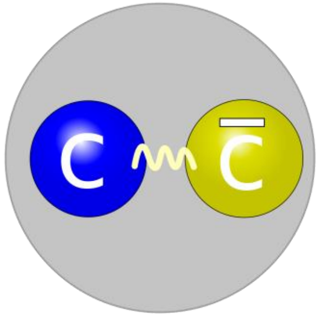
Recent Results on Quarkonium Production from ALICE in Nuclear Collisions

16th International Conference on
Heavy Quarkonia
26 Feb – 01 Mar, 2024
IISER Mohali, India

Neelkamal Mallick
Indian Institute of Technology Indore, India
(On behalf of the ALICE Collaboration)
Neelkamal.Mallick@cern.ch

Motivation

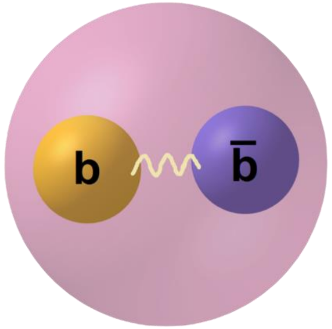


WHAT

Bound state of heavy quark and antiquark; **charmonia** $(c\bar{c})$ and **bottomonia** $(b\bar{b})$

WHY

- Produced via hard scattering processes (large Q^2) at the initial stage of the collision
- Interacts with the medium throughout its evolution
- Several in-medium mechanisms owing to the production



HOW

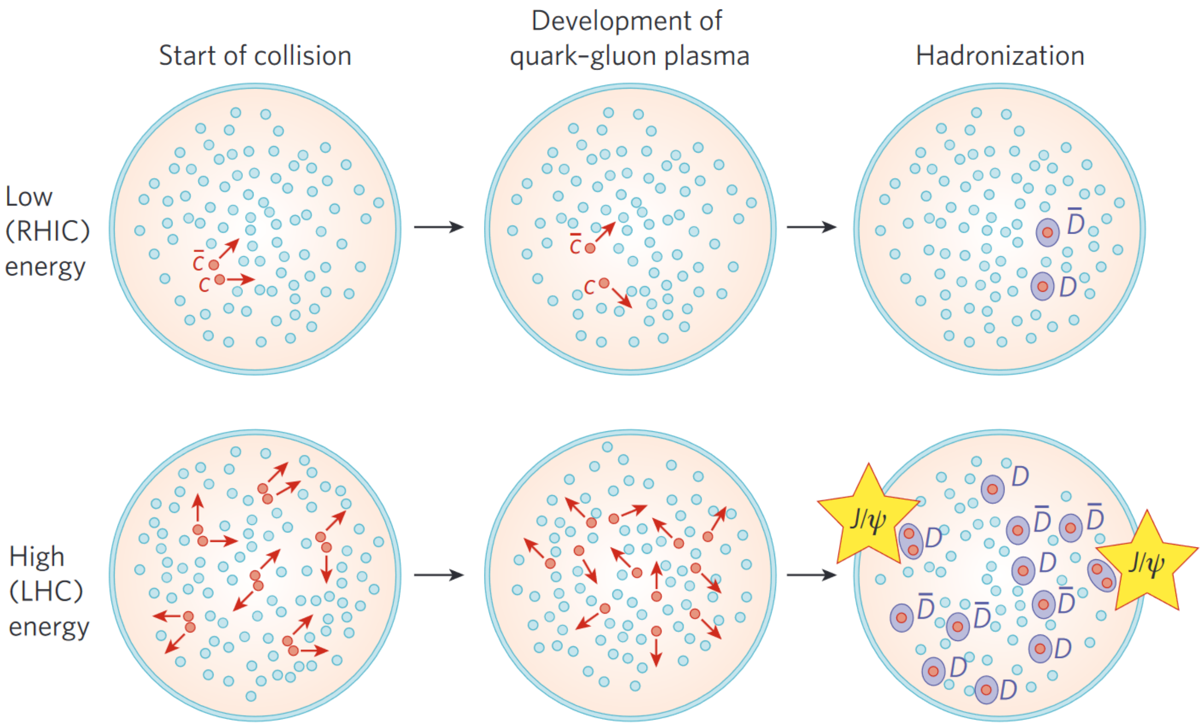
- Production of **charmonia (J/ψ, $\psi(2S)$)** and **bottomonia ($\Upsilon(1S)$, $\Upsilon(2S)$)**
- Measurement of nuclear modification factor (R_{AA}) (Requires a baseline: pp collisions)
- Elliptic flow (v_2)
- Polarization

In this talk

- Recent results from LHC Run 2 Data, Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

