

Quarkonia Measurements in STAR

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Outline:

- Introduction
- J/ψ results
- Υ results
- Outlook

BROOKHAVEN
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a passion for discovery

 **Office of
Science**
U.S. DEPARTMENT OF ENERGY



Quarkonia in sQGP

How does quarkonium behave in the presence of sQGP?

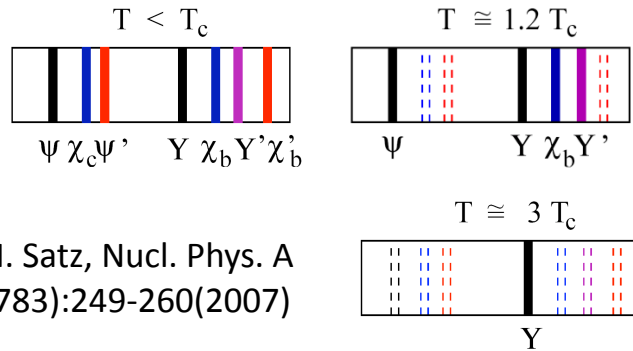
- Color screening¹⁾
- Recombination²⁾
- Heavy quark (radiative & collisional) energy loss³⁾
- Decay feed-down
- Comover & cold matter effects in hadronic phase & initial stage

1) T. Matsui and H. Satz, *Phys. Lett. B*178, 416 (1986)

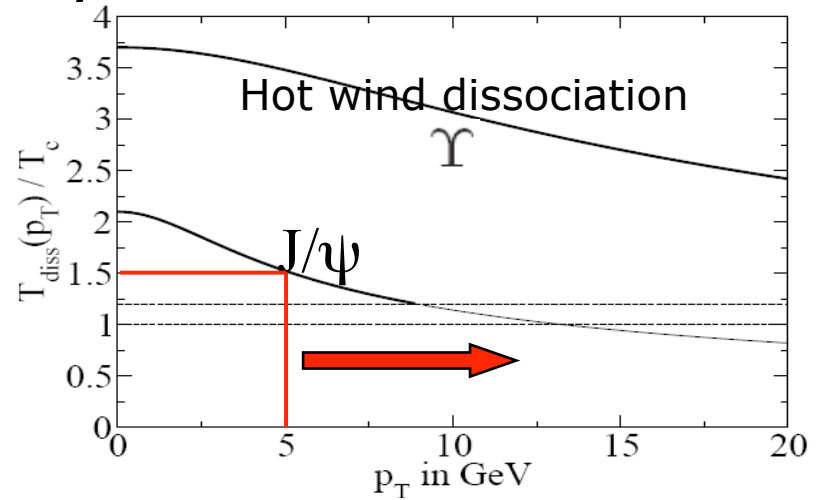
2) R. L. Thews and M. L. Mangano, *Phys. Rev. C*73, 014904 (2006)

3) M. B. Johnson et al., *Phys. Rev. Lett.* 86, 4483 (2001) and
R. Baier et al., *Ann. Rev. Nucl. Part. Sci.* 50, 37 (2000)

High p_T J/ψ in heavy ion collisions



H. Satz, Nucl. Phys. A (783):249-260(2007)



H. Liu, K. Rajagopal and U.A. Wiedemann
 PRL 98. 182301(2007) and hep-ph/0607062

J/ψ suppression at low p_T could be from suppressed excited states (ψ' , χ_c)
 F. Karsch, D. Kharzeev and H. Satz, PLB 637, 75 (2006)

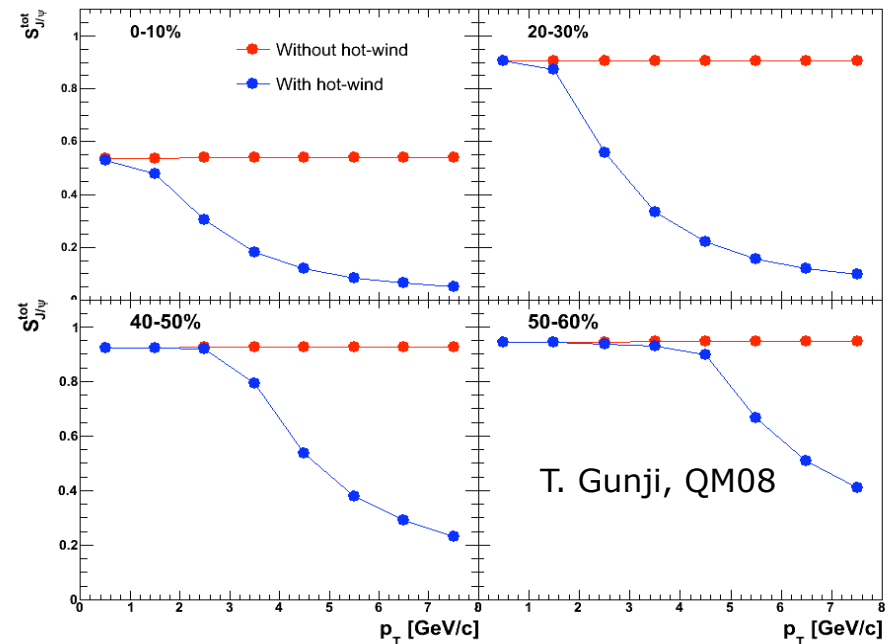
High p_T direct J/ψ suppression → related to hot wind dissociation?

2-component approach

Predicted decrease R_{AA}
 X. Zhao and R. Rapp, hep-ph/07122407

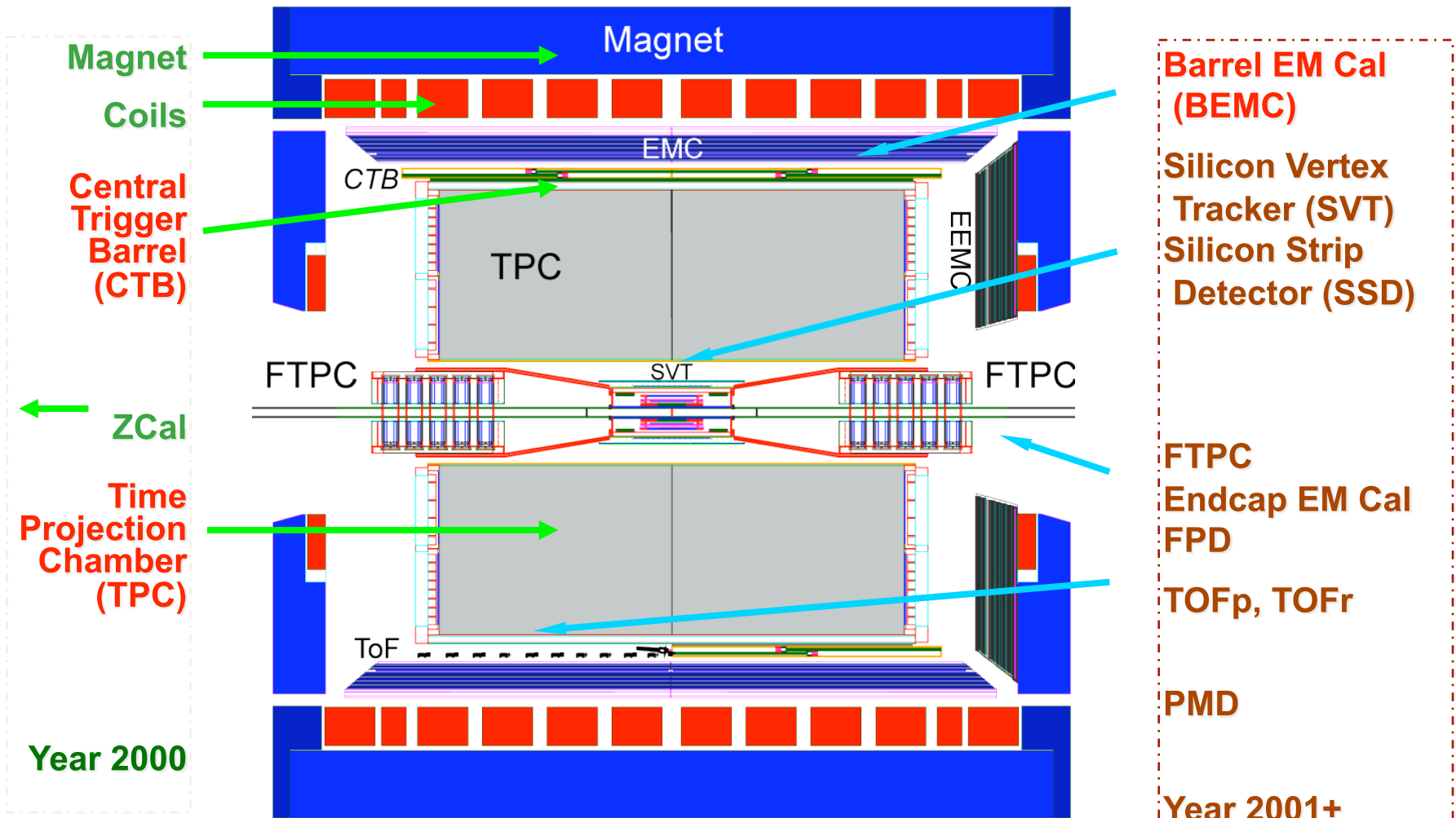
Color singlet model predicted an increase R_{AA} (formed outside of medium)

K. Farsch and R. Petronzio, PLB 193(1987), 105
 J.P. Blaizot and J.Y. Ollitrault, PLB 199(1987), 499



The STAR Detector

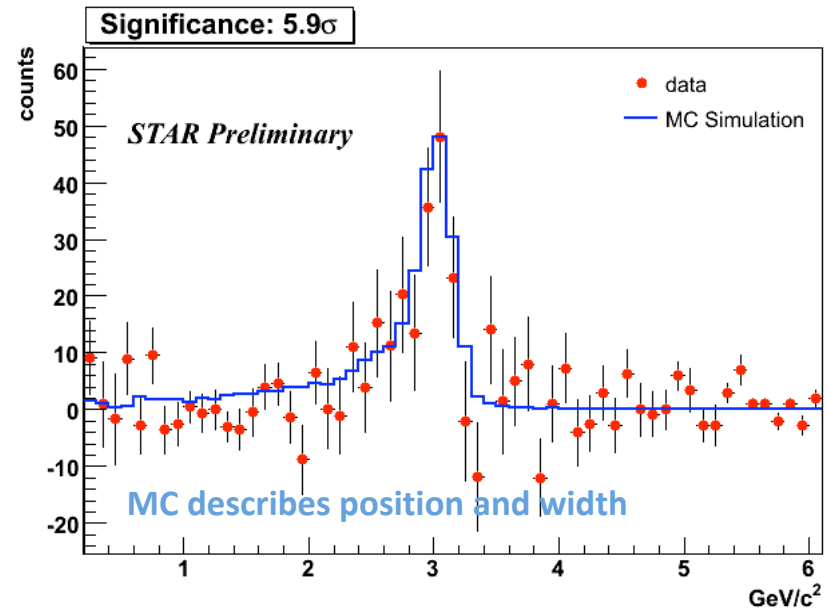
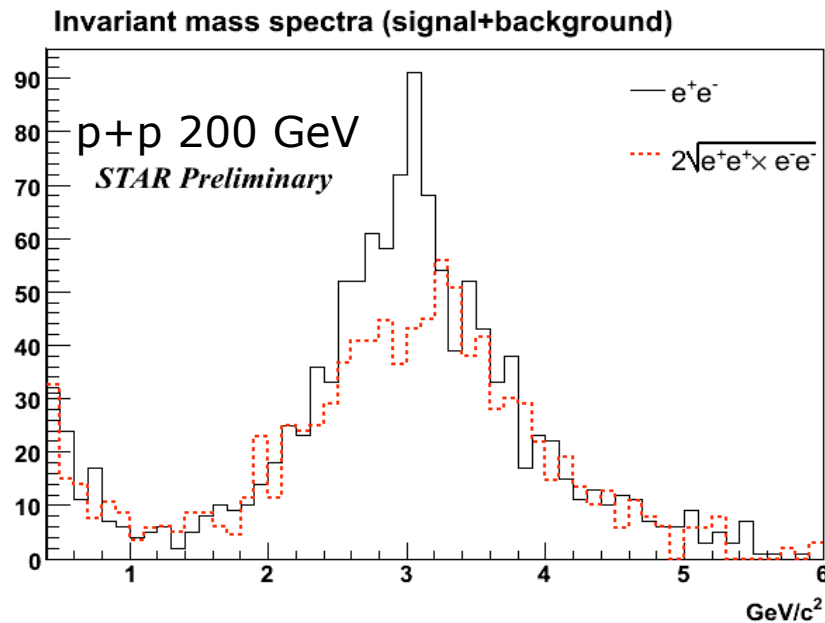
Large acceptance: 2π coverage at mid-rapidity



Future upgrade: Time of Flight, DAQ1000, Heavy Flavor Tracker, Muon Telescope Detector

Low p_T J/ψ in p+p at 200 GeV

J/ψ trigger: $2 \times E_e > 1.2 \text{ GeV} \Rightarrow J/\psi: 0 < p_T < 5.5 \text{ GeV}/c$

