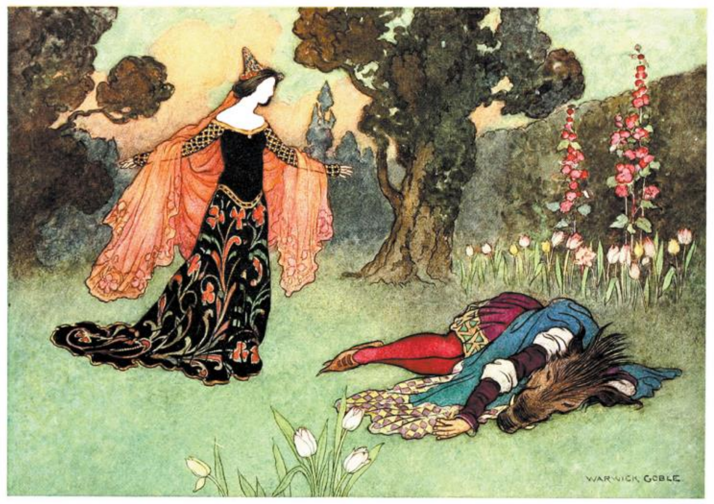
בס"ד

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



Missing Beauty

Zvi Citron

Work done with A. Milov and I Aizenberg (arXiv:2203.11831)

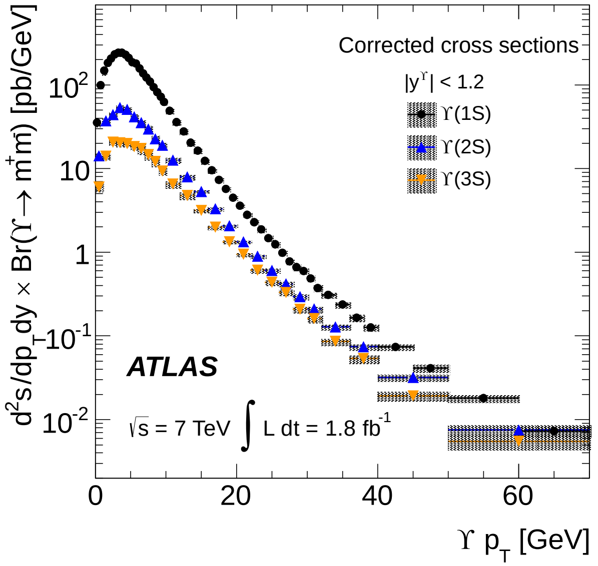
ISMD2022

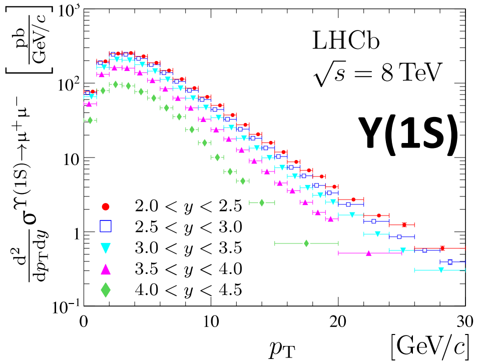
Big Picture

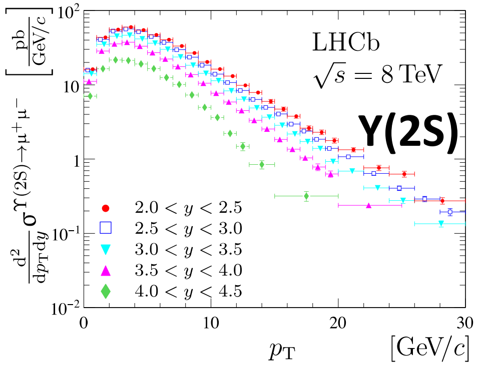
- Soft sector observables that were once (uniquely) associated with a QGP have been measured in pp collisions
  - Most prominently “flow” which persists to low multiplicity pp & even photo-nuclear interactions
  - Strangeness enhancement
- It’s more difficult to tell this story with hard sector observables
- Looking at Upsilon mesons and trying to bridge soft-hard gap

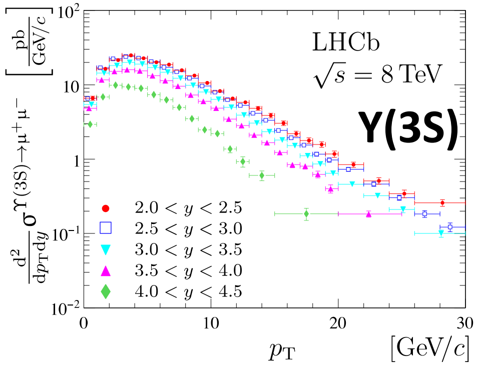
What Do We Know about Upsilon Production at the LHC?

- Production cross-section seems well measured
- Some questions remain regarding polarization, importance of χ_b feed-down etc



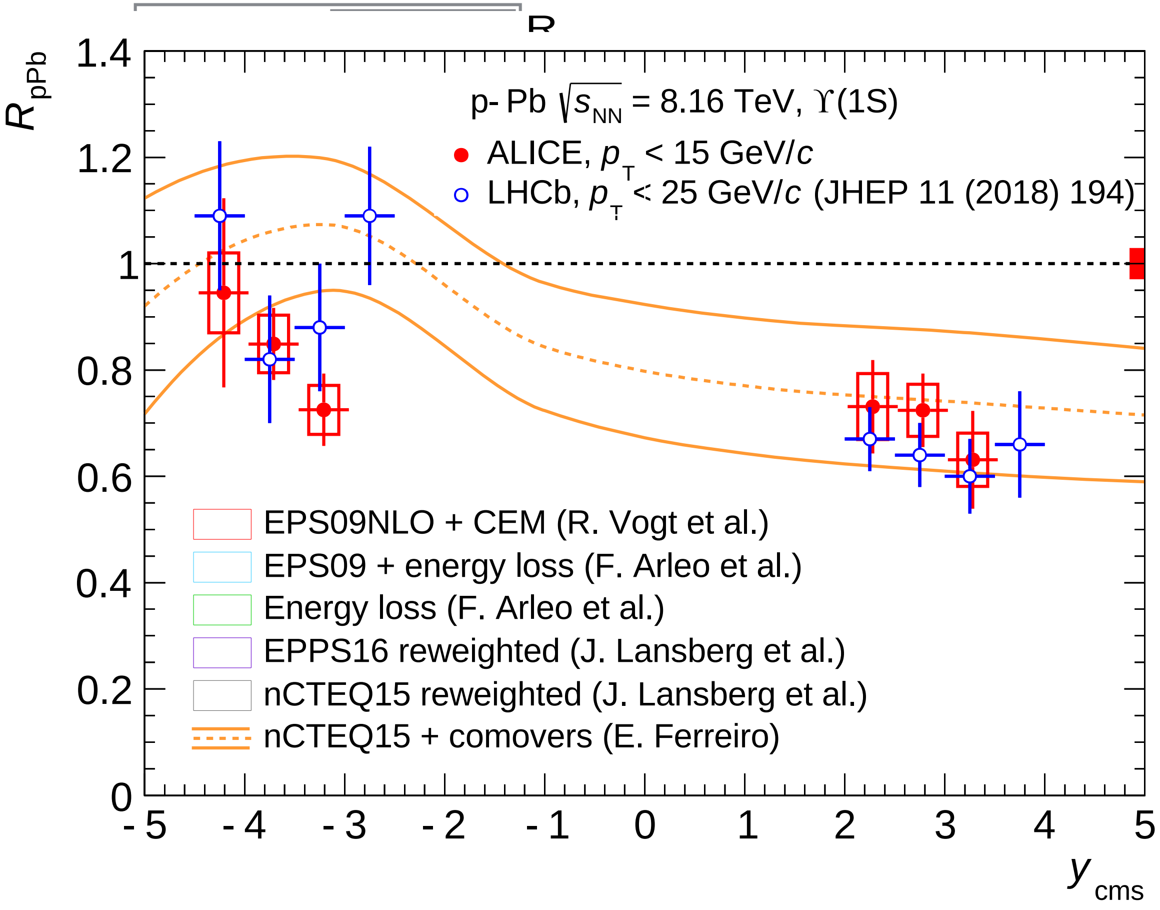






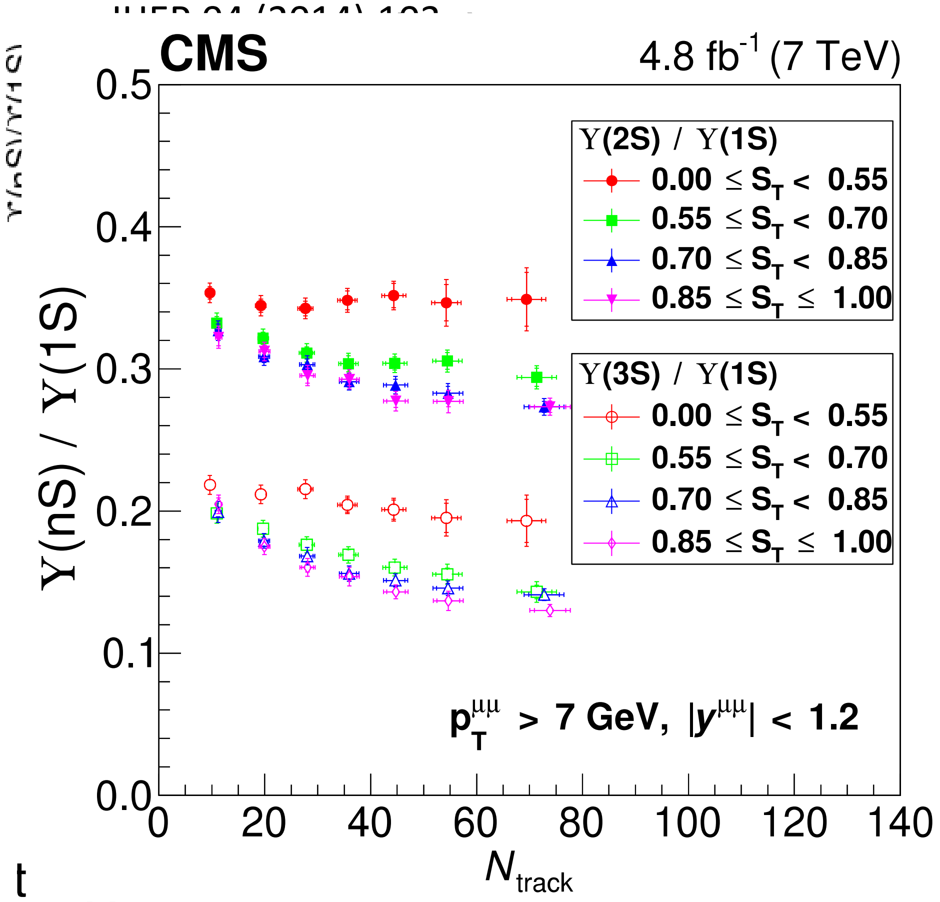
What Do We Know about Upsilon Production *and collectivity* at the LHC?

- From a heavy-ion perspective Υ(nS) states could be a thermometer for a QGP
- 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”



CMS Measurement of Υ(nS) and pp Multiplicity

- CMS results all the way back in 2014 challenge this picture by showing a decrease in excited Υ 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**



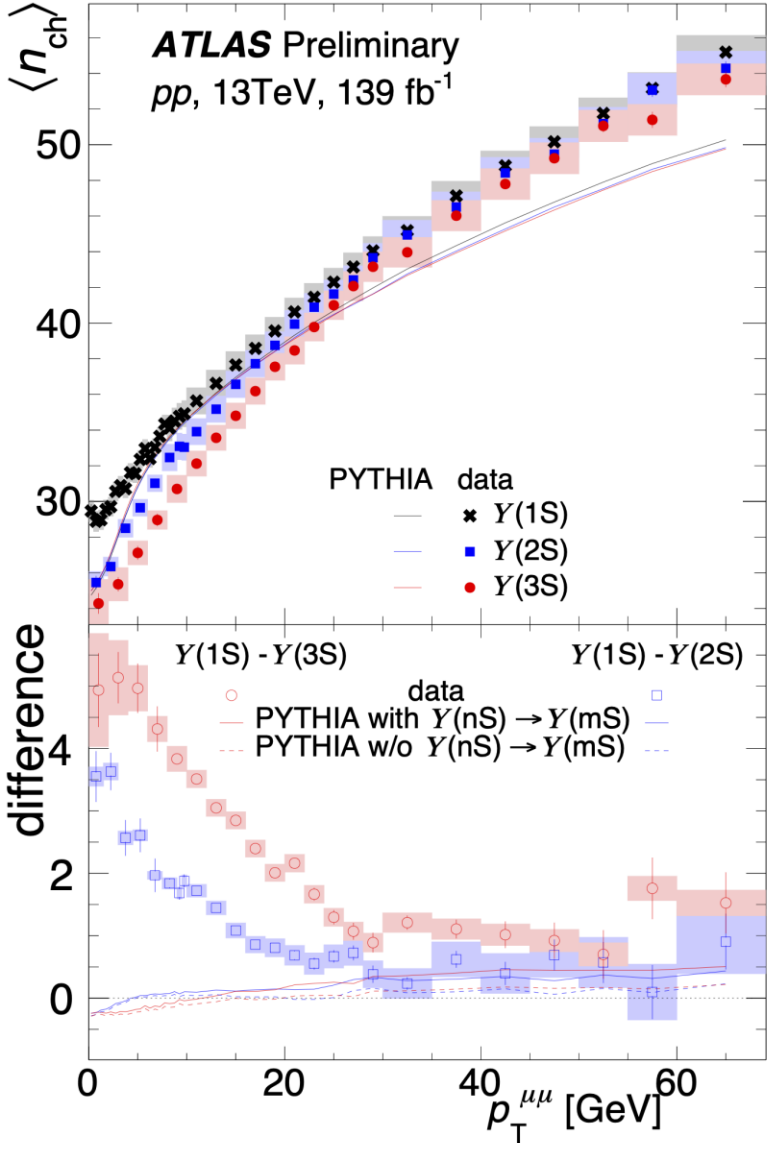
$$S_T \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2},$$

