Vue d'ensemble sur les quarkonia: effets dus au plasma

Discussion

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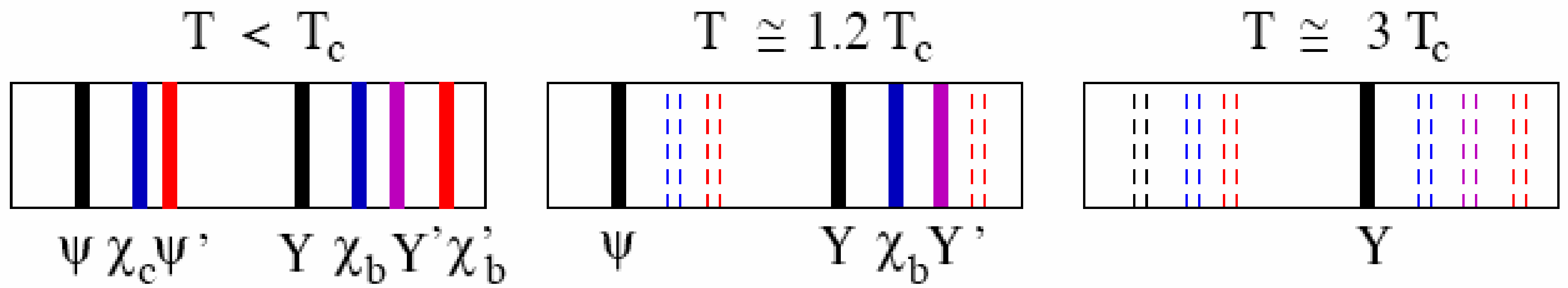
Journées QGP-France, Étretat, 3-5 juillet 2006

Introduction (1)

- tout est parti d'une idée *simple* (Matsui-Satz, 1986)
- retravaillée sans cesse depuis
  - résultats expérimentaux (NA38/50/60, PHENIX)
  - calculs sur réseaux
    - 1 Mflops - 0,6 Tflops - 10 Tflops
    - Maximum Entropy Method
  - accord réseaux / potentiels : F = U - TS
- qualitativement
  - disparition successive des quarkonia lourds quand T croît, suivant taille et/ou énergie de liaison
  - **thermomètre** de la matière dense



Introduction (2)

- aujourd'hui
- nombreuses présentations
  - résultats expérimentaux existants
  - possibilités ouvertes par de plus grandes énergies au LHC
  - exposés théoriques
- discussions après chaque exposé
- discussion précédente sur les effets de matière nucléaire froide
- autour de quelles questions pourrions-nous aborder cette discussion sur les effets dus au plasma ?

Questions

- idée *simple*, modèles trop *simplistes* ?
  - interpellation de H. Satz par B. Müller à HP06
- selon B. Müller
  - ‘Do we have a coherent theoretical framework for heavy quarkonia? NO’
  - ‘No theoretical framework exists, in which to treat medium modifications to (Q-Qbar) spectral function, (in-)elastic dissociation by the medium, recombination in a unified manner’

Questions

- production
  - 'Do we understand the production mechanism of J/Psi well enough to extract the information on QGP?'
    (Qiu HP06)
  - Factorization of NRQCD model clearly fails for low pT, might work for large pT
- dissociation
  - gluonique en couplage fort
  - par écrantage en couplage faible
- transport, recombinaison, …
- l'origine du J/Psi est-elle la même en p+A et A+A qu'en p+p, à savoir 60% directe, 40% de résonances de plus grande masse ?

Questions

- Incertitudes
  - bonne utilisation par théoriciens ?
  - besoin d'incertitudes théoriques
- SPS
  - NA50 : que reste-t-il à publier ?
  - résultats de NA50 et NA60 en accord ?
  - p+A à 158 GeV/c : pour quand ?
- RHIC
  - Résultats 'définitifs' de PHENIX : pour quand ?
  - J/Psi : suppression anormale
    modèles : nombre en augmentation (anormale)
    comment faire le tri ?
- Quelle complémentarité entre RHIC et LHC ?
  - RHIC : longs runs, RHIC II
  - LHC : un mois par an
- Au LHC, comment se comparent ALICE, CMS et ATLAS ?

Questions

- Complémentarité avec autres sondes du plasma ?
  - jets
  - photons
- Quelques remarques
  - La connexion entre théorie et expérience ne peut pas être plus forte que son point le plus faible (Wiedemann, HP06)
    - quel est-il pour les quarkonia ?
  - Les modèles doivent s'attacher à reproduire l'ensemble des résultats
    - Psi' en S+U (NA50)
    - distributions en rapidité et impulsion transverse
  - 'Thou shalt not publish only results for unphysical results' (Cacciari, journées 'quarkonia', Orsay, avril 2005)
    - ne pas publier que 'rapport à la production attendue' en fonction de 'densité d'énergie'

Documents supplémentaires

- Conclusions
- NLO (+NLL) QCD does a good job in predicting real and unbiased bottom (and charm) hadroproduction data.
- Part of the success is due to the possibility of controlling, from the theory side, the whole chain from parton to hadron, carefully matching perturbative and non-perturbative contributions.
- Experiments should avoid publishing only deconvoluted/extrapolated quantities, which might include strong biases from MonteCarlo:
- “Thou shalt not publish only results for unphysical objects”

Matsui-JPsi20Satz70-T25

Hard look at signature criteria

- It should be a direct consequence of some specific (expected) property of the plasma.
- It should be possible to detect the effect experimentally. (feasibility)
- No alternative explanation for the effect. (uniqueness condition)

Matsui-JPsi20Satz70-T26

Why we thought J/ψ is an ideal probe?

