Diffractive pQCD mechanisms of exclusive production of $b\bar{b}$ dijets and W^+W^- pairs in proton-proton collisions

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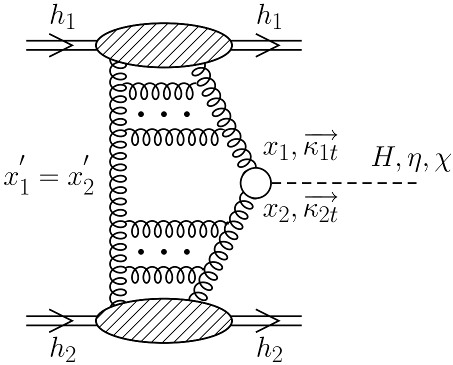
Deep-inelastic scattering 2012

Bonn, March 26 - 30, 2012

Introduction

- The $pp \to ppW^+W^-$ reaction was studied recently assuming two-photon fusion (Royon et al.)
- triple γWW and quartic $\gamma\gamma W^+W^-$ couplings in the Standard Model and beyond is interesting and fundamental problem
- Exclusive reaction: $pp \to pXp$
  ($X = H, Z, \eta', \eta_c, \eta_b, \chi_c, \chi_b$, jj, $c\bar{c}$, $b\bar{b}$).
  At high energy - one of many open channels (!)
  $\Rightarrow$ rapidity gaps.

The QCD mechanism for exclusive Higgs production



3-body process

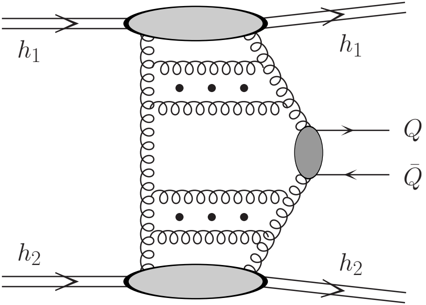
KMR: on-shell matrix element

Pasechnik-Szczurek-Teryaev: off-shell matrix element

Maciula, Pasechnik, Szczurek,

Phys. Rev. **D82** (2010) 114011; Phys. Rev. **D83** (2011) 114034.

The QCD mechanism for exclusive $q\bar{q}$ production



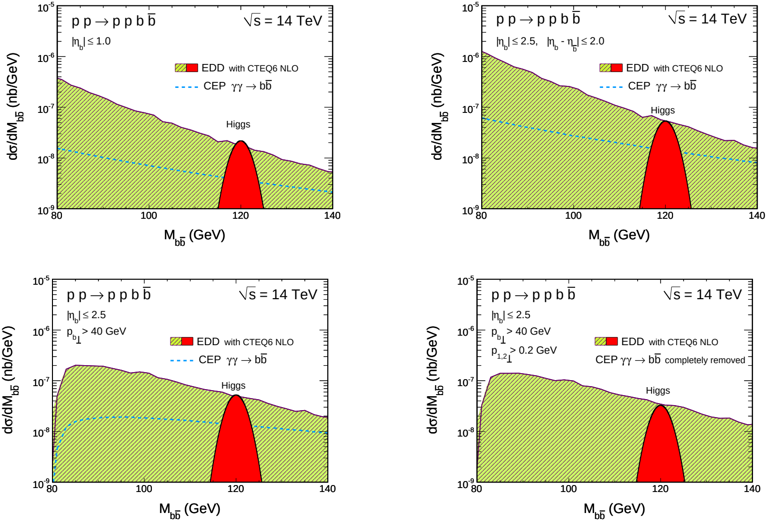
$q\bar{q} = b\bar{b}$: background to exclusive Higgs production

