Charmonium in the QGP

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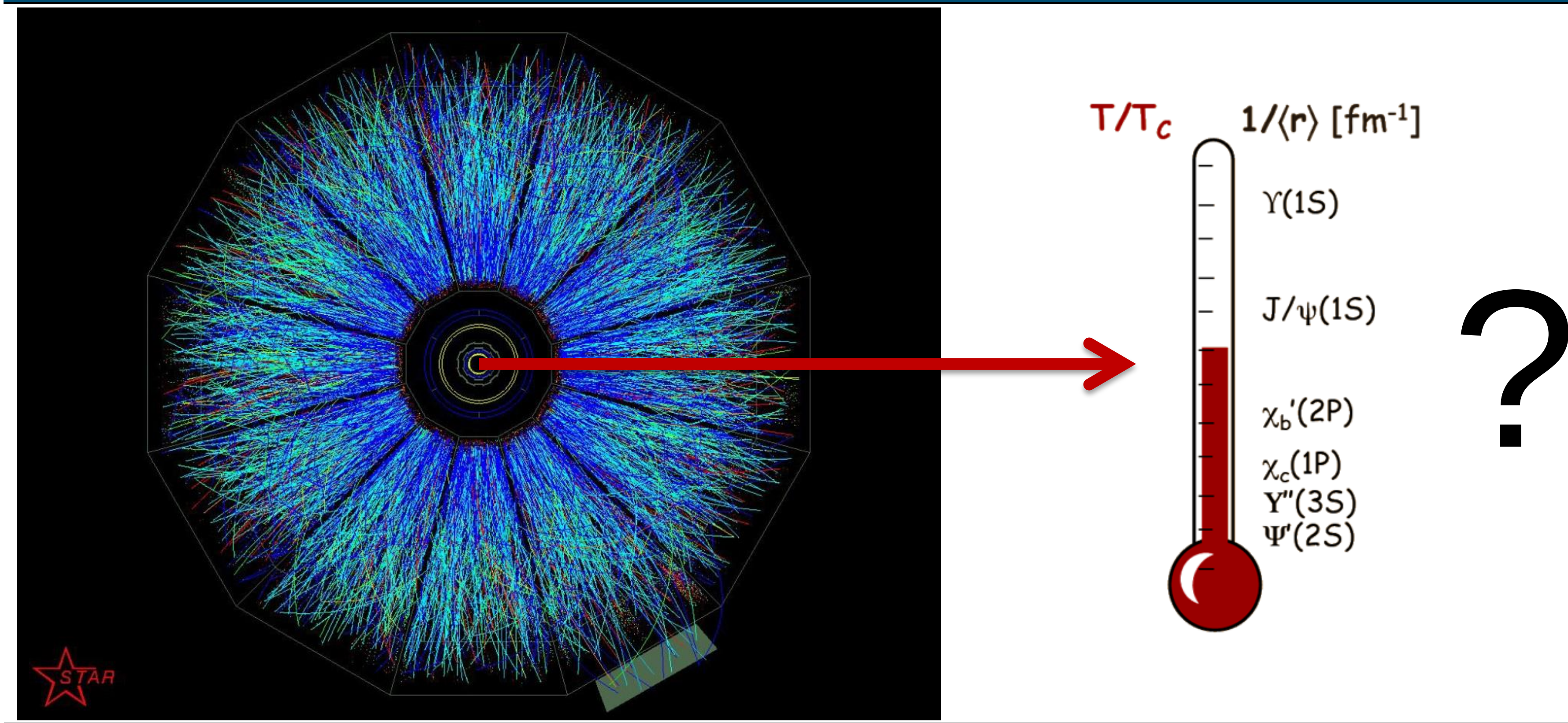
…as a probe of the quark-gluon plasma



Outline

I. **Motivation and the main idea of probing the QGP with charmonium**

II. Quarkonium properties

→ *charmonium*

III. Charmonium at different temperatures

→ *string breaking, recoupling, color screening*

IV. Theoretical models to describe charmonium dissociation

→ *Schwinger model, potential models, lattice QCD results*

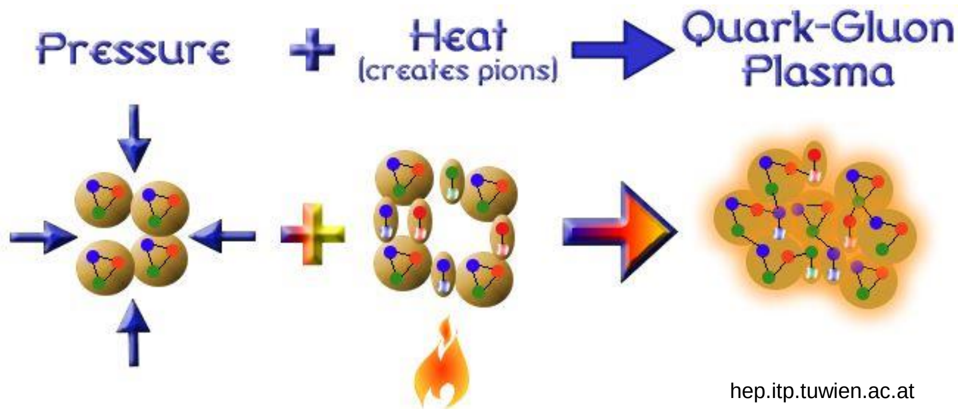
V. Charmonium in heavy-ion collisions

→ *suppression or enhancement*
→ *experimental results*
→ *statistical hadronization model*

VI. Summary and outlook

I.) Motivation

- At high temperatures or/and pressure strongly interacting matter becomes a plasma of deconfined quarks and gluons → **QGP**
- Use in-medium behavior of heavy quark bound states (i.e. **charmonium**) as a probe to study the deconfinement and the properties of the QGP



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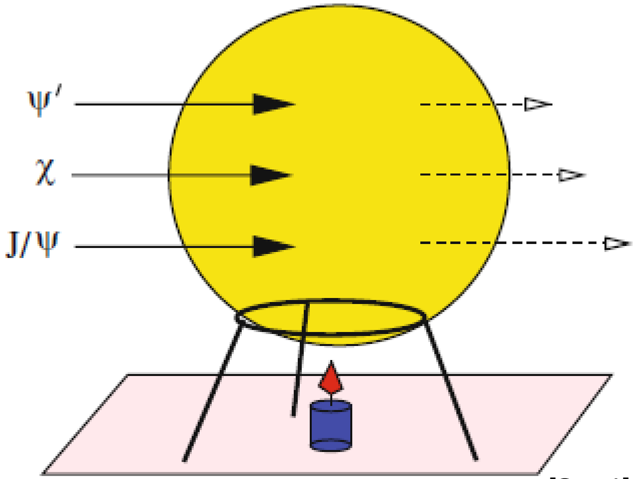
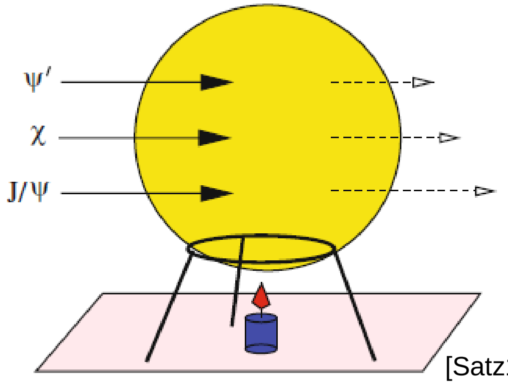


[Satz1]

The main idea of probing the QGP with charmonium

- High mass, heavy-quark pairs are expected to be created predominantly in the early stage of hadronic collisions.
- The evolution of this state of matter is expected to take place in later stages of the collision and is therefore believed to modify the measured rates of quarkonia.
- ***The main idea:*** Implant charmonia into the QGP and observe their modification, in terms of suppressed (or enhanced) production in nucleus-nucleus collisions with or without plasma formation.