$$S^T_{xy} = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

$S_T = 0$ → jet-like
$S_T = 1$ → not jet-like

Underlying Event
ATLAS Measurement of Y(nS) and ~~Multiplicity~~

- 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 at higher multiplicity



ATLAS-CONF-2022-023

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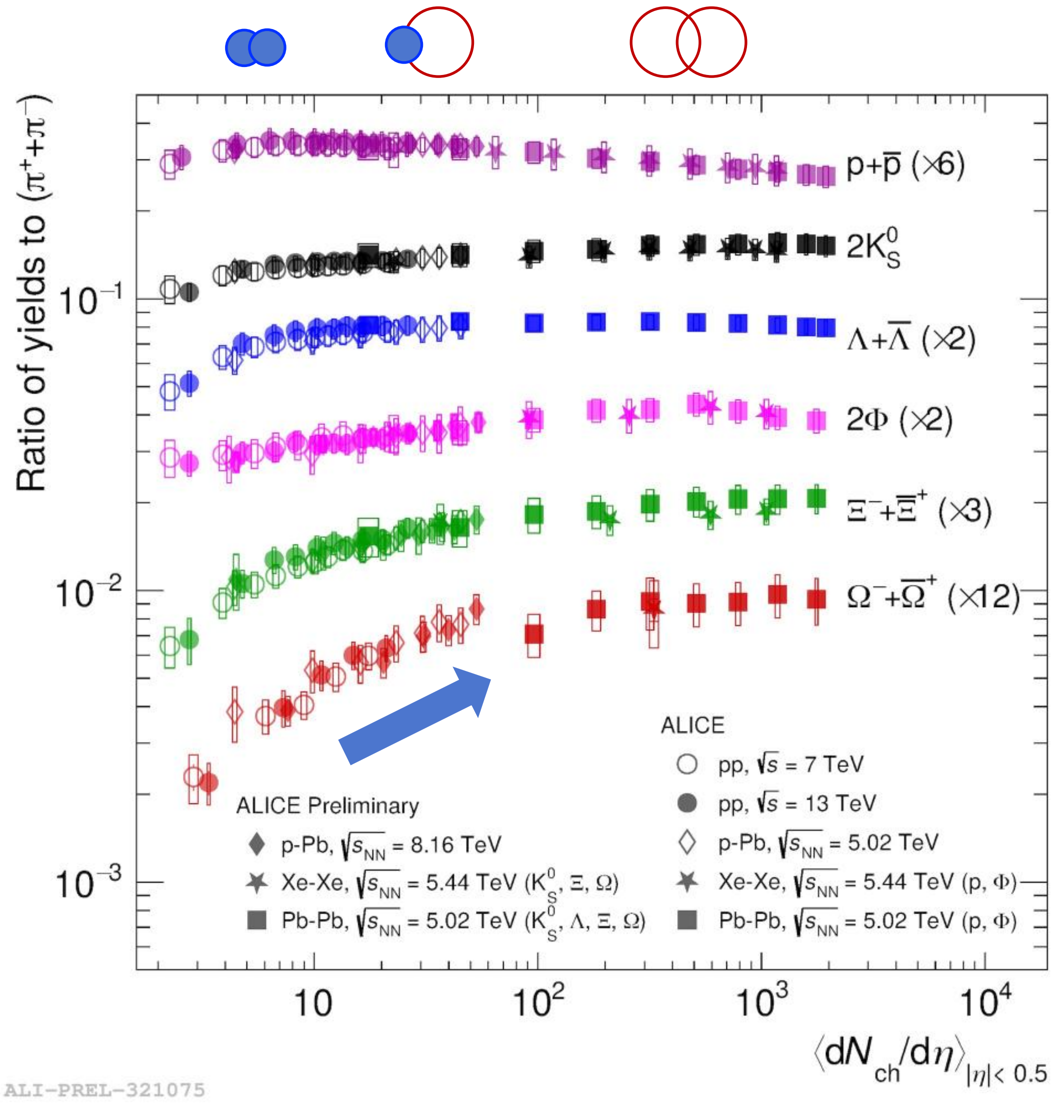
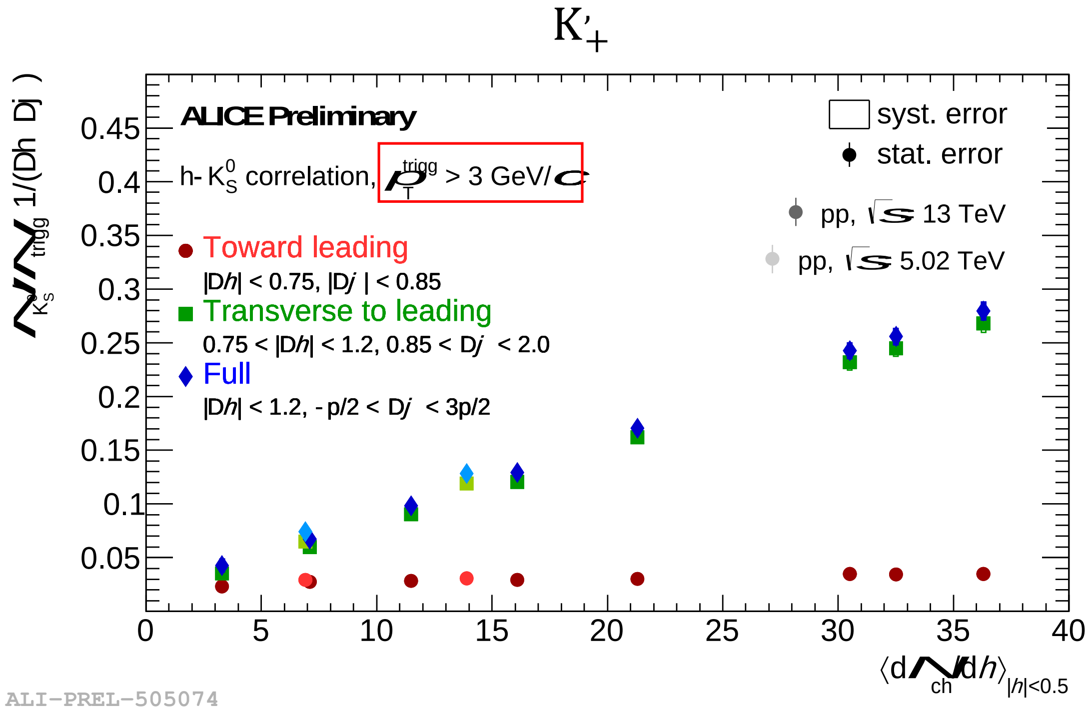
A Strange Digression

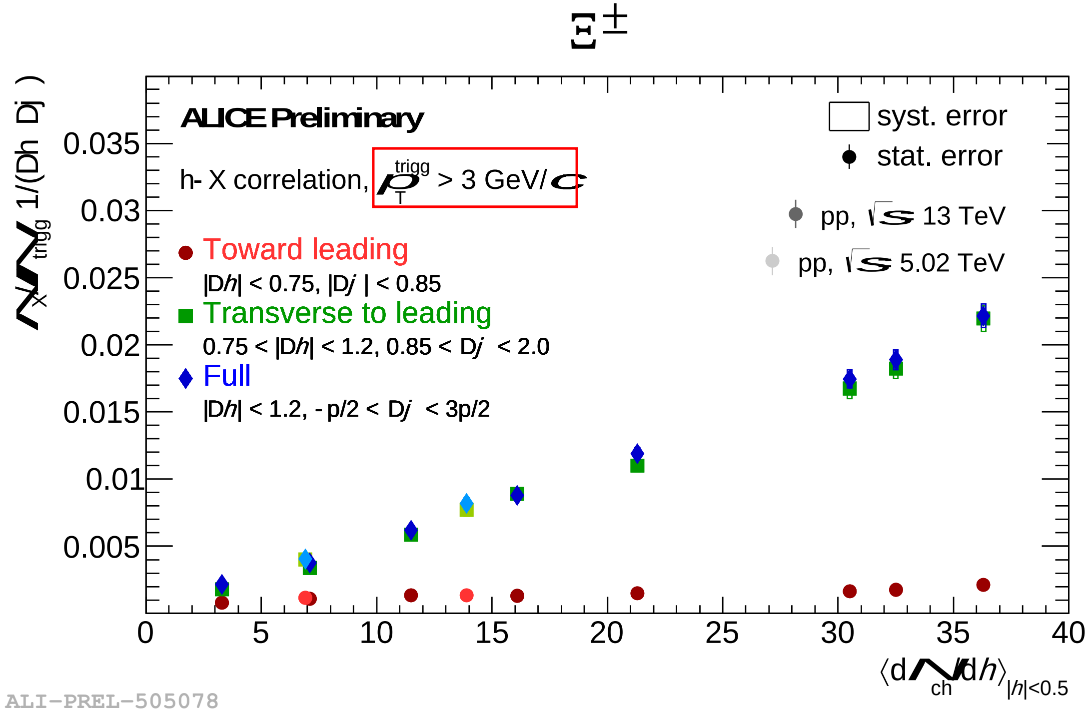
- Enhancement of strange hadrons is one of the signature pp collectivity results
- Recent ALICE analyses seek to understand its nature …



A Strange Digression

- Enhanced strange hadrons are transverse to leading particle in event
- Strangeness enhancement is occurring outside of jets, perhaps implying that it's a UE effect …





Is there Υ(nS) Suppression in pp Collisions?

- Do the CMS and ATLAS results show some QGP like melting?
- Is it even a suppression? Maybe it's a lower state enhancement? (missing beauty or extra beauty)
  - **→In any case seems to be a hard – UE correlated phenomenon**
- Significant suppression/enhancement should show up in the cross-section …
  - Low p_T is hard to calculate in pQCD, higher orders & twists etc

Transverse Mass Scaling as a Baseline

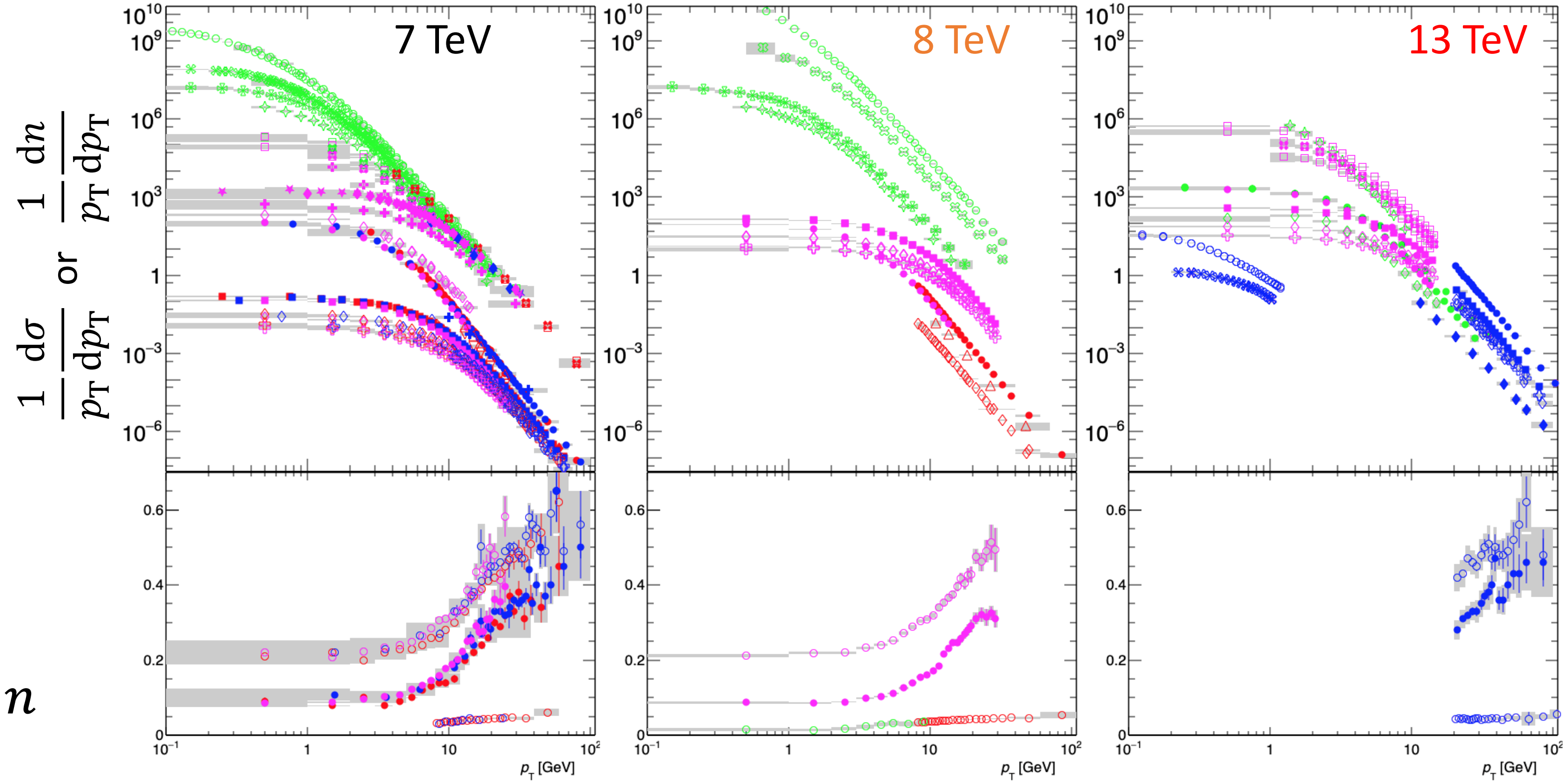
- We take an empirical (~data driven) approach to defining a baseline cross-section expectation – **transverse mass** scaling

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}m_\mathrm{T}} \propto \left(1 + \frac{m_\mathrm{T}}{nT}\right)^{-n} \qquad m_\mathrm{T} = \sqrt{p_\mathrm{T}^2 + m_0^2}$$

- M_T scaling works, i.e. (with some caveats) it fits the data
  - We are **not** making some blast-wave model and describing as much as possible
- Fit all available LHC meson measurements (7,8, & 13 TeV)