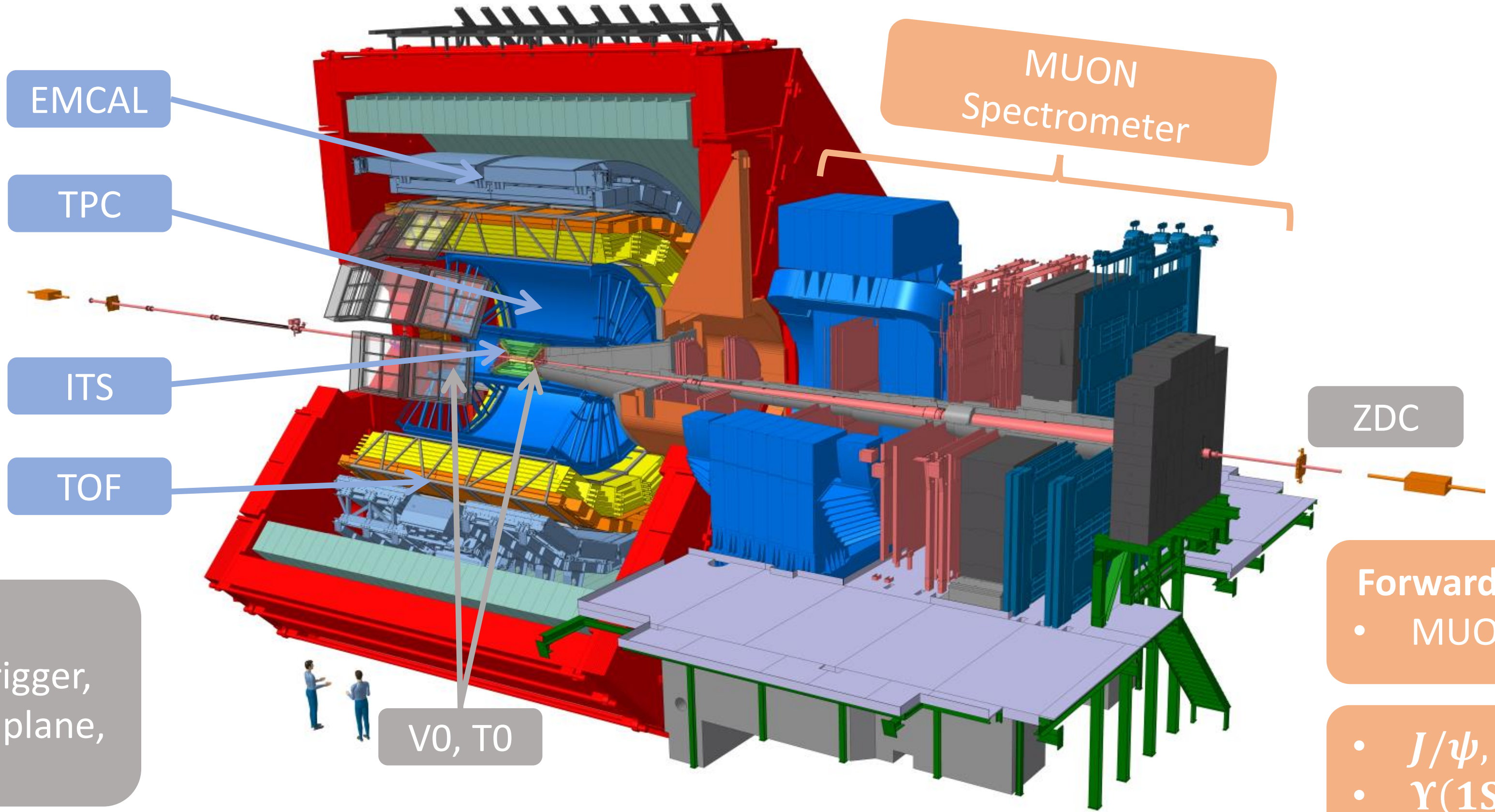
Quarkonia in Heavy-Ion Collisions

- **Quarkonia Suppression:** Quarkonia states are expected to be suppressed in the presence of hot and dense medium due to color screening and dynamic dissociation
- Color screening due to the production of large amount of color charges at higher energies
- **Sequential Melting:** Differences in their binding energy leads to a sequential suppression of various quarkonia states by increasing the temperature of the medium
- **Quarkonia (Re)generation:** Higher production cross section of the $c\bar{c}$ pair at the LHC energies→ Enhanced quarkonia production through statistical production at the phase boundary or through coalescence of charm quarks in the plasma
- **CNM Effects:** Modification of the parton distribution function in presence of nuclear environment



T. Matsui and H. Satz, PLB 178 (1986) 416
A Rothkopf, Phys. Rept. 858 (2020) 1-117
P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196
R. Thews et al, Phys. Rev. C 63 (2001) 054905

ALICE Apparatus (Run 2 Configuration)



V0, T0, ZDC
Minimum Bias Trigger, Centrality, Event plane, Luminosity

Forward rapidity, $-4.0 < \eta < -2.5$
- MUON: Trigger, Tracking, PID

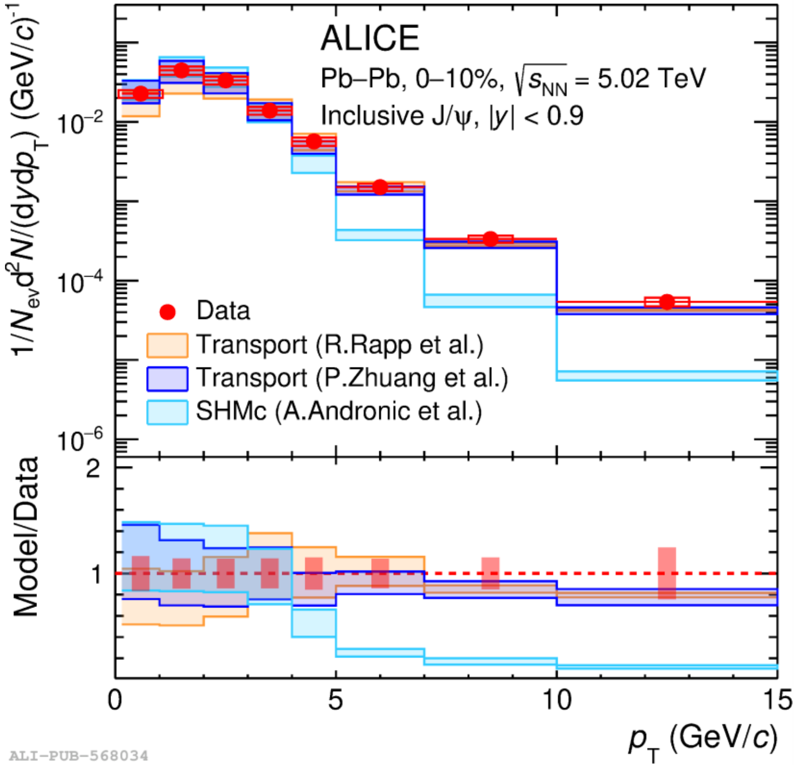
- $J/\psi, \psi(2S) \rightarrow \mu^{+} + \mu^{-}$
- $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \rightarrow \mu^{+} + \mu^{-}$

Midrapidity, $|\eta| < 0.9$
- ITS, TPC, TOF: Vertexing, Tracking, Multiplicity, PID
- EMCAL: electron trigger, PID

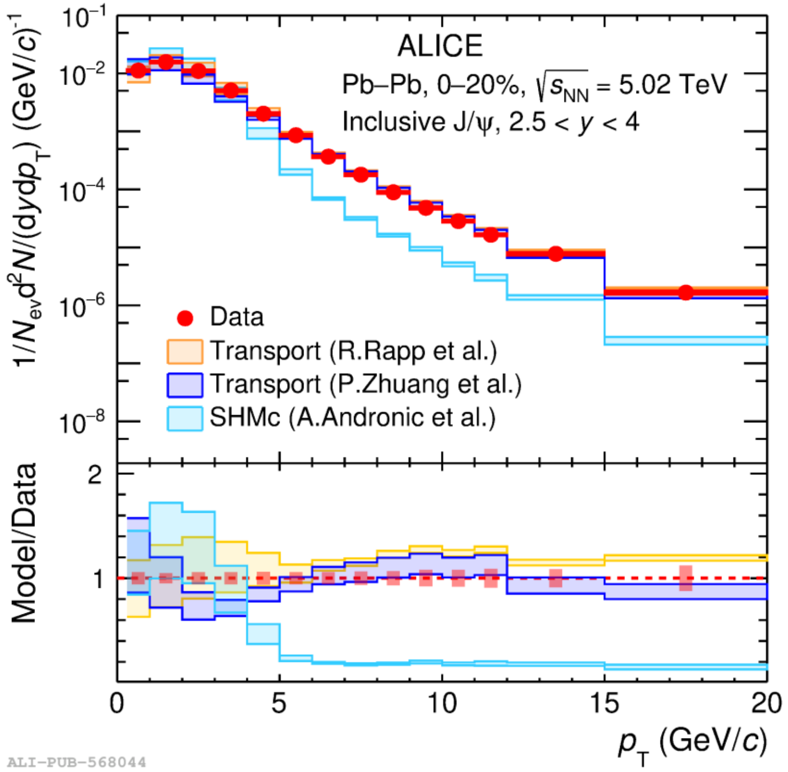
- $J/\psi, \psi(2S) \rightarrow e^{+} + e^{-}$ (prompt)
- B-hadron→ $J/\psi \rightarrow e^{+} + e^{-}$(nonprompt)

