Heavy Flavor at RHIC

- A Comparative View

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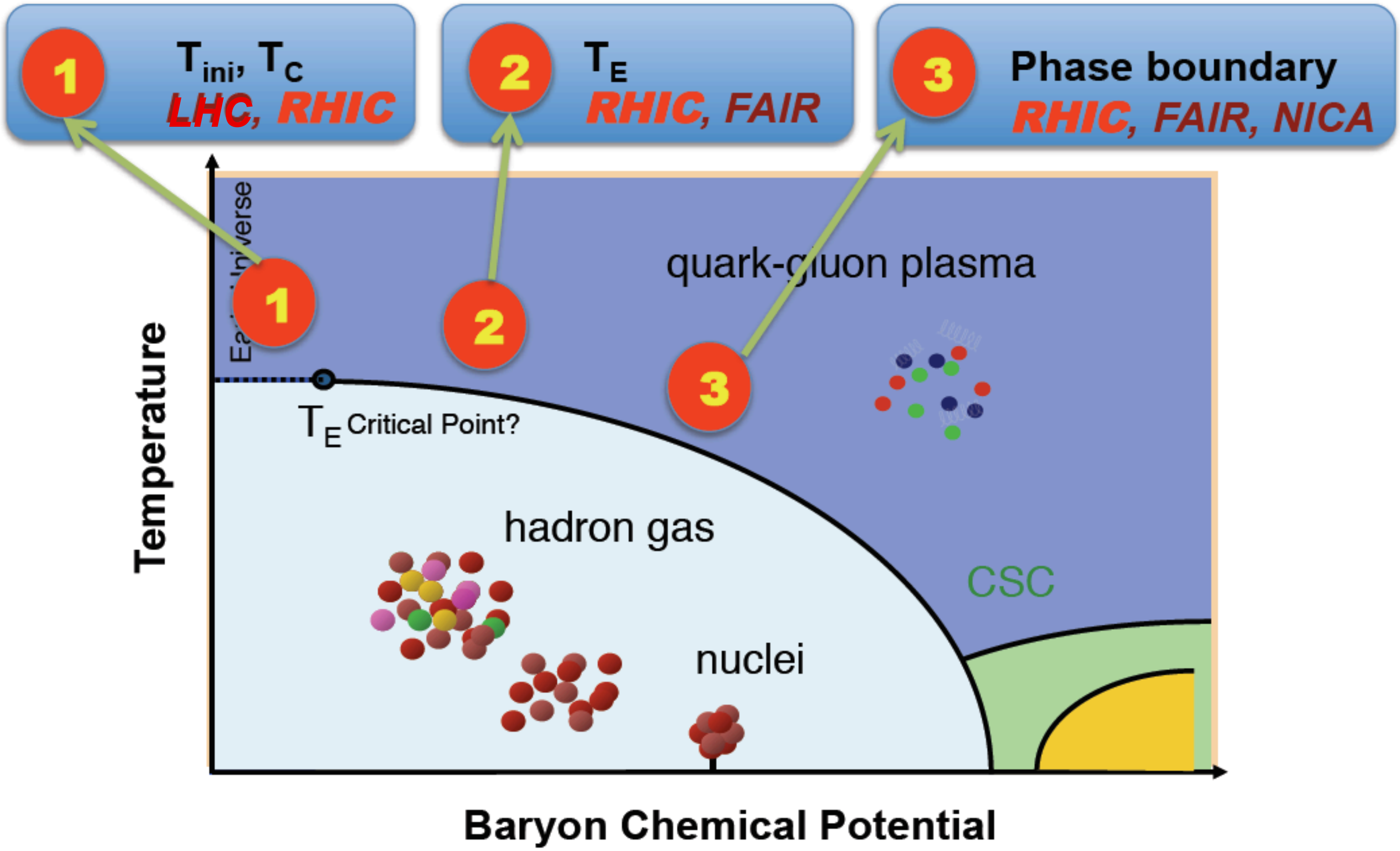
Heavy Ion Frontiers

Heavy Flavor Program - Quantify the medium properties

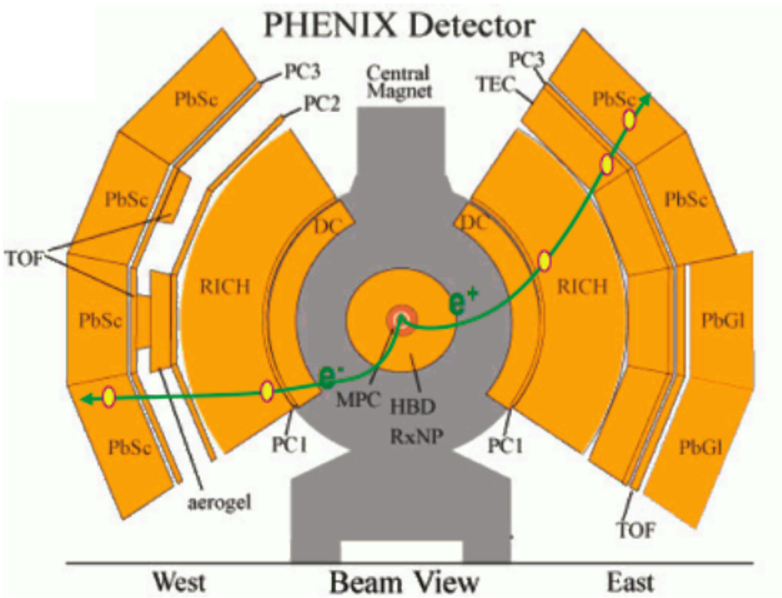


Outline

- Experiments
- What We've Learned
- Future Prospects
- Summary

Detectors

PHENIX

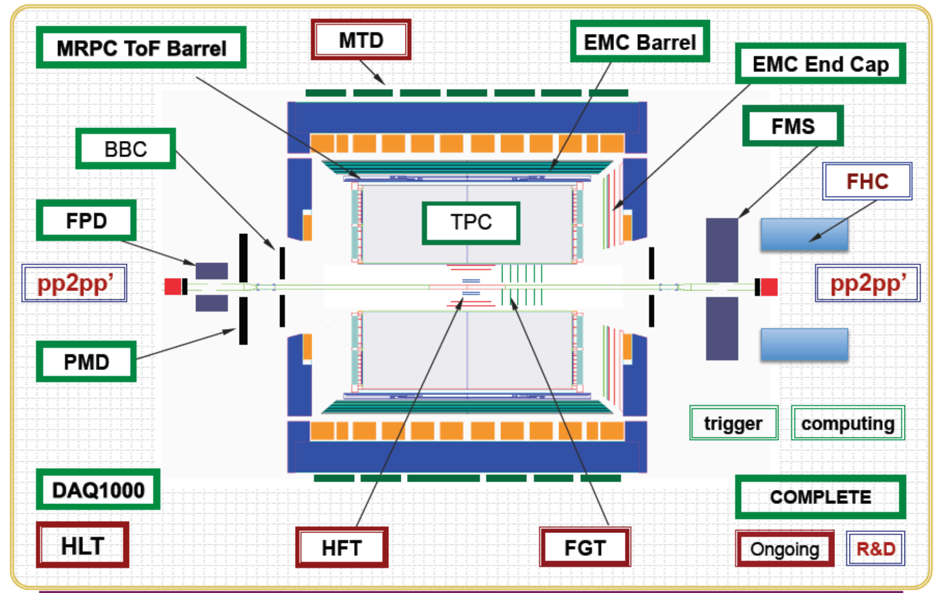


Central Arms: $|\eta|<0.35$, $\Delta\phi = 2 \times \pi/2$
tracking, electron/hadron PID

Forward/backward Arms: $1.2<|\eta|<2.4$, $\Delta\phi = 2\pi$
muon tracking PID

DAQ rate ~ several kHz

STAR



$|\eta|<1$, $\Delta\phi = 2\pi$
Tracking, electron/hadron PID

DAQ rate ~ 1 kHz

Measurements

	PHENIX	STAR
Open charm hadrons	-	Mid-y
Heavy flavor decay leptons*	$e^{+/-}$ @ mid-y $\mu^{+/-}$ @ forward-y	$e^{+/-}$ @ mid-y
J/ψ Upsilons	e^+e^- @ mid-y $\mu^+\mu^-$ @ forward-y	e^+e^- @ mid-y

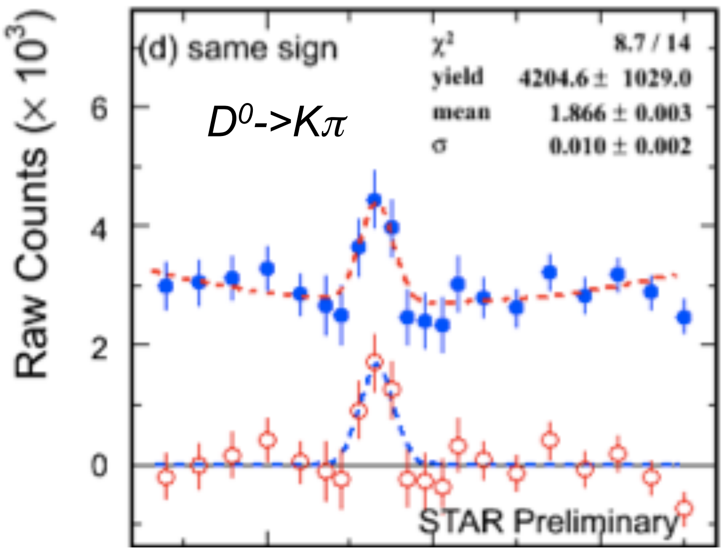
On Quakonia:
PHENIX advantage: efficient electron trigger down to low p_T in p+p
- high statistics in p+p

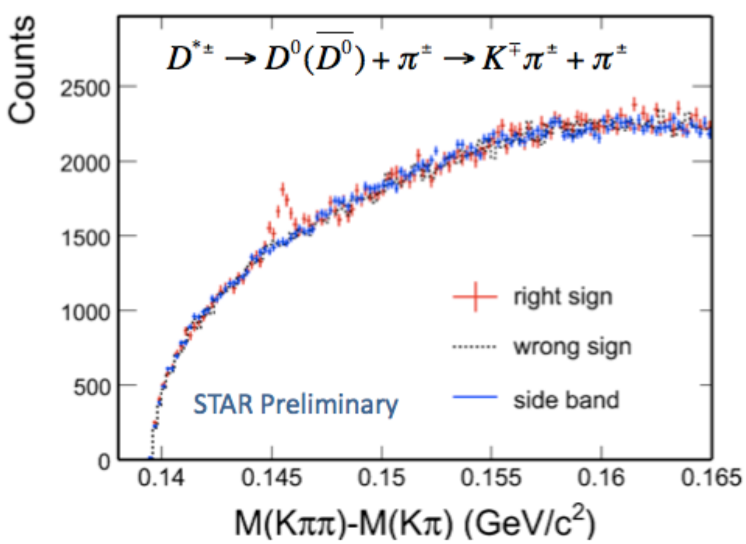
STAR advantage: single electron trigger on high p_T J/ψ and Upsilon to take full luminosity and large mid-rapidity acceptance

* See presentations on Friday morning session

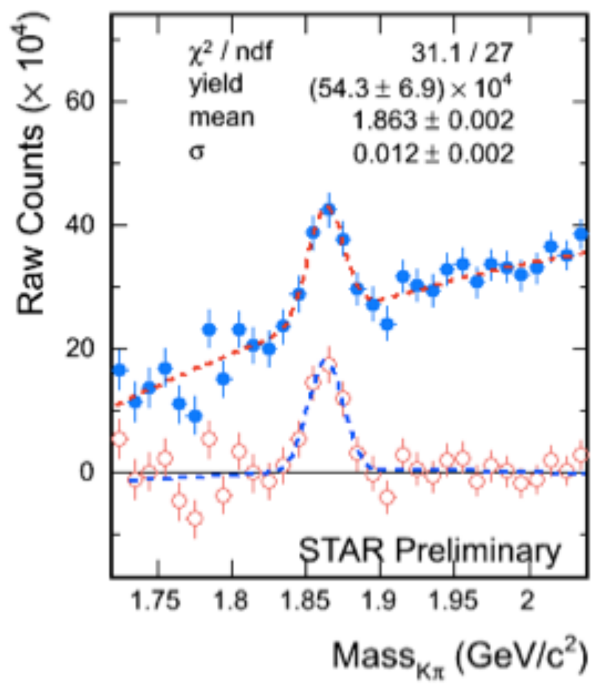
Reconstruction of Open Charm Hadrons

- No secondary vertex reconstruction so far.
- STAR took advantage of the large acceptance, and beat combinatorial background with statistics





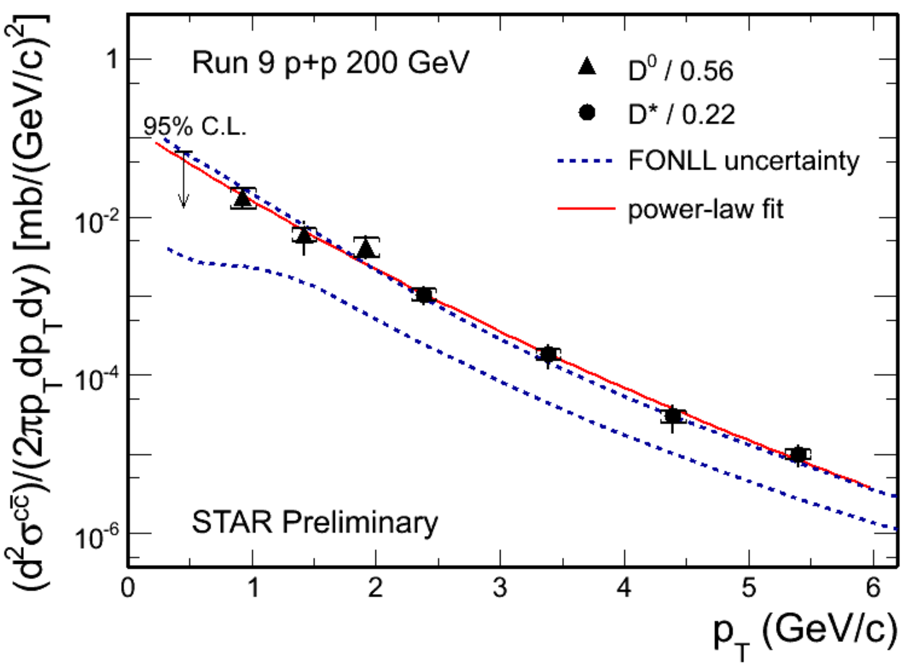
p+p @ 200 GeV



Au+Au @ 200 GeV

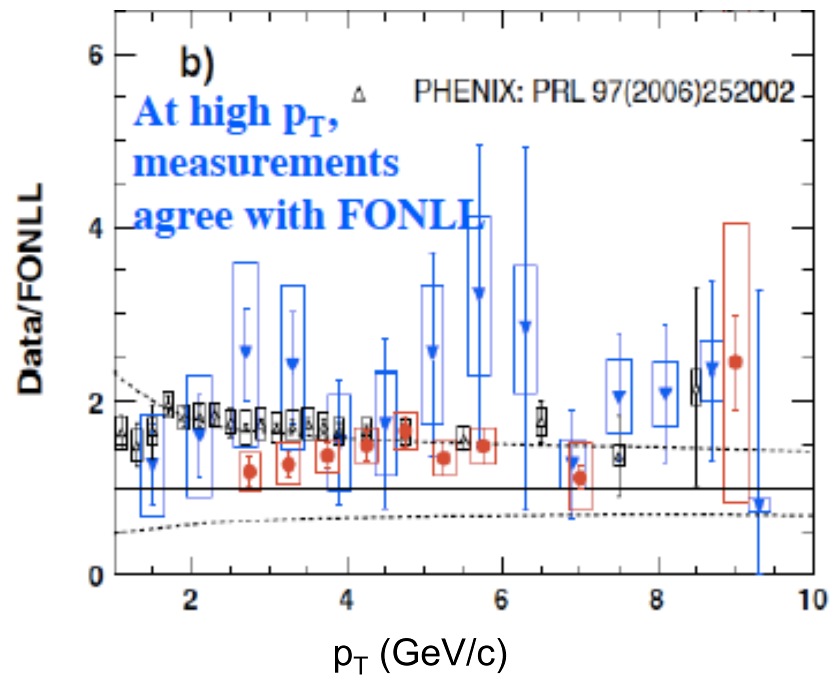
Charm Production Cross Section in p+p

Open charm hadrons



Y. Zhang, QM 11

Non-photonic electrons

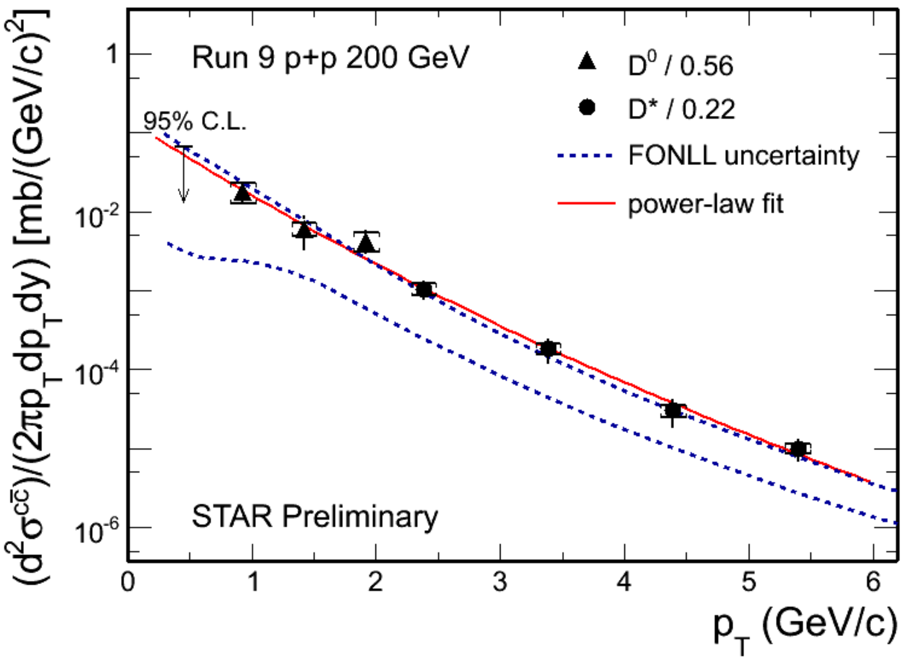


STAR, PRD 83 (2011) 052006

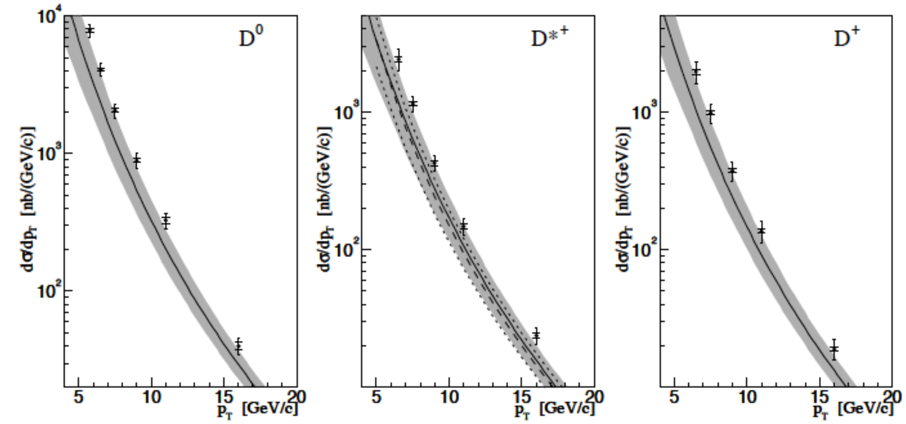
p_T shape at p_T(D)>1 GeV/c agrees with the FONLL upper limit.
- Similar behavior for high p_T non-photonic electrons.

