Double heavy meson production through double parton scattering

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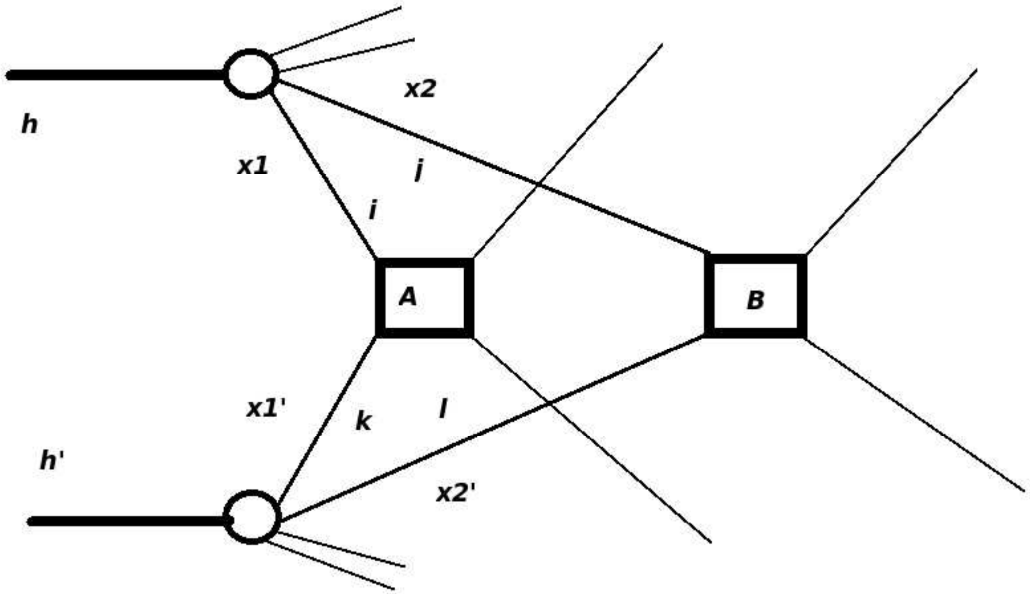
1. Double parton interaction

In the last years it has become obvious that multiple parton interactions play an important role in hadron-hadron collisions at high energies and are one of the most common, yet poorly understood phenomenon at the LHC.

The presence of such multiple parton interactions in high-energy hadronic collisions has been convincingly demonstrated by the AFS, UA2, CDF and D0 Collaborations, using events with the four-jets and $\gamma + 3$-jets final states.

The possibility of observing two separate hard collisions was pointed at long ago.

With the only assumption of factorization of the two hard parton subprocesses A and B



the inclusive cross section of a double parton scattering process in a hadron collision is written in the following form

$$\sigma^{AB}_{DPS} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2; \mathrm{b}_1, \mathrm{b}_2; Q_1^2, Q_2^2) \hat{\sigma}^A_{ik}(x_1, x_1^{'}, Q_1^2) \hat{\sigma}^B_{jl}(x_2, x_2^{'}, Q_2^2)$$

$$\times \Gamma_{kl}(x_1^{'}, x_2^{'}; \mathrm{b}_1 - \mathrm{b}, \mathrm{b}_2 - \mathrm{b}; Q_1^2, Q_2^2) \times dx_1 dx_2 dx_1^{'} dx_2^{'} d^2b_1 d^2b_2 d^2b,$$

where b is the impact parameter — the distance between the centers of colliding (the beam and the target) hadrons in the transverse plane.

$\Gamma_{ij}(x_1, x_2; \mathbf{b_1}, \mathbf{b_2}; Q_1^2, Q_2^2)$ **are the double parton distribution functions, which depend on the longitudinal momentum fractions** x_1 **and** x_2**, and on the transverse position** $\mathbf{b_1}$ **and** $\mathbf{b_2}$ **of the two partons entering the hard processes** A **and** B **at the scales** Q_1 **and** Q_2**.**

$\hat{\sigma}^A_{ik}$ **and** $\hat{\sigma}^B_{jl}$ **are the parton-level subprocess cross sections.**

The factor $m/2$ **appears due to the symmetry of the expression for interchanging parton species** i **and** j**:** $m = 1$ **if** $A = B$**, and** $m = 2$ **otherwise.**

Further assumptions:

- **Decoupling of the longitudinal and transversal variables:**

$$\Gamma_{ij}(x_1, x_2; \mathrm{b}_1, \mathrm{b}_2; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) f(\mathrm{b}_1) f(\mathrm{b}_2),$$

where $f(\mathbf{b_1})$ **is supposed to be a universal function for all kinds of partons with the fixed normalization,**

$$\int f(\mathrm{b}_1) f(\mathrm{b}_1 - \mathrm{b}) d^2 b_1 d^2 b = \int T(\mathrm{b}) d^2 b = 1,$$

and $T(\mathbf{b}) = \int f(\mathbf{b_1}) f(\mathbf{b_1} - \mathbf{b}) d^2 b_1$ **is the overlap function.**

