# Production of $W^+W^-$ pairs via $\gamma^*\gamma^* \to W^+W^-$ subprocess with photon transverse momenta

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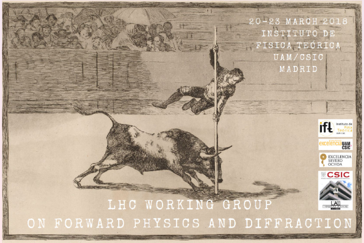


# Inclusive production of $W^+W^-$ pairs

two different approach are possible:

- collinear - factorization
  - M. Łuszczak, A. Szczurek and Ch. Royon, JHEP 1502 (2015) 098
- $k_t$ - factorization
  - G. Gil da Silveira, L. Forthomme, K. Piotrzkowski, W. Schafer, A. Szczurek, JHEP 1502 (2015) 159
  - M. Luszczak, W. Schafer and A. Szczurek, Phys.Rev. D93 (2016) 074018
  - M. Luszczak, W. Schafer and A. Szczurek, arXiv:1802.03244

in collinear - factorization approach one needs photons as parton in proton:

- MRST
- NNPDF
- LUX

# QED parton distributions

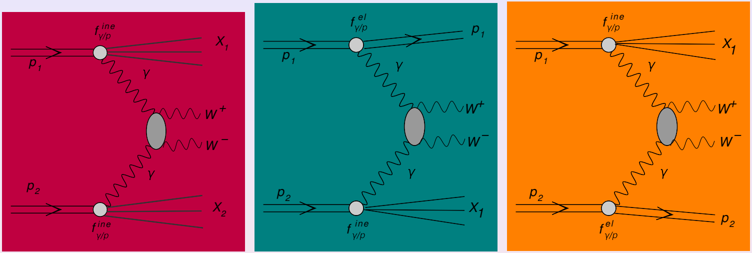
- MRST-QED parton distributions
  - QED-corrected evolution equations for the parton distributions of the proton

$$
\begin{aligned}
\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{qq}(y)\ q_i(\frac{x}{y},\mu^2) + P_{qg}(y)\ g(\frac{x}{y},\mu^2)\Big\} \\
&+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\Big\{\tilde{P}_{qq}(y)\ e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\ e_i^2 \gamma(\frac{x}{y},\mu^2)\Big\} \\
\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{gq}(y)\ \sum_j q_j(\frac{x}{y},\mu^2) + P_{gg}(y)\ g(\frac{x}{y},\mu^2)\Big\} \\
\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{\gamma q}(y)\ \sum_j e_j^2\ q_j(\frac{x}{y},\mu^2) + P_{\gamma\gamma}(y)\ \gamma(\frac{x}{y},\mu^2)\Big\}
\end{aligned}
$$

- NNPDF2.3 parton distributions
  - fit to deep-inelastic scattering (DIS) and Drell-Yan data
- LUXqed17 parton distributions
  - integral over proton structure functions $F_2(x,Q^2)$ and $F_L(x,Q^2)$

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

- $\gamma\gamma$ processes contribute also to inclusive cross section

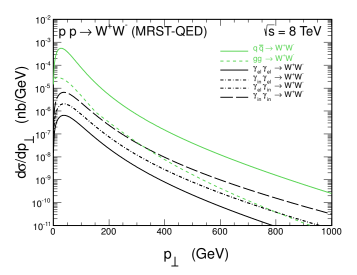


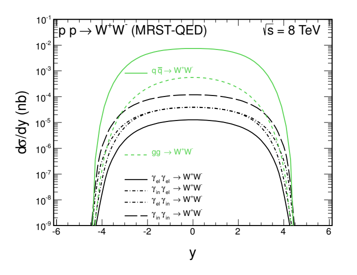

$$\frac{d\sigma^{\gamma_{in}\gamma_{in}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1\gamma_{in}(x_1,\mu^2)\; x_2\gamma_{in}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

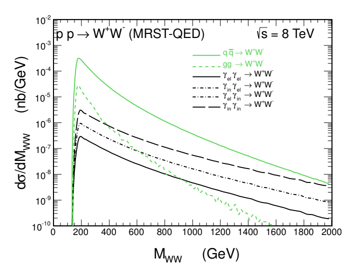
$$\frac{d\sigma^{\gamma_{el}\gamma_{in}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1\gamma_{el}(x_1,\mu^2)\; x_2\gamma_{in}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

$$\frac{d\sigma^{\gamma_{in}\gamma_{el}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1\gamma_{in}(x_1,\mu^2)\; x_2\gamma_{el}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

