Quarkonia in small systems

Jana Crkovská[1,2,3]

[1] on leave from the Institut de Physique Nucléaire d'Orsay, CNRS-IN2P3, Université Paris-Sud, Université Paris-Saclay
[2] Pôle Emploi
[3] about to start at the Los Alamos National Laboratory NM

Quarkonia as Tools
13-19 January 2019, Aussois

Outline

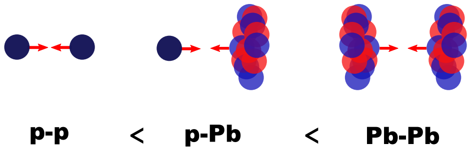
1. Small systems in the Heavy Ion world
2. Remider: quarkonia as probes of QGP
3. Nuclear matter effects in p-Pb
4. Collectivity in p-Pb
5. Quarkonia vs multiplicity in pp and p-Pb

What are small systems?

Traditional HI POV

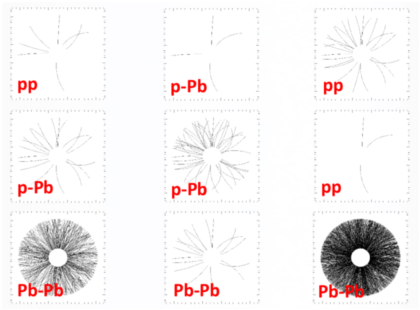
pp and **p-Pb** where we do not expect QGP to form.

- "Small" qualifies the **size of the colliding system**.
- In other words "system *a priori* too small to show characteristics of heavy ion physics" but which show them nevertheless.



Alternative POV

- "Small" qualifies the **size of the created medium**.
- On average corresponds to size of the coliding system.
- But individual events may show a different story - charged particle multiplicity N_{ch}.



Reminder: quarkonia as probes of the QGP I

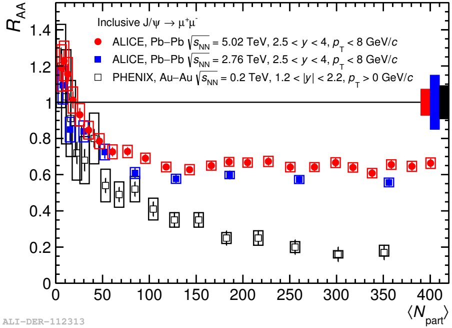
Original idea from Matsui & Satz: J/ψ (quarkonia) Debye screened by the free colour charges in QGP.

Higher $\sqrt{s_{NN}} \Rightarrow$ warmer plasma $\Rightarrow$ more suppression.

Nuclear modification factor quantifies the nuclear effects on quarkonium production.

$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \cdot \sigma_{pp}}$$

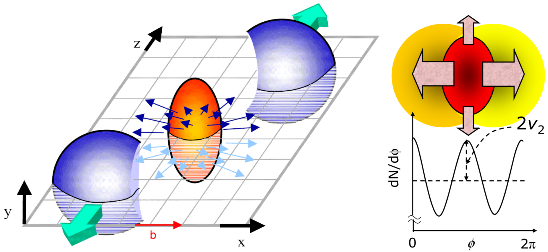
Yield in AA scaled by yield in pp multiplied by the nuclear overlap.



Increase in HF production at LHC compared to RHIC

$\Rightarrow$ possible regeneration of quarkonia form thermalised heavy quarks in the plasma.
Less relevant for bottomonium (b still way less abundant than c).

Reminder: quarkonia as probes of the QGP II

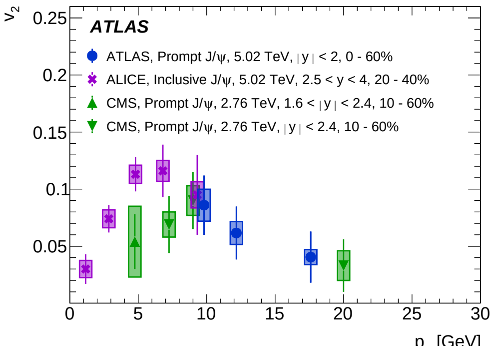


azimuthal distribution of charged particles

$$f(p_{\mathrm{T}}, \varphi, \eta) \sim 1 + \sum 2v_n \cos[n(\varphi - \Psi_{\mathrm{n}})]$$

flow coefficients $v_n = \langle \cos[n(\varphi - \Psi_{\mathrm{n}})] \rangle$

- Non-zero elliptic flow v_2 measured for prompt (inclusive) J/ψ at the LHC whilst $v_2 \approx 0$ at RHIC.
- **Low-p_{T}**: consistent with the regeneration scenario.
- **High-p_{T}**: models underestimate the data. Additionnal component from initial magnetic field?



Flow of charm quarks ⇒ creation of thermalised medium.
Does beauty thermalise too?

Cold nuclear matter effects

To study the **cold nuclear matter effects**, we measure J/ψ production in nuclear systems in absence of the QGP - such conditions met in **proton-nucleus collisions**.

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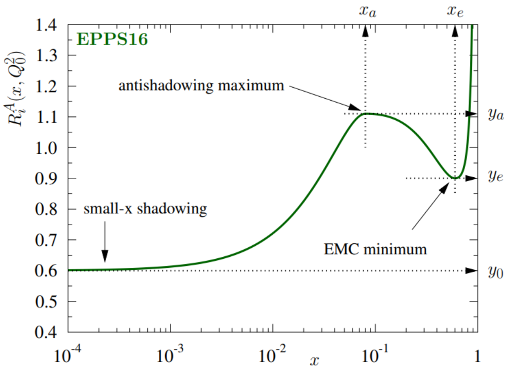
Nuclear modification of PDFs

- *Gluon shadowing/antishadowing*: Parton distribution functions are modified by the nuclear environment $\Rightarrow \mathrm{J}/\psi$ **suppression** or **enhancement** as a function of the parton momentum fraction x in the nucleon.

In $2 \to 1$ approximation

$$x = \frac{M_{\mathrm{J}/\psi}}{\sqrt{s}} e^{\pm y}.$$



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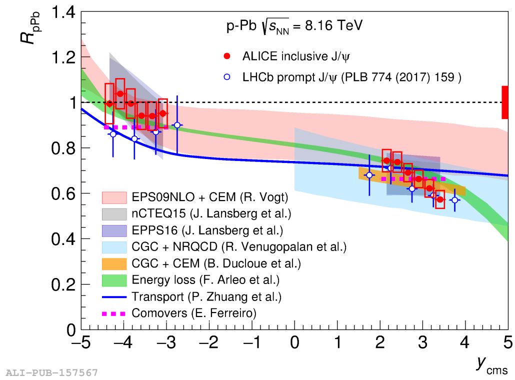
Dissociation with comovers

- Interaction of J/ψ with the comoving matter breaks the bound state $\Rightarrow J/\psi$ **suppression**.

Nuclear modification of quarkonia in pA

ALICE: JHEP 1807 (2018) 160
LHCb: JHEP 11 (2018) 194



J/ψ show stronger suppression at forward rapidity while ~ 1 at backward rapidity.

