J/ψ suppression and low mass dileptons in the NA60 experiment

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Abstract. The NA60 experiment, at CERN SPS, has studied muon pairs production in p-A and A-A collisions at 158 GeV. After an introduction to explain why the dimuon measurements are a useful tool to investigate the formation of a deconfined medium and how these measurements can be performed, from an experimental point of view, a review of the status of the field is presented, with particular emphasis on the NA60 results. The NA60 experimental apparatus, in fact, allows to perform high precision measurements, and therefore to obtain high quality results. Concerning the so called “low mass region” ($0.2 < M_{\mu\mu} < 2.5$ GeV), an excess above the yield expected from known meson decays is observed in In-In collisions and interpreted as thermal radiation, dominated by π annihilation through the ρ . Furthermore, the associated space-time averaged ρ spectral function shows a strong broadening, but no shift in mass. The extraction of the inverse slope parameter T_{eff} , from the transverse momentum spectra, allows an even deeper understanding. T_{eff} rises with mass up to the ρ , followed by a sudden decrease. While the initial rise is consistent with the expectations for the radial flow of a hadronic decay source, the decline signals a transition to an emission source with much smaller flow, which may be of partonic origin. The “high mass region” ($M_{\mu\mu} > 2.9$ GeV) is dominated by the J/ψ whose suppression is usually considered one of the main signatures for the formation of a deconfined medium. However also cold nuclear matter effects, not related to the hot matter, may reduce the J/ψ yield. Therefore, the study of p-A collisions allows the determination of the J/ψ behaviour in cold nuclear matter, representing the reference with respect to which the J/ψ yield in A-A collisions must be compared. NA60 results show that indeed an “anomalous suppression” is present in central In-In collisions. However, it is clear that to correctly quantify the amount of suppression exceeding the one due to cold nuclear matter, a precise determination of this reference must be performed. To advance in this direction, NA60 has also collected high quality p-A data at the same energy as the one of the A-A interactions.

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Dense Matter in Heavy Ion
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Outline

- ➔ **What does the NA60 experiment study?**
NA60 is a fixed target experiment at CERN SPS, which studies dileptons produced in
 - p-A collisions @ 158 GeV and 400 GeV
 - In-In collisions @ 158 GeV
- ➔ **Why do we study dileptons?**
look for signatures of QGP formation
- ➔ **How can we study dileptons?**
basic requirements to be satisfied building a dilepton experiment
- ➔ **Recent NA60 results on:**
 - J/ψ
 - Low mass region

Why and how we study dileptons...

What do we want to study?

➔ What do we want to study?

We want to study the transition from nuclear matter to a deconfined state of quarks and gluons (QGP), predicted by QCD at high enough temperature and density.

This transition occurred in the earliest stages of the evolution of the Universe

➔ How can we study this status of the matter in the laboratory?

With experiments colliding high-energy heavy nuclei, to produce hot and dense strongly interacting matter over extended volumes and lasting a finite time.

Studying the created matter with a probe

➔ How can we observe the properties of the created matter?

We study how the matter produced in heavy ion collisions affects well understood probes as a function of the temperature of the system

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Find a good probe and calibrate it

➔ Which probe should we use to test the QCD matter?

The probe must be produced early in the collision evolution, so that it is there before the matter to be probed

➔ What else do we need?

- ➔ another probe not affected by the dense QCD matter, to be used as a baseline reference
- ➔ “trivial” collision systems, to understand how the probe is affected by the “new physics”

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Dileptons: tool for QGP study...

➔ We now focus on those probes which we can investigate by studying the invariant mass spectrum reconstructed from their decay into lepton pairs

Dileptons are an ideal tool for QGP studies

- Dileptons directly probe the entire space-time evolution of the fireball, since they are continuously emitted during the evolution.
- Since they are not subject to strong interactions, they are not significantly affected by the medium at later stages of the collision and they freely escape from the interaction zone.

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...but there are also problems

Lots of physics processes contribute to the dilepton mass spectrum

2 consequences

➔ The physics content is very rich, but it is not easy to disentangle trivial and "interesting" sources (especially in the continuum)

➔ Even for interesting sources we measure an integral yield over the various stages of the collision: which dileptons do come from the deconfined phase ?

Modifications due to QCD phase transition

How do we measure dileptons?

➡ Which elements should be taken into account when designing a dimuon experiment ?

- **Mass resolution**
→ Necessary in order to **separate resonances** close to each other
- **Vertexing accuracy**
→ Necessary in order to **separate prompt from displaced sources**
- **Running at high luminosity**
→ Necessary to measure **rare processes** (as the ones involving dileptons)
- **Acceptance window**
→ Crucial to address certain physics observables (e.g. **low mass continuum**)
- **Background level**
→ Fundamental for continuum analysis
- **Centrality determination in A-A collisions**
→ Important to distinguish central collisions, where conditions for QGP formation may be reached

➡ Let's analyze typical dimuon set-ups

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Standard way of measuring dimuons (NA50, PHENIX, ALICE...)

