# Investigating the $J/\psi$ flow

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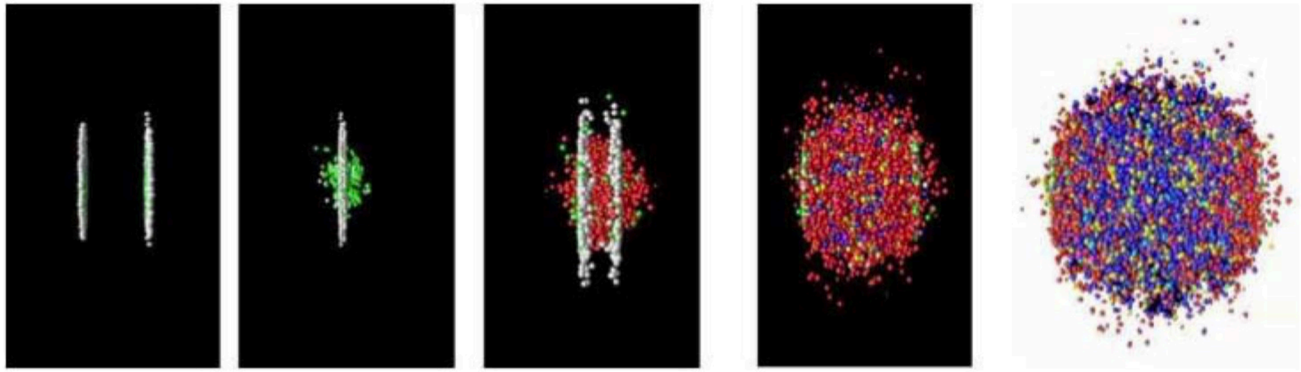
# Forming the QGP and studying it

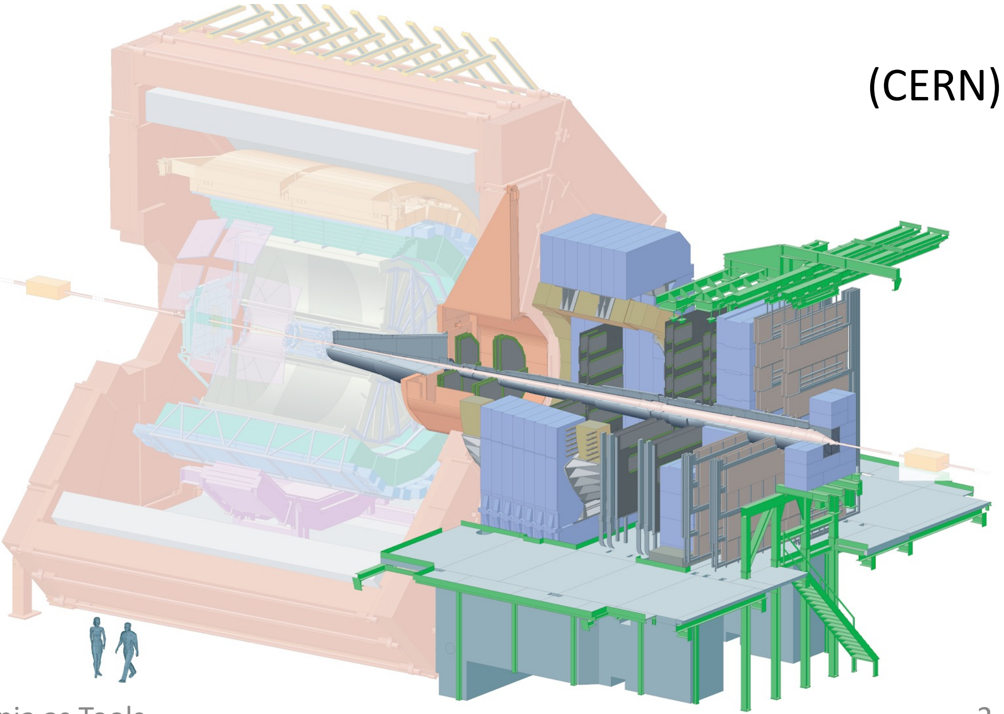
**Study of Quark-Gluon Plasma (QGP)**

- Deconfined state of matter
- Freely-roaming color charges



**Formation through Heavy-ion collisions**

Pb-Pb ⇒ Formation of QGP
Pb-p, p-p ⇒ Reference (Cold Nuclear Matter (CNM) effects, assume no QGP formation)



(CERN)

