

Review of heavy-quarkonium results at the LHC

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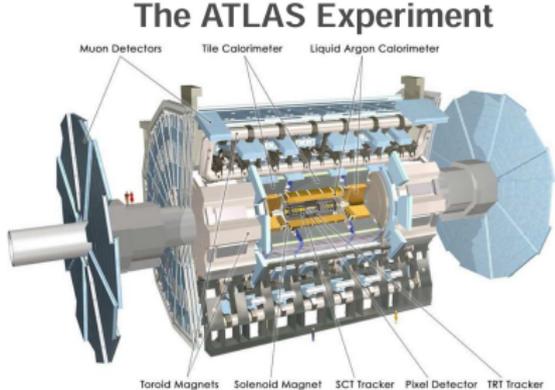
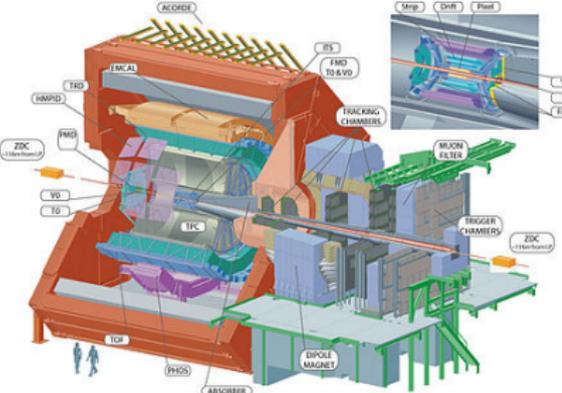
BNL, June 20, 2017



Outline

1. LHC introduction
2. 2.76 TeV Pb–Pb highlights and first 5 TeV Pb–Pb results
3. Fixed target opportunities with LHCb
4. 5.02 TeV and 8.16 TeV p–Pb results
5. Conclusions and Outlook

LHC: the players



CMS DETECTOR

- Total length: 14.00 m
- Central diameter: 7.50 m
- Angular length: 148.7°
- Magnets: 4.0 T

INNER DETECTOR CORE

- 10.00 m

INNER TRACKER

- 1.00 m

SEMI-CONDUCTIVE CALORIMETER

- 1.00 m

ALUMINA TRACKER

- 1.00 m

SEMI-CONDUCTIVE CALORIMETER

- 1.00 m

ALUMINA TRACKER

- 1.00 m

SEMI-CONDUCTIVE CALORIMETER

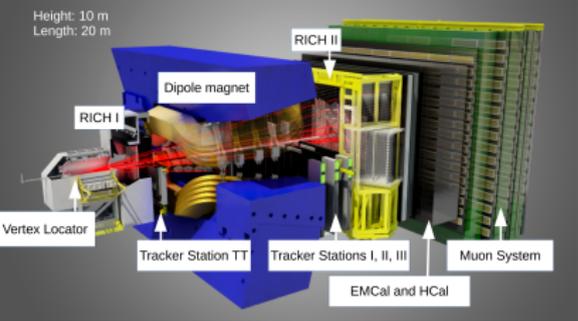
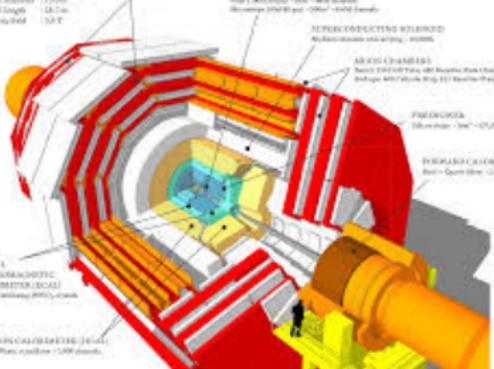
- 1.00 m

ALUMINA TRACKER

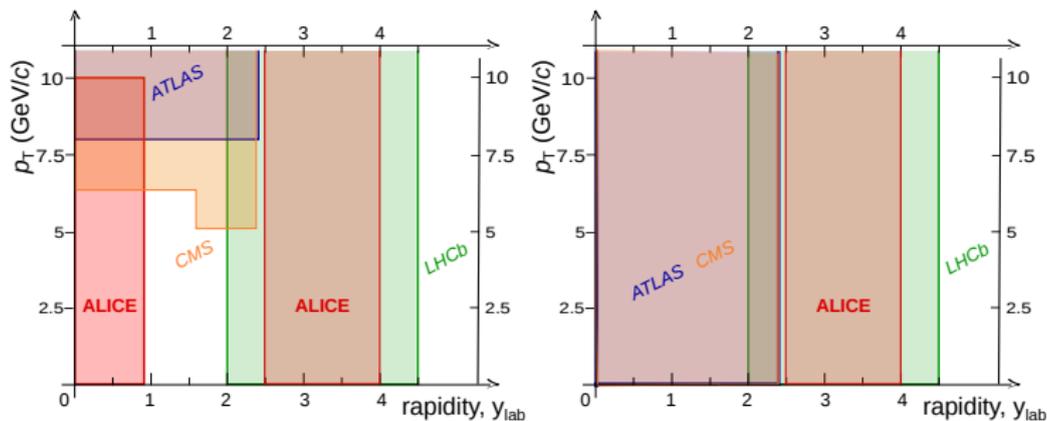
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SEMI-CONDUCTIVE CALORIMETER

- 1.00 m



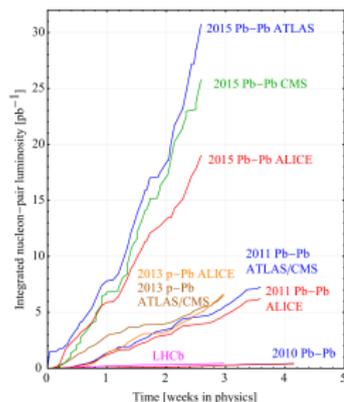
LHC: the players and their quarkonium in dileptons acceptance



Acceptance of published pPb measurements from 2013 for J/ψ LHS, and Υ .