- Place a **huge hadron absorber** to reject hadronic background
- Implement a **trigger system**, based on fast detectors, to select muon candidates (1 in 10^{-4} interactions, in Pb-Pb collisions at SPS energy)
- Reconstruct muon tracks in a **spectrometer** (magnetic field + tracking detectors)
- Correct for **multiple scattering** and **energy loss**
- Extrapolate muon tracks back to the target
→ **Vertex reconstruction** is usually rather **poor** ($\sigma_z \sim 10$ cm)

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Consequences of a limited mass resolution

- ➔ Difficult to see the ψ' as a shoulder of the J/ψ
Impossible to separate ρ and ω

V. DISCUSSION OF RESULTS

A. Nonobservation of Resonances

The invariant mass of the muon pair was the variable of primary interest for a simultaneous and, of course, highly related search made for "resonant" states. Any massive vector mesons would be expected to enhance the continuum near the resonance mass. As seen both in the observed mass spectrum (Fig. 4) and in the resultant cross sections $d\sigma/dq$ (Figs. 6–10) there is no forcing evidence of any resonant structure.

Possible solutions

- ➔ Radical solution: **eliminate** the hadron absorber

Done by E789 when measuring ψ' in p-Au at 800 GeV
→ 16 MeV dimuon mass resolution at the J/ψ

Drawbacks:

- no dimuon continuum physics
- tracking chambers overwhelmed with hadron tracks

- ➔ Add a **vertex detector** and **match** the muon tracks to tracks in the target region

Done by HELIOS-1

→ 20 MeV dimuon mass resolution at the ω

Drawbacks:

- worked only for p-Be at 450 GeV
- in p-W there were too many tracks in the drift chambers

- ➔ Presently being done by NA60, with **silicon tracking planes**, even in the high multiplicity environment of central heavy-ion collisions, thanks to radiation tolerant silicon pixel detectors

NA60: a second generation experiment

➔ The NA60 concept:

Use a silicon tracker in the vertex region to track muons before they suffer multiple scattering and energy loss in the hadron absorber.

These tracks are matched in coordinate and momentum space with those of the muon chambers

- ➔ Improve mass resolution
- ➔ Determine origin of the muons

Smearing sources

➔ Why is track matching so important in the improvements of the resolution?

The invariant mass resolution for the muon spectrometer has **two components**:

- ➔ **Multiple scattering** dominates the resolution for low momentum muons

$$\theta_s = \frac{21.2 \text{ MeV}}{\beta c p} z \sqrt{x/X_0}$$

The variance θ_s of the angle distribution is proportional to $1/p$

- ➔ **Tracking accuracy** which dominates the resolution at high momenta ($\delta p/p$ proportional to p)

$$\frac{\delta p}{p} = \sqrt{\frac{720}{N+5}} \frac{\epsilon}{L^2} \frac{p}{0.3 \cdot B}$$

- ➔ At $m_{\mu\mu} \sim 1 \text{ GeV}$, track matching is a very effective way for increasing the momentum resolution

- ➔ This is no more the case at $m_{\mu\mu} \sim 3 \text{ GeV}$ where multiple scattering contribution is no more important

Improvement in mass resolution

Vertex resolution

➔ The selection of the target where the interaction took place requires a **good z-vertex resolution**
in NA60: $\sim 200 \mu\text{m}$

➔ Good accuracy on the determination of the transverse coordinates of the interaction point is needed to **separate the prompt dimuons from the charm decays**
in NA60: $\sim 20 \mu\text{m}$

High luminosity

➔ Achieving good statistics in the study of rare processes requires the highest possible luminosities:

➔ high beam intensities incident on thick targets

➔ Problems:

High beam intensity requires:

- Fast detectors (especially the ones on the beam line, such as beam hodoscopes and ZDCs)
 - Radiation hard detectors
 - Efficient beam pile-up rejection

Thick target ($> 10\text{-}20\% \lambda_I$) implies:

- Interaction pile-up and/or reinteraction
 - ➔ May significantly bias the centrality measurement
 - Depending on the centrality detector
 - a peripheral event may be seen as central (multiplicity)
 - a central event may be seen as peripheral (forward energy)

➔ A reasonable limit has to be chosen, to keep systematics induced by these effects at a reasonable level

➔ NA60 values for In-In collisions @ 158 GeV:

Beam intensity of $5 \cdot 10^7$ ions/burst with 5s burst on $18\% \lambda_I$ target
➔ Luminosity $\sim 10^{35} \text{ cm}^{-2}$

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Trigger

High luminosity ➔ High interaction rate

If one wants to collect every interaction

- Enormous amount of (useless) events
- Dead time $\sim 100\%$
- Impossible to study rare processes

Need a fast and very selective trigger system to collect only interesting events among the many collisions

NA60 trigger:

➔ fully based on NIM/CAMAC electronics

- Identify two muon candidates by means of coincidences between scintillators
- Fast (decision in $< 500 \text{ ns}$)

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Acceptances

Acceptance is the probability that a dimuon produced with certain kinematical values (m , y , p_T , $\cos(\theta)$) is detected by the experiment

It's a **multidimensional** function of several variable, as p_T , y , $\cos\theta$, mass
e.g. the acceptance as a function of dimuon p_T depends on the distribution that we have assumed for the other kinematical variables

Usual acceptance evaluation technique
(1-D approach)

- Generate events according to some theoretical model and track them in the apparatus
- Reconstruct the events through a Monte Carlo simulation program, reproducing the detector limitations and the analysis selection procedure
- Get the acceptance as a function of the kinematical variable i as

$$A(i) = N_{\text{reconstructed}}(i) / N_{\text{generated}}(i)$$

The dipole magnetic field in the vertex region improves significantly the acceptance for **low mass** and **low p_T** opposite sign dimuons

Background sources

In order to understand the physics signal it's important to have under control the background contributions

In the standard dimuon experiment main sources of background are the **(uncorrelated) decays of π and K**

→ minimized by having the hadron absorber **as close as possible** to the collision point

Which subtraction techniques are used for the combinatorial background?