**What to look at ?**

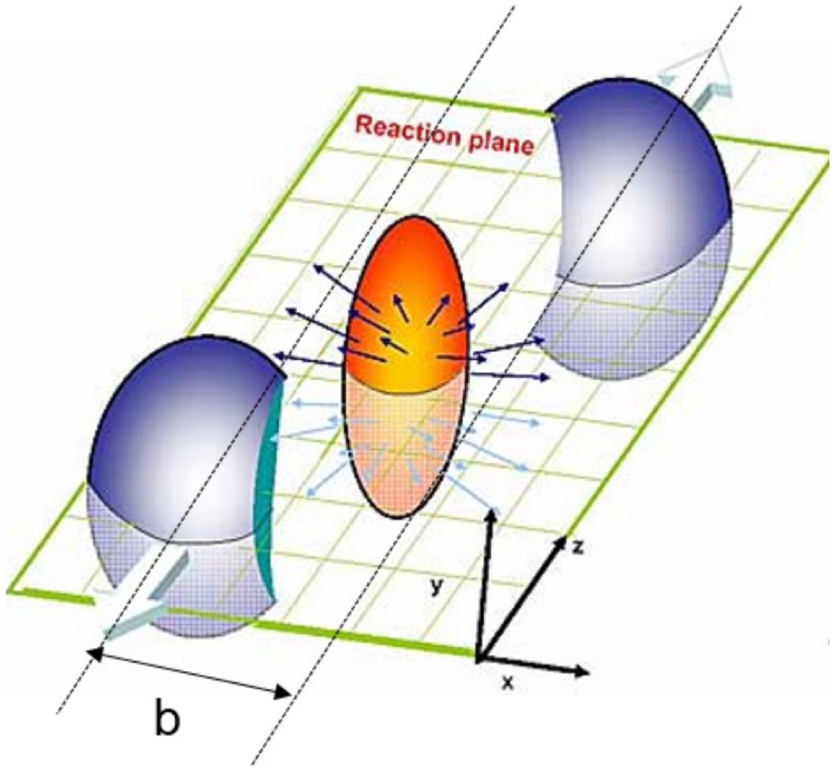
Focus on quarkonium ($Q\bar{Q}$)

Formed before the QGP
Influenced by color charges
Insight on QGP properties (e.g. Temperature)

# What is flow ?

In Heavy-ion collisions, anisotropic collision region

- Anisotropies in momentum distribution
- Long-range correlations of produced particles




Taken from Universe, 2017

[arXiv:nucl-ex/9805001]

Azimuthal correlations of particles quantified by Fourier coefficients in $\phi$ angle distribution (wrt event plane if large multiplicity), or 2-particle correlations (in smaller systems)

$$\frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left( 1 + \sum_n 2v_n \cos[n(\phi - \Psi_n)] \right)$$

$$\frac{dN^{pairs}}{d\Delta\phi} \propto (1 + \sum_{n=1}^{\infty} 2v_n^2 \cos(n\Delta\phi)).$$

$v_2$ (elliptic) related to the initial geometry of the collision
$v_3$ (triangular) related to fluctuations

Flow is a signature of QGP formation as it shows collective behaviours

Constrains theoretical models

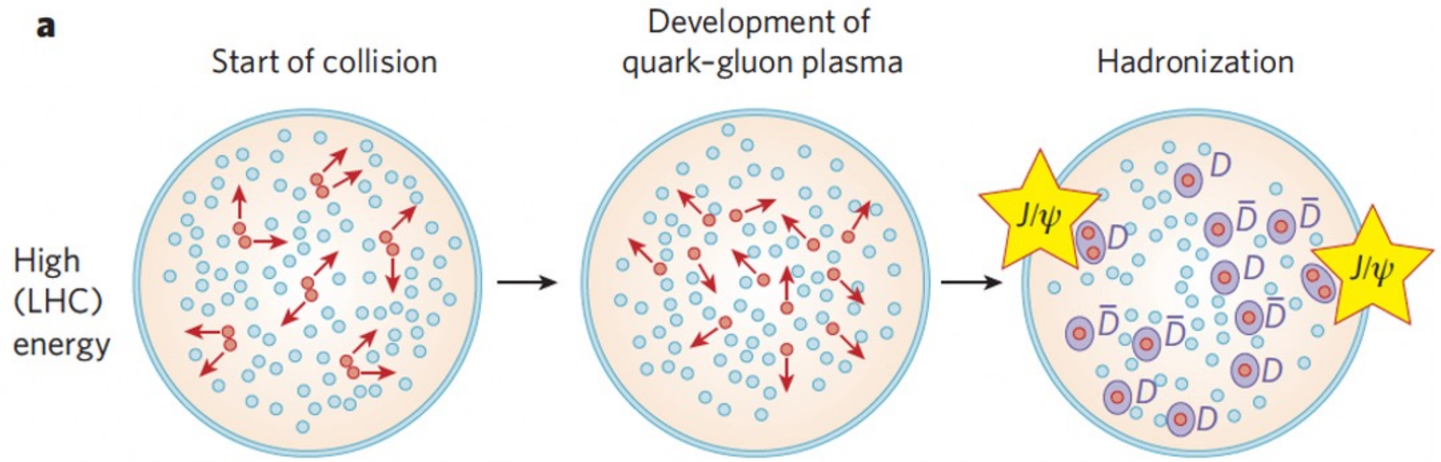
# Explaining the $J/\psi$ flow

**Final State effects**

Flow is **acquired through QGP evolution** (geometry-related)

