Quarkonia

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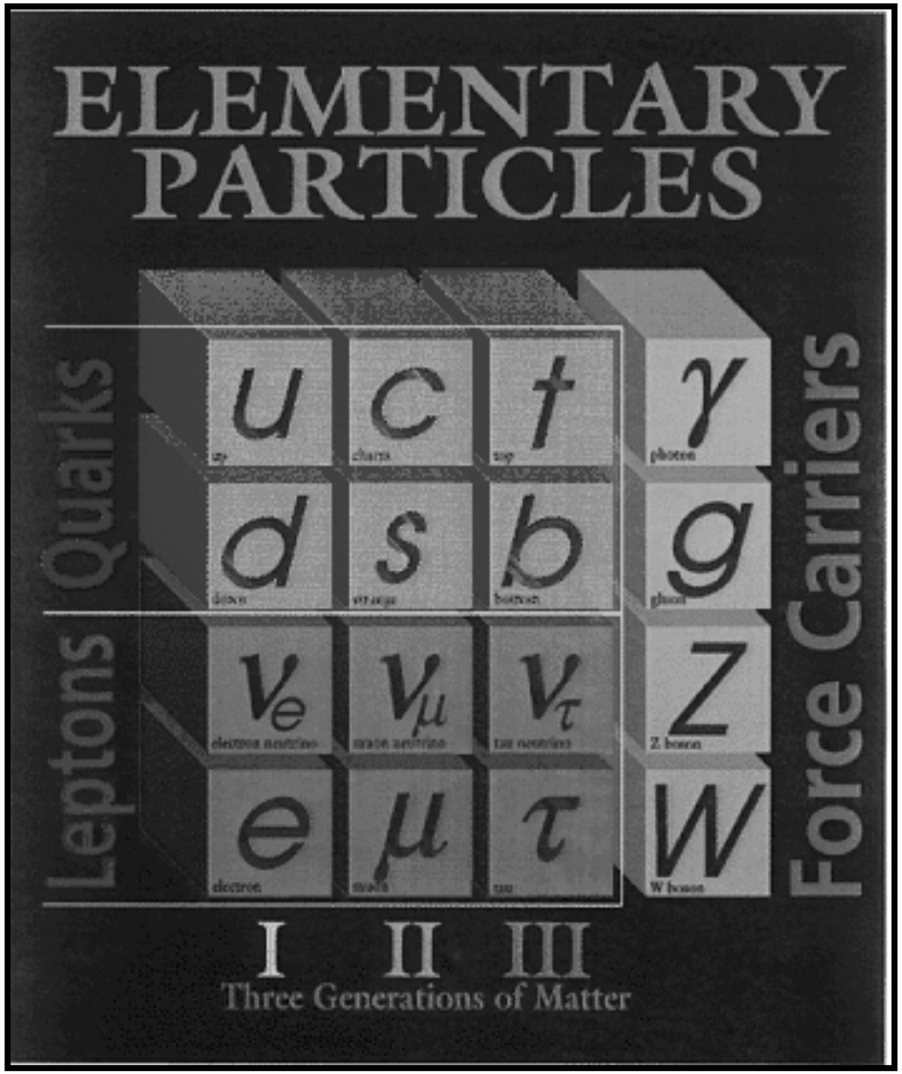
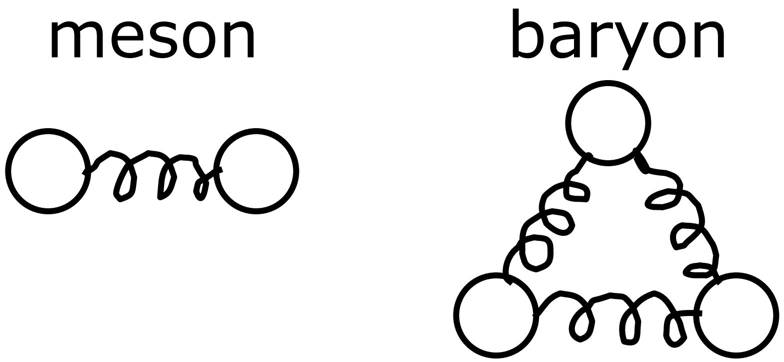
ALICE Experiment 201

Building Blocks of Matter

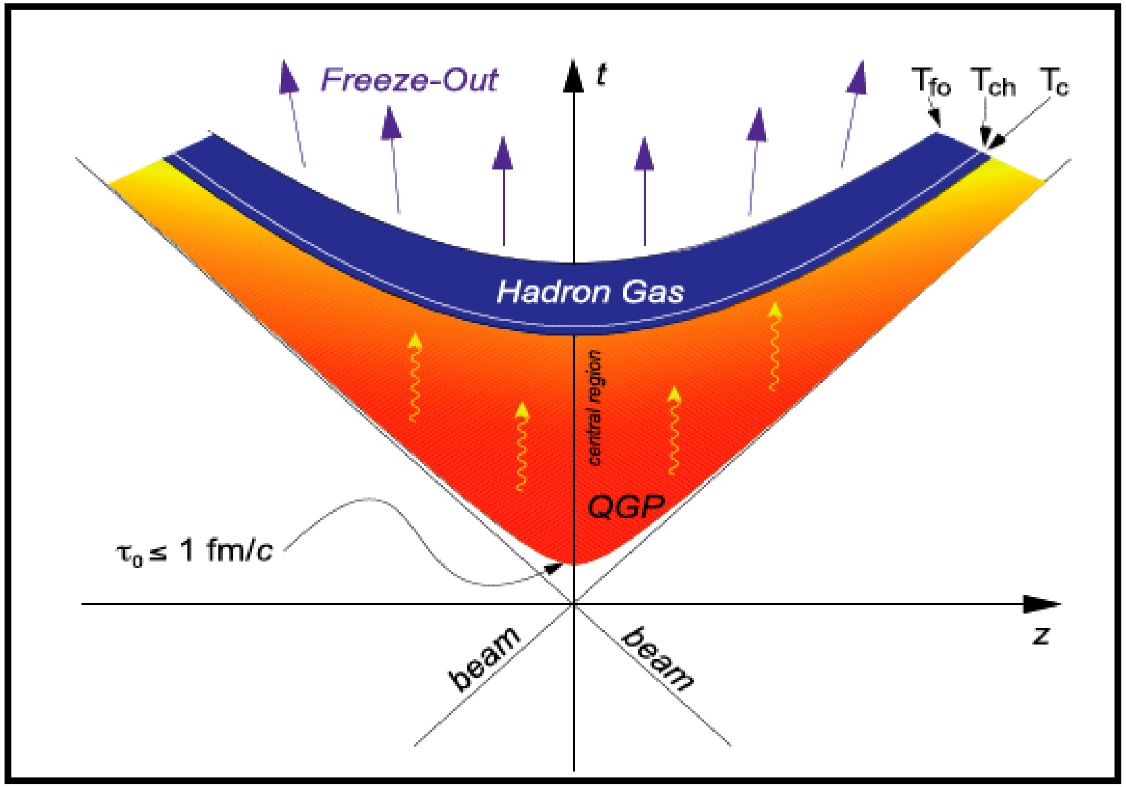


1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:



3) Gluons and quarks, or partons, typically exist in a color singlet state: confinement.

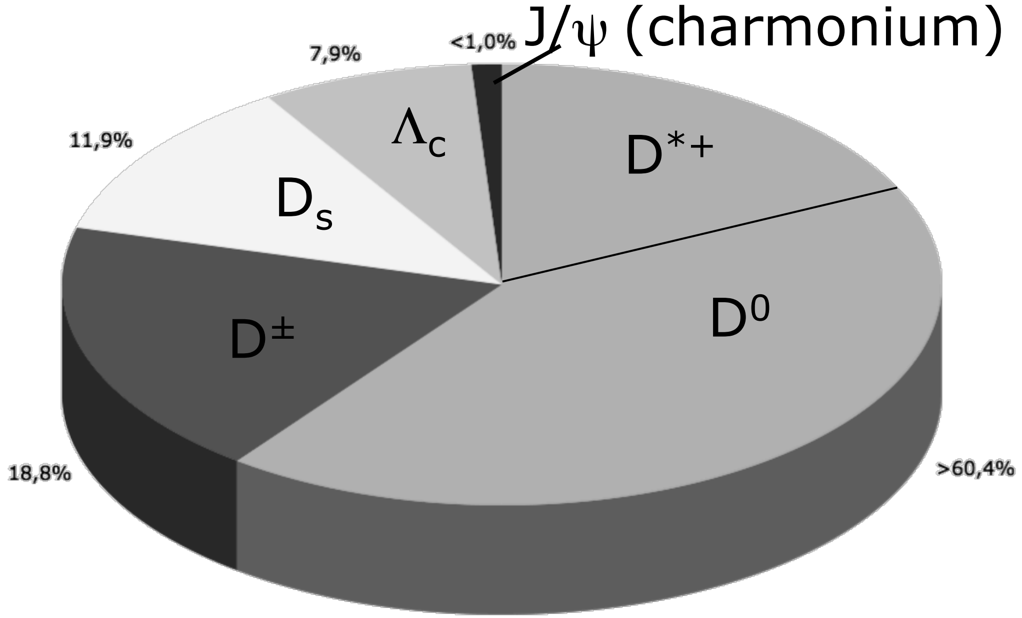
Time Scales



Plot: courtesy of R. Stock.

