Heavy quarkonium in the Quark-Gluon Plasma: the Effective Field Theory approach

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Quarks and gluons: QCD

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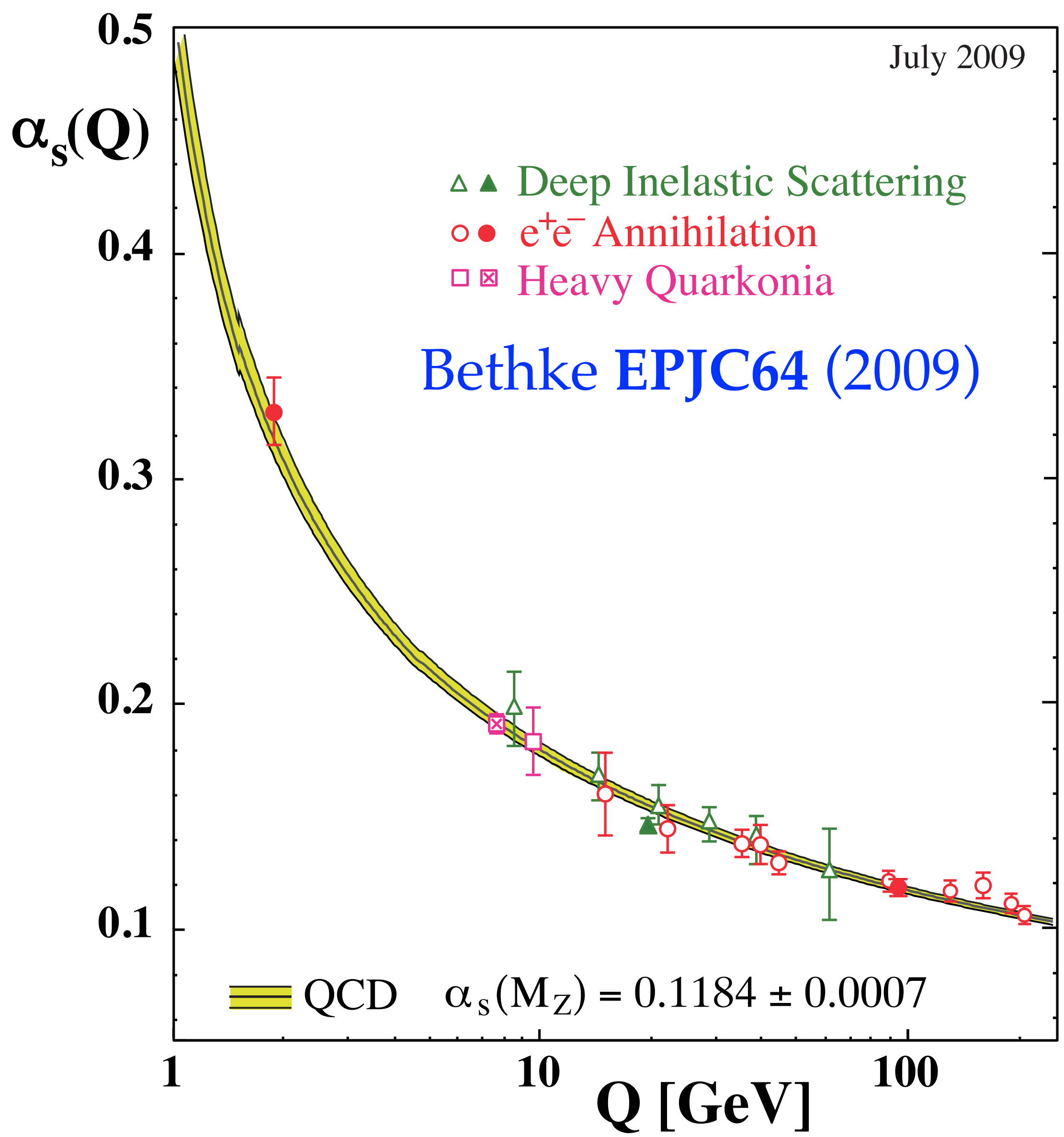
- QCD is the theory of the strong interactions of quarks and gluons. Its quantization causes the coupling constant to run with the energy and introduces the scale $\Lambda_{QCD} \simeq 200\,\mathrm{MeV}$



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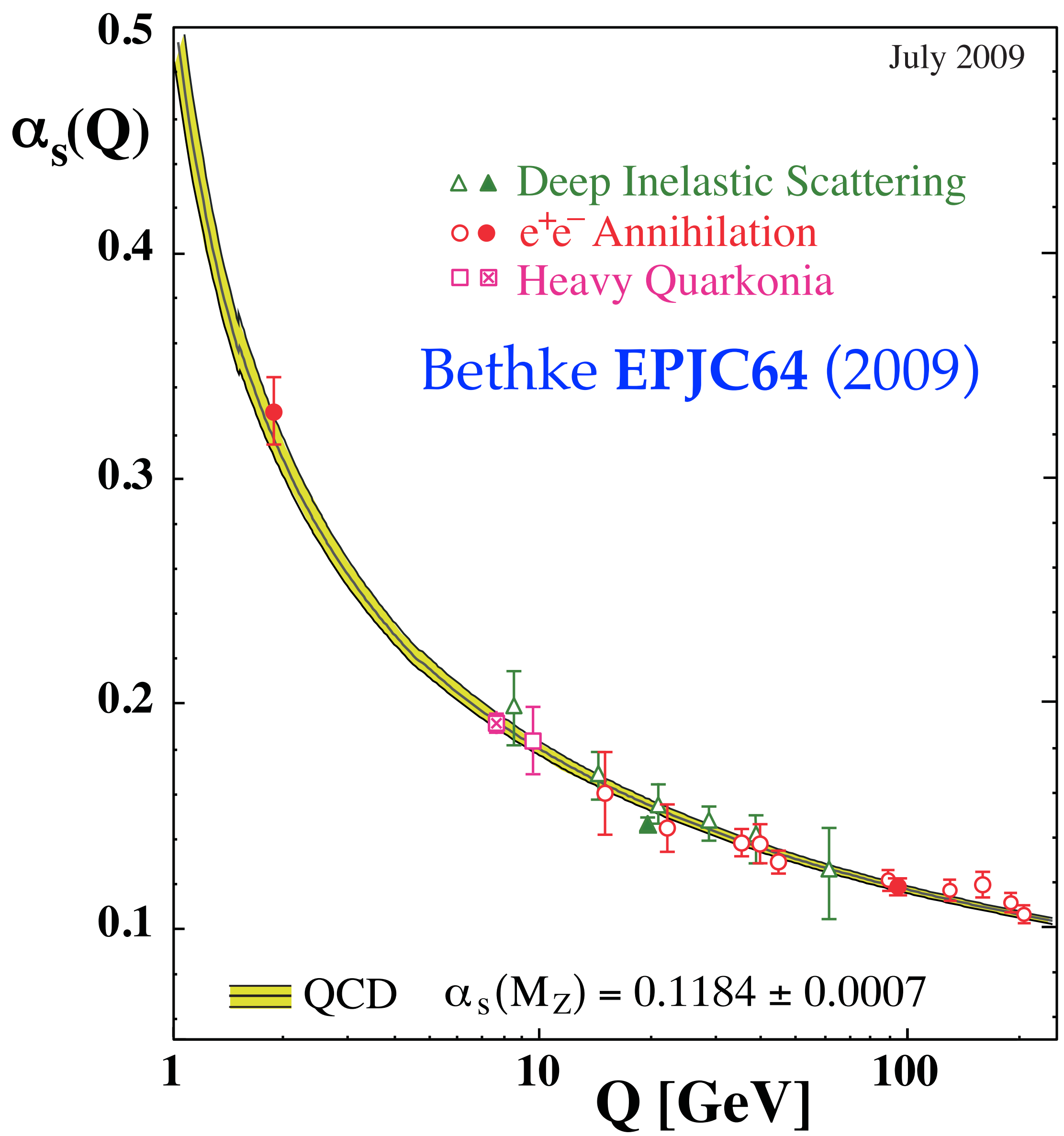

Asymptotic freedom

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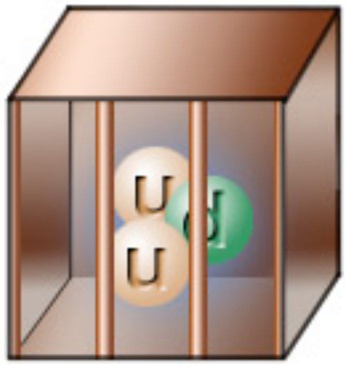
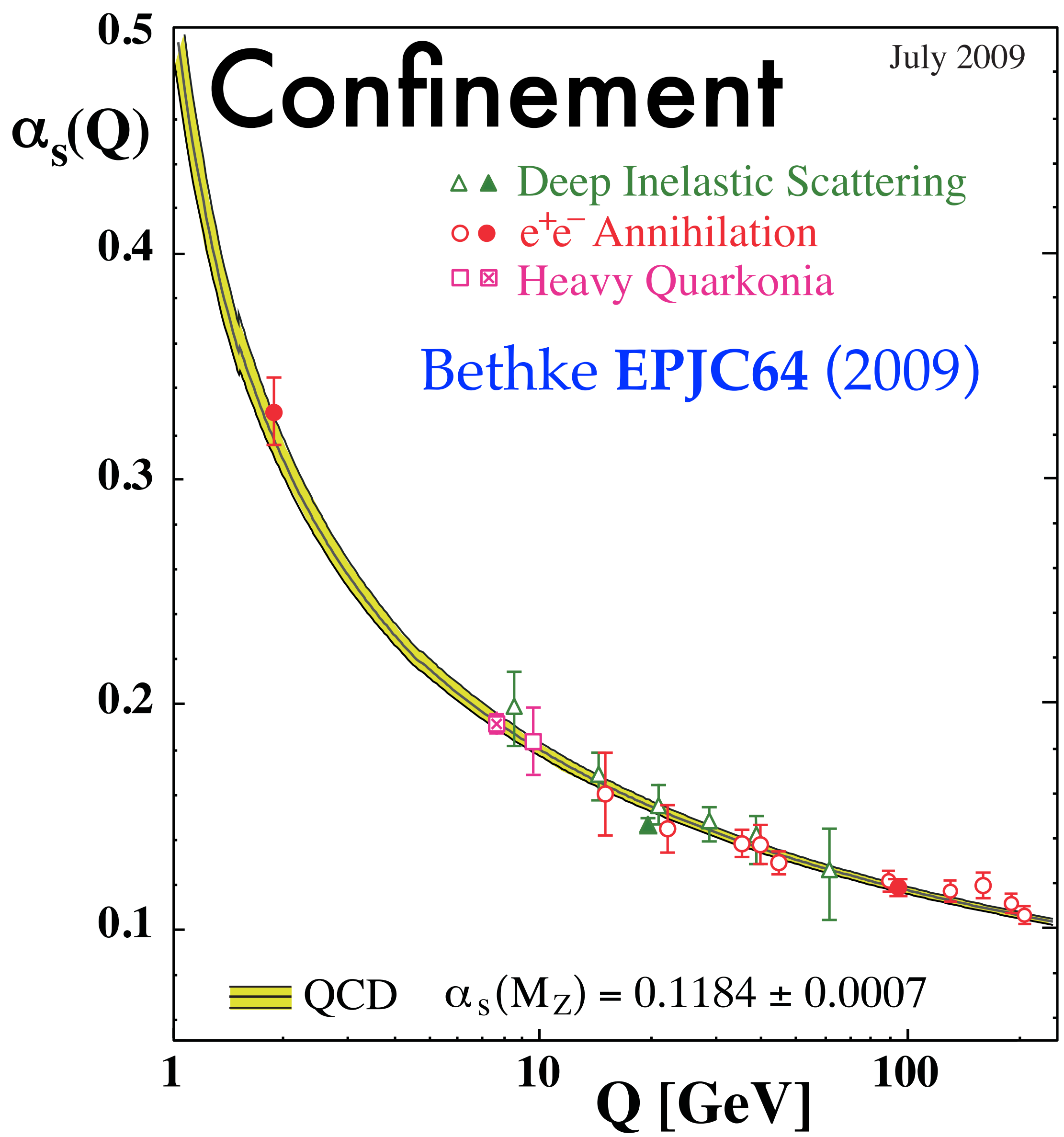
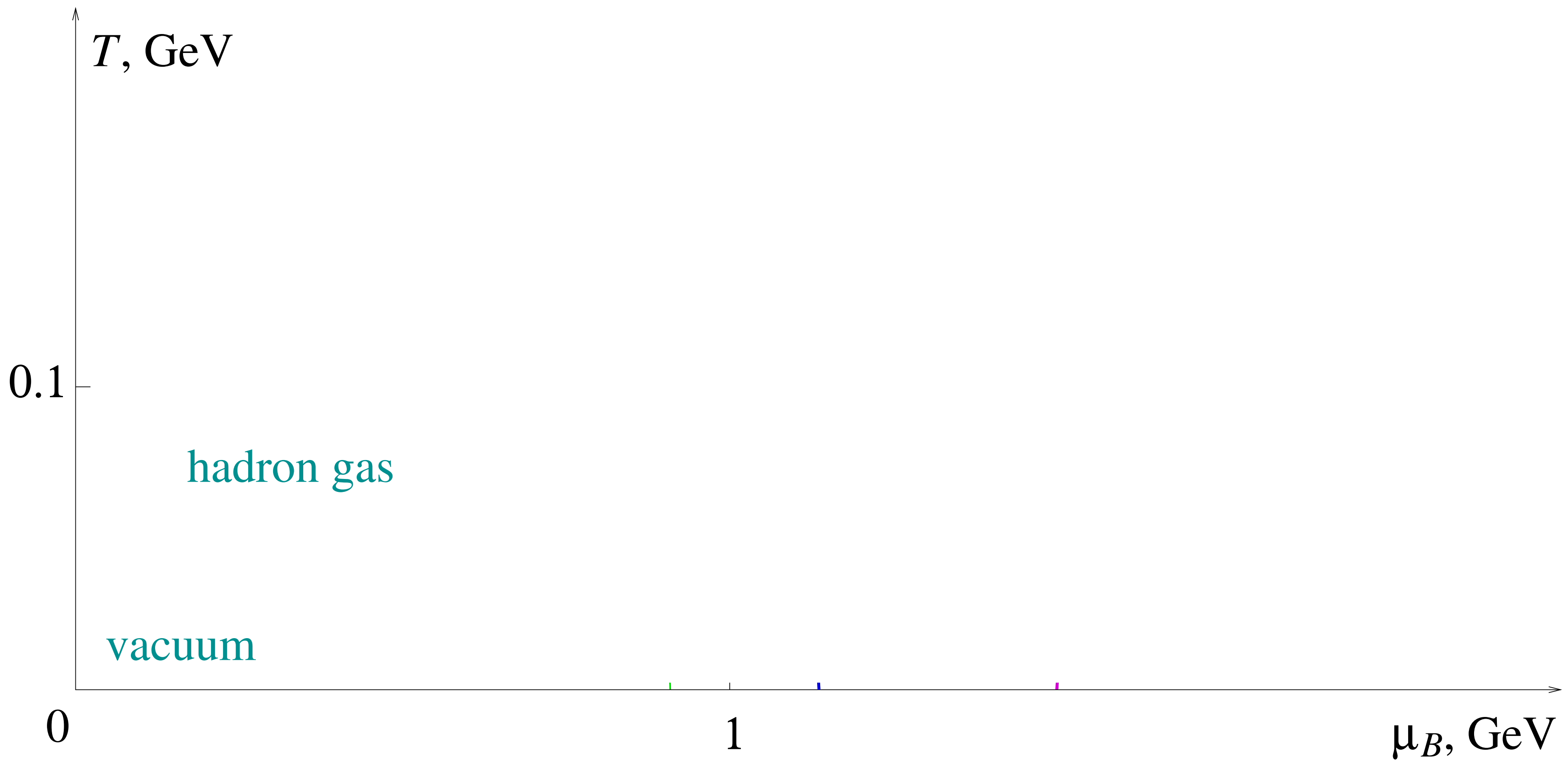




