Production of l^+l^- and W^+W^- pairs in exclusive and semiexlusive processes at the LHC

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Challenges in Photon Induced Interactions
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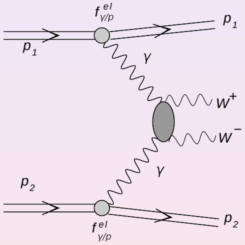
$pp \to W^+W^-X$ is fundamental in particle physics

- background to the observation of the Higgs boson in the W^+W^- channel
- used to test Standard Model gauge boson couplings



photon-photon contribution

- O. Kepka and C. Royon, Phys. Rev. D78 (2008) 073005;
- E. Chapon, C. Royon and O. Kepka, Phys. Rev. D81 (2010) 074003
- N. Schul and K. Piotrzkowski, Nucl. Phys. B **179-180** (2008) 289
- T. Pierzchała and K. Piotrzkowski, Nucl. Phys. B **179-180** (2008) 257

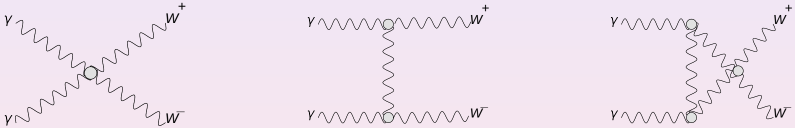
dominates at W pair masses

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

three-boson $WW\gamma$ and four-boson $WW\gamma\gamma$ couplings

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

the Born diagrams



the elementary tree-level cross section

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

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, work in progress

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

- MRST
- NNPDF

QED parton distributions

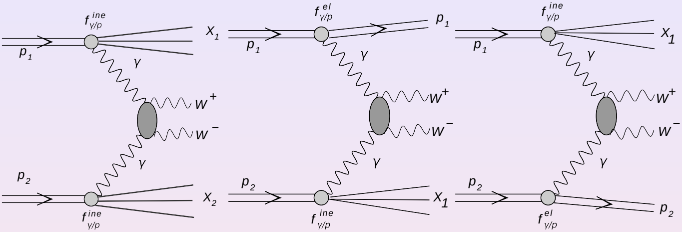
- **MRST-QED parton distributions**
  - the factorization of the QED-induced collinear divergences leads to QED-corrected evolution equations for the parton distributions of the proton
  - combined QCD + QED evolution

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

- **NNPDF2.3 parton distributions**
  - a photon PDF obtained from a fit to deep-inelastic scattering (DIS) and Drell-Yan (both low mass, on-shell W and Z production, and high mass) data
  - QCD corrections included up to NLO or NNLO

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

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

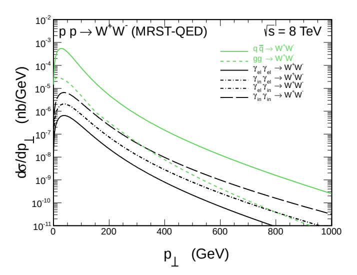


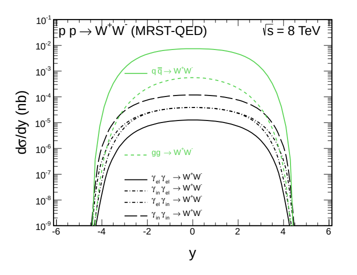
$$\frac{d\sigma^{\gamma_{in}\gamma_{in}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1\gamma_{in}(x_1,\mu^2)\; x_2\gamma_{in}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

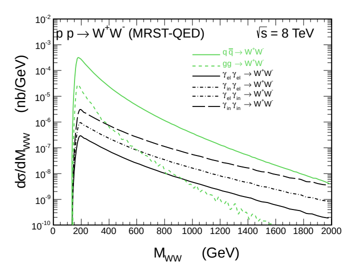
$$\frac{d\sigma^{\gamma_{in}\gamma_{el}}}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1\gamma_{in}(x_1,\mu^2)\; x_2\gamma_{el}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}$$

