Υ production at RHIC and CERN

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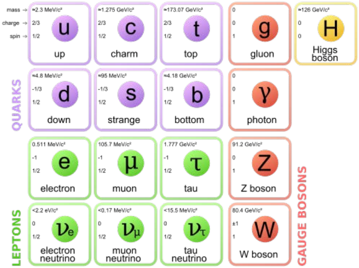
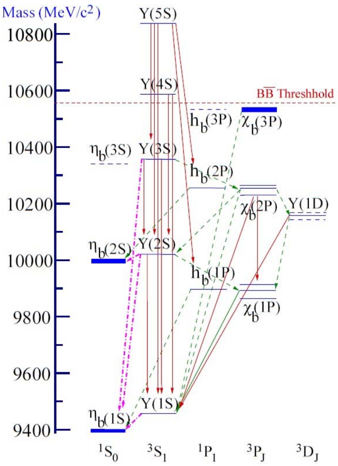
What is the Υ ?

- Υ is a $b\bar{b}$ bound state
- Potential models can describe their structure
- Perturbation theory might describe their production rate
- They can serve as probe of QGP



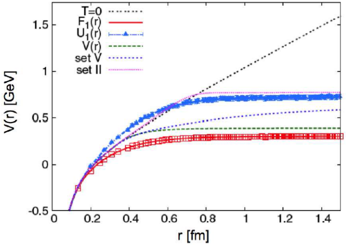
[http://en.wikipedia.org/wiki/File:Standard-Model-of-Elementary-Particles.svg]



[Patrignani, Pedlar, and Rosner (2013),ARXIV:1212.6552]

Description of Quarkonia

- Important masses:
  - $m_b \approx 4.18\,\text{GeV}$
  - $m_B \approx 5.28\,\text{GeV}$
  - $m_\Upsilon \approx 9.46\,\text{GeV}$
- Υ is a narrow resonance:
  - $m_\Upsilon < 2m_B$
  - OZI rule
- Effect of virtual b and $\overline{b}$ quarks is negligible, quantum mechanical potential calculation is applicable
- Potential calculations: $v_b^2 \approx 0.1$ (for charmonium $v_c^2 \approx 0.3$)
- Non-relativistic theories can be applied



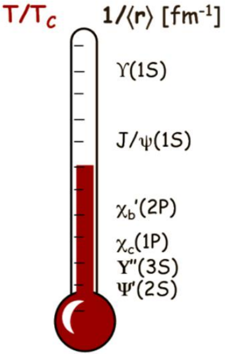
[Mocsy (2009),ARXIV:0811.0337]

- Low temperature: Cornell potential $V(r) = kr - 4/3\frac{\alpha_s}{r}$
- High temperature (QGP): Debye-screened potentials

Motivation

Suppression of quarkonia could signal QGP, and could serve as a thermometer (Debye-screening). Bottomonia differs from charmonia in the following ways:

- $m_b \approx 4.2\,\mathrm{GeV} > m_c \approx 1.3\,\mathrm{GeV} \rightarrow$ non-relativistic approximations work better
- Initial state nuclear suppression is lower due to the higher mass
- $m_\Upsilon >> T$, bottomonia production is dominated by hard processes
- Bottom quarks are rare $\rightarrow$ probability of recombination is low



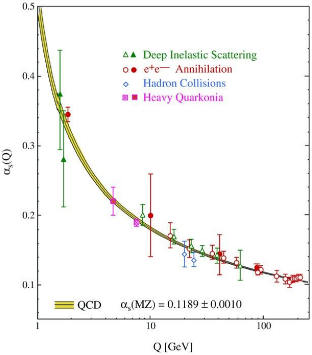
[dnp-old.nscl.msu.edu/current/quarkonia-2009-08.html]