Two sources for the $J/\psi$ flow:

- (Re)combination of charm quarks (flow inheritence)
  - At freeze-out
  - Dynamic transport model
- Path-length dependent suppression (primary $J/\psi$)




[*Nature* **448,** 302–309 (2007)]

# A first: PHENIX-STAR (Au-Au $\sqrt{s_{NN}} = 200$ GeV)

## Motivation:

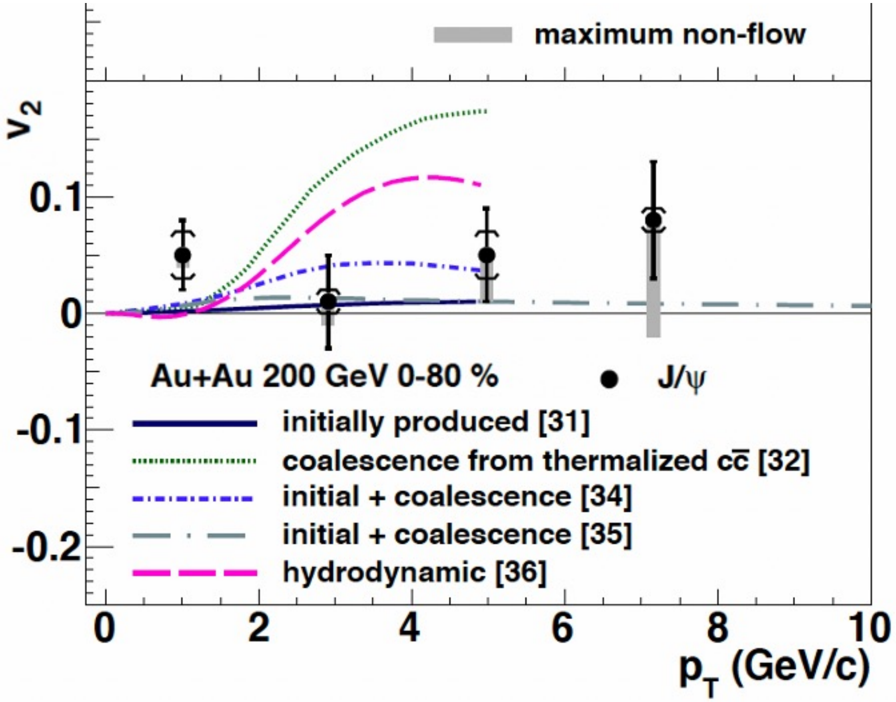
How is the $J/\psi$ produced ? Is it through regeneration ?

## Observations:

- $v_2$ compatible with 0 above 2 GeV/c
- Compatible with initial state and/or transport
- Rules out coalescence at freeze-out

$J/\psi$ regeneration is not dominant at RHIC

[arXiv:1212.3304]
Data from 2010



# Pb-Pb, $J/\psi$ regenerates

[arXiv:2005.14518]

## Pb-Pb ALICE (Run2, inclusive, 5.02 TeV)

Higher energy than RHIC: more c and thermalisation of c

Comparison to transport model (TAMU, X. Du et al.)

(which reproduces nicely $R_{AA}$ behaviour)