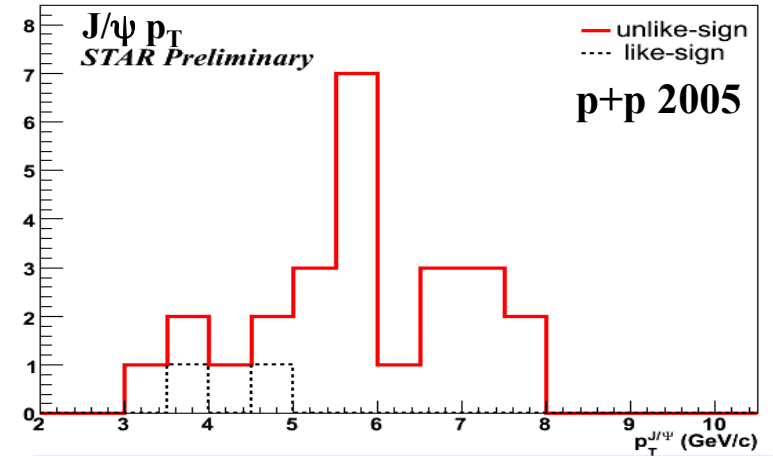
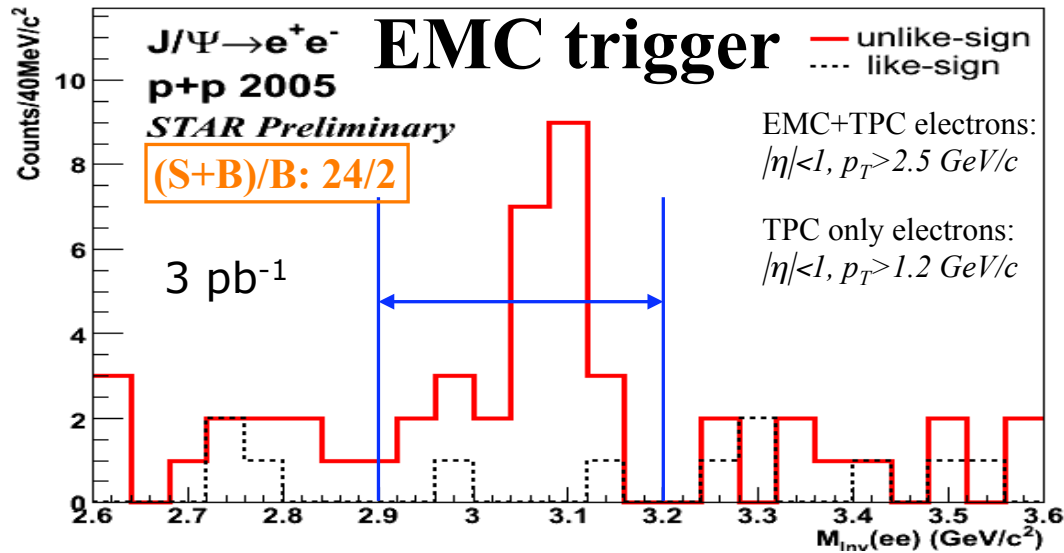


STAR has J/ψ capabilities at low p_T

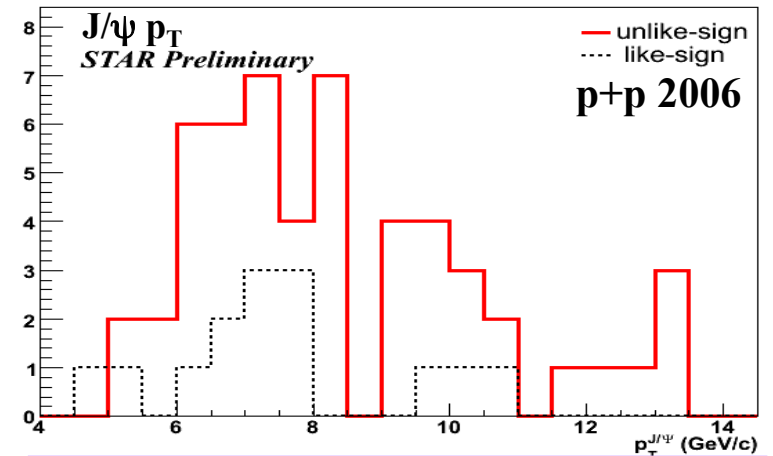
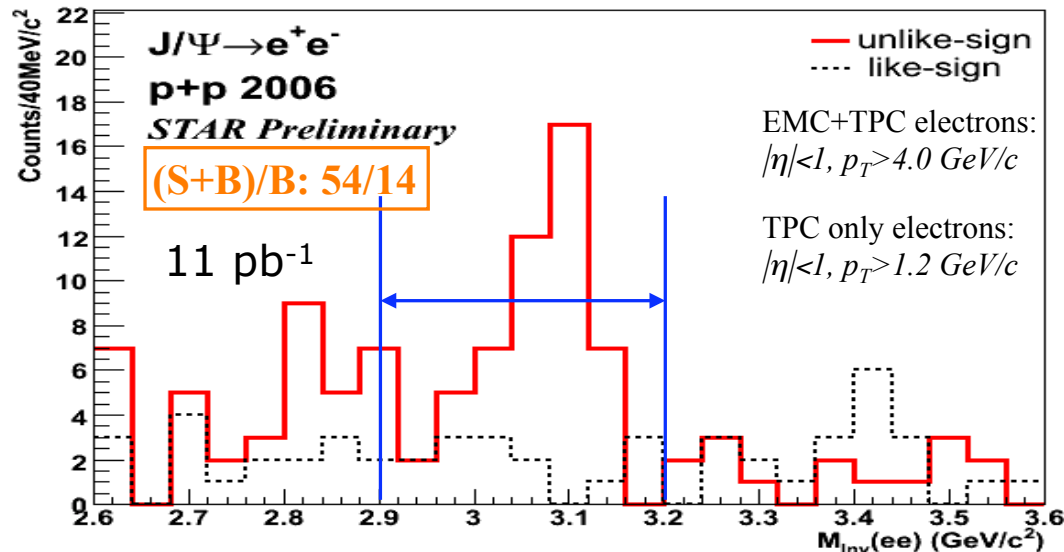
Mass and width consistent with MC simulations, low mass tail from electron bremsstrahlung

Integrated p+p luminosity at 200 GeV: 0.4 pb^{-1}

High p_T J/ψ in p+p at 200 GeV

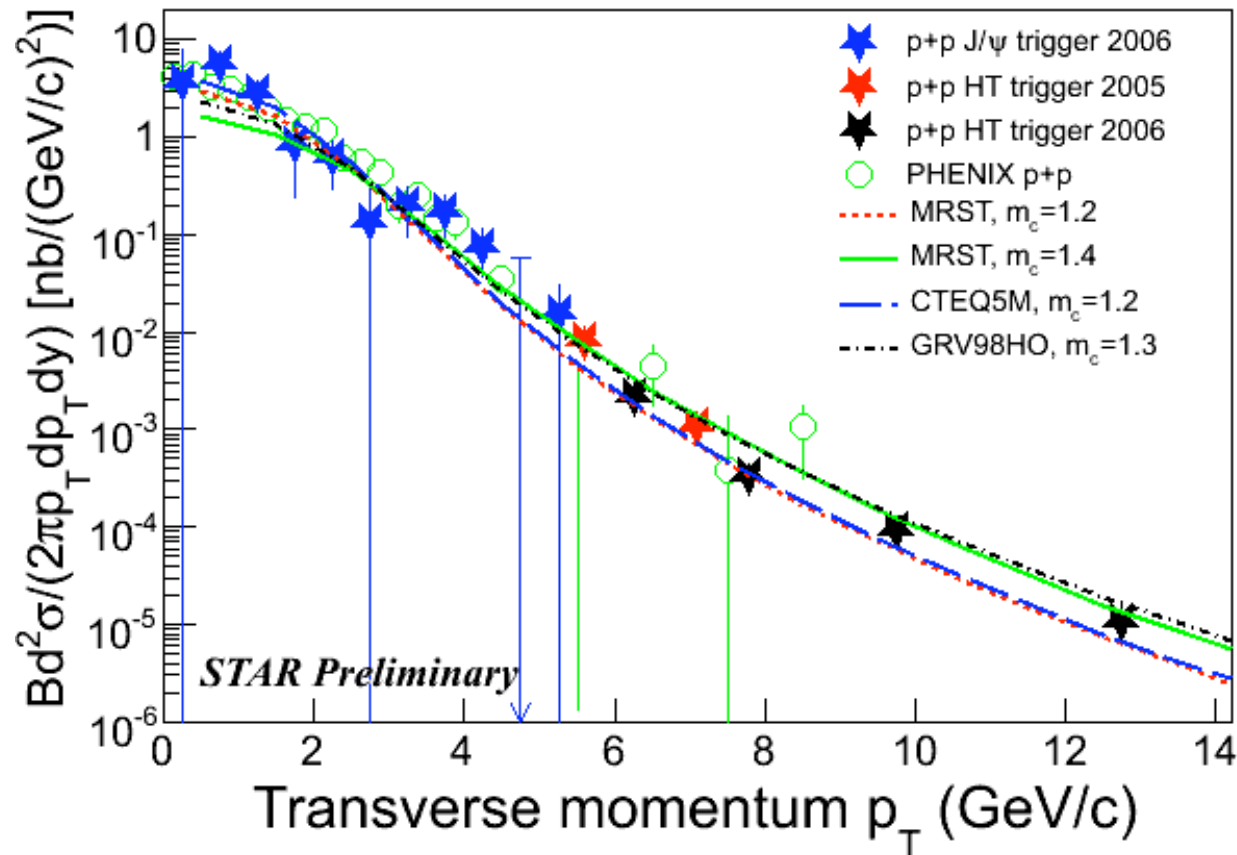


No background at $p_T > 5 \text{ GeV}/c$



Reach higher p_T ($\sim 14 \text{ GeV}/c$)

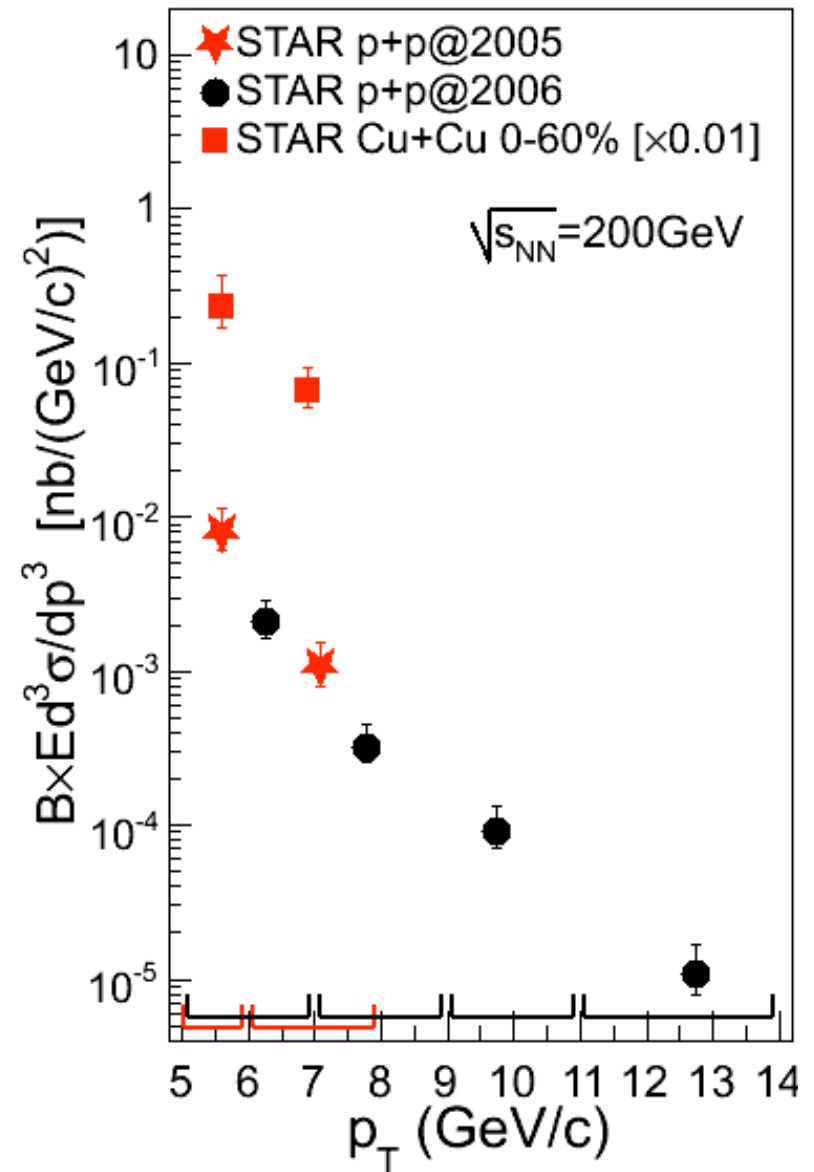
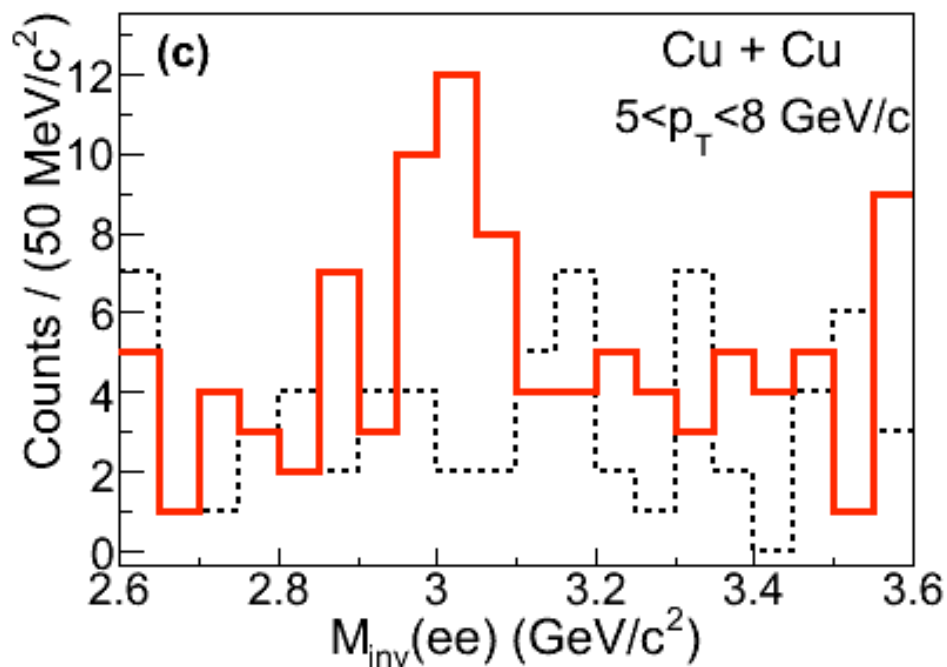
J/ψ spectra in p+p at 200 GeV



