# Experimental summary of the next decade with heavy quarks and quarkonium

Lijuan Ruan
(*Brookhaven National Laboratory*)

Outline:

- **The recent results**
- **The future measurements**
- **Summary**

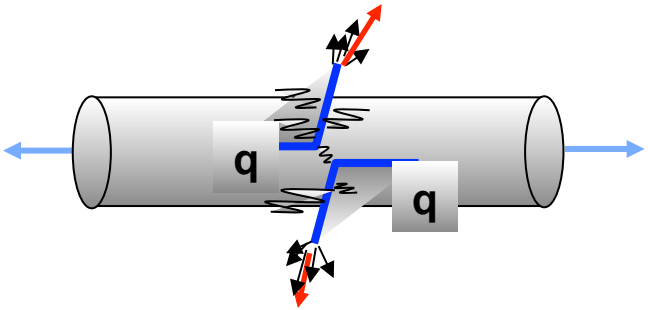
# What have we learnt over the last 15 years

**At RHIC and LHC, strongly interacting Quark-Gluon Plasma created. It is a liquid-like.**

**What we still need to know about the liquid:**

- **When high energy parton, g, q, Q traverses the liquid, how does the parton lose energy?**
- **If we throw Q into the liquid, does it flow and thermalize with the liquid?**
- **If we throw QQbar into the liquid, does the potential between them change? Color screening?**
- **Do we observe signature of chiral symmetry restoration in the hot, dense liquid?**
- **……**

# Why heavy flavor?




RHIC: Nucl. Phys. A 757 (2005)

$M_c \approx 1.3$ GeV

$M_b \approx 4.8$ GeV

$>> T_c, \Lambda_{QCD}, M_{uds}$

Produced at initial impact through hard process, penetrating probe.

**Fragmentation for p+p collisions for hadrons at $p_T$ > 2 GeV/c: convolution of PDF⊗pQCD⊗FF**

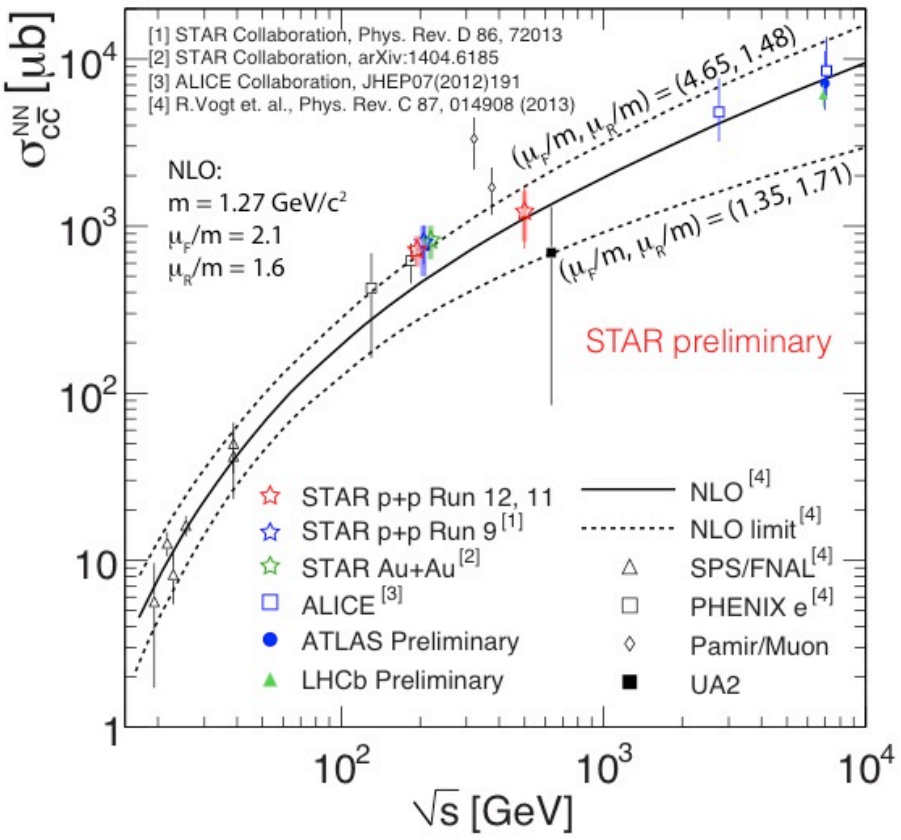
**In central Au+Au collisions at RHIC: Fragmentation + energy loss at $p_T$ > 6 GeV/c**

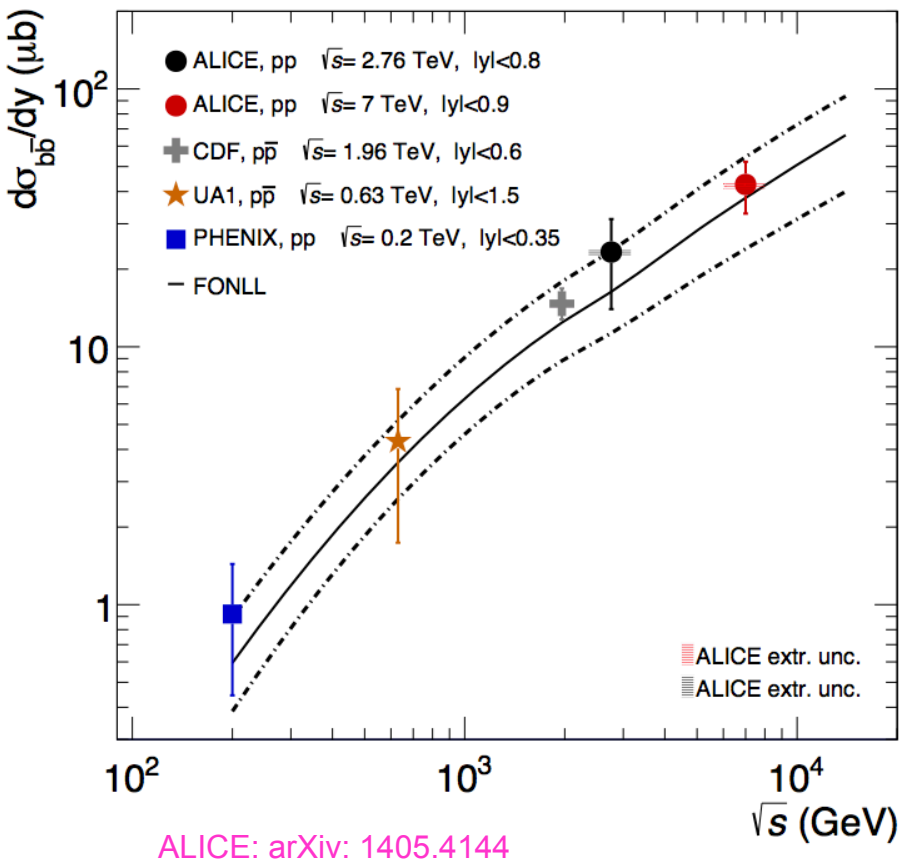
**Recombination/Coalescenece for hadron production at 2-6 GeV/c**

At high $p_T$ > 6 GeV/c, study color charge and mass dependence of energy loss: D,B,π $R_{AA}$

At low to intermediate $p_T$, study heavy quark diffusion coefficient, thermalization, and recombination with light quark.