- The pattern is consistent with initial- and final-state effect models.

$$R_{\text{p-Pb}} = \frac{\sigma^{pPb}}{A \cdot \sigma^{pp}}$$

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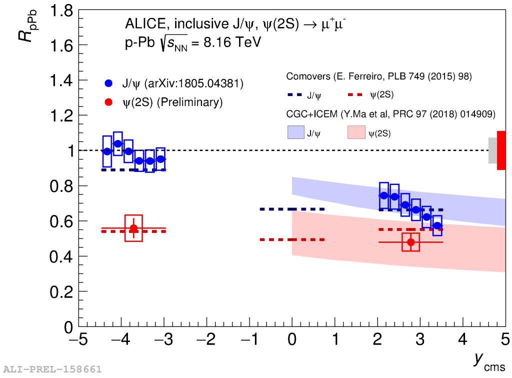

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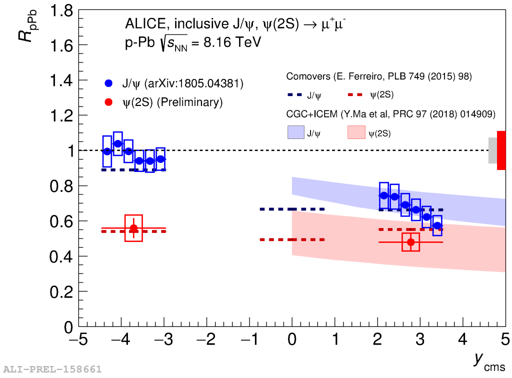

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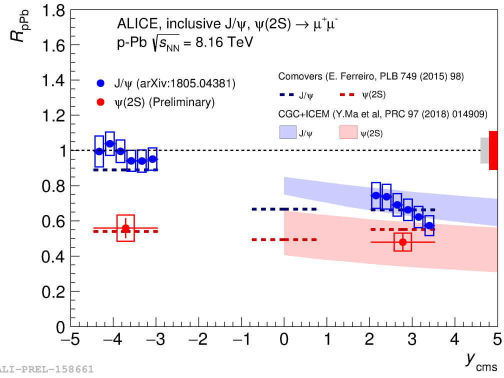

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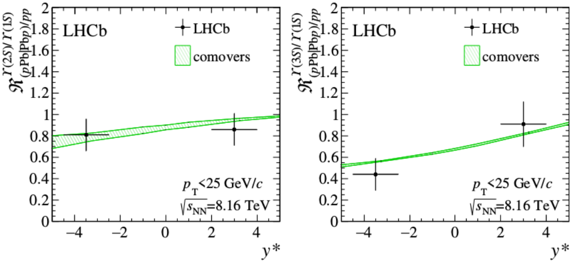
Higher Υ states also show hints of stronger suppression than $\Upsilon(1S)$ which can be explained by higher break-up rate with comovers.



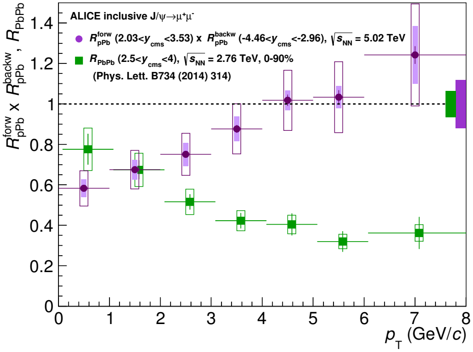
CNM effects in AA?

With certain assumptions*, one can estimate the CNM effects in AA as

$$R_{\mathrm{pPb}} \times R_{\mathrm{Pbp}}$$

At low-p_{T}, $R_{\mathrm{pPb}} \times R_{\mathrm{Pbp}} < R_{\mathrm{PbPb}}$ which could be in hand with the expected contribution from recombination in Pb-Pb.

At higher-p_{T}, $R_{\mathrm{pPb}} \times R_{\mathrm{Pbp}} > R_{\mathrm{PbPb}}$ favours the scenario when the quarkonia are suppressed due to hot nuclear matter effects.



* the assumptions are:

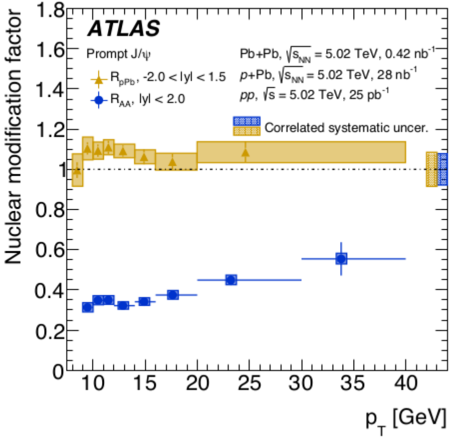
- shadowing is the dominant CNM effect
- the effect can be factorised on the 2 nuclei
- one neglects the $x_{Bjorken}$ shift between p-Pb and Pb-Pb

CNM effects in AA?

J/ψ: ATLAS, EPJC 78 (2018) 762
Υ: ATLAS, EPJC 78 (2018) 171

High-p_T prompt and non-prompt quarkonia give $R_{pA} \sim 1$.

- Similar rapidity coverage as for R_{AA}, there is only weak rapidity dependence at midrapidity



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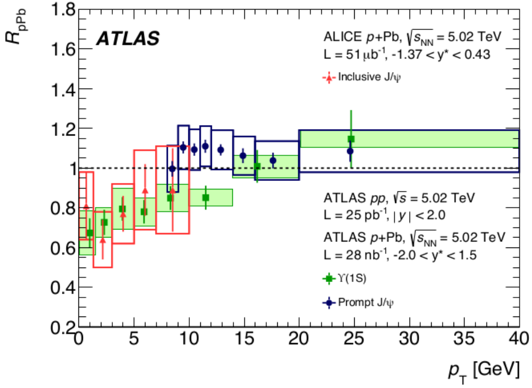

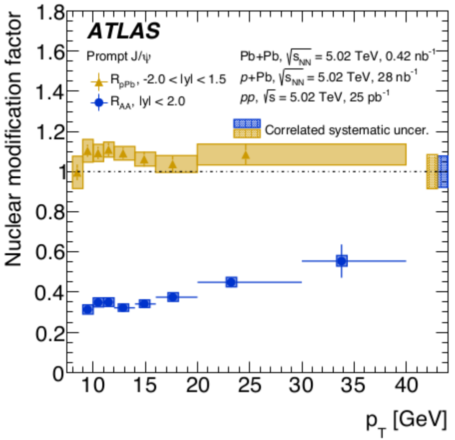

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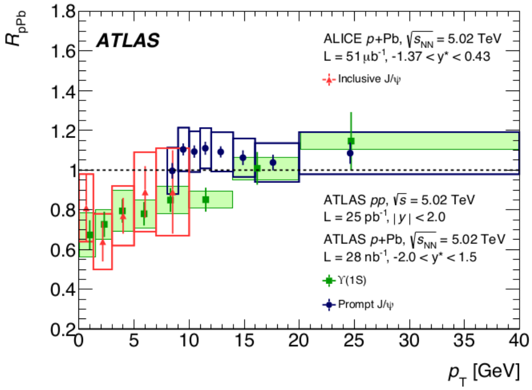
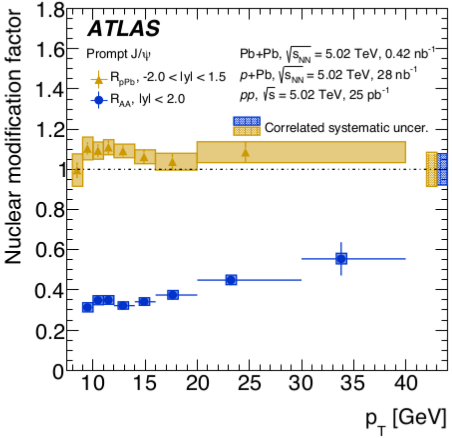




At high-p_{T} suppression in AA mainly from QGP.