[Satz1]

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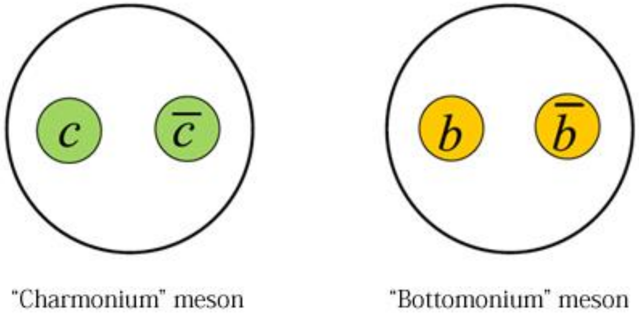
II.) Short remainder on quarkonium

- Quarkonium ($\mathrm{Q\bar{Q}}$) are flavourless mesons build of a heavy quark and its own antiquark
  → i.e. the **charmonium ($\mathrm{c\bar{c}}$)** or bottonium ($\mathrm{b\bar{b}}$)
  (toponium does not exists → very short lifetime of the top quark)

- Build of heavy quarks: $m_c \cong 1.3\ \mathrm{GeV}$, $m_b \cong 4.7\ \mathrm{GeV}$

- Charmonium stable under strong decay until $M_{c\bar{c}} < 2\ M_D \cong 2 * 1.9\ \mathrm{GeV}$ with $D = \mathrm{c\bar{u}}$ (lightest "open" charm meson)
  (for bottonium $M_{b\bar{b}} < 2\ M_B \cong 2 * 5.3\ \mathrm{GeV}$)



[http://legacy.kek.jp/intra-e/press/2012/011014/]

Binding of a quarkonium ($Q\bar{Q}$) system

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- Because of heavy quark masses use **non-relativistic Schrödinger equation in centre-of-mass system**:

$$-\frac{\mathbf{1}}{\boldsymbol{m}}\{\boldsymbol{\nabla}^{2}(\boldsymbol{r})+\boldsymbol{V}(\boldsymbol{r})\}\boldsymbol{\psi}_{\boldsymbol{i}}(\boldsymbol{r})=(\boldsymbol{M}_{\boldsymbol{i}}-\mathbf{2}\boldsymbol{m})\boldsymbol{\psi}_{\boldsymbol{i}}(\boldsymbol{r})$$

- Binding energy:

$$\Delta E = 2M_{D,B} - M_i$$

- Cornell Potential (vacuum with limit $M_Q \to \infty$):

$$\boldsymbol{V}(\boldsymbol{r})=\boldsymbol{\sigma}\boldsymbol{r}-\frac{\boldsymbol{\alpha}}{\boldsymbol{r}}$$

effective coulomb potential (gauge term)

confining force (string term)

- squared average bound-state radii:

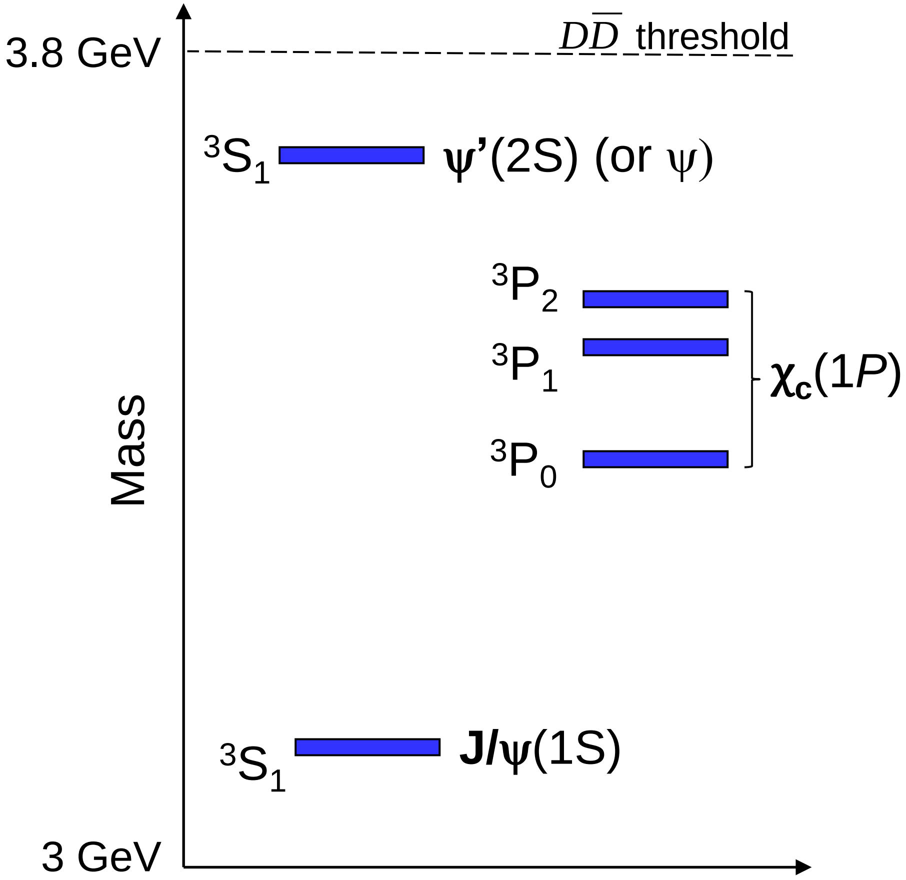
$$\langle r_i^2\rangle = \frac{\int d^3r r^2 |\psi_i(r)|^2}{\int d^3r |\psi_i(r)|^2}$$

The charmonium – a heavy quark bound state

- Lowest charmonium bound states: J/ψ, χ_c and ψ'
- Lifetimes about 10^{-13} s
- Small radii ~ 0.3 fm (compared to typical hadron radii ~ 1 fm)

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

[Satz1]



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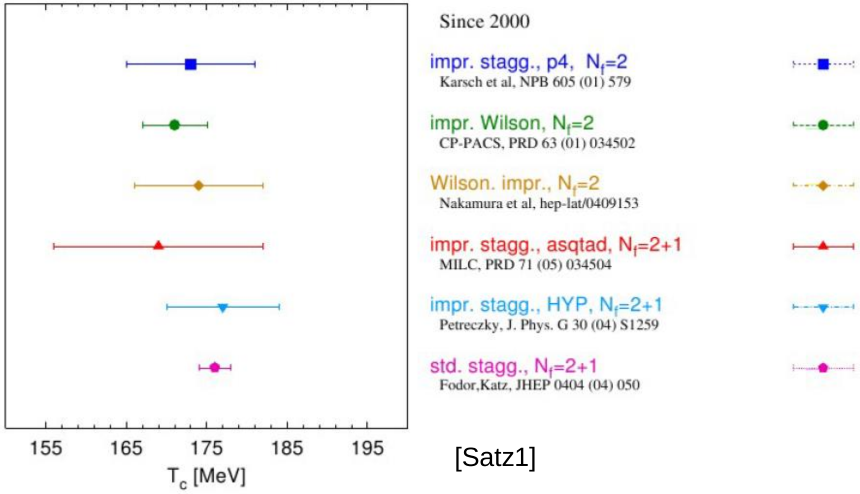
Question: How do charmonia dissociate?

- Three mechanisms have been identified, corresponding to the behaviour for $\boldsymbol{T=0}$, $\boldsymbol{0<T<T_c}$ and $\boldsymbol{T \geq T_c}$
- T_c is the critical temperature of deconfinement ~ 160 - 170 MeV (obtained by lattice QCD studies) [F. Karsch, J. Phys. G 31 (2005) S633] [Z. Fodor, PoS CROD07 (2007)]



[Satz1]

$T = 0$: String breaking of a static $Q\bar{Q}$ pair

Assumptions:

- A $Q\bar{Q}$ pair in vacuum at $T = 0$, with the limit $M_Q \to \infty$
- Cornell Potential: $V(r) = \sigma r - \frac{\alpha}{r}$
- Free Energy: $F(r) \sim \sigma r$
- String tension: $\sigma \cong 0.2\ \mathrm{GeV}^2 = 1\ \mathrm{GeV/fm}$
- Gauge coupling: $\alpha \cong \frac{\pi}{12}$

