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Measurement of the inelastic cross section in proton–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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The inelastic hadronic cross section in proton–lead collisions at a centre-of-mass energy per nucleon pair of 5.02 TeV is measured with the CMS detector at the LHC. The data sample, corresponding to an integrated luminosity of $\mathcal{L} = 12.6 \pm 0.4$ nb^{-1}, has been collected with an unbiased trigger for inclusive particle production. The cross section is obtained from the measured number of proton–lead collisions with hadronic activity produced in the pseudorapidity ranges $3 < \eta < 5$ and/or $-5 < \eta < -3$, corrected for photon-induced contributions, experimental acceptance, and other instrumental effects. The inelastic cross section is measured to be $\sigma_{\text{inel}}(\text{pPb}) = 2061 \pm 3(\text{stat}) \pm 34(\text{syst}) \pm 72(\text{lumi})$ mb. Various Monte Carlo generators, commonly used in heavy ion and cosmic ray physics, are found to reproduce the data within uncertainties. The value of $\sigma_{\text{inel}}(\text{pPb})$ is compatible with that expected from the proton–proton cross section at 5.02 TeV scaled up within a simple Glauber approach to account for multiple scatterings in the lead nucleus, indicating that further net nuclear corrections are small.

1. Introduction

The measurement of the inelastic cross section in proton–lead collisions, $\sigma_{\text{inel}}(\text{pPb})$, at a centre-of-mass energy per nucleon pair of 5.02 TeV performed by the CMS experiment at the CERN LHC is presented. The inelastic cross section (also called "particle-production" [1] or "absorption" [2] cross section in previous studies) is defined to include all hadronic events, including contributions from diffractive processes, except those from the quasi-elastic excitation of the lead nucleus—estimated to amount to about 100 mb for the pPb system [3]. Inelastic electromagnetic (photon–proton) collisions are also excluded from the measurement.

While being one of the most inclusive observables in hadronic collisions, the inelastic cross section is one of the least theoretically accessible quantities, as it cannot be determined from first-principles calculations of the theory of the strong interaction, quantum chromodynamics. In proton–proton (pp) and nucleus–nucleus collisions at the LHC, particles produced in hadronic interactions come mostly from the hadronisation of quarks and gluons, either produced in semi-hard scatterings ("minijets") [4] or emitted at very forward rapidities from "spectator" partons, as well as from soft diffractive processes in "peripheral" interactions. From the measured inelastic proton–proton (or nucleon–nucleon) cross section at a given collision energy, one can theoretically derive the corresponding proton–nucleus and nucleus–nucleus cross sections by means of Glauber [5,6] or Gribov–Regge [7] multiple-scattering approaches that take into account the known transverse matter profile of nuclei. Key quantities for the experimental comparison between nucleus–nucleus and pp collisions—such as the nuclear overlap function, the number of nucleon–nucleon collisions and of participant nucleons [8,9]—are also commonly computed through such approaches. Validating the Glauber and Gribov–Regge predictions with proton–nucleus collisions at LHC energies has important implications beyond collider physics. Such approaches constitute crucial ingredients in the Monte Carlo modelling of cosmic ray air showers at the highest energies [10], for which the inelastic cross sections measured in the laboratory must be extrapolated over a wide energy range. In fact, the inelastic proton–air (mostly proton–nitrogen and proton–oxygen) cross section introduces one of the largest uncertainties for air shower simulations [11,12].

The Glauber multiple-collision model, based on the eikonal limit (i.e. straight-line trajectories of the colliding nucleons), is the simplest and most economical approach often used to derive inclusive proton–nucleus quantities from the pp cross sections and, vice versa, to obtain pp cross sections from the cosmic ray measurements [13]. However, some of the approximations applied in the model—foremost the absence of short-range nucleon correlations [14] and of inelastic screening [15]—impact the computed

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cross section values. This is observed for fixed-target proton–carbon data [16–20] and estimated for collider [21,22] as well as ultra-high cosmic ray [13] energies, where corrections to the proton–air cross section of the order of 10% have been obtained. Short-range correlations increase the number of nucleon–nucleon collisions at small impact parameters yielding a larger nucleus–nucleus cross section. On the other hand, screening affects the number of nucleons that are diffractively excited in the multiple collisions but revert back to their ground state before the scattering process is completed, thereby reducing the nuclear cross section. Different implementations of such effects exist in the current hadronic interaction models [15,23–29]. A measurement of σ_{inel} in pPb collisions at the LHC can test if the precision of the standard Glauber calculation is sufficient, and at which energies corrections to the Glauber approach may become relevant.

