EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

Expression of Interest

for an experiment to study charm production with proton and heavy ion beams

(CHIC: Charm in Heavy Ion Collisions)

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Abstract

We propose an experiment to perform a systematic study of charmonia production in heavy ion collisions at SPS. Taking advantage of significant advances in electromagnetic calorimetry, the measurement of low energy photons from χ_c decays should now be achievable. Together with recent measurements made at RHIC and at LHC on J/ψ and Υ production, such a measurement will offer the opportunity to use quarkonia as a direct test of phase transition and lattice QCD calculations. In a one month data taking one can expect the collection of thousands of χ_c. This new and dedicated experiment is designed to also study, under optimal conditions, Cold Nuclear Matter (CNM) effects in a larger rapidity range than previously explored by the NA50/NA60 experiments. This measurement of nuclear effects in absence of Quark Gluon Plasma formation will provide a clear and unambiguous reference for the study of Hot and Dense Matter (HDM) effects, a reference which is today needed to deduce an unambiguous interpretation of the results already obtained.

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1. Introduction

Twenty five years ago, CERN pioneered the study of quarkonium production in heavy ion collisions at the SPS with the aim of characterizing the QGP phase transition and testing lattice QCD predictions. In 1997, the NA50 experiment observed an anomalous suppression of J/ψ production in Pb-Pb collisions [1]. Since then, these quarkonium studies have been extended to regimes of significantly higher energies as reached at BNL-RHIC and CERN-LHC. In addition with the results obtained at RHIC on J/ψ and more recently at LHC on quarkonium states, hints of the theoretically expected sequential suppression [2] start to emerge.

Nevertheless, the experimental validation of such a scenario as well as the characterization of the phase transition require full control of the feed-down sequence. In particular, a precise measurement of quarkonium 1P states which significantly contribute to the yields of quarkonium states is mandatory. For charmonium, the measurement of χ_c suppression together with J/ψ and ψ' is needed to prove the sequential suppression scenario. Such measurements should be performed under dedicated experimental conditions where the energy density is appropriate for the physics case.

Moreover, Cold Nuclear Matter effects which affect the extraction of Hot and Dense Matter effects must be thoroughly measured and well under control. Despite all the experimental results already obtained on J/ψ production in p-A collisions, they are still not well understood, especially at small Bjorken x (x_B) and large Feynman x (x_F) where these effects are expected to be large.

In the following we propose a new fixed target experiment at SPS energies in order to provide the information needed to prove (or disprove) quarkonium color screening, thus opening the gate for a full overall understanding of quarkonium behavior in ultra-relativistic heavy ion collisions. First, based on the NA50 experiment results obtained in Pb-Pb collisions, we show that the measurement of χ_c production together with J/ψ and ψ' would provide a precise and detailed answer at SPS energies. Second, we discuss the interest of a thorough p-A program to disentangle and quantify the various processes that could affect quarkonium production in Cold Nuclear Matter. Finally, we quickly review the experimental setup and its expected performances.

2. Physics program

2.1. Charmonium production in A-A collisions

J/ψ and ψ' production studies in heavy ion collisions at SPS energies have been previously studied by the NA38, NA50 and NA60 experiments [1][3][4][5][6][7]. Figure 1, extracted from [6] shows, for various interacting systems, the ratio between the measured charmonium yields, normalized to Drell-Yan dimuons, and the corresponding expected "normal nuclear absorption", where the latter is computed from p-A results. The quantity L, the length of nuclear matter seen by the $c\bar{c}$ pair, is calculated through the Glauber model formalism [8] of nucleus-nucleus collisions. The figure shows that the departure from ordinary nuclear absorption occurs at a lower value of L for ψ' than for J/ψ.

