Υ suppression in PbPb-collisions at the LHC

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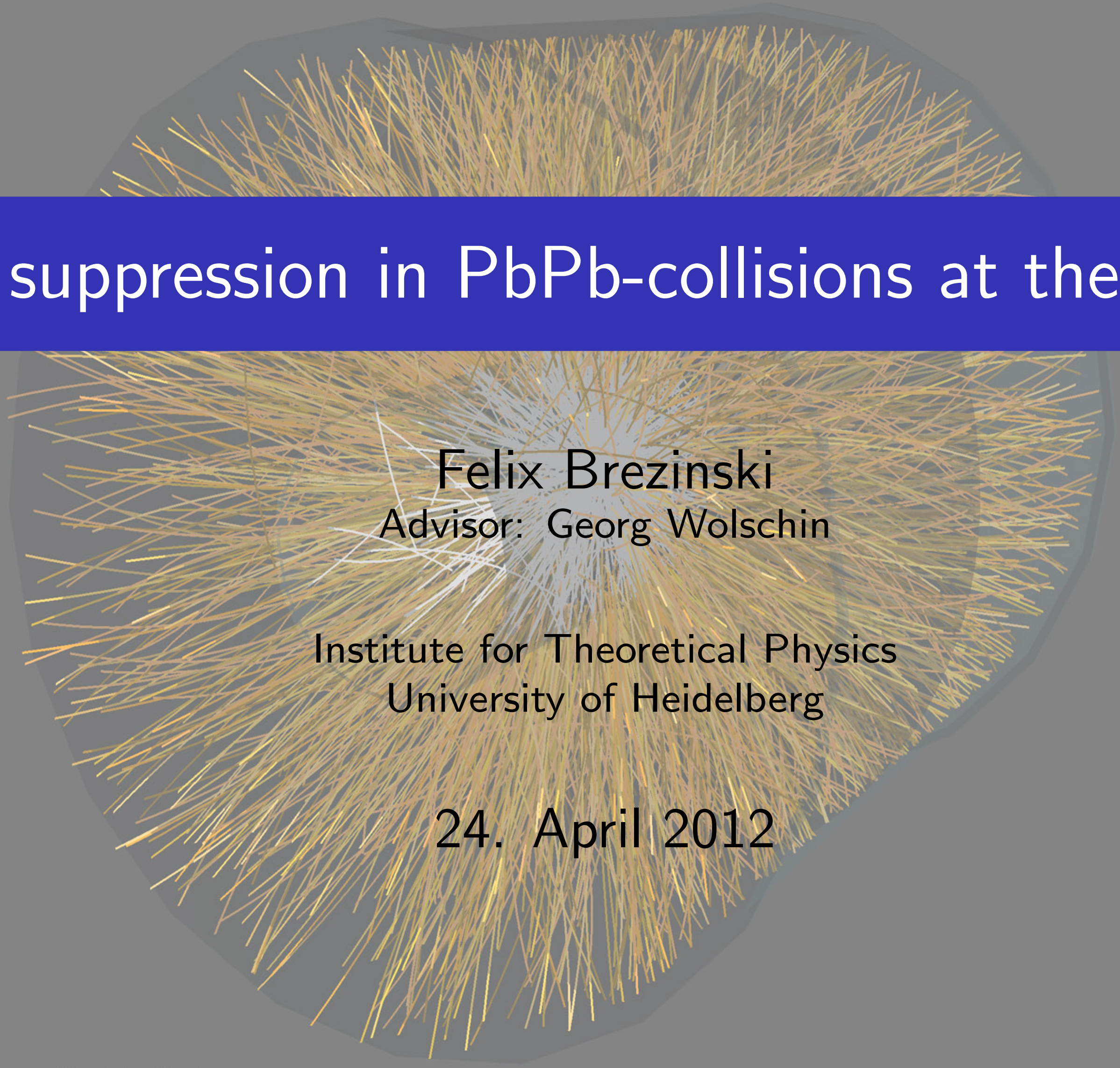
24. April 2012



PbPb-collision @ ALICE

Outline

QGP and quarkonia in heavy ion collisions

- Heavy ion collisions are the only known way to produce QCD matter in the laboratory
- The possibly created quark-gluon plasma (QGP) has a very short lifetime (a few fm$/c$)
- Only the final, hadronic state can be detected
- Heavy quark bound states (quarkonia mesons), i.e. $c\bar{c}$ and $b\bar{b}$ serve as one of the most promising probes for the QGP

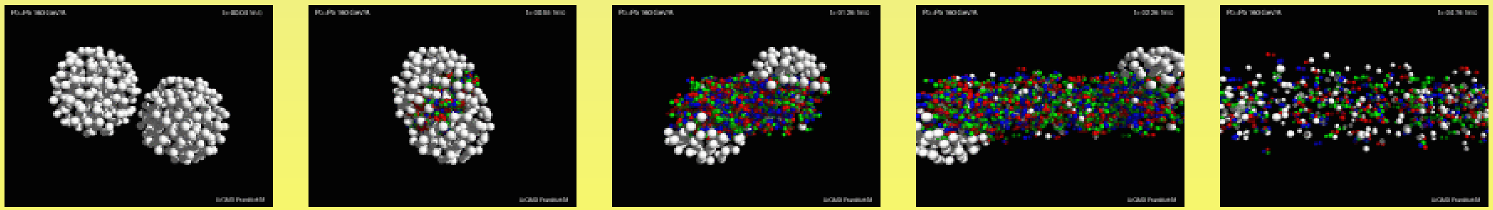
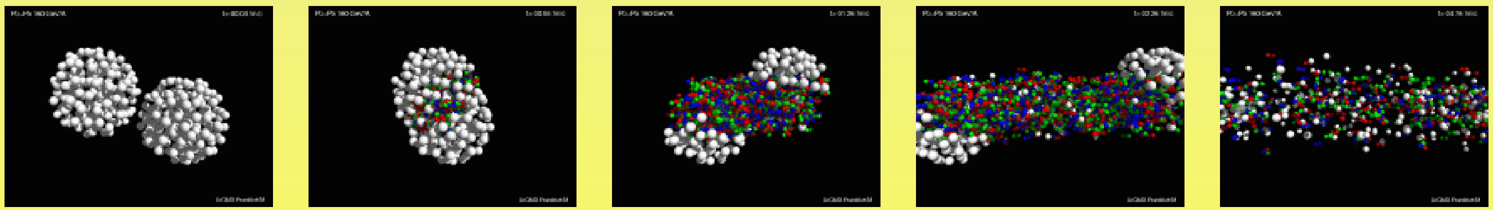


Figure: Schematic illustration of a PbPb-collision (H. Weber and The UrQMD-Collaboration, 2012).

QGP and quarkonia in heavy ion collisions

- Quarkonia are sensitive to the early collision phase (production timescale $\tau \sim 1/m_Q = 0.08 - 0.02$ fm$/c$)
- Any change in the quarkonium yield as compared to pp-collisions allows for conclusions about the medium
- In previous accelerators only J/ψ ($c\bar{c}$) was produced in a sufficient amount to be used as a probe
- At the LHC suppression of the Υ ($b\bar{b}$) can be studied for the first time



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- Quarkonium suppression has been studied theoretically, and experimentally at SPS, RHIC (PHENIX, 2009), and LHC (ALICE, 2011; CMS 2011).

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$\Rightarrow$ Bottomium is expected a cleaner probe for the QGP.

The action for heavy quark, thermal QCD

- We consider euclidean QCD with three light, mass-less and one heavy flavor

$$S_E = \int d^4x_E \Big[-\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \\ + \sum_{f=u,d,s} \bar{q}_f(-i\not{D})q_f + \bar{Q}(-i\not{D} + M)Q \Big].$$

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- Integrating out the light flavors yields a self-energy contribution to the in-medium gluon propagators
- Projecting onto $Q\bar{Q}$-bound states in the Hamiltonian formalism leads to the pNRQCD action (Brambilla et al., 2011; Pineda and Soto, 1998)

Arriving at pNRQCD

- In terms of the color singlet and octet fields S and O and relative and center-of-mass coordinates $\vec{r}$ and $\vec{R}$, the pNRQCD action reads

$$S_E = S_{\text{US-gluons}} + \int d\tau d^3r d^3R \left[S^\dagger \left(\partial_\tau + H_1\right) S + \right.$$

$$\left. + O^{a\dagger} \left(D_\tau + H_8\right) O^a + \frac{g\,\vec{r}\vec{E}^a}{\sqrt{2N_c}} \left(S^\dagger O^a + O^{a\dagger} S\right) + \dots \right],$$

with the respective Hamiltonians,

$$H_{1/8} = -\frac{\Delta_R}{4M} - \frac{\Delta_r}{M} + V_{1/8}(r).$$

The heavy quark interaction potentials

- Medium-contributions may be calculated in the hard thermal loop (HTL) approximation, so the potentials read to first order

$$V_1(r) = -C_F\alpha_s\Big(m_D + \frac{e^{-m_D r}}{r} - iT\phi(m_D r)\Big),$$

$$V_8(r) = +\frac{\alpha_s}{2N_c}\Big(m_D + \frac{e^{-m_D r}}{r} - iT\phi(m_D r)\Big),$$

with the HTL-Debye mass $m_D = gT\sqrt{N_c/3 + N_f/6}$ and

$0 \leq \phi(x) = \int_0^\infty dz \frac{2z}{(1+z^2)^2}\left(1 - \frac{\sin xz}{xz}\right) < 1.$

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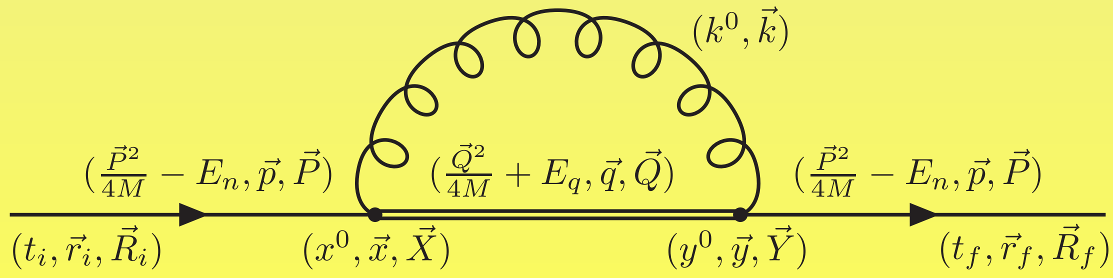
$$\Gamma_{\text{damp}} = \langle 2\,\mathrm{Im}\,V \rangle$$

- Gludissociation emerges from the dipole interaction, $\vec{r}\vec{E}^a$,

$$\Gamma_{\text{diss}} = \mathrm{Im}\left[\quad \right]$$



Υ suppression at CMS

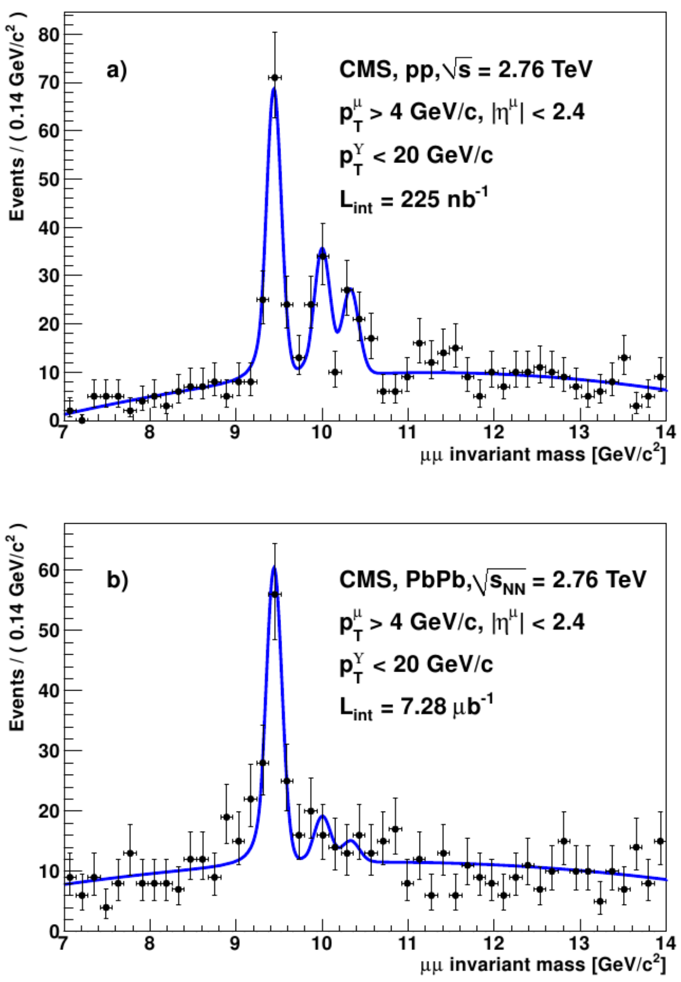


Figure: Dimuon spectrum from the 2010 CMS PbPb-run (Chatrchyan et al., 2011).

CMS (2011) has measured the nuclear suppression factor for the $\Upsilon(1S)$ to

$$R_{AA}(\Upsilon(1S)) = 0.62 \pm 0.11 \pm 0.10$$

and the relative yield of the excited states to (Chatrchyan et al., 2011)

$$\frac{\Upsilon(2S+3S)}{\Upsilon(1S)} = 0.24^{+0.13}_{-0.12} \pm 0.02.$$

The phenomenological approach

Let us consider the bottomium family

$$\Upsilon(1\mathrm{S}), \quad \chi_b(1\mathrm{P}), \quad \Upsilon(2\mathrm{S}), \quad \chi_b(2\mathrm{P}), \quad \Upsilon(3\mathrm{S}).$$

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- Calculate the wave-functions and width according to the pNRQCD action for the three processes
  - Debye screening (prevents formation of bottomia)
  - Landau damping (from $\mathrm{Im}\,V$)
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- Calculate the total suppression in the fireball, integrated over the impact parameter b
- Calculate the fraction of dimuon decays, $\Upsilon(\mathrm{nS}) \to \mu^+\mu^-$

The wave functions

- We use a screened Cornell potential (Karsch et al., 1988),

$$V(r) = \frac{\sigma}{m_D}\left(1 - e^{-m_D r}\right) - \alpha_{\text{eff}}\left(m_D + \frac{e^{-m_D r}}{r}\right),$$

with $\alpha_{\text{eff}} = 0.471$, $\sigma = 0.192$ GeV^2 from $T = 0$-fits (Jacobs et al., 1986).

