Prompt J/ψ and ϒ(nS) production in jets using proton-proton collisions at the LHC

Lizardo Valencia Palomo

UNIVERSIDAD DE SONORA
TODO LO ILUMINAN
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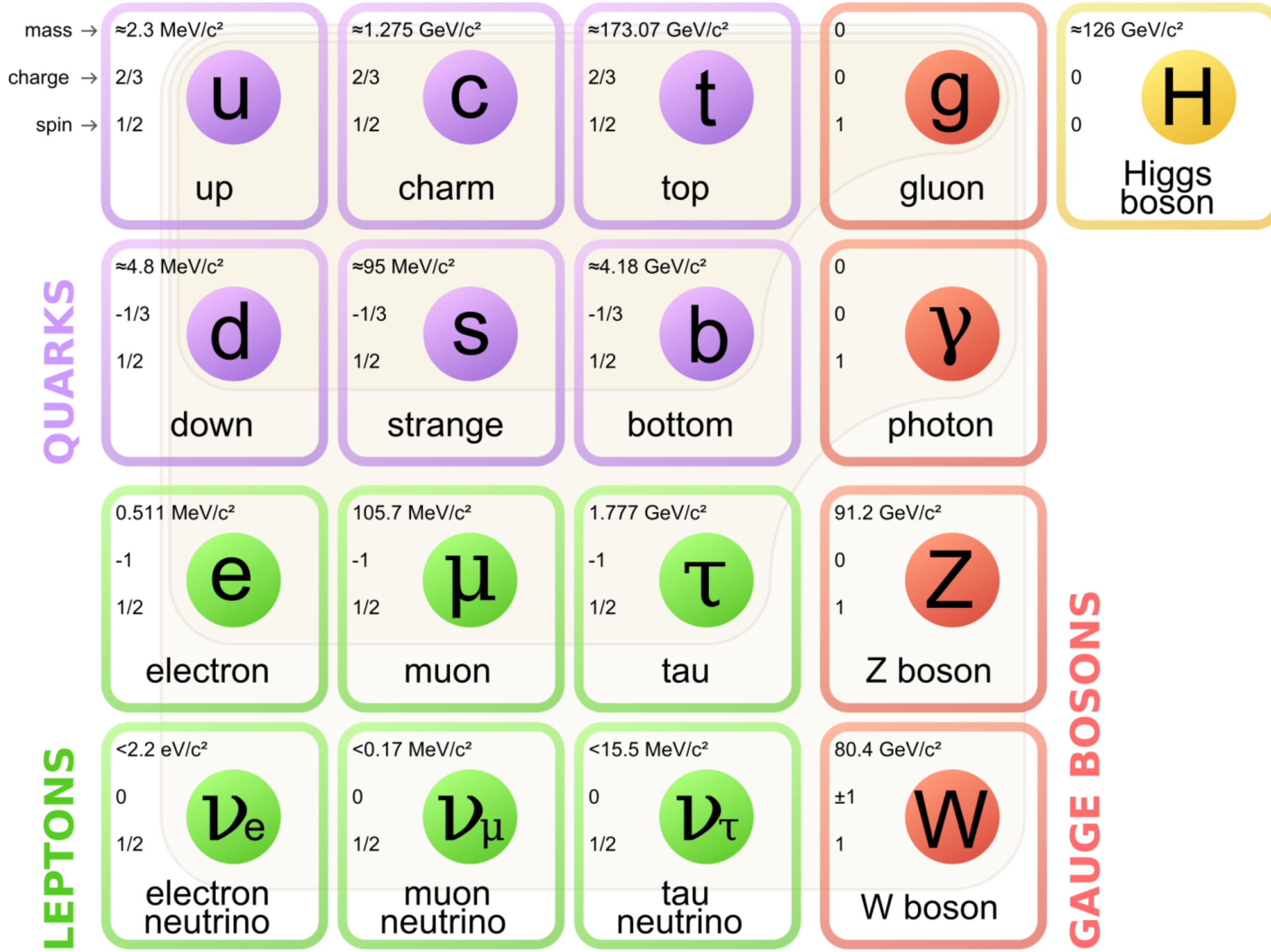
The Standard Model



Quarkonia production

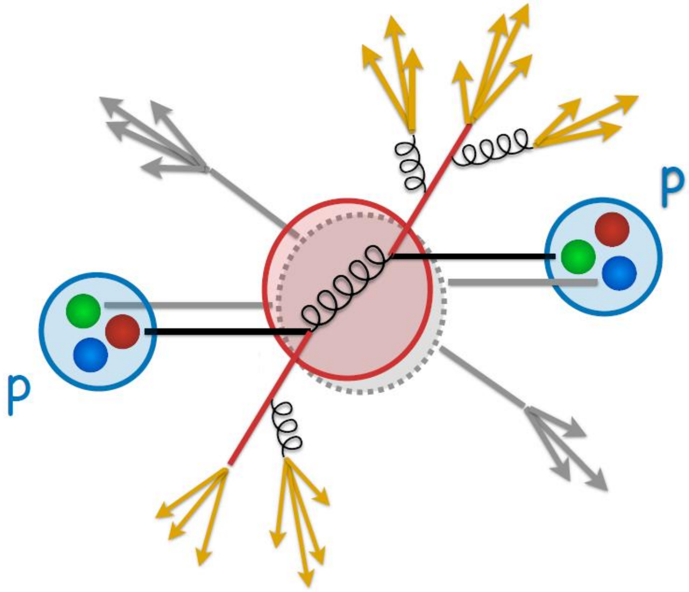
Quarkonia are bound states of a heavy quark and anti-quark: J/ψ and ϒ(nS).