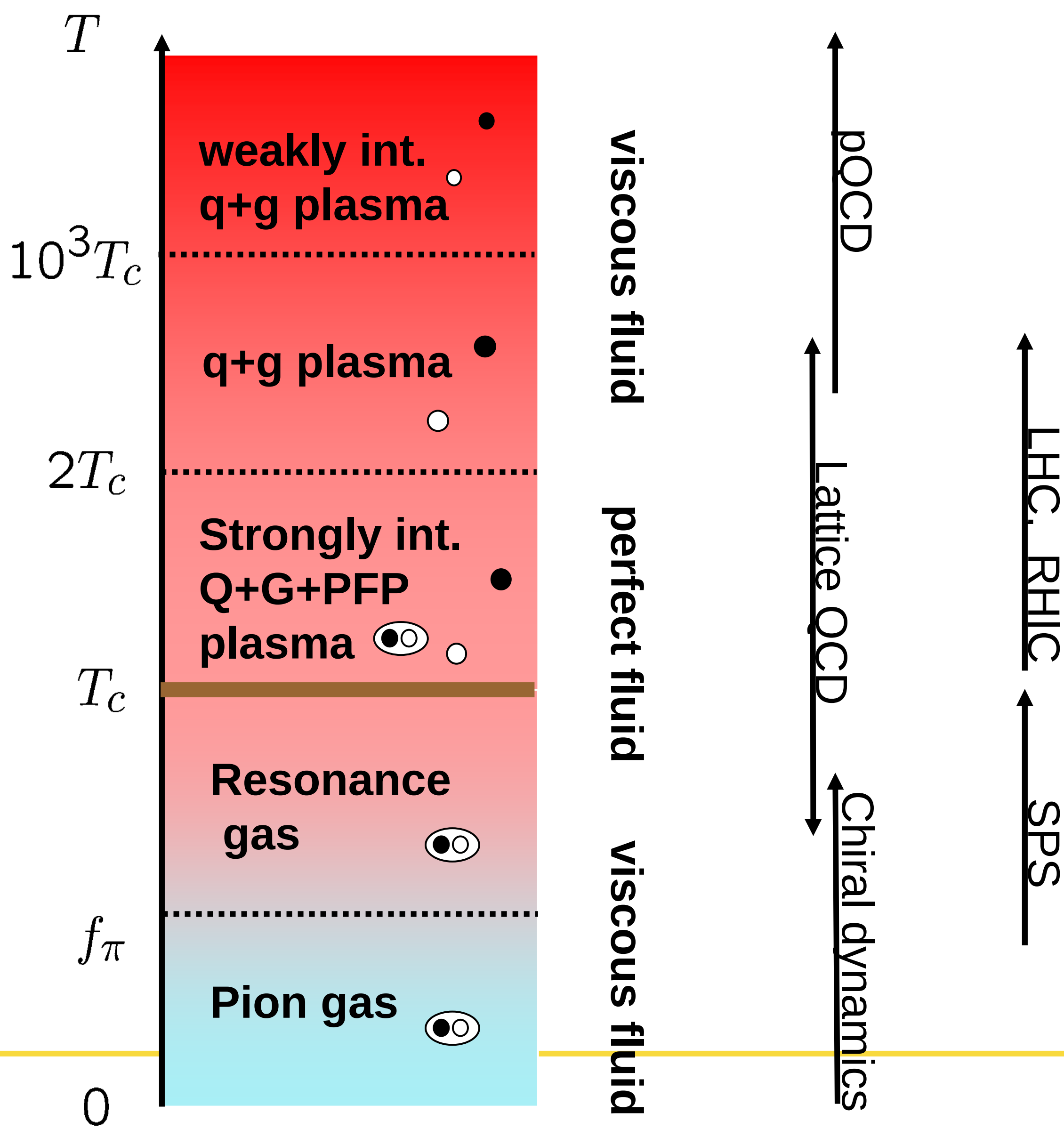
1. It's a simple system.
2. It's hard to create it.
3. It's hard to destroy it.
4. It's easy to see it.

Hatsuda-JPsi20Satz70-T2

After 20 years,
we are now able to study charmonia at finite T directly from lattice QCD

- Ccomputer power : 1 Mflops(VAX) → ··· → 0.6Tflops (CP-PACS) → ··· → 10 Tflops (QCDOC)
- New data analysis : e.g. Maximum Entropy Method

Hatsuda-JPsi20Satz70-T24



A possible "picture" of hot QCD

Zajc-JPsi20Satz70-T4

Signal	RHIC Exp. (Au+Au)	RHIC I (>2008)	RHIC II	LHC ALICE$^+$
$J/\psi \rightarrow e^+e^-$	PHENIX	3,300	45,000	9,500
$J/\psi \rightarrow \mu^+\mu^-$		29,000	395,000	740,000
$\Upsilon\Upsilon \rightarrow e^+e^-$	STAR	830	11,200	2,600
$\Upsilon\ \Upsilon \rightarrow \mu^+\mu^-$	PHENIX	80	1,040	8,400

Zajc-JPsi20Satz70-T24

No Suppression of Models…

Zajc-JPsi20Satz70-T31

RHIC-II - Heavy Flavor Yields

Signal	RHIC Exp.	Obtained	RHIC I (>2008)	RHIC II	LHC/ALICE+
$J/\psi \rightarrow e^+e^-$	PHENIX	~800	3,300	45,000	9,500
$J/\psi \rightarrow \mu^+\mu^-$		~7000	29,000	395,000	740,000
$\Upsilon \rightarrow e^+e^-$	STAR	-	830	11,200	2,600
$\Upsilon \rightarrow \mu^+\mu^-$	PHENIX	-	80	1,040	8,400
$B \rightarrow J/\psi \rightarrow e^+e^-$	PHENIX	-	40	570	N/A
$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$		-	420	5,700	N/A
$\chi_c \rightarrow e^+e^- \gamma$	PHENIX	-	220	2,900*	N/A
$\chi_c \rightarrow \mu^+\mu^- \gamma$		-	8,600	117,000*	N/A
$D \rightarrow K\pi$	STAR	$\sim 0.4 \times 10^6$ (S/B~1/600)	30,000**	30,000**	8000

Heavy quark potential

- The internal energy U can be obtained from the free energy F by the ordinary thermodynamics relation:

  - $F = U - TS$

- where

  - $S = -\partial F/\partial T$

$$U = -T^2 \frac{\partial(F/T)}{\partial T}$$

- F and U coincide at T=0

What is the mechanism of dissociation?

In cold matter, dissociation rate is relatively small due to the softness of gluon distributions in confined matter, but it is large, $O(1\ \mathrm{fm}^{-1})$, in hot QCD matter

DK & H. Satz '94

Dissociation mechanism - gluo-effect

E.Shuryak '78
G.Bhanot, M.Peskin '79

dominates if $\dfrac{\epsilon}{T} \gg 1$ (strong coupling regime)

Screening dominates if $\dfrac{\epsilon}{T} \ll 1$ (weak coupling)

Kharzeev-JPsi20Satz70-T17

J/Ψ above Tc: alive and well?