Structure of the talk

Quarkonia production in pp collisions

QCD

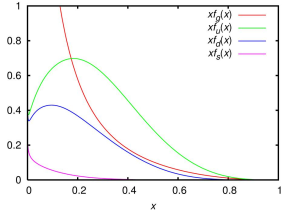
- QCD describes strong interaction, but extremely complex
- Production of $b\bar{b}$ happens at high energy scale
- QCD coupling constant is small at high energies
- QCD describes quarks and gluons, initial hadrons are unknown quantum state of them
- For Υ production, the quarks need to hadronize, which is a non-perturbative process



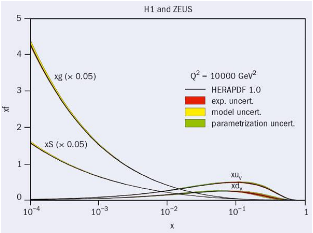
[Bethke (2007),HEP-EX/0606035]

Factorization of QCD

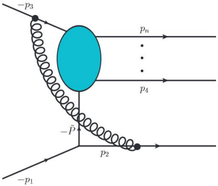
- For the discription of the initial state usually we use Parton Distribution Functions (PDF). This gives the expectation value density of quarks and gluons in the nucleus
- Hard scattering is described by pQCD
- Fragmentation is also taken into account with probabilities



$Q^2 = 4\ \mathrm{GeV}^2$,CTEQ6
[http://en.wikipedia.org/wiki/Parton]



[CERN Courier January/February 2010]

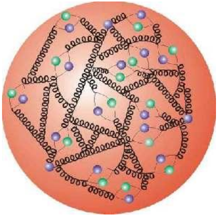


[Catani, Florian, and Rodrigo (2012),ARXIV:1211.7274]

Factorization intuitively

- Parton model: hadron is an unknown state of quarks and gluons
- Lorentz-contraction: $d = d_0\sqrt{1 - v^2} << d_0$
- Time-dilatation: $t_{int} = \frac{\tau_{int}}{\sqrt{1-v^2}} >> \tau_{int}$
- $t_{coll} << t_{int}$ limit: hadrons are stationary and "free" (AF!)
- Partons have definit momentum
- No interference between IS, FS and hard processes
- Probabilities can be used (fragmentation functions, PDF-s)

[Relativistic Heavy Ion Collider]



[Deutsches Elektronen-Synchrotron]

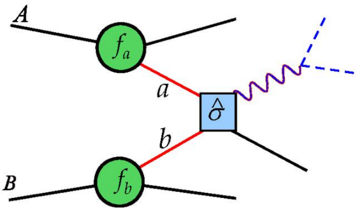
[Collins, Soper, and Sterman (1988), HEP-PH/0409313]

Factorization intuitively II.

$$d\sigma_{AB->c+X} = \sum_a \sum_b \int_0^1 d\xi_a \int_0^1 d\xi_b f_{a/A}(\xi_a) f_{b/B}(\xi_b) d\sigma'_{ab->c+X}$$

Applications:

- DIS: $l + A \to l' + X$
- $e^+ + e^- \to A + X$
- Drell-Yan processes
  - $A + B \to \mu^+ + \mu^- + X$
  - $A + B \to W + X$
- $A + B \to$ jet $+X$
- $A + B \to$ heavy quark $+X$



[http://www.scholarpedia.org/article/Bjorken-scaling]

Production of quarkonia

$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\overline{Q}[n]+X) \cdot \left\langle \mathcal{O}^H[n] \right\rangle$$

- n: color, angular momentum collective index
- $d\hat{\sigma}$: Cross section for small relative momentum $Q\overline{Q}$ production
- $\langle \mathcal{O}^H \rangle$: Non-perturbative transition probability of $Q\overline{Q}[n] \rightarrow H$
- Quantum numbers of $Q\overline{Q}[n]$ and $H(\lambda)$ can differ!
- Hard momentum scale: m_Q, production of $Q\overline{Q}[n]$
- Soft(er) momentum scale: $m_Q v << m_Q$, average momentum in the hadron, hadronization
- We wish to calculate $\langle \mathcal{O}^H[n] \rangle$ in a low energy effective field theory (EFT) $\rightarrow$ NRQCD
- The EFT should contain all possible terms consistent with symmetries of QCD, high energy physics is "integrated out"

