Heavy-flavour production in heavy-ion collisions

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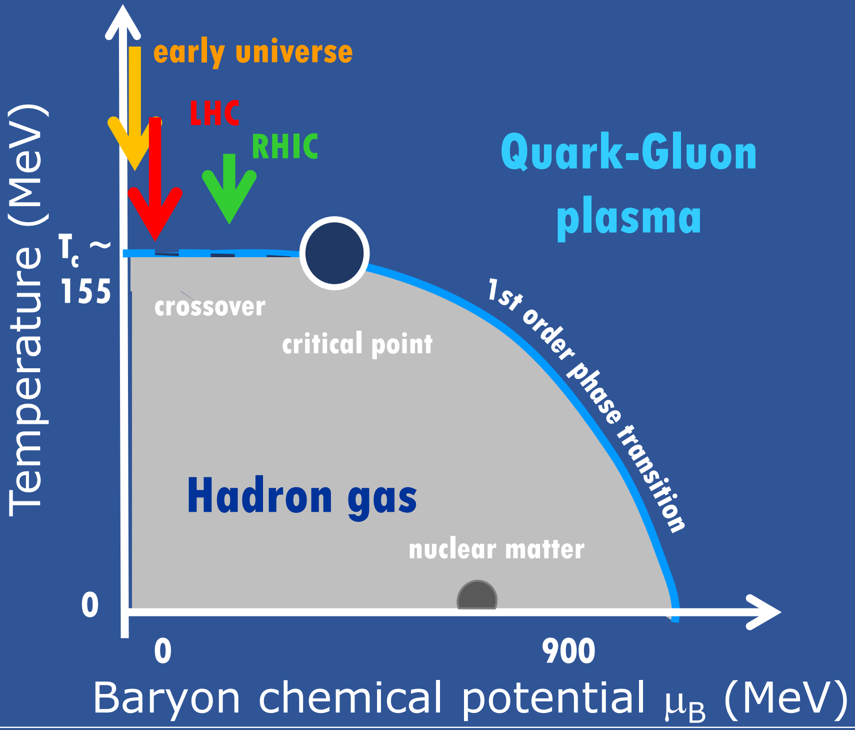
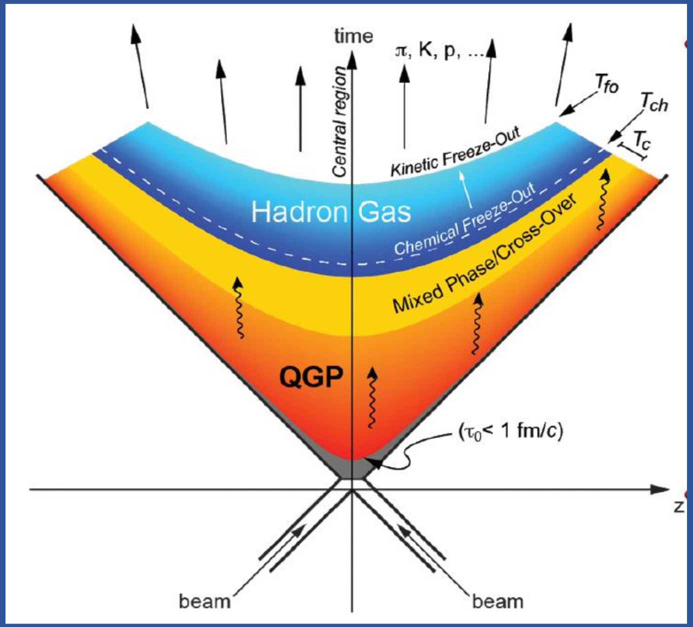
- (Brief) physics motivation and general highlights from LHC
- Recent results on open and closed heavy quark production
- Conclusions



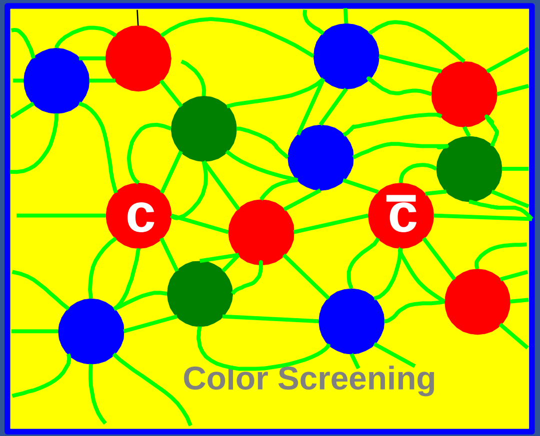
Physics motivation

- Heavy quarks produced **early** in the history of the collisions (formation time <0.1 fm/c) → probe the entire evolution of the created system

- **Open charm/beauty**
  - Energy loss of heavy quarks → **QGP transport properties**
  - Anisotropic flow → **Thermalization of the system**
  - "Chemical composition" → **Hadronization mechanisms**



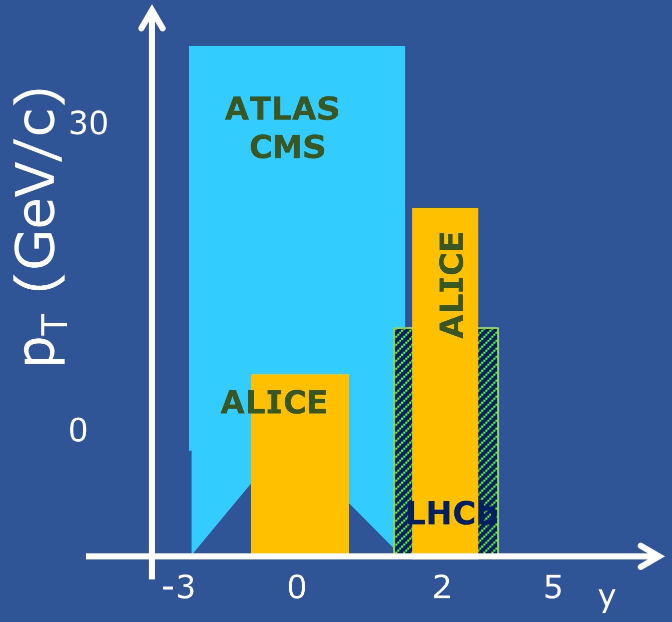
- **Charmonium/bottomonium**
  - Suppression effects → **QGP "thermometer"**
  - Recombination → **Heavy quark dynamics in the QGP**
  - Anisotropic flow → **Heavy-heavy vs heavy-light**



Answers but also open questions from data collected at the LHC!

The LHC experimental program

- **Complementarity** between experiments, also due to their different kinematic coverage. **For J/ψ** (Pb-Pb collisions)



Exp.	System	$\sqrt{s_{NN}}$ (TeV)	
ALICE, ATLAS, CMS, LHCb	PbPb, XeXe	2.76, 5.02, 5.44	**Hot matter effects**
	pPb	5.02, 8.16	**Cold matter effects**
	pp	2.76, 5, 7, 8, 13	**"Reference"**

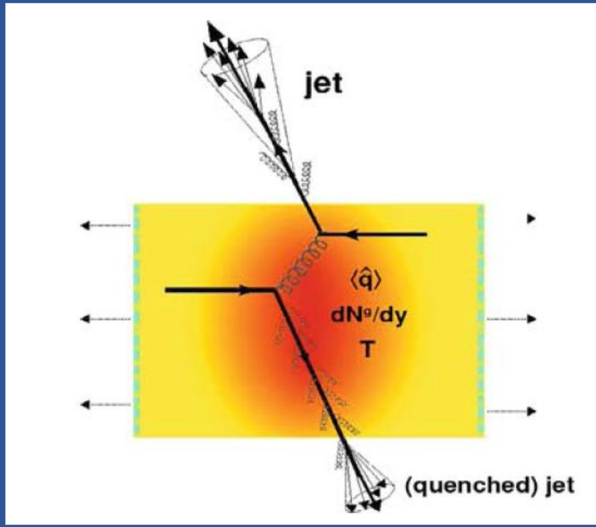
- In parallel, RHIC experimental program still active (STAR experiment)
  - Maximum energy → $\sqrt{s_{NN}}$=0.2 TeV
  - Beam energy scan → 3 < $\sqrt{s_{NN}}$ < 7.7 GeV (fixed-target), 7.7 < $\sqrt{s_{NN}}$ < 19.6 GeV (collider)

QGP studies – highlights from LHC

Energy loss of hard partons in the QGP

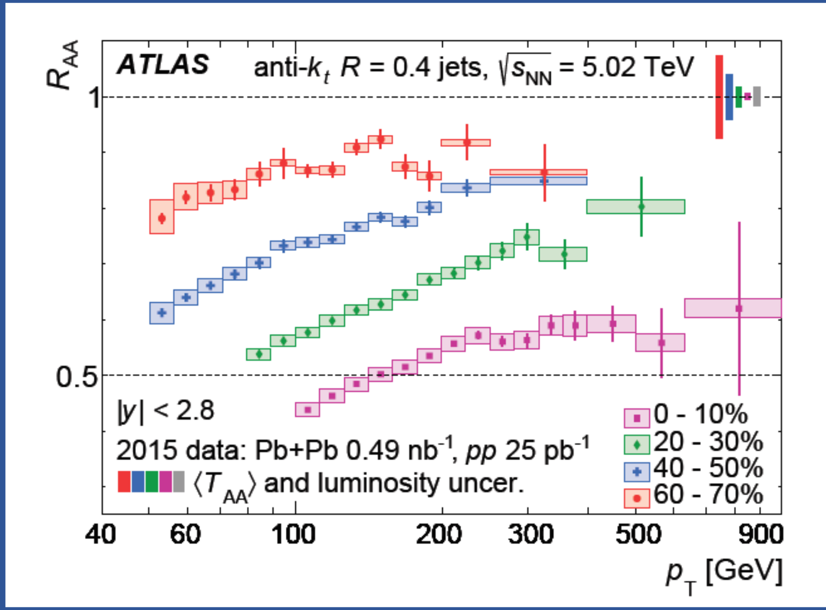
Relevant quantity → $R_{AA} = \dfrac{Y^{AA}/dp_T}{\langle N_{coll}\rangle\, Y^{pp}/dp_T}$

(Y^{ii} → yield per inelastic event)

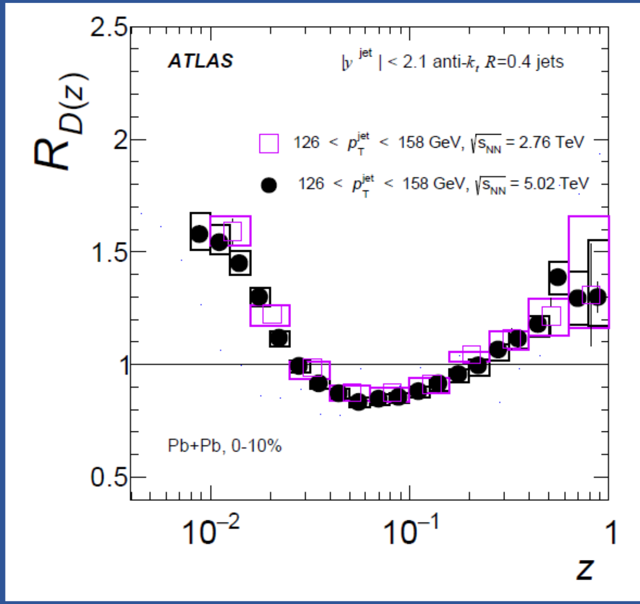


Suppression of jets, and modification of their properties, observed up to p_T ~ 1 TeV

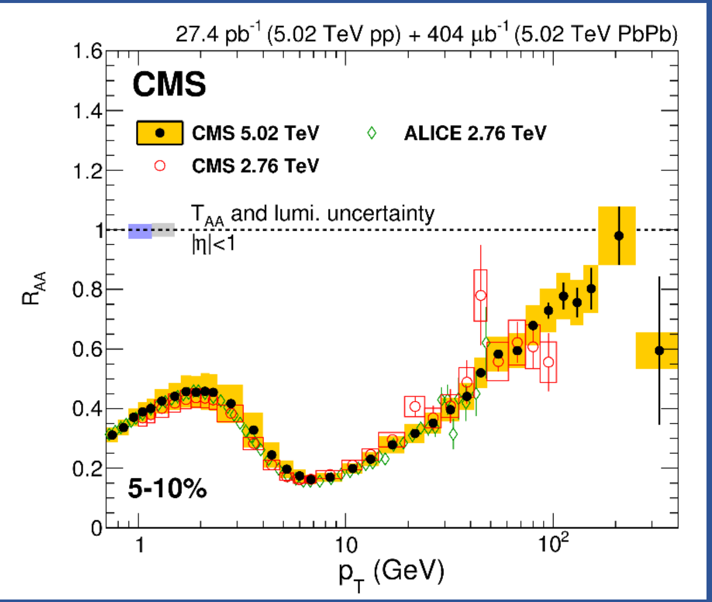
Suppression of high-p_T hadrons



ATLAS, Phys. Lett. B 790 (2019) 108



ATLAS, PRC 98, 024908 (2018)

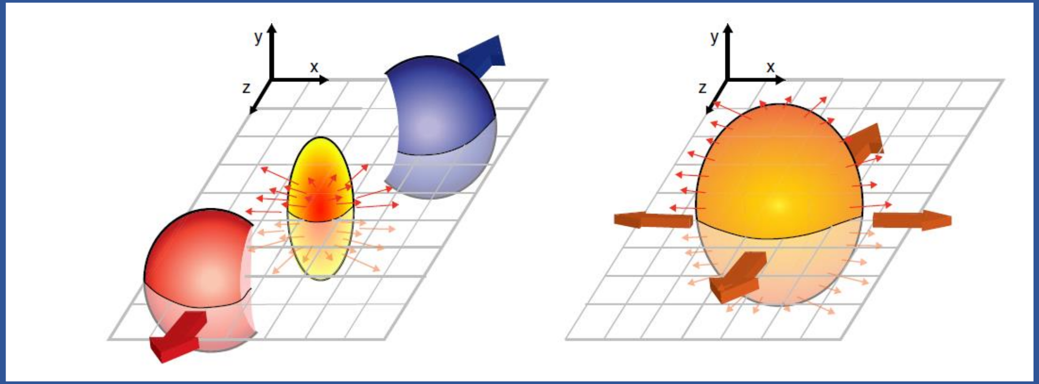


CMS, JHEP 04 (2017) 039

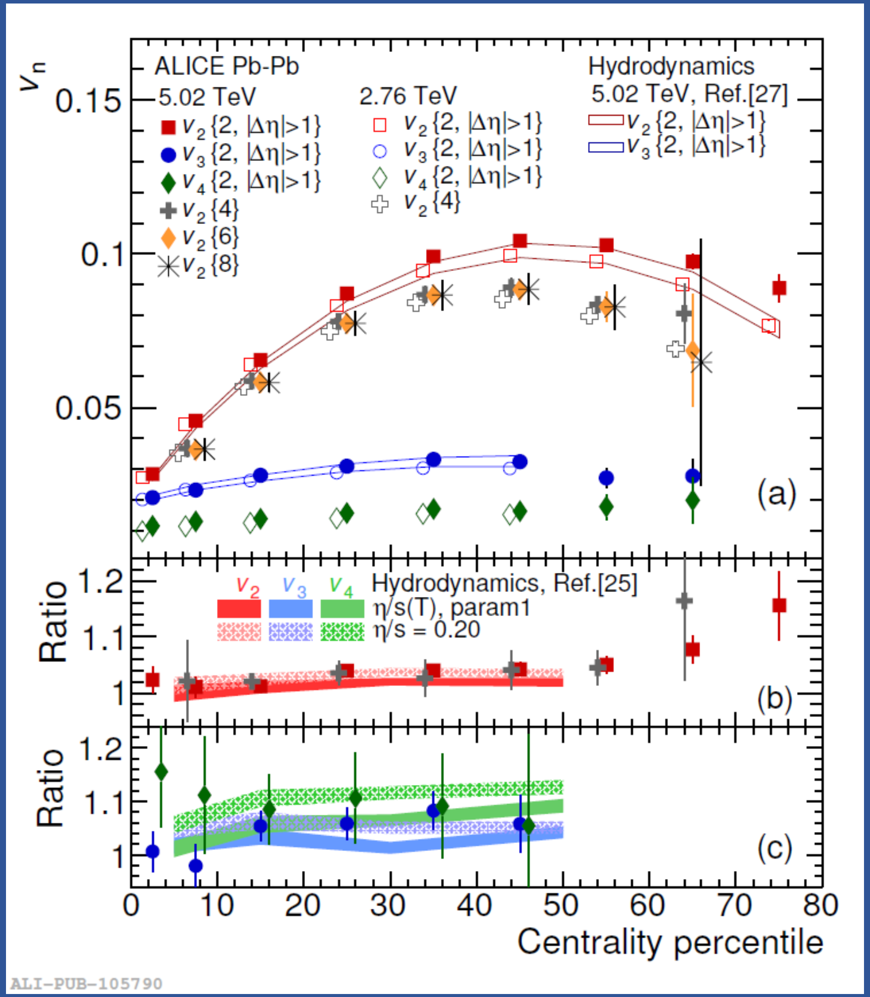
QGP studies – highlights from LHC

(Early) thermalisation of the fireball

- Different **pressure gradients** in the anisotropic fireball
  → **spatial anisotropy** of produced particles