# Heavy flavor total cross section




ALICE: arXiv: 1405.4144

**Charm cross section follows $N_{bin}$ scaling from p+p to Au+Au collisions**

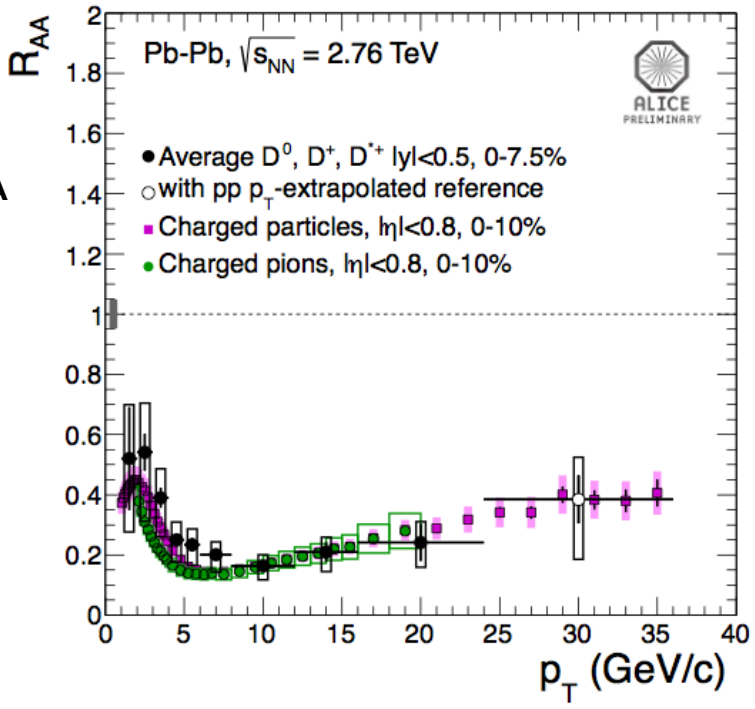
**Expect to get 60 ccbar and 2 bbbar pairs in central Pb+Pb collisions at 2.76 TeV**

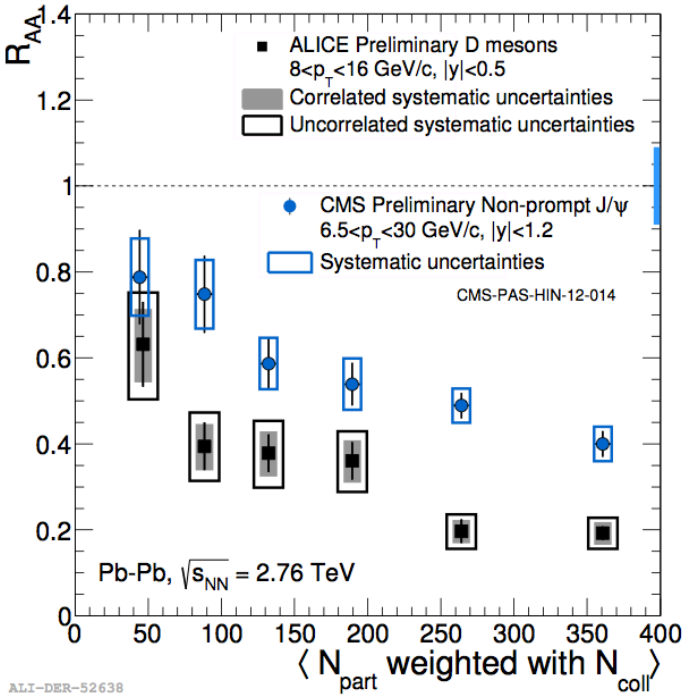
**Expect to get 15 ccbar and 0.1 bbbar pairs in central Au+Au collisions at 200 GeV**

**Coalescence from bbbar to ϒ is negligible at RHIC.**

# Constrain energy loss mechanism

D $R_{AA}$



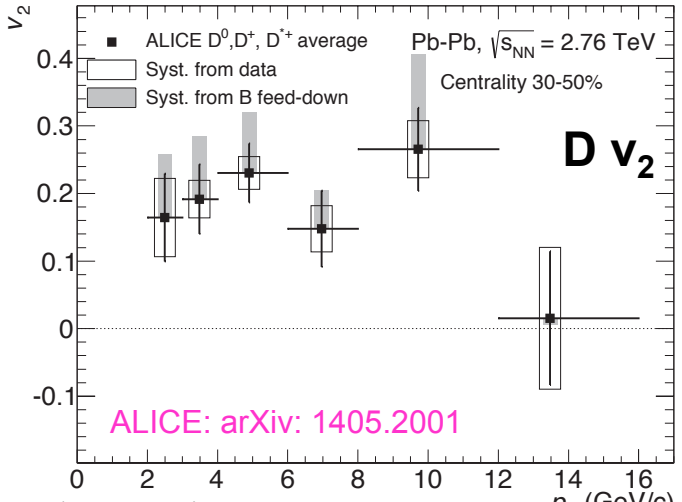

B→J/ψ $R_{AA}$

D $R_{AA}$

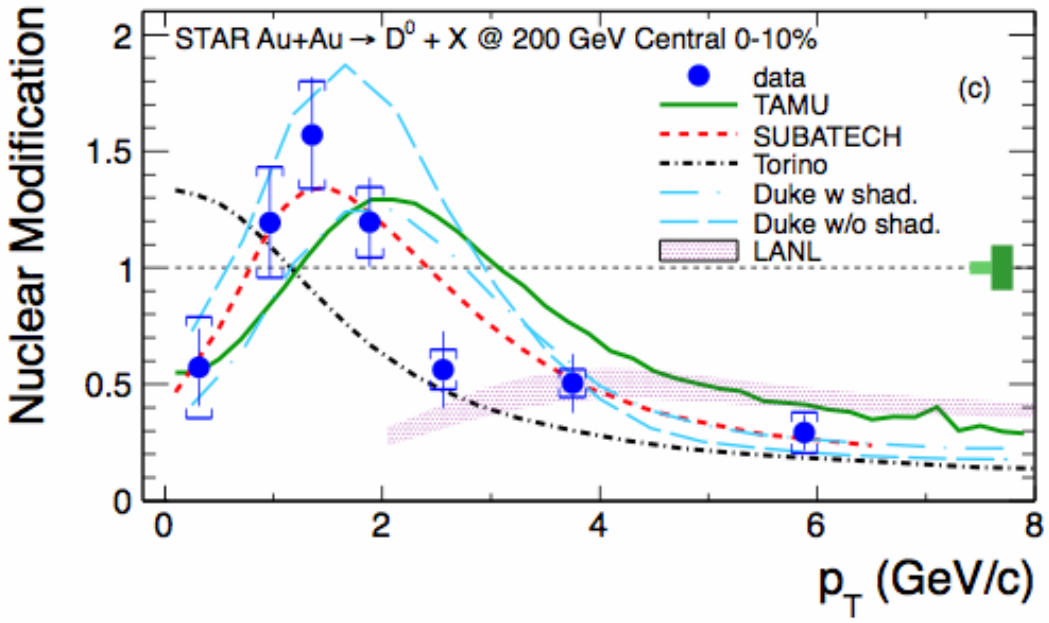
- At $p_T$> 6 GeV/c:

$R_{AA}(D) \approx R_{AA}(\pi) < R_{AA}(B \rightarrow J/\psi)$; substantial $v_2$ for D meson at 2-10 GeV/c.

probe color charge and mass dependence of energy loss



# Low $p_T$ to constrain diffusion coefficient




STAR: arXiv: 1404.6185, accepted by PRL

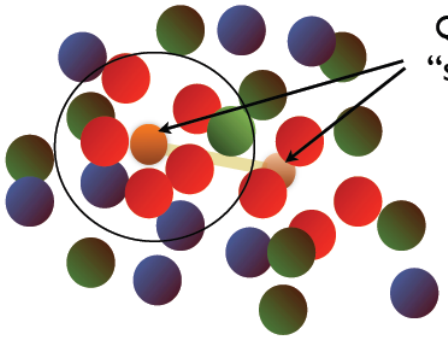
- **A maximum at $p_T$~2 GeV/c: consistent with models including strong coupling of the heavy quarks to the QGP and their hadronization via coalescence:**
- **Heavy quark diffusion coefficient $D_S(2\pi T)$=3-5 at ~$T_c$ constrained by RHIC and LHC measurements** (He, Fries, Rapp PRL110(2013)112301).
- **Need precise measurements to constrain diffusion coefficient further.**