# Results for MRSTQ parton distributions

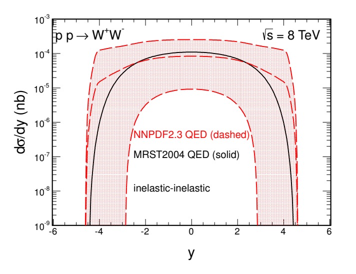


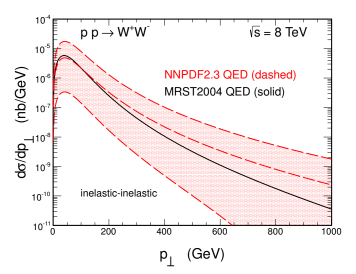




M. Luszczak, A. Szczurek and Ch. Royon, JHEP 1502 (2015) 098

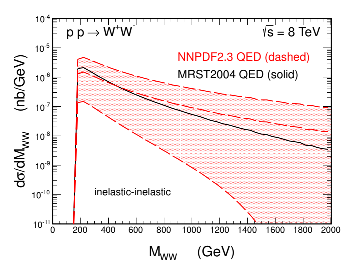
# Results for NNPDF2.3 QED photon distributions




- the statistically most probable result (middle dashed line) as well as one-sigma uncertainty band (shaded area)
- very difficult to obtain the photon distributions from fits to experimental data
- limiting to both rapidities in the interval -2.5 $< y <$ 2.5 the uncertainty band becomes relatively smaller

# NNPDF2.3 QED photon distributions




- big uncertainties can be observed especially for large $WW$ invariant masses, i.e. in the region where searches for anomalous triple and quartic boson couplings are studied

M. Łuszczak, A. Szczurek and Ch. Royon, JHEP 1502 (2015) 098

## Some comments on recent studies on $\gamma\gamma W^+W^-$ boson couplings

- in D0 collaboration analysis the inelastic contributions are not included when extracting limits on anomalous couplings
- the CMS collaboration requires an extra condition of no charged particles in the central pseudorapidity interval
- when comparing calculations to the experimental data the inelastic contributions are estimated by rescaling the elastic-elastic contribution by an experimental function depending on kinematical variables obtained in the analysis of the $\mu^+\mu^-$ continuum
- it is not clear whether such a procedure is consistent for $W^+W^-$ production, where leptons come from the decays of the gauge bosons and the invariant mass and transverse momentum of the $W^+W^-$ pair is very different than the invariant mass and transverse momentum of the corresponding dimuons

this cannot be checked in the approach with collinear photons

requires the inclusion of photon transverse momenta!

# $k_T$-factorization approach

- the unintegrated photon fluxes can be expressed in terms of the hadronic tensor

$$\mathcal{F}^{\mathrm{in.el}}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) = \frac{\alpha_{\mathrm{em}}}{\pi} (1 - z) \left( \frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \right)^2 \cdot \frac{p_B^\mu p_B^\nu}{s^2} W^{\mathrm{in,el}}_{\mu\nu}(M_X^2, Q^2) dM_X^2$$

- they enter the cross section for $W^+W^-$ production

$$\frac{d\sigma^{(i,j)}}{dy_1 dy_2 d^2\boldsymbol{p}_1 d^2\boldsymbol{p}_2} = \int \frac{d^2\boldsymbol{q}_1}{\pi \boldsymbol{q}_1^2} \frac{d^2\boldsymbol{q}_2}{\pi \boldsymbol{q}_2^2} \mathcal{F}^{(i)}_{\gamma^*/A}(x_1, \boldsymbol{q}_1) \mathcal{F}^{(j)}_{\gamma^*/B}(x_2, \boldsymbol{q}_2) \frac{d\sigma^*(p_1, p_2; \boldsymbol{q}_1, \boldsymbol{q}_2)}{dy_1 dy_2 d^2\boldsymbol{p}_1 d^2\boldsymbol{p}_2}$$

- the longitudinal momentum fractions of $W^+W^-$ are obtained from the rapidities and transverse momenta of final state

$$x_1 = \sqrt{\frac{\boldsymbol{p}_1^2 + m_W^2}{s}} e^{y_W} + \sqrt{\frac{\boldsymbol{p}_2^2 + m_W^2}{s}} e^{y_W} ,$$

$$x_2 = \sqrt{\frac{\boldsymbol{p}_1^2 + m_W^2}{s}} e^{-y_W} + \sqrt{\frac{\boldsymbol{p}_2^2 + m_W^2}{s}} e^{-y_W}$$

