Production of heavy particle pairs via photon-photon processes at the LHC

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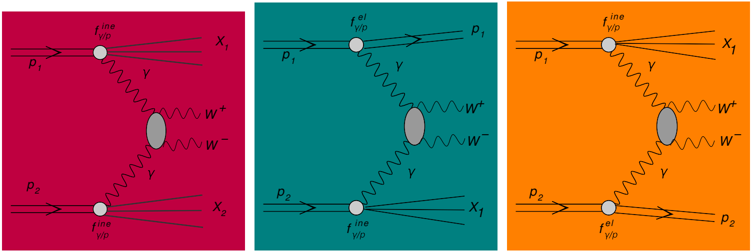
Introduction ($p + p$ collisions)

- 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
- 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



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

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

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

QED parton distributions

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

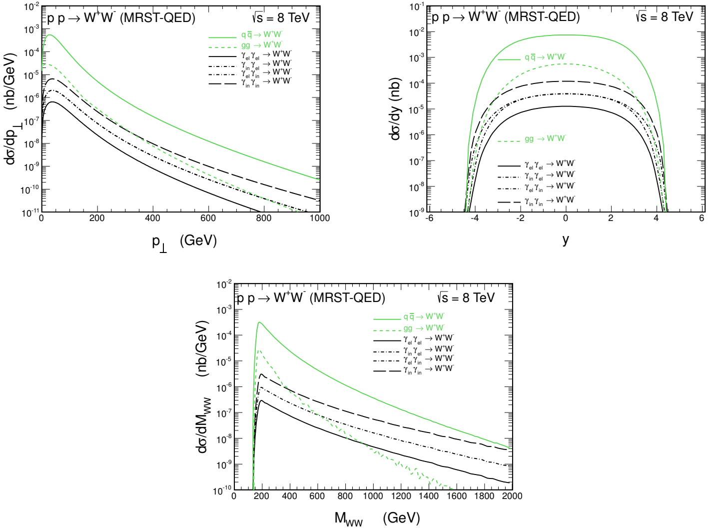
$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{qq}(y)\, q_i(\frac{x}{y},\mu^2) + P_{qg}(y)\, g(\frac{x}{y},\mu^2)\right\} + \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{\tilde{P}_{qq}(y)\, e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\, e_i^2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

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

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

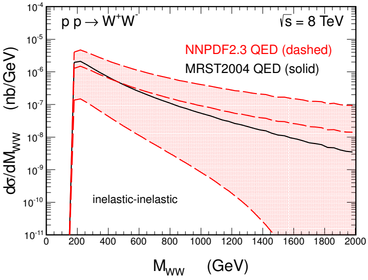
- NNPDF2.3 parton distributions
  - fit to deep-inelastic scattering (DIS) and Drell-Yan data
- LUXqed17 parton distributions
  - integral over proton structure functions $F_2(x,Q^2)$ and $F_L(x,Q^2)$

Results for MRSTQ parton distributions



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

NNPDF2.3 QED photon distributions



- big uncertainties 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
- 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

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

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

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

- 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

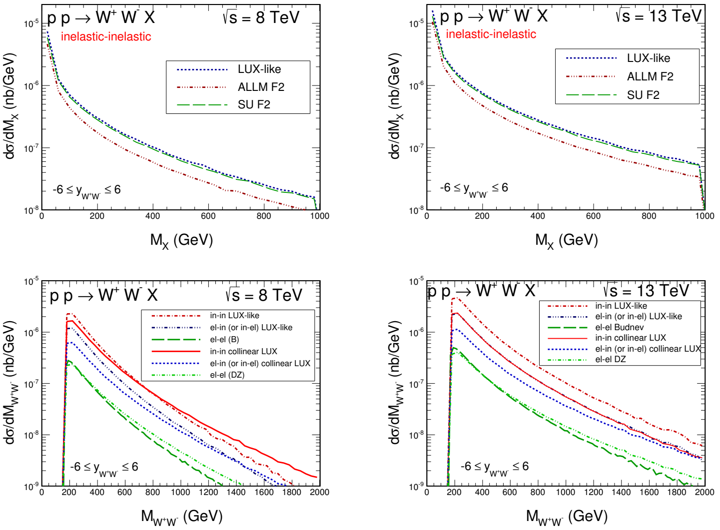
$$dn^{\mathrm{in,el}} = \frac{dz}{z} \frac{d^2\boldsymbol{q}}{\pi \boldsymbol{q}^2} \mathcal{F}^{\mathrm{in,el}}_{\gamma^* \leftarrow A}(z, \boldsymbol{q})$$

