J/ψ v_2 azimuthal anisotropy

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Forming the QGP and studying it

Study of Quark-Gluon Plasma (QGP)

- Deconfined state of matter
- Freely-roaming color charges

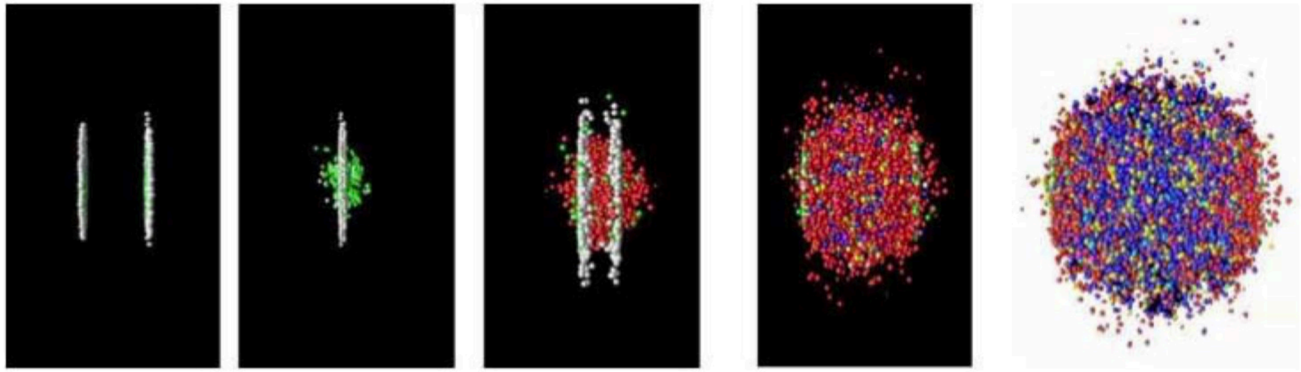
Formation through Heavy-ion collisions

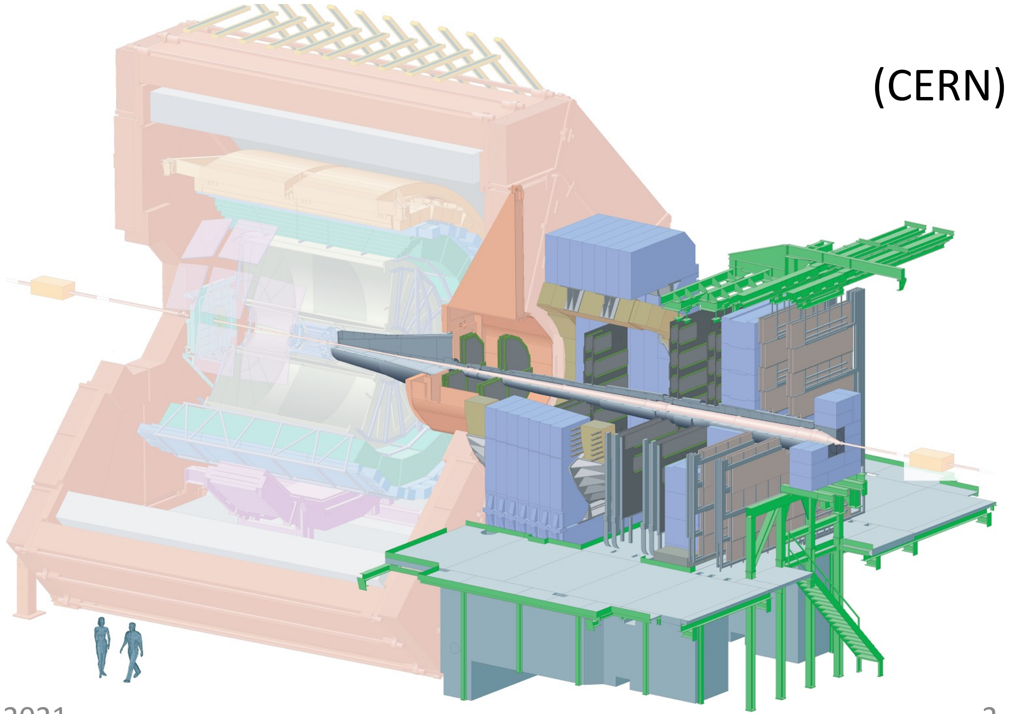
Pb-Pb ⇒ Formation of QGP
Pb-p, p-p ⇒ Reference (Cold Nuclear Matter (CNM) effects, assume no QGP formation)

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)