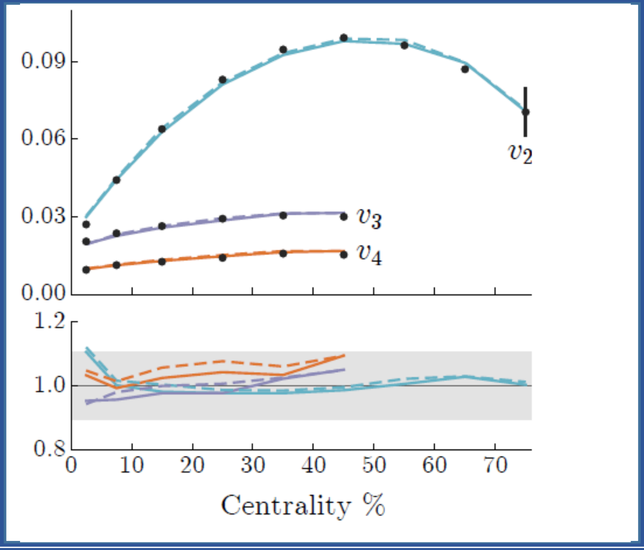


ALICE, PRL 116 (2016) 132302



Relevant quantity → elliptic flow $\mathbf{v_2 = \langle \cos(2(\phi-\psi_{RP}))\rangle}$

- Bayesian analyses (include also other observables) give η/s compatible with $1/4\pi$
  → **perfect fluid**



Bernhard et al., PRC94(2016) 024907

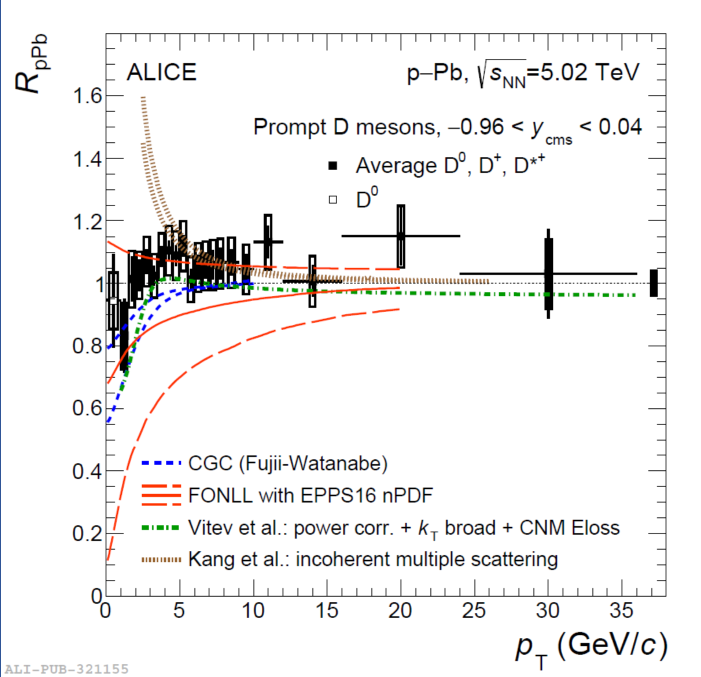
LHC results in agreement with calculations of **hydrodynamic models**

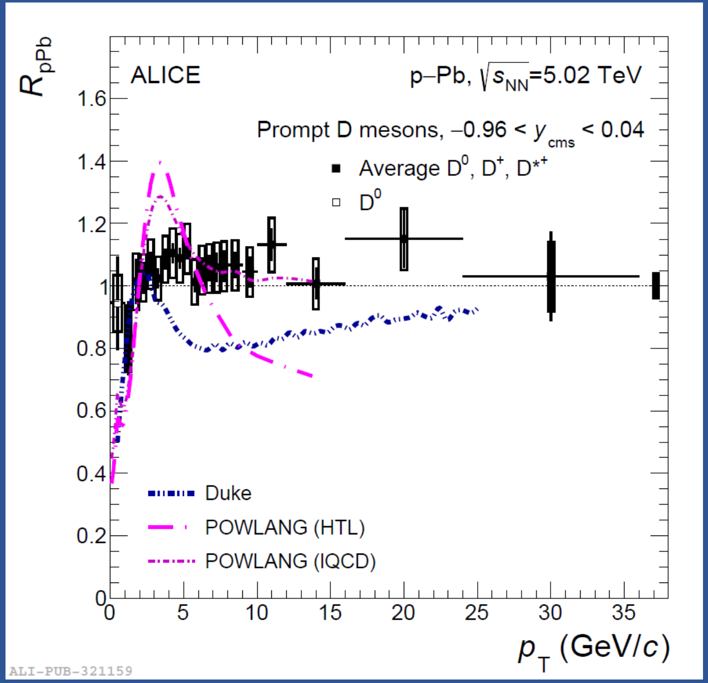
Heavy quark energy loss

- ❑ High-p_T studies → investigate energy loss mechanisms
  - ❑ **Is this a hot nuclear matter effect ?**
  - ❑ Is there a flavor dependence ?
  - ❑ Radiative vs collisional processes

→ p-Pb: R_{pPb} compatible with unity for p_T>3 GeV/c → **cold nuclear matter (CNM) effects are weak**

- ❑ Results described by models including **CNM effects only**
- ❑ Large **uncertainties** on nuclear **shadowing** calculations
- ❑ Data do not favour "radial-flow"-like peak around 3-4 GeV/c, nor decreasing trend at higher p_T





ALICE, arxiv:1906.03425

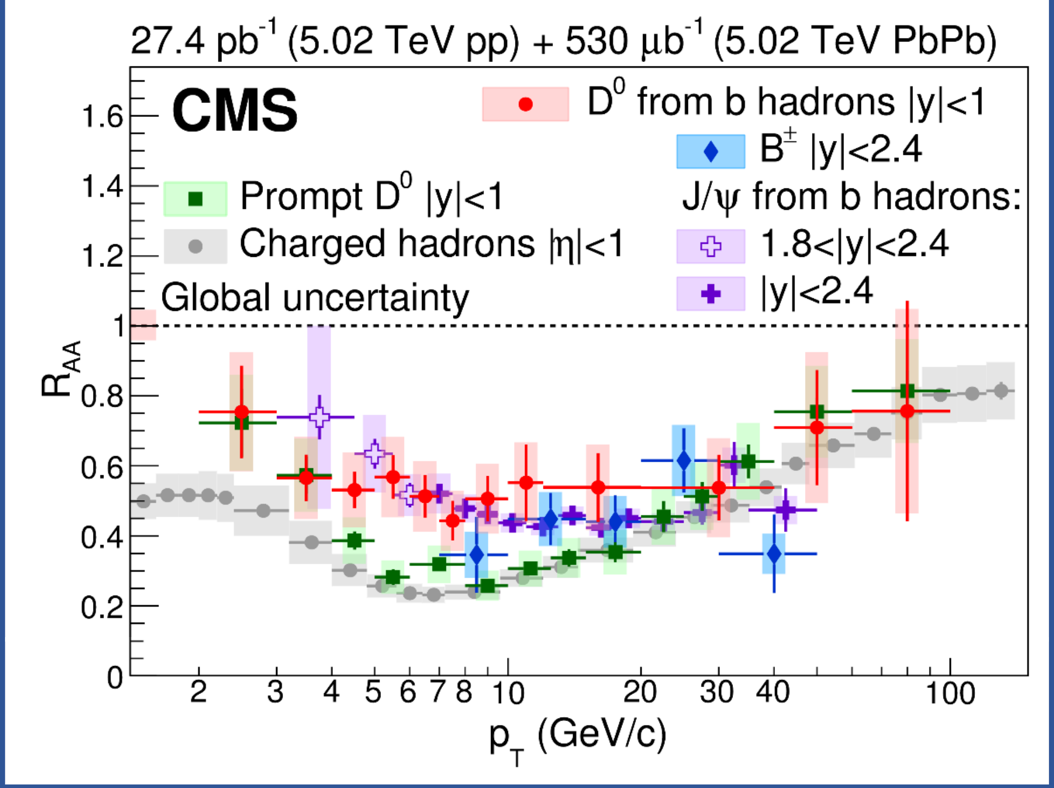
Heavy quark energy loss

- ❑ High-p_T studies → investigate energy loss mechanisms
  - ❑ Is this a hot nuclear matter effect ?
  - ❑ **Is there a flavor dependence ?**
  - ❑ Radiative vs collisional processes

Energy loss expected to depend
→ On parton **color charge** (g vs q)
→ On parton **mass** (heavy vs light q)

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Baier at al. (BDMPS), NPB483(1997)291
Dokshitzer et al., PLB 519(2001)199



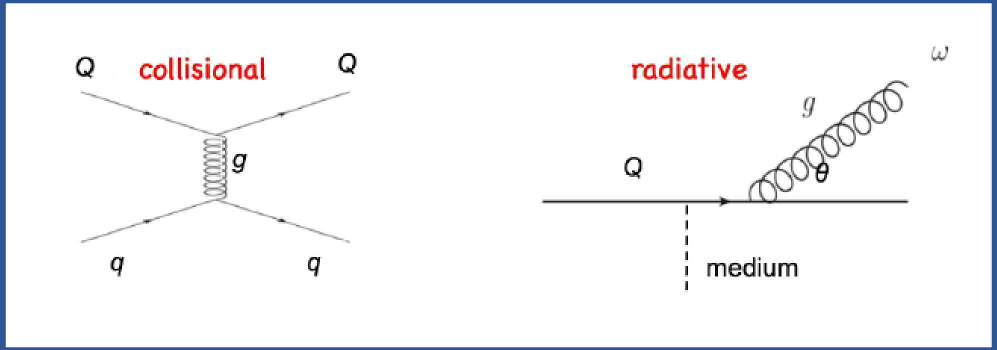
CMS, Phys. Rev. Lett. 123, 022001 (2019)

- ❑ Experimental observations
  - ❑ **Similar suppression** for charm and beauty mesons at high p_T
  - ❑ Hint of **m_Q ordering** at intermediate p_T

    → hierarchy **$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?**
  - ❑ Less evident for **D vs π**
    - ❑ Need to consider that color charge dependency of energy loss can be compensated by the softer fragmentation and p_T spectrum of gluons

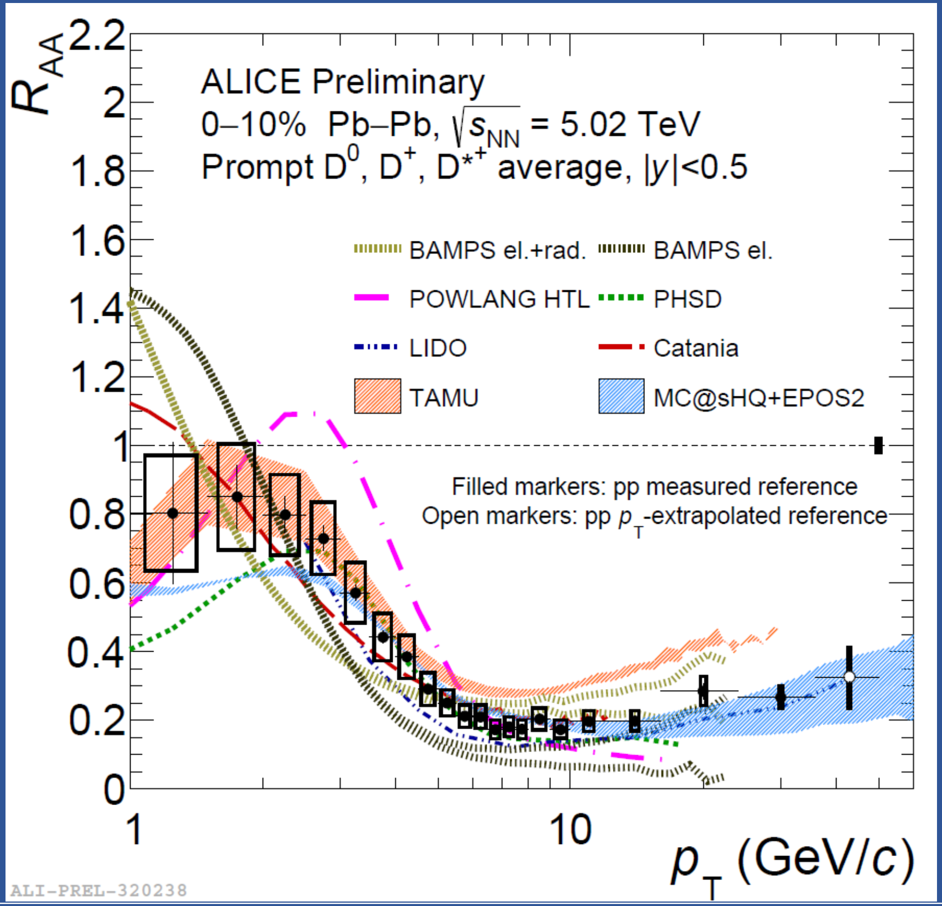
Comparison with models

- High-p_T studies → investigate energy loss mechanisms
  - Is this a hot nuclear matter effect ?
  - Is there a flavor dependence ?
  - **Radiative vs collisional processes**