4-body process

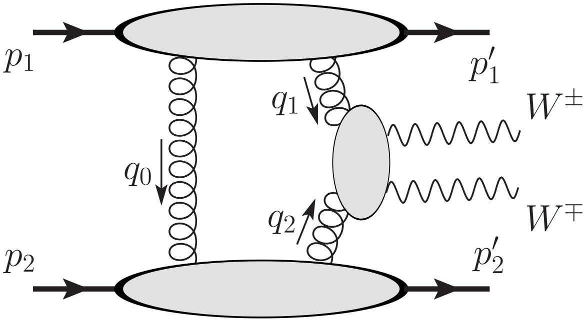
with exact matrix element (without $J_z = 0$ selection rule)

with exact kinematics in the full phase space

M_{bb} spectrum, cuts



The QCD mechanism for exclusive W^+W^- production



Similar in spirit to exclusive production of $H, q\bar{q}, gg$.
Lebiedowicz, Pasechnik, Szczurek, arXiv:1203.1832

Kinematics

Sudakov decomposition:

$$q_1 = x_1 p_1 + q_{1\perp}\,, \quad q_2 = x_2 p_2 + q_{2\perp}\,, \quad 0 < x_{1,2} < 1,$$
$$q_0 = x' p_1 - x' p_2 + q_{0\perp} \simeq q_{0\perp}\,, \quad x' \ll x_{1,2}, \tag{1}$$

where $x_{1,2}, x'$ are the longitudinal momentum fractions for active and screening gluons
$q_\perp^2 \simeq -|\mathbf{q}|^2$.
In the forward scattering limit:

$$t_{1,2} = (p_{1,2} - p'_{1,2})^2 \simeq {p'}^2_{1,2\perp} \to 0,$$
$$q_{0\perp} \simeq -q_{1\perp} \simeq q_{2\perp}\,. \tag{2}$$

Kinematics, continued

It is convenient to introduce the Sudakov expansions for $W^{\pm}$ boson momenta

$$k_{+} = x_1^{+} p_1 + x_2^{+} p_2 + k_{+\perp}, \quad k_{-} = x_1^{-} p_1 + x_2^{-} p_2 + k_{-\perp} \tag{3}$$

leading to

$$x_{1,2} = x_{1,2}^{+} + x_{1,2}^{-}, \quad x_{1,2}^{+} = \frac{m_{+\perp}}{\sqrt{s}} e^{\pm y_{+}}, \quad x_{1,2}^{-} = \frac{m_{-\perp}}{\sqrt{s}} e^{\pm y_{-}}, \tag{4}$$

$$m_{\pm\perp}^2 = m_W^2 + |\mathbf{k}_{\pm\perp}|^2 , \tag{5}$$

In the forward limit:
$\mathbf{k}_{+\perp} = -\mathbf{k}_{-\perp}$.

$$\sigma_{l^+\nu l^-\nu} \simeq \sigma_{WW} \times \mathrm{BR}(W^+ \to l^+\nu)\,\mathrm{BR}(W^- \to l^-\nu) , \tag{6}$$

Diffractive amplitude for $pp \to ppW^+W^-$

$$\mathcal{M}_{\lambda_+\lambda_-}(s,t_1,t_2) \simeq is\frac{\pi^2}{2}\int d^2\mathbf{q}_0\, V_{\lambda_+\lambda_-}(q_1,q_2,k_+,k_-) \frac{f_g(q_0,q_1;t_1)f_g(q_0,q_2;t_2)}{\mathbf{q}_0^2\,\mathbf{q}_1^2\,\mathbf{q}_2^2},$$

where $\lambda_+,\, \lambda_- = \pm 1, 0$ are the polarisation states of the produced $W^\pm$ bosons

$f_g(r_1, r_2; t)$ is the off-diagonal unintegrated gluon distribution function (UGDF), which depends on the longitudinal and transverse components of both gluon momenta r_1 and r_2 emitted from the proton lines.