- **Factorization of parton distributions:**

$$D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_h^i(x_1; Q_1^2) D_h^j(x_2; Q_2^2).$$

Then the cross section of the double parton scattering can be expressed in a simple form

$$\sigma_{\rm DPS}^{\rm AB} = \frac{m}{2} \frac{\sigma_{\rm SPS}^A \sigma_{\rm SPS}^B}{\sigma_{\rm eff}},$$

$$\sigma_{\rm eff} = [\int d^2b (T(\mathrm{b}))^2]^{-1},$$

where

$$\sigma_{\rm SPS}^A = \sum_{i,k} \int D_h^i(x_1; Q_1^2) f(\mathrm{b}_1) \hat\sigma_{ik}^A(x_1, x_1^{'}) D_{h'}^k(x_1^{'}; Q_1^2) f(\mathrm{b}_1 - \mathrm{b}) dx_1 dx_1^{'} d^2b_1 d^2b$$

is the inclusive cross section of single hard scattering.

These simplifying assumptions, though rather customary in the literature and quite convenient from a computational point of view, are not sufficiently justified and are under the revision now. We restrict ourselves to this simple form for d.p.s. regarding it as the first estimation of the contribution from the double parton scattering to the inclusive double heavy meson production.

The presence of the correlation term in the two-parton distributions results in the decrease of the effective cross section $\sigma_{\rm eff}$ with the growth of the resolution scales Q_1 and Q_2, while the dependence of $\sigma_{\rm eff}$ on the total energy at fixed scales is rather weak.

A.M. Snigirev, Phys. Rev. D81 (2010) 065014;

C. Flensburg, G. Gustaffson, L. Lönnblad, JHEP 1106 (2011) 066.

Thus, in fact, we obtain the minimal estimate of the contribution under consideration.

2. Double heavy meson production

Recently the LHCb Collaboration has reported a first measurement of the process of double J/ψ production (LHCb-CONF-2011-009):

$$\sigma^{J/\psi J/\psi} = 5.6 \pm 1.1 \pm 1.2 \text{ nb}$$

with both J/ψ's in the rapidity region $2 < y^{J/\psi} < 4.5$ and with the transverse momentum $p_T^{J/\psi} < 10$ GeV/c in pp-collsions at $\sqrt{s} = 7$ Tev. The single inclusive J/ψ production cross section within the same kinematical cuts (LHCb-CONF-2010-010) is:

$$\sigma_{\text{SPS}}^{J/\psi} = 7.65 \pm 0.19 \pm 1.10^{+0.87}_{1.27} \ \mu\text{b}.$$

Then we can obtain a simple estimation of the contribution from the double parton scattering at the same kinematical conditions:

$$\sigma_{\text{DPS}}^{J/\psi J/\psi} = \frac{1}{2}\frac{\sigma_{\text{SPS}}^{J/\psi}\sigma_{\text{SPS}}^{J/\psi}}{\sigma_{\text{eff}}} \simeq 2.0 \text{ nb}, \textbf{with}\, \sigma_{\text{eff}} = 15 \text{ mb}.$$

This value is comparable with the cross section through the "standard" mechanism of the double J/ψ yield

$$\sigma_{\rm SPS}^{J/\psi J/\psi} = 4.15 \text{ nb}$$

A.V. Berezhnoy, A.K. Likhoded,
A.V. Luchnsky, A.A. Novoselov, arXiv:1101.5881 [hep-ph].

Then the theoretical prediction for the contribution from both scattering modes to the $J/\psi J/\psi$ cross section

$$\sigma_{\rm SPS}^{J/\psi J/\psi} + \sigma_{\rm DPS}^{J/\psi J/\psi} = 6.15 \text{ nb},$$

is close to the cross section of double J/ψ production, observed by the LHCb Collaboration.
First indication to the double parton scattering in the double J/ψ production (?)
Large theoretical uncertainties come from the scale in α_s, J/ψ wave function, gluon distributions. Altogether give a factor of 2 or 3.