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

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

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

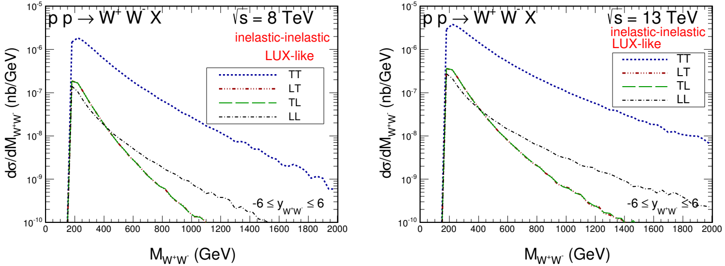
$$\begin{aligned} \mathcal{F}^{\mathrm{el}}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) &= \frac{\alpha_{\mathrm{em}}}{\pi} \Big\{ (1-z) \Big(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \Big)^2 \frac{4 m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4 m_p^2 + Q^2} \\ &+ \frac{z^2}{4} \frac{\boldsymbol{q}^2}{\boldsymbol{q}^2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


p p → W+ W- X
√s = 8 TeV
inelastic-inelastic
LUX-like
ALLM F2
SU F2
-6 ≤ y_W+W- ≤ 6
dσ/dM_X (nb/GeV)
M_X (GeV)
p p → W+ W- X
√s = 13 TeV
inelastic-inelastic
LUX-like
ALLM F2
SU F2
-6 ≤ y_W+W- ≤ 6
dσ/dM_X (nb/GeV)
M_X (GeV)
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 ≤ y_W+W- ≤ 6
dσ/dM_W+W- (nb/GeV)
M_W+W- (GeV)
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 ≤ y_W+W- ≤ 6
dσ/dM_W+W- (nb/GeV)
M_W+W- (GeV)

Results, spin decompositions

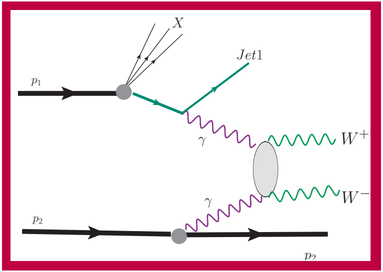
contribution	8 TeV	13 TeV
TT	0.405	0.950
LL	0.017	0.046
LT + TL	0.028 + 0.028	0.052 + 0.052
SUM	0.478	1.090

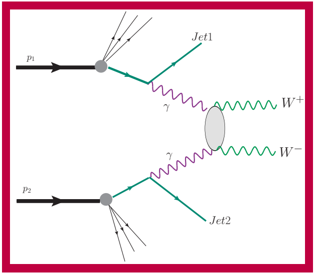
Table: Contributions of different polarizations of W bosons for the inelastic-inelastic component for the LUX-like structure function. The cross sections are given in pb.



Rapidity gap survival factors caused by remnant fragmentation

- Our main aim is to estimate gap survival factor associated with the remnant hadronisation, which destroys the rapidity gap

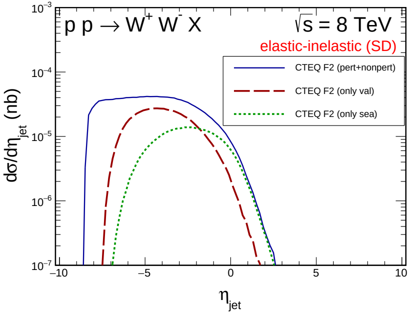


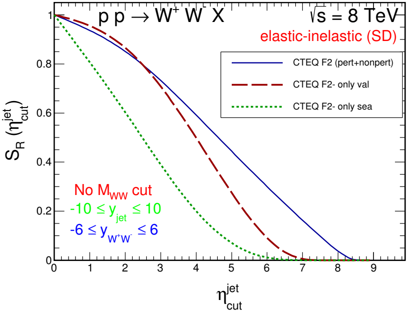


- We use an implementation of the above process in CepGen for the Monte-Carlo generation of unweighted events
- The hadronisation of remnant states X and/or Y systems is performed using the Lund fragmentation algorithm implemented in Pythia8, and interfaced to CepGen. We model the incoming photon as emitted from a valence (up) quark collinear to the incoming proton direction