$T = 0$: String breaking of a static $Q\bar{Q}$ pair

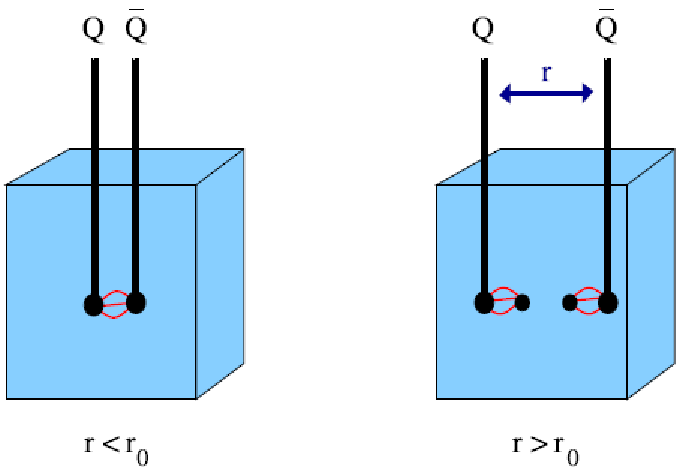
- String breaks if energy is above production threshold of D or B Meson:

$$F_0 = 2(M_D - m_c) \cong 1.2 \text{ GeV}$$
$$F_0 = 2(M_B - m_b) \cong 1.2 \text{ GeV}$$

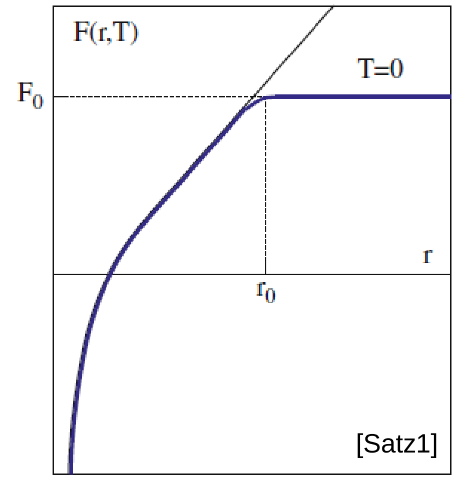
- From this deduce the string-breaking radius for charmonium and bottomium:

$$r_0 = \frac{1.2 \text{ GeV}}{\sigma} \cong 1.5 \text{ fm}$$

→ energy required for string breaking is a **property of the vacuum itself**, virtual $Q\bar{Q}$ pairs are brought on-shell by the field between the heavy quarks
→ **confinement**



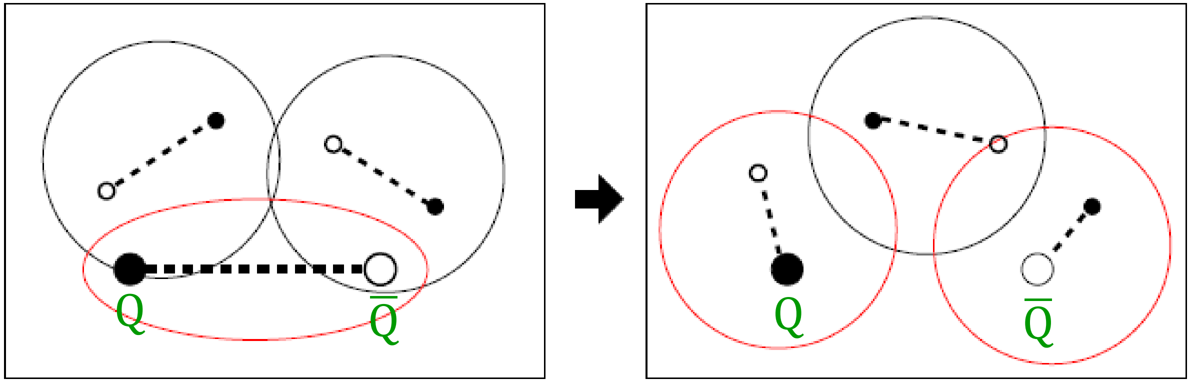
[Satz1]



$0 < T < T_c$: $Q\bar{Q}$ in-medium string breaking with the help of recoupling

- Now light mesons (i.e. pions) are included
- By a switch in bonding a $Q\bar{Q}$ meson is turned into two heavy-light mesons
- **If temperature is increased**
  → the hadron density also increases
  → this increases the recoupling probability
  → distance up to which the heavy quarks are still bind also becomes shorter
  → **the potential will break earlier**

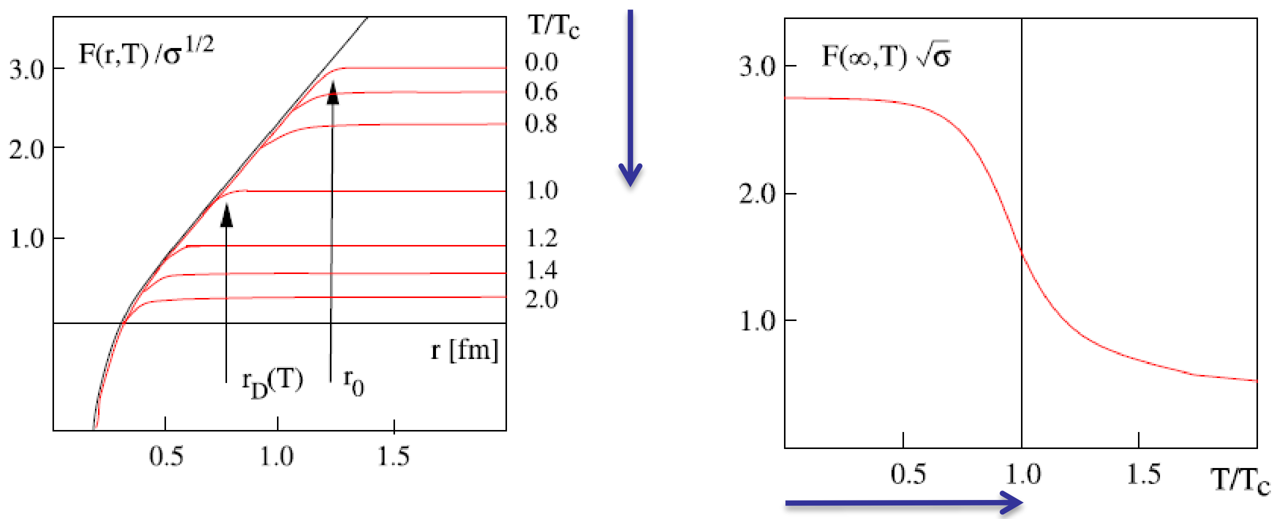
→ “effective screening”



[Satz1]

What happens if we go closer to T_c?

- Density of produced hadrons will increase strongly.
- *Form lattice results:* The free energy and the string-breaking radius r_T decrease rapidly near T_c



[Satz1]

Slide-in: Debye screening in a plasma

- *To understand charmonium at $T \geq T_c$ in QGP, first have a short look on Debye screening in a electromagnetic plasma.*

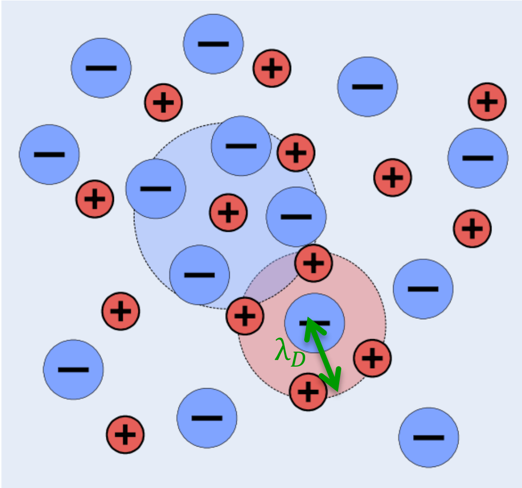
- A test charge in a plasma is surrounded by charges of the opposite charge.

- This reduces the long range Coulomb potential:

$$\frac{e^2}{r} \rightarrow \frac{e^2}{r}\exp(-\mu r)$$

with Debye radius $\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_i}{n_e e^2}}$

and Debye mass $\mu_D = 1/\lambda_D$



[http://de.wikipedia.org/wiki/Debye-H%C3%BCckel-Theorie]

→ At λ_D the Coulomb potential of a test charge drops to $1/e$.
→ Thus the test charge is effectively screened from charges outside the Debye sphere.

