Quarkonium Binding and Dissociation:
The Spectral Analysis of the QGP

Helmut Satz

Universität Bielefeld, Germany

Hard Probe
Cafe

CERN, Geneva 1994
LBL, Berkeley 1994
ECT*, Trento 1995
INT, Seattle 1996
CFIF, Lisbon 1997
INT, Seattle 1998
JYFL, Jyväskylä 1999
BNL, New York 2000
NBI, Copenhagen 2001

Hard Probes 2006

Asilomar/California

Statistical QCD: $\exists$ deconfinement transition, QGP

How to probe QGP?

- e-m signals (real or virtual photons)
- quarkonia ($Q\bar{Q}$ pairs)
- jets (fast partons)

Ultimate aim: *ab initio* calculation of in-medium behaviour of probe

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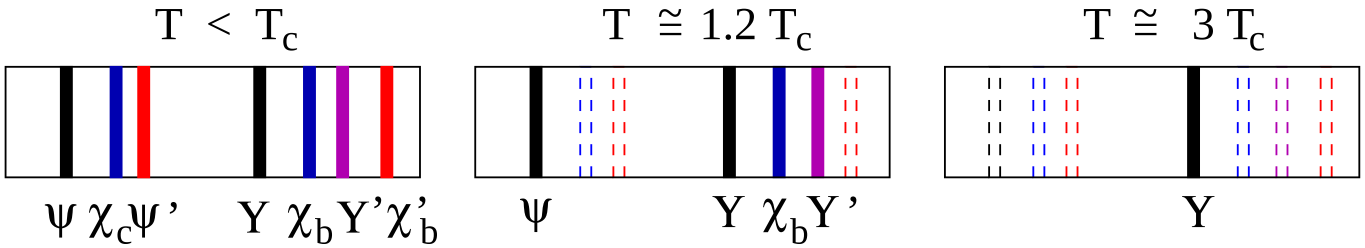
⇒ spectral analysis of quarkonia in QGP ⇐

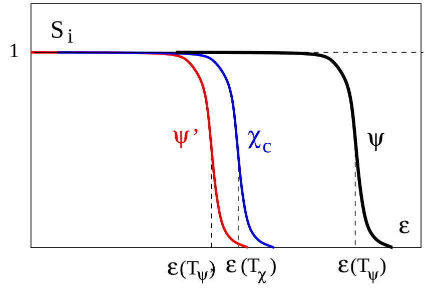
Theoretical basis :

- QGP consists of deconfined colour charges, hence
  $\exists$ colour charge screening for $Q\bar{Q}$ probe
- screening radius $r_D(T)$ decreases with temperature T
- when $r_D(T)$ falls below binding radius r_i of $Q\bar{Q}$ state i,
  Q and $\bar{Q}$ cannot bind, quarkonium i cannot exist
- quarkonium dissociation points T_i, through $r_D(T_i) = r_i$,
  specify temperature of QGP



Experimental basis:

- measure quarkonium production in AA collisions as function of collision energy, centrality, A
- determine onset of (anomalous) suppression for the different quarkonium states
- correlate experimental onset points to thermodynamic variables (temperature, energy density)
- compare thresholds in survival probabilities S_i of states i to QCD predictions



⇒ direct comparison:

experimental results vs. quantitative QCD predictions

In-Medium Behaviour of Quarkonia: Theory

Quarkonia:
heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV) or beauty ($m_b \simeq 4.7$ GeV)
stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks ⇒ quarkonium spectroscopy via non-relativistic potential theory

Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

confining ("Cornell") potential $V(r) = \sigma\ r - \frac{\alpha}{r}$

string tension $\sigma \simeq 0.2$ GeV^2, gauge coupling $\alpha \simeq \pi/12$

⇒ quarkonium masses M_i and radii r_i

$\Rightarrow$ **good account of quarkonium spectroscopy**

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	**3.10**	**3.53**	**3.68**	**9.46**	**9.99**	**10.02**	**10.26**	**10.36**
ΔE [GeV]	**0.64**	**0.20**	**0.05**	**1.10**	**0.67**	**0.54**	**0.31**	**0.20**
ΔM [GeV]	**0.02**	**-0.03**	**0.03**	**0.06**	**-0.06**	**-0.06**	**-0.08**	**-0.07**
radius [fm]	**0.25**	**0.36**	**0.45**	**0.14**	**0.22**	**0.28**	**0.34**	**0.39**

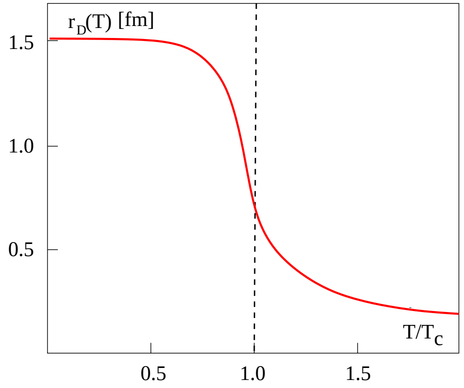
NB: error in mass determination ΔM is less than 1 %

Ground states:

tighly bound $\Delta E = 2M_{D,B} - M_0 \gg \Lambda_{QCD}$, **small** $r_0 \ll r_h$

What happens to binding in QGP?

Colour screening ⇒ binding becomes weaker and of shorter range



when force range/screening radius become less than binding radius, Q and $\bar{Q}$ cannot "see" each other ⇒ quarkonium dissociates

⇒ quarkonium dissociation points determine temperature, energy density of medium

How to calculate quarkonium dissociation temperatures?

- Model heavy quark potential $V(r,T)$, solve Schrödinger equation:

  Karsch et al. 1988
  Digal et al. 2001

  $$T_{J/\psi} \gtrsim T_c,\ T_\chi \ \&\ T_{\psi'} \lesssim T_c$$

- **Determine heavy quark potential $V(r,T)$ in finite T lattice QCD, solve Schrödinger equation**

Shuryak & Zahed 2004
Wong 2004, 2005
Alberico et al. 2005
Digal et al. 2005
Mocsy & Petreczky 2005, 2006

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

- **Calculate quarkonium spectrum in finite T lattice QCD**

charmonia quenched:

Umeda et al. 2001
Asakawa & Hatsuda 2004
Datta et al. 2004
Iida et al. 2005

charmonia unquenched:

Morrin et al. 2005

bottomonia quenched

Datta et al. 2005
Velytsky et a. 2006

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	> 2.0	< 1.1	**?**

$T_\Upsilon \gtrsim 2\ T_c$, $T_{\chi_b} \lesssim 1.15\ T_c$ [?]

$\Rightarrow J/\psi$, Υ **survive up to** $T \geq 2\ T_c \Rightarrow \epsilon_{J/\psi} \geq 25$ **GeV/fm**^{3}

χ_c **and** ψ' **melt near** $T_c \Rightarrow \epsilon_{\psi',\chi} \simeq 0.5 - 2$ **GeV/fm**^{3}

Caveat: survival, but modifications?
radii, widths as $f(T)$**?**
compare lattice & potential studies **Mocsy & Petreczky 2006**

What were the new theory inputs?

- **colour singlet free energy in lattice QCD**
- **free → internal energy in potential models**
- **direct finite** T **lattice calculations for quarkonia**

What does this imply for quarkonium production as QGP probe in nuclear collisions?

