Heavy Flavour and Quarkonia in Heavy-Ion Collisions: New Insights from RHIC and the LHC

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Hard probes in non-equilibrium QCD matter,
ICTS, Bangalore, March 2026

Why Heavy-Flavour Studies in Heavy-Ion Collisions?

Heavy quarks (c, b) provide **unique probes of the Quark–Gluon Plasma (QGP)** created in relativistic heavy-ion collisions.

Early production

- Heavy quarks are produced in **initial hard scatterings**
- Formation time $\sim 0.1\ fm/c$, earlier than QGP formation → they experience the **entire space–time evolution of the medium**

Well-controlled production

- Large masses $(m_c, m_b \gg \Lambda_{QCD})$
- Production calculable in **perturbative QCD**

Sensitive probes of QGP properties

Heavy-flavour measurements provide insight into:

- **Parton energy loss** in the medium
- **Heavy-quark diffusion and transport coefficients**
- **Degree of thermalization of heavy quarks**
- **Hadronization mechanisms (fragmentation vs recombination)**

Complementary probes

- **Open heavy flavour** → heavy-quark transport
  Quarkonia → color screening and regeneration dynamics

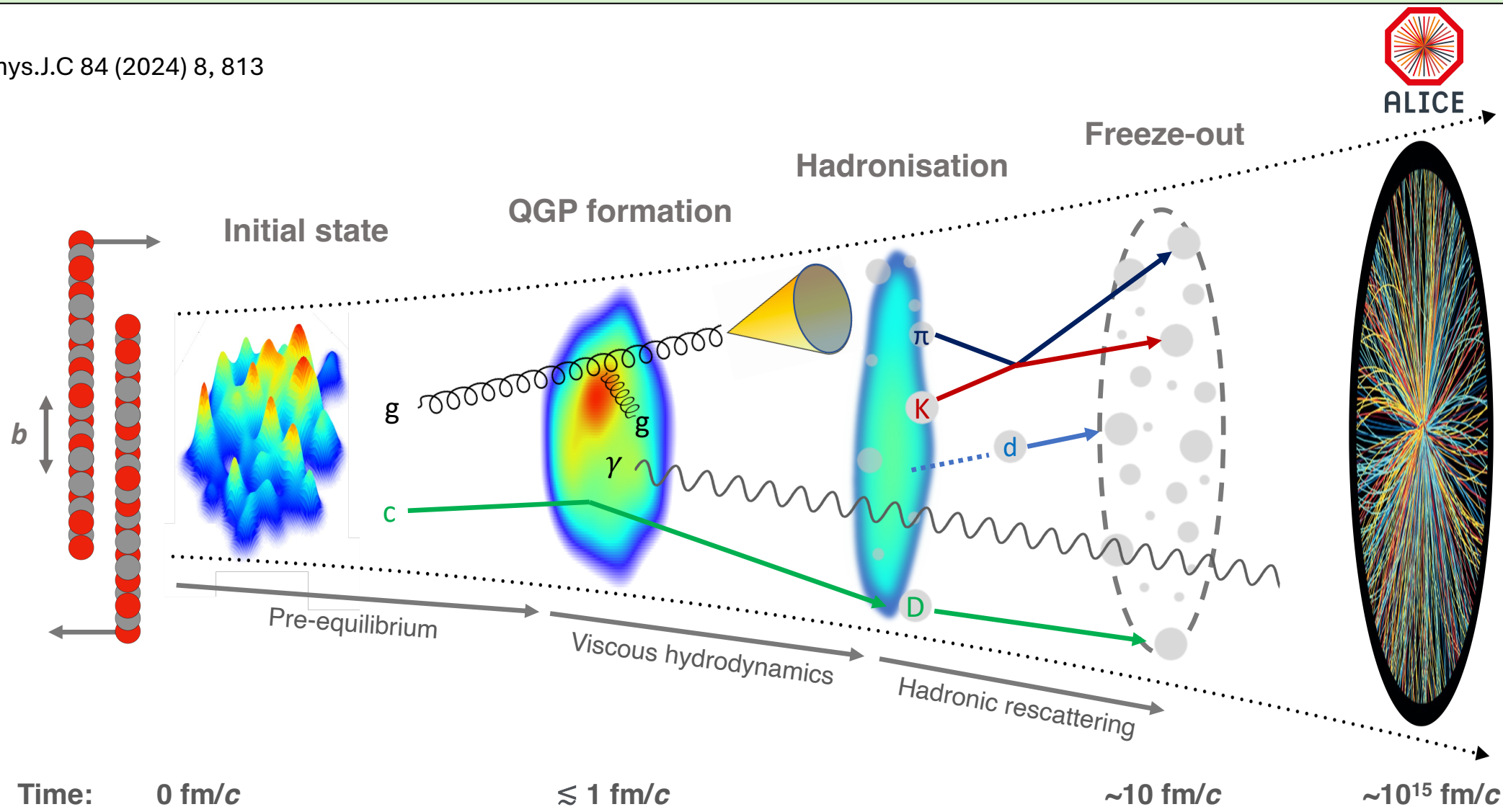
Quark Gluon Plasma: produced at RHIC & LHC

RELATIVISTIC HEAVY ION COLLIDER

LARGE HADRON COLLIDER

Relativistic heavy-ion collisions

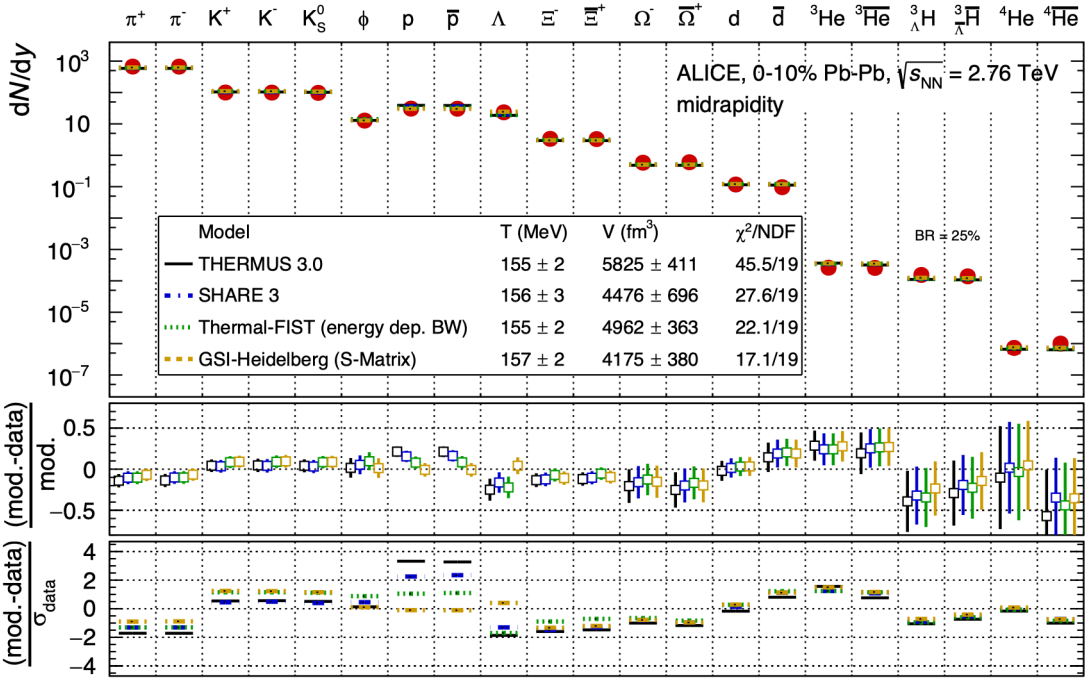
ALICE: Eur.Phys.J.C 84 (2024) 8, 813

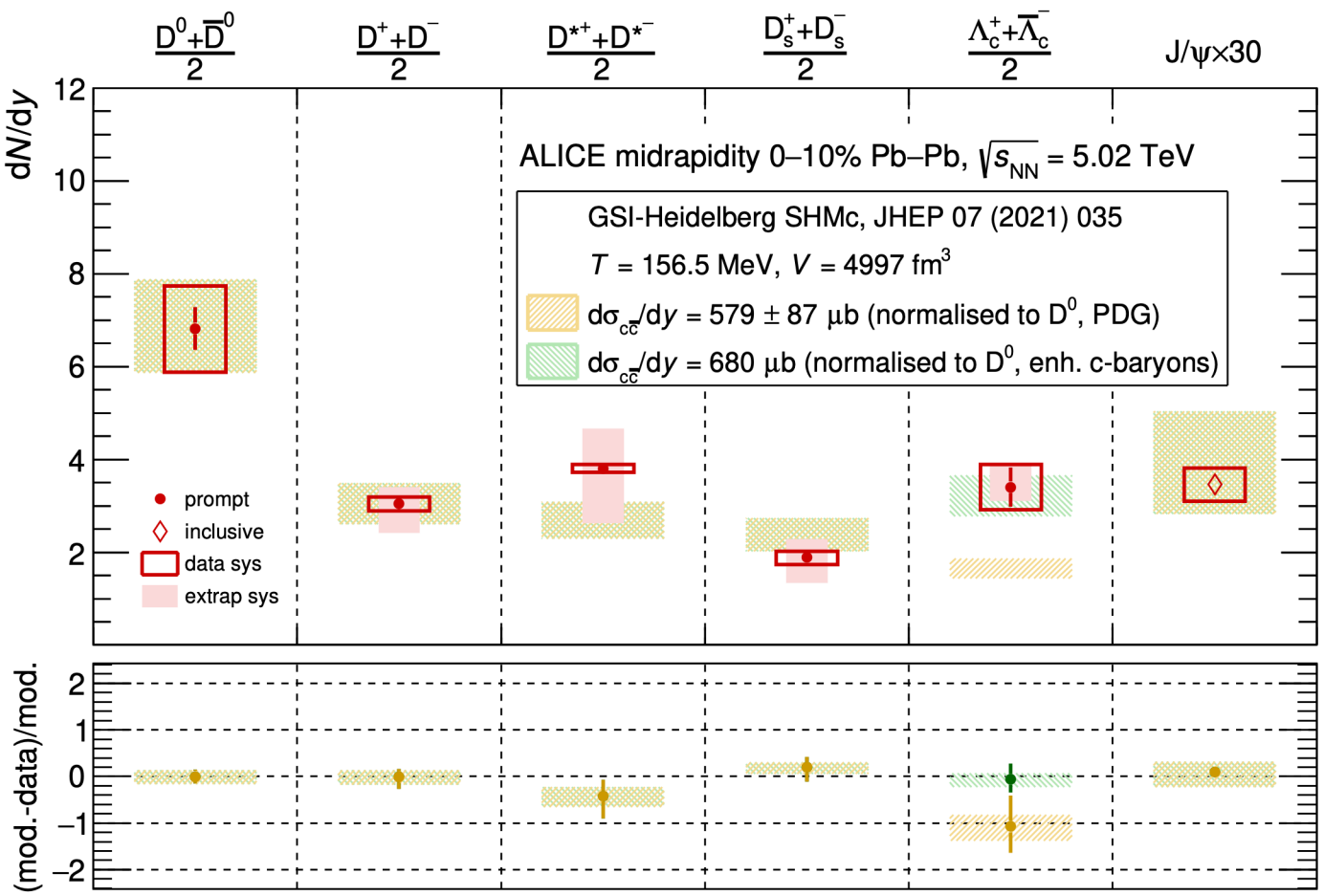


We can test QCD in non-perturbative regime and finite temperature.

Thermalization

$$n = \frac{1}{V}\frac{\partial(T \ln Z)}{\partial \mu} = \frac{V T . m_i^2 g_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k} \left(e^{\beta k \mu_i}\right) K_2\left(\frac{k m_i}{T}\right)$$





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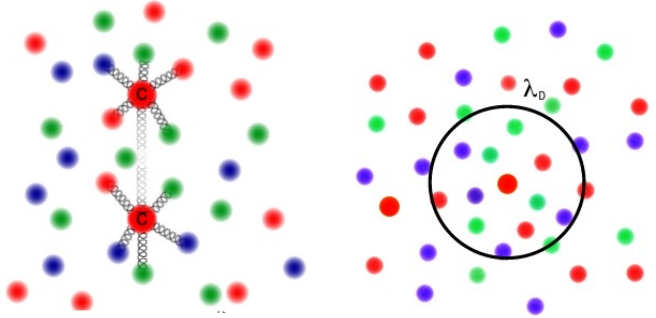
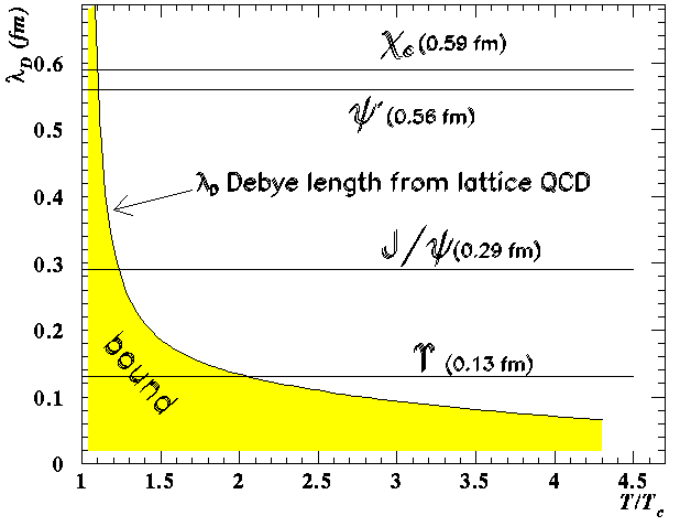


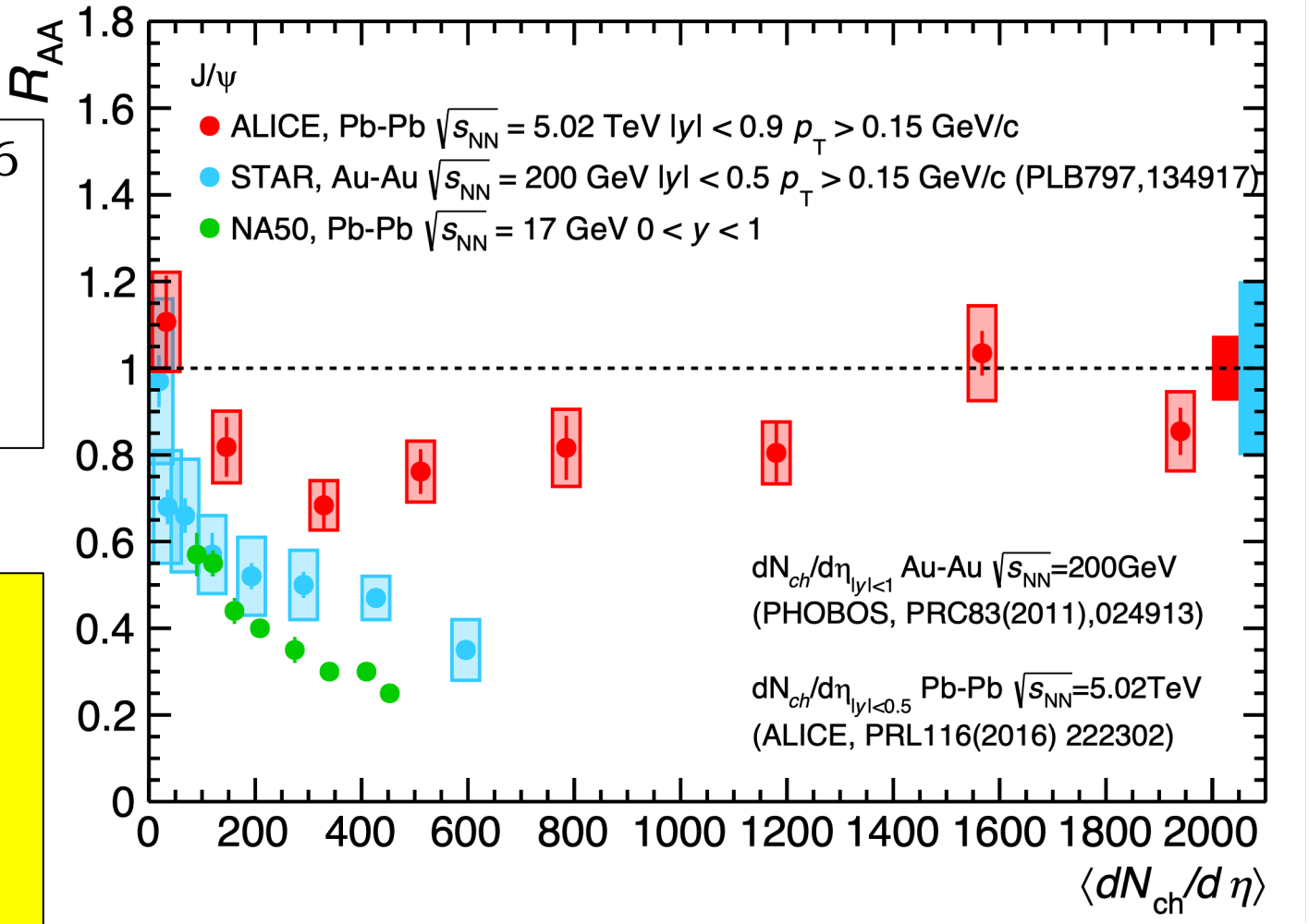
J/ψ suppression (SPS-RHIC-LHC)

Matsui & Satz (Phys. Lett. B178 (1986) 416

In the QGP the screening radius could become smaller than the J/Ψ radius, effectively screening the quarks from each other!



J/ψ production will be suppressed if QGP is formed



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Selected Results from RHIC (STAR)

Typical experiment – STAR @ RHIC

ETOF (-1.6 < η < -1.1,
-2.1 < η < -1.5 in FXT)

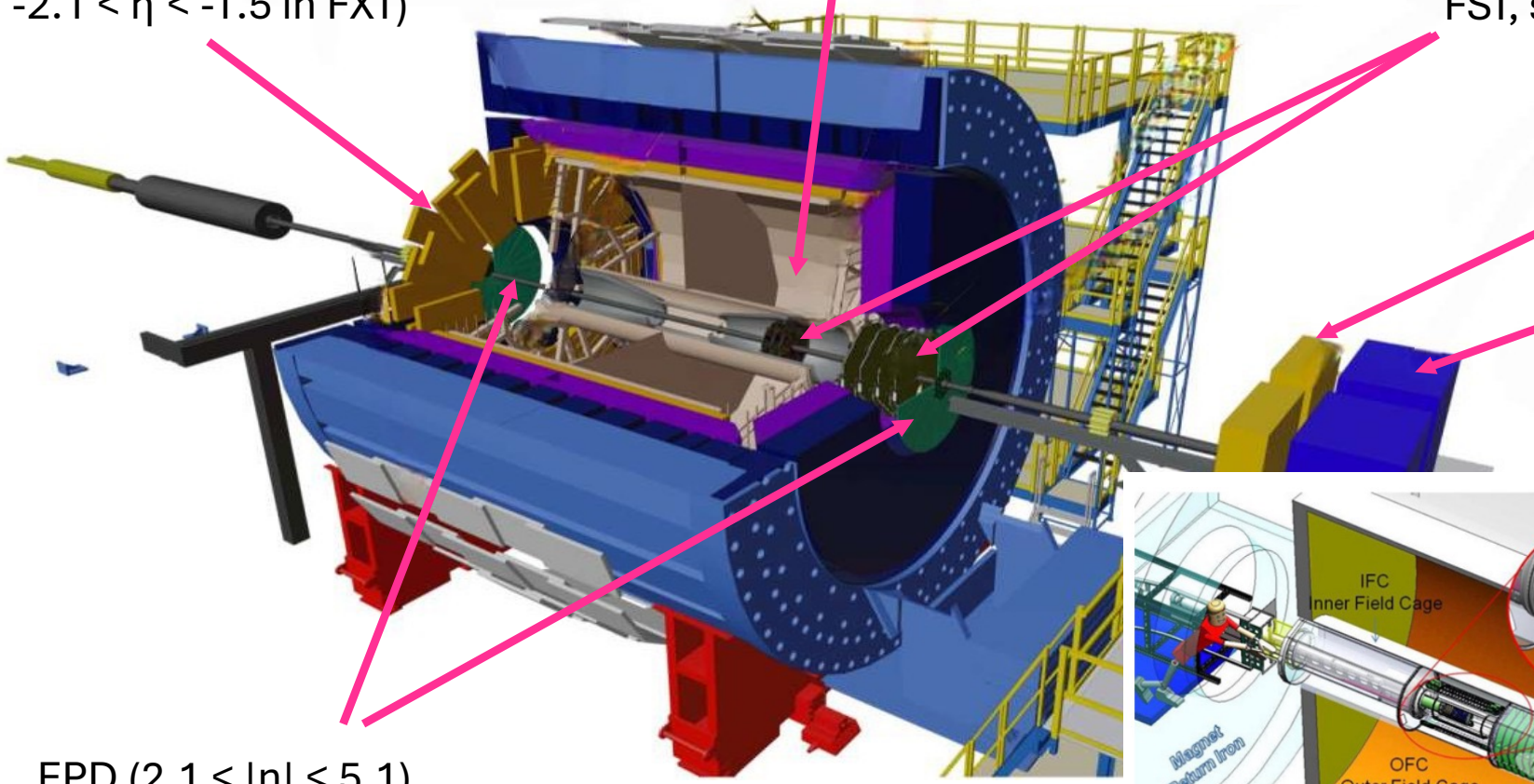
iTPC (-1.5 < η < 1.5)

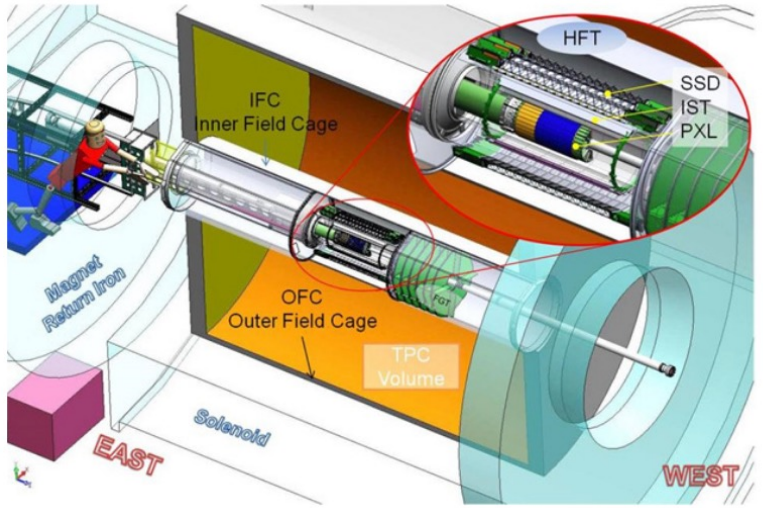
FST, sTGC (2.5 < η < 4.0)

FCS, ECAL (2.5 < η < 4.0)

FCS, HCAL
(2.5 < η < 4.0)

EPD (2.1 < |η| < 5.1)





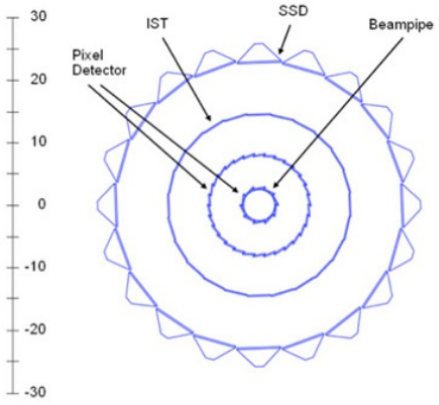


Figure 1: Schematic view of the HFT inside the TPC inner field cage.

