In-Medium Charmonium Production in Proton-Nucleus Collisions

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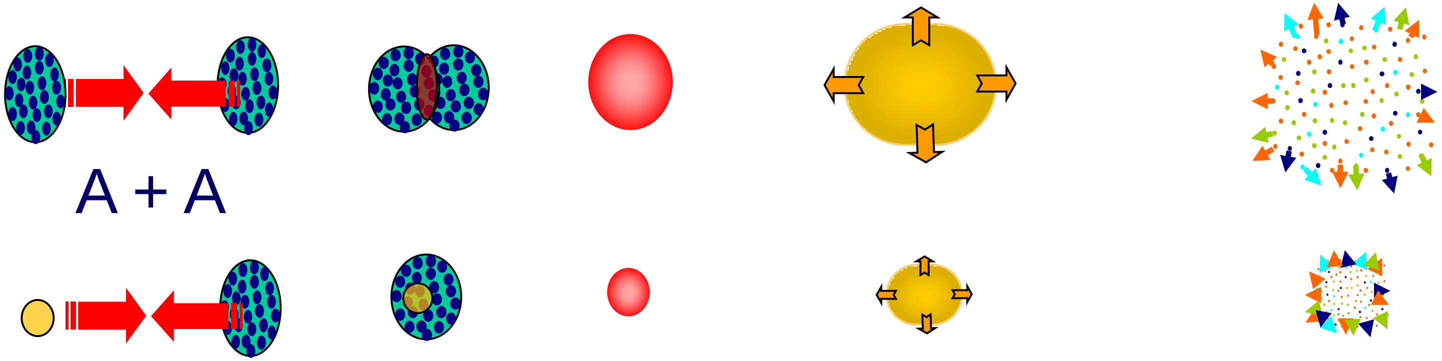
Outline

- Introduction
- Quarkonium Transport Approach
  - Rate Equation
  - Success of the Approach in AA Collisions
- p/dA Collisions with Data: R_{pA} and v_2
  - Nuclear Modification Factor R_{pA}
  - Elliptic Flow v_2
- Summary

X. Du, R. Rapp, JHEP03(2019)015

Why p/d-A Collisions? Why Quarkonium?



Ion-Ion

A + A

Small system

p/d + A

Collide QGP Hadron Matter Freeze out

Questions in p/d-A collisions:

- Medium Effects (in such small system)?
- Anisotropies (different from A+A collisions)?

Heavy Quarkonium, J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, ...as a probe:

1. Survive in QGP ($E_{BINDING}>T_c$), 2. Small velocity (potential picture works),

3. Large masses (baseline from hard production)

4. Various species (bound/melt at different parts of potential), …

→Ideal for probing strong force / $Q\bar{Q}$ potential in medium

Transport Approach

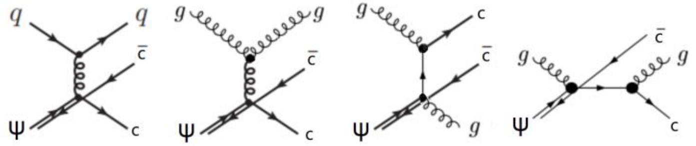
Kinetic Rate Equation

$$\frac{\mathrm{d}N_\Psi(\tau)}{\mathrm{d}\tau} = -\boxed{\Gamma_\Psi(T(\tau))}\left[N_\Psi(\tau) - \boxed{N_\Psi^{\mathrm{eq}}(T(\tau))}\right]$$

primordial regeneration

Transport Coefficients

- 🟦 Reaction Rates $\Gamma_\Psi(T(\tau))$ → NLO Quasi-Free



- 🟨 Equilibrium Limits $N_\Psi^{\mathrm{eq}}(T(\tau))$ → From Heavy quark conservation

$$N_\Psi^{\mathrm{eq}} = V_{\mathrm{FB}}\gamma_c^2 d_\Psi \int \frac{d^3p}{(2\pi)^3} f_\Psi^{\mathrm{eq}}(E_p;T)$$

Key Parameters

- 🟦 Coupling α_s → Affects Reaction Rates
  Fixed from Previous Calculations compared with data
- 🟨 Thermal Relaxation Time → Modifies Equilibrium Limit
  Extracted from Heavy Quark Diffusion Simulations

