Production of $W^+W^-$ pairs
via subleading processes at the LHC

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Plan of the talk

- Introduction
- $\gamma\gamma \rightarrow W^+ W^-$ reaction
- Inclusive production of $W^+ W^-$ pairs
  - $q\bar{q} \rightarrow W^+ W^-$ mechanism
  - MRST-QED parton distributions
  - Naive approach to photon flux
  - Resolved photons
  - Single diffractive production
  - Results

- Conclusions

Based on:
M. Luszczak, Ch. Royon and A. Szczurek, paper in preparation
The exclusive $pp \rightarrow ppW^+W^-$ reaction is particularly interesting in the context of $\gamma\gamma WW$ coupling.

The general diagram for the $pp \rightarrow ppW^+W^-$ reaction via $\gamma el\gamma el \rightarrow W^+W^-$ subprocess.
The three-boson $WW\gamma$ and four-boson $WW\gamma\gamma$ couplings, which contribute to the $\gamma\gamma \rightarrow W^+ W^-$ process in the leading order:

\[
\mathcal{L}_{WW\gamma} = -ie(A_\mu W^-_\nu \overset{\leftrightarrow}{\partial^\mu} W^{+\nu} + W^-_\mu W^+_{\nu} \overset{\leftrightarrow}{\partial^\mu} A^\nu + W^+_\mu A^-_{\nu} \overset{\leftrightarrow}{\partial^\mu} W^{-\nu}),
\]

\[
\mathcal{L}_{WW\gamma\gamma} = -e^2 (W^-_\mu W^{+\nu} A^-_{\nu} A^\nu - W^-_\mu A^\mu W^+_{\nu} A^\nu),
\]

where the asymmetric derivative has the form

\[
\overset{\leftrightarrow}{X \partial^\mu} Y = X \partial^\mu Y - Y \partial^\mu X.
\]
\( \gamma \gamma \rightarrow W^+ W^- \) reaction

- The Born diagrams for the \( \gamma \gamma \rightarrow W^+ W^- \) subprocess
\[ \frac{d\hat{\sigma}}{d\Omega} = \frac{3\alpha^2 \beta}{2\hat{s}} \left( 1 - \frac{2\hat{s}(2\hat{s} + 3m_W^2)}{3(m_W^2 - \hat{t})(m_W^2 - \hat{u})} + \frac{2\hat{s}^2(\hat{s}^2 + 3m_W^4)}{3(m_W^2 - \hat{t})^2(m_W^2 - \hat{u})^2} \right), \]

\[
\beta = \sqrt{1 - 4m_W^2/\hat{s}} \]

is the velocity of the \( W \) bosons in their center-of-mass frame and the electromagnetic fine-structure constant \( \alpha = e^2/(4\pi) \simeq 1/137 \) for the on-shell photon.
The exclusive diffractive mechanism of central exclusive production of $W^+W^-$ pairs in proton-proton collisions at the LHC (in which diagrams with intermediate virtual Higgs boson as well as quark box diagrams are included) was discussed

- P. Lebiedowicz, R. Pasechnik and A. Szczurek, Phys. Rev. **D81** (2012) 036003

and turned out to be negligibly small.
Relevant leading-order matrix element, averaged over quark colors and over initial spin polarizations, summed over final spin polarization and cross section are well known.
Inclusive $\gamma \gamma \rightarrow W^+ W^-$ mechanism

- $\gamma \gamma$ processes contribute also to inclusive cross section. We consider in addition 3 new mechanisms.
- If at least one photon is a “real” constituent of the nucleon then the mechanisms presented are possible:
MRSTQ parton distributions

The factorization of the QED-induced collinear divergences leads to QED-corrected evolution equations for the parton distributions of the proton.