Transverse Mass Scaling as a Baseline – LHC Meson Data

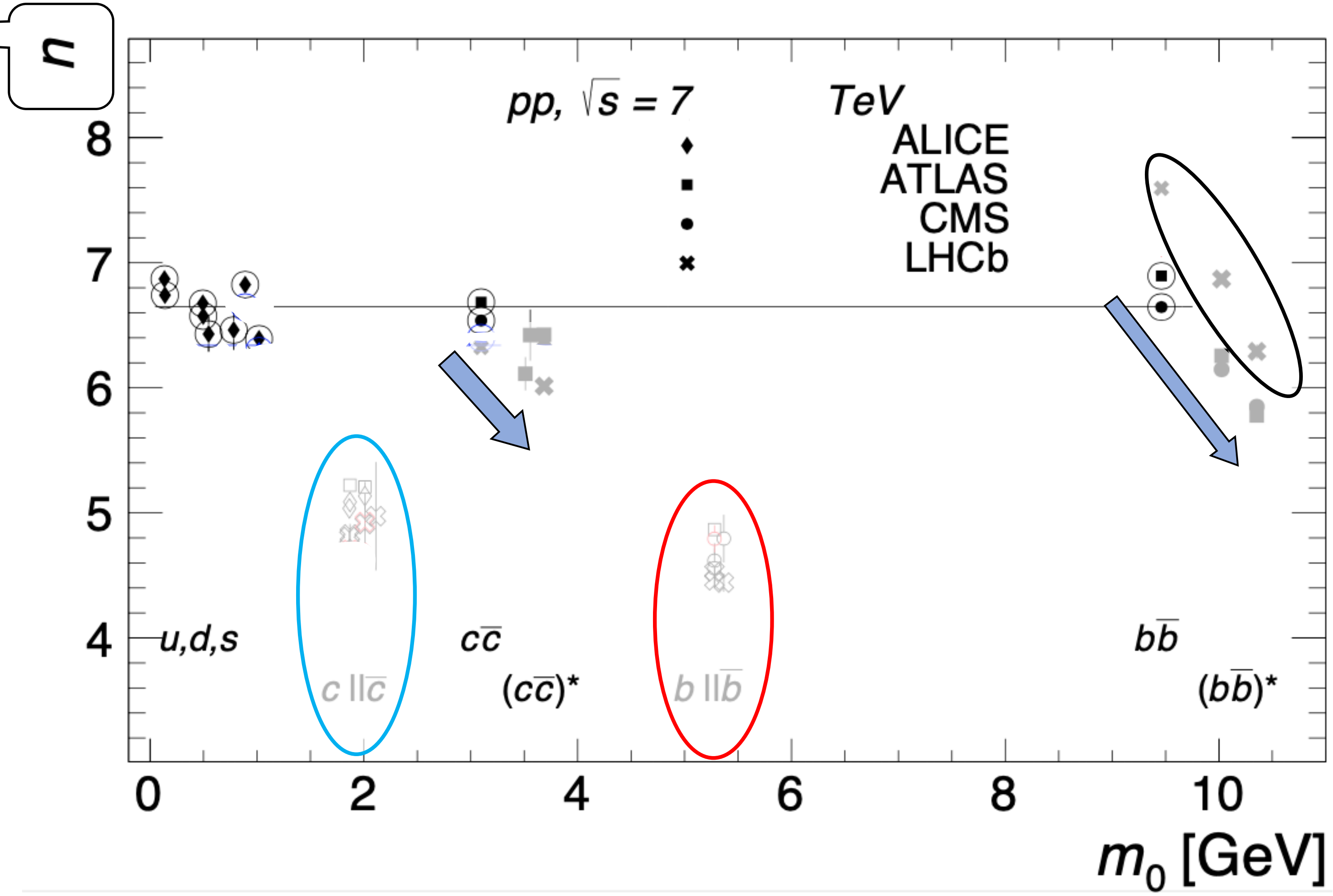
- 4 LHC experiments
- $\sqrt{s}$=7, 8, 13 TeV
- 18 species + iso-partners
- 72 data samples:
  - 1509 data points



- 15 quarkonia ratios:
  - 327 data points
- Fit to $\frac{d\sigma}{dm_T} \propto \left[1+\frac{m_T}{nT}\right]^{-n}$
- (T is fixed to 254 MeV)

Transverse Mass Scaling as a Baseline – Defining a Common Fit

$$\frac{d\sigma}{dm_T} \propto \left[1 + \frac{m_T}{nT}\right]^{-n}$$



Open flavor mesons ($c||\bar{c}$ and $b||\bar{b}$) have harder spectra (lower *n*)

LHCb data (high-y) at the same $\sqrt{s}$ are higher than midrapidity data

Excited quarkonia ($(c\bar{c})^*$ and $(b\bar{b})^*$) have lower *n*

u, d, s & $q\bar{q}$ are fit simultaneously
n = 6.65 $\sqrt{s} = 7$ TeV

and higher energies as well
n = 6.34 $\sqrt{s} = 8$ TeV
n = 5.44 $\sqrt{s} = 13$ TeV

T is fixed to 254 MeV

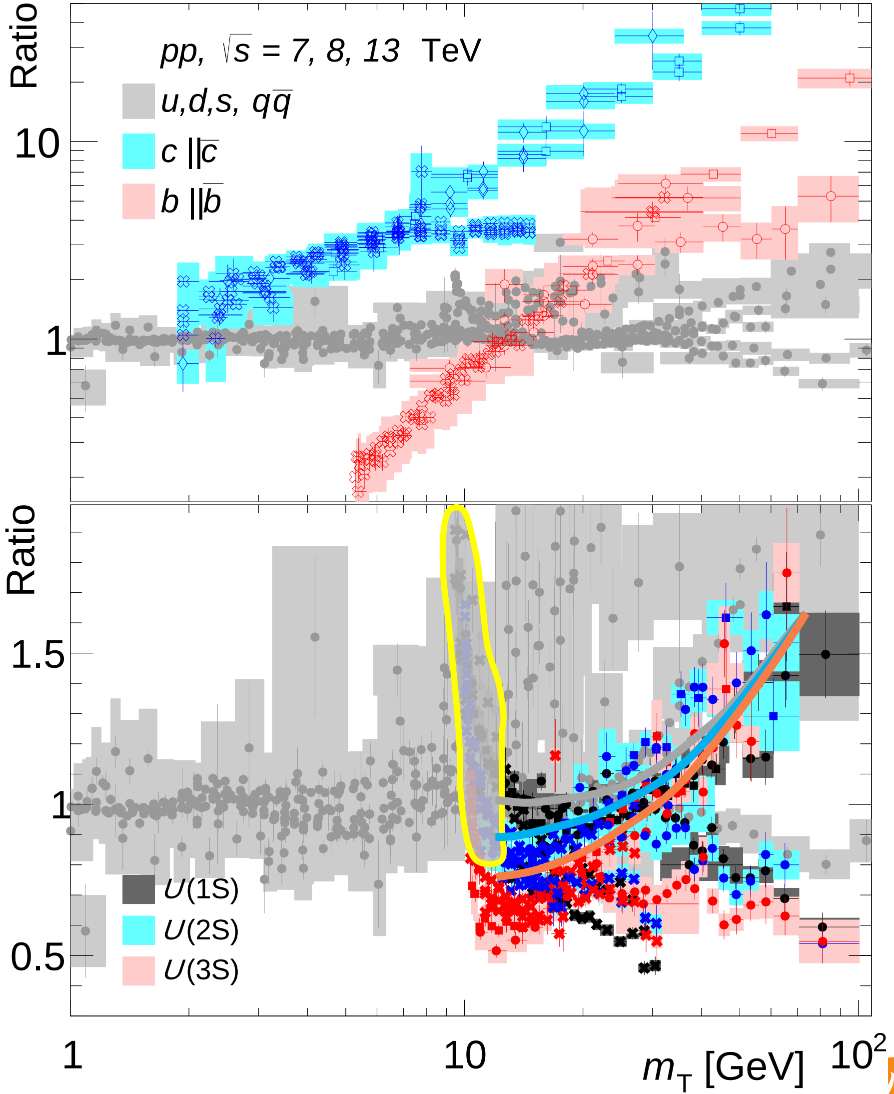
Particle Ratios Relative to Common Fit

Common fit is not perfect (small experimental differences across measurements) but works

Open HF is harder and $b||\bar{b}$ is harder than $c||\bar{c}$

Spike at low p_T of $\Upsilon(nS)$ likely due to non-prompt component from χ_b decays
χ_b feed-downs are ~same into all $\Upsilon(nS)$

Lower n for $\left(b\bar{b}\right)^*$ is not a harder spectrum, but a deficit at low and intermediate p_T



Quarkonia ratios: expected & measured

Normalized at $p_T > 50$ GeV

$$\lim_{\Delta m, p_T \ll m_{q\bar{q}}} \left[\frac{nT + \sqrt{p_T^2 + (m_{q\bar{q}} + \Delta m)^2}}{nT + \sqrt{p_T^2 + m_{q\bar{q}}^2}} \right]^{-n} = 1 - \frac{n\Delta m}{nT + m_{q\bar{q}}}$$

$\Upsilon(nS)/\Upsilon(1S)$ expected and measured are not the same

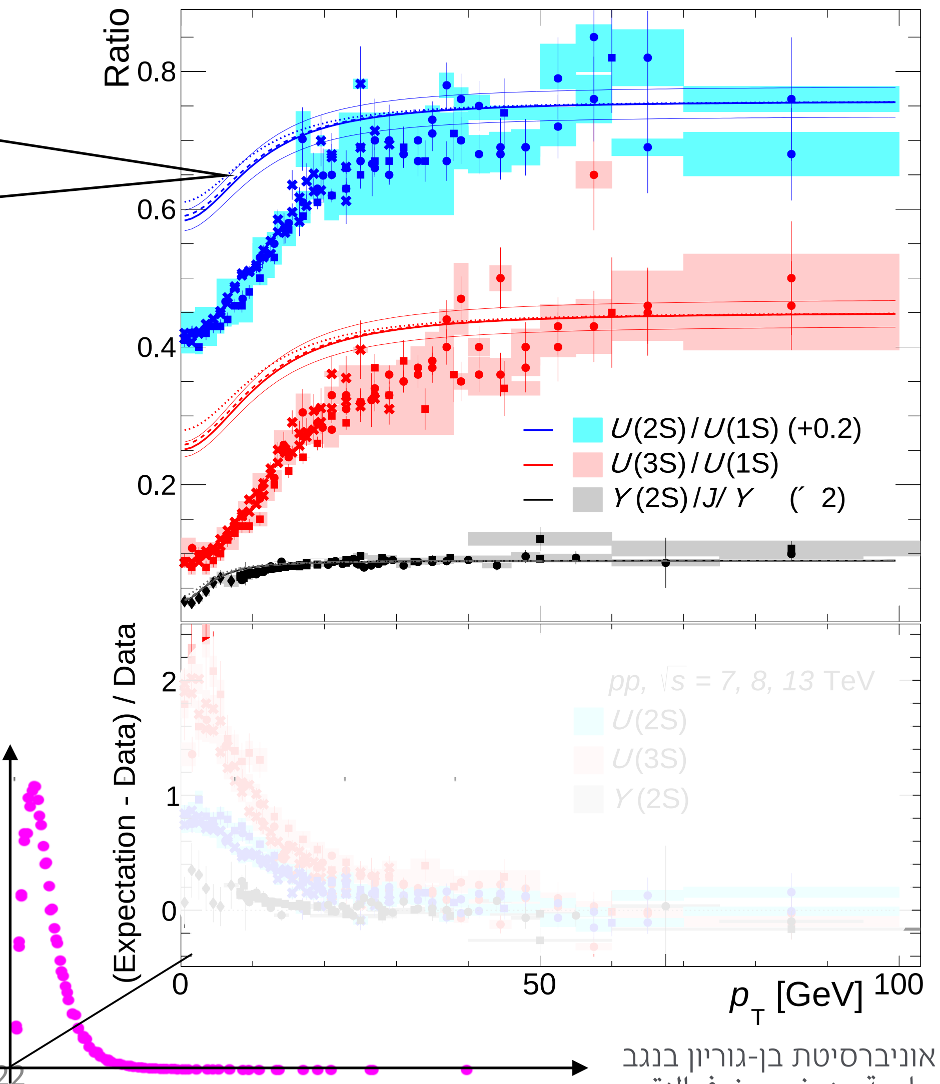
No known effects can bridge differences for $(b\bar{b})^*$

$$\text{Missing beauty} = \frac{\text{Expected}}{\text{Measured}} - 1$$

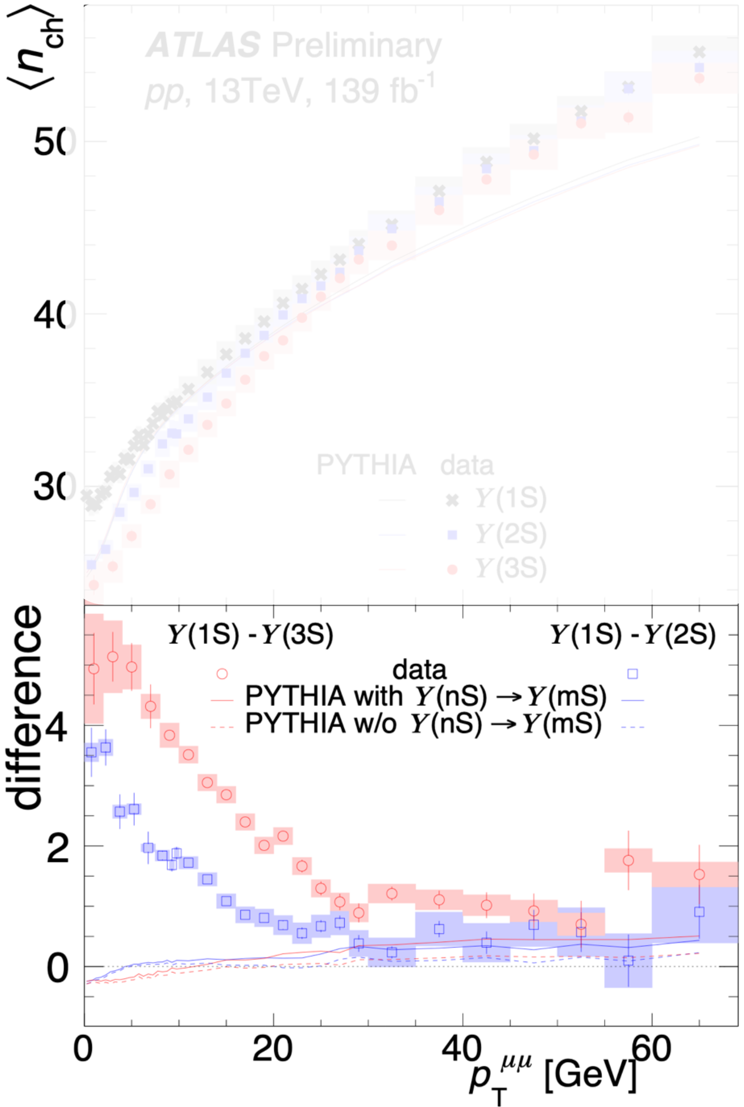
Multiplying by experimental spectra

for $\Upsilon(2S)$ factor 1.6 is missing

for $\Upsilon(3S)$ factor 2.4!



