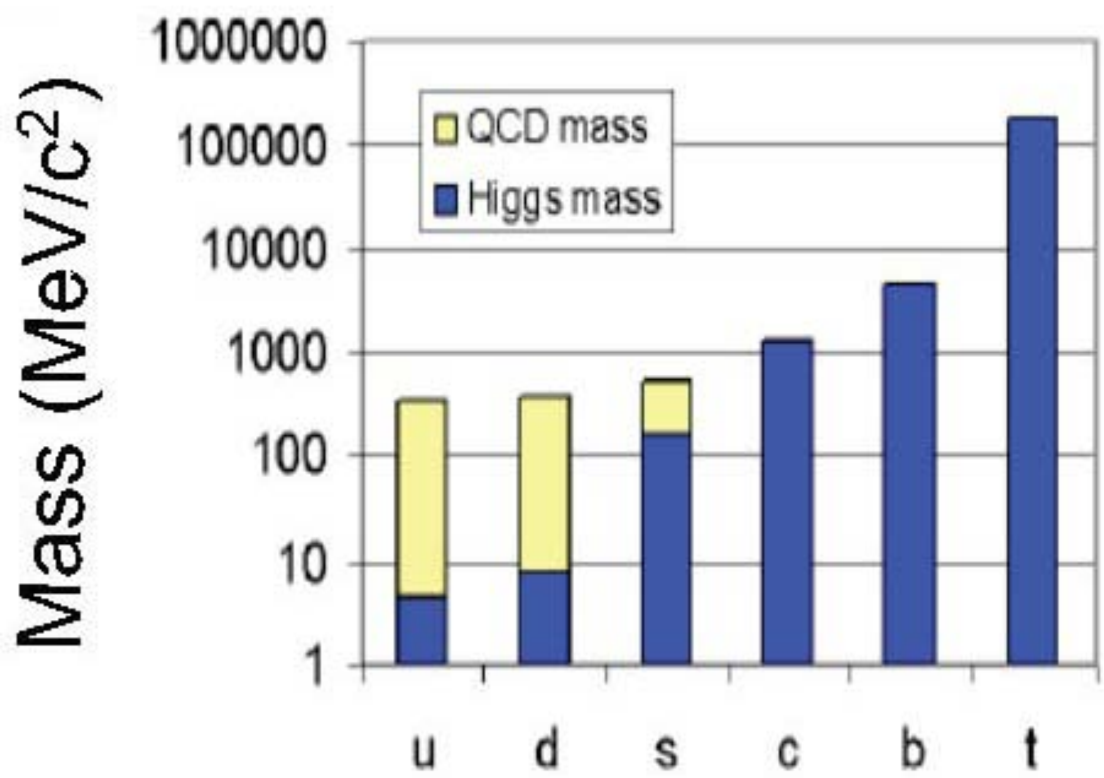
Heavy flavor production at RHIC

Lijuan Ruan
(*Brookhaven National Laboratory*)

Outline:

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

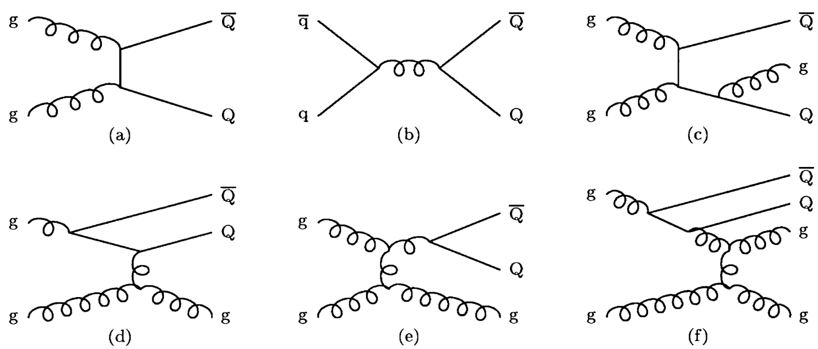
The mass



Heavy flavor mass, comes from the Higgs mechanism, no effect from the QCD chiral symmetry breaking.

Light flavor mass, affected by chiral symmetry breaking.

Heavy flavor and quarkonium production



$M_c \approx 1.3$ GeV
$M_b \approx 4.8$ GeV >> T_c, Λ_{QCD}, M_{uds}

Produced at initial impact through hard process, penetrating probe.

Produced by gluon fusion, quark-antiquark annihilation, gluon emission, flavor excitation, and gluon splitting …

Charm quark into hadrons (~10% to baryon, ~1% into J/ψ, and others to mesons)

QQbar transition into quarkonium through color singlet, color octet, and color evaporation approaches.

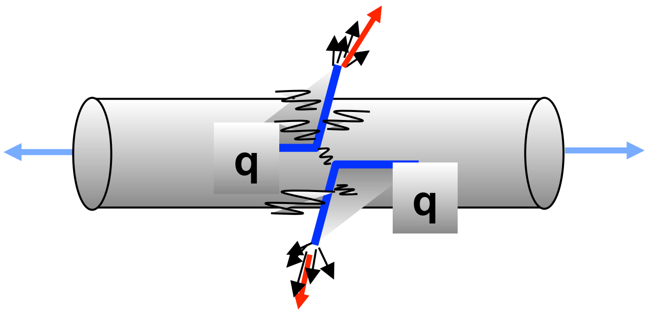
What have we learnt over the last 15 years

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

Produced at initial impact through hard process, penetrating probe.

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

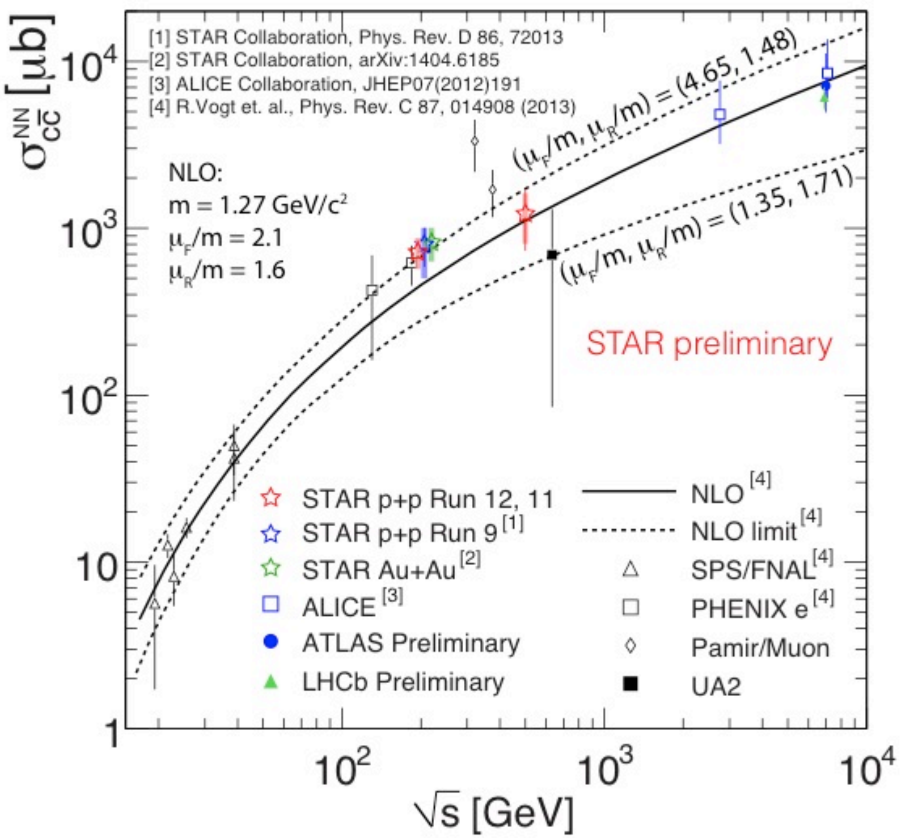
At low to intermediate p_T, study heavy quark diffusion coefficient, thermalization, and recombination with light quark.

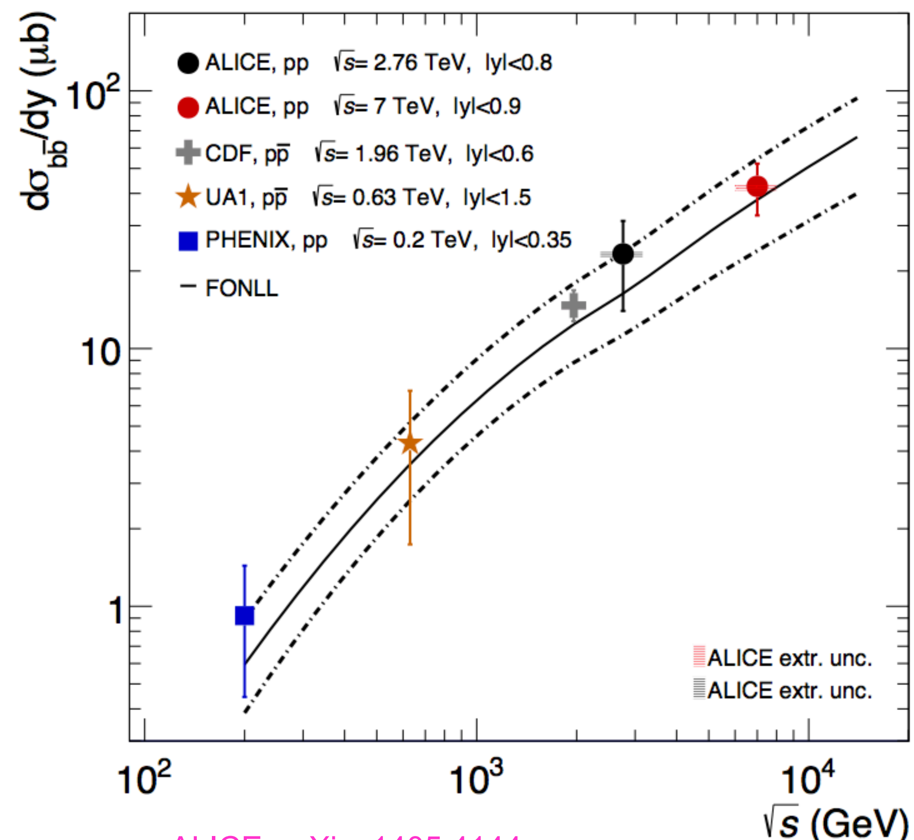
Fragmentation for p+p collisions for hadrons at $p_T > 2$ GeV/c: convolution of PDF⊗pQCD⊗FF

