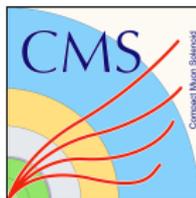


# Quarkonium production in nuclear collisions with CMS

Guillaume Falmagne

Laboratoire Leprince-Ringuet, Palaiseau (France)

On behalf of the CMS collaboration



QWG, March 19th, 2021

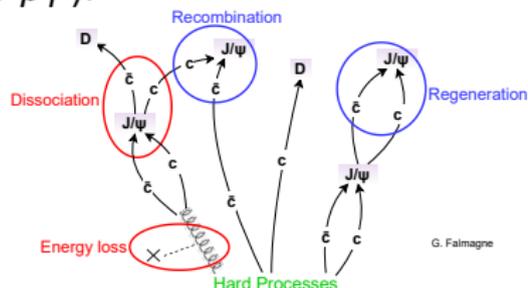
# Quarkonia in hot matter

Quark-gluon plasma (deconfined color medium) created in heavy-ion collisions: **cold nuclear matter not sufficient** to describe PbPb modification.  
Main effects of hot nuclear matter on quarkonia:

- **Dissociation** mechanisms (mostly low-mid  $p_T$ ):  
dynamical + static (**Debye screening**)  
+ sequential suppression  
+ Landau damping + comovers + ...

- **Charm recombination** (low  $p_T$ ):  
200  $c\bar{c}$  pairs in 0-5% centrality PbPb collisions!  
Transport model, statistical hadronisation, ...

- **Partonic energy loss** for the precursor parton plays a role too:  
**collisional** (mostly low  $p_T$ )  
+ **radiative** (could be dominant at high  $p_T$ , with universal behaviour)



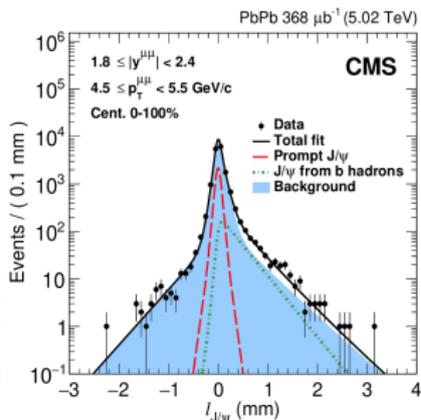
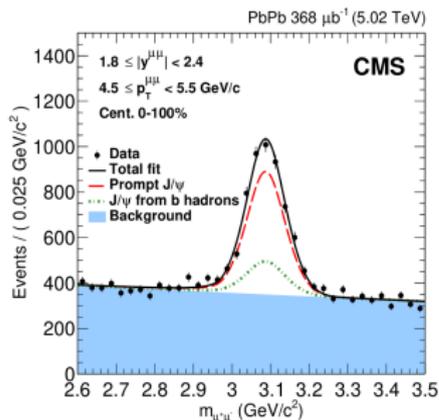
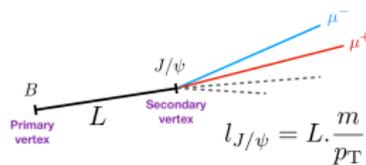
G. Falmagne

# Recent CMS results

- Prompt + Non-Prompt  $J/\psi$  modification in PbPb collisions (EPJC 78, 509 (2018))
- $\Upsilon(1S), (2S), (3S)$  modification in PbPb collisions (PLB 790, 270 (2019))
- Azimuthal anisotropy of  $\Upsilon(1S)$  and  $\Upsilon(2S)$  in PbPb collisions (submitted, arXiv:2006.07707 )
- Fragmentation of jets containing a  $J/\psi$  in PbPb collisions (preliminary)