Connecting the Dots



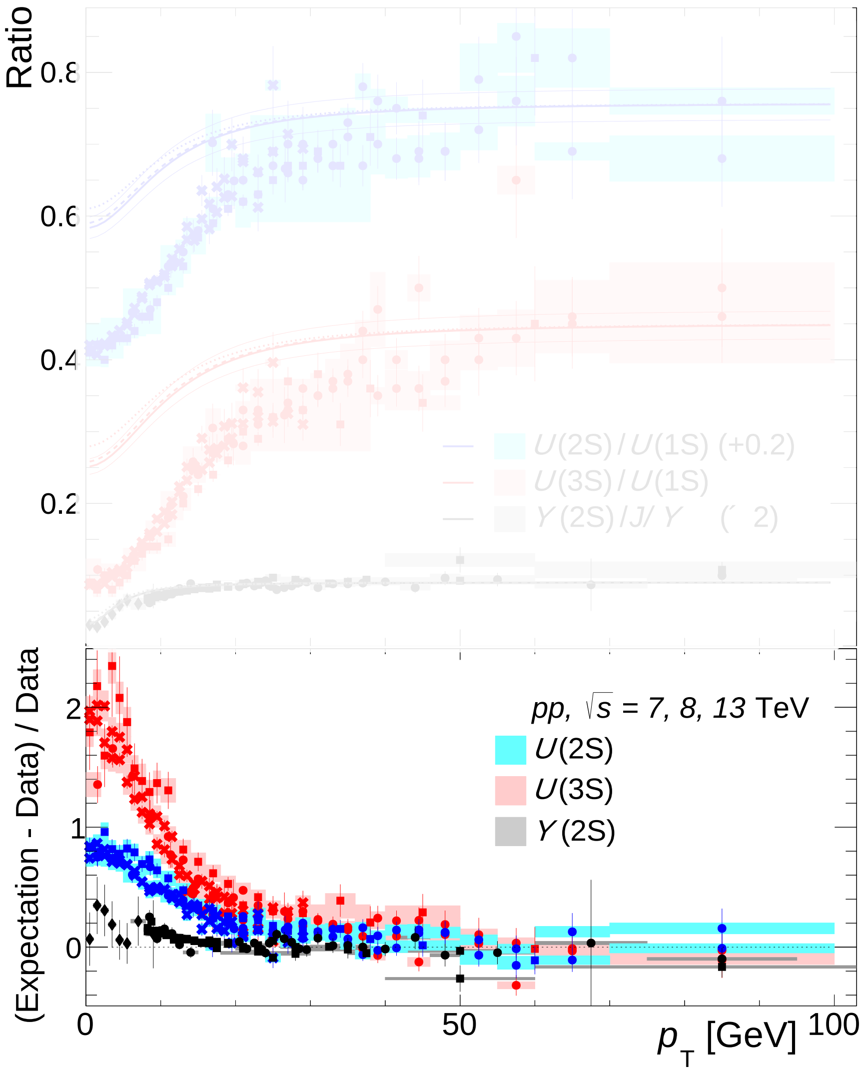
Two different analysis:
- -- particle ratios
- -- n_{ch}

n_{ch} by two experiments:
- -- CMS
- -- ATLAS

Linking effect to the UE:
- -- ATLAS by kinematics
- -- CMS by sphericity

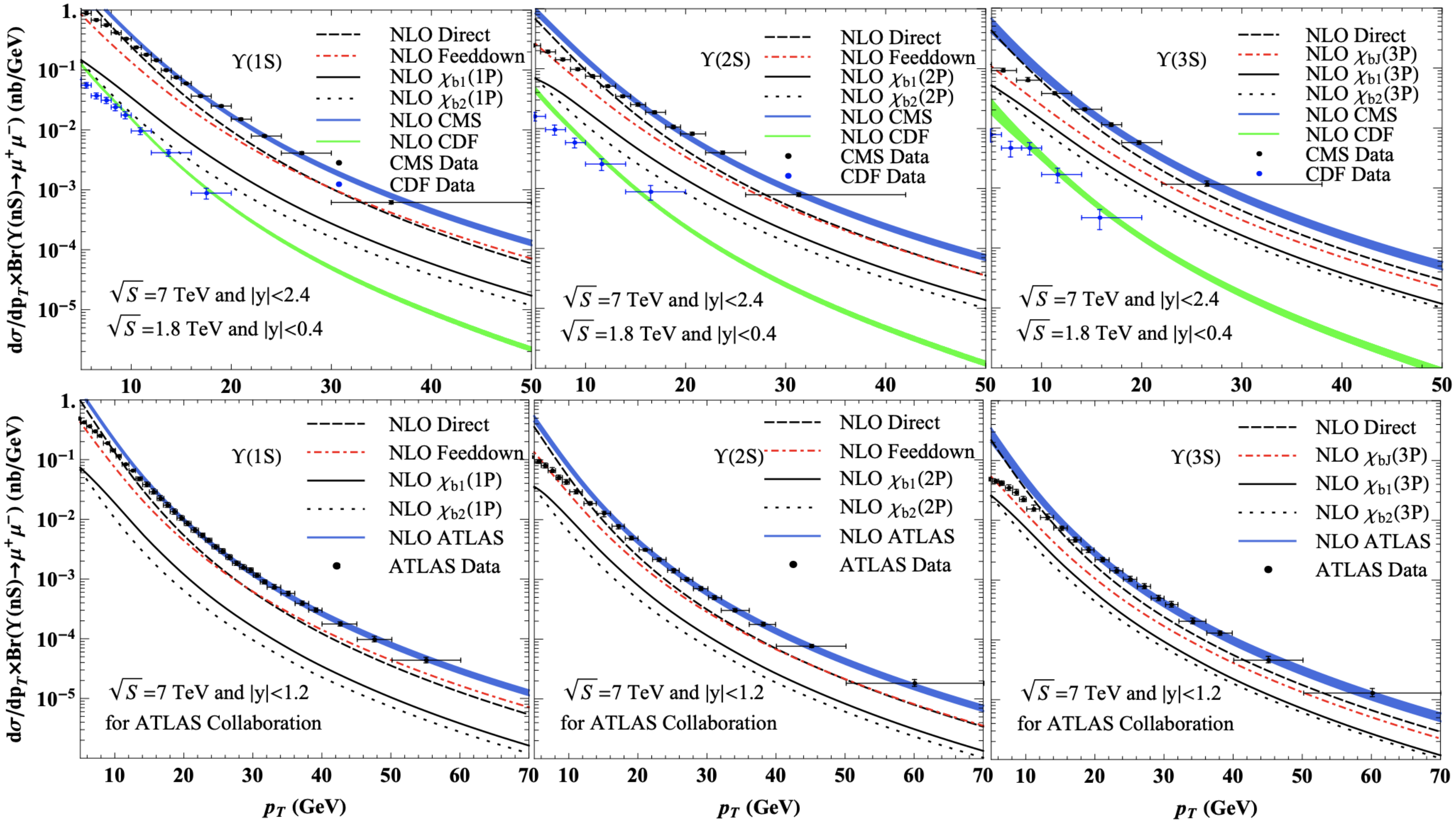
Show similar features:
- -- p_T dependence
- -- species ordering

Two manifestations of the same effect:
- -- UE suppresses $\Upsilon(nS)$



pQCD Calculations of Cross-Sections

PRD94, 014028 (2016)



χ_b feed-downs into $\Upsilon(nS)$ are similar for different species.

Calculations and the data show clear differences

Discrepancies are larger for higher $\Upsilon(nS)$ and lower p_T

It looks like the ratios would rather follow m_T – scaling cures rather than the data

$\Upsilon(1S)$ curve overshoots the data

Very Beautiful but is it Charming?

It would be natural to assume that the effect is related to the $q\bar{q}$ binging energy. Then $\psi(2S)$ must show strong effect. But it does not.

(n_{ch} for $\psi(2S)$ can be measured with the same approach …)

EPJC (2018) 78:731

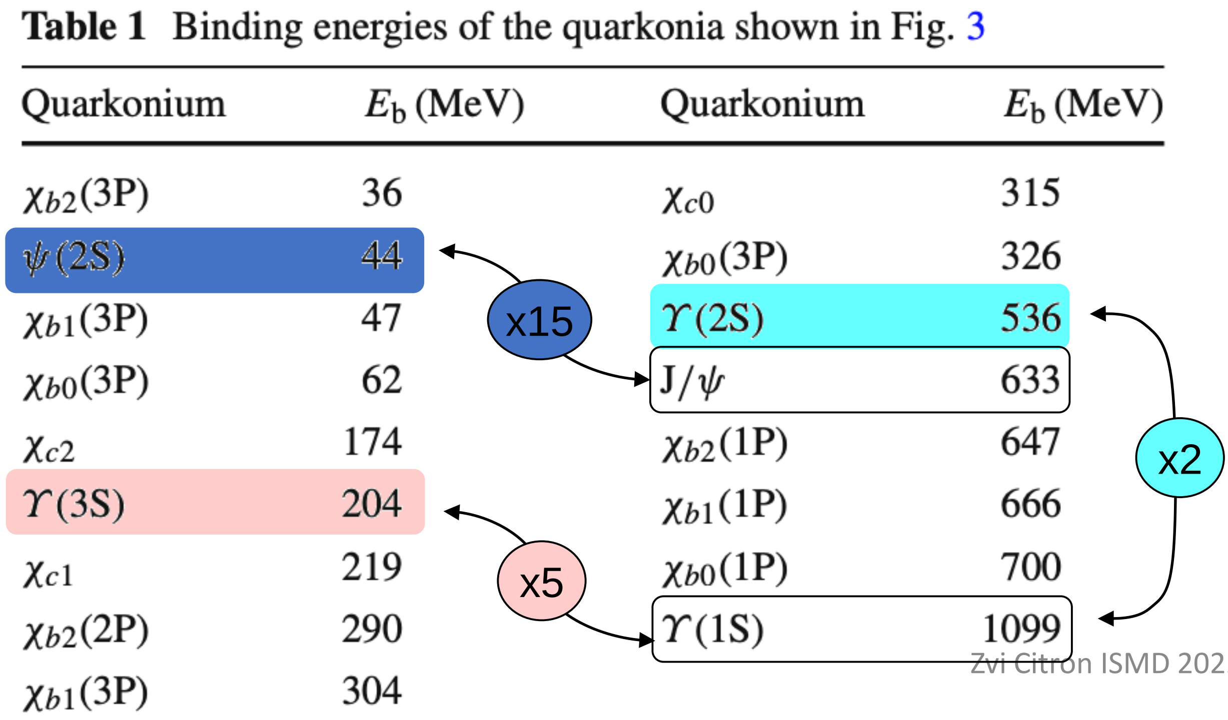
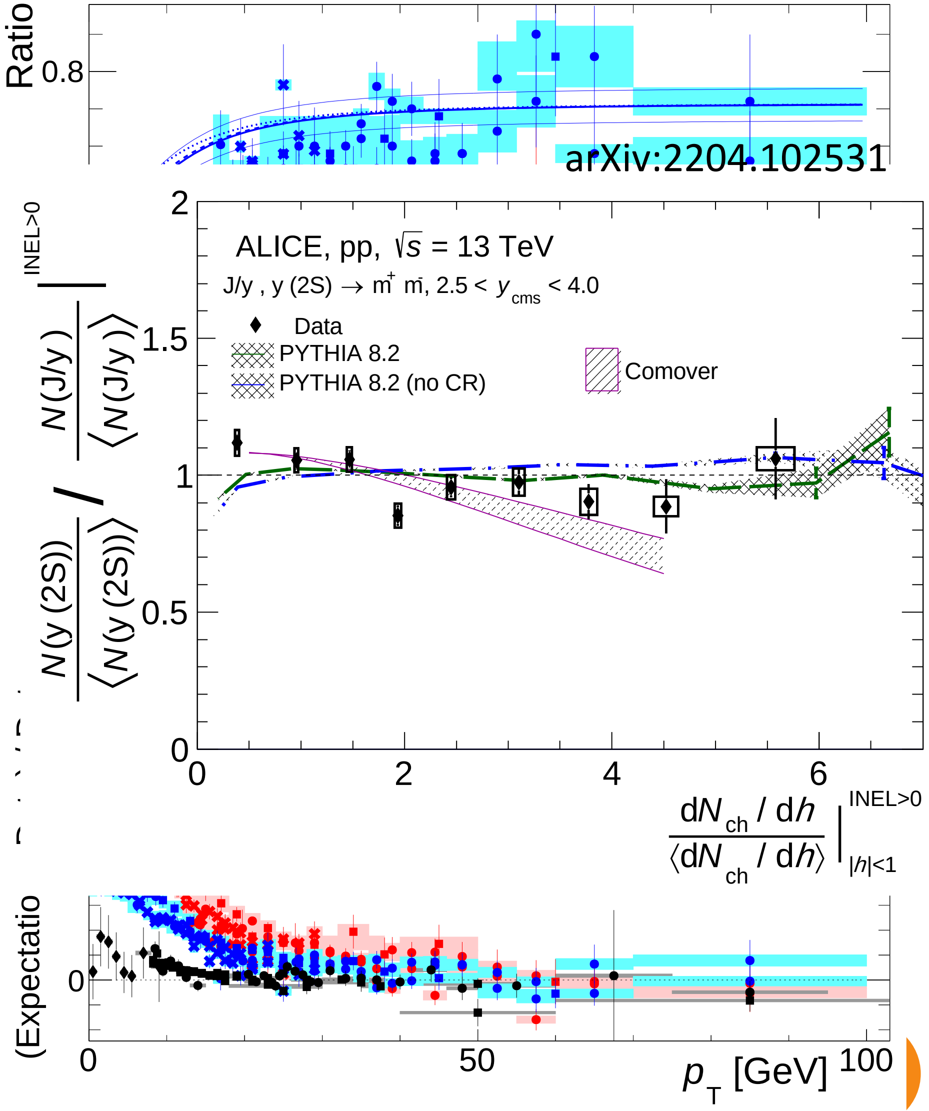


