Photon-induced processes

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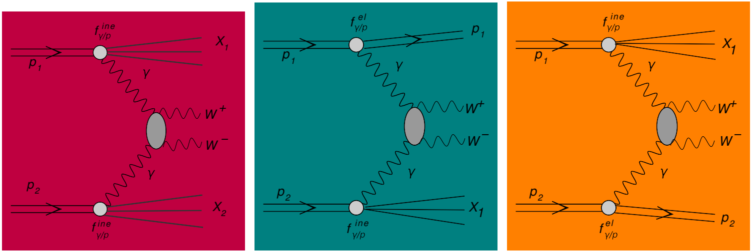
Introduction ($p + p$ collisions)

- Precise calculations of various electroweak reactions in *pp* collisions at the LHC need to account for, on top of the higher-order corrections, the effects of photon-induced processes.
- production of lepton pairs
  - **M. Luszczak, W. Schafer and A. Szczurek**, Phys.Rev. D93 (2016) 074018
  - **B. Linek, M. Luszczak and A. Szczurek**, paper in preparation
- pairs of electroweak bosons
  - **M. Luszczak, A. Szczurek and Ch. Royon**, JHEP 1502 (2015) 098
  - **M. Luszczak, W. Schafer and A. Szczurek**, JHEP 1805 (2018) 064
  - **L. Forthomme, M. Luszczak, W. Schafer and A. Szczurek**, Phys.Lett. B789 (2019) 300-307
- production of $t\bar{t}$ pairs
  - **M. Luszczak, L. Forthomme, W. Schafer and A. Szczurek**, JHEP 02 (2019) 100

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

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



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

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

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

QED parton distributions

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

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

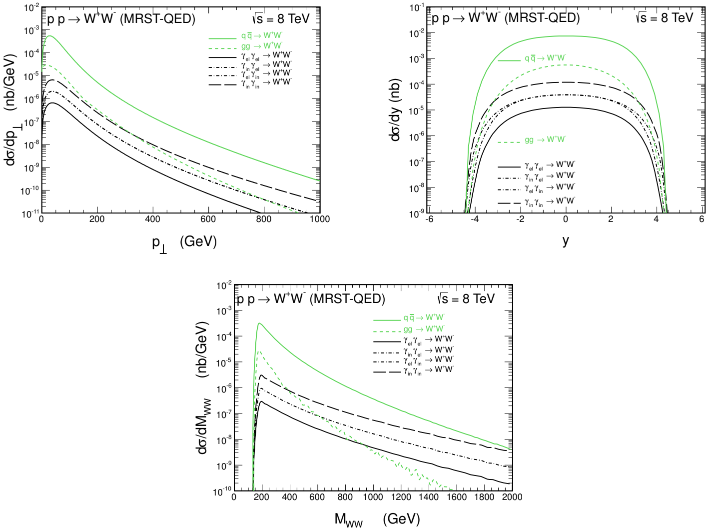
$$\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{gq}(y)\, \sum_j q_j(\frac{x}{y},\mu^2) + P_{gg}(y)\, g(\frac{x}{y},\mu^2)\right\}$$

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

- ## NNPDF2.3 parton distributions
  - fit to deep-inelastic scattering (DIS) and Drell-Yan data

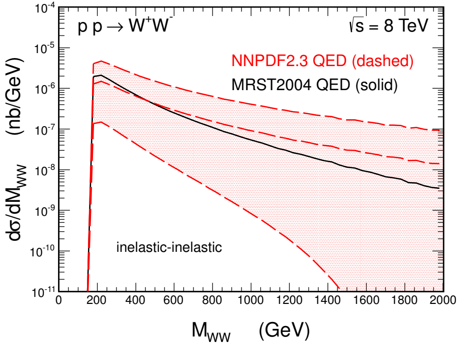
- ## LUXqed17 parton distributions
  - integral over proton structure functions $F_2(x,Q^2)$ and $F_L(x,Q^2)$

