MISSING BEAUTY OF PROTON–PROTON INTERACTIONS*

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From the first principles, particles with the same quark content and similar masses should have similar kinematic distributions. Transverse mass scaling may be employed to estimate possible differences in the momentum distribution of such particles. Based on this scaling, the excited bottomonium states measured at the LHC are found to be significantly different from $\Upsilon(1S)$ to the extent that the integrated yield of $\Upsilon(2S)$ is 1.6 times less and $\Upsilon(3S)$ 2.4 times less than would be explained by the mass difference. This contribution explains how the estimate is worked out and relates it to other measurements performed at the LHC.

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Recent measurements conducted by the ATLAS [1], CMS [2, 3], and LHCb [4] experiments show that in proton–proton (pp) collisions, the yield of excited quarkonia states, $(q\bar{q})^\star$, with respect to the ground state, $q\bar{q}$, diminishes with the event multiplicity. The magnitude of the effect increases at low transverse momentum (p_{T}) of the particle. This effect should have an impact on the p_{T} distribution of the $(q\bar{q})^\star$ which can be measured in an independent analysis. An approach to do that can be based on the assumption that particles with the same quark content and close mass should have similar momentum distributions. This assumption is appropriate for the Υ-meson family, in which the masses of the $\Upsilon(2S)$ and $\Upsilon(3S)$ are larger than the mass of $\Upsilon(1S)$ by 6% and 9.5%, respectively.

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In a broader sense, this assumption is the basis of the transverse mass (m_{T}) scaling, stating that particles produced in pp collisions have the same m_{T} distribution, where $m_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m^2}$ and m is the particle rest mass. The m_{T}-scaling is widely exploited in many phenomenological studies [5–9] and is often used in the form of

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\mathrm{T}}} \propto \left(1 + \frac{m_{\mathrm{T}}}{nT}\right)^{-n} . \tag{1}$$

The m_{T}-scaling phenomenon is equivalent to the fact that the exponent n and parameter T are universal for all particles, although different for mesons and baryons (*e.g.* [8] and references therein). This analysis considers only mesons. The scaling behavior of heavy mesons is studied in comparison to light quark species and is used to understand the ratios between excited and ground quarkonia states measured in experiments.

A comprehensive study of the m_{T} distributions of the mesons at three LHC energies $\sqrt{s} = 7, 8$, and 13 TeV is performed in [10]. It uses 72 data samples of 18 mesons and their isospin partners. Figure 1 shows the parameter n obtained in fits of individual data samples. When fitting data with the form of Eq. (1), parameters n and T are strongly correlated, therefore T is fixed to 254 MeV. This value is similar to many other studies conducted at LHC energies and it can be somewhat different at different energies. It is shown later that the derived conclusions are indifferent to the exact value of T, which is also checked by varying it by ±50 MeV in the analysis.

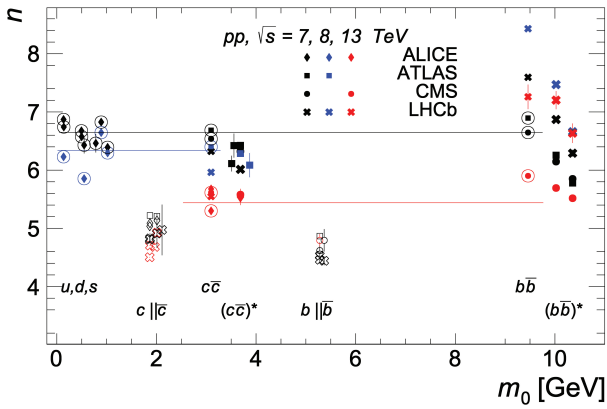


Fig. 1. Measured n for different species. Colors correspond to collision energies, symbol shapes denote experiments. Error bars are uncertainties of the fits. Circled points are used for common fits of the *u, d, s*, and $q\bar{q}$ mesons. Results of the fits are shown by horizontal lines. From reference [10].

Several trends are visible in Fig. 1. Particles produced in collisions with higher $\sqrt{s}$ have harder spectra (lower n). The magnitude of n depends on the quark content of the particle. Open heavy flavor mesons $(q||\bar{q})$ demonstrate significantly harder spectra compared to other species and harder for the open bottom $(b||\bar{b})$ than for open charm $(c||\bar{c})$.

At each collision energy, the LHCb results for Υ-mesons are above others because they are measured at higher rapidity. Comparing results at the same energy as it is done in [5] shows that n increases with rapidity. Figure 1 shows that the exponent n for u, d, s, and $q\bar{q}$ mesons is similar. At the same time, $(q\bar{q})^{\star}$ have lower values of n than the ground state: $n_{J/\Psi} > n_{\Psi(2S)}$, and for bottomonia states: $n_{\Upsilon(1S)} > n_{\Upsilon(2S)} > n_{\Upsilon(3S)}$.

