Heavy-flavour meson production at RHIC

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Outline

- Introduction

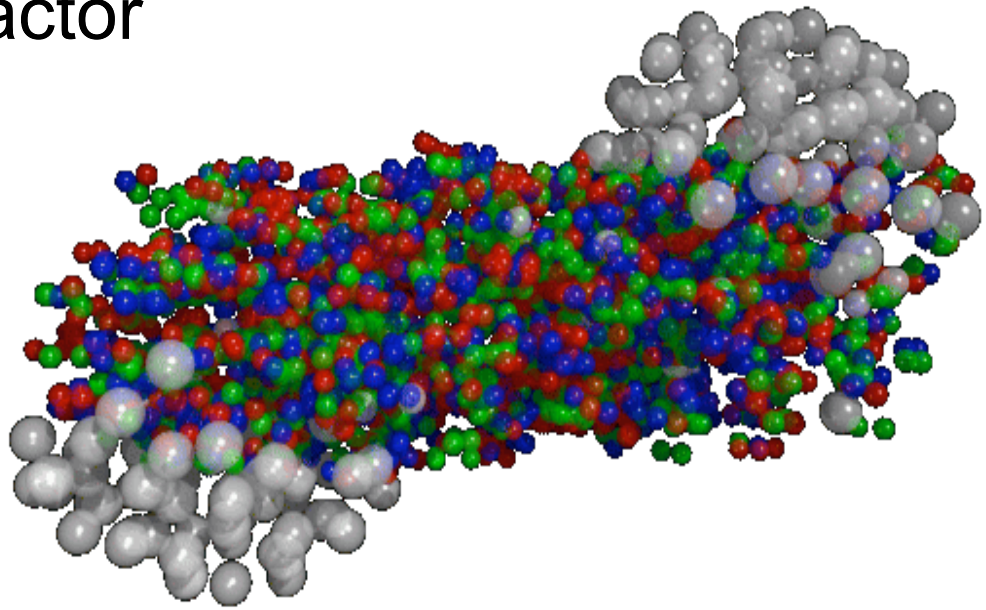
  - heavy-flavour production and energy loss in QCD matter

- Total charm production cross section

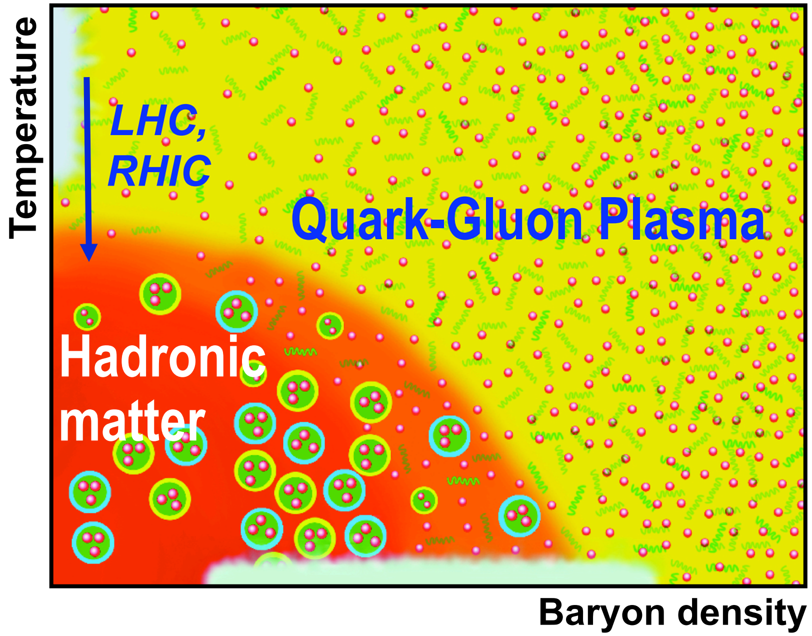
- Nuclear modification factor

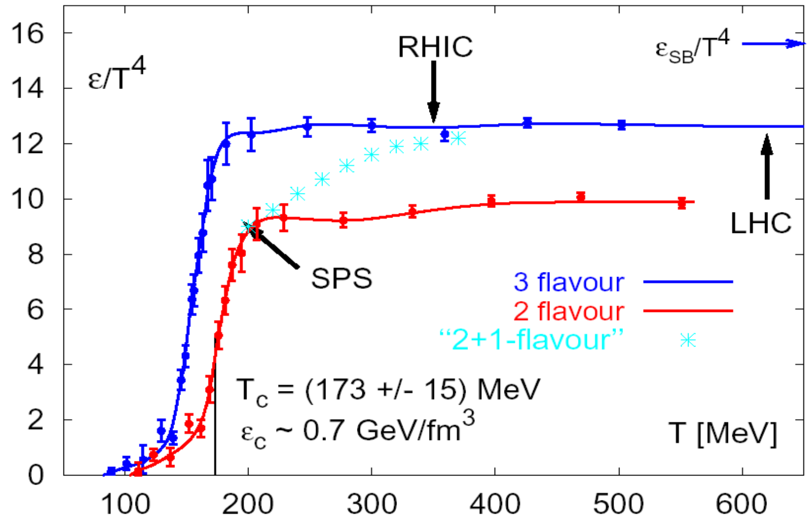
- Heavy-flavour azimuthal correlations

- Summary

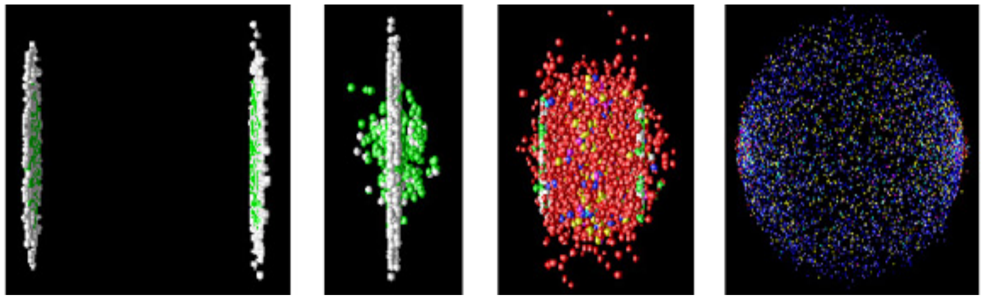


Matter in extremes: the QGP

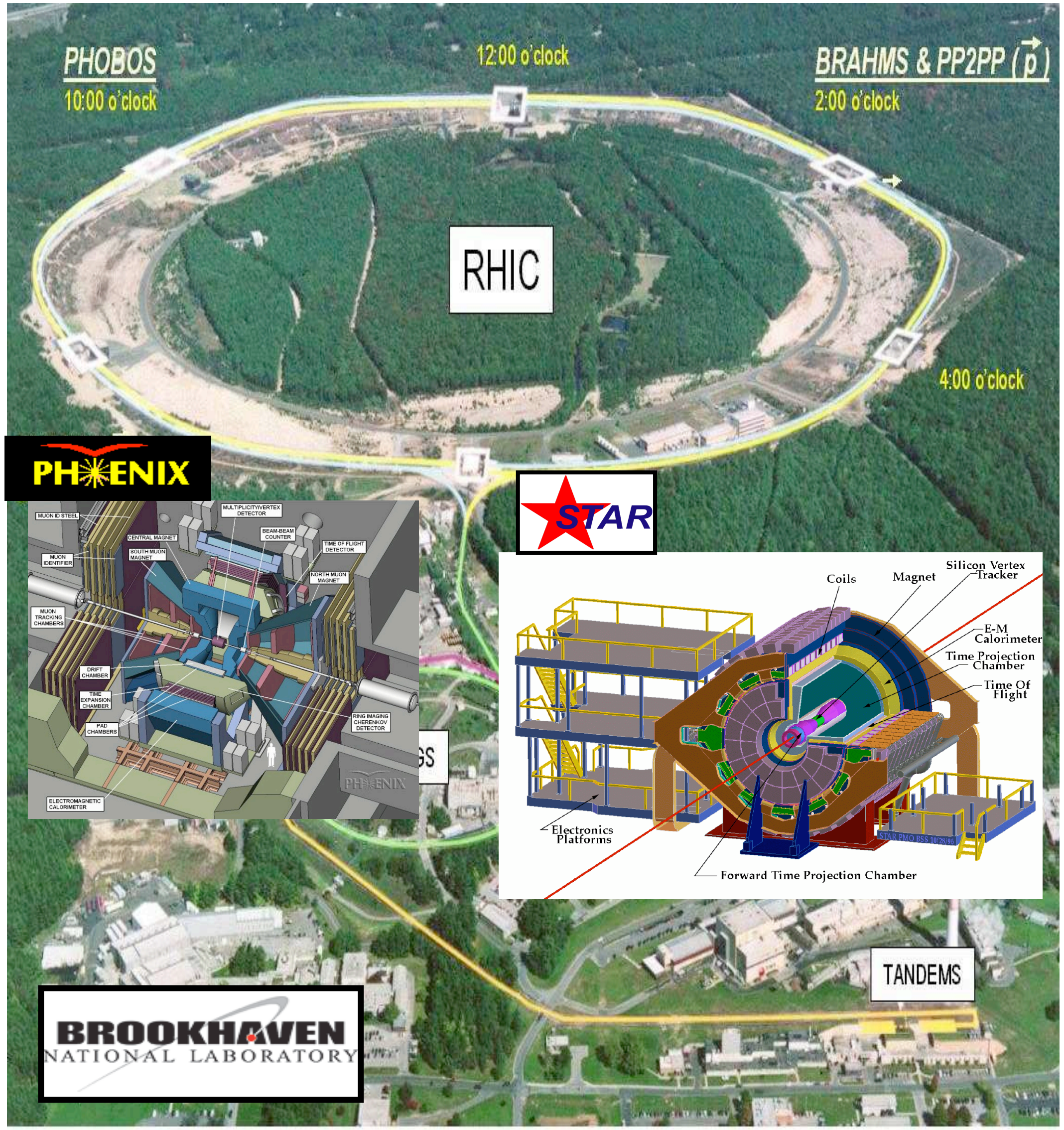




- Study strongly interacting matter under extreme conditions: high temperature and high density
- Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the Quark-Gluon Plasma
- Experimental access via high energy heavy-ion collisions

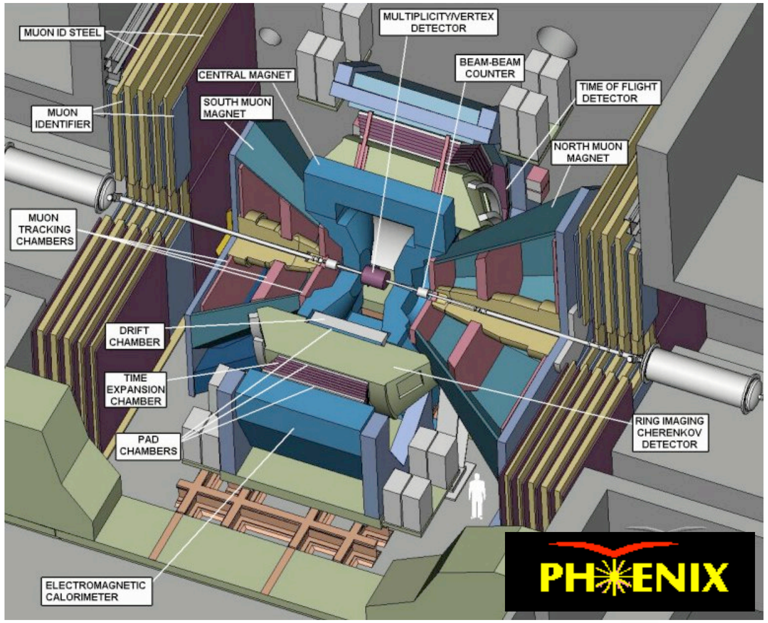


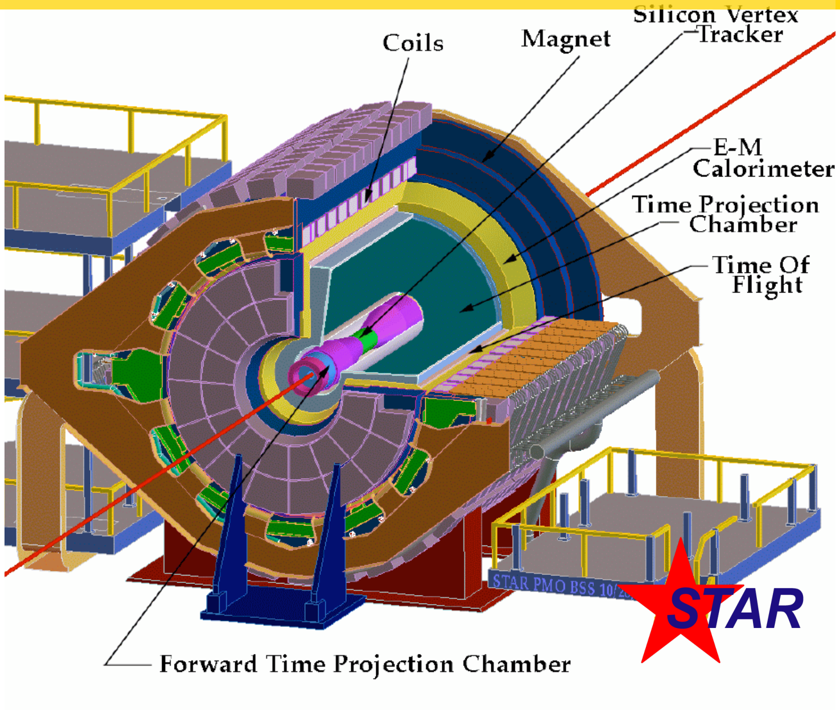
The RHIC accelerator at BNL



- **Relativistic Heavy Ion Collider** at Brookhaven National Laboratory (USA)
- Two concentric superconducting magnet rings, 3.8 km circumference
- Counter-rotating ion beams
- Data taking since 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

Detectors at RHIC

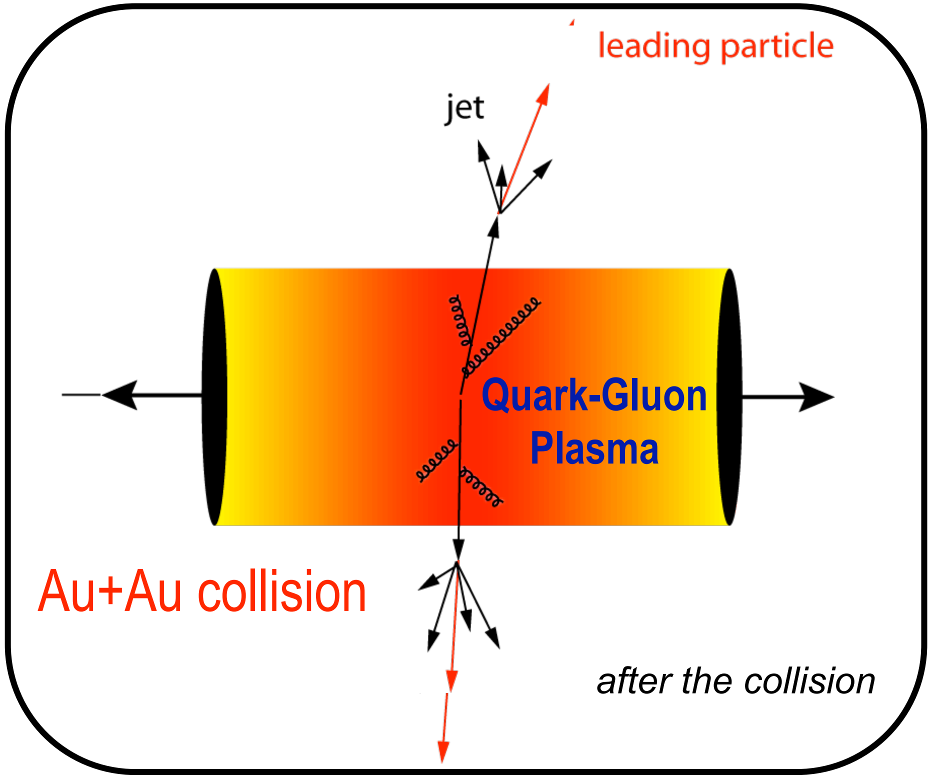




- Designed for leptonic measurements
- DC, PC, TEC, RICH, EMC and Muon tracking - low radiation length
- Open heavy flavours
  - muons (muon arms at forward rapidities)
  - electrons
- Quarkonia states

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

Probing hot and dense QCD matter



- Simplest way to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile
- Heavy-ion collisions
  - hard processes serve as calibrated probe (pQCD)
  - traversing through the medium and interact strongly
  - suppression provides density measure
  - General picture: energy loss via medium induced gluon radiation (Bremsstrahlung)