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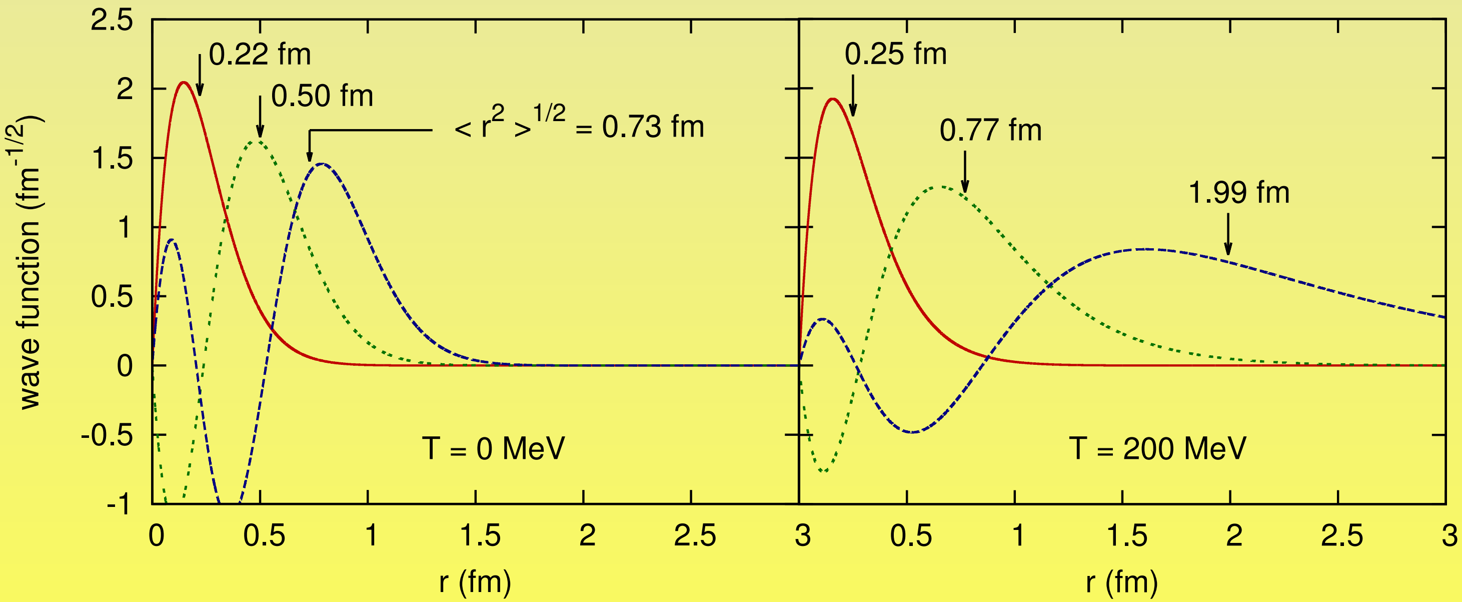
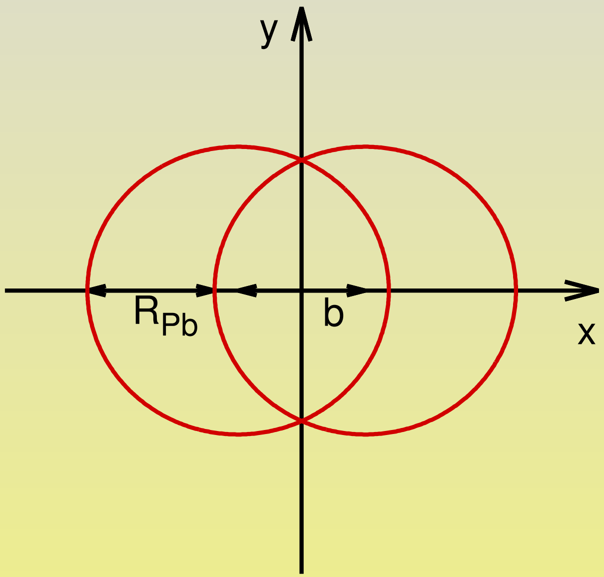


Figure: Radial wave functions of Υ(1S,2S,3S) (red, green, blue).

Modeling the fireball



- The lead-number density is modeled by the Woods-Saxon potential (de Vries et al., 1987)

$$n_{\mathrm{Pb}}(\vec{x}) = \frac{n_0}{1 + e^{(|\vec{x}|-R)/a}},$$

$R = 6.68$ fm, $a = 0.546$ fm,
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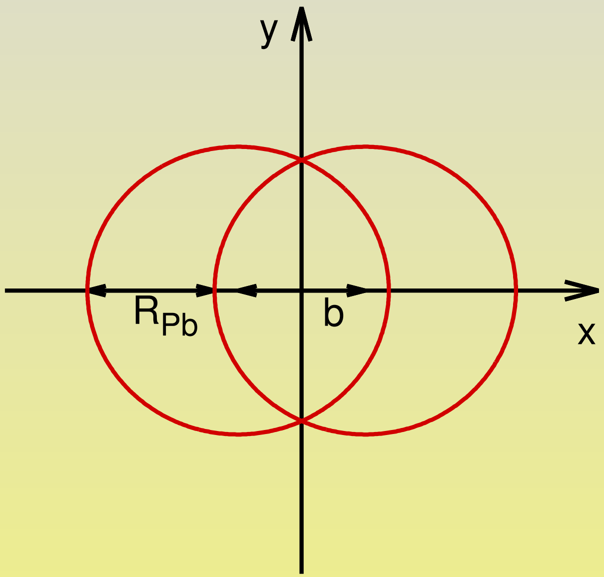

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- Nuclear thickness and overlap

$$S_A^{\pm}(b, x, y) = \int dz \, n_{\mathrm{Pb}}(x \pm b/2, y, z)$$

$$S_{AA}(b, x, y) = S_A^{+}(b, x, y) S_A^{-}(b, x, y)$$

- Bottomium-population

$$N_{b\bar{b}}(b, x, y) \propto N_{\mathrm{coll}}(b, x, y) \propto S_{AA}(b, x, y)$$

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$$T(b,t,x,y) = T_c \frac{S_{AA}(b,x,y)}{S_{AA}(0,0,0)} \left(\frac{V(0,t_{\text{QGP}})}{V(b,t)} \right)^{1/4},$$

with $T_c = 170$ MeV and V expanding with velocity $v_z = 0.9\,c$, $v_x = v_y = 0.6\,c$ in the lab frame.

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$$\Gamma_{\text{diss}} + \Gamma_{\text{damp}} = \Gamma(T(b,t,x,y)).$$

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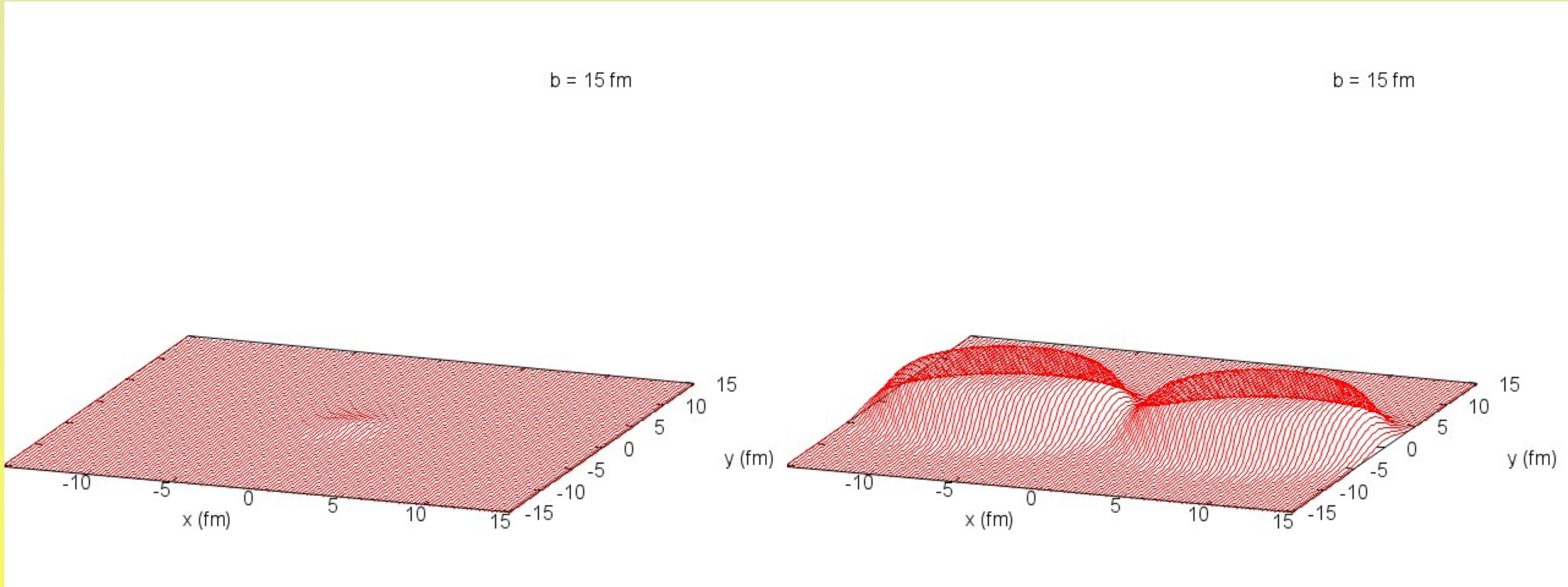
- Dissociation in the fireball leads to a preliminary suppression factor of

$$R_{AA}^{\mathsf{prel}} = \frac{\int d^2b \int dxdy \, S_{AA}(b,x,y) e^{-\int_{t_F}^{\infty} dt \, \Gamma(T(b,t,x,y))}}{\int d^2b \int dxdy \, S_{AA}(b,x,y)}$$

Relative occupation of $\Upsilon(1S)$ and total density

$S_{AA} e^{-\int dt\, \Gamma}$, for $\Upsilon(1S)$ $\qquad n_{\mathrm{Pb,tot}} = n^{+}_{\mathrm{Pb}} + n^{-}_{\mathrm{Pb}}$



$$b = 15 \text{ fm}$$

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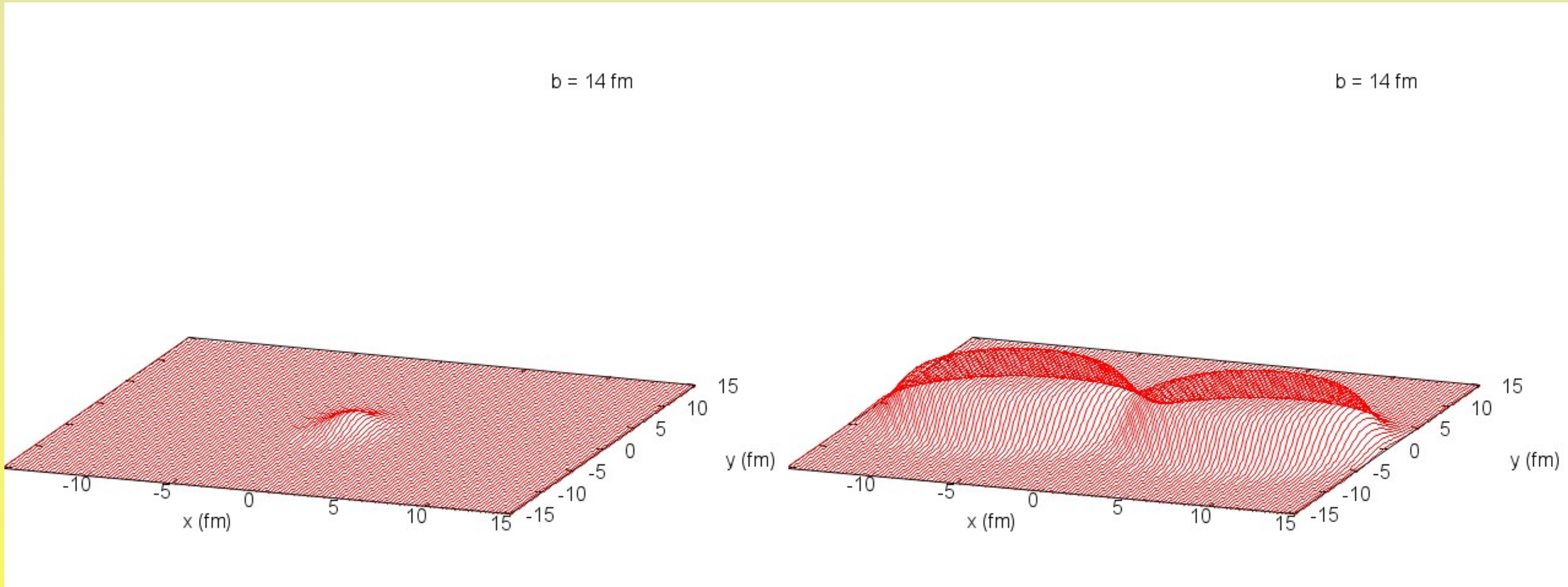

$$b = 14 \text{ fm}$$

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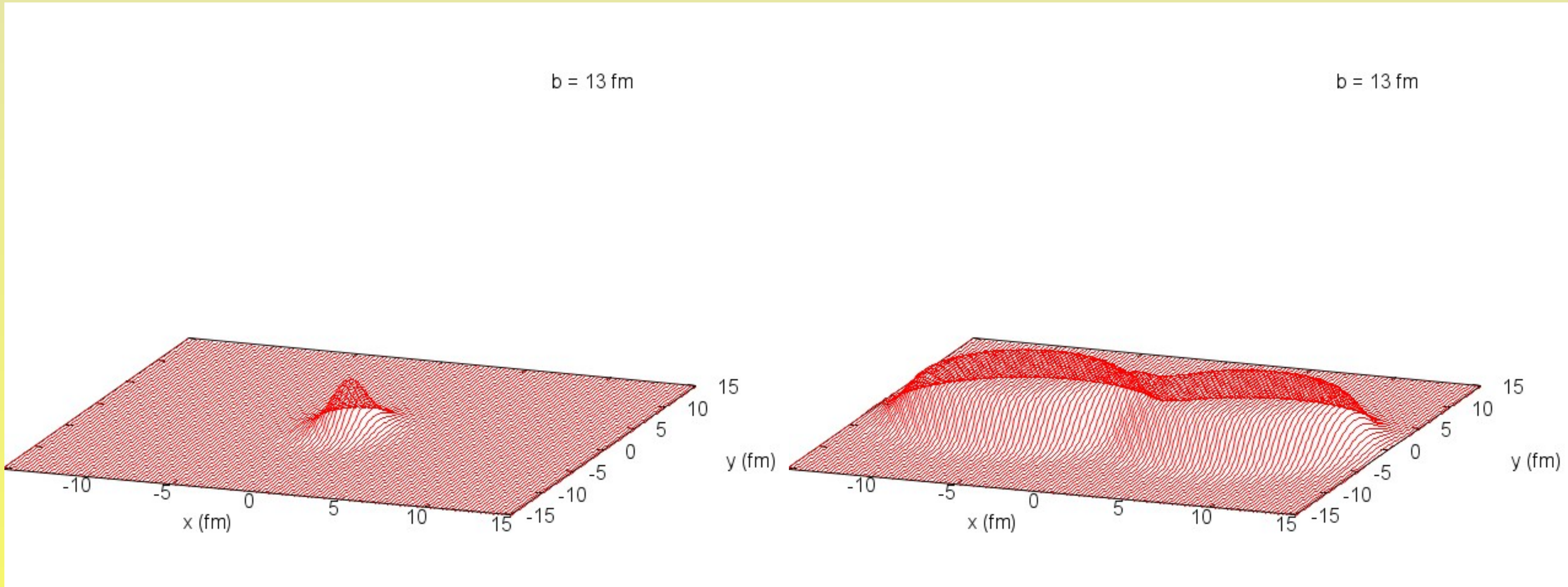

$$b = 13 \text{ fm}$$

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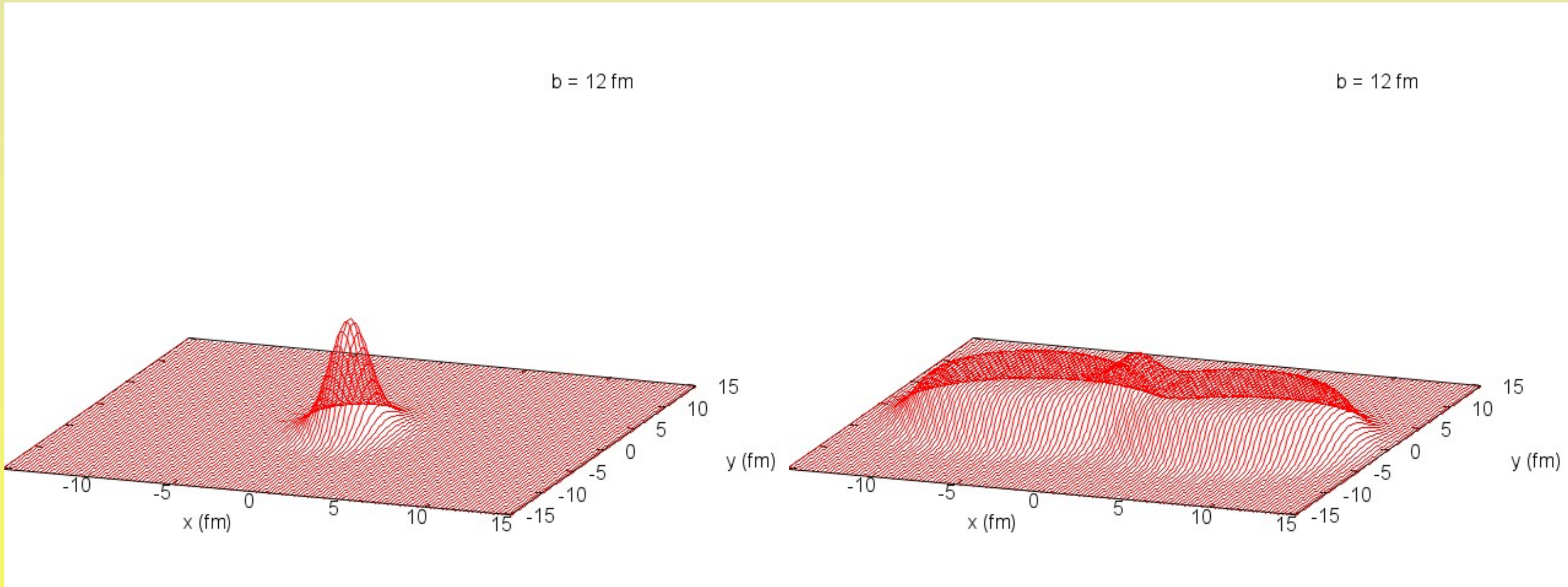

