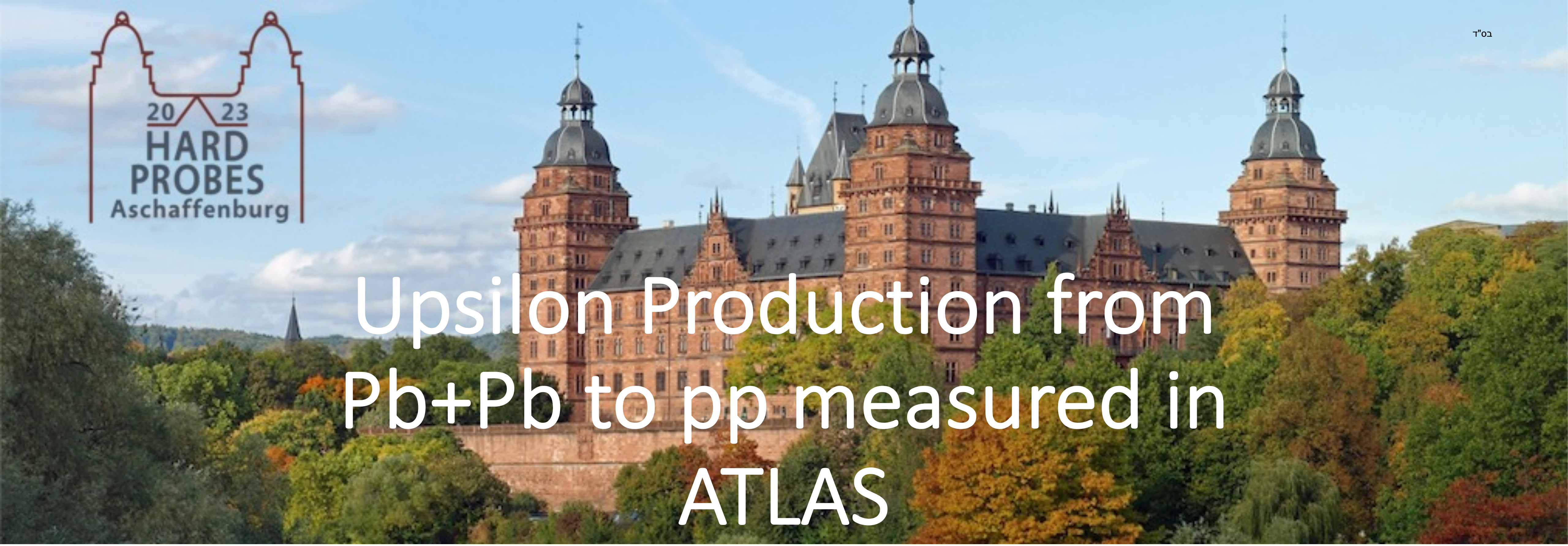
בס"ד



Upsilon Production from Pb+Pb to pp measured in ATLAS

Zvi Citron for ATLAS

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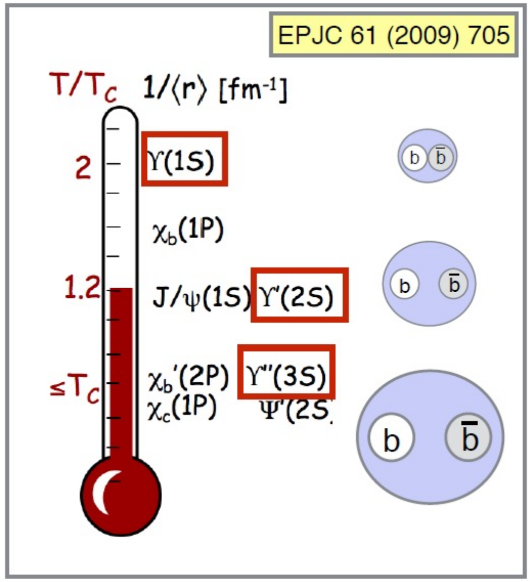
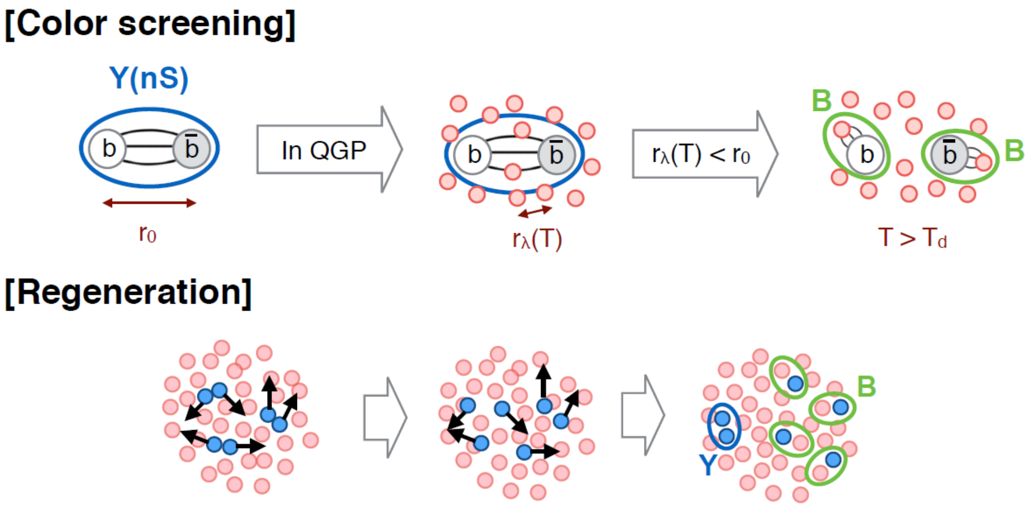
What Do We Know about Upsilon Production *and collectivity* at the LHC?



- From a heavy-ion perspective Υ(nS) states could be a “thermometer” for a QGP
- Different prompt fraction, regeneration compared to charmonia states
- **So let’s measure in Pb+Pb vs pp**



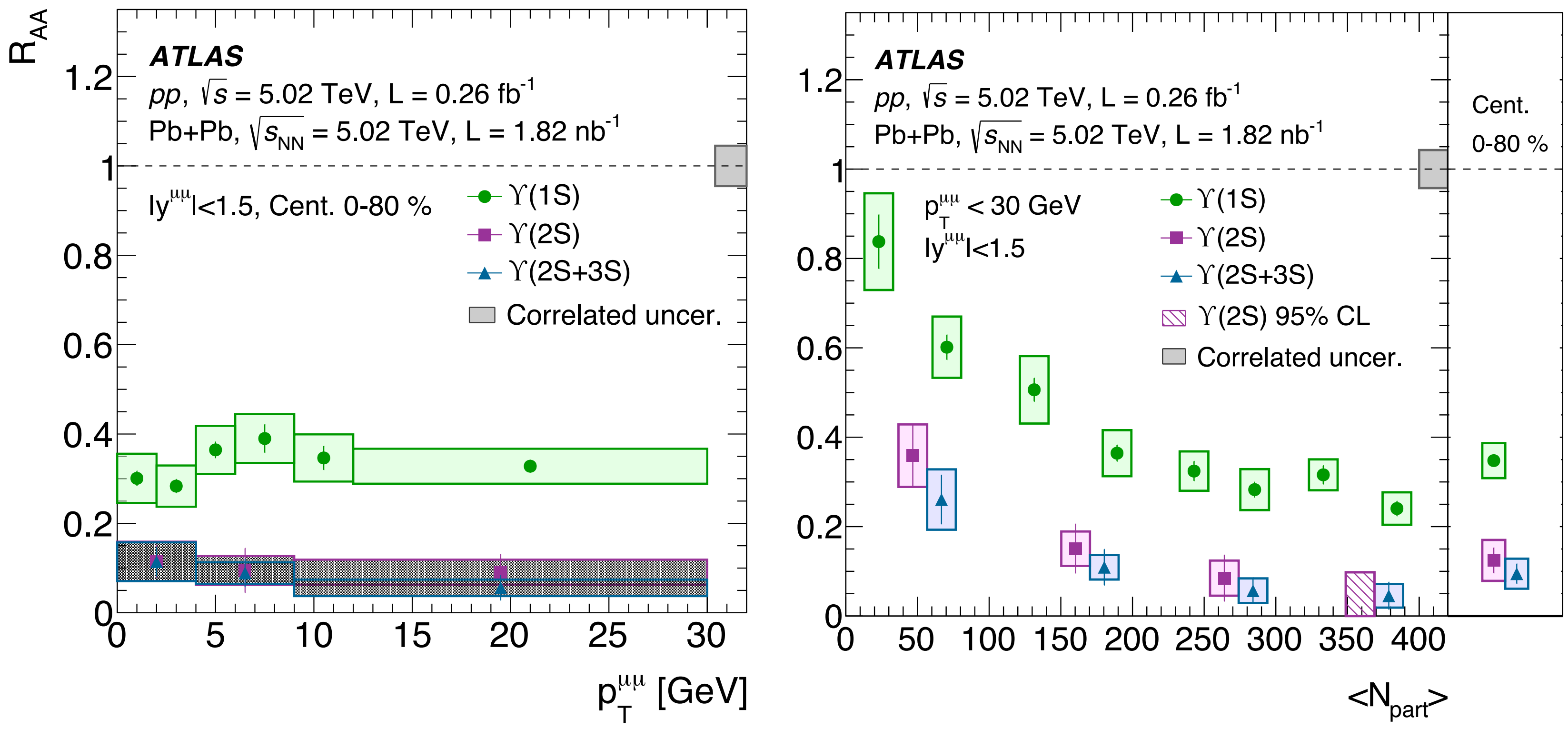
Upsilon Mesons in 5.02 TeV Pb+Pb & pp

arXiv:2205.03042

- Nuclear Modification

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

- Centrality and species dependent trends as expected
  - Minimal p_T dependence



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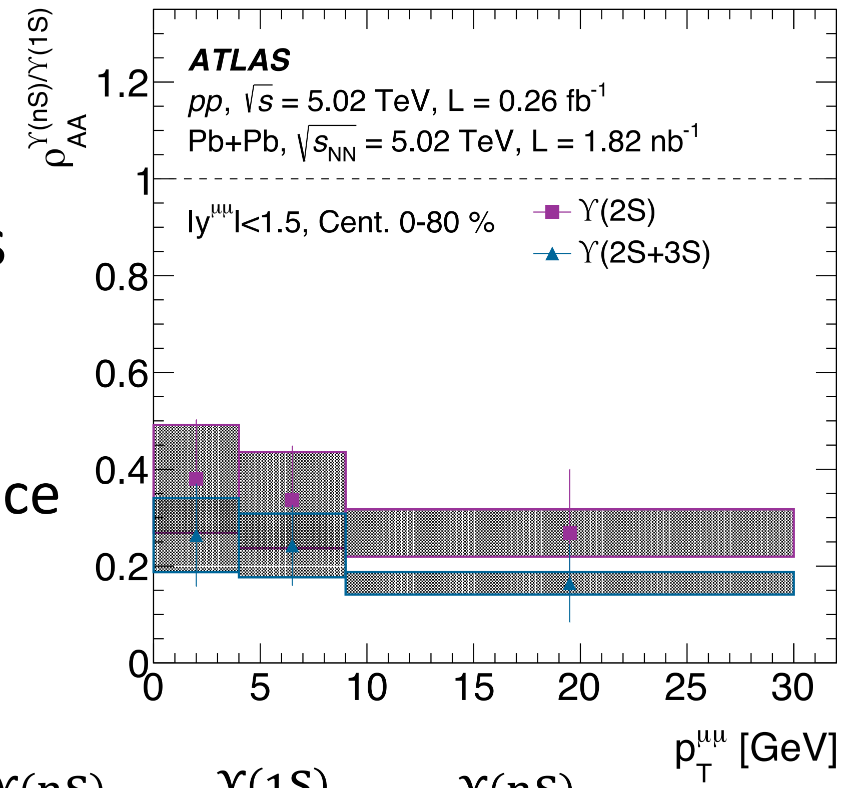
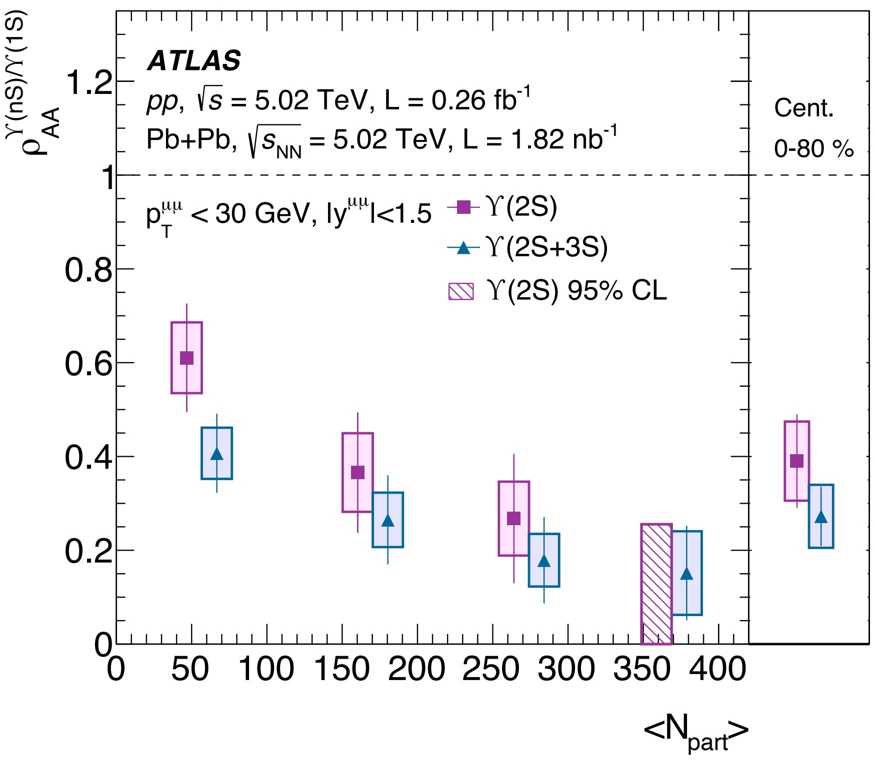
- Nuclear Modification

