Recent heavy flavor results from STAR

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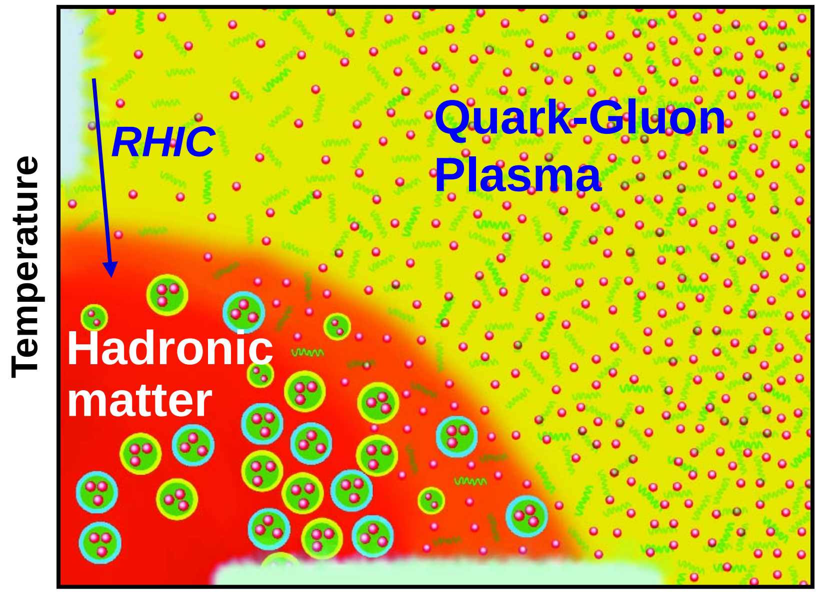
Outline

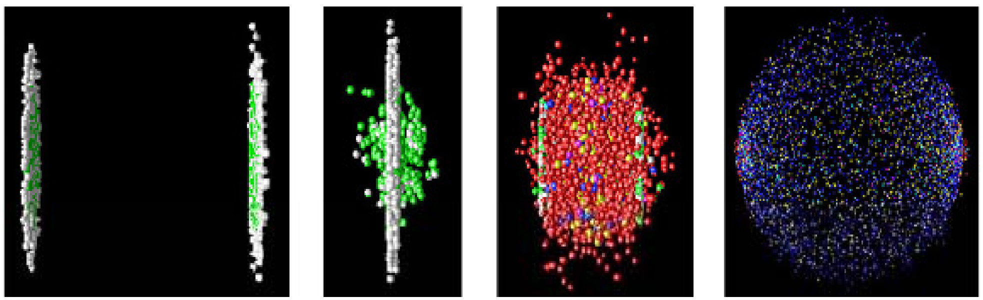
- Introduction: The Heavy-ion program
- The STAR experiment at RHIC
- Heavy flavor (charm and bottom) production and in-medium energy loss
- A selection of current results
  - Charm cross-section
  - Energy loss measurements using non-photonic electrons from semi-leptonic heavy flavor decays
  - Disentangle charm and bottom via electron – hadron / D^0 correlations
  - Quarkonia (Υ)
  - First results on D_s^+
- Summary and conclusions

Matter in extremes: the QGP

QCD phase diagram of nuclear matter



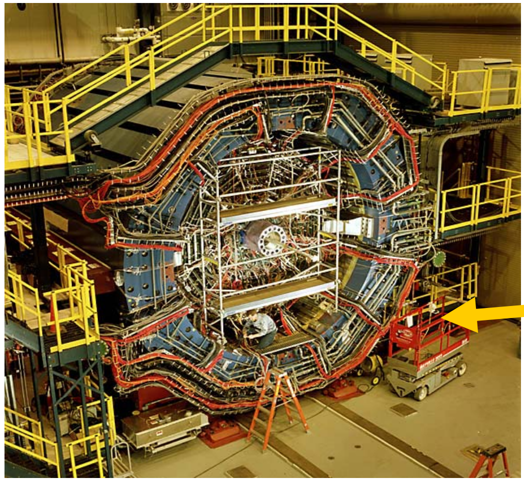
High energy heavy-ion collision



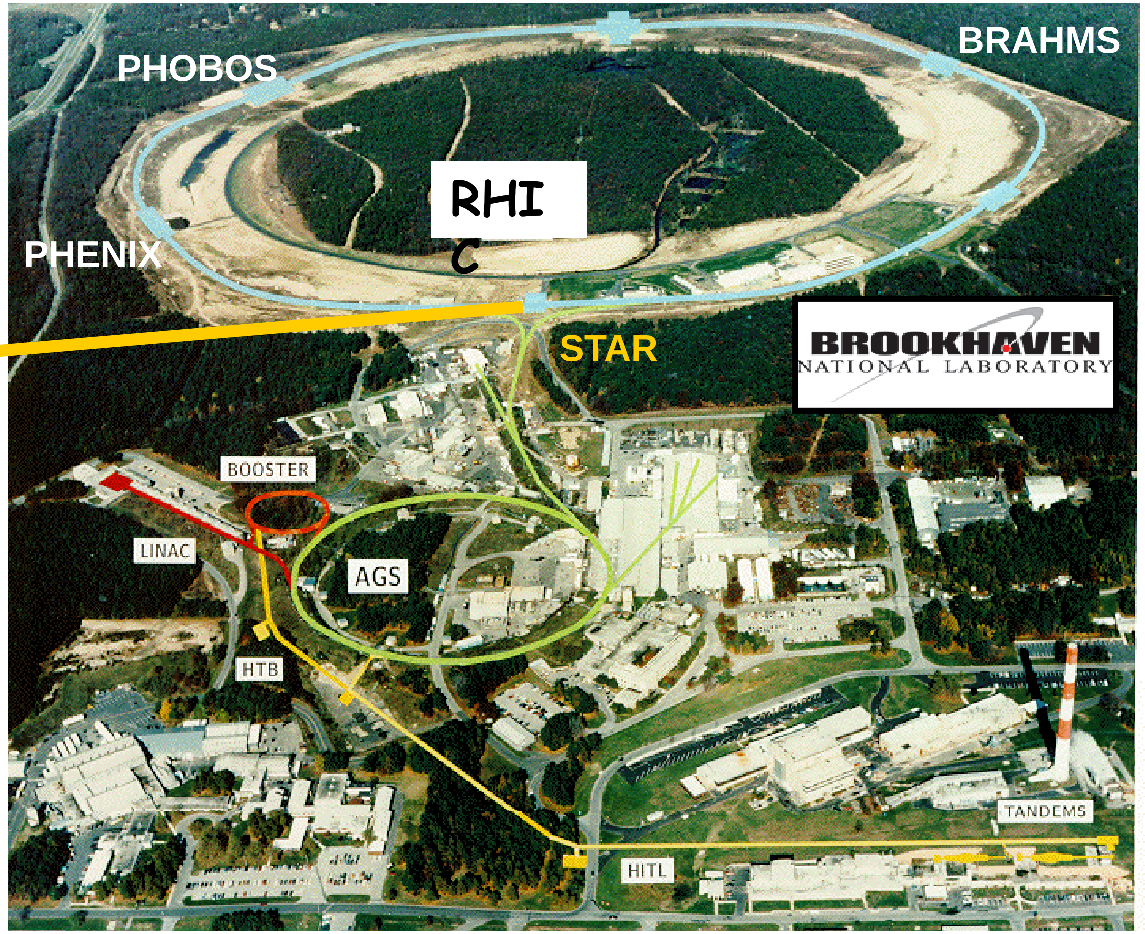
- Study strongly interacting matter under extreme conditions
- Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the Quark-Gluon Plasma
- At RHIC energies: Partons are expected to loose energy in the hot and dense QCD matter

The RHIC accelerator at BNL

STAR detector



Relativistic heavy-ion collider facility



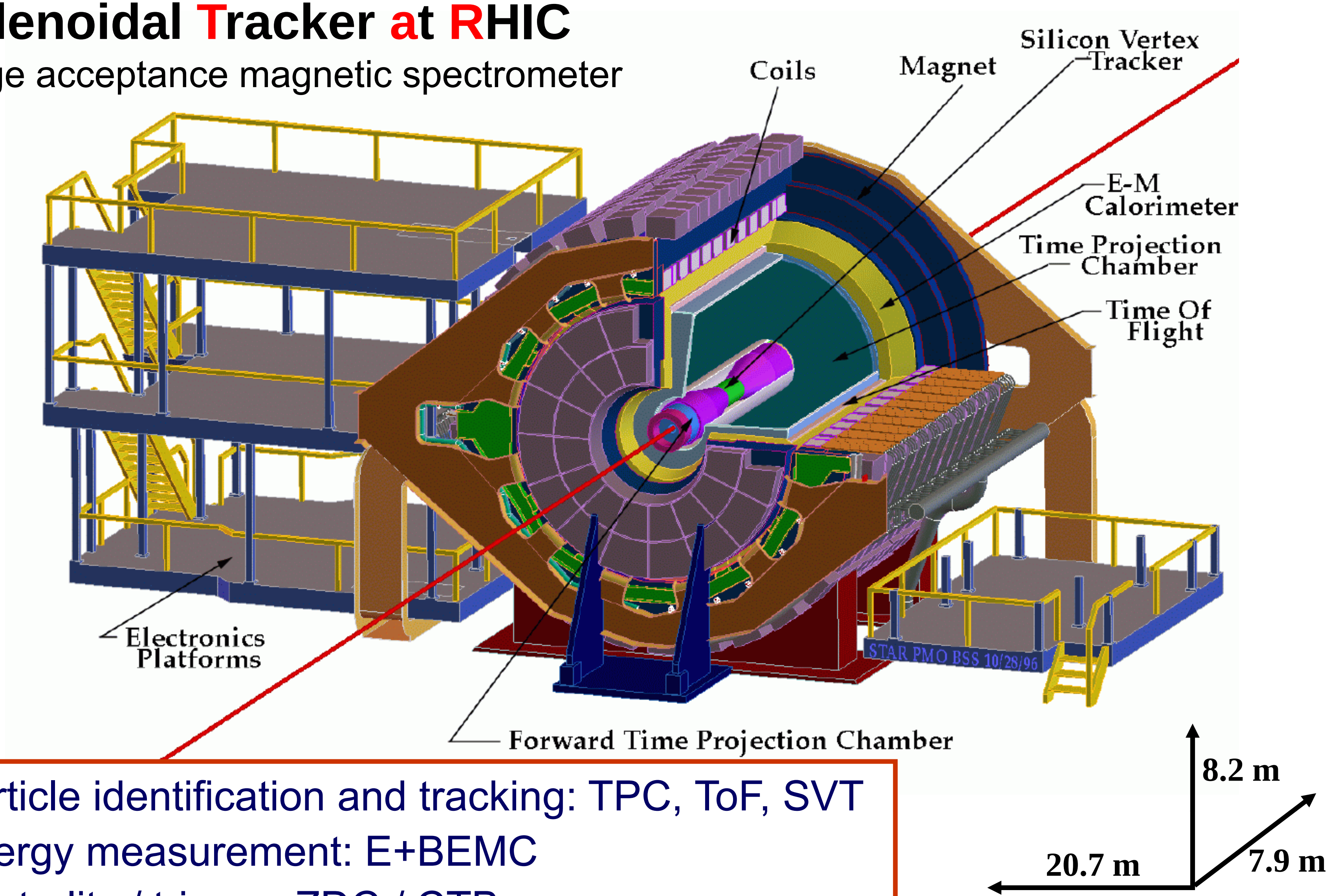
- Au+Au, $\sqrt{s_{NN}}$ = 19.6, 62.4, 130, 200 GeV
- Cu+Cu, $\sqrt{s_{NN}}$ = 200 GeV
- d+Au, $\sqrt{s_{NN}}$ = 200 GeV
- polarized p+p, $\sqrt{s}$ = 200 GeV

Two concentric rings, 3.8 km circumference, counter-rotating ion beams, 6 collisions points

