5.4.11

Quarkonia as Probes in QCD

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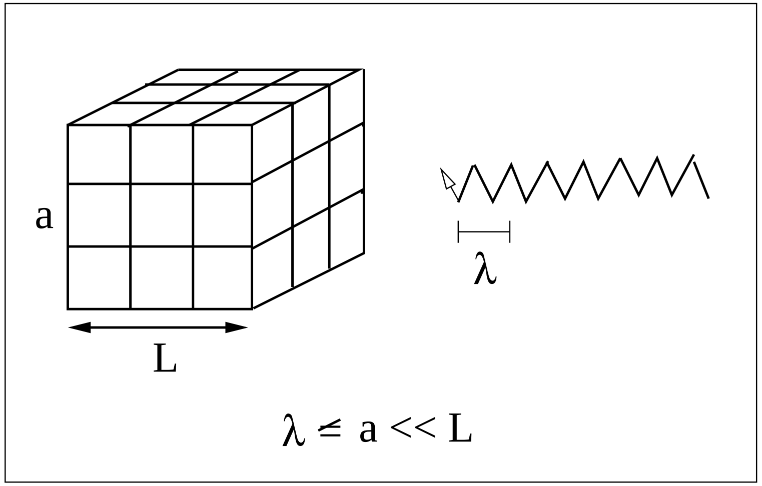
Quarkonium Production **Wien, April 18, 2011**

What is a probe?



resolve substructure

state of matter

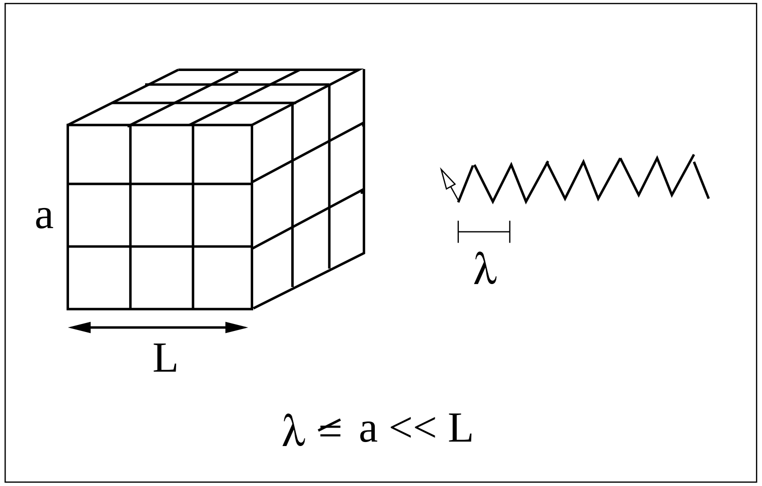
What is a probe?

Substructure in QCD:

hadrons, quarks, gluons

hadrons $\sim$ 1 fm

constituent quarks $\sim$ 0.3 fm



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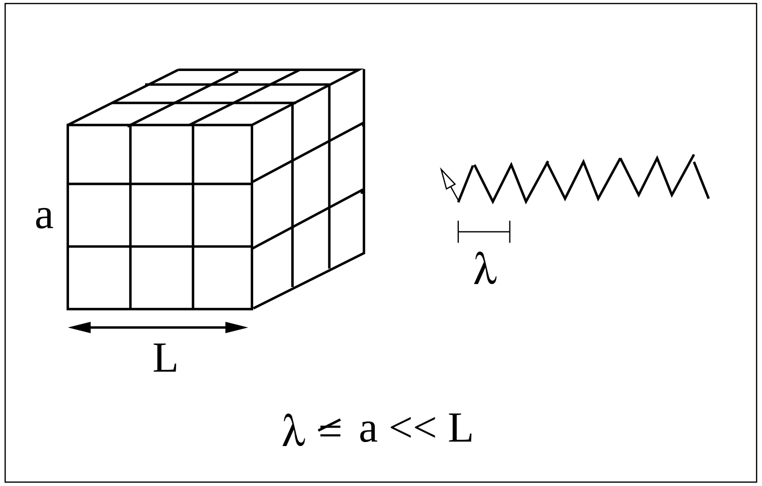