Asymptotic freedom

The phase diagram of QCD

- In the temperature/baryon chemical potential plane:



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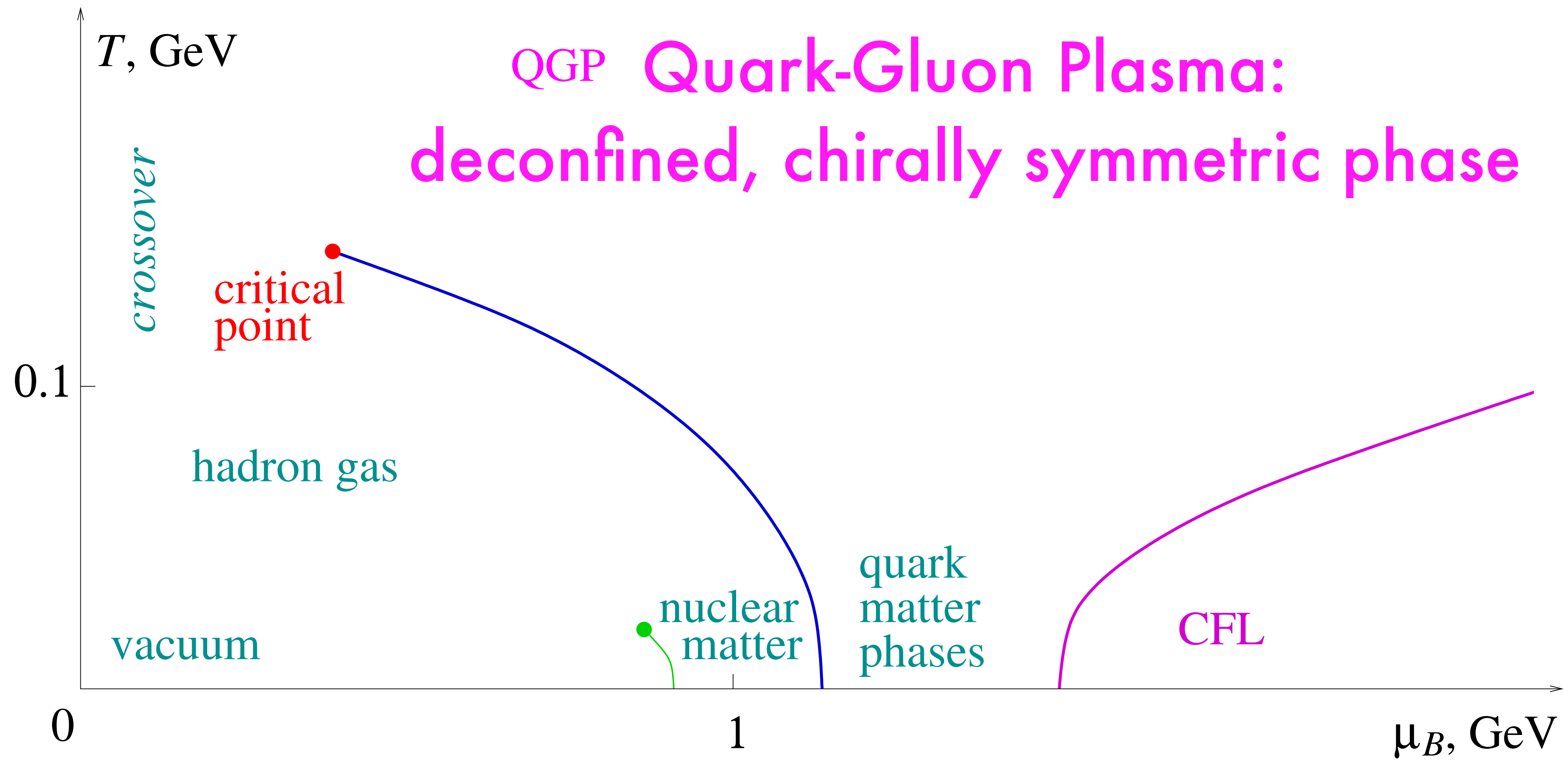


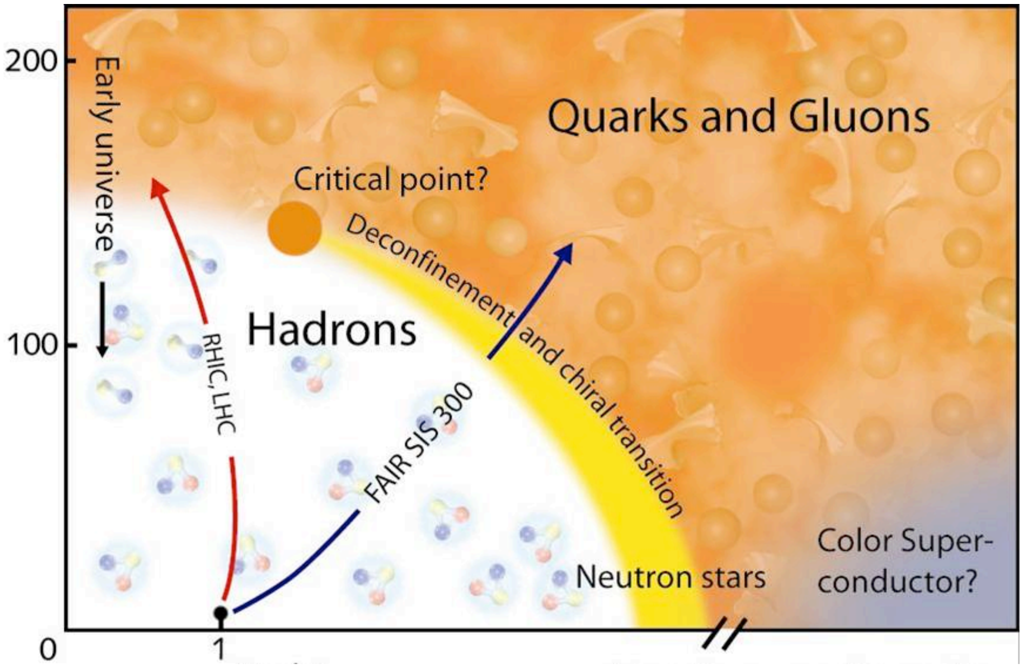
- In the upper-left region, lattice QCD indicates a (pseudo)critical temperature T_c~160 MeV ~2×10^{12} K

- For comparison, sun's core: T~1.5×10^7 K

Heavy ion collision experiments

Heavy ion collision experiments

- Past experiments at the CERN SPS, currently at the RHIC (BNL) and the LHC and future at FAIR (GSI). Energies *per nucleon pair*:
200 GeV at RHIC, 2.76 TeV at LHC



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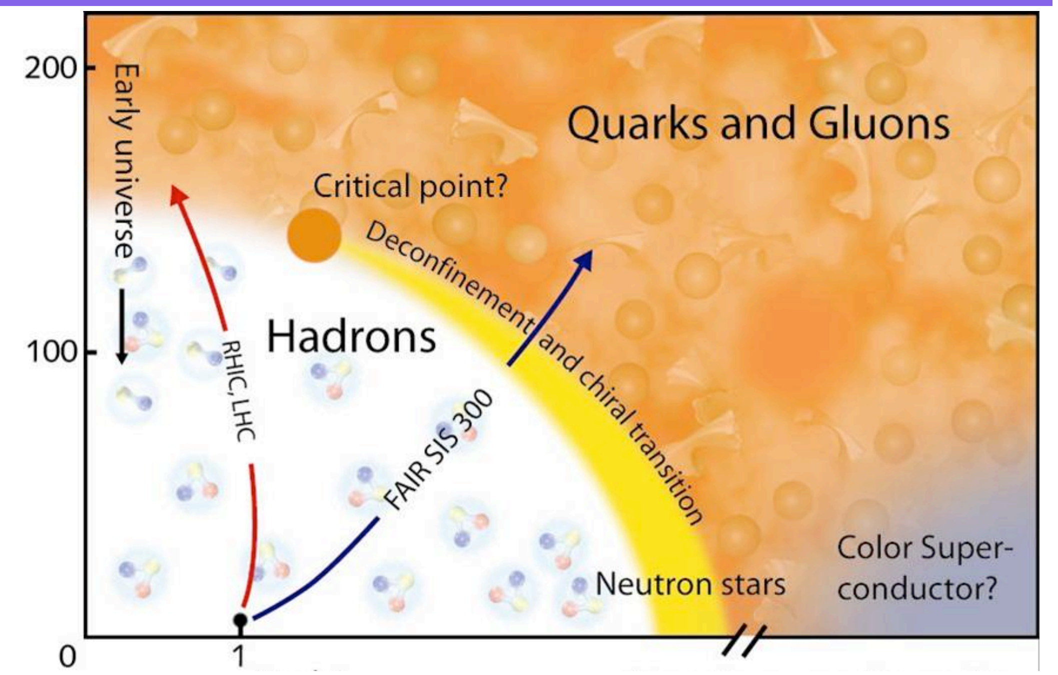

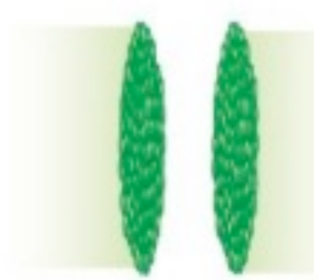

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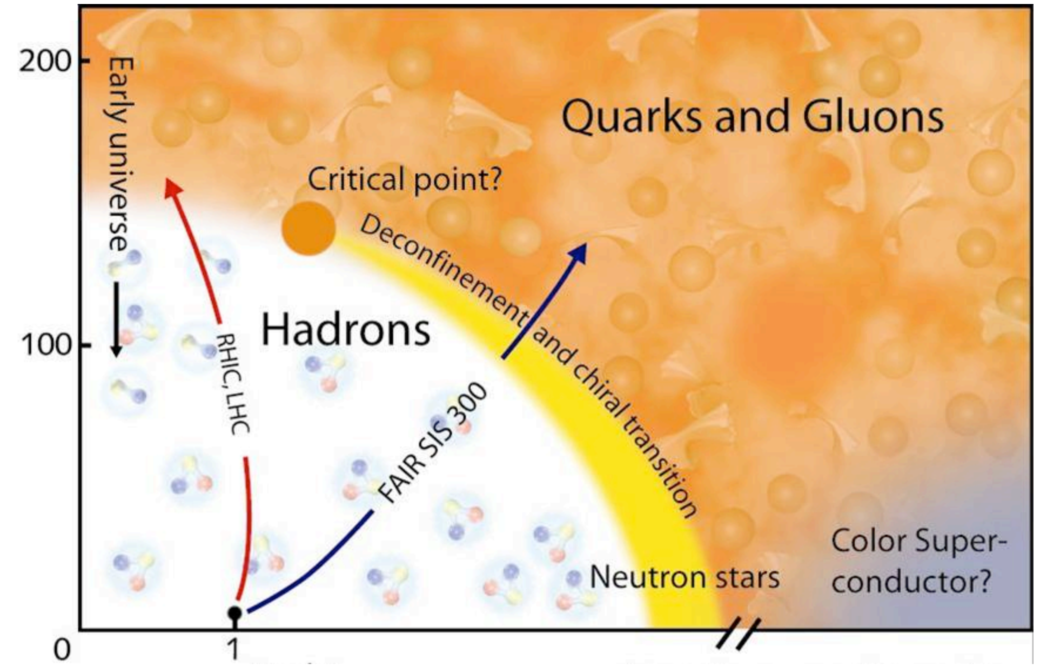

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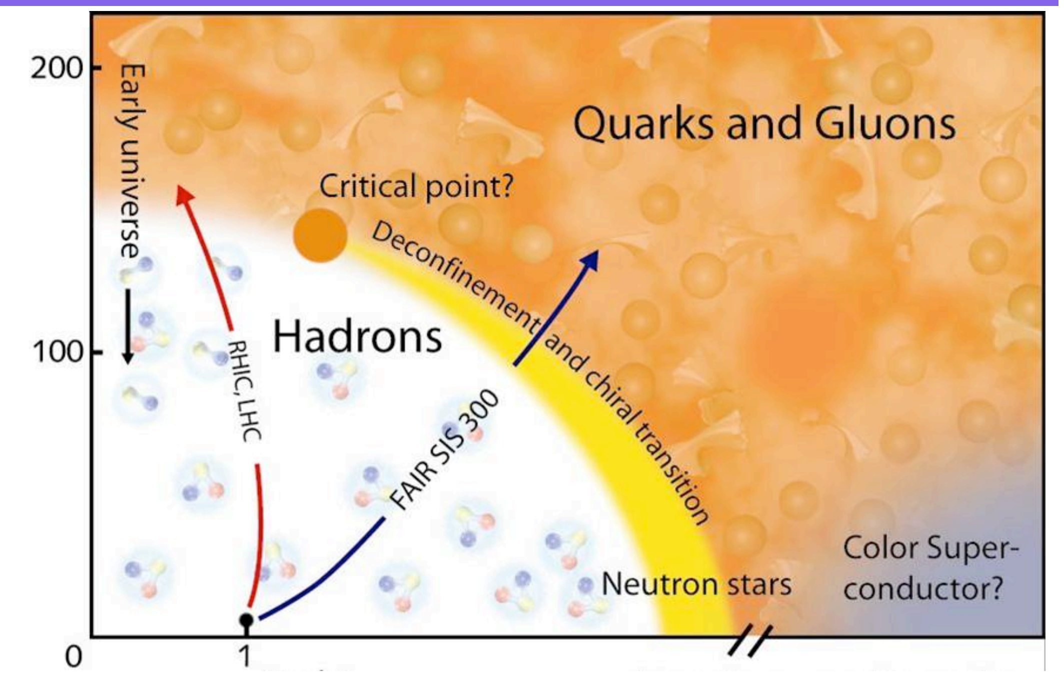

