Production of W^+W^- pairs via subleading processes at the LHC

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Plan of the talk

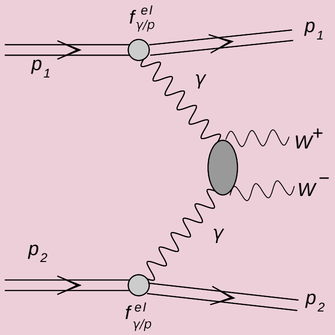
- Introduction
- $\gamma\gamma \to W^+W^-$ reaction
- Inclusive production of W^+W^- pairs
  - $q\bar{q} \to W^+W^-$ mechanism
  - MRST-QED parton distributions
  - Naive approach to photon flux
  - Resolved photons
  - Single diffractive production
  - Results
- Conclusions

Based on:

M. Luszczak, Ch. Royon and A. Szczurek, paper in preparation

$pp \to ppW^+W^-$ 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

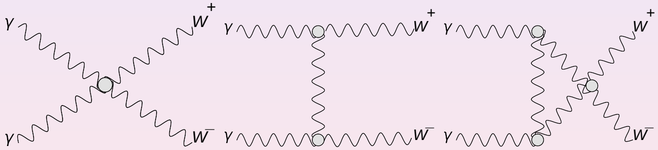
The three-boson $WW\gamma$ and four-boson $WW\gamma\gamma$ couplings, which contribute to the $\gamma\gamma \to W^+W^-$ process in the leading order:

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

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

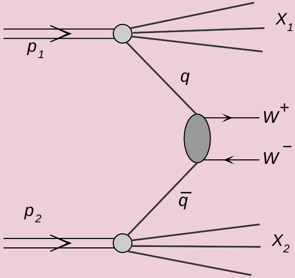
The exclusive diffractive mechanism

The exclusive diffractive mechanism of central exclusive 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

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

and turned out to be negligibly small.

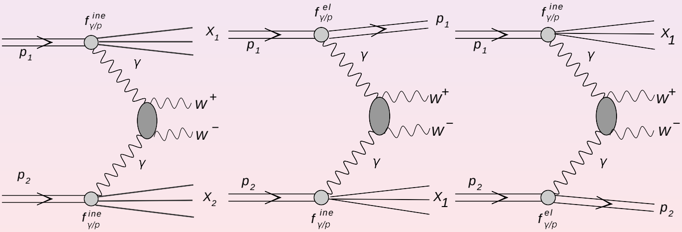
$q\bar{q} \to W^+W^-$ mechanism



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
- If at least one photon is a "real" constituent of the nucleon then the mechanisms presented are possible:



MRSTQ parton distributions

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

$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{qq}(y)\, q_i(\frac{x}{y},\mu^2) + P_{qg}(y)\, g(\frac{x}{y},\mu^2)\Big\}$$

$$+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\Big\{\tilde{P}_{qq}(y)\, e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\, e_i^2 \gamma(\frac{x}{y},\mu^2)\Big\}$$

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

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

MRSTQ parton distributions

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

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

$$\mathrm{P}_{\gamma q} = C_F^{-1} P_{gq},$$
$$\mathrm{P}_{q\gamma} = T_R^{-1} P_{qg},$$
$$\mathrm{P}_{\gamma\gamma} = -\tfrac{2}{3} \textstyle\sum_i e_i^2 \, \delta(1-y)$$

momentum is conserved:

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

Cross section for photon-photon processes

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

- 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:

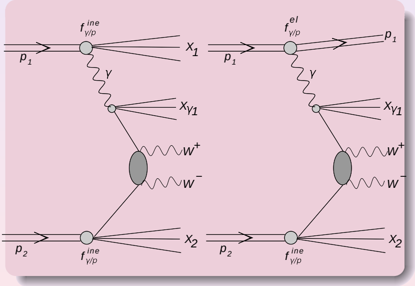
$$f_\gamma(z) = \frac{\alpha_{em}}{2\pi} \frac{1+(1-z)^2}{2} \log\left(\frac{Q_1^2}{Q_2^2}\right) .$$

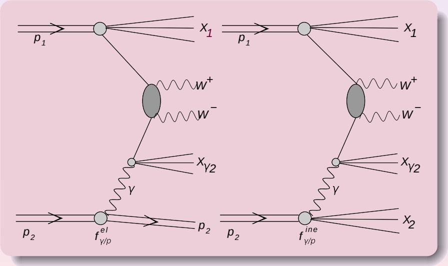
- the choice of scales:

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

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:

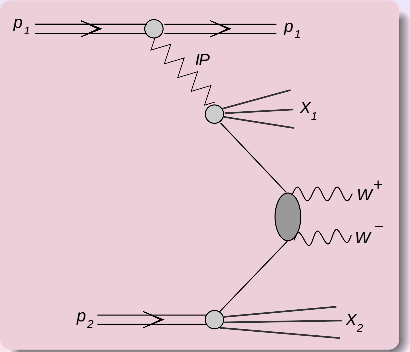
$$f^{\gamma}_{q/p} = f_{\gamma/p} \otimes f_{q/\gamma}$$

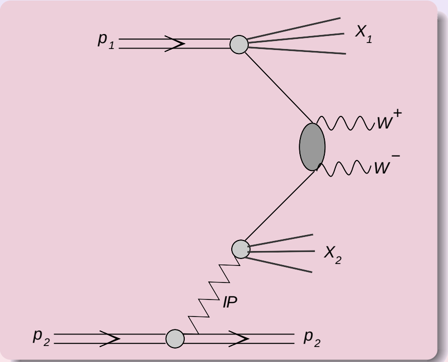
which mathematically means:

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

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 $q_{f/\mathbf{P}}(\beta,\mu^2)$:

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

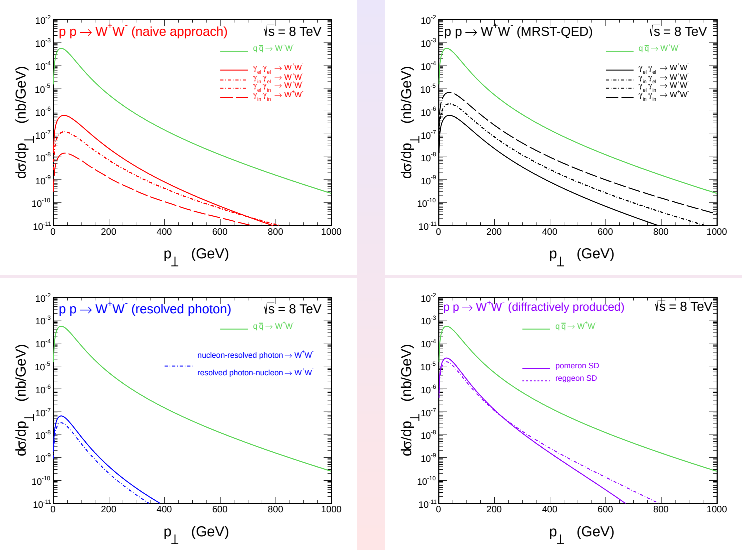
The flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$:

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

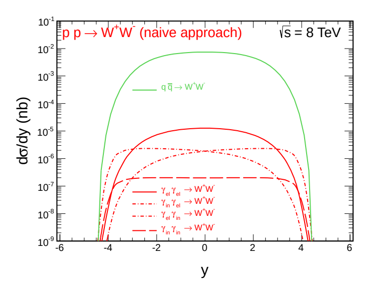
with t_{min}, t_{max} being kinematic boundaries.

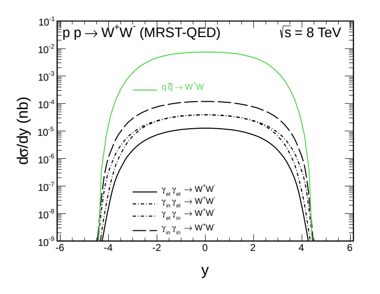
Both pomeron flux factors $f_{\mathbf{P}}(x_{\mathbf{P}},t)$ as well as quark/antiquark distributions in the pomeron were taken from the H1 collaboration analysis of diffractive structure function at HERA.