Substructure in QCD:

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resolve substructure

state of matter

Probes in QCD:

- hard photons (DIS)
- hard gluons (jets)
- quarkonia (J/ψ, Υ)

Quarkonium Physics

- **Spectroscopy**
- **Decay**
- **Production**
- **In-Medium Behavior**
- **Determination of QCD Parameters**

⇒ *Quarkonium Working Group*

N. Brambilla et al. (QWG), *Heavy Quarkonium Physics*, **CERN-2005-005**

N. Brambilla et al. (QWG), *Heavy Quarkonium: Progress, Puzzles, and Opportunities*, **TUM-EFT 11/10**

Quarkonia as probe of deconfinement and QGP

- quarkonia have larger binding energies, smaller radii than usual hadrons
- can therefore survive color screening up to $T > T_c$
- dissociation points of different quarkonium states provide

spectral analysis of QGP

1. What does the probe look like? $\Rightarrow$ the spectrum
2. How can we make the probe? $\Rightarrow$ production dynamics
3. How can we use the probe? $\Rightarrow$ collision aspects

1. The Spectrum

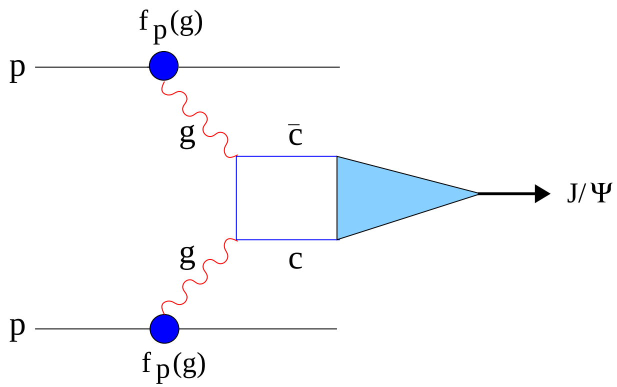
- **In Vacuum**
  - potential models/Schrödinger equation
  - direct lattice studies
  - NRQCD, pNRQCD

$$\left\{2m_c - \frac{1}{m_c}\nabla^2 + \left[\sigma\, r - \frac{\alpha}{r}\right]\right\}\Phi_i(r) = M_i\Phi_i(r)$$

- **In Medium**
  - potential models
  - potential from $Q\bar{Q}$ lattice studies
  - direct finite T lattice studies
  - finite T NRQCD, pNRQCD
  - weak coupling studies

2. Production Dynamics

- **In Vacuum**



- **In Medium**

– $Q\bar{Q}$ **production**
  – **PDF**
  – **LO, NLO, NNLO,...**

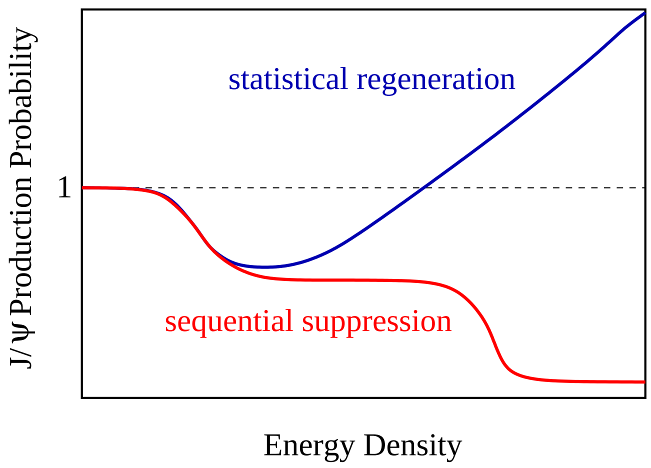
– **color neutralisation**
  – **color singlet, color octet, NLO...**
  – **color evaporation**

– **initial state effects**
  – **shadowing**
  – **higher twist, parton energy loss**

– **final state effects**
  – **cold nuclear matter**
  – **hadron interactions**
  – **parton interactions, color screening**