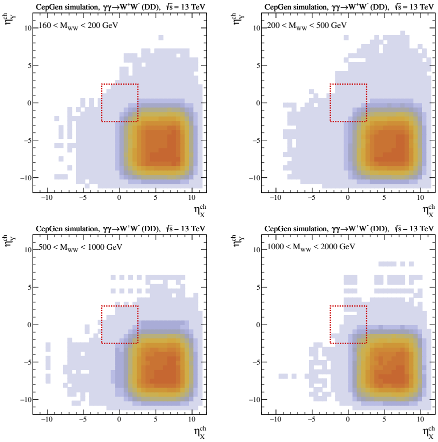
Parton level approach for single dissociation

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



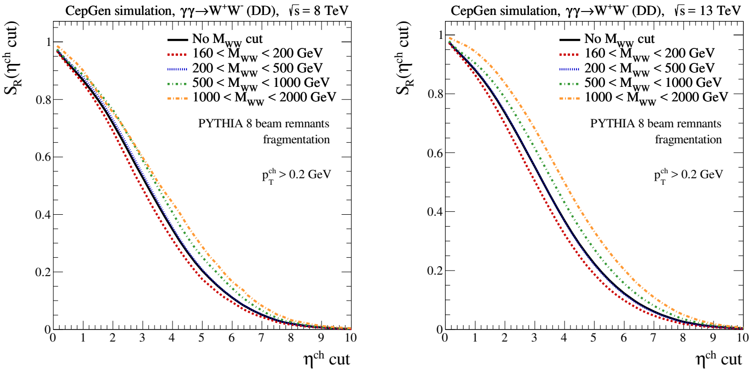


Double dissociation



- distributions in pseudorapidity of particles from X ($\eta_X^{\rm ch}$) and Y ($\eta_Y^{\rm ch}$) for different ranges of masses of the centrally produced system

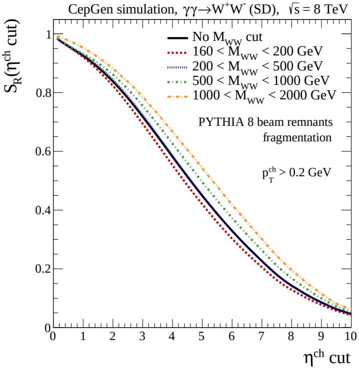
Double dissociation

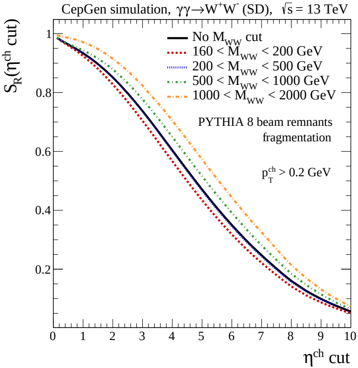


we predict a strong dependence on η_{cut}

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

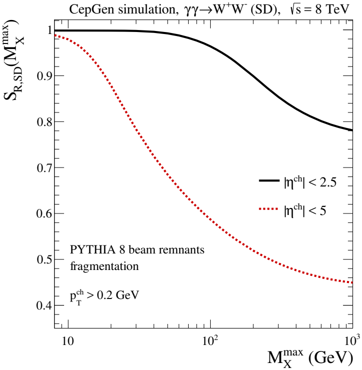
Single dissociation





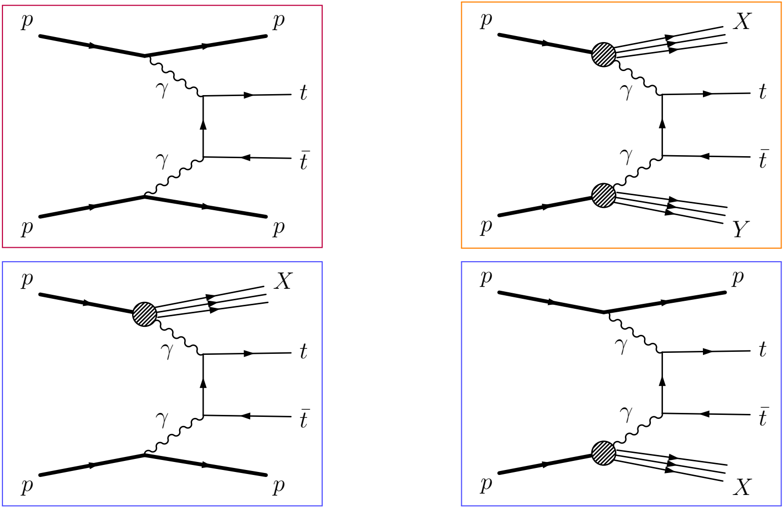
$$S_{R,DD} \approx (S_{R,SD})^2$$

Single dissociation



- We observe that for an $\eta_{\rm cut}$ value of 2.5 the rapidity gap survival factor S_R stays very close to 1 for $M_X^{\rm max} < 100$ GeV
- Increasing the mass of the dissociative system leads to graduate destroying of the (pseudo)rapidity gap, arbitrarily fixed here to be $-2.5 < \eta < 2.5$ (ATLAS, CMS)

