Aspects of Higgs Production at the LHC

Errol Gotsman*

Department of Particles Physics, School of Physics and Astronomy
Raymond and Beverly Sackler Faculty of Exact Science
Tel Aviv University, Tel Aviv 69978, Israel

We discuss the main features and predictions of the GLMM model, which is based on a QCD motivated theoretical approach, and successfully describes the experimental data on total, elastic and diffractive cross sections. In addition we calculate the survival probability for a SM Higgs at the LHC, and compare our results with those of the Durham group.

1 Introduction

Over the past few years the subject of ”soft physics” has reemerged from the shadows, and has aroused the interest of the phenomenological community. This in no small way, due to the realization that the calculation of the probability of detecting a diffractive hard pQCD process e.g. Higgs production at the LHC, also depends on the underlying secondaries which are produced by ”soft” rescattering. Central diffractive production e.g. (Higgs boson, 2 jets, 2 γ's, χc), are accompanied by gaps in rapidity, between the two outgoing projectiles, and the centrally produced particles, which makes their detection easier. The subject of the survival of these rapidity gaps was initiated over twenty years ago [1], and has been refined over the interim period [2], [3].

2 Details of our Model

The details on which our two channel (GLM) model is based i.e. the Good-Walker (G-W) mechanism [4] can be found in [2]. See also U. Maor’s talk in these proceedings. It is well known that G-W neglects the diffractive production of large mass states (Mueller diagrams [5]), and to successfully describe the diffractive data, these need to be included by adding the relevant triple Pomeron contributions (see L.H. diagrams in Fig.1). In addition it is also necessary to include diagrams containing Pomeron loops, as shown in the R.H. diagrams in Fig.1.

To simplify the problem of summing the Pomeron loop diagrams, we assume that at high energies only the triple Pomeron interaction is essential, this conjecture has been proved in perturbative QCD (see Refs.[6] [7]). Mueller [8] has shown that in the leading log x approximation of pQCD for a large number of colours (Nc ≫ 1), the correct degrees of freedom are colourless dipoles.

*e-mail: gotsman@post.tau.ac.il
2.1 Summing Interacting Pomeron Diagrams

In the leading order approximation of pQCD, only one Pomeron (dipole) splitting into two Pomerons (dipoles), and two Pomerons (dipoles) merging into one Pomeron (dipole) are considered. All other Pomeron vertices do not appear in the leading log $x$ approximation of pQCD. We therefore restrict ourselves to sum only Pomeron diagrams containing triple Pomeron vertices. We add a caveat, that we neglect the $4\mathcal{P}$ term (which is needed for s channel unitarity), however, this term is only significant at energies $W > 10^5$, which is at the limit of the validity of our model.

To make the calculation tractable we further assume that the slope of the Pomeron trajectory $\alpha'_P = 0$. The results of our numerical fit to the relevant data, which we will discuss later, $(\alpha'_P = 0.01)$ lends credence to this assumption.

The theory which includes all the above ingredients can be formulated in terms of a generating function\[9, 10\]

$$Z(y, u) = \sum_n P_n(y) u^n,$$

where, $P_n(y)$ is the probability to find $n$-Pomerons (dipoles) at rapidity $y$. At rapidity $y = Y = \ln(s/s_0)$ we can impose an arbitrary initial condition. For example, demanding that there is only one fastest parton (dipole), which is $P_1(y = Y) = 1$, while $P_{n>1}(y = Y) = 0$. In this case we have the following initial condition for the generating function

$$Z(y = Y) = u.$$   

(2)

At $u = 1$

$$Z(y, u = 1) = 1,$$

(3)

which follows from the physical meaning of $P_n$ as a probability. The solution, with these two conditions, will give us the sum of enhanced diagrams.

For the function $Z(u)$ the following simple equation can be written (see Ref.2 and references therein)

$$-\frac{\partial Z(y, u)}{\partial y} = -\Gamma(1 \rightarrow 2) u (1 - u) \frac{\partial Z(y, u)}{\partial u} + \Gamma(2 \rightarrow 1) u (1 - u) \frac{\partial^2 Z(y, u)}{\partial^2 u},$$

(4)
where, $\Gamma(1 \rightarrow 2)$ describes the decay of one Pomeron (dipole) into two Pomerons (dipoles), while $\Gamma(2 \rightarrow 1)$ relates to the merging of two Pomerons (dipoles) into one Pomeron (dipole).