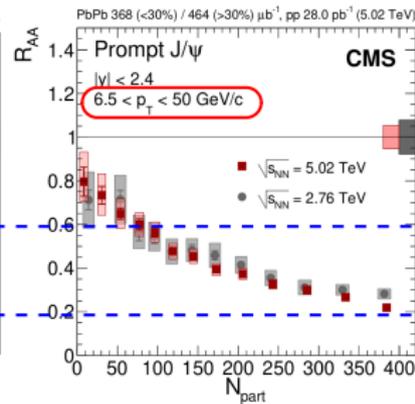
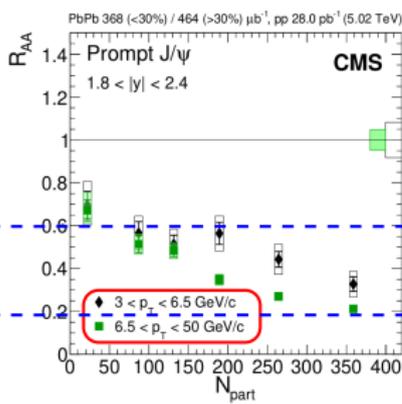
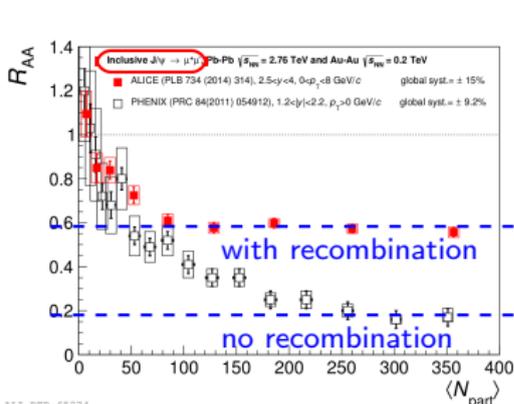
# Prompt and non-prompt J/ψ signal extraction

- CMS excellent at reconstructing mid-high  $p_T$  muons  
 → good dimuon mass resolution
- To separate prompt and non-prompt (= not pointing to primary vertex) J/ψ:
  - 2D fit mass + pseudo-proper decay length  $l_{J/\psi}$
  - Most parameters fixed by 1D fits to data, except normalisations and non-prompt signal lifetime



# Prompt J/ψ low- $p_T$ vs high- $p_T$

In general, well described by transport models.



Inclusive (low- $p_T$ ) J/ψ:

- If  $T$  (or  $\sigma_{c\bar{c}}$ ) is high enough (LHC  $\sqrt{s_{NN}}$ )  
→ important recombination
- Standard comparison of  $R_{AA}(N_{part})$  ALICE-PHENIX

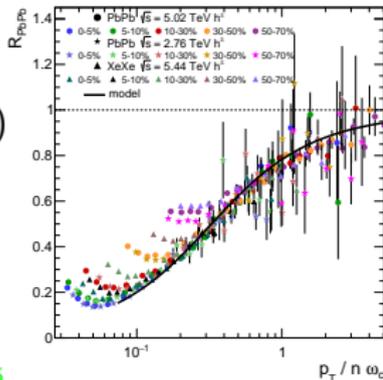
$p_T(J/\psi) > 6.5$  GeV:

- Almost no recombination
- At (very) high- $p_T$ , large-size bound state is formed late  
→ small Debye screening  
→ (partonic, radiative) energy loss could become important?

# high- $p_T$ J/ψ and partonic energy loss

- Debye screening, collisional energy loss, recombination, ... fade away at (very) high  $p_T$  → mostly **radiative energy loss** suppresses partons
- Universal shape for  $R_{AA}(p_T)$**  for light hadrons, from partonic energy loss
- Can be **extended to J/ψ** = dominantly a **fragmenting gluon** at  $p_T \gg m$  ...
- CMS + ATLAS J/ψ (and D) high- $p_T$  measurements are consistent with a universal  $R_{AA}(p_T)$

light hadrons  
(XeXe, PbPb  
at two energies)



M. Spousta

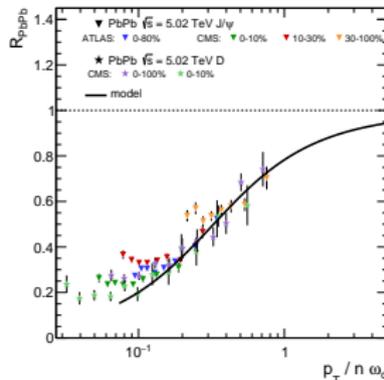
PLB 767 (2017) 10

+ F. Arleo

PRL 119 (2017) 062302

PoS, HardProbes2018, 075

J/ψ and D  
PbPb



# Is J/ψ only produced 'early'?

Standard NRQCD usually merges

- **fixed-order** perturbative QCD
- **non-perturbative** long-distance matrix elements (LDME) for hadronisation

