Subleading processes in production of W^+W^- pairs in proton-proton collisions

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Plan of the talk

- Introduction
- Exclusive $pp \to ppW^+W^-$ reaction
- Different mechanisms of inclusive production of W^+W^- pairs
  - $q\bar{q} \to W^+W^-$ and $gg \to W^+W^-$ mechanisms
  - $\gamma\gamma \to W^+W^-$ (electroweak corrections)
  - Resolved photons
  - Single diffractive production of W^+W^-
  - Double parton scattering
  - Results
- Conclusions

Based on:

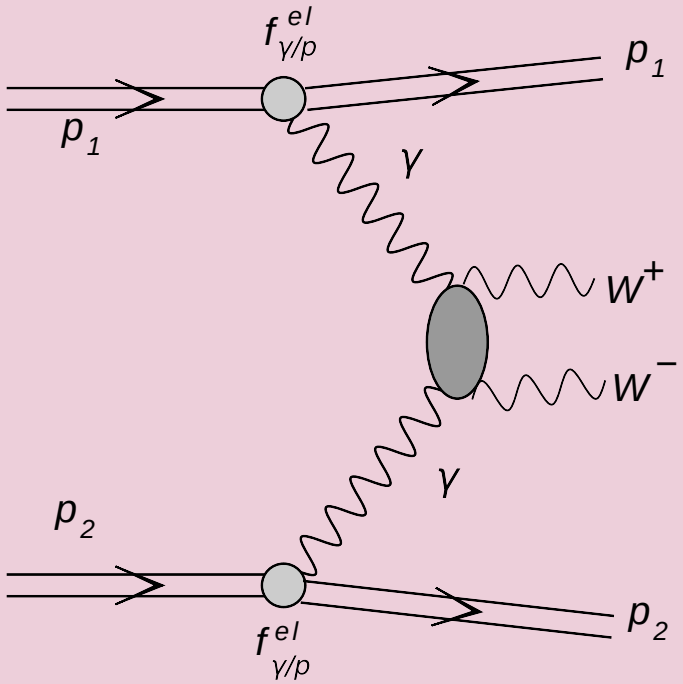
M. Łuszczak, A. Szczurek and Ch. Royon, JHEP 1502 (2015) 098, arXiv:1409.1803

Introduction

- Inclusive cross section for W^+W^- production in proton-proton scattering was measured by the ATLAS and CMS collaborations.
- The cross section was calculated at NLO collinear approach (some missing strength ?)
- Many processes are not included in the so-called Standard Model approach
- Production of W^+W^- with no activity close to μ^+e^- or μ^-e^+ vertices was measured by the CMS and recently by ATLAS.
- It was argued that inclusive W^+W^- cross section could be described via double-parton scattering mechanism and competes with the $H \to W^{*,+}W^-, W^{*,-}W^+$

$pp \to ppW^+W^-$ reaction

- The exclusive $pp \to ppW^+W^-$ reaction is particularly interesting in the context of $\gamma\gamma WW$ coupling
- The general diagram for the $pp \to ppW^+W^-$ reaction via $\gamma_{el}\gamma_{el} \to W^+W^-$ *subprocess*



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

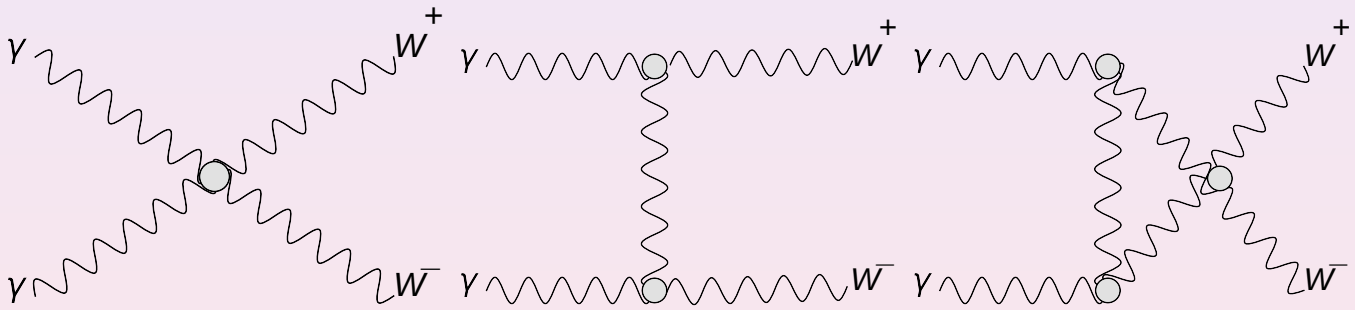
The three-boson $WW\gamma$ and four-boson $WW\gamma\gamma$ couplings, which contribute to the $\gamma\gamma \to W^+W^-$ process in the leading order:

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

where the asymmetric derivative has the form
$X \overleftrightarrow{\partial^\mu} Y = X\partial^\mu Y - Y\partial^\mu X$.

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

- The Born diagrams for the $\gamma\gamma \to W^+W^-$ subprocess



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

The elementary tree-level cross section for the $\gamma\gamma \to W^+W^-$ subprocess can be written in the compact form in terms of the Mandelstam variables

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

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

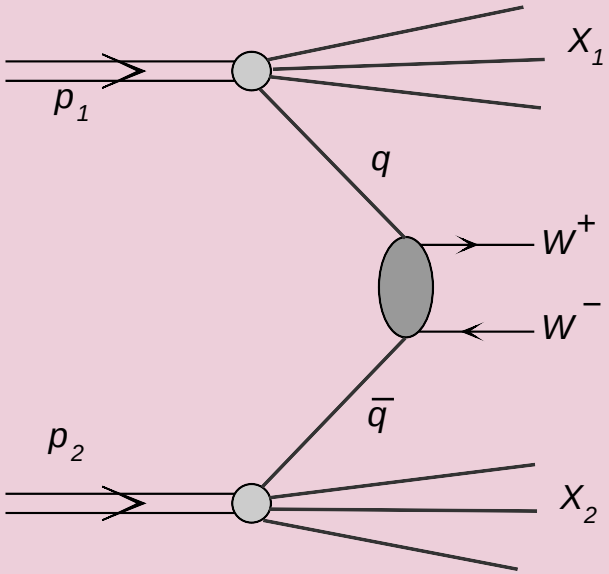
The exclusive diffractive mechanism

The exclusive diffractive KMR mechanism of central 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 in

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

and turned out to be negligibly small.

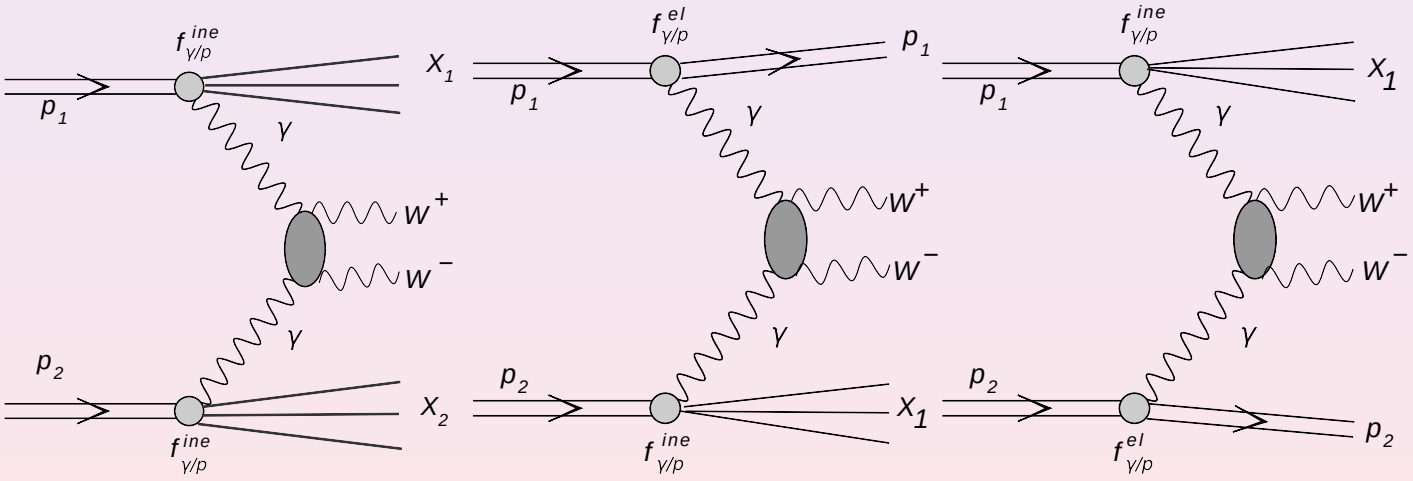
$q\bar{q} \to W^+W^-$ mechanism



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

- $\gamma\gamma$ processes contribute also to inclusive cross section. We consider in addition 3 new mechanisms



Inclusive production of W^+W^- pairs

Two different approach are possible:
- collinear - factorization:
(M. Łuszczak, A. Szczurek and Ch. Royon, JHEP 1502 (2015) 098, arXiv:1409.1803)
- 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, work in progress)

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

MRSTQ parton distributions

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

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

MRSTQ parton distributions

In addition to usual P_{qq}, P_{gq}, P_{qg}, P_{gg} spliting functions new spliting functions apper.

