

Monte Carlo simulations

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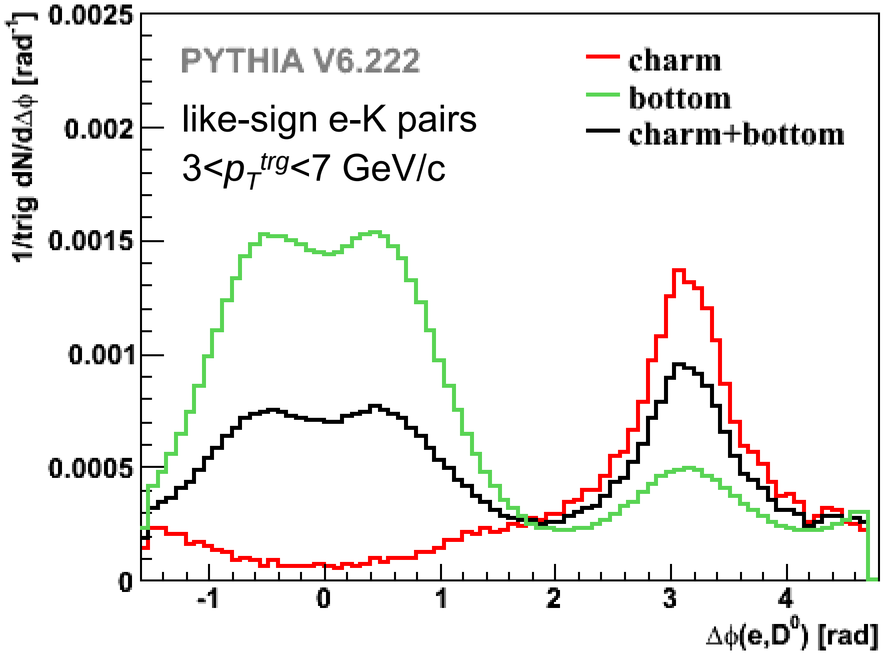
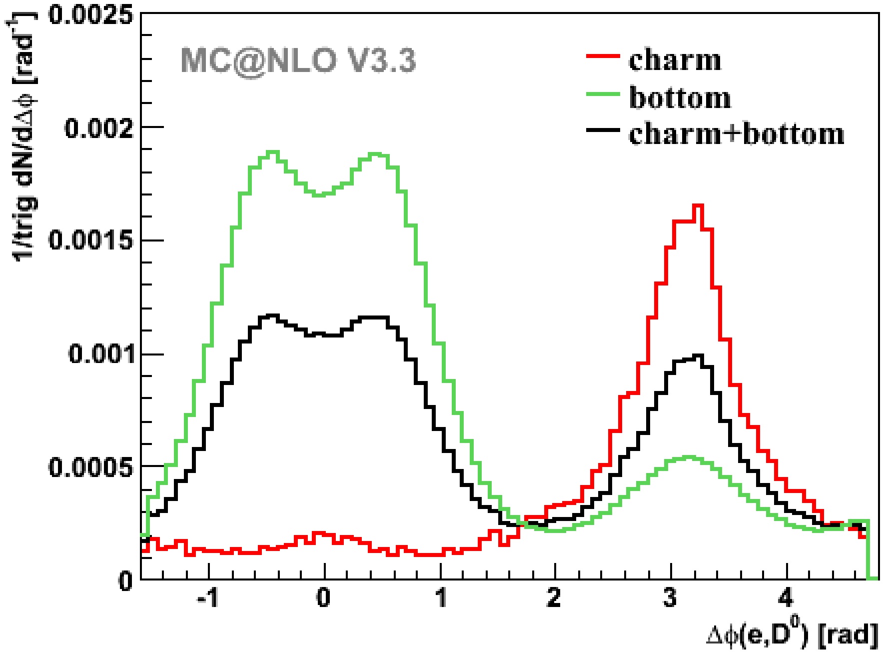
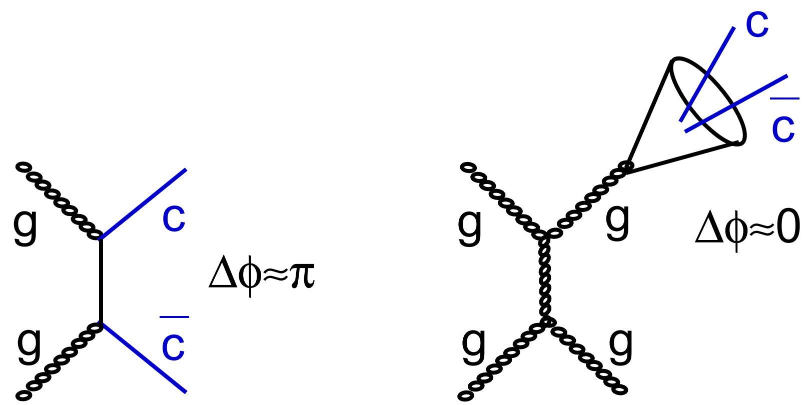




