LARGE RAPIDITY GAPS SURVIVAL PROBABILITIES AT LHC*

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We calculate the probability of large rapidity gaps in high energy hadronic collisions using a model based on QCD minijets and soft gluon emission down into the infrared region. Comparing with other models we find a remarkable agreement among most predictions.

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1. Introduction

The possibility of the existence of large rapidity gaps in hadronic collisions was suggested a number of years ago [1, 2]. In [1], the occurrence of rapidity regions deprived of soft hadronic debris was proposed as a means to search for Higgs bosons produced by interactions between colour singlet particles, *e.g.* W, Z bosons emitted by initial state quarks, but with a warning against the possibility of soft collisions which would populate these regions.

For an estimate, an expression for the Large Rapidity Gaps Survival Probability (LRGSP) was proposed, namely

$$\left\langle |S|^2 \right\rangle = \frac{\int d^2\boldsymbol{b}\ A^{AB}(b,s)|S(b)|^2\sigma_H(b,s)}{\int d^2\boldsymbol{b}\ A^{AB}(b,s)\sigma_H(b,s)}\,, \tag{1}$$

where $|S(b)|^2$ is the probability in impact parameter space that two hadrons A, B got through each other without detectable inelastic interactions, $A^{AB}(b,s)$ is the b-distribution for collisions involved in interactions in which only low p_t particle emission can take place, and $\sigma_H(b,s)$ is the cross-section for producing, say, a Higgs boson, in such hadronically deprived silent configuration. To use the above equation, one needs to estimate the probability of *not* having inelastic collisions, $|S(b)|^2 = P_{\text{no-inel}}(b)$ and the distribution for low-p_t interactions, namely the probability $A^{AB}(b,s)$ to find those collisions for which two hadrons A and B at distance $\boldsymbol{b}$ will not undergo large p_t collisions. Introducing for the scattered partons a cut-off p_{tmin}, above which the scattering process can be described by perturbative QCD, we need to estimate the b-distribution of all the collisions with $p_t < p_{\text{tmin}}$. In order to calculate $P_{\text{no-inel}}$, one can approximate the bulk of hadron–hadron collisions with a sum of Poisson distributions for k independent collisions distributed around an average $\bar{n} \equiv n(b,s)$, namely

$$P_{\text{no-inel}} = 1 - \sum_k \Pi\{k,\bar{n}\} = 1 - \sum_{k=1}^{\infty} \frac{\bar{n}^k e^{-\bar{n}}}{k!} = e^{-n(b,s)} \tag{2}$$

which also leads to the following expressions for the total and inelastic cross-sections

$$\sigma_{\text{inel}}^{AB} = \int d^2\boldsymbol{b}\left[1 - e^{-n(b,s)}\right] \tag{3}$$

and

$$\sigma_{\text{tot}}^{AB} = 2\int d^2\boldsymbol{b}\left[1 - e^{-\frac{n(b,s)}{2}}\cos\operatorname{Re}\chi(b,s)\right]\,, \tag{4}$$

where $n(b,s)/2$ can be identified with the imaginary part of the eikonal function $\chi(b,s)$. Approximating $\operatorname{Re}\chi(b,s) = 0$, allows a simple way of calculating σ_{tot} if one has a model for $n(b,s)$. A possible strategy to calculate the LRGSP is then to build a model for the total cross-section and then insert the relevant b-distributions in Eq. (1). The basic quantity to evaluate is thus

$$n(b,s) = n^{\text{NP}}(b,s) + n^{\text{hard}}(b,s) = A^{\text{NP}}(b,s)\sigma_{\text{NP}}(s) + A^{\text{hard}}(b,s)\sigma_{\text{hard}}(s)\,, \tag{5}$$

where we have split the average number of collisions between those with outgoing partons below (NP) and above (hard) the cut-off p_{tmin}. In the next section we shall describe our model [3,4] for total cross-section, comparing its results to other models. Then, we shall use the b-distributions from our model to evaluate the LRGSP at LHC, again comparing it to different model results.