Results for MRSTQ parton distributions



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

NNPDF2.3 QED photon distributions



big uncertainties for large *WW* invariant masses

- very difficult to obtain the photon distributions from fits to experimental data

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

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

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

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

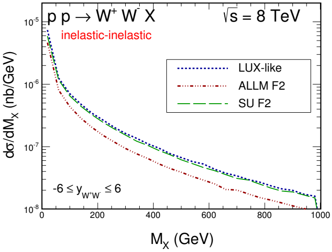
Unintegrated photon fluxes

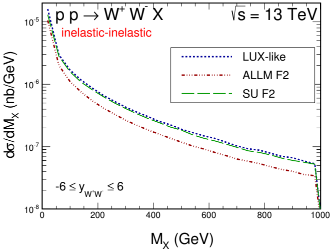
- the inelastic fluxes need the proton structure functions $F_2(\mathrm{Bj}, \mathrm{Q}^2)$ and $F_L(\mathrm{Bj}, \mathrm{Q}^2)$.

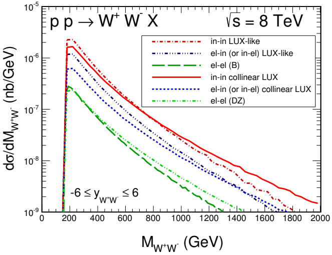
$$\begin{aligned}\mathcal{F}^{\mathrm{in}}_{\gamma^*\leftarrow A}(z, \boldsymbol{q}) &= \frac{\alpha_{\mathrm{em}}}{\pi}\Big\{(1-z)\Big(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2}\Big)^2 \frac{F_2(x_{\mathrm{Bj}}, Q^2)}{Q^2 + M_X^2 - m_p^2} \\ &+ \frac{z^2}{4x_{\mathrm{Bj}}^2}\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2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

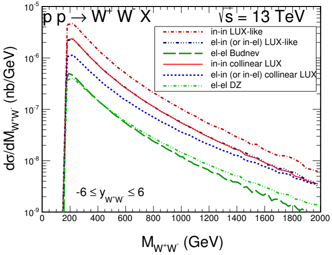
- elastic pieces only require the standard electromagnetic form factors of a proton

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


p p → W+ W- X
√s = 8 TeV
inelastic-inelastic
LUX-like
ALLM F2
SU F2
-6 ≤ yW+W- ≤ 6
dσ/dMX (nb/GeV)
MX (GeV)
10-5
10-6
10-7
10-8
0
200
400
600
800
1000


p p → W+ W- X
√s = 13 TeV
inelastic-inelastic
LUX-like
ALLM F2
SU F2
-6 ≤ yW+W- ≤ 6
dσ/dMX (nb/GeV)
MX (GeV)
10-5
10-6
10-7
10-8
0
200
400
600
800
1000

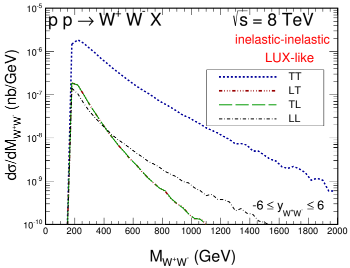

p p → W+ W- X
√s = 8 TeV
in-in LUX-like
el-in (or in-el) LUX-like
el-el (B)
in-in collinear LUX
el-in (or in-el) collinear LUX
el-el (DZ)
-6 ≤ yW+W- ≤ 6
dσ/dMW+W- (nb/GeV)
MW+W- (GeV)
10-5
10-6
10-7
10-8
10-9
0
200
400
600
800
1000
1200
1400
1600
1800
2000

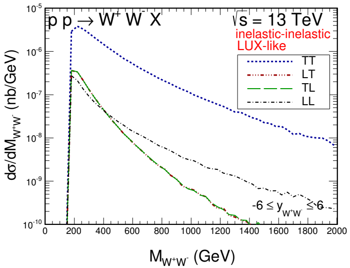

p p → W+ W- X
√s = 13 TeV
in-in LUX-like
el-in (or in-el) LUX-like
el-el Budnev
in-in collinear LUX
el-in (or in-el) collinear LUX
el-el DZ
-6 ≤ yW+W- ≤ 6
dσ/dMW+W- (nb/GeV)
MW+W- (GeV)
10-5
10-6
10-7
10-8
10-9
0
200
400
600
800
1000
1200
1400
1600
1800
2000