In-Medium Behaviour of Quarkonia: Phenomenology

J/ψ production in AA collisions:

- **observed modifications due to**
  - **cold nuclear matter of target and projectile**
  - **secondary medium produced in collision**
- **observed J/ψ production contains**
  - **directly produced $1S$ states**
  - **decay products from χ_c(1P) and ψ'(2S) production**

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Operational solution:

- identify effects due to cold nuclear matter by
  - pA or dA studies
  - Glauber analysis in terms of σ^i_{abs} for $i = J/\psi$, χ_c, ψ'

    includes initial & final state effects: shadowing, parton energy loss,
    pre-resonance/resonance absorption

- **for AA collisions, use σ^i_{abs} and Glauber analysis to**
  - **obtain prediction for normal J/ψ suppression**
  - **identify anomalous J/ψ suppression**
  - **parametrize through survival probability**

$$S_i = \frac{(dN_i/dy)_{\rm exp}}{(dN_i/dy)_{\rm Glauber}} \quad \text{for quarkonium state } i$$

- **assume J/ψ origin in pA and AA same as in pp:**
  - **60 % direct $1S$, 30 % decay of $1P$, 10 % decay of $2S$**
  - **NB: could this be checked experimentally?**

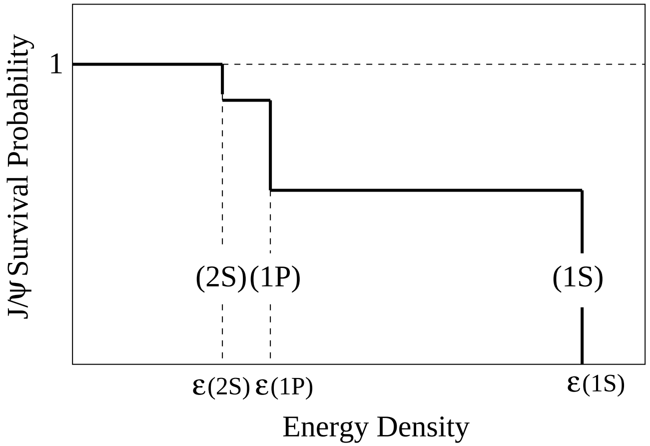
If AA collisions produce a fully equilibrated QGP:

$\Rightarrow$ **sequential suppression of J/ψ, Υ** $\Leftarrow$

$\Rightarrow$ **thresholds predicted by statistical QCD** $\Leftarrow$

Sequential J/ψ suppression:

Karsch & HS 1991
Gupta & HS 1992
Digal et al. 2001
Karsch, Kharzeev & HS 2005



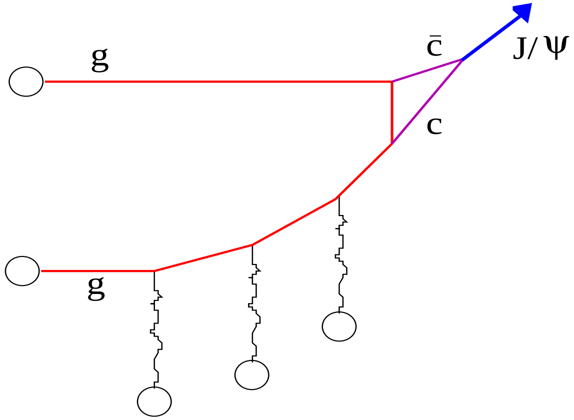
If $J/\psi(1S)$ survives up to $2\ T_c \sim \epsilon \geq 25$ GeV/fm^3:

- all anomalous suppression observed at SPS and RHIC due to dissociation of excited states χ_c and ψ'
- onset of anomalous suppression at $\epsilon(T_c) \simeq 1$ GeV/fm^3
- J/ψ survival probability for central $Au-Au$ collisions at RHIC same as for central $Pb-Pb$ collisions at SPS

Cross-check: J/ψ transverse momentum behaviour

- **initial state parton scattering causes p_T broadening of charmonia; random walk in pA collisions →**

$$\langle p_T^2 \rangle_{pA} = \langle p_T^2 \rangle_{pp} + N_c^A \delta_0$$



N_c^A **number of collisions**

before parton fusion to $c\bar{c}$

(Glauber, include σ_{abs})