- **QGP life time**
  10 fm/c ≈ $3 \cdot 10^{-23}$ s
- **thermalization time**
  0.2 fm/c ≈ $7 \cdot 10^{-25}$ s
- **formation time**
  (e.g. charm quark):
  $1/2m_c = 0.08$ fm/c
  ≈ $3 \cdot 10^{-25}$ s
- **collision time**
  $2R/\gamma = 0.005$ fm/c
  ≈ $2 \cdot 10^{-26}$ s

Where does all the charm go ?

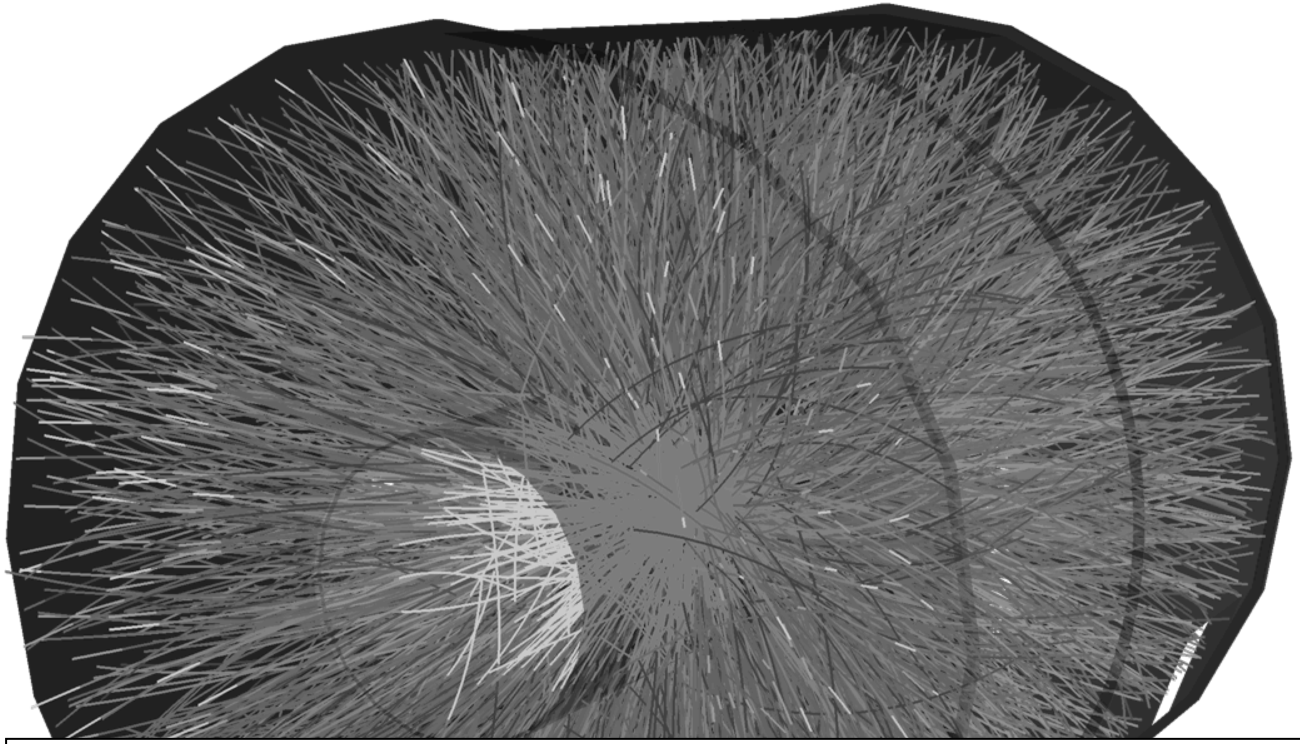


- **Total charm** cross section: **open-charmed** hadrons, e.g. **D^0, D^+, D^{*+},** Λ_c, … and **c,b → e(μ)** + X
- Quarkonia, e.g. **J/ψ** carries ≈**1%** of **total charm**

Outline

- Introduction
- Charmonium production
- Bottomonium production
- Summary

Erste Bleikollisionen in ALICE !



ALICE is designed for

- Highest multiplicities $dN/d\eta$ up to 6000
- Excellent tracking & particle identification down to lowest momentum ~ 100 MeV/c

6 ATeV

33E693

Discovery of charmonium

J: AGS at Brookhaven Lab., NY
$p + Be \rightarrow \mu\mu$

ψ: SPEAR at SLAC, CA
$e^+ + e^- \rightarrow$ hadrons

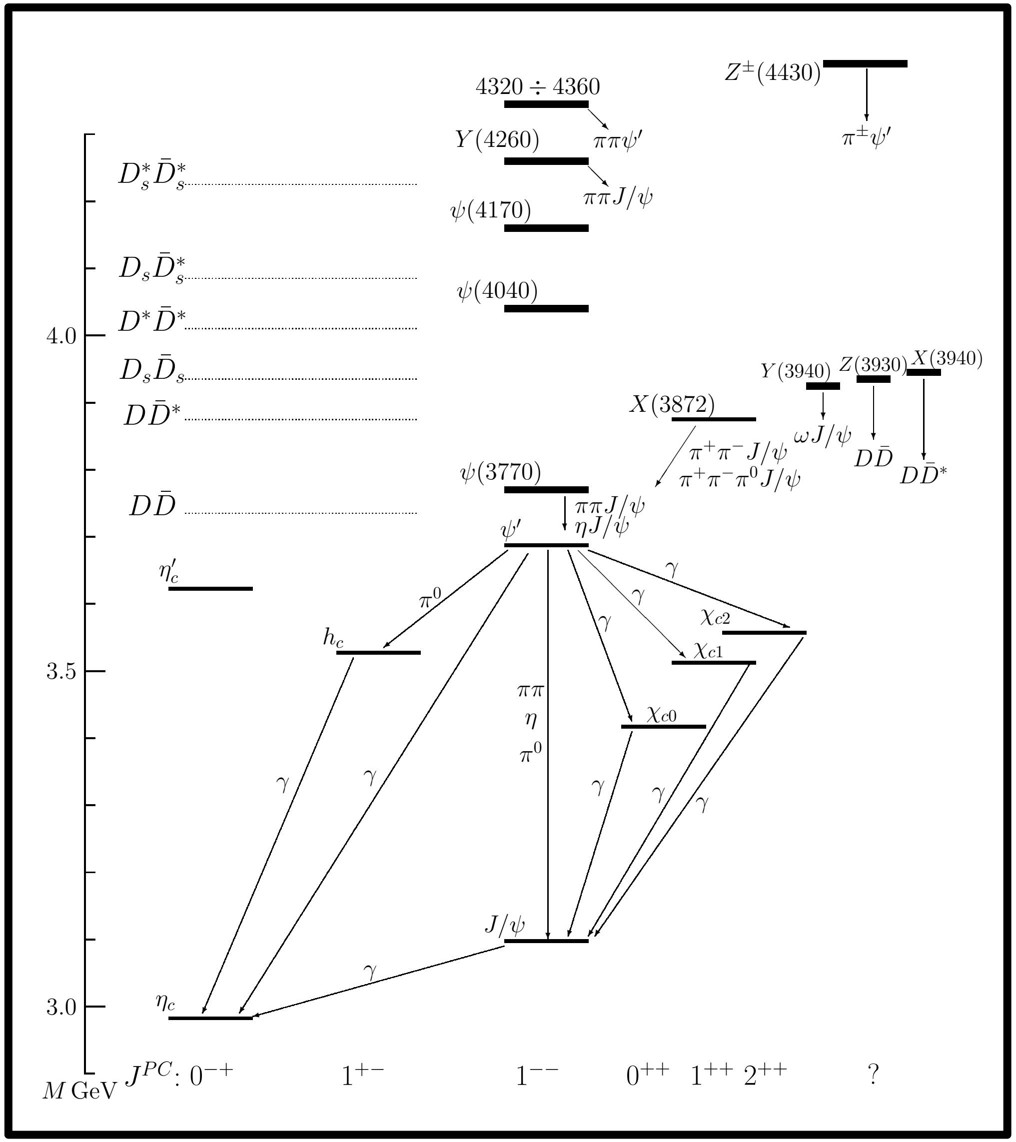
$m_{J/\psi}$ = 3.1 GeV, $J^{PC} = 1^{-}$ states

Published back-to-back:
Phys. Rev. Lett. 33 (1974) 1404 & 1406

Nobel Prize 1976 for Samuel Ting and Burton Richter

Predicted by Sheldon Glashow and James Bjorken

Charmonium (c-cbar)



- Bound state of charm- and anti-charm quark
- Hidden-charm meson
- $m_{J/\psi}$ = 3.1 GeV,
  $r_{J/\psi}$ = 0.45 fm,
  $J^P = 1^-$ states

- Ψ’: radial excitation, ψ(2s)

Plot: M.B. Voloshin,
Prog. Part .Nucl .Phys. 61 (2008) 455-511.