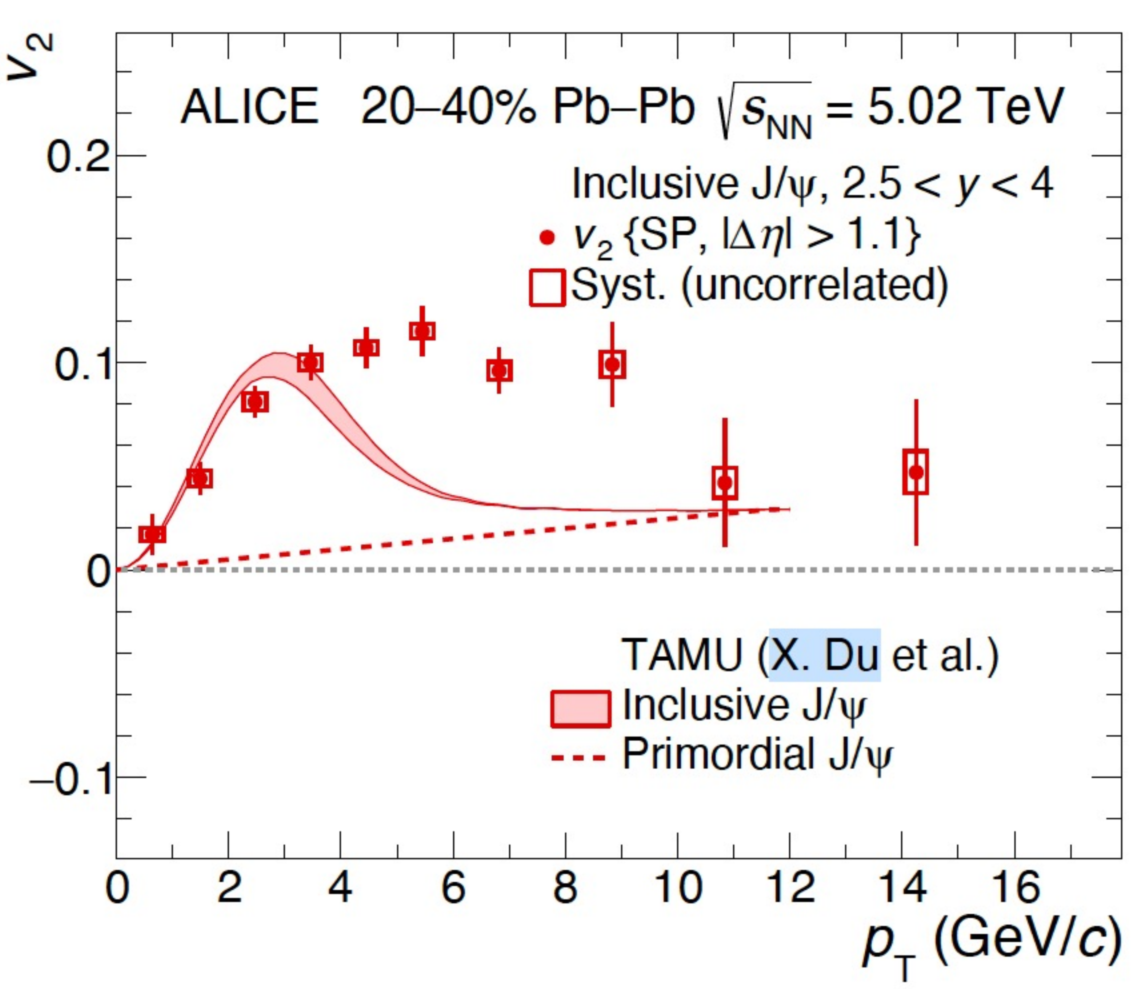
Overall behaviour OK-ish:

- Increase at low- $p_T$ (recombined c quarks)
- Decrease at high- $p_T$ (less recombination)
- Non-0 asymptote (only path-length dependence in primordial $J/\psi$ bring a small $v_2$)

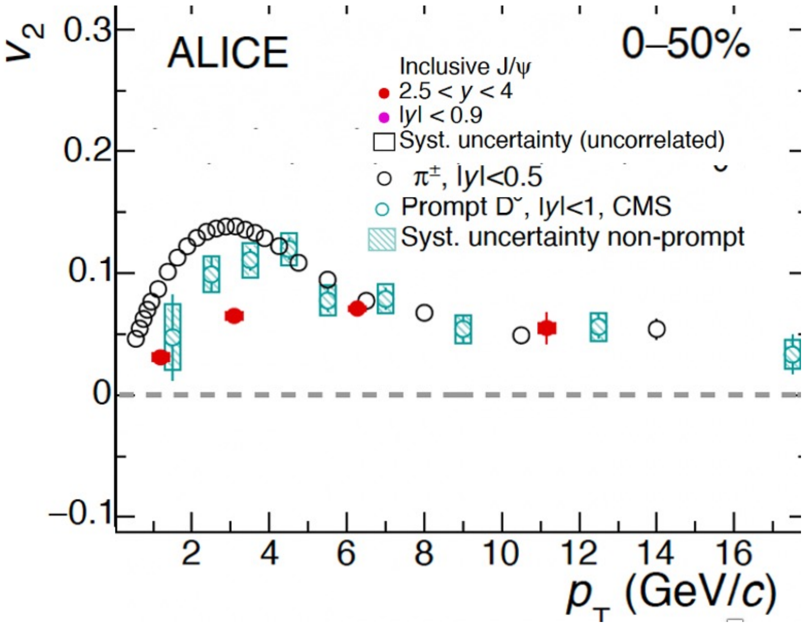
Data (low- $p_T$) shows that $J/\psi$ regenerates