- Near-side
  - B decays (dominant)
- Away-side
  - charm flavor creation (dominant)
  - small B contribution

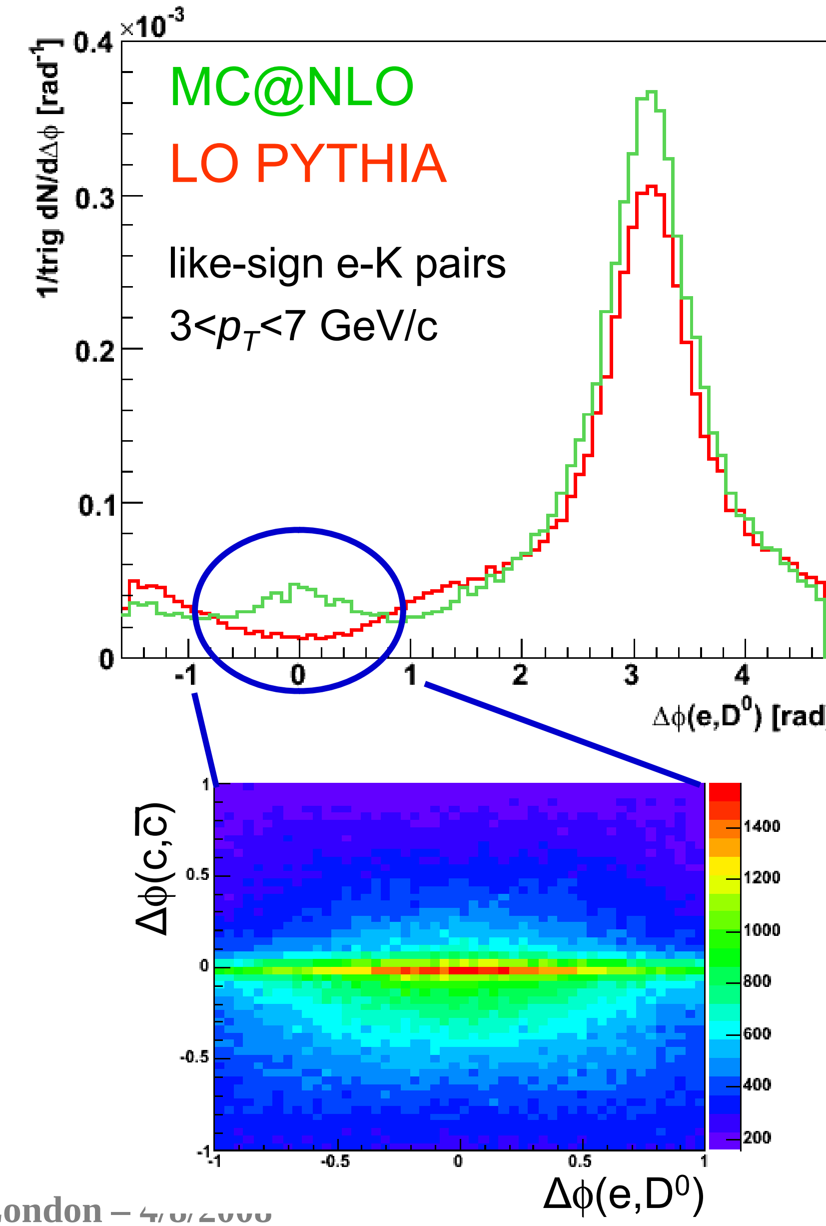
- Away-side
  - B decays (dominant)
  - small charm contribution

