Mueller Navelet jets, jet gap jets and anomalous $WW\gamma\gamma$ couplings in $\gamma$-induced processes at the LHC

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We describe two different important measurements to be performed at the LHC. The Mueller Navelet jet and jet gap jet cross section represent a test of BFKL dynamics and we perform a NLL calculation of these processes and compare it with recent Tevatron measurements. The study of the $WW\gamma\gamma$ couplings at the LHC using the forward detectors proposed in the ATLAS Forward Physics project as an example allows to probe higgsless and extradimension models via anomalous quartic couplings since the reach is improved by four orders of magnitude with respect to the LEP results.

I. MUELLER NA VELET JETS AT THE LHC

In this section, we give the BFKL NLL cross section calculation for Mueller Navelet processes at the Tevatron and the LHC. Since the starting point of this study was the description of forward jet production at HERA, we start by describing briefly these processes.

A. Forward jets at HERA

Following the successful BFKL [1] parametrisation of the forward-jet cross-section $d\sigma/dx$ at Leading Order (LO) at HERA [2, 3], it is possible to perform a similar study using Next-to-leading (NLL) resummed BFKL kernels. Forward jets at HERA are an ideal observable to look for BFKL resummation effects. The interval in rapidity between the scattered lepton and the jet in the forward region is large, and when the photon virtuality $Q^2$ is close to the transverse jet momentum $k_T$, the DDLAP cross section is small because of the $k_T$ ordering of the emitted gluons. In this short

\[ \frac{d\sigma}{dx} \]

FIG. 1: Comparison between the H1 $d\sigma/dx$ measurement with predictions for BFKL-LL, BFKL-NLL (S3 and S4 schemes) and DGLAP NLO calculations (see text). S4, S3 and LL BFKL cannot be distinguished on that figure.
report, we will only discuss the phenomenological aspects and all detailed calculations can be found in Ref. [4] for forward jets at HERA and in Ref. [5] for Mueller Navelet jets at the Tevatron and the LHC.

B. BFKL NLL formalism

The BFKL NLL [6] longitudinal transverse cross section reads:

$$\left. \frac{d\sigma}{dx J} \right|_{k^2_T} = \frac{\alpha_s(k^2_T)}{k^2_T Q^2} f_{eff}(x J, k^2_T) \int d\gamma \left( \frac{Q^2}{k^2_T} \right)^{\gamma} \phi_{T,L}^e(\gamma) e^{\alpha(s) Q_{eff}(\gamma, \alpha(k^2_T)) Y}$$

where $x J$ is the proton momentum fraction carried by the forward jet, $\chi_{eff}$ is the effective BFKL NLL kernel and the $\phi$s are the transverse and longitudinal impact factors taken at LL. The effective kernel $\chi_{eff}(\gamma, \alpha)$ is defined from the NLL kernel $\chi_{NLL}(\gamma, \omega)$ by solving the implicit equation numerically

$$\chi_{eff}(\gamma, \alpha) = \chi_{NLL}[\gamma, \alpha, \chi_{eff}(\gamma, \alpha)] .$$

The integration over $\gamma$ in Eq. (1) is performed numerically. It is possible to fit directly $d\sigma/dx$ measured by the H1 collaboration using this formalism with one single parameter, the normalisation. The values of $\chi_{NLL}$ are taken at NLL [6] using different resummation schemes to remove spurious singularities defined as S3 and S4 [7]. Contrary to LL BFKL, it is worth noticing that the coupling constant $\alpha_S$ is taken using the renormalisation group equations, the only free parameter in the fit being the normalisation.

To compute $d\sigma/dx$ in the experimental bins, we need to integrate the differential cross section on the bin size in $Q^2$, $x J$ (the momentum fraction of the proton carried by the forward jet), $k^2_T$, while taking into account the experimental cuts. To simplify the numerical calculation, we perform the integration on the bin using the variables where the cross section does not change rapidly, namely $k^2_T/Q^2$, $\log 1/x J$, and $1/Q^2$. Experimental cuts are treated directly at the integral level (the cut on $0.5 < k^2_T/Q^2 < 5$ for $J$) or using a toy Monte Carlo. More detail can be found about the fitting procedure in Appendix A of Ref. [3].

