Latest results from NA50 experiment on $J/\Psi$ suppression in Pb-Pb collisions

- Introduction on $J/\Psi$ suppression studies
- The NA38 and NA50 experiments
- Review of NA38 results; their interpretation within the framework of quarkonium production models
- Review of NA50 results; the two analysis methods; the comparison of data with conventional hadronic models; the evidence of a new state of nuclear matter (the message of Feb. 10$^{th}$ 2000 CERN Press Release)
- Conclusions

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M. Monteno (INFN Torino)

for the NA50 Collaboration
**J/Ψ suppression in nuclear collisions**

- Proposed in 1986 (*Matsui-Satz*) as a signal of colour deconfinement.
- then observed in O-U and S-U collisions (*NA38*).
- but observed also in p-A collisions (*NA38,NA51*) and understood as ordinary nuclear absorption of resonance state in a confined medium.

*Onset of deconfinement* expected as an additional J/Ψ suppression beyond the ordinary nuclear absorption.

*Anomalous J/Ψ suppression* reported by *NA50 Coll.* since (first results from Pb-Pb collisions (1995); confirmed later.

Today… conclusions can be drawn from the systematic study of all the data collected by *NA38/NA51/NA50* (from p-p to Pb-Pb).
NA50 experimental apparatus

Same spectrometer as for NA38 and NA51
EM calorimeter \( (E_T) \)
Zero Degree Calorimeter \( (E_{ZDC}) \)
Multiplicity Detector \( (N_{\text{ch}}) \)

Measurements of:
1) absolute cross-sections of charmonia and DY
2) \( B_{\mu\mu} \frac{\sigma^W}{\sigma^{DY}} \) vs. centrality of collisions
The standard charmonia analysis

- Selected $\mu^+\mu^-$ events
- $2\mu$ invariant mass spectrum analyzed
- Spectrum fitted above 2.9 GeV/$c^2$ as a superposition of 5 contributions: $J/\psi, \psi', \text{Drell-Yan}, \text{DD semileptonic decays and background (from π,K uncorrelated decays)}$
- This study can be performed in different centrality classes, using as estimator for centrality: $E_T, E_{ZDC}$ (measured) $b, L$ (can be calculated)
Study of p, O, S induced reactions on different targets

Charmonium production = hard process

It is appropriate to compare, for different colliding systems, a cross-section per nucleon-nucleon collision:

$$\frac{B_{\mu\mu} \sigma_{J/\Psi}}{A \times B}$$

Usual parameterization for \(\sigma\):

$$\sigma = \sigma_0 (A \times B)^\alpha$$

The global fit to NA38-NA51 data, leads to:

$$\alpha_{J/\Psi} = 0.918 \pm 0.015$$

⇒ Less than linear scaling
Schuler’s parameterization for $J/\Psi$ cross section in p-A

Data from $J/\Psi$ hadroproduction experiments at several CM energies parameterized by G.A. Schuler (CERN-TH.7170/94)

The scaling properties with A of $J/\Psi$ yield measured in p-A collisions is interpreted as due to final state interactions between charmonium state and the surrounding nuclear matter.
The \( J/\Psi \) over Drell-Yan ratio

For a study as a function of centrality, and for the comparison of different systems in nucleus-nucleus collisions, the product \( A \times B \) in \( B_{\mu \mu} \sigma^{J/\Psi}/(A \times B) \) can be replaced by the *Drell-Yan cross-section*, which is proportional to the number of elementary nucleon-nucleon collisions.

\[
R(E_T) = \frac{B_{\mu \mu} \sigma^{J/\Psi}}{\sigma^{DY}}
\]

 Advantage: common systematic errors washed-out in the ratio

 Disadvantage: sensitivity of results to the shape of Drell-Yan \( E_T \) spectrum, or to its fluctuations at low statistics.
Experimental data fitted by: \[ C \exp(-\rho_0\sigma_{abs} L) \]

Where \( L \) (function of \( E_T \)) is the path length in the nuclear matter, calculated using the Glauber model.