# Unintegrated photon fluxes from Budnev

- the quantity to compare is the differential equivalent photon spectrum

$$dn^{\rm in,el} = \frac{dz}{z}\,\frac{d^2\boldsymbol{q}}{\pi\boldsymbol{q}^2}\,\mathcal{F}^{\rm in,el}_{\gamma^*\leftarrow A}(z,\boldsymbol{q})$$

- for the inelastic piece

$$\begin{aligned}\mathcal{F}^{\rm in}_{\gamma^*\leftarrow A}(z,\boldsymbol{q}) \quad &= \quad \frac{\alpha_{\rm em}}{\pi}\Big\{(1-z)\Big(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2+z(M_X^2-m_A^2)+z^2m_A^2}\Big)^2\frac{F_2(x_{\rm Bj},Q^2)}{Q^2+M_X^2-m_p^2}\\ &+ \quad \frac{z^2}{4x_{\rm Bj}^2}\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2+z(M_X^2-m_A^2)+z^2m_A^2}\frac{2x_{\rm Bj}F_1(x_{\rm Bj},Q^2)}{Q^2+M_X^2-m_p^2}\Big\}\end{aligned}$$

- for the elastic piece

$$\begin{aligned}\mathcal{F}^{\rm el}_{\gamma^*\leftarrow A}(z,\boldsymbol{q}) \quad &= \quad \frac{\alpha_{\rm em}}{\pi}\Big\{(1-z)\Big(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2+z(M_X^2-m_A^2)+z^2m_A^2}\Big)^2\frac{4m_p^2G_E^2(Q^2)+Q^2G_M^2(Q^2)}{4m_p^2+Q^2}\\ &+ \quad \frac{z^2}{4}\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2+z(M_X^2-m_A^2)+z^2m_A^2}G_M^2(Q^2)\Big\}\end{aligned}$$

# Matrix element

we obtain for the helicity-matrix element

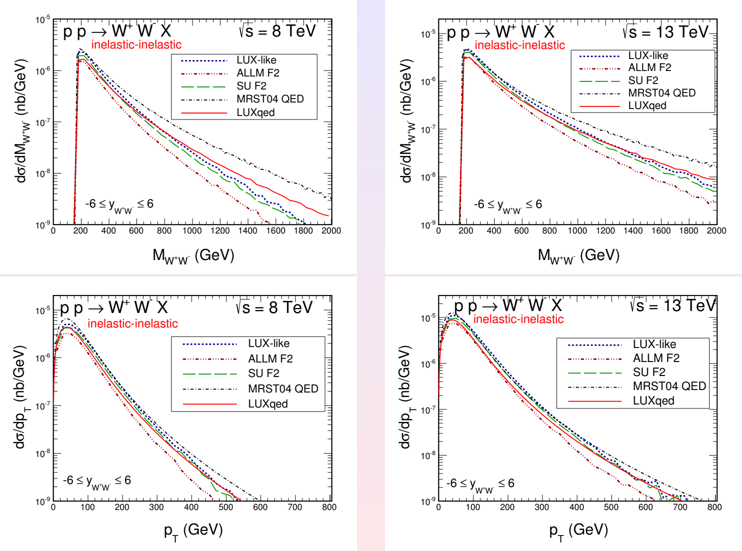
$$\begin{aligned} M(\lambda_{W^+}\lambda_{W^-}) &= \frac{1}{|\vec{q}_{\perp 1}||\vec{q}_{\perp 2}|}\Big\{(\vec{q}_{\perp 1}\cdot\vec{q}_{\perp 2})\cdot\Big(\mathcal{M}(++;\lambda_{W^+}\lambda_{W^-})+\mathcal{M}(--;\lambda_{W^+}\lambda_{W^-})\Big) \\ &- i[\vec{q}_{\perp 1},\vec{q}_{\perp 2}]\Big(\mathcal{M}(++;\lambda_{W^+}\lambda_{W^-})-\mathcal{M}(--;\lambda_{W^+}\lambda_{W^-})\Big) \\ &- \Big(q^x_{\perp 1}q^x_{\perp 2}-q^y_{\perp 1}q^y_{\perp 2}\Big)\Big(\mathcal{M}(+-;\lambda_{W^+}\lambda_{W^-})+\mathcal{M}(-+;\lambda_{W^+}\lambda_{W^-})\Big) \\ &- i\Big(q^x_{\perp 1}q^y_{\perp 2}+q^y_{\perp 1}q^x_{\perp 2}\Big)\Big(\mathcal{M}(+-;\lambda_{W^+}\lambda_{W^-})-\mathcal{M}(-+;\lambda_{W^+}\lambda_{W^-})\Big) \quad (1)\end{aligned}$$