Dominant at low p_T

Dominant at high p_T

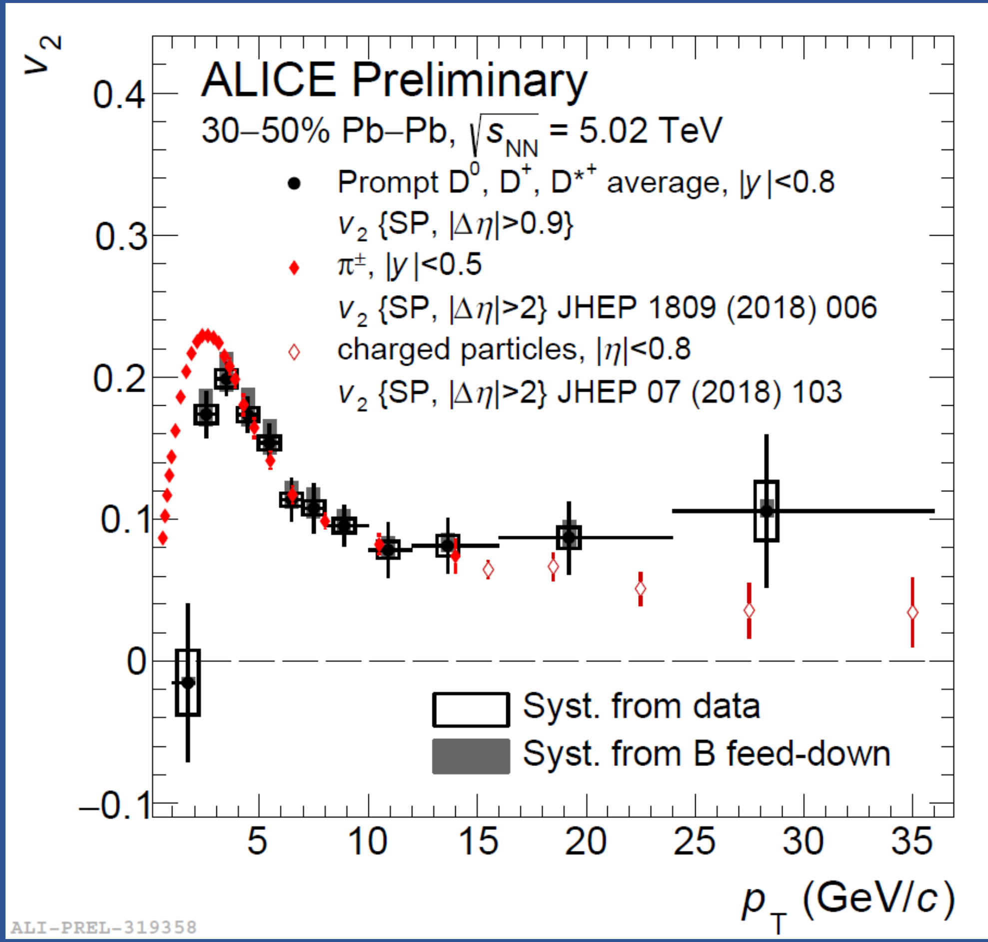


- ALICE **high statistics data set** Pb-Pb 2018
  → Fine binning and low-p_T reach

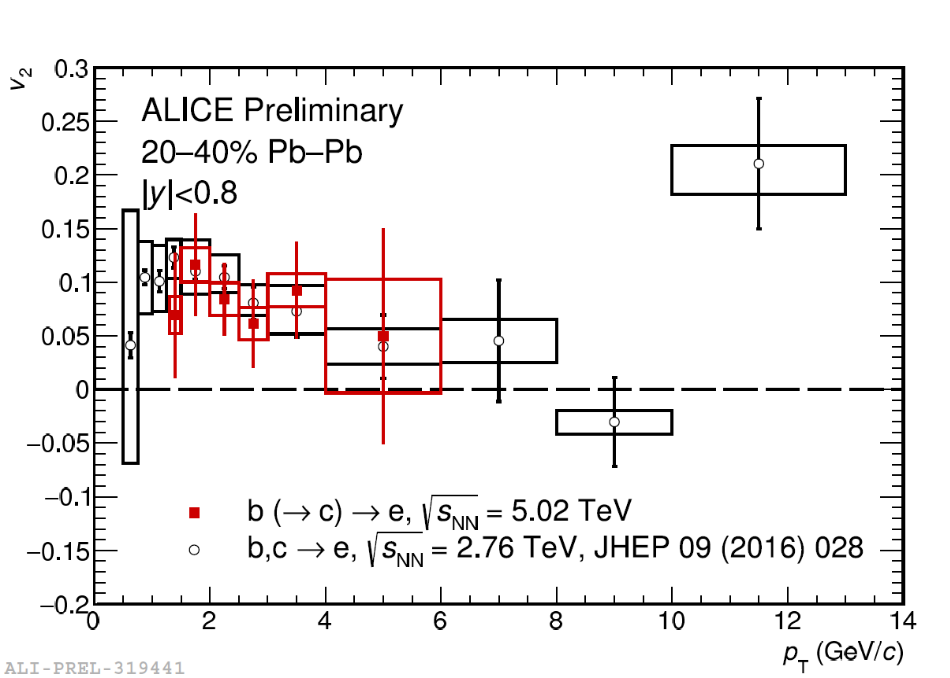
- TAMU, POWLANG, BAMPS → no radiative Eloss
  - Deviation from exp data at high p_T may signal onset of radiative energy loss

- More generally, **interplay of CNM (shadowing), collisional and radiative energy loss, coalescence and realistic medium evolution** required to describe data

Thermalization: charm and beauty v_2



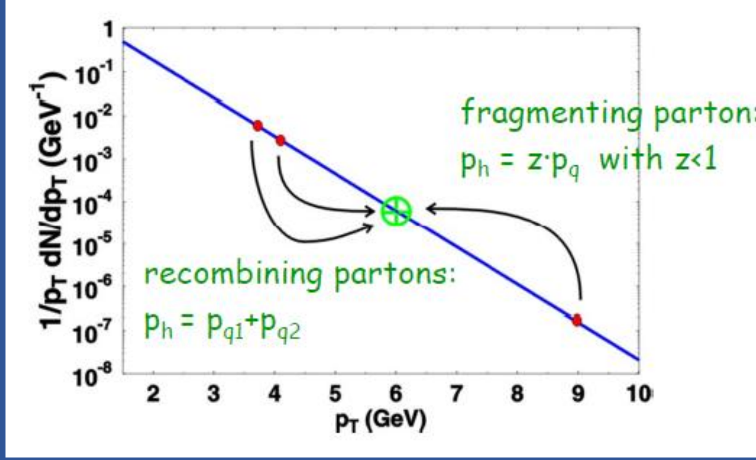
- **v_2 >0 for low p_T charm** → strong indication for heavy-quark thermalization in QGP
- Less information available for **beauty → hints for non-zero v_2** at low p_T

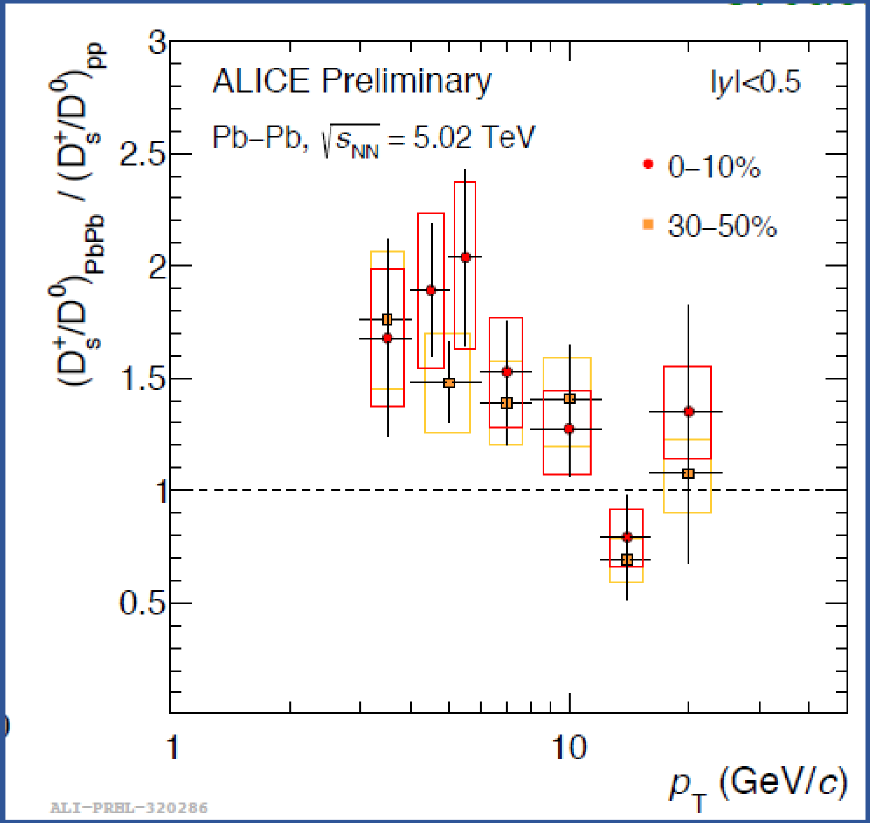


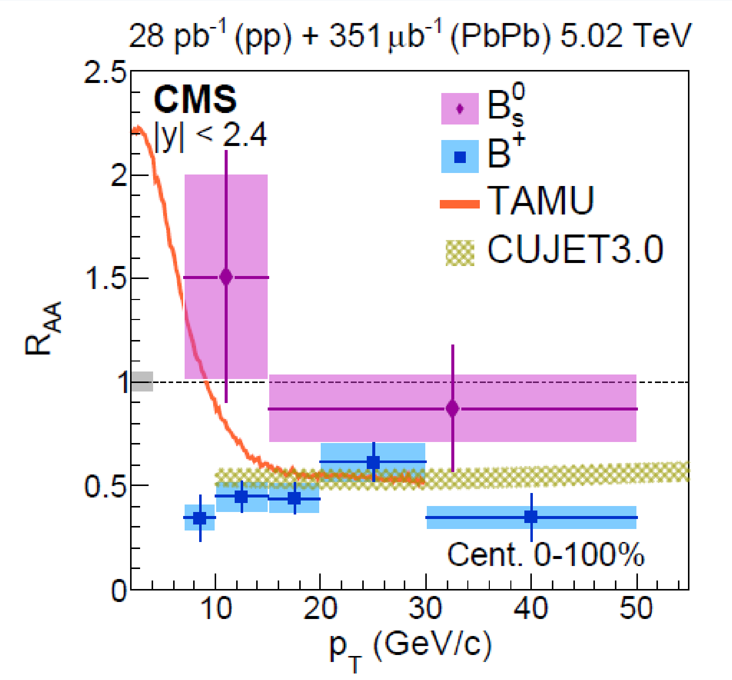
- **Slightly lower v_2 for D wrt charged particles at low p_T**
- Similar v_2 for p_T>4 GeV/c
- **Non-zero v_2 at high p_T related to different pathlength in the medium**

Charm/beauty "chemistry": D_S vs D^0 (B_s vs B^+)

Test of recombination scenario







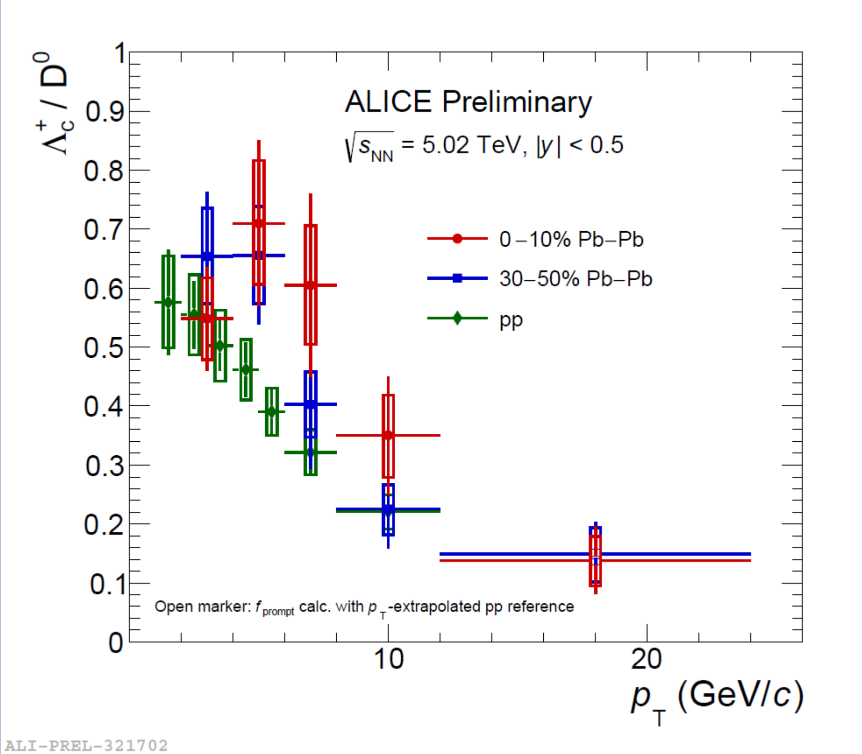
CMS, PLB 796 (2019) 168

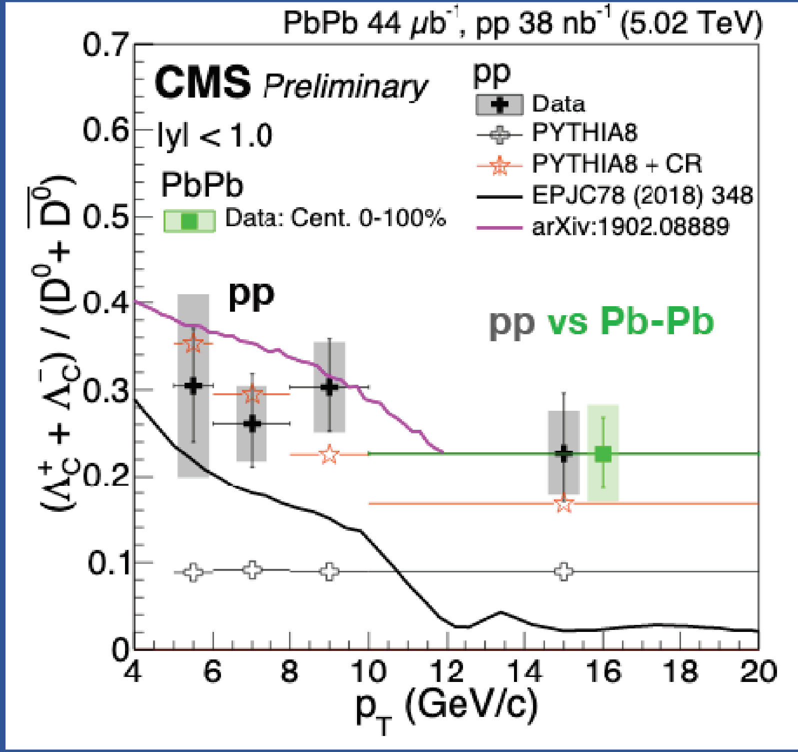
- ❑ **Enhanced D_S/D^0** at low p_T with respect to pp
  → Qualitatively as expected in a scenario with **strangeness enhancement in the QGP and hadronization via recombination**