Bad description of the $p_T$-dependence at high-$p_T$

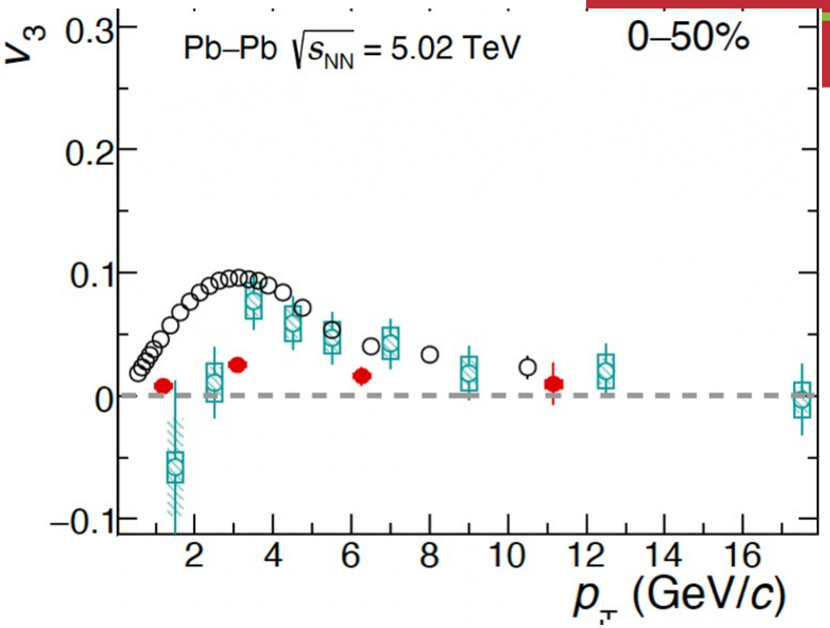
- Missing mechanism ?



# Pb-Pb, probing further than regeneration




[arXiv:1709.05260, arXiv:2005.14518]




$v_{2,J/\psi} > 0$ significant at mid-$p_T$

Species-independent asymptote at high-$p_T$: common mechanism

- For pions, flow from parton energy loss but $J/\psi$ is colourless
- How can it be explained ?

- Mass hierarchy of $v_2$ and $v_3$ and similar magnitudes: coherent charm quark thermalisation and hydrodynamics

$v_{3,J/\psi} > 0$ ($> 5\sigma$ between 2 and 5 GeV/c in 0-50%)

c are sensitive to initial fluctuations: collectivity

# The LHC experiments agree

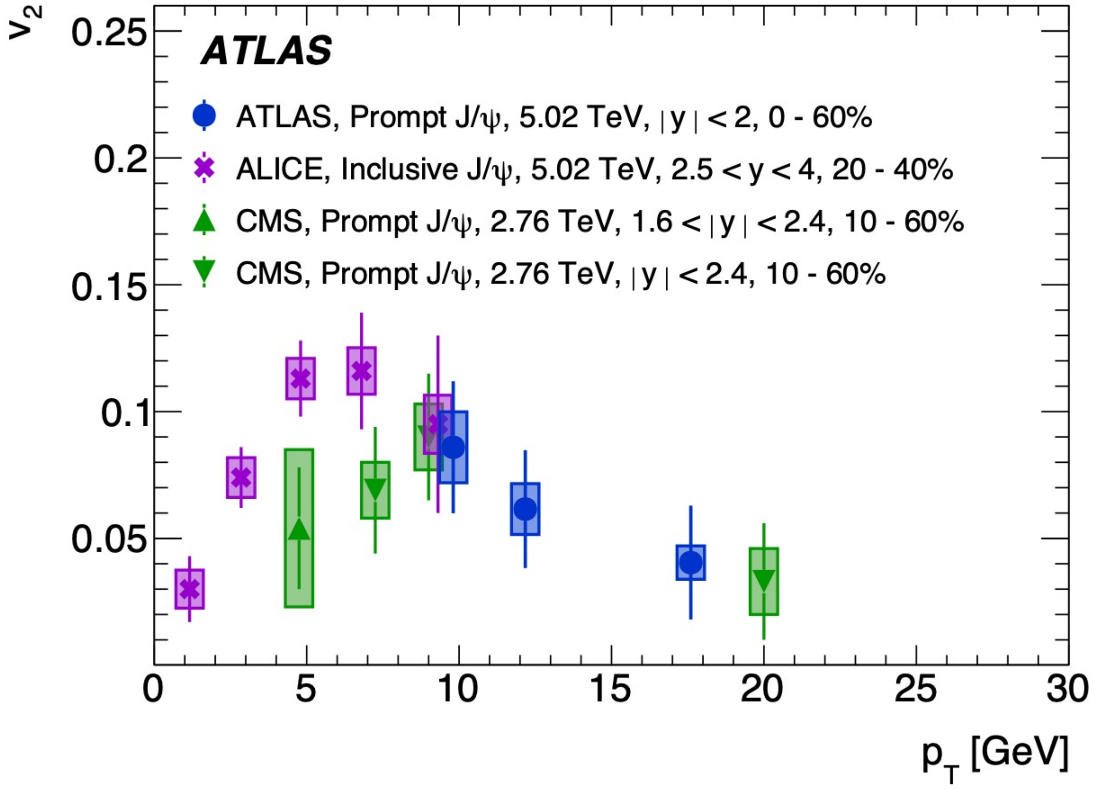
## ATLAS (Run2, **prompt**) 5.02 TeV and CMS (Run2, **prompt**) 2.76 TeV

[arXiv:1807.05198, arXiv:1610.00613]

