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Study of ψ' and χ_c decays as feed-down sources of J/ψ hadro-production

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Abstract

The interpretation of the J/ψ suppression patterns observed in nuclear collisions, at CERN and RHIC, as a signature of the formation of a deconfined phase of QCD matter, requires knowing which fractions of the measured J/ψ yields, in pp collisions, are due to decays of heavier charmonium states. From a detailed analysis of the available mid-rapidity charmonium hadro-production cross sections, or their ratios, we determine that the J/ψ feed-down contributions from ψ' and χ_c decays are, respectively, $(8.1 \pm 0.3)\%$ and $(25 \pm 5)\%$. These proton-proton values are derived from global averages of the proton-nucleus measurements, assuming that the charmonium states are exponentially absorbed with the length of matter they traverse in the nuclear targets.

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1 Introduction and motivation

In the very hot and dense, strongly interacting matter produced in high-energy nuclear collisions, it is expected that the QCD binding potential is screened, the screening level increasing with the energy density of the created system [1]. Depending on the screening level, it may happen that the charmonium states "dissolve" into open charm mesons [2]. Since different quarkonium states have different binding energies, they are expected to dissolve at successive "thresholds" in the energy density or temperature of the medium [3]. In particular, the ψ' and χ_c states should be easier to "melt" than the more strongly bound J/ψ state. Therefore, a "spectral analysis" of the charmonium production yields, in several collision systems (from light to heavy nuclei) and in several collision centralities (from peripheral to central), should provide very interesting information concerning the nature of the produced matter.

Experimentally, it has not yet been possible to directly measure the production yields of the χ_c state in heavy-ion collisions. However, it is well known that a significant fraction of the J/ψ mesons observed in pp collisions are, in fact, produced by χ_c radiative decays. The J/ψ production yield measured in heavy-ion collisions could thus show a significant level of suppression, even if the collision system under scrutiny has not reached high enough energy densities to melt the directly produced J/ψ state. In particular, it could very well be that the J/ψ suppression pattern measured at the SPS and RHIC is essentially due to the melting of the ψ' and χ_c states [3].

The picture is made more complex by the fact that already in proton-nucleus collisions the charmonium production cross sections scale less than linearly with the number of binary nucleon-nucleon collisions. As we will recall in this paper, this "normal nuclear absorption" has been seen (at the CERN-SPS and at Fermilab) to be significantly stronger for ψ' mesons than for J/ψ mesons. While the existing χ_c data are much less accurate, there is no reason to assume that the χ_c and J/ψ mesons have the same "nuclear dependence". A stronger χ_c "normal nuclear absorption" would decrease the yield of J/ψ mesons produced from χ_c decays and, hence, would account for part of the "anomalous J/ψ suppression" seen in heavy-ion collisions. How much of that "anomaly" might be due to the normal nuclear absorption of the ψ' and χ_c mesons depends on the fractions of J/ψ mesons produced by ψ' and χ_c decays. These considerations underline the importance of knowing these fractions, in elementary collisions, as accurately as possible.

In the existing literature, the feed-down fractions are generally assumed to be around 10 % for the ψ' and around 30 or 40 % for the χ_c, usually without mentioning experimental measurements or their uncertainties. Yet, the J/ψ feed-down fraction from ψ' decays can be rather precisely determined, from data collected by SPS and Fermilab experiments. The χ_c case has been much less investigated but recent measurements, by the HERA-B experiment, indicate a J/ψ feed-down fraction from χ_c decays of around 20 %, considerably lower than the previously assumed values.

This paper presents a quantitative analysis of the presently available data on feed-down contributions to J/ψ hadro-production, at fixed target energies. The relevant measurements are presented and reviewed in Section 2. New "world averages" (including uncertainties) of the J/ψ feed-down fractions from ψ' and χ_c decays are then derived and discussed, in Sections 3 and 4.