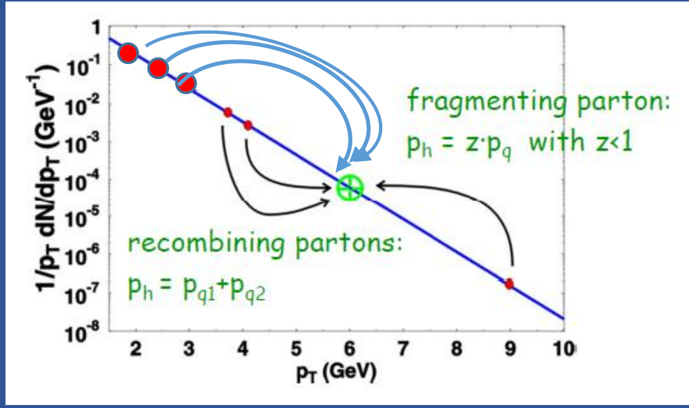
- ❑ Hints **also in the B_s sector**, to be confirmed with larger statistics data

Charmed baryon: Λ_c/D^0

CMS, arXiv:1906.03322







Hint of **larger Λ_c/D^0 in Pb-Pb** wrt pp in **$4<p_T<6$ GeV/c**

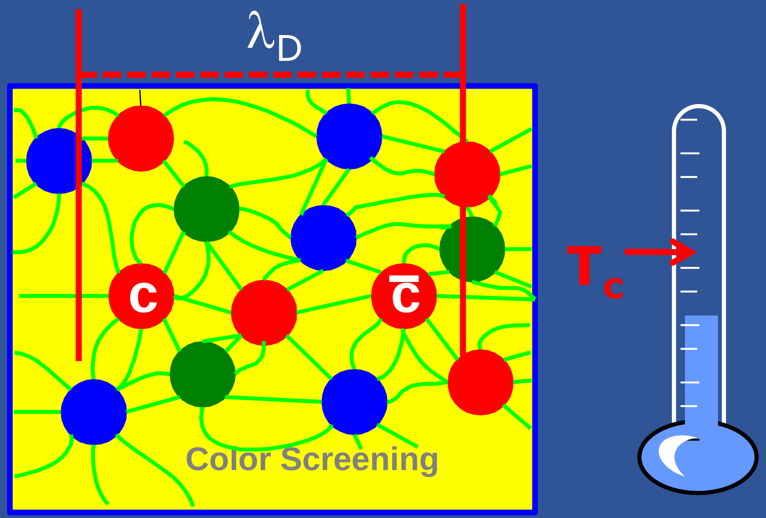
Similar Λ_c/D^0 in pp and Pb-Pb **at high p_T**

In case of recombination a **baryon enhancement is expected** (also in a statistical hadronization scenario)

- Warning: even in pp it is not straightforward to reproduce the data (breaking FF universality ??)
  → PYTHIA8 needs adding a "color reconnection mechanism" (Christiansen and Skands, JHEP08(2015)003),
  FONLL +stat. hadronization with excited charm-baryon states can also describe pp data (Rapp, arXiv:1902.08889)

From open heavy flavor to heavy quarkonium

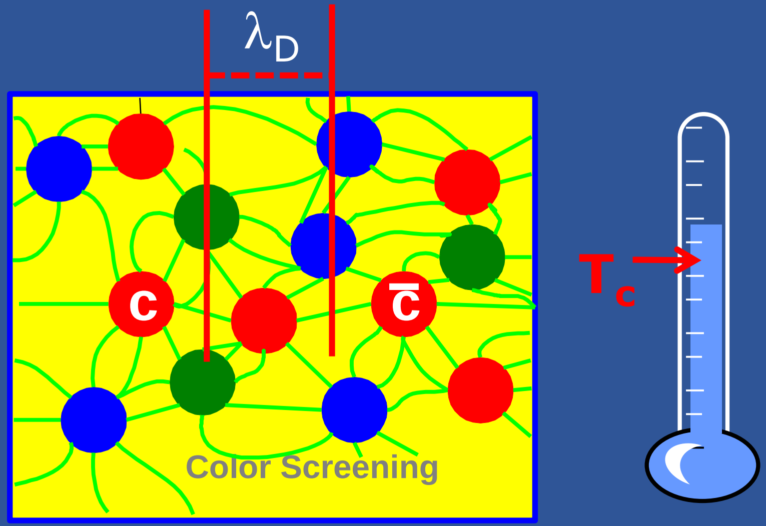
Quarkonia → complementary information wrt open heavy flavours



Quarkonium melting
→ **QGP thermometer**

From open heavy flavor to heavy quarkonium

Quarkonia → complementary information wrt open heavy flavours



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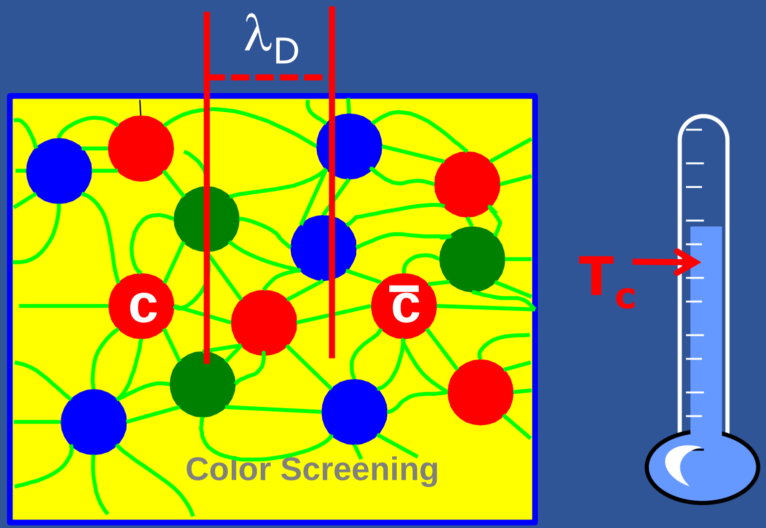
Quarkonia → complementary information wrt open heavy flavours



Quarkonium melting
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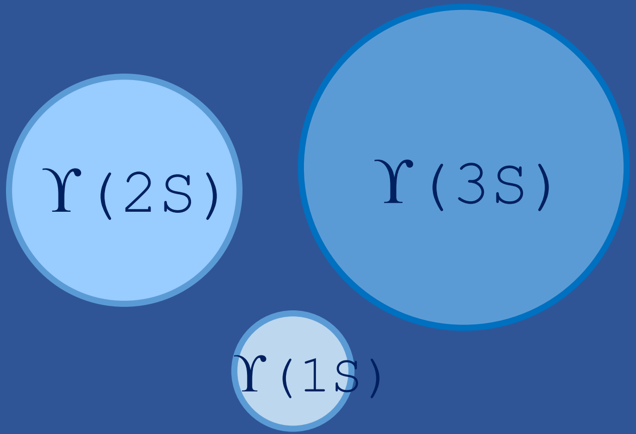
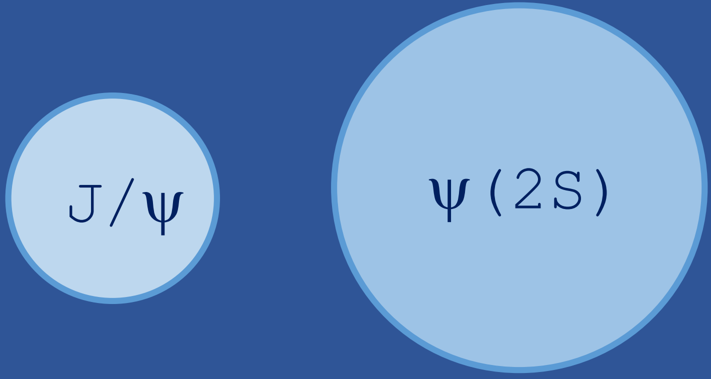
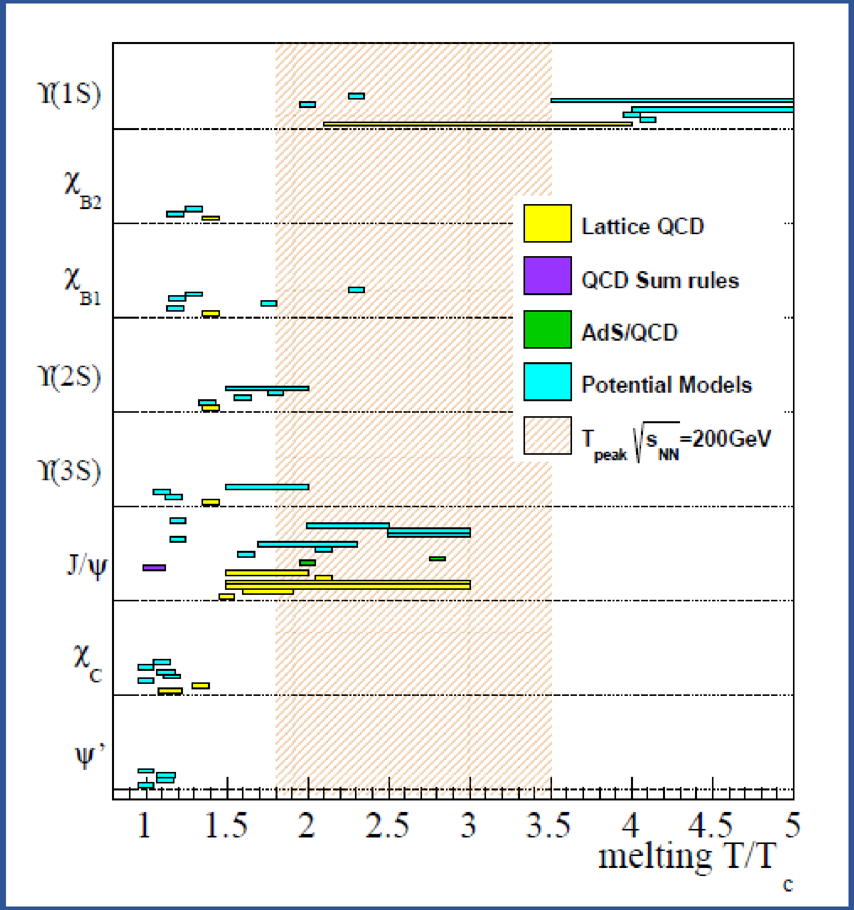


Sequential suppression



(almost to scale)



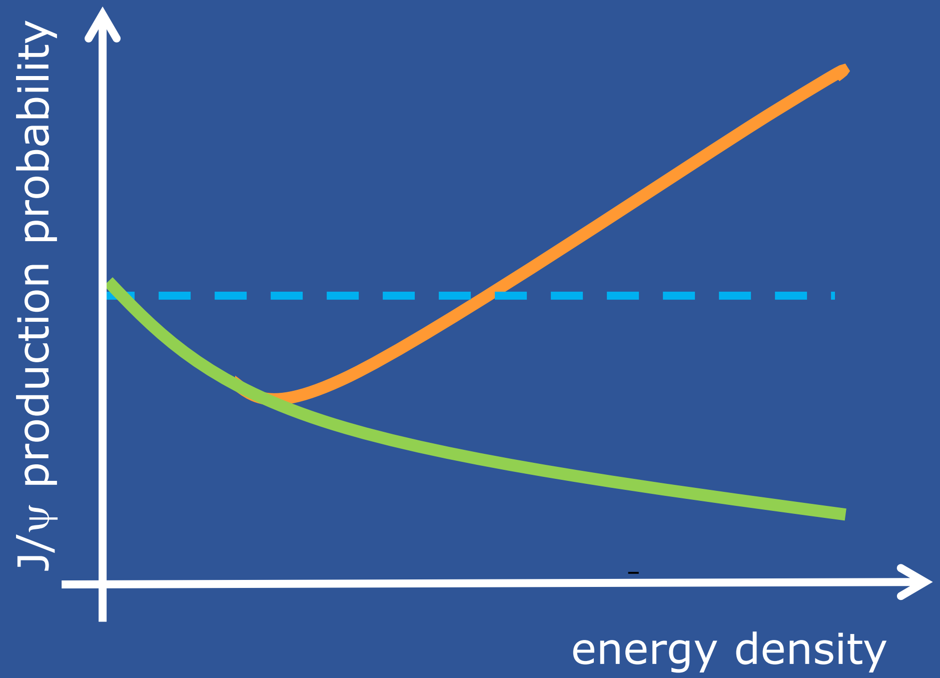
PHENIX, PRC91 (2015)024913

Tightly bound states can survive up to $T>>T_C$

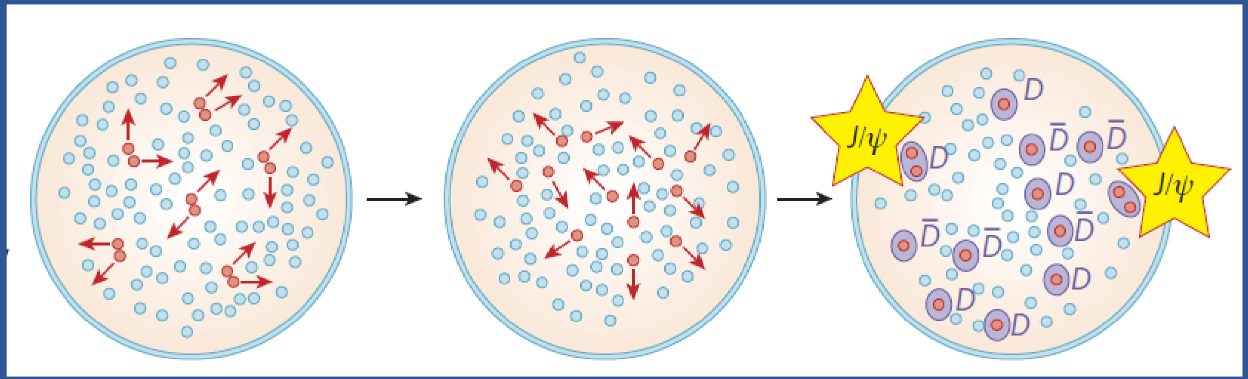
Recombination

P. Braun-Muzinger,J.Stachel, PLB490(2000)196
R.Thews et al,PRC63:054905(2001)

Central AA coll	$N_{c\bar{c}}$ per event	$N_{b\bar{b}}$ per event
RHIC, 200 GeV	~10	-
LHC, 5.02 TeV	~115	~3