Gluon splitting contribution

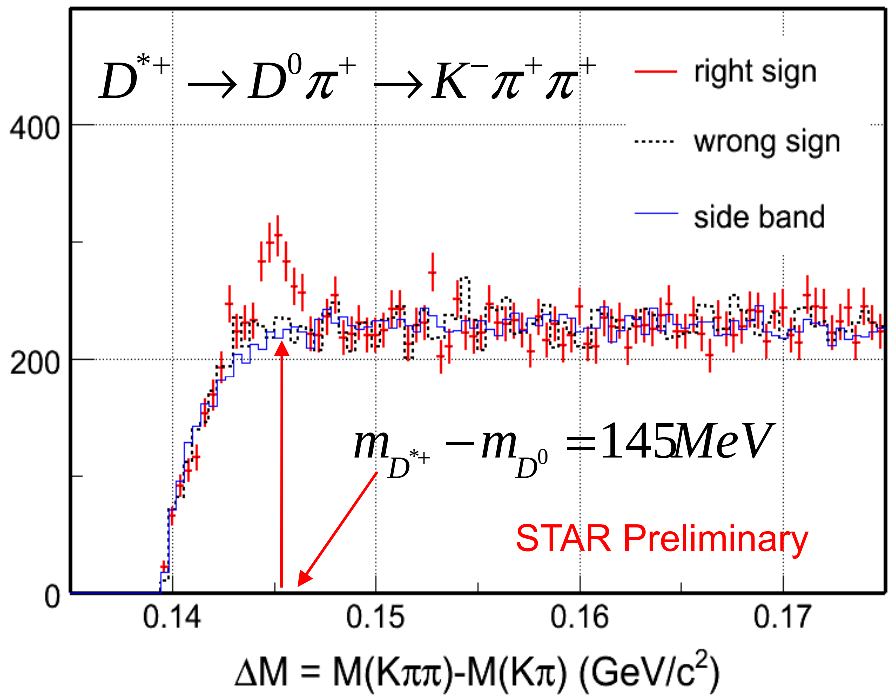


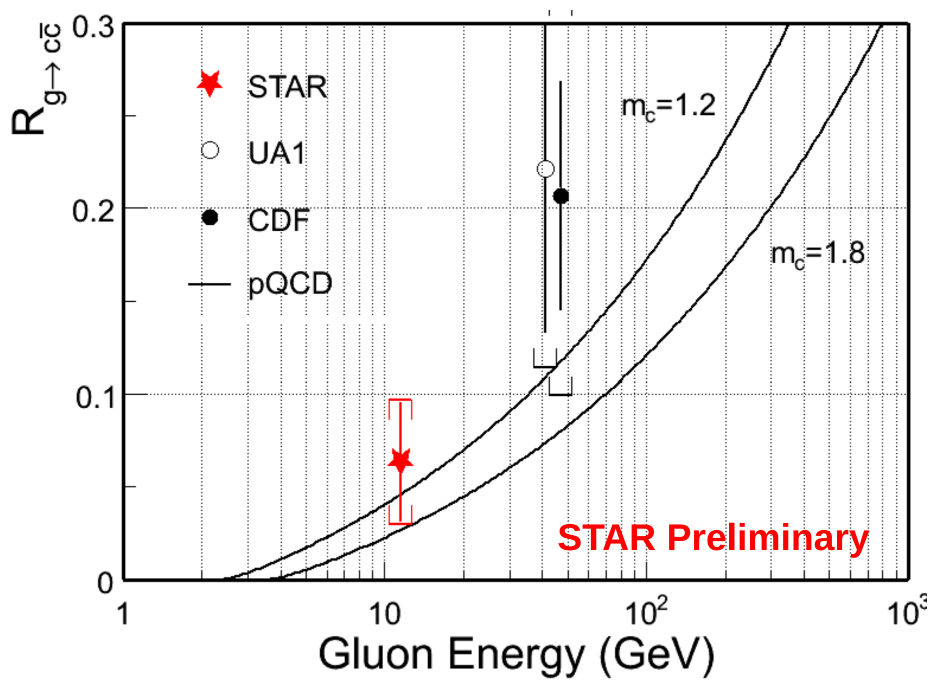
flavor creation (LO) gluon splitting (NLO)

- MC@NLO event generator: NLO QCD computations with a realistic parton shower model
- Away-side: Remarkable agreement of peak shape between LO PYTHIA and MC@NLO
- Near-side: GS/FC ≈ 5%
$\rightarrow$ small gluon splitting contribution



STAR measurement of D* in jet





- Access to charm content in jets
- Data consistent with pQCD calculation for gluon splitting rate
- Gluon splitting contribution to total charm production is ~6%

