Associated gauge bosons and D/B mesons production at the LHCb and double parton interactions

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in collaboration with

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Outline

1. **Motivation**
2. **Theoretical framework**
3. **Parameters**
4. **Numerical results**
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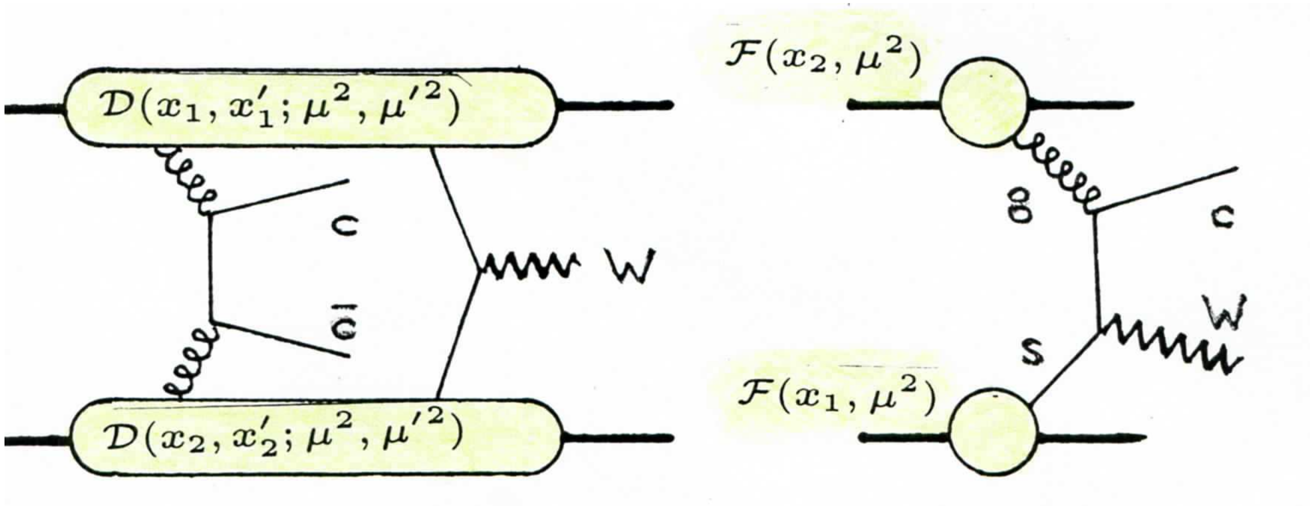
Motivation

Recently we have shown [Baranov et al., Phys. Lett. B746, 100 (2015)] that the same-sign $WD^{(*)}$ production in ATLAS kinematics region ($p_T(l) > 20$ GeV, $|\eta(l)| < 2.5$, $p_T(\nu) > 25$ GeV, $p_T(D^{(*)}) > 8$ GeV, $|\eta(D^{(*)})| < 2.2$) can be an indicative process, in which double parton scattering (DPS) contribution can dominate over single parton scattering (SPS).

Observable	SPS	DPS
$Br^{W\to l\nu}\sigma(W^+D^-)$	18.7	2.7
$Br^{W\to l\nu}\sigma(W^+D^+)$	1.0	2.7
$Br^{W\to l\nu}\sigma(W^-D^+)$	17.9	1.9
$Br^{W\to l\nu}\sigma(W^-D^-)$	1.4	1.9

One can expect, that in forward production in LHCb kinematics the DPS contribution will dominate even more clearly and even for the opposite sign $WD^{(*)}$ production.
Also it is interesting to expand the analysis to the associated WB and ZD production.