2 Overview of available measurements

In this section we briefly review the existing measurements of ψ' and χ_c hadro-production, which can be used to constrain the corresponding fractions of indirectly produced J/ψ's. These fractions are defined with respect to the total (inclusive) J/ψ yield:

$$R(\psi') = \frac{N(\mathrm{J}/\psi \text{ from } \psi')}{N_{\mathrm{incl}}(\mathrm{J}/\psi)} = \frac{\sigma(\psi') \cdot B(\psi' \to \mathrm{J}/\psi X)}{\sigma(\mathrm{J}/\psi)} \quad , \tag{1}$$

and analogous for $R(\chi_c)$.

The ψ' mainly decays into a J/ψ and a pair of pions. However, most experiments measure the J/ψ and ψ' dilepton decays, reporting results for the yield ratio

$$\rho(\psi') = \frac{\sigma(\psi') \cdot B(\psi' \to l^+l^-)}{\sigma(\mathrm{J}/\psi) \cdot B(\mathrm{J}/\psi \to l^+l^-)} \quad . \tag{2}$$

This quantity is directly related to the ψ'-to-J/ψ feed-down fraction, $R(\psi')$, through a simple combination of branching ratios,

$$R(\psi') = \left[\frac{B(\mathrm{J}/\psi \to l^+l^-)}{B(\psi' \to l^+l^-)} \; B(\psi' \to \mathrm{J}/\psi \; X) \right] \rho(\psi') = (4.53 \pm 0.13) \; \rho(\psi') \quad , \tag{3}$$

where the numerical values were derived from the PDG tables [4].

The $R(\chi_c)$ values are obtained dividing the number of J/ψ's resulting from the radiative decays $\chi_c \to \mathrm{J}/\psi \; \gamma$ by the total number of observed J/ψ's.

The running conditions of the experiments providing these measurements are summarized in Tables 1 and 2. Most experiments made use of proton or pion beams of different energies incident on several target nuclei, but collider experiments have also provided some results. The different detectors covered x_{F} intervals extending from slightly backward to very forward values. Average x_{F} values have been estimated for each experiment, either from the measured distributions or from the variation of the statistical errors in the efficiency-corrected spectra.

While all the relevant experiments are listed in these tables, only a restricted sub-sample of data is used in the present analysis. Most importantly, we do not use results obtained on the basis of forward x_{F} data. In fact, it is well established (in particular by E866 [15], for $x_{\mathrm{F}} > 0.2$) that the J/ψ and ψ' production cross sections measured at high x_{F}, in nuclear targets, exhibit a much stronger nuclear absorption than the corresponding mid-rapidity values. A significant role in this behaviour should be played by nuclear effects on the parton distribution functions of the target nucleons and by the energy loss of the beam partons (or of the produced state) traversing

