Quarkonium in PYTHIA8

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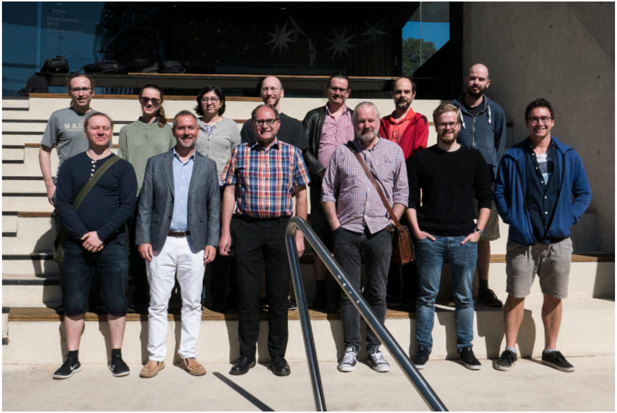
On behalf of the PYTHIA8 collaboration



Outline

What is PYTHIA8?

- Hard subprocesses
- Parton showers
- Multiple interactions
- Hadronisation
- Decays
- ...

[arXiv:2203.11601, A comprehensive guide to the physics and usage of PYTHIA8]

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And there is Quarkonia everywhere

[arXiv:2203.11601, A comprehensive guide to the physics and usage of PYTHIA8]

Hard subprocesses

Hard processes involving charmonium and bottomonium are provided using NRQCD, including both colour-singlet and -octet contributions.

$$\mathrm{d}\sigma(\mathrm{pp} \to H + X) = \sum_{s,L,J} \mathrm{d}\hat{\sigma}(\mathrm{pp} \to \mathrm{Q\bar{Q}}[^{2s+1}L_J] + X)\langle \mathcal{O}^H[^{2s+1}L_J] \rangle$$

$$\begin{aligned}\left| H[^{2s+1}L_J] \right\rangle &= \mathcal{O}(1) \left| \mathrm{Q\bar{Q}}[^{2s+1}L_J^{(1)}] \right\rangle + \mathcal{O}(v) \left| \mathrm{Q\bar{Q}}[^{2s+1}(L \pm 1)_{J'}^{(8)}]\mathrm{g} \right\rangle \\ &\quad + \mathcal{O}(v^2) \left| \mathrm{Q\bar{Q}}[^{2s+1}(L \pm 1)_{J'}^{(8)}]\mathrm{gg} \right\rangle + \ldots\end{aligned}$$

$$\begin{aligned} H \in\ & \{\mathrm{J}/\psi, \psi(2S), \chi_{c0}, \chi_{c1}, \chi_{c2}, \psi(3770), \\ & \Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \chi_{b0}, \chi_{b1}, \chi_{b2}\}\end{aligned}$$

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A standardised interface to HELACONIA is also included.

Looks like standard partonic 2 $\rightarrow$ 2 sub-processes:

- $\mathrm{g} + \mathrm{g} \rightarrow H + \mathrm{g}$
- $\mathrm{g} + \mathrm{q} \rightarrow H + \mathrm{q}$
- $\mathrm{q} + \bar{\mathrm{q}} \rightarrow H + \mathrm{g}$

Also, only for ${}^3S_1$ colour singlet states

- $\mathrm{g} + \mathrm{g} \rightarrow H + \gamma$
- $\mathrm{g} + \mathrm{g} \rightarrow H + H'$
- $\mathrm{q} + \bar{\mathrm{q}} \rightarrow H + H'$

Note that colour octet states will show up in the PYTHIA `Event` with (non-standard) id on the form $\mathtt{99n_qn_sn_rn_Ln_J}$ (e.g. `J/psi[3S1(8)] = 9941003`).

By default there is a mass split between the singlet and octet states (200 MeV), and every octet will decay into the corresponding singlet state plus a soft gluon before hadronisation.

Note also that an octet state will participate in the parton shower as a massive gluon.

Parton showers

For large transverse momentum there will arise large logarithms in the quarkonium cross sections: $\log(p_\perp/m_H)$

- Resum and evolve inclusive fragmentation functions
- *Unsum* and produce exclusive events with parton shower

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Soon to be included in PYTHIA8

[Naomi Cooke, Phil Ilten, LL, Steve Mrenna]

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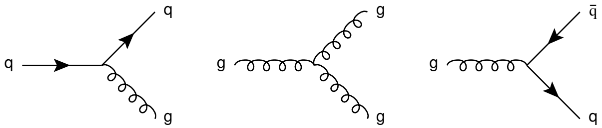
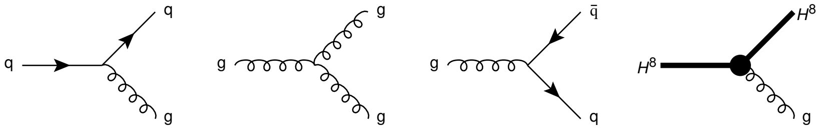
Standard QCD splittings