\[ \frac{\partial q_i(x, \mu^2)}{\partial \log \mu^2} = \frac{\alpha S}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{qq}(y) q_i\left(\frac{x}{y}, \mu^2\right) + P_{qg}(y) g\left(\frac{x}{y}, \mu^2\right) \right\} \]

\[ + \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left\{ \tilde{P}_{qq}(y) e_i^2 q_i\left(\frac{x}{y}, \mu^2\right) + P_{q\gamma}(y) e_i^2 \gamma\left(\frac{x}{y}, \mu^2\right) \right\} \]

\[ \frac{\partial g(x, \mu^2)}{\partial \log \mu^2} = \frac{\alpha S}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{gq}(y) \sum_j q_j\left(\frac{x}{y}, \mu^2\right) + P_{gg}(y) g\left(\frac{x}{y}, \mu^2\right) \right\} \]

\[ \frac{\partial \gamma(x, \mu^2)}{\partial \log \mu^2} = \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{\gamma q}(y) \sum_j e_j^2 q_j\left(\frac{x}{y}, \mu^2\right) + P_{\gamma\gamma}(y) \gamma\left(\frac{x}{y}, \mu^2\right) \right\} \]
MRSTQ parton distributions

In addition to usual $P_{qq}, P_{gq}, P_{qg}, P_{gg}$ splitting functions new splitting functions appear.

$$\tilde{P}_{qq} = C_F^{-1}P_{qq},$$

\[
P_{\gamma q} = C_F^{-1}P_{gq},
\]

\[
P_{q\gamma} = T_R^{-1}P_{qg},
\]

\[
P_{\gamma\gamma} = -\frac{2}{3}\sum_i e_i^2 \delta(1 - y)
\]

momentum is conserved:

$$\int_0^1 dx \times \left\{ \sum_i q_i(x, \mu^2) + g(x, \mu^2) + \gamma(x, \mu^2) \right\} = 1$$
Cross section for photon-photon processes

\[
\frac{d\sigma^{\gamma in\gamma in}}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1 \gamma_{in}(x_1, \mu^2) x_2 \gamma_{in}(x_2, \mu^2) |M_{\gamma\gamma \to W^+ W^-}|^2
\]

- include only cases when nucleons do not survive a collision and nucleon debris is produced instead
Cross section for photon-photon processes

\[
\begin{align*}
\frac{d\sigma^{\gamma_{\text{in}}\gamma_{\text{el}}}}{dy_1 dy_2 d^2 p_t} &= \frac{1}{16\pi^2 \hat{s}^2} x_1 \gamma_{\text{in}}(x_1, \mu^2) x_2 \gamma_{\text{el}}(x_2, \mu^2) |M_{\gamma\gamma \rightarrow W^+ W^-}|^2 \\
\frac{d\sigma^{\gamma_{\text{el}}\gamma_{\text{in}}}}{dy_1 dy_2 d^2 p_t} &= \frac{1}{16\pi^2 \hat{s}^2} x_1 \gamma_{\text{el}}(x_1, \mu^2) x_2 \gamma_{\text{in}}(x_2, \mu^2) |M_{\gamma\gamma \rightarrow W^+ W^-}|^2 \\
\frac{d\sigma^{\gamma_{\text{el}}\gamma_{\text{el}}}}{dy_1 dy_2 d^2 p_t} &= \frac{1}{16\pi^2 \hat{s}^2} x_1 \gamma_{\text{el}}(x_1, \mu^2) x_2 \gamma_{\text{el}}(x_2, \mu^2) |M_{\gamma\gamma \rightarrow W^+ W^-}|^2
\end{align*}
\]