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

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

$$P_{q\gamma} = T_R^{-1} P_{qg}, \tag{2}$$

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

momentum is conserved:

$$\int_0^1 dx \, x \left\{ \sum_i q_i(x,\mu^2) + g(x,\mu^2) + \gamma(x,\mu^2) \right\} = 1$$

NNPDF2.3 parton distributions

- QCD corrections included up to NLO or NNLO;
- QED corrections included to LO;
- 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;
- all other PDFs constrained by the same data included in the NNPDF2.3 PDF determination

Cross section for photon-photon processes

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

- include only cases when nucleons do not survive a collision and nucleon debris is produced instead

Cross section for photon-photon processes

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

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

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

The elastic photon fluxes are calculated using the Drees-Zeppenfeld parametrization, where a simple parametrization of nucleon electromagnetic form factors was used

Naive approach to photon flux

- 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

$$xf_{\gamma/p}(x) = \sum_q \int_x^1 dx_q f_q(x_q, \mu^2) e_q^2 \left(\frac{x}{x_q}\right) f_{\gamma/q}\left(\frac{x}{x_q}, Q_1^2, Q_2^2\right)$$

Naive approach to photon flux

- the flux of photons in a quark/antiquark was parametrized as:

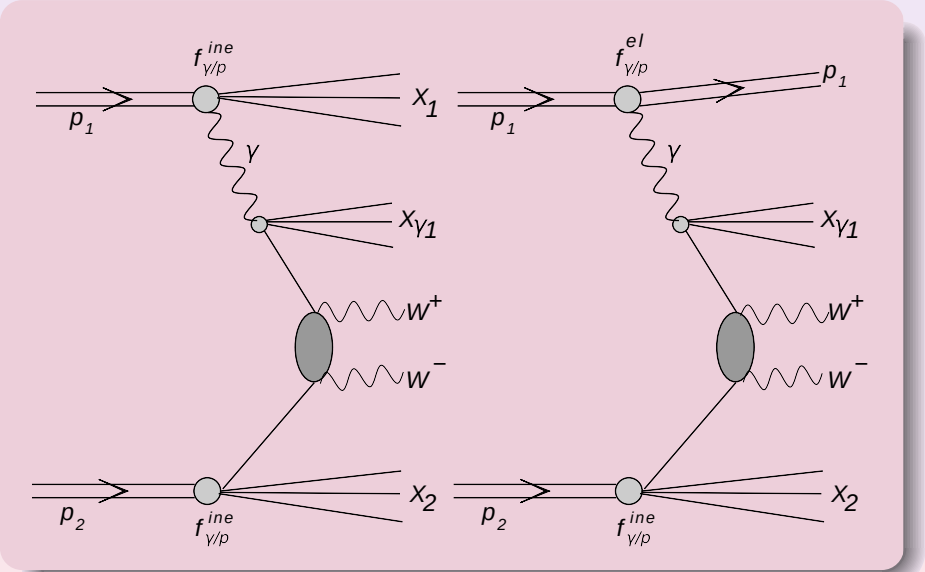
$$f_\gamma(z) = \frac{\alpha_{em}}{2\pi} \frac{1+(1-z)^2}{2} \log\left(\frac{Q_1^2}{Q_2^2}\right) .$$

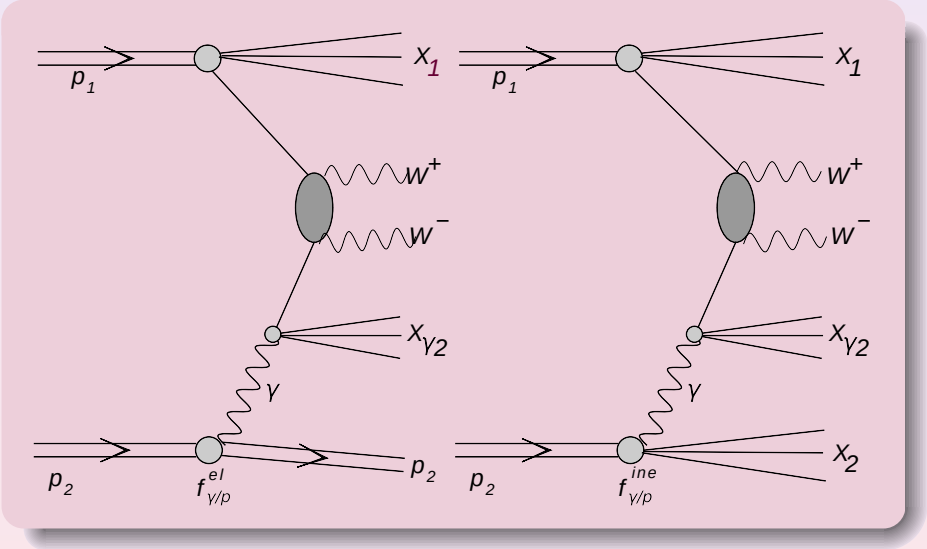
- the choice of scales:

$$\begin{aligned} Q_1^2 &= \max(\hat{s}/4 - m_W^2, 1\mathrm{GeV}^2) \\ Q_2^2 &= 1\mathrm{GeV}^2 \\ \mu^2 &= \hat{s}/4 . \end{aligned}$$

Resolved photons

For completness we include also the following processes





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:

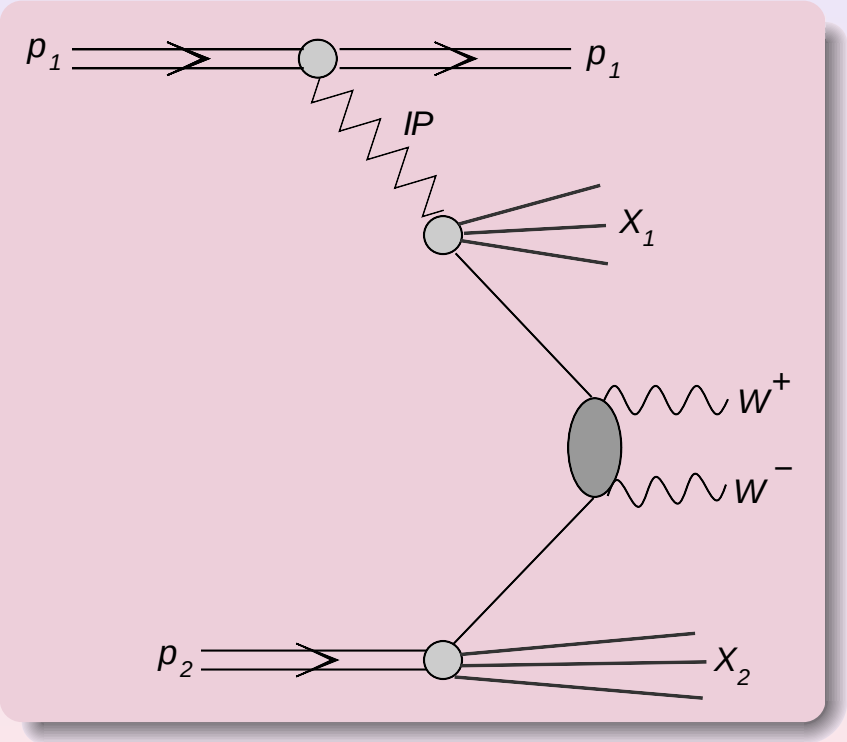
$$f^{\gamma}_{q/p} = f_{\gamma/p} \otimes f_{q/\gamma}$$

