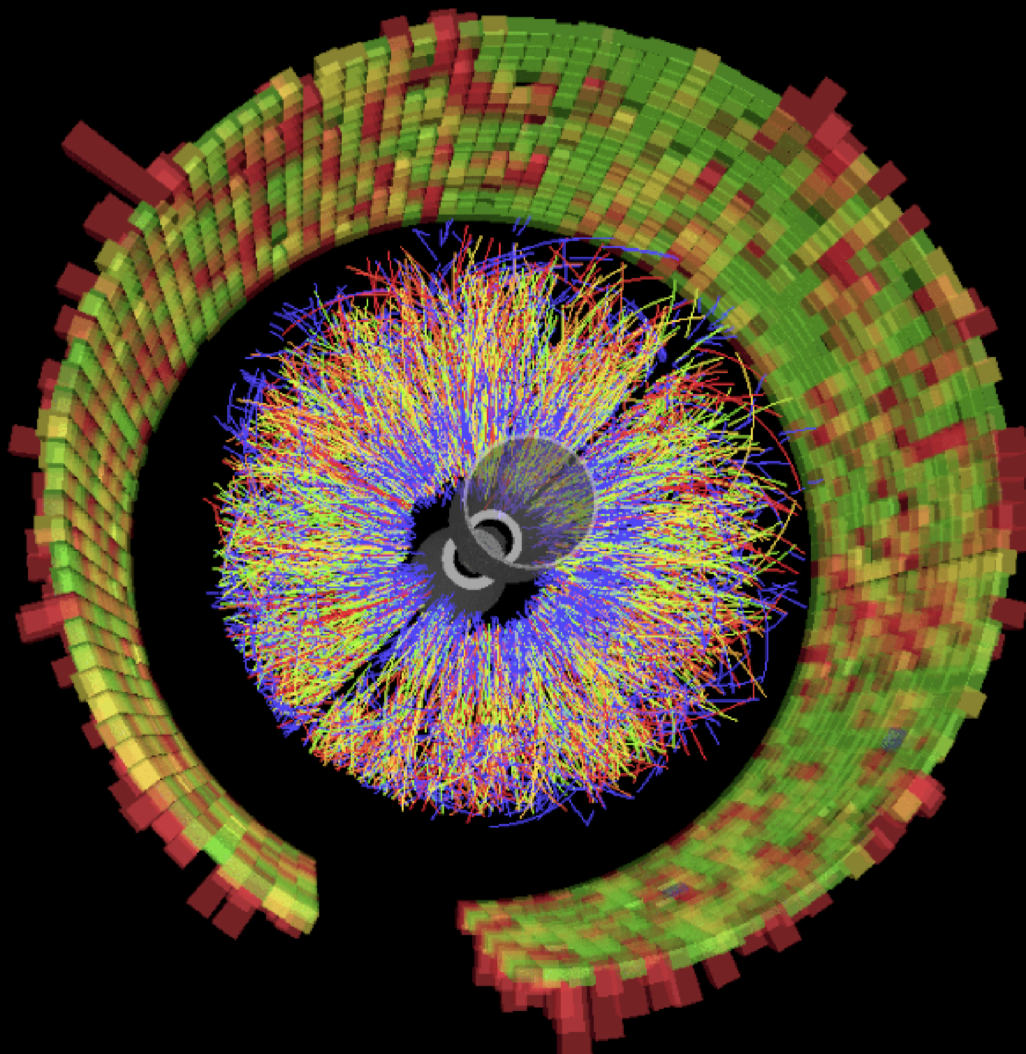


Heavy Flavor Physics with the STAR Experiment

Frank Laue(BNL)
for the
STAR Collaboration

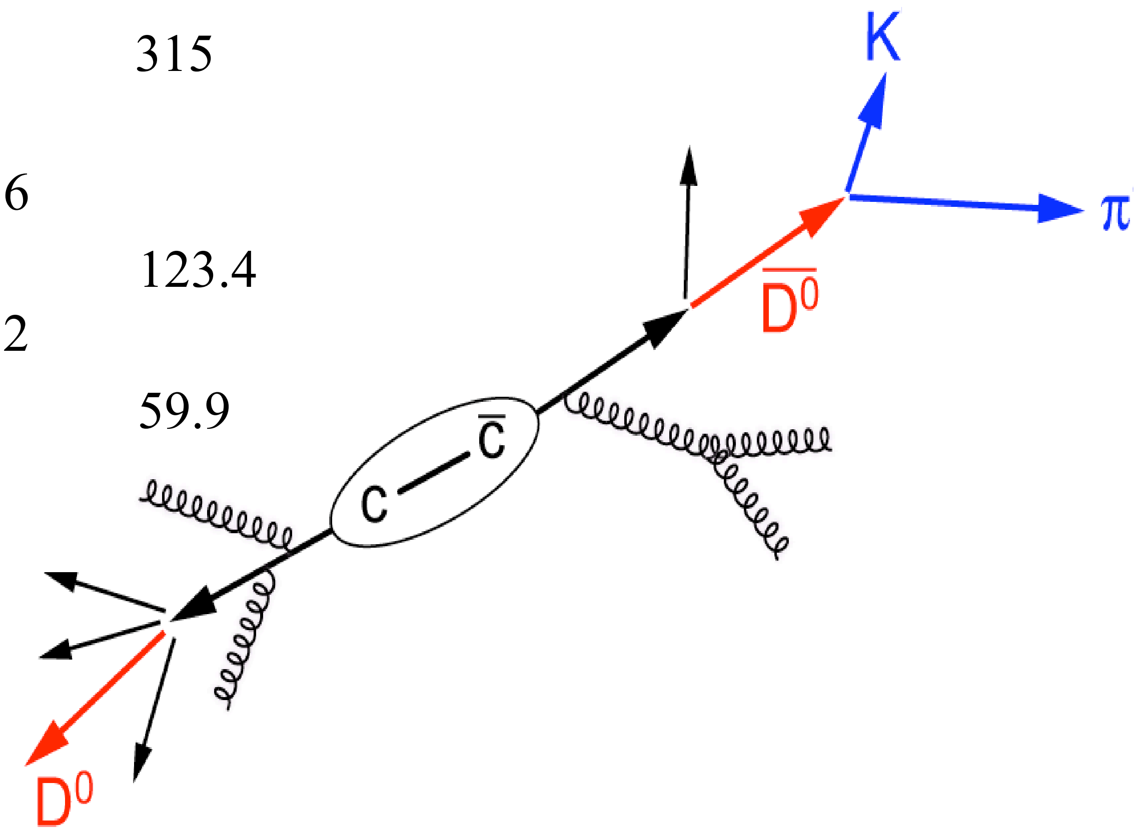
AGS/RHIC Users Meeting
June-21th 2005

Outline

- Current Analysis/Results
  - Open Charm Production
    - D mesons
      - d+Au: charm cross-section
      - Au+Au: (⇒ QM'05)
  - Non-photonic single electrons
    - p+p: the reference
    - d+Au: cold nuclear matter effects
    - Au+Au: (⇒ QM'05)
  - Thermalization of heavy quarks ?
    - Au+Au: v2 of non-photonic electrons
- Future
  - Quarkonia: J/Ψ and ϒ (trigger)
  - Detector upgrades
- Summary and Outlook

Detection of Heavy Flavor via Hadronic Decays

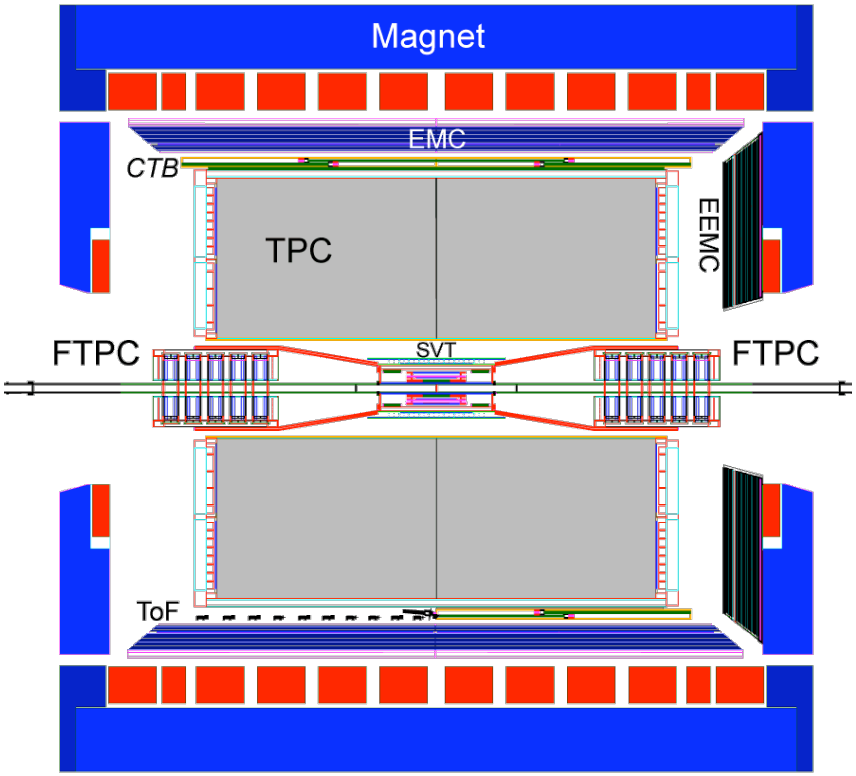
	Channel	B.R.(%)	cτ(μm)
✓	$D^0 \to K\pi$	3.8	123.4
✓	$D^{\pm} \to K\pi\pi$	9.1	315
✓	$D^{*\pm} \to D^0\pi$	68	
	$D^0 \to K\pi$	(3.8) 2.6	
★	$D^0 \to \rho K\pi$	6.2	123.4
	$\rho \to \pi^+\pi^-$	(100) 6.2	
★	$\Lambda_c \to pK\pi$	5	59.9



multi-particle final states⇒ large acceptance

(w/o secondary vertex, brute force mixed event analysis)

Detecting D-Mesons via Hadronic Decays



TPC:

- High tracking efficiency for tracking hadrons (~90%)
- $\delta p/p \sim 1\%$ at 1 GeV/c
- large acceptance $|\eta|<1$
- PID (dE/dx) limits:
  - p up to 1 GeV/c
  - K, π up to 0.7 GeV/c

SVT:

- current vertex'ing performance not sufficient to resolve typical charm secondary vertices ($c\tau \sim 120(D^0)$ - $315(D^\pm)$ μm) $\Rightarrow$ background $\uparrow$

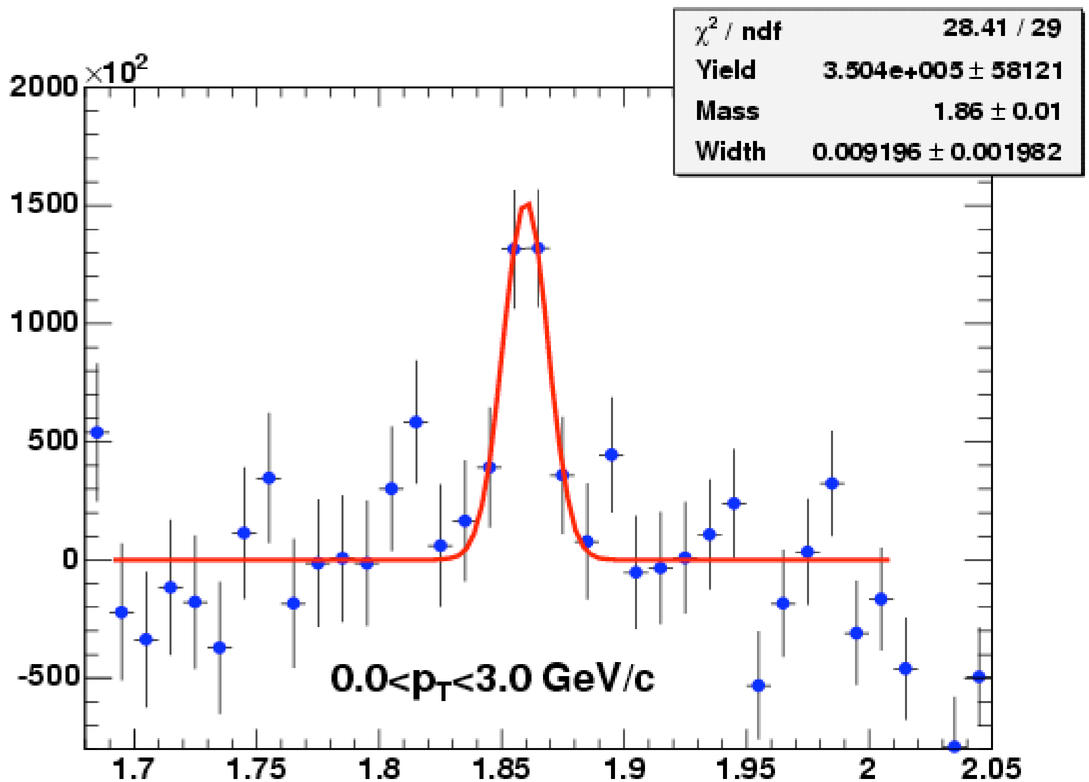
Hadrons in STAR:

★TPC: tracking, PID
★SVT: vertex'ing, PID
★ZDC/CTB: centrality/trigger

$\Rightarrow$ Current analyses are based on TPC alone

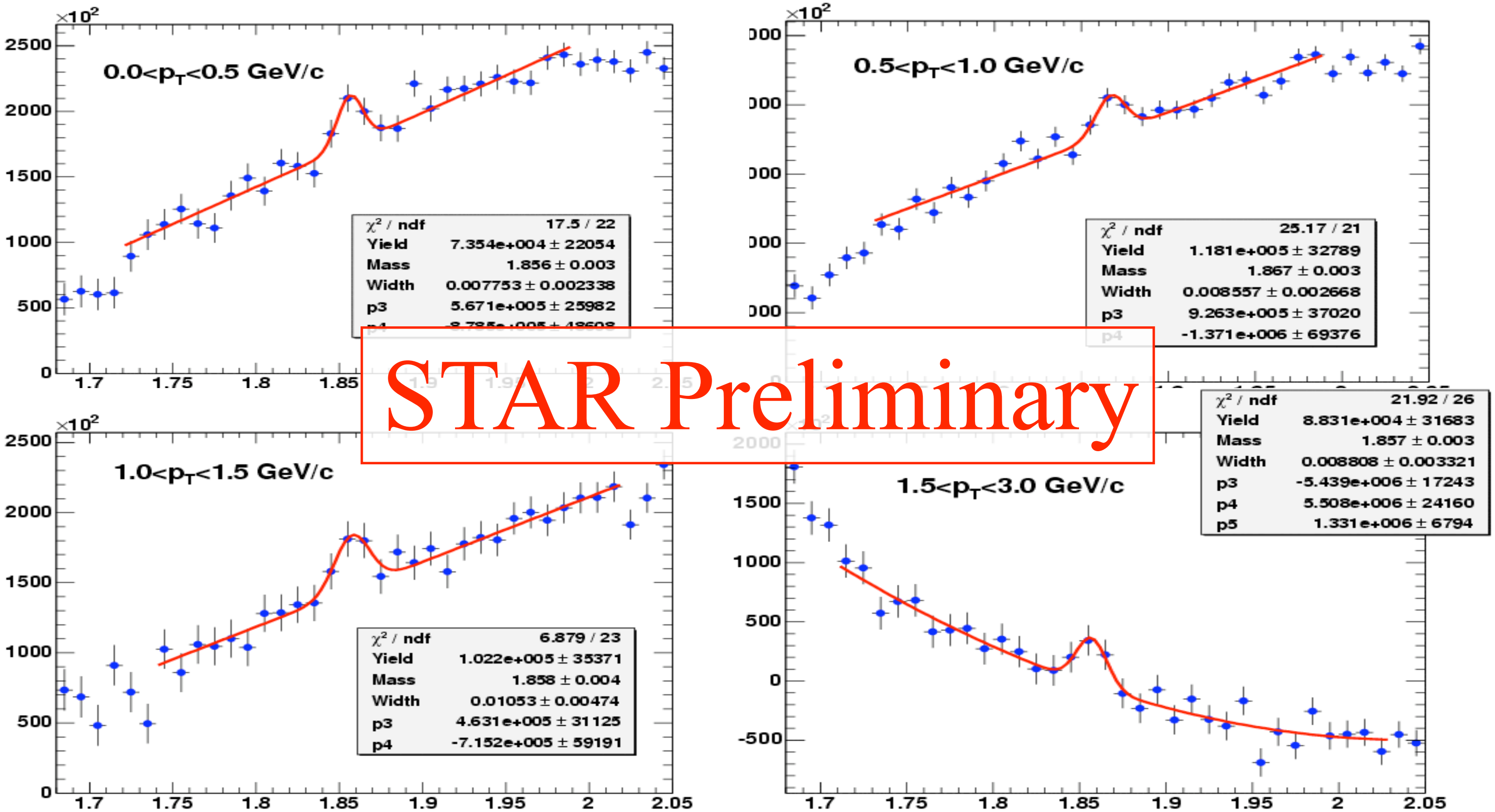
D^0-Meson Reconstruction

~11M minimum bias Au+Au events at √sNN = 200 GeV
0-80% collision centrality selected