- ▶ Muon trigger systems luminosity limited: ALICE muon, CMS/ATLAS/LHCb
- ▶ ALICE central barrel at midrapidity MB triggers or centrality triggers: read-out limited
- ▶ LHCb occupancy limit: 60-50% in centrality in PbPb
- ▶ ATLAS/CMS: down to 0/1 GeV/c at $y \approx 2$, large background in AA
- ▶ non-dilepton channels for χ/η -states probably only in pPb conceivable with current statistics/detectors

LHC heavy-ion performance



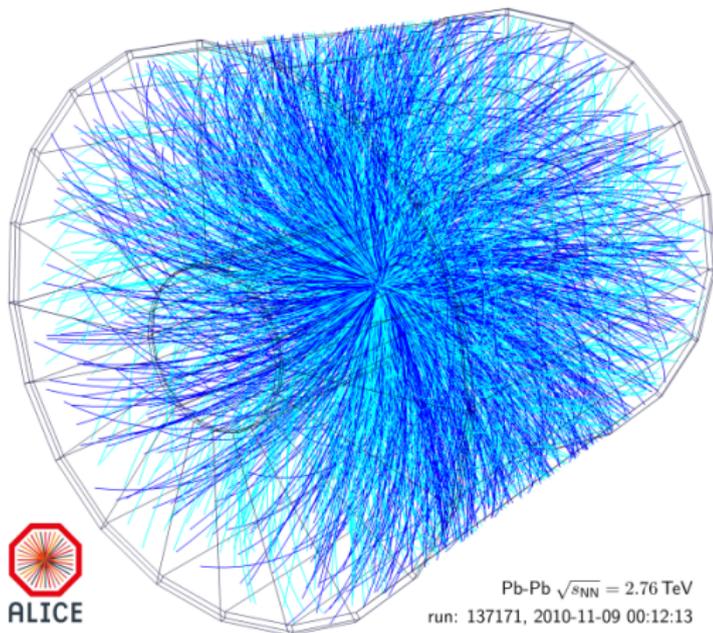
JINST 3 (2008) S08005.

Experiment	2015 Pb-Pb 5 TeV
ALICE central	150 mio MB evts. (0.02 nb^{-1})
ALICE muon	0.225 nb^{-1} analysed
CMS	0.464 nb^{-1} analysed
ATLAS	0.515 nb^{-1} analysed
LHCb	50 mio MB evts., 50-100% tracking

modified version from [arXiv:1609.01135](https://arxiv.org/abs/1609.01135), references therein.

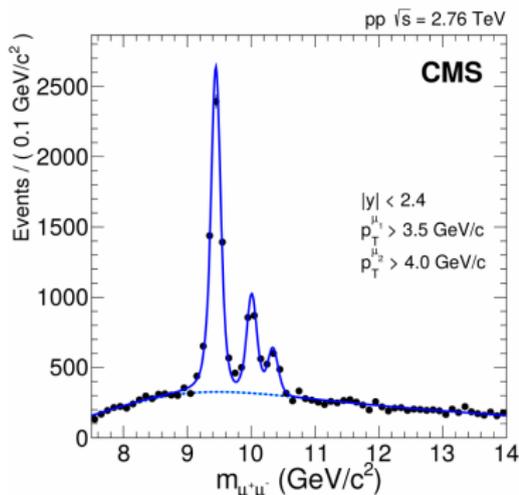
- ▶ ALICE 2015 in PbPb at 5 TeV already levelled at 8 kHz for beginning of fill
- ▶ 2.76 TeV PbPb and 5.02 TeV pPb: main results final; 5 TeV PbPb from 2015 and 8.16 TeV from 2016 coming up
- ▶ 5 TeV pp reference run: sufficient for ATLAS/CMS/LHCb/ALICE Muon forward; long run for ALICE central barrel later this year
- ▶ charm/beauty cross sections $O(10)/O(60)$ larger compared to RHIC
- ▶ large statistics and new kinematic regime at high- p_T : $p_{T,Q\bar{Q}} \gg m_{Q\bar{Q}}$
collections for further reading: [ALICE final](#), [CMS](#), [ATLAS final](#), [ATLAS prelim](#), [LHCb](#)

Results PbPb

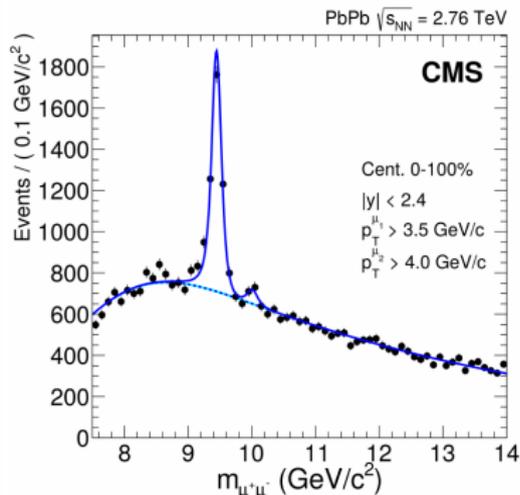


- ▶ only data points when available and no model calculations, no time for open heavy-flavour including non-prompt J/ψ although crucial for understanding
- ▶ try to keep rather descriptive

2011 data 2.76 TeV PbPb results: Υ with CMS

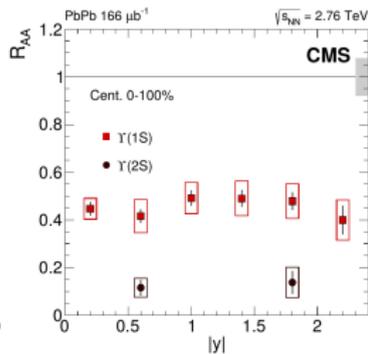
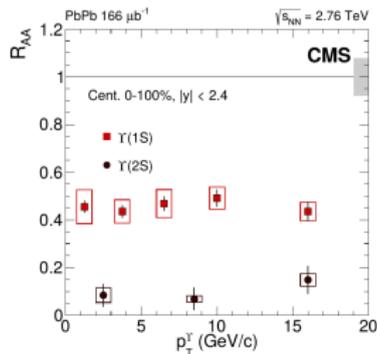


taken from [arxiv:1611.01510](https://arxiv.org/abs/1611.01510)

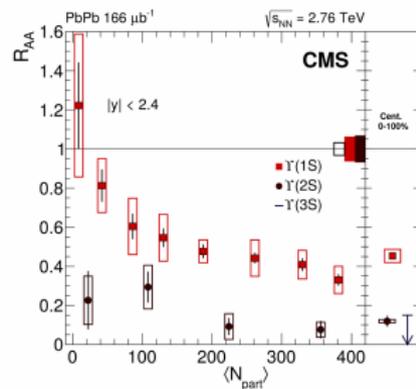


- ▶ probably most iconic heavy-ion plot from the LHC with the "sequential" suppression
- ▶ final results at 2.76 TeV available since end of last year

