

# Rencontres QGP-France, Etretat : Quarkonium $v_2$ at forward rapidity in Pb-Pb collisions at 5.02 TeV

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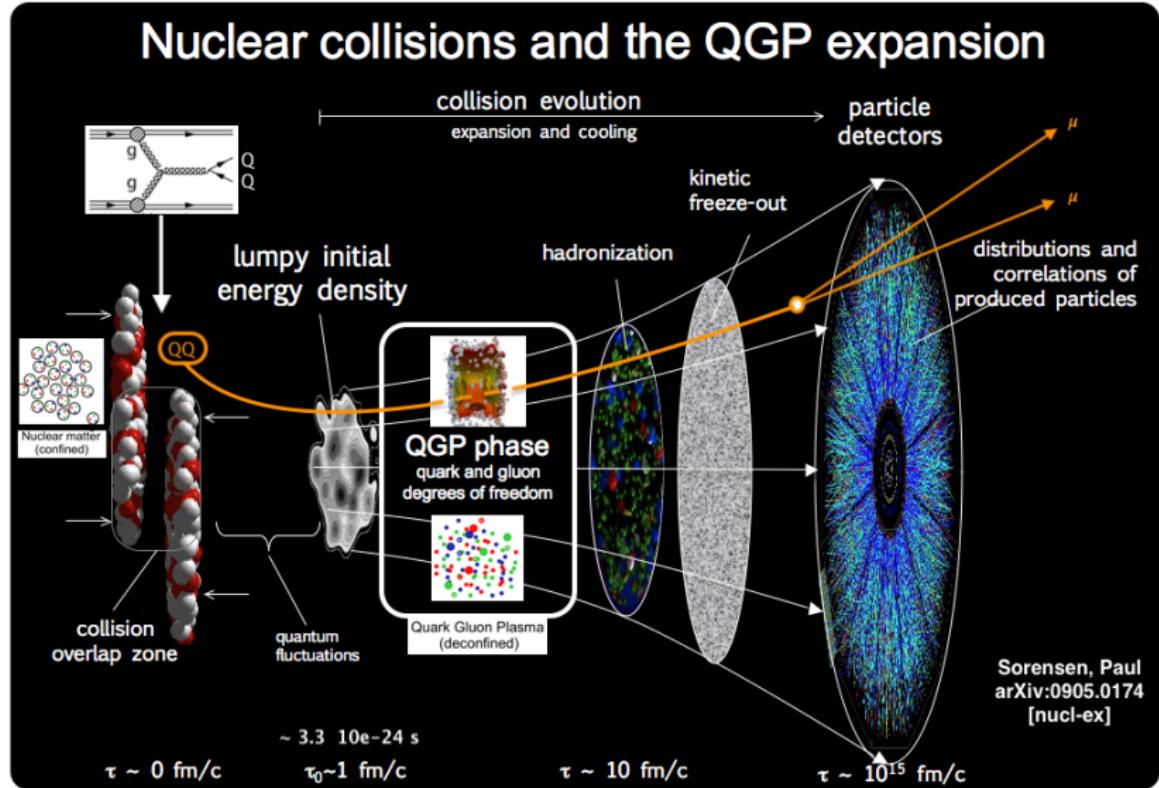
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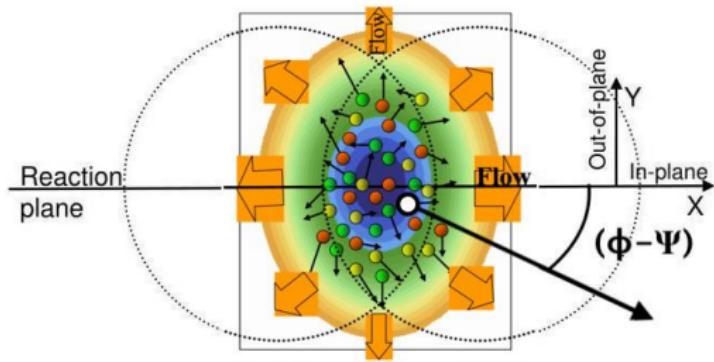
# Outline

- ① Physics motivation
- ② Data set and calibration
- ③ Quarkonium  $v_2$  in Pb-Pb collision
  - $J/\psi$  and  $\Upsilon(1S)$   $v_2$  extraction
  - Study of systematic uncertainties
  - $v_2(p_T, N_{part}, y)$  dependencies
- ④ Conclusion

# Probing the medium with quarkonium



# Collective behavior : the elliptic flow $v_2$



- **Azimuthal particles distribution** measured with respect to reaction plane (decomposed by Fourier series, where  $n$  : harmonic ):

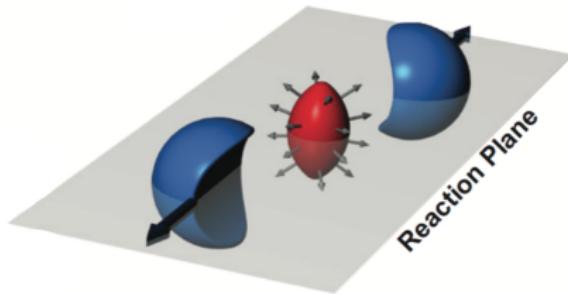
$$\frac{dN}{d\phi} \propto \left( 1 + 2 \sum_{n=1}^{+\infty} v_n \cos [n(\phi - \Psi_n)] \right) \quad (1)$$