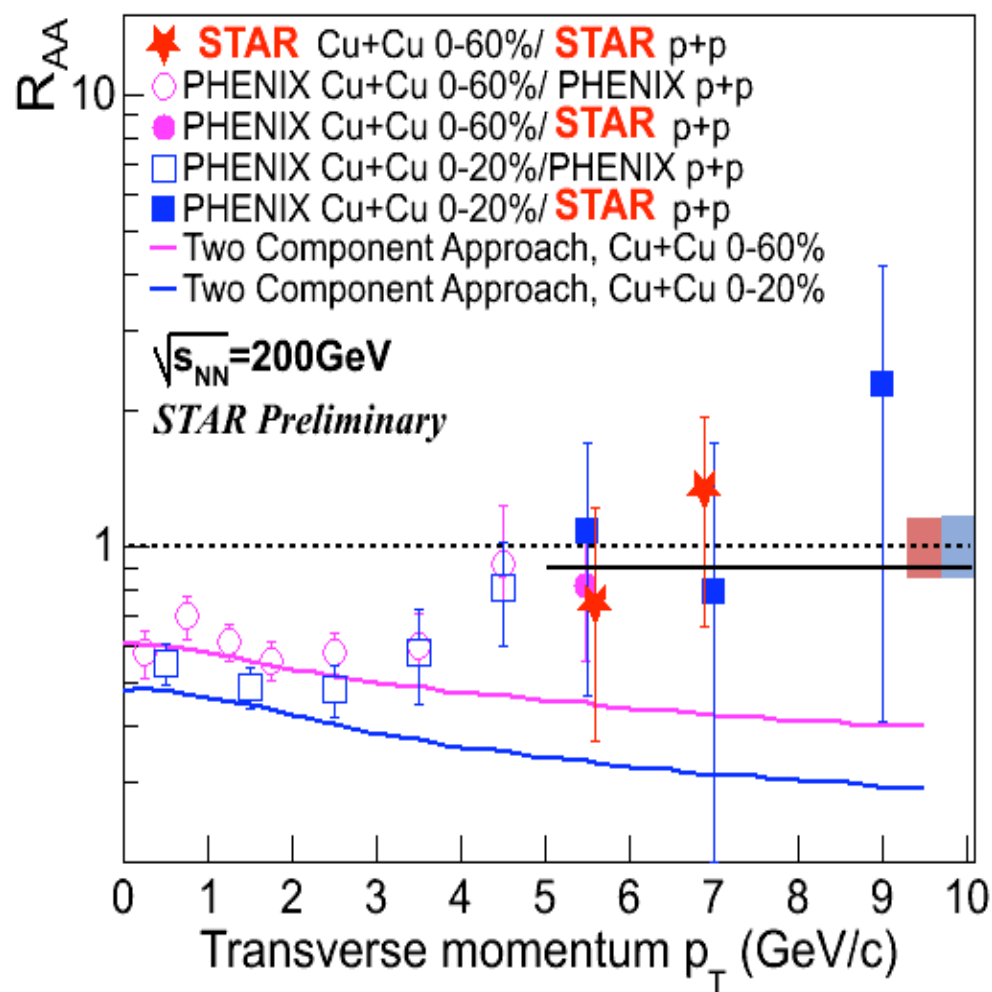
- Significantly extend p_T range of previous measurements in p+p at RHIC to 14 GeV/c
- Agreement of charm measurements between STAR and PHENIX
- Consistent with Color Evaporation calculations (R. Vogt, Private communication)

J/ ψ in Cu+Cu

- Signal with good S/B ratio
- p_T range overlaps with p+p data
- Luminosity: 0.9 nb^{-1}



Nuclear modification factor R_{AA}



- Double the p_T range to $10 \text{ GeV}/c$
- Consistent with no suppression at high p_T :

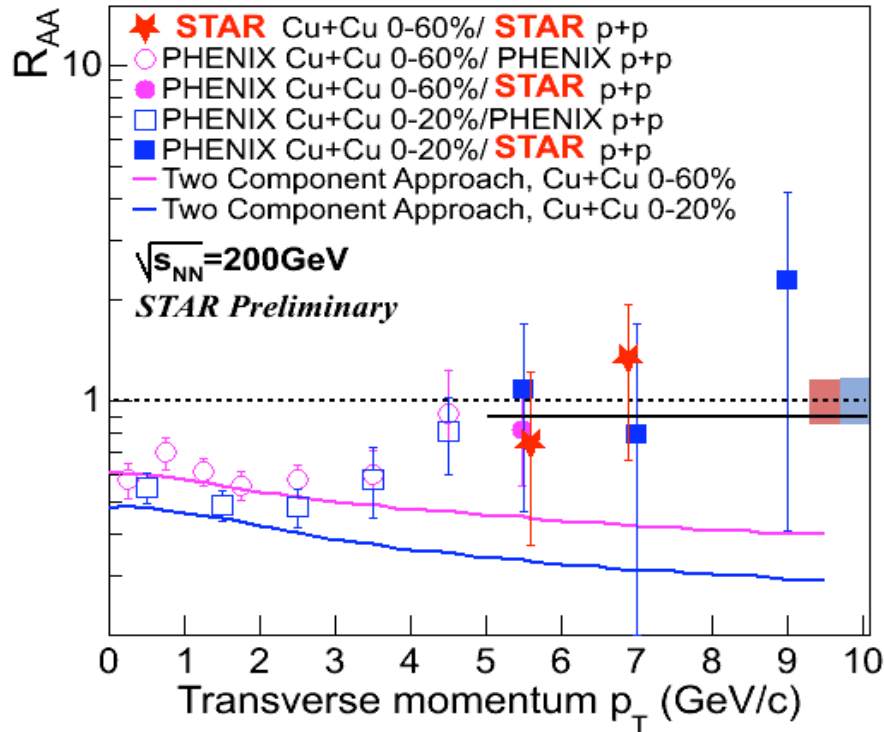
$$R_{AA}(p_T > 5 \text{ GeV}/c) = 0.9 \pm 0.2$$

2σ above low- p_T data

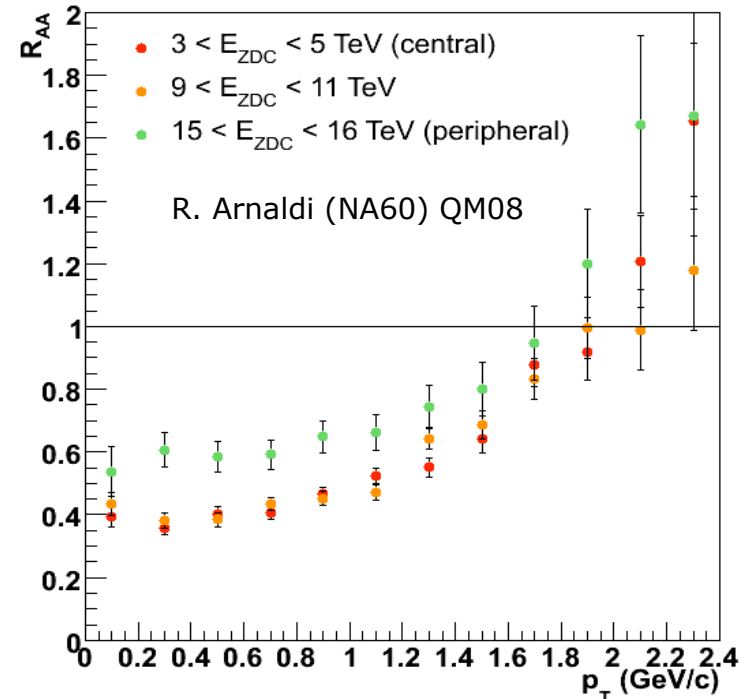
- Indicates R_{AA} increase from low p_T to high p_T

- Doesn't agree with AdS/CFT prediction
- Formed outside of medium?
- **Not affected by heavy quark/gluon energy loss?**
- **Decay from other particles?**

R_{AA} Comparison to NA60



RHIC: Cu+Cu, $\sqrt{s_{NN}} = 200 \text{ GeV}$
 consistent with no suppression at $p_T > 5 \text{ GeV}$



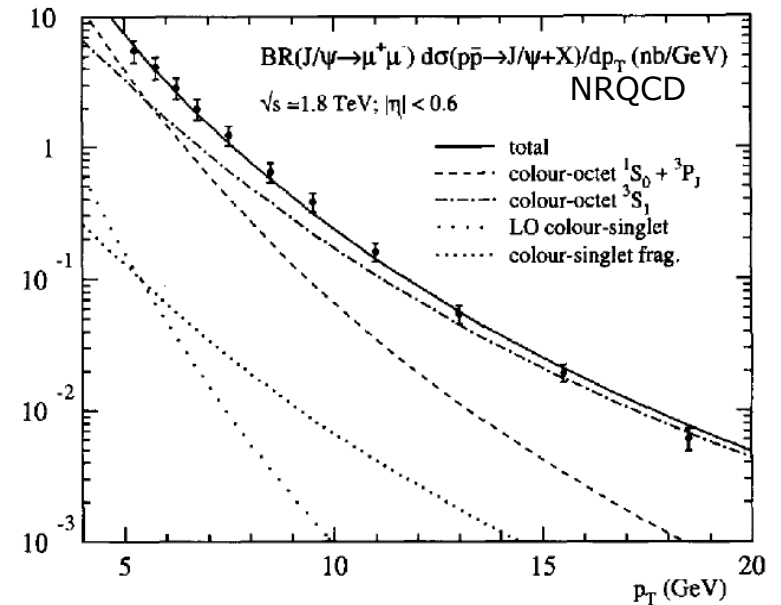
SPS: In+In, $\sqrt{s_{NN}} = 17.3 \text{ GeV}$,
 consistent with no suppression at $p_T > 1.8 \text{ GeV}$

Cronin
 $pA \rightarrow pp$
 Thermal fit

Important to understand production mechanism →

Quarkonium Production Mechanism

- Color singlet model (CSM) ¹⁾ → pQCD
- Color octet model (COM) ²⁾ → NRQCD
- Color evaporation model (CEM) ³⁾
- ...
- Gluon fusion
- Heavy quark fragmentation ⁴⁾
- Gluon fragmentation ⁵⁾
- Decay feed-down
- ...



What's the production mechanism at RHIC energy?