Distinction prompt/non-prompt $J/\psi$ (depending on B feed-down)

Combining results between the experiments shows a nice agreement (despite uncertainties and centrality effects)

Fully confirms the flow of c



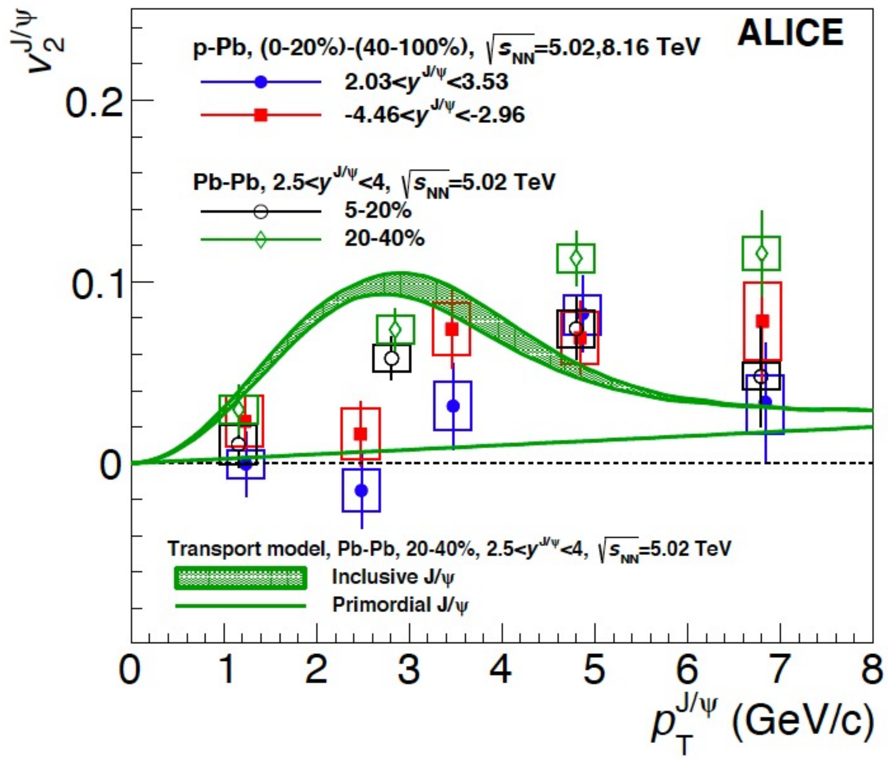

So in Pb-Pb: $J/\psi$ regeneration, c flow, validation of hydrodynamics and transport model despite missing mechanism

# p-Pb, exploration of smaller systems

## ALICE (Run2, inclusive, 5.02 and 8.16 TeV)

[arXiv:1709.06807]

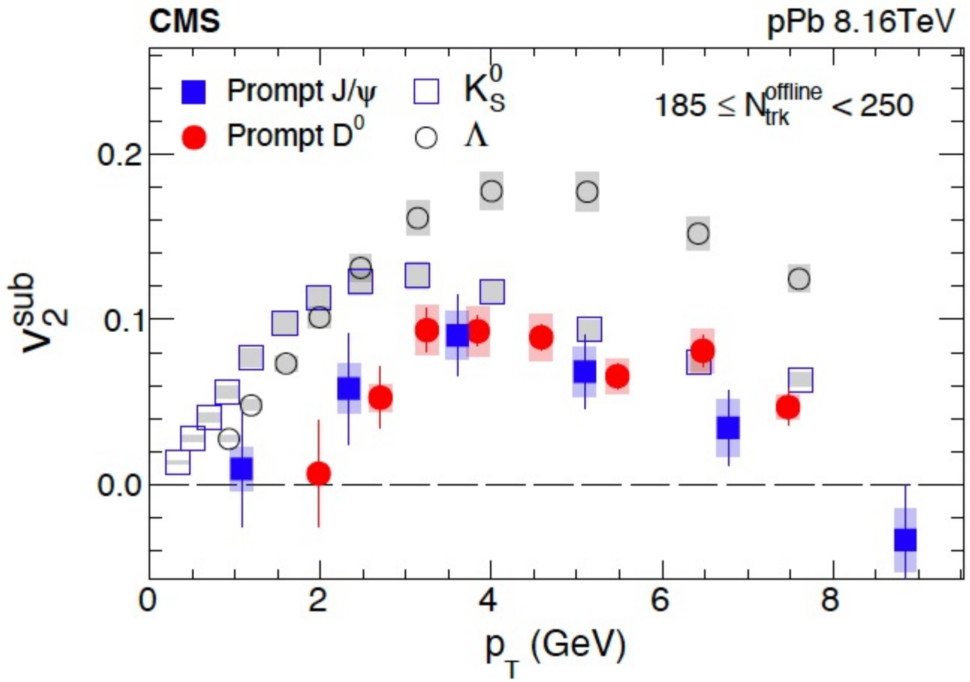
- $v_{2,J/\psi} > 0$ ($> 5\sigma$) for $3 < p_T < 6$ GeV/c
- Values in p-Pb close to Pb-Pb, suggests common mechanism
- Low-$p_T$ $v_2$ compatible with 0 : barely any recombination in p-Pb
- Should be no sizeable $v_2$ from path-length dependence