Comparisons of the k_T-factorization with LHCb at $\sqrt{s} = 7$ Tev

S.P. Baranov, Phys. Rev. D84 (2011) 054012:

The only restriction is $2 < y^{J/\psi} < 4.5$
Acceptance is corrected for $p_t(\mu) > 650$ **MeV**

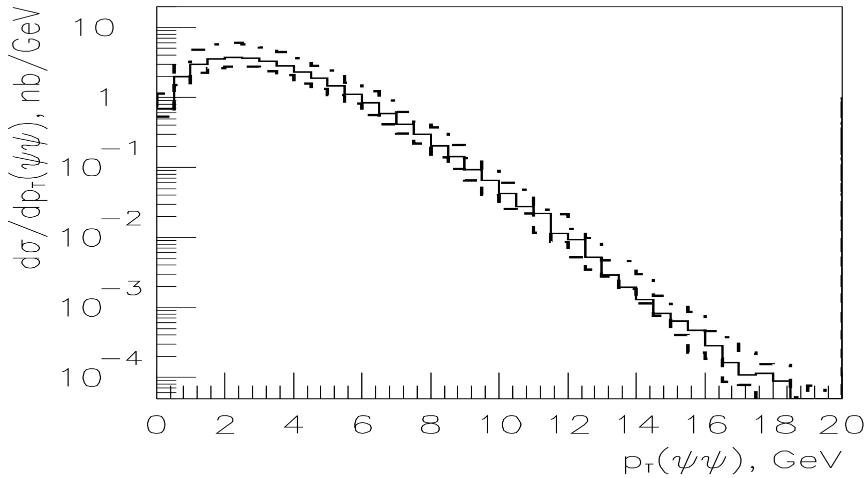
With $|R_{J/\psi}(0)|^2$**=0.8 GeV**^{3}, $|R'_\chi(0)|^2$**=0.075 GeV**^{5}, $\alpha_s(\hat{s}/4)$,
and CCFM A0 gluon densities we obtain

$$\left.\begin{array}{l}\sigma_{\rm SPS}^{\rm direct}(J/\psi) = 7.1\ \mu{\rm b}\\ \sigma_{\rm SPS}(\chi_1) = 1.5\ \mu{\rm b}\\ \sigma_{\rm SPS}(\chi_2) = 5.1\ \mu{\rm b}\end{array}\right\}\sigma_{\rm SPS}^{\rm prompt}(J/\psi) = 8.7\ \mu{\rm b}\ [\textbf{LHCb result} \simeq 10\ \mu{\rm b}]$$

$$\left.\begin{array}{l}\sigma_{\rm DPS}(J/\psi + J\psi) = 2\ {\rm nb}\\ \sigma_{\rm SPS}(J/\psi + J/\psi) = 4\ {\rm nb}\end{array}\right\}\quad [\textbf{LHCb result} = 5.6 \pm 1.1 \pm 1.2\ {\rm nb}]$$

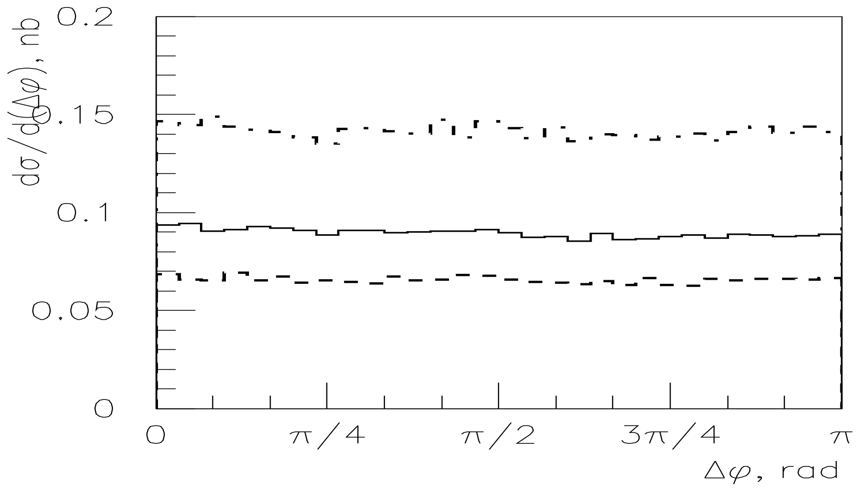
$\sigma_{\rm DPS}$ **is hardly identifiable over the theoretical uncertainty in** $\sigma_{\rm SPS}$.

J/ψ pair transverse momentum



$$F(x, k_t^2, \mu_F^2) = A+,\ \underline{A0},\ A-$$

Azimuthal correlations



$$F(x, k_t^2, \mu_F^2) = A+,\ \underline{A0},\ A-$$

Initial state radiation destroys correlations between the two J/ψ's. It was confirmed by an independent calculations:

C.H. Kom, A. Kulesza, W.J. Stirling, Phys. Rev. Lett. 107 (2011) 082002.