Summary

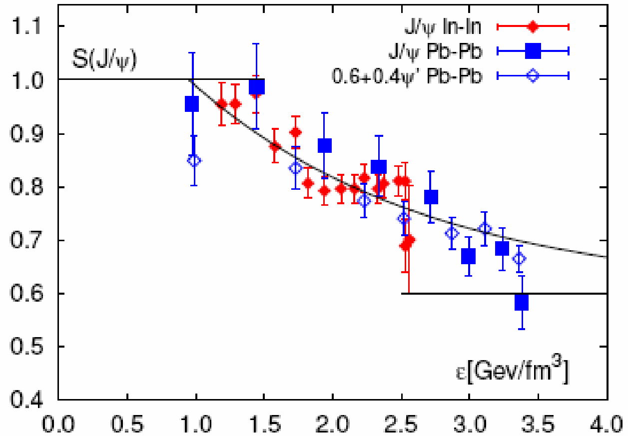
1. 20 years after, the problem of J/ψ behavior in quark-gluon plasma remains in the focus of attention

2. This problem may well keep the key to understanding the strongly coupled plasma, much like the surprising properties of J/ψ were central to understanding QCD

More work has to be done…

EoS and Charmonium Suppression

F. Karsch, D. Kharzeev, H. Satz, hep-ph/0512239.



charmonium yield (SPS)

- from centrality (or b) to energy density (ϵ) using Bjorken formula

- data consistent with no direct J/ψ suppression; only missing feed-down from χ_c
- Where does direct J/ψ suppression set in? $\Rightarrow$ HIC
- Where should direct J/ψ suppression set in? $\Rightarrow$ LGT
- relate T_{diss}/T_c to energy density using lattice EoS

Can we reach a consistent (LGT vs. HIC) picture for heavy quark bound state properties at high temperature ?

$\Rightarrow J/\psi$, 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 $\rightarrow$ 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?

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

But: $\exists$ alternative account of results?

Crucial aspect of QGP J/ψ suppression:

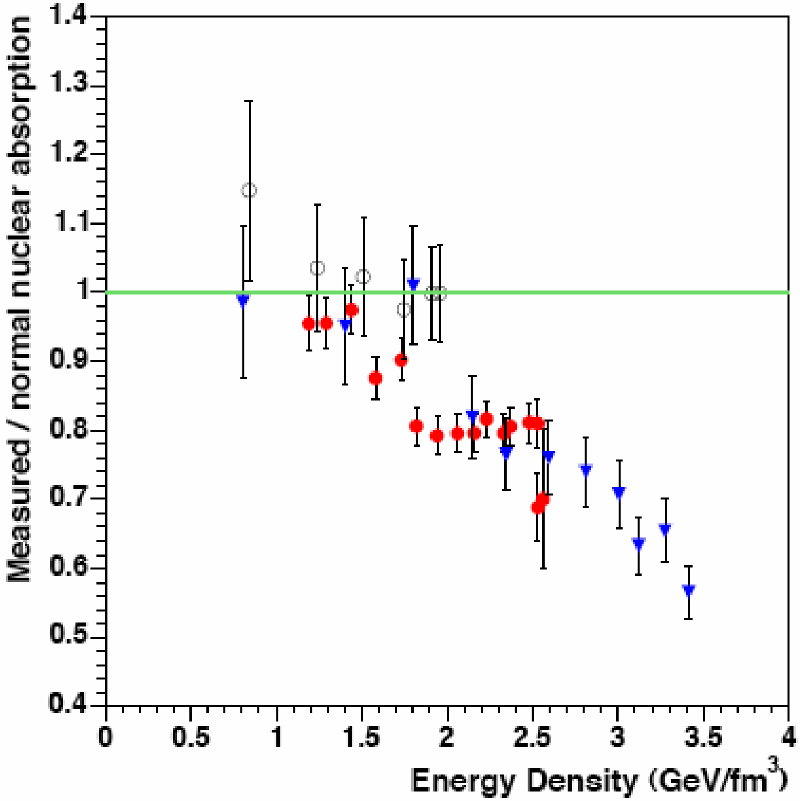
dissociated charmonia never “recreated” in hadronizing QGP, since thermal $c/\bar{c}$ abundance negligible

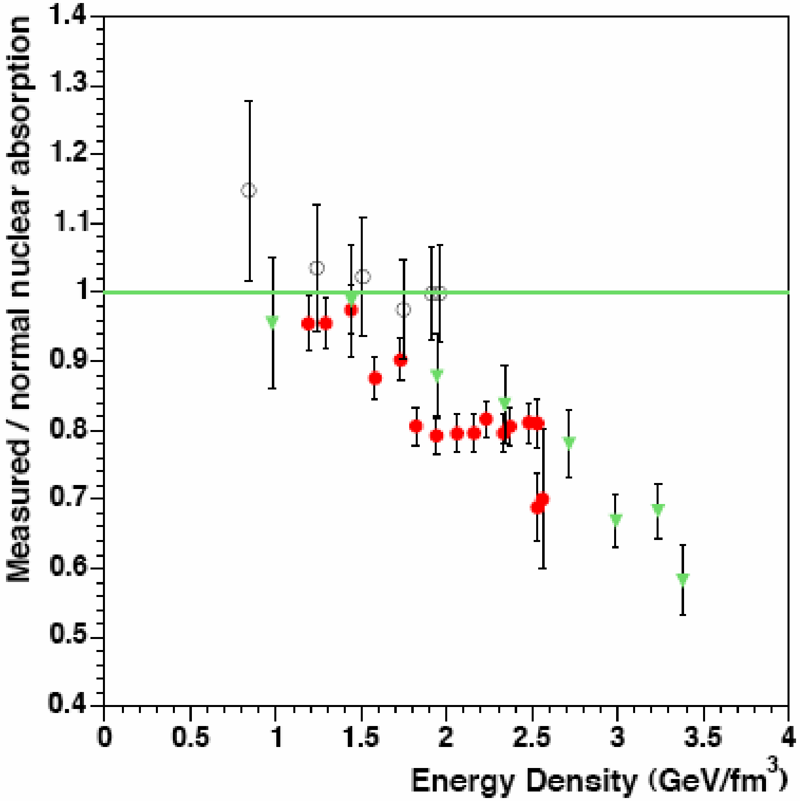
what happens for non-thermal $c/\bar{c}$ production?