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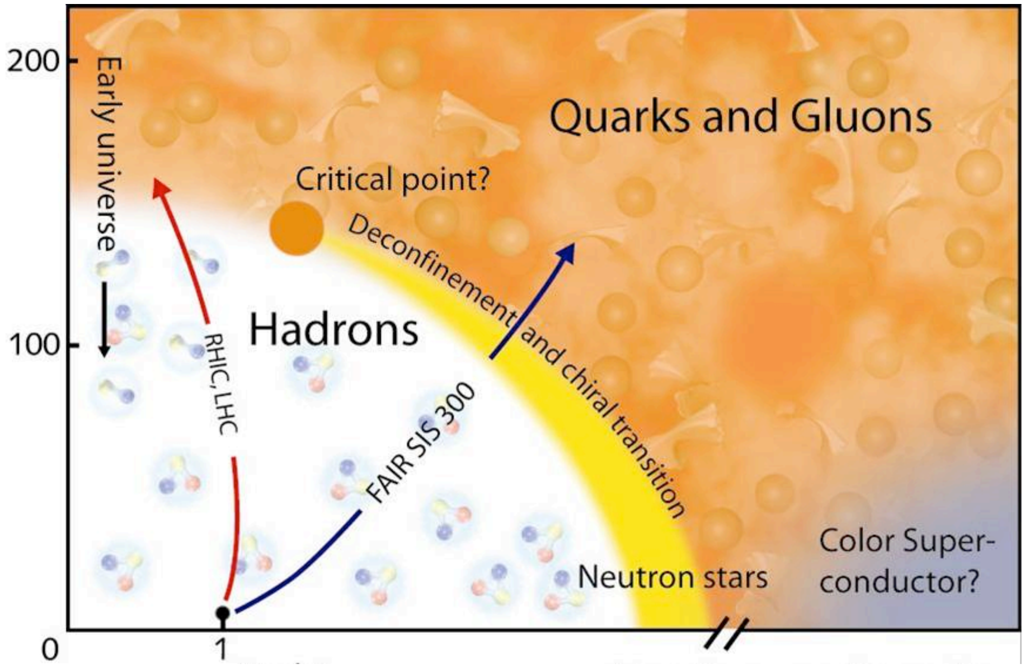

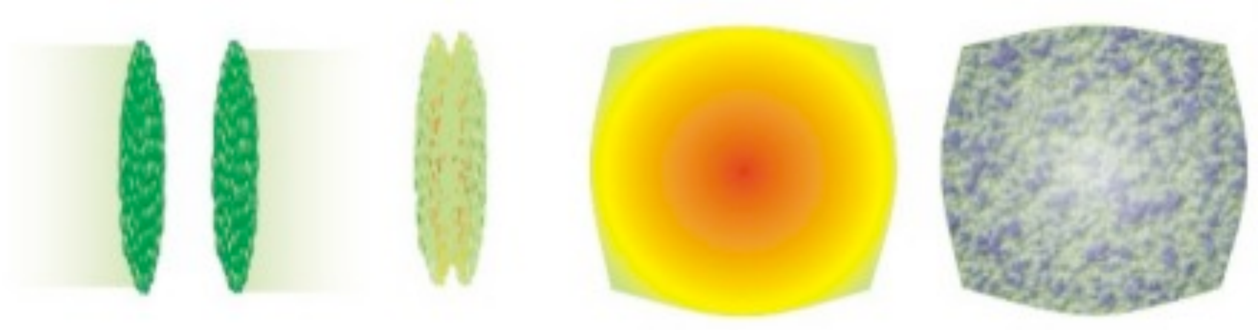

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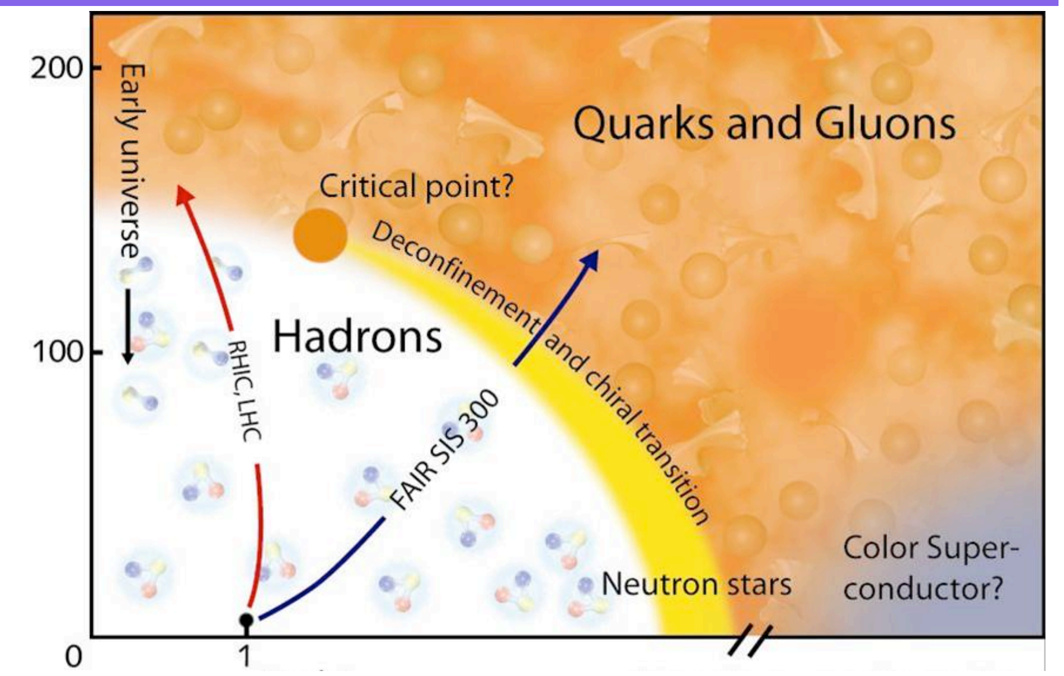

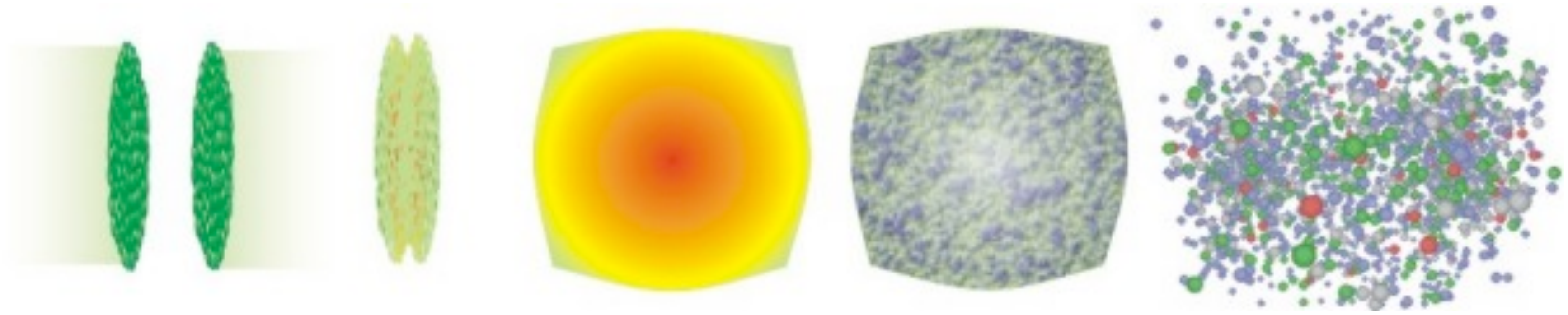

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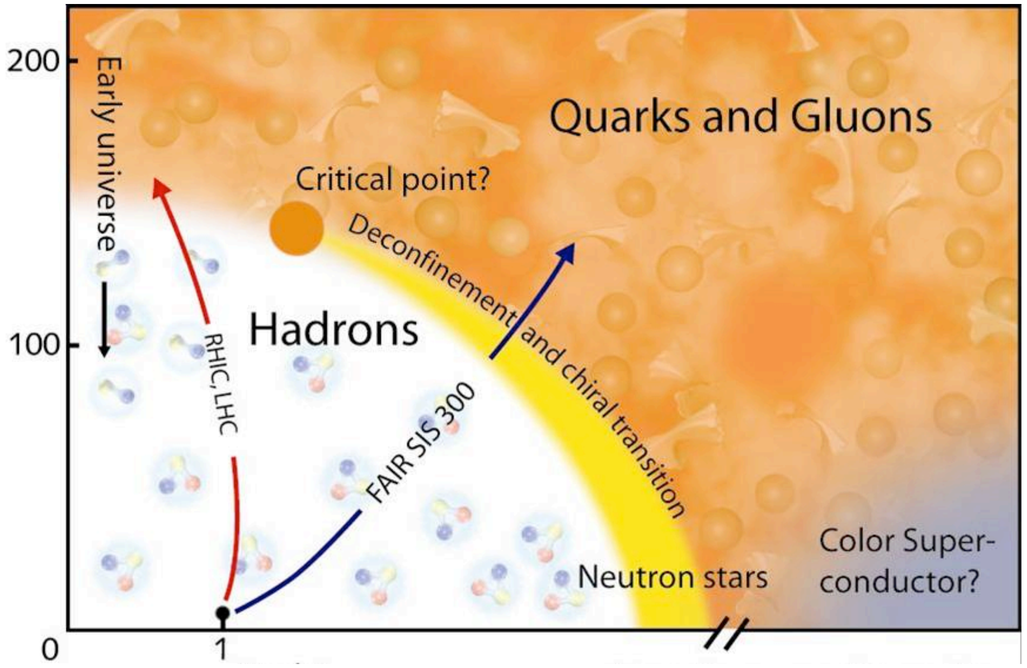
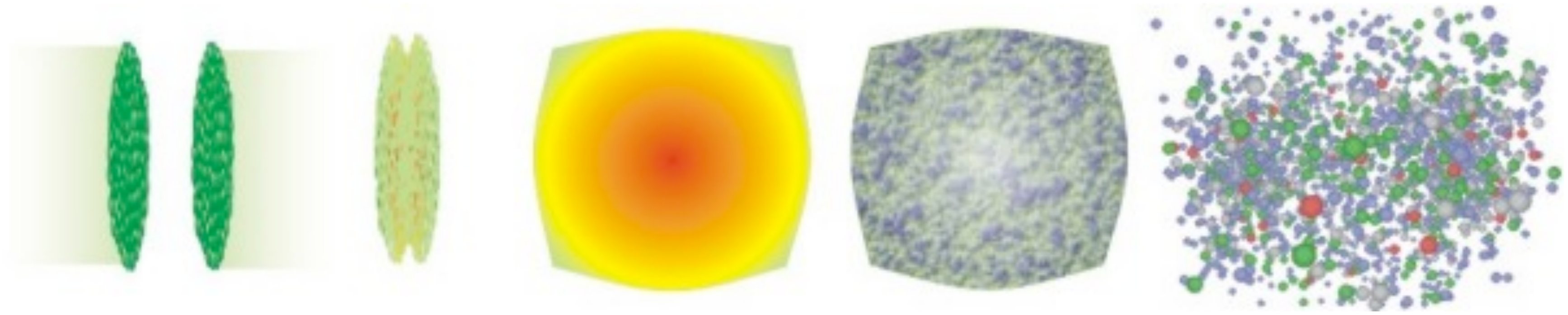
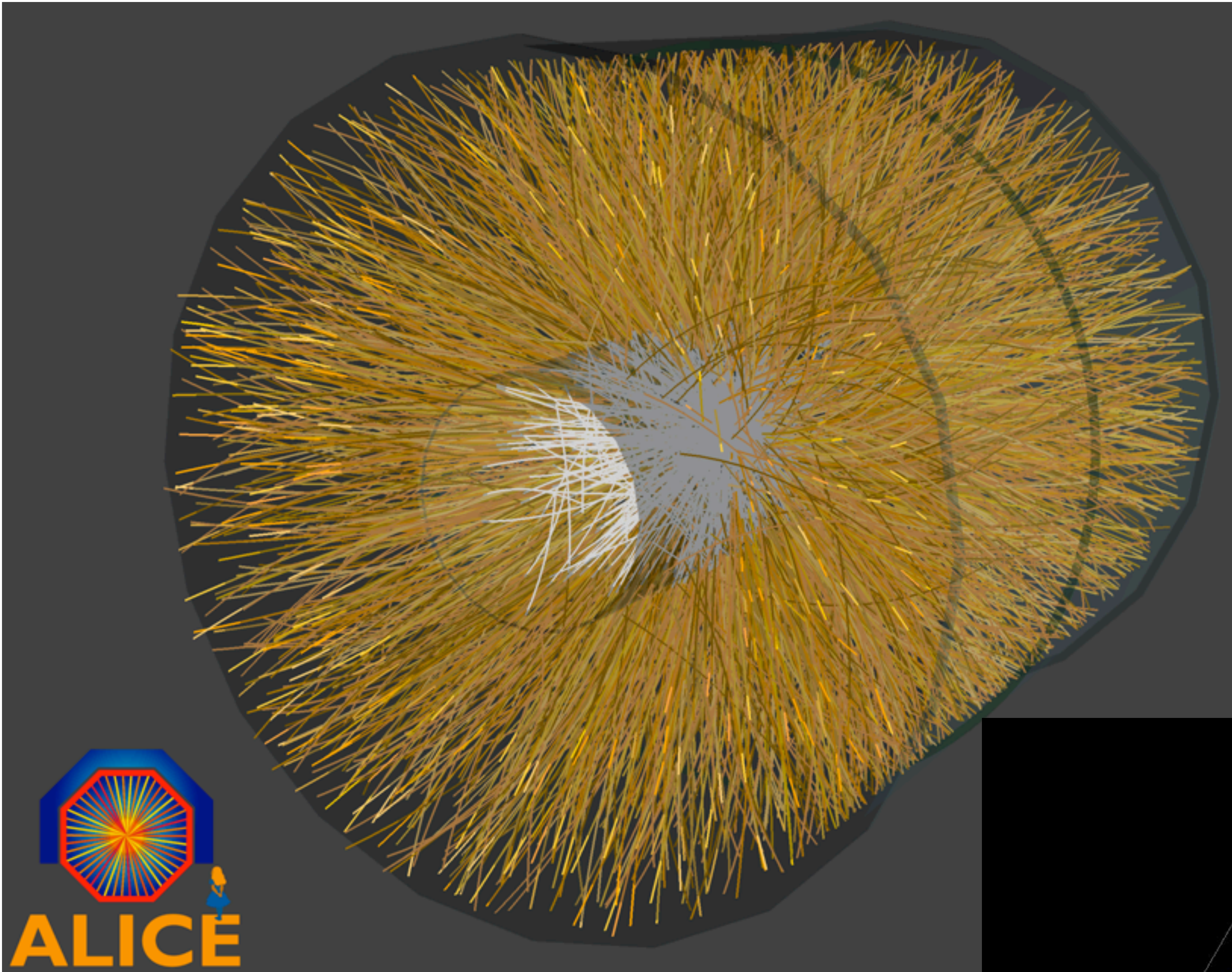