δ_0 **kick per collision, determined in pA**

- **in AA collisions, initial state parton scatterings in target & projectile; random walk →**

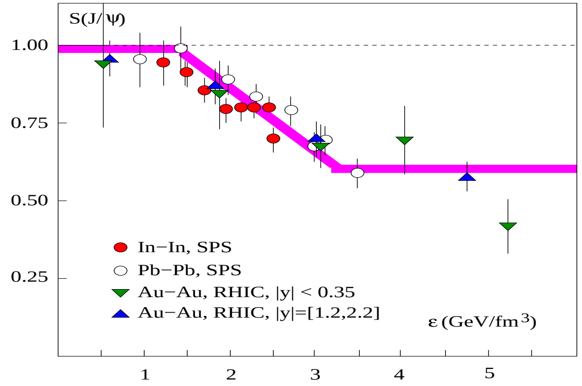
$$\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + N_c^{AA} \delta_0$$

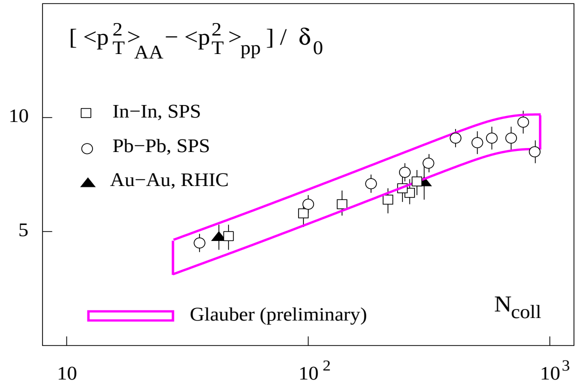
N_c^{AA} **total number of collisions in target and projectile before $c\bar{c}$ fusion (again Glauber, include σ_{abs})**

- **If observed J/ψ in central AA collisions undisturbed $J/\psi(1S)$, centrality dependence of p_T broadening fully predicted by initial state parton scattering**

Karsch, Kharzeev, HS 2005
Lourenço, Thews, HS - in progress

Expected Behaviour for SPS and RHIC Experiments:





Conclude: Present results are compatible with equilibrium QGP formation

NB: this is NEW and largely due to the following TH & EX changes

- **finite T lattice QCD suggests (caveat: width) direct J/ψ suppression at energy densities beyond RHIC range; previous TH onset values much lower**
- **SPS $In-In$ data suggest onset of anomalous suppression at $\epsilon \simeq 1$ GeV/fm^3; previous EX onset values much higher, $2-2.5$ GeV/fm^3**
- **within statistics, no further drop of survival rate below 50 - 60 %; second drop in SPS $Pb-Pb$ no longer claimed**

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But: $\exists$ alternative account of results?

Crucial aspect of QGP J/ψ suppression:

dissociated charmonia never "recreated" in hadronizing QGP, since thermal $c/\bar{c}$ abundance negligible

what happens for non-thermal $c/\bar{c}$ production?

Regeneration Scenario

Basic Input: Braun-Munzinger & Stachel 2001; Thews et al. 2001; Grandchamps and Rapp 2002

- $c\bar{c}$ production is hard process $\sim N_{coll}$, in contrast to u, d, s (soft hadron) production $\sim N_{part}$

  [breaks down at high energy, parton saturation]

- increase collision energy → **increase charm content** in produced system [check RHIC vs. SPS, D/h vs. thermal?]