2. Experimental setup and Monte Carlo simulations

The measurement presented here is based on pPb data taken with the CMS experiment at the LHC at the beginning of 2013. A detailed description of the apparatus can be found in [30]. The main detector used in this analysis is the hadron forward (HF) calorimeter that covers the pseudorapidity interval $3 < |\eta| < 5$. The calorimeter is composed of quartz fibres in a steel matrix with a 0.175×0.175 segmentation in the azimuthal angle ϕ (in radians) and pseudorapidity η. The quartz fibres pick up the Cherenkov light produced by the charged component of showers. This light is then measured by photodetector tubes. The hadronic and electromagnetic signals of each segment, as derived from fibres of two different lengths and depths, are combined to form a *tower* signal.

The data used in this analysis comprise an integrated luminosity of $\mathcal{L} = 12.6 \pm 0.4\ \text{nb}^{-1}$. This dataset combines the integrated luminosities of the two possible directions of the proton and lead beams: $5.0 \pm 0.2\ \text{nb}^{-1}$ and $7.6 \pm 0.3\ \text{nb}^{-1}$, for the proton beam going respectively in the clockwise (negative η) and anticlockwise (positive η) direction. The events are collected using an unbiased trigger, only requiring the presence of both beams in the interaction point, as determined by the “Beam Pickup Timing for the eXperiments” (BPTX) devices. Detector noise is studied with events that are randomly read out in the absence of both beams in the detector. The luminosity determination technique was calibrated by means of a van der Meer scan [31] for both beam directions independently, with an uncertainty of 3.5% [32].

A Monte Carlo event simulation based on a GEANT4 detector description [33] is used to model the experimental response and derive the reconstruction efficiencies. Different event generators are used to simulate hadronic proton–nucleus collisions. Three models are based on the Gribov–Regge formalism: DPMJET 3.06 [34], EPOS-LHC [25], and QGSJETII–04 [26]; and a fourth one is based on a minijet+Glauber approach: HIJING 1.383 [35]. In addition, particle production from photon–proton (γp) interactions in “ultraperipheral” collisions, at impact parameters larger than the sum of proton and lead radii, needs to be taken into account [36]. Given the large Pb ion charge, and the associated large “equivalent photon flux” of its electromagnetic field [36], inelastic photon–proton collisions result in a non-negligible particle production contribution. Pure photon–photon interactions, mostly producing exclusive electron–positron pairs, and photon–nucleus interactions (where the photon emitted from the proton collides with the Pb ion) have orders-of-magnitude smaller visible cross sections and are neglected. Photon–proton processes are generated with the STARLIGHT programme [37] combined either with DPMJET 3.05 or PYTHIA 6.4.26 [38].

3. Event selection and analysis

In this analysis three types of cross sections are measured: (i) σ_{obs} after removal of noise and correction for pileup, (ii) σ_{vis} after further removal of electromagnetic contributions and translation into a hadron-level quantity, and (iii) σ_{inel} including the final extrapolation to the total inelastic hadronic cross section. Two different approaches are used to determine the number of inelastic events: (1) a **single-arm** event selection that requires a localised calorimetric energy signal above a given threshold in the HF detector either at positive or negative pseudorapidities, and (2) a **double-arm** event selection that requires a localised signal above threshold in both HF detectors. The advantage of using these two event selections is that they have very different sensitivities to diffractive and photon–proton events as well as to detector noise. Denoting by $E_{\text{HF+}}$ ($E_{\text{HF-}}$) the highest energy measured in an HF tower at positive (negative) pseudorapidity, an event is tagged as a candidate for an inelastic collision if it has a value of

$$E_{\text{HF}} = \begin{cases} \max(E_{\text{HF+}}, E_{\text{HF-}}) & \text{for single-arm selection} \\ \min(E_{\text{HF+}}, E_{\text{HF-}}) & \text{for double-arm selection} \end{cases} \tag{1}$$

above a given threshold.

