Electroweak boson production in double parton scattering

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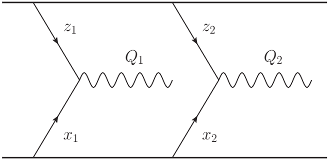
Introduction

- We study W^+W^- and Z^0Z^0 electroweak boson production in double parton scattering (DPS) .
- We use the QCD evolution equations for double parton distribution functions (DPDFs) in our studies.
- In particular, we are interested in the impact of splitting terms in the evolution equations on the DPS cross sections.

Outline

- Double parton scattering and DPDF
- QCD evolution equations for DPDF and their solution
- Relative transverse momentum dependence of DPDF
- Electroweak boson production in DPS
- The role of the single splitting contribution
- Summary

Double parton scattering



- DPS cross section in collinear approximation

$$\sigma_{AB} = \frac{N}{2} \sum_{f_1 f_2 f_1' f_2'} \int dx_1 dx_2\, dz_1 dz_2\, \frac{d^2\mathbf{q}}{(2\pi)^2}\, D_{f_1 f_2}(x_1, x_2, Q_1, Q_2, \mathbf{q}) \\ \times \hat{\sigma}^A_{f_1 f_1'}(Q_1)\, \hat{\sigma}^B_{f_2 f_2'}(Q_2)\, D_{f_1' f_2'}(z_1, z_2, Q_1, Q_2, -\mathbf{q})$$

- Double parton distribution functions (DPDF) in a hadron

$$D_{f_1 f_2}(x_1, x_2, Q_1, Q_2, \mathbf{q})\,, \qquad 0 < x_1 + x_2 \leq 1$$

- $\mathbf{q}$ is a relative transverse momentum of two partons.

QCD evolution equations

- For equal hard scales and zero relative transverse momentum

$$D_{f_1 f_2}(x_1, x_2, t) \equiv D_{f_1 f_2}(x_1, x_2, Q, Q, \mathbf{q} = 0)$$

- Evolution equations in LLA

$$\begin{aligned}
\partial_t D_{f_1 f_2}(x_1, x_2, t) &= \sum_{f'} \int_{x_1}^{1-x_2} \frac{du}{u} P_{f_1 f'}\left(\frac{x_1}{u}\right) D_{f' f_2}(u, x_2, t) \\
&+ \sum_{f'} \int_{x_2}^{1-x_1} \frac{du}{u} P_{f_2 f'}\left(\frac{x_2}{u}\right) D_{f_1 f'}(x_1, u, t) \\
&+ \frac{1}{x_1 + x_2} \sum_{f'} P_{f' \to f_1 f_2}\left(\frac{x_1}{x_1 + x_2}\right) D_{f'}(x_1 + x_2, t)
\end{aligned}$$

$+$ DGLAP evolution equations for single PDFs $D_f(x, t)$.

- Evolution parameter

$$t \equiv t(Q) = \int_{Q_0^2}^{Q^2} \frac{\alpha_s(\mu^2)}{2\pi} \frac{d\mu^2}{\mu^2}$$

Evolution equations for Mellin moments

- For Mellin moments (in flavour matrix notation)

$$\tilde{D}(n_1, n_2, t) = \int_0^1 dx_1 \int_0^1 dx_2\, x_1^{n_1}\, x_2^{n_1}\, \Theta(1 - x_1 - x_2)\, D(x_1, x_2, t)$$

$$\tilde{D}(n, t) = \int_0^1 dx\, x^n\, D(x, t)$$

and matrices of anomalous dimensions

$$\gamma_n = \int_0^1 dx\, x^n P(x)\,, \qquad \tilde{\gamma}_{n_1 n_2} = \int_0^1 dx\, x^{n_1} (1-x)^{n_2} P(x)$$

- Non-homogeneous first order linear differential equations

$$\partial_t \tilde{D}(n_1, n_2, t) = \underbrace{\gamma_{n_1}\, \tilde{D}(n_1, n_2, t) + \tilde{D}(n_1, n_2, t)\, \gamma_{n_2}^T}_{homogeneous} + \underbrace{\tilde{\gamma}_{n_1 n_2}\, \tilde{D}(n_1 + n_2, t)}_{non-hom.}$$

Solution to evolution equations

- Solution = General solution to homogenous equation
  + Particular solution to non-homomogeneous equation.