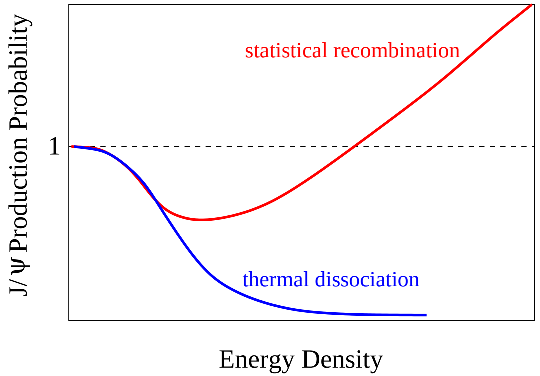
- c or $\bar{c}$ from a given nucleon-nucleon collision can at hadronization bind with charm constituents from different collisions (“off-diagonal” pairs)

  ∃ new **exogamous** charmonium production mechanism; c and $\bar{c}$ in such charmonia have different parents, in contrast to **introgamous** production in pp

High energy ⇒ **enhanced J/ψ production** in AA re pp

When does this set in?

Present work assumes



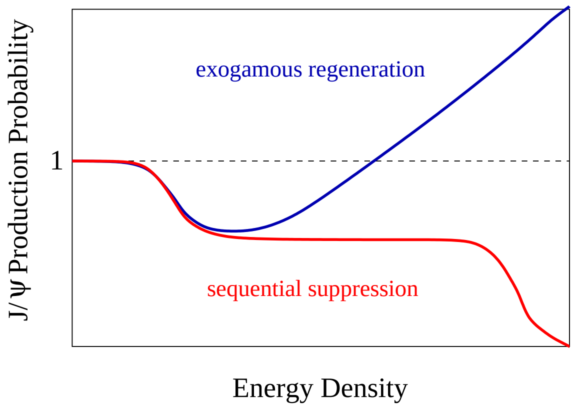
- direct J/ψ production strongly suppressed for $\epsilon \geq 3$ GeV/fm^3 (in contrast to lattice results)
- statistical combination of all $c\bar{c}$ (with or without wave function correction)
- at RHIC energy, new exogamous J/ψ just compensate drop of direct introgamous rate; at LHC, off-diagonal production → J/ψ enhancement

How to distinguish between

– sequential suppression in equilibrium QGP and

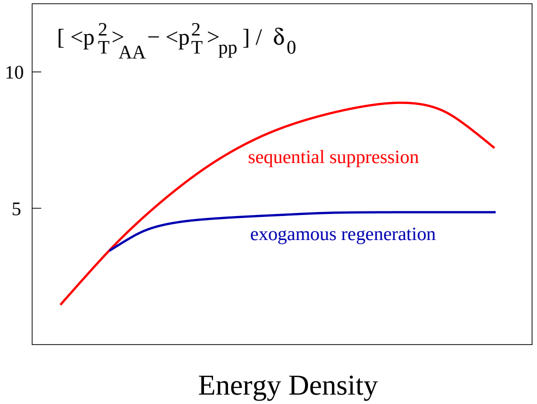
– J/ψ regeneration by charm increase?

- overall J/ψ survival: suppression vs. enhancement at high energy densities



- p_T behaviour: initial state parton scattering vs. final state charm production

  Karsch, Kharzeev & HS 2005
  Mangano & Thews 2005



- in general, regeneration → quarkonium momentum distributions $\sim$ convolution of open charm momenta