- **Reaction plane (RP)** : define by *beam axis z* and *impact parameter b*

## Flow vector and EP angle

- Estimation of the **reaction plane** (RP) by the  $\mathbf{Q}_n$  vector ( $N$  : number of charged particles in an event, tracklets in SPD)

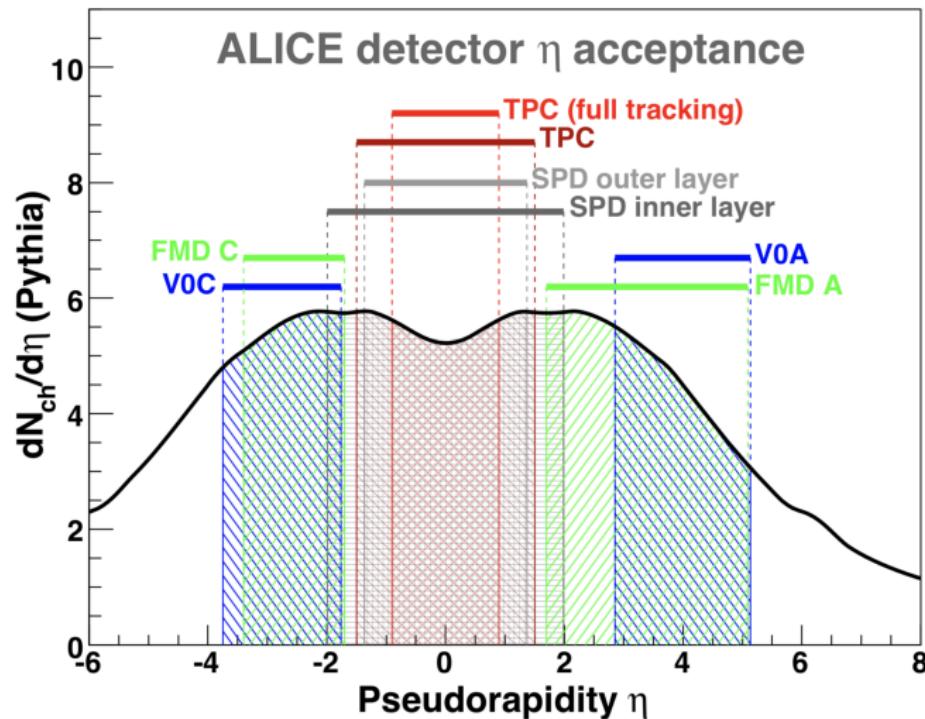
$$\mathbf{Q}_n = \sum_{j=1}^N e^{in\phi_j} = |Q_n|e^{in\Psi_n} \quad (2)$$



- Then, to determine the *Event Plane* (EP) angle  $\Psi_n$  :

$$\Psi_n = \frac{1}{n} \arctan\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \quad (3)$$

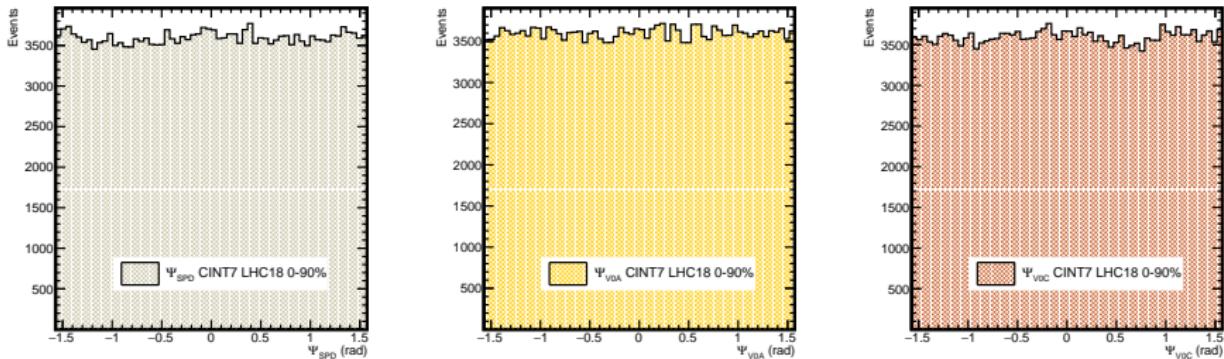
# Position of detectors (with different $\eta$ range)



# Event plane angle $\Psi_2$ distribution

Calibration steps on flow vector  $\mathbf{Q}_2$  (run-by-run basis, as function of  $z_{vertex}$  and centrality), based on the article : arxiv0707.4672

- ① Gain equalization for channels in V0A, V0C
- ② Re-centering and width equalization for SPD, V0A, V0C
- ③ Alignment only for V0A, V0C
- ④ Twist and re-scale correction for non-uniform acceptance



All the corrections on flow vector  $\mathbf{Q}_2$  lead to a flattened  $\Psi_2$  distribution  
(applied for MB events in SPD, V0A, V0C)

# Extraction of the $v_2$ coefficient

$J/\psi$  and  $\Upsilon$  reconstructed via :  $\mu^+\mu^-$  decay channel, at forward rapidity  $2.5 < y < 4$ . Integrated luminosity  $L = 0.75 \text{ nb}^{-1}$ .