Charm Production Cross Section in p+p

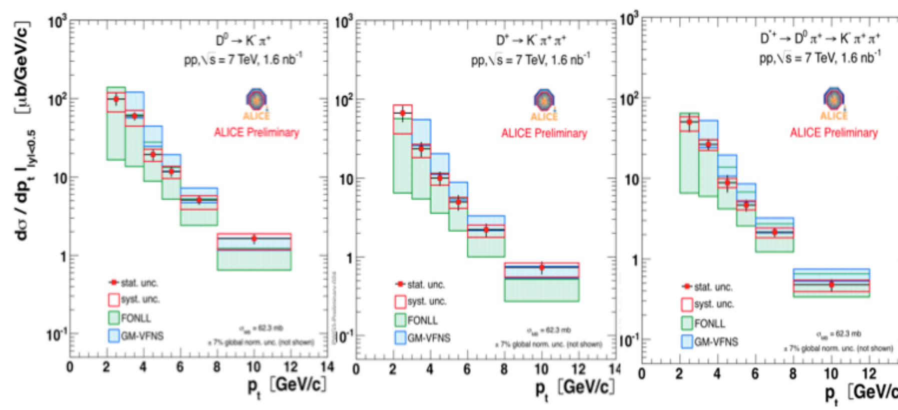
STAR p+p @ 200 GeV *Y. Zhang, QM 11*



CDF $p+\bar{p}$ @ 1.96 TeV *PRL 91 (2003) 241804*

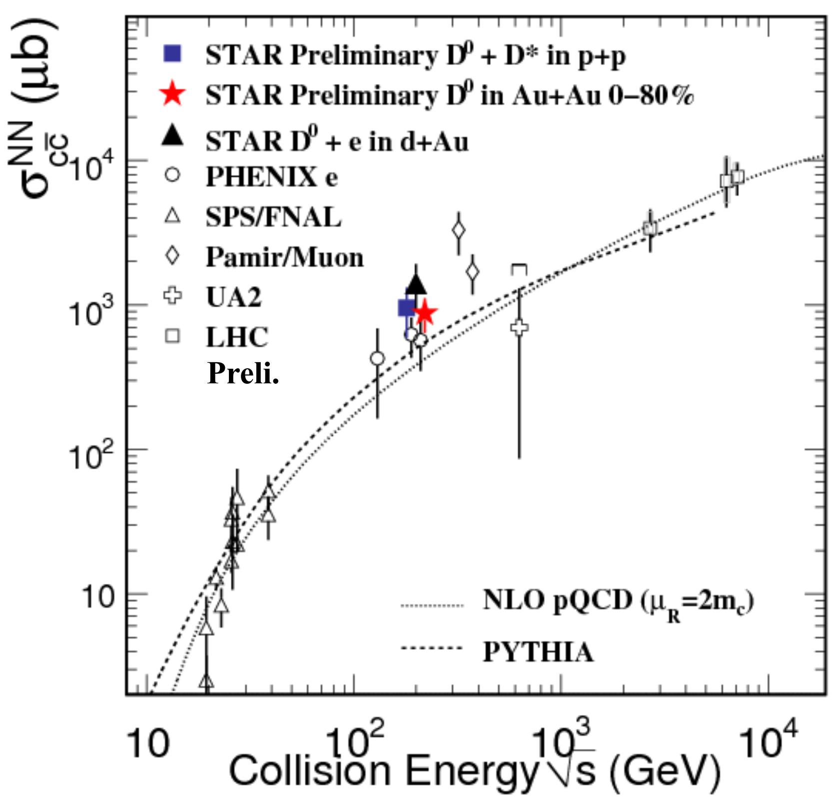


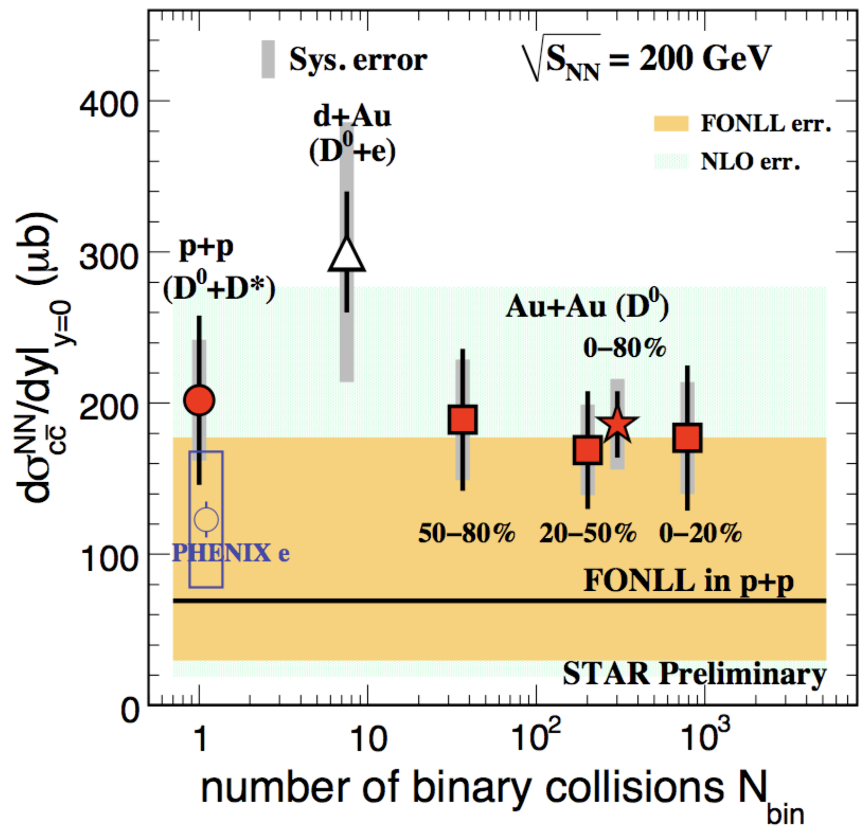
ALICE p+p @ 7 TeV *J. Shukraft, QM 11*



Note: interestingly
similar observations at CDF and ALICE.
Constrains to theory calculations

Total Charm Cross Section



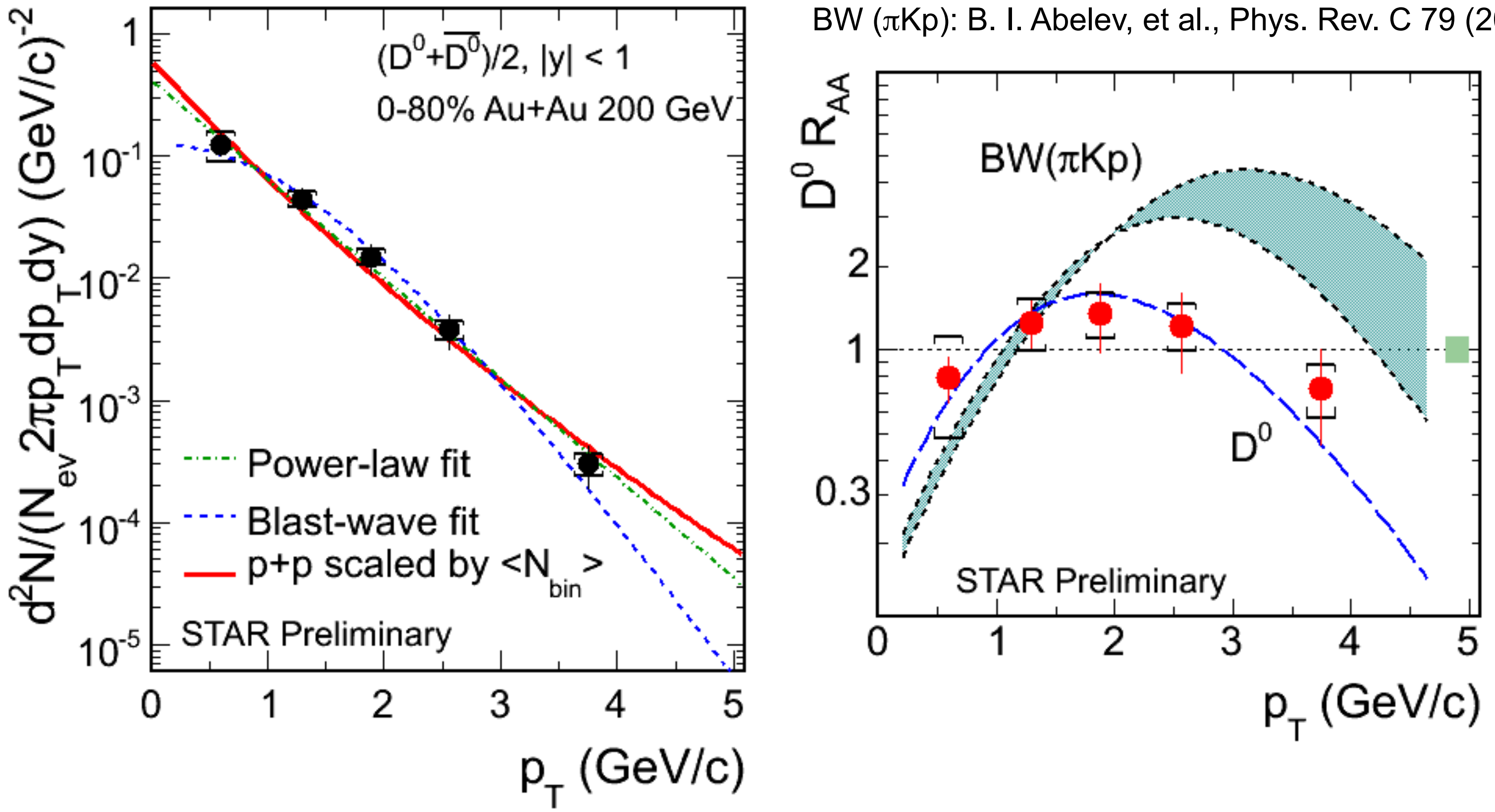


Energy dependence of total charm cross section -> Constrain the pQCD calculations
Mid-rapidity total cross section shows Nbin scaling -> dominate from initial hard collisions

Total charm cross sections from p+p to central A+A collisions
-> essential to determine the charmonia regeneration rate in A+A collisions

Open Charm in Au+Au

BW (πKp): B. I. Abelev, et al., Phys. Rev. C 79 (2009) 34909.

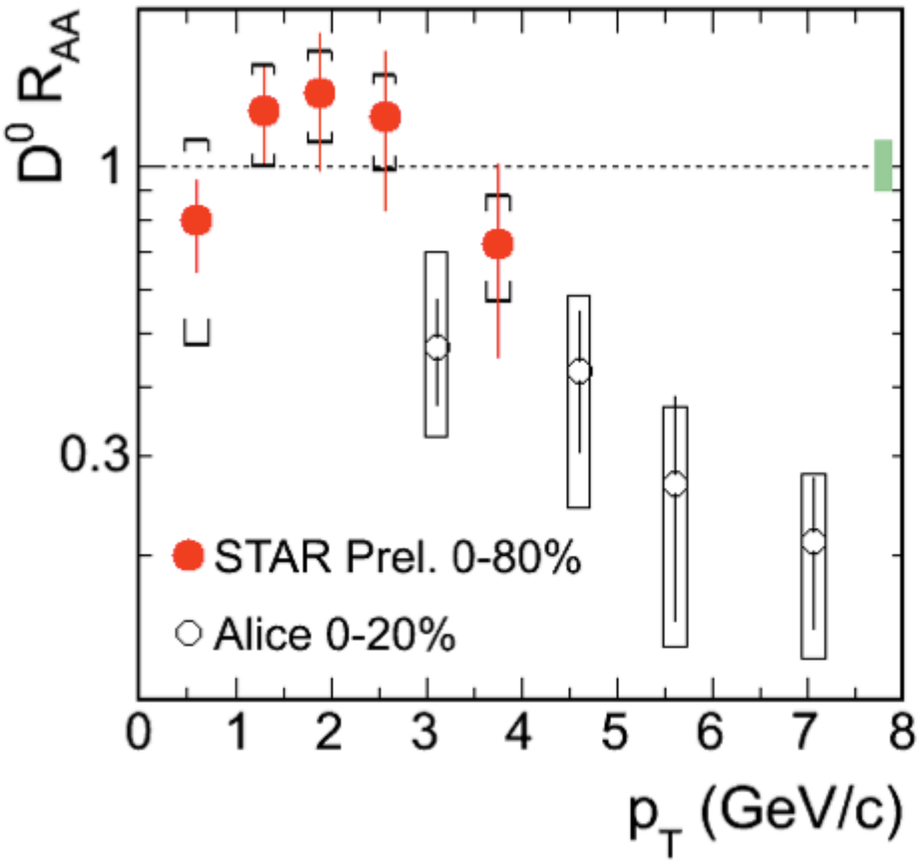


No obvious suppression at p_T < 3 GeV/c.

Blast-wave predictions with light hadron parameters are different from data.

=> D^0 freeze out earlier than light hadrons.

Compared With LHC Data

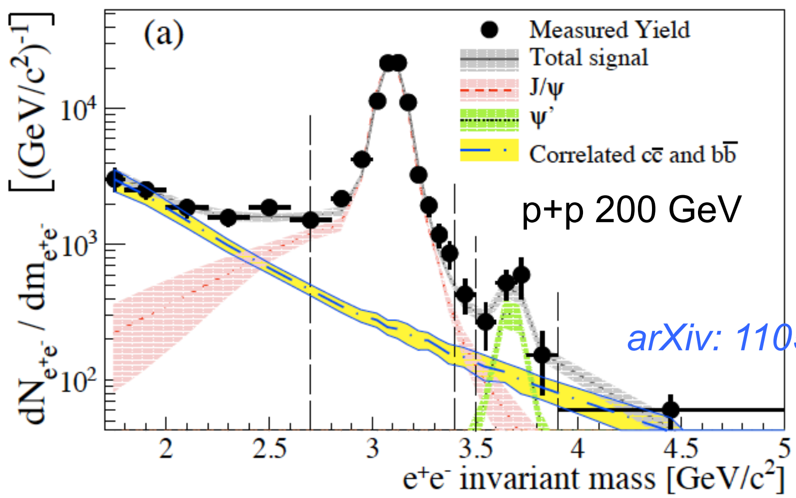


Note: RHIC data are not using silicon vertex detector
- Expect significant improvements in the near future

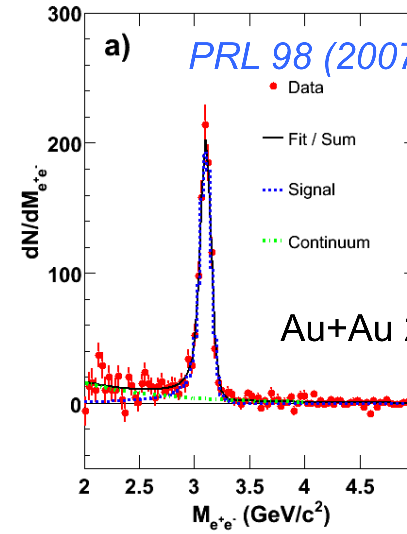
• RHIC and LHC data seems to lie on the same trend.
• D^0 starts to show suppression at ~ 3 GeV/c
Caveats – D_s, Λ_c fraction enhancement (p_T dependent)?

J/ψ signals

PHENIX

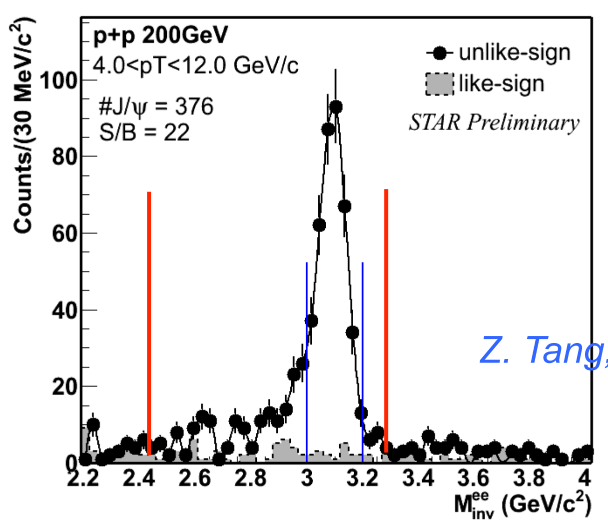


arXiv: 1105.1966

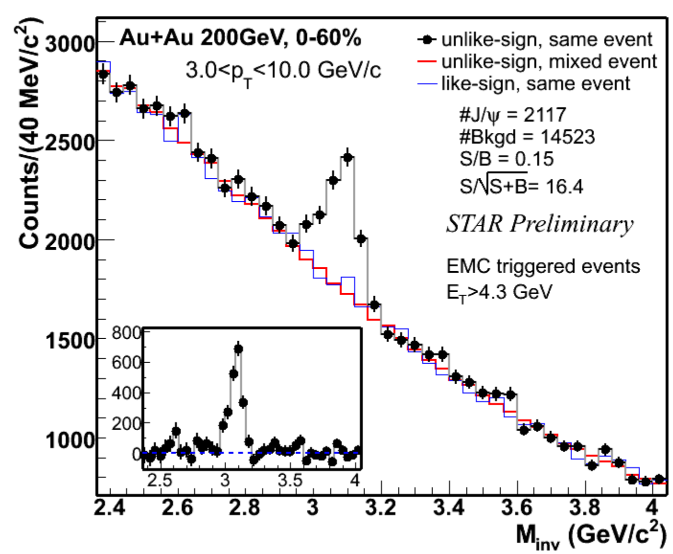


PRL 98 (2007) 232002

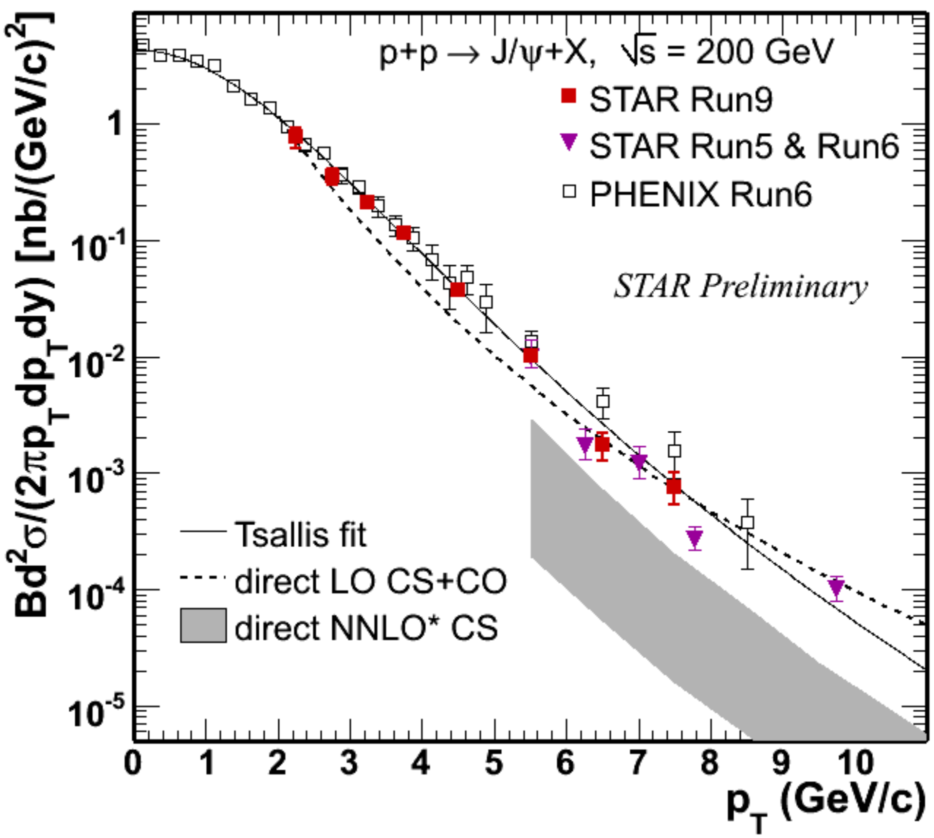
STAR

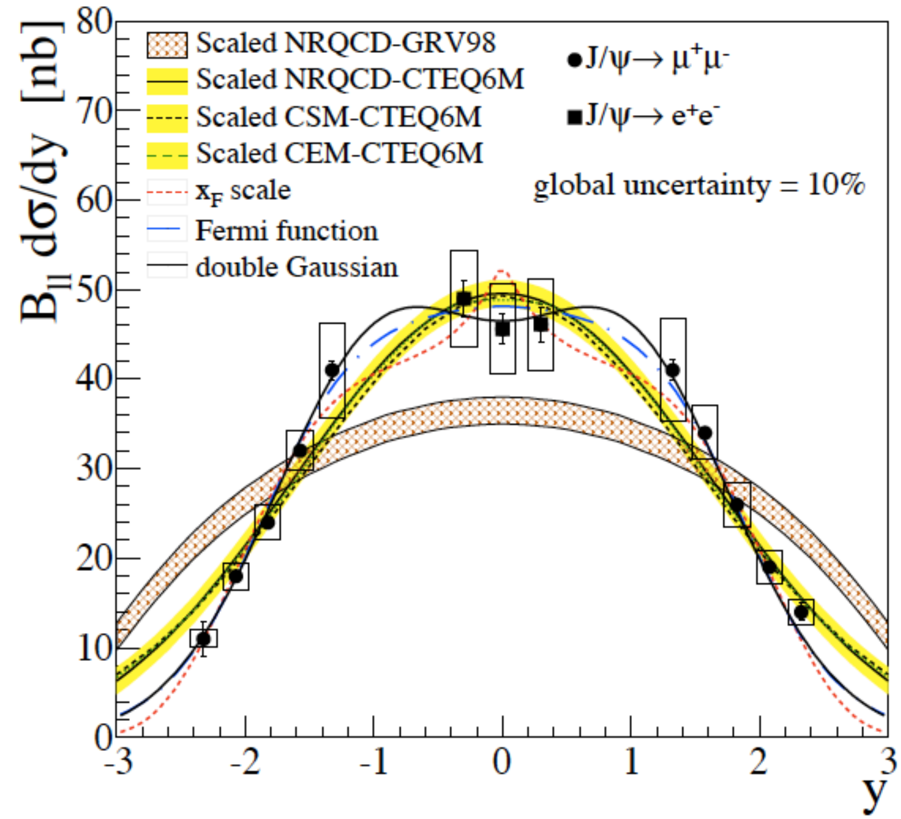


Z. Tang, QM 11



J/ψ Production in p+p Collisions

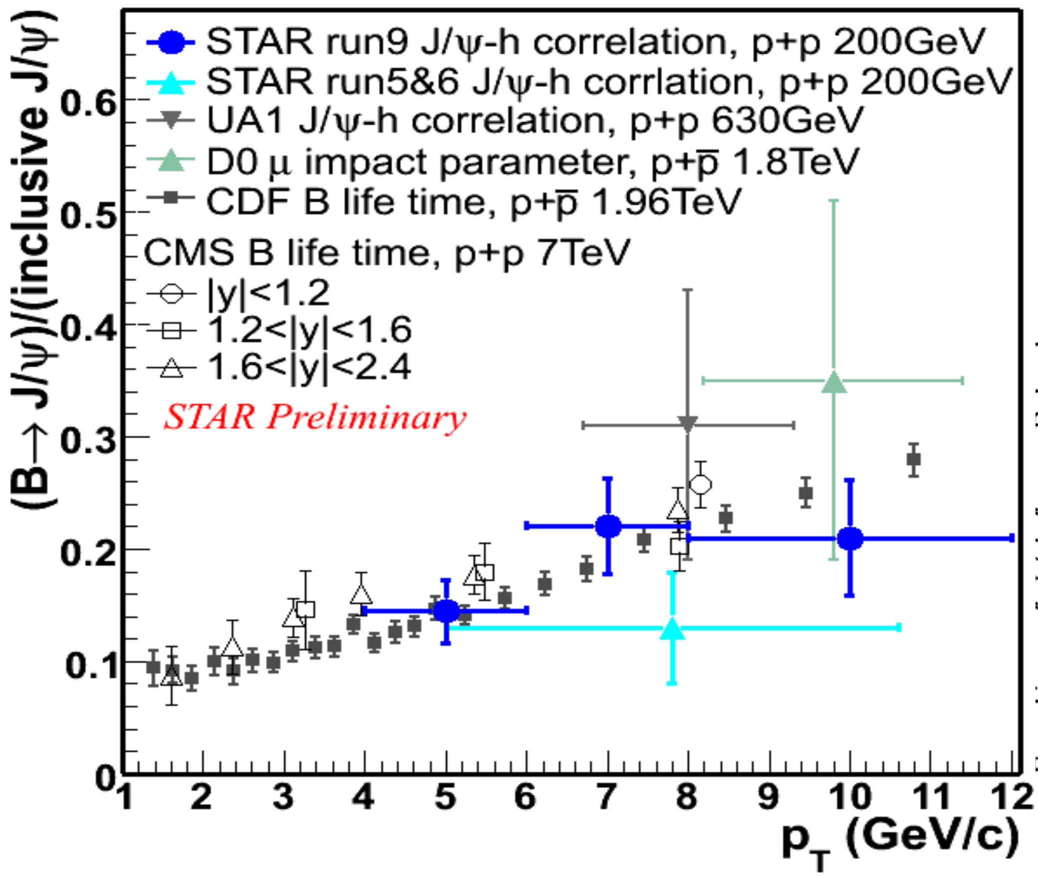




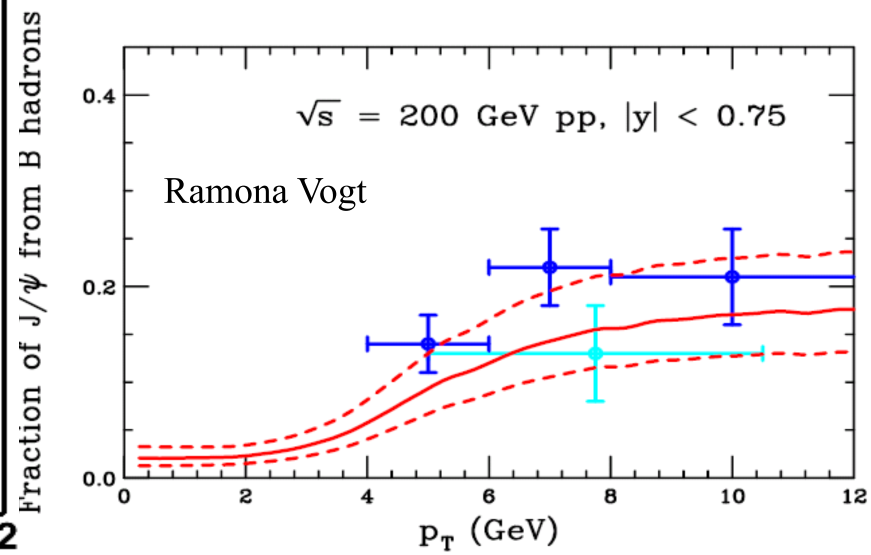
PHENIX: PRD 82 (2010) 012001, arXiv: 1105.1966, STAR: PRC 80 (2009) 041902®