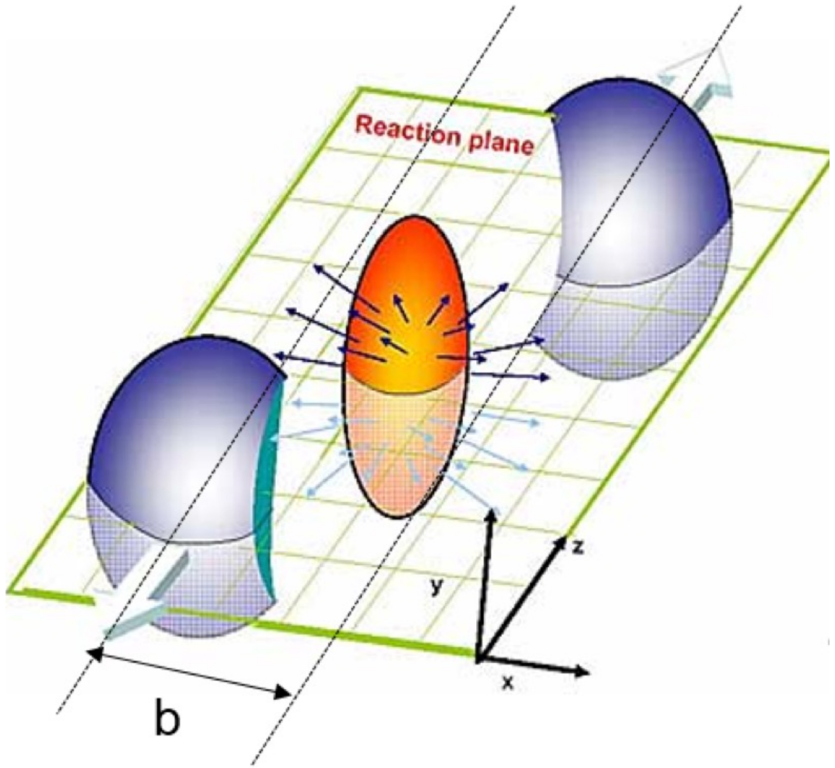


(CERN)

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 ϕ angle distribution (wrt event plane if large multiplicity), or 2-particle correlations (in smaller systems)

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

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

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

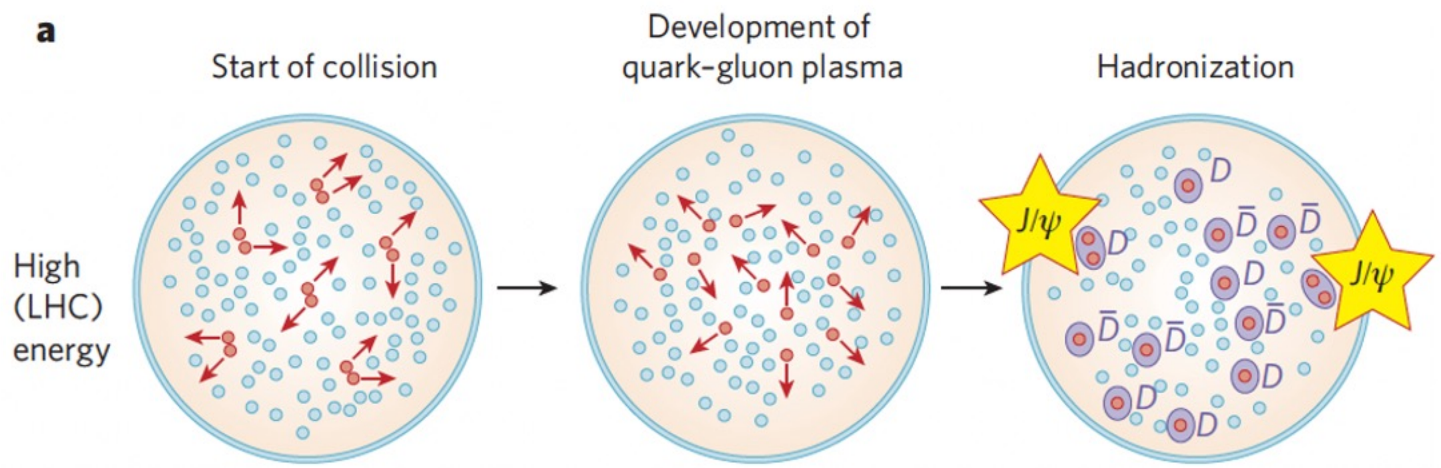
Explaining the J/ψ flow

Final State effects

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

Two sources for the J/ψ flow:

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



[*Nature* **448,** 302–309 (2007)]

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

Motivation:

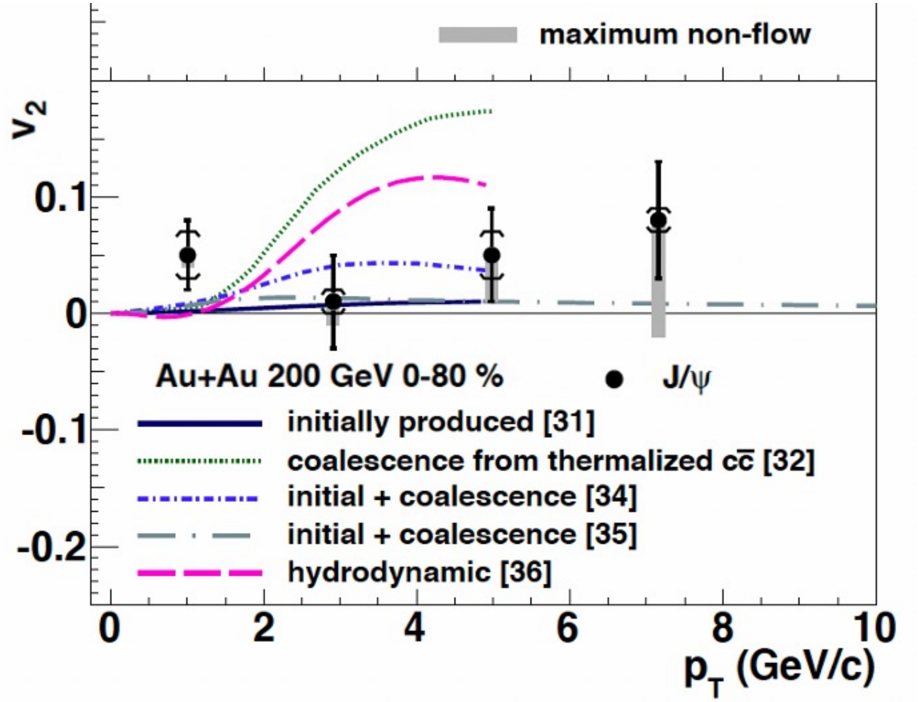
How is the J/ψ produced ? Is it through regeneration ?