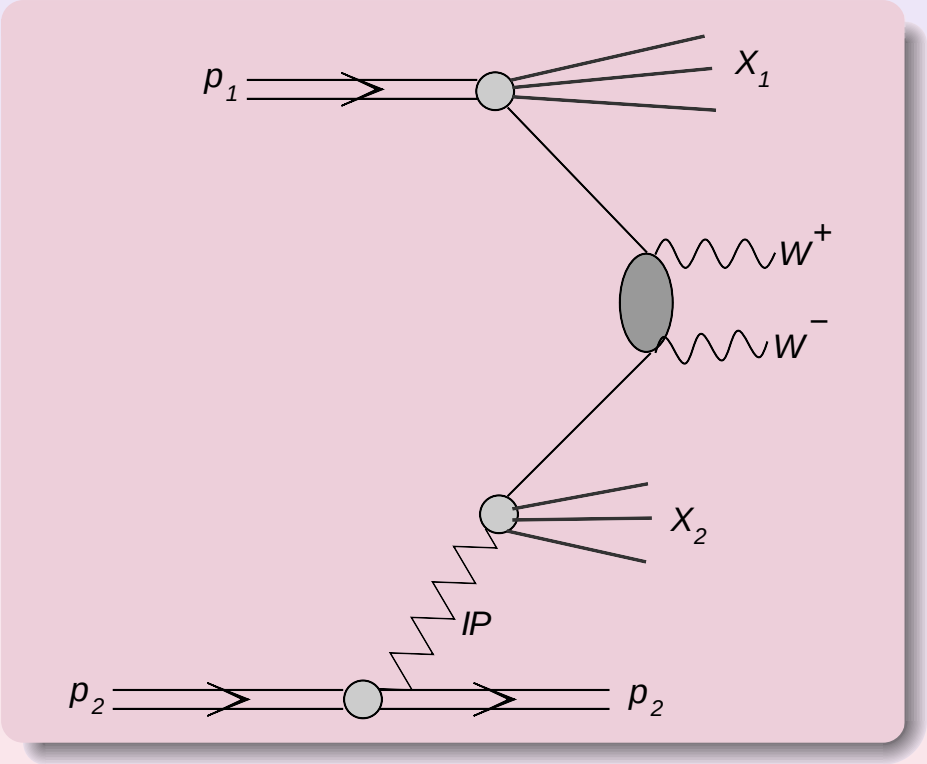
which mathematically means:

$$x f^{\gamma}_{q/p}(x) = \int_x^1 dx_\gamma f_{\gamma/p}(x_\gamma, \mu_s^2) \left(\frac{x}{x_\gamma}\right) f\left(\frac{x}{x_\gamma}, \mu_h^2\right) .$$

Technically first $f_{\gamma/p}$ in the proton is prepared on a dense grid for $\mu_s^2 \sim 1$ 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.

Single diffractive production of W^+W^- pairs





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.

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

$$+\Big(x_1\bar{q}_f^D(x_1,\mu^2)\,x_2\,q_f(x_2,\mu^2)\Big)\Big],$$

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

$$+\Big(x_1\bar{q}_f^D(x_1,\mu^2)\,x_2\,q_f^D(x_2,\mu^2)\Big)\Big]$$

The matrix element squared for the $q\bar{q} \to W^+W^-$ process is the same as previously for non-diffractive processes

Formalism

The 'diffractive' quark distribution of flavour f can be obtained by a convolution of the flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$ and the parton distribution in the Pomeron $q_{f/\mathbf{P}}(\beta, \mu^2)$:

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

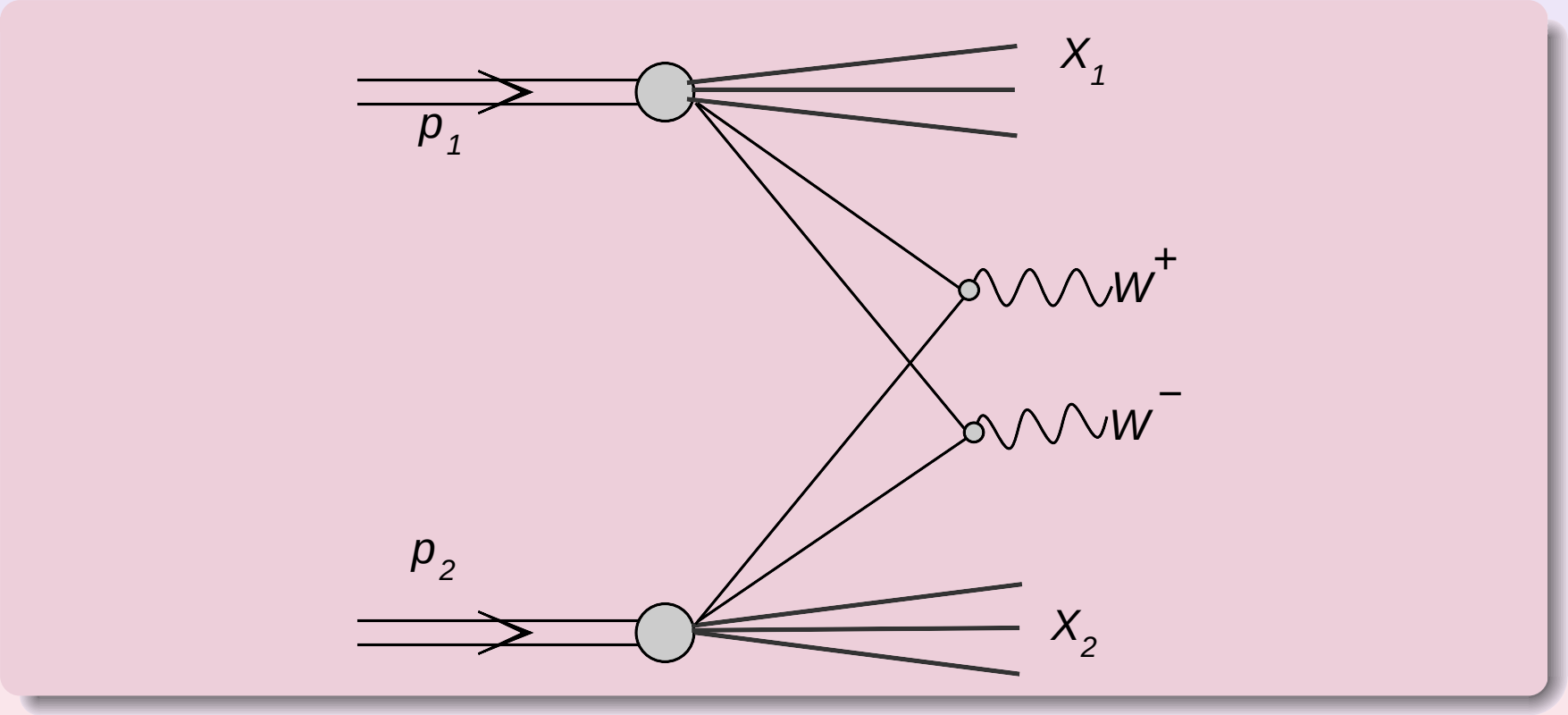
The flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$:

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

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

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

Double parton scattering



Gaunt-Stirling, Krasny-Płaczek, Golec-Lewandowska

Double parton scattering

In leading-order one can get only some (academic) distributions:

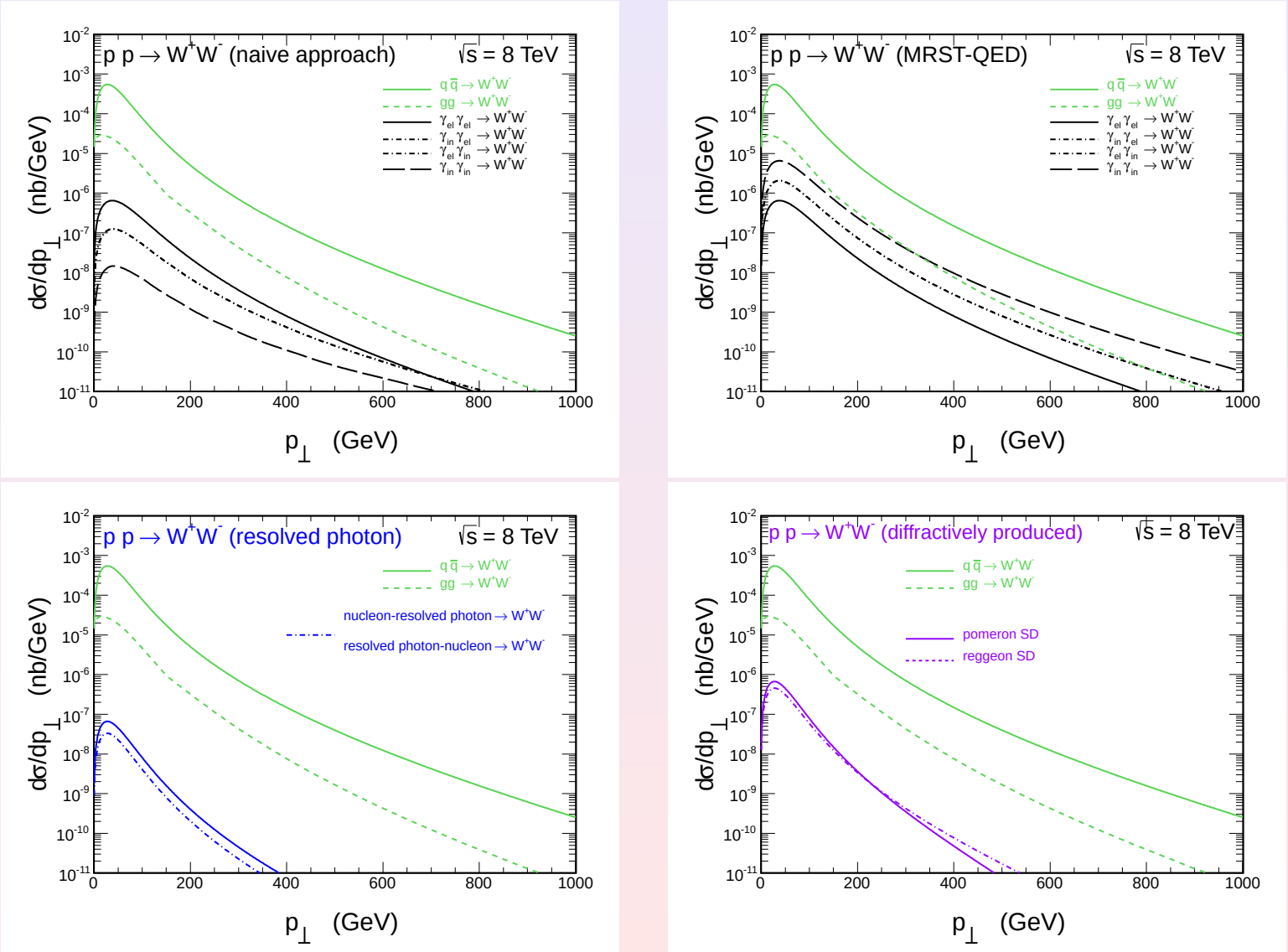
$$\frac{d\sigma}{dy_{W^+}dy_{W^-}} = \frac{1}{\sigma_{eff}}\frac{d\sigma_{W^+}}{dy_1}\frac{d\sigma_{W^-}}{dy_2} \,. \tag{3}$$

or

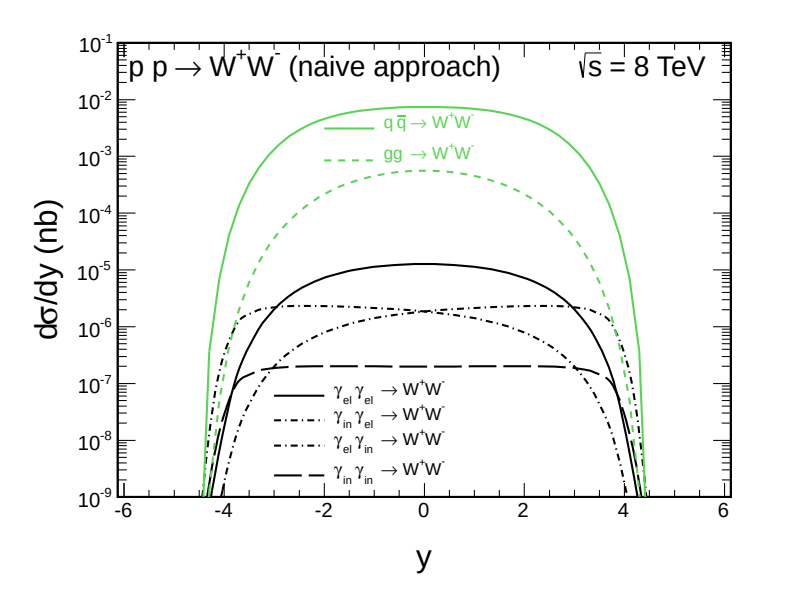
$$\frac{d\sigma}{dy_{W^+}}, \frac{d\sigma}{dy_{W^-}}, \frac{d\sigma}{dM_{WW}}, \frac{d\sigma}{dy_{W^+W^-}}. \tag{4}$$

σ_{eff} is related to overlap of quark/antiquark distribution in the transverse impact-parameter space.
We know phenomenological value of $\sigma_{eff} \approx 15$ mb for gluon-gluon initiated processes.
In principle, it could be very different for W^+, W^- production.

Results


p p → W+W- (naive approach)
√s = 8 TeV
p p → W+W- (MRST-QED)
√s = 8 TeV
p p → W+W- (resolved photon)
√s = 8 TeV
nucleon-resolved photon → W+W-
resolved photon-nucleon → W+W-
p p → W+W- (diffractively produced)
√s = 8 TeV
pomeron SD
reggeon SD
q q̄ → W+W-
gg → W+W-
γel γel → W+W-
γin γel → W+W-
γel γin → W+W-
γin γin → W+W-
dσ/dp⊥ (nb/GeV)
p⊥ (GeV)