The observed distribution of E_{HF} is well reproduced by the combined hadronic inelastic, photon–proton, and detector noise contributions as shown in the top (bottom) panel of Fig. 1 for the single-arm (double-arm) selection. The size of the various contributions to the HF energy deposition is determined from data and simulations. The signal is identified as that coming from hadronic collisions whereas the backgrounds arise from electromagnetic photon–proton interactions and detector noise. The expected number of photon–proton collisions is $N_{\gamma\text{p}} = f_{\gamma\text{p}}\sigma_{\gamma\text{p}}\mathcal{L}$, where $f_{\gamma\text{p}}$ is the fraction of simulated photon–proton events passing the selection and $\sigma_{\gamma\text{p}}$ is the predicted STARLIGHT cross section. The number of misidentified events produced by electronic noise in the detector is $N_{\text{noise}} = N f_{\text{noise}}$, where f_{noise} is the fraction of events read out randomly in the absence of beams that pass the selection criteria, and N is the number of events recorded with the unbiased trigger. The estimate of N_{noise} includes $N_{\text{obs+noise}} = N_{\text{obs}} f_{\text{noise}}$ events that contain also an observed inelastic collision, where N_{obs} is the number of observed inelastic events. The double-counted events are explicitly subtracted from N_{noise}. The uncertainty on N_{noise} is derived from variations in different data-taking periods. The background induced by beam-gas collisions is found to be negligible deduced from the fraction of events selected with the trigger indicating the presence of a single beam in the interaction point.

Of the number of inelastic hadronic collisions, N_{inel}, the ones that are observed by the detector and pass the event selection are defined as N_{had}. The purity of the event selection is $N_{\text{had}}/\left(N_{\text{had}} + N_{\gamma\text{p}} + N_{\text{noise}}\right)$, and the acceptance is given by the ratio $\epsilon_{\text{acc}} = N_{\text{had}}/N_{\text{inel}}$. Both the purity and the acceptance depend on the energy threshold used for the selection. Higher purity is achieved for the double-arm selection, since photon–proton interactions lead to a typical final state where most of the secondary products are asymmetrically emitted towards the direction of the proton beam. Noise events are also suppressed by the coincidence requirement. The acceptance is in general smaller for the double-arm selection due to the smaller chance of selecting diffractive events characterised by large rapidity gaps devoid of activity in one or both HF sides.

The dependence of ϵ_{acc} on the HF tower energy threshold is shown in Fig. 2. For the single-arm selection the working point is chosen to be $E_{\text{HF}} > 8$ GeV. This value is the result of a compromise between acceptance (about 93–94%) and contamination, while the

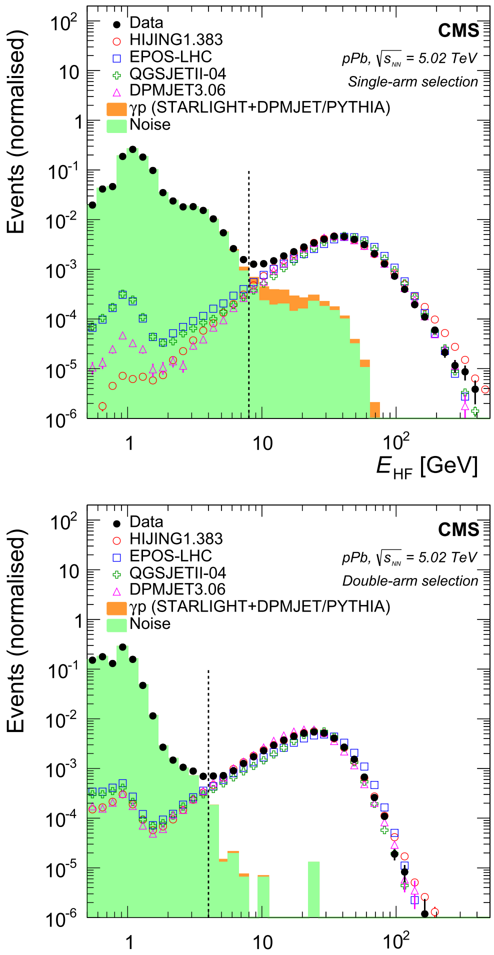

Fig. 1. Distribution of the energy deposited in the HF calorimeter (E_{HF}) for the single-arm (top) and double-arm (bottom) event selections. The data sample, shown exemplarily for one period with stable run conditions, comprises 1.31 nb^{-1} recorded with an unbiased trigger. The contribution from noise is obtained from a random trigger normalised to the same number of triggers as that in the collision data. The average number of photon–proton processes simulated with STARLIGHT+DPMJET and STARLIGHT+PYTHIA is treated as background and stacked on top. Four hadronic interaction models (EPOS, DPMJET, HIJING, and QGSJETII) are overlaid and normalised to the number of data events with $E_{\mathrm{HF}} > 10$ GeV, where the contribution from the background is small. The vertical line represents the threshold energy of 8 GeV (4 GeV) for the single-arm (double-arm) selection used in this analysis.