Signal significance: 6 sigma
Mass agrees with PDG, Width expected from detector resolution

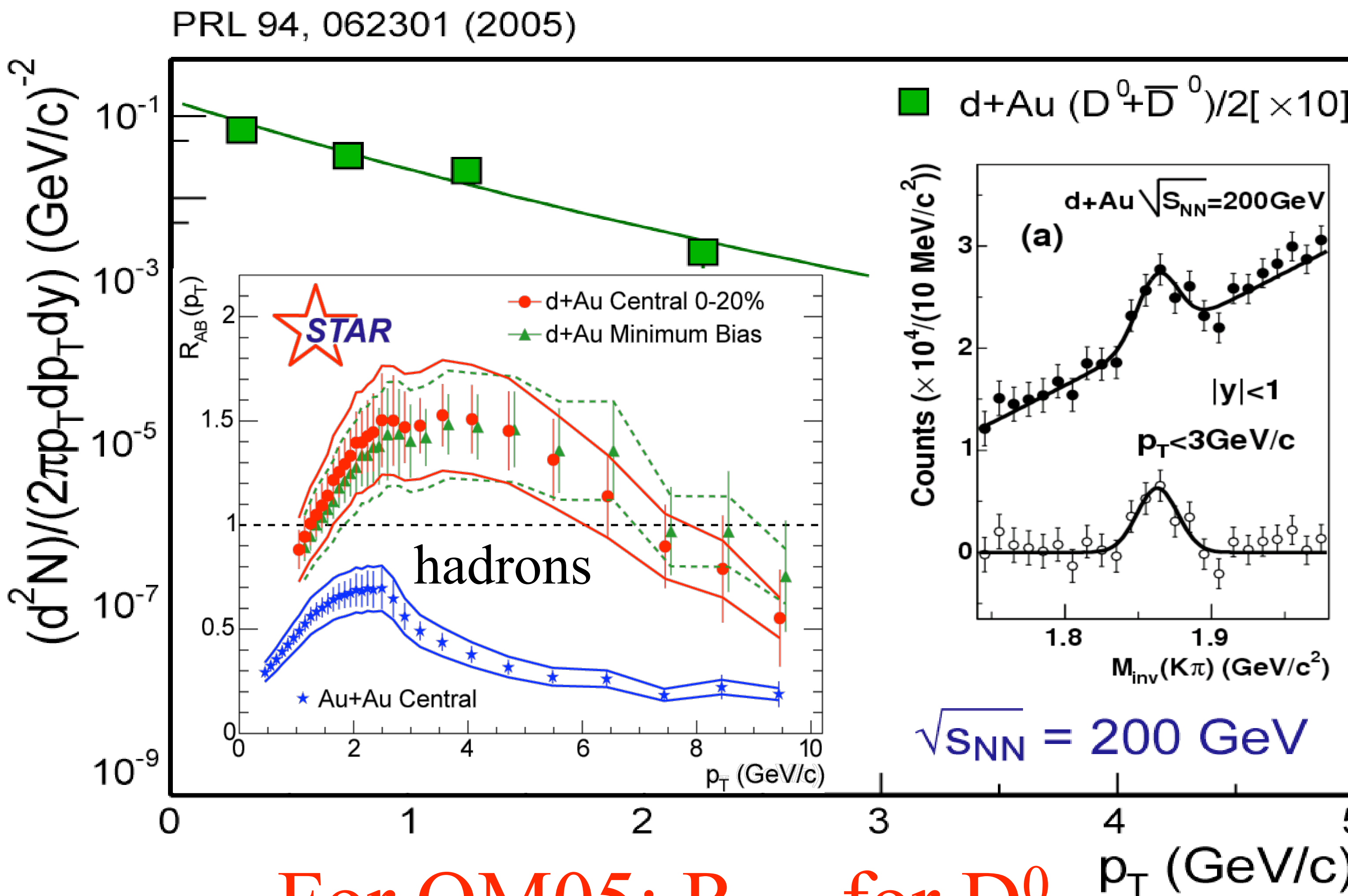
Preliminary D0 Results in Au+Au at 200 GeV



- ★ changing residual background shapes due to worsening PID at higher pT
- ★ efficiency calculations (spectra) in progress; ready for QM2005

D^0 Mesons in d+Au

dN/dy = 0.028±0.004(stat)±0.008(sys)   ⟨pT⟩ = 1.24±0.8 GeV/c



For QM05: R_{AA} for D^0

Detecting Charm/Beauty via Semileptonic D/B Decays

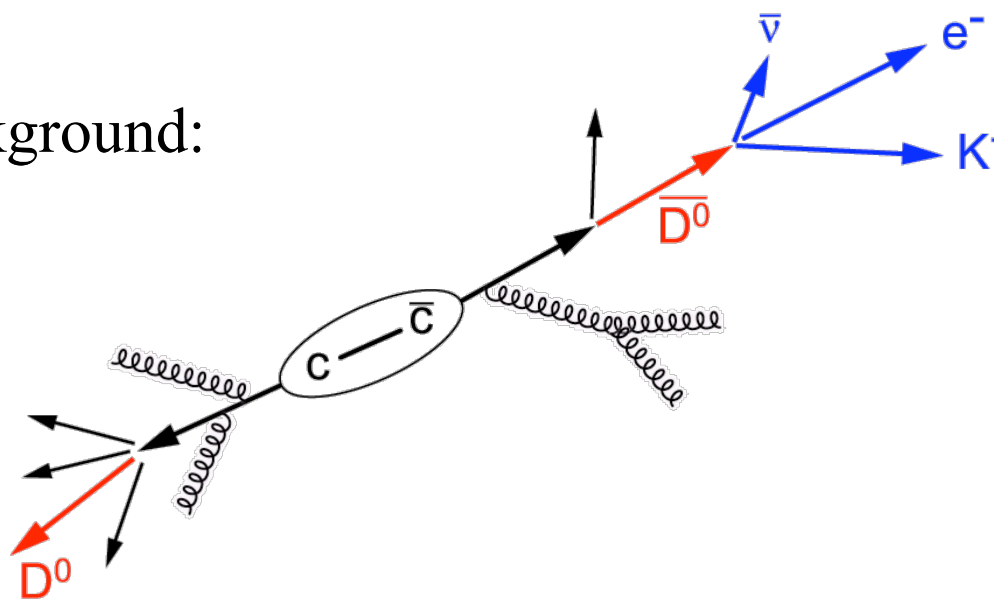
Semileptonic Channels:

- ★ $c \rightarrow e^{+} + \text{anything}$ (B.R.: 9.6%)
  - ★ $D^{0} \rightarrow e^{+} + \text{anything}$ (B.R.: 6.87%)
  - ★ $D^{\pm} \rightarrow e^{\pm} + \text{anything}$ (B.R.: 17.2%)
- ★ $b \rightarrow e^{+} + \text{anything}$ (B.R.: 10.9%)
  - ★ $B^{\pm} \rightarrow e^{\pm} + \text{anything}$ (B.R.: 10.2%)

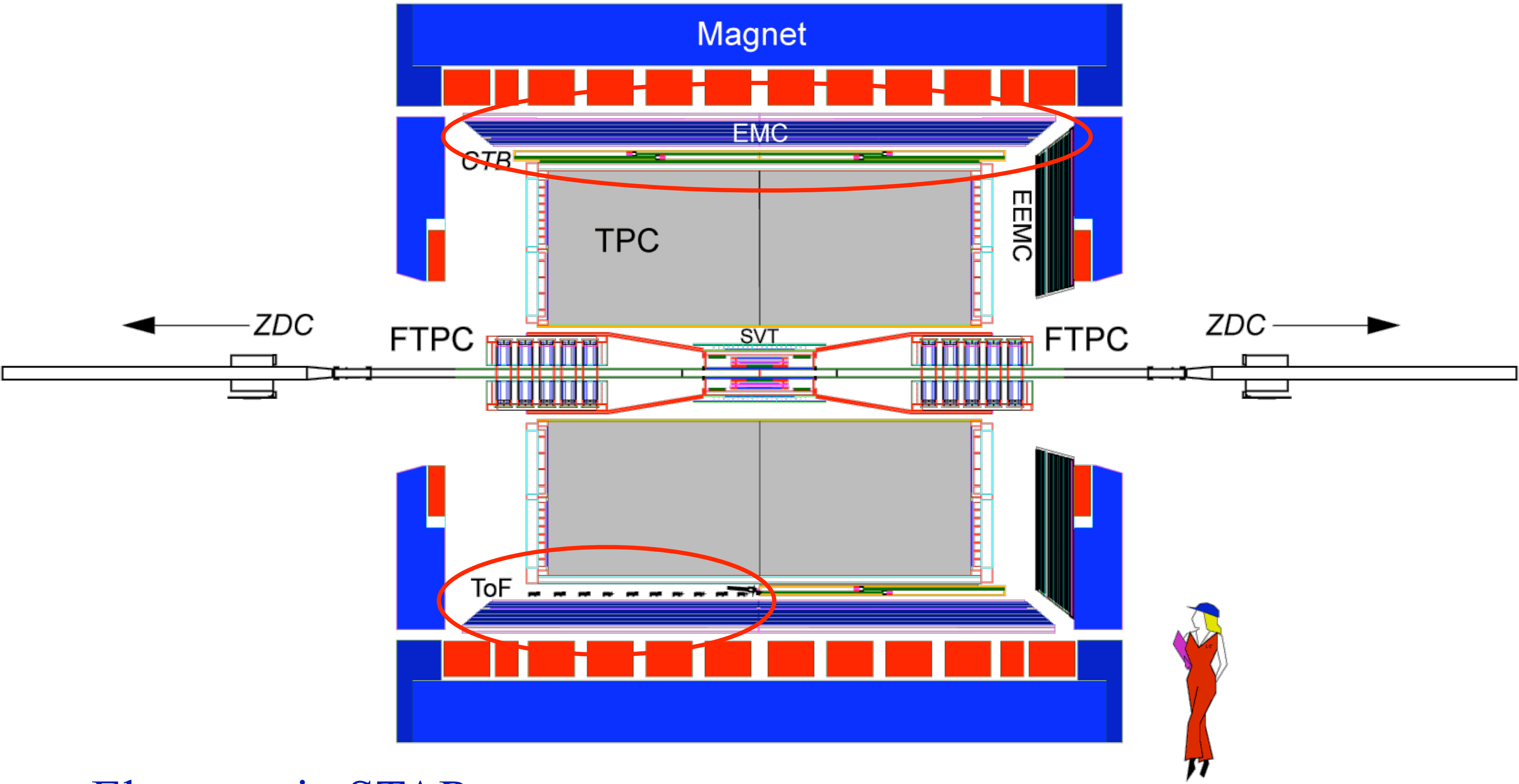
⇒ single "*non-photonic*" electron continuum

"*Photonic*" Single Electron Background:

- ★ γ conversions ($\pi^{0} \rightarrow \gamma\gamma$)
- ★ π^{0}, η, η' Dalitz decays
- ★ ρ, ϕ, … decays (small)
- ★ K_{e3} decays (small)



Detecting Charm/Beauty via Semileptonic D/B Decays



Electrons in STAR:

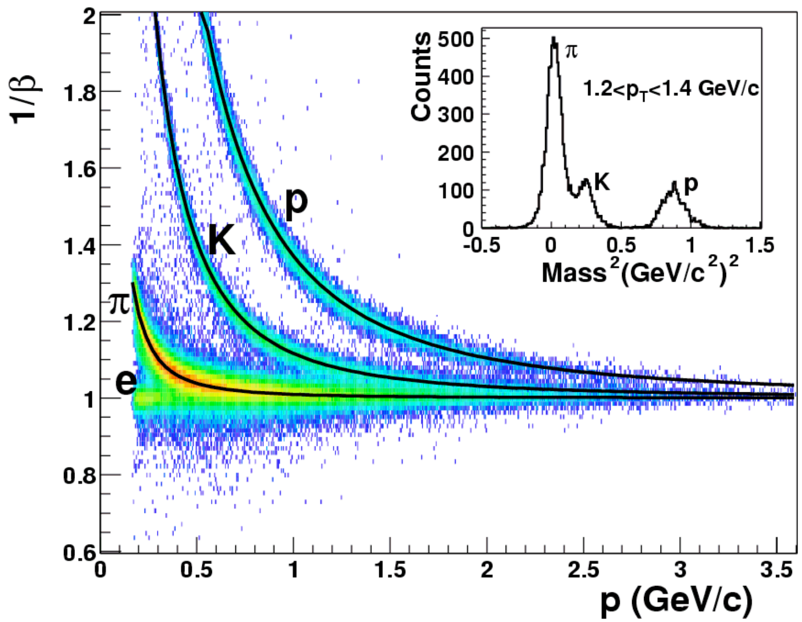
- ★TPC: tracking, PID
- ★BEMC (tower, SMD): PID
- ★EEMC (tower, SMD): PID
- ★ToF patch: PID ($\Delta\phi \approx \pi/30$ $-1 < \eta < 0$)

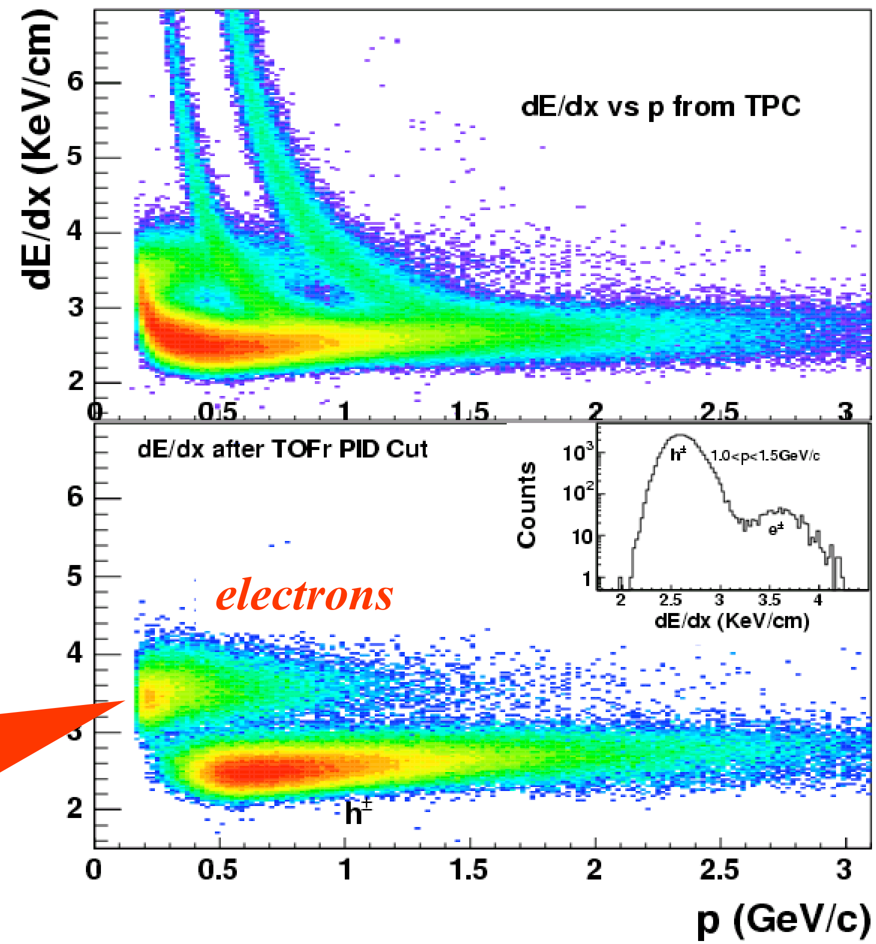
Electron ID in STAR – ToF Patch

MRPC – ToF (prototype):

$\Delta\phi \approx \pi/30$

$-1 < \eta < 0$





Electron identification:

TOF $|1/\beta-1| < 0.03$

TPC dE/dx electrons

Electron ID in STAR – EMC

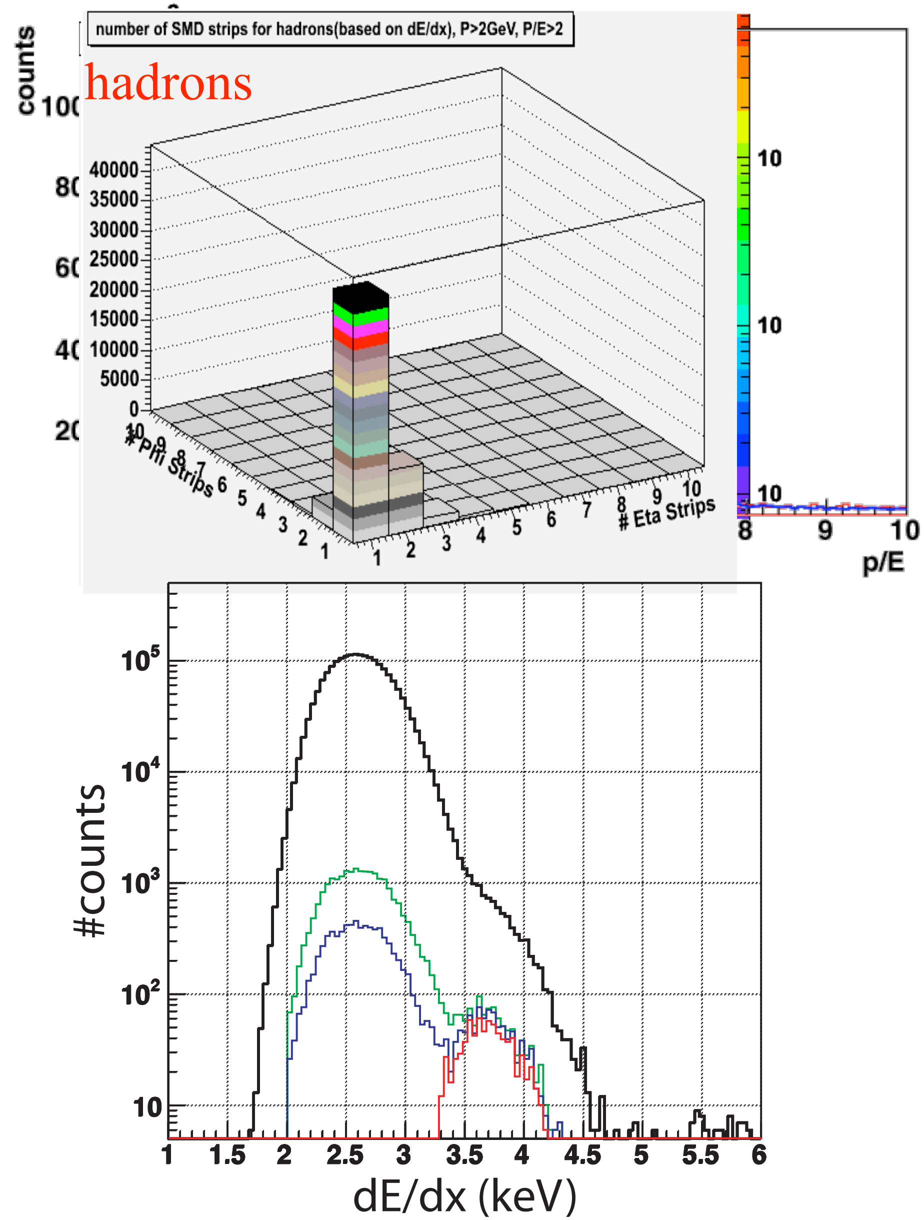
1. TPC: dE/dx vs p for p>2GeV

2. EMC: Tower E >1.5GeV

3. EMC: Tower E $\Rightarrow$ p/E

4. EMC: Shower Max Detector (SMD) shape to reject hadrons

- ✘ *e/h* ~ 100
- ✘ *h* discrimination power ~10^5
- ✘ Works best for p > 1.5 GeV/c, perfect complement to the ToF

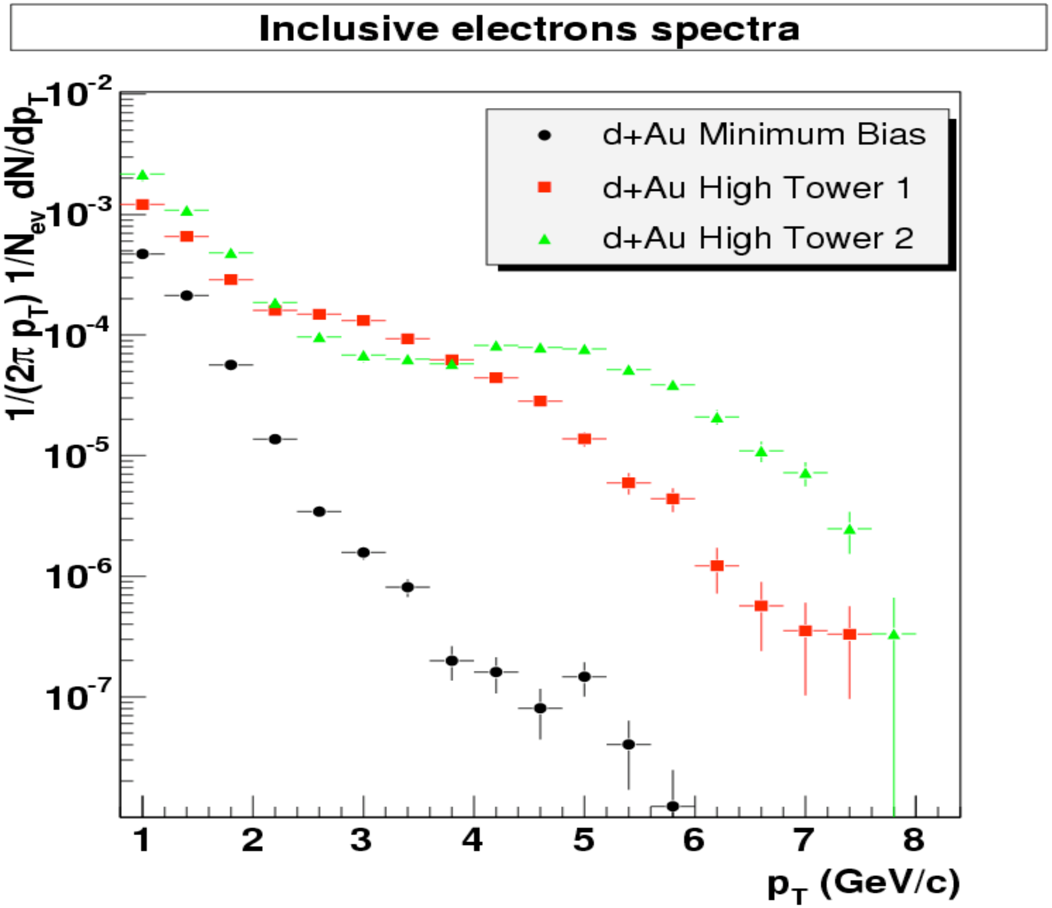


Triggering Capabilities from the EMC

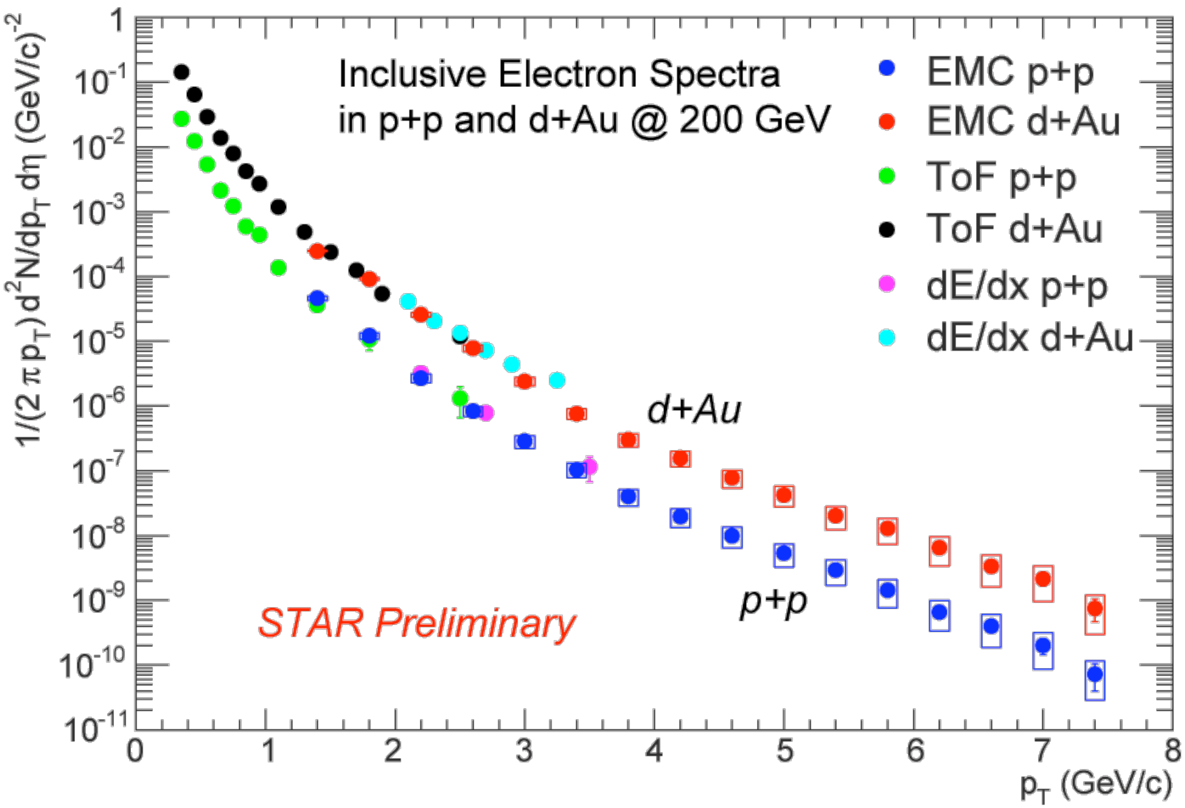
EMC provides a Level 0 high-pT electron trigger

- Runs for every RHIC crossing (10 MHz)
- Multiple ET thresholds in prescale ladder
  - For this plot, 2.5 and 5 GeV
- Enhancement proven to be >1000 for pT > 5 GeV/c

- More sophisticated triggers already working (JPsi, Jet)



Inclusive Single Electrons p+p/d+Au



ToF + TPC:
0.3 GeV/c < p_T < 3 GeV/c

TPC only:
2 < p_T < 3.5 GeV/c

EMC + TPC:
p_T > 1.5 GeV/c

Good overlap between different detectors.

Inclusive → non-photonic spectra : How to assess photonic background?

PHENIX 1: cocktail method

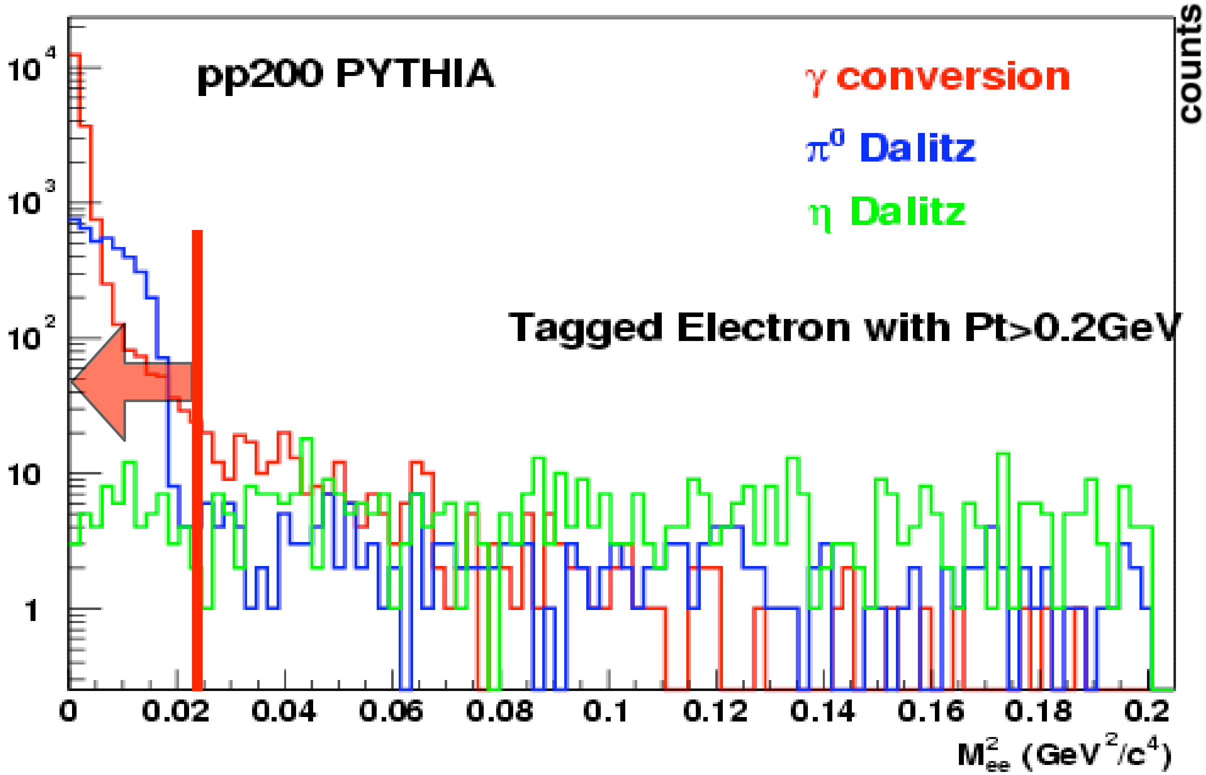
PHENIX 2: converter method

STAR: measurement of main background sources

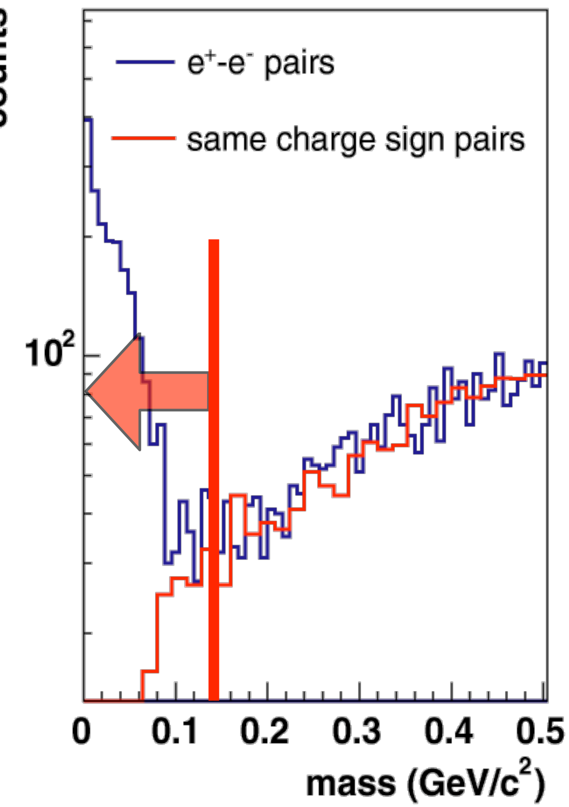
Photonic Electron Background Subtraction in pp and dAu

Method:

1. Select an primary electron/positron (tag it)
2. Loop over opposite sign tracks anywhere in TPC
3. Reject tagged track when $m < m_{cut} \sim 0.1 - 0.15$ MeV/c^2
4. Cross-check with like-sign