Experiment	Collision system	E_{beam} [GeV]	Phase space	$\langle x_{\mathrm{F}} \rangle$
E331 [5]	p-C	225	$0 < x_{\mathrm{F}} < 0.7$	$\simeq 0.3$
E444 [6]	p-C	225	$0 < x_{\mathrm{F}} < 0.9$	$\simeq 0.35$
E705 [7]	p-Li	300	$-0.1 < x_{\mathrm{F}} < 0.5$	$\simeq 0.2$
E288 [8]	p-Be	400	$-0.6 < x_{\mathrm{F}} < 0.8$	$\simeq 0.1$
NA38 [9]	p-W/U p-C/Al/Cu/W	200 450	$-0.4 < y_{\mathrm{cm}} < 0.6$	$\simeq 0$
NA51 [10]	p-H/D	450	$-0.4 < y_{\mathrm{cm}} < 0.6$	$\simeq 0$
NA50 96/98 [11]	p-Be/Al/Cu/ Ag/W	450	$-0.5 < y_{\mathrm{cm}} < 0.5$	$\simeq 0$
NA50 2000 [12]	p-Be/Al/Cu/ Ag/W/Pb	400	$-0.425 < y_{\mathrm{cm}} < 0.575$	$\simeq 0$
E771 [13]	p-Si	800	$-0.05 < x_{\mathrm{F}} < 0.25$	$\simeq 0.1$
E789 [14]	p-Au	800	$-0.03 < x_{\mathrm{F}} < 0.15$	$\simeq 0.06$
E866 [15]	p-Be/Fe/W	800	$-0.1 < x_{\mathrm{F}} < 0.8$	$\simeq 0.3$
HERA-B [16]	p-C/Ti/W	920	$-0.35 < x_{\mathrm{F}} < 0.1$	-0.065
WA39 [17]	$\pi^{\pm}$-W	39.5	$-0.5 < x_{\mathrm{F}} < 0.8$	$\simeq 0.2$
E537 [18]	π^{-}-W	125	$0 < x_{\mathrm{F}} < 1$	$\simeq 0.3$
WA11 [19]	π^{-}-Be	150	$-0.4 < x_{\mathrm{F}} < 0.9$	$\simeq 0.3$
E331 [5]	π^{+}-C	225	$0 < x_{\mathrm{F}} < 0.9$	$\simeq 0.35$
E444 [6]	$\pi^{\pm}$-C	225	$0 < x_{\mathrm{F}} < 1$	$\simeq 0.4$
E615 [20]	π^{-}-W	253	$0.3 < x_{\mathrm{F}} < 1$	$\simeq 0.6$
E705 [7]	$\pi^{\pm}$-Li	300	$-0.1 < x_{\mathrm{F}} < 0.5$	$\simeq 0.2$
E672-706 [21]	π^{-}-Be	515	$0.1 < x_{\mathrm{F}} < 0.8$	$\simeq 0.4$
Experiment	Collision system	$\sqrt{s}$ [GeV]	Phase space	$\langle x_{\mathrm{F}} \rangle$
ISR [22]	pp	58 (avg.)	$y_{\mathrm{cm}} \simeq 0$	0

Table 1: Global features characterizing the existing measurements of the ψ'-to-J/ψ cross-section ratio in proton-nucleus, pion-nucleus and proton-proton collisions.

the nuclear matter. Other effects may also contribute, such as intrinsic heavy-quark components of the scattering nucleons and interactions with other produced hadrons ("comovers"), as discussed in Ref. [33]. The data at high x_{F} may, therefore, reflect a non-trivial cocktail of production and absorption mechanisms, certainly not easy to disentangle and quantify. For this reason, in this paper we concentrate on the analysis of the mid-rapidity data, a choice consistent with our goal of determining reference values for the interpretation of the existing observations of quarkonium suppression in nucleus-nucleus collisions, also made at mid-rapidity. This means, in particular, that the data obtained in pion-nucleus collisions, always significantly extending towards high x_{F} values, are left out from the present analysis. Further details on the data selection are discussed in the following paragraphs. A broader analysis of the

Experiment	Collision system	E_{beam} [GeV]	Phase space	$\langle x_{\rm F} \rangle$
E369-610-673 [23]	p-Be	225 (avg.)	$0.1 < x_{\rm F} < 0.6$	0.32
E705 [24]	p-Li	300	$-0.1 < x_{\rm F} < 0.5$	$\simeq 0.2$
E771 [25]	p-Si	800	$-0.05 < x_{\rm F} < 0.25$	$\simeq 0.1$
HERA-B 2000 [26]	p-C/Ti	920	$-0.25 < x_{\rm F} < 0.15$	-0.035
HERA-B 2003 [27]	p-C/W	920	$-0.35 < x_{\rm F} < 0.15$	-0.065
SERPUKHOV-140 [28]	π^--H	38	$0.3 < x_{\rm F} < 0.8$	$\simeq 0.5$
WA11 [29]	π^--Be	185	$-0.4 < x_{\rm F} < 0.9$	$\simeq 0.3$
E369-610-673 [23]	π^--Be (mostly)	209 (avg.)	$0 < x_{\rm F} < 0.8$	0.43
E705 [24]	$\pi^\pm$-Li	300	$-0.1 < x_{\rm F} < 0.5$	$\simeq 0.2$
E672-706 [30]	π^--Be	515	$0.1 < x_{\rm F} < 0.8$	$\simeq 0.4$
Experiment	Collision system	$\sqrt{s}$ [GeV]	Phase space	$\langle x_{\rm F} \rangle$
ISR [31]	pp	58 (avg.)	$y_{\rm cm} \simeq 0$	0
CDF [32]	p$\bar{\rm p}$	1800	$\lvert y_{\rm cm}\rvert < 0.6$	0