- use measured $\mu^+\mu^+$ and $\mu^-\mu^-$ distributions

$$N^{+-} = 2\sqrt{N^{++}N^{--}}$$

if acceptance is symmetric and no charge correlation between particles decaying into muons (true for high multiplicity events)

- event mixing technique

combining μ^+ and μ^- belonging to different events in such a way as to account acceptance and trigger conditions

In the experiments, as NA60, where the muons are matched to tracks in the vertex region:

- **Strong reduction of the combinatorial background** (e.g. $S/B = 1/7$ for $M < 2$ GeV)
- **But fake matches exist**

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Fake matches

➔ Fake match: muon matched to a wrong track in the vertex telescope

Can be important in high multiplicity events (negligible in pA or peripheral AA)

➔ Simple technique: match with the smallest χ^2 is retained. But is it correct or fake?

Fake matches can be studied and subtracted using an **overlay Monte Carlo**:

- MC muons are superimposed to real events (in the vertex telescope)
- Reconstructed as real events, fake matches can be tagged and the fraction relative to correct matched muons is then evaluated

➔ **NA60:**

M~1 GeV → background from fake matches is factor 15 smaller than comb₂ bck.

M~3 GeV → background from fake matches is negligible

Centrality determination

➔ **Why do we want to measure the centrality of the collisions?**

➔ This information is useful, since in A-A collisions the conditions for QGP formations occur most likely in central interactions

➔ Centrality estimators

- Impact parameter, b
- N. of nucleons participating to the collisions, N_{Part}
- Number of collisions, N_{coll}
-

They are not directly accessible in the experiments.

The relation between these variables is established within the Glauber model

➔ Experimentally, to obtain centrality information:

- we measure quantities which have a centrality dependence, as
 - the number of tracks measured in the vertex telescope
 - the energy released by nucleons not taking part to the collisions in a zero degree calorimeter
- we relate these quantities to the centrality estimators taking into account that the quantities we measure are affected by the experimental resolution ²²

Centrality measurement: E_{ZDC}

➔ **Example: centrality determination from the energy released in the Zero Degree Calorimeter (ZDC)**

The ZDC measures the energy of the (spectator) nucleons which have not taken part to the collision (N_{spect})

$$N_{\text{spect}}(b) = A - N_{\text{part}}(b)/2$$

➔ We have to define the relation between E_{ZDC} and the centrality variables

$$E_{\text{ZDC}} = N_{\text{spect}}(b) \times 158 \text{ GeV} + \alpha N_{\text{part}}(b)$$

↑
measured quantity
↑
centrality estimators obtained from the Glauber model

➔ The free parameters in the relation, to take into account

- the small contribution of secondary particles emitted in the ZDC angular acceptance ($\eta > 6.3$)
 - the smearing due to the ZDC experimental resolution ($\sim 9\%$ at the peak)
- are tuned on the data

➔ Once the correlation between E_{ZDC} and N_{spect} is found, using the Glauber₂₃ model we can estimate the corresponding N_{part} , L , N_{coll} ...

Glauber model

➔ Geometrical model to describe the collision between two nuclei with impact parameter b

➔ **Assumptions:** Nucleus-nucleus collisions are described as a superposition of independent nucleon-nucleon collisions

➔ **Ingredients:**

- the nucleon-nucleon inelastic cross-section ($\sim 30 \text{ mb}$ at SPS energies)
- the nuclear profile densities e.g a Wood-Saxon distribution

➔ **Output:**

Allow to obtain several information as a function of the impact parameter b :

- number of participant nucleons
- number of collisions
- overlap region
- ...

To summarize...

- ➔ How NA60 deals with the elements needed to design a dimuon experiment ?
- **Mass resolution**
→ thanks to the matching $\left\{ \begin{array}{l} \text{from 70 to 20 MeV at } m_{\mu\mu} \sim 1 \text{ GeV} \\ \text{from 100 to 70 MeV at } m_{\mu\mu} \sim 3 \text{ GeV} \end{array} \right.$
 - **Vertexing accuracy**
→ 200 μm in the z direction and 20 μm in the transverse coordinates
 - **High luminosity**
→ compromise between high luminosities and problems connected with it
 - **Acceptance window**
→ good acceptance coverage down to low m and p_T
 - **Background level**
→ under control, fundamental, in particular, for continuum analysis
 - **Centrality determination in A-A collisions**
→ possible to define the centrality with good accuracy
- ➔ **NA60 has optimized the chance of detecting dileptons with respect to the previous generation experiments**

Some photos of the NA60 apparatus...

The invariant mass spectrum

Now that we have seen how an experiment can detect dimuons,

which probes
can we study
in order to
search for the
QGP phase
transition?

Origin of the low-mass excess,
connected with chiral symmetry
restoration?

Origin of the intermediate mass
excess, connected with thermal
dilepton production?

Origin of the J/ψ suppression,
comparing results obtained in
several colliding systems

The High Mass region

The charmonium

What is the charmonium?