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

Heavy flavor total cross section





ALICE: arXiv: 1405.4144

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

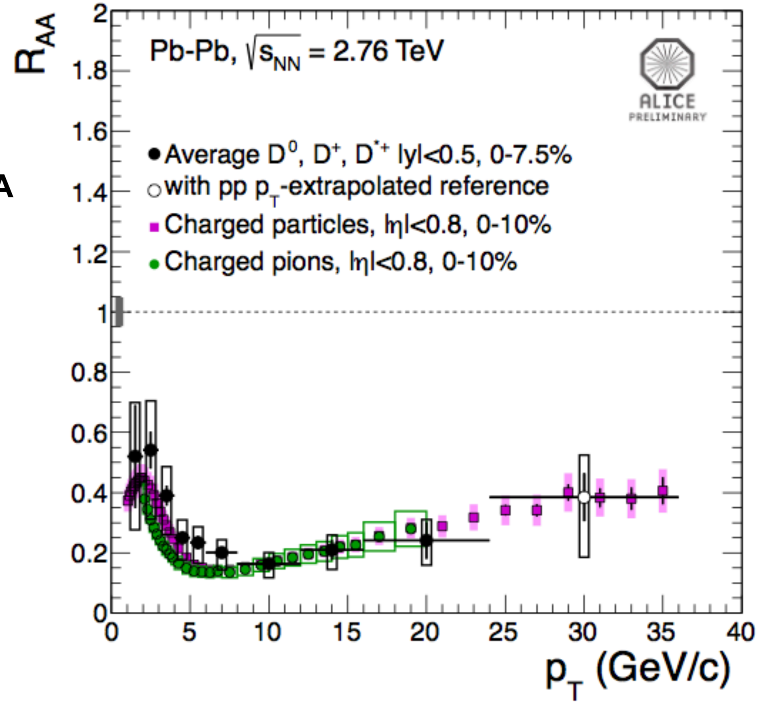
Expect to get 60 ccbar and 2 bbbar pairs in central Pb+Pb collisions at 2.76 TeV

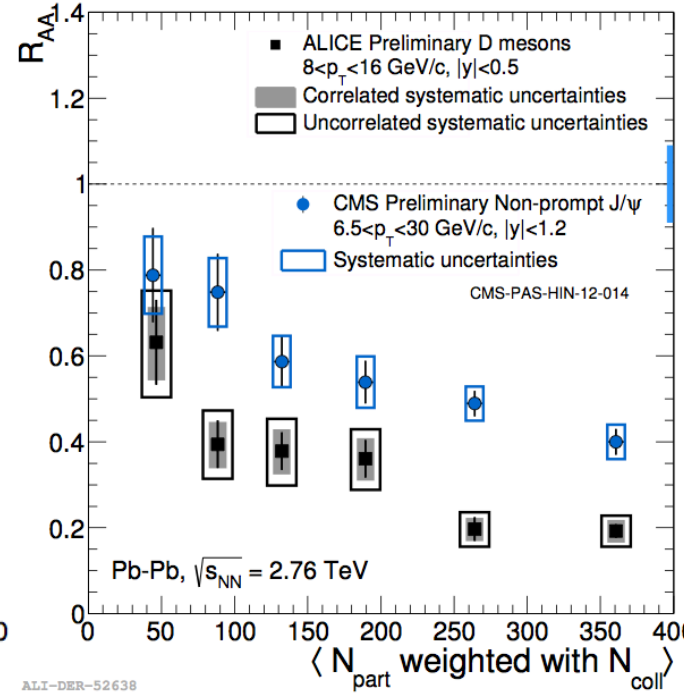
Expect to get 15 ccbar and 0.1 bbbar pairs in central Au+Au collisions at 200 GeV

Coalescence from bbbar to Υ is negligible at RHIC.

Constrain energy loss mechanism

D R_{AA}





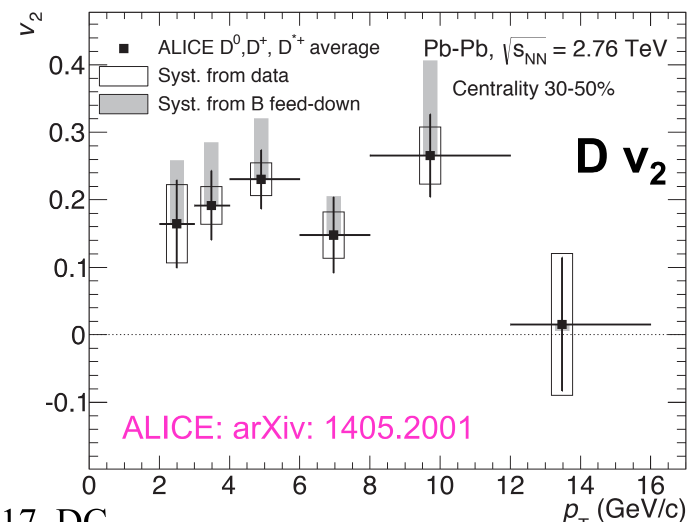
B→J/ψ R_{AA}

D R_{AA}

- At p_T> 6 GeV/c:

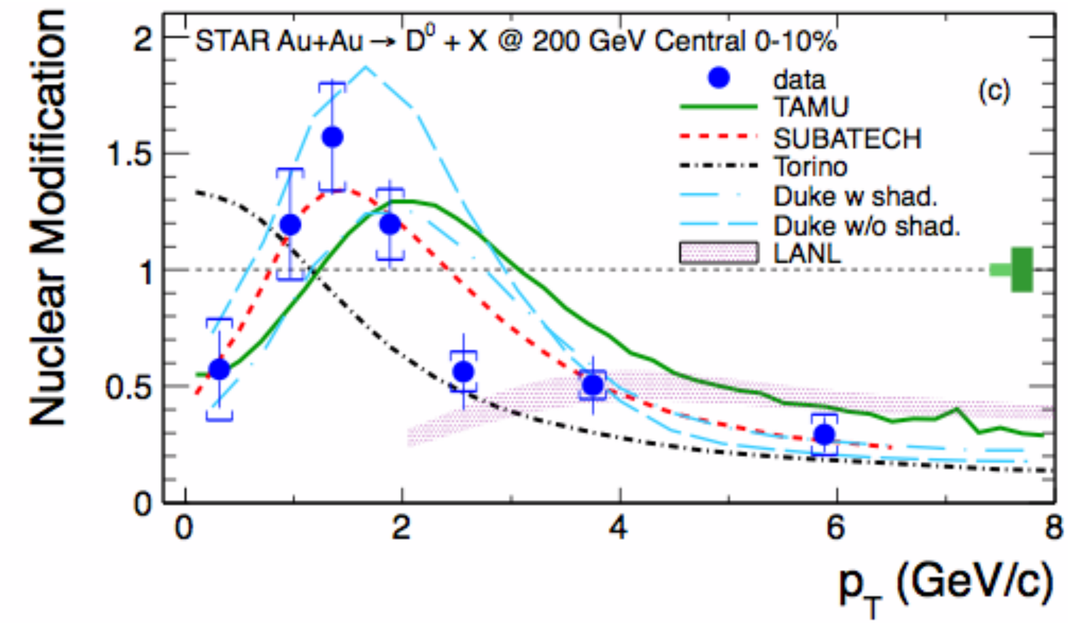
$R_{AA}(D) \approx R_{AA}(\pi) < R_{AA}(B\rightarrow J/\psi)$;
substantial v_2 for D meson at 2-10 GeV/c.