Table 1 Binding energies of the quarkonia shown in Fig. 3

Quarkonium	E_b (MeV)	Quarkonium	E_b (MeV)
$\chi_{b2}(3P)$	36	χ_{c0}	315
$\psi(2S)$	44	$\chi_{b0}(3P)$	326
$\chi_{b1}(3P)$	47	$\Upsilon(2S)$	536
$\chi_{b0}(3P)$	62	J/ψ	633
χ_{c2}	174	$\chi_{b2}(1P)$	647
$\Upsilon(3S)$	204	$\chi_{b1}(1P)$	666
χ_{c1}	219	$\chi_{b0}(1P)$	700
$\chi_{b2}(2P)$	290	$\Upsilon(1S)$	1099
$\chi_{b1}(3P)$	304		



Co-mover Interaction Model

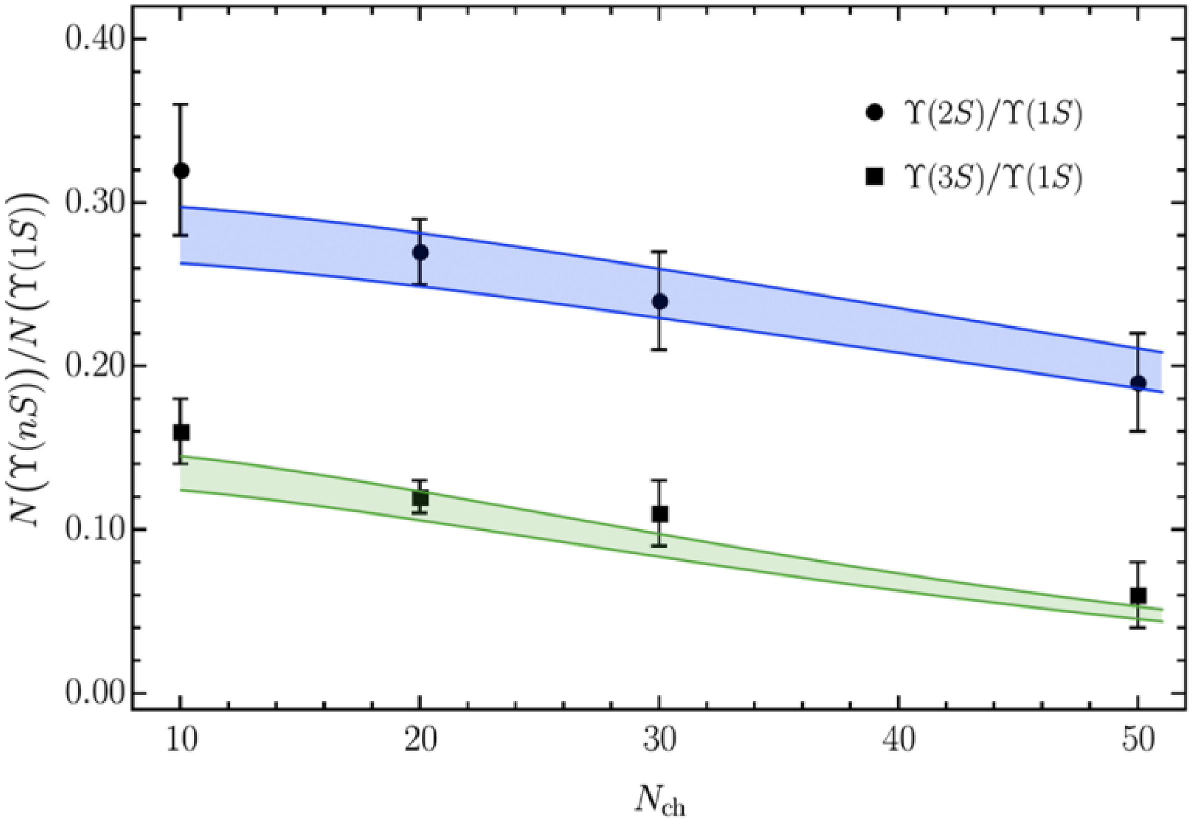
EPJC 81, 669 (2021)

- 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, although recently it was successfully applied to *pp.*

- 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, $\Delta\varphi$ $\Delta\eta$

- Can it explain Δn_{ch} for $J/\psi - \psi(2S)$? Other systems?



Summary (Conclusions?)

- 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
- Global meson analysis including Upsilons suggest there is significant relative suppression
- More work is needed on data side
  - Check rapidity
  - Check other species etc
- And model side
  - Can existing models see this effect?
  - New ideas?

Extra Slides

Underlying Event
ATLAS Measurement of Υ(nS) and ~~Multiplicity~~

- 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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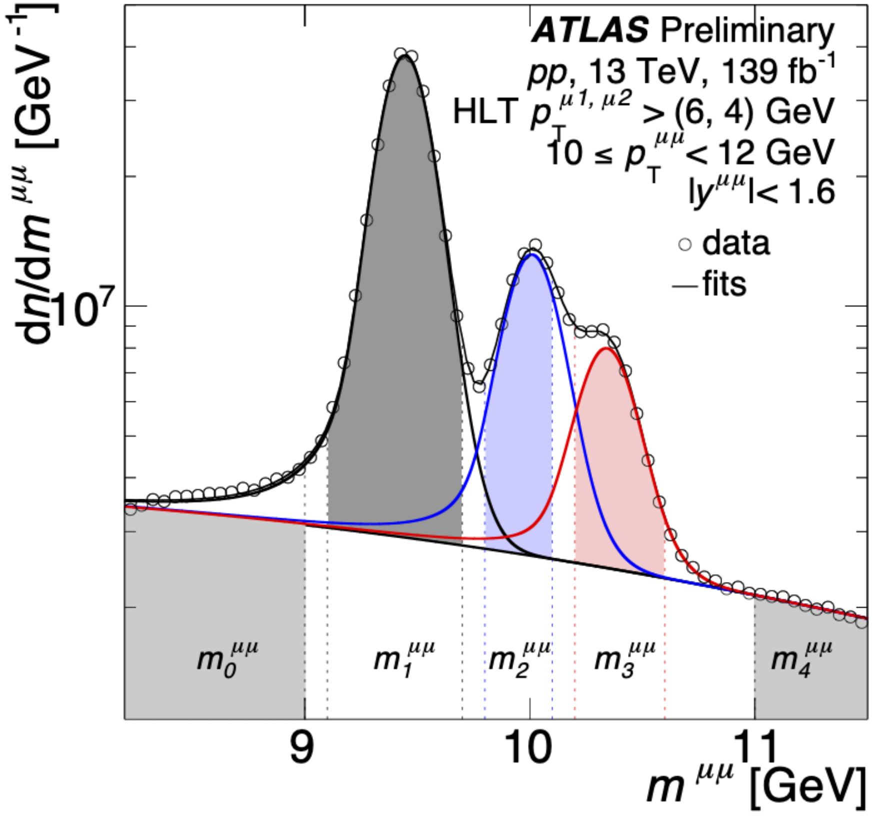
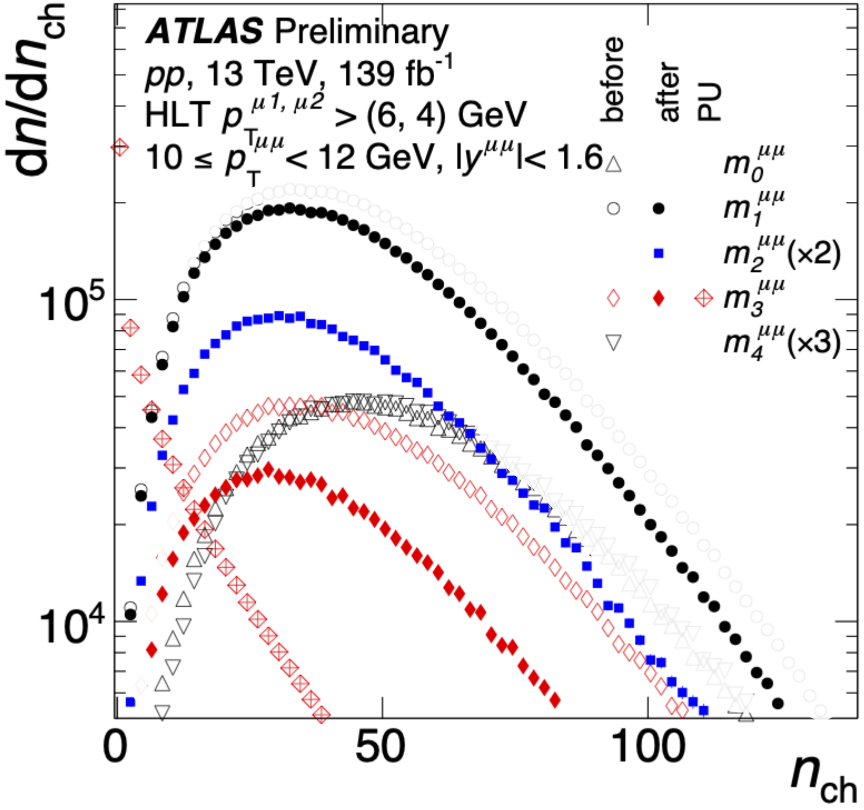
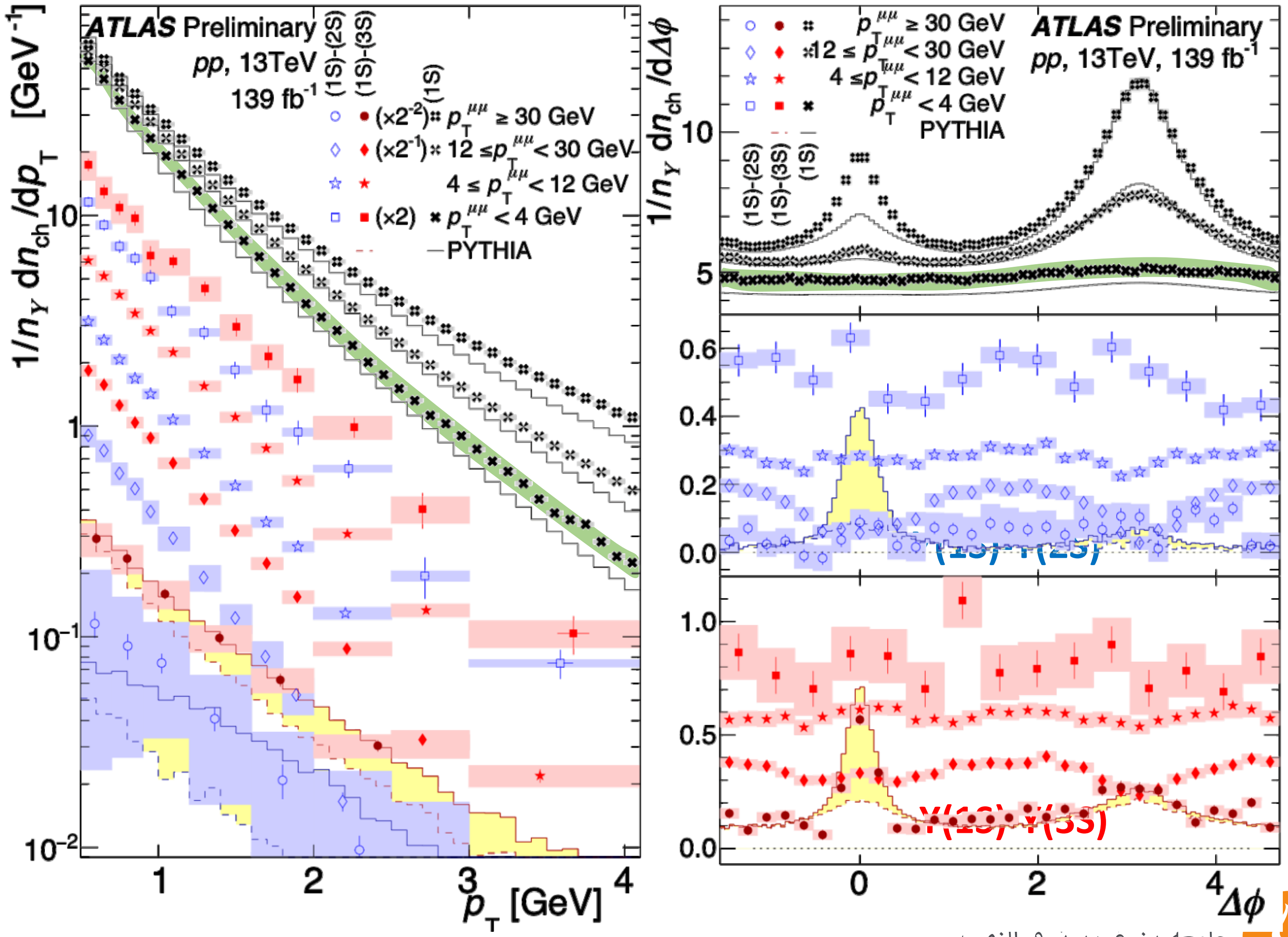




ATLAS Measurement of Υ(nS) and ~~Multiplicity~~ Underlying Event

ATLAS-CONF-2022-023

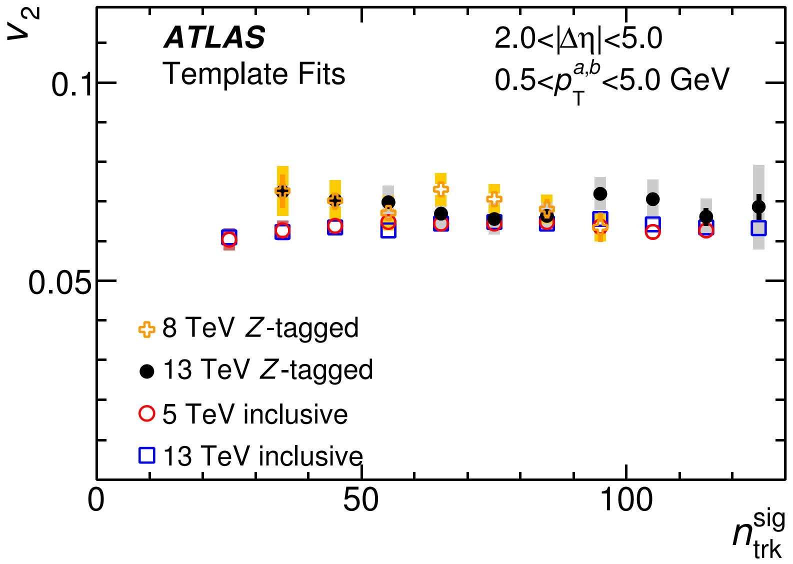
- Measure the total multiplicity in the event (and particle kinematics) for each Upsilon state
- Precise control of background and pile-up
- Use differential particle kinematics to reach for the UE
- Compare excited to ground states