Results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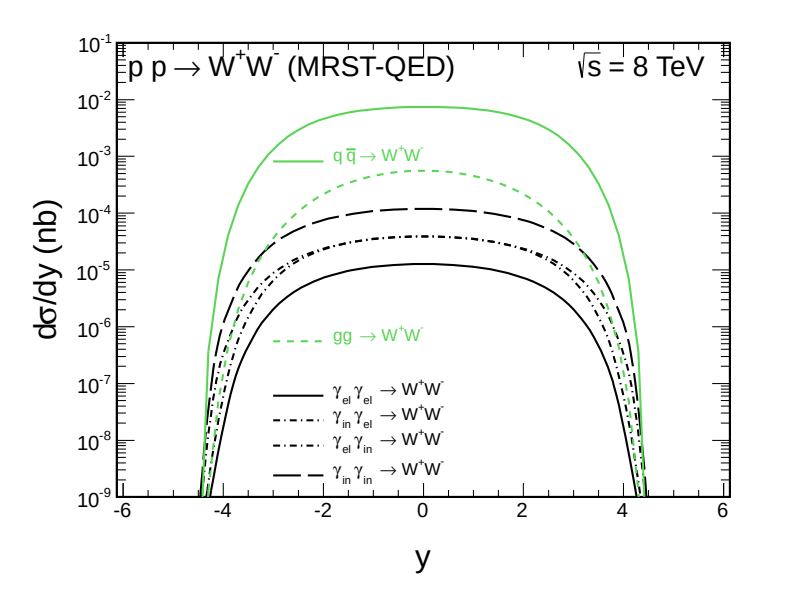
γel γel → W+W-
γin γel → W+W-
γel γin → W+W-
γin γin → W+W-
dσ/dy (nb)
y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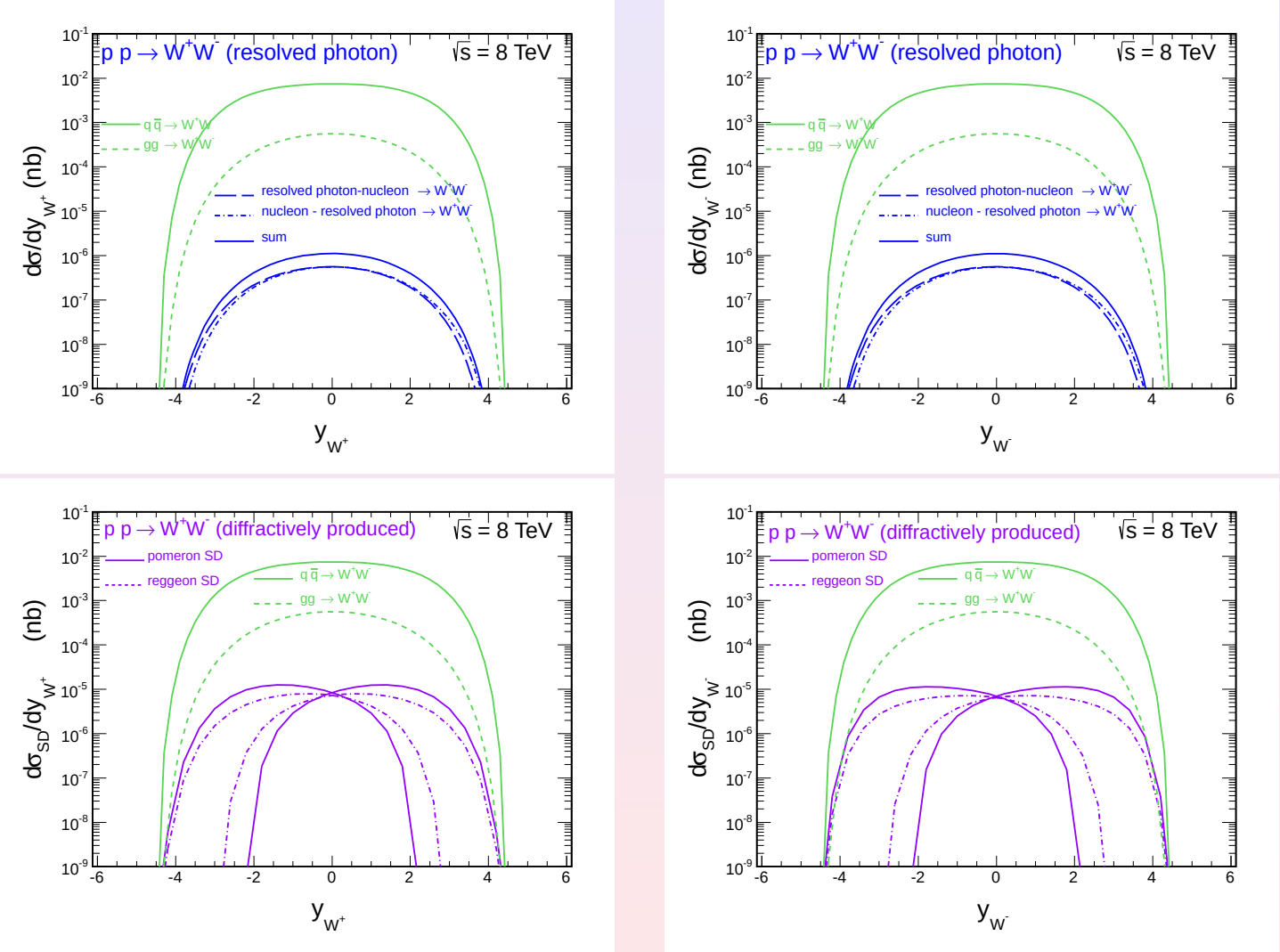
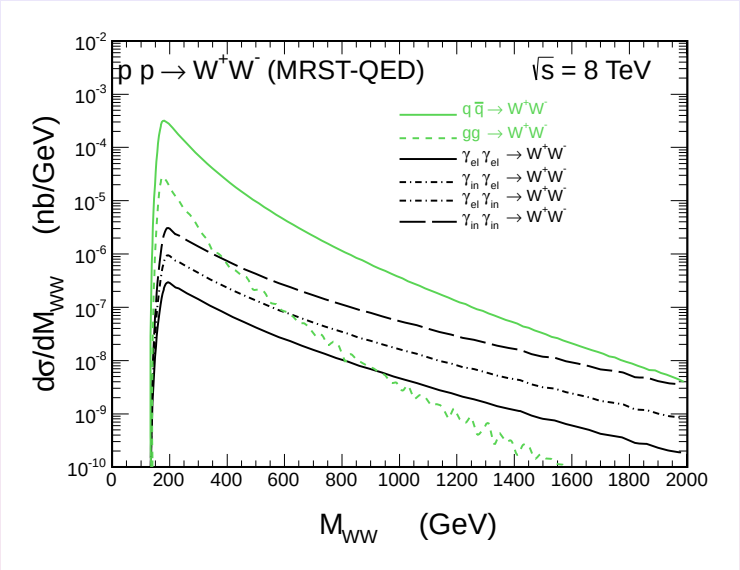
γin γel → W+W-
γel γin → W+W-
γin γin → W+W-
dσ/dy (nb)
y

Results


p p → W+W- (resolved photon)
√s = 8 TeV
q q̄ → W+W-
gg → W+W-
resolved photon-nucleon → W+W-
nucleon - resolved photon → W+W-
sum
dσ/dy_W+ (nb)
dσ/dy_W- (nb)
p p → W+W- (diffractively produced)
pomeron SD
reggeon SD
dσ_SD/dy_W+ (nb)
dσ_SD/dy_W- (nb)
y_W+
y_W-

Results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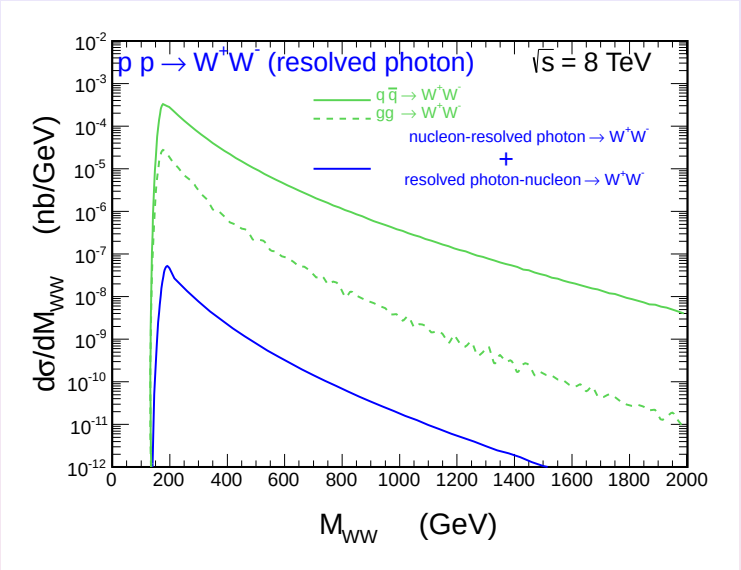
gg → W+W-
γel γel → W+W-
γin γel → W+W-
γel γin → W+W-
γin γin → W+W-
dσ/dMWW (nb/GeV)
MWW (GeV)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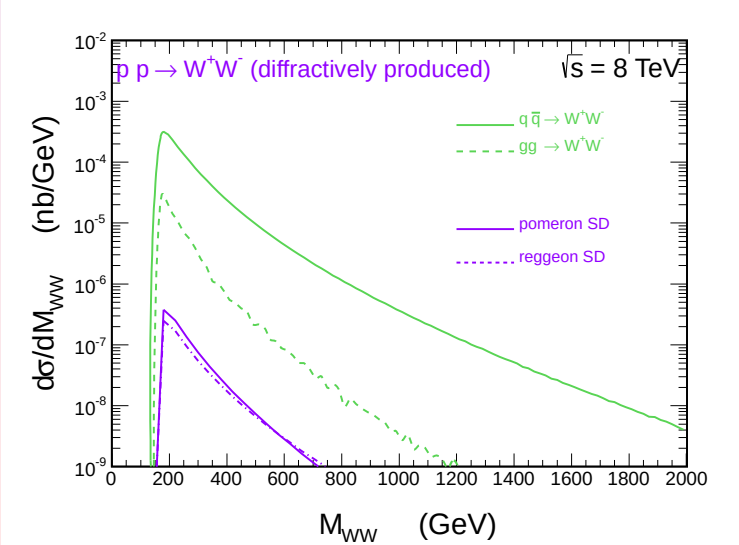
+
resolved photon-nucleon → W+W-
dσ/dMWW (nb/GeV)
MWW (GeV)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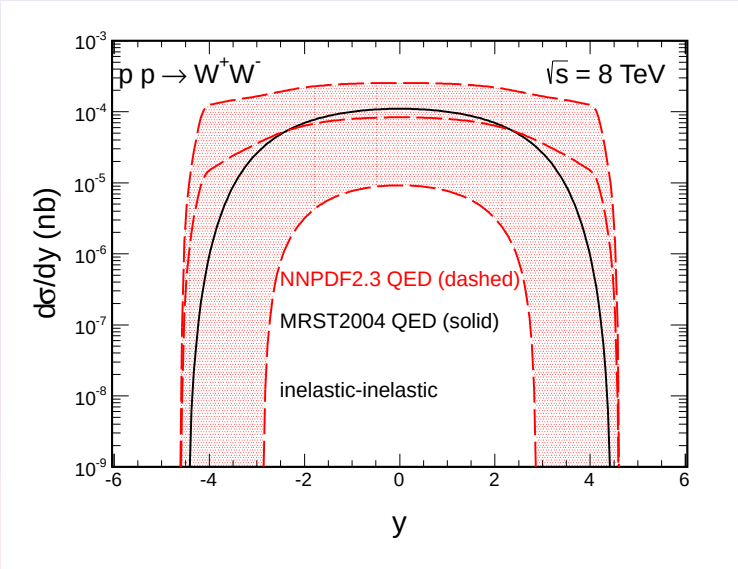
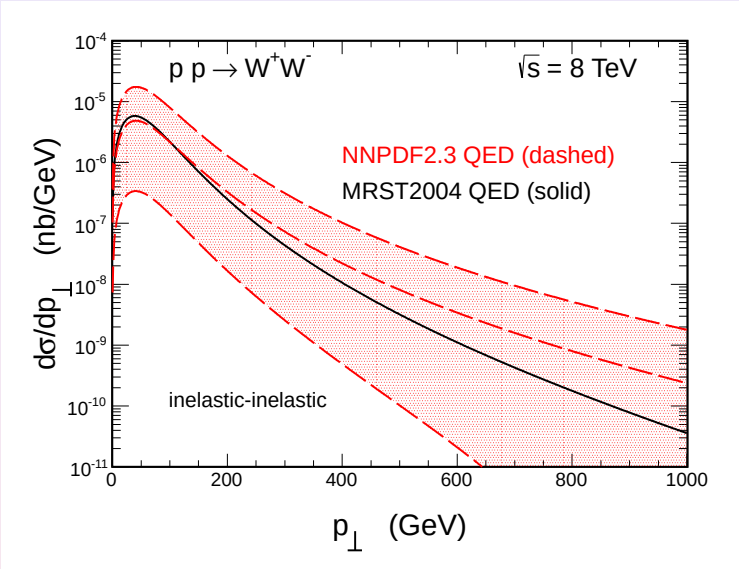
pomeron SD
reggeon SD
dσ/dMWW (nb/GeV)
MWW (GeV)

