EFFECTS OF MAGNETIC FIELDS ON HEAVY FLAVOURS

Andrea Rucci

Dipartimento di Fisica dell'Università di Pisa, Pisa

Incontro sulla fisica con ioni pesanti ad LHC
26-27 May 2015, Bologna

Intro, *physical conditions*

Magnetic field are expected to be created in non-central heavy-ion collsions:
$\rightarrow |e|B \sim 0.2 - 0.3$ GeV^2 in Pb+Pb at LHC (Skokov,2009)
$\rightarrow$ timescales for B decay are still debated, depending on the thermal medium properties (most pessimistic case: $0.1 - 0.5$ fm)

Heavy flavoured mesons
$\rightarrow$ Low-momentum: produced during initial stage, **strong interaction** with the thermal-medium
$\rightarrow$ High-momentum: produced during initial stage, only **slight interaction** with the thermal-medium

HIGH-MOMENTUM QUARKONIUM MAY BE USED TO PROBE THE INITIAL MAGNETIC FIELD

$$\text{collision } (t_0 = 0) \longrightarrow \begin{cases} \text{quarkonium formation } (t_f \sim 0.5\text{fm/c}) \\ \text{magnetic field (worst case } t_B \sim 0.1 - 0.5\text{fm/c}) \end{cases}$$

Intro, *the $q\bar{q}$ interaction*

The interaction of a heavy quark-antiquark pair in the confining phase is well described by the so-called **Cornell form** of the **static potential**

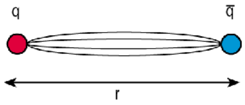
$$V_C(r) = -\frac{\alpha}{r} + \sigma r + \mathcal{O}(m^{-2})$$

with $\sigma \simeq (420\ \text{MeV})^2$ and $\alpha \sim 0.2 - 0.3$

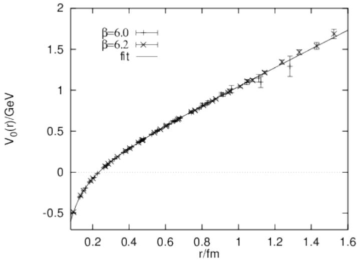
The confining behaviour is due to the linear term given by the **string tension** σ.

The LQCD framework is suitable for the study of the static potential

WHAT ABOUT THE POTENTIAL IF WE TURN ON A MAGNETIC FIELD?

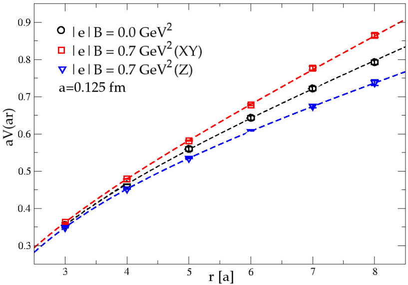


String in a $q\bar{q}$ pair.



Example of the static potential from LQCD (Bali, 2008)

Intro, *magnetic field effects*



Static potential in the presence of magnetic field (Bonati et al., 2014)

Some **infos**:
1. Constant and uniform external magnetic field.
2. Results at T=0 and potential evaluated only on the coordinate axes

Recent lattice results (Bonati et al., 2014) show that an external **magnetic field affects** the static potential.

Possible parametrization for $V_C(r)$

$$V_C(r,\theta,B) = -\frac{\alpha(\theta,B)}{r} + \sigma(\theta,B)r$$

with

$$\alpha(\theta,B) = \frac{\alpha_0}{\epsilon_1^{\alpha}\sqrt{1+\epsilon_2^{\alpha}\sin^2\theta}}$$

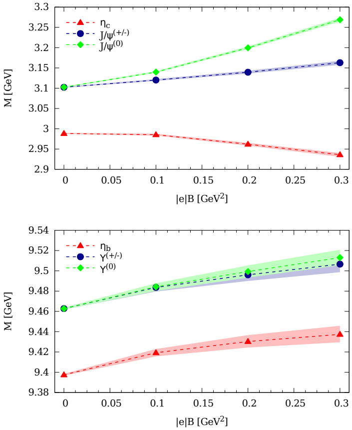
$$\sigma(\theta,B) = \sigma_0\epsilon_1^{\sigma}\sqrt{1+\epsilon_2^{\sigma}\sin^2\theta}$$

CAN WE EXPECT PHENOMENOLOGICAL AND MEASURABLE EFFECTS?

