12th MPI at LHC

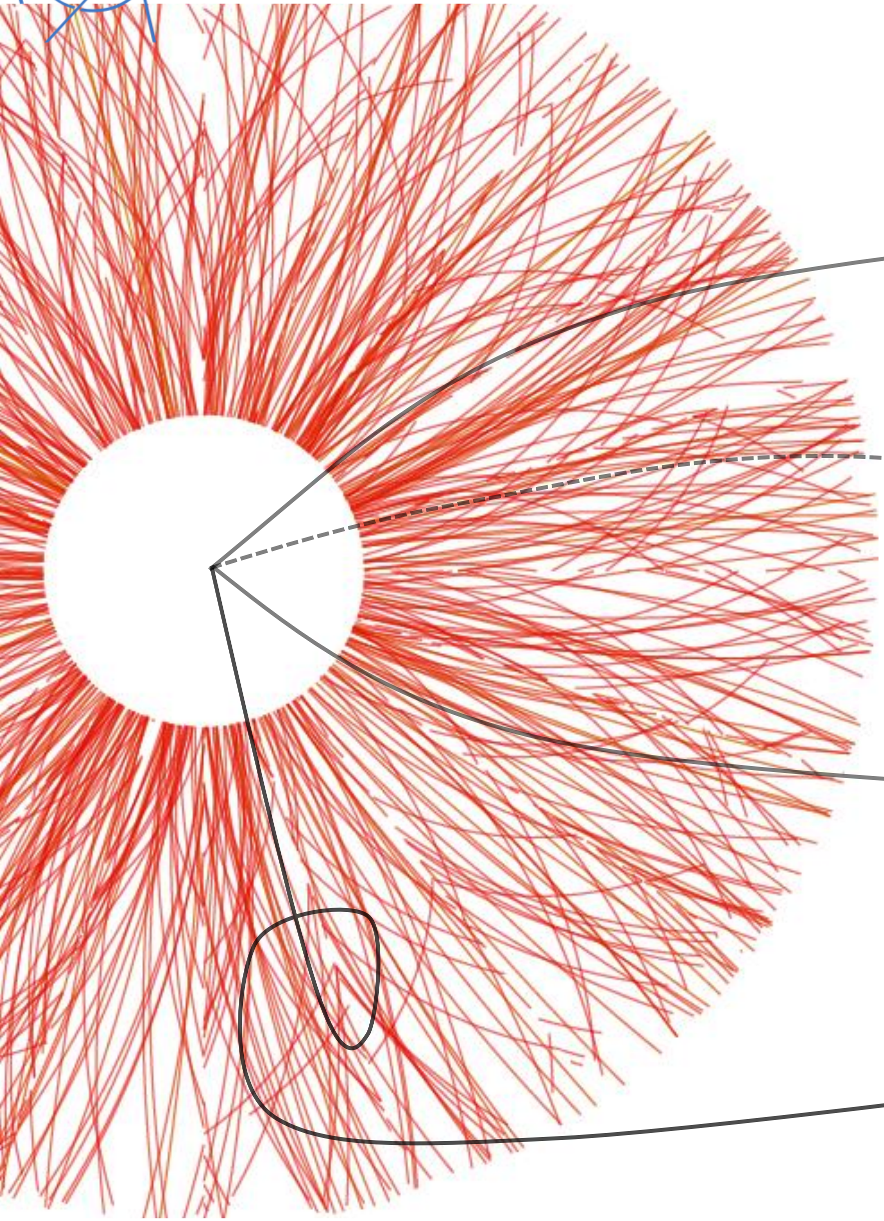
Overview on quarkonia and heavy-flavor physics at the LHC

Luca Micheletti (INFN Torino)

On behalf of **ALICE**, **ATLAS**, **CMS** and **LHCb** collaborations

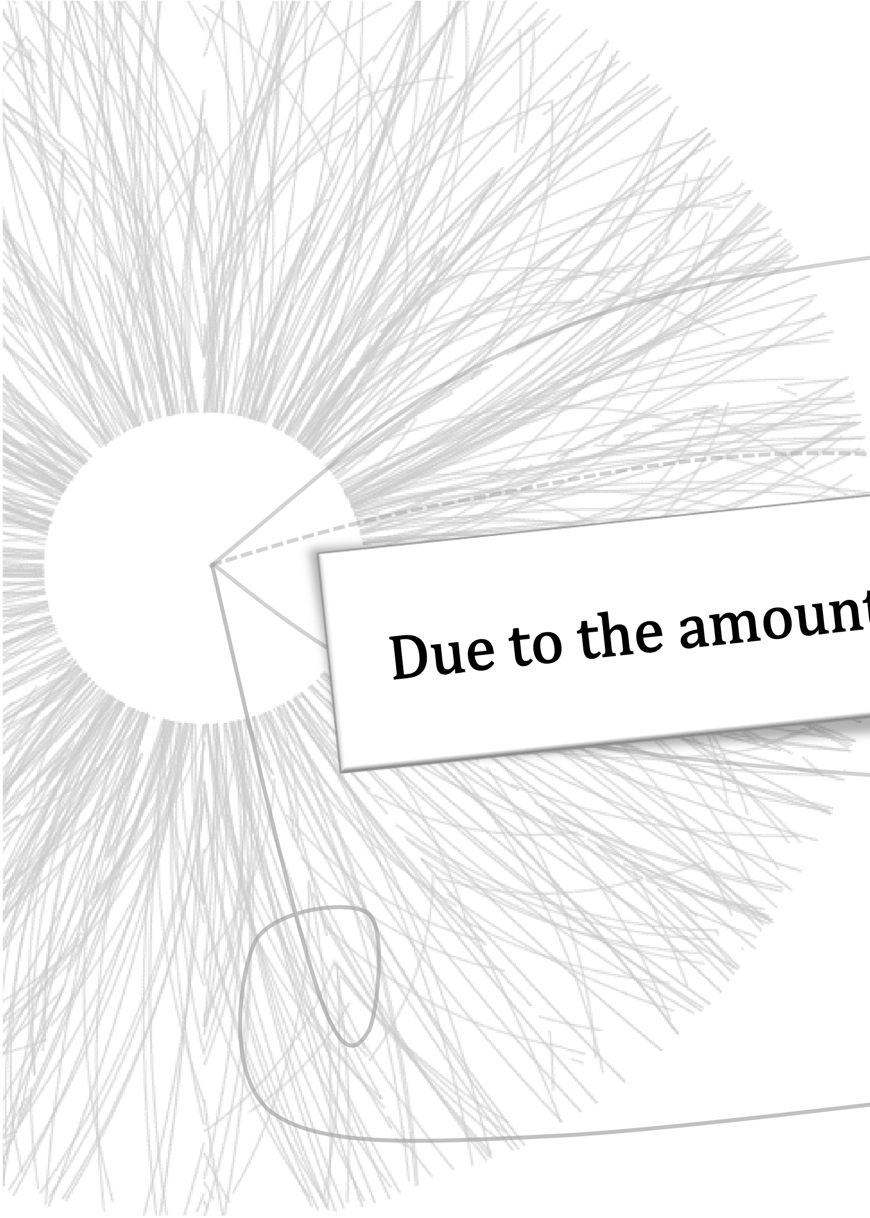
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Outline



- General introduction
- LHC results in p–Pb collisions
- LHC results in Pb–Pb collisions
- Summary

Outline



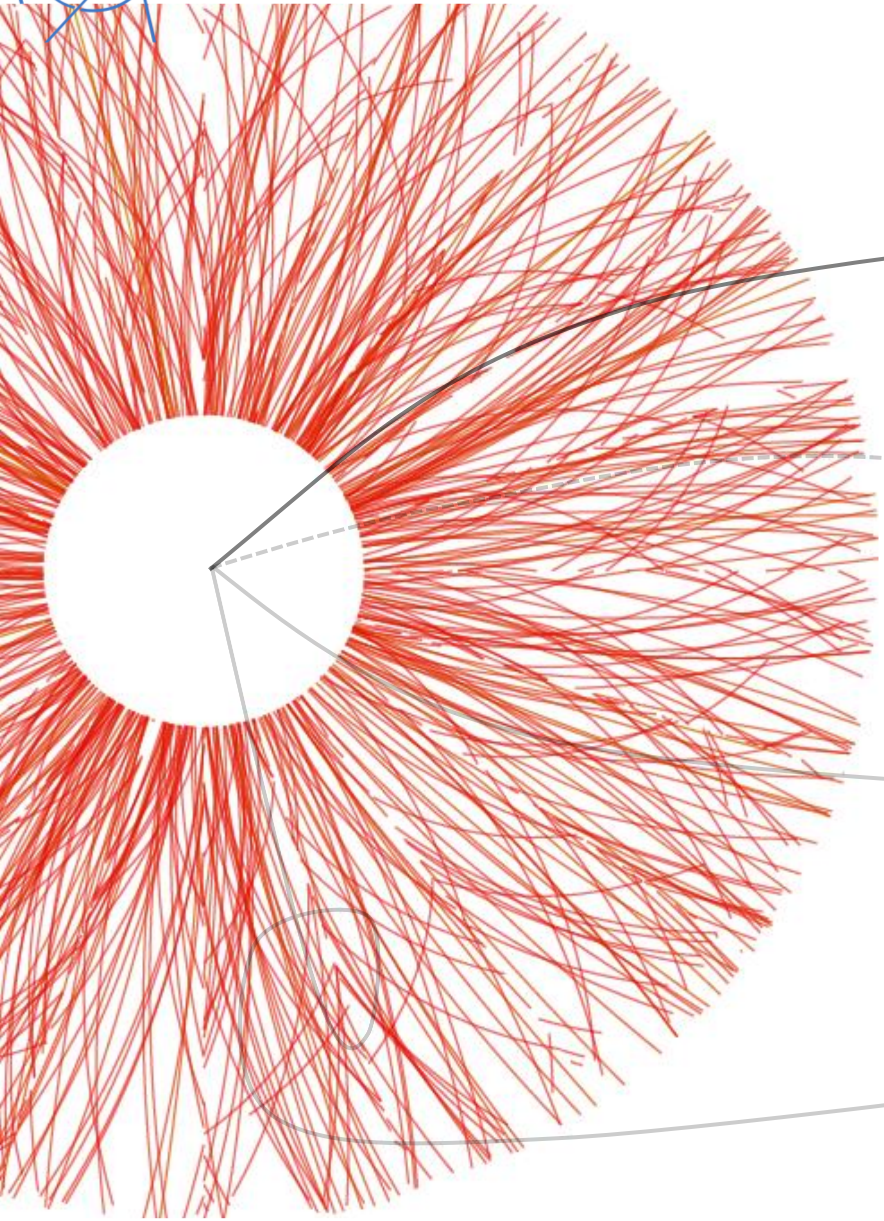
General introduction

Due to the amount of results, only a selection of them will be shown!

LHC results in Pb–Pb collisions

Summary

Outline



General introduction

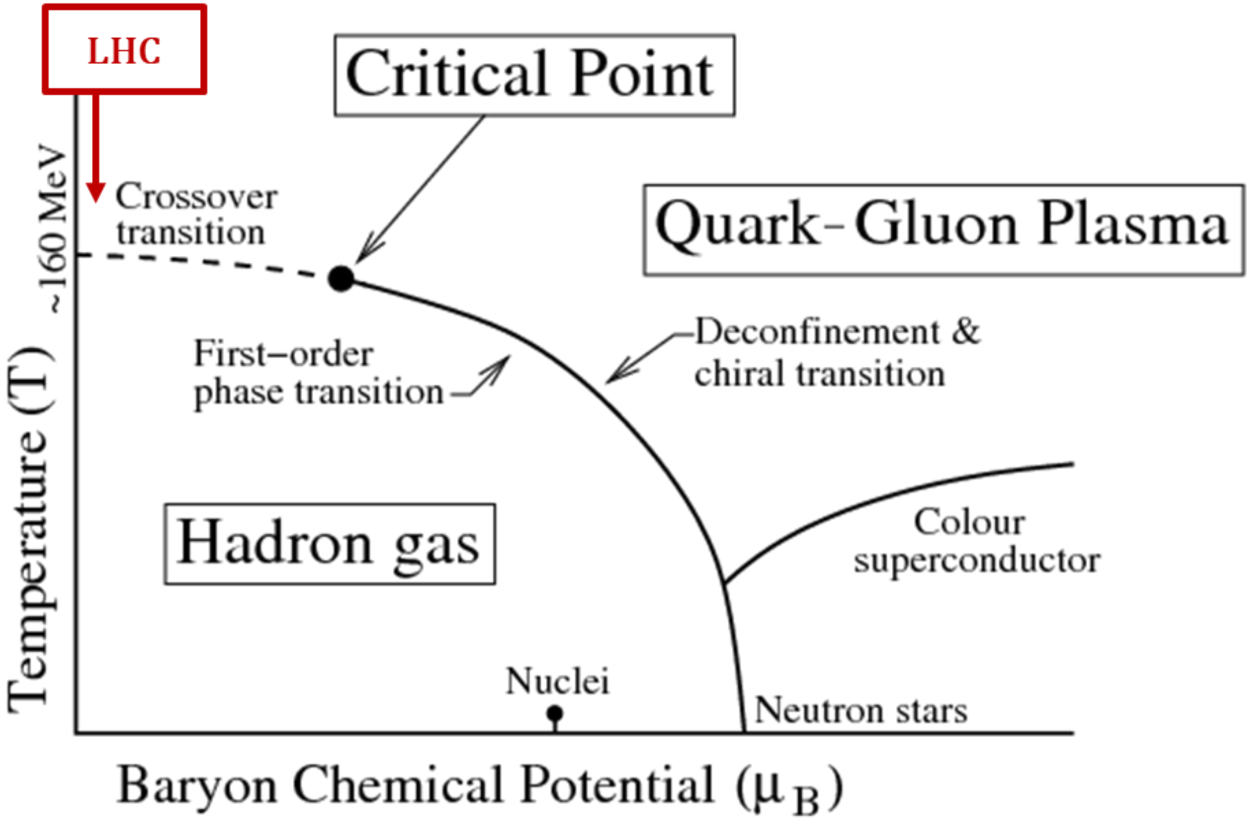
LHC results in p–Pb collisions

LHC results in Pb–Pb collisions

Summary

Heavy flavors & QGP

- Quark-Gluon plasma (**QGP**): state of matter in which quarks and gluons are no more confined into hadrons



➢ From Lattice QCD calculations:
   - $\varepsilon_c \sim 0.5\ \mathrm{GeV/fm^3}$
   - $T_c \sim 150\ \mathrm{MeV}$

➢ Very rapid space/time evolution

$$\tau_{\mathrm{QGP}} \sim 10\ \mathrm{fm}/c$$

Heavy flavors & QGP

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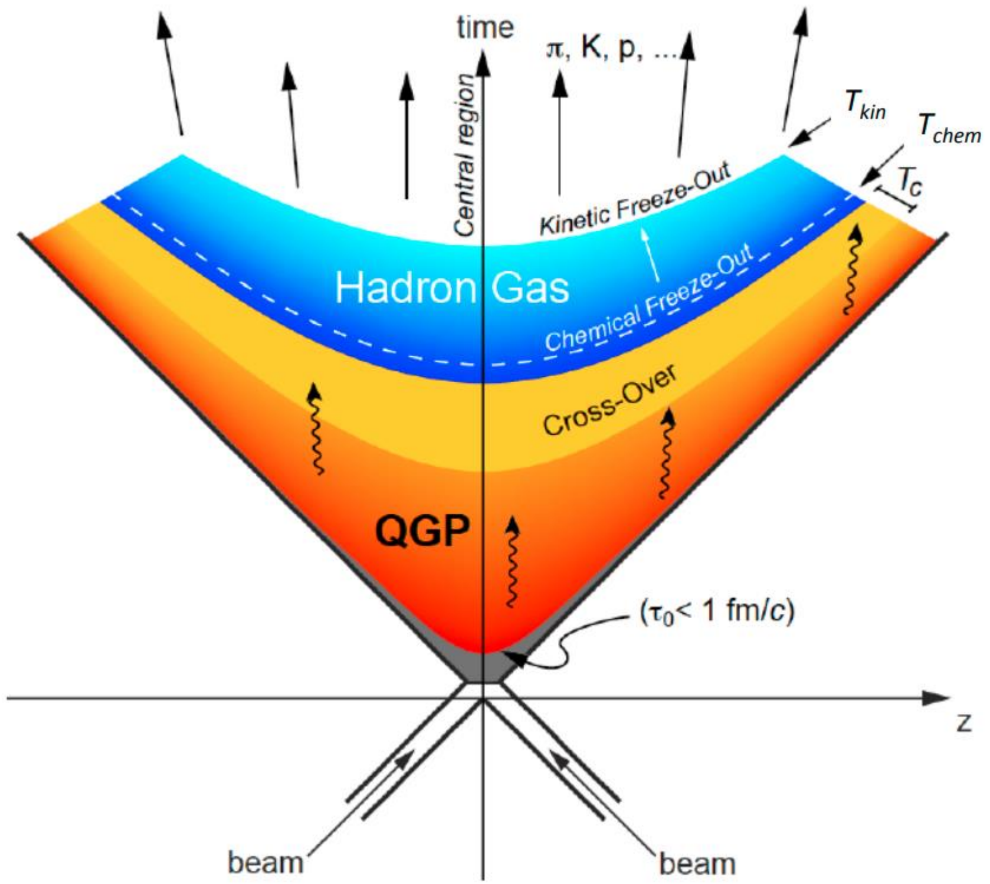

➢ From Lattice QCD calculations:
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  - $T_c \sim 150\ \mathrm{MeV}$

➢ Very rapid space/time evolution

$$\tau_{\mathrm{QGP}} \sim 10\ \mathrm{fm}/c$$

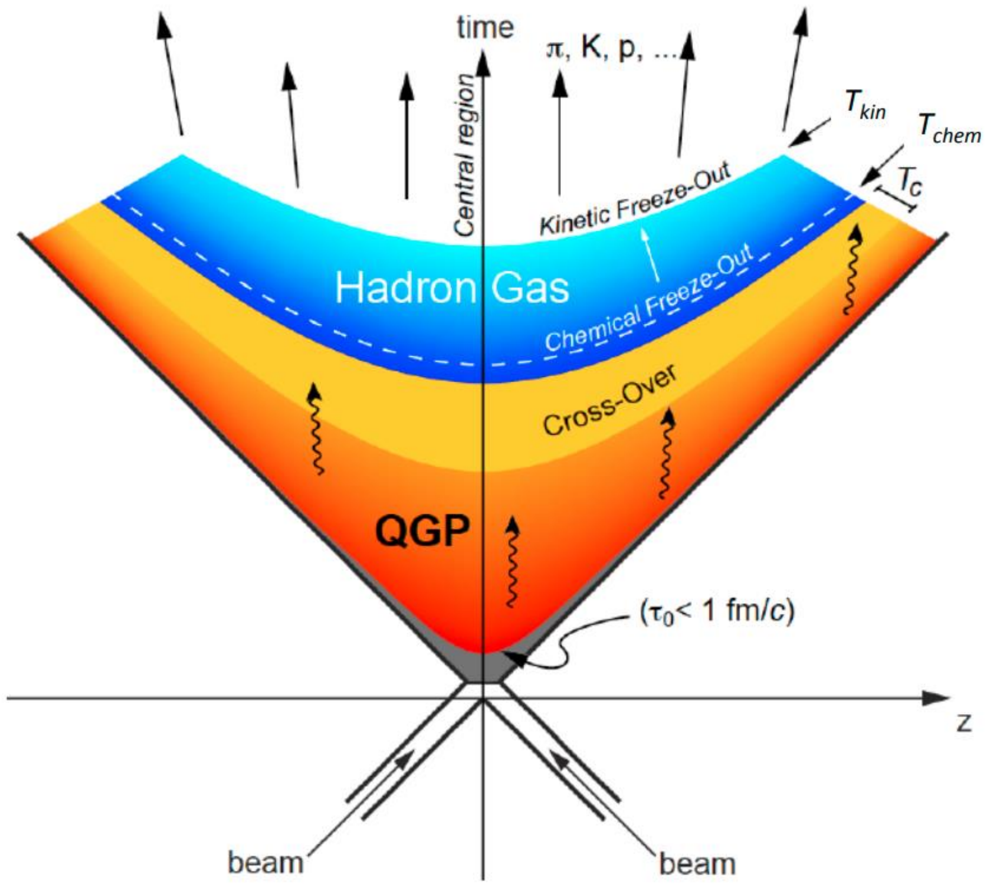
- Heavy quarks produced in the **first phases of the collision**

$$\tau_{\mathrm{HQ}} \sim 0.05 - 0.1\ \mathrm{fm}/c$$

! Open HF and quarkonia ideal probes to study QGP

Heavy flavors & QGP

- Quark-Gluon plasma (**QGP**): state of matter in which quarks and gluons are no more confined into hadrons



- Open heavy-flavor hadrons and quarkonia experience the **evolution of the QGP**

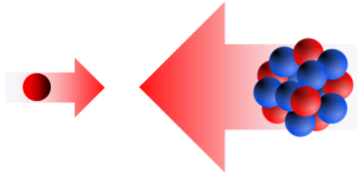
  - Open Heavy Flavors (**HF**)
    - **Partonic energy** loss characterization in QGP
    - **Coalescense** vs **Fragmentation**

  - Quarkonia
    - **Quarkonium suppression**
    - **Regeneration** of heavy quarkonia in QGP

Collision systems and observables

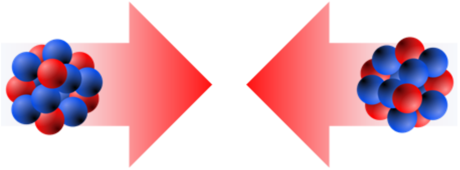
Two different systems are under study

p−Pb



Cold Nuclear Matter effects
(CNM)

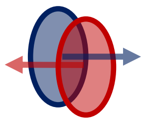
Pb−Pb



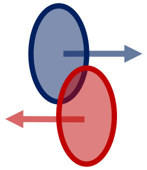
Hot Nuclear Matter effects
(QGP)

Key observable: Production

$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$



Central collision



Peripheral collision

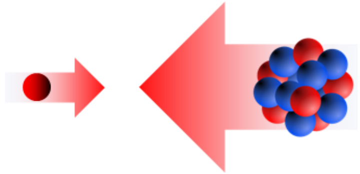
Nuclear Modification Factor : quantifies the effect due to the formation of cold/hot nuclear matter

- ❑ $R_{AA} = 1 \quad \Longrightarrow$ No medium effect
- ❑ $R_{AA} \neq 1 \quad \Longrightarrow$ Medium effect (?)

