Quarkonium in cold and hot matter

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J/ψ and its suppression

1. Debye screening in a plasma modifies the QCD potential, so that $\bar{c}c$ does not bind into J/ψ (Matsui and Satz, 1986)
2. Cold nuclear matter also shows J/ψ suppression both from the initial state (Gavai and SG, 1989) and from the final state (Gavin and Gyulassy, 1989)
3. Thermal modification of the potential occurs at too high a temperature to be visible below LHC energies (Asakawa $++$, 2001; Datta $+++$, 2004)
4. At high energy J/ψ may be relatively enhanced due to independent $\bar{c}c$ recombination (Thews $++$, 2001)

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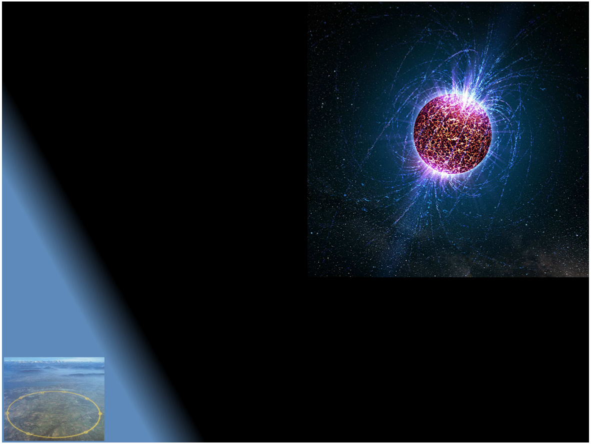
Lesson learnt in 25 years

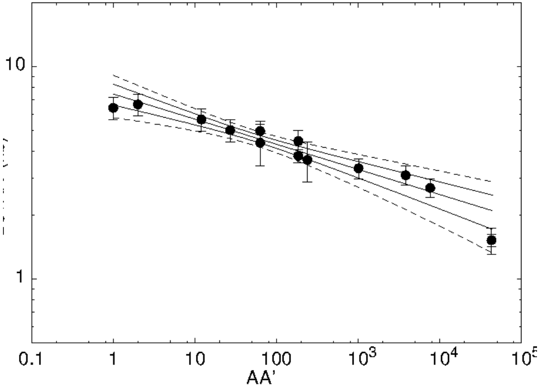
Need to understand and remove cold matter effects in order to see signal of hot matter in J/ψ and Υ-family suppression.

A gedanken experiment



Is TeV p on neutron star reaction same as very low energy p-U collision? Is energy is entangled with size?

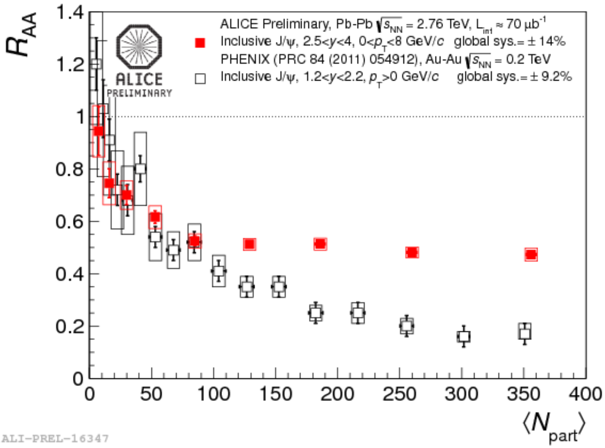
A real experiment



Size scales simply at fixed energy

Gavai and SG, 1997; reanalysis of NA50, 1996

Should energy be fine-tuned?



How does hot matter do this?

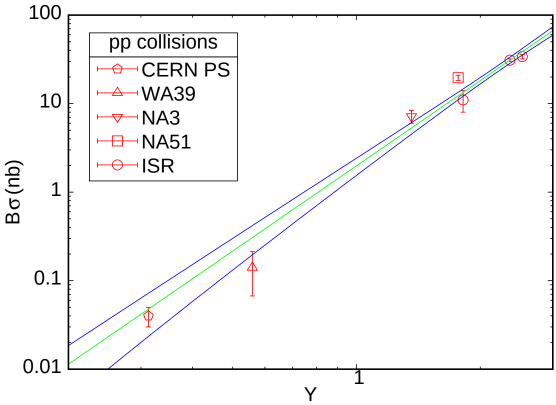
Das (ALICE), arXiv:1212.2704

Dimensional analysis

1. Total cross section, σ, for inclusive production $p+A\to h+X$ depends on small number of variables: CM energy $\sqrt{S}$, M_p, M_A and M_h.
2. Nuclear binding effects can be neglected: $M_A = AM_p$, *i.e.*, neglect effects of about 1%. Also neglect order 1% effect of isospin. Fermi motion due to nuclear binding, so can be neglected except within 1% of threshold energy, $\sqrt{S}_{th}$.
3. Dimensional argument: $\sigma S_{th} = f(Y, A, H)$ where $2Y = \log(S/S_{th})$ and $H = M_h/M_p$.
4. Does f depend on Y and A simultaneously, or does the effect on A factorize? For small A, for large A, $\cdots$