Non-Relativistic QCD (NRQCD)

$$\mathcal{L}_{NRQCD} = \psi^\dagger \left(iD_0 + \frac{\vec{D}^2}{2m_q} \right) \psi + \chi^\dagger \left(iD_0 - \frac{\vec{D}^2}{2m_q} \right) \chi + \mathcal{L}_{light} + \delta\mathcal{L}$$

$\delta\mathcal{L}$ contains all possible interactions consistent with symmetries

$$\begin{aligned}\delta\mathcal{L}_{bilinear} &= \frac{c_1}{8m_Q^3}\psi^\dagger \vec{D}^4 \psi + \frac{c_2}{8m_Q^2}\psi^\dagger \left(\vec{D} \cdot g\vec{E} - g\vec{E} \cdot \vec{D} \right) \psi \\ &+ \frac{c_3}{8m_Q^2}\psi^\dagger \left(i\vec{D} \times g\vec{E} - g\vec{E} \times i\vec{D} \right) \cdot \vec{\sigma}\psi + \frac{c_4}{2m_Q}\psi^\dagger g\vec{B} \cdot \vec{\sigma}\psi \\ &+ \ldots\end{aligned}$$

$$\delta\mathcal{L}_{4-\mathrm{fermion}} = \sum_i \frac{d_i}{m_Q^2} (\psi^\dagger \mathcal{K}_i \chi)(\chi^\dagger \mathcal{K}'_i \psi)$$

$$D_\mu = \partial^\mu + igA^\mu, \quad E^i = G^{0i}, \quad B^i = 1/2\epsilon^{ijk} G^{jk}. \qquad (1)$$

Taylor expansion in v

Can we determine the v dependence of the building blocks of our theory?

- $r_\Upsilon \sim 1/(m_Q v)$
- $\int d^3 r \psi^\dagger \psi = 1 \to \psi \sim (m_Q v)^3/2$
- $\int d^3 r \psi^\dagger \frac{\vec{D}^2}{2m_Q} \psi = 1 \to \vec{D} \sim m_Q v$
- From equation of motion: $g\vec{E} \sim m_Q^2 v^3$ and $g\vec{B} \sim m_Q^2 v^4$

Transition between the hadron H and a $Q\overline{Q}$ state:

$$\left\langle \mathcal{O}^H[n] \right\rangle = \sum_{X,\lambda} \left\langle 0 \left| \chi^\dagger \mathcal{K}_n \psi \right| H(\lambda) + X \right\rangle \left\langle H(\lambda) + X \left| \psi^\dagger \mathcal{K}'_n \chi \right| 0 \right\rangle$$

- Chromoelectric transitions: $\Delta L = \pm 1, \Delta S = 0$
- Chromomagnetic transitions: $\Delta L = 0, \Delta S = \pm 1$
- $\left\langle \mathcal{O}^H[n = 1(8), {}^{2S+1}L_J] \right\rangle \sim v^{3+2L+2E+4M}$
- Color-singlet transition probabilities can be calculated from potential models, but unluckily color-octet transition probabilities have to be fitted

Color state of the quark pair

A $Q\overline{Q}$ can either be in a color singlet, or a color octet state: $3 \times \overline{3} = 1 + 8$. Hadrons are always in singlet state. Different models take this into account differently.