$T \geq T_c$: Colour screening in the QGP

[original idea: T.Matsui & H.Satz, Physics Letter B178 (1986) 416]

- *Now:* charge → colour charge
- QGP: a medium of unbound colour charges
  → *here* it is assumed to be at full thermal equilibrium!
- Quarks and gluons are **screened**, just as electric charges in a plasma experience Debye screening.
- Simple screened "Schwinger potential" form:

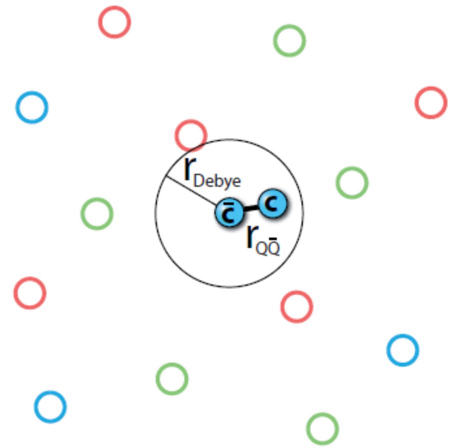
$$\boldsymbol{V(r,T) = \frac{\sigma}{\mu}(1 - e^{-\mu r}) - \frac{\alpha}{r} e^{-\mu r}}$$

with colour screening mass $\mu(\mathrm{T}) = \frac{1}{r_D(\mathrm{T})}$

and colour screening radius $r_D(T)$

→ For $\mu = 0$, vacuum form is recovered

→ For large r: $V(r,T) \rightarrow \frac{\sigma}{\mu}$ → *interesting implication!!!*



[Frederick Kramer, Dissertation (2012), Goethe-Universität]

$T \geq T_c$: Colour screening of charmonium

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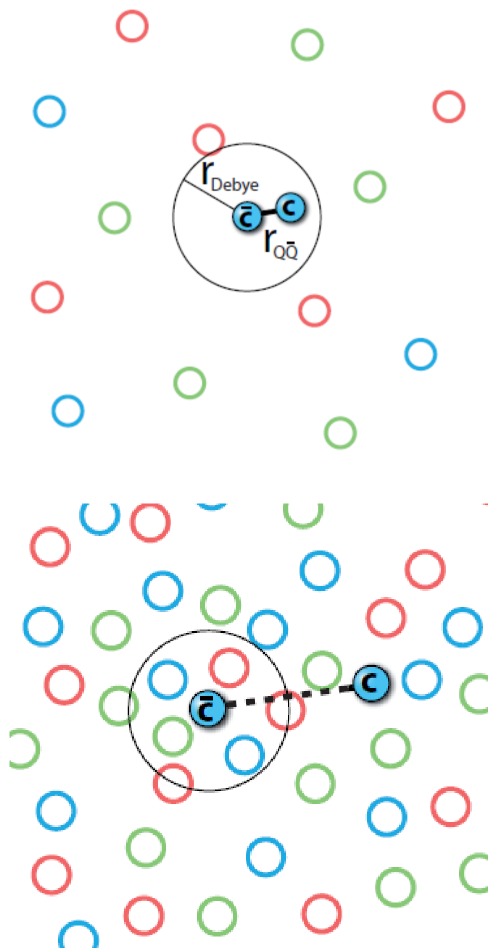
- Implant a charmonium into such a medium.

- By **increasing the temperature**
  → the medium increases in density
  → characteristic **colour screening radius r_D decreases**

- If $r_D \ll r_{Q\bar{Q}}$: the two heavy charm quarks cannot "see" each other and hence the bound state will "melt".

- A single charm quark sees many other quarks and antiquarks and therefore can move around freely (surrounded by a gluon polarised cloud).
  → **deconfinement**



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Sequential melting of charmonium in the QGP

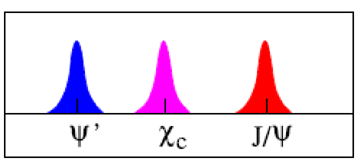
[original idea: T.Matsui & H.Satz, Physics Letter B178 (1986) 416]

- For each quarkonium state i the resulting Schrödinger equation provides the dissociation value r_i: $r > r_i$ bound state, $r \leq r_i$ dissociated.

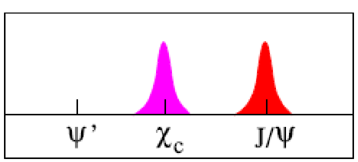
- If temperature dependence of the screening radius is known, the dissociation radius r_i then determines the corresponding dissociation temperature T_i

- Each charmonium state dissociates at a different temperature, depending on the binding energy/radius

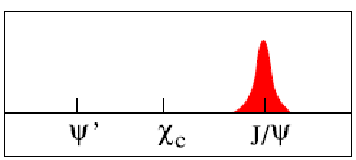
→ this could provide a **thermometer of the QGP**



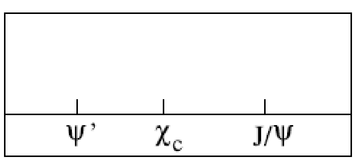
$T < T_c$



$T = 1.15\ T_c$



$T = 1.5\ T_c$



$T = 3\ T_c$

[Satz1]

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Mass (GeV)	3.10	3.53	3.68
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IV.) Theoretical models to calculate quarkonium dissociation points in a QGP

Two different approaches are used:

1) Solve the Schrödinger equation with a **temperature-dependent potential** $\boldsymbol{V(r,T)}$ with estimations from lattice QCD:
   → a) use Schwinger Model, b) use Lattice Potential Models

2) Calculate the quarkonium spectrum directly in **finite temperature lattice QCD**

1a) The Schwinger Model

[F. Karsch, M.-T. Mehr and H. Satz, Z. Phys. C 37 (1988) 617]

Schrödinger equation: $-\frac{1}{m}\{\nabla^2(r) + V(r,T)\}\psi_i(r) = (M_i - 2m)\psi_i(r)$

Screened "Schwinger potential":

$V(r,T) = \frac{\sigma}{\mu}(1 - e^{-\mu r}) - \frac{\alpha}{r}e^{-\mu r}$, $T > 0$, with screening mass: $\mu(T) = \frac{1}{r_D(T)}$

- Solve Schrödinger equation and determine bound-state energies $M_i(\mu)$
- Bound states disappears at some $\mu = \mu_i$
  → use $\mu(T) \cong 4T$ from first lattice estimates to determine T_i
- *Results for charmonium:*
  ψ' and χ_c become dissociated around $T = T_c$
  J/ψ survives up to about $T = 1.2T_c$

→ *$\mu(T)$ assumed in its high energy form, lattice studies today show different behaviour near T_c*
→ *Schwinger form is 1D the reality is 3D*

1b) Lattice Potential Models

[S. Digal, P. Petreczky and H. Satz, Phys. Lett. B 514 (2001) 57]

- Determine the internal energy $U(r,T)$ of a $\mathrm{Q\overline{Q}}$ pair at separation distance r from lattice results for the corresponding free energy $F(r,T)$.

- Use thermodynamic relation of the free energy:

$$\boldsymbol{F(T) = U(T) - TS(T)}$$

$$\boldsymbol{U(r,T) = F(r,T) - T\left(\frac{\partial F(r,T)}{\partial T}\right)_V}$$

- Assuming that the internal energy provides the temperature dependence of the heavy quark potential, use results from $N_f = 2$ lattice QCD and solve the Schrödinger equation with $\boldsymbol{V(r,T) = U(r,T)}$

- *<u>Results for charmonium</u>:*
  ψ' and χ_c become dissociated around $T = 1.1T_c$
  J/ψ survives up to about $T = 2T_c$

→ *J/ψ internal energy leads to much higher binding than the Schwinger Model*
→ *still some ambiguity if U or F is the right potential* → $aU + (1-a)F$, *with* $0 \leq a \leq 1$

Deeper look into Lattice Potential Models

- Screening can be evaluated more generally for a given free energy

$$F(r) \sim r^q$$

with $q = 1$ (Cornell potential), $q = -1$ (Coulomb term) in $d = 3$ dimensions

- Calculate screening separately for the free energy:

$$\boldsymbol{F(r,T) = F_s(r,T) + F_c(r,T) = \sigma r f_s(r,T) - \frac{\alpha}{r} f_c(r,T)}$$

- Use boundary conditions:

$$f_s(r,T) = f_c(r,T) = 1 \text{ for } T \to 0 \text{ (there is no medium)}$$
$$f_s(r,T) = f_c(r,T) = 1 \text{ for } r \to 0 \text{ (medium has no effect)}$$