# Quarkonium as a QGP thermometer

## color screening

### Matsui-Satz: screening the potential

Screening in a deconfined medium: effective charge of Q and $\bar{Q}$ reduced



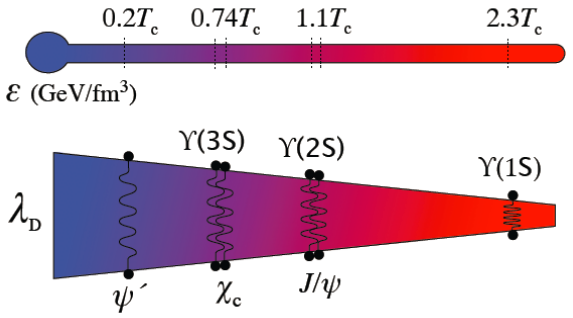
Q and $\bar{Q}$ cannot "see" each other

$r_D < r_{Q\bar{Q}}$

Assume: medium effects described with a T-dependent potential

$$-\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$$

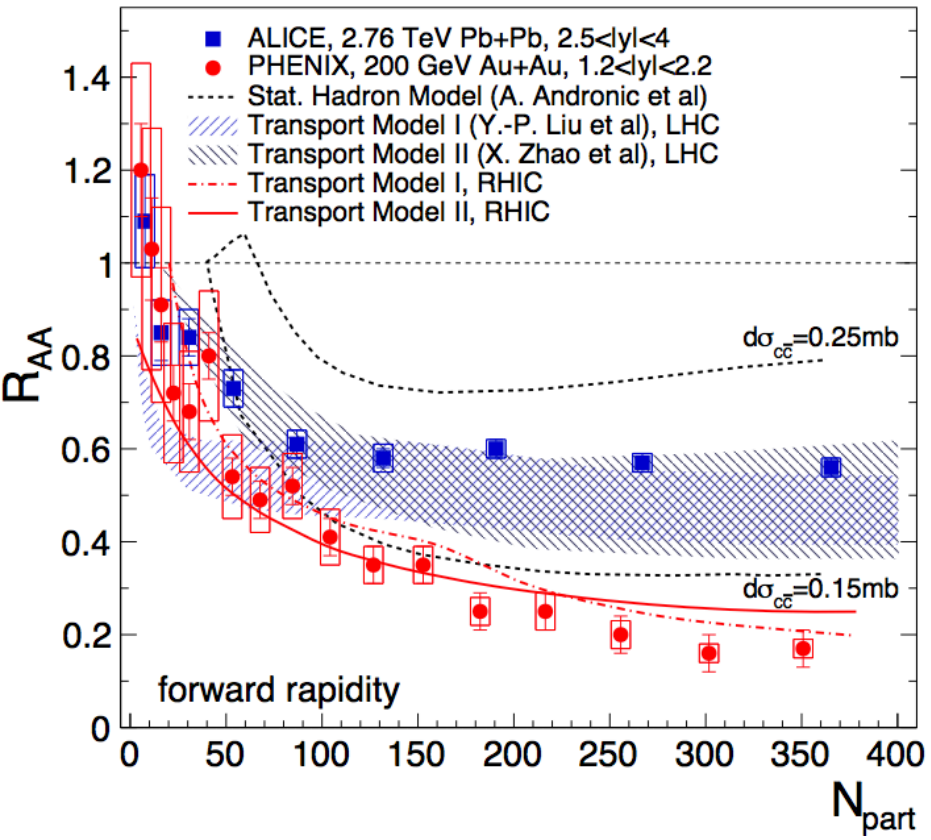
Courtesy from A. Mocsy




**Different quarkonium states:**
**Heavy but small,**
**0.28, 0.56, 0.78 fm for** $\Upsilon$(1S), $\Upsilon$(2S), $\Upsilon$(3S).
**provide distance scales to probe QGP:**
**different dissociation temperatures,**