Electron-hadron azimuthal correlations

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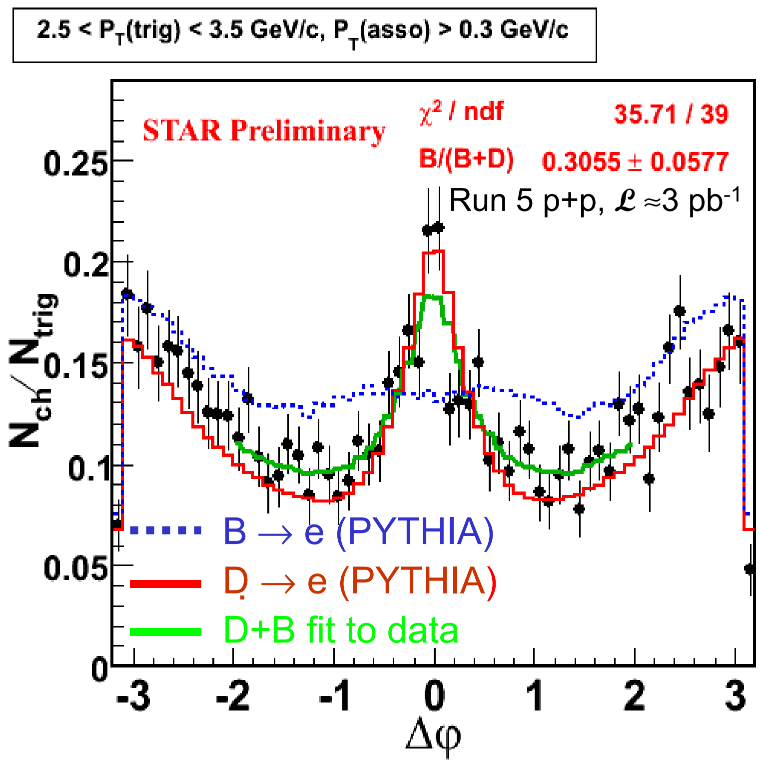
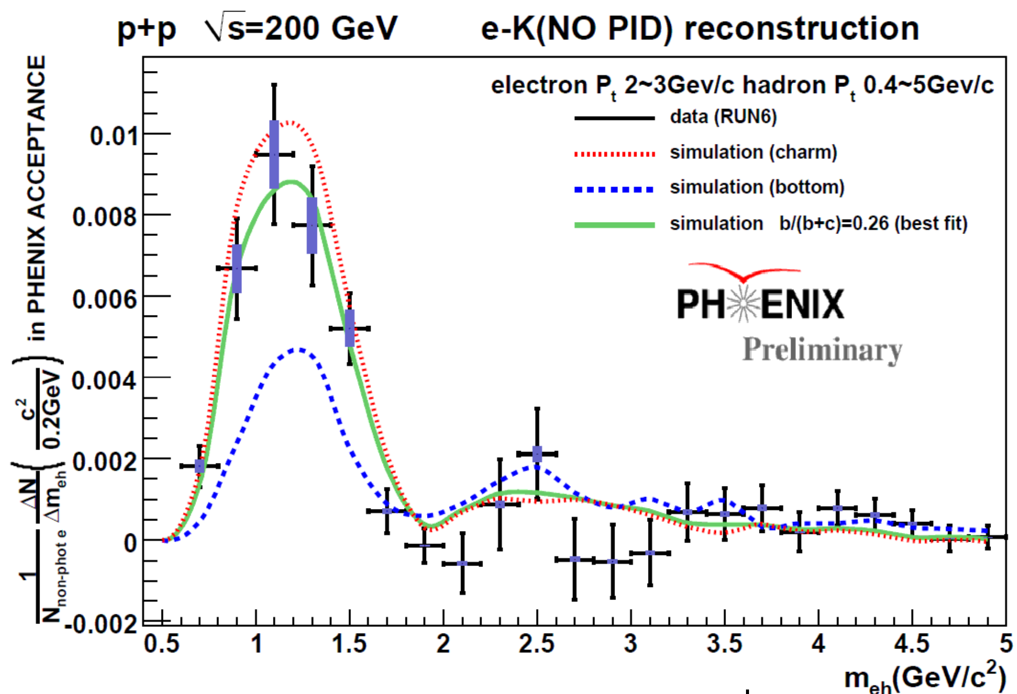
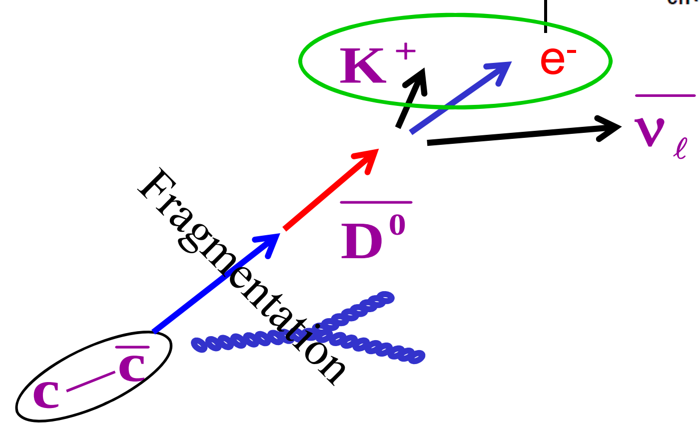




