Quarkonium anisotropic flow and nuclear modification factor in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with ALICE

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University of Oslo

Quarkonium production in heavy-ion collisions

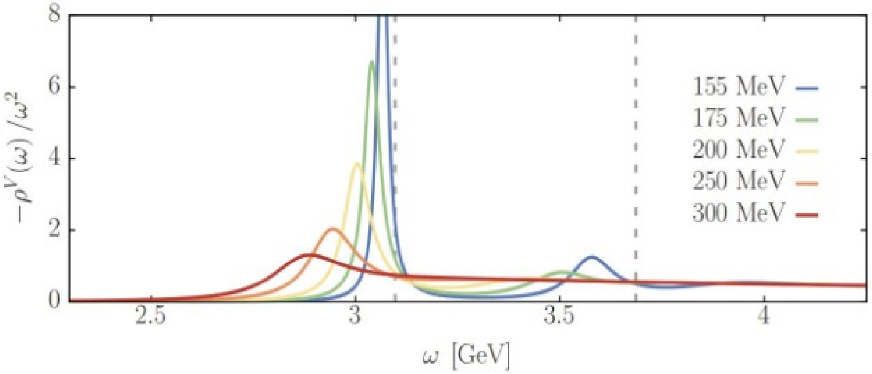
Heavy quarks (charm and beauty) in the Quark–Gluon Plasma (QGP):

- Produced early in the collision, through **hard partonic scatterings** → experience the entire evolution of the system

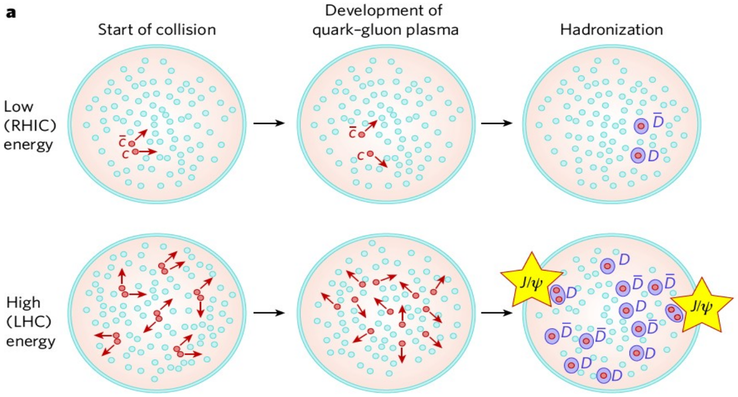
Quarkonium production:

- Probe in-medium QCD force (de-confinement)
- Medium transport properties
- **Suppression** due to color screening and medium-induced dissociation Matsui and Satz, PLB 178 (1986) 416
- **At LHC energies**: large $c\bar{c}$ pairs production → stronger **regeneration** effects

In-medium S-wave spectral functions for charmonium

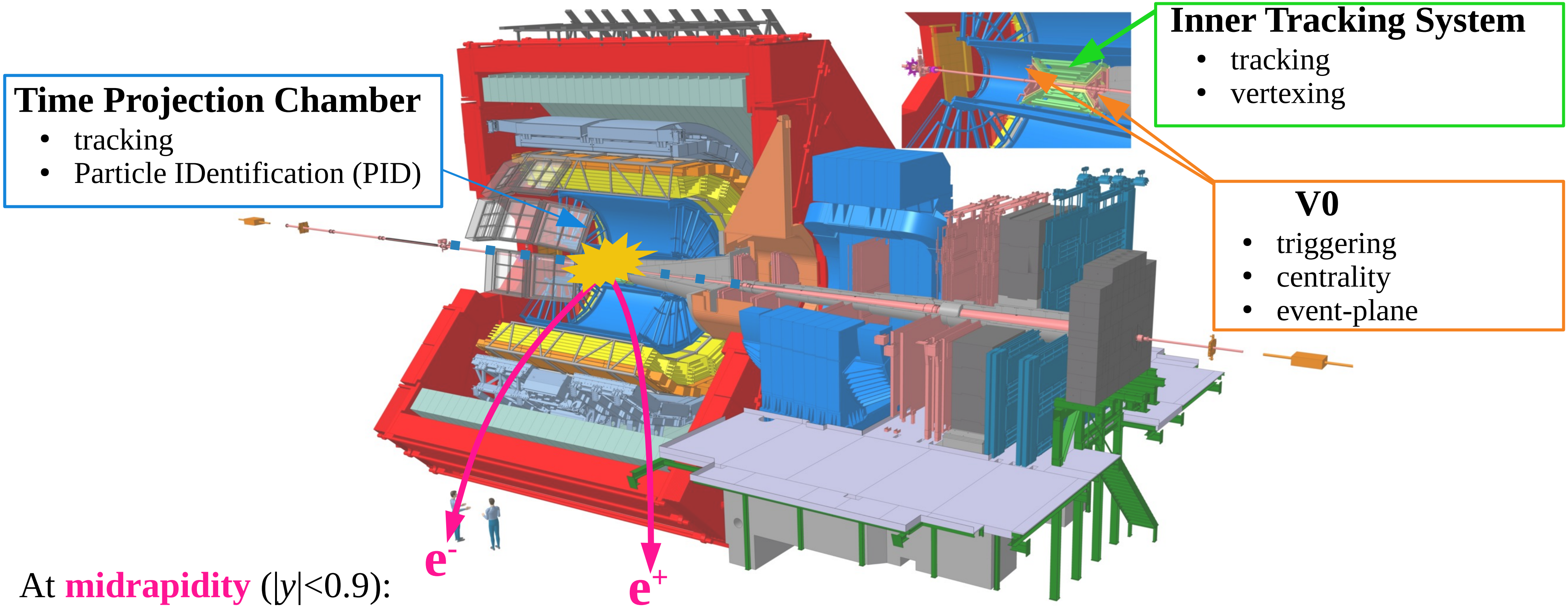


Lafferty, Rothkoph PRD 101 (2020) 056010



Braun-Munzinger, Stachel, PLB 490 (2000) 196,
Braun-Munzinger, Stachel, Nature 448 (2007) 302
Thews, Schroedler, Rafelski, PRC 63 (2001) 054905

ALICE (A Large Ion Collider Experiment)



Time Projection Chamber

- tracking
- Particle IDentification (PID)

Inner Tracking System

- tracking
- vertexing

V0

- triggering
- centrality
- event-plane

At **midrapidity** ($|y|<0.9$):

- Dielectron decay channel
- Inclusive J/ψ measurements down to $p_T = 0$
- Separation of **prompt** and **non-prompt** J/ψ (proxy for open beauty hadrons)