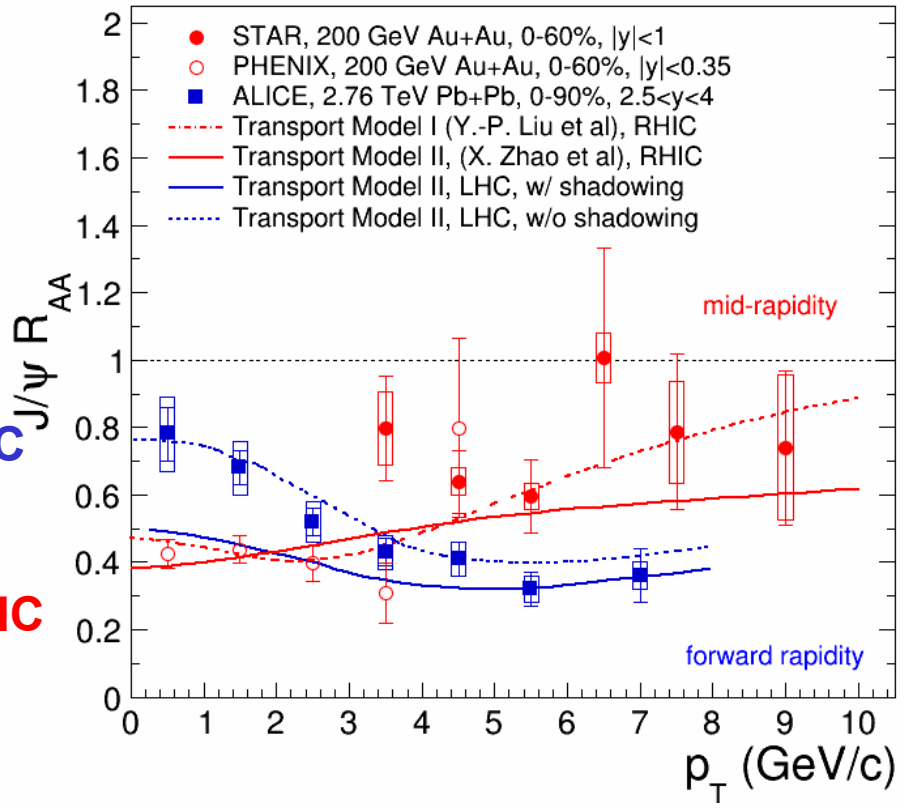
**thermometer for QGP.**

# J/ψ suppression pattern




LHC

RHIC

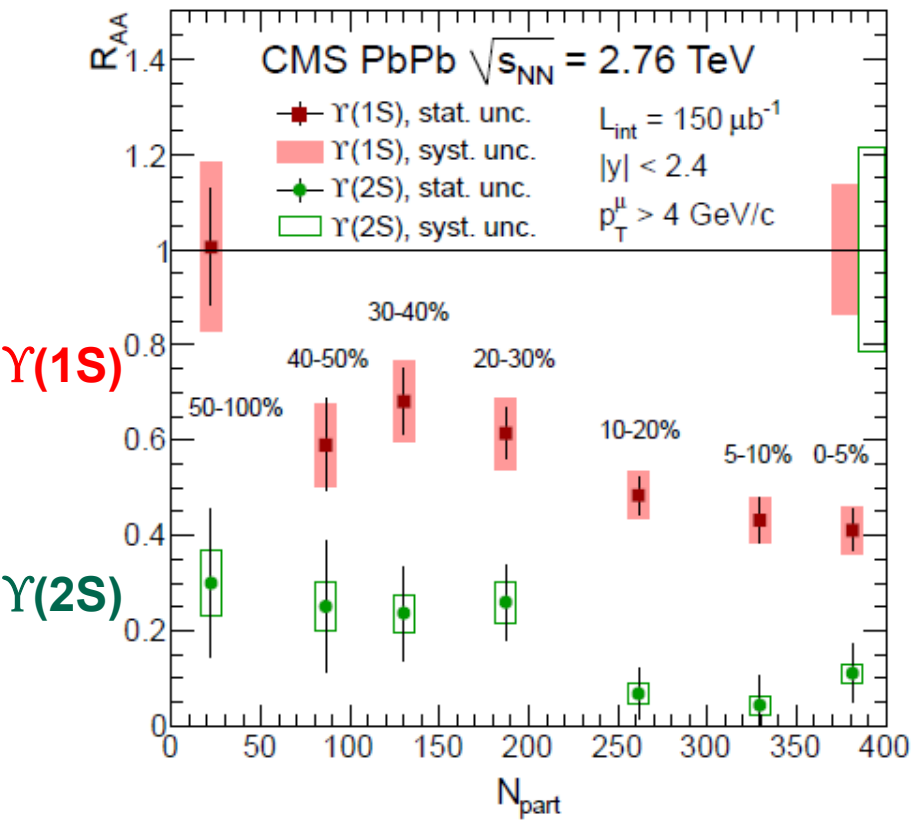


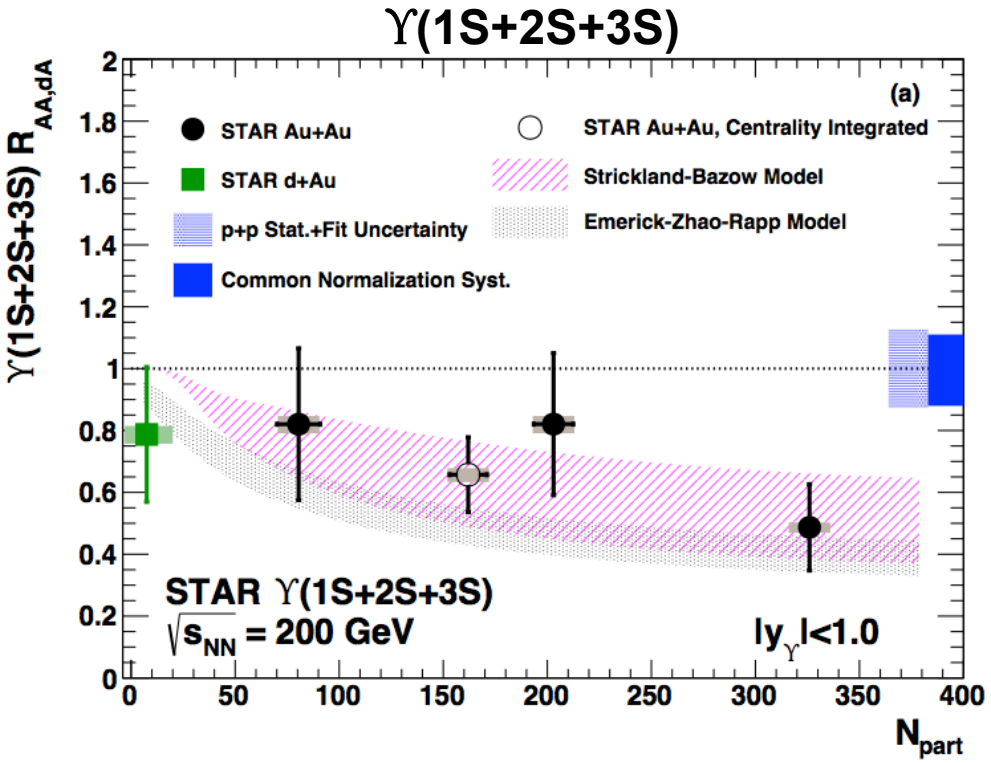

consistent with more significant contribution from ccbar recombination at LHC energies

Interplay between color screening and recombination: describe the J/ψ suppression pattern and flow measurements

PHENIX: PRC84(2011)054912, PRL98(2007)232301
ALICE: PLB734(2014)314
STAR: PLB722(2013)55

# Sequential melting for different Υ




**Υ(1s) suppression magnitude consistent with excited states suppression.**

**Υ(2S) strongly suppressed, Υ(3S) completely melted.**

CMS: PRL109(2012)222301
STAR: PLB735(2014)127

# Achievements and Open questions

**Heavy flavor:**
total cross section follows $N_{bin}$ scaling.
very interesting feature in D meson $R_{AA}$ at $p_T$<5 GeV at RHIC.
At high $p_T$, $R_{AA}(D) \sim R_{AA}(\pi) < R_{AA}(B \rightarrow J/\psi)$ at LHC.
D meson flows.

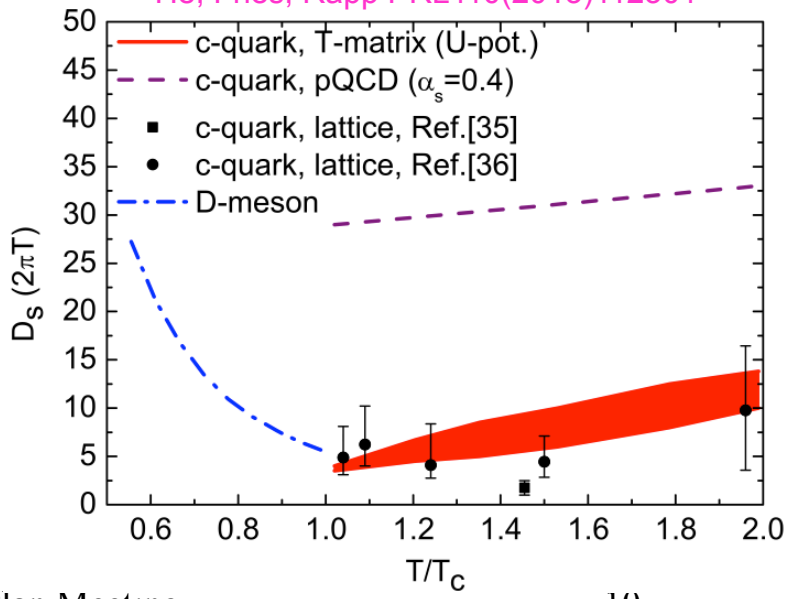
**Quarkonia:** the centrality and $p_T$ dependence of J/ψ suppression pattern at RHIC and LHC can be interpreted as the interplay of two key ingredients: recombination and color screening;
ϒ(2S) strongly suppressed, ϒ(3S) completely melted.

We are in the era to study color screening features of hot, dense medium

Questions: How does heavy flavor diffusion coefficient depend on temperature?

How does the in-medium QCD force depend on temperature? …

He, Fries, Rapp PRL110(2013)112301



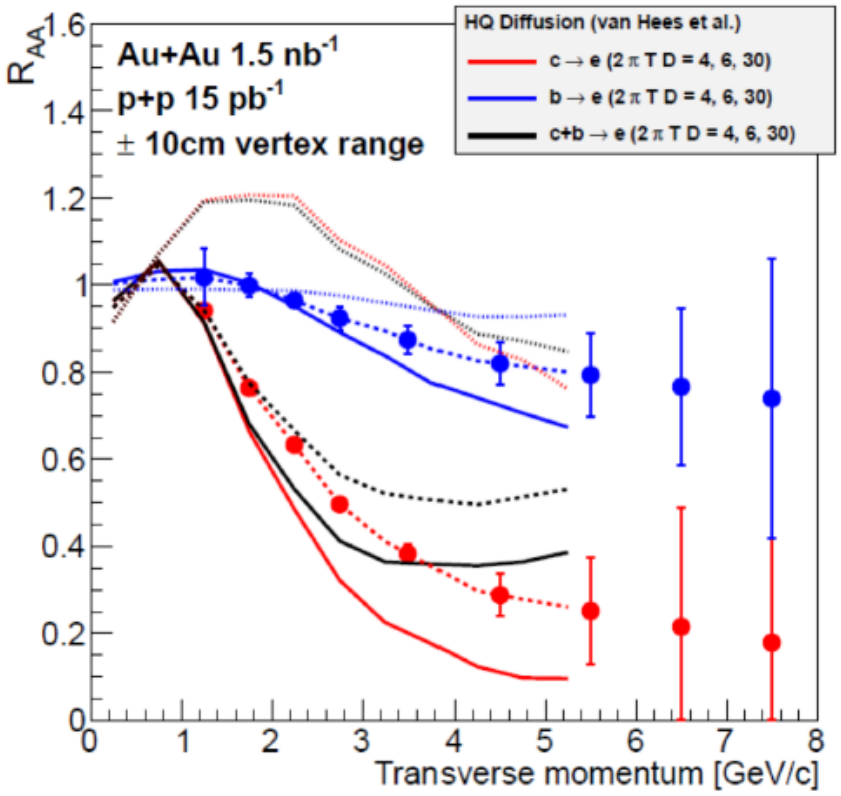
# To the future

To quantitatively access the temperature dependent diffusion coefficient and color-screening feature…

| Facility | Current measurements | Future measurements |
|---|---|---|
| RHIC heavy flavor | D $R_{AA}$,<br>e from charm and bottom decays | e, muon from charm and bottom, separately, D with better precision, $\Lambda_c$,<br>charm-charm correlation, heavy flavor tagged jet, B from non-prompt J/psi |
| LHC heavy flavor | D, B from non-prompt J/ψ, leptons from charm and bottom decays,<br>B-tagged jet, fully reconstructed B in pPb | Improve low and intermediate $p_T$ measurements, fully reconstructed B meson in PbPb |
| RHIC quarkonia | Υ(1S+2S+3S), J/ψ, ψ(2S) in dAu/pp | Υ(1S), Υ(2S), Υ(3S), J/ψ with better precision at low and intermediate $p_T$, possible ψ(2S) and J/ψ tagged jet (away side) |
| LHC quarkonia | Υ(1S), Υ(2S), Υ(3S), J/ψ, ψ(2S) | Improve precision, especially for Υ in peripheral collisions. |

Measurements In blue are presented.

