Correlation between Upsilon(nS) Mesons and the Underlying Event in pp Collisions
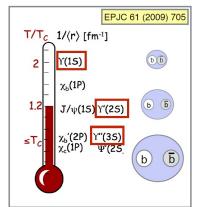
Zvi Citron for ATLAS

Big Picture

- Soft sector signatures 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

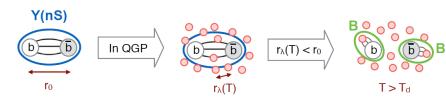- Looking at Upsilon mesons and trying to bridge soft-hard gap

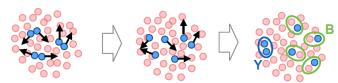# What Do We Know about Upsilon Production and the QGP?

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

- Behaves differently than charmonium in medium
  - Little recombination
  - Little path length dependence

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

What Do We Know about Upsilon Production and the QGP?

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

- Behaves differently than charmonium in medium
  - Little recombination
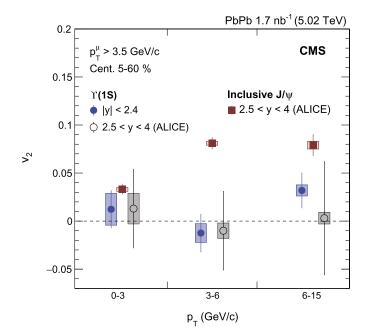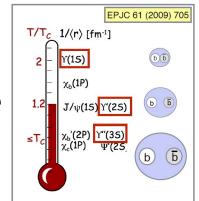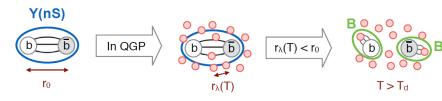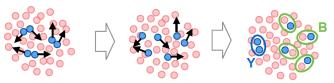 - Little path length dependence

- Default approach: measure in Pb+Pb and compare to pp

EPJC 61 (2009) 705

[Color screening]

[Regeneration]

PbPb 1.7 nb⁻¹ (5.02 TeV)

p_T^μ > 3.5 GeV/c
Cent. 5-60 %

Υ(1S)
● |y| < 2.4
○ 2.5 < y < 4 (ALICE)

Inclusive J/ψ
■ 2.5 < y < 4 (ALICE)

CMS

ATLAS EXPERIMENT

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev
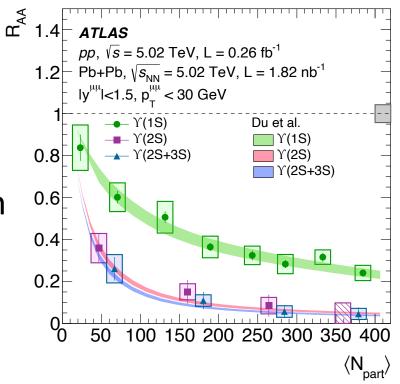
Upsilon Mesons in 5.02 TeV Pb+Pb & pp
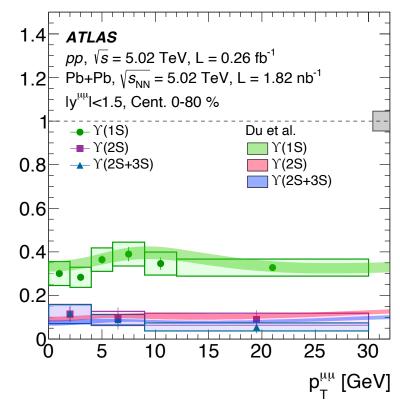
- Nuclear Modification

$$R_{AA} = \frac{N_{\Upsilon;AA}}{\langle T_{AA} \rangle \times \sigma^{pp \to \Upsilon}}$$

- Centrality and species dependent trends as expected from in-medium disassociation

- Looks like early (high T) disassociation → suppression compared to pp

ATLAS EXPERIMENT

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

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

JHEP 04 (2014) 103

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
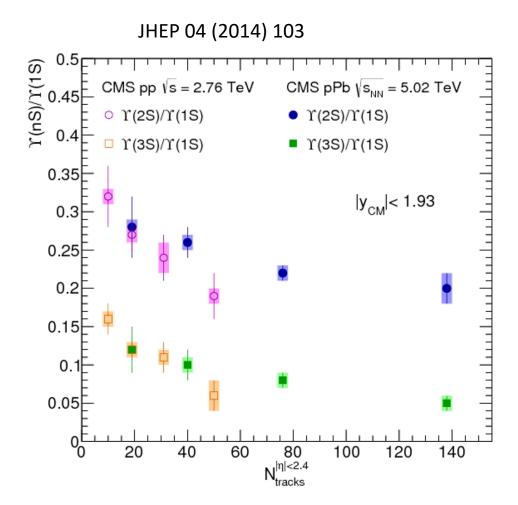Ben-Gurion University of the Negev