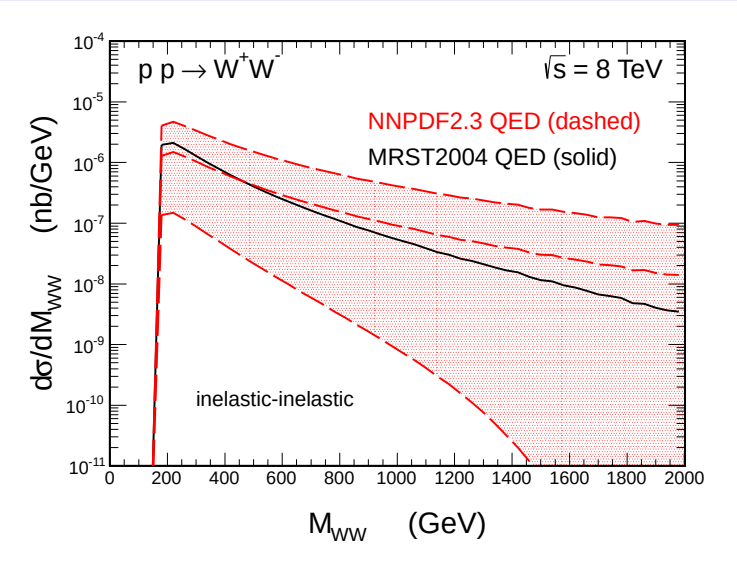
NNPDF2.3 QED photon distributions





- 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

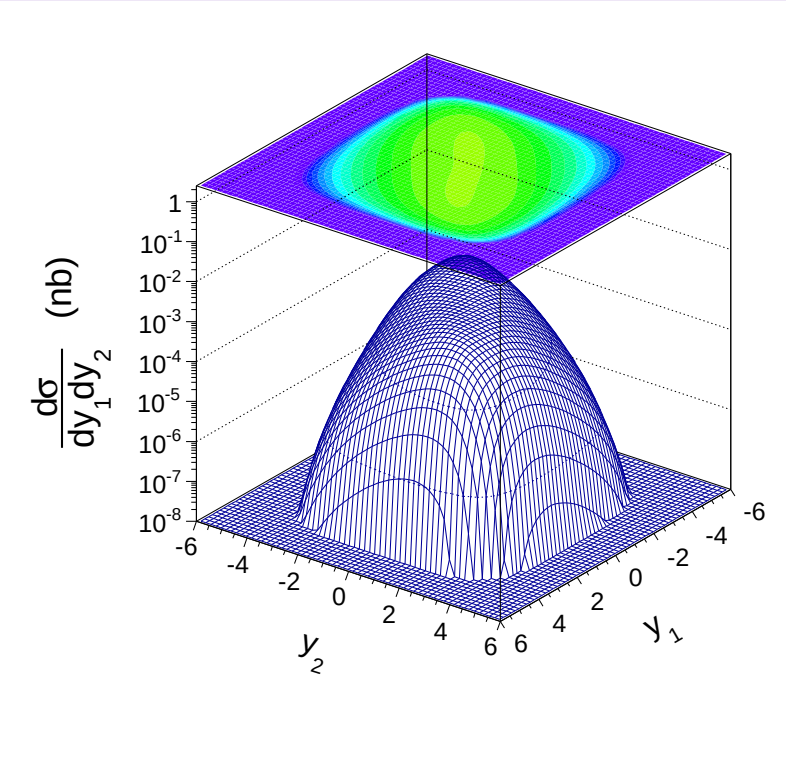
NNPDF2.3 QED photon distributions



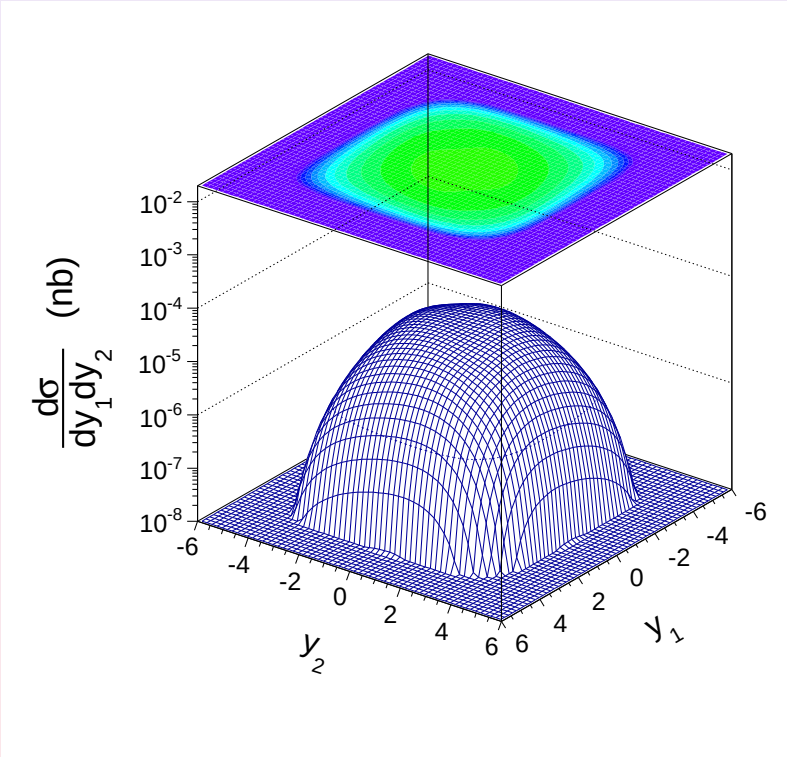
- Big uncertainties can be observed especially for large *WW* invariant masses, i.e. in the region where searches for anomalous triple and quartic boson couplings are studied.