# The VTX – study heavy flavor dynamics



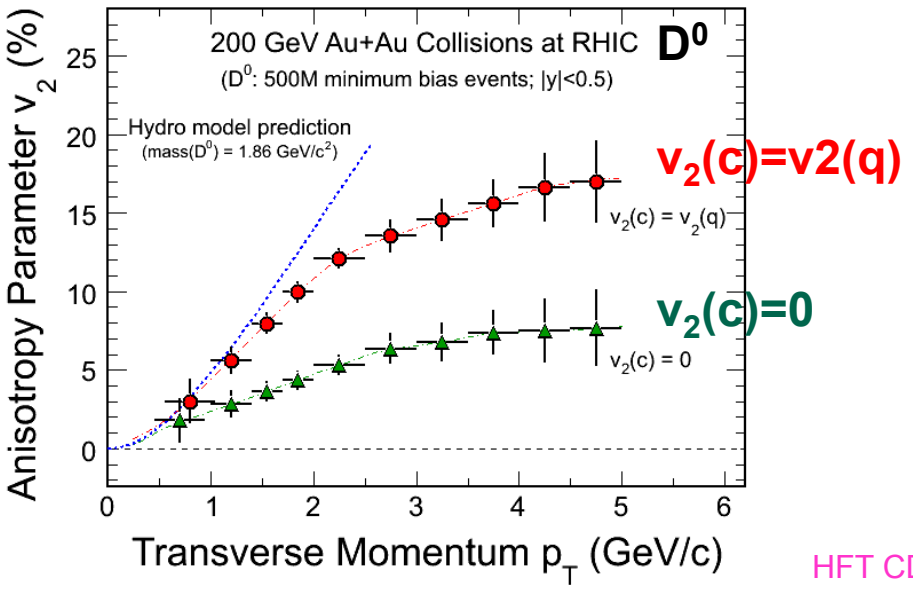

b→e

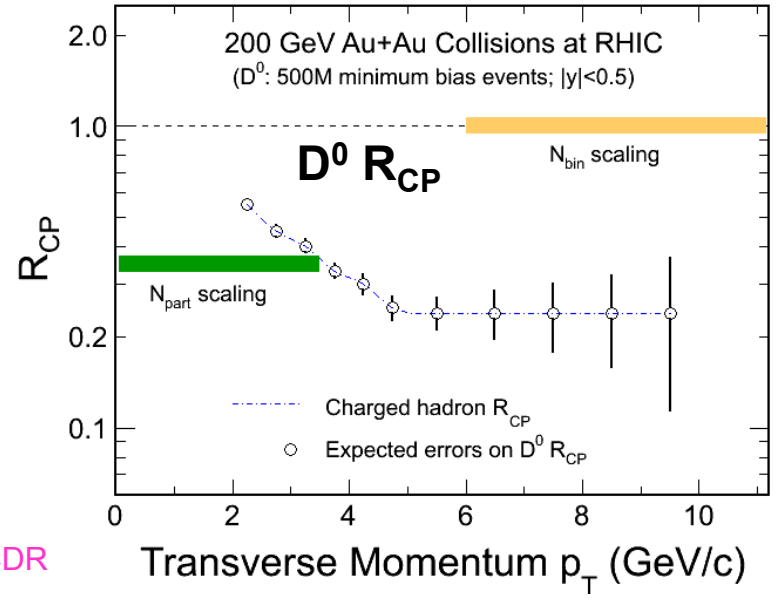
c→e

$R_{AA}$: electron from charm and bottom decay, separately with VTX at PHENIX

Constrain heavy quark diffusion coefficient.

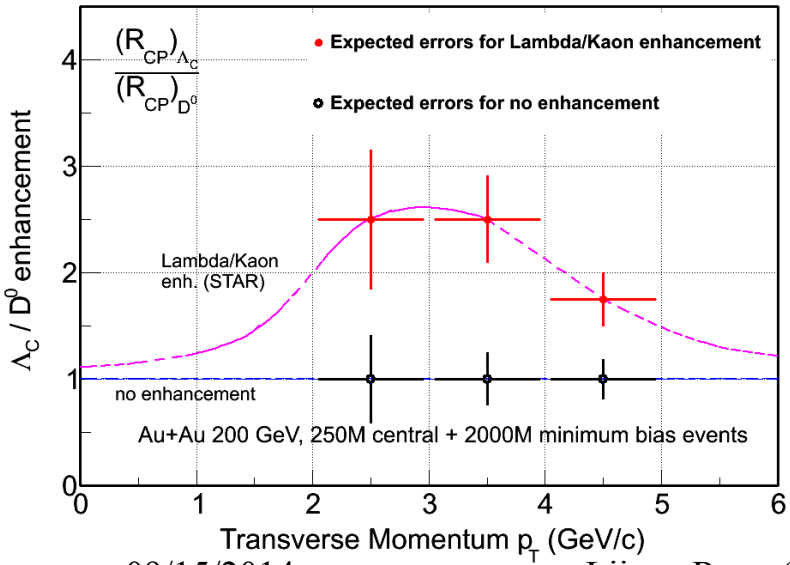
# The HFT – study heavy flavor dynamics




HFT CDR

$R_{CP}(\Lambda_c) / R_{CP}(D^0)$

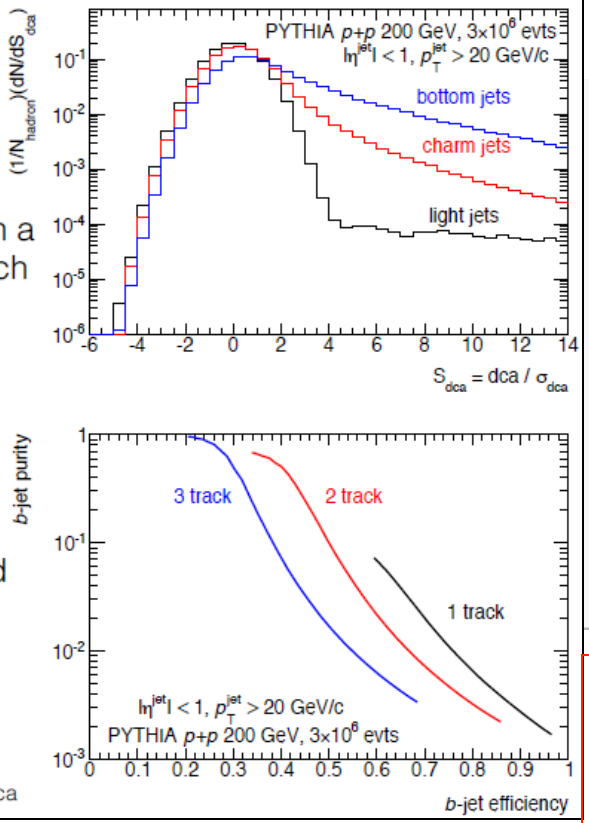



$v_2$, baryon/meson ratios, $R_{CP}$ to understand heavy quark dynamics in the medium: heavy quark transport coefficients, thermalization with medium, energy loss mechanism.

# B-jet and B→J/ψ for 2020+ at RHIC

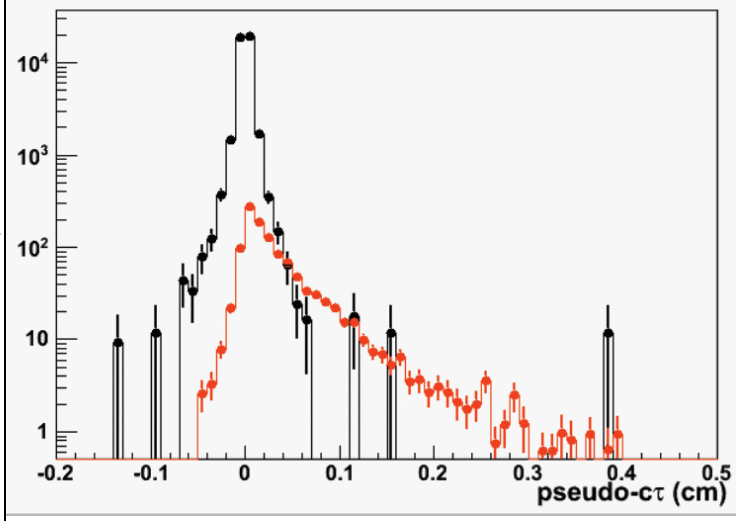
## *b*-jet tagging with the VTX

- sPHENIX has explored *b*-jet tagging through requiring tracks in the jet with a large 2-D distance of closest approach (d.c.a) to the primary vertex
  - exploits the long flight time of B hadrons
- Truth-level study with parameterized d.c.a. resolution, $\sigma_{dca}$ = 70 μm
  - Top: d.c.a. significance of charged particles, with $K_L^0$ and $\Lambda^0$ decays removed
  - Bottom: *b*-jet efficiency vs. *b*-jet purity for cuts requiring 1, 2, 3 or more tracks with some minimum $S_{dca}$