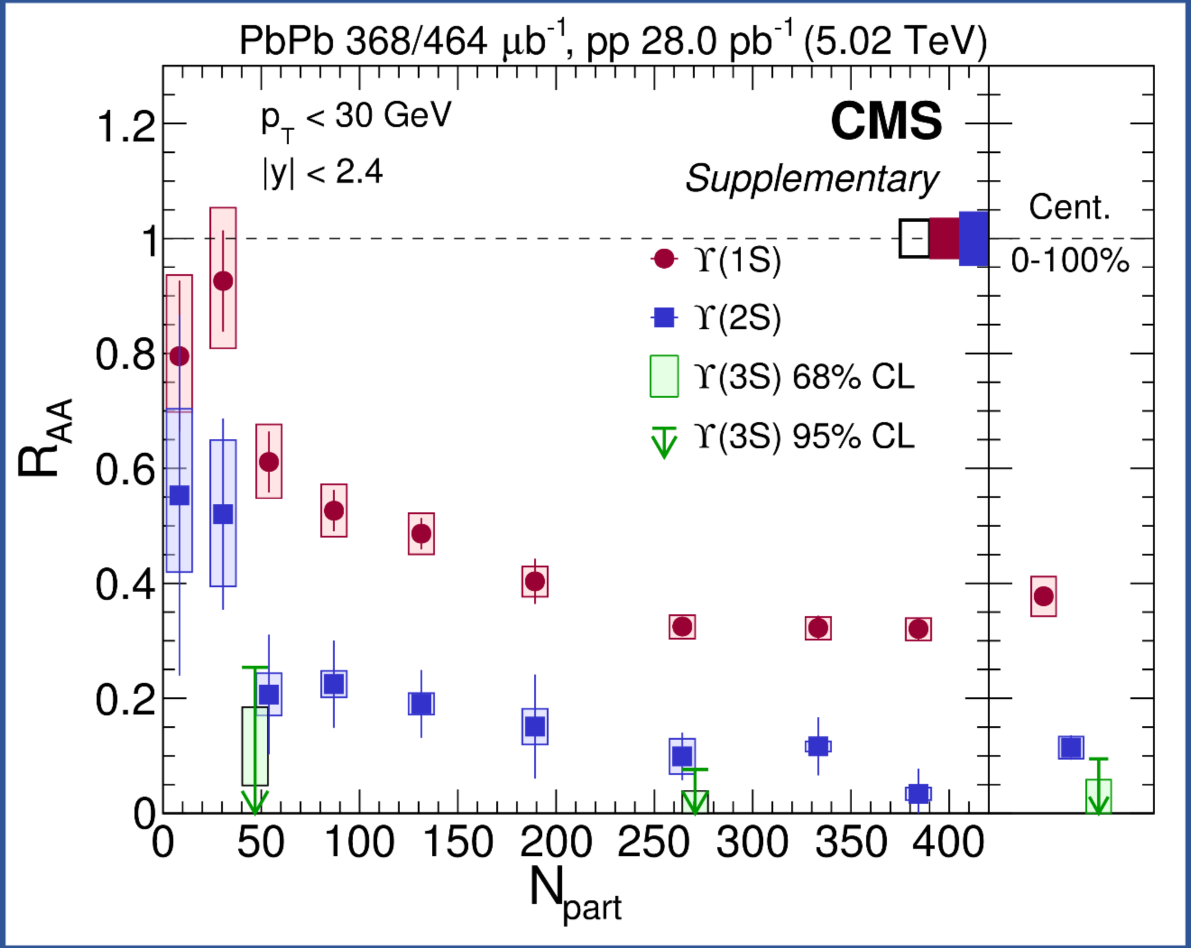


- Collider energy → heavy quark abundance
- **Recombination of heavy quarks** when the system hadronizes (or even during QGP evolution) may enhance quarkonium production



- Potentially **important for charmonium**
- Less relevant for bottomonium

Recent results on ϒ resonances in Pb-Pb



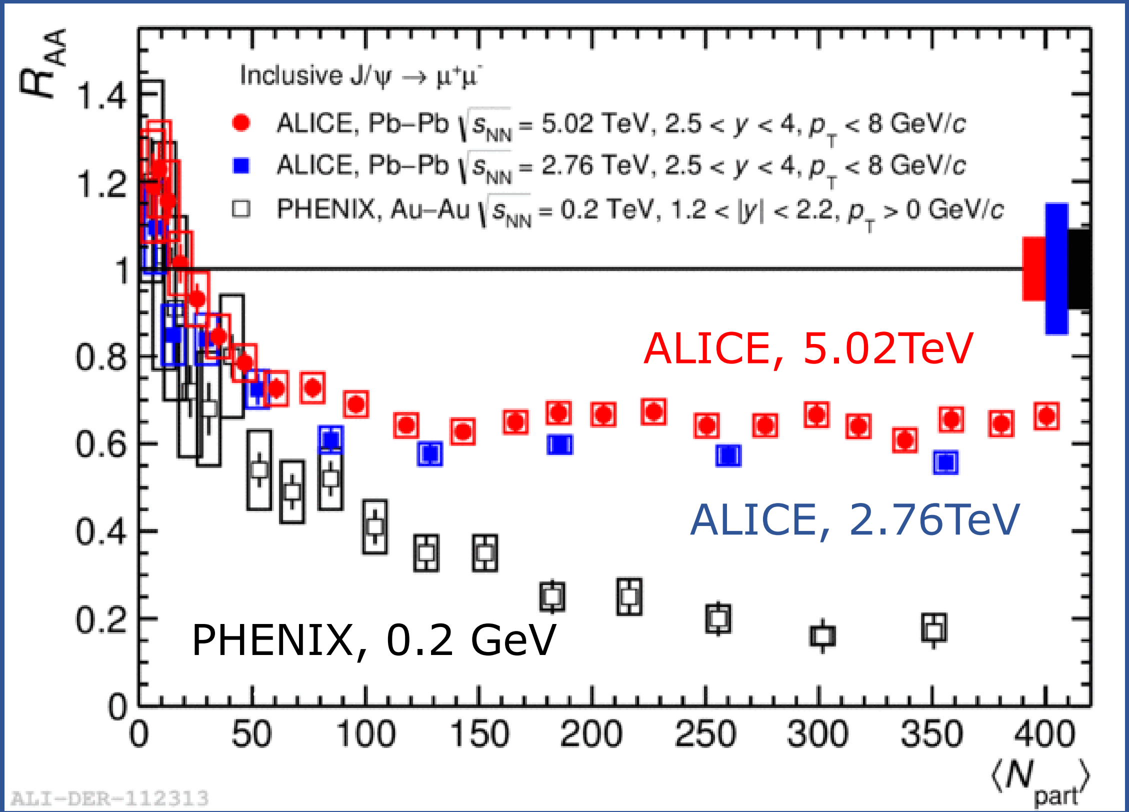
CMS, Phys. Lett. B790 (2019) 270

Strong suppression for all ϒ(nS)
(factor ~2 for ϒ(1S), ~9 for ϒ(2S))

- lower R_{AA} values for excited states **compatible with sequential suppression hypothesis**
- suppression of **directly produced ϒ(1S)?**
  → Feed down contribution ~ 30%
  → CNM
- Only **upper limit** on ϒ(3S)

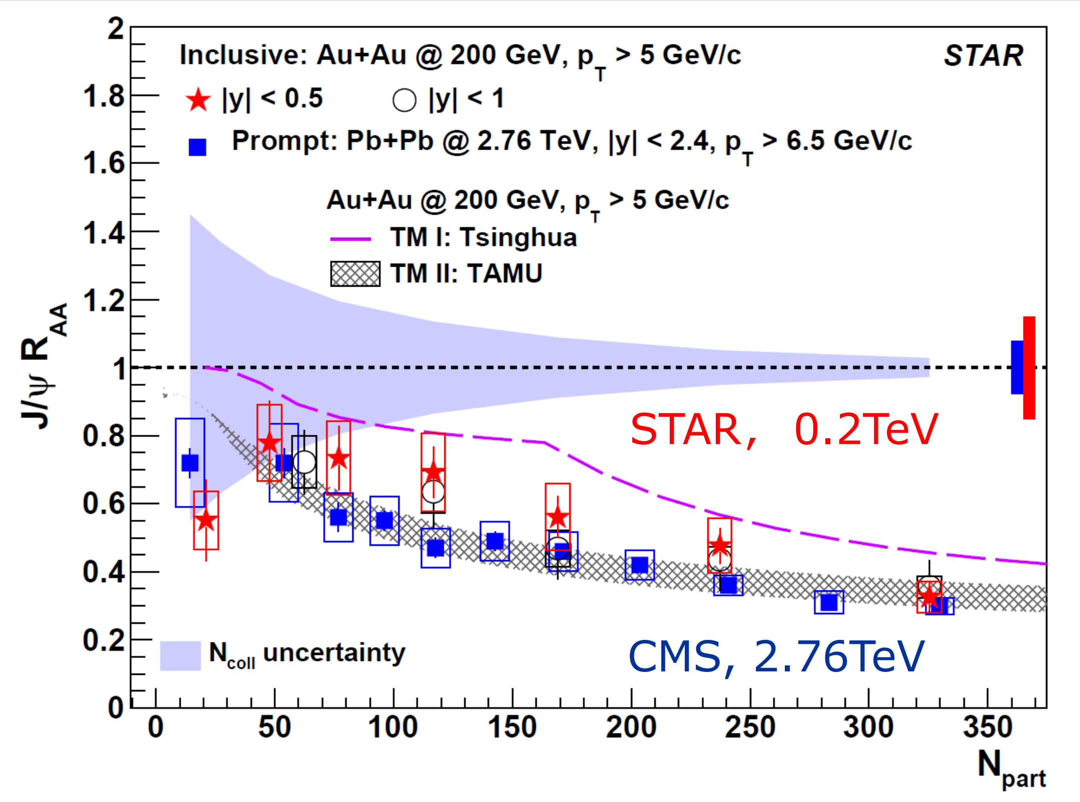
J/ψ "suppression"

Low p_T J/ψ



ALICE, PLB766 (2017) 212

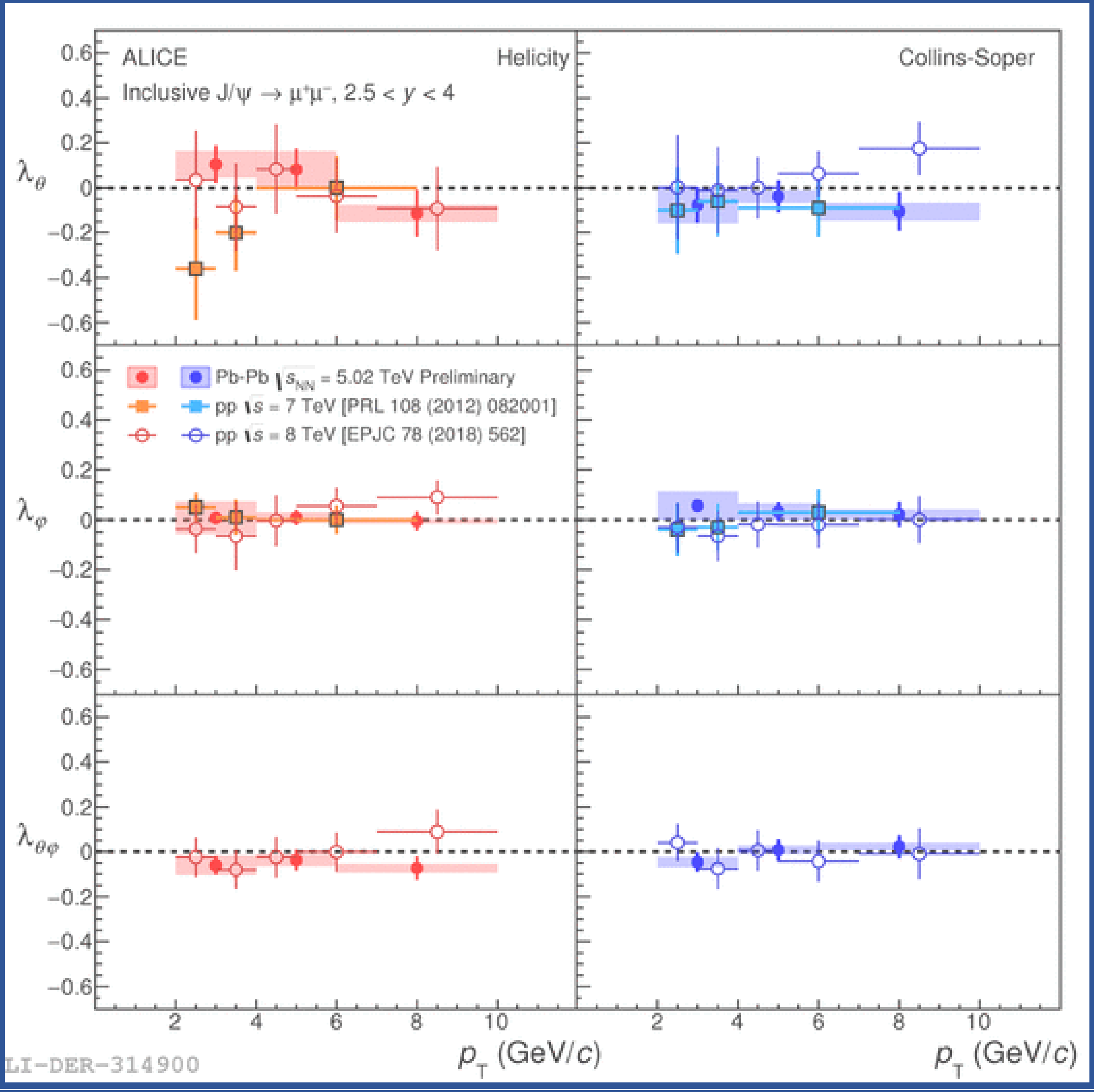
High p_T J/ψ



STAR, arXiv:1905.13669, CMS, EPJC77 (2017) 252

Possible interpretation:
- **RHIC** energy → **suppression** effects dominate
- **LHC** energy → **suppression + regeneration**

J/ψ polarization in Pb-Pb collisions



- **First measurement in nuclear collisions** at LHC energy (only a previous result from NA60 at CERN SPS)
- Study angular distribution of decay muons in the quarkonium rest frame
- Helicity and Collins-Soper ref. frames

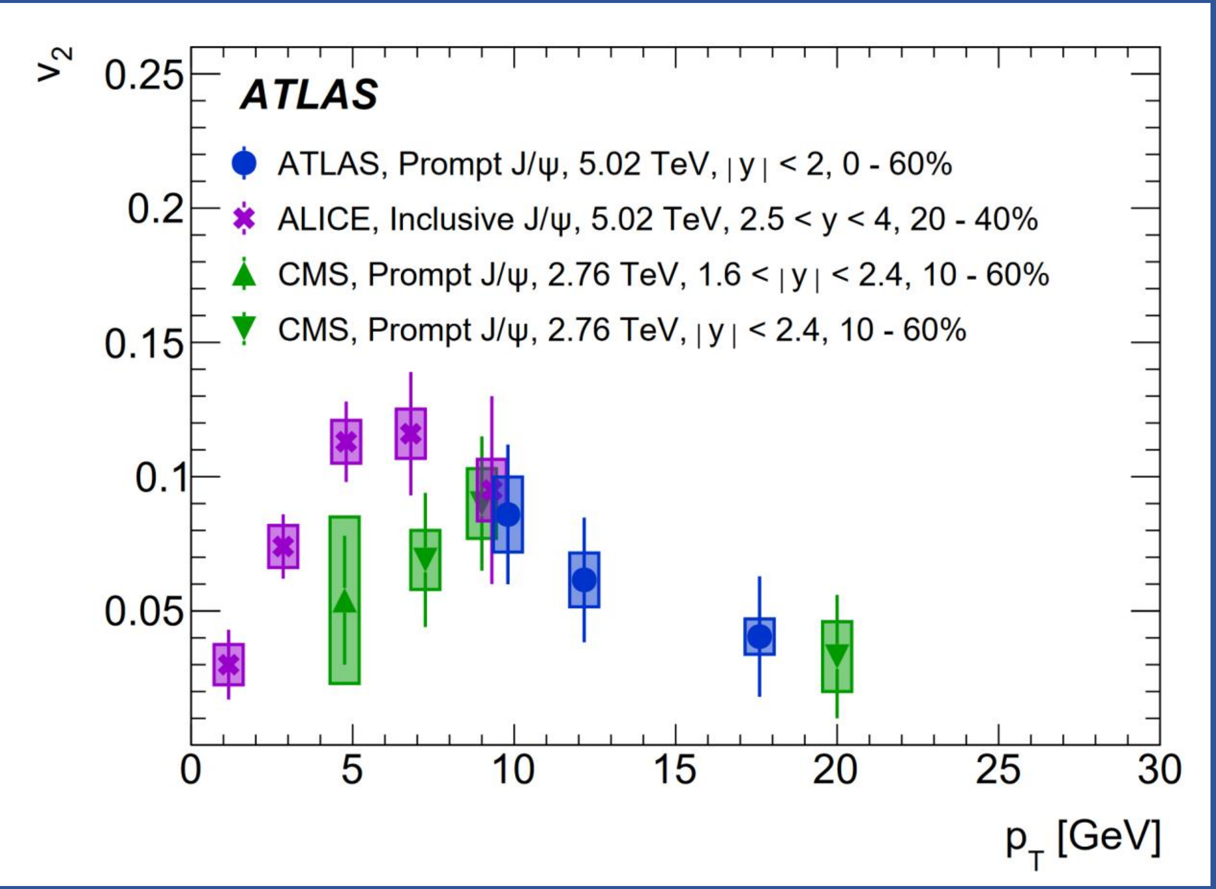
$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos 2\varphi+\lambda_{\theta\varphi}\sin 2\theta\cos\varphi\right)$$