Quantification of medium effects

- Measure the particle yield(p_T) in Au+Au and in p+p collisions

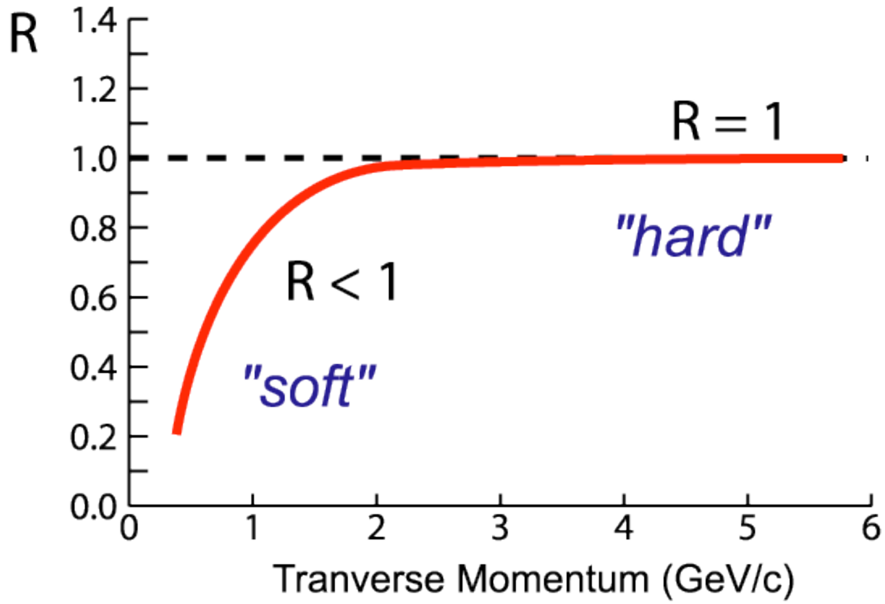
- Nuclear modification factor

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

- If no "nuclear effects"

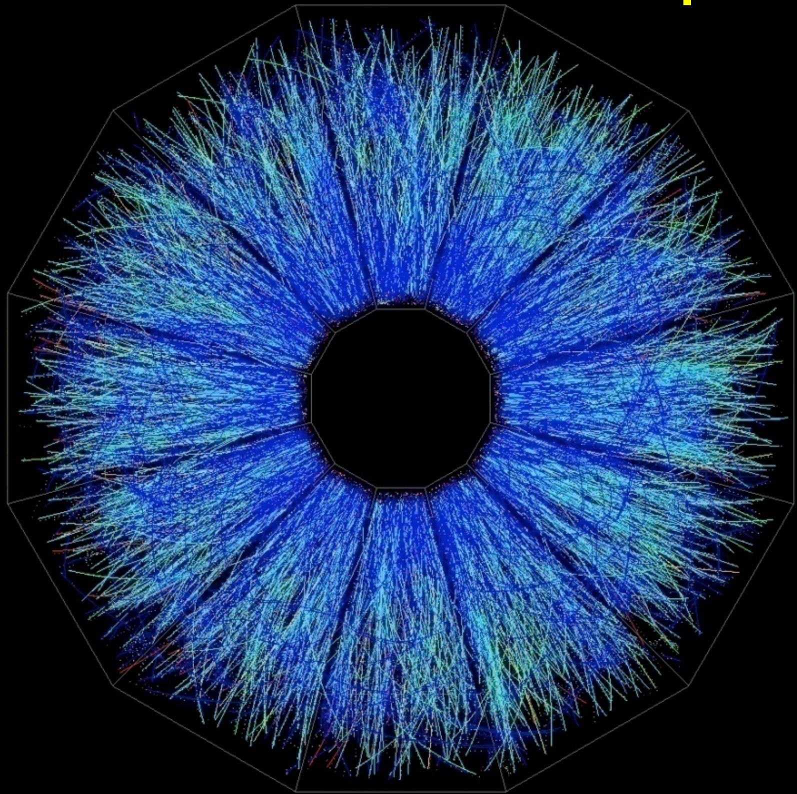
  - R < 1 in regime of soft physics

  - R = 1 at high-p_T where hard scattering dominates



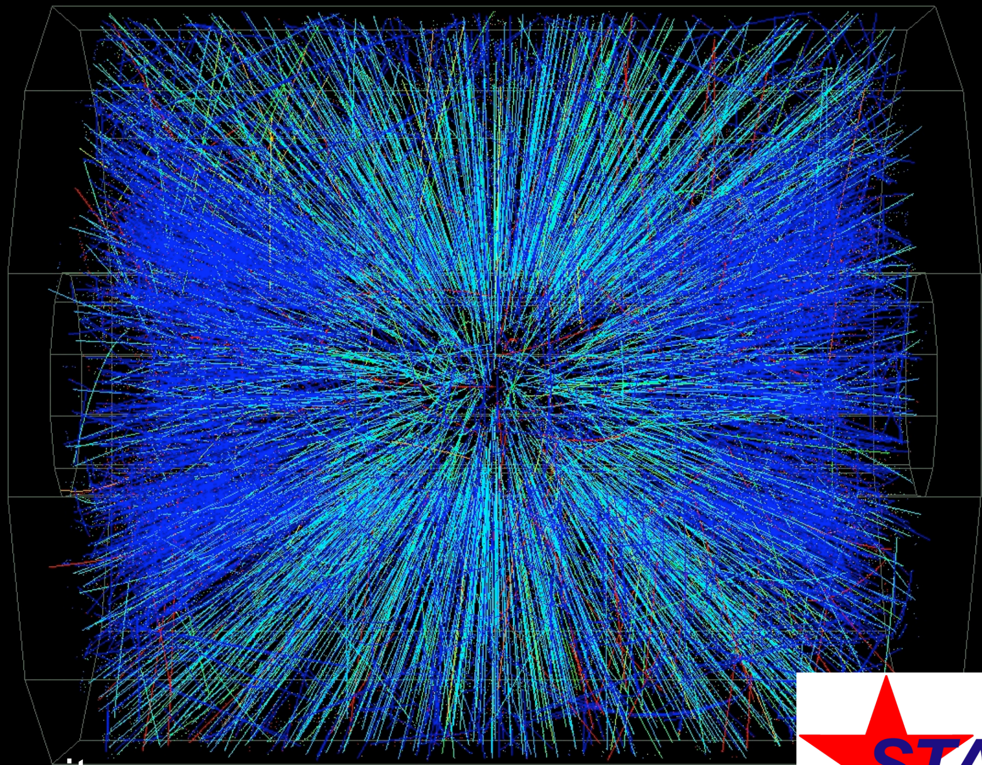
Suppression: R < 1 at high-p_T

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



Central event obtained with STAR TPC

typically 1000 to 2000 tracks per event



Energy density at RHIC (Bjørken estimate)

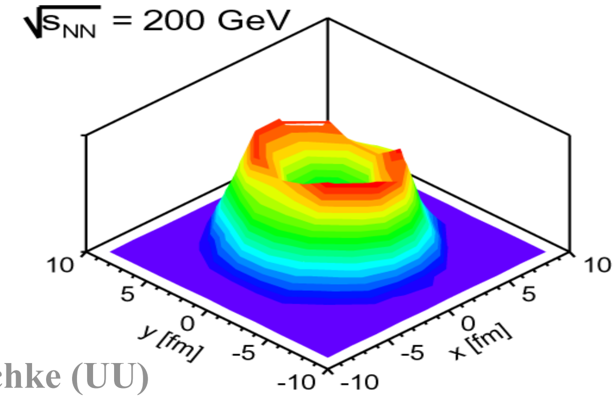
$$\varepsilon = \frac{1}{\pi R^2 \tau_0} \frac{dN}{dy} = 5 - 15\,\mathrm{GeV/fm^3}$$

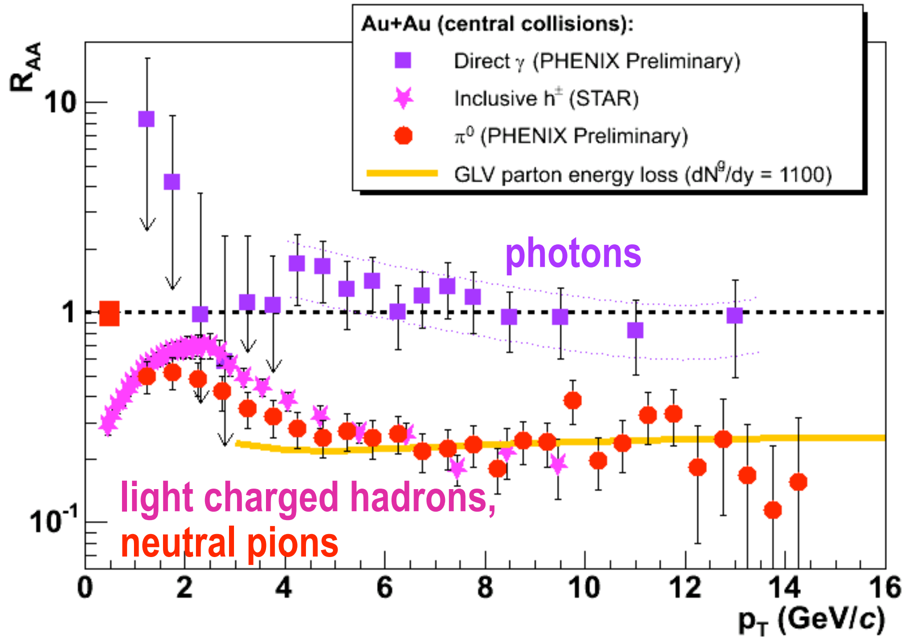
more than 30× normal nuclear matter density

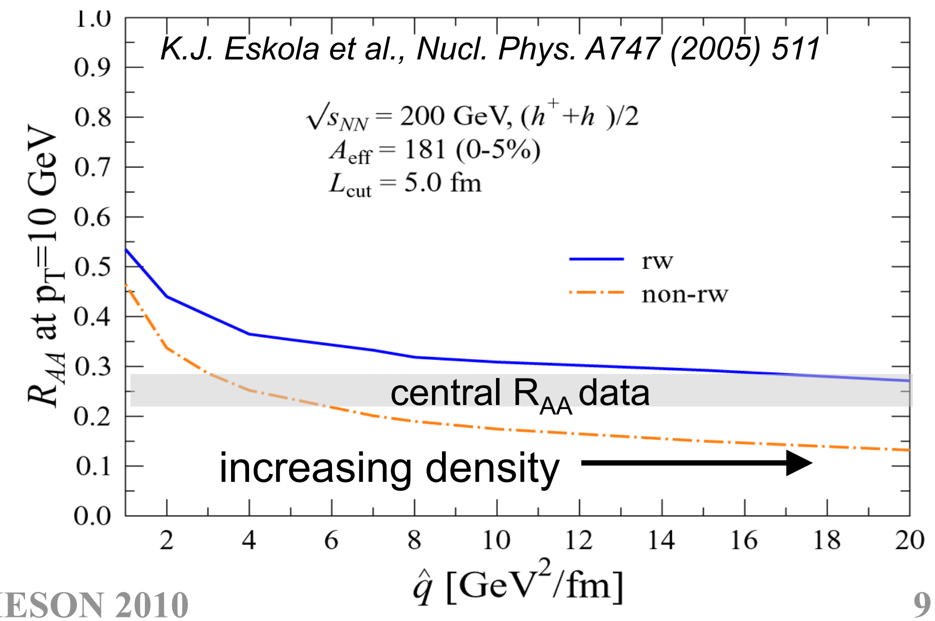
(UU)

Light hadron spectra at RHIC

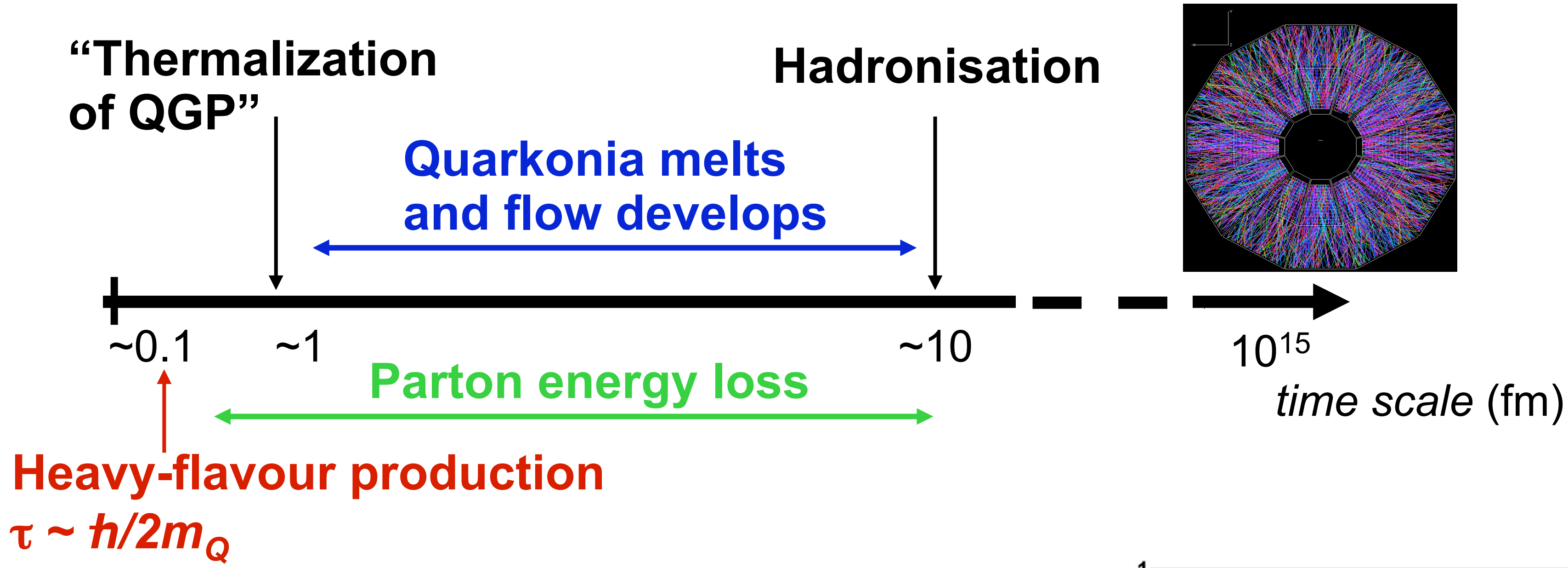
- Strong suppression in central Au+Au collisions
- Suppression well described by energy loss models
- Medium density 30-50 times normal nuclear matter
- Surface bias effectively leads to saturation of R_{AA} with density
- Limited sensitivity to the region of highest energy density



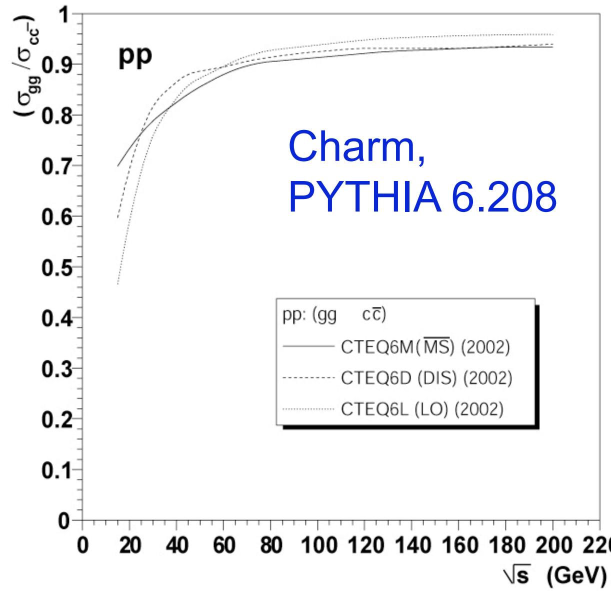




Heavy quark production



- Primarily produced by gluon fusion in early stage of collision: production rates calculable in pQCD
- Sensitivity to initial state gluon distribution
  M. Gyulassy and Z. Lin, Phys. Rev. C51, 2177 (1995)
- Heavy quarks provide information about the hottest initial phase of the collision
- Higher penetrating power: $m_Q >> T_c, \Lambda_{QCD}$