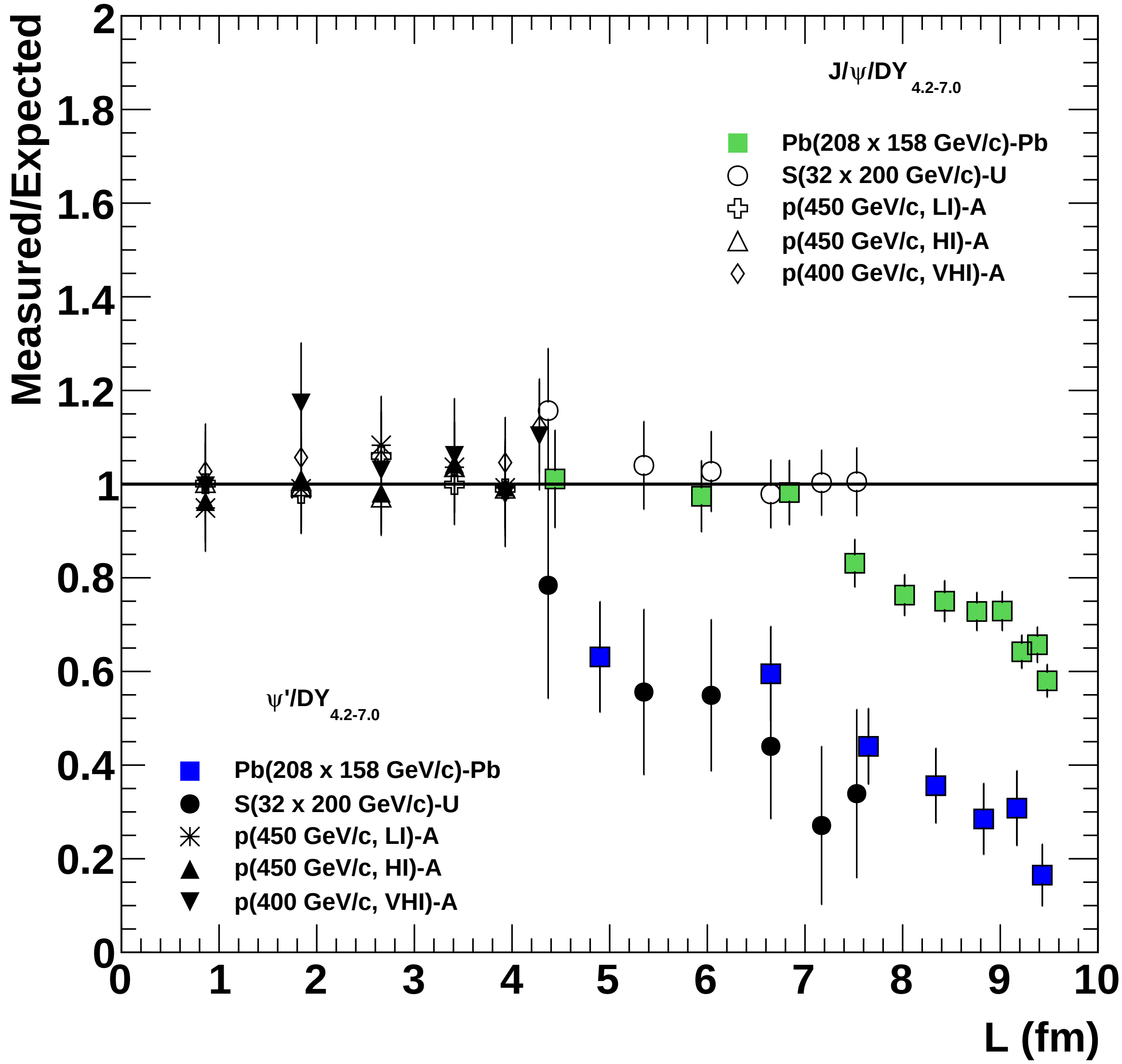

Figure 1: The ratio "measured over expected" for the relative yields $B'_{\mu\mu}\sigma(\psi')/\sigma(DY)$ and $B_{\mu\mu}\sigma(J/\psi)/\sigma(DY)$, as a function of L. Figure taken from [6].

The observed suppression patterns are compatible with the sequential suppression scenario where one expects the ψ' resonance to be screened by the QGP at a smaller L (smaller energy density) than the J/ψ. An alternative scenario, not involving QGP, is the suppression of the resonances by their interaction with comoving hadrons, the so-called comovers [9]. In this case, because of its smaller binding energy, the ψ' is more suppressed than the J/ψ. Figure 2 illustrates the two mecanisms:

- In the screening scenario (figure 2, left), the three charmonium states, ψ', J/ψ and χ_c, are suppressed at different threshold energy densities. Because of ψ' and χ_c feed-downs (~10% and ~30% respectively), a sequential suppression should be observed when measuring the J/ψ yield. Experimentally, because of the small ψ' contribution and its small production yield, it is very difficult to test the sequential screening by measuring J/ψ and ψ' only. Checking whether the onset of χ_c suppression coincides with a sizeable suppression of J/ψ would be a much more conclusive test.

- In the comovers scenario (figure 2, right), the three charmonium states start to be suppressed at the same energy density but with a different slope. In this case, the ψ' and χ_c feed-downs should only affect the slope of the inclusive J/ψ suppression. Note that neither the absolute values nor the ratio of the comovers-J/ψ and the comovers-ψ' interaction cross sections (respectively $\sigma_{comovers-J/\psi}$ and $\sigma_{comovers-\psi'}$) are theoretically well-known. One can only consider that, because of their binding energies, $\sigma_{comovers-J/\psi}$ is smaller than $\sigma_{comovers-\psi'}$.

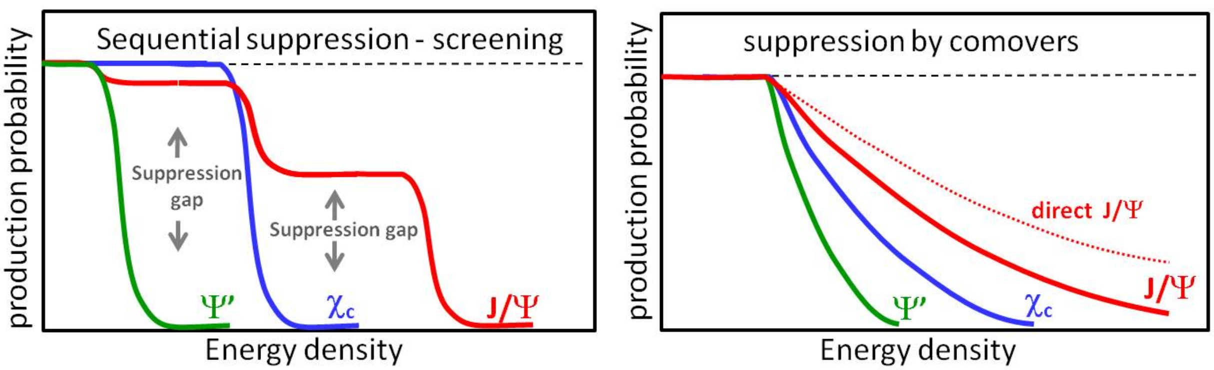

Figure 2: Left: quarkonium suppression due to color screening. Right: quarkonium suppression due to interactions with comoving hadrons.