Int. J. Mod. Phys. A 29 (2014) 1430044

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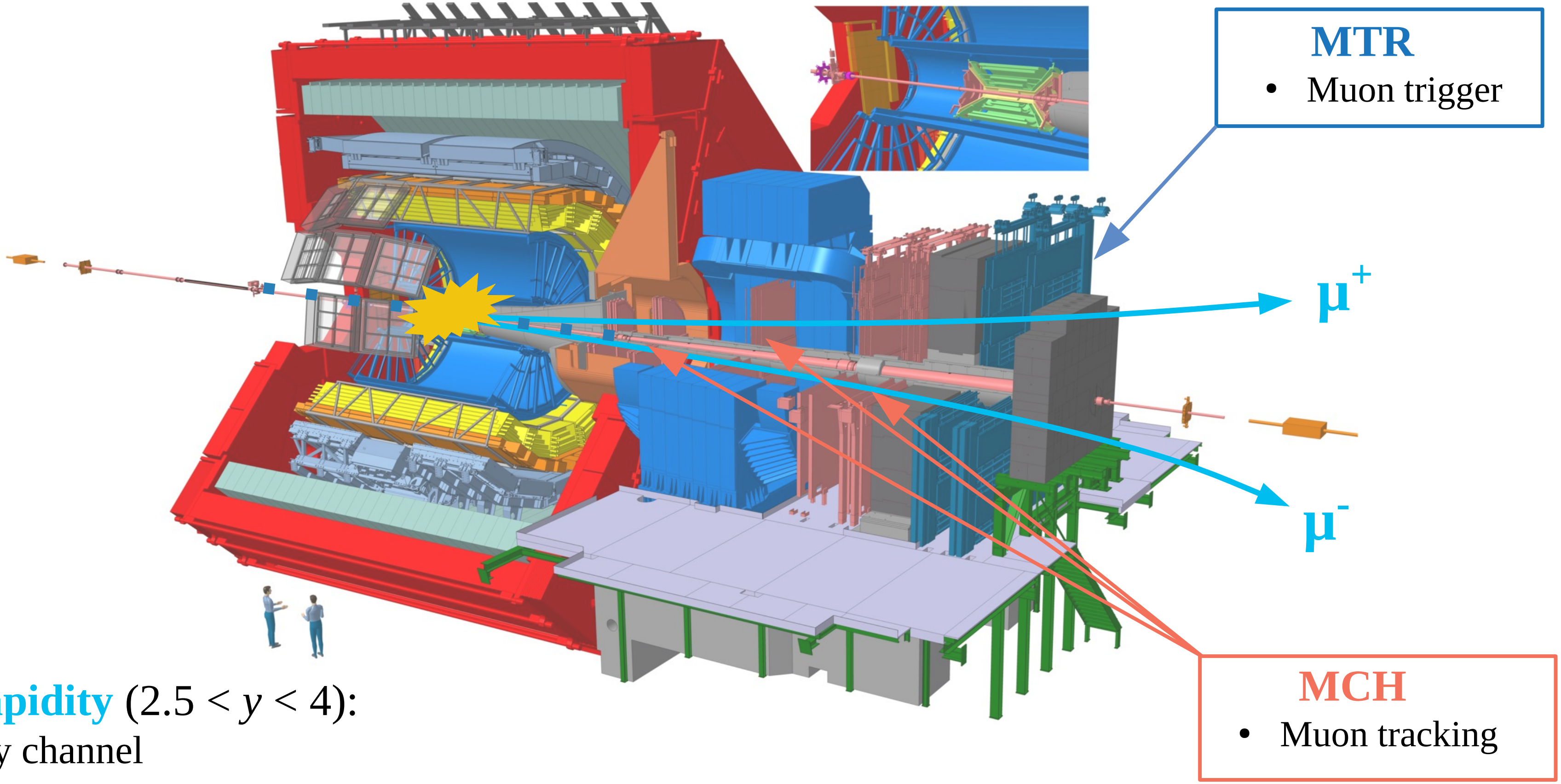


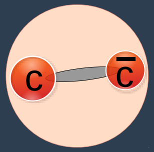
MTR
- Muon trigger

MCH
- Muon tracking

At **forward rapidity** ($2.5 < y < 4$):
- Dimuon decay channel
- Several charmonia and bottomonia states measured (J/ψ, ψ(2S), Υ(1S), Υ(2S))
- Inclusive quarkonium measurements down to $p_T = 0$

Int. J. Mod. Phys. A 29 (2014) 1430044

Charmonium



J/ψ nuclear modification factor

- Medium effects are quantified via the **nuclear modification factor** R_{AA}:

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \times \frac{(dN/dy)_{\mathrm{AA}}}{(dN/dy)_{\mathrm{pp}}}$$