Resulting free energy $F(r,T)$

[V. V. Dixit, Mod. Phys. Lett. A5 (1990) 227]

The resulting free energy obtained from Debye-Hückel theory:

$$\boldsymbol{F(r,T) = F_s(r,T) + F_c(r,T)}$$

- with Coulomb term:

$$F_c(r,T) = -\frac{\alpha}{r}\left[e^{-\mu r} + \mu r\right]$$

- and String term:

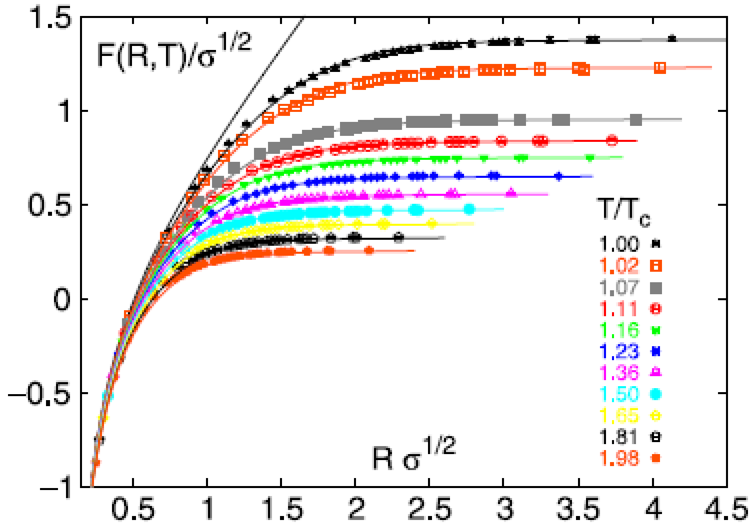
$$F_s(r,T) = -\frac{\sigma}{\mu}\left[\underbrace{\frac{\Gamma(1/4)}{2^{3/2}\Gamma(3/4)}} - \underbrace{\frac{\sqrt{\mu r}}{2^{3/2}\Gamma(3/4)}K_{1/4}\left[(\mu r)^2\right]}\right]$$

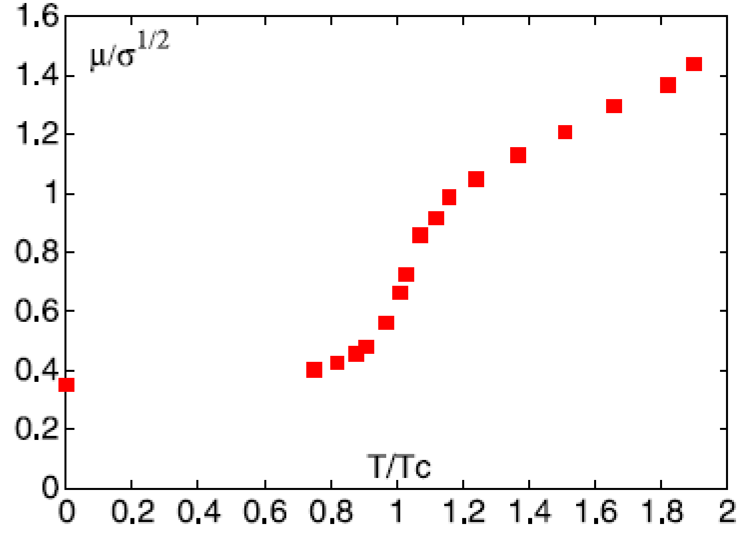
Large distance limit due to colour screening

Gaussian cut-off in $x = \mu r$
Bessel function:
$K_{1/4}(x^2) \sim \exp(-x^2)$

Screening fits to the $Q\bar{Q}$ free energy

[S. Digal et al., Eur. Phys. J. C 43 (2005) 71]





[Satz1]

- Screening fits to the $Q\bar{Q}$ free energy $F(r,T)$ for $T \geq T_c$ calculated in two-flavour QCD.
- Debye mass $\mu(T)$ (only parameter), determined from free energy $F(r,T)$ fits.
  → first increases rapidly, then perturbative form $\mu{\sim}T$

$Q\bar{Q}$ binding potential

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- From resulting free energies $F_c(r,T)$ and $F_s(r,T)$ get for the $Q\bar{Q}$ binding potential by using the thermodynamic relation $\mathrm{V(r,T)} = U(r,T) = F(r,T) - T\left(\frac{\partial F(r,T)}{\partial T}\right)_V$ and rewrite the potential:

$$V(r,T) = V(\infty,T) + \tilde{V}(r,T)$$

with

$$\tilde{V}(r\to\infty,T) = 0$$

and

$$V(r\to\infty,T) = c_1\frac{\sigma}{\mu} - \alpha\mu + T\frac{d\mu}{dT}\left[c_1\frac{\sigma}{\mu^2} + \alpha\right],$$

with $c_1 = \Gamma(1/4)\ 2^{3/2}\Gamma(3/4)$

- $V(\infty,T)$ describes the energy of the cloud of quarks and gluons in a Debye sphere around the heavy quark relative to the cloud without a heavy quark.

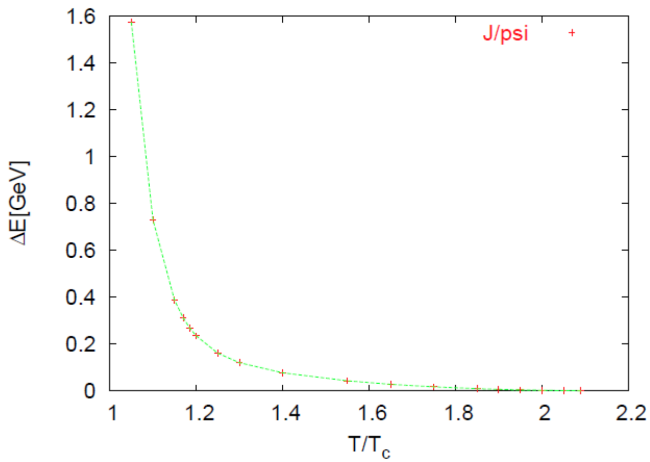
Full Schrödinger equation to determine $c\bar{c}$ dissociation temperature

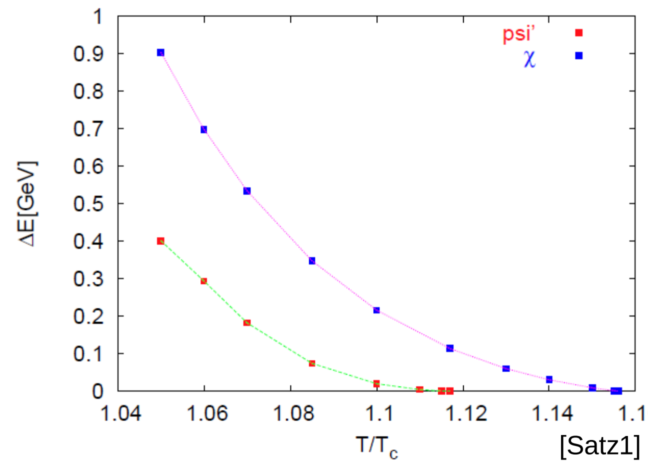
- Put the potential $\tilde{V}(r,T)$ into the Schrödinger equation:

$$\left\{\frac{1}{m_c}\nabla^2 - \tilde{V}(r,T)\right\}\Phi_i(r) = \Delta E_i(T)\Phi_i(r)$$

where $\Delta E_i(T) = V(\infty,T) - (M_i - 2m_c)$ is the binding energy of the charmonium state i.

- $E_i(T) = 0$ determines the dissociation temperature T_i for that state i.