2011 data 2.76 TeV PbPb results: Υ with CMS

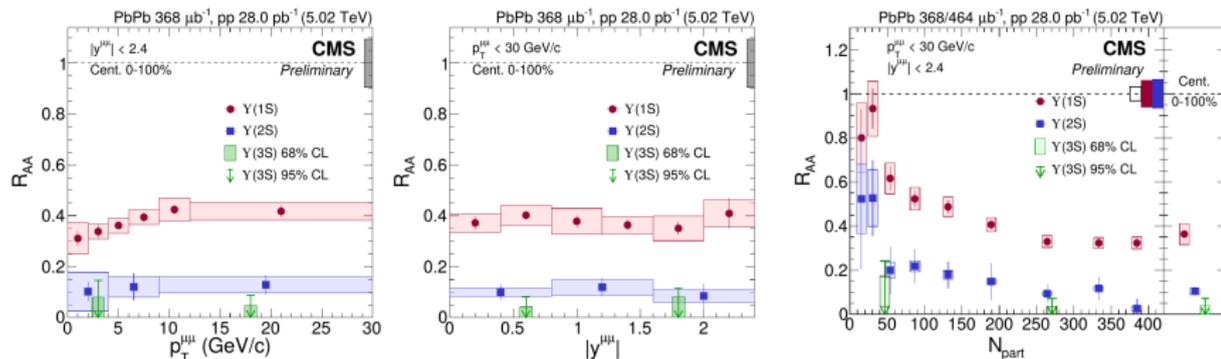


taken from [arxiv:1611.01510](https://arxiv.org/abs/1611.01510)



- ▶ $R_{AA}(\Upsilon(1S))$ about 50%, $R_{AA}(\Upsilon(2S))$ about 10%, $\Upsilon(3S)$ not seen
- ▶ no kinematic dependences within CMS acceptance within uncertainties
- ▶ approach to unity for R_{AA} only observed in $\Upsilon(1S)$, lack of statistics for precise trend in peripheral collisions for $\Upsilon(2S)$

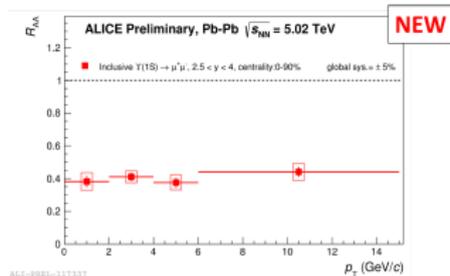
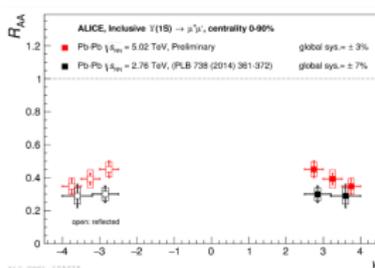
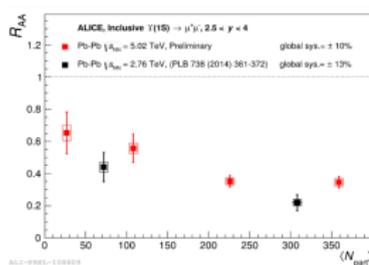
2015 data 5 TeV: Υ results CMS



taken from [HIN-16-023](#)

- ▶ preliminary results at 5 TeV consistent with findings at 2.76 TeV
- ▶ larger statistical power in peripheral collisions: $R_{AA} \Upsilon(2S)$ closer to unity in peripheral collisions
- ▶ better constraints on $\Upsilon(3S)$: $R_{AA}(\Upsilon(3S)) < R_{AA}(\Upsilon(2S))$

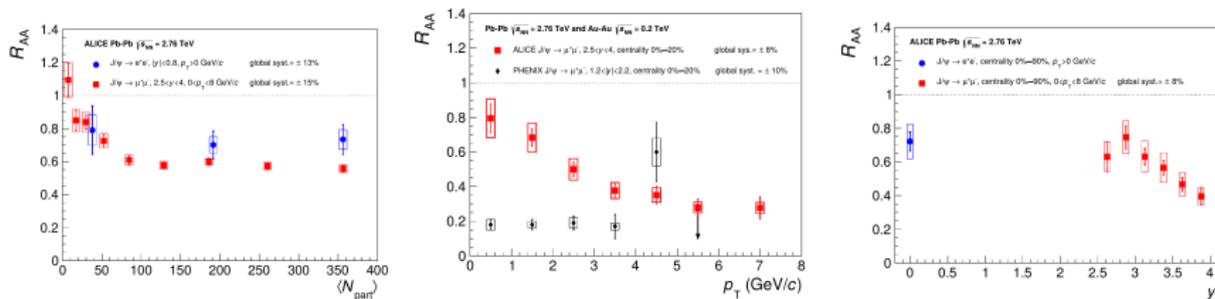
Υ results from ALICE



taken from talk by [Lardeux/Das](#) at QM 17, 2.76 TeV result: [arXiv:1405.4493](#)

- ▶ final R_{AA} 2.76 TeV results for $\Upsilon(1S)$ below result from CMS at midrapidity
- ▶ 5 TeV results: slightly higher central values measured and hint of increasing trend within acceptance: let's wait for the final word
- ▶ p_T -dependence flat as in CMS: however $p_T \approx O(M_{b\bar{b}})$

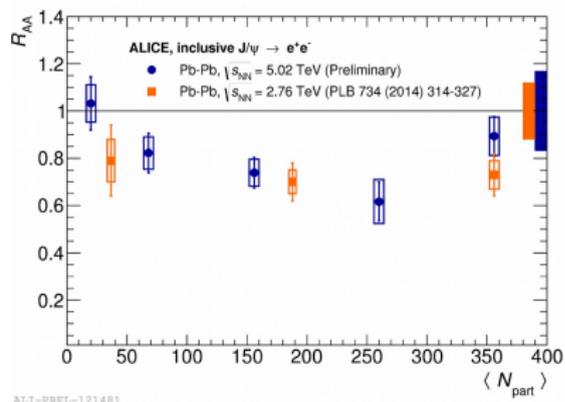
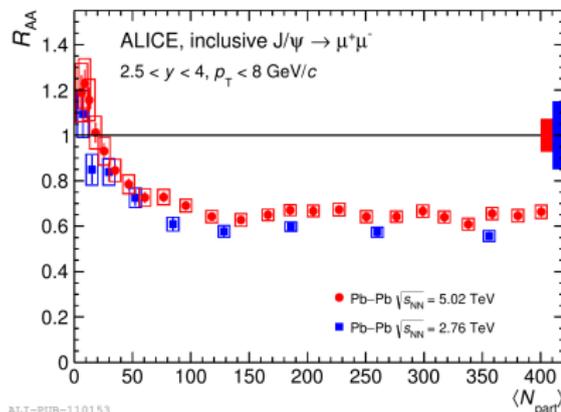
2.76 TeV PbPb: J/ψ with ALICE



taken from [arXiv:1311.0214](https://arxiv.org/abs/1311.0214), further results in [arXiv:1504.07151](https://arxiv.org/abs/1504.07151), [arXiv:1506.08804](https://arxiv.org/abs/1506.08804)