The NLL fits [4] can nicely describe the H1 data [8] for the S4 and S3 schemes [2, 3] ($\chi^2 = 0.48/5$ and $\chi^2 = 1.15/5$ respectively per degree of freedom with statistical and systematic errors added in quadrature). The curve using a LL fit is indistinguishable in Fig. 1 from the result of the BFKL-NLL fit. The DGLAP NLO calculation fails to describe the H1 data at lowest $x$ (see Fig. 1). We also checked the effect of changing the scale in the exponential of Eq. (1) from $k^2_T Q$ to $2k^2_T Q$ or $k^2_T Q/2$ which leads to a difference of 20% on the cross section while changing the scale to $k^2_T Q^2$ modifies the result by less than 5% which is due to the cut on $0.5 < k^2_T/Q^2 < 5$. Implementing the higher-order corrections in the impact factor due to exact gluon dynamics in the $\gamma^* \to q\bar{q}$ transition [9] changes the result by less than 3%.

The H1 collaboration also measured the forward jet triple differential cross section [8] and the results are given in Fig. 2. We keep the same normalisation coming from the fit to $d\sigma/dx$ to predict the triple differential cross section. The BFKL LL formalism leads to a good description of the data where $r = k^2_T/Q^2$ is close to 1 and deviates from the data when $r$ is further away from 1. This effect is expected since DGLAP radiation effects are supposed to occur when the ratio between the jet $k^2_T$ and the virtual photon $Q^2$ is further away from 1. The BFKL NLL calculation including the $Q^2$ evolution via the renormalisation group equation leads to a good description of the H1 data on the full range. We note that the higher order corrections are small when $r \sim 1$, when the BFKL effects are supposed to dominate. By contrast, they are significant as expected when $r$ is different from one, i.e. when DGLAP evolution becomes relevant. We notice that the DGLAP NLO calculation fails to describe the data when $r \sim 1$, or in the region where BFKL resummation effects are expected to appear.

In addition, we checked the dependence of our results on the scale taken in the exponential of Eq. (1). The effect is a change of the cross section of about 20% at low $p_T$ increasing to 70% at highest $p_T$. Taking the correct gluon kinematics in the impact factor lead as expected to a better description of the data at high $p_T$ [2].

C. Mueller Navelet jets at the Tevatron and the LHC

Mueller Navelet jets are ideal processes to study BFKL resummation effects [10]. Two jets with a large interval in rapidity and with similar transverse momenta are considered. A typical observable to look for BFKL effects is the measurement of the azimuthal correlations between both jets. The DGLAP prediction is that this distribution should peak towards $\pi$-ie jets are back-to-back- whereas multi-gluon emission via the BFKL mechanism leads to a smoother
distribution. The relevant variables to look for azimuthal correlations are the following:

\[ \Delta \eta = y_1 - y_2 \]
\[ y = \frac{(y_1 + y_2)}{2} \]
\[ Q = \sqrt{k_1 k_2} \]
\[ R = \frac{k_2}{k_1} \]

where \( y_{1,2} \) and \( k_{1,2} \) are respectively the jet rapidities and transverse momenta. The azimuthal correlation for BFKL reads:

\[
2\pi \frac{d\sigma}{d\Delta \eta dR d\phi} \int \frac{d\sigma}{d\Delta \eta dR} = 1 + \frac{2}{\sigma_0(\Delta \eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta \eta, R) \cos(p \Delta \phi)
\]

where in the NLL BFKL framework,

\[
\sigma_p = \int_{y_c}^{\infty} \frac{dQ}{Q^3} \frac{\alpha_s(Q^2/R)}{\alpha_s(Q^2 R)} \left( \int_{\nu c}^{\tilde{y}_c} dy x_1 f_{\text{eff}}(x_1, Q^2/R) x_2 f_{\text{eff}}(x_2, Q^2 R) \right) \\
\int_{1/2-\infty}^{1/2+\infty} \frac{d\gamma}{2\pi} R^{-2\gamma} e^{\alpha(Q^2) x_{\text{eff}}(p, \gamma, \alpha) \Delta \eta}
\]
and $\chi_{eff}$ is the effective resummed kernel. Computing the different $\sigma$ at NLL for the resummation schemes S3 and S4 allowed us to compute the azimuthal correlations at NLL. As expected, the $\Delta\Phi$ dependence is less flat than for BFKL LL and is closer to the DGLAP behaviour [5]. In Fig. 3 we display the observable $1/\sigma d\sigma/d\Delta\Phi$ as a function of $\Delta\Phi$, for LHC kinematics. The results are displayed for different values of $\Delta\eta$ and at both LL and NLL accuracy using the S4 resummation scheme. In general, the $\Delta\Phi$ spectra are peaked around $\Delta\Phi = 0$, which is indicative of jet emissions occurring back-to-back. In addition the $\Delta\Phi$ distribution flattens with increasing $\Delta\eta = y_1 - y_2$. Note the change of scale on the vertical axis which indicates the magnitude of the NLL corrections with respect to the LL-BFKL results. The NLL corrections slow down the azimuthal angle decorrelations for both increasing $\Delta\eta$ and $R$ deviating from 1. We also studied the $R$ dependence of our prediction which is quite weak [5] and the scale dependence of our results by modifying the scale $Q^2$ to either $Q^2/2$ or $2Q^2$ and the effect on the azimuthal distribution is of the order of 20%. The
effect of the energy conservation in the BFKL equation [3] is large when $R$ goes away from 1. The effect is to reduce the effective value of $\Delta \eta$ between the jets and thus the decorrelation effect. However, it is worth noticing that this effect is negligible when $R$ is close to 1 where this measurement will be performed.