Transverse Momentum Spectra

Midrapidity



Forward rapidity



ALICE Collaboration, Phys. Lett. B 849 (2024) 138451
SHMc: A. Andronic et al.,Phys. Lett. B 797 (2019) 134836
Transport: P. Zhuang et al., Phys. Rev. C 89 (2014) 054911
Transport: R. Rapp et al., Eur. Phys. J. A 57 (2021) 122

- Includes the entire dataset collected during Run 2 with ALICE → Improves precision, extends p_T coverage
- Low p_T yield explained via charm coalescence with transport models and statistical approach
- High p_T yield is explained via both the transport models
- SHMc model underestimates data at higher p_T

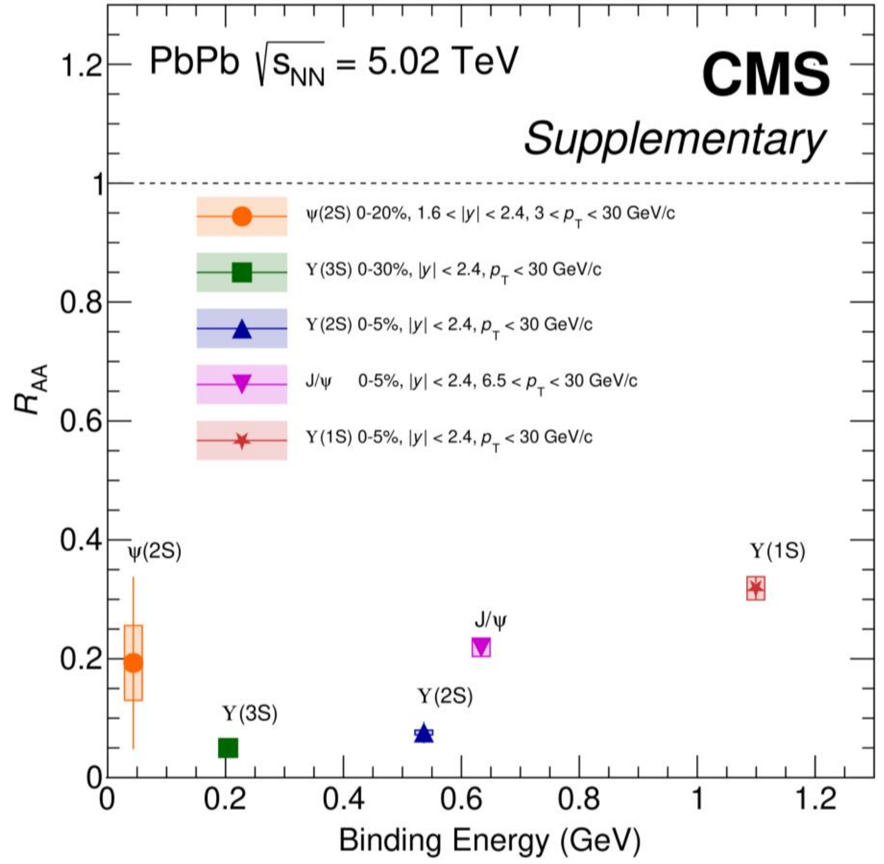
Nuclear Modification Factor (R_{AA})

- Defined as the ratio of yields in heavy-ion collisions to that of pp collisions scaled to the number of binary collisions

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{d^2N_{\mathrm{AA}}/(dy\, dp_{\mathrm{T}})}{\langle N_{\mathrm{coll}}\rangle\, d^2N_{\mathrm{pp}}/(dy\, dp_{\mathrm{T}})}$$

  - $R_{\mathrm{AA}} > 1$: Enhancement
  - $R_{\mathrm{AA}} < 1$: Suppression
  - $R_{\mathrm{AA}} = 1$: No Nuclear effect

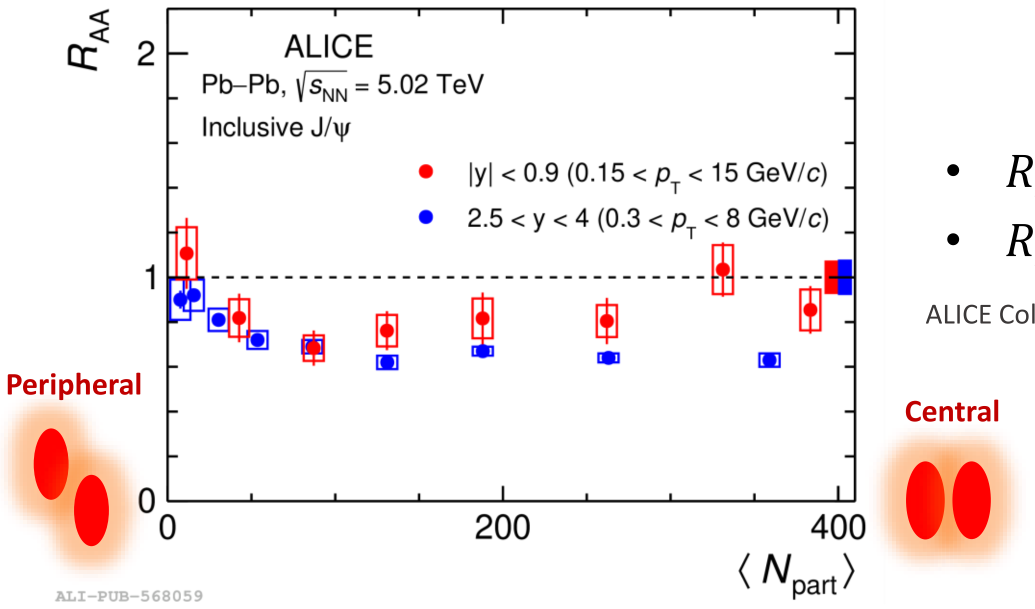
- In presence of a medium, the production of quarkonia can alter greatly as compared to pp collisions through sequential suppression, dissociation, regeneration, and CNM effects
- R_{AA} vs. Binding Energy → confirms sequential suppression



https://cms-results.web.cern.ch/cms-results/public-results/publications/HIN-21-007/index.html#Figure-aux_021