The elastic photon fluxes are calculated using the Drees-Zeppenfeld parametrization, where a simple parametrization of nucleon electromagnetic form factors was used.
the photon distribution in the proton is a convolution of the distribution of quarks in the proton and the distribution of photons in the quarks/antiquarks

\[ f_{\gamma/p} = f_q \otimes f_{\gamma/q} \]

which can be written mathematically as

\[ xf_{\gamma/p}(x) = \sum_q \int_x^1 dx_q f_q(x_q, \mu^2) e_q^2 \left( \frac{x}{x_q} \right) f_{\gamma/q} \left( \frac{x}{x_q}, Q_1^2, Q_2^2 \right) \]
the flux of photons in a quark/antiquark was parametrized as:

\[ f_\gamma(z) = \frac{\alpha_{em}}{2\pi} \frac{1 + (1 - z)^2}{2} \log \left( \frac{Q_1^2}{Q_2^2} \right). \]

the choice of scales:

\[ Q_1^2 = \max(\hat{s}/4 - m_W^2, 1^2) \]
\[ Q_2^2 = 1^2 \]
\[ \mu^2 = \hat{s}/4. \]
Resolved photons

For completeness we include also the following processes:

\[ \text{Resolved photons} \]

\[ p_1 \rightarrow f^{\text{ine}}_{W^+} x_1 \]

\[ p_2 \rightarrow f^{\text{ine}}_{W^+} x_2 \]

\[ y \rightarrow W^+ \]

\[ y \rightarrow W^- \]

\[ x_{Y1} \]

\[ x_{Y2} \]

\[ p_1 \rightarrow f^{\text{el}}_{W^+} x_1 \]

\[ p_2 \rightarrow f^{\text{el}}_{W^-} x_2 \]

\[ p_1 \rightarrow W^+ \]

\[ p_2 \rightarrow W^- \]

\[ x_1 \]

\[ x_2 \]
Resolved photons

- extra photon remnant debris (called $X_{\gamma,1}$ or $X_{\gamma,2}$ in the figure) appears in addition
- the “photonic” quark/antiquark distributions in a proton must be calculated as the convolution:

$$f_{q/p}^{\gamma} = f_{\gamma/p} \otimes f_{q/\gamma}$$

which mathematically means:

$$x f_{q/p}^{\gamma}(x) = \int_{x}^{1} dx_{\gamma} f_{\gamma/p}(x_{\gamma}, \mu_{s}^{2}) \left( \frac{x}{x_{\gamma}} \right) f \left( \frac{x}{x_{\gamma}}, \mu_{h}^{2} \right).$$

Technically first $f_{\gamma/p}$ in the proton is prepared on a dense grid for $\mu_{s}^{2} \sim 1 \text{ GeV}^{2}$ (virtuality of the photon) and then used in the convolution formula. The second scale is evidently hard $\mu_{h}^{2} \sim M_{WW}^{2}$. The new quark/antiquark distributions of photonic origin are used to calculate cross section as for the standard quark-antiquark annihilation subprocess.
If we study processes with **rapidity gap** extra gap survival factor must be included!
Single diffractive production of $W^+W^-$ pairs

- apply the resolved pomeron approach
- one assumes that the Pomeron has a well defined partonic structure, and that the hard process takes place in a Pomeron–proton or proton–Pomeron (single diffraction) or Pomeron–Pomeron (central diffraction) processes.

\[
\frac{d\sigma_{SD}}{dy_1 dy_2 dp_t^2} = K \left| \frac{M}{16\pi^2 s^2} \right|^2 \left[ (x_1 q_f^D(x_1,\mu^2) x_2 \bar{q}_f(x_2,\mu^2)) \right] \\
+ \left( x_1 \bar{q}_f^D(x_1,\mu^2) x_2 q_f(x_2,\mu^2) \right)
\]

\[
\frac{d\sigma_{CD}}{dy_1 dy_2 dp_t^2} = K \left| \frac{M}{16\pi^2 s^2} \right|^2 \left[ (x_1 q_f^D(x_1,\mu^2) x_2 \bar{q}_f^D(x_2,\mu^2)) \right] \\
+ \left( x_1 \bar{q}_f^D(x_1,\mu^2) x_2 q_f^D(x_2,\mu^2) \right)
\]