Charm–Strange Meson Production as a Probe of QGP Hadronization

Heavy quarks as probes of the QGP

- ❑ Produced early in hard scatterings
- ❑ Experience the full evolution of the medium

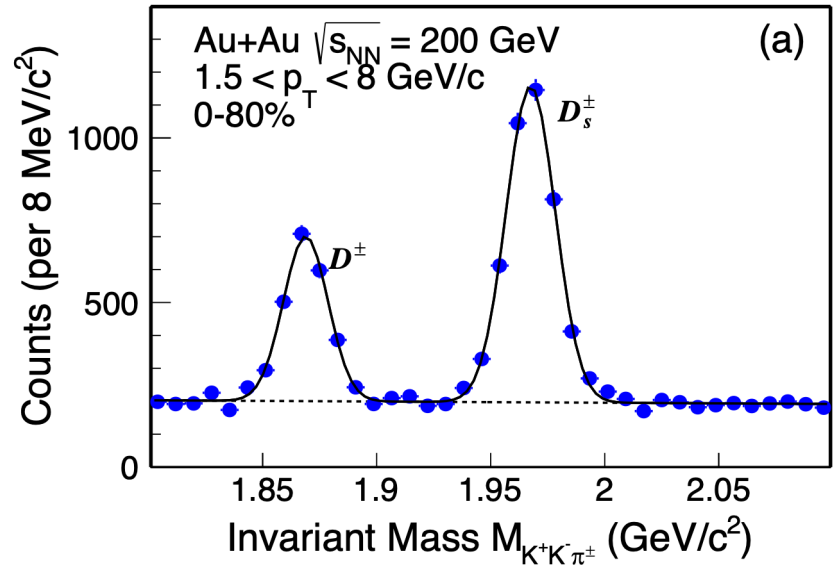
Charm hadronization mechanisms:

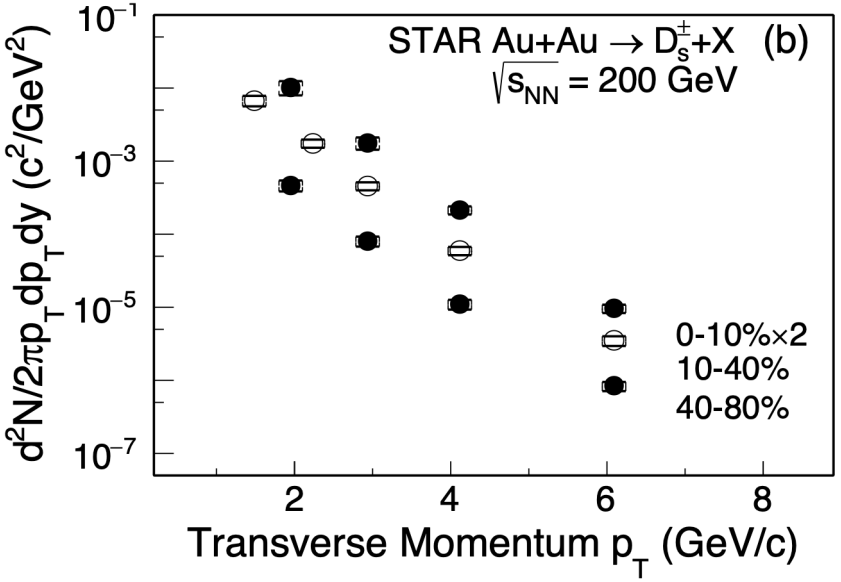
Fragmentation (pp collisions): $c \rightarrow D^0, D^{\pm}, D_s$

Coalescence (in QGP) : $c + s \rightarrow D_s$

Key physics idea:

- ❑ Strange quarks are **abundant in the QGP**
- ❑ Charm quarks may **recombine with strange quarks** → Expected enhancement of D_s/D^0





PHYSICAL REVIEW LETTERS 127, 092301 (2021)

Enhancement of $Ds/D0$: Evidence for Coalescence Hadronization

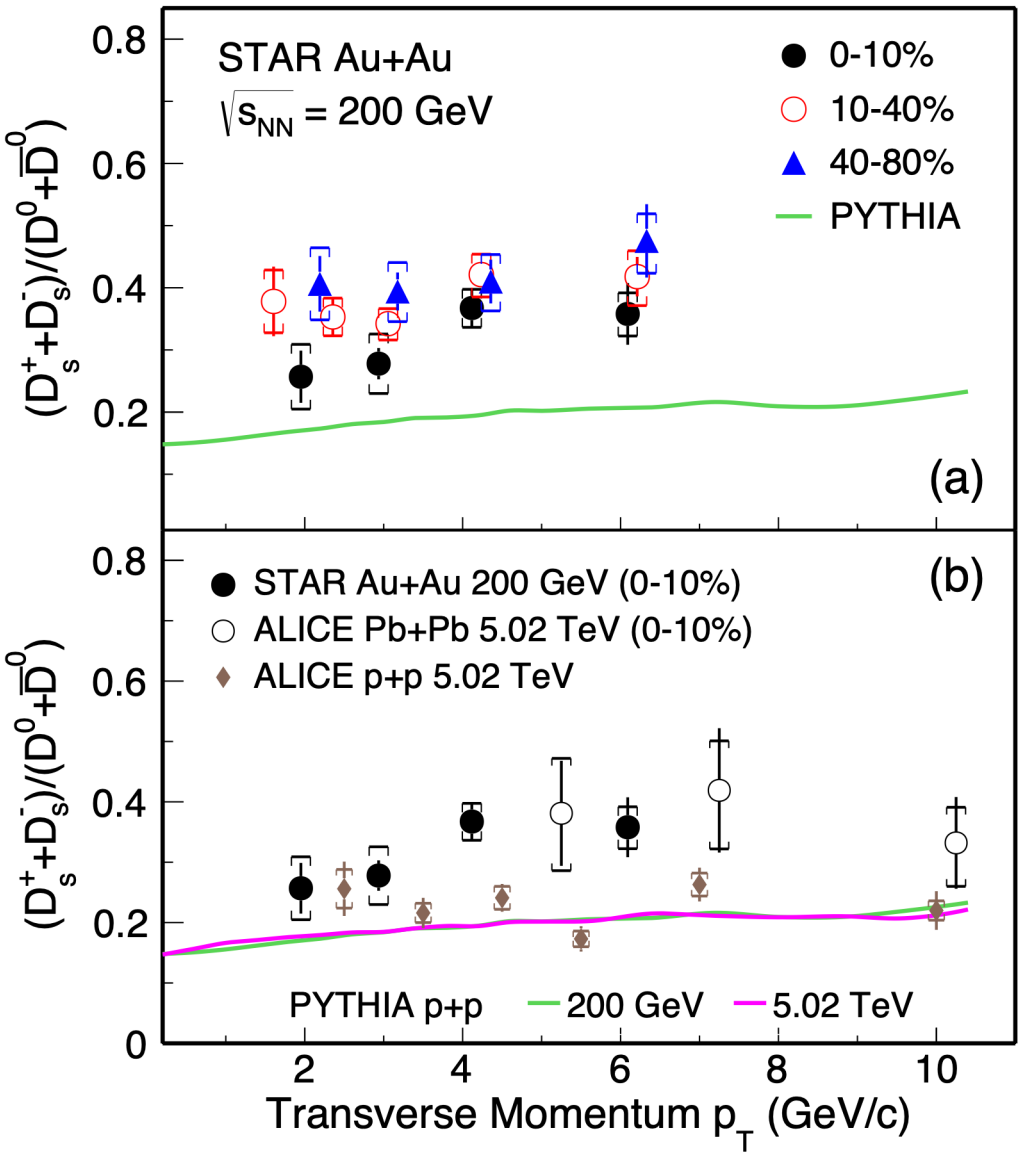
Observable: $\frac{D_s}{D^0}$, compares charm hadronization with and without strange quarks.

- In **Au+Au collisions** : $D_s/D^0 \approx 1.2 - 2\times$ larger than PYTHIA expectations for pp.
- No strong centrality or p_T dependence within uncertainties.

Key implication: Enhanced strange-quark abundance in the QGP.

Interpretation: Model calculations including **charm–strange coalescence** reproduce the data.

Physics conclusion: Charm quarks **recombine with strange quarks in the QGP**, modifying heavy-flavor hadronization.



PHYSICAL REVIEW LETTERS 127, 092301 (2021)

Charm Baryon Production in Heavy-Ion Collisions

Charm hadronization in QCD

In elementary collisions:

$$c \rightarrow D^0, D^{\pm}, D_s, \Lambda_c$$

via **fragmentation**.

Measured fragmentation fraction:

$$\frac{c \rightarrow \Lambda_c}{c \rightarrow D^0} \sim 0.1$$

in e^+e^-, ep, and ppcollisions.

In heavy-ion collisions

The QGP provides abundant light quarks.

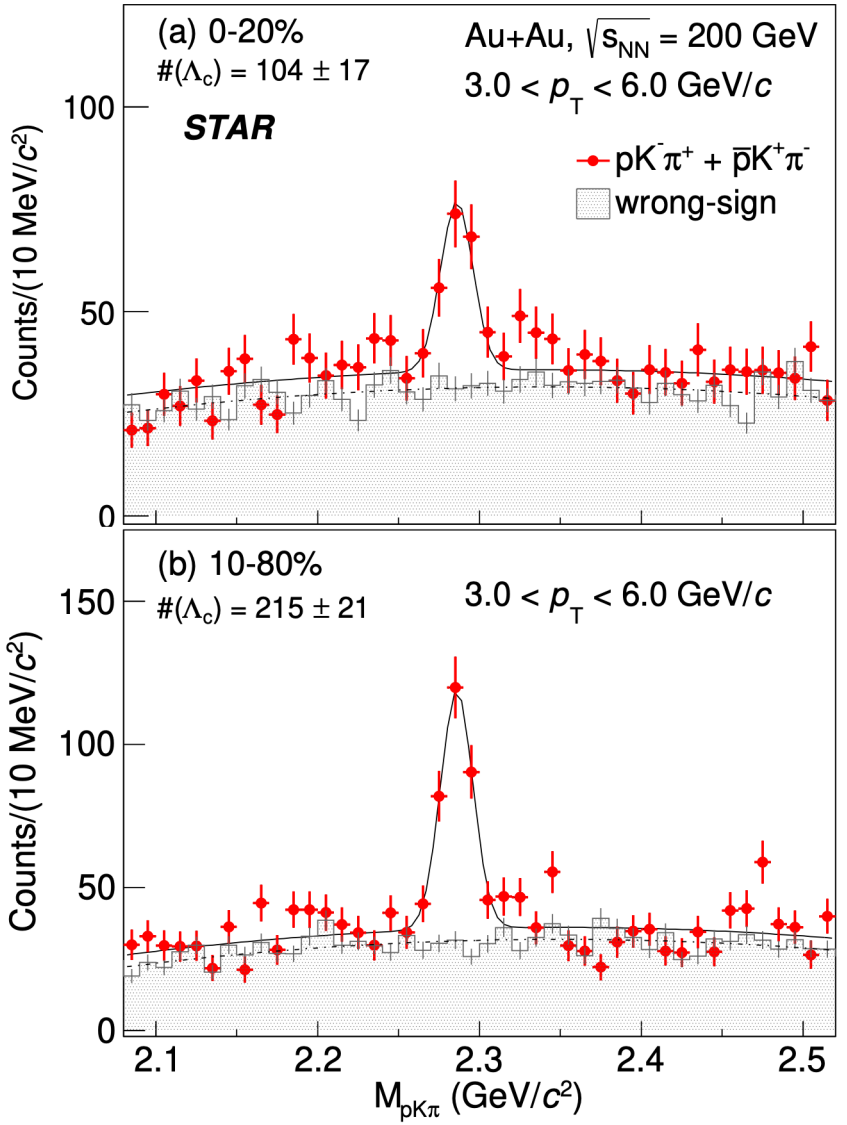
Charm quarks may hadronize via **coalescence**

$$c + q + q \rightarrow \Lambda_c$$

Prediction:

Large enhancement of

$$\Lambda_c/D^0$$



PHYSICAL REVIEW LETTERS 124, 172301 (2020)

Large Enhancement of Λc/D0

Observable: $\frac{\Lambda_c}{D^0}$

Measured at midrapidity.

Result: $\Lambda_c/D^0 \approx 1$

in region $3 < p_T < 6\ GeV/c$

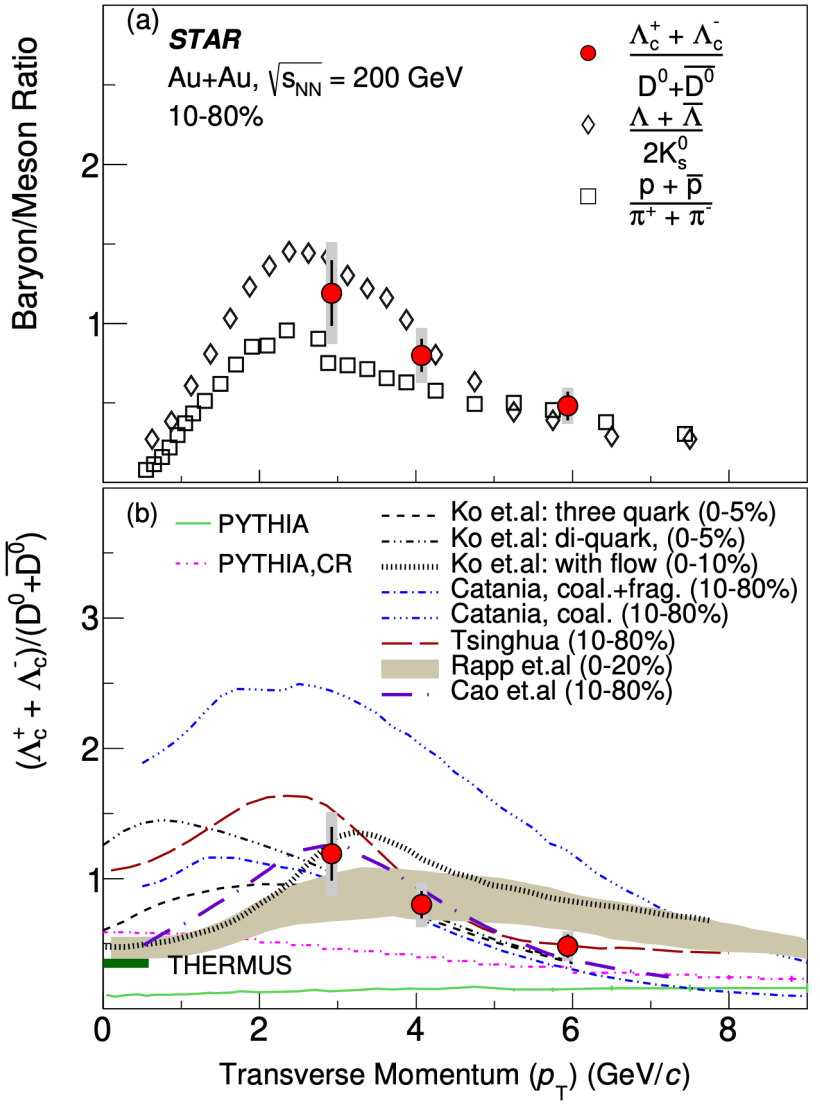
in central Au+Au collisions.

This is **much larger than PYTHIA expectations for pp collisions**.

Key implication

Charm quarks **recombine with light quarks in the QGP**.

→ Charm baryon production is **strongly enhanced**.



Physics interpretation

The Λc/D0 ratio:

- ❑ comparable to baryon/meson ratios for **light hadrons**
- ❑ increases toward **more central collisions**
- ❑ Models including **coalescence hadronization** reproduce the data.

PHYSICAL REVIEW LETTERS 124, 172301 (2020)

Strong Suppression of $D0$ Mesons

Motivation

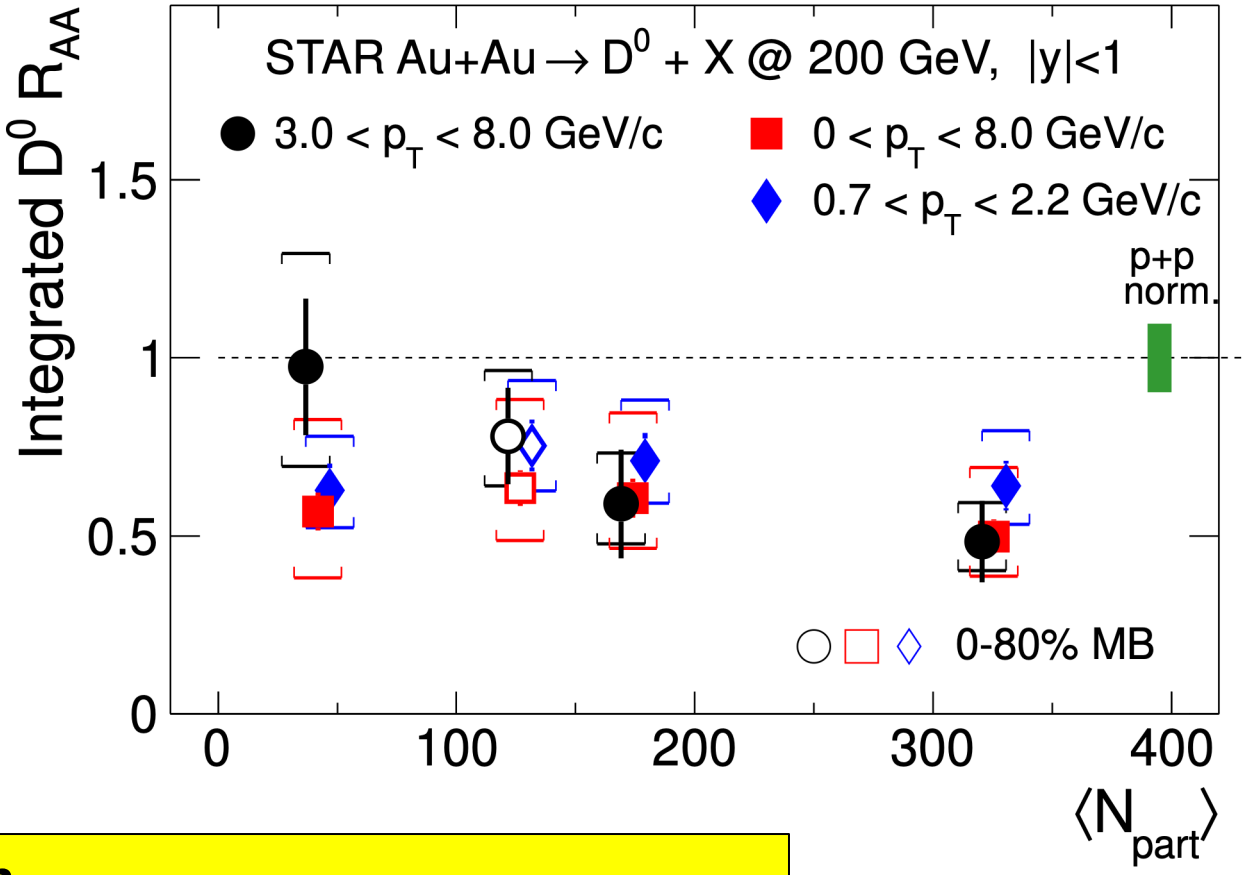
Heavy quarks are produced predominantly in **initial hard scatterings**.

Therefore they probe the **entire evolution of the quark–gluon plasma**.

Observable:

$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{bin}\, dN_{pp}/dp_T}$$

Measures medium modification relative to binary scaling.



Key result

In central Au+Au collisions: $R_{AA} \approx 0.5$

For $p_T > 3\ GeV/c$ indicating strong suppression.

Physics interpretation

Charm quarks **lose significant energy in the QGP**.

The suppression level is comparable to

- ❑ light hadrons
- ❑ heavy-flavour decay electrons.

PHYSICAL REVIEW LETTERS 121, 229901(E) (2018)

Sequential Suppression of Bottomonium in Heavy-Ion Collisions

In a deconfined medium:

- Color screening reduces the heavy-quark potential
- Quarkonium states dissociate when

$$r_{\bar{Q}Q} > \lambda_D$$

where λ_D is the Debye screening length.

Prediction:

$$\Upsilon(3S) > \Upsilon(2S) > \Upsilon(1S)$$

in terms of **suppression strength**.

