CHARM2018:
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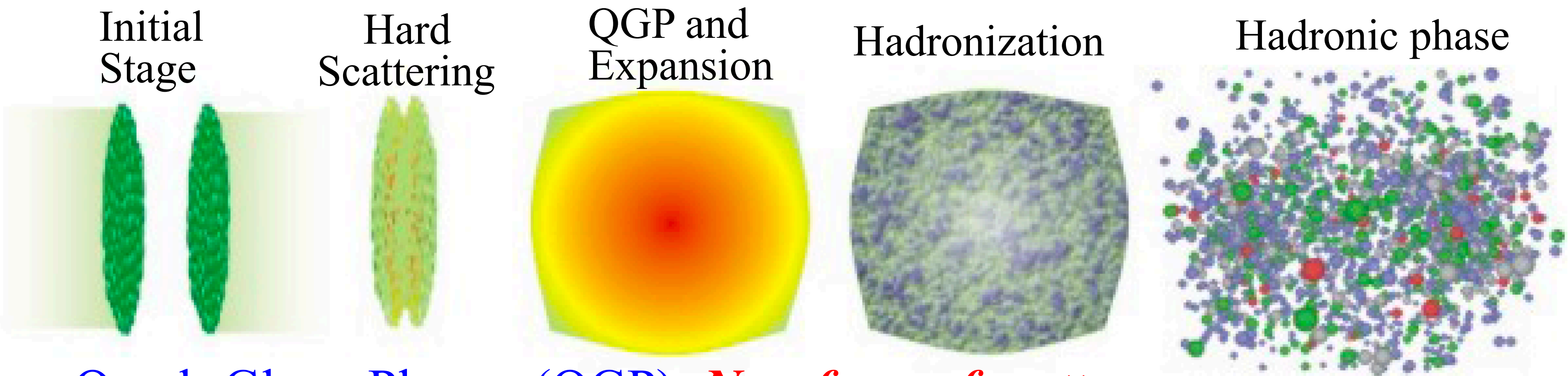
Experimental Review of Quarkonium Production in Heavy-ion (AA) Collisions

Zebo Tang （唐泽波）
Department of Modern Physics,
University of Science and Technology of China (USTC)
State Key Laboratory of Particle Detection and Electronics

Introduction to Heavy-ion Collisions



Quark-Gluon Plasma (QGP): ***New form of matter***

- Quark and gluon degrees of freedom (deconfinement)
- Strong coupling (perfect liquid, emergent properties)

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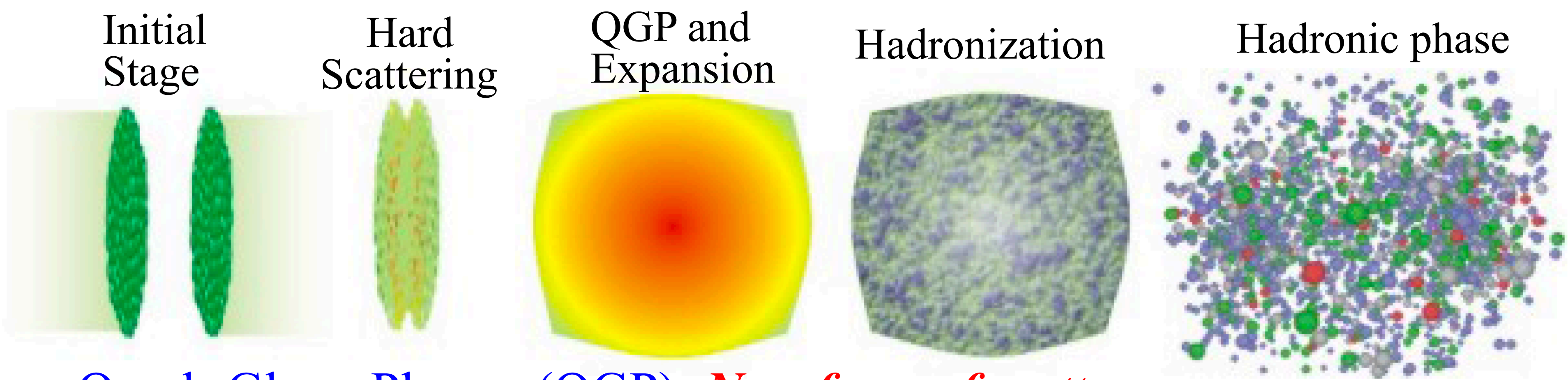
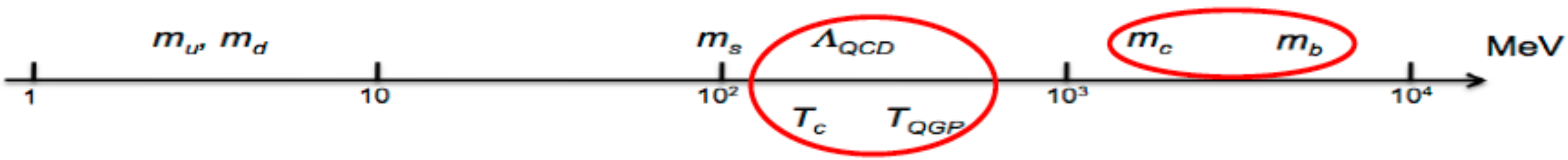


Quark-Gluon Plasma (QGP): ***New form of matter***

- Quark and gluon degrees of freedom (deconfinement)
- Strong coupling (perfect liquid, emergent properties)

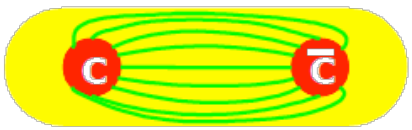
Heavy quark: ***Penetrating probe of QGP***

- Dominantly produced in the early stage
- Experience the whole evolution of QGP

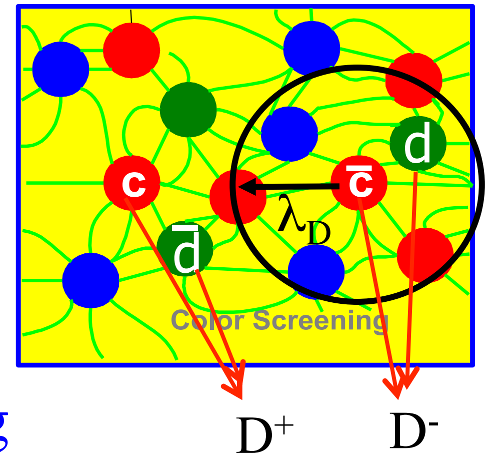


Quarkonium Melting in QGP

In vacuum



In QCD medium



$$\lambda_D \propto \frac{1}{T}$$

Dissociation in QGP due to color-screening

➔ ***Signature of QGP formation*** *T. Matsui, H. Sazt, PLB174, 416 (1986)*

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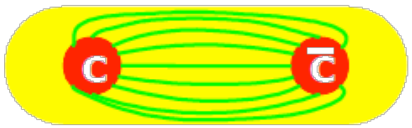

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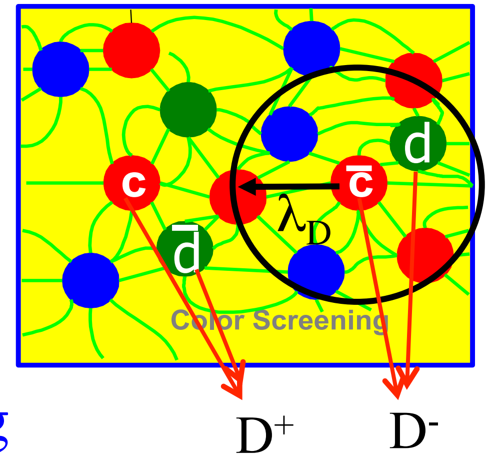

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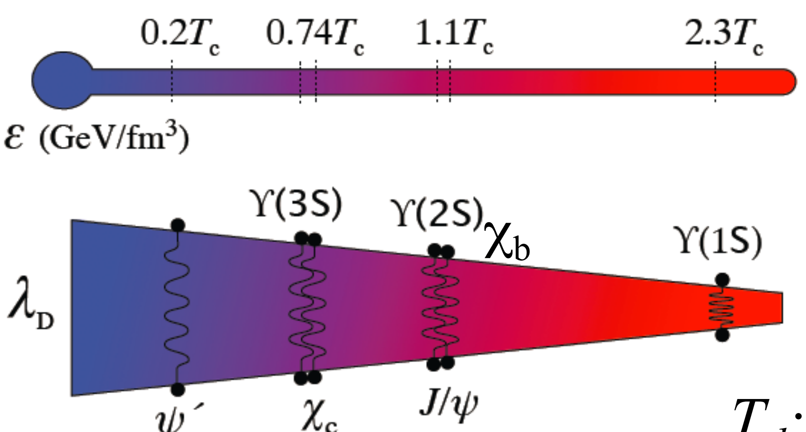