- Wide p_T / rapidity coverage in the inclusive J/ψ spectra.
- Provide significant inputs/constrains to the J/ψ production mechanism.
- High statistics also allows to study other quantities e.g. polarization.

(B→J/ψ) / (inclusive J/ψ)



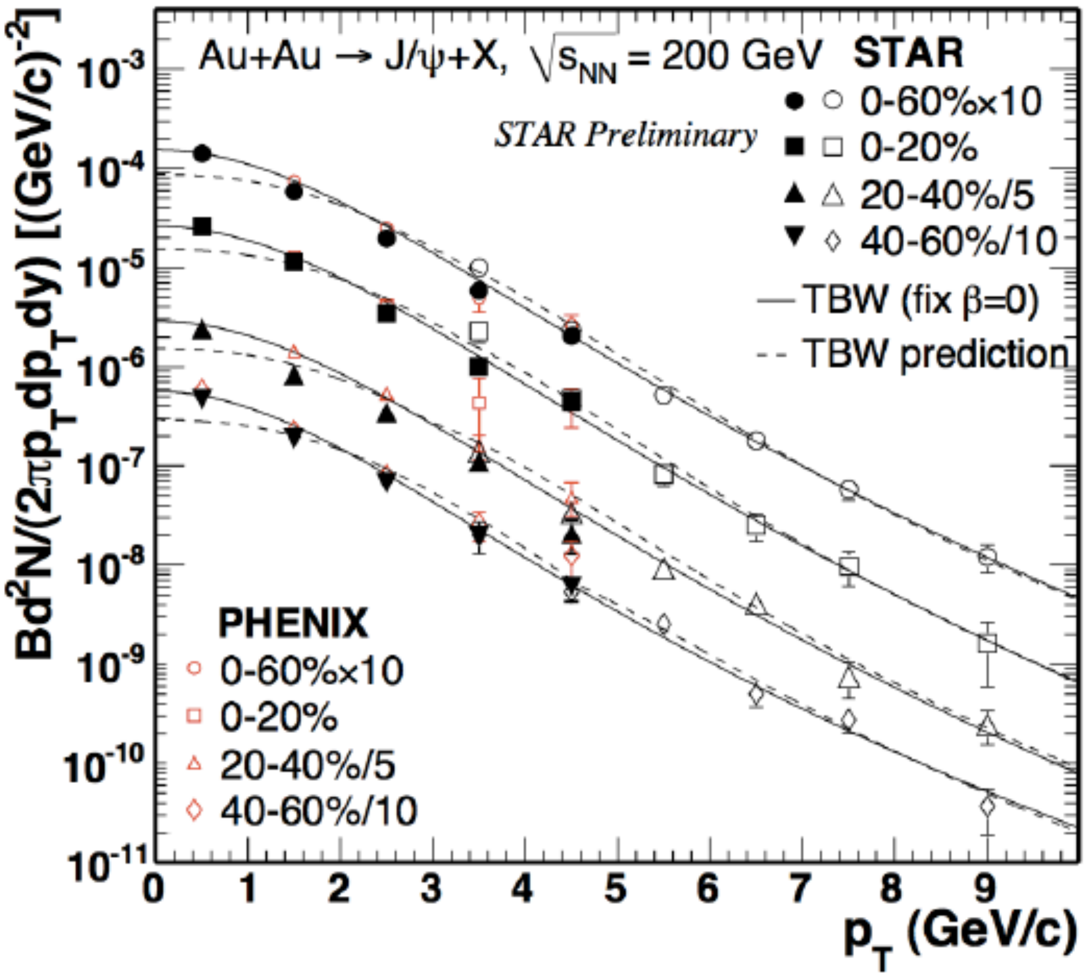
*PRC**80**, 041902(R), 2009*
*PLB**200**, 380, 1988*
*PLB**370**, 239, 1996*
*PRD**71**, 032001, 2005*
*EPJC**71**, 1575, 2011*



Workshop on Heavy Quark Production in Heavy-ion Collisions, Jan. 6, 2011, Purdue University

- Extracted from near side J/ψ-h correlation based on fit to PYTHIA model expectations.
- No significant beam energy dependence
- Can be used to constrain B production

J/ψ spectra in 200GeV Au+Au collisions

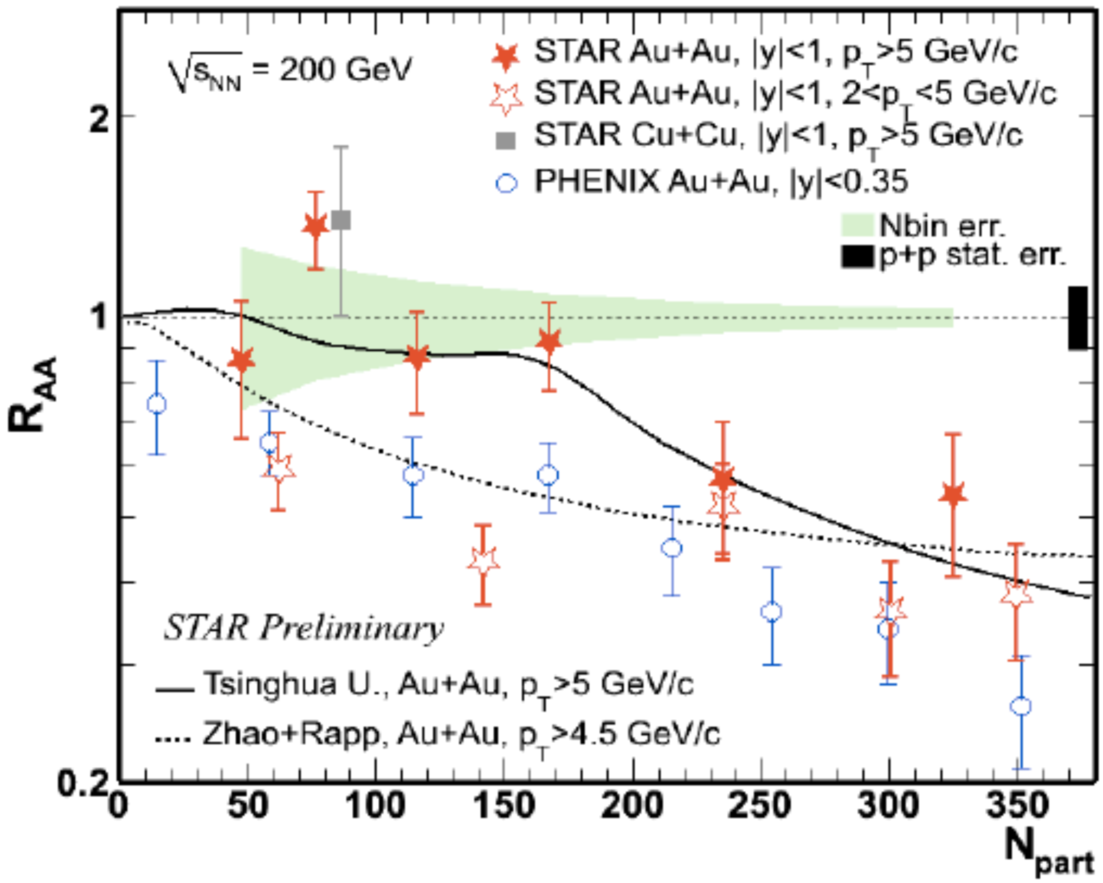


Good agreement between STAR and PHENIX
Note: $|y|<0.35$ vs. $|y|<1$

J/ψ spectra significantly softer than the prediction from light hadrons
→ Much smaller radial flow?
→ Regeneration at low p_T?

Tsallis Blast-Wave model:
Z. Tang *et al.*, JPG 37, 085104 (2010)

R_{AA} vs. Npart



Tsinghua U., PLB 678 (2009) 72 and private communication

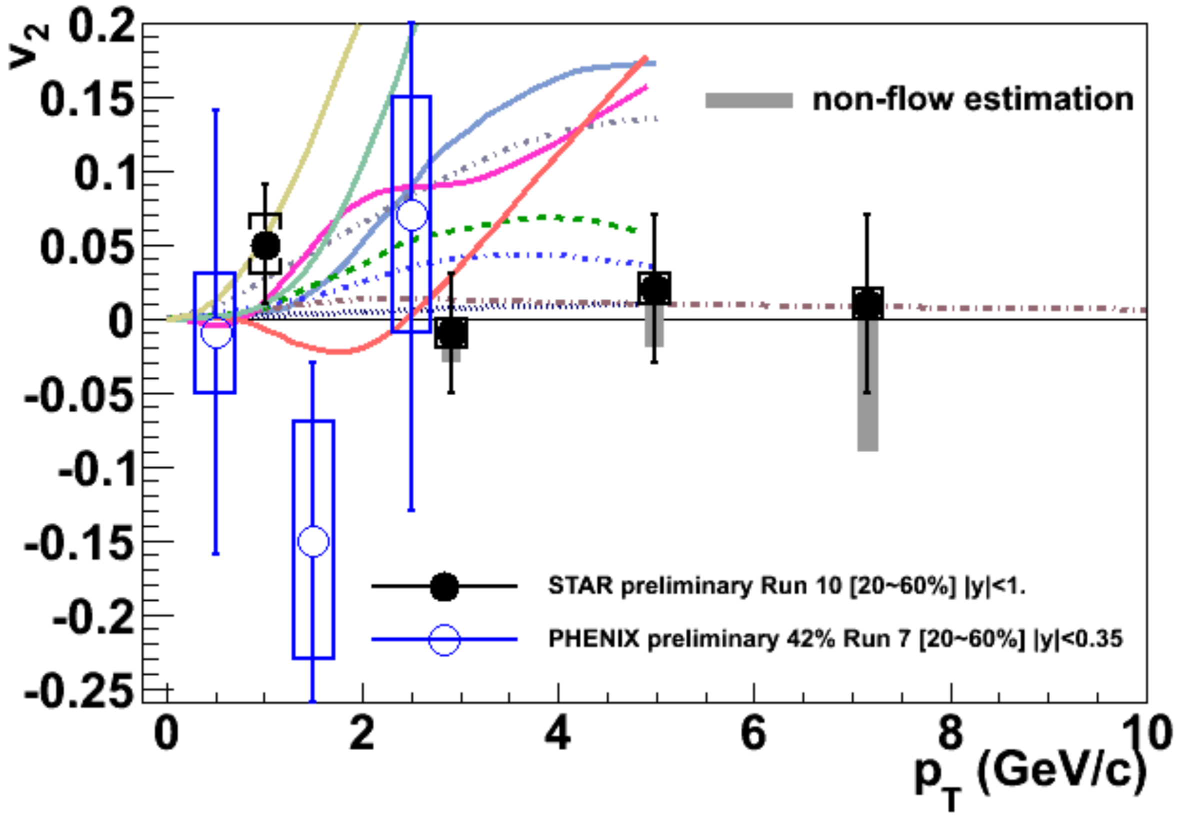
Zhao and Rapp, PRC 82 (2010) 064905 and private communication

Z. Tang, QM11
C. Powell, EPS-11
PHENIX, PRL 98 (2007) 232301

- Suppression in central collisions at high p_T
- System size dependent due to J/ψ formation time effect?
- Escaping at high p_T (without jet quenching effect)?

J/ψ elliptic flow v_2

A clean probe to charm quark v2 if J/ψ is formed via coalescence

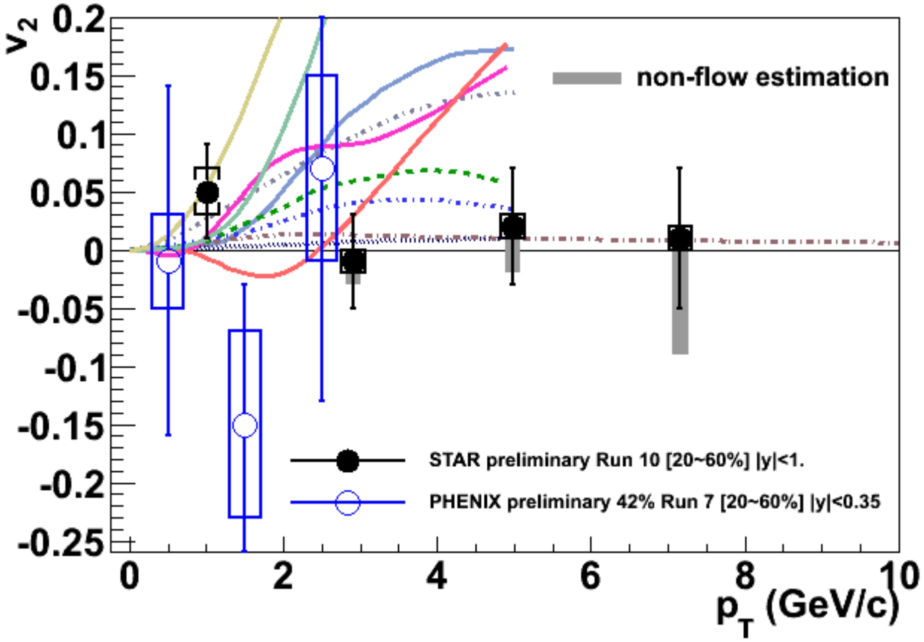


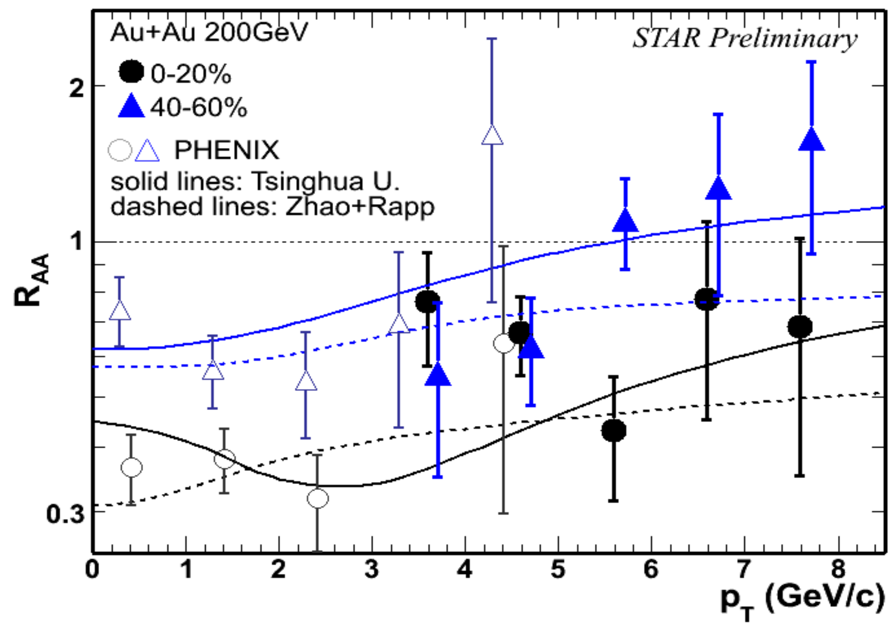
[1] V. Greco, C.M. Ko, R. Rapp, PLB 595, 202.
[2] L. Ravagli, R. Rapp, PLB 655, 126.
[3] L. Yan, P. Zhuang, N. Xu, PRL 97, 232301.
[4] X. Zhao, R. Rapp, 24th WWND, 2008.
[5] Y. Liu, N. Xu, P. Zhuang, Nucl. Phy. A, 834, 317.
[6] U. Heinz, C. Shen, priviate communication.

- Consistent with zero at p_T > 2 GeV/c
- Disfavor coalescence from thermalized charm quarks

A) Charm quark doesn't flow if J/ψ is formed via coalescence.
B) J/ψ is not formed via coalescence.

v_2 and R_{AA}

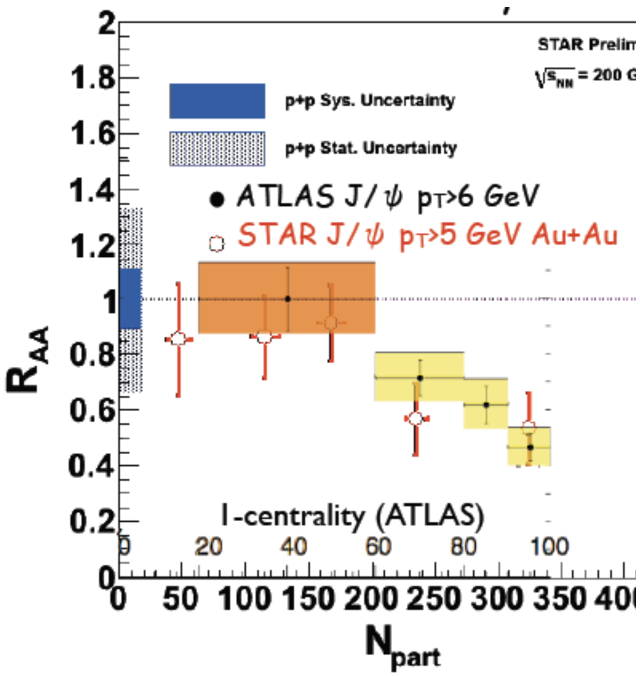


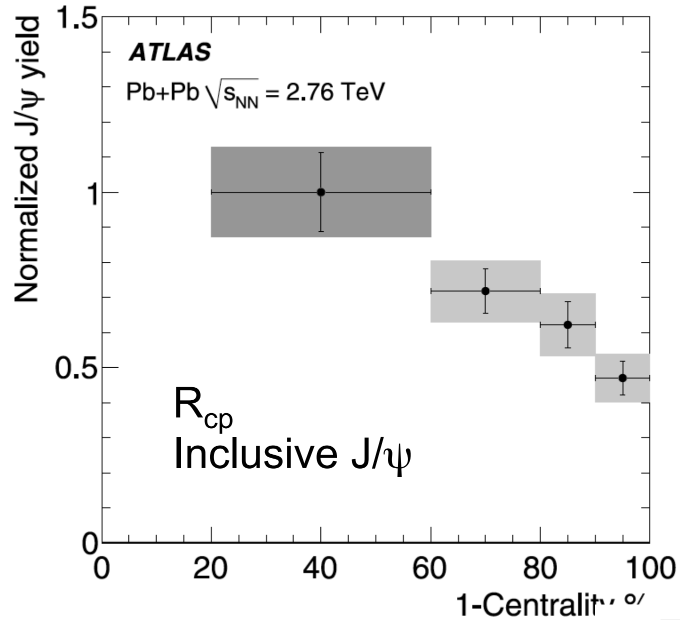


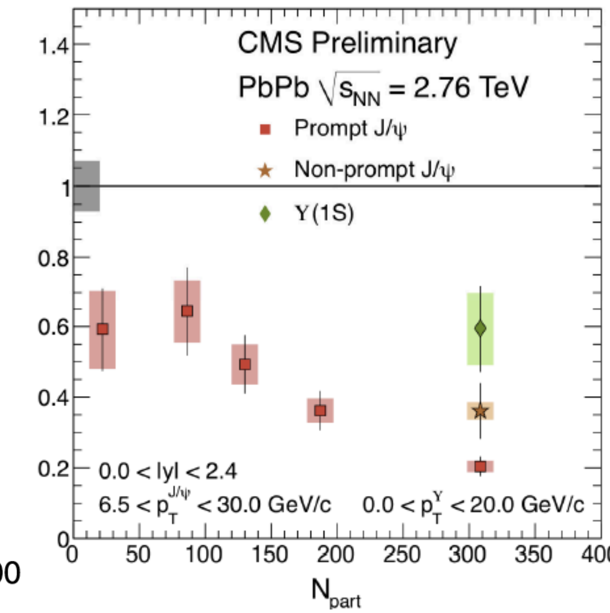
Initial production vs charm quark coalescence
High p_T low p_T

