Exclusive photoproduction of vector mesons and Z/γ^*

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We review selected aspects of exclusive diffractive photoproduction at the Tevatron and discuss the prospects for the early LHC running. This talk [1] is based on the results presented in Ref. [2], with some updates due to recent experimental results.

I. INTRODUCTION

Exclusive diffractive Higgs boson production at the LHC, $pp \to p + H + p$, has attracted increasing attention in recent years as an alternative way to explore the Higgs sector [3]. However, the theoretical uncertainties are comparatively large relative to the inclusive production. In particular, the generalised (or skewed) unintegrated gluon distribution, which can be written in terms of the usual gluon distribution, enters to the fourth power, and is required in the region of small x and low scales $\sim$ 1–2 GeV where the gluon distributions obtained from global fits have large uncertainties. While current Tevatron and early LHC data will prove vital in checking the predictions, it is also important to look for complementary processes to constrain the various ingredients of the calculation. One such process, where the gap survival factor is expected to be much closer to 1, is exclusive photoproduction, $\gamma p \to E + p$, where the photon is radiated from one of the two incoming hadrons; see Fig. 1.

II. EXCLUSIVE PHOTOPRODUCTION

Exclusive diffractive vector meson production, $\gamma^{(*)}p \to V + p$, and deeply virtual Compton scattering (DVCS), $\gamma^* p \to \gamma + p$, have been extensively studied at HERA. These processes provide a valuable probe of the gluon density at small x [4–6].

To obtain the hadron–hadron cross section for exclusive production of a massive final state E with rapidity y, we need to multiply the photon–hadron cross section by the flux $\mathrm{d}n/\mathrm{d}k$ of quasi-real photons with energy[1] $k \simeq (M_E/2)\exp(y) \simeq W^2/(2\sqrt{s})$ [7]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(h_1 h_2 \to h_1 + E + h_2) = k\frac{\mathrm{d}n}{\mathrm{d}k}\sigma(\gamma p \to E + p), \quad (1)$$

together with a second term with $y \to -y$ to account for the contribution from the interchange of the photon emitter and the target, neglecting interference. We also neglect absorptive corrections, and only present cross sections integrated over final-state momenta, then these effects are expected to be largely washed out, with a rapidity gap survival factor $S^2 \sim 0.7$–0.9. Alternative calculations including a detailed treatment of these effects can be found in Refs. [8–11].

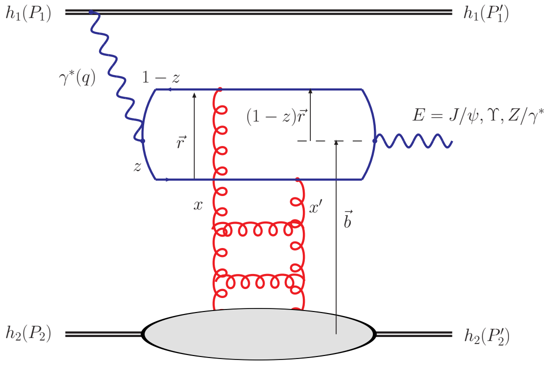

FIG. 1: Exclusive photoproduction of a massive final state $E = J/\psi, \Upsilon, Z/\gamma^*$ in hadron–hadron collisions.

The photon energy spectrum $\mathrm{d}n/\mathrm{d}k$ in Eq. (1) is given by a modified equivalent-photon (Weizsäcker–Williams) approximation [7, 12]:

$$\frac{\mathrm{d}n}{\mathrm{d}k} = \frac{\alpha_{\mathrm{em}}}{2\pi k}\left[1 + \left(1 - \frac{2k}{\sqrt{s}}\right)^2\right] \times \left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right), \quad (2)$$

where $A = 1 + (0.71\,\mathrm{GeV}^2)/Q^2_{\mathrm{min}}$, $Q^2_{\mathrm{min}} \simeq k^2/\gamma_L^2$ and $\gamma_L = \sqrt{s}/(2m_p)$ is the Lorentz factor of a single beam.[2]