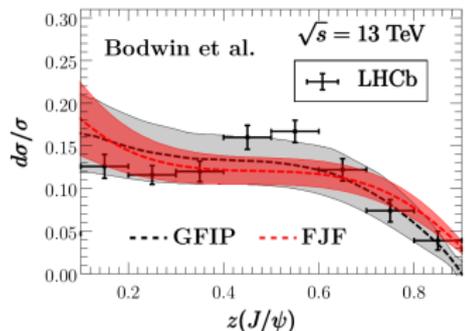
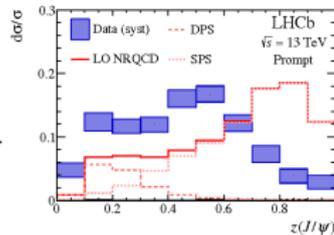
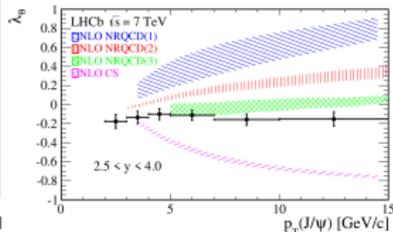
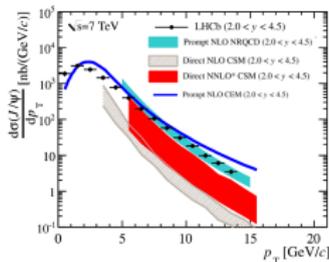
→ Variety of LDME cannot describe both cross section and polarisation

→ **Fragmentation** could play a role? Wrong in PYTHIA! →

- Hint: need to consider **parton shower** before J/ψ hadronisation! → Measure

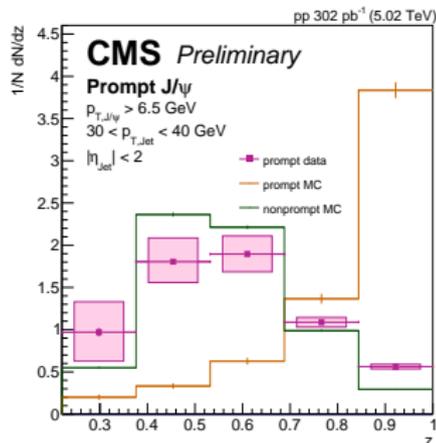
$$z = \frac{p_T(J/\psi)}{p_T(\text{jet})}$$

- Including fragmentation jet functions (FJF/GFIP) in NRQCD [Bain et al., PRL 119, 032002](#)  
→ good description of LHCb  $z(J/\psi)$  measurement



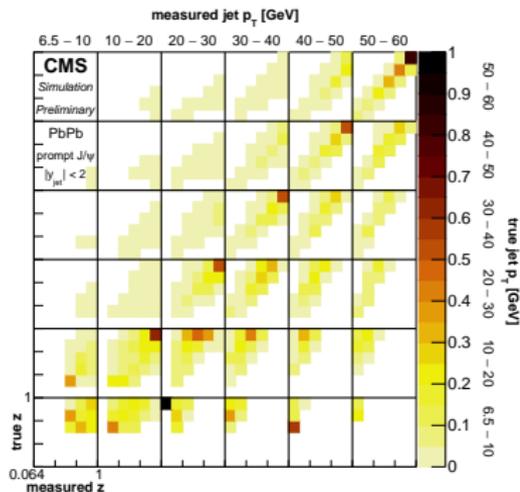
# Confirmation by CMS

- CMS measurement of  $z(J/\psi)$  in pp confirms that PYTHIA is wrongly showering the  $J/\psi$  precursor
- Prompt data closer to non-prompt (*i.e.*  $b$ -quarks) than to prompt...
  - $J/\psi$  are more 'jetty' than in generators/usual models...
  - $J/\psi$  is not always produced before QGP expands!
- But then... QGP effects on partons (energy loss) should also affect the parton shower parent of the  $J/\psi$ !
  - Measure  $R_{AA}(z)$  to check it!