probe color charge and mass dependence of energy loss



D v_2

Low p_T to constrain diffusion coefficient

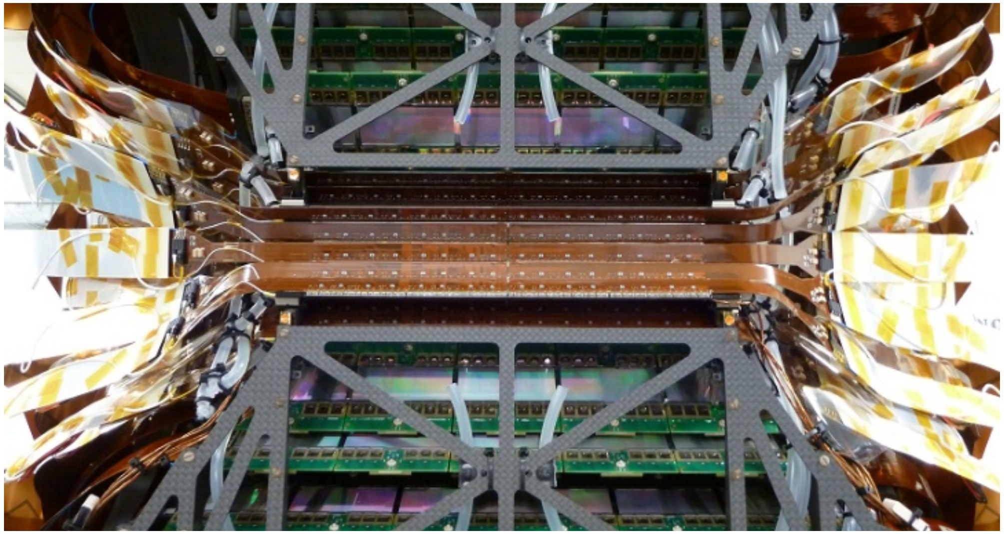


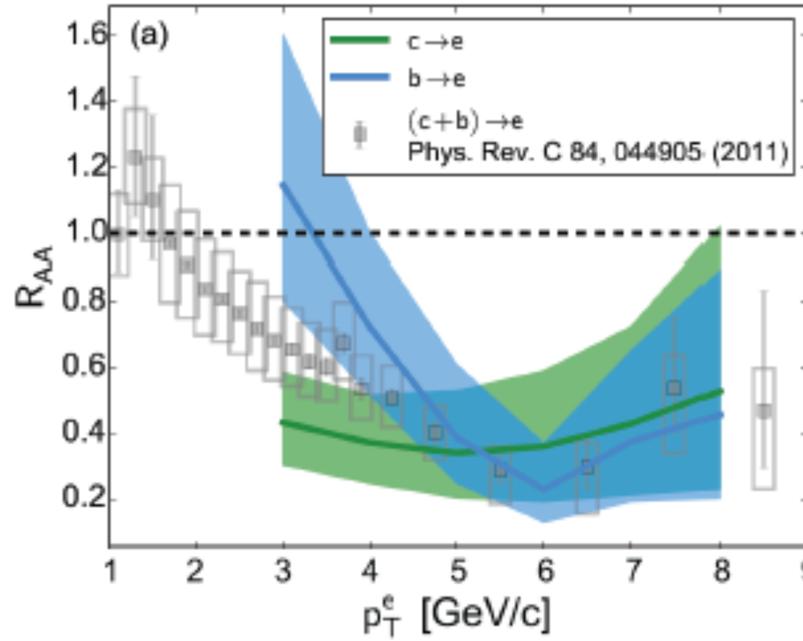
STAR: arXiv: 1404.6185, accepted by PRL

- A maximum at p_T~1.5 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).

Electrons from charm and bottom with PHENIX VTX

Phys. Rev. C 93 (2016) 034904



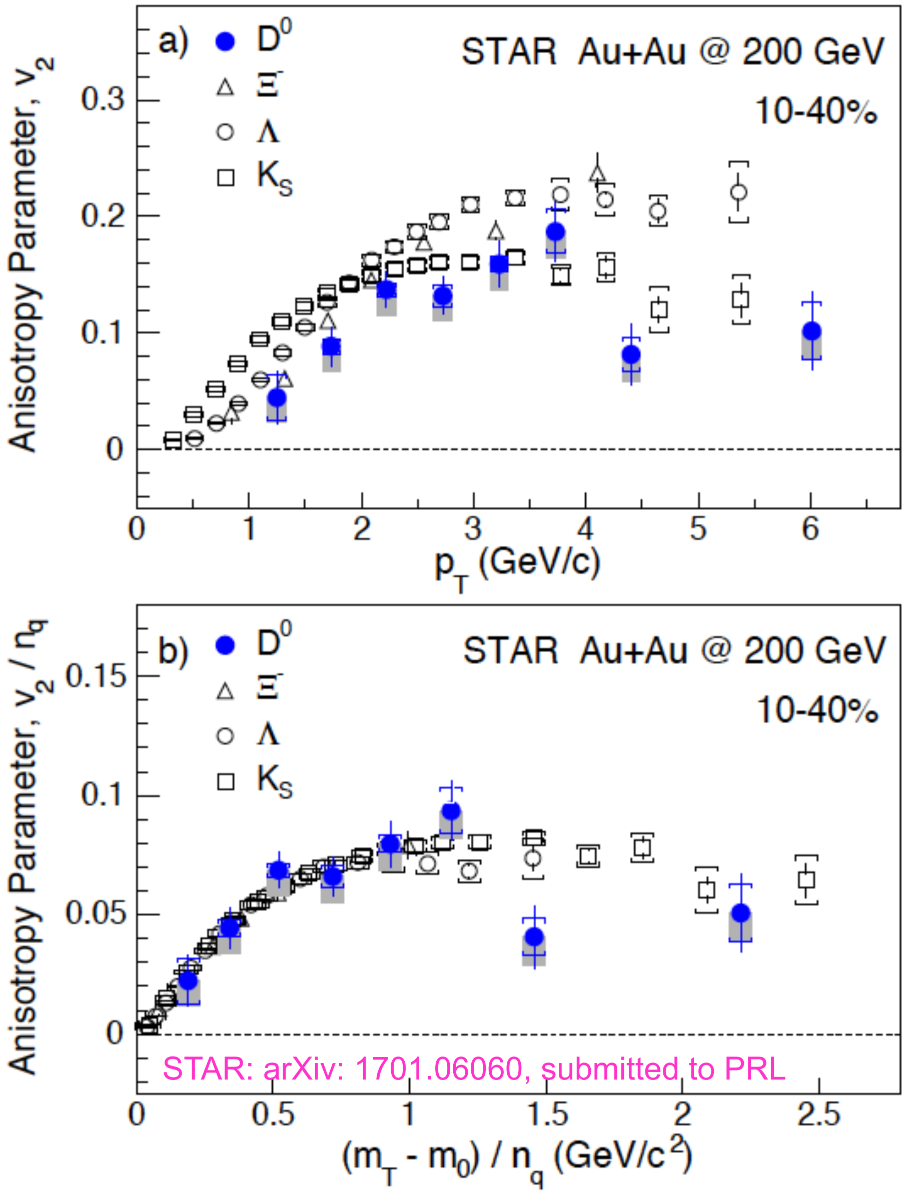


separate charm from beauty in semileptonic decays

first measurement from 2011

Much more data from Runs 2014-2016.

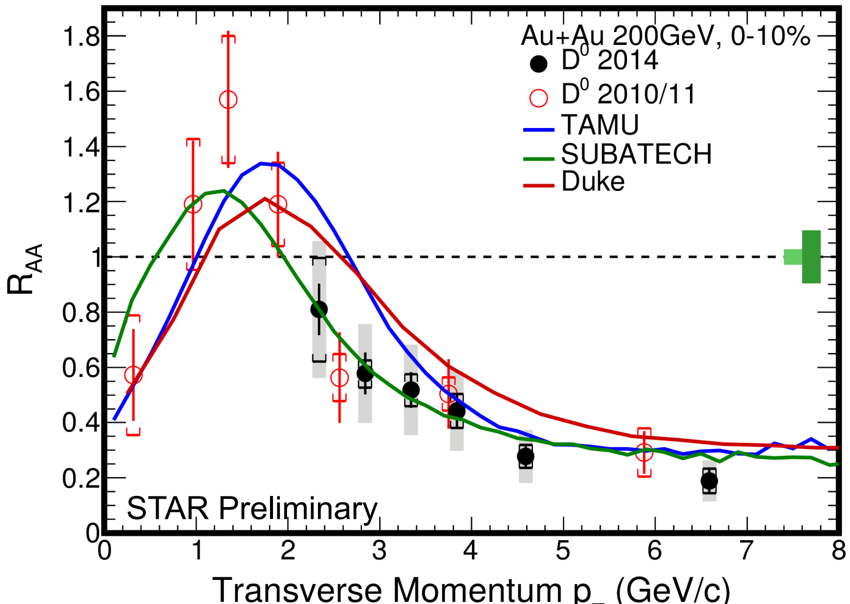
Open charm with the HFT

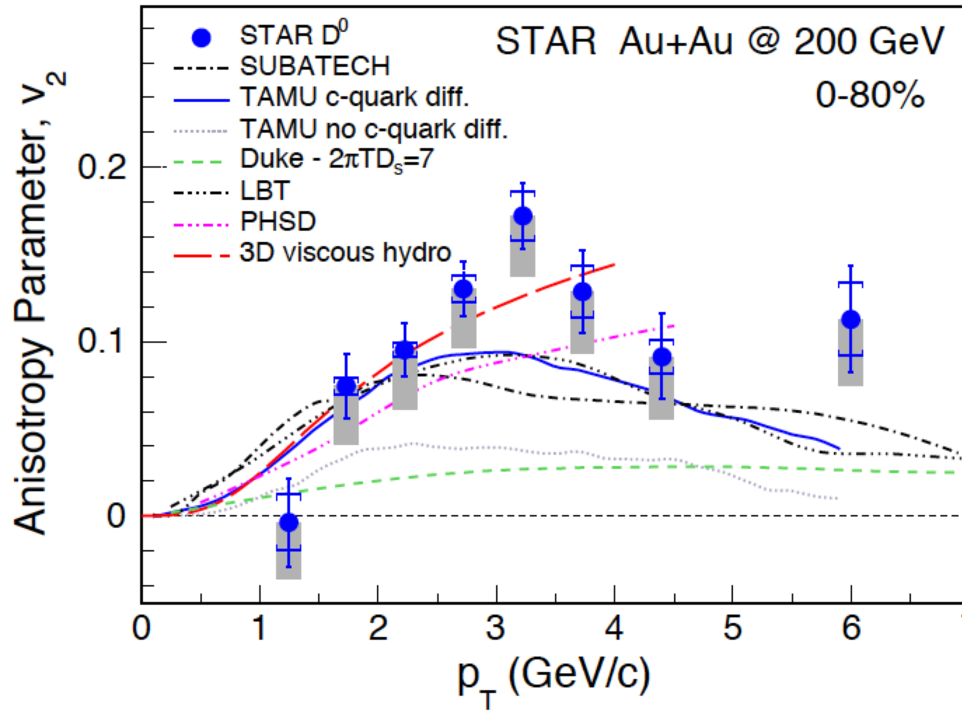


Charm quark flows, interacts with medium strongly.

