$J/\psi \ \nu_2$ 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**

\[ \text{Pb-Pb} \rightarrow \text{Formation of QGP} \]
\[ \text{Pb-p, p-p} \rightarrow \text{Reference (Cold Nuclear Matter (CNM) effects, assume no QGP formation)} \]

**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)
What is flow?

In Heavy-ion collisions, anisotropic collision region
- Anisotropies in momentum distribution
- Long-range correlations of produced particles

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)

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

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

$v_2$ (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

Taken from Universe, 2017
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 inheritance)
  - At freeze-out
  - Dynamic transport model
- Path-length dependent suppression (primary $J/\psi$)

[Nature 448, 302–309 (2007)]
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

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

$v_2, J/\psi > 0$ 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

**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)

- $v_{2,J/\psi} > 0 \ (> 5\sigma)$ 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

[arXiv:1709.06807]
p-Pb, exploration of smaller systems

CMS (Run2, prompt, 8.16 TeV)

• 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 !

[arXiv:1810.01473]
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!
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 $J/\psi$ observed through dimuon decay in forward spectrometer)
  - Measure particle correlations with respect to $\Delta \eta$ (pseudorapidity) and $\Delta \phi$ (azimuthal angle)
  - Compute "per trigger yields"*
  - ~Subtract Central and Peripheral yields to get rid of non flow-effects
  - Measure $V_{2,\text{tracklet}-J/\psi}, V_{2,\text{tracklets}}$ and deduce $v_{2,J/\psi} = \frac{V_{2,\text{tracklet}-J/\psi}}{\sqrt{V_{2,\text{tracklets}}}}$

\[
Y^i(\zeta_{\text{vtx}}, M_{\mu\mu}, p_T^{\mu\mu}, \Delta \phi, \Delta \eta) = \frac{1}{N_{\text{trig}}^{i}(\zeta_{\text{vtx}}, M_{\mu\mu}, p_T^{\mu\mu})} \frac{d^2N_{\text{assoc}}^{i}(\zeta_{\text{vtx}}, M_{\mu\mu}, p_T^{\mu\mu})}{d\Delta \phi d\Delta \eta} = \frac{1}{N_{\text{trig}}^{i}(\zeta_{\text{vtx}}, M_{\mu\mu}, p_T^{\mu\mu})} \frac{SE^i(\zeta_{\text{vtx}}, M_{\mu\mu}, p_T^{\mu\mu}, \Delta \phi, \Delta \eta)}{ME^i(\zeta_{\text{vtx}}, M_{\mu\mu}, p_T^{\mu\mu}, \Delta \phi, \Delta \eta)},
\]

*Number of associated particle pairs found in a bin of $\Delta \eta, \Delta \phi, z_{\text{vertex}}$, invariant mass, $p_T$, centrality
Number of reference particles triggered on in a bin of $z_{\text{vertex}}$, invariant mass, $p_T$, centrality

ALICE, p-Pb publication
[arXiv:1709.06807]
Event selection

<table>
<thead>
<tr>
<th>Event Selection</th>
<th>(Di)Muon Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{contrib}} &gt; 0$</td>
<td>$R_{\text{abs}}$ in [17.6, 89.5]</td>
</tr>
<tr>
<td>$\sigma_{Z_{\text{vtx, SPD}}} &lt; 0.25 \text{ cm}$</td>
<td>Match a trigger track with $p_T &gt; 0.5$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>Z_{\text{vtx}}</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{\text{SPD}}</td>
</tr>
<tr>
<td>$\Delta \Phi_{\text{tracklets}} &lt; 10 \text{ mrad}$</td>
<td>Dimuon charge = 0</td>
</tr>
<tr>
<td>(azimuth difference between inner and outer SPD layers) – standard, equivalent to $p_T$ cut</td>
<td>$\gamma_{\text{dimu}}$ in acceptance</td>
</tr>
<tr>
<td>Pile-up rejection</td>
<td>$p_T \frac{J/\psi}{c}$ in [0; 12] GeV /c</td>
</tr>
</tbody>
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Other methods of V2 extraction

• ZYAM – Similar to Ext1 and 2 but the baselines are subtracted from the yields
  
  \[ \text{Fourier analysis of } (Y_C - B_C) - (Y_P - B_P) \]
  
  (similar to p-Pb, just changes the calculations to get to \( V_2 \))

Template fits: \( Y_C = A(\text{ridge}) + F \times \text{Peripheral yields} \)

• Template fit - by Quentin and Cvetan
  
  \[ \text{Fit of } Y_C = B_C (1 + 2v_{2,2} \cos(2\Delta\phi)) + F \times (Y_P - B_P) \]

• 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
    
    \[ \text{Fit of } Y_C = G (1 + 2v_{2,2} \cos(2\Delta\phi)) + F \times Y_P \]

• Template fit + Peripheral ZYAM – ATLAS [PRL – 116,172301 (2016)]
  
  \[ \text{Fit of } Y_C = G (1 + 2v_{2,2} \cos(2\Delta\phi)) + F \times (Y_P - B_P) \]
### Conclusions and Outlook on $J/\psi$ flow

**At LHC energies**

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