1) R. Baier et al., PLB 102, 364 (1981)

2) M. Kramer, Progress in Particle and Nuclear Physics 47, 141 (2001)

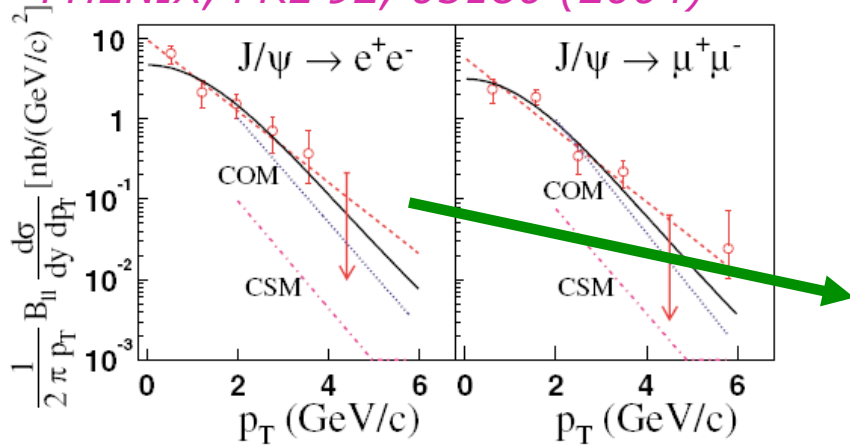
3) H. Fritzsche, PLB 67, 217 (1977)

4) Cong-Feng Qiao, hep-ph/0202227

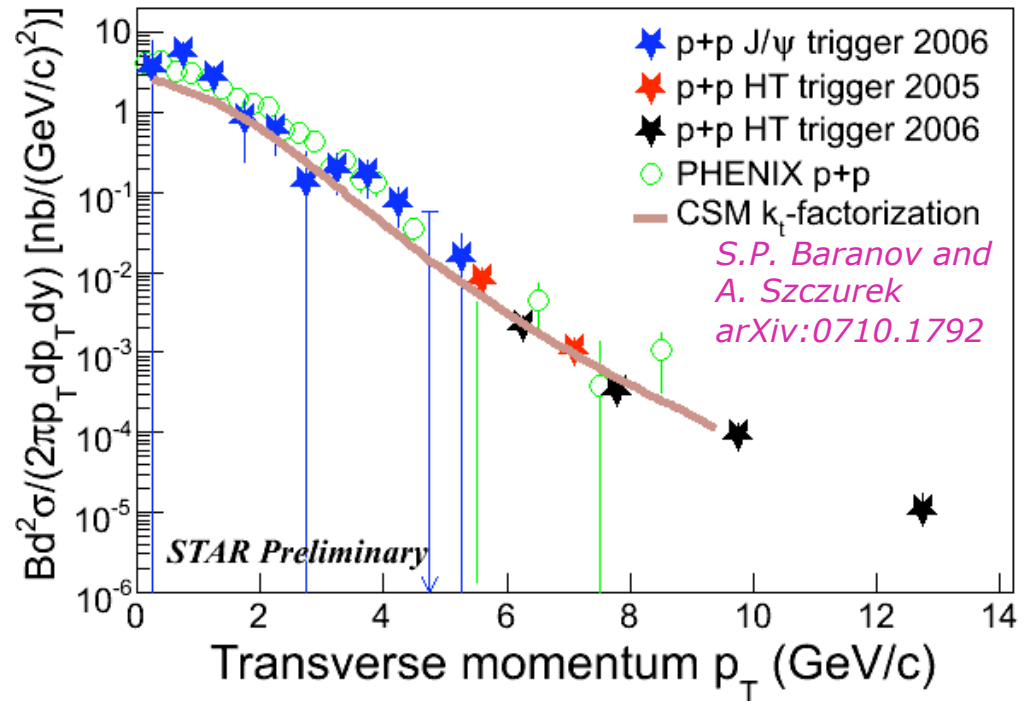
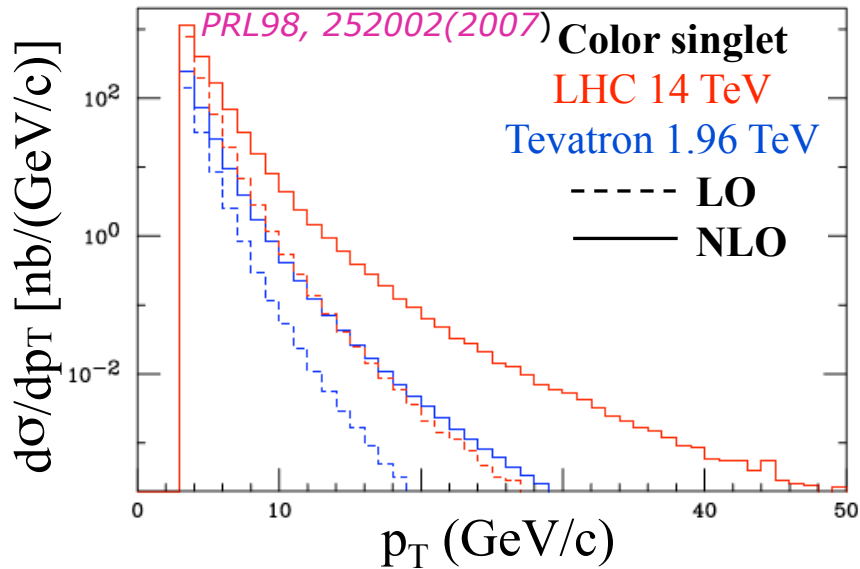
5) K. Hagiwara et al., hep-ph/0705.0803

CSM with k_t -factorization

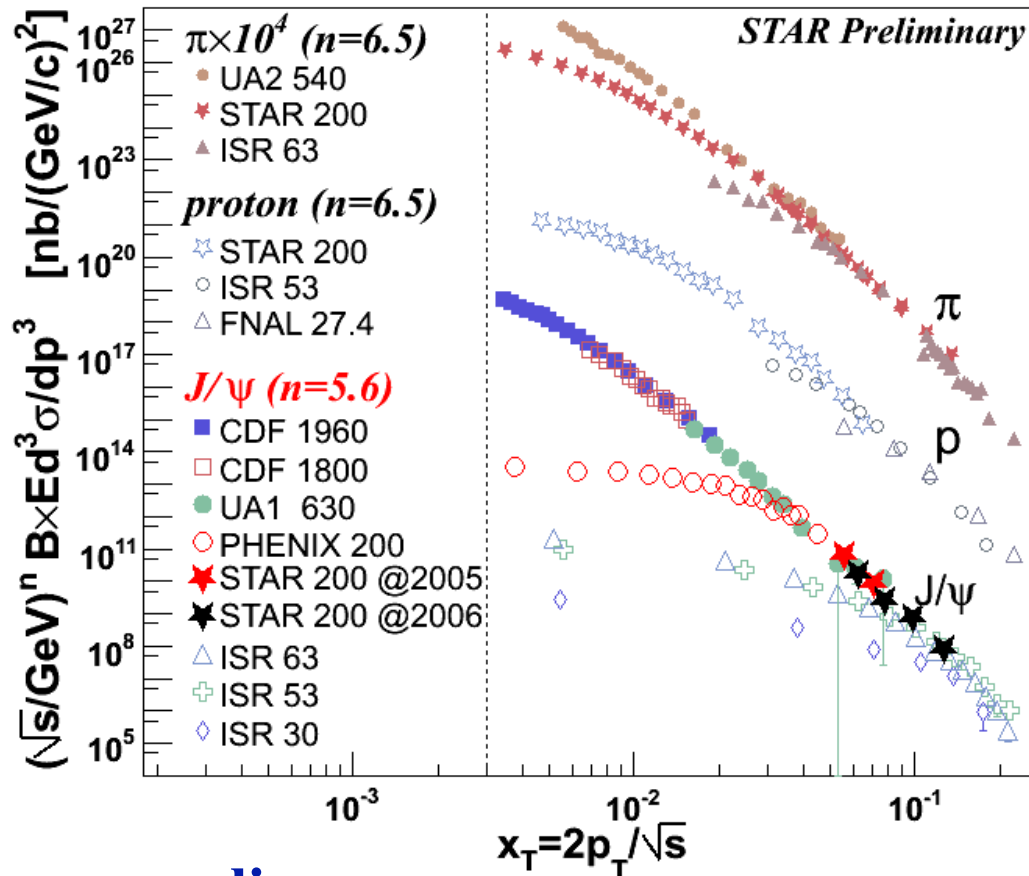
PHENIX, PRL 92, 05180 (2004)



CSM can also describe the data with some improvement like the k_t -factorization approach



x_T scaling



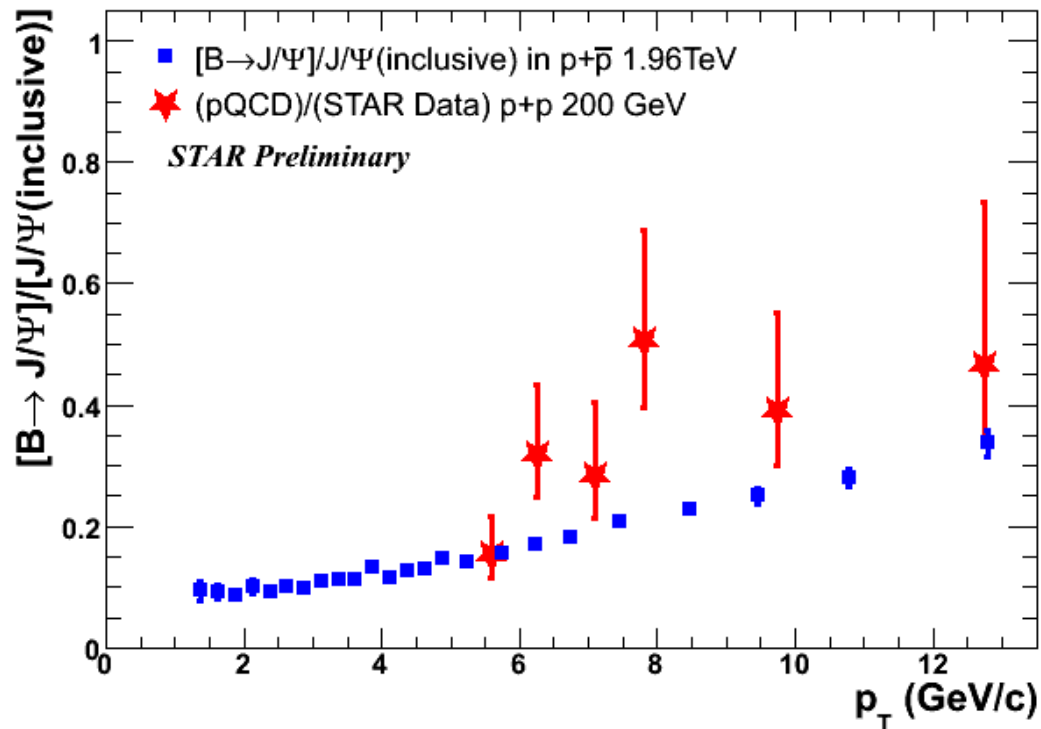
n is related to the number of point-like constituents taking an active role in the interaction

$n=8$: diquark scattering
 $n=4$: QED-like scattering

x_T scaling:

- π and proton: $n=6.5 \pm 0.8$ *PLB 637, 161(2006)*
- J/ψ : $n=5.6 \pm 0.2$
- J/ψ production: closer to $2 \rightarrow 2$ scattering

$(B \rightarrow J/\psi)/(inclusive J/\psi)$



1) Generated B spectrum is from pQCD (highest possible values)

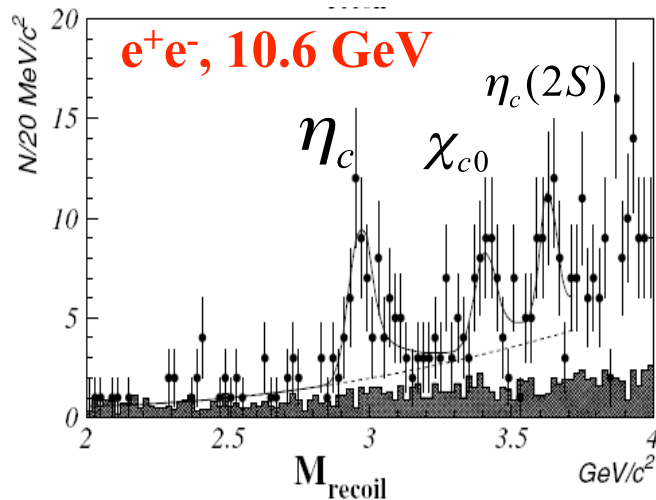
*M. Cacciari, P. Nason and R. Vogt
PRL 95(2005),122001*

2) Decay $B \rightarrow J/\psi$, kinematics and branch ratio are from CLEO measurements

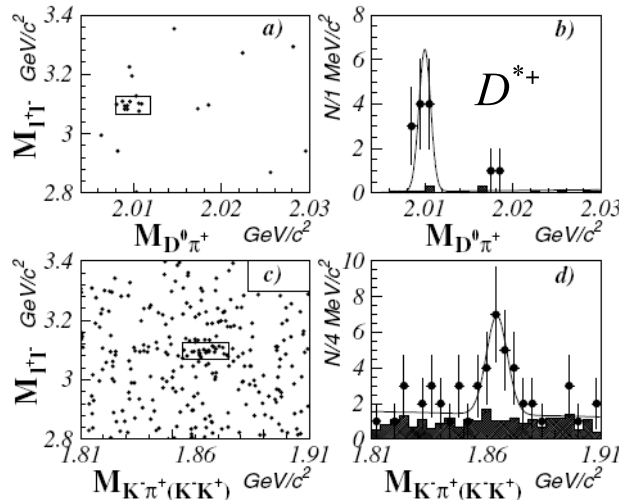
*CLEO collaboration
PRL 89(2002),282001*

- $B \rightarrow J/\psi$ might contribute significantly to the inclusive J/ψ yields at high p_T (>5 GeV/c)
- No experimental B spectra at RHIC yet
- Can be used to constrain B production

More J/ψ production puzzles



$$M_{\text{recoil}} = \sqrt{(\sqrt{s} - E_{J/\psi}^*)^2 - p_{J/\psi}^{*2}}_{\eta_c}$$



Belle, PRL 89, 142001(2002)

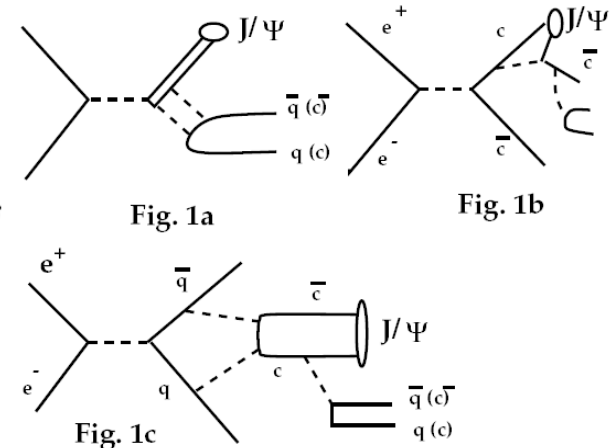


FIG. 1. The production of J/ψ in e^+e^- annihilation.