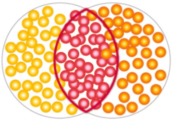
Correlations in big and small systems

ALICE, PRL 107 (2011) 032301

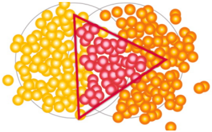
azimuthal distribution of charged particles

$$f(p_{\mathrm{T}},\varphi,\eta) \sim 1+\sum 2v_n \cos\left[n(\varphi-\Psi_{\mathrm{n}})\right]$$

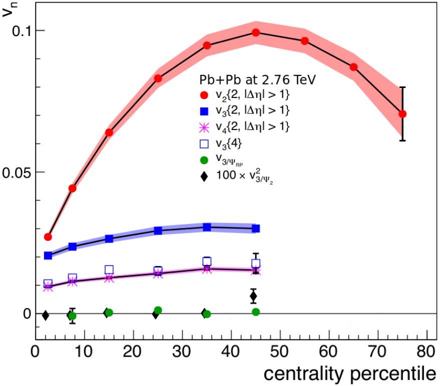
Space anisotropy ⇒ momentum anisotropy.



geometry ⇒ elliptic flow
$v_2 = \langle \cos\left[2(\varphi-\Psi_2)\right]\rangle$



fluctuations ⇒ triangular flow
$v_3 = \langle \cos\left[3(\varphi-\Psi_3)\right]\rangle$



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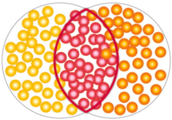

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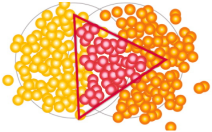

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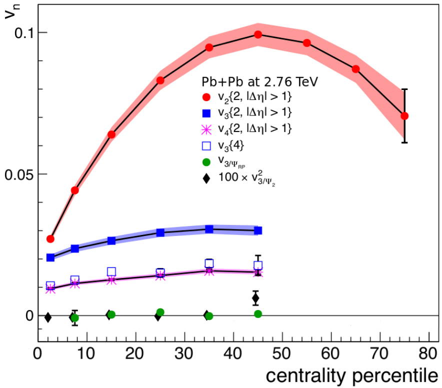


Experiment: Difficult to determine symmetry plane

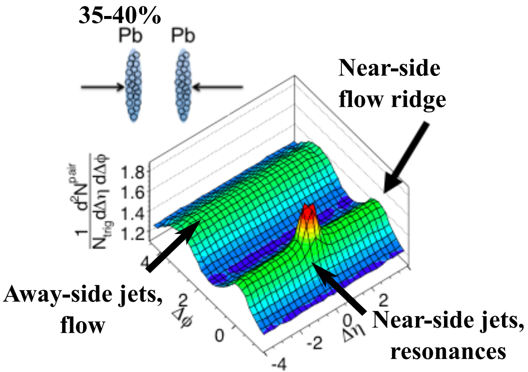
⇒

use multi-particle correlations.

Correlations in big and small systems (cont.)

PbPb: CMS, JHEP 7 (2011) 76
pPb: CMS, PLBB 718 (2013) 795
pp: CMS, JHEP 09 (2010) 091

Pb-Pb show typical double ridge structure:



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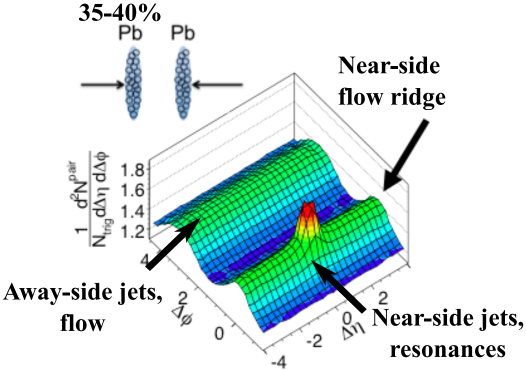

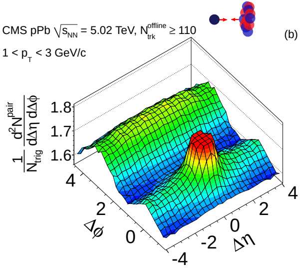

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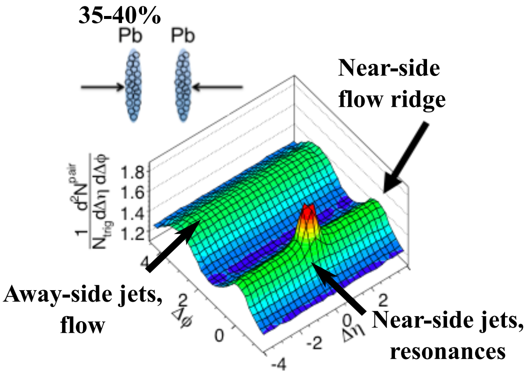

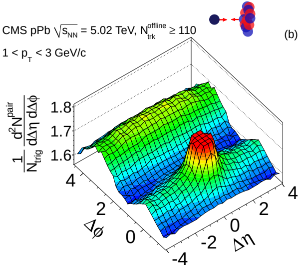

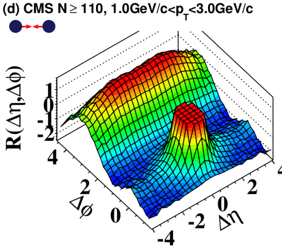

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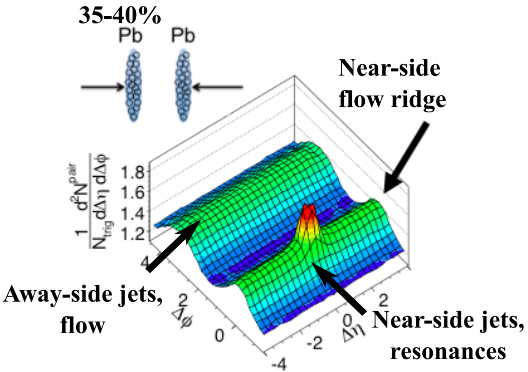

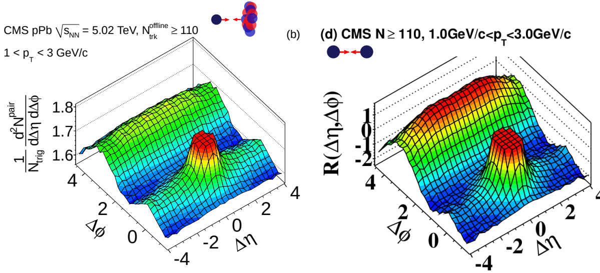

Signs of collectivity in high-multiplicity collisions of small systems at the LHC and RHIC

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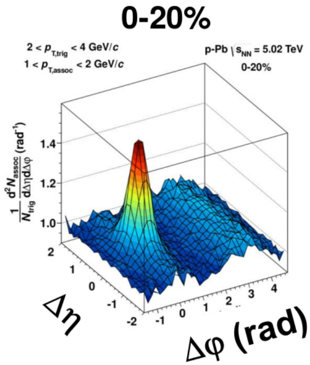
but is it of hydrodynamical origin?

Correlations in big and small systems (cont.)