Nuclear Modification Factor (R_{AA}) for J/ψ

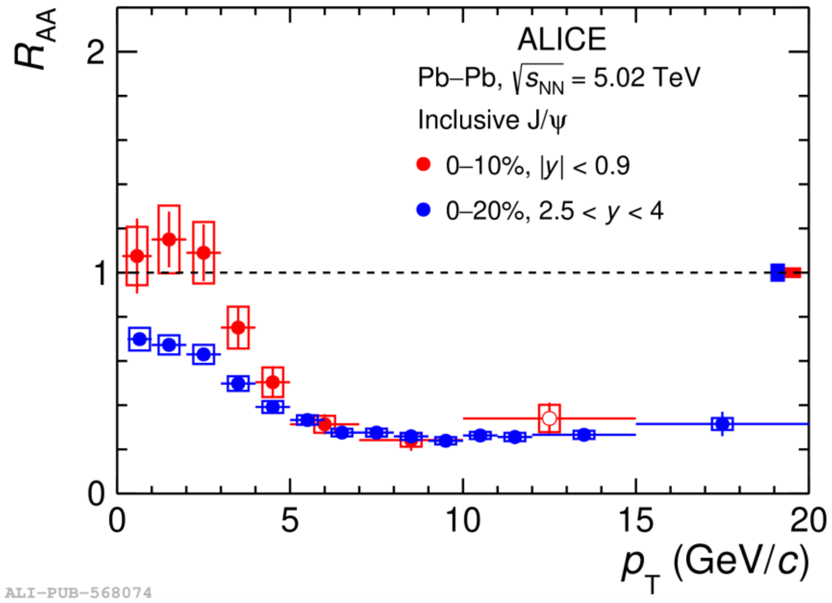
Centrality Dependence



- $R_{\mathrm{AA}} > 1$: Enhancement
- $R_{\mathrm{AA}} < 1$: Suppression

ALICE Collaboration, Phys. Lett. B 849 (2024) 138451

p_{T} Dependene

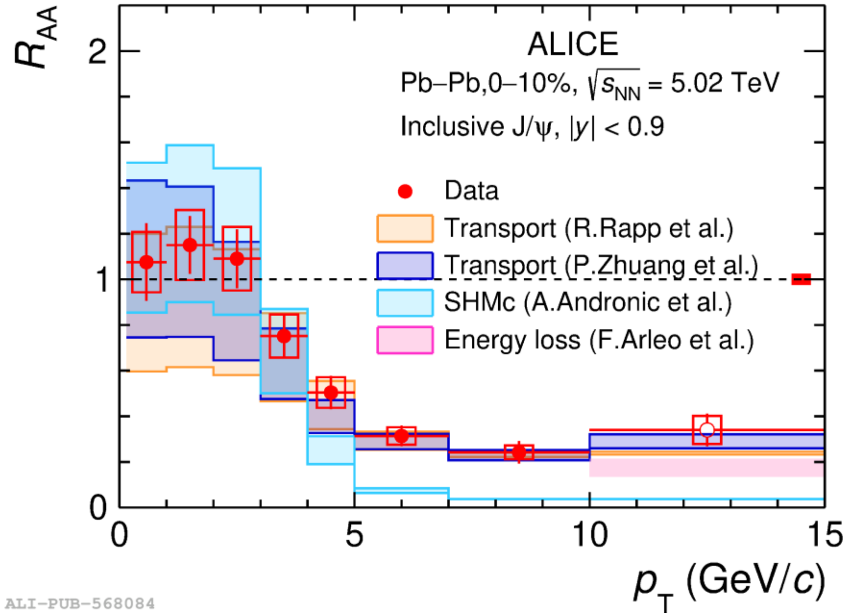


- J/ψ suppression observed from semi-central to central collisions
- Almost flat trend→ Interplay between suppression and (re)generation effects
- For $\langle N_{\mathrm{part}} \rangle > 100$, less suppression for midrapidity case → Higher $d\sigma_{c\bar{c}}/dy$ and larger fraction of J/ψ produced via (re)generation

- At low-p_{T}, recombination of uncorrelated charm quarks counterbalances the suppression
  →Stronger (re)generation effect
  →Strong dependence of R_{AA} on local charm quark density
- At higher p_{T}: Converge to similar values → Weaker dependence on rapidity

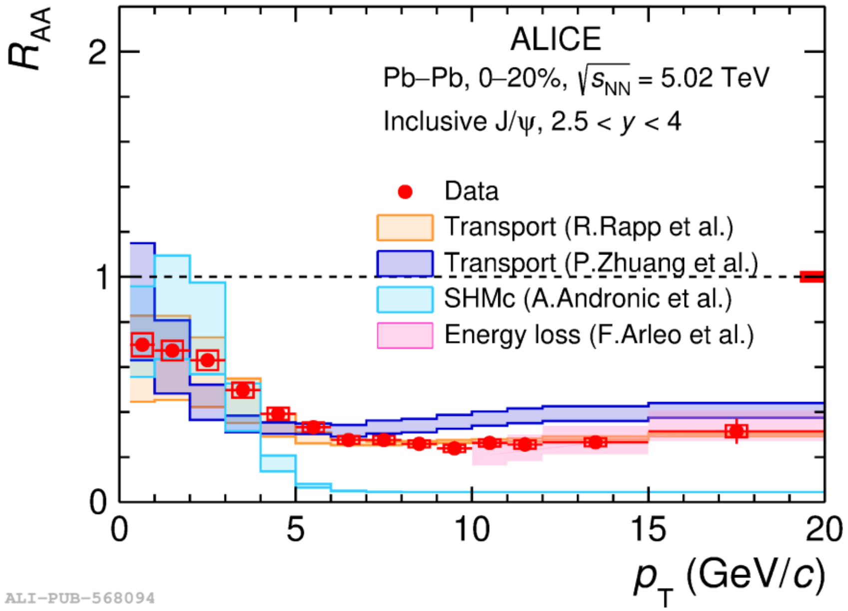
Model Comparison

Midrapidity



ALI-PUB-568084

Forward rapidity



ALI-PUB-568094

- For $p_{\rm T} > 10$ GeV/c, energy loss model describes the data very well
- Fragmentation of high-energy partons→ Dominant method of hadron production
- Energy loss due to multiple scattering→ Greater suppression at higher $p_{\rm T}$

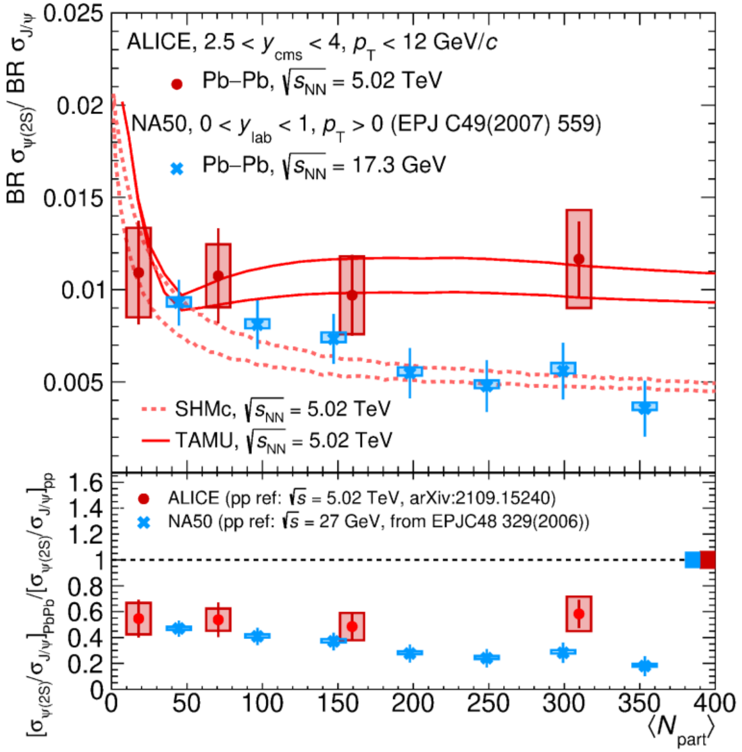
- SHMc model in good agreement with low-$p_{\rm T}$ $R_{\rm AA}$
- SHMc underestimates data for $p_{\rm T} > 5$ GeV/c