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- The elliptic flow coefficient  $v_2$  is measured using azimuthal correlation between  $\phi_{\mu\mu}$  and the EP angle  $\Psi_2$ , as the following formula :

$$v_2 = \frac{v_2^{obs}}{R_2} = \frac{\langle \langle \cos 2(\phi_{\mu\mu} - \Psi_2) \rangle \rangle}{R_2} \quad (4)$$

- $\langle \langle \dots \rangle \rangle$  : mean over all dimuons, and all events
- $\alpha(m_{\mu\mu}) = \frac{S}{S+B}$  is extracted from the invariant mass fit
- $v_2^{sig}$  : is extracted by fitting the total  $v_2$  of all the dimuon pair :

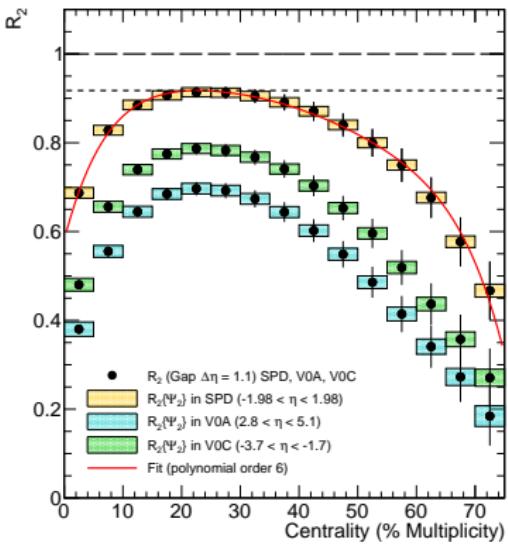
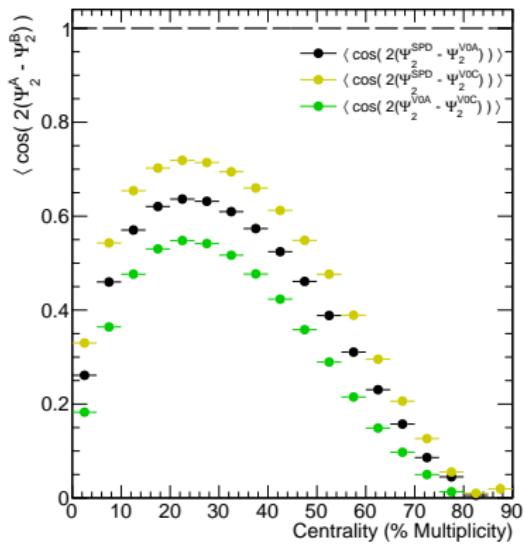
$$v_2 = v_2^{bkg}(1 - \alpha) + v_2^{sig}\alpha \quad (5)$$

- $v_2^{bkg}$  is parametrized by a polynomial, chebyshev polynomial (order 0,1,2)

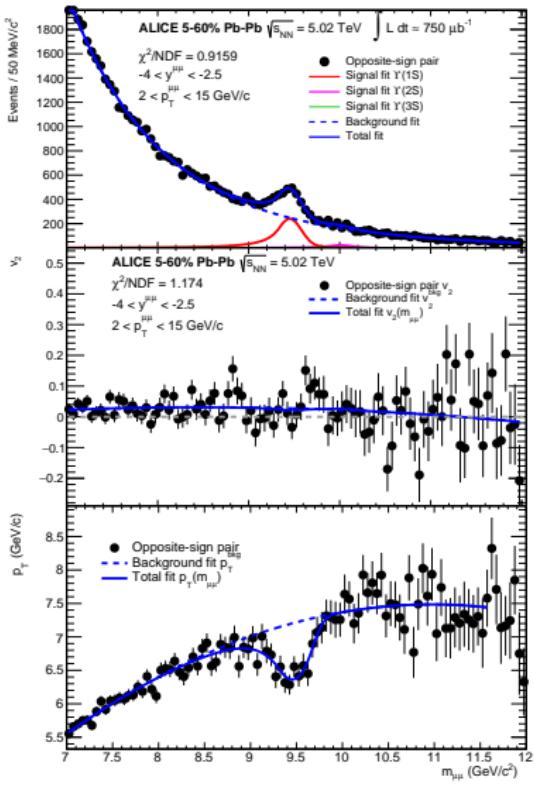
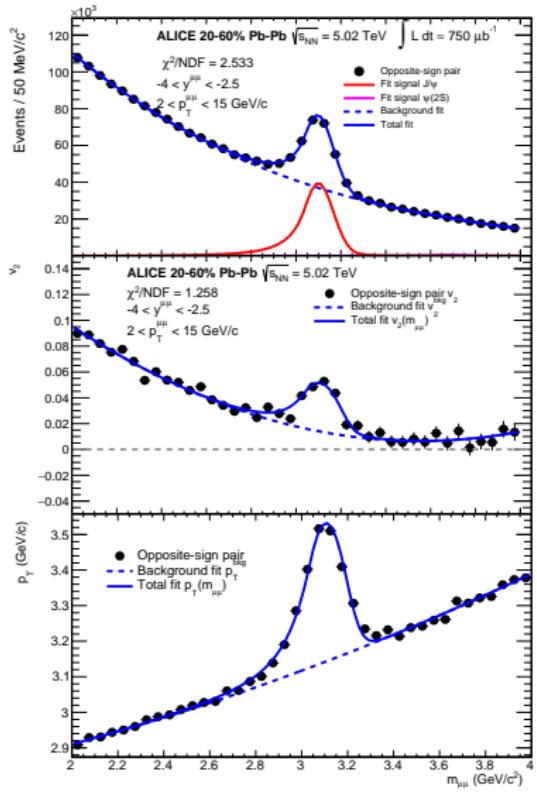
# Event plane resolution $R_2$