Collision systems and observables

Two different systems are under study

p–Pb



Cold Nuclear Matter effects
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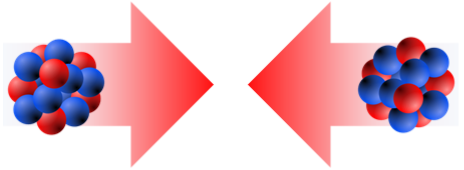
Pb–Pb



Hot Nuclear Matter effects
(QGP)

Key observable: Collectivity

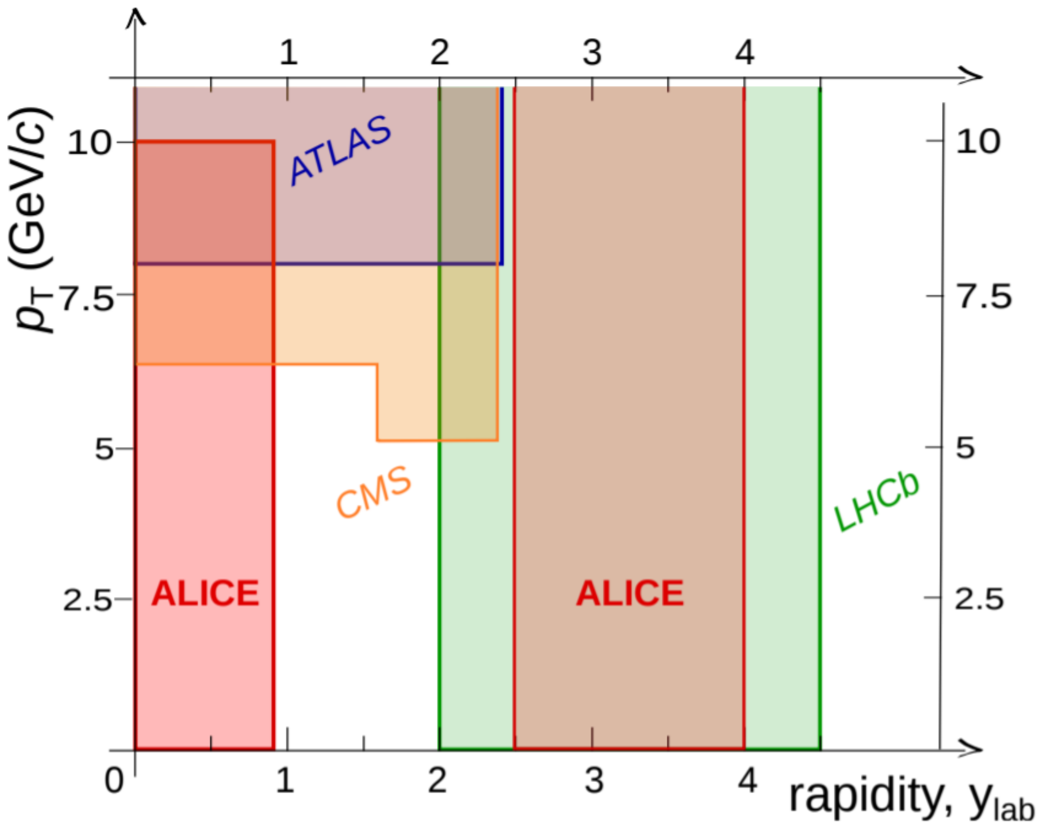
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \qquad v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

Anisotropic flow: quantifies the anisotropy in the azimuthal distribution w.r.t. the reaction plane (Ψ_{RP})

- At low p_T : investigate **collective motion** and **thermalization**
- At high p_T: investigate path-lenght dependence of the **energy loss**

The LHC experiments

- LHC offers a unique opportunity to explore HF/quarkonium production in a very wide kinematic range



! Complementarity of all the LHC experiments

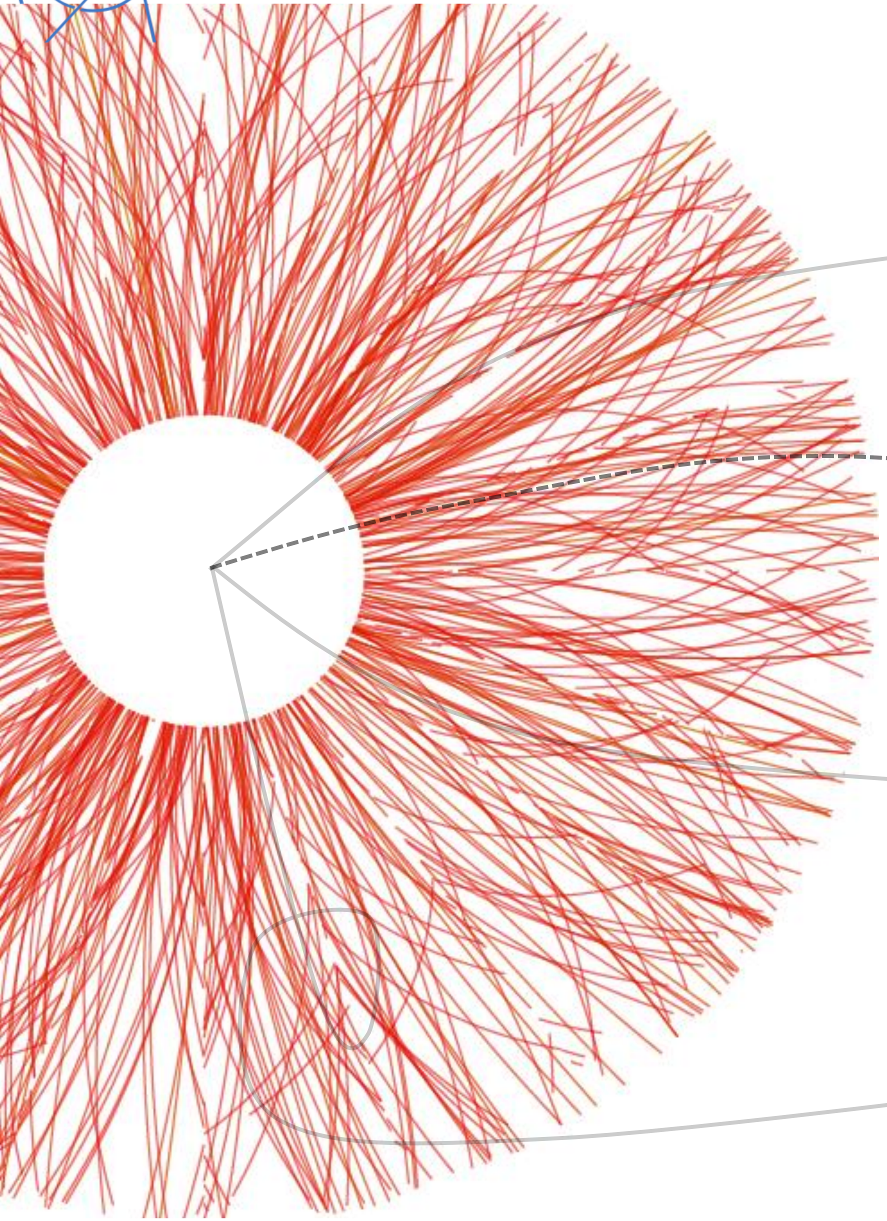
ALICE
- **Forward** & **midrapidity** coverage
- HF and quarkonia down to **zero** p_T

CMS
- **Midrapidity** coverage
- Wide **(high)** p_T coverage

LHCb
- Large **forward** rapidity coverage
- HF and quarkonia down to **zero** p_T

ATLAS
- **Midrapidity** coverage
- Wide **(high)** p_T coverage

Outline



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LHC results in p–Pb collisions

LHC results in Pb–Pb collisions

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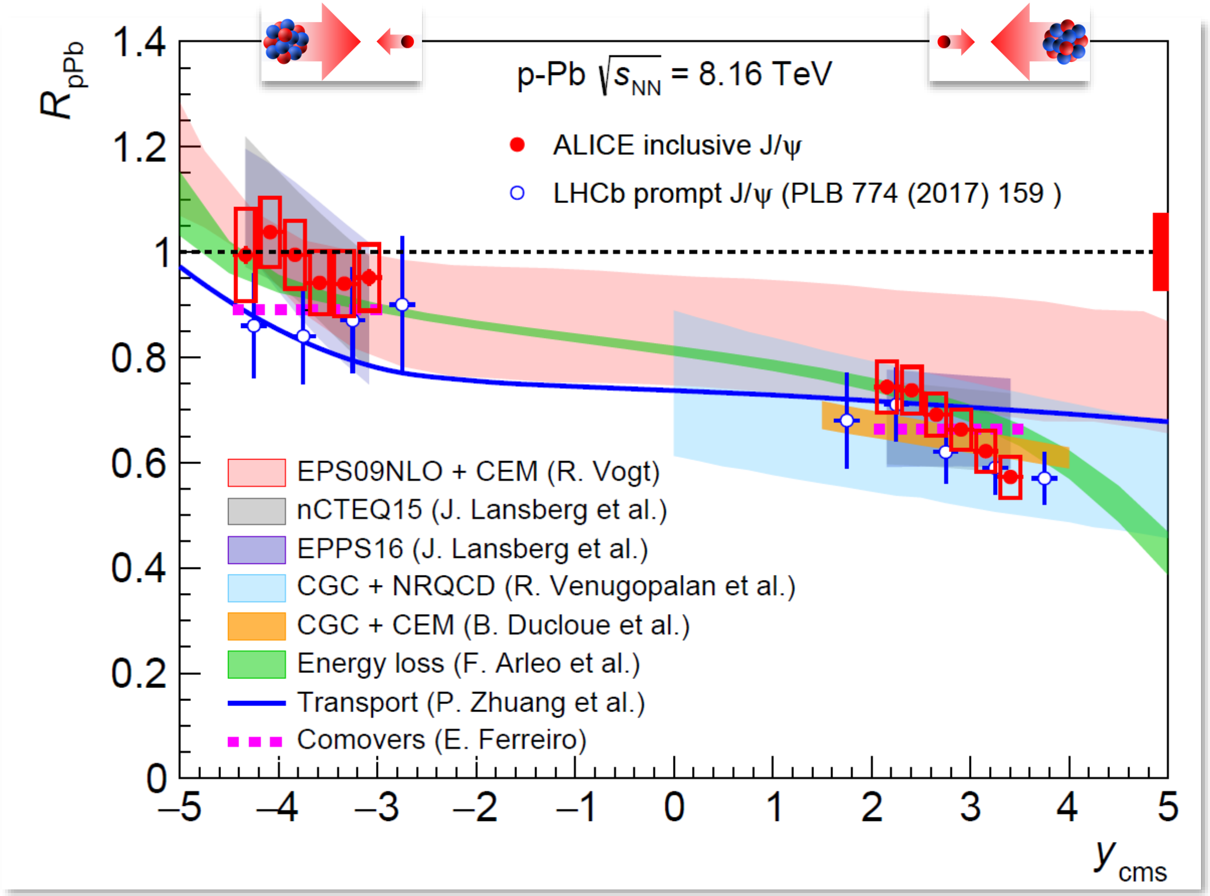
Quarkonia in p-Pb collisions



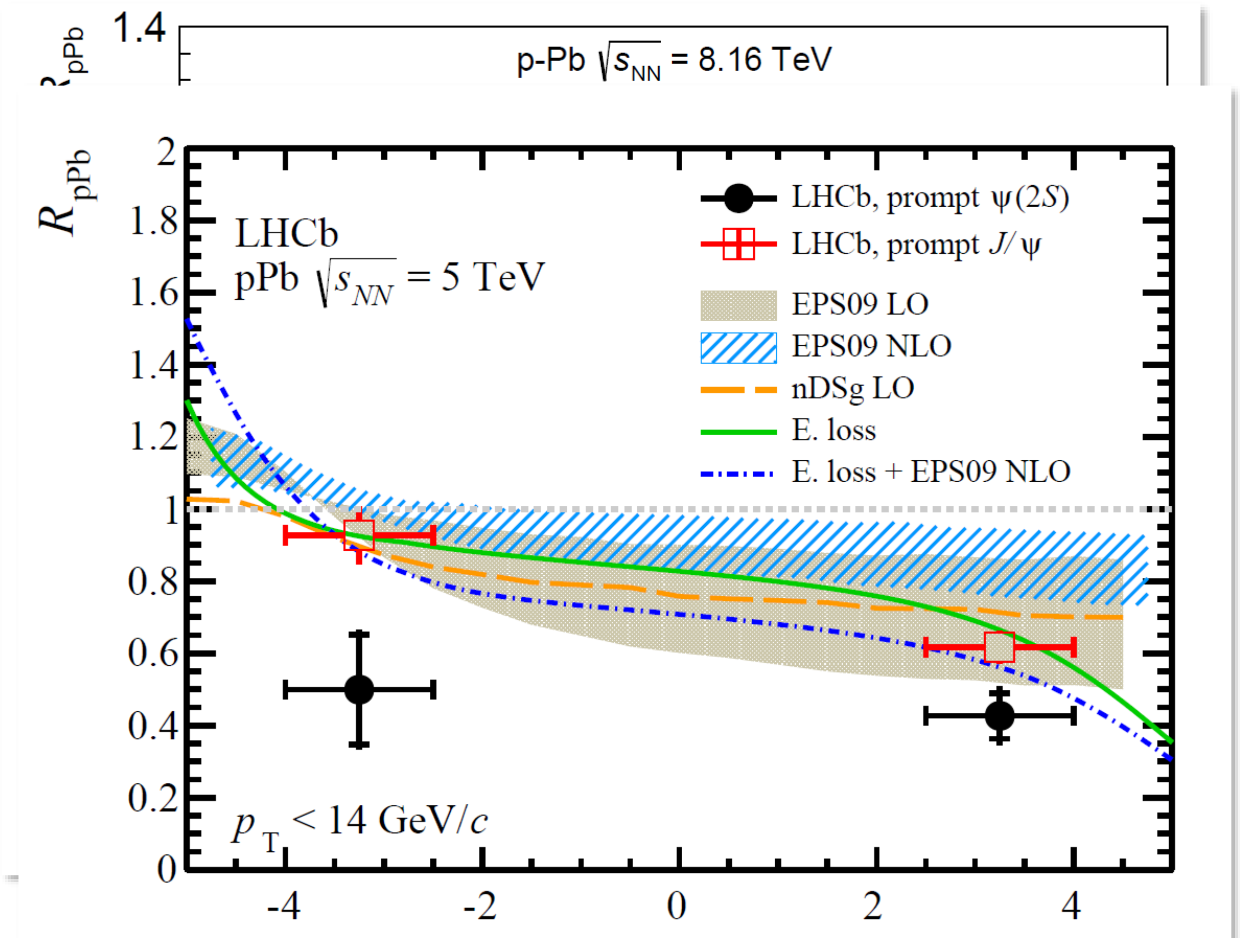
JHEP 07 (2018) 160   PLB 774 (2017)

ALICE and LHCb measured the J/ψ R_{pA} in the forward and in the backward rapidity regions

- Stronger J/ψ suppression at forward rapidity
- Good agreement with models including **shadowing**[1,2,3], **CGC**[4,5], **energy loss**[6], **transport models**[7] and interaction with **comovers**[8]

[1] arxiv:1707.09973
[2] arxiv:1712.07024
[3] arxiv:1712.07024
[4] arxiv:1707.07266
[5] arxiv:1605.05680
[6] arxiv:1407.5054
[7] arxiv:1607.07927
[8] arxiv:1411.0549

Quarkonia in p-Pb collisions



JHEP 1603 (2016) 133

ALICE and LHCb measured the $\psi(2S)$ R_{pA} in the forward and in the backward rapidity regions

- Similar suppression as a function of y
- Models including **shadowing**[1,2,3], **energy loss**[4,5] do not describe this larger $\psi(2S)$ suppression at backward rapidity

[1] arxiv:1305.4569

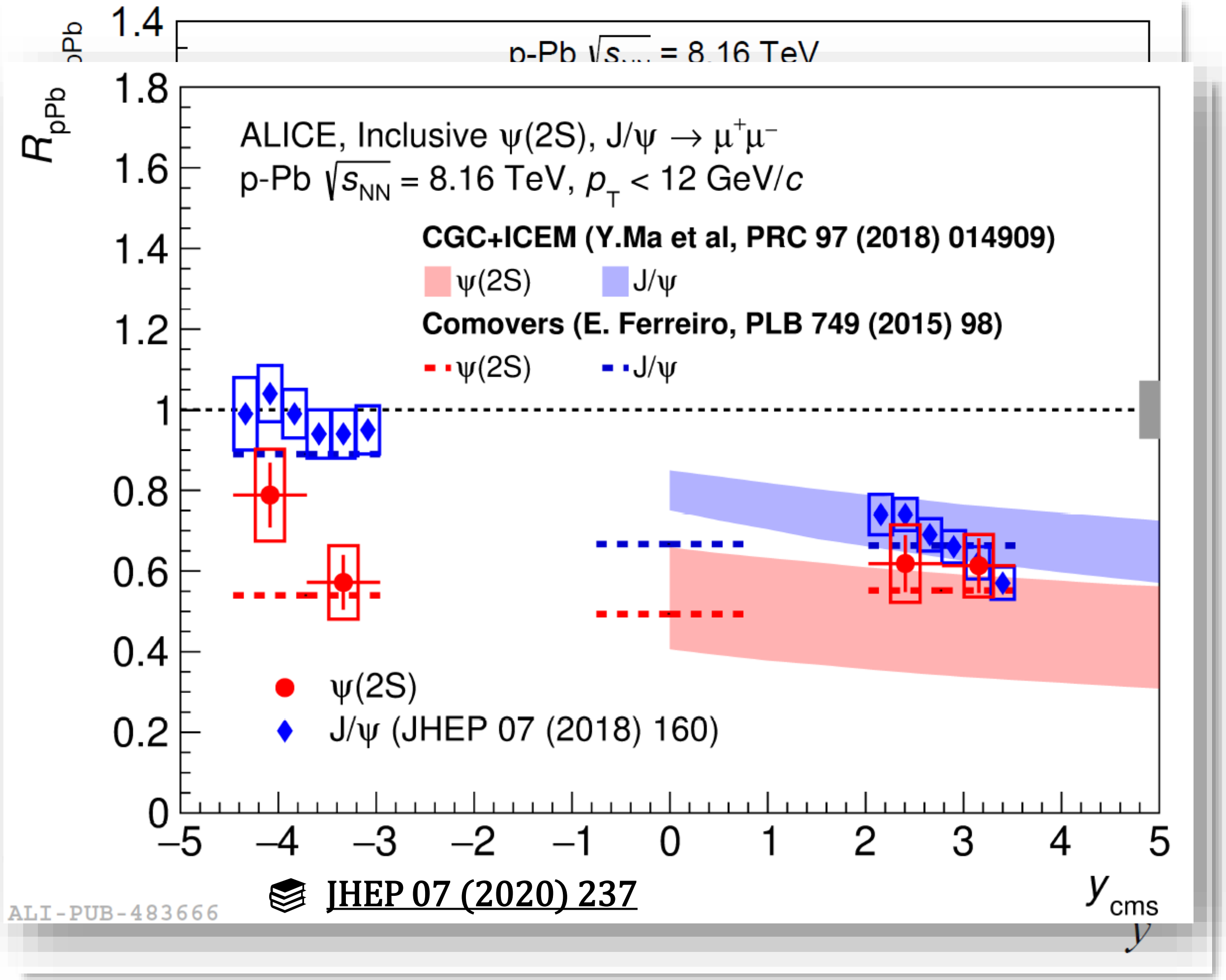
[2] arxiv:1402.1747

[3] arxiv:1301.3395

[4] arxiv:1212.0434

[5] arxiv:1212.0434

Quarkonia in p-Pb collisions



JHEP 07 (2020) 237

ALICE and LHCb measured the ψ(2S) R_{pA} in the forward and in the backward rapidity regions