Time scales of charm production

- formation time of charm quark:
  $1/2m_c = 0.08$ fm/c
- thermalization time:
  0.2 fm/c
- to build up wavefunction of J/ψ takes typically 1fm/c

→ At LHC energies, QGP formed before J/ψ can exist

→ J/ψ unbound in QGP, thus no melting of J/ψ (does not exist in the first place)

→ Generation of J/ψ at the phase boundary, i.e. at Tc

J/ψ suppression: the original idea

Matsui and Satz, Phys. Lett. B 178 (1986) 416.

Color screening will prevent bound ccbar states, i.e.

suppression of charmonium signals QGP formation

No J/Ψ if $\lambda_D < r_{J/\psi}$

Debye length $\lambda_D \sim 1/(g(T)\ T$, so J/ψ is thermometer

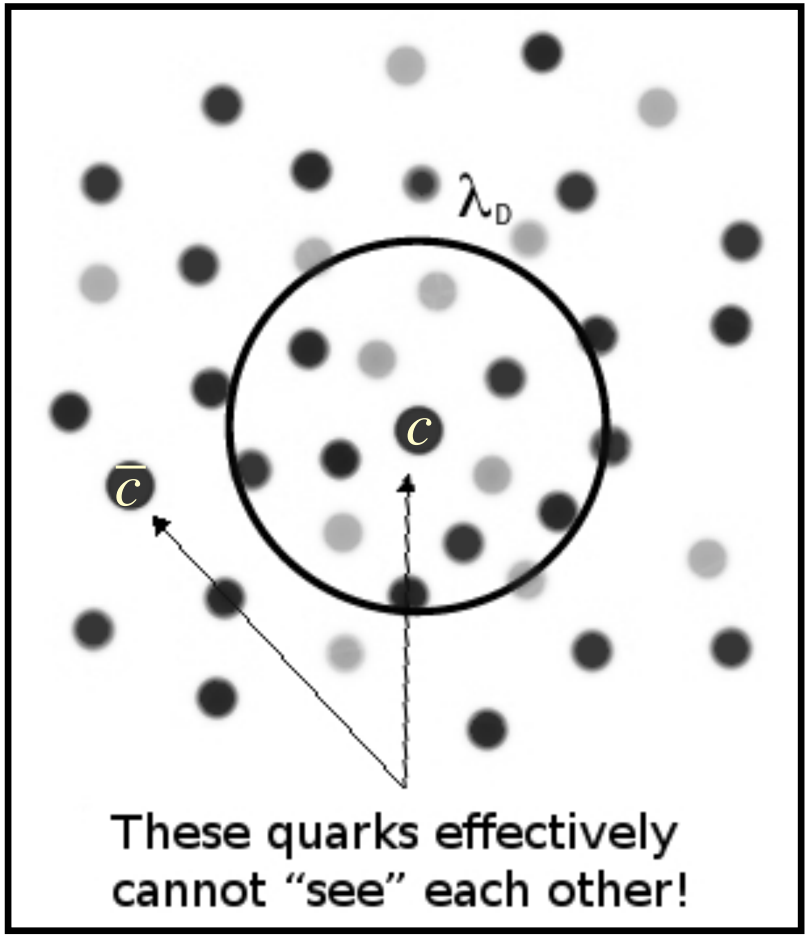
Thermal picture: $n_{partons} = 5.2\ T^3$ for 3 flavors

For T = 500MeV, $n_{partons} = 84/fm^3$

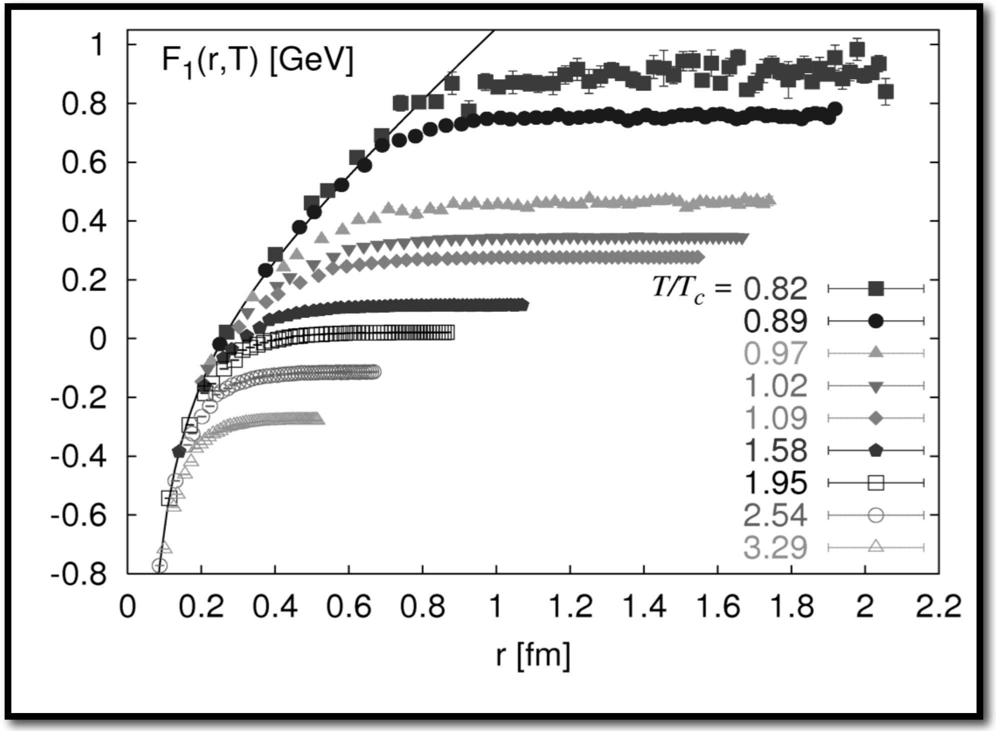
Mean separation r = 0.2fm < $r_{J/\psi}$