Diffractive amplitude for $pp \longrightarrow ppW^+W^-$

The gauge-invariant $gg \to W^+_{\lambda_+} W^-_{\lambda_-}$ hard subprocess amplitude $V_{\lambda_+\lambda_-}(q_1, q_2, k_+, k_-)$ is given by

$$V_{\lambda_+\lambda_-} = n^+_\mu n^-_\nu V^{\mu\nu}_{\lambda_+\lambda_-} = \frac{4}{s}\frac{q^\nu_{1\perp}}{x_1}\frac{q^\mu_{2\perp}}{x_2} V_{\lambda_+\lambda_-,\mu\nu},$$
$$q^\nu_1 V_{\lambda_+\lambda_-,\mu\nu} = q^\mu_2 V_{\lambda_+\lambda_-,\mu\nu} = 0\,, \tag{7}$$

where $n^\pm_\mu = p^\mu_{1,2}/E_{p,cms}$, $E_{p,cms} = \sqrt{s}/2$.

$$V^{\mu\nu}_{\lambda_+\lambda_-}(q_1, q_2, k_+, k_-) = \epsilon^{*,\rho}(k_+, \lambda_+)\epsilon^{*,\sigma}(k_-, \lambda_-) V^{\mu\nu}_{\rho\sigma}\,, \tag{8}$$

$V^{\mu\nu}_{\rho\sigma}$ calculated with automatic programs.

The amplitude for $pp \longrightarrow ppQ\bar{Q}$

$\epsilon^*_\mu(k_+, \lambda_+)$ and $\epsilon^*_\nu(k_-, \lambda_-)$ can be defined easily in the proton-proton center-of-mass frame with z-axis along the proton beam as

$$\epsilon(k,0) = \frac{E_W}{m_W}\left(\frac{k}{E_W}, \cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta\right),$$
$$\epsilon(k,\pm1) = \frac{1}{\sqrt{2}}(0, \mathrm{i}\sin\phi \mp \cos\theta\cos\phi, -\mathrm{i}\cos\phi \mp \cos\theta\sin\phi, \pm\sin\theta).$$

such that $\epsilon^\mu(\lambda)\epsilon^*_\mu(\lambda) = -1$ and $\epsilon^*_\mu(k_+, \lambda_+)k_+^\mu = \epsilon^*_\nu(k_-, \lambda_-)k_-^\nu = 0$.
In the forward limit $\phi_- = \phi_+ + \pi$.

The amplitude for $pp \longrightarrow ppQ\bar{Q}$

The diffractive amplitude is averaged over the color indices and over the two transverse polarizations of the incoming gluons. The relevant color factor which includes summing over colors of quarks in the loop (triangle or box) and averaging over gluon colors according to the definition of unintegrated gluon distribution function is

$$\frac{1}{{N_c}^2 - 1} \times \sum_{ij} t^a_{ij} t^a_{ji} \,. \tag{9}$$

The matrix element V_{λ_+,λ_-} contains twice the strong coupling constant $g_s^2 = 4\pi\alpha_s$.
We take the running coupling constant $\alpha_s(M^2_{WW})$

Mechanisms of exclusive diffractive production

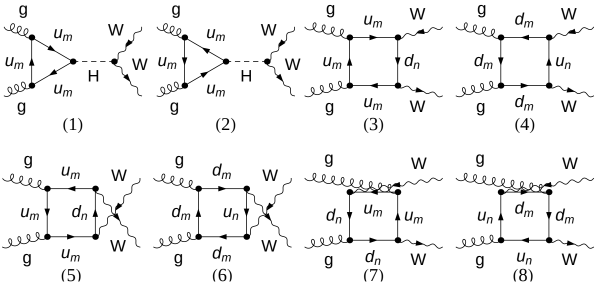


Figure: Representative mechanisms of the hard subprocess $gg \to W^{\pm}W^{\mp}$.