**Prompt J/ψ**

**B→J/ψ (non-prompt)**



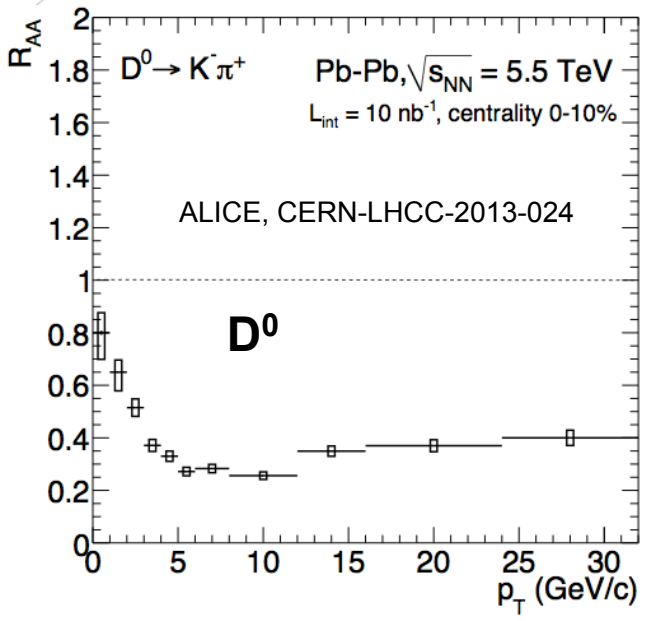

STAR: separate **non-prompt J/ψ** from **prompt J/ψ**.

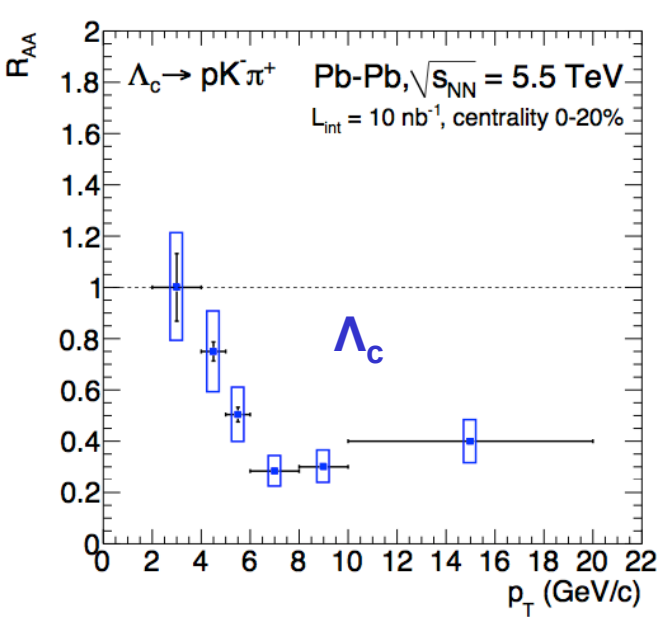
In 2020+, statistics will be further improved by a factor of 2.

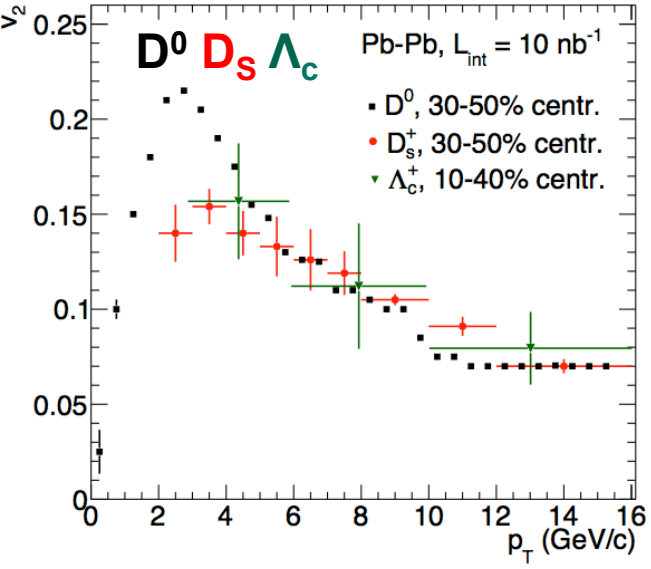
sPHENIX: b-jet tagging is promising

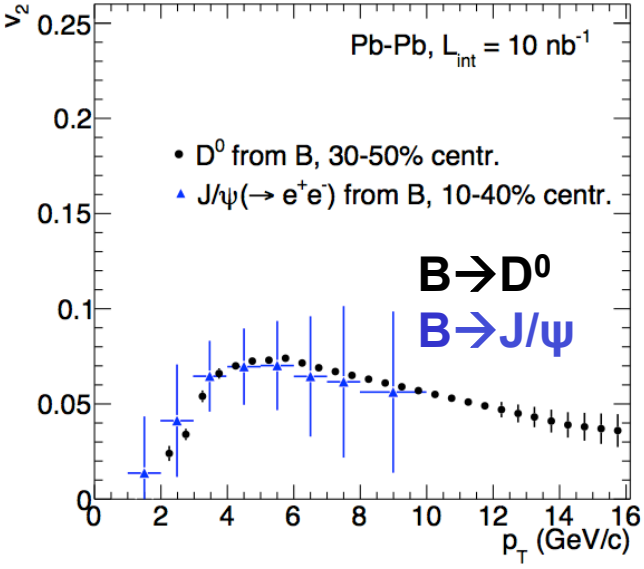
Constrain mass dependent radiative energy loss