Dynamical picture: J/ψ → g + c + cbar

Debye Screening and Quarkonia

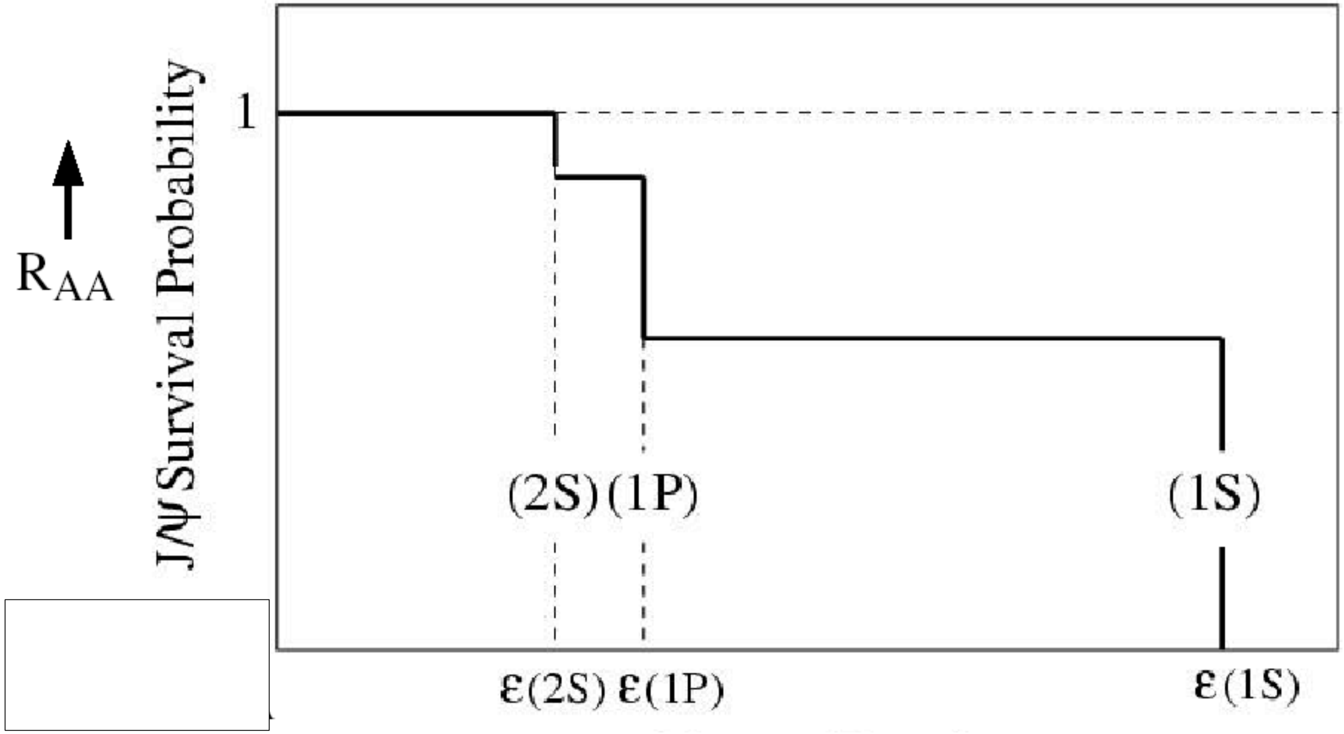


These quarks effectively cannot “see” each other!



RBC Bielefeld group, hep-lat/0610041.

Schematical Picture

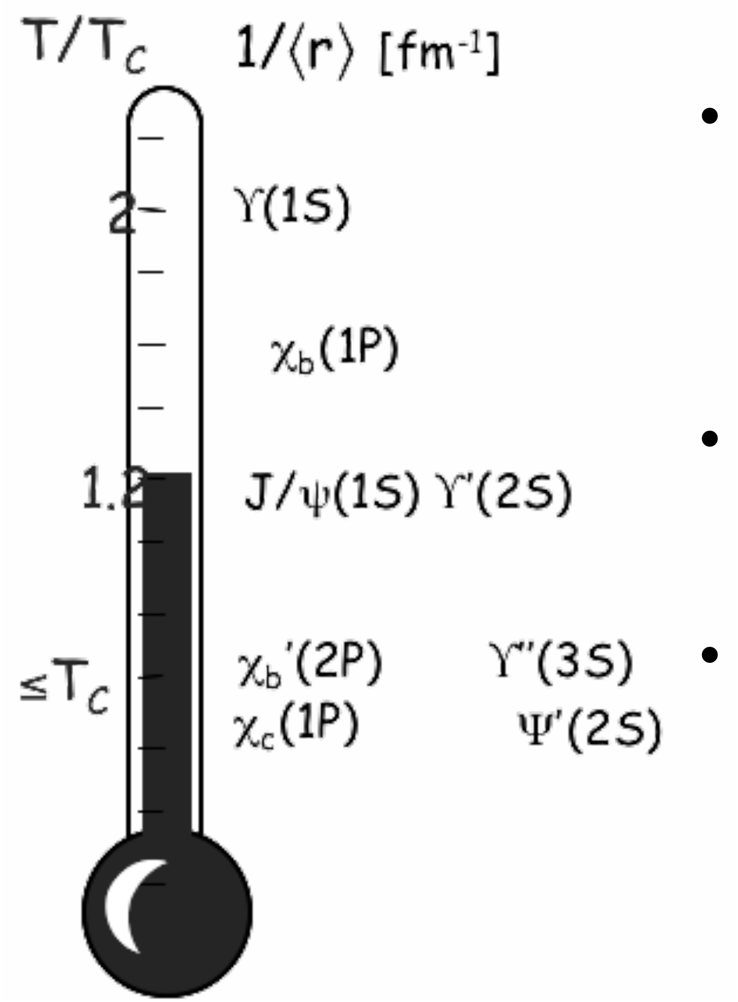


Suppose J/ψ does not melt

→ R_{AA} should saturate > 0.6

→ no more feeding from χ_c and ψ' → J/ψ + X

Quarkonia as a Thermometer



- Expect melting of bottomonium (b-bbar) at Tdeconfined ≈ 2 Tc

- Expect melting of charmonium (c-cbar) at $T_{deconfined}$ ≈ 1.2 Tc
- Absolute numbers model-dependent

A.Mocsy, EJC 61 (2009) 705.