$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = \mathrm{PDF}(x_a, Q^2)\ \mathrm{PDF}(x_b, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q\bar{q}}} \otimes D_{\mathrm{q}\to\mathrm{h}}(z_q, Q^2)$$

Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

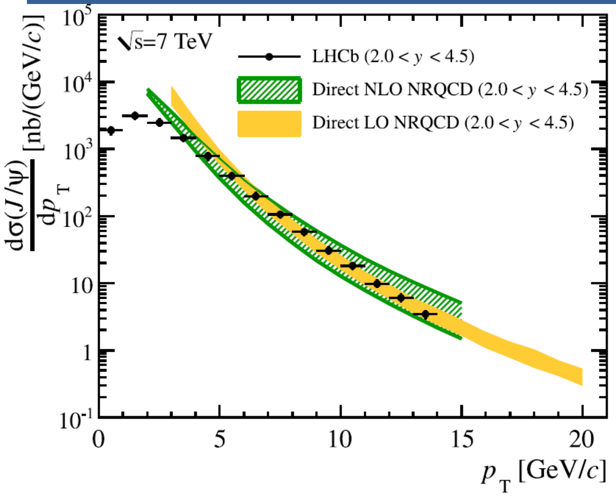
Fragmentation functions (non perturbative)

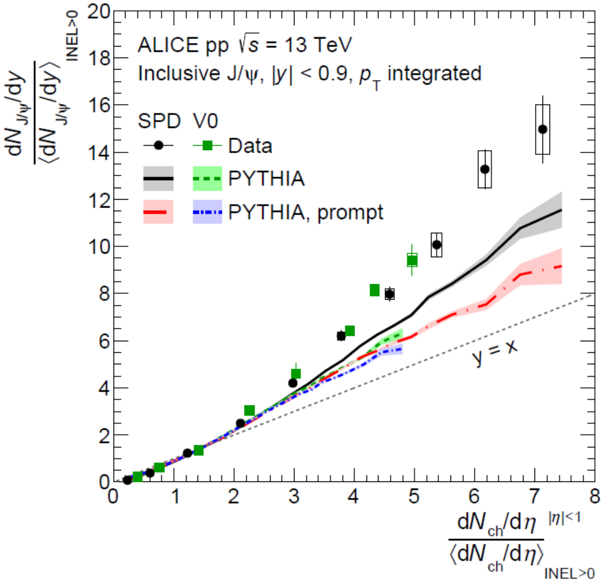


Charmonia states ($c\bar{c}$):

- Prompt: directly produced in the interaction point.
- Non-prompt: originated from the decay of beauty hadrons. Experimentally characterized by a displaced vertex.

Production models





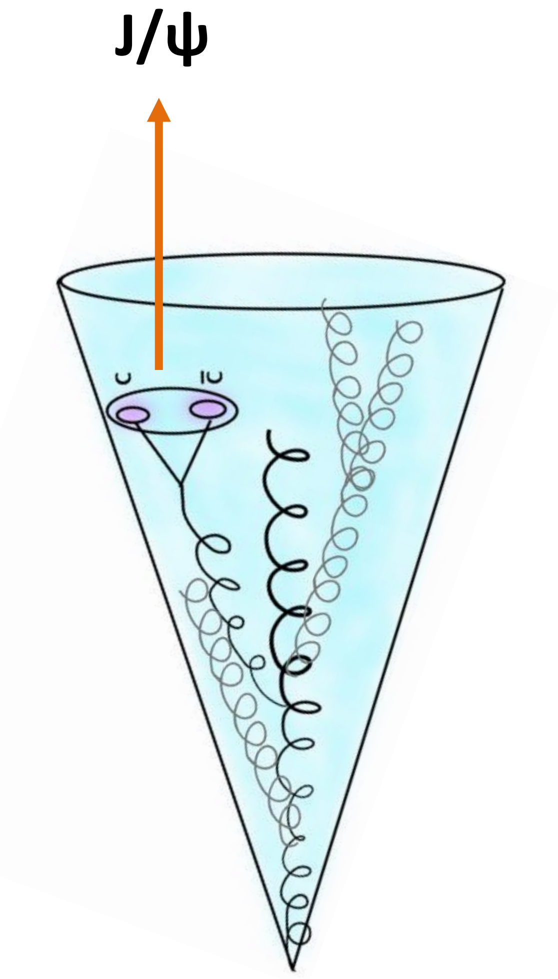
Color Singlet Model: the main assumption is that the $Q\bar{Q}$ pair emerging from the partonic scattering is directly produced as a color singlet state.

Color Evaporation Model: no assumption on the color of the pre-resonance state. If the $Q\bar{Q}$ pair is produced in a color octet state, it neutralizes the color by emisión of a gluon (“color evaporation”).

NRQCD: heavy quaks treated non-relativistically. Hadronization described by Long Distance Matrix Elements.

Quarkonia have extensively been studied at the LHC: non of the existing models can correctly describe the wealth of available data.

J/ψ production in jets



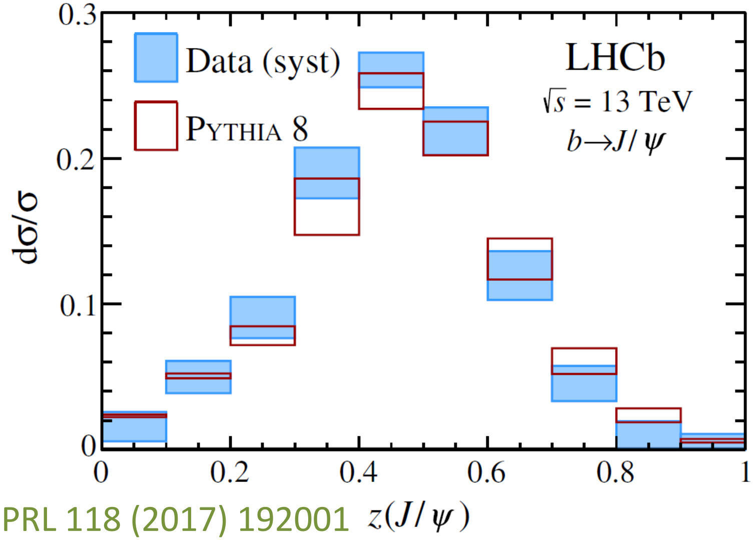
Not only production cross sections reported: as a function of the multiplicity, polarization, mean transverse momentum, etc.

New measurement: fragmentation of jets containing prompt and non-prompt J/ψ.

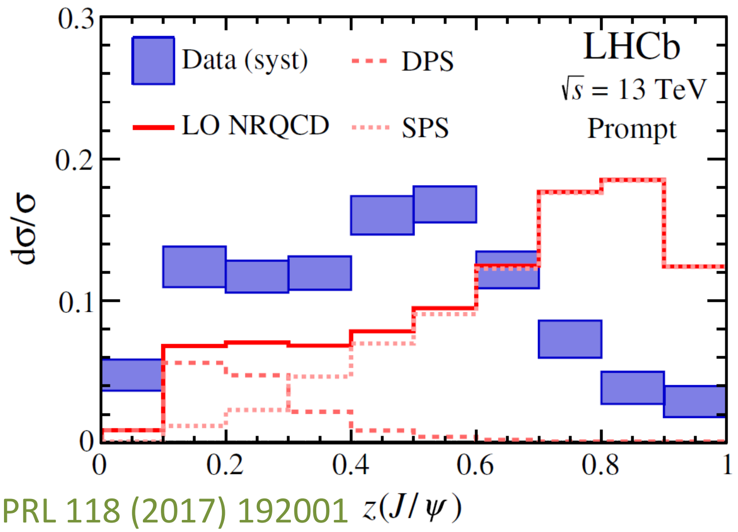
$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

Results reported by LHCb and CMS at $\sqrt{s}$ = 13 and 5.02 TeV, respectively. LHCb can measure down to *z* = 0 (no restriction on the J/ψ p_T) while CMS applies a sharp p_T cut on the charmonia state (p_T > 6.5 GeV) so 0.22 < *z* < 1.