To test the phase transition and discriminate between the two scenarios, one must measure the three charmonium states. Because of its ~30% feed-down contribution to the J/ψ yield, the χ_c is a much better candidate than the ψ' to test the sequential suppression. In addition, the measurement of its suppression pattern should probe if comovers play an important role in the charmonium suppressions. Indeed, because of its smaller binding energy when compared to the J/ψ, larger when compared to the ψ', the χ_c suppression pattern should stand in between the ψ' and J/ψ ones (as shown on figure 2). Figure 3 shows the expected difference of the χ_c suppression pattern between the two scenarios. In the screening scenario, since the J/ψ stays unsuppressed until $L \sim 7.2$ fm, the χ_c cannot be suppressed before this length[1]. In the comovers scenario[2], it is already suppressed

[1] According to the sequential screening, the J/ψ suppression at $L \sim 7.2$ fm would be due to the melting of its feed-down resonances.

[2] The χ_c suppression pattern due to comovers has been obtained by adjusting the best combination of $\sigma_{comovers-J/\psi}$, $\sigma_{comovers-\psi'}$ and $\sigma_{comovers-\chi_c}$ to the data, hence $\sigma_{comovers-J/\psi}$=0.2 mb, $\sigma_{comovers-\chi_c}$=1.0 mb and $\sigma_{comovers-\psi'}$=2.0 mb.

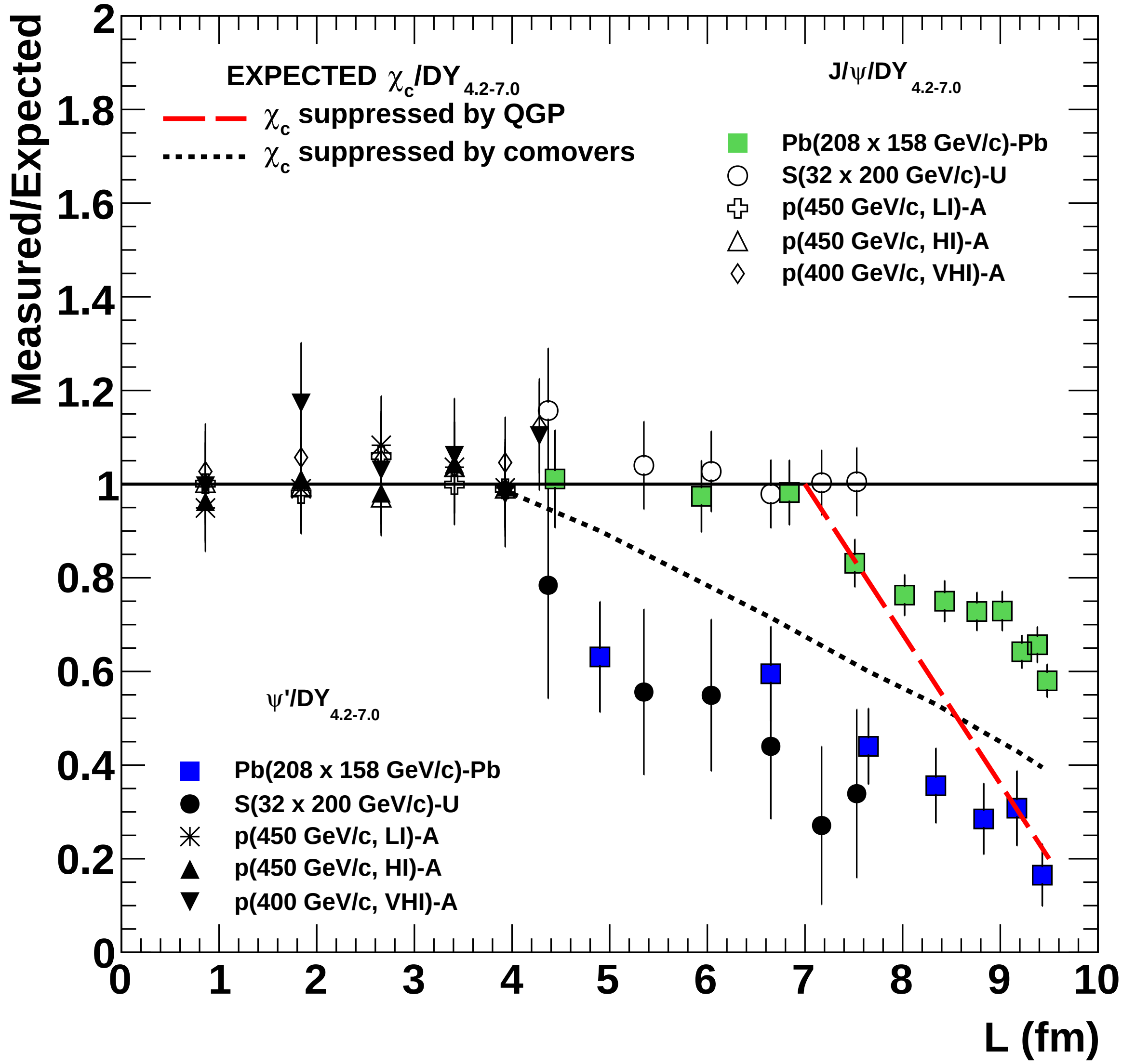

Figure 3: Ratio between the Measured charmonium yields, normalized to Drell-Yan dimuons, and the corresponding Expected "normal nuclear absorption", as a function of L. The red line shows the expected χ_c pattern if suppressed by a QGP. The black line shows the expected χ_c pattern if suppressed by comovers.

by ~40% at this value of L.

Figure 3 clearly shows that the measurement of the three charmonium states is needed to prove the sequential suppression scenario. It is also important to note that the J/ψ/DY trend in Pb-Pb collisions is compatible with p-A and S-U results for the most peripheral Pb-Pb collisions which indicates that the energy density range obtained at SPS energies is the most appropriate to test the charmonium sequential suppression.