*B.L. Lofe and D.E. Kharzeev
PRD 69, 014016 (2004)*

$$(e^+e^- \rightarrow J/\psi + c\bar{c}) / (e^+e^- \rightarrow J/\psi + X) = 0.59^{+0.15}_{-0.13} \pm 0.12$$

$0.82 \pm 0.15 \pm 0.14$ from new analysis.

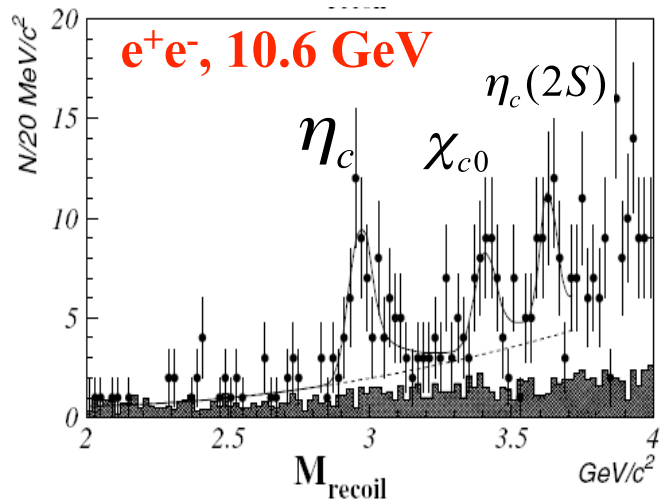
T. Uglov, EPS 2003

While CEM predict 0.049 *D. Kang, et al., PRD 71, 094019 and hep-ph/0412381*

NRQCD predict ~ 0.1 *K. Liu and Z. He, PRD 68, 031501 (2003)*

**What happens?: In p+p collisions;
At higher energy (200 GeV)**

More J/ψ production puzzles

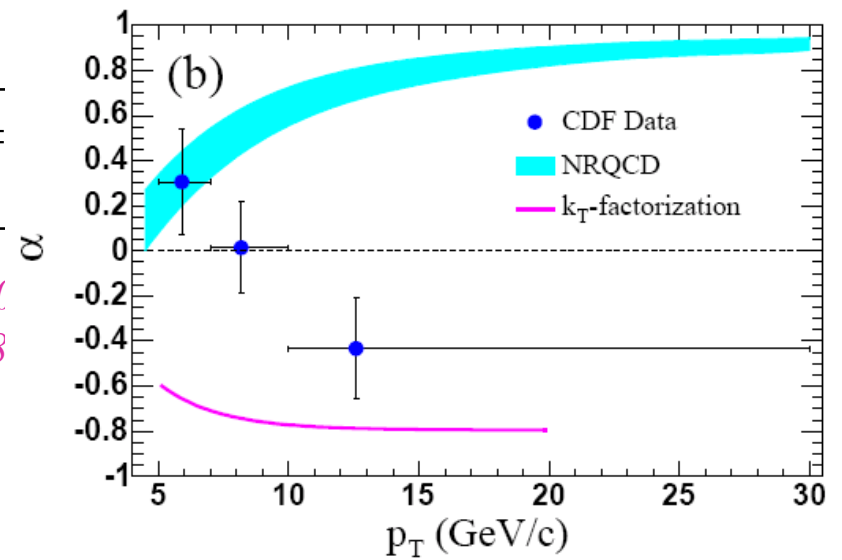
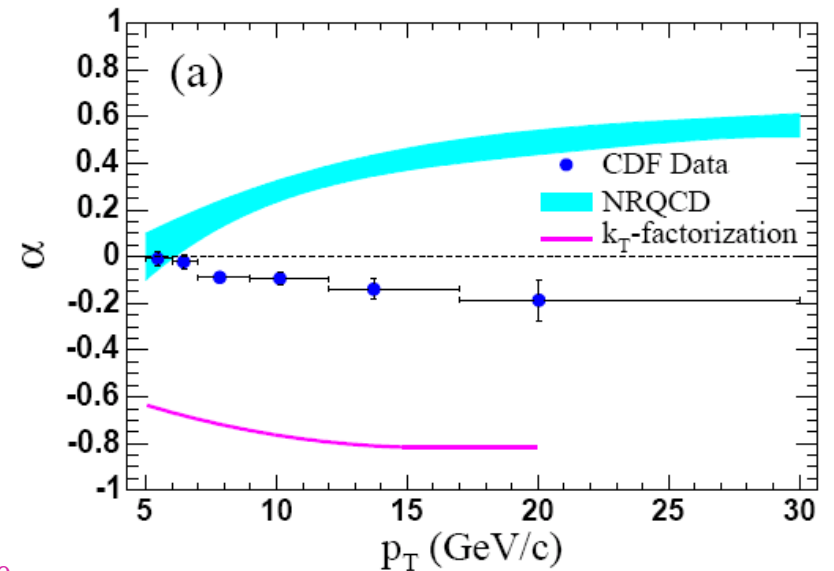


$$M_{recoil} = \sqrt{(\sqrt{s} - E_{J/\psi}^*)^2 - p_{J/\psi}^{*2}}_{\eta_c} \quad \text{Belle, PRL 89, 1420}$$

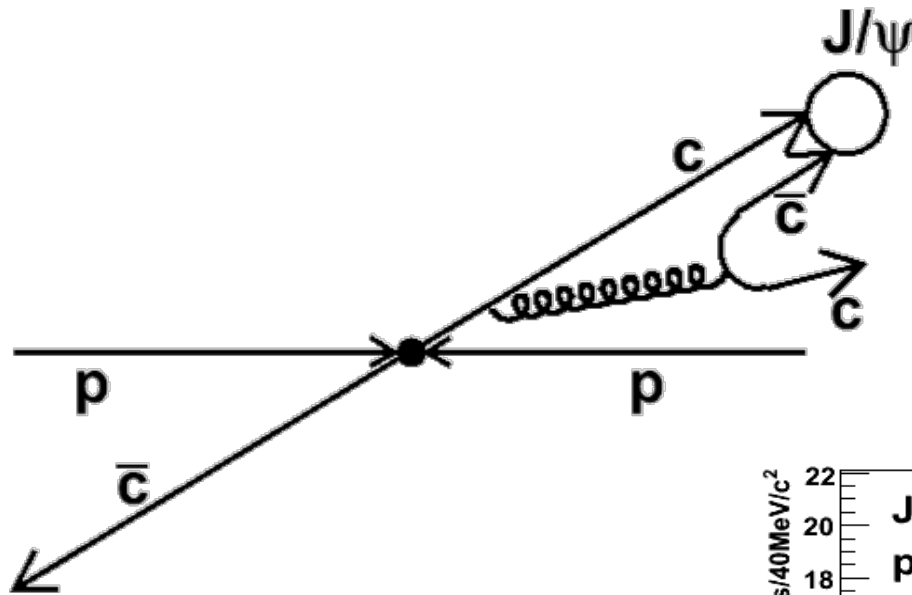
$$\frac{(e^+e^- \rightarrow J/\psi + c\bar{c})}{(e^+e^- \rightarrow J/\psi + X)} = 0.59^{+0.15}_{-0.13} \pm 0.82 \pm 0.15 \pm 0.14 \text{ from new analysis.} \quad T.$$

While CEM predict 0.049 *D. Kang, et al., PRD 71, (*
 NRQCD predict ~ 0.1 *K. Liu and Z. He, PRD 68*

**What happens?: In p+p collisions;
 At higher energy (200 GeV)**



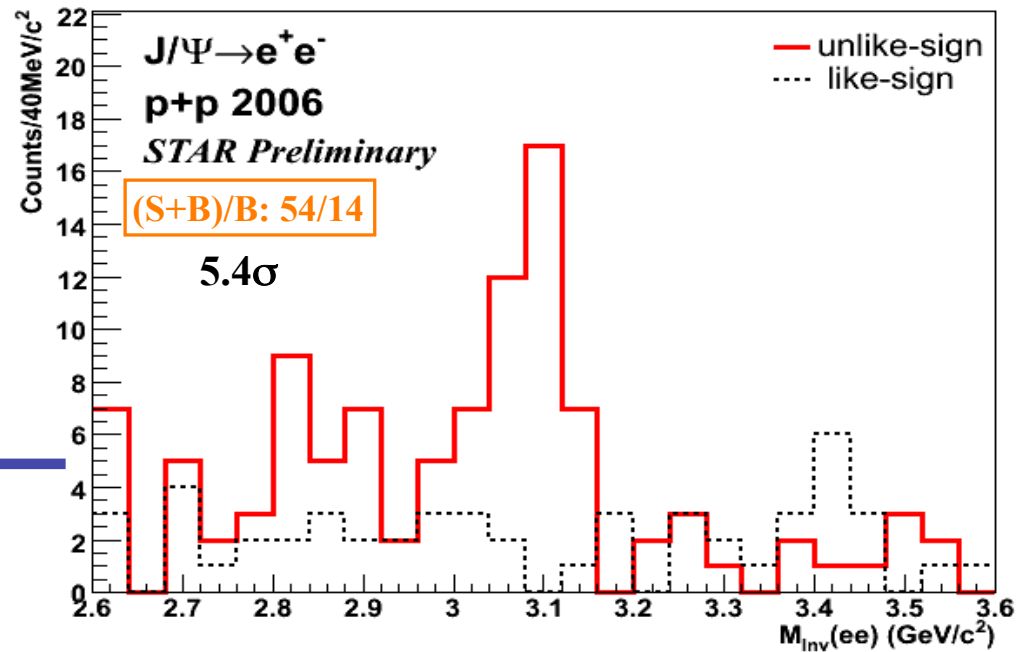
J/ψ-hadron correlation



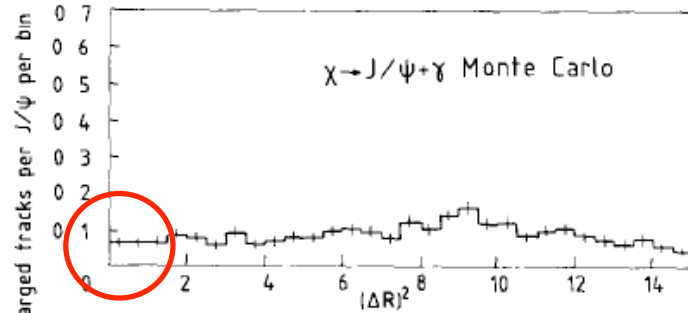
Near side correlation

Heavy quark fragmentation

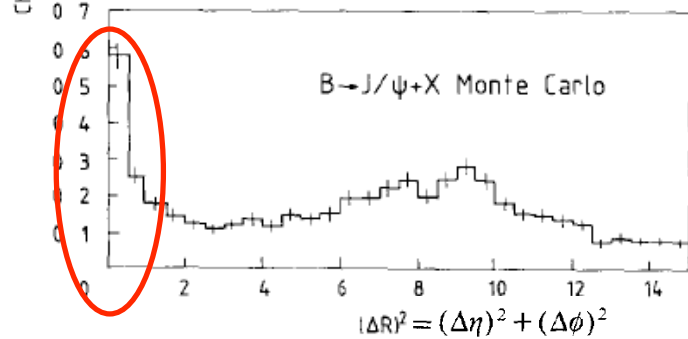
Good S/B ratio makes this measurement possible



Disentangle contributions via Correlations



1) $g + g \rightarrow \chi + g$
 $\rightarrow J/\psi + \gamma$
no near side correlation