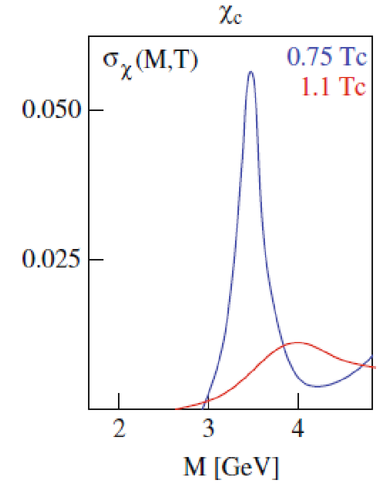
[Satz1]

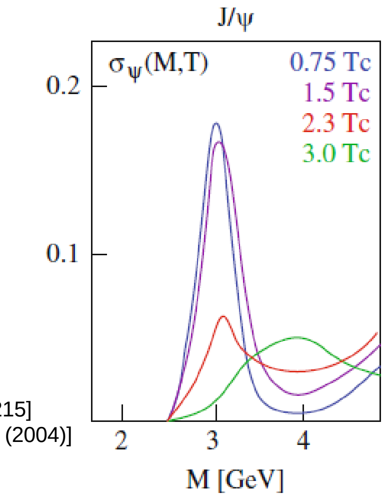
→ ψ' and χ_c become dissociated around $T = 1.1T_c$, J/ψ survives up to about $T = 2T_c$

2) Ideal case: Finite temperature lattice QCD

- Calculate $c\bar{c}$ spectral function $\sigma(\Omega, T)$ in the appropriate quantum channel as a function of the temperature T and the $c\bar{c}$ energy Ω.
- Bound states show up as resonances
- Simulate at different temperatures to find dissociation points
- *<u>Results</u>:*
  χ_c becomes dissociated $T \geq 1.1T_c$
  J/ψ persists up to $1.5 < T/T_c < 2.3$

→ *discretisation introduced by the lattice limits the resolution of the peak*
→ *very powerful computers needed*





[Satz1]

[T. Umeda et al., Int. J. Mod. Phys. A16 (2001) 2215]
[M. Asakawa and T. Hatsuda, Phys. Rev. Lett. 92 (2004)]
[S. Datta et al., Phys. Rev. D 69 (2004) 094507]
[H. Iida et al., hep-lat/0509129]

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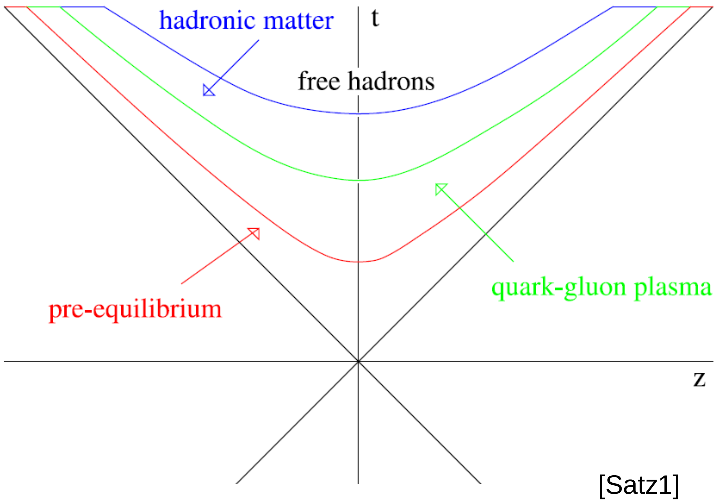
Time scales in nuclear collisions

- The original idea by T.Matsui & H.Satz (1986):

  1.) charmonium formation
  2.) QGP formation
  3.) sequential melting of charmonium in the QGP
  4.) decay of remaining charmonia and detection in particle detectors



[Satz1]

Sequential charmonium suppression

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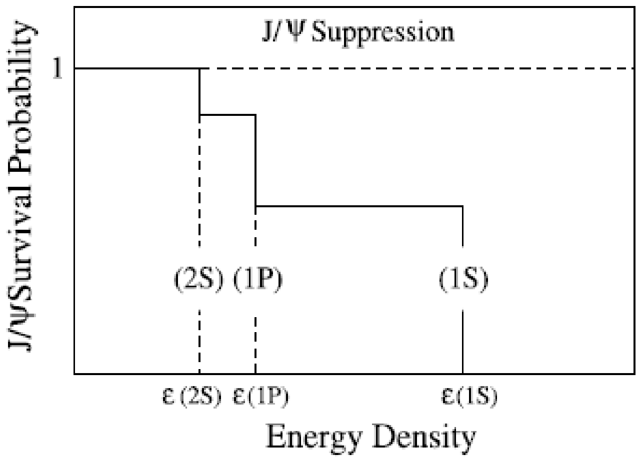
- J/ψ measured in hadron-hadron collisions are not all directly produced 1S charmonium states:

→**Feed-down:**
- 60% (direct J/ψ(1*S*))
- 40% (χ_c(1*P*) → J/ψ + anything)
- 10% (ψ'(2*S*) → J/ψ + anything)



[Satz1]

- With **increasing temperature or energy density**,

→first the J/ψ originating from ψ' decay
→then those from χ_c decay,
→then the directly produced J/ψ's will disappear

Slide in: What is the suppression factor R_{AA}?

[P. Braun-Munzinger, J. Stachel, arXiv:0901.2500v1]

- *Note:* charmonium suppression (or enhancement) is quantified by the **nuclear modification factor R_{AA}.**

$$R_{AA} = \frac{dN_{AA,\mathrm{J/\psi}}/dy}{N_{coll}\, dN_{pp,\mathrm{J/\psi}}/dy}$$

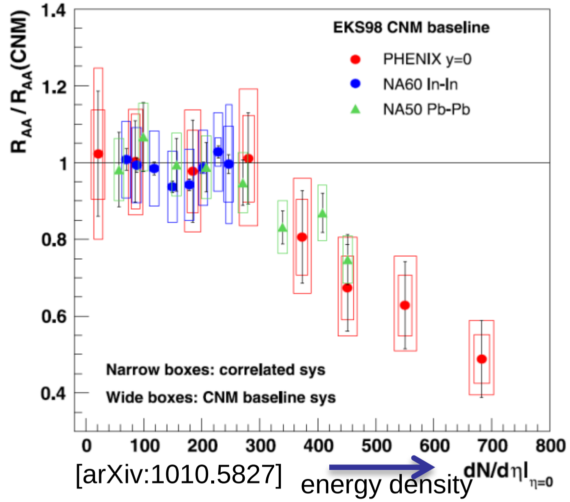
- It relates the charmonium yield in nucleus-nucleus (AA) collisions to that expected for superposition of independent nucleon-nucleon (pp) collisions.
- $dN_{AA,\mathrm{J/\psi}}/dy$ is the rapidity density of the J/ψ yield integrated over transverse momentum and N_{coll} the number of binary collisions for a given centrality class.
- (simple: $R_{AA} = \mathrm{medium/vacuum}$)

Experimental results from SPS, RHIC and LHC

[N. Brambilla et al., arXiv:1010.5827 (2011)]
[B. Abelev et al., Phys. Rev. Lett. 109, 072301 (2012)]
[ALICE, ATLAS, CMS, arXiv:1208.1615 (2012)]

- SPS and RHIC data ($\sqrt{s} = 17 - 200$ GeV):

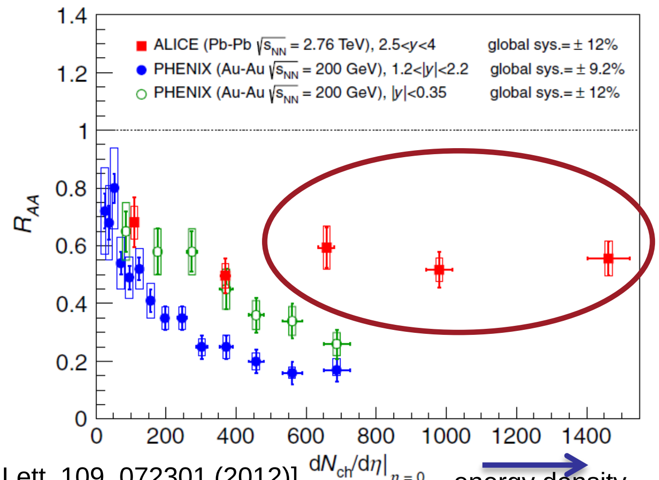
→ anomalous J/ψ suppression of about $40 - 50\%$ for central collisions
→ *explanation:* suppression of the excited states χ_c and ψ' and the survival of the directly produced J/ψ
→ "fingerprint" of a QGP



[arXiv:1010.5827] energy density

- LHC data ($\sqrt{s} = 2.76$ TeV):

→ **difference** between results from RHIC and LHC
→ **less suppression** when increasing the energy density