- Color Singlet Model: $\langle \mathcal{O}^H[n = 8, {}^{2S+1}L_J] \rangle = 0$
- Color Evaporation Model: no correlation between color and angular momentum

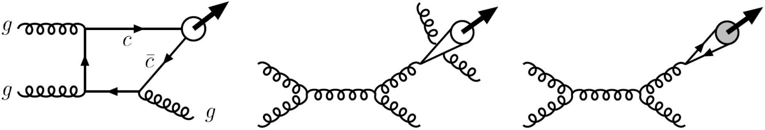
$$d\sigma^{CEM}(H + X) = f_H \int_{2m_Q}^{2m_{Qq}} dM_{Q\overline{Q}} \frac{d\sigma(Q\overline{Q} + X)}{dM_{Q\overline{Q}}}$$

- NRQCD: both color singlet and color octet processes are calculated in a systematic way

CSM calculations can have infrared divergences because of soft gluon emission $\rightarrow$ there is need to take color octet processes into account

In NRQCD $\langle \mathcal{O}^H[n = 1(8), {}^{2S+1}L_J] \rangle$ are phenomenological parameters.

Feynman diagrams



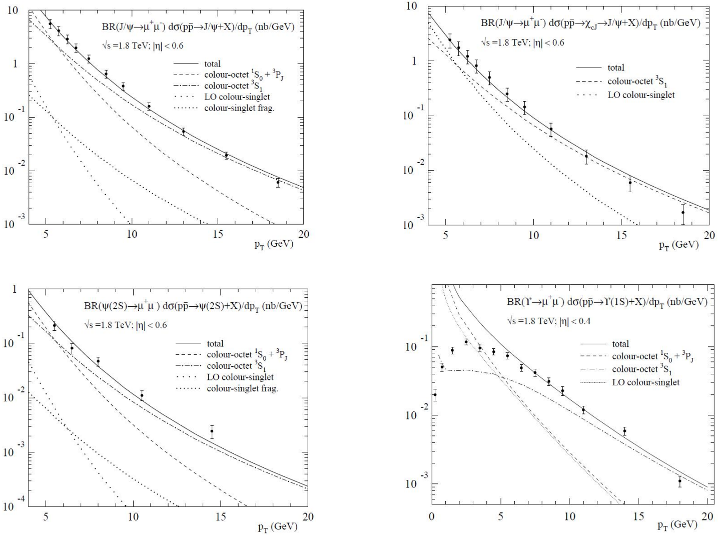
(a) leading-order color-singlet

(b) color-singlet fragmentation

(c) color-octet fragmentation

$\sim \alpha_s^3 \frac{(2m_Q)^4}{p_t^8}$	$\sim \alpha_s^5 \frac{1}{p_t^4}$	$\sim \alpha_s^3 \frac{1}{p_t^4}$
$\left\langle \mathcal{O}^{\Upsilon}[1, {}^3S_1] \right\rangle$	$\left\langle \mathcal{O}^{\Upsilon}[1, {}^3S_1] \right\rangle$	$\left\langle \mathcal{O}^{\Upsilon}[8, {}^3S_1] \right\rangle$
$v^{3+2L+2E+4M} = v^3$	$v^{3+2L+2E+4M} = v^3$	$v^{3+2L+2E+4M} = v^7$

Comparison with experiments

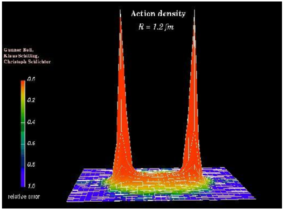


[Kramer (2001), HEP-PH/0106120]

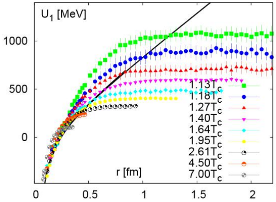
Quarkonia in QGP

Finite temperature potentials

- Quarkonia in QGP is usually described with a temperature dependent potential.
- Plasma anisotropy can also be taken into account, which also effects the potential
- Debye-screening makes the potential range finite.
- Potential can get nonzero imaginary part from two effects:
  - gluonic Landau-damping (energy transfer from soft gluons to $Q\overline{Q}$)
  - singlet to octet transitions



[Bali, Schilling, and Schlichter (1995), HEP-LAT/9409005]



[Bicudo et al. (2008), ARXIV:0804.4225]

Complex potential?