Results

$q\bar{q} \to W^+W^-$



$\gamma_{ine}\gamma_{ine} \to W^+W^-$

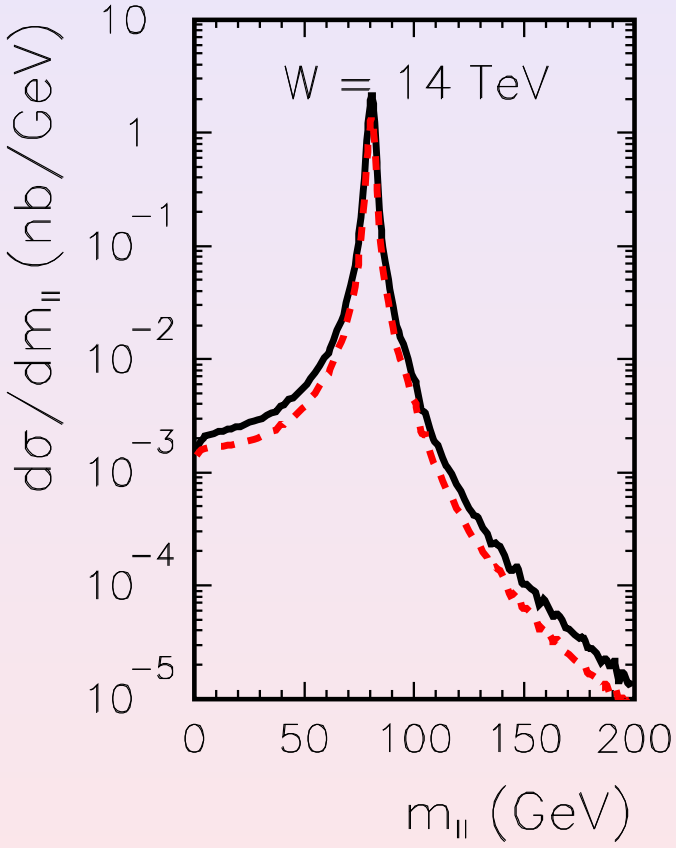


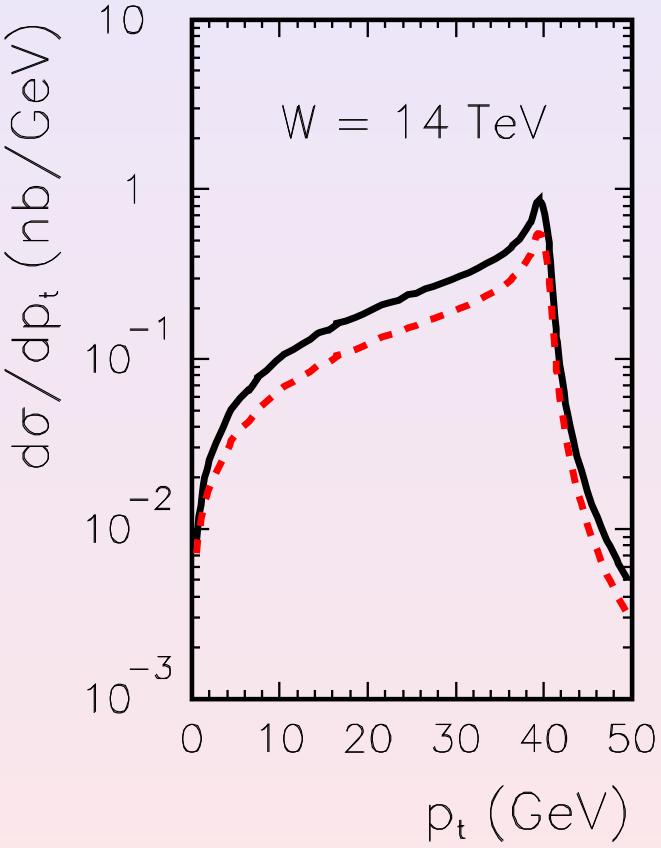
Results

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				
D0	13.8 pb				
ATLAS		54.4 pb			large extrapolation
CMS		41.1 pb			large extrapolation
$q\bar{q}$	9.86	27.24	33.04	70.21	dominant (LO, NLO)
gg	$5.17\ 10^{-2}$	1.48	1.97	5.87	subdominant (NLO)
$\gamma_{el}\gamma_{el}$	$3.07\ 10^{-3}$	$4.41\ 10^{-2}$	$5.40\ 10^{-2}$	$1.16\ 10^{-1}$	new, anomalous $\gamma\gamma WW$
$\gamma_{el}\gamma_{in}$	$1.08\ 10^{-2}$	$1.40\ 10^{-1}$	$1.71\ 10^{-1}$	$3.71\ 10^{-1}$	new, anomalous $\gamma\gamma WW$
$\gamma_{in}\gamma_{el}$	$1.08\ 10^{-2}$	$1.40\ 10^{-1}$	$1.71\ 10^{-1}$	$3.71\ 10^{-1}$	new, anomalous $\gamma\gamma WW$
$\gamma_{in}\gamma_{in}$	$3.72\ 10^{-2}$	$4.46\ 10^{-1}$	$5.47\ 10^{-1}$	1.19	anomalous $\gamma\gamma WW$
$\gamma_{el,res} - q/\bar{q}$	$1.04\ 10^{-4}$	$2.94\ 10^{-3}$	$3.83\ 10^{-3}$	$1.03\ 10^{-2}$	new, quite sizeable
$q/\bar{q} - \gamma_{el.res}$	$1.04\ 10^{-4}$	$2.94\ 10^{-3}$	$3.83\ 10^{-3}$	1.0310^{-2}	new, quite sizeable
$\gamma_{in,res} - q/\bar{q}$					new, quite sizeable
$q/\bar{q} - \gamma_{in.res}$					new, quite sizeable
double scattering	$1.2\ 10^{-2}$	0.26	0.36	1.28	not included in NLO studies
$\mathbf{P}p$	$2.82\ 10^{-2}$	$9.88\ 10^{-1}$	1.27	3.35	new, relatively small
$p\mathbf{P}$	$2.82\ 10^{-2}$	$9.88\ 10^{-1}$	1.27	3.35	new, relatively small
$\mathbf{R}p$	$4.51\ 10^{-2}$	$7.12\ 10^{-1}$	$8.92\ 10^{-1}$	2.22	new, relatively small
$p\mathbf{R}$	$4.51\ 10^{-2}$	$7.12\ 10^{-1}$	$8.92\ 10^{-1}$	2.22	new, relatively small