Experimental results



PRL 118 (2017) 192001



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LHCb: results at forward rapidity ($2.5 < \eta(\text{jet}) < 4$) with $p_T(\text{jet}) > 20$ GeV.

Pythia 8 can correctly describe the non-prompt component, but it clearly fails to describe the prompt one, in particular for $z \approx 1$.

CMS: measurements performed at mid rapidity ($|\eta(\text{jet})| < 2$) with $30 < p_T(\text{jet}) < 40$ GeV.

For both experiments Pythia overestimates the data when $z \approx 1$, indicating that the LO NRQCD results from the event generator predicts that prompt J/ψ are produced with a small degree of surrounding jet activity.

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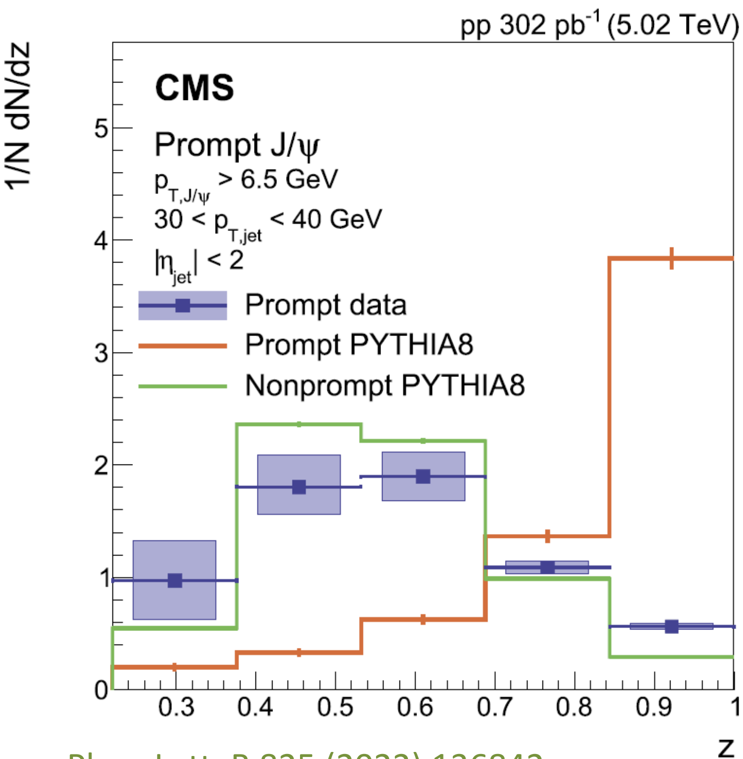

Phys. Lett. B 825 (2022) 136842

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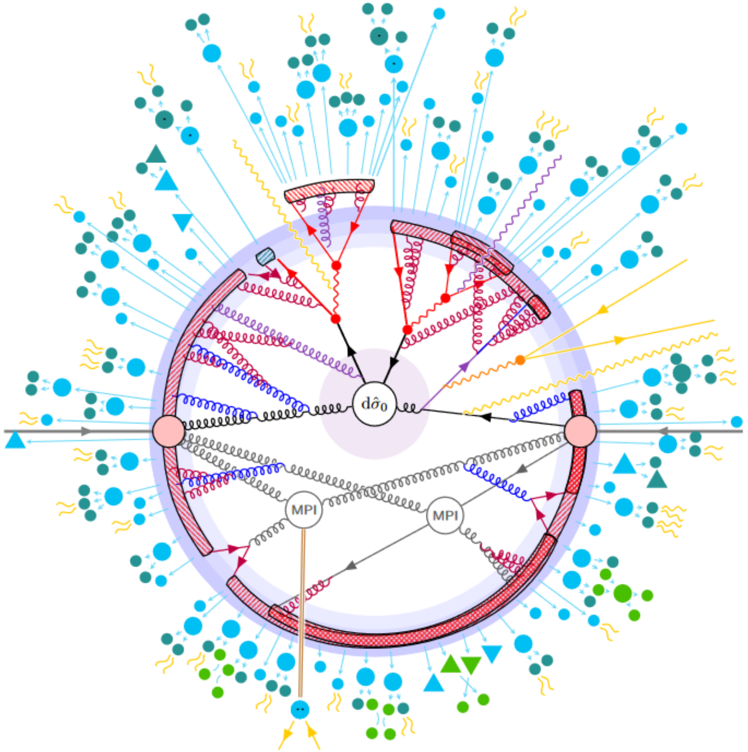
Useful concepts



Parton shower: ISR, FSR, BR and MPI.

MPI: additional scatterings, besides the hard one, from partons in the protons. Crucial to explain UE.

Pythia represents confinement as strings or clusters. Fragmentation follows the Lund string model.

No CR: partons tagged by color with a very large number of colors ➔ different MPI are independent.

CR: Partons from unrelated MPI are color connected. Needed for correct description of particle production at the LHC.

CR-BLC (CR-QCD): string length minimization combined with SU(3) color algebra. Junction structures, far richer topologycal compositions.

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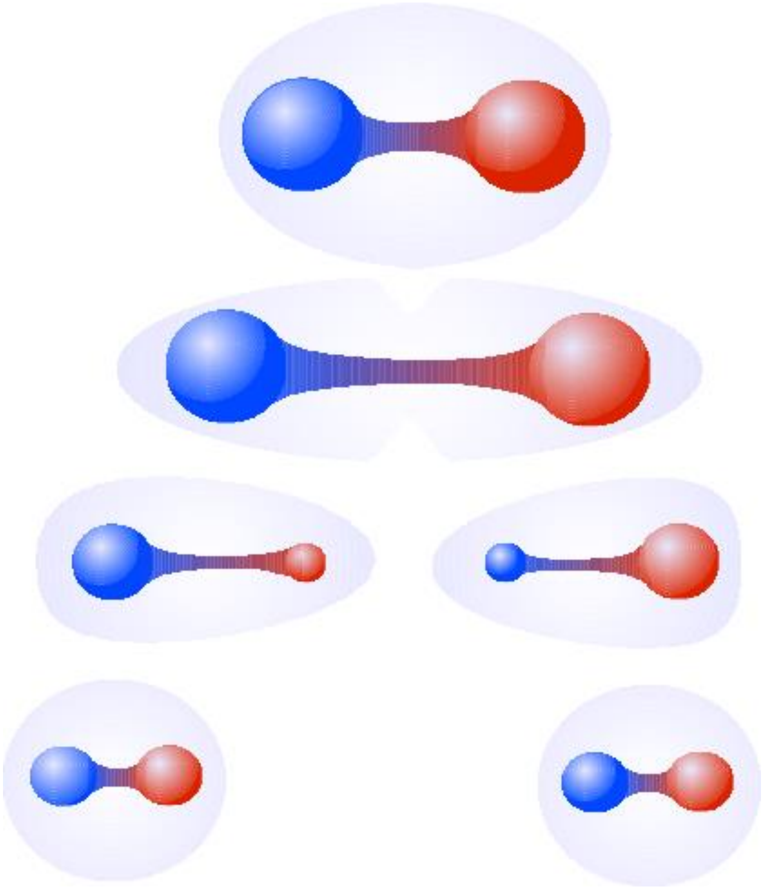