$$b = 12 \text{ fm}$$

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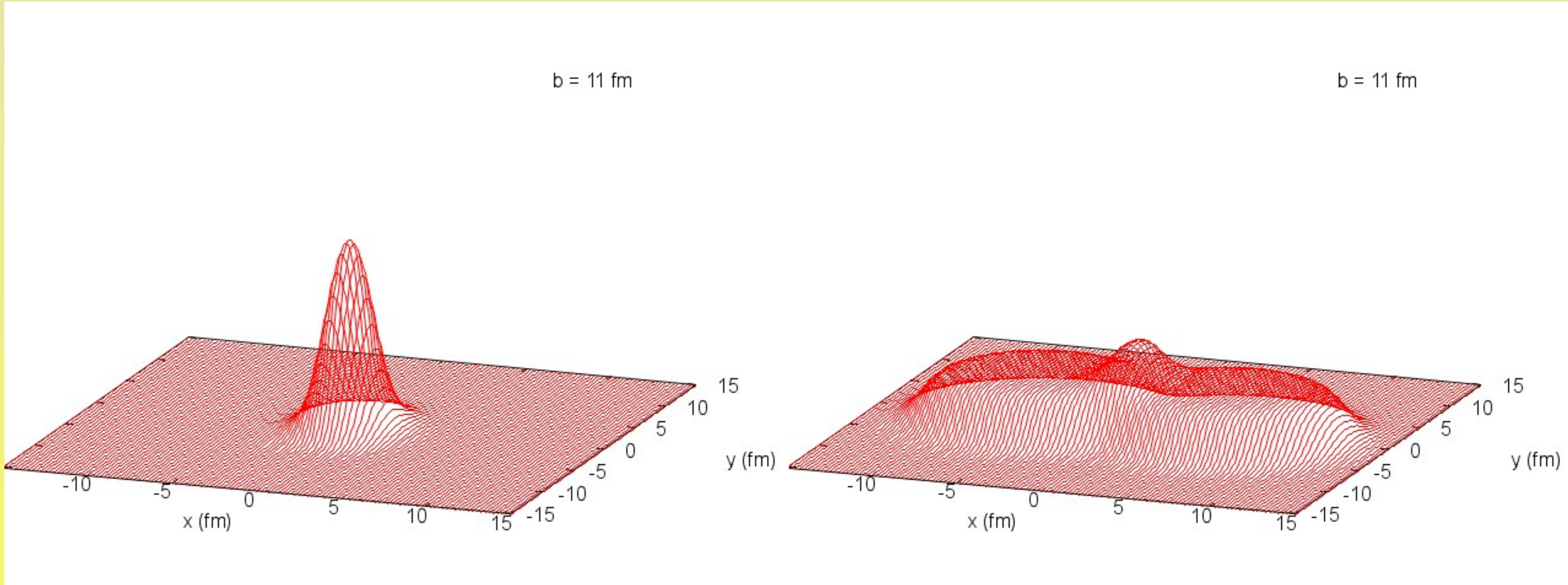

$b = 11$ fm

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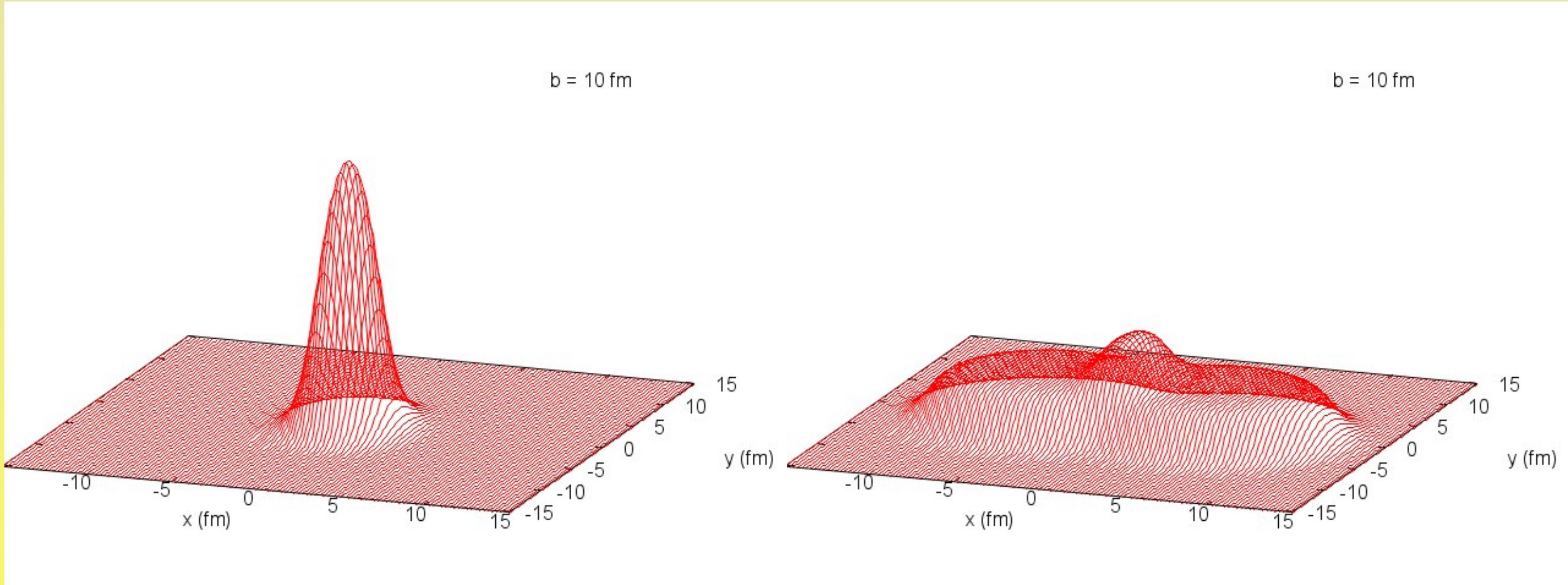

$$b = 10 \text{ fm}$$

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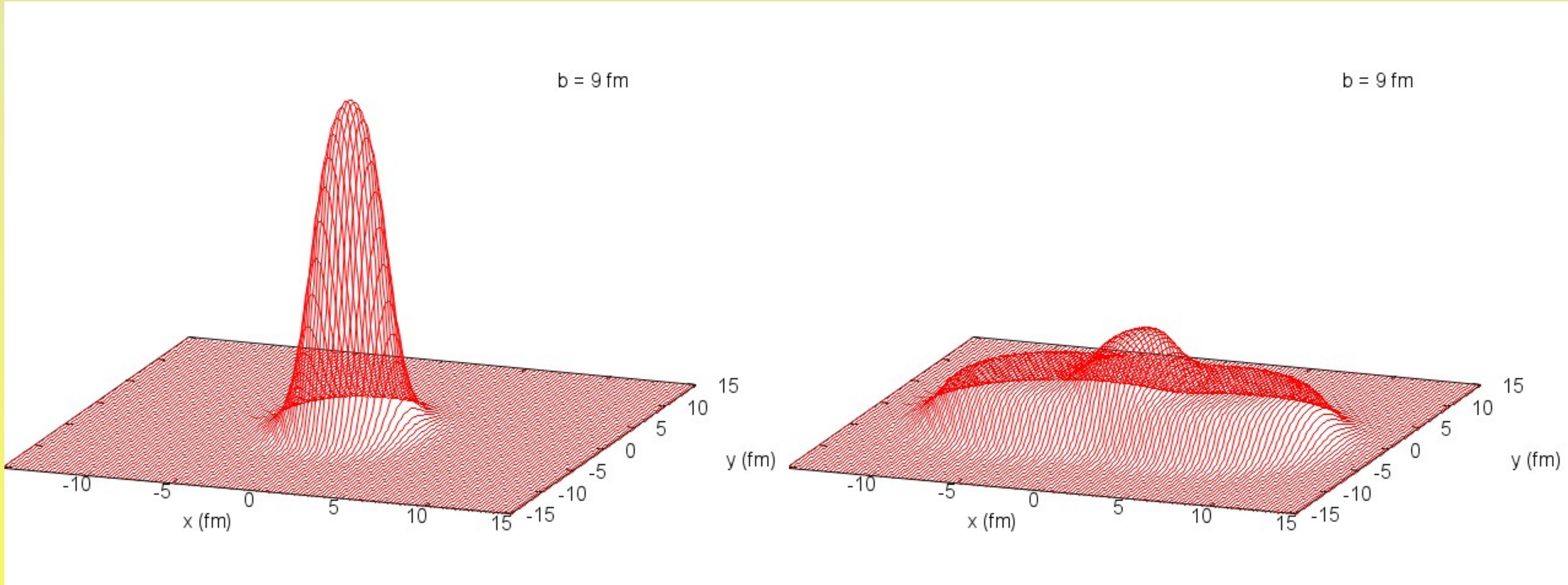

$$b = 9 \text{ fm}$$

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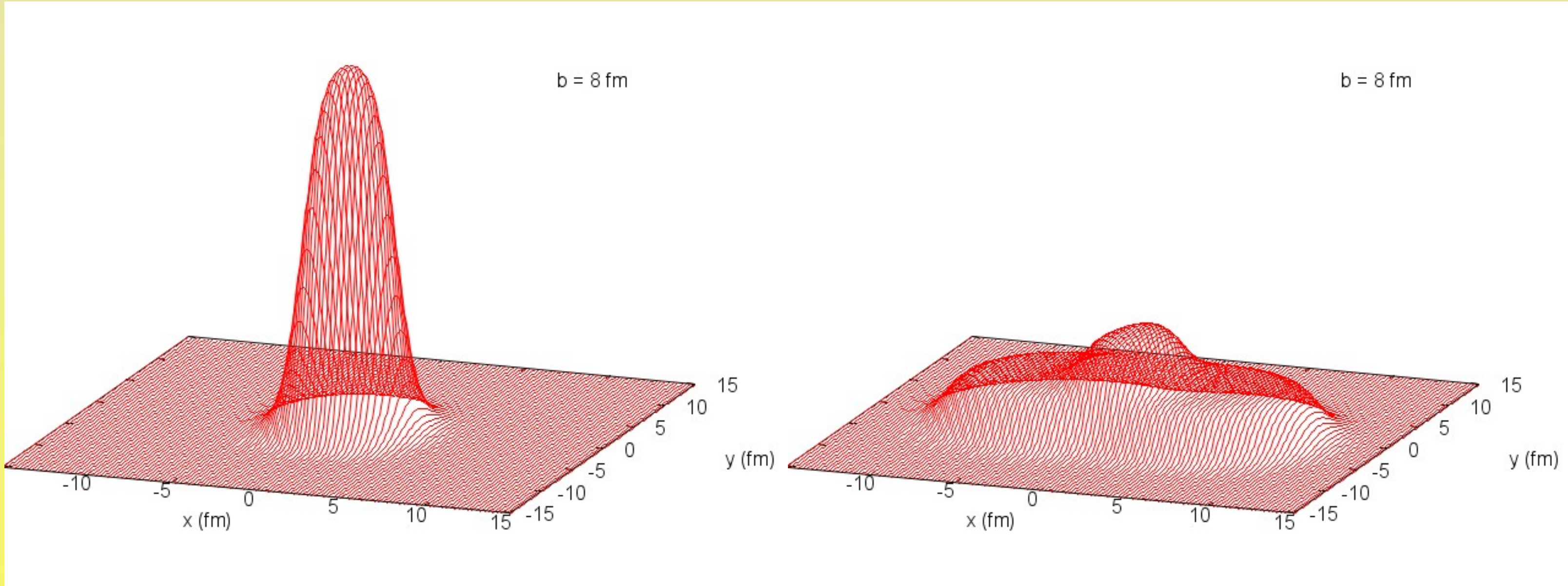

$$b = 8 \text{ fm}$$

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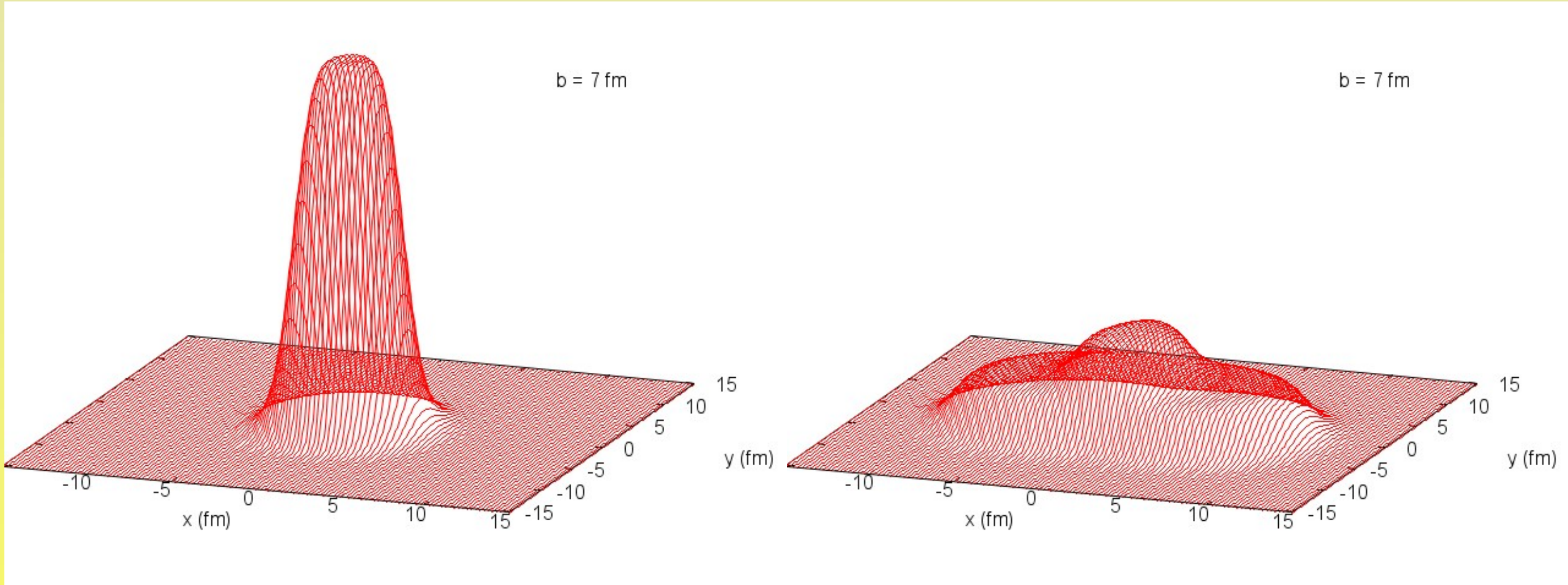