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

Results for MRSTQ parton distributions

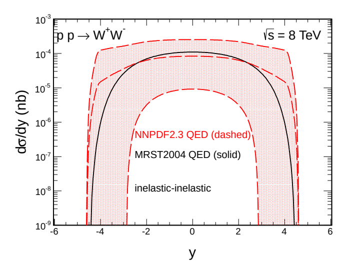


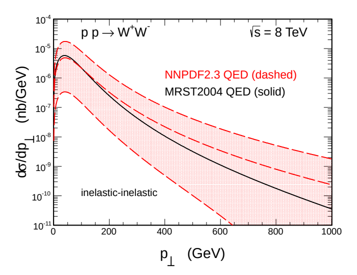




M. Luszczak, A. Szczurek and Ch. Royon, JHEP 1502 (2015) 098

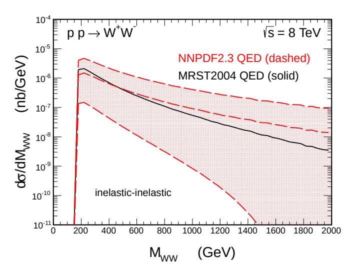
Results for NNPDF2.3 QED photon distributions





- the statistically most probable result (middle dashed line) as well as one-sigma uncertainty band (shaded area)
- the uncertainty band is very large
- this demonstrates that it is very difficult to obtain the photon distributions from fits to experimental data
- we have checked that 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 present approach with collinear photons

and requires the inclusion of photon transverse momenta!

k_T-factorization approach

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

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

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

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

- 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

$$dn^{\rm in,el} = \frac{dz}{z} \frac{d^2\boldsymbol{q}}{\pi \boldsymbol{q}^2} \mathcal{F}^{\rm in,el}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) \tag{4}$$

$$\begin{aligned} \mathcal{F}^{\rm in}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) &= \frac{\alpha_{\rm em}}{\pi} \Big\{ (1-z) \Big(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \Big)^2 \frac{F_2(x_{\rm Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2} \\ &+ \frac{z^2}{4x_{\rm Bj}^2} \frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \frac{2x_{\rm Bj} F_1(x_{\rm Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2} \Big\} \end{aligned} \tag{5}$$

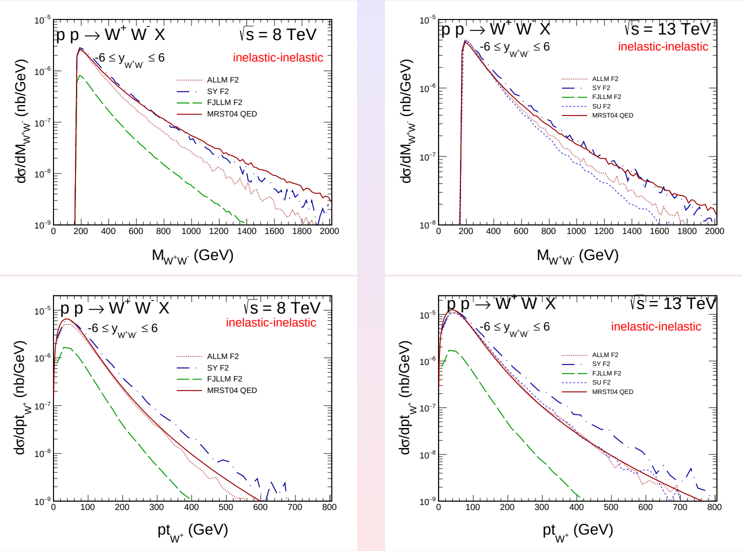
- for the elastic piece

$$\begin{aligned} \mathcal{F}^{\rm el}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) &= \frac{\alpha_{\rm em}}{\pi} \Big\{ (1-z) \Big(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \Big)^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2} \\ &+ \frac{z^2}{4} \frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} G_M^2(Q^2) \Big\} \end{aligned} \tag{6}$$