Z Boson (hard) Tagged pp Collisions for 2PC

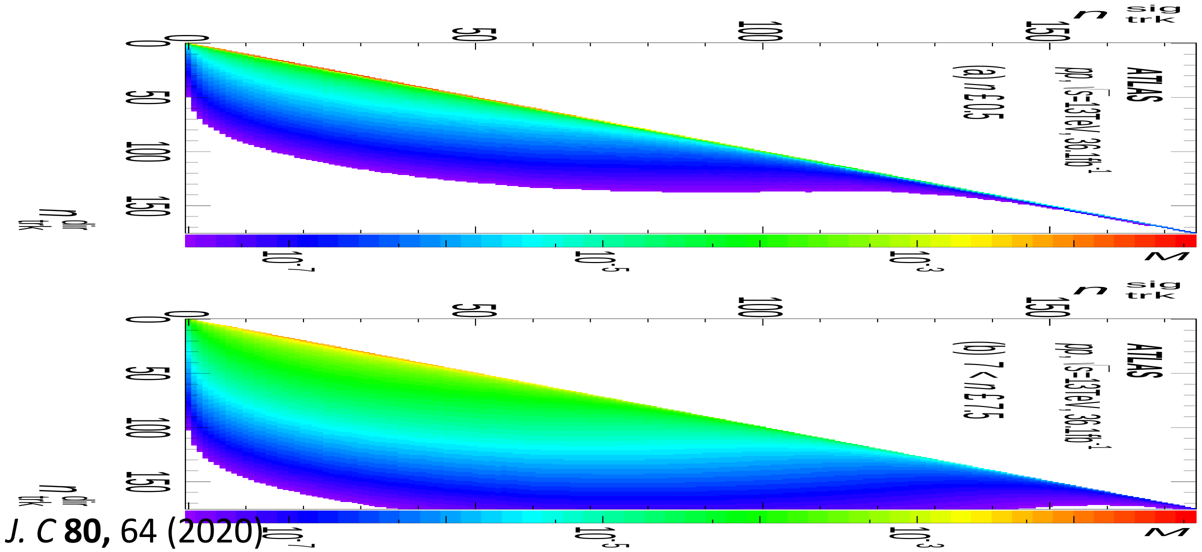
- Our first effort in this direction was studying v_2 via 2-particle correlations in pp collisions ‘tagged’ by a Z boson
- (At the time) we were asking a somewhat different question: Does the presence of a hard scattering in the collision change “*something-like-geometry*” and consequently the observed “*flow*”?
  - The answer is not really

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

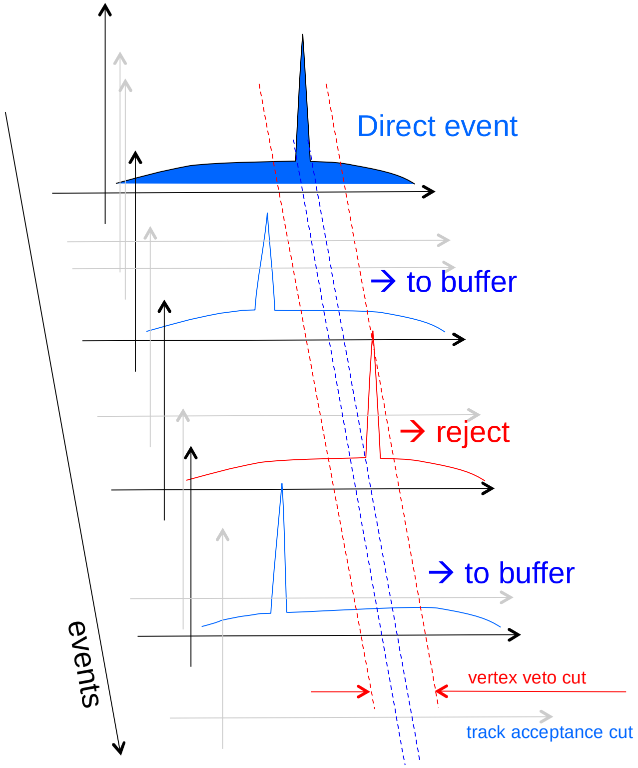


Z Boson (hard) Tagged pp Collisions for 2PC

- 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 … maybe HF …

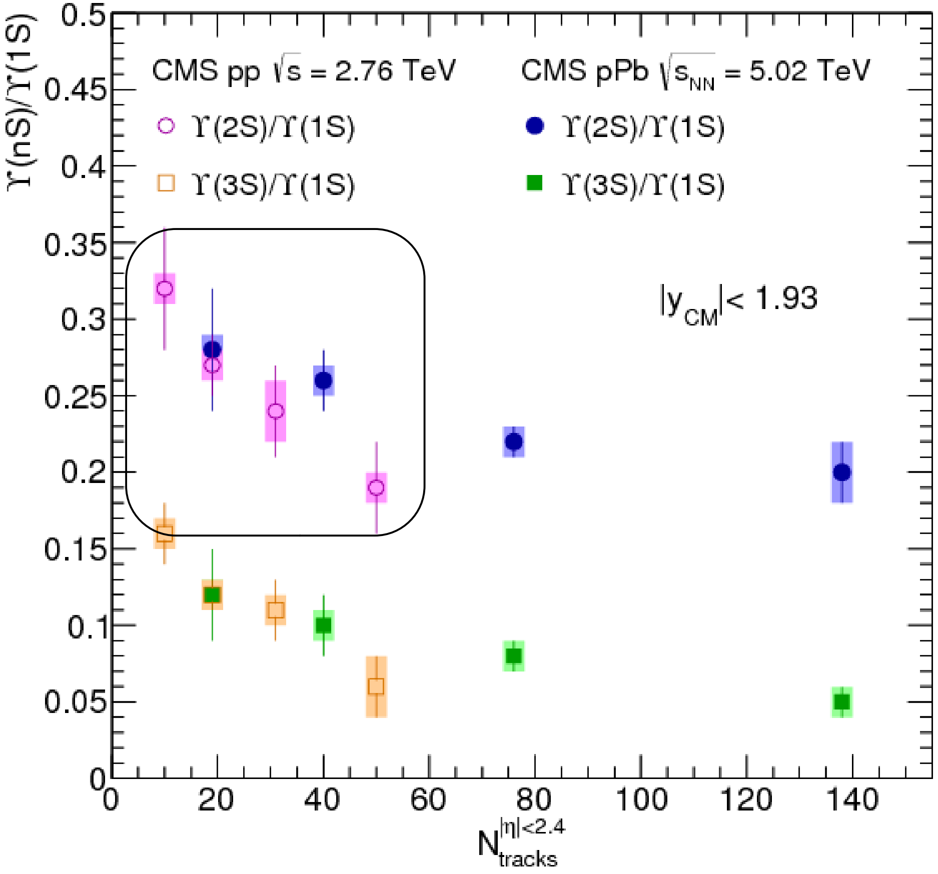


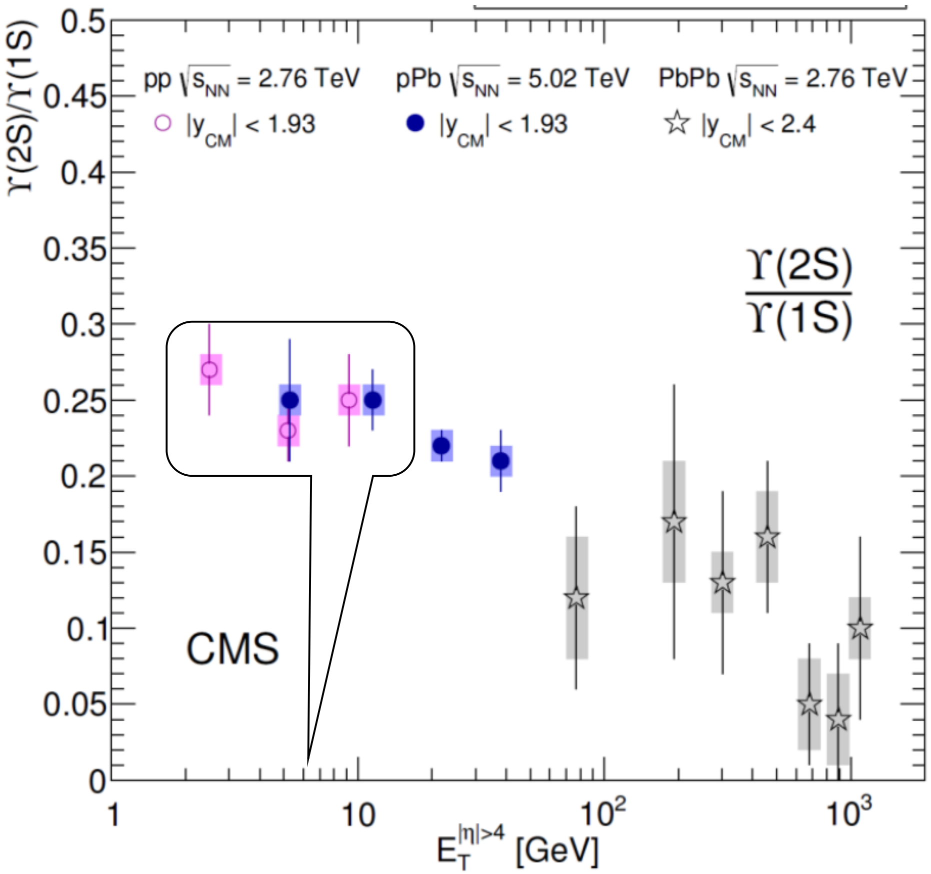
Eur. Phys. J. C **80,** 64 (2020)



Does the rapidity matter?

JHEP 04 (2014) 103

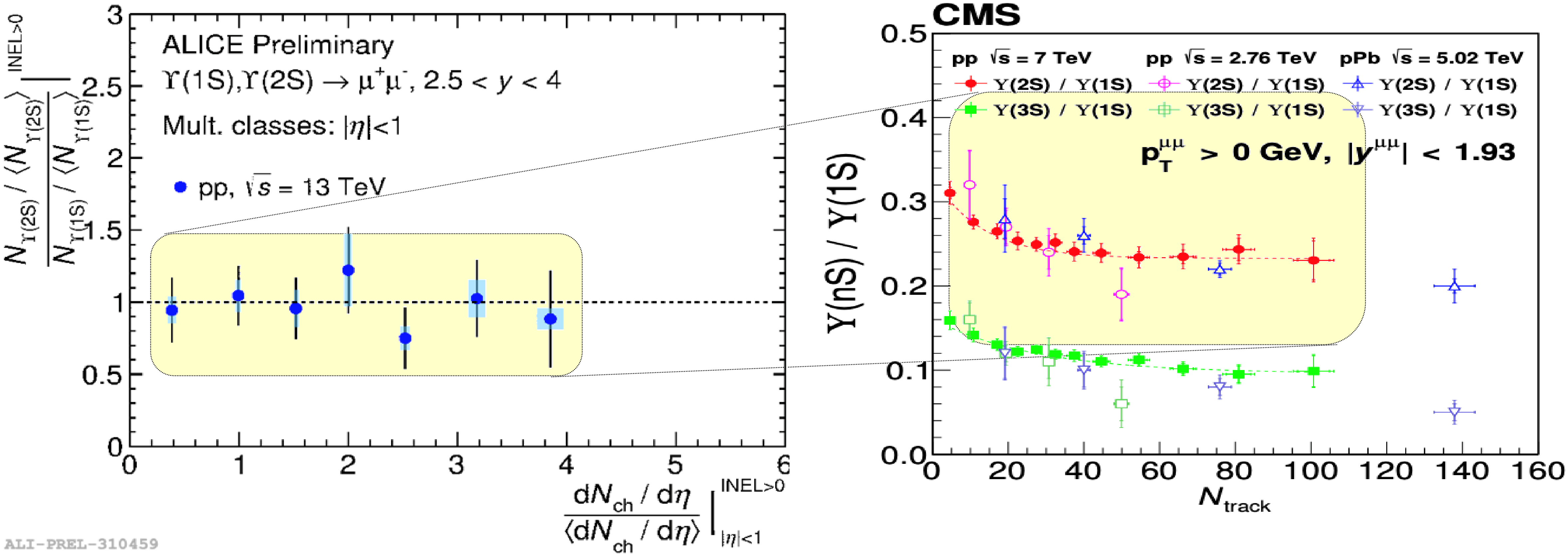




Introducing midrapidity-forward gap flattens the dependence as mentioned in HP2018 summary talk: https://indico.cern.ch/event/634426/contributions/3003672/

But it may be due to loss of resolution…

Does the rapidity matter?