A measurement of the cross-section $d\sigma^{\text{gg} \to \text{XJ}JY}/d\Delta \eta dR d\Delta \Phi$ at the Tevatron (Run 2) or the LHC will allow for a detailed study of the BFKL QCD dynamics since the DGLAP evolution leads to much less jet angular decorrelation (jets are back-to-back when $d\Delta \phi$ is close to 1). In particular, measurements with values of $\Delta \eta$ reaching 8 or 10 will be of great interest, as these could allow to distinguish between BFKL and DGLAP resummation effects and would provide important tests for the relevance of the BFKL formalism.

To illustrate this result, we give in Fig. 3 the azimuthal correlation in the CDF acceptance. The CDF collaboration installed the mini-Plugs calorimeters aiming for rapidity gap selections in the very forward regions and these detectors can be used to tag very forward jets. A measurement of jet $p_T$ with these detectors would not be possible but their azimuthal segmentation allows a $\phi$ measurement. In Fig. 4, we display the jet azimuthal correlations for jets with a $p_T > 5$ GeV and $\Delta \eta = 6, 8, 10$ and 11. For $\Delta \eta = 11$, we notice that the distribution is quite flat, which would be a clear test of the BFKL prediction.

II. JET GAP JETS AT THE TEVATRON AND THE LHC

In this section, we describe another possible measurement which can probe BFKL resummation effects and we compare our predictions with existing D0 and CDF measurements [11].

A. BFKL NLL formalism

The production cross section of two jets with a gap in rapidity between them reads

$$\frac{d\sigma^{pp \to \text{XJ}JY}}{dx_1 dx_2 dE_T^2} = S f_{\text{eff}}(x_1, E_T^2)f_{\text{eff}}(x_2, E_T^2) \frac{d\sigma^{\text{gg} \to \text{gg}}}{dE_T^2},$$

(3)

where $\sqrt{s}$ is the total energy of the collision, $E_T$ the transverse momentum of the two jets, $x_1$ and $x_2$ their longitudinal fraction of momentum with respect to the incident hadrons, $S$ the survival probability, and $f$ the effective parton density functions [11]. The rapidity gap between the two jets is $\Delta \eta = \ln(x_1 x_2 s/p_T^2)$.

The cross section is given by

$$\frac{d\sigma^{\text{gg} \to \text{gg}}}{dE_T^2} = \frac{1}{16\pi} |A(\Delta \eta, E_T^2)|^2$$

(4)

in terms of the $gg \to gg$ scattering amplitude $A(\Delta \eta, p_T^2)$.

In the following, we consider the high energy limit in which the rapidity gap $\Delta \eta$ is assumed to be very large. The BFKL framework allows to compute the $gg \to gg$ amplitude in this regime, and the result is known up to NLL accuracy

$$A(\Delta \eta, E_T^2) = \frac{16N_c \pi a_s^2}{C_F E_T^2} \sum_{p=-\infty}^\infty \int \frac{d\gamma}{2i\pi} \frac{[p^2 - (\gamma - 1/2)^2]}{[(\gamma - 1/2)^2 - (p - 1/2)^2][1 - (p + 1/2)^2]} \exp \{\alpha_s(\mu^2) \chi_{\text{eff}}(2p, \gamma) \bar{\chi}(E_T^2) |\Delta \eta|\}$$

(5)

with the complex integral running along the imaginary axis from $1/2 - i \infty$ to $1/2 + i \infty$, and with only even conformal spins contributing to the sum, and $\bar{\alpha} = \alpha_s N_c/\pi$ the running coupling.