The STAR detector

Solenoidal Tracker at RHIC

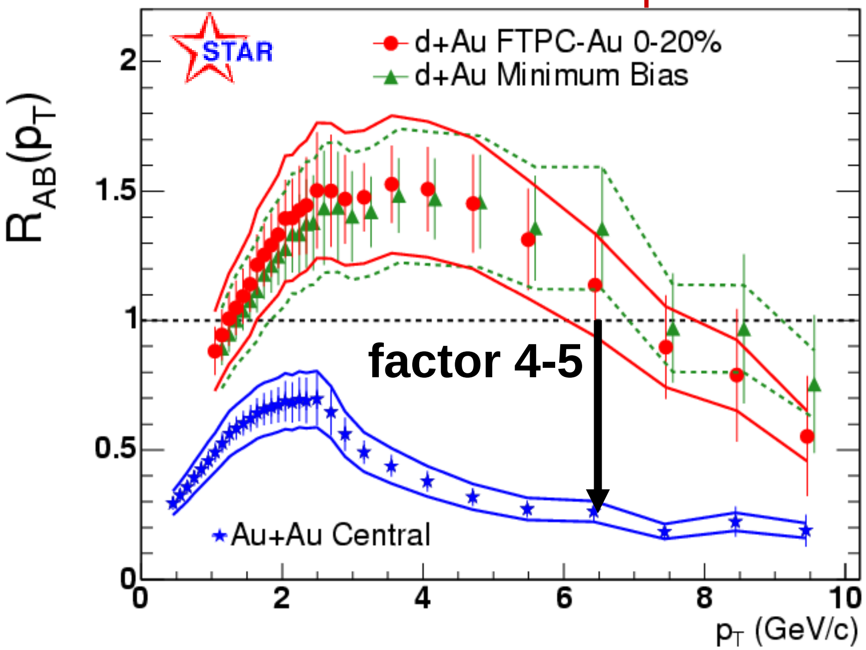
Large acceptance magnetic spectrometer



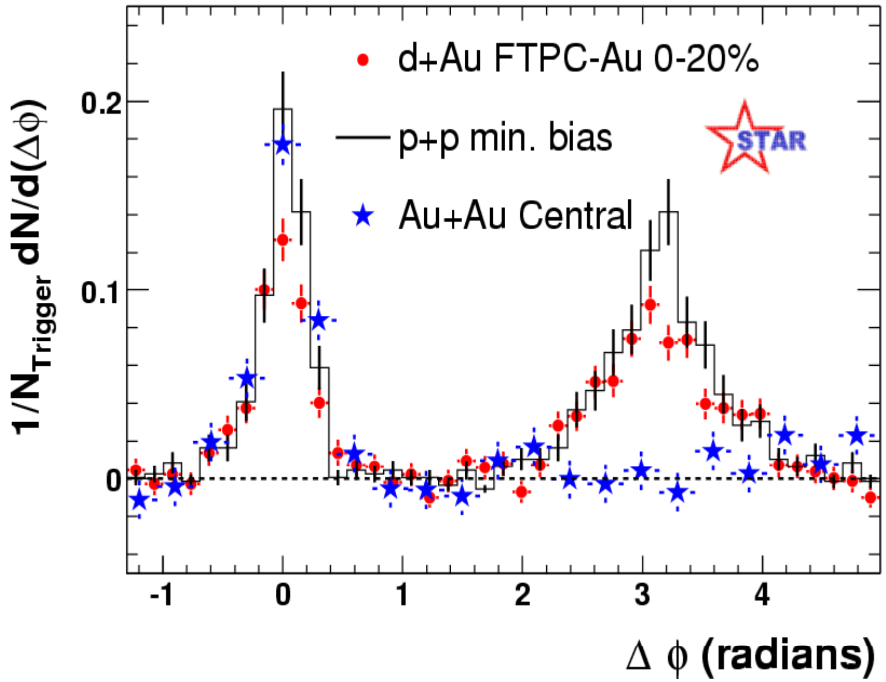
- Particle identification and tracking: TPC, ToF, SVT
- Energy measurement: E+BEMC
- Centrality / trigger: ZDC / CTB

Exciting results from light quarks

Inclusive hadron spectra



Di-hadron correlation



- Strong high-p_T particle suppression in central Au+Au

→ Parton energy loss in created medium

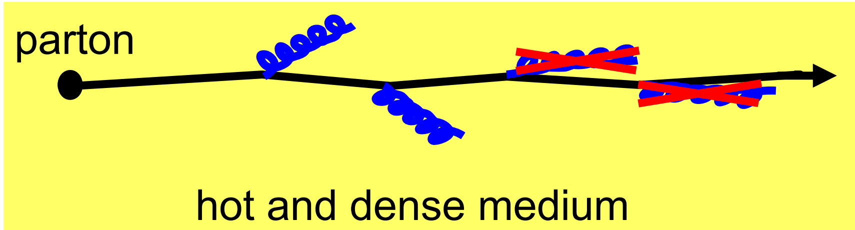
→ Strong evidence for a dense, opaque, non-viscous state of matter (perfect liquid)

STAR results from the first three years,
Nucl. Phys. A757, 102 (2005)

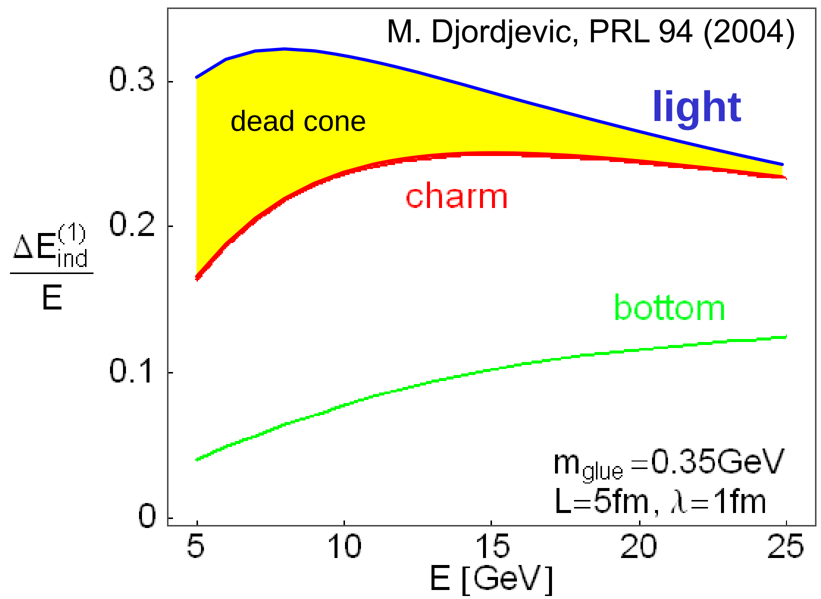
- What are the in-medium effects for heavy quarks?

In-medium energy loss of heavy quarks

- Due to their large mass heavy quarks are primarily produced by gluon fusion
  → production rates can be calculated by pQCD
  → sensitivity to initial state gluon distribution
  M. Gyulassy and Z. Lin, PRC 51, 2177 (1995)



- Heavy quarks loose less energy due to suppression of small angle gluon radiation (dead-cone effect)
  Dokshitzer and Kharzeev, PLB 519, 199 (2001)



- Amount of collisional and radiative energy losses seems to be similar
  M.G. Mustafa, PRC72, 014905 and
  A.K. Dutt-Mazumder et al., PRD71, 094016 (2005)

Heavy flavour measurements in STAR

- Hadronic decay channels

  $D^0 \rightarrow K\pi$ (B.R.: 3.83%)

  $D^* \rightarrow D^0\pi$, $D^\pm \rightarrow K\pi\pi$

$\rightarrow$ Direct clean probe (signal in invariant mass distribution)

$\rightarrow$ Difficulty: large combinatoric background (especially in high multiplicity environments)

$\rightarrow$ Event-mixing and/or vertex tracker needed to obtain signal

- Semi-leptonic channels (incl. modes)

  $c \rightarrow \ell^+$ + anything (B.R.: 9.6%) ℓ = e or μ

  $D^0 \rightarrow \ell^+$ + anything (B.R.: 6.87%)

  $D^\pm \rightarrow \ell^\pm$ + anything (B.R.: 17.2%)

  $b \rightarrow \ell^-$ + anything (B.R.: 10.9%)

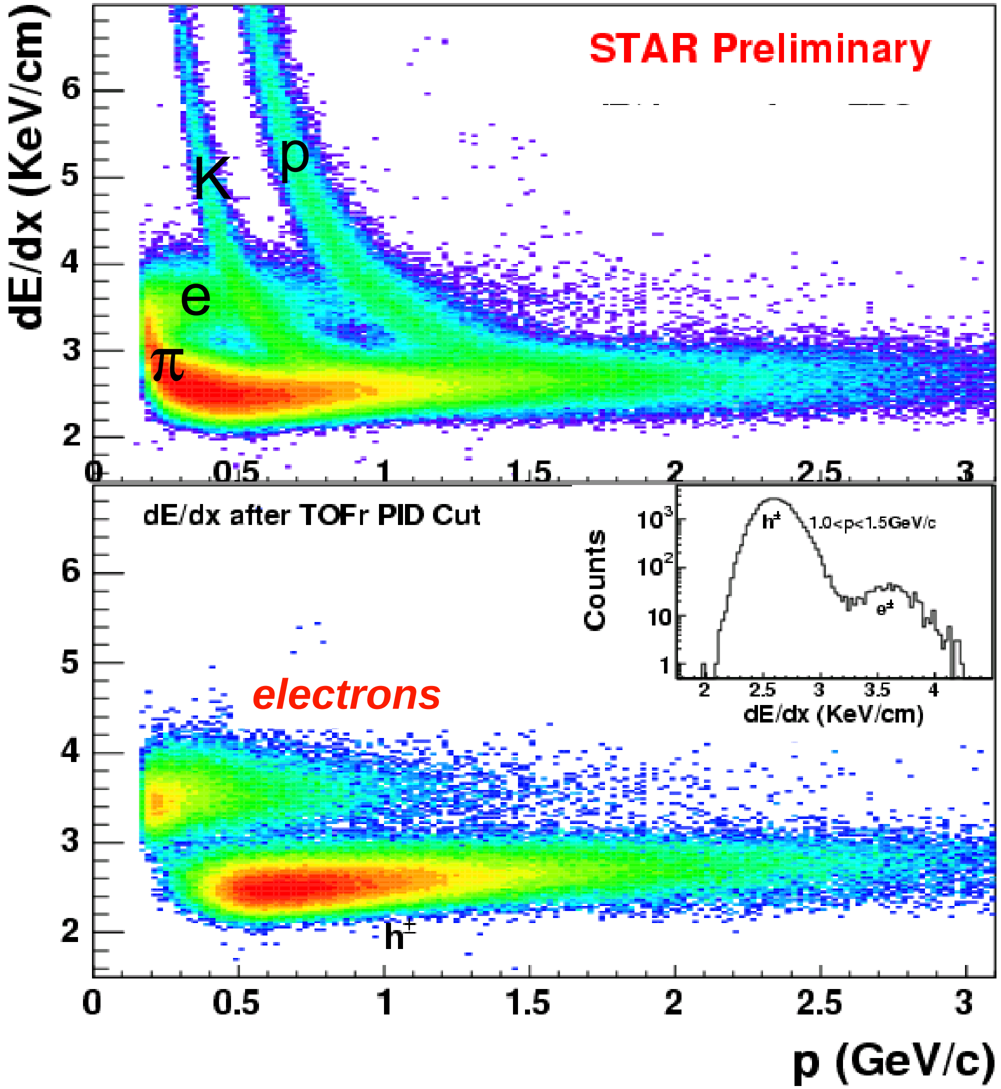
  $B^\pm \rightarrow \ell^\pm$ + anything (B.R.: 10.2%)

$\rightarrow$ Single (non-photonic) electrons sensitive to charm and bottom

$\rightarrow$ Robust electron trigger

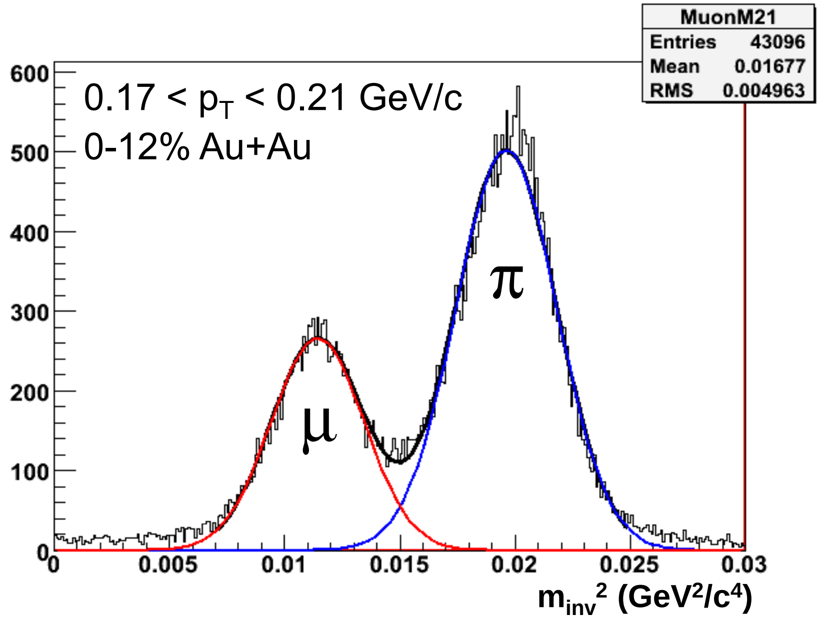
Electron identification - ToF

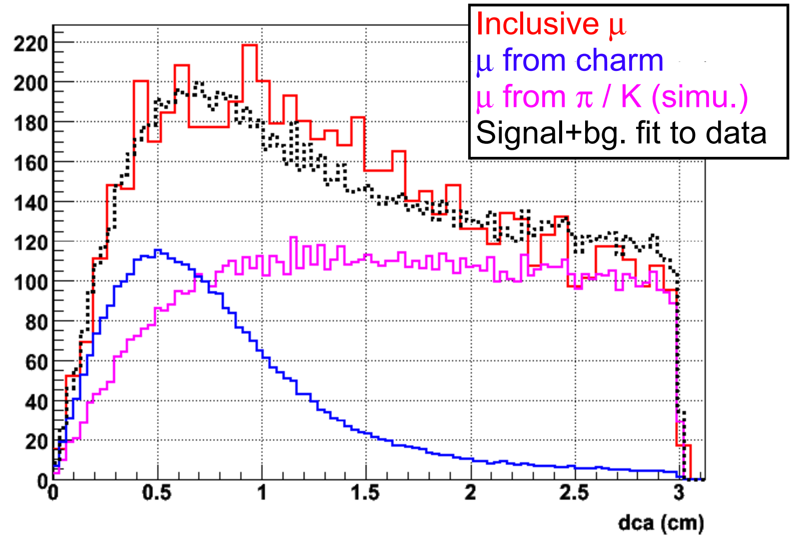
- ToF patch (prototype)
  - $\Delta\phi \approx \pi/30$
  - $0 > \eta > -1$
- Electron ID
  - $|1/\beta-1| < 0.03$
  - TPC dE/dx
- Momentum range:
  - $p_T < 4$ GeV/c