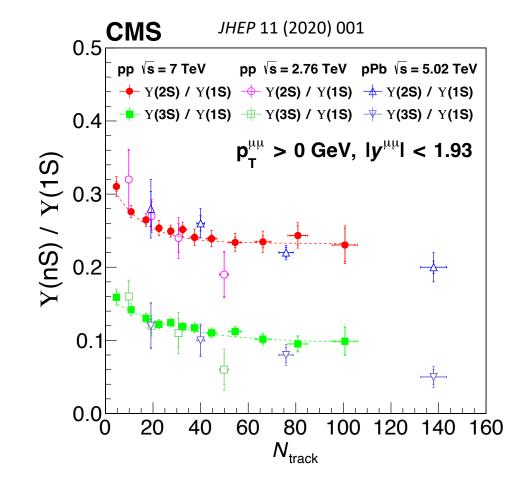# CMS Measurement of Y(nS) and pp Multiplicity

- 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

- More detailed measurements in 2020

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

ATLAS Measurement of Y(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

ATLAS-CONF-2022-023

- Full Run 2 high luminosity dataset, sampled with di-muon triggers
- Reconstruct Y(nS) → μμ
- Reconstruct inclusive charged particles

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev
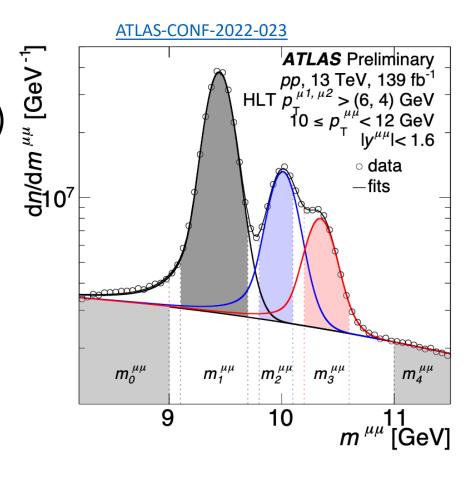
ATLAS Measurement of Y(nS) and UE

- 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

ATLAS-CONF-2022-023

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

ATLAS Measurement of Y(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

ATLAS-CONF-2022-023

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev
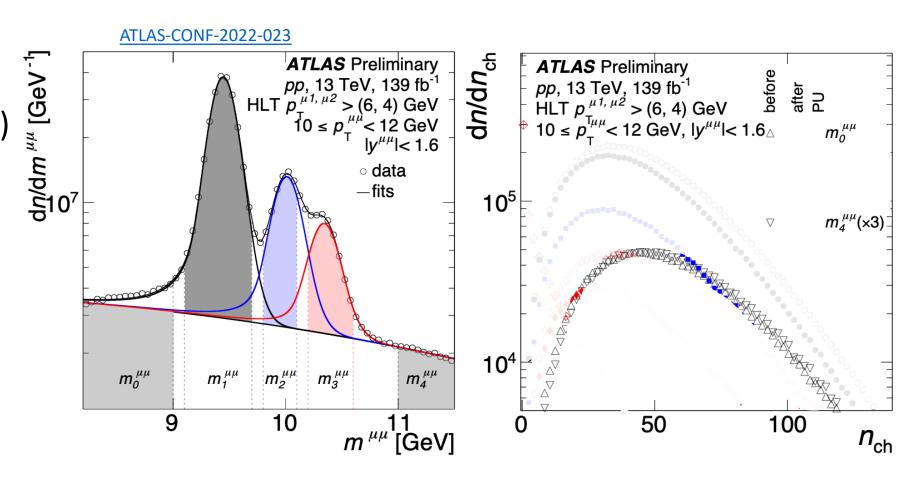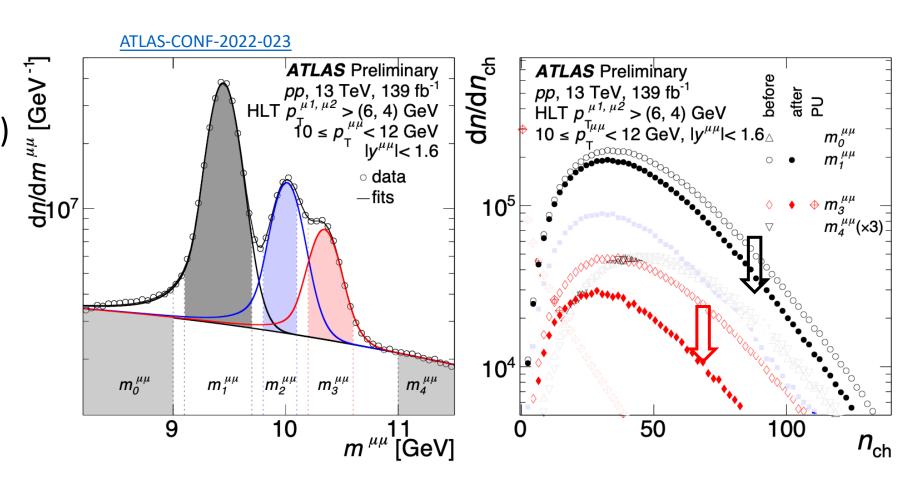
ATLAS Measurement of Y(nS) and UE