Observations:

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

J/ψ regeneration is not dominant at RHIC

[arXiv:1212.3304]
Data from 2010



Pb-Pb, J/ψ regenerates

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:

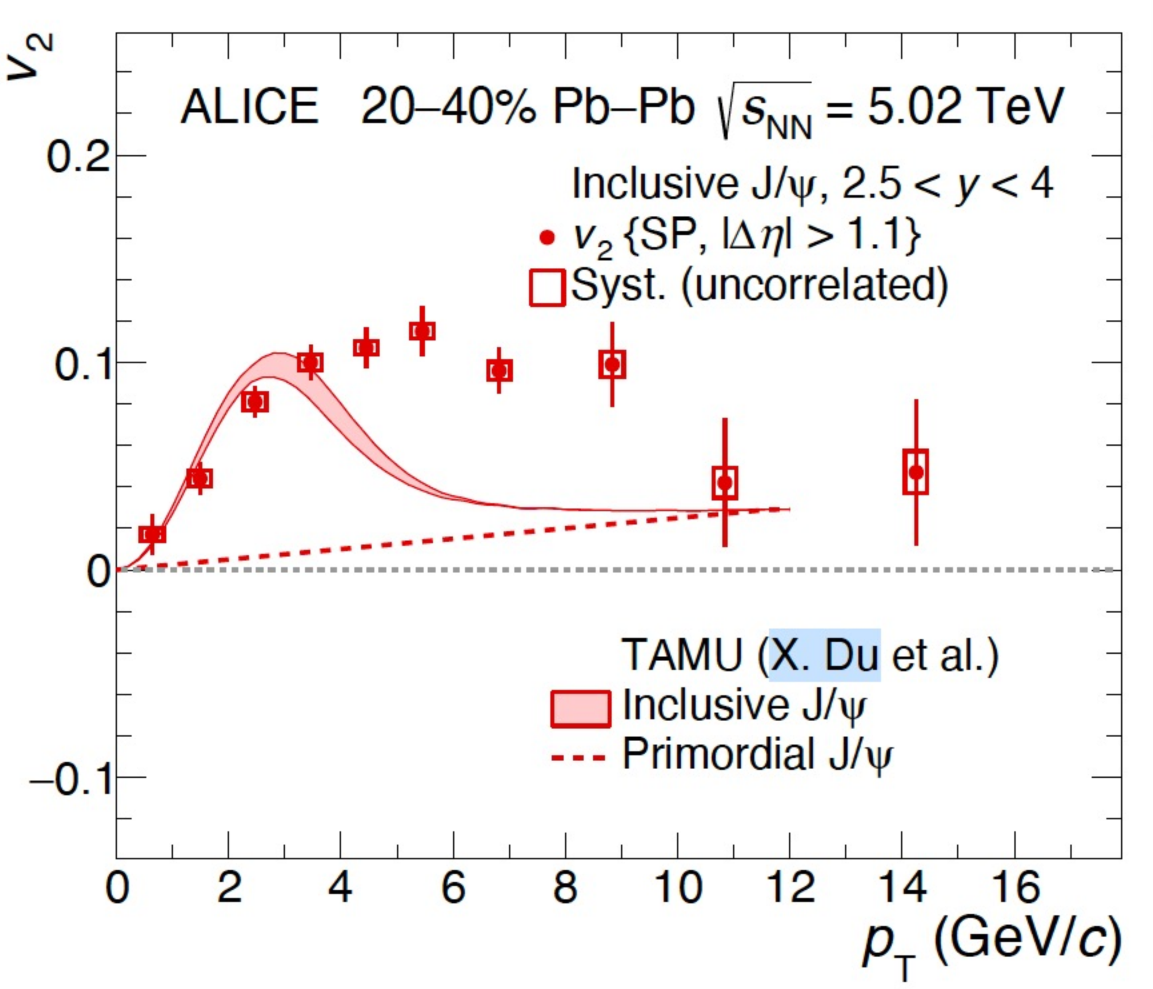
- Increase at low- p_T (recombined c quarks)
- Decrease at high- p_T (less recombination)
- Non-0 asymptote (only path-length dependence in primordial J/ψ bring a small v_2)

Data (low- p_T) shows that J/ψ regenerates

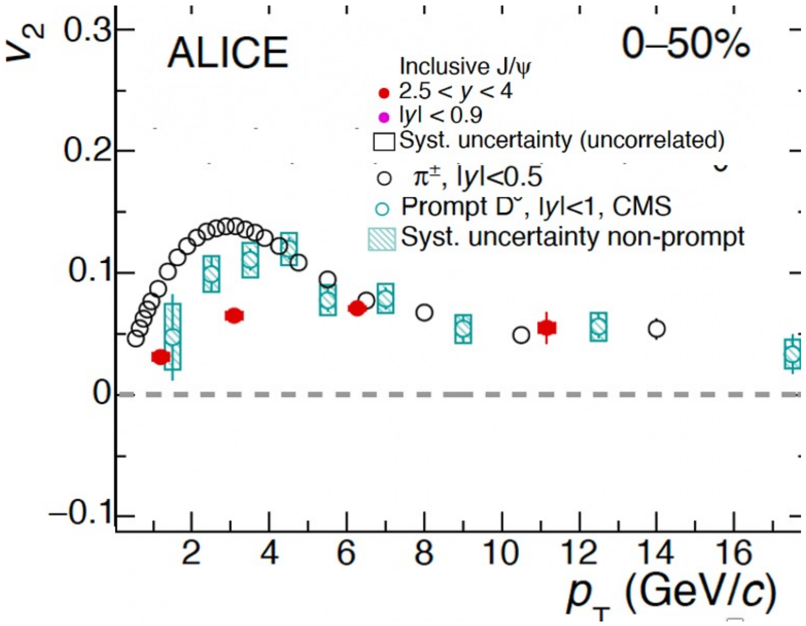
Bad description of the p_T-dependence at high-p_T