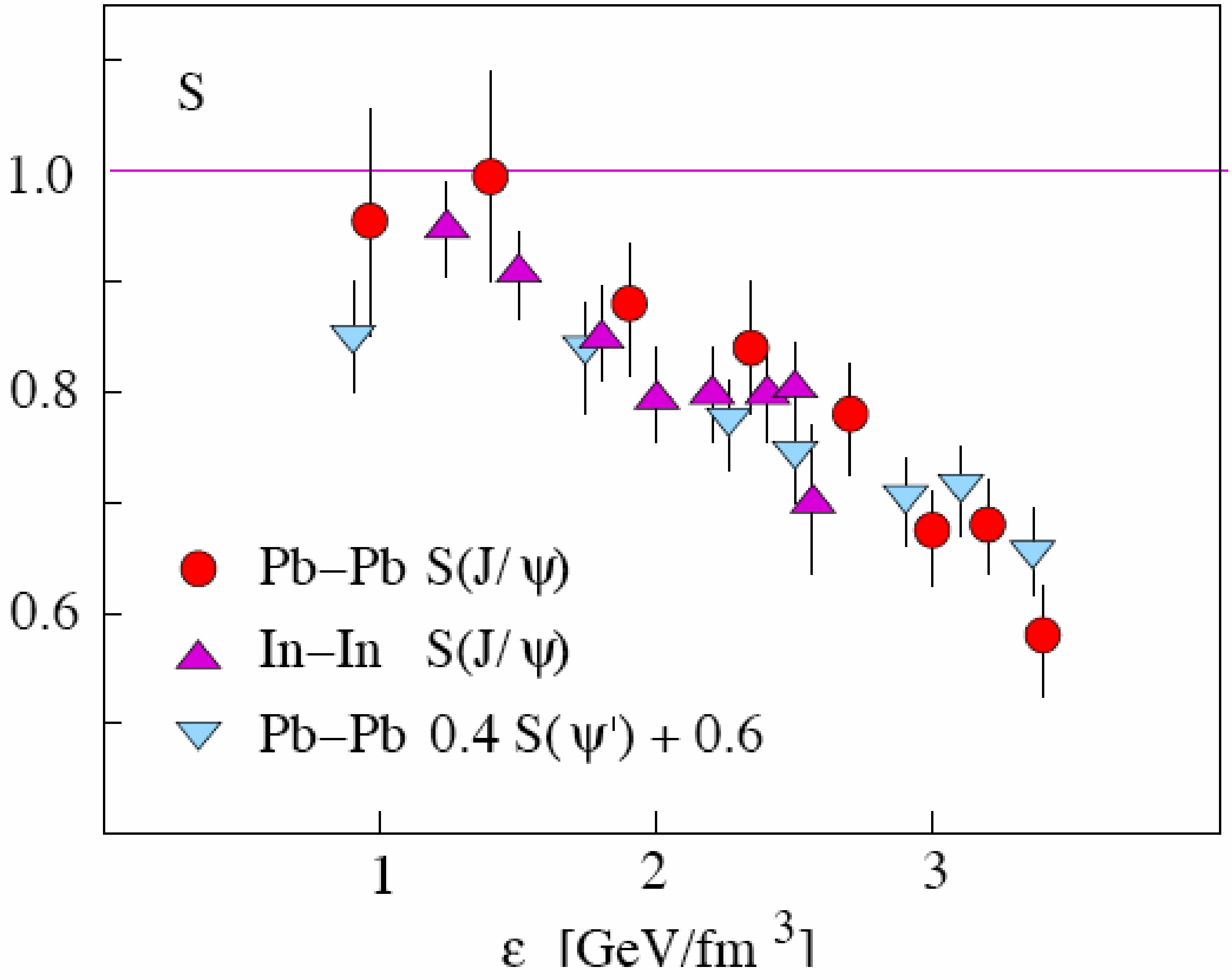
Conclusions

- in statistical QCD, the spectral analysis of quarkonia provides a well-defined way to determine temperature and energy density of the QGP
- 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

Satz-HP06-T27





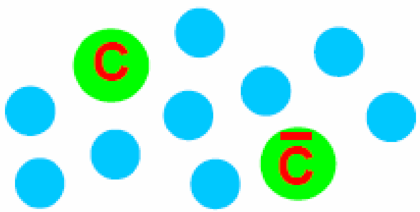

S
1.0
0.8
0.6
Pb–Pb S(J/ψ)
In–In S(J/ψ)
Pb–Pb 0.4 S(ψ') + 0.6
1
2
3
ε [GeV/fm 3]

J/ψ Suppression in QGP

- Heavy quarkonium provides a non-relativistic system, potentially, very similar to a QED bound state

Charm: $\frac{v^2}{c^2} \sim \frac{k_Q^2}{m_Q^2} \sim \frac{|M^2 - 4m_c^2|}{4m_c^2} \sim 0.3$ **Bottom:** $\frac{v^2}{c^2} \sim 0.1$