Results, spin decompositions

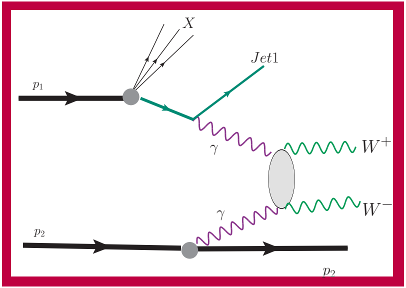
contribution	8 TeV	13 TeV
TT	0.405	0.950
LL	0.017	0.046
LT + TL	0.028 + 0.028	0.052 + 0.052
SUM	0.478	1.090

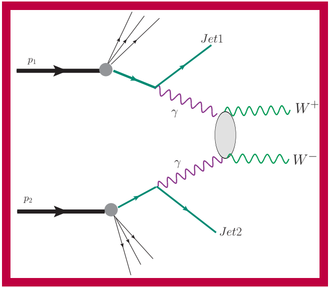
Table: Contributions of different polarizations of W bosons for the inelastic-inelastic component for the LUX-like structure function. The cross sections are given in *pb*.





Rapidity gap survival factors caused by remnant fragmentation





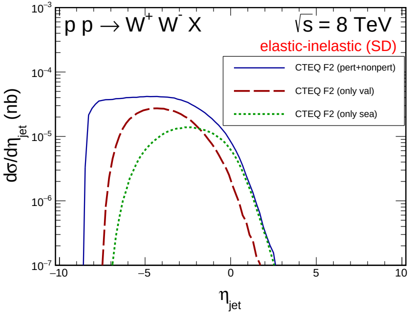
implementation of the above process

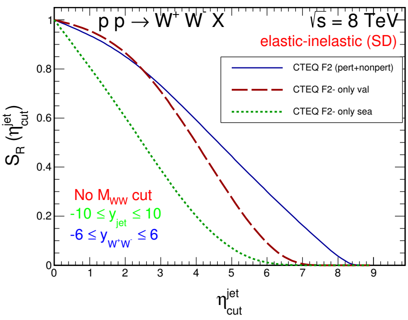
in CepGen for the Monte-Carlo generation of unweighted events

the hadronisation of remnant states X and/or Y systems

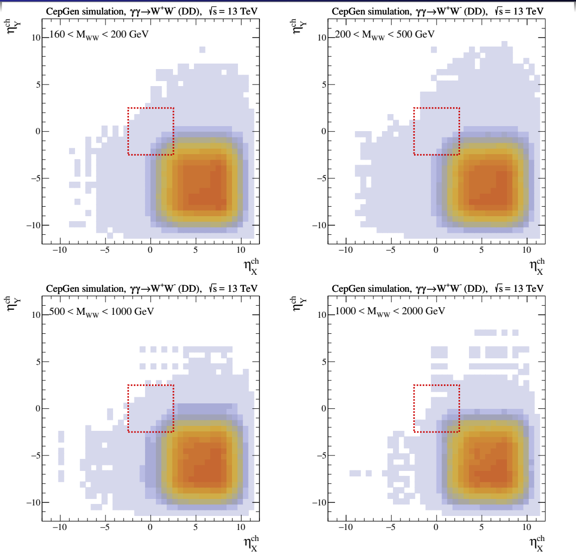
is performed using the Lund fragmentation algorithm implemented in Pythia8, and interfaced to CepGen.

$$S_R(\eta_{\mathrm{cut}}) = 1 - \frac{1}{\sigma} \int_{-\eta_{\mathrm{cut}}}^{\eta_{\mathrm{cut}}} \frac{\mathrm{d}\sigma}{\mathrm{d}\eta_{\mathrm{jet}}} \mathrm{d}\eta_{\mathrm{jet}}$$