Key Inputs

- 🟦 In-Medium $Q\bar{Q}$ Potential/Binding Energy
- 🟨 Heavy Quark/-onium pp Cross Section -> fugacity factor γ_c
- 🟨 Initial State Effects (nPDF)
- 🟥 Fireball Evolution

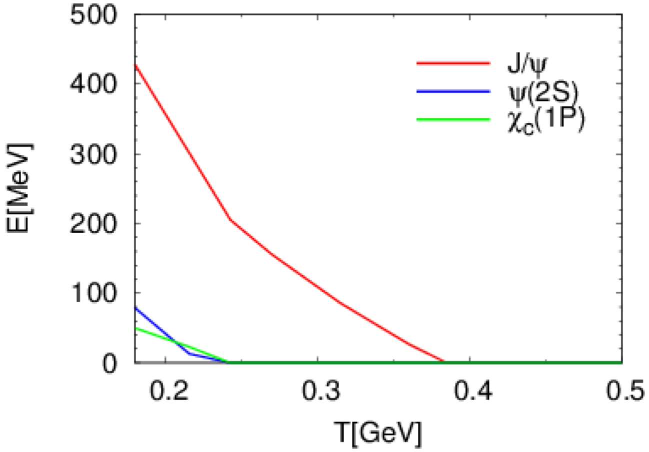
From Potential to Observables

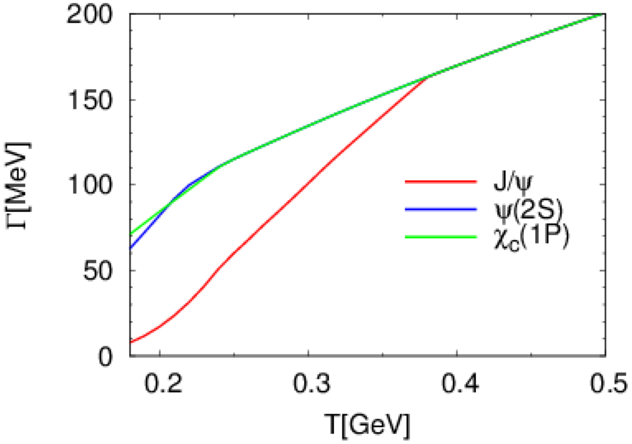
In-Medium $Q\bar{Q}$ Potential

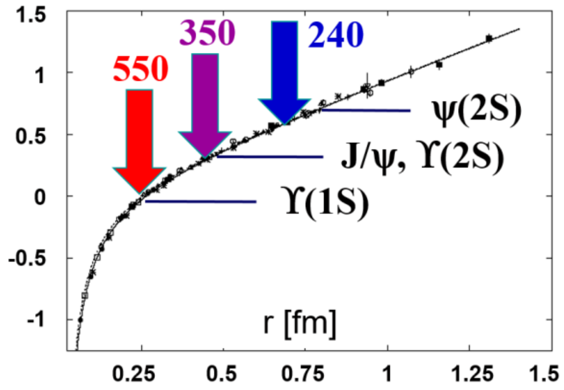
Transport → Observables

Quarkonium Binding Energies →

Reaction Rates $\Gamma_\Psi(T(\tau))$







- Hierarchy:
  - →Different Melting temperatures for J/ψ, ψ(2S), ….
  - Sequential Suppression …
  - Sequential Regeneration …
- Probing In-Medium Potential

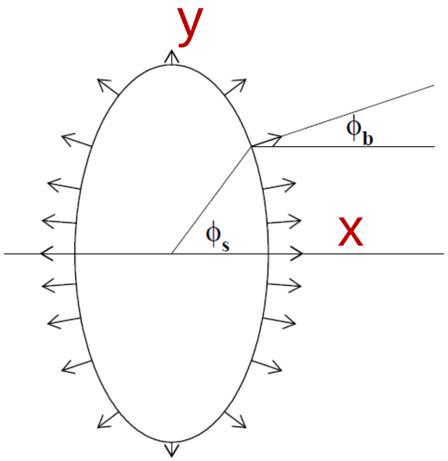
Elliptic Fireball Evolution

1.Need temperature evolution to solve the rate equation (medium effects)

Entropy conserved: $S_{\mathrm{tot}} = s(T)V_{\mathrm{FB}}(\tau)$ ⟹ Temperature $T(\tau)$