Using the functional $Z$, we calculate the scattering amplitude\textsuperscript{10, 11}, using the following formula:

$$N(Y) \equiv \text{Im} A_{el}(Y) = \sum_{n=1}^{\infty} \frac{(-1)^n}{n!} \frac{\partial^n Z(y, u)}{\partial^n u}|_{u=1} \gamma_n(Y = Y_0, b),$$

where, $\gamma_n(Y = Y_0, b)$ is the scattering amplitude of $n$-partons (dipoles) at low energy.

The generating function approach has the advantage that it can be solved analytically (see Ref.\textsuperscript{12}), using the MPSI \textsuperscript{13} approximation. The exact expression for the Pomeron Green’s function is given by

$$G_{IP}(Y) = 1 - \exp \left( \frac{1}{T(Y)} \right) \left( \frac{1}{T(Y)} \right) \Gamma \left( 0, \frac{1}{T(Y)} \right),$$

where $\Gamma (0, x)$ is the incomplete gamma function, and $T(Y) = \gamma e^{\Delta_{IP} Y}$. $\gamma$ denotes the amplitude of the two dipole interaction at low energy. The MPSI approximation only takes into account the first term of the expression of the enhanced diagrams, neglecting other terms, as they are suppressed as $e^{-\Delta Y}$. Consequently, this approximation is only reliable in the region $Y \leq \min[1, \gamma, 1, \alpha'_{IP}, \beta, \omega]$.  

### 3 Determining the Parameters of the Model and Results of the Fit

The pertinent details of our fit to the experimental data, and our determination of the relevant parameters of the model, needed to describe the soft interactions, are contained in \textsuperscript{2}. In this section we only mention the salient features, and results of the fit. Our fit is based on

55 experimental data points, which includes the $p$-$p$ and $\bar{p}$-$p$ total cross sections, integrated elastic cross sections, integrated single and double diffraction cross sections, and the forward slope of the elastic cross section in the ISR-Tevatron energy range. The model gives a good reproduction of the data, with a $\chi^2/d.o.f. \approx 1$. In addition to the quantities contained in the data base, we obtain a good description of the CDF \textsuperscript{14} differential elastic cross sections and the single diffractive mass distribution at $t = 0.05 \text{GeV}^2$. An important advantage of our approach, is that the model provides a very good reproduction of the double diffractive (DD) data points. Other attempts to describe the DD data e.g. (see Refs.\textsuperscript{15, 16}), were not successful in reproducing the DD experimental results over the whole energy range.

In Table 1 we list the values of the parameters obtained by a least squares fit to the experimental data, both for the G-W formalism (elastic data only), and for the G-W formalism plus enhanced graphs (elastic plus diffractive data). In Table 2 we compare our results with results

|          | $\Delta_{IP}$ | $\beta$ | $\alpha'_{IP}$ | $g_1$ | $g_2$ | $m_1$ | $m_2$ | $\chi^2/d.o.f.$ |
|----------|--------------|--------|---------------|------|------|------|------|----------------|
| GW       | 0.120        | 0.46   | 0.012         | 1.27 | 3.33 | 0.913| 0.98 | 0.87           |
| GW+$\bar{p}$-enh. | 0.335        | 0.34   | 0.010         | 5.82 | 239.6| 1.54 | 3.06 | 1.00           |

Table 1: Fitted parameters for GLMM GW and GW+$\bar{p}$-enhanced models.
of the two versions of the model proposed by the Durham group [15 and 3]. In Fig. 2 we display the predictions of the GLMM model’s values for the various cross sections. Note that $\sigma_{el}$ and $\sigma_{sd}$ have completely different energy dependence, unlike the predictions of [3]. At an energy of 7 TeV the predictions of GLMM are (in mb): $\sigma_{tot} = 86.0$, $\sigma_{el} = 19.5$, $\sigma_{sd} = 10.7$, $\sigma_{dd} = 5.9$ and the forward slope $B_{el} = 19.4$ GeV$^{-2}$.