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

- Centrality and species dependent trends as expected
  - Minimal p_T dependence
- Double ratio cancels uncertainties



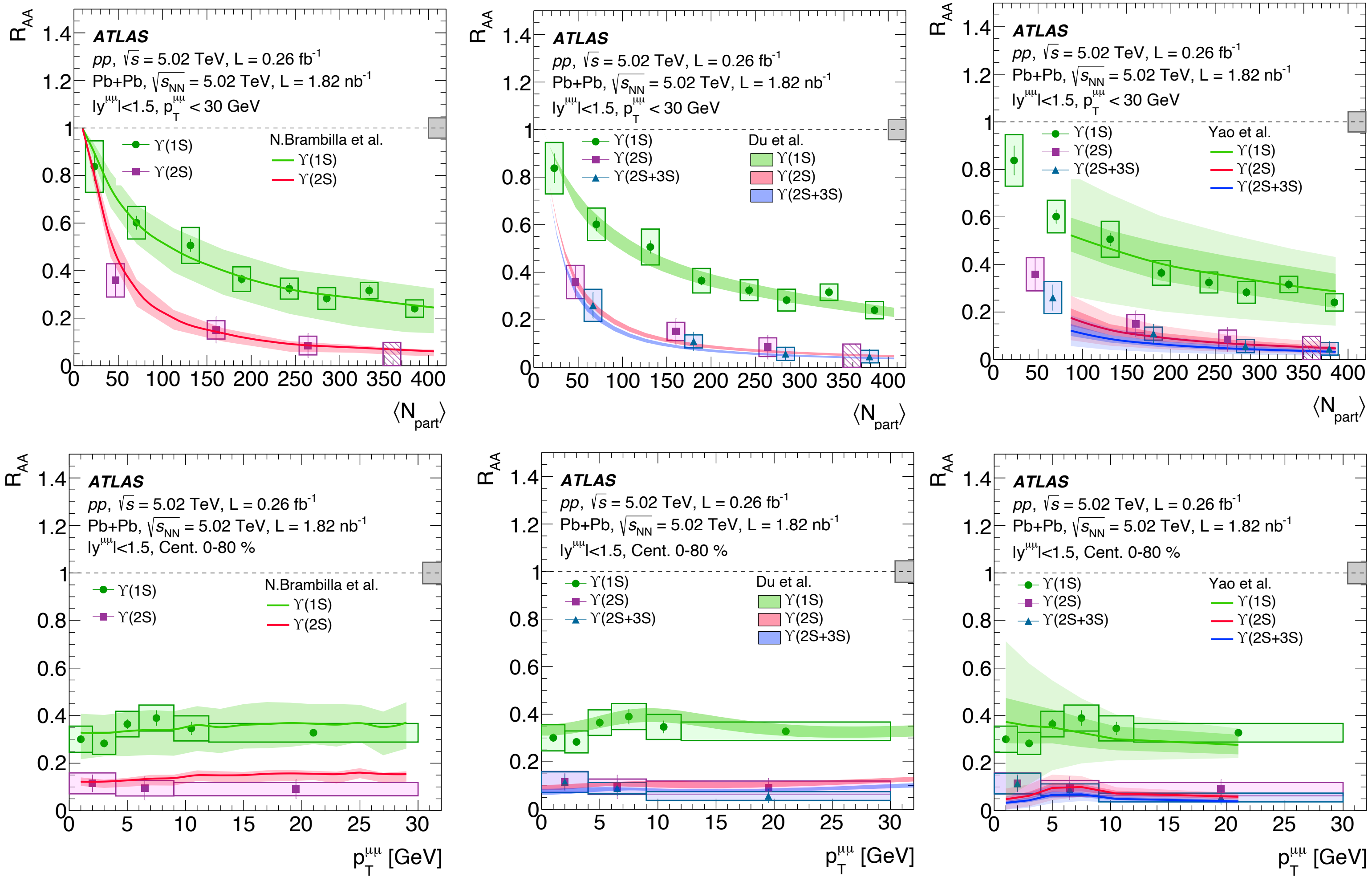


$$\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})} = \frac{N_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})}}{N_{\mathrm{AA}}^{\Upsilon(1\mathrm{S})}} \times \frac{\sigma_{pp}^{\Upsilon(1\mathrm{S})}}{\sigma_{pp}^{\Upsilon(\mathrm{nS})}} = \frac{R_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})}}{R_{\mathrm{AA}}^{\Upsilon(1\mathrm{S})}}$$

Comparison with Models

arXiv:2205.03042

- Different approaches to explain the suppression
- **All** invoke deconfinement
  - Brambilla – NRQCD: two transport coefficients
  - Du – kinetic rate equation
  - Yao – coupled HF transport in QGP
- All agree well with data …



N.Brambilla et al., PRD 104 (2021) 094049

M.H.X. Du and R. Rapp, PRC 96 (2017) 054901

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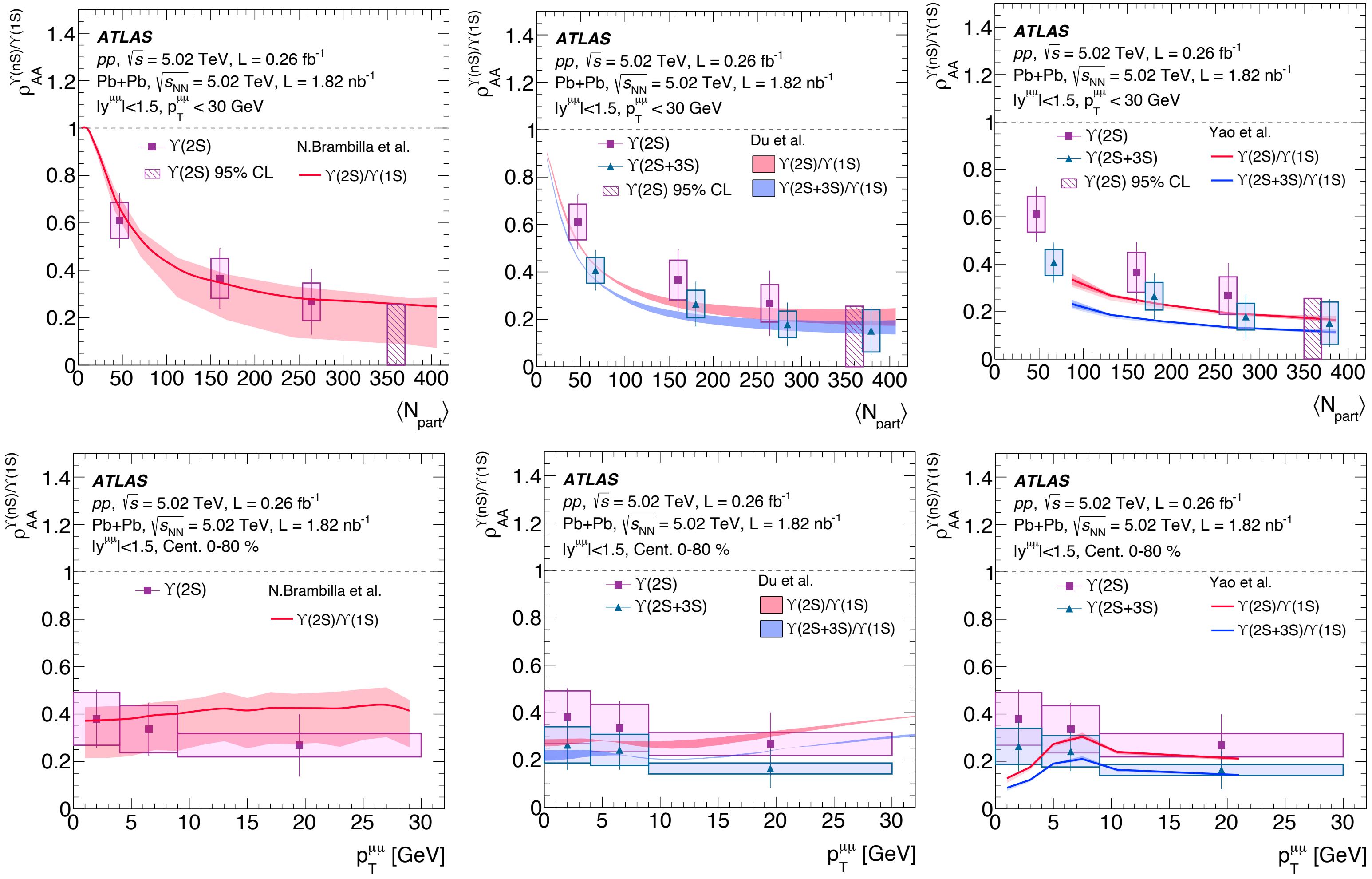

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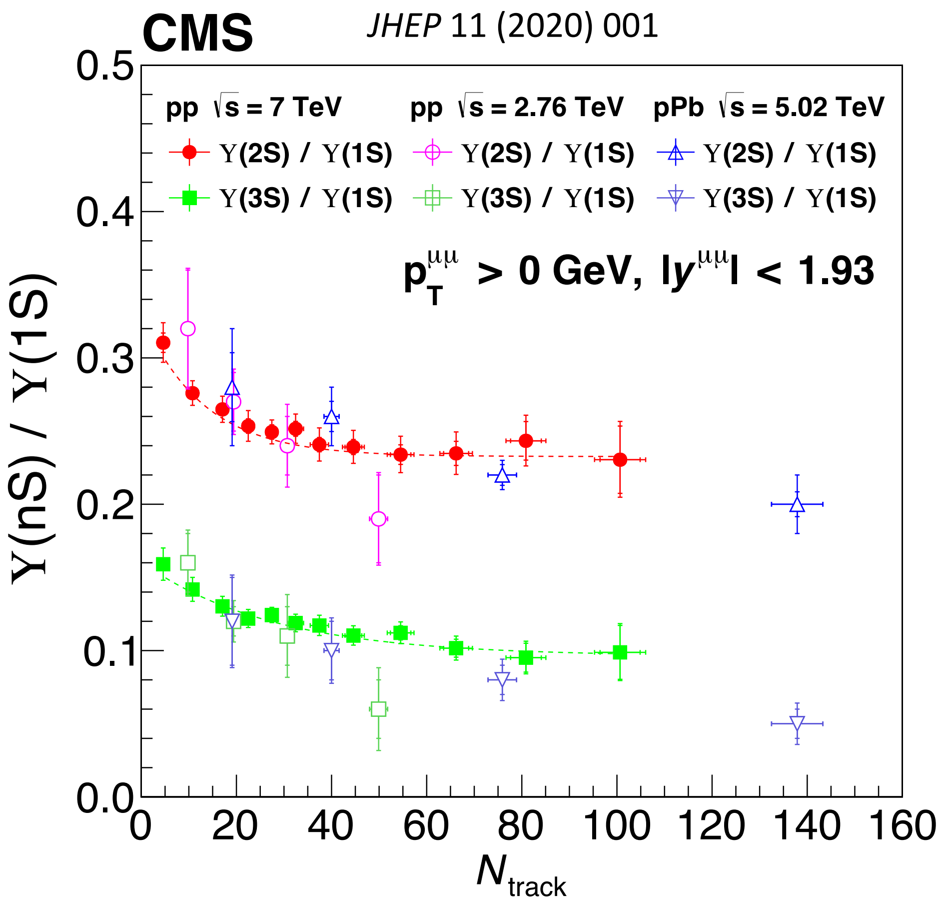
CMS Measurement of Υ(nS) and pp Multiplicity