If the photon-induced contribution to exclusive vector meson production is known precisely enough, there is potential for *odderon* discovery. The odderon is the C-odd partner of the Pomeron, and in perturbative QCD is modelled by exchange of three gluons in a colour-singlet state. Cross sections were calculated using k_T-factorisation in Ref. [13] for different scenarios. However, no attempt was made to tune the photoproduction contribution to HERA data, hence the odderon-to-photon ratios are more reliable than the absolute cross sections. The odderon-to-photon ratios for $\mathrm{d}\sigma/\mathrm{d}y|_{y=0}$ at the Tevatron are 0.3–0.6 (J/ψ) and 0.8–1.7 (Υ), while the LHC ratios are smaller at 0.06–0.15 (J/ψ) and 0.16–0.38 (Υ) [13]. Moreover, odderon exchange leads to a different meson

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[1] The photon–hadron and hadron–hadron centre-of-mass energies are labelled W and $\sqrt{s}$, respectively.

[2] The results of Ref. [2] were erroneously obtained with A^2 instead of A^3 in the last term of Eq. (2). The results presented here have been corrected, although the numerical impact is completely negligible.

p_T distribution than the photon-induced contribution. In the following, we restrict attention to photoproduction.

To calculate the exclusive γp cross section in Eq. (1) we use the dipole model approach for exclusive diffractive processes [14], where the amplitude factorises into the light-cone wave functions of the incoming and outgoing particle and a dipole cross section describing the interaction of the $q\bar{q}$ dipole with the proton. The parameterisation of the dipole cross section is given in terms of a DGLAP-evolved gluon density, fitted to F_2 data, with Gaussian impact parameter (b) dependence, denoted "b-Sat" model [15, 16], which has already been shown to give a good (parameter-free) description of a wide variety of HERA data on exclusive $\gamma^* p \to V + p$ ($V = \rho, \phi, J/\psi, \gamma$) and inclusive $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$, F_L, $F_2^{\rm D}$. Note that although the "b-Sat" model incorporates saturation effects via the eikonalisation of the gluon density, these saturation effects are expected to be only moderate for J/ψ production and negligible for Υ and Z^0 production. We use a "boosted Gaussian" vector meson wave function [16, 17].

III. RESULTS FOR TEVATRON AND LHC

A. Exclusive J/ψ production

In Fig. 2(a) we show the γp cross section as a function of W, where we indicate the W values corresponding to central production ($y = 0$) at the Tevatron and LHC. The "b-Sat" model predictions are normalised to best fit the HERA J/ψ data [18, 19] by a factor 1.08. Also shown are the results of a direct power-law fit to the HERA data, which gives $\sigma(\gamma p \to J/\psi + p) = (2.96\,\text{nb})(W/\text{GeV})^{0.721}$. In Fig. 2(b) we show the rapidity distributions at the Tevatron and LHC given by Eq. (1). The fact that $y = 0$ corresponds to W values where precise HERA data are available means that the uncertainties in the predictions are small. CDF have recently measured $\mathrm{d}\sigma/\mathrm{d}y|_{y=0} = (3.92 \pm 0.62)$ nb [20]. The "b-Sat" model prediction of 3.4 nb multiplied by $S^2 \simeq 0.9$ [9] and an estimated odderon contribution of a factor 1.3–1.6 [13] gives a total theory prediction of (4.0–4.9) nb, in agreement with the Tevatron data. At the LHC, measurement of exclusive J/ψ production is unlikely to be possible by ATLAS or CMS due to lack of a low-p_T trigger on leptons, but the measurement should be possible by ALICE [21] and by LHCb.