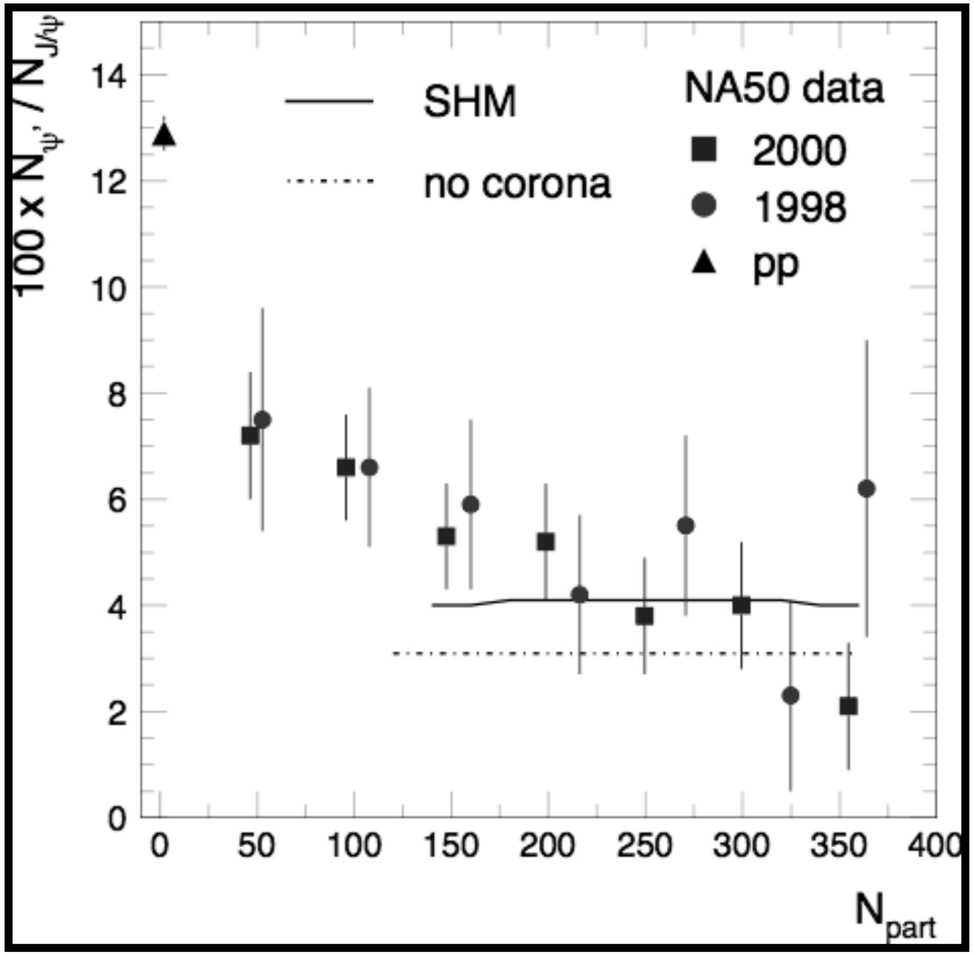
Reminder on Statistical Model

B. ψ' to J/ψ ratio

$m_{J/\psi}$ = 3.1 GeV, $m_{\psi'}$ = 3.6 GeV, look up $K_2(m/Tch)$

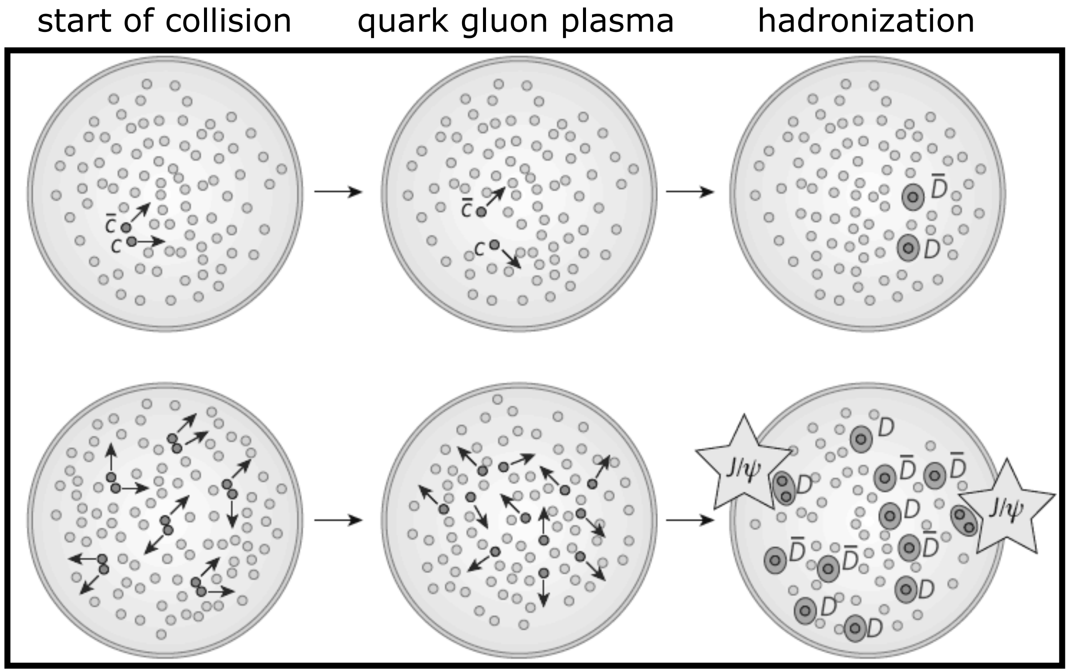
Ratio = 3%

Charmonium production



- In central Pb+Pb collisions at top SPS energy:
- J/ψ' to J/ψ ratio approaches thermal limit
- Indicates kinetic equilibration of charm

J/ψ (charm-anticharm) Production



P. Braun-Munzinger and J. Stachel, Nature 448 (2007) 302.

- **Low energy** (SPS):

screening of J/ψ

⇒ **suppression**

- **High energy** (LHC):

generation at phase boundary

⇒ **enhancement**

- **additional production** mechanism at **high-energy**
- fingerprint of **de-confinement**

Some remarks

- number of charm quarks conserved throughout collision
- charm quarks are only produced in early stage
- No annihilation of charm quarks
- thermal production of charm unlikely: ~$\exp(-2m_c/T)$, $T << m_c$
- thus, charm is only re-shuffled amongst charmed hadrons
- effects of statistical hadronization of charm beyond current experimental sensitivity for open charmed hadrons (99% of all charm
- effects sizeable for charmonium (1% of all charm)

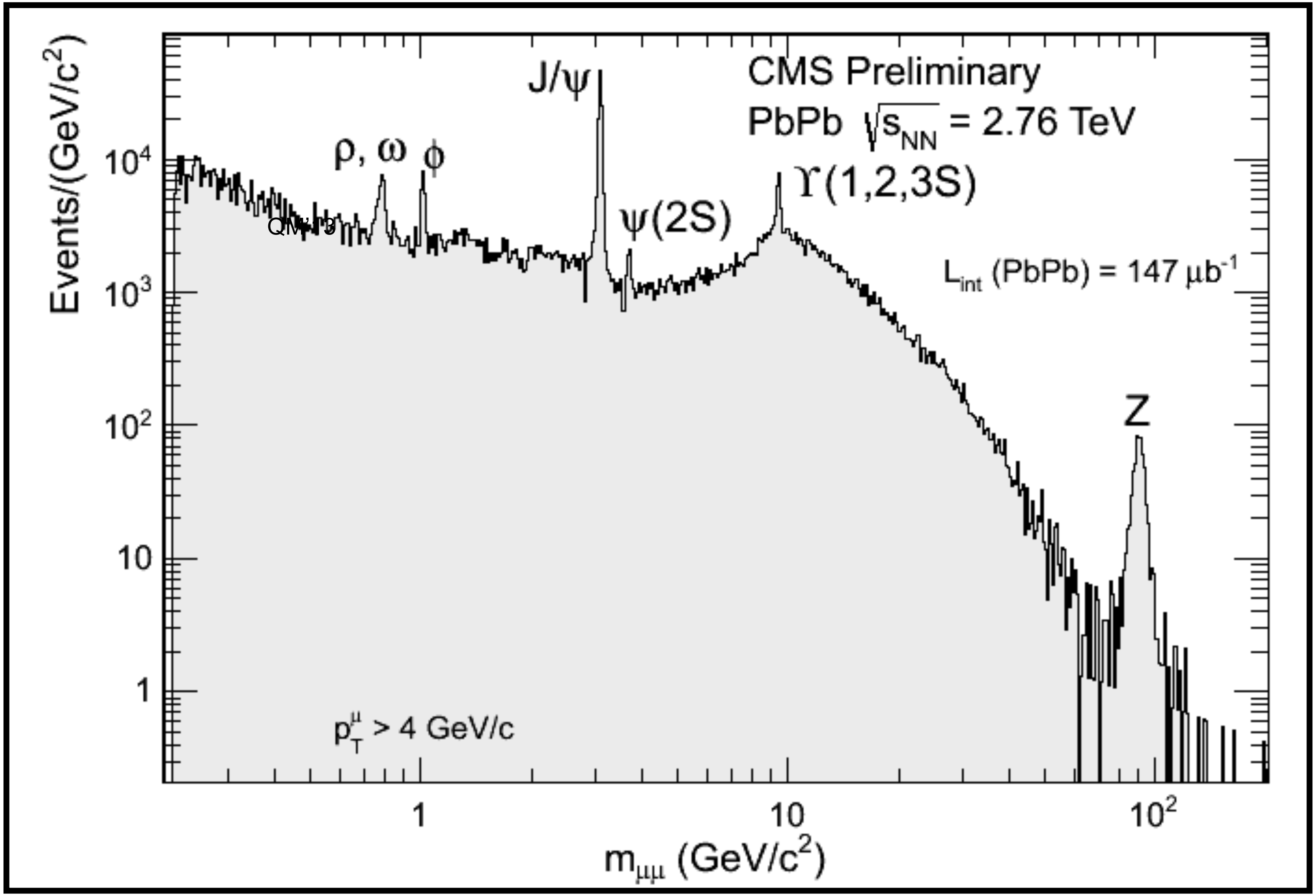
Charmonium detection

$J/\Psi \rightarrow e^+ + e^-$ (BR = 6%)	doable, also with trigger
$J/\Psi \rightarrow \mu^+ + \mu^-$ (BR = 6%)	doable, also with trigger
$\Psi' \rightarrow e^+ + e^-$ (BR = 0.8%)	lower rate, otherwise same as above
$\Psi' \rightarrow \mu^+ + \mu^-$ (BR = 0.8%)	lower rate, otherwise same as above
$X_{c1} \rightarrow J/\Psi + \gamma$ (BR = 34%)	hard, needs detection of soft photon
$X_{c2} \rightarrow J/\Psi + \gamma$ (BR = 20%)	hard, needs detection of soft photon
$\eta_c \rightarrow \gamma + \gamma$ (BR = 1.8×10^{-4})	a real challenge (!)

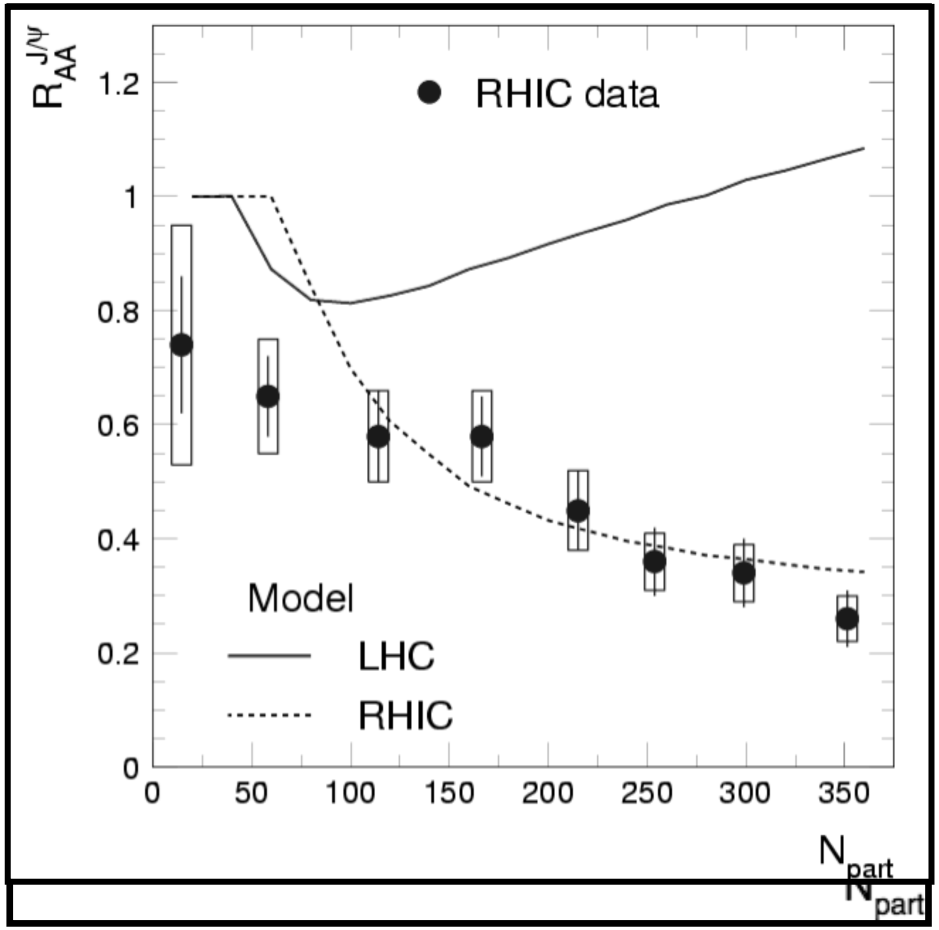
→ Need **dileptons** to address **charmonium** production