|         | Tevatron          | LHC              | W=10^4 GeV        |
|---------|-------------------|------------------|-------------------|
|         | GLMM KMR(07) KMR(08) | GLMM KMR(07) KMR(08) | GLMM KMR(07) KMR(08) |
| $\sigma_{tot}$ | 73.3 74.0 73.7 | 73.3 74.0 73.7 | 73.3 74.0 73.7 |
| $\sigma_{el}$ | 16.3 16.3 16.4 | 16.3 16.3 16.4 | 16.3 16.3 16.4 |
| $\sigma_{sd}$ | 9.8 10.9 13.8 | 11.8 13.3 19.0 | 14.4 15.7 24.2 |
| $\sigma_{dd}$ | 5.4 7.2 | 6.1 13.4 | 6.3 17.3 |
| $\frac{\sigma_{el}+\sigma_{dif}}{\sigma_{tot}}$ | 0.43 0.46 | 0.42 0.53 | 0.41 0.57 |

Table 2: Comparison of GLMM, KMR(07) and KMR(08) cross sections in mb.

4 Survival Probability for Central Diffractive Production of the Higgs Boson

A general review of survival probability calculations can be found in [16]. We denote by $\langle |S^2| \rangle$ the probability that the Large Rapidity Gap (LRG) survives, and is not filled by secondaries from eikonal and enhanced rescattering effects (see Fig. 3). The expression for the survival probability can be written $\langle |S^2| \rangle = \frac{N(s)}{D(s)}$ where

$$N(s) = \int d^2b_1 d^2b_2 \left[ \sum_{i,k} < p| i > < p| k > A_H^i(s,b_1) A_H^k(s,b_2)(1 - A_S^{i,k} ((s,(b_1 + b_2))))^2 \right],$$

and

$$D(s) = \int d^2b_1 d^2b_2 \left[ \sum_{i,k} < p| i > < p| k > A_H^i(s,b_1) A_H^k(s,b_2) \right]^2.$$

$A_S(b,s)$ denotes the "soft" strong amplitude of our model [2]. While for the "hard" amplitude $A_H(b,s)$, we assume an input Gaussian b dependence, i.e. $A_H^i(s) = A_H^i(s) \Gamma^H_{i,k}(b)$.
Figure 3: a) the survival probability in the G-W mechanism, b) illustrates the origin of the additional factor $\langle | S_{enh}^2 | \rangle$.

with

$$\Gamma_{i,k}^H(b) = \frac{1}{\pi R_{i,k}^H} e^{-\frac{b^2}{2R_{i,k}^H}}.$$  

The "hard" radii are constants determined from HERA data on elastic and inelastic $J/\Psi$ production. We introduce two hard b-profiles $A_{pp}^H(b) = \frac{V_{p \rightarrow p}}{2\pi B_{Hel}^H} \exp\left(-\frac{b^2}{2B_{Hel}^H}\right)$, and $A_{pdif}^H(b) = \frac{V_{p \rightarrow dif}}{2\pi B_{Hel}^H} \exp\left(-\frac{b^2}{2B_{Hel}^H}\right)$. The values $B_{el}^H = 5.0 \text{ GeV}^{-2}$ and $B_{in}^H = 1 \text{ GeV}^{-2}$ have been taken from ZEUS data. The value $B_{el}^H = (3.6) \text{ GeV}^{-2}$ was used in [2], this has now been changed in light of the latest measurements of the "hard" slope, by the H1 group. This is in contrast to KMR treatment [15] where they assume: $A_{pp}^H(b) = A_{pdif}^H(b) \propto \exp\left(-\frac{b^2}{2B_{in}^H}\right)$ with $B_{el}^H = B_{in}^H = 4 \text{ or } 5.5 \text{ GeV}^{-2}$ The sensitivity of our results to the parameters of the "hard" amplitude are shown in Fig.4 (the L.H. figure), note that for $B_{in}^H = 1 \text{ GeV}^{-2}$, changing the value of $B_{el}^H$ from 3.6 to 5.0 GeV$^{-2}$, increases $\langle | S_{2ch}^2 | \rangle$ by $\approx 70 \%$. Our results for $\langle | S^2 | \rangle = \langle | S_{2ch}^2 | \rangle \times \langle | S_{enh}^2 | \rangle$ is given by the full line in Fig.4 (R.H. figure), it decreases with increasing energy, due to the behaviour of $\langle | S_{enh}^2 | \rangle$.