Sequential suppression

Different bottomonium states have different sizes and binding energies:

State	Binding strength
Y(1S)	most tightly bound
Y(2S)	intermediate
Y(3S)	weakly bound

Evidence for Sequential Bottomonium Suppression

Suppression quantified using the nuclear modification factor:

$$R_{AA} = \frac{Yield_{AA}}{N_{coll} \times Yield_{pp}}$$

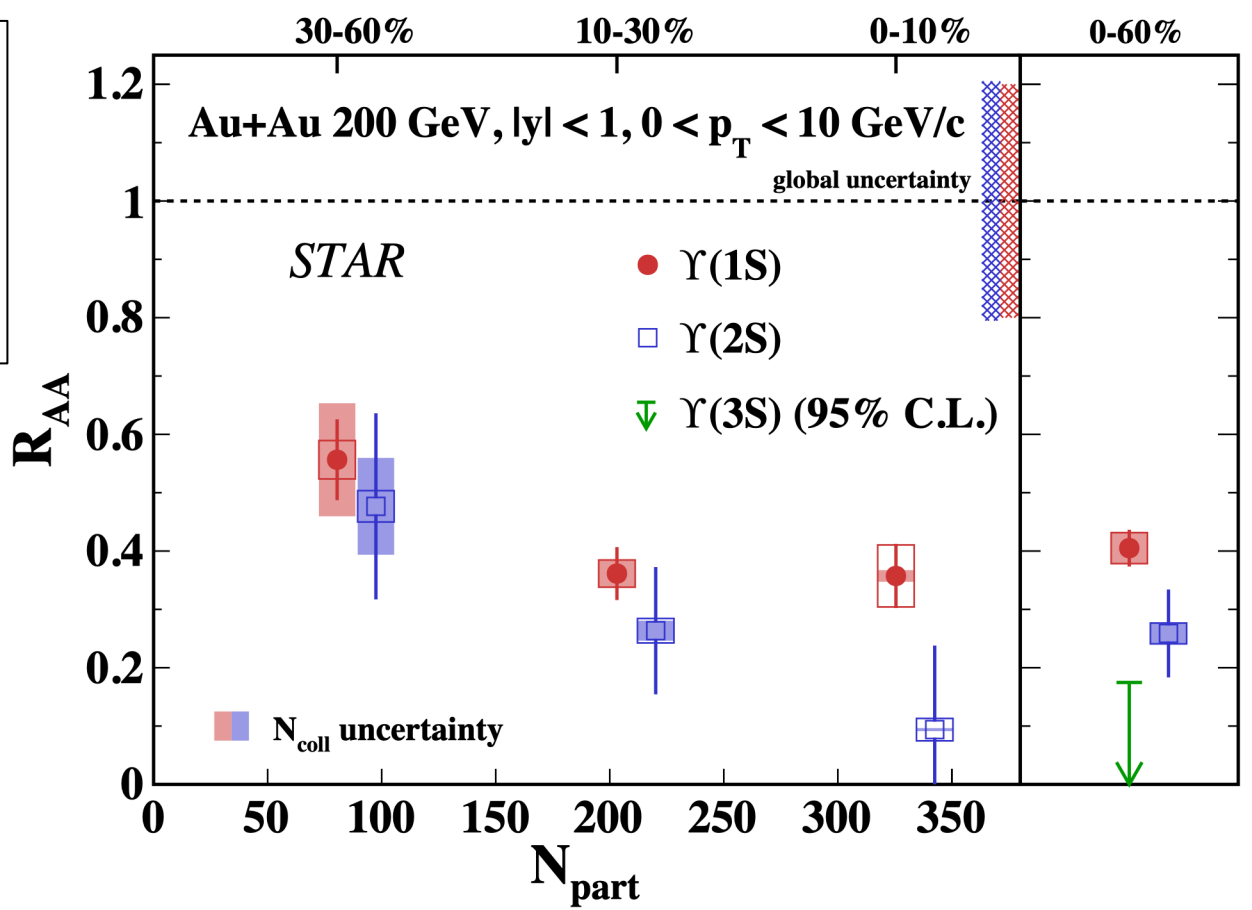
Results (0–60% centrality):

- ❑ **Υ(1S)** : $R_{AA} \approx 0.40$
- ❑ **Υ(2S)** : $R_{AA} \approx 0.26$
- ❑ **Υ(3S)** : $R_{AA} < 0.17$

Implications

- ❑ Evidence for **color screening in the QGP**
- ❑ Medium temperature high enough to melt excited states
- ❑ Sequential suppression consistent with LHC observations

Bottomonium remains a **clean probe of QGP properties** due to small regeneration effects.



Key observation

$\Upsilon(3S) > \Upsilon(2S) > \Upsilon(1S)$ in suppression strength.

PHYSICAL REVIEW LETTERS 130, 112301 (2023)

Elliptic Flow of Charm Hadrons at RHIC

Motivation

Heavy quarks are produced in **initial hard scatterings** and propagate through the QGP. Their azimuthal anisotropy provides information on **heavy-quark interaction with the medium**.

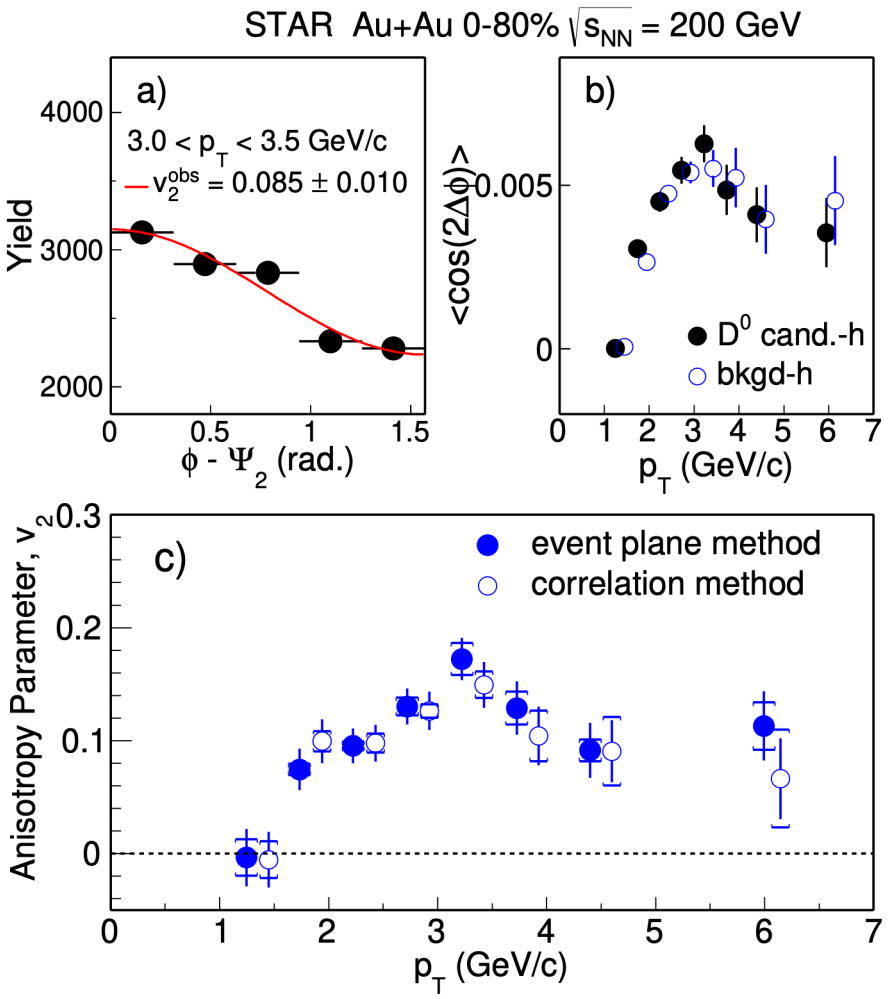
Observable: $v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$

Elliptic flow reflects the **collective response of particles to the initial spatial anisotropy**.

Physics implication

Charm quarks:

- ❑ strongly interact with the medium
- ❑ acquire **collective flow** → evidence for **near-thermalization in the QGP**.



PRL 118, 212301 (2017)

Evidence for Strong Charm–Medium Interaction

Key results

D0 mesons exhibit **significant elliptic flow**.

The measured v2:

- follows **mass ordering at low p_T**
- approaches **light-hadron flow at higher p_T**.

Constituent-quark scaling

When plotted as v_2/n_q vs $(m_T - m_0)/n_q$

D^0 follows the **same trend as light hadrons**.

Transport properties

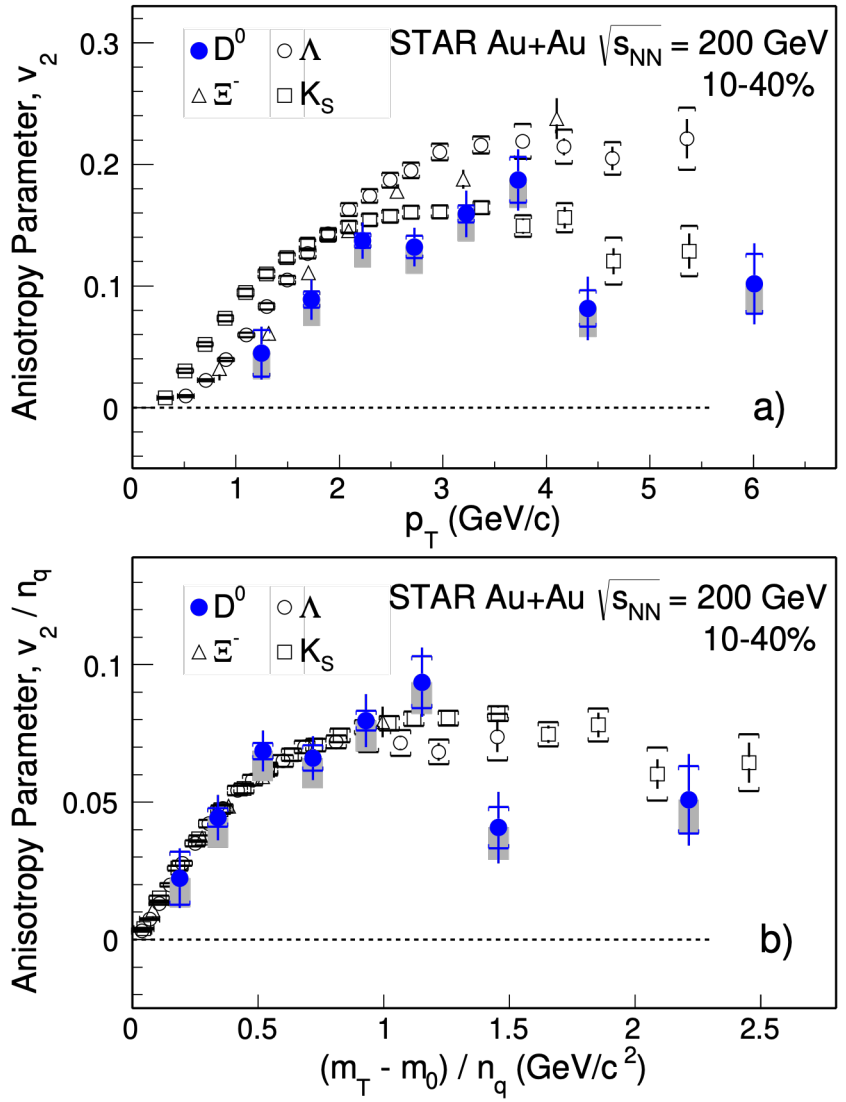
Models describing both

- $D^0 R_{AA}$
- $D^0 v_2$

require charm diffusion coefficient

$$2\pi T D_s \sim 2 - 12$$

consistent with **lattice QCD estimates**.



PRL 118, 212301 (2017)

Using J/ψ Flow to Probe Charm Thermalization

Motivation

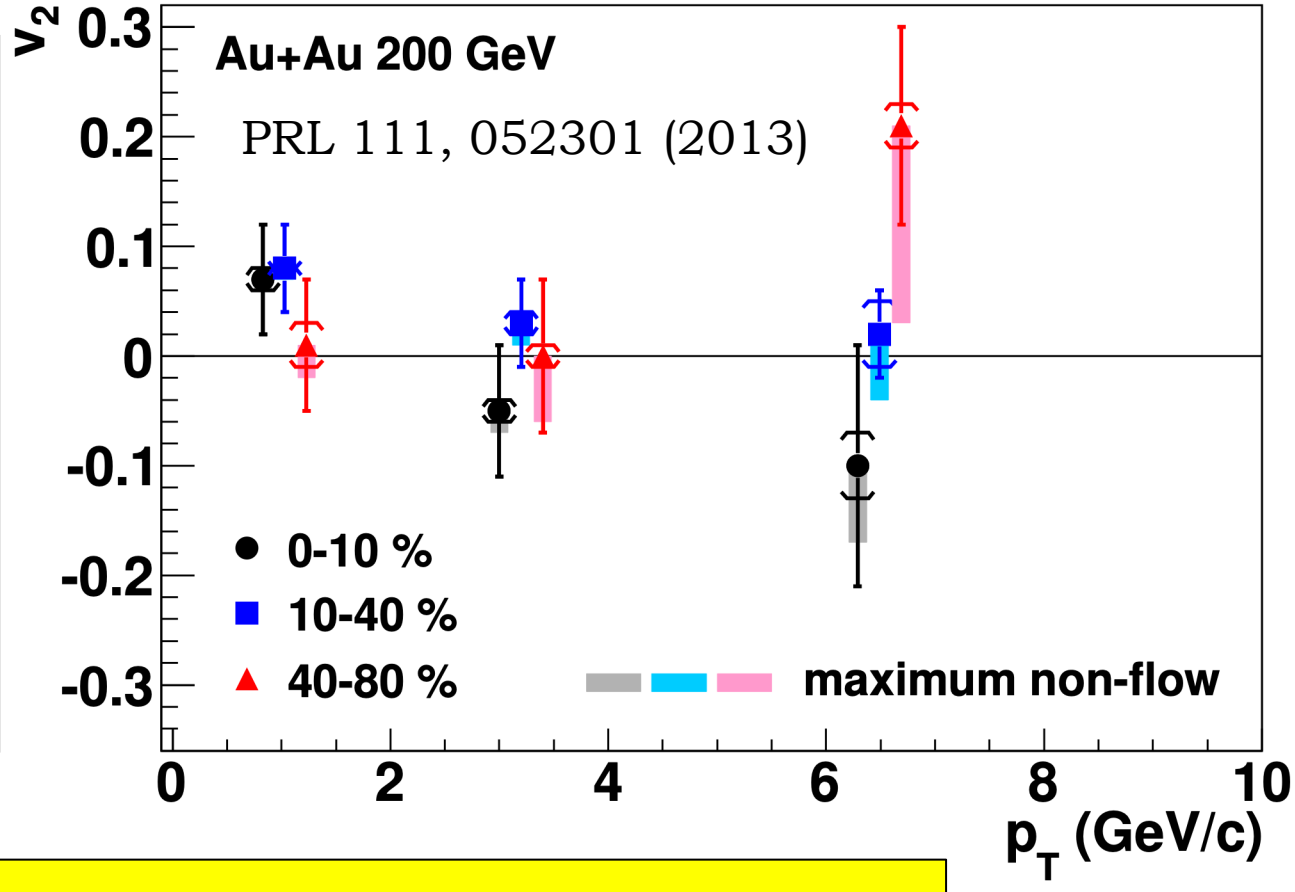
Quarkonium production in heavy-ion collisions is influenced by

- ❑ color screening in the QGP
- ❑ cold nuclear matter effects
- ❑ regeneration from charm quarks.

Measuring **elliptic flow**

$$v_2 = \langle \cos 2(\phi - \Psi_2) \rangle$$

helps distinguish these mechanisms.



Physics expectation

If J/ψ forms from **recombination of thermalized charm quarks**:

- ❑ it should inherit the **collective flow of the medium**
- ❑ large $v_2$comparable to light hadrons is expected.
- ❑ If produced via **initial hard processes**:, $v_2$should be **close to zero**.

J/ψ Elliptic Flow is Consistent with Zero

Key result

For $p_T > 2\ GeV/c$ the measured $v_2(J/\psi)$ is **consistent with zero within uncertainties**.

Implication

This observation disfavors the scenario where J/ψproduction at RHIC is **dominated by coalescence of thermalized charm quarks**.

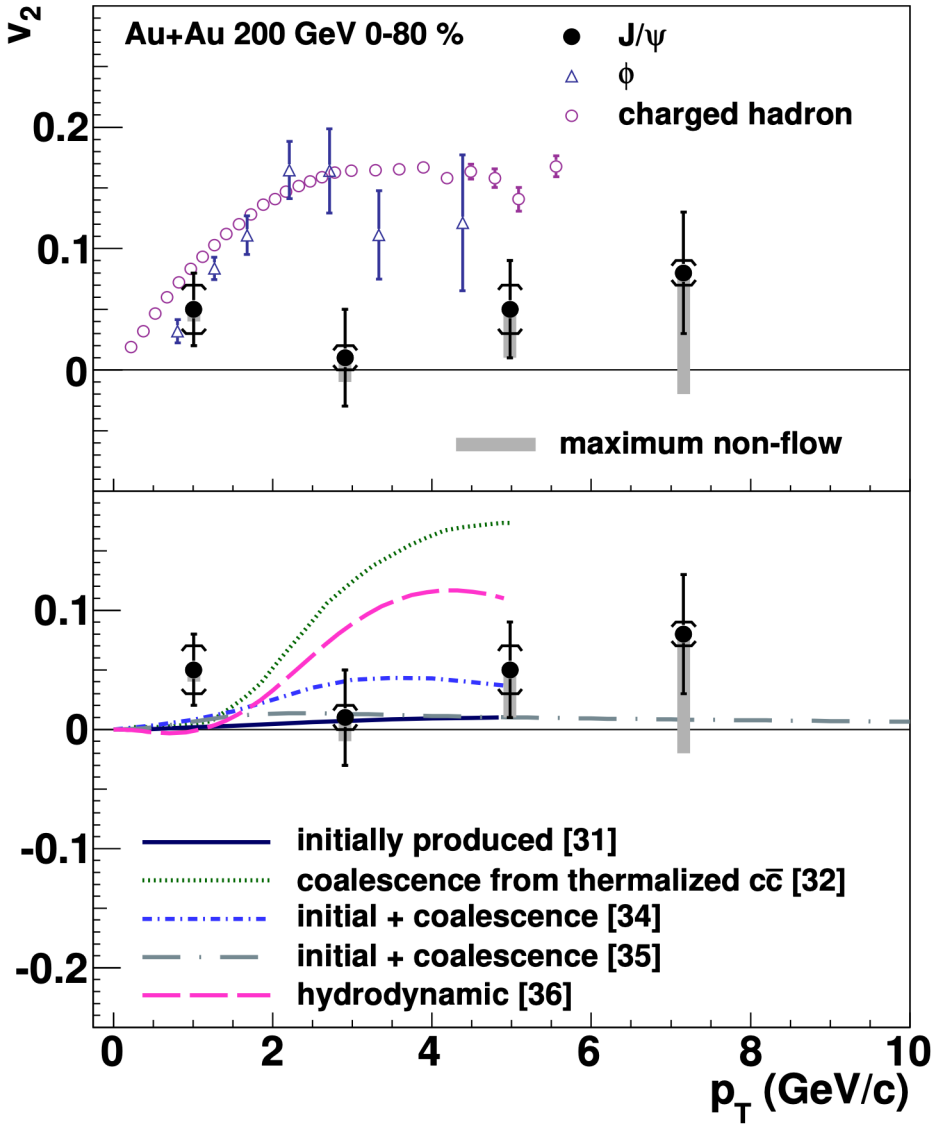
Interpretation

Models including both

- ❑initial production
- ❑partial regeneration

are consistent with the data.

J/ψ production at RHIC appears to be **dominated by primordial production rather than recombination** at moderate p_T.



PRL 111, 052301 (2013)

Directed Flow of Heavy Quarks

Directed flow

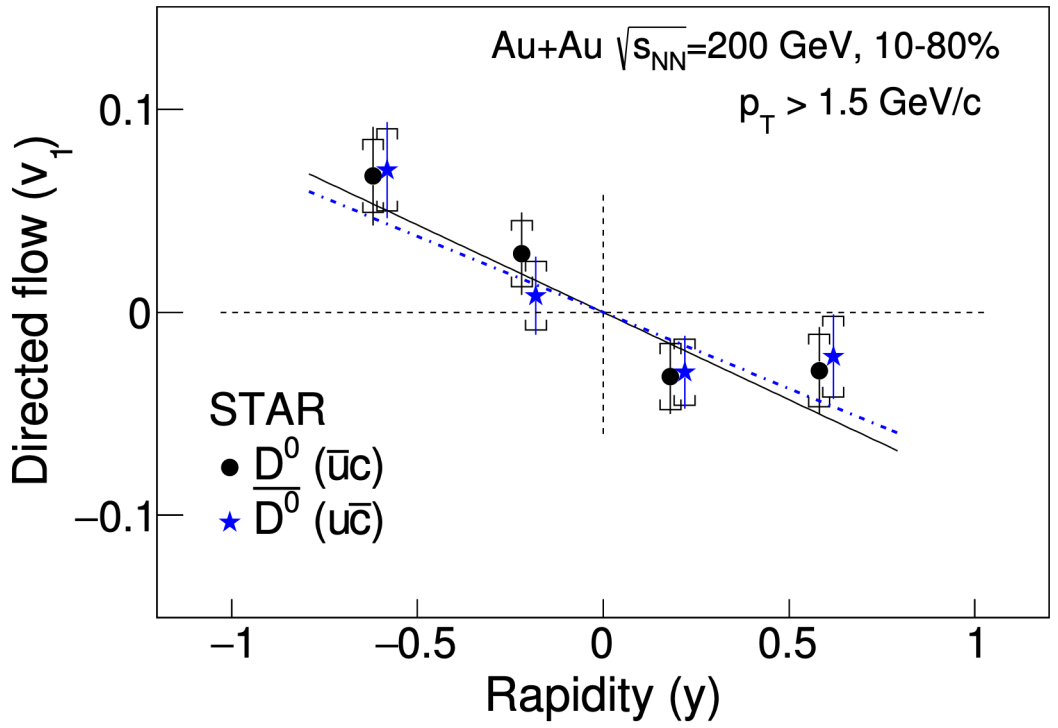
$$v_1 = \langle \cos(\phi - \Psi_{RP}) \rangle$$

- First harmonic of azimuthal particle distribution
- Sensitive to **early-stage dynamics** of heavy-ion collisions.

Why heavy quarks are special

- Produced in **initial hard scatterings**
- Experience the **entire evolution of the QGP**
- Relaxation time comparable to QGP lifetime.

Therefore: Heavy-quark flow probes **initial conditions and transport properties**.



Prediction

Hydrodynamic calculations with a **tilted QGP source** predict

$|v_1(D)| \gg |v_1(\textit{light hadrons})|$

because heavy quarks are dragged by the tilted medium.

PHYSICAL REVIEW LETTERS 123, 162301 (2019)

Directed Flow of Heavy Quarks

Measured observable:

Slope of directed flow $\frac{dv_1}{dy}$

Result:

$$\frac{dv_1}{dy}(D^0) = -0.080 \pm 0.017(stat) \pm 0.016(syst)$$

in 10–80% Au+Au collisions.

Key observation:

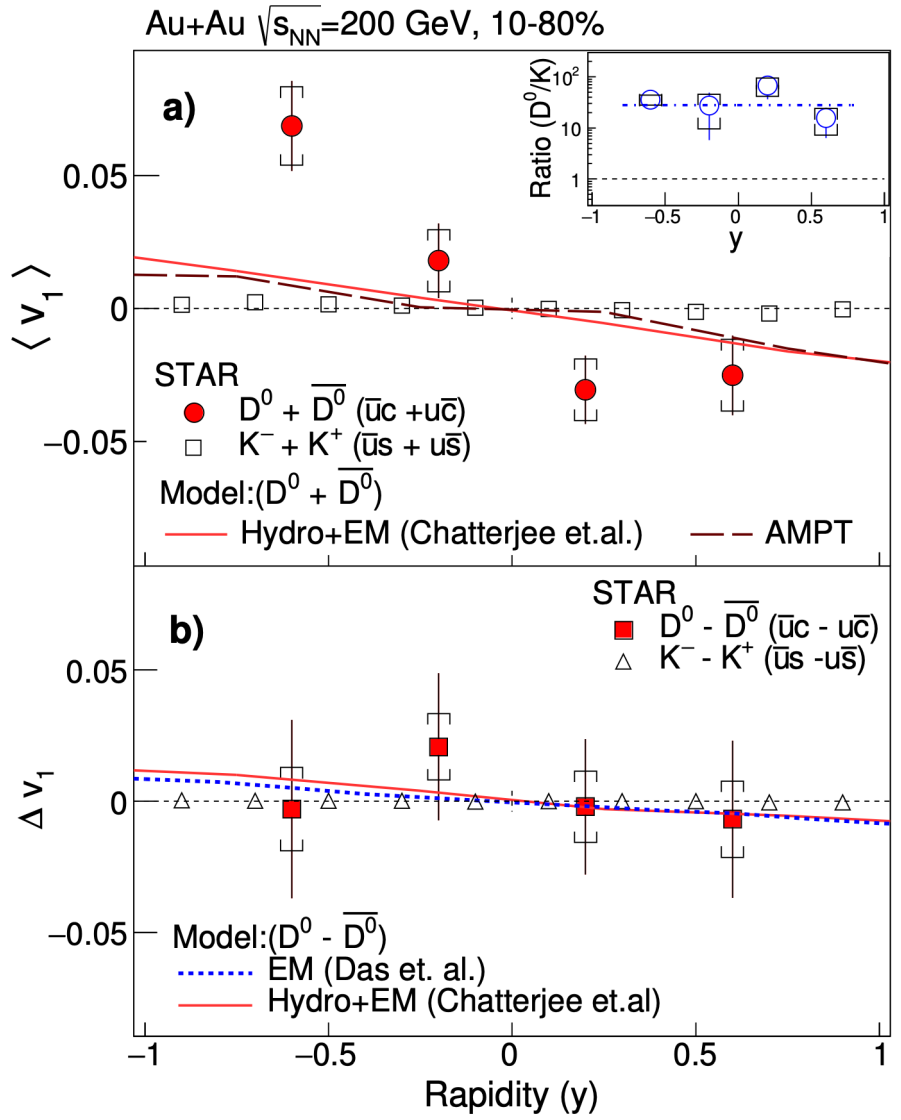
The magnitude of the D^0 directed flow slope is

$\sim 25\times$

larger than that for charged kaons.