- Missing mechanism ?

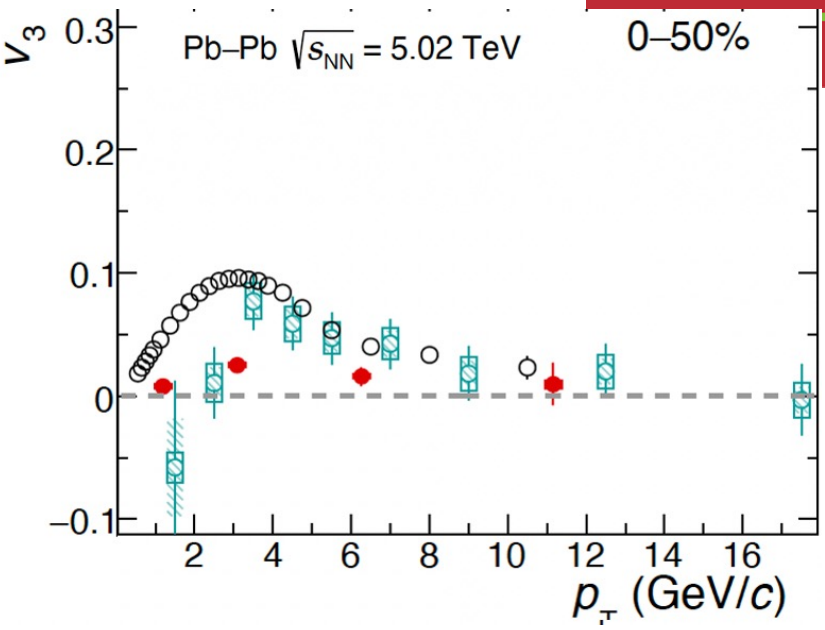
[arXiv:2005.14518]



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/ψ 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

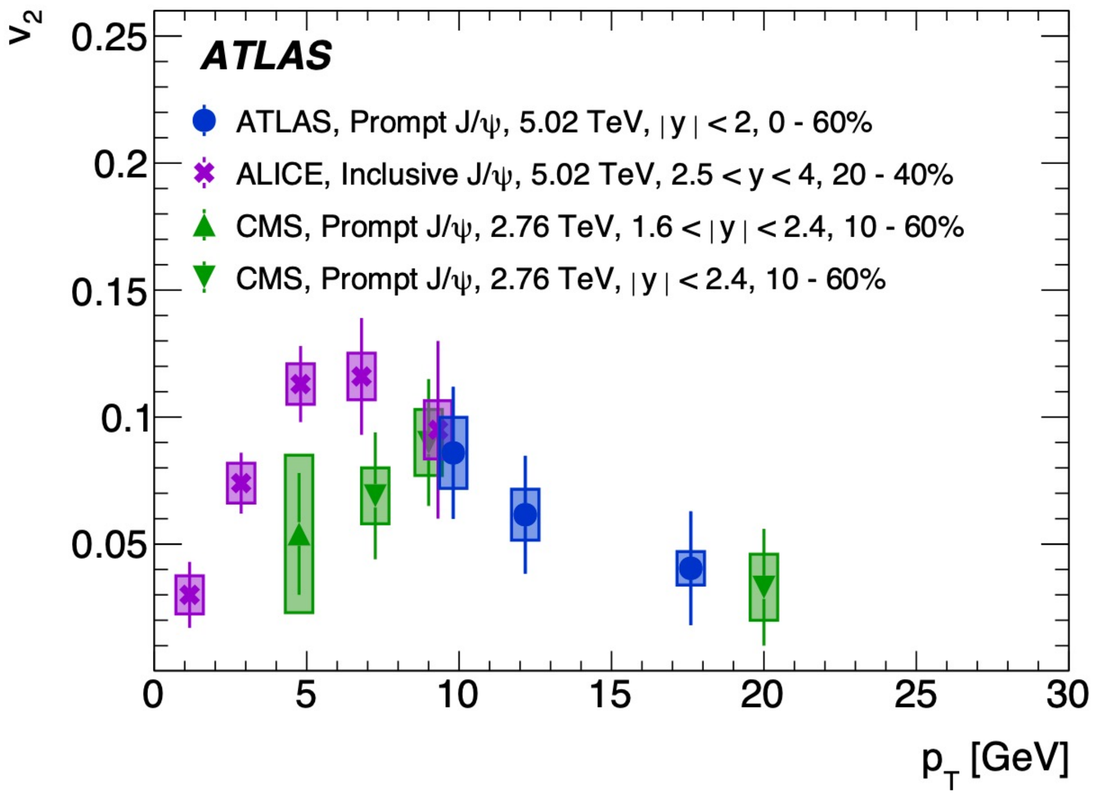
[arXiv:1807.05198, arXiv:1610.00613]