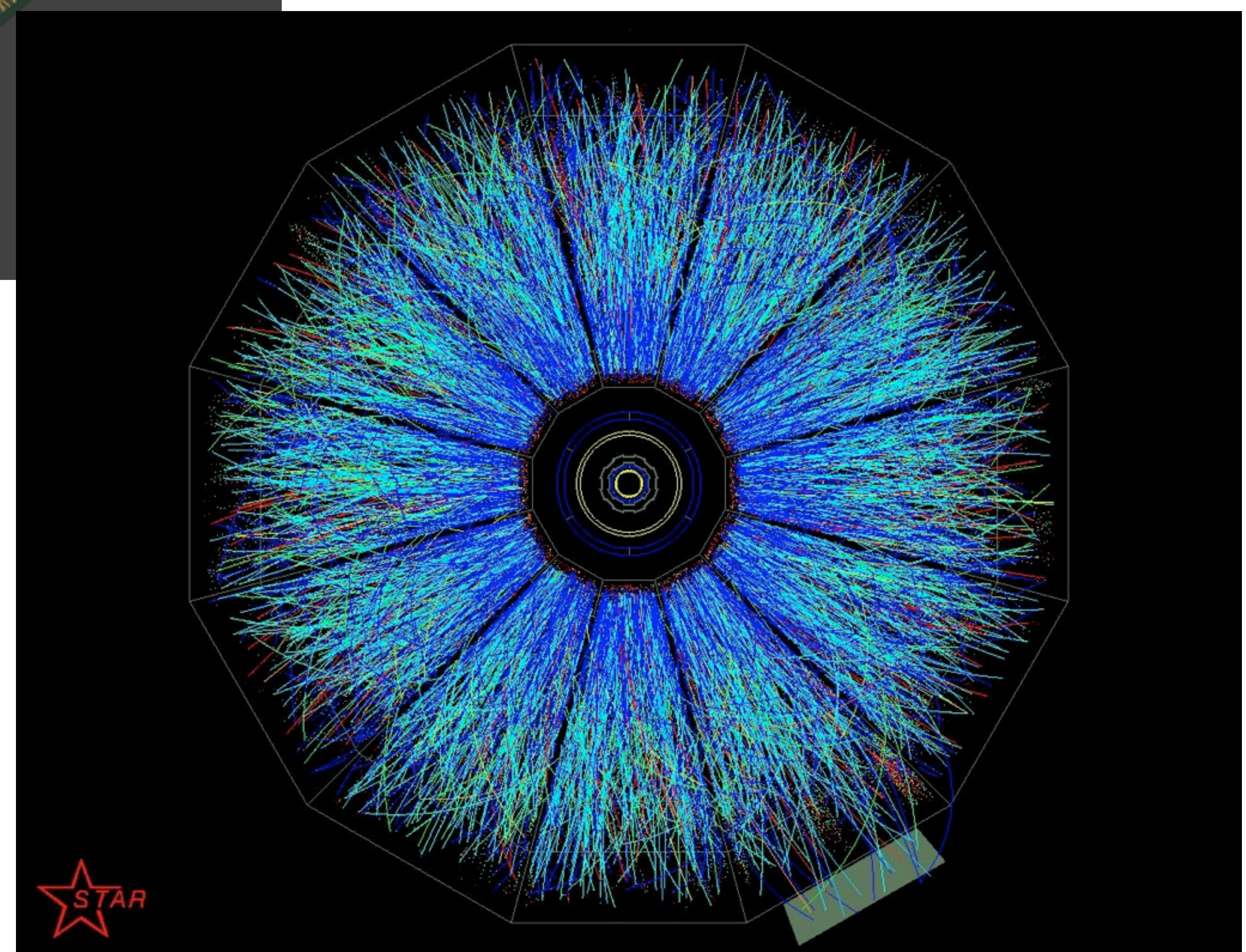


- The highest particle multiplicities are measured in these experiments, such as $dN_{\mathrm{ch}}/d\eta = 1584 \pm 4\,(stat.) \pm 76\,(sys.)$ ALICE **PRL105** (2010)



- Characterization of the medium through **two** classes of observables
  - **Bulk** properties (hydro, flow, etc...)
  - **Hard probes** (jets, e/m probes, quarkonia...)

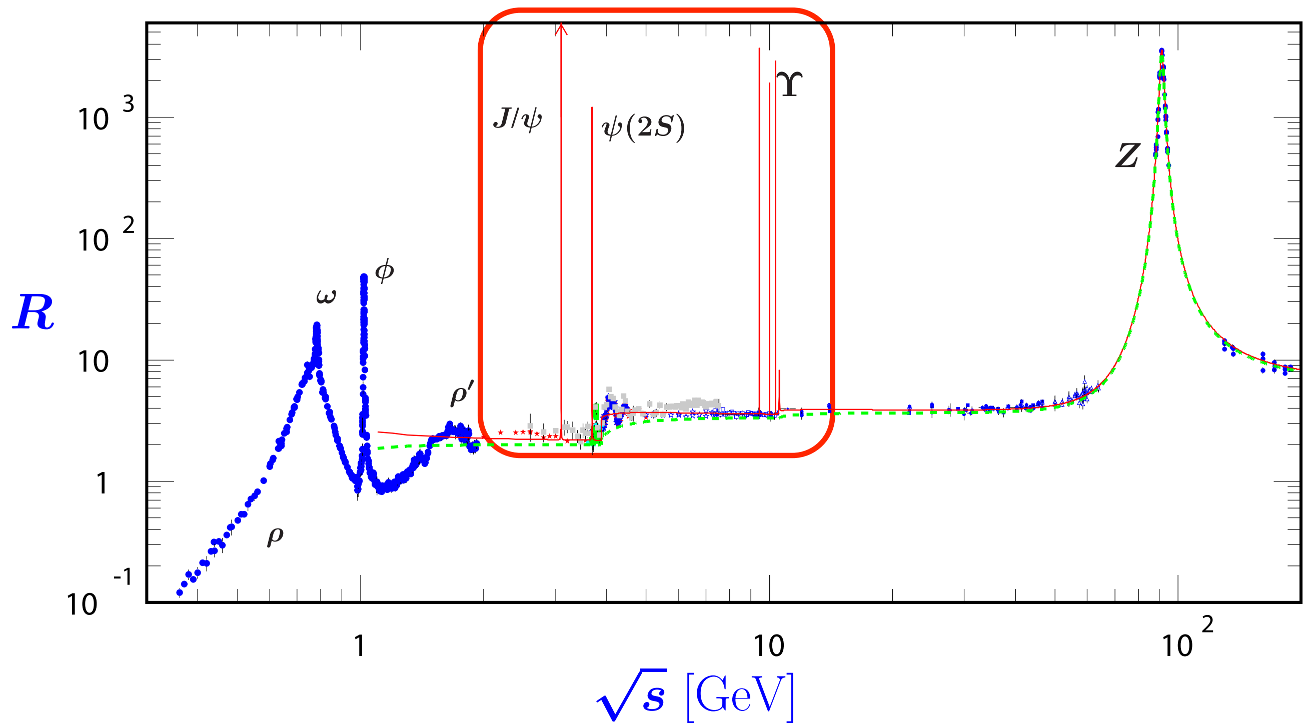
- **Hard probes:** *high-energy* particles *not in equilibrium* with the medium.
- Medium *tomography* and characterization of its properties, such as deconfinement



Heavy quarkonia

- The masses of the c (~1.5 GeV), b (~4.5 GeV) and t (~175 GeV) are much larger than Λ_{QCD}.
  They are called *heavy quarks*, and their quark-antiquark bound states $Q\overline{Q}$ are called *quarkonia*

- The lower resonances of charmonium and bottomonium are to a good deal *non-relativistic* and *perturbative*.



Quarkonium as a hard probe

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

- *Hypothesis*: colour screening leads to the disappearance of the bound state
- A suppressed J/ψ yield is observed in the dilepton channel
  Matsui Satz **PLB178** (1986)

Quarkonium suppression in experiments

- Typical observable: the **nuclear modification factor**

$$R_{AA} = \frac{\mathrm{Yield}_{AA}}{\mathrm{Yield}_{pp} \times N_{bin}}$$

- $R_{AA} \neq 1 \Rightarrow$ deviations from binary scaling. Causes:
  - Cold Nuclear Matter effects (affect production and early stages).
  - Hot Medium effects, such as screening. Reduce R_{AA}
  - Recombination effects. Increase R_{AA}

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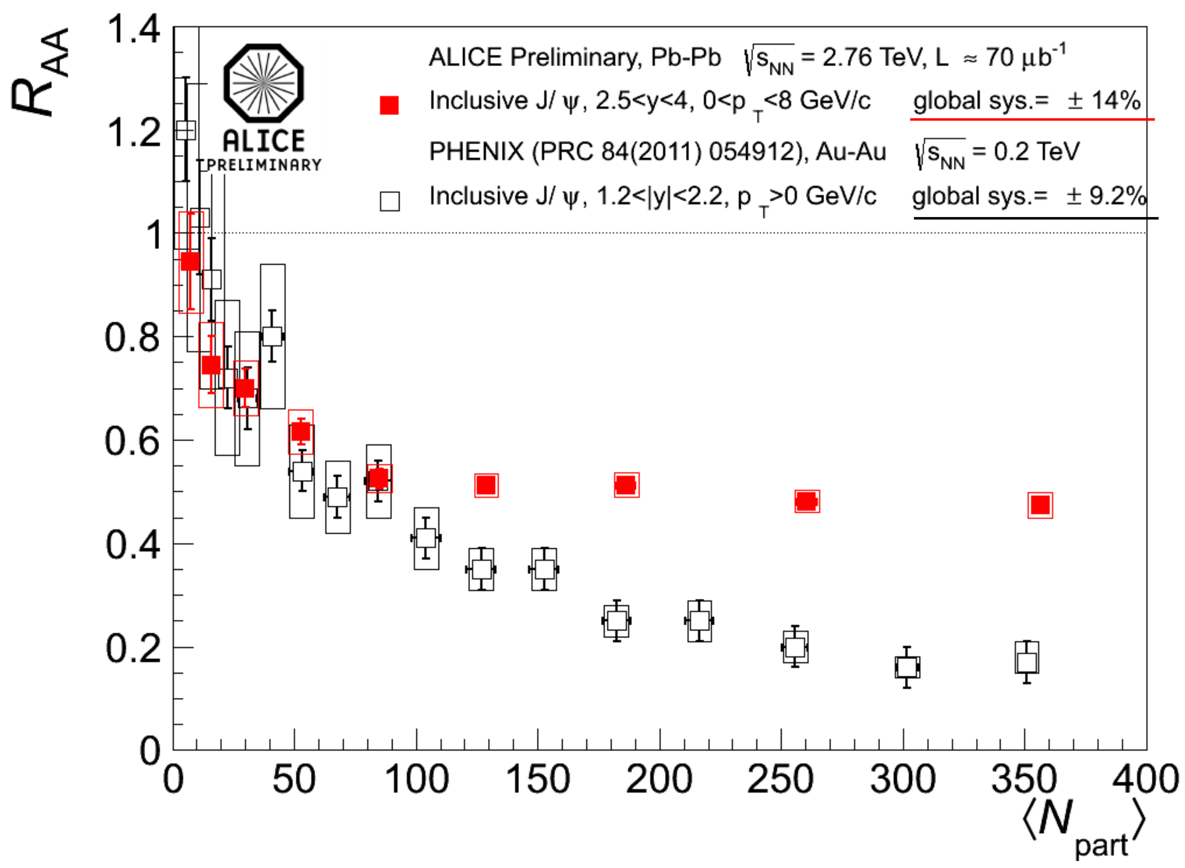
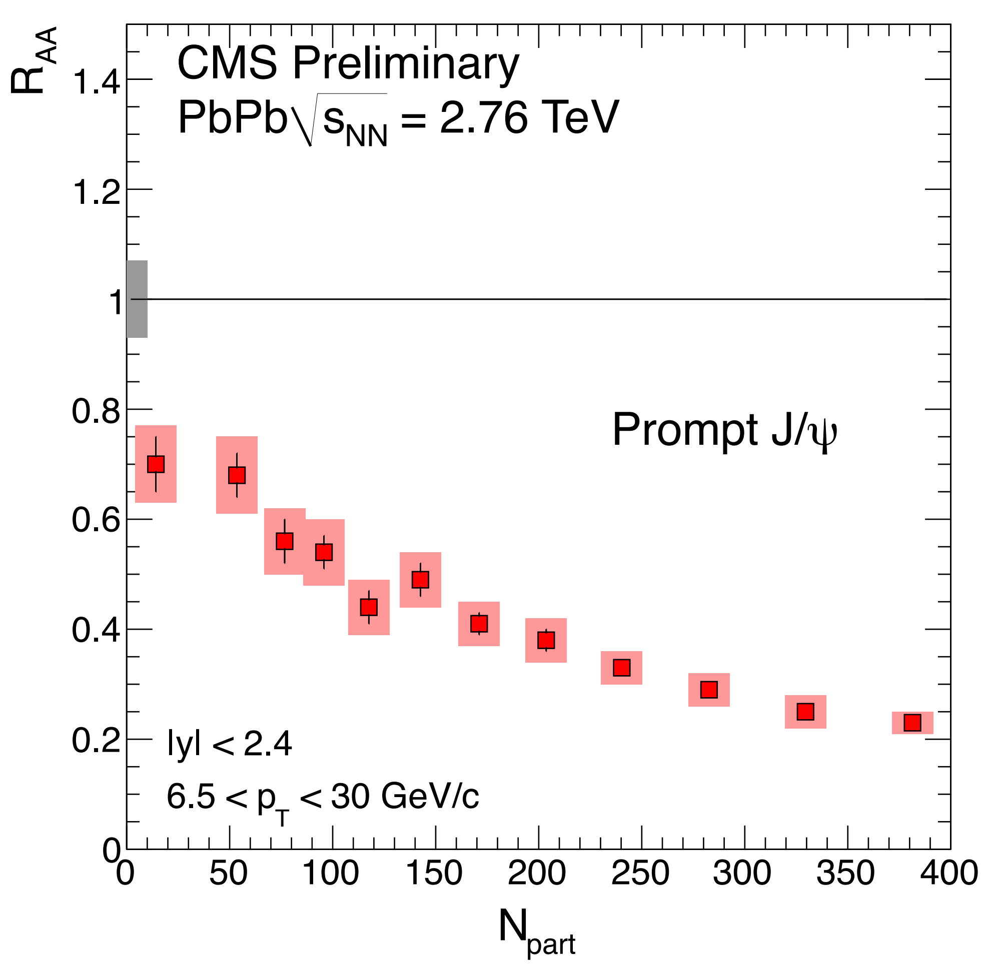
Charmonium suppression in experiments