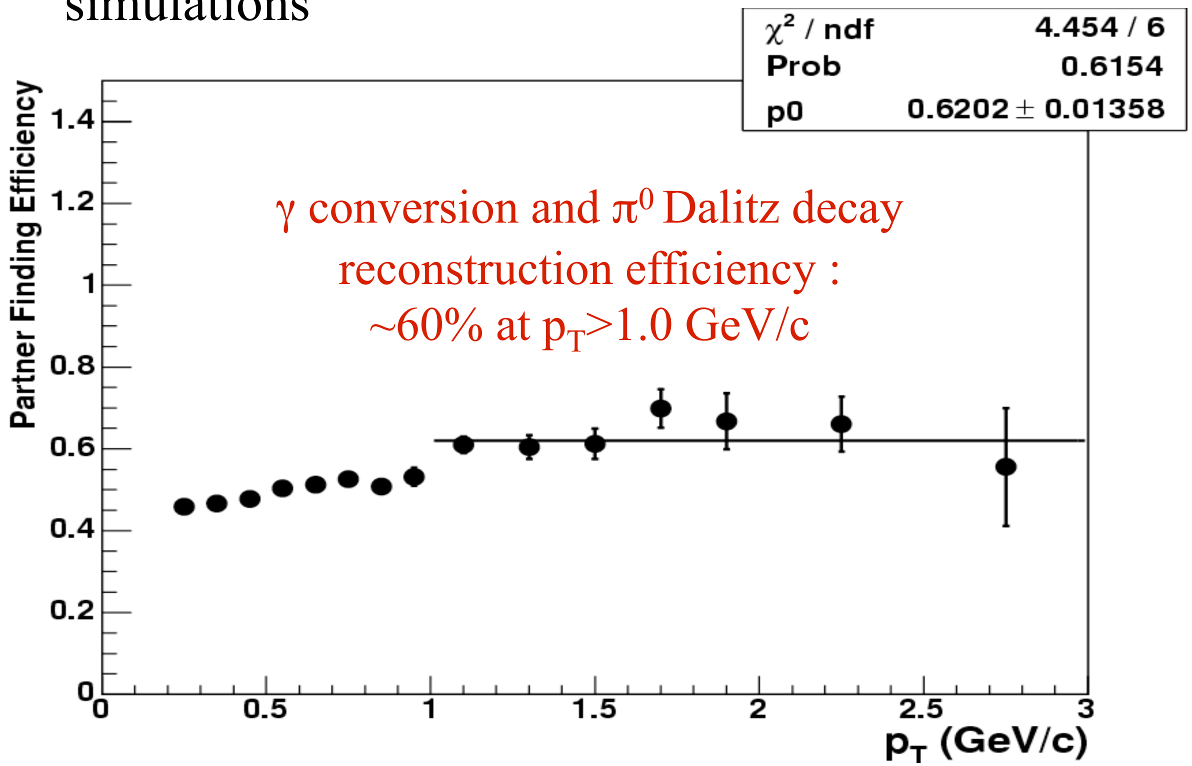
Au+Au @200GeV

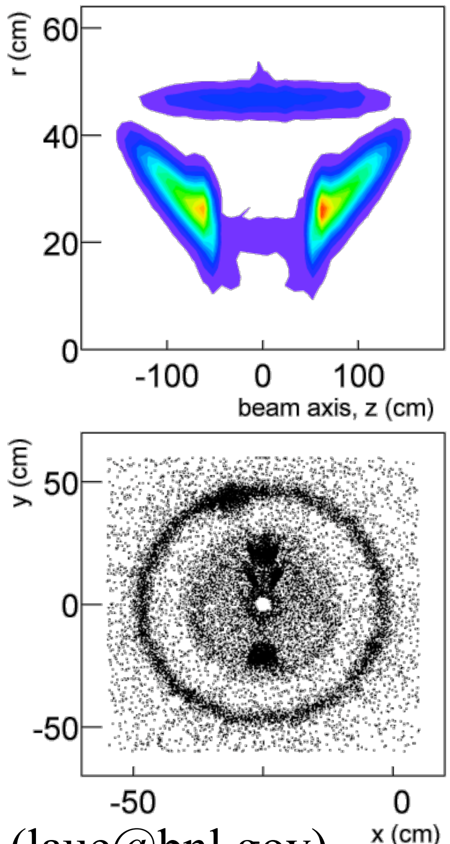


Photonic Single Electron Background Subtraction

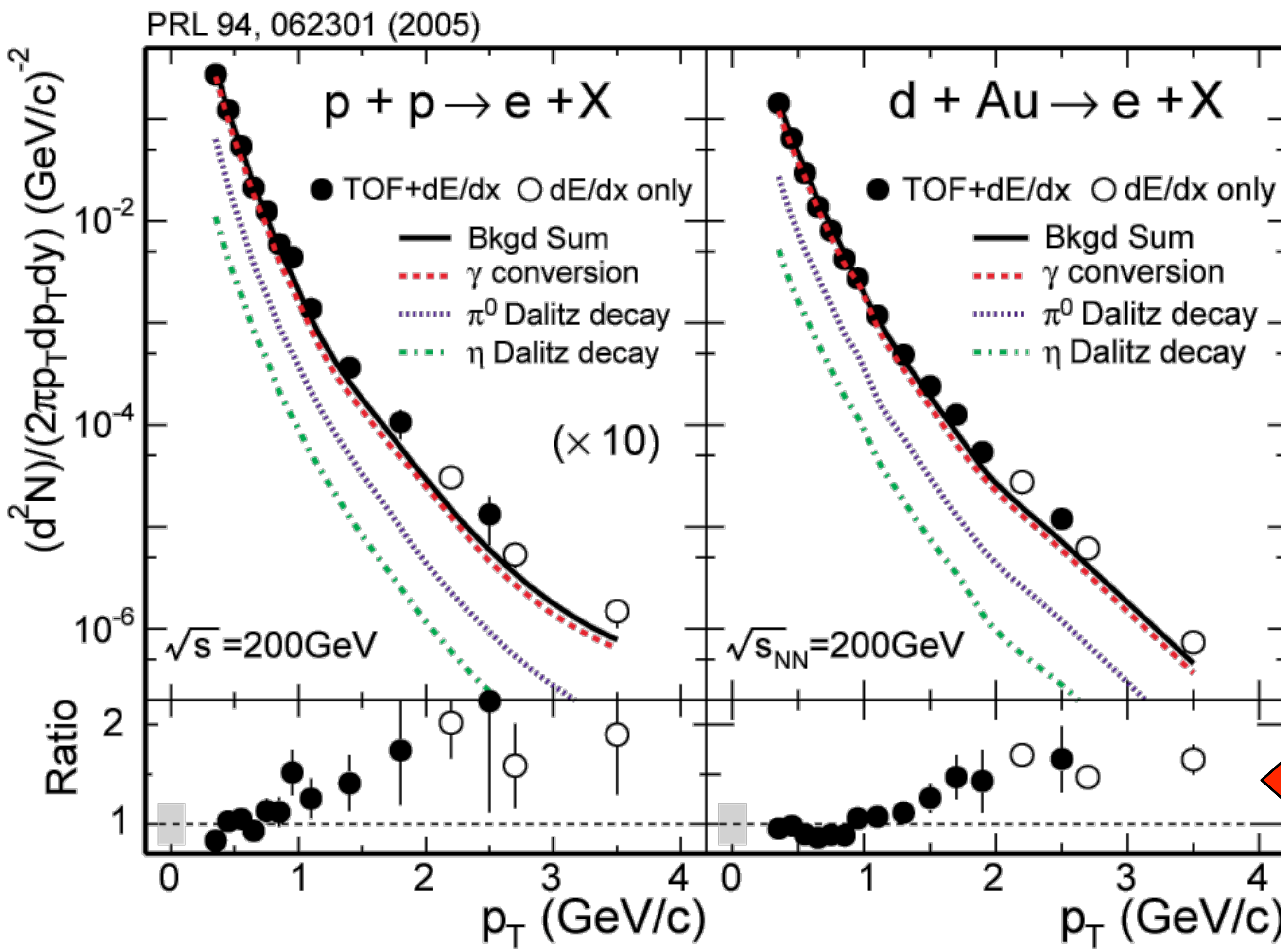
Rejection Efficiency:

- Simulation/Embedding
  - background flat in p_T
  - weight with measured π^0 spectra (PHENIX)
- γ, π^0 Dalitz decay reconstruction efficiency ~60%
- Relative contributions of remaining sources: PYTHIA/HIJING + detector simulations





Photonic Single Electron Background Subtraction

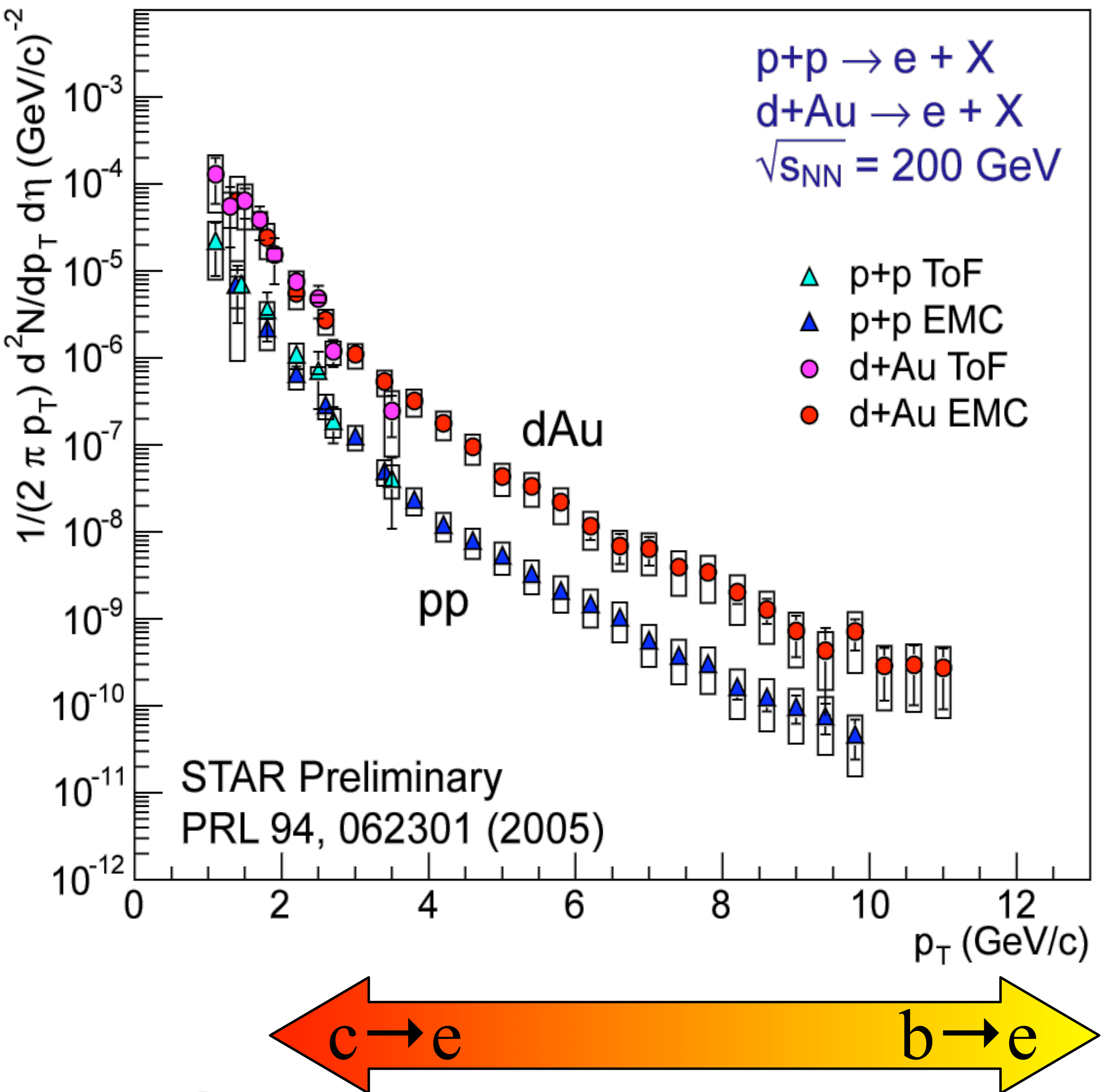


Excess over background

p_T dependent hadron contamination (5-30%) subtracted

(year 2 data, no EMC)

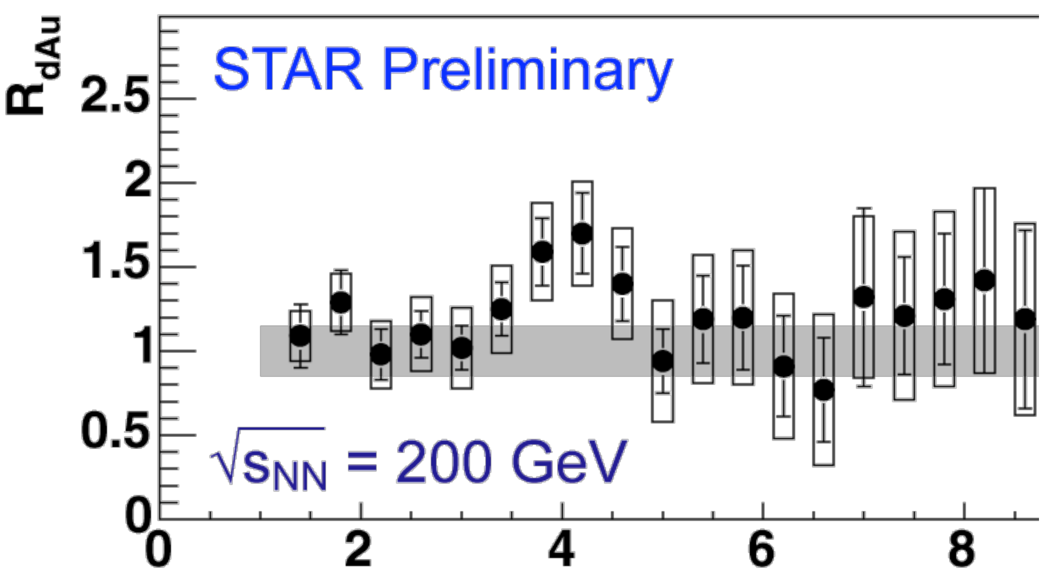
Non-Photonic Single Electron Spectra in p+p and d+Au

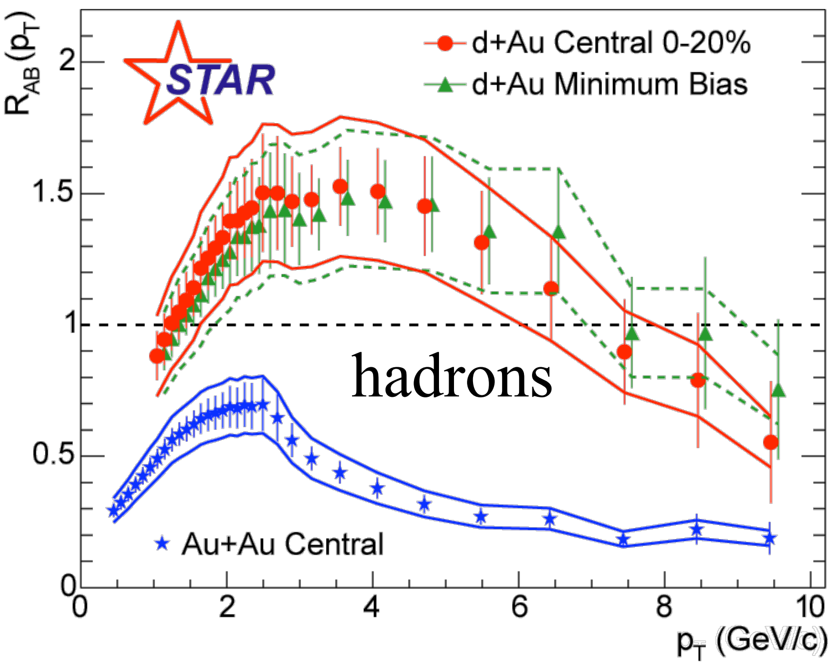


- ★ 6 order of mag.
- ★ nice overlap between detectors
- ★ EMC extends out pT reach well into the bottom regime
- ★ Au+Au data ready for QM 2005
  - ★ R_{AA} for electrons

Nuclear Effects R_{dAu} ?