$$b = 7 \text{ fm}$$

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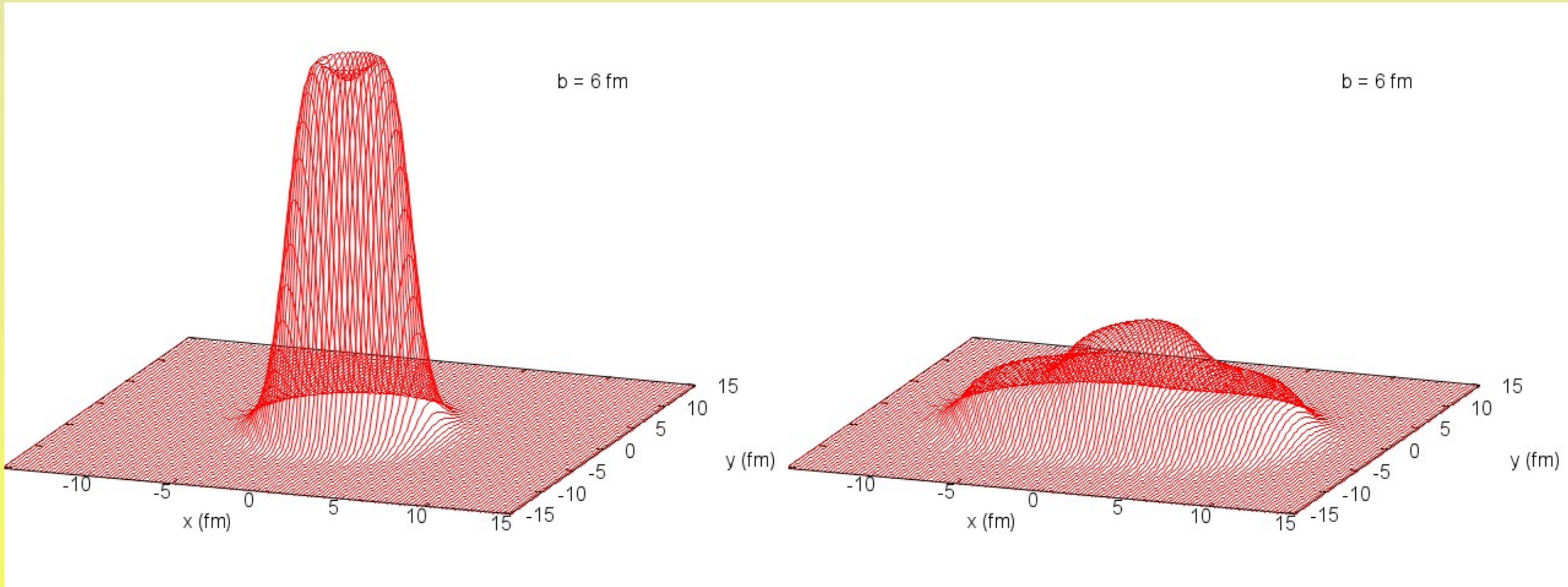

$b = 6$ fm

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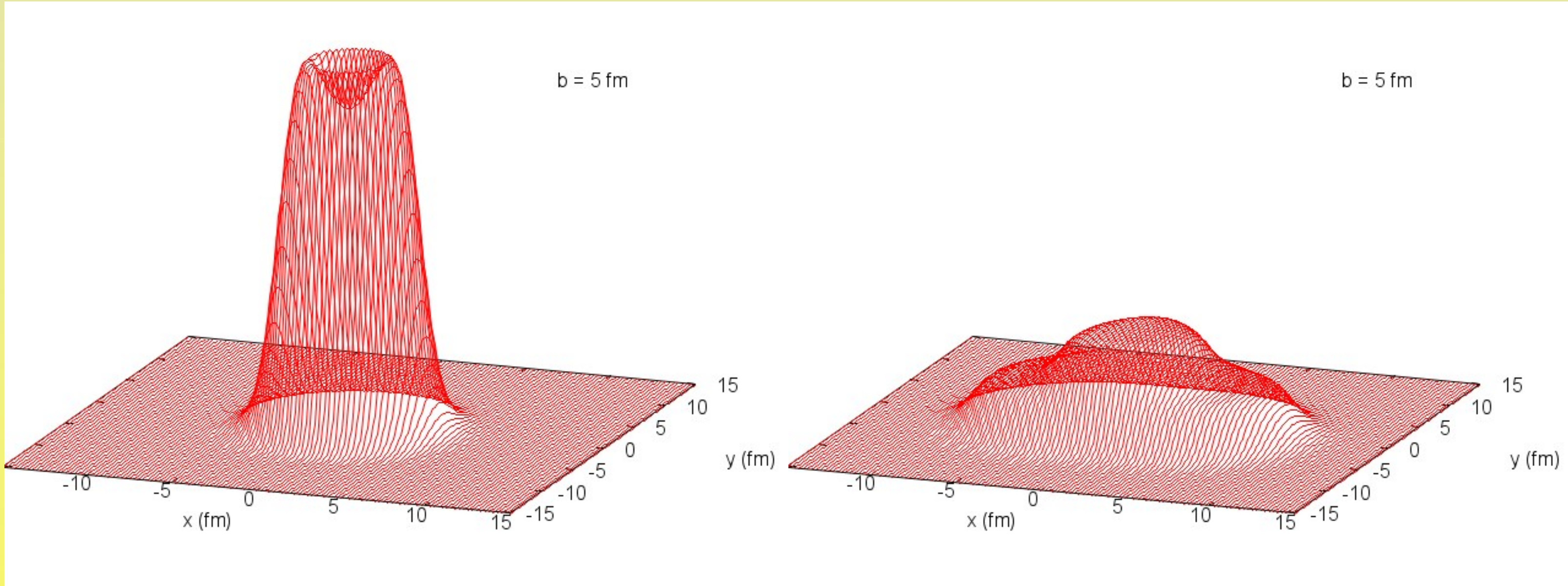

$$b = 5 \text{ fm}$$

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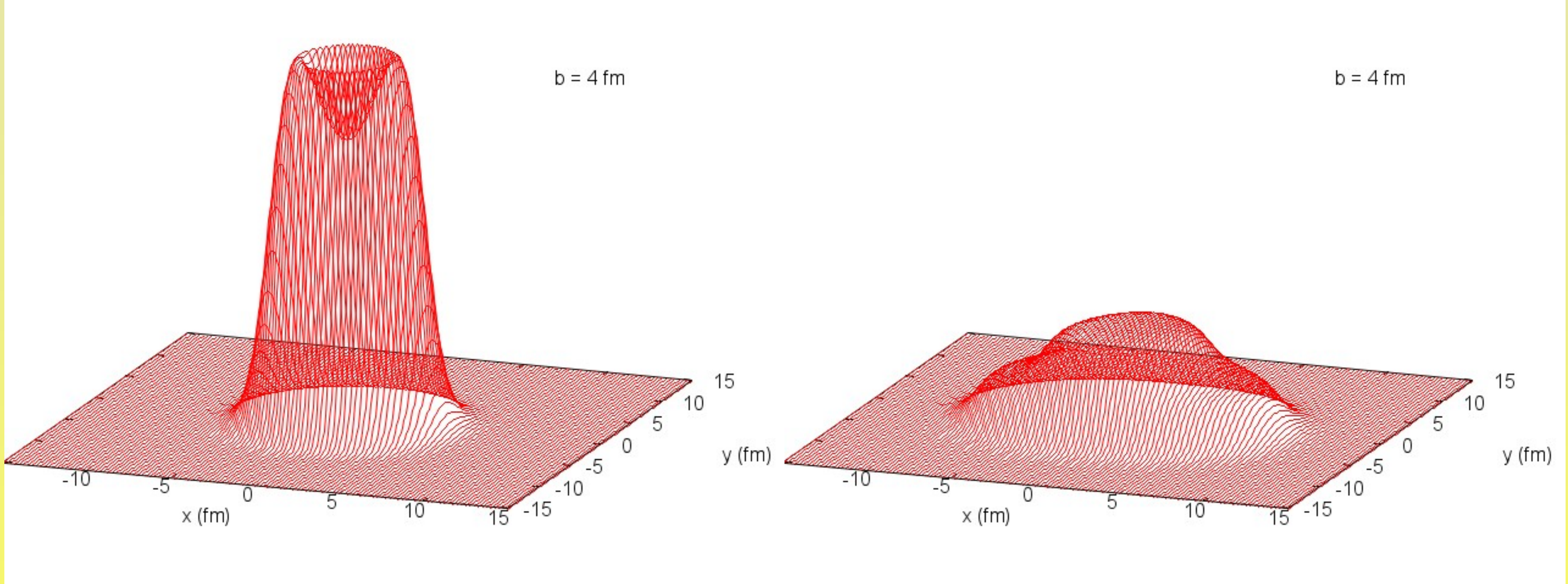

$$b = 4 \text{ fm}$$

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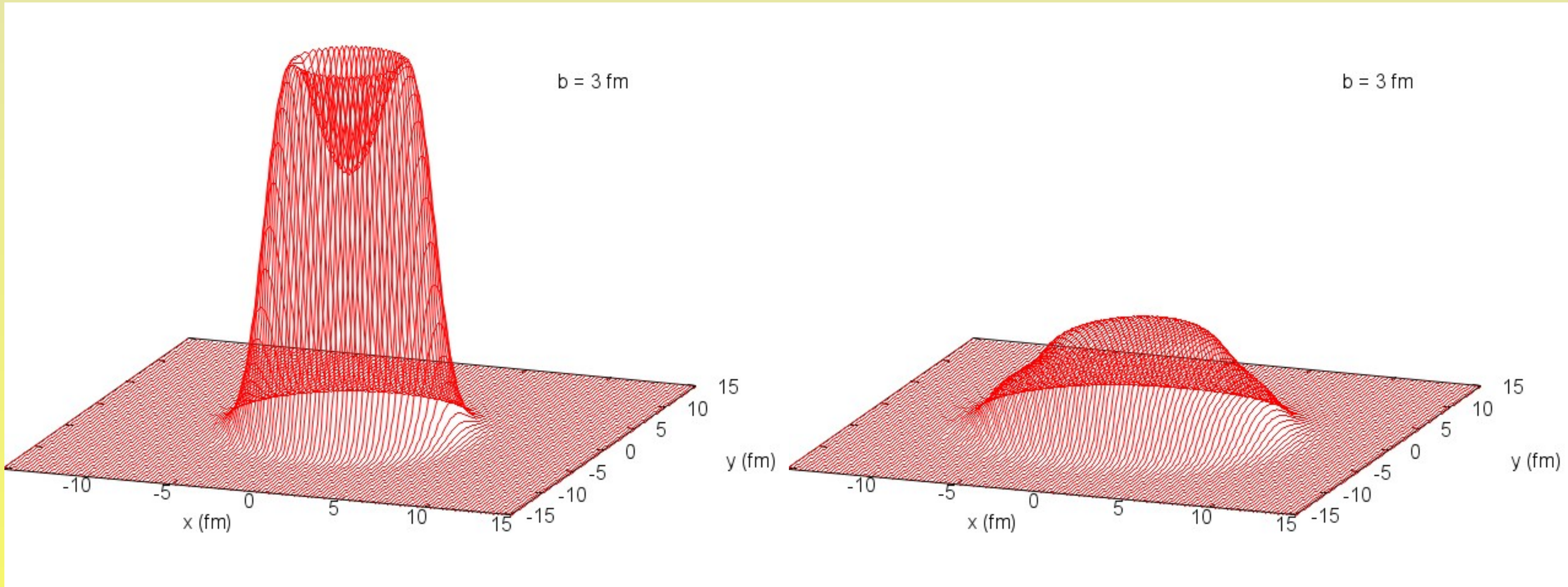

$$b = 3 \text{ fm}$$

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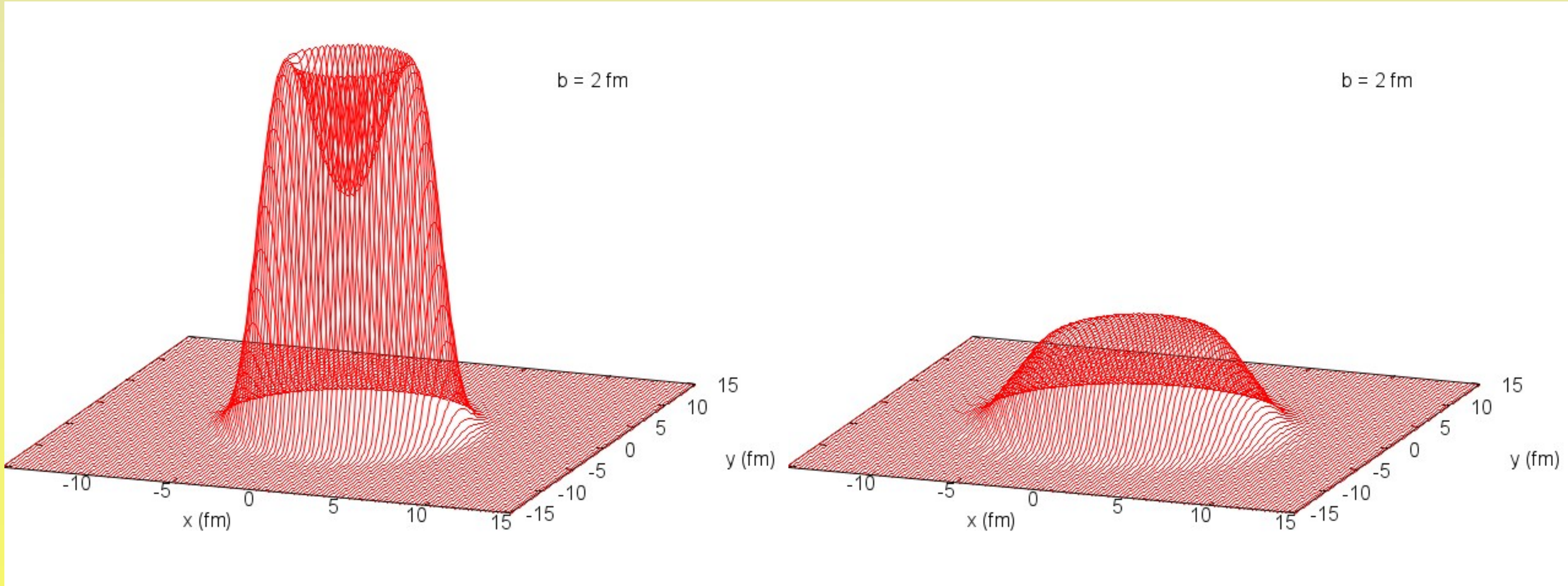