- CMS results all the way back in 2014 show a decrease in excited Υ states compared to the ground state vs pp multiplicity
- (More detailed measurements in 2020)
- Let's make a **detailed study of Upsilon production and inclusive tracks**



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ATLAS Measurement of Υ(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

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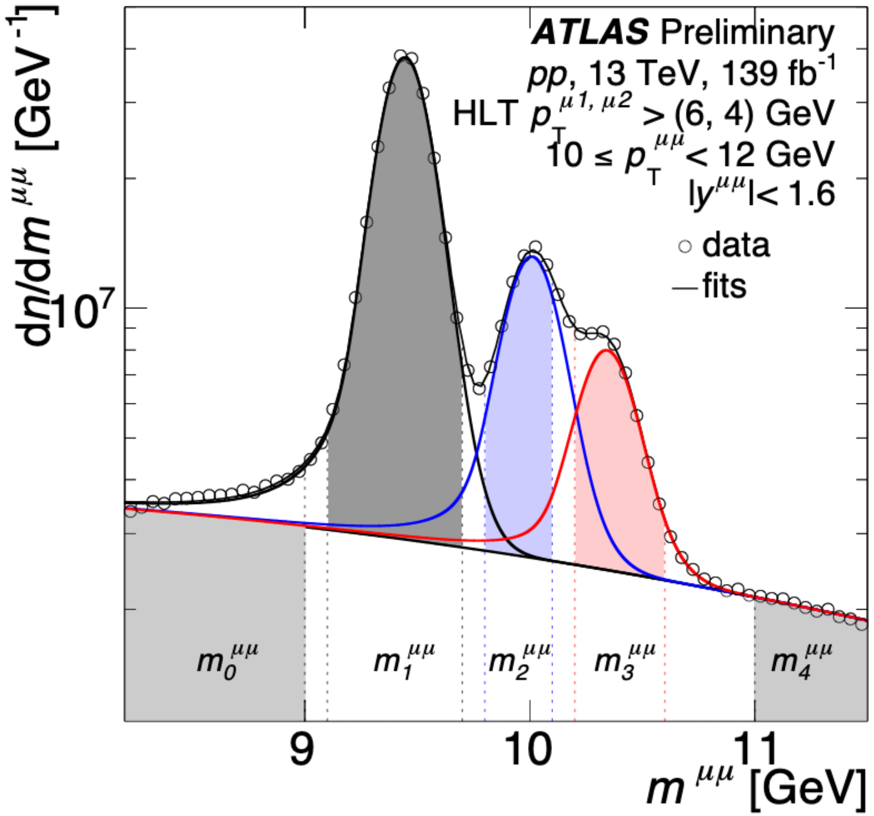
ATLAS-CONF-2022-023



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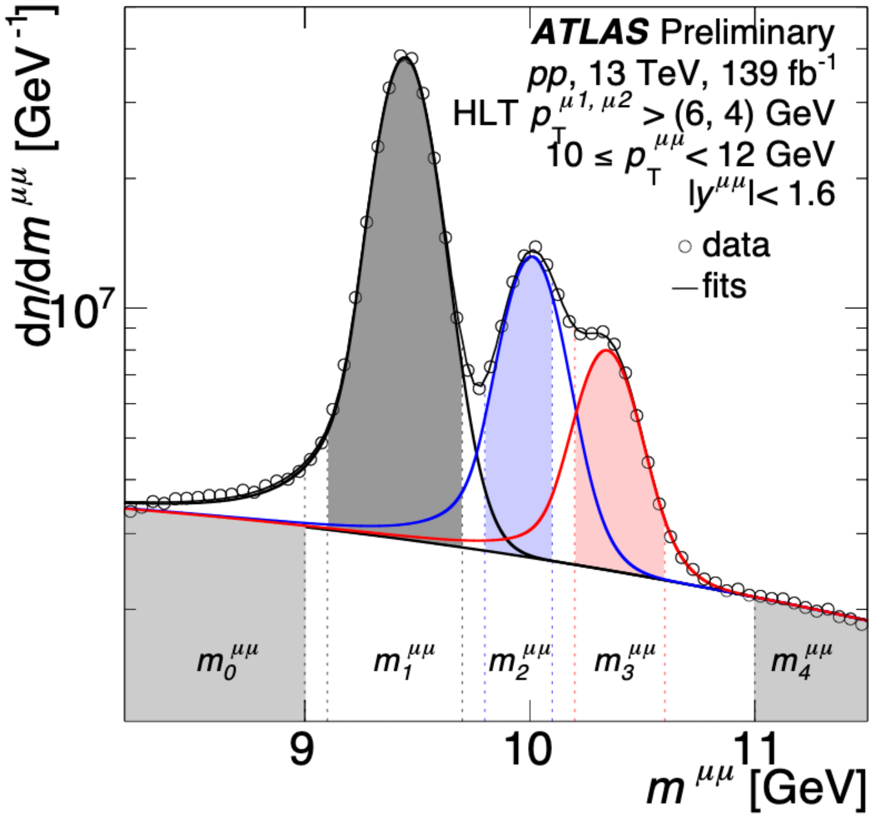

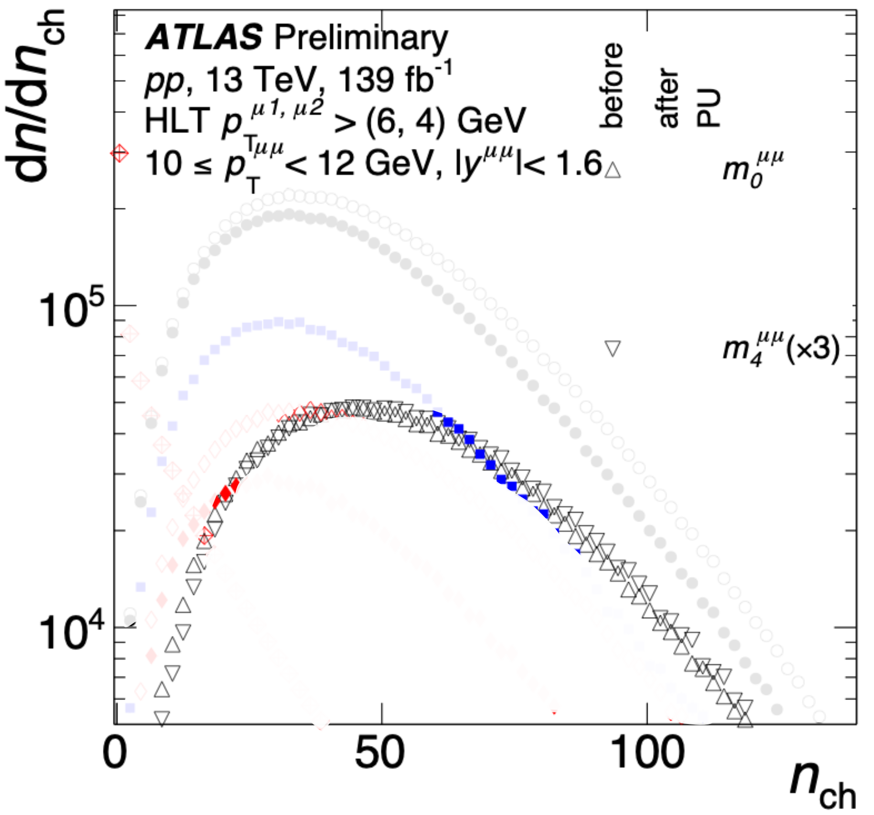

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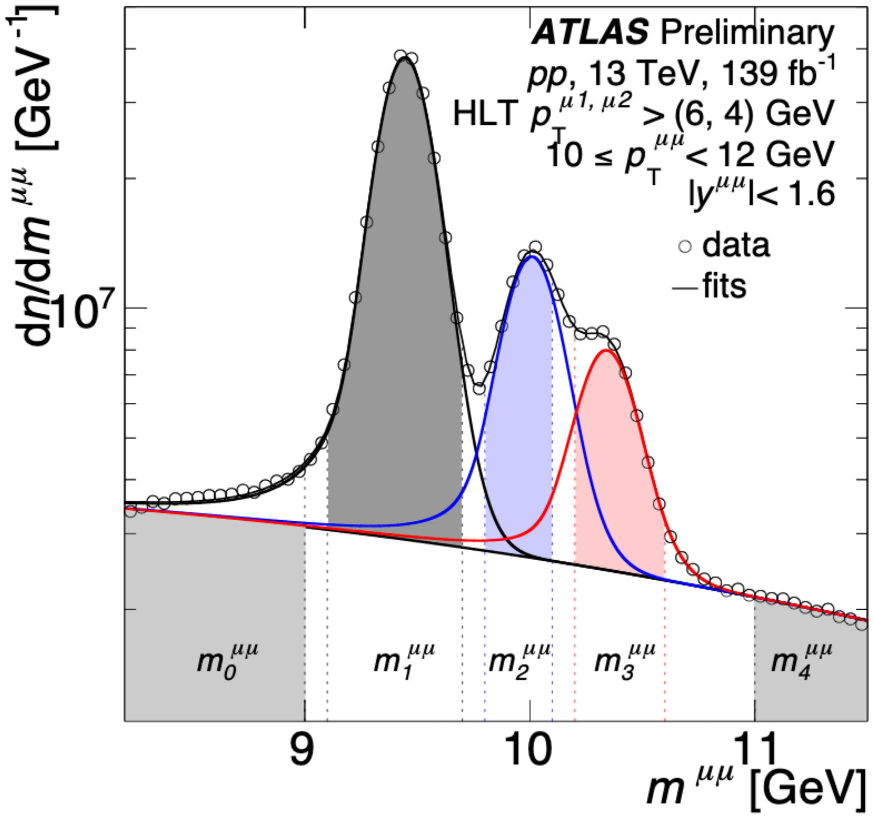