T_d depends on quarkonium size

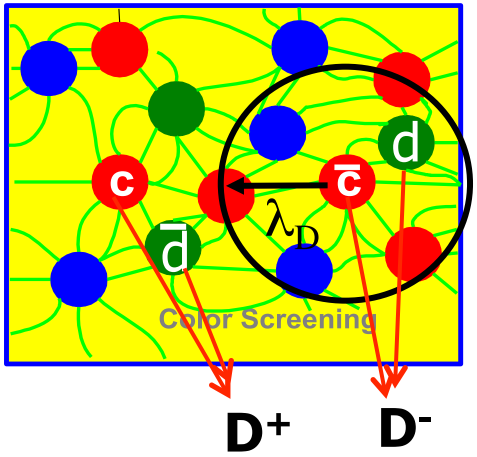
➔ ***Sequential melting***

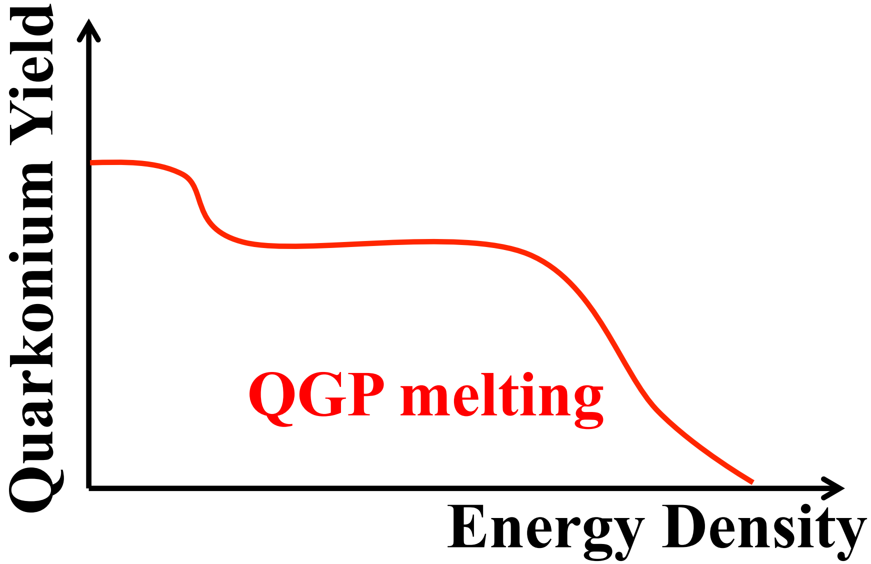
➔ QGP Thermometer

T_d: dissociation temperature

Quarkonium Regeneration in QGP

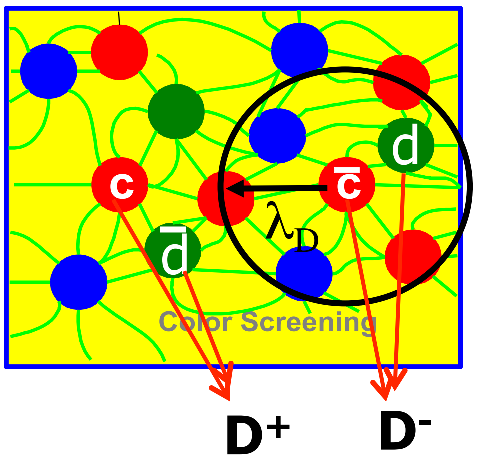
Melting in QGP





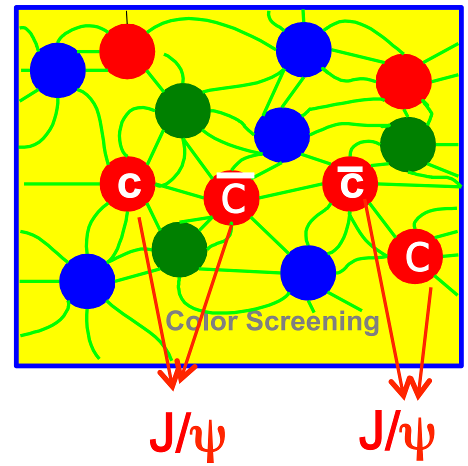
Quarkonium Regeneration in QGP

Melting in QGP



vs.

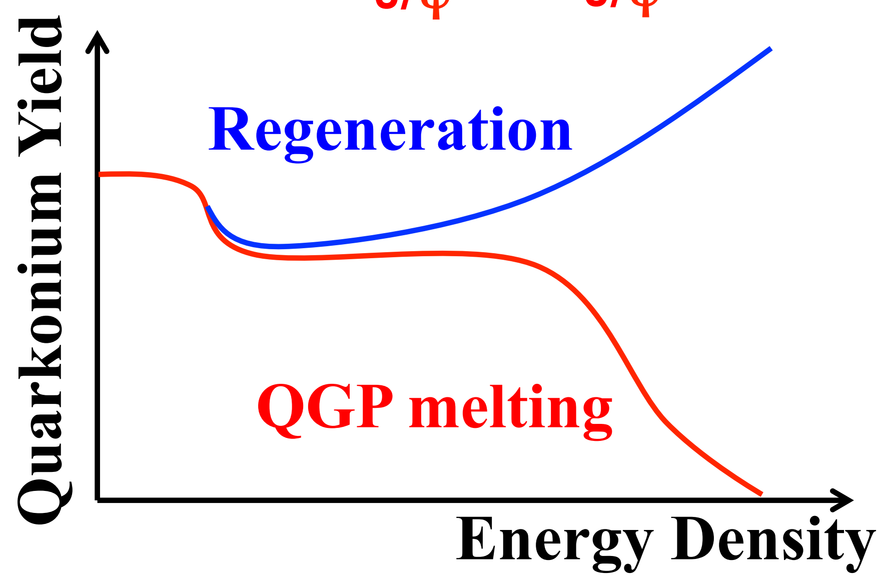
Regeneration in QGP



Regeneration in QGP due to quark coalescence

➔***Deconfinement is a prerequisite***

$$\propto N_{c\bar{c}}^2$$



Quarkonium in Heavy-ion Collisions

Quarkonium production also modified by cold nuclear matter (CNM) effects on top of hot matter effects [see P. Robbe's talk]

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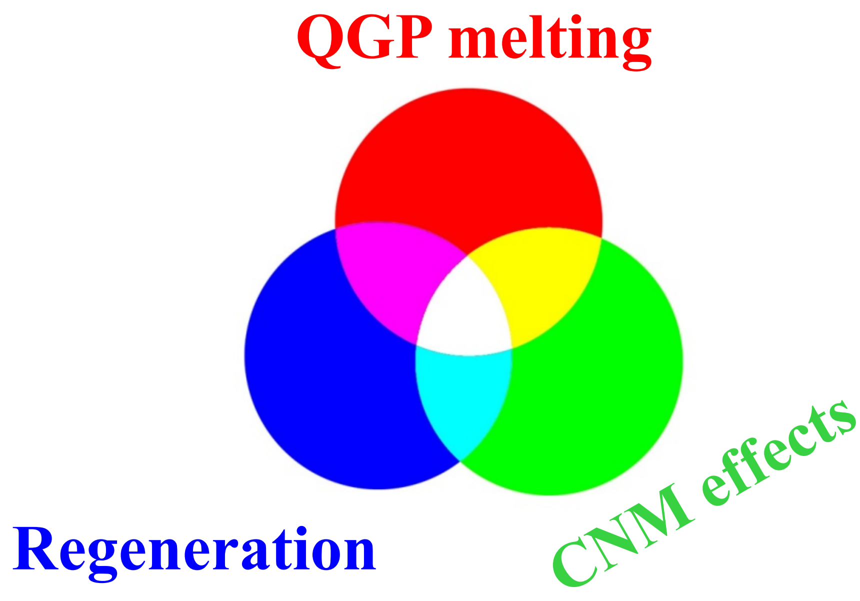
Quarkonium production in heavy-ion collisions are the interplay of color-screening/melting, regeneration and CNM effects

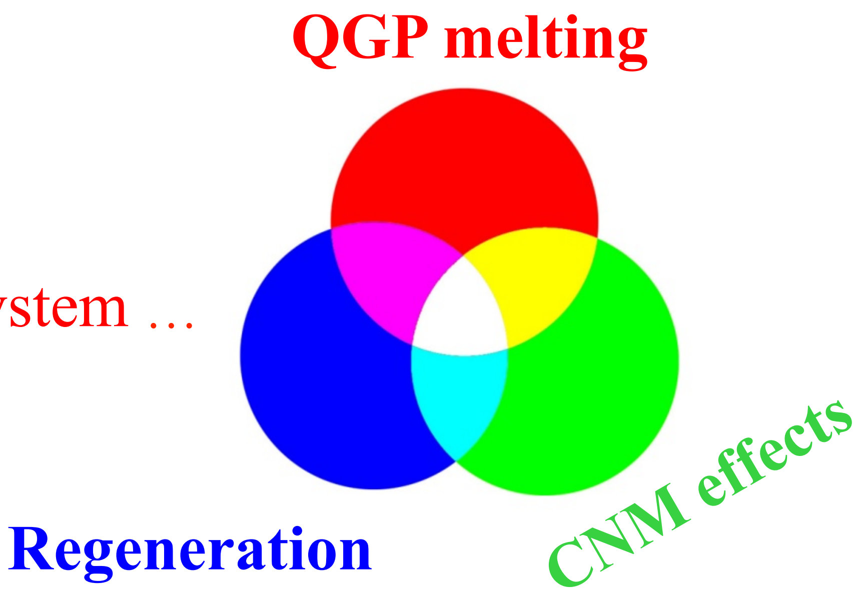


Quarkonium in Heavy-ion Collisions

Quarkonium production also modified by cold nuclear matter (CNM) effects on top of hot matter effects [see P. Robbe's talk]

Quarkonium production in heavy-ion collisions are the interplay of color-screening/melting, regeneration and CNM effects

Each of the effect has different
species, p_T, rapidity,
collision centrality, energy, system …
dependence



Observable: Nucl. Modification Factor R_{AA}

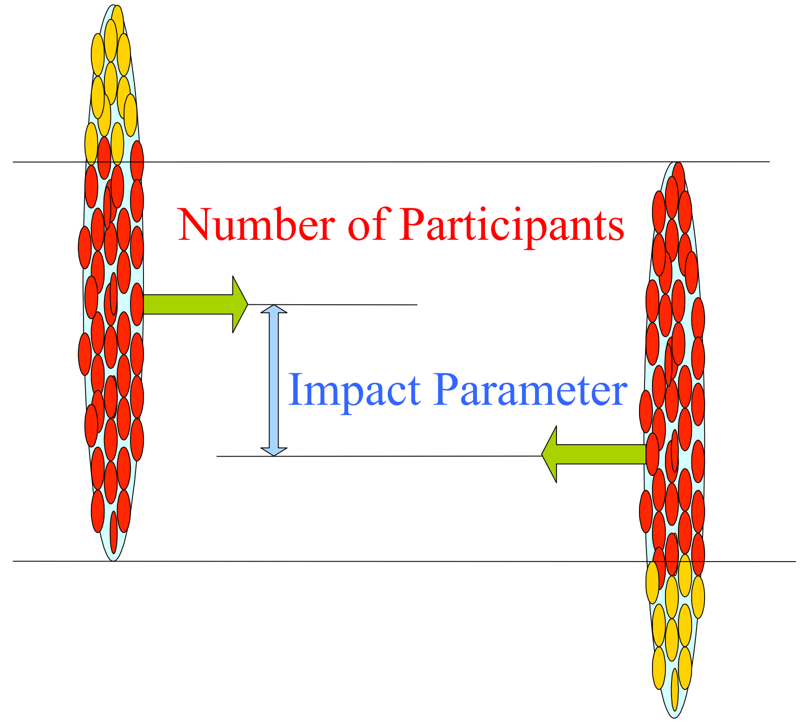
$$R_{AA} = \frac{dN^{AA}_{Q\bar{Q}}}{N_{binary} \cdot dN^{pp}_{Q\bar{Q}}} = \frac{dN^{AA}_{Q\bar{Q}}}{N_{bin} \cdot d\sigma^{pp}_{Q\bar{Q}} / \sigma_{pp}}$$