Physics interpretation

- ❑ Strong sensitivity of heavy quarks to **initial tilt of the QGP fireball**
- ❑ Consistent with **hydrodynamic and transport model predictions**



PHYSICAL REVIEW LETTERS 123, 162301 (2019)

Excess J/ψ Production at Very Low p_T

Motivation

J/ψ production in heavy-ion collisions is governed by

- ❑ color screening in QGP
- ❑ regeneration from charm quarks
- ❑ cold nuclear matter effects

These mechanisms describe J/ψ production at

$$p_T > 0.2\ GeV/c$$

reasonably well.

STAR measured J/ψ production at extremely low transverse momentum

$$p_T < 0.2\ GeV/c$$

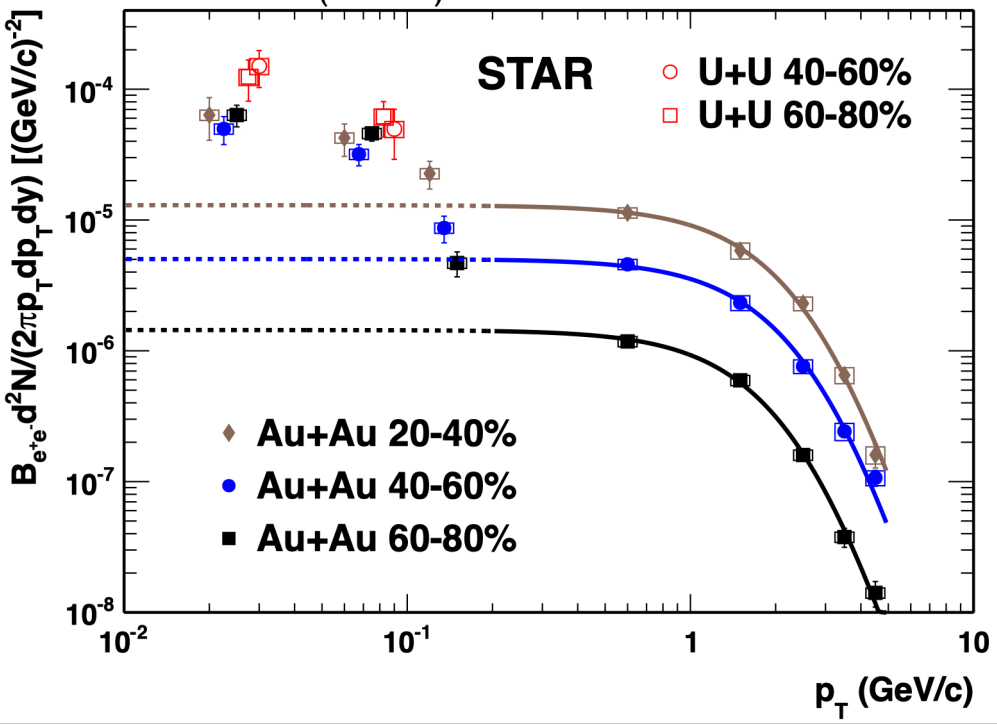
in

- Au+Au collisions ($\sqrt{s_{NN}} = 200$ GeV)
- U+U collisions ($\sqrt{s_{NN}} = 193$ GeV)

via

$$J/\psi \rightarrow e^+e^-$$

PHYSICAL REVIEW LETTERS 123, 132302 (2019)



Key observation: The measured yields at very low p_T **significantly exceed** expectations from hadronic production. This suggests an **additional production mechanism**.

Evidence for Coherent Photon-Induced J/ψ Production

At extremely low transverse momentum

$$p_T < 0.2\ GeV/c$$

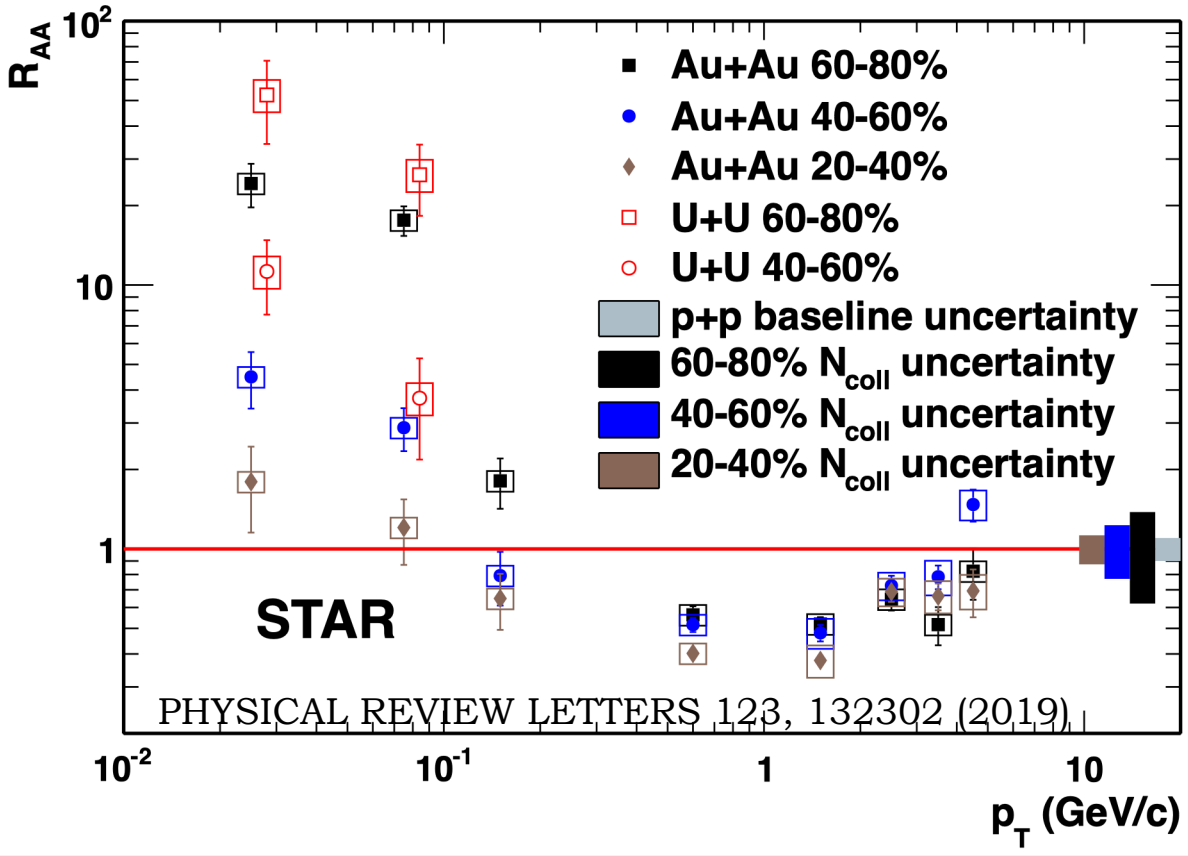
the nuclear modification factor shows dramatic enhancement.

For example: $R_{AA} \sim 24$ in peripheral Au+Au collisions and $R_{AA} \sim 52$ in peripheral U+U collisions.

Physics implication

Coherently produced J/ψ at very low p_T

- ❑ probes **nuclear gluon distributions**
- ❑ may provide a **novel probe of QGP**.

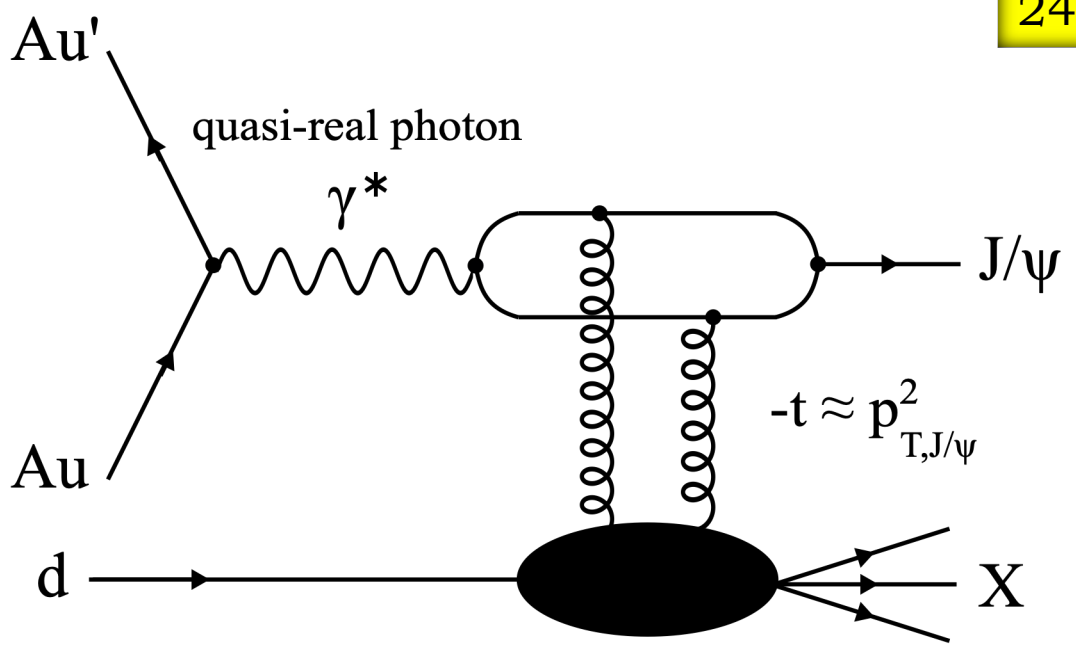


The enhancement cannot be explained by

- ❑ hot medium effects
- ❑ cold nuclear matter effects
- ❑ charm regeneration

A plausible mechanism is **coherent photon–nucleus interactions** $\gamma + A \rightarrow J/\psi + A$ occurring **even in hadronic collisions**.

J/ψ Photoproduction in d+Au Ultraperipheral Collisions



Ultraperipheral collisions (UPC)

- ❑ Impact parameter : $b > R_A + R_B$
- ❑ No hadronic interaction
- ❑ Dominated by **photon–nucleus interactions**
- ❑ **Process** : $\gamma + d \rightarrow J/\psi + X$

where

- $X = d \rightarrow$ **coherent production**
- $X = p + n$ or fragments $\rightarrow$ **incoherent production**

Why J/ψ photoproduction is important

Cross section approximately scales as

$$\sigma \propto \left[xg(x, Q^2)\right]^2$$

→ **direct probe of gluon density**

Goal of the measurement

- ❑ Study **gluonic structure of the deuteron**
- ❑ Separate coherent and incoherent diffraction
- ❑ Investigate nuclear breakup using **forward neutron tagging**

PHYSICAL REVIEW LETTERS 128, 122303 (2022)

Differential Cross Section and Constraints on Gluon Structure

Observable : $\frac{d\sigma}{dt}(\gamma + d \to J/\psi + X)$ With $-t \approx p_T^2(J/\psi)$

Key features of the measurement:

- ❑ **Total diffractive cross section**
- ❑ **Neutron-tagged events** → sensitive to **incoherent scattering**

Comparison with theory:

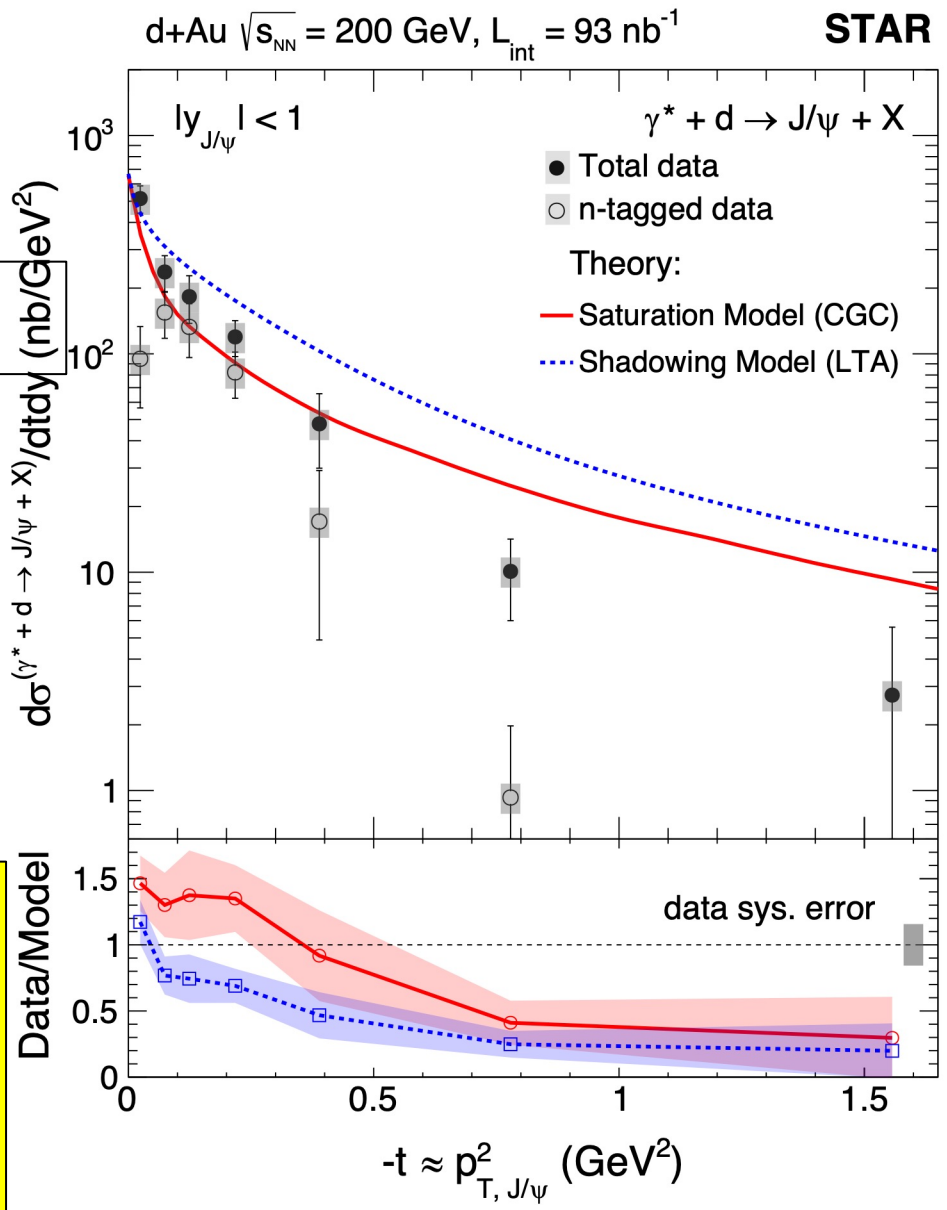
- ❑ **CGC saturation model**
- ❑ **Leading Twist nuclear shadowing model**

Main observation

- ❑ Data are **better described by saturation model (CGC)**.

Implications:

- ❑ Sensitive to **gluon density distribution in deuteron**
- ❑ Provides constraints on **coherent vs incoherent diffraction**
- ❑ Baseline for future **Electron–Ion Collider measurements**



Exclusive J/ψ Photoproduction in Ultraperipheral Au+Au Collisions

Ultraperipheral heavy-ion collisions (UPC)

- ❑ Large impact parameter $b > 2R_A$
- ❑ Dominated by **photon–nucleus interactions**

$$\gamma + A \rightarrow J/\psi + A^{(*)}$$

Coherent photoproduction

- ❑ Photon interacts with **entire nucleus**
- ❑ Nucleus remains intact
- ❑ Very small p_T

Incoherent photoproduction

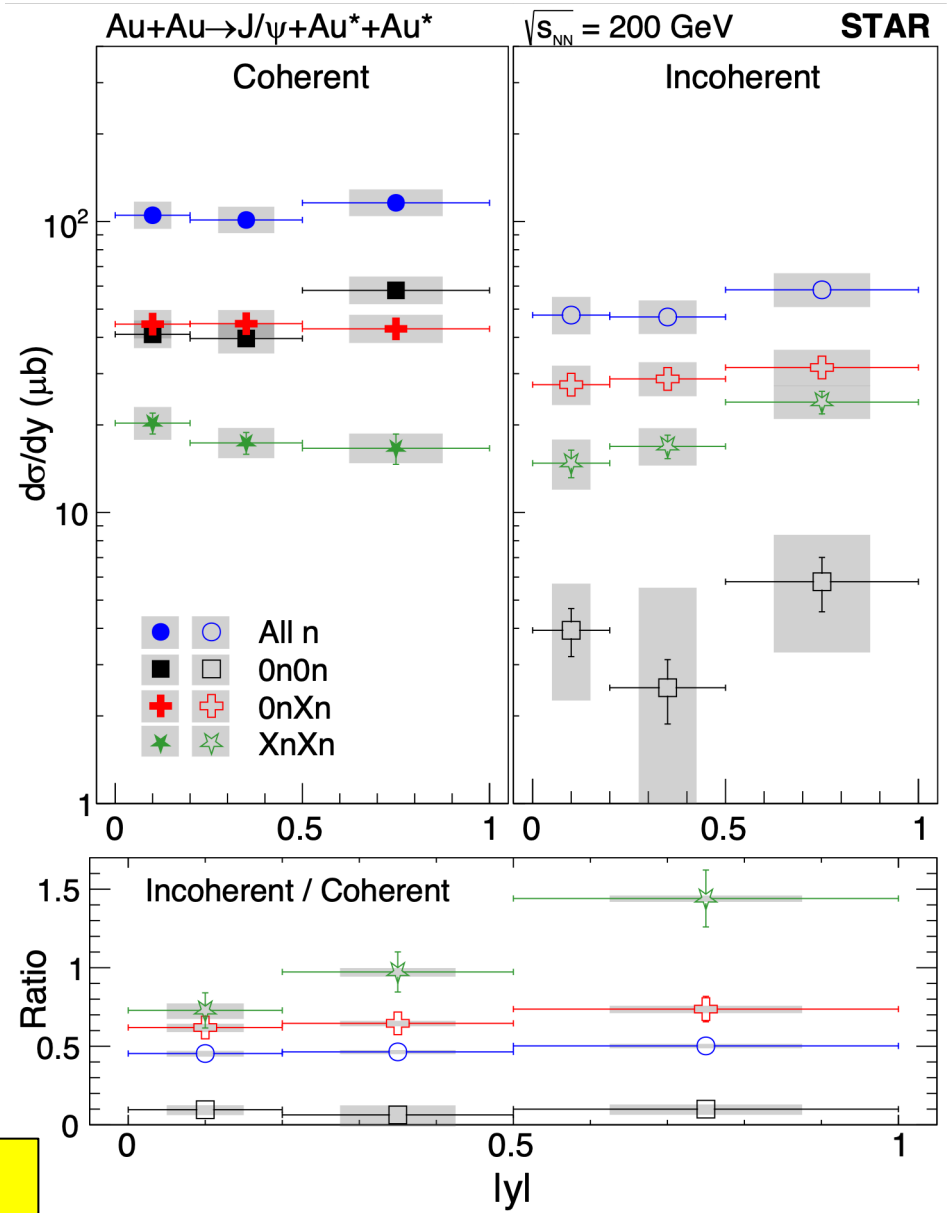
- ❑ Photon interacts with **individual nucleon**
- ❑ Nucleus breaks up
- ❑ Larger p_T

Physics sensitivity

- ❑ Gluon distributions in nuclei
- ❑ Nuclear shadowing
- ❑ Spatial fluctuations of gluons

First RHIC measurement of

- ❑ ψ(2S) photoproduction
- ❑ Nuclear suppression for **incoherent J/ψ**



PHYSICAL REVIEW LETTERS 133, 052301 (2024)

Strong Nuclear Suppression Observed

Nuclear suppression factor: $S_A = \frac{\sigma_{\gamma A}}{\sigma_{\gamma p}}$

Results at $W_{\gamma N} \approx 25\ GeV$

Coherent production : $S_{Au}^{coh} \approx 0.71$

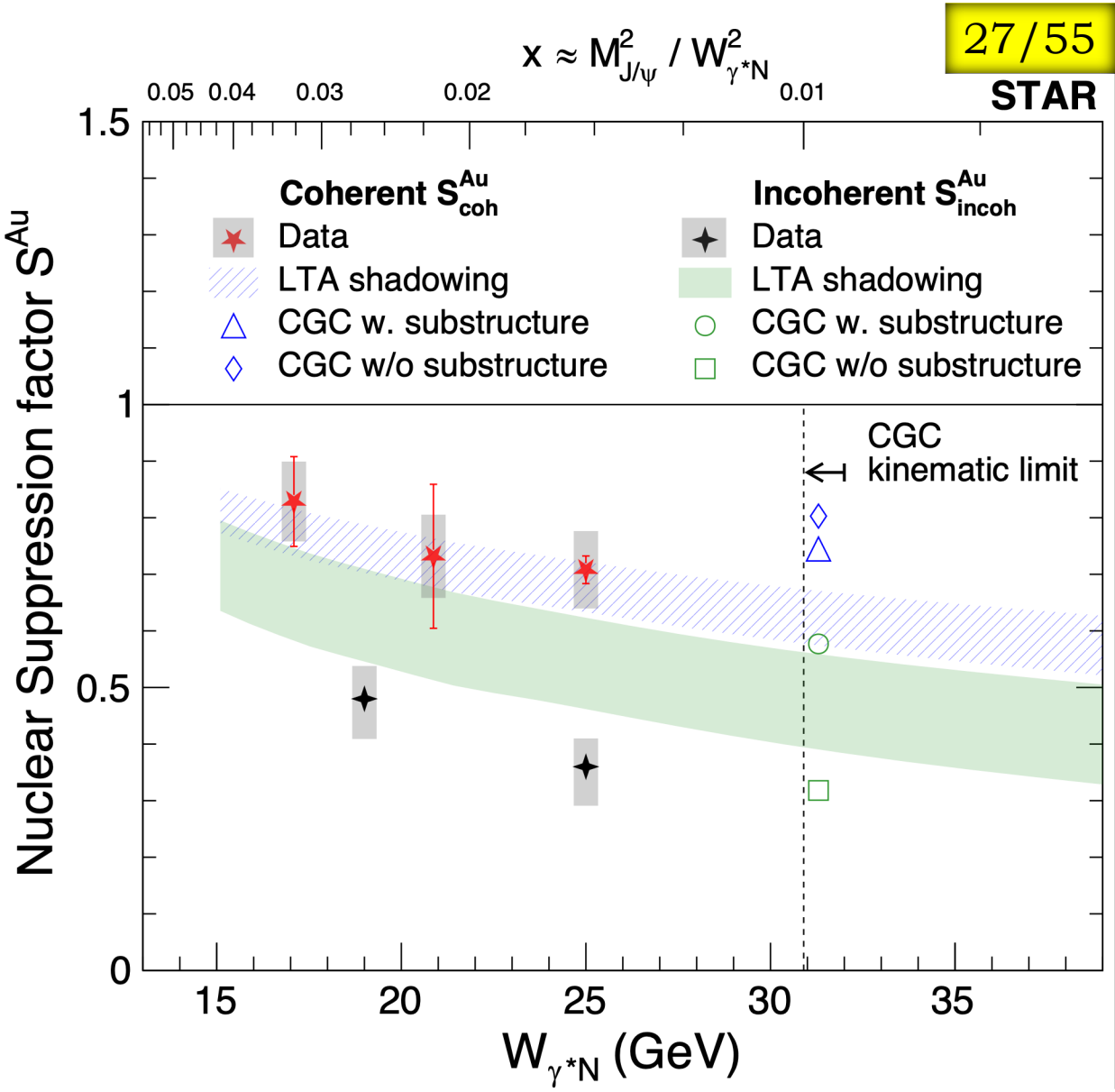
%30→ ~suppression relative to free proton

Incoherent production: $S_{Au}^{incoh} \approx 0.36$

%60→ ~suppression

Implications:

- Strong **nuclear shadowing of gluons** (gA(x)<Agp(x))
- Sensitive to **nucleon-level fluctuations (incoherent ~ variance of gluon density)**
- Important constraint on **nuclear PDFs** $\sigma \propto [xg(x,Q^2)]^2$
- Relevant for future **Electron–Ion Collider** measurements.