3. Collision Aspects

- **In Vacuum** – feed-down
- **In Medium** – sequential suppression
  – spectral analysis of medium
  – corona
  – regeneration



How does the Production of Quarkonia differ from that of "usual" Hadrons?

usual hadrons: consist of u, d, s quarks

basic observation in all high energy multihadron production:

statistical production of usual hadrons

partition function of ideal resonance gas

$$\ln Z(T) = V \sum_i \frac{d_i \gamma_s^{n_i}}{(2\pi)^3} \phi(m_i, T)$$

Boltzmann factor $\phi(m_i, T) = 4\pi m_i^2 T K_2(m_i/T)$

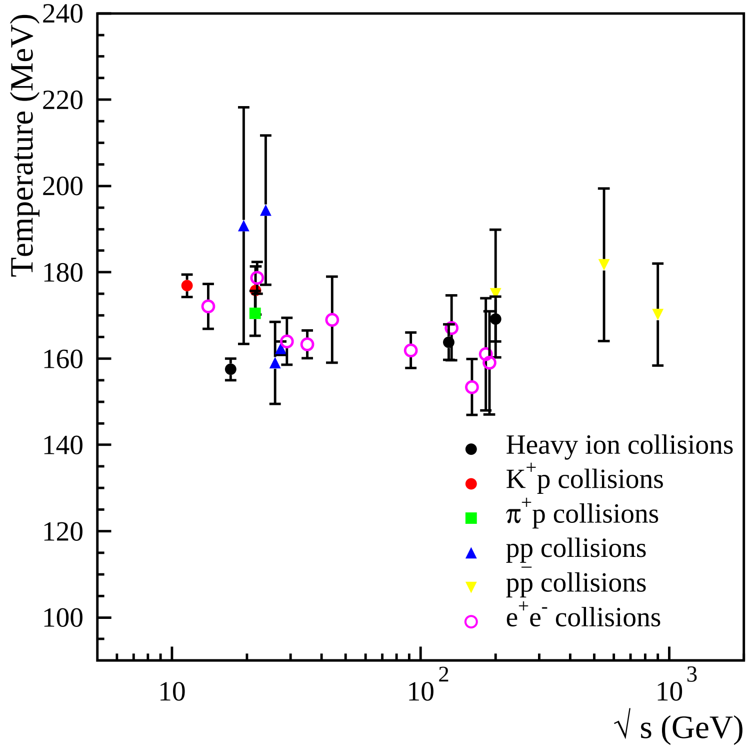
hadronisation temperature $T = T_H$,

strangeness reduction factor γ_s

all relative abundances given in terms of T_H and γ_s

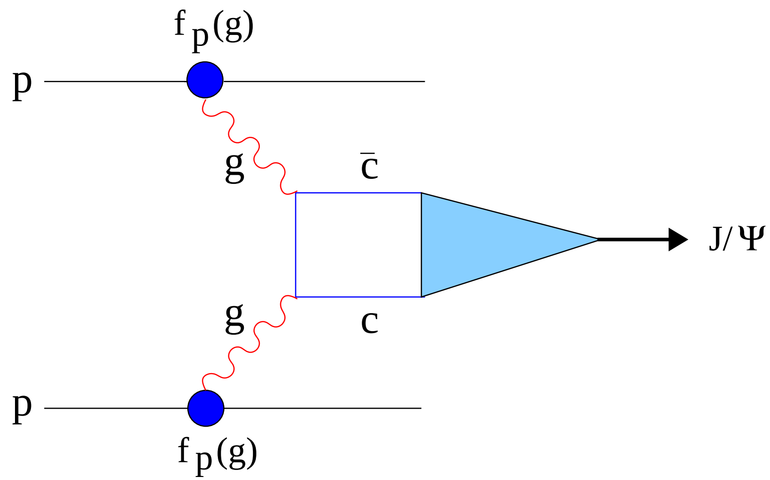
$$\frac{N_i}{N_j} = \frac{d_i \gamma_s^{n_i} \phi(m_i, T)}{d_j \gamma_s^{n_j} \phi(m_j, T)}$$

determines universal hadronisation temperature $T_H \simeq 175$ MeV



What about quarkonium production?