$$\tilde{D}(n_1, n_2, t) = \mathrm{e}^{\gamma_{n_1} t}\, \tilde{D}_0(n_1, n_2)\, \mathrm{e}^{\gamma_{n_2}^T t}$$

$$+ \int_0^t dt'\, \mathrm{e}^{\gamma_{n_1}(t-t')}\, \tilde{\gamma}_{n_1 n_2}\, \tilde{D}(n_1 + n_2, t')\, \mathrm{e}^{\gamma_{n_2}^T (t-t')} \qquad (1)$$

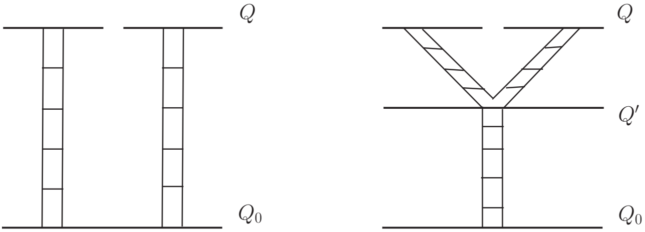
+ solution for single PDF

$$\tilde{D}(n, t) = \mathrm{e}^{\gamma(n)\, t}\, \tilde{D}_0(n)$$

- Need to impose initial conditions $\tilde{D}_0(n_1, n_2)$ and $\tilde{D}_0(n)$ at $t = 0$.
  (Gaunt, Stirling 2009)

Graphical illustration

- Solution (1) is the sum of two terms

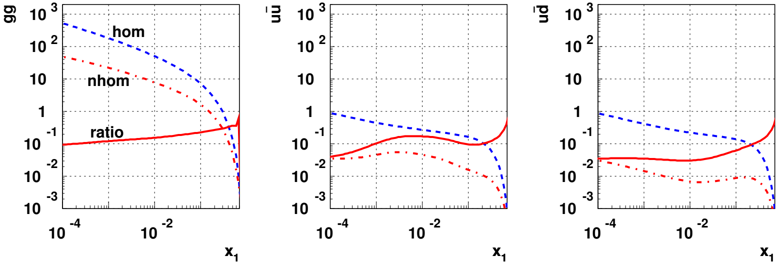


$$D(x_1, x_2, Q) = D^{(hom)}(x_1, x_2, Q) + D^{(nhom)}(x_1, x_2, Q)$$

- Two partons from a hadron + two partons from splitting of a point like parton.

Numerical solution

Plots of $x_1 x_2 D_{f_1 f_2}(x_1, x_2, Q)$ for fixed $x_2 = 10^{-2}$ and $Q^2 = 10^3\ \mathrm{GeV}^2$



For $x_1, x_2 < 10^{-1}$, the splitting part of the solution is significantly smaller

$$\frac{D^{(nhom)}}{D^{(hom)}} \sim 10^{-1}$$

Relative transverse momentum dependence

- Homogeneous solution with the factorized **q**-dependence:

$$\tilde{D}^{(1)}(n_1, n_2, t, \mathbf{q}) = \tilde{D}^{(hom)}(n_1, n_2, t)\, F_{2g}^2(\mathbf{q})$$

with two-gluon nucleon form factor (Blok, Dokshitzer, Frankfurt, Strikman 2009)

$$F_{2g}(\mathbf{q}) = \frac{1}{\left(1 + \mathbf{q}^2/m_g^2\right)^2}$$

where m_g - effective gluon mass. Strong suppression for $\mathbf{q}^2 \gg m_g^2$.

- Splitting part of the solution with modified lower integration limit

$$\tilde{D}^{(2)}(n_1, n_2, t, \mathbf{q}) = \int_{t(\mathbf{q})}^{t} dt'\, \mathrm{e}^{\gamma_{n_1}(t-t')}\, \tilde{\gamma}_{n_1 n_2}\, \tilde{D}(n_1 + n_2, t')\, \mathrm{e}^{\gamma^T_{n_2}(t-t')}$$

- No form factor suppression due to splitting from a point-like parton.