Results


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

Results


p p → W+W- (naive approach)
√s = 8 TeV
dσ/dy (nb)
y
q q̄ → W+W-
γel γel → W+W-
γin γel → W+W-
γel γin → W+W-
γin γin → W+W-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dσ/dy (nb)
y
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γel γin → W+W-
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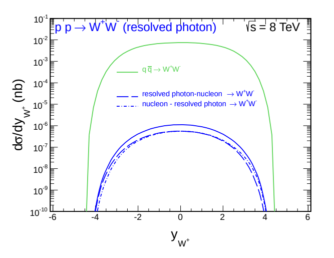
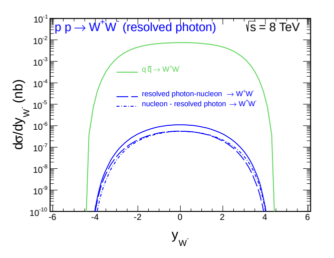
Results


p p → W+W- (resolved photon)
√s = 8 TeV
q q̄ → W+W-
resolved photon-nucleon → W+W-
nucleon - resolved photon → W+W-
dσ/dy_W+ (nb)
y_W+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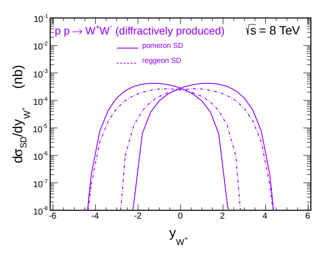
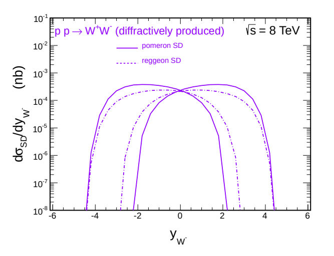
resolved photon-nucleon → W+W-
nucleon - resolved photon → W+W-
dσ/dy_W- (nb)
y_W-


p p → W+W- (diffractively produced)
√s = 8 TeV
pomeron SD
reggeon SD
dσ_SD/dy_W+ (nb)
y_W+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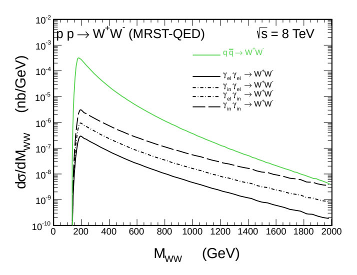
√s = 8 TeV
pomeron SD
reggeon SD
dσ_SD/dy_W- (nb)
y_W-

Results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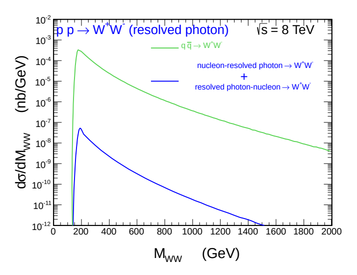
√s = 8 TeV
q q̄ → W+W-
γel γel → W+W-
γin γel → W+W-
γel γin → W+W-
γin γin → W+W-
dσ/dMWW (nb/GeV)
MWW (GeV)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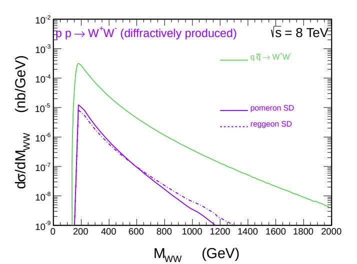
√s = 8 TeV
q q̄ → W+W-
nucleon-resolved photon → W+W-
+
resolved photon-nucleon → W+W-
dσ/dMWW (nb/GeV)
MWW (GeV)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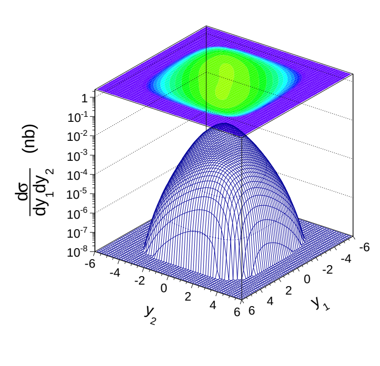
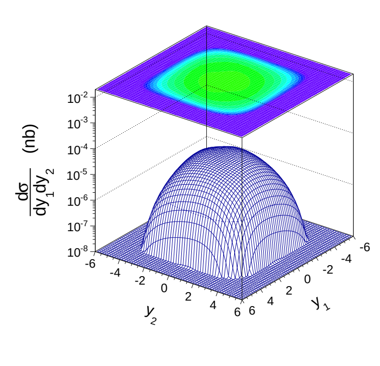
pomeron SD
reggeon SD
dσ/dMWW (nb/GeV)
MWW (GeV)

Results


$\frac{d\sigma}{dy_1 dy_2}$ (nb)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
y_2
y_1


$\frac{d\sigma}{dy_1 dy_2}$ (nb)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
y_2
y_1

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(++)	0.57 10^{-2}	0.11	0.14	0.40	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

Conclusions

- Large contribution of photon induced processes
- 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
- In the future we have to include decays of W bosons