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

Distinction prompt/non-prompt J/ψ (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



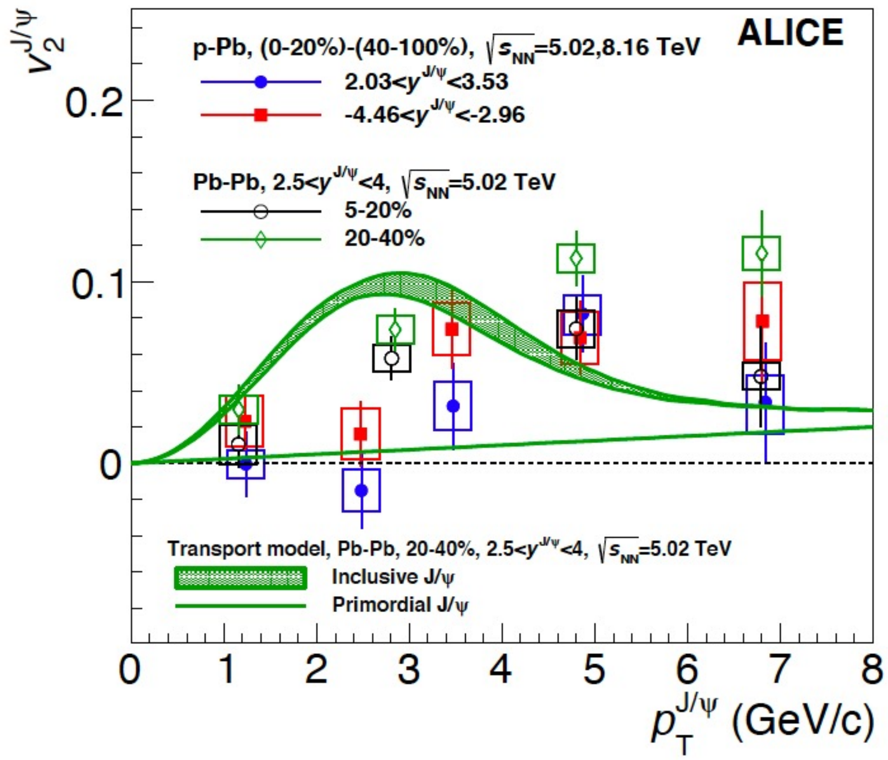
So in Pb-Pb: J/ψ regeneration, c flow, validation of hydrodynamics and transport model despite missing mechanism

p-Pb, exploration of smaller systems

ALICE (Run2, inclusive, 5.02 and 8.16 TeV)

[arXiv:1709.06807]

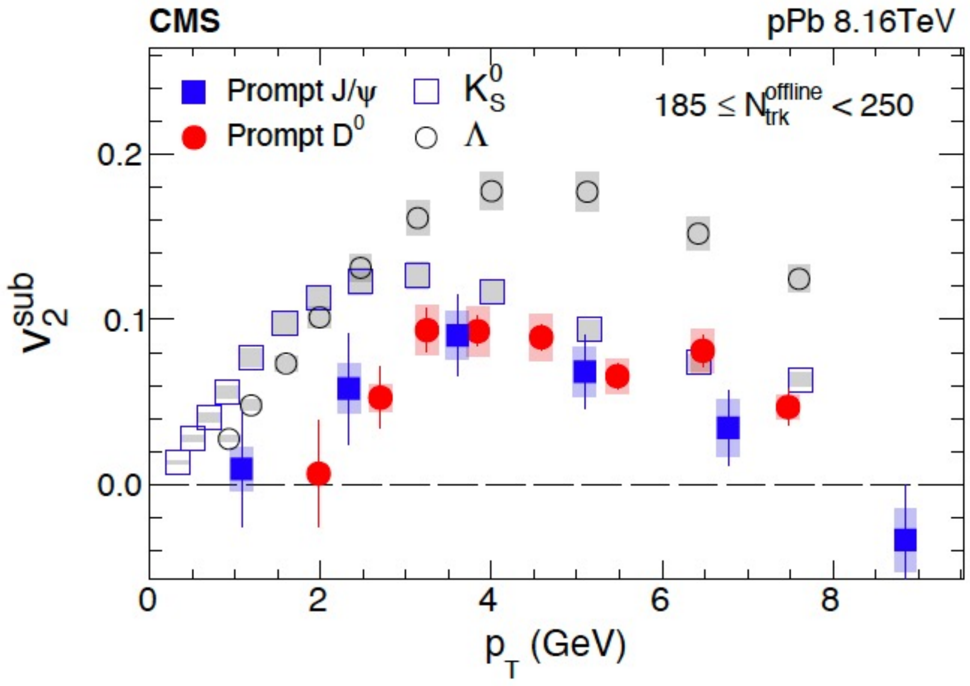
- $v_{2,J/\psi} > 0$ ($> 5\sigma$) for $3 < p_T < 6$ GeV/c
- Values in p-Pb close to Pb-Pb, suggests common mechanism
- Low-p_T v_2 compatible with 0 : barely any recombination in p-Pb
- Should be no sizeable v_2 from path-length dependence



p-Pb, exploration of smaller systems

CMS (Run2, prompt, 8.16 TeV)

[arXiv:1810.01473]



- Prompt J/ψ $v_2 > 0$ 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/ψ), 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