B. Exclusive Υ production

Only very sparse data are available on exclusive Υ photoproduction at HERA, and consequently, there is a much larger uncertainty in the theory predictions extrapolated to the Tevatron and LHC. Indeed, until very recently, only two data points with very large errors were published [22, 23], together with a further two preliminary ZEUS data points [24]. A power-law fit made in Ref. [2] to these four data points, shown in Fig. 3(a), gave $\sigma(\gamma p \to \Upsilon + p) = (0.119\,\text{nb})(W/\text{GeV})^{1.63}$. The two preliminary ZEUS data points, especially the point at highest W, moved down slightly in the final measurement [25], with a reduction in the size of the uncertainty, so that a revised power-law fit to the four published data points gives $\sigma(\gamma p \to \Upsilon + p) = (0.968\,\text{nb})(W/\text{GeV})^{1.14}$, also shown in Fig. 3(a). The "b-Sat" model predictions have a very similar W dependence to this revised power-law fit, but lie more than a factor two below the data for the default choice of $m_b = 4.5$ GeV and the "boosted Gaussian" Υ wave function. Given that there are uncertainties in these two choices, which are expected to mainly affect the normalisation but not the W dependence, we have simply rescaled the "b-Sat" predictions by a factor 2.16 to best fit the final HERA Υ data. In Fig. 3(b) we show the rapidity distributions at the Tevatron and LHC given by Eq. (1). Note that the results of Ref. [2] for the LHC rapidity distribution, using the preliminary ZEUS Υ data, indicated a large difference between the rescaled "b-Sat" predictions and the HERA power-law fit. But with the new published ZEUS data, the two predictions are in much better agreement. Of course, the fact that the central value of the power-law fit changes so much when two of the data points shift within their experimental errors, see Fig. 3(a), means that the uncertainty on the power-law parameterisation is large. Ideally, the errors on the two parameters in the power-law fit (given by the experimental errors on the 4 HERA data points), would be propagated through to the Tevatron and LHC rapidity distributions. An early attempt in this direction, but only for the error in the normalisation and not in the power, was made in Ref. [7].

Candidate exclusive Υ events have been found by CDF and the cross section measurements are eagerly awaited. Note that the odderon contribution to exclusive Υ production at the Tevatron is predicted to be about the same or even greater than the photon-induced contribution [13]. A feasibility study has been carried out by CMS for 100 pb^{-1} of integrated luminosity [26].

The effect of the decay lepton acceptance of the Tevatron and LHC experiments has been studied in Ref. [27], where the results of the power-law fit from Ref. [2] (using the preliminary ZEUS data) were compared with predictions obtained using an alternative parameterisation of the dipole cross section. Note that LHCb has the potential to measure exclusive Υ production for more forward lepton pseudorapidities than ATLAS or CMS.

C. Exclusive Z/γ^* production

DVCS at HERA, $\gamma^* p \to \gamma + p$, is theoretically cleaner than exclusive vector meson production since there is no uncertainty from the wave function. The existing data are well described by the "b-Sat" dipole model [16, 28], although they are not as precise as the HERA data on exclusive J/ψ production. The DVCS process in