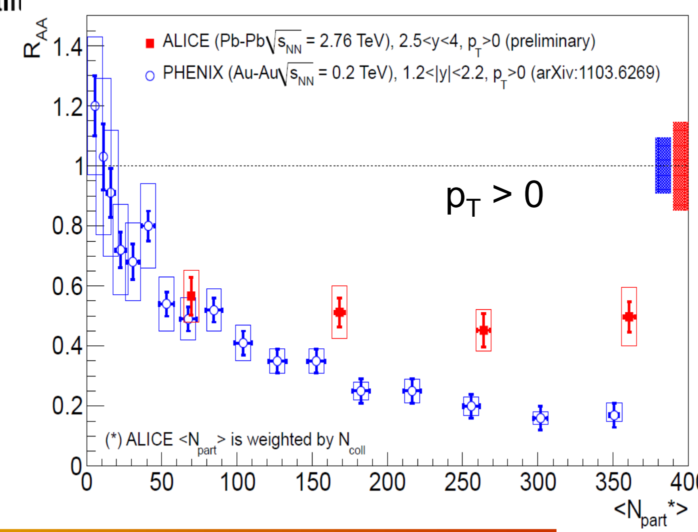
v_2 measurement is from mid-central collisions. Coalescence contribution may be not sizable
The fraction changes with centrality -> would be nice to see the centrality dependence of v_2

RHIC vs. LHC





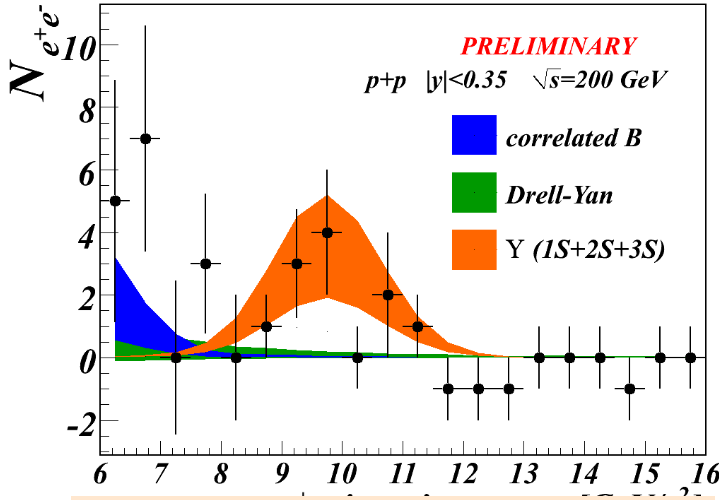


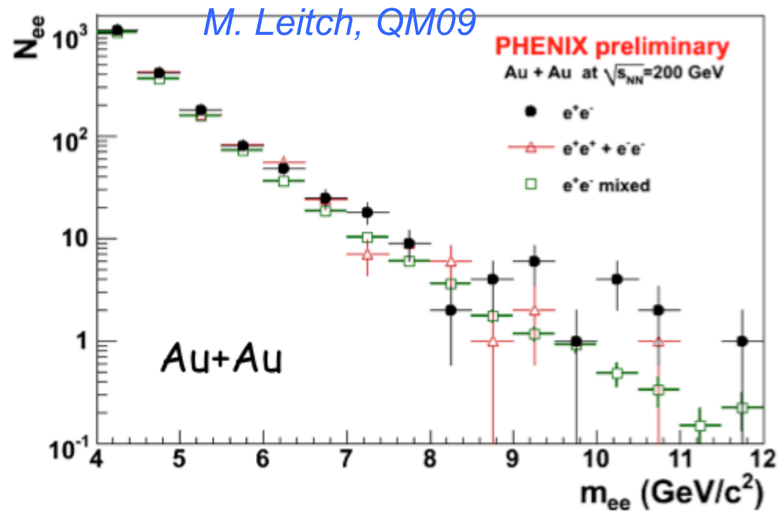


Need further systematic studies on both RHIC and LHC to understand the J/ψ production

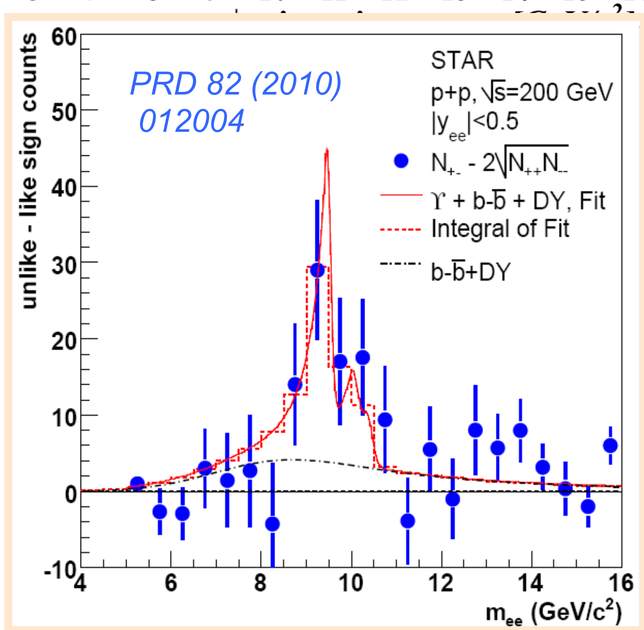
Upsilon Signals

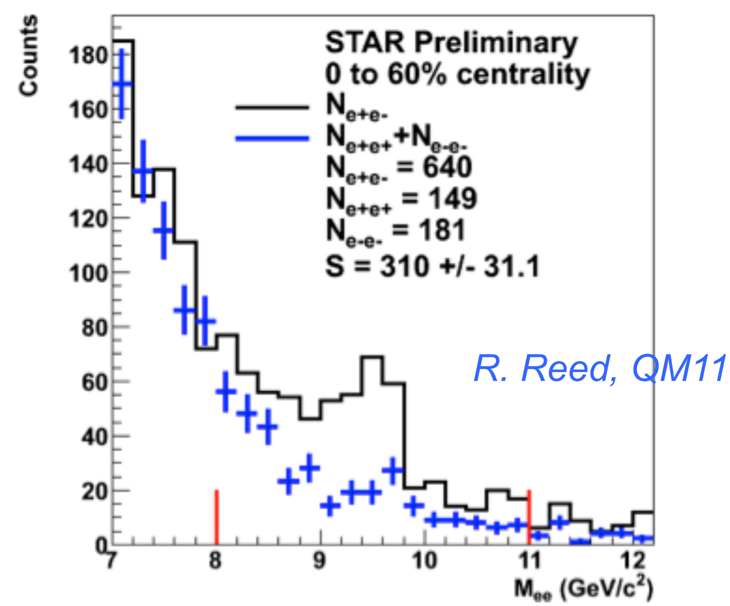
PHENIX



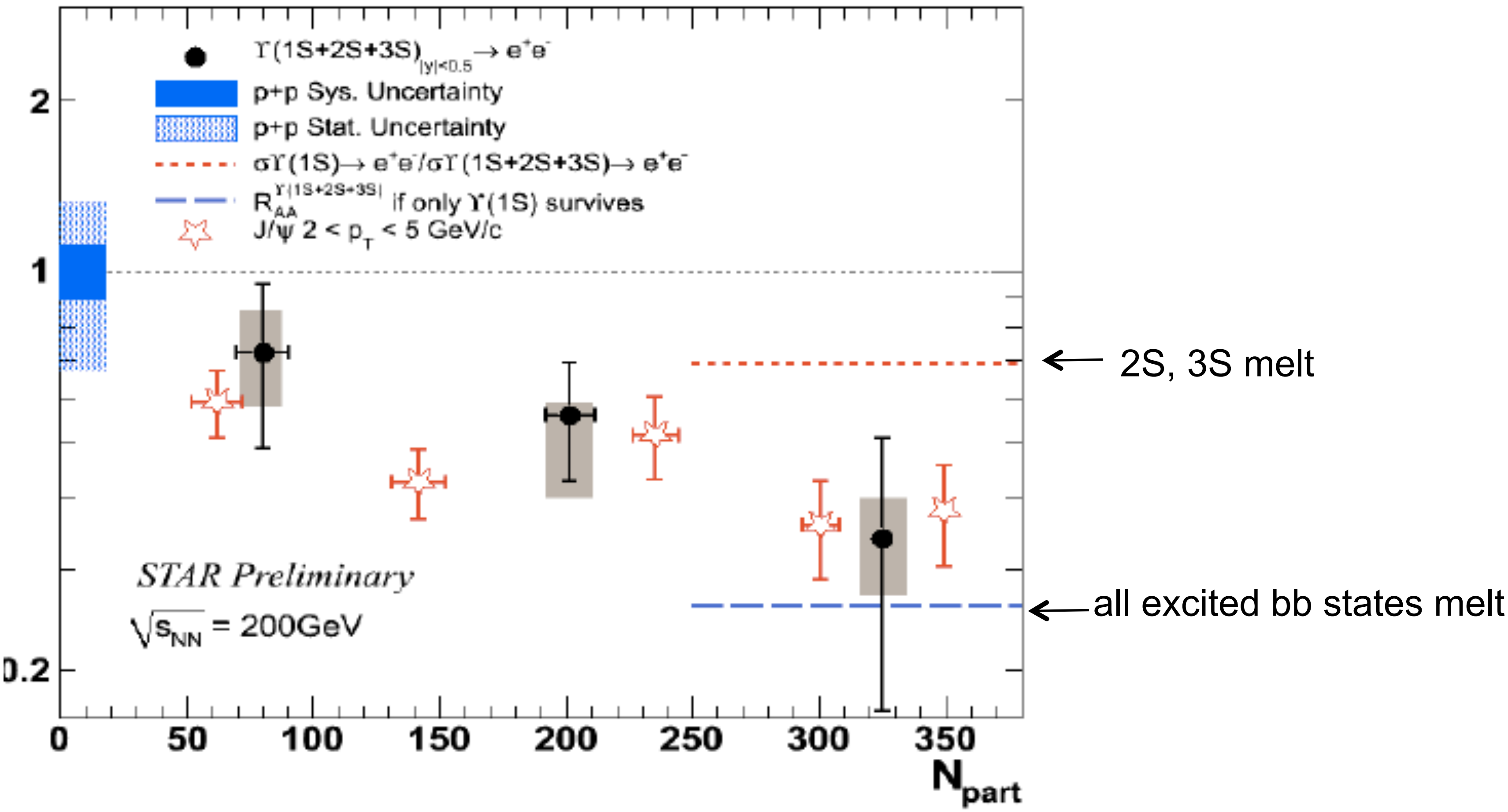


STAR





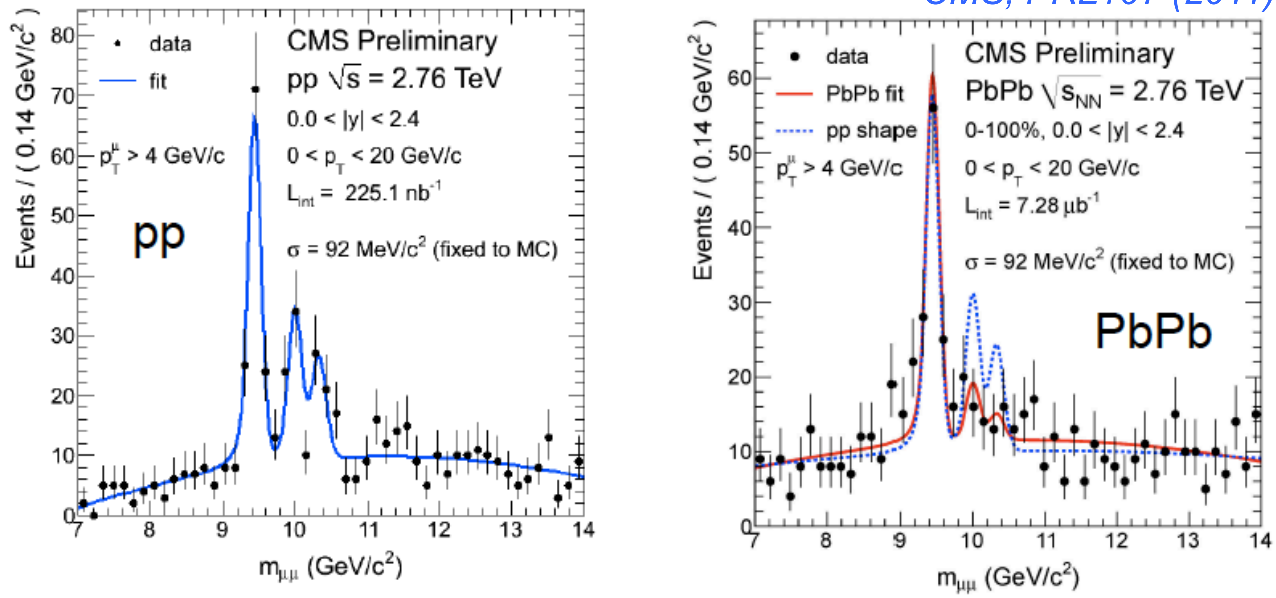
Upsilon(1S+2S+3S) R_{AA}



- In favor that only Upsilon(1S) survives
- Cold nuclear effect (shadowing / anti-shadowing?)
- Looking forward to high precision at RHIC-II in the future.

Compared with CMS

CMS, PRL107 (2011) 052302



$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

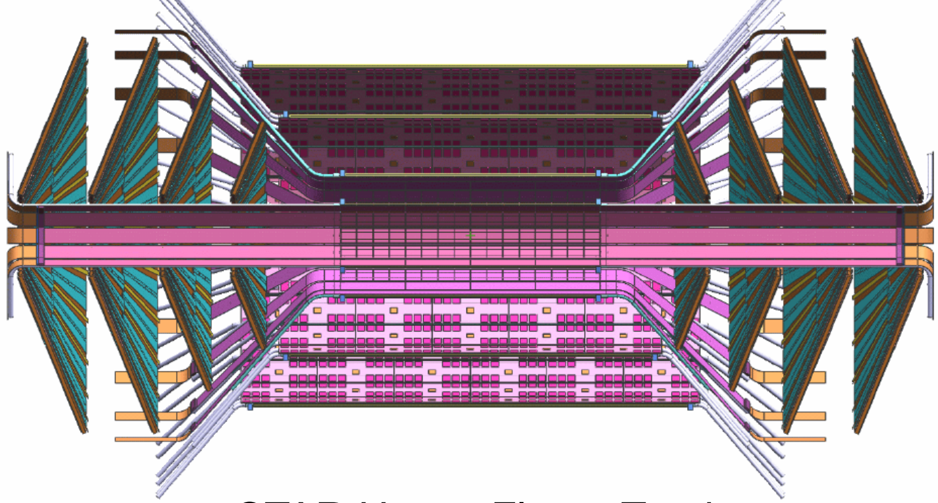
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

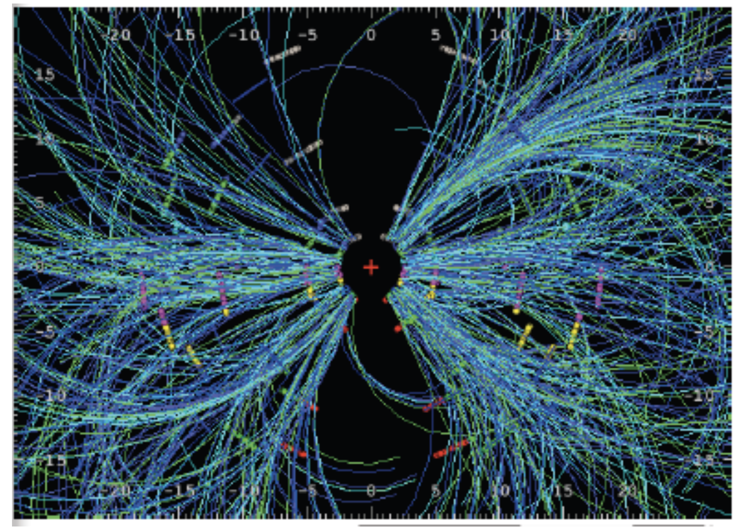
$R_{AA}(\Upsilon(1S))$ ~ 0.6 ⟶ $R_{AA}(\Upsilon(1S+2S+3S))$ ~ 0.42

- Generally in consistency between RHIC and LHC given large uncertainties.
- However, (anti-)shadowing, cold nuclear absorption, recombination contributions may be different at RHIC vs LHC

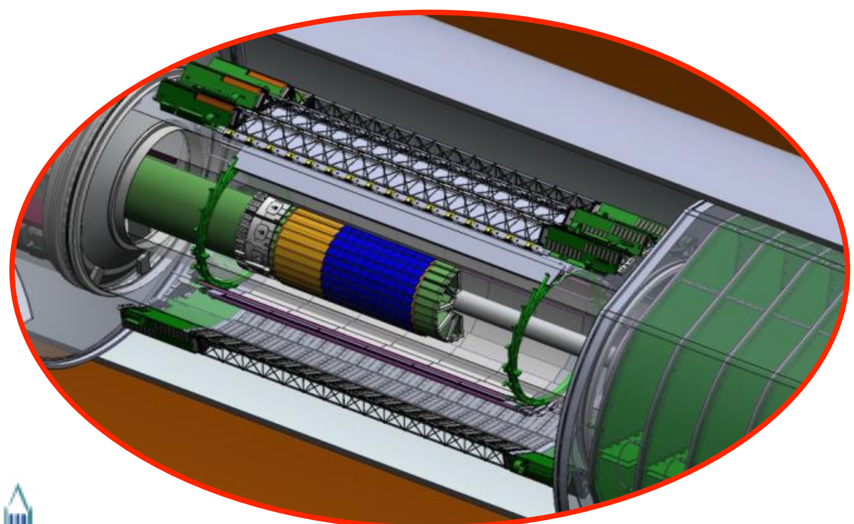
PHENIX and STAR Upgrades

PHENIX VTX and FVTX

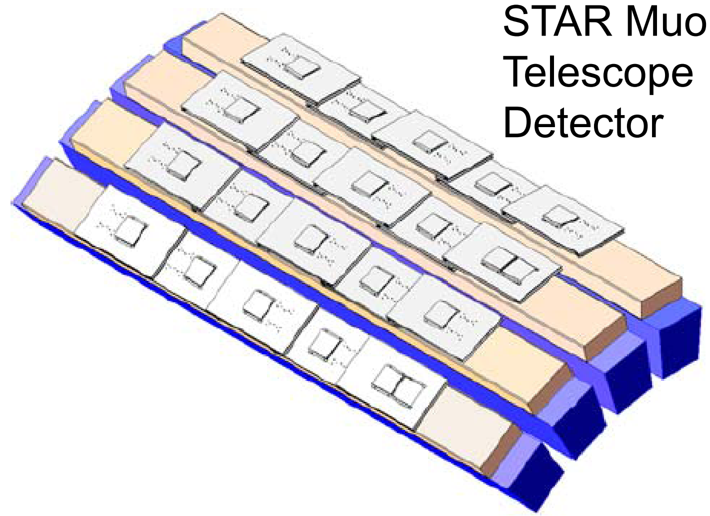




STAR Heavy Flavor Tracker



STAR Muon Telescope Detector

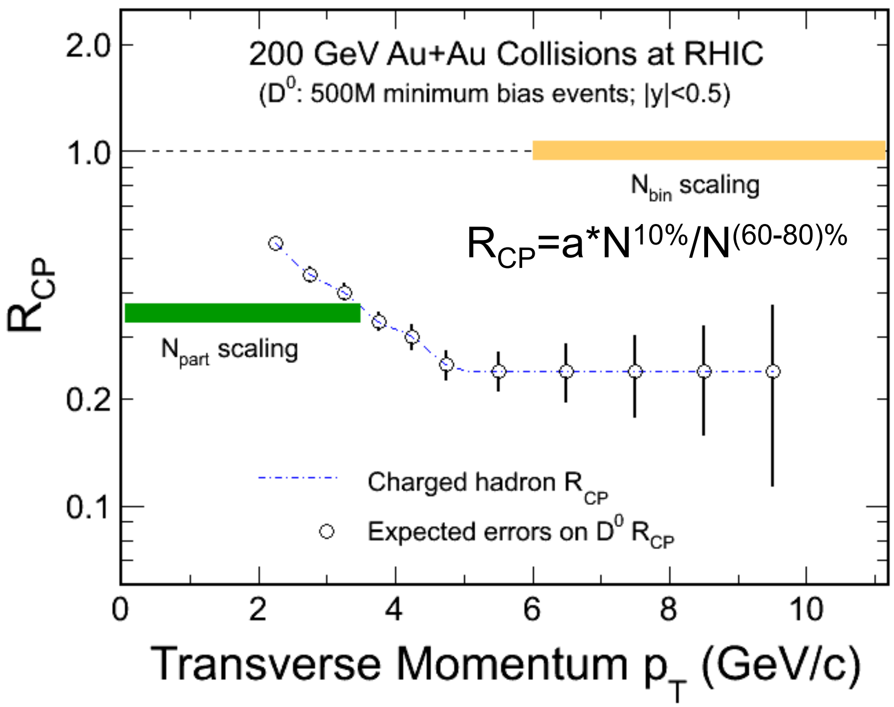


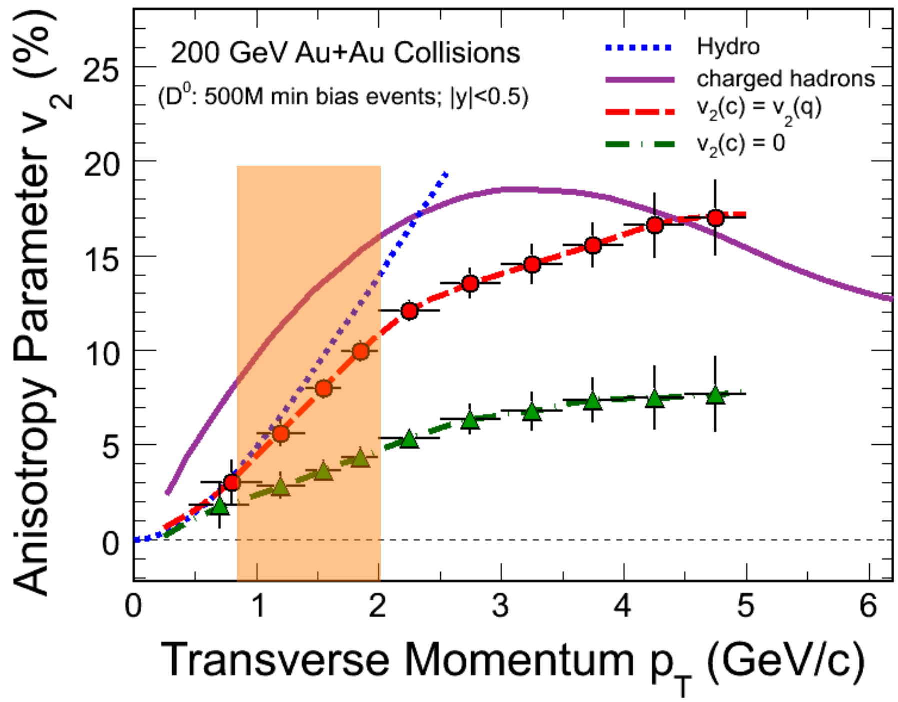
Heavy Flavor Physics Focus

Precision measurements on open HF (hadrons and NPE) in p+p and A+A collisions
- R_{AA} to address energy loss mechanisms
- Elliptic flow v_2 (and R_{AA}) to probe the medium thermalization degree.
- Large acceptance allows correlation measurements.