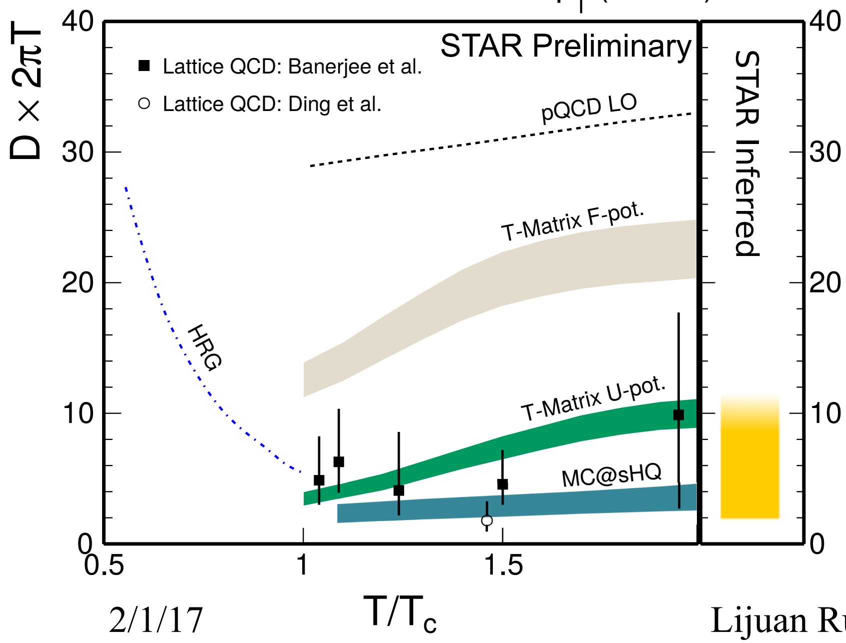
D meson v_2 follows mass ordering at low p_T, follow the kET scaling. Indicate that charm quark reaches local thermalization in the medium.

Open charm with the HFT





STAR: arXiv: 1701.06060, submitted to PRL



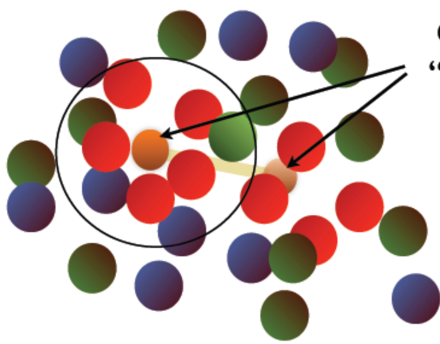
Models with charm diffusion coefficient ($D\times 2\pi T$) of 2-12 describe STAR R_{AA} and v_2 data.

Quarkonium as a QGP indicator

color screening

Matsui-Satz: screening the potential

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

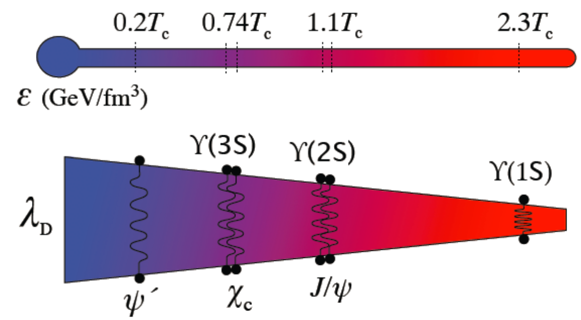


Q and $\bar{Q}$ cannot "see" each other
$r_D < r_{Q\bar{Q}}$

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 ϒ(1S), ϒ(2S), ϒ(3S).
provide distance scales to probe QGP:
different dissociation temperatures.

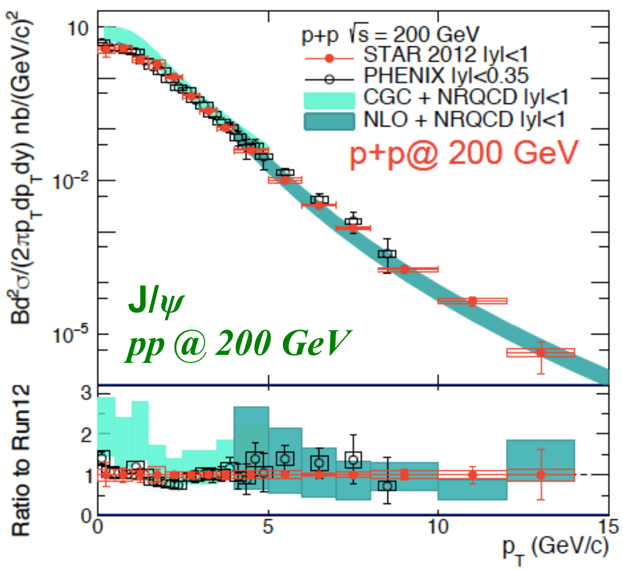
A+A collisions: **color screening, gluon dissociation, recombination**; **jet quenching, formation time; cold nuclear matter effect requires measurements:**

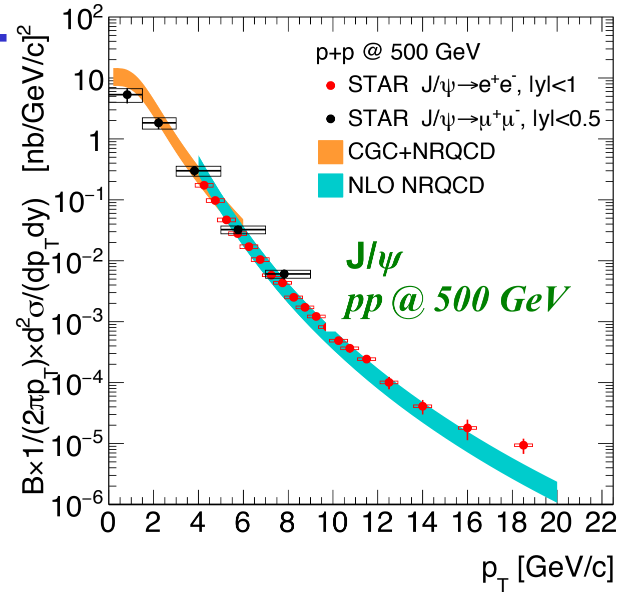
1) energy, collision system size, centrality, rapidity, and p_T dependences in heavy ion collisions