- ▶ Qualitatively different w.r.t. RHIC
- ▶ low- p_T component commonly identified as J/ψ produced during deconfined stage and/or at phase boundary
- ▶ first measurement of prompt/non-prompt J/ψ down to $p_{T,J/\psi} = 1.5$ GeV/c ($y \approx 0$): no surprises $R_{prompt} \approx R_{inclusive}$ as expected (not shown)
- ▶ hint of similar p_T dependence as at forward rapidity also at midrapidity (not shown)

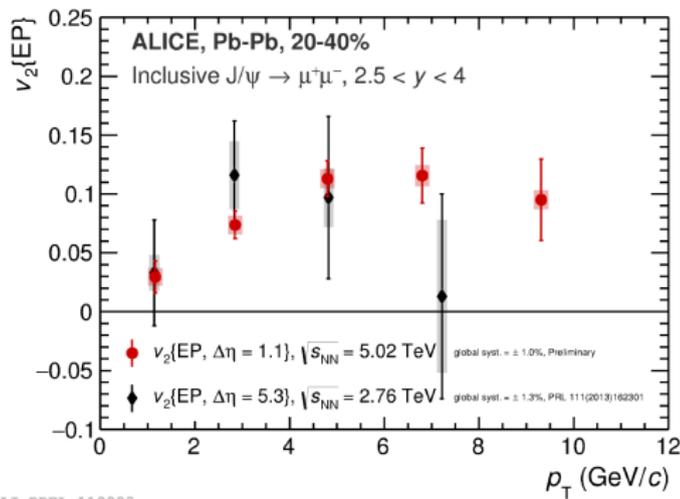
2015 data 5 TeV: PbPb J/ ψ results ALICE



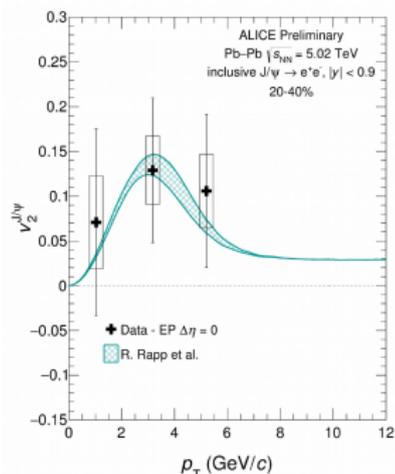
ALICE forward arm published: [arXiv:1606.08197](https://arxiv.org/abs/1606.08197), ALICE central barrel preliminary: Jimenez Bustamante at [QM '17](#)

- ▶ confirmed behaviour at forward rapidity, hint of larger R_{AA}
 - in peripheral collisions see impact of "ultra-low p_T " excess first seen in [arXiv:1509.08802](https://arxiv.org/abs/1509.08802) analogue to UPC, but at $b < 2R$
- ▶ significantly better statistical power at midrapidity in semi-central
- ▶ midrapidity suffering from worse interpolated pp reference at 5 TeV compared to 2.76 TeV (preciser thanks to CDF)

2015 data 5 TeV: PbPb J/ ψ flow ALICE



ALI-PREL-118883

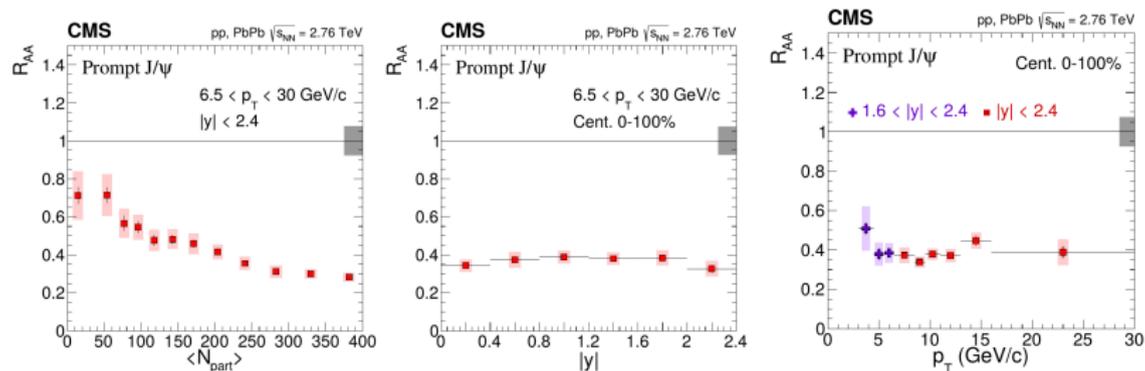


ALI-PREL-118882

2.76 TeV result [arXiv:1303.5880](https://arxiv.org/abs/1303.5880) preliminary Tarhini's QM' 17, ALICE central barrel preliminary: Jimenez Bustamante at QM '17.

- ▶ sign of finite large v_2 solidified at higher beam energy at forward rapidity
- ▶ midrapidity measurements with 150 mio MB events starts to probe finite v_2

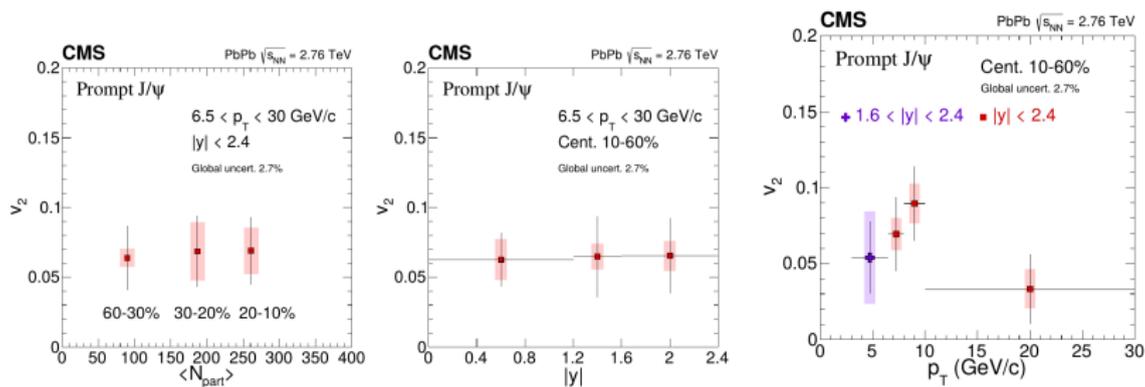
2.76 TeV PbPb: intermediate-high p_T J/ψ with CMS



taken from [arXiv:1610.00613](https://arxiv.org/abs/1610.00613)