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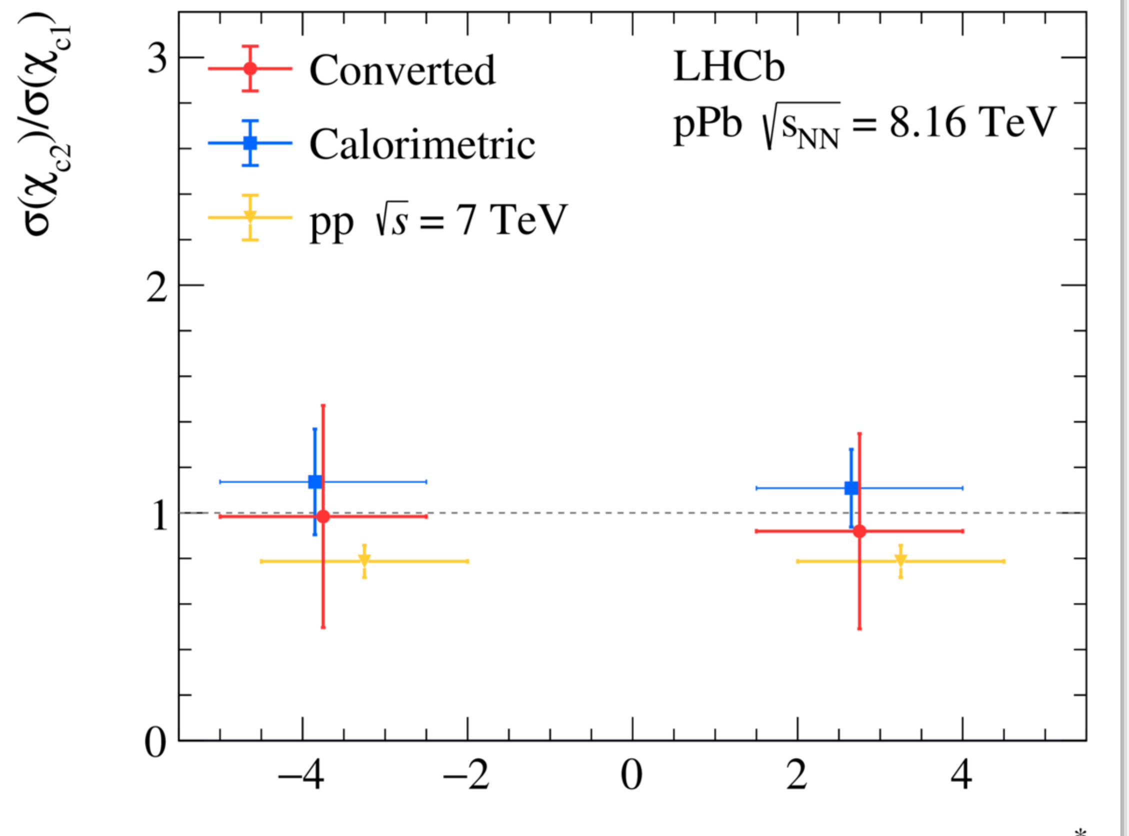
[1] arxiv:1305.4569 [3] arxiv:1301.3395
[2] arxiv:1402.1747 [4] arxiv:1212.0434
[5] arxiv:1212.0434

- ψ(2S) is better described by models including **final state effects** as **Comovers**[1] and **CGC+ICEM**[2]

[1] arxiv:1411.0549 [2] arxiv:1707.07266

Quarkonia in p-Pb collisions



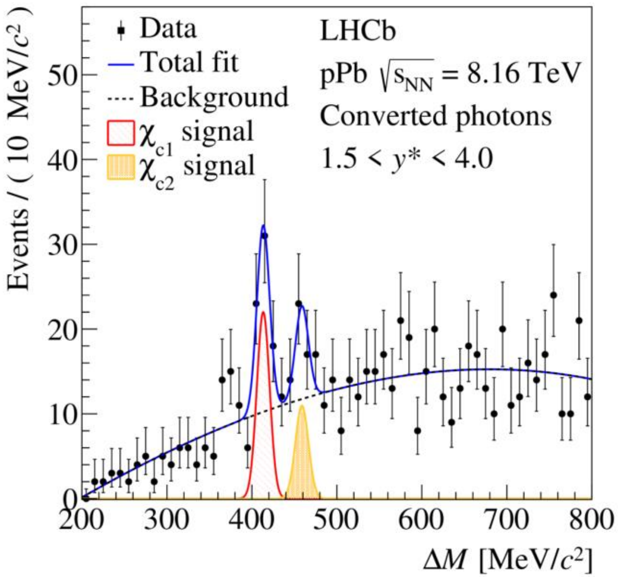
See Cesar Luis da Silva presentation

LHCb measured the χ_{c2} and χ_{c1} cross section ratio in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

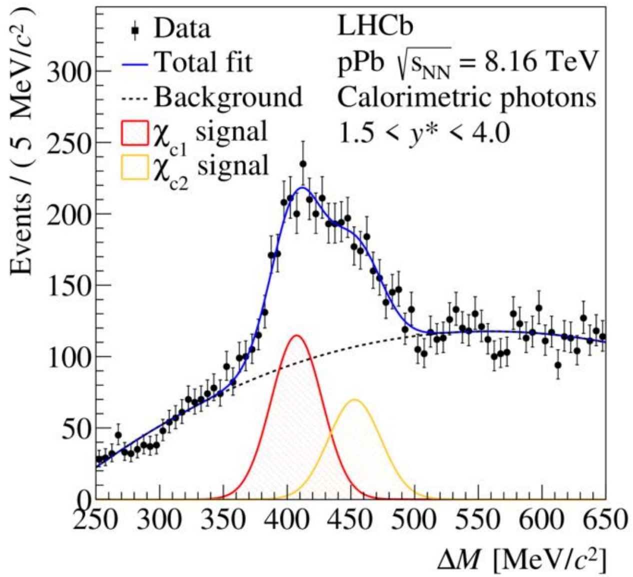
Phys. Rev. C 103, 064905 (2021)

$$\Delta E(J/\psi) > \Delta E(\chi_c) > \Delta E(\psi(2S))$$

Converted γ

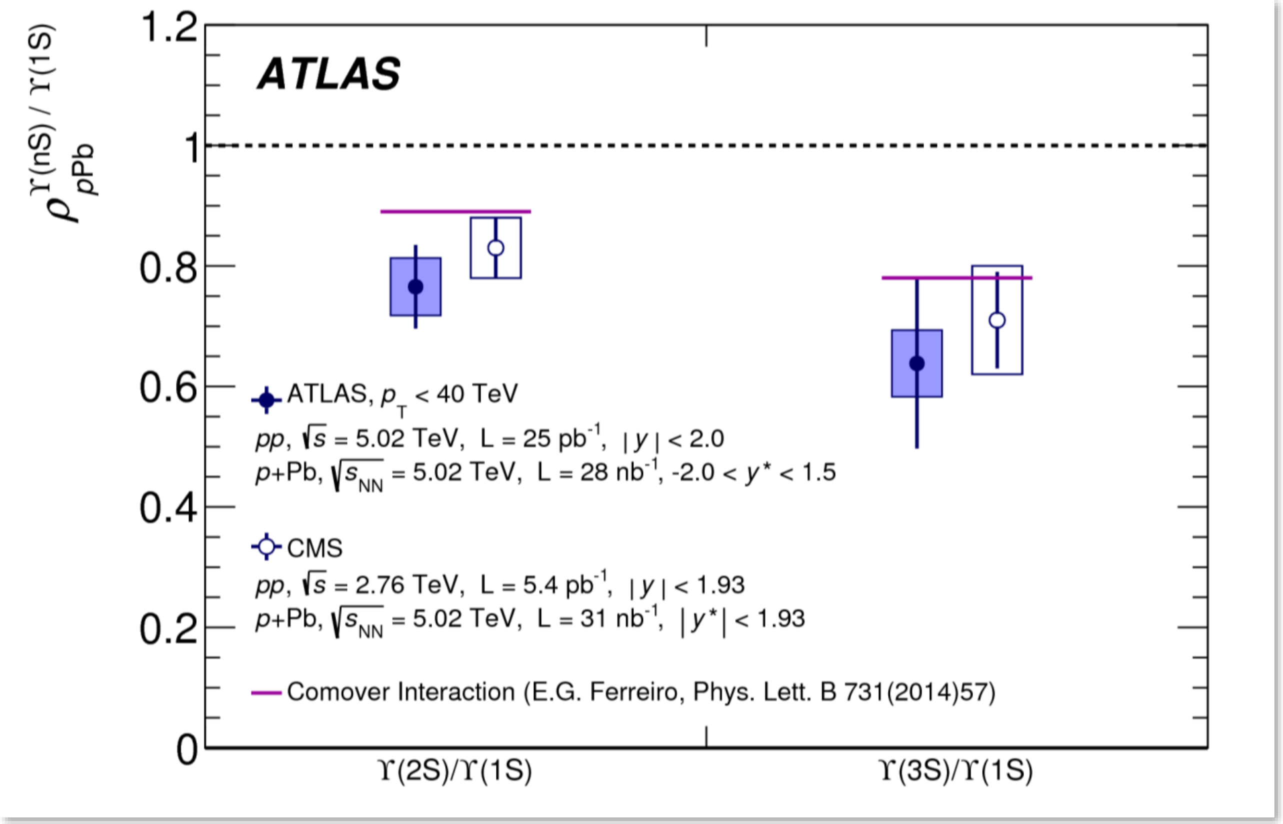


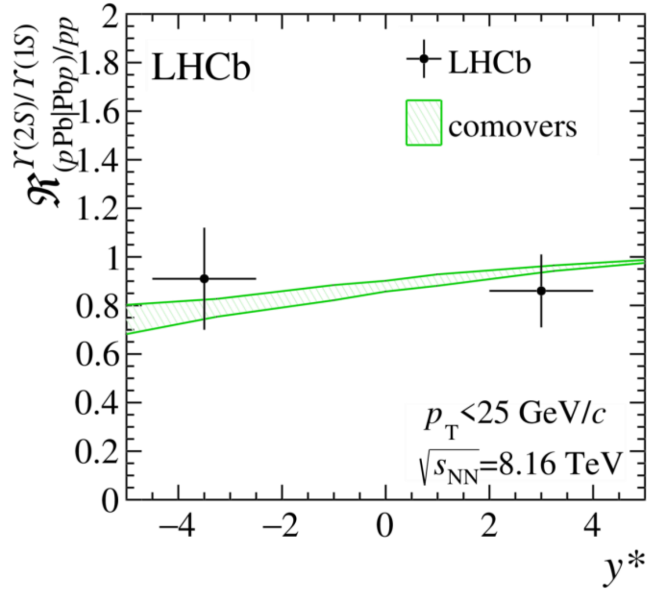
Calorimetric γ

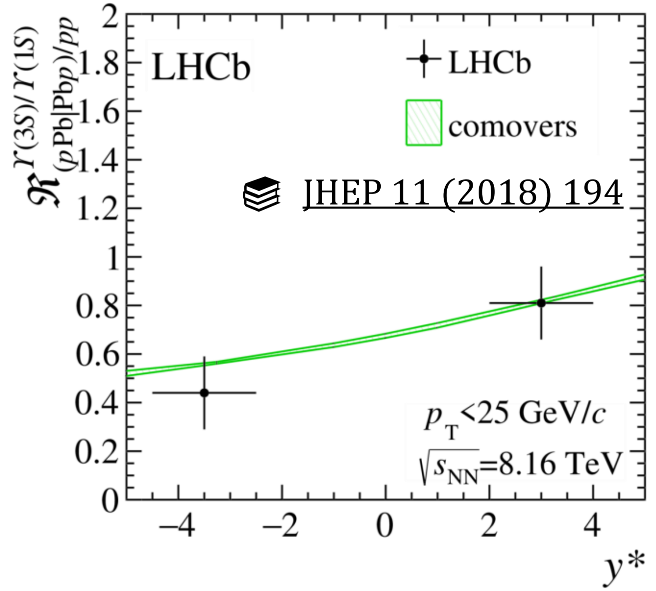


- First measurement of χ_{c2} and χ_{c1} production in nuclear collisions
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is consistent with unity for backward and forward rapidity

Quarkonia in p-Pb collisions







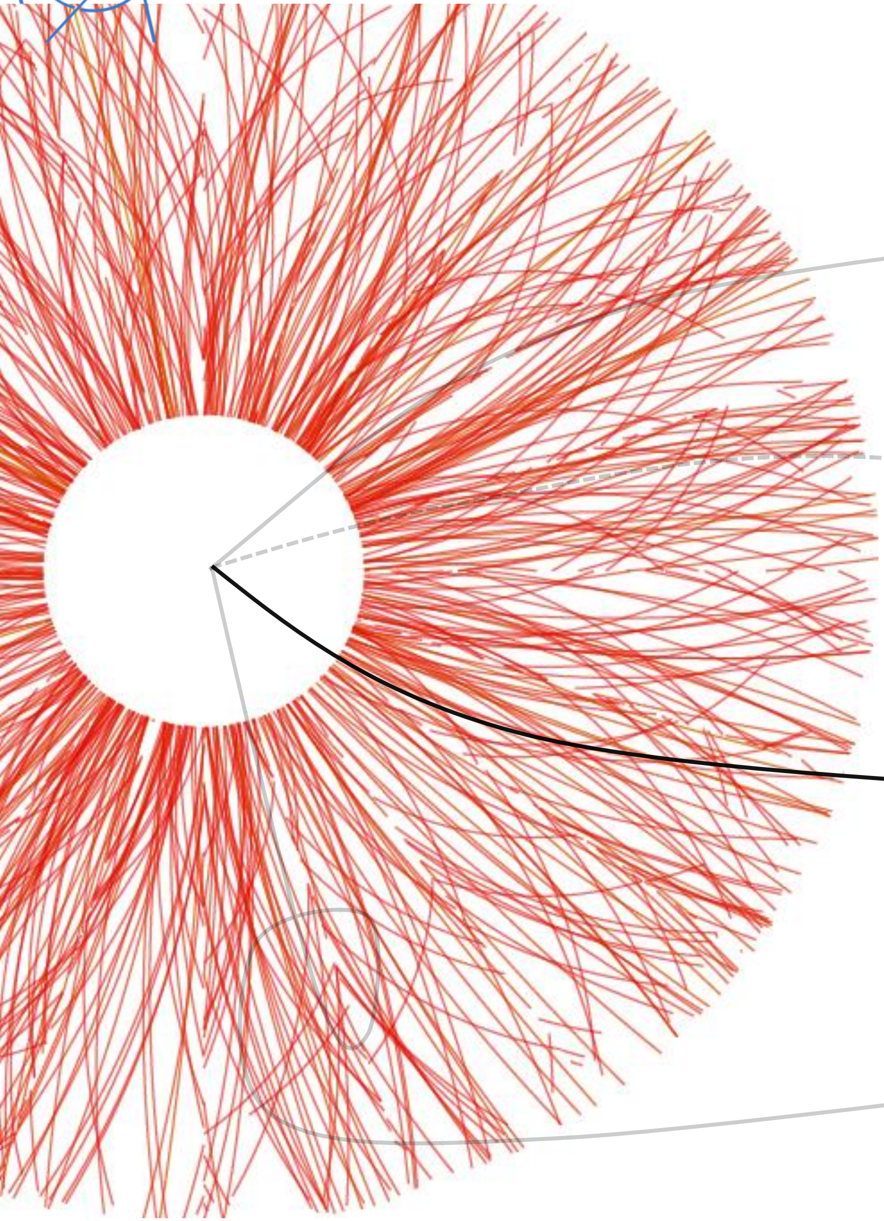
JHEP 11 (2018) 194

ATLAS, CMS and LHCb studied Υ(nS) production

EPJC 78 (2018) 171 JHEP 04 (2014) 103

- Results are in agreement with the **comover model**
- Indication of larger of Υ(2S) and Υ(3S) suppression w.r.t. Υ(1S)

Outline



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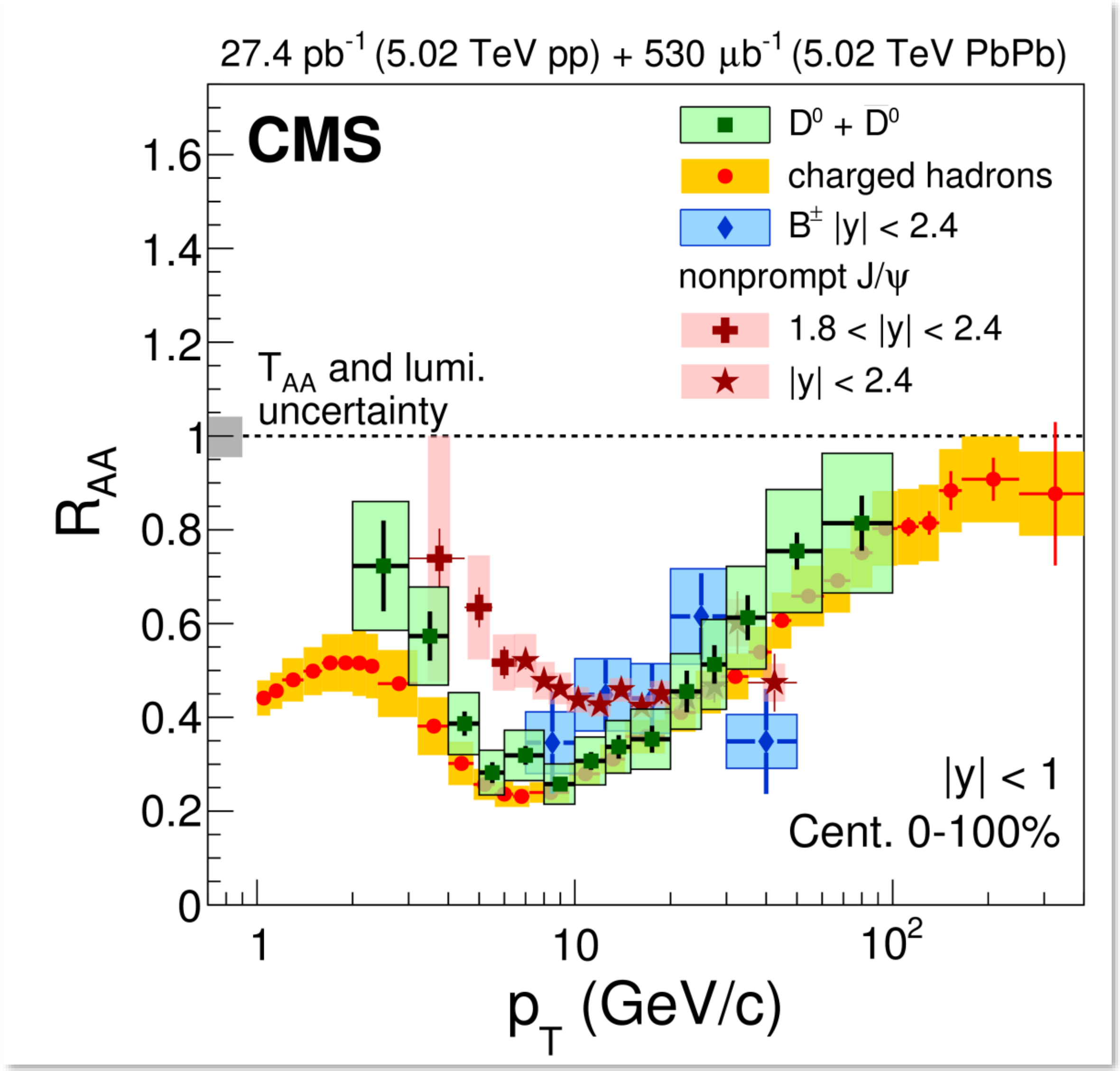
D-mesons in Pb-Pb collisions



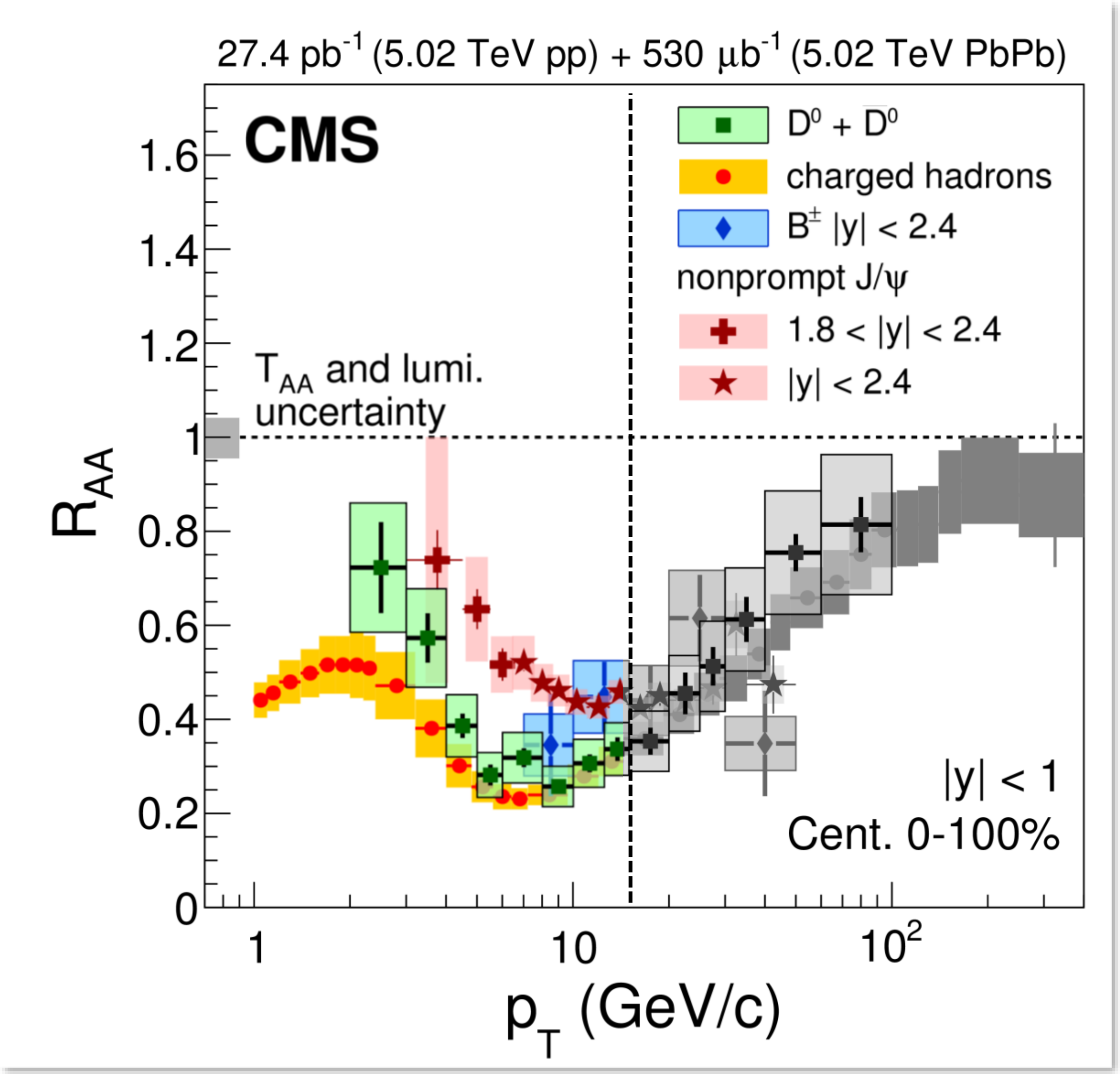
CMS measured the D and B-mesons nuclear modification factor at midrapidity in a wide p_T range