Table 2: Global features characterizing the existing measurements of the $R(\chi_c)$ feed-down ratio in proton-nucleus, pion-nucleus and proton-(anti)proton collisions.

existing measurements, trying to take into account possible kinematic dependencies induced by nuclear effects, will be the topic of a future investigation.

The current experimental knowledge concerning ψ' production in proton-nucleus collisions is essentially determined by the accurate measurements performed by NA50/NA51 at the CERN-SPS and by E866 at Fermilab, using several target nuclei. Thanks to their several million reconstructed J/ψ events, these measurements provide precise determinations of the ψ'-to-J/ψ cross-section ratio and of its nuclear dependence. Given their much lower level of precision, the other existing measurements (obtained in several kinematical windows and using a single target nucleus) have no influence on a global average and were, therefore, left out of the present analysis.

The NA50 data sets were obtained at 450 [11] and 400 GeV [12], respectively with five and six targets. Two statistically independent 450 GeV data samples were collected, at different proton beam intensities. In our study we used their average, after considering the corrections reported in Ref. [12].

The J/ψ and ψ' results of E866 [15] were reported as ratios between the yields obtained with heavy and light targets (W/Be and Fe/Be), as a function of $x_{\rm F}$. These measurements provide heavy-over-light *ratios* of $\rho(\psi')$, which cannot help determining the feed-down fraction value but constrain the difference between the nuclear absorption rates of the two charmonium states. Although data points exist up to $x_{\rm F} = 0.8$, we restricted our study to the range $x_{\rm F} < 0.2$, where only the W/Be ratio was reported.

Also the χ_c measurements mentioned in Table 2 deserve a few remarks. The error we quote for the E705 value reflects the systematic uncertainties mentioned in their paper [24]. Although the E771 publication [25] provides no explicit value for $R(\chi_c)$, it should be possible to derive it from the quoted χ_{c1} and χ_{c2} cross sections or, alternatively, from the yields of reconstructed χ_{c1}, χ_{c2} and J/ψ mesons, using the quoted efficiencies. It turns out, however, that these two methods lead to significantly different results. Moreover, the information provided is insufficient to properly evaluate the $R(\chi_c)$ uncertainty. Therefore, we did not consider the E771 measurement in our analysis.

It is worth noting that the HERA-B 2003 $R(\chi_c)$ results [27] include a systematic uncertainty (of around 10 %) due to the dependence of the detector's acceptance on the assumed J/ψ polarization, taking into account that J/ψ's from χ_c decays may have a polarisation different from the directly produced ones. This effect was not considered by the previous experiments, given the poor statistical accuracy of their measurements.

Given the considerations expressed above, we have selected for our analysis the $\rho(\psi')$ and $R(\chi_c)$ measurements listed in Table 3.

3 J/ψ feed-down from ψ' decays

The experimental points selected for the determination of the J/ψ feed-down contribution from ψ' decays are shown in Fig. 1, as a function of the size of the target nucleus (in the case of the SPS data) or of $x_{\rm F}$ (in the case of E866). These measurements clearly show that the ψ' and J/ψ states are differently absorbed by the nuclear medium.