Energy loss of heavy quarks

- Probe deeper into the medium

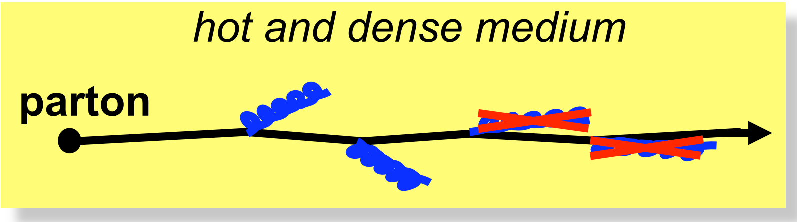
Dead-cone effect

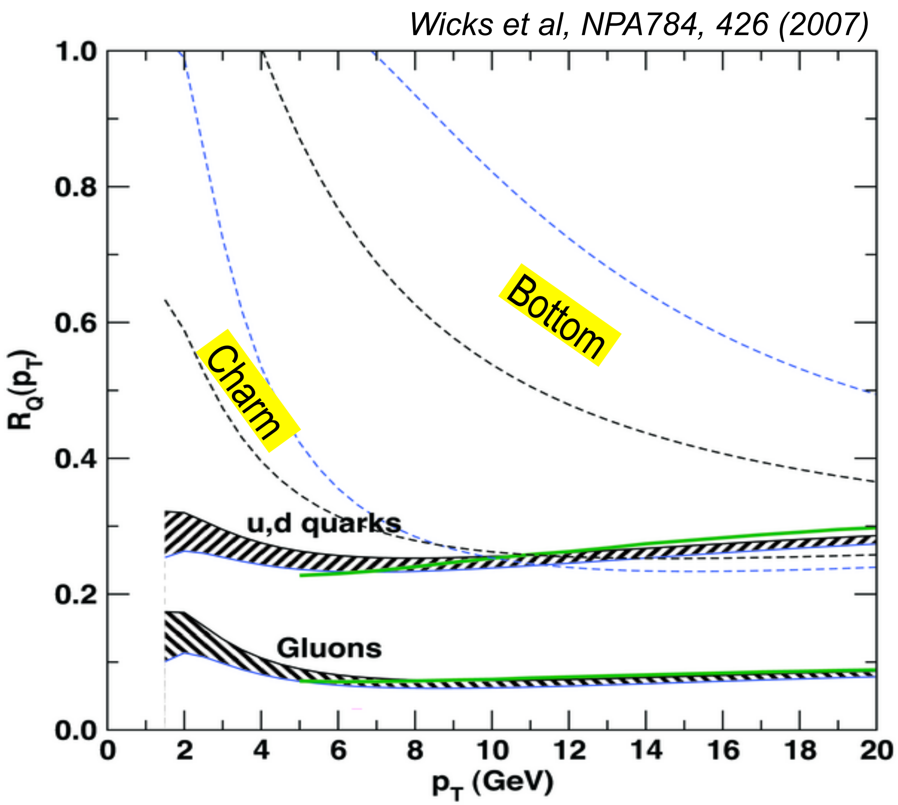
gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

Dokshitzer & Kharzeev, PLB 519, 199 (2001), hep-ph/0106202

- Less energy loss:

  $\Delta E_g > \Delta E_{LQ} > \Delta E_{HQ}$





Gluon radiation probability:

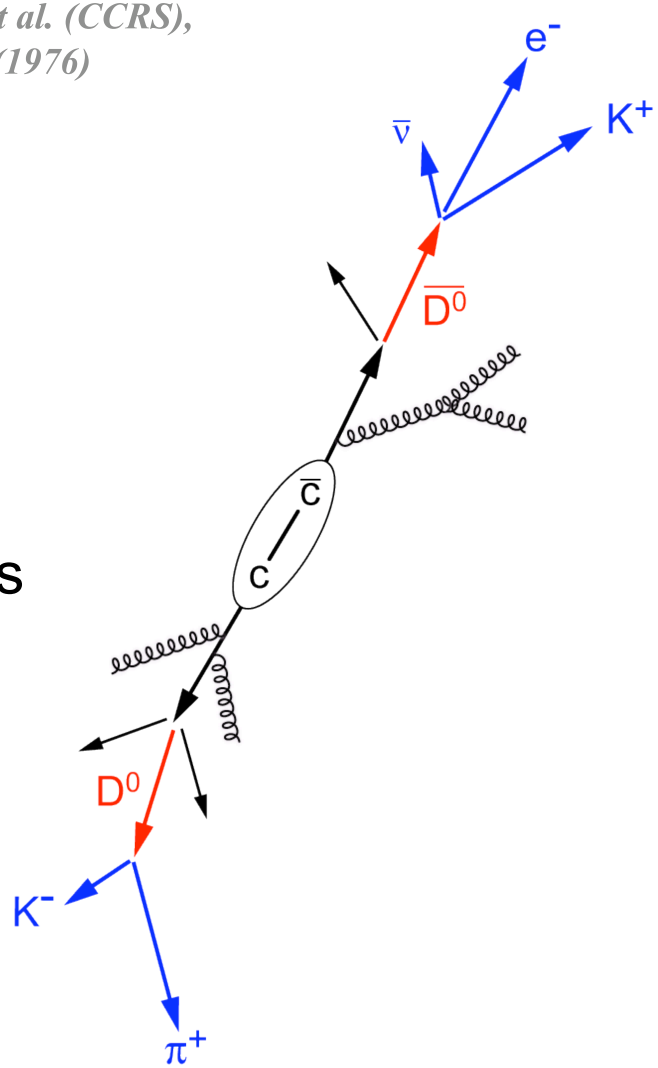
$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \frac{\omega \frac{dI}{d\omega}\Big|_{LIGHT}}{\left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

Detection of heavy-flavour particles

- Semi-leptonic decay of charm and bottom mesons
  - ***c* → lepton + *X*** (BR = 9.6%)
    - $D^0 \rightarrow e^+ + X$ (BR = 6.87%)
    - $D^0 \rightarrow \mu^+ + X$ (BR = 6.5%)
  - ***b* → lepton + *X*** (BR = 10.86%)
  - robust electron trigger
  - needs handle on photonic background

F.W. Buesser et al. (CCRS), NPB 113, 189 (1976)

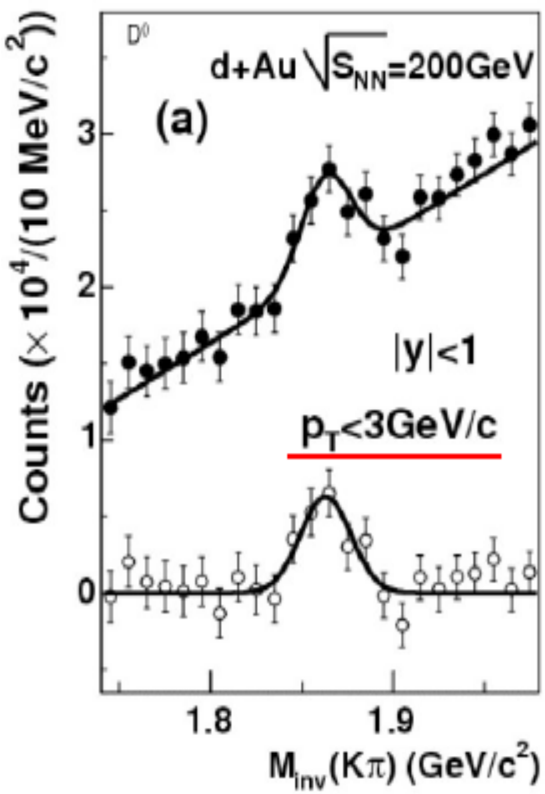
single or non-photonic electron



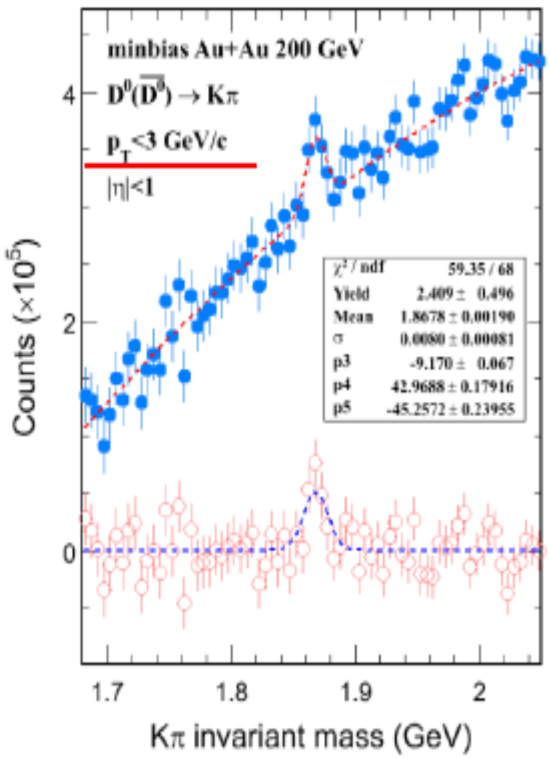
- Full reconstruction of open charmed mesons
  - $\boldsymbol{D^0 \rightarrow K^- + \pi^+}$ (BR = 3.89%)
  - direct clean probe: signal in invariant mass distribution
  - difficulty: large combinatorial background; especially in a high multiplicity environment
  - event mixing and/or vertex tracker needed

D^0 reconstruction in STAR

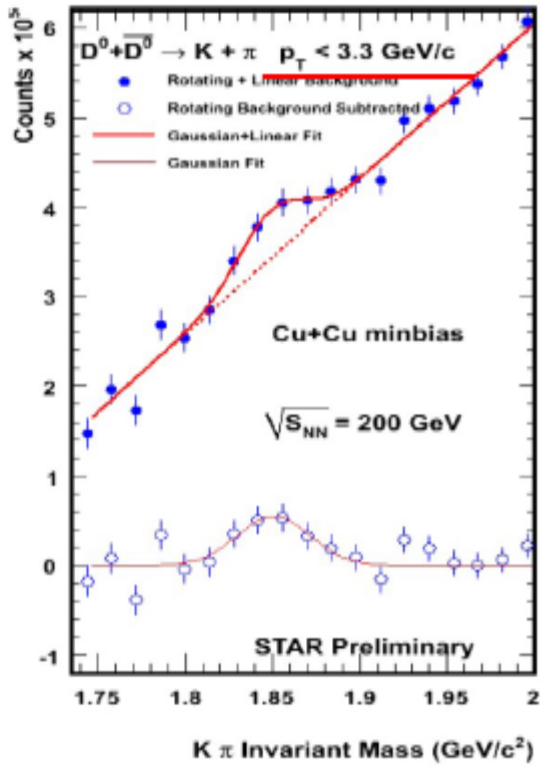
d+Au 200 GeV
PRL 94 (2005) 062301



Au+Au 200 GeV
arXiv:0805.0364 [nucl-ex]



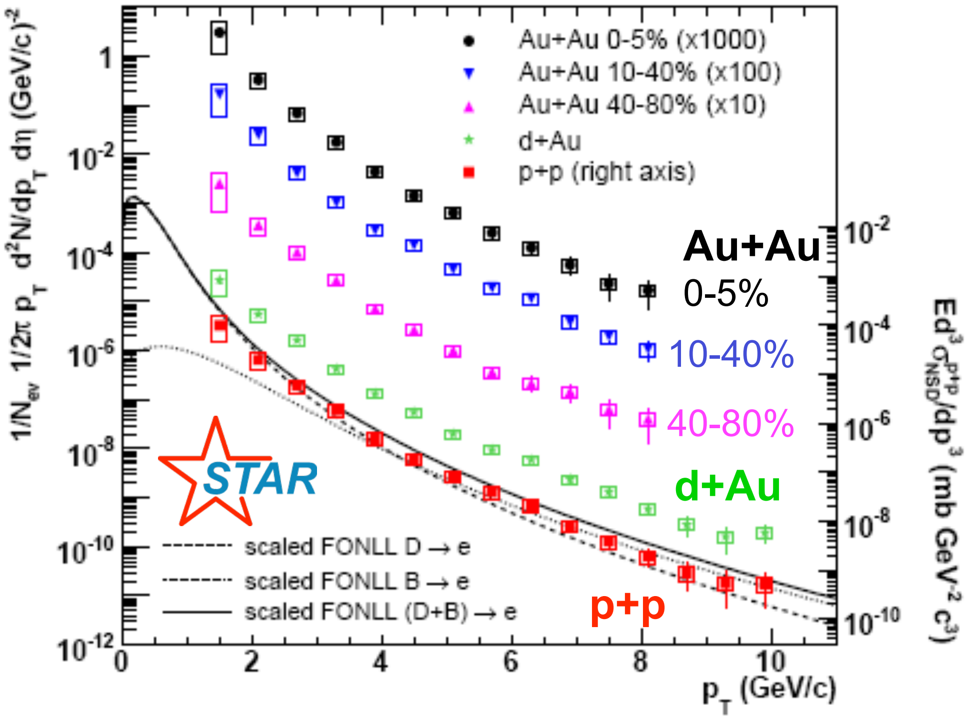
Cu+Cu 200 GeV
A. Shabetai, QM 2008



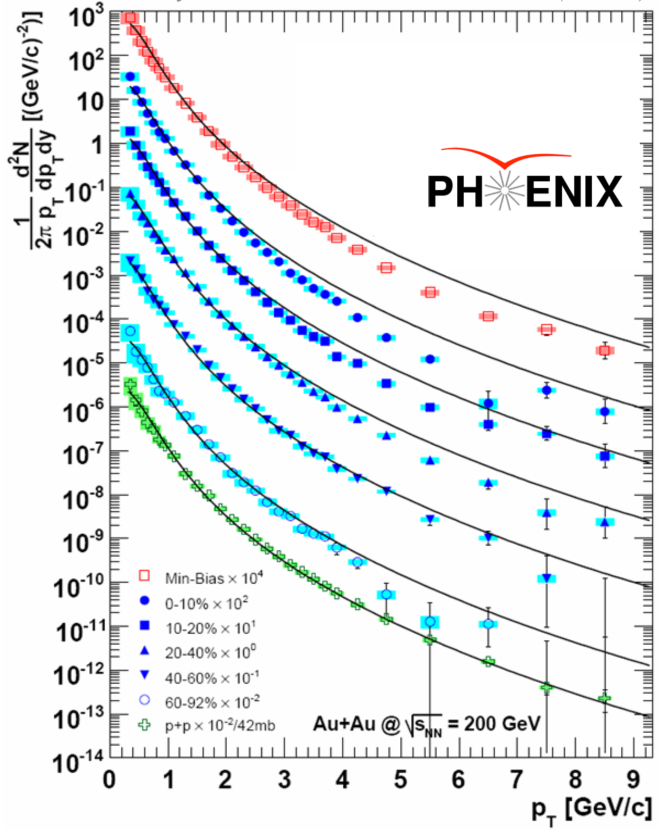
- First identified open charmed mesons in heavy-ion collisions
- Current measurements limited to low-p_T

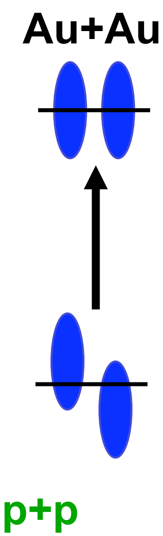
Single electron spectra

Phys. Rev. Lett. 98 (2007) 192301



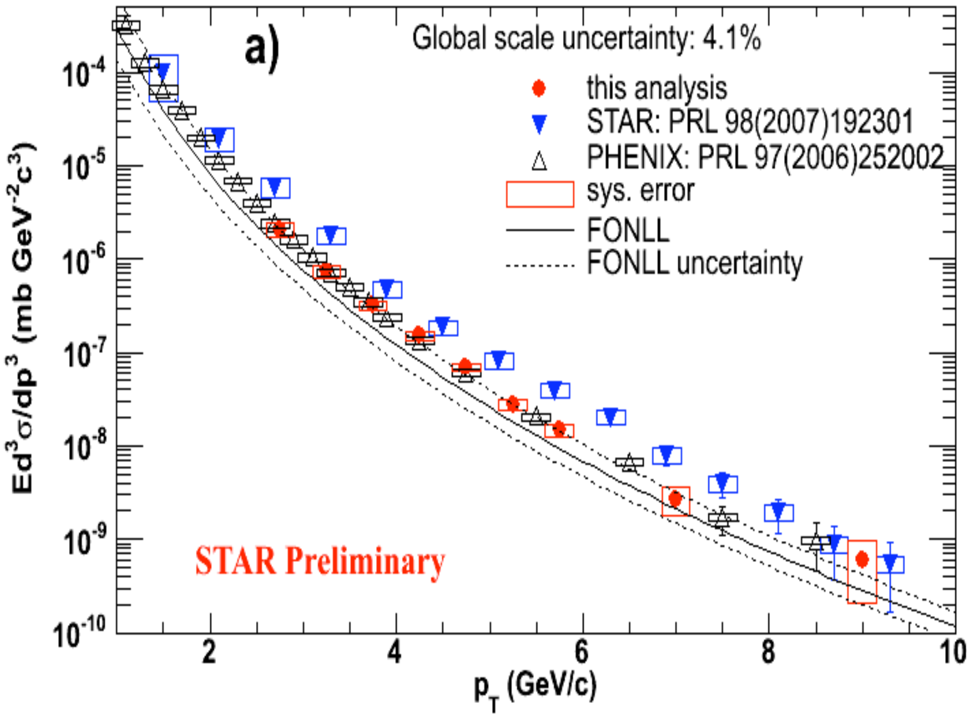
Phys. Rev. Lett. 98, 172301 (2007)

