Comments on low mass dissociation at the LHC in the context of the discrepancy between the ATLAS and TOTEM measurements of $\sigma_{tot}$

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Abstract

The cross section for low mass dissociation at LHC energies is estimated in a partly data driven approach. The result is compared to the Monte Carlo estimate from the QGSJET-II-03 model used by the TOTEM experiment in the determination of $\sigma_{tot}$ via the luminosity-independent method. Significant differences are found and possible consequences are explored and discussed.

1 Introduction

With the term low mass diffraction or dissociation into a low mass system we mean a low $p_t$ process of the type illustrated in Fig. 1, where the topologies single and double dissociation are shown. These topologies are characterized by the exchange of the Pomeron in the $t$-channel or in the language of QCD an exchange of a color singlet state of gluons. With low mass in this context we refer to processes where the mass of the dissociated system is less than $\approx 3$–$4$ GeV for single dissociation and in the case of double dissociation both systems have a mass less than $\approx 3$–$4$ GeV.

The cross section for these type of reactions are both hard to measure and challenging to theoretically estimate. In general it is difficult to measure diffraction at high energy colliders but especially for diffractive systems with a low mass. For low mass systems a large fraction of the diffractively produced particles are emitted in the very forward direction and lost in the beam pipe. Also the theoretical estimates of low mass diffraction are notorious difficult and inexact. Often the Good-Walker approach [2] is used but such an approach is associated with a number of uncertainties.
The size of the low mass cross section has of course an interest in itself but there is also an interest related to the measurements of the total cross section ($\sigma_{\text{tot}}$). Actually, the uncertainties related to low mass dissociation constitute the largest uncertainty of the total cross section measurements by the TOTEM experiment using the so-called luminosity-independent method [3][4][5].

Using the luminosity-independent method the total cross section is given by:

$$\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{(dN_{el}/dt)_{t=0}}{(N_{el} + N_{inel})}$$

where $N_{el}$ and $N_{inel}$ stand for the elastic and inelastic rate, $(dN_{el}/dt)_{t=0}$ is the elastic differential rate extrapolated to $t = 0$ and $\rho$ is the ratio of the real to imaginary part of the elastic scattering amplitude in the forward direction. $N_{inel}$ is measured except in the very forward direction and thus an estimate of the rate from low mass dissociation is required.

TOTEM uses Monte Carlo program QGSJET-II-03 [6] to estimate how much is undetected between $M_x \approx 3$-4 GeV and the proton mass. The mass of the diffractive system, $M_x$, is related to the commonly used variable $\xi$ through $\xi = M_x^2 / s$ with $s$ being the center-of-mass energy squared.

The Monte Carlo estimates used by TOTEM are given in Table 1. The authors of Refs. [3][4][5] are aware of the difficulty to make a precise estimate and give uncertainties representing half of the correction.

The strong energy dependence in going from 7 TeV to 13 TeV i.e. from 4% to 7% appears somewhat unnatural to us given that the cross sections in the LHC regime rather vary as...
Table 1: Corrections used by TOTEM for low mass dissociation

| √s TeV | Low mass limit GeV | Correction % of σ_{inel} | σ_{inel} mb | Correction mb |
|--------|---------------------|--------------------------|-------------|--------------|
| 7      | 3.4                 | 4                        | 72.9        | 2.9          |
| 8      | 3.6                 | 4.8±2.4                  | 74.7        | 3.6±1.8      |
| 13     | 4.6                 | 7.1±3.55                 | 79.5        | 5.6±2.8      |

logarithms of the center-of mass energy or as a power law but with a small power of order \( \approx 0.1 \).

We asked ourselves if there is another way of estimating low mass dissociation not relying exclusively upon Monte Carlo estimates but rather using at least a partly data driven approach.

2 Measurements of inelastic cross sections at 7 TeV and 13 TeV

Table 2 and Table 3 summarize measurements of the inelastic cross sections at \( \sqrt{s}=7 \) TeV and at \( \sqrt{s}=13 \) TeV. There are the measurements of the total inelastic cross section \( (\sigma_{inel} = \sigma_{tot} - \sigma_{el}) \) from ATLAS-ALFA and from TOTEM. In addition there are fiducial cross section measurements, in a limited kinematical range, from ALICE, ATLAS and CMS. In the case of 7 TeV the measurements are for masses \( M_x \) above 16 GeV, while in the case of 13 TeV the measurements are for masses above 13 GeV. As can be seen there is good agreement between the different measurements of fiducial cross section in between the experiments. As also indicated in the tables one obtains by subtraction the inelastic cross section for masses below 16 GeV, respectively below 13 GeV.