Incoherent production is significantly more suppressed than coherent production

Summary of Heavy-Flavor Results at RHIC

Heavy quarks probe multiple aspects of QCD matter:

- ❑ transport properties of the QGP
- ❑ early-time collision geometry
- ❑ hadronization mechanisms
- ❑ quarkonium production dynamics

Early-time dynamics

Large directed flow of D^0 | dv_1/dy |$\gg$ *light hadrons*

→ sensitivity to **tilted initial geometry of the fireball**

Hadronization in the QGP

- **Enhanced charm hadron ratios**

$$D_s/D^0 \uparrow, \Lambda_c/D^0 \uparrow$$

→ evidence for **coalescence hadronization**

Production baseline

- Bottom contribution to heavy-flavor electrons measured in $p+p$
- B decays contribute **~50% at** $p_T \sim 5$**GeV/c**
- Provides crucial baseline for heavy-quark energy loss studies

Summary of Heavy-Flavor Results at RHIC

Transport in the QGP

❑ **Strong suppression of D^0 mesons**

$$R_{AA}(D^0) \approx 0.5$$

→ significant **charm-quark energy loss**

❑ **Large elliptic flow of D^0**

$$v_2(D^0) > 0$$

→ charm quarks strongly **couple to the medium**

Quarkonium probes

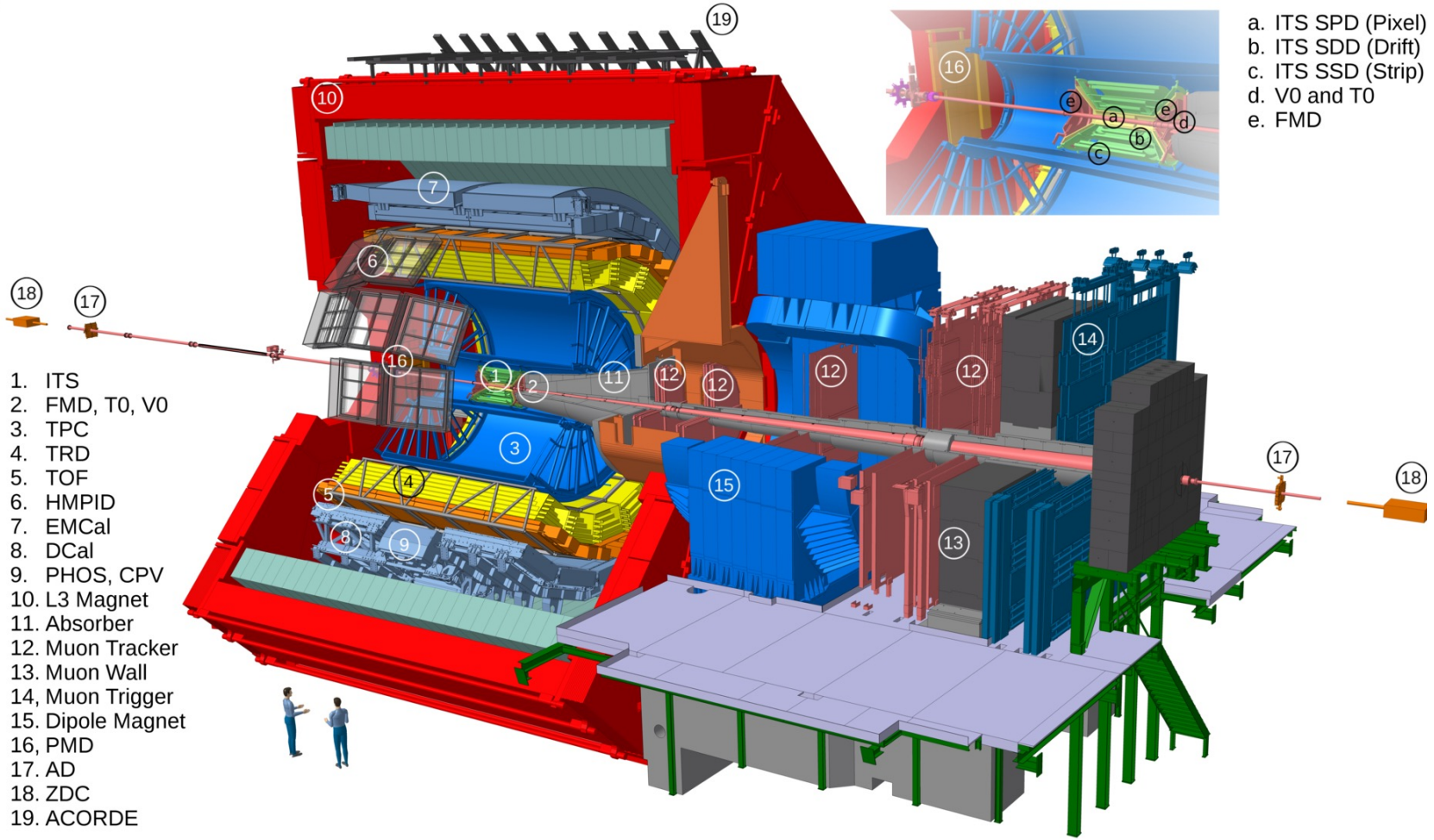
❑ **J/ψ elliptic flow ≈ 0 for $p_T > 2$ GeV/c**

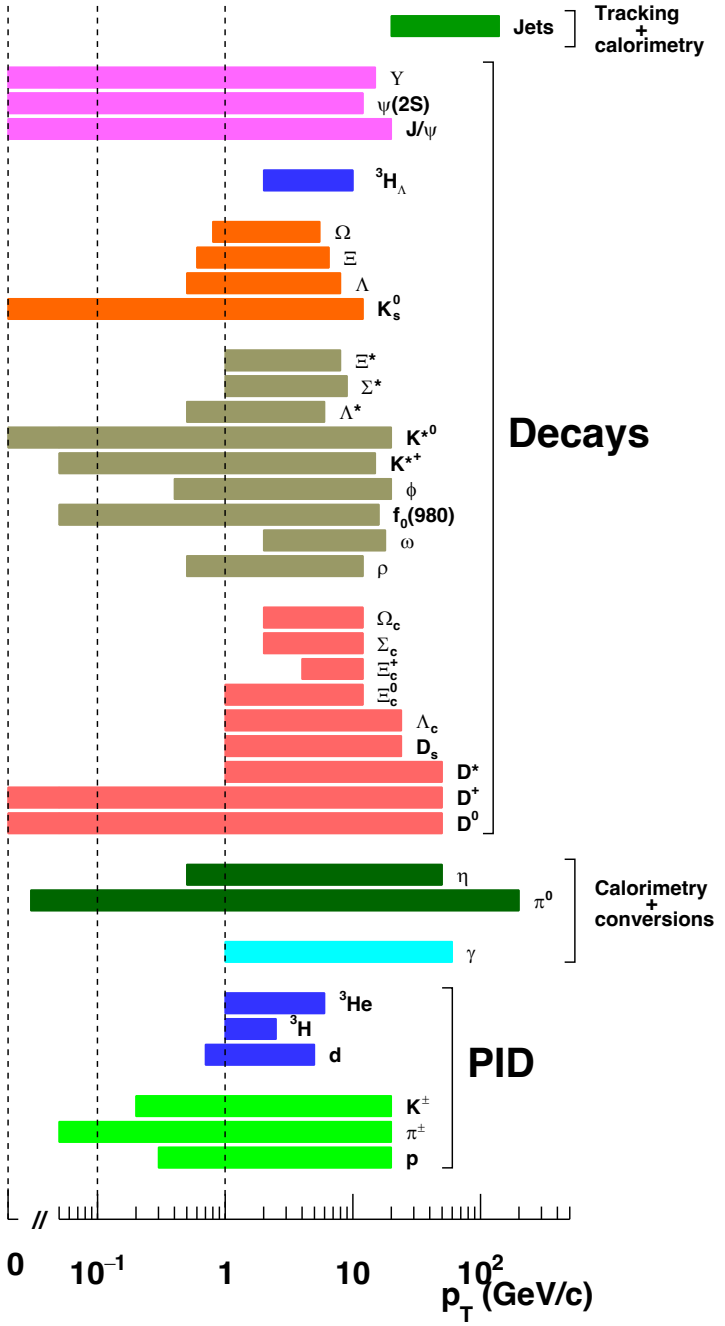
→ high-p_T J/ψ dominated by **primordial production**

Taken together, these RHIC measurements show that heavy quarks interact strongly with the QGP, participate in its collective dynamics, and hadronize through recombination with medium quarks.

Selected Results from LHC (ALICE)

Typical experiment – ALICE @ LHC





Probes: T ~ 90-800 MeV, μ_B ~ 0 MeV and $\alpha_s \approx 1 \rightarrow 0.1$.

ALICE: Eur.Phys.J.C 84 (2024) 8, 813

Charm Baryon Production at the LHC

Charm hadronization

Heavy-flavour hadrons are produced via

$$c \to D, \Lambda_c, \Xi_c, \Omega_c$$

In perturbative QCD calculations:

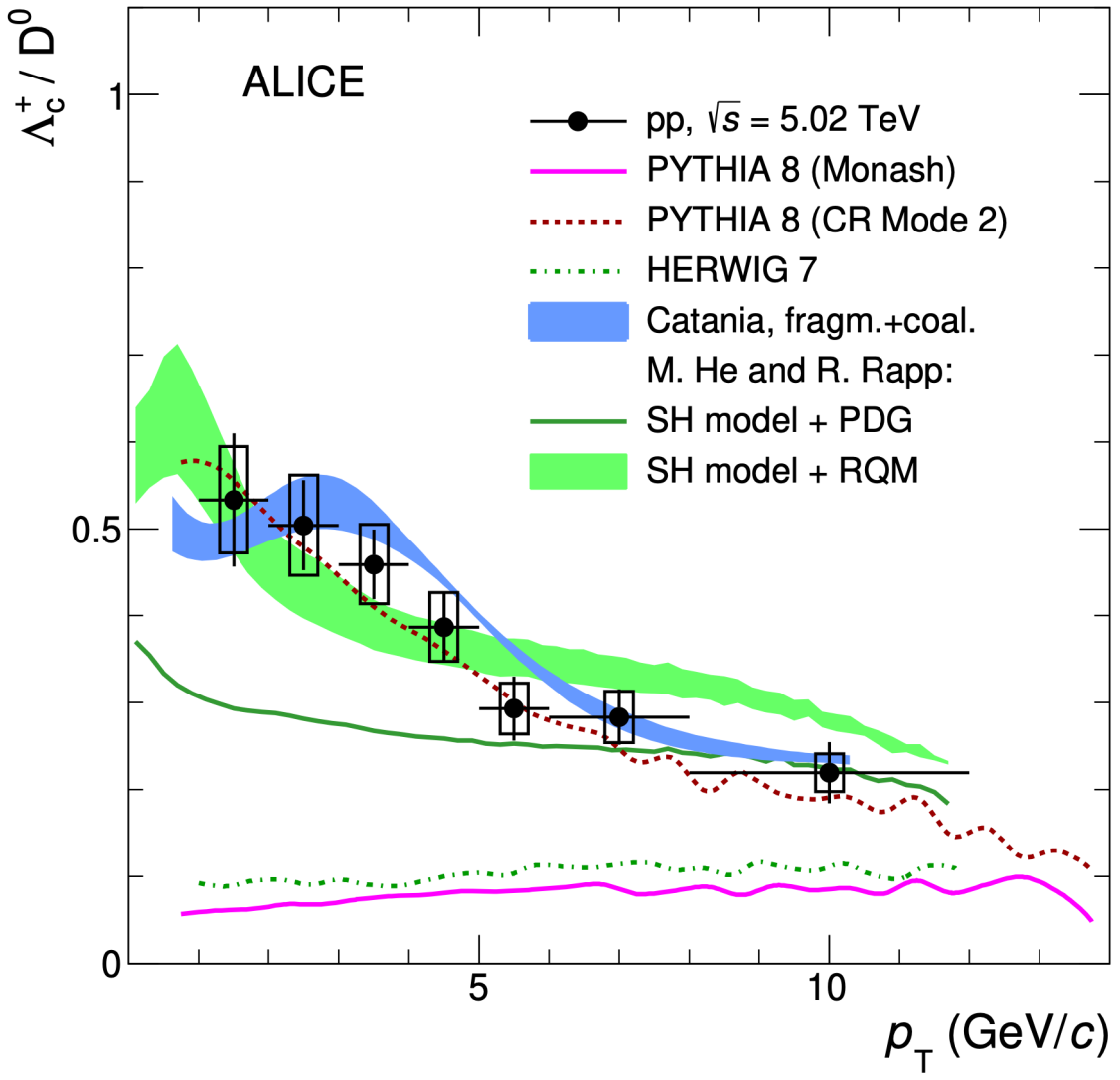
- ❑ heavy quarks hadronize via **fragmentation**
- ❑ fragmentation functions assumed **universal** (based on e^+e^- and ep data).

Key observation

$$\Lambda_c^+/D^0 \sim 0.4 - 0.5$$

at low p_T
which is **3–5× larger** than predicted by fragmentation models.

Standard fragmentation **fails to describe charm baryon production**.



PHYSICAL REVIEW LETTERS 127, 202301 (2021)

Evidence for Non-Universal Charm Hadronization

The ratio Λ_c^+/D^0
- ❑ decreases with p_T
- ❑ peaks around

$$p_T \sim 2 - 4\ GeV/c$$

Similar behavior seen for

$$\Lambda/K_s^0, p/\pi$$

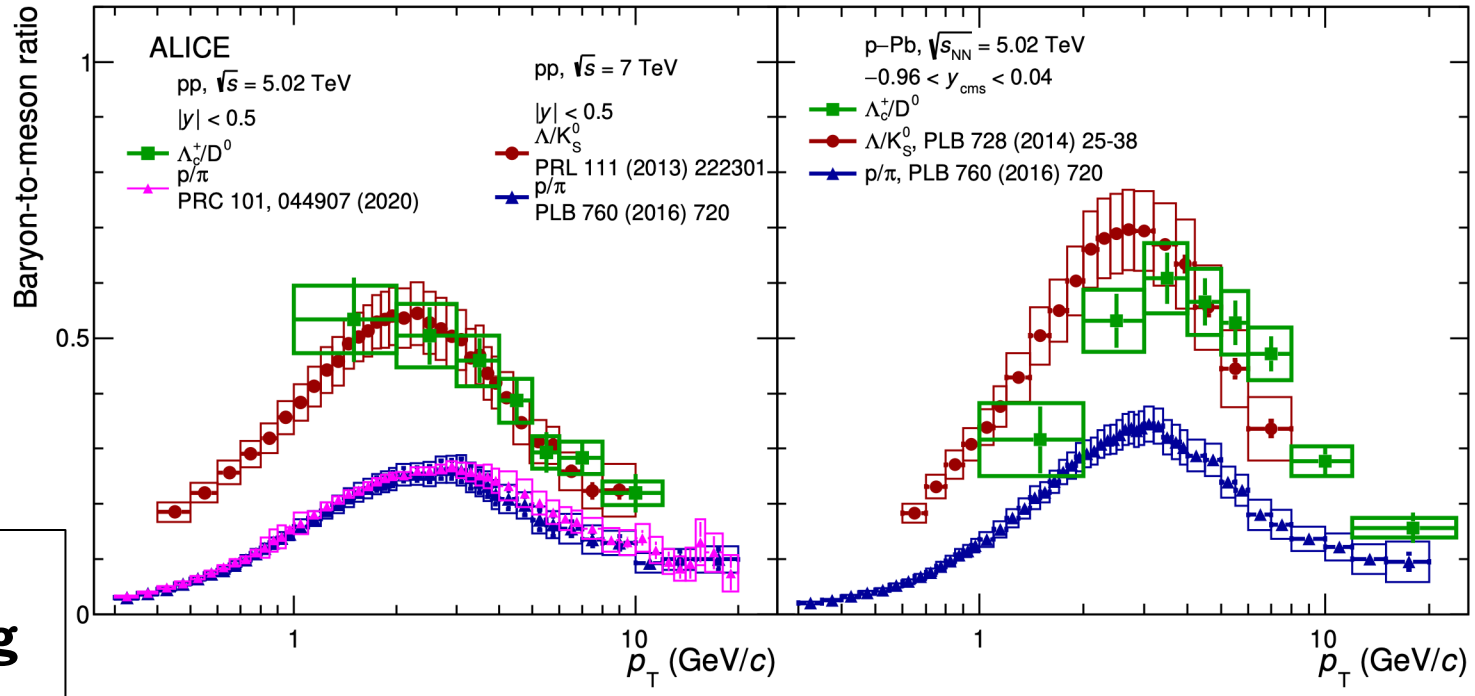
baryon-to-meson ratios.

Possible explanations:

1. **Color reconnection beyond leading color**
2. **Statistical hadronization with additional charm baryon states**
3. **Coalescence of charm quarks with light quarks**

Models including **coalescence + fragmentation** describe the data best.

PHYSICAL REVIEW LETTERS 127, 202301 (2021)



Key physics message

Charm hadronization in hadronic collisions

is *not universal*

and may involve **collective or recombination mechanisms**.

Sequential Suppression of Charmonium in the QGP

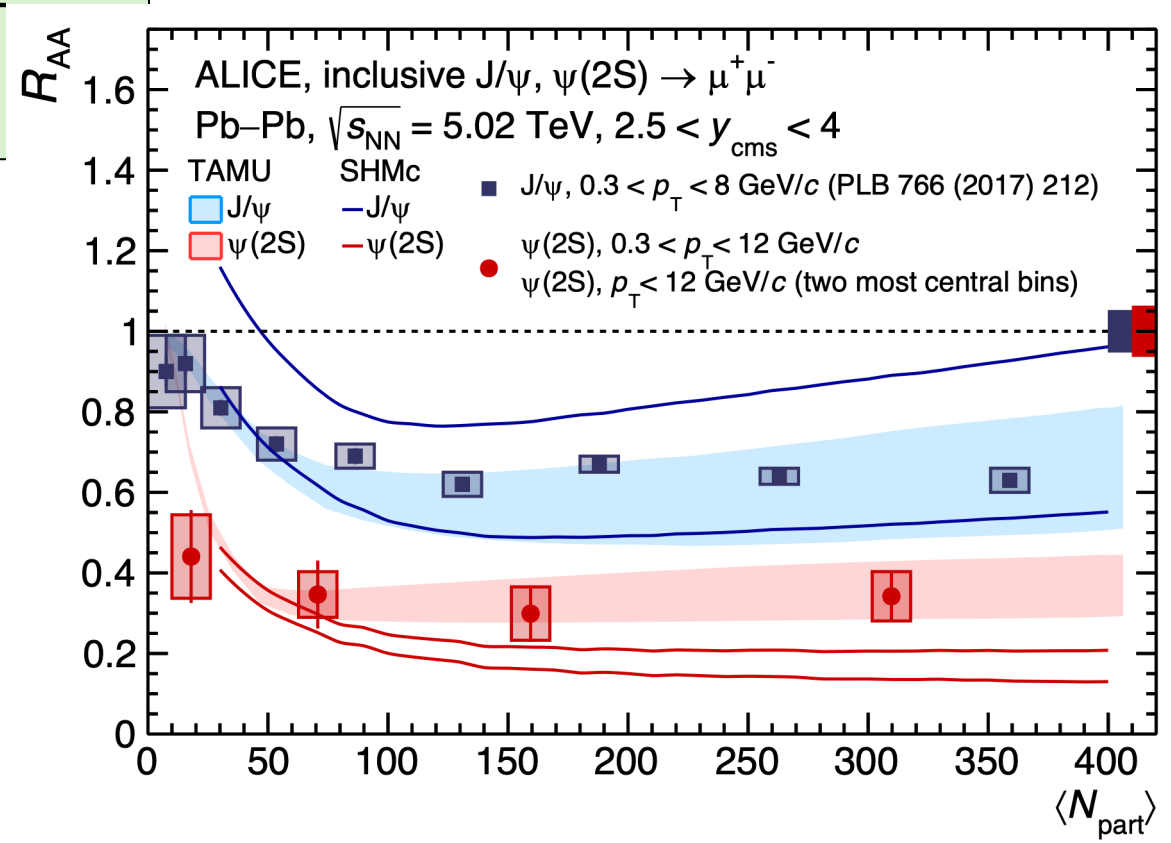
Charmonium as a probe of QGP

Heavy quarkonia dissolve in the QGP due to **color screening**

$$Q\bar{Q} + QGP \rightarrow dissociation$$

Different states have very different **binding energies**

State	Binding Energy
(J/\psi)	~640 MeV
(ψ(2S))	~50 MeV



Key observation

$\psi(2S)$ is **significantly more suppressed** than J/ψ.