- 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

ATLAS-CONF-2022-023
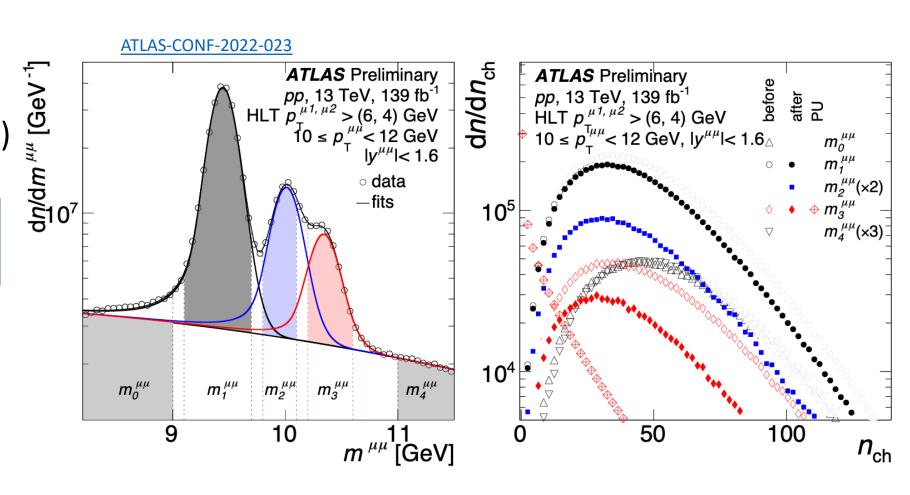
ATLAS Measurement of Y(nS) and UE

- 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

ATLAS-CONF-2022-023

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev
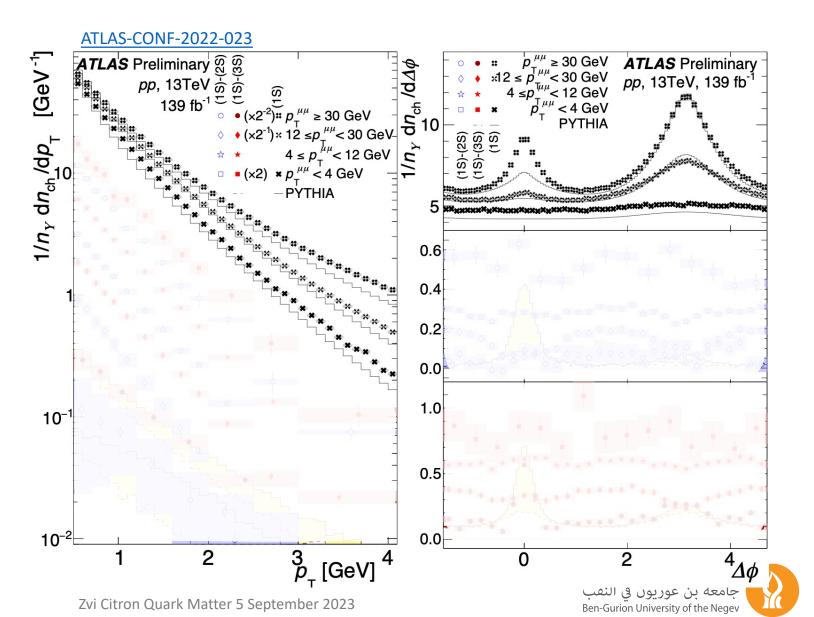
ATLAS Measurement of Y(nS) and UE