Substract short-range correlations from long-range $\Rightarrow \mathbf{v_2^{sub}}$.



high multiplicity

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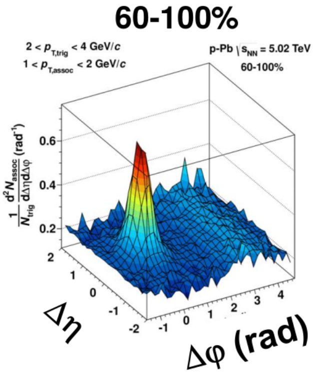

low multiplicity

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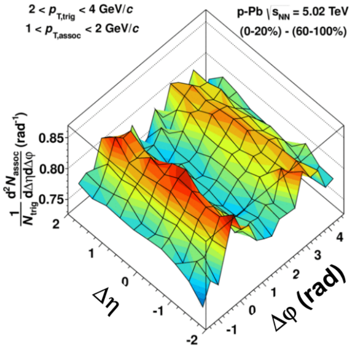
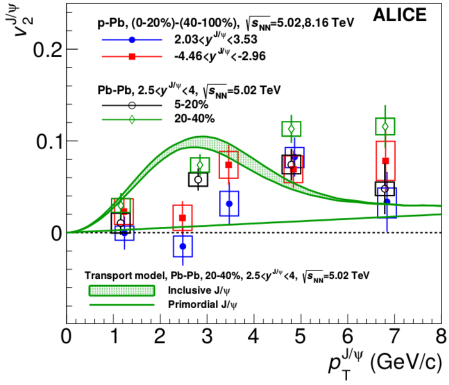


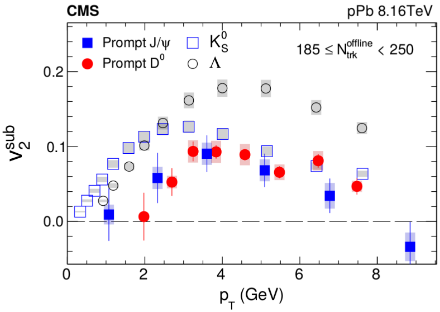
ALICE, PLB719 (2013) 29

J/ψ elliptic flow in p-Pb

ALICE: forward J/ψ correlated with mid-y $h^{\pm}$

- consistent $v_2^{J/\psi,\ \mathrm{sub}}$ between 5.02 and 8.16 TeV
- p-Pb results compatible with Pb-Pb $v_2^{J/\psi}$





CMS: flow of prompt J/ψ compared with D and light hadrons

- charm develops weaker collectivity than light quarks in small system

Similar underlying mechanism in p-Pb and Pb-Pb?

Charged particle multiplicity studies

The charged particle multiplicity N_{ch} describes the final state and carries information on the production mechanisms.

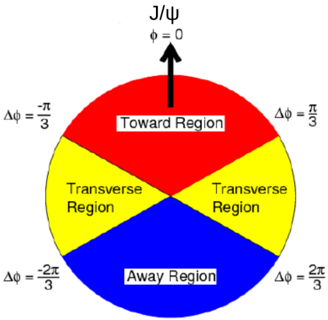
In a pp event N_{ch} is correlated with the number of parton-parton scatterings aka **Multi-Parton Interactions (MPI)**.

In a p-Pb event N_{ch} is correlated with the number of binary-binary scatterings: **MPI, NN interacions, and CNM**.

Correlating HF with multiplicity allows us to study the interplay between the hard scattering and the underlying event.

Questions:

- ? Different correlation for charm and beauty?
- ? Auto-correlations between HF and multiplicity estimator (η gap)?
- ? How does the collision energy play in all this? Hardness of the probe?
- ? Possible signs of QGP-like effects in high multiplicity events.



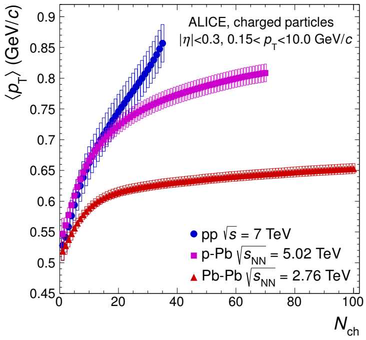
Probing collectivity with multiplicity

Charged hadron $\langle p_T \rangle$ behaves differently in pp, p-Pb, and Pb-Pb.

- in pp: increase of $\langle p_T \rangle$ with multiplicity favours MPI
- Pb-Pb: $\langle p_T \rangle$ saturates due to rescattering of the constituents in the medium
- p-Pb: flow at high multiplicity?

What can we see when we take quarkonia instead of charged particles?
Some predict suppression of J/ψ in high-multiplicity pp akin to A-A.

Can multiplicity studies help us study collectivity in small systems?



Observables

Relative multiplicity:

$$\frac{N_{\mathrm{ch}}}{\langle N_{\mathrm{ch}} \rangle}$$

Charged particle multiplicity, number of tracks, transverse energy, . . .

- Numerator characterises each event.
- Denominator is averaged over the full datasample.

Relative yields:

$$\frac{N^{i}_{\mathrm{J}/\psi}}{\langle N_{\mathrm{J}/\psi} \rangle}$$

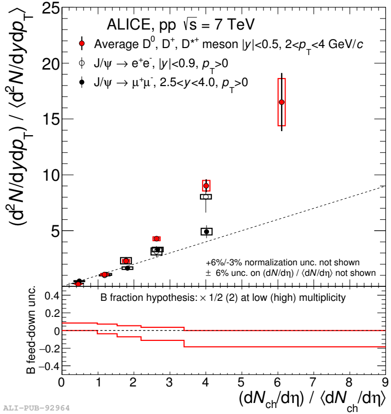
i defines the multiplicity interval

- Numerator quantifies the number of quarkonia in bin i.
- Denominator gives the average number of quarkonia in the datasample.

Multiplicity dependence of quarkonia in LHC Run 1 data

ALICE measured J/ψ and D mesons versus midrapidity N_{ch}

- Forward $\mathrm{J}/\psi \sim$ linear, mid stronger-than-linear increase.
- At midrapidity, open charm, hidden charm and beauty all show quantitatively identical behaviour.



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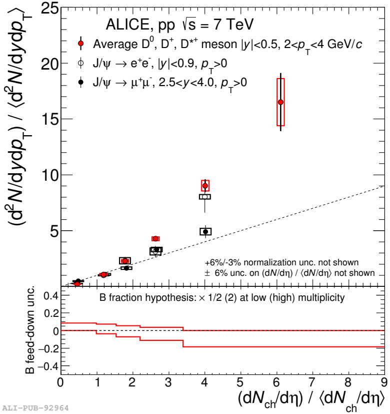

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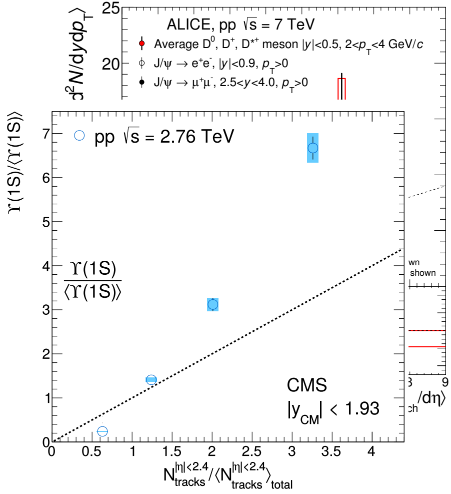
CMS measured midrapidity Υ versus event activity

- $\Upsilon(1\mathrm{S})$, J/ψ, and D data without η-gap show the same trend.
- But $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ without η-gap show linear increase.