$\mathrm{N}_{\mathrm{coll}}$ - number of binary collisions

No modification → $R_{\mathrm{AA}} = 1$

Enhancement → $R_{\mathrm{AA}} > 1$

Suppression → $R_{\mathrm{AA}} < 1$

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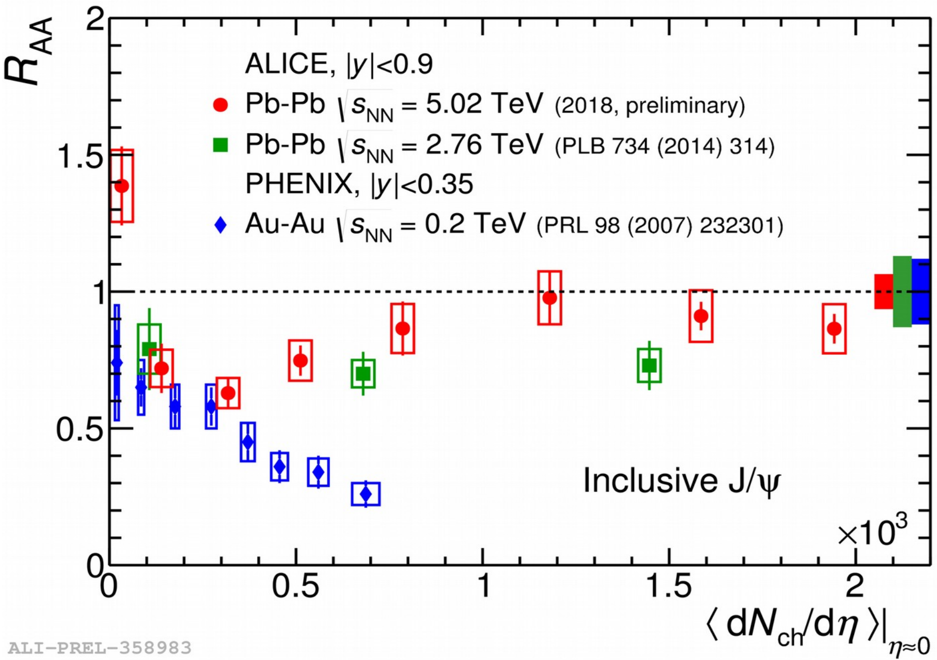
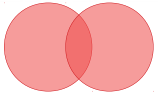
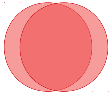
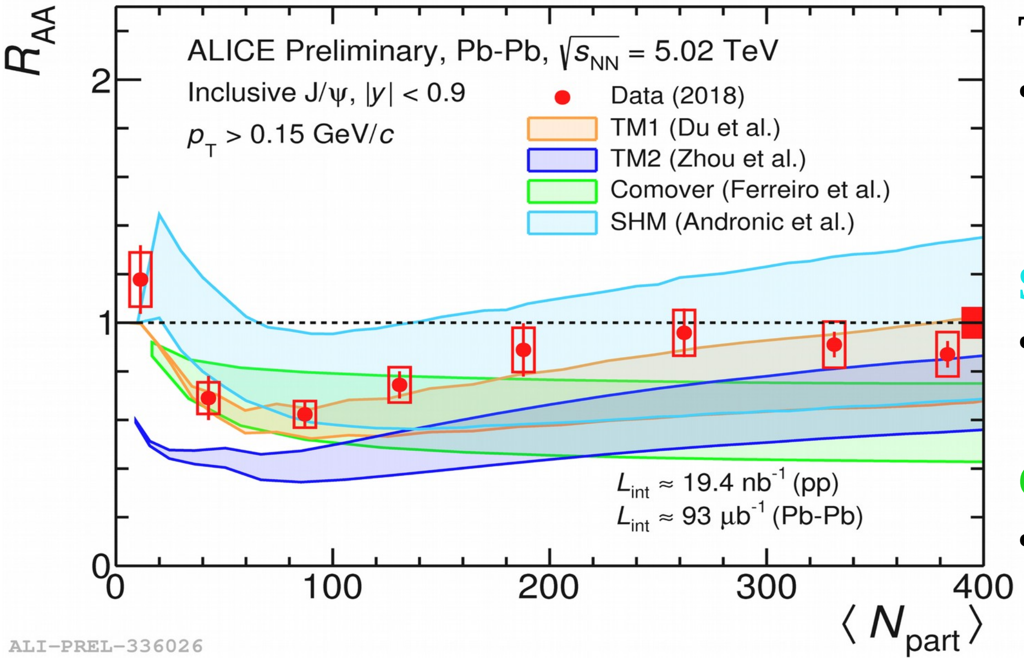






- Similar suppression observed at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV
- J/ψ R_{AA} larger at LHC than at RHIC despite the much larger energy density

J/ψ R_{AA} vs centrality – comparison to models



Transport Models (TM1, TM2)

- Continuous dissociation and regeneration in QGP and hadronic phase

Du et al., NPA 943 (2015) 147, Zhou et al., PRC 89 (2014) 054911

Statistical Hadronization Model (SHM)

- All charmed particles generated at the chemical freeze-out Andronic et al., PLB 797 (2019) 134836

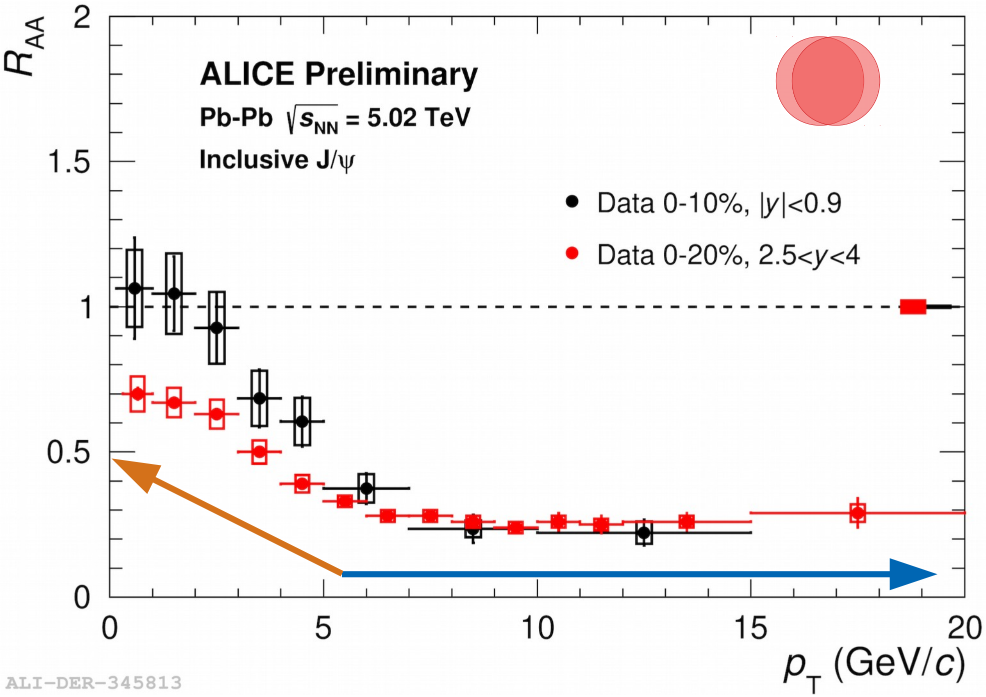
Comover interaction model

- Suppression via comovers and J/ψ regeneration

Ferreiro, PLB 731 (2014) 57-63

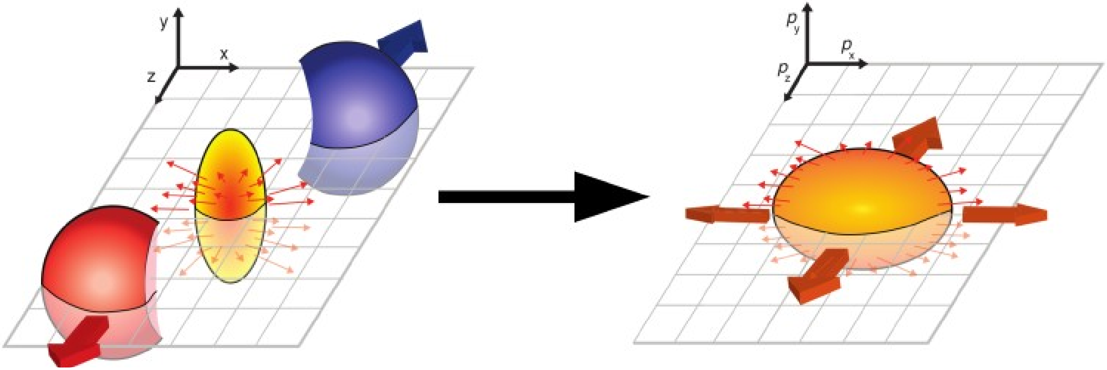
- Agreement with models that implement a certain amount of regeneration