- 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

ATLAS-CONF-2022-023

ATLAS Measurement of Y(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

ATLAS-CONF-2022-023
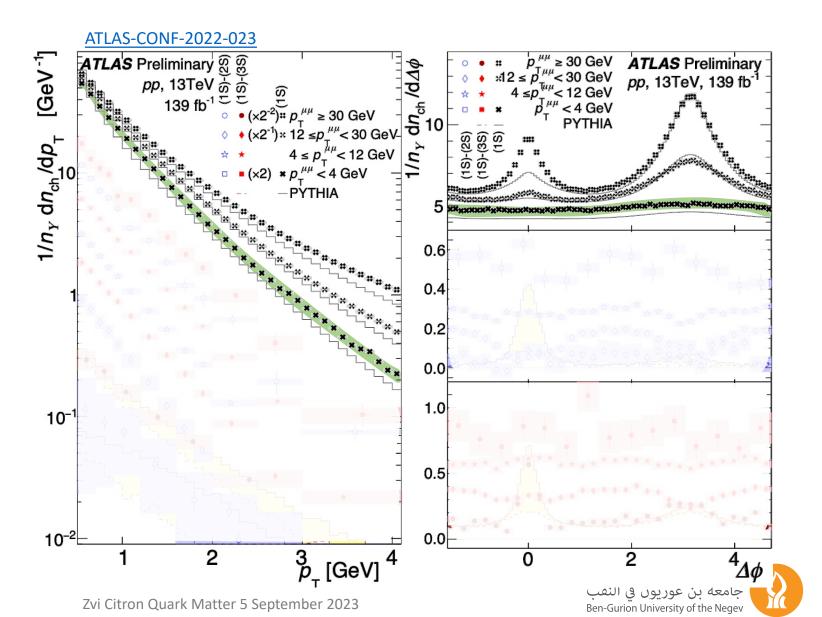
ATLAS Measurement of Y(nS) and UE

- 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

ATLAS-CONF-2022-023

جامعه بن عوريون في النمب
Ben-Gurion University of the Negev
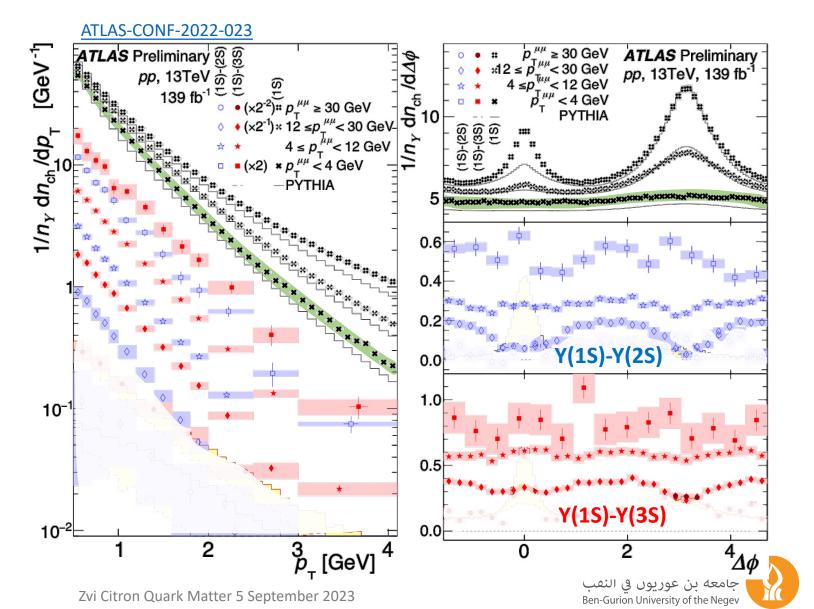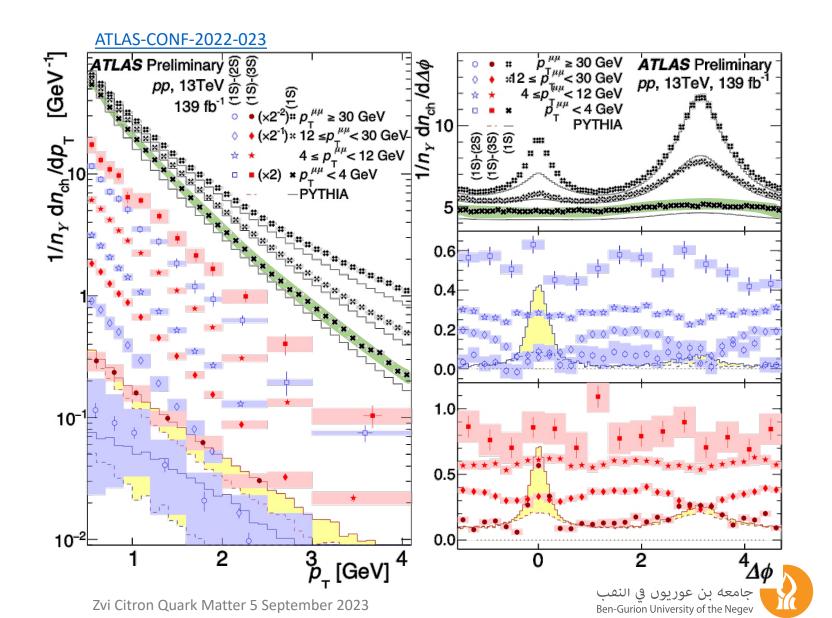
ATLAS Measurement of Y(nS) and UE