Muon identification - ToF

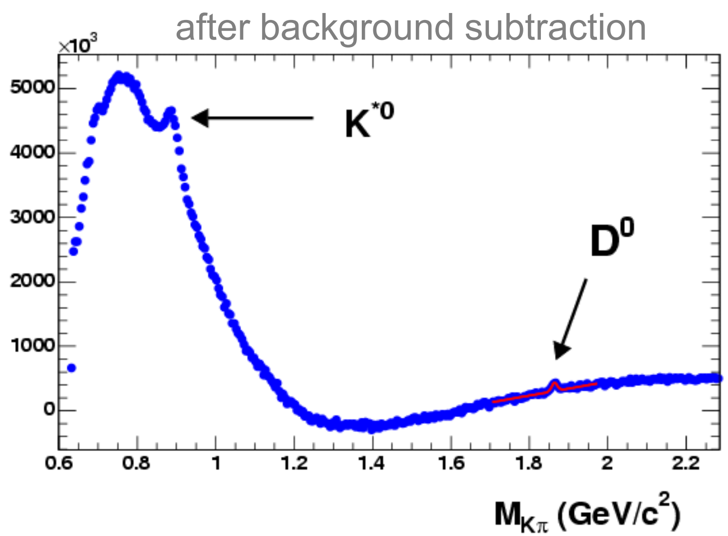
- Low-p_T (p_T < 0.25 GeV/c) muons can be measured with TPC + ToF
- Separate different muon contributions using MC simulations:
  - K and π decay
  - charm decay
  - DCA (distance of closest approach) distribution is very different

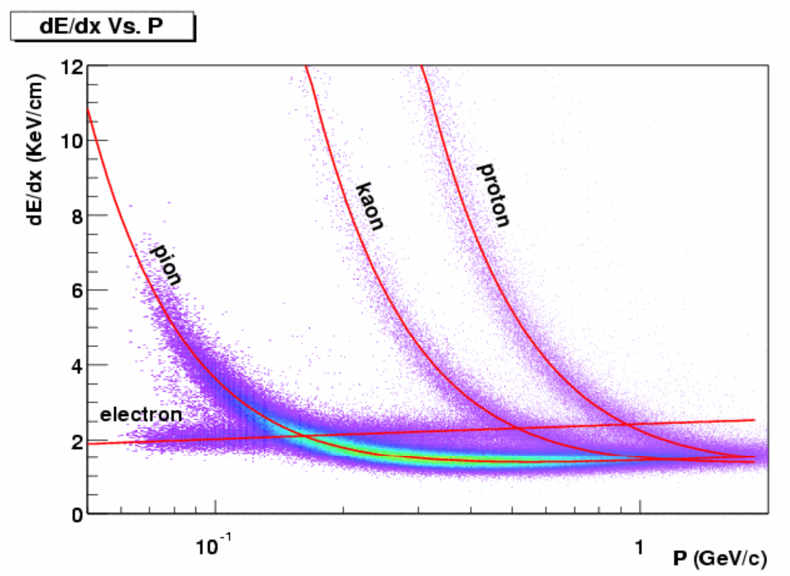


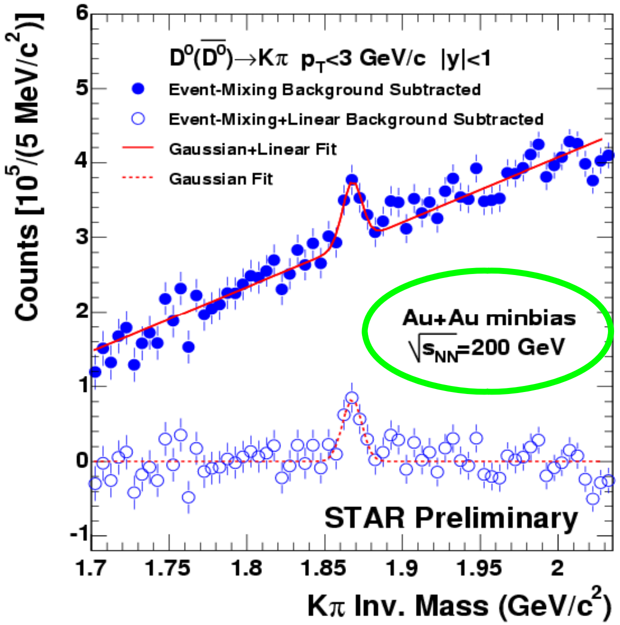


Open charm reconstruction - TPC

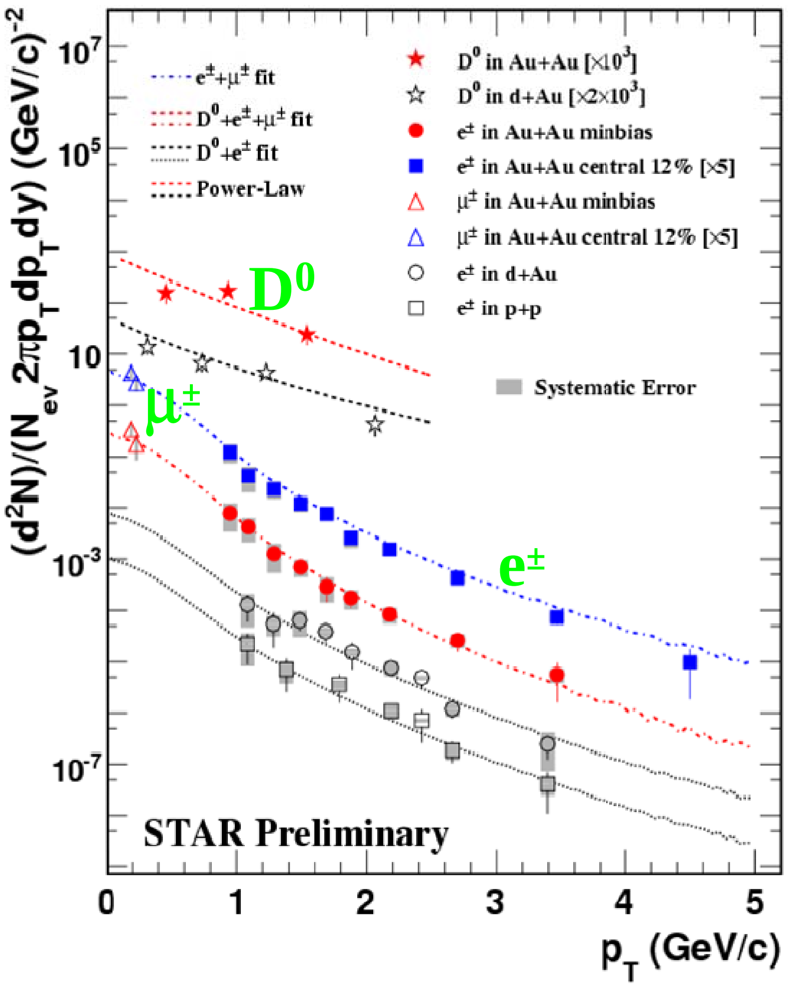
- Hadronic decay channel:
  $D^0 \rightarrow K + \pi$ (B.R. 3.8%)
  - PID in TPC using dE/dx
  - limited to a certain p range
- No reconstruction of displaced vertex up to now
- Background description using mixed event technique (details in PRC 71, 064902 (2005))

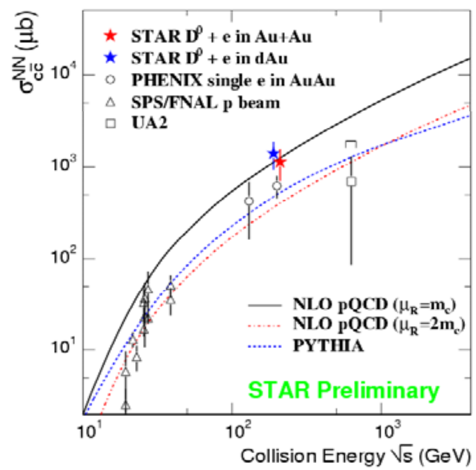


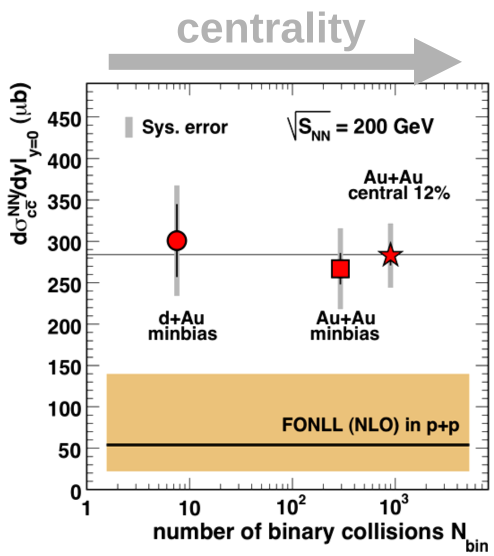




Charm cross section







σ^{NN}_{cc} = 1.40 ± 0.11 ± 0.39 mb
in 0-12% central Au+Au

- D^0, $e^{\pm}$, and $\mu^{\pm}$ combined fit covering ~95% of cross section
- σ^{NN}_{cc} higher than NLO calculations
- $d\sigma^{NN}_{cc}/dy$ follows binary collision scaling (N_{bin}) → charm production from initial state, as expected
- Publication in preparation

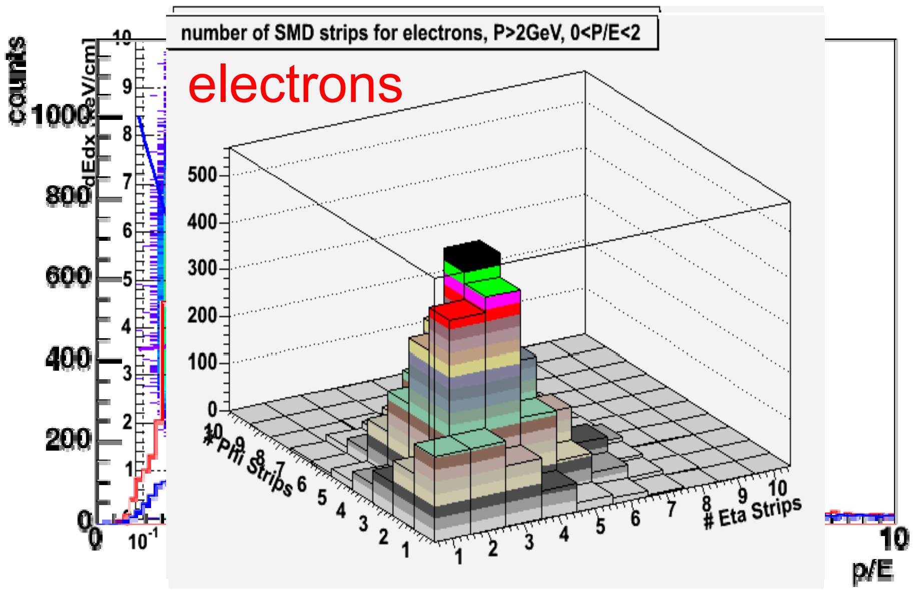
pp and d+Au results already published in PRL 94, 062301 (2005)