For hard processes:

$R_{AA} = 1$, no suppression

$R_{AA} < 1$, suppression

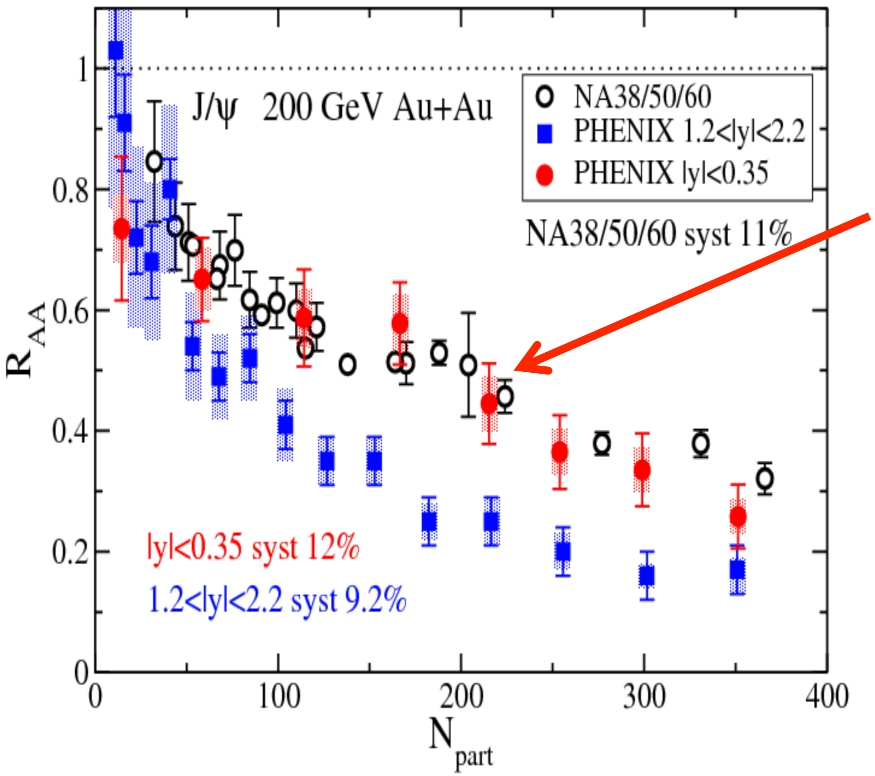
$R_{AA} > 1$, enhancement



N_{part}: No. participants

N_{binary}: No. binary nucleon-nucleon collisions

Inclusive J/ψ Suppression



RHIC: 200 GeV Au+Au collisions

SPS: 17.2GeV Pb+Pb collisions

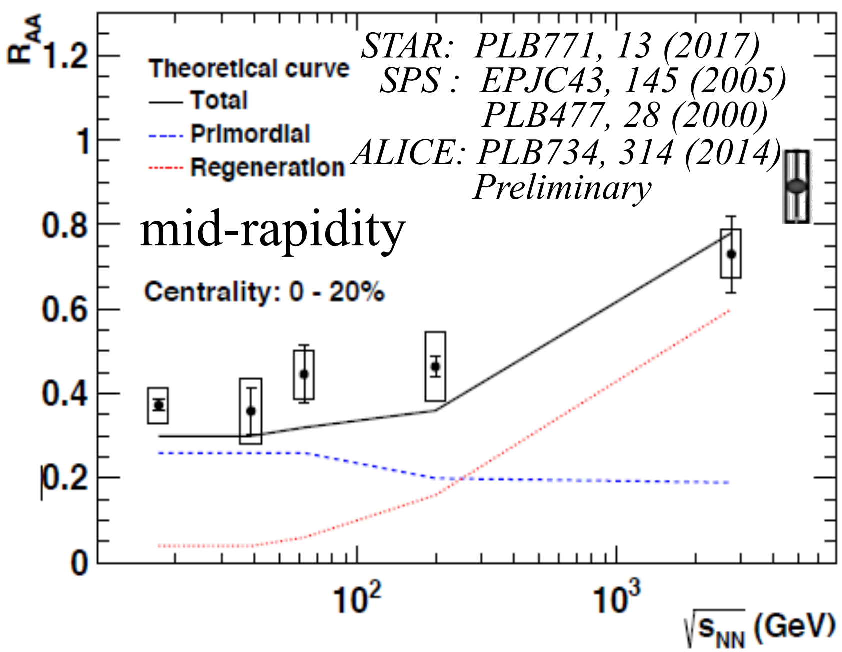
Mid-rapidity:

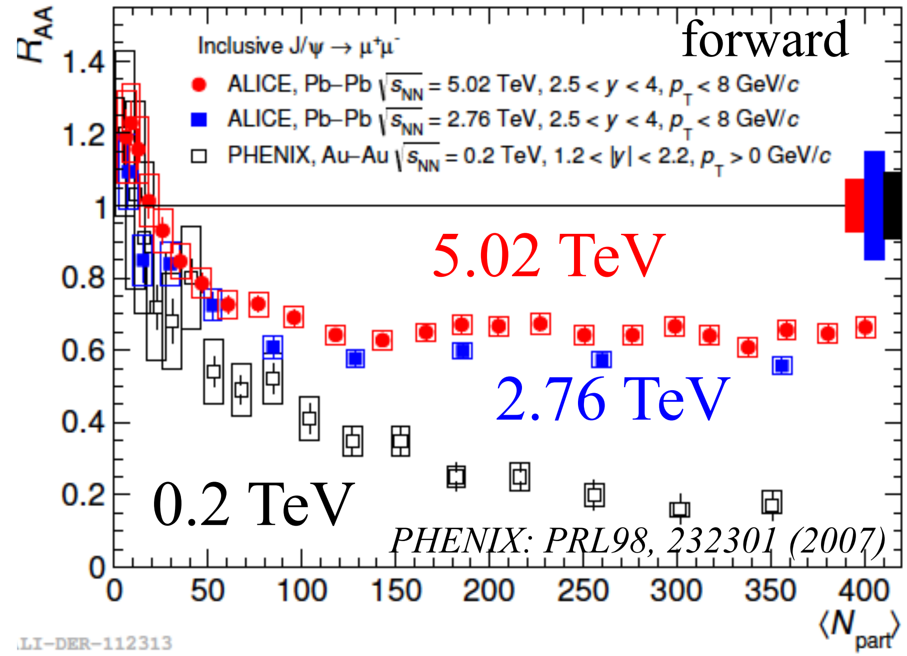
- Strong suppression observed at both SPS and RHIC
  - Increases towards central coll.