Nuclear Modification Factor: $$R_{dAu} = \frac{d^2N_{dAu}/dp_T d\eta}{T_{dAu} d^2\sigma_{pp}/dp_T d\eta}; \text{ where } T_{dAu} = \langle N_{bin}^{dAu} \rangle / \sigma_{pp}^{inel}$$





Within errors compatible with $R_{dAu} = 1$ …

… but also with $R_{dAu}(h^{\pm})$

NOTE: R_{dAu} for a given p_T comes from heavy mesons from a wide p_T range

$\langle p(D) \rangle > \langle p(e) \rangle$ (~ ×1.5-3) ⇒ makes interpretation difficult

Obtaining the Charm Cross-Section $\sigma_{c\bar{c}}$

From D^0 mesons alone:

- $N_{D0}/N_{cc} \sim 0.54 \pm 0.05$
- Fit function from exponential fit to m_T spectra

Combined fit:

- Assume D^0 spectrum follows a power law function
- Generate electron spectrum using particle composition from PDG
- Decay via routines from PYTHIA
- Assume: $dN/dp_T(D^0, D^*, D^{\pm}, \ldots)$ have same shape only normalization

In both cases for d+Au → p+p:

- $\sigma_{pp}^{inel} = 42$ mb
- $N_{bin} = 7.5 \pm 0.4$ (Glauber)
- $|y|<0.5$ to 4π: $f = 4.7 \pm 0.7$ (PYTHIA)
- $R_{dAu} = 1.3 \pm 0.3 \pm 0.3$

Charm Cross-Section $\sigma_{c\bar{c}}$

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

	$dN(D^0)/dy\|_{y=0}$ (10^{-2})	$d\sigma^{NN}_{c\bar{c}}/dy\|_{y=0}$ (mb)
D^0	$2.8 \pm 0.4 \pm 0.8$	$0.29 \pm 0.04 \pm 0.08$
$D^0 + e^{\pm}$	$2.9 \pm 0.4 \pm 0.8$	$0.30 \pm 0.04 \pm 0.09$

$\times$ 4.7 ($|y|<0.5 \rightarrow 4\pi$)

pp Charm Cross-Section

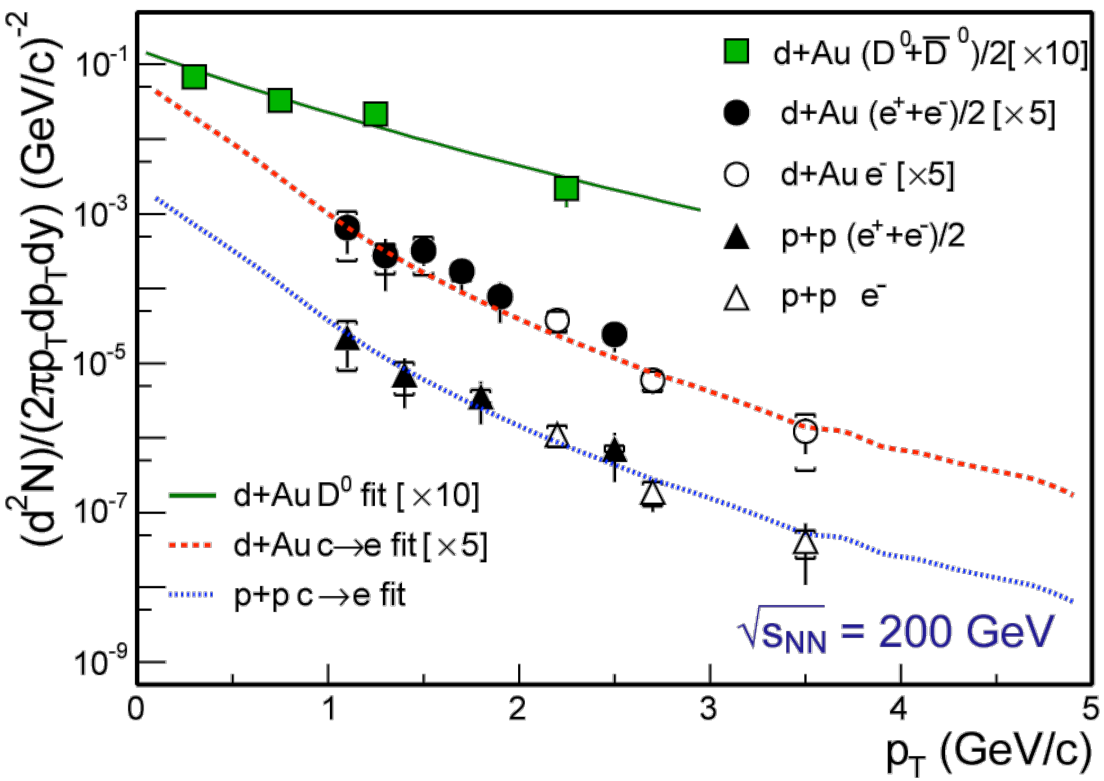
From D^0 alone:

$\sigma_{cc} = 1.3 \pm 0.2 \pm 0.4$ mb

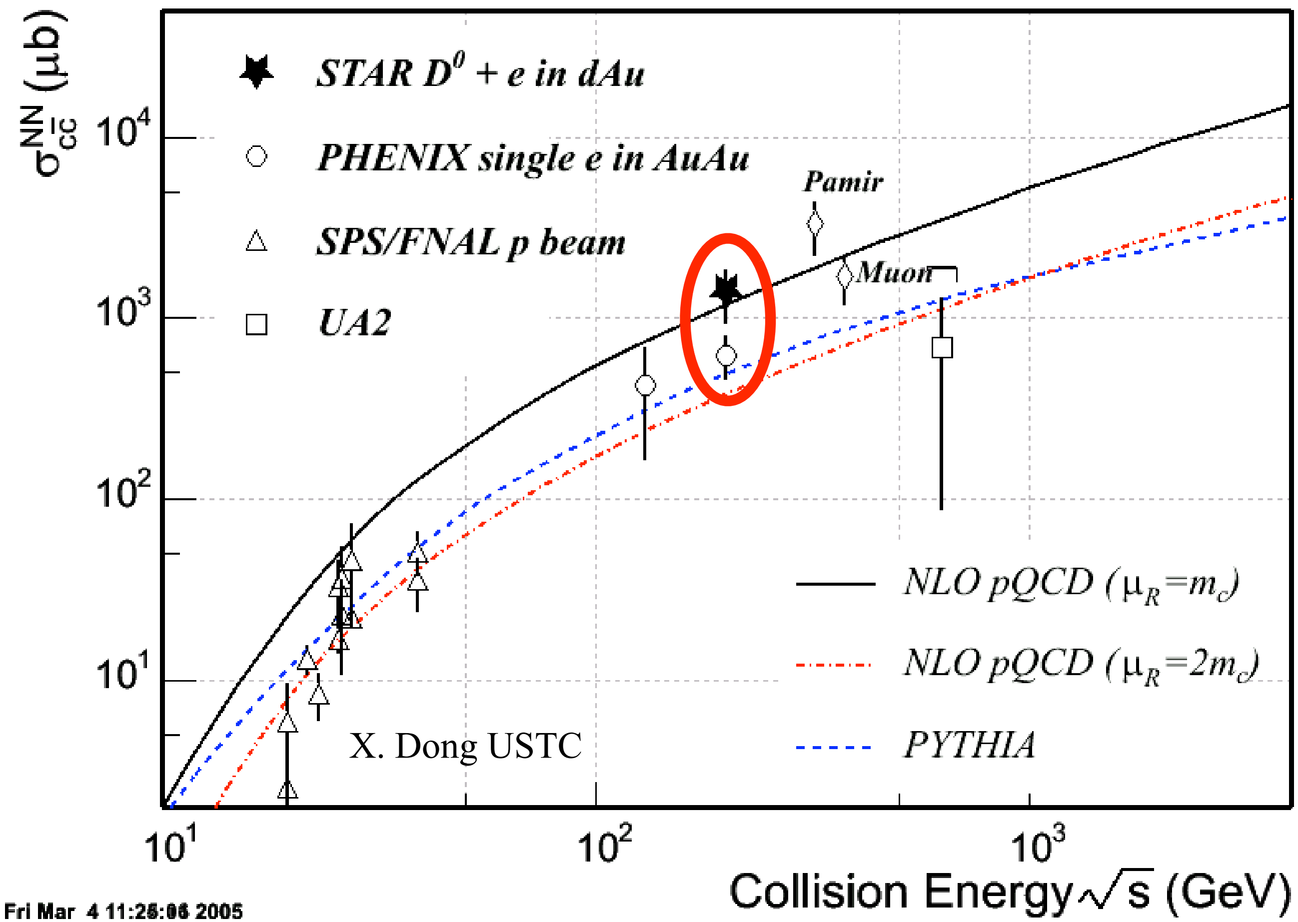
From combined fit:

$\sigma_{cc} = 1.4 \pm 0.2 \pm 0.4$ mb

PRL 94, 062301 (2005)



Charm Total Cross Section



Can we confirm or rule out Cosmic Ray experiments? (Pamir, Muon, Tian Shan) under similar conditions?

NPB (Proc. Suppl.) 122 (2003) 353

Nuovo Ciment. 24C (2001) 557

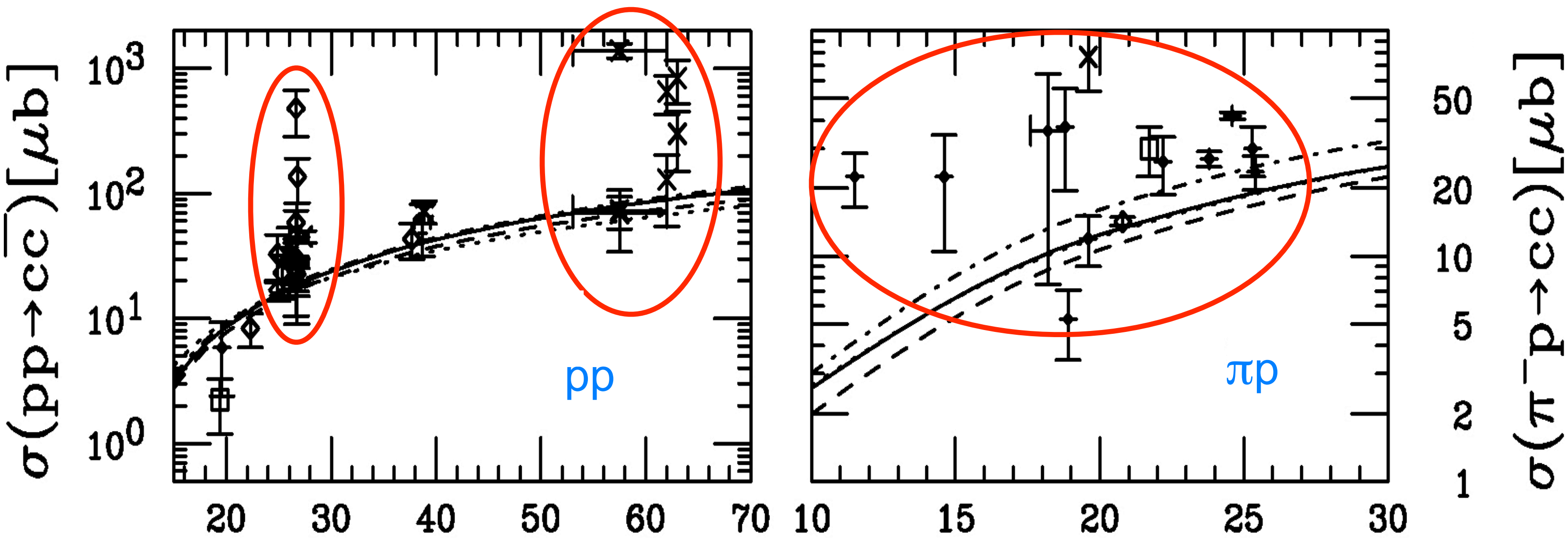
PHENIX,STAR: stat. error only

- NLO calculations under-predict current σ_{cc} at RHIC
- More precise data is needed ⇒ high statistics D mesons in pp

Discrepancy between STAR and PHENIX ?

STAR from d+Au: $\sigma_{cc} = 1.4 \pm 0.2 \pm 0.4$ mb (PRL94,062301)
PHENIX from p+p (preliminary): $\sigma_{cc} = 0.709 \pm 0.085 + (+0.332,-0.281)$ mb
PHENIX from min. bias Au+Au: $\sigma_{cc} = 0.622 \pm 0.057 \pm 0.160$ mb (PRL94,082301)

Reality check: 1.4 ± 0.447 mb and 0.71 ± 0.343 mb are not so bad (2σ) given the currently available statistics (soon be more!)

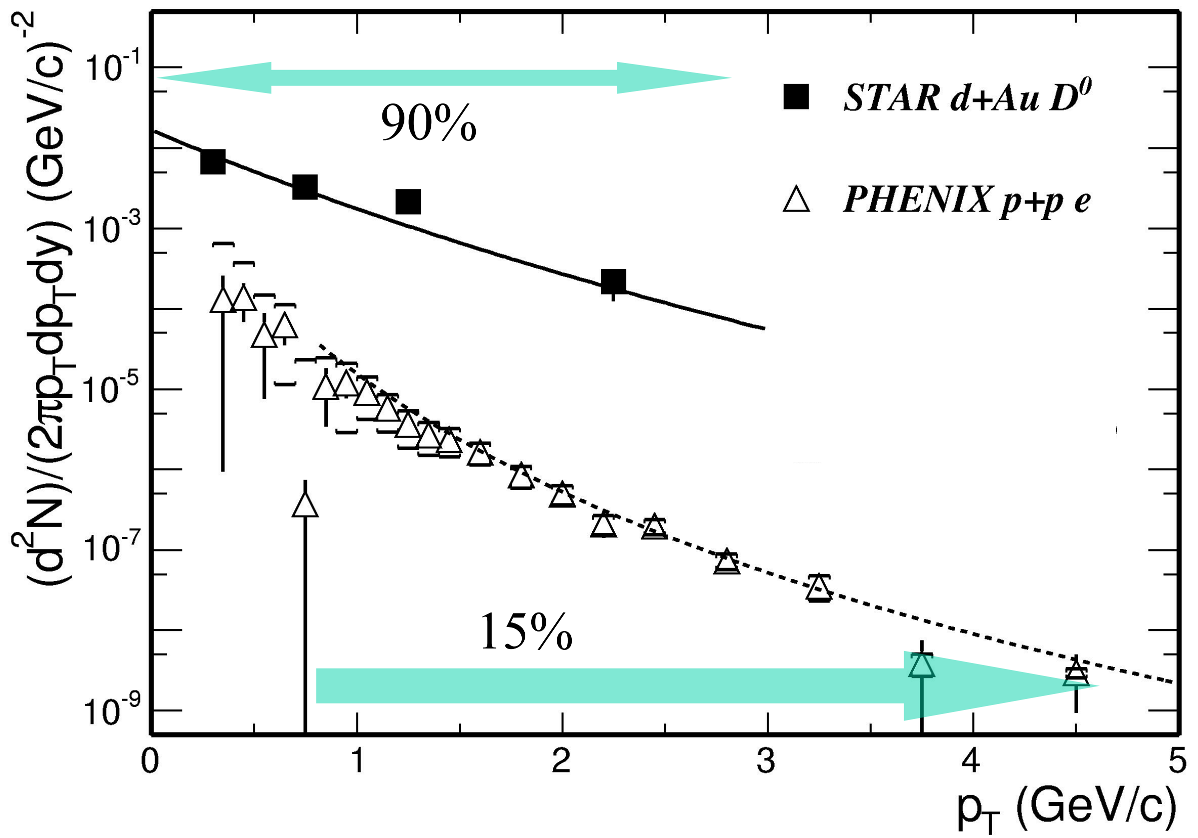


SPS, FNAL (fixed target) and ISR (collider) experiments

Discrepancy between STAR and PHENIX ?