- ▶ CMS results consistent with ALICE in common acceptance
- ▶ strong suppression, large v_2
- ▶ limit $p_{T,c\bar{c}} \gg m_{c\bar{c}}$ new for quarkonium

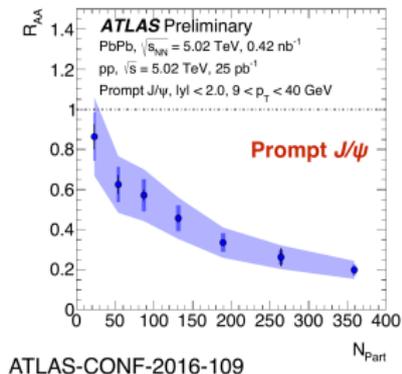
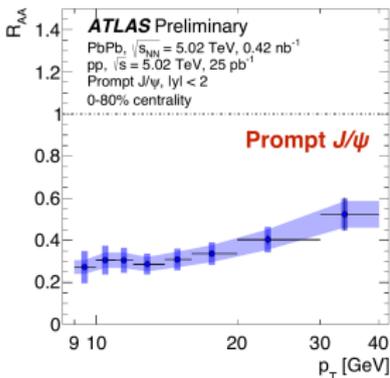
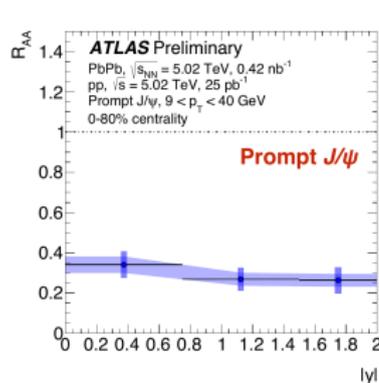
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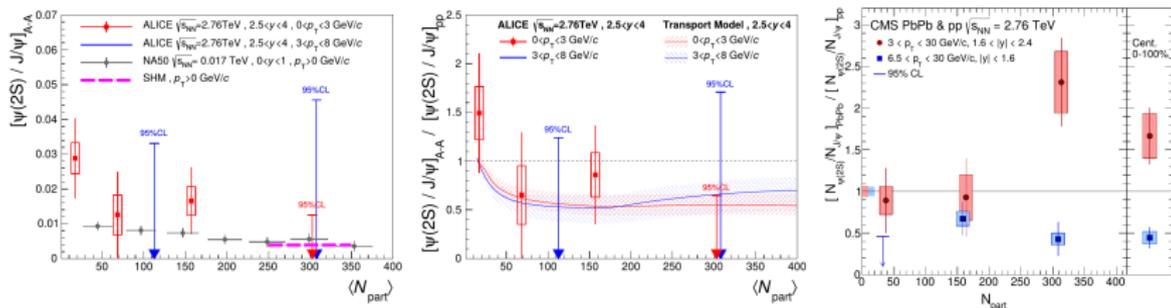
5 TeV PbPb: high p_T J/ψ ATLAS



taken from QM'17 talk Lopez

- ▶ preliminary results from ATLAS at highest p_T so far: up to $40 \text{ GeV}/c$
- ▶ consistent with CMS taking all uncertainties and slightly different acceptance into account
- ▶ high- p_T $\psi(2S)$ above $p_T > 9 \text{ GeV}/c$ (not shown): consistent with CMS \rightarrow additional suppression by about a factor 2
- ▶ limit $p_{T,c\bar{c}} \gg m_{c\bar{c}}$ new for quarkonium

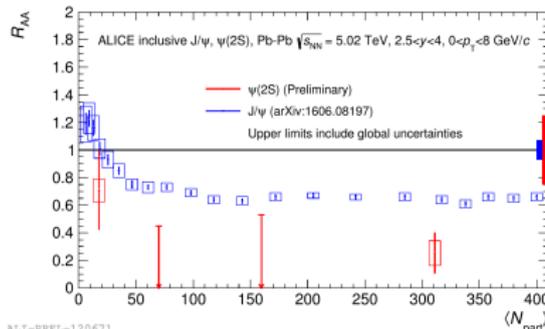
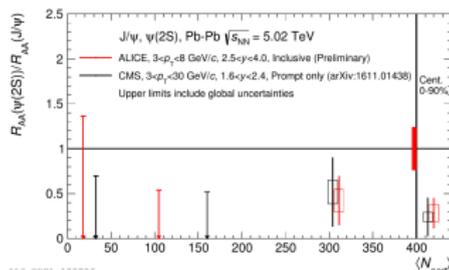
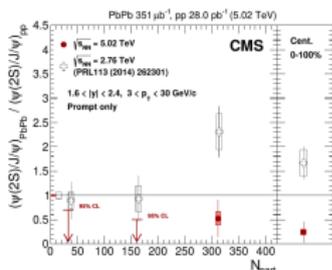
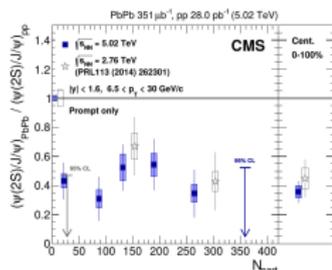
2011 data 2.76 TeV: $\psi(2S)$ results ALICE forward and CMS



LHS: [arXiv:1506.08804](https://arxiv.org/abs/1506.08804); RHS: [arXiv:1410.1804](https://arxiv.org/abs/1410.1804)

- ▶ cancellation of certain uncertainties both on model and experimental side in ratio
- ▶ difficult measurement for ALICE (resolution); difficult at low p_T for CMS (acceptance edge)
- ▶ unexpected behaviour, naively difficult to reconcile despite different acceptances

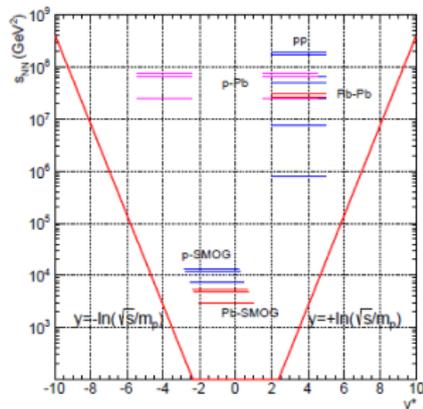
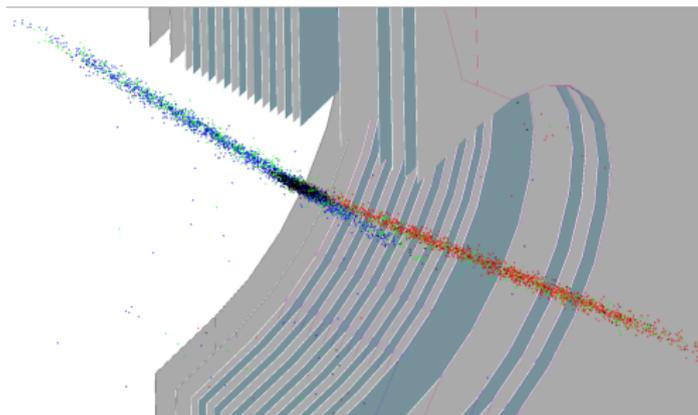
5 TeV vs. 2.76 TeV: $\psi(2S)$ results CMS and ALICE