Precision measurements on quarkonia production
- To provide significant constrains to understand the quarkonia production mechanism in p+p collisions
- To access as many quarkonia as possible to map out the melting pattern
- Upsilon families will be one of the focuses as they are expected to be much cleaner at RHIC without too much additional regeneration from the medium.

Physics Projections





Assuming D^0 R_{cp} distribution as charged hadron

500M Au+Au m.b. events at 200 GeV.

- Charm R_{AA} ⇨

Energy loss mechanism!

Interaction with QCD matter!

Assuming D^0 v_2 distribution from quark coalescence.

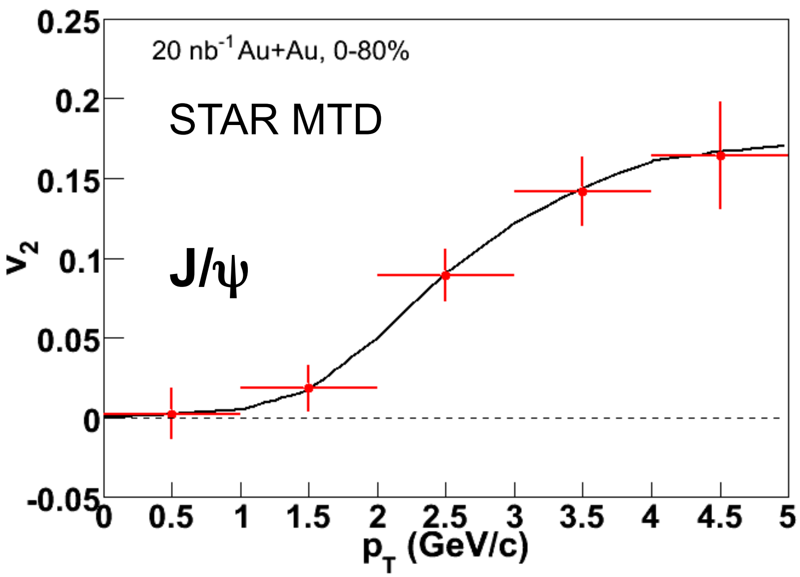
500M Au+Au m.b. events at 200 GeV.

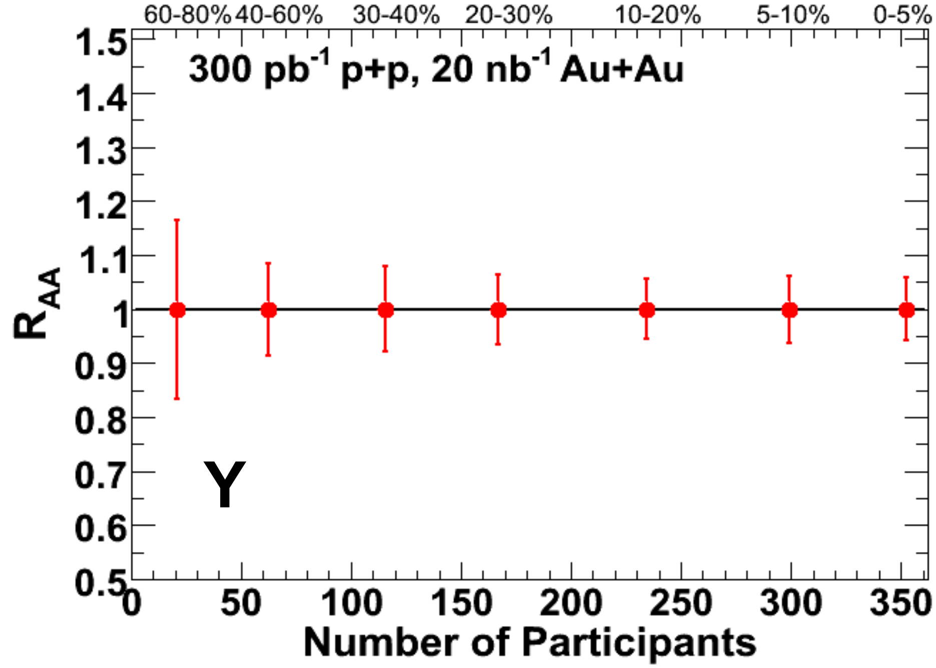
- Charm v_2 ⇨

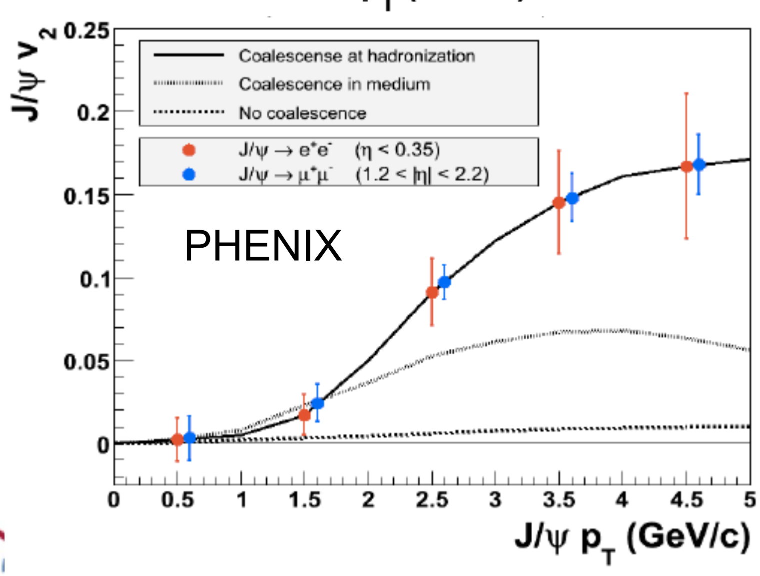
Thermalization degree!

Drag coefficients!

Quarkonia at RHIC-II







STAR MTD (at mid-rapidity) – di-muon
- complementary measurement on J/ψ
- allowing separation of three Upsilon states

Final Remarks

RHIC experiments have achieved significant amount of findings on the heavy flavor production in the last decade.

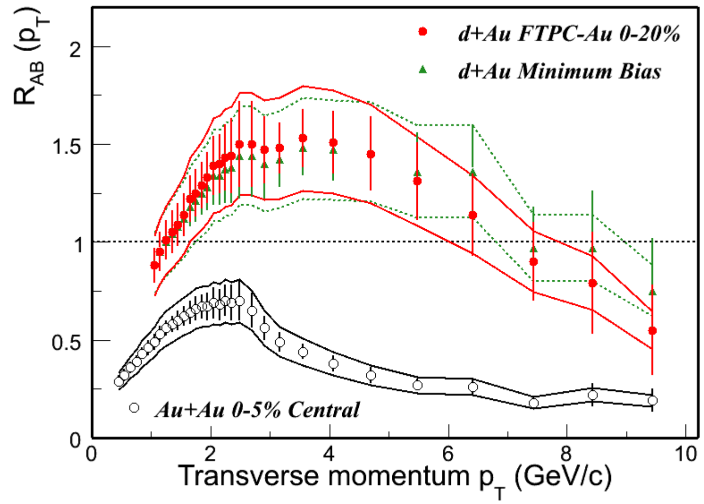
Heavy flavor physics will be one of the key measurements in quantifying the medium properties at the RHIC II era with help of the detector subsystem upgrades.

RHIC heavy flavor program will be complementary and remain competitive with the LHC experiments ongoing. Some of the measurements will be unique at RHIC.

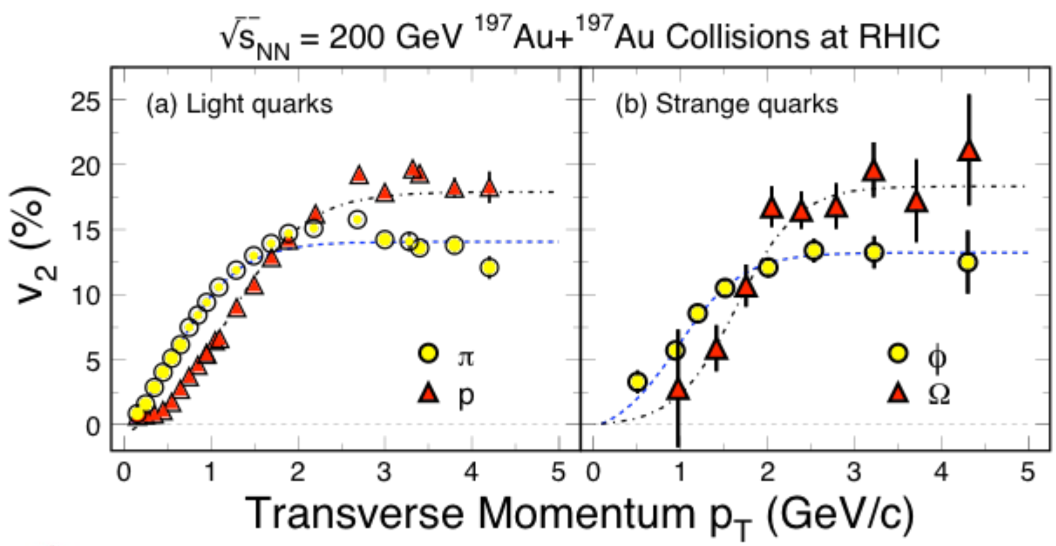
- High precision open charm hadron measurements down to low p_T to address the charm-medium interactions, thus the medium thermalization.
- Bottomonia production expected to be clean at RHIC, recombination process is completely negligible.

…

What we've learned



- High p_T:
  - Jet quenching
- Low p_T:
  - Hydrodynamic behavior
  - Multi-strange hadrons flow
- Intermediate p_T:
  - Number of Constituent Quark scaling
  - Multi-strange hadrons flow as light hadrons

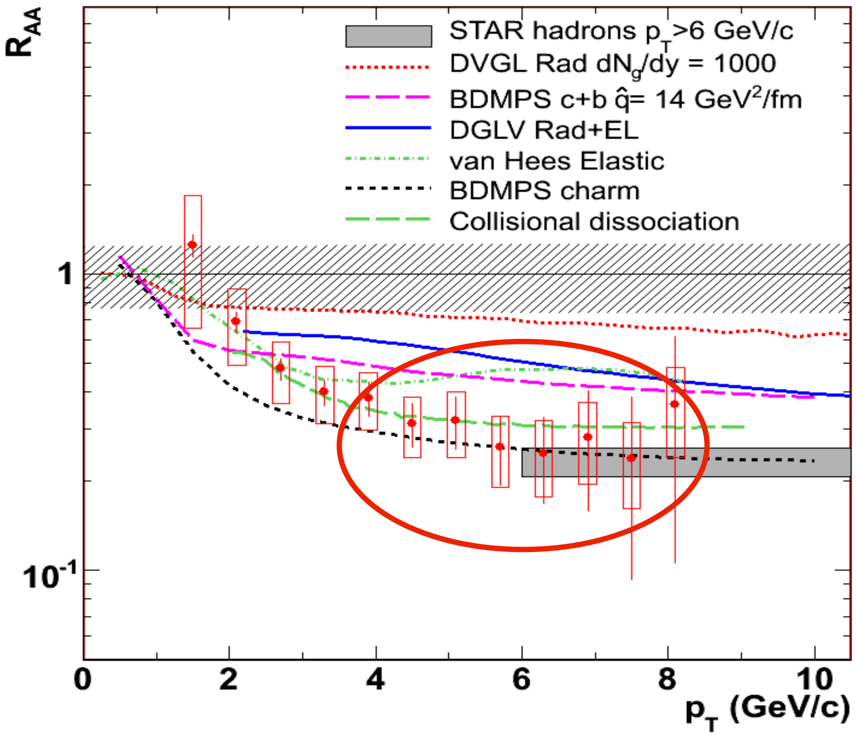


A hot and dense matter with strong partonic collectivity has been formed at RHIC!

STAR: NPA 757, 102 (2005); QM2009

Heavy Quark ΔE in hot QCD medium

STAR PRL 98 (2007) 192301



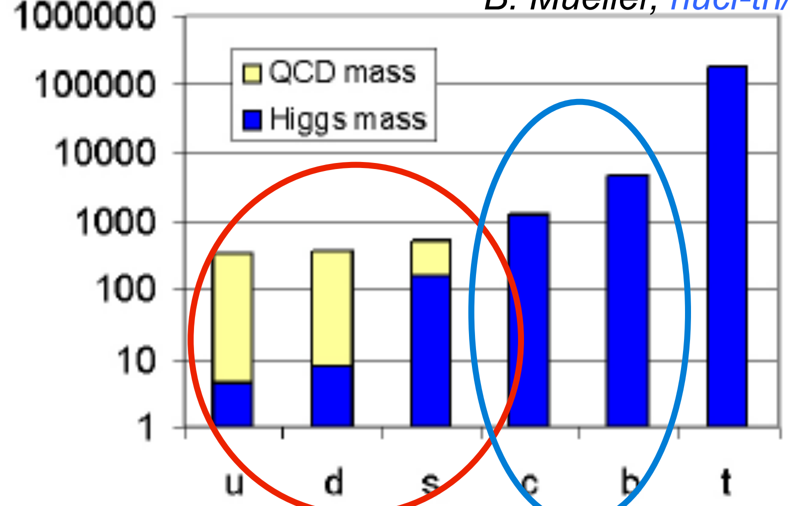
- ➢Heavy quark decay electrons
  - mixture of charm and bottom decays
- ➢$R_{AA}(e) \sim R_{AA}(h)$
- ➢Contradict to the naïve radiative energy loss mechanism

- ➢ Re-visit the energy loss mechanisms
- ➢ Require direct measurements of charm or bottom hadrons for clear understanding

Heavy Quarks to Probe Early Thermalization

- ➢ Heavy quarks created at early stage of HIC, and sensitive to the partonic re-scatterings.
- ➢ Heavy quark collectivity/flow to quantify the thermalization degree at the top energy.
- ➢ Thermalization - essential to the RHIC Beam Energy Scan program.

B. Mueller, nucl-th/0404015

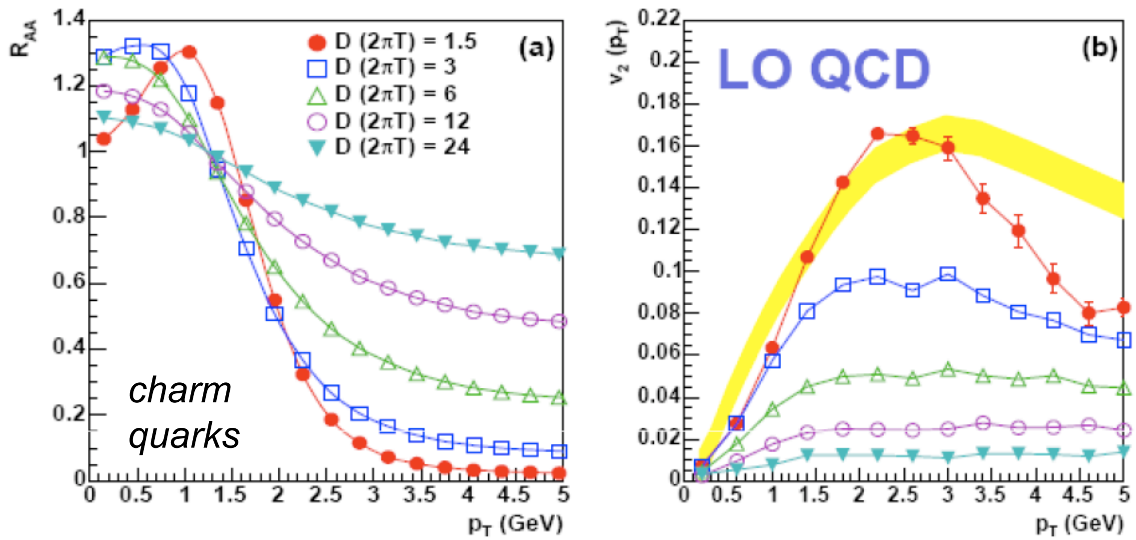


Brownian Motion in Thermal System

Medium transport property
Diffusion constant

$$D \propto \eta/(sT)$$

G. Moore & D. Teaney, PRC 71(2005)064904
H. van Hees & R. Rapp, PRC 71(2005)034907



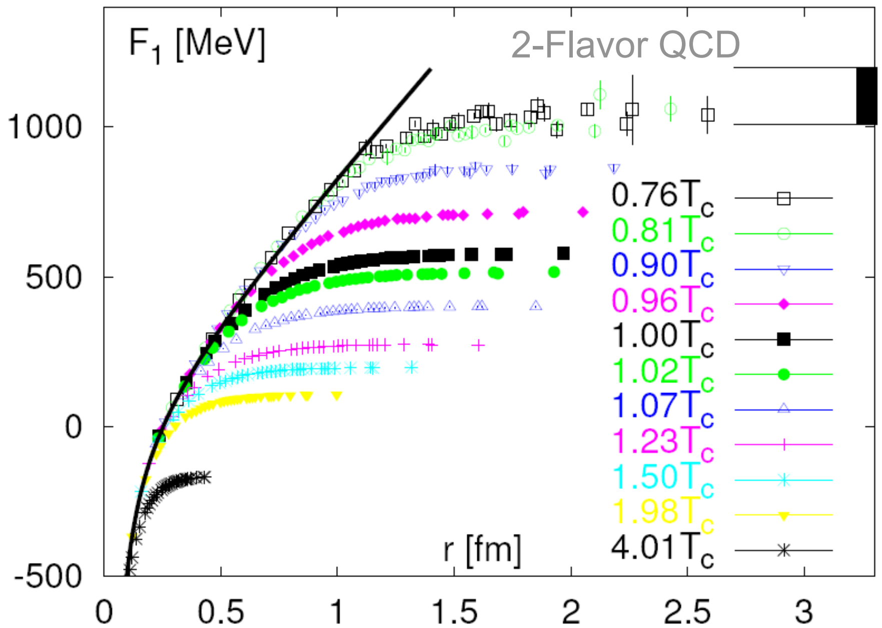
Heavy Quarkonia - QGP Thermometer

Quarkonia suppression due to color screening - a classic QGP signature

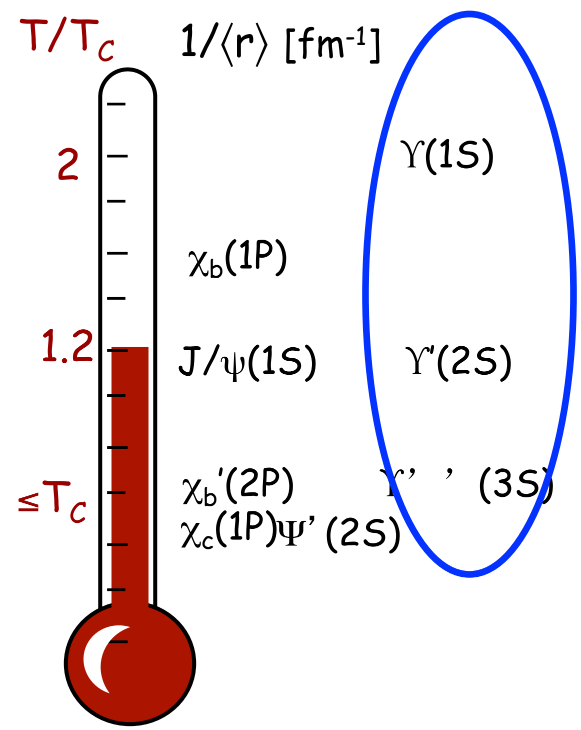
T. Matsui and H. Satz, PLB 178 (1986) 416