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

Data doesn’t warrant any gap dependence

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

The m_T scaling

Proposed by R. Hagedorn [*N.Cim.Sup.*3 (1965) 147-186] and observed by the ISR [PLB 47, 75 (1973)]

$$P(p_\mathrm{T}) \propto \frac{1}{(m_\mathrm{T})^\lambda} \exp\left[-\frac{m_\mathrm{T}}{T_a}\right] \qquad m_T = \sqrt{p_\mathrm{T}^2 + m_0^2}$$

Today is more commonly used in Tsallis form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_\mathrm{T}} \propto \left[1 + \frac{m_\mathrm{T}}{nT}\right]^{-n}$$

m_T scaling is useless to measure cross sections, but it can link spectral shapes of different particles, for example $\Upsilon(nS)$ to $\Upsilon(1S)$

for example, ALICE: EPJC81 (2021) 256

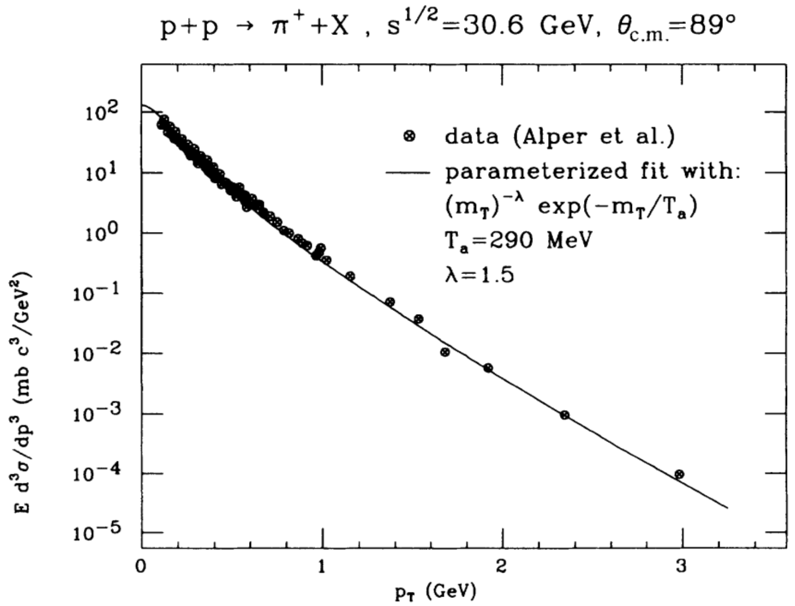
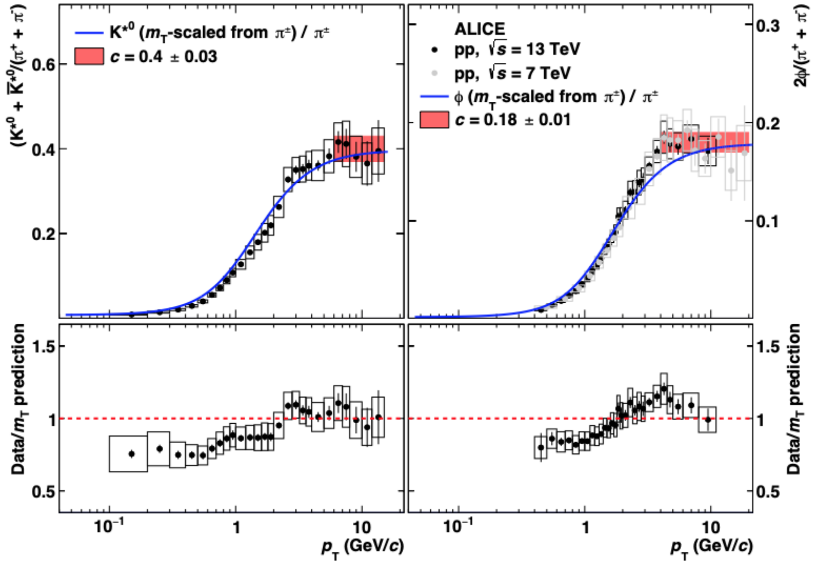
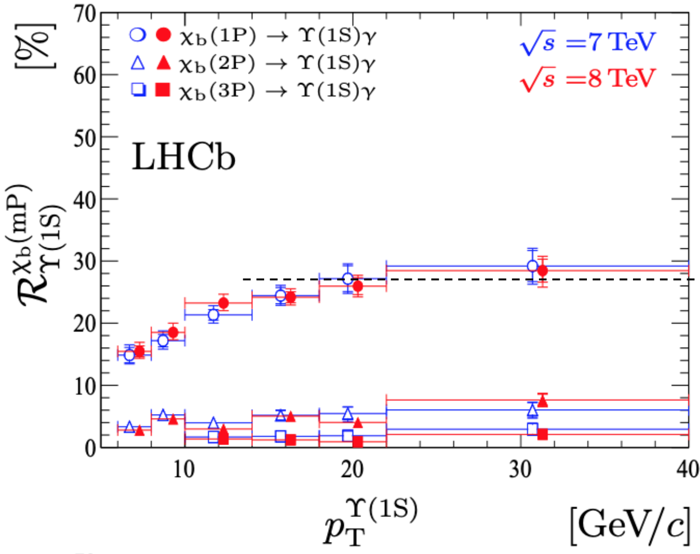


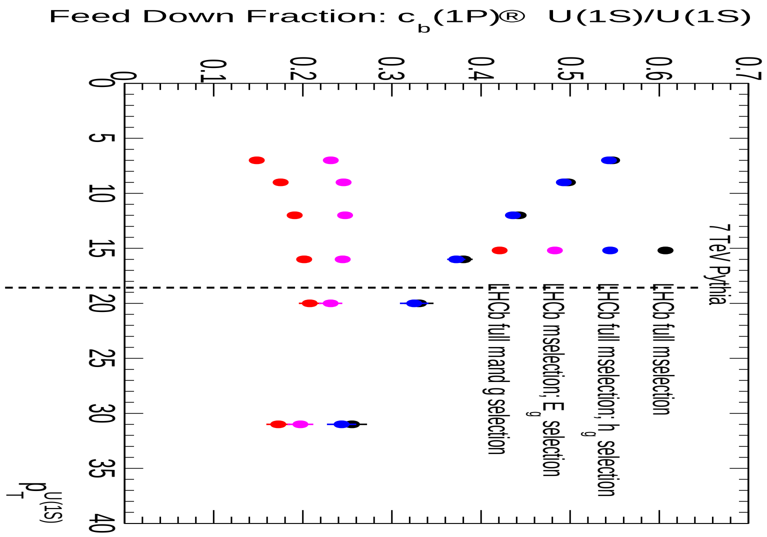
FIG. 3. *p-p* data from Alper *et al.*, fit here with $m_T^{-\lambda}\exp(-m_T/T_a)\times$const, having T_a=200 MeV and λ=1.5.

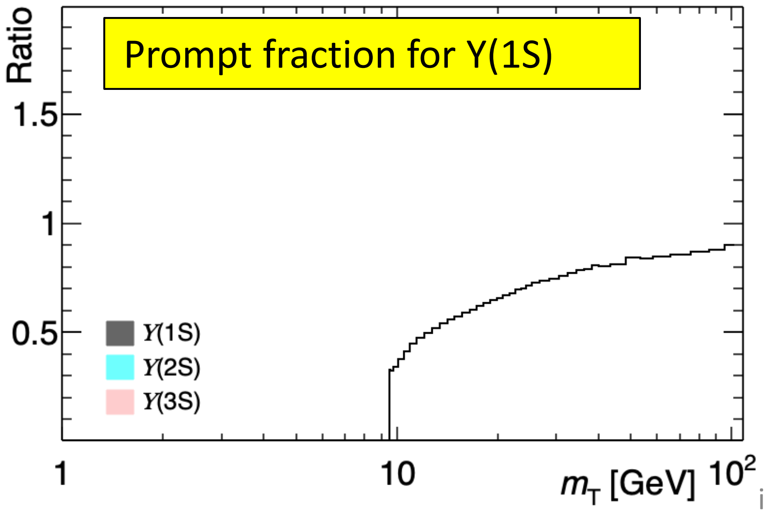


Pythia validation

The LHCb results shown on the left are generally consistent with Pythia shown on the right which reproduces the magnitude of the ratios.







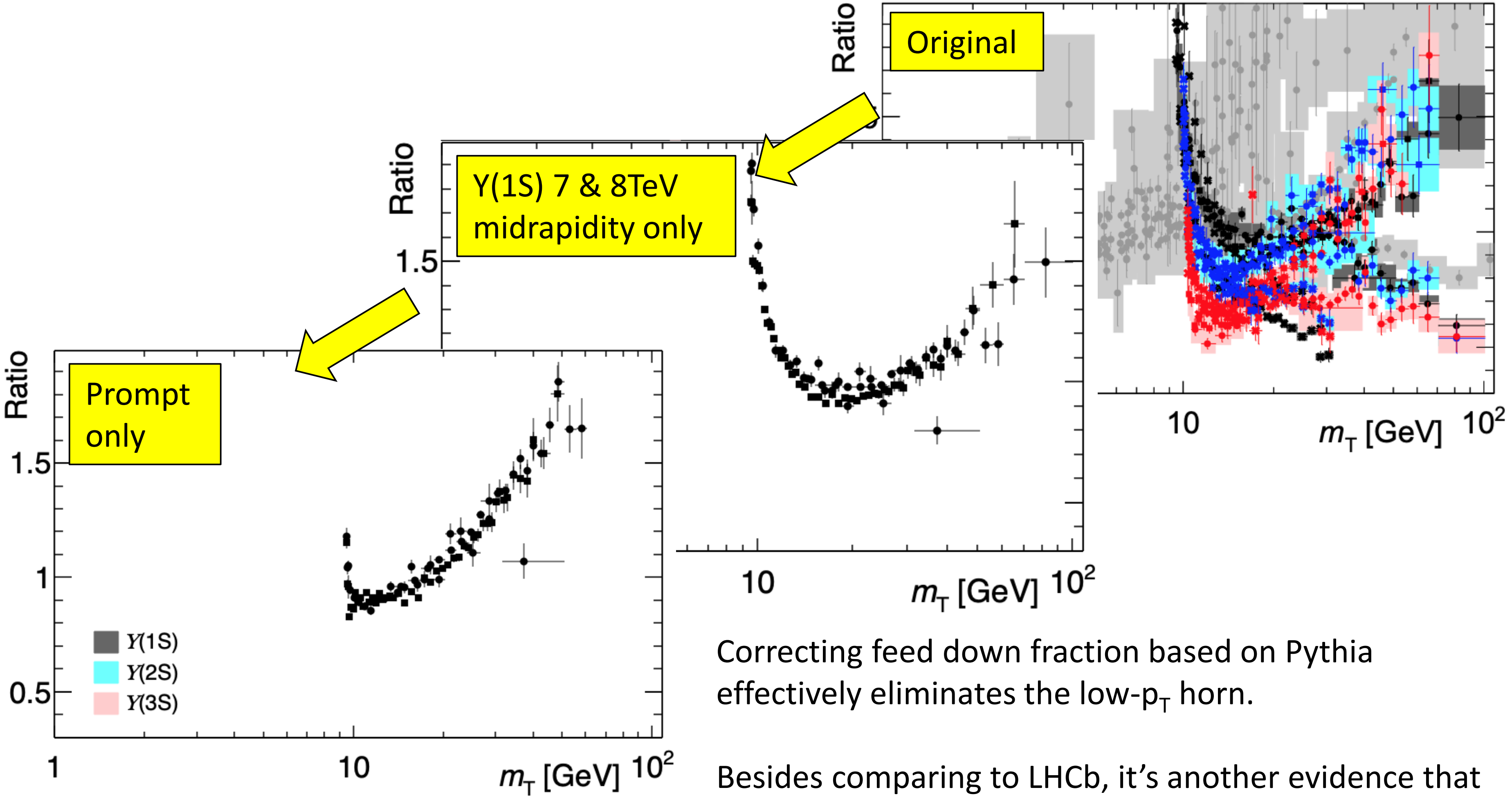
From the same Figure 3 of the LHCb publication one can make two other important observations.

1. $\chi_b(nP) \to \Upsilon(nS)$ are approximately the same for all n
2. $\chi_b(mP) \to \Upsilon(nS)$ with $m > n$ are smaller compared to $m = n$ contribution

Pythia only has $\chi_b(1P) \to \Upsilon(1S)$ decay mode, which is shown as a function of m_T

Prompt vs. total

One can use this result to remake the lower panel of Figure 2 with only the prompt fraction. To make the exercise clearer we first removed curves measured for higher *n*S and for 13 TeV.

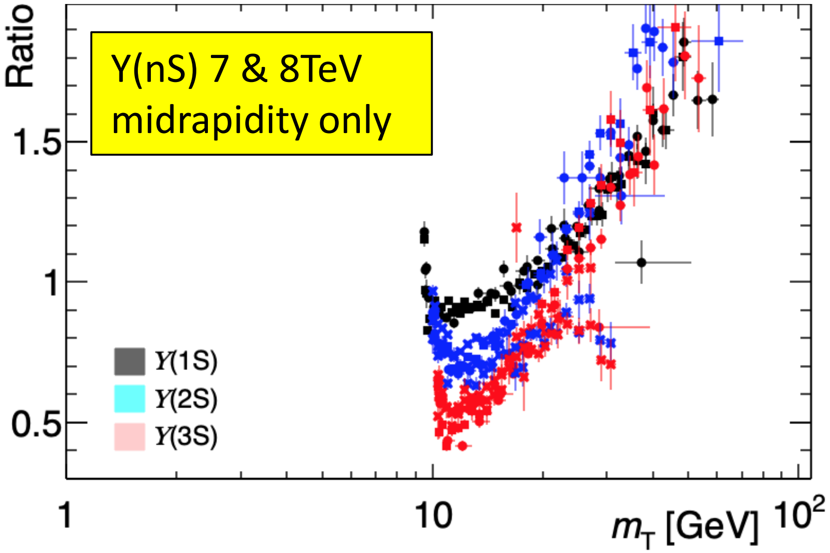


Correcting feed down fraction based on Pythia effectively eliminates the low-p_T horn.

Besides comparing to LHCb, it's another evidence that feed downs in Pythia are reasonable.

Prompt vs total (excited)

As an exercise, we apply the same Y(1S) prompt fraction also to Y(2S) and Y(3S), which significantly reduces horns in the ratios of these particles (to the common parameterization).

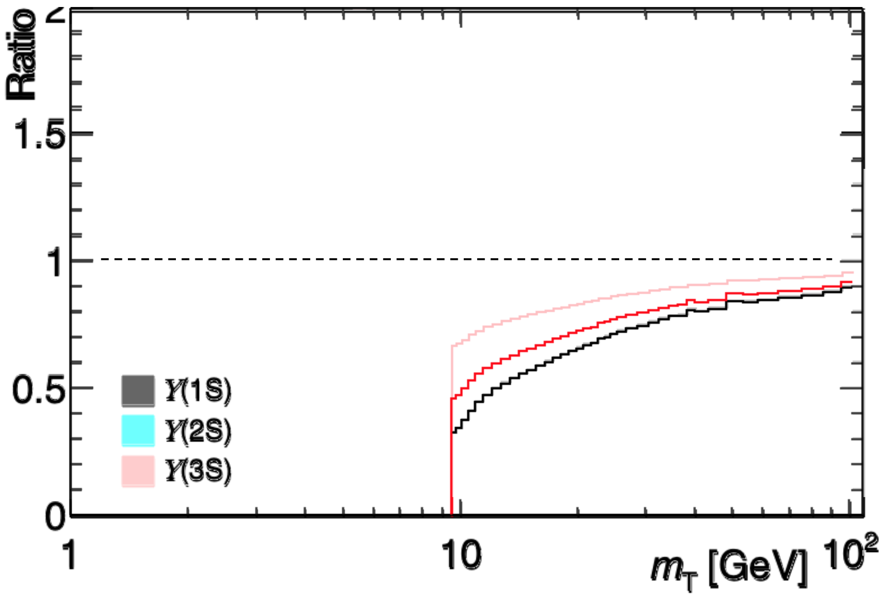


Although this is even less justified correction for Y(2S) and Y(3S) than it is for Y(1S), and it is applied regardless of the particle mass, the improvement in the figure is a strong argument in favor of the assumption made in [57] that is used in our paper:

The feed downs into different Y(nS) states are approximately similar.