- J/ψ suppression has been measured at SPS, RHIC and now LHC. SPS~RHIC



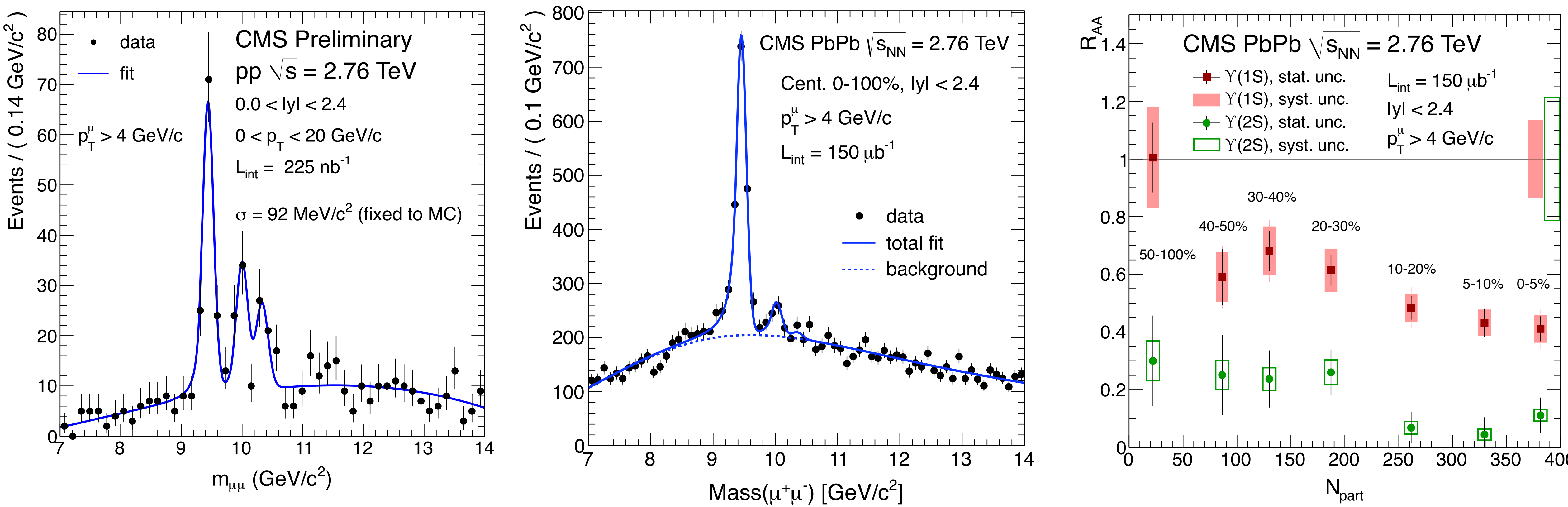
Scomparin QM2012



CMS-HIN-12-014

Bottomonium: the new frontier

- First quality data on the Υ family from CMS



- Sequential suppression of Υ(1S) and Υ(2S)
  CMS, **1208.2826**

Overview of dissociation

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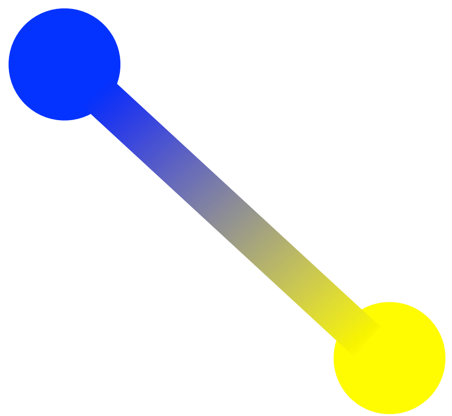
- Matsui/Satz: dissociation induced by colour screening of the interaction



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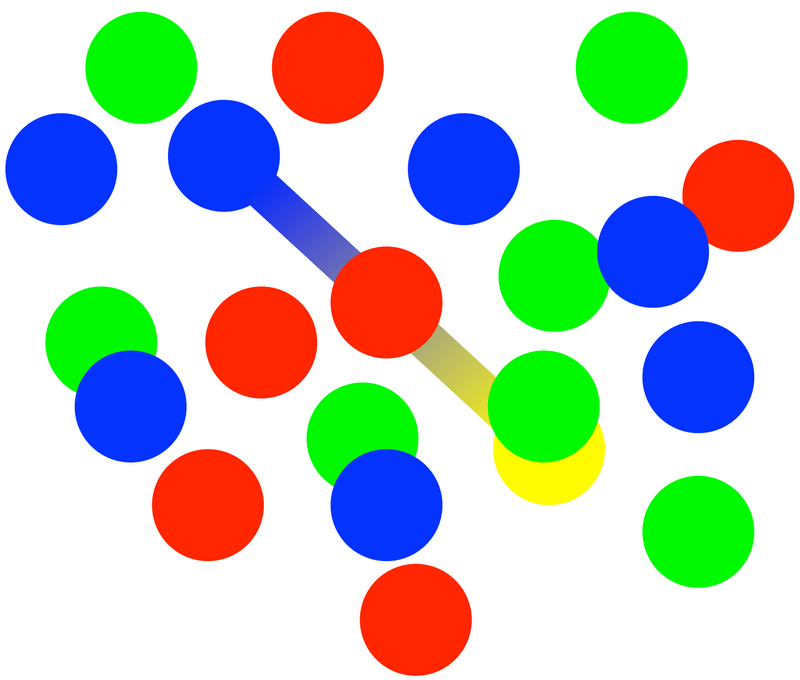

$$V(r) \sim -\alpha_s \frac{e^{-m_D r}}{r}$$

$$r \sim \frac{1}{m_D} \longrightarrow$$ **Bound state dissolves**

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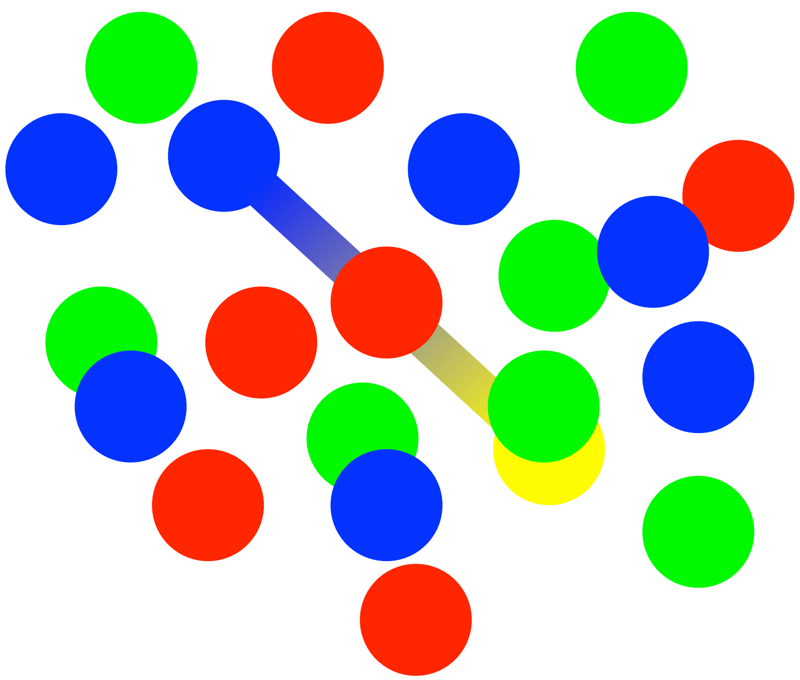

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- Since then, dissociation has been studied with potential models, lattice spectral functions, AdS/CFT and now with EFTs

Potential models

- *Assume* Schrödinger equation, all medium effects in a T-dependent potential

$$i\partial_t\psi(r,T) = \left(-\frac{\nabla^2}{m} + V(r,T)\right)\psi(r,T)$$

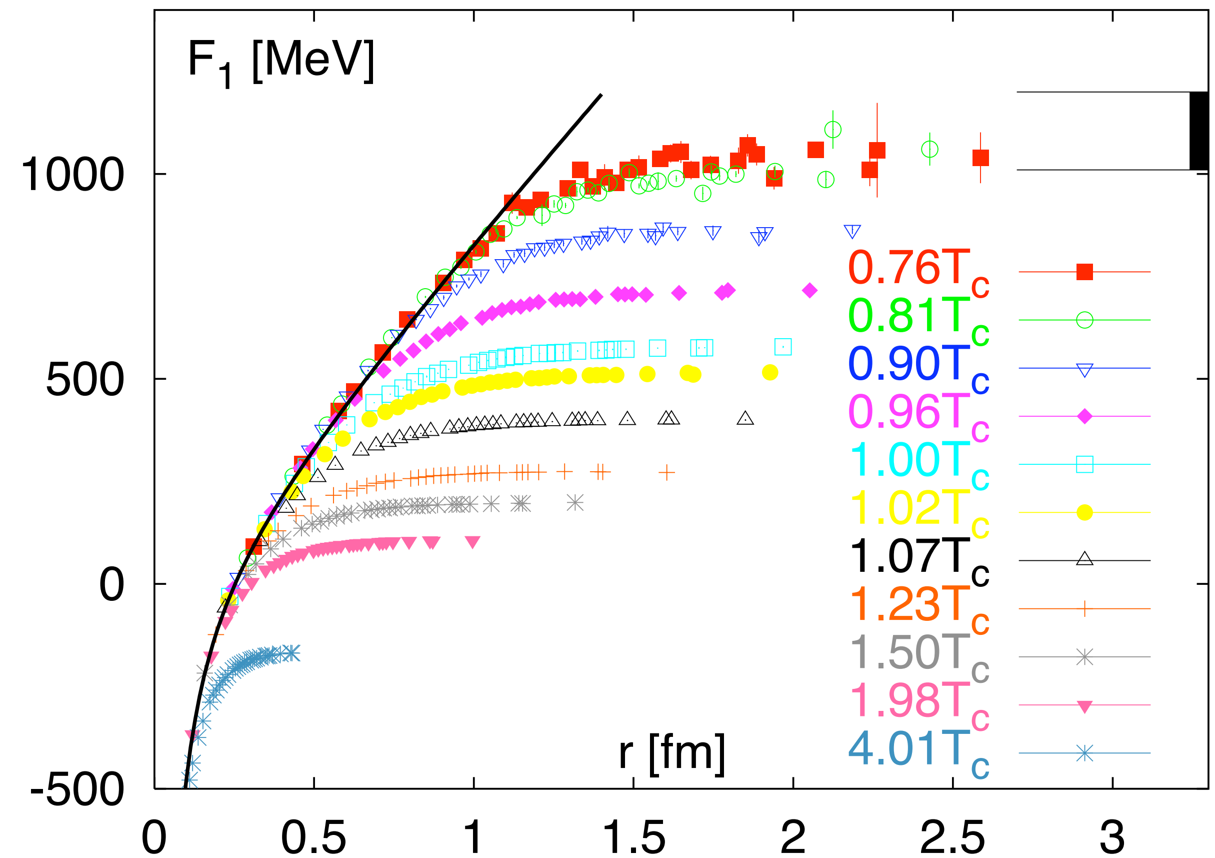
- *Assume*

$$V = F_1$$

potential corresponding to a free energy or

$$V = U = F - TS$$

internal energy measured on the lattice



Kaczmarek Zantow hep-lat/0510094

Digal, Petreczky, Satz 01
Wong 05-07
Mannarelli, Rapp 05
Mocsy, Petreczky 05-08
Alberico, Beraudo, Molinari, de Pace 05-08
Cabrera, Rapp 2007
Wong, Crater 07
Dumitru, Guo, Mocsy, Strickland 09
Rapp, Riek 10
Emerick, Zhao, Rapp 11

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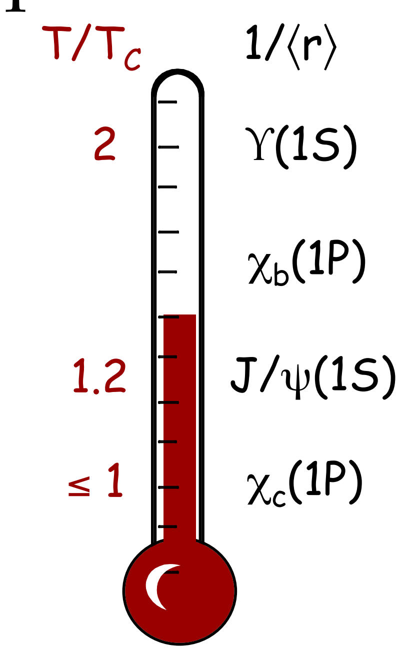
- Issues:
  - No clear relation to QCD and ab-initio derivation of the potential
  - Gauge-dependent correlators
  - Are all effects incorporated?
- Qualitative agreement on a picture of sequential dissociation



Effective Field Theories

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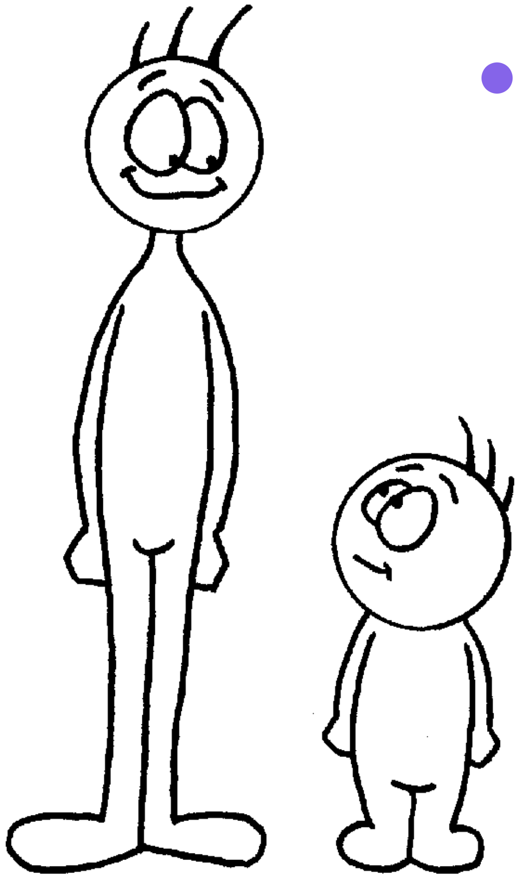

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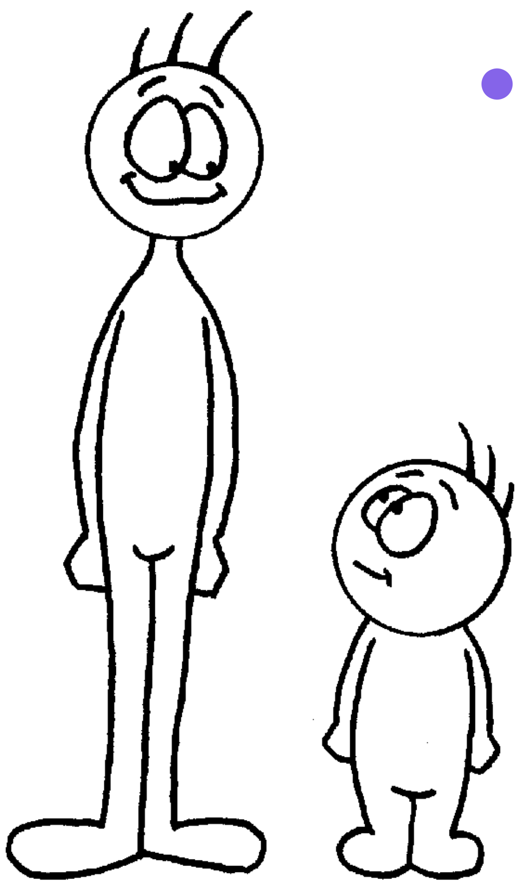