In order to determine the ψ'-to-J/ψ feed-down fraction in pp collisions, $R^0(\psi')$, all selected measurements were simultaneously fitted within the framework of the Glauber formalism [34], using the so-called "ρL parametrization":

$$\sigma(pA \to \psi) \;/\; A\,\sigma(pN \to \psi) \;=\; \exp(-\sigma_{\rm abs}\,\rho\,L) \quad ,$$

where ρ is the nuclear density and L is the nuclear path length traversed by the charmonium state, of absorption cross section $\sigma_{\rm abs}$. The $\rho\,L$ values were determined through a Glauber calculation, for each nuclear target, taking into account the appropriate nuclear density profiles, as described in Ref. [12]. The fit provides two parameters: the $R^0(\psi')$ "reference" feed-down fraction (corresponding to $L = 0$) and the difference between the ψ' and J/ψ absorption cross sections, where the J/ψ term does not include the ψ' decay contribution (to remove auto-correlation effects).

It should be kept in mind that this parametrization represents a rather simplified description of the nuclear absorption process, convoluting in a single *effective* absorption cross section a multitude of physical effects. In particular, $\sigma_{\rm abs}$ is assumed to be a "universal quantity", independent of the collision energy and of the kinematical properties of the produced charmonium states. It also implicitly incorporates the nuclear modifications of the parton distribution functions, possible energy loss mechanisms, formation time effects, etc. Following most previous studies of charmonium

Experiment	Target nucleus	L [fm]	$\rho(\psi')$ [%]
NA51	H	0	1.57 ± 0.05
	D	0.13	1.67 ± 0.06
NA50 96/98	Be	0.86	1.720 ± 0.041
	Al	1.84	1.725 ± 0.035
	Cu	2.66	1.645 ± 0.026
	Ag	3.41	1.580 ± 0.026
	W	3.93	1.528 ± 0.035
NA50 2000	Be	0.86	1.745 ± 0.086
	Al	1.84	1.889 ± 0.079
	Cu	2.66	1.593 ± 0.082
	Ag	3.41	1.599 ± 0.085
	W	3.93	1.422 ± 0.079
	Pb	4.28	1.461 ± 0.068
Experiment	$\langle x_{\mathrm{F}} \rangle$		$\rho(\psi')_{\mathrm{W}}$ / $\rho(\psi')_{\mathrm{Be}}$
E866	-0.065		0.904 ± 0.068
	-0.019		0.900 ± 0.038
	0.027		0.932 ± 0.030
	0.075		0.932 ± 0.031
	0.124		0.939 ± 0.036
	0.173		0.881 ± 0.048
Experiment	Target nucleus	L [fm]	$R(\chi_c)$ [%]
ISR	p	0	35 ± 6
E705	Li	0.80	30 ± 6
HERA-B 2000	C	1.22	36 ± 10
	Ti	2.30	33 ± 17
HERA-B 2003	C	1.22	20.2 ± 3.3
	W	3.93	21.1 ± 4.4

Table 3: The $\rho(\psi')$ and $R(\chi_c)$ measurements selected for the present analysis. The L values correspond to an average nuclear density of 0.17 fm^{-3}.

absorption in nuclear matter, we use this simple parametrization in the analysis presented in this paper, where we focus on the mid-rapidity results; this issue will be revisited in the future, in the scope of a broader investigation.

A global fit to all data points leads to the dashed lines in Fig. 1, with a chi-square probability of only 1 %, clearly indicating that the model is unable to properly account for the NA51 measurements, performed with hydrogen and deuterium targets (the two leftmost points in the middle panel). Maybe the fact that protons and deuterons are exceptionally light nuclei places them out of the domain of applicability of the model we are using because they are not large enough to be traversed by fully formed