Relative transverse momentum dependence

- The general form of the DPDFs in the x-space

$$D(x_1, x_2, Q, \mathbf{q}) = \underbrace{D^{(1)}(x_1, x_2, Q, \mathbf{q})}_{\textit{strongly suppressed}} + \underbrace{D^{(2)}(x_1, x_2, Q, \mathbf{q})}_{\textit{not suppressed}}$$

- DPS cross section can be written as the sum (Ryskin, Snigirev 2011)

$$\sigma_{AB} = \sigma_{AB}^{(11)} + \sigma_{AB}^{(12+21)} + \sigma_{AB}^{(22)}$$

where

$$\sigma_{AB}^{(ij)} = \frac{N}{2} \sum_{f_i, f_i'} \int dx_1 dx_2\, dz_1 dz_2\, \frac{d^2\mathbf{q}}{(2\pi)^2}\, D_{f_1 f_2}^{(i)}(x_1, x_2, Q, \mathbf{q})$$

$$\times \quad \hat{\sigma}_{f_1 f_1'}^{A}(Q)\, \hat{\sigma}_{f_2 f_2'}^{B}(Q)\, D_{f_1' f_2'}^{(j)}(z_1, z_2, Q, -\mathbf{q})$$

- We do not consider $\sigma_{AB}^{(22)}$ (two splitting contribution) - Jo Gaunt talk.

Electroweak boson production in DPS

- Pocket formula for DPS cross section for W^+W^- production

$$\frac{d^2\sigma_{W^+W^-}}{dy_1 dy_2} = \frac{1}{\sigma_{\rm eff}} \frac{d\sigma_{W^+}}{dy_1} \frac{d\sigma_{W^-}}{dy_2}$$

with $\sigma_{\rm eff} \approx 15$ mb and single scattering cross sections

$$\frac{d\sigma_{W^\pm}}{dy_{1,2}} = \frac{2\pi G_F}{3\sqrt{2}} \frac{M_W^2}{s} \sum_{qq'} |V_{qq'}|^2 \{q(x_{1,2})\,\overline{q}'(z_{1,2}) + \overline{q}(x_{1,2})\,q'(z_{1,2})\}$$

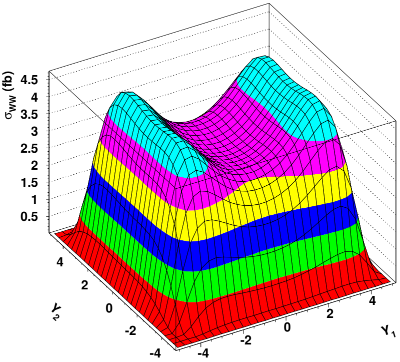
and parton momentum fractions

$$x_{1,2} = \frac{Q}{\sqrt{s}}\,\mathrm{e}^{y_{1,2}}, \qquad z_{1,2} = \frac{Q}{\sqrt{s}}\,\mathrm{e}^{-y_{1,2}}$$

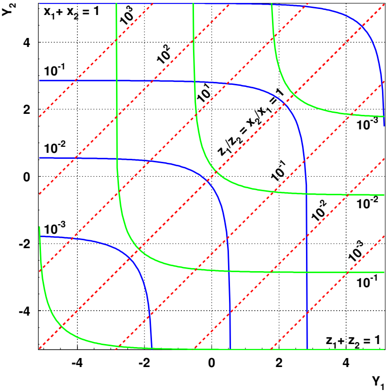
- PDFs are taken at the hard scale $Q = M_W$ and $\sqrt{s} = 14\ \mathrm{TeV}^2$

Pocket formula results

W^+W^- cross section



W^+W^- rapidity plane



Analysis with evolution equations

- Standard contribution

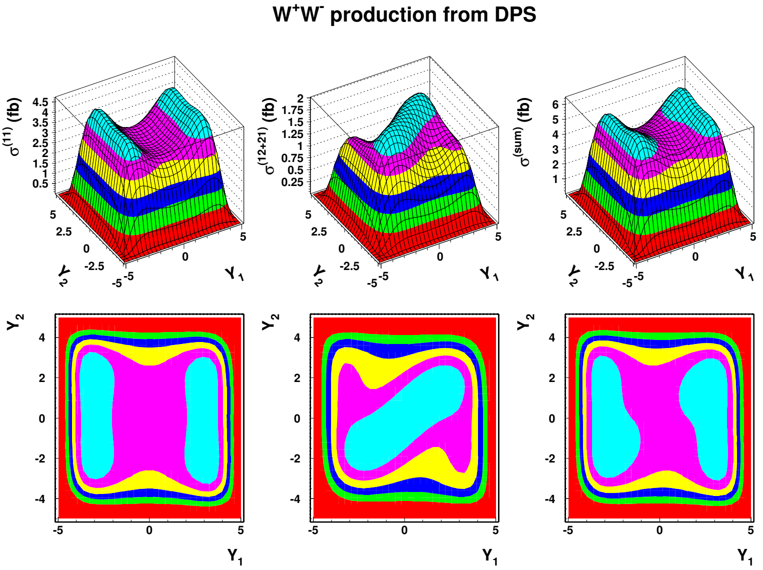
$$\frac{d\sigma^{(11)}}{dy_1 dy_2} = \frac{m_g^2}{28\pi}\,\sigma_{hard}^2\, D^{(1)} \times D^{(1)}$$