2) understand p+p, p+A production mechanisms

Charmonium cross-section in pp

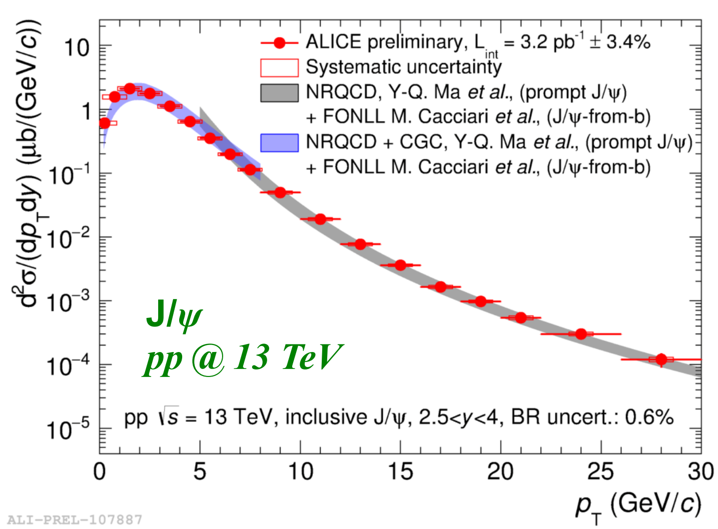
STAR

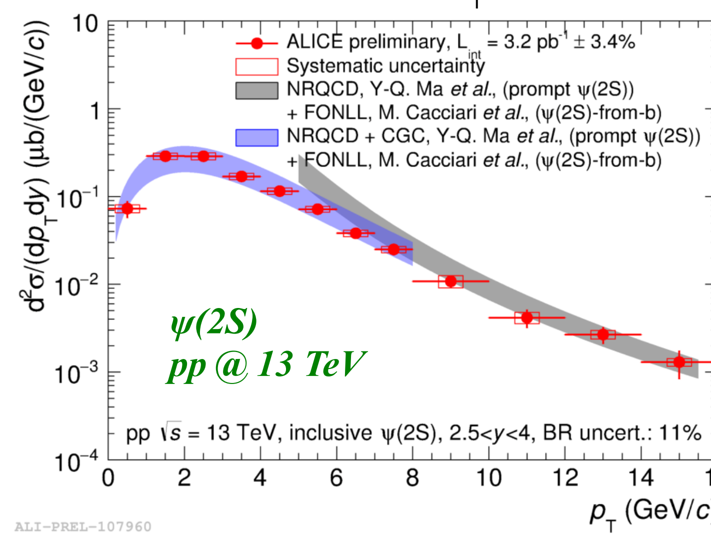




Theory:
PRL 106 (2011) 042002
PRL 113 (2014) 192301
JHEP 1210 (2012) 137

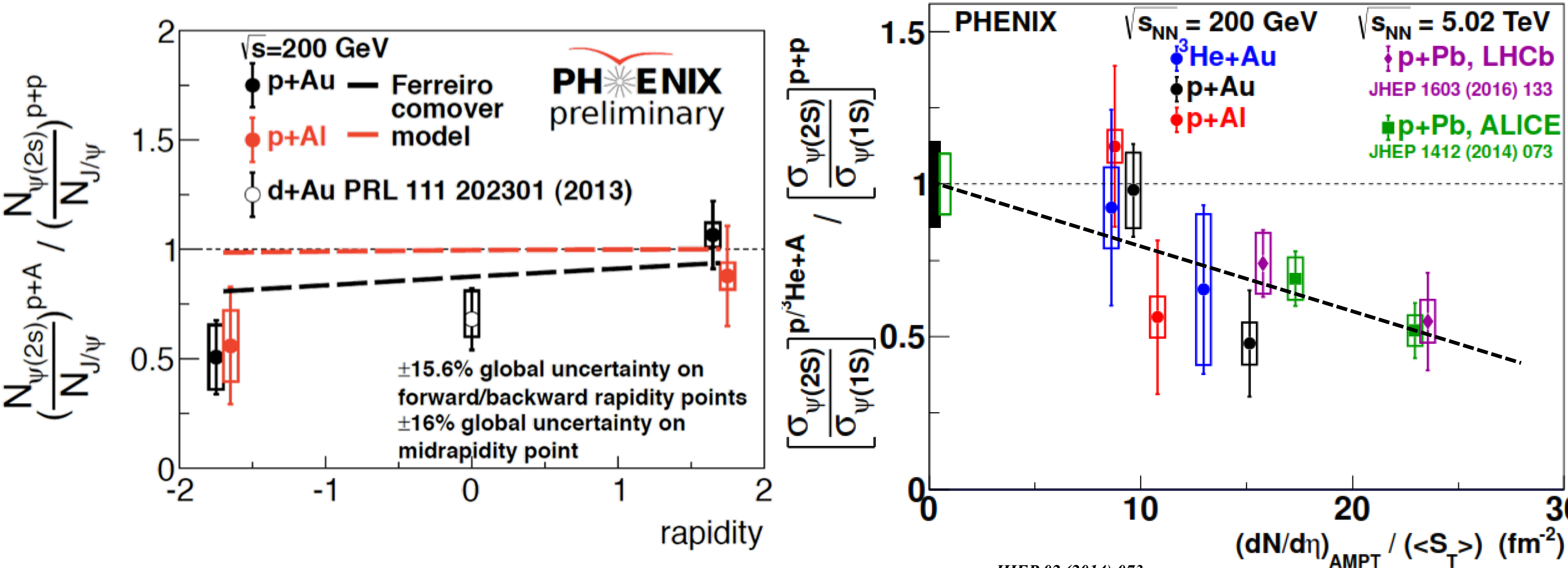
ALICE





- Good understanding of charmonium cross section for $\sqrt{s}$ = 0.2 – 13 TeV

$R_{p(d)A}[\psi(2S)]$ versus $R_{p(d)A}(J/\psi)$



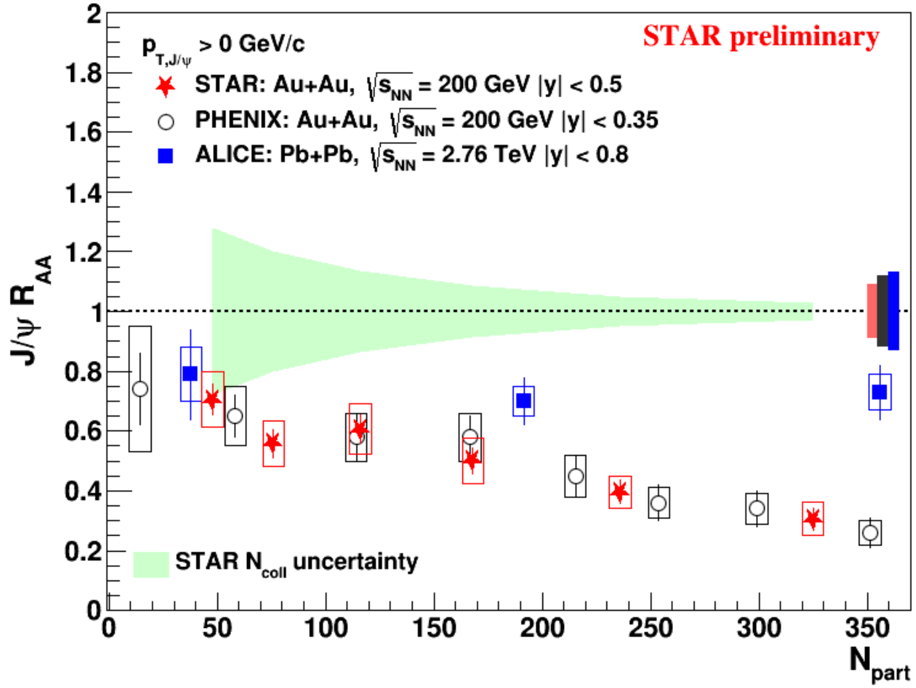
JHEP 02 (2014) 073
JHEP 03 (2016) 133
PRL 111 (2013) 202301

RHIC: $R_{p(d)A}[\psi(2S)] < R_{p(d)A}(J/\psi)$ on the A going direction and at midrapidity

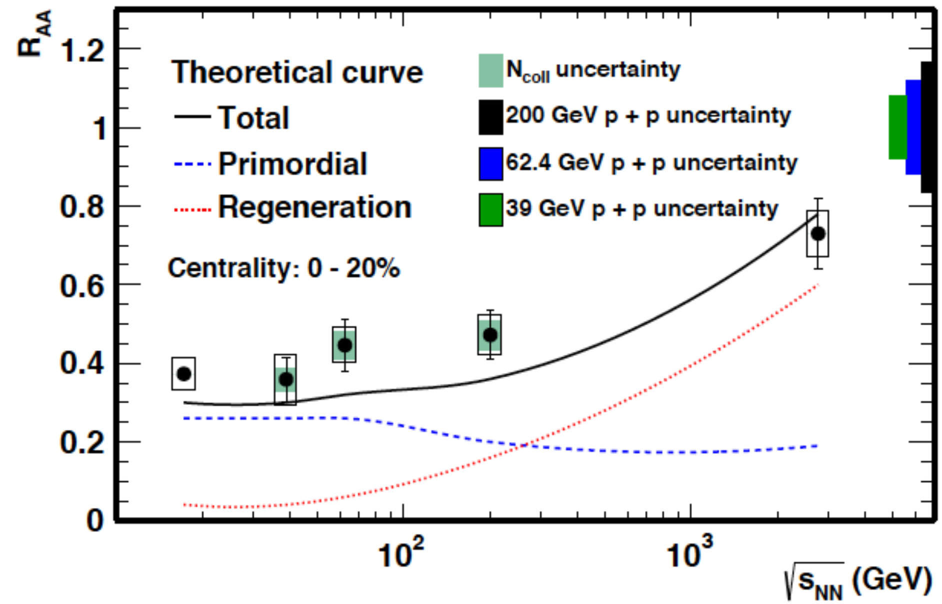
LHC: $R_{pA}[\psi(2S)] < R_{pA}(J/\psi)$ on the A and p going direction and at mid rapidity

Consistent with co-mover suppression picture.