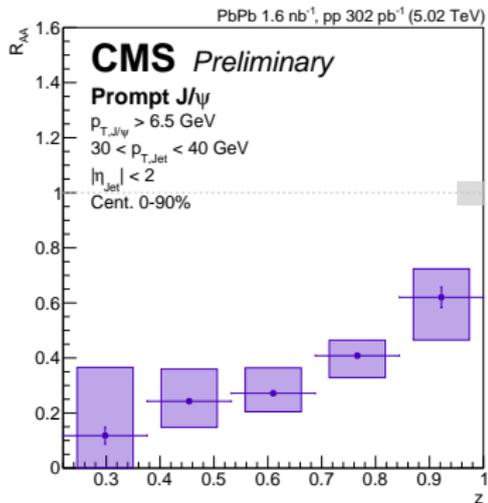
# Measuring $J/\psi$ in jets

- Extract  $J/\psi$  signal from 2D fit (mass-lifetime)
- anti- $k_T$  jet algorithm with  $R = 0.3$ , where **dimuons** consistent with a  $J/\psi$  are **replaced by the  $J/\psi$  candidate**
- In PbPb, subtract underlying event (constituent method) from jet momentum
- Look at **'fixed'** jet  $p_T \in [30, 40]$  GeV, and  $p_T(J/\psi) > 6.5\text{GeV}$
- **Unfolding of migration both in  $z$  and in  $p_T(\text{jet})$  bins** (iterative D'Agostini method)



# $R_{PbPb}(z)$ of $J/\psi$

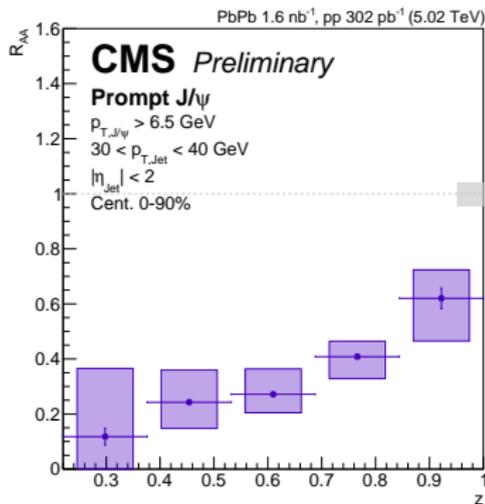
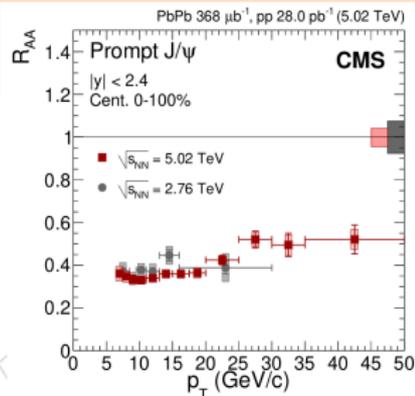
Rising  $R_{AA}(z)$  trend!



# $R_{PbPb}(z)$ of $J/\psi$

Rising  $R_{AA}(z)$  trend could be:

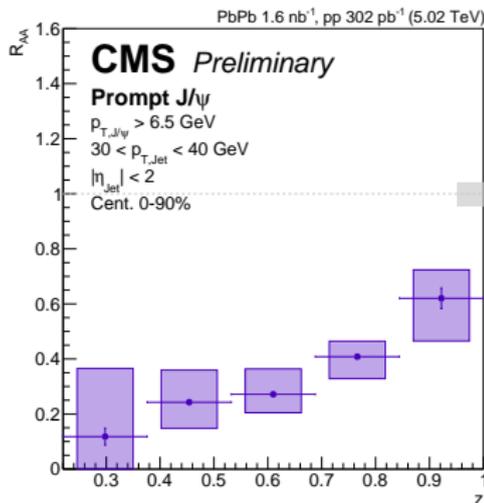
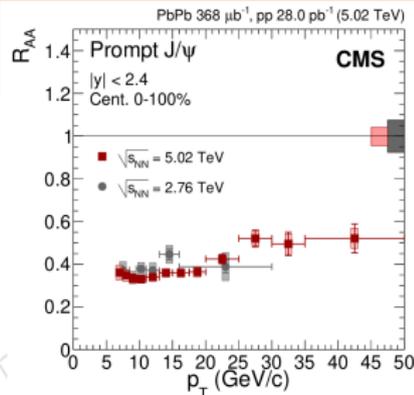
- higher  $z \sim$  higher  $p_T(J/\psi)$ 
  - follows  $R_{AA}(p_T)$  trend
  - consistent with **radiative energy loss of jet constituents** (one constituent becoming the  $J/\psi$ ) = source of high- $p_T$   $J/\psi$  suppression.