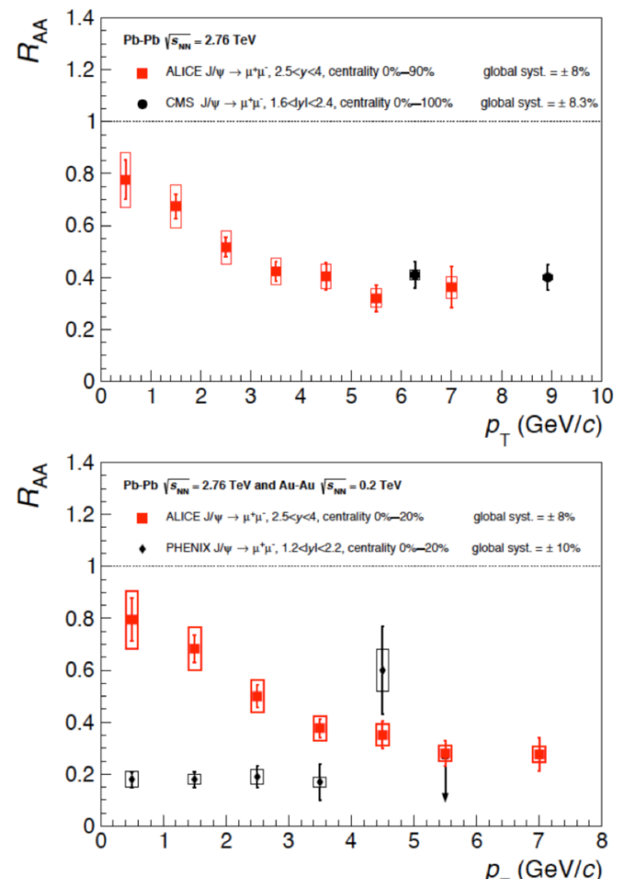
[B. Abelev et al., Phys. Rev. Lett. 109, 072301 (2012)] energy density

p_T dependence of J/ψ R_{AA}

[ALICE, arXiv:1311.0214, 2013]

- Clear p_T dependence of J/ψ suppression observed.
- At forward-rapidity the J/ψ R_{AA} exhibits a strong p_T dependence and decreases by a factor of 2 from low p_T to high p_T.
- This behavior exhibits a large difference with that observed by PHENIX at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$.
- This result suggests that a fraction of the J/ψ yield is produced via (re)combination of charm quarks

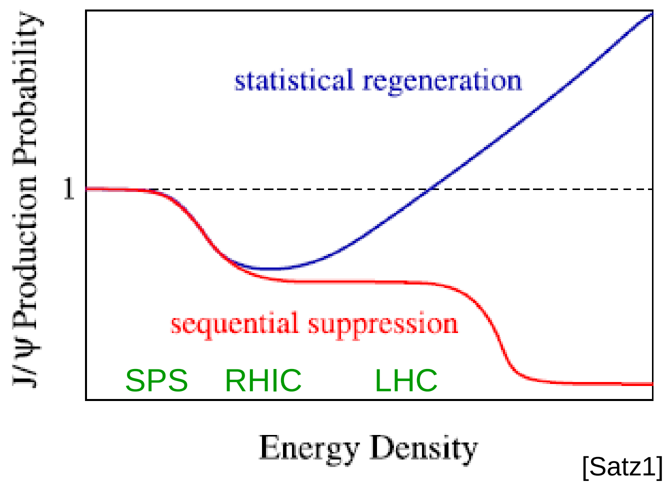
→ enhancement of J/ψ takes place dominantly at low p_T



[ALICE, arXiv:1311.0214, 2013]

Statistical regeneration of charmonium

[original idea: P. Braun-Munzinger & J. Stachel, Phys. Lett. B490, 196 (2000)]
[A. Andronic et al., J. Phys. G38, 124081 (2011)]



[Satz1]

- Medium produced in high energy nuclear collisions differs from deconfined state of matter studied in finite temperature QCD
  → it is not at full thermal equilibrium

- *Basic idea:* Nuclear collisions at very high energies initially produce more then thermally expected charm, leading to a new form of combinatorial charmonium production at hadronization.

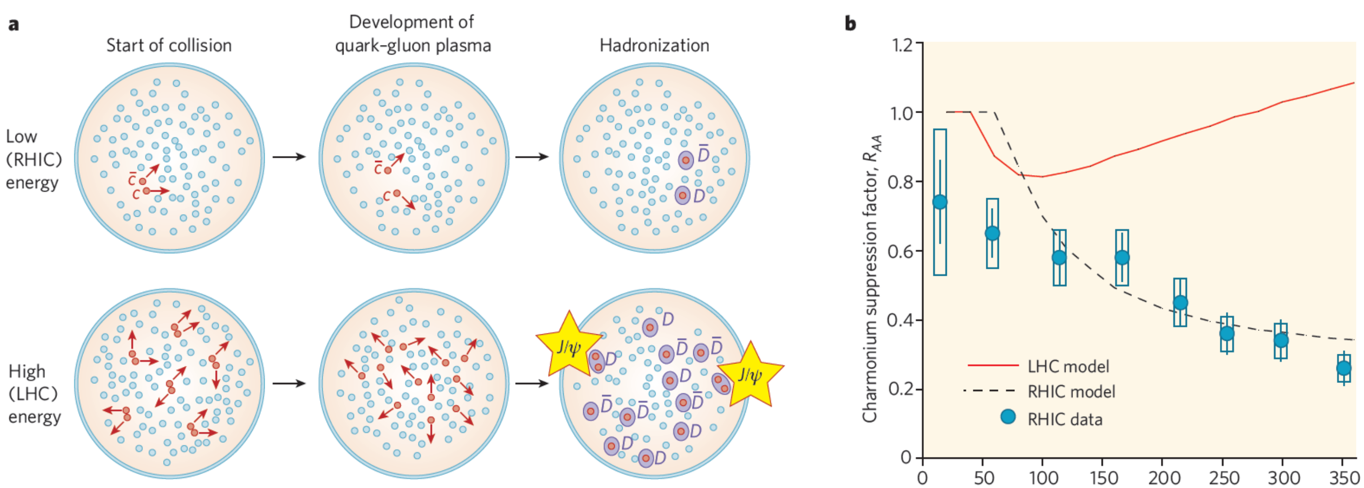
New model: statistical hadronization model

[original idea: P. Braun-Munzinger & J. Stachel, Phys. Lett. B490, 196 (2000)]
[A. Andronic et al., J. Phys. G38, 124081 (2011)]

At high LHC energies:

→ different time scales: $t_{collision} \ll \tau_{QGP}$ (at SPS and RHIC $t_{collision} \cong \tau_{QGP}$)
→ much more charm quark pairs are produced
→ all charm quarks are produced in hard collisions, $N_{c\bar{c}} = const.$
→ all charmonia are dissolved in QGP
→ no feed-down from higher charmonia
→ J/ψ production through statistical regeneration at the “cooler” base boundary

$$N_{J/\psi} \sim N_{c\bar{c}}{}^2$$



[P. Braun-Munzinger, J. Stachel, Nature Vol. 448, No. 7151 pp 269-312 (2007)]

Outline

I. Motivation and the main idea of probing the QGP with charmonium

II. Quarkonium properties

→ *charmonium*

III. Charmonium at different temperatures

→ *string breaking, recoupling, color screening*

IV. Theoretical models to describe charmonium dissociation

→ *Schwinger model, potential models, lattice QCD results*

V. Charmonium in heavy-ion collisions

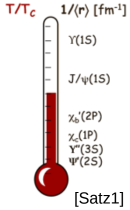
→ *suppression or enhancement*
→ *experimental results*
→ *statistical hadronization model*

VI. Summary and outlook

Summary & outlook

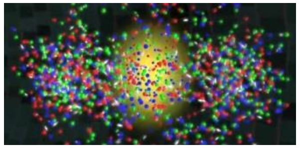
Consequences at high LHC energies:

→ It seems that charmonium could not any longer serve as a thermometer?