J/ψ suppression pattern



STAR Collaboration, SQM2016



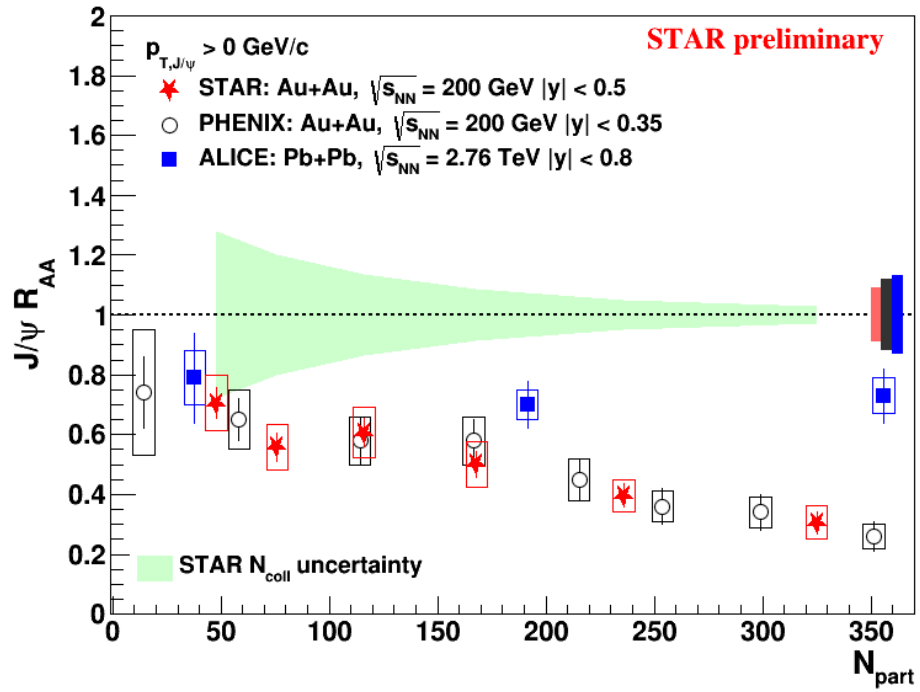
STAR Collaboration, 1607.07517

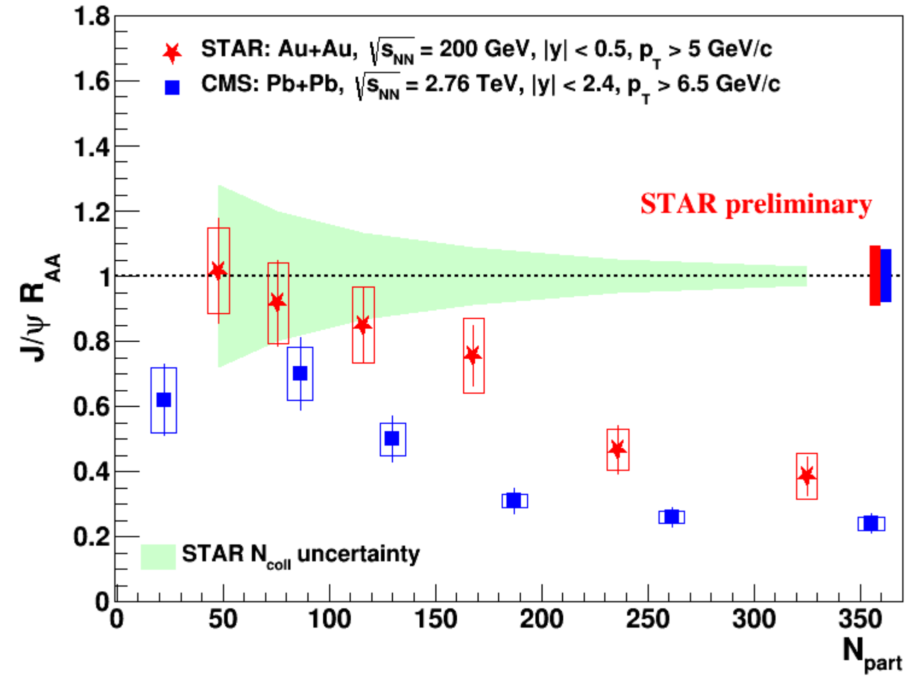
J/ψ through its dileptonic decay: indicator of deconfinement

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

J/ψ suppression pattern





STAR Collaboration, SQM2016

J/ψ through its dileptonic decay: indicator of deconfinement

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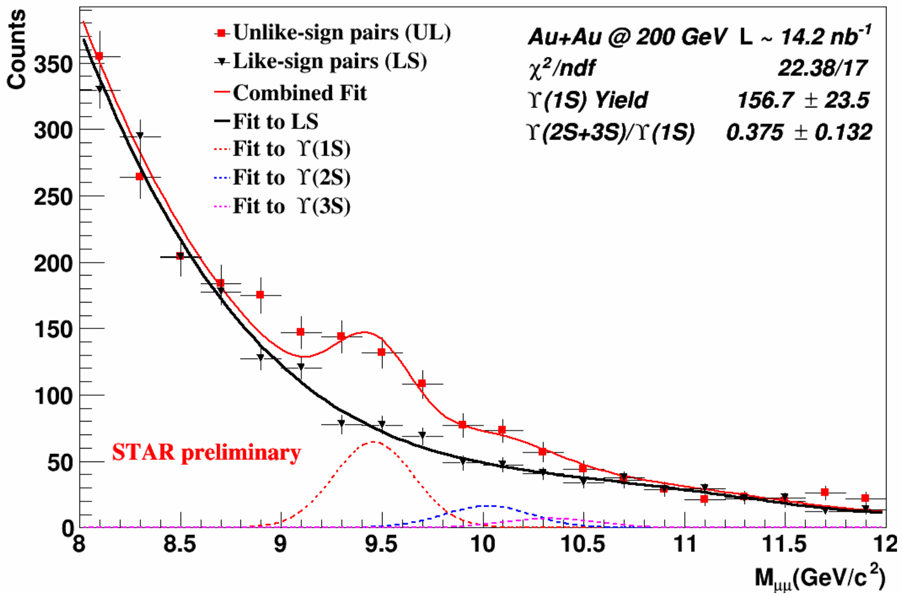
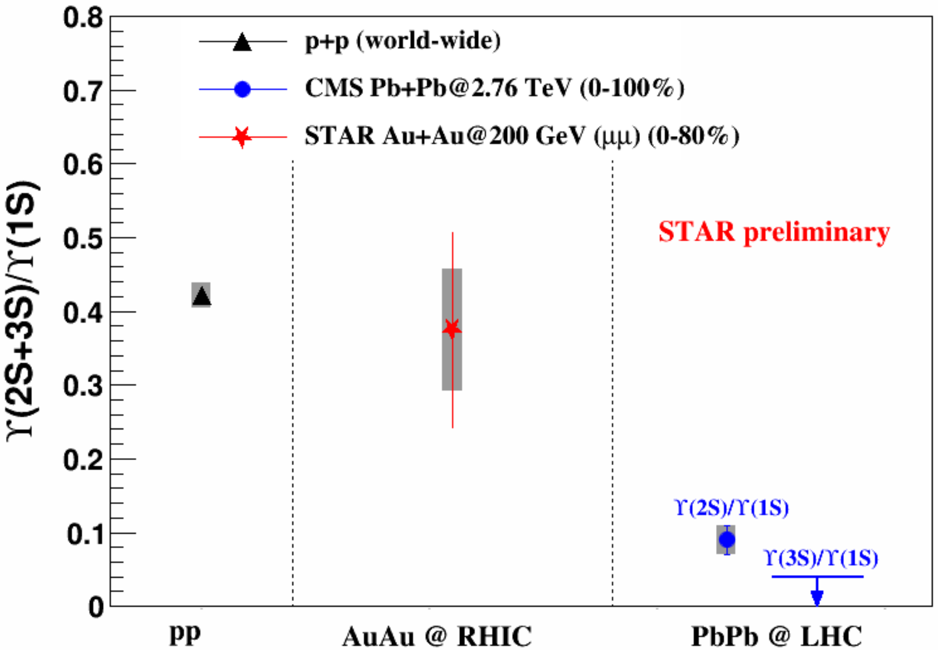
Interplay between color screening and recombination: describe the J/ψ suppression pattern and flow measurements

Different ϒ states ratio

STAR Collaboration, SQM2016





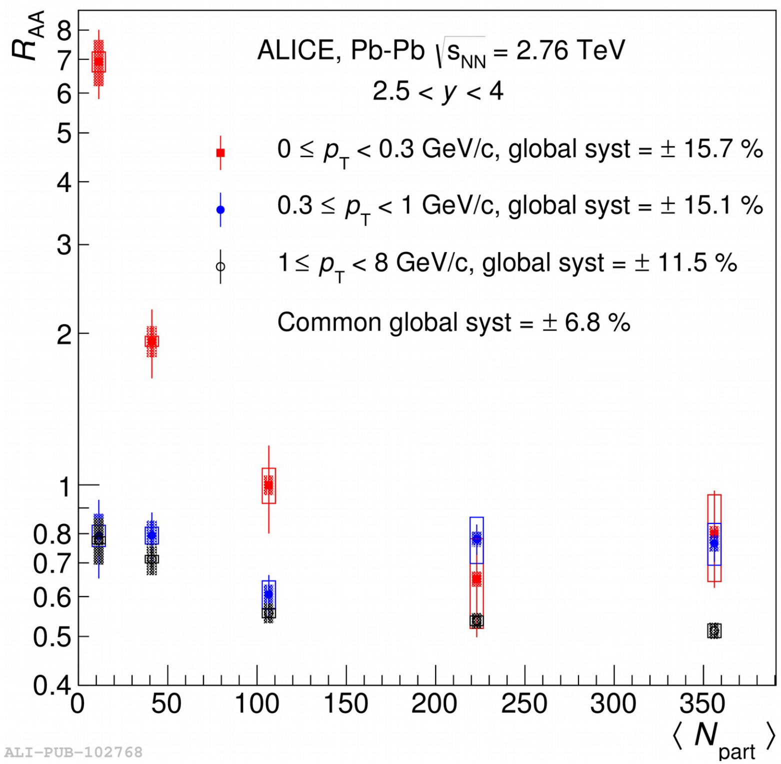
0.28, 0.56, 0.78 fm for ϒ(1S), ϒ(2S), ϒ(3S).

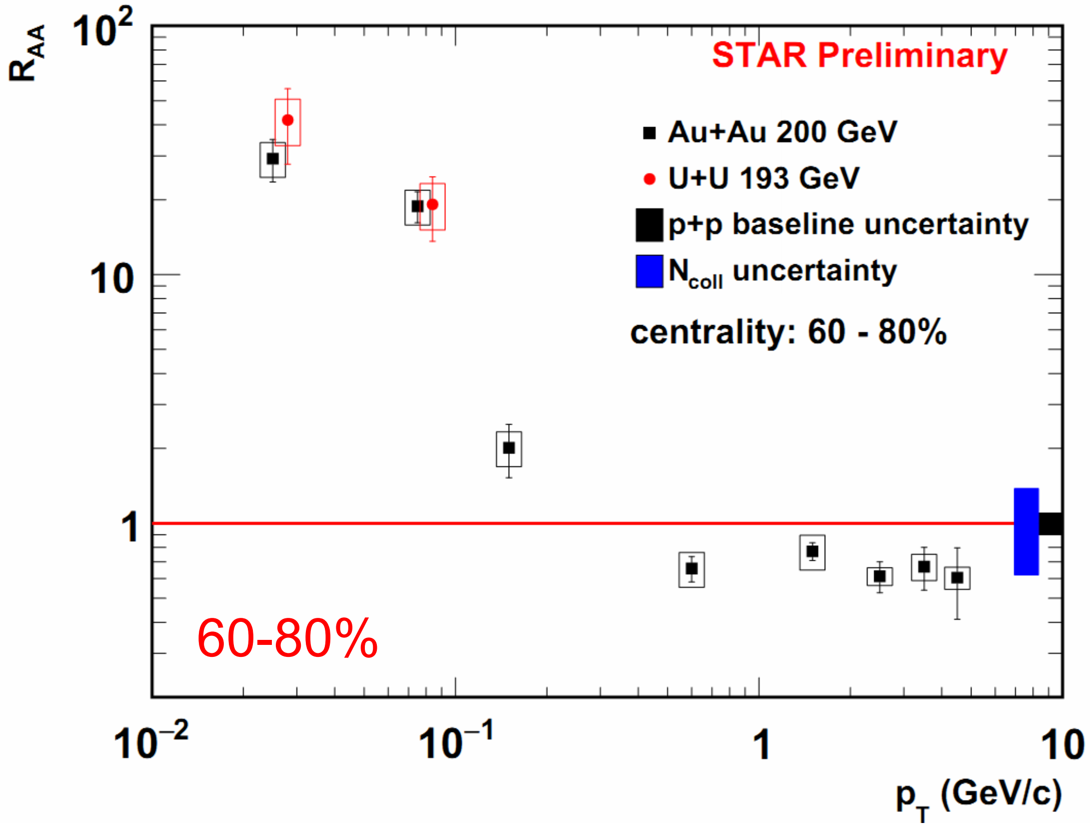
Negligible contribution from b and bbar recombination at RHIC

A better probe to study color-screening feature of QGP.