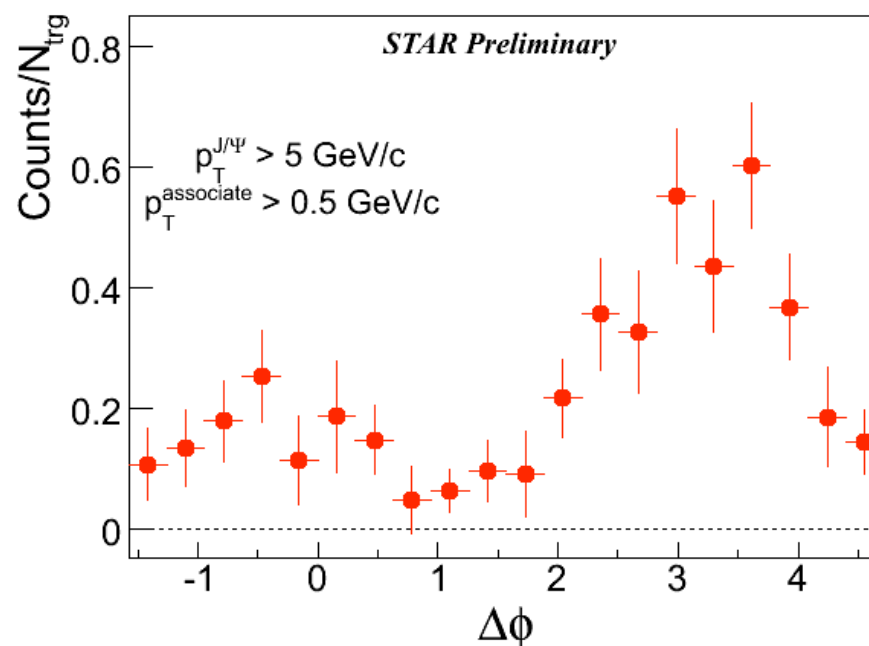
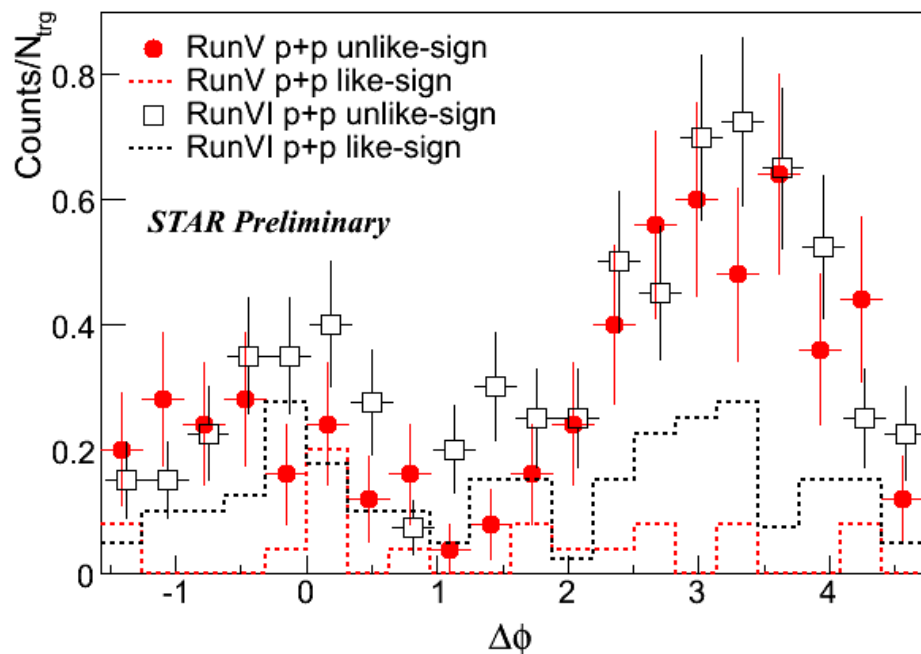


2) $g + g \rightarrow b + \bar{b}$
 $\rightarrow B_{hadron} + X$
 $\rightarrow J/\psi + X$
strong near side correlation

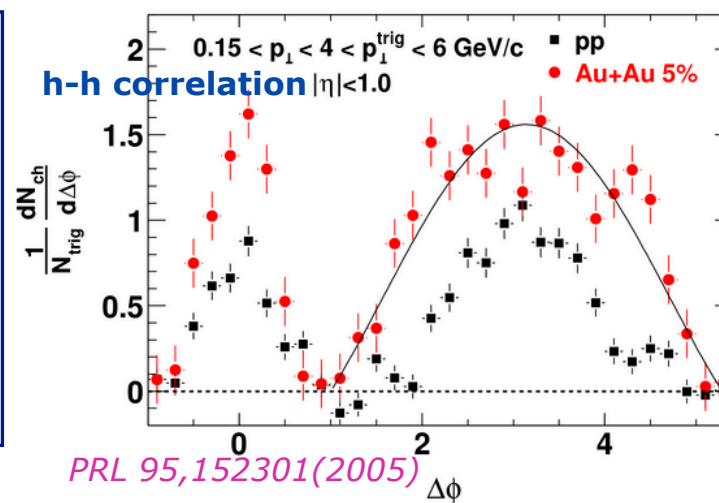
PLB 200, 380(1988) and PLB 256,112(1991)

- **J/ψ-hadron correlation can also shed light on different source contribution to J/ψ production**
- **May be used to distinct CSM and COM ?**

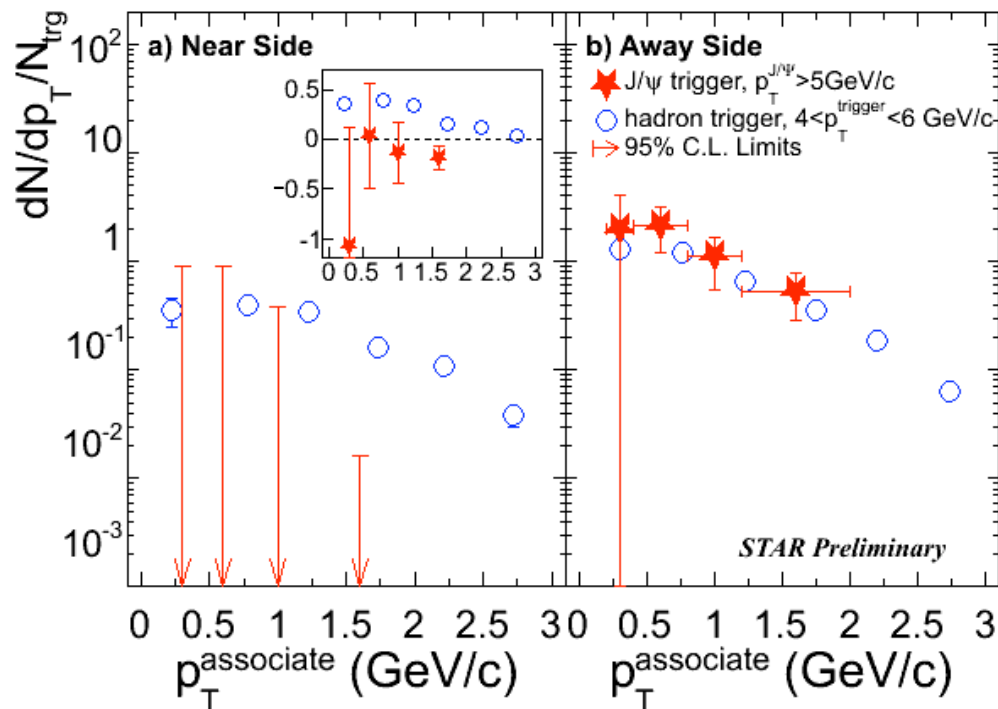
J/ ψ -hadron correlation in p+p



- No significant near side J/ ψ -hadron azimuthal angle correlation
- Constrain B meson's contribution to J/ ψ yield
- Hints of CSM?



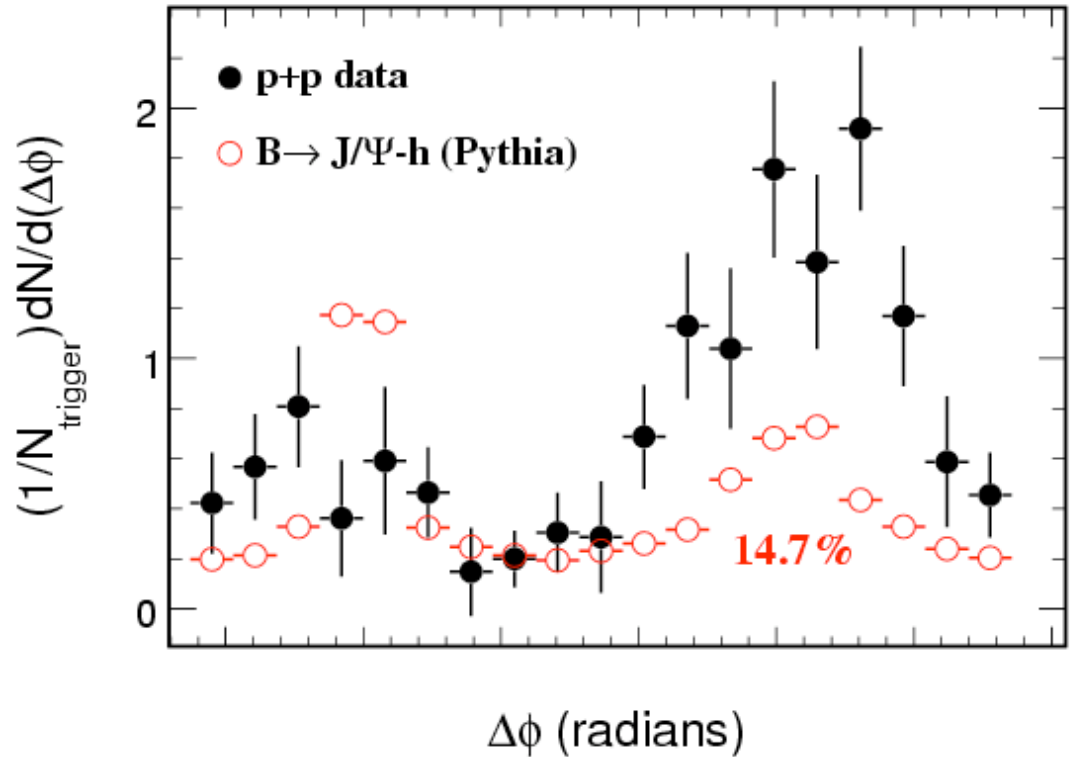
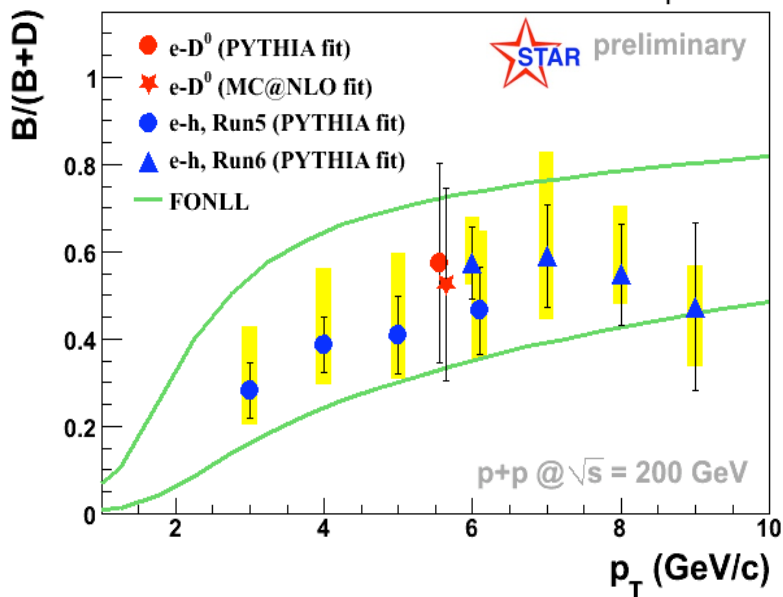
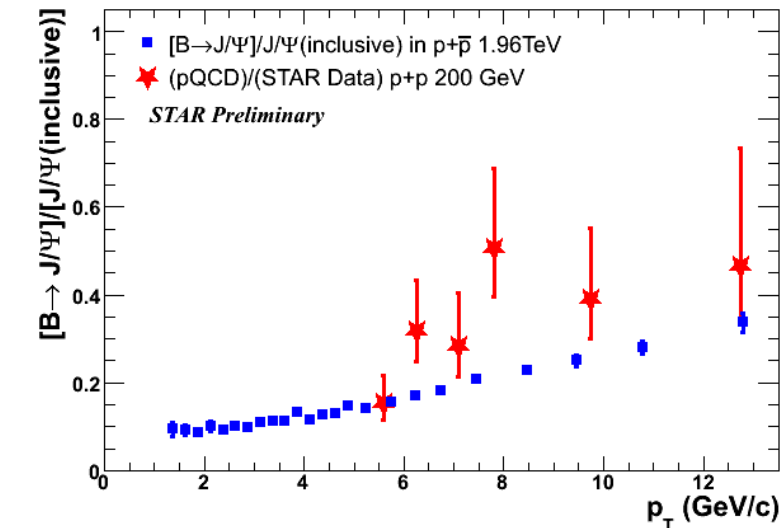
Yields in near/away side



Associated hadron spectra with leading J/ψ:

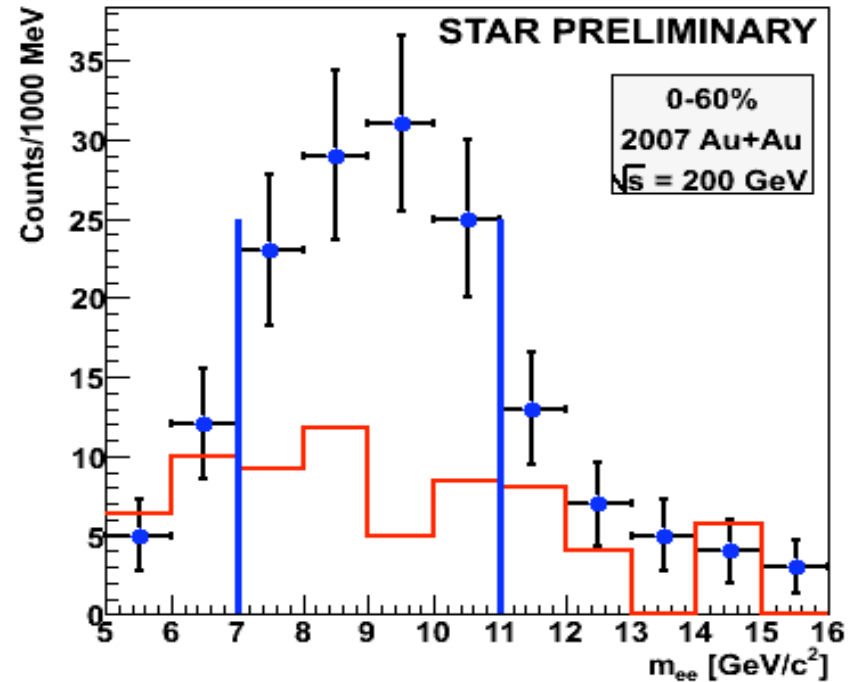
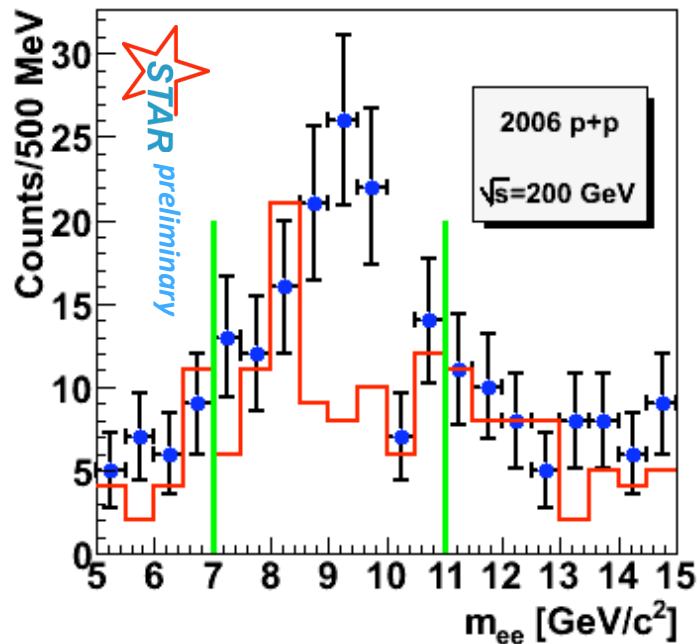
- **Away side:** Consistent with leading charged hadron correlation measurement (h-h)
 \Rightarrow away-side from **gluon or light quark fragmentation**
- **Near side:** Consistent with no associated hadron production
 $B \rightarrow J/\psi$ not a dominant contributor to inclusive J/ψ
constrain J/ψ production mechanism

Constrain Bottom yields



- pQCD predicts significant $B \rightarrow J/\Psi$
- Correlations shows low B contribution
- Can be used to further constrain B yields
- PYTHIA productions all show strong near-side correlation \Rightarrow higher order production mechanism?

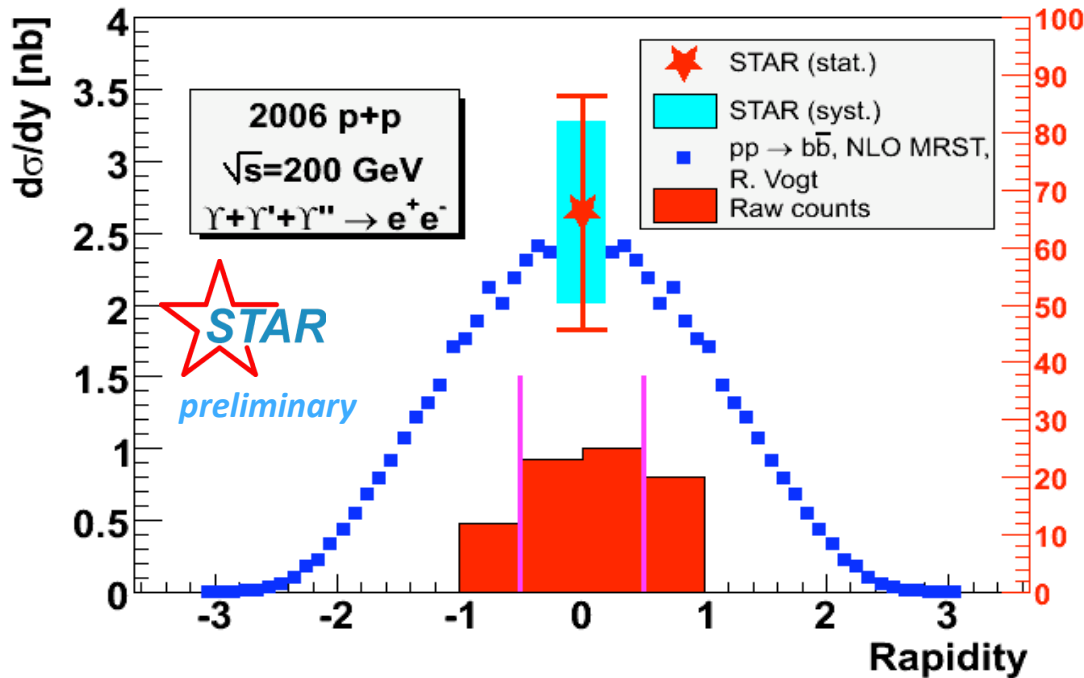
Y Signal in p+p and Au+Au



- Y(1S+2S+3S) total yield: integrated from 7 to 11 GeV from background-subtracted m_{ee} distribution
- Significance of signal is 3σ
- Note: Contribution from Drell-Yan ($\sim 9\%$) ignored here

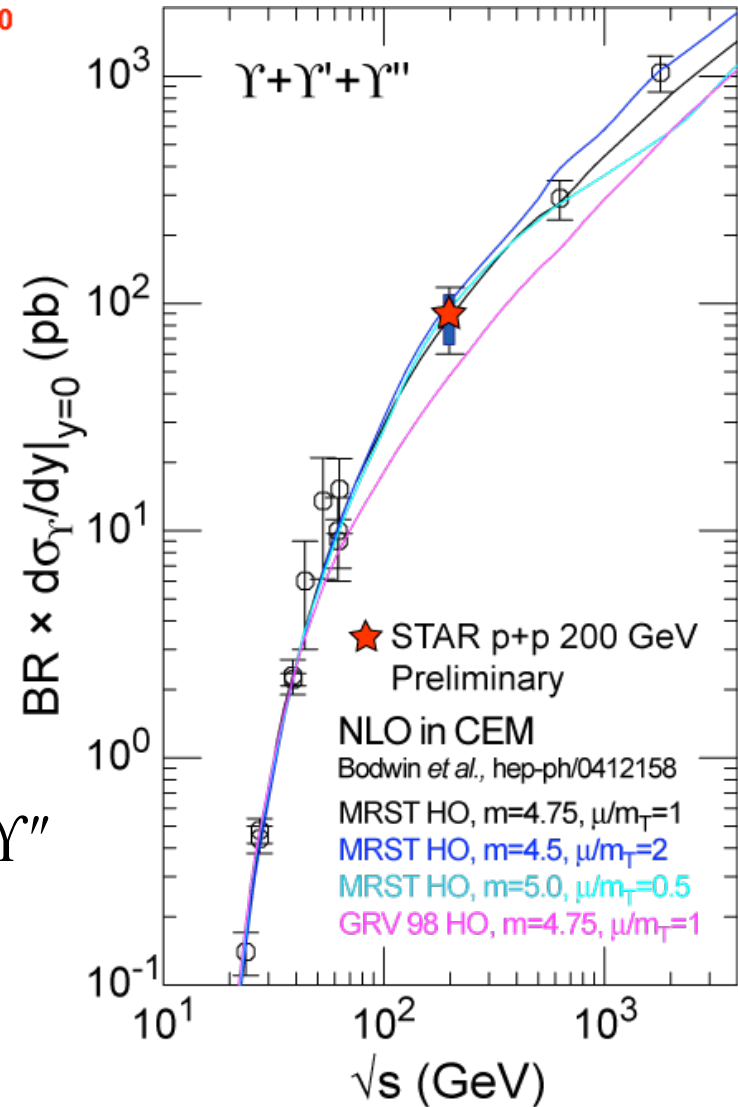
- 4σ signal
- First measurement of Υ in nucleus-nucleus collisions ever
- R_{AA} in progress

Υ cross-section in p+p



$$B_{ee} \times (d\sigma/dy)_{y=0} = 91 \pm 28(\text{stat.}) \pm 22(\text{syst.}) \text{ pb}$$

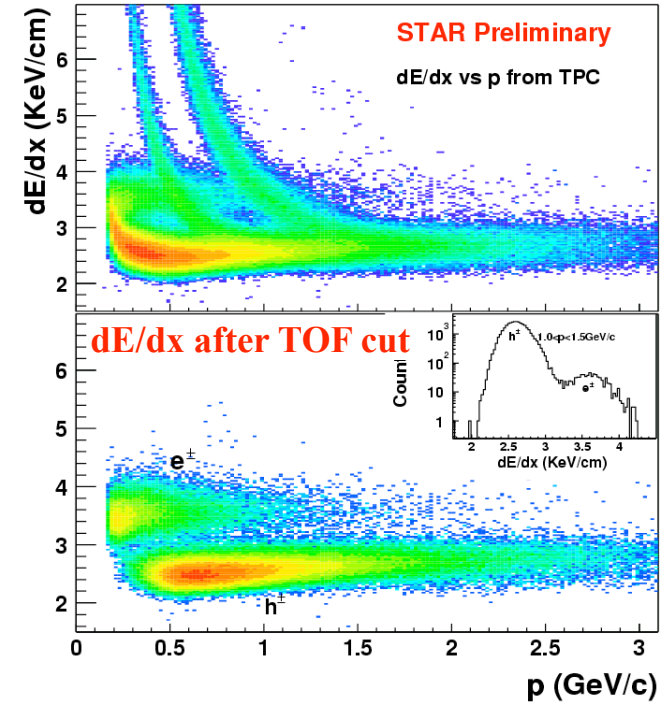
STAR 2006 $\sqrt{s}=200$ GeV p+p $\Upsilon+\Upsilon'+\Upsilon'' \rightarrow e^+e^-$ cross section **consistent** with **pQCD** and **world data**



Future dramatic improvement of J/ψ at low p_T

EMC+TOF (large acceptance):

- J/Ψ production
- Different states predicted to melt at different T in color medium
- Charmonia(J/ψ), bottonia (Υ)