J/ψ: ALICE, PLB 712 (2012) 165-17
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Multiplicity dependence of quarkonia in LHC Run 1 data

ALICE measured J/ψ and D mesons versus midrapidity N_{ch}

- Forward $J/\psi \sim$ linear, mid stronger-than-linear increase.
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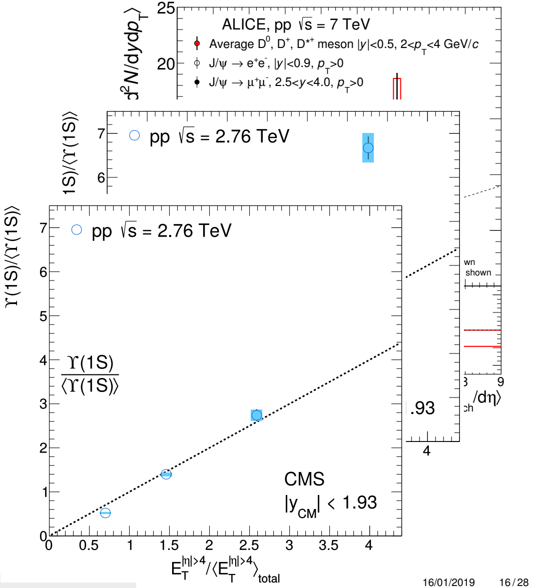

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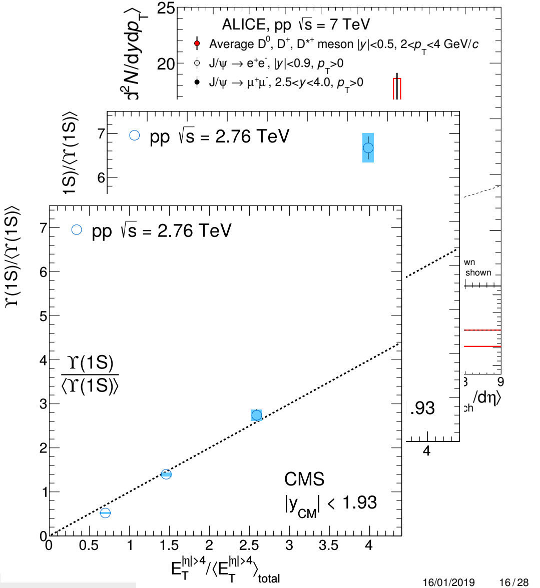
⇒ **Importance of η-gap?**

⇒ **Does hardness of the probe play a role?**



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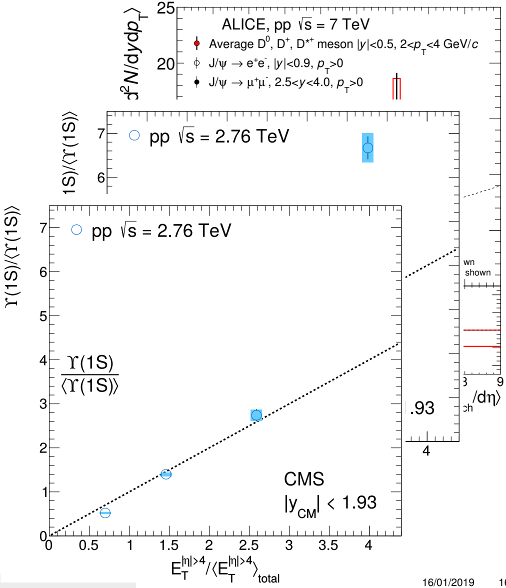
Large uncertainties and low reach in multiplicity - to confirm these suspissions we need larger statistics and new measurements.



Multiplicity dependence of quarkonia in LHC Run 2 data

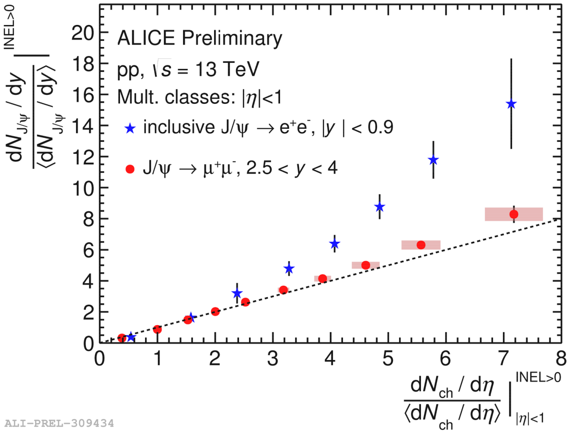
Several new results from ALICE for forward quarkonia versus midrapidity multiplicity.

Reach in multiplicity nearly doubled wrt Run 1⇒

- confirmed linear increase for J/ψ with η-gap
- confirmed stronger-than-linear increase for J/ψ w/o η-gap

Correlation of yields and multiplicity does not depend on hadronisation process - instead related to $Q\bar{Q}$ production.

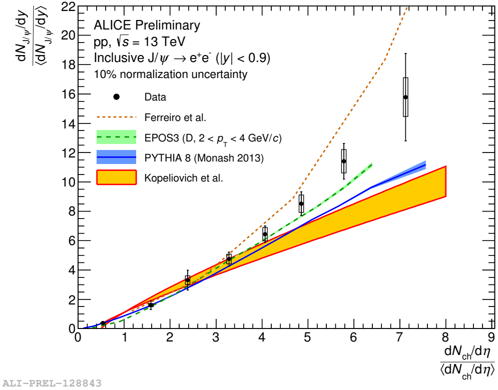
Rapidity gap is important - possible autocorrelations between HF and UE.



Multiplicity dependence of J/ψ in models

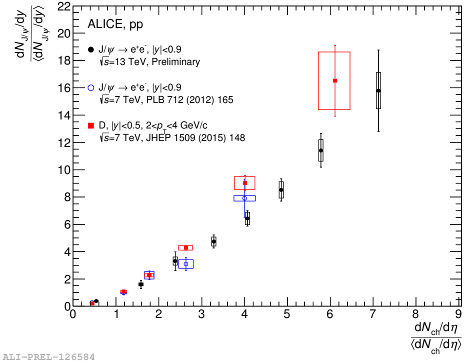
EPOS3: Phys. Rept. 350 (2001) 93–289
PYTHIA8: Comput.Phys.Commun. 191 (2015) 159-177
Ferreiro: PRC 86 (2012) 034903
Kopeliovich: PRD 88 (11) (2013) 116002

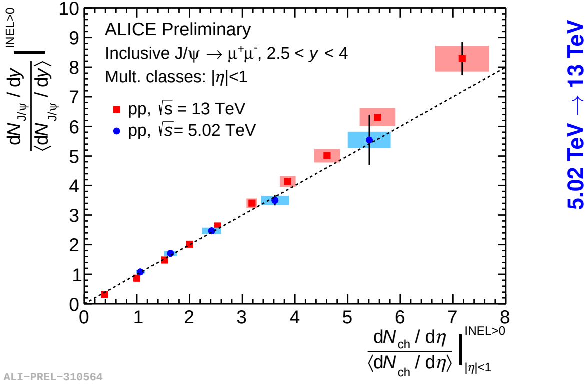
- data compared with available models - different MPI implementation
  - EPOS3 - MPI via Pomeron exchange + hydrodynamic expansion
  - PYTHIA8 - several processes: MPI, hard scattering,
  - Kopeliovich - higher Fock states in the protons leading to higher gluon densities in collision
  - Ferreiro - percolation of colour strings resulting in stronger suppression of soft processes (N_{ch}) than of hard processes ($N_{J/\psi}$)
- consistent within uncertainties with all models



Multiplicity dependence of quarkonia versus energy

J/ψ 7TeV: ALICE, PLB 712 (2012) 165-175
D 7 TeV: ALICE, JHEP 1509 (2015) 148
J/ψ 200 GeV: STAR, arXiv:1805.03745





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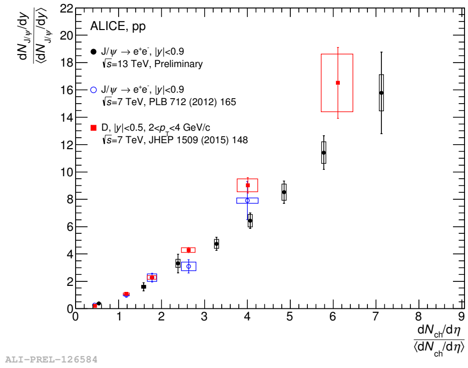

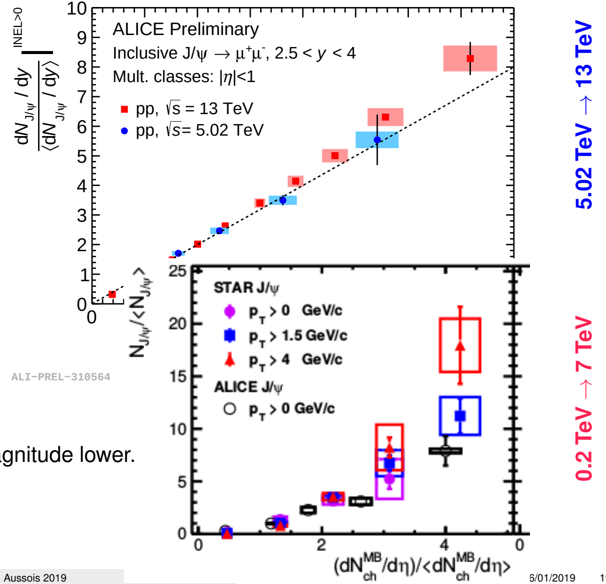

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- This extends down to RHIC energies - one order of magnitude lower.