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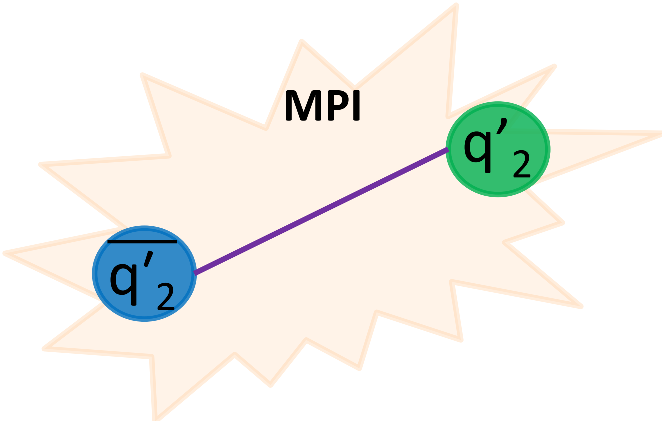

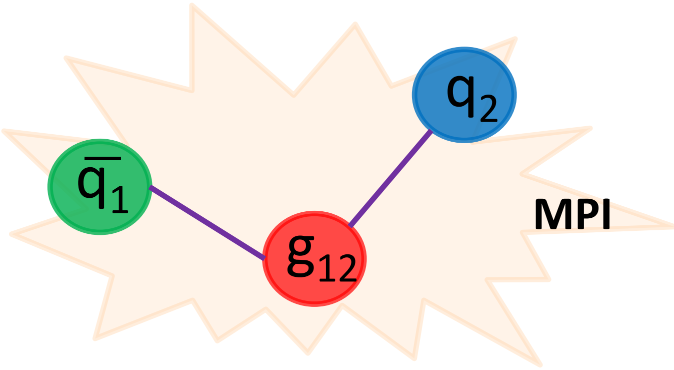

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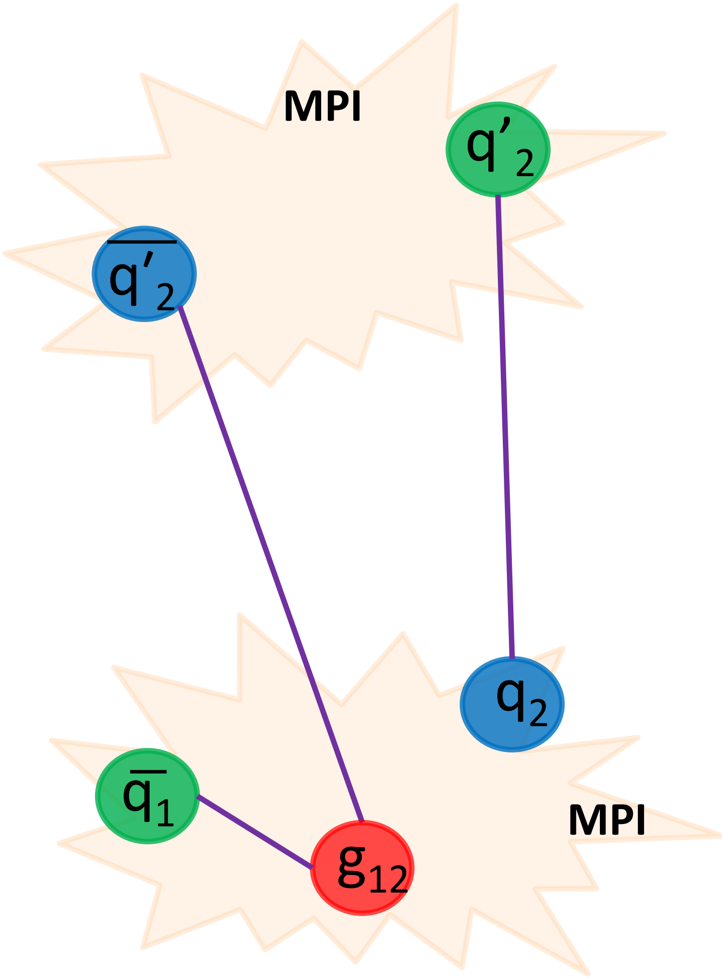

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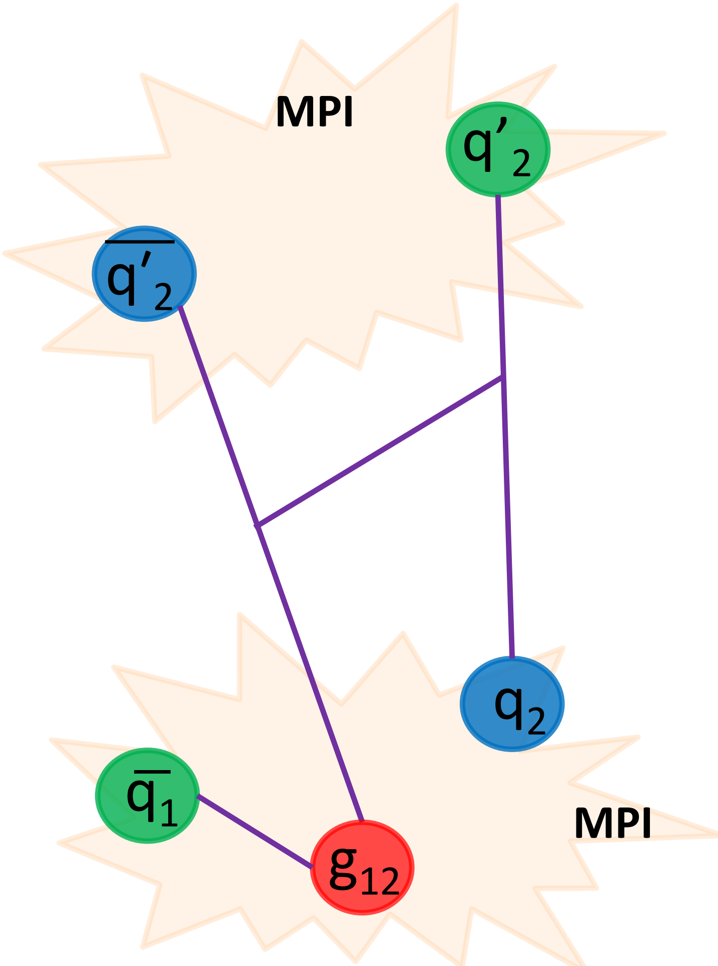