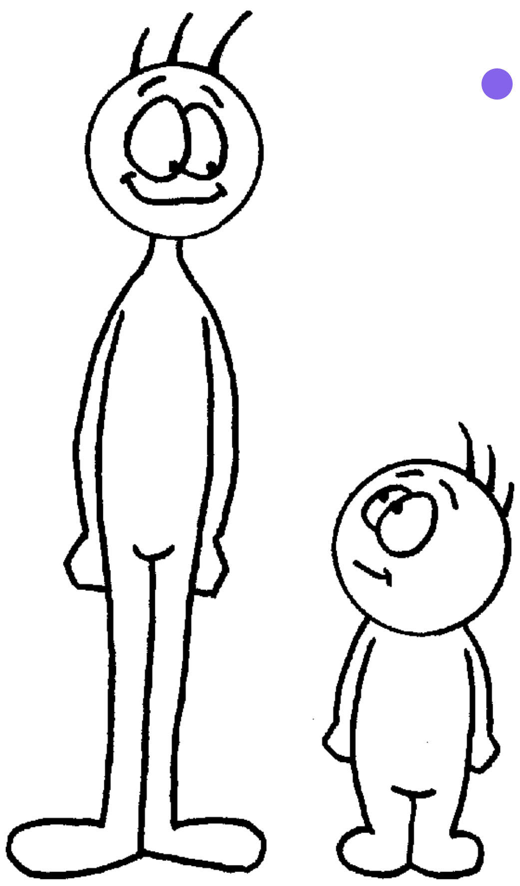
- An EFT is constructed by integrating out modes of energy and momentum larger than the cut-off ($\mu \ll \Lambda$)

$$\mathcal{L}_{\mathrm{EFT}} = \sum_n c_n(\mu/\Lambda) \frac{O_n}{\Lambda^{d_n - 4}}$$

Wilson coefficient

Low-energy operator/ large scale

Effective Field Theories



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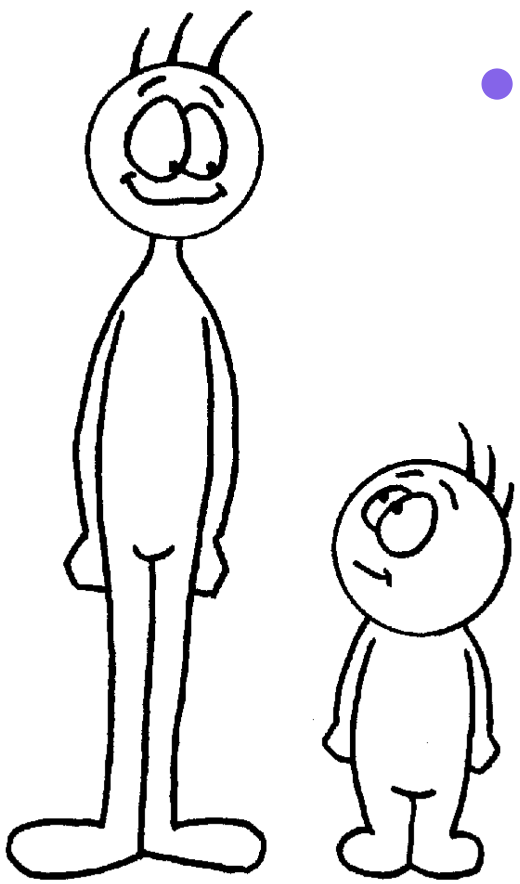

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- The procedure can be iterated $\ldots \ll \mu_2 \ll \Lambda_2 \ll \mu_1 \ll \Lambda_1$

At zero temperature

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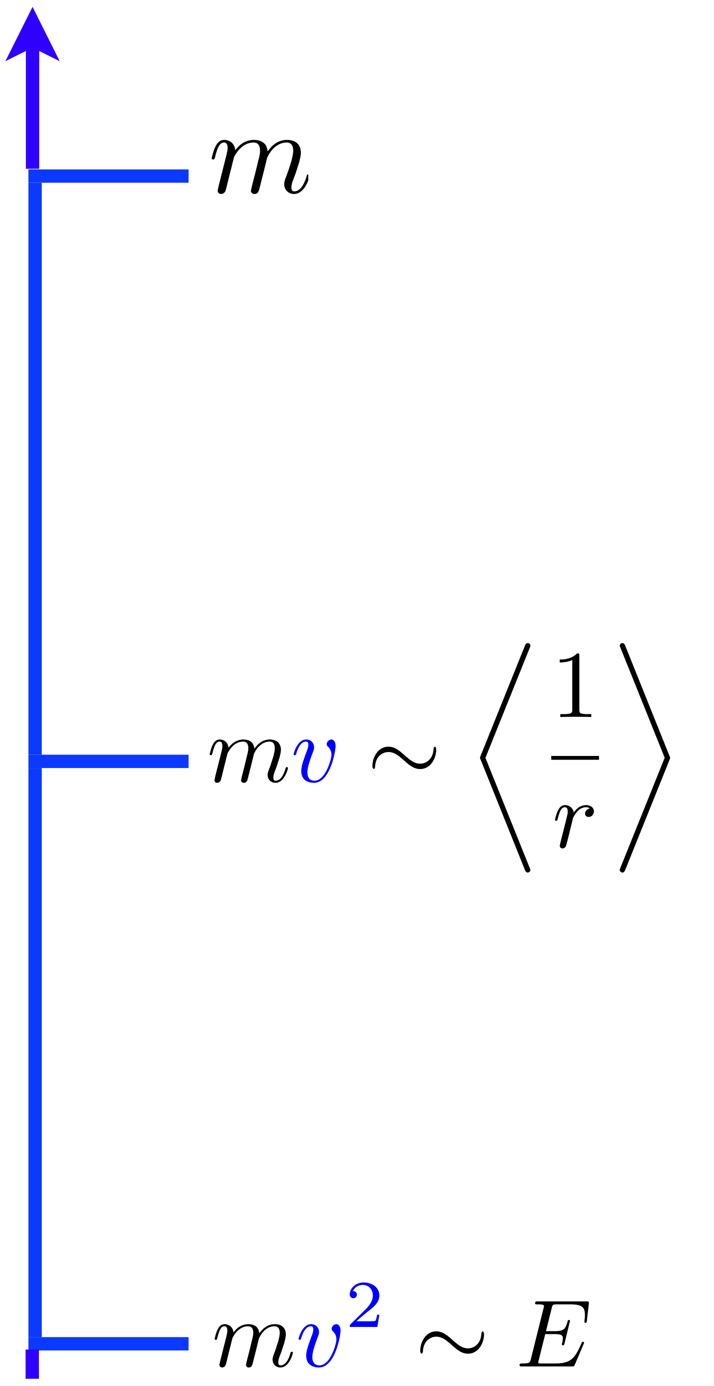
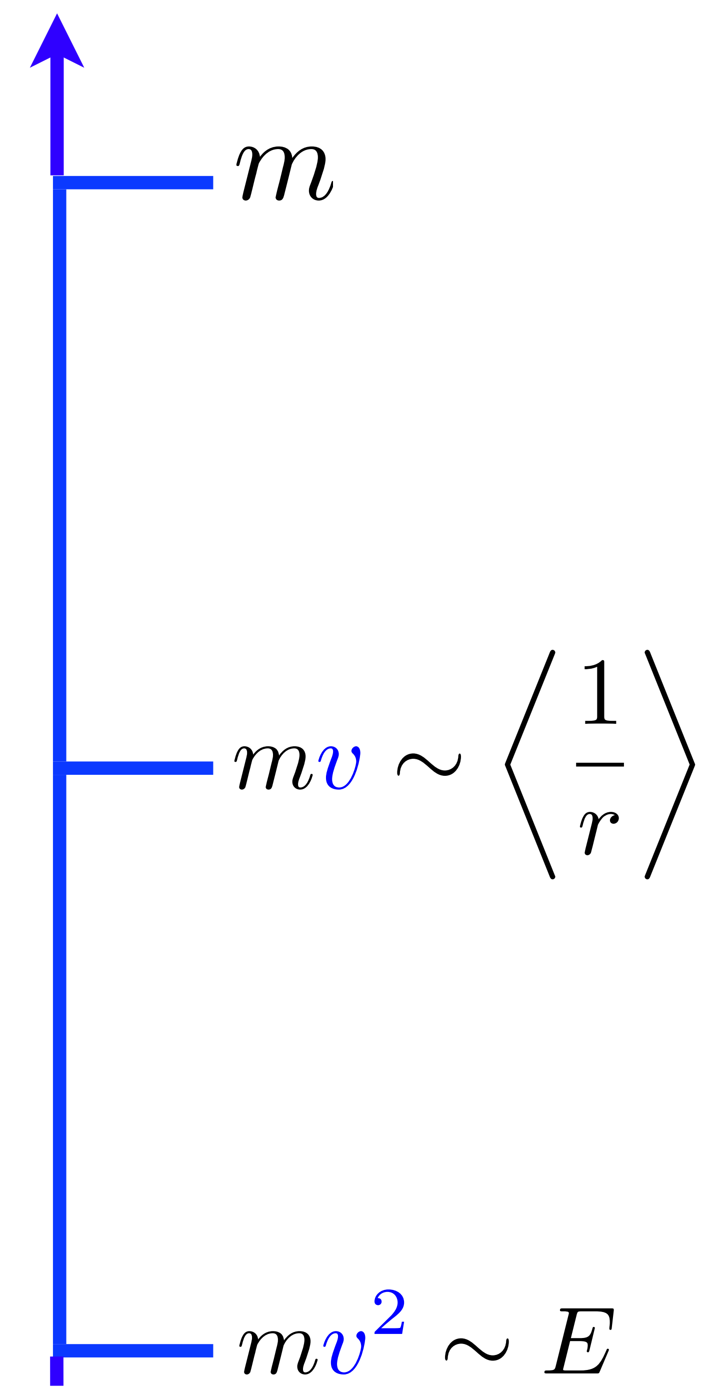
- *Non-relativistic* $Q\overline{Q}$ *bound states* are characterized by the *hierarchy* of the **mass, momentum transfer** and **kinetic/binding energy** scales

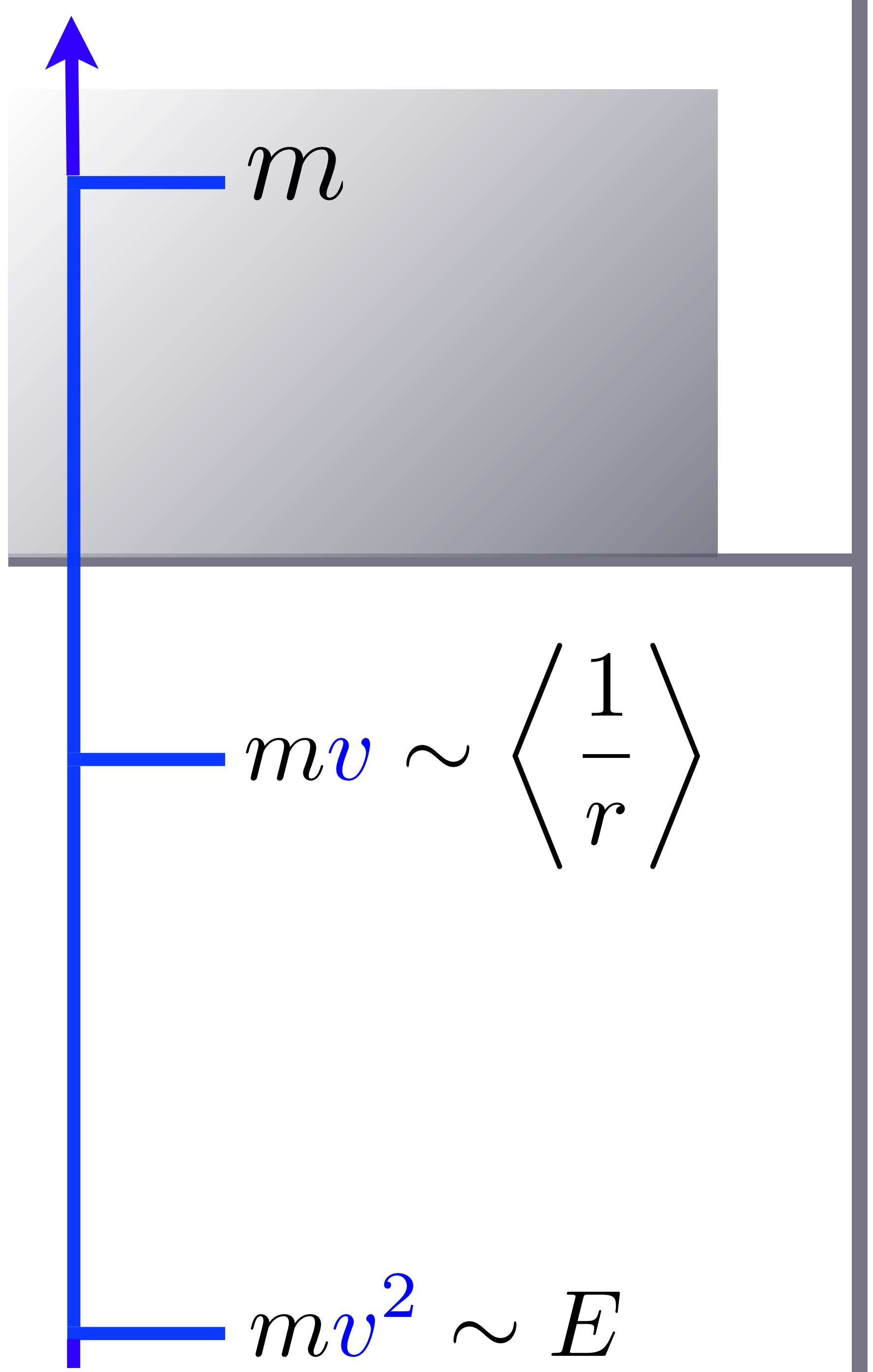


At zero temperature

- *Non-relativistic* $Q\overline{Q}$ *bound states* are characterized by the *hierarchy* of the **mass, momentum transfer** and **kinetic/binding energy** scales
- Expand observables in terms of the ratio of the scales, v
- Construct a *hierarchy of EFTs.* Equivalent to QCD order-by-order in the expansion parameter