What does a complex potential impose in quantum mechanics?

$$\hat{H}\psi = E\psi, \qquad \hat{H} = -\frac{\hbar^2 \triangle}{2m} + V_1(x) + iV_2(x)$$

- Hamiltonian is not Hermitian, since $(iV_2(x))^* = -iV_2(x)$
- Eigenvalues of Hamiltonian are not necessarily real $\rightarrow$ energies can get imaginary part

If the imaginary part of the potential is small, we can apply perturbation theory:

$$E_j^{(1)} = E_j^{(0)} + i \langle \psi_j | V_2 | \psi_j \rangle$$

The wave function describes a decaying particle:

$$\psi_j(x,t) = \varphi(x) e^{-iEt - \Gamma t/2} \rightarrow \int d^3x \psi_j \psi_j^* \sim e^{-\Gamma t}$$

QGP as an anisotropic plasma

Gluon phase-space distribution in a local rest frame:

$$f(t, \mathbf{x}, \mathbf{p}) = f_{iso}\left(\sqrt{\mathbf{p}^2 + \xi(\mathbf{p}\cdot\mathbf{n})^2}/p_{hard}\right),$$

where:

- f_{iso} corresponds to the isotropic Bose-Einstein distribution
- ξ is the momentum-space anisotropy parameter
- p_{hard} is a temperature-like quantity describing typical momentum scale

From the static gluon propagator one can get the quark potential:

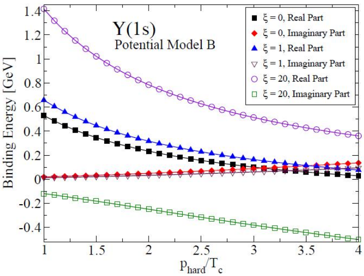
$$\mathcal{R}[V] = -\frac{a}{r}(1+\mu r)e^{-\mu r} + \frac{2\sigma}{\mu}(1-e^{-\mu r}) - \sigma r e^{-\mu r} - \frac{0.8\sigma}{m_Q^2 r}$$

$$\mathcal{I}[V] = -\alpha_s C_F T\left(\phi(r/m_d) - \xi\left(\psi_1(r/m_D,\theta) + \psi_2(r/m_D,\theta)\right)\right)$$

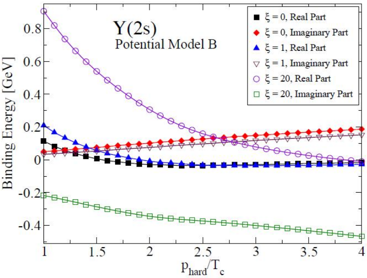
The potential

- 3D Schrödinger equation can be solved numerically to obtain the energy of the states
- Decay width is assigned to the states:

$$\Gamma(\tau, \mathbf{x}, y) = \begin{cases} 2\mathcal{I}[E_{bind}(\tau, \mathbf{x}, y)] & \text{if} \quad \mathcal{R}[E_{bind}(\tau, \mathbf{x}, y)] > 0 \\ 10\text{GeV} & \text{if} \quad \mathcal{R}[E_{bind}(\tau, \mathbf{x}, y)] < 0 \end{cases}$$



(d) $\Upsilon(1s)$ binding energy

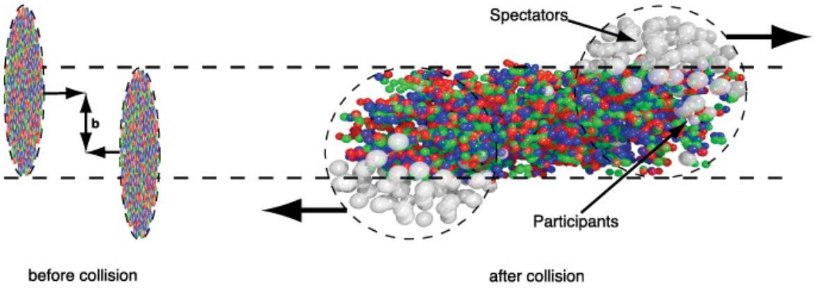


(e) $\Upsilon(1s)$ binding energy

[Strickland and Bazow (2012), ARXIV:1112.2761]