  →Missing sources: primordial J/ψ or non-prompt J/ψ from B-hadron

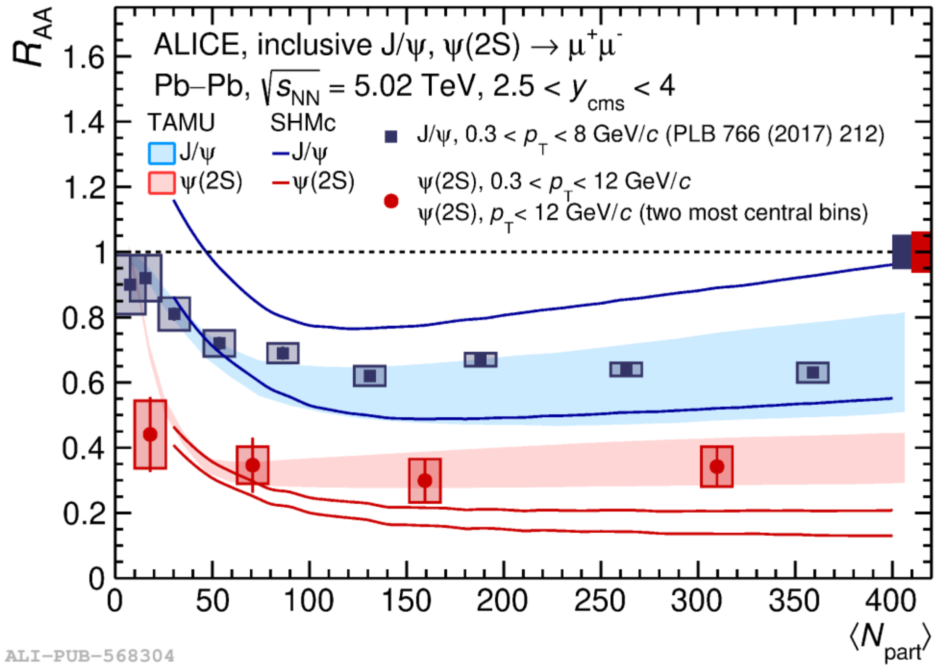
  →Underestimated amount of radial flow acquired by charm quarks
- Better quantitative agreement seen for the transport models than the SHMc model

ALICE Collaboration, Phys. Lett. B 849 (2024) 138451
SHMc: A. Andronic et al.,Phys. Lett. B 797 (2019) 134836
Transport: P. Zhuang et al., Phys. Rev. C 89 (2014) 054911
Transport: R. Rapp et al., Eur. Phys. J. A 57 (2021) 122

Nuclear Modification Factor (R_{AA}) for $\psi(2S)$



ALI-PUB-568299



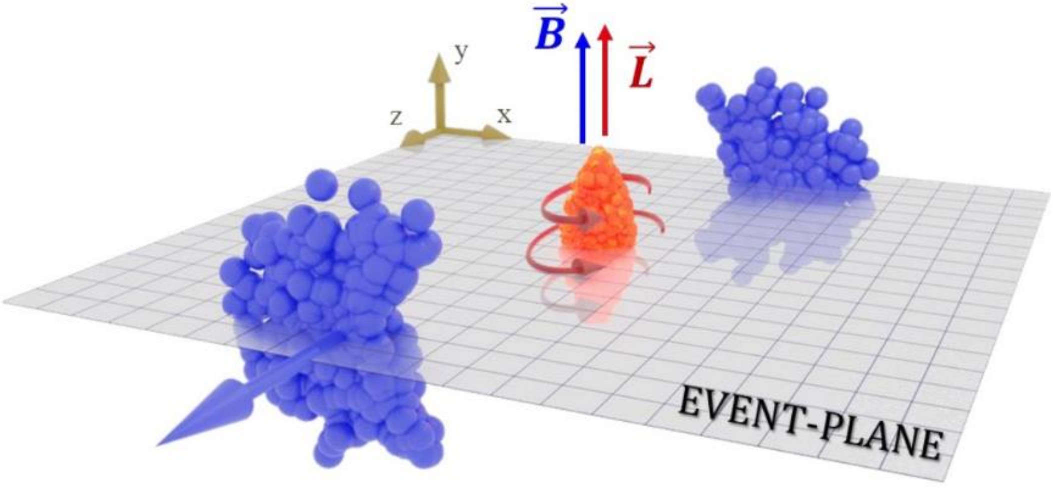
ALI-PUB-568304

ALICE Collaboration, Phys.Rev.Lett. 132 (2024) 4, 042301
TAMU: R. Rapp et al., Nucl. Phys. A. 943 (2015) 147
SHMc: A. Andronic et al., PLB 797 (2019) 134836

- $\psi(2S)$ is more suppressed than J/ψ due to its larger size and smaller binding energy→ Sequential melting
- Flat centrality dependence with slight increasing trend → first hint of (re)generation for $\psi(2S)$
- Larger $\psi(2S)$-to- J/ψ ratio at the LHC than SPS towards central collisions
- TAMU model reproduces R_{AA} for both J/ψ and $\psi(2S)$ and also $\psi(2S)$-to- J/ψ ratio
- SHMc underestimates $\psi(2S)$ R_{AA} and $\psi(2S)$-to- J/ψ ratio in central collisions

Polarization

- Polarization is the measurement of a particle's spin alignment in a given direction
- In two-body decays, the spin-alignment will be reflected in the angular distribution of the decay particles
- Polarization can be influenced by:
    1. Production of vorticity due to large angular momentum
    2. Creation of strong initial magnetic field