primary production via partonic interaction dynamics



given parton distribution functions from DIS,
$c\bar{c}$ production is perturbatively calculable (cum grano salis)

J/ψ binding is not, but it is independent of collision energy:

$$R[(J/\psi)/c\bar{c}] \sim |\phi_{J/\psi}(0)|^2 \neq f(s)$$

results for/from <u>elementary collisions</u>:

- $(dN_{c\bar{c}}/dy) \sim s^a$
- $(dN_{\rm ch}/dy) \sim \ln s$
- $N_{c\bar{c}}/N_{\rm ch}$ grows with collision energy;

  in contrast $N_{s\bar{s}}/N_{\rm ch} \simeq$ const.

$\Rightarrow$ heavy flavor production is dynamical and not statistical

- $(dN_{J/\psi}/dy)/(dN_{c\bar{c}}/dy) \simeq 0.02$,

  statistical weight 0.003; experimental result more than a factor 5 bigger; $N_\rho/N_{\rm ch}$ in accord with statistical prediction

$\Rightarrow$ partioning of heavy flavor production into hidden vs. open is dynamical and not statistical

- $(dN_{\psi'}/dy)/dN_{J/\psi}/dy) \simeq 0.2$,

  statistical weight 0.04; experimental result about a factor 5 bigger; N_ρ/N_ω in accord with statistical prediction

⇒ quarkonium binding is dynamical and not statistical;
ratios of states ∼ wave functions, not Boltzmann factors

task for theory:
find QCD description of quarkonium production in elementary collisions

question to experiment:
does QGP formation in nuclear collisions provide a new mechanism for the binding of $c\bar{c}$ pairs to quarkonium, in accord with statistical predictions?

What can we (perhaps soon) learn from the LHC?

Schrödinger eq'n $$\left\{2m_c - \frac{1}{m_c}\nabla^2 + \left[\sigma\, r - \frac{\alpha}{r}\right]\right\}\Phi_i(r) = M_i\Phi_i(r)$$

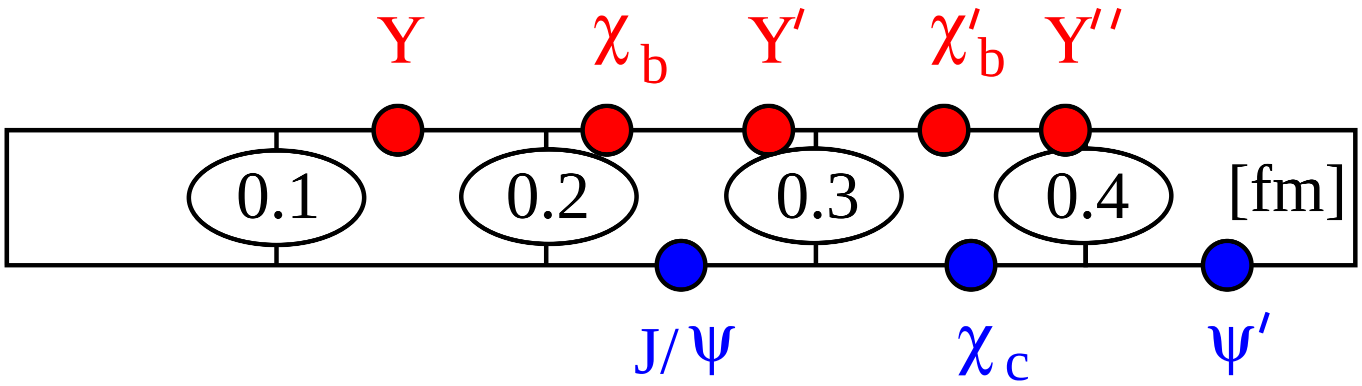
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)

excellent account of full quarkonium spectroscopy:

spin-averaged masses , binding energies, bound state radii.