Double parton scattering



Two independent interactions $\hat{\sigma}^A$ and $\hat{\sigma}^B$ at a time:

$$\sigma^{\mathrm{AB}}_{\mathrm{DPS}} = \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_1'; \mathbf{b_1}, \mathbf{b_2}; Q^2, Q'^2)\hat{\sigma}^A_{ik}(x_1, x_2, Q^2) \times\Gamma_{kl}(x_2, x_2'; \mathbf{b_1}-\mathbf{b}, \mathbf{b_2}-\mathbf{b}; Q^2, Q'^2)\hat{\sigma}^B_{jl}(x_1', x_2', Q'^2) \times dx_1\, dx_2\, dx_1'\, dx_2'\, d^2b_1\, d^2b_2\, d^2b$$

where $\Gamma(x, x'; \mathbf{b_1}, \mathbf{b_2}; Q^2, Q'^2)$ are double parton distribution functions, b_i being the impact parameters and Q^2 the probing scales

Double parton scattering

Further assumptions:

Decoupling of longitudinal and transversal variables

$$\Gamma_{ij}(x,x';\mathbf{b_1},\mathbf{b_2};Q^2,{Q'}^2) = \mathcal{D}_{ij}(x,x';Q^2,{Q'}^2)f(\mathbf{b_1})f(\mathbf{b_2})$$

Factorization of parton distributions

$$\mathcal{D}_{ij}(x,x';Q^2,{Q'}^2) = \mathcal{F}_i(x,Q^2)\mathcal{F}_j(x',{Q'}^2)$$

results in $\sigma^{\mathrm{AB}}_{\mathrm{DPS}} = \frac{\sigma^A_{\mathrm{SPS}}\sigma^B_{\mathrm{SPS}}}{\sigma_{\mathrm{eff}}}$ **with** $\sigma_{\mathrm{eff}} = 15$ **mb.**

However, this formula is valid only for small longitudinal momenta fractions, where the evident restriction on the total parton momenta $x + x' < 1$ **can be neglected.**

Double parton scattering: correction factor

In a more accurate approach [Korotkikh, Snigirev, Phys. Lett. B594, 171 (2004); Gaunt, Stirling, JHEP 1003, 005 (2010); Chang et al., Phys. Rev. D87, 034009 (2013); Rinaldi et al., Phys. Rev. D87, 114021 (2013); Golec-Biernat, Lewandowska, Phys. Rev. D90, 014032 (2014); Ceccopieri, Phys. Lett. B734, 79 (2014); Snigirev et al., Phys. Rev. D90, 014015 (2014)]

$$\mathcal{D}_{ij}(x,x';Q^2,{Q'}^2)=\mathcal{F}_i(x,Q^2)\mathcal{F}_j(x',{Q'}^2)(1-x-x')^n$$

the kinematical constraints are smoothly put in with the correction factor $(1-x-x')^n$, where $n>0$ is a phenomenological parameter. One often chooses $n=2$. This choice of the phase space factor can be partly justified in the framework of perturbative QCD and results in double parton distribution functions which satisfy the momentum sum rules reasonably well. To feel the size of the possible effect we also tried $n=3$.

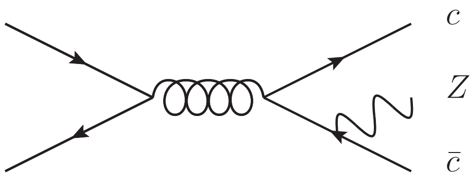
Double parton scattering: correction factor

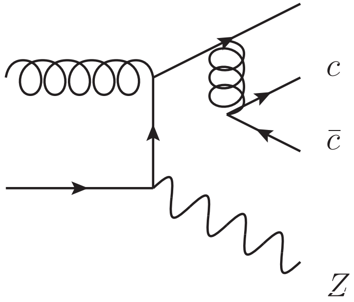
Including of the correction factor $(1-x-x')^n$ into the consideration can be motivated by measurements of the associated production of Z-bosons and D^0 or D^+ mesons at the LHCb [LHCb Collab., JHEP 1401, 091 (2014)]:

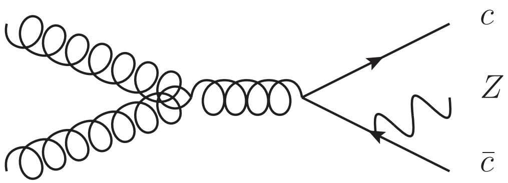
Channel	Data	SPS	DPS
Z^0D^0	2.50	0.64	3.28
Z^0D^+	0.44	0.28	1.29
sum	2.94	0.92	4.57

One can see, that while the SPS contribution underestimates the measured cross sections, the additional DPS contribution lies significantly higher, than the experimental data. This may show, that the usual factorized form of the DPS cross section is not valid in this kinematics and should be corrected.