PLB 782 (2018) 474

PRL 119 (2017) 152301

- D^0 $(c\bar{u})$ $\to K^\pm\pi^\mp$
- $B^\pm(u\bar{b}/\bar{u}b)$ $\to$ J/ψ $K^\pm$

D-mesons in Pb-Pb collisions



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PLB 782 (2018) 474

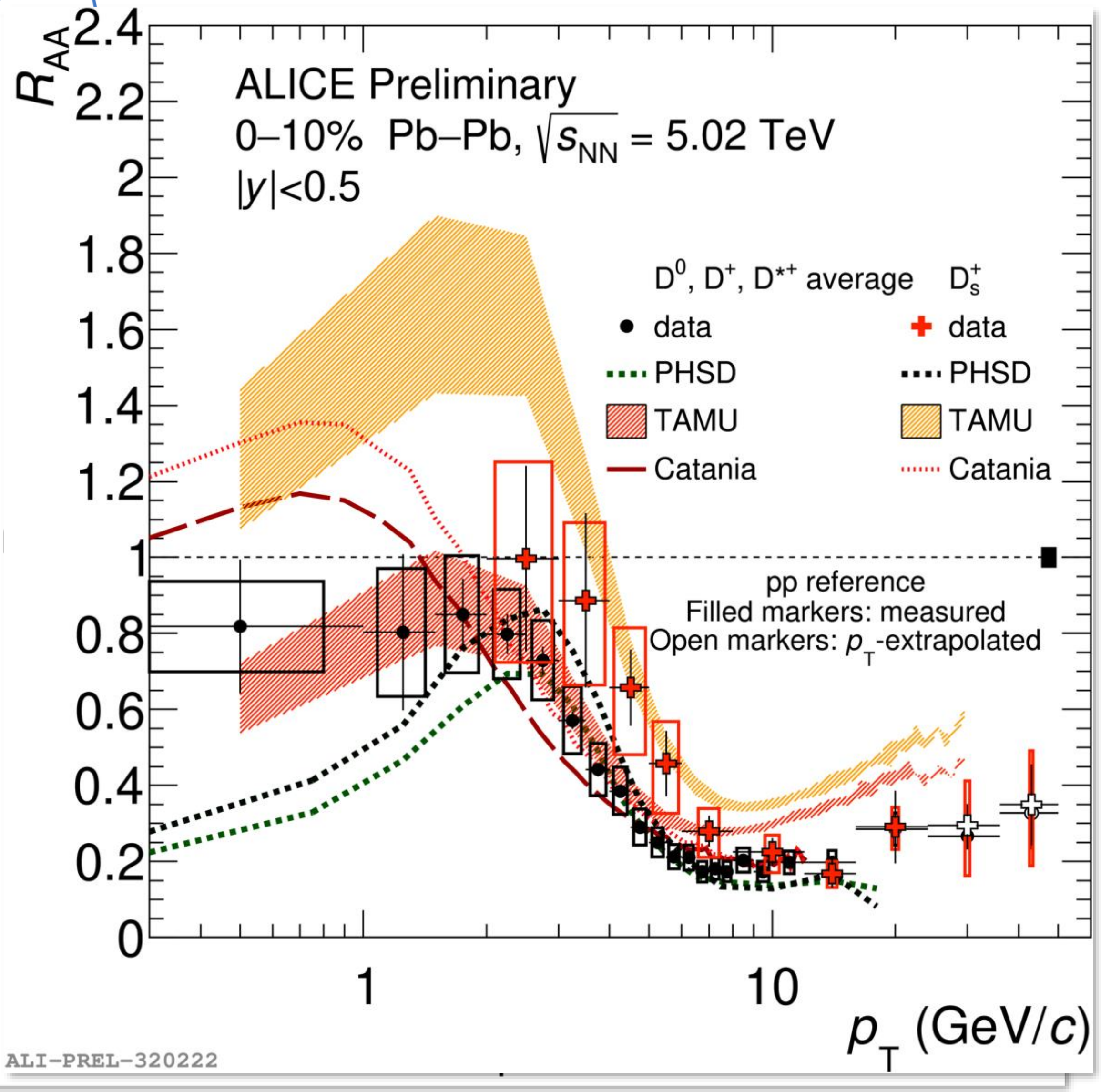
PRL 119 (2017) 152301

- $D^0\ (c\bar{u})\ \rightarrow K^{\pm}\pi^{\mp}$
- $B^{\pm}(u\bar{b}/\bar{u}b)\ \rightarrow\ J/\psi\ K^{\pm}$

➢ Differet trend for $\boldsymbol{p_T < 20\ \mathrm{GeV}/c}$ for different hadron species

➢ For $\boldsymbol{p_T > 20\ \mathrm{GeV}/c}$ universal trend for all the hadron species (dominated by energy loss?)

D-mesons in Pb-Pb collisions



ALICE measured D-mesons R_{AA} down to zero p_T

- $D^0\ (c\bar{u}) \rightarrow K^{\pm}\pi^{\mp}$
- $D^+(c\bar{d}) \rightarrow K^{\pm}\pi^{\mp}\pi^{\mp}$
- $D^{*+}(c\bar{s}) \rightarrow D^0\pi^+ \rightarrow K^{\pm}\pi^{\mp}\pi^{\mp}$
- $D_s^+(c\bar{d}) \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$

➢ Measurements in fair agreement with models including **energy loss +quark recombination**

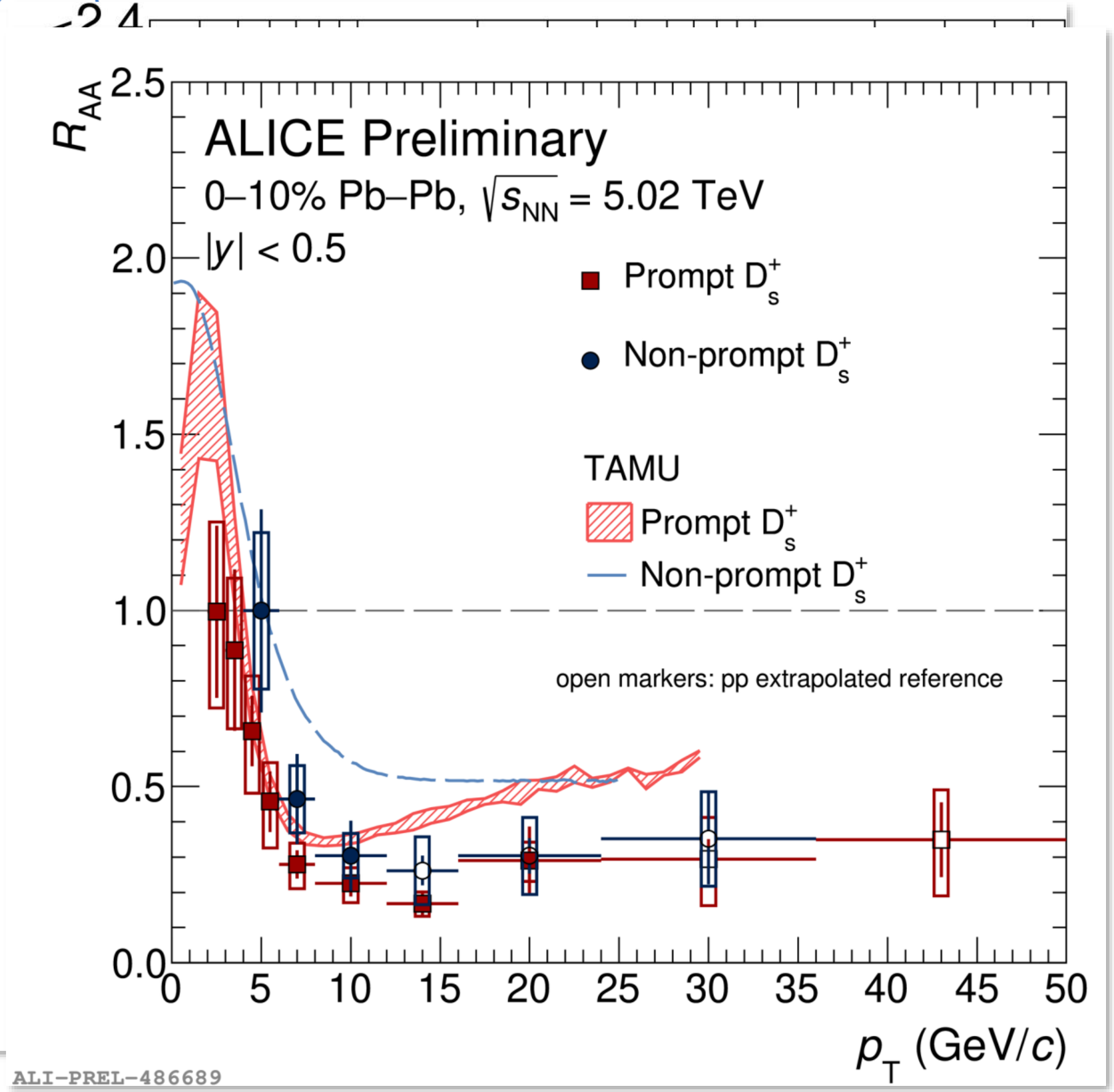
Phys. Rev. C 92, 014910 (2015)

Phys. Lett. B 807 (2020)

Phys. Lett. B 807 (2020)

Hint of a smaller suppression for the D_s^+ for $p_T < 10$ GeV/c attributed to **strangeness rich environment** of the QGP + **hadronization via recombination**

D-mesons in Pb-Pb collisions

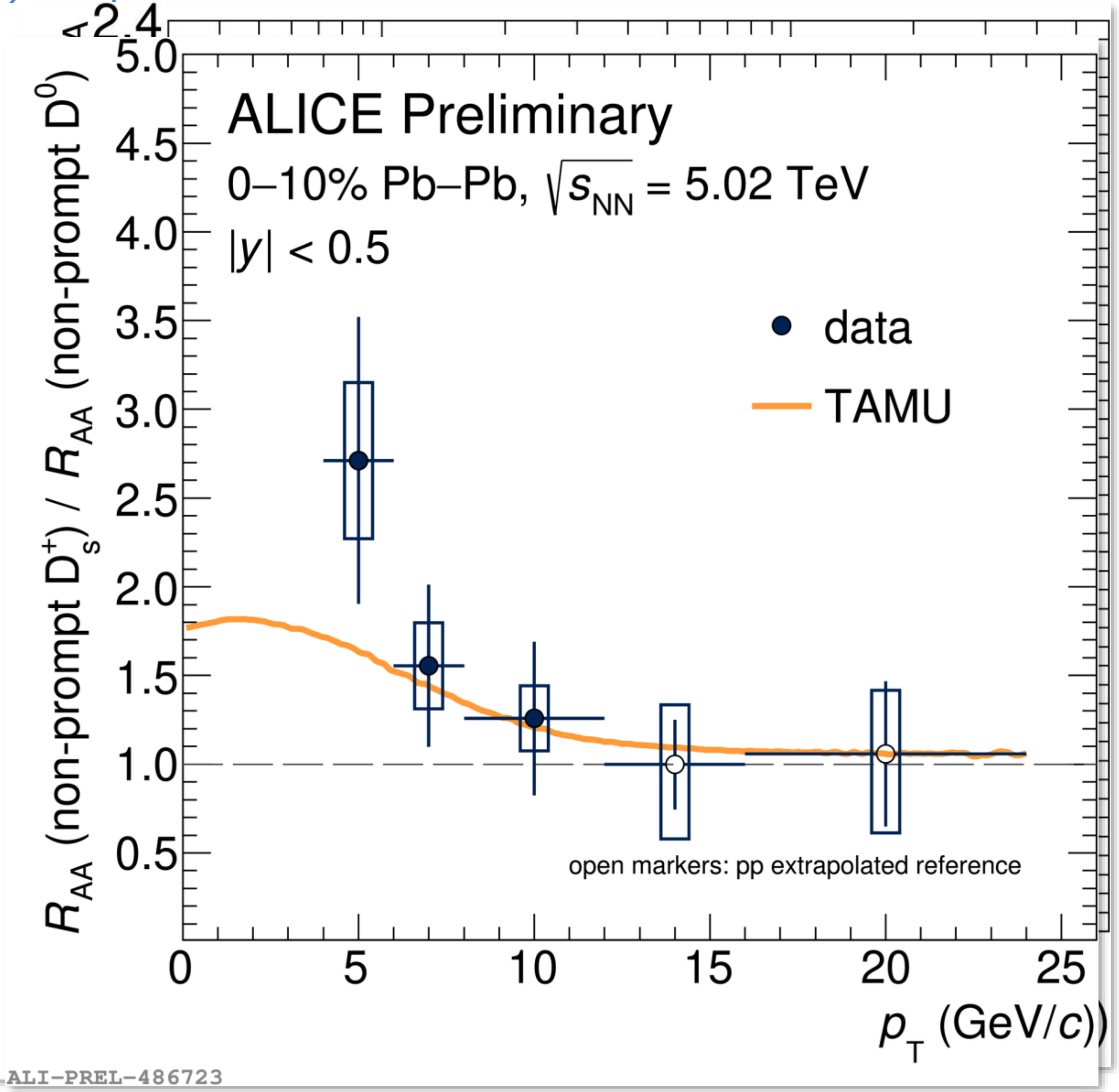


ALICE measured **non-prompt D_s^+** R_{AA} in central collisions (0-10%) for the first time

- D^0 ($c\bar{u}$) $\rightarrow K^{\pm}\pi^{\mp}$
- D_s^+ ($c\bar{d}$) $\rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$

➢ **TAMU** model qualitatively describes the difference in the R_{AA}, overestimating the absolute values

D-mesons in Pb-Pb collisions



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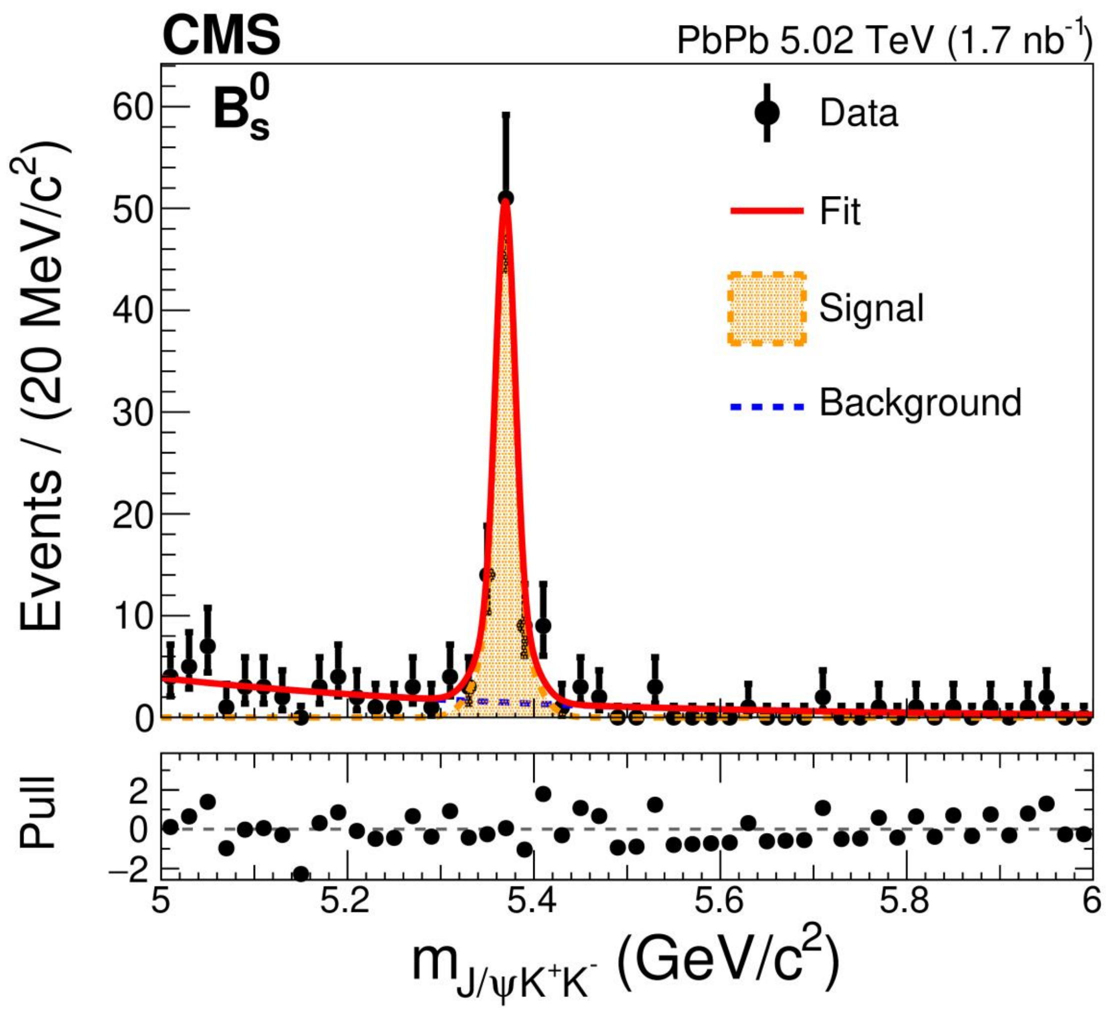
➢ **TAMU** model qualitatively describes the difference in the R_{AA}, overestimating the absolute values

➢ ~ 50% of non-prompt D_s^+ from B_s^0

Hint of non-prompt $R_{AA}(D_s^+)/R_{AA}(D^0) > 1$ possibly due to enhanced production of B_s^0 from beauty hadronization via coalescence

B-mesons in Pb-Pb collisions

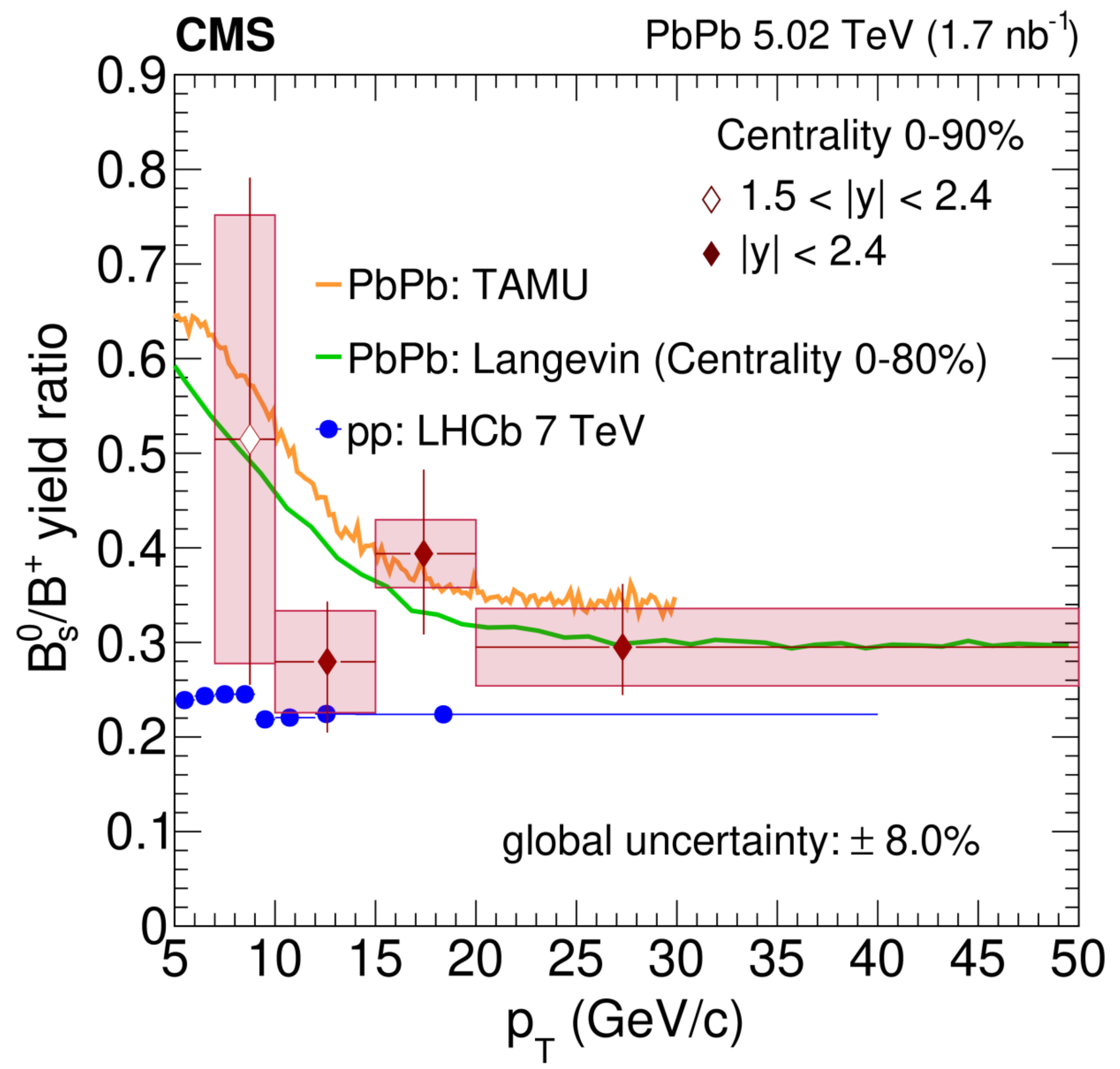


CMS performed the first significant observation ($>5\sigma$) of B_s^0 in Pb-Pb collisions

arXiv.org:2109.01908

- $B_s^0\,(s\bar{b}) \rightarrow J/\psi + \phi \rightarrow \mu^+\mu^- + K^+K^-$
- $B^+(u\bar{b}) \rightarrow J/\psi + K^+$

