

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

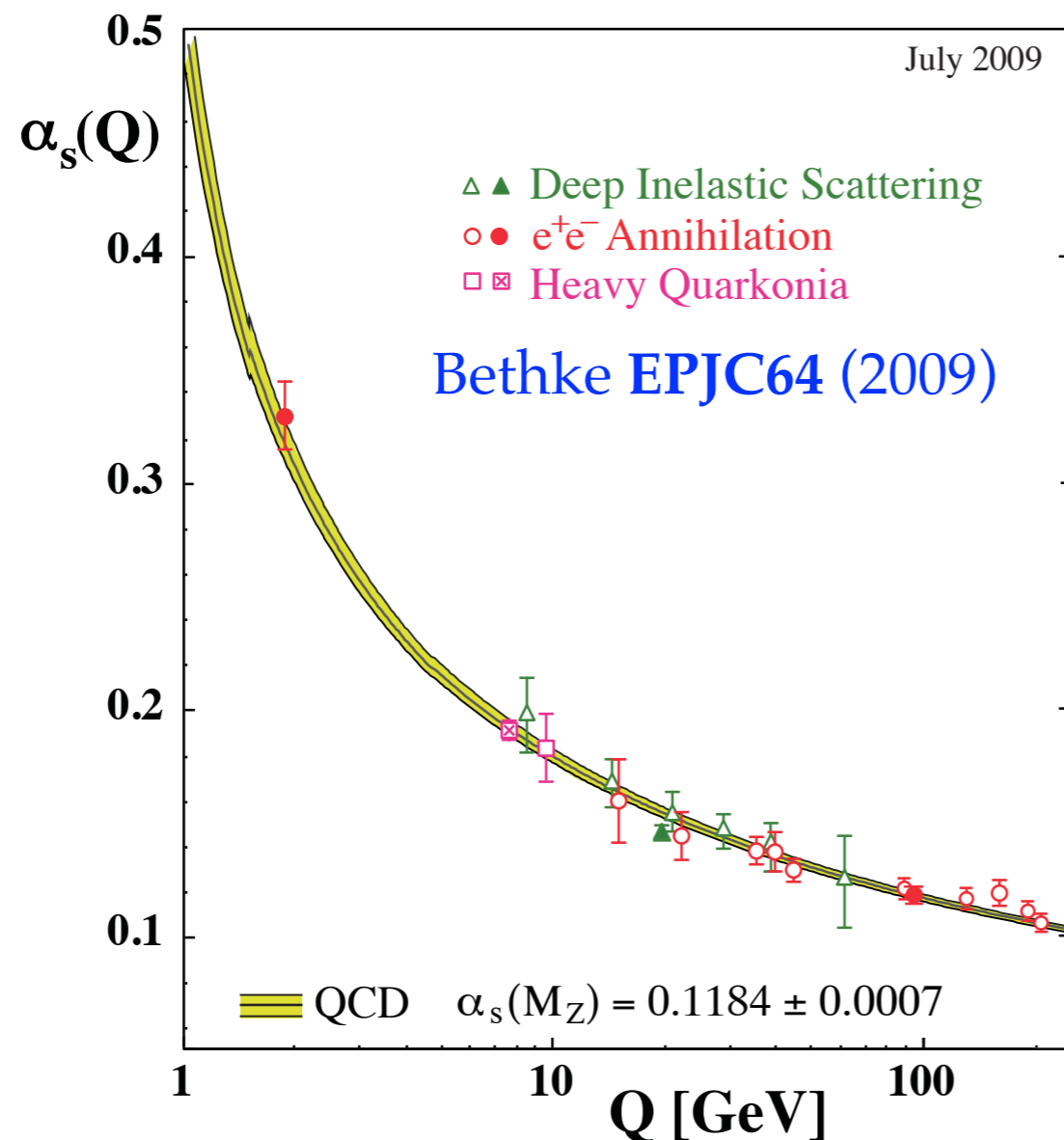
Jacopo Ghiglieri, McGill University, Montreal