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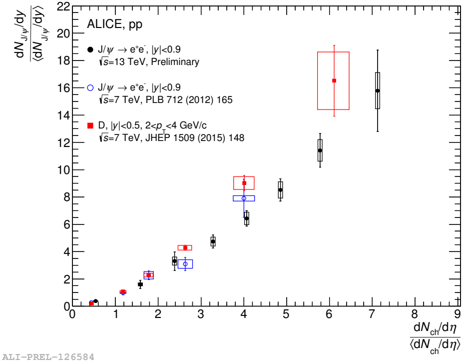

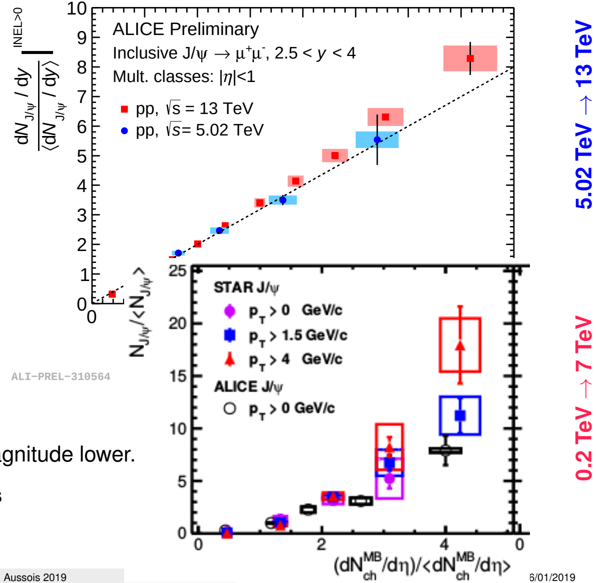

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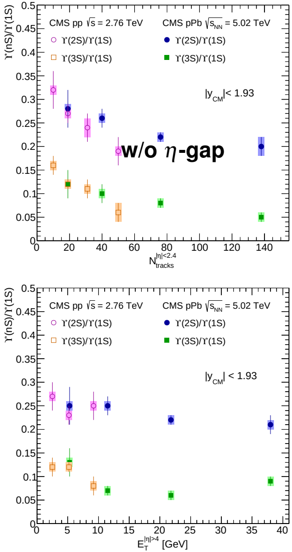
Correlating relative quantities removes energy dependence.

2.76TeV: CMS, JHEP 04 (2014) 103
7TeV: CMS-PAS-BPH-14-009

Suppression of higher bottomonia states in small systems

- In pp 2.76 TeV midrapidity $\Upsilon(2S)$ and $\Upsilon(3S)$ seam to be more suppressed with increasing midrapidity multiplicity.
- The data show weak dependence observed when Υ correlated with forward multiplicity.



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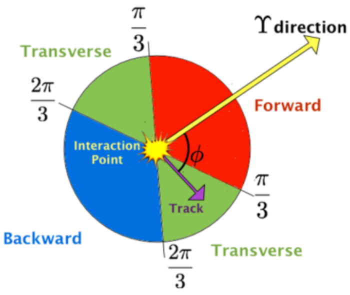
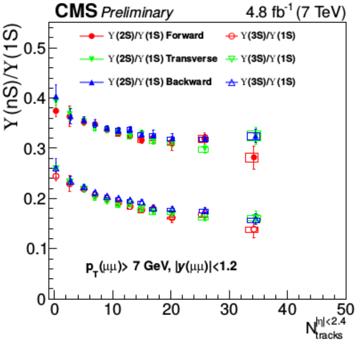
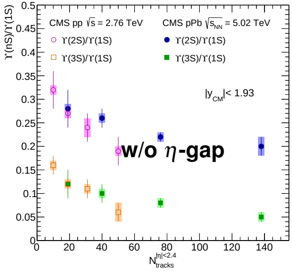
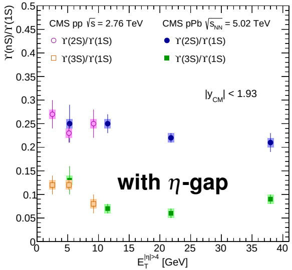
- The data show weak dependence observed when Υ correlated with forward multiplicity.
- Higher statistics in pp 7 TeV - preliminary CMS results **suggest suppression is there in pp independent of the η-gap**.

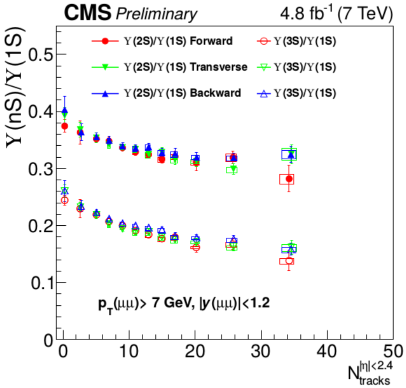


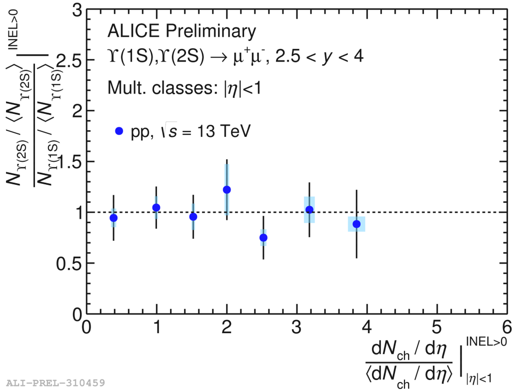






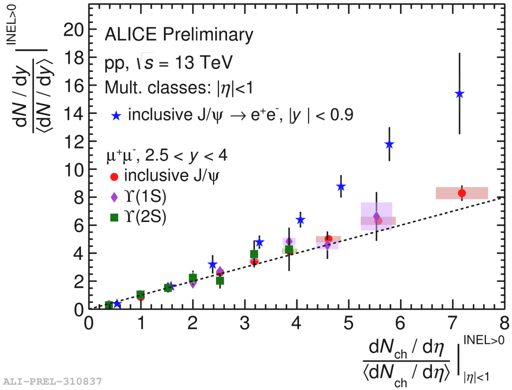
Suppression of higher bottomonia states in small systems (cont.)

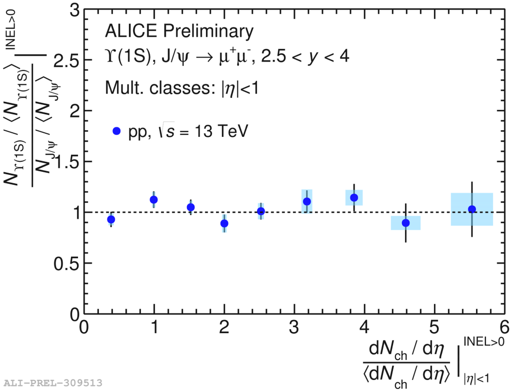




- Preliminary CMS results suggest stronger multiplicity-dependent suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$ w. r. t. $\Upsilon(1S)$.
- ALICE measured ratio of **relative** $\Upsilon(1S)$ and $\Upsilon(2S)$ at forward versus midrapidity N_{ch} → double ratio is flat in multiplicity.