# Results, integrated cross sections

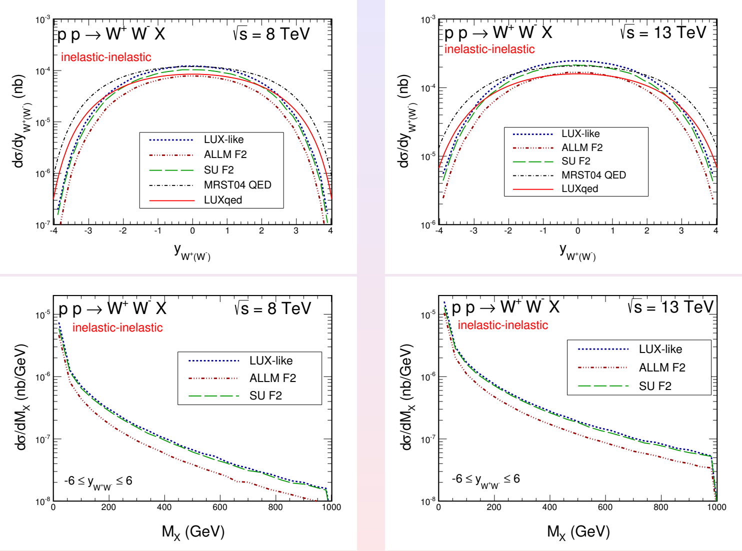
| contribution | 8 TeV | 13 TeV |
|---|---|---|
| LUX-like | | |
| $\gamma_{el}\gamma_{in}$ | 0.214 | 0.409 |
| $\gamma_{in}\gamma_{el}$ | 0.214 | 0.409 |
| $\gamma_{in}\gamma_{in}$ | 0.478 | 1.090 |
| ALLM97 F2 | | |
| $\gamma_{el}\gamma_{in}$ | 0.197 | 0.318 |
| $\gamma_{in}\gamma_{el}$ | 0.197 | 0.318 |
| $\gamma_{in}\gamma_{in}$ | 0.289 | 0.701 |
| SU F2 | | |
| $\gamma_{el}\gamma_{in}$ | 0.192 | 0.420 |
| $\gamma_{in}\gamma_{el}$ | 0.192 | 0.420 |
| $\gamma_{in}\gamma_{in}$ | 0.396 | 0.927 |
| LUXqed collinear | | |
| $\gamma_{in+el}\ \gamma_{in+el}$ | 0.366 | 0.778 |
| MRST04 QED collinear | | |
| $\gamma_{el}\gamma_{in}$ | 0.171 | 0.341 |
| $\gamma_{in}\gamma_{el}$ | 0.171 | 0.341 |
| $\gamma_{in}\gamma_{in}$ | 0.548 | 0.980 |
| Elastic- Elastic | | |
| $\gamma_{el}\gamma_{el}$ (Budnev) | 0.130 | 0.273 |
| $\gamma_{el}\gamma_{el}$ (DZ) | 0.124 | 0.267 |

Table : Cross sections (in *pb*) for different contributions and different F2 structure functions: LUX-like, ALLM97 and SU, compared to the relevant collinear distributions with MRST04 QED and LUXqed distributions.

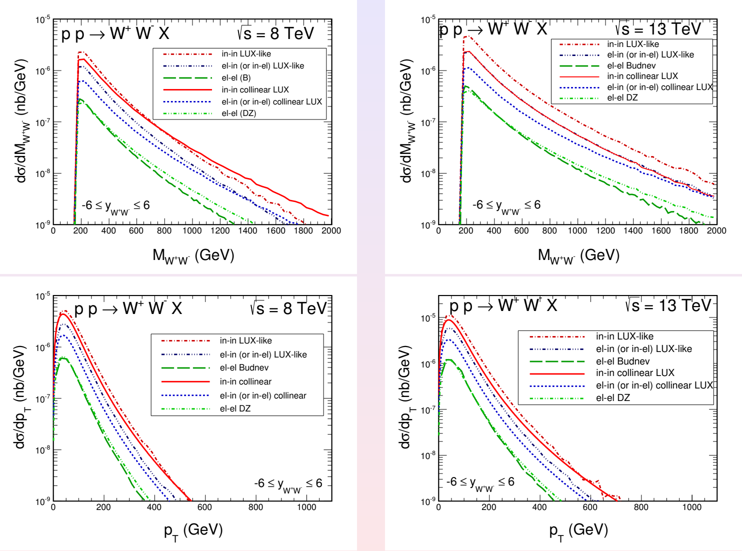
# Results for $k_T$-factorization approach