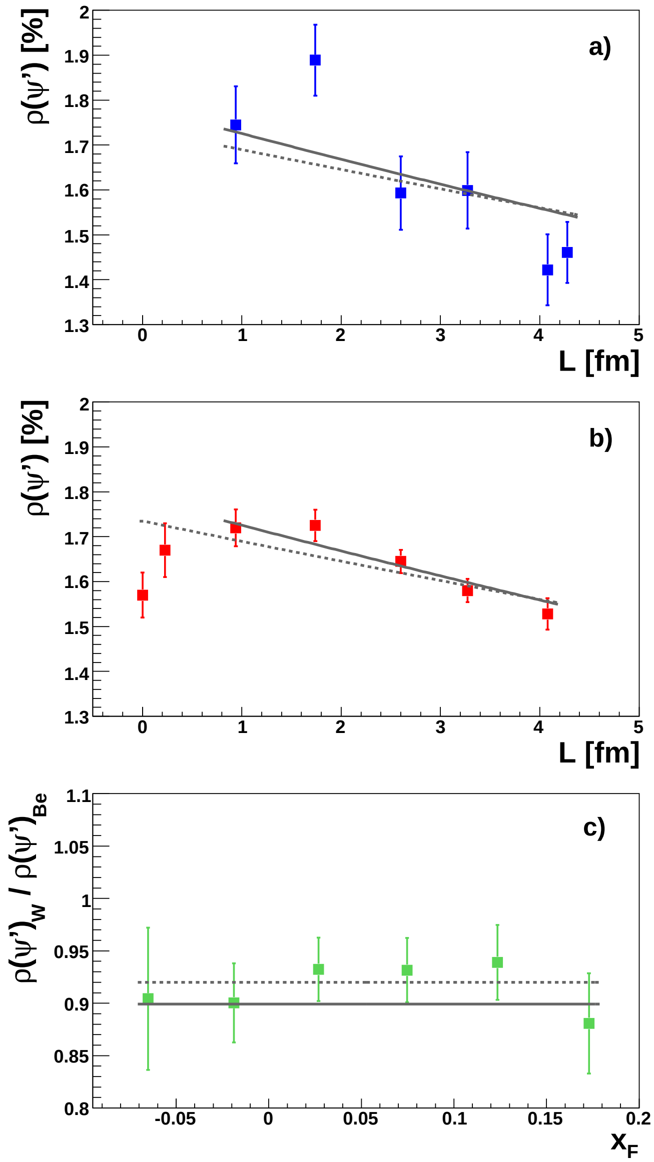

Figure 1: The $\rho(\psi')$ values as a function of the nuclear path length, L, from NA50/51 measurements at 400 GeV (a) and 450 GeV (b), and the $\rho(\psi')_{\mathrm{W}} / \rho(\psi')_{\mathrm{Be}}$ ratio measured by E866, in the $-0.1 < x_{\mathrm{F}} < 0.2$ window (c). The curves are the result of the global fit described in the text, including (dashed lines) or excluding (solid lines) the NA51 points.

charmonium states. It should also be noted that the use of "nuclear density profiles" in the Glauber calculation of the proton and deuteron $\rho\, L$ values is not as reliable as in the case of the heavier nuclei. Furthermore, it is not clear that the same value, 0.17 nucleon/fm^3, should be used as average nuclear density for all nuclei, including protons and deuterons, when extracting L from the calculated $\rho\, L$ values. Without