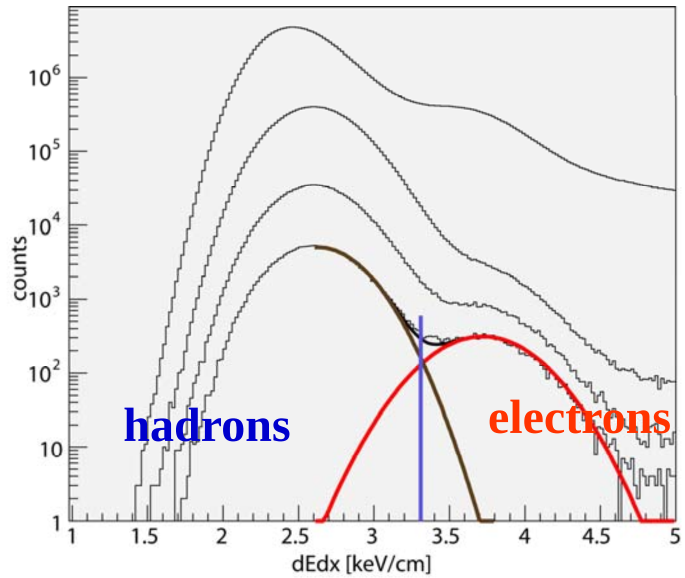
Electron identification - EMC

Advantage: triggering to enrich high-p_T particle sample

1. TPC: dE/dx for **p_T > 1.5 GeV/c**
   - Only primary tracks (reduces effective radiation length)
   - Electrons can be discriminated well from hadrons up to 8 GeV/c
   - Allows to determine the remaining hadron contamination after EMC
2. EMC:
   a) Tower E & p/E
   b) Shower Max Detector (SMD)
      - Hadrons/Electron shower develop different shape
      - Use # hits in Shower Max to discriminate

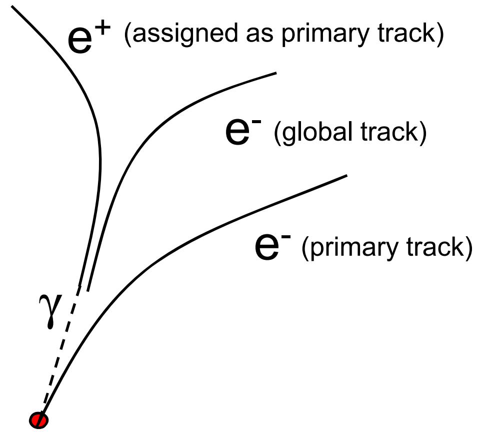
- 85-90% purity of electrons (p_T dependent)
- hadron discrimination power ~10^3-10^4

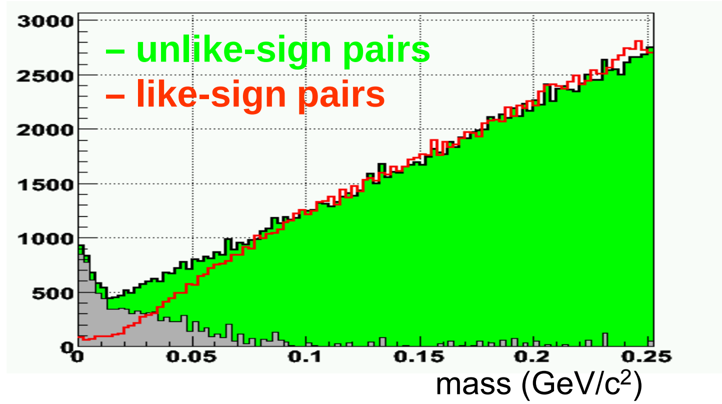


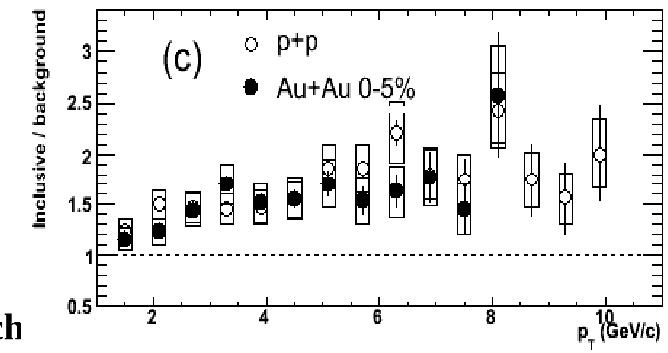


Photonic background

- Measured electrons have a photonic and non-photonic contribution
- Photonic contribution from gamma conversions and (π^0, η) Dalitz decays
- Procedure
  - electron candidates are combined with TPC tracks which passed loose *dE/dx* cuts around electron band
  - invariant mass is calculated at dca of TPC tracks: $m_{inv}^2 = 2E_1E_2(1-\cos\Theta)$
- Electrons with low invariant mass ($m_{inv} < 0.15\ GeV/c^2$) are rejected
- Correct for background rejection efficiency for non-reconstructed conversions

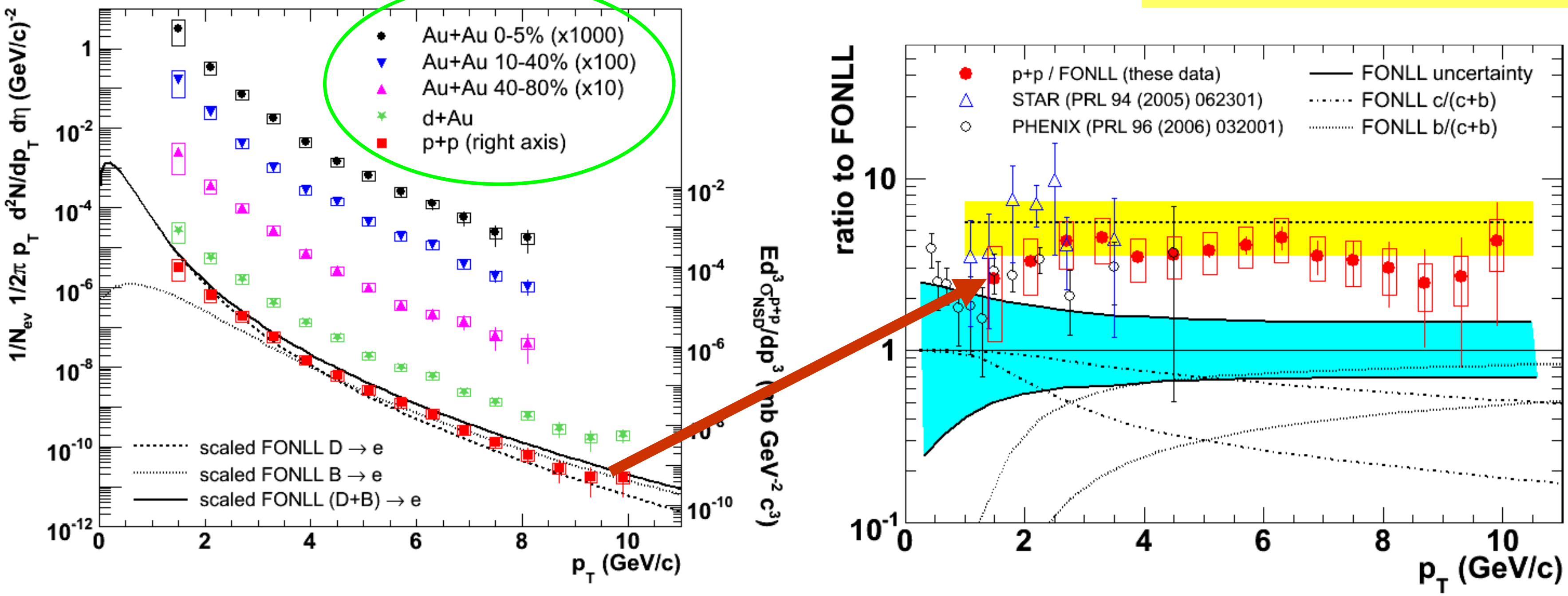






Non-photonic electron spectra

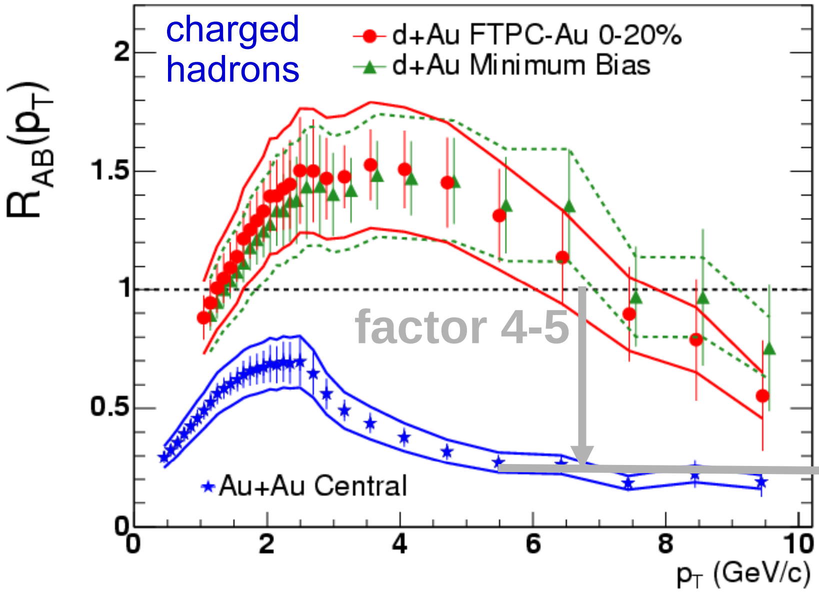
p+p at $\sqrt{s_{NN}}$ = 200 GeV

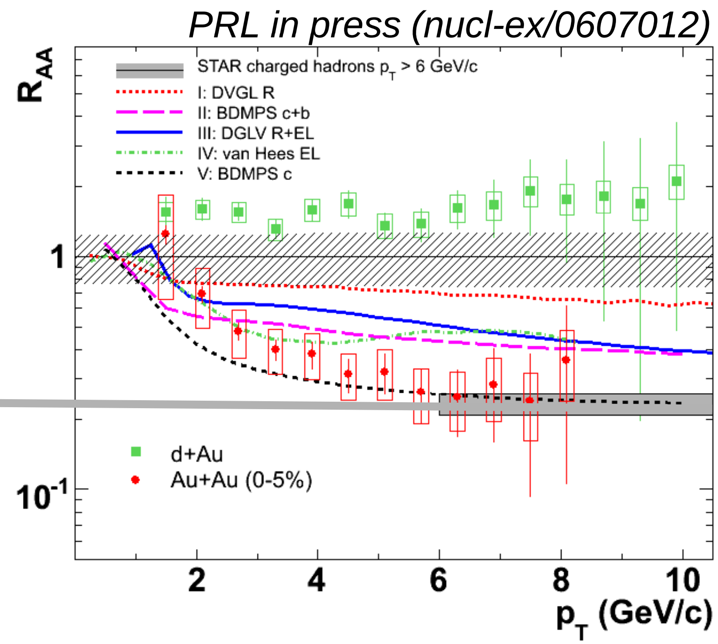


- FONLL calculation factor of about 5 lower
- Spectra shape well described
- Publication: Phys. Rev. Lett. in press (nucl-ex/0607012)

Nuclear modification factor R_{AA}

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV





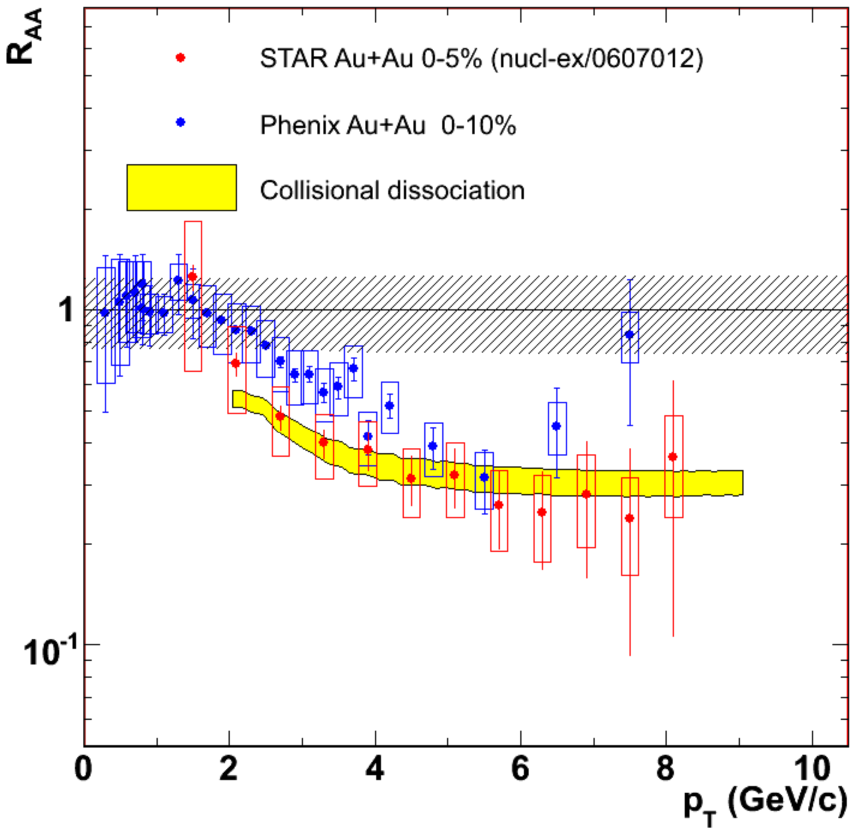
Nuclear modification factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$$\text{where } T_{AA} = N_{Coll}/\sigma^{NN}_{inelast}$$