OTHER INTERESTING PROCESSES

- $\chi_c + \chi_c$

  The production of the P-states is suppressed relative to the production of S-wave states by two orders of magnitude because of the wave functions $|R_{J/\psi}(0)|^2 \gg |R'_{\chi_c}(0)|^2/m_\chi^2$ leading to the inequality $\sigma_{\rm SPS}^{J/\psi J/\psi} \gg \sigma_{\rm SPS}^{\chi_c\chi_c}$.
  Color-octet (CO) contributions do not change this inquality. Non relativistic QCD hierarchy in powers of v shows $\sigma_{octet}^{\chi_c\chi_c} \simeq \sigma_{singlet}^{\chi_c\chi_c}$.

  The inclusive production of single J/ψ and χ_c states shows nearly the same rates. The reason comes from the fact that the χ_c mesons are produced in a direct $2 \to 1$ gluon-gluon fusion $g + g \to \chi_c$, while the J/ψ mesons are produced in a $2 \to 2$ subprocess $g + g \to J/\psi + g$ with additional final state gluon. It means the invariant mass of the produced system is typically much higher in the J/ψ case than in the χ_c case.

The suppression factors coming from the lower wave function on the χ_c side, and from the higher final state mass and extra α_s coupling on the J/ψ side nearly compensate each other making the inclusive production cross sections comparable in size: $\sigma^{\chi_c}_{\rm SPS} \simeq \sigma^{J/\psi}_{\rm SPS}$.

As a consequence, we get $\sigma^{\chi_c\chi_c}_{\rm DPS} \simeq \sigma^{J/\psi J/\psi}_{\rm DPS}$ and $\sigma^{\chi_c\chi_c}_{\rm DPS} \gg \sigma^{\chi_c\chi_c}_{\rm SPS}$. Thus the production of a $\chi_c\chi_c$ pairs would yield a clear and unambiguous indication of the double parton scattering process.

The detecting the decay photon $\chi_c \to J/\psi + \gamma$ brings sertain difficulties in the experiment, but the task seems still feasible as the production cross section is not small.

$\sigma_{\rm DPS} \simeq$ **0.1 nb (for $J/\psi J/\psi$ final state).**

- $J/\psi + \chi_c$

In the SPS mode, this process is forbidden at the LO by the charge parity conservation but is possible at the NLO, $g + g \to J/\psi + \chi_c + g$. The corresponding cross section is then suppressed by one extra power of α_s and by the χ_c wave function.

Alternatively, it can proceed via the soft final-state gluon radiation (the CO model). The estimation of the cross section are then more model dependent and rather uncertain, but even with the largest acceptable values for the CO matrix elements one arrives at a suppression factor of about two orders of magnitude.
For the DPS mode we still expect no suppression, $\sigma_{\rm DPS}^{J/\psi\chi_c} \simeq \sigma_{\rm DPS}^{J/\psi J/\psi}$.

$\sigma_{\rm DPS} \simeq \mathbf{1\ nb}$ **(for $J/\psi J/\psi$ final state).**

Experimental disadvantage: low-energy photons.

- $J/\psi + \Upsilon$

  This process is not possible at the LO in the SPS mode and only can occur either at the NNLO $\mathcal{O}(\alpha_s^6)$, or via the CO transitions, or by means of the production and decay of P-wave mesons ($g + g \to \chi_c + \chi_b$ followed by $\chi_c \to J/\psi + \gamma$ and $\chi_b \to \Upsilon + \gamma$).

  So, the SPS mode is always suppressed: either by the extra powers of α_s, or by the CO matrix elements, or by the P-state wave function, and the DPS mode becomes the absolutely dominant one: $\sigma_{\rm DPS}^{J/\psi\,\Upsilon} \gg \sigma_{\rm SPS}^{J/\psi\,\Upsilon}$. CO predictions: $\sigma_{\rm SPS}^{J/\psi\,\Upsilon} \simeq$ 7 pb

  P. Ko, Jungil Lee, Chaehyun Yu, JHEP 01 (2011) 070.

  $\sigma_{\rm DPS} \simeq$ **70 pb**

- $\Upsilon + \Upsilon$

  $\sigma_{\rm SPS}^{\Upsilon\Upsilon} = 8.7$ **pb**, $\sigma_{\rm DPS}^{\Upsilon\Upsilon} = 0.4$ **pb**,

  A. Novoselov, arXiv:1106.2184 [hep-ph]

3. Conclusion

The processes of heavy quarkonia pair production $J/\psi J/\psi$, $\chi_c\chi_c$, $J/\psi\chi_c$, $J/\psi\Upsilon$ can serve as probes of the double parton scattering at the LHC and can stimulate important steps towards understanding the multiparticle QCD dynamics.

- $J/\psi + J/\psi$
  advantage: easily obsrvable, disadvantage: background from SPS with similar kinematics.
- $J/\psi + \chi_c, \chi_c + \chi_c$
  advantage: very low backgraund, disadvantage: difficulties in detecting soft photons.
- $J/\psi + \Upsilon$
  advantage: very low backgraund, disadvantage: relatively low cross section.