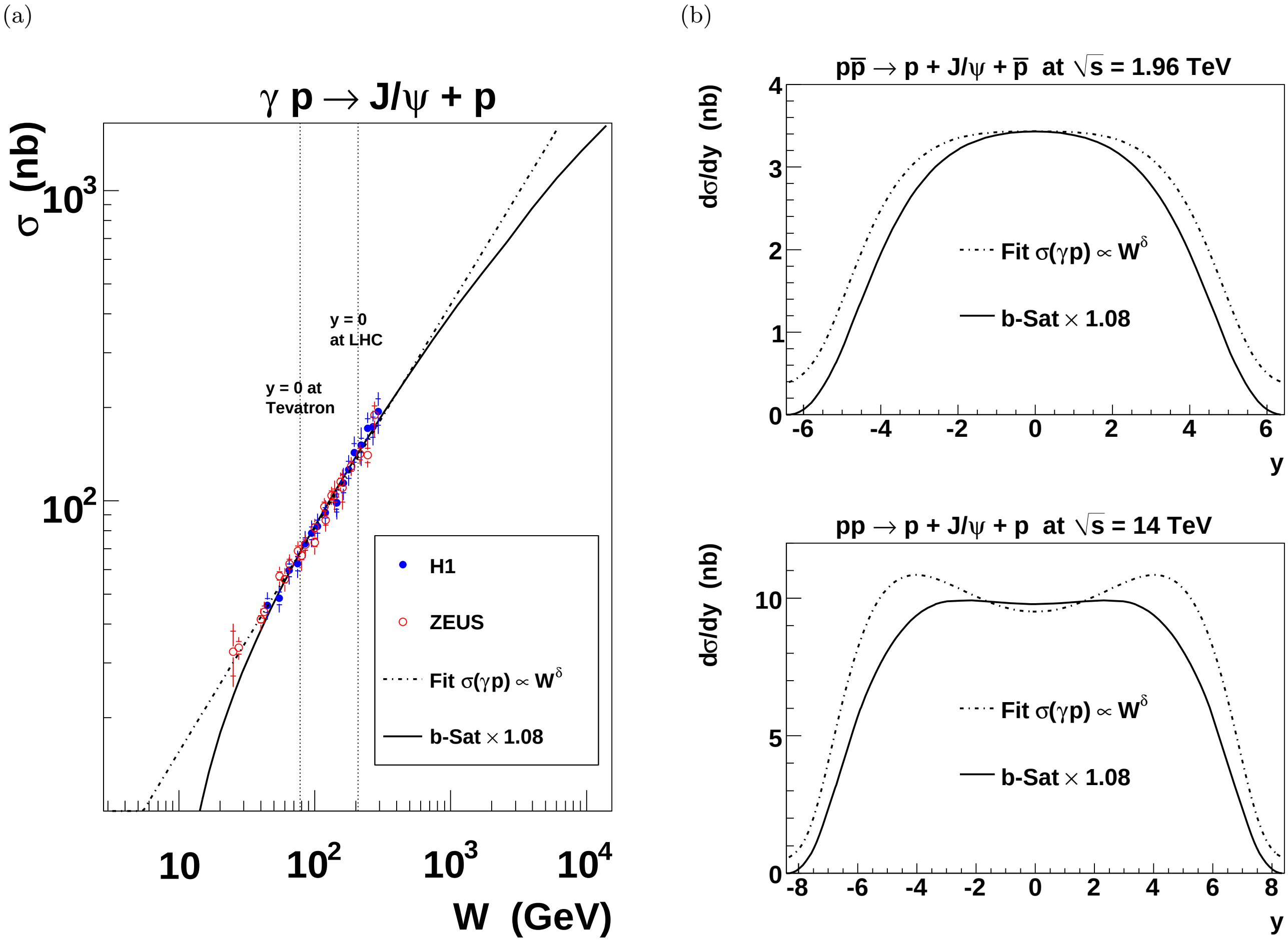

FIG. 2: Exclusive J/ψ photoproduction in hadron–hadron collisions. No absorptive corrections are included.

ep scattering interferes with the purely electromagnetic Bethe–Heitler (BH) process where the real photon is instead emitted from either the incoming or outgoing electron. The BH process is precisely calculable in QED and is therefore subtracted in existing DVCS measurements at HERA. Analogous processes to DVCS at hadron–hadron colliders are exclusive Z^0 photoproduction, $\gamma p \to (Z^0 \to \ell^+\ell^-) + p$, and timelike Compton scattering (TCS), $\gamma p \to (\gamma^* \to \ell^+\ell^-) + p$. Similarly to the DVCS case, there is interference of TCS with the pure QED subprocess ($\gamma\gamma \to \ell^+\ell^-$) which is precisely calculable and can be reduced with suitable cuts [29].