Based on these observations, the values of n for u, d, s and ground-state $q\bar{q}$ mesons measured at midrapidity (circled data points in Fig. 1) are fit to extract a common n. There are 12, 5, and 3 data samples at $\sqrt{s} = 7$, 8, and 13 TeV, respectively. The $\sqrt{s} = 7$ TeV values are fit to a linear function, which becomes constant for $T = 254$ MeV. Due to the low number of selected data sets at higher energies, the 8 and 13 TeV data are initially fit to a constant. The values of $n\,(\sqrt{s} = 7, 8, 13\ [\text{TeV}]) = (6.65, 6.34, 5.44)$, are shown in Fig. 1 with lines.

Figure 2 shows the $\Upsilon(nS)$ results at 3 collision energies, divided by the common fit. The Υ-points are shown in different colors, regardless of energy, and points that are used in the common fit are shown in gray. The latter demonstrate reasonable agreement with unity, although at high-p_{T}, $q\bar{q}$ spectra tend to rise up to a factor of 2, somewhat similar to what can be seen in Ref. [5]. Using Eq. (1), at high m_{T}, this translates to $\mathrm{d}n/n \approx 1/n \times \mathrm{d}\sigma/\sigma \approx 15$–$18\%$ deviation of n from the 'true scaling' value, which is comparable or even smaller than the difference in n at three mea-

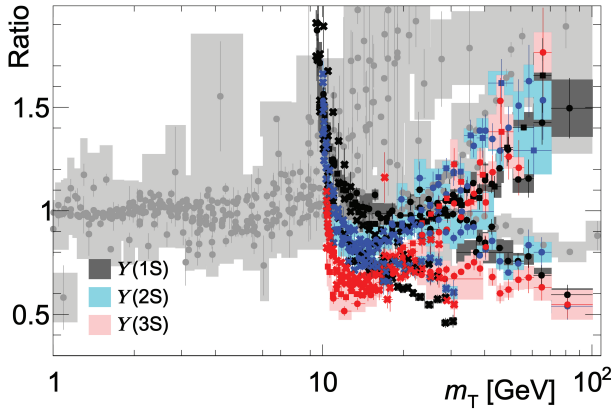


Fig. 2. Spectra of individual particles divided by the common fit. Measurements used in the common fit are shown in gray. From reference [10].

sured energies. Similarly, the LHCb results which are measured at high rapidity, yield a value of n that is larger approximately by 1 (see Fig. 1) and constitutes approximately the same 20% deviation from the common n.

A significant rise for all $\Upsilon(nS)$ states at low p_{T}, *i.e.* $m_{\mathrm{T}} \gtrsim m$, is clearly visible. The contribution of $\chi_b(1\mathrm{P}) \to \Upsilon(1S)$ has been estimated using Pythia 8 [11] simulations to work out the prompt fraction of $\Upsilon(1S)$. Inclusive data used in the analysis and the prompt fraction estimated from Pythia 8 are shown in Fig. 3 with full and open circles, respectively. The prompt

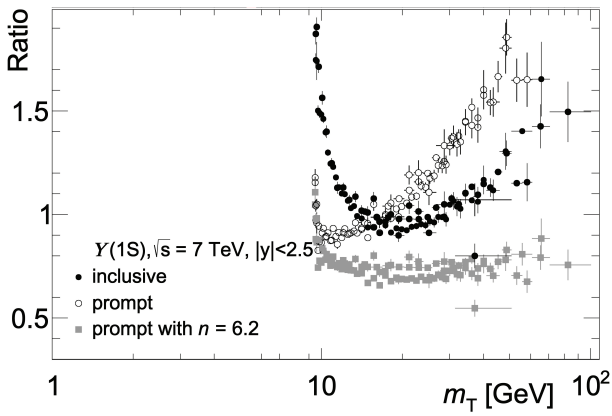


Fig. 3. Spectra of $\Upsilon(1S)$ at $\sqrt{s} = 7$ TeV at midrapidity divided by the common fit: as used in the analysis (full circles), a prompt fraction (empty circles), using different n in a common fit (squares). Points are shifted vertically for visibility.

fraction has only a weak excess at $m_{\mathrm{T}} \gtrsim m$, but it still rises at high p_{T}. Decreasing n by 8% flattens the ratio, as shown in the figure with squares. Nevertheless, inclusive data with $p_{\mathrm{T}} > 5$ GeV are used in the fit, because prompt fractions for $\Upsilon(nS)$ are not yet reliably measured experimentally nor fully modeled successfully.