Assuming different feed down fractions

We test the effect of same chi_b feed-down assumption by changing the feed down curve by a larger 20%, as shown in the plot, and applying one curve to Y(nS) and another curve to Y(1S). Applying them in either order moves the ratios up or down.

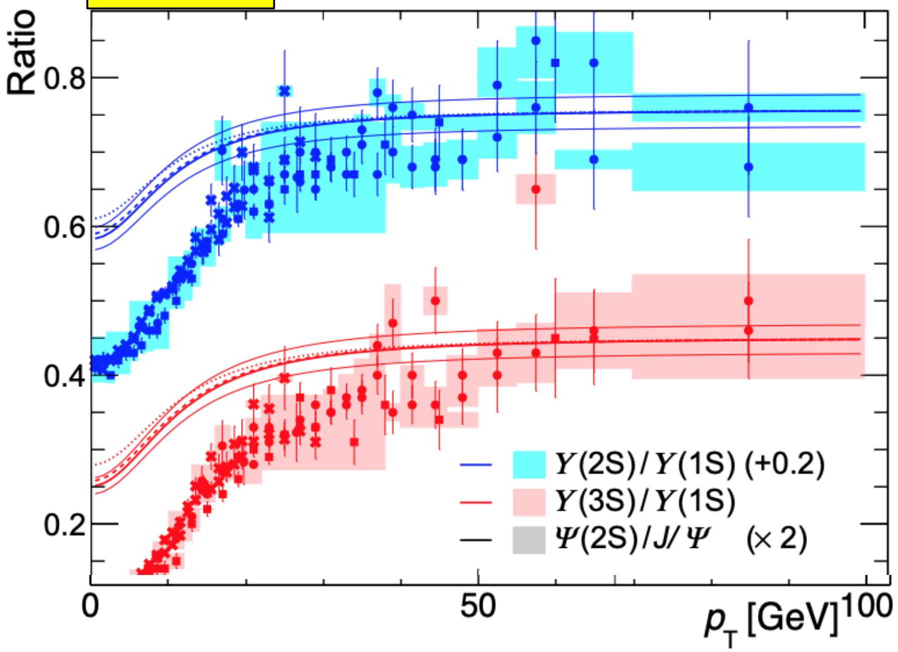


Pythia:
50% change
20% change
Prompt fraction

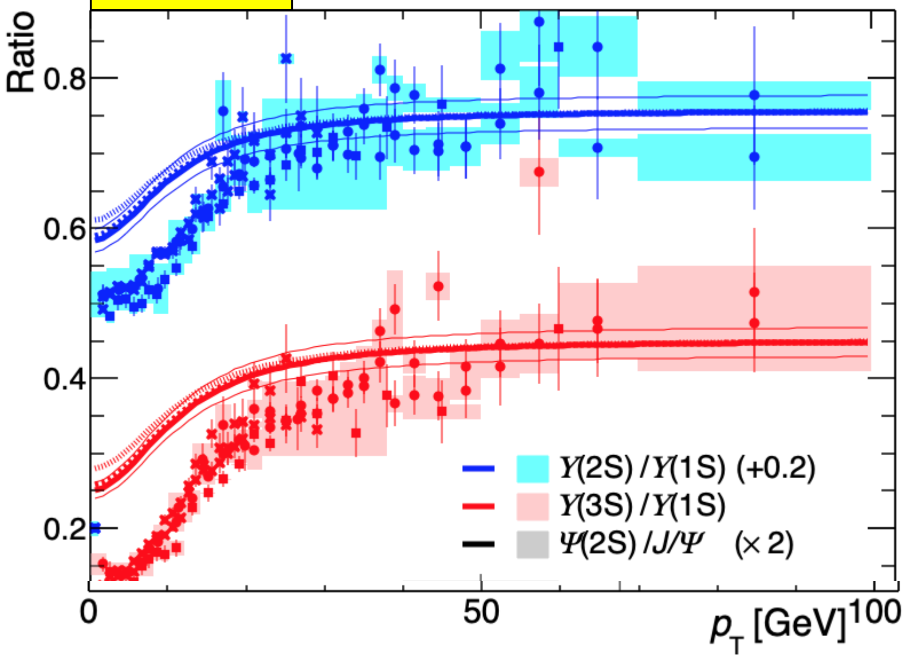
The case that moves ario.

Impact on the ratios

Original



Modified

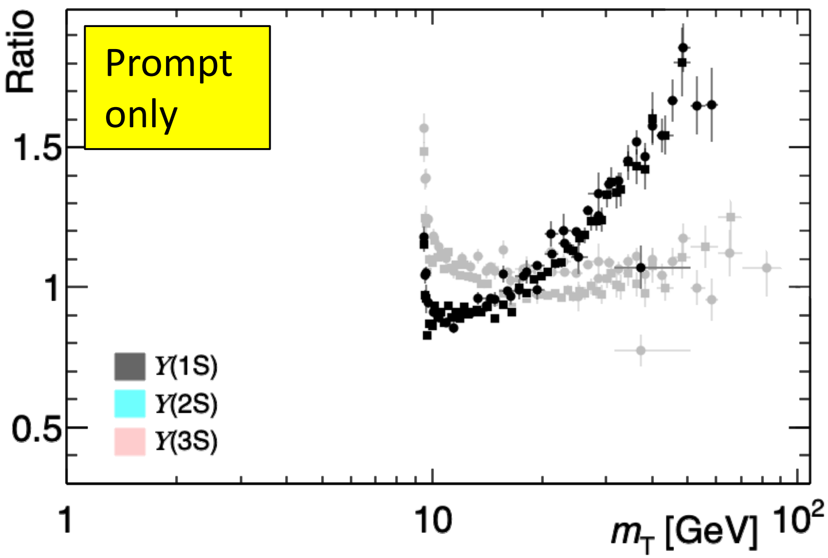


Changing feed down fraction by 20% does not eliminate the effect. To eliminate it in Υ(2S) one needs to assume a 50% change and a bigger change for Υ(3S).

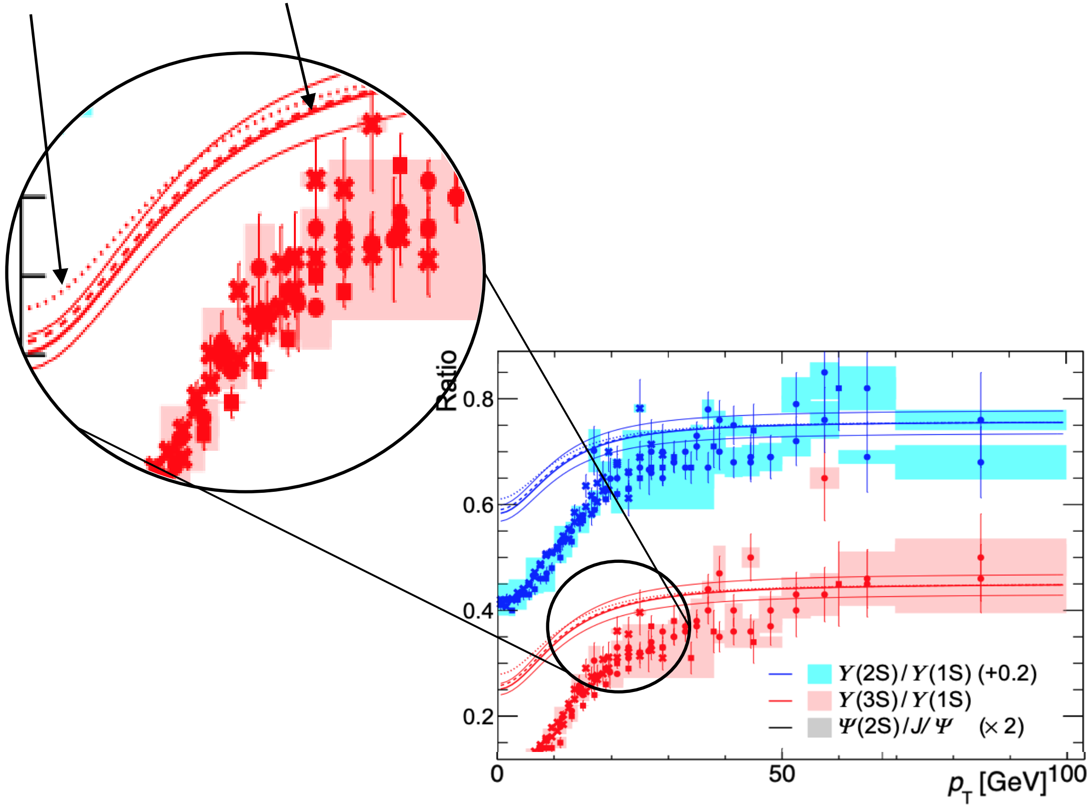
Regarding the CMS result, which we believe is the manifestation of the same physical phenomenon. We want to note, that $\chi_b(mP) \rightarrow \Upsilon(nS)\gamma$ decays make no impact on the charged-hadron multiplicity, therefore cannot explain this result at all.

Sensitivity to the power (n)

This somewhat relates to the question of sensitivity to nT, addressed earlier. The sensitivity of our results to n is higher than to T. However, it is not changing any conclusions either. For example, the tail of the curve after correcting for feed down goes up. Choosing n to be 8% lower for the common fit, produces grey points that are flat. However, this is much less than the variations between different energies.



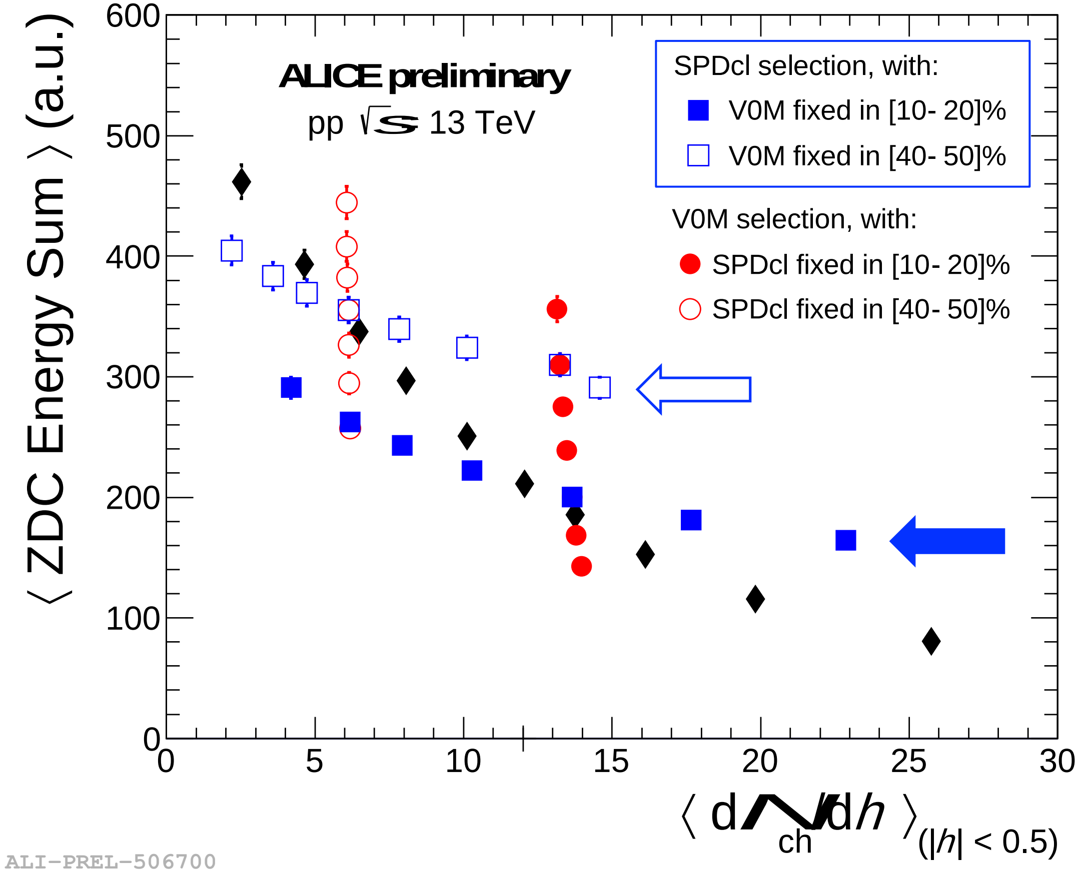
The effect on the results shown in Figure 3 due to changing n between different energies is still small: this is a much bigger (19%) difference between the 7 and 13 TeV results $n = 6.65$ and $n = 5.44$.



Copied from Chiara DeMartin @QM

Multiplicity vs Effective Energy in ALICE

NEW!



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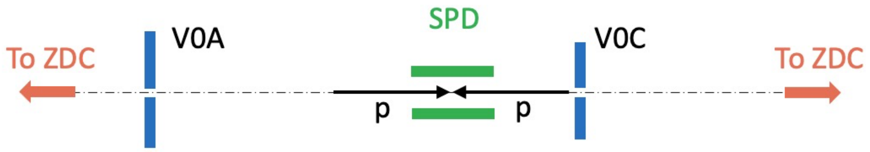

SPD classes:
Percentile classes based on the number of clusters in the SPD (|! | < 0.8)

○ ● SPD class fixed + V0M selections:

Fix the multiplicity at midrapidity and vary the effective energy

☐ ■ V0M class fixed + SPD selections:

Reduce the span of the effective energy and vary the multiplicity at midrapidity

A **multi-differential analysis in combined V0M and SPD classes** allows to disentangle the effective energy and the multiplicity at midrapidity