2.2. Charmonium production in p-A collisions

The study of charmonium production in proton induced collisions is crucial for a correct interpretation of the charmonium suppression patterns observed in heavy-ion collisions. It is, indeed, very important to establish a robust baseline with respect to which we can clearly identify new phenomena such as QGP. It is, in addition, crucial to understand the physics mechanisms underlying charmonium productions [10]. Several effects responsible for nuclear suppression in p-A collisions can be studied:

- Final state effects such as the interaction of the evolving $c\bar{c}$ pair with the target nucleons leading to a break up of the charmonium states, thus providing information on bound state formation times.
- Initial state effects such as parton shadowing (or antishadowing) in the target nucleus [11] which may suppress (or enhance) the probability of charmonium production, providing information on the $c\bar{c}$ pair production kinematics [12]. Similarly, saturation effects can also be studied.
- Parton energy loss effects in quarkonium production, see for instance [13].

Several experiments have studied J/ψ and ψ' production in p-A collisions from $\sqrt{s_{NN}}$~20 GeV to $\sqrt{s_{NN}}$=200 GeV (at LHC a p-Pb run at $\sqrt{s}$=5 TeV is scheduled for january 2013). However, mostly due to small statistics, little is known about χ_c production in p-A collisions (for a review of all the experimental data, see [16]). Moreover, the data collected by the NA60 experiment at $\sqrt{s_{NN}}$=17.2 GeV (158 GeV in the lab frame) to study J/ψ and ψ' production in p-A collisions [14], cover a rapidity range too small to establish a robust and unambigous reference for the study of charmonium production in A-A collisions.

As a consequence, the achievement of a p-A program, covering a large rapidity range at both $\sqrt{s}$=29.1 GeV and $\sqrt{s}$=17.2 GeV, to study J/ψ, ψ' and χ_c production on different targets would provide key information on the physics mechanism underlying charmonium production and needed baselines for the study of a phase transition in Pb-Pb collisions.

3. Experimental apparatus

The experiment proposed in this document will mainly consist of three detector components: a vertexing and tracking telescope, an electromagnetic calorimeter and a trigger system.The detector design is driven by two motivations:

- Since Hot and Dense Matter (HDM) effects, such as QGP, depend on the energy density, they are large at mid rapidity. This region has been investigated by all the experiments involved in quarkonium measurement, in heavy ion collisions. We adopt the same strategy, both because the HDM effects are larger and because previous measurements are available for comparison. Thus, the detector must be able to measure χ_c production in A-A collisions within the rapidity range $y_{CMS} \in [-0.5, 0.5]$ in the center-of-mass of the collision.