Dissertationspreis-Symposium der DPG
Dresden, 04.03.2013

Quarks and gluons: QCD

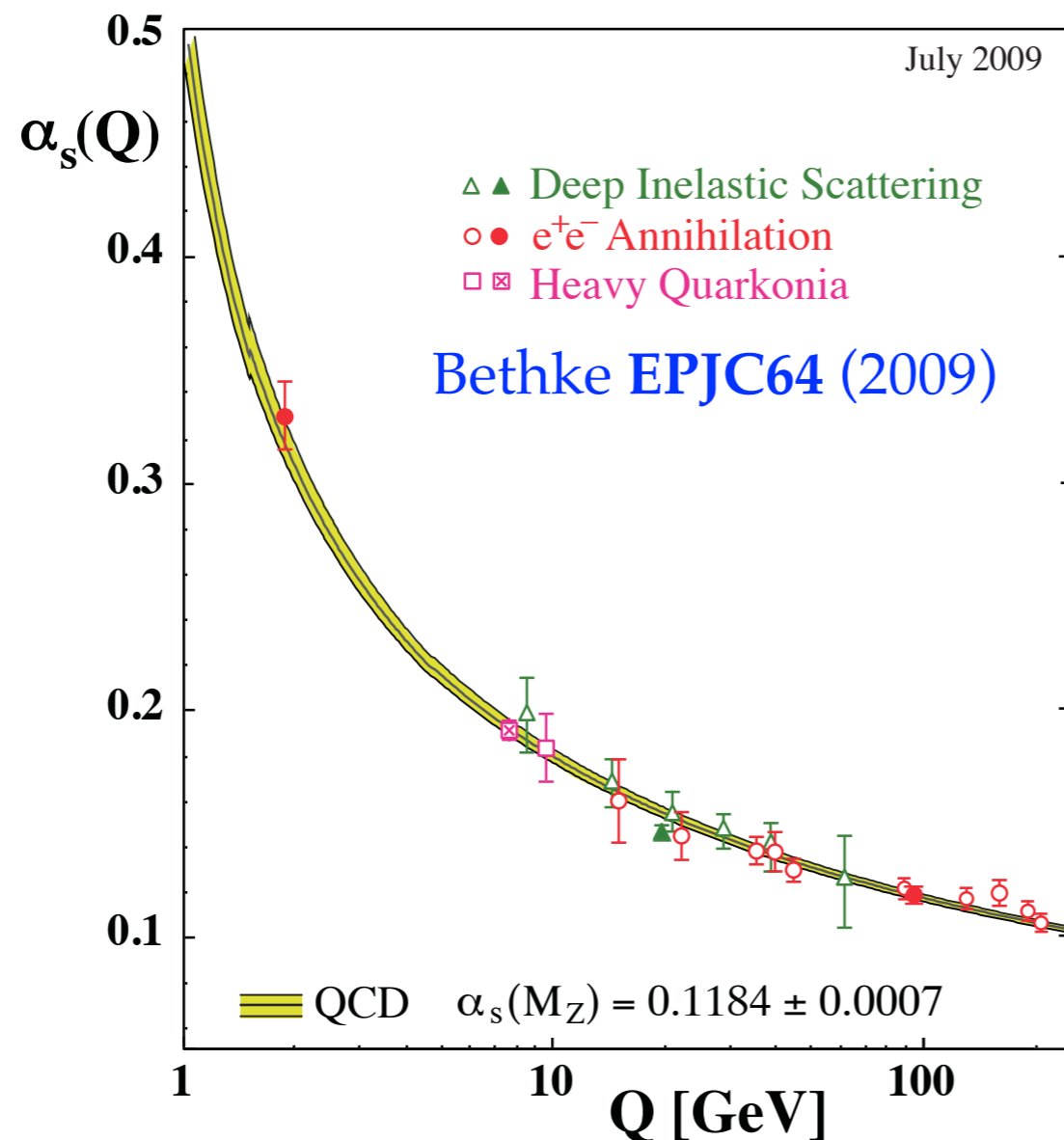
Quarks and gluons: QCD

- 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 $\Lambda_{\text{QCD}} \simeq 200 \text{ MeV}$



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