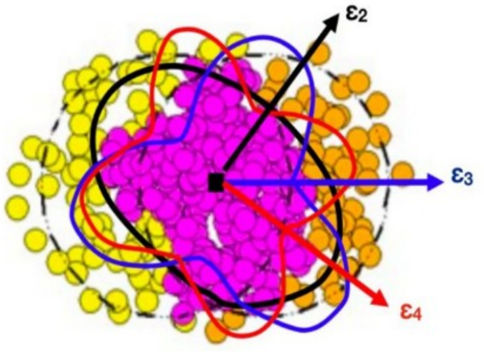
J/ψ R_{AA} vs p_T



- **Low p_T**: J/ψ suppression strongly depends on rapidity
    - In the regeneration scenario this is explained by higher charm cross section at midrapidity
- **High p_T**: strong J/ψ suppression, independent of rapidity and p_T up to 20 GeV/c (energy loss effects)

Anisotropic flow





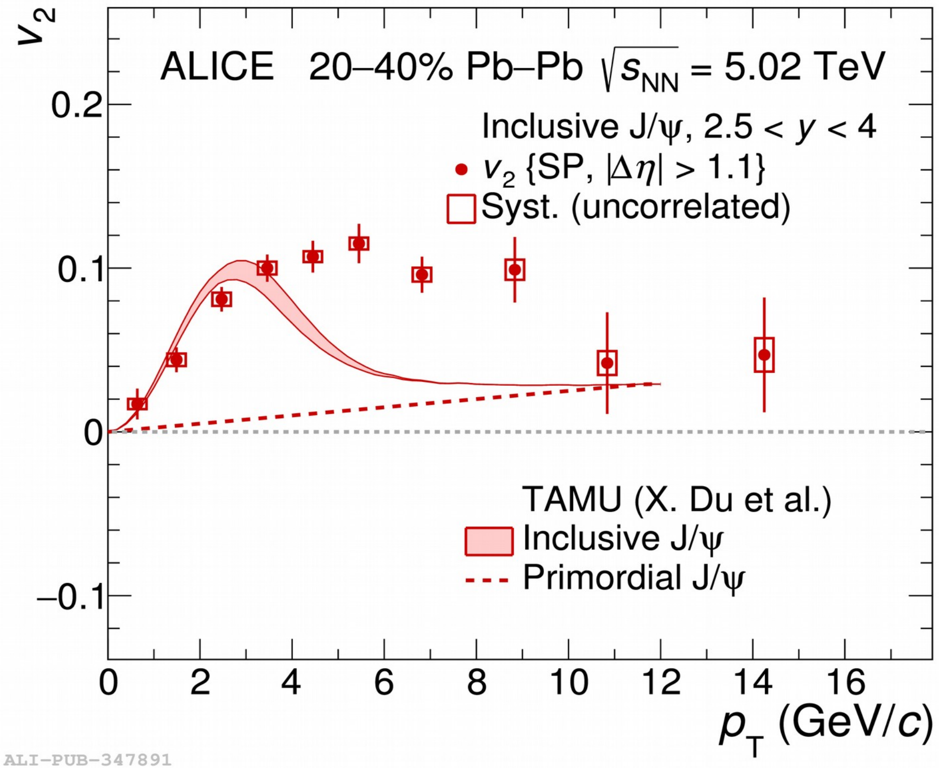
- Initial spatial anisotropy → momentum-space anisotropy due to the pressure gradients inside QGP

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi_n\right)\right)\right) \qquad v_n=\langle\cos\left(n\left(\phi-\Psi_n\right)\right)\rangle$$

- Anisotropic flow quantified via v_n coefficients of Fourier expansion of particle azimuthal distribution
- At low-p_T: sensitive to bulk QGP properties
- At high-p_T: sensitive to in medium energy loss and path length effects

J/ψ elliptic flow

JHEP 10 (2020) 141



- Significant positive J/ψ v_2 up to high p_T
- **Low p_T (p_T < 5 GeV/*c*)**: Large v_2 (expected for J/ψ production via regeneration)
- **High p_T**: v_2 remains high up to 15 GeV/*c*
  - Underestimated by transport model
  - Challenging for models to describe both R_{AA} and v_2 → missing mechanism (e.g. energy loss) ?

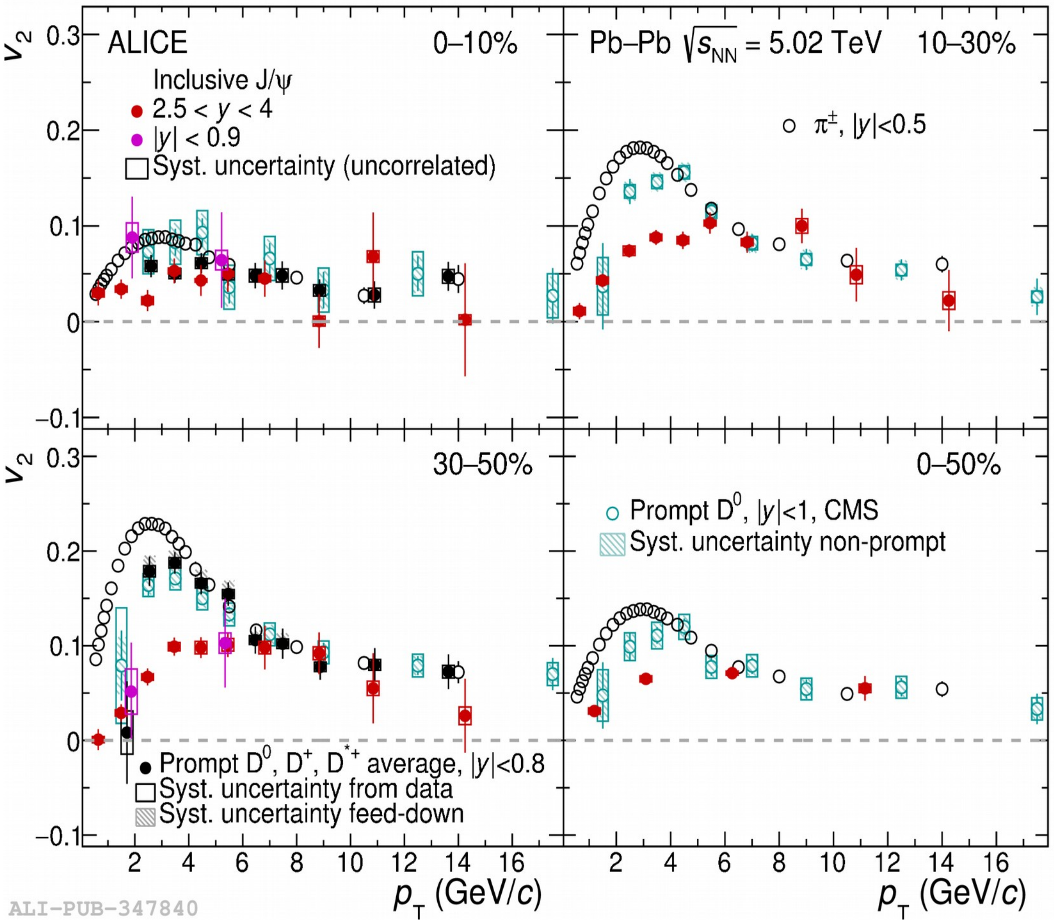
J/ψ v_2 results vs D-mesons vs $\pi^{\pm}$