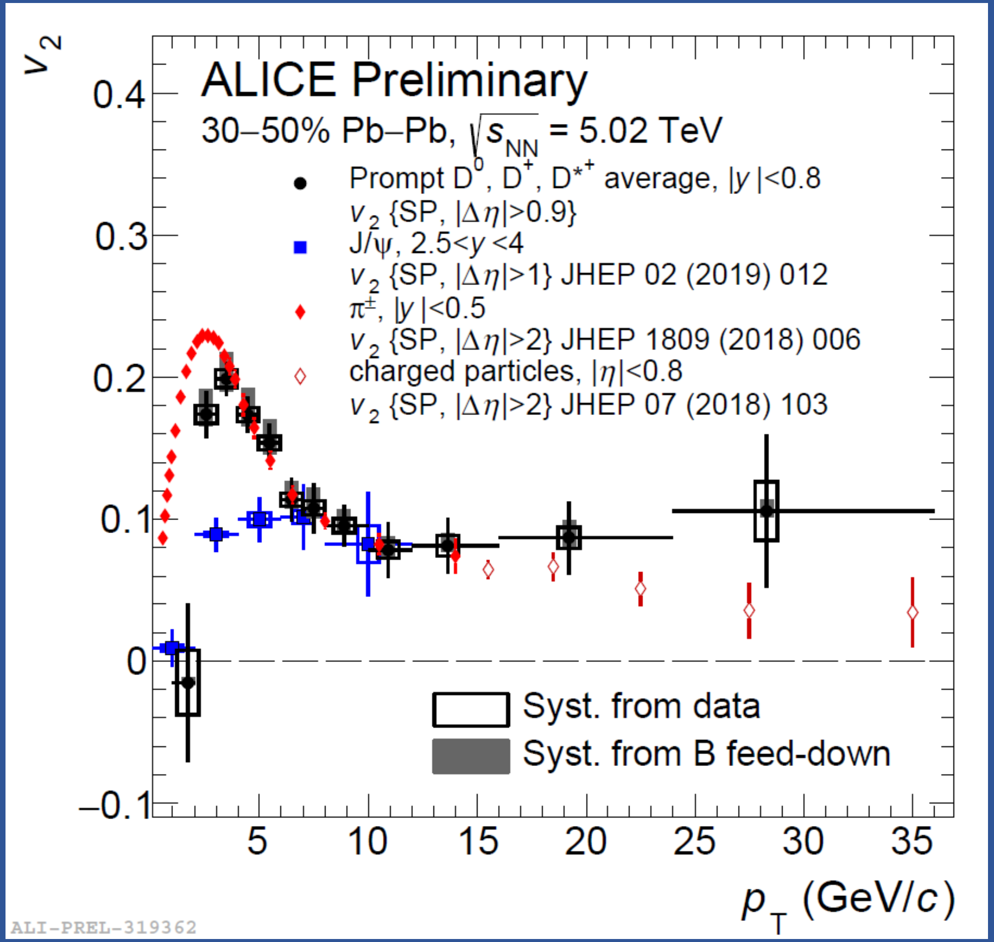
- **No polarization also in pp collisions**

- Next steps: study **polarization** with respect to the **event plane of the collisions**, for semi-peripheral events → influence of **magnetic field and/or fluid with non-zero vorticity**

Elliptic flow of J/ψ

ALICE, PRL 119 (2017) 242301, JHEP 1902 (2019) 012
ATLAS, EPJC 78 (2018) 784
CMS, EPJC 77 (2017) 252

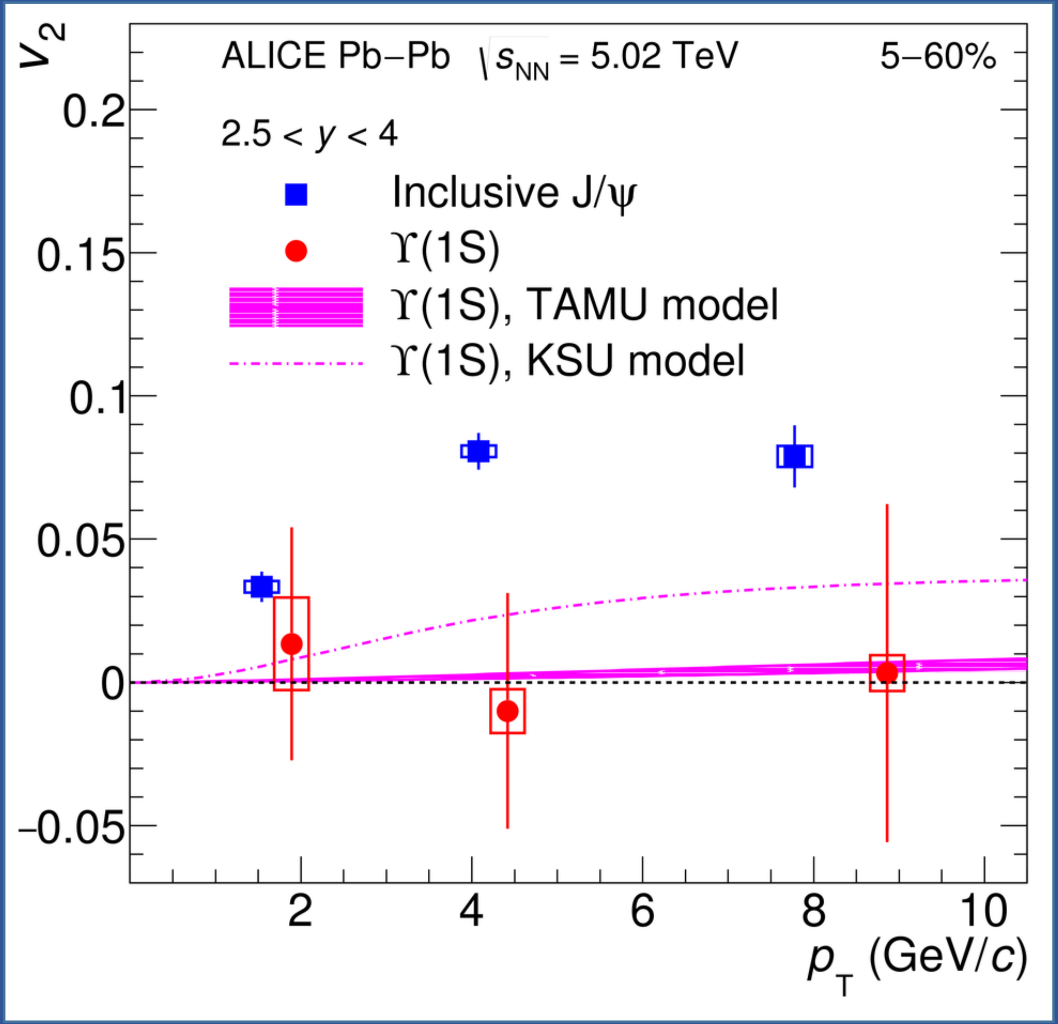




- **J/ψ from recombination** should inherit the thermalized charm flow
- v_2 reaches **~10% for p_T ~ 5-7 GeV/c** and remains **significant up to ~ 20 GeV/c**

- **Low and intermediate p_T** (<6 GeV/c) → clear **ordering**, $v_n(J/\psi)<v_n(D^0)<v_n(h^{\pm})$
- **High p_T,** common value, in-medium path length dependent energy loss effect ?

Is bottomonium flowing ?



ALICE, arXiv:1907.03169

First measurement of ϒ(1S) elliptic flow in AA, based on 2015+2018 samples

- **ϒ(1S) v_2 is consistent with zero** over the full p_T range, in 5-60% centrality
- v_2 compatible with the **small values predicted by theory models**
- Very small v_2 expected from
  - Negligible regeneration component
  - ϒ(1S) suppression occurs early in the fireball evolution (high T) when path length differences in the suppression are small
- **J/ψ v_2 is 2.6σ higher than the ϒ(1S)** one in 2<p_T<5 GeV/c

Conclusions

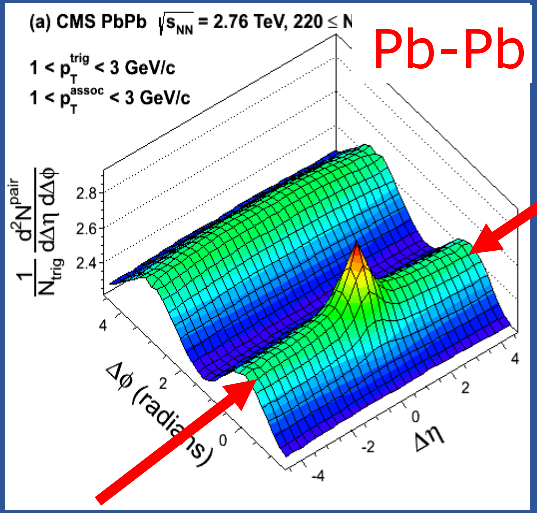
- Heavy quarks → powerful observable for investigating QGP properties
- Lots of results, rich phenomenology, strong theory effort for the interpretation

- Open heavy flavor
  - Strong energy loss in the QGP, hints for quark mass and color charge hierarchy
  - Collective flow, strong indications for thermalization of heavy quarks
  - Significant effects on heavy flavor chemistry (D_S/D^0,B_S/B^+)
  - Possible enhancement of charm baryons in Pb-Pb (hadronization via recombination)

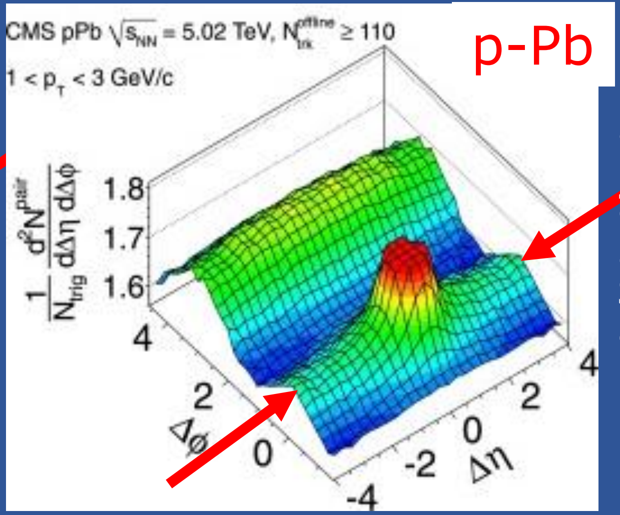
- Quarkonia
  - Evidence for suppression hierarchy, as expected for sequential suppression
  - Strong recombination effects for J/ψ, related to the formation of a thermalized QGP
  - Charm quarks flow with the medium, less flow for bottomonia ($v_2(\Upsilon(1S))\sim0$)
  - No polarization for J/ψ in Pb-Pb collisions

- Expect further improvement in measurement quality in LHC run 3 (see next talk)

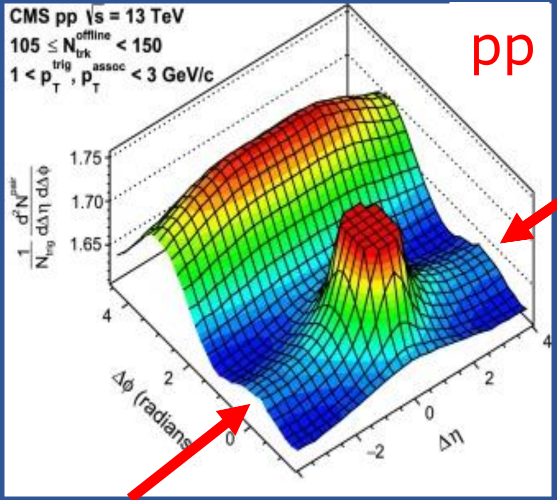
QGP studies – highlights from LHC



JHEP 07 (2011) 076



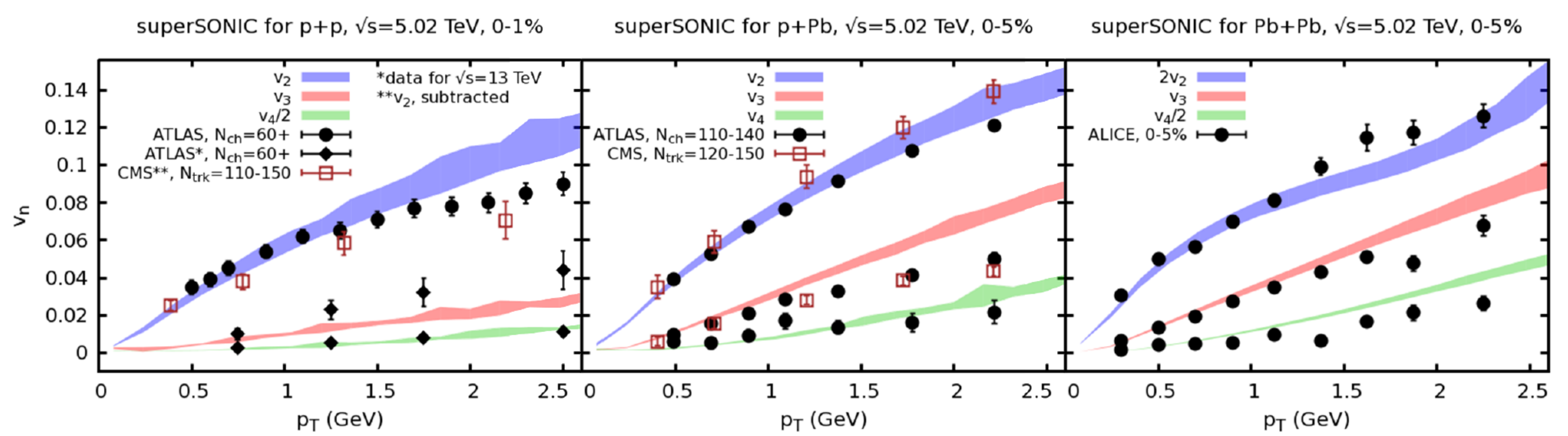
PLB 718 (2013) 795



PLB 765 (2017) 193

Collective (QGP-like) effects visible in high multiplicity pp and p-Pb

- 2-particle correlation → Ridge at $\Delta\phi=0$ (large $\Delta\eta$) in Pb-Pb attributed to **collective flow of an expanding QGP**
- Feature visible **also in p-Pb and pp!** Due to gluon correlations in the initial state? QGP??

