γ flow in Pb-Pb collisions

Quarkonia as tools - Aussois 2020

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1 The story of a rock

2 Generalities about quarkonium flow in heavy ion collisions

3 Overview of model predictions for bottomonium flow

4 Recent results on Υ flow in Pb-Pb collisions
Once upon a time, a rock ... who wondered if it could flow?
Why do we need to study the flow of quarkonia?

Flow in AA collisions

1. Initial spatial anisotropy
2. Momentum space anisotropy

Why? In principle due to:
- frequent parton interactions
- pressure gradients

Azimuthal particle distribution decomposed by Fourier series ($v_2$ called elliptic flow):

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

$n$: harmonic, $\varphi$ azimuthal angle and $\Psi_n$ angle providing estimation of reaction plane
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**$Q\bar{Q}$ - medium interaction**

- Quarkonia are excellent probe to study the medium

Primordial heavy quark pairs production

Beam-line view
Why do we need to study the flow of quarkonia?

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Beam-line view

Elliptic flow $v_2 > 0$
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Beam-line view
Overview of model predictions for bottomonium flow

**Du, He, Rapp (TAMU)**
**PRC.96.054901**

**Brief description of transport model**

- Boltzmann equation accounting for both:
  - suppression (dissociation)
  - regeneration (coalescence)
- Spectral properties from lQCD
- Modeling the medium evolution
  - Main uncertainty source: shadowing, total open-heavy flavor cross-section
Overview of model predictions for bottomonium flow

Du, He, Rapp (TAMU)
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- Predicts a very low $\Upsilon(1S) v_2$ (large binding energy)
- T dependent binding energy
  - Dissociation at larger $T$
  - Limited to earlier stages of QGP evolution
- Very small regeneration component
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- Predicts: $v_2^{\Upsilon(2S)} \approx 3 \cdot v_2^{\Upsilon(1S)}$
  ($\Upsilon(2S)$ smaller binding energy)
  - Dissociation at lower $T$
  - Experiences long duration of QGP evolution
Overview of model predictions for bottomonium flow

Bhaduri, Borghini, Jaiswal, Strickland (BBJS)
arXiv.1809.06235

**Я flow explained with anisotropic escape mechanism**

- 3+1D quasi-particle anisotropic hydrodynamic simulation to model the space-time evolution
- No recombination component

- Strong centrality dependence
- Predicts negative $v_2$ at very low $p_T$ for centrality below 40%
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- Contributions from \(\Upsilon(2S), \chi_b(1P, 2P)\)
- \(\approx 75\%\) direct \(\Upsilon(1S)\) at low-\(p_T\)
- \(\approx 50\%\) direct \(\Upsilon(1S)\) at high-\(p_T\)
Method for extracting the coefficients $v_n$ in Pb-Pb collisions

### Candidate properties from $\Upsilon \rightarrow l^+l^-$
- Define complex unitary vector $u_n$ using dilepton properties (with $\varphi$)

$$u_n = e^{in\varphi} \quad (2)$$

### Characterize a Pb-Pb event
- Define $Q_n$ using $N$ charged particles:

$$Q_n = \sum_{j=1}^{N} e^{in\varphi_j} \quad (3)$$
Method for extracting the coefficients $v_n$ in Pb-Pb collisions

Candidate properties from $\Upsilon \to l^+l^-$

- Define complex unitary vector $u_n$ using dilepton properties (with $\varphi$)

$$u_n = e^{in\varphi}$$

Define $Q_n$ using $N$ charged particles:

$$Q_n = \sum_{j=1}^{N} e^{in\varphi_j}$$

Finally, using 3 sub-event (detectors A,B,C) correction with large $\Delta \eta$ in order to suppress the non-flow effects:

$$v_n = \frac{v_{n}^{\text{obs}}}{R_n} = \frac{\langle \langle u_n Q^*_n A \rangle \rangle}{\sqrt{\langle Q_n A Q^*_n B \rangle \langle Q_n A Q^*_n C \rangle \langle Q_n B Q^*_n C \rangle}}$$
Finally, using 3 sub-event (detectors A,B,C) correction with large $\Delta \eta$ in order to suppress the non-flow effects:

$$v_2 = \frac{\langle \langle u_2 Q_{2A}^* \rangle \rangle}{\sqrt{\langle Q_{2A} Q_{2B}^* \rangle \langle Q_{2A} Q_{2C}^* \rangle \langle Q_{2B} Q_{2C}^* \rangle}}$$