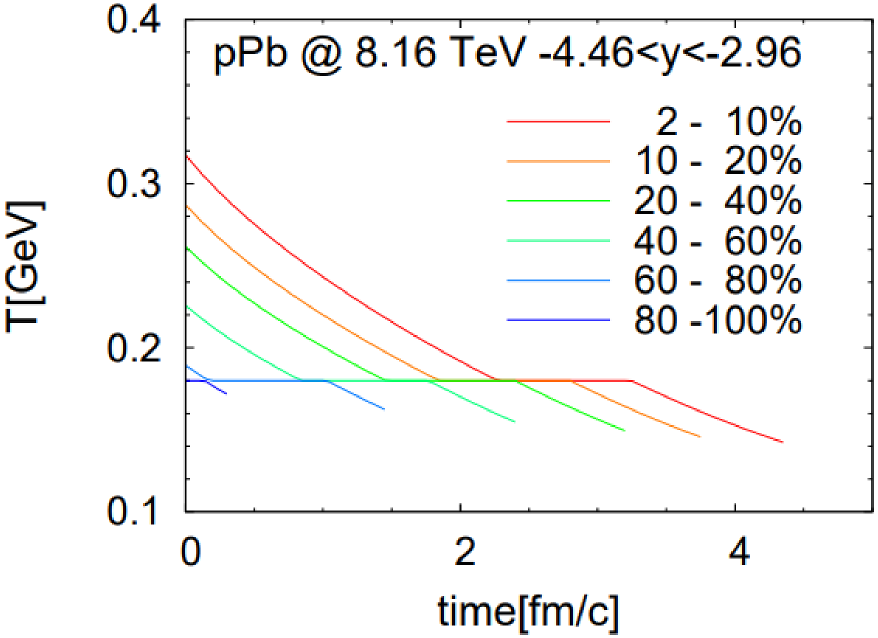
2.Provide elliptic geometry of background medium (anisotropies)

Elliptic medium expansion: $V_{\mathrm{FB}} = (z_0 + v_z\tau)\,\pi R_x(\tau)R_y(\tau)$



Key Fireball Parameters:

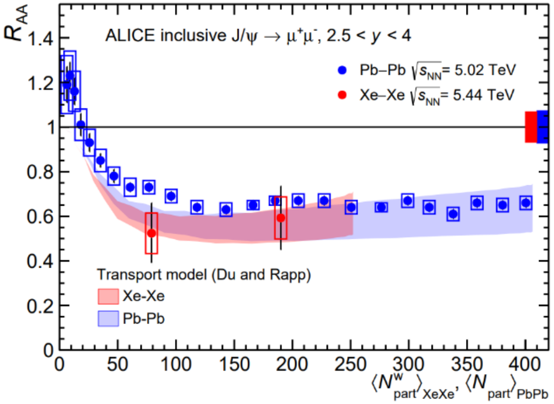
→ Guided from light hadron spectra and v_2