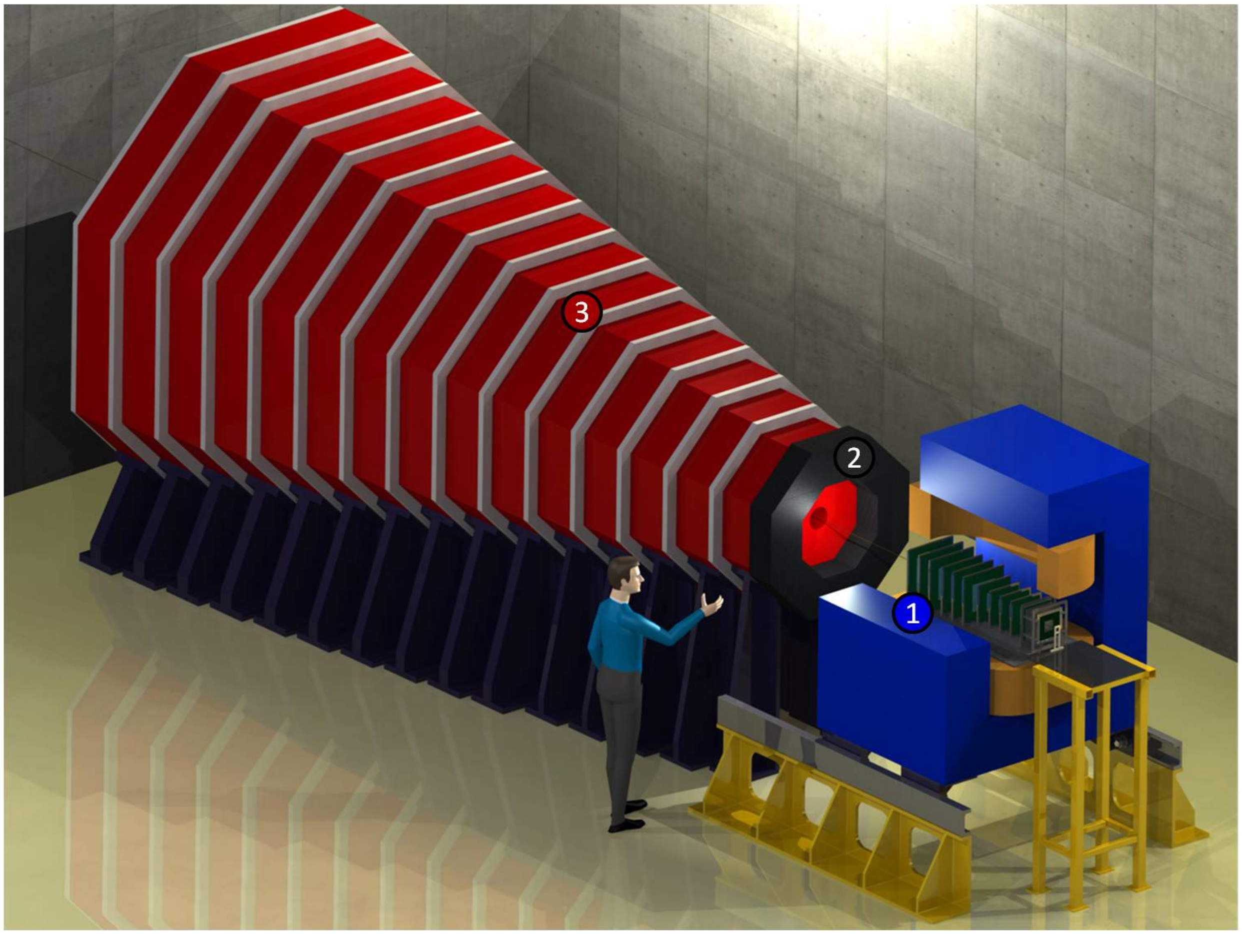

Figure 4: Experimental apparatus: 1) Vertex and tracking. 2) Electromagnetic calorimeter. 3) Absorber/trigger system.

- To improve the studies of Cold Nuclear Matter effects already made by the NA50/NA60 experiments, the spectrometer must be able to cover a larger rapidity range. With an appropriate design, we estimated that the rapidity coverage can reach $y_{CMS} \in [-0.5, 2]$ in p-A collisions.

These two requirements lead to the detector design shown in Figure 4. The apparatus is thus made of:

1. *A vertexing and tracking system:* We base our design on the performances observed for the NA60 experiment pixel telescope which was made of 16 planes of silicon sensors reaching a total amount of 800 000 pixels of 425×50 μm^2. This 40 cm long detector was located within a 2.5 T dipolar magnetic field. With such an apparatus, the momentum resolution for a typical muon ($P_\mu \sim 15$ GeV/c) from J/ψ decay was of the order of $\Delta P/P \sim 6\%$. We estimate that a similar detector extended over a one meter long dipolar field of 2.5 T would lead to momentum resolution of 1% giving a J/ψ mass resolution on the order of 20 MeV/c^2, five times better than what has been done before and sufficient to fully separate J/ψ and ψ' states. In addition,

such a good resolution would strongly improve the signal/background ratio which is often problematic when dealing with central heavy ion collisions. Note that it is for the purpose of simplicity that we based our extrapolation on the NA60 telescope technology; it is obvious that a more detailed study should be made taking advantage of the new silicon technologies available today.

2. *Electromagnetic calorimeter:* Because of the very high multiplicity in A-A collisions, a very highly segmented calorimeter is mandatory in order to be able to isolate and measure each photon reaching the calorimeter. Such a detector is being developed by the CALICE collaboration [15]. In its current implementation, this detector is made of 30 layers of W+Si, corresponding to 24 X_0 in 20 cm, with silicon pads of 0.5×0.5 cm^2. The average Moliere radius R_M of such a detector is smaller than 2 cm, thus allowing to isolate the photon from the χ_c decay even in a very busy environment[3]. We have estimated that, for a typical 5% most central Pb-Pb collision, such a calorimeter located at a distance of 205 centimeters from the vertex would lead to an occupancy rate such that the average distance between two photons from π_0 or η decays would be larger than 2 cm for $y_{CMS} < 0.5$. The energy resolution of such a detector would be better than $\Delta E/\sqrt{E} \sim 20\%$. Note that a full simulation will be needed in order to estimate whether a detector placed at 205 cm can separate photons with a good enough separation efficiency and no energy resolution degradation or whether it should be placed downstream[4].
3. *Absorber/trigger system:* When measuring $J/\psi \to \mu^+\mu^-$ one has to deal with a huge background arising from $\pi^{+/-}$ and $K^{+/-}$ decays. Typically, for central Pb-Pb collisions, of the order of 400 charged particles are produced in one rapidity unit at mid rapidity. Most of the particles are $\pi^{+/-}$ of which more than 99.98% decay into low momentum muons. In order to limit the trigger rate and the signal contamination, it is necessary to absorb these hadrons or their decay muons before they reach the trigger detectors. We estimated that a 4.5 m long Fe absorber would absorb most of the muons coming from pion decays. With an estimated Pb-Pb Minbias event ratio of $\sim 3.10^{-4}$ we expect a trigger rate of ~ 300 Hz for a 10^7 Pb ions/sec beam delivered on a 0.4 cm thick Pb target. The trigger detector technique to be used is still an open question and is not discussed in the present document. We note that, considering the low trigger rate, several techniques could be investigated for this purpose. We also note that in order to maximize the trigger performances, it would be worth to investigate the possibility to magnetize the Fe absorber, allowing to trigger on the charge and invariant mass of the dimuon candidates.

The large rapidity coverage requested by the p-A program can be obtained with two detector configurations as can be seen on figure 5 : Backward, where the tracker covers $y_{CMS} \in [-0.5, 1.0]$ and the calorimeter iris is open; Forward, where the tracker covers $y_{CMS} \in [0.5, 2.0]$ and the calorimeter iris is closed. Note however that this last configuration cannot be used in a Pb-Pb operating mode. Because of the high particle multiplicity, the particle flux hitting the detector precludes the

[3] Although $R_M \sim 0.9$ cm for tungsten, because of the silicon layers, the overall R_M is closer to 2 cm.

[4] Note that at $z \sim 4$ m, the average distance between two incoming photons becomes larger than 4 cm, more than twice the effective Moliere radius, implying full separation efficiency.

separation of photons from background.