→ Similar arguments hold for **bottomonium Υ(1), Υ(2s), Υ(3s)**

Dimuons from CMS at LHC



Statistical Hadronization of Charm



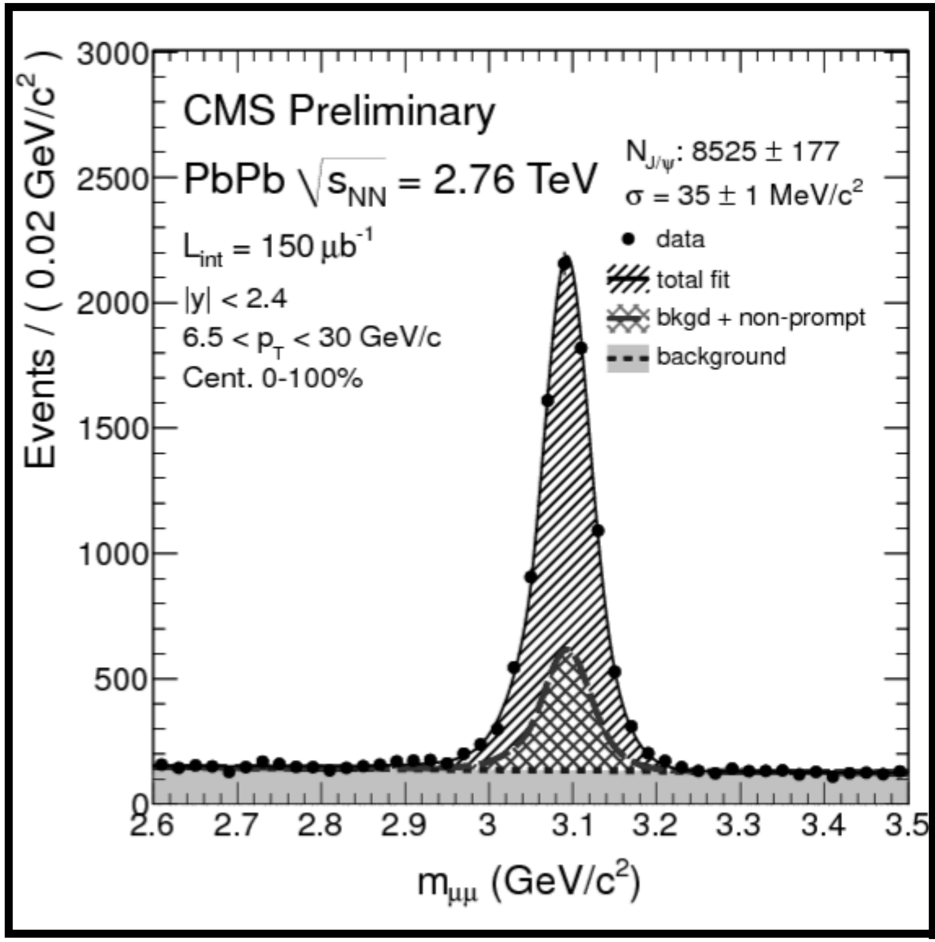
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys. Lett. B 652 (2007) 259.

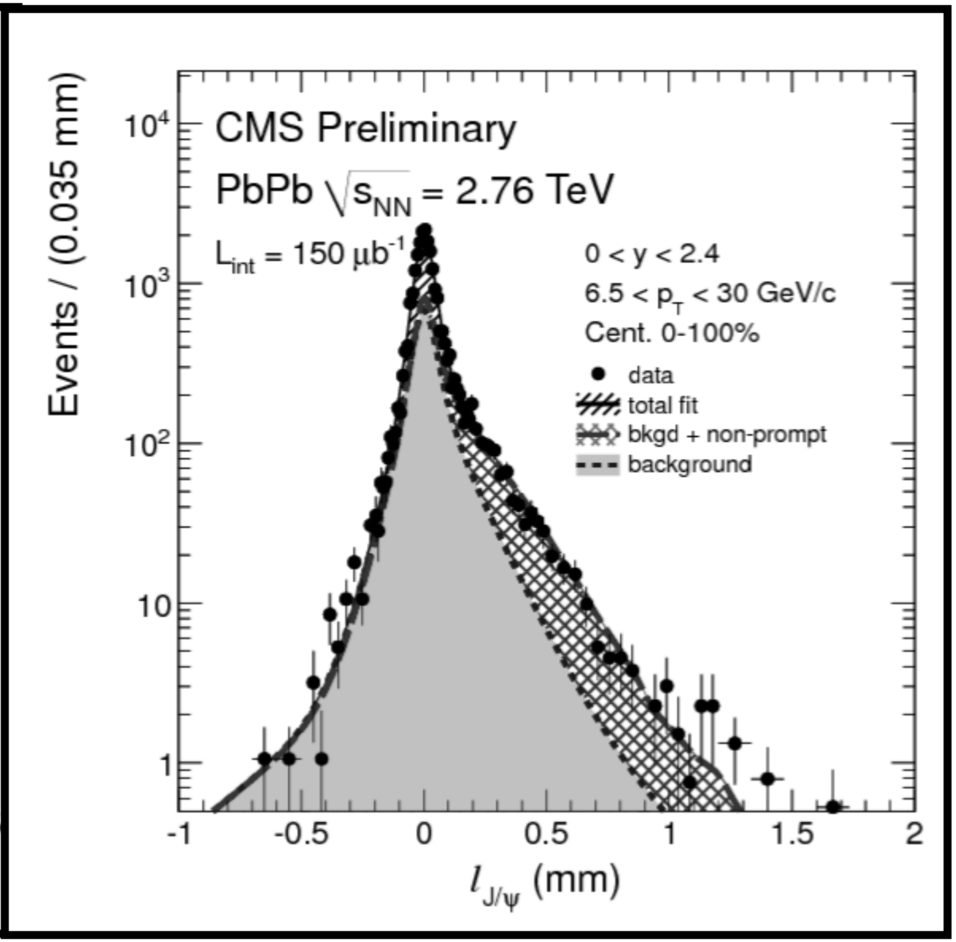
- up to **100 charm** quark pairs in a single **Pb+Pb collision at LHC**
- **generation** of **J/ψ** from **deconfined quarks**
- **depends** on **total number** of **charm quarks** $N_{J/\psi} \sim (N_{ccbar})^2$