Production of $t\bar{t}$ pairs



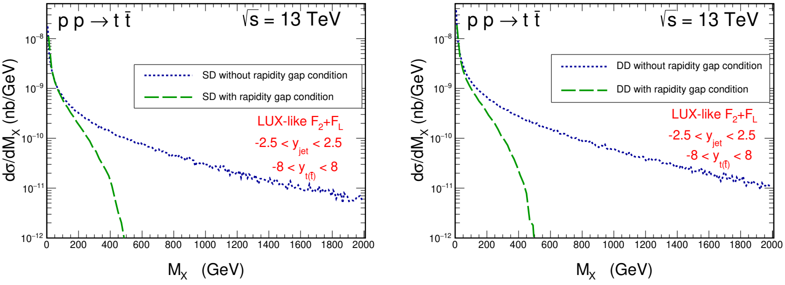
Production of $t\bar{t}$ pairs

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

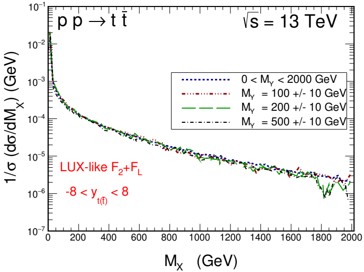
Table: Cross section in fb at $\sqrt{s} = 13$ TeV for different components (left column) and the same when the extra condition on the outgoing jet $|y_{\rm jet}| > 2.5$ is imposed.

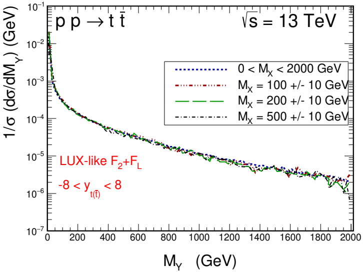
right panel $\rightarrow$results when a rapidity gap (that means no additional particle production except the t or $\bar{t}$) in the central region, for $-2.5 < y < 2.5$ is required in addition

Production of $t\bar{t}$ pairs



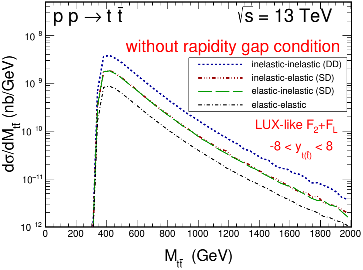
- distributions in outgoing proton remnant masses M_X and/or M_Y
- population of large M_X or M_Y masses is associated with the emissions of jets visible in central detectors (i.e. with -2.5 $< y_{\rm jet} <$ 2.5)
- the rapidity gap requirement introduces a rather sharp cut-off in the large-mass tail of the M_X-distribution

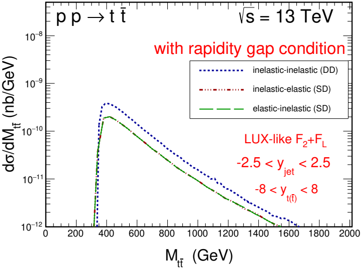




- distributions in M_X for a fixed M_Y (left) and in M_Y for a fixed M_X (right)
- the distributions are arbitrarily normalized to the same integral
- all the distributions coincide (this means that the two-dimensional distribution can be factorized)

Production of $t\bar{t}$ pairs





- conditions on outgoing light quark/antiquark jets are imposed
- the extra condition leads to a lowering of the cross section with only very small modification of the shape in $M_{t\bar{t}}$

Conclusions

- We have discussed the quantity called remnant gap survival factor for the $pp \to W^+W^-$ and $pp \to t\bar{t}$ reaction initiated via photon-photon fusion.
- We use a recent formalism developed for the inclusive case which includes transverse momenta of incoming photons.
- First we have calculated the gap survival factor for single dissociative process on the parton level. In such an approach the outgoing parton (jet/mini-jet) is responsible for destroying the rapidity gap.
- 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.