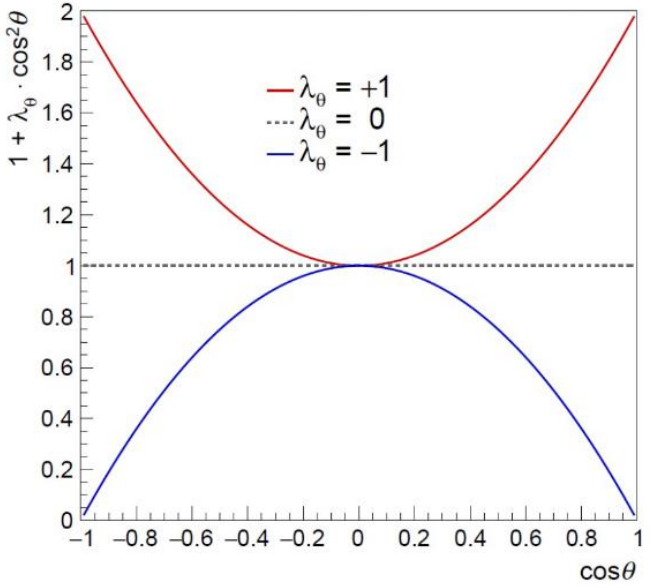


$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right)$$

$\lambda_\theta = 1$: Transverse Polarization

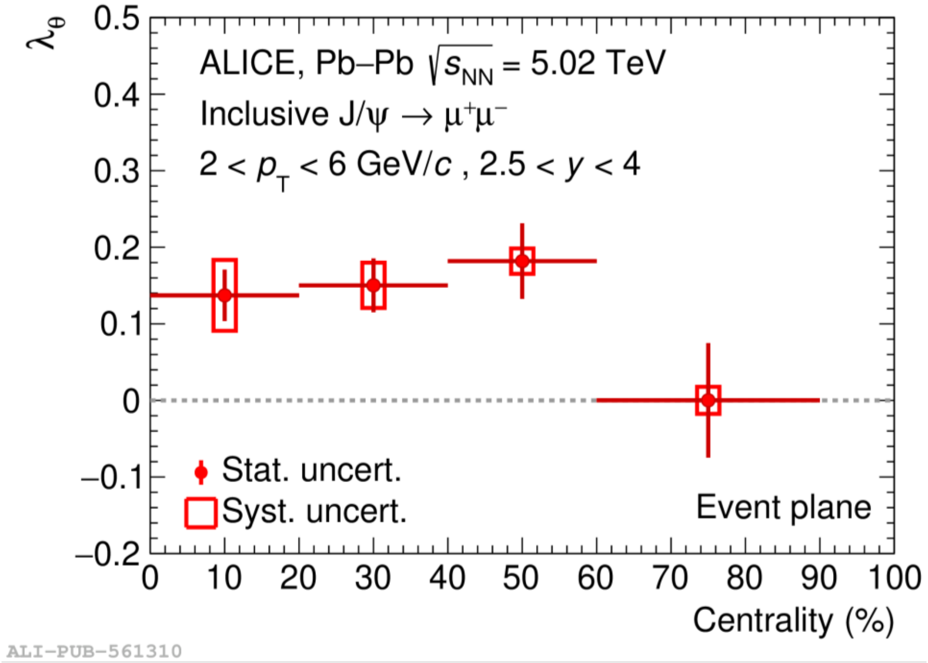
$\lambda_\theta = -1$: Longitudinal Polarization

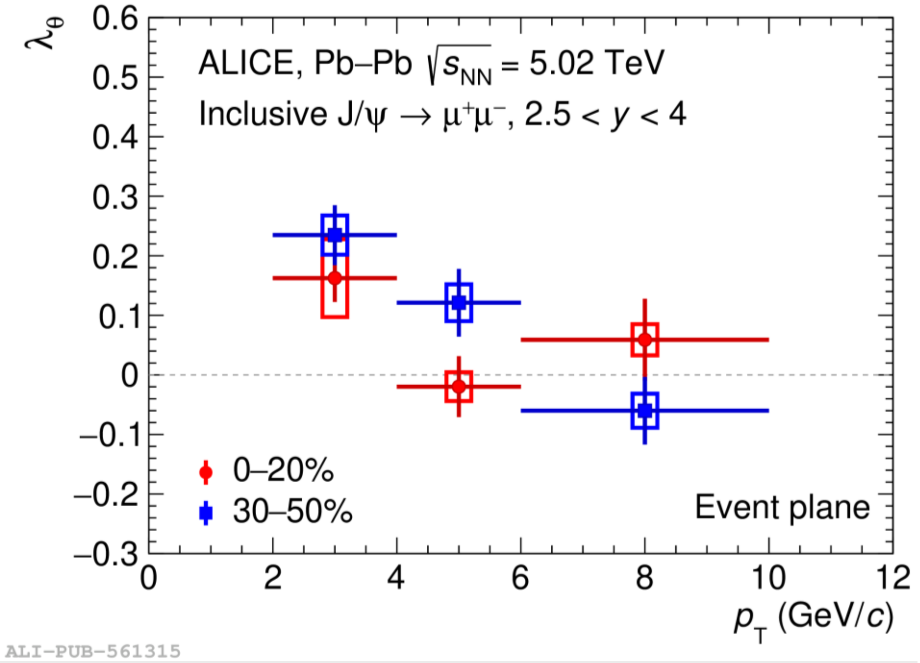
$\lambda_\theta = 0$: Unpolarized



P.Faccioli et. al., Eur. Phys. J. C 69, 657 (2010)
Kharzeev et al., NPA 803 (2008)
Becattini et al., PRC 77 (2008) 024906

Polarization of Inclusive J/ψ





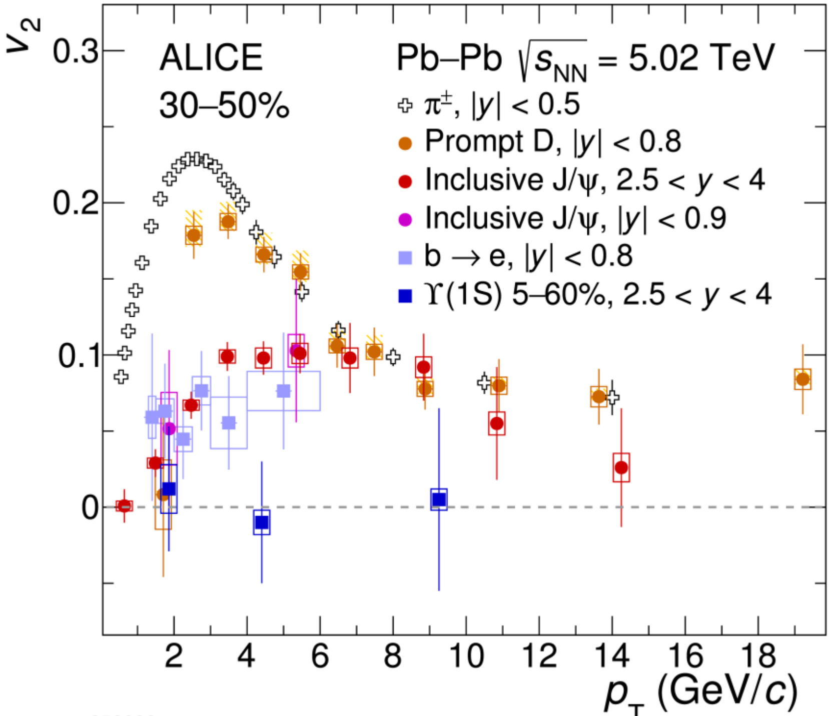
$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right)$$