Thus a **sequential melting pattern** is expected.

PHYSICAL REVIEW LETTERS 132, 042301 (2024)

Strong Suppression of ψ(2S) at the LHC

Nuclear modification factor

$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}}{d\sigma_{pp}}$$

Measures medium effects relative to pp.

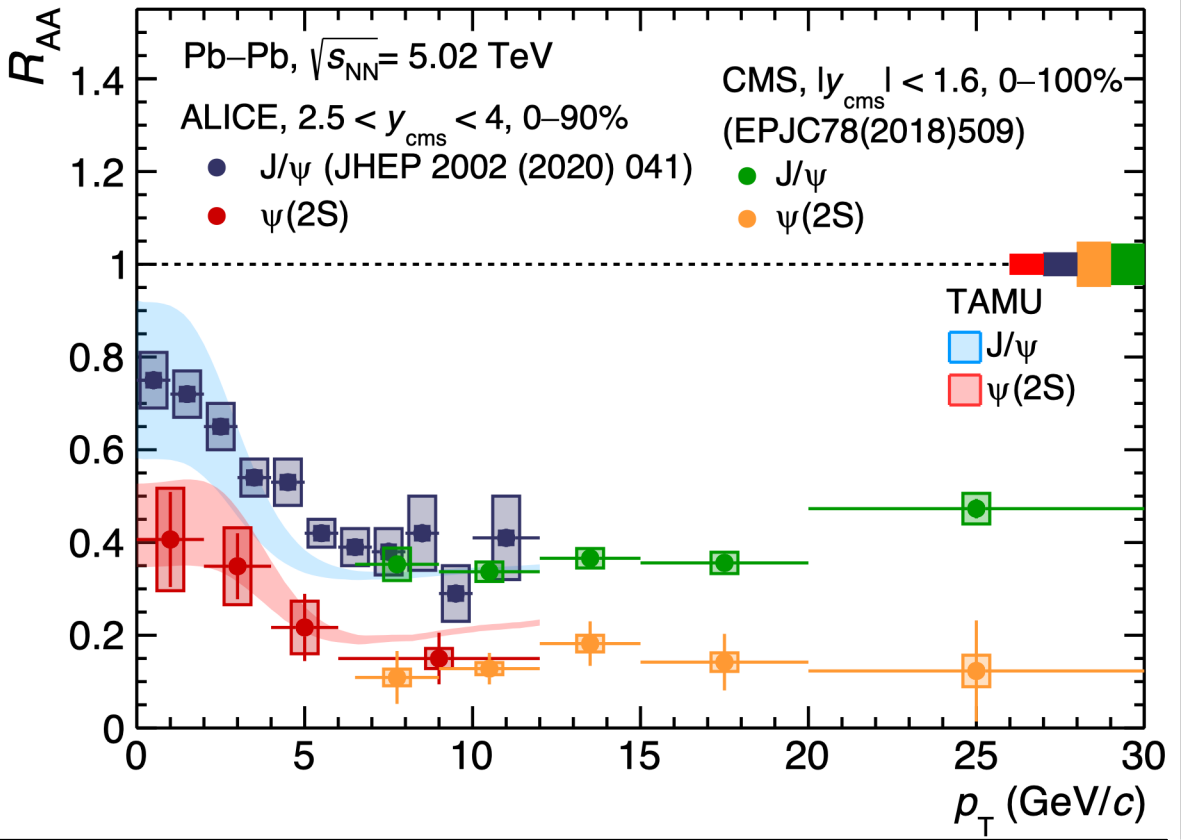
Experimental observations

- $\psi(2S)$ strongly suppressed in Pb–Pb
- typical value $R_{AA}(\psi(2S)) \approx 0.4$
- suppression stronger than for J/ψ at high p_T $R_{AA} \sim 0.15$

Results consistent with **transport models including**

- ❑ dissociation in the QGP
- ❑ recombination of charm quarks.

Transport calculations reproduce the data better than statistical hadronization models.



Sequential suppression of charmonium states

$$\psi(2S) > J/\psi \text{ suppression}$$

reflecting the **different binding energies of the states**.

PHYSICAL REVIEW LETTERS 132, 042301 (2024)

D-Meson Elliptic Flow as a Probe of QGP Transport

Heavy quarks as probes of the QGP

Heavy quarks

- ❑ produced in **initial hard scatterings**
- ❑ experience the **entire evolution of the medium**.

Their azimuthal anisotropy

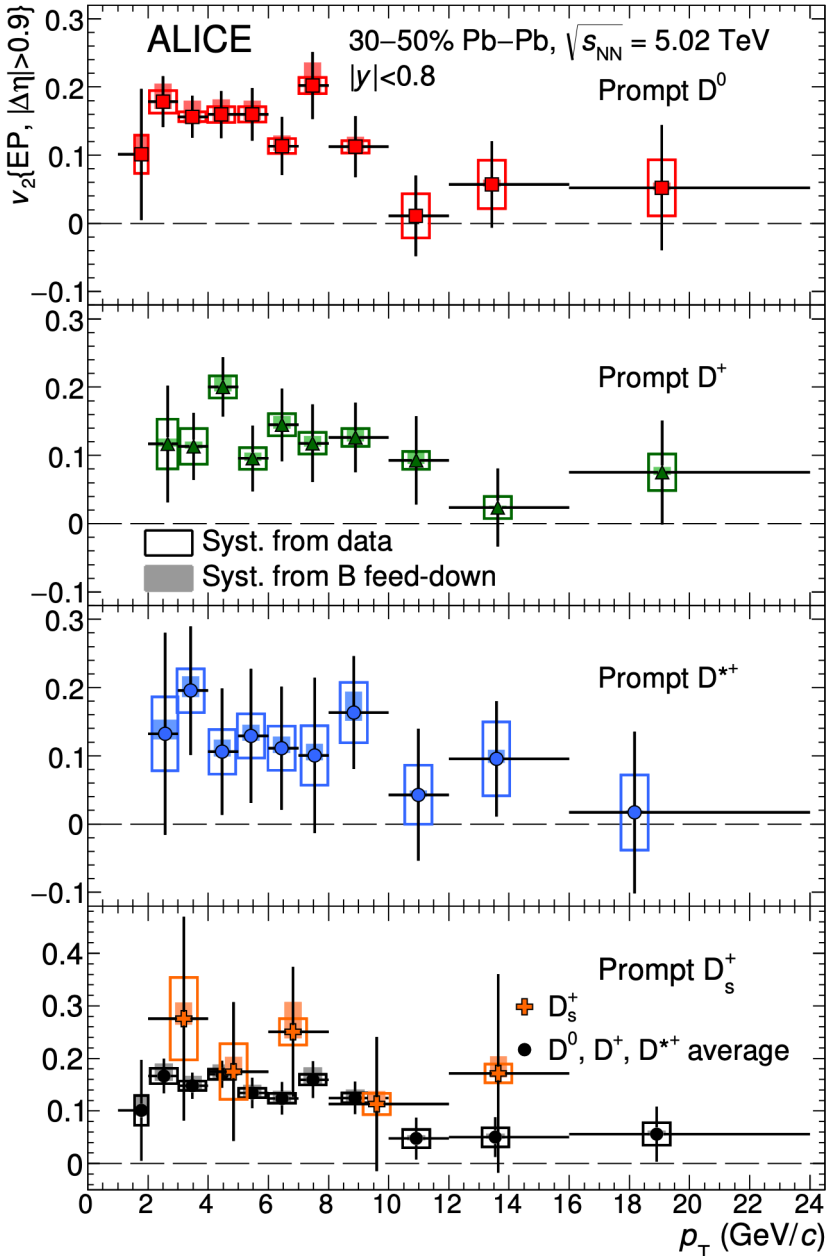
$$v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$$

measures the **collective response of heavy quarks to the medium**.

Measured particles

- D^0
- D^+
- D^{*+}
- D_s^+

via hadronic decays.



PHYSICAL REVIEW LETTERS 120, 102301 (2018)

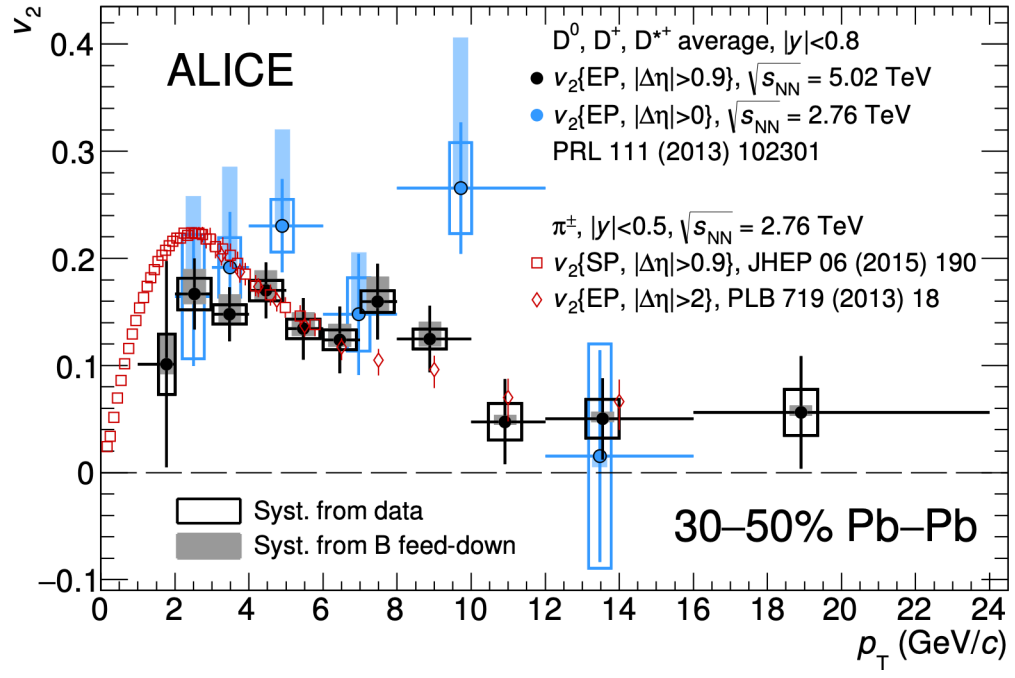
Charm Quarks Participate in Collective Flow

Key observations: Significant positive D-meson elliptic flow $v_2 > 0$ in $2 < p_T < 10$ GeV/c; indicating **strong interaction of charm quarks with the QGP**.

The magnitude of D-meson v_2

- comparable to that of **charged pions** at intermediate p_T.
- This suggests that **charm quarks partially thermalize in the medium**.

Charm quarks develop significant elliptic flow → evidence for **strong coupling between heavy quarks and the QGP medium**.



Implications for QGP transport

The measurements constrain the **heavy-quark diffusion coefficient**

$$2\pi T D_s \approx 1.5\text{–}7$$

near the QGP critical temperature.

PHYSICAL REVIEW LETTERS 120, 102301 (2018)

J/ψ Elliptic Flow at the LHC

Motivation

Quarkonium production in heavy-ion collisions is governed by competing mechanisms:

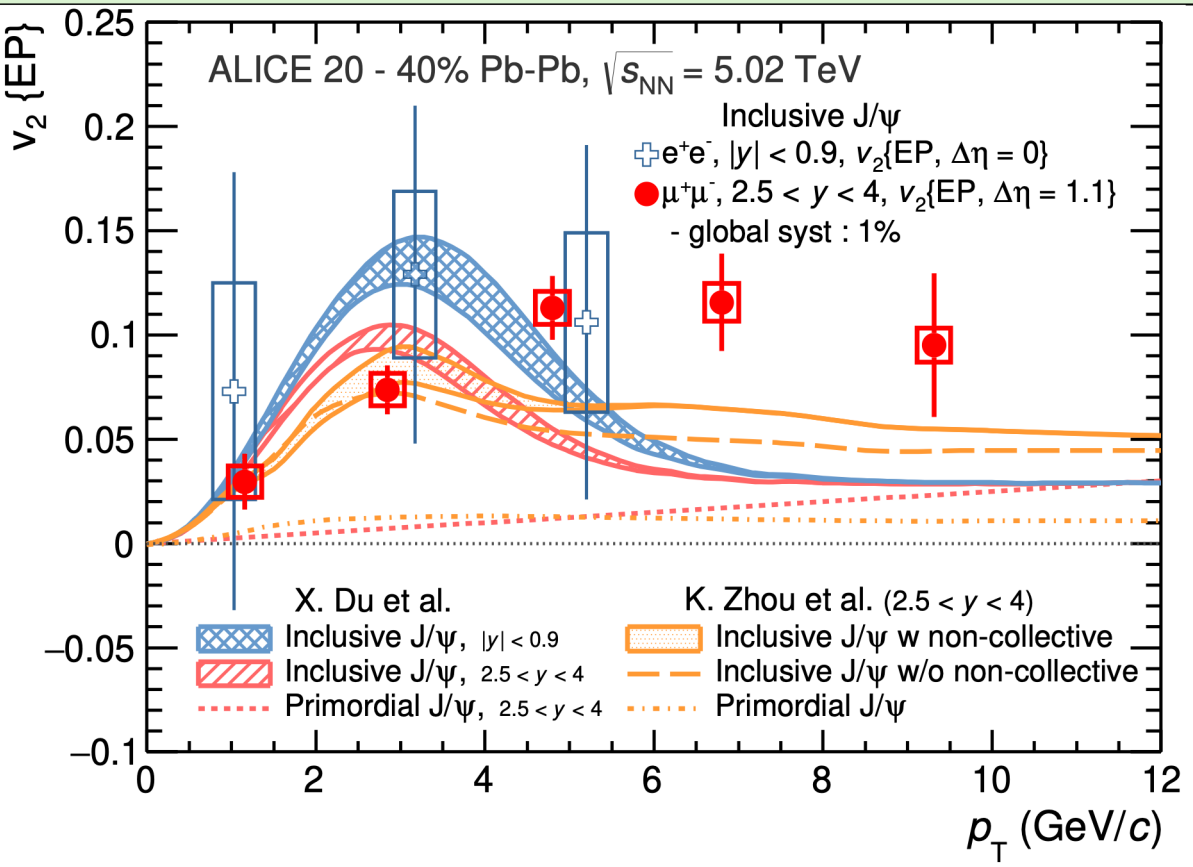
- ❑ **Color screening → suppression**
- ❑ **Charm recombination → regeneration**

Elliptic flow v_2 provides an additional probe of these mechanisms.

If charm quarks thermalize in the QGP,

$$c + \bar{c} \rightarrow J/\psi$$

via recombination, the produced J/ψ can inherit the **collective flow of the medium**.



PRL 119, 242301 (2017)

Elliptic flow coefficient

$$v_2 = \langle \cos 2(\phi - \Psi) \rangle$$

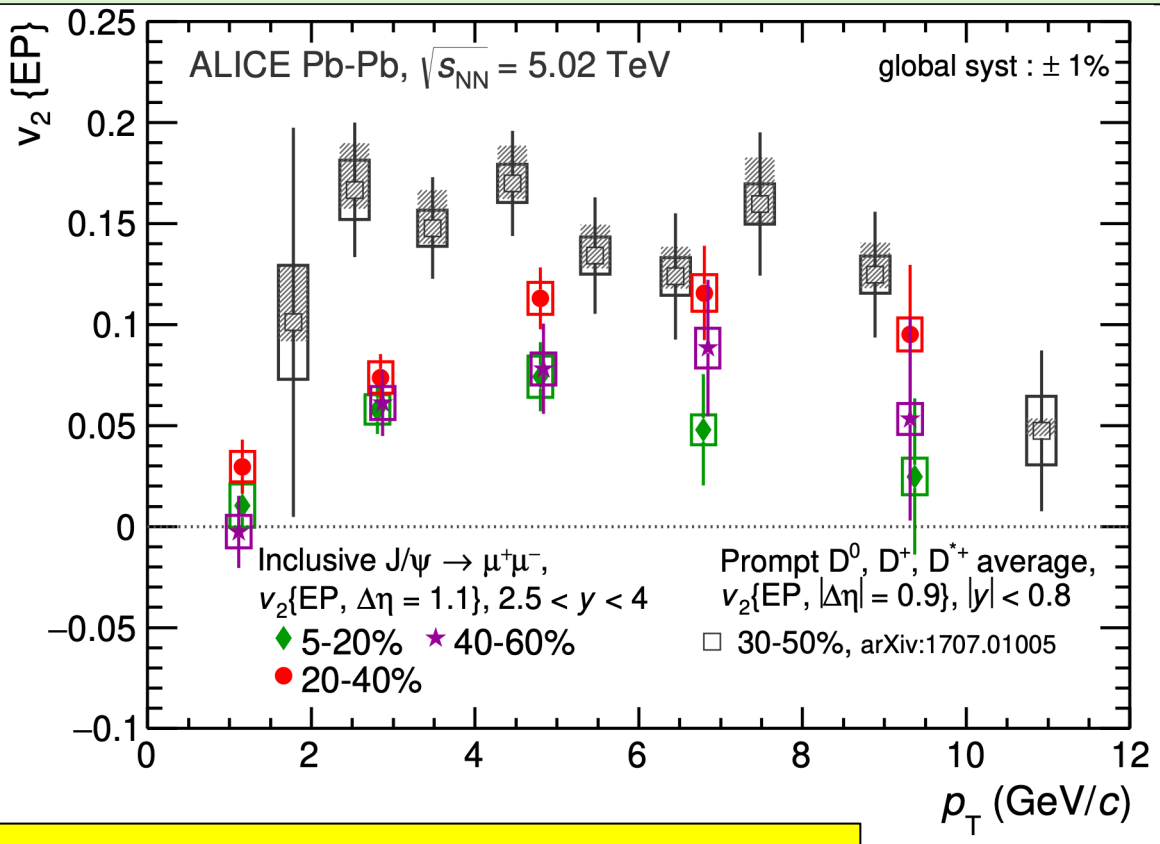
measures the **azimuthal anisotropy relative to the reaction plane**.

Evidence for Charm Quark Collectivity

A **significant positive J/ψ elliptic flow** is observed $2 < p_T < 8\ GeV/c$ With $v_2 \approx 0.1$; in semicentral collisions.

The significance of non-zero $v_2$reaches 6.6σ; in the region $4 < p_T < 6$ GeV/c.

PRL 119, 242301 (2017)



Large J/ψflow indicates

- ❑ **Charm quarks interact strongly with the QGP**
- ❑ **Partial thermalization of charm quarks**
- ❑ **Regeneration of J/ψ from deconfined charm quarks**.

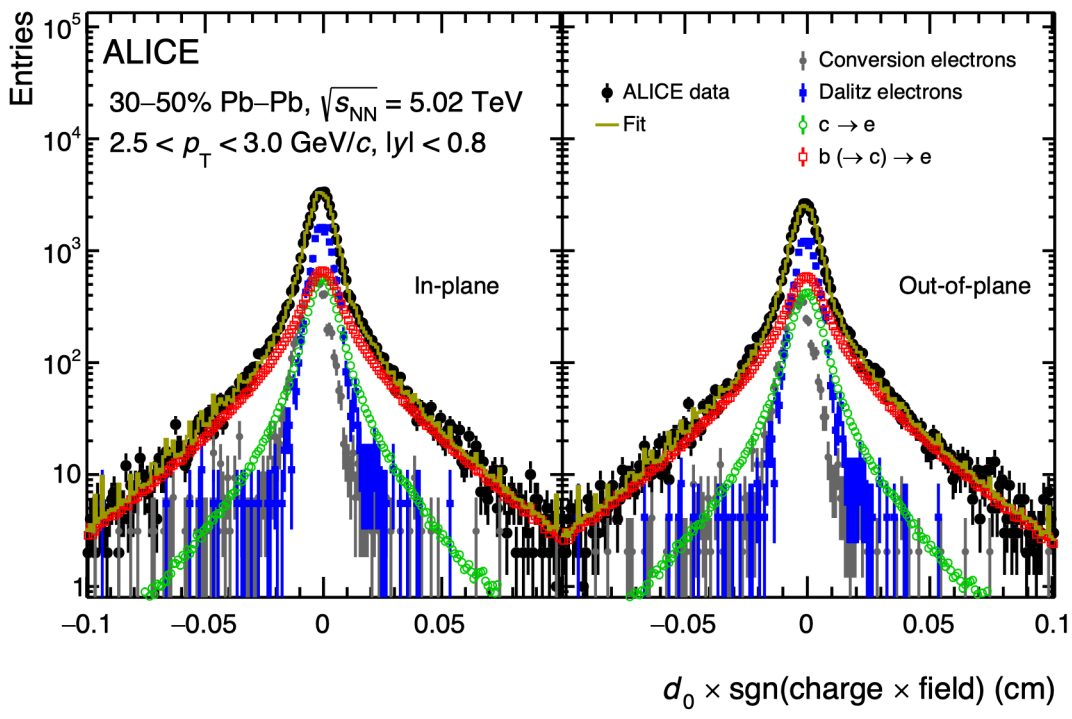
Transport models reproduce the magnitude of $v_2$at low $p_T$through **strong recombination contributions**.

Beauty Quarks as Probes of QGP Transport

Heavy quarks in heavy-ion collisions
Heavy quarks (c, b)
❑ produced in **initial hard scatterings**
❑ propagate through the QGP
They lose energy via
❑ **radiative energy loss**
❑ **collisional scattering**
Thus heavy flavour probes the **transport properties of the QGP**.

Key observable
Azimuthal anisotropy: v_2
reflects the **collective expansion of the medium**
Low p_T : $p_T < 3\ GeV/c$
→ sensitive to **thermalization**
High p_T
→ sensitive to **path-length dependent energy loss**.

PHYSICAL REVIEW LETTERS 126, 162001 (2021)



Measurement strategy
Measure v_2 ; of **electrons from beauty-hadron decays**
Beauty decays are identified via
❑ **large impact parameter**
❑ due to long lifetime $c\tau \sim 500\ \mu m$
This allows separation from charm and background electrons.