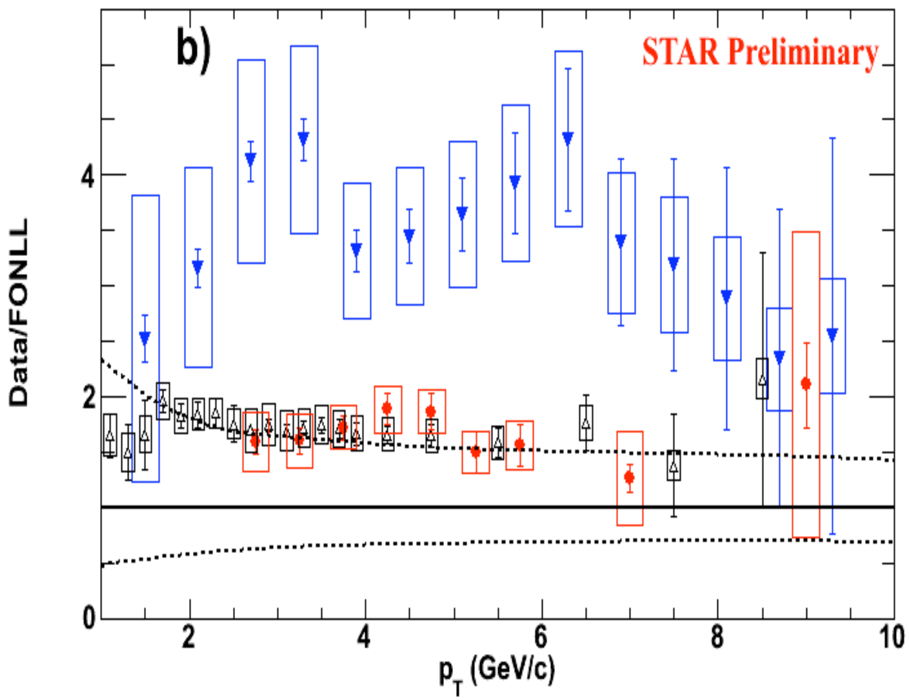




- Spectra measured up to 10 GeV/c
- Integrated yield follows binary collision scaling
- Yield strongly suppressed at high p_T for central Au+Au

Comparison with FONLL



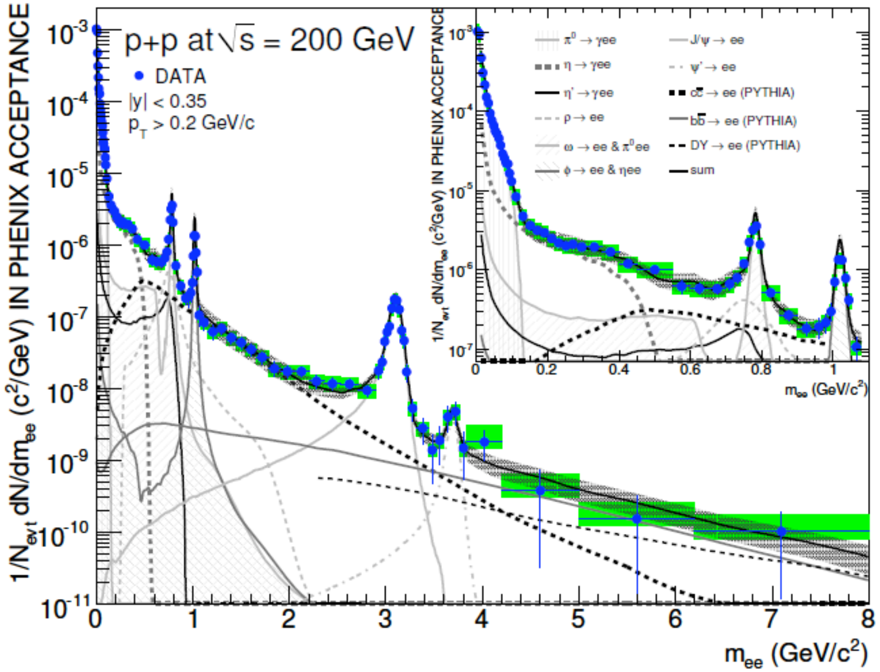


- STAR and PHENIX single electron spectra in 200 GeV p+p collisions are consistent within errors at p_T > 2.5 GeV/c

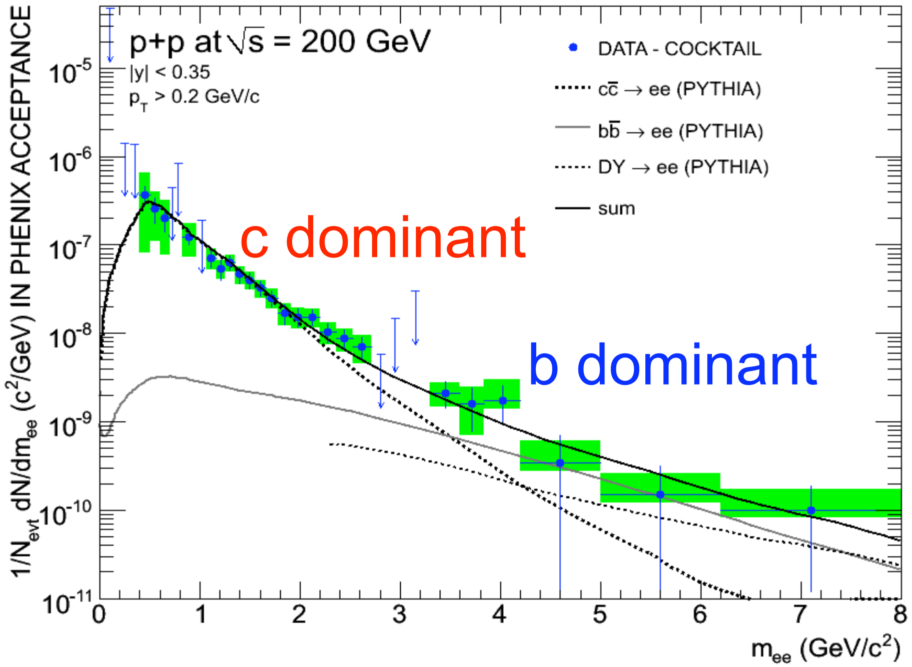
- Result consistent with NLO pQCD (large uncertainties; primarily from scale choice and parton density functions)

Di-electron measurement in PHENIX

Phys. Lett. B670, 313 (2009)



after subtraction of cocktail



- "Cocktail" of backgrounds constructed from measured background sources
- Comparison to charm, bottom and Drell-Yan from PYTHIA

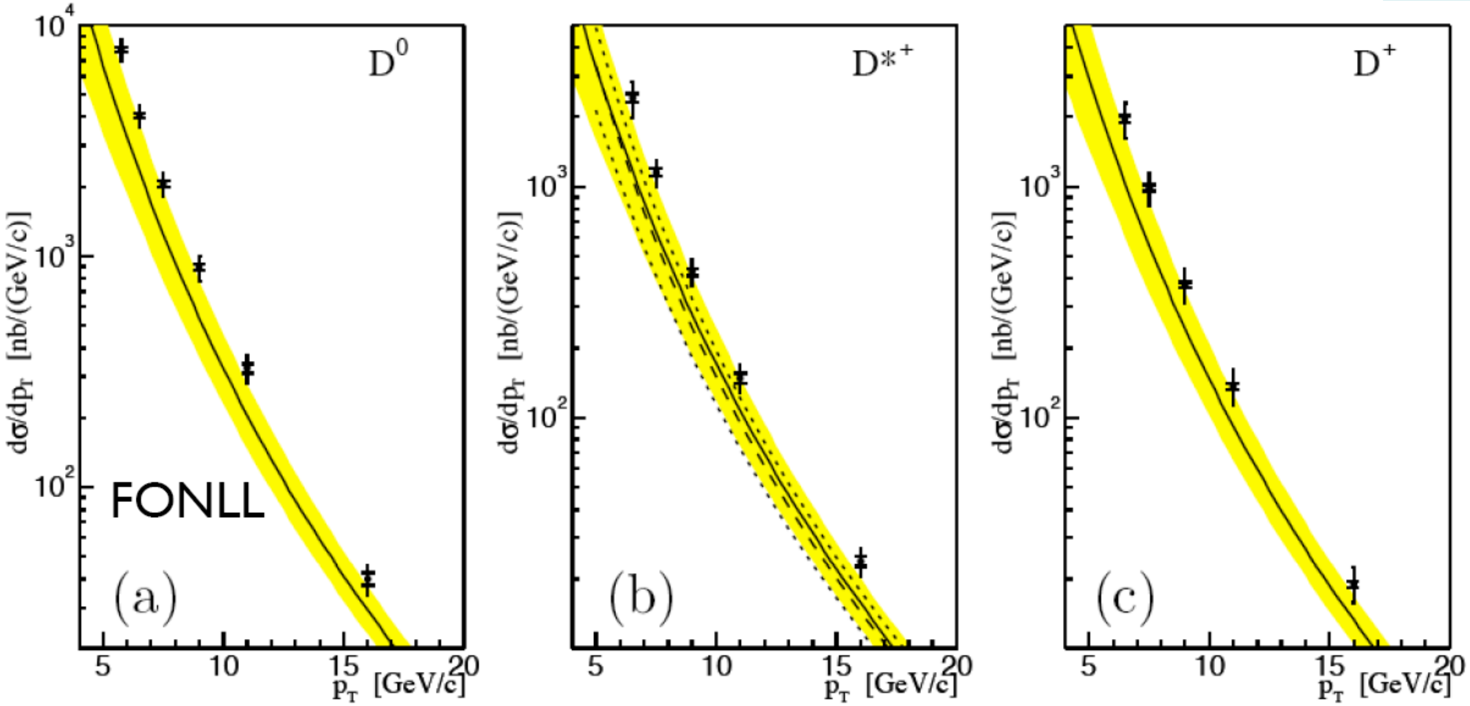
  σ_{cc}= 518 ± 47(stat) ± 135(sys) ± 190(model) μb

  σ_{bb}= 3.9 ± 2.4(stat) +3/-2(sys) μb
- In good agreement with single electrons *Phys. Rev. Lett. 103, 082002 (2009)*

Open-charmed meson spectra from CDF

$p\bar{p}$ @ 1.96 TeV
5.8 pb^{-1}

CDF Run II   c → D data   [PRL 91:241804,2003]

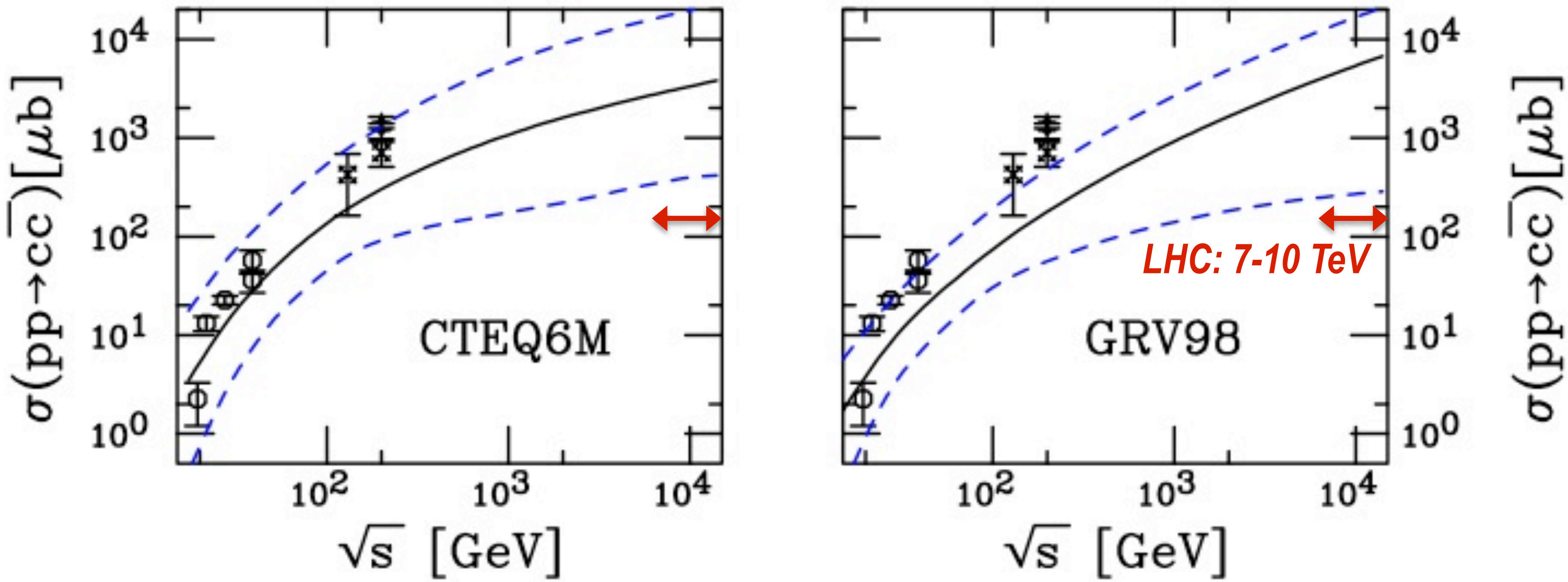


• Deviation of 50-100% at moderate and high-p_T, but consistent within errors

• Theoretically not fully understood …even in *pp* collisions

Charm production cross section

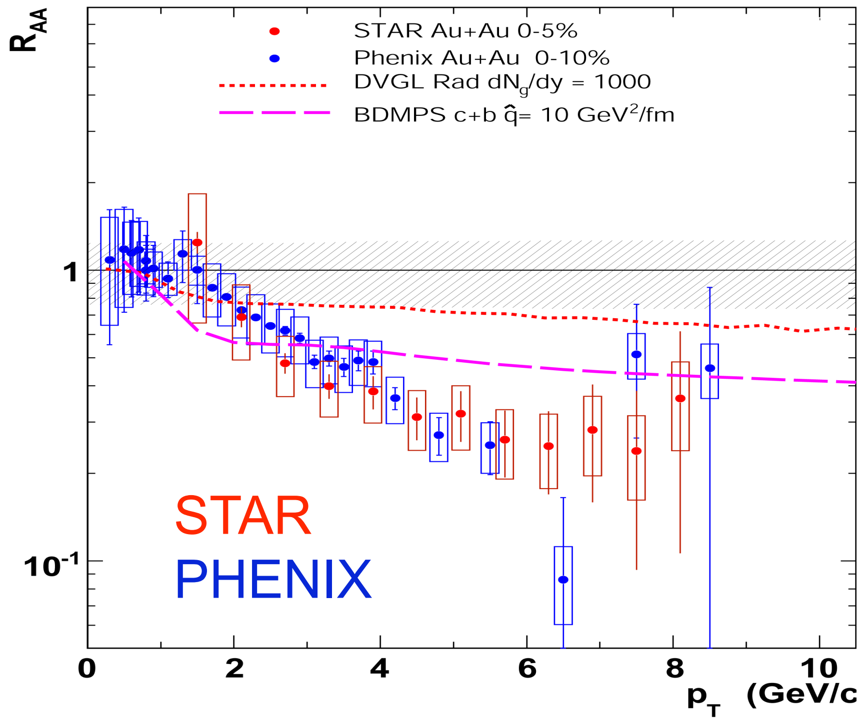
NLO pQCD, CTEQ6M parton densities
R. Vogt, private communication, 2009

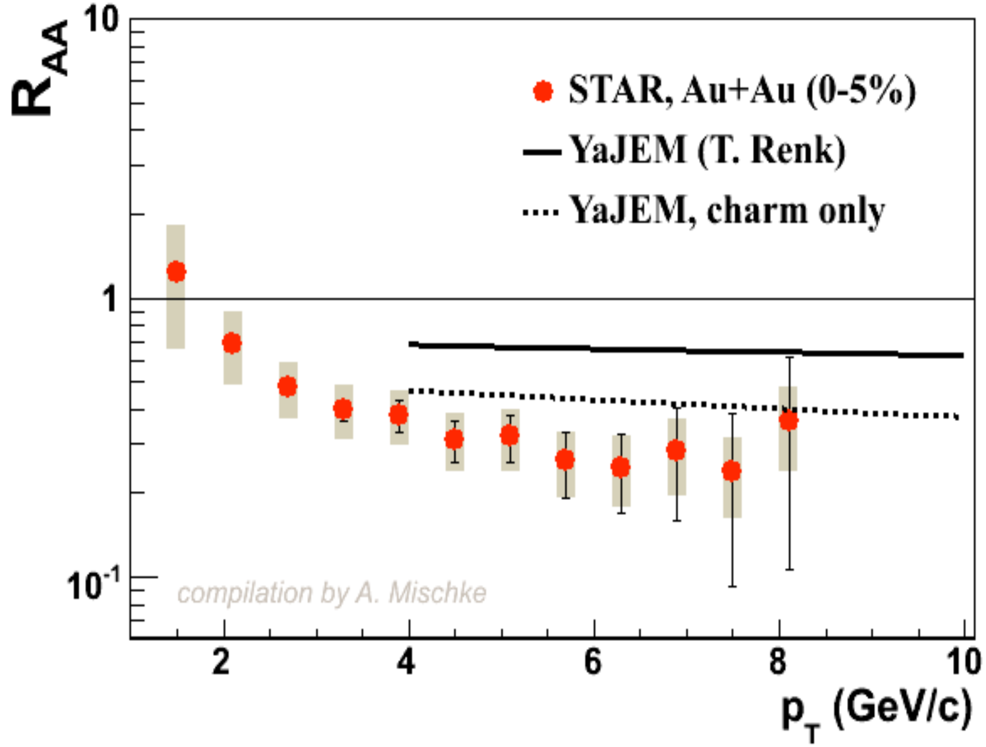


- Large uncertainties → more data needed to constrain model parameters
- Parton spectra from pQCD input for energy loss models