- Non-photonic electrons at high-p_T are suppressed to the same extent as light quark hadrons in Au+Au
- Not expected due to dead-cone effect

Comparisons to models



Describing the suppression is difficult for models

- Radiative energy loss with typical gluon densities is not enough
  Djordjevic et al., PLB 632 (2006) 81
- Models involving a very opaque medium agree better
  Armesto et al., PLB 637 (2006) 362
- Collisional energy loss / resonant elastic scattering
  Wicks et al., nucl-th/0512076 and
  van Hees and Rapp, PRC 73 (2006) 034913
- Heavy quark fragmentation and dissociation in the medium → strong suppression for charm and bottom
  Adil and Vitev, hep-ph/0611109

Disentangle charm and bottom: first approach

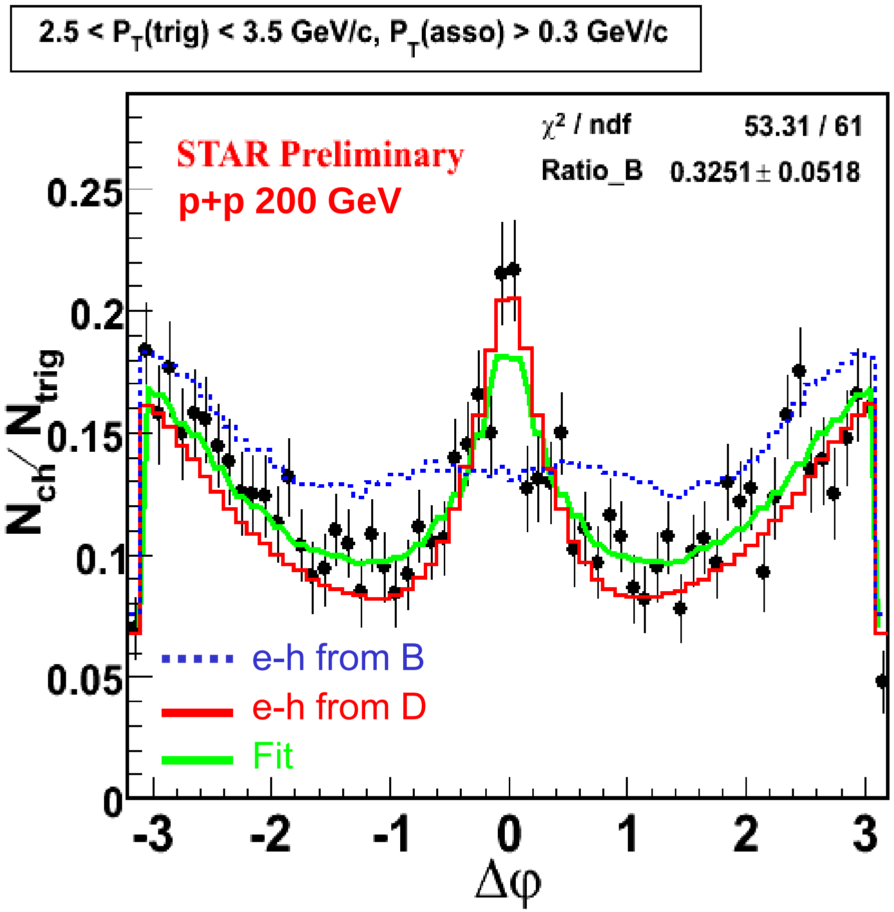
- Different fragmentation of associated jets
- Study non-photonic electron-hadron azimuthal correlations in p+p
- B much heavier than D mesons

→ sub-leading electrons get larger kick from B (decay kinematics)

→ near-side e-h correlation is broadened

- Extract relative bottom contribution using PYTHIA simulations:

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

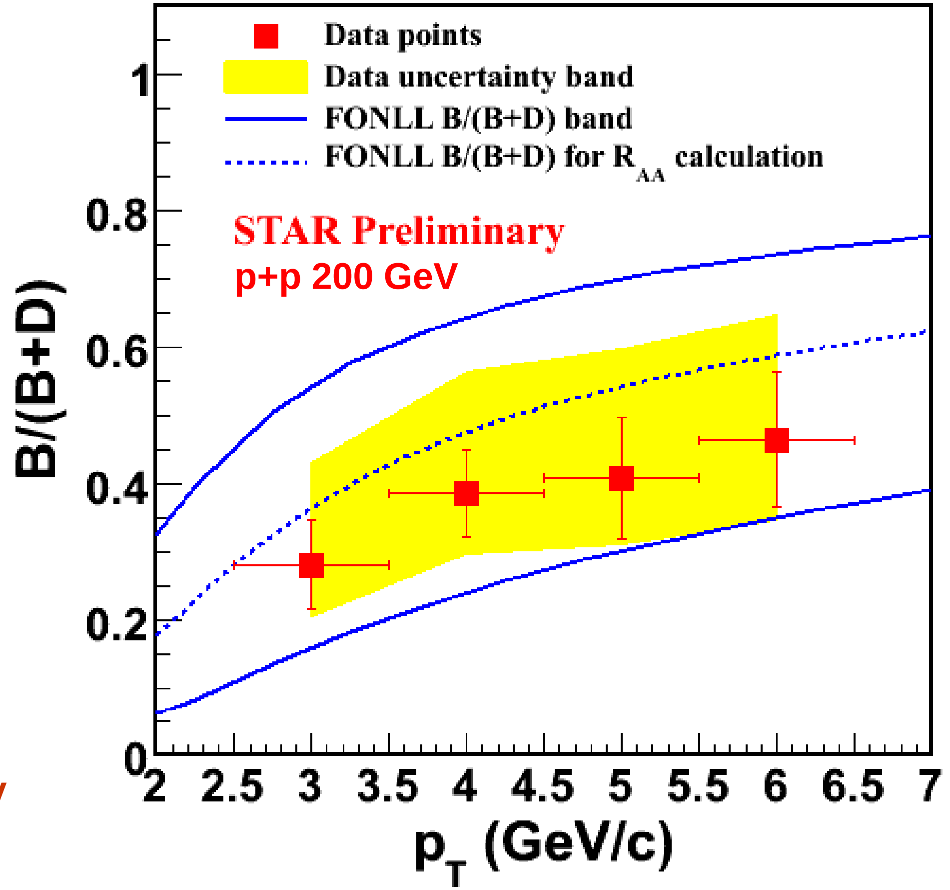


B contribution to np-electrons

- Non-zero bottom contribution
- Flavour contribution consistent with FONLL
- Caveats
  - subtraction of (large) back-ground
  - model dependent (PYTHIA)
  - photonic background rejection efficiency under study
- Results need to be confirmed by direct D/B meson measurements

→ STAR detector upgrade: Heavy flavor tracker
(vertex resolution σ ≤ 50 μm)

QM 2006



Heavy flavor tagged correlations

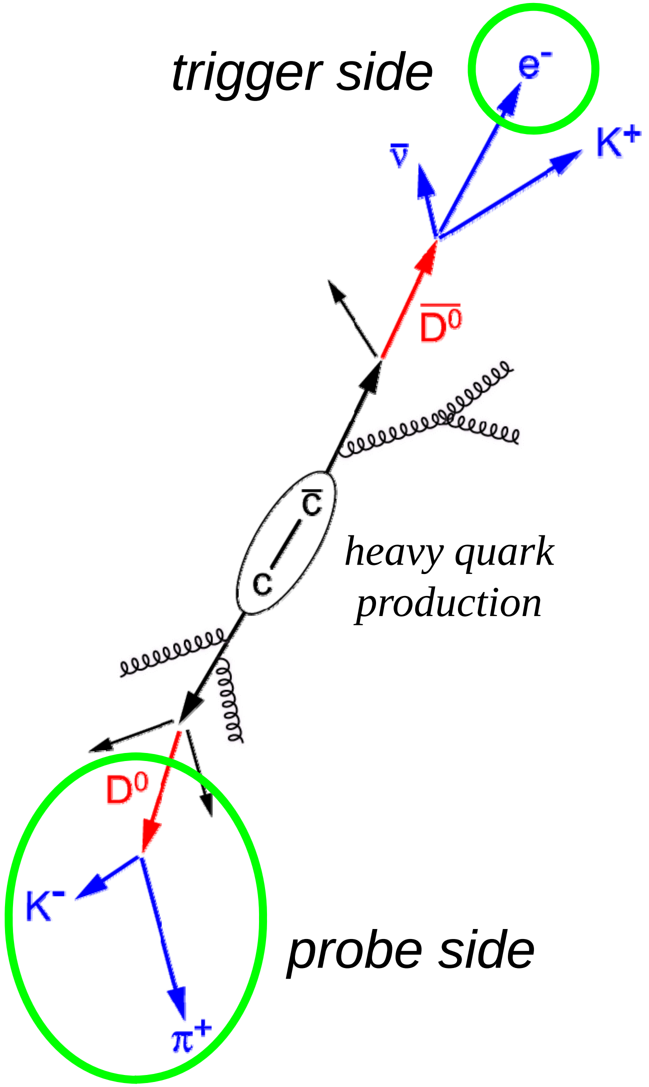
• Advantage: STAR has large acceptance ($|\eta| < 1$ and full azimuth)

• Underlying production mechanism can be identified using second charm/bottom particle

• Experimental approach

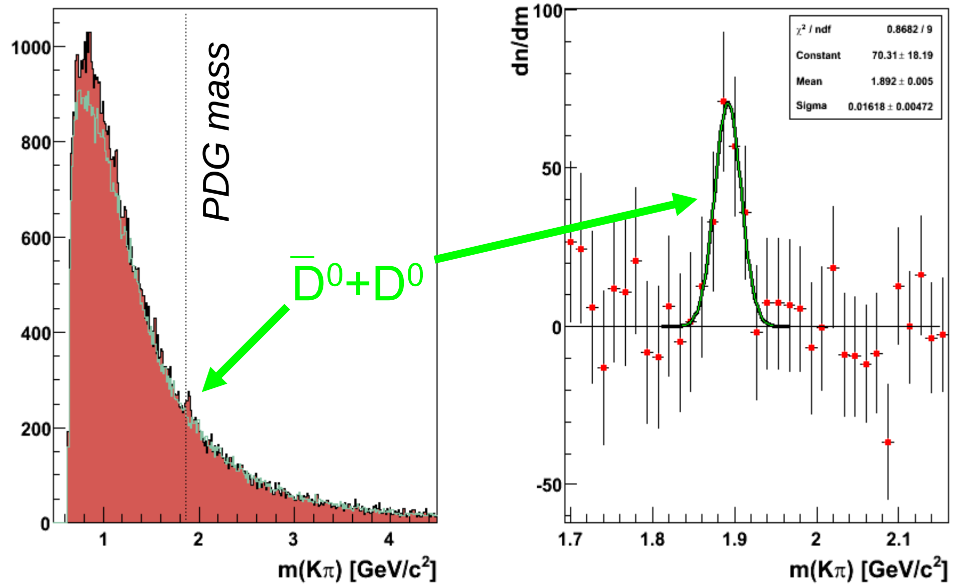
- non-photonic electrons from semi-leptonic c/b decays are used to trigger on c-cbar or b-bbar pairs

- associate D^0 mesons are reconstructed via their hadronic decay channel (probe)