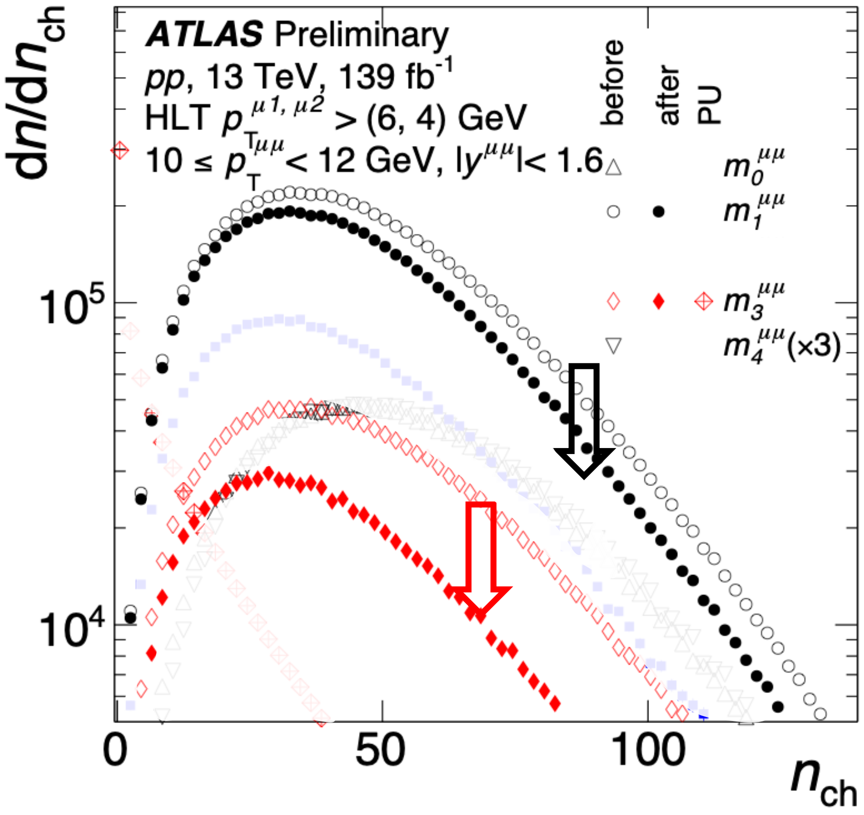

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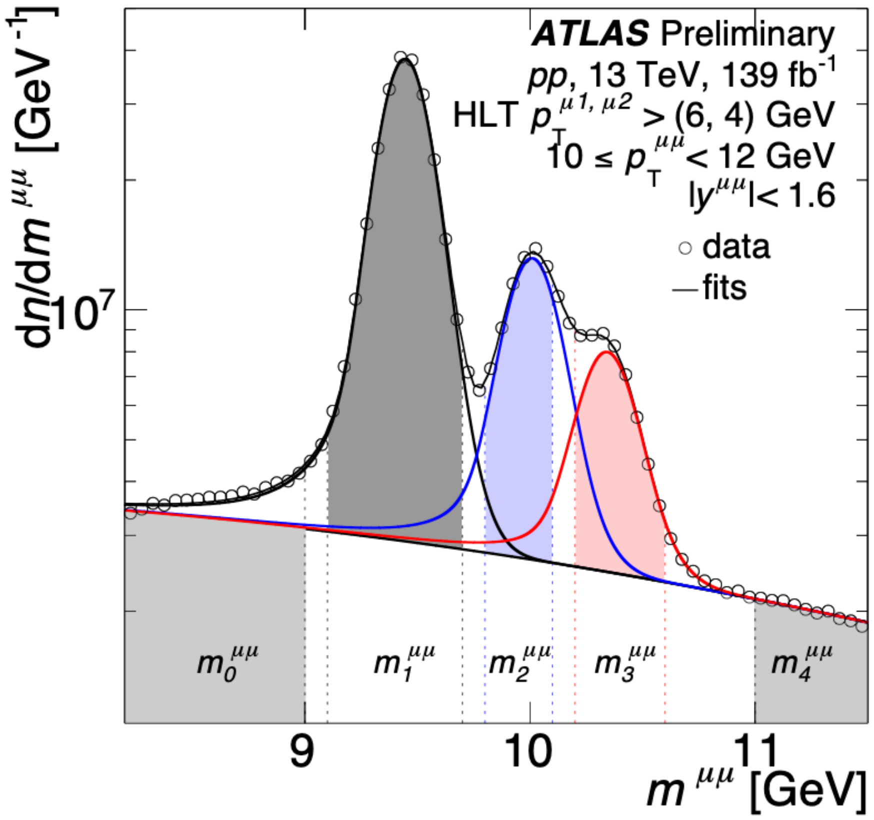

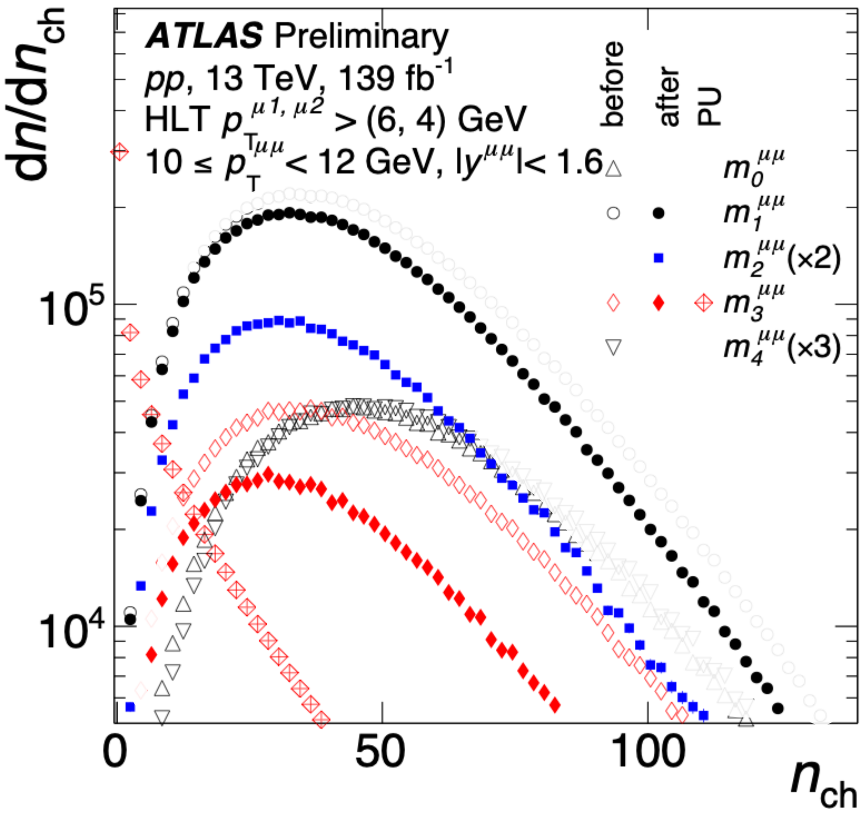

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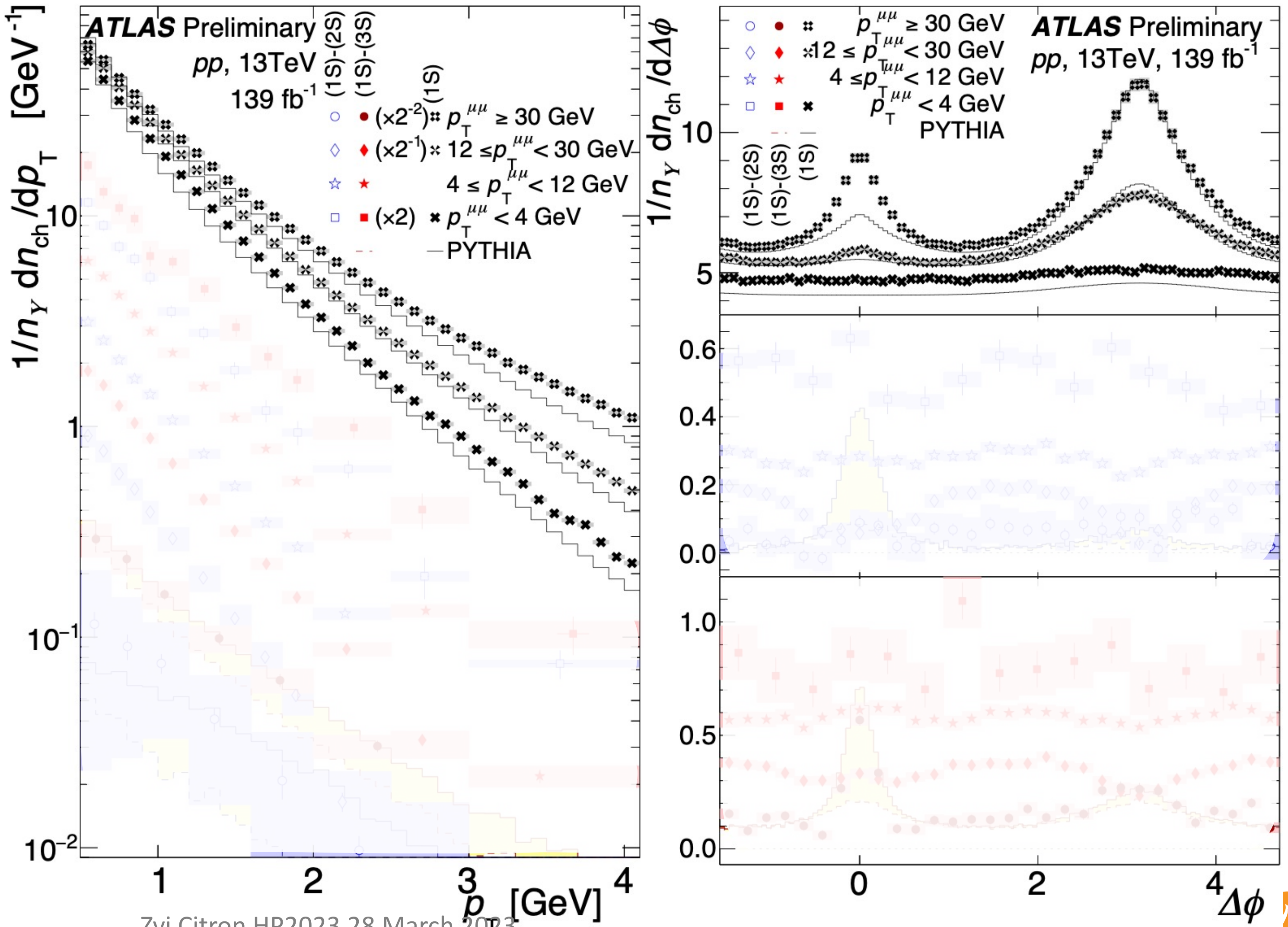

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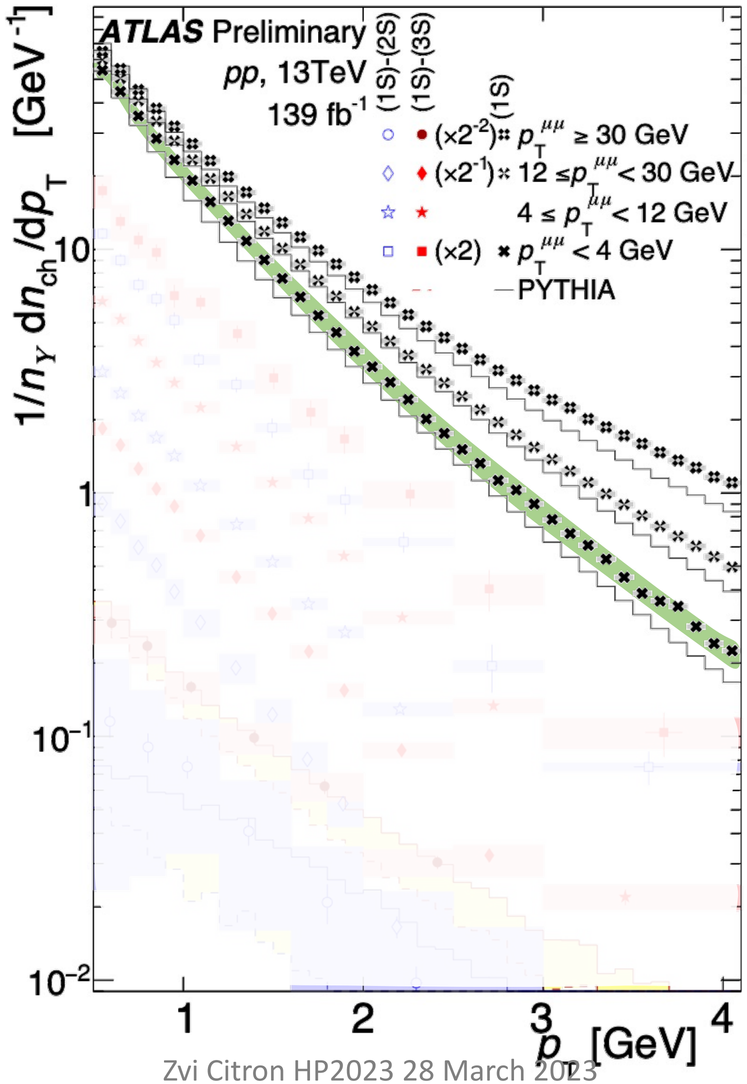