Sequential dissociation - Quarkonia as a QGP thermometer

H. Satz, NPA 783 (2007) 249c; A. Mocsy & P. Petreczky, PRL 99 (2007) 211602



O. Kaczmarek & F. Zantow, PRD 71 (2005) 114510



A. Mocsy & P.Petreczky, PRL 99 (2007) 211602

DOE milestone 2016

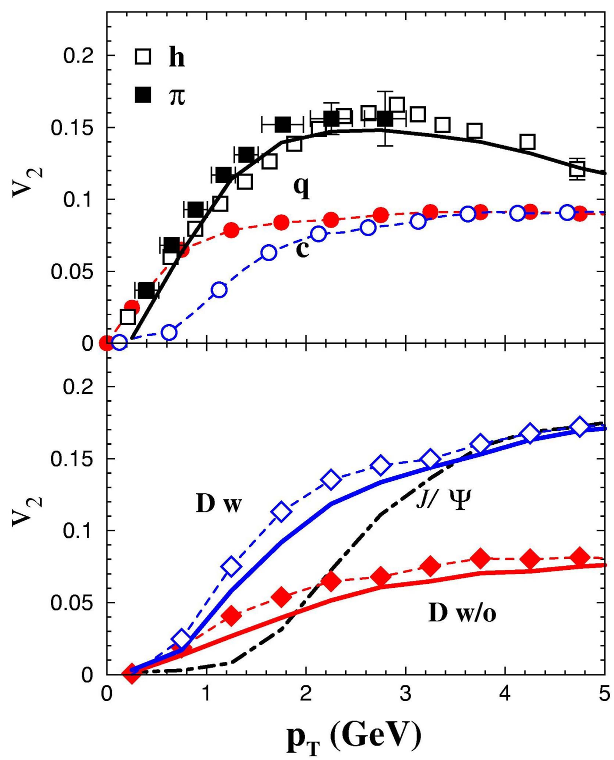
Measure production rates, high p_T spectra, and correlations in heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV for identified hadrons with **heavy flavor** valence quarks to constrains the mechanism for parton energy loss in the quark-gluon plasma

Charm Quark Hadronization

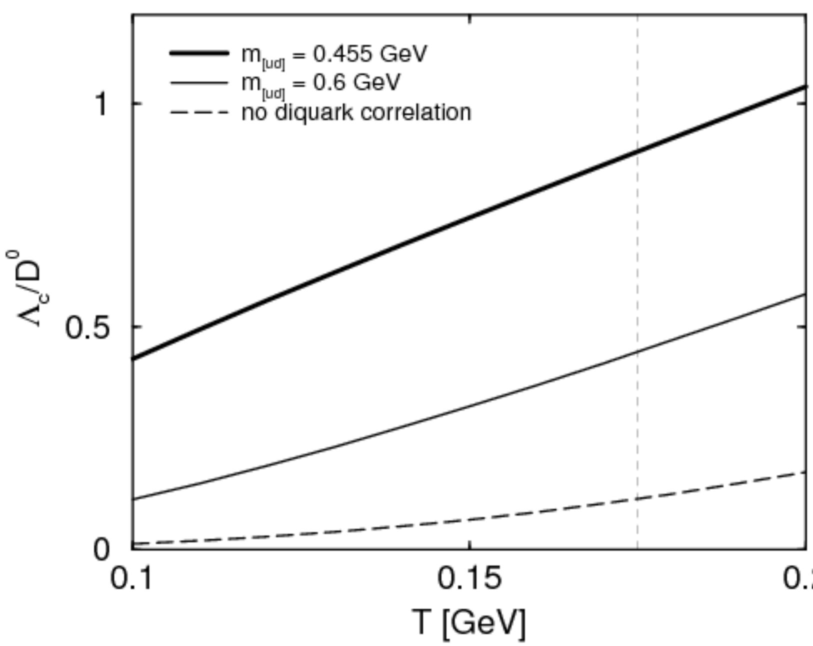
Direct (hard) fragmentation in elementary collisions.
However, in heavy ion collisions …

✓ Coalescence approach

V. Greco et al., PLB 595(2004)202

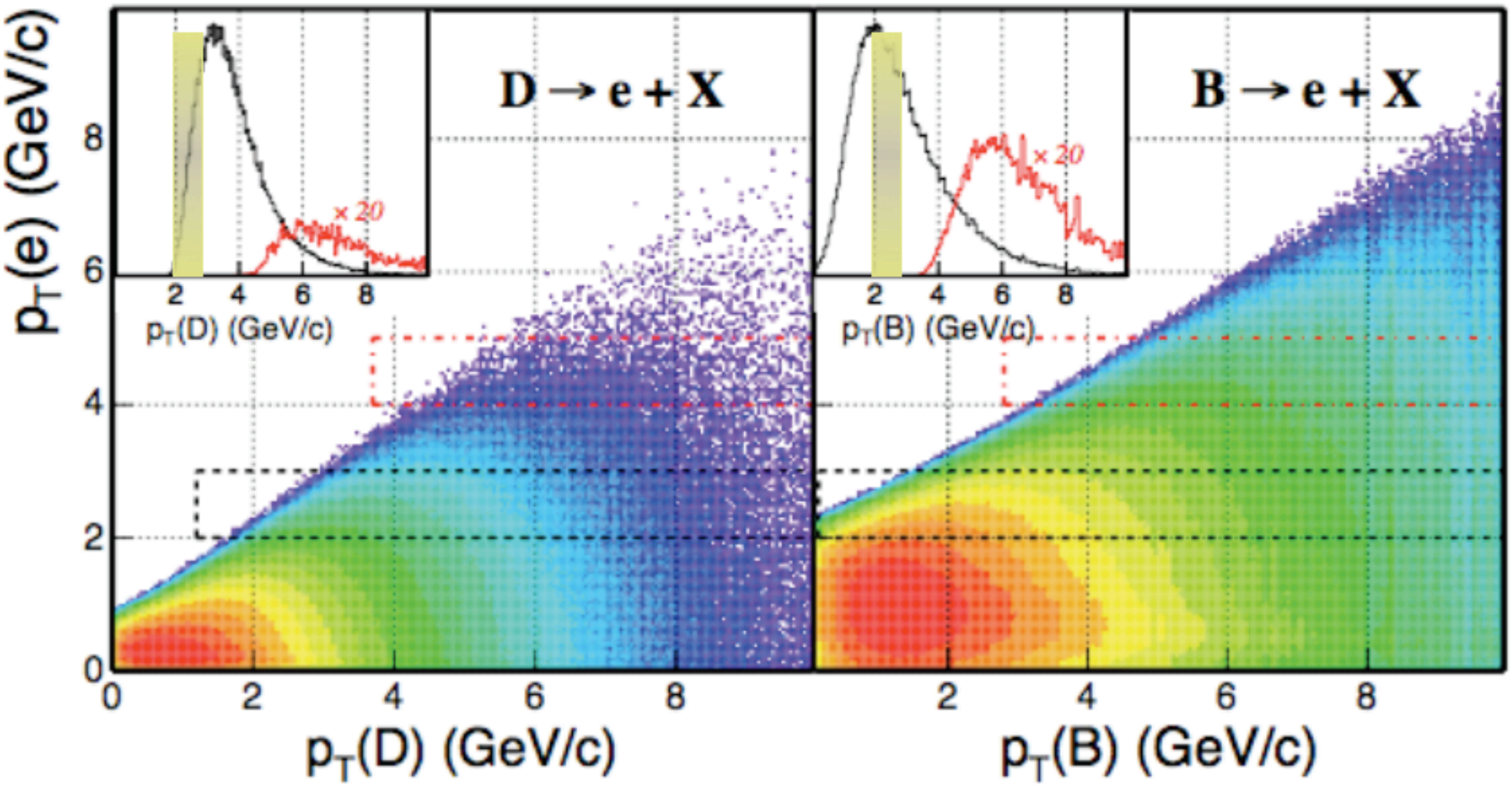


Charm baryon enhancement ?
- coalescence of c and di-quark



Lee, et. al, PRL 100 (2008) 222301

Electrons - Incomplete Kinematics



New micro-vertex detector is needed for precision measurements on charmed hadrons production in heavy ion collisions

STAR Approach

<u>Detection capability at mid-rapidity, full azimuth</u>

large and uniform acceptance

allowing precision correlation measurements

1) Direct topological reconstruction of open charmed hadrons in HI collisions

- No ambiguities in the charm hadron kinematics
- No ambiguities in the charm/bottom hadron mixture
- Significantly improved significance by reconstructing the secondary decay vertices.

2) Quarkonia measurements via both di-electron/di-muon channels

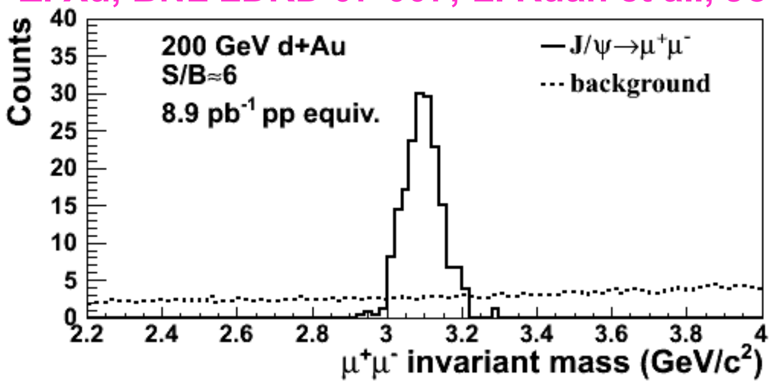
- Triggerable di-muon channel to sample full luminosity
- No bremmestrahlung tail in di-muon channel so allow separation of three Upsilon states

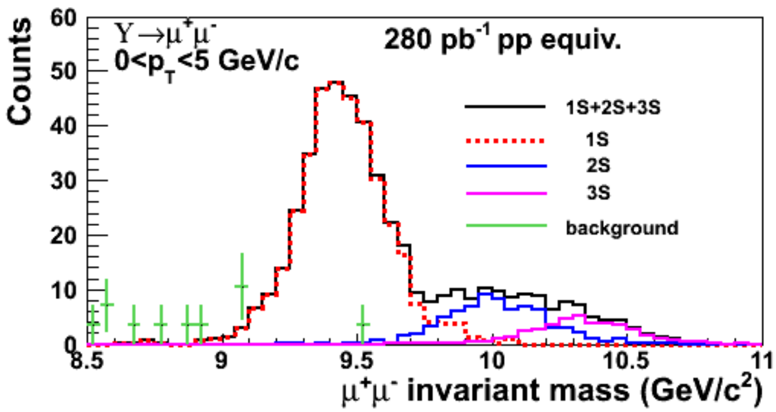
STAR Decadal Plan Documents:

http://www.bnl.gov/npp/docs/STAR_Decadal_Plan_Final%5B1%5D.pdf

High Mass Di-muon Capabilities

Z. Xu, BNL LDRD 07-007; L. Ruan et al., Journal of Physics G: Nucl. Part. Phys. 36 (2009) 095001





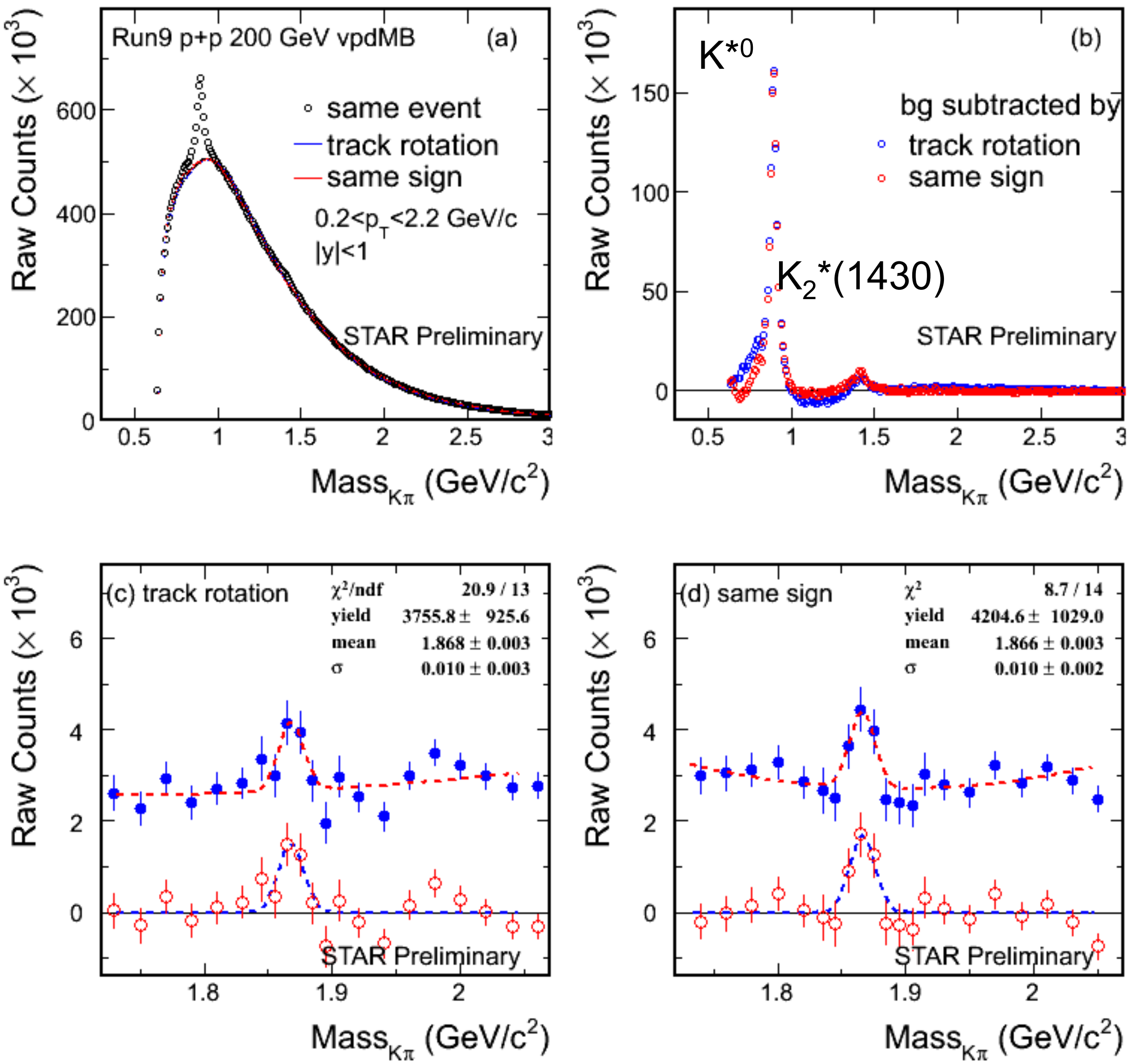
1. J/ψ: S/B=6 in d+Au and S/B=2 in central Au+Au
2. With HFT, study B→J/ψ X; J/ψ→μμ using displaced vertices
3. Excellent mass resolution: separate different upsilon states

Heavy flavor collectivity and color screening, quarkonia production mechanisms:
J/ψ R_{AA} and v_2; upsilon R_{AA} …

Quarkonium dissociation temperatures – Digal, Karsch, Satz

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

D0 signal in p+p 200 GeV



$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$

B.R. = 3.89%

p+p minimum bias 105 M

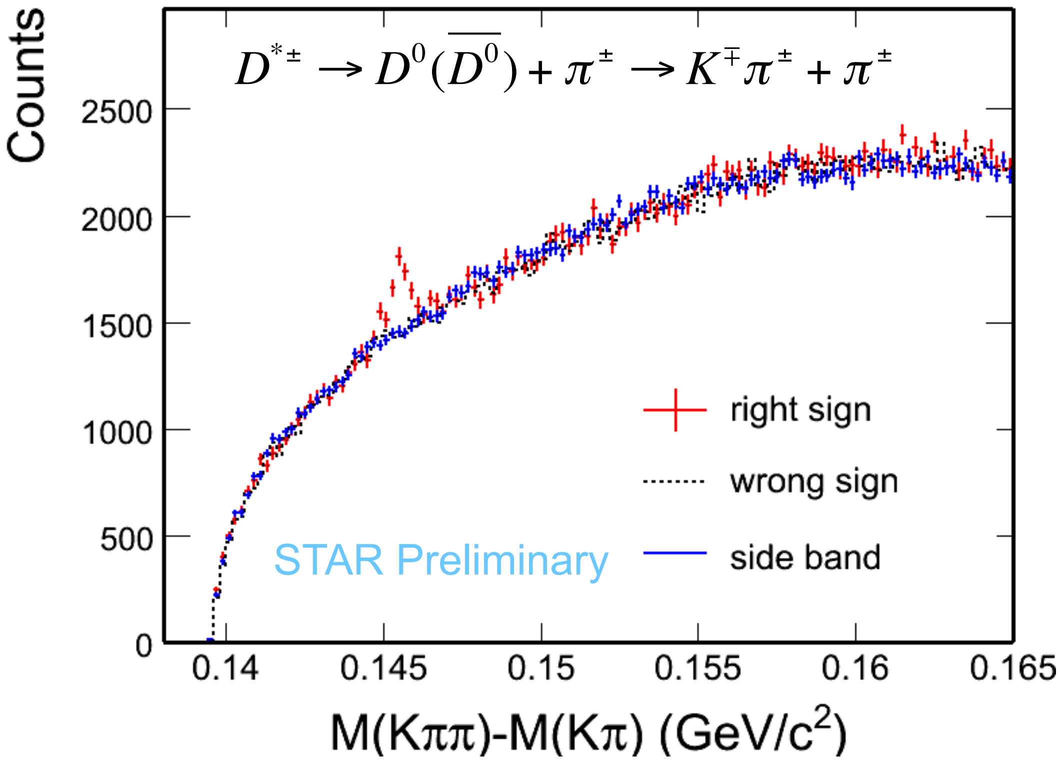
4-σ signal observed.

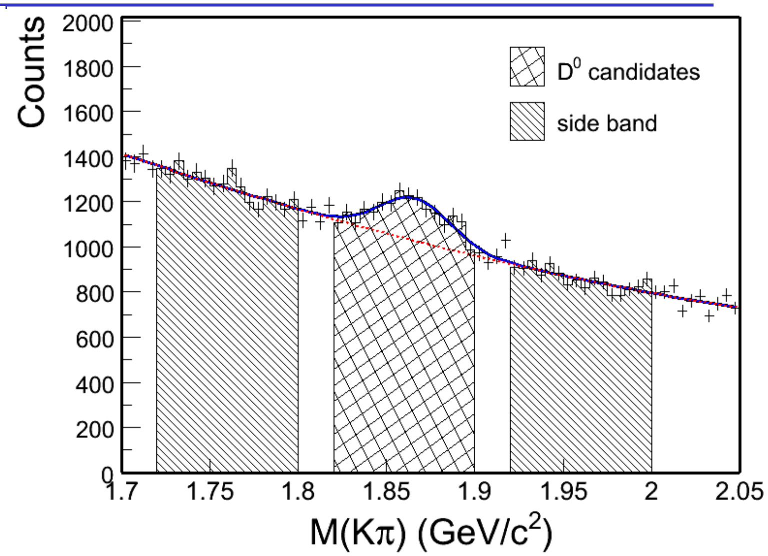
Different methods reproduce combinatorial background.

Consistent results from two background methods.

PDG mass = 1864.5 ± 0.4 MeV

D* signal in p+p 200 GeV





B.I.~Abelev, *et al., PRD 79 (2009) 112006.*

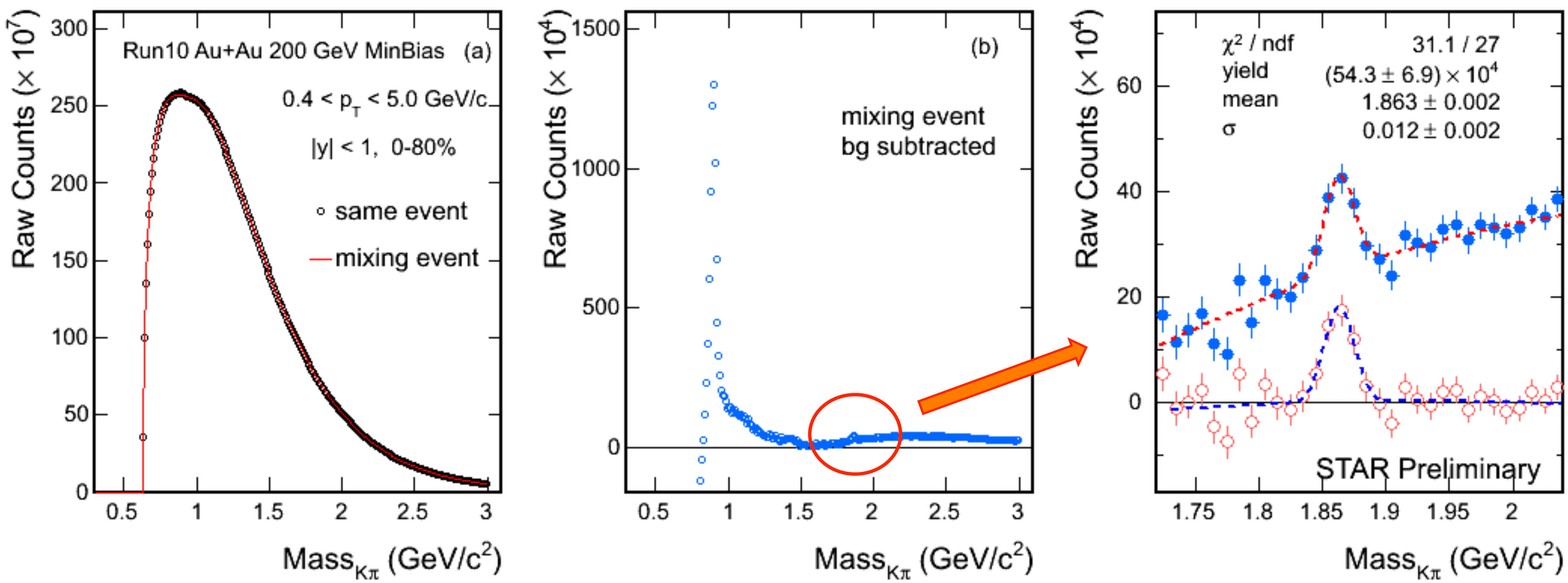
Minimum bias 105M events in p+p 200 GeV collisions.