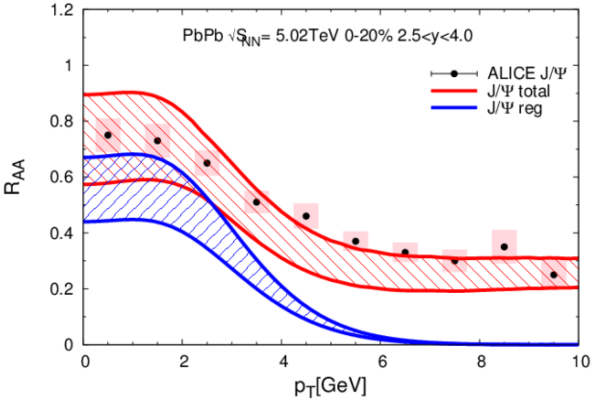
Temperature Evolution

Success of Transport Approach in AA

Charmonium

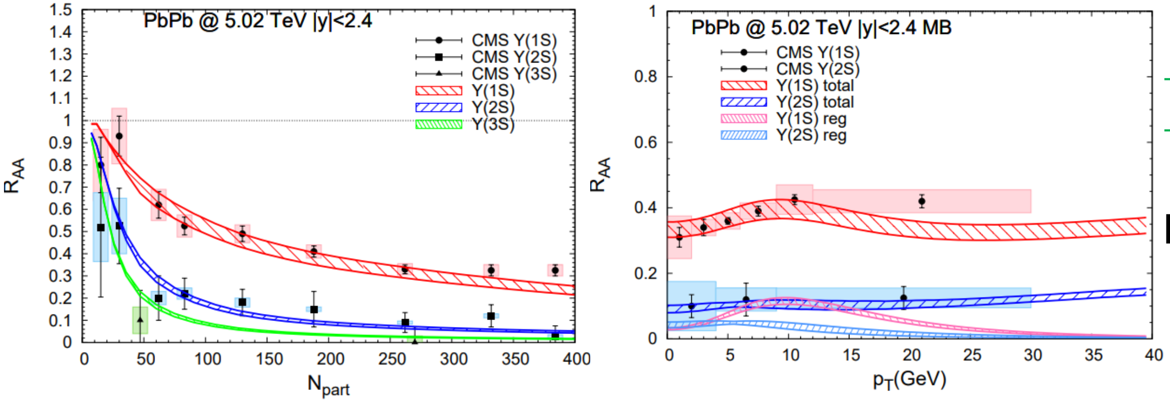


ALICE, PLB785 (2018) 419



See also: ALI-PREL-126572

Bottomonium



X. Du, M. He, R. Rapp, PRC96 (2017), no.5, 054901

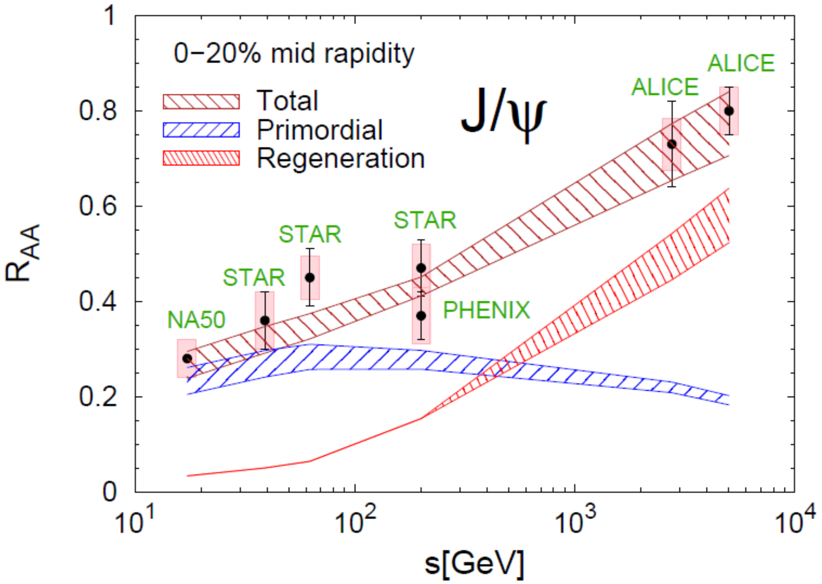
Simultaneous description of ground and excited states:
→Sequential suppression

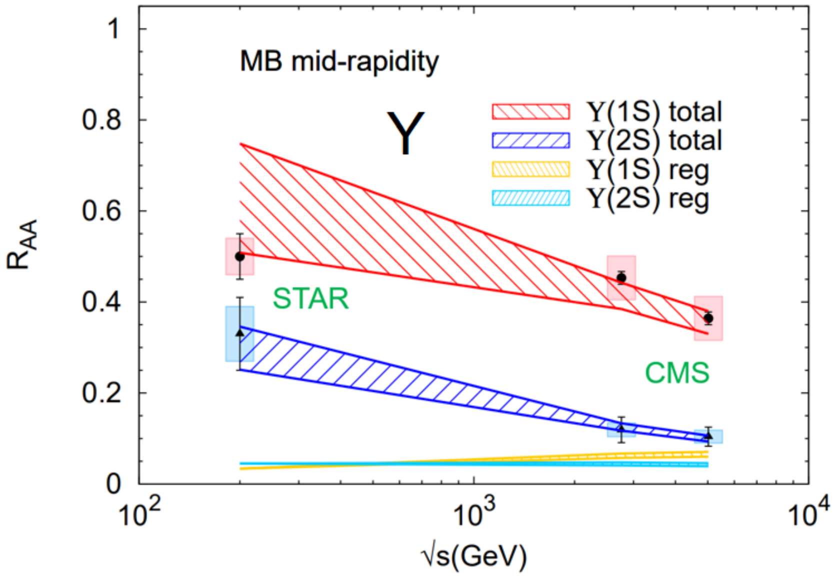
Momentum spectra:
→ Demonstrate regeneration
→ Degree of heavy quark Thermalization