Compute the EP resolution  $R_2$  from the 3 sub-detectors ( $\Delta\eta = 1.1$ ):

$$R_2(\Psi_{2,SPD}) = \sqrt{\frac{\langle \cos 2(\Psi_2^{SPD} - \Psi_2^{V0A}) \rangle \langle \cos 2(\Psi_2^{SPD} - \Psi_2^{V0C}) \rangle}{\langle \cos 2(\Psi_2^{V0A} - \Psi_2^{V0C}) \rangle}} \quad (6)$$



# Quarkonium $v_2$ in Pb-Pb collisions



# Systematic uncertainty

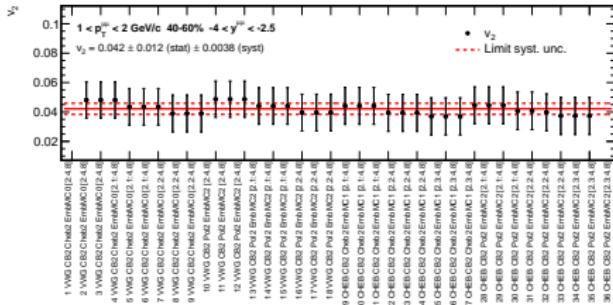
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Source of systematic uncertainties :

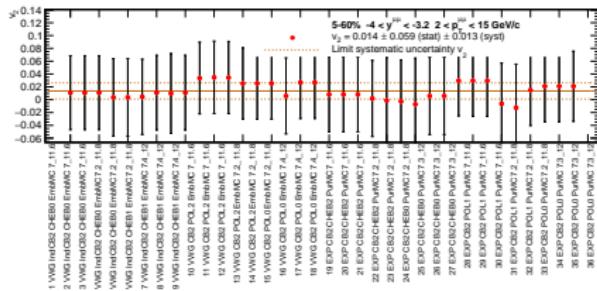
- **$J/\psi$  and  $\Upsilon$  reconstruction efficiency** (relate to detector occupancy)
  - ▶ Evaluate from Embedding MC ( $J/\psi$  and  $\Upsilon$  decays were simulated with azimuthally isotropic distribution) for each centrality,  $y$  and  $p_T$  class
- **Signal extraction** : computed for each centrality,  $y$  and  $p_T$  class
- **EP resolution  $R_2$**  : which is determined to be 1 % (it is correlated with *the centrality determination*)
- Other systematic uncertainties affecting the measurement independently of the azimuthal dimuon angles  $\phi_{\mu\mu}$ , should a priory not impact the measured  $v_2$ .

# Signal extraction

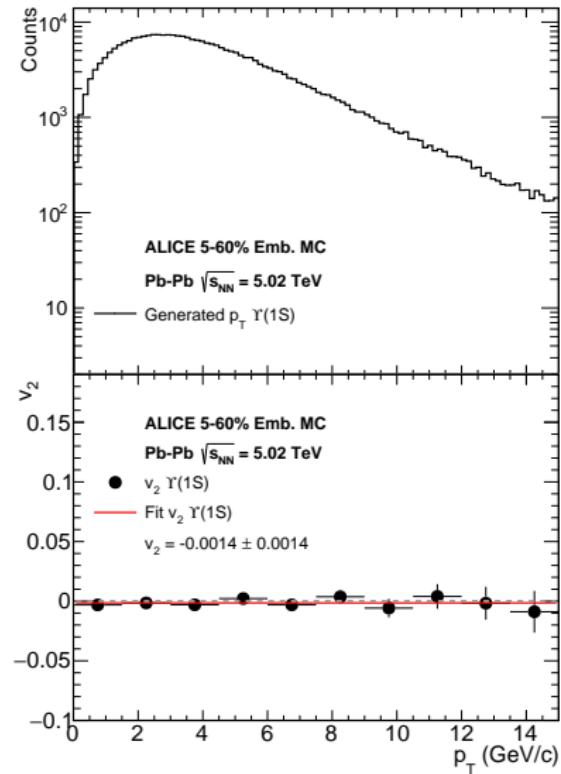
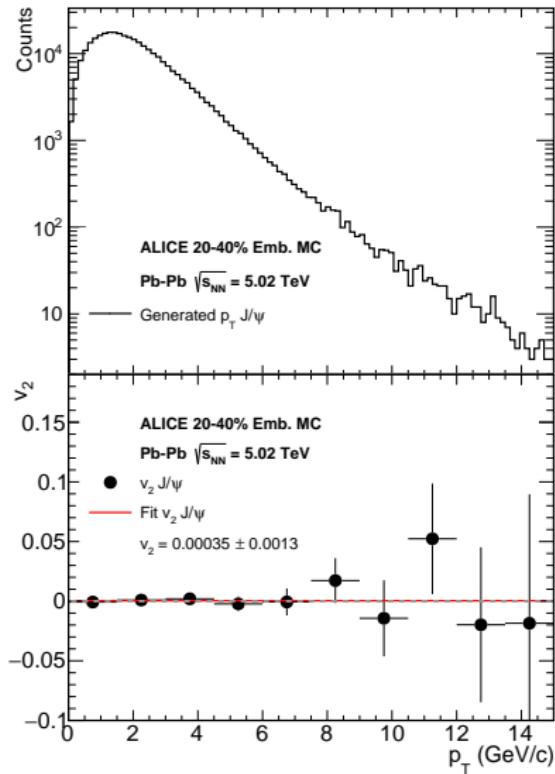
Systematic uncertainty on  $v_2$  from signal extraction for  $J/\psi$ :