Evidence for Beauty Quark Flow

Key observation
Positive elliptic flow observed

$$v_2 > 0$$

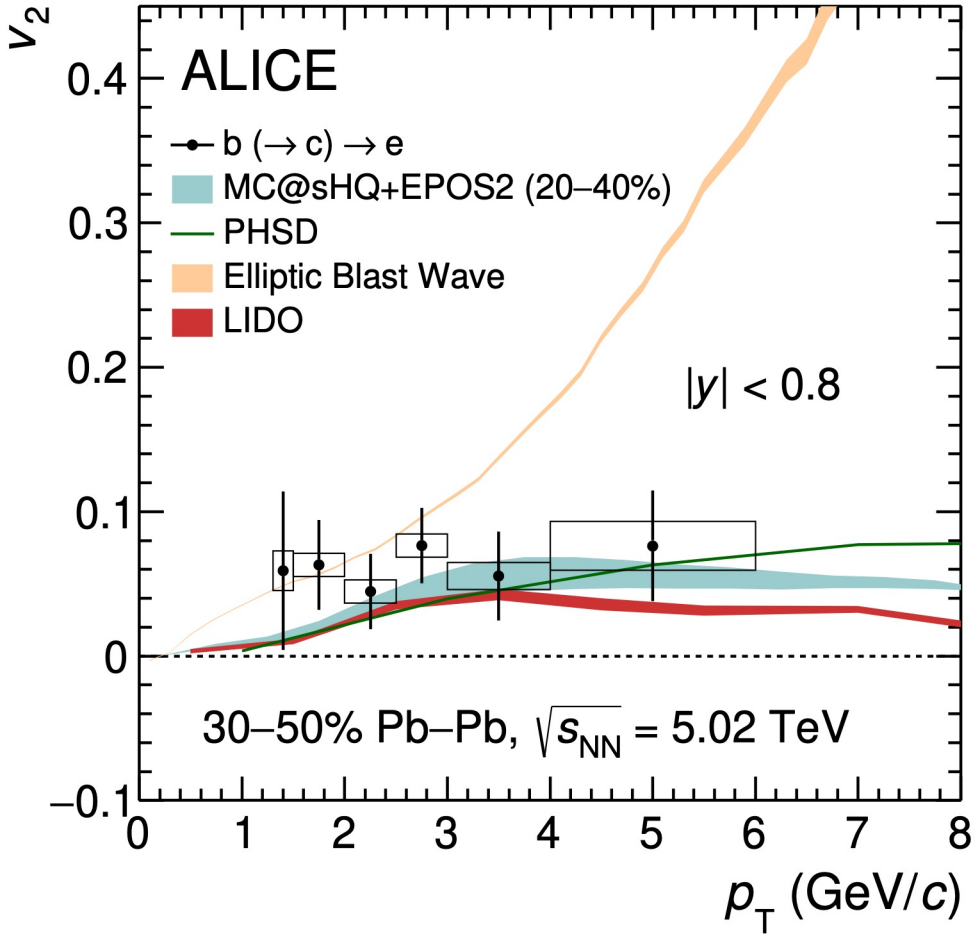
with significance 3.75σ
This is the **first measurement of beauty flow in this low-p_T region**.

The result indicates that **beauty quarks interact strongly with the QGP**
Transport models with collisional + radiative energy loss
describe the data within uncertainties.

Even very heavy quarks

$$m_b \sim 5\ GeV$$

participate in the **collective expansion of the QGP**.
This provides strong constraints on **heavy-quark diffusion coefficients**.



PHYSICAL REVIEW LETTERS 126, 162001 (2021)

Bottomonium Elliptic Flow as a Probe of QGP Dynamics

Motivation

Heavy quarkonia probe the QGP through

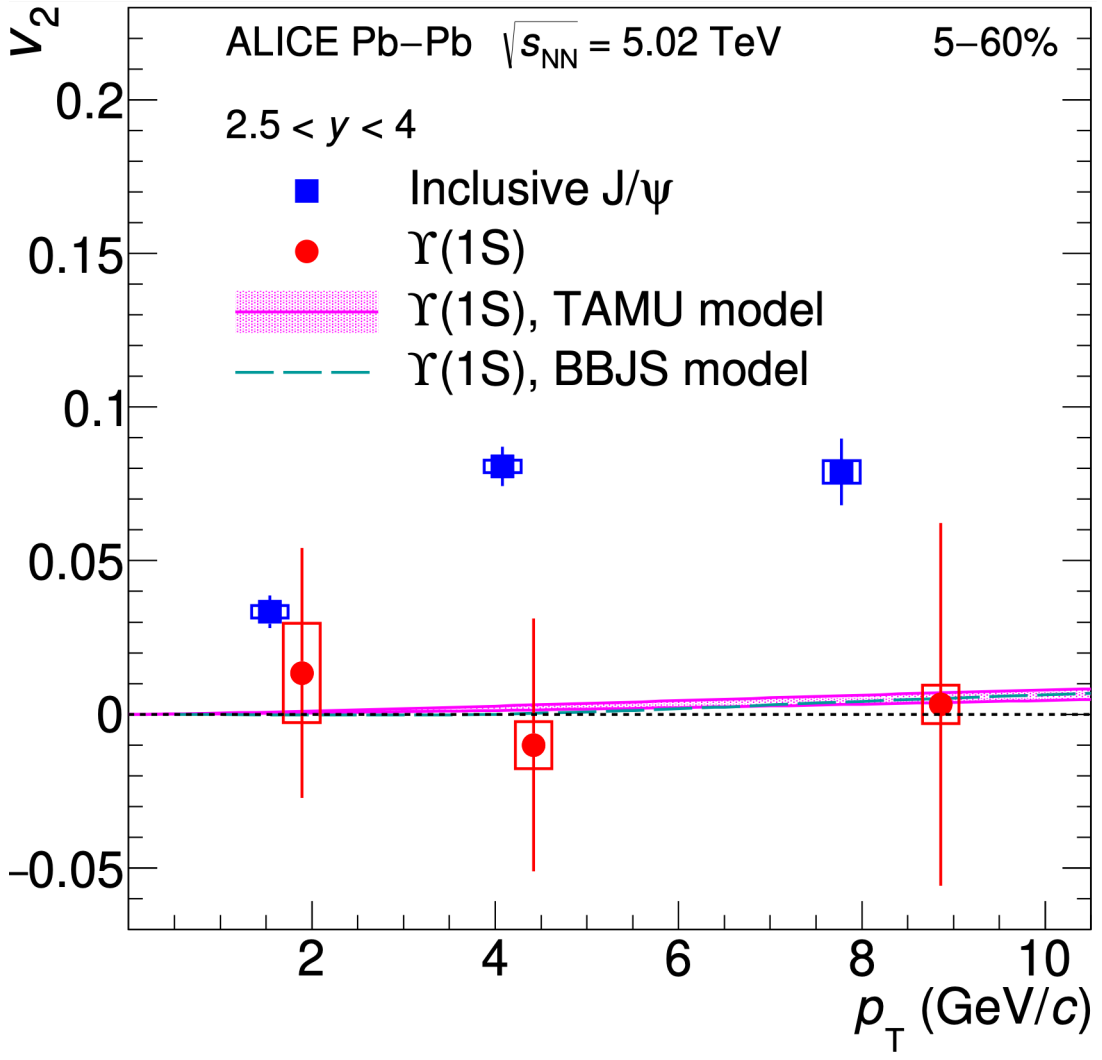
- ❑ **color screening**
- ❑ **dissociation in the medium**
- ❑ possible **regeneration from heavy quarks**
- ❑ Charmonia (J/ψ)
- ❑ strong evidence for **regeneration at LHC energies**.

Bottomonium as a cleaner probe

Bottomonium states $b\bar{b}$ have

- ❑ **larger binding energy**
- ❑ **much smaller regeneration probability**

Therefore $\Upsilon(1S)$, production is expected to be dominated by **suppression in the early QGP stage**.



PHYSICAL REVIEW LETTERS 123, 192301 (2019)

Experimental Result: $\Upsilon(1S)$Flow

Measured elliptic flow : $v_2(\Upsilon(1S))$ measured for $0 < p_T < 15\ GeV/c$ in $5-60\%$ *centrality*

Key observation: The measured $\Upsilon(1S)$elliptic flow is

$$v_2 \approx 0$$

within uncertainties.

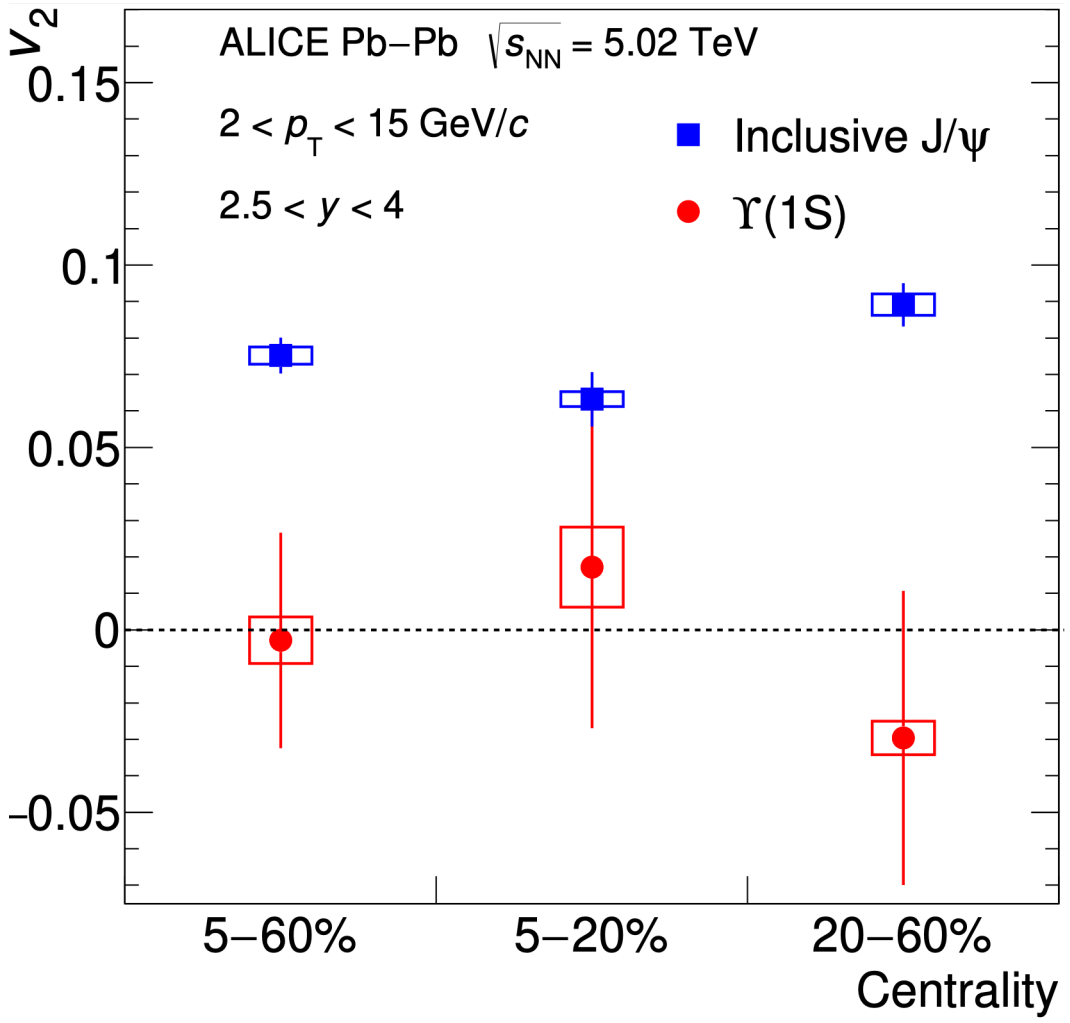
Comparison with charmonium

$$v_2(\Upsilon(1S)) < v_2(J/\psi)$$

difference ≈ **2.6σ**.

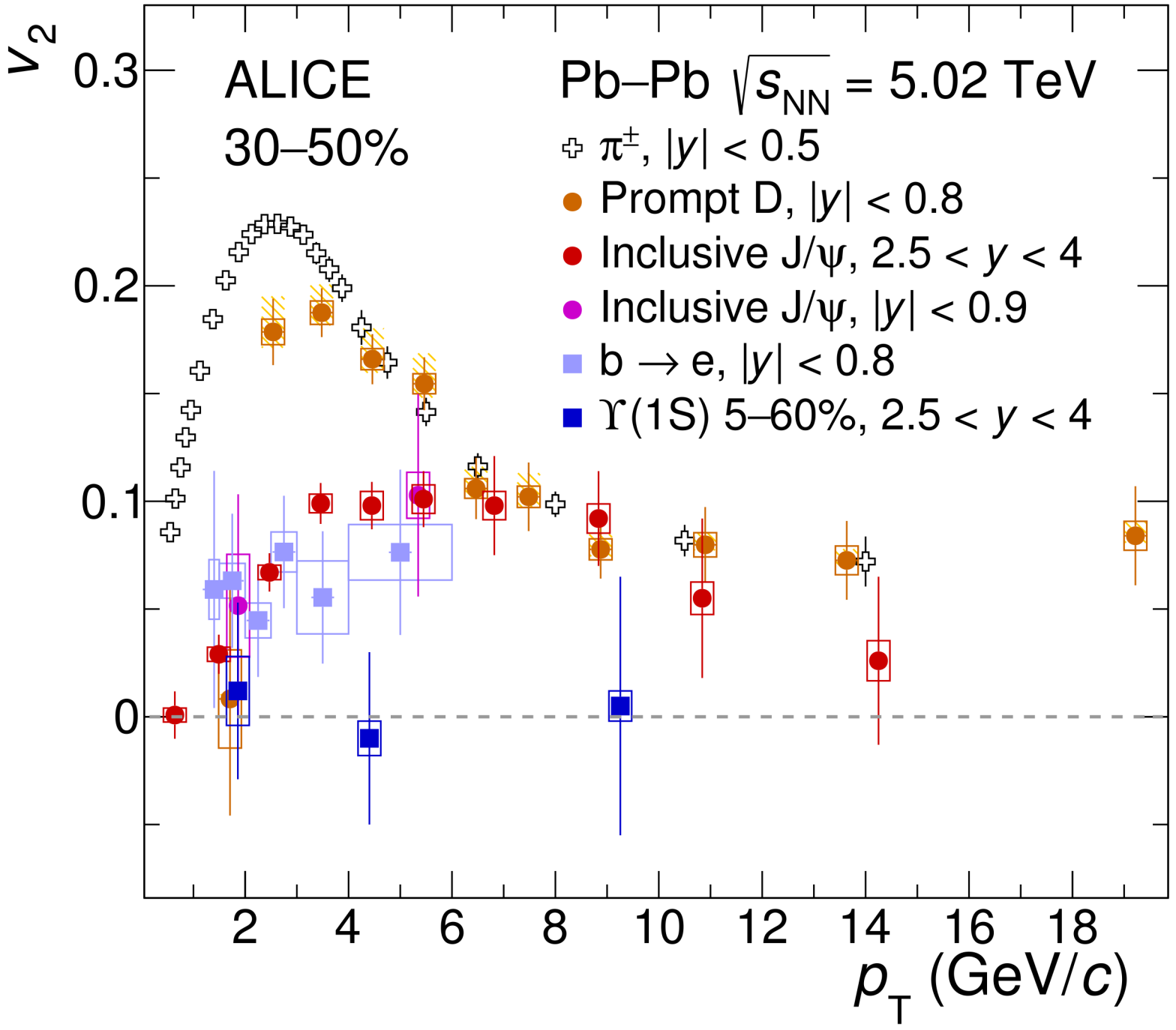
The result is consistent with a scenario where

- ❑ $\Upsilon(1S)$production is dominated by **early dissociation regeneration is negligible**
- ❑ While J/ψproduction contains a **significant regeneration component**.



PHYSICAL REVIEW LETTERS 123, 192301 (2019)

Heavy Flavor flow Summary



Charge-Dependent Directed Flow as a Probe of Early EM Fields

Physics motivation

Non-central heavy-ion collisions generate

•extremely strong **electromagnetic fields**

$$B \sim 10^{18} - 10^{19}\ Gauss$$

in the first $< 0.5\ fm/c$ of the collision

These fields can induce **charge-dependent flow** via

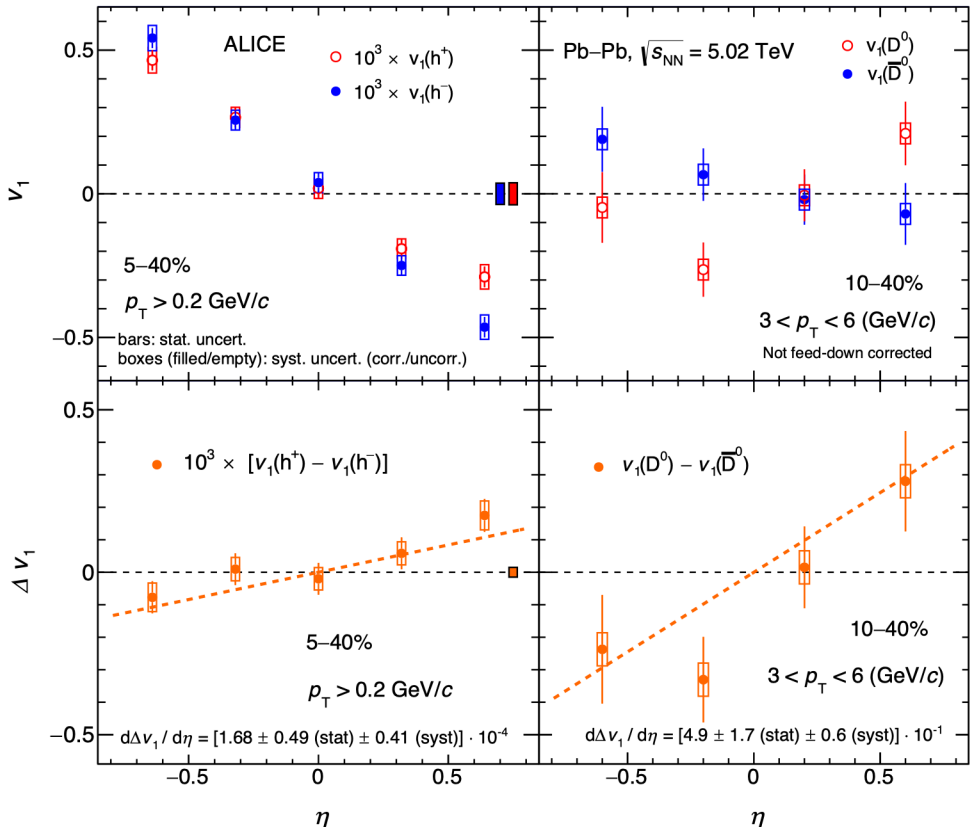
- ❑ Lorentz force
- ❑ Coulomb interaction with spectators.

Heavy-quark sensitivity

Charm quarks

- ❑ produced **very early**
- ❑ experience the **largest electromagnetic fields**

Therefore $\Delta v_1(D) = v_1(D^0) - v_1(\bar{D}^0)$ is expected to be **much larger than for light hadrons**.



Directed flow v_1 is the first harmonic coefficient of azimuthal anisotropy

$$v_1 = \langle \cos(\phi - \Psi_{SP}) \rangle$$

measured relative to the **spectator plane**.

PHYSICAL REVIEW LETTERS 125, 022301 (2020)

Experimental Observation of Charge-Dependent Directed Flow

Charged hadrons:

$$\frac{d\Delta v_1}{d\eta} = (1.68 \pm 0.49 \pm 0.41)\times 10^{-4}$$

with significance ≈ **2.6σ**.

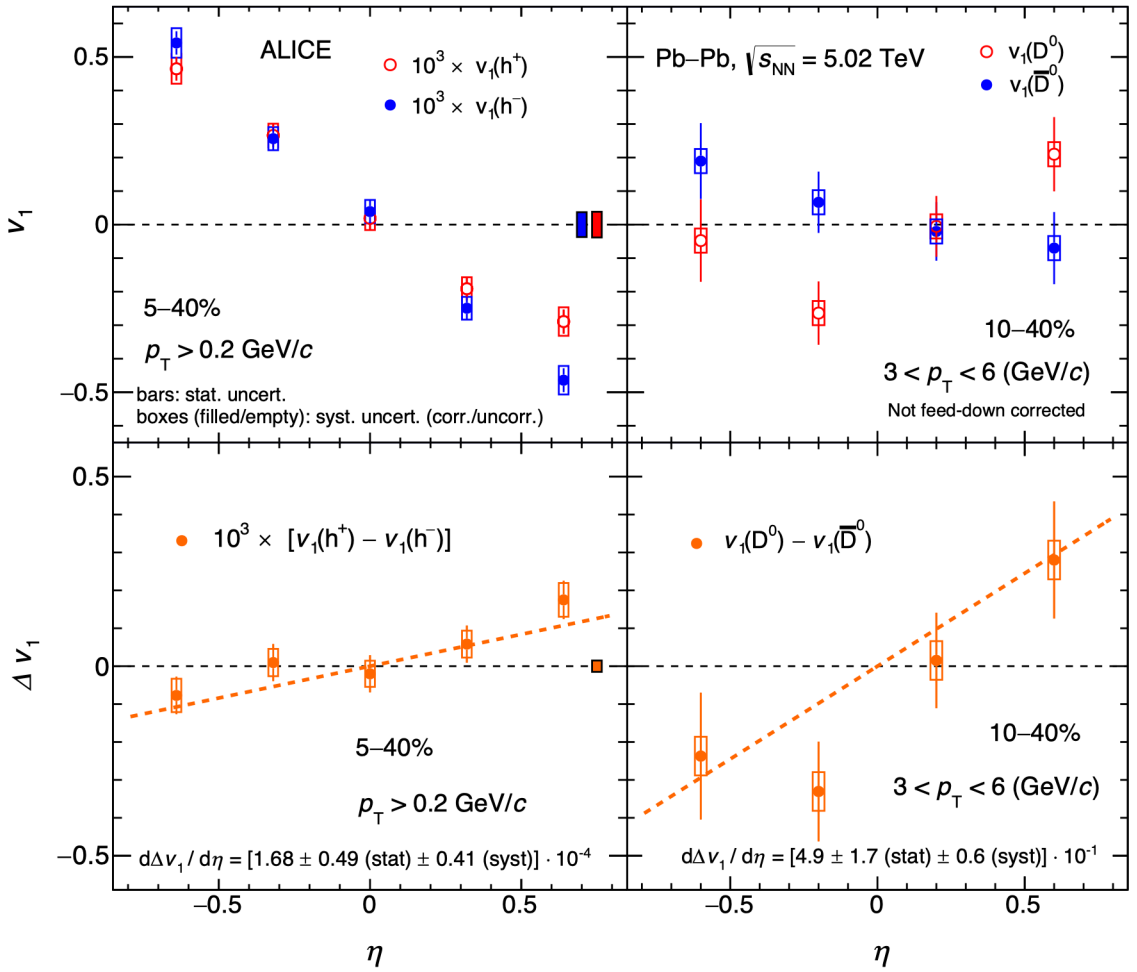
Charm mesons: For D^0 and $\bar{D}^0$

$$\frac{d\Delta v_1}{d\eta} = (4.9 \pm 1.7 \pm 0.6)\times 10^{-1}$$

≈ **three orders of magnitude larger than for light hadrons**.

The large difference between light and heavy flavors indicates

- ❑ strong sensitivity of charm quarks to **early-time electromagnetic fields**
- ❑ interplay between **magnetic field dynamics** and **tilted initial geometry**.