Charm/Bottom-onium difference:
Charmonium:
→ Large regeneration
→ Close to thermal
Bottomonium:
→ Small regeneration
→ Far from thermal

Has predictive power

Success of Transport Approach in AA





R. Rapp, X. Du, NPA967 (2017) 216

J/ψ Excitation Function:

→ Further demonstration of regeneration

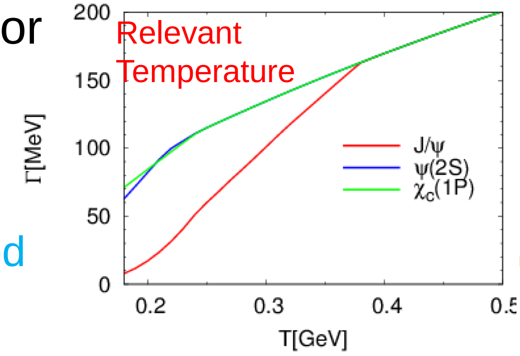
J/ψ and Υ(2S):
similar binding energies
BUT
different excitation functions

→ Due to Large regeneration for J/ψ

Centrality Dependent R_{dA}/R_{pA} at RHIC/LHC

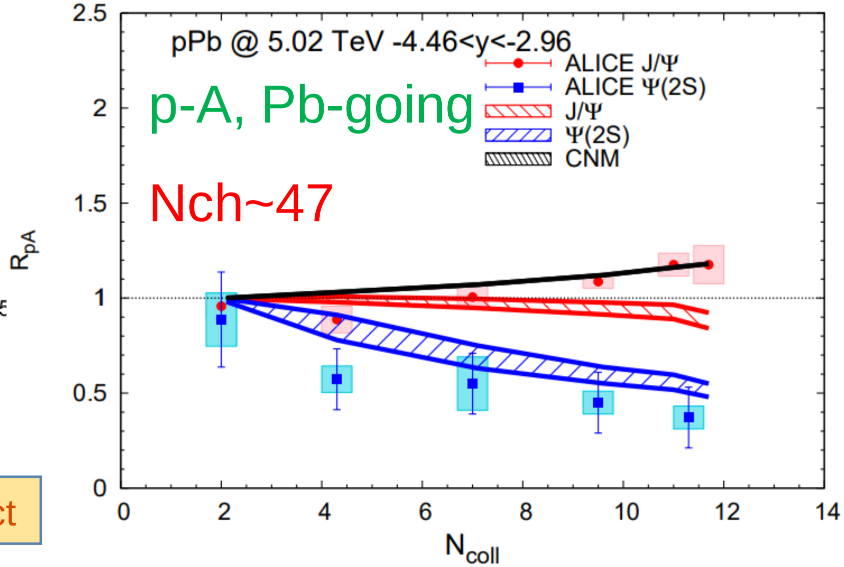
Nuclear modification factor

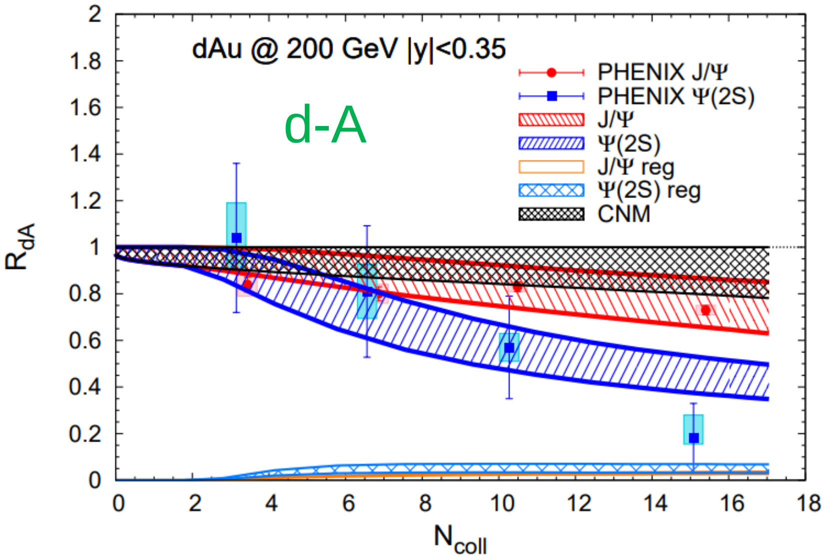
$$R_{pA} = \frac{N_{pA}}{N_{coll} N_{pp}}$$