B-mesons in Pb-Pb collisions



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- $B^+(u\bar{b}) \rightarrow J/\psi + K^+$

Hint of enhancement in Pb-Pb collisions w.r.t. pp collisions

➢ Results compatible with the predictions of the **transport model** (TAMU) and **hydro** (Langevin) which include **energy loss** and **recombination** contribution to the B_s^0

Phys. Lett. B 735 (2014)

Phys. Lett. B 807 (2020)

Charmonia in Pb-Pb collisions

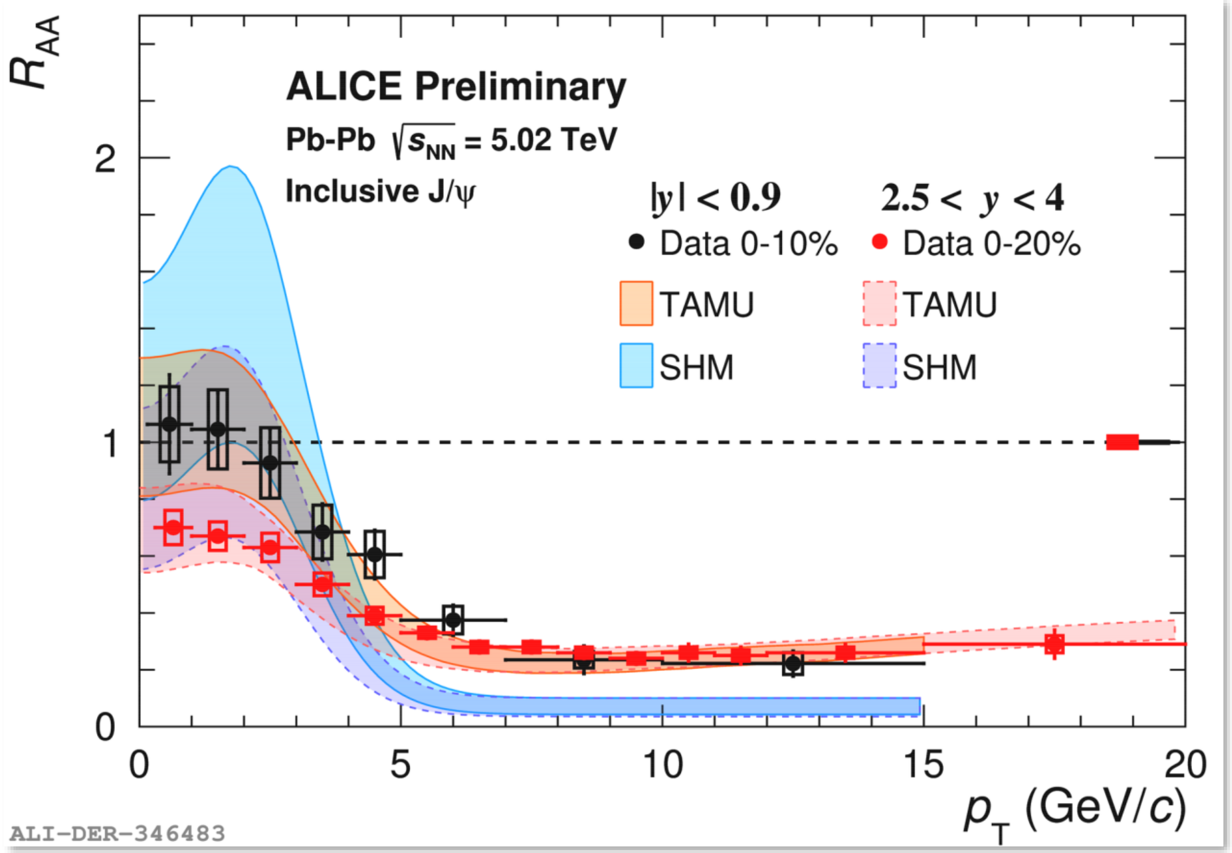
ALICE measured J/ψ R_{AA} down to zero p_T in the forward and midrapidity regions

- ➢ Larger suppression at forward w.r.t. mid rapidity in the low p_T region
- ➢ Statistical Hadronization Model (**SHM**) describes data for $p_T < 5$ GeV/c

  Phys Lett B797 (2019)

- ➢ **Transport model** agrees in the full p_T range

  Nucl. Phys. A943 (2015)



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Phys Lett B797 (2019)

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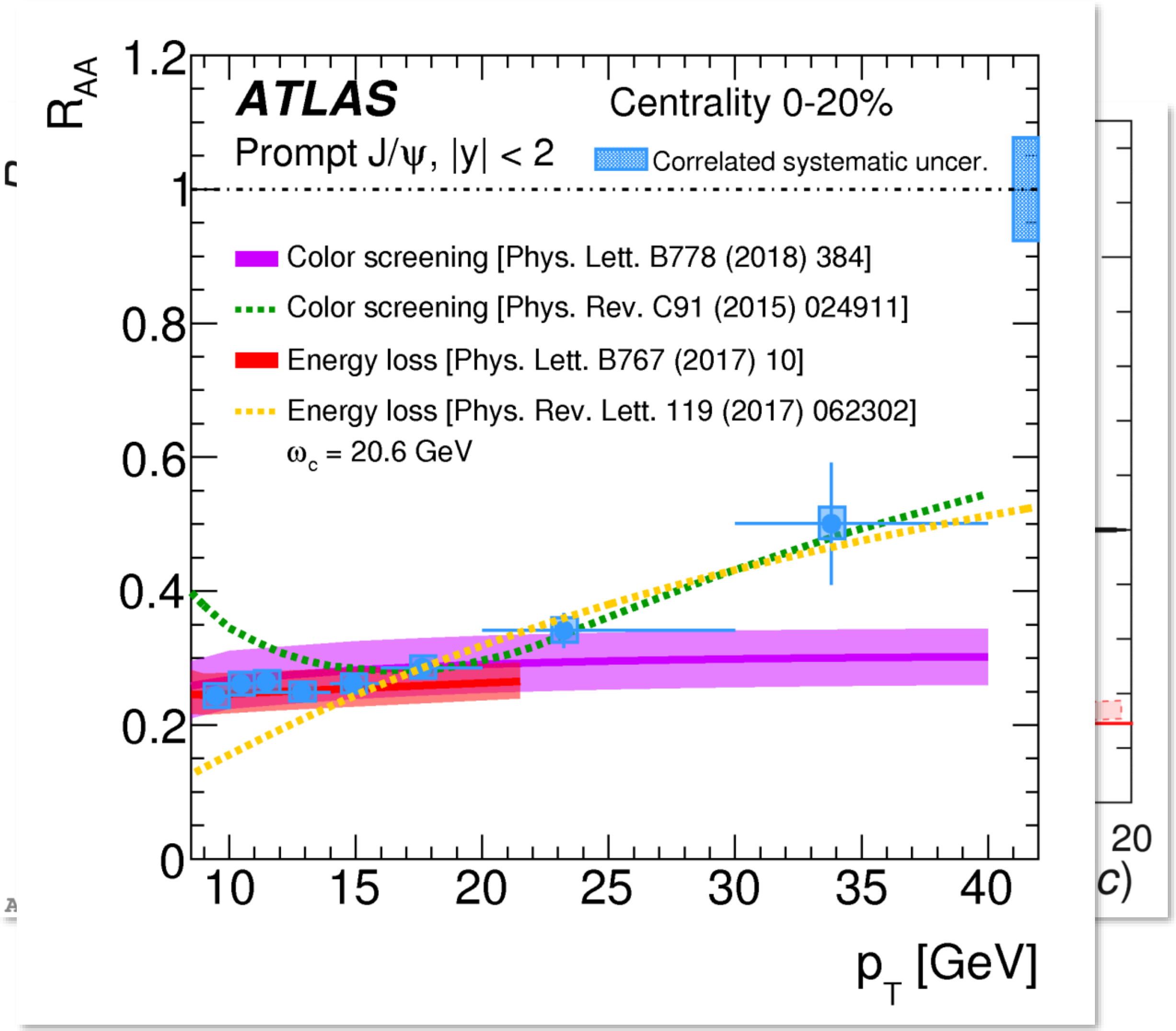
Nucl. Phys. A943 (2015)

ATLAS measured J/ψ R_{AA} up to $p_T < 40$ GeV/c in central collisions at mid-rapidity

Eur. Phys. J. C 78 (2018) 762

- ➢ **Color screening** and **energy loss** agrees with some tensions with data



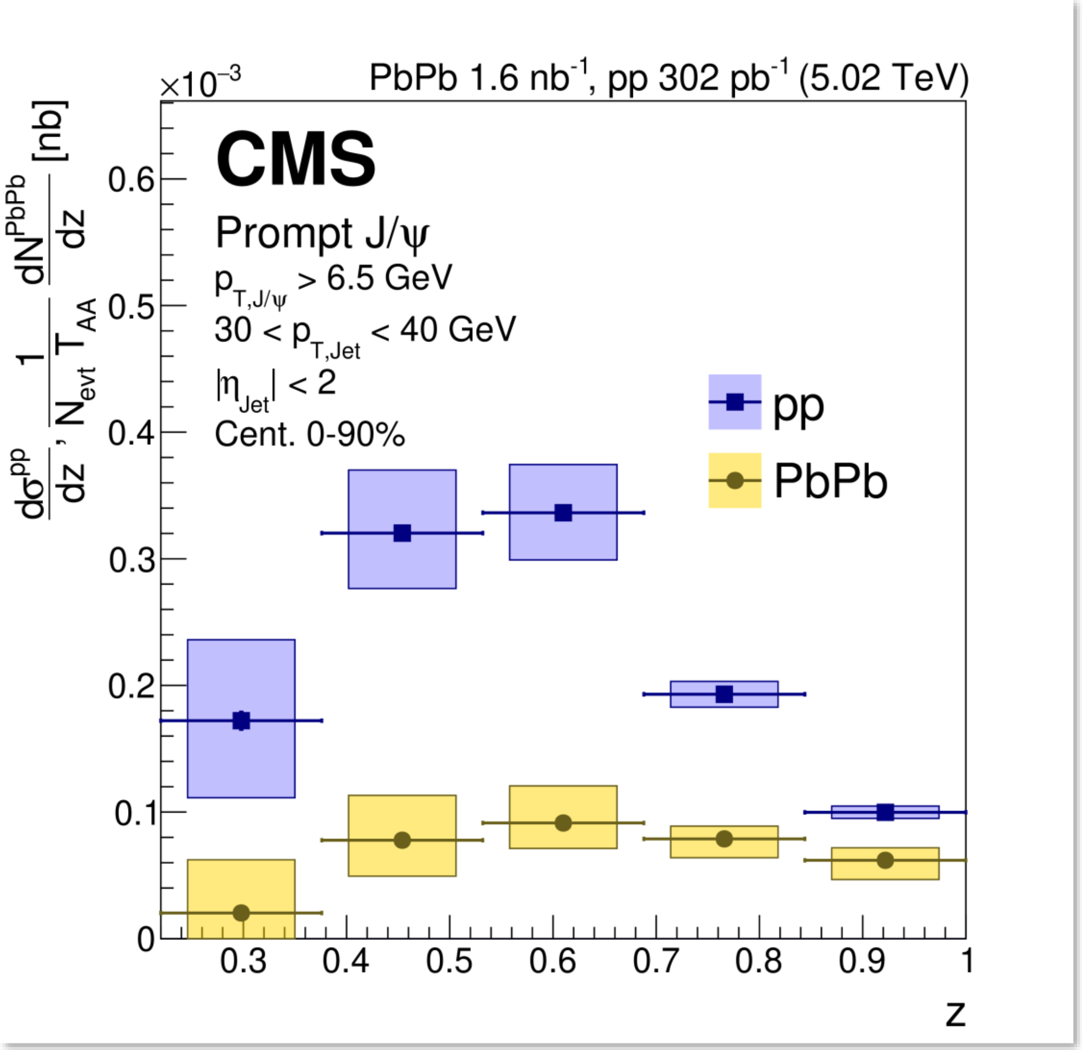
Charmonia in Pb-Pb collisions

- CMS measured prompt J/ψ production in jets in Pb-Pb collisions

arXiv:2106.13235

$$\text{Jet activity} \Rightarrow z = \frac{p_T\,(J/\psi)}{p_T\,(\text{Jet})}$$

➢ J/ψ more suppressed in Pb-Pb than pp in all z bins



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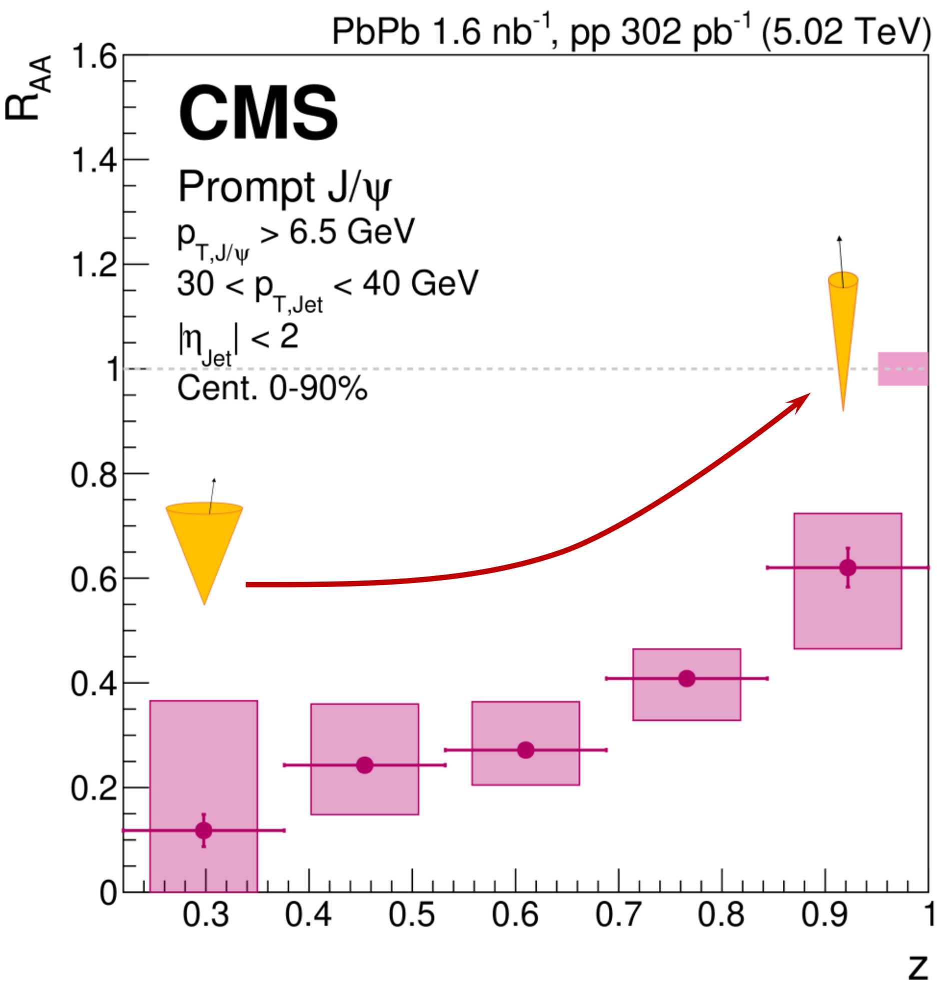
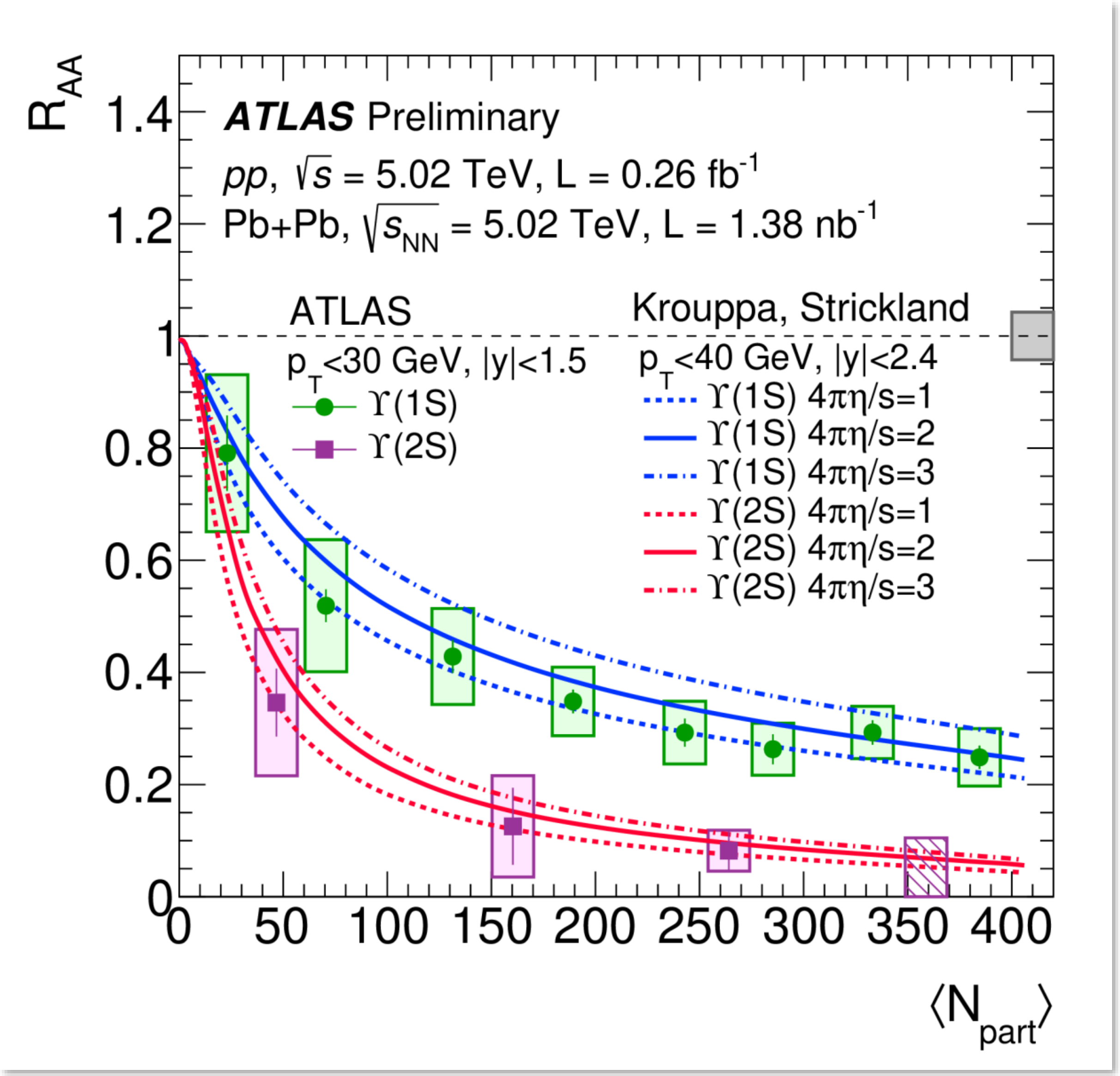
- J/ψ more suppressed in Pb-Pb than pp in all z bins
- Isolated J/ψ less suppressed than J/ψ with large jet activity
  - J/ψ with lower z are produced later in the parton shower interacting more with the **QGP**

Results in agreement with the scenario of **jet quenching** as relevant mechanism for J/ψ suppression