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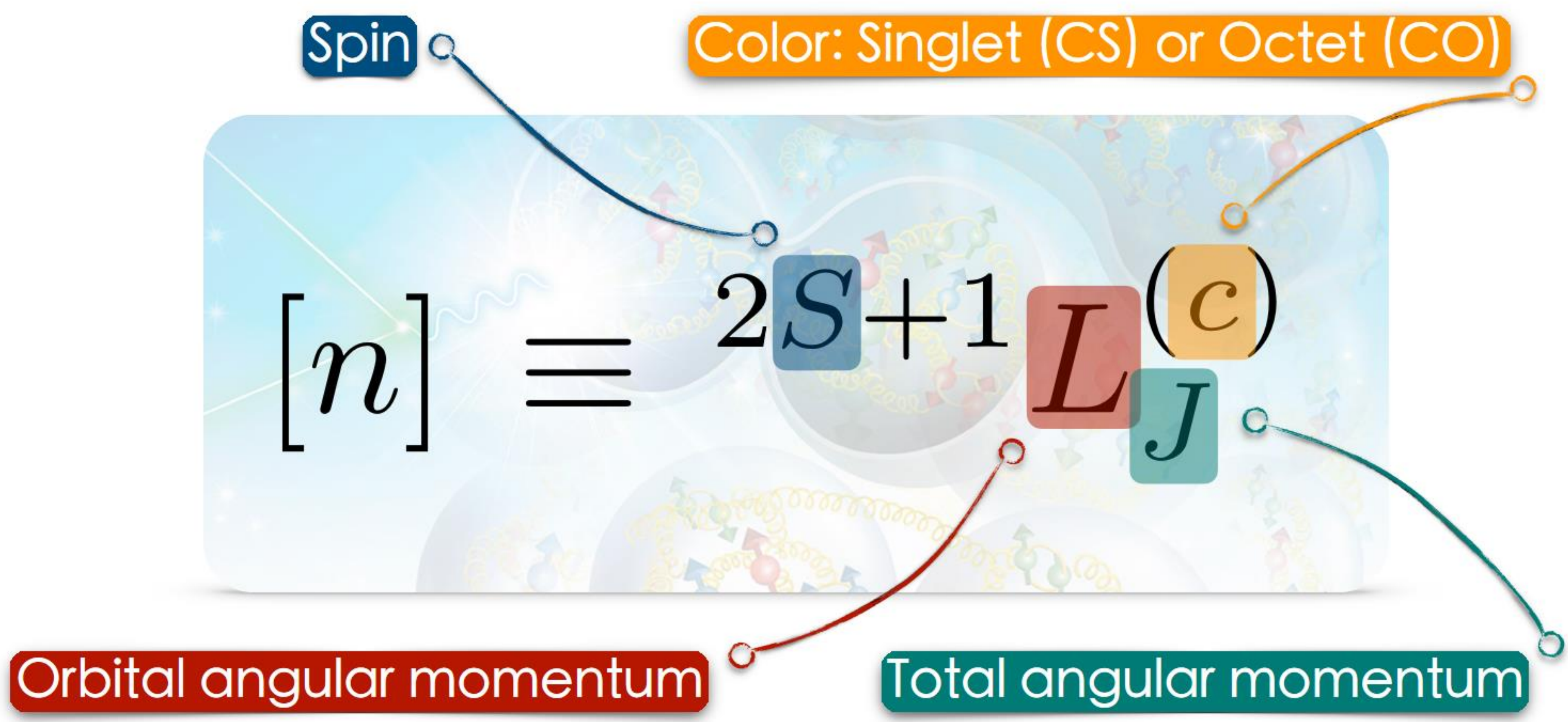
Spectroscopic notation

Spectroscopic notation for quarkonia



$$[n] \equiv {}^{2S+1}L_J^{(c)}$$

$$J = L + S$$

Backup

New quarkonia shower

Inability of Pythia 8 to describe experimental results is an indication that quarkonia can be produced through different mechanisms to those mentioned before.

New quarkonia production implements quarkonia splittings during the parton shower. For J/ψ and ϒ(nS) the available splitting kernels are

$$Q \to Q\bar{Q}[^3S_1^{(1)}]Q,\ g \to Q\bar{Q}[^3S_1^{(1)}]gg \quad \text{and} \quad g \to Q\bar{Q}[^3S_1^{(8)}]$$