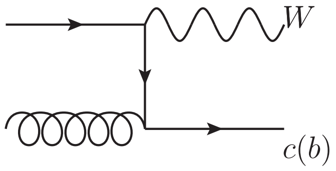
Considered subprocesses for SPS. Z production.

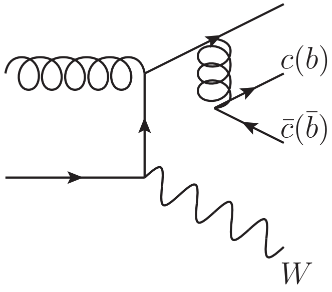


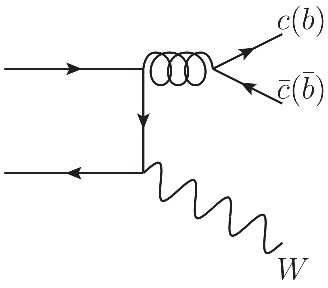


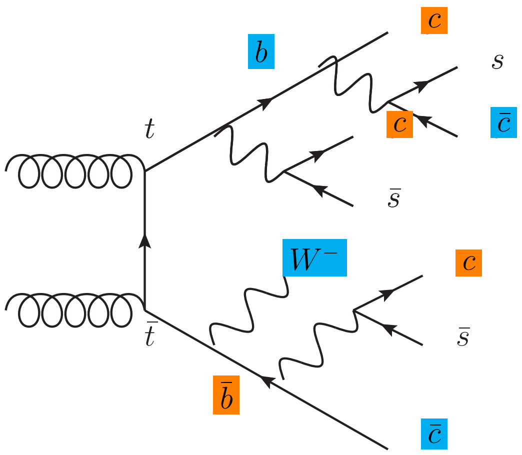


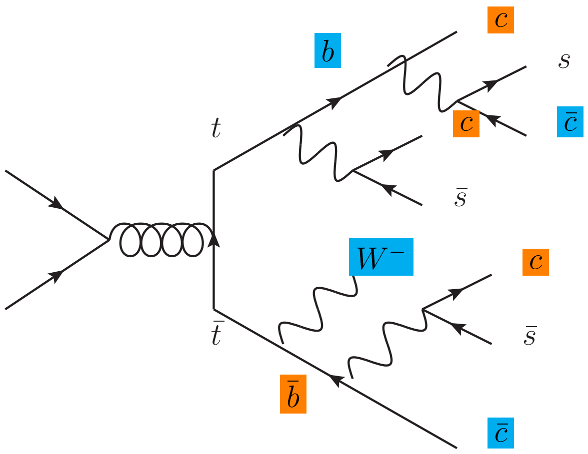
Considered subprocesses for SPS. W production.

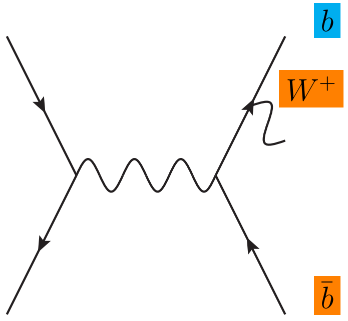












Parameters

We employ the k_T-factorization approach (see, for instance, [Small x Collab., Eur. Phys. J., C48, 53 (2006)]) with KMR k_T-dependent parton distributions [Kimber et al., Phys. Rev. D63, 189 (2009)] for relatively light states ($c\bar{c}$ or $b\bar{b}$) and conventional collinear factorization with MSTW2008 parton densities [Martin et al., Eur. Phys. J., C63, 189 (2009)] for states containing W or Z bosons.

We used running strong and electroweak coupling constants normalized to $\alpha_s(m_Z^2)$=0.118; $\alpha(m_Z^2)$=1/128; $\sin^2\Theta_W$=0.2312; the factorization and renormalization scales were chosen as $\mu_R^2=\mu_F^2=m_T^2(W/Z)\equiv m_{W/Z}^2+p_T^2(W/Z)$ for gauge boson production, and $\mu_R^2=\mu_F^2=m^2(c/b)$ for heavy quark pair production; the quark masses were set to m_c=1.5 GeV, m_b=4.5 GeV, m_t=175 GeV.

c- and b-quarks were converted into D^+ and B mesons using Peterson fragmentation function with ϵ_c=0.06 and ϵ_b=0.006, respectively, and normalized to $f(c\to D^+)=0.268$, $f(b\to B^-)$=0.40 and $f(b\to\bar{B}^0)$=0.40.