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

$\langle \langle \ldots \rangle \rangle$ means: average over all particles and all events and $\alpha = \frac{S}{S+B}$
From pPb to PbPb: sequential $\Upsilon(1S, 2S, 3S)$ suppression in CMS

- Clear sequential $\Upsilon$ suppression from pPb to PbPb collisions
- CMS has better mass resolution than ALICE, which gives the access to $\Upsilon(2S) v_2$ extraction
Results about $\gamma$ flow
Recent results on $\Upsilon$ flow in Pb-Pb collisions

**ALICE**

PRL.123.192301

- **ALICE**: in 5-60%, $2 < p_T < 15$ GeV/c
- $\Upsilon(1S)$ $v_2$ is lower than $J/\psi$ $v_2$ by 2.6 $\sigma$

**CMS**

(QM 2019)

- **CMS**: First measurement of $\Upsilon(2S)$ $v_2$ in 10-90% also compatible with 0.
- Provide new inputs on production mechanisms (different regeneration)
Recent results on $\Upsilon$ flow in Pb-Pb collisions

Both measurement compatible with 0 and with all current model predictions
Confirms that the $\Upsilon(1S)$ dissociation is limited to the early stage of the QGP evolution
Good agreement with both experiments

\[ \text{HIN-19-002} \]

PbPb 1.7 nb\(^{-1}\) (5.02 TeV)

CMS

Preliminary

\( p_T^n > 3.5 \text{ GeV} \)

Cent. 5-60 %

\( |y| < 2.4 \)

\( 2.5 < |y| < 4 \) (ALICE arXiv:1907.03169)
So the rock seems to hold on so far …

(it may not be the end of the story)
What can we learn from these first Υ flow measurements?

- Υ(1S) $v_2$ compatible with 0 and good agreement with all model predictions (transport, hydrodynamic,...)
- ALICE shown that Υ(1S) $v_2$ is lower than J/ψ $v_2$ by 2.6 $σ$ in 5-60% and $2 < p_T < 15$ GeV/c
- CMS shown a positive Υ(1S) $v_2$ in 10-90% corresponding to $6 < p_T < 10$ GeV/c by 2.5 $σ$
  - First measurement of Υ(2S) $v_2$ can provide new inputs on production mechanisms (different regeneration)
- Confirms that the Υ(1S) dissociation is only limited to the early stage of the QGP evolution
  - where $T$ is such large than the most tightly bound state of $b$ quark can be dissociate
- Waiting for Run 3 at LHC to improve precision measurement
Thank you for your attention
Projection for the Run 3:

![Graphs showing CMS projections for PbPb collisions at 5.02 TeV for different p_T regions and Y flow in heavy ion collisions.](image-url)
Inelastic reaction rates:

\[ \text{arXiv:1704.07923} \]
J.P. Lansberg arXiv:1903.09185

(a) Low $P_T \ Upsilon(1S)$
(b) Low $P_T \ Upsilon(2S)$
(c) Low $P_T \ Upsilon(3S)$
(d) High $P_T \ Upsilon(1S)$
(e) High $P_T \ Upsilon(2S)$
(f) High $P_T \ Upsilon(3S)$
Evolution of $c$ and $\bar{c}$ pair in the medium:

Quarkonium Transport in URHICs

- Production + evolution of $c\bar{c}$ wave pack.
  - $\tau_{\text{form}} \sim 1\,\text{fm/c}$
- $c$-quark diffusion in QGP
  - $\tau_{c}^{\text{eq}} \sim 5\,\text{fm/c}$
- $c + \bar{c} \leftrightarrow \psi$
- QGP kinetics
  - $\tau_{\psi}^{\text{eq}} \sim 1/\Gamma_{\psi}$
- $\sim T_{\text{melt}}$: $\psi$ can form
- $\sim T_{pc}$: $c$ and $\bar{c}$ hadronize
- Hadronic kinetics

arXiv:1704.07923
Overview of model predictions for bottomonium flow

Hong, Lee
arXiv.1909.07696

Yao, Ke, Xu, Bass, Müller
arXiv.1812.02238

- Boltzmann transport equations, use gluo-dissociation and inelastic parton scattering
  - derived from potential non-relativistic QCD (pNRQCD)
  - dissociation and regeneration terms

- $b$ distribution determined by a Fokker-Planck equation using:
  - heavy quark diffusion constant $D$
- perturbation theory (hard thermal loop HTL)

- Real-time open heavy quark distribution

![Graph showing $v_2$ vs. $p_T$ for different $D(2\pi T)$ values](image)

![Graph showing $v_2$ vs. $q_T$ for different $D(2\pi T)$ values](image)