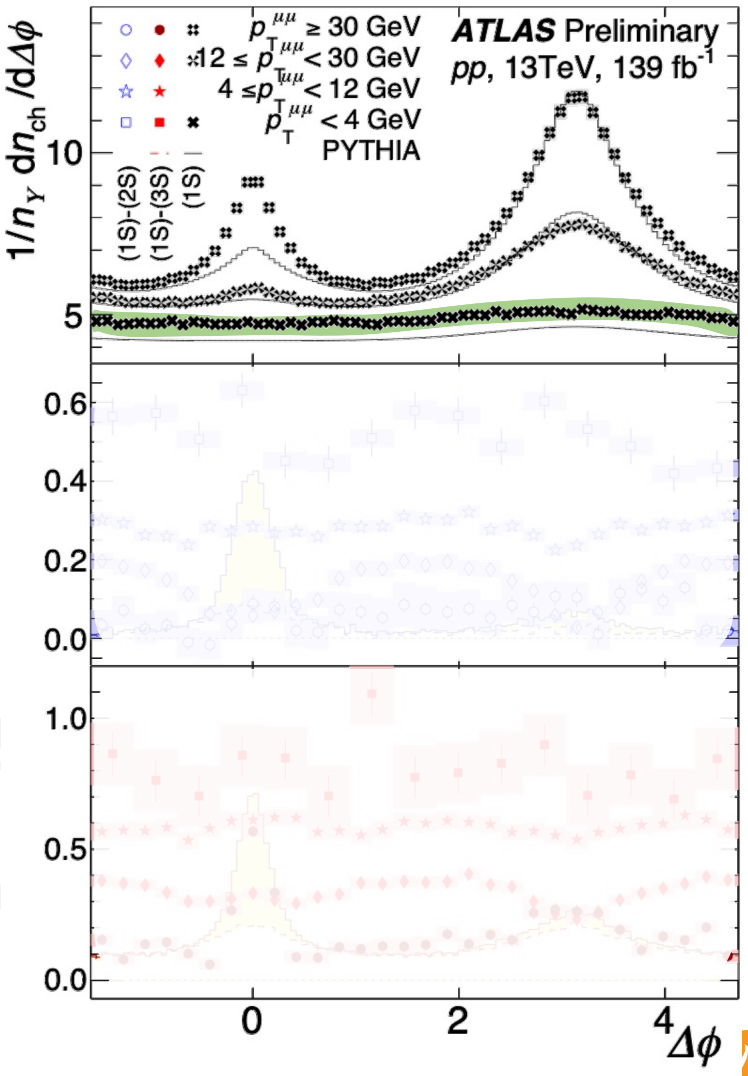

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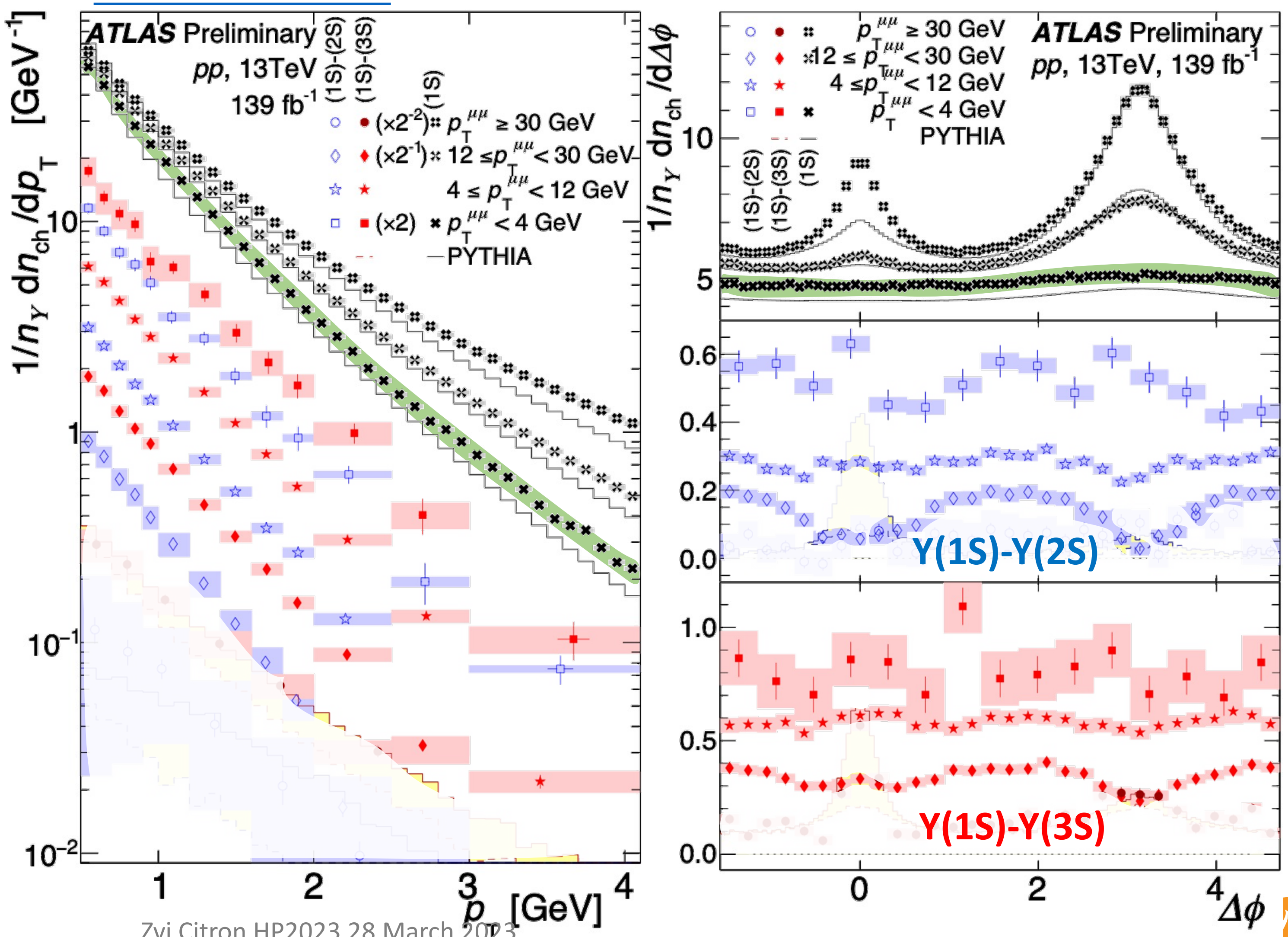

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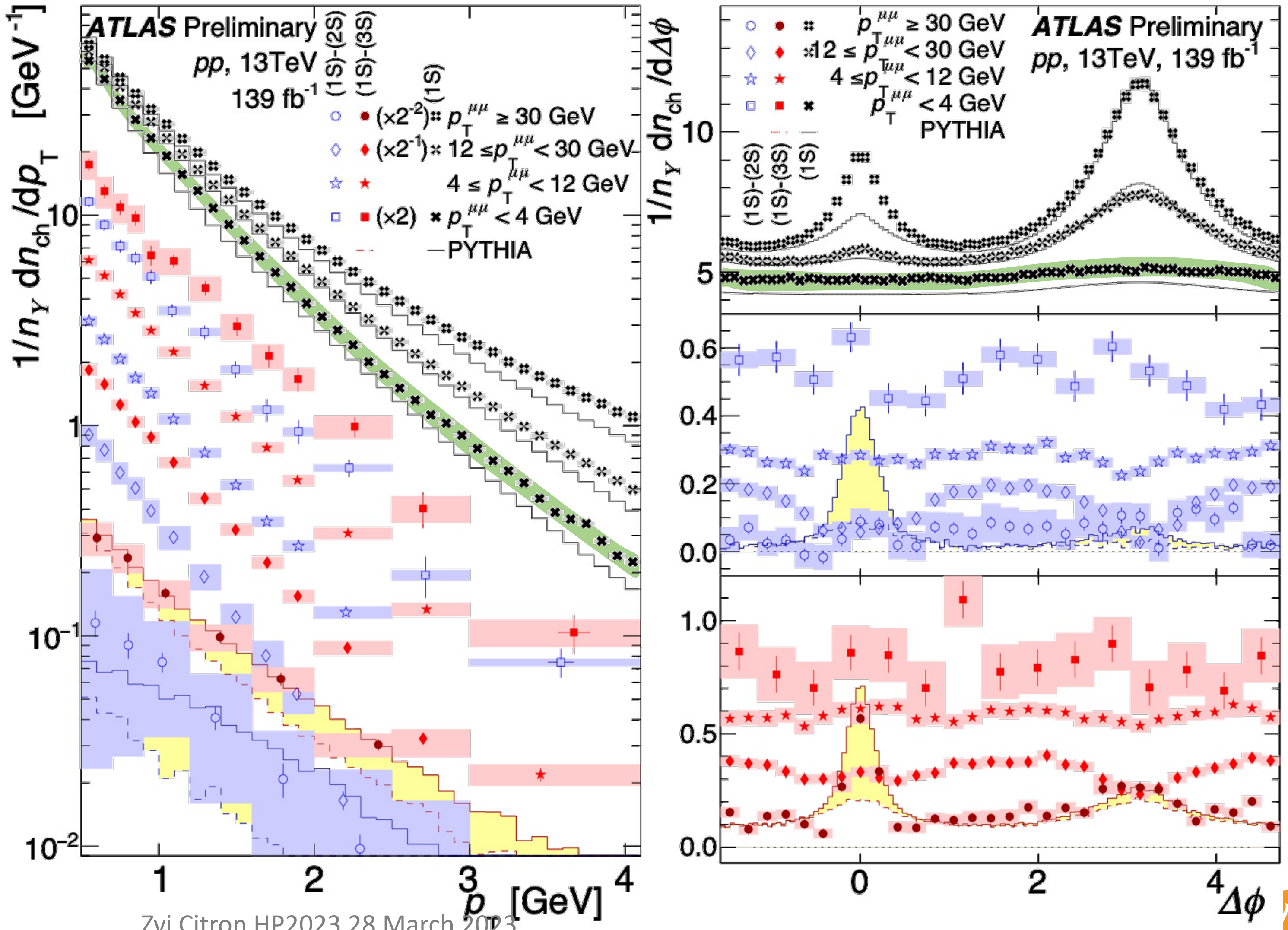
ATLAS-CONF-2022-023



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ATLAS-CONF-2022-023

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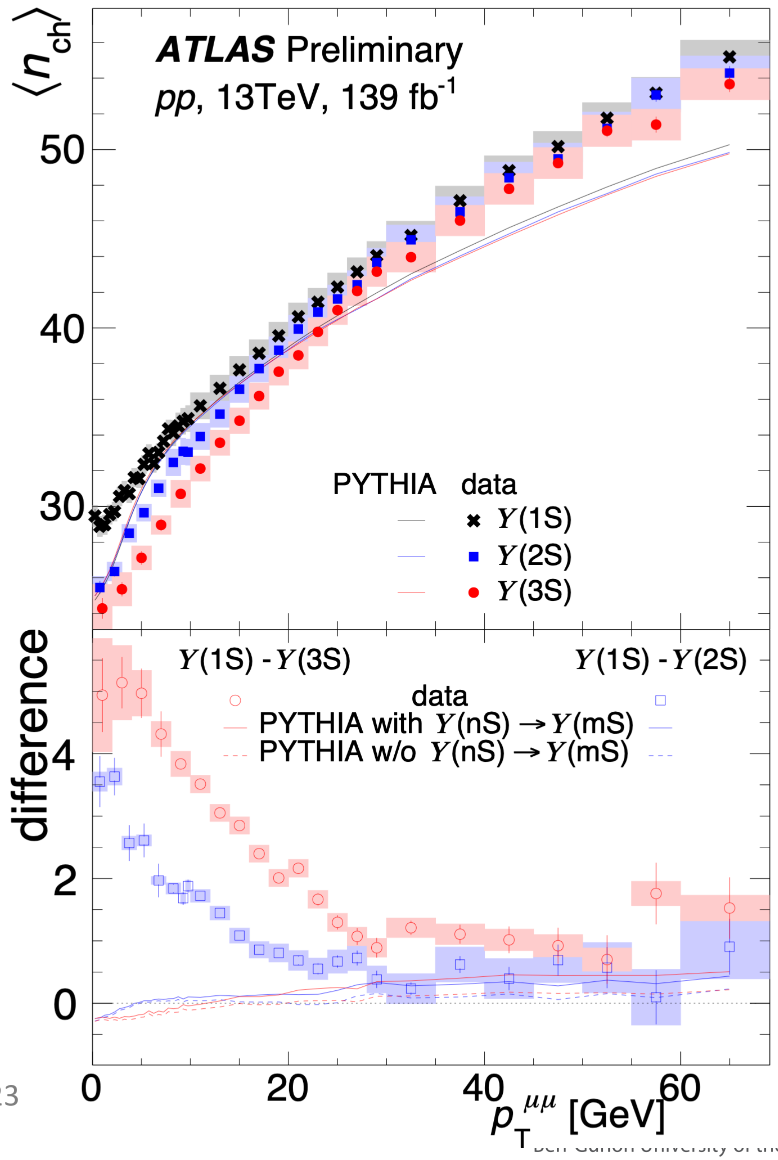