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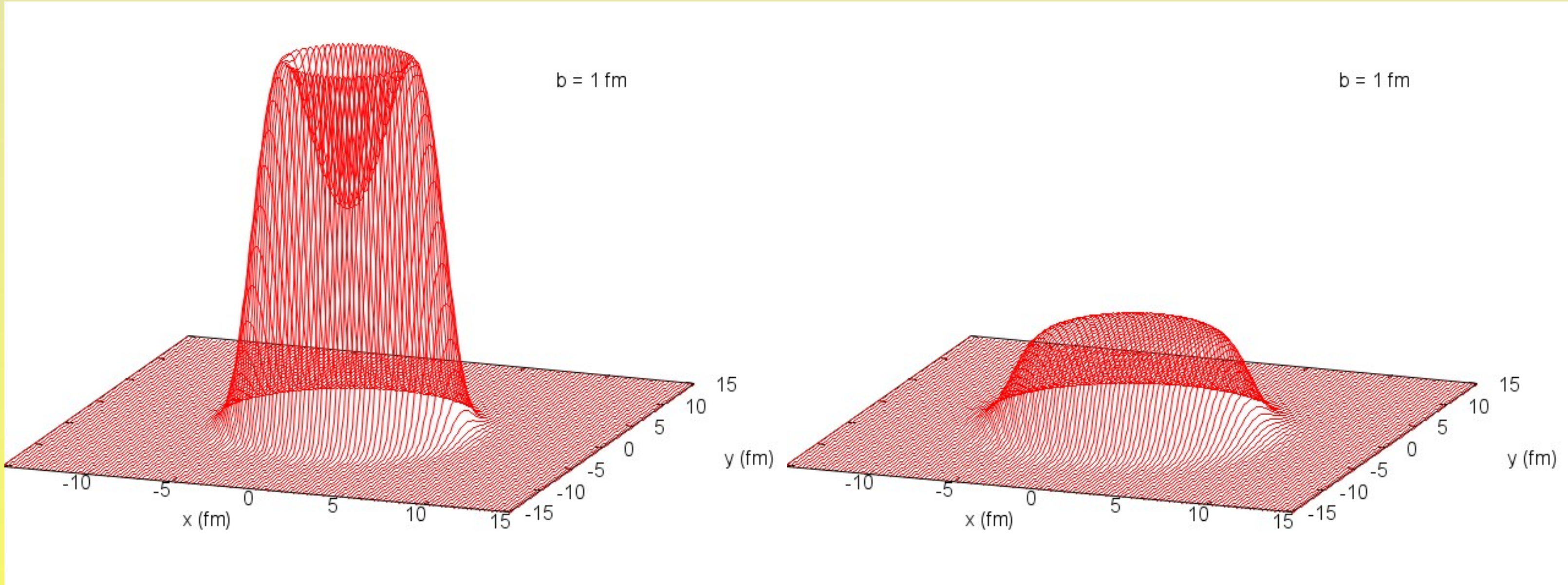

$b = 1$ fm

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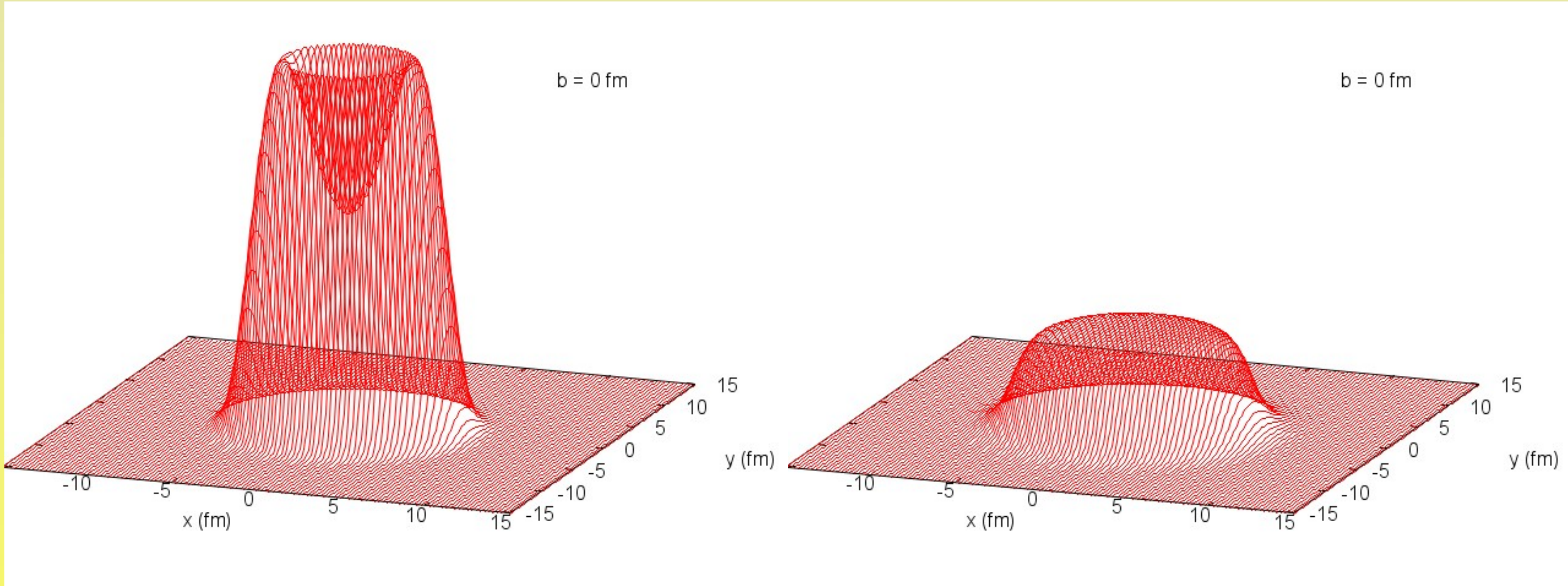
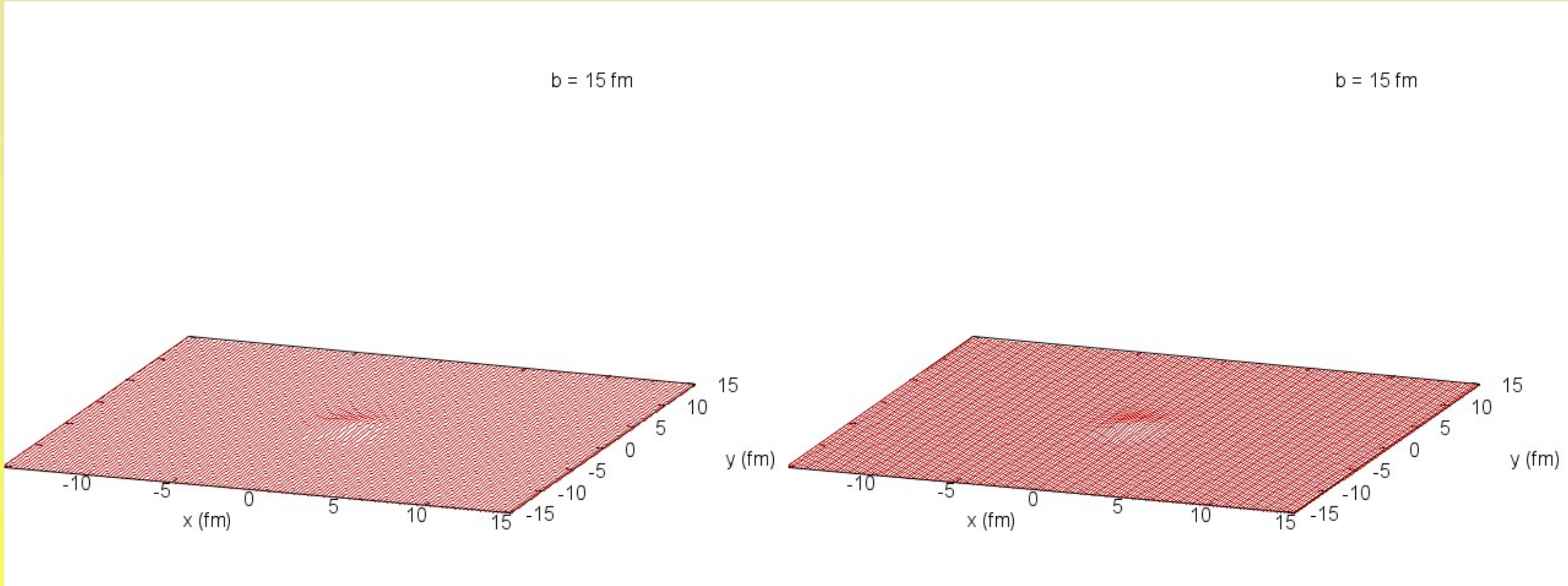


$b = 0$ fm

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

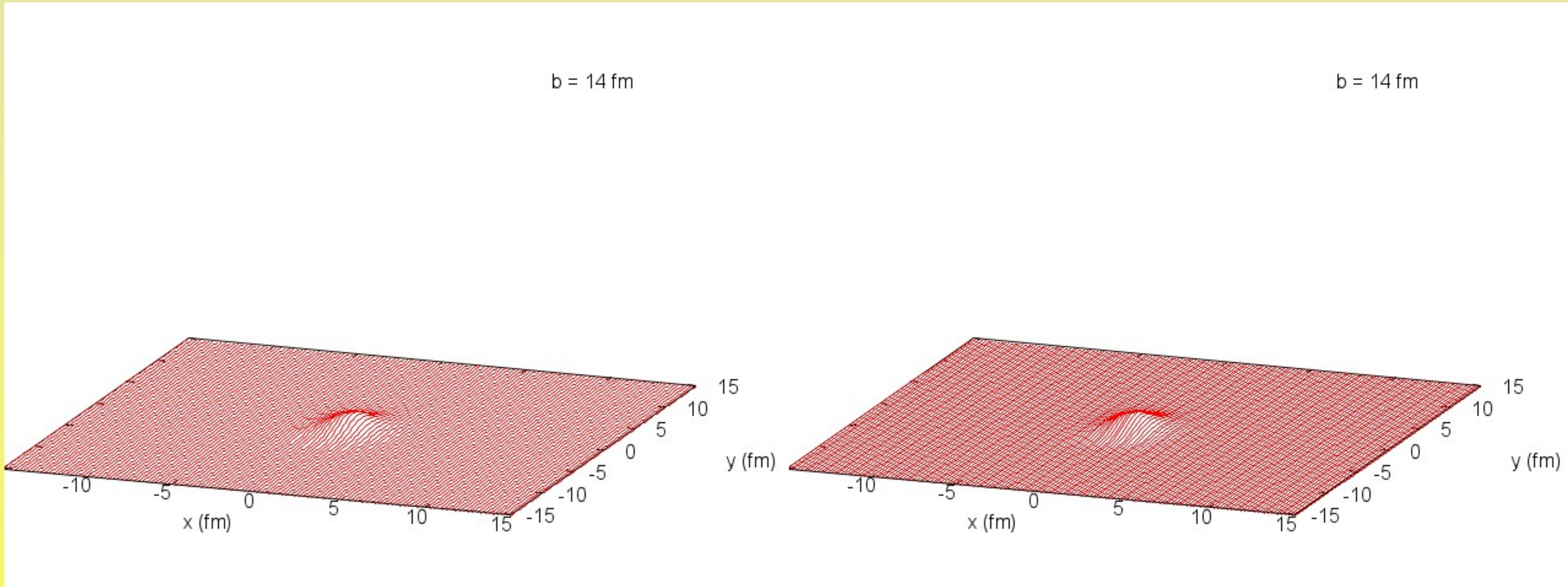
$S_{AA} e^{-\int dt\, \Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA} e^{-\int dt\, \Gamma}$, for $\Upsilon(2S)$



$$b = 15 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

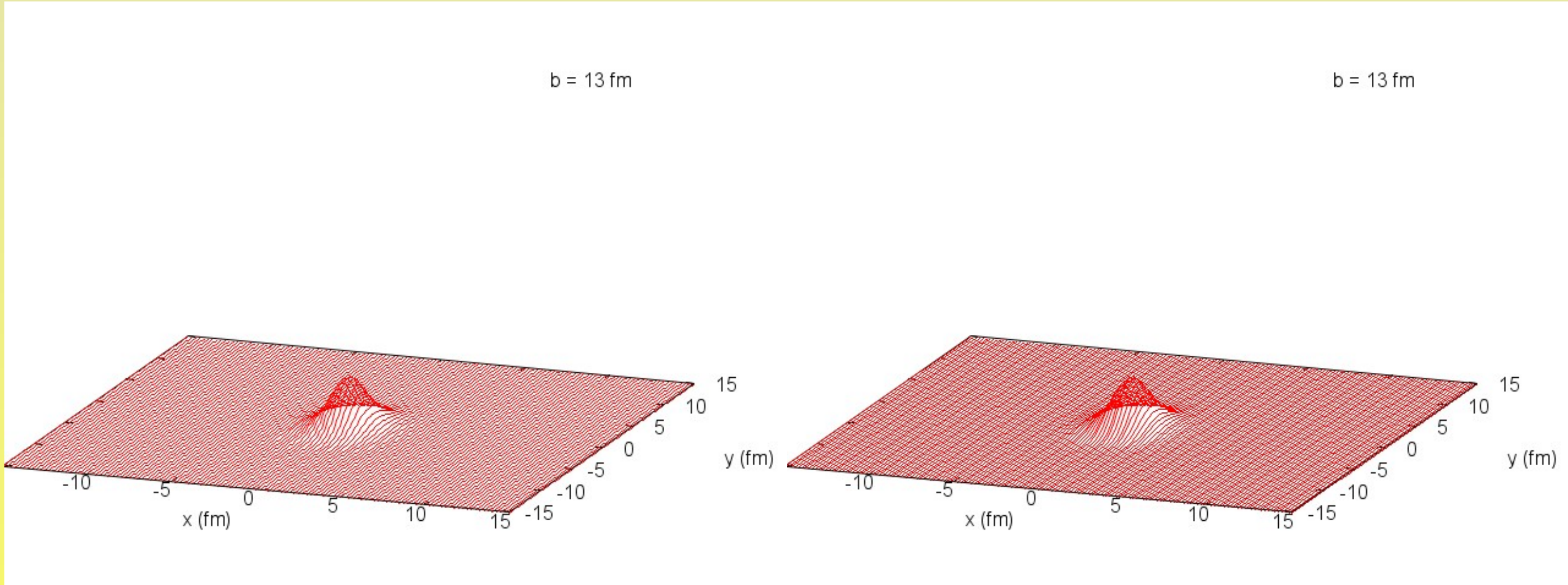
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 14 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

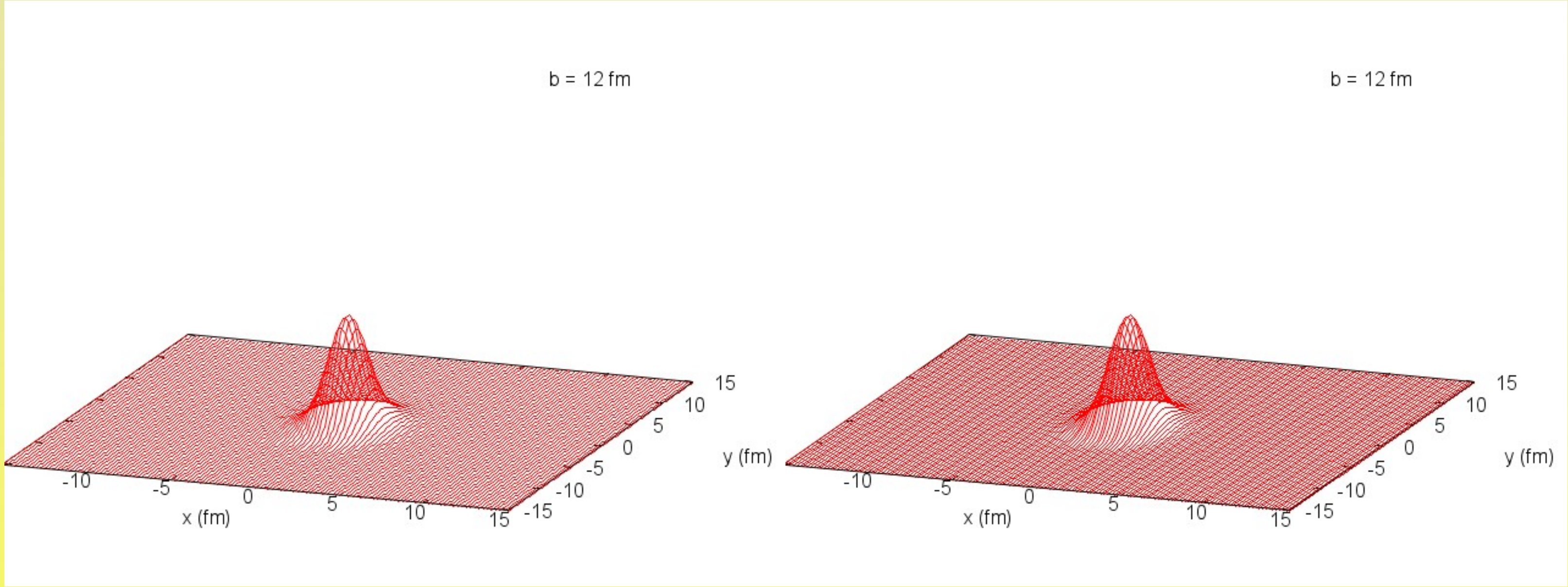
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 13 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