For the indirect contributions we also assumed 100% branching fraction for $t\to bW$ and used inclusive branching fractions $Br(\bar{B}^0\to D^+X)=37\%$, $Br(B^0\to D^+X)=3\%$, $Br(B^-\to D^+X)=10\%$, $Br(B^+\to D^+X)=2.5\%$.

Numerical Results

Charm-associated Z production

ZD production cross sections times the $Z \to l^+l^-$ branching (in pb) at $\sqrt{S} = 7$ TeV integrated over the fiducial region $p_T(l) > 20$ GeV, $2 < \eta(l) < 4.5$, $2 < p_T(D) < 12$ GeV, $2 < y(D) < 4$. n denotes the power in the correction factor $(1 - x - x')^n$.

channel	data	SPS	DPS(n=0)	DPS(n=2)	DPS(n=3)
Z^0D^0	2.50	0.6	2.4	1.15	0.95
Z^0D^+	0.44	0.25	0.95	0.5	0.4
sum	2.94	0.85	3.35	1.65	1.35

The data are taken from [LHCb Collab., JHEP 1401, 091 (2014)].

Charm-associated $W^\pm$ production

WD production cross sections times the $W \to l\nu$ branching (in pb) at $\sqrt{S} = 7$ TeV integrated over the fiducial region $p_T(l) > 20$ GeV, $2 < \eta(l) < 4.5$, $2 < p_T(D) < 12$ GeV, $2 < \eta(D) < 4$.

DPS contributions

subprocess	W^+D^+	W^+D^-	W^-D^-	W^-D^+
$gg \to c\bar{c},\ \ u\bar{d} \to W^+$	12.3	12.3	–	–
$gg \to c\bar{c},\ \ d\bar{u} \to W^-$	–	–	8.9	8.9

SPS contributions

subprocess	W^+D^+	W^+D^-	W^-D^-	W^-D^+
$g\bar{s}, g\bar{d} \to W\bar{c}$	–	1.7	–	–
$gs, gd \to Wc$	–	–	–	2.0
$u\bar{d} \to Wc\bar{c}$	0.8	0.8	–	–
$d\bar{u} \to Wc\bar{c}$	–	–	0.4	0.4
$gu \to Wdc\bar{c}$	1.9	1.9	–	–
$g\bar{d} \to W\bar{u}c\bar{c}$	0.16	0.16	–	–
$gd \to Wuc\bar{c}$	–	–	0.8	0.8
$g\bar{u} \to W\bar{d}c\bar{c}$	–	–	0.14	0.14
$gg \to t\bar{t} \to$ decays	0.01	0.01	0.01	0.01
$q\bar{q} \to t\bar{t} \to$ decays	0.015	0.02	0.015	0.02

All DPS contributions are presented here without phase space corrections; they have to be multiplied by a correction factor of 0.48 for n=2 or 0.38 for n=3.

Beauty-associated $W^{\pm}$ production

WB production cross sections times the $W \to l\nu$ branching (in pb) at $\sqrt{S} = 7$ TeV integrated over the fiducial region $p_T(l) > 20$ GeV, $2 < \eta(l) < 4.5$, $2 < p_T(B) < 12$ GeV, $2 < \eta(B) < 4.5$. Here B^+ and B^- denote the sum of B^+ and B^0 and the sum of B^- and $\bar{B}^0$ mesons, respectively.