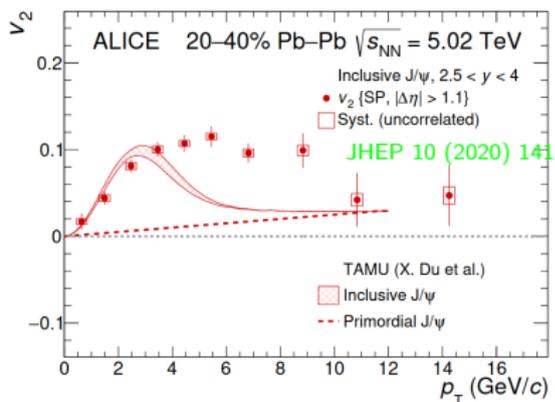
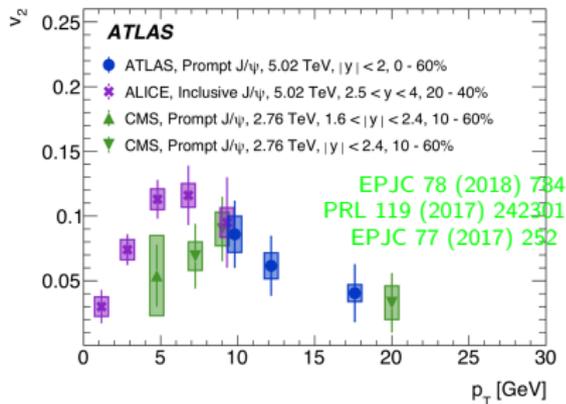
# $R_{PbPb}(z)$ of $J/\psi$

Rising  $R_{AA}(z)$  trend could be:

- higher  $z \sim$  higher  $p_T(J/\psi)$ 
  - follows  $R_{AA}(p_T)$  trend
  - consistent with **radiative energy loss of jet constituents** (one constituent becoming the  $J/\psi$ ) = source of high- $p_T$   $J/\psi$  suppression.
- Requiring an **isolated**  $J/\psi$  (high  $z$ ) could mean to select **more color-singlet** (QGP-insensitive)  $J/\psi$ , which do not undergo energy loss!



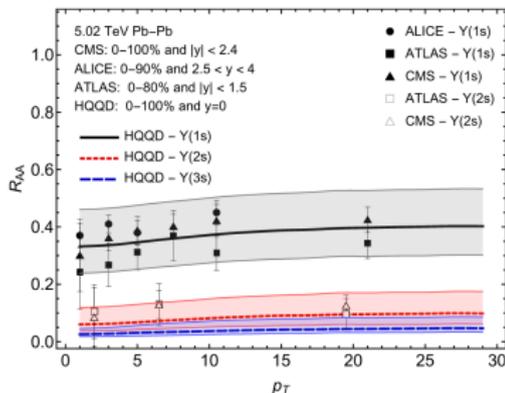
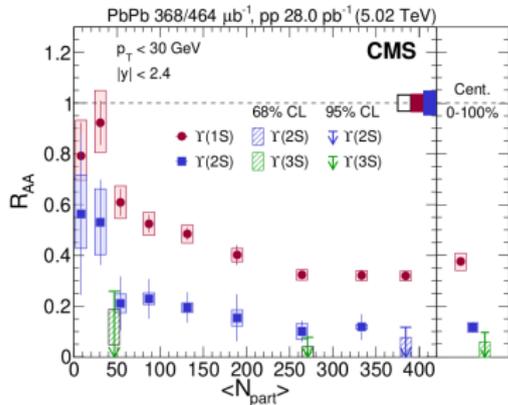
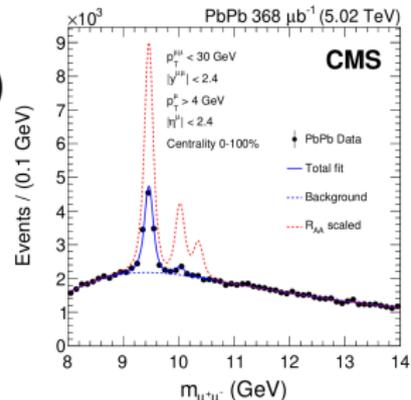
# J/ψ azimuthal asymmetry



- Low  $p_T$  shows that charm 'flows' → partially thermalised charm inherits collectivity from bulk
- High  $p_T$  shows non-zero  $v_2$  → path-length dependence of energy loss (almond shape of the medium implies more energy loss for out-of-plane than in-plane J/ψ)
  - Experimental evidence ( $v_2$ ,  $R_{AA}(z)$ ,  $R_{AA}(p_T)$ ) consistent with radiative energy loss being an essential J/ψ suppression mechanism at high  $p_T$
  - Is it the case for  $\Upsilon$  too?