Effects on the Heavy-Flavours, *mass spectrum I*

Dynamics of heavy quarks bound states may be described in a non-relativistic framework
→ using a (static) potential model
→ inserting a magnetic field in the system (also coupled to spins)
→ using parameters to reproduce lattice and experimental data

It is possible to study the mass spectrum and other relevant observables of the lower part of the **charmonium** and **bottomonium** spectra



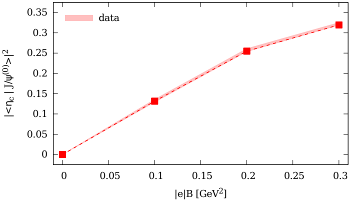
Masses of the 1S states with magnetic field
(Bonati et al., in preparation)

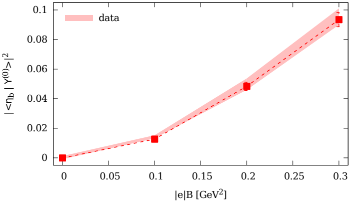
Effects on the Heavy-Flavours, *mass spectrum II*

The presence of a magnetic field affects the meson spectrum in several ways
→ modification of the masses (up to $\sim 60-70$ MeV for $c\bar{c}$ and $5-10$ MeV for $b\bar{b}$ at $|e|B \sim 0.3$ GeV^2)
→ particle spin components splitting
→ mixing between meson states

Expected phenomenological effects
→ mass differences may allow to open new decay channels
→ decay rates contamination due to mixings

OPEN QUESTION: ARE THESE EFFECTS EXPERIMENTALLY OBSERVABLE?



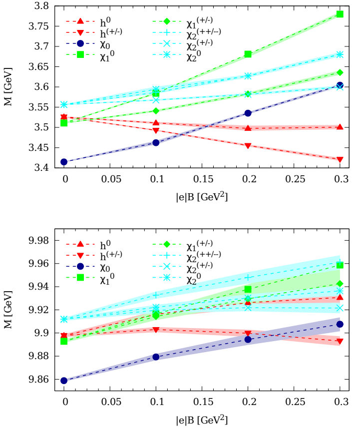


Mixing between 1S triplet and singlet for $c\bar{c}$ and $b\bar{b}$ (Bonati et al., in preparation)

Effects on the Heavy-Flavours, *mass spectrum III*

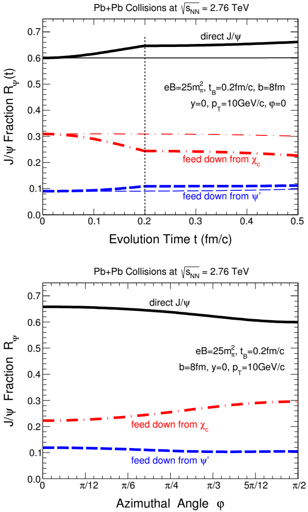
Possible experimental signatures of decay channels contamination due to mixing in the 1S states (Alford, 2014)
→ dilepton decays: reduction of Υ decays and increase of η_b ones
($\Delta M \simeq 63$ MeV at B=0)
→ the same for J/ψ with η_c
($\Delta M \simeq 115$ MeV at B=0)

It is possible to extend the study to the first excited states 1P: the h and χs mesons of $c\bar{c}$ and $b\bar{b}$
→ New mixings and decay contaminations?
→ Crossing between energy levels?



Mass spectrum of 1P states of $c\bar{c}$ and $b\bar{b}$
(Bonati et al., in preparation)

Effects on the Heavy-Flavours, *production I*

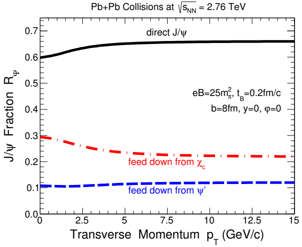


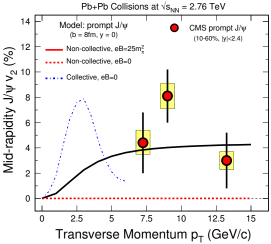
J/Ψ production fraction (Guo et al., 2015).

Attempt to solve dynamical equations for the meson production fraction (Guo et al., 2015)
→ still in a non-relativistic framework
→ study of the time-evolution of $c\bar{c}$ wave-packages
→ using parameters able to reproduce $B = 0$ data $(p + p)$

Some **infos:**
→ physical conditions of $Pb + Pb$ collisions $(b \simeq 8$ fm$)$
→ charmonium formation time $t_f \simeq 0.5$ fm/c
→ (assumed) B orthogonal to the beam direction and with life time $t_B \simeq 0.1 - 0.2$ fm/c
→ focus on J/Ψ, χ_c and Ψ'

Effects on the Heavy-Flavours, *production II*





J/Ψ production fraction and v_2 (Guo et al., 2015).