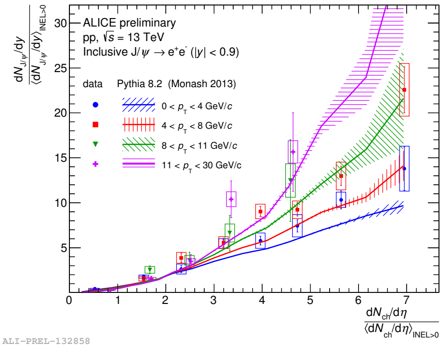
Multiplicity dependence of quarkonia versus probe’s mass





- We saw hints of the same increase for J/ψ and Υ but no direct comparison (different axes, rapidity ranges etc.).
- Ratio of J/ψ and $\Upsilon(1\mathrm{S})$ at forward versus midrapidity N_{ch} $\rightarrow$ double ratio is flat in multiplicity.

Multiplicity dependence of quarkonia versus p_T

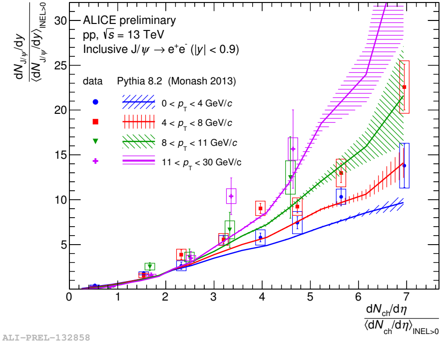


Data for midrapidity J/ψ versus midrapidity N_{ch} were split into 4 bins

- Hints of dependence on probe's p_T reported by ALIE and STAR are supported by PYTHIA.
- But yields in all bins are consistent within uncertainty!

D 7 TeV: ALICE, JHEP 1509 (2015) 148

Multiplicity dependence of quarkonia versus p_{T}



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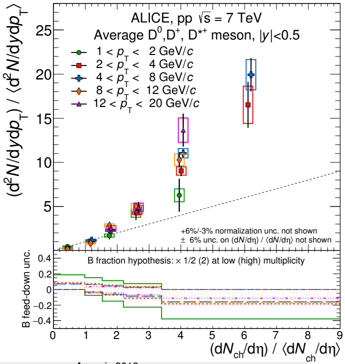
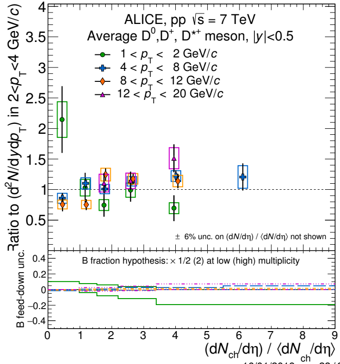
- Similar conclusion to the latter was drawn from average D mesons.





D 7 TeV: ALICE, JHEP 1509 (2015) 148

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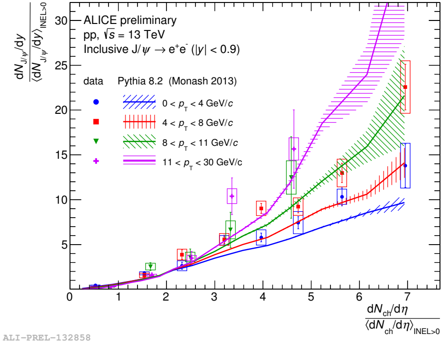

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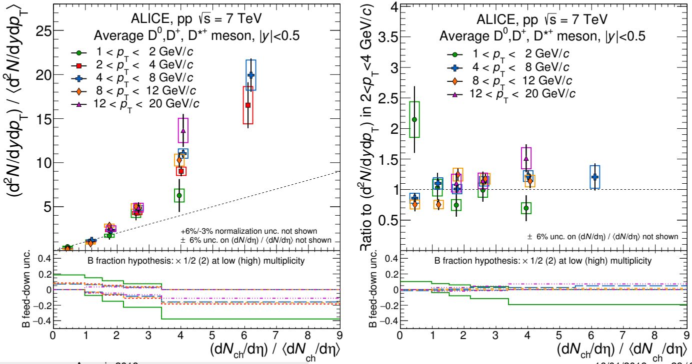
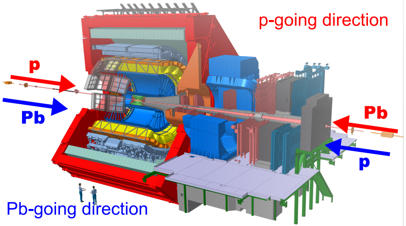


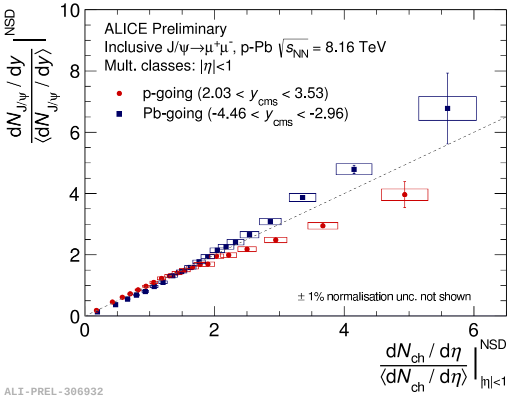
So far no conclusive answer on hardness dependence.

Charm versus multiplicity in p-Pb

Inclusive J/ψ versus midrapidity N_{ch} from ALICE:

- Backward J/ψ consistent with linear increase.
- From $\sim 2\times$ the average multiplicity, forward yields are suppressed.





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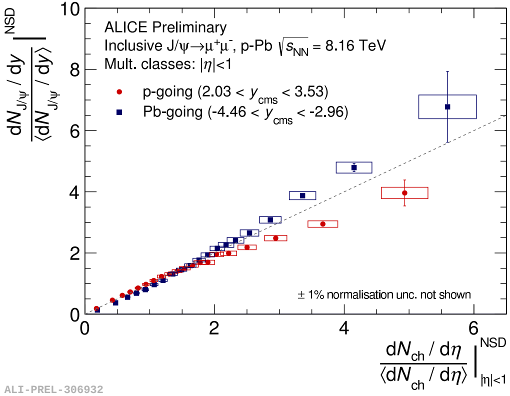

J/ψ 5TeV: ALICE, PLB 776 (2018) 91

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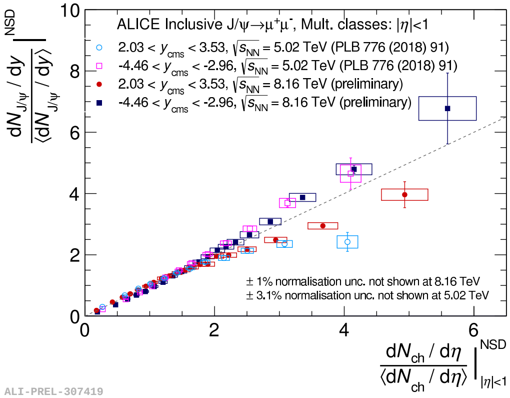
- The same behaviour at 8 and 5 TeV in both rapidity intervals.

Also in p-Pb, relative quantities remove energy dependence.