- RHIC ~ SPS

  Detailed balance of melting, regeneration and CNM effects

Collisions Energy Dependence





- SPS→RHIC→LHC

  Primordial → Regeneration

- 2.76 TeV → 5.02 TeV

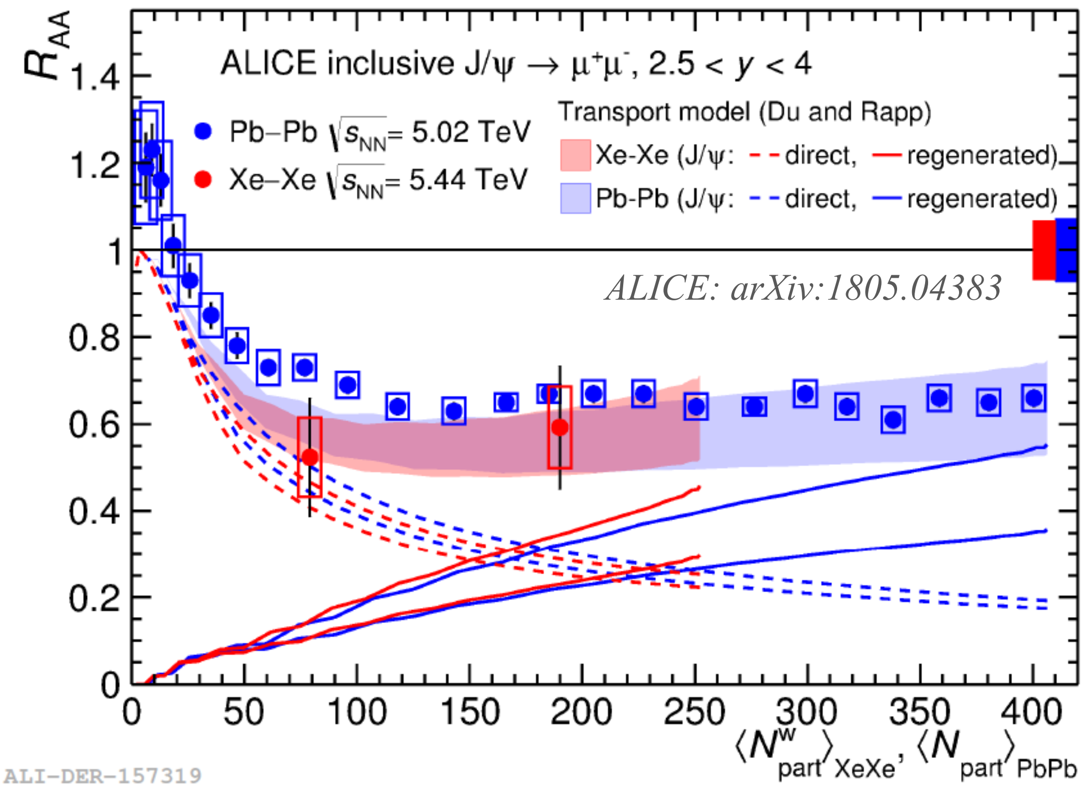
  Flat at N_{part}>100

  Increase is not significant

Can consistently described by Transport models

From a CNM domain to a Regeneration domain

Collision System Dependence

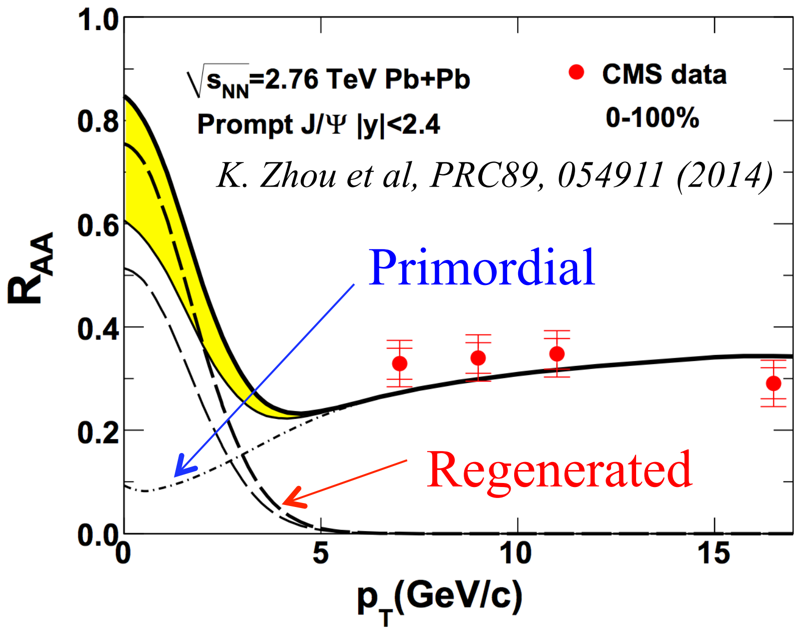


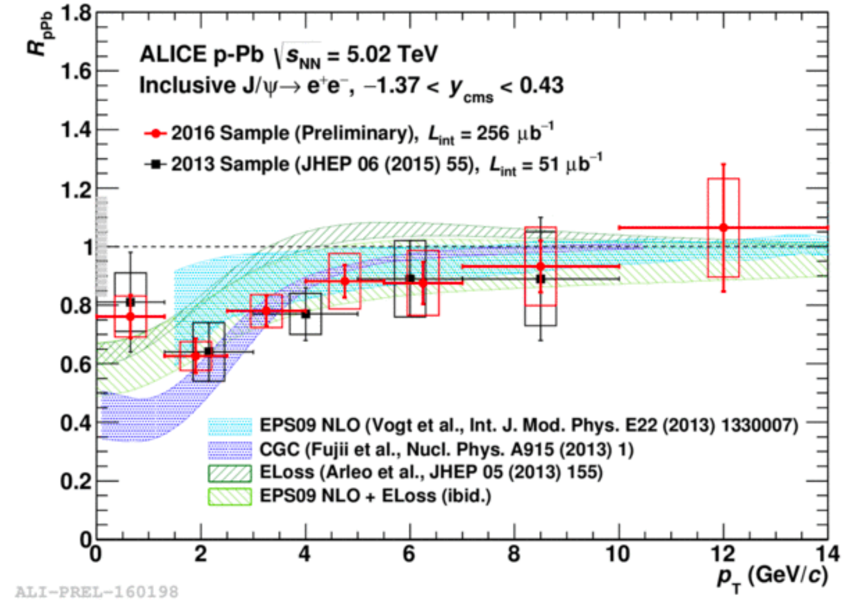
$A_{Xe} = 129$

$A_{Pb} = 208$

- Similar level of suppression seen in Xe+Xe and Pb+Pb
- Similar energy and N_{part} → Similar melting and regeneration
  Detailed balance

High-p_T J/ψ: clean from Rege. and CNM





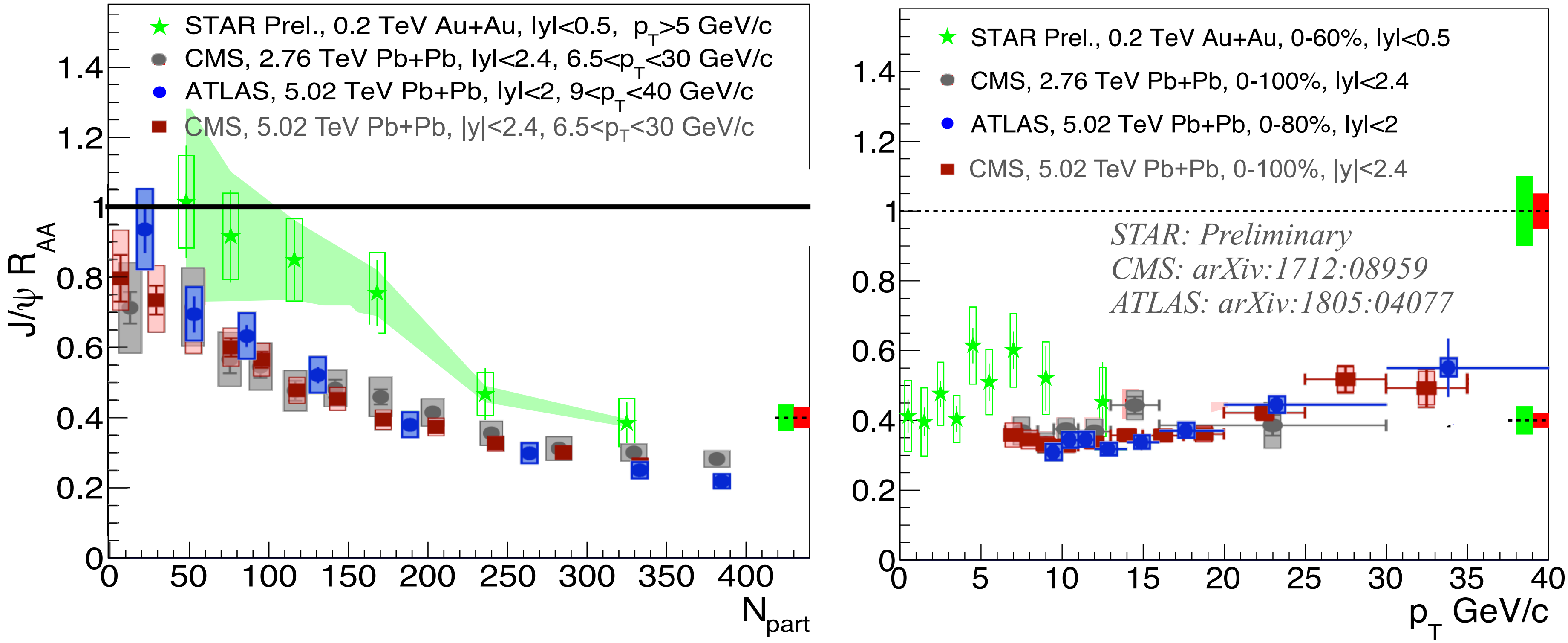
Regeneration contribution decrease quickly with p_T

Negligible at p_T>5 GeV/c

R_{pPb} increase with p_T and consistent with unity at high p_T

CNM effects not important at high-p_T

High-p_T J/ψ suppression



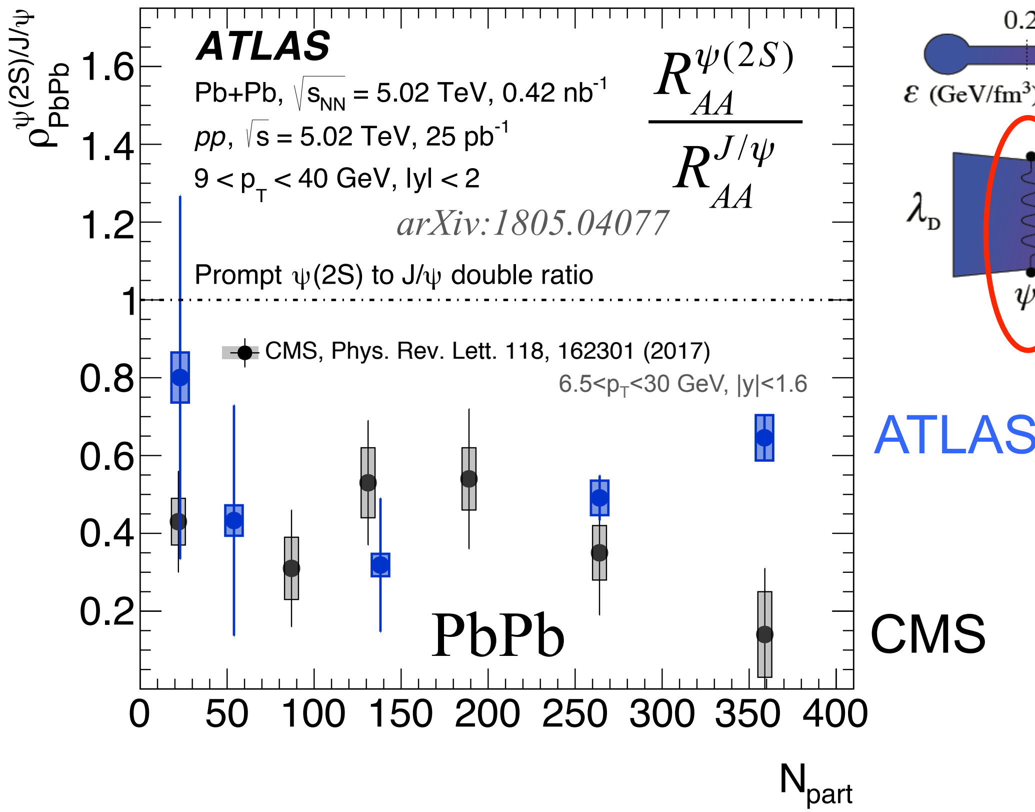
High-p_T J/ψ R_{AA} decreases towards central collisions

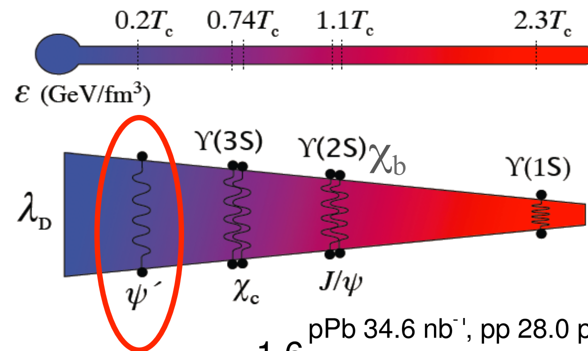
Strong suppression in central collisions

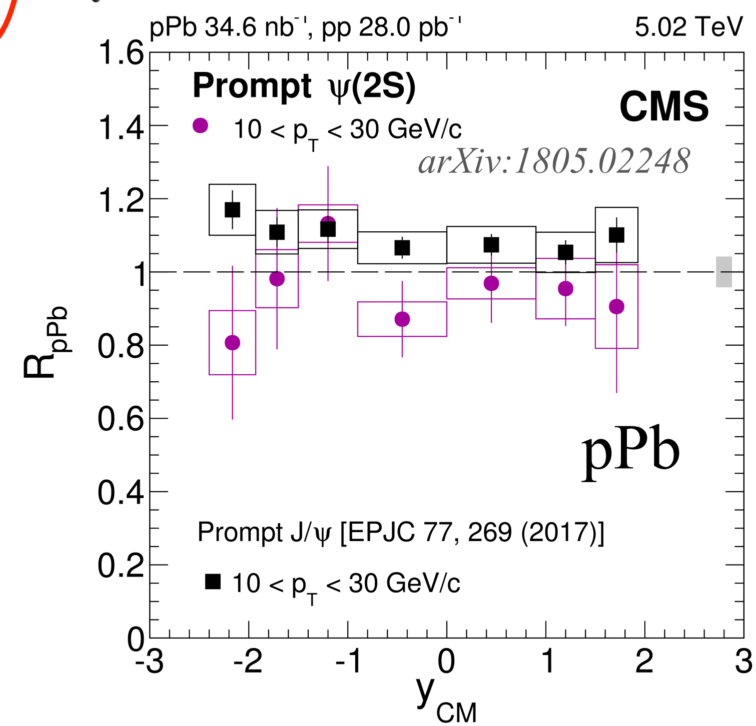
$$R_{AA}^{RHIC/0.2TeV} > R_{AA}^{LHC/2.76TeV} >\sim R_{AA}^{LHC/5.02TeV}$$