It's a bound $c\bar{c}$ state stable under strong decay

- $m_c \sim 1.3 \text{ GeV}$
- $m_{cc} < 2m_D$ where D is the open charm meson

The binding of the c and cbar quarks can be expressed using the potential:

$$V(r) = -\frac{\alpha}{r} + kr$$

Coulombian contribution, induced by a gluon exchange between q and qbar

Confinement term

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Debye screening

What happens to a cc pair placed in the QGP?

The QGP consists of deconfined colour charges
→ the binding of a qq pair is subject to the effects of colour screening

Two effects affect the qqbar pair in a QGP medium:

- The "confinement" contribution disappears
- The high color density induces a screening of the coulombian term of the potential

$$V(r) = -\frac{\alpha}{r} + kr$$

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

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Debye screening (2)

→ The screening radius $\lambda_D(T)$ (i.e. the maximum distance which allows the formation of a bound cc pair) decreases with the temperature T

At a given T :

if resonance radius $< \lambda_D(T)$
→ resonance can be formed

if resonance radius $> \lambda_D(T)$
→ no resonance can be formed

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Charmonium suppression

→ This is the idea behind the suggestion (by Matsui and Satz) of the J/ψ as a signature of QGP formation

Phys.Lett. B178 (1986) 416

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Sequential screening

→ The charmonium states can be characterized by

- the binding energy
- radius

state	J/ψ	χ_c	ψ'
Mass(GeV)	3.10	3.53	3.68
ΔE (GeV)	0.64	0.20	0.05
r_o (fm)	0.25	0.36	0.45

More bound states have smaller size

→ The Debye screening condition $r_0 > \lambda_D$ will occur at different temperatures

$T < T_c$

$T \sim 1.1 T_c$

$T \sim T_c$

$T \gg T_c$

Sequential suppression of the resonances

↓
thermometer for the temperature reached in the HI collisions

Charmonium decay and feed-down

$J/\psi(1S)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
Γ_1 hadrons	(87.7 ± 0.5) %
Γ_2 virtual $\gamma \rightarrow$ hadrons	(13.50 ± 0.30) %
Γ_3 e^+e^-	(5.94 ± 0.06) %
Γ_4 $\mu^+\mu^-$	(5.93 ± 0.06) %

→ In NA60 J/ψ are studied through their decay:

$$J/\psi \rightarrow \mu^+\mu^-$$

$\psi(2S)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)	C_i
Γ_1 hadrons	(97.85 ± 0.13) %	
Γ_2 virtual $\gamma \rightarrow$ hadrons	(1.73 ± 0.14) %	
Γ_3 light hadrons		
Γ_4 e^+e^-	(7.43 ± 0.18) × 10 ⁻³	
Γ_5 $\mu^+\mu^-$	(7.4 ± 0.8) × 10 ⁻³	
Γ_6 $\tau^+\tau^-$	(3.0 ± 0.4) × 10 ⁻³	

→ Many of the measured J/ψ mesons are produced by the decay of other particles: χ_c, ψ'

Decays into $J/\psi(1S)$ and anything

Mode	Fraction (Γ_i/Γ)
Γ_7 $J/\psi(1S)$ anything	(56.9 ± 0.9) %

→ Taking into account the measured production rates and the resonances branching ratios, we obtain:

$$N_{J/\psi}^{meas} = \underbrace{N_{J/\psi}}_{60\%} + \underbrace{N_{\chi_c \rightarrow J/\psi X}}_{30\%} + \underbrace{N_{\psi' \rightarrow J/\psi X}}_{10\%}$$

$\chi_{c1}(1P)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
Γ_{34} $\gamma J/\psi(1S)$	(35.9 ± 1.9) %

Radiative decays

→ Feed down may affect physics conclusions

Reference collision systems

➔ How can we say that we observe a **suppression** of the J/ψ ?

We need an **unsuppressed** reference (to set a baseline)

J/ψ production in pp collisions

➔ How can we understand if the suppression that we observe in nucleus-nucleus collisions is due to trivial sources or not?

We need a large systematics from p-p to p-A to A-A collisions (with various projectile-target combinations), **collected in the same kinematical domain**

A suppression effect already visible in p-A and then smoothly increasing in A-A is hardly due to a genuine deconfinement effect

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Reference physics processes

➔ It is also important to have an unsuppressed reference process that can be used for an easier normalization of the J/ψ yield

➔ The chosen reference must

- have a production mechanism as close as possible to the J/ψ one (g-g fusion)
- not be sensitive to the created medium

Drell-Yan:

- ☺ very robust on theory grounds
- ⊗ lacks statistics at the SPS and is buried under charm/beauty decays at RHIC/LHC
- ⊗ probes the q/anti-q distributions, not the gluons which produce charmonium states

Open Charm:

- ☺ its production mechanism is similar to the J/ψ one
- ⊗ heavy flavor production may also be affected by "new physics"

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The Drell-Yan

- ➔ At SPS energies, Drell-Yan is often used as a reference for J/ψ studies
- ➔ It's production cross section is proportional to the number of binary nucleon-nucleon collisions

- ➔ The DY cross section per nucleon-nucleon is constant, both in p-A and A-A collisions
- ➔ Drell-Yan is not sensitive to initial/final state effects
- ➔ Studying J/ψ / DY $\rightarrow$ common systematic errors cancel out

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What happens if the resonance is not well chosen?