DPS contributions

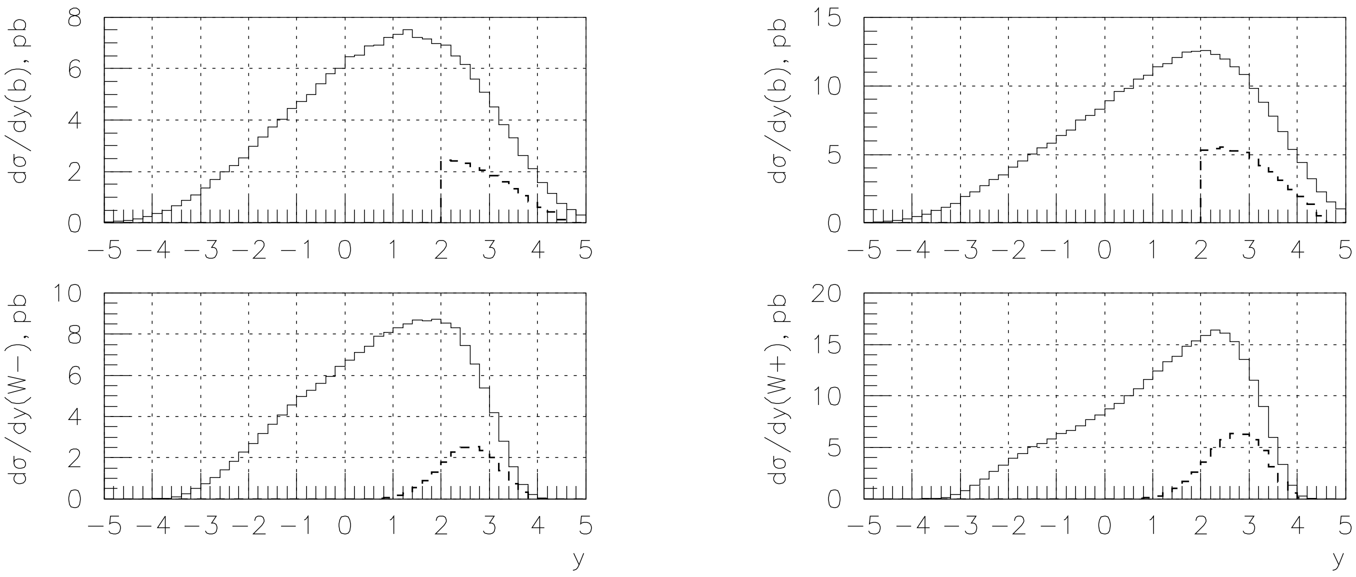
subprocess	W^+B^+	W^+B^-	W^-B^-	W^-B^+
$gg \to b\bar{b}, \;\; u\bar{d} \to W^+$	5.5	5.5	–	–
$gg \to b\bar{b}, \;\; d\bar{u} \to W^-$	–	–	4.0	4.0

SPS contributions

subprocess	W^+B^+	W^+B^-	W^-B^-	W^-B^+
$u\bar{d} \to W b\bar{b}$	1.2	1.2	–	–
$d\bar{u} \to W b\bar{b}$	–	–	0.5	0.5
$gu \to W d b\bar{b}$	2.7	2.7	–	–
$g\bar{d} \to W \bar{u} b\bar{b}$	0.22	0.22	–	–
$gd \to W u b\bar{b}$	–	–	1.1	1.1
$g\bar{u} \to W \bar{d} b\bar{b}$	–	–	0.2	0.2
$gg \to t\bar{t} \to WWb\bar{b}$	0.030	0.045	0.030	0.045
$q\bar{q} \to t\bar{t} \to WWb\bar{b}$	0.055	0.060	0.055	0.060
$u\bar{d} \to t\bar{b} \to Wb\bar{b}$	0.0018	0.0042	0.0018	0.0042
$d\bar{u} \to b\bar{t} \to W\bar{b}b$	0.0002	0.0005	0.0002	0.0005

Correction factors for DPS: 0.45 (n=2) and 0.36 (n=3).