Best fit of data: \( \sigma_{abs} = 6.4 \pm 0.8 \text{ mb} \)
In S-U stronger suppression of $\Psi'$ than that fitted from p-A data

p-A data fitted with: \[ C \exp \left( - \rho_0 \sigma_{abs} L \right) \]

Best fit gives: \[ \sigma_{abs}^{\psi'} = 24 \pm 5 \, \text{mb} \]
ψ' / ψ versus AB (from p-A to S-U collisions)

- The ratio ψ'/ψ is observed to be constant with AB in p-A collisions ⇒ J/ψ and ψ' suffer the same nuclear absorption in p-A collisions

- Instead S-U collisions distinguish the two charmonia states suppressing more strongly the ψ'

\[
\frac{B_{\mu\mu}}{B_{\mu\mu}} \bigg\langle \sigma^{\psi'} \bigg\rangle = 1.64 \% \\
\Delta \alpha = \alpha^{\psi'} - \alpha^{\psi} = 0.016 \pm 0.009
\]
Review on quarkonium production models

At high energies quarkonium production proceeds predominantly through *gluon fusion*:

\[
\text{gluon fusion (hard process)} \Rightarrow \text{perturbative QCD}
\]

2 stages

\[
\text{bound state formation (larger time scale)} \Rightarrow \text{non perturbative dynamics}
\]

Different models proposed to explain exp. data, also the ones from Tevatron (i.e. inclusive distributions of \( J/\Psi \) and \( \Psi' \) at CDF and D0)

Does hold a **FACTORIZATION THEOREM** to separate the dynamics of the two stages of quarkonium production?

\[
|\Psi\rangle = a_0 |c\bar{c}\rangle + a_1 \left( |c\bar{c}\rangle_s g \right) + ...
\]

\[\Rightarrow \text{yes} \quad \text{Colour Evaporation Model}
\]

\[\Rightarrow \text{no} \quad \text{Colour Singlet Model + Colour Octet Mechanism}\]
Interpretation of J/Ψ suppression data (before NA50)

**Experimental findings**

- Exponential pattern for J/Ψ, Ψ’ absorption law vs. L
- The same scaling vs. L was observed for J/Ψ and Ψ’ in p-A collisions
- $\sigma_{\text{abs}} = 5$-7 mb from the fit
  but
  $\sigma_{\text{abs}}$ (J/Ψ-h) from short distance QCD and photo-production experiments are smaller by at least a factor 2
- Ψ’ more suppressed in S-U

**Modelization**

- Nuclear absorption of charmonia in ordinary nuclear matter (final state interactions).
- **BUT** charmonium production proceeds through 2 stages
  1) *c\overline{c}* pair creation
     (coloured state: pre-resonance)
     $\tau_c \sim 1/(2 m_c)$
  2) colour neutralization of *c\overline{c}*
     and bound state formation
     $\tau_f \sim 1/\Lambda_{\text{QCD}}$

**Explanation of data**

- $\gamma c \tau_f > R(A)$ in p-A
- *(c\overline{c})_8* exits from target nucleon before formation of the bound state $\Rightarrow$ same suppression for J/Ψ and Ψ’ in p-A
- Ordinary nuclear absorption $\exp(-\rho \sigma_{\text{abs}} L)$
  with
  $\sigma_{\text{abs}} = \sigma_{\text{abs}}(c\overline{c}-n) \neq \sigma_{\text{abs}} (J/Ψ-h)$
- More extended volume in S-U.
  Resonances J/Ψ, Ψ’ fully formed show different behaviour. Ψ’ is more easily dissociated.
Anomalous $J/\Psi$ suppression in Pb-Pb collisions

$Anomaly = deviation of data from the expectations of ordinary nuclear absorption$

- Firstly reported in 1995 (low statistics $\Rightarrow$ only 5 $E_T$ bins)
- Confirmed in 1996 (larger statistics $\Rightarrow$ 15 $E_T$ bins, but with a bias at high $E_T$, due to the reinteractions in the thicker target)
- Run of 1998 optimised for high $E_T$

“anomaly”:

$R = 0.77 \pm 0.04$

- Very high statistical discrepancy of the anomaly
- Onset of the anomaly: $b \sim 8 \text{ fm}$

An anomalous suppression pattern is seen for the first time within the same data sample
The minimum-bias analysis

Def. of minimum-bias event: when a Pb ion “interacts” in the Pb target and some hadronic energy is measured in the ZDC

- Drell-Yan data sample largely biased by fluctuations. That affects the ratio $\sigma_{J/\Psi}/\sigma_{DY}$
- Drell-Yan $E_T$ spectrum can be estimated from the huge sample of min.bias events, according to

$$\left(\frac{dN}{dE_T}\right)_{DY} = \left(\frac{dN}{dE_T}\right)_{MB,exp} \times \left(\frac{dN}{dE_T}\right)_{DY,th}$$

The calculation of the theoretical ratio $(dN/dE_T)_{DY} / (dN/dE_T)_{MB}$ was done using the Glauber model.