Table 2: Measurements of the inelastic cross sections at 7 TeV

| Experiment | \( \sigma_{inel} \) [mb] | Experiment | \( \sigma_{M_x>16 \text{ GeV}} \) [mb] | \( \sigma_{M_x<16 \text{ GeV}} \) [mb] |
|------------|--------------------------|------------|-------------------------------|-------------------------------|
| ATLAS-ALFA [7] | 71.3±0.9                | ALICE [1]  | 62.1±2.4                      | 60.8±1.4                      |
| TOTEM [3]   | 72.9±1.5                 | ATLAS [8]  | 60.3±2.1                      | 60.2±2.6                      |
|             |                          | CMS [9]    |                               |                               |
| Weighted mean | 71.8±0.7                |            |                               |                               |

3 Estimates of low mass dissociation

To use the data in Table 2 and Table 3 for an evaluation of low mass dissociation one has to do some estimates of how much of the cross section is to be found in the region between \( M_x \approx \)}
13–16 GeV and $M_x \approx 3–4$ GeV. Our main point in this note is to argue that such an estimate might be more reliable than an estimate of what is happening between the proton mass and $M_x \approx 3–4$ GeV. As mentioned in the introduction there are many difficulties related to the estimate of the cross section in the low mass region e.g. how many Good-Walker states are needed? On the other hand there is some kind of consensus that above the low mass region the so called triple Pomeron diagram, illustrated in Fig. 2, dominates. At lower masses, on the contrary, it is not clear to what extent this diagram is important. At lower masses there are also uncertainties related to the importance of diagrams where one of the Pomerons ($R_3$ in Fig. 2) is replaced by a secondary Reggeon (see e.g. Ref. [13] or Ref. [14]).

Figure 2: Triple-Reggeon Feynman diagram occurring in the calculation of the amplitude for single diffraction corresponding to the dissociation of hadron b in the interaction with hadron a. Each of the Reggeon legs can be a Pomeron or a secondary Reggeon. The figure is taken from Ref. [1].

At 13 TeV the situation is rather encouraging with respect to the cross section in the range $13 \text{ GeV} > M_x > 4.1 \text{ GeV}$. There is data from the CMS experiment measuring a cross section of 1.1 mb on one side of the interaction point corresponding to 2.2 mb for the two sides [12]. There are also Monte Carlo calculations for the same mass range given in Table 4 with values between 2 mb and 3 mb [12]. Finally we have used the KMR model [15] to estimate the cross
section in this same mass range. The result is 2.4 mb agreeing with the CMS measurements and the different Monte Carlo estimates. Below we will use the 2.2 mb of the CMS measurement.

Table 4: Monte Carlo estimates of the fractional increase of $\sigma_{inel}$ in the region $13 \text{ GeV} > M_x > 4.1 \text{ GeV}$ at $\sqrt{s}=13 \text{ TeV}$. Taken from Ref. [12].

| Monte Carlo       | % of $\sigma_{inel}$ | One side [mb] | Two sides [mb] |
|-------------------|-----------------------|---------------|---------------|
| EPOS-LHC          | 1.76                  | 1.2           | 2.4           |
| QGSJETII-04       | 2.36                  | 1.6           | 3.2           |
| PYTHIA8 MBR       | 2.32                  | 1.6           | 3.2           |

At 7 TeV there is no measurement in the region range $16 \text{ GeV} > M_x > 3.4 \text{ GeV}$ but we can do several estimates. The result of different Monte Carlo estimates are shown in the appendix of Ref. [16] in a number of graphs. Looking at the graphs corresponding to the Monte Carlo programs listed in Table 4 we get values of the order of a couple of mb’s. The KMR model [15] gives 3 mb. There is also ATLAS data [17] measured just above $M_x=16 \text{ GeV}$ indicating 1 mb/unit of rapidity gap and using this below $M_x=16 \text{ GeV}$ would give 3.1 mb in the range $16 \text{ GeV} > M_x > 3.4 \text{ GeV}$. In the following we will use 3 mb.

Putting together the information from the last column in Table 2 and Table 3 together with the estimates in this section we get by subtraction the cross section for low mass dissociation at 7 TeV and 13 TeV. The obtained values are given in Table 5 together with the values that has been used by TOTEM for comparison. Observe that the uncertainty on the estimated values are just the propagation of the uncertainty of the numbers used and does not include any uncertainties related to assumptions made to estimate the cross section in the range $M_x \approx 3–4 \text{ GeV}$ to $M_x \approx 13–16 \text{ GeV}$. This means that the uncertainties certainly are underestimated. Also observe that at 13 TeV we had to make a small correction between the $M_x=4.1 \text{ GeV}$ from the CMS measurement as compared to the $M_x=4.6 \text{ GeV}$ used by TOTEM. The correction was estimated to 0.2 mb.

It must also be said that in the considerations above we have not made the distinction between single dissociation and double dissociation. The estimation given above from the KMR model contains only single dissociation. Double dissociation is thought to be of considerable less importance being down with more than an order of magnitude relative to single dissociation [18]. This is also confirmed by the CMS data at 13 GeV discussed above which agree with the KMR estimate.