[arXiv:1911.01438](https://arxiv.org/abs/1911.01438) for CMS, ALICE preliminary from Tarhini at QM '17

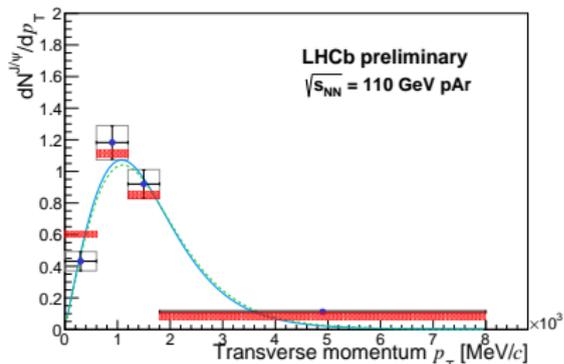
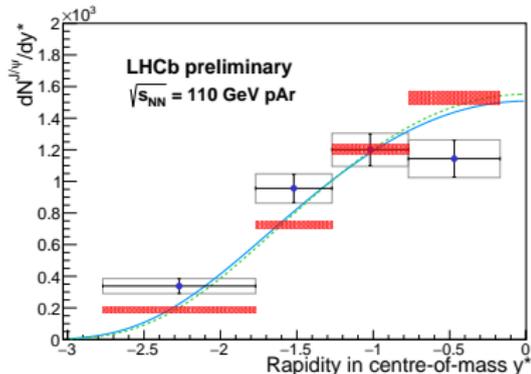
- ▶ most surprising 2.76 TeV result not seen at 5 TeV by CMS
- ▶ CMS rechecked old data with new code: same outcome as published
- ▶ ALICE preliminary at 5 TeV consistent with CMS albeit different y acceptance, R_{AA} for $p_T > 3$ GeV/c over full p_T range similar within uncertainties

Fixed target at the LHC



- ▶ gas injection system designed for beam imaging studies to improve luminosity in collider mode: can be used for fixed-target physics!
- ▶ $O(10^{-7})$ mbar with He, Ne, Ar, use about 0.4m length along beam direction, luminosities $O(1)$ nb $^{-1}$ so far
- ▶ unique opportunity for heavy-ion physics: large boost at midrapidity in nucleon-nucleon centre-of-mass frame
- ▶ different noble gases as target possible
- ▶ both pA as well as $Pb-A$ collisions

Fixed target at the LHC: first results



taken from [LHCb-CONF-2017-001](#)

- ▶ preliminary results: no hint of large intrinsic charm component nor strong anti-shadowing from D^0 or J/ψ
- ▶ $J/\psi/D^0$ ratio flat as function of rapidity
- ▶ large data sample in p-He with similar statistical power for heavy-flavour on tape
- ▶ tentative plan: increase statistics by about a factor 10 in pA during next years
- ▶ large PbAr data sample on tape as well: analysis not yet started

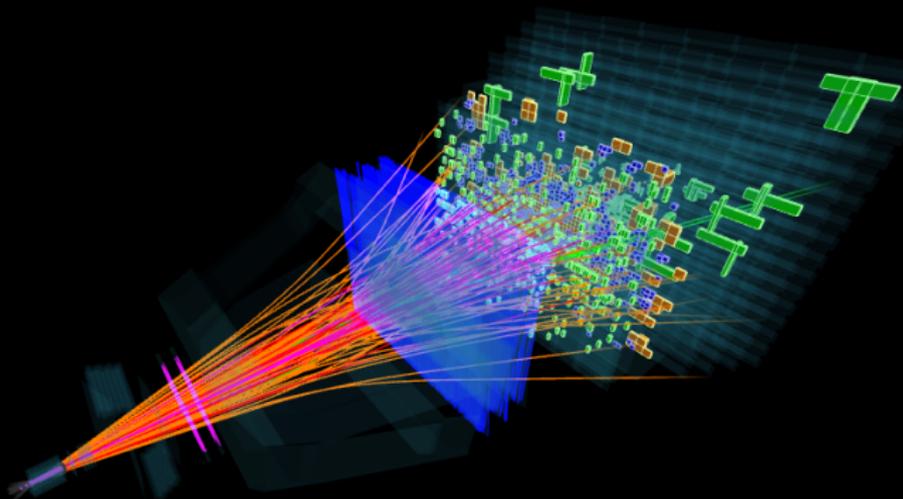
p Pb Results



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Run 187340

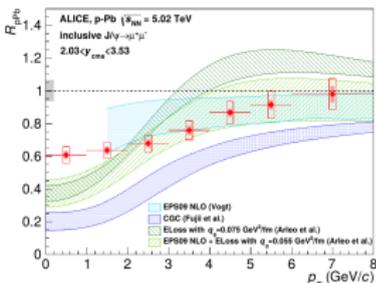
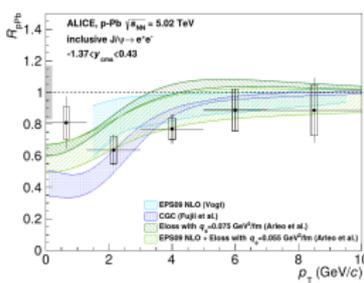
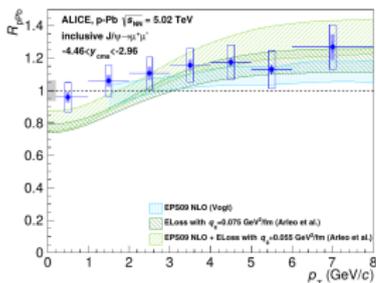
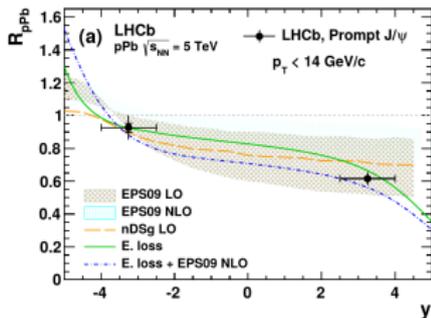
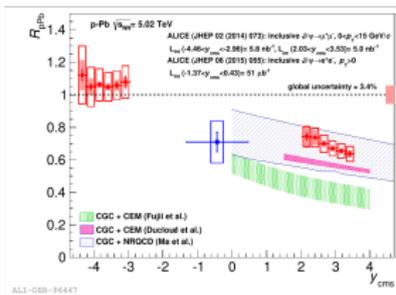
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2016 p Pb LHCb event display