The matrix element squared for the $q\bar{q} \rightarrow W^+W^-$ process is the same as previously for non-diffractive processes.
The 'diffractive' quark distribution of flavour $f$ can be obtained by a convolution of the flux of Pomerons $f_{P}(x_{P})$ and the parton distribution in the Pomeron $q_{f/P}(\beta, \mu^{2})$:

$$q_{f}^{D}(x, \mu^{2}) = \int d\beta \delta(x-x_{P}\beta) q_{f/P}(\beta, \mu^{2}) f_{P}(x_{P}) = \int_{x_{P}}^{1} \frac{dx_{P}}{x_{P}} f_{P}(x_{P}) q_{f/P}(\frac{x}{x_{P}}, \mu^{2}).$$

The flux of Pomerons $f_{P}(x_{P})$:

$$f_{P}(x_{P}) = \int_{t_{min}}^{t_{max}} dt f(x_{P}, t),$$

with $t_{min}$, $t_{max}$ being kinematic boundaries.

Both pomeron flux factors $f_{P}(x_{P}, t)$ as well as quark/antiquark distributions in the pomeron were taken from the H1 collaboration analysis of diffractive structure function at HERA.
Results

**Inclusive production of $W^+W^-$ pairs**

**Conclusions**

**Formalism**

**Results**

\[
\frac{d\sigma}{dp} (\text{GeV})
\]

\[
\sigma (\text{nb/GeV})
\]

- **(naive approach)**
  - $W^+W^- \rightarrow pp$
  - $W^+W^- \rightarrow qq$
  - $W^+W^- \rightarrow \gamma\gamma$
  - $W^+W^- \rightarrow \gamma\text{hadrons}$

- **(MRST-QED)**
  - $W^+W^- \rightarrow pp$
  - $W^+W^- \rightarrow qq$
  - $W^+W^- \rightarrow \gamma\gamma$
  - $W^+W^- \rightarrow \gamma\text{hadrons}$

- **(resolved photon)**
  - $W^+W^- \rightarrow pp$
  - $W^+W^- \rightarrow qq$
  - $W^+W^- \rightarrow \gamma\gamma$
  - $W^+W^- \rightarrow \gamma\text{hadrons}$

- **(diffractively produced)**
  - $W^+W^- \rightarrow pp$
  - $W^+W^- \rightarrow qq$
  - $W^+W^- \rightarrow \gamma\gamma$
  - $W^+W^- \rightarrow \gamma\text{hadrons}$

\[
\frac{d\sigma}{dp} (\text{GeV})
\]

\[
\sigma (\text{nb/GeV})
\]

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\]
Results

\[ p \ p \rightarrow W^+W^- \text{ (naive approach)} \quad \sqrt{s} = 8 \text{ TeV} \]

\[ p \ p \rightarrow W^+W^- \text{ (MRST-QED)} \quad \sqrt{s} = 8 \text{ TeV} \]
Inclusive production of $W^+W^-$ pairs

**Results**

**Plan of the talk**
- Introduction
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**Formalism**

**Results**

\[ p p \rightarrow W^+W^- (\text{resolved photon}) \quad \sqrt{s} = 8 \text{ TeV} \]

\[ p p \rightarrow W^+W^- (\text{diffractively produced}) \quad \sqrt{s} = 8 \text{ TeV} \]

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Results

\[ p p \rightarrow W^+ W^- (\text{MRST-QED}) \quad \sqrt{s} = 8 \text{ TeV} \]

\[ p p \rightarrow W^+ W^- (\text{resolved photon}) \quad \sqrt{s} = 8 \text{ TeV} \]

\[ p p \rightarrow W^+ W^- (\text{diffractively produced}) \quad \sqrt{s} = 8 \text{ TeV} \]