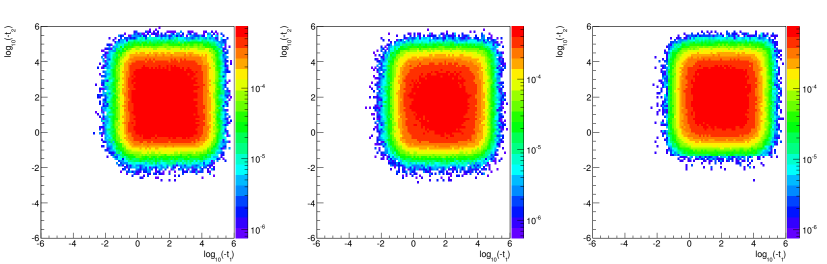
# Results for $k_T$-factorization approach



# Results for $k_T$-factorization approach



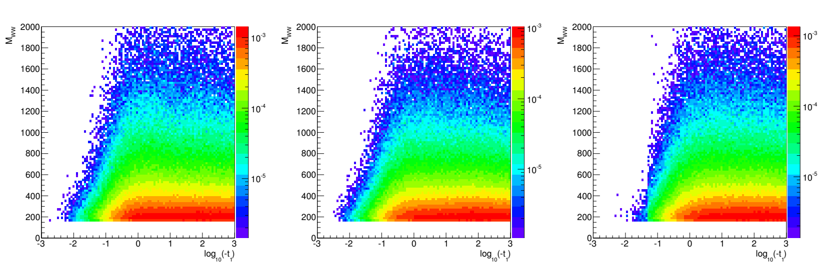
# Results, correlation variables




Large virtualities of photons, contradicts collinear approach

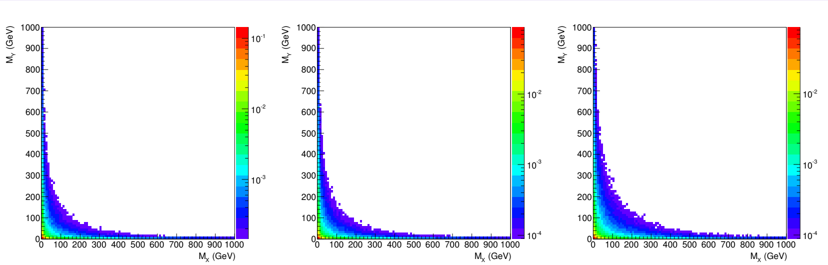
Similar pattern for different parametrizations of structure functions

# Results, correlation variables




Large $M_{WW}$ large $|t_1|$ or $|t_2|$ - strongly virtual photons

# Results, correlation variables




There seem to be a correlation between $M_X$ and $M_Y$

When one is large, the second seems rather small

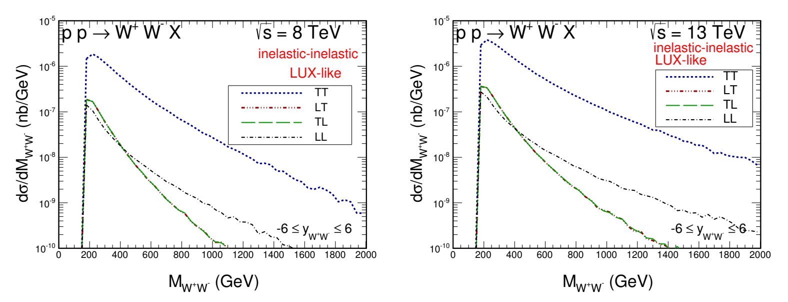
needs more attention

# Results, spin decompositions

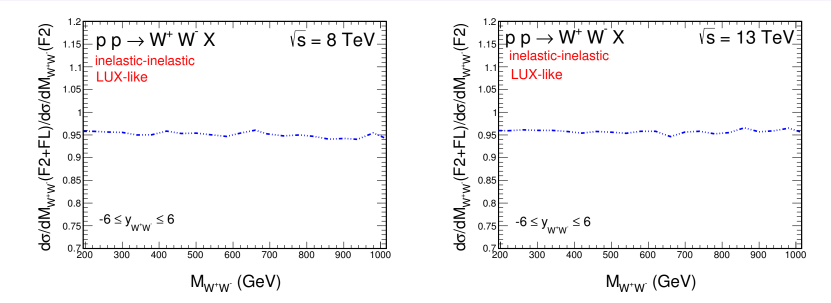
| contribution | 8 TeV | 13 TeV |
|---|---|---|
| TT | 0.405 | 0.950 |
| LL | 0.017 | 0.046 |
| LT + TL | 0.028 + 0.028 | 0.052 + 0.052 |
| SUM | 0.478 | 1.090 |