- Clear mass ordering at **low p_T** ($v_2^{\pi} > v_2^{D} > v_2^{J/\psi}$)
- $v_2^{\pi} \approx v_2^{D} \approx v_2^{J/\psi}$ at **high p_T**
  - Constraints for in-medium energy loss models
- v_2 grows from central to semi-central collisions
- Positive J/ψ v_2 at midrapidity with 3σ significance
- Measurements of J/ψ v_2 at mid- and forward-y are compatible

J/ψ: JHEP 10 (2020) 141

D: ALICE, PLB 813 (2021) 136054 ; CMS, PRL 120 (2018) 202301

π: JHEP 1809 (2018) 006



ALI-PUB-347840

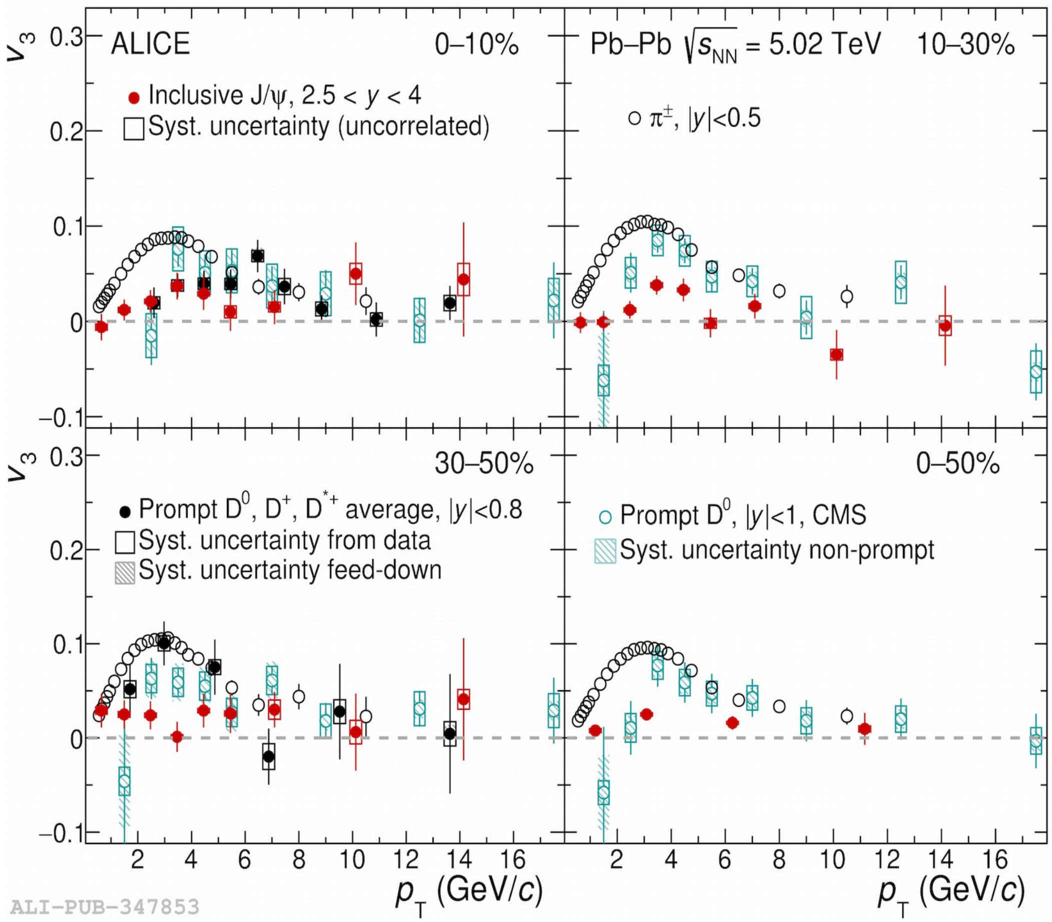
J/ψ v_3 results vs D-mesons vs $\pi^{\pm}$

- Observation of a positive J/ψ v_3 at forward-y in both central and semi-central collisions
- Mass hierarchy at low p_T also holds for the triangular flow
- v_3 shows weak centrality dependence

J/ψ: JHEP 10 (2020) 141

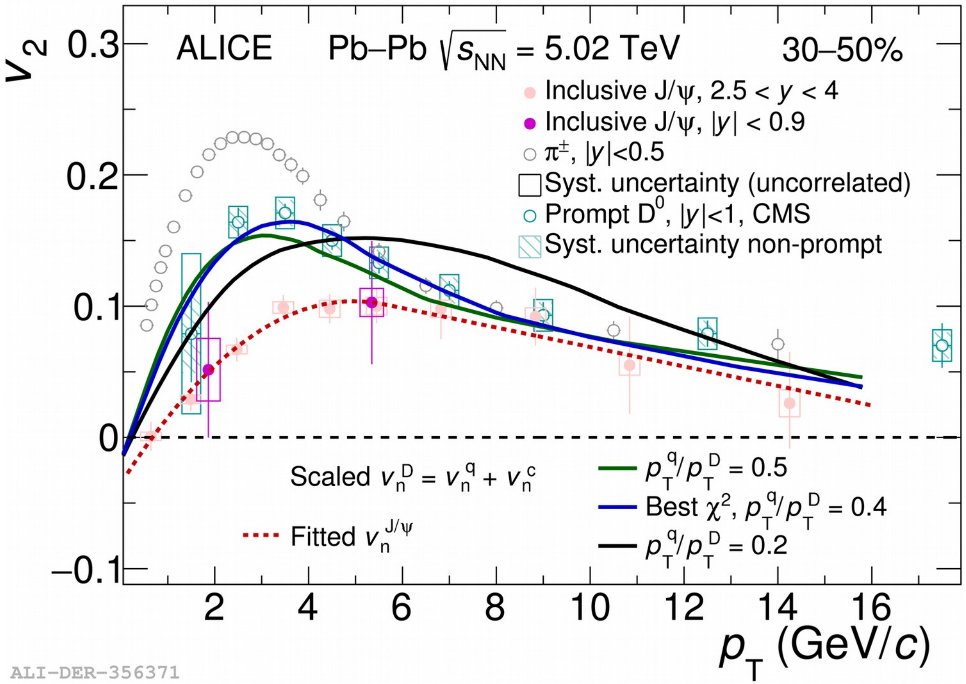
D: ALICE, PLB 813 (2021) 136054 ; CMS, PRL 120 (2018) 202301