- Single splitting contribution

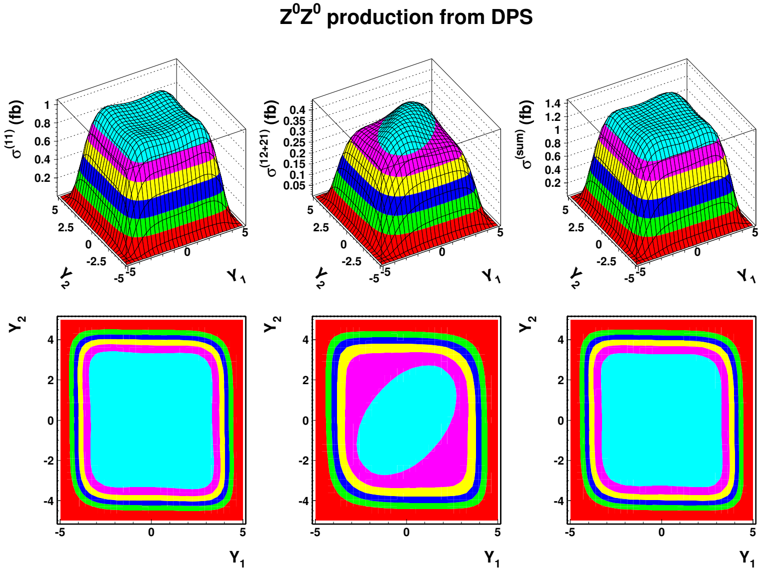
$$\frac{d\sigma^{(12+21)}}{dy_1 dy_2} = \frac{m_g^2}{12\pi}\,\sigma_{hard}^2 \left\{ D^{(1)} \times D^{(2)} + D^{(2)} \times D^{(1)} \right\}$$

- Prefactors from integration of F_{2g}^4 and F_{2g}^2, respectively, over **q**.
- We use $m_g = 1.5\ \mathrm{GeV}$ to get $\sigma_{\mathrm{eff}} \approx 15\ \mathrm{mb}$.
- DPDFs from numerical solutions to the evolution equations.

Analysis with evolution equations



Analysis with evolution equations



Single splitting contribution

- The single splitting contribution is important.
- Contribution to the total DPS cross sections is sizable.

in [fb]	$\sigma_{tot}^{(11)}$	$\sigma_{tot}^{(12+21)}$	$\sigma_{tot}^{(12+21)}/\sigma_{tot}^{(11)}$
W^+W^-	256	97	0.38
Z^0Z^0	61	22	0.36

- It changes the correlation pattern in rapidity for W^+W^- production in DPS.

Single splitting contribution

- Its significance can also be illustrated in terms of the effective cross section

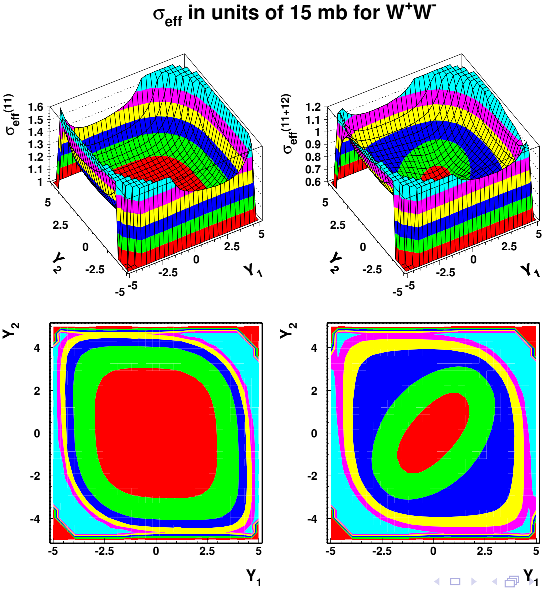
$$\sigma_{\text{eff}} = \frac{N}{2} \frac{(d\sigma_A/dy_1)(d\sigma_B/dy_2)}{d\sigma_{AB}/dy_1 dy_2}$$

for two cases:

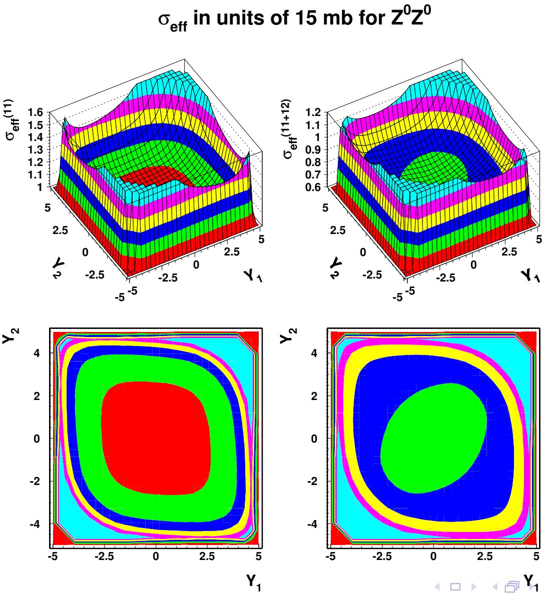
$$\sigma_{AB} = \sigma_{AB}^{(11)} \qquad \sigma_{AB} = \sigma_{AB}^{(11)} + \sigma_{AB}^{(12+21)}$$

- σ_{eff} is a function of boson rapidities: $\sigma_{\text{eff}}(y_1, y_2)$.

σ_{eff} for W^+W^- production



σ_{eff} for $Z^0 Z^0$ production



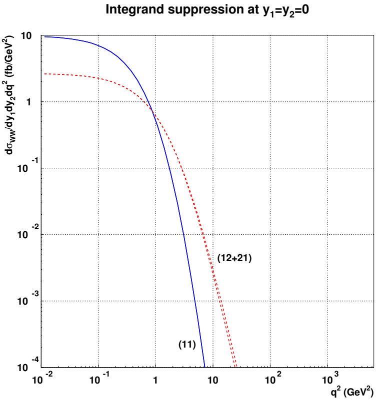
Summary

- The W^+W^- and Z^0Z^0 electroweak boson production in DPS has been studied in detail with the evolution equations for DPDFs.
- The significance of the single splitting contribution to DPS cross sections has been quantified.
- The single splitting contribution contributes up to 40 % to standard analyses.
- The single splitting contribution changes the standard correlation in rapidity of the produced W^+W^- bosons in DPS.

Backup slides

Single splitting contribution

$$\frac{d\sigma^{(ij)}_{W^+W^-}}{dy_1 dy_2 d\mathbf{q}^2} \text{ as a function of } \mathbf{q}^2 \text{ for } y_1 = y_2 = 0$$



Modification of the lower integration limit in $D^{(nhom)}$ unimportant.

Single splitting contribution

The single splitting contribution is less suppressed with rising $\mathbf{q}^2$ due to single form factor F_{2g}^2 in comparison to the double form factor F_{2g}^4 in the no splitting contribution. Thus from $\mathbf{q}$-dependence

$$\sigma^{(12+21)} : \sigma^{(11)} = 2.33 : 1$$

But

$$\frac{d\sigma^{(11)}_{W^+W^-}}{dy_1 dy_2} = \frac{m_g^2}{28\pi} DPDF^{(1)} \cdot DPDF^{(1)}$$

$$\frac{d\sigma^{(12+21)}_{W^+W^-}}{dy_1 dy_2} = \frac{m_g^2}{12\pi} \left\{ DPDF^{(1)} \cdot DPDF^{(2)} + DPDF^{(2)} \cdot DPDF^{(1)} \right\}$$

and the splitting part $DPDF^{(2)}$ is much smaller ($\sim 10^{-1}$) than the homogeneous part $DPDF^{(1)}$. Thus $\sigma^{(11)}$ wins.