probability to have a tower above the threshold does not depend much on the beam direction. The double-arm selection uses $E_{\mathrm{HF}} > 4$ GeV yielding 99% purity and 91% acceptance. The value ϵ_{acc} for a specific E_{HF} threshold is determined by averaging over the results of the EPOS and QGSJETII models. The results of HIJING and DPMJET, which do not include nuclear effects for diffraction, are not considered for this purpose. Indeed, we have verified that both latter models are unable to describe the very-forward energy spectra measured with the CASTOR detector ($-6.6 < \eta < -5.2$) in events with large rapidity gaps, which are particularly sensitive to diffractive interactions.

The uncertainties on the ϵ_{acc} and $N_{\gamma\mathrm{p}}$ values are estimated from the maximum absolute differences obtained from the results of different event generators, averaged over a wide E_{HF} interval between 2 and 10 GeV. The uncertainties on ϵ_{acc} are 0.005 (0.014) and of $N_{\gamma\mathrm{p}}/\mathcal{L}$ are 11 mb (0.05 mb) for the single-arm (double-arm) event selections.

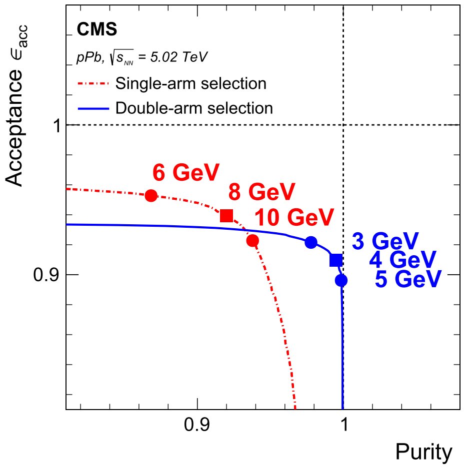

Fig. 2. Acceptance versus purity of the two event selections, as derived from the EPOS and QGSJETII generators. The symbols indicate different values of the E_{HF} thresholds. The chosen thresholds are marked with squares.

In this analysis no vertex reconstruction is performed and the impact of contributions from additional pileup (PU) collisions recorded in any given event is consistently evaluated with the HF detector. The number of simultaneous collisions is Poisson-distributed with an expectation value corresponding to the interaction probability λ. If one collision is selected with probability ϵ_{acc}, then i simultaneous collisions are selected with probability $P_i \approx 1-(1-\epsilon_{\mathrm{acc}})^i$. The approximation assumed in the equation, which does not account for energy deposits of multiple events in the HF towers, was verified to be valid by means of a toy Monte Carlo simulation. The number of collisions is then corrected with the factor $f_{\mathrm{PU}} = \epsilon_{\mathrm{acc}}\lambda / \sum_{i=1}^{\infty} P_i \,\mathrm{Poisson}(i;\lambda)$. The interaction probability λ, which amounts to 2–8% depending on the data-taking period, is calculated recursively from the ratio of the number of inelastic events to the number of unbiased triggers. The pileup correction increases the measured cross section by 2% for both event selections, and introduces an uncertainty on the final pPb cross section that is smaller than 0.1%.

To facilitate the direct comparison of the results to model predictions, detector level quantities, such as E_{HF}, are translated to hadron-level quantities. For this purpose, p_{HF} is defined equivalently to Eq. (1) but replacing E_{HF} by the largest absolute value among the momenta, $|\vec{p}|$, of all generated final-state particles (with lifetimes above 1 cm/c), within the pseudorapidity intervals of the HF calorimeters ($3 < |\eta| < 5$), excluding muons and neutrinos. A correction factor c_{vis}, obtained from simulations, is used to translate the measured cross section into a hadron-level quantity, defined by the ratio of the number of visible events, which fulfil a given requirement on p_{HF}, to the number of observed events, which pass the selection on E_{HF}. Thus, c_{vis} is larger than unity for requiring $p_{\mathrm{HF}} > 0$, but will approach zero for very high thresholds. The threshold can be chosen freely, and for the present analysis the requirement on the minimal value of p_{HF} is chosen such that the fractions of events passing this selection and passing that on E_{HF} are equal. The factor c_{vis} then becomes equal to unity and has no numerical effect on the central value of the derived cross section. This procedure leads to the choice of selecting events that fulfil the requirement $p_{\mathrm{HF}} > 21.3$ GeV/c (11.3 GeV/c) for the single-arm (double-arm) analysis. For the chosen thresholds, the mean of the c_{vis} values of all four hadronic interaction models is unity and the slight dependence on models is taken into account as a systematic uncertainty on c_{vis} equal to the standard deviation of the four values.

Table 1
Central values and uncertainties for the two event selections for noise cross section contribution ($N_{\text{noise}}/\mathcal{L}$) and the fraction of noise events (f_{noise}) as derived from data. Additionally, the quantities acceptance (ϵ_{acc}), electromagnetic cross section contribution ($N_{\gamma\text{p}}/\mathcal{L}$), and hadron-level correction factor (c_{vis}) as derived from simulations are listed.

Selection	$N_{\text{noise}}/\mathcal{L}$ [mb]	f_{noise}	ϵ_{acc}	$N_{\gamma\text{p}}/\mathcal{L}$ [mb]	c_{vis}
Single-arm	102 ± 25	$(2.0 \pm 0.5) \times 10^{-3}$	0.939 ± 0.005	63 ± 11	1.000 ± 0.004
Double-arm	9 ± 3	$(1.8 \pm 0.8) \times 10^{-4}$	0.910 ± 0.014	0.33 ± 0.05	1.000 ± 0.002

The values of the acceptance, backgrounds, and correction factors are summarised in Table 1.

The number of observed inelastic events, N_{obs}, is derived from the number of events passing the event selection, N_{sel}, and is corrected for noise (N_{noise}), double counting ($N_{\text{obs+noise}}$), and pileup (f_{PU}). Dividing this number by the integrated luminosity yields the *observed* cross section:

$$\sigma_{\text{obs}} = \frac{N_{\text{obs}}}{\mathcal{L}} = \left(N_{\text{sel}} - N_{\text{noise}} + N_{\text{obs+noise}}\right) \frac{f_{\text{PU}}}{\mathcal{L}}. \tag{2}$$

Using the relation $N_{\text{obs+noise}} = N_{\text{obs}} f_{\text{noise}}$ one obtains

$$\sigma_{\text{obs}} = \frac{1}{\mathcal{L}} \frac{N_{\text{sel}} - N_{\text{noise}}}{1/f_{\text{PU}} - f_{\text{noise}}}. \tag{3}$$

The *visible* cross section for hadronic collisions is derived by subtracting the photon–proton contamination and applying the correction factor c_{vis}. Its numerical value is, by definition, equal to the part of the observed cross section related to hadronic collisions:

$$\sigma_{\text{vis}} = \frac{1}{\mathcal{L}} \frac{N_{\text{sel}} - N_{\text{noise}} - N_{\gamma\text{p}}}{1/f_{\text{PU}} - f_{\text{noise}}} c_{\text{vis}}. \tag{4}$$

The *inelastic* cross section is obtained by correcting for the limited detector acceptance (ϵ_{acc}):

$$\sigma_{\text{inel}} = \frac{1}{\mathcal{L}} \frac{N_{\text{sel}} - N_{\text{noise}} - N_{\gamma\text{p}}}{1/f_{\text{PU}} - f_{\text{noise}}} \frac{1}{\epsilon_{\text{acc}}}. \tag{5}$$

The ratio of the visible hadronic cross section obtained with the single-arm selection to the one obtained with the double-arm selection is sensitive to the fraction of diffractive pPb events. The measured value of this ratio allows one to constrain the diffractive cross section, σ_{diff}, in the models. In order to be compatible within 2 standard deviations of the data, the EPOS diffractive cross section cannot be scaled up or down by more than ±13% from its default value, while for QGSJETII those limits are ±20%. This propagates into an $\epsilon_{\text{acc}}(\sigma_{\text{diff}})$ uncertainty on σ_{inel}, conservatively assumed to be symmetric, of 0.8% (1.1%). For this and the following uncertainties, the first number is related to the single-arm selection and the bracketed one to the double-arm selection. The model-dependence of the acceptance corrections results in an uncertainty for ϵ_{acc}(models) of 0.5% (1.6%) for the two selections, respectively.

Since less than half of the diffractive events, mostly with a high-mass diffractive system, pass the hadron-level selection, the uncertainty on c_{vis} is smaller than that on ϵ_{acc}. The 1 standard deviation differences found among the four hadronic interaction models on the hadron-level correction, c_{vis}, propagate into uncertainties on σ_{vis} of 0.4% (0.2%) for the single-arm (double-arm) selection. The subtraction of photon–proton events (with the $N_{\gamma\text{p}}$ uncertainty shown in Table 1), results in an uncertainty of 0.6% (<0.1%) on σ_{inel} and σ_{vis}. The uncertainty on N_{noise} propagates into a 1.3% (0.2%) uncertainty in the final cross sections. The effect on the event selection of the radiation damage in the HF fibres is assessed by rescaling the signals of the simulated HF response to match data in segments of pseudorapidity. The rescaling factors are calculated using the average response produced by EPOS, HIJING, and QGSJETII. These scaling factors are found to be consistent with the observed radiation damage of HF and range from 1 to 0.67, depending on pseudorapidity. The amount of radiation damage is estimated from a comparison of $\mathrm{d}E/\mathrm{d}\eta$ distributions measured in proton–proton collisions at $\sqrt{s} = 2.76$ TeV recorded in 2013 and in 2010. The systematic uncertainty induced on the cross section by this approach is estimated by repeating the measurement without the radiation damage correction, which introduces an effect of 1.7% (0.8%) on the cross section. As a further check of the HF tower energy resolution, the cross sections are computed by increasing the selection thresholds to $E_{\text{HF}} > 10$ GeV (5 GeV). To account for both effects, a systematic uncertainty on the cross section of 0.6% (0.4%) is added. The cross sections measured for the two beam directions are found to be consistent. Consequently, no dedicated systematic uncertainty is assigned to this effect.

Table 2
List of the systematic uncertainties, propagated into the final pPb cross sections, for the two event selections.

Source of uncertainty	Single-arm	Double-arm
Noise subtraction (N_{noise})	1.3%	0.2%
Pileup correction (f_{PU})	<0.1%	<0.1%
Acceptance (ϵ_{acc}(models))	0.5%	1.6%
Acceptance ($\epsilon_{\text{acc}}(\sigma_{\text{diff}})$)	0.8%	1.1%
Hadron-level correction (c_{vis})	0.4%	0.2%
Photon–proton subtraction ($N_{\gamma\text{p}}$)	0.6%	<0.1%
Detector simulation	1.7%	0.8%
HF energy thresholds	0.6%	0.4%
Integrated luminosity ($\mathcal{L}$)	3.5%	3.5%

All the different sources of uncertainty of the measurement are listed in Table 2 for the single-arm and double-arm event selections. The three derived cross sections have different systematic uncertainties since not all contributions are relevant to each of them. For σ_{inel}, all uncertainties but the one due to the hadron-level correction contribute. The total uncorrelated systematic uncertainty is therefore 2.5% (2.2%) for the single-arm (double-arm) selection. For σ_{vis}, the dominant uncertainty is due to the hadron-level correction instead of the correction for ϵ_{acc}. The value of the uncertainty is therefore reduced to 2.3% (0.9%). The uncertainties for detector simulation and photon–proton correction do not contribute to σ_{obs} and, hence, its uncertainty becomes 1.4% (0.5%). For all cross sections, a (dominant) integrated luminosity uncertainty of 3.5% is added. The main contributions to the latter arise from the model used to describe the beam profile, the length scale of the beam displacement, and the bunch-to-bunch variations [32].

4. Results and summary

The measured cross sections for the single-arm and double-arm event selections are listed in Table 3, compared to the predictions of the hadronic interaction models DPMJET, EPOS, and QGSJETII. Due to the different acceptance, the extrapolations from the hadron-

Table 3
Summary of cross sections obtained from the two different event selections. The acceptance definition for σ_{vis} is based on the production of stable particles within $3 < |\eta| < 5$ with momentum $p_{\text{HF}} > 21.3$ GeV/c (11.3 GeV/c) for the single-arm (double-arm) event selections.