Extraction of relative B contribution using PYTHIA simulations

$$\Delta\phi_{measured} = R \cdot \Delta\phi_B + (1 - R) \cdot \Delta\phi_D$$



Relative B→e contribution

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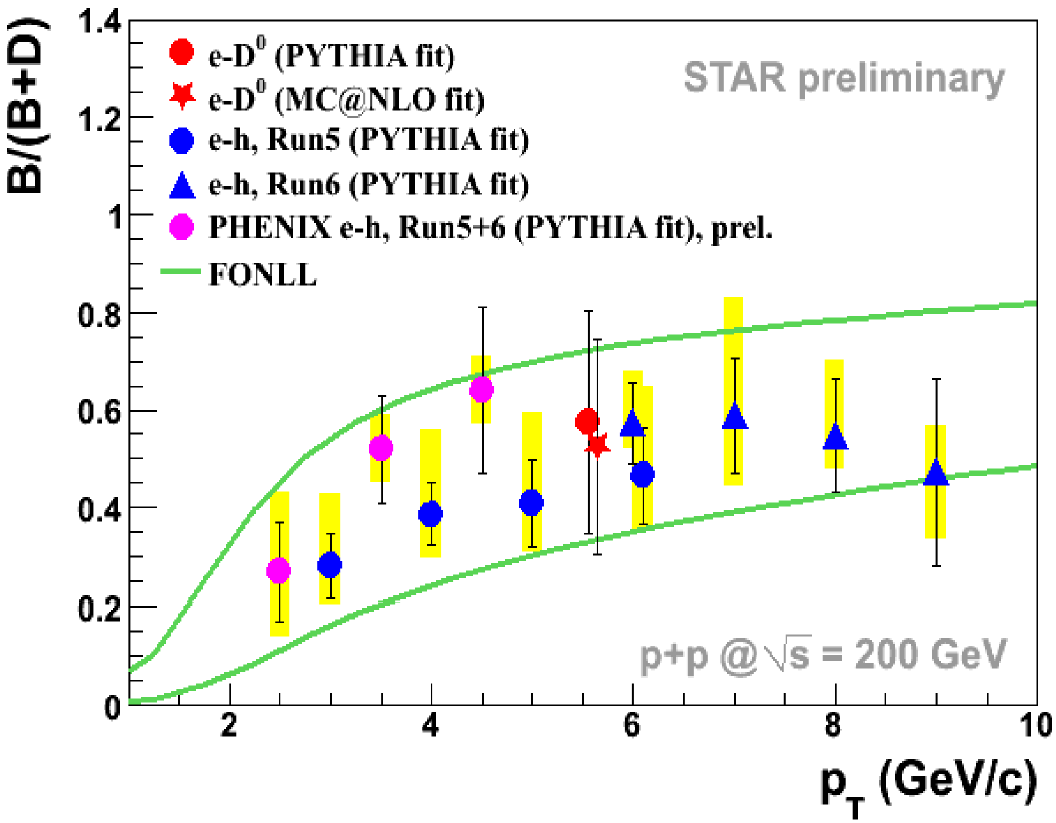
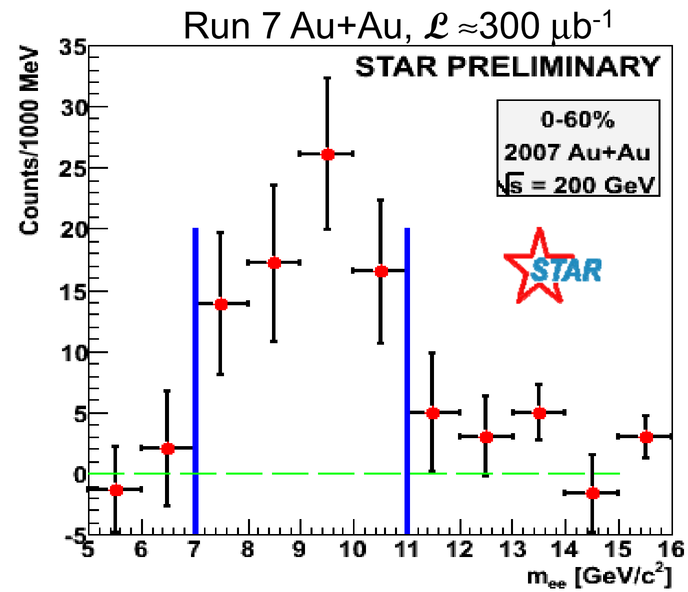


- Good agreement among different analyses
- Comparable D and B contributions
- Data consistent with FONLL calculations