Looking forward for measurable effects
→ prompt J/Ψ enhancement and χ_c suppression
→ greater for high p_T's (saturation due to a competition between Lorentz force and time of interaction)

Another experimental signature could be seen in the event anisotropy $v_2(\eta, p_T)$

$$v_2(\eta, p_T) = \frac{\int_0^{2\pi} d\varphi N_{J/\Psi}(\eta, p_T, \varphi) cos(2\phi)}{\int_0^{2\pi} d\varphi N_{J/\Psi}(\eta, p_T, \varphi)}$$

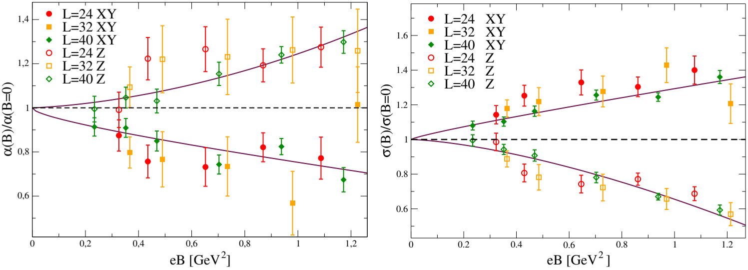
	$B = 0$	$B \neq 0$
hydro	"as usual"	???
no hydro	$v_2 = 0$ (trivial)	Guo et al., 2015

RELIABILITY OF THE RESULTS:
DEPENDENCE ON THE *B* DETAILS?

THANK YOU

Backup, *anisotropy in the static potential*

The magnetic-induced anisotropy of the static potential (Bonati et al., 2014) is observed at the level of the potential parameters α and σ



Static potential parameters (Bonati et al., 2014).

Behaviour in a magnetic field B and along the coordinate axes d

$$\frac{O_d(|e|B)}{O(|e|B=0)} = 1 + A^{O_d}(|e|B)^{C^{O_d}} \qquad \text{with } O = \sigma, \alpha \text{ and } \mathrm{d} = x, y, z$$

Backup, *non-relativistic $q\bar{q}$ bound state model*

A quark-antiquark bound state is described by the hamiltonian

$$\hat{H} = \sum_{i=1}^{2} \frac{1}{2m} \left[\hat{\vec{p}}_i - q_i \vec{A}(\vec{x}_i)\right]^2 + V(\vec{x}_1, \vec{x}_2) - (\vec{\mu}_1 + \vec{\mu}_2) \cdot \vec{B}$$

where $-(\vec{\mu}_1 + \vec{\mu}_2) \cdot \vec{B} = -\frac{gq}{4m}(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{B}$ acts mixing triplet and singlet states.

Magnetic field B breaks the rotational symmetry and hence neither the kinetic nor the canonical momentum are conserved. Using COM coordinates, symmetric gauge and introducing the pseudomomentum operator $\hat{K}$, the hamiltonian takes the form

$$\hat{H} = \frac{\vec{K}^2}{2M} - \frac{q}{M}(\vec{K} \times \vec{B}) \cdot \vec{r} - \frac{\nabla^2}{2\mu} + \frac{q^2}{2\mu}(\vec{B} \times \vec{r})^2 + V(\vec{r}) - (\vec{\mu}_1 + \vec{\mu}_2) \cdot \vec{B}$$

where

$$M = 2m_q \qquad \mu = \frac{m_q}{2} \qquad \vec{r} = \vec{x}_1 - \vec{x}_2 \qquad \hat{K} = \sum_{i=1}^{2} \left(\hat{\vec{p}}_i + \frac{1}{2} q_i \vec{B} \times \vec{x}_i\right)$$

Backup, *static potential parametrization*

Supported by lattice results (Kawanai et al., 2012) and previous studies (Alford et al., 2014), the static potential parametrization we adopted is

$$V_C(r,\theta,B) = -\frac{\alpha(\theta,B)}{r} + \sigma(\theta,B)r + (\vec{\sigma}_1 \cdot \vec{\sigma}_2)\gamma e^{-\beta r}$$

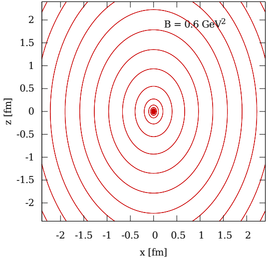
where the spin-spin term is responsable for the singlet and triplet mass splitting (for example, J/Ψ and η_c)

Potential parameters $\sigma(\theta,B)$ and $\alpha(\theta,B)$ depends both on the magnitude of the magnetic field and its direction.
Their form is based on the ansatz

$$\frac{\alpha}{r} \to \frac{\alpha}{\sqrt{\epsilon^{\alpha}_{xy}(x^2+y^2)+\epsilon^{\alpha}_{z}z^2}}$$

$$\sigma r \to \sigma\sqrt{\epsilon^{\sigma}_{xy}(x^2+y^2)+\epsilon^{\sigma}_{z}z^2}$$

where the ϵs are related to the coefficients A, C in (Bonati et al., 2014).