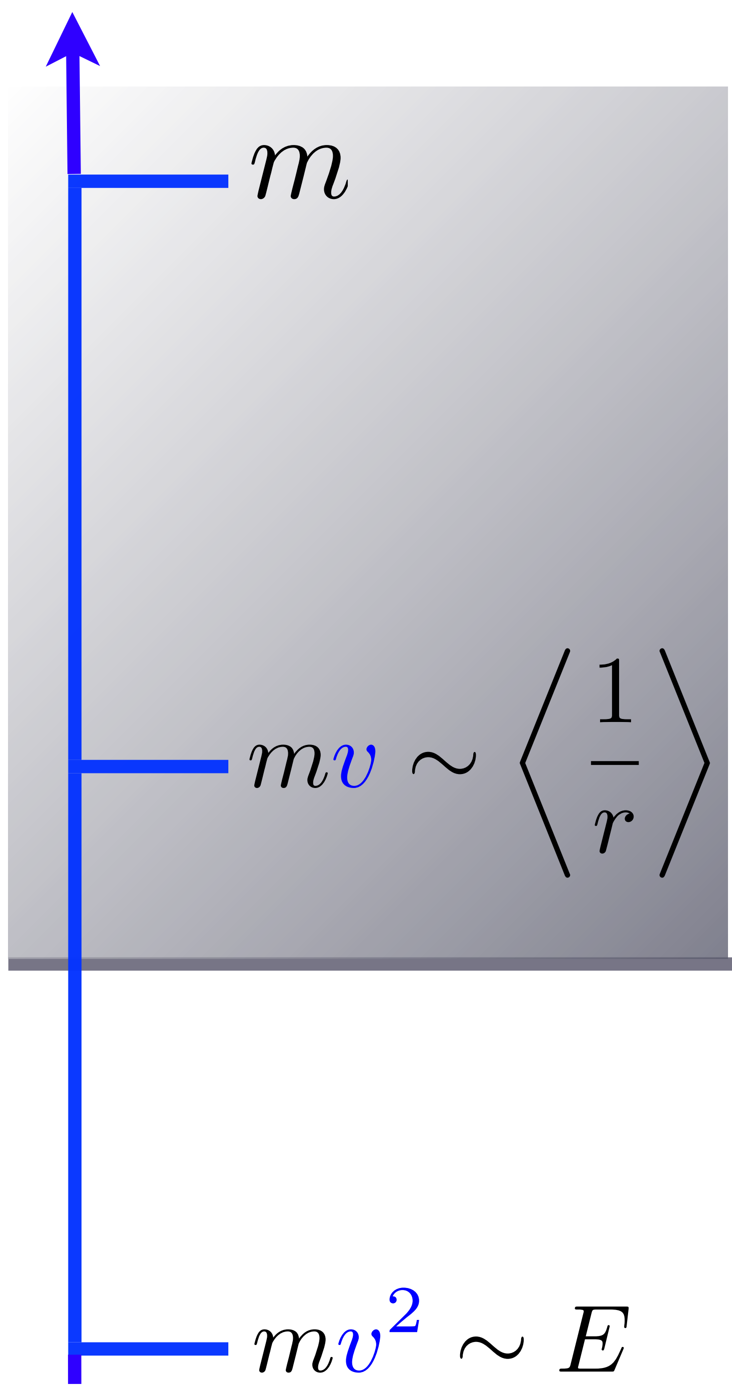
Integrating out the mass scale: Non-Relativistic QCD (NRQCD)



- The mass is integrated out and the theory becomes non-relativistic
- Factorization between contributions from the scale m and from lower-energies
- Ideal for production and decay studies

$$\mathcal{L}_{\mathrm{NRQCD}} = \sum_n c_n(\mu/m) \frac{O_n}{m^{d_n-4}}$$

Caswell Lepage **PLB167** (1986)
Bodwin Braaten Lepage **PRD51** (1995)



The scale *mv*: potential NRQCD (pNRQCD)

- Modes with momentum *mv* are integrated out
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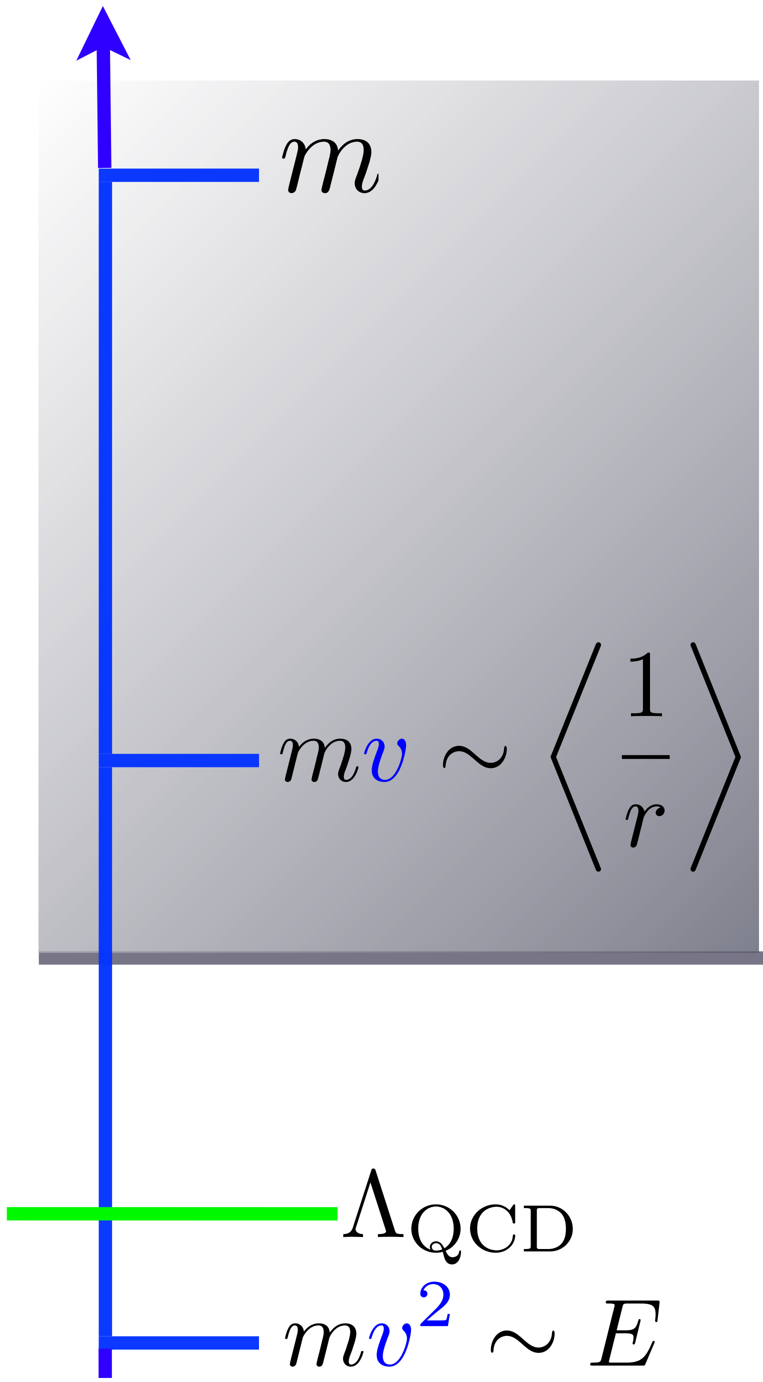

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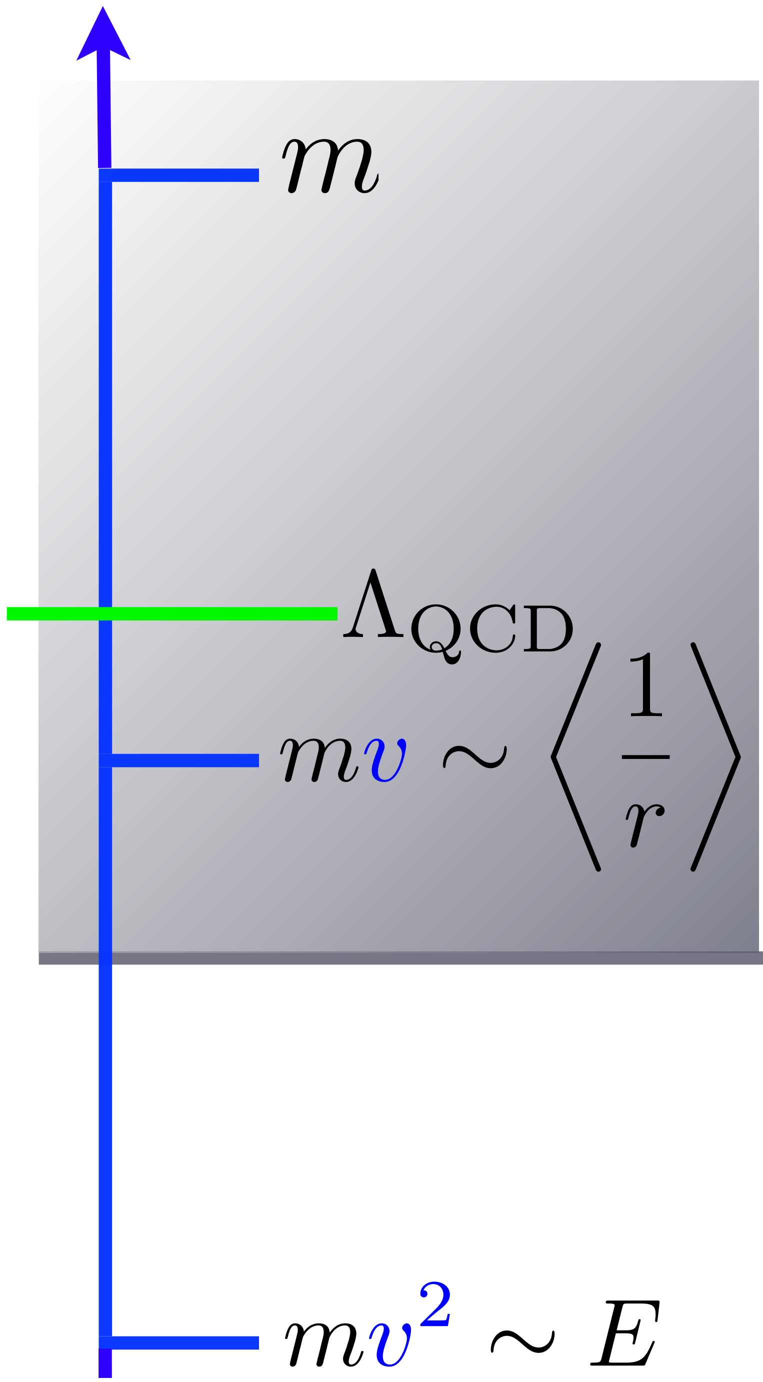
$$\mathcal{L} = \mathcal{L}_{\text{light}} + \text{Tr}\left\{ \text{S}^\dagger \left[i\partial_0 + \frac{\nabla^2}{m} - V_s \right] \text{S} + \text{O}^\dagger \left[iD_0 + \frac{\nabla^2}{m} - V_o \right] \text{O} \right\}$$
$$+\text{Tr}\left\{ \text{O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,\text{S} + \text{S}^\dagger \mathbf{r}\cdot g\mathbf{E}\,\text{O} \right\} + \frac{1}{2}\text{Tr}\left\{ \text{O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,\text{O} + \text{O}^\dagger \text{O}\mathbf{r}\cdot g\mathbf{E} \right\} + \dots$$

Pineda Soto **NPPS64** (1998)
Brambilla Pineda Soto Vairo **NPB566** (2000)



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Goals of the thesis

- Main goal: extend the well-established $T=0$ NR EFT framework to finite temperatures to address systematically heavy quarkonia in the medium
- Modern and rigorous definition of the potential and derivation from QCD at finite temperature, systematically taking into account the imaginary parts that lead to the thermal width
- Calculations of in-medium spectra and widths
- Clarification of the relation between the thermodynamical free energies and the EFT potentials

The thermodynamical scales

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- The thermal medium introduces new scales in the physical problem
  - The temperature
  - The electric screening scale (Debye mass)
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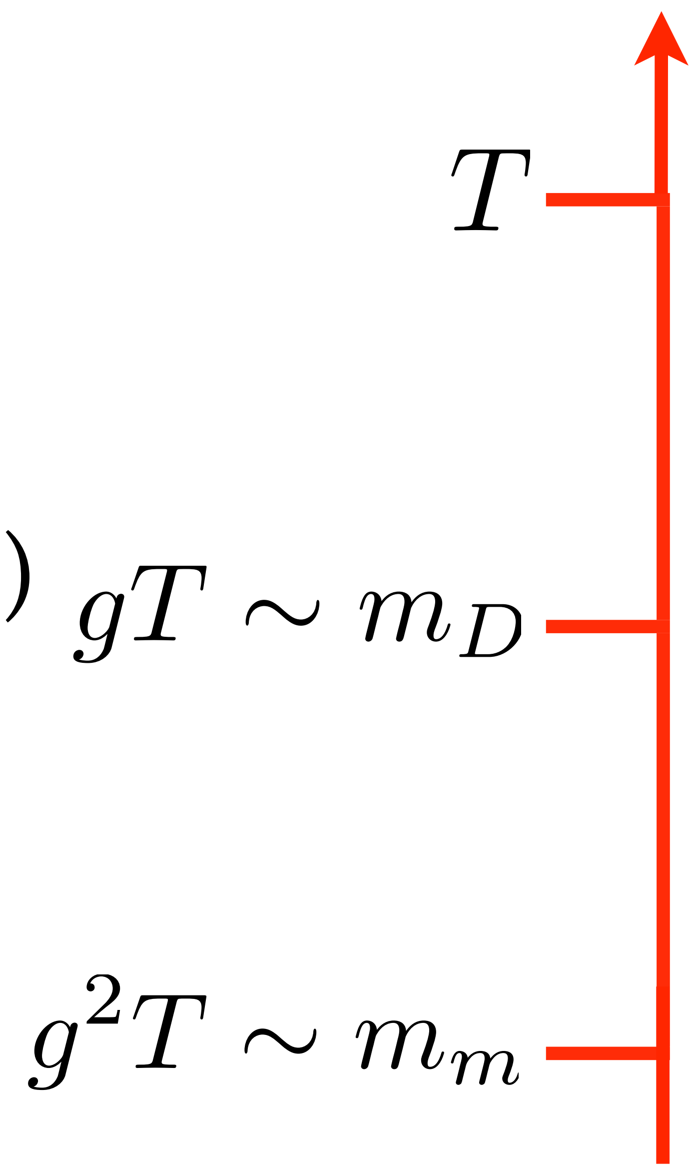

Finite-temperature NR EFT how-to

$$m \gg mv \sim m\alpha_{\rm s} \sim \langle 1/r \rangle \gg mv^2 \sim m\alpha_{\rm s}^2 \sim E$$

?

$$T \gg m_D \sim gT \gg m_m \sim g^2 T$$

- Assume a global hierarchy between the bound-state and thermodynamical scales
- Many different possibilities have been considered in the relevant macroregions $T \ll mv$, $T \sim mv$ and $T \gg mv$ (with $T \ll m$)
- Proceed from the top to systematically integrate out each scale, creating a tower of EFTs. Make use of existing EFTs (*T=0* NR EFTs, finite *T* EFTs such as HTL)
- Once the scale *mv* has been integrated out the colour singlet and octet potentials appear