Bottomonia in Pb-Pb collisions

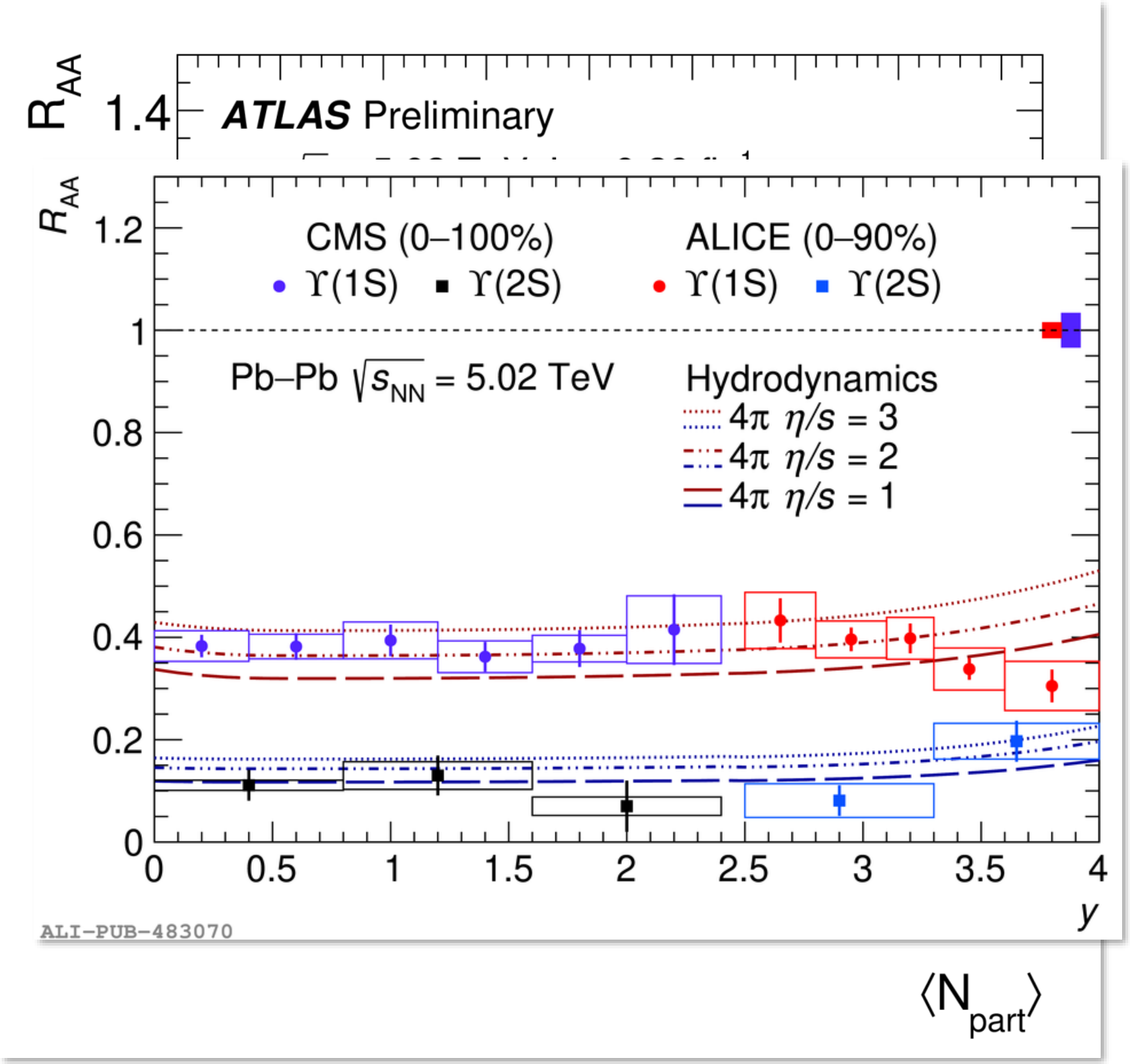


ATLAS measured ϒ(nS) nuclear modification factor in Pb-Pb collisions

- ➢ Results in agreement with model including **hydro + in-medium dissociation**

arXiv:1605.03561

Bottomonia in Pb-Pb collisions



ATLAS measured $\Upsilon(\mathrm{nS})$ nuclear modification factor in Pb-Pb collisions

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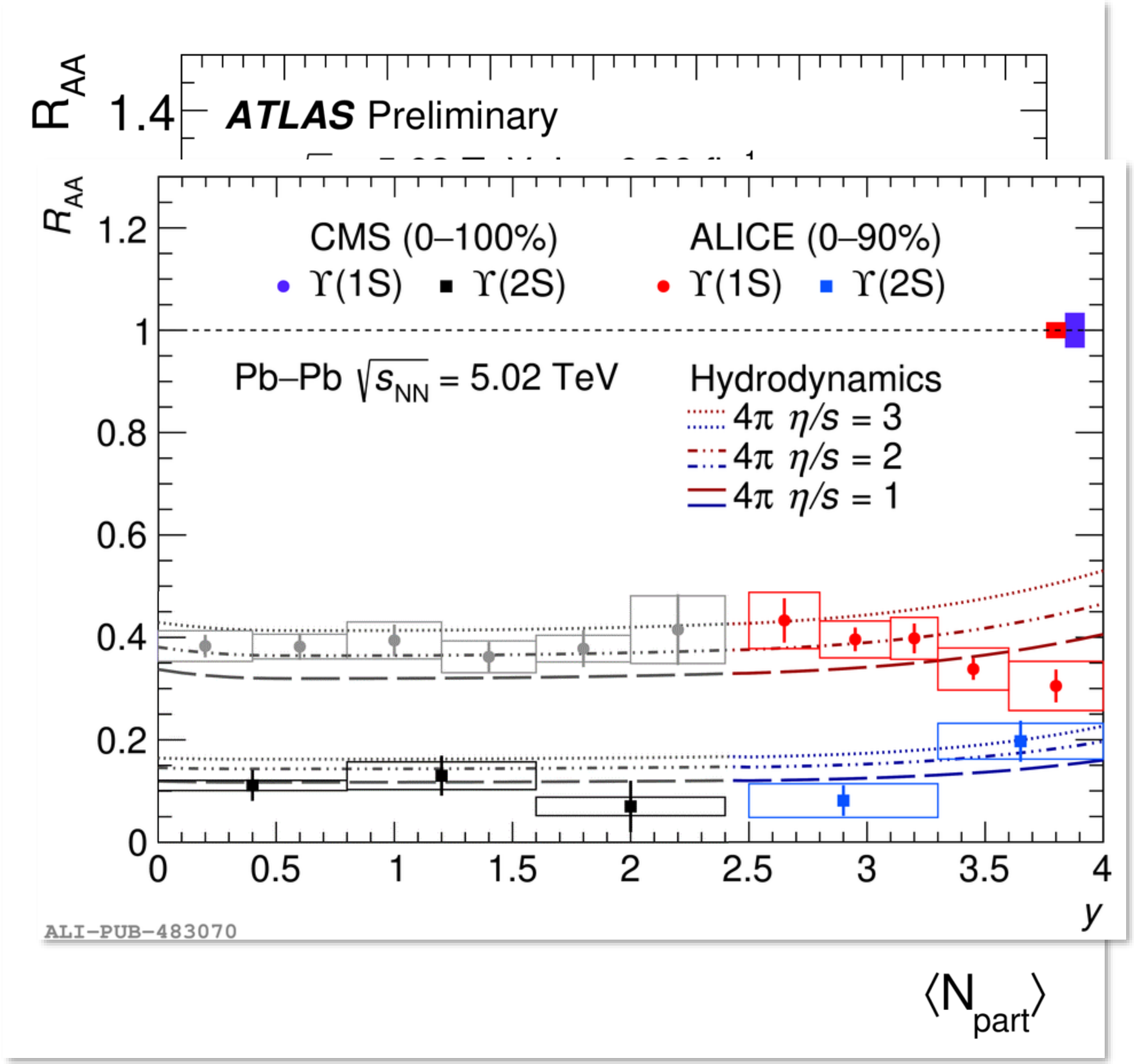
arXiv:1605.03561

ALICE and CMS measured the $\Upsilon(\mathrm{nS})$ R_{AA} as a function of rapidity in the range $0 < y < 4$

Bottomonia in Pb-Pb collisions



ATLAS measured Υ(nS) nuclear modification factor in Pb-Pb collisions

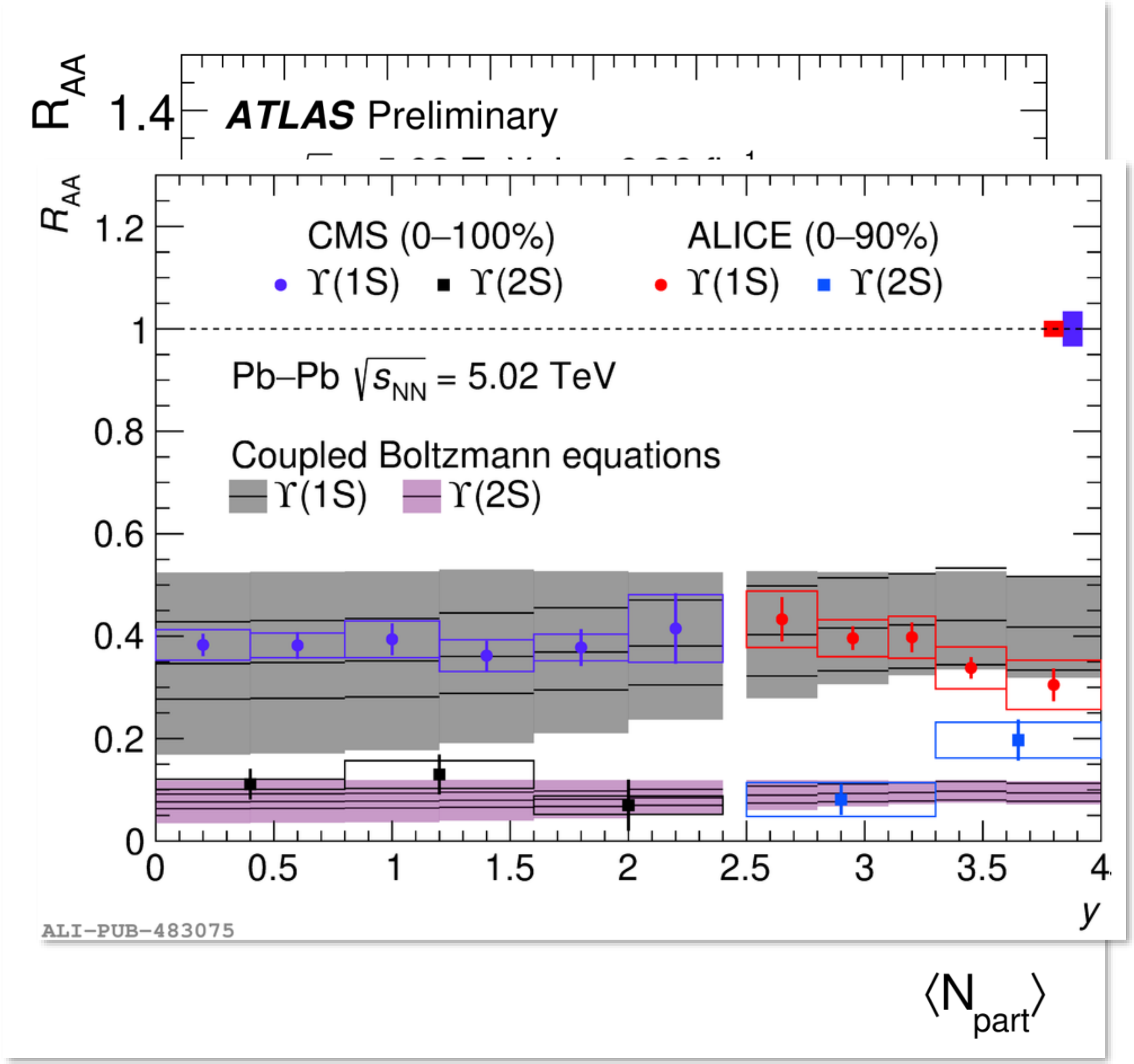
➢ Results in agreement with model including **hydro + in-medium dissociation**

arXiv:1605.03561

ALICE and CMS measured the Υ(nS) R_{AA} as a function of rapidity in the range $0 < y < 4$

➢ Results at forward rapidity goes in the opposite direction w.r.t. **Hydro model**

Bottomonia in Pb-Pb collisions



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➢ Results in agreement with model including **hydro + in-medium dissociation**

arXiv:1605.03561

ALICE and CMS measured the $\Upsilon(nS)$ R_{AA} as a function of rapidity in the range $0 < y < 4$

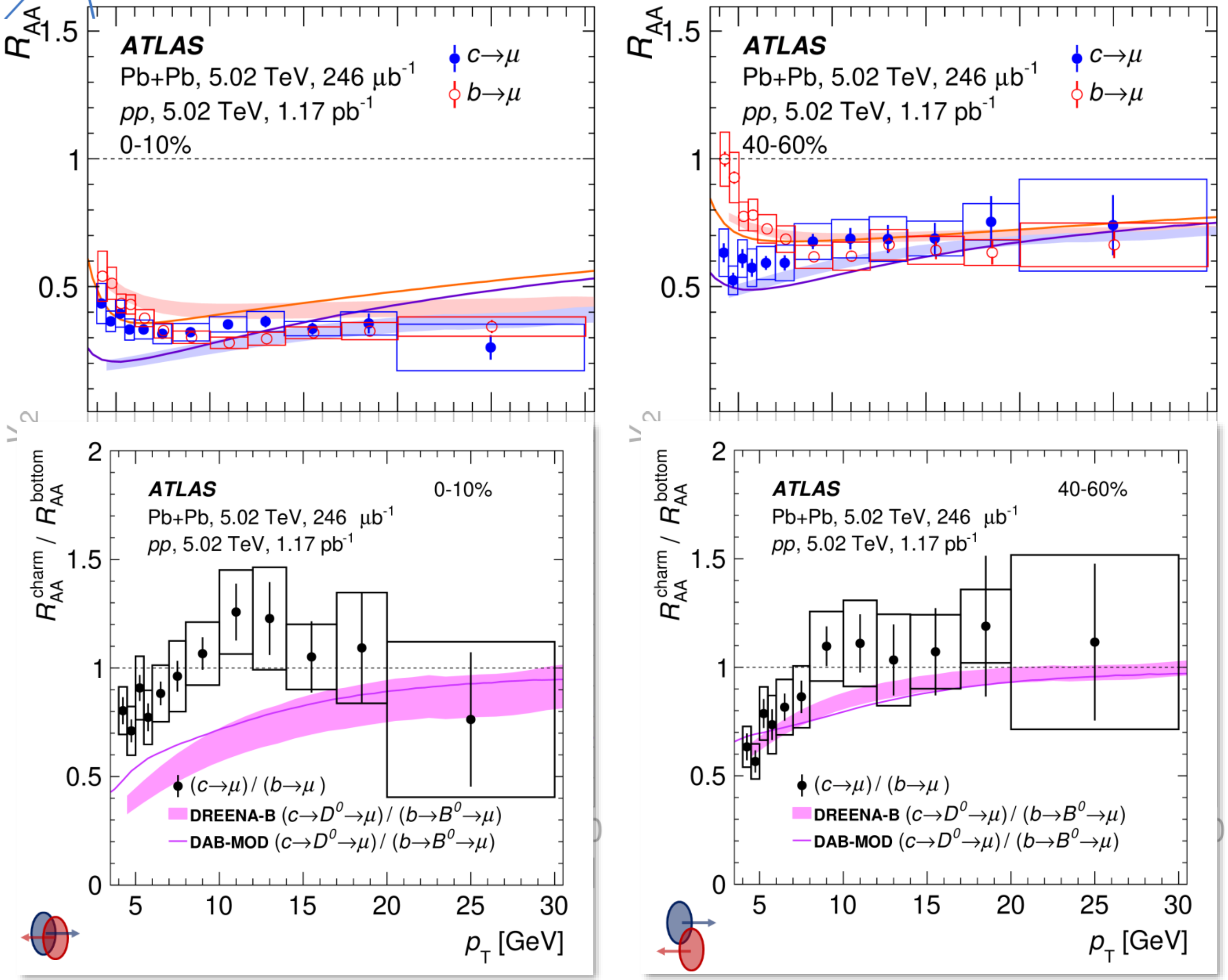
➢ Results at forward rapidity goes in the opposite direction w.r.t. **Hydro model**

➢ **Coupled Boltzman equations** provide an improved agreement even if qualitatively the trend seems still different

JHEP 01 (2021) 046

? Missing mechanism in the predictions?

Muons from heavy quarks in Pb-Pb collisions



ATLAS measured the R_{AA} for muons from charm and bottom hadrons

arXiv:2109.00411

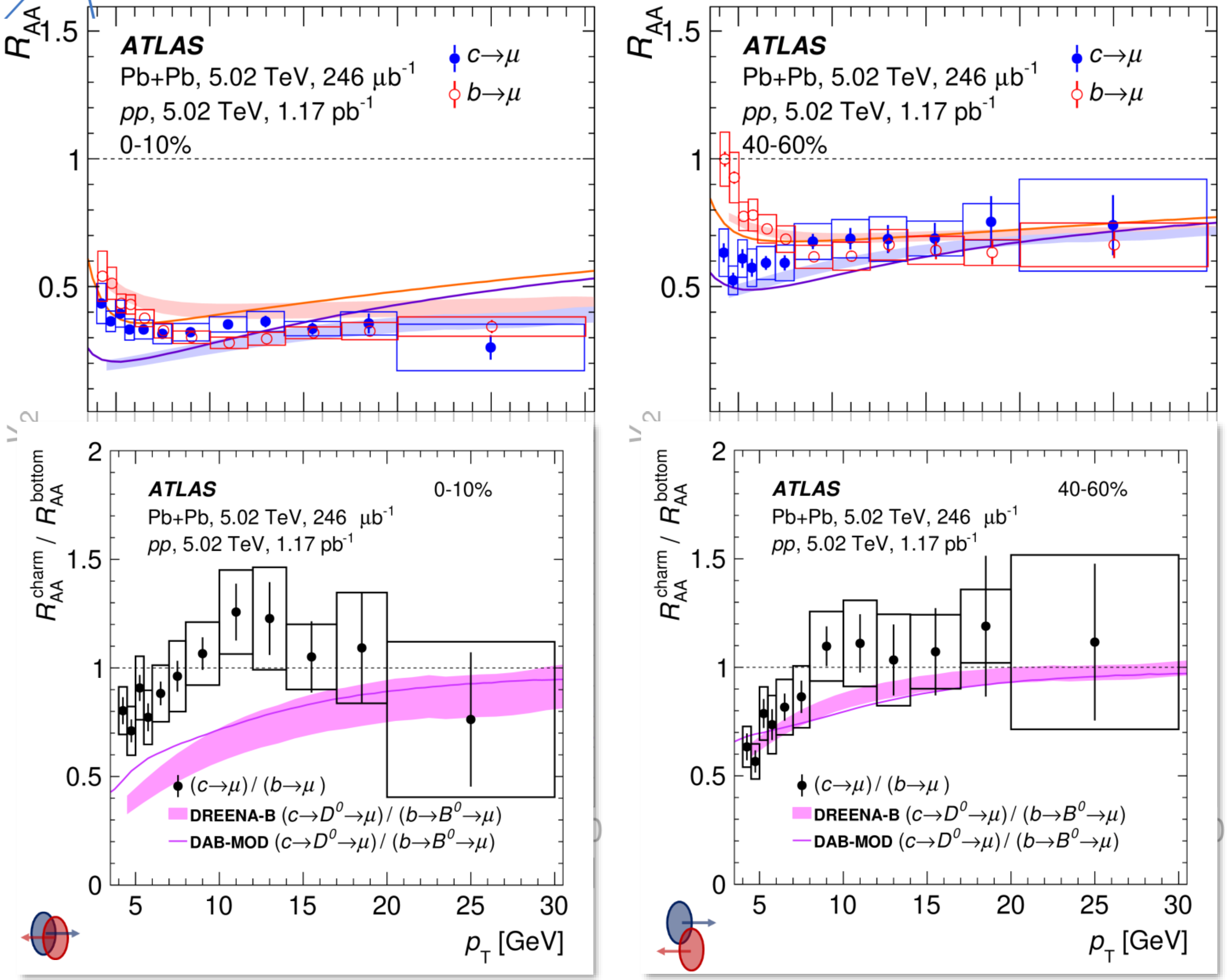
➢ Muons from charm more suppressed than muons from bottom hadrons