Combined fit of STAR D^0 and PHENIX electrons:

No discrepancy: σ_{cc}=1.1± 0.1 ± 0.3 mb



STAR: PRL 94, 062301 (2005)

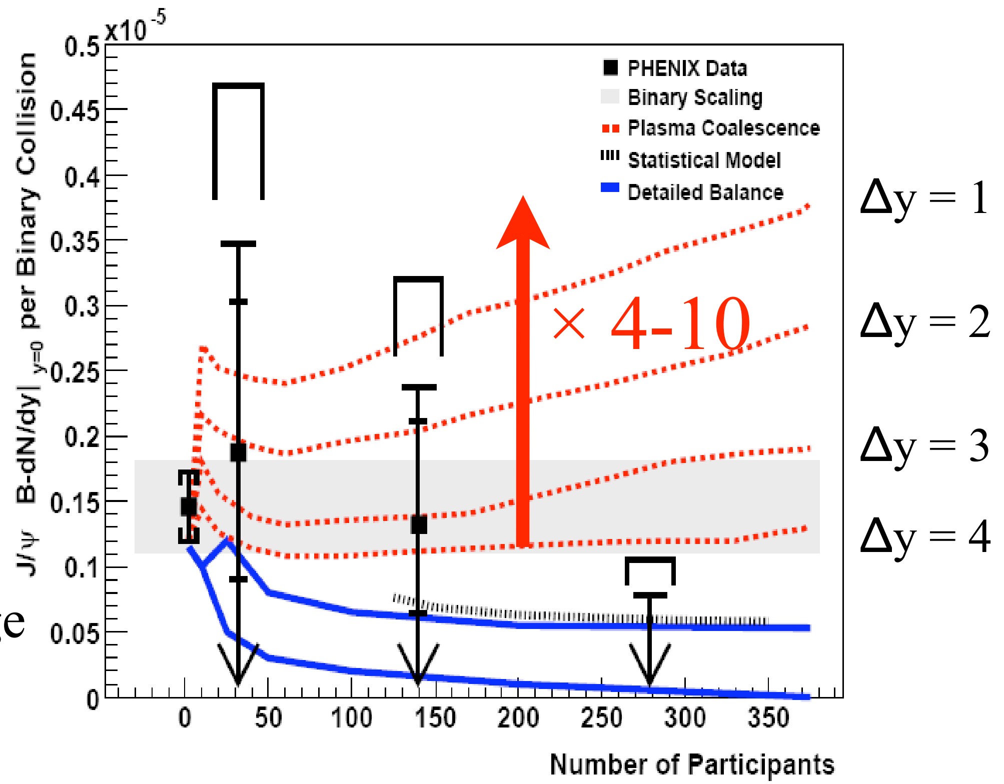
PHENIX p+p (QM04): S. Kelly et al. JPG30(2004) S1189

Consequences of High Cross-Section: J/Ψ Recombination

Statistical model (e.g. A. Andronic et. al. PLB 571,36(2003)) :
Large $c\bar{c}$ yield in heavy ion collisions:

- ★ J/Ψ production through recombination
- ★ possible J/Ψ enhancement

- ★ In stat models: σ_{cc} typically from pQCD calculations (~390 μb)
- ★ STAR σ_{cc} =1.4mb ⇒ much larger enhancement for J/Ψ production in central Au+Au collisions (×4-10)
- ★ PHENIX's upper limit would invalidate the expectation from large σ_{cc} !?!



NLO/FONLL

Recent calculations in NLO (e.g. R. Vogt et al. hep-ph/0502203)

- Calculations depend on:
  - quark mass m_c
  - factorization scale μ_F (typically $\mu_F = m_c$ or 2 m_c)
  - renormalization scale μ_R (typically $\mu_R = \mu_F$)
  - parton density functions (PDF)
- Hard to obtain large σ with $\mu_R = \mu_F$ (which is used in PDF fits)

Fixed-Order plus Next-to-Leading-Log (FONLL)

- designed to cure large logs for $p_T >> m_c$ where mass is not relevant

K factor (NLO → NNLO) ?

m (GeV)	μ_F/m_T	μ_R/m_T	σ(all y) (μb)	σ(|y| ≤ 0.75) (μb)	σ(1.2 ≤ |y| ≤ 2.2) (μb)
$\sqrt{s}$ = 200 GeV					
1.3	1	1	367.4	130.9	54.75
1.5	1	1	234.2	85.69	34.70
1.7	1	1	151.2	56.71	22.32
1.5	0.5	0.5	368.8	118.5	56.93
1.5	0.5	1	110.3	38.18	16.65
1.5	1	0.5	649.4	231.0	97.21
1.5	2	2	180.4	66.15	26.77
1.5	2	1	317.5	114.9	47.20
1.5	1	2	129.4	47.74	19.12

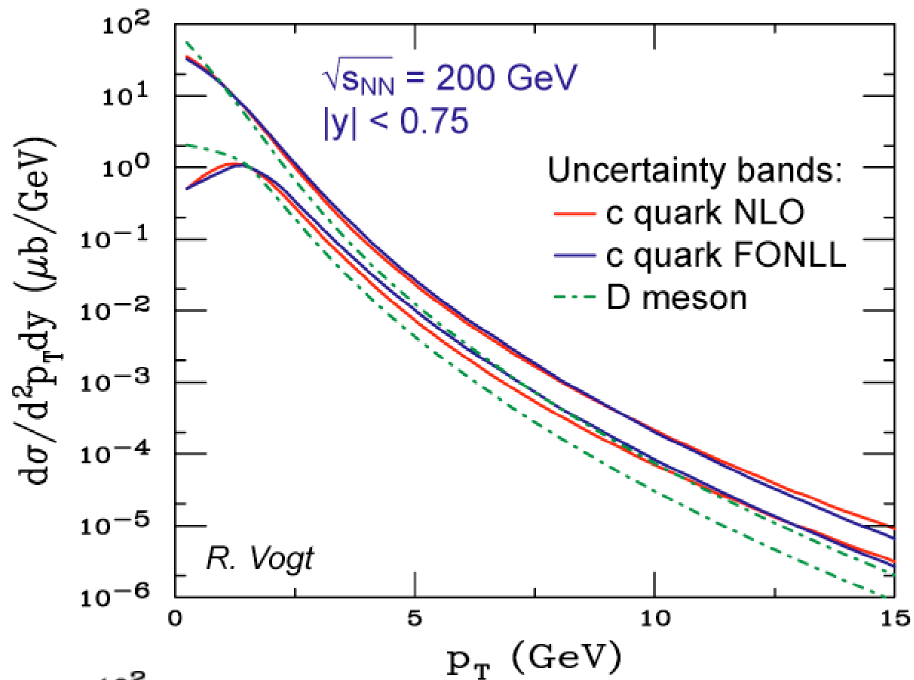
$$\sigma_{c\bar{c}}^{FONLL} = 256^{+400}_{-146}\,\mu b;\ \ \sigma_{c\bar{c}}^{NLO} = 244^{+381}_{-134}\,\mu b$$

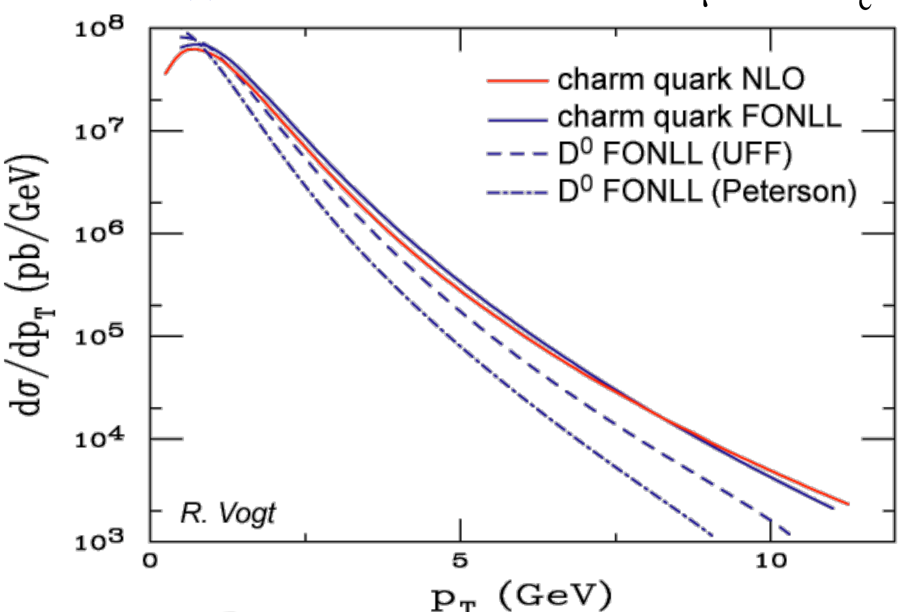
$$\sigma_{bb}^{FONLL} = 1.87^{+0.99}_{-0.67}\,\mu b$$

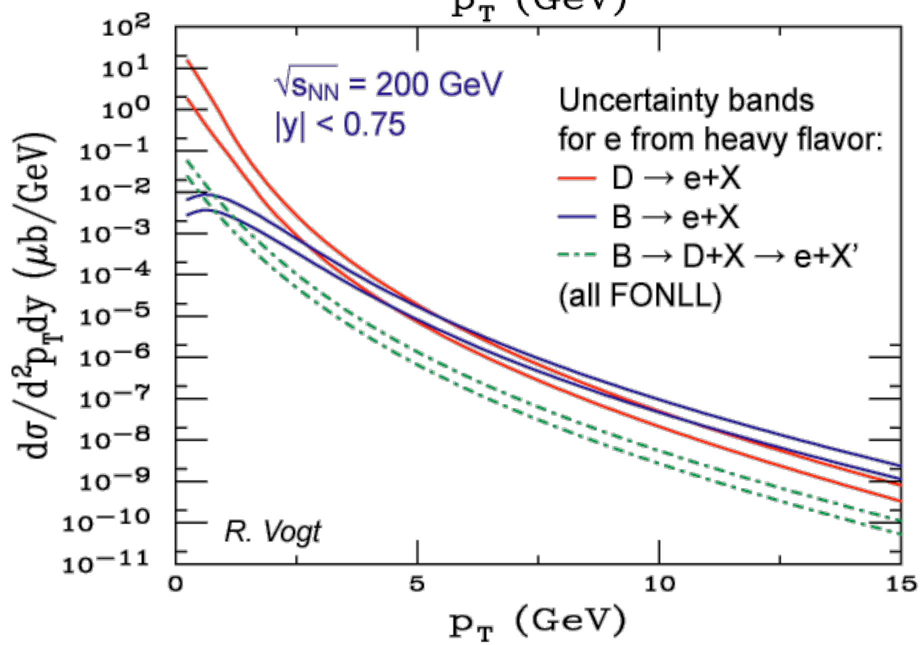
from hep-ph/0502203

NLO/FONLL

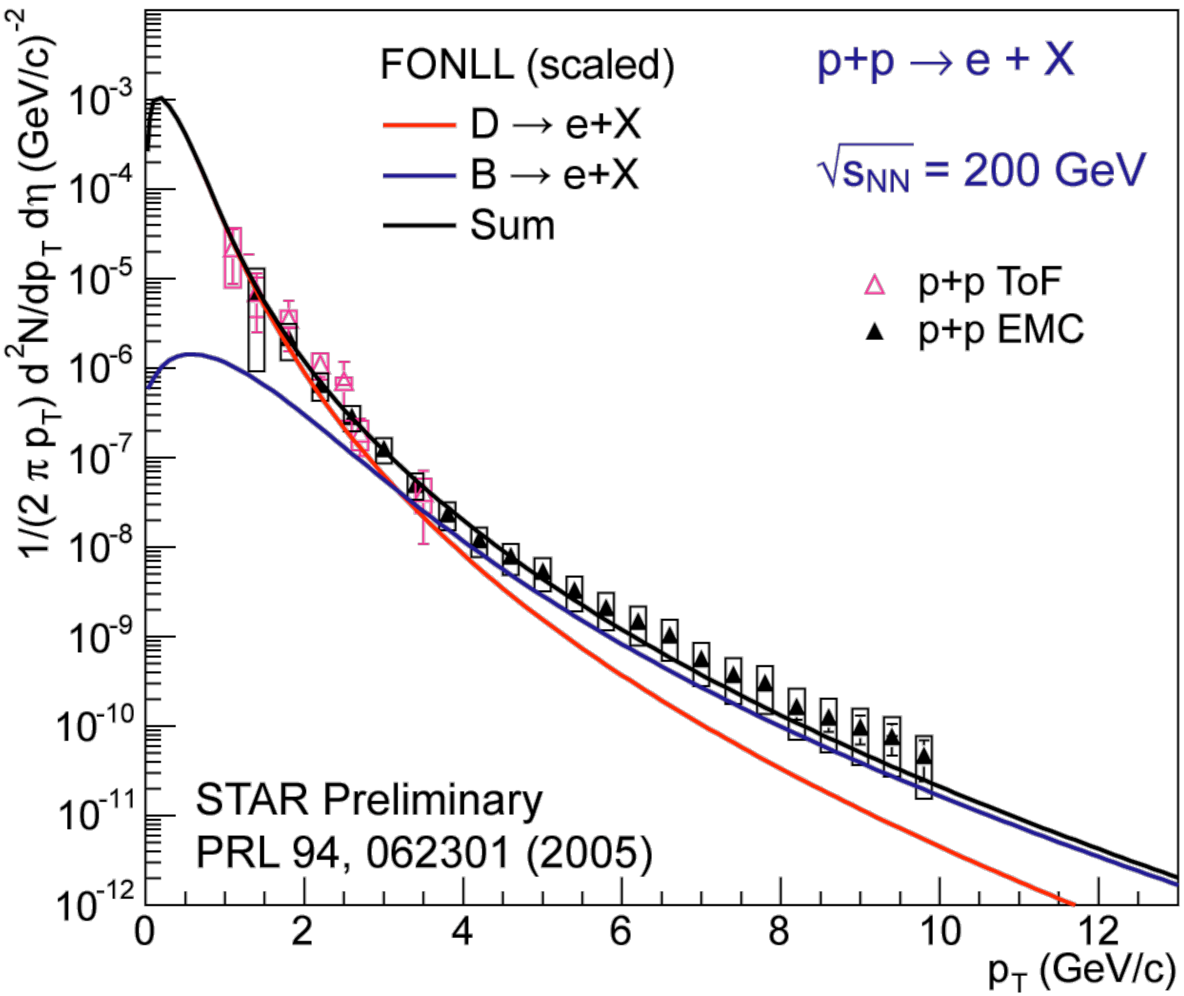
- ★ For p_T spectra $\mu^2 \propto m_T^2$
  - ★ for σ calculations $\mu^2 \propto m^2$
- ★ p_T integrated σ < direct calculated σ
- ★ FONLL higher over most p_T than NLO
- ★ Choice of FF plays big role
- ★ Uncertainty bands:
  - ★ reflect uncertainties in μ and m_c







Comparison: Non-Photonic Electrons with FONLL



FONLL calculations:

Charm:

scaled by $\sigma_{STAR}/\sigma_{FONLL}$

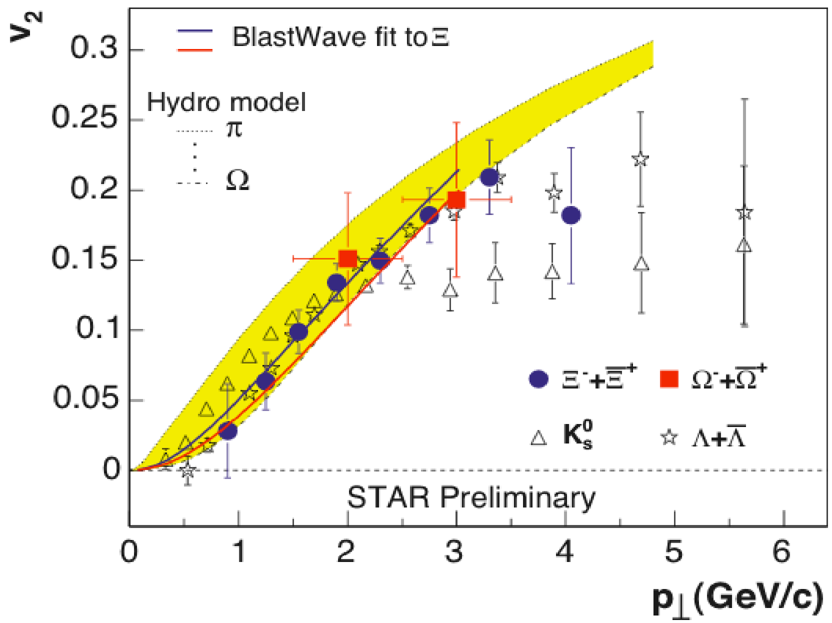
Bottom:

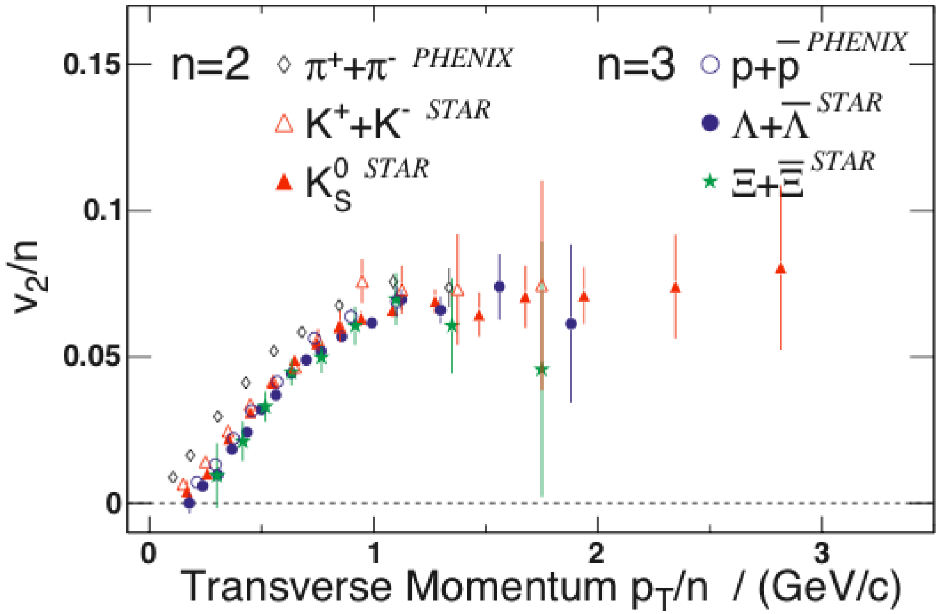
Can be estimated from fit of sum to data (numbers soon)

Errors used: data + FONLL uncertainty bands

Plenty of room for bottom !!!