- ➔ When the reference is not accurate, conclusions are often biased

As an example: first results from NA38

J/ψ suppression in O-U collisions

Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).

$N_{J/\psi}$
Cont. (2.7-3.5)
Fit to the continuum
was done for
 $m_{\mu\mu} > 1.7$ GeV

J/ψ is suppressed
by a factor 2 !

- Nuclear absorption was not accurately known
- Seemed to be not enough to explain the data!

NA38, Phys.Lett. B220(1989) 47

- QGP ?
- Hadronic comovers ?

➔ Both conclusions were wrong !

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What happens to a J/ψ in A-A collisions?

What happens to a J/ψ produced in A-A collisions?

At SPS energies J/ψ has been studied by

NA38 $\rightarrow$ S-U collisions @ 200 GeV
 NA50 $\rightarrow$ Pb-Pb collisions @ 158 GeV
 NA60 $\rightarrow$ In-In collisions @ 158 GeV

To understand what happens to a J/ψ in A-A collisions, first of all, according to what we have previously discussed, we need to answer the following question:

What happens to a J/ψ produced in p-p and p-A collisions?

In fact, in p-p and p-A collisions the conditions required for the QGP formation are not satisfied $\rightarrow$ p-A and p-p data provide us a fundamental reference to understand the J/ψ behaviour in A-A collisions

To set this reference, at SPS energies several measurements have been done:

NA38/NA51/NA50 :
 450 and 400 GeV protons on p, d and nuclear targets
 NA60
 400 and 158 GeV protons on nuclear target

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J/ψ in p-A collisions

p-A collisions at SPS do not reach the conditions for QGP formation
 $\rightarrow$ hence no J/ψ suppression is, in principle, expected

However, there is a significant reduction of the number of J/ψ produced in nucleon-nucleon collisions

J/ψ are absorbed by the "normal nuclear matter"

How can we estimate the J/ψ absorption cross section in nuclear matter?

Once produced, the J/ψ has to cross the length L of nuclear matter, before exiting the nucleus, and, during the crossing, it can be absorbed (interacting with the nucleons).

$\leftarrow$ p-A collision

If the nuclear absorption cross section is $\sigma_{abs}^{J/\psi}$, the J/ψ cross section in p-A can be written as

$$\sigma_{pA}^{J/\psi} = A \sigma_{pp}^{J/\psi} e^{-\sigma_{abs}^{J/\psi} \rho L}$$

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Normal nuclear absorption

$$\sigma_{pA}^{J/\psi} = A \sigma_{pp}^{J/\psi} e^{-\sigma_{abs}^{J/\psi} \rho L}$$

→ $\sigma_{abs}^{J/\psi}$ and the $\sigma_{pp}^{J/\psi}$ can be extracted from a Glauber calculation which describes the p-A data.

NA50 determined σ_{abs} from a global fit to the 400 and 450 GeV p-A data

→ Of course, less bound states, as the ψ' , will have a larger σ_{abs} $\sigma_{pA}^{\psi'} \gg \sigma_{pA}^{J/\psi}$

The J/ψ normal nuclear absorption is also present in A-A collisions
→ it has to be taken into account in order to understand if there is a further J/ψ suppression, on top of it, maybe due to QGP

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Caveat

- **CAVEAT:**
- p-A data have been collected at 400/450 GeV
 - A-A data have been collected at a lower energy (i.e. 158 GeV)

A rescaling procedure has to be applied in order to take into account the

- different energy
- different phase space domain

→ **Main assumptions** used up to now

- $\sigma_{J/\psi}^{abs}$ does not depend on energy

→ the slope of the nuclear absorption reference is fixed

$$\sigma_{J/\psi}^{abs} @158\text{GeV} = \sigma_{J/\psi}^{abs} @400/450\text{GeV}$$

- J/ψ production σ depends on energy

→ the normalization of the nuclear abs. reference is rescaled with the help of older data at 200 GeV and using a parameterization ("Schuler") of energy and kinematical dependence of J/ψ production σ

for the first time NA60 has collected pA data at the same energy as the one of the A-A collisions

What is σ_{abs} ?

➔ What really is $\sigma_{\text{abs}}^{J/\psi}$?

- It is not a real cross section for charmonium absorption by nucleons in the nucleus. It is rather an effective quantity used to parametrize all initial and final state nuclear effects
- What is crossing the nucleus? → Mainly theoretical problem
 - pre-resonant $\bar{c}c$ state, fully formed resonance
- Are we measuring primary J/ψ ? → Mainly experimental problem
 - feed-down from ψ' and χ_c

➔ If $\sigma_{\text{abs}}^{J/\psi} \neq \sigma_{\text{abs}}^{\psi'} \neq \sigma_{\text{abs}}^{\chi_c}$

- Can we use $\sigma_{\text{abs}}^{J/\psi, \text{eff}}$ obtained in p-A collisions as a baseline for nuclear absorption in A-A collisions?
- Could be partly biased, since the fraction of measured J/ψ coming from higher-lying resonances can vary between p-A and A-A, due to different suppression mechanisms in the two systems

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Normal nuclear absorption in A-A collisions

- ➔ From p-A data we obtain $\sigma_{\text{abs}}^{J/\psi}$ and the $\sigma_{\text{pp}}^{J/\psi}$ needed to define the J/ψ normal absorption contribution.
- ➔ We need to extrapolate the normal nuclear absorption from p-A to A-A collisions and to obtain its centrality dependence.