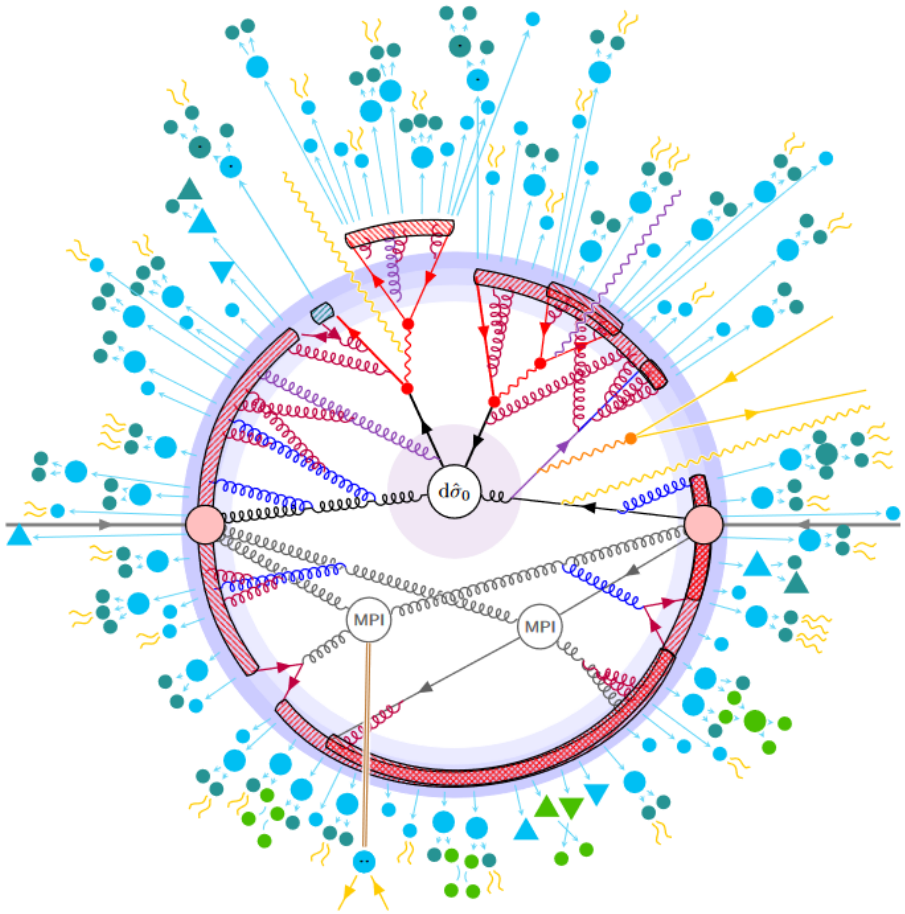
The missing splittings are gluon and heavy quark splittings to colour-octet states:

$$g \to Q\bar{Q}[^1S_0^{(8)}]g,\ \ g \to Q\bar{Q}[^3P_J^{(8)}]g,\ \ Q \to Q\bar{Q}[^1S_0^{(8)}]Q \quad \text{and} \quad Q \to Q\bar{Q}[^3P_J^{(8)}]Q$$

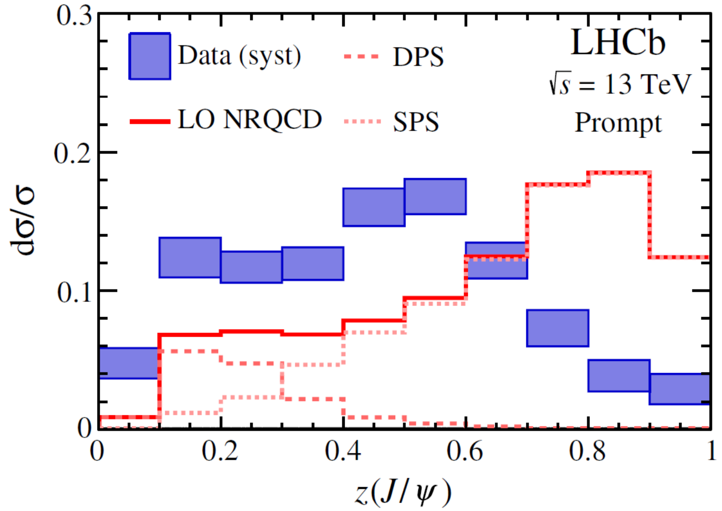
Gluon initiated splittings are omited as they enter at α_s^2 while $g \to Q\bar{Q}[^3S_1^{(8)}]$ enters at order α_s.

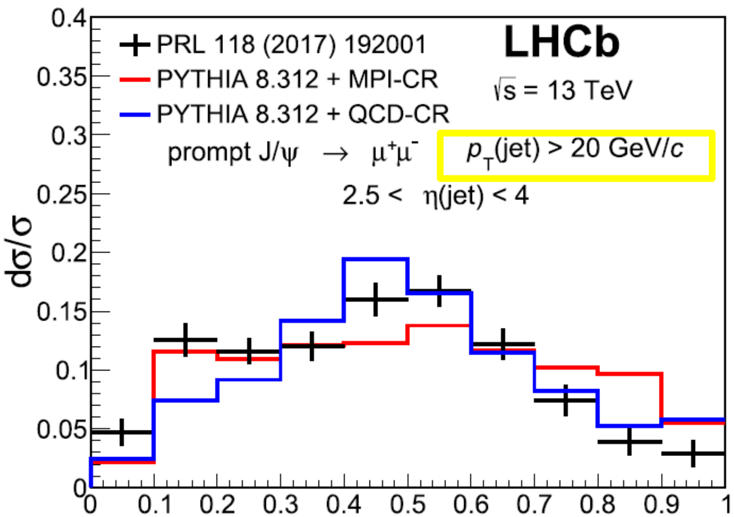
Heavy quark initiated splittings are suppressed relative to their corresponding color singlet splittings.

New quarkonia shower: summary



New quarkonia shower results





Eur. Phys. J. Plus 140 (2025) 544

Top: original results.

Bottom: black markers are the experimental data. Solid lines are Pythia results implementing the new quarkona shower.

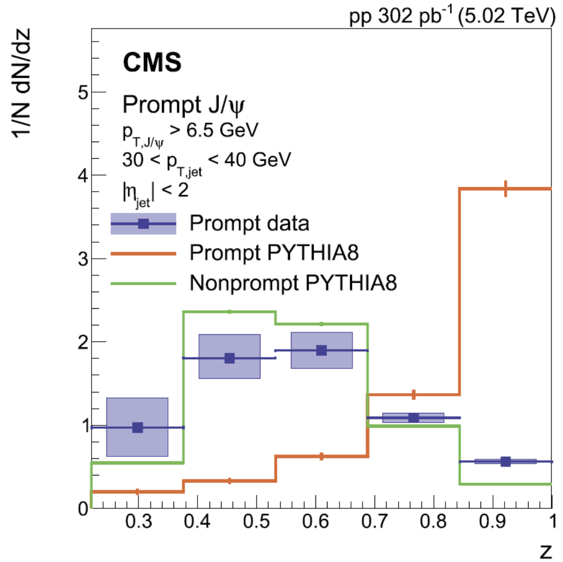
Red line employs the MPI color reconnection approach (same as in original result). Blue line implements the QCD-based scheme.

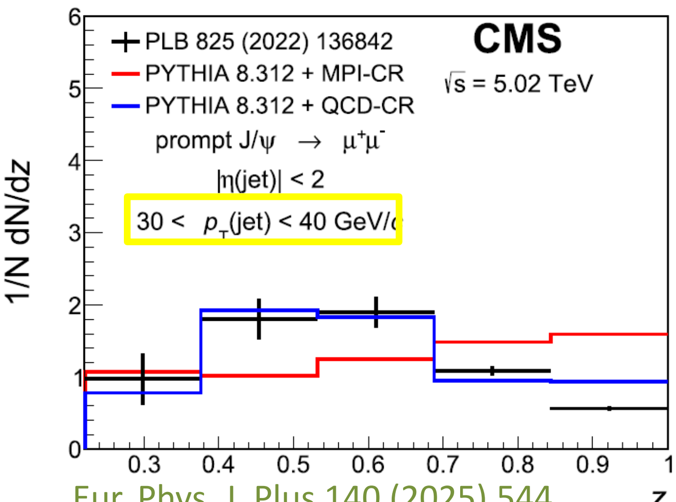
Noticeable effect for $0.7 < z < 1$: new quarkonia shower tends to flatten out the simulation.