Bhaduri and SG, arXiv:1304.3787

The limit of no matter



$$\sigma \propto Y^{3.2\pm0.3} \qquad (A = 1,\ Y \ll 1),$$

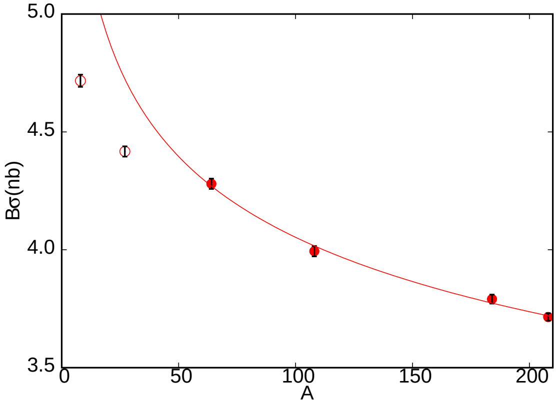
Dimensional arguments at higher energy

When $S \gg S_{th}$, then set the scale by S. If $x = M_h/\sqrt{S} \simeq 1$ and $A \simeq 1$ then single scale problem; $\sigma S = F(x)$ where $F(x)$ should be computable in perturbative QCD. However, exclusive hadronization in the final state: open question. NRQCD?

If $x \simeq 1$ and $A \gg 1$ then two-scale problem. If a tractable problem then one could expect in this limit either $F(x, A) = \widetilde{F}(x)$ or $F(x, A) = A^\alpha \widetilde{F}(x)$. Observation: supports the second case. The power α connects to physics at lower energy.

If $x \ll 1$ then back to multi-scale problem; A becomes important again. $\sigma S = F(x, A)$, but $F(x, A)$ may need resummation.
Tribedy, talk later today

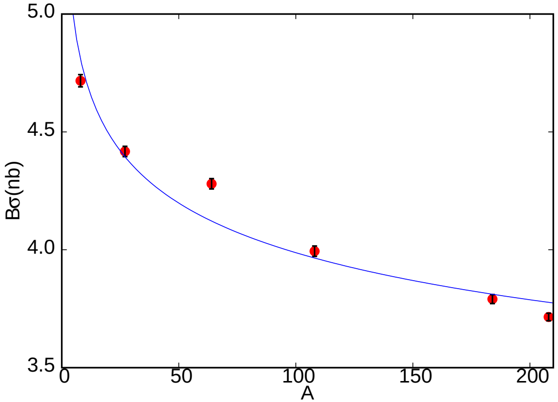
A power law



For large A and fixed Y one may be able to write $\sigma \propto A^{\alpha}$.

NA50, 2006

A power law



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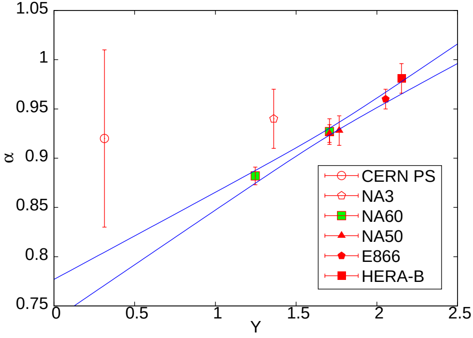
The parametrization not expected to work for all A.

NA50, 2006

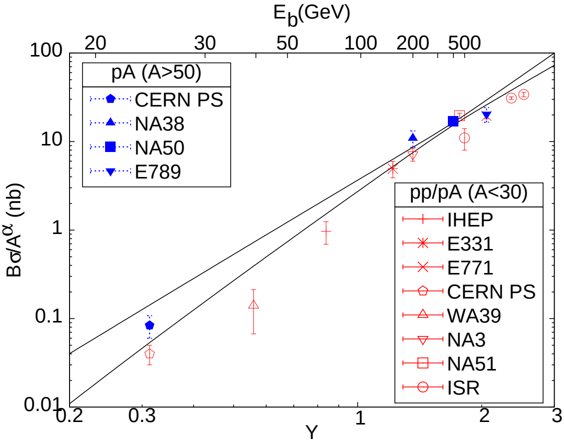
Multi-fractal scaling: additive renormalization



$\sigma \propto A^{\alpha}$: $\alpha = (0.64\pm0.02) + (0.10\pm0.01)Y + (0.012\pm0.002)H.$