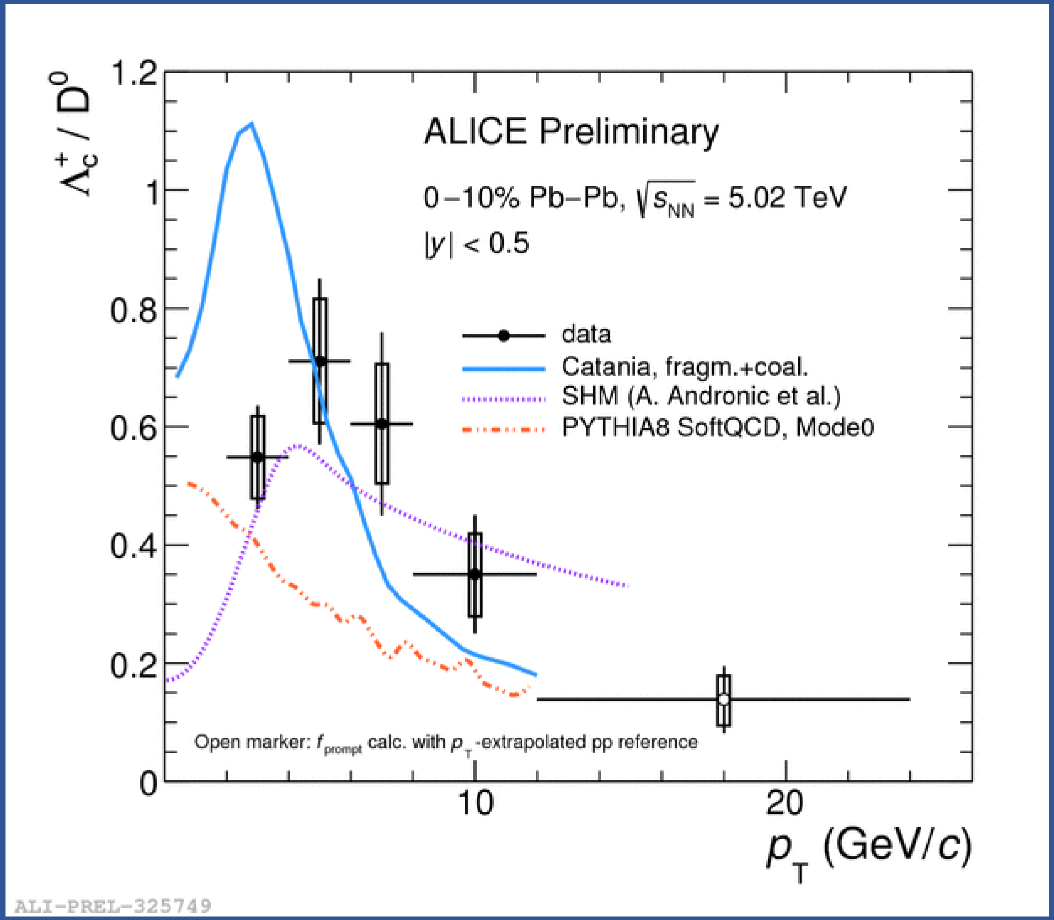


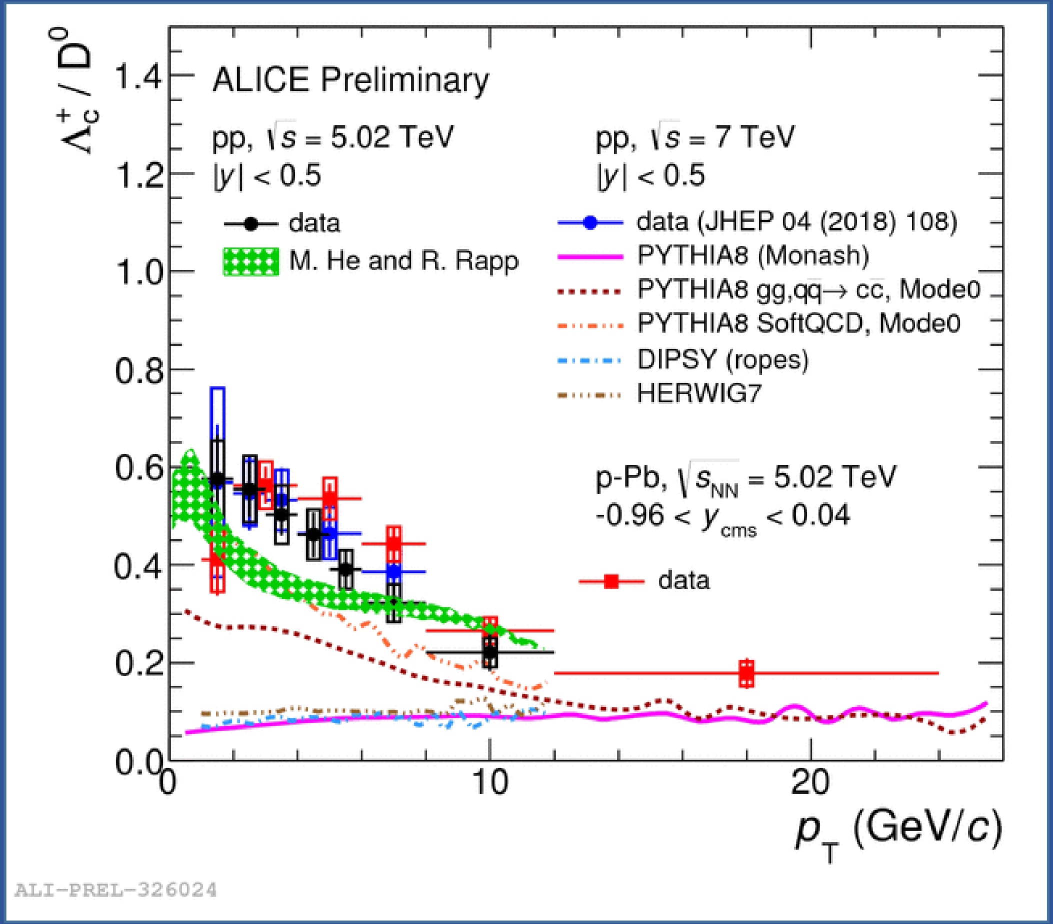
- Describe flow using a **single choice for fluid parameters** (shear and bulk viscosity)

→ "One fluid to rule them all"

Weller and Romatschke, PLB 774(2017) 351

Model comparisons for Λ_c/D^0

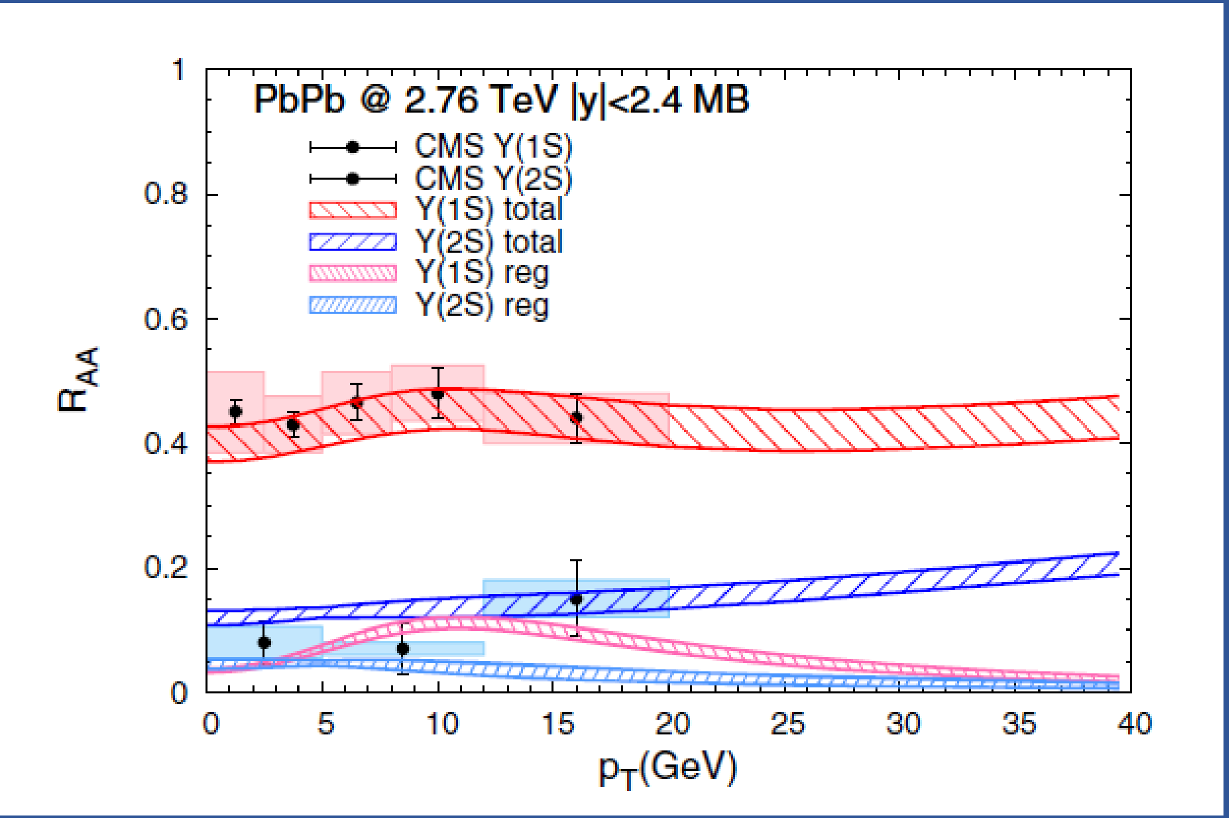




- ❑ Λc/D0 in Pb-Pb consistent with charm quark hadronization via coalescence and with a statistical hadronization model

- ❑ pp data from ALICE difficult to explain even including CR mechanism in PYTHIA8
- ❑ FONLL+stat. hadronization with excited charm-baryon states works better

Recent results on ϒ resonances in Pb-Pb



Rapp, PRC96(2017) 054901

Strong suppression for all ϒ(nS)
(factor ~2 for ϒ(1S), ~9 for ϒ(2S))

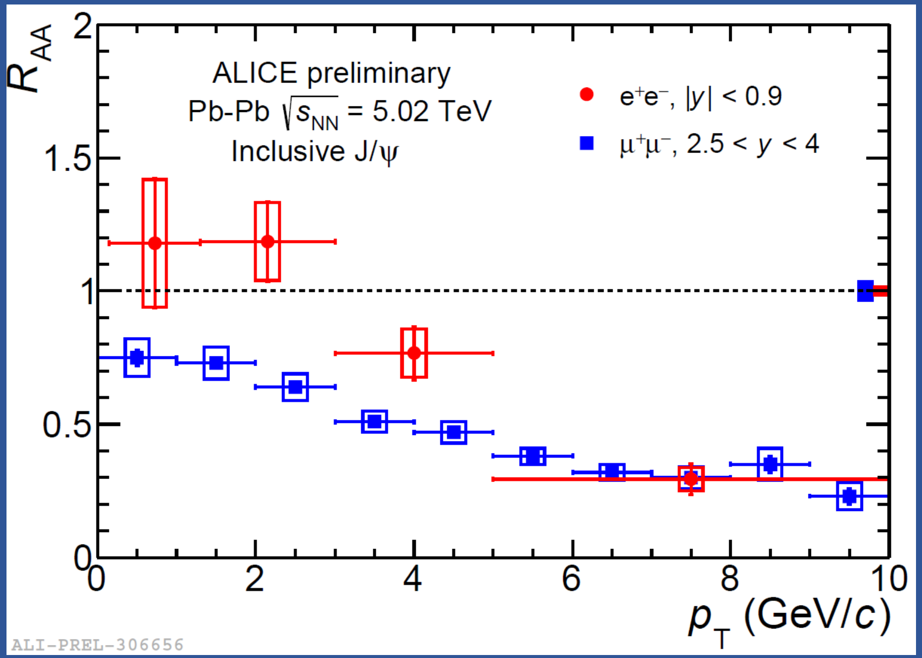
- lower R_{AA} values for excited states **compatible with sequential suppression hypothesis**
- suppression of **directly produced ϒ(1S)?**
  → Feed down contribution ~ 30%
  → CNM
- Only **upper limit** on ϒ(3S)

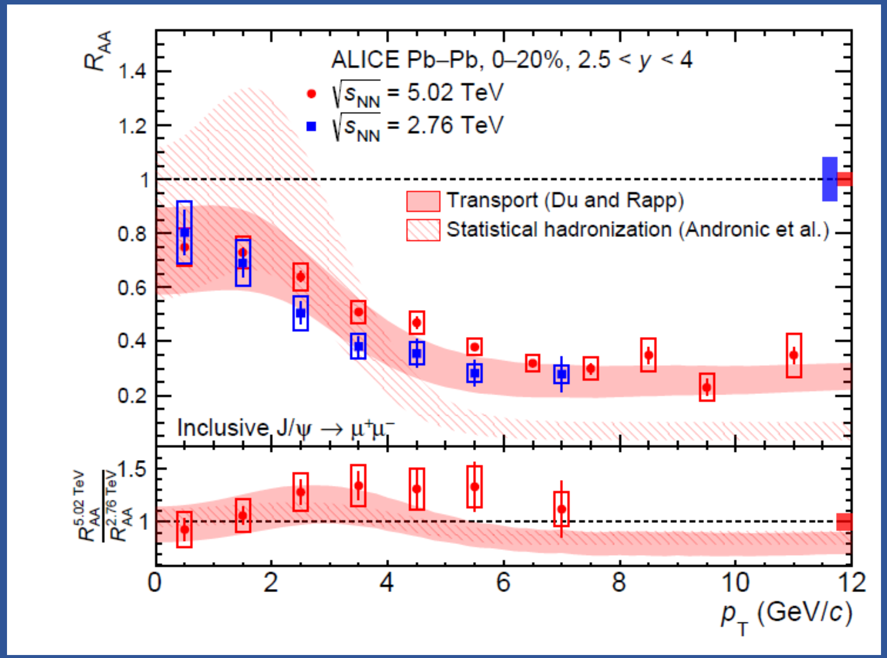
- Good agreement with models, recombination contribution weak but not negligible