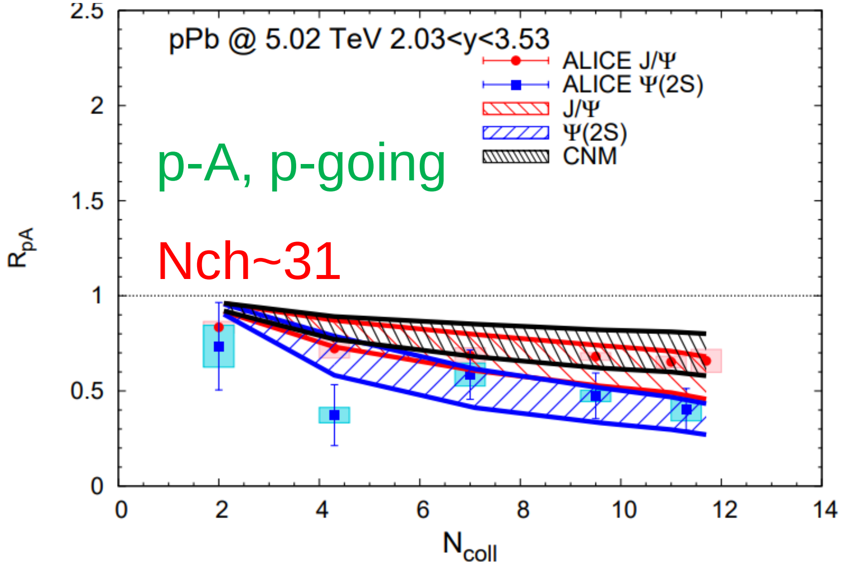


- J/Ψ very little suppressed
- Ψ(2S) more suppressed
- Pb-going larger J/Ψ, Ψ(2S) gap than p-going
- Small regeneration contribution