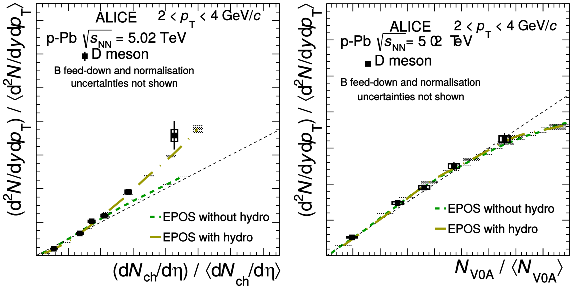


D: ALICE, JHEP 8 (2016) 1
J/ψ: ALICE, PLB 776 (2018) 91

Charm versus multiplicity in p-Pb (cont.)

Midrapidity D mesons:

- The increase dependends on whether we take multiplicity at mid- or at forward y.
- One possible explanation could be hydro.



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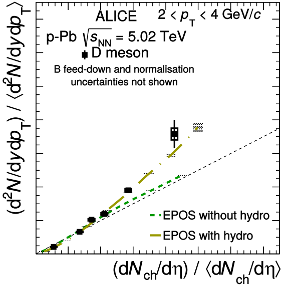
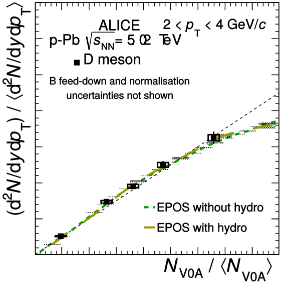
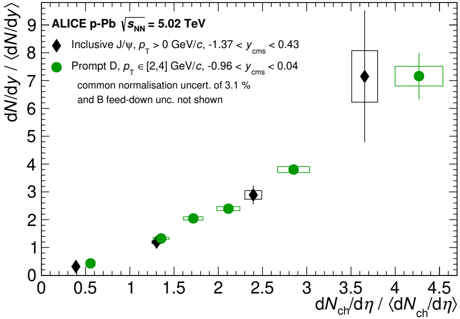




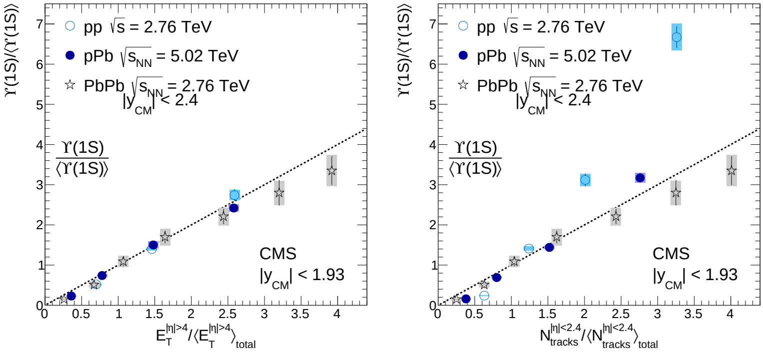


- At midrapidity, J/ψ show hints of stronger-than-linear increase as in case of D.

May we expect some signs of collectivity?

CMS, JHEP 04 (2014) 103
ATLAS: EPJC 78 (2018) 17

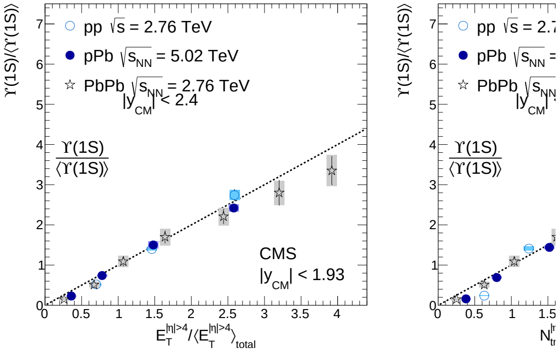
Beauty vs multiplicity in p-Pb

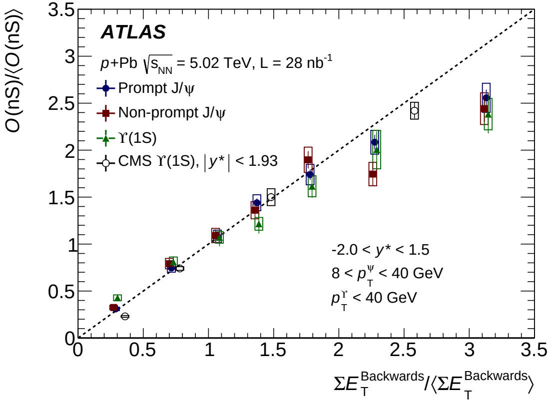


- Bottomonia all show linear increase with multiplicity with and without η-gap - but lower reach in multiplicity!

Beauty vs multiplicity in p-Pb

CMS, JHEP 04 (2014) 103
ATLAS: EPJC 78 (2018) 17





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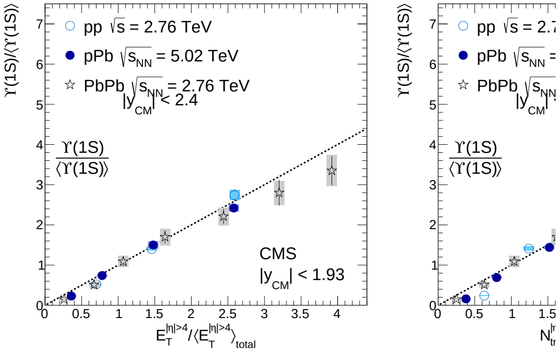

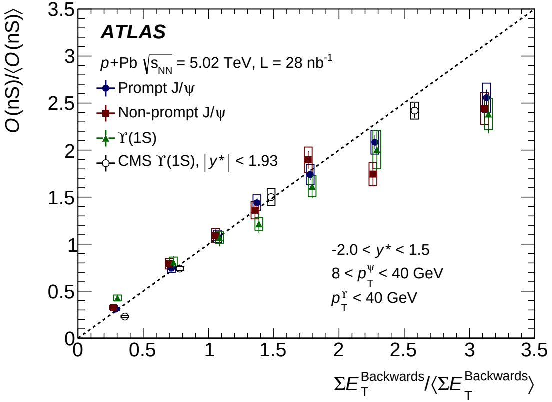

- Bottomonia all show linear increase with multiplicity with and without η-gap - but lower reach in multiplicity!
- Same behaviour for hidden charm, open and hidden beauty.

Suggest that increase is independent of hadronisation.
Concerning multiplicity estimator dependence, need to measure higher multiplicities.

What to take away

nuclear modification in p-Pb

- Different suppression for higher quarkonia states that suggest different final-state effects.
- At low-p_{T}, difficult extrapolation of CNM effects from p-Pb into Pb-Pb. Expect non-negligible CNM effects in Pb-Pb at the LHC.
- High-p_{T} data suggest that there is little contribution of CNM into suppression in Pb-Pb.

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collectivity in small systems

- Long-range multi-particle correlations in LHC high-multiplicity pp and p-Pb events show collectivity. Yet to decide whether it is or not of hydro origin?
- Charmed particle flow but develop weaker collectivity than light hadrons.
- Possibly the same underlying mechanism in p-Pb and Pb-Pb?

What to take away

quarkonia versus multiplicity

- Correlating relative quantities removes energy dependence in pp and p-Pb.
- Nature of increase independent of hadronisation or mass of the probe.
- (Non-)Existence of η-gap between the probe and UE affects the correlation.
- There are hints of p_{T} dependence, however not conclusive.
- Some model comparison of open HF in p-Pb suggest hydrodynamical behaviour $\Rightarrow$ motivation to check the same with charmonia or even beauty.
- CMS measured relative suppression of higher Υ states as is observed in p-Pb $\Rightarrow$ motivation to check if the same will hold for $\psi(2\mathrm{S})$?