Let us give some more details on formula 5. The NLL-BFKL effects are phenomenologically taken into account by the effective kernels $\chi_{\text{eff}}(p, \gamma, \bar{\alpha})$. The NLL kernels obey a consistency condition which allows to reformulate the problem in terms of $\chi_{\text{eff}}(\gamma, \bar{\alpha})$. The effective kernel $\chi_{\text{eff}}(\gamma, \bar{\alpha})$ is obtained from the NLL kernel $\chi_{\text{NLL}}(\gamma, \omega)$ by solving the implicit equation $\chi_{\text{eff}}(\gamma, \bar{\alpha}) = \chi_{\text{NLL}}(\gamma, \bar{\alpha})$ as a solution of the consistency condition as it was also performed for forward jets.

In this study, we performed a parametrised distribution of $d\sigma^{\text{gg} \to \text{gg}}/dE_T^2$ so that it can be easily implemented in the Herwig Monte Carlo [12] since performing the integral over $\gamma$ in particular would be too much time consuming in a Monte Carlo. The implementation of the BFKL cross section in a Monte Carlo is absolutely necessary to make a direct comparison with data. Namely, the measurements are sensitive to the jet size (for instance, experimentally the gap size is different from the rapidity interval between the jets which is not the case by definition in the analytic calculation).
B. Comparison with D0 and CDF measurements

Let us first notice that the sum over all conformal spins is absolutely necessary. Considering only $p=0$ in the sum of Equation 5 leads to a wrong normalisation and a wrong jet $E_T$ dependence, and the effect is more pronounced as $\Delta \eta$ diminishes.

The D0 collaboration measured the jet gap jet cross section ratio with respect to the total dijet cross section, requesting for a gap between -1 and 1 in rapidity, as a function of the second leading jet $E_T$, and $\Delta \eta$ between the two leading jets for two different low and high $E_T$ samples ($15 < E_T < 20$ GeV and $E_T > 30$ GeV). To compare with theory, we compute the following quantity

$$\text{Ratio} = \frac{\text{BFKL NLL HERWIG}}{\text{Dijet Herwig}} \times \frac{\text{LO QCD}}{\text{NLO QCD}}$$

in order to take into account the NLO corrections on the dijet cross sections, where BFKL NLL HERWIG and Dijet Herwig denote the BFKL NLL and the dijet cross section implemented in HERWIG. The NLO QCD cross section was computed using the NLOJet++ program [13].

The comparison with D0 data [14] is shown in Fig. 5. We find a good agreement between the data and the BFKL calculation. It is worth noticing that the BFKL NLL calculation leads to a better result than the BFKL LL one (note that the best description of data is given by the BFKL LL formalism for $p = 0$ but it does not make sense theoretically to neglect the higher spin components and this comparison is only made to compare with previous LL BFKL calculations).

The comparison with the CDF data [14] as a function of the average jet $E_T$ and the difference in rapidity between the two jets is shown in Fig. 6, and the conclusion remains the same: the BFKL NLL formalism leads to a better description than the BFKL LL one.

C. Predictions for the LHC

Using the same formalism, and assuming a survival probability of 0.03 at the LHC, it is possible to predict the jet gap jet cross section at the LHC. While both LL and NLL BFKL formalisms lead to a weak jet $E_T$ or $\Delta \eta$ dependence, the normalisation is found to be quite different (see Fig. 7) leading to higher cross section for the BFKL NLL formalism.
FIG. 6: Comparisons between the CDF measurements of the jet-gap-jet event ratio with the NLL- and LL-BFKL calculations. The NLL calculation is in fair agreement with the data. The LL calculation leads to a worse description of the data.

FIG. 7: Ratio of the jet gap jet to the inclusive jet cross sections at the LHC as a function of jet $p_T$ and $\Delta \eta$.