Electron-D^0 azimuthal correlations

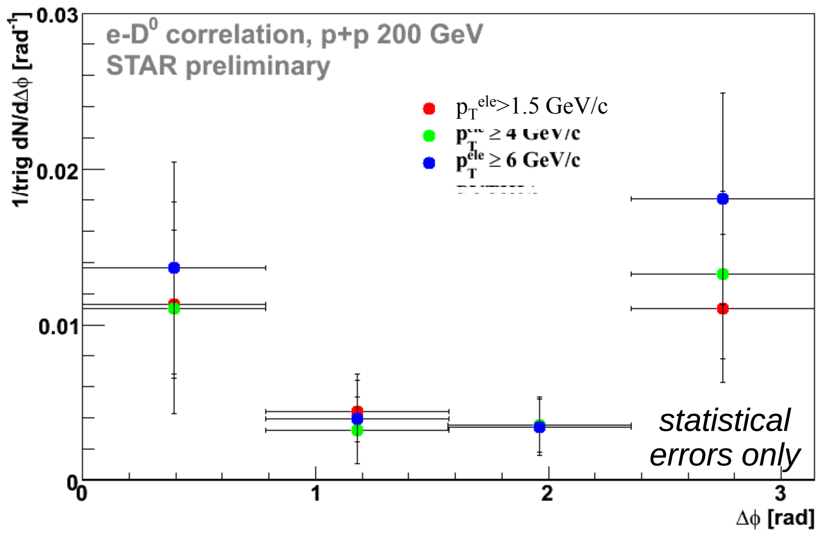
p+p $\sqrt{s_{NN}}$ = 200 GeV, $\int Ldt$ = 9 pb^{-1}



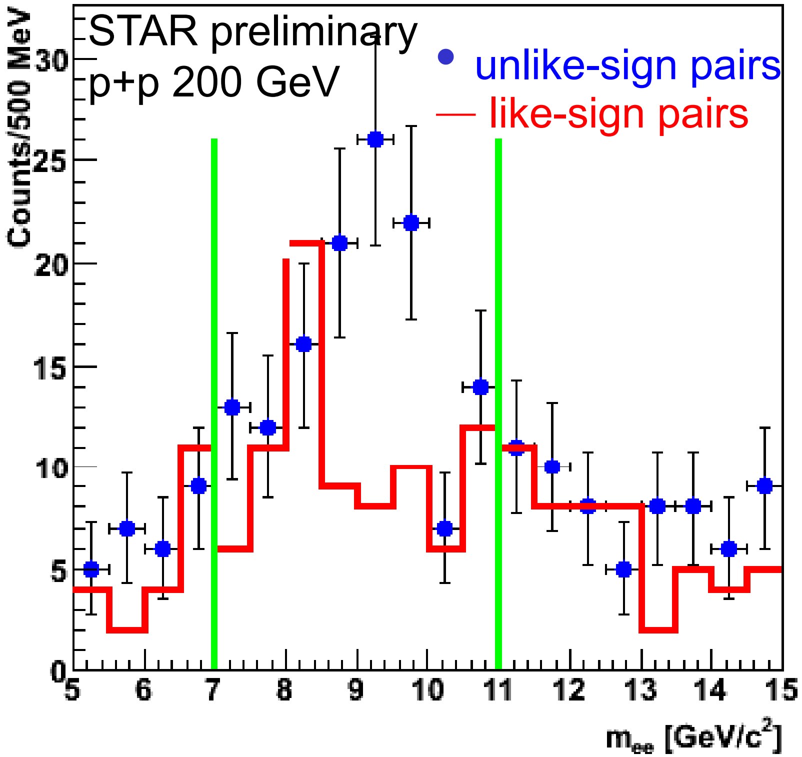
- Clear D^0 signal
  - S/B ratio factor ~100 better than signal w/o electron trigger
- Near- and away-side correlation peak with similar yields observed

→ Evidence for heavy flavor correlations

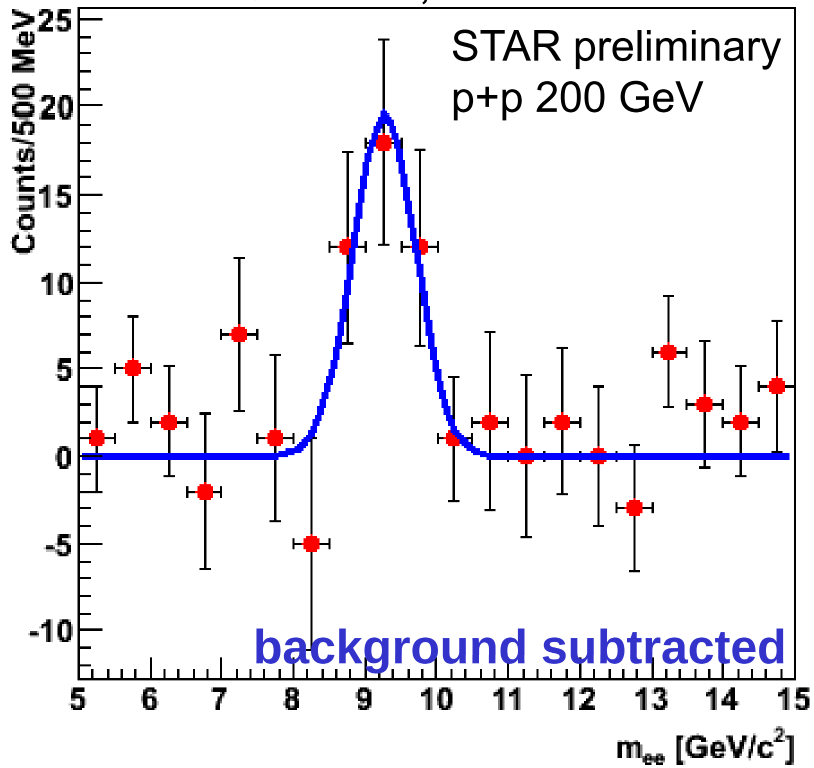
- Next: Separate charm and bottom contribution as well as sub-processes (e.g. gluon splitting) using
  - dedicated simulations
  - charge-sign requirement on (e, D^0) pairs



Quarkonia in STAR



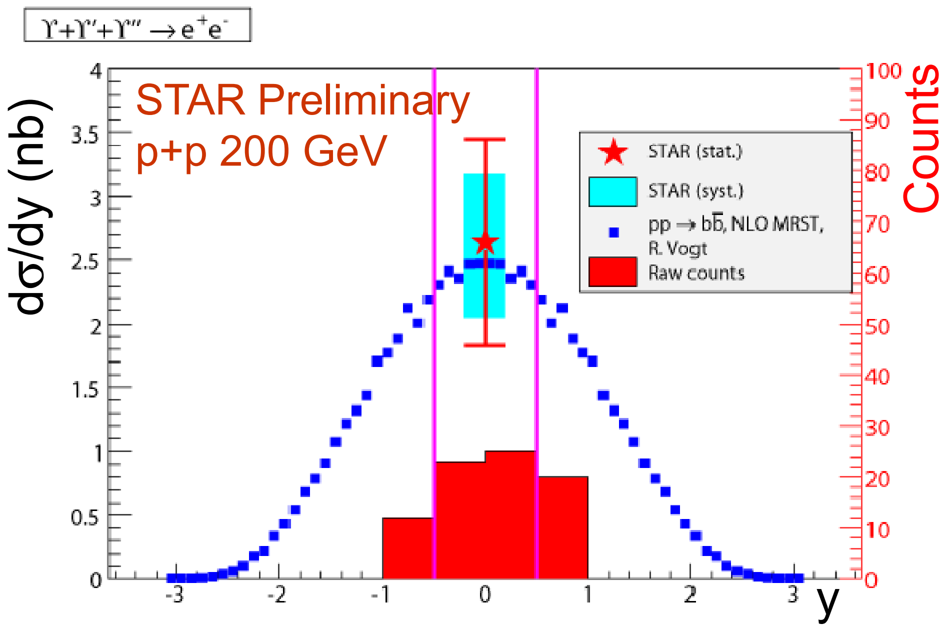
QM 2006, nucl-ex/0701075



- <u>Prediction:</u> Melting of Quarkonia states in QGP phase
- Color screening between heavy quark pairs, e.g., J/ψ suppression
Matsui and Satz, PLB 178, 416 (1986)

- Large dataset sampled in Run VI
- Measure ϒ(1s+2s+3s) dσ/dy at y=0
- Peak width consistent with expected mass resolution

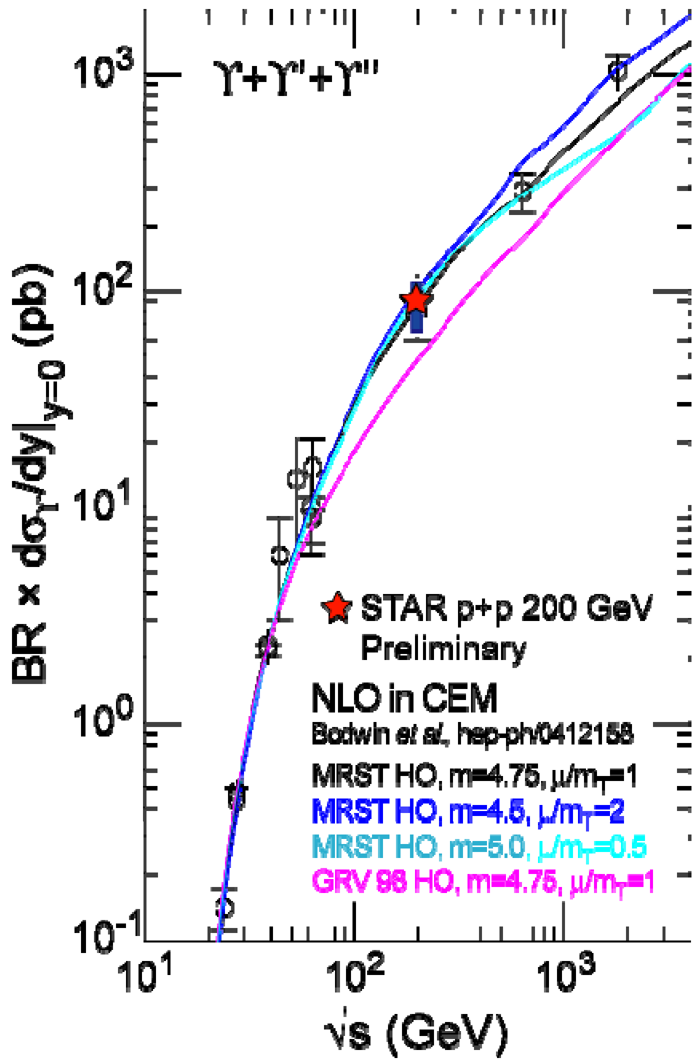
Mid-rapidity $\Upsilon(1s+2s+3s)$ cross-section



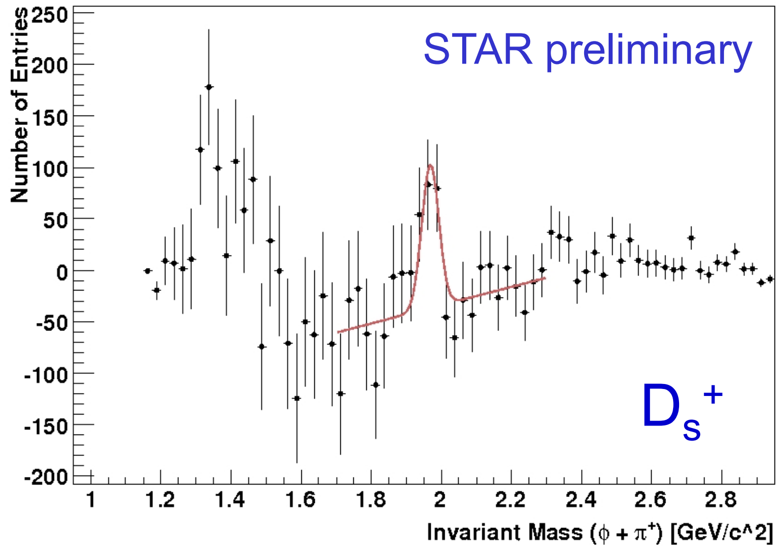
- Integrated yield at mid-rapidity: $|y|<0.5$
- $\Upsilon(1s+2s+3s) \rightarrow e^+e^-$:

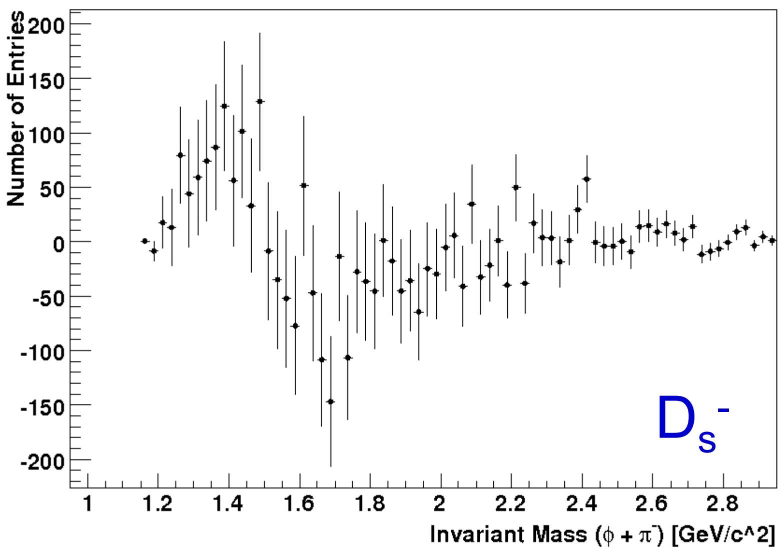
  $BR_{ee} \times d\sigma/dy = 91 \pm 28(\text{stat.}) \pm 22(\text{sys.})$ pb