# p-Pb, exploration of smaller systems

## CMS (Run2, prompt, 8.16 TeV)

[arXiv:1810.01473]




- Prompt $J/\psi$ $v_2 > 0$ on a wide $p_T$ interval
- Vague mass ordering
  - Maybe hydrodynamics do not fully apply ?
  - Is there another flow origin ?
- Consistent $v_2$ values and trends between species (esp. $D^0$ and $J/\psi$), not the case in Pb-Pb !

# p-Pb, theories of flow

## Theoretical models

- Transport model (TAMU, X. Du et al.)

Model way below the experimental data

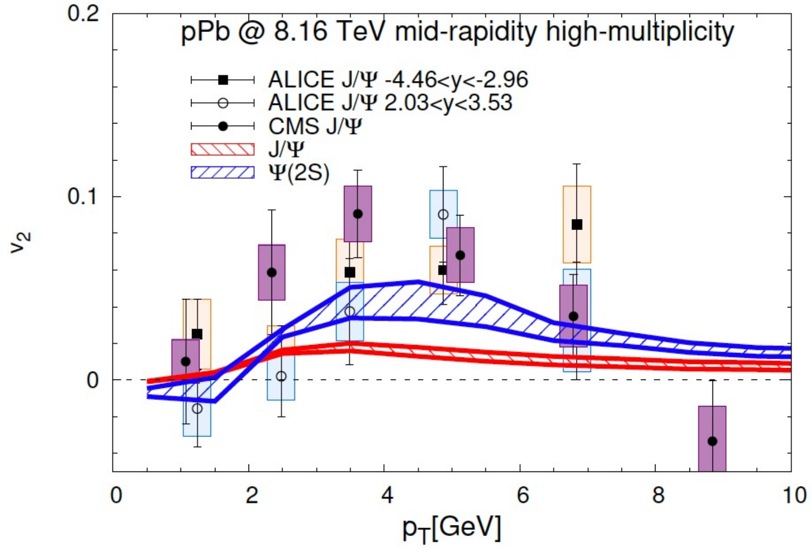
Missing mechanism

- Initial state effects – CGC (C. Zhang et al.)

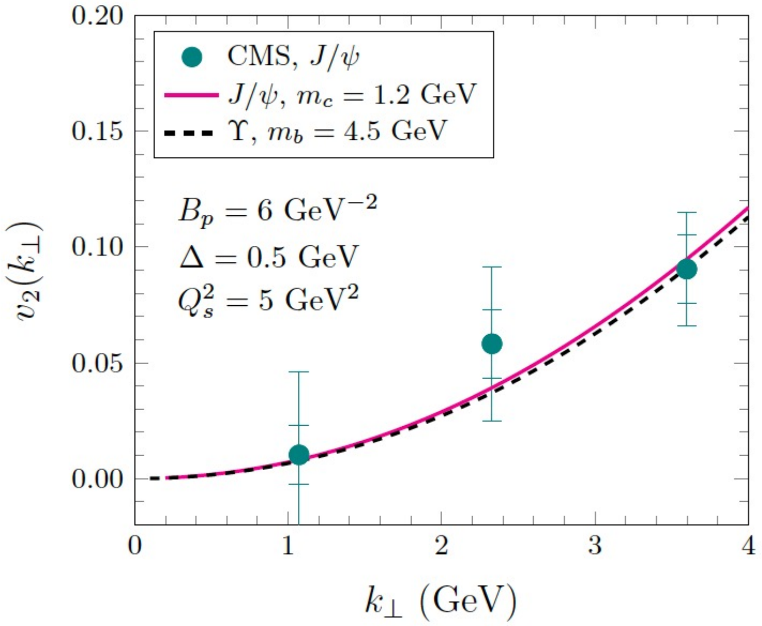
Idea: Flow is **here from the start**

- Long-range correlations come from initial momentum/color correlations (CGC framework)

Nice agreement with both ALICE and CMS data




[arXiv:1808.10014]