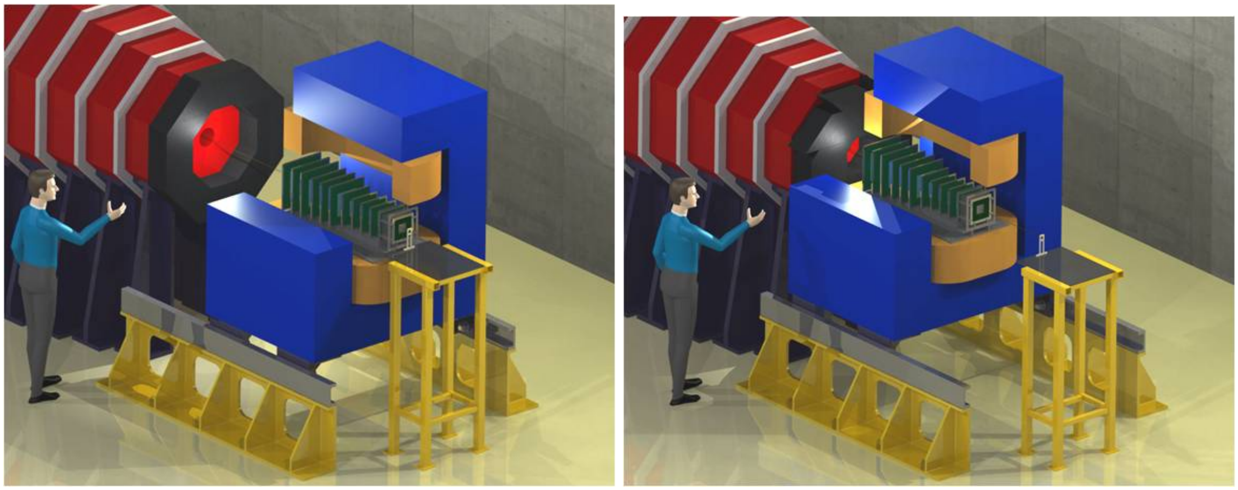

Figure 5: rapidity configurations. Left: $y_{CMS} \in [-0.5; 1]$. Right: $y_{CMS} \in [0.5; 2]$.

4. Detector performances

4.1. Performances in Pb-Pb collisions

In order to estimate the expected performances of our apparatus, we use the EPOS event generator [17]. We have generated 200,000 Pb-Pb minBias events, which, based on the typical beam intensity measured in [6], corresponds to a five days data taking with a $10\%\lambda_I$ Pb target. Among

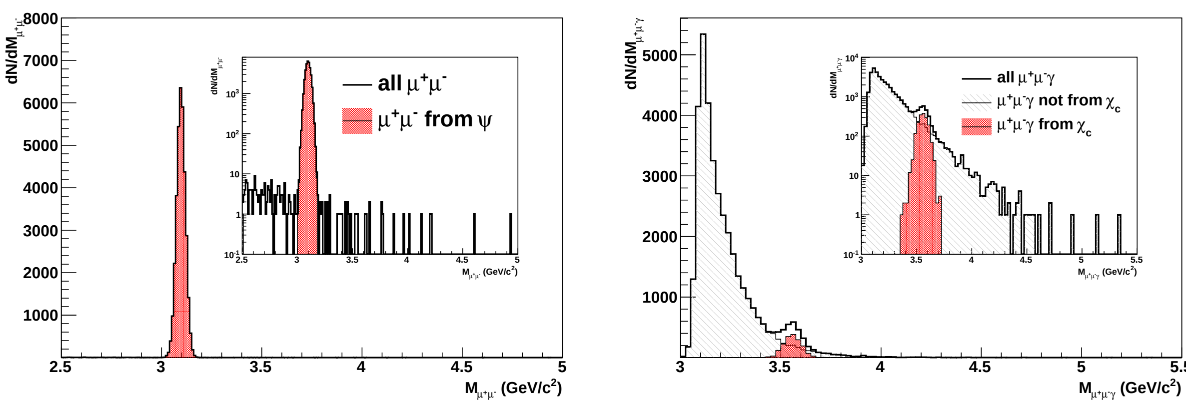

Figure 6: Left: muon pair invariant mass spectrum; the J/ψ contribution is represented in red. Right: muon pair+photon invariant mass spectrum; the χ_c contribution is represented in red.

these events, 70% (140,000 events) contain an embedded J/ψ (generated with PYTHIA), 30% (60,000 events) contain an embedded χ_c (generated with PYTHIA). After detector resolutions

($\Delta P/P = 1\%$ for muons and $\Delta E/\sqrt{E} = 20\%$ for photons) and after acceptance and selection cuts are applied, we obtain an $acceptance \times efficiency$ of 17.4 % for the J/ψ, 2.8 % for the χ_c. The mass resolutions are 20 MeV/c^2 for the J/ψ 45 MeV/c^2 for the χ_c. Corresponding mass plots are shown in Figure 6.

4.2. Performances in p-A collisions

In order to perform a thorough p-A program a large rapidity range is mandatory. As discussed in section 3, we foresee $y_{CMS} \in [-0.5; 2]$. The corresponding x_B and x_F ranges for the two beam energies $\sqrt{s}$=17.2 GeV and $\sqrt{s}$=29.1 GeV are given in table 1. Figure 7 shows a comparison of the

E_{beam} ($\sqrt{s}$)	experiment	y_{CMS}	x_B	x_F
158 (17.2) GeV	NA50	[0;1]	[0.07;0.18]	[0;0.42]
	CHIC	[-0.5;2]	[0.02;0.30]	[-0.19;1]
450 (29.1) GeV	NA50	[-0.4;0.6]	[0.06;0.16]	[-0.09;0.14]
	CHIC	[-0.9;1.6]	[0.02;0.26]	[-0.22;0.51]

Table 1: Bjorken-x $x_2 = (M_{J/\psi}/\sqrt{s}) \times \exp(-y_{CMS})$ and Feynman-x $x_F = (2M_{J/\psi}/\sqrt{s}) \times \sinh(y_{CMS})$ corresponding to the NA50 and CHIC rapidity domains at both $\sqrt{s_{NN}}$=17.2 GeV and $\sqrt{s_{NN}}$=29.1 GeV.

accessible kinematical domain with theoretical models. In x_2, the large $y_{CMS} \in [-0.5; 2]$ coverage will allow to test the entire anti-shadowing region; In x_F, it will allow to test the saturation domain as well as part of the negative x_F domain where formation time can be studied.