# Charm and Bottom for 2020+ at LHC



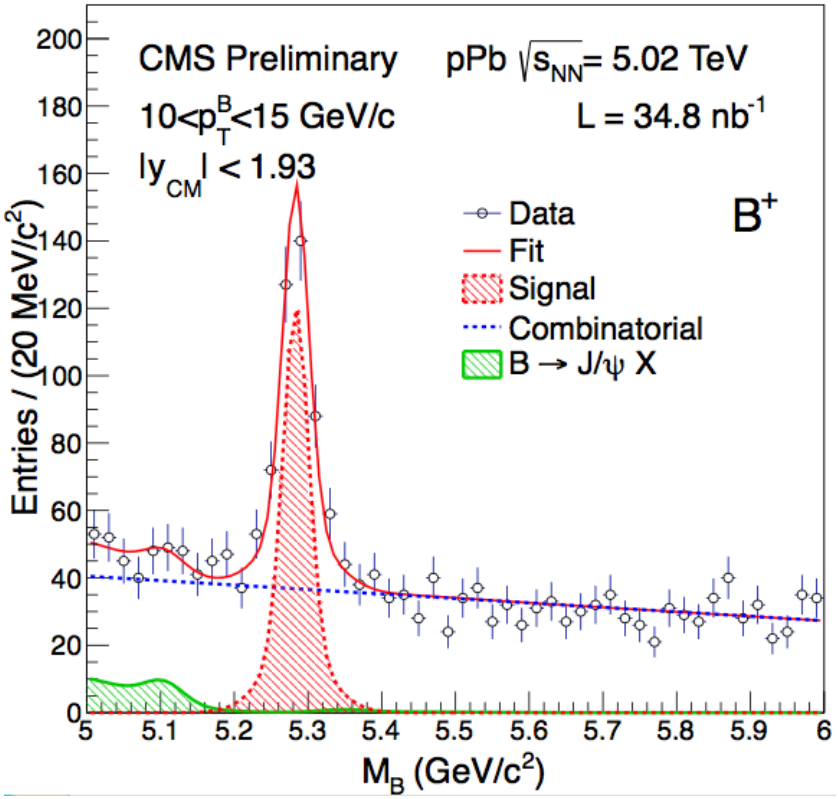



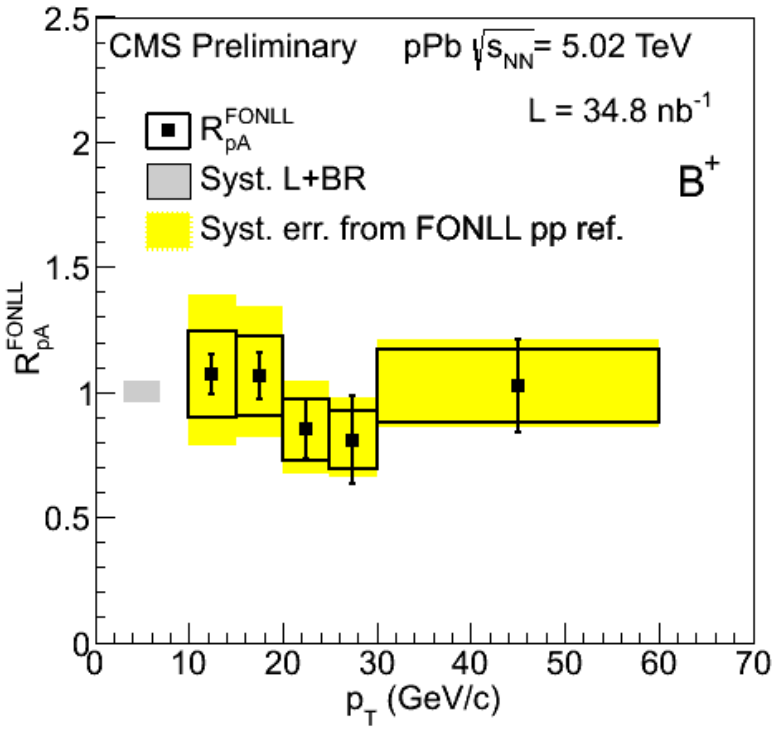




Precise charm and bottom $R_{AA}$ and $v_2$ measurements down to very low $p_T$ at ALICE (C. Nattrass).

Critical to obtain the heavy flavor diffusion coefficient and to constrain the recombination contribution to quarkonia.

# Fully reconstruct B meson at CMS



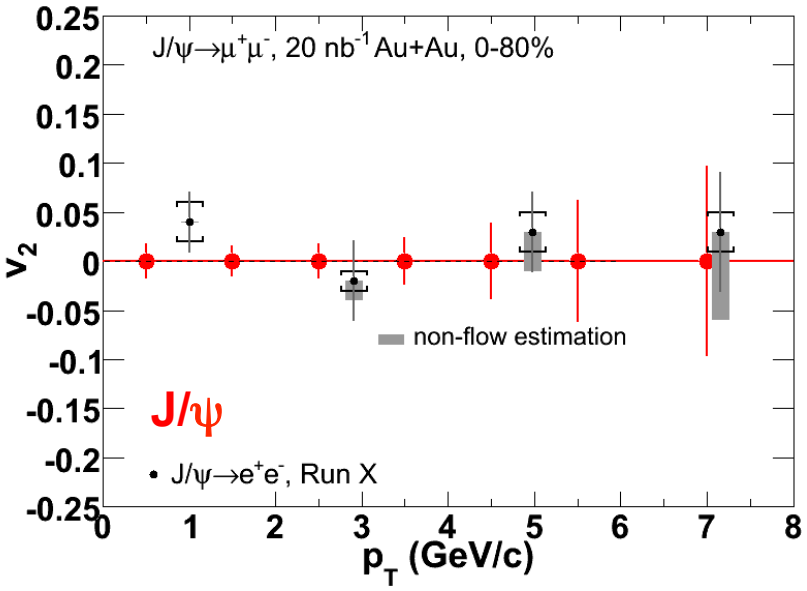



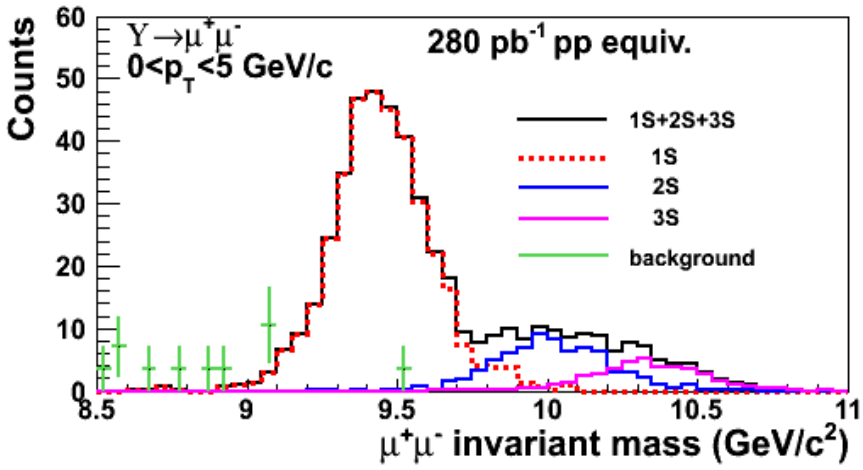

$B^+ \rightarrow J/\psi\ K^+$

Fully reconstructed B mesons in pPb collisions

In the future: do it in PbPb collisions, constrain mass dependent radiative energy loss

# STAR MTD: Quarkonium measurements for Run14+16

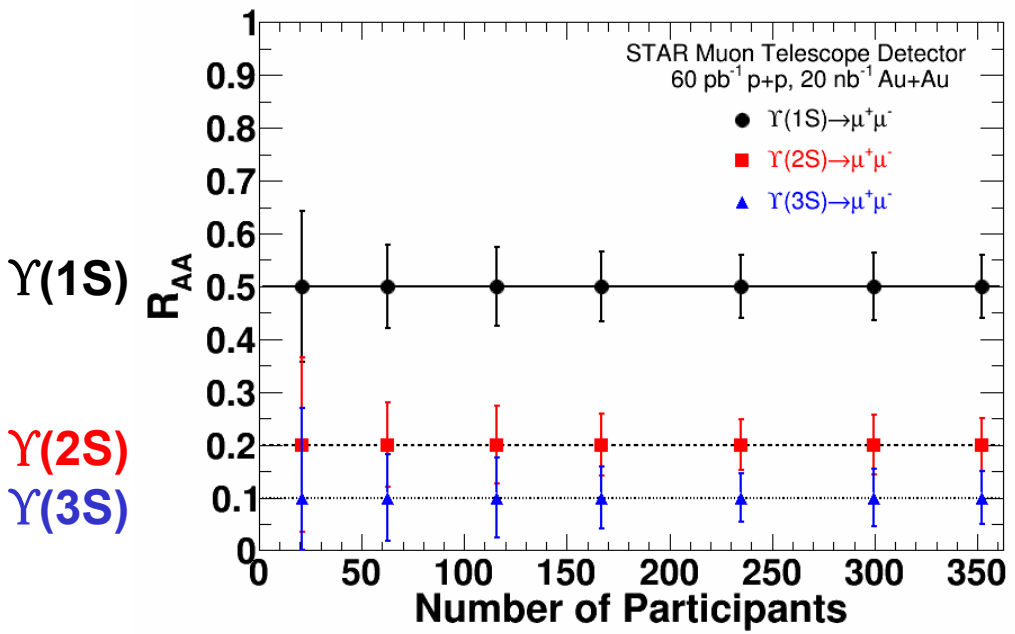


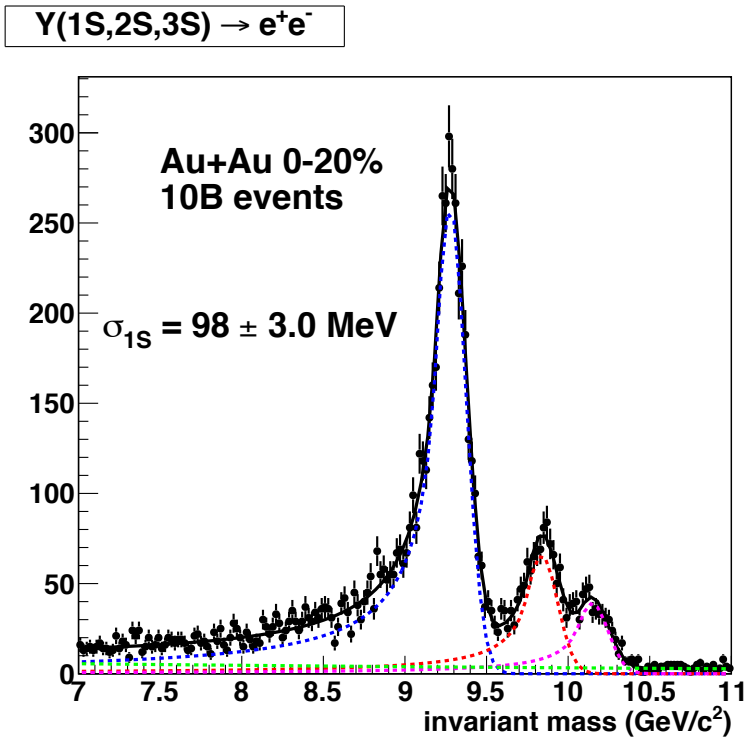

Does J/ψ flow?