PHYSICAL REVIEW LETTERS 125, 022301 (2020)

J/ψ Polarization Relative to the Event Plane

Motivation

Heavy-ion collisions generate extremely large

- ❑ **orbital angular momentum**
- ❑ **magnetic fields** $B \sim 10^{20}$ *Gauss*

These can induce **spin alignment of vector mesons**.

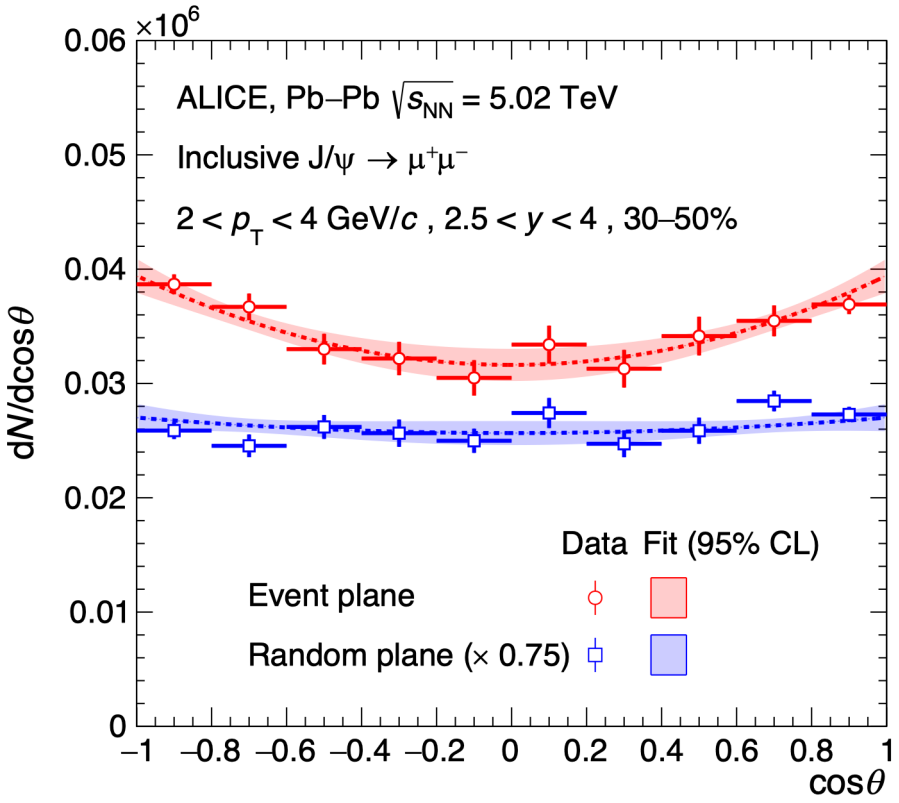
Polarization measured **relative to the event plane**

→ sensitive to

- ❑ **QGP vorticity**
- ❑ **early electromagnetic fields**

This reference frame is directly connected to the **global angular momentum of the system**.

PHYSICAL REVIEW LETTERS 131, 042303 (2023)



Polarization is measured through the angular distribution $W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1 + \lambda_\theta \cos^2\theta\right)$ Where θ= angle between decay muon and polarization axis. $\lambda_\theta = 0$ → **no polarization**.

Evidence for Small Transverse J/ψPolarization

A **small but significant transverse polarization** is observed.
Maximum effect

$$\lambda_\theta \sim 0.2$$

with significance up to

$$3.9\sigma$$

for

$$2 < p_T < 4\ GeV/c$$

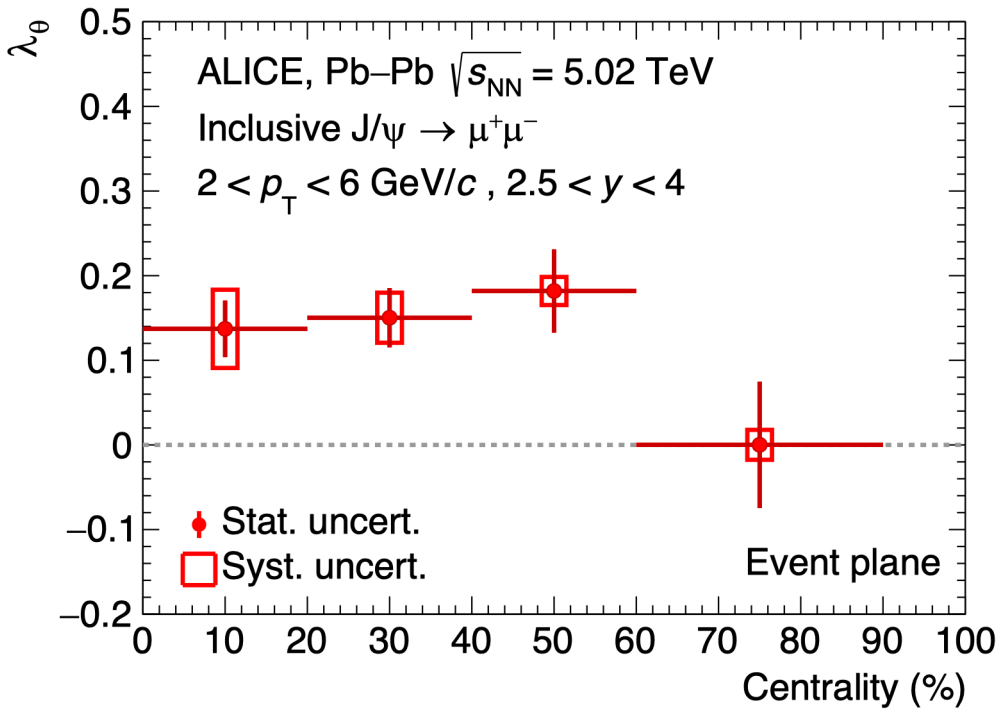
and semicentral collisions.

The observed polarization may be connected to

- ❑**vorticity of the QGP**
- ❑**spin–orbit coupling in the medium**

The effect is **similar to spin alignment seen for light vector mesons**.

PHYSICAL REVIEW LETTERS 131, 042303 (2023)



Charmonium polarization may provide a **new probe of the rotational dynamics of the QGP**.

Spin Alignment of Open Heavy-Flavour Vector Mesons

Motivation

Non-central heavy-ion collisions generate

- ❑ **Large angular momentum**
- ❑ **Extremely strong magnetic fields**

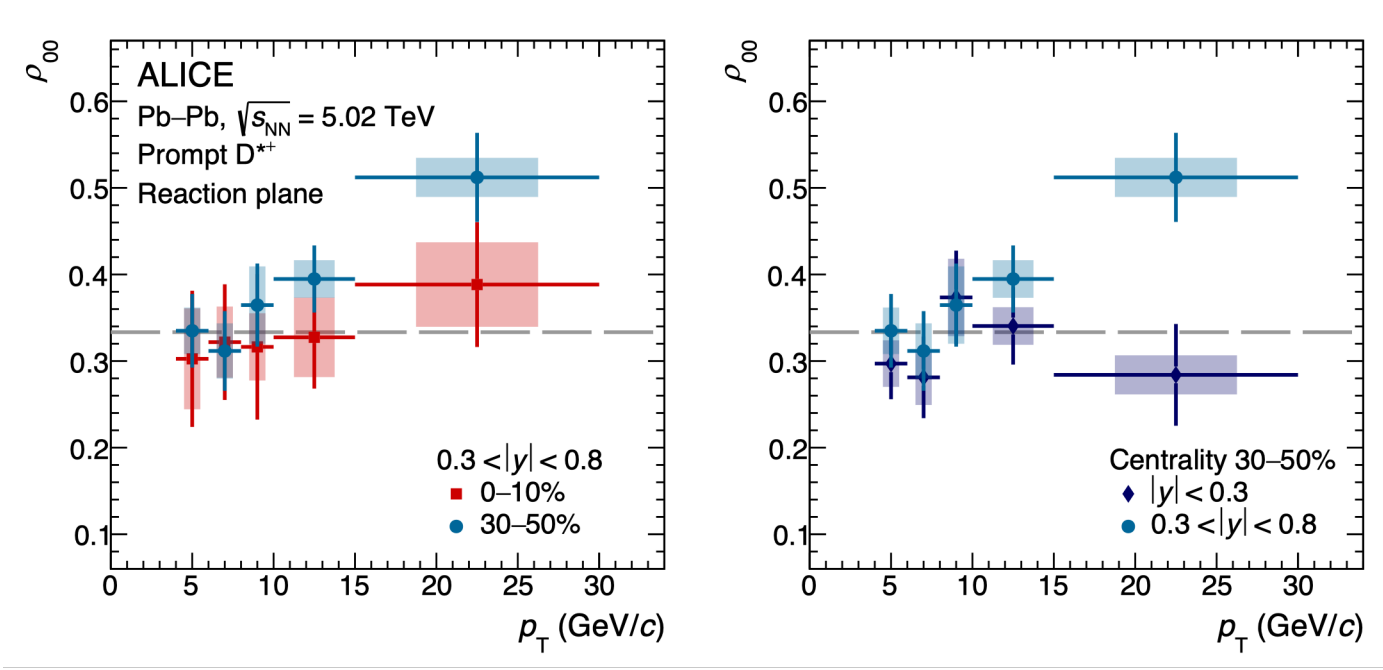
These can polarize quarks produced in the early stage of the collision.

The polarization can be transferred to final-state hadrons and studied via **spin alignment**.

Spin alignment is measured from the angular distribution

$$\frac{dN}{d\cos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

where θ^* is the decay angle in the meson rest frame.



JHEP10(2025)094

Observable

Vector-meson spin alignment is quantified using ρ_{00} the diagonal element of the spin-density matrix.

- ❑ **No alignment:** $\rho_{00} = 1/3$
- ❑ **Deviation from** $1/3 \rightarrow$ spin alignment.

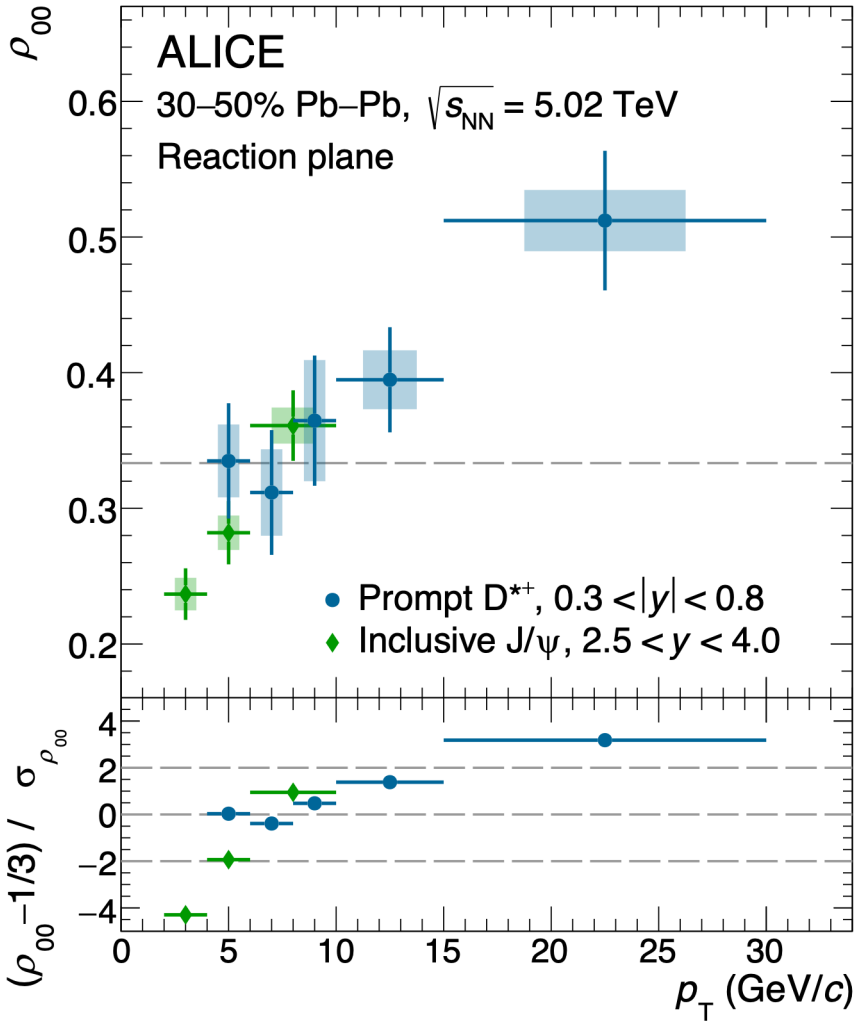
Evidence for Charm-Quark Polarization

Spin alignment of open charm mesons provides a **new probe of early-time QGP dynamics**, including

- ❑ magnetic fields
- ❑ vorticity
- ❑ heavy-quark spin transport.

Main observations

- ❑ In **central collisions**, $\rho_{00} \approx 1/3$
- ❑ In **mid-central collisions**, $\rho_{00} > 1/3$appears at high p_T
- ❑ Maximum deviation observed at $15 < p_T < 30$ GeV/c
- ❑ with significance ≈ **3.1σ**.



Possible origin of the effect:

- ❑ **Polarization of charm quarks by early magnetic fields**
- ❑ **Vorticity-induced spin polarization**
- ❑ **Spin correlations during hadronization**

High-p_T charm quarks may retain polarization because of **shorter interaction time in the QGP**.

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Imaging Gluon Fluctuations with Incoherent J/ψ Production

Photonuclear vector meson production
In ultraperipheral heavy-ion collisions

$$\gamma + Pb \rightarrow J/\psi + X$$

Two processes contribute:

Coherent production

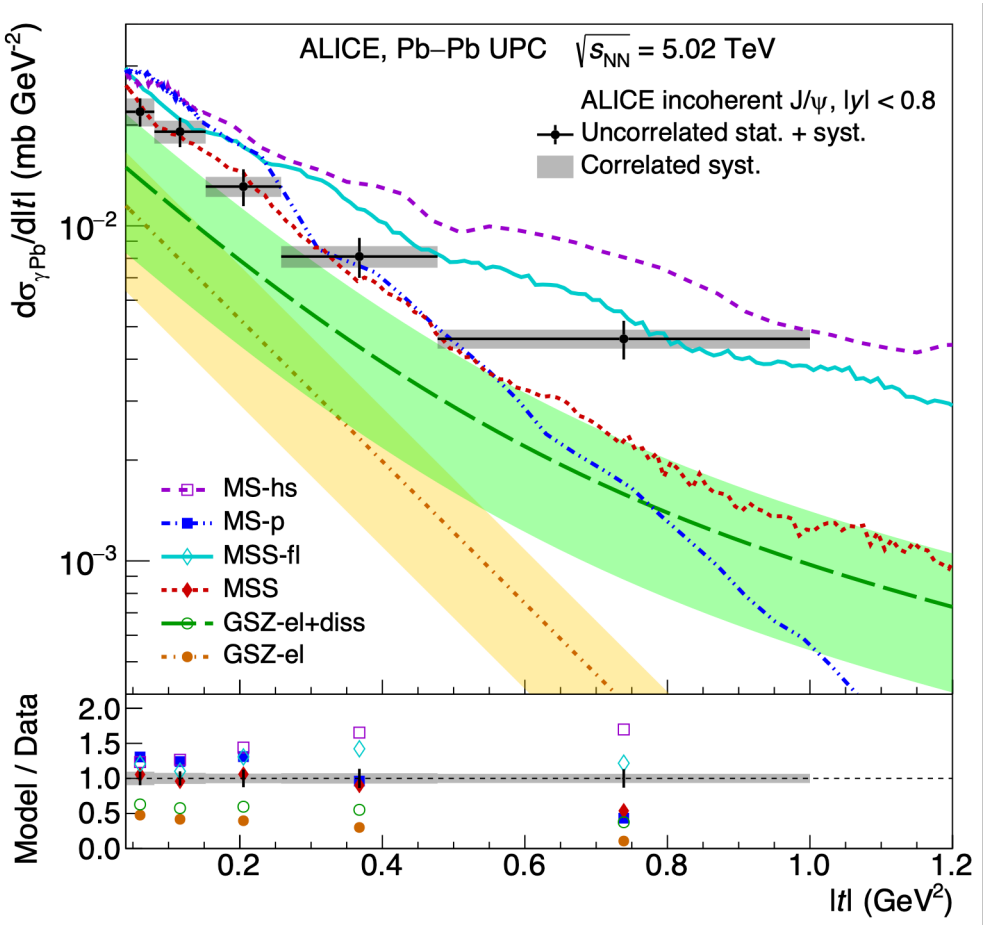
$$\gamma + A \rightarrow J/\psi + A$$

•photon interacts with the **whole nucleus**
•probes **average gluon density**

Incoherent production

$$\gamma + A \rightarrow J/\psi + A^*$$

•photon interacts with **individual nucleons**
•sensitive to **event-by-event fluctuations of the gluon field**



Momentum transfer $|t| \approx p_T^2$ is related to the **transverse spatial structure of the target.** Large $|t|$ probes **smaller spatial structures**.

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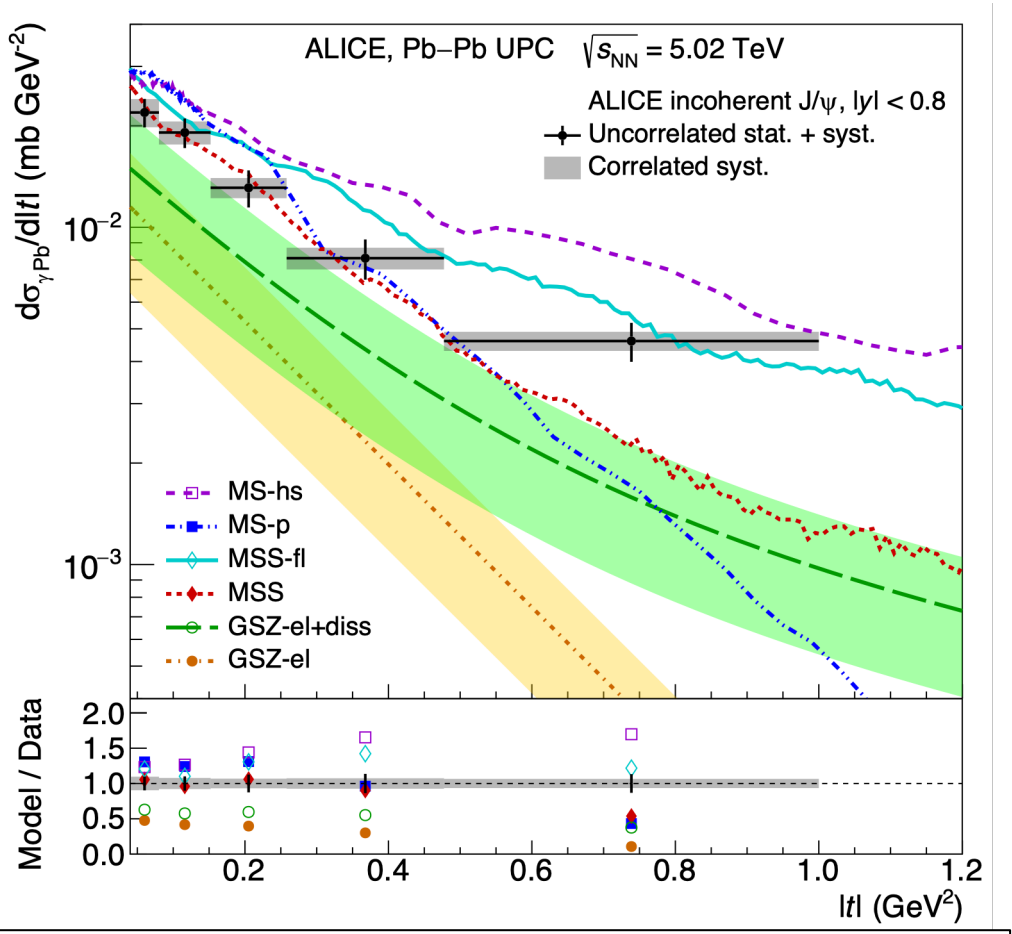
Evidence for Subnucleon Gluon Fluctuations

ALICE measures $\frac{d\sigma}{d|t|}$ for incoherent J/ψ photoproduction in Pb–Pb UPCs $\sqrt{s_{NN}} = 5.02\ TeV, |y| < 0.8$ in the range $0.04 < |t| < 1\ GeV^2$ corresponding to $x \sim 10^{-3}$

Models **without gluon fluctuations**
→ predict **steeper $|t|$ dependence**
Models **with subnucleon fluctuations (hot spots)**
→ reproduce the measured spectrum much better.

Incoherent J/ψ photoproduction probes
- ❑ **variance of the gluon density**
- ❑ **nucleon substructure fluctuations**
- ❑ **initial-state geometry of heavy-ion collisions**



These measurements provide constraints on
- ❑ **nuclear gluon distributions**
- ❑ **saturation physics**
- ❑ **future Electron–Ion Collider studies**.

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Summary of Heavy-Flavor Results at LHC

Heavy quarks probe **multiple stages of heavy-ion collisions**

- ❑ Early stage → production of heavy quarks
- ❑ Medium stage → energy loss and collective flow
- ❑ Hadronization → recombination effects
- ❑ Spin physics → possible sensitivity to **vorticity and magnetic fields**

Heavy-flavour spin physics

- First measurement of D^{*+} **spin alignment**

$$\rho_{00} > \frac{1}{3}$$

observed at high p_T

→ possible sensitivity to

- **initial magnetic fields**
- **vorticity of the QGP**
- **heavy-quark polarization**

Summary of Heavy-Flavor Results at LHC

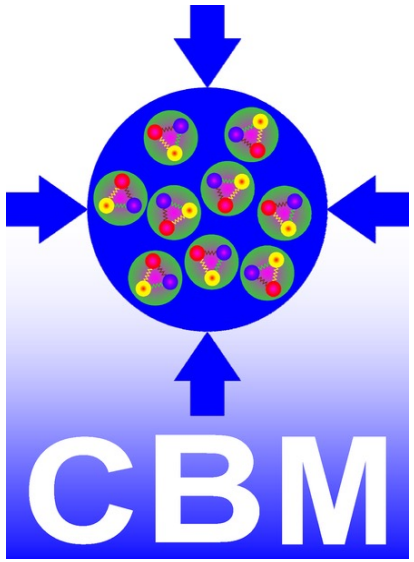
Open Heavy Flavour
Strong interaction of heavy quarks with the QGP

- Significant **D-meson suppression** at high p_T
  →evidence for **large heavy-quark energy loss**
- Large **elliptic flow** v_2 of D mesons
  → heavy quarks participate in **collective expansion**
- Enhanced Λ_c/D^0 and D_s/D^0 ratios
  → indicates **hadronization via quark recombination**

Quarkonia

- **Competition between suppression and regeneration**
- **J/ψ suppression weaker at the LHC than RHIC**
  → consistent with **regeneration from abundant charm quarks**
- **Positive J/ψ elliptic flow** v_2 observed
  → charm quarks partially **thermalized in the medium**
- **Spin alignment measurements** suggest possible **charm-quark polarization**

Acknowledgements



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