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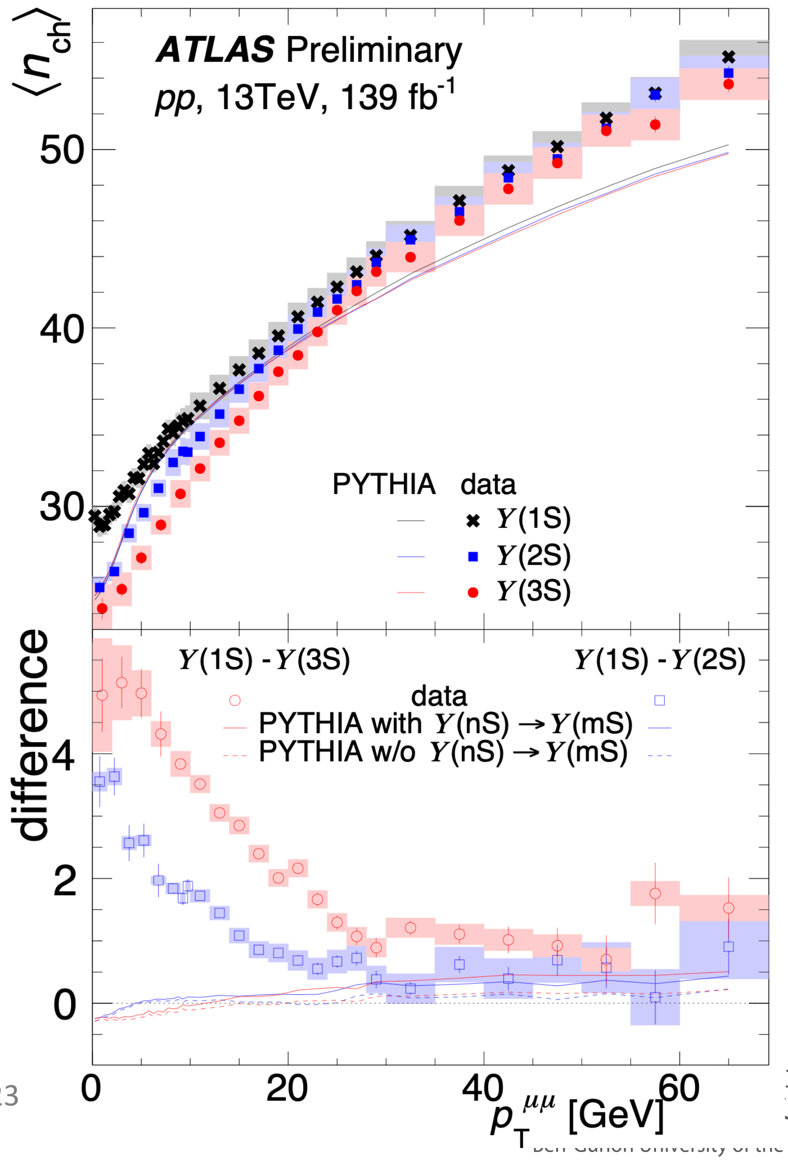
- Shift in UE multiplicity across different excitation states can be understood as suppression of excited states at higher multiplicity



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**

Quarkonia Ratios Expected From m_T Scaling

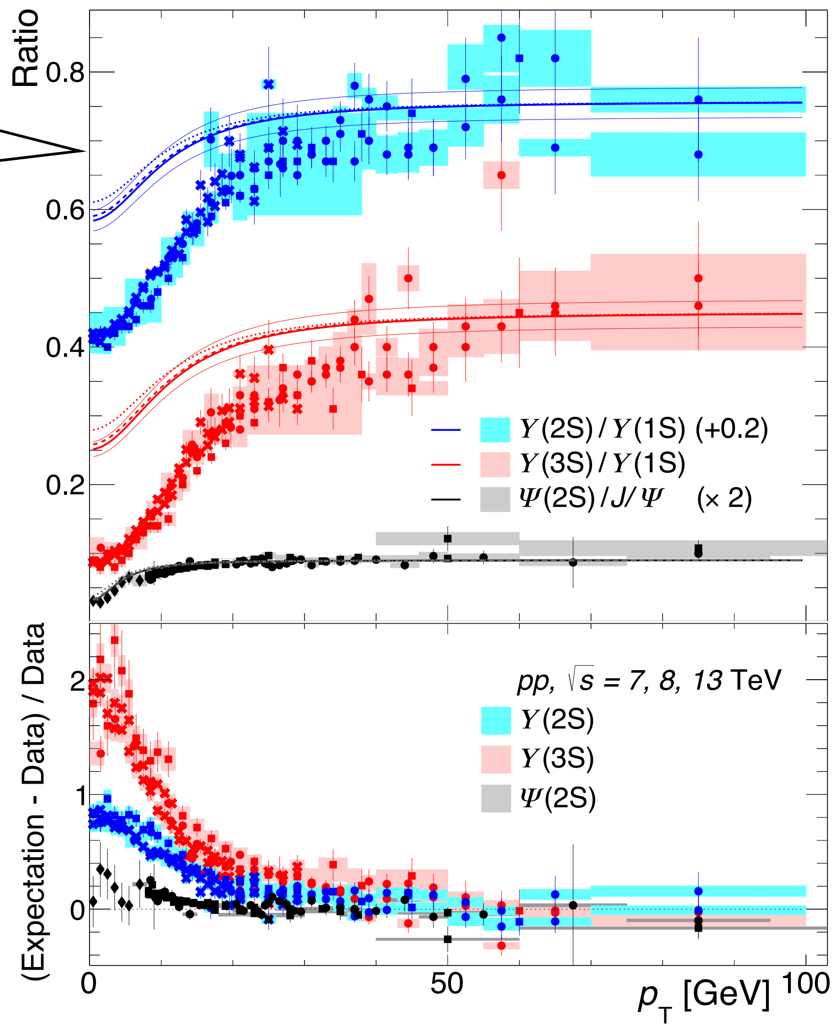
PRD **107**, 014012

- 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!

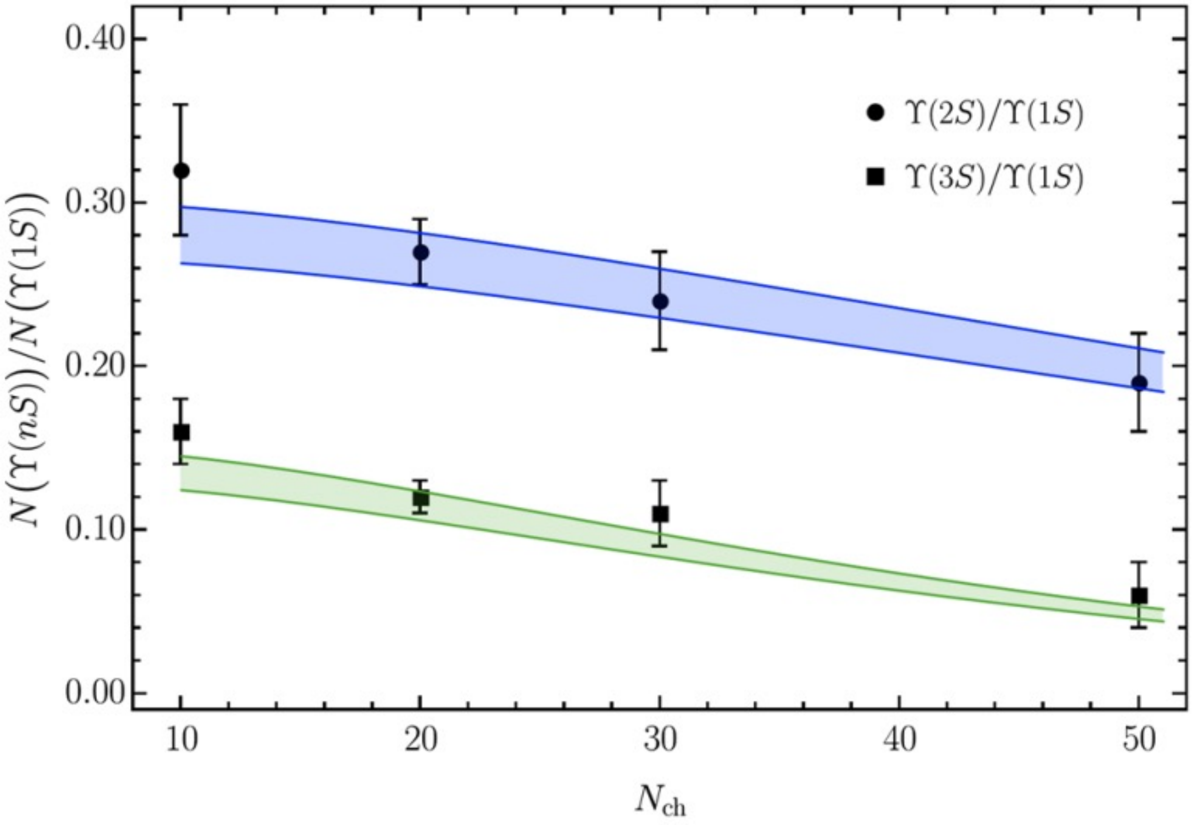
$$1 - \frac{n\Delta m}{nT + m_{q\bar{q}}}$$



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

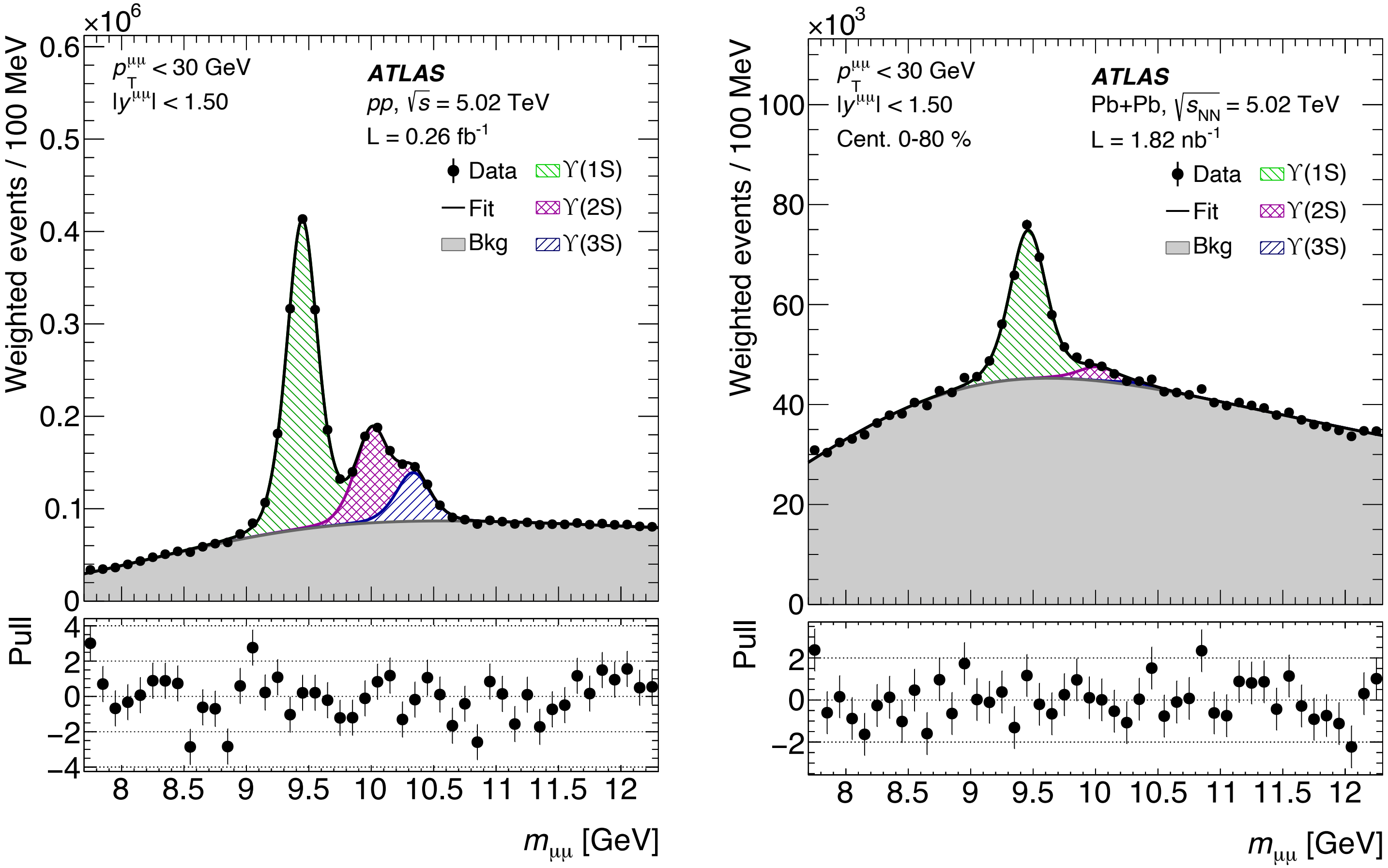
- Comparing **Pb+Pb** and pp Upsilon production implies some deconfinement
  - Current data doesn’t yet distinguish between deconfinement models
- Evidence from Upsilon mesons that there is some non-trivial interaction between the “UE” and a hard scattering in **pp** collisions
  - Appears to be a suppression of excited states
  - Effect is large and significant