consider bound state radii:



color screening:

dissociation when QGP screening radius $\leq$ bound state radius

in-medium quarkonium studies $\Rightarrow$ dissociation temperatures, energy densities

in progress; until then, three groups

L: ψ', χ_c, Υ'', χ'_b

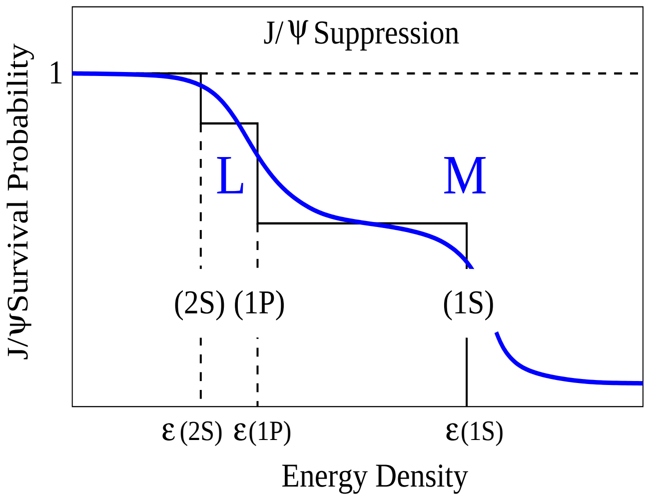
M: J/ψ, Υ', χ_b

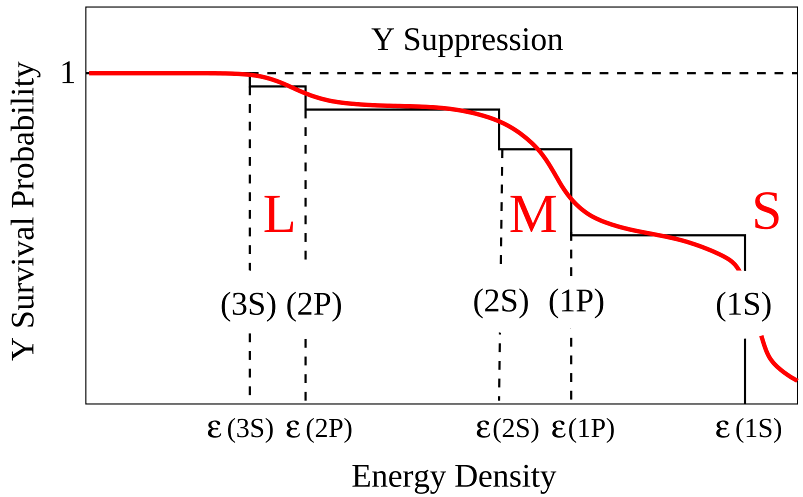
S: Υ

sequential suppression of J/ψ and Υ:
observed states are due to direct and feed-down production

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
%	60 ± 6	10 ± 5	30 ± 7

state	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
%	50 ± 10	27 ± 10	11 ± 6	11 ± 5	1 ± 0.5





NB:
J/ψ feed-down from B decay to be removed in comparison.

General qualitative picture:

Where J/ψ disappears, except for corona effect and B decay, Υ production drops to about 50 %.

Dissociation points and L, M, S splittings are in principle calculable through in-medium QCD quarkonium studies.

$\Rightarrow$ <u>Possible</u> direct comparison between QCD results and data.

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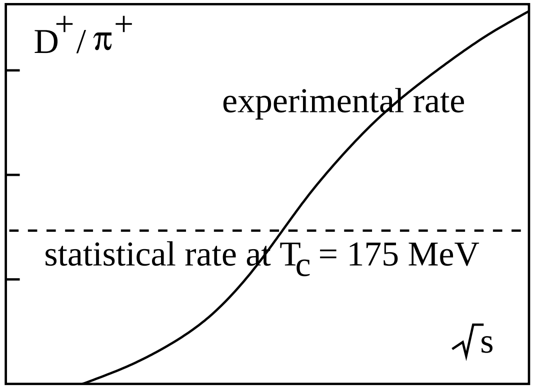
$\Downarrow$