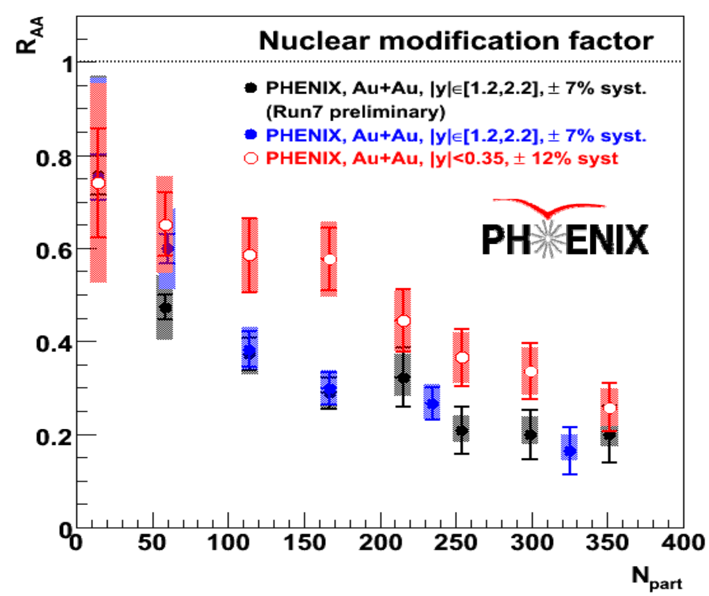
Together with R_{AA} measurement of non-photonic electrons in Au+Au
→ suggests significant suppression of bottom in the medium

Quarkonia Production

- STAR
  - J/Ψ production at high p_T (up to 14 GeV/c)
  - J/Ψ – hadron correlations
  - First ϒ signal in Au+Au



- Phenix
  - Comprehensive J/Ψ measurements (pp, d+Au, Cu+Cu and Au+Au – at forward- and midrapidity)



See talk by H. Pereira da Costa in today's afternoon session

Conclusions

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- Charm production cross-section
  - important baseline measurements for Quarkonia studies
  - follows binary collision scaling $\rightarrow$ no room for thermal production
- Non-photonic electron spectra
  - energy loss in Au+Au is much larger than expected
- Flow measurements
  - charm is thermalized
- Electron-D^0 azimuthal correlations
  - experimental access to charm and bottom contributions
  - small gluon-splitting contribution
  - bottom contributes significantly to non-photonic electron yields at high p_T $\rightarrow$ bottom is suppressed

Conclusions (cont'd)

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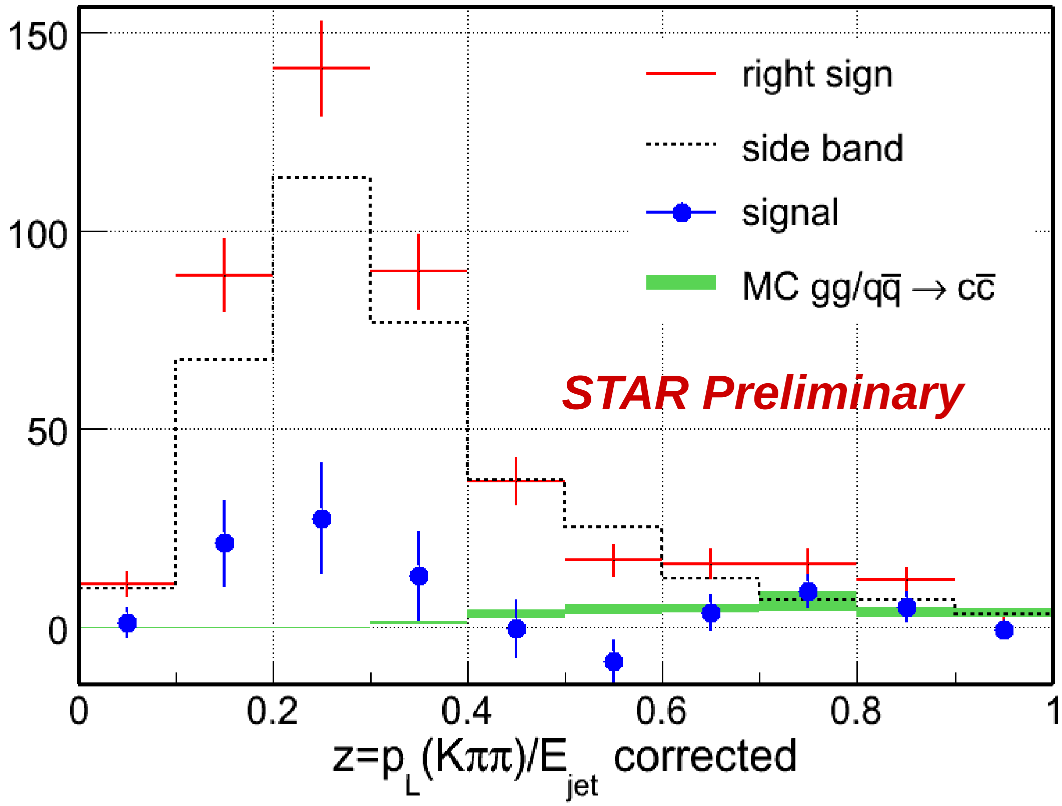
- Heavy flavor is an important tool to understand Heavy Ion physics at RHIC
- Heavy flavor is challenging
  - measurements are complicated and needs a lot of statistics
- The future is promising…
  - STAR and Phenix upgrades visioning heavy flavor measurements
  - RHIC II upgrades will provide more luminosity