- Color screening in QGP suppresses the formation of J/ψ



Potential: $V_{Q\bar{Q}}(r) \Rightarrow V_{Q\bar{Q}}(r,T)$

Wave function: $\Phi_{Q\bar{Q}}(r) \Rightarrow \Phi_{Q\bar{Q}}(r,T)$

J/ψ formation rate $\propto \left|\Phi_{Q\bar{Q}}(r,T)\right|^2$

J/ψ suppression ⇔ medium properties

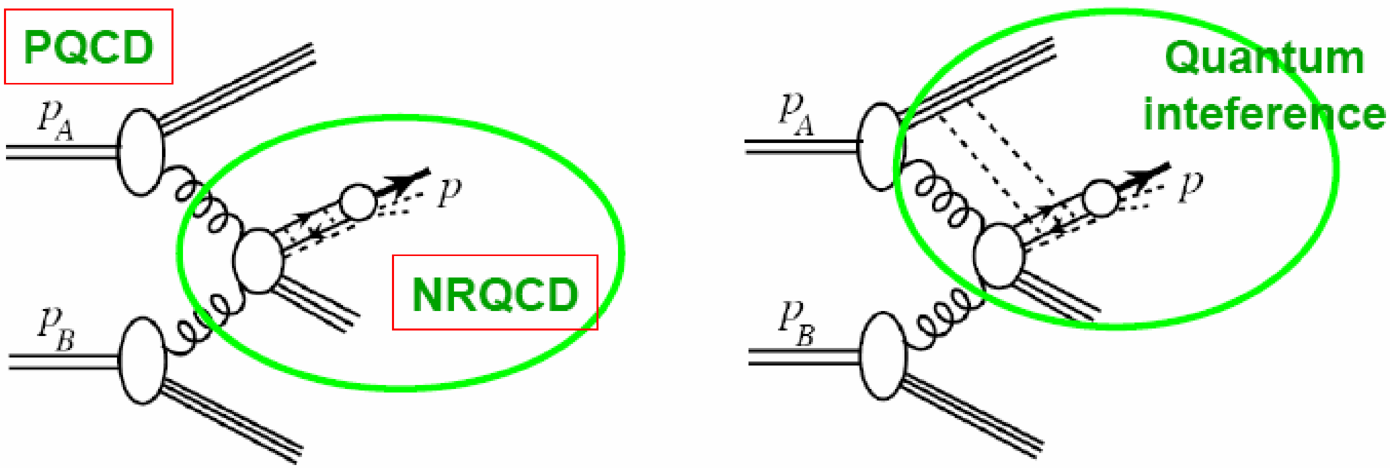
Matsui & Satz (1986)

- **Calibration:**
  Do we understand the production mechanism of J/ψ well enough to extract the information on QGP?

Surprises – theoretically

- None of the factorized production models, including NRQCD model, were proved theoretically

- Factorization of NRQCD model clearly fails for low p_T



- Factorization of NRQCD model might work for large p_T

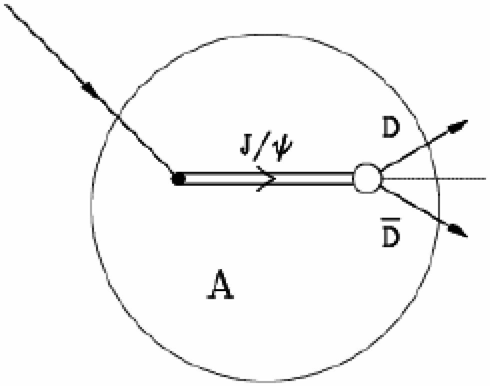
Spectator interactions are suppressed by $(1/p_T)^n$

J/ψ suppression

- J/ψ is unlikely to be formed at the same time when the heavy quark pair was produced

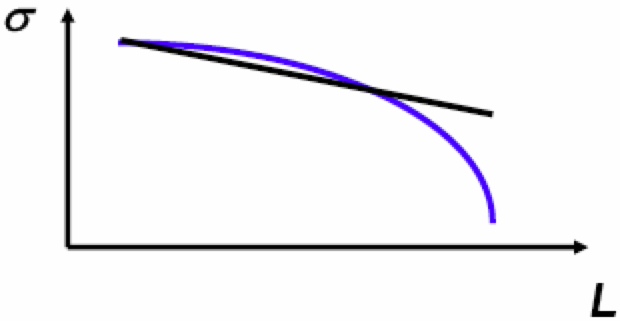
- If J/ψ were produced at the collision point:

  Expect Glauber model to work with a constant J/ψ – nucleon absorption



- If J/ψ were formed much later:

  Effective cross section for breaking the coherence of a heavy quark pair may not be a constant