Extra Slides

Upsilon Mesons in 5.02 TeV Pb+Pb & pp

arXiv:2205.03042

- Selections:
  - Υ(n)S → $\mu\mu$
  - p_T < 30 GeV, |y|<1.5
  - [Centrality 0-80%]
- Extraction:
  - Signal = Crystal Ball + Gauss
  - Bkg = pol2 or $erf \times exp$
- Raw data already shows evolution of excited states in Pb+Pb

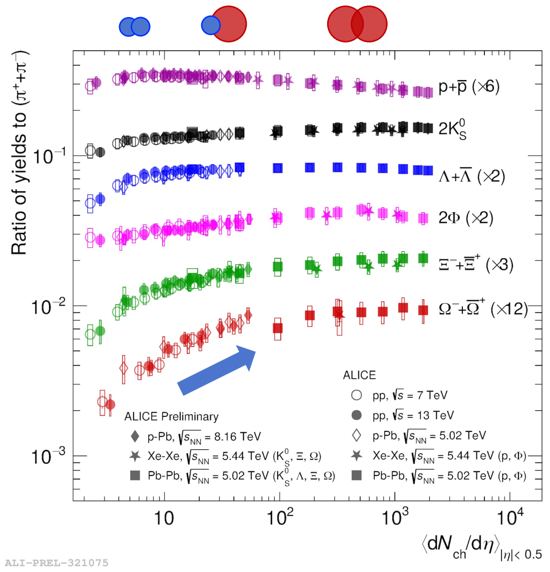


Systematics

Collision type	Sources	$\Upsilon(1S)$ [%]	$\Upsilon(nS)$ [%]	$\Upsilon(nS)/\Upsilon(1S)$ [%]
	Luminosity	1.6	1.6	-
	Acceptance	0.3–9.3	0.2–4.1	-
pp collisions	Efficiency	2.7–7.0	2.8–4.0	3.0–7.1
	Signal extraction	3.1–10.2	4.3–11.9	4.5–12.2
	Bin migration	<1	<1	-
	Primary-vertex association	2.0	2.0	-
	$\langle T_{AA} \rangle$	0.8–8.2	0.8–8.2	-
	Acceptance	0.3–9.3	0.2–4.1	-
Pb+Pb collisions	Efficiency	4.0–15.0	3.9–25.3	4.4–28.8
	Signal extraction	3.8–16.3	14.6–28.7	16.6–31.5
	Bin migration	<2	<2	-
	Primary-vertex association	3.4	3.4	-

But what about pp?

- 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
- Can we tell a similar Upsilon story?
- Here we look at **Upsilon meson correlations with inclusive charged particles** to try to bridge the soft-hard gap



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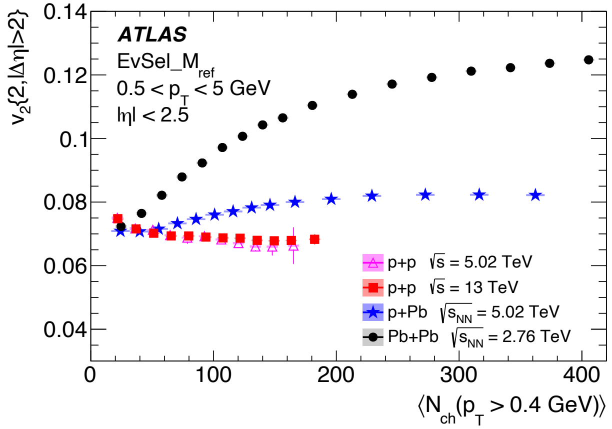
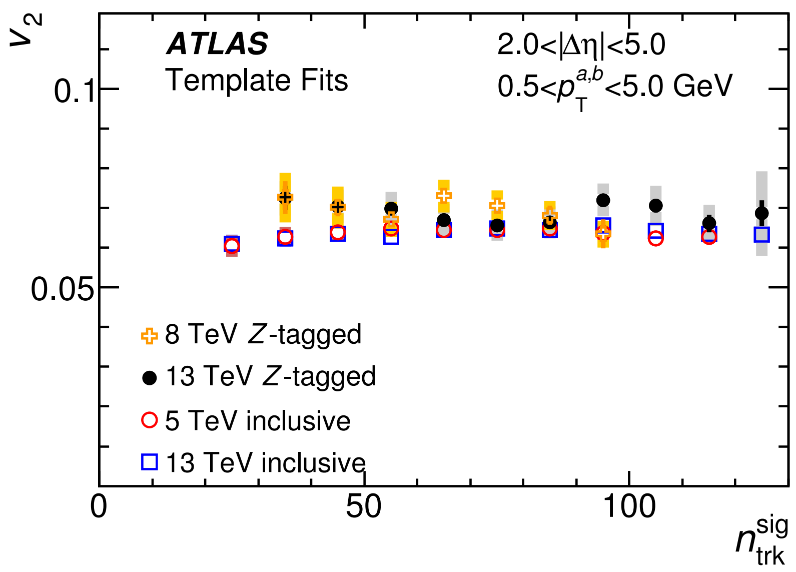


Eur. Phys. J. C 77 (2017) 428

A Previous Hard-Soft Study: Two-particle correlations in Z Boson Tagged pp Collisions

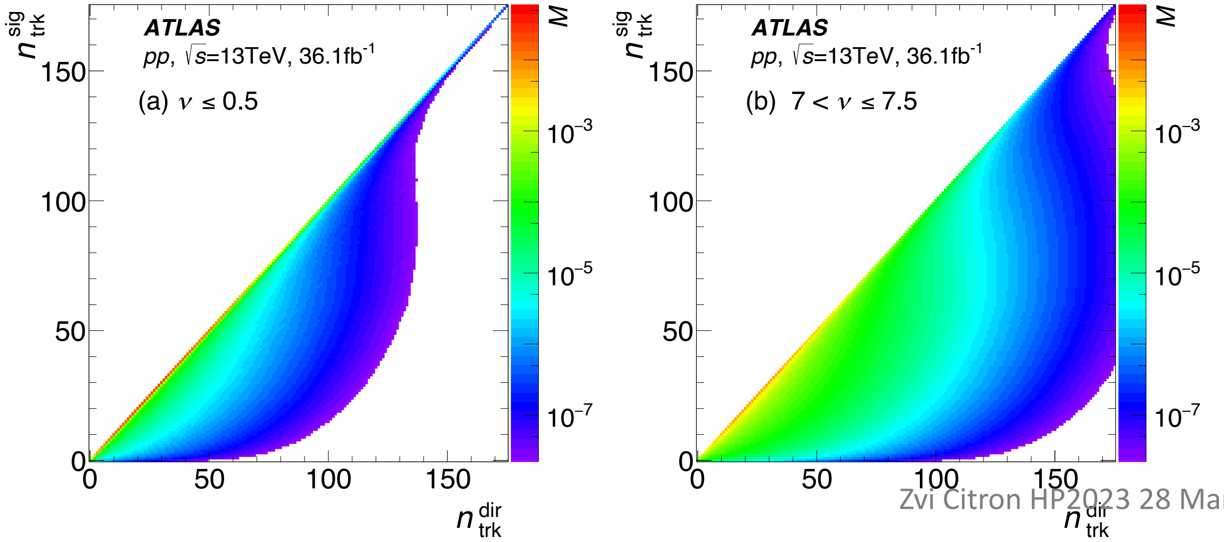
- In a previous study we asked: Does the presence of a hard scattering in the collision change "*something-like-geometry*" and consequently the observed "*flow*"?
- To answer we studied v_2 via 2-particle correlations in pp collisions 'tagged' by a Z boson
- The answer to above question is not really

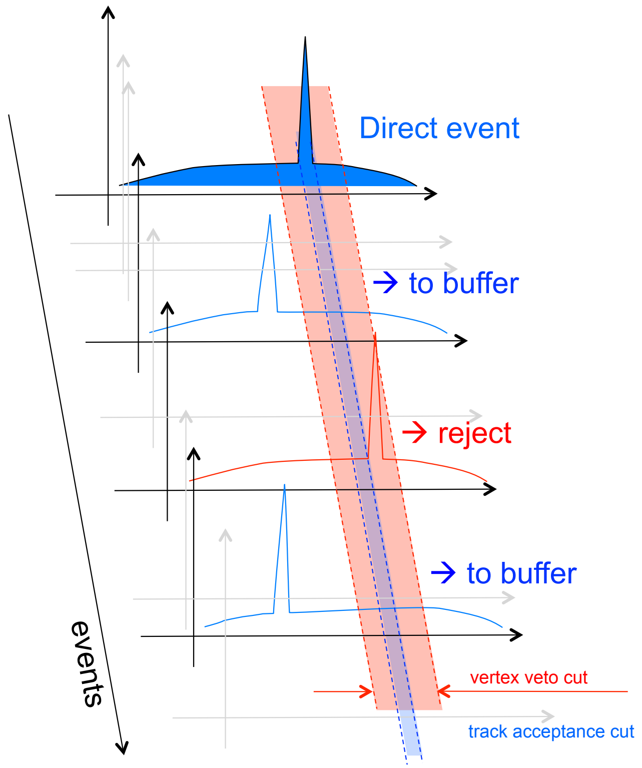
Eur. Phys. J. C **80,** 64 (2020)



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**!