Beauty-associated $W^{\pm}$ production

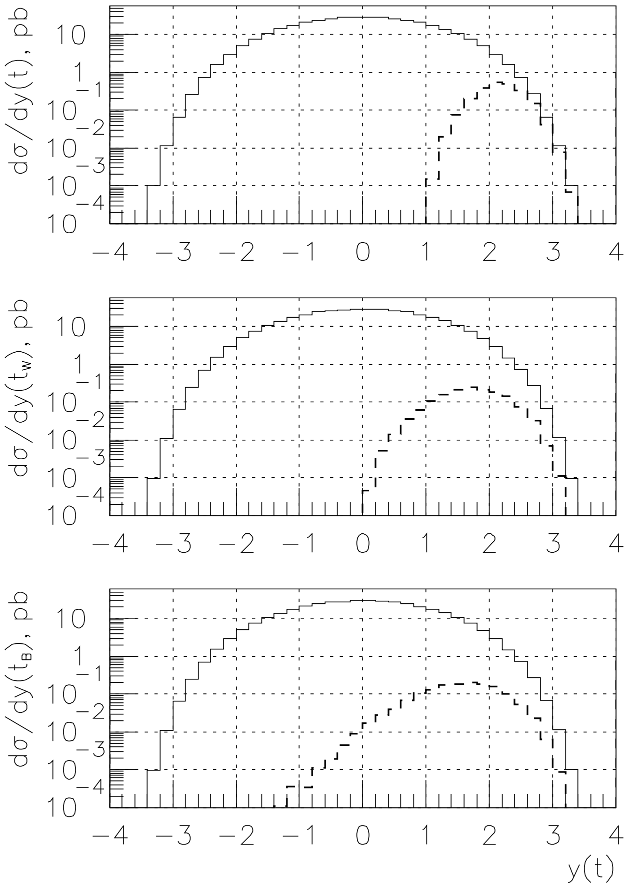


(a) (b)

Rapidity distributions of the b-quarks (upper panels) and W bosons (lower panels) produced in association in the process $d\bar{u}\to W^-b\bar{b}$. Left panel — W^-b production, right panel — W^+b production. Solid curves, original spectra; dashed curves, left after imposing the LHCb kinematic cuts.

Beauty-associated $W^{\pm}$ production

Rapidity distributions of the top-quarks or antiquarks. Opposite sign $W^{\pm}b^{\mp}$ events: top quarks converting into a $W^{\pm}b^{\mp}$ pair (upper panel). Same sign $W^{\pm}b^{\pm}$ events: top quarks producing W bosons (middle panel); top quarks producing beauty quarks (lower panel). Solid curves, original spectra; dashed curves, left after imposing the LHCb kinematic cuts.



Conclusions

1. The correction factor $(1 - x - x')^n$, allowing to take into account effects of the limited partonic phase space, gives significant suppression of the $W/Z + D/B$ DPS production cross section. Numerically, the corrections amount to a factor of 2 in the total rates and lead to better agreement with the available data on ZD production than it seemed before.

2. The production of same-sign $W^{\pm}D^{\pm}$ states in the forward region is dominated by the DPS mechanism. Hence this process can be recommended as a DPS indicator.

3. LHCb kinematics opens doors for a still new indicative process, which is the beauty-associated production of gauge bosons W. The charge of the accompanying b-quark is irrelevant. Here we benefit from the asymmetric rapidity selection cuts, which correspond to large positive light-cone momentum values of the incoming partons. The essential values can easier be reached with two independent partons in DPS than with a single parton in SPS, thus giving favor to DPS production.

BACK UP

k_T-factorization approach

In the k_T-factorization approach one can calculate a process cross section with the following formula:

$$d\sigma(A+B\to X)=\int dx_1\,dx_2\times$$

$$\times\sum_{i,j}\int d^2\mathbf{k}_{1T}\,d^2\mathbf{k}_{2T}\,f_{i/A}(x_1,\mathbf{k}_{1T}^2)f_{j/B}(x_2,\mathbf{k}_{2T}^2)d\hat{\sigma}(i^*+j^*\to X).$$

$f_{i/A}(x_1,\mathbf{k}_{1T}^2)$ **is the unintegrated (i.e. k_T-dependent) parton distribution. We adopt KMR unintegrated gluon distribution, which can be obtained from conventional collinear parton densities via a special procedure. As the collinear input we used MSTW2008 parton distributions set.**

Off-shell matrix elements are calculated according to the usual Feynman rules. The only exception comes in a different way of gluon polarization summation:

$$\sum\epsilon^{\mu}\epsilon^{*\nu}=\frac{k_T^{\mu}k_T^{\nu}}{|k_T|^2}$$