- 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

ATLAS-CONF-2022-023

جامعه بن عوريون في النمب
Ben-Gurion University of the Negev

ATLAS Measurement of Y(nS) and UE

ATLAS-CONF-2022-023

- 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

ATLAS Measurement of Y(nS) and UE
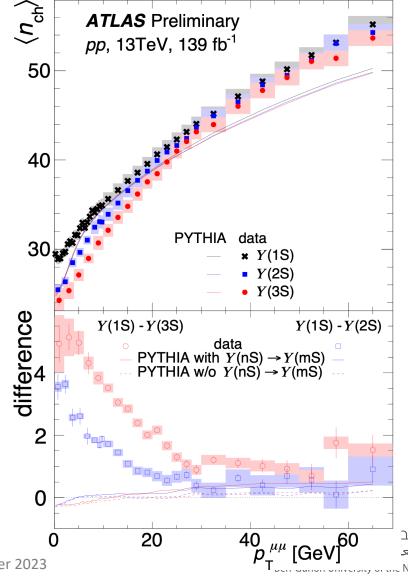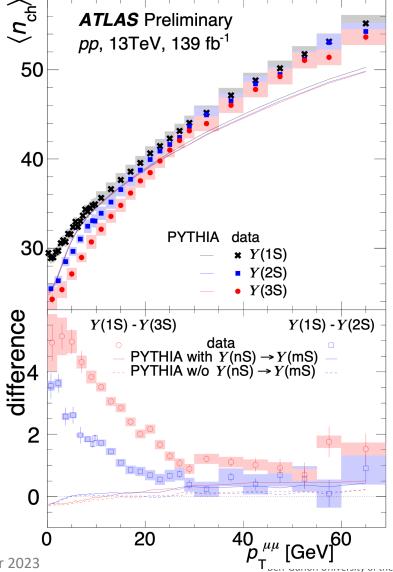
ATLAS-CONF-2022-023

- 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

- Shift in UE multiplicity across different excitation states can be understood as suppression of excited states at higher multiplicity
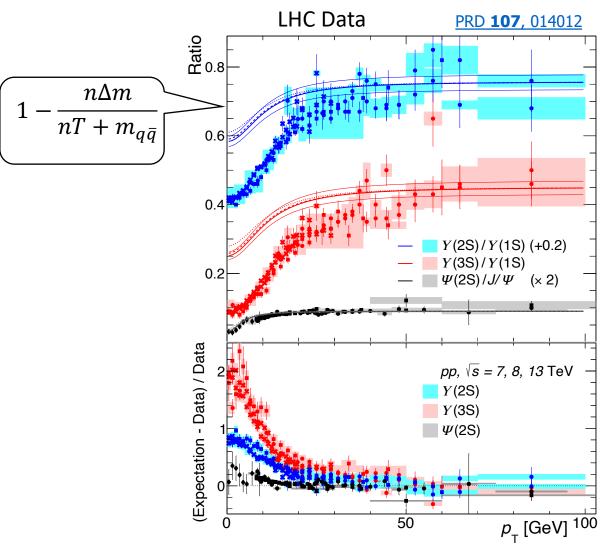
Is there Y(nS) Suppression in pp Collisions?

- 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**

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Quarkonia Ratios Expected From m_T Scaling

- Transverse mass scaling lets one define an expectation for the excited states relative to the ground states

$$1 - \frac{n\Delta m}{nT + m_{q\bar{q}}}$$

- 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!

LHC Data

PRD **107**, 014012

$Y(2S) / Y(1S)$ (+0.2)
$Y(3S) / Y(1S)$
$\Psi(2S)/J/\Psi$ (× 2)

pp, $\sqrt{s}$ = 7, 8, 13 TeV
$Y(2S)$
$Y(3S)$
$\Psi(2S)$

Ratio

(Expectation - Data) / Data

p_T [GeV]

ATLAS EXPERIMENT

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Quarkonia Ratios Expected From m_T Scaling

- 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
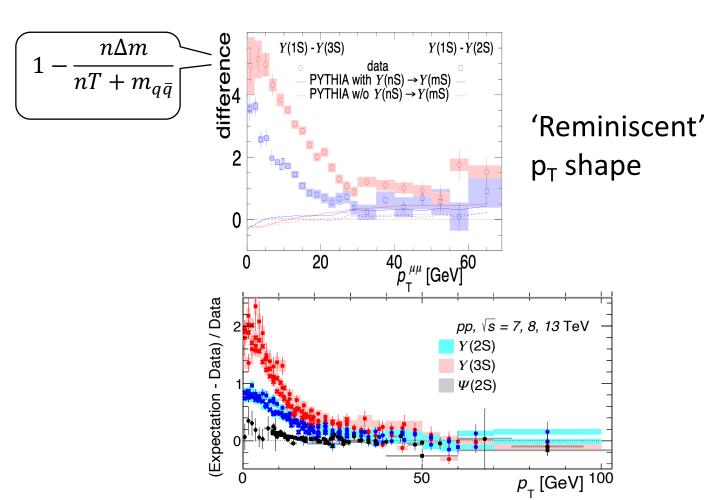 - for $\Upsilon(2S)$ factor of 1.6 are missing
  - for $\Upsilon(3S)$ factor of 2.4!