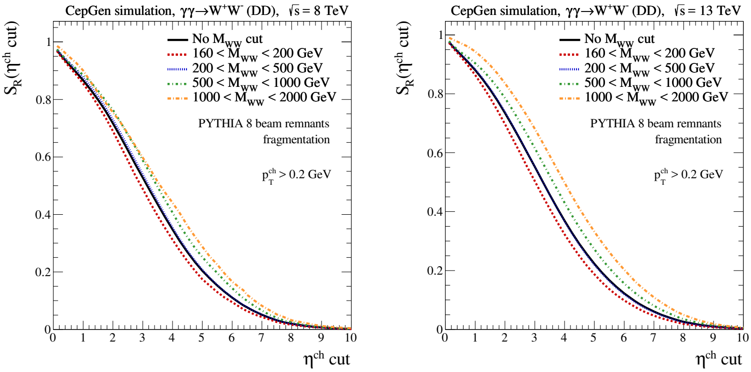




Double dissociation



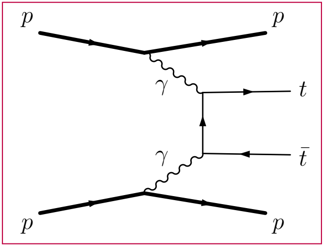
- distributions in pseudorapidity of particles from X ($\eta_X^{\rm ch}$) and Y ($\eta_Y^{\rm ch}$)

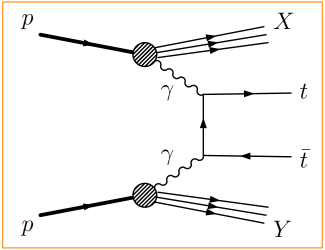


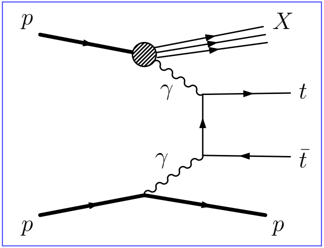
we predict a strong dependence on η_{cut}

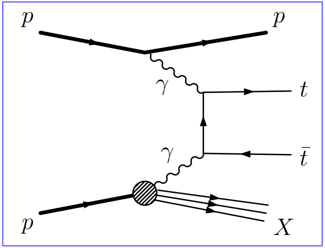
- it would be valuable to perform experimental measurements with different η_{cut}

Production of $t\bar{t}$ pairs









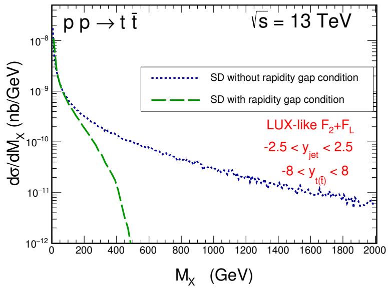
Contribution	No cuts	$y_{\rm jet}$ cut
elastic-elastic	0.292	0.292
elastic-inelastic inelastic-elastic	0.544	0.439
inelastic-inelastic	0.983	0.622
all contributions	2.36	1.79

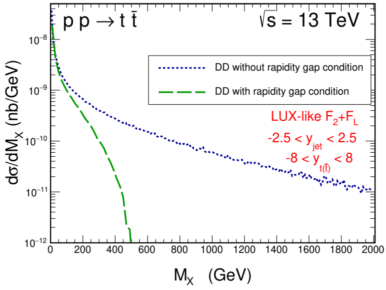
Table: Cross section in fb at $\sqrt{s} = 13$ TeV for different components (left column) and the same when the extra condition on the outgoing jet $|y_{\rm jet}| > 2.5$ is imposed.

right panel $\rightarrow$results when a rapidity gap (that means no additional particle production except the t or $\bar{t}$) in the central region, for $-2.5 < y < 2.5$ is required in addition