Wave functions for an outgoing Z/γ^* with *timelike* $q^2 = M^2 > 0$ were derived in Ref. [2]. Differences were found with respect to the usual *spacelike* case, $q^2 = -Q^2 < 0$, such that the amplitude for $\gamma p \to Z^0 + p$ is *not* simply the DVCS amplitude at $Q^2 = M_Z^2$ with a different coupling. In particular, we pick up a *real* contribution to the amplitude related to the contribution of an on-shell $q\bar{q}$ pair in addition to the usual imaginary part. In the dipole picture, direct numerical integration over the dipole size r proved to be difficult due to a wildly oscillatory integrand. This problem was solved by taking the analytic continuation to complex r, then choosing an appropriate integration contour [2]. Alternatively, there are no such problems if working in transverse momentum space and using k_T-factorisation [11]. We show the results in Fig. 4, where it can be seen that the cross sections at $y = 0$ are enhanced by 5% at the Tevatron and 21% at the LHC in the (correct) timelike case compared to the (incorrect) spacelike case. (The odderon contribution to exclusive Z^0 production is expected to be strongly suppressed [2].) The recent calculations of Ref. [11] found cross sections larger by a factor ∼3, presumably due mainly to differences in the gluon density at the relevant $x \sim M_Z/\sqrt{s}$, while absorptive corrections were found to lower the cross section by a factor 1.5–2.

CDF have made a search for exclusive Z^0 production at the Tevatron [30]. Eight candidate events were found in 2.20 (2.03) fb^{-1} of data in the electron (muon) channel with $M_{\ell\ell} > 40$ GeV and $\eta_\ell < 4$, consistent with the QED prediction for $\gamma\gamma \to \ell^+\ell^-$. No candidate events were found in the Z^0 mass window, allowing an upper limit to be placed for the exclusive Z^0 cross section of $\sigma < 0.96$ pb at 95% confidence-level, compared to the theory prediction of 0.3 fb [2], i.e. 3000 times lower than the experimental limit. The theory prediction of $\sigma = 13$ fb [2] at the LHC looks slightly more promising.