There is now a very good agreement between data and the Monte Carlo.

For CMS experimental results cearly favours the QCD-CR model.

New quarkonia shower results





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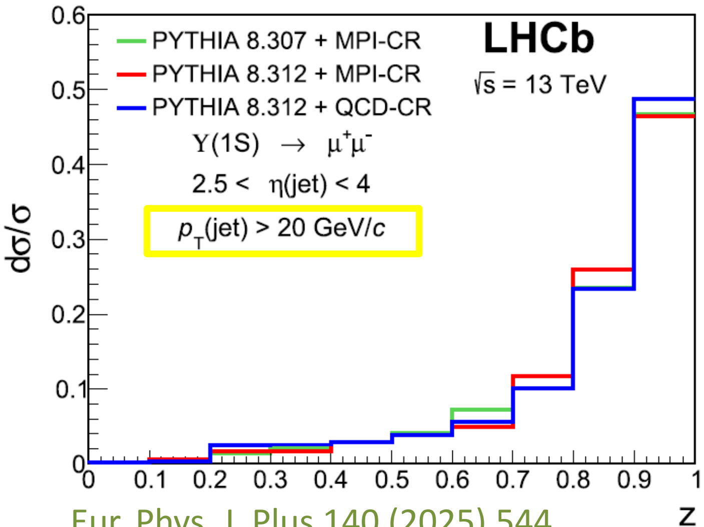
What about Upsilon (1S)?



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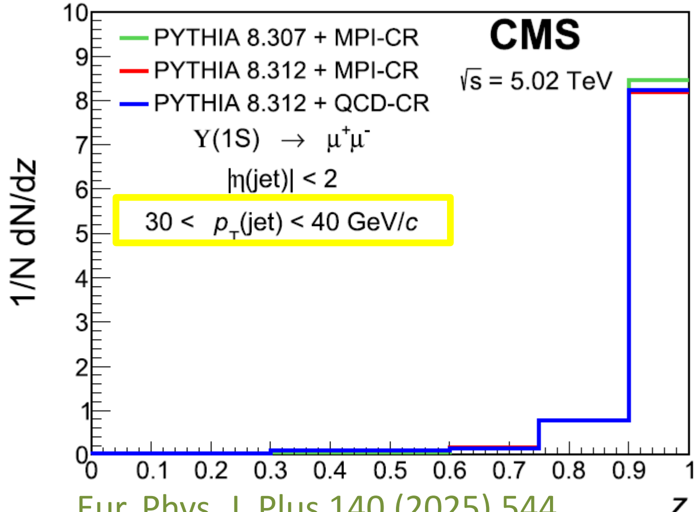

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Prediction for future measurements. First exercise performed in the same kinematic range as for J/ψ, but extended down to p_T = 0 for CMS. As a consequence there is no lower limit for *z*.

Pythia predicts most of the ϒ(1S) to be produced isolated: basically no difference when new quarkonia shower is included (all curves overlapped).

ϒ(1S): heavy resonance, requires partons with very high energy to create an ϒ(1S) in the shower.

By increasing the p_T threshold for the jet the curves start to disentangle: posible to discriminate the predictions with and without the new quarkonium shower.

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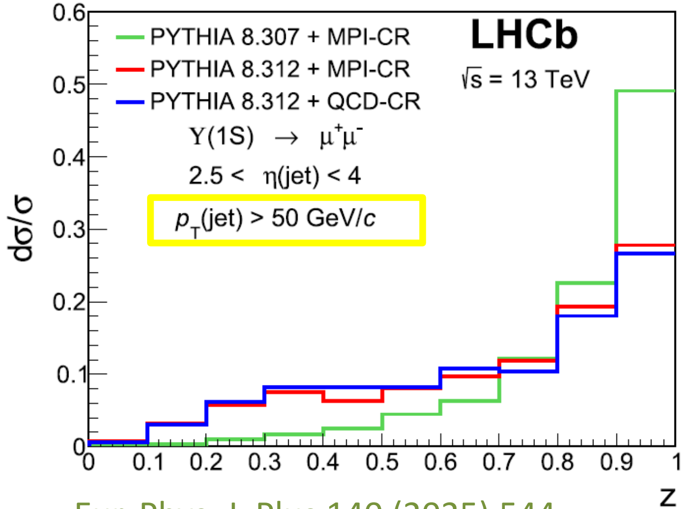

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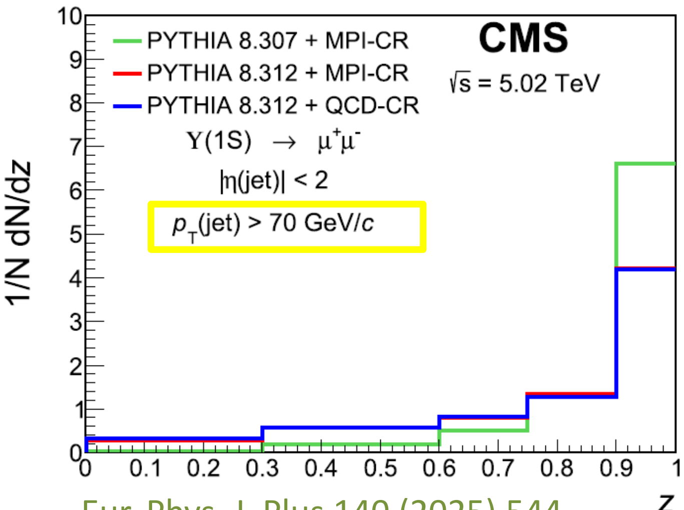