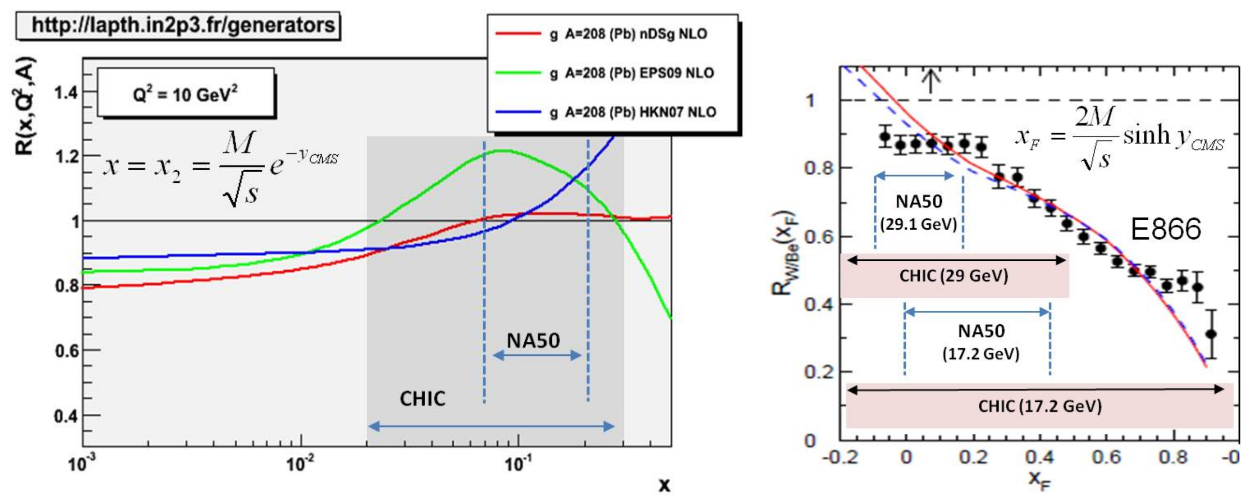

Figure 7: Left: NA50 and CHIC x_2 coverage compared with various (anti)shadowing models. Right: NA50 and CHIC x_F coverage compared with data collected by the E866 experiment [18] and an energy loss theoretical model [13].

5. Beam requirements and expected event rates in PbPb collisions

For the χ_c study, we based our estimate on the same beam intensity as delivered to the NA50 experiment in [6], hence $5{\times}10^7$ ions per burst. Table 2 reports the number of ψ' and J/ψ as recorded by NA50 in both 1998 ($7\%\lambda_I$ Pb target) and 2000 ($10\%\lambda_I Pb$ target) 30-day data taking period each[6], leading to $\sim$ 180,000 J/ψ and $\sim$ 1300 ψ'.