➢ Models including **energy loss** and **heavy quarks diffusion** in the QGP are in fair agreement with data

arXiv:1805.04786

arXiv:1906.10768

Muons from heavy quarks in Pb-Pb collisions



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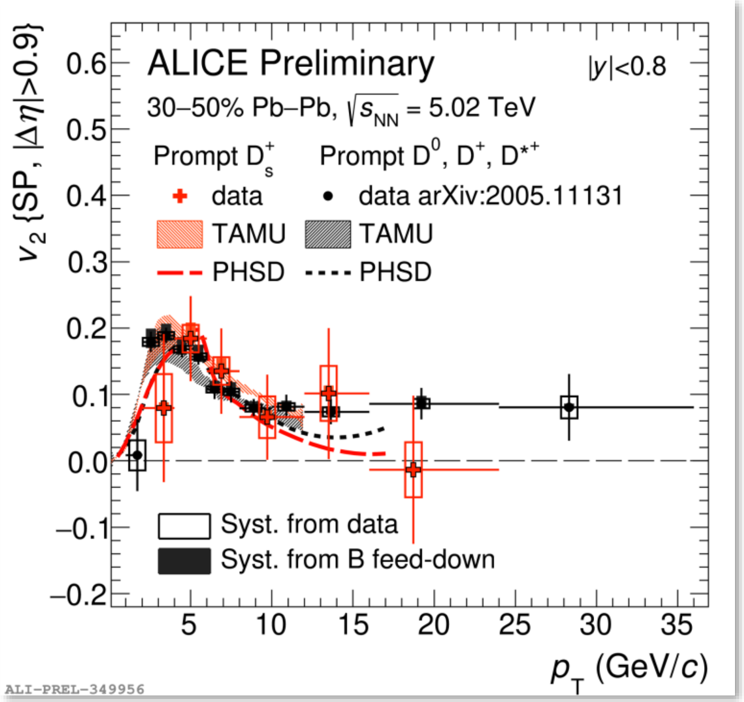
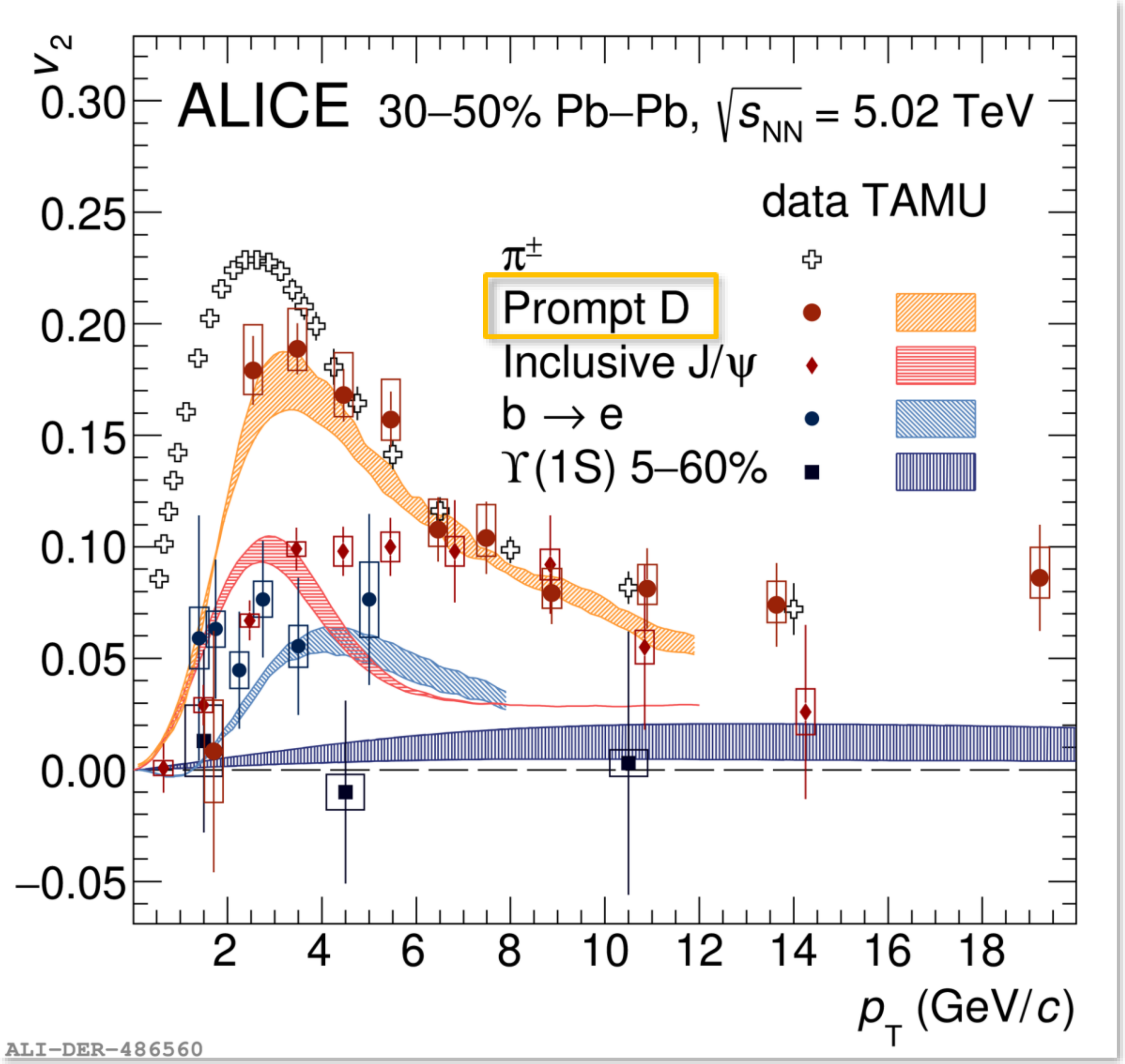
Access to the **initial QGP geometry** and **heavy quarks diffusion** via the simultaneous description of v_2/v_3 and the muons R_{AA}

HF and quarkonia elliptic flow

ALICE measured D-mesons v_2 in Pb-Pb collisions

- ➢ Positive v_2 indicates charm quark participation to QGP collective motion
- ➢ $v_2(\text{strange}) \sim v_2(\text{non}-\text{strange})$

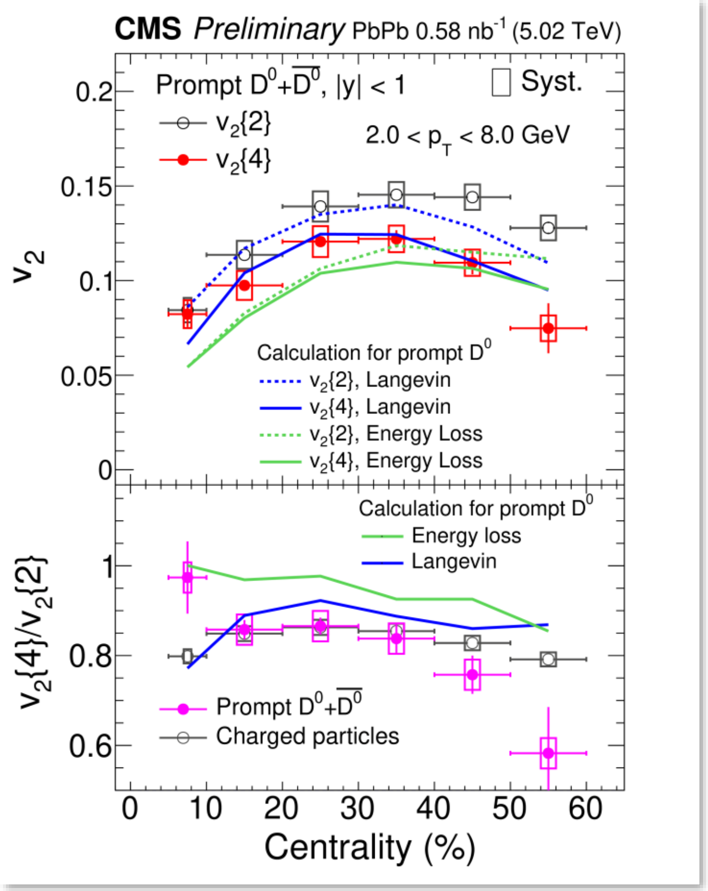


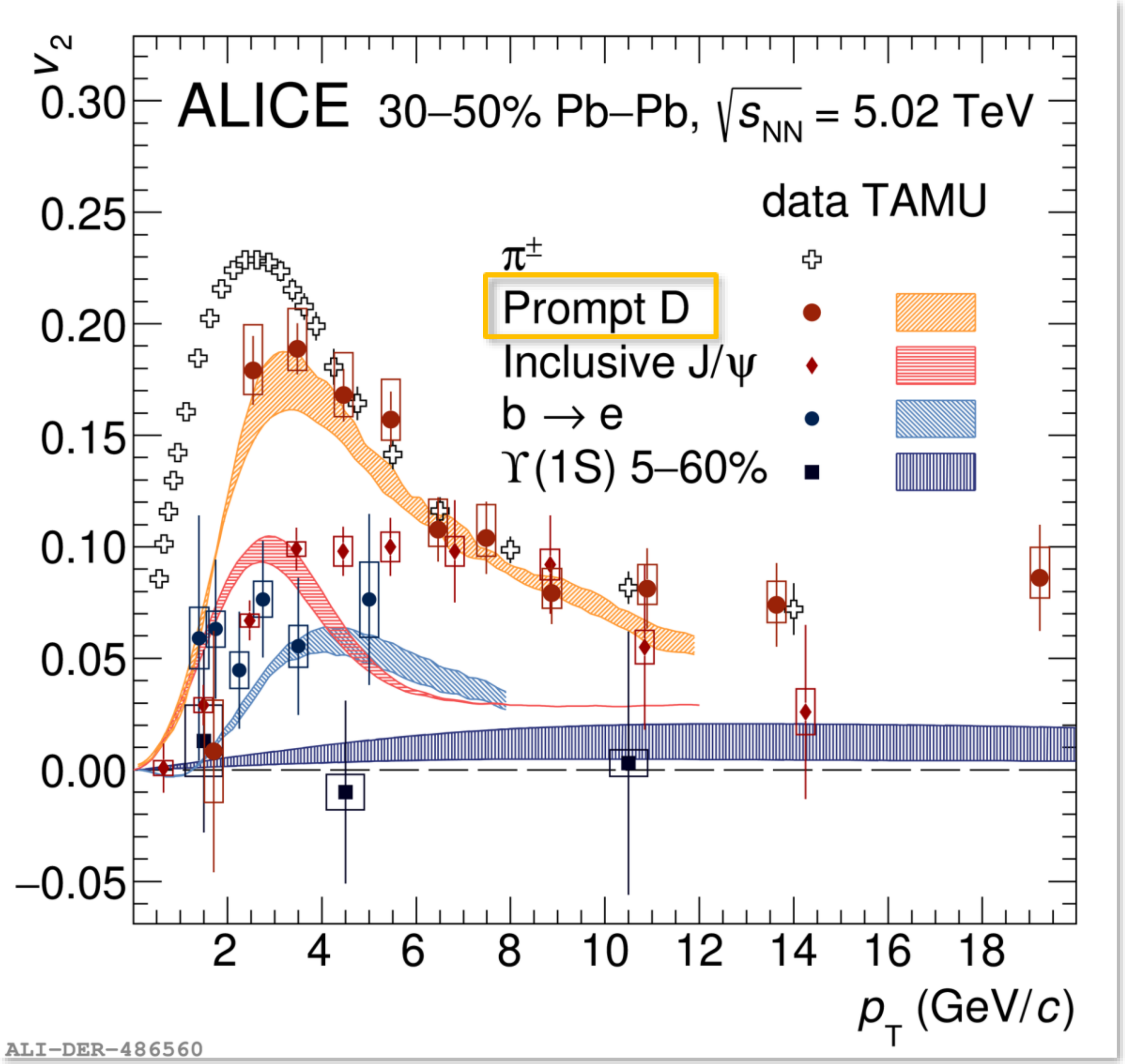


PLB 735 445-450 (2014)   PRC 92 014910 (2015)

HF and quarkonia elliptic flow

- CMS measured D-mesons v_2 in Pb-Pb collisions
  - ➢ v_2 increases from most central to 30-40%, then decreases to peripheral collisions



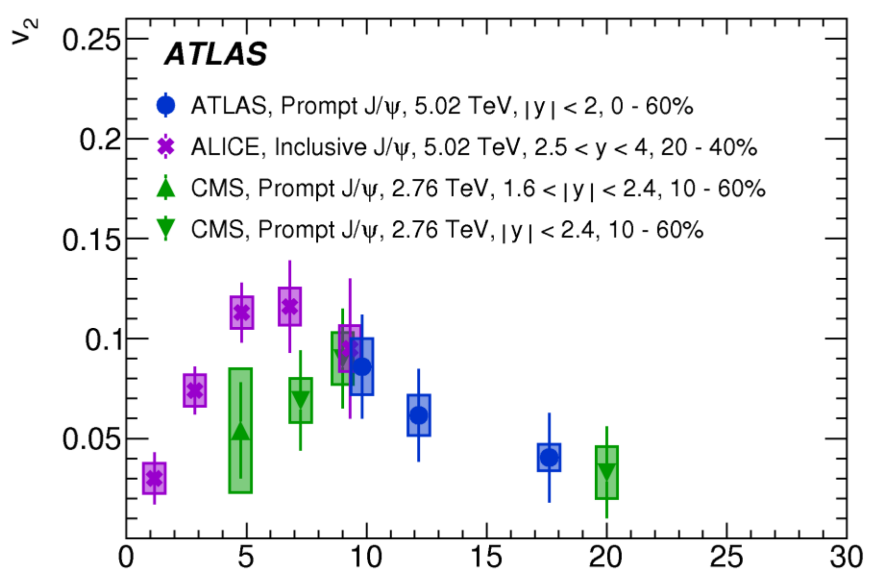


HF and quarkonia elliptic flow

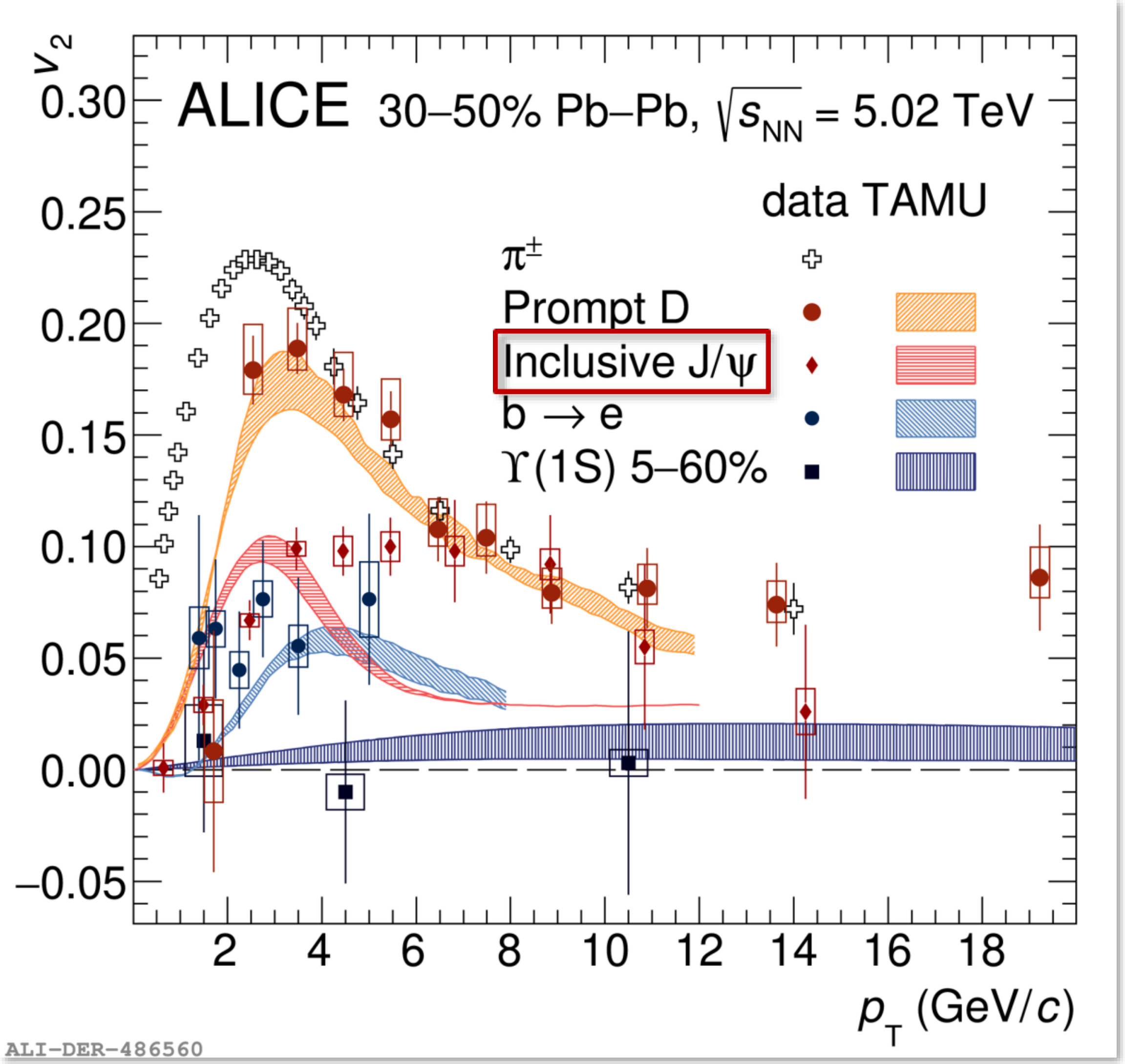
ALICE, ATLAS and CMS measured J/ψ v_2 in Pb-Pb collisions in different centrality and y ranges

➢ Positive v_2 in semicentral collisions

➢ Compatible with the scenario of **kinetic equilibration** of charm quark inside the QGP



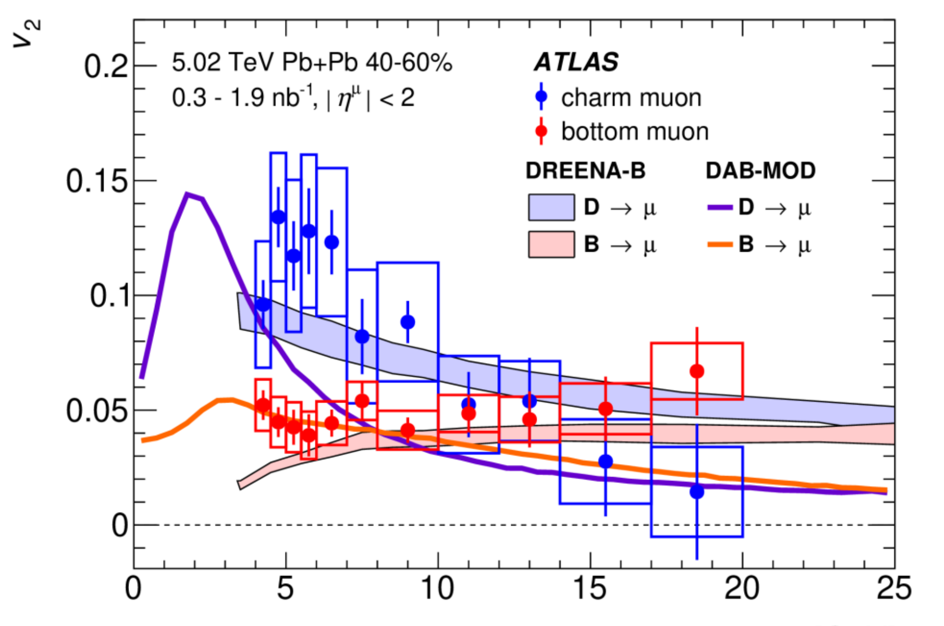
Eur. Phys. J. C 78 (2018) 784



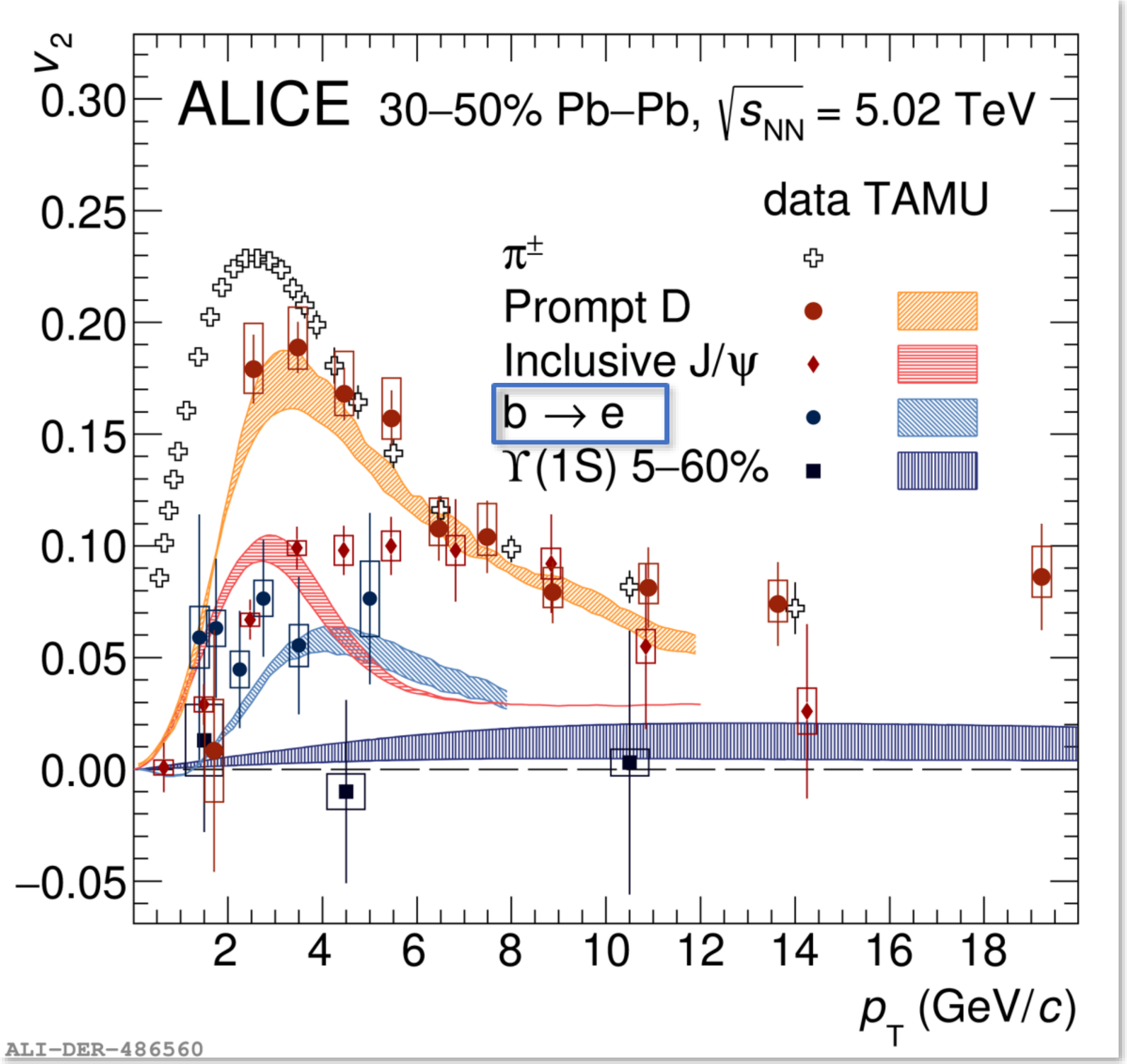
HF and quarkonia elliptic flow

ALICE, ATLAS measured **lepton from b v_2** in Pb-Pb collisions in semicentral collisions