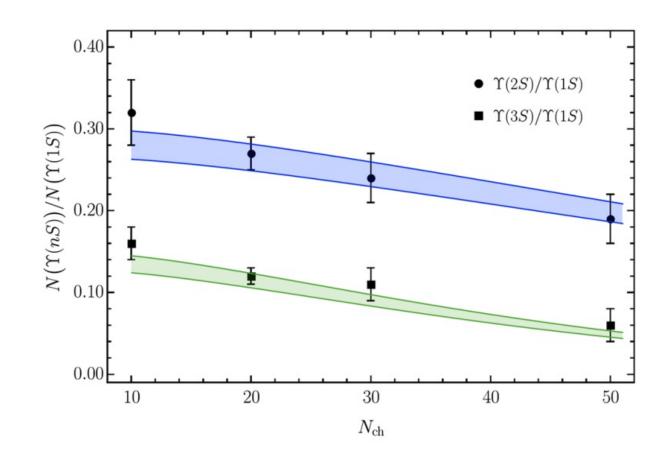$$1 - \frac{n\Delta m}{nT + m_{q\bar{q}}}$$

'Reminiscent' p_T shape

Co-mover Interaction Model (CIM)

EPJC 81, 669 (2021)

- 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.

- Could it reproduce ATLAS data? Cross-sections?

Summary

- Comparing Pb+Pb and pp Upsilon production seems to fit some QGP expectations

- But pp "baseline" is not trivial

- Evidence from Upsilon mesons that there is some non-trivial interaction between the "UE" and a hard scattering in **pp** collisions
  - Appears to be a suppression of excited states
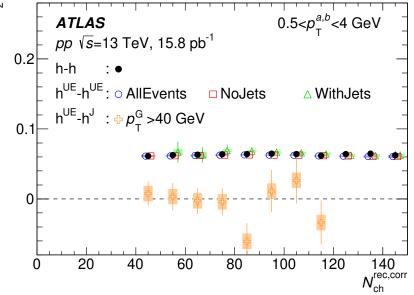 - Effect is large and significant

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Extra Slides

Does An
ATLAS R

- Easy to summarize as "UE doesn't know about jets (i.e. hard scatter)"

- Easy summaries notwithstanding I don't think there is real tension

- Jet/non-jet flow measurement tells us that the ridge is not sensitive to hard contribution

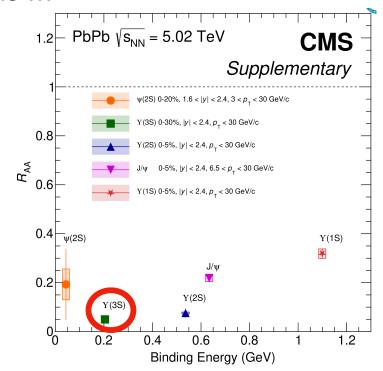- Excited upsilon suppression is still correlated with UE/bulk particles

These results demonstrate that the magnitude of the v_2 is not affected when removing tracks associated with jets, or by the presence or absence of jets in the event.

... suggest a complete "factorization" between hard-scattering processes and the physics responsible for the ridge
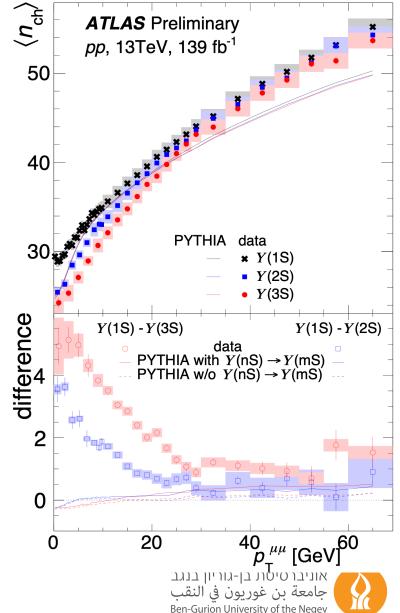
Is it all just binding energy? What About Charmonium?

- Logical to assume that the effect is related to the $q\bar{q}$ binding energy, but then $\psi(2S)$ must show a lot more suppression.