A hint of ϒ(2S+3S) less suppressed at RHIC than at LHC!

Very low pt J/ψ: largely enhanced!

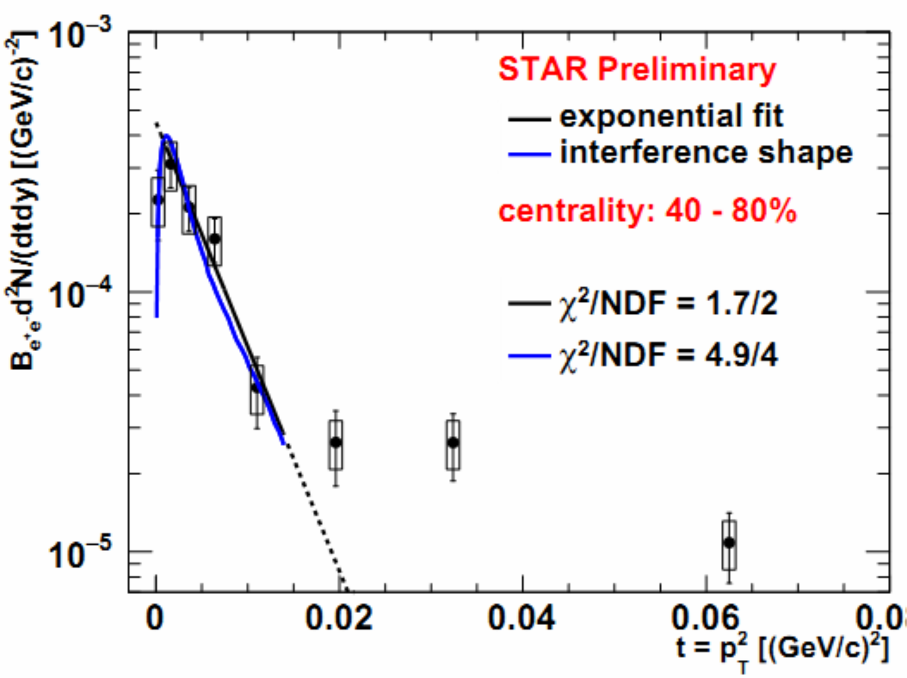


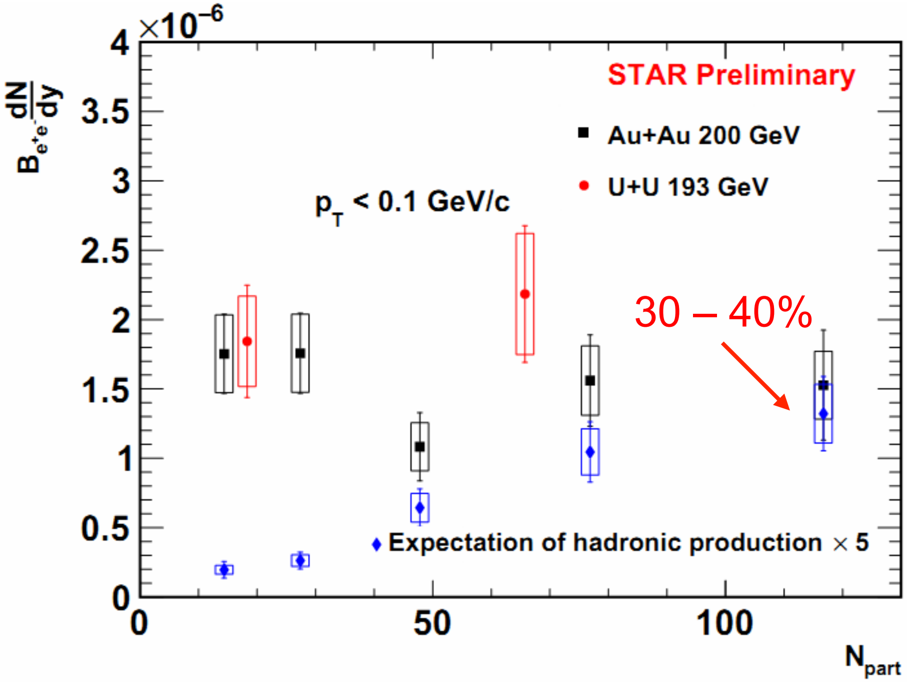


Large enhancement of J/ψ yield observed in peripheral A+A collisions!

Prominent centrality and p_T dependence.

J/ψ yield :$t=p_T^2$ and centrality dependence



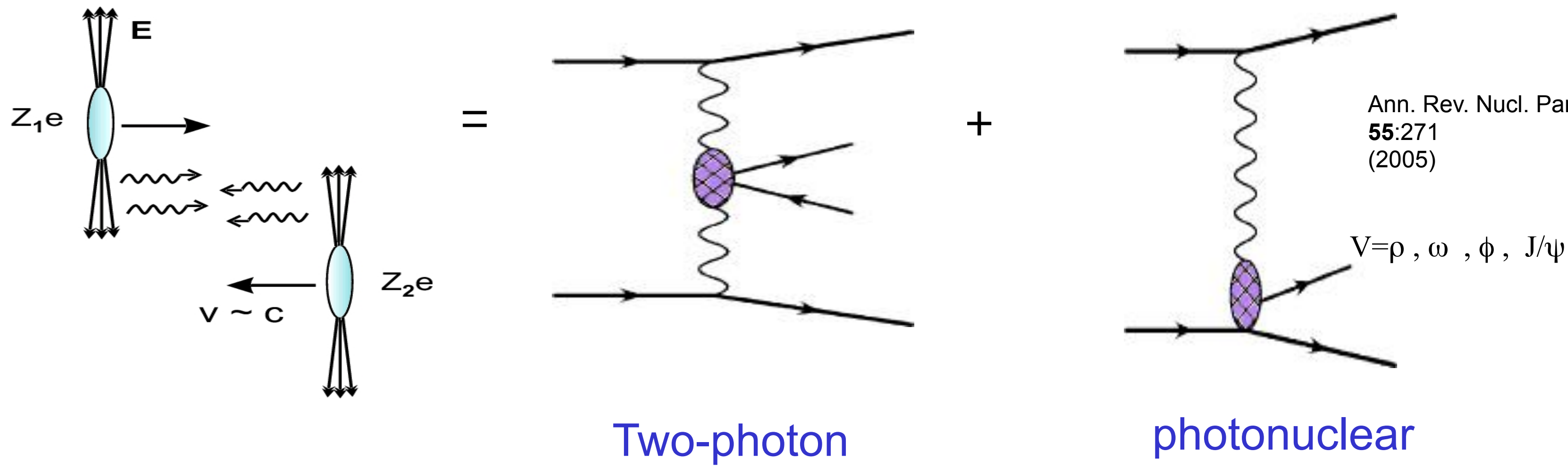


Slope parameter consistent with the size of the Au nucleus. Interference structure observed. Coherent photon-nucleus interactions?

No significant centrality dependence of the excess yield! Interplay between photon flux cancellation in the overlapped area and the distance of the spectators of the two nuclei?

Simulations ongoing and need theoretical inputs!

Coherent photonuclear and two-photon processes



Ann. Rev. Nucl. Part. Sci. **55**:271 (2005)

Studied extensively in ultra-peripheral collisions

How is **the J/ψ from coherent photonuclear process affected by hot and cold QCD matter! Why do we still be able to observe** these J/ψs**?**
A new tool to study enriched multi-body dynamics on the strong QCD force!

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 and the v_2 follows the mass ordering and kET scaling.

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;

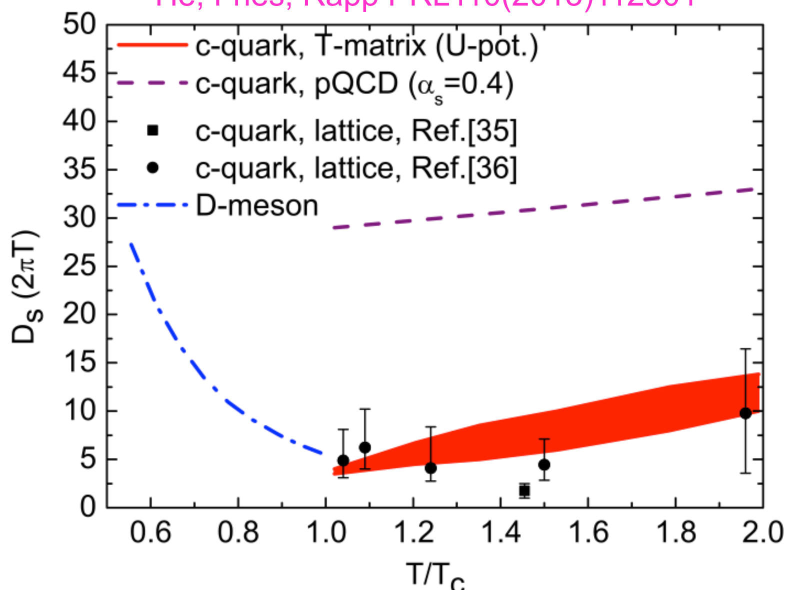
Sequential melting for Υ(1S, 2S, 3S) at LHC.