Table : Contributions of different polarizations of $W$ bosons for the inelastic-inelastic component for the LUX-like structure function. The cross sections are given in *pb*.

# Results, spin decompositions

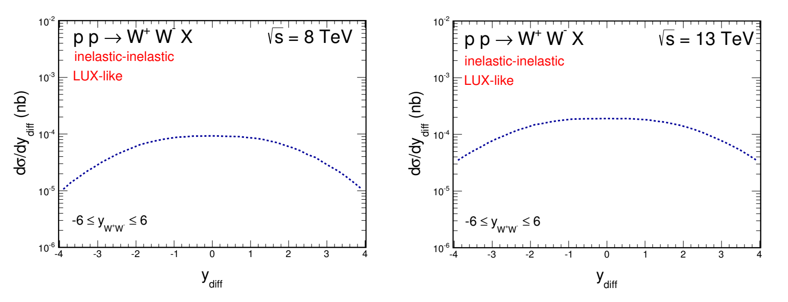


# Results, longitudinal structure function




Small effect, decreasing the cross section

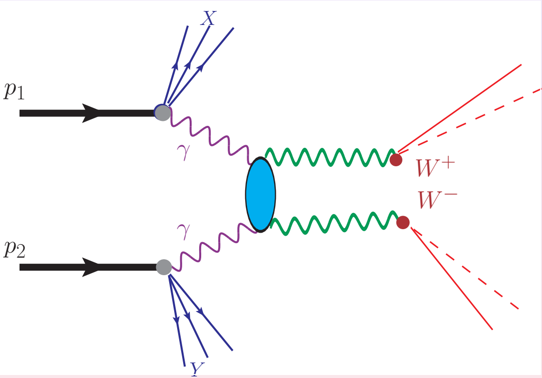
# Results, rapidity distance between $W$ bosons




Very broad distribution

# Future studies

So far we have calculated $\gamma\gamma \to W^+W^-$ inclusive cross section.
This is not what is done in dedicated studies.




ATLAS and CMS measure leptons and check rapidity gaps.

# Future studies

- Include decays of $W$ bosons:
  $W^+ \to \mu^+, W^- \to e^-$ or
  $W^+ \to e^+, W^- \to \mu^-$
- Include hadronization of remnants (quark-diquark model + PYTHIA)
- Calculate gap survival factor (see the previous point)
  - include soft gap survival factors (functions)
  - check how particles from remnants destroy the gap

# Conclusions

- The matrix elements derived by Nachtmann et al. have been used.
- We have obtained cross section of about 1 pb for the LHC energies. This is about 2 % of the total integrated cross section dominated by the quark-antiquark annihilation and gluon-gluon fusion.
- Different combinations of the final states (elastic-elastic, elastic-inelastic, inelastic-elastic, inelastic-inelastic) have been considered.
- The unintegrated photon fluxes were calculated based on modern parametrizations of the proton structure functions from the literature.
- Several differential distributions in $W$ boson transverse momentum and rapidity, $WW$ invariant mass, transverse momentum of the $WW$ pair, mass of the remnant system have been presented.
- Several correlation observables have been studied. Large contributions from the regions of large photon virtualities $Q_1^2$ and/or $Q_2^2$ have been found putting in question the reliability of leading-order collinear-factorization approach.

# Conclusions

- We have presented a decomposition of the cross section into different polarizations of both $W$ bosons. It has been shown that the $W$ (transversally polarized) contribution dominates and constitutes a little bit more than 80 % of the total cross section.
- The $LL$ (both $W$ longitudinally polarized) contribution is interesting in the context of studying $WW$ interactions or searches beyond the Standard Model.
- We have quantifield the effect of inclusion of longitiudinal structure function into the transverse momentum dependent fluxes of photons. A rather small, approximataly $M_{WW}$ - independent, effect was found.
- The discussed here $\gamma\gamma \to W^+W^-$ mechanism leads to rather large rapidity separations of $W^+$ and $W^-$ boson