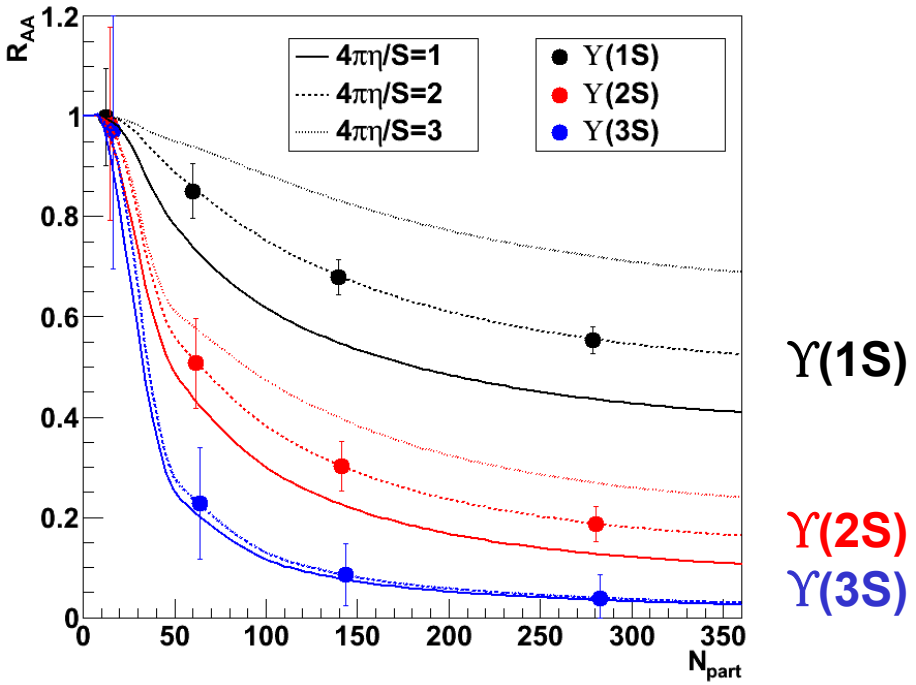
Sequential melting for different Upsilon states.

Constrain the color screening feature and initial temperature of QGP evolution



# sPHENIX: Quarkonium measurements for 2020+




Υ(1S)

Υ(2S)

Υ(3S)

**sPHENIX will provide more precise measurements (A. Frawley).**

**Constrain color screening feature and initial temperature of QGP evolution.**

# Summary

Our current measurements demonstrate that

- heavy flavor quarks are strongly coupled to the medium.
- different ϒ states are sequentially melted.

The data start to constrain heavy quark diffusion coefficient and QQbar potential in hot, dense matter semi-quantitatively.

The data of next decade will put stringent constrains on

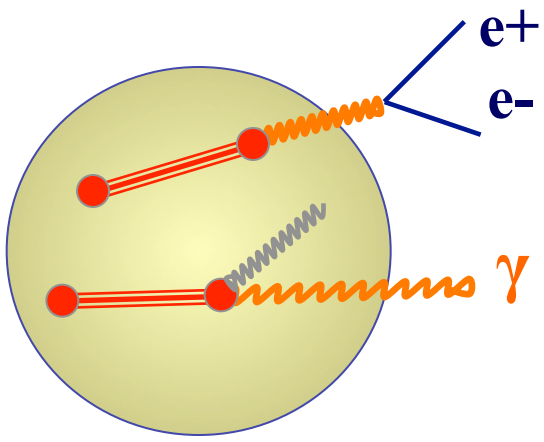
- temperature-dependent heavy quark diffusion coefficient.
- charm and bottom thermalization.
- temperature-dependent in-medium QCD force.
- mass-dependent radiative energy loss.

Do we observe signature of chiral symmetry restoration in the hot, dense liquid?

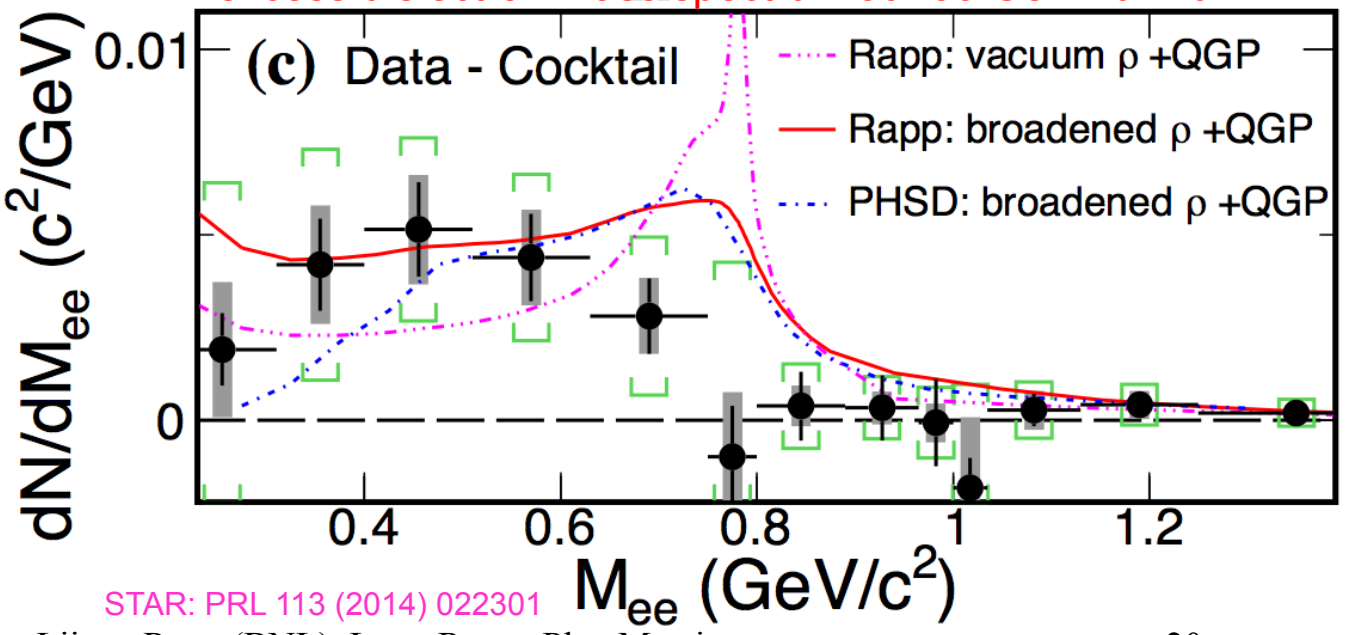
The precise charm and e-muon measurements will enable precise dilepton measurements in the intermediate mass region.

# To search for chiral symmetry restoration

| In cold vacuum | Hot, dense matter |
|---|---|
| Vector meson spectral function:<br>Quark condensate formed,<br>Chiral symmetry breaking, different mass distributions for the chiral partners (ρ, a1). | condensate disappear, chiral symmetry restored, mass differences disappear.<br>Observable: a broadened ρ spectral function and ultimately the peak structure disappears! |




excess dielectron mass spectrum at 200 GeV Au+Au




STAR: PRL 113 (2014) 022301

# The future dilepton and photon program

RBRC workshop of thermal photons and dileptons in heavy ion collisions, Aug 20-22, 2014, BNL
(Input from the community: Rapp/Akiba/Gabor/Gale/…)

- **To link dilepton measurements to chiral symmetry restoration (P. Hohler) need more precise measurement at $\mu_B = 0$.**
- **The slope in the intermediate mass region represents the true average temperature T of the medium.**
- **The low-mass dilepton emission depends on T, total baryon density, and life time, and enables systematic life-time measurements.**
  **(F. Geurts for more details)**
- **"With complementary information from direct photons (T. Sakaguchi), by clarifying the puzzling observation of their collective flow pattern, a consistent picture of electromagnetic radiation from QCD matter is within reach." (Quote from Rapp/Akiba)**