Qiu,vary,zhang (2003), Accardi,Kang,Qiu

Mocsy-HP06-T17

- temperature-dependent screened potentials inconsistent with lattice QCD

- screening not responsible for quarkonia dissociation

- we are in the strong coupling regime where dissociation is due to gluons

stay tuned, you'll here more soon …

conclusion

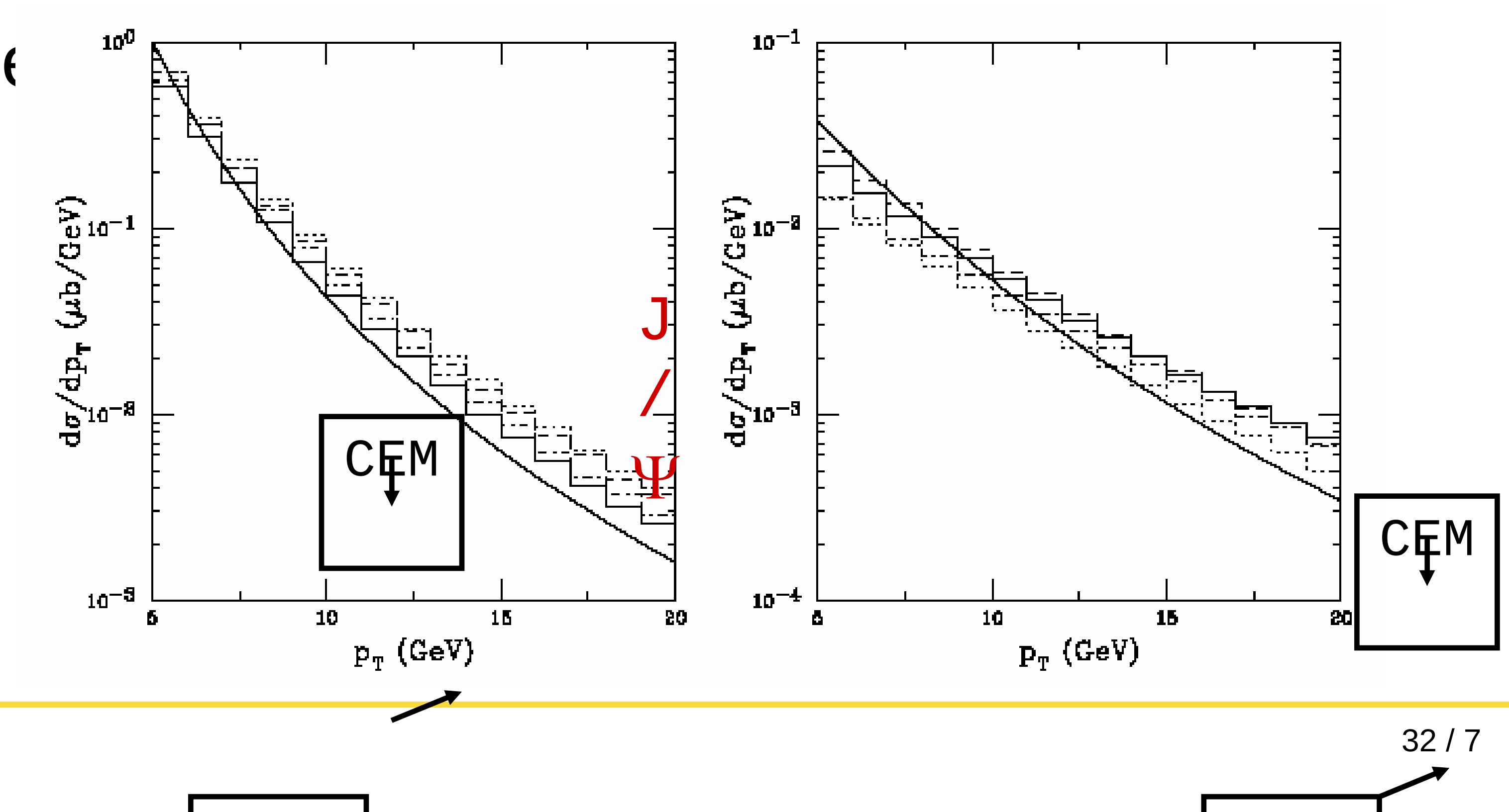
State of theory

Do we have a coherent theoretical framework ?

- High-p_T hadrons: YES
- High-p_T di-hadrons (or γ + hadron): MAYBE
- Single jets: YES
- γ-jet correlations: YES
- Heavy quarkonia: NO
- High invariant mass lepton pairs: YES
- High p_T photons: MAYBE
- *W* and *Z* bosons: NO

Quarkonium production

pQCD framework: Either NRQCD factorization including color octet components of the (Q-Qbar) state and feed-down from excited states or color e

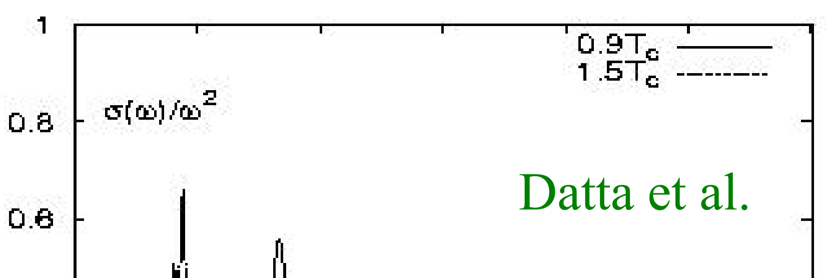


No comparable theoretical framework exists, to treat medium modifications to (Q-Qbar) s function, (in-)elastic dissociation by the recombination in a unified manner.

(a) Spectral function:

LQCD simulations, with analytic continuation to real time, suggest T_d ~ 1.5 - 2T_c for J/Ψ and Υ.

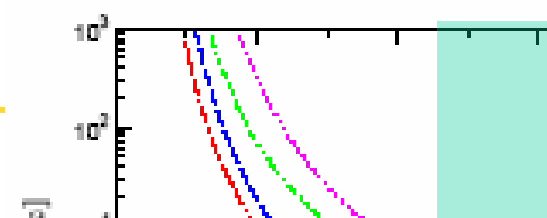
But width Γ(T) unknown.



(b) Inelastic dissociation:

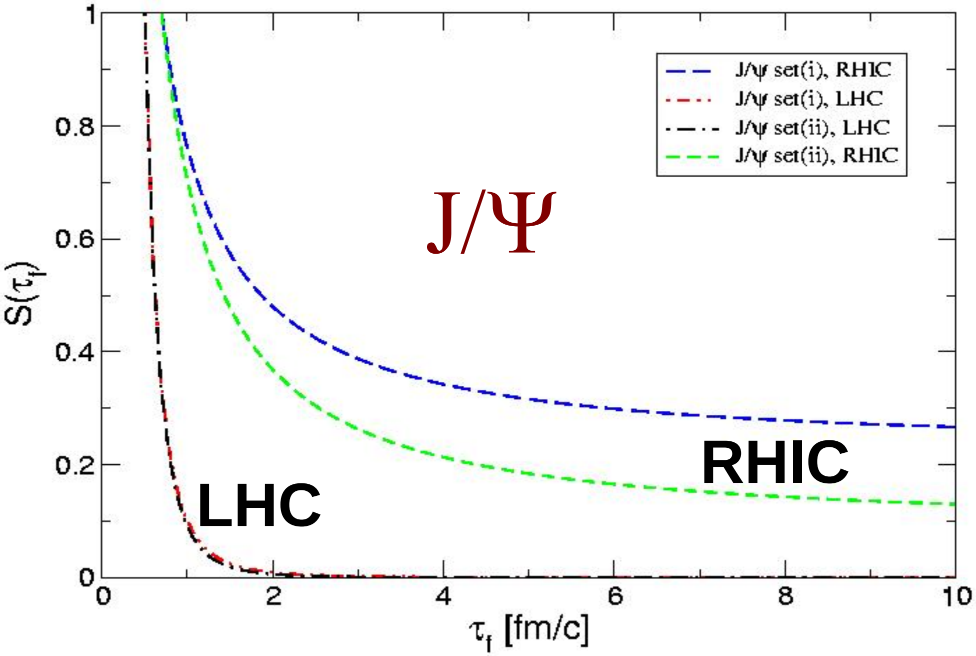
pQCD calculatio gluon absorptio substantial ra LHC conditions.

$\int d\tau\, \rho_g(\tau) \approx \rho_0 \tau_0 \ln$



Quarkonium emission II

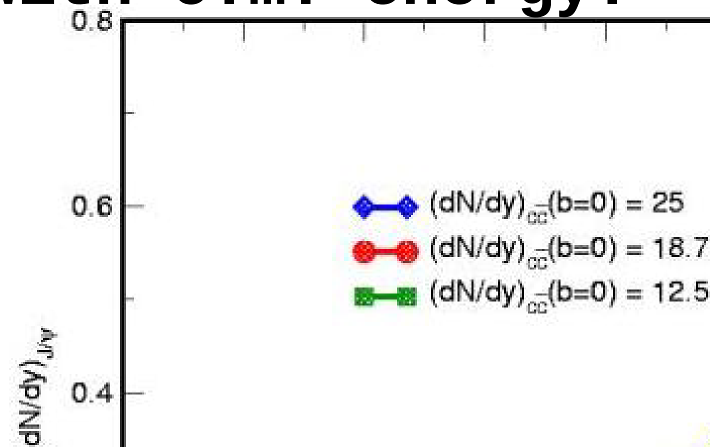
Ionization by thermal gluons:



If gluons are responsible for parton energy loss, they must

Recombination is un if *c*-quarks are "de thermalized.