Systematic uncertainty on  $v_2$  from signal extraction for  $\Upsilon(1S)$ :

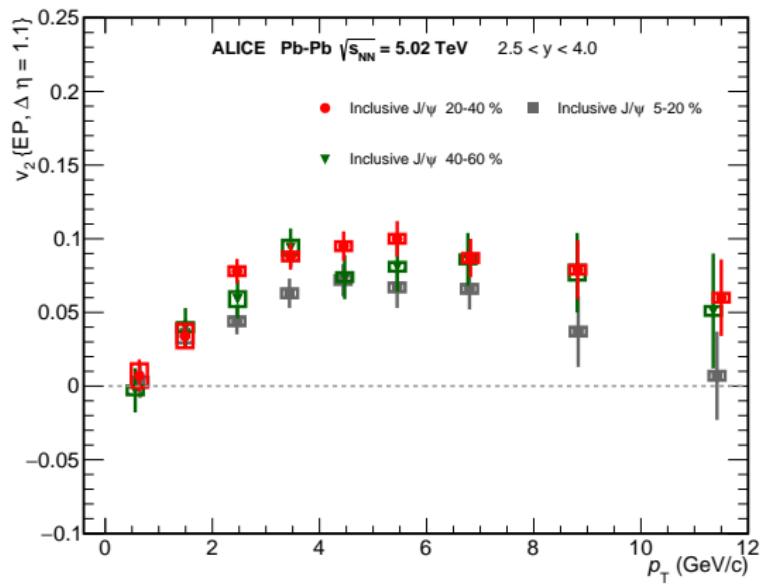


# Systematic uncertainty from Embedding MC

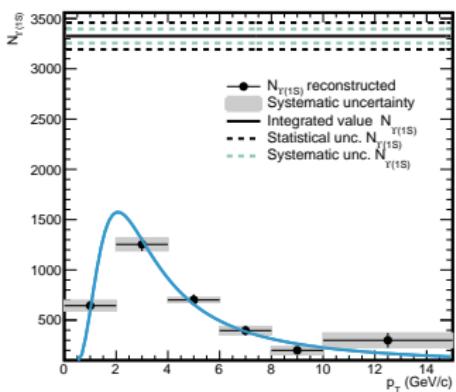
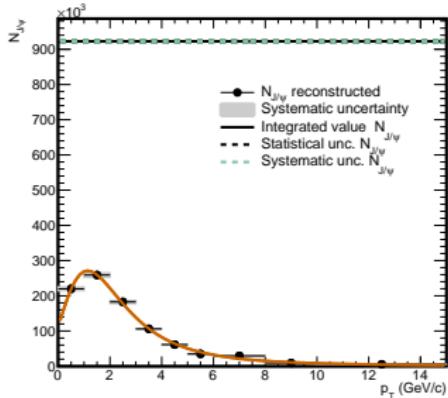
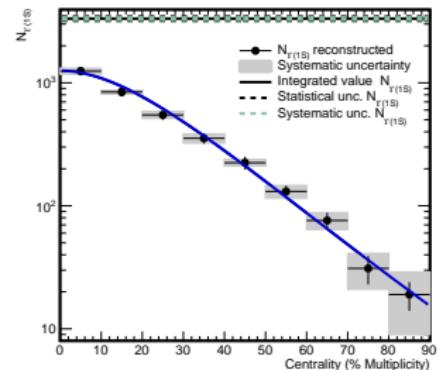
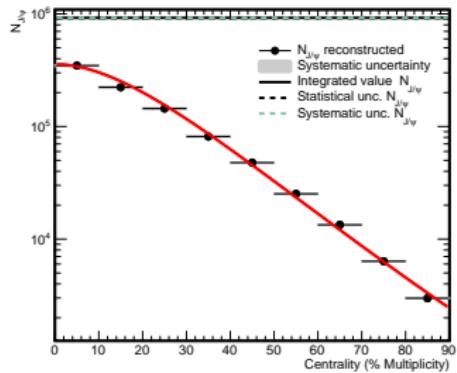