Intermediate Higgs contribution

$$V_{gg\to h^0\to W^+W^-}(q_1,q_2,k_+,k_-) = \delta^{(4)}(q_1+q_2-k_+-k_-)\times \tag{10}$$
$$V_{gg\to h^0}(q_1,q_2,p_{h^0})\,\frac{i}{M_{WW}^2-m_{h^0}^2+iM_{WW}\Gamma^h_{\rm tot}}\,V_{h^0\to W^+W^-}(k_+,k_-,\lambda_+,\lambda_-),$$

$$V_{gg\to h^0}\simeq \frac{i\delta^{ab}}{v}\,\frac{\alpha_s(\mu_F^2)}{\pi}\,(\mathbf{q}_{1\perp}\cdot\mathbf{q}_{2\perp})\,\frac{2}{3}\left(1+\frac{7}{120}\,\frac{M_{WW}^2}{m_{\rm top}^2}\right)\,,\qquad v=\left(G_F\sqrt{2}\right)^{-1/2}.$$

The second tree-level $H^0\to W^+W^-$ "decay" amplitude reads:

$$V_{H^0\to W^+W^-}\simeq i m_W\,\frac{e}{\sin\theta_W}\,\epsilon^*(k_+,\lambda_+)\cdot\epsilon^*(k_-,\lambda_-)\,, \tag{11}$$

Gluon $k_\perp$-dependent densities in the forward limit

$$\begin{aligned} f_g(q_0, q_{1,2}; t_{1,2}) &= R_g f_g(x_{1.2}, \mathbf{q}^2, \mu_F^2) \exp(b t_{1,2}/2) = \\ & R_g \frac{\partial}{\partial \ln \mathbf{q}^2} \left[x g(x_{1,2}, \mathbf{q}^2) \sqrt{T_g(\mathbf{q}^2, \mu_F^2)} \right] \exp(b t_{1,2}/2) \,, \end{aligned}$$

where the diffractive slope $b = 4$ GeV^{-2}
T_g is the Sudakov form factor

$$T_g(\mathbf{q}^2, \mu_F^2) = \exp\left(- \int_{\mathbf{q}^2}^{\mu_F^2} \frac{d\mathbf{k}^2}{\mathbf{k}^2} \frac{\alpha_s(\mathbf{k}^2)}{2\pi} \int_0^{1-\Delta} \left[z P_{gg}(z) + \sum_q P_{qg}(z) \right] dz$$

where

$$\Delta = \frac{|\mathbf{k}|}{|\mathbf{k}| + M_{WW}} \,. \qquad (12)$$

We take $\mu_F^2 = M_{WW}^2$.
$T_g(\mathbf{q}^2, \mu_F^2)$ for extremely large scales μ_F^2 is needed
the integration is performed in $\log_{10}(k^2/k_0^2)$.

Phase space in the forward limit

$$\sigma = \int \frac{1}{2s}\overline{|\mathcal{M}|^2}(2\pi)^4\delta^4(p_1 + p_2 - p_1' - p_2' - p_+ - p_-) \frac{d^3p_1'}{(2\pi)^3 2E_1'}\frac{d^3p_2'}{(2\pi)^3 2E_2'}\frac{d^3p_+}{(2\pi)^3 2E_+}\frac{d^3p_-}{(2\pi)^3 2E_-};,$$

where $\overline{|\mathcal{M}|^2} = \sum_{\lambda_+,\lambda_-}^{0,\pm 1} \mathcal{M}(\lambda_+,\lambda_-)\mathcal{M}^*(\lambda_+,\lambda_-)$.

eight-dimensional integral

The evaluation of the corresponding hard subprocess amplitude $V_{\lambda_+\lambda_-}$ and convolution with the gluon uPDFs in the diffractive amplitude and full phase space integration is extremely time consuming.