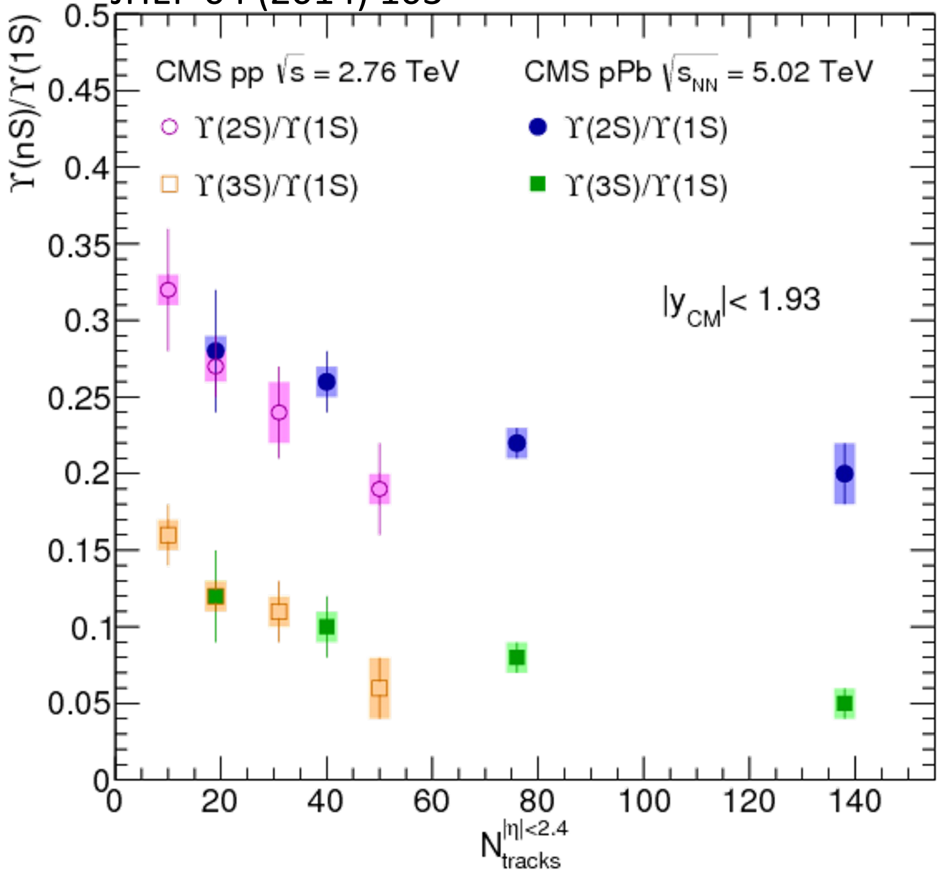


Eur. Phys. J. C **80,** 64 (2020)

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



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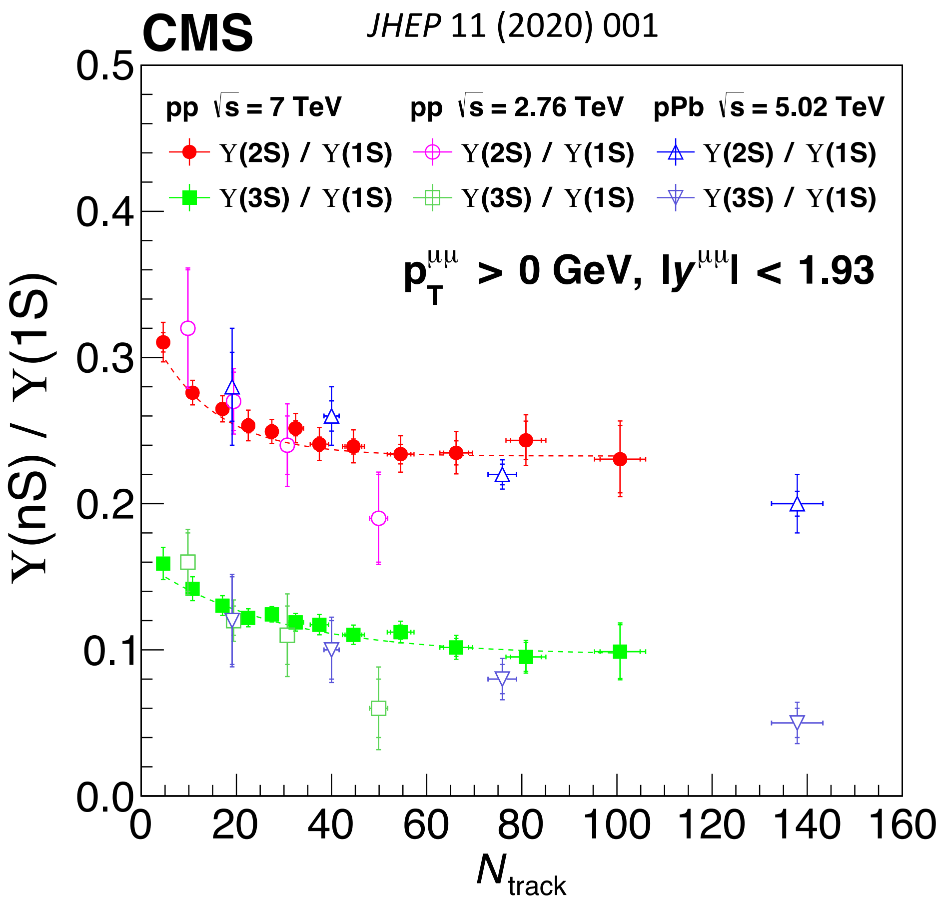
- More detailed measurements in 2020



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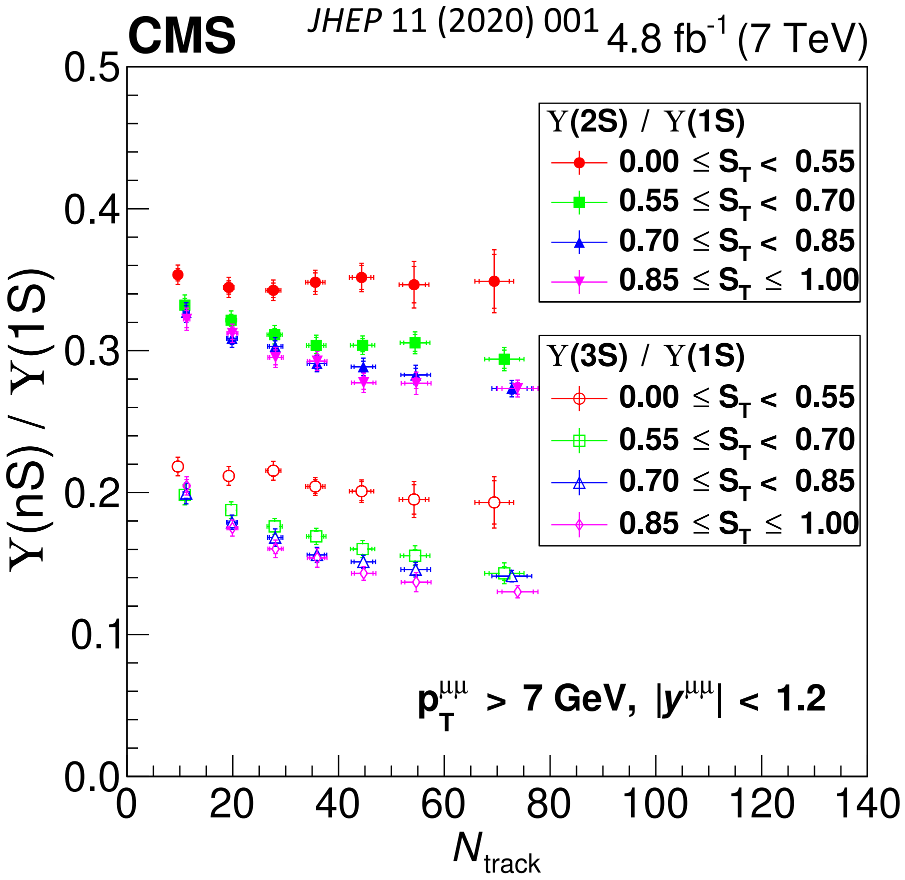
CMS Measurement of Υ(nS) and pp Multiplicity

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

- 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
  - Including analysis of event geometry via spherocity, which suggests effect **is connected with UE not jets**



$S_T = 0$ → jet-like

$S_T = 1$ → not jet-like

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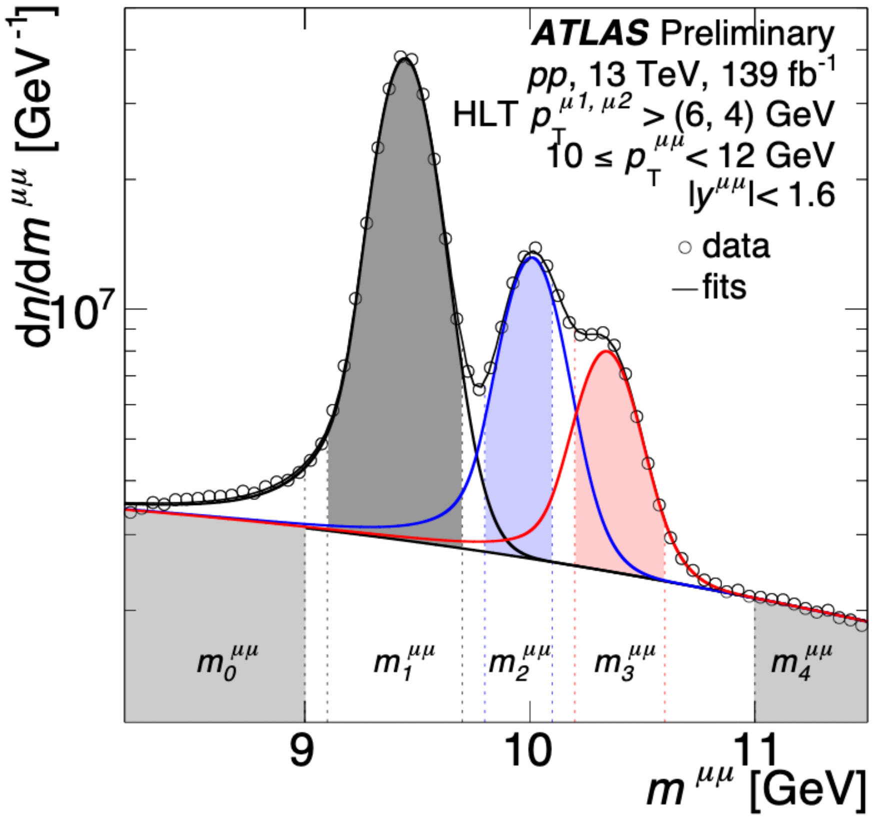
Technical Fit Things



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

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

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

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

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

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

$$k_n = \frac{\langle F_{\text{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\text{bkg}}(m)\rangle|_{m_n^{\mu\mu}}}{\langle F_{\text{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\text{bkg}}(m)\rangle|_{m_0^{\mu\mu}}}$$

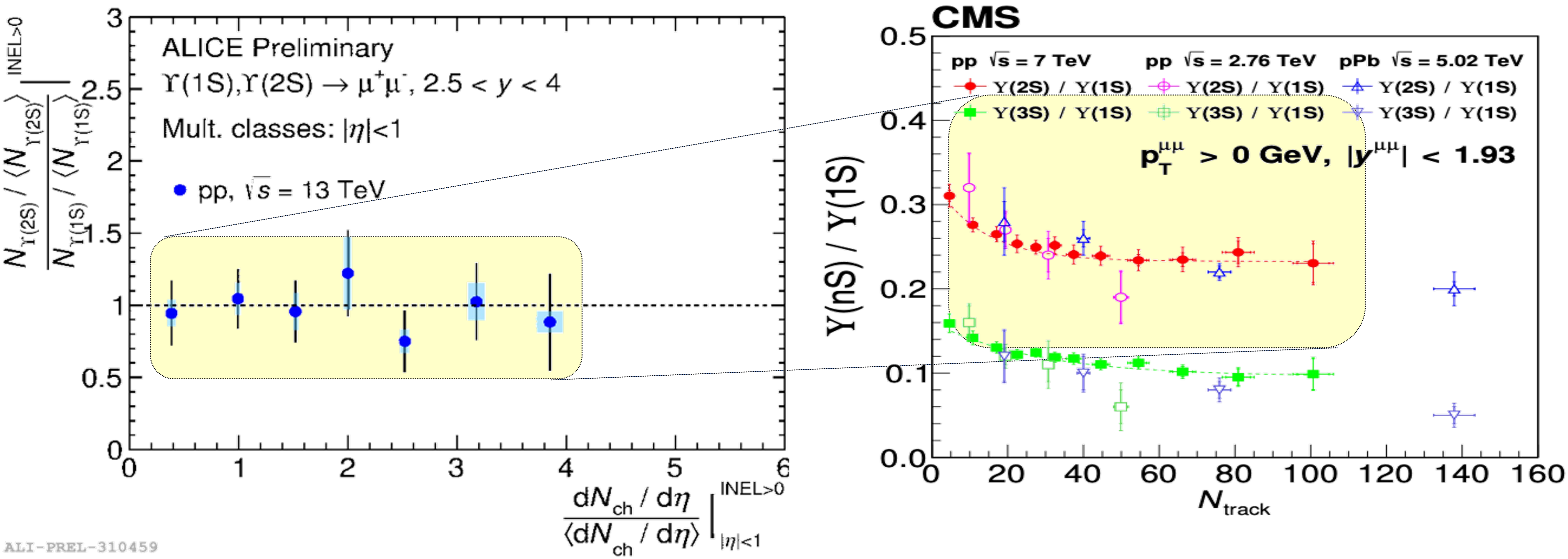
Systematics Summary

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

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

Shown here in "units" of n_{ch} but propagated to all quantities

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