In Table 5 it can be seen that at 7 TeV there is a striking difference between the estimate of low mass dissociation used by TOTEM and the present estimate. The difference is less pronounced at 13 TeV.
Figure 3: Comparison of ATLAS and TOTEM measurements of $\sigma_{tot}$. To the left is shown the actual situation. To the right is shown what happens if the low mass estimates of this note are used.

Table 5: Partly data driven low mass dissociation cross section compared to the Mont Carlo estimated used by TOTEM.

| $\sqrt{s}$ [TeV] | $M_x < (GeV)$ | Low mass $\sigma_{inel}$ [mb] | Used by TOTEM [mb] |
|------------------|--------------|-------------------------------|-------------------|
| 7                | 3.4          | 8.0±1.6                       | 2.9               |
| 8                | 3.6          | 8.2±1.4                       | 3.6±1.8           |
| 13               | 4.6          |                               | 5.6±2.8           |

4 Consequences of using different low mass corrections

It is easy to adjust the TOTEM measurement for a given input in terms of low mass dissociation. This is what has been done in Fig. 3. This figure shows to the left the TOTEM values of $\sigma_{tot}$ and to the right the adjusted TOTEM values calculated according to the low mass dissociation contribution estimated here. The original uncertainties given by TOTEM have been kept. There is no data available for 8 TeV and we have used the value obtained at 7 TeV. The values of $\sigma_{tot}$ are compared to those of ATLAS [7, 10, 20] before and after the adjustment. One can observe that the original very significant difference between the two experiments transforms to a more or less normal fluctuation between two independent measurements.

It should be emphasised that this adjustment of the TOTEM values is just an attempt to investigate what the consequences are for different inputs of the low mass dissociation estimate.
Figure 4: Comparison of TOTEM measurements of $\sigma_{\text{tot}}$ using Coulomb normalisation and using the luminosity-independent method. Two different approaches have been used to perform the Coulomb normalisation independently of the luminosity-independent method. Details are given in Ref. [19]. The figure shows, on the right side, the implications of the low mass corrections estimated in this note.

and should by no means be considered as a recommended adjustment of the TOTEM data.

As will be seen in the next section there are also objections that can be raised against those adjusted values of $\sigma_{\text{tot}}$.

5 Discussion

A priori, there are at least three objections that can be raised against the adjusted TOTEM values of $\sigma_{\text{tot}}$. We will discuss all three here below in order below in order of increasing concern.

1. TOTEM has used Coulomb normalisation at 13 TeV independently of the luminosity-independent method [19]. The situation is summarised in Fig. 4. The values of $\sigma_{\text{tot}}$ of TOTEM using Coulomb normalisation are compared to the value from the luminosity-independent measurement before and after the low mass dissociation adjustment. As can be seen there is actually no issue here. The values from Coulomb normalisation are compatible with both the values of $\sigma_{\text{tot}}$ obtained by TOTEM and the value of $\sigma_{\text{tot}}$ obtained here by adjusting the low mass contribution.
2. At an early stage of the 7 TeV analysis TOTEM used a luminosity estimate given to them by the CMS experiment and having an uncertainty of 4% [21]. TOTEM used this luminosity estimate to determine $\sigma_{tot}$ with two different methods: the luminosity-dependent method and the $\rho$-independent method [3]. In this case the situation is more critical. The data points are shown before and after the adjustment in Fig. 5. On one hand, using the original TOTEM values, the agreement is excellent. However after the adjustment the spread is significantly increased. Here the 4% luminosity measurement from CMS plays a crucial role both for the luminosity-dependent method and the $\rho$-independent method. A correction of a couple of % would not harm the compatibility before the adjustment and make everything more compatible after the adjustment.

3. At 7 TeV TOTEM has made a fiducial measurement of $\sigma_{inel}$ for masses $M_x > 3.4$ GeV. From this measurement TOTEM has derived an upper limit of 6.31 mb at 95% confidence level for the cross section for events with diffractive masses below 3.4 GeV at 7 TeV [22]. This is of course in contrast to the value found here and quoted in Table 5 of $8.0 \pm 1.6$ mb. It is the same fiducial measurement that causes the rather high value of $\sigma_{tot}$ after adjustment of the $\rho$-independent method seen to the right in Fig 5. Clearly there is a contradiction at some level between the estimates of low mass diffraction in this note and the TOTEM fiducial measurement at 7 TeV. On the other hand the contradiction between the TOTEM and ATLAS measurements of $\sigma_{tot}$ is even more striking and we are exploring possible explanations for those discrepancies.
6 Conclusion

This note is intended only as an attempt to evaluate the contribution of low mass dissociation in a partly data driven approach and then investigate possible consequences of such an estimation.

The overall conclusion of this note is:

If it turns out that low mass dissociation at LHC is somewhat underestimated then the discrepancy between the TOTEM and ATLAS measurement of $\sigma_{\text{tot}}$ would not be as dramatic as now but instead rather acceptable.

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