Single electron R_{AA}

One of the most surprising results from RHIC



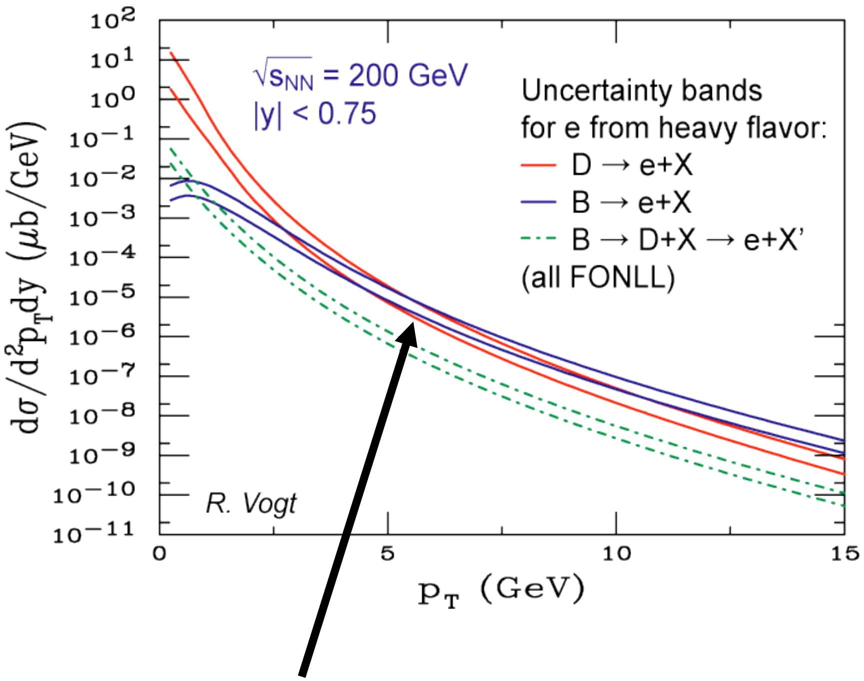


- Electron yield at high-p_T stronger suppressed than expected
- Models implying D and B energy loss are inconclusive yet
- Large suppression requires extreme conditions

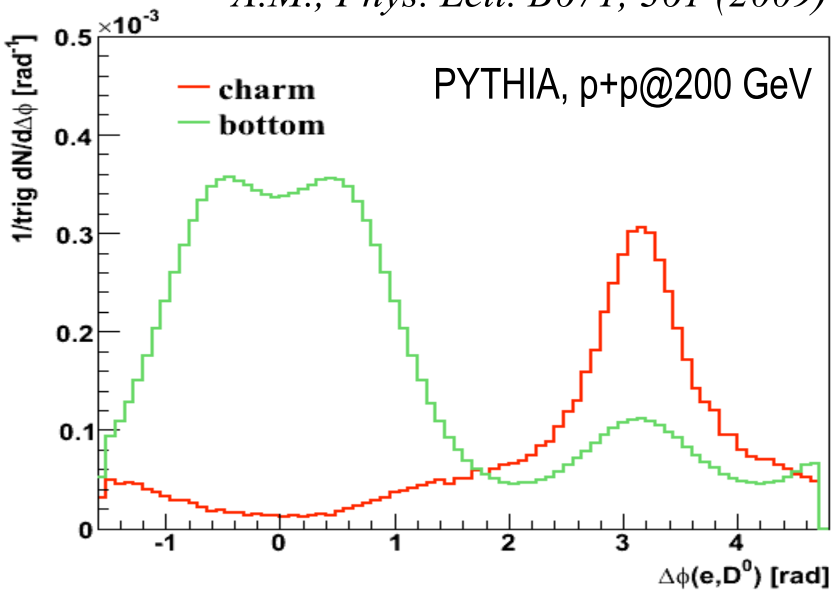
calculation using DGLV formalism: dN_g/dy = 3500

Bottom contribution to single electrons

M. Cacciari et al., PRL 95, 122001 (2005)



A.M., Phys. Lett. B671, 361 (2009)

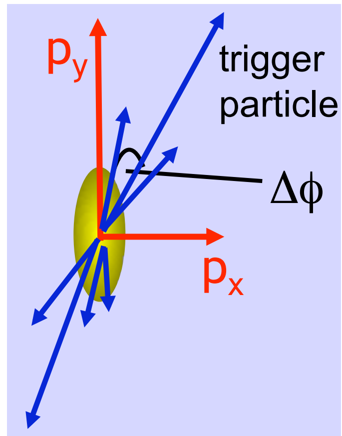


- NLO pQCD: large uncertainty in D/B meson crossing point: $3 < p_T < 10$ GeV/c
- Separate D and B contribution experimentally

Electron – D^0 meson azimuthal angular correlations

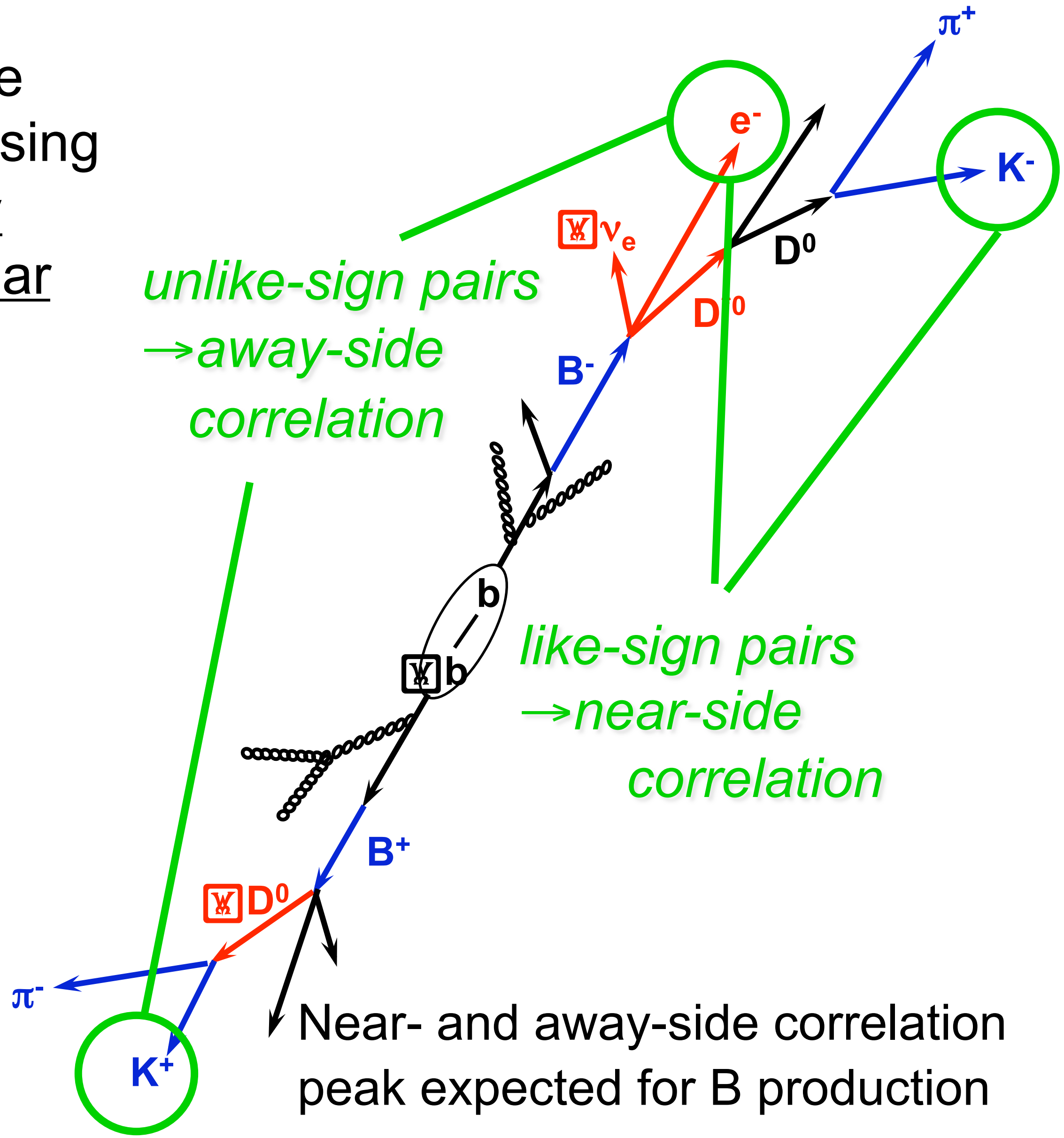
- near-side ($\Delta\phi \approx 0$): bottom dominant

- away-side ($\Delta\phi \approx \pi$): charm dominant



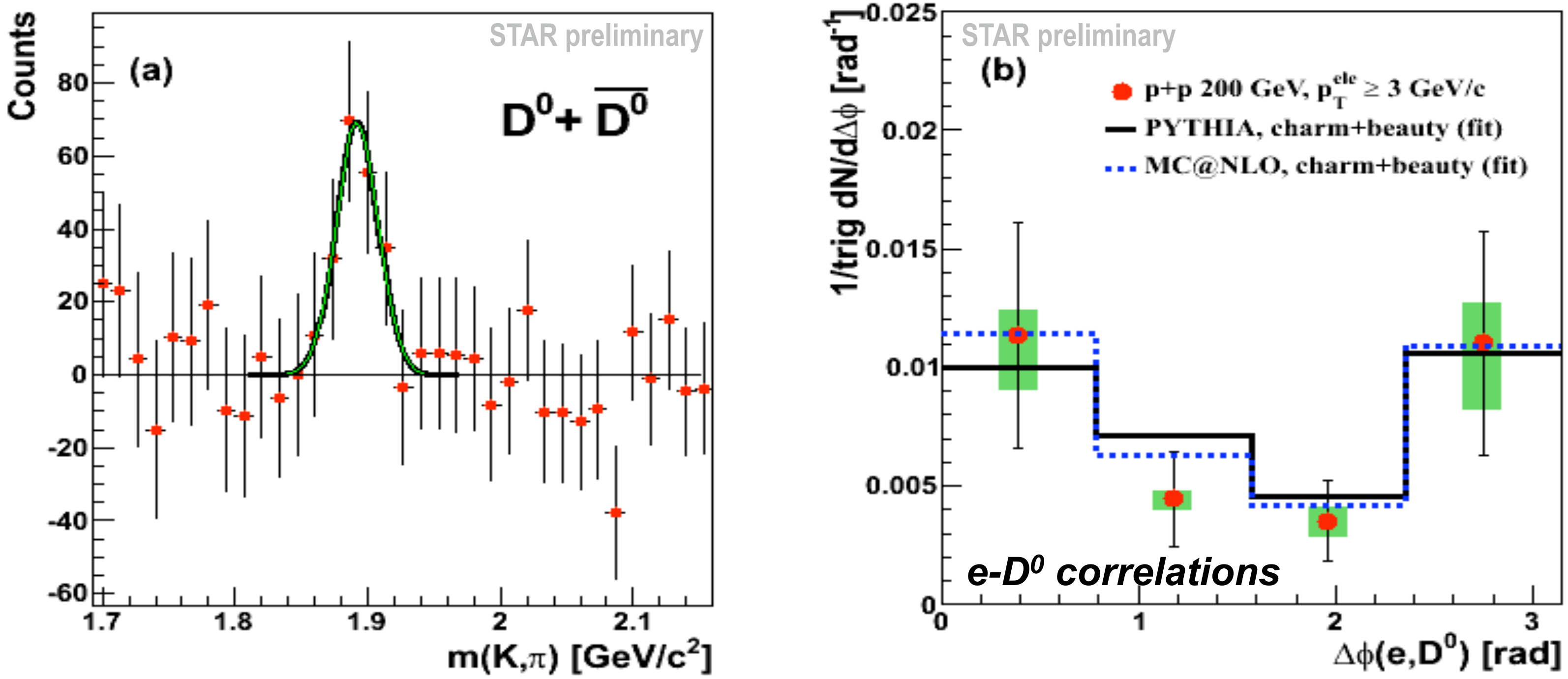
Electron tagged correlations

Identify and separate charm and bottom using their <u>decay topology</u> and <u>azimuthal angular correlation</u> of their decay products



Heavy-flavour particle correlations in STAR

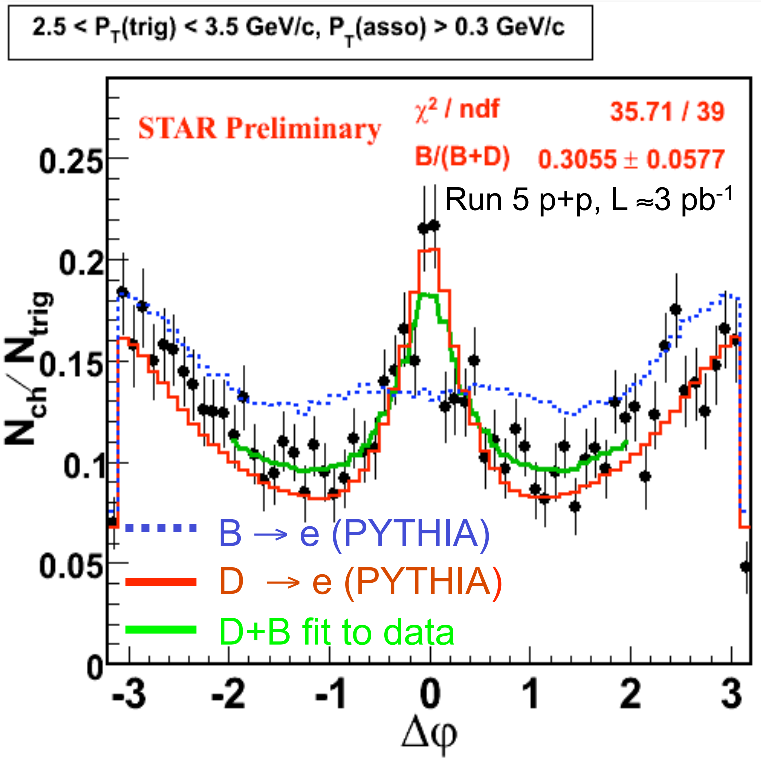
p+p@200 GeV

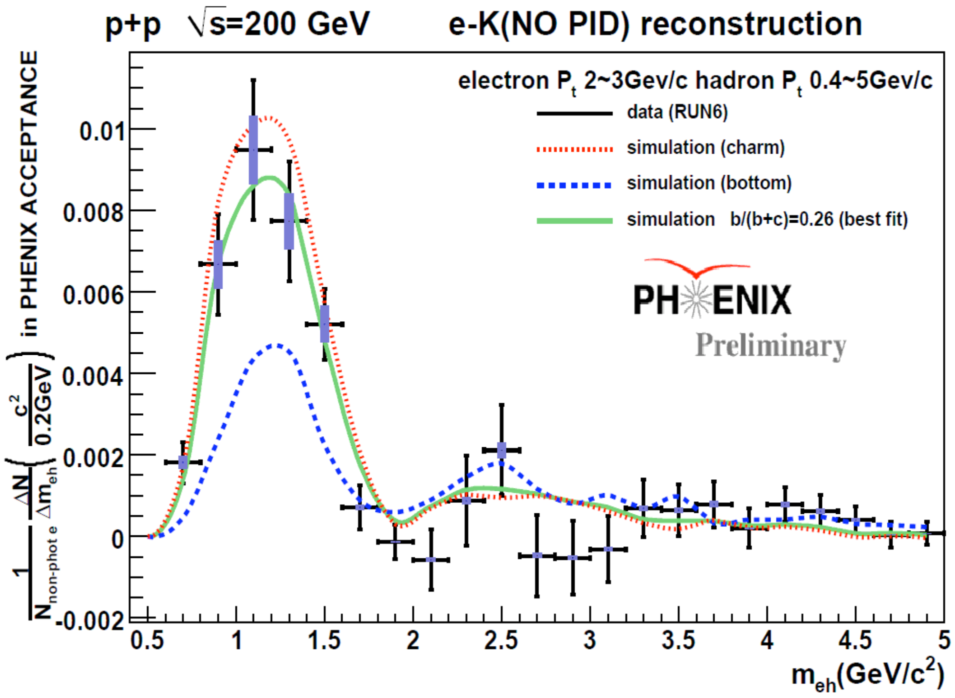


A.M. et al., Eur. Phys. J. A38 (2008); J. Phys. G35, 104117 (2008)