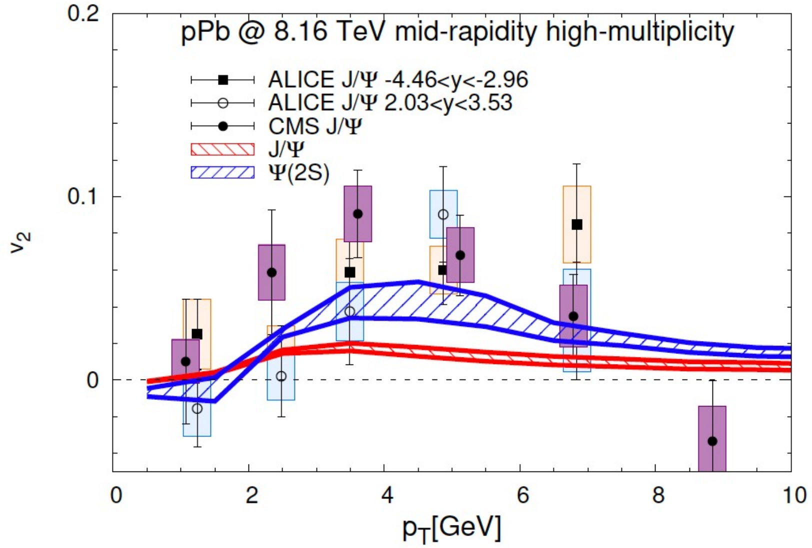
Missing mechanism

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

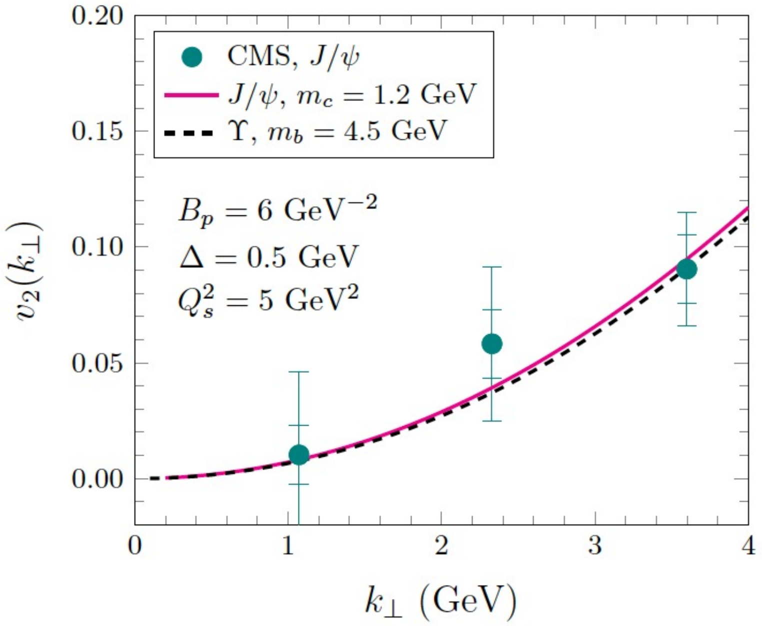
Idea: Flow is **here from the start**

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

Nice agreement with both ALICE and CMS data



[arXiv:1808.10014]



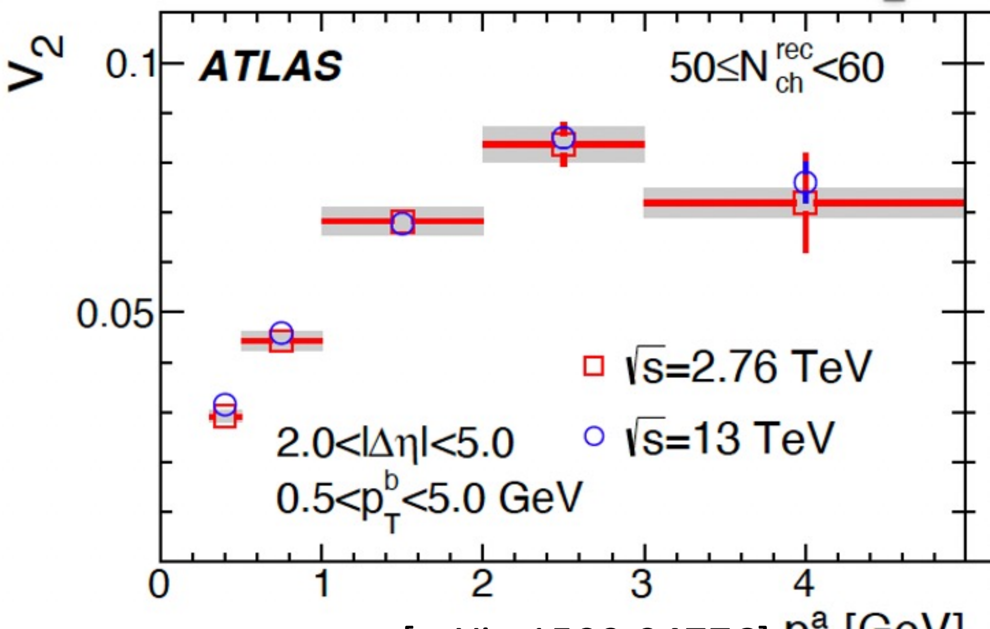
[arXiv:1901.10320]