III. QUARTIC ANOMALOUS COUPLINGS AT THE LHC

In the third part of this report, we discuss a completely different topic, namely the possibility to probe anomalous quartic couplings between photons and $W$ or $Z$ bosons at the LHC with an unprecedent precision using forward detectors to be installed in CMS and ATLAS experiments [15]. In the Standard Model (SM) of particle physics, the couplings of fermions and gauge bosons are constrained by the gauge symmetries of the Lagrangian. The measurement
FIG. 8: Sketch diagram showing the two-photon production of a central system.

of $W$ and $Z$ boson pair productions via the exchange of two photons allows to provide directly stringent tests of one of the most important and least understood mechanism in particle physics, namely the electroweak symmetry breaking \cite{16}. The non-abelian gauge nature of the SM predicts the existence of quartic couplings $WW\gamma\gamma$ between the $W$ bosons and the photons which can be probed directly at the Large Hadron Collider (LHC) at CERN. The quartic coupling to the $Z$ boson $ZZ\gamma\gamma$ is not present in the SM. Quartic anomalous couplings between the photon and the $Z$ or $W$ bosons are specially expected to occur in higgsless or extradimension models \cite{17}.

A. Photon exchange processes in the SM

The process that we intend to study is the $W$ pair production shown in Fig. 8 induced by the exchange of two photons \cite{15,18}. It is a pure QED process in which the decay products of the $W$ bosons are measured in the central detector and the scattered protons leave intact in the beam pipe at very small angles, contrary to inelastic collisions. Since there is no proton remnant the process is purely exclusive; only $W$ decay products populate the central detector, and the intact protons can be detected in dedicated detectors located along the beam line far away from the interaction point.

The cross section of the $pp \to pWWp$ process which proceeds through two-photon exchange is calculated as a convolution of the two-photon luminosity and the total cross section $\gamma\gamma \to WW$. The total two-photon cross section is 95.6 fb.

All considered processes (signal and background) were produced using the Forward Physics Monte Carlo (FPMC) generator. The aim of FPMC is to produce different kinds of processes such as inclusive and exclusive diffraction, photon-exchange processes. FPMC was interfaced to as fast simulation of the ATLAS detector \cite{21}. To reduce the amount of considered background, we only use leptonic (electrons and muons) decays of $Z$ and $W$ bosons. The following backgrounds were considered: $\gamma\gamma \to l\bar{l}$ — two-photon dilepton production, $DPE \to l\bar{l}$ — dilepton production through double pomeron exchange, $DPE \to W^+W^- \to ll\nu\bar{\nu}$ — diboson production through double pomeron exchange.

After simple cuts to select exclusive $W$ pairs decaying into leptons, such as a cut on the proton momentum loss of the proton ($0.0015 < \xi < 0.15$) — we assume the protons to be tagged in the ATLAS Forward Physics detectors \cite{19} —, on the transverse momentum of the leading and second leading leptons at 25 and 10 GeV respectively, on $E_T > 20$ GeV, $\Delta\phi > 2.7$ between leading leptons, and $160 < W < 500$ GeV, the diffractive mass reconstructed using the forward detectors, the background is found to be less than 1.7 event for 30 fb$^{-1}$ for a SM signal of 51 events. In this channel, a $5\sigma$ discovery of the Standard Model $pp \to pWWp$ process is possible after 5 fb$^{-1}$.

B. Quartic anomalous couplings

The parameterization of the quartic couplings based on \cite{22} is adopted. We concentrate on the lowest order dimension operators which have the correct Lorentz invariant structure and obey the $SU(2)_L$ custodial symmetry in order to fulfill the stringent experimental bound on the $\rho$ parameter. The lowest order interaction Lagrangians which
compared to LEP experiments, and it is possible to reach the values expected in Higgsless or extra-dimension models. We note that we can gain almost four orders of magnitude in the sensitivity to anomalous quartic gauge couplings in a clean way. The reach on anomalous triple gauge couplings is much less improved at the LHC compared to LEP experiments [24].

The forward detectors proposed for installation at 220 and 420 m in ATLAS and CMS. involve two photons are dim-6 operators. The following expression for the effective quartic Lagrangian is used

$$\mathcal{L}_0^H = \frac{-e^2 a_0^W}{8 \Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^{-\alpha} - \frac{e^2}{16 \cos^2 \theta_W \Lambda^2} a_0^Z F_{\mu\nu} F^{\mu\nu} Z^\alpha Z_\alpha$$

$$\mathcal{L}_0^C = \frac{-e^2 a_C^W}{16 \Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^{-\beta} + W^{-\alpha} W^{+\beta}) - \frac{e^2}{16 \cos^2 \theta_W \Lambda^2} a_C^Z F_{\mu\alpha} F^{\mu\beta} Z^\alpha Z_\beta$$

(7)

where $a_0$, $a_C$ are the parametrized new coupling constants and the new scale $\Lambda$ is introduced so that the Lagrangian density has the correct dimension four and is interpreted as the typical mass scale of new physics. In the above formula, we allowed the $W$ and $Z$ parts of the Lagrangian to have specific couplings, i.e. $a_0 \rightarrow (a_0^W, a_0^Z)$ and similarly $a_C \rightarrow (a_C^W, a_C^Z)$.