- Near-side correlation yield essentially from B decays only
- Away-side: ≈75% from charm and ≈25% from beauty

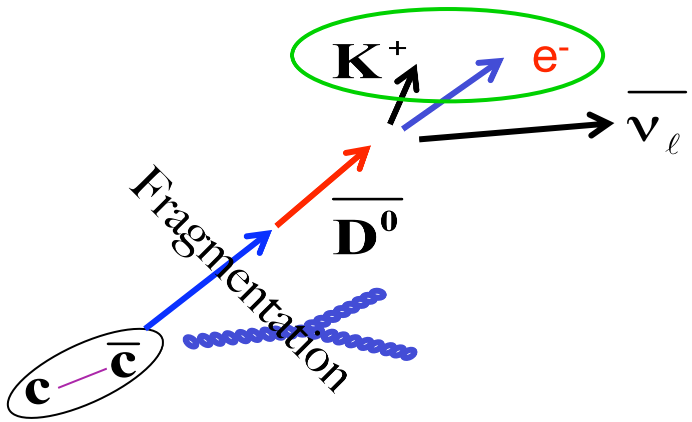
Electron-hadron azimuthal correlations



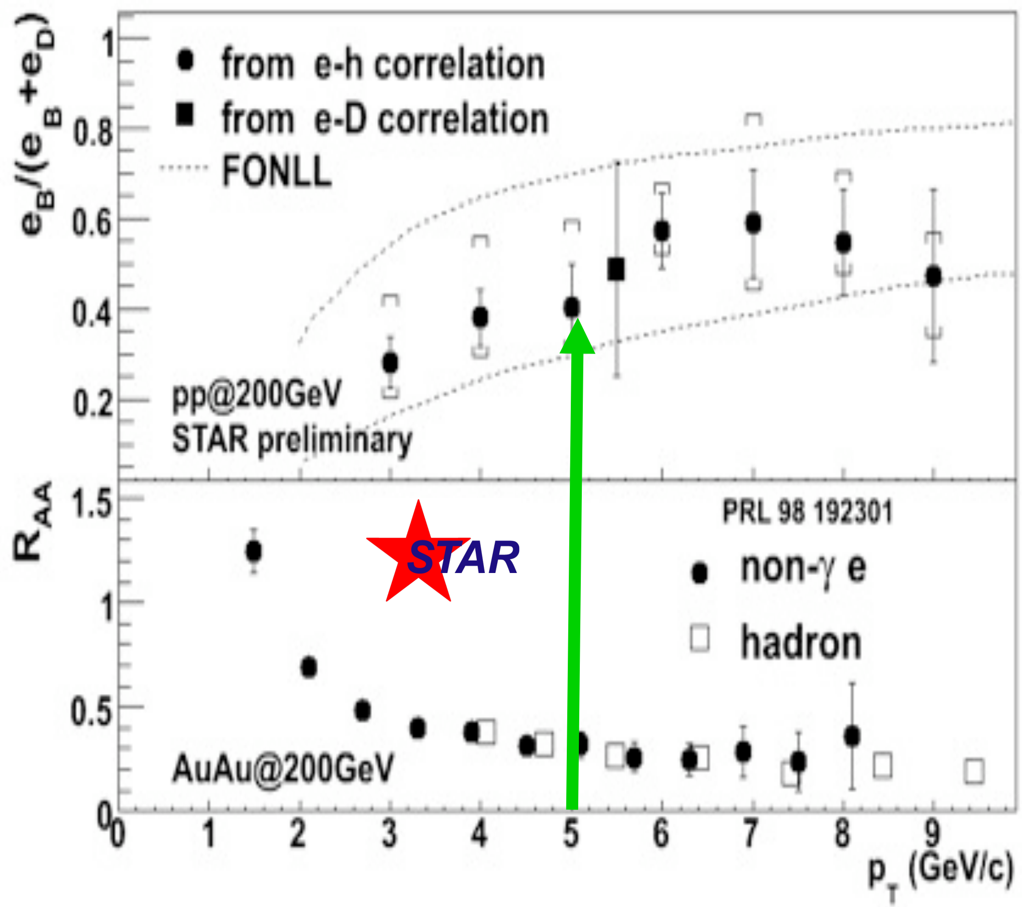


- Exploit different fragmentation of associated jets
- Extraction of relative B contribution using PYTHIA:

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



Relative bottom contribution to single electrons

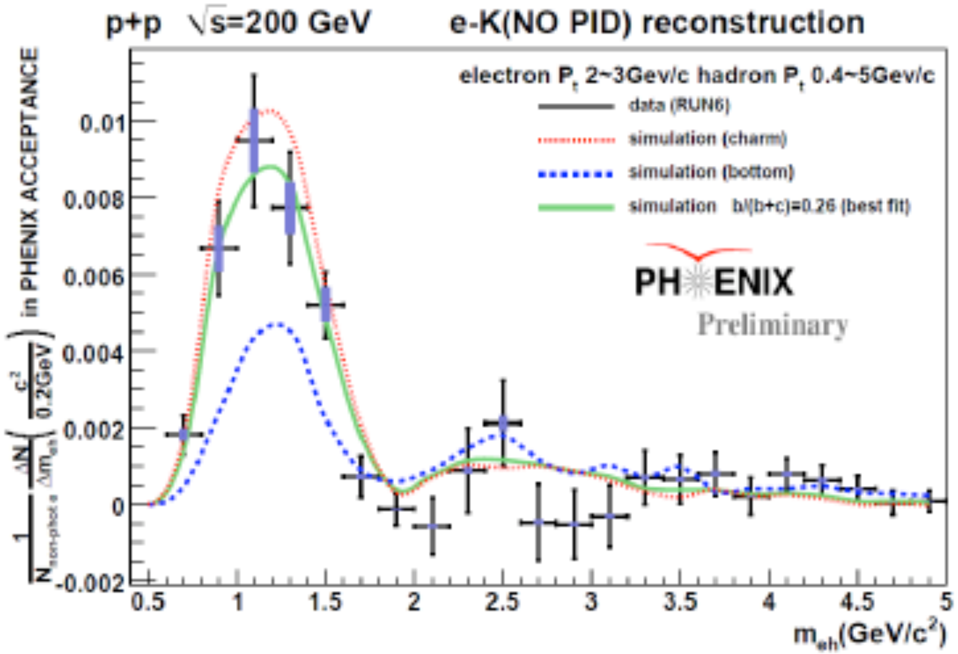


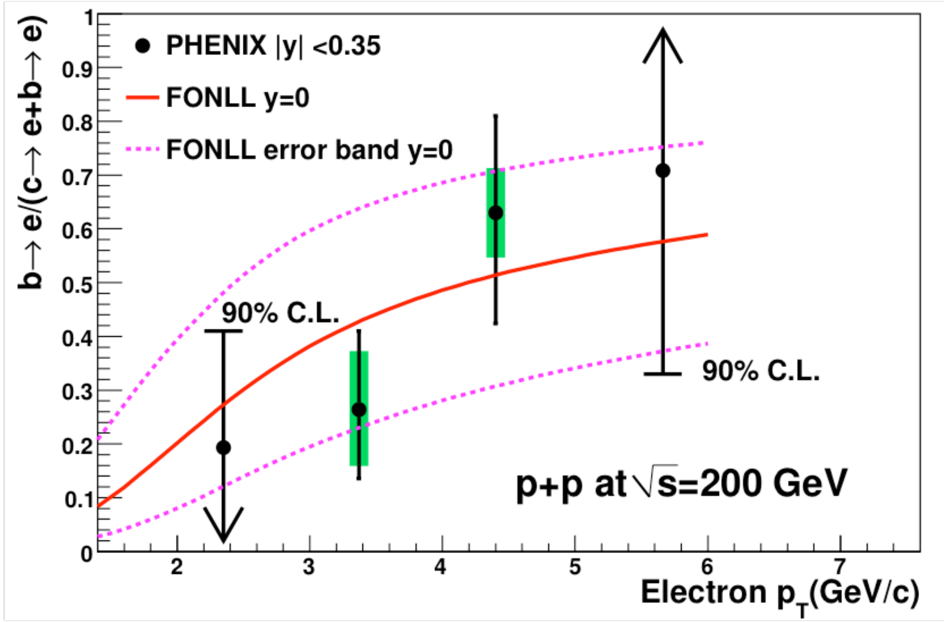
J. Phys. G35, 104117 (2008)

- B and D contributions comparable at p_T > 5 GeV/c and consistent with FONLL
- Similar result from PHENIX (PRL 103, 082002)
- Bottom stronger suppressed than expected?

Electron-hadron correlations in PHENIX

p+p@200 GeV

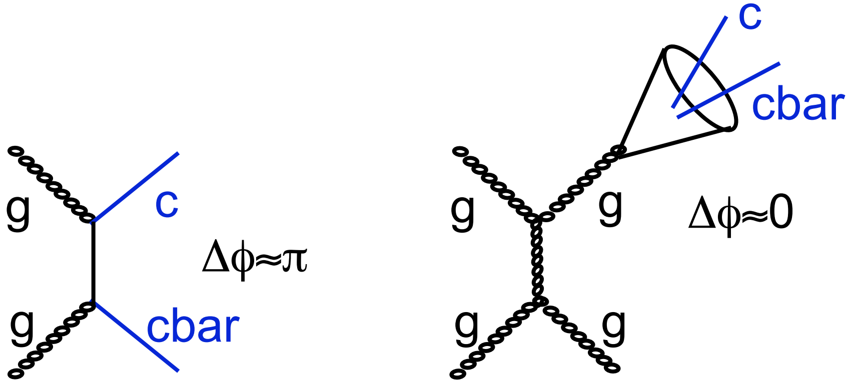




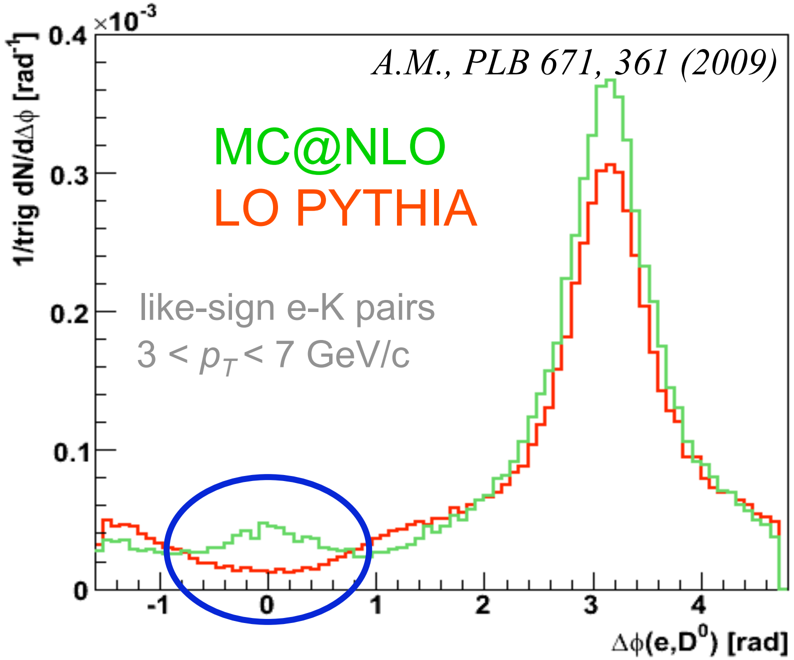
Phys. Rev. Lett.103, 082002 (2009)

- Use e-K invariant mass
- Statistics limited

NLO processes: gluon splitting



flavor creation (LO) **gluon splitting (NLO)**

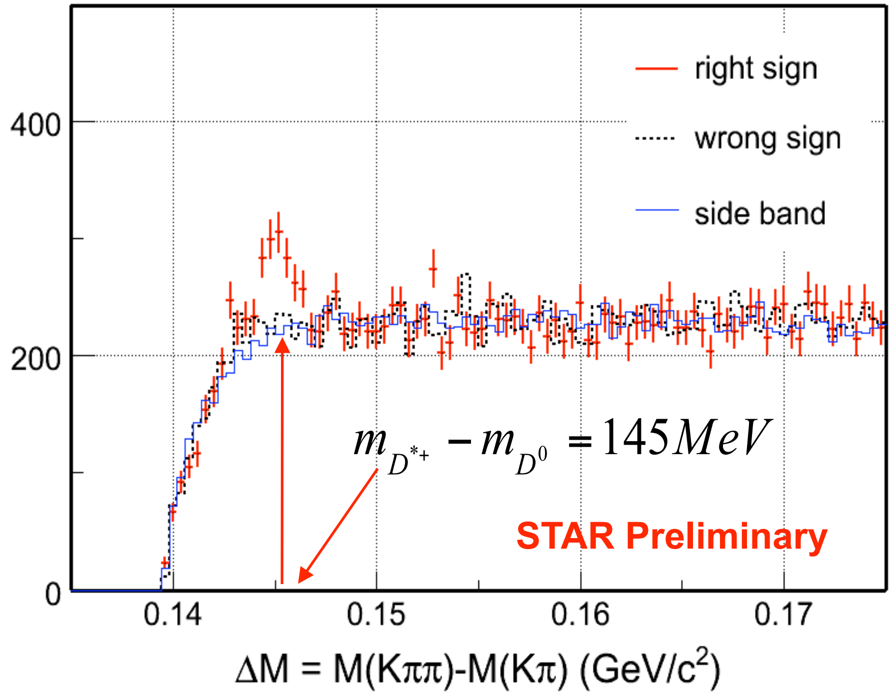


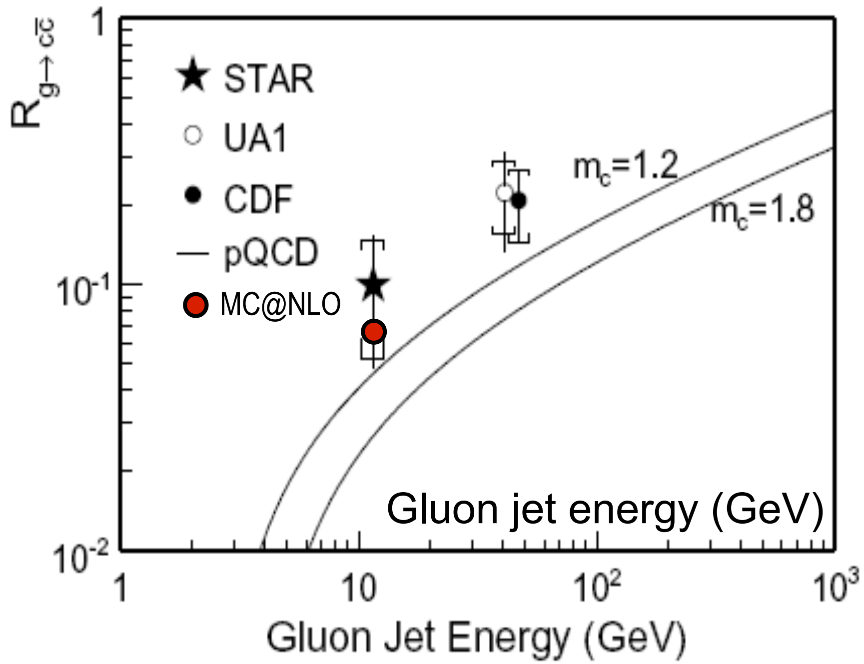
- Estimated using e-D0 azimuthal correlations in p+p at 200 GeV in MC@NLO computation

- Away-side peak: Good agreement of peak shape between LO PYTHIA and MC@NLO

- Near-side peak: GS/FC (6.5±0.5)% → small gluon splitting contribution

"D* in jet" measurement in STAR





- Access to charm content in jets
- Gluon splitting rate to total ccbar production consistent with pQCD and MC@NLO
- Gluon splitting contribution to total charm production ~6%

Summary

• Heavy quarks are particularly good probes to study the properties of hot QCD matter (especially transport properties)

• Energy loss of heavy quarks in the medium larger than expected → energy loss mechanism not fully understood yet
- bottom stronger suppressed as expected?