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

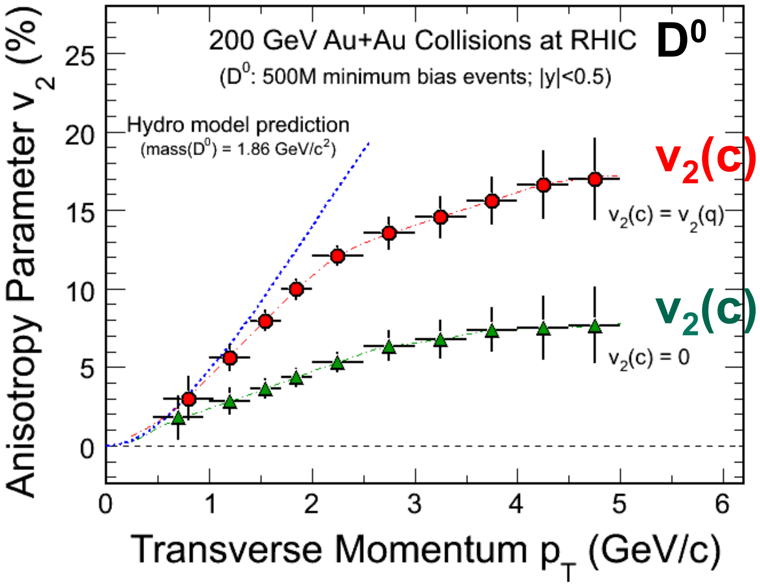
Questions: How does heavy flavor diffusion coefficient depend on temperature?

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

He, Fries, Rapp PRL110(2013)112301

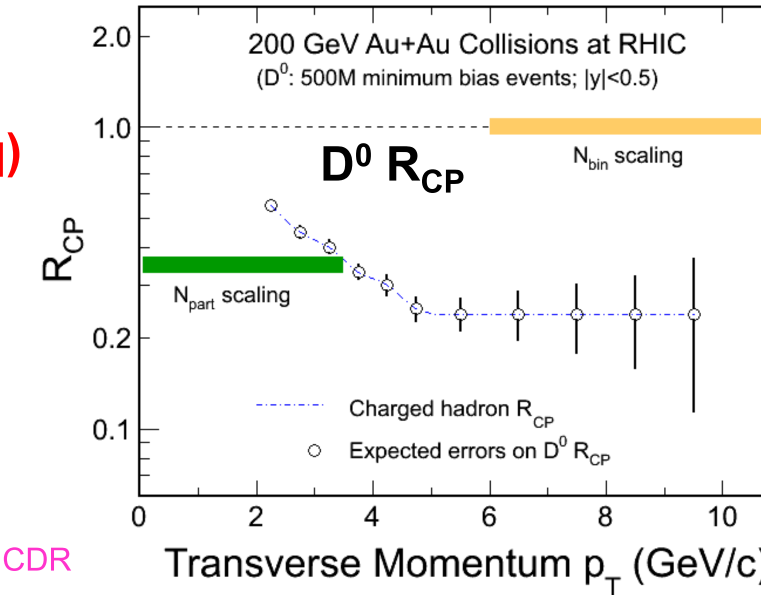


The HFT – study heavy flavor dynamics



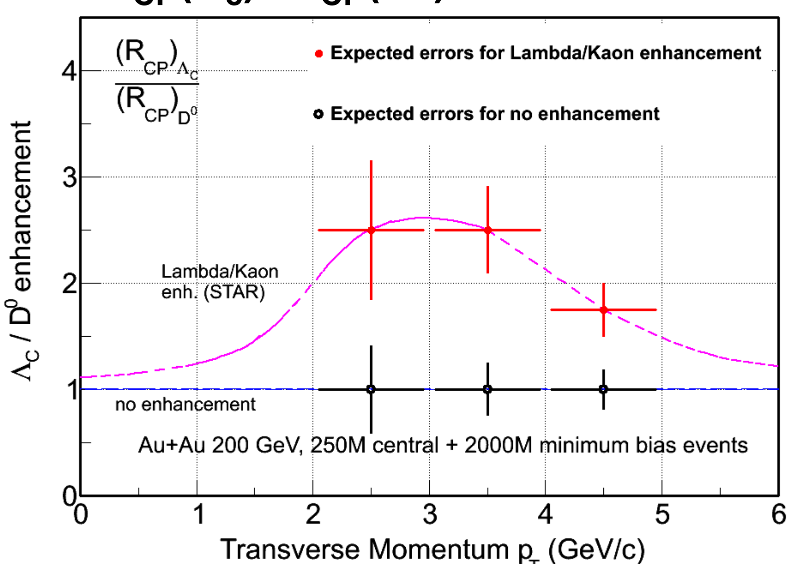
$v_2(c)=v2(q)$

$v_2(c)=0$



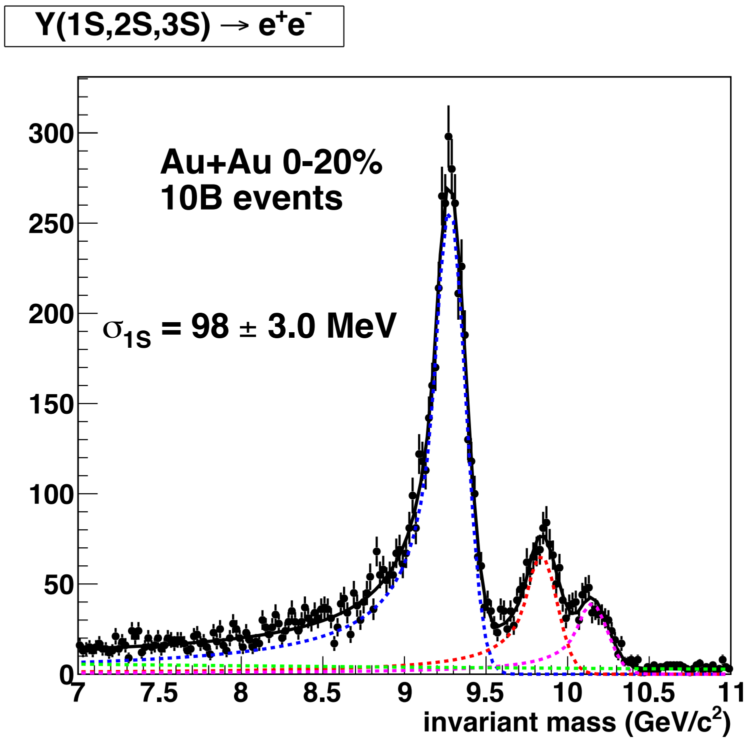
HFT CDR

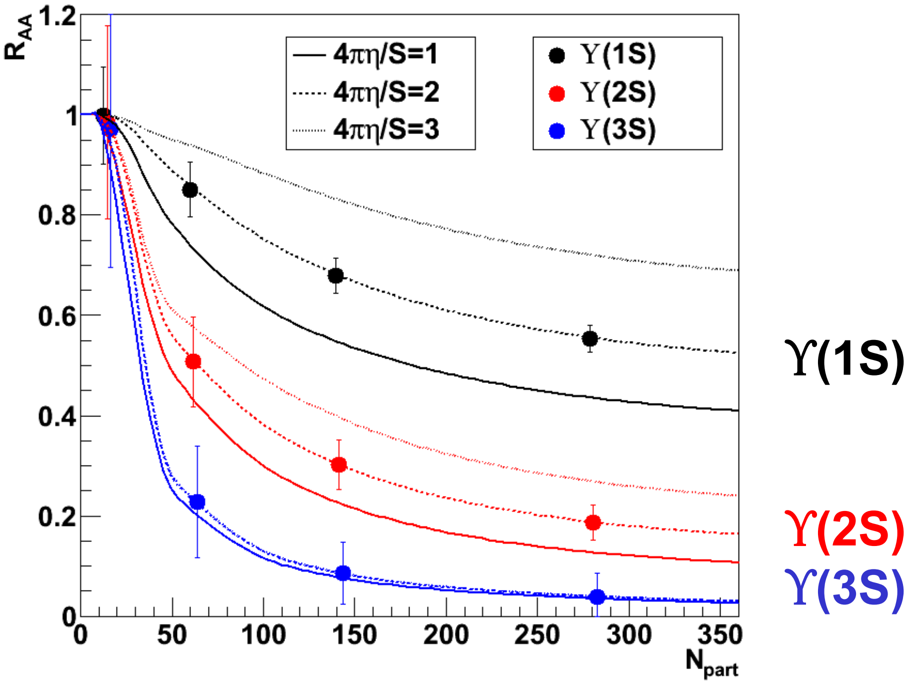
$R_{CP}(\Lambda_c)/R_{CP}(D^0)$



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.

sPHENIX: Quarkonium measurements for 2020+





sPHENIX will provide more precise measurements.

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.

Open questions on quarkonia

Turn qualitative features into quantitative understanding!

- Understand our p+p reference: CS versus CO contributions et al.
- Knowing the p+p production mechanism is crucial in order to obtain a complete picture in heavy ion collisions: for example, a colored object will lose energy when traversing the medium. Has this effect been considered in theoretical calculations?

- Dynamic modeling is critical!

Will the coherent photo-nuclear quarkonium production be helpful to probe the in-medium QCD force?