QGP Melting in effect

High-p_T ψ(2S) in Pb+Pb vs. p+Pb





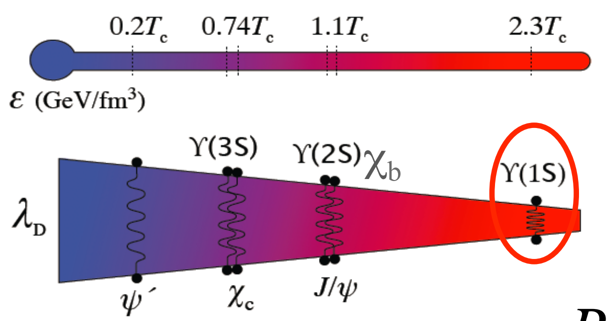


Stronger suppression than J/ψ

Double ratio smaller than in pPb

➔ Sequential suppression

Υ(1S) Suppression in A+A Collisions

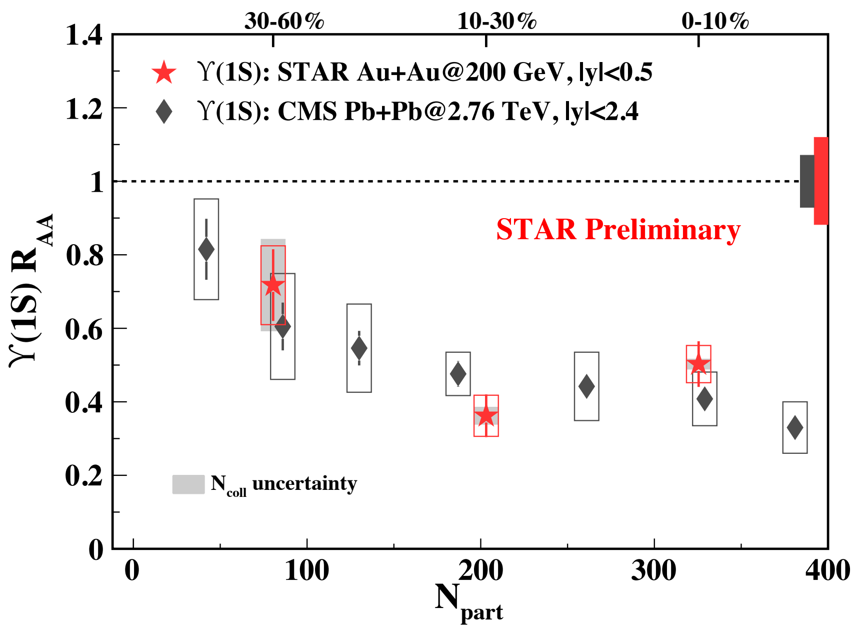


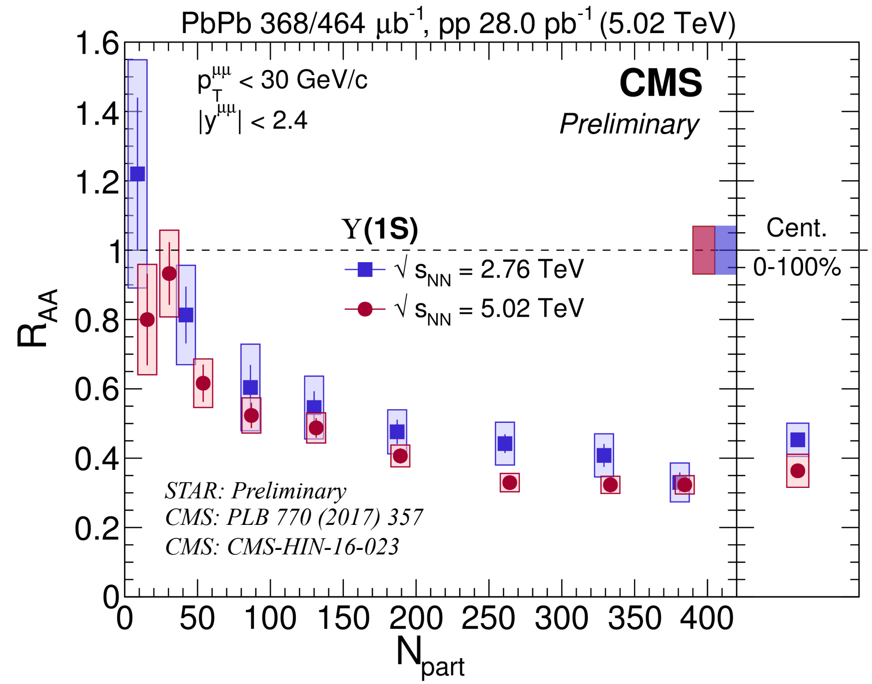
- Υ(1S): smallest size, highest T_d
- ~30% from excited states decay at low-p_T

Strong suppression in central collisions

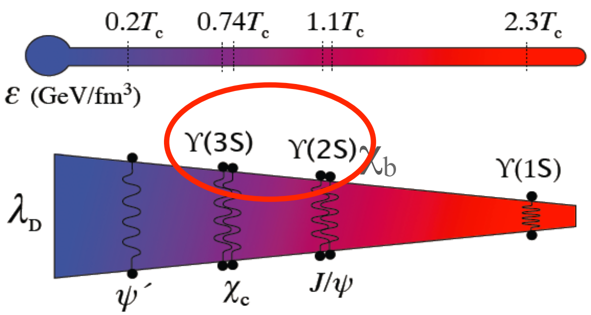
$$R_{AA}^{0.2TeV} \sim R_{AA}^{2.76TeV} > R_{AA}^{5.02TeV}$$

Onset direct Υ(1S) suppression?





Excited Υ Suppression in A+A Collisions

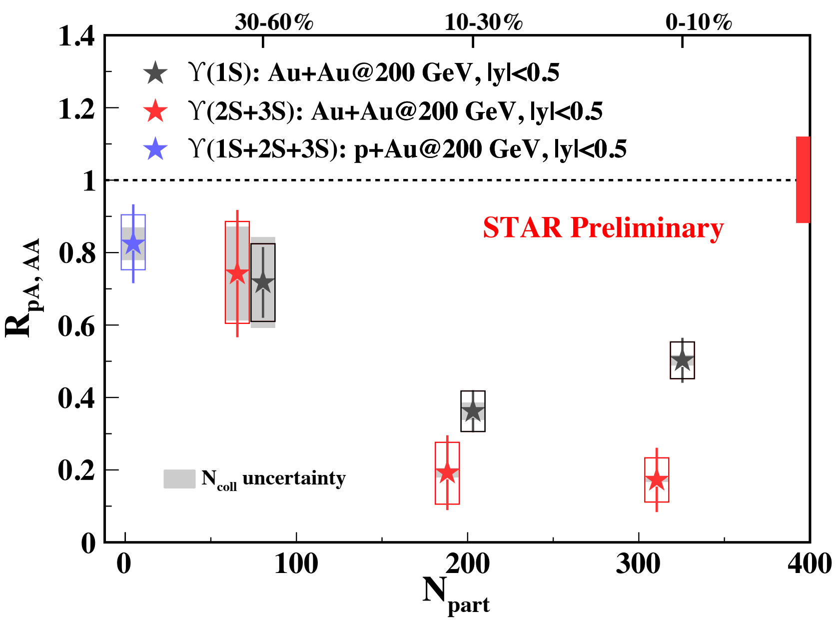


$R_{AA}^{peripheral} > R_{AA}^{centrl}$

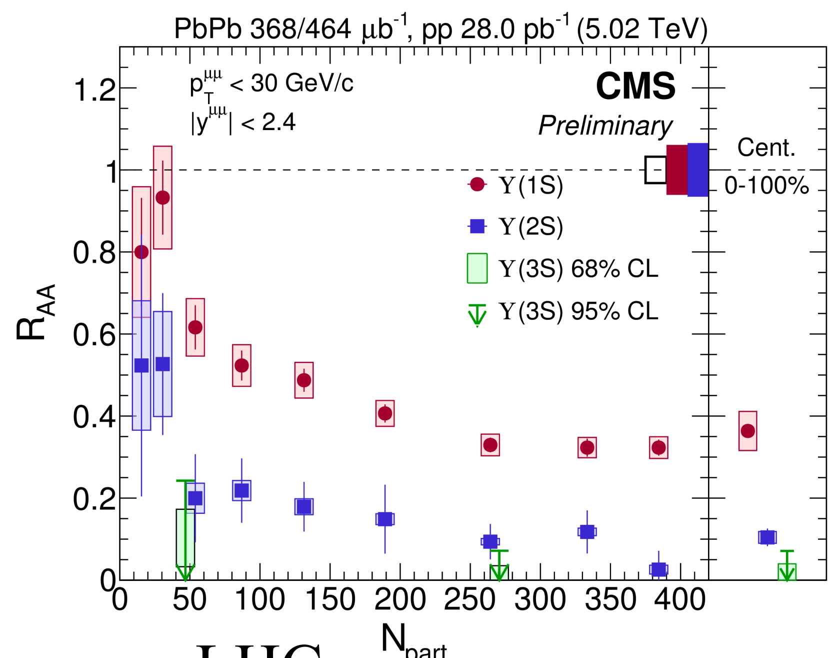
RHIC: $R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{\Upsilon(1S)}$ in central