Impossible: statistical J/ψ formation at hadronization

Statistical hadronization of charmonia



- $c\bar{c}$ production is a dynamical "hard process": with increasing energy, charm to light quark ratio increases

- assume
  - charm quarks form part of equilibrium QGP at T_c
  - equilibrium QGP at T_c hadronizes statistically
  - charmonium production via statistical $c\bar{c}$ fusion

- "secondary" charmonium production by fusion of c and $\bar{c}$ produced in different primary collisions

- insignificant at "low" energy, since very few charm quarks; could be dominant production mechanism at high energy

- **simplified illustration...assume at "LHC" per event**

100 $c\bar{c}$ pairs   1000 $q\bar{q}$ pairs

charm supersaturation;
chemical equilibrium: charm/light $\sim 10^{-3}$ at $T_c = 175$ MeV

primary rates:

1 J/ψ, 99 D, 99 $\bar{D}$, 901 light hadrons $\Rightarrow$ $R_{AA} \simeq 1$

statistical combination of given quark abundances:

10 J/ψ, 90 D, 90 $\bar{D}$, 910 light hadrons $\Rightarrow$ $R_{AA} \simeq 10$

ratio of hidden/open charm

$\Rightarrow$ $(J/\psi)/D \simeq 0.1$ instead of 0.01 in pp

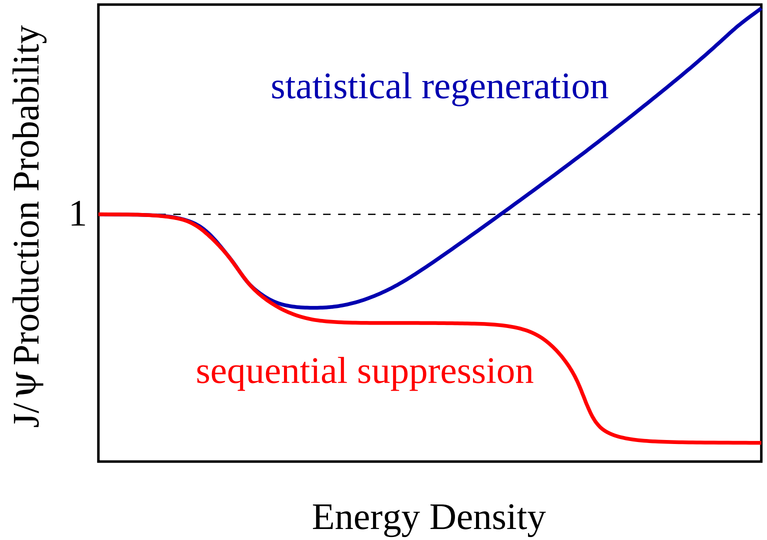
For statistical recombination, re scaled pp rate

$\Rightarrow$ J/ψ production strongly enhanced

$\Rightarrow$ ratio of hidden/open charm strongly enhanced

while for sequential suppression, both are strongly reduced

two readily distinguishable predictions for anomalous J/ψ production



also: dynamical vs. statistical momentum spectra

NB: model of statistical quarkonium binding

mechanism existing only in AA?