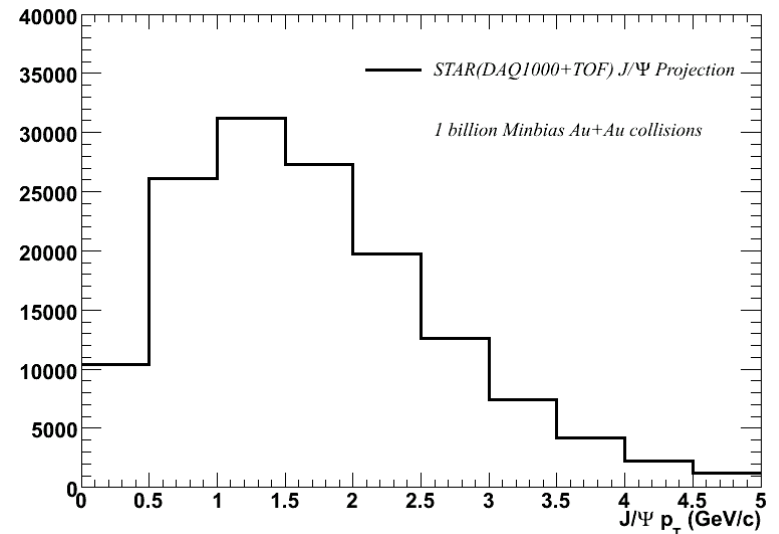


Quarkonium dissociation temperatures - Digal, Karsch, Satz

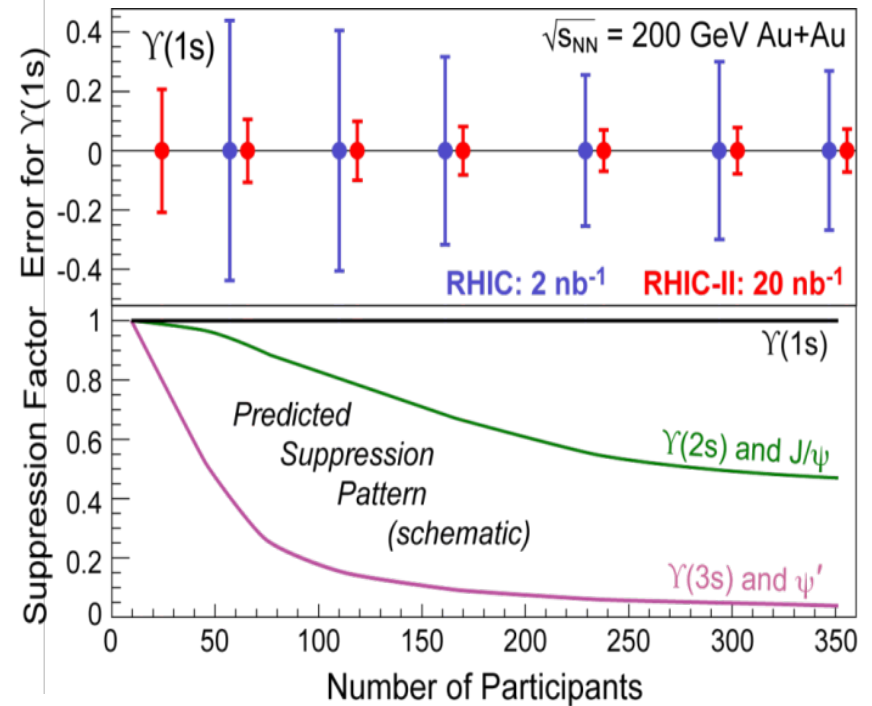
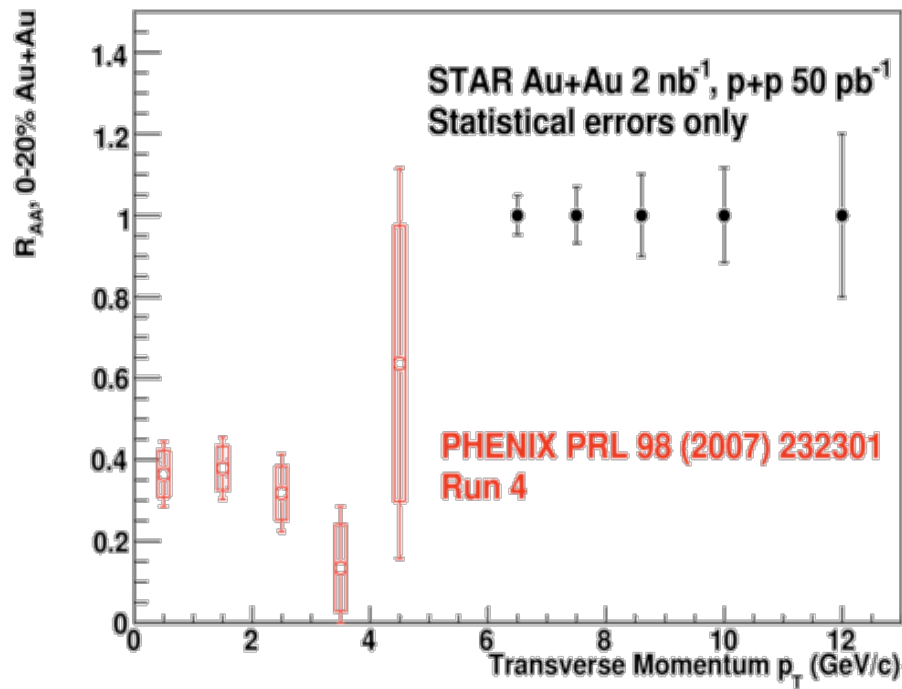
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\eta(1S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

J/ψ yields from 10^9 minbias Au+Au events:
 $43.8 \times 10^{-9} / 0.040 \times 10^9 \times 292 \times 0.5 \times 1.8 \times 0.5 =$
 $144,000 \rightarrow 0.3\% \text{ v2 error}$

$\sigma_{J/\psi}$ σ_{pp} N N_{bin} ϵ γ R_{AA}



High luminosity for Υ & high- p_T J/ψ



Time-Of-Flight:

Electron identification

RHIC II + DAQ1000:

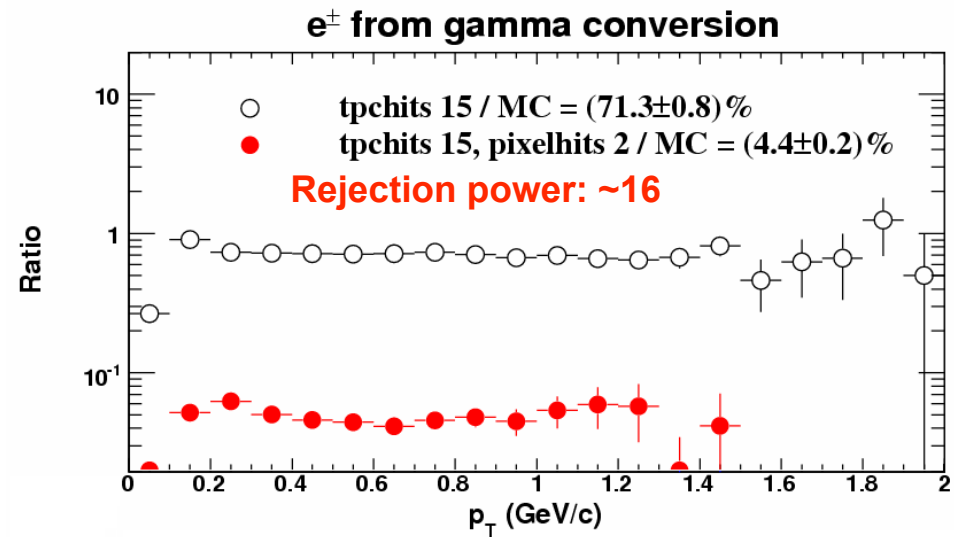
Enhance statistics

Longer term: Quarkonia in STAR

Heavy Flavor Tracker:

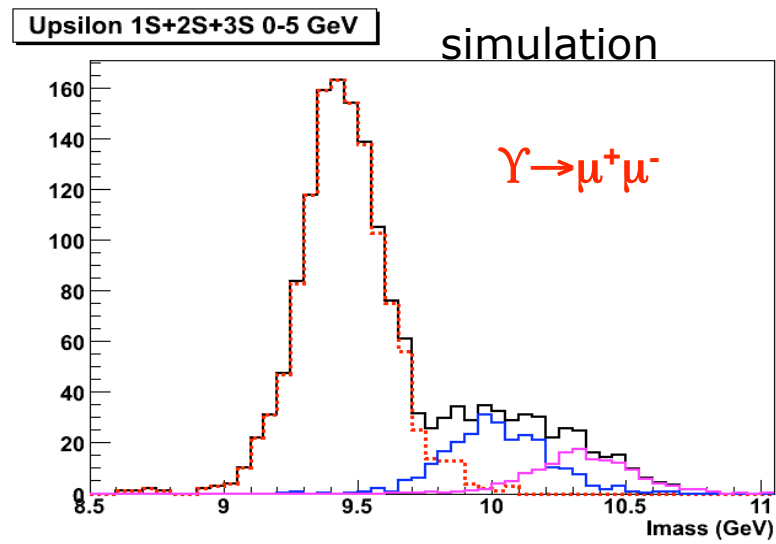
$\gamma \rightarrow e^+e^-$ rejection

Topologically reconstruct
 J/ψ from B decay



Muon Telescope Detector:

Muon
identification



Summary (J/ψ)

- **J/ψ spectra in 200 GeV p+p collisions at STAR**

1. Extend the p_T range up to ~ 14 GeV/c
2. Spectra can be described by CEM and CSM.
3. High p_T J/ψ follows x_T scaling with $n=5.6$
4. Spectra at high p_T can be used to constrain B production

- **J/ψ-hadron azimuthal correlation in p+p**

1. No significant near side correlation
Expect strong near-side correlation from $B \rightarrow J/\psi + X$
Provides constrains on J/ψ production mechanism
2. Away-side spectra consistent with h-h correlation
Indicates gluon or light quark fragmentation

- **J/ψ R_{AA} from 200 GeV Cu+Cu collisions at STAR**

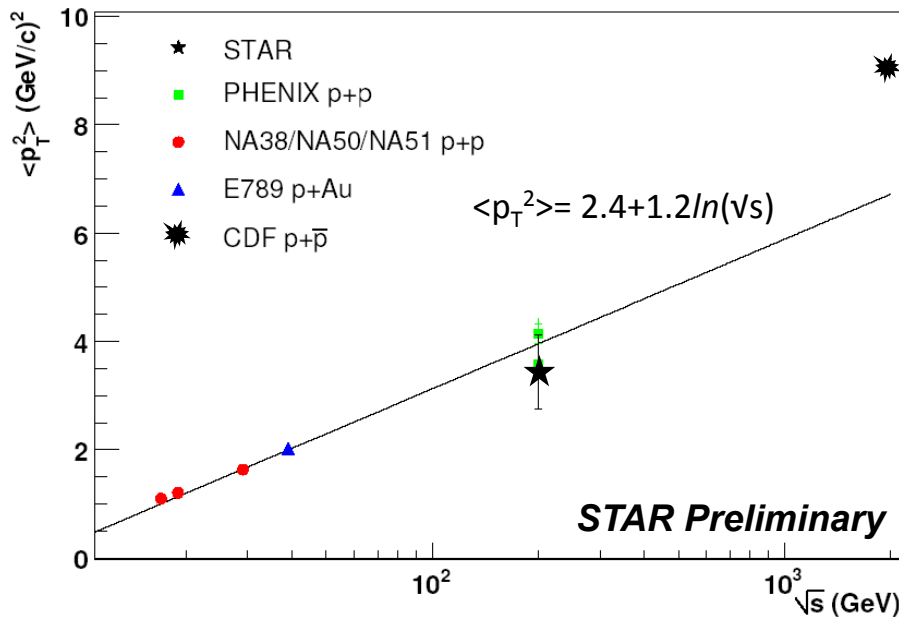
1. Extend R_{AA} from $p_T = 5$ GeV/c to 10 GeV/c
2. Indication of R_{AA} increasing at high p_T

Near Future: J/ψ results from Run 7 Au+Au, Υ R_{AA} , Run 8 d+Au CNM effects,
Future runs: with TOF (improved e PID at low p_T and 1kHz STAR DAQ)

Backup slides

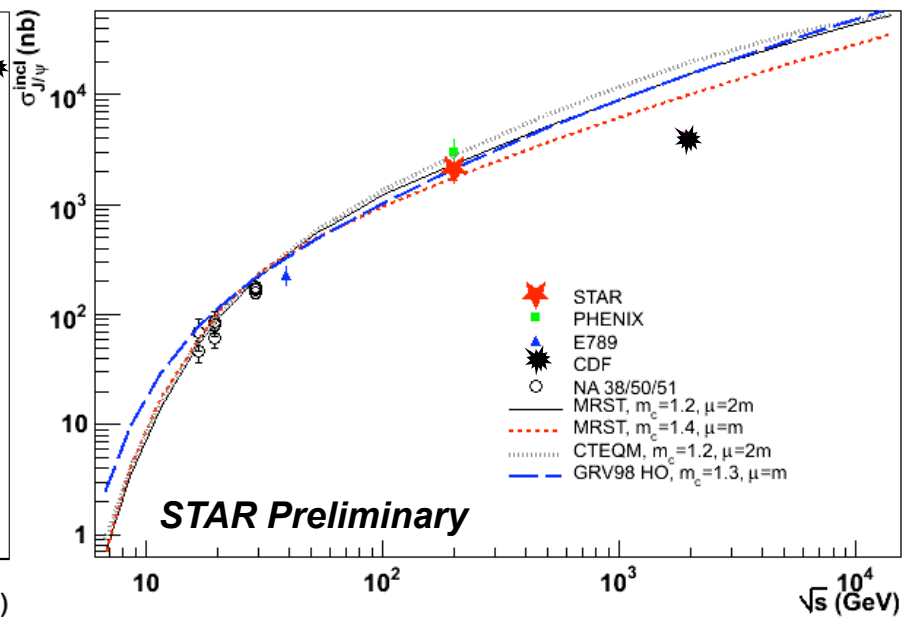
mean p_T^2 and cross section

STAR Measurement & world data



$$\langle p_T^2 \rangle = 3.43 \pm 0.68 (GeV/c)^2$$

CEM can also describe the total cross section



CEM calculation
 M. Bejidian et al.,
 hep-ph/0311048

Datasets

Triggered data

p+p data sample:

- 1. J/ψ triggered events in year 2006
- Integrated luminosity: 377 (nb)^{-1}
- 2. Υ triggered events in year 2006
- Integrated luminosity: 9 (pb)^{-1}

Au+Au data sample:

- 1. Υ triggered events in year 2007
- Integrated luminosity: $300 \text{ (}\mu\text{b)}^{-1}$
- pp-equivalent: 12 (pb)^{-1}

High- p_T J/ψ

p+p data sample:

- 1. EMC triggered events in year 2005
 $E_T > 3.5 \text{ GeV}$
Integrated luminosity: 3 (pb)^{-1}
- 2. EMC triggered events in year 2006
 $E_T > 5.4 \text{ GeV}$
Integrated luminosity: 11 (pb)^{-1}

Cu+Cu data sample:

- 1. EMC triggered events in year 2005
 $E_T > 3.75 \text{ GeV}$
Integrated luminosity: 0.9 (nb)^{-1}
pp-equivalent: 3 (pb)^{-1}