LHC: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$

Sequential suppression



RHIC



LHC

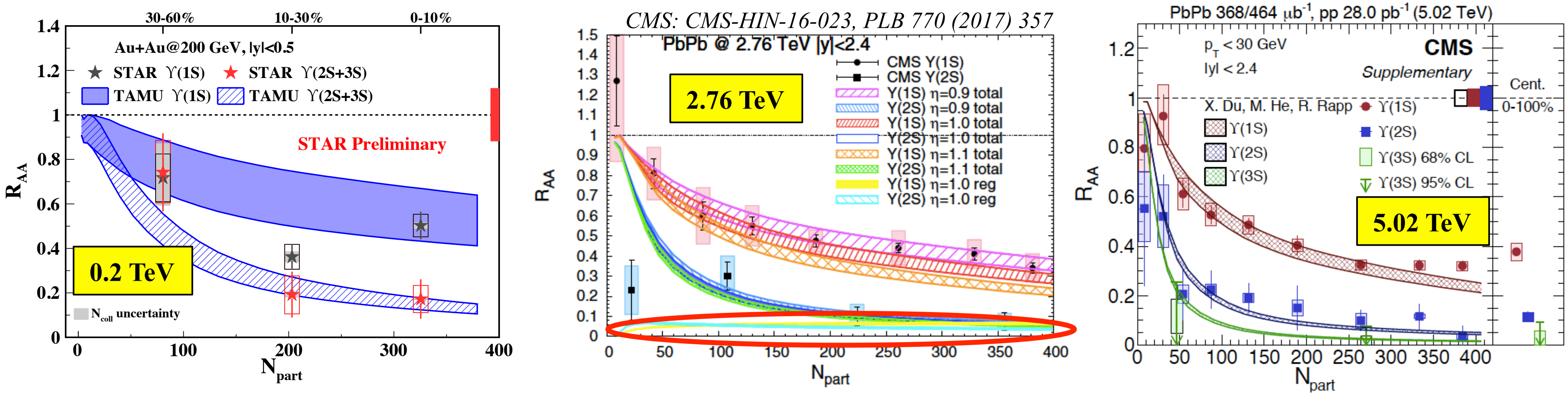
Υ Family Suppression vs. TAMU model

T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration

X. Du, M. He, R. Rapp PRC 96 (2017) 054901

	Υ(1S)	Υ(2S)	Υ(3S)
T_d (MeV)	500	240	190

√s (TeV)	0.2	2.76	5.02
T_0^{QGP}(MeV)	310	555	594



- Good description of Υs suppression from RHIC to LHC energies
- Non-negligible regeneration, especially for Υ(2S)

QGP Thermometer?

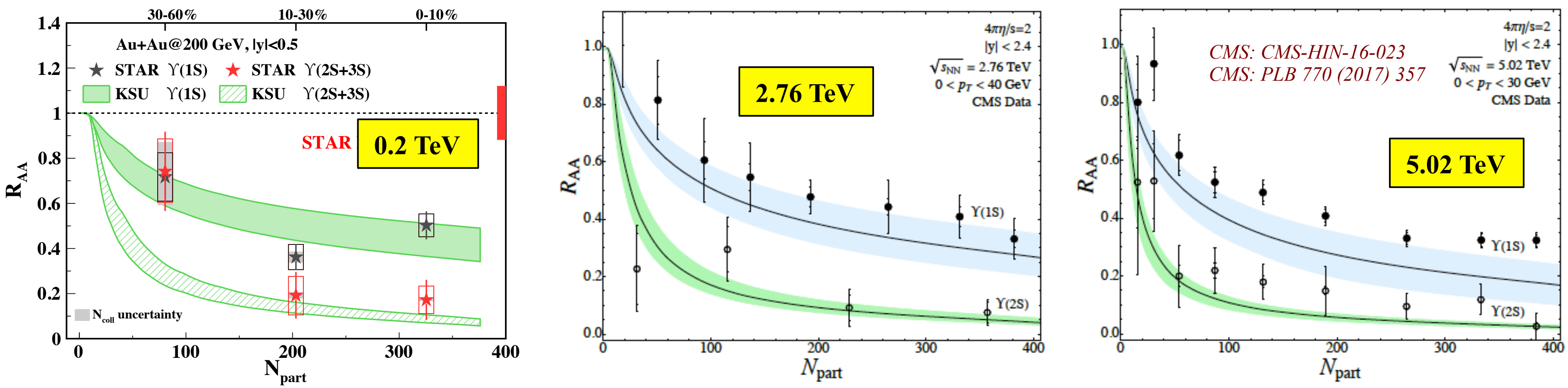
Υ data vs. lattice-potential model

Complex potential (lQCD); aHydro medium; No regeneration or CNM

B. Krouppa, A. Rothkopf, M. Strickland
PRD 97 (2018) 016017

	Υ(1S)	Υ(2S)	Υ(3S)
T_d (MeV)	600	230	170

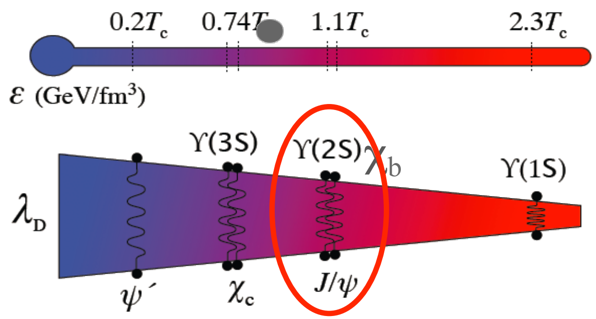
√s (TeV)	0.2	2.76	5.02
T_0^{QGP}(MeV)	440	545	632

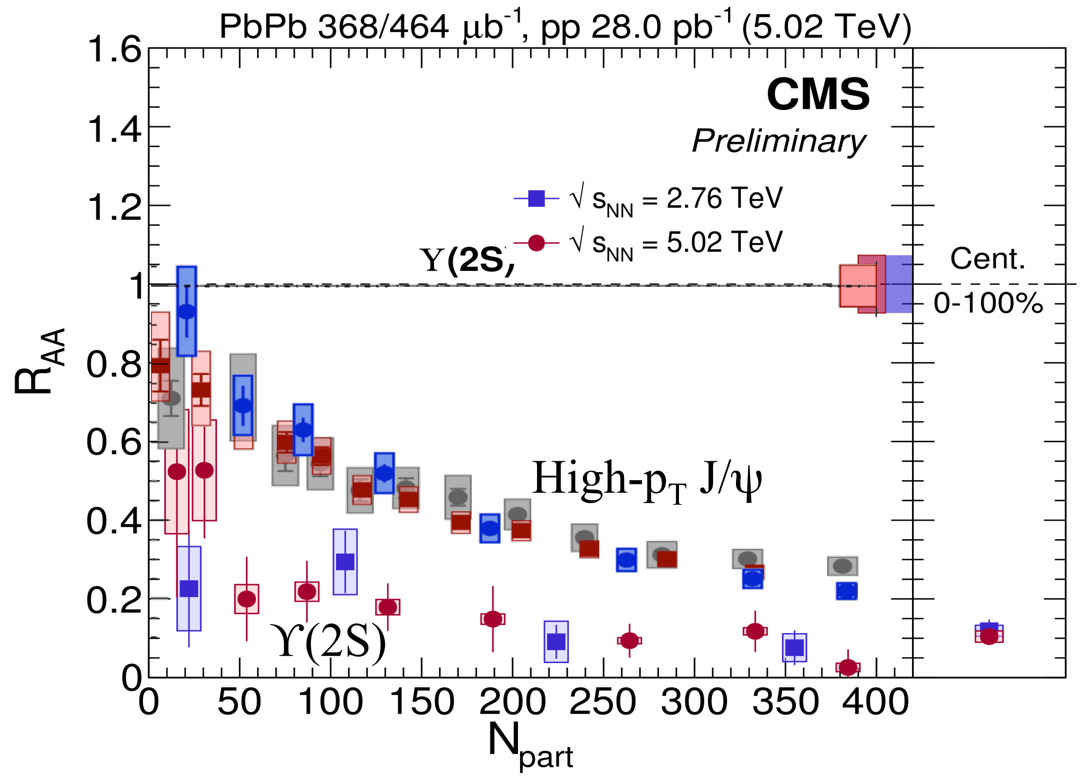


- Describe RHIC data reasonably well
- Consistently below the experimental data at LHC. Regeneration may help.

QGP Thermometer? Stay tuned…

Υ(2S) vs. high-p_T J/ψ





Υ(2S) vs. J/ψ:

Similar size → Similar T_d

Υ(2S) exhibits significant stronger suppression than high-p_T J/ψ

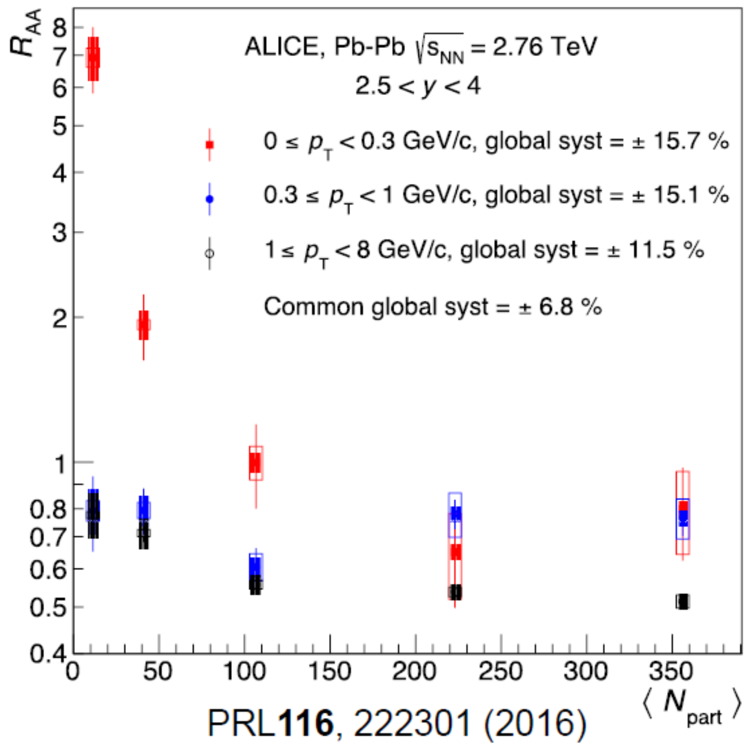
Velocity matters?

Formation time effect? Hadronic dissociation?