Our results and the Durham group’s results for Survival Probability are given in Table 3. At an energy of 7 TeV we predict a value $\langle | S^2 | \rangle \approx 0.6\%$. We have also succeeded in summing

|          | Tevatron | LHC (14 TeV) | $W=10^7$ GeV |
|----------|----------|-------------|--------------|
| $S_{2ch}^2(\%)$ | 5.3 | 2.7-4.8 | 3.9 | 1.2-3.2 | 3.2 | 0.9-2.5 |
| $S_{enh}^2(\%)$ | 28.5 | 100 | 6.3 | 100 | 33.3 | 33.3 | 100 |
| $S^2(\%)$ | 1.51 | 2.7-4.8 | 0.24 | 1.2-3.2 | 1.5 | 0.11 | 0.9-2.5 |

Table 3: Comparison of results obtained for Survival Probability in Tel Aviv and Durham models

the semi-enhanced contribution (see R.H. side of Fig.1) to the Survival Probability, and find that it is almost energy independent, and has a value $\approx 100\%$ at Tevatron and LHC energies [17].

5 Discussion and Conclusions

We present a model for soft interactions having two components: (i) G-W mechanism for elastic and low mass diffractive scattering, and (ii) Pomeron enhanced contributions for high
mass diffractive production. In addition we find from our fit that the slope of the Pomeron \( \alpha_{IP} \approx 0.01 \). This is consistent with what one expects in pQCD, since for a BFKL Pomeron 
\( \alpha_{IP} \propto 1/Q_s^2 \) as \( s \to \infty \). Having \( \alpha_{IP} \to 0 \), provides a necessary condition that links 
strong (soft) interactions with the hard interactions described by pQCD. A key hypothesis in 
our model is that the soft processes are not "soft", but originate from short distances. We have 
only one Pomeron. There is no requirement for a "soft" and "hard" Pomeron. This is in accord 
with Hera data for \( F_2 \), which is smooth throughout the transition region [18].

To illustrate our achievements and problems, we compare our approach with the work of 
the Durham group [15][3]. The main difference in the underlying philosophy of the two groups 
is that, the Durham approach is based on the parton model where there is only a short range 
rapidity interaction between partons, while we, due to exchange of gluons in QCD, have a long 
range rapidity interaction. Both approaches consider \( \alpha_{IP} \), as being small. In both programs 
the Pomeron interaction was taken into account. The difference between the two approaches is 
that KMR made an \textit{ad hoc} "reasonable" assumption, that the multi-Pomeron vertices have the 
following form, for the transition of \( n \) Pomerons to \( m \) Pomerons

\[
g_m^n = n m \lambda^{n+m-2} g_N/2 = n m \lambda^{n+m-3} g_{3F}/2. \tag{7}
\]

No theoretical arguments or theoretical models were offered in support of this assumption, 
which certainly contradicts the pQCD approach [3][4]. In spite of these differences, the values 
obtained for the \( \sigma_{ot} \) and \( \sigma_{el} \) are in surprisingly close agreement (see Table 2). It is only in the 
latest version of the Durham model [3], which includes three components of the Pomeron, with 
different transverse momenta of the partons in each component (to mimic BFKL diffusion in \( k_t \)), 
that there are fairly large discrepancies in the diffractive sector i.e. \( \sigma_{sd} \) and \( \sigma_{dd} \). KMR [3] find 
that at higher energies \( \sigma_{sd} \) and \( \sigma_{dd} \) have comparable values and similar energy dependence, this 
is not so in our description [2] (see Fig.2). We note that the results presented by Poghosyan at 
this conference for \( \sigma_{sd} \) and \( \sigma_{dd} \) [19] agree both in magnitude and energy dependence with those