(Semi-)realistic ca with full geometry needed, but the con potentially large, with c.m. energy.



Wiedemann-HP06-T9

- Benchmark **J.W. Qiu**

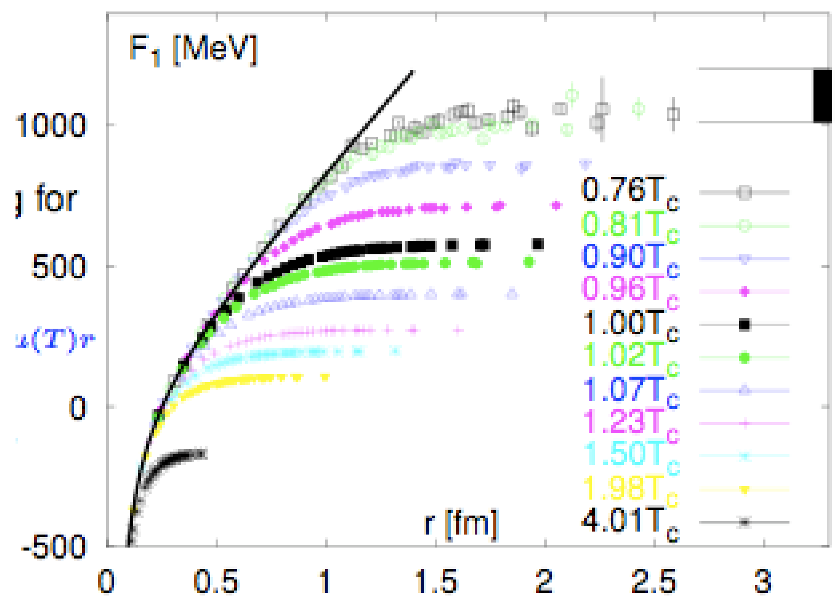
$$\frac{\left|M^2 - 4m_Q^2\right|}{4m_Q^2} \ll 1$$

Unlike HQ-production, transition from HQ-pair to quarkonium is sensitive to soft physics.

Can the medium of HICs serve as a tool to disentangle different quarkonium production mechanisms?

- Lattice QCD describes quarkonium dissociation at rest in thermal environment.

F. Karsch



Weakest link between theory and data: collective dynamics

- Exogamous production of quarkonium is an interesting medium effect, but somewhat obscures the gauging of the quarkonium thermometer. How can one disentangle recombination and dissociation processes?

B. Thews

Wiedemann-HP06-T14

Punchline of this talk

- The connection between theory and data is only as strong as its weakest link. There are numerous examples, that for the sector of Hard Probes, the weakest link is currently the modeling of the produced matter.

- Many properties of the produced matter can be calculated in well-defined settings

  - Lattice QCD (+ strong coupling, - no real time dynamics)
  - AdS/CFT (+ strong coupling, + real time dynamics, - not QCD)
  - HTL (- weak coupling, + real time dynamics)

- Embedding hard probes in a realistic geometrical and dynamical setting (hydrodynamics, dissipative hydrodynamics) is a prerequisite for:
  - determining numerically sensible values for medium properties tested by hard probes
  - characterizing at least qualitatively many of the collective effects present in dense matter (I.e Mach cones)

What is RHIC II?

RHIC II is a **luminosity upgrade** to RHIC that will produce the following improvements in performance:

		---- Luminosity Delivered / week ---		
Species	**units**	**Obtained**	**RHIC 2008**	**RHIC II**
p+p	pb^{-1}	~6*	26	33
d+Au	nb^{-1}	4.5	--	62
Cu+Cu	nb^{-1}	2.4	--	25
Au+Au	mb^{-1}	160	327	2500

Note: Because the collision diamond has $\sigma = 20$ cm at RHIC and $\sigma = 10$ cm at RHIC II, the gain in **usable luminosity** is larger than the ratio of delivered luminosity when going to RHIC II.

There are also a number of planned detector upgrades for PHENIX and STAR that are crucial to the RHIC II physics program.

* Run 6, the last 5 weeks

Heavy flavor yields at RHIC II - PHENIX

200 GeV Au+Au for a 12 week physics run. Other species comparable.

Signal	|h|	Obtained	RHIC I (> 2008)	RHIC II
$J/\psi \rightarrow e^+e^-$	< 0.35	~ 800	3,300	45,000
$J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4	~ 7000	29,000	395,000
$\psi' \rightarrow e^+e^-$	< 0.35		60	800
$\psi' \rightarrow \mu^+\mu^-$	1.2-2.4		520	7,100
$\chi_c \rightarrow e^+e^- \gamma$	< 0.35		220	2,900*
$\chi_c \rightarrow \mu^+\mu^- \gamma$	1.2-2.4		8,600	117,000*
$Y \rightarrow e^+e^-$	< 0.35		30	400
$Y \rightarrow \mu^+\mu^-$	1.2-2.4		80	1,040
$B \rightarrow J/\psi \rightarrow e^+e^-$	< 0.35		40	570
$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4		420	5,700

* Large backgrounds, quality uncertain as yet.

Heavy flavor yields at RHIC II - STAR

200 GeV Au+Au for a 12 week physics run.

Signal	|h|	Obtained	RHIC I (> 2008)	RHIC II
$J/\psi \to e^+e^-$	< 1.0		16,200	220,000
$\psi' \to e^+e^-$	< 1.0		300	4,000
$Y \to e^+e^-$	< 1.0		830	11,200
$B \to J/\psi \to e^+e^-$	< 1.0		190	2,500
$D \to K\pi$	< 1.0		30,000*	30,000*

* From 100 Hz of minimum bias triggers (Thomas Ullrich).

Note: p+p yields are proportionately higher for J/ψ because trigger is more efficient in p+p than in Au+Au.