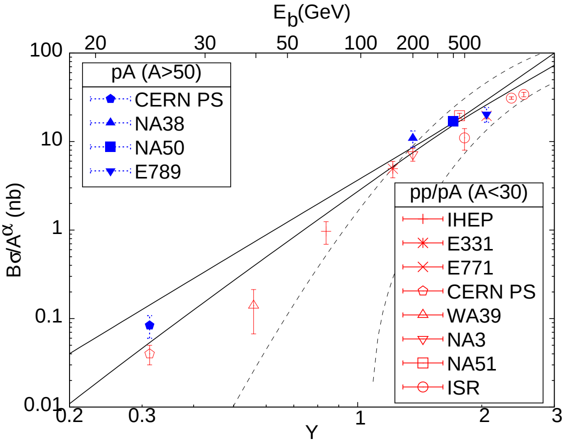
Implies renormalized $A_R = A/(Y_0 + Y)^{\mu}$. Explains J/ψ, Υ, π, K, ρ and ω, but not ψ' or ϕ: more than just Glauber model.

The scaling law and counting rules



$$B\sigma S_{th} = (3.2 \pm 0.5) A^{\alpha(Y)} Y^{\beta}, \qquad \beta = 3.0 \pm 0.3.$$

The scaling law and counting rules

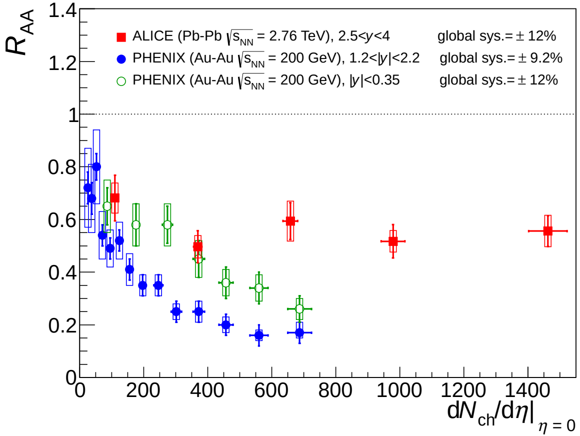


$$\sigma \propto (1 - e^{-Y})^{\gamma}, \qquad \gamma \simeq 11.$$

Cold matter: to-do list for experiments

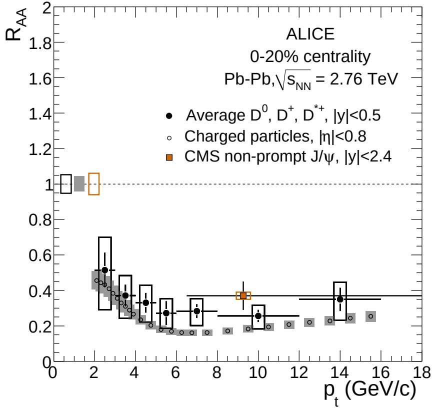
1. Cross over from hadron to quark interactions: at what value of Y does this occur? Does this depend on the final state hadron?
2. Non-perturbative factorization: what is the effect of changing the incoming hadron from proton to (say) pion at $Y \ll 1$? May have interesting implications for CP violation experiments.
3. The Glauber model: used widely, but never subjected to stress tests. Large universality class of multifractal exponents may indicate that the Glauber model is "accidental". More tests?
4. Scaling laws imply renormalization group transformations: strongly constrain low-energy effective theories of hadron interactions which can arise from QCD. More detailed measurements of the anomalous dimensions α and β?
5. Extend this RG analysis to less inclusive measurements.

J/ψ unsuppression



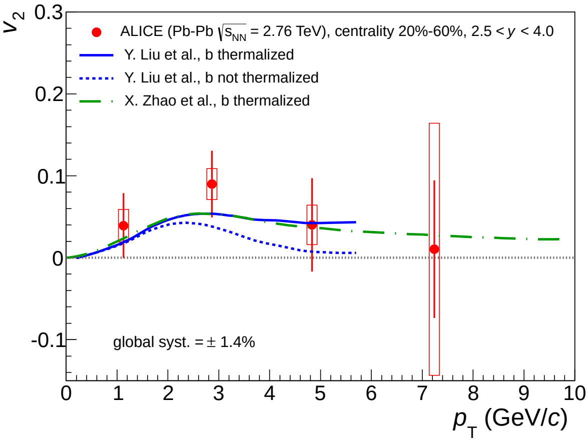
ALICE, arXiv:1202.1383

D meson suppression



ALICE, arXiv:1203.2160

J/ψ flow



ALICE, arXiv:1303.5880

Heavy quark diffusion

Two scales for thermal heavy quarks in medium: M and T. For heavy quark: $E \simeq T$, $P \simeq \sqrt{MT}$. For light partons: $e \simeq p \simeq T$. Change in heavy quark momentum due to single kick from light particles: $\Delta P/P = T/M$. Need order M/T independent kicks to change momentum appreciably. Then

$$\frac{dP}{dt} = -\eta P + \xi(t), \qquad \langle \xi(t)\xi(t')\rangle = \kappa\delta(t-t').$$