Strong Elliptic Flow at RHIC





Strong elliptic flow at RHIC (consistent with hydro limit ?)

- ★ Scaling with Number of Constituent Quarks (NCQ)
  - ★ partonic degrees of freedom !?
- ★ (v_2/n) vs. (p_T/n) shows no mass and flavor dependence
- ★ Strong argument for partonic phase with thermalized light quarks

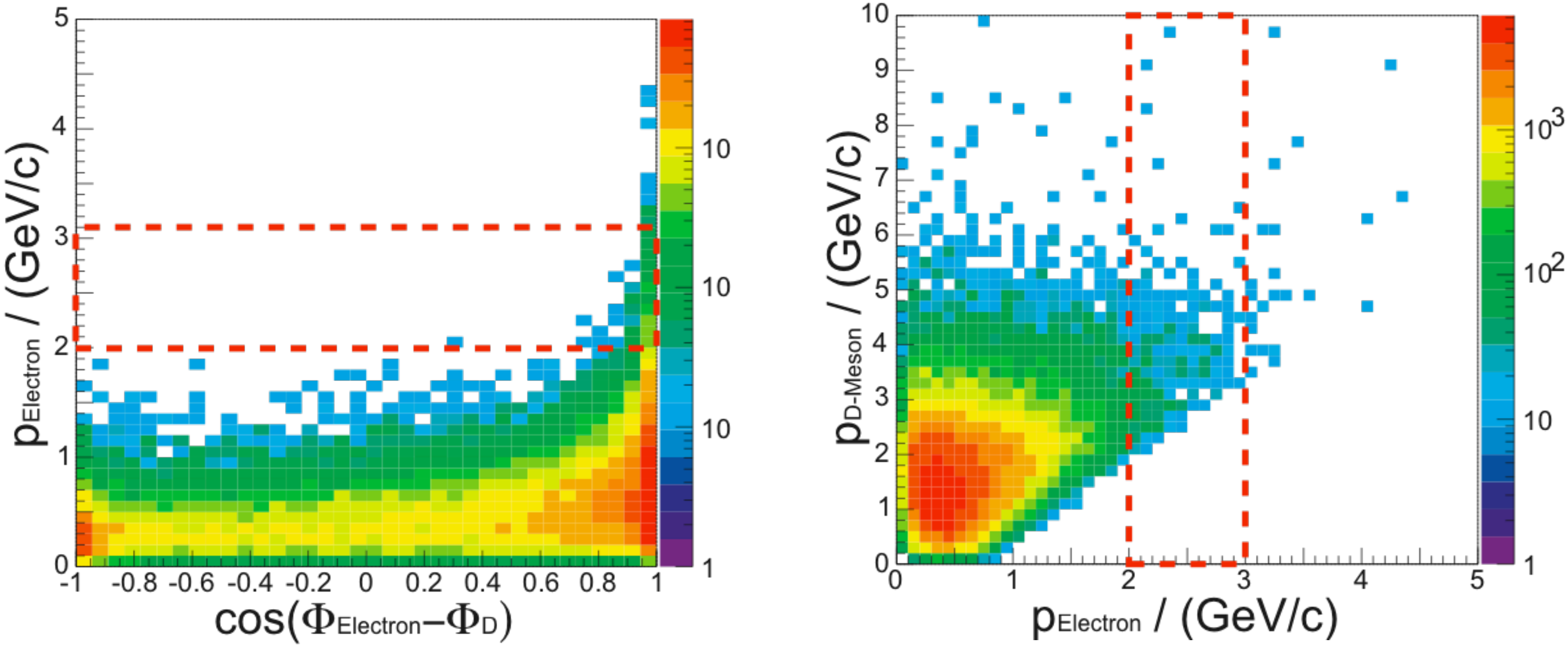
What's about charm?

- ★ Naïve kinematical argument: need $M_q/T \sim 7$ times more collisions to thermalize
- ★ v_2 of charm closely related to R_{AA}

How to Measure Charm v_2

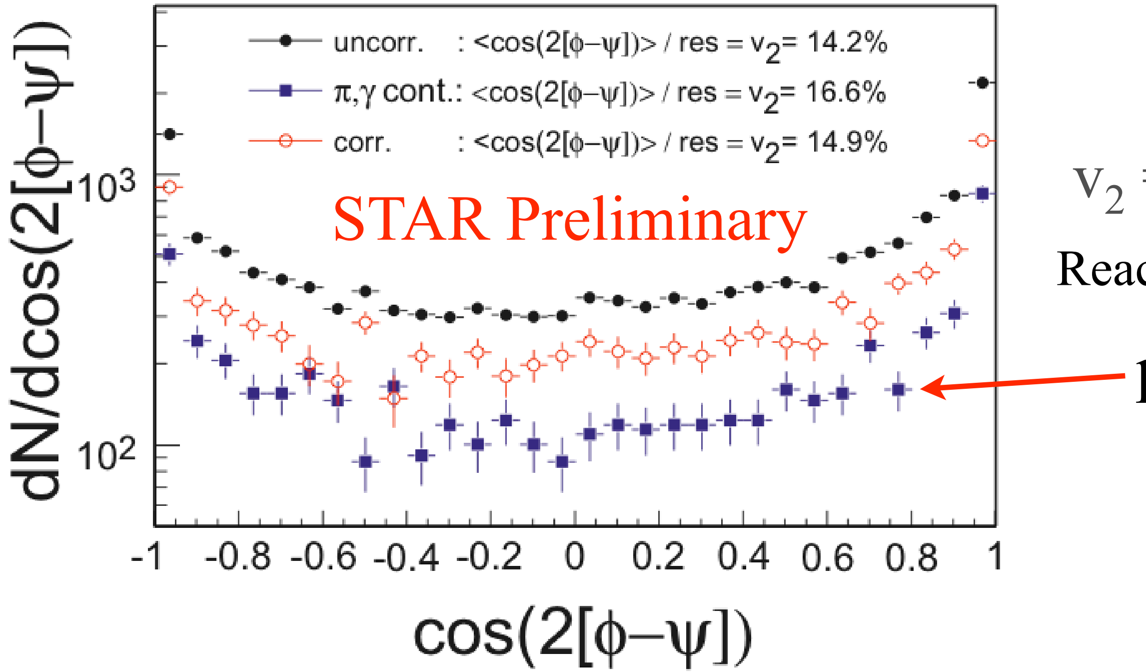
Best: D mesons ⇒ need large statistics, high background ⇒ not yet

Alternative: Measure v_2 of electrons from semileptonic charm decays



- ★ Emission angles are well preserved above p = 2 GeV/c
- ★ 2-3 GeV Electrons correspond to ≈3-5 GeV D-Mesons

Analysis: v_2 of Non-Photonic Electrons



$$v_2 = \langle\cos(2[\Phi\text{-}\Psi])\rangle \;/\; \Psi^{res}$$

Reaction plane resolution $\Psi^{res} \sim 0.7$

- Same procedures as for single electrons (incl. background subtraction)
  - But much harder cuts (plenty of statistics)
  - Special emphasis on anti-deuteron removal
  - γ-conversions, π^0-Dalitz electrons removed via invariant mass
- Remaining 37% photonic electron background subtracted with v_2^{max}=17%
- Reaction plane resolution $\Psi^{res} \sim 0.7$
- Consistency check: PYTHIA + MEVSIM (v^2 generator) + analysis chain ⇒ OK

v_2 of Non-Photonic Electrons

Phenix : Min. Bias

Star: 0-80%

STAR: stat. errors only

Phenix:

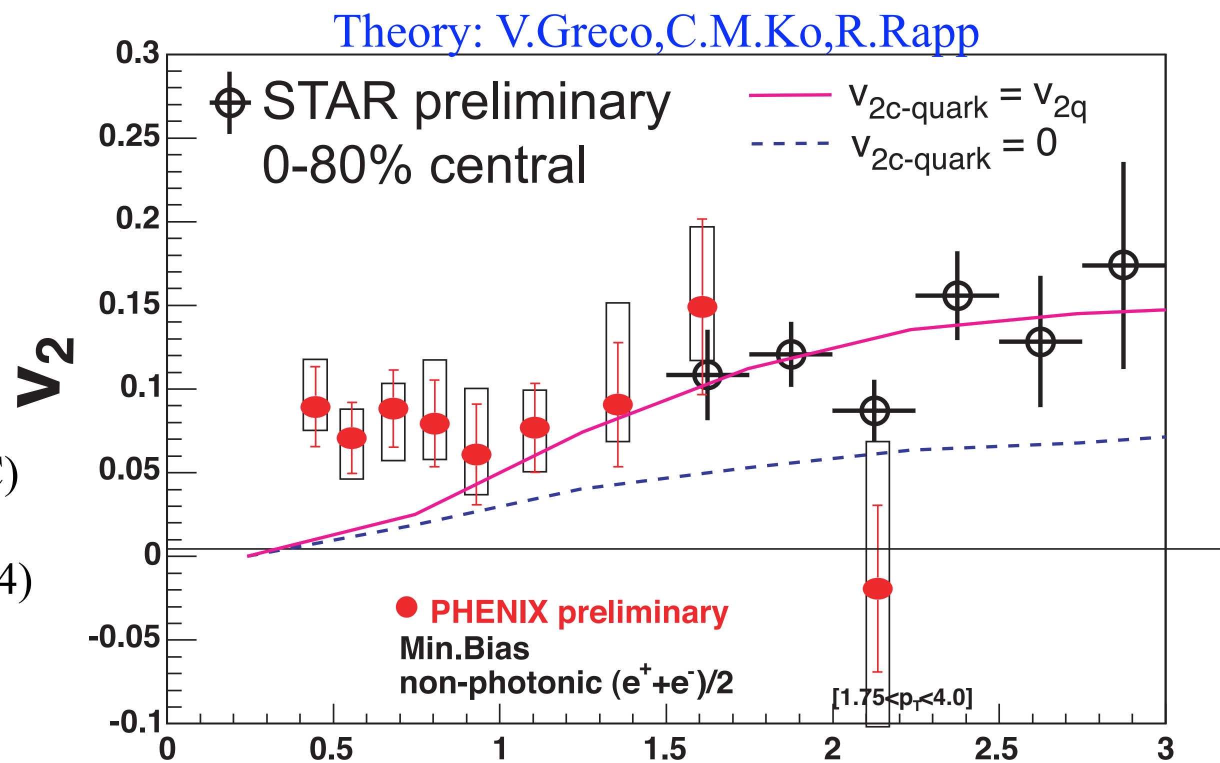
nucl-ex/0404014 (QM2004)

nucl-ex/0502009 (submitted to PRC)

Star:

J. Phys. G 190776 (Hot Quarks 2004)

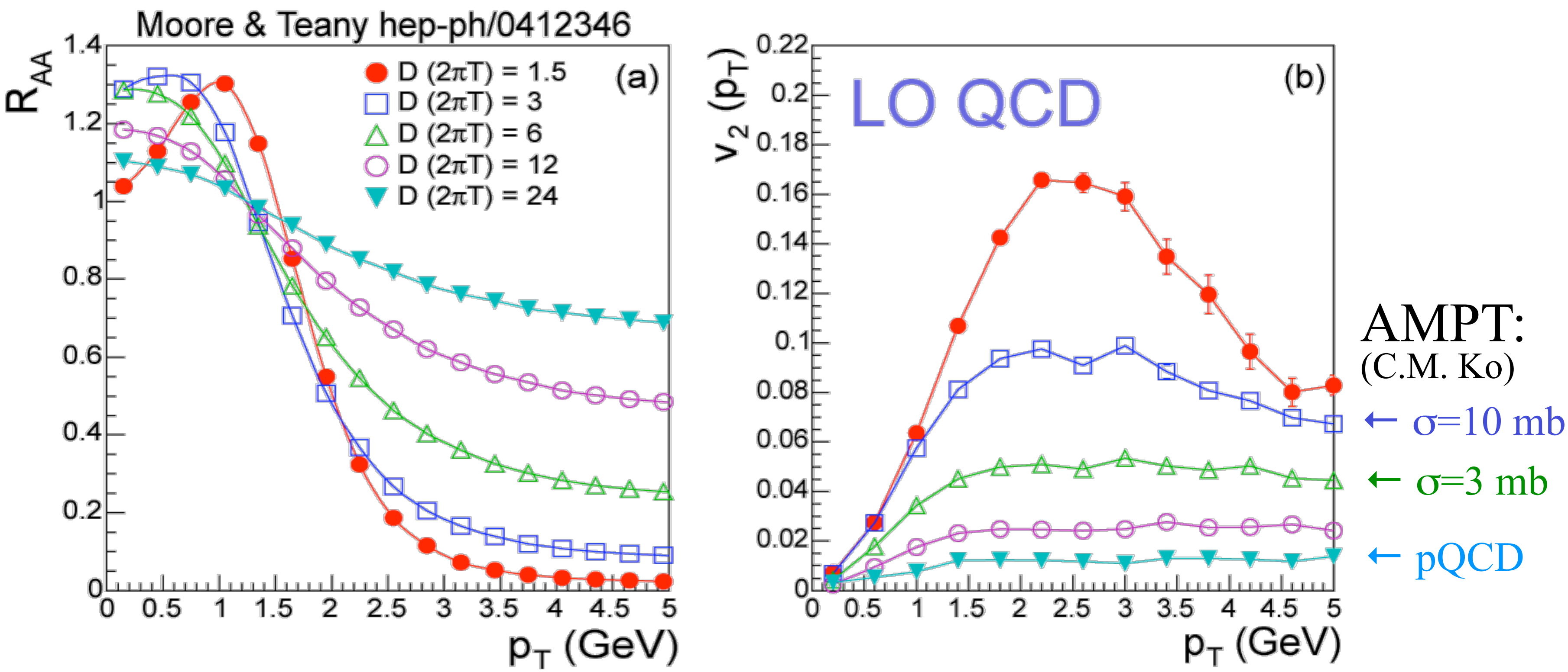
J. Phys. G 194867 (SQM 2004)



⇒ Indication of strong non-photonic electron v_2

- ★ consistent with $v_2(c) = v_2$(light quark)
- ★ smoothly extending from PHENIX results
- ★ Teany/Moor ⇒ D $(2\pi T) = 1.5$ ($\alpha_s = 1$?) ⇒ expect substantial suppression R_{AA}
- ★ Greco/Ko ⇒ Coalescence model (shown above) appears to work well

Charm Elliptic Flow from the Langevin Model



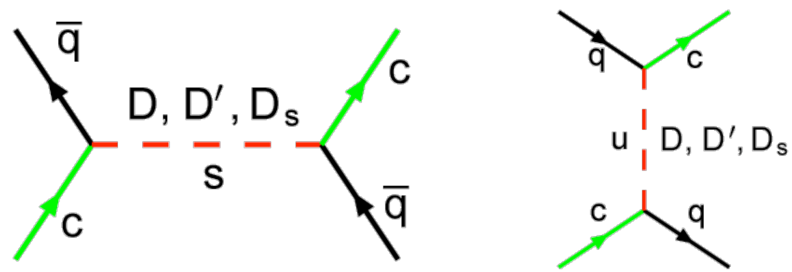
- Diffusion coefficient in QGP: $D = T/M\eta$ (η momentum drag coefficient)
- Langevin model for evolution of heavy quark spectrum in hot matter
- Numerical solution from hydrodynamic simulations
- pQCD gives $D\times(2\pi T) \approx 6(0.5/\alpha_s)^2$

Charm Elliptic Flow through Resonance Effects

Van Hees & Rapp, PRC 71, 034907 (2005)

- Assumption: survival of resonances in the QGP
- Introducing resonant heavy-light quark scattering
- heavy particle in heat bath of light particles (QGP) + fireball evolution