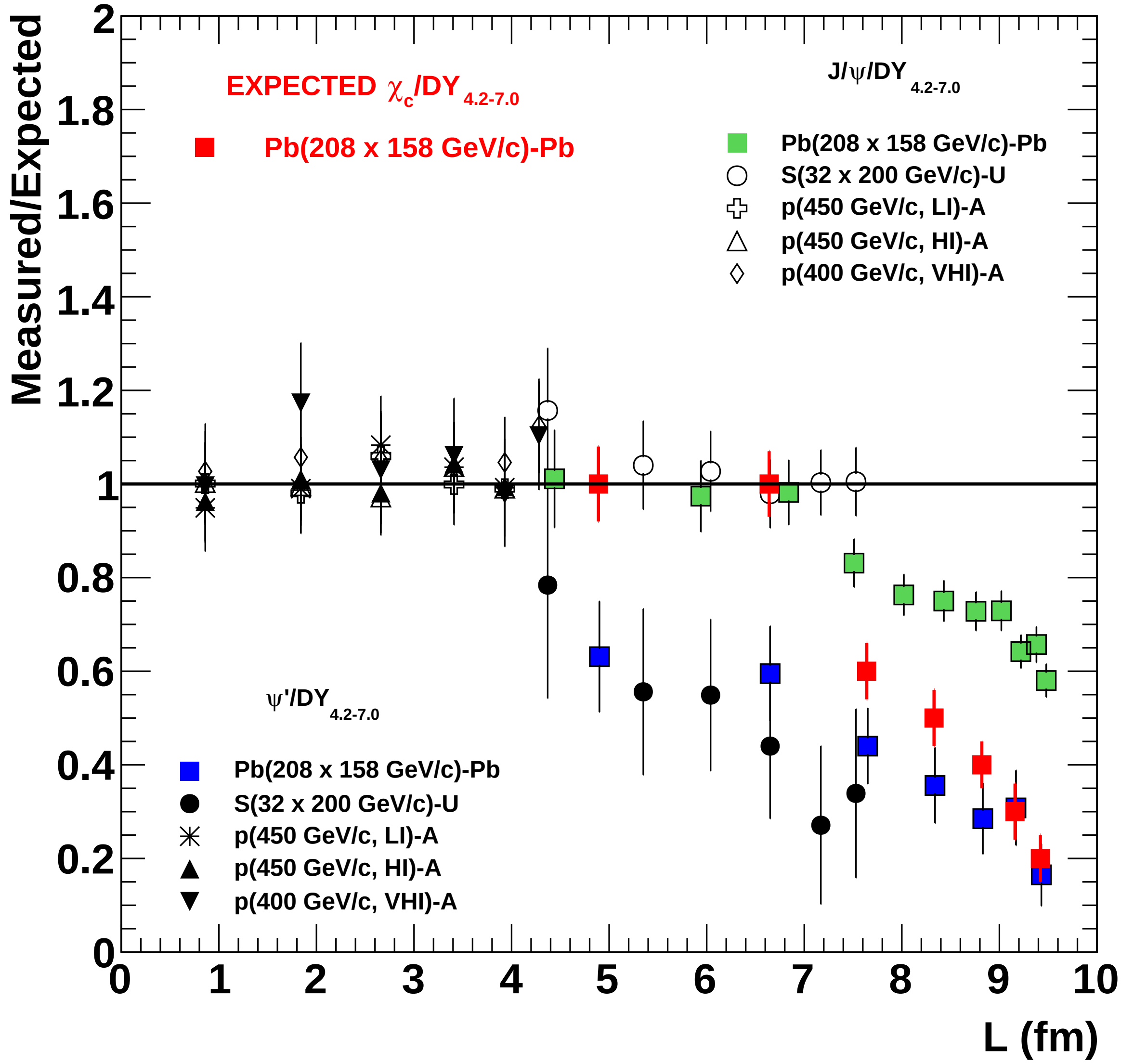

Figure 8: Expected performances for a 40-day Pb-Pb data taking with CHIC. Red points show the expected precision obtained with 3000 χ_c recorded.

E_T range (GeV)	ψ'	J/ψ	χ_c as ψ'	χ_c as J/ψ
3-20	186±25	16942±146	406	677
20-35	243±31	25229±181	530	1010
35-50	227±35	27276±192	495	1091
50-65	193±36	27681±196	421	1107
65-80	154±36	27315±200	336	1093
80-95	159±37	25111±193	647	1004
95-150	110±40	28570±209	240	1143
total	1272	178124	3075	7125

Table 2: Expected χ_c rate based on ψ' and J/ψ numbers reported in [6]. Two extreme scenarios have been considered: "χ_c as ψ'" where χ_c suffers the same suppression as ψ'; "χ_c as J/ψ" where χ_c suffers the same suppression as J/ψ.

Within our detector acceptance, we expect ~180,000 J/ψ and ~1300 ψ' in a typical 40-day data taking period with a 10%λ_I Pb target[5]. For the χ_c, depending on the two extreme scenarios, we expect, whether χ_c is suppressed as ψ' or χ_c is suppressed as J/ψ, between ~3000 and ~7000 χ_c respectively (see table 2). Figure 8 shows the expected performances in the configuration "χ_c as ψ'" where red points are possible χ_c Measured/Expected ratio.

5.1. p-A collisions

In table 3 we reproduce the numbers reported by the NA50 experiment in [19] where:

- the size of the target is given in interaction length (λ_I) units,
- $< I_{protons} >$ is the average number of protons delivered per burst,
- "Total $N_{protons}$" is the total number of protons delivered to the target,
- $N_{\mu\mu}^{+-}$ is the number of muon pairs within $M_{\mu^+\mu^-} \in [2.7; 3.5]$ GeV.

Target	size (λ_I)	$< I_{protons} >$ ($\times 10^8$)	Total $N_{protons}$ ($\times 10^{12}$)	$N_{\mu\mu}^{+-}$ (2.7 - 3.5)
Be	60 %	21.7	50.7	368 000
Al	52 %	23.0	63.4	602 000
Cu	28 %	27.0	45.5	762 000
Ag	30 %	24.8	43.8	821 000
W	19 %	23.5	28.5	524 000

Table 3: Number of opposite sign muon pairs recorded with different target by the NA50 experiment in [19]. Within the invariant mass range [2.7;3.5] GeV/c^2 J/ψ signal is by far the larger contribution (see [19] for more details).

Note that each data sample corresponds to a ~1 week run. With the current SPS operation, delivering proton beam to the LHC several months per year, we expect to be able to collect a significantly larger amount of data.

[5]Considering the 17.4% $acc.\times eff.$ for CHIC compared to 12.5% for NA50: 30 days $\times \frac{(7\%+10\%)\lambda_I}{10\%\lambda_I} \times \frac{12.5\%}{17.4\%} \sim$ 37days

6. Conclusion

In summary, we propose a new fixed target experiment at CERN-SPS in order to accurately study charmonia production in proton and heavy ion induced collisions. In heavy ion collisions, the measurement of χ_c together with J/ψ and ψ' will provide crucial information on deconfined matter. In proton-nucleus reactions, the study with several targets of the three charmonium states in large x_B and x_F ranges will provide key information on Cold Nuclear Matter effects and a robust baseline with respect to which we can clearly identify specific phenomena occuring in heavy ion induced collisions.

Experimentally, we propose to adopt the same strategy as used for modern particle physics apparatus: we intend to measure muons before they reach the hadron absorber. For the photon coming for χ_c decay we foresee to use an ultra-granular electromagnetic calorimeter *à la* CALICE. For the triggering system, an instrumented magnetized Fe absorber is envisionned.

With such an apparatus, we expect a mass resolution of ~20 MeV/c^2 (~45 MeV/c^2) for the J/ψ (χ_c). For a typical 40-day run with Pb beam delivered to a 10% interaction length Pb target, we expect to collect more than 3000 χ_c.

Finally, even though it is not discussed in the present document, our experimental apparatus is very well suited to explore other important physics subjects such as open charm or low mass lepton pairs production in heavy ion collisions.

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