Backup

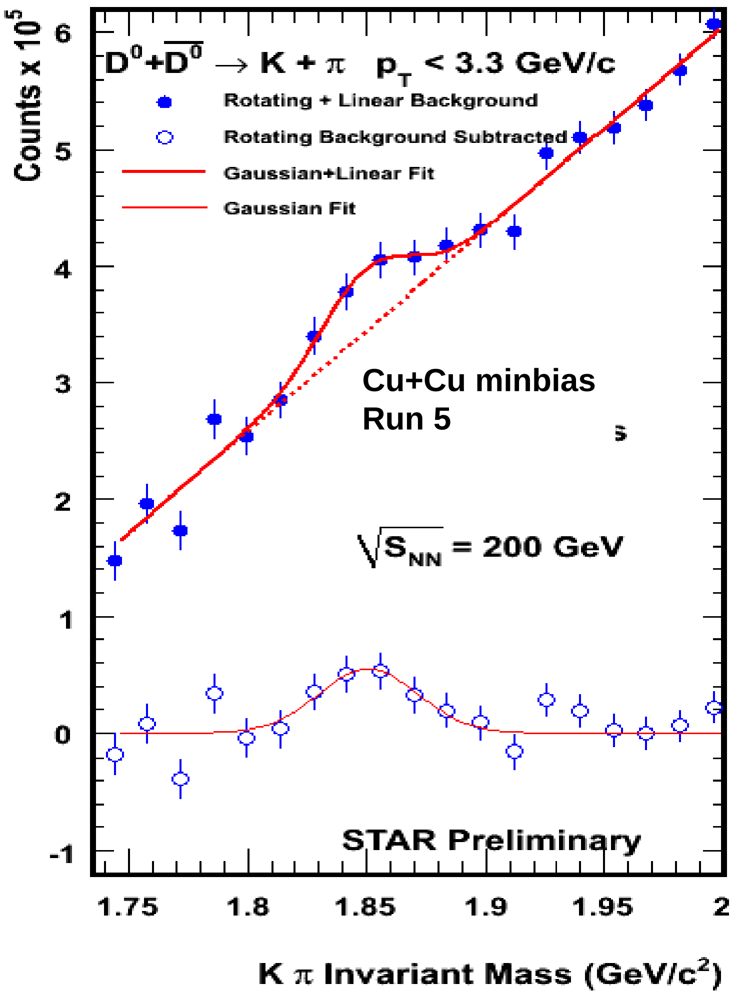
D* in jet measurement

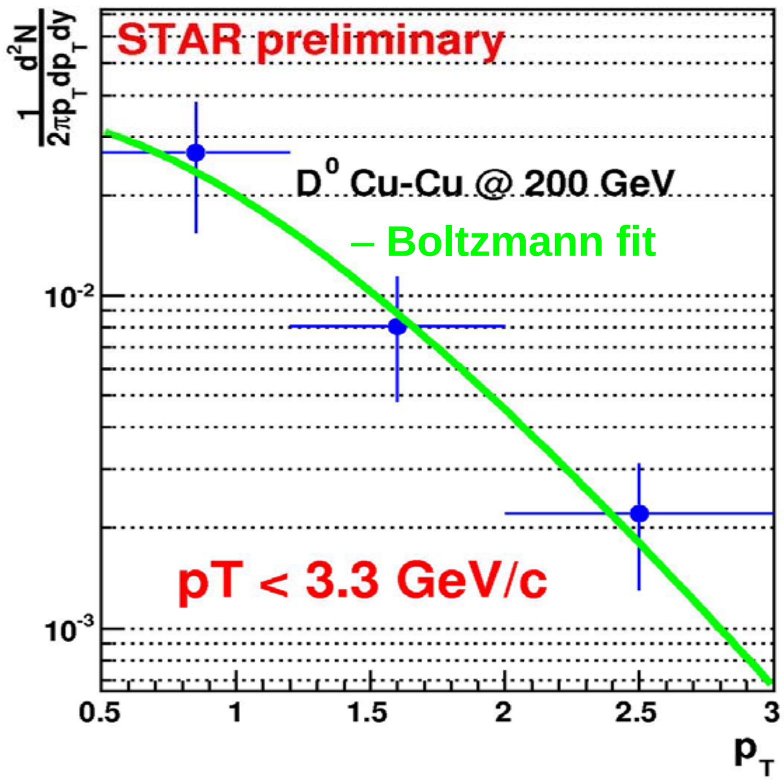


Run V p+p, jet patch triggered data:
1.7 M jets > 8 GeV/c

- Magnitude at high z region is suppressed due to trigger, and it is consistent with MC simulation for only direct flavor creation process
- Excess at low z region is expected to be from gluon splitting process