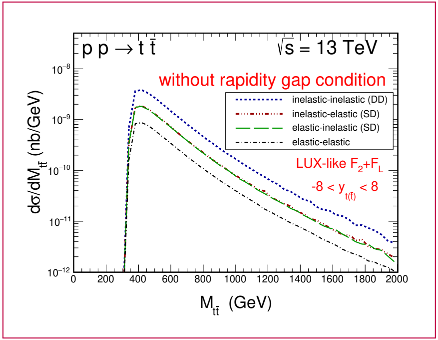
SD (left)

DD (right)

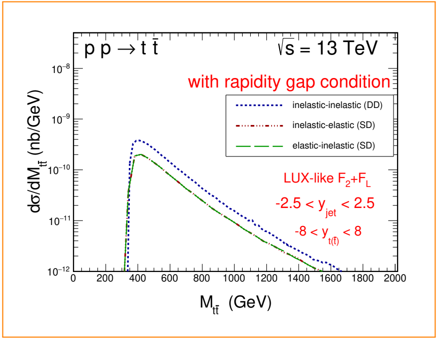




without rapidity gap condition



with rapidity gap condition



Central dilepton production with rapidity gap and with forward protons

The ATLAS collaboration analysis impose the consistency requirements:

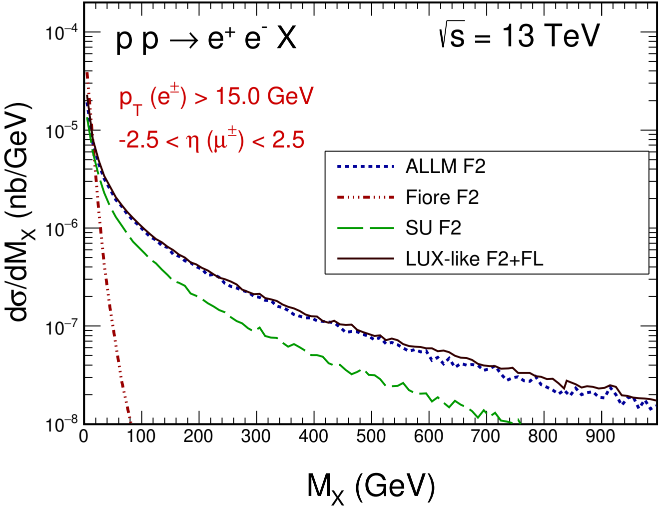
$$\xi_1 = \xi_{ll}^{+} \ , \ \xi_2 = \xi_{ll}^{-}$$

- The longitudinal momentum fractions of the photons werecalculated in the ATLAS analysis as:

$$\begin{aligned} \xi_{ll}^{+} &= \left(M_{ll}/\sqrt{s}\right) \exp(+Y_{ll}) \ , \\ \xi_{ll}^{-} &= \left(M_{ll}/\sqrt{s}\right) \exp(-Y_{ll}) \ . \end{aligned}$$

Only lepton variables enter the formula

- We use the same formula in our analysis


p p → e+ e- X
√s = 13 TeV
pT (e±) > 15.0 GeV
-2.5 < η (μ±) < 2.5
ALLM F2
Fiore F2
SU F2
LUX-like F2+FL
dσ/dMX (nb/GeV)
MX (GeV)
10−4
10−5
10−6
10−7
10−8
0
100
200
300
400
500
600
700
800
900