π: JHEP 1809 (2018) 006



Constituent-quark scaling

JHEP 10 (2020) 141



- D-meson flow obtained as:

$$v_2^D(p_T^D) \propto v_2^q(p_T^q) + v_2^c(p_T^c)$$

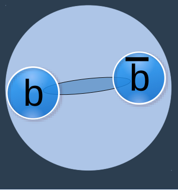
$$v_2^{u,d}(p_T^q) = v_2^\pi(2p_T^q)/2$$

$$v_2^c(p_T^c) = v_2^{J/\psi}(2p_T^c)/2$$

- Need assumption on quark p_T sharing:
  - → $p_T^q/p_T^D = 0.2$
  - → $p_T^q/p_T^D = 0.4$
  - → $p_T^q/p_T^D = 0.5$

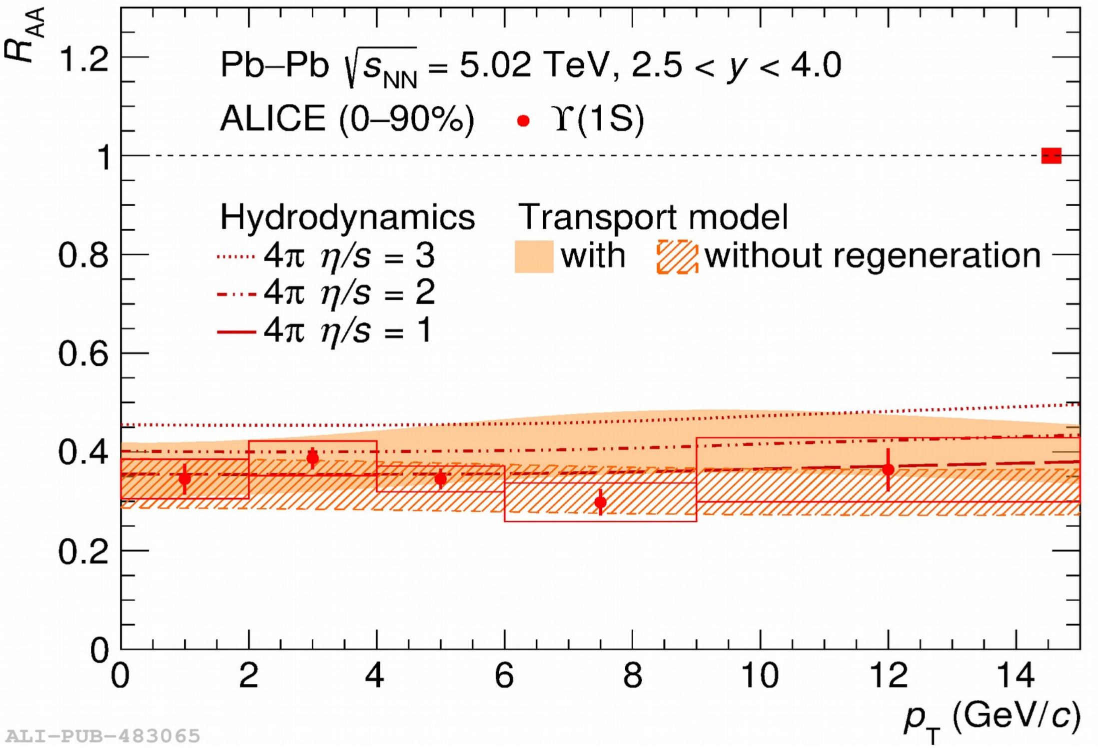
- Extension of the quark coalescence picture to describe D-meson flow:
  - Consider two flow components, one for the light and the other for the charm quarks
  - Assumption on the p_T sharing between the constituent quarks in D-meson
    - Counter-intuitively, equal or nearly equal p_T sharing gives the best agreement

Bottomonium



Υ(1S) R_{AA} vs p_T

arXiv:2011.05758



Transport model

Du et al., PRC 96 (2017) 054901

- Interplay of dissociation and regeneration inside QGP
- Medium evolves as an expanding isotropic fireball

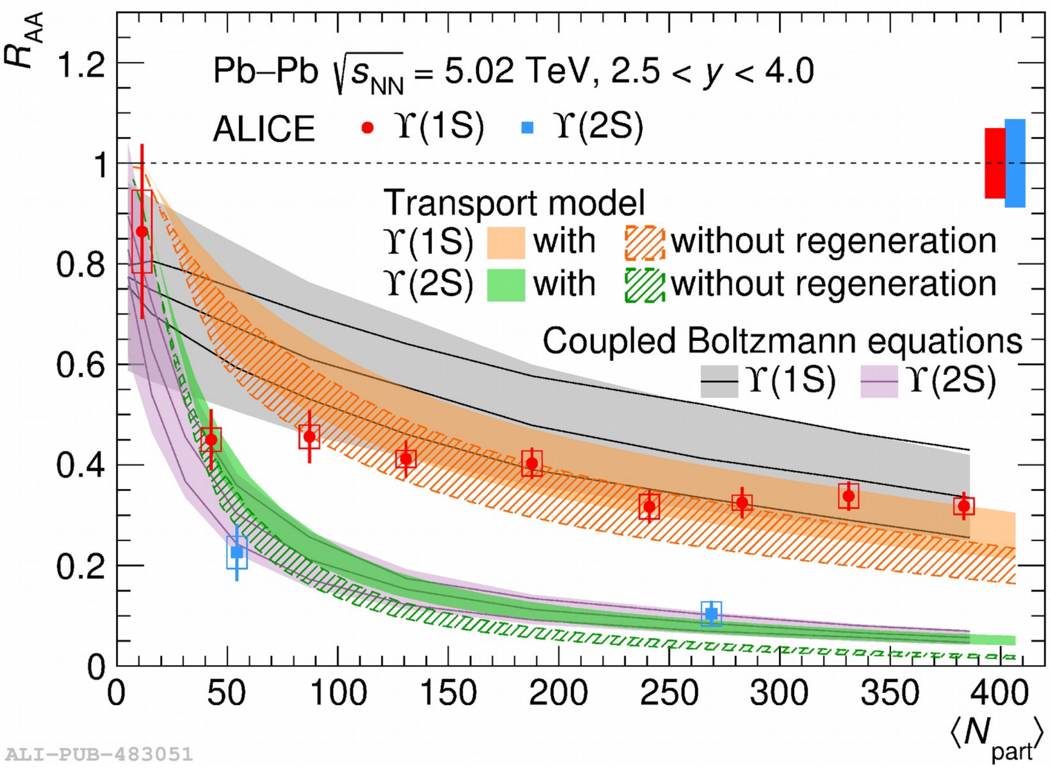
Hydrodynamical model

Krouppa,Strickland, Universe 2016 2(3) 16

- Thermal modification of heavy-quark potential inside anisotropic plasma
- Medium is described with viscous hydrodynamics
- Regeneration phenomenon is not included