# Quarkonium $v_2$ in Pb-Pb collisions

Centrality	$\langle N_{part} \rangle$	$R_2$ (weighted by $N_{J/\psi}$ reconstructed)
5-20 %	$287 \pm 4$	$0.853 \pm 0.008$ (syst)
20-40 %	$160 \pm 3$	$0.911 \pm 0.009$ (syst)
40-60 %	$70 \pm 2$	$0.839 \pm 0.008$ (syst)



# $J/\psi$ and $\Upsilon(1S)$ production

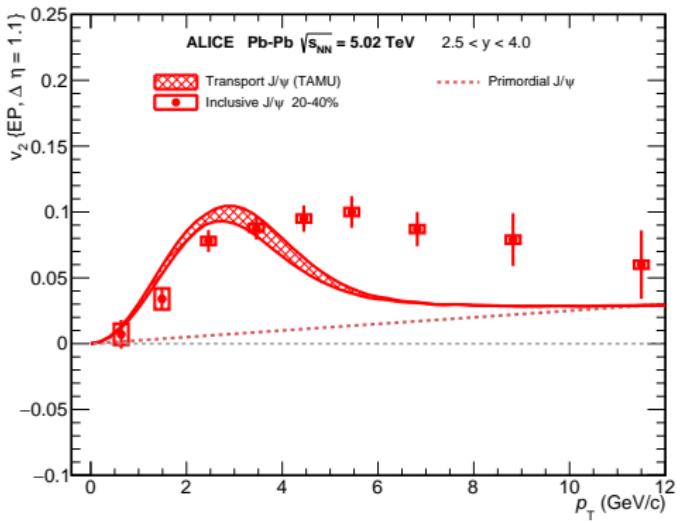


# Quarkonium $v_2$ in Pb-Pb collisions

- Probe  $J/\psi$  regeneration from thermalized charm quark at low- $p_T$ .
- Path-length regime (for primordial  $c\bar{c}$ ) for high- $p_T$  particles

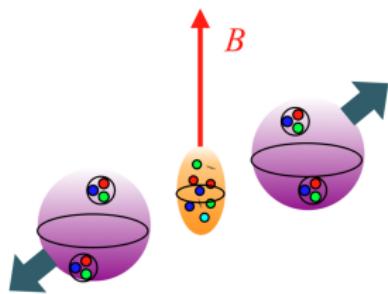
- ➊  $v_2$  from regenerated  $J/\psi$  created by thermalized charm quark in the medium
- ➋  $v_2$  from primordial  $J/\psi$  formed + feedown
- ➌  $v_2$  from non-prompt  $J/\psi$  : B hadrons decays

Comparison with transport model (Du and Rapp arXiv:1504.00670),  $v_2$  as a function of  $p_T$  in  $2.5 < y < 4$  in 20-40 %.



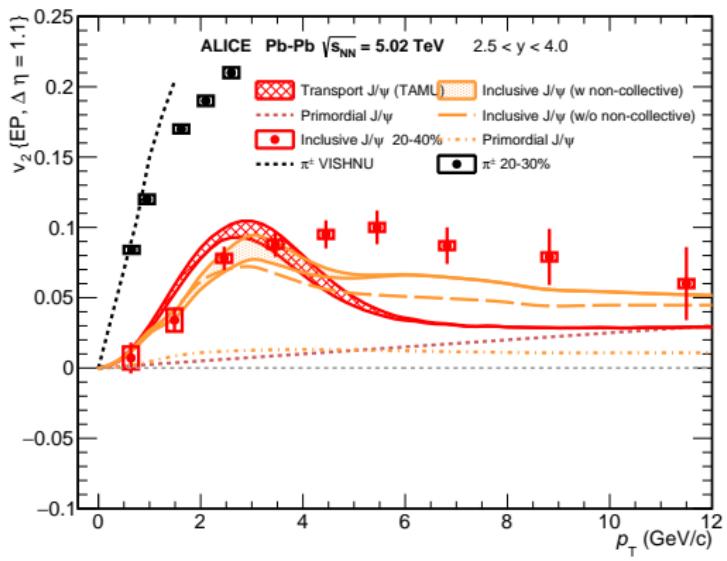
# Quarkonium $v_2$ in Pb-Pb collisions

Proton **spectators** create electric charges asymmetry



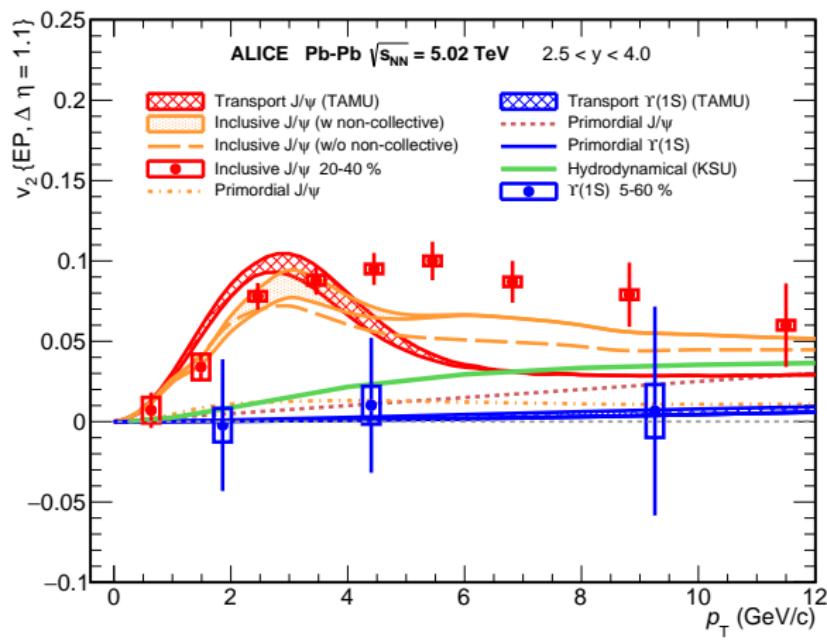
additional strong magnetic field during system expansion, intense at early stage of collision  
(arXiv:1512.03689)