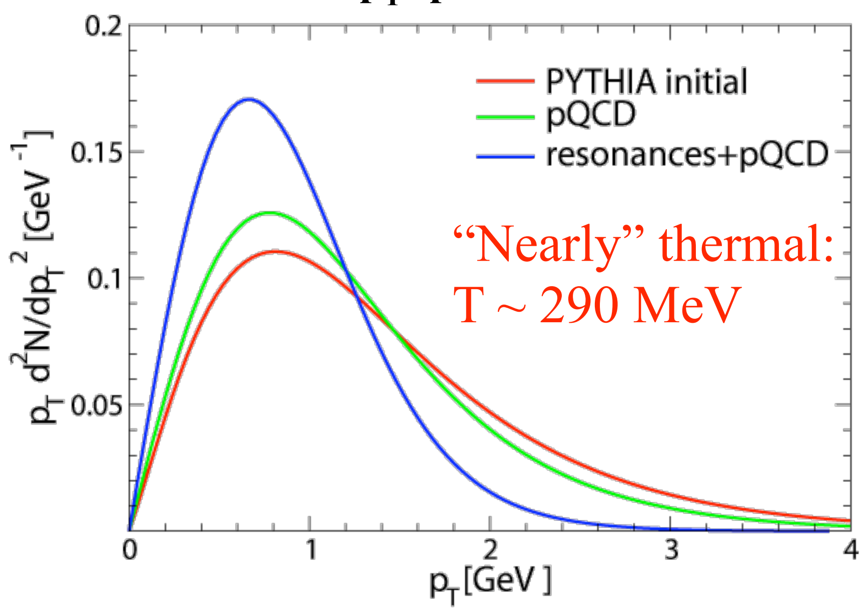
heavy-light-(anti-)quark scattering



Including scalar, pseudoscalar, vector, and axial vector D-like-mesons gives:

$$\sigma_{cq\rightarrow cq}(s^{1/2}=m_D)\approx 6\text{ mb}$$

time-evolved c p_T spectra in local rest frame



Cross-section is isotropic ⇒ the transport cross section is 6 mb, about 4 times larger than from pQCD t-channel diagrams

Topological EMC triggers

- Large acceptance $|\eta|<1$, high tracking efficiency (90%), good $e^{\pm}$ id, 10^5 hadron rejection
  - J/Ψ: acceptance × efficiency ($p_T^e > 1.2$ GeV/c) ~ 10%
  - Υ: Acceptance × efficiency ($p_T^e > 3.5$ GeV/c) ~ 14%
- Signal-to-Background Ratios
  - S/B > 1: 1 for Υ
  - S/B = 1:25 – 1:100 for J/Ψ

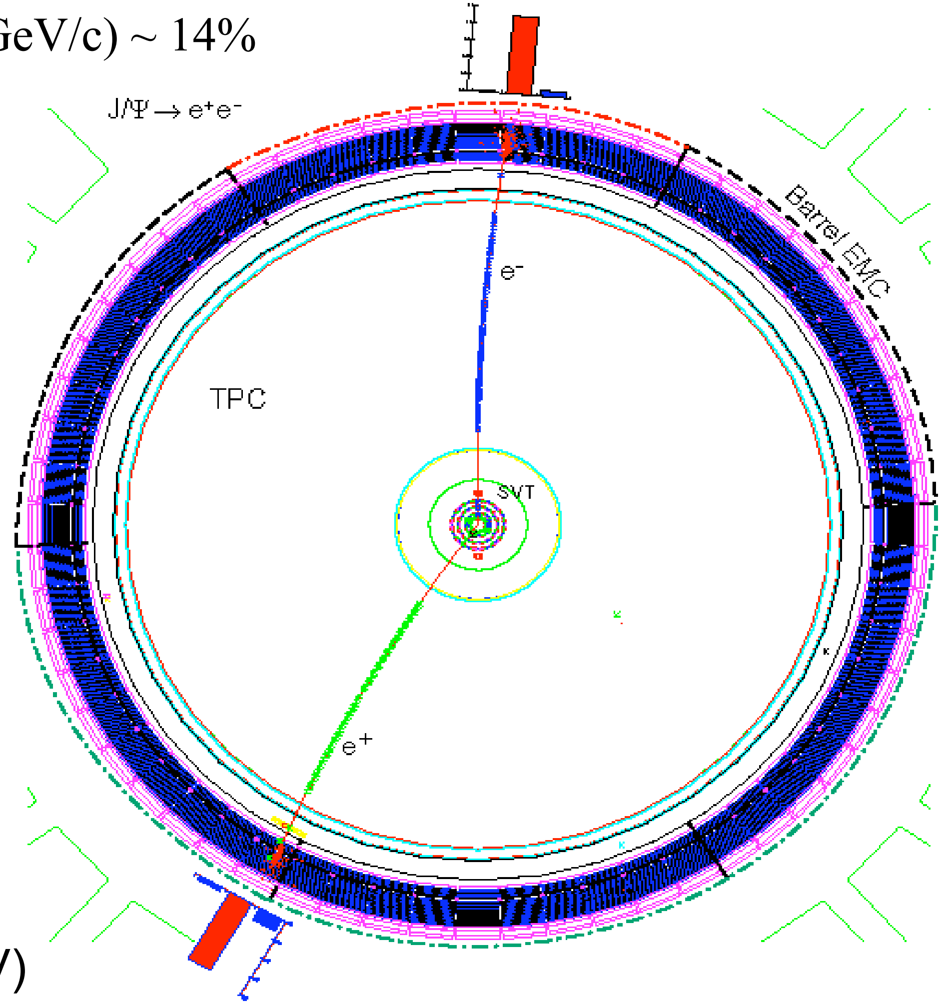
    $S_{eff} = S/(2(B/S)+1)$

    Υ significance close to that of J/Ψ
- Without Trigger (min. bias running):
  - Min bias (100 Hz): 18 J/Ψ
  - 0.02 Υ per hour running

Topological EMC triggers

- Upsilon (all collisions systems)
- J/Psi (light systems or high-p_T)
  - Acc. $|y|<1$: L0 Eff

Acc. $|y|<1$	L0 Eff
0.11 (½ barrel)	0.61 (E>1GeV)
0.22 (¾ barrel)	0.37 (E>1.2GeV)



Quarkonia Trigger in STAR

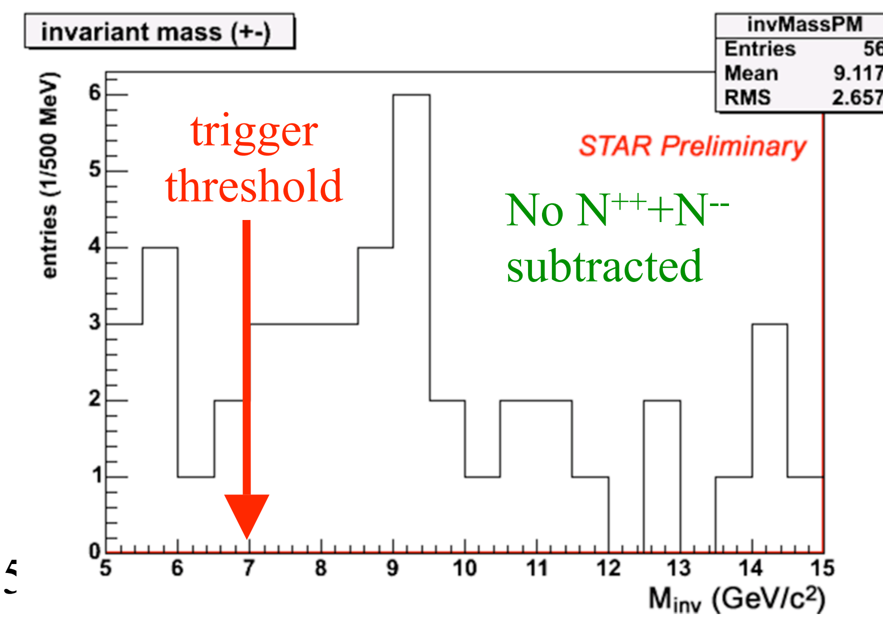
$J/\Psi \rightarrow e^+ e^-$:

- ★ L0-trigger: 2 EMC tower with E > 1.2 GeV (~60° apart)
- ★ L2-trigger (software): veto γ, better E, $2.5 < M_{inv} < 3.5$ GeV/c^2
- ★ Efficiency currently too low in Au+Au (pp only) ⇒ need full ToF

$\Upsilon \rightarrow e^+ e^-$:

- ★ L0-trigger: 1 EMC tower with E > 3.5 GeV
- ★ L2-trigger (software): $M_{inv} > 7$ GeV/c^2
- ★ High Efficiency (80%) – works in Au+Au

- ★ Tests in Au+Au show it works
- ★ small background
- ★ counts = expectations
- ★ Need full EMC for that
  - ★ 2004 ½ barrel EMC
  - ★ 2005 ½ - ¾ barrel EMC

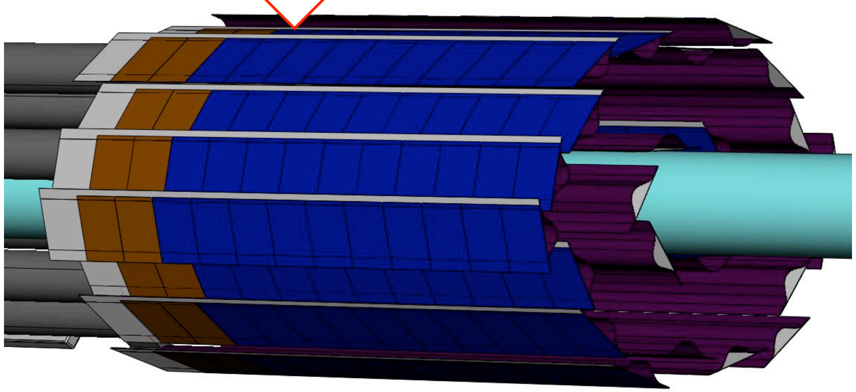


STAR Upgrades to come: Full ToF-barrel and HFT

Heavy Flavor Tracker (HFT)

- Two layers
  - 1.6 cm radius
  - 4.8 cm radius
- 24 ladders
  - 2 cm by 20 cr
- MIMOSA A nor (CMOS)
  - Precise nd low power
  - 50 μ r cooling
  - 0.36% ra length

secondary vertex reconstruction



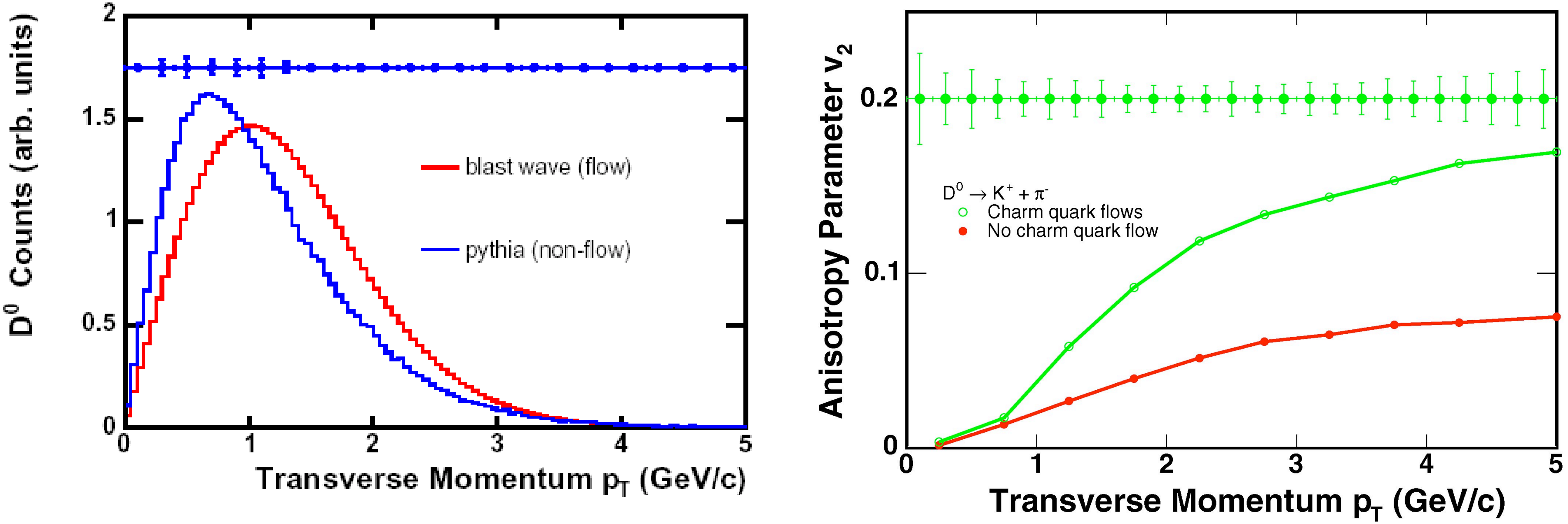
Time-of-Flight: MRPC

- π/K separation up to 1.6 GeV/c
- p/K separation up to 3 GeV/c
- Thus cover wider of (p,K,π) p_T
- Full ToF:

excellent particle id

More demanding reconstruction

$D^0 \rightarrow K\,\pi$ using HFT, 50M events



- From only 50M events, additional rejection power of HFT leads to extremely small uncertainties in both spectra and v_2
- Charm quark flow can be fully addressed with this upgrade

Also: Measure $D_s \rightarrow \phi + \pi$

Summary (current Analysis)

Heavy Flavor Production in RHI is the next big topic that needs to be addressed

- **STAR has solid baseline measurements in pp and d+Au +(Au+Au)**
  - D^0 in d+Au from p_T = 0 - 3 GeV/c
  - D* in d+Au mesons from p_T = 1.5 – 6 GeV/c
  - Non-photonic single electrons in p+p and d+Au from 1.5 – 10 GeV/c
- **Measurements indicate a large σ_{cc} in pp at RHIC**
  - $d\sigma/dy|_{y=0} = 0.30 \pm 0.04(stat) \pm 0.09(sys)$ mb
  - NLO pQCD calculations under predict this value (~ a factor of 3-5)
  - Large σ_{cc} appear to rule out expectation of J/ψ enhancement from some charm coalescence and statistical models
- **Preliminary results on v_2 of non-photonic electrons indicate substantial elliptic flow of charm in Au+Au collisions at RHIC**
  - consistent with $v_{2c} = v_{2light\text{-}q}$ theory calculations
  - consistent (smoothly extending) with PHENIX results
  - try to extend to higher p_T range (possibly b dominated

Summary (Future Heavy Flavor Program)

- STAR has proven capabilities for EM probes and heavy flavor measurements at RHIC
  - PMD: Photon multiplicity
  - FPD: forward γ and electron detection - high x_F physics
  - Electron identification using three detector systems (TPC, TOF, EMC) from 1 to >10 GeV/c
  - Direct reconstruction of charmed mesons
- Presenty shortcomings in PID, vertexing, and acceptance due partial installation of TOF, EMC

STAR has a clear path for improving its capabilities in the near future

- Completion and extension of calorimetric coverage
- Extension of TOF coverage to full azimuth for electrons and combinatoric background rejection in direct reconstruction
- Upgrade of Data Acquisition to increase effective luminosity and untriggered data samples
- Installation of the heavy flavor tracker for displaced vertices for heavy flavor physics and photonic electron rejection

Low Mass Vector Mesons and Thermal Dileptons Will Become Part of STAR's Program

STAR Collaboration

545 Collaborators from 51 Institutions in 12 countries

Argonne National Laboratory
Institute of High Energy Physics - Beijing
University of Bern
University of Birmingham
Brookhaven National Laboratory
California Institute of Technology
University of California, Berkeley
University of California - Davis
University of California - Los Angeles
Carnegie Mellon University
Creighton University
Nuclear Physics Inst., Academy of Sciences
Laboratory of High Energy Physics - Dubna
Particle Physics Laboratory - Dubna
University of Frankfurt
Institute of Physics. Bhubaneswar
Indian Institute of Technology. Mumbai
Indiana University Cyclotron Facility
Institut de Recherches Subatomiques de Strasbourg
University of Jammu
Kent State University
Institute of Modern Physics. Lanzhou
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
Max-Planck-Institut fuer Physics
Michigan State University
Moscow Engineering Physics Institute

City College of New York NIKHEF
Ohio State University
Panjab University
Pennsylvania State University
Institute of High Energy Physics - Protvino
Purdue University
Pusan University
University of Rajasthan
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SUBATECH
Texas A&M University
University of Texas - Austin
Tsinghua University
Valparaiso University
Variable Energy Cyclotron Centre. Kolkata
Warsaw University of Technology
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Wayne State University
Institute of Particle Physics
Yale University
University of Zagreb