- ▶ Focus on low- p_T results, results at high- p_T but mostly consistent with unity for R_{pPb}
- ▶ due to equal rigidity imposed by LHC dipole magnet design for both beams nucleon-nucleon centre-of-mass frame boosted by 0.465 units in rapidity w.r.t. lab-frame

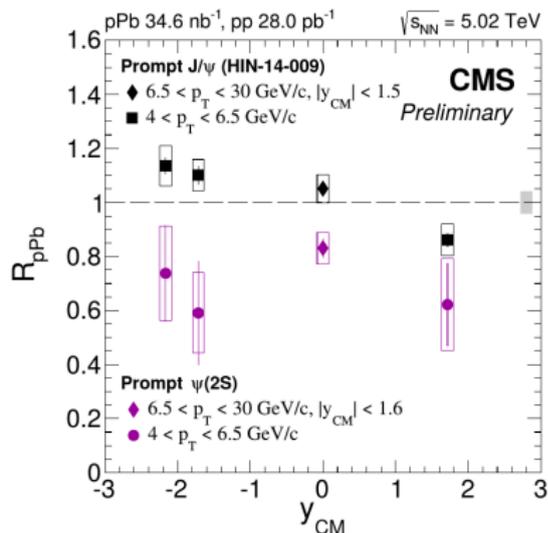
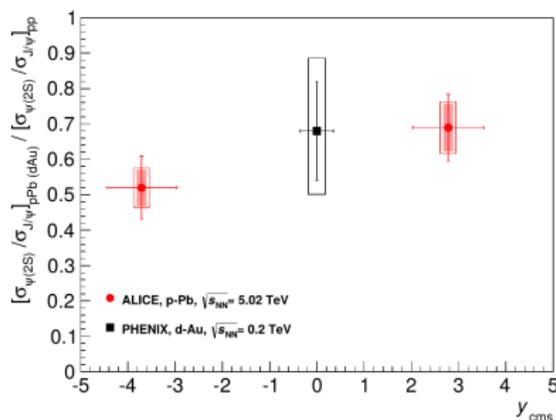
2013 pPb results at 5 TeV: J/ψ ALICE and LHCb



ALICE: [arXiv:1308.6726](https://arxiv.org/abs/1308.6726) [arXiv:1506.07179](https://arxiv.org/abs/1506.07179), [arXiv:1506.08808](https://arxiv.org/abs/1506.08808), LHCb J/ψ: [arXiv:1308.6729](https://arxiv.org/abs/1308.6729)

- ▶ strong modifications at forward rapidity down to R_{pPb} of around 0.5
- ▶ backward rapidity consistent with unity
- ▶ p_T dependence: asymptotic approach to unity
- ▶ both nuclear PDF, coherent energy loss and CGC calculations can explain dependences in their applicability range: no strong discriminative power

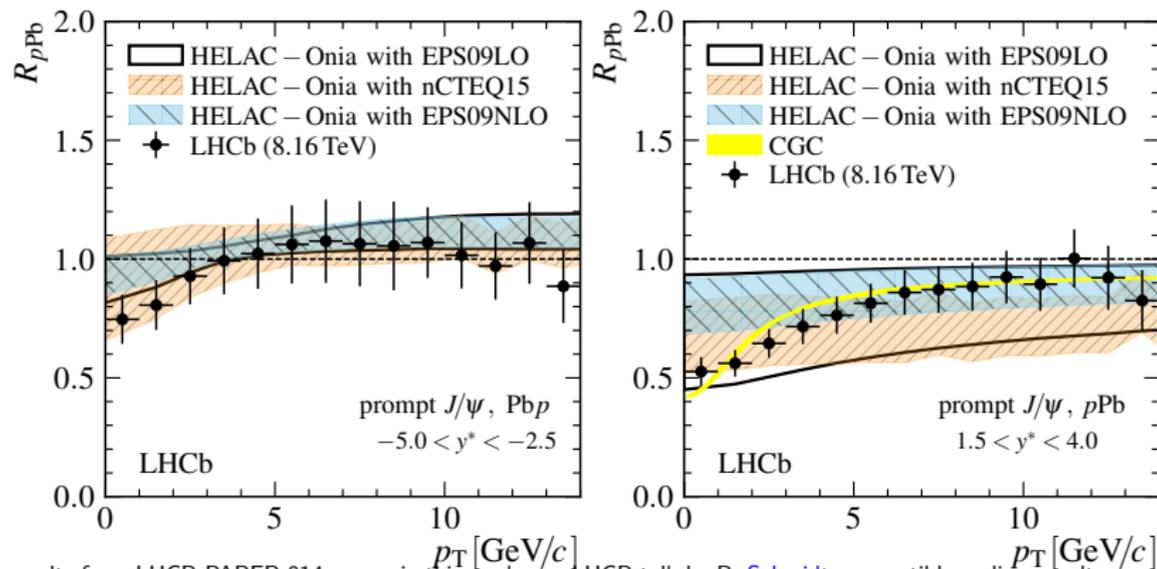
2015 pPb results $\psi(2S)$ ALICE, LHCb and CMS



$\psi(2S)$ ALICE: [arXiv:1405.3796](https://arxiv.org/abs/1405.3796) [arXiv:1603.02816](https://arxiv.org/abs/1603.02816), LHCb: [arXiv:1601.07878](https://arxiv.org/abs/1601.07878) CMS prelim.: [CMS-HIN16-015](https://arxiv.org/abs/1603.02816)

- ▶ $\psi(2S)$ more strongly suppressed than J/ψ as at RHIC reported by PHENIX by about a factor 2
- ▶ hints of kinematic dependence: weaker additional suppression at forward rapidity and at high- p_T
- ▶ so far statistically limited

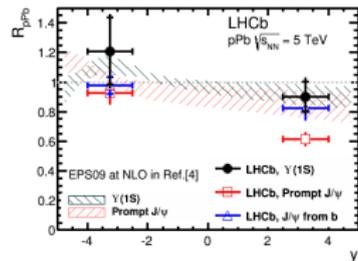
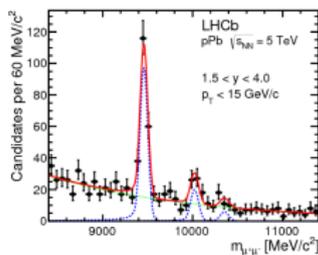
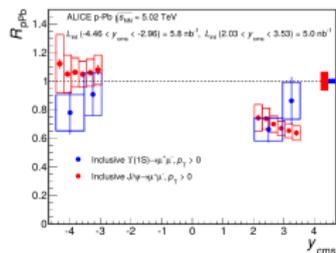
2016 pPb results J/ψ ALICE and LHCb



results from LHCb-PAPER-014, on arxiv this week, see LHCP talk by B. Schmidt, compatible prelim. results shown at Quark Matter by ALICE