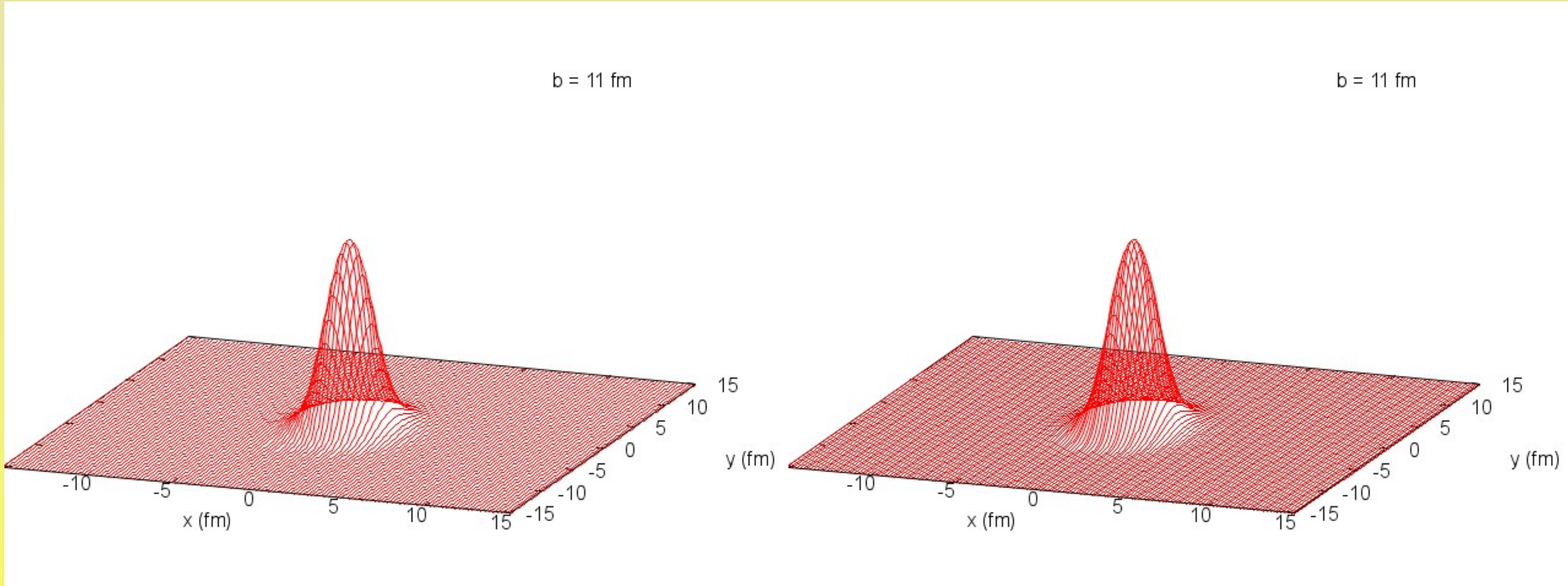
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 12 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

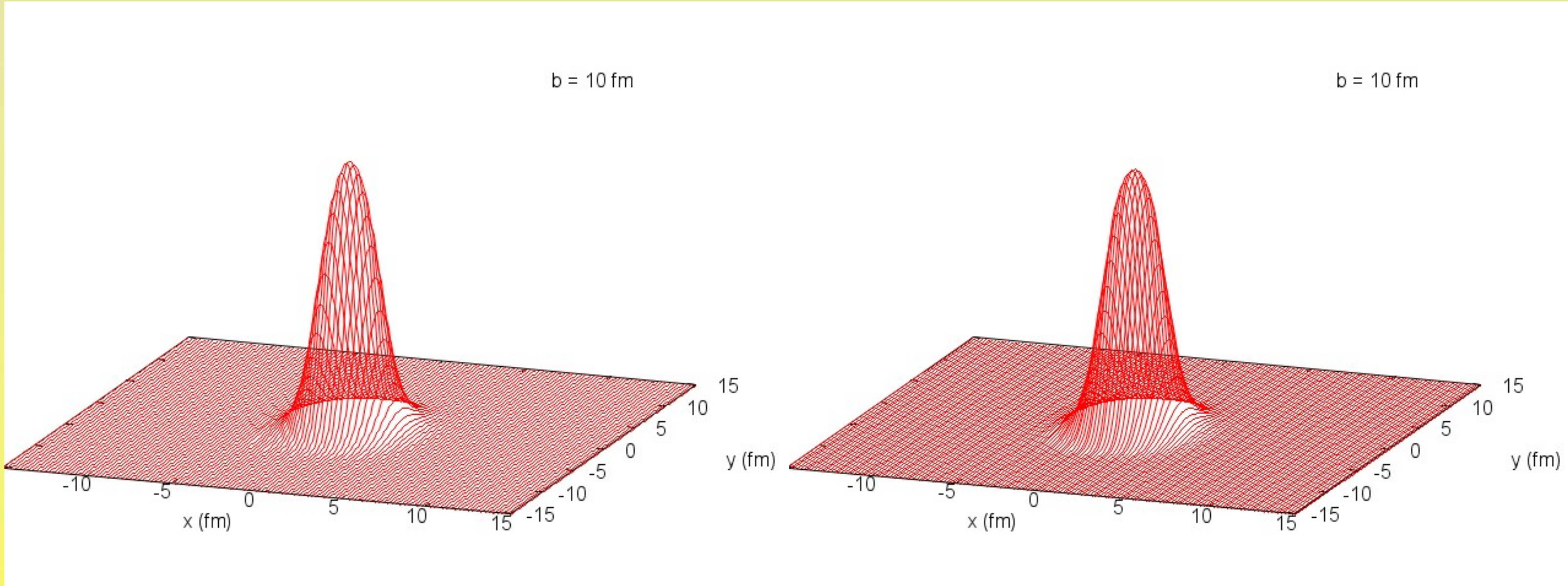
$$S_{AA}e^{-\int dt\,\Gamma}, \text{ for } \Upsilon(1S) \qquad S_{AA}e^{-\int dt\,\Gamma}, \text{ for } \Upsilon(2S)$$



$$b = 11 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

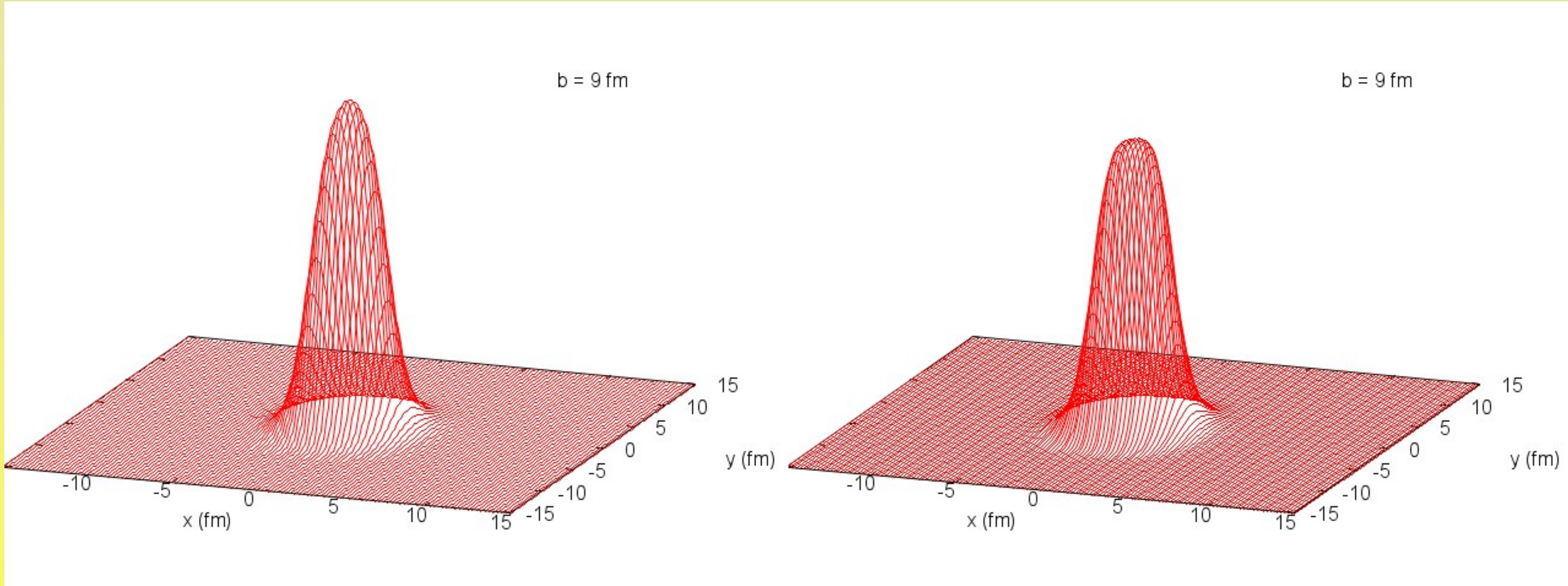
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$b = 10$ fm

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

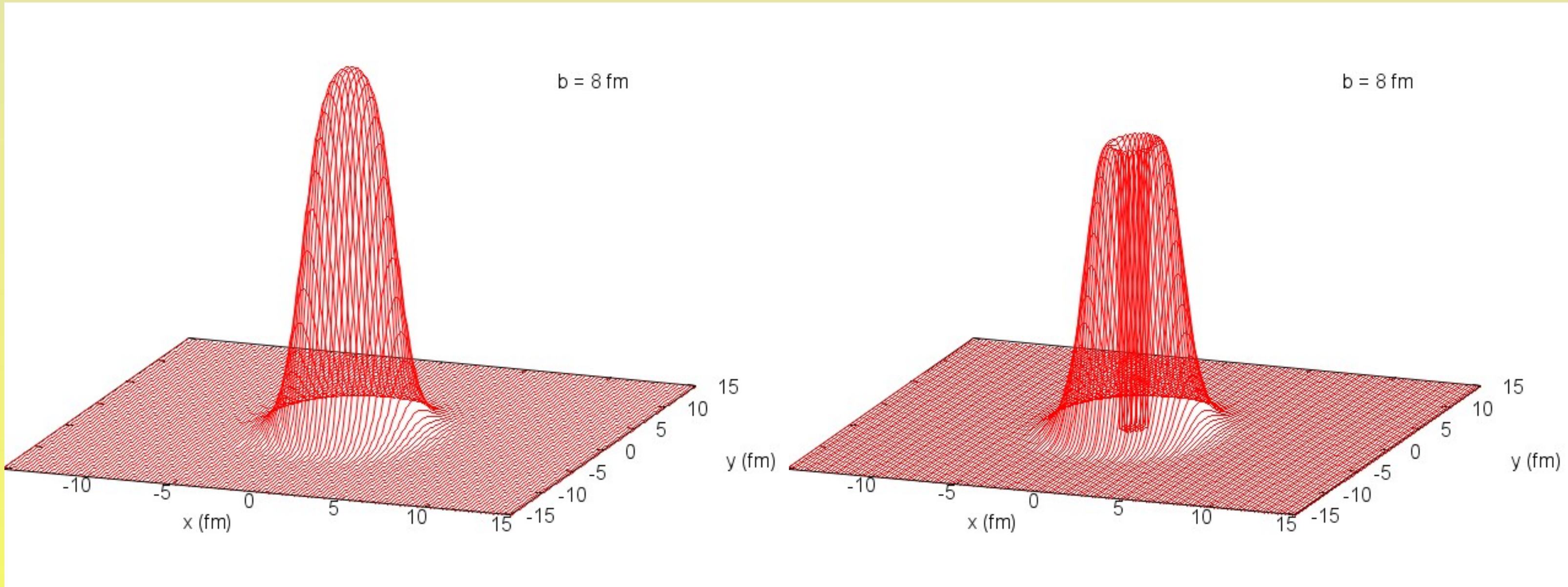
$S_{AA} e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $S_{AA} e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$b = 9$ fm

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

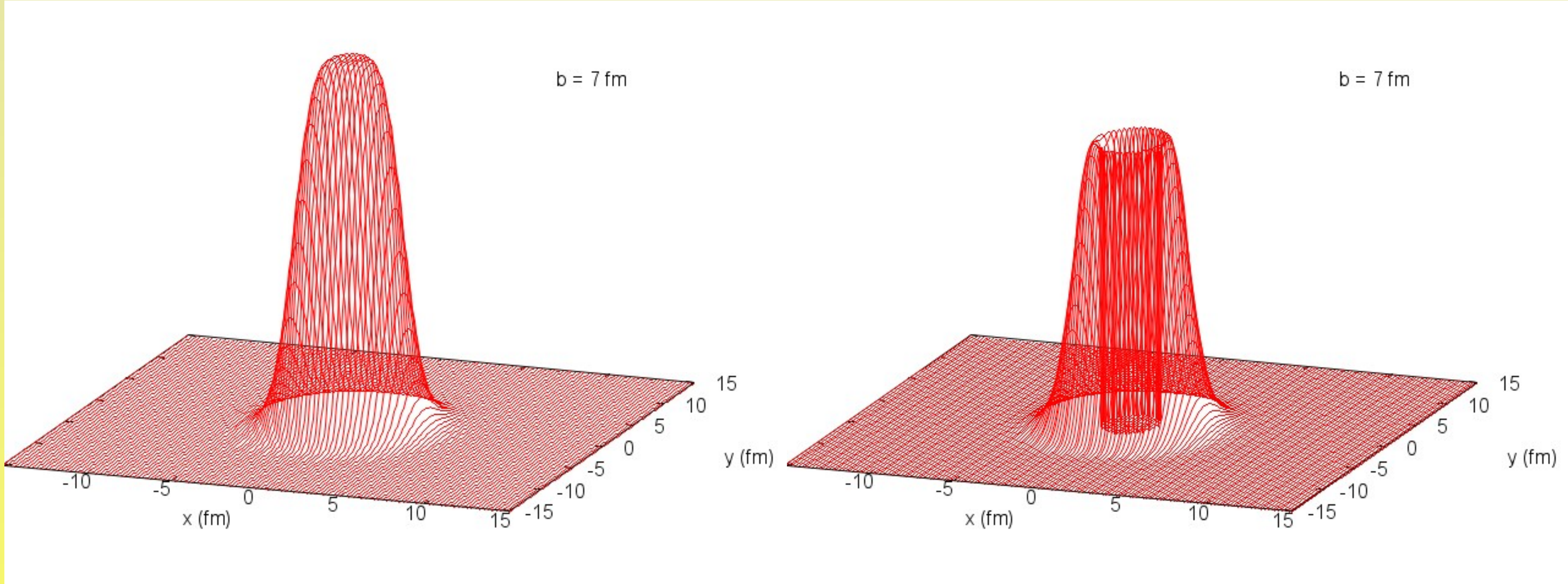
$$S_{AA}e^{-\int dt\,\Gamma}, \text{ for } \Upsilon(1S) \qquad S_{AA}e^{-\int dt\,\Gamma}, \text{ for } \Upsilon(2S)$$



$$b = 8 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

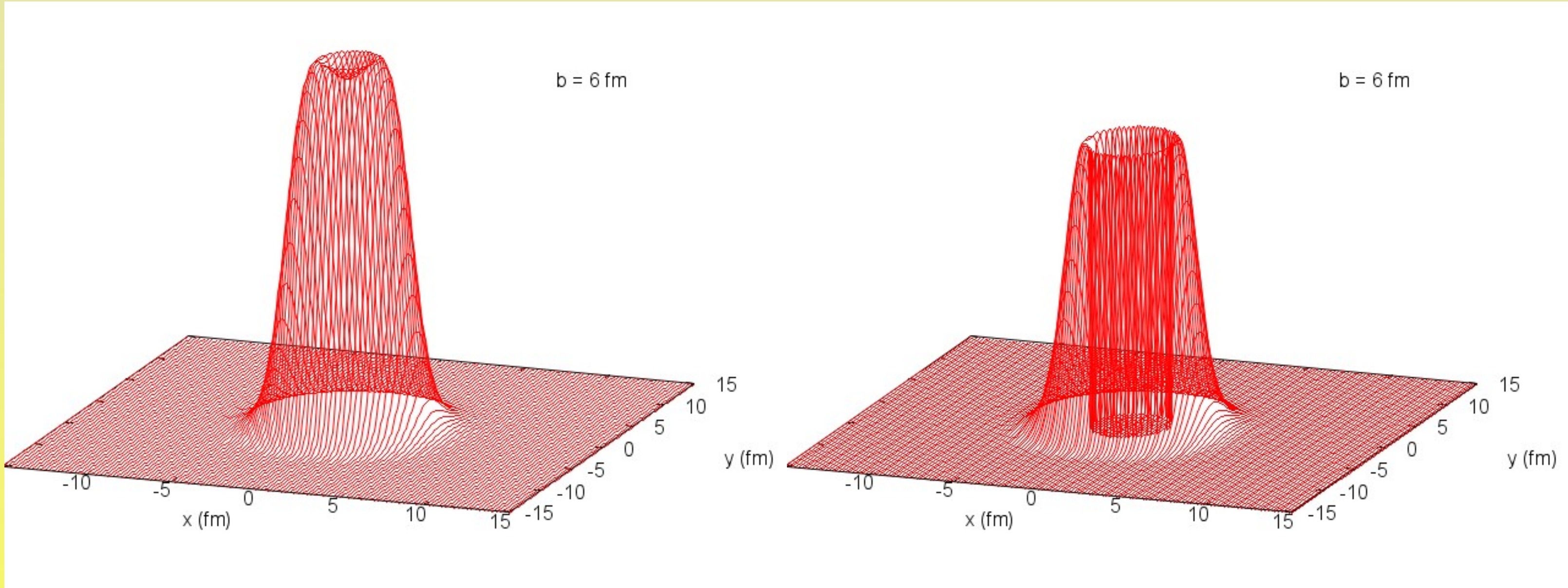
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 7 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