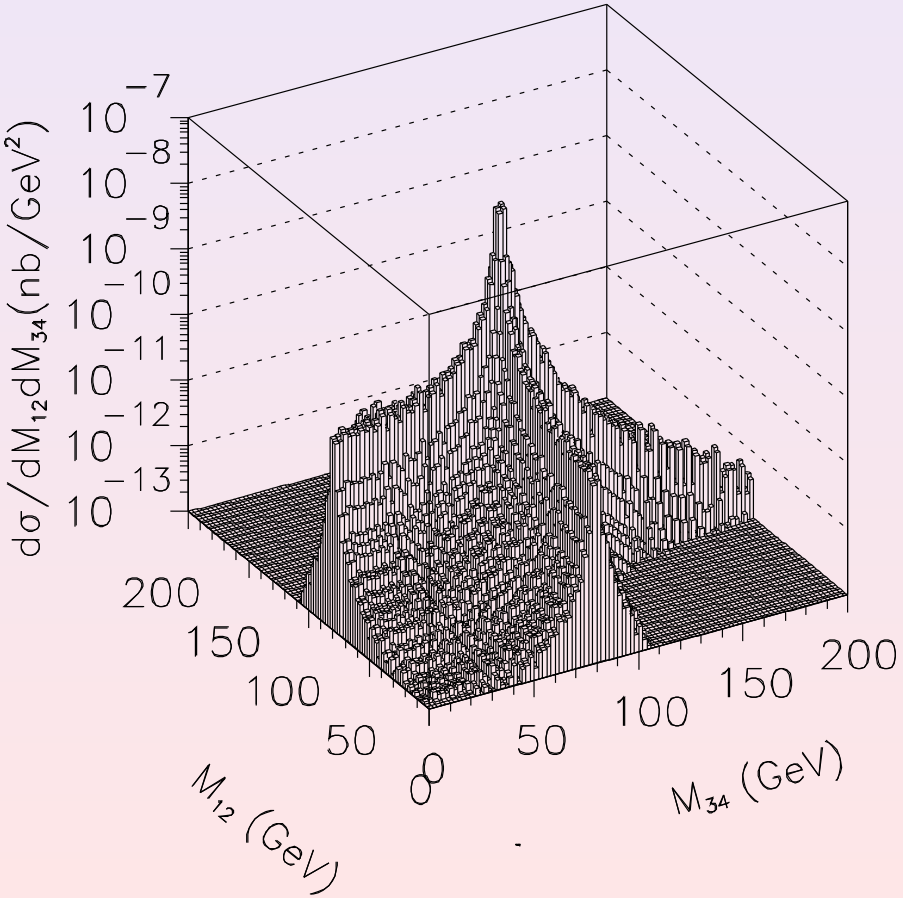
Double Parton Scattering

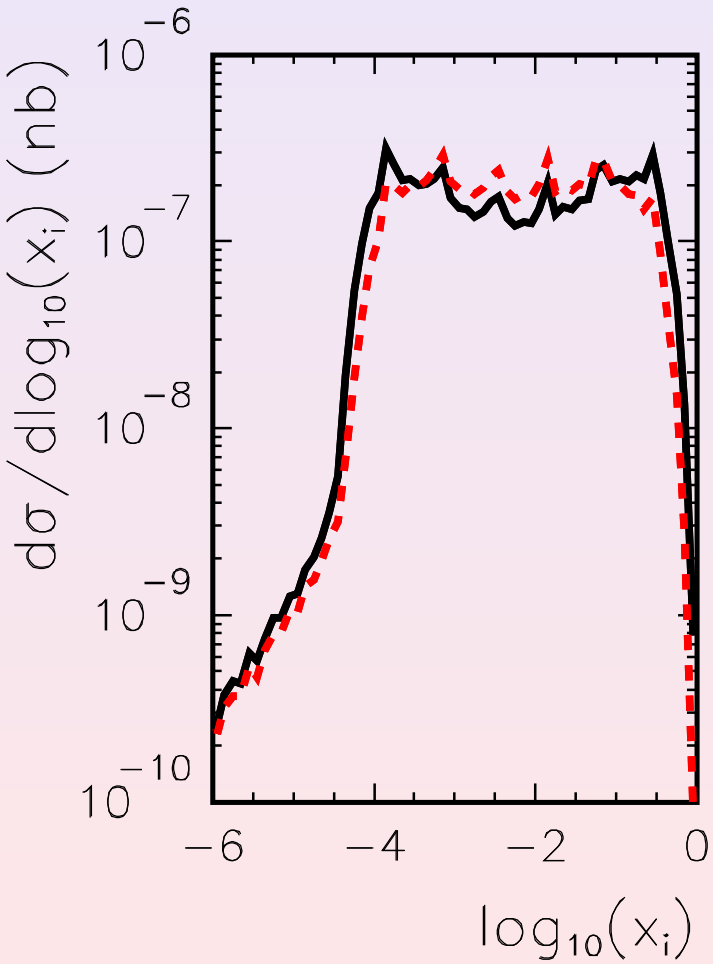




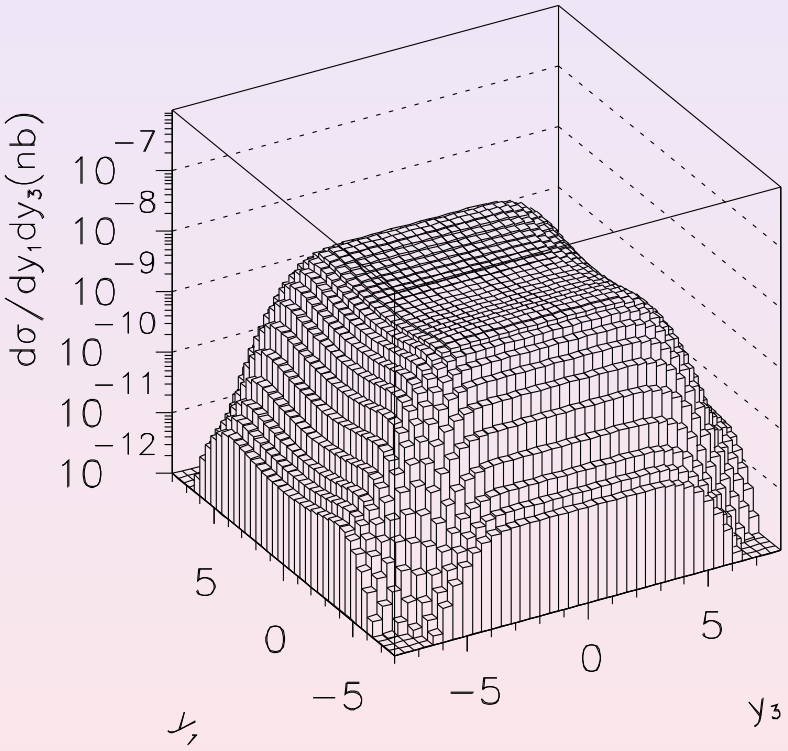
W^+ - solid black line, W^- - dashed red line

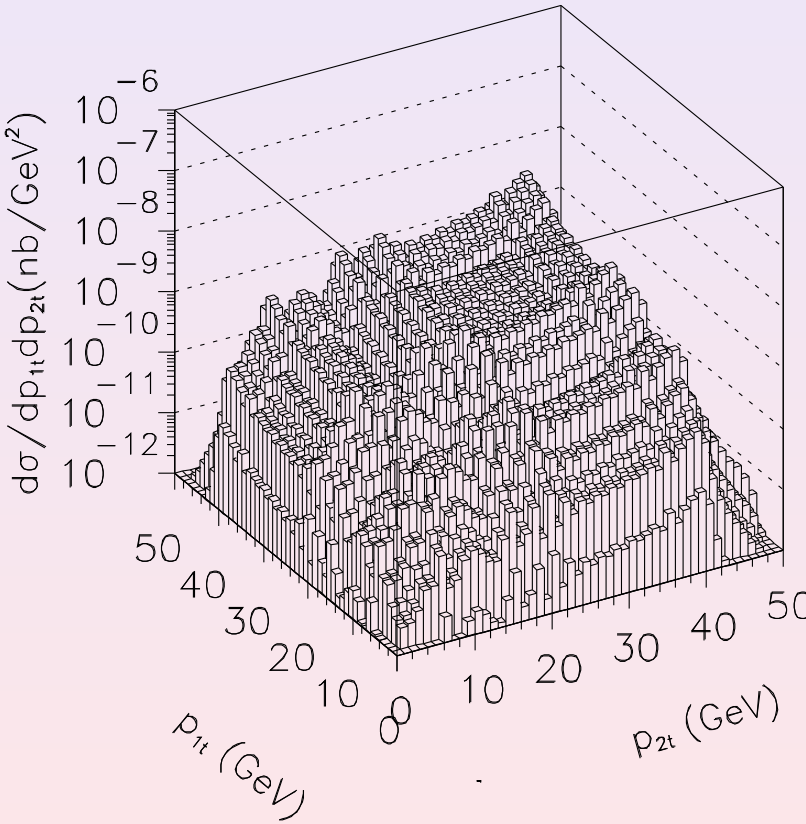
Double Parton Scattering





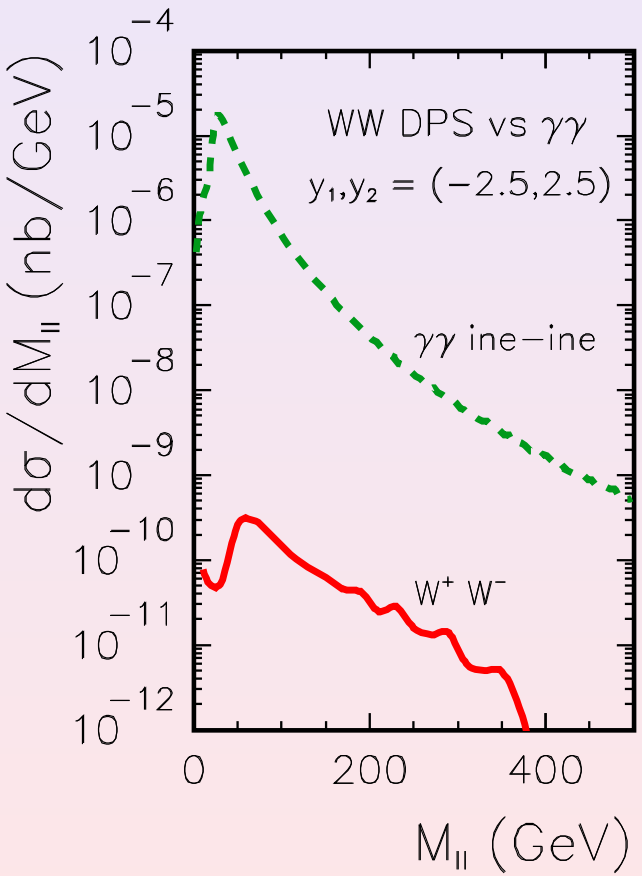
DPS observed in the l^+l^- channel





cross section of the order of 1 fb at LHC

DPS observed in the l^+l^- channel



- DPS only a small contribution in the $\mu^+\mu^-$ system
- Drell-Yan and $\gamma\gamma \to \mu^+\mu^-$ are dominant mechanisms
- $e^+\mu^-$ and $e^-\mu^+$ should be better

Same-sign W-boson production

- For the same-sign W pair production (W^+W^+ or W^-W^- there is no competition of SPS $2 \to 2$ $ij \to W^\pm W^\pm$ partonic subprocesses.
- $2 \to 3$ and $2 \to 4$ processes are possible
- Other DPS processes.
- There could be also some $3 \to 2$ processes but the theory of such processes is not well developed.

Conclusions

- Large contribution of photon induced processes, especially at large M_{WW}
- 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
- DPS contribution also not completely under control (growing with energy)
- In the future we have to include decays of W bosons