Anisotropic static potential (Bonati et al., in preparation).

Backup, *solving the non-relativistic $q\bar{q}$ model*

Bound-state model solved numerically
→ physical system enclosed in a Euclidean discretized volume
→ eigenstates are obtained by studying the evolution of test wavefunctions $\psi_T(\vec{r},\tau)$through

$$\left(\frac{\partial}{\partial\tau} + \hat{H}\right)\psi_t(\vec{r},\tau) = 0$$

and extracting the large time behaviour from

$$\psi_t(\vec{r},\tau) = \sum_a c_a \Phi_a e^{-E_a\tau}$$

→ spin part is taken into account by costructing the hamiltonian matrix
→ eigenstate and observables are finally obtained by diagonalizing the hamiltonian

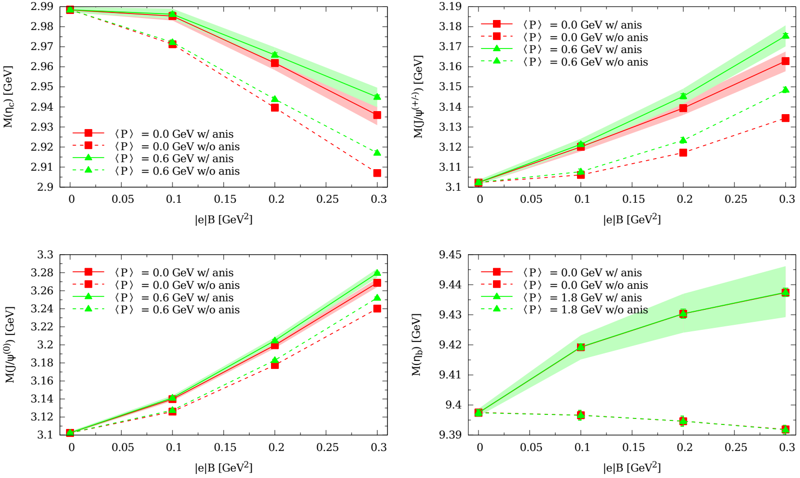
The procedure is performed for various spatial spacings
→ physical results obtained through a continuum limit

Some **details**
→ physical volume $V \sim$(6 fm)^3
→ spacings from 0.250 GeV^{-1} to 0.625 GeV^{-1}
→ simulations performed both in the presence and absence of the magnetic anisotropy in the static potential

Backup, *some results from (Bonati et al., in preparation)*

Because of B in the $q\bar{q}$ hamiltonian, the COM motion is not decoupled

$\rightarrow$ the total momentum P_{kin} contributes to the masses



Charmonium and Bottomonium 1S states (Bonati et al., in preparation).

Backup, *some details from (Guo,2015)*

Some **details**

→ Hamiltonian of a $q\bar{q}$ system interacting through the potential

$$V_C(r,\theta,B) = -\frac{\alpha(\theta,B)}{r} + \sigma(\theta,B)r + (\vec{\sigma}_1 \cdot \vec{\sigma}_2)\gamma e^{-\beta r}$$

→ Magnetic field with distribution ($t < t_b = 0.2$ fm/c)

$$\vec{B} = \begin{cases} B\hat{y}, & \frac{x^2}{(R_A - b/2)^2} + \frac{y^2}{(b/2)^2} + \frac{\gamma^2 z^2}{(b/2)^2} < 1 \\ 0, & \text{others} \end{cases}$$

→ for $Pb + Pb$ collisions with centrality 40% at energy $\sqrt{s_{NN}} = 2.76$ TeV: $R_A = 6.6$ fm, $b = 8$ fm and $\gamma = 1400$

The relative motion of a $c\bar{c}$ pair is initially described by an Gaussian wave package. Then the package is evolved

$$\psi_r(0)\, e^{-\frac{(\vec{r}-\vec{r_0})^2}{\sigma_0^2}} \rightarrow \psi_r(t)\, e^{-\frac{(\vec{r}-\vec{r_0})^2}{\sigma_t^2}}$$

with $\sigma_t^2 = \sigma_0^2 + v^2 t^2$.

Parameters are fixed by $p + p$ data at charmonium formation time $t_f = 0.5$ fm/c

→ $r_0 = 0.68$ fm

→ $\sigma_0 = 0.02$ fm

→ expansion velocity $v = 0.72c$

→ $\sigma_{t_f} = 0.38$ fm