- ▶ confirmation of findings at 5 TeV with larger statistics
- ▶ ALICE LHCb will allow double differential investigations of $\psi(2S)$
- ▶ 0.5 mio J/ψ per beam direction for LHCb: χ_c will be also available to clarify modifications with a new state under disposal

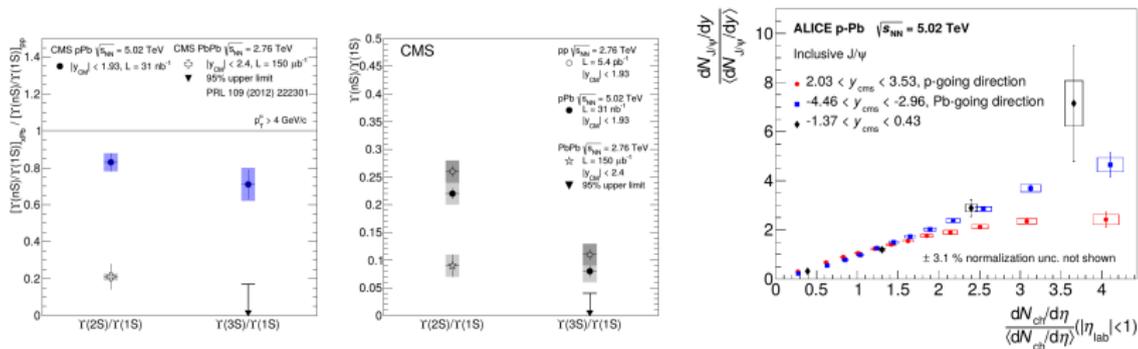
2013 pPb results Υ ALICE and LHCb



ALICE: [arXiv:1410.2234](https://arxiv.org/abs/1410.2234), LHCb: [arXiv:1405.5152](https://arxiv.org/abs/1405.5152).

- ▶ at 5 TeV statistically limited
- ▶ $\Upsilon(1S)$ behaviour consistent with expected pattern from nuclear pdf
- ▶ 8.16 TeV will allow for much more detailed studies: ALICE muon arm 2-4 times more statistics
- ▶ CMS/ATLAS about factor 6 more statistics, LHCb factor 10 and 40 times more statistics!

2013 pPb results Υ CMS and J/ψ ALICE multiplicity dependence



CMS: [arXiv:1312.630](https://arxiv.org/abs/1312.630), ALICE: [arXiv:1704.00274](https://arxiv.org/abs/1704.00274)

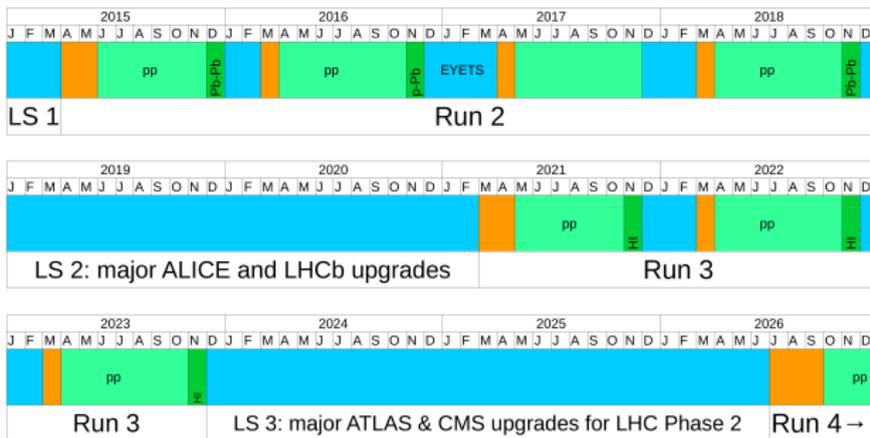
- ▶ so far only self-normalised ratios or species-by-species ratios as function of multiplicity released
- ▶ "suppression" of excited states seen as for $\psi(2S)$
- ▶ observed multiplicity dependence: state dependent
- ▶ multiplicity dependence dependent on acceptance of multiplicity measurement: both seen by CMS and by ALICE for J/ψ
- ▶ multiplicity dependence of self-normalised ratios similar in pp and in pPb

Conclusions

Rich quarkonium programme at the LHC

- ▶ low- p_T J/ψ : major qualitatively different measurement w.r.t. RHIC: sign of additional component from deconfined stage or from phase boundary
- ▶ CMS Υ measurements continue to get more precise: in conjunction with ALICE at forward rapidity constraining power for models
- ▶ LHC: phase space allows for high- p_T production studies
 $p_{T,Q\bar{Q}} > 3 - 10 M_{Q\bar{Q}}$: different order of scales, different physics, interesting on its own right
- ▶ Pb-Pb results with larger luminosity at $\sqrt{s_{NN}} = 5$ TeV than at $\sqrt{s_{NN}} = 2.76$: results just starting to become available: stay tuned
- ▶ 1st 8.16 TeV p-Pb results shown: potential to constrain or falsify nuclear PDF in kinematic region relevant for quarkonium and test of CGC calculations by comparison of $\psi(2S)$, χ_C and $\Upsilon(2S), (3S)$ and open heavy-flavour: more statistics up to a factor 40
- ▶ ALICE, CMS, LHCb active on fully reconstructed open-heavy flavour in p-Pb and PbPb: central for the understanding

Outlook



taken from [arXiv:1609.01135](https://arxiv.org/abs/1609.01135)

Short Xe-Xe run in 2017 in discussion: not useful for heavy-flavour

PbPb 2018: similar/better statistics as 2015 and ALICE central barrel $\times 2$ faster read-out

ALICE and LHCb upgrades next door (2020)

- ▶ Run 3 and 4: 50 kHz PbPb levelled interaction rate to ALICE, about 3nb^{-1} per AA year, same or more to ATLAS/CMS
- ▶ ALICE in continuous read-out and MAPS silicon for central barrel and muon arm
- ▶ LHCb with improved centrality reach: new pixel and outer-tracker optimised for 5 times more tracks in *pp*
- ▶ heavy-flavour including quarkonium: flagship improvements by upgrades
- ▶ Lots of work and exciting times ahead with Run 2 and future data takings

Back-up: D^0 in pPb