➔ The nuclear absorption curve as a function of centrality, in A-A collisions, is obtained:

- computing the J/ψ survival probability to the crossing of the nuclear matter as a function of the impact parameter b , using the Glauber model
- linking the impact parameter with a experimental quantity related to the centrality of the collisions (for example the energy E_{zdc} released in a zero degree calorimeter)

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Previous J/ψ results (NA38/NA50)

What was the J/ψ scenario “before NA60”?

The J/ψ yield is compared to the Drell-Yan which is not affected by the created medium

Current interpretation:

p-A → define the J/ψ absorption in cold nuclear matter

S-U → no anomalous suppression

Pb-Pb → J/ψ anomalous suppression, increasing with centrality

Let's move to the NA60 In-In results!

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J/ψ suppression in In-In collisions

Now we can study the J/ψ yield in In-In collisions, to be compared

- with the expectation of the normal nuclear absorption
- with the previous J/ψ results

Two different approaches have been used by NA60 to investigate the centrality dependence of the J/ψ production.

They correspond to two different ways of normalizing the J/ψ yield.

Study of the ratio J/ψ / DY (as done by NA50)

Study of the J/ψ sample standalone

Different event selections are applied, according to the analysis approach, e.g.

J/ψ / DY analysis → matching is not required, in order not to lose DY events because of the matching efficiency

J/ψ analysis → matching is required, in order to have a “clean” sample of J/ψ

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J/ψ / Drell-Yan

➡ How can we extract the number of J/ψ and DY events?

Signal mass shapes from Monte Carlo (PYTHIA and GRV94 LO pdf) reconstructed as the real data

Combinatorial background from π and K decays (<3% contribution under J/ψ)

Since we study the ratio $J/\psi / DY$
→ systematic errors affecting both
processes cancel out

With a multi-step fit :

- a) $M > 4.2 \text{ GeV}$: normalize the DY
- b) $2.2 < M < 2.5 \text{ GeV}$: normalize the charm
(with DY fixed)
- c) $2.9 < M < 4.2 \text{ GeV}$: get the J/ψ yield
(with DY & charm fixed)

J/ ψ events ~ 45000
DY events ($M > 4.2$ GeV) ~ 320

Limited DY statistics prevents from a detailed study versus centrality within this approach ⁴⁷

J/ψ / Drell-Yan (2)

➡ We observe a decrease of the J/ψ / DY versus centrality

➡ To quantify the amount of suppression not due to cold matter effects we plot

Npart	J/ψ/DY
63	28.8 ± 3.2
123	16.1 ± 1.6
175	17.8 ± 1.6

Anomalous suppression is present in In-In collisions

Reasonable agreement with previous Pb-Pb data

but more quantitative conclusions are prevented by the reduced DY statistics

need to study the centrality dependence of the J/ψ yield with another analysis approach

J/ψ yield

➔ Directly compare data to the expected J/ψ centrality distribution, calculated assuming nuclear absorption (with $\sigma_{\text{abs}} = 4.18 \text{ mb}$) as the only suppression source

R. Arnaldi et al. (NA60), PRL99, 132302 (2007)

➔ ~29000 J/ψ → study of the J/ψ centrality dependence no more limited by low Drell-Yan statistics

➔ The absorption curve has no absolute normalization.

require the ratio measured/expected, integrated over centrality, to be equal to the same quantity from the (J/ψ)/DY analysis (0.87 ± 0.05)

As already observed with the previous analysis approach:

Observed J/ψ suppression exceeds nuclear absorption 49

J/ψ yield compared to nucl. absorption

➔ Compare the J/ψ pattern with the expectation from the nuclear absorption curve:

➔ Onset of the suppression at Npart ~ 100

➔ Small statistical errors

Careful study of systematic errors is needed
Sources:

- Uncertainty on normal nuclear absorption parameters ($\sigma^{\text{abs}}(\text{J}/\psi)$ and $\sigma^{\text{pp}}(\text{J}/\psi)$)
- Uncertainty on relative normalization between data and absorption curve
- Uncertainty on centrality determination (affects relative position of data and abs. curve)
 - Glauber model parameters
 - E_{ZDC} to N_{part}

➔ • ~10% error centrality indep. → does not affect shape of the distribution 50
• (Most) Central points affected by a considerable error

Comparison with NA50 Pb-Pb

➡ Good agreement with Pb-Pb in the common N_{part} region

➡ Anomalous suppression sets in at $\epsilon \sim 1.5 \text{ GeV}/\text{fm}^3$ ($\tau_0 = 1 \text{ fm}/c$)

➡ What is the best scaling variable for the onset ?

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→ Clear answer requires more accurate Pb-Pb suppression pattern

Theoretical models

➡ Which are the medium effects on a produced quarkonium?

➡ **Suppression by comover hadrons**

Charmonium can be dissociated through interactions with hadrons in the medium formed in the collisions.

➡ Main feature of the comover approach: smooth dependence on centrality

➡ Many free parameters to be fixed, to reasonable values, from the experimental data

➡ **Suppression by color screening**

Charmonium is dissociated by color screening, as already discussed. Discussion on the dissociation temperatures is on going (potential models, lattice QCD calculations...)