- Υ(1S) R_{AA} shows no significant dependence on p_T
- In agreement with hydrodynamic and transport model expectations

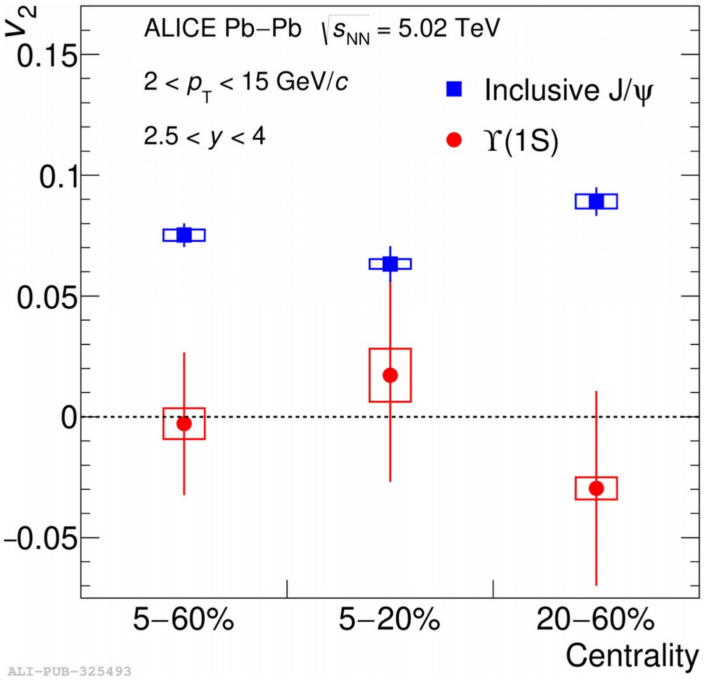
Υ R_{AA} vs centrality

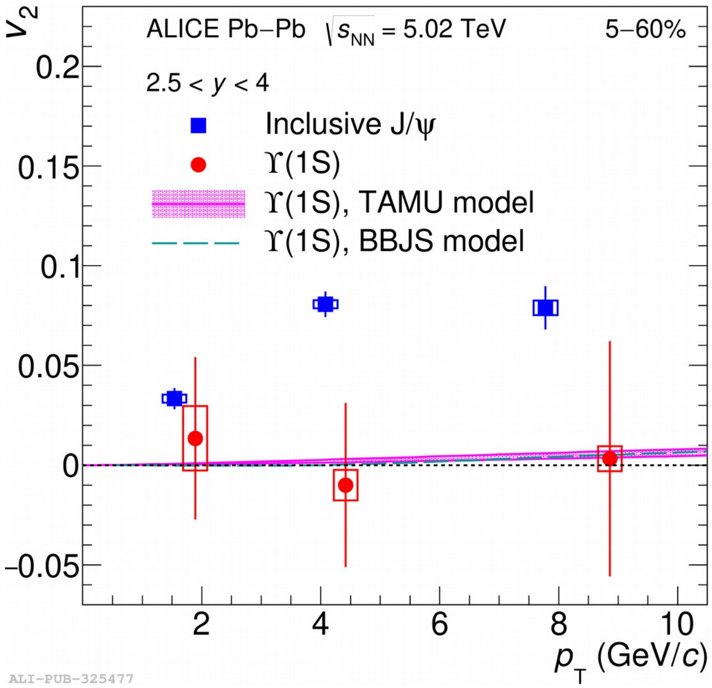


- Stronger suppression towards the most central collisions, in agreement with the model calculations
- Υ(2S) R_{AA} smaller by a factor 3 than Υ(1S)

ϒ (1S) elliptic flow

PRL 123 (2019) 192301





TAMU: Du et al., PRC 96 (2017) 054901

BBJS: Bhaduri et al., PRC 100 (2019) 051901

- ϒ(1S) v_2 compatible with 0, while all the other hadrons have a positive v_2
- ϒ(1S) v_2 lower with respect to J/ψ v_2 in $2 < p_T < 15$ GeV/c
- Latest CMS results confirm this measurement PLB 819 (2021) 136385
- In agreement with models predicting little regeneration (TAMU) or not (BBJS)

Summary

Charmonia

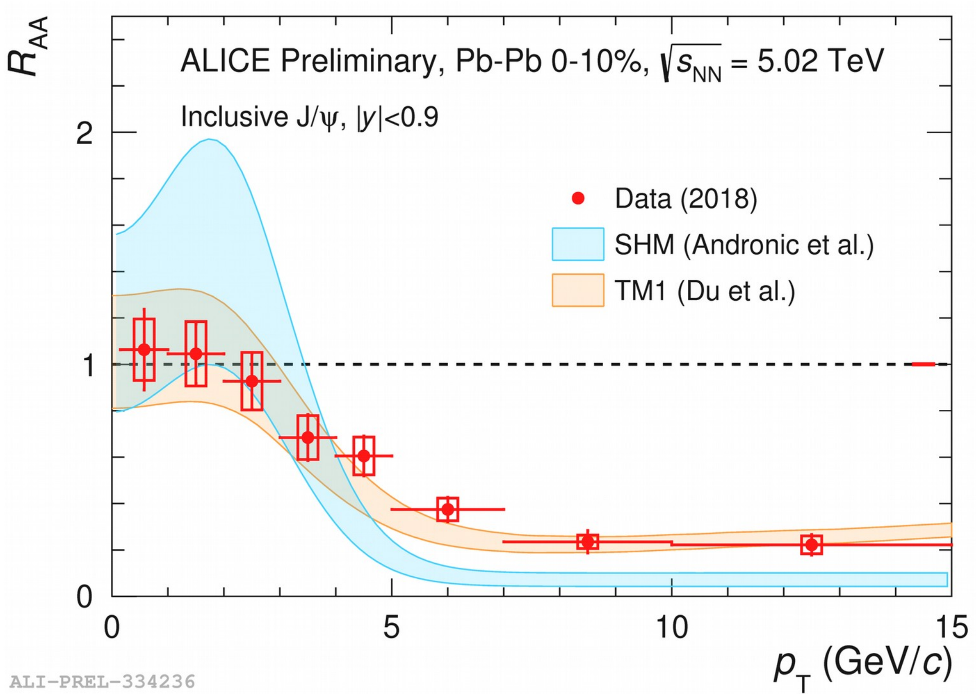
- J/ψ production predominantly via regeneration at low p_T
- Strong J/ψ suppression, independent of rapidity at high p_T
- J/ψ v_2 suggests charm quarks thermalization
- Clear mass hierarchy for both v_2 and v_3 at low p_T
- J/ψ and D-mesons are consistently described assuming a common underlying charm quark flow