Hints in p-p

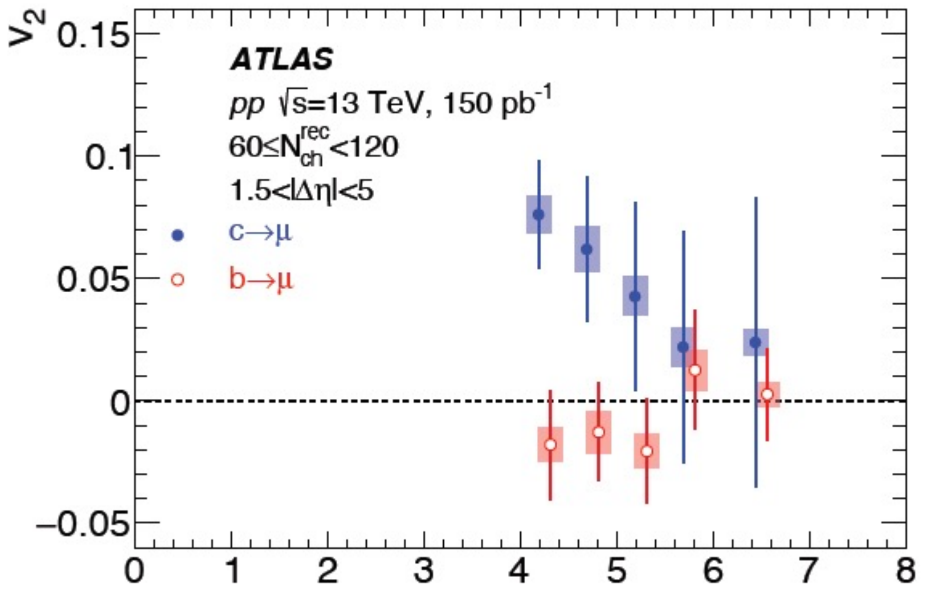
- Charged particles v_2 (ATLAS, CMS)
- Similar trend with p-A and A-A collisions
  - Similar mechanism ?

- 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/ψ p-p flow to determine if c flows or not !



[arXiv:1509.04776]



[arXiv:1909.01650]

Analysis description (from p-Pb analysis)

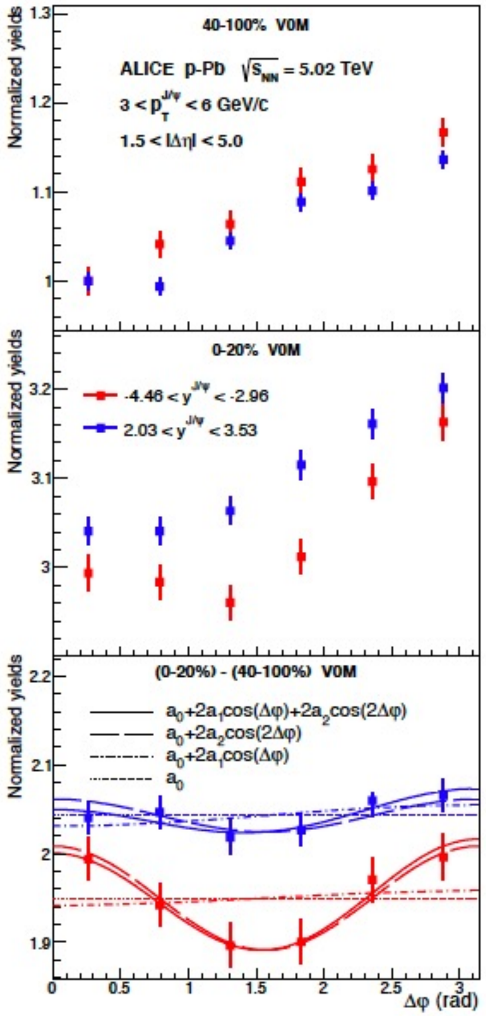
- Separate high and low multiplicity collisions (“central” and “peripheral”)
  - Make pairs of particles: dimuon-tracklet or tracklet-tracklet

  (tracklet: charged particle track in the central barrel, whereas J/ψ observed through dimuon decay in forward spectrometer)
  - Measure particle correlations with respect to Δη (pseudorapidity) and $\Delta\phi$ (azimuthal angle)
  - Compute “per trigger yields”*
  - ~Subtract Central and Peripheral yields to get rid of non flow-effects
  - Measure $V_{2,tracklet-J/\psi}, V_{2,tracklets}$ *and deduce* $v_{2,J/\psi} = \frac{V_{2,tracklet-J/\psi}}{\sqrt{V_{2,tracklets}}}$

$$
\begin{aligned}
* \quad Y^i(z_{\rm vtx}, M_{\mu\mu}, p_{\rm T}^{\mu\mu}, \Delta\varphi, \Delta\eta) &= \frac{1}{N^i_{\rm trig}(z_{\rm vtx}, M_{\mu\mu}, p_{\rm T}^{\mu\mu})} \frac{{\rm d}^2 N^i_{\rm assoc}(z_{\rm vtx}, M_{\mu\mu}, p_{\rm T}^{\mu\mu})}{{\rm d}\Delta\varphi {\rm d}\Delta\eta} \\
&= \frac{1}{N^i_{\rm trig}(z_{\rm vtx}, M_{\mu\mu}, p_{\rm T}^{\mu\mu})} \frac{SE^i(z_{\rm vtx}, M_{\mu\mu}, p_{\rm T}^{\mu\mu}, \Delta\varphi, \Delta\eta)}{ME^i(z_{\rm vtx}, M_{\mu\mu}, p_{\rm T}^{\mu\mu}, \Delta\varphi, \Delta\eta)},
\end{aligned}
$$