Simplification:

$$d\sigma \equiv \frac{1}{2s}\overline{|\mathcal{M}|^2}\, d^4\mathrm{PS}$$

$$= \frac{1}{2s}\overline{|\mathcal{M}|^2}\,\frac{1}{2^4}\,\frac{1}{(2\pi)^8}\,\frac{1}{E_1'E_2'}\,\frac{1}{4}\, dt_1 dt_2 d\phi_1 d\phi_2\, \frac{p_{m\perp}}{4}\mathcal{J}^{-1}\, dy_+ dy_- dp_{m\perp} d\phi_m\ ,$$

where $p_{m\perp} = |\mathbf{p}_{+\perp} - \mathbf{p}_{-\perp}|$ ϕ_m is the corresponding azimuthal

Phase space in the forward limit

For the sake of simplicity, assuming exponential slope of t-dependence of the KMR UGDFs and in the consequence approximately exponential dependence of the cross section on t_1 and t_2 ($\exp(bt_1)$ and/or $\exp(bt_2)$)

$$d\sigma \approx \qquad \frac{1}{2s}\overline{|\mathcal{M}|^2}\Big|_{t_{1,2}=0} \frac{1}{2^4}\frac{1}{(2\pi)^8}\frac{1}{E_1'E_2'}\frac{1}{4}\frac{1}{b^2}(2\pi)^2\frac{p_{m\perp}}{4}\mathcal{J}^{-1}\,dy_+dy_-dp_{m\perp}d\phi_m\,.$$

In this approximation – no correlations between outgoing protons on ϕ_m – the phase space integration can be further reduced to three dimensions.

The Jacobian $\mathcal{J}$ is given by

$$\mathcal{J} = \left|\frac{p_{1z}'}{\sqrt{m_p^2 + p_{1z}'^2}} - \frac{p_{2z}'}{\sqrt{m_p^2 + p_{2z}'^2}}\right|. \qquad (13)$$

$\gamma\gamma \to W^+W^-$ process

$pp \to ppW^+W^-$ calculated already by Royon et al.
The Standard Model couplings:

$$
\begin{aligned}
\mathcal{L}_{WW\gamma} &= -ie(A_\mu W^-_\nu \overleftrightarrow{\partial^\mu} W^{+\nu} + W^-_\mu W^+_\nu \overleftrightarrow{\partial^\mu} A^\nu + W^+_\mu A_\nu \overleftrightarrow{\partial^\mu} W^{-\nu}) \\
\mathcal{L}_{WW\gamma\gamma} &= -e^2(W^-_\mu W^{+\mu} A_\nu A^\nu - W^-_\mu A^\mu W^+_\nu A^\nu) \qquad (14)
\end{aligned}
$$

where the asymmetric derivative has the form
$X \overleftrightarrow{\partial^\mu} Y = X\partial^\mu Y - Y\partial^\mu X$.

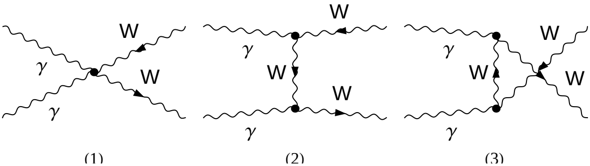


Figure: The Born diagrams for the $\gamma\gamma \to W^\pm W^\mp$ subprocess.

$\gamma\gamma \to W^+W^-$ mechanism

$$\frac{d\sigma}{d\Omega} = \frac{3\alpha^2\beta}{2s}\left(1 - \frac{2s(2s+3m_W^2)}{3(m_W^2-t)(m_W^2-u)} + \frac{2s^2(s^2+3m_W^4)}{3(m_W^2-t)^2(m_W^2-u)^2}\right), \tag{15}$$

where $\beta = \sqrt{1-4m_W^2/s}$ is the velocity of the W bosons in their center-of-mass frame.