Summary

- Low-p_T J/ψ:
  - Interplay of CNM, QGP melting and regeneration
  - Clear regeneration signal at LHC
- High-p_T J/ψ:
  - Clean probe of QGP melting
  - Increasing suppression from RHIC to LHC
  - Melting in QGP
- ϒ family and high-p_T ψ(2S):
  - Consistent with sequential melting
    - High-p_T ψ (2S) < high-p_T J/ψ
    - ϒ(3S) < ϒ(2S) < ϒ(1S)
- More qualitative, rather than quantitative
  - More efforts needed to extract QGP properties
  - Experiments: Improve precision; new observables …

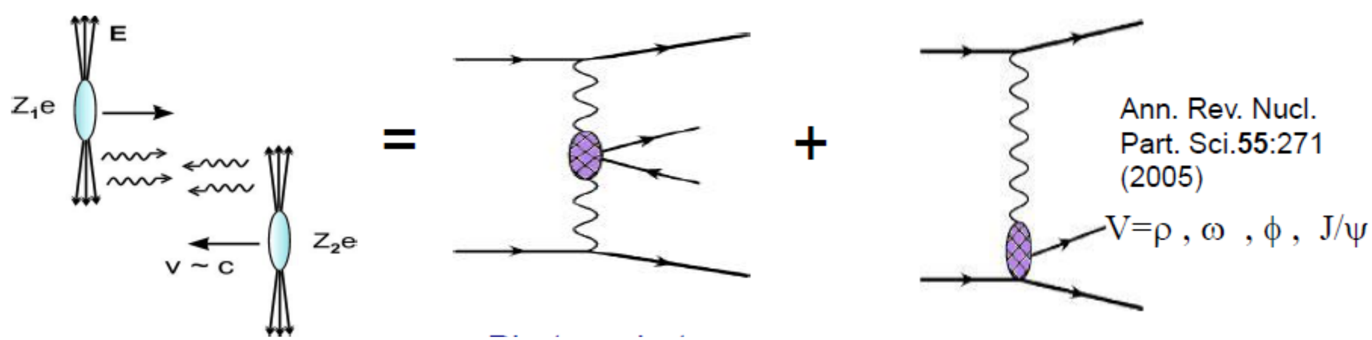
Very low-p_T J/ψ in peripheral A+A



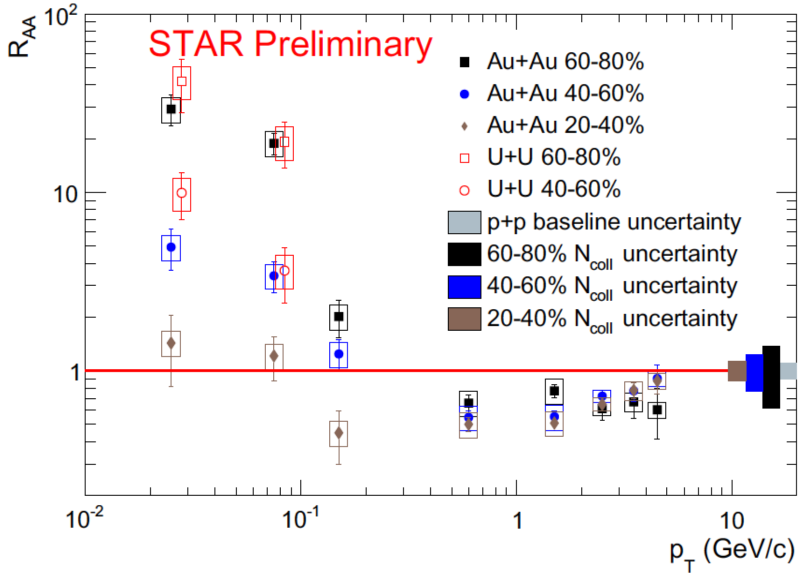
PRL **116**, 222301 (2016)

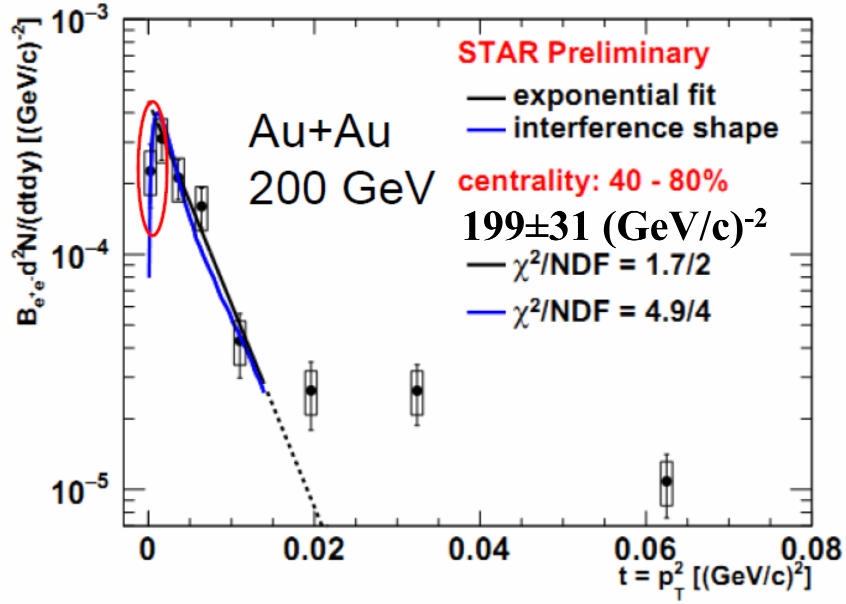
- Significant enhancement at very low p_T in (semi-)peripheral Pb+Pb Collisions
  Coherent photon-nucleus interaction?

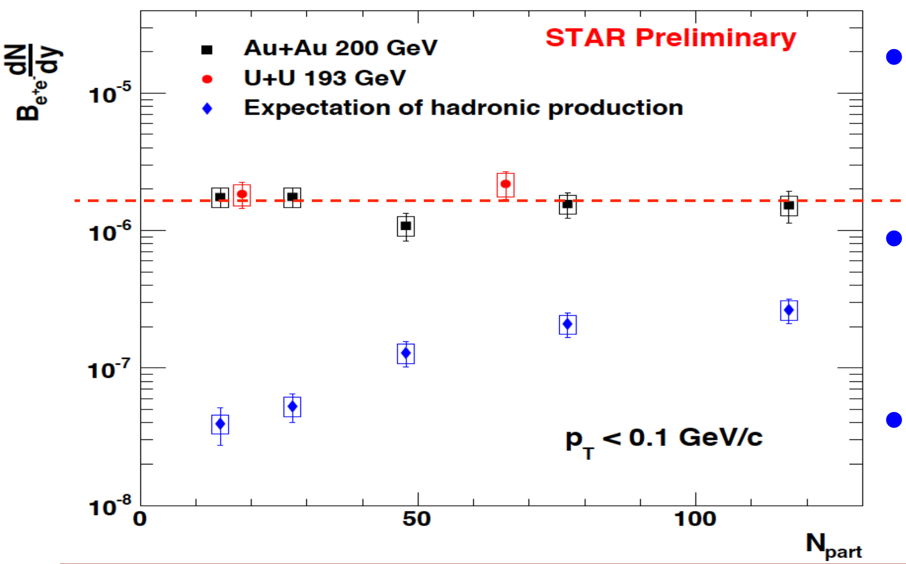
- A domain where regeneration is negligible
- Almost at rest in the medium



Very low-p_T J/ψ at STAR





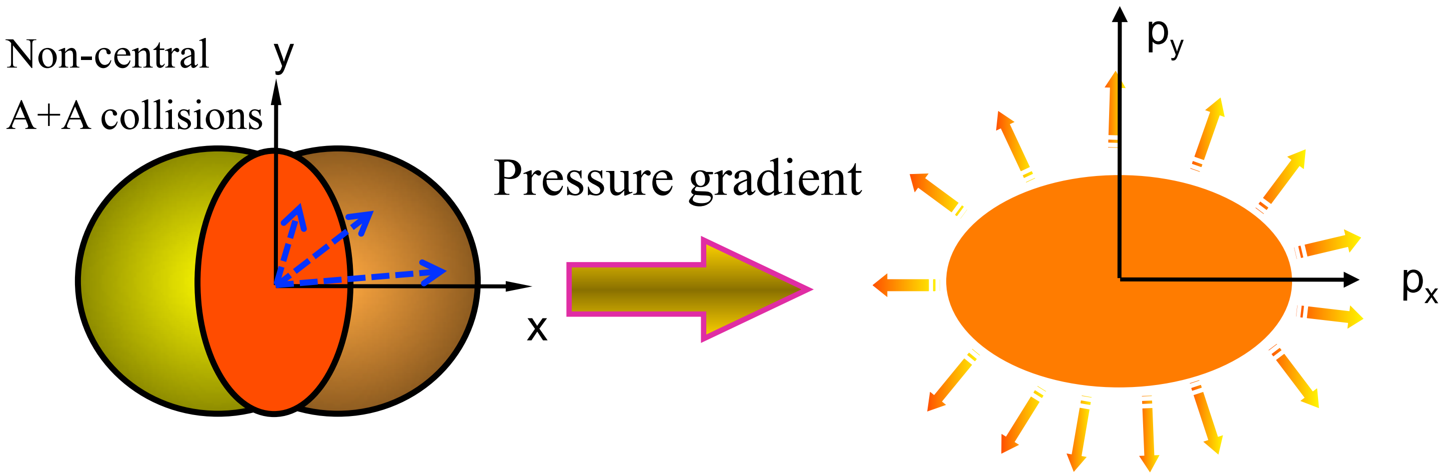


- Excess observed at p_T<0.1 GeV/c, yield has no obvious cent. depend.
- *t* dist. consistent with interference
  Slope consistent with that in UPC
- Production mechanism under investigation