➡ Onset for the suppression

➡ **Enhancement by recombination**

In the QGP hadronization, charmonium formation can occur by binding a c and a $\bar{c}$ from different nucleon-nucleon collisions, as well as from the same. This recombination is possible only if heavy quark multiplicity is high

➡ Enhancement of J/ψ production

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➡ At SPS energies, charm multiplicity $\sim 0.2 \rightarrow$ no recombination is possible

Comparison of data and theoretical models

Suppression by hadronic comovers ($\sigma_{co} = 0.65$ mb, tuned for Pb-Pb collisions)

Dissociation and regeneration in QGP and hadron gas

Percolation, with onset of suppression at $N_{part} \sim 140$

- ➡ Size of the anomalous suppression reasonably reproduced
- ➡ Quantitative description not satisfactory

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Theoretical “postdictions”

- Compare J/ψ yield to calculations assuming
 - Nuclear absorption
 - Maximum possible absorption in a hadron gas ($T=180$ MeV)
- Extra-suppression in Pb-Pb and (to a lesser extent) in In-In

- Based on HSD transport approach
- Size of comover absorption fitted on NA50 Pb-Pb data
- Quantitative description not satisfactory for both scenarios

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Comparison with RHIC results

→ R_{AA}

The agreement between SPS/NA38+NA50+NA60 and RHIC/PHENIX is more than remarkable.....

...but difficult to understand!

→ Measured / Expected

Different $\sqrt{s}$
 Different shadowing
 Different nuclear absorption

ψ' in p-A and In-In collisions

→ p-A collisions

The ψ' value measured by NA60 at 158 GeV is in good agreement with the normal absorption pattern, calculated from 450 (400) GeV data

→ Wait for new results in pA @ 158 GeV (but statistics may be very low...)

→ In-In collisions

Study limited by statistics ($N_{\psi'} \sim 300$)
 Normalized to Drell-Yan yields

- Most peripheral point does not show an anomalous suppression
- Good agreement with Pb-Pb

Conclusions on J/ψ

- ➡ J/ψ suppression is an interesting signature to search for QGP
- ➡ It has been extensively studied at CERN SPS by NA38/NA50 and now NA60
- ➡ Current interpretation of the SPS data:
 - **p-A** → only absorption in nuclear matter
 - **S-U** → only absorption by nuclear matter
 - **Pb-Pb** → anomalous suppression in central collisions
 - **In-In** → small effect
- ➡ But the scenario is not yet clear...there are still points which have to be investigated...
 - What is suppressed? Is the directly produced J/ψ or the J/ψ coming from the less bound ψ' and χ_c ?
 - Why at SPS and RHIC a similar J/ψ suppression is observed?

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The Low mass region

The low mass region

→ The study of the low mass region allows the investigation of phenomena related to **chiral symmetry restoration**

→ **M < 1 GeV**
thermal dilepton production is largely mediated by the ρ , ω , ϕ

	$\Gamma_{tot} [MeV]$
$\rho(770)$	150 (1.3 fm/c)
$\omega(782)$	8.6 (23 fm/c)
$\phi(1020)$	4.4 (44 fm/c)

→ ...but...

→ ρ is particularly important because:

- ρ life time $\ll \tau_{\text{collision}}$ (> 10 fm/c)
- continuous "regeneration" by $\pi\pi$

$$\pi\pi \rightarrow \rho^* \rightarrow \ell\ell$$

properties of ρ in hot and dense matter unknown (related to the mechanism of mass generation)

properties of hot and dense medium unknown (general goal of studying nuclear collisions)

→ coupled problem of two unknowns:
need to learn on both

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Differences wrt the J/ψ study

J/ψ

- Long life ($\Gamma=93$ keV)
- Decays outside of the "hot" region
- QGP modifies the production yields, but not its spectral function (mass, width)

ρ

- Short life ($\Gamma=148$ MeV)
- It may decay (in $\mu^+\mu^-$) inside the "hot" region
- QGP modifies its spectral function

Chiral symmetry restoration

- ➔ At $T=0$, quarks “dress” with gluons forming constituent q that make up hadrons
bare quark mass $m_q \sim 0 \rightarrow$ constituent quark mass $M_q \sim 300 \text{ MeV}$
- ➔ In a “hot” medium, dressing melts and $M_q \rightarrow 0$
- ➔ For $m_q \sim 0 \rightarrow$ the QCD lagrangian is chirally symmetric
if $M_q \neq 0 \rightarrow$ spontaneous chiral symmetry breaking
if $M_q = 0 \rightarrow$ chiral symmetry restoration
- ➔ Explicit connection between spectral properties of hadrons
(masses,widths) and the value of the chiral condensate $\langle q\bar{q} \rangle$?

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ρ theoretical predictions

➔ Brown-Rho scaling:

mesons mass is directly related to the quark condensate

$$\frac{m_\rho^*}{m_\rho} \approx \frac{\langle q\bar{q} \rangle^*}{\langle q\bar{q} \rangle}$$

Mass shift towards lower values, for increasing T

➔ Rapp-Wambach broadening scenario

Medium modifications of the ρ are encoded in the vector propagator computed in a many body approach. From D_ρ we can extract information on mass and width.

$$D_\rho = [M^2 - m_\rho^{(0)2} - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]^{-1}$$

ρ “melts” in hot and dense matter

- pole position roughly unchanged
- broadening mostly through baryon interactions

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Previous SPS results

➔ **NA45/CERES:** results on p-Be/Au, S-Au and Pb-Au

➔ first measurement of strong excess radiation above meson decays;
➔ vacuum- ρ excluded

- $\pi^+ \pi^-$ annihilation without ρ modification
- ρ Mass shift (Brown-Rho)
- Increase of the ρ width (Rapp-Wambach)

statistical accuracy and resolution insufficient to unambiguously determine the in-medium spectral properties of the ρ

➔ Difficult to distinguish among the different scenarios

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NA60 invariant mass spectrum in In-In

➔ How can we extract information on the in medium modification of the ρ ?