In the EPA approximation the total cross section for the $pp \to pp(\gamma\gamma) \to W^+W^-$ can be written as in parton model

$$\sigma = \int dx_1 dx_2\, f_1^{WW}(x_1)\, f_2^{WW}(x_2)\, \sigma_{\gamma\gamma\to W^+W^-}(\hat{s})\,. \tag{16}$$

We take Weizsäcker-Williams equivalent photon fluxes of protons from Drees and Zeppenfeld.

$$\begin{aligned} x_1 &= \frac{m_\perp}{\sqrt{s}}(\exp(y_+)+\exp(y_-))\,, \\ x_2 &= \frac{m_\perp}{\sqrt{s}}(\exp(-y_+)+\exp(-y_-))\,. \end{aligned} \tag{17}$$

$\gamma\gamma \to W^+W^-$ mechanism

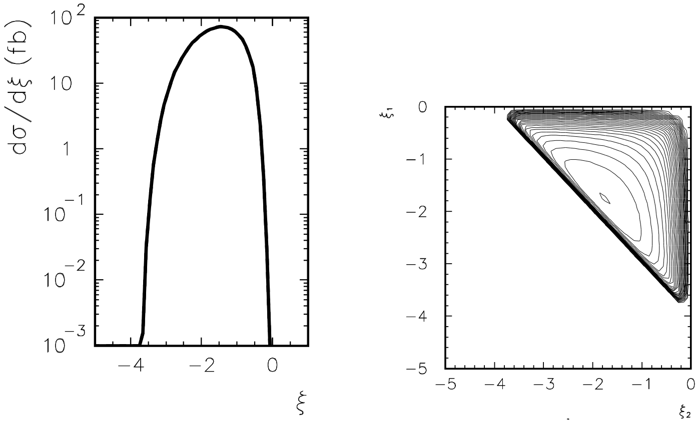


Figure: The lines were calculated within EPA approximation with Drees and Zeppenfeld photon fluxes. $\xi_{1,2} = \log_{10}(x_{1,2})$ where $x_{1,2}$ are photon longitudinal fractions with respect to parent protons.

Inclusive production of W^+W^- pairs

$$\frac{d\sigma}{dy_+ dy_- d^2 p_{W\perp}} = \frac{1}{16\pi^2 \hat{s}^2} x_1 g(x_1,\mu_F^2) x_2 g(x_2,\mu_F^2) \overline{|\mathcal{M}_{gg\to W^+W^-}(\lambda_1,\lambda_2,\lambda_+,\lambda_-)|^2} \tag{18}$$

The distributions in rapidity of W^+ (y_+), rapidity of W^- (y_-) and transverse momentum of one of them $p_{W\perp}$ can be calculated. The distribution in invariant mass can be obtained by appropriate binning.

The matrix element obtained from automatic code calculation and checked against existing calculations.

Results

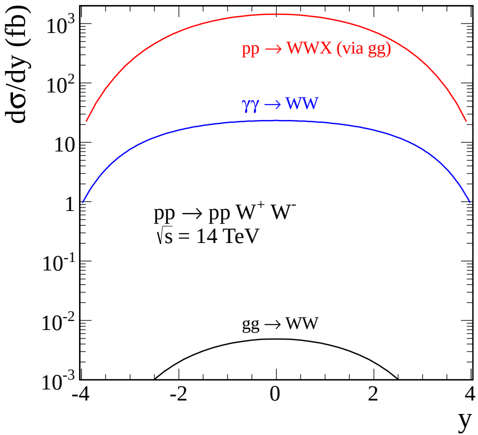


Figure: Rapidity distribution of W bosons.

$M_H = 120$ GeV in triangles

Results

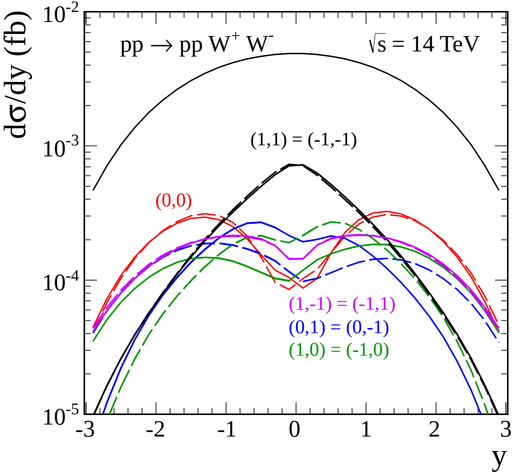


Figure: Polarization components to rapidity distribution of W bosons.