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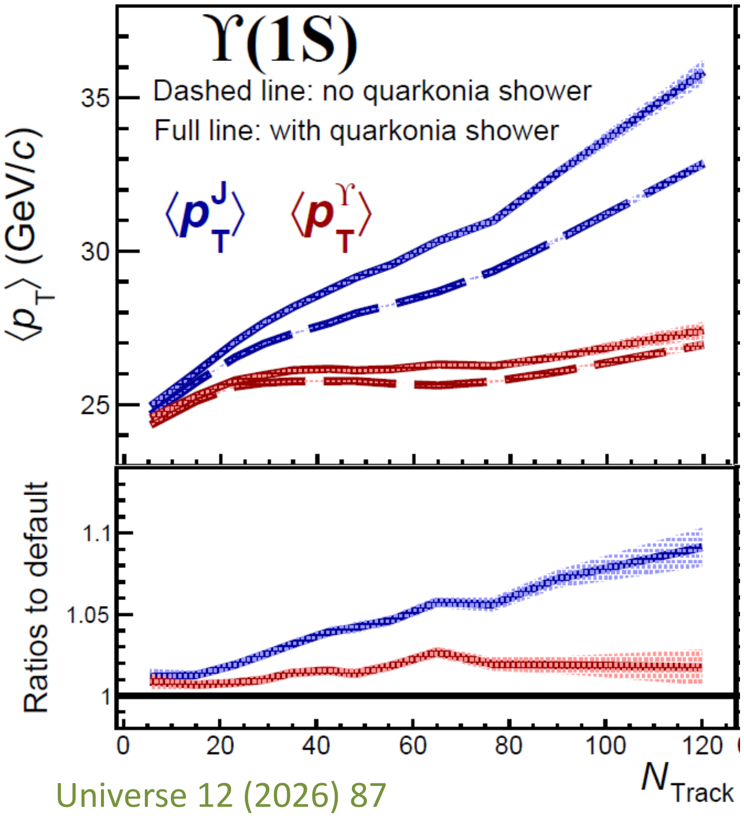
Upsilon(nS) in jets

CMS: jet p_T > 20 GeV



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Low multiplicities: highly probable for jets to be solely composed by a Υ(nS) so $<p_T^{\Upsilon}> \approx <p_T^{J}>$.

High multiplicities: more particles to be clustered in the jet so $<p_T^{\Upsilon}>$ smaller than $<p_T^{J}>$.

Including the new quarkonia shower hardens both $<p_T>$, natural consequence of the new quarkonia splittings during the parton shower. Effect hidden when simply using *z*.

New quarkonia shower has a larger impact for high multiplicity events, but it is much more important for the jets than for the Υ(nS).

Another possibility to test the new quarkonia shower!

Summary

Quarkonia production in hadronic collisions is far from being understood.

In this sense fragmentation of jets containing J/ψ and ϒ(nS) can be used to test models.

The new quarkonia parton shower improves Pythia 8 descritpion of J/ψ in jets. Including the new QCD-based CR further improves the agreement between data and simulation.

For ϒ(nS), the new quarkonia parton shower can be tested in high p_{T} jets (p_{T} > 70 GeV) or in high multiplicity events with low p_{T} jets (p_{T} > 20 GeV).

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Thanks for your attention

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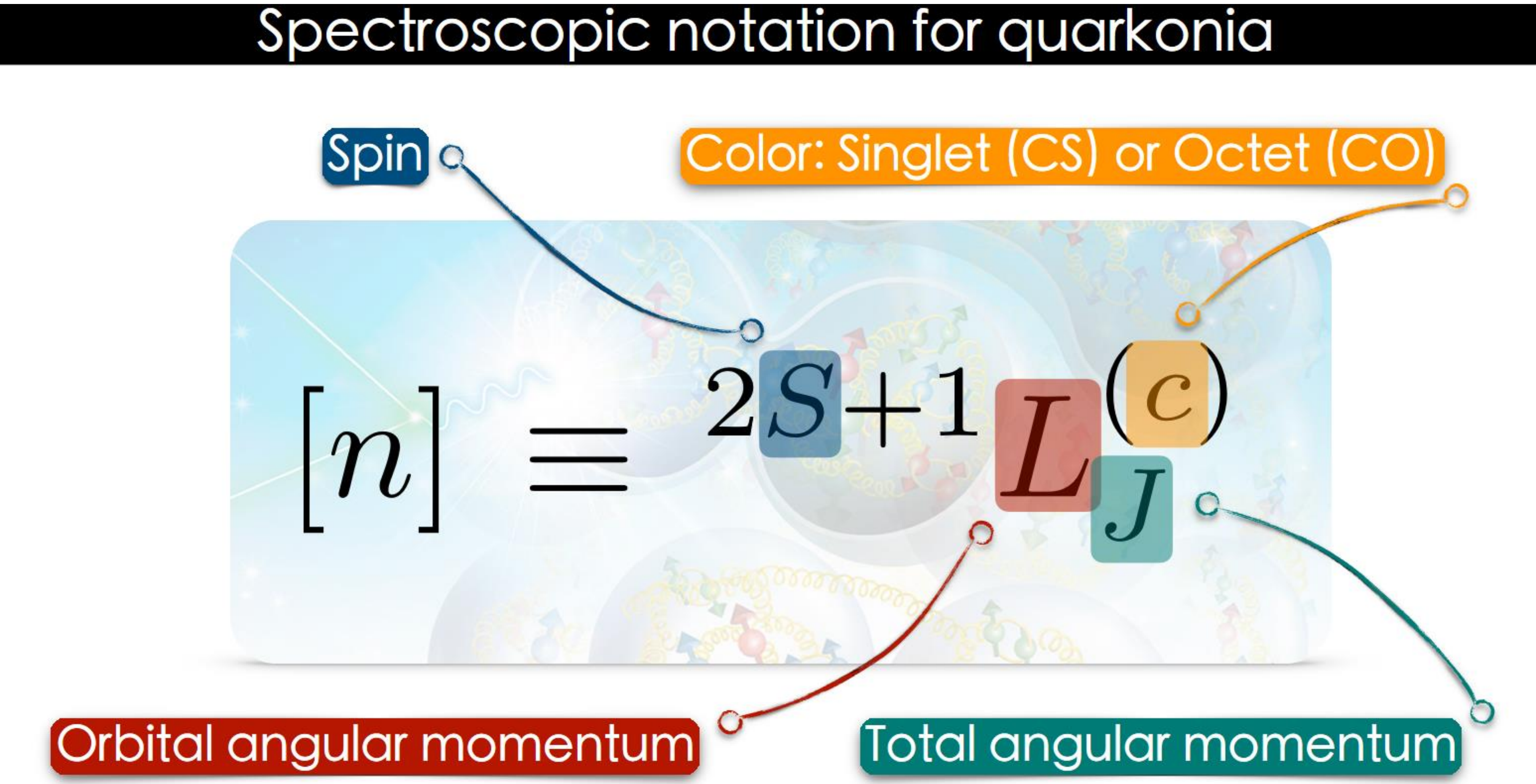

$J = L + S$

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