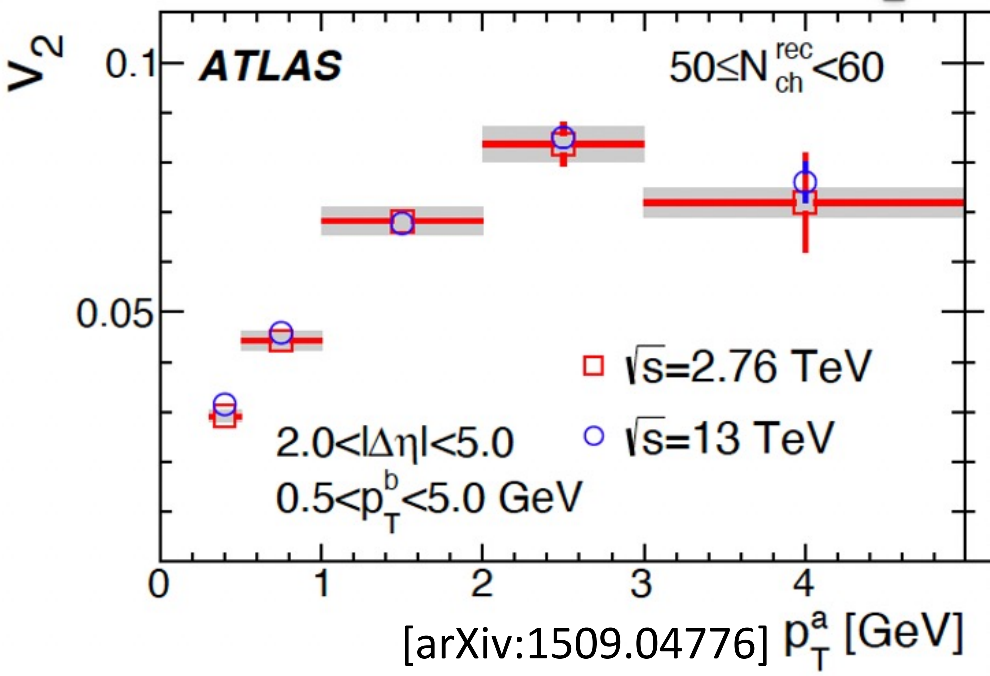

[arXiv:1901.10320]

# Hints in p-p

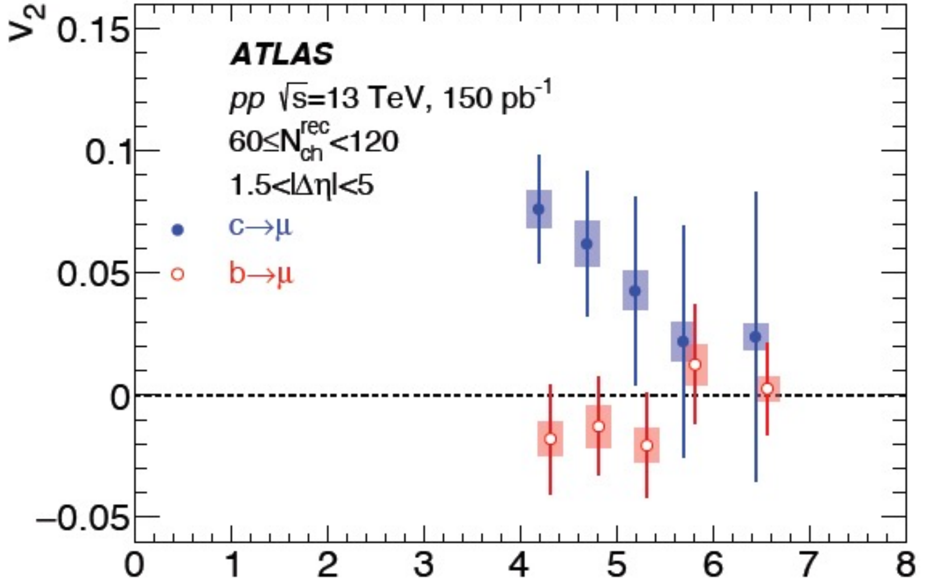
- Charged particles $v_2$ (ATLAS, CMS)
- Similar trend with p-A and A-A collisions
  - Similar mechanism ?

- c and b through muon decay (ATLAS)
- b-hadrons $v_2$ consistent with 0
- c-hadrons $v_2 > 0$. Is c flowing or are only lighter quarks flowing ?

Need to study $J/\psi$ p-p flow to determine if c flows or not !



[arXiv:1509.04776]



[arXiv:1909.01650]

# Conclusions and **Outlook**

| At LHC energies | | |
|---|---|---|
| A-A | p-Pb | p-p |
| • c quarks participate in collective effects<br>• Showed that $J/\psi$ was regenerated from thermalised c quarks<br>• Flow behaviour follows hydrodynamics and transport model<br>• Missing mechanism at high-$p_T$ to explain $J/\psi$ flow, **what is it ?**<br>• **Investigate higher harmonics and their correlations (Run 3 and 4) ?** | • c quarks participate in collective effects<br>• Common flow mechanism between Pb-Pb and p-Pb<br>• Hydrodynamics fragile and transport model fails<br>• **What is the origin of flow in p-Pb ?** | • Charged particles show collective effects<br>• Suggest common flow mechanism between all systems<br>• c could flow, **need to check by looking at $J/\psi$ flow (work in progress !)**<br>• **Theories in p-p ? May help for flow in bigger systems** |