RHIC II / LHC complementarity

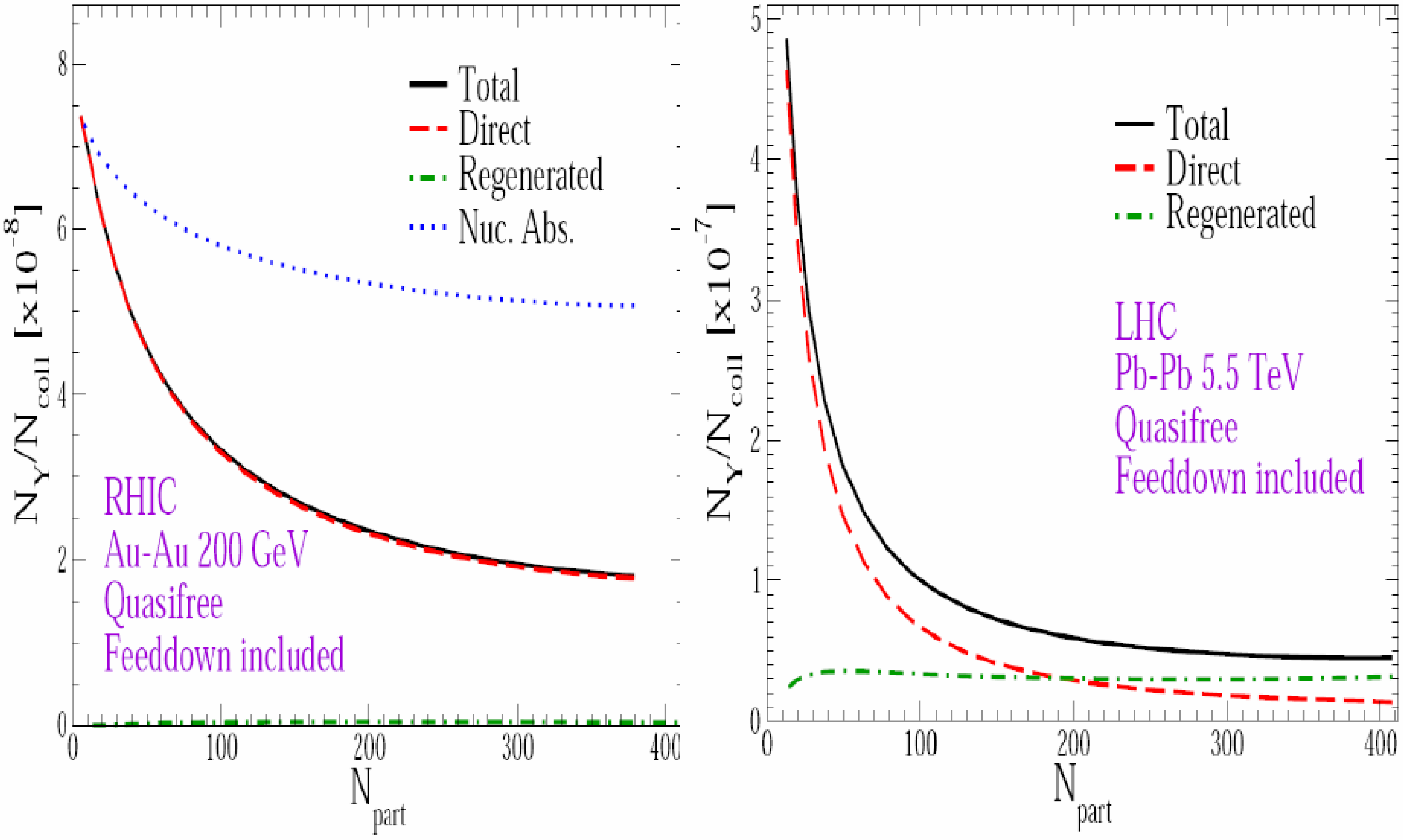
RHIC II will provide ~ 36 times as much integrated luminosity per year as LHC. Compare with 13 times higher J/ψ and 55 times higher Υ cross sections at LHC. **The yields per year will be very similar.**

	RHIC II	LHC
HF yields	----------- similar	-------------
QGP temperature	$2T_c$	$4T_c$
QGP lifetime	~7 fm/c	~17 fm/c
N_{cc}	10	115
N_{bb}	0.05	5
J/ψ	bound	unbound
J/ψ form.[1]	suppr.+coalescence	coalescence
Υ(1S)	bound	bound
Υ(1S) form.[2]	suppr.	suppr.+coalescence
Open b		easier (cross section ↑)
Open c		harder (b feed down ↑)

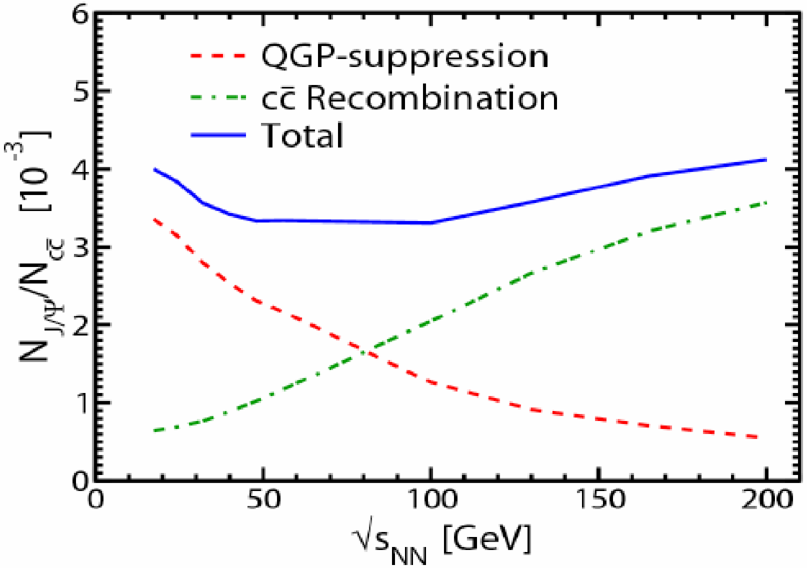
1. LHC data should help resolve ambiguity from suppr./coalescence at RHIC.
2. RHIC data should help resolve ambiguity from suppr./coalescence at LHC.

Frawley-QWG-T42

Y(1S) at RHIC and LHC. From Grandchamp et al., hep-ph/0507314.
Coalescence is predicted to be unimportant at RHIC, dominant at LHC.



Lower energy J/ψ at RHIC II



Two component model calculation of J/ψ yield in AuAu collisions vs collision energy by Grandchamp and Rapp, N.P. **A715**, 545 (2003). According to this model, **suppression dominates** at 62 GeV.

Measurements of J/ψ rapidity and p_T distributions should be feasible even before RHIC II. We have seen a J/ψ signal in a short 62 GeV CuCu run.