$R_{PbPb}(\Upsilon)$ 

- **Smaller recombination** ( $\sigma_{b\bar{b}} = \frac{1}{20}\sigma_{c\bar{c}}$ )  
 → easier interpretation (neglecting feed-down)
- Excellent probe of the **sequential suppression**:  
 $\Upsilon(3S)$  is 'large', and extremely suppressed!
- Mostly **dissociation** processes (low-mid  $p_T$ ) +  
 partonic **energy loss** (radiative loss dominant for  
 $p_T \gg m$ , but not accessible by current data)

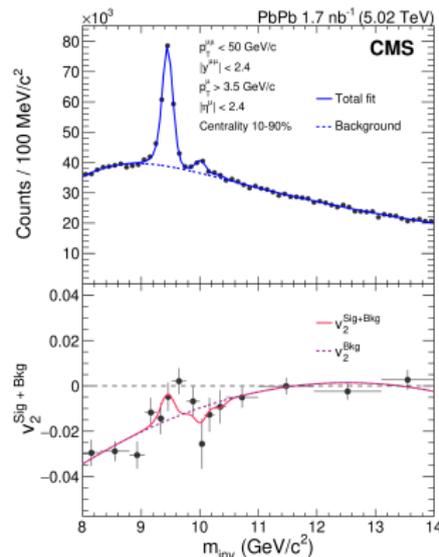


Well-described  
 too by (e.g.)  
 heavy-quark  
 quantum  
 dynamics

arXiv:2010.05457

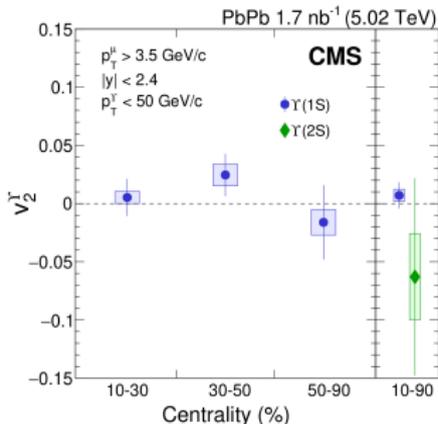
$v_2(\Upsilon)$ 

- Low- $p_T$ : Does it **flow**?  $b$  collective behaviour as  $c$ ?  
At  $p_T \gg m$ : radiative energy loss could matter  $\rightarrow$  **path-length dependence would give  $v_2 > 0$** .  
 $\rightarrow$  Measure  $v_2(\Upsilon)$  to assess this
- $v_2$  of  $\Upsilon$  candidate from **scalar product method** (from three sub-events from tracker and two hadron-forward calorimeters)
- First a mass fit to fix shape parameters, then a **simultaneous 2D mass and  $v_2$  fit** with free normalisations and background parameters
- Signal  $v_2$  assumed independent of mass.  
2nd-order polynomial for background  $v_2$ .



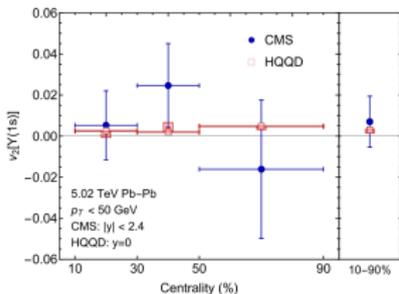
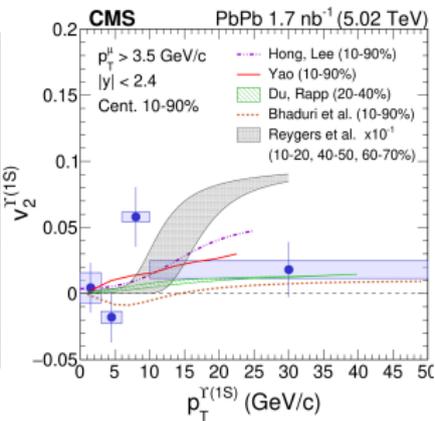
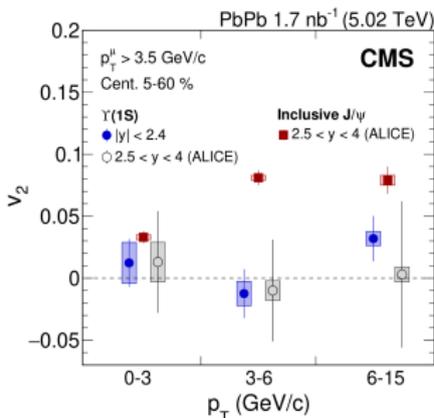
$v_2(\Upsilon)$  results