→ **Suppression** at RHIC

→ **Enhancement** at **LHC**

Prompt J/ψ and from B → J/ψ + X

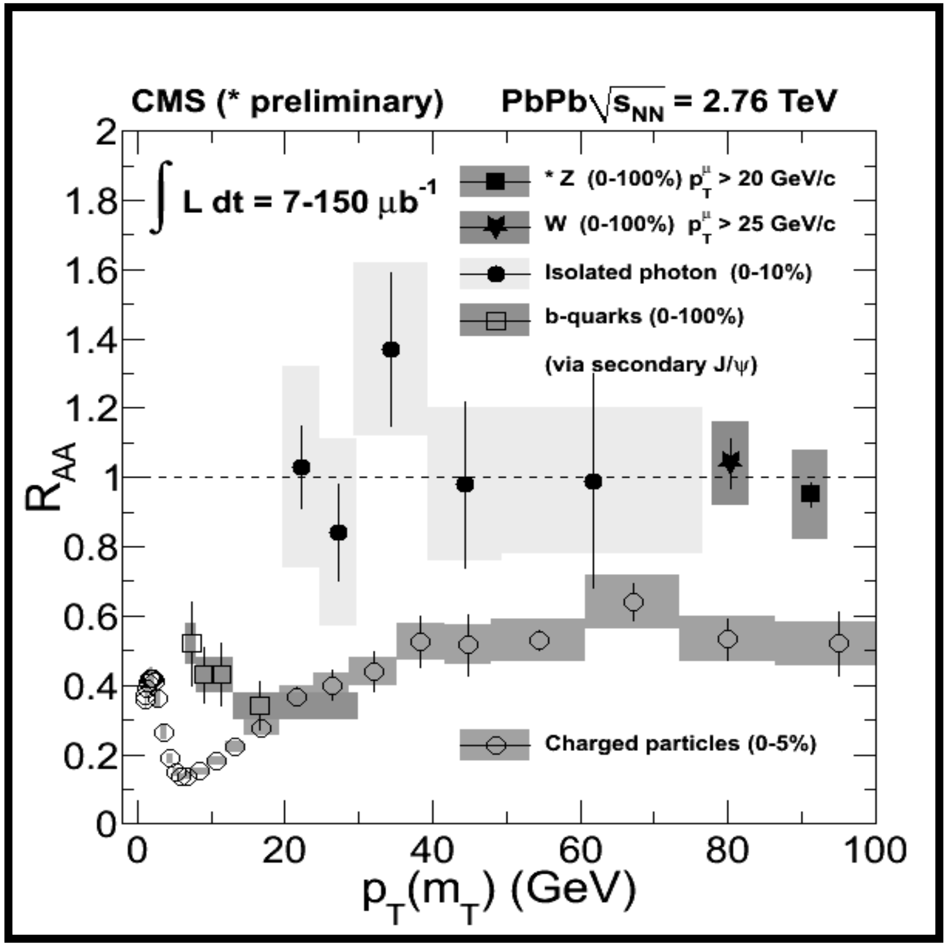




- **disentangle prompt** from **secondary** production by proper decay length (exponential decay of J/ψ from B)

- **tag B-meson** production

Comparison to other hadrons



- Mass ordering in R_{AA}?

  J/ψ ← B (upper)

  D (middle)

  π (lower)

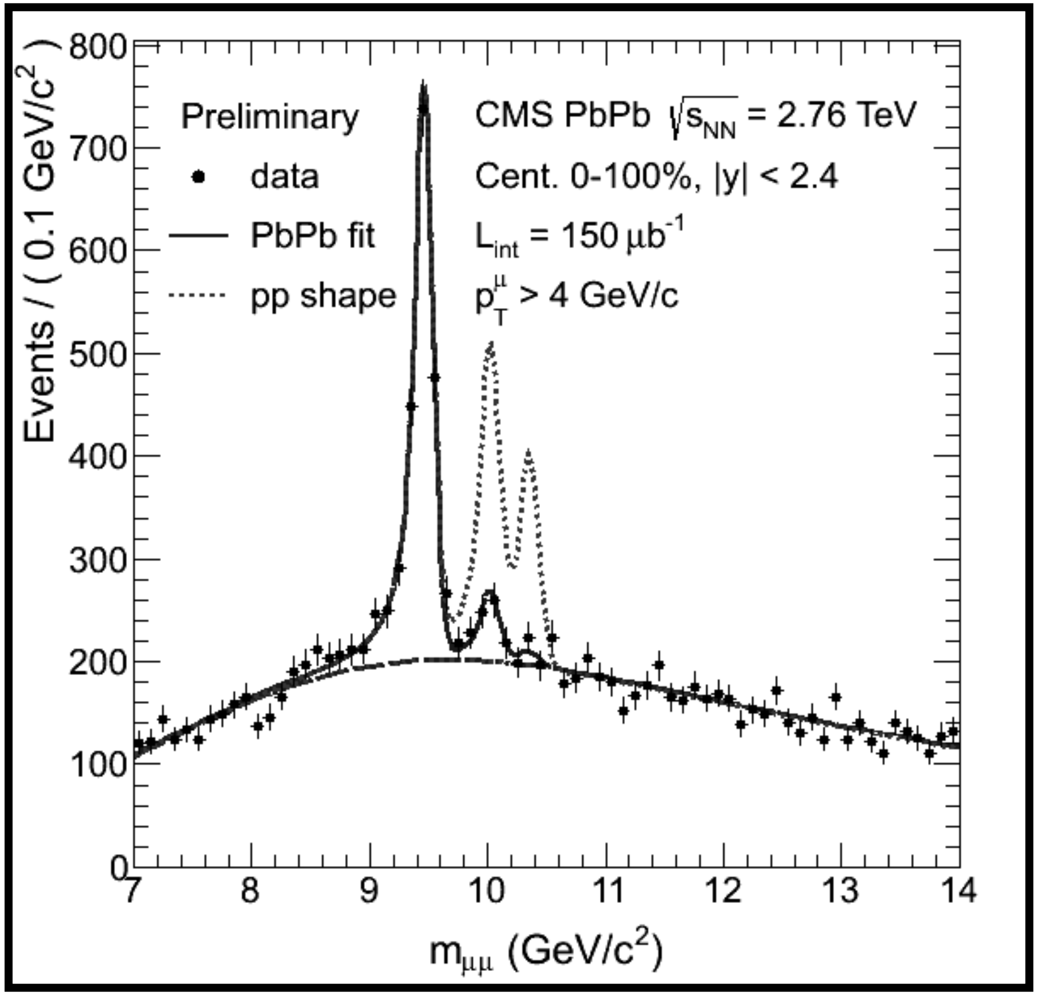
- γ,W,Z-bosons:

  R_{AA} ≈ 1 (!)

  checks normalization, does not probe the medium

ALICE, arXiv:1203.2160 [nucl-ex],
CMS Z-boson: Phys. Rev. Lett. 106 (2011)212301.