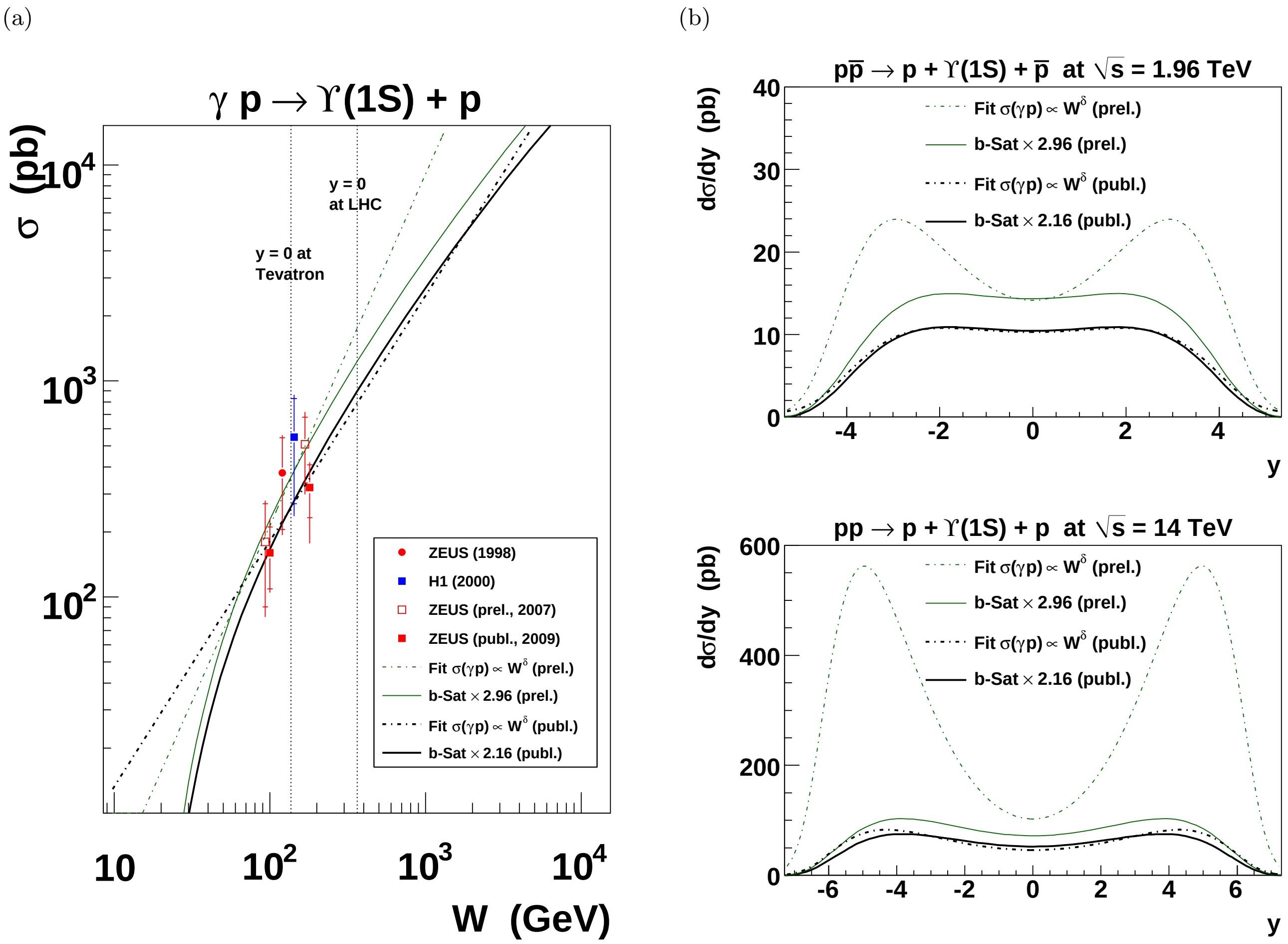

FIG. 3: Exclusive ϒ photoproduction in hadron–hadron collisions. No absorptive corrections are included.

IV. SUMMARY

A summary table of predictions is given in Table I, where the event rates (but not the cross sections) include the appropriate leptonic branching ratio. The ϒ cross sections have been revised with respect to Ref. [2]. Note that the Tevatron and LHC design luminosities are assumed in all cases as an illustrative comparison of the event rates for different processes, but these are not realistic values for early LHC running. In particular, exclusive J/ψ production is likely to be measured only at ALICE where the nominal luminosity (and so the event rate) is smaller by a factor of 2000 and at LHCb where the corresponding reduction factor is 50.