No significant evidence  
of  $v_2 > 0$  for  $\Upsilon(1S)$  nor  $\Upsilon(2S)$



Excludes high  
collectivity from  
 $b$  quarks (low- $p_T$ ),  
unlike charm

But leaves room  
for recombination, or  
path-length-dependent  
energy loss



# Conclusion

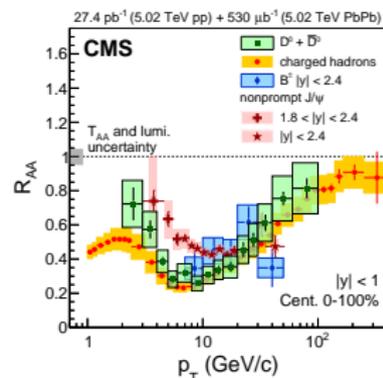
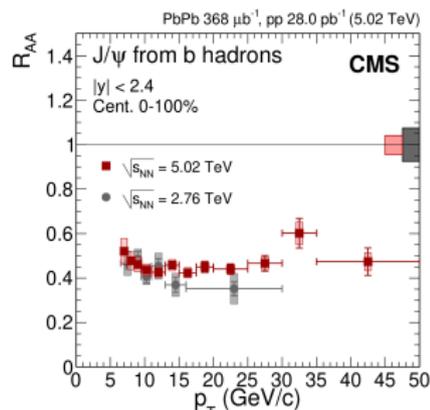
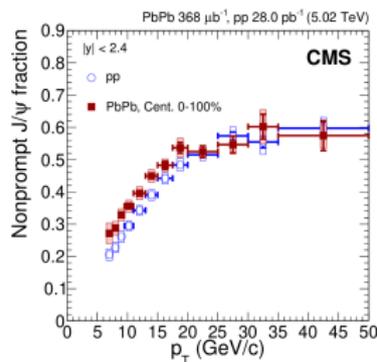
- Rich CMS results on quarkonia!
- $J/\psi$  are **not necessarily produced early** in a PbPb collision, especially at high  $p_T$
- $v_2(J/\psi) > 0$  both at low *and* high  $p_T$
- Radiative partonic **energy loss** appears to accommodate  $J/\psi$  **high- $p_T$**  behaviour
- **No evidence yet for  $v_2 \neq 0$**  for  $\Upsilon$
- Much more to come:  $B_c$  meson shedding light on recombination,  $\Upsilon$  in jets, ...

**BACKUP**

# Non-prompt $J/\psi$ ( $b$ -quark energy loss)

- Golden channel  $J/\psi$  from  $B \rightarrow J/\psi X$  (isolated via pseudo-proper decay length fit)
- Probes mostly  $b$ -quark energy loss (but kinematics of  $B$  meson are smeared)
- Can be compared to open heavy flavour and light hadrons  $\rightarrow$  hint of quark-mass dependence of energy loss (dead-cone etc.)?