• Electron-h/D^0 azimuthal correlations

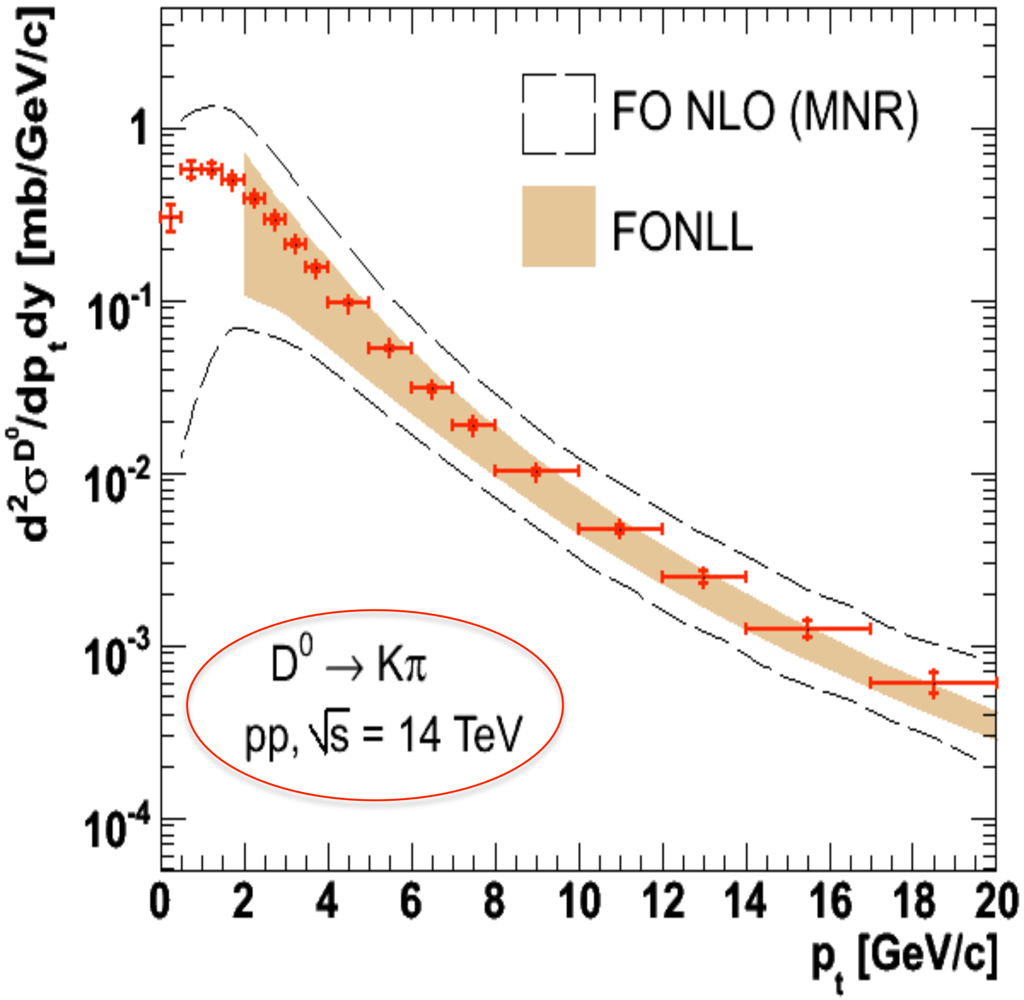
- experimental access to charm and bottom contributions
- small gluon-splitting contribution
- bottom contributes significantly to single electron yields at high p_T

• Heavy-flavor correlation measurements are challenging and need a lot of statistics

• Improve open charm measurements with detector and machine upgrades

Backup

Charm cross section in ALICE at CERN-LHC



- First promising decay channels
  - $D^* \to D^0\pi_s$, $D^0 \to K\pi$, $D^+ \to K^-\pi^+\pi^+$
  - D,B $\to$ e + X

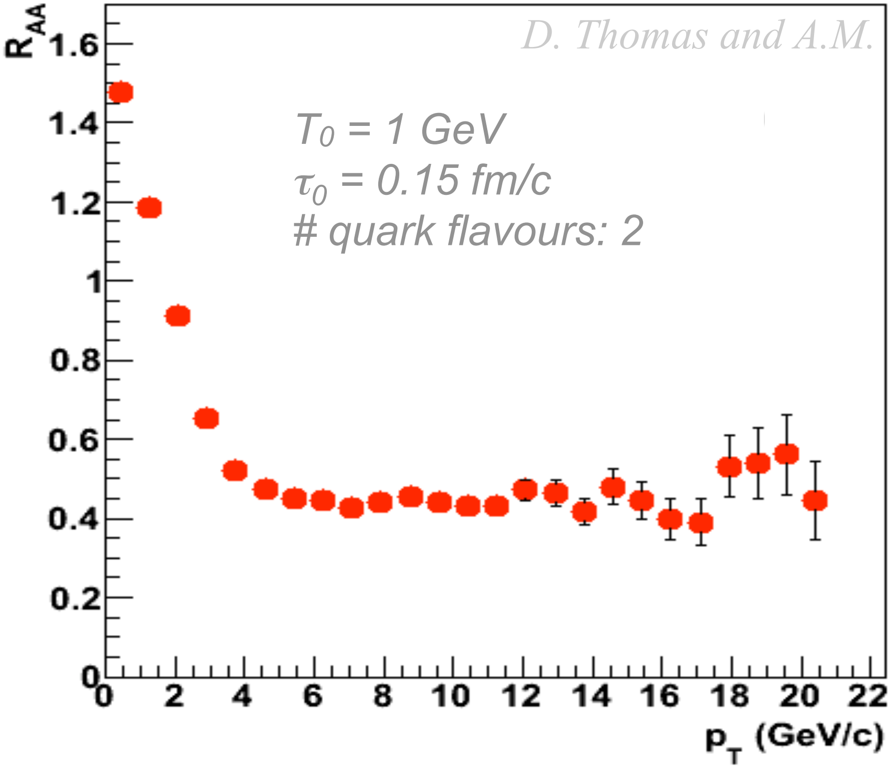
- ALICE has the capability to measure open charm down to p_T = 0 in *pp* and p-Pb (1 GeV/c in Pb-Pb)

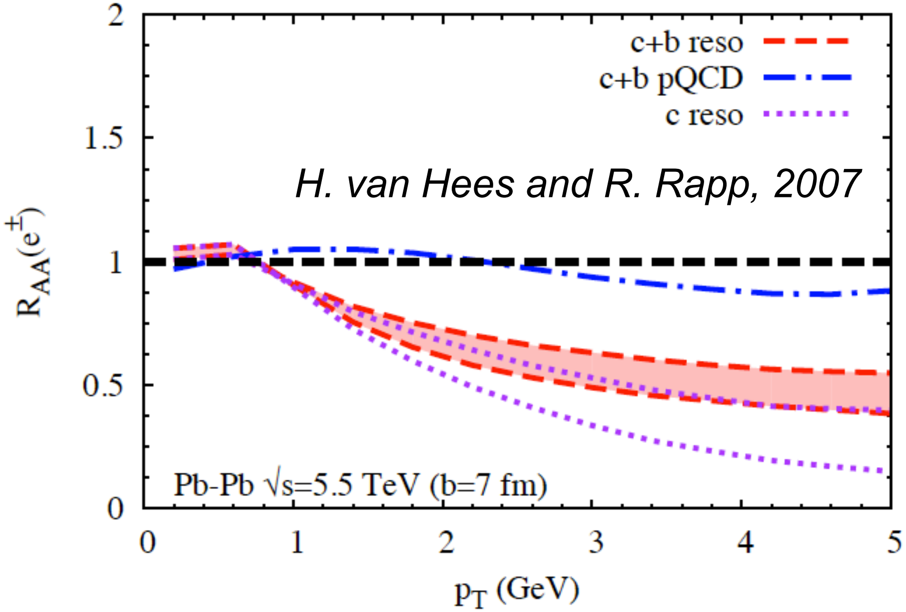
- ITS: impact parameter resolution better than 50 μm for p_T > 1.5 GeV/c

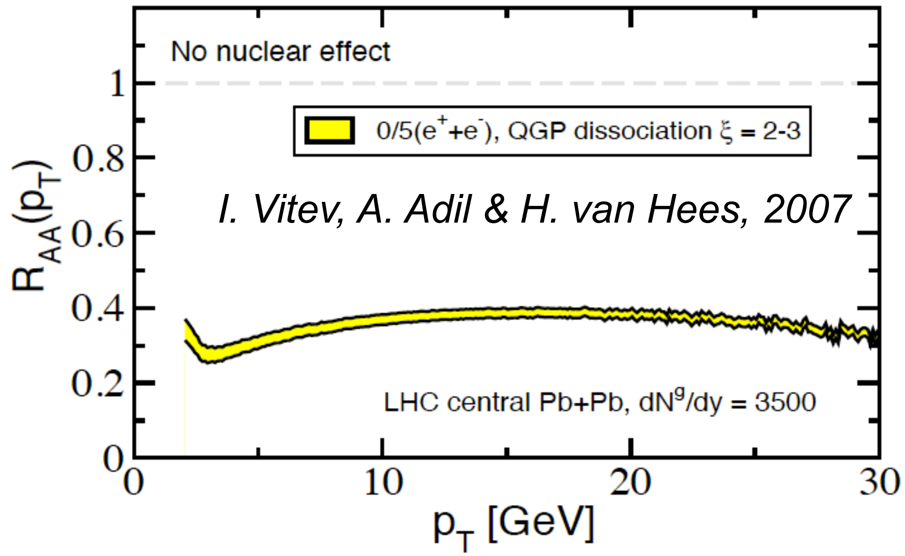
$$\sigma^{c\bar{c}}_{LHC} \approx 25 \times \sigma^{c\bar{c}}_{RHIC}$$
$$\sigma^{b\bar{b}}_{LHC} \approx 100 \times \sigma^{b\bar{b}}_{RHIC}$$

Single electron R_{AA} at CERN-LHC

Pyquen: Pb+Pb(5%) @ 5.5 TeV







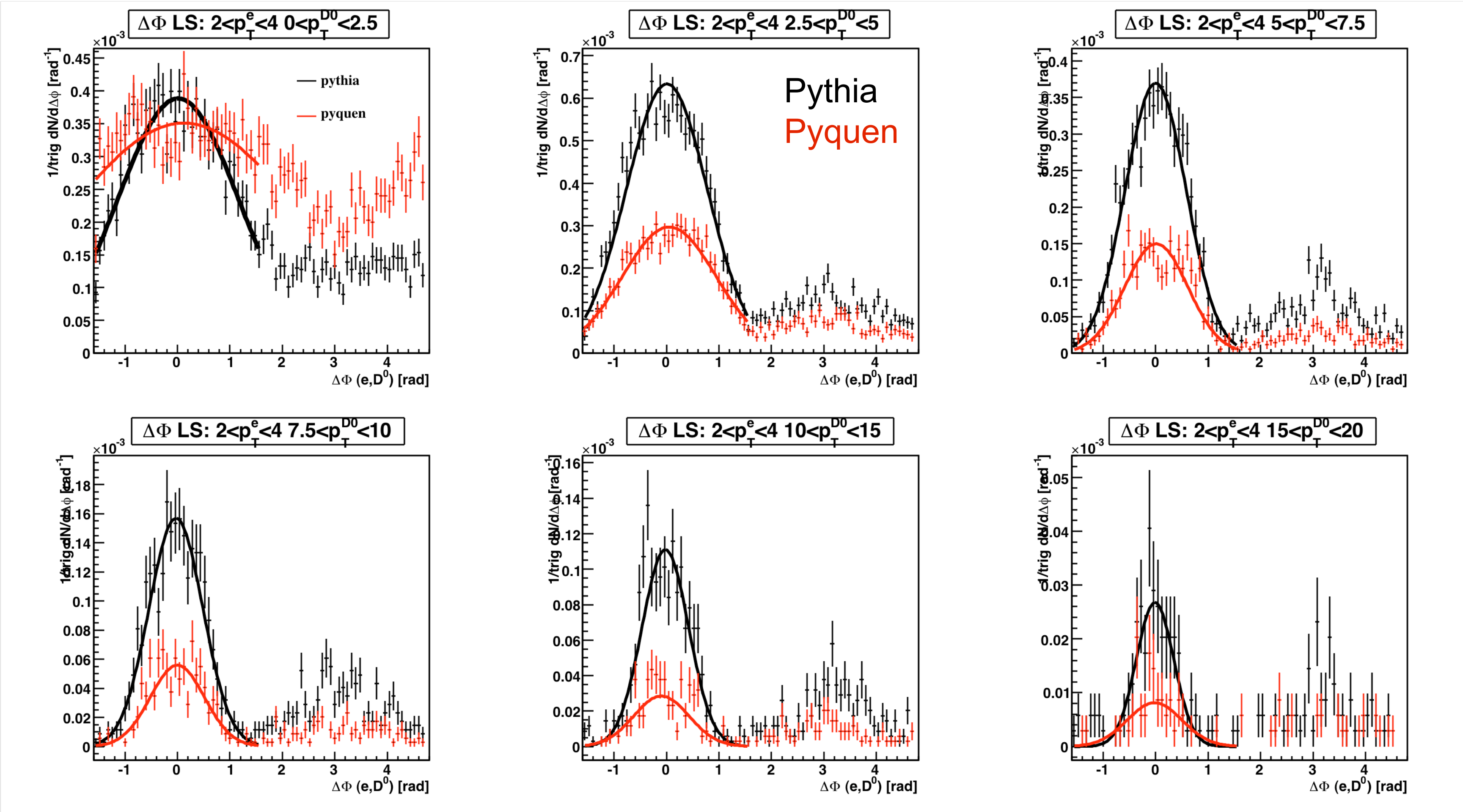
Pyquen

- Pythia afterburner
- Radiative (generalisation of BDMPS) and collisional energy loss (high-pT approximation)

Single electron – D^0 angular correlations

$2 < p_T^{trigger\ ele} < 4$ GeV/c

Pyquen: Pb+Pb(5%) @ 5.5 TeV



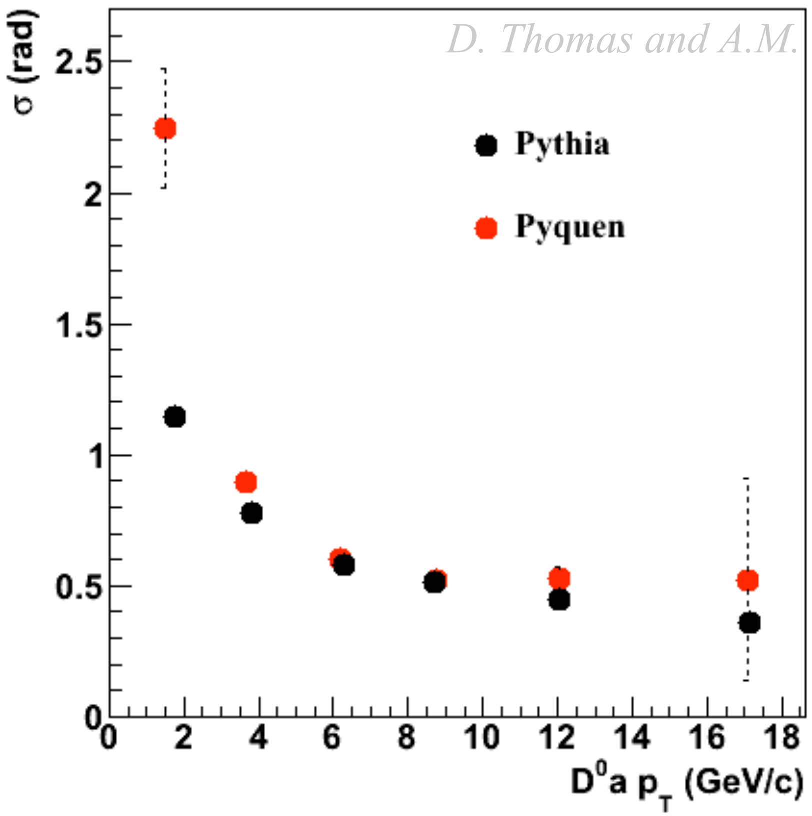
- Near side: B decays + gluon splitting charm
- Away side: charm flavour creation