2. The eikonal minijet model for total cross-section

To build a realistic model for σ_{tot}, one needs to understand what makes the cross-section rise with a slope compatible with the limits imposed by the Froissart theorem, namely $\sigma_{tot} \leq \log^2 s$. In our model, the rise in σ_{tot} is driven by the rise of low-x (perturbative) gluon–gluon interactions, while the saturation imposed by the Froissart bound comes from initial state emission of infrared gluons which temper the too fast rise of the minijet cross-section. The rise is calculated using perturbative QCD for collisions producing partons with $p_t > p_{tmin} \approx 1 \div 2$ GeV, using hard parton scattering cross-sections, and the experimentally measured and DGLAP evolved parton densities (PDF's) in the scattering hadrons. Thus parton densities and the elements of perturbative QCD are the only input needed for the calculation of σ_{hard}. The rate of rise of this cross-section with energy is determined by p_{tmin} and the low-x behaviour of the parton densities. As noted before, the rise with energy of the cross-section obtained with this is much steeper than that consistent with the Froissart bound, but in our model this rise is tempered by soft gluon emission. The saturation mechanism takes place through the b-distribution obtained from the Fourier transform of the resummed infrared gluon distribution. This distribution is energy dependent and given by [5]

$$A(b, s) = A_0 \int d^2 \boldsymbol{K}_t e^{-i\boldsymbol{K}_t \cdot \boldsymbol{b}} \Pi(\boldsymbol{K}_t) = \frac{e^{-h(b, q_{max})}}{\int d^2 \boldsymbol{b} e^{-h(b, q_{max})}} \equiv A_{BN}(b, q_{max}),$$

(6)

where the function $h(b, q_{max})$ is obtained through summing soft gluons [5] and requires integration of soft gluon momenta from zero to q_{max} the maximum transverse momentum allowed by kinematics to single soft gluons. The saturation of the Froissart bound is due to the increasing acollinearity of "hard" partons produced by initial state soft gluon emission. The single soft gluon distribution needed for the calculation of $h(b, q_{max})$ requires using infrared k_t gluons and different models with a frozen or singular $\alpha_{strong}(k_t)$ produce different saturation effects. We have shown [6] that the frozen model is inadequate to quench the rise due to minijets, since we see that the early rise in proton–antiproton collisions requires minijets with $p_{tmin} \approx 1$ GeV,

but then the total cross-section rises too much. Put differently, but equivalently, raising p_{tmin} to fit higher energy values of the cross-section, say at the Tevatron, would require $p_{\mathrm{tmin}} \approx 2$ GeV but miss the early rise. Instead, we find that a singular α_{s} produces an adequate s-dependent saturation effect. Singular expressions for α_{s} are discussed in the literature, in particular for quarkonium phenomenology [7]. Our choice is a singular, but integrable expression for the strong coupling constant in the infrared region, namely

$$\alpha_{\mathrm{s}}(k_{\mathrm{t}}) \approx \frac{12\pi}{33 - 2N_{\mathrm{f}}} \left(\frac{\Lambda_{\mathrm{QCD}}}{k_{\mathrm{t}}} \right)^{2p}, \qquad k_{\mathrm{t}} \to 0, \tag{7}$$

where the scale factor is chosen to allow a smooth interpolation to the asymptotic freedom expression for α_{s}, namely we choose

$$\alpha_{\mathrm{s}}(k_{\mathrm{t}}) = \frac{12\pi}{33 - 2N_{\mathrm{f}}} \frac{p}{\log \left(1 + p \left(\frac{k_{\mathrm{t}}}{\Lambda_{\mathrm{QCD}}} \right)^{2p} \right)}. \tag{8}$$