No fitting procedure was used.
\( \sigma_{\Psi}/\sigma_{DY} \) ratio versus \( E_T \)

- Superimposed the results obtained from 1996 and 1998 data samples, with the two different analysis methods (the solid line is the prediction of normal absorption models).

- Rejected: 1996 data at \( E_T > 90 \) GeV
  1998 data at \( E_T < 50 \) GeV

  The shapes are compatible.

- Excellent agreement of the two analysis for 30 GeV < \( E_T < 55 \) GeV where the “drop” of the \( J/\Psi \) yield is observed.

- \( E_T \) dependence is described now with much more accuracy. In the region of the discontinuity:

\[
\frac{\sigma_{E_T}}{E_T} \approx 10 \text{ \%}
\]

The size of the discontinuity appears as we expect for a sharp transition in that \( E_T \) range.
**Conventional hadronic models**

Other models proposed to explain anomalous J/Ψ suppression. They involve *conventional physics* ⇒ without phase transition to QGP.

They consider (in addition to normal nuclear absorption) the additional effect of final state interactions with co-moving hadrons (mainly pions), the so-called *comovers*, surrounding the formed J/Ψ.

*No discontinuity* of the J/Ψ survival probability can be obtained within such models.

There are various models, that assume different hypotheses on the density of comovers, and their cross section with J/Ψ. Their predictions have been compared with NA50 data.
NA50 Pb-Pb data versus hadronic models (with comovers)

NA50 data

- Sharp onset of the anomalous $J/\Psi$ suppression at $E_T \sim 40$ GeV
- A second “drop” of $J/\Psi$ suppression pattern at $E_T \sim 90$ GeV

Theor. predictions

- Smooth decrease of $J/\Psi$ suppression pattern (no discontinuity)
- Saturation at high $E_T$

Geiss et al; cc pairs dissociation by strings
Spieles et al; Ultrarelativistic quantum molecular dynamics model
Kahana et al. : LUCIFER (Cascade theory with multiscattering formalism)
Armesto et al. : Dual Parton Model
**J/Ψ suppression versus energy density**

**Bjørken’s model:**

\[
\varepsilon = \frac{\frac{dE_T}{dy}}{c \tau \times A_T} \quad \bigg|_{y^+ = 0}
\]

**First drop:**

\[\varepsilon \sim 2.3 \text{ GeV/fm}^3\]

**Second drop:**

\[\varepsilon \sim 3.1 \text{ GeV/fm}^3\]
A possible interpretation of the two “steps”

We know that \( \sim 40\% \) of produced \( J/\psi \) come from \( \chi_c \) decays

Radius \( r_\chi \sim 0.4 \text{ fm} > r_\psi \sim 0.2 \text{ fm} \)

Binding energy \( \Delta E_\chi \sim 0.3 \text{ GeV} < \Delta E_\psi \sim 0.6 \text{ GeV} \)

\[ \Rightarrow \chi_c \text{ is more easily dissociated than the } J/\psi \]

Therefore we can assume that our data are suggesting two critical values of \( \varepsilon \):

At \( \varepsilon \sim 2.3 \text{ GeV/fm}^3 \) dissociation of \( \chi_c \)

At \( \varepsilon \sim 3.1 \text{ GeV/fm}^3 \) dissociation of \( J/\psi \)
Conclusions

- The analysis of the data collected by NA50 in 1998 extended and clarified the results previously established by the NA38 and NA50 collaborations.
- The study of $J/\Psi$ suppression pattern up to the most central Pb-Pb collisions shows a clear step-wise pattern, with no indications of a saturation in the collisions corresponding to the highest energy densities and temperatures.
- These results exclude the presently available conventional hadronic models of $J/\Psi$ suppression, while they find a natural explanation in the framework of the formation of a new state of matter.
- It will be necessary to confirm that the critical behaviour observed in NA50 data is really the colour deconfinement of QCD.