Finite polarization condition $\lambda_\theta \neq 0$

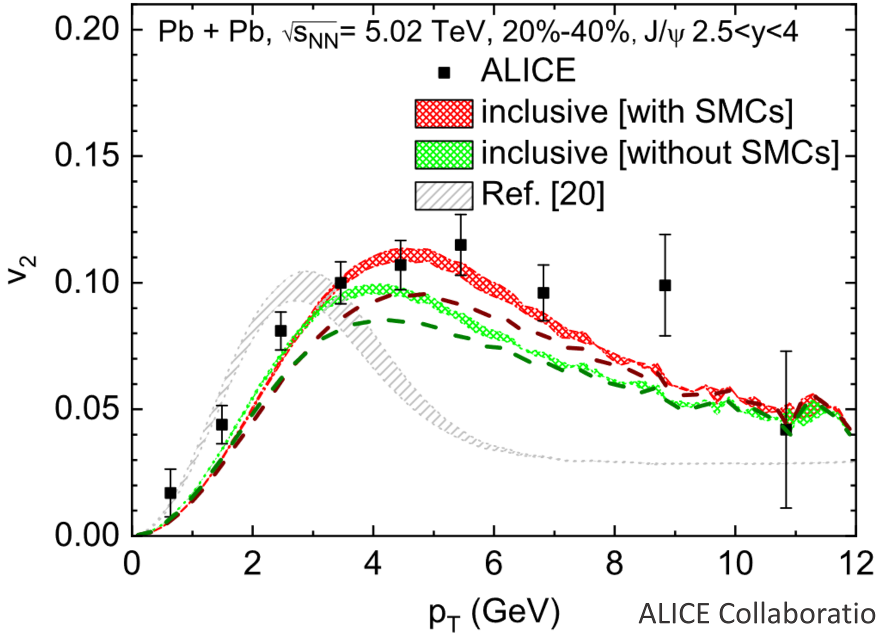
ALICE Collaboration, Phys.Rev.Lett. 131 (2023) 042303
P.Faccioli et. al., Eur. Phys. J. C 69, 657 (2010)
Kharzeev et al., NPA 803 (2008)
STAR Collaboration, Nature 548, 62 (2017)
PRC 77 (2008) 024906

- First measurement of inclusive J/ψ polarization with respect to the event plane of the collision
- Small but significant transverse polarization at low p_{T} in midcentral collisions→ potential polarization from parent beauty hadrons
- Effect could be connected to large vorticity and/or existence of a strong initial magnetic field

Elliptic Flow (v_2)



ALI-PUB-352028



ALICE Collaboration, JHEP 10 (2020) 141
Phys.Rev.Lett. 128 (2022) 16, 162301
Ref.[20]: : R. Rapp et al., Nucl. Phys. A. 943 (2015) 147
*SMC: space-momentum correlations

- Elliptic flow for J/ψ in midrapidity and forward rapidity compared to $\pi^{\pm}$, prompt D meson and $\Upsilon(1S)$
- Increasing trend up to mid p_T → flow of charm hadrons confirmed
- Both forward and midrapidity measurements are compatible → charm flow is independent of rapidity
- Clear mass hierarchy in low-p_T ($p_T < 6$ GeV/c)
- At high-p_T, all species converge into single curve → contribution from path-length dependent effects like energy loss

Summary

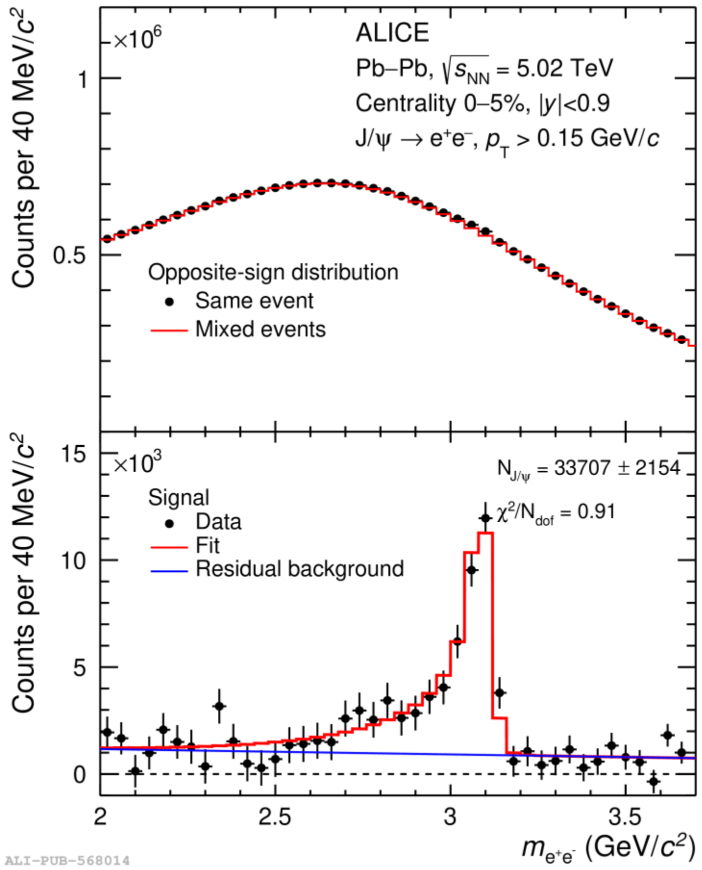
- Presented the LHC Run 2 results for Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the ALICE detectors
- **From Nuclear Modification factor**
  1. R_{AA} trend as a function of p_{T} and centrality supports the (re)generation scenario for both J/ψ, ψ(2S)
  2. Transport models with temperature dependent dissociation and coalescence terms are in agreement with data within the uncertainties
  3. No rapidity dependence of R_{AA} at high p_{T}
- **From Polarization**
  1. First measurement using the Event Plane frame
  2. Small but significant transverse polarization for J/ψ at low p_{T} in midcentral collisions
- **From Elliptic Flow**
  1. Possible existence of charm thermalization
  2. Finite elliptic flow for D meson and J/ψ, almost zero elliptic flow for $\Upsilon(1S)$
  3. At higher p_{T}, particle species independent flow is observed

