Upsilon-Underlying Event Correlations in pp Collisions at ATLAS

Zvi Citron for ATLAS

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Big Picture: Why are we looking at $\Upsilon$-UE correlations

- Soft sector observables that were once (uniquely) associated with a QGP have been measured in pp collisions
  - Most prominently “flow” which persists to low multiplicity pp & even photo-nuclear interactions
  - Strangeness enhancement
- It’s more difficult to tell this story with hard sector observables
- Here we look at Upsilon meson correlations with inclusive charged particles to try to bridge the soft-hard gap
A Previous Hard-Soft Study: Two-particle correlations in Z Boson Tagged pp Collisions

• In a previous study we asked: Does the presence of a hard scattering in the collision change “something-like-geometry” and consequently the observed “flow”?

• To answer we studied $v_2$ via 2-particle correlations in pp collisions ‘tagged’ by a Z boson

• The answer to above question is not really
A Previous Hard-Soft Study: Two-particle correlations in Z Boson Tagged pp Collisions

- Developed techniques for HI-style analysis in high-luminosity pp collisions
  - We learned how to look at all tracks in the event even with high pile-up conditions
  - Starting thinking about where else this could be used ... *Upsilon mesons!*

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>from the same run as Direct</td>
</tr>
<tr>
<td>( n_{\text{int}} )</td>
<td>the same integer value as in Direct (before reduction)</td>
</tr>
<tr>
<td>( z_{\text{vtx}} )</td>
<td>identical to Direct</td>
</tr>
<tr>
<td>(</td>
<td>z_{\text{vtx}}</td>
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<td>w</td>
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Distributions of \( n_{\text{trk}} \) in different event categories is shown in Fig. 18 together with the mean values of those distributions. Black markers show the total number of tracks in event. Red marker show number tracks in Direct event and blue markers are tracks in Mixed events. Magenta markers are distribution of \( n_{\text{trk}} \) in non-PV vertices, Pileup events.

What Do We Know about Upsilon Production at the LHC?

• Production cross-section seems well measured in pp collisions
• Some questions remain regarding polarization, importance of $\chi_b$ feed-down etc
What Do We Know about Upsilon Production and collectivity at the LHC?

• From a heavy-ion perspective $\Upsilon(nS)$ states could be a thermometer for a QGP

![Diagram of Upsilon Production and collectivity at the LHC]
What Do We Know about Upsilon Production and collectivity at the LHC?

• From a heavy-ion perspective $Y(nS)$ states could be a thermometer for a QGP

• We can measure the nuclear modification factor in heavy-ion collisions to compare AA to pp production

![Graph showing multiplicity vs. $R_{AA}$](attachment:image.png)

$$R_{AA} = \frac{N_{Y;AA}}{(T_{AA}) \times \sigma_{pp \rightarrow Y}}$$

$T_{AA}$ is the nuclear overlap function
What Do We Know about Upsilon Production and collectivity at the LHC?

• From a heavy-ion perspective $\Upsilon(nS)$ states could be a thermometer for a QGP

• We can measure the nuclear modification factor in heavy-ion collisions to compare AA to pp production
  • pA could give us some sense of the influence of “cold nuclear effects”

$$R_{pA} = \frac{\sigma pA \rightarrow \Upsilon}{A \times \sigma pp \rightarrow \Upsilon}$$
CMS Measurement of $\Upsilon(nS)$ and pp Multiplicity

• CMS results all the way back in 2014 challenge this picture by showing a decrease in excited $\Upsilon$ states compared to the ground state vs pp multiplicity.

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CMS Measurement of Y(nS) and pp Multiplicity

- CMS results all the way back in 2014 challenge this picture by showing a decrease in excited Y states compared to the ground state vs pp multiplicity.

Graph showing CMS results:

- CMS results for pp at 
  - \(\sqrt{s} = 7\) TeV
  - \(\sqrt{s} = 2.76\) TeV
  - \(\sqrt{s} = 5.02\) TeV

Yield ratios (1S)/Y(2S) vs pp multiplicity for different collision energies.

- \(p_T^{\mu}\) > 0 GeV, |y| < 1.93
CMS Measurement of $\Upsilon(nS)$ and pp Multiplicity

- CMS results all the way back in 2014 challenge this picture by showing a decrease in excited $\Upsilon$ states compared to the ground state vs pp multiplicity.
- More detailed measurements in 2020
  - Including analysis of event geometry via sphericity, which suggests effect is connected with UE not jets.

\begin{align*}
S_T = 0 & \rightarrow \text{jet-like} \\
S_T = 1 & \rightarrow \text{not jet-like}
\end{align*}
ATLAS Measurement of $\Upsilon(nS)$ and UE

- Measure the total multiplicity in the event (and particle kinematics) for each Upsilon state
- Precise control of background and pile-up
- Use differential particle kinematics to reach for the UE
- Compare excited to ground states
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- Shift in UE multiplicity across different excitation states can be understood as suppression of excited states at higher multiplicity

ATLAS Preliminary
$pp$, 13TeV, 139 fb$^{-1}$

$\langle n_{ch} \rangle$

**$\Upsilon(1S)$**, **$\Upsilon(2S)$**, **$\Upsilon(3S)$**

![Graph showing the difference in UE between excited and ground states](image)

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Is there Y(nS) Suppression in pp Collisions?

• As event multiplicity (should be UE) grows larger, excited Y states are, compared to the ground state, relatively less likely to be found.

• Do the CMS and ATLAS results show some “QGP-like” quarkonium “melting”?

• Is it even a suppression? Maybe it’s a lower state enhancement?

→ In any case seems to be a hard – UE correlated phenomenon.
Co-mover Interaction Model (CIM)

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- Within CIM, quarkonia are broken by collisions with comovers – i.e. final state particles with similar rapidities.

- CIM is typically used to explain $p+A$ and $A+A$ systems, matches CMS Upsilon pp data.

- With the new data, CIM can be tested on $pp$ to reproduce $\Upsilon(nS) - \Upsilon(1S)$ differences
  - in cross section
  - in $n_{ch}$
  - in hadron kinematic distributions: $p_T, \Delta \varphi, \Delta \eta$
Quarkonia Ratios Expected From $m_T$ Scaling

arXiv:2203.11831

- Transverse mass scaling lets one define an expectation for the excited states relative to the ground states
- Works well ~universally for light mesons at LHC energies
- Looking at Upsilon meson cross-sections shows missing excited states at low $p_T$
  - for $\Upsilon(2S)$ factor of 1.6 are missing
  - for $\Upsilon(3S)$ factor of 2.4!
Summary

• Strong evidence from Upsilon mesons that there is some non-trivial interaction between the “UE” and a hard scattering

• ATLAS & CMS have independent approaches that both point to UE driven modification of relative abundance of ground state vs excited state Upsilon mesons
  • Modification appearst to be a suppression of excited states

• **Seems we don’t understand Upsilon hadronization as it depends on the UE**

• More investigations can be made in the data
  • Check rapidity dependence
  • Check other species etc

• Effect is large and significant
  • Can existing models see this effect?
  • New ideas?