Bottomonia

- Stronger suppression of Υ states in central collisions with Υ(2S) suppressed more than Υ(1S)
- No p_T dependence of Υ(1S) R_{AA}
- Υ(1S) v_2 consistent with 0

Backup

J/ψ R_{AA} vs p_T - comparison to models



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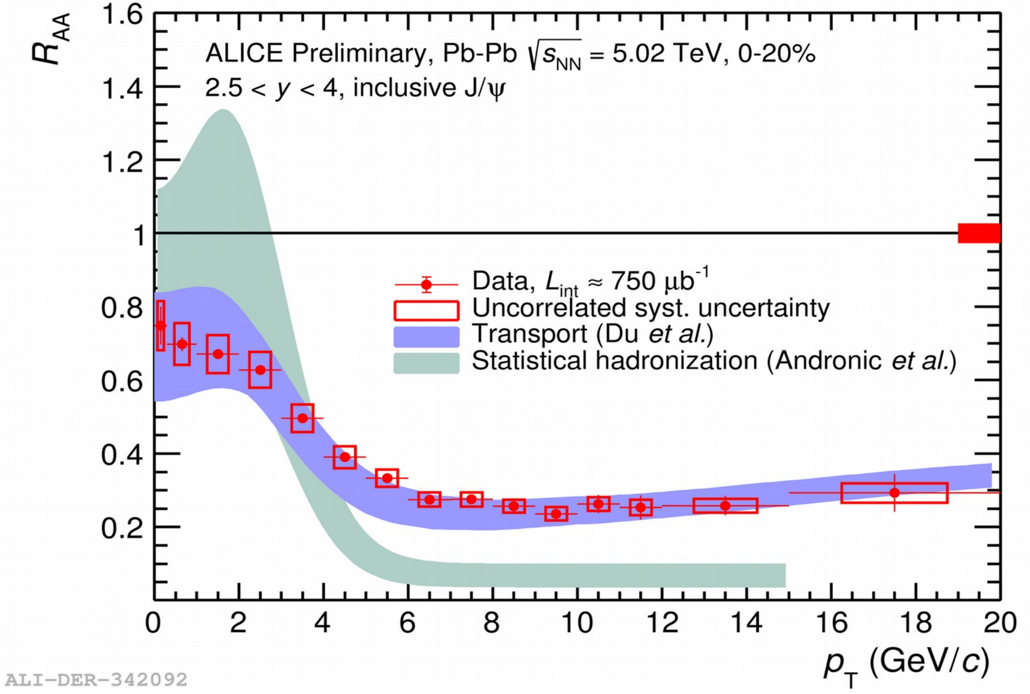


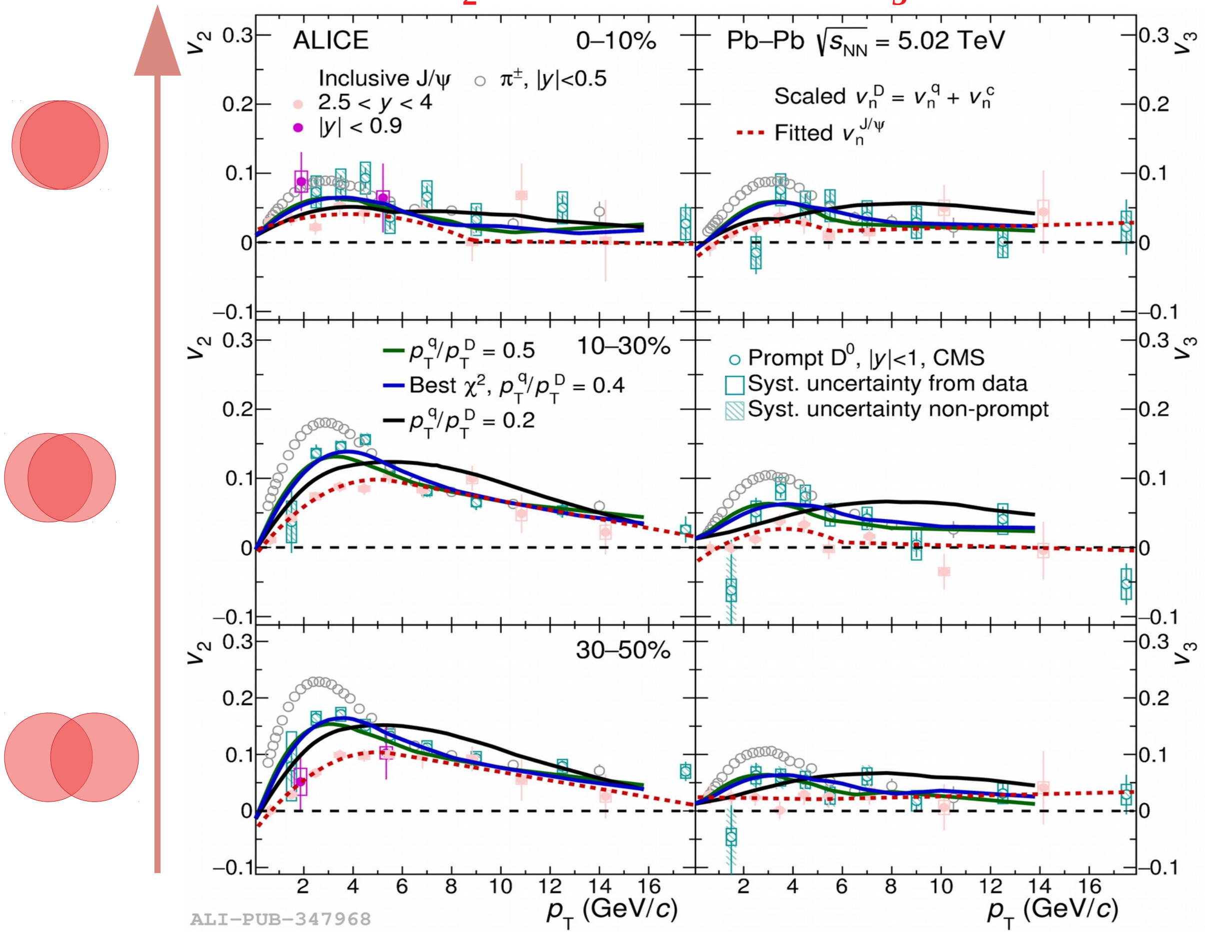
ALI-DER-342092

- Data described very well by TM1 over the whole p_T and rapidity range
- SHM calculation is used together with a hydrodynamic freezeout parameterization
  - Describes the data qualitatively for $p_T < 4$ GeV/c

Constituent-quark scaling

JHEP 10 (2020) 141

v_2 v_3



- Scaling works for both v_2 and v_3 over the entire p_T range and for all centrality classes
- Supports conclusion on recombination of flowing charmed quarks