Thank you

Back Up

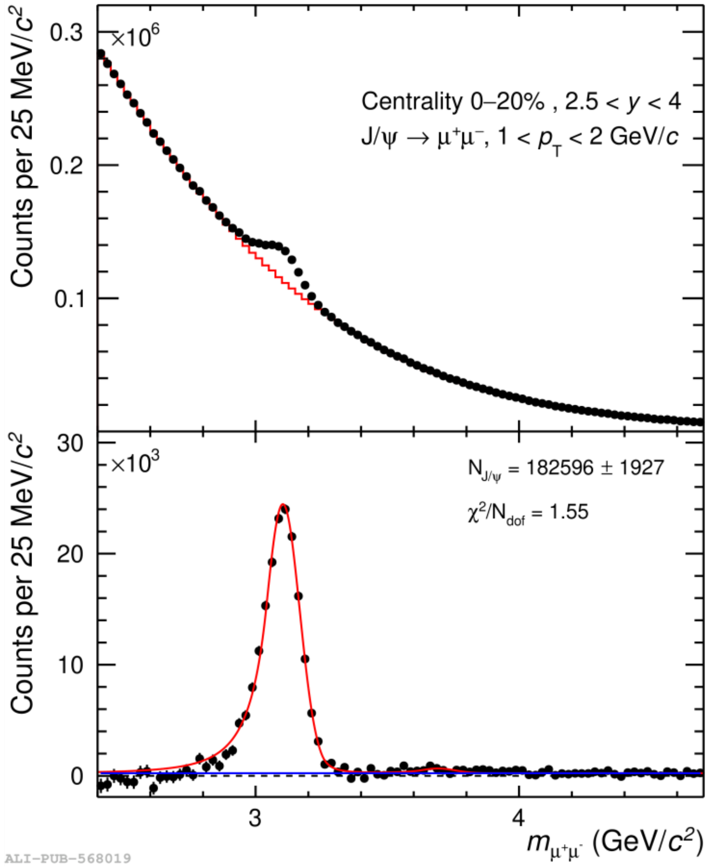
Signal Extraction

Midrapidity



ALI-PUB-568014

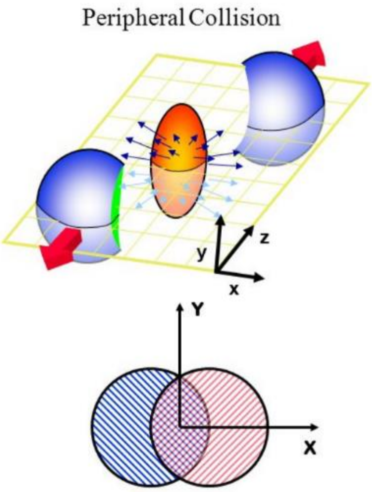
Forward rapidity

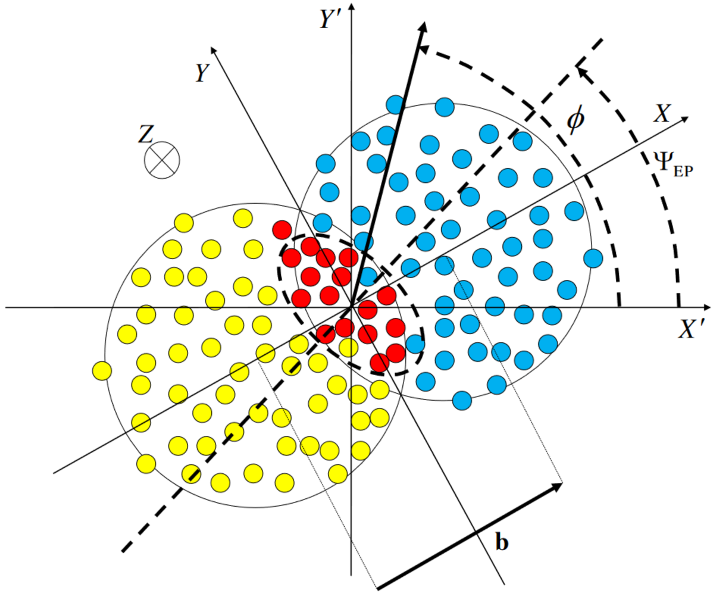


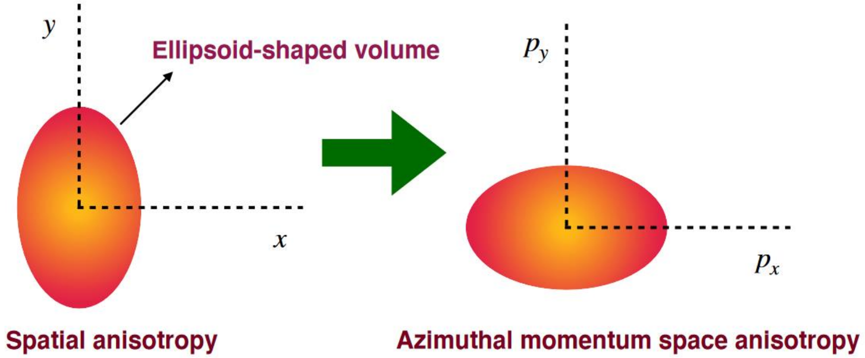
ALI-PUB-568019

Phys. Lett. B 849 (2024) 138451

Anisotropic Flow







$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_{\rm T}dp_{\rm T}dy}\left[1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_{\rm EP})]\right]$$

$$v_n(p_{\rm T},y) = \langle\cos(n(\phi-\Psi_{\rm EP}))\rangle$$

- Initial spatial anisotropy in noncentral heavy-ion collisions creates anisotropic pressure gradients
- In presence of a medium, the pressure gradients get converted into final state momentum anisotropy
- Transverse collective expansion characterized by different flow coefficients (e.g. $n = 2$, v_2 is elliptic flow)
- Depends on the transport coefficients (η/s, ζ/s) and the equation of state of the system

U. Heinz and R. Snellings, Annu. Rev. Nucl. Part. Sci. 63, 123 (2013).
CMS Collaboration, JHEP02(2024)106

Theoretical Models

- **Statistical Hadronization Model (SHM):**
  1. All charm quarks are produced during the initial hard partonic interactions (no feed-down)
  2. Assumes charm thermalization in QGP
  3. Yield of charmed hadrons are determined at chemical freeze-out from thermal weights obtained from light-flavored hadrons
- **Transport Model (P. Zhuang et al.):**
  1. Real time evolution of J/ψ, $\psi(2S)$, and χ_c production using Boltzmann-type rate equation
  2. Includes both dissociation and coalescence terms
  3. Includes non-prompt J/ψ with beauty quarks being propagated through QGP using Langevin equation
- **Transport Model (R. Rapp et al.):**
  1. Similar transport model based on kinetic rate equation for real time evolution of J/ψ, $\psi(2S)$, and χ_c
  2. Dissociation term employs an inelastic parton scattering cross section (from NLO pQCD)
  3. Includes effect of in-medium reduced binding energy
  4. Charmonium dissociation temperature obtained from lattice QCD calculations

SHMc: A. Andronic et al.,Phys. Lett. B 797 (2019) 134836
Transport: P. Zhuang et al., Phys. Rev. C 89 (2014) 054911
Transport: R. Rapp et al., Eur. Phys. J. A 57 (2021) 122