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Results

\[
\frac{d\sigma}{dy_1 dy_2} (\text{nb})
\]

\[
\frac{d\sigma}{dy_1 dy_2} (\text{nb})
\]
## Results

Contributions of different subleading processes to the total cross section (pb)

| contribution                  | 1.96 TeV     | 7 TeV       | 8 TeV       | 14 TeV      | comment                                      |
|-------------------------------|--------------|-------------|-------------|-------------|----------------------------------------------|
| CDF                           | 12.1 pb      | 54.4 pb     | 33.04 pb    | 70.21 pb    | large extrapolation                           |
| D0                            | 13.8 pb      | 41.1 pb     |             |             |                                              |
| ATLAS                         |              |             |             |             |                                              |
| CMS                           |              |             |             |             |                                              |
| $q\bar{q}$                    | 9.86         | 27.24       | 1.48        | 7.0       | dominant (LO, NLO)                           |
| $gg$                          | $5.17 \times 10^{-2}$ | $1.48$     | $1.97$      | $5.87$      | subdominant (NLO)                            |
| $\gamma_{el}\gamma_{el}$     | $3.07 \times 10^{-3}$ | $4.41 \times 10^{-2}$ | $5.40 \times 10^{-2}$ | $1.16 \times 10^{-1}$ | new, anomalous $\gamma\gamma WW$               |
| $\gamma_{el}\gamma_{in}$     | $1.08 \times 10^{-2}$ | $1.40 \times 10^{-1}$ | $1.71 \times 10^{-1}$ | $3.71 \times 10^{-1}$ | new, anomalous $\gamma\gamma WW$               |
| $\gamma_{in}\gamma_{el}$     | $1.08 \times 10^{-2}$ | $1.40 \times 10^{-1}$ | $1.71 \times 10^{-1}$ | $3.71 \times 10^{-1}$ | new, anomalous $\gamma\gamma WW$               |
| $\gamma_{in}\gamma_{in}$     | $3.72 \times 10^{-2}$ | $4.46 \times 10^{-1}$ | $5.47 \times 10^{-1}$ | $1.19$      | new, quite sizeable                           |
| $\gamma_{el,res} - q/\bar{q}$ | $1.04 \times 10^{-4}$ | $2.94 \times 10^{-3}$ | $3.83 \times 10^{-3}$ | $1.03 \times 10^{-2}$ | new, quite sizeable                           |
| $q/\bar{q} - \gamma_{el,res}$ | $1.04 \times 10^{-4}$ | $2.94 \times 10^{-3}$ | $3.83 \times 10^{-3}$ | $1.0310^{-2}$ | new, quite sizeable                           |
| $\gamma_{in,res} - q/\bar{q}$ |               |             |             |             |                                              |
| $q/\bar{q} - \gamma_{in,res}$ |               |             |             |             |                                              |
| double scattering (++)        | $0.57 \times 10^{-2}$ | $0.11$     | $0.14$      | $0.40$      | not included in NLO studies                   |
| $Pp$                          | $2.82 \times 10^{-2}$ | $9.88 \times 10^{-1}$ | $1.27$      | $3.35$      | new, relatively small                         |
| $pP$                          | $2.82 \times 10^{-2}$ | $9.88 \times 10^{-1}$ | $1.27$      | $3.35$      | new, relatively small                         |
| $Rp$                          | $4.51 \times 10^{-2}$ | $7.12 \times 10^{-1}$ | $8.92 \times 10^{-1}$ | $2.22$      | new, relatively small                         |
| $pR$                          | $4.51 \times 10^{-2}$ | $7.12 \times 10^{-1}$ | $8.92 \times 10^{-1}$ | $2.22$      | new, relatively small                         |

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Conclusions

- Large contribution of photon induced processes
- Inelastic-inelastic photon-photon contribution large when photon treated as parton in the nucleon
- Resolved photon contribution are rather small
- Diffractive production with rapidity gap interesting by itself (could be measured ?)
- Diffractive contribution to inclusive cross section unclear
- In the future we have to include decays of W bosons