Mangano & Thews 2005

Conclusions

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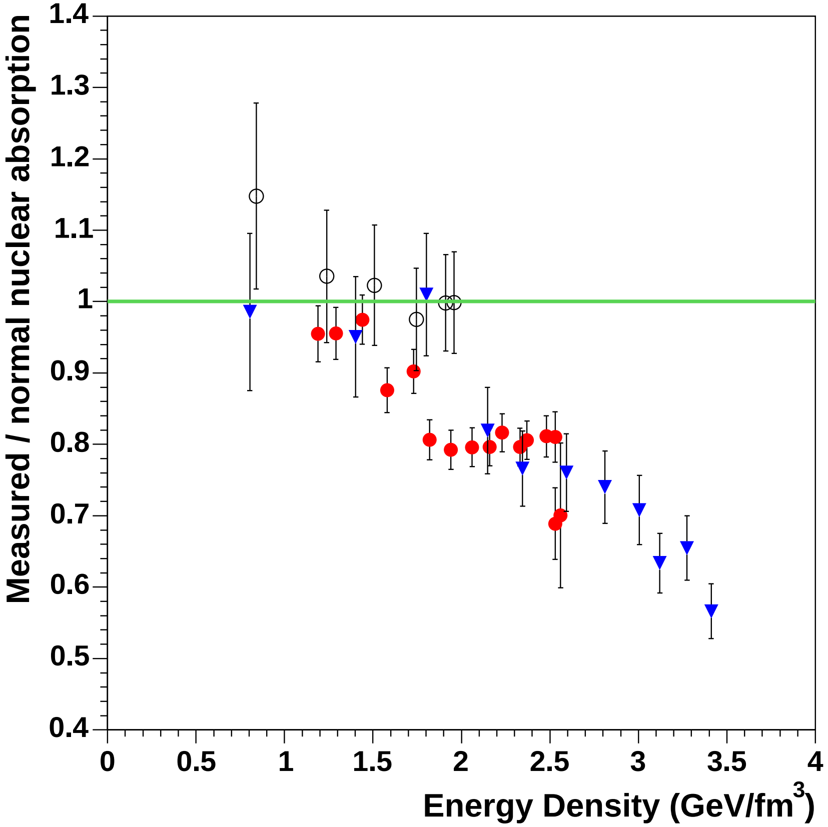
- if nuclear collisions produce an equilibrium QGP, the study of quarkonium production provides a direct way to connect experiment and statistical QCD
- for a QGP with increasing charm content, off-diagonal quarkonium formation by statistical combination may destroy this connection