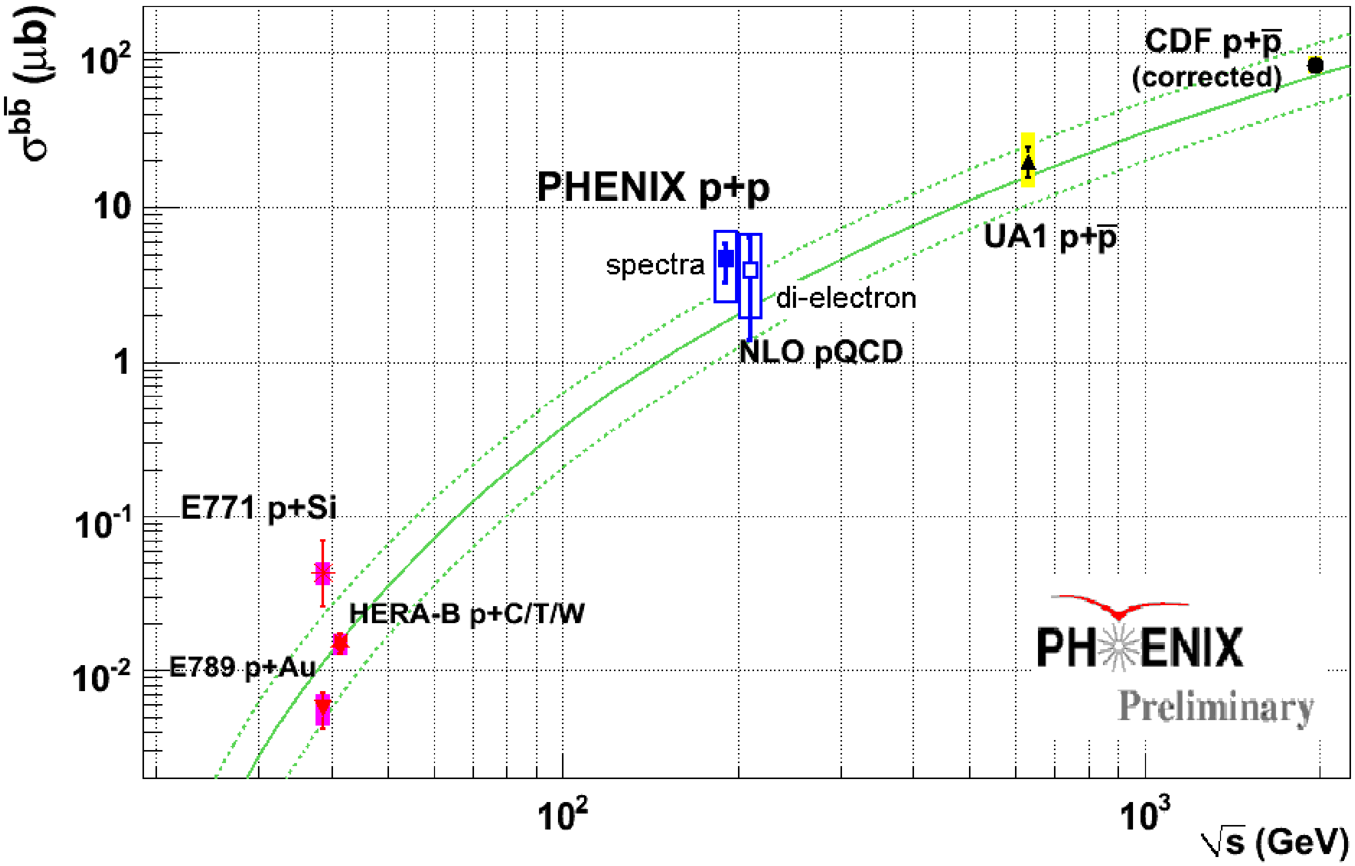
Open charm in Cu+Cu





$$\sigma_{c\bar{c}}^{NN} = 1.30 \pm 0.25\ (stat.)\ mb$$

Total bottom cross section



- Several extrapolations used (pT, rapidity and mass)
- Different methods agree
- Agreement with NLO pQCD