Comparison with other transport model (K. Zhou et al. arXiv:1502.04407),  $v_2$  as a function of  $p_T$  in  $2.5 < y < 4$ , in 20-40 %.



# Quarkonium $v_2$ in Pb-Pb collisions

Comparison with models of  $v_2$  for  $J/\psi$  and  $\Upsilon(1S)$  as a function of  $p_T$  in forward rapidity  $2.5 < y < 4$ . **Hydrodynamical** (KSU : arXiv:1809.06235) and **Transport** Model (TAMU : arXiv:1706.08670) can explain  $\Upsilon(1S)$   $v_2$

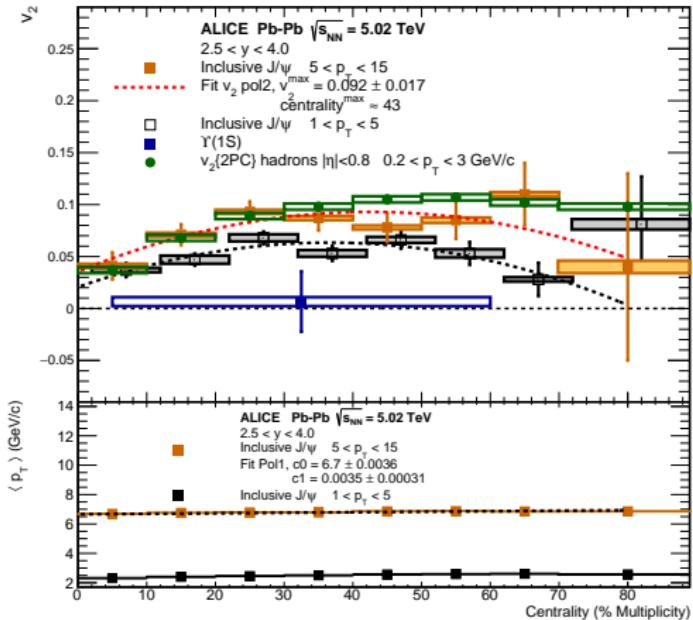


# $v_2$ as function of $N_{part}$

- Probe the **initial spatial geometry** of the collision (eccentricity) and initial density fluctuations

- $v_2^{max}$  in 40-50 %, corresponding to  $\langle N_{part} \rangle \approx 70 \pm 2$
- $J/\psi v_2$  follow the behavior of inclusive hadrons  $v_2$  for central collisions, only for  $p_T > 5$  GeV/c

Quarkonium  $v_2$  as a function of centrality, for the  $p_T$  range : 1 – 5, 5 – 15 GeV/c (for  $J/\psi$ ) and 2 – 15 GeV/c ( $\Upsilon(1S)$ )

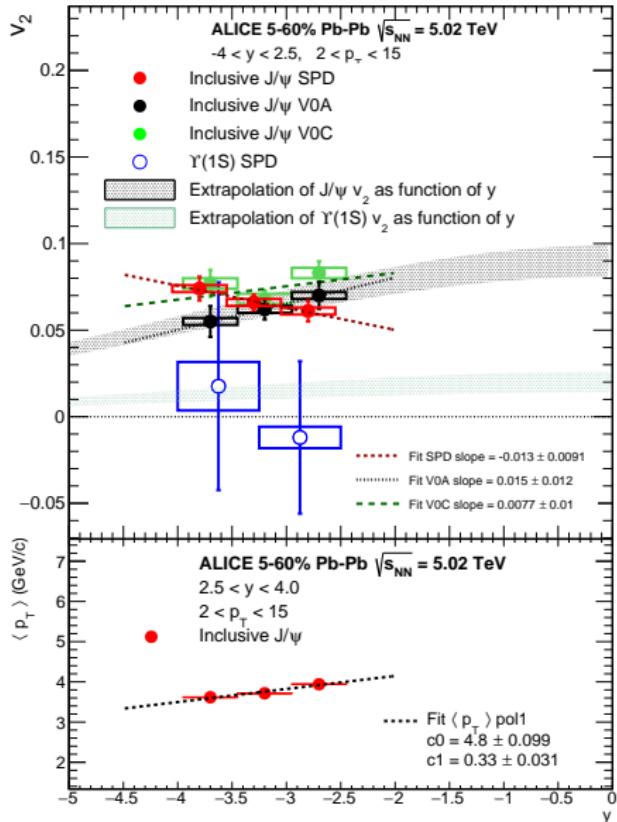


# $v_2$ as function of rapidity

- Relate to **initial energy density**  $\epsilon$  and number of initial created  $Q\bar{Q}$  pair
- Probing **decorrelation** effect with  $\Delta\eta$  (with different detectors)