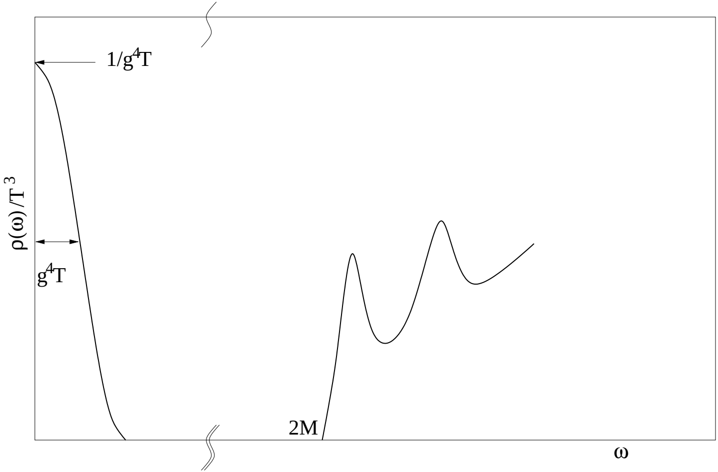
In steady state,

$$\eta = \frac{\kappa}{2MT}, \qquad \text{and} \qquad D = \frac{2T^2}{\kappa}.$$

Moore and Teaney, 2005; Rapp and van Hees, 2005; Mustafa 2005

D: heavy quark diffusion constant determines how quickly it thermalizes. Cross check of the quarkonium estimates need open flavour v_2 and heavy quark diffusion.

Heavy quark spectral functions



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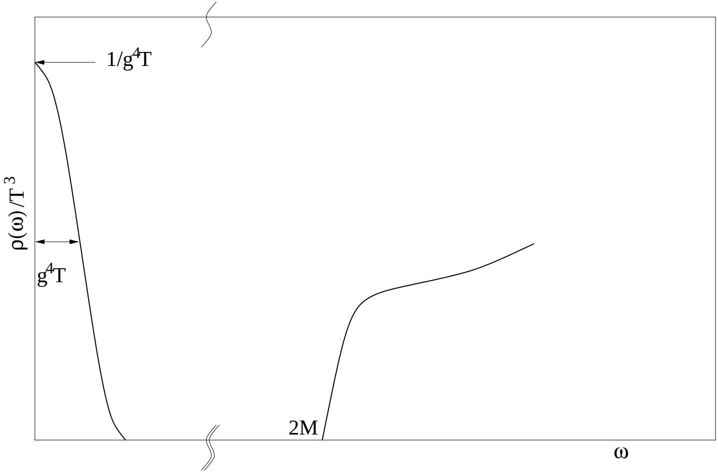
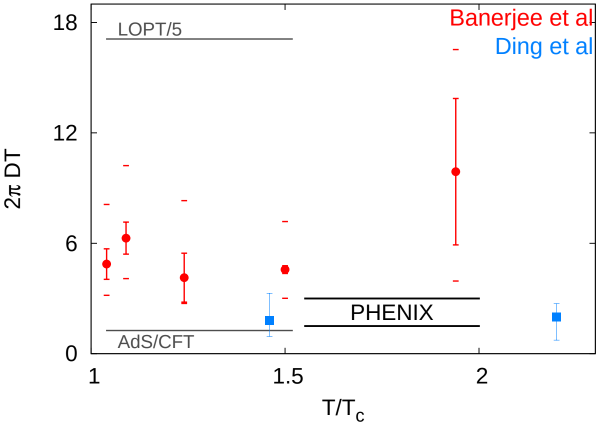


Lattice measurement



Banerjee et al, 2012

Heavy quarks and quarkonia

Cold matter

Data supports a scaling law which mixes energy and size into a single renormalized size variable: $A_R = A/(Y_0 + Y)^\mu$ where $Y = \log \sqrt{S/S_{th}}$. As a result, near threshold the total inclusive cross section is

$$\sigma \propto A^{\alpha(Y,H)} Y^\beta,$$

where the exponents are applicable to a wide variety of final state particles. Experiments for $Y < 1$ at CBM can give baseline needed for LHC and RHIC.

Hot matter

LHC sees quarkonium suppression, since $R_{AA} < 1$. However, R_{AA} is larger than seen at RHIC, and significant elliptic flow is seen. If this is due to recombination of exogamous $\bar{c}c$ pairs, then the heavy quark diffusion constant, D, gives a cross check. This is measured in lattice computations.