- Would be great to measure UE-J/ψ and UE-$\psi(2S)$ correlations …
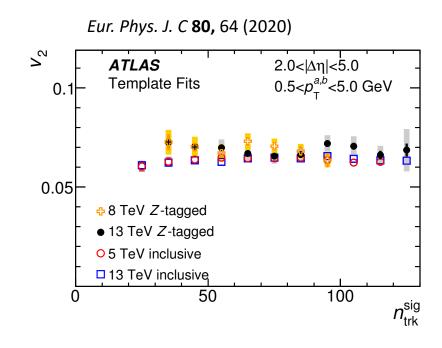
Ota Kukral's talk
Wed, 17:10, Ballroom D

$\Upsilon(3S)$

אוניברסיטת בן-גוריון בנגב
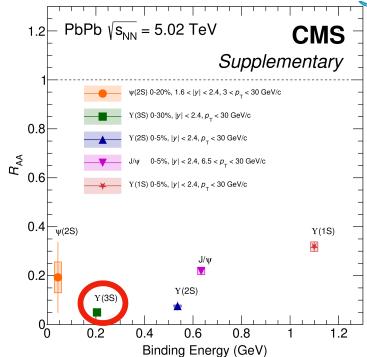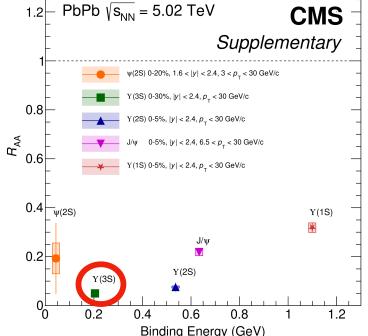جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Is it all just binding energy? What About Charmonium?

- Logical to assume that the effect is related to the $q\bar{q}$ binding energy, but then $\psi(2S)$ must show a lot more suppression.

$\Upsilon(3S)$
- Would be great to measure UE-J/ψ and UE-$\psi(2S)$ correlations …

**Ota Kukral's talk
Wed, 17:10, Ballroom D**

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

ATLAS EXPERIMENT

A Previous Hard-Soft Study: Two-particle correlations in Z Boson Tagged pp Collisions
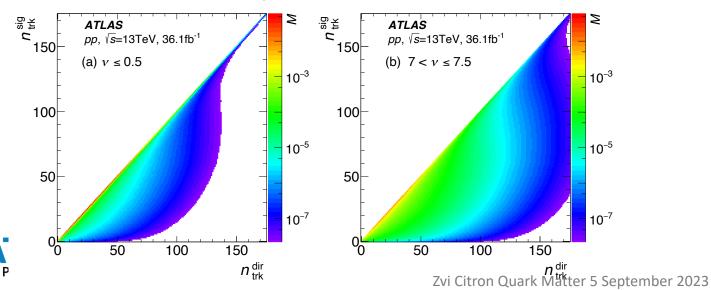
- In a previous study we asked: Does the presence of a hard scattering in the collision change "*something-like-geometry*" and consequently the observed "*flow*"?

- 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

Eur. Phys. J. C **80,** 64 (2020)

ATLAS Template Fits

$2.0<|\Delta\eta|<5.0$
$0.5<p_T^{a,b}<5.0$ GeV

- 8 TeV Z-tagged
- 13 TeV Z-tagged
- 5 TeV inclusive
- 13 TeV inclusive
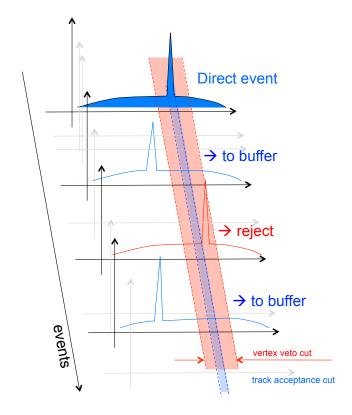
v_2

v_2 ratio to 13 TeV inclusive

n_{trk}^{sig}

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**!
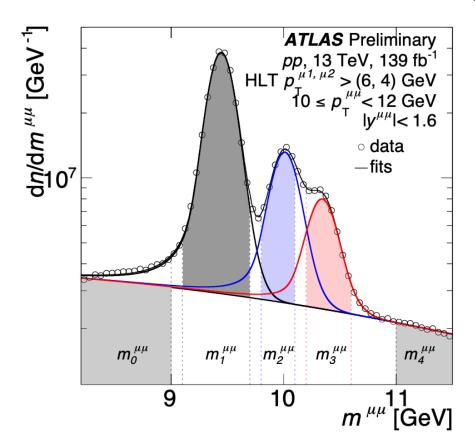

Eur. Phys. J. C **80,** 64 (2020)

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Technical Fit Things

$$\text{fit}(m) = \sum_{nS} N_{\Upsilon(nS)} F_n(m) + N_{\text{bkg}} F_{\text{bkg}}(m)$$

$$F_n(m) = (1-\omega_n)CB_n(m) + \omega_n G_n(m) \quad \text{Crystal Ball + Gaussian}$$

$$F_{\text{bkg}}(m) = \sum_{i=0}^{3} a_i(m-m_0)^i; a_0 = 1 \quad \text{Polynomial}$$

