Polarisation problem, HQSS etc...

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(Spin?) Puzzles of Heavy Quarkonia

If AA and pA collisions are not considered, then there seems to exist a unified picture of **un-polarised** J/ψ, χ_{cJ} and $\Upsilon(nS)$ production in NRQCD:

- Un-polarised single inclusive cross sections of J/ψ in pp, ep and e^+e^- collisions ($+$ χ_{cJ} and $\Upsilon(nS)$ in pp) are described by NRQCD fits
- Global description is possible with one set of LDMEs
- Bulk of (un-polarised) double-J/ψ cross section is described by *double colour-singlet* ($^3S_1^{(1)}$) contribution, **which is expected by NRQCD.** The $\Delta y \gg 1$ region can be accounted for by DPS.

Main phenomenological problems:

- Polarisation problem
- Heavy-Quark Spin Symmetry violation in η_c production
- Quarkonium + W/Z ???

failure of robust **predictions** *of NRQCD*? However two of them seem to be related with our treatment of heavy quark's spin.

Polarisation problem

- The **global** NRQCD fit allows one to *constrain all LDMEs independently.* **(not the case if only** pp **is included!)**
- This results into large ${}^3S_1^{(8)}$ contribution at high-p_T, which is *strongly transversly polarised.*
- The experimental data indicate the *un-polarised* mixture of states at $\sim$ all values of p_T.
- An attempt to include polarisation data ruins the global fit.

Restricting to pp-data one has:

- There are *strong cancellations* between contributions of P-wave and other states at NLO, *both for cross section and polarisation parameters.*
- This cancellations allow to fit the pp cross sections and polarisation at the same time.

Is just the universality of LDMEs for pp **vs.** ep **and** e^+e^- **violated?**

Heavy Quark Spin Symmetry

- Interaction with soft gluons ($E_g \ll m_Q$) is independent on the spin of a heavy quark up to corrections $O(E_g/m_Q)$
- Manifests itself in the spectrum of D and B mesons as doublets of spin-0 and spin-1 (*) states:

$$m(B^*_{0,\pm}) - m(B_{0,\pm}) = 45MeV,\ m(D^*_{0,\pm}) - m(D_{0,\pm}) = 140MeV,$$

  which is $\ll O(400MeV)$ of the splitting with excited states.
- **Is assumed in the polarisation transfer model from octet to singlet states of NRQCD, in particualr for $^3S_1^{(8)}$.**
- Leads to HQSS-relations between LDMEs of η_c and J/ψ:

$$\begin{aligned}
\left\langle \mathcal{O}^{\eta_c}\left[{}^1S_0^{(1/8)}\right]\right\rangle &= \frac{1}{3}\left\langle \mathcal{O}^{J/\psi}\left[{}^3S_1^{(1/8)}\right]\right\rangle + O(v^2),\\
\left\langle \mathcal{O}^{\eta_c}\left[{}^3S_1^{(8)}\right]\right\rangle &= \left\langle \mathcal{O}^{J/\psi}\left[{}^1S_0^{(8)}\right]\right\rangle + O(v^2),\\
\left\langle \mathcal{O}^{\eta_c}\left[{}^1P_1^{(8)}\right]\right\rangle &= 3\left\langle \mathcal{O}^{J/\psi}\left[{}^3P_0^{(8)}\right]\right\rangle + O(v^2).
\end{aligned}$$

Test of HQSS-relations

- CS-model ($^1S_0^{(1)}$) describes LHCb data. CO-contrs. lead to significant overshoot. $\Rightarrow$ **HQSS-relations fail.**
- Feeddown from h_c is negligible.
- $^3S_1^{(8)}$ *state drives the overshoot.*

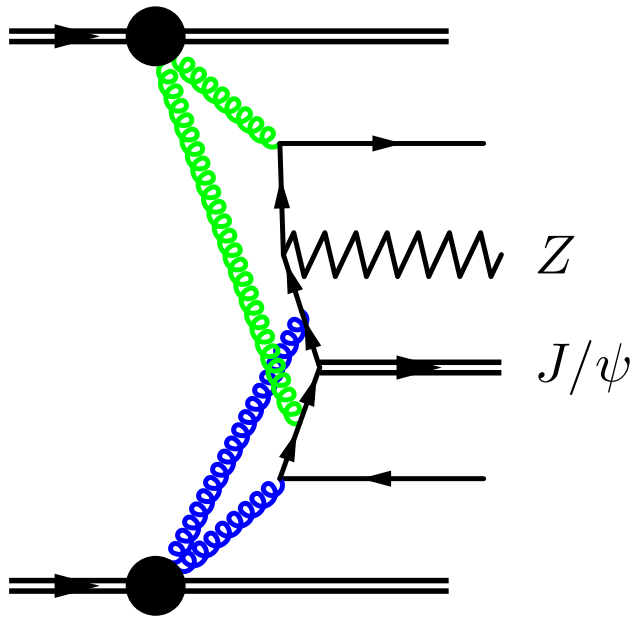
Conservative solution to all quarkonium puzzles: LDMEs are non-universal **and** the HQSS is broken.

- **However, if HQSS is violated then we can not trust the polarisation calculation!**
- Then the non-universality assumption becomes un-necessary

My speculation: Maybe HQSS is not applicable to the production?

- m_Q is not the largest scale, $p_T \gg m_Q$, so gluons with $m_Q \sim E_g \ll p_T$ are "soft" (logarithmically enchanced)
- **However, how gluons with $E_g \sim m_Q$ manage not to break the bound state?** "Magic mechanism" is needed.

Coalescence-DPS mechanism for $J/\psi + W/Z$???



New observables?

- Study $\Delta\phi$ (anti-)correlation in double J/ψ as function of Δy to probe coalescence-DPS mechanism.
- Quarkonium in jet + jet substructure???
- ...