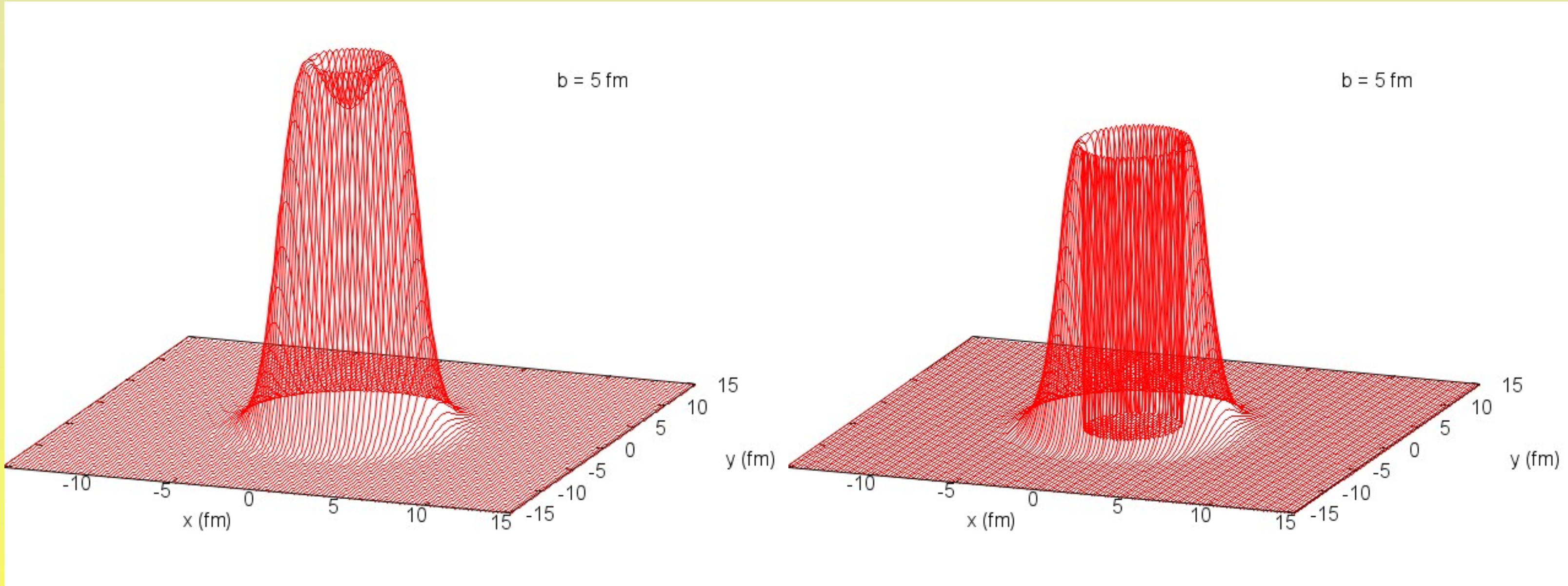
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 6 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

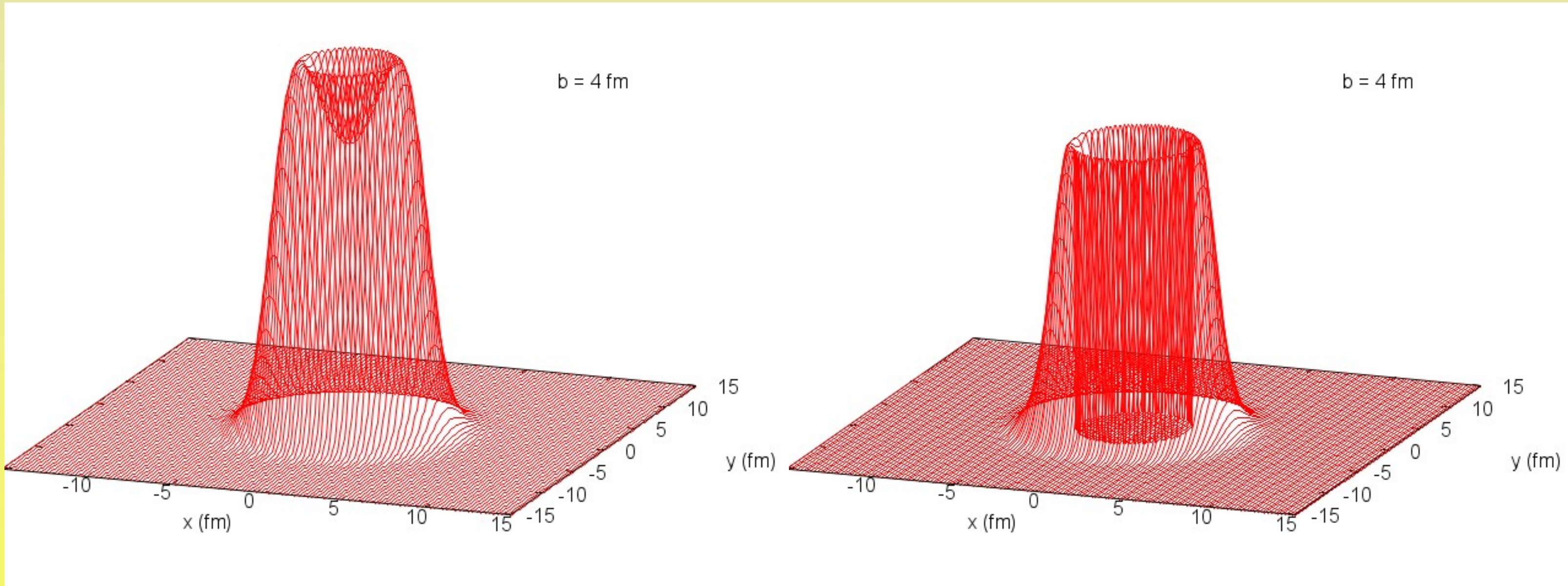
$S_{AA} e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad S_{AA} e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 5 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

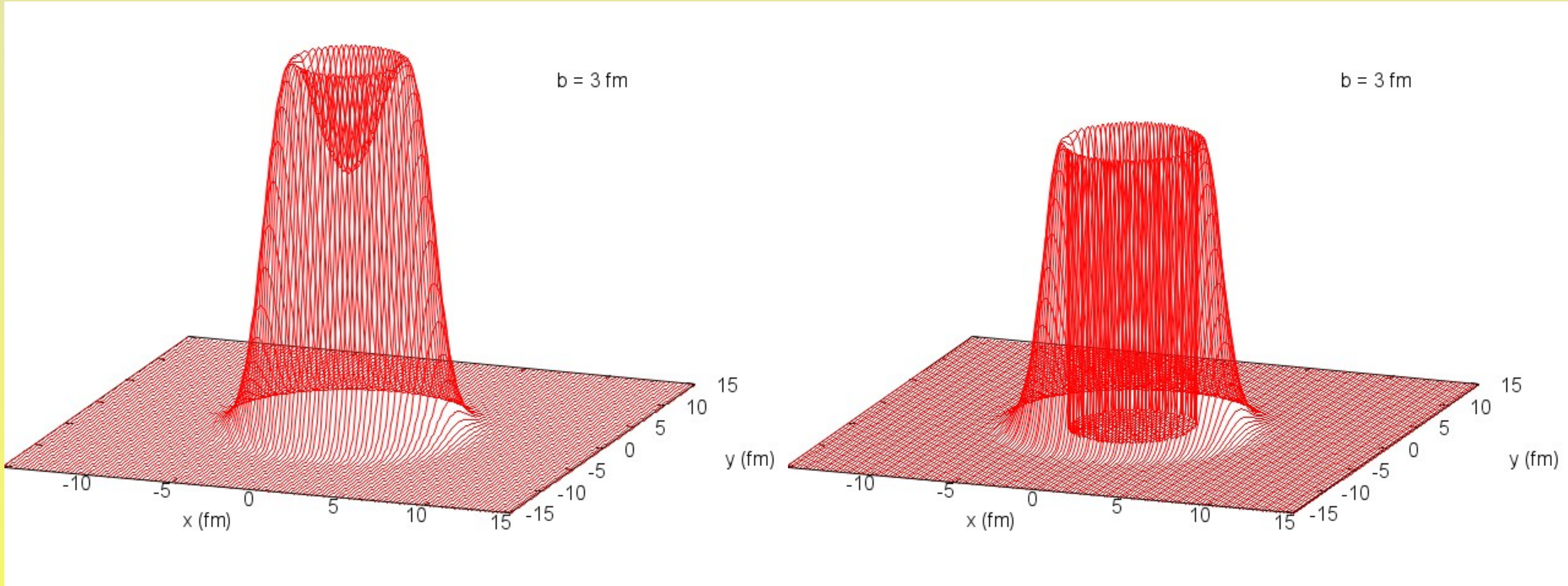
$S_{AA} e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA} e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 4 \text{ fm}$$

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

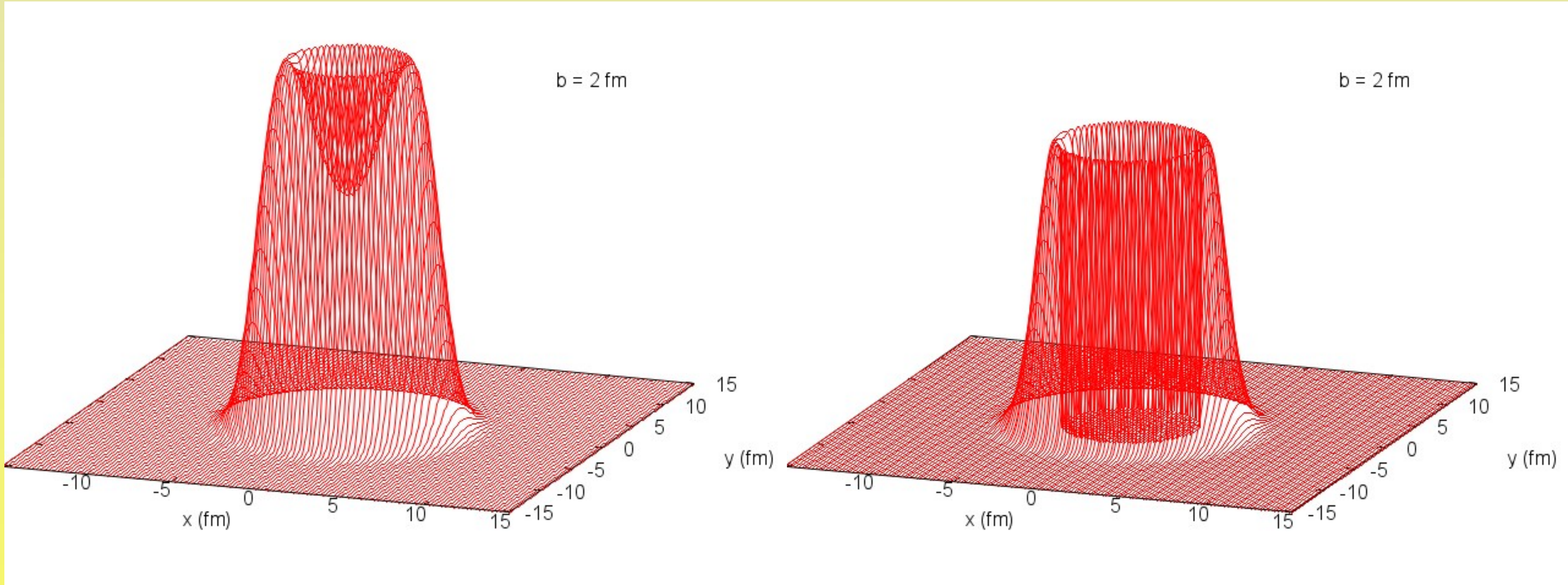
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$b = 3$ fm

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

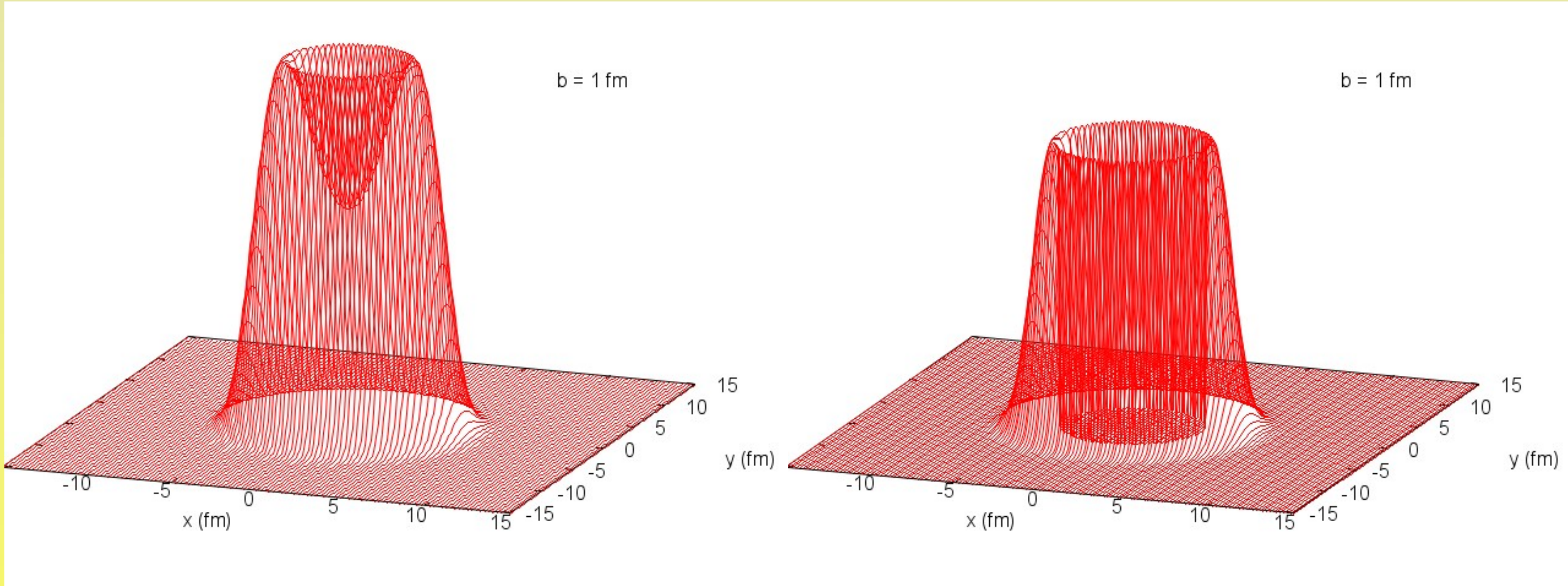
$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 2 \text{ fm}$$