- Consistent with NLO pQCD calculations and world data trend
- Next: Au+Au measurement in RHIC Run VII



First D_s^+ signal at RHIC



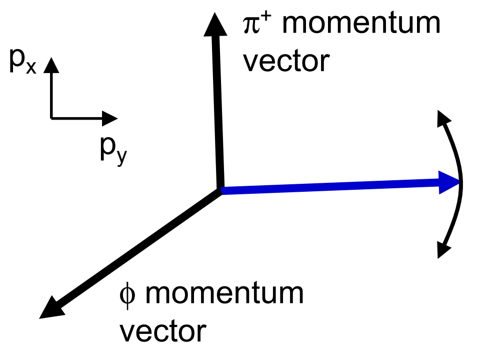


- Recent analysis in d+Au 200 GeV
- Decay channels (B.R.: 3.6%):

  $D_s^+ \rightarrow \phi + \pi^+ \rightarrow K^+ + K^- + \pi^+$

  $D_s^- \rightarrow \phi + \pi^-$

- Rotated event technique

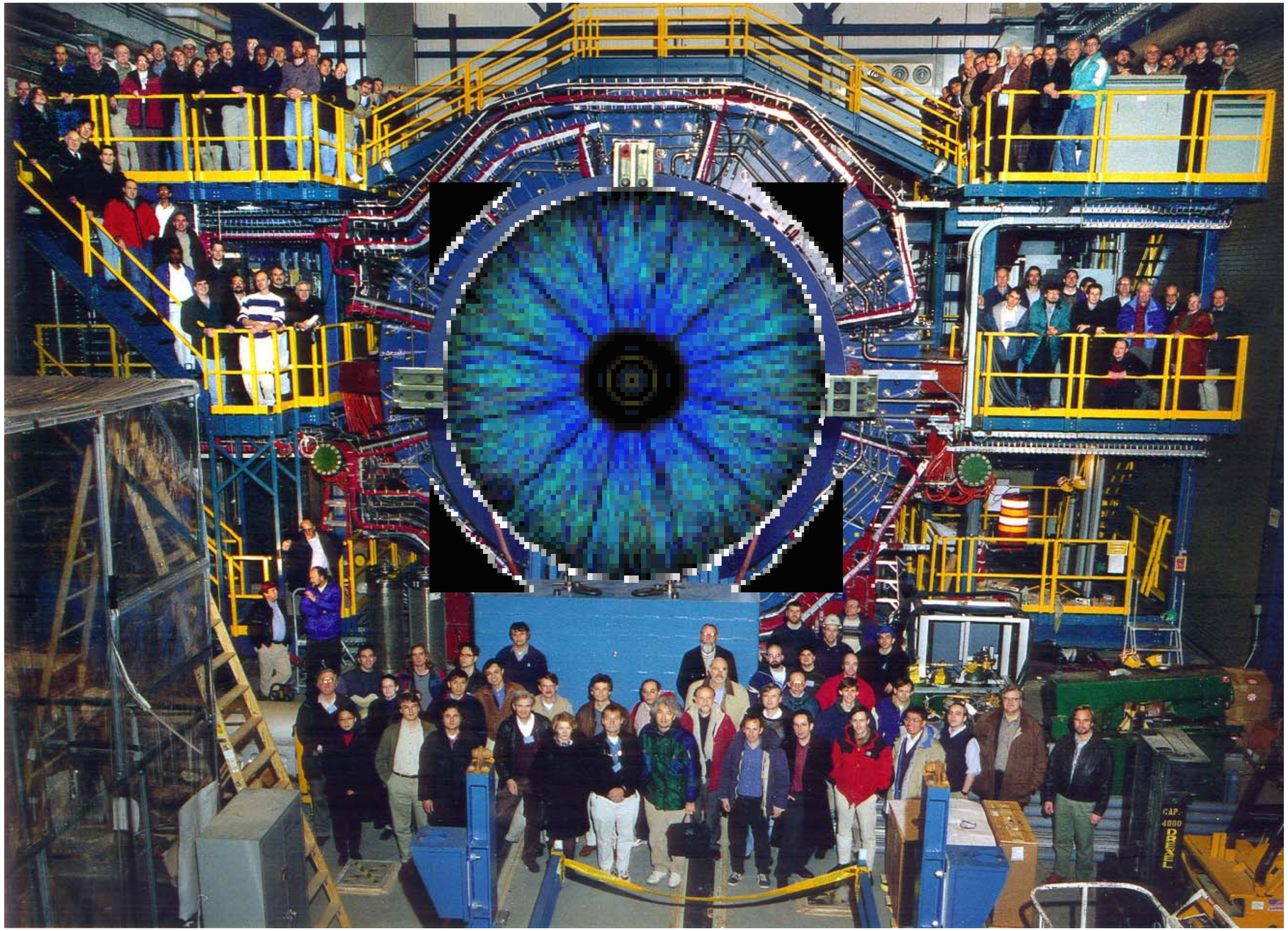


Summary and conclusions

- Charm production cross-section
  - is larger than expected from NLO
  - follows binary collision scaling (no room for thermal production)
- Non-photonic electron spectra
  - electron yield in p+p is ~5 times higher than FONLL
  - energy loss in heavy-ion collision is much larger than expected
- Electron-hadron / D^0 correlations
  - powerful tool to disentangle charm and bottom
- Quarkonia
  - Υ cross-section consistent with pQCD and world data trend
- More exciting results are about to come with the detector upgrades (full barrel ToF and HFT [active pixel sensor technology])

The STAR collaboration

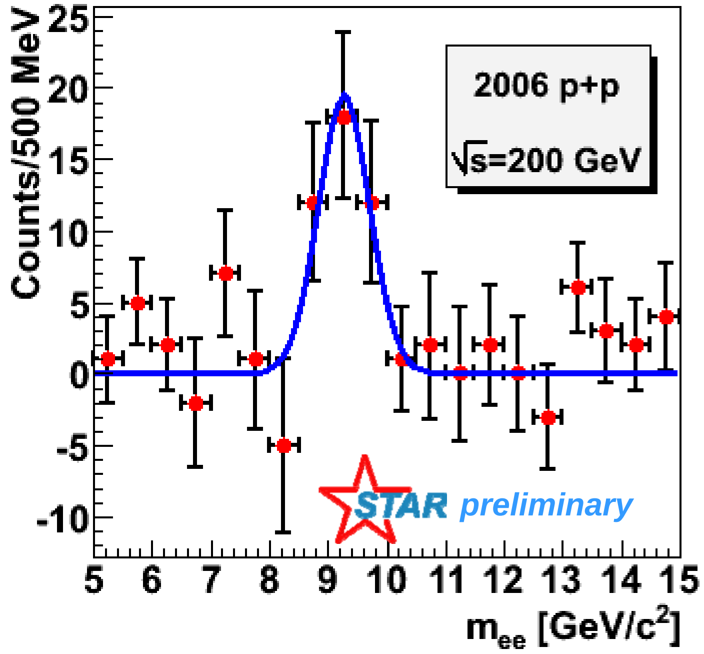
51 institutes from 12 countries, 544 collaborators



Backup

Υ cross section and uncertainties

$$BR_{ee} \times \left(\frac{d\sigma}{dy}\right)_{y=0} = \frac{N_{\Upsilon}}{dy \times \varepsilon_{\Upsilon} \times \int \mathcal{L}dt}$$



$$\int \mathcal{L}dt = (5.6 \pm 0.8)\ \text{pb}^{-1}$$

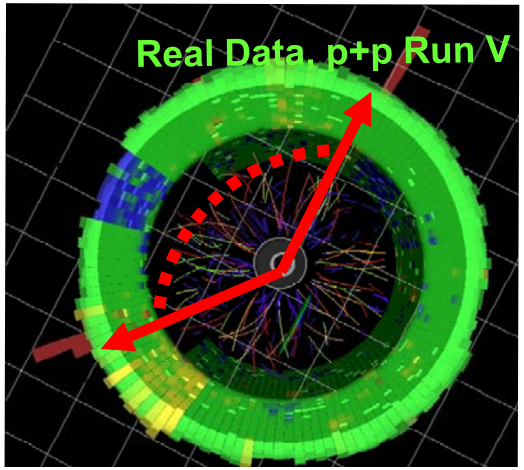
$$\varepsilon_{\Upsilon} = \varepsilon_{geo} \times \varepsilon_{L0} \times \varepsilon_{L2} \times \varepsilon^2(e) \times \varepsilon_{mass}$$

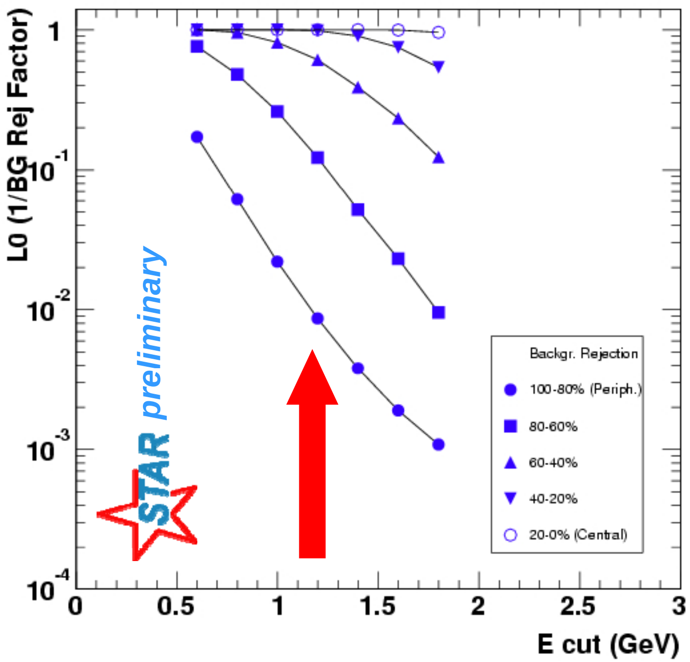
ε_{geo}	0.263±0.019
ε_{L0}	0.928±0.049
ε_{L2}	0.855±0.048
$\varepsilon^2(e)$	0.47±0.07
ε_{mass}	0.96±0.04
ε_{Υ}	**0.094±0.018**

- ε_{geo} : geometrical acceptance
- ε_{L0} : efficiency of L0
- ε_{L2} : efficiency of L2
- $\varepsilon(e)$: efficiency of e reco
- ε_{mass}: efficiency of mass cut

J/ψ trigger in STAR

- L0 (hardware)
  - J/ψ topology trigger: two towers above $E_T \approx 1.2$ GeV
  - Separated by 60° in φ
- L2 (software)
  - Match EMC high tower to CTB slat ⇒ photon rejection
  - Tower clustering
  - Cut on $m_{ee}=\sqrt{2E_1E_2(1-\cos\theta)}$
  - Cut on cosθ
- High background contamination ~1.5 GeV/c
- Rejection~100 ⇒ not sampling full luminosity
- Challenging analysis!!!
- Efficiency × acceptance ≈ 12%