- ➢ Positive v_2 in semicentral collisions but scenario of **beauty quark full thermalization** disfavoured



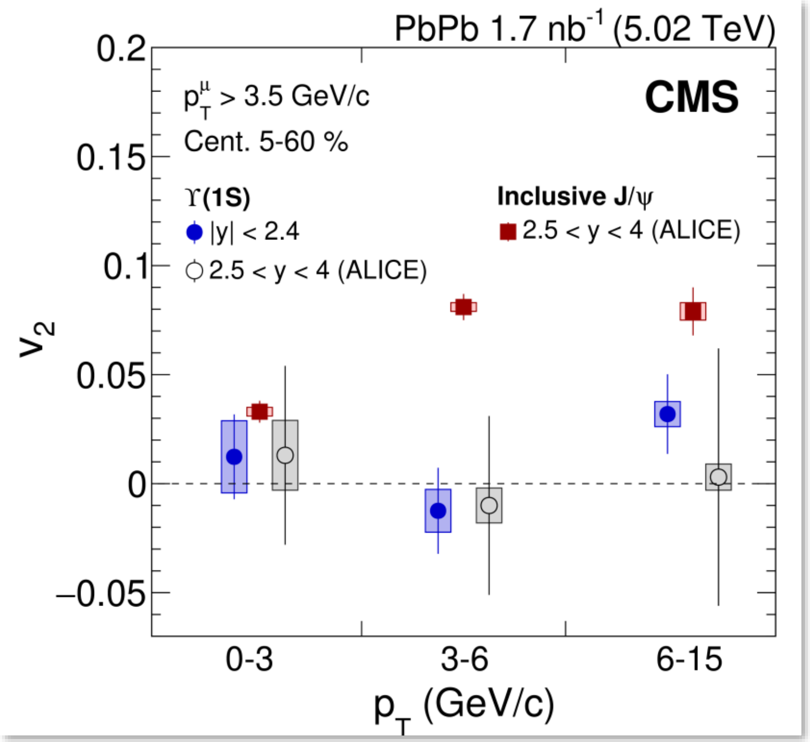
Phys.Lett.B 807 (2020) 135595

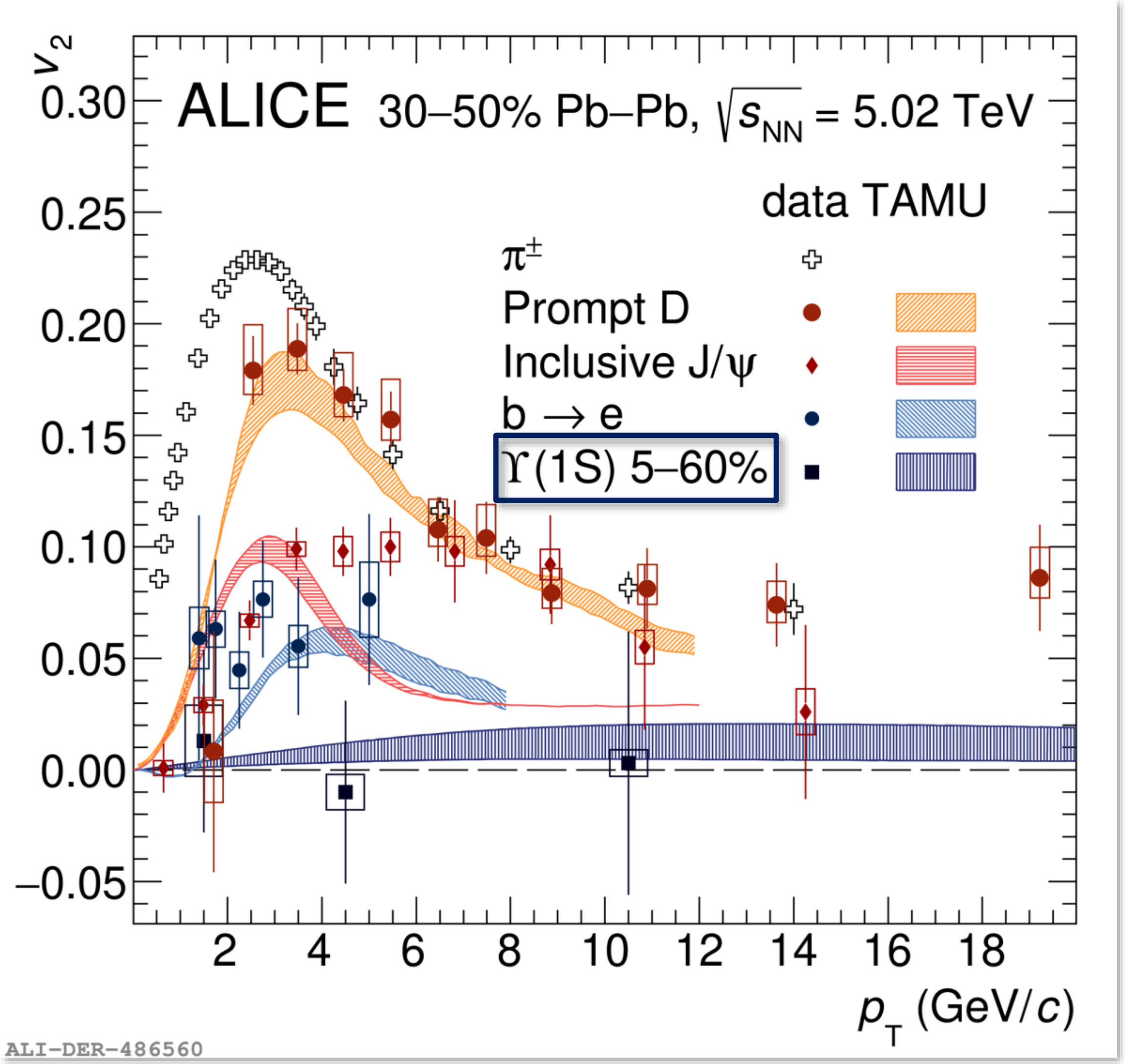


HF and quarkonia elliptic flow

ALICE, CMS measured the $\Upsilon(\mathrm{nS})$ v_2 in Pb-Pb collisions

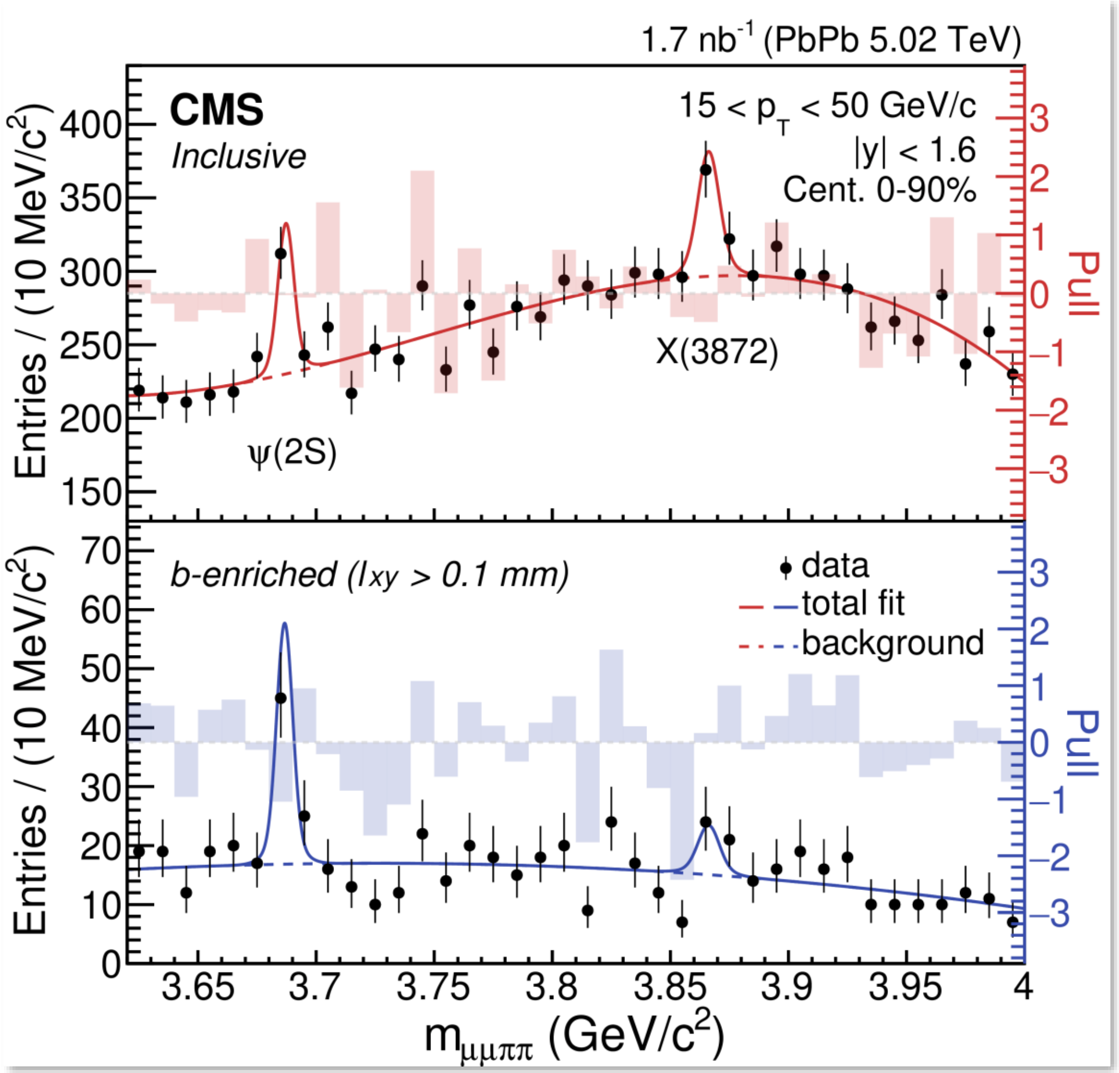
- ➢ v_2 compatible with zero
- ➢ In agreement with models with and without **bottomonia regeneration**





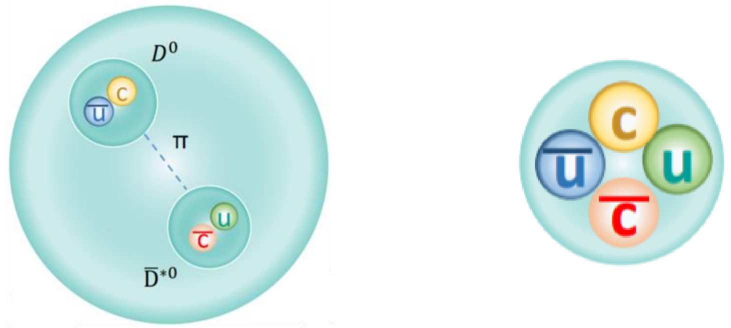
PLB 819 (2021) 136385 PRL 123, 192301 (2019)

Exotica



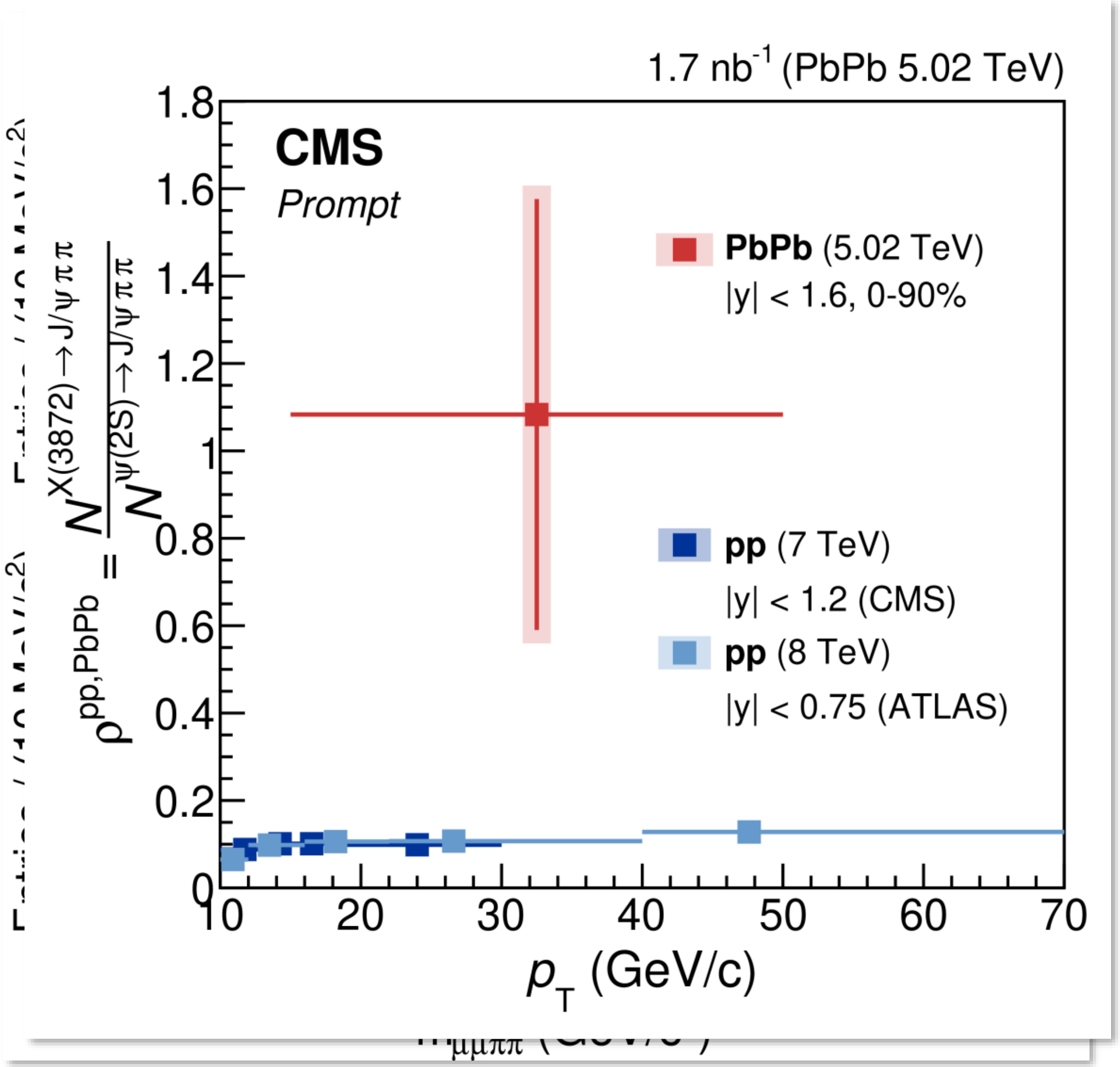
CMS performed the first significant measurement of the X(3872) in Pb-Pb collisions

arXiv:2102.13048



Tetraquark or $D^0 - D^{*0}$ molecule?

Exotica



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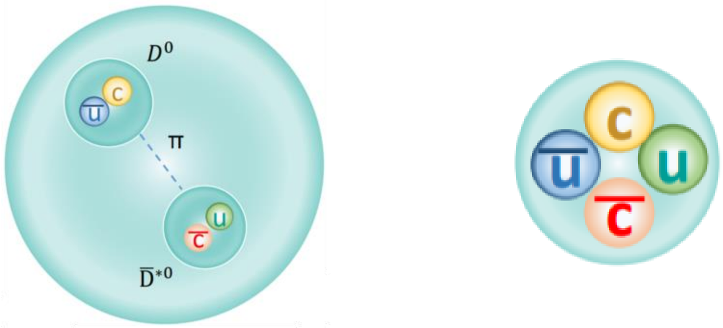
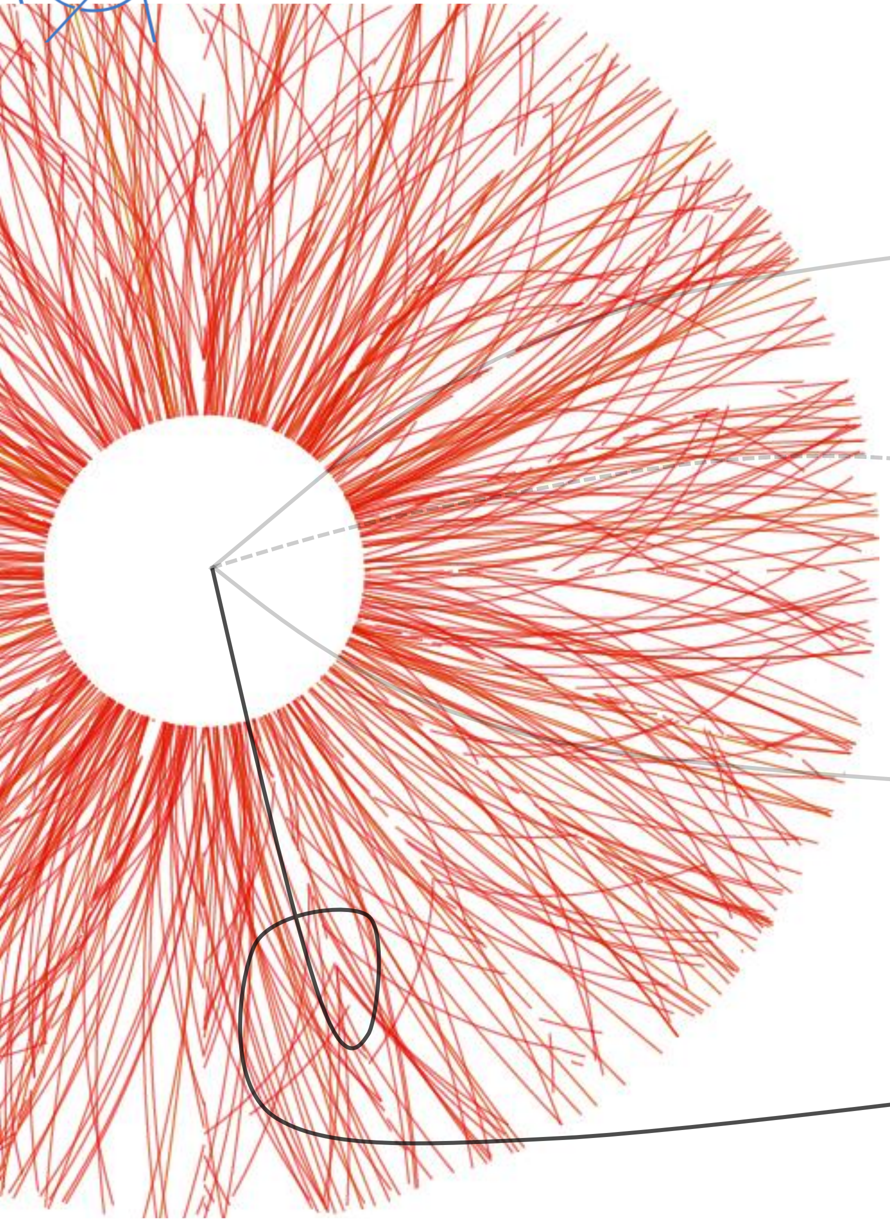


Tetraquark or $D^0 - D^{*0}$ molecule?

The ratio X(3872) / ψ(2S) is compatible with 1 within the uncertainties

➢ Crucial input for theoretical predictions

Outline



General introduction

LHC results in p—Pb collisions

LHC results in Pb—Pb collisions

Summary

Summary

p−Pb collisions

- J/ψ suppression in agreement with models including **CNM effects**
- **ψ(2S)** and **ϒ(2S/3S)** larger suppression consistent with **final state effects** (comovers,…)
- **σ(χ_{c2})/σ(χ_{c1})** compatible with unity and with the results in pp collisions

Pb−Pb collisions

- **HF** and **quarkonia** significantly **suppressed** in central Pb-Pb collisions
  - Hint for enhanced **strange** hadron production at low p_{T}
  - Missing mechanism in the description of **bottomonia** at forward rapidity?
- Positive v_2 for D-mesons and J/ψ and B-hadrons
  - c and b quarks participate to **QGP collective motion**
- **X(3872)**: exotic states as new tools in the study of the QGP

12th MPI at LHC

Backup

B-mesons in Pb-Pb collisions