The $WW$ and $ZZ$ two-photon cross sections rise quickly at high energies when any of the anomalous parameters are non-zero. The cross section rise has to be regulated by a form factor which vanishes in the high energy limit to construct a realistic physical model of the BSM theory. We therefore modify the couplings by form factors that have the desired behavior, i.e. they modify the coupling at small energies only slightly but suppress it when the center-of-mass energy $W_{\gamma\gamma}$ increases. The form of the form factor that we consider is the following

$$a \rightarrow \frac{a}{(1 + W^2 / \Lambda^2)^n}$$

(8)

where $n=2$, and $\Lambda \sim 2$ TeV.

The cuts to select quartic anomalous gauge coupling $WW$ events are similar as the ones we mentioned in the previous section, namely $0.0015 < \xi < 0.15$ for the tagged protons, $E_T > 20$ GeV, $\Delta \phi < 3.13$ between the two leptons. In addition, a cut on the $p_T$ of the leading lepton $p_T > 160$ GeV and on the diffractive mass $W > 800$ GeV are requested. After these requirements, we expect about 0.7 background events for an expected signal of 17 events if the anomalous gauge coupling is about four order of magnitude lower than the present LEP limit ($|a_0^W / \Lambda^2| = 5.4 \times 10^{-6}$) for a luminosity of 30 fb$^{-1}$. The strategy to select anomalous gauge coupling $ZZ$ events is analogous and the presence of three leptons or two like sign leptons are requested. Fig 9 displays the $p_T$ distribution of the leading lepton for signal and the different considered backgrounds. After these requirements, we expect about 0.7 background events for an expected signal of 17 events if the anomalous gauge coupling is about four order of magnitude lower than the present LEP limit ($|a_0^W / \Lambda^2| = 5.4 \times 10^{-6}$) for a luminosity of 30 fb$^{-1}$. The strategy to select anomalous gauge coupling $ZZ$ events is analogous and the presence of three leptons or two like sign leptons are requested. Table 1 gives the reach on anomalous couplings at the LHC for a luminosity of 30 and 200 fb$^{-1}$ compared to the present OPAL limits [23]. We note that we can gain almost four orders of magnitude in the sensitivity to anomalous quartic gauge couplings compared to LEP experiments, and it is possible to reach the values expected in Higgsless or extra-dimension models which are of the order of $5 \times 10^{-6}$. The tagging of the protons using the ATLAS Forward Physics detectors is the only method at present to test such small values of quartic anomalous couplings and thus to probe the higgsless models in a clean way. The reach on anomalous triple gauge couplings is much less improved at the LHC compared to LEP experiments [24].

To conclude, the ATLAS Forward Physics program (and the CMS one) will allow to study Higgsless models with an unprecedent precision as well as to probe the Higgs boson by allowing its mass and spin measurements [25] using the forward detectors proposed for installation at 220 and 420 m in ATLAS and CMS.
| Couplings | OPAL limits [GeV$^{-2}$] | Sensitivity @ $\mathcal{L} = 30$ (200) fb$^{-1}$ |
|-----------|--------------------------|--------------------------|
| $a_0^W/A^2$ | [-0.020, 0.020] | 5.4 $10^{-6}$ (2.7 $10^{-6}$) |
| $a_Z^W/A^2$ | [-0.052, 0.037] | 2.0 $10^{-5}$ (9.6 $10^{-6}$) |
| $a_0^Z/A^2$ | [-0.007, 0.023] | 1.4 $10^{-5}$ (5.5 $10^{-6}$) |
| $a_Z^Z/A^2$ | [-0.029, 0.029] | 5.2 $10^{-5}$ (2.0 $10^{-5}$) |

TABLE I: Reach on anomalous couplings obtained in $\gamma$ induced processes after tagging the protons in the final state in the ATLAS Forward Physics detectors compared to the present OPAL limits. The 5$\sigma$ discovery and 95% C.L. limits are given for a luminosity of 30 and 200 fb$^{-1}$

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