Standard QCD splittings and bremsstrahlung from octet onia states



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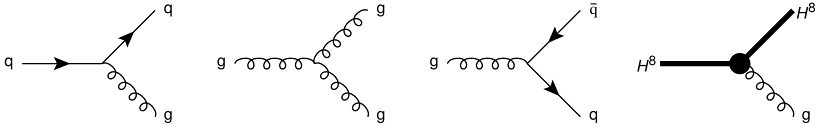
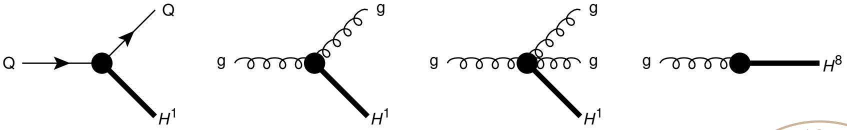


Add quarkonium production



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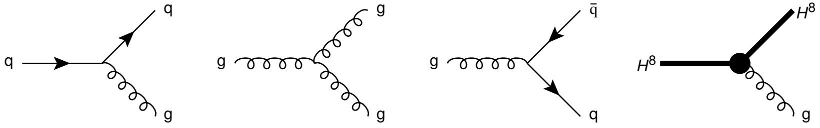

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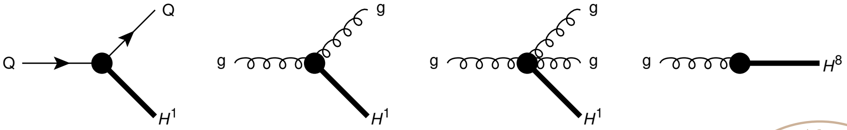


And let them Compete!

In the parton shower language, logarithms sum up to *No-emission probabilities* (c.f. Sudakov form factors)

By ordering the emissions in some scale, ρ, we get the probability of something happening *next*:

$$dP_{\mathrm{next}} = P(\rho,z)\times\exp\left(-\int_{\rho}^{\rho_0}P(\rho',z)d\rho' dz\right)d\rho dz$$
$$= P(\rho,z)\times\Delta(\rho_0,\rho)d\rho dz$$

The no-emission probabilities factorise:

$$dP_{\mathrm{next,a}} = P_a(\rho,z)\times\Delta_a(\rho_0,\rho)\Delta_b(\rho_0,\rho)\Delta_c(\rho_0,\rho)\cdots d\rho dz$$

- How do we choose scales for the quarkonium splittings to get a relevant competition?
- How do we avoid double counting octet and singlet splittings?
- How do we avoid double counting with hard subprocess (LO/NLO) MEs?

We need to think about ME/PS matching/merging.

Multiple quarkonium & multi-parton interactions

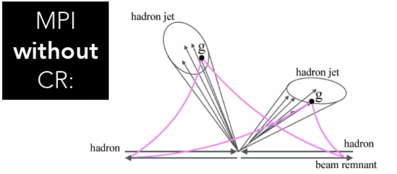
- Double onia sub-process
- Double parton scattering
- All quarkonium processes are available as multi-parton scattering processes (switched on by default)

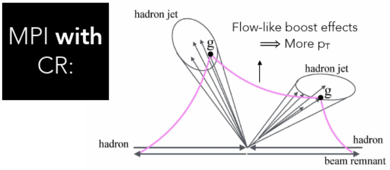
Note that the MPI QCD cross sections are regulated by

$$\hat{\sigma} \longrightarrow \hat{\sigma} \times \frac{\alpha_S(p_\perp^2 + p_{\perp 0}^2(s))}{\alpha_S(p_\perp^2)} \times \frac{p_\perp^4}{\left(p_\perp^2 + p_{\perp 0}^2(s)\right)^2}$$

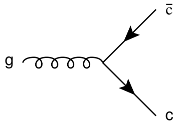
to take saturation into account.

Colour reconnections

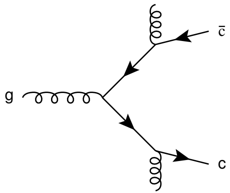




A c-quark from one scattering can be reconnected with an $\bar{c}$ from another. If the resulting string has too low mass, it will be collapsed to the closest available charmonium state.



Note that a $c\bar{c}$ pair from a shower splitting will never be reconnected.



Note that a $c\bar{c}$ pair from a shower splitting will never be reconnected.

Except if they radiate (and you are using the *QCD* colour reconnection model).

Lund String Model

No quarkonium states are formed in the string fragmentation.
(Except indirect production via B-decays).

$$P_{c/u} \sim e^{-\pi \frac{m_c^2 - m_u^2}{\kappa}} \sim 10^{-11} = \text{zero in PYTHIA8}$$

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For the rope model in heavy ion collisions we can have higher κ

Decays

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Hadronic rescattering

As of version 8.303, PYTHIA includes a full hadronic rescattering machinery (à la UrQMD)

Could in principle destroy or produce quarkonium states. Especially in heavy ion collisions.

Conclusions

PYTHIA8 loves quarkonium! And more love is on the way:

- Shower production of quarkonium
- Matching/Merging
- Rope hadronisation in HI
- Shoving in HI
- Colour reconnection in HI

Thanks!

Vetenskapsrådet

MCnet
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erc
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CLASH