Figure 4: L.H. figure: The dependence of \( S^2 \) at the LHC on \( B_H^H \) and \( B_{H_{in}} \). R.H. figure: Energy 
dependence of \( S^2 \) for centrally produced Higgs. The full (dashed) line is for \( B_H^H = 5.0 \) (3.6) 
GeV\(^{-2} \).
obtained in the GLMM model. There is also disagreement in the result for the calculation of the Survival Probability. In [3], the Survival Probability is now multiplied by a "renormalizing" factor \( \langle p_t^2 \rangle B \) and referred to as \( \langle S^2_{eff} \rangle \). The result for LHC energy is \( \langle S^2_{eff} \rangle = 0.015^{+0.015}_{-0.005} \). It is not clear whether there is in addition a factor \( \langle S^2_{enh} \rangle \approx \frac{1}{3} \), that needs to be incorporated. If affirmative, then the discrepancy between our result and that of the Durham group for \( \langle S^2 \rangle \) at Tevatron energies is small, but the discrepancy becomes larger for the LHC energy range, as we predict that \( \langle S^2_{enh} \rangle \) decreases as the rapidity between the projectiles increases, while Durham claim little (if any) energy dependence for \( \langle S^2_{enh} \rangle \).

6 Acknowledgments

This research was supported in part by BSF grant # 20004019 and by a grant from Israel Ministry of Science and the Foundation for Basic Research of the Russian Federation.

7 Bibliography

References

[1] Y.L. Dokshitzer, S.I. Troian and V.A. Khoze, Sov. J. Nucl. Phys. 46 712 (1987); Y.L. Dokshitzer, V.A. Khoze and T. Sjöstrand, Phys. Lett. B274 116 (1992); J.D. Bjorken, Intr. J. Mod. Phys. A7 4189 (1992); Phys. Rev. D47 101 (1993); E. Gotsman, E. Levin and U. Maor, Phys. Lett. B309 199 (1993).

[2] E. Gotsman, E. Levin, U, Maor and J.S. Miller, Eur. Phys. J. C57 269 (2008).

[3] M.G. Ryskin, A.D. Martin and V.A. Khoze, Eur. Phys. J. C60 249 (2009).

[4] M.L. Good and W.D. Walker, Phys. Rev. D20 1857 (1980).

[5] A.H. Mueller, Phys. Rev. D2 2963 (1970).

[6] J. Bartels, M. Braun and G.P. Vacca, Eur. Phys. J. C40 419 (2205); J. Bartels and C. Ewerz, JHEP 9909 026 (1999); J. Bartels and M. Wusthoff, Z. Phys. C6 157 (1995); A.H. Mueller and B. Patel, Nucl. Phys. B425 471 (1994); J. Bartels, Z. Phys. C60 471 (1993).

[7] M.A. Braun: Phys. Lett. B632 297 (2006), Eur. Phys. J. C16 337 (2000); Phys. Lett. B483 115 (2000); Eur. Phys. J. C33 113 (2004); M.A. Braun and G.P. Vacca, Eur. Phys. J. C6 147 (1999).

[8] A.H. Mueller, Nucl. Phys. B415 373 (1994); B437 107 (1995).

[9] A.H. Mueller, Nucl. Phys. B415 107 (1995).

[10] E. Levin and M. Lubinsky, Nucl. Phys. A763 172 (2005); Phys. Lett. B607 131 (2005); Nucl. Phys. A730 191 (2004).

[11] Y.V. Kovchegov, Phys. Rev. D60 034008 (1999).

[12] M. Kozlov and E. Levin, Nucl. Phys A779 142 (2006).

[13] A.H. Mueller and B. Patel, Nucl. Phys. B425 471 (1994); A.H. Mueller and G.P. Salam, Nucl. Phys. B475 293 (1996); G.P. Salam, Nucl. Phys. B461 512 (1996); E. Iancu and A.H. Mueller, Nucl. Phys. A730 460 (2004).

[14] CDF Collaboration, Phys. Rev. D50, 5535 (1994).

[15] M.G. Ryskin, A.D. Martin and V.A. Khoze, Eur. Phys. J. C54 199 (2008).

[16] E. Gotsman, E. Levin, U. Maor, E. Naftali, and A. Prygarin, in :HERA and the LHC- A Workshop on the Implications of HERA for LHC Physics: Proceedings Part A, p. 221 (2005). arXiv:hep-ph-0601012

[17] E. Gotsman, E. Levin and U. Maor (to be published).

[18] H1 Collaboration, arXiv:hep-ex/0904.0929 (2009)

[19] A.B. Kaidalov and M.G. Poghosyan, arXiv:hep-ph/0909.5156