Results

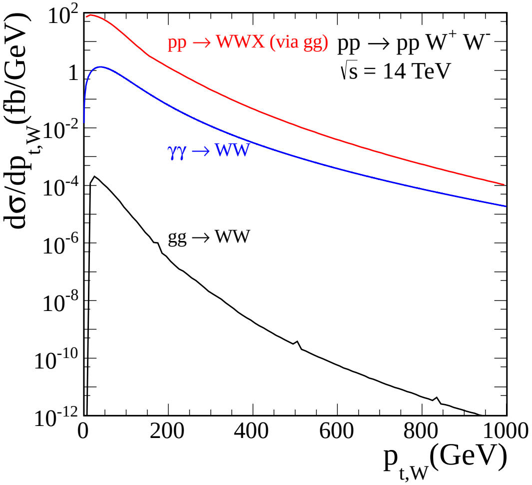


Figure: Distribution in transverse momentum of one of the W bosons.

Results

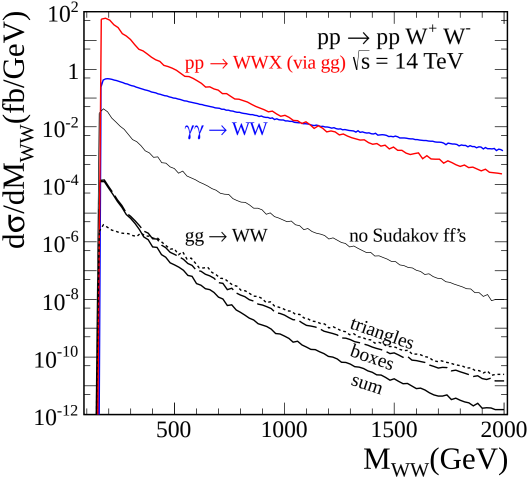


Figure: Distribution in W^+W^- invariant mass. The result when Sudakov form factor is put to 1 is shown for comparison.

Results

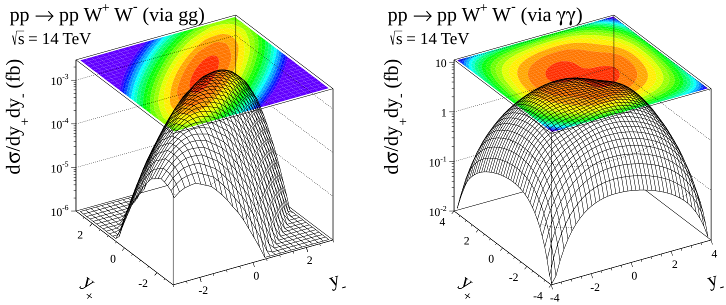


Figure: Two-dimensional distribution in rapidity of W^+ and W^- bosons. Diffractive mechanism (left panel), two-photon mechanism (right panel).

Conclusions

- We have calculated differential cross sections for $pp \to ppW^+W^-$
- Two mechanisms have been considered:
  (a) photon-photon fusion known from the literature,
  (b) a new diffractive mechanism
- Two diffractive subprocesses have been considered:
  (a) intermediate boxes,
  (b) intermediate triangles with intermediate virtual Higgs boson.
- The cross section for the diffractive mechanism is much smaller than that for the two-photon mechanism.
- We observe negative interference between box contribution and triangle contribution.
- Experimentally one could focus on the diffractive component but the cross section is small.
- The $pp \to ppW^+W^-$ reaction is therefore very promissing laboratory for testing triple and quartic boson coupling.