$v_2$  as a function of rapidity for 2 – 15 GeV/c, in 5-60 %

- Not clear dependence of  $v_2(y)$  but it could be depend by which detector is used



# Conclusion

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## Inclusive $J/\psi$ $v_2$ in Pb-Pb at 5.02 TeV

- Confirm **regeneration mechanisms at low  $p_T$** , with full Run 2 Data.
- Tensions with models beyond 4 GeV/c but additional **strong magnetic field during system expansion** can help to understand higher  $v_2$  at intermediate  $p_T$
- Need a global picture of  $v_2(p_T, N_{part}, y)$  for interpretations :
  - ▶ **Initial geometry** of non-central collision (centrality  $\approx 40\%$ ) in favors of a maximal  $v_2$
  - ▶ Not clear dependence of  $v_2$  vs.  $y$ , but seems to be biased by which  $\Delta\eta$  are used (from sub-detectors... decorrelation effects)

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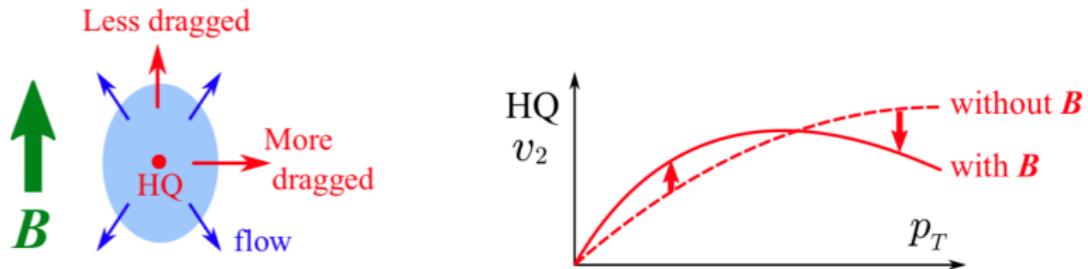
## $\Upsilon(1S)$ $v_2$ in Pb-Pb at 5.02 TeV

- $v_2$  **compatible with 0** within uncertainties (not/or weakly participating to medium collective flow), **lower than  $J/\psi$**  (by approximately  $2.5\sigma$ )
- $v_2$  compatible with current Hydro and Transport models

**Thank you for your attention !**

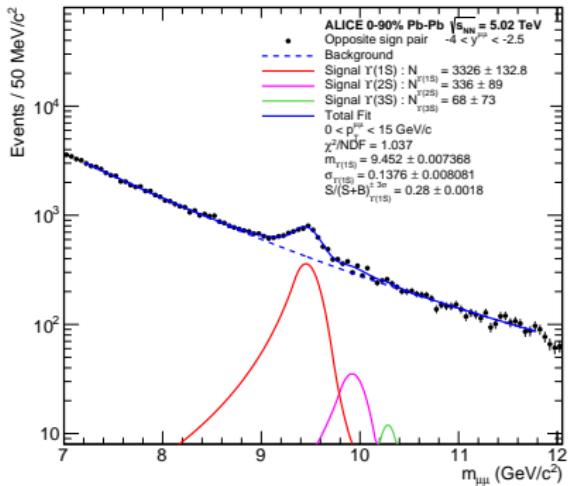
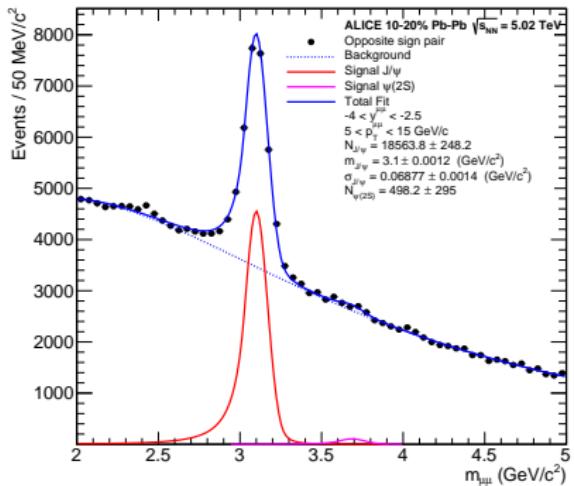
# Strong magnetic field effect on HQ $v_2$

- Transport description for heavy quark (arXiv:1512.03689) :
  - ▶ **QGP expansion in presence of strong electromagnetic fields**
  - ▶ Heavy quark (HQ) in finite temperature plasma are subject to **random kicks from thermally excited quarks and gluons**, their motion is described by the Langevin equations



- Hydro description (arXiv:1706.05326) :
  - ▶ **2 + 1 dimensional reduced magneto-hydrodynamical** expansion of hot and dense nuclear matter
  - ▶ Energy-momentum tensor need to be conserved  $\partial_\nu T^{\mu\nu} = 0$  and is separate in 2 components :  $T^{\mu\nu} = T_{matter}^{\mu\nu} + T_{field}^{\mu\nu}$

# Signal extraction (plots examples)



For more details about production of quarkonia: arxiv1903.09185  
and for quarkonia in QGP: arxiv1302.2180

# Signal extraction (plots examples)