We obtain for the helicity-matrix element

$$
\begin{aligned}
M(\lambda_{W^+}\lambda_{W^-}) &= \frac{1}{|\vec{q}_{\perp 1}||\vec{q}_{\perp 2}|}\Big\{(\vec{q}_{\perp 1}\cdot\vec{q}_{\perp 2})\cdot\Big(\mathcal{M}(++;\lambda_{W^+}\lambda_{W^-})+\mathcal{M}(--;\lambda_{W^+}\lambda_{W^-})\Big)\\
&- i[\vec{q}_{\perp 1},\vec{q}_{\perp 2}]\Big(\mathcal{M}(++;\lambda_{W^+}\lambda_{W^-})-\mathcal{M}(--;\lambda_{W^+}\lambda_{W^-})\Big)\\
&- \Big(q^x_{\perp 1}q^x_{\perp 2}-q^y_{\perp 1}q^y_{\perp 2}\Big)\Big(\mathcal{M}(+-;\lambda_{W^+}\lambda_{W^-})+\mathcal{M}(-+;\lambda_{W^+}\lambda_{W^-})\Big)\\
&- i\Big(q^x_{\perp 1}q^y_{\perp 2}+q^y_{\perp 1}q^x_{\perp 2}\Big)\Big(\mathcal{M}(+-;\lambda_{W^+}\lambda_{W^-})-\mathcal{M}(-+;\lambda_{W^+}\lambda_{W^-})\Big) \quad (7)
\end{aligned}
$$

Results for k_T-factorization approach



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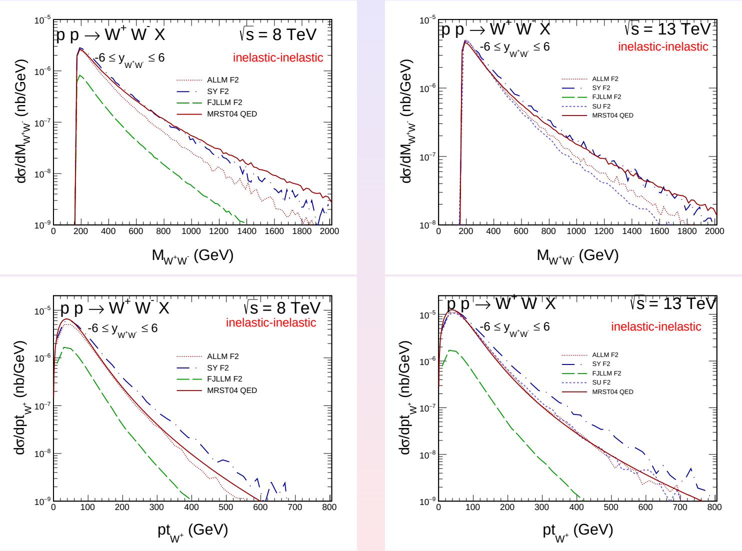

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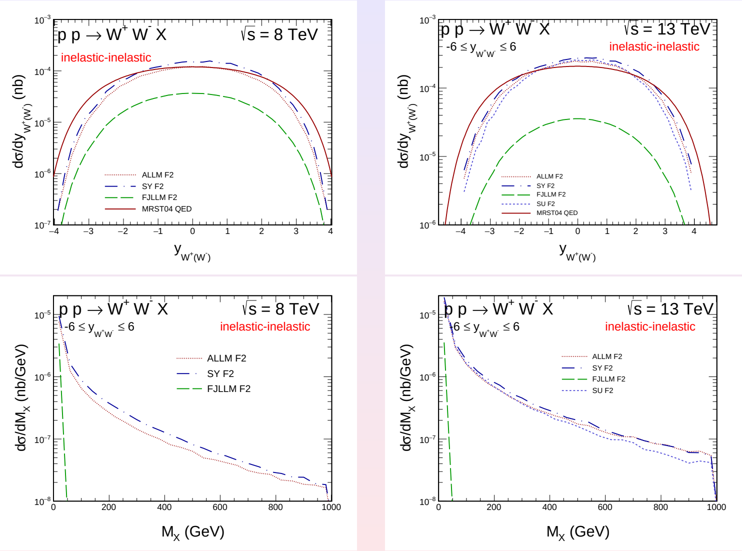