Observable: Anisotropy Coefficient v_2

Coordinate space:
Initial asymmetry

Momentum space:
Final asymmetry



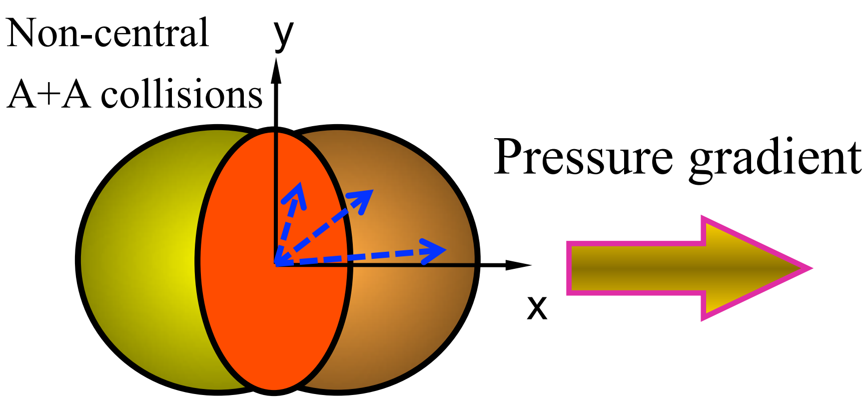
$$\frac{dN}{d\phi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)$$

v_2: *Elliptic flow*

Observable: Anisotropy Coefficient v_2

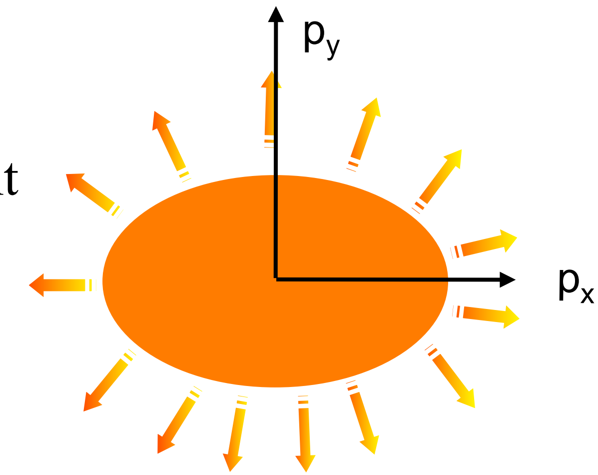
Coordinate space:

Initial asymmetry



Momentum space:

Final asymmetry

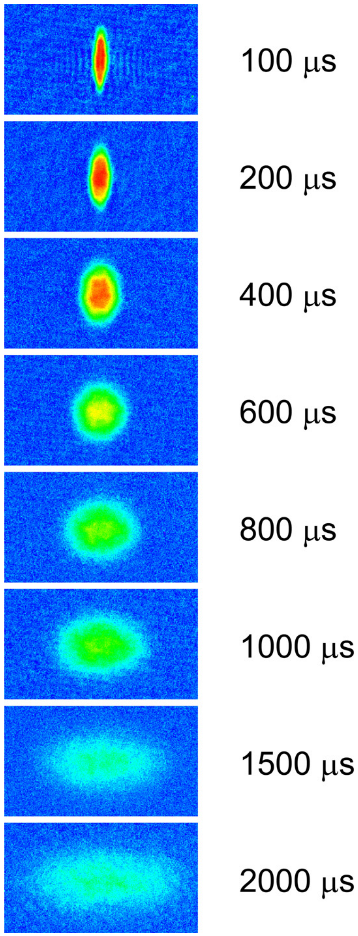


$$\frac{dN}{d\phi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)$$

v_2: Elliptic flow

Ultra-clod Fermi-gas

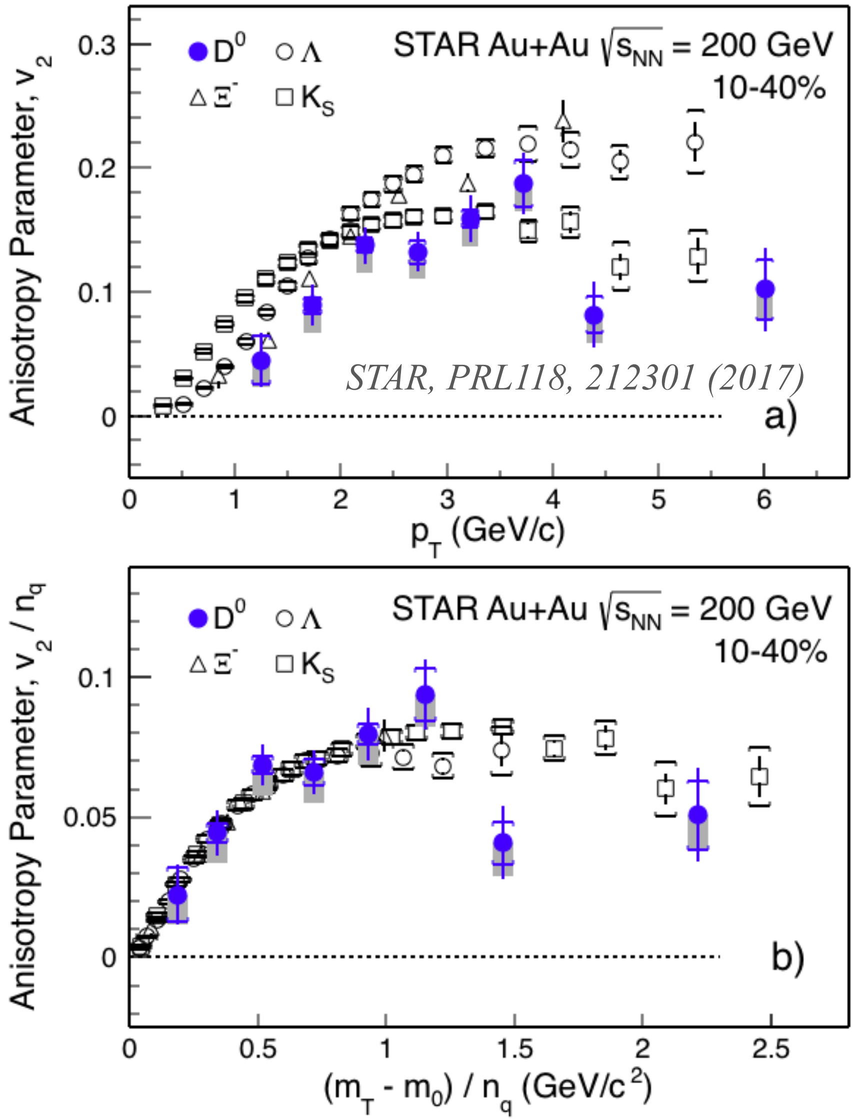
K. O'Hara et al. Science 298, 2179 (2002)



Collective flow is a general feature of strongly interacting systems

Heavy quarks can obtain non-zero flow from the system if interact with the system strongly

D^0 v_2 in Au+Au at 200 GeV



Follow mass ordering at low-p_T

Hadrodynamics

Follow meson/baryon separation at intermediate-p_T

Quark coalescence

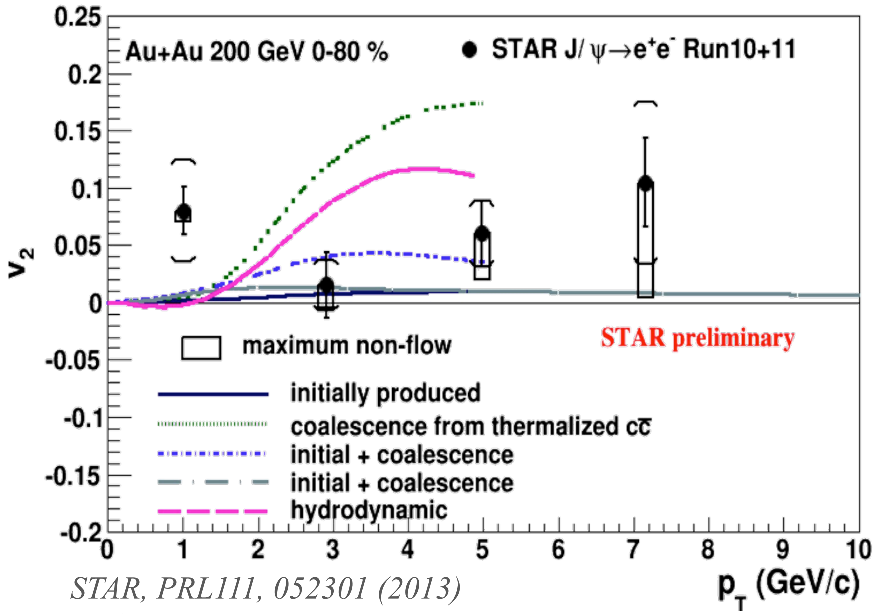
Charm quarks exhibit the same strong flow are the light quarks

May be close to thermal equilibrium *"Brownian motion"*

Regenerated J/ψ expected to inherent charm quark flow

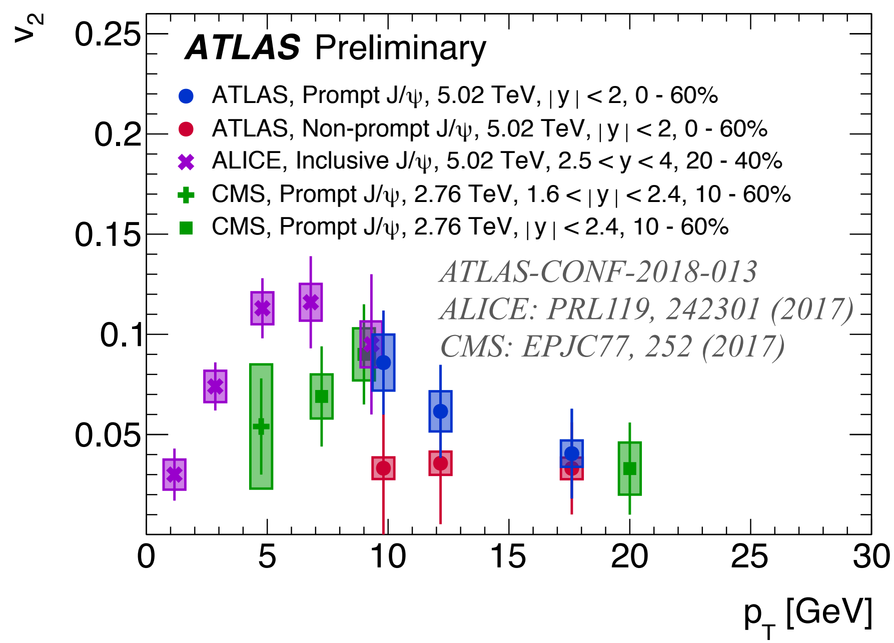
J/ψ v_2 in A+A Collisions

RHIC



STAR, PRL111, 052301 (2013)
And Preliminary

LHC



Consistent with 0 @ p_T>2 GeV/c

Significant v_2 observed

Not dominantly produced by regeneration for p_T>2 GeV/c

Agrees with regeneration picture

Experiments

Accelerator	Detector	Mid-y	Forward	Notes
RHIC	PHENIX	e^+e^-	$\mu^+\mu^-$	Decommissioned
	STAR	e^+e^- $\mu^+\mu^-$		
LHC	ALICE	e^+e^-	$\mu^+\mu^-$	
	ATLAS	$\mu^+\mu^-$		High p_T muon
	CMS	$\mu^+\mu^-$		High p_T muon
	LHCb		$\mu^+\mu^-$	pPb and (semi-)peripheral PbPb

Challenging in heavy-ion collisions:

hard to trigger on; large (combinatorial) background