➔ Improving { the statistics
the mass resolution

➔ As previously discussed, in order to get the signal, we have to subtract the background contributions:

- { Combinatorial background
- { Fake matches

➔ Thanks to the very good mass resolution (20 MeV at the ω) and to the high statistics, the η , ω , ϕ are clearly visible (for the first time in the dilepton channel in AA)

➔ Two different approaches to understand the data:

Peripheral events:

description of the spectrum with a known hadronic cocktail

Central events:

isolation of the "excess" radiation by subtracting the known meson decay sources

Excess dimuons

Peripheral events

well described by meson decay cocktail:

2-body decays: ρ , ω , ϕ , η
 Dalitz decays: η , ω , η' ,
 open charm: DD

More central data

isolation of excess by subtraction of the measured decay cocktail (without ρ), based solely on local criteria for the major sources η Dalitz, ω and ϕ

existence of excess dimuons⁶⁵

Phys. Rev. Lett. 96 (2006) 162302

Study as a function of centrality

Peripheral collisions

no cocktail ρ and no DD subtracted

clear excess above the cocktail ρ (bound to the ω with $\rho/\omega=1.0$)

excess centered at the nominal ρ pole rising with centrality

monotonic broadening with centrality

"melting" of the ρ

Central collisions

Results integrated over p_T Eur.Phys.J.C 49 (2007) 235

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Comparison with theory

Phys. Rev. Lett. 96 (2006) 162302

Data and predictions, after acceptance filtering, can be interpreted as the ρ spectral function, averaged over space-time and momenta

- Dropping ρ mass (BR) disfavoured
- Hadronic models predicting strong broadening/no mass shift (RW) in fair agreement with data

→ The mass region $M > 1 \text{ GeV}$ is not properly described...

Predictions by Rapp (2003) for all scenarios

Theoretical yields normalized to data for $M < 0.9 \text{ GeV}$

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What about $M > 1 \text{ GeV}$?

Hees/Rapp Phys.Rev.Lett. (2006)

Mass region above 1 GeV described in terms of **hadronic processes**, 4π ...

Renk/Ruppert, hep-ph/0702012

Mass region above 1 GeV described in terms of **partonic processes**, qq ...

→ How to distinguish?

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Transverse momentum spectra (2)

→ Dilepton transverse momentum distributions reflect the following contributions:

- p_T - dependence of **spectral function**, weak
 - T - dependence of **thermal distribution** of “mother” hadrons/partons
 - M - dependent **radial flow** (v_T) of “mother” hadrons/partons
- note: final-state lepton pairs themselves only weakly coupled

properties of the
expanding fireball

→ Differences between hadrons and dileptons p_T spectra

- hadron p_T spectra determined at freeze-out T_f
- dilepton p_T spectra superposition from **all fireball stages**
 - early emission: **high T** , low v_T (small flow)
 - late emission: low T , **high v_T** (large flow)

→ Final spectra from space-time folding over T - v_T history from $T_i \rightarrow T_f$ (including low-flow partonic phase)

→ p_T distributions may give hints on the **hadronic or partonic nature** of the emitting source

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Transverse momentum spectra

Phys. Rev. Lett. 100 (2008) 022302

transverse mass: $m_T = (p_T^2 + M^2)^{1/2}$

→ Strong mass dependence of m_T spectra

→ From the fit to the m_T spectra:

$$\frac{1}{m_T} \frac{dN}{dm_T} \sim \exp(-m_T/T_{\text{eff}})$$

- **$M < 1$ GeV**: monotonic flattening of the slopes
→ T_{eff} increases
- **$M > 1$ GeV**: slope steepens again
→ small T_{eff}

→ Strong steepening at low m_T , opposite to what expected from radial flow

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Evolution of T_{eff} with mass

→ Strong rise of T_{eff} with dimuon mass, followed by a sudden drop for $M > 1$ GeV

→ Rise consistent with radial flow of a hadronic source (here $\pi\pi \rightarrow \rho \rightarrow \mu\mu$), taking the freeze-out ρ as the reference

T_{eff} of $\rho > T_{\text{eff}}$ of dimuons

→ Drop signals sudden transition to low-flow source, i.e. source of partonic origin (here $q\bar{q} \rightarrow \mu\mu$)

→ Combining M and p_T of dileptons seems to overcome hadron-parton duality

Conclusions on Low Masses

→ Thermal dilepton production dominated by $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$ is the major contribution to the lepton pair excess in heavy-ion collisions at SPS energies in the region $M < 1$ GeV

→ In-medium ρ spectral function identified;
→ no significant mass shift of the intermediate ρ , only broadening;
→ connection to chiral restoration?

→ First observation of radial flow of thermal dileptons
→ mass dependence tool to identify the nature of the emitting source;
→ mostly partonic radiation for $M > 1$ GeV?