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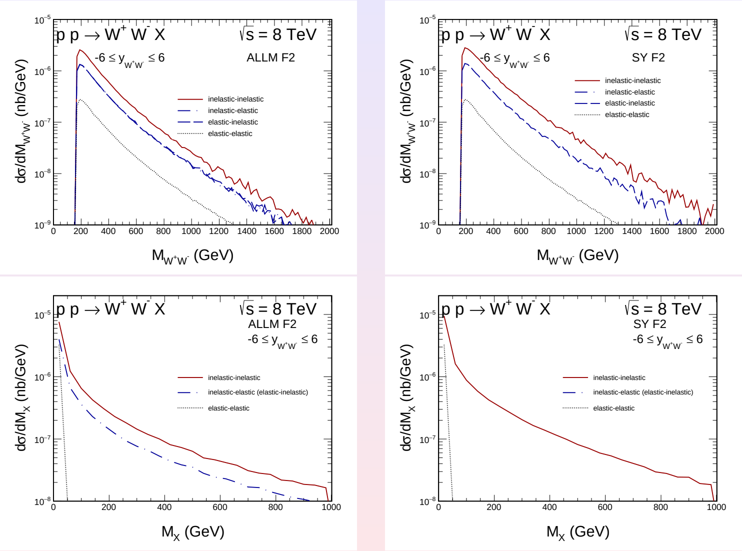
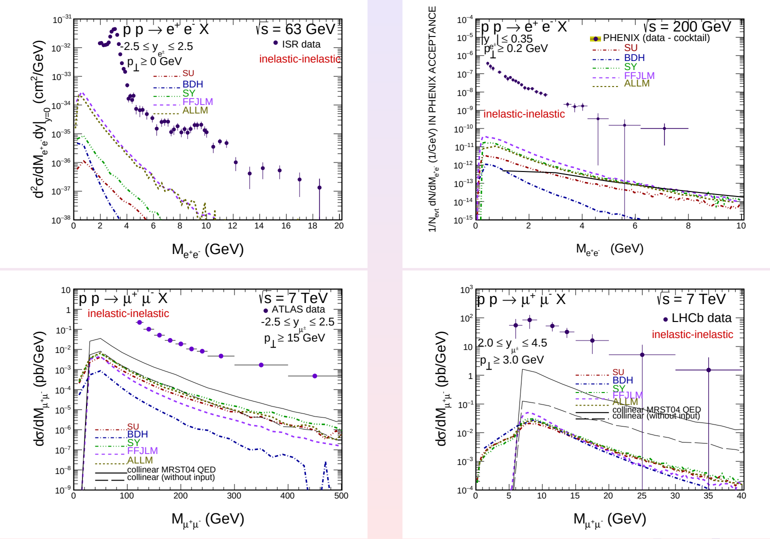


Cross sections for two-photon $pp \to l^+ l^- X$ process

M. Luszczak, W. Schafer and A. Szczurek, Phys.Rev. D93 (2016) 074018

(k_T-factorization approach)



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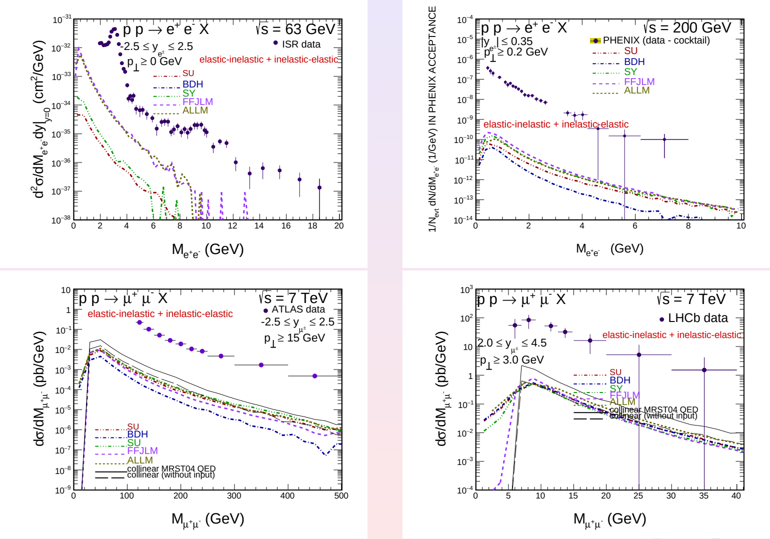

Conclusions

- Large contribution of photon induced processes
- Inelastic-inelastic photon-photon contribution large when photon treated as parton in the nucleon
- The inelastic contributions sum up to the cross section of the order of 0.5 - 1 pb at the LHC energies
- The photon-photon contributions are particularly important at large WW invariant masses, i.e. probably also large invariant masses of charged leptons where its contribution is larger than that for gluon-gluon fusion
- The elastic-inelastic or inelastic-elastic contributions are interesting by themselves - since they are related to the emission of forward/backward protons they could be potentially measured in the future with the help of forward proton detectors
- In the future we have to include decays of W bosons