contribution	c.s. in fb without ξ-cuts	c.s. in fb with ξ-cuts
elastic-elastic, cut on proton 1	358.68	5.4591
elastic-elastic, cut on proton 2	......	5.4592
elastic-inelastic, cut on proton 1, SU, 0-100 GeV	427.8949	10.0190 (3.3492)
inelastic-elastic, cut on proton 2 SU, 0-100 GeV	427.0130	10.0186 (3.3491)
elastic-inelastic, VDM (no Ω), 0-100 GeV	98.0215 (2UN)	
inelastic-elastic, VDM (no Ω), 0-100 GeV	98.0297 (2UN)	
elastic-inelastic SU partonic	449.1076 (2UN)	
inelastic-elastic SU partonic	449.0985 (2UN)	
elastic-inelastic, cut on proton 1, ALLM	468.6102 (2UN)	11.8292
inelastic-elastic, cut on proton 2, ALLM	468.6102 (2UN)	11.8294
elastic-inelastic, new Szczurek	461.5330 (2UN)	12.6046 [14.1823] (5.9311)
inelastic-elastic, new Szczurek	461.5750 (2UN)	12.6032 [14.1806] (5.9309)
elastic-inelastic, ALLM	571.871 (GEN)	9.711
inelastic-elastic, ALLM	571.562 (GEN)	9.621
elastic-inelastic, LUX-like, $F_2 + F_L$	635.215 (GEN)	19.894
inelastic-elastic, LUX-like, $F_2 + F_L$	635.102 (GEN)	19.831
elastic-inelastic, LUX-like, F_2 only	.... (GEN)	......
inelastic-elastic, LUX-like, F_2 only	656.702 (GEN)	......
elastic-inelastic, cut on proton 1, resonances	38.6709 (2UN)	0.57872
inelastic-elastic, cut on proton 2 resonances	38.6639 (2UN)	0.57872
elastic-inelastic, cut on proton 1, Δ^{+}	28.5844 (2UN)	0.42755
inelastic-elastic, cut on proton 2 Δ^{+}	28.5814 (2UN)	0.42763

Tablica: Integrated cross section for $\mu^+\mu^-$ with one p in 0.035 $< \xi_{ll}^{\pm} <$ 0.08. Here $p_{1t}, p_{2t} >$ 15 GeV and -2.5 $< y_1, y_2 <$ 2.5. In the paranthesis result with $p_{t,sum} <$ 5 GeV. 2UN – doubly unintegrated photon distribution and GEN – generator version.

reaction	no soft S_G	with soft S_G	$< S_G >$
-2.5 $< Y_{ll} <$ 2.5			
elastic-elastic	0.54438	0.50402	0.926
inelastic-elastic	0.89595	0.64283	0.717
elastic-inelastic	0.89587	0.64254	0.717
inelastic-inelastic	1.62859	0.24172	0.15
-2.5 $< y_1, y_2 <$ 2.5 in addition			
elastic-elastic	0.42268	0.39355	0.931
inelastic-elastic	0.69241	0.51092	0.738
elastic-inelastic	0.69246	0.51087	0.738
ξ cut in addition			
elastic-elastic, cut on ξ_1	0.00762	0.00675	0.886
elastic-elastic, cut on ξ_2	0.00762	0.00675	0.886
inelastic-elastic, cut on ξ_2	0.02718	0.01416	0.521
elastic-inelastic, cut on ξ_1	0.02717	0.01416	0.521
$p_{t,pair} <$ 5 GeV in addition			
elastic-elastic	....	....	.....
inelastic-elastic, cut on ξ_2	0.008035 (2000)	0.00435	0.541
elastic-inelastic, cut on ξ_1	0.008056 (2000)	0.00436	0.541

Tablica: Integrated cross section for $\mu^+\mu^-$ production in pb for $\sqrt{s}$ = 13 TeV using SUPERCHIC program. $0.035 < \xi_{ll}^{\pm} < 0.08$. To calculate absorption effects we used model no 4 as implemented in the SUPERCHIC generator.

Conclusions

- We use a recent formalism developed for the inclusive case which includes transverse momenta of incoming photons.
- We have found that the hadronisation only mildly modifies the gap survival factor calculated on the parton level. This may justify approximate treatment of hadronisation of remnants.
- We have also made calculations with the popularSUPERCHIC generator and compared corresponding results to the results of our code(s). In general, the results are almost identical.
- We have calculated also soft rapidity gap survival factor(probability of no hadron emission in the range of the main (ATLAS, CMS) detector) as a function of M_{ll},transverse momentum of the dilepton pair, mass of the proton remnant and Y_{ll}.
- The soft gap survival factor for single dissociative contribution strongly depends on whether proton is measured or not. It is significantly smaller when proton is measured.
- We have also calculated gap survival factor due to mini(jet) emission by checking whether the minijet enters or not the main detector.