The singularity in the infrared is regulated by the parameter p, which has to be < 1 for the integral in $h(b, q_{\mathrm{max}})$ to converge. The next input for phenomenological tests of our model is the number of non-perturbative (NP) collisions. We approximate it as

$$n^{\mathrm{NP}} = A_{\mathrm{BN}}^{\mathrm{NP}} \sigma_0 \left(1 + \frac{2\epsilon}{\sqrt{s}} \right) \tag{9}$$

with $\epsilon = 0, 1$ for the process pp or $p\bar{p}$. We choose a constant $\sigma_0 \approx 48$ mb and use for $A_{\mathrm{BN}}^{\mathrm{NP}}$ the same model as for the hard collisions, but we restrict q_{max} to be no larger than $\approx 20\% p_{\mathrm{tmin}}$, since these collisions are limited to $p_{\mathrm{t}} < p_{\mathrm{tmin}}$. The same function $A_{\mathrm{BN}}^{\mathrm{NP}}$ is then used for the LRGSP calculation, as discussed in the next section where both the estimated σ_{total} as well as the LRGSP will be presented and compared with other models.

3. Total cross-sections and survival probability

Applying the above described model to the calculation of total cross-sections, gives the results shown in the left panel of Fig. 1. To obtain this figure, we have used different PDF's and slightly different values for the parameters p, σ_0 and p_{tmin} and the variations are indicated by the band. We have shown [3] that the asymptotic behaviour of this cross-section can be fitted with a $\log^2 s$ type behaviour. This is a phenomenological confirmation that the model satisfies Froissart bound.
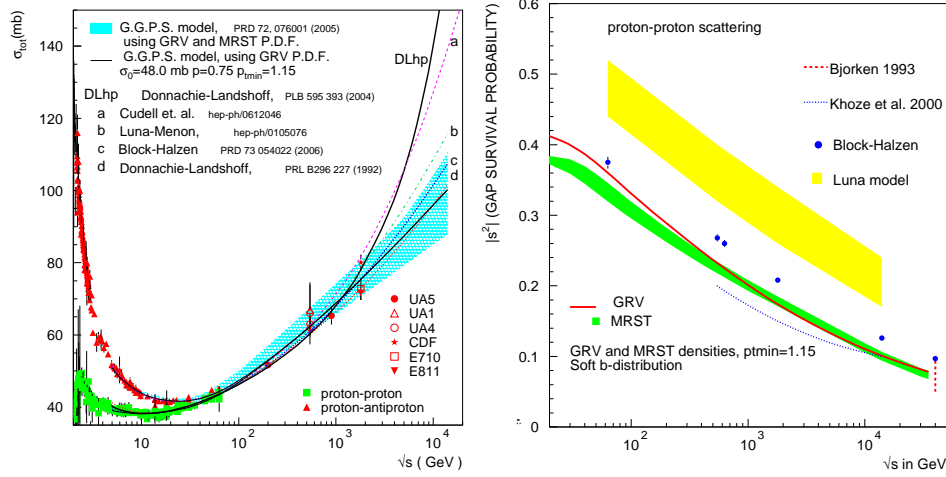
Fig. 1. Total cross-section data [8] and models [9] (left) and survival probability for large rapidity gaps for different models [10] (right).

We do not see in our model any hard Pomeron behaviour beyond the initial rise and predict a value $\sigma_{\rm tot}^{\rm LHC} = 100^{+10}_{-13}$(mb). The LRGSP can now be calculated using the two quantities $e^{-n(b,s)}$ and $A_{\rm BN}^{\rm NP}(b,s)$ which were input in the calculation of the total cross-section. The right panel of Fig. 1 shows such evaluations, with the pale grey (yellow) band corresponding to various MRST densities [11], the central full line to using GRV densities [12] and the other lines and bands representing comparisons with other models, as indicated. The most interesting result of this figure is that the predictions for LHC agree reasonably well amongst each other, namely $|S|^2 = 5 \div 10\%$, in spite of the fact that the various models differ greatly in details and the way in which they achieve results for total cross-sections consistent with the Froissart bound. Thus the model estimates for the LRGSP are quite robust.

4. Conclusions

We have built a model for $\sigma_{\rm tot}$ which incorporates hard and soft gluon effects, satisfies the Froissart bound and can be used reliably to study other minimum bias effects *e.g.* the Survival Probability of Large Rapidity Gaps. It can also be extended to calculations of total γp and $\gamma\gamma$ cross-sections.

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