$$\begin{pmatrix} P(m_0^{\mu\mu}) \\ P(m_1^{\mu\mu}) \\ P(m_2^{\mu\mu}) \\ P(m_3^{\mu\mu}) \\ P(m_4^{\mu\mu}) \end{pmatrix} = \begin{pmatrix} 1-f_{01} & f_{01} & 0 & 0 & 0 \\ k_1(1-s_1) & s_1 & 0 & 0 & (1-k_1)(1-s_1) \\ k_2(1-s_2-f_{21}-f_{23}) & f_{21} & s_2 & f_{23} & (1-k_2)(1-s_2-f_{21}-f_{23}) \\ k_3(1-s_3-f_{32}) & 0 & f_{32} & s_3 & (1-k_3)(1-s_3-f_{32}) \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} P_0 \\ P(\Upsilon(1S)) \\ P(\Upsilon(2S)) \\ P(\Upsilon(3S)) \\ P_4 \end{pmatrix}$$

$$s_n = \frac{\int_{m_n^{\mu\mu}} N_{\Upsilon(nS)} F_n(m)\, dm}{\int_{m_n^{\mu\mu}} \text{fit}(m)\, dm}$$

$$f_{nk} = \frac{\int_{m_n^{\mu\mu}} N_{\Upsilon(kS)} F_k(m)\, dm}{\int_{m_n^{\mu\mu}} \text{fit}(m)\, dm}$$

$$k_n = \frac{\langle F_{\text{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\text{bkg}}(m)\rangle|_{m_n^{\mu\mu}}}{\langle F_{\text{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\text{bkg}}(m)\rangle|_{m_0^{\mu\mu}}}$$
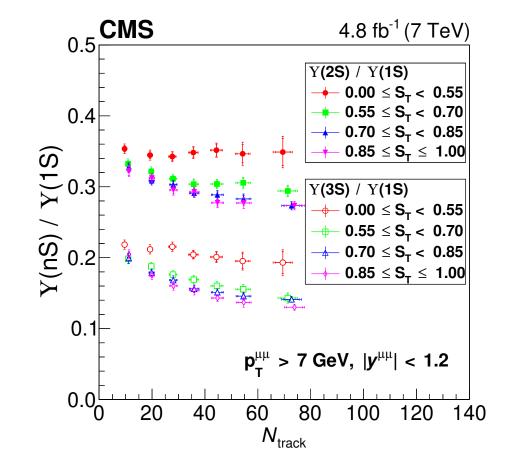
CMS Measurement of Y(nS) and pp Multiplicity

- CMS re
  2014 c
  showir
  Y state
  grounc

- More
  in 202

  - Incl
    geo
    sug
    wit

$$S_{\mathrm{T}} \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2},$$

$$S_{xy}^T = \frac{1}{\sum_i p_{\mathrm{T}i}} \sum_i \frac{1}{p_{\mathrm{T}i}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

$S_T = 0 \rightarrow$ jet-like
$S_T = 1 \rightarrow$ not jet-like

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Systematics Summary

	$p_\mathrm{T}^{\mu\mu} \leq 4$ GeV	$4 < p_\mathrm{T}^{\mu\mu} \leq 12$ GeV	$12 < p_\mathrm{T}^{\mu\mu} \leq 30$ GeV	$p_\mathrm{T}^{\mu\mu} > 30$ GeV
$\Upsilon(1\mathrm{S})$	$0.5 - 0.6$	$0.5 - 0.7$	$0.7 - 0.8$	$0.8 - 0.9$
$\Upsilon(2\mathrm{S})$	$0.6 - 0.6$	$0.5 - 0.7$	$0.7 - 0.8$	$0.8 - 1.0$
$\Upsilon(3\mathrm{S})$	$0.9 - 1.3$	$0.5 - 0.8$	$0.7 - 0.8$	$0.8 - 0.9$
$\Upsilon(1\mathrm{S}) - \Upsilon(2\mathrm{S})$	$0.11 - 0.15$	$0.06 - 0.10$	$0.12 - 0.21$	$0.2 - 0.5$
$\Upsilon(1\mathrm{S}) - \Upsilon(3\mathrm{S})$	$0.6 - 0.9$	$0.14 - 0.36$	$0.14 - 0.15$	$0.16 - 0.19$

Table 1: Systematic uncertainties for measurements of $\langle n_\mathrm{ch} \rangle$ and their differences for different $\Upsilon(n\mathrm{S})$ states and for the difference between $\langle n_\mathrm{ch} \rangle$ measured for $\Upsilon(1\mathrm{S}) - \Upsilon(n\mathrm{S})$. The values are the number of charged particles with $0.5 \leq p_\mathrm{T} < 10$ GeV and $|\eta| < 2.5$.

Shown here in "units" of n_ch but propagated to all quantities

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

Does the rapidity matter?

ALICE result on forward (normalized) $\Upsilon(2S)/\Upsilon(1S)$ vs (normalized) tracks at midrapidity

Looks flat unlike CMS, but must be careful about sensitivity of observables

A direct answer should come from $\Delta\eta$ – analysis