[Satz1]

→ **<u>BUT:</u>** The enhancement of J/ψ is a also a “fingerprint” of a QGP, in which charm quarks are effectively **deconfined.**



→ Have to turn to bottomium stages, where (re)formation through recombination appears unlikely (CMS Collaboration, arXiv:1105.4894 (2011))

Bibliography

[Satz1] H.Satz, *Extreme States of Matter in Strong Interaction Physics*, Springer 2012, Lecture Notes in Physics Volume 841

H.Satz et al., *The Physics of the Quark-Gluon Plasma*, Springer 2010, Lecture Notes in Physics Volume 785

T. Matsui and H. Satz, Physics Letter B178 (1986) 416

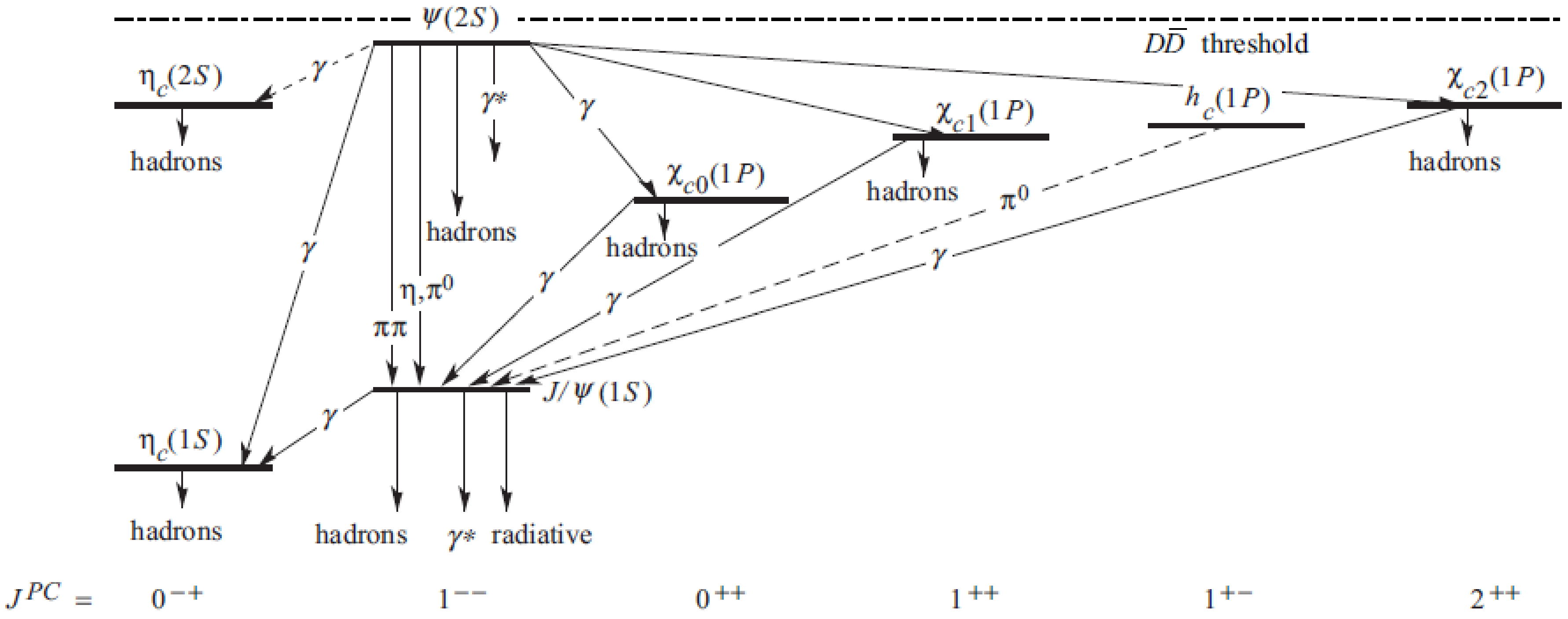
H.Satz, arXiv:hep-ph/0512217 (2005)

P. Braun-Munzinger, J. Stachel, arXiv:0901.2500 (2009)

P. Braun-Munzinger, *Lecture 3: the charmonium story*, 2013

Thank you for your attention!!!

Backup



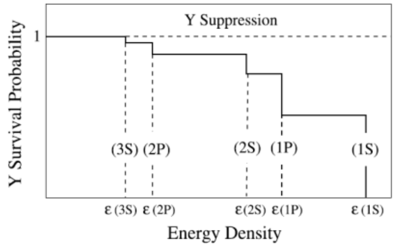
J/ψ decay channels -> e+e- (~6%) or -> μ+μ- (~6%)
Γ = 93 keV, τ~1/Γ ~10^-20 s

Also bottomium states can be usefully to probe the QGP

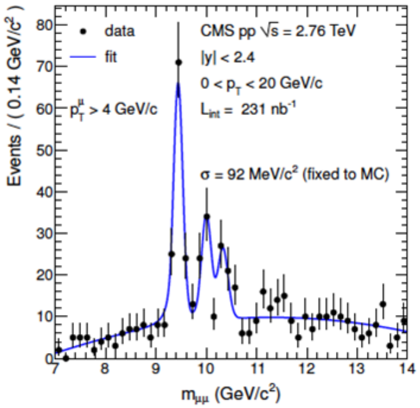
- $b\bar{b}$ i.e. Υ states have higher binding energies
→ useful at high LHC energies

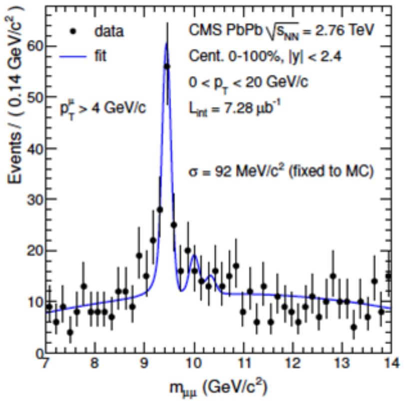
State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
exp. mass [GeV]	3.07	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔM [GeV]	0.02	−0.03	0.03	0.06	−0.06	−0.06	−0.08	−0.07
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

$\underbrace{J/\psi \quad \chi_c \quad \psi'}_{\text{charmonium}}$ $\underbrace{\Upsilon \quad \chi_b \quad \Upsilon' \quad \chi_b' \quad \Upsilon''}_{\text{bottomium}}$



[Satz1]





Bottomonium production in pp (up) and Pb−Pb (down) collisions

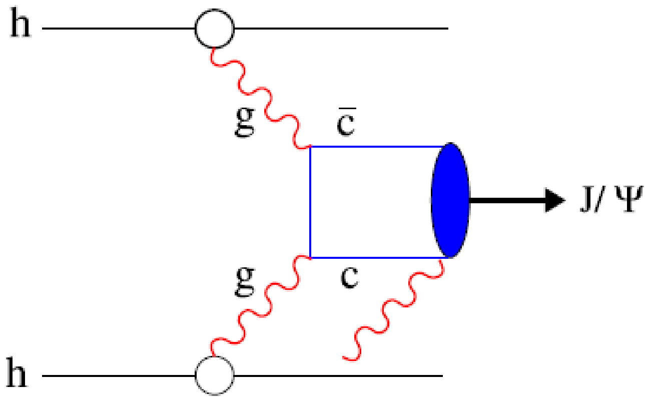
[Phys. Rev. Lett. 107, 052302 (2011)]

- CMS results for p-p compared to Pb-Pb collisions:
→ Υ(2S) and Υ(3S) suppression ~70%
→ Υ(1S) suppression ~ 40%

Charmonium production in hadronic collisions

- Quarkonium production in hadron–hadron collisions:

1.) production of a heavy quark pair by gluon fusion in early hard scattering processes
2.) colour neutralization to a colour singlet state (very small fraction)
3.) physical bound state, i.e. J/ψ



[Satz1]

- Different models to calculate production rate:
  * Color Singlet Model (CSM),
  * Color Evaporation Model (CEM)
  * NRQCD, includes Color Octet (CO) contributions

Outlook: Formation of charmonia by transport model

[X. Zhao and R. Rapp, Nucl. Phys. A859, 114 (2011)]
[Y.-P. Liu et al., Phys. Lett. B678, 72 (2009)]

- Spectral properties of charmonia are constrained by correlators from thermal lattice QCD and subsequently implemented into a Boltzmann equation accounting for both suppression and regeneration reactions.

- Cold nuclear matter effects (shadowing, absorption)

- Suppression in hot medium

- Feed down from B mesons

- J/ψ from regeneration (≥ 50%)