Geometry of a HIC

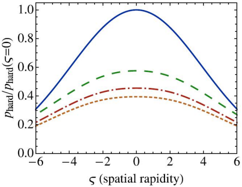
- Longitudinal direction: motion of nuclei (z)
- Transverse plane (x, y)
- Closest distance of nuclei: impact parameter (b)
- Different parts of the plasma can have different rapidity (ζ)



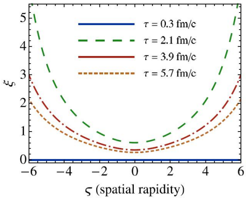
[Snellings (2011), ARXIV:1102.3010]

Evolution of QGP created by a HIC

- Picture: plasma created instantaneously at all (x, y) points with a rapidity distribution, flowing in the longitudinal direction
- Dynamical evolution: anisotropic hydrodynamics (AHYDRO) using Boltzmann-equation
- Goal: $p_{hard}(x, y, \zeta, \tau), \xi(x, y, \zeta, \tau)$
- The different (x, y) points are treated independently, effectively $1 + 1D$ systems
- Inhomogenity comes from the different initial conditions



[Strickland and Bazow (2012), ARXIV:1112.2761]



[Strickland and Bazow (2012), ARXIV:1112.2761]

Initial conditions of the plasma I.

Initially nucleons are described by a Woods-Saxon distribution:

$$n_{A,B}(r) = \frac{n_0}{1 + e^{(r-R)/d}}$$

Nucleus thickness function describes the density of nucleons at an (x, y) point of the transverse plane:

$$T_{A,B}(x, y) = \int_{-\infty}^{\infty} dz\, n_{A,B}(\sqrt{x^2 + y^2 + z^2})$$

Overlap density of the nucleons (number of binary collisions):

$$n_{AB}(x, y, b) = T_A(x + b/2, y)\, T_B(x - b/2, y)$$

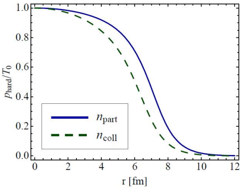
Number of wounded nucleons:

$$n_{part}(x, y, b) = T_A(x + b/2, y) \left(1 - \left(1 - \frac{\sigma_{NN} T_B(x - b/2, y)}{B}\right)^B\right) + A \leftrightarrow B$$

Initial conditions of the plasma II.

Initial $p_{hard}(x, y)$ distribution can be guessed with either the number of collisions, or the number of participants, or taking both into account. Simplest:

$$p_{hard}(\tau = 0) = T_0 \left(\frac{n_{part}(x, y, b)}{n_{part}(0, 0, 0)} \right)^{1/3}$$



[Strickland and Bazow (2012), ARXIV:1112.2761]

Spatial rapidity distribution:

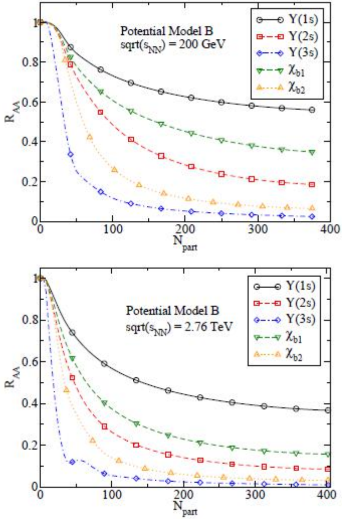
$$n(\zeta) = n_0 \exp\left(-\frac{-\zeta^2}{2\sigma_\zeta^2} \right)$$

Putting all together

The process of calculation:

- Initial conditions are chosen
- Evolution of p_{hard} and ξ are calculated in the function of (x, y, ζ)
- Plasma evolution is stopped, when temperature decreases to $192\mathrm{MeV}$
- Υ production is taken to be proportional to number of collisions at each x, y
- Schrödinger-equation is solved at each point, to get the evolution of the energies
- Nuclear suppression factor is calculated for all x, y, ζ using the decay widths

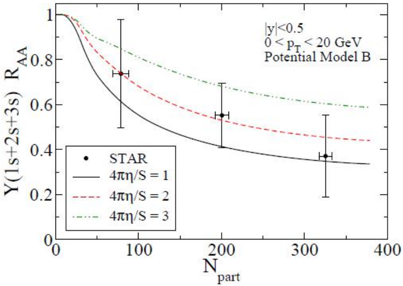
Nuclear suppression factor

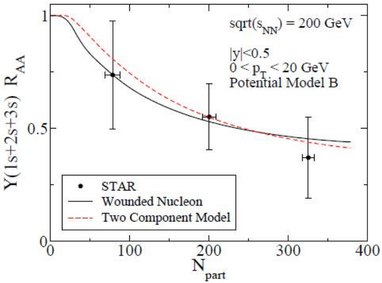


Shear viscosity over entropy density is $4\pi\eta/\mathcal{S} = 1$, momentum cut $0 < p_t < 20\,\mathrm{GeV}$, rapidity $|y| < 0.5$ for RHIC, $|y| < 2.4$ for LHC.
[Strickland and Bazow (2012), ARXIV:1112.2761]

Theory vs experiment I.

Unluckily current experimental data for the nuclear suppression factor is not so accurate. It is hard to fit the parameters of the model.



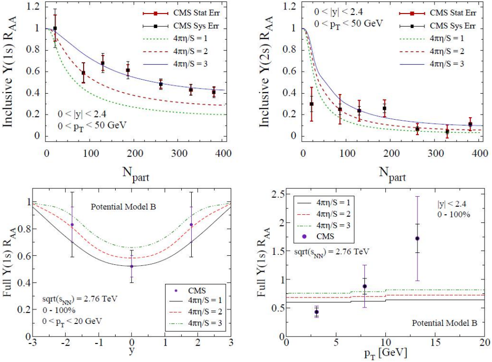


[Strickland (2013), ARXIV:1210.7512]
[Reed (2011), ARXIV:1109.3891]

Theory vs experiment II.

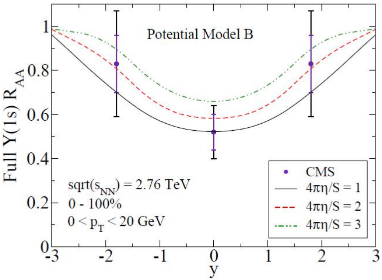
Higher bottomonia excited states can feed-down to for example $\Upsilon(1s)$ and $\Upsilon(2s)$. This is taken into account the following way:

$$R_{AA}^{full}[\Upsilon(ns)] = \sum_{i \in \{Q\overline{Q}\,\text{states}\}} f_i R_{i,AA}$$

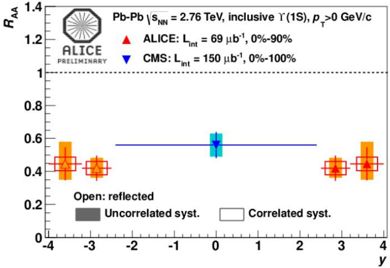


[Strickland (2013), ARXIV:1210.7512]
[CMS CMS-PAS-HIN-10-006]

Alice data



[Strickland (2013), ARXIV:1210.7512]



[Khan (2013), ARXIV:1310.2565]

Summary

What did we learn?

- Factorization of QCD
- Description of quarkonia production with effective field theories
- Description of QGP as an anisotropic plasma
- Behaviour of quarkonia in QGP

Thank you for your kind attention!