	Selection	σ_{obs} (mb)	σ_{vis} (mb)	σ_{inel} (mb)
Data	Single-arm	2003±76	1937±82	2063±89
	Double-arm	1873±66	1872±68	2059±85
EPOS-LHC	Single-arm	–	1947	2082
	Double-arm	–	1883	
QGSJETII–04	Single-arm	–	2059	2181
	Double-arm	–	1998	
DPMJET 3.06	Single-arm	–	2116	2166
	Double-arm	–	2055	

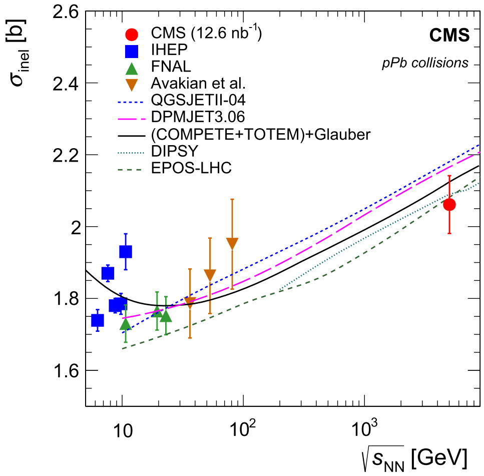

Fig. 3. Inelastic hadronic cross sections for pPb collisions as a function of the centre-of-mass energy. The measurement described here (circle, with error bars obtained from the quadratic sum of all uncertainties) is compared to lower energy data (squares and triangles) [2,39,40] and to different model predictions (curves).

level to the inelastic cross section are of different magnitude, but the models reproduce well the approximately 65 mb difference between the two selections. The values of the inelastic cross sections obtained from the single-arm and double-arm methods agree well within the uncertainties.

The final σ_{inel} value is obtained by taking the weighted average of the measured values in the two event selections. The statistical uncertainties and the uncertainty on the luminosity are correlated between the selections. The degree of correlation among the remaining systematic uncertainties is much smaller and they are taken as uncorrelated. This yields a final result for the inelastic hadronic cross section of

$$\sigma_{\text{inel}}(\text{pPb}) = 2061 \pm 3(\text{stat}) \pm 34(\text{syst}) \pm 72(\text{lumi})\ \text{mb}.$$

This result is shown in Fig. 3 compared to other measurements at different centre-of-mass energies and to various theoretical predictions. A pPb cross section was also measured by the ALICE Collaboration, amounting to 2090–2120 mb with an uncertainty of 70 mb [41]. A direct comparison of this observed cross section to the one measured in the present analysis is not possible due to the unknown to us ALICE detector acceptance and possible contamination from noise and photon–proton interactions.

The inelastic cross section measured by the CMS experiment is compared to the Glauber-model prediction (solid curve in Fig. 3) obtained using a pp inelastic cross section at $\sqrt{s} = 5.02$ TeV of 70.0 ± 1.5 mb, derived from the COMPETE parametrisation [42] including the measurement of the TOTEM Collaboration at $\sqrt{s} =$ 7 TeV [43] (where the assigned uncertainty is that measured by the latter). The Glauber calculation yields 2130 ± 40 mb and is compatible with the measurement presented here indicating that effects neglected by the calculation (such as nucleon correlations and screening) are either small or approximately cancel out. The experimental result is also consistent with the prediction of the DIPSY model [44,45] based on a dipole-model approach including parton saturation and multiple-scattering. Among the Gribov–Regge models, the EPOS prediction is compatible with the measurement within uncertainties, whereas DPMJET and QGSJETII predict a value more than 1 standard deviation above the data, with a larger discrepancy appearing for the σ_{vis} cross sections (Table 3). The EPOS and QGSJETII models are commonly used for cosmic ray air shower simulations. Thus, at the corresponding cosmic ray proton energies of $E_{\text{cr}} = s/(2m_{\text{p}}) = 10^{16.1}$ eV, where m_{p} is the mass of the proton, there are no indications for data-model deviations above ≈5% in the proton–lead collisions studied here. Note, however, that our measurement deals with an ion much heavier than those involved in proton–air interactions. Corrections to the Glauber model are possibly larger in the latter case [3,13]. In summary, the measurement of the cross sections in pPb collisions presented here is the first such fully corrected measurement at multi-TeV energies and, thus, provides important constraints on hadronic interaction models commonly used in high-energy heavy ion and cosmic ray physics.

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