Two methods to reconstruct combinatorial background: wrong sign and side band.

8-σ signal observed.

<u>Background combinations:</u>
Wrong sign:
D^0 and π^-, $\overline{D}^0$ and π^+
Side band:
1.72< M(Kπ) < 1.80 or
1.92 < M(Kπ) < 2.0 GeV/c^2

D^0 signal in Au+Au 200 GeV



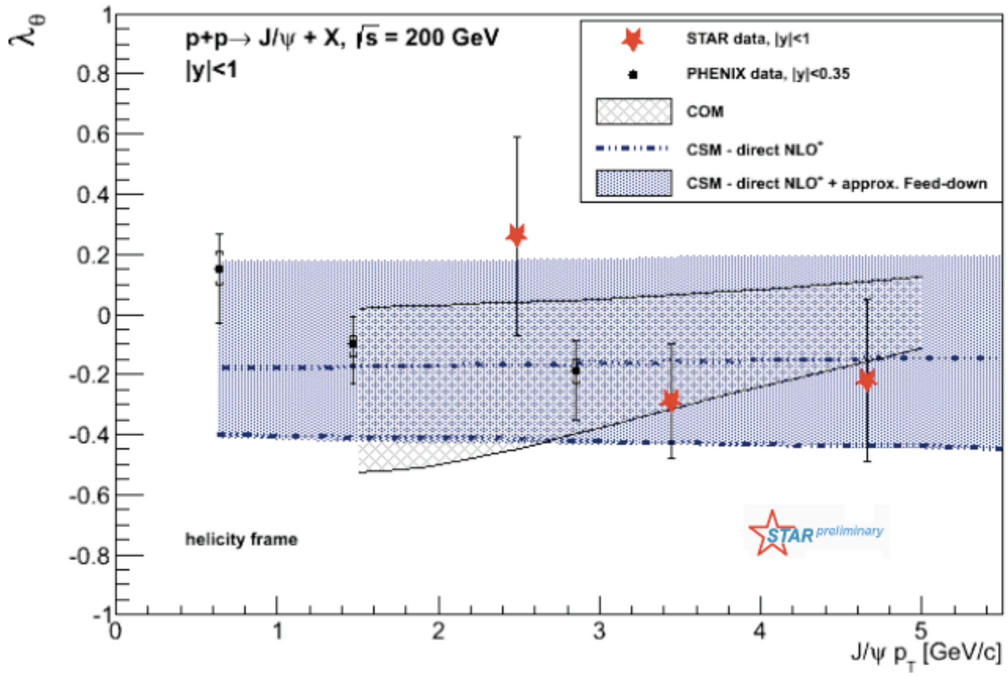
Year 2010 minimum bias 0-80% 280M Au+Au 200 GeV events.

8-σ signal observed.

Mass = 1863 ± 2 MeV (PDG value is 1864.5 ± 0.4 MeV)

Width = 12 ± 2 MeV

J/ψ Polarization in p+p collisions



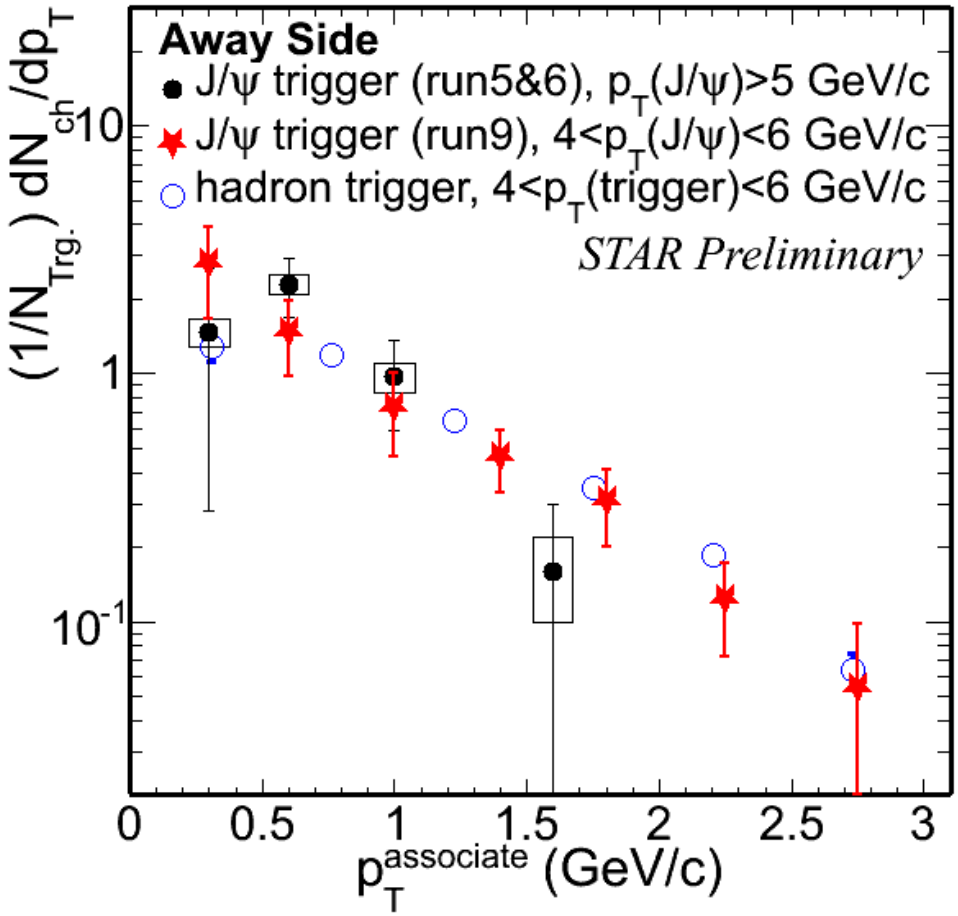
$$\frac{d\sigma}{d\cos\theta^*} = A(1 + \lambda\cos^2\theta^*),$$

Results shown are in helicity frame

PHENIX: PRD 82 (2010) 012001

New opportunity to understand the J/ψ production mechanism in p+p collisions
Limited by statistics currently, looking forward to RHIC-II high statistics

Away side associated hadron p_T spectra



STAR, PRL95, 152301 (2005)

Consistent with hadron-hadron correlation

➔away-side seems to come from gluon/light quark fragmentation

Heavy Quarkonia Program

A) Up to 2013 (TPC+TOF+EMC)

Charmonia:

low p_T from minibias sample - limited statistics

high p_T from single electron HT trigger - efficient and can sample the full luminosity

will carry on at RHIC II

Bottomonia:

di-electron channel - material effect from inner tracker / limited statistics

B) 2014 and beyond (HFT+TPC+TOF+EMC+MTD)

Charmonia:

di-muon channel covers from low to high p_T

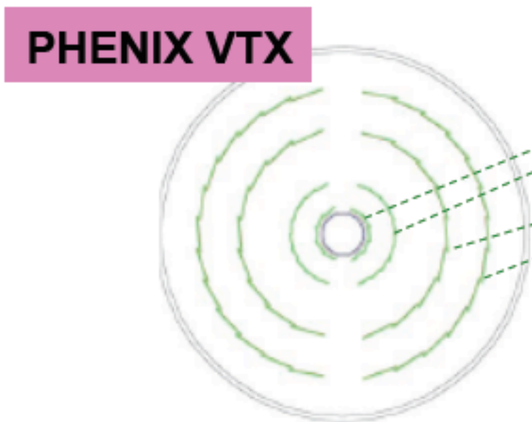
high p_T from single electron HT trigger

Bottomonia:

di-muon channel - excellent in mass resolution and able to sample full luminosity

di-electron channel within HFT acceptance - limited statistics

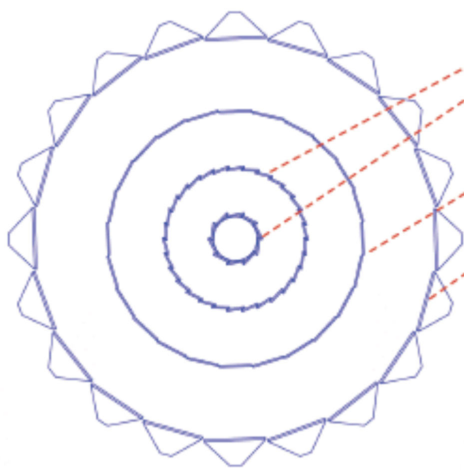
STAR HFT vs. PHENIX VTX



- 2-layer Si hybrid pixels: $x/x_0 \sim 1.2\%$ per layer;
  2.5cm inner radius; fast readout
- 2-layer Si strips, $x/x_0 \sim 2\%$

  $0.5 \leq p_T \leq 6$ GeV/c: $e^{\pm}$
  $2 < p_T \leq 6$ GeV/c: D-mesons…
  $1 < p_T \leq 6$ GeV/c: $B \rightarrow J/\psi$

STAR HFT



- 2-layer CMOS: $x/x_0 \sim 0.37\%$ per layer;
  2.5cm inner radius; 200μs integration
- 1-layer* Si strips
- SSD: $x/x_0 \sim 1\%$

e, $D^{0,\pm,s,*}$, Λ_c, B…

$0.5 < p_T < 10$ GeV/c: v_2, R_{AA}

D-D correlation functions

Compelling Physics with HFT

1) The STAR HFT measurements (p+p and Au+Au)

(1) Heavy-quark cross sections: $D^{0,\pm,*}$, D_S, Λ_C , B…

(2) Both spectra ($R_{AA,}$ R_{CP}) and v_2 in a wide p_T region.

(3) Charm hadron correlation functions

(4) Full spectrum / v_2 of the heavy quark hadron (separated) decay electrons

2) Compelling Physics

a) Establish elementary charm and bottom cross sections

b) Characterize the medium through parton energy loss

c) Determine the degree of thermalization via heavy quark flows

d) Analyze hadro-chemistry in the charm sector

e) Study the bottom behavior in medium via the separation of charm contributions

MTD Detecting Probes

- **di-muon pairs** from heavy quarkonia decays
- **single muons** from the semi-leptonic decays of heavy flavor hadrons
- **e-mu correlations** to distinguish HF production from initial di-lepton production

Advantages over electron channels:

no γ conversion, much less Dalitz decay contribution

Much less combinatorial background

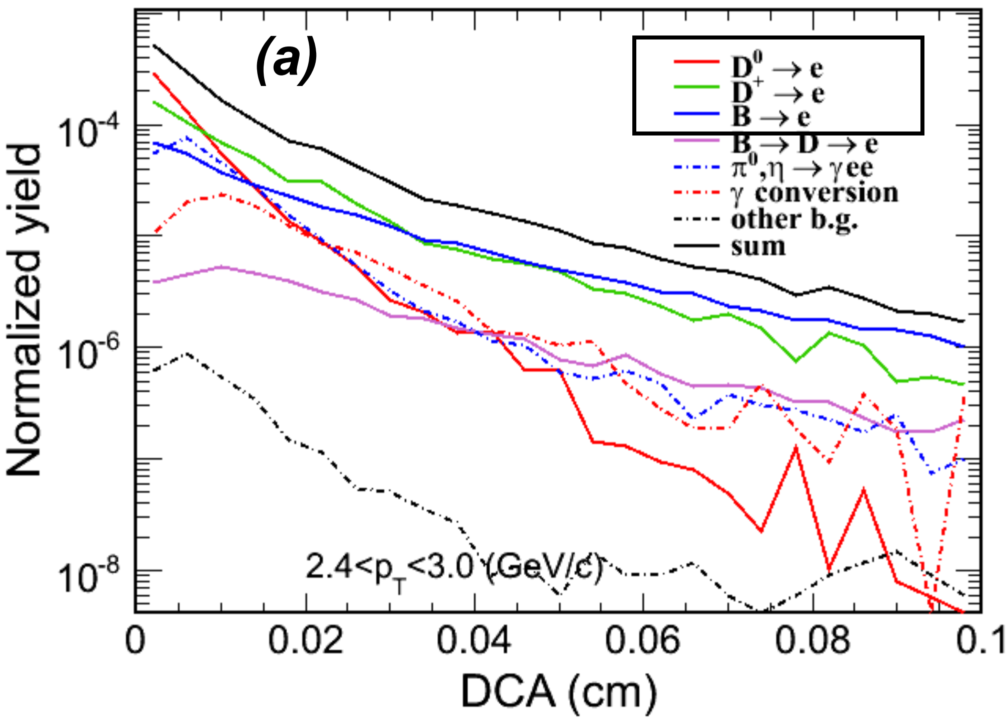
less affected by radiative losses in the detector materials

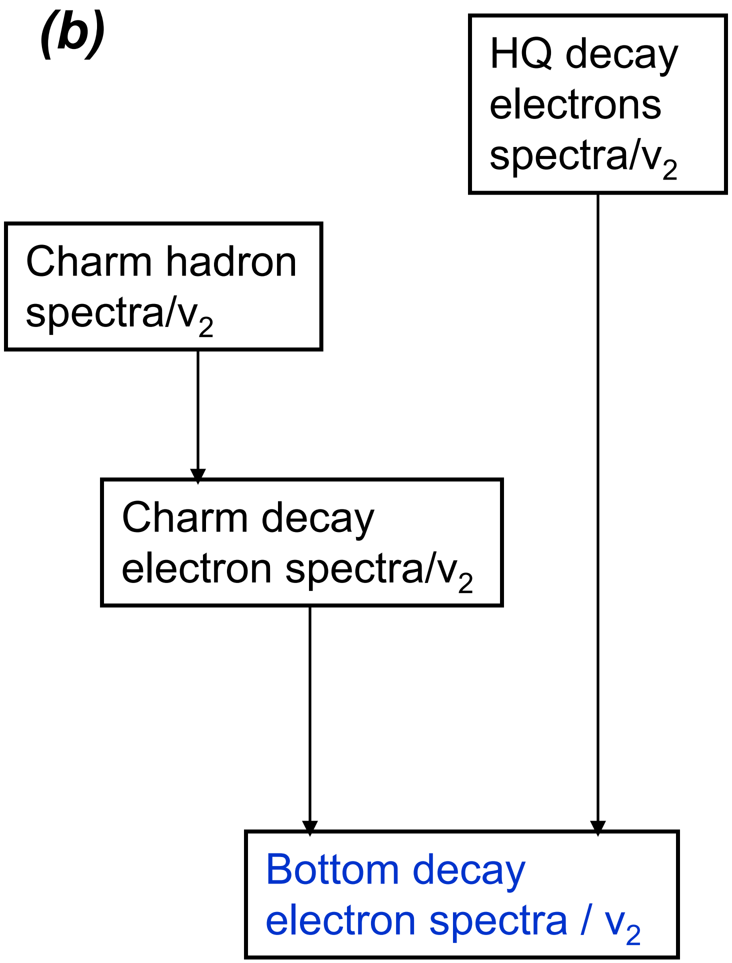
excellent mass resolution, allowing separation of three Upsilon states

triggerable in Au+Au

sample full luminosity from low to high p_T for J/ψ in central AA collisions

Access Bottom Production via Electrons



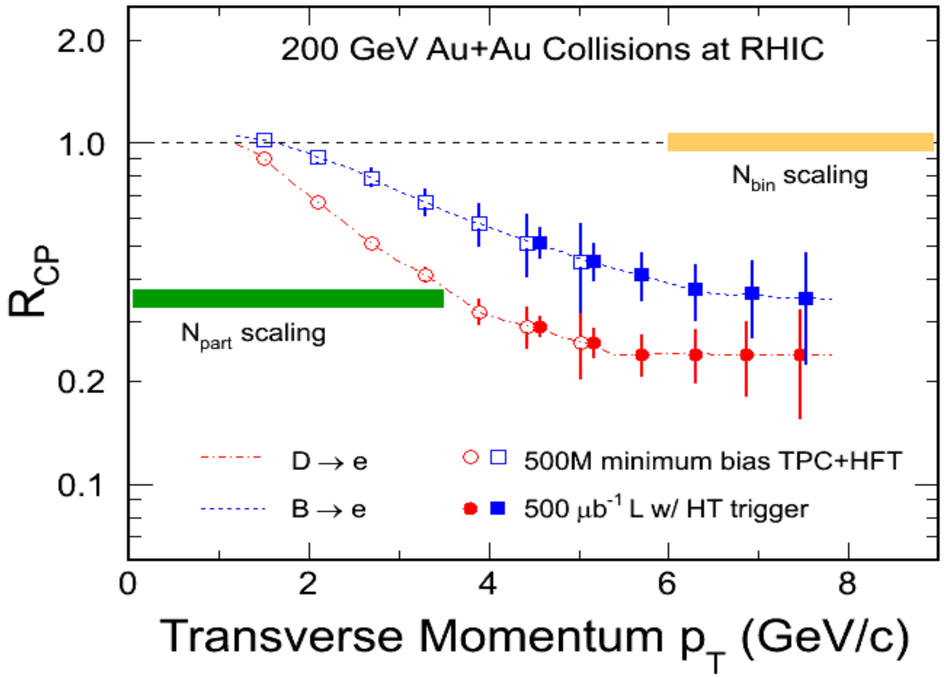


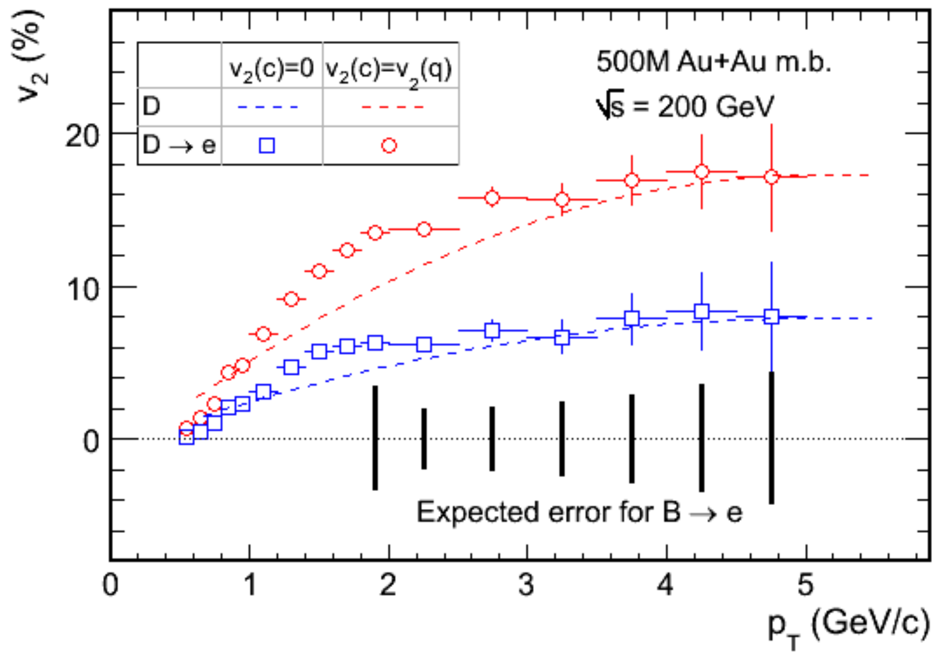
Two approaches:

a) Statistical fit with model assumptions

b) With known charm hadron spectrum
to constrain or be used in subtraction

Statistical Projections on e_B Spectra / v_2

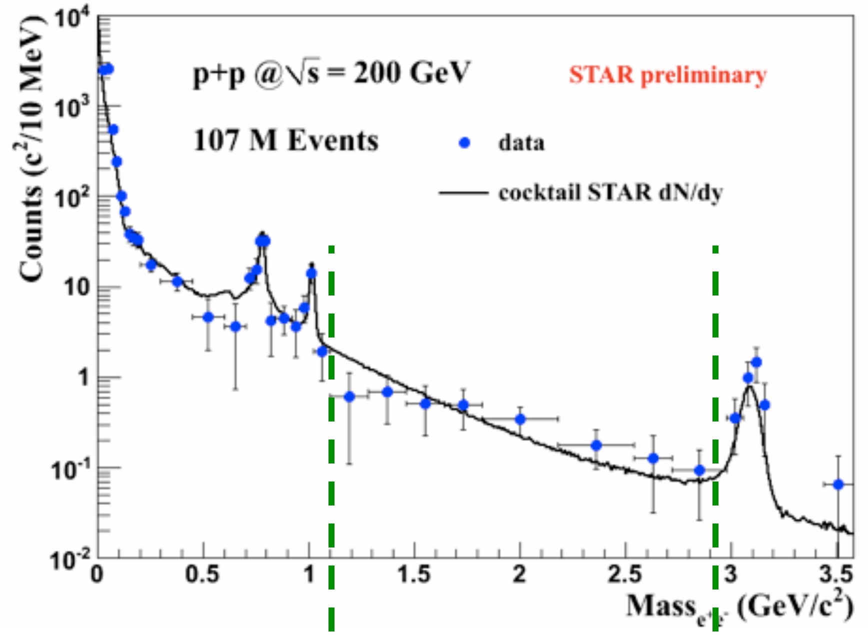


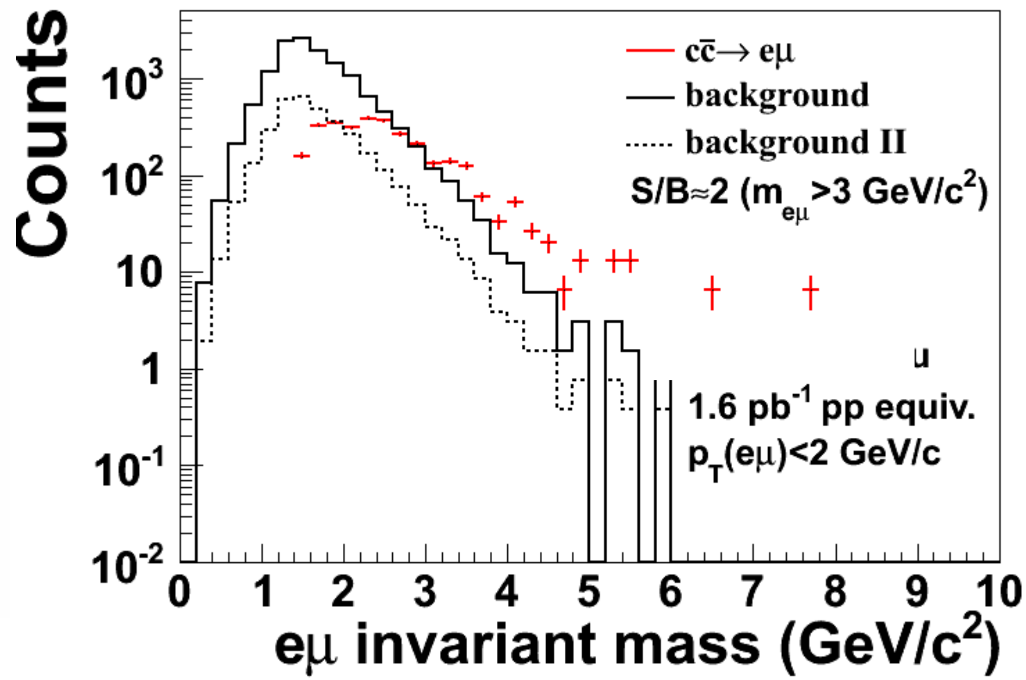


Curves: H. van Hees et al. Eur. Phys. J. C 61 (2009) 799

➢ (B→e) spectra obtained via the subtraction of charm decay electrons from inclusive NPEs:
no model dependence, reduced systematic errors.