The ratios of all $(q\bar{q})^{\star}/q\bar{q}$ measured at the LHC are shown in Fig. 4. The ratio curves derived from m_{T}-scaling are drawn normalized to data at $p_{\mathrm{T}} > 50$ GeV and uncertainties are shown with thin solid lines. Dashed lines correspond to higher energies. The shape of the curves can be directly derived from Eq. (1) and is governed by their minimum-to-maximum span

$$\frac{\min}{\max} \approx 1 - \frac{\Delta m}{nT + m} n\,, \tag{2}$$

where m corresponding to $\Upsilon(1S)$ is equal to 9.46 GeV and Δm is 0.9 GeV for $\Upsilon(3S)$. Equation (2) makes it clear that the value of T has only a minor effect on the shape because $nT \ll m$. Since $\Delta m \ll m$, even for $\Upsilon(3S)$, the ratio before n in Eq. (2) is ≈ 0.08, therefore, the two curves for $\sqrt{s} = 7$ and

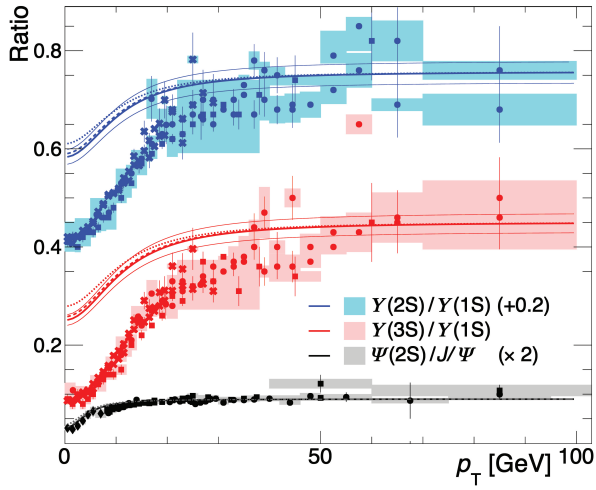


Fig. 4. Measured $(q\bar{q})^\star/q\bar{q}$ ratios (markers) and m_T-scaling prediction normalized to the data at $p_T > 50$ GeV with normalization uncertainties (solid lines). The dashed (dotted) lines correspond $\sqrt{s} = 8$ (13) TeV. From reference [10].

13 TeV are close to each other. As discussed above, residual non-flatness of the common fit and the rapidity dependence have similar or smaller impacts on n compared to $\sqrt{s}$. None of these effects can explain the drastic difference between the experimentally measured $(b\bar{b})^\star/b\bar{b}$ ratios and the curves shown in Fig. 4. To reconcile $\Upsilon(2S)/\Upsilon(1S)$-ratio curve with the data, the feed downs from Pythia 8 that are consistent with the LHCb results [12] and nearly eliminate the peak at $m \lesssim m_T$ in Fig. 3 should be increased by 2.5 and even more than that for $\Upsilon(3S)$, which is not plausible.

To quantify the discrepancy between the data and the m_T-scaling prediction one can build the particles' 'missing fraction': $(q\bar{q})^\star_{\text{expected}}/(q\bar{q})^\star_{\text{measured}} - 1$. This fraction is shown in the left panel of Fig. 5. Assuming the m_T-scaling scenario and the $\Upsilon(1S)$-meson production cross section, expected $\Upsilon(2S)$ production at low p_T is approximately twice higher than the measurement and $\Upsilon(3S)$ is roughly three times higher.

The discrepancy between the measured production rates of $(b\bar{b})^\star$ in pp collisions and rates expected from the m_T-scaling approach may share a common origin with the results reported in [3, 10]. This would explain the striking similarity between the 'missing fraction' and the difference in the number of tracks in the underlying event measured by the ATLAS experiment. This comparison is demonstrated in the two panels of Fig. 5. It would mean that charged particles present in pp collisions reduce the production rate of $(b\bar{b})^\star$. Using the 'missing fraction' and the measured differential cross section of $\Upsilon(nS)$ states (for the full list of references see [10]), one can es-

timate that the measured cross sections of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons are 'suppressed' by factors of 1.6 and 2.4 compared to the expectation from the production rates of $\Upsilon(1S)$.

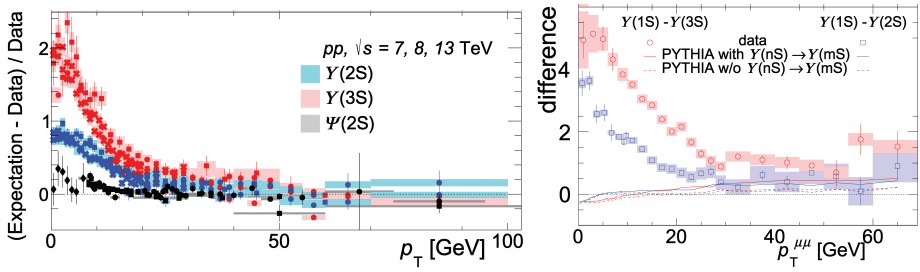


Fig. 5. Left: 'missing fraction' of $(b\bar{b})^\star$ from reference [10]. Right: difference in the number of tracks in events with $\Upsilon(nS)$ states from reference [1].

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