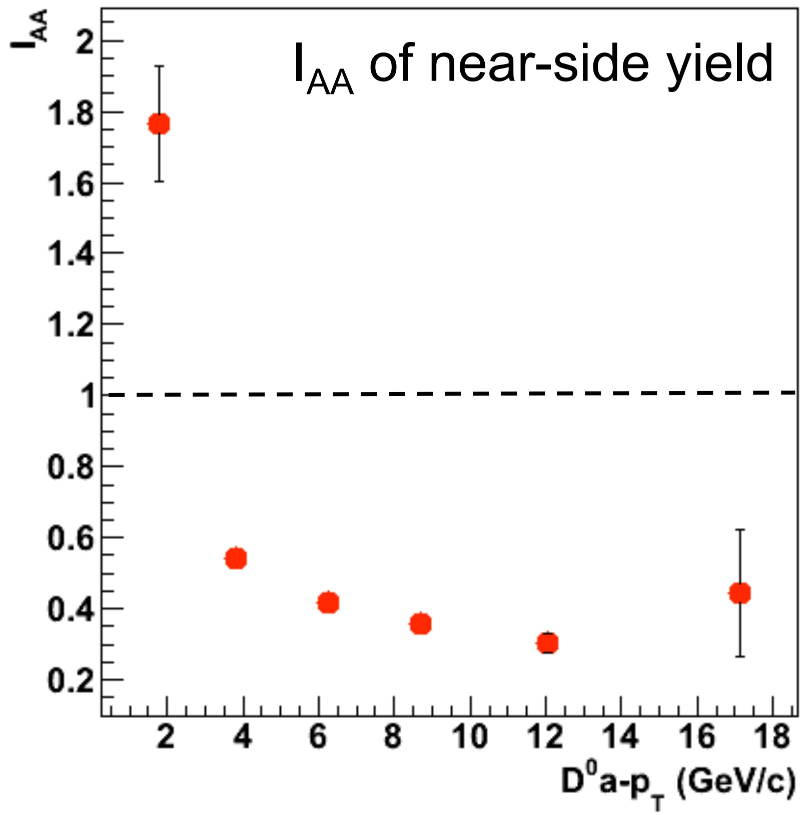
900M events

$\Delta\phi(e, D^0)$: Near-side width and I_{AA}

$2 < p_T^{trigger\ ele} < 4$ GeV/c

Pyquen: Pb+Pb(5%) @ 5.5 TeV



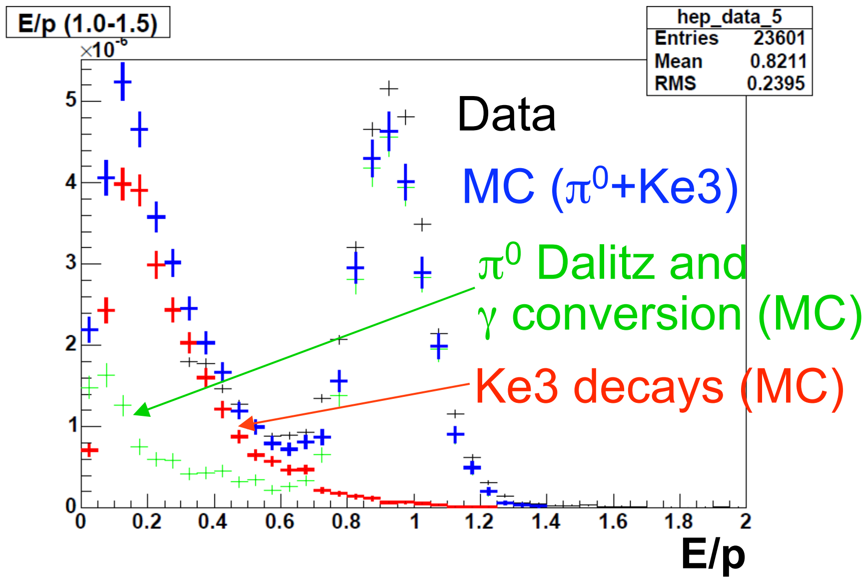


- Broader peak for Pyquen than Pythia
- Suppression of D^0 yield for Pyquen
- Next: fragmentation function

Electron identification

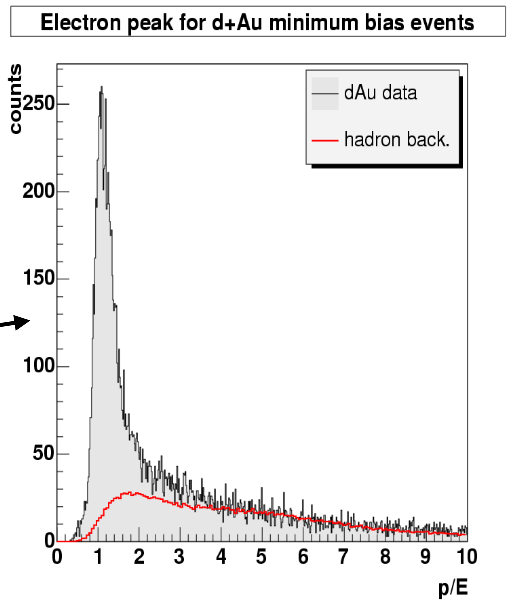
PHENIX

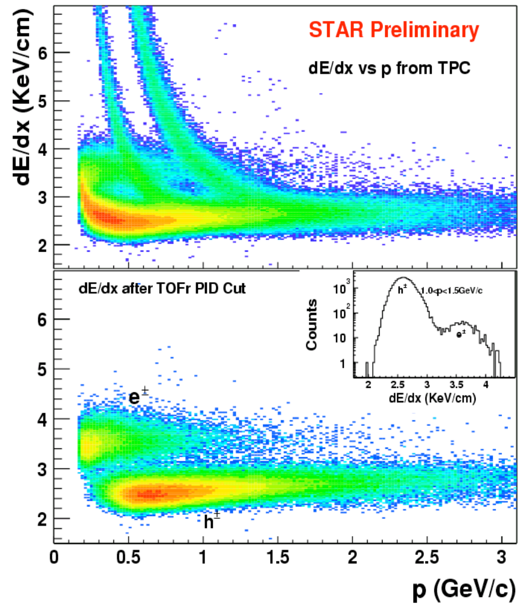
- Electromagnetic calorimeter and RICH at mid rapidity
  - ➢ $p_T < 5$ GeV/c



STAR

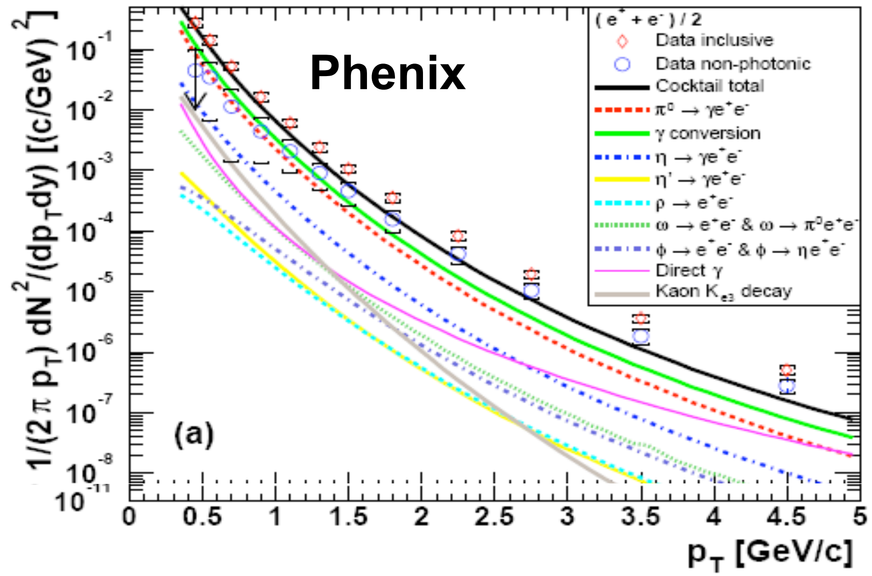
- ToF + TPC
  - ➢ $p_T < 4$ GeV/c
- EMCal + TPC
  - ➢ $p_T > 1.5$ GeV/c

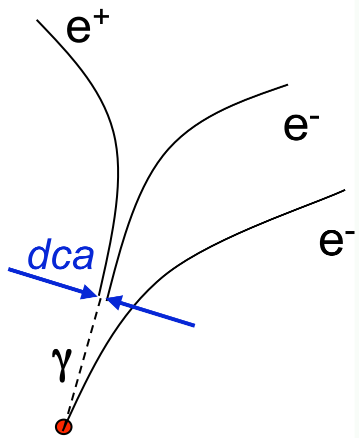


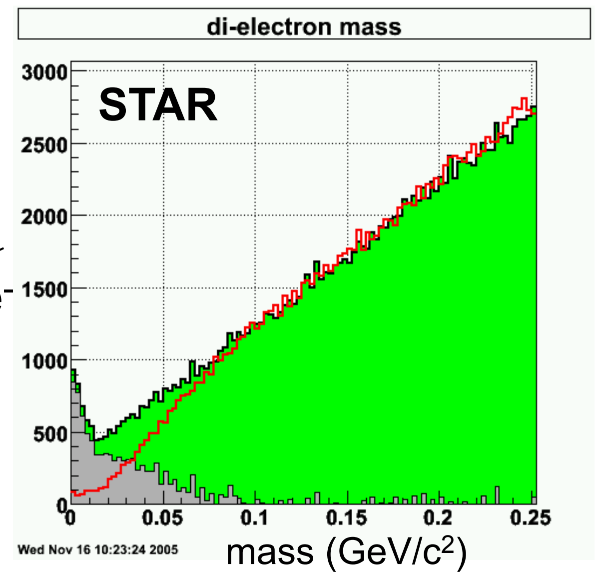


Electron background sources

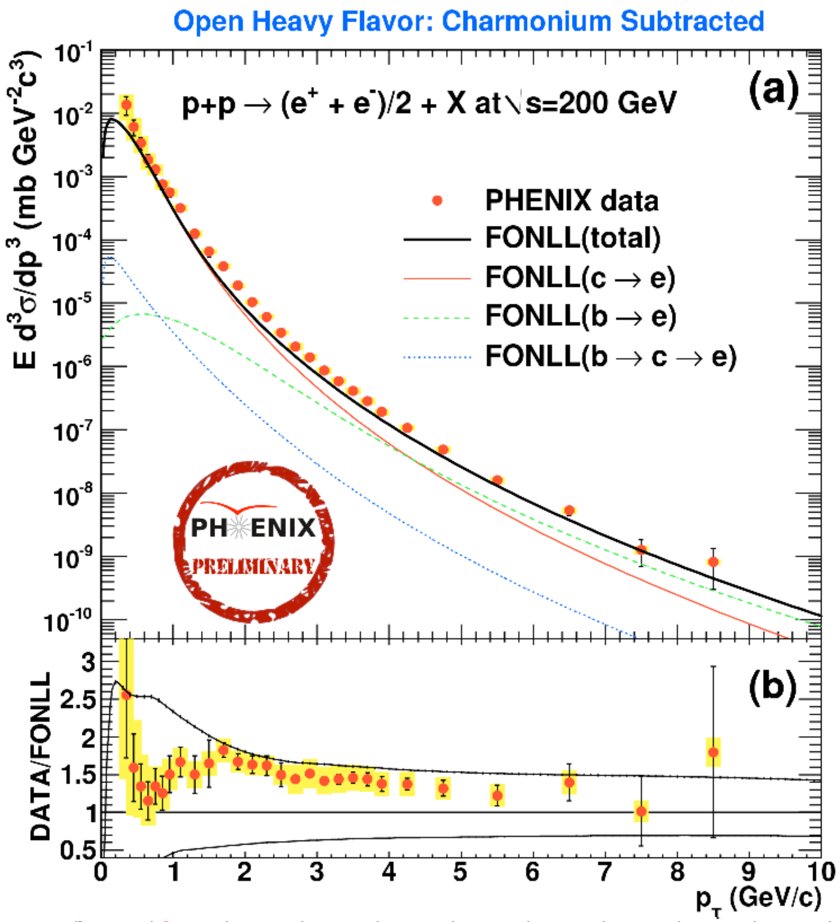
- Photonic electron background
  - $\gamma \rightarrow e^+ + e^-$ (small for Phenix)
  - $\pi^0 \rightarrow \gamma + e^+ + e^-$
  - η, ω, ϕ, etc.
- Phenix is almost material free $\rightarrow$ their background is highly reduced compared to STAR
- Background is subtracted by two independent techniques - very good consistency between them
  - converter method (1.68% X_0)
  - cocktail method
- STAR determines photonic background using invariant mass

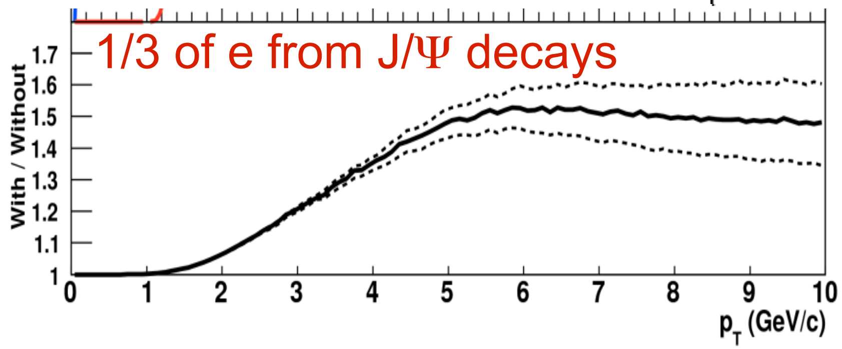






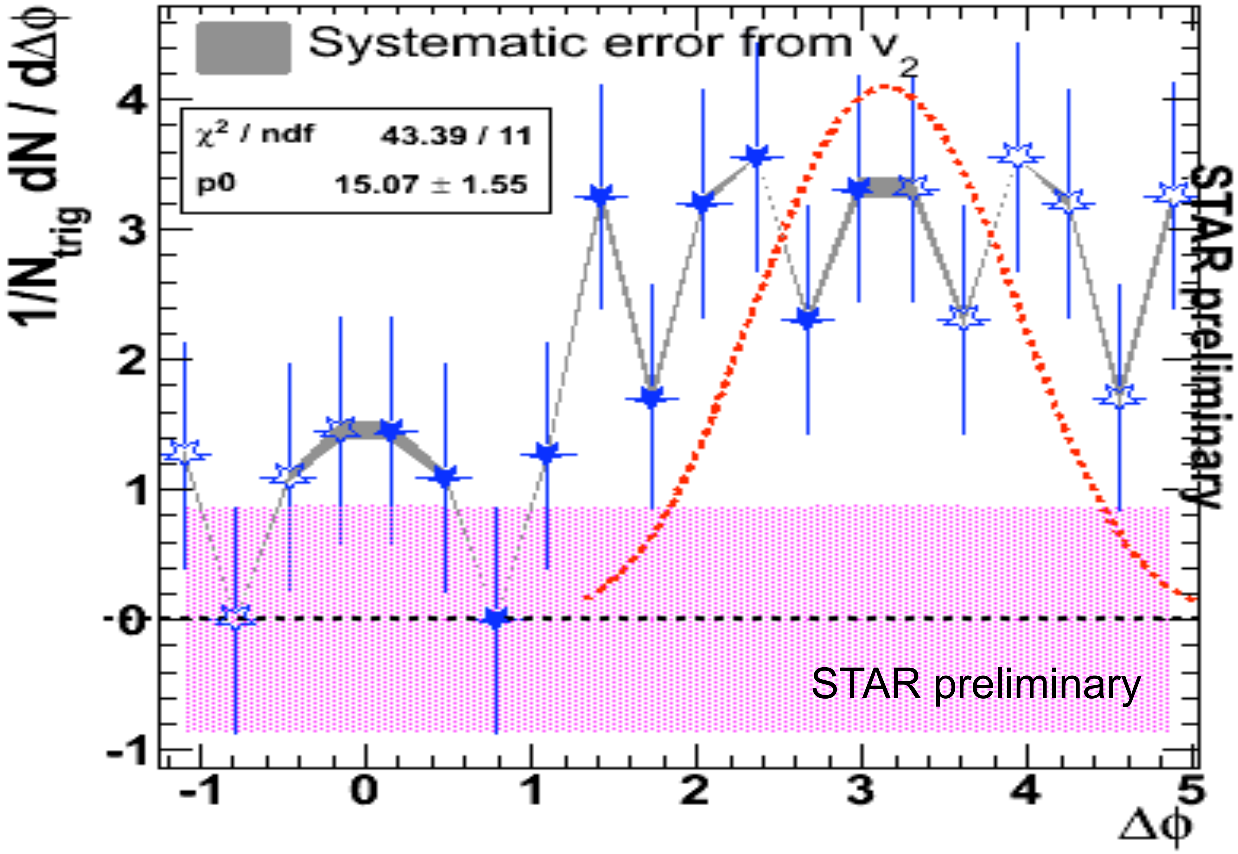
Charmonium contribution to single electrons





- New study takes J/Ψ→ $e^{\pm}$+X contribution into account
- 1/3 of single electrons are from J/Ψ decays for $p_T > 5$ GeV/c → up to 16% decrease in open heavy
- But what is R_{AA} of high-p_T J/Ψ ?
- Background contribution from K^0_s decays may also play a role (especially at low-p_T) → under investigation

Single electron-hadron correlations in Au+Au



- Away-side modification?
- Improved statistics and better background rejection needed
- Similar analysis in PHENIX