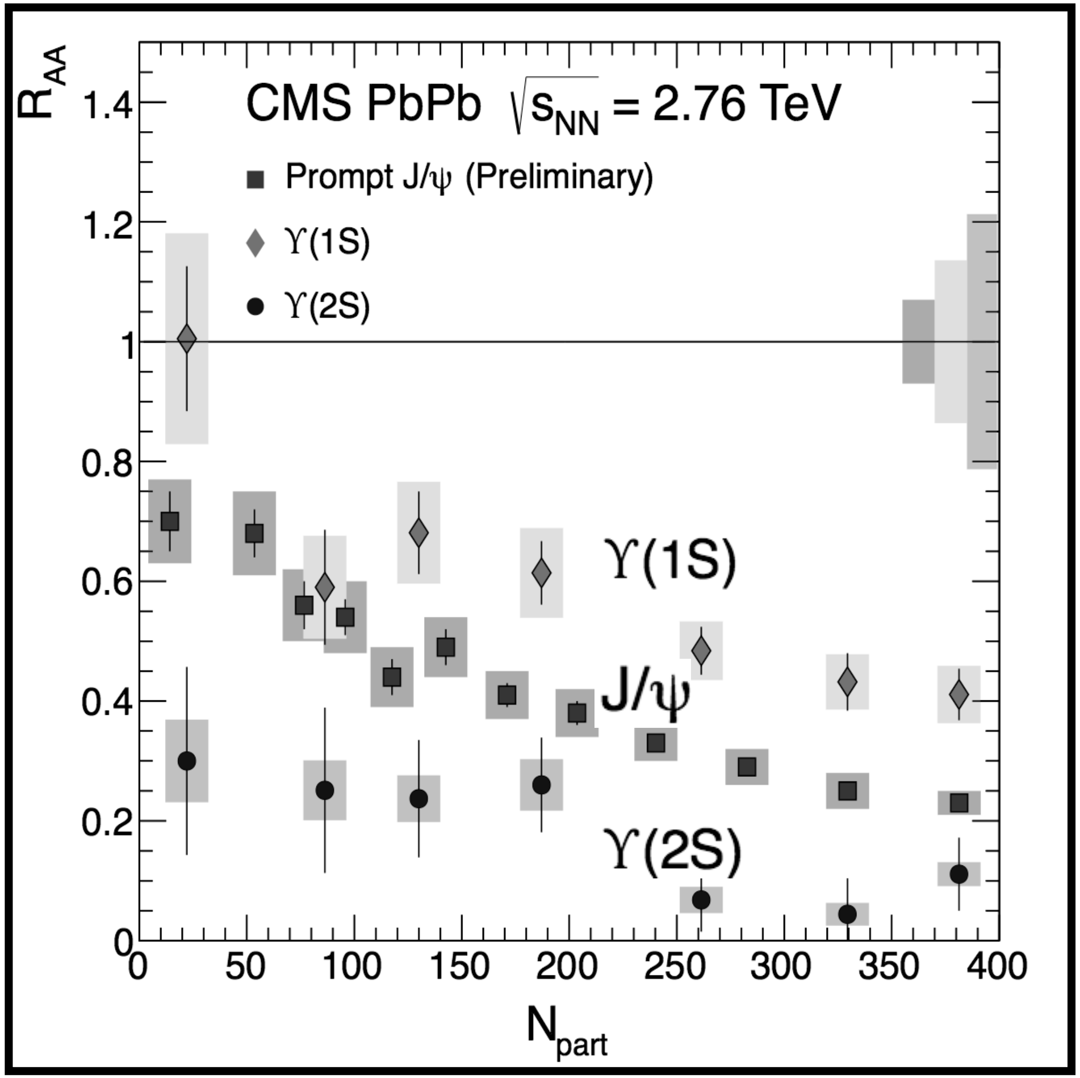
Sequential Υ suppression



Observation of sequential suppression of Υ family

When compared to pp collisions

Quarkonium-thermometer



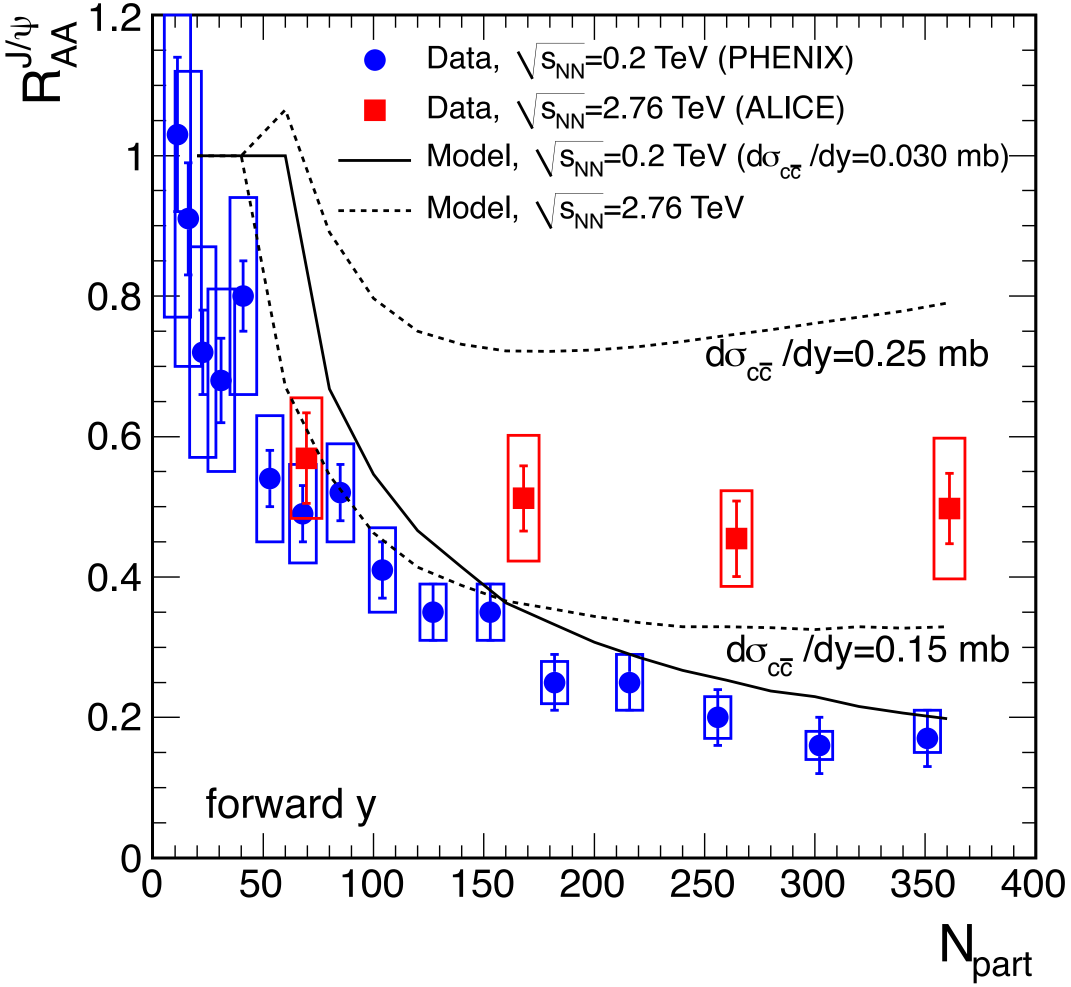
Apparent hierarchy in R_{AA} of different quarkonium states

However: J/ψ from CMS are from high-p_T > 6.5 GeV/c

Not necessarily equilibrated in QGP

CMS-PAS HIN-11-011

LHC versus RHIC energies



Enhancement at LHC

$N_{J/\psi} \sim (N_{ccbar})^2$

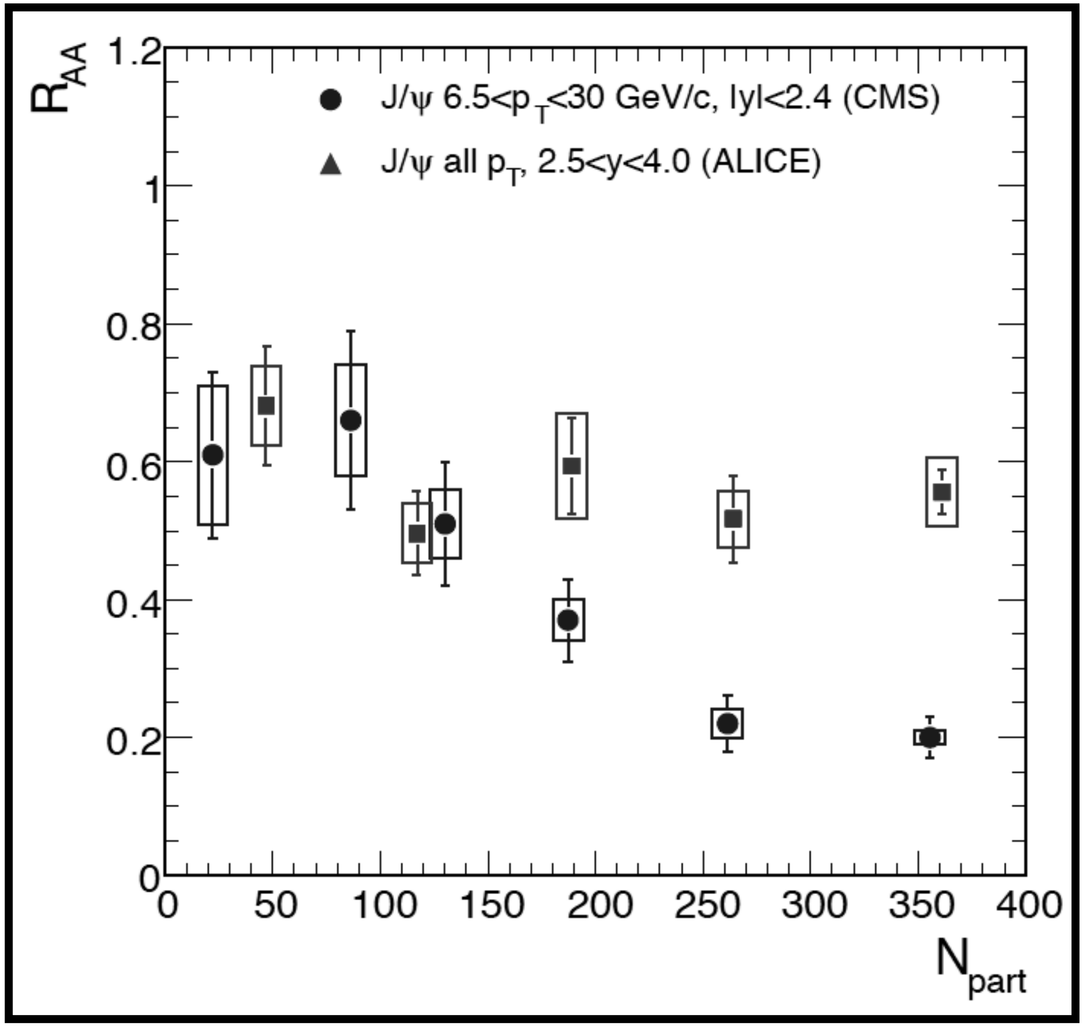
Suppression at RHIC

What is different?

Charm production at

LHC is **10x RHIC**

ALICE versus CMS at LHC



- charmonium less suppressed at low momentum (ALICE)

or (in other words)

- **More generation** in the bulk (at **low p_T**)
- suppresion at high-p_T likely due to energy loss (as for D-mesons)

Lesson learnt

- Quarkonia (charmonium and bottomonium) and their production are unique probes of QGP
- Story has evolved over the last 30 years and is rather intricate
- ϒ family apparently shows sequential melting with more strongly bound ϒ(1) less suppressed than ϒ(2s)
- J/ψ at high momentum shows suppression similar to open charmed hadrons (energy loss)
- J/ψ shows effects of generation at the phase boundary due to statistical hadronization of charm at low momentum (bulk)

→ Harbinger of de-confinement