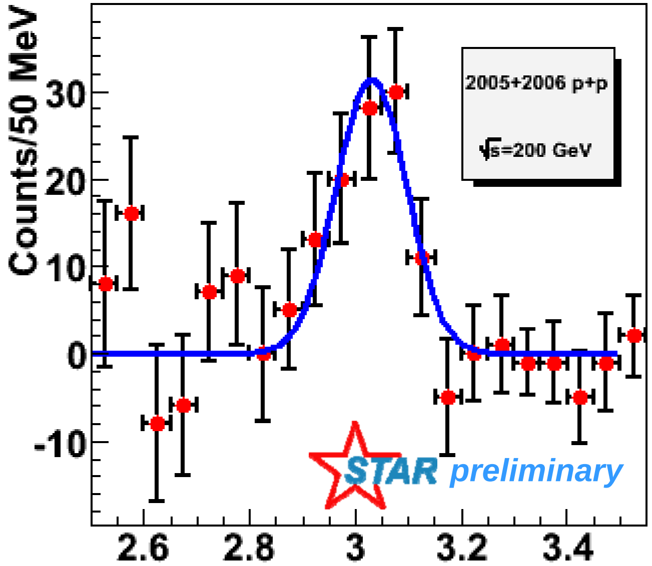


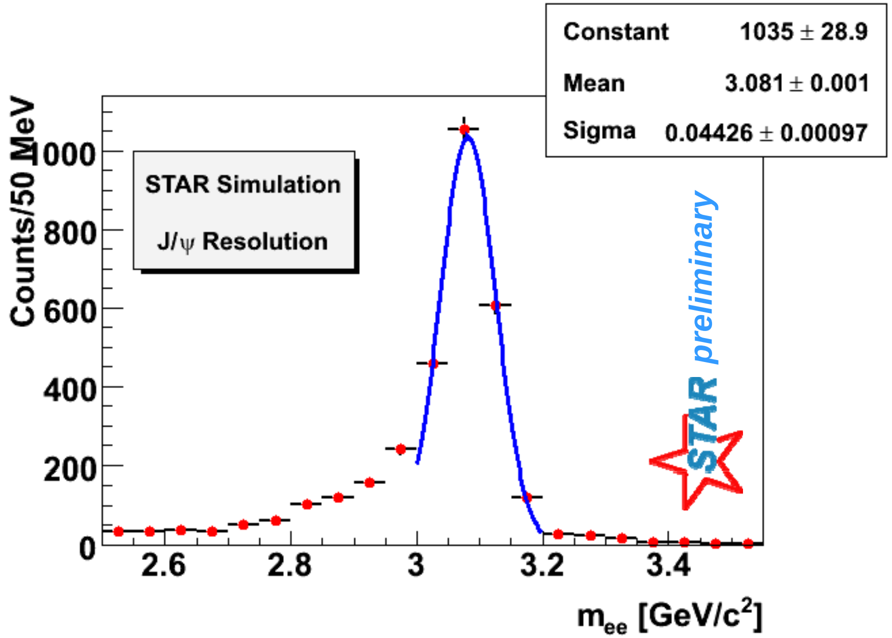


J/ψ signal in STAR

Slowly getting started with J/ψ:

- Signal in 200 GeV p+p from 2005
  - Tested and working trigger in p+p
  - No trigger for Au+Au until full ToF in 2009
- Also signal in Au+Au with TPC only
  - Large hadron contamination
  - Need full EMC





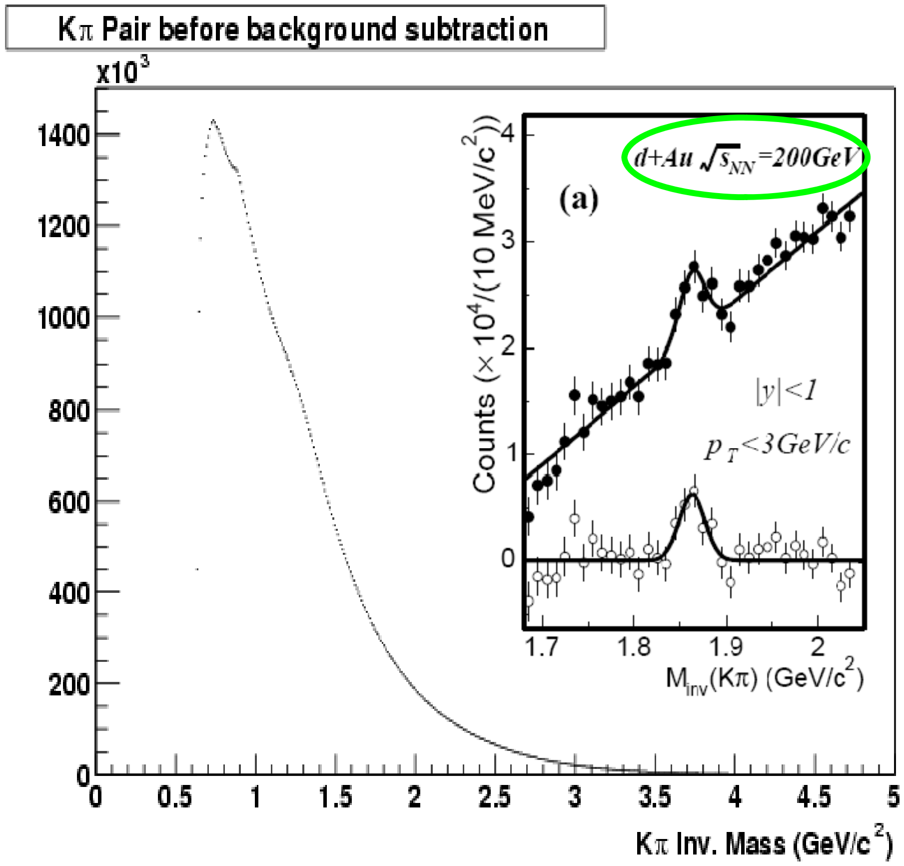
Open charm measurements
- The usual reconstruction technique -

- Via hadronic decay channel

  $D^0 \rightarrow K^- \pi^+$ (B.R.: 3.83%)

- Difficulty: large combinatoric background (especially in high multiplicity environments)

- Event-mixing and/or vertex tracker needed to obtain signal



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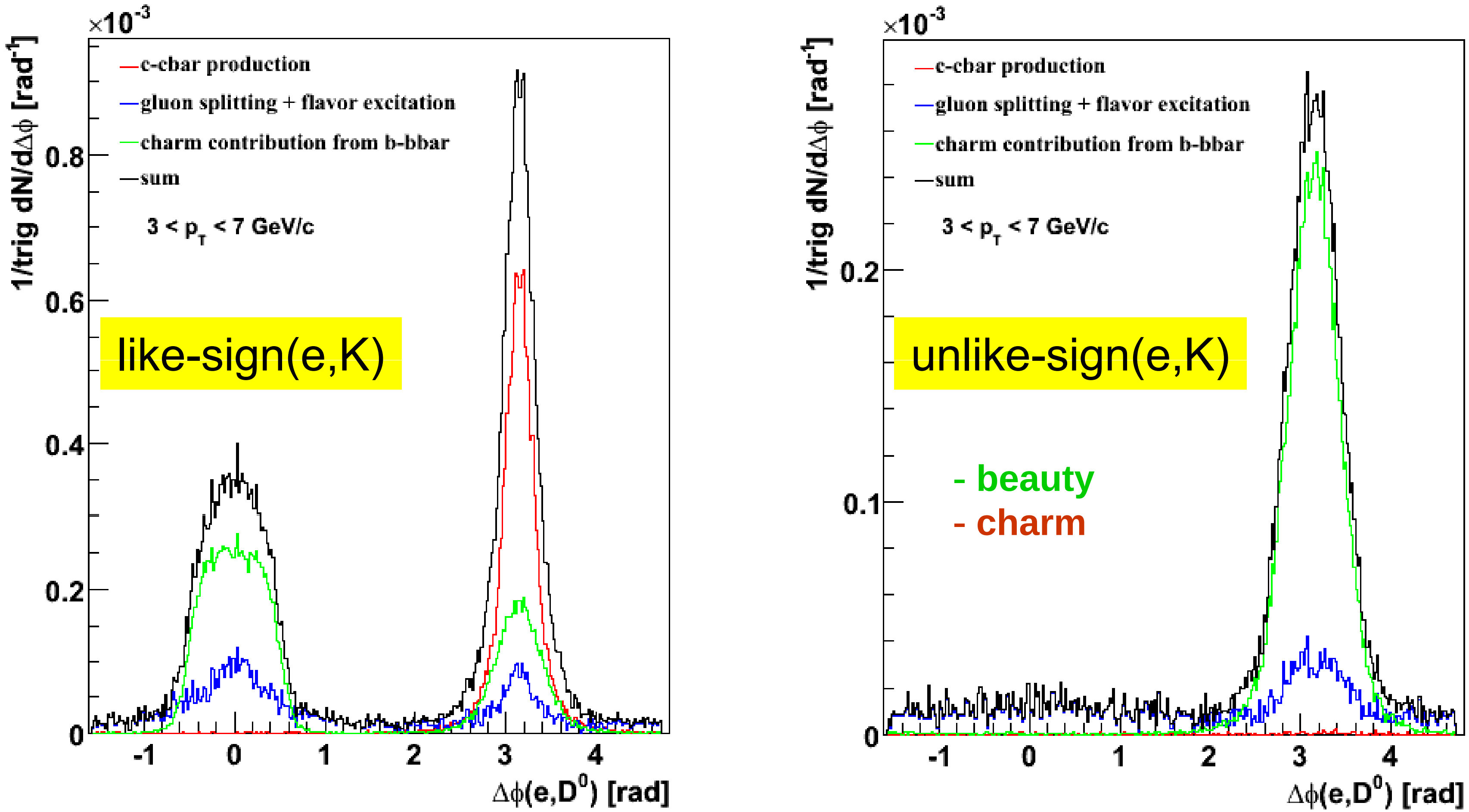
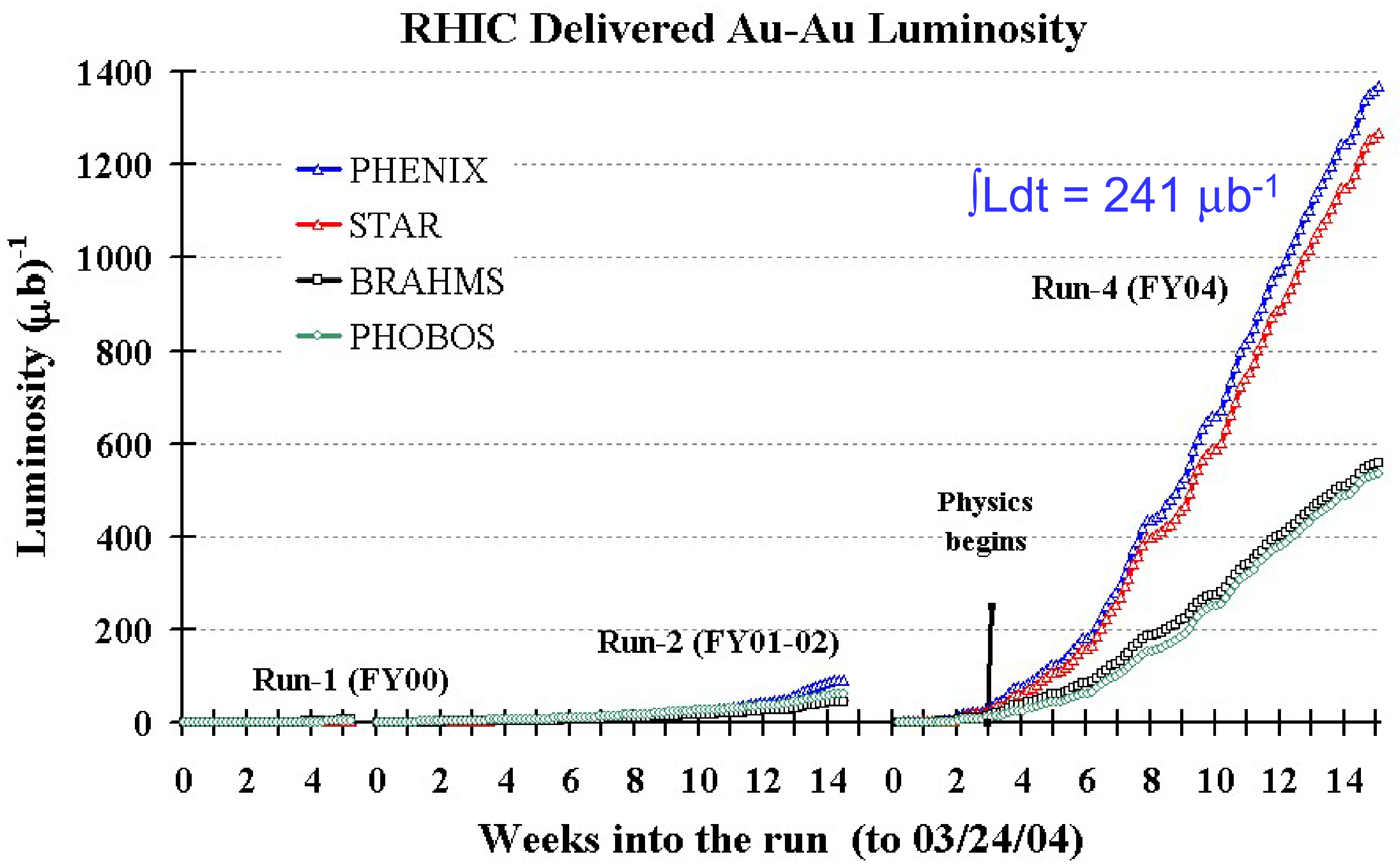
What is the D^0 contribution from charm and bottom decays?



PYTHIA (V6.222) simulations

CKIN(3) = 20

RHIC performance



Most 200 GeV Au+Au results are from the FY04 run

Side-view STAR experiment