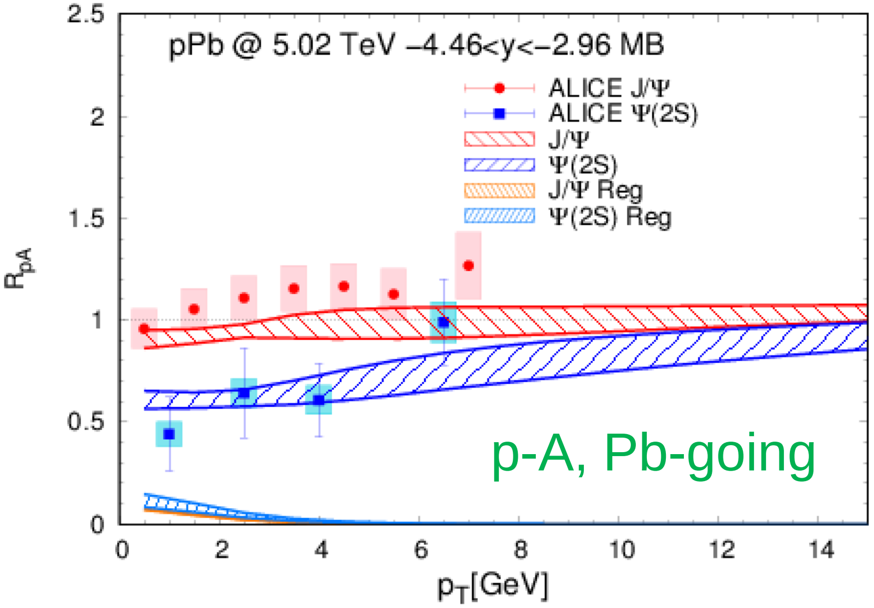
Medium effect

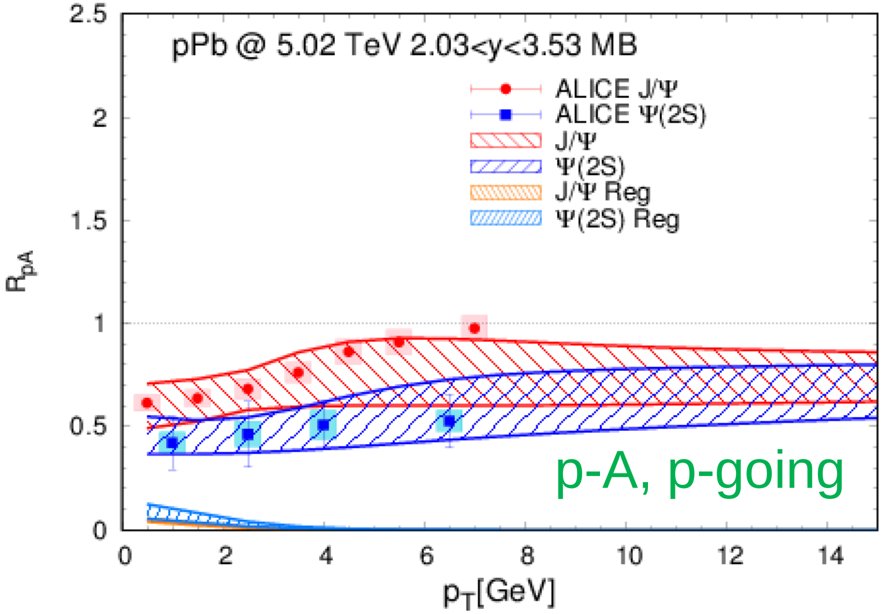






p_T Dependent R_{pA} at the LHC





- Small regeneration contribution:

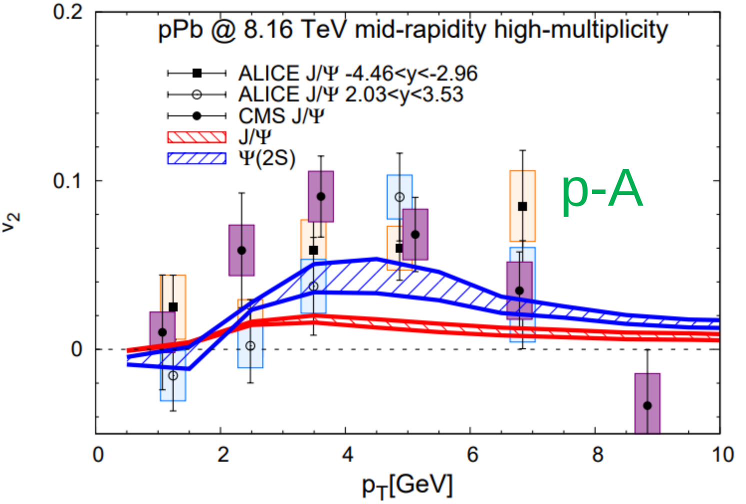
  Verified by moderate p_T dependence

→ Thermalized and regenerated charmonium accumulates at low-p_T

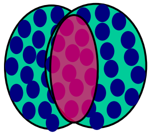
Elliptic Flow (v_2) at the LHC

Elliptic flow (v_2):

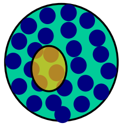
$$\frac{d^2N}{d^2p_T} = \frac{1}{2\pi}\frac{dN(p_T)}{p_T dp_T}(1+2v_2(p_T)\cos(2\phi)+\dots)$$



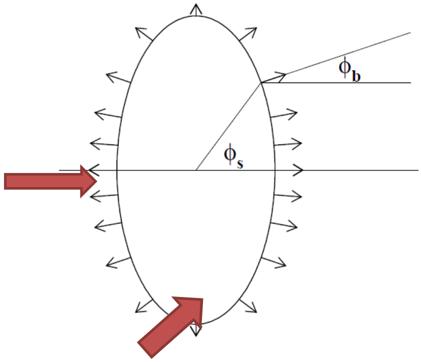
- Anisotropy in A-A: non-central collision



- Anisotropy in p-A: fluctuation



- v_2 in primordial: leakage effect (geometry)
- v_2 in regeneration: flow effect



- In Plane
- Large flow

- Out of Plane
- Small flow

- v_2 compare to experimental data: Puzzle?

Data suggests large J/ψ v_2 but small J/ψ suppression

Large v_2 not from hot medium effect alone, from initial state effect?

Summary

- There is hot medium effect in pA collisions
  → J/ψ and ψ(2S) R_{pA} "gap" (ψ(2S) R_{pA} < J/ψ R_{pA})
  → R_{pA} "gap" larger at Pb-going, smaller at p-going
- J/ψ regeneration is small in pA collisions
  → J/ψ $R_{pA}(p_T)$ has no peak at low p_T
- Initial state effect might be important for a simultaneous description of R_{pA} and v_2 in pA collisions
  → Small J/ψ suppression but large J/ψ v_2

Thank you!