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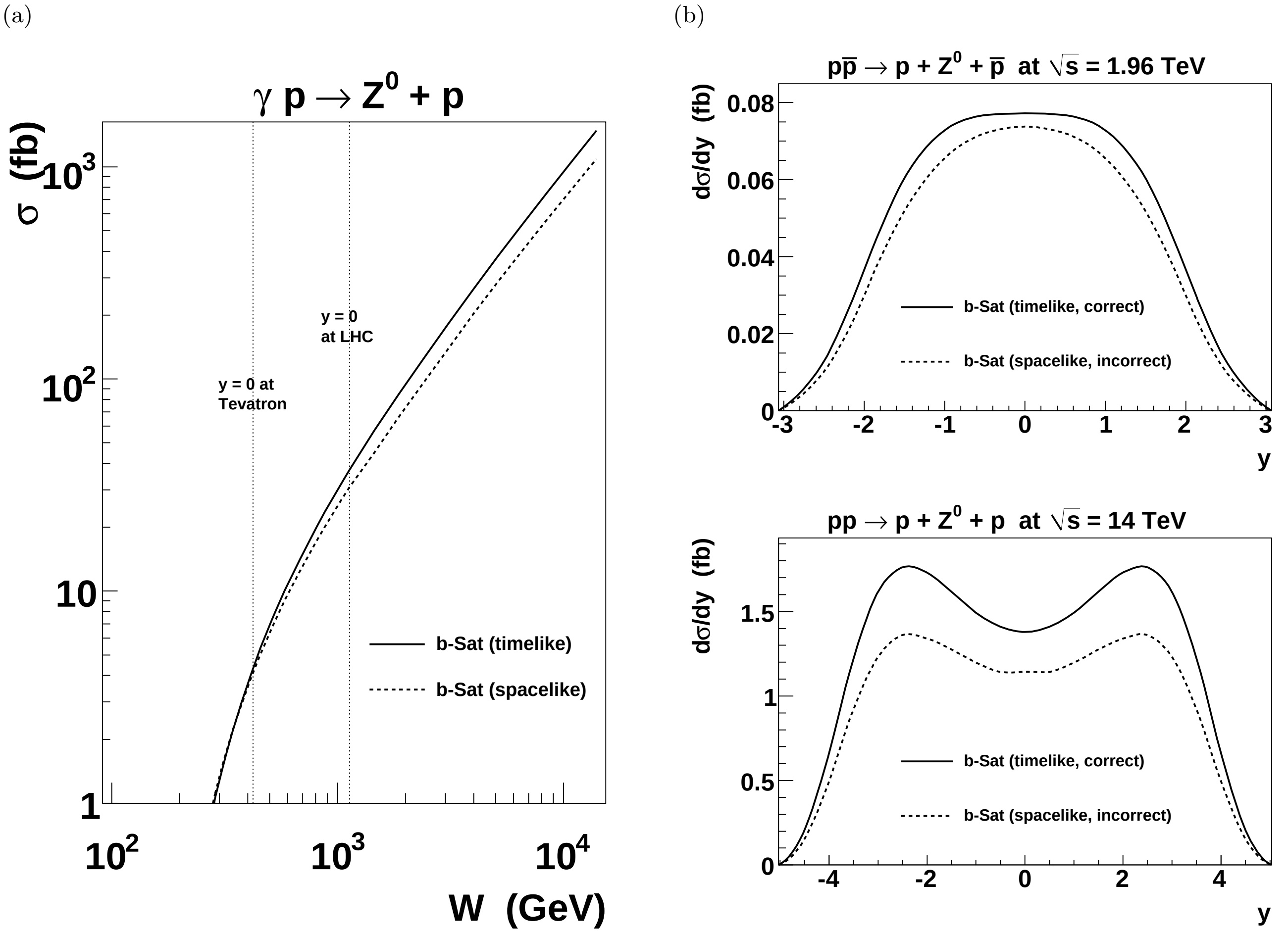

FIG. 4: Exclusive Z^0 photoproduction in hadron–hadron collisions. No absorptive corrections are included.

J/ψ	$\mathrm{d}\sigma/\mathrm{d}y\vert_{y=0}$ (nb)	σ (nb)	Event rate (s^{-1})
Tevatron	3.4	28	0.33
LHC	9.8	120	71

$\Upsilon(1S)$	$\mathrm{d}\sigma/\mathrm{d}y\vert_{y=0}$ (pb)	σ (pb)	Event rate (hr^{-1})
Tevatron	10	83	1.5
LHC	53	771	688

Z^0	$\mathrm{d}\sigma/\mathrm{d}y\vert_{y=0}$ (fb)	σ (fb)	Event rate (yr^{-1})
Tevatron	0.077	0.30	0.065
LHC	1.4	13	134

TABLE I: Event rates include leptonic branching ratio and assume a luminosity $\mathcal{L} = 2 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (Tevatron) and $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (LHC). No gap survival factor included.

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