For $c\bar{c}$ production in pp at LHC, per rapidity interval

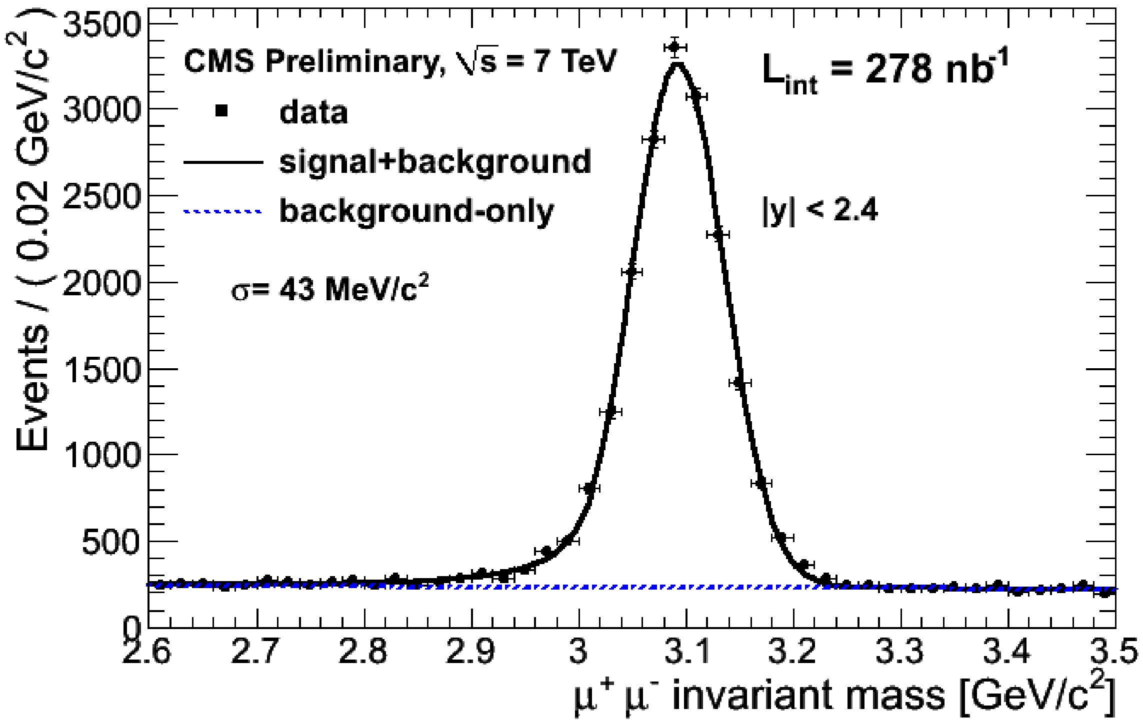
$$\exists \text{ per } c\bar{c} \text{ pair } \sim 10\ q\bar{q} \text{ pairs}$$