Relative occupation of Υ(1S) and Υ(2S)

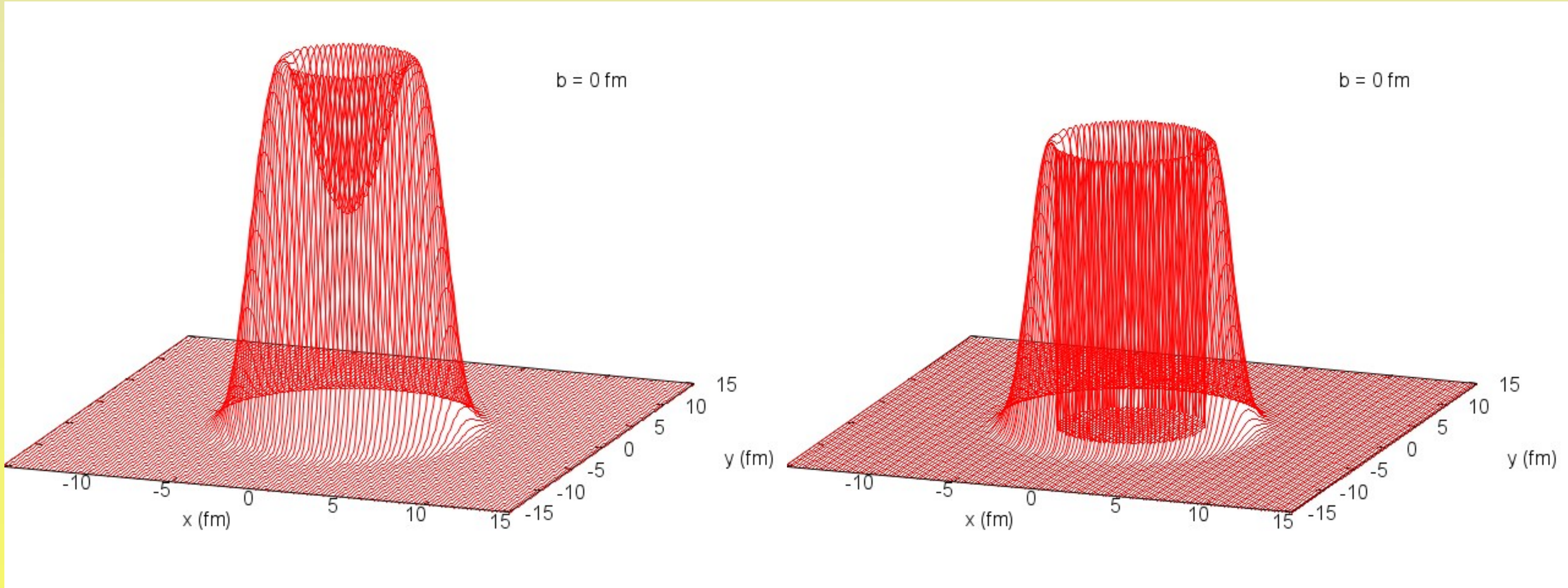
$S_{AA}e^{-\int dt\,\Gamma}$, for Υ(1S) $S_{AA}e^{-\int dt\,\Gamma}$, for Υ(2S)



$b = 1$ fm

Relative occupation of $\Upsilon(1S)$ and $\Upsilon(2S)$

$S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(1S)$ $\quad$ $S_{AA}e^{-\int dt\,\Gamma}$, for $\Upsilon(2S)$



$$b = 0 \text{ fm}$$

The decay cascade

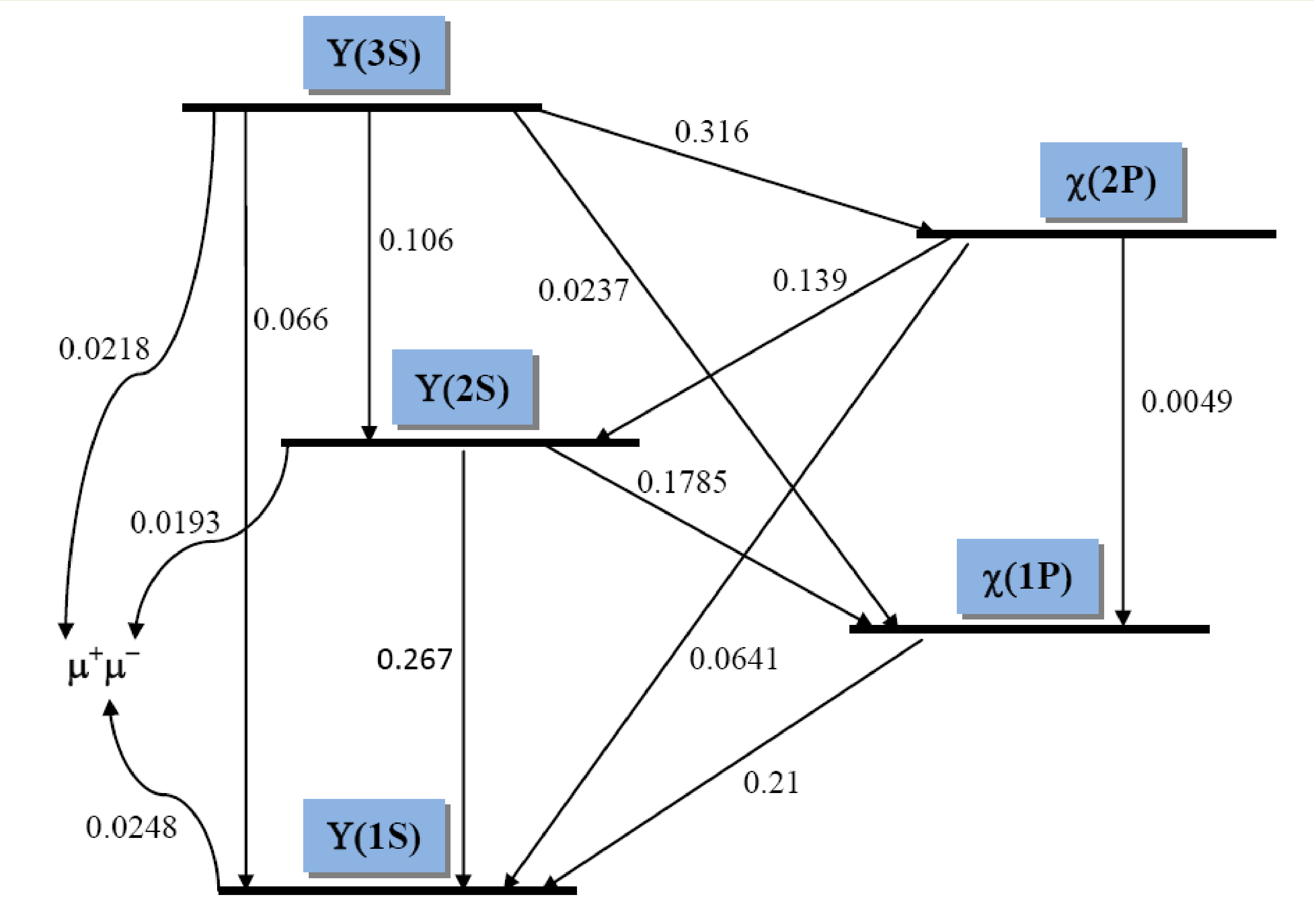


Figure: Branchings for decays within the Υ family and into $\mu^{\pm}$ (Nakamura and Particle Data Group, 2010).

The nuclear suppression factor $R_{AA}(\Upsilon(1S))$

- The full suppression factor of a state $I =$ 1S, 2S, 3S, 1P, 2P is obtained from the branching ratios, preliminary suppression factors and initial populations,

$$R_{AA}(I) = \frac{\sum_{I \leq J} \mathcal{C}_{IJ} N^{\text{init}}(J) R_{AA}^{\text{prel}}(J)}{\sum_{I \leq J} \mathcal{C}_{IJ} N^{\text{init}}(J)}$$

The nuclear suppression factor $R_{AA}(\Upsilon(1\text{S}))$

- The full suppression factor of a state $I =$ 1S, 2S, 3S, 1P, 2P is obtained from the branching ratios, preliminary suppression factors and initial populations,

$$R_{AA}(I) = \frac{\sum_{I \le J} \mathcal{C}_{IJ} N^{\text{init}}(J) R_{AA}^{\text{prel}}(J)}{\sum_{I \le J} \mathcal{C}_{IJ} N^{\text{init}}(J)}$$

- The initial populations N^{init} (normalized to the $\Upsilon(1\text{S})$-yield) are taken from the 2010 CMS pp-run Chatrchyan et al. (2011) and the CDF measurement (Affolder et al., 2000),

$$N^{\text{init}}(1\text{S}) = 0.458, \qquad N^{\text{init}}(1\text{P}) = 1.29,$$
$$N^{\text{init}}(2\text{S}) = 0.371, \qquad N^{\text{init}}(2\text{P}) = 0.976,$$
$$N^{\text{init}}(3\text{S}) = 0.387.$$

Latest Results

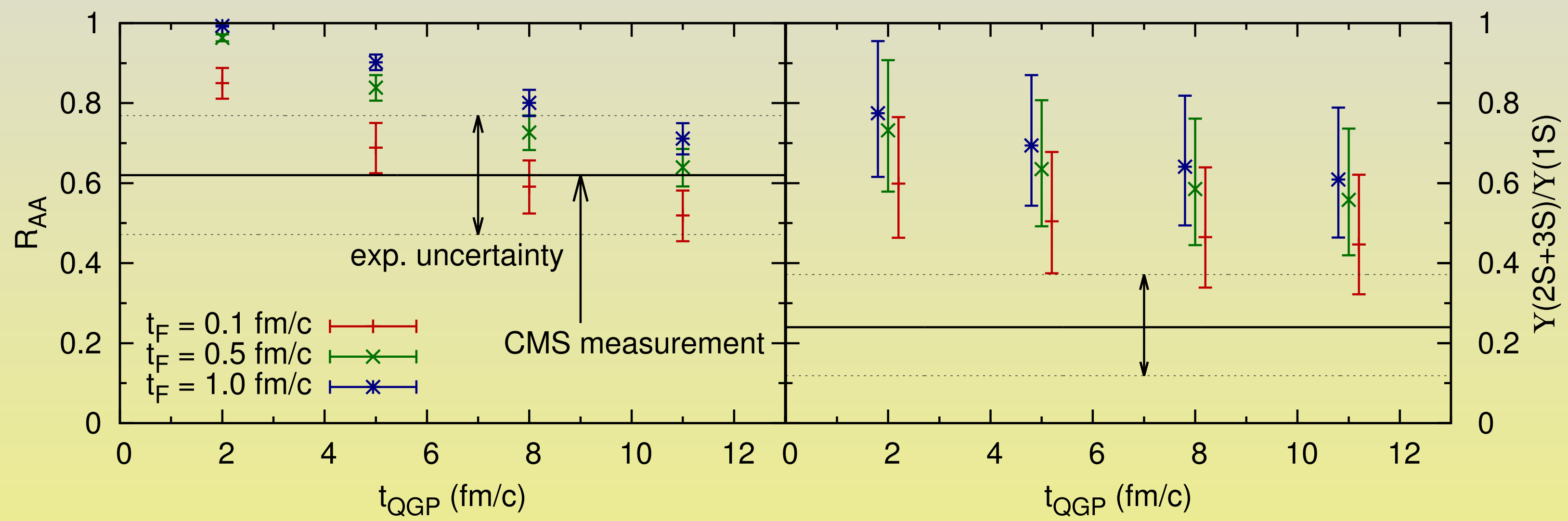
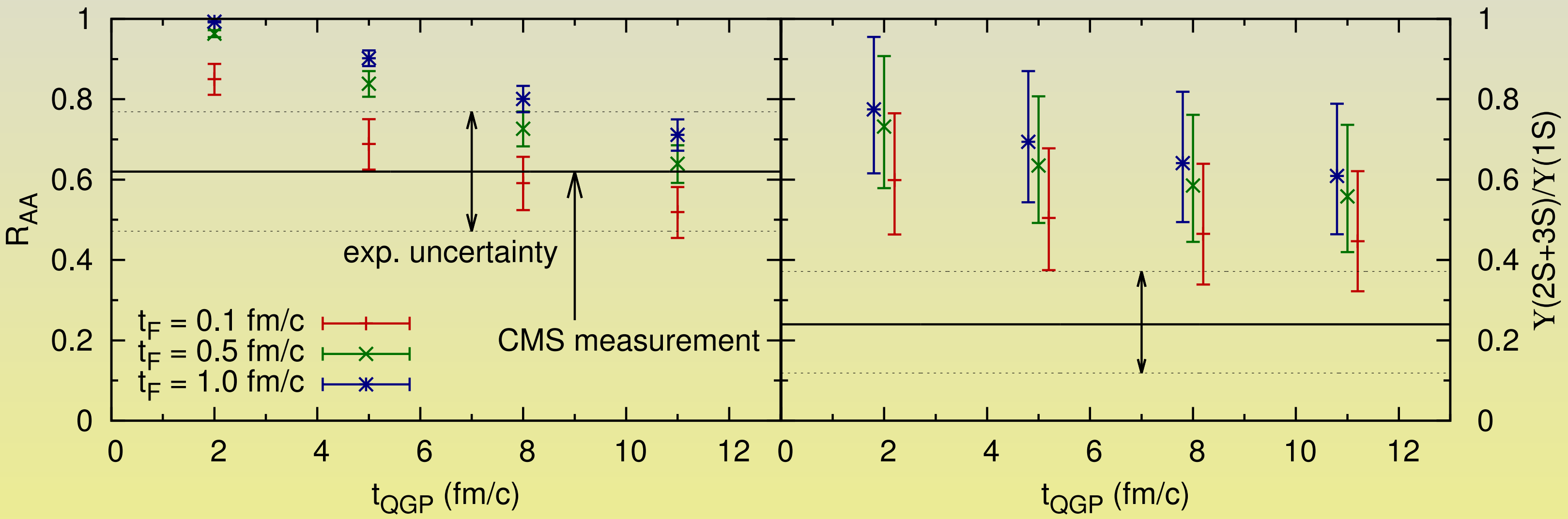


Figure: Results of the model calculation: $R_{AA}(\Upsilon(1S))$ (left) and $\Upsilon(2S+3S)/\Upsilon(1S)$ (right) vs t_{QGP} for different t_F.

- Free parameters are t_{QGP} and t_F. Here the maximum temperature at Υ-formation ranges from $T(0, t_F, 0, 0) = 200$ - 800 MeV
- R_{AA} partially agrees but mostly R_{AA} and $\Upsilon(2S+3S)/\Upsilon(1S)$ are both too large

Latest Results



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- R_{AA} partially agrees but mostly R_{AA} and $\Upsilon(2S+3S)/\Upsilon(1S)$ are both too large
- At this stage, "too large" is *better* than agreement!

Outlook and challenges

- The first new particle to be discovered by the LHC turns out to be the $\chi_b(3\text{P})$ (mass $m \approx 10.53$ GeV) (ATLAS Collaboration, 2011)

  $\chi_b(3\text{P})$ is not so rare but the decay rates are unknown
- Refinement of the theoretical treatment of quarkonia in a thermal medium
- Estimate of other suppression mechanisms like nuclear shadowing and final state interactions and of direct recombination (as opposed to statistical recombination)
- p_T-dependent calculation
- Many possible improvements of the fireball-model

Thank you for your attention.

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