Number of associated particle pairs found in a bin of Δη, $\Delta\phi$, z_{vertex}, invariant mass, p_t, centrality

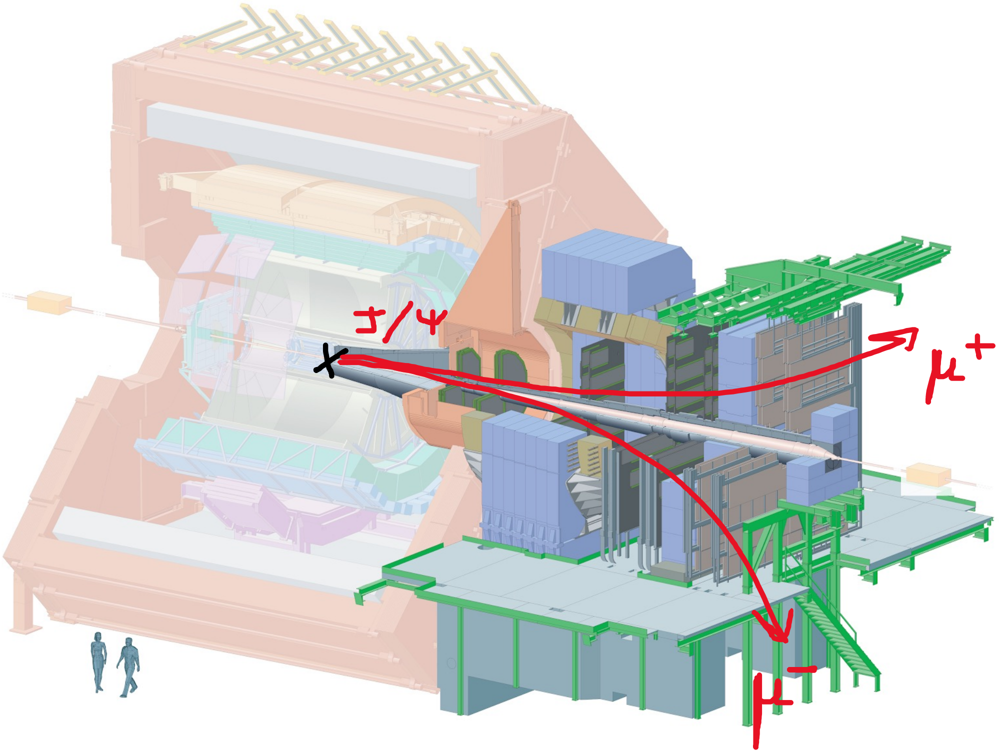
Number of reference particles triggered on in a bin of z_{vertex}, invariant mass, p_t, centrality



ALICE, p-Pb publication [arXiv:1709.06807]

Event selection

Event Selection	(Di)Muon Selection
$N_{contrib} > 0$ $\boldsymbol{\sigma_{Z_{vtx,SPD}}}$ **< 0.25 cm** $\lvert Z_{vtx}\rvert < 10$ cm $\lvert\eta_{SPD}\rvert < 2$ $\Delta\Phi_{tracklets} < 10\ mrad$ (azimuth difference between inner and outer SPD layers) – standard, equivalent to p_T cut **Pile-up rejection**	$R_{abs}\ in\ [17.6, 89.5]$ Match a trigger track with $p_T > 0.5\ GeV$ pDCA < 6σ $\eta_{muon}\ in\ acceptance$ Dimuon charge = 0 $y_{dimu}\ in\ acceptance$ $p_{T\,J/\psi}\ in\ [0; 12]\ GeV/c$



Other methods of V2 extraction

- ZYAM – Similar to Ext1 and 2 but the baselines are subtracted from the yields

$$Fourier\ analysis\ of\ (\boldsymbol{Y_C}-\boldsymbol{B_C})-(\boldsymbol{Y_P}-\boldsymbol{B_P})$$

(similar to p-Pb, just changes the calculations to get to V_2)

Template fits: $\boldsymbol{Y_C}=\boldsymbol{A(ridge)}+\boldsymbol{F}*\boldsymbol{Peripheral\ yields}$

- Template fit - by Quentin and Cvetan

$$Fit\ of\ \boldsymbol{Y_C}=\boldsymbol{B_C}\left(\boldsymbol{1}+\boldsymbol{2v_{2,2}}\cos(\boldsymbol{2\Delta\phi})\right)+\boldsymbol{F}*(\boldsymbol{Y_P}-\boldsymbol{B_P})$$

- Template fit – ATLAS [PRL – 116,172301 (2016)]
  - G is a fixed parameter to ensure the integrals on both side of the equation are the same

$$Fit\ of\ \boldsymbol{Y_C}=\boldsymbol{G}\left(\boldsymbol{1}+\boldsymbol{2v_{2,2}}\,\boldsymbol{cos}(\boldsymbol{2\Delta\phi})\right)+\boldsymbol{F}*\boldsymbol{Y_P}$$

- Template fit + Peripheral ZYAM – ATLAS [PRL – 116,172301 (2016)]

$$Fit\ of\ \boldsymbol{Y_C}=\boldsymbol{G}\left(\boldsymbol{1}+\boldsymbol{2v_{2,2}}\,\boldsymbol{cos}(\boldsymbol{2\Delta\phi})\right)+\boldsymbol{F}*(\boldsymbol{Y_P}-\boldsymbol{B_P})$$

Conclusions and **Outlook** on J/ψ flow

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