e-mu correlations





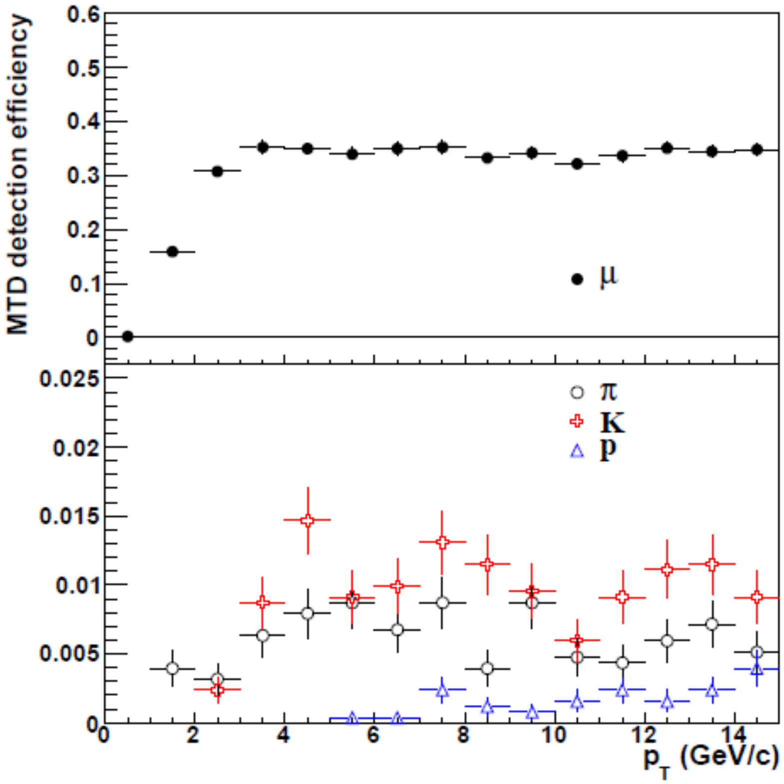
ccbar
Drell-Yan
Thermal radiation

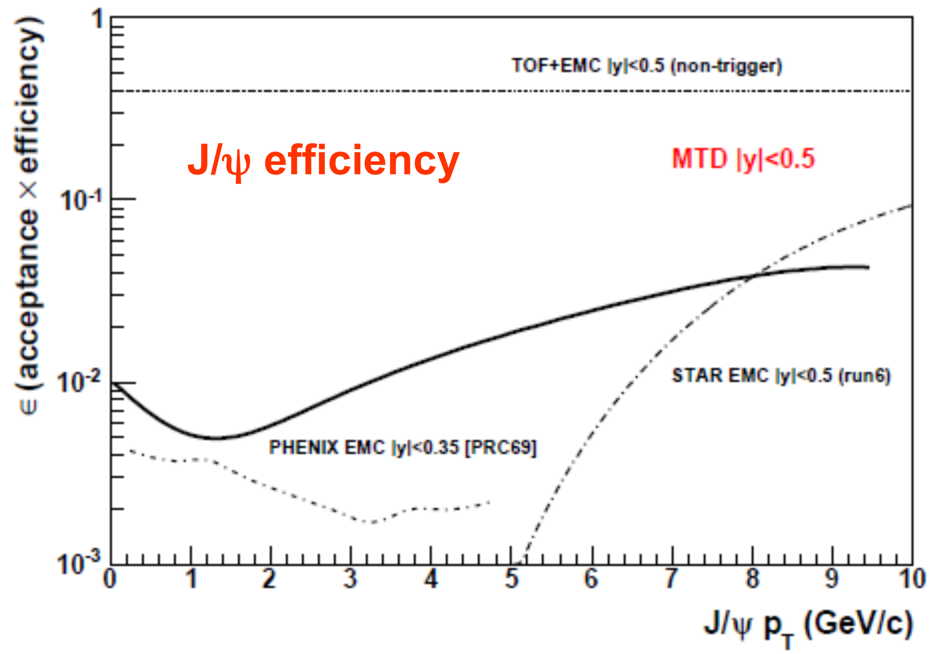
L. Ruan et al., JPG 36 (2009) 095001

eμ correlation with Muon Telescope Detector at STAR from ccbar:

S/B=2 (M_{eu}>3 GeV/c² and $p_T(e\mu)$<2 GeV/c)
S/B=8 with electron pairing and tof association

J/ψ with MTD

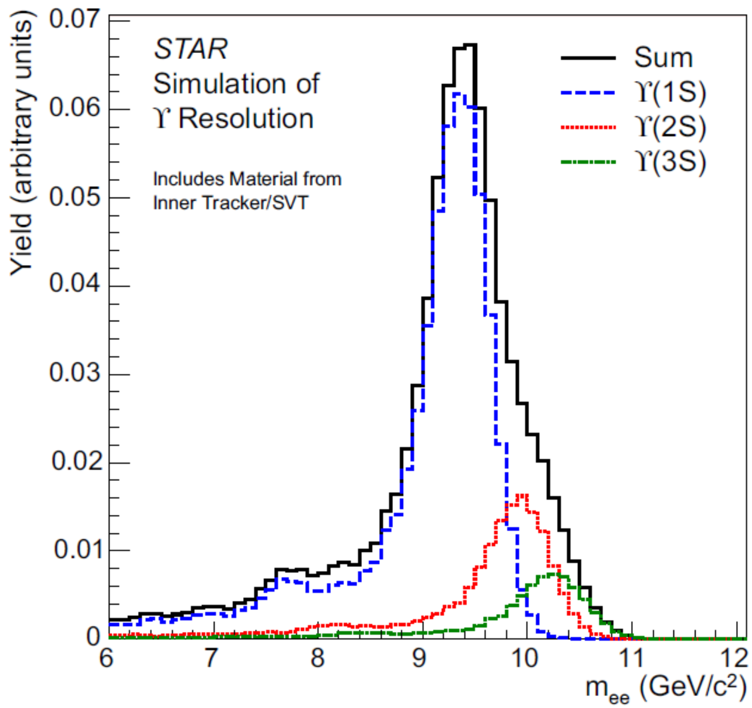




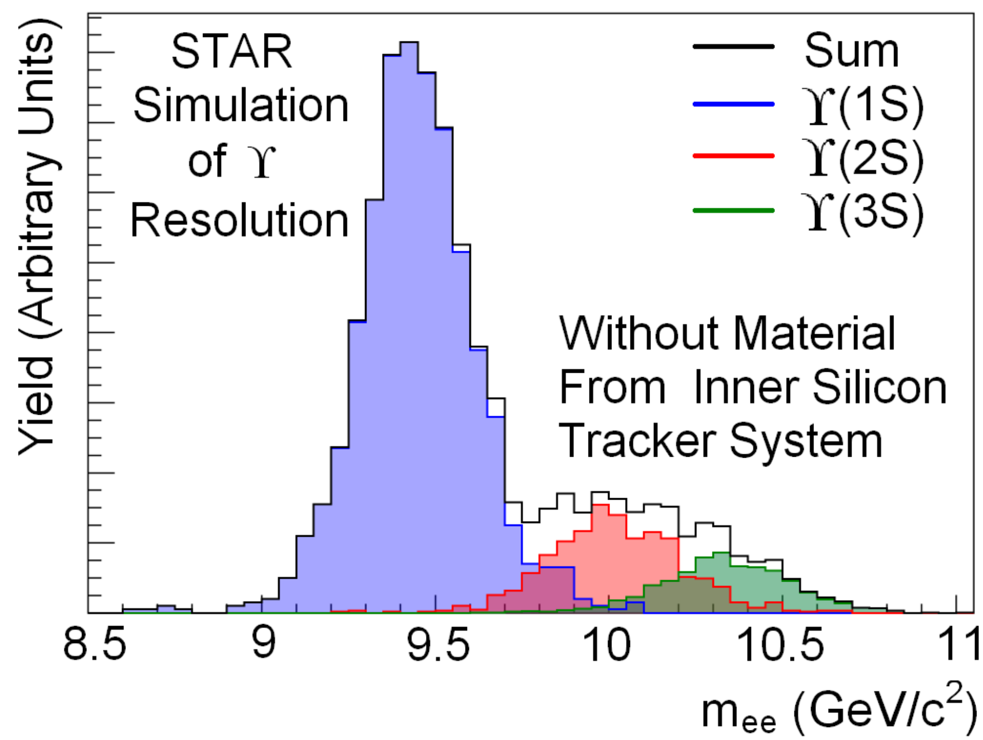
1. muon efficiency at |η|<0.5: 36%, pion efficiency: 0.5-1% at p_T>2 GeV/c
2. dimuon trigger enhancement factor from online trigger: 40-200 in central Au+Au collisions

Upsilon Mass Resolution with MTD

Di-electrons with material from inner tracker



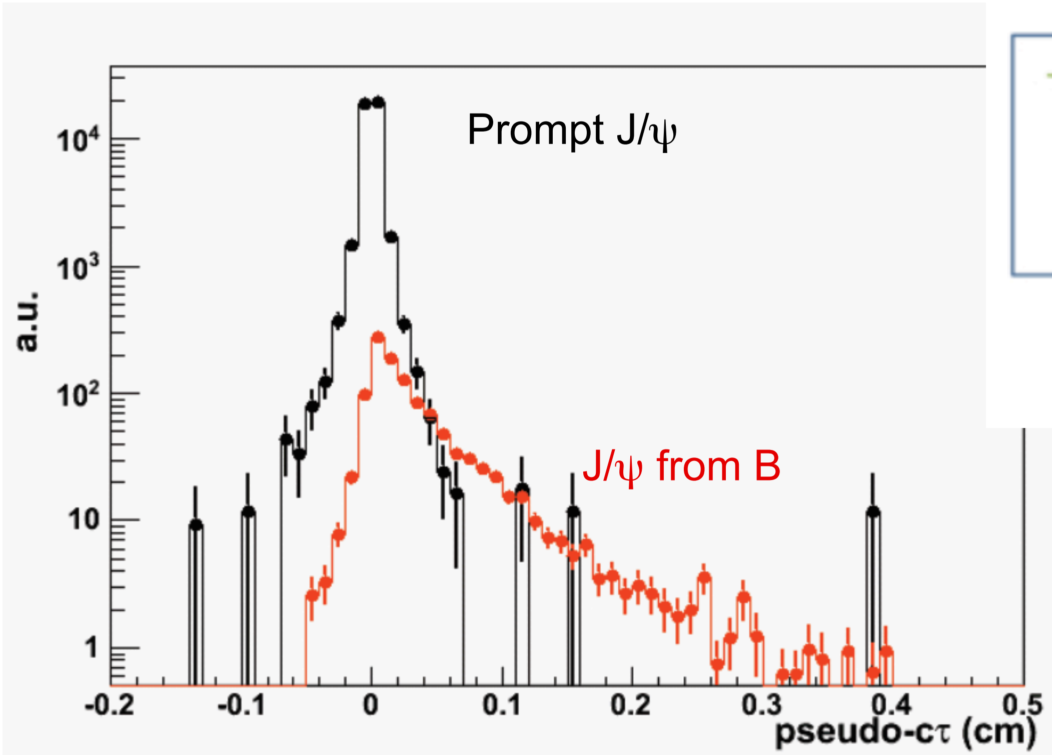
Di-electrons with no material from inner tracker
Di-muons from any case

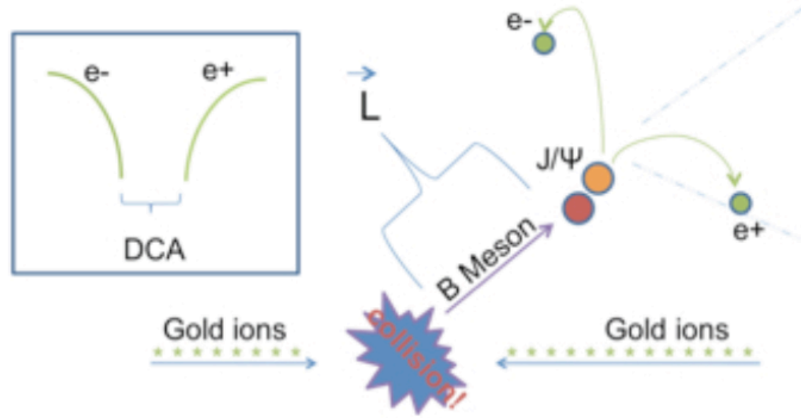


2008 to 2013: di-electrons are a good probe for Upsilons
however, limited by statistics / luminosity

2014 - : di-electrons suffer from inner HFT material - hard to separate three states
di-muons will be a great probe to measure different Upsilon states with RHIC II

B→J/ψ + X with HFT+TPC+MTD



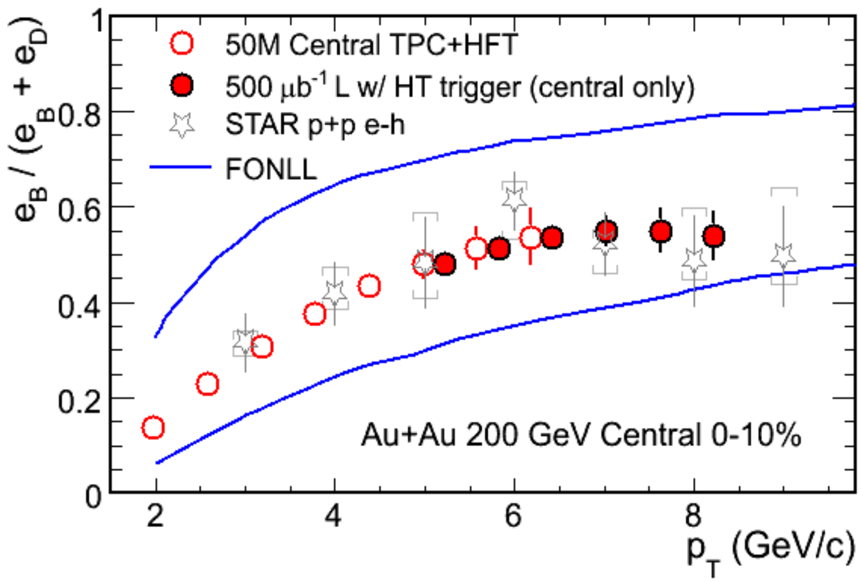


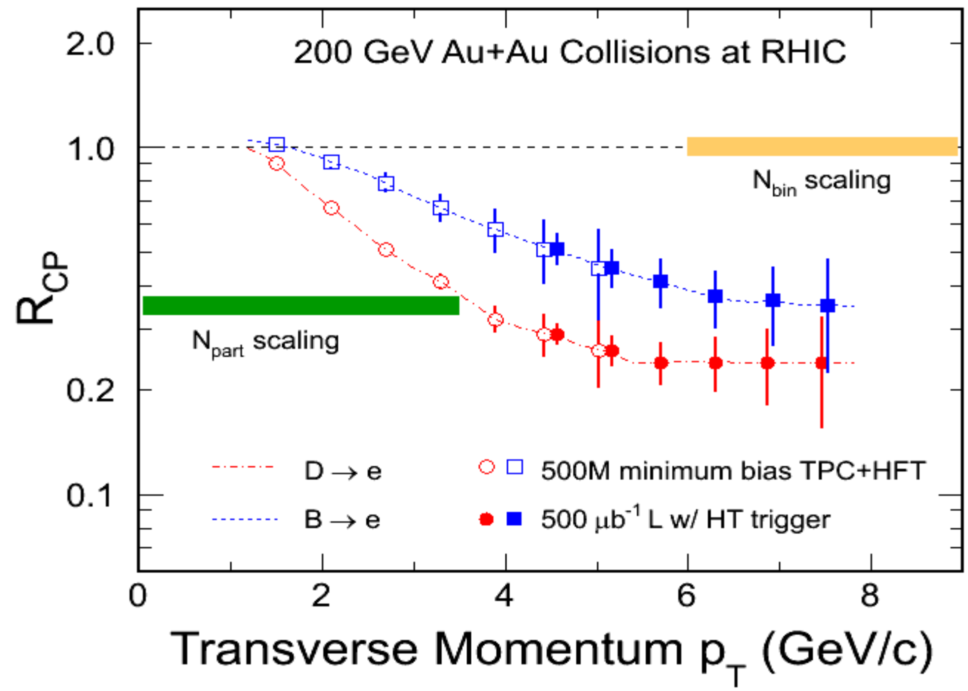
$$c\tau' = \vec{L} \cdot \frac{\overrightarrow{p_T^{\psi}}}{|p_T^{\psi}|} \cdot \frac{M_{\psi}}{p_T^{\psi}}$$

- HFT to separate B decay J/ψ from prompt J/ψ
- MTD to reconstruct J/ψ from di-muon decays

Statistical Projections on e_B Spectra

Need update





Curves: H. van Hees *et al*. Eur. Phys. J. **C61**, 799(2009).

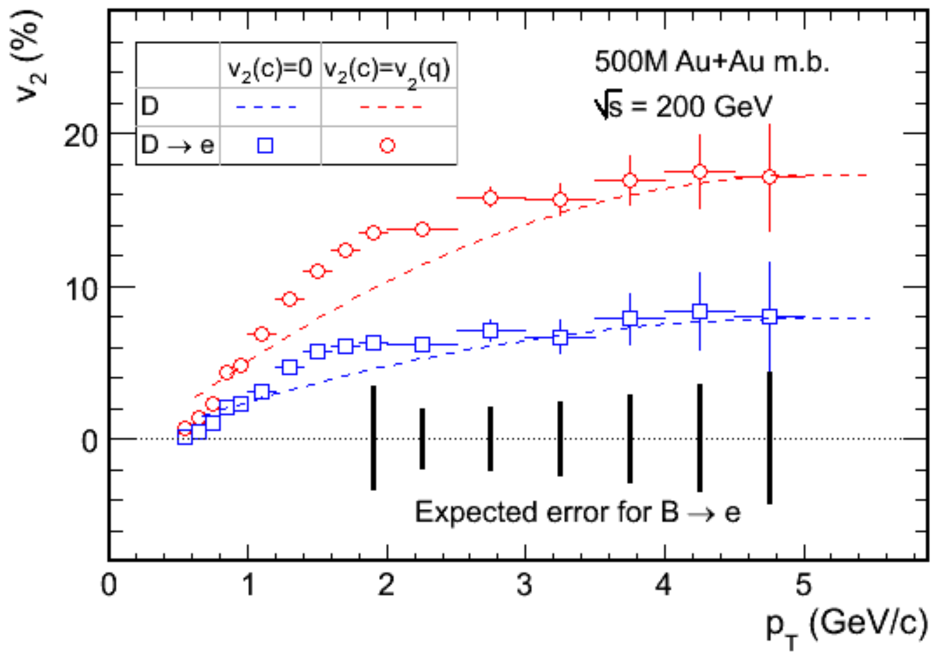
➢ (B→e) spectra obtained via the subtraction of charm decay electrons from inclusive NPEs: no model dependence, reduced systematic errors.

Statistical Projections on e_B v_2

~~Need update~~

Assuming D meson v_2 from quark coalescence (curves).

$r * v_2(e_B) + (1-r) * v_2(e_D) = v_2(NPE)$
r is the $e_B/(e_D+e_B)$ ratio
$v_2(e_D)$ is D → e v_2
$v_2(e_B)$ is B → e v_2 , which can be extracted from this equation.



Dashed-curves: Assumed D^0-mesom $v_2(p_T)$
- in coalescence model

Symbols: *D decay e $v_2(p_T)$*

Vertical bars: errors for *b decay e $v_2(p_T)$* from 200 GeV 500M minimum bias Au + Au events

Physics Run Plan

1) First run with HFT: Au+Au 200 GeV
    a) v_2 and R_{cp} of D-mesons with 500M minimum bias collisions
2) Second run with HFT: p+p 200 GeV
    a) R_{AA} of D-mesons
3) Third run with HFT: Au+Au 200 GeV high statistics
    a) Systematic studies of v_2 and R_{AA}
    b) Λ_c baryon with sufficient statistics
    c) Charm correlation / Electron pairs