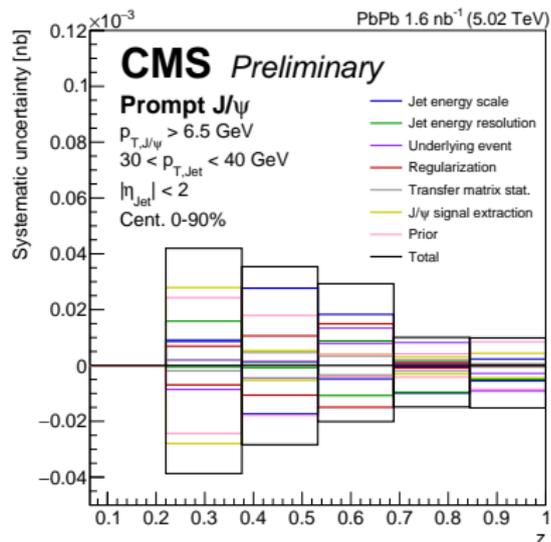
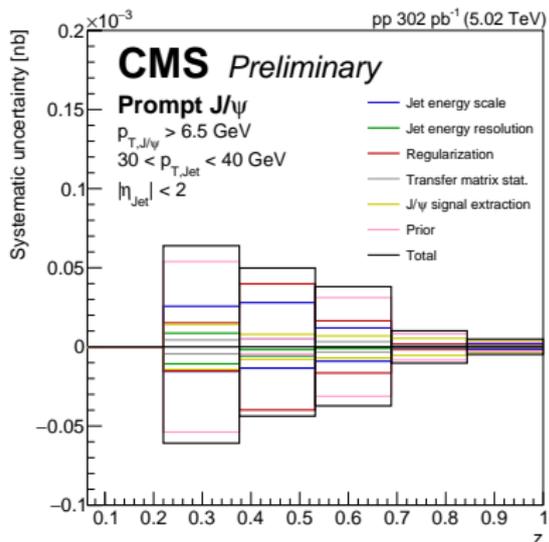
- Beware of the non-prompt fraction in inclusive  $J/\psi$  results (but expected  $< 20\%$  for  $p_T < 5$  GeV)



## Back to recombination... $B_c$ golden probe

- $b$ -quark could recombine with  $c$ -quark travelling in the medium +  $B_c$  is hard to produce in a single hard scattering (pp)
  - $B_c$  could be *dramatically* enhanced in PbPb collisions!
  - ( $2 < R_{PbPb} < 18$  in [PRC 87 \(2013\), 014910](#),  $\sim 10^3$  in [PRC 62 \(2000\), 024905](#))
  - Bridges the  $J/\psi$  and  $\Upsilon$
  - + discriminates Debye screening vs recombination!
- Analysis of semi-leptonic  $B_c^+ \rightarrow J/\psi \mu^+ \nu$  channel, (partially reconstructed but higher branching fraction)
- 2D fit of BDT variable and trimuon mass variable
- Results coming soon ...

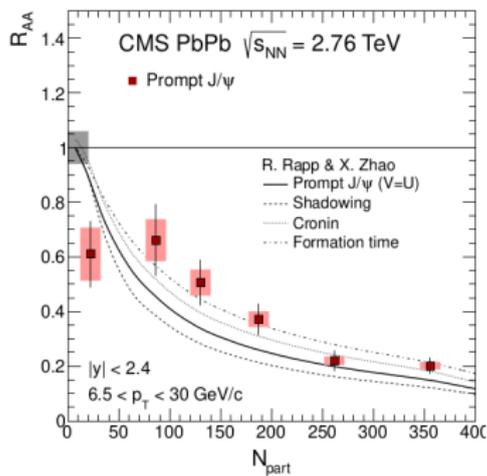
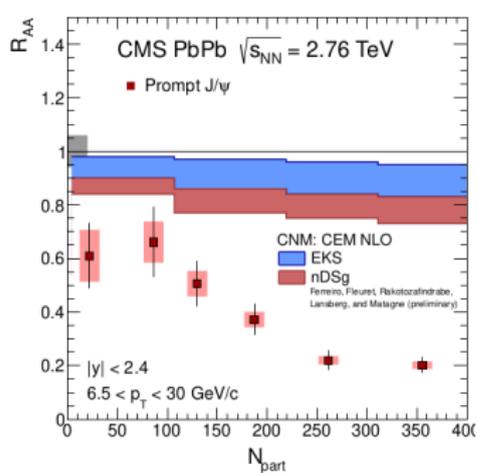
# $J/\psi$ in jets systematics



## $v_2(\Upsilon)$ systematics

- Signal (free some parameters) and background (vary model) fit functions
- Acceptance and efficiency corrections:
  - with or without weighting the MC  $p_T$  spectrum)
  - Tag-and-probe uncertainties
- Event-level selection

# $R_{PbPb}(J/\psi)$ theory comparisons



# $R_{PbPb}(\Upsilon)$ theory comparisons