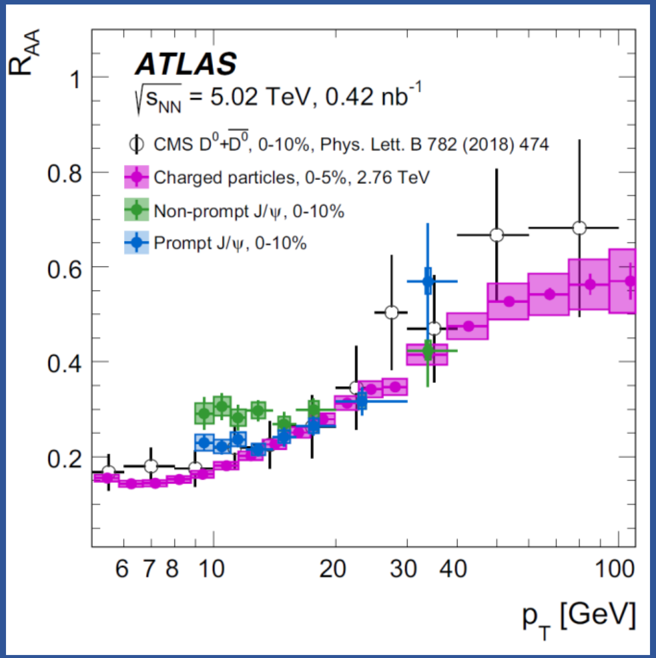
p_T dependence

ALICE, arXiv:1909.03158

ATLAS, EPJ C 78 (2018) 762



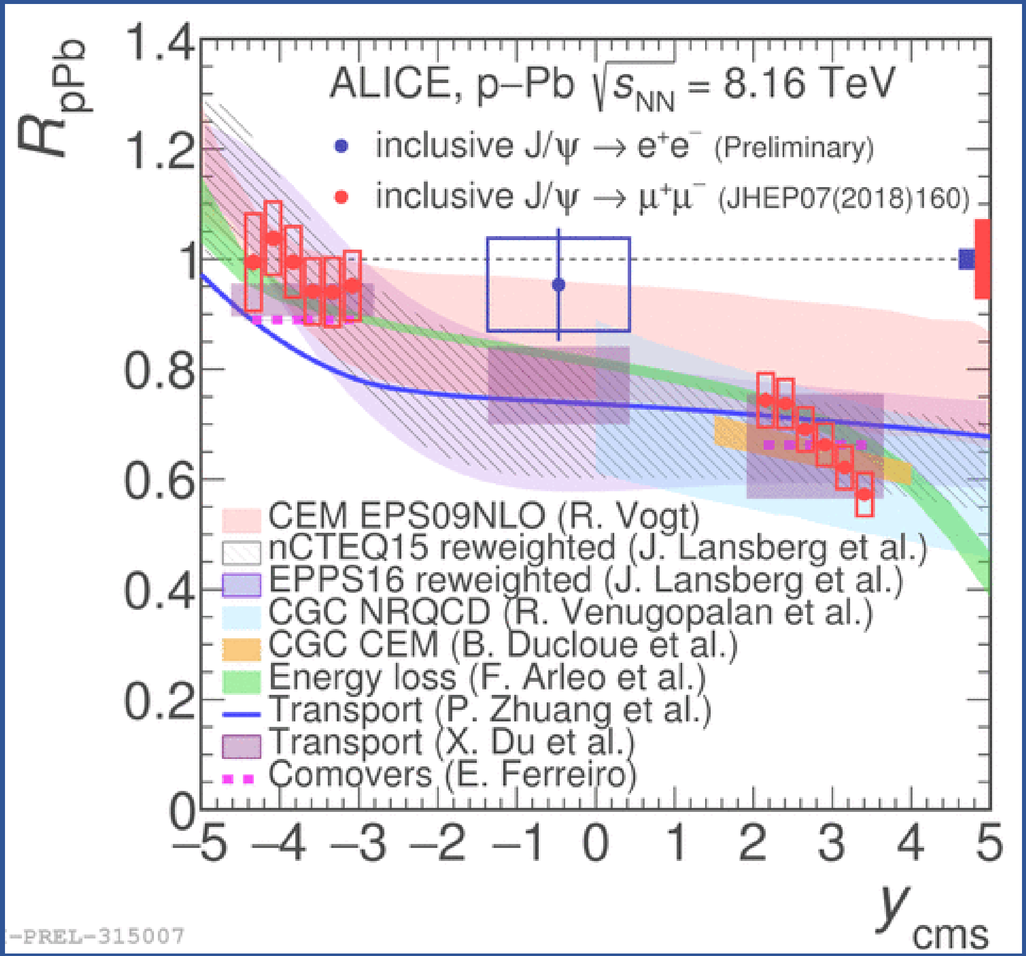




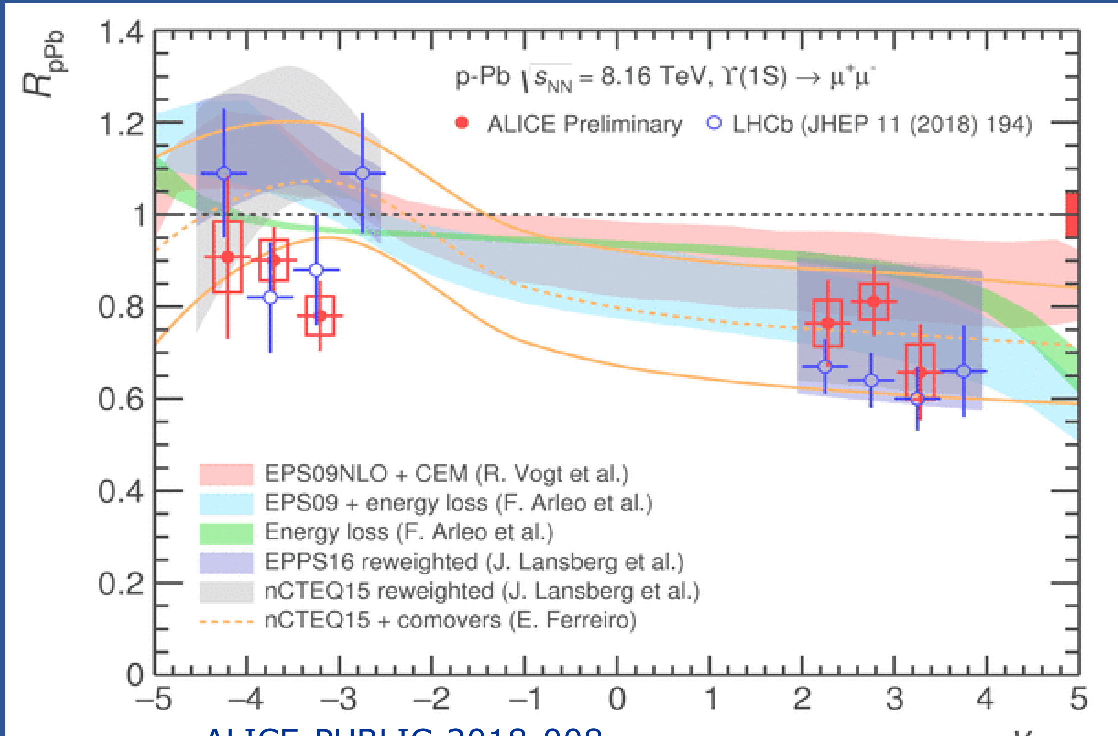
- Central vs forward y: **stronger increase towards low p_T at central y**
- Good agreement with **theory models (SHM, transport)** except at high p_T for SHM, where only corona production contributes
- Compatible with **regeneration dominance at low p_T**
- Very high p_T: remarkable **similarity between R_{AA}** for
  - Charged particles
  - D-mesons
  - Prompt J/ψ
  - Non-prompt J/ψ

Common mechanism related to energy loss ?

CNM effects on quarkonium



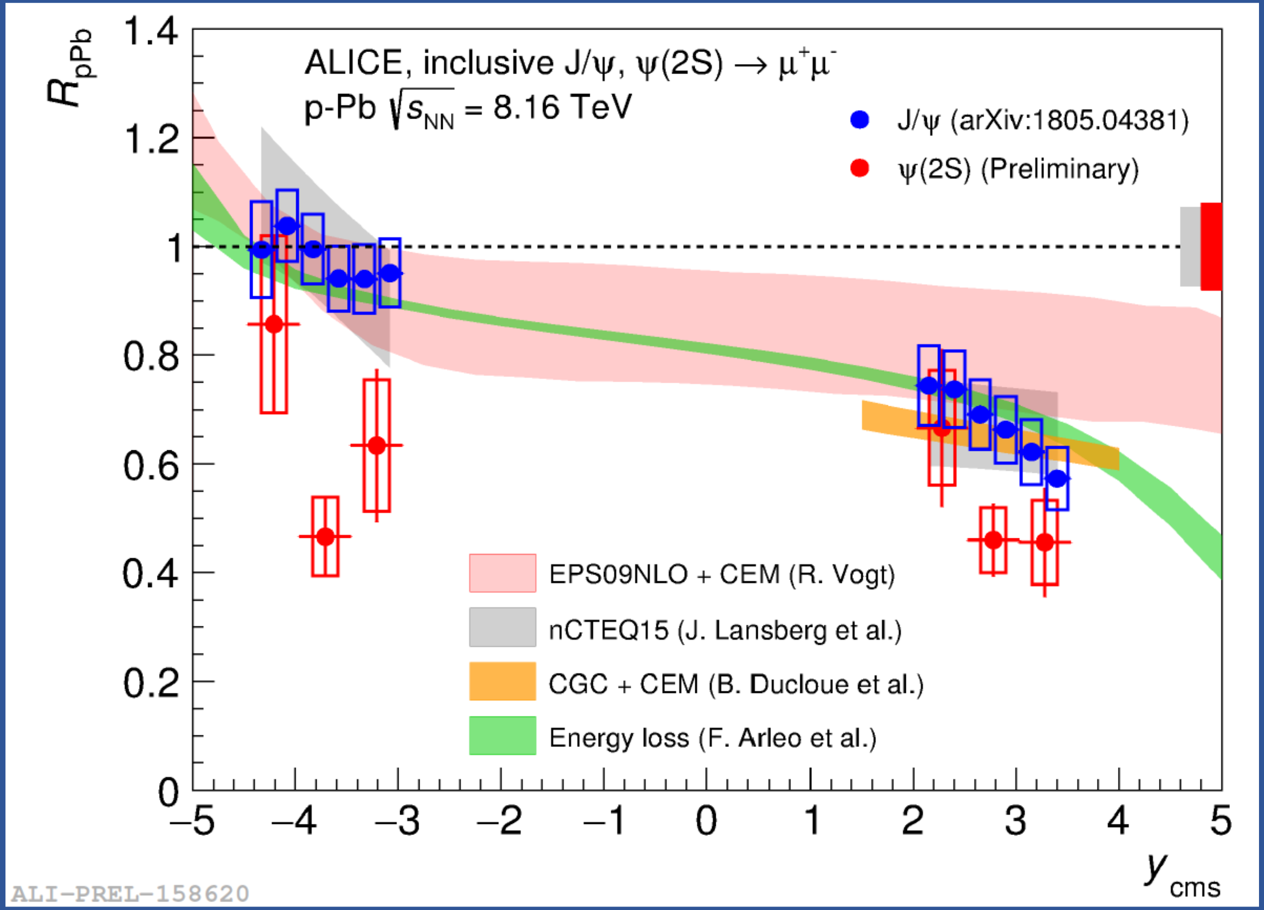
- **Suppression** stronger at **forward-y (p-going)**
- **Suppression** stronger at **low p_T** (not shown)
- Shadowing and energy loss models fairly describe data

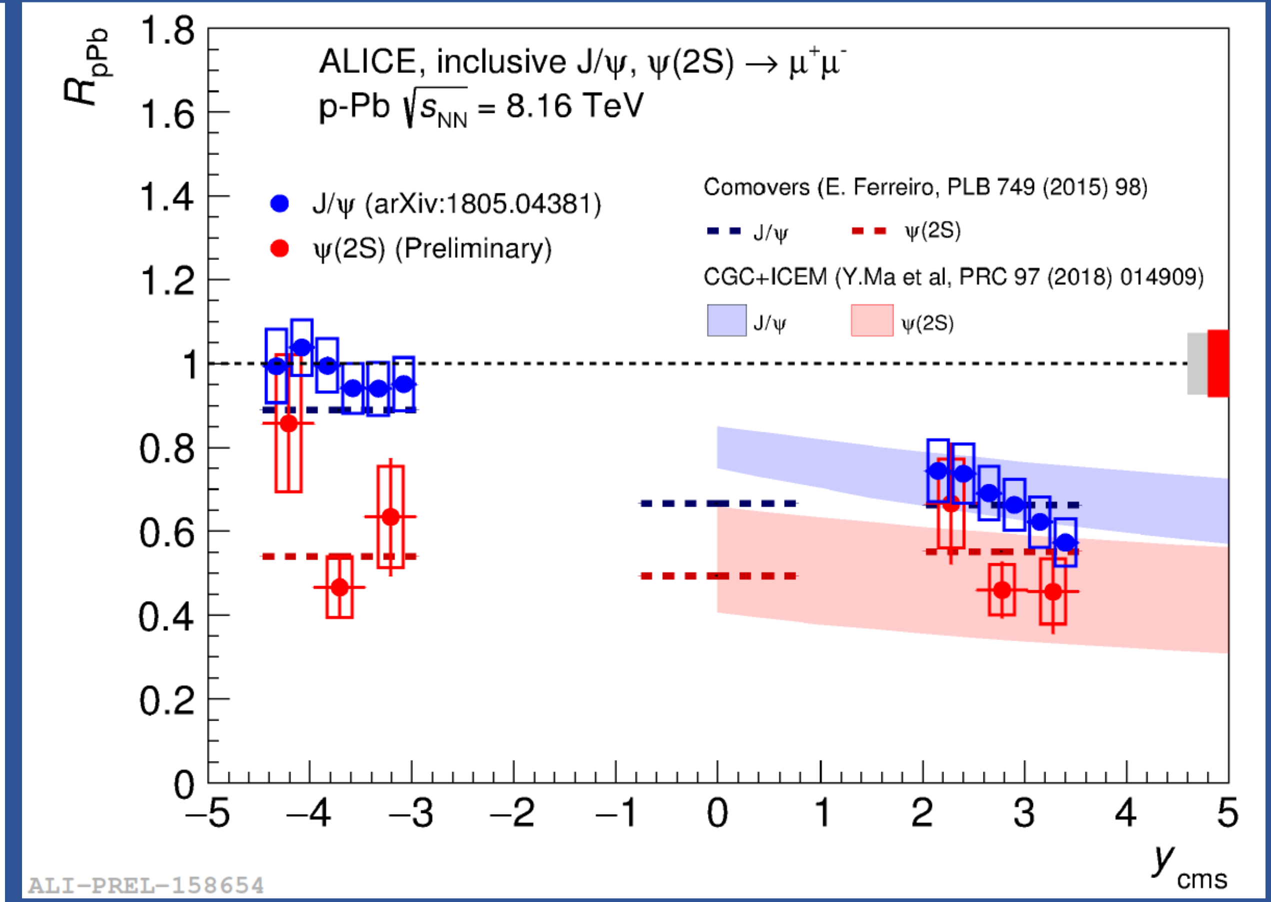


ALICE-PUBLIC-2018-008

- Tool for **constraining nPDF** and important ingredient for the **interpretation of Pb-Pb results**

ψ(2S) vs J/ψ in p-Pb





- **Stronger ψ(2S) suppression with respect to J/ψ** at backward-y (Pb-going)
- Not compatible with shadowing only

- Including **final state interactions** a fair agreement with data is reached