statistical combination implies

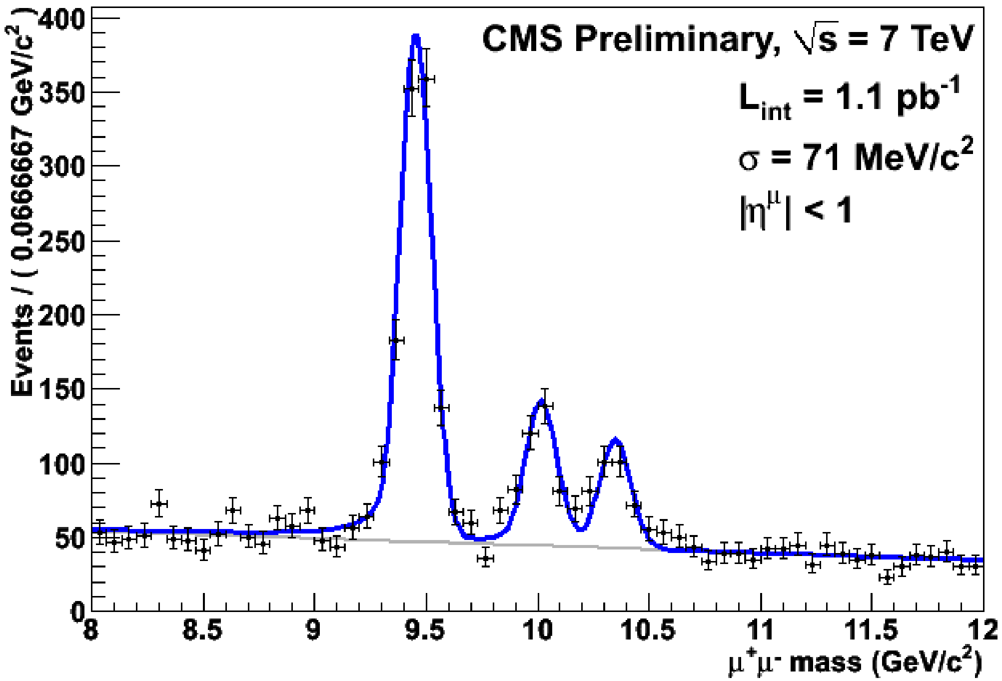
– **ratio hidden/open charm ~ 0.1**

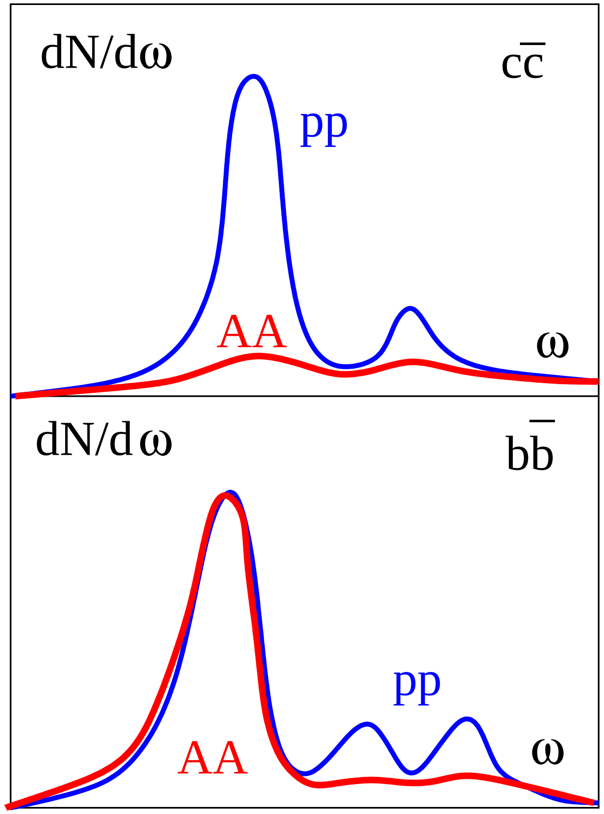
– **experimental ratio ~ 0.01**

at T_c,
$c\bar{c}$ separation scale too large to allow charmonium binding?

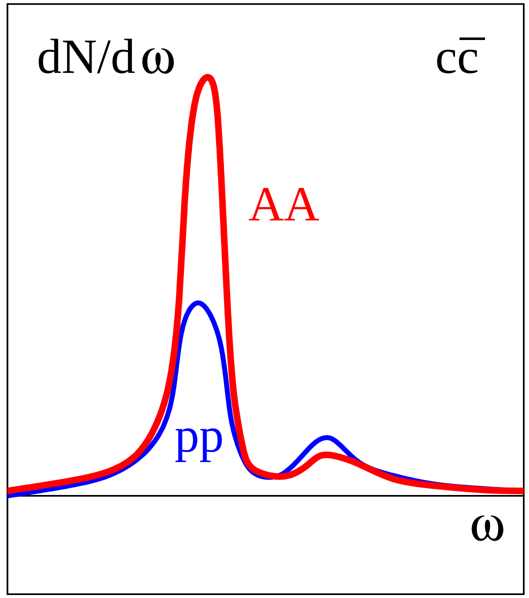


CMS Preliminary, √s = 7 TeV
data
signal+background
background-only
σ= 43 MeV/c²
L_int = 278 nb⁻¹
|y| < 2.4
Events / (0.02 GeV/c²)
μ⁺ μ⁻ invariant mass [GeV/c²]
0
500
1000
1500
2000
2500
3000
3500
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5


CMS Preliminary, √s = 7 TeV
L_int = 1.1 pb^-1
σ = 71 MeV/c^2
|η^μ| < 1
Events / (0.0666667 GeV/c^2)
μ+μ- mass (GeV/c^2)
0
50
100
150
200
250
300
350
400
8
8.5
9
9.5
10
10.5
11
11.5
12



sequential suppression
by color screening:
only (possible) survivor is Υ



statistical regeneration:
more J/ψ than in
scaled pp

Conclusions

Given reference measurements of open charm/bottom production,

experimental quarkonium studies at the LHC can ask

conceptual questions and provide

conceptual answers to these.

Quantitative details require specific theory/model input.