Measured / normal nuclear absorption
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
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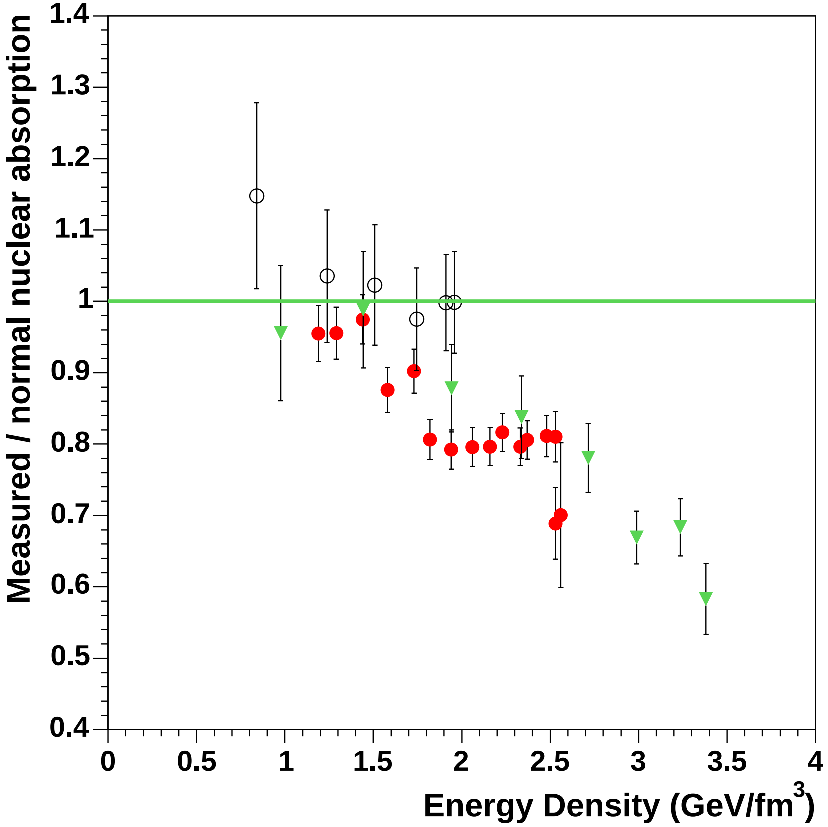
1
1.5
2
2.5
3
3.5
4
Energy Density (GeV/fm^3)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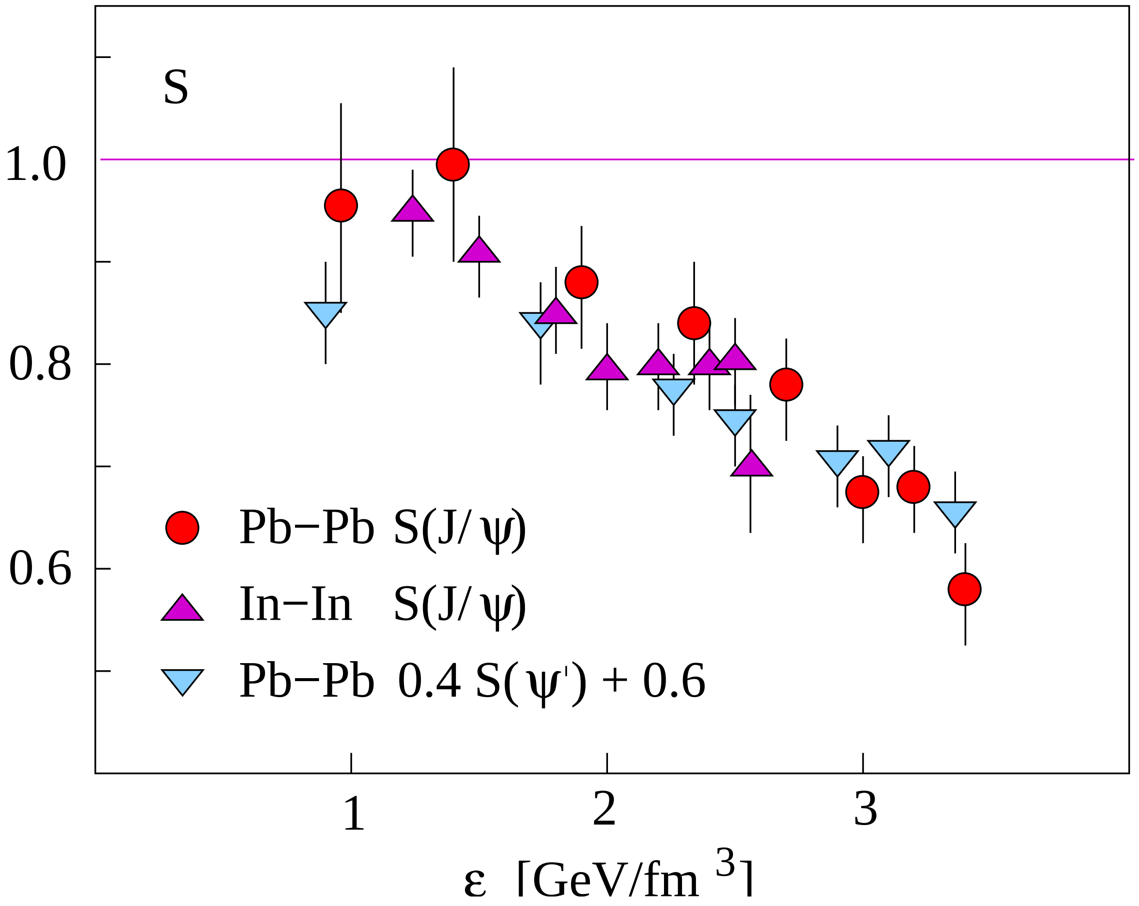
S
1.0
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0.6
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2
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ε [GeV/fm 3]
● Pb−Pb S(J/ψ)
▲ In−In S(J/ψ)
▼ Pb−Pb 0.4 S(ψ') + 0.6