The screening region: $T \gg mv$

- For *T>>1/r~m$_D$* we provide an EFT derivation and rigorous definition of the potential first obtained by Laine *et al.*

$$V_{\rm HTL} = -C_F \alpha_{\rm s} \left(\frac{e^{-m_D r}}{r} + m_D - i \frac{2T}{m_D r} f(m_D r) \right)$$

Laine Philipsen Romatschke Tassler **JHEP0703** (2007)

The screening region: $T \gg mv$

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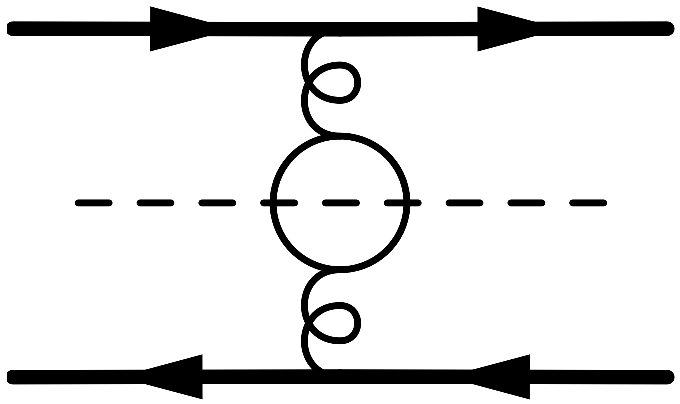
- Re $V \Rightarrow$ screening. Im $V \Rightarrow$ width induced by collisions with the medium. Im V >> Re V for $r \sim \frac{1}{m_D}$

Landau Damping



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$$V_s(r) = -C_F \frac{\alpha_s}{r} - \frac{C_F}{2} \alpha_s \, r \, m_D^2 - i \frac{C_F}{6} \alpha_s \, r^2 \, T \, m_D^2 \left(-2\gamma_E - \ln(r m_D)^2 + \frac{8}{3} \right) + \dots$$

- When $T \sim m \alpha_s^{2/3} \Rightarrow \mathrm{Im} V \sim \mathrm{Re} V$
  New criterion for a dissociation temperature
  Brambilla JG Petreczky Vairo **PRD78** (2008) Escobedo Soto **PRA78** (2008) Laine **0810.1112** (2008)

The perturbation region: $mv \gg T$

- When $mv >> T >> mv^2$ the thermal medium acts as a perturbation to the potential.
  Relevant for the ground states of bottomonium:
  $mv \sim 1.5$ GeV, $T < 1$ GeV

- The EFT obtained by integrating out the temperature from pNRQCD is called $\mathrm{pNRQCD_{HTL}}$

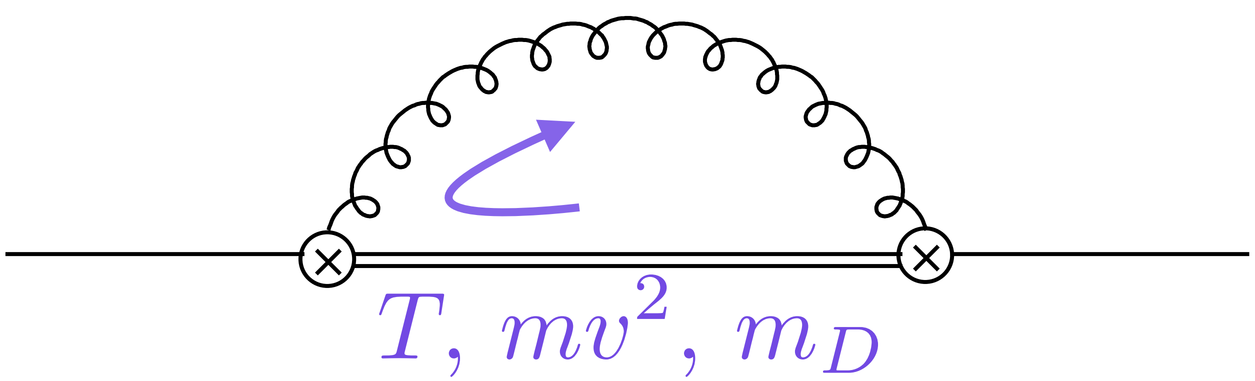
$$\mathcal{L}_{\mathrm{pNRQCD_{HTL}}} = \mathcal{L}_{\mathrm{HTL}} + \mathrm{Tr}\left\{\mathrm{S}^\dagger\left[i\partial_0 - h_s - \delta V_s\right]\mathrm{S} + \mathrm{O}^\dagger\left[iD_0 - h_o - \delta V_o\right]\mathrm{O}\right\}$$
$$+\mathrm{Tr}\left\{\mathrm{O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,\mathrm{S} + \mathrm{S}^\dagger \mathbf{r}\cdot g\mathbf{E}\,\mathrm{O}\right\} + \frac{1}{2}\mathrm{Tr}\left\{\mathrm{O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,\mathrm{O} + \mathrm{O}^\dagger\mathrm{O}\mathbf{r}\cdot g\mathbf{E}\right\} + \dots$$

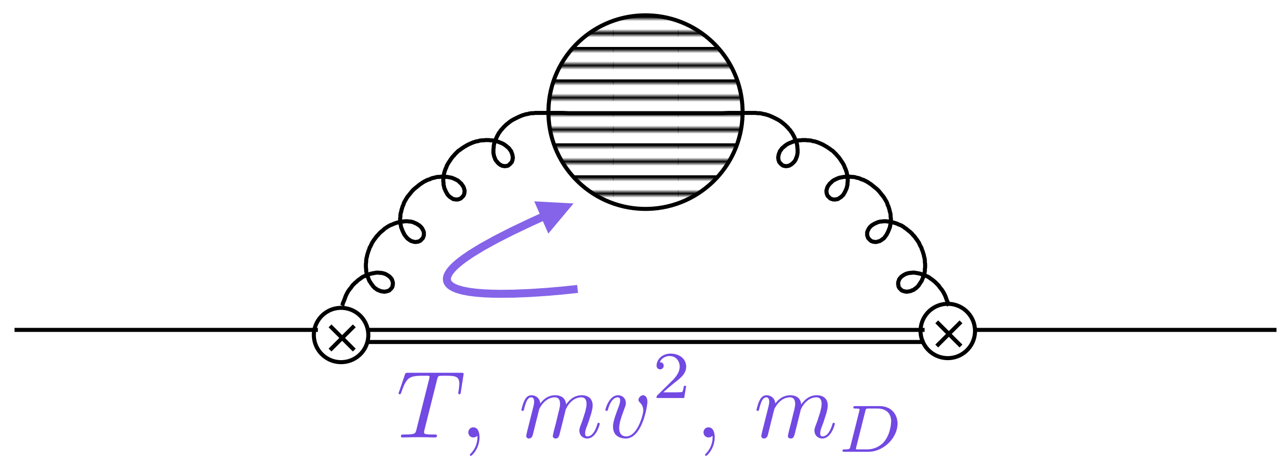
Brambilla Escobedo JG Soto Vairo **JHEP1009** (2010)
Brambilla Escobedo JG Vairo **JHEP1107** (2011)

The perturbation region: $mv \gg T$

- Within this theory we computed the spectrum and the thermal width of the $\Upsilon(1S)$ to order $m\alpha_s^5$ in the power counting of the EFT

- We must evaluate loop diagrams in the EFTs





The perturbation region: $mv \gg T$

- As an example, the 1S width reads

$$\Gamma_{1S} = \frac{1156}{81}\alpha_s^3 T + \frac{7225}{162} E_1 \alpha_s^3 - \frac{4}{3} a_0^2 \alpha_s T m_D^2 \left(\ln \frac{E_1^2}{T^2} + 2\gamma_E - 3 - \log 4 - 2\frac{\zeta'(2)}{\zeta(2)} - \frac{8}{3} I_{1S} \right) - \frac{32\pi}{3} \ln 2\, a_0^2 \alpha_s^2 T^3$$

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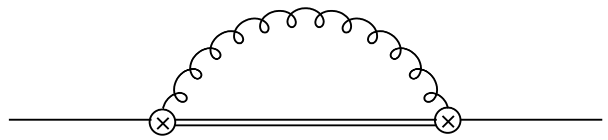
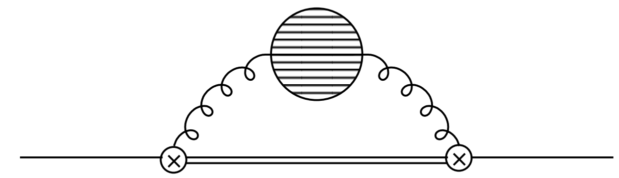
- Two mechanisms: singlet-to-octet thermal breakup and Landau damping

The p … $v \gg T$



Singlet-to-octet



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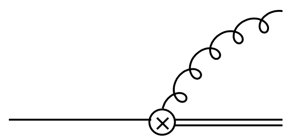
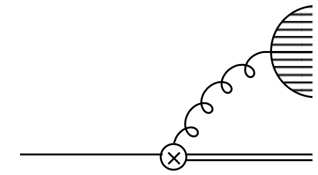


Singlet-to-octet



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Potentials and free energies

- The Polyakov loop (PL) and the Polyakov-loop correlator (PLC) are related to the thermodynamical free energies of a static quark and of a static $Q\overline{Q}$ pair.

$$\langle L \rangle \equiv 1/N_c \left\langle \mathrm{Tr}\,\mathrm{P}\exp\left(-ig\int_0^{1/T} d\tau A_0(\mathbf{x},\tau)\right)\right\rangle = e^{-\frac{F_Q(T)}{T}} \qquad \langle L^\dagger(\mathbf{0})L(\mathbf{r})\rangle = e^{-\frac{F_{Q\overline{Q}}(r,T)}{T}}$$

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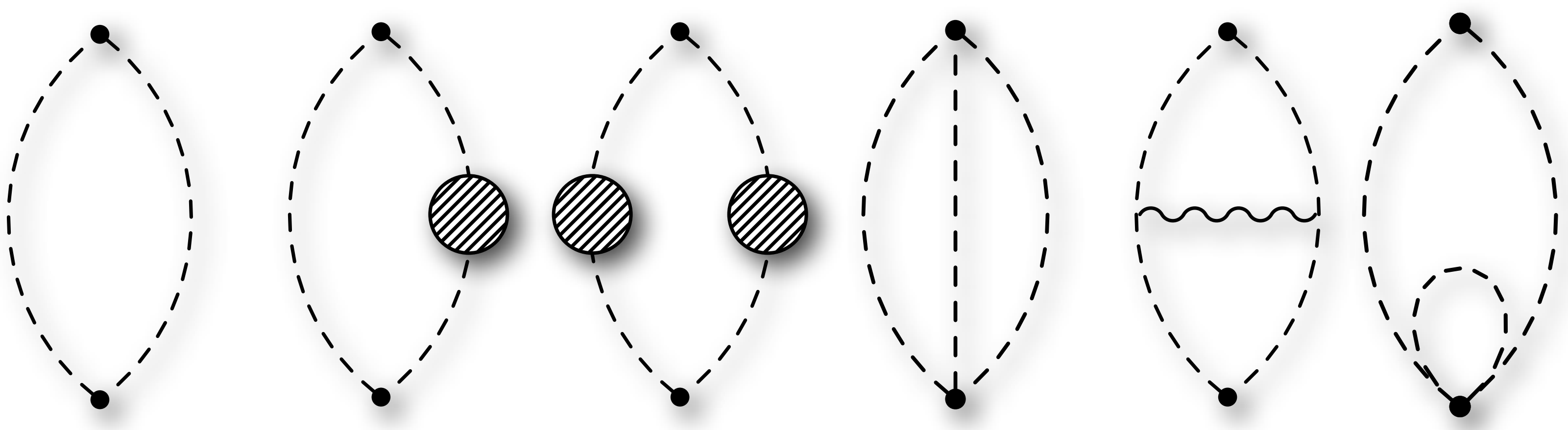
- We have computed both in perturbation theory. For the PL we correct the long-standing result, for the PLC our results, obtained for short distances, are new



Brambilla JG Petreczky Vairo **PRD82** (2010)

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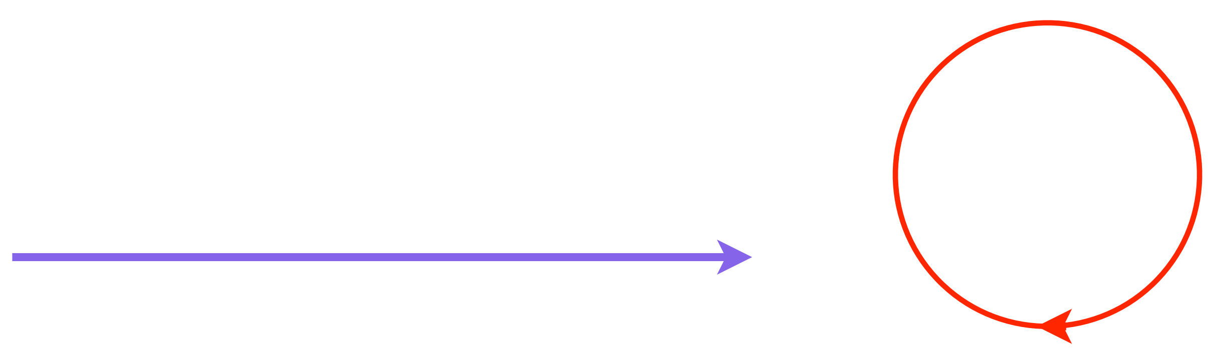
$$\mathrm{Im}(F) = 0, \mathrm{Im}(V) \neq 0 \qquad \mathrm{Re}(F) \neq \mathrm{Re}(V)$$

- Intuitively

$$t \to \infty \neq it = \frac{1}{T}$$



Brambilla JG Petreczky Vairo **PRD82** (2010)

Conclusions

- Construction of an EFT framework for heavy quarkonia at finite temperature. Within this framework we can
  - Systematically take into account corrections and include all medium effects
  - Give a rigorous QCD derivations of the potential, bridging the gap with potentials models which appear as leading-order picture here
  - Compute potentials, spectra and widths in different regimes, with particular relevance for the new frontier of $\Upsilon(1S)$ phenomenology
  - Study the relation between potentials and free energies

Outlook

- Take our EFT framework to the strong-coupling region, again following the path of the $T=0$ EFT. Lattice progress is needed, work in progress
- Phenomenological application to the $\Upsilon(1S)$
- Relation between our EFT widths and the previous approaches:
  Brambilla Escobedo JG Vairo **JHEP1112** (2011), in prep. (2013)
- Application of the methodology to other problems, such as heavy quark energy loss

Publications

- Brambilla JG Petreczky Vairo **PRD78** (2008)
- Brambilla JG Vairo **PRD81** (2010)
- Brambilla Escobedo JG Soto Vairo **JHEP1009** (2010)
- Brambilla JG Petreczky Vairo **PRD82** (2010)
- Brambilla Escobedo JG Vairo **JHEP1107** (2011)
- Brambilla Escobedo JG Vairo **JHEP1112** (2011)
- Berwein Brambilla JG Vairo, **1212.4413** in press on **JHEP** (2012)
- Brambilla Escobedo JG Vairo, in preparation (2013)