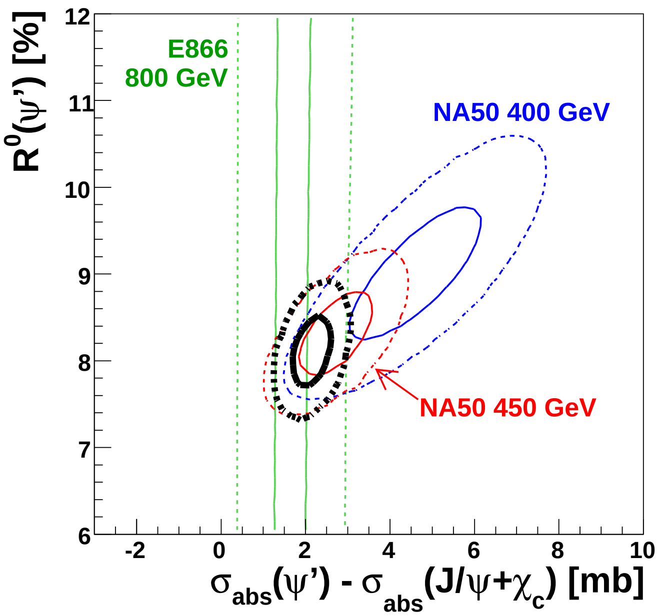

Figure 2: 68 % (solid lines) and 99 % (dashed lines) confidence level contours for the bi-dimensional probability distribution of the parameters $R^0(\psi')$ and $\sigma_{\rm abs}(\psi') - \sigma_{\rm abs}({\rm J}/\psi + \chi_c)$. The thick black contours delimit the region favoured by the global fit, while the thin coloured (or grey) ones reflect the individual data sets.

the pp and p-D points, the best description of the data is represented by the solid lines, with a chi-square probability of 27 %, reflecting a much better compatibility between the data and the model used in our fit. The corresponding feed-down fraction is

$$R^0(\psi') = (8.1 \pm 0.3)\,\% \quad . \tag{4}$$

Including the NA51 points decreases the result to $(7.9 \pm 0.3)\,\%$, a negligible change despite the visible degradation of the fit quality.

The correlation between the two fit parameters is shown in Fig. 2, as a bi-dimensional contour plot. Although the three data sets give compatible results, they nevertheless indicate that the difference between the charmonium absorption cross sections decreases with increasing collision energy.

4 J/ψ feed-down from χ_c decays

The $R(\chi_c)$ values collected in Table 3 are shown in Fig. 3 as a function of L. The curve is the result of a fit analogous to the one explained in the previous section, using the "ρL parametrization" and leaving free the difference between the effective absorption cross sections of the χ_c mesons and of the J/ψ mesons not coming from χ_c decays. Given the conjecture, suggested by the ψ' analysis, that measurements

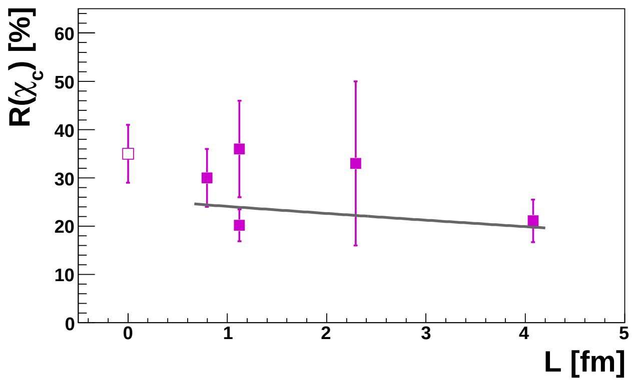

Figure 3: The $R(\chi_c)$ measurements used in the present analysis as a function of the nuclear path length L. The curve is the result of the fit described in the text (excluding the first point).

performed with very light nuclei are not accountable within the simple absorption model adopted here, the pp point is excluded from the fit. The resulting feed-down fraction (for $L = 0$) is

$$R^0(\chi_c) = (25 \pm 5)\,\% \quad , \tag{5}$$

with a fit χ^2 probability of 25 %.

The $R^0(\chi_c)$ value considerably depends on the difference between the absorption cross sections of the two charmonium states (see Fig. 4). Therefore, a more precise $R^0(\chi_c)$ value can be obtained if an improved understanding of charmonium absorption in nuclear targets significantly reduces the allowed range of $\sigma_{\rm abs}(\chi_c) - \sigma_{\rm abs}({\rm J}/\psi)$.

5 Summary

We presented and reviewed the presently available ψ' and χ_c hadro-production measurements, and derived global averages of the J/ψ feed-down fractions from ψ' and χ_c decays, at mid-rapidity:

$$R^0(\psi') = (8.1 \pm 0.3)\,\% \quad , \quad R^0(\chi_c) = (25 \pm 5)\,\% \quad . \tag{6}$$

These averages reflect measurements performed at collision energies up to $\sqrt{s} \sim$ 60 GeV. At much higher energies, CDF measured $R(\chi_c) = (30 \pm 7)\,\%$ in p$\bar{\rm p}$ collisions at $\sqrt{s}$ = 1800 GeV [32] and PHENIX reported preliminary values obtained in pp collisions at $\sqrt{s}$ = 200 GeV: $R(\psi') = (8.6 \pm 2.5)\,\%$ and $R(\chi_c) < 42\,\%$ (at 90 % C.L.) [35]. More precise measurements would be needed to probe an eventual energy dependence of the J/ψ feed-down fractions from decays of heavier charmonium states.

Since most of the existing measurements were performed with nuclear targets, the derivation of the $R^0(\psi')$ and $R^0(\chi_c)$ values relevant for elementary collisions ($L = 0$) requires modelling the influence of the nuclei on the production yields of the three

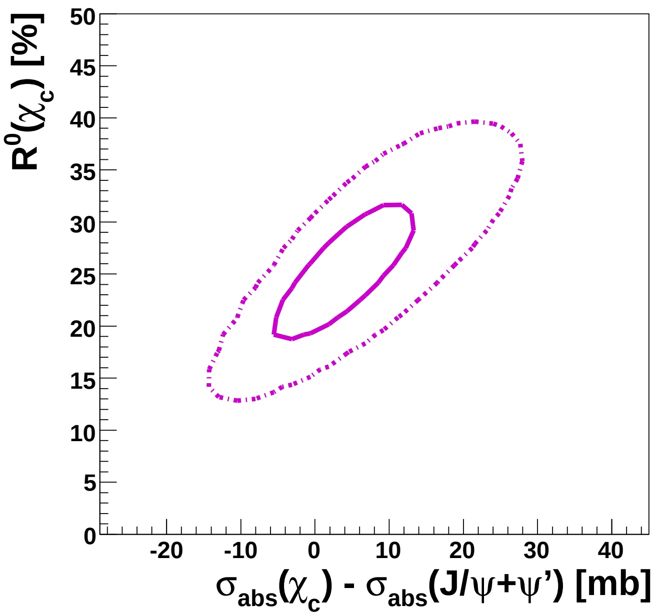

Figure 4: 68 % and 99 % confidence level contours for the bi-dimensional probability distribution of the fit parameters $R^0(\chi_c)$ and $\sigma_{\mathrm{abs}}(\chi_c) - \sigma_{\mathrm{abs}}(\mathrm{J}/\psi + \psi')$.

charmonium states. In the study reported in this paper we followed a widespread model where the three charmonium states are analogously absorbed while traversing the nuclear matter, with three (a priori different) effective absorption rates. This rather simple model provides a reasonable description of the available measurements if we restrict the analysis to the mid-rapidity data and exclude values obtained with "exceptionally light nuclei" (protons and deuterons). The extension of our analysis to a broader set of measurements requires an improved phenomenological model, which should reflect the following observations. It is only for nuclear targets heavier than beryllium that the J/ψ and ψ' nuclear absorption rates are significantly different. This difference decreases when the collision energy increases and when we approach forward x_{F}. The $R(\chi_c)$ value derived from data collected with heavy nuclei and at small $|x_{\mathrm{F}}|$, 0.22 ± 0.03, is significantly smaller than the value derived from data collected with light nuclei and at forward x_{F}, 0.36 ± 0.02.

These might be indications that a proper understanding of charmonium absorption requires considering that the objects traversing the nuclear matter are not fully formed J/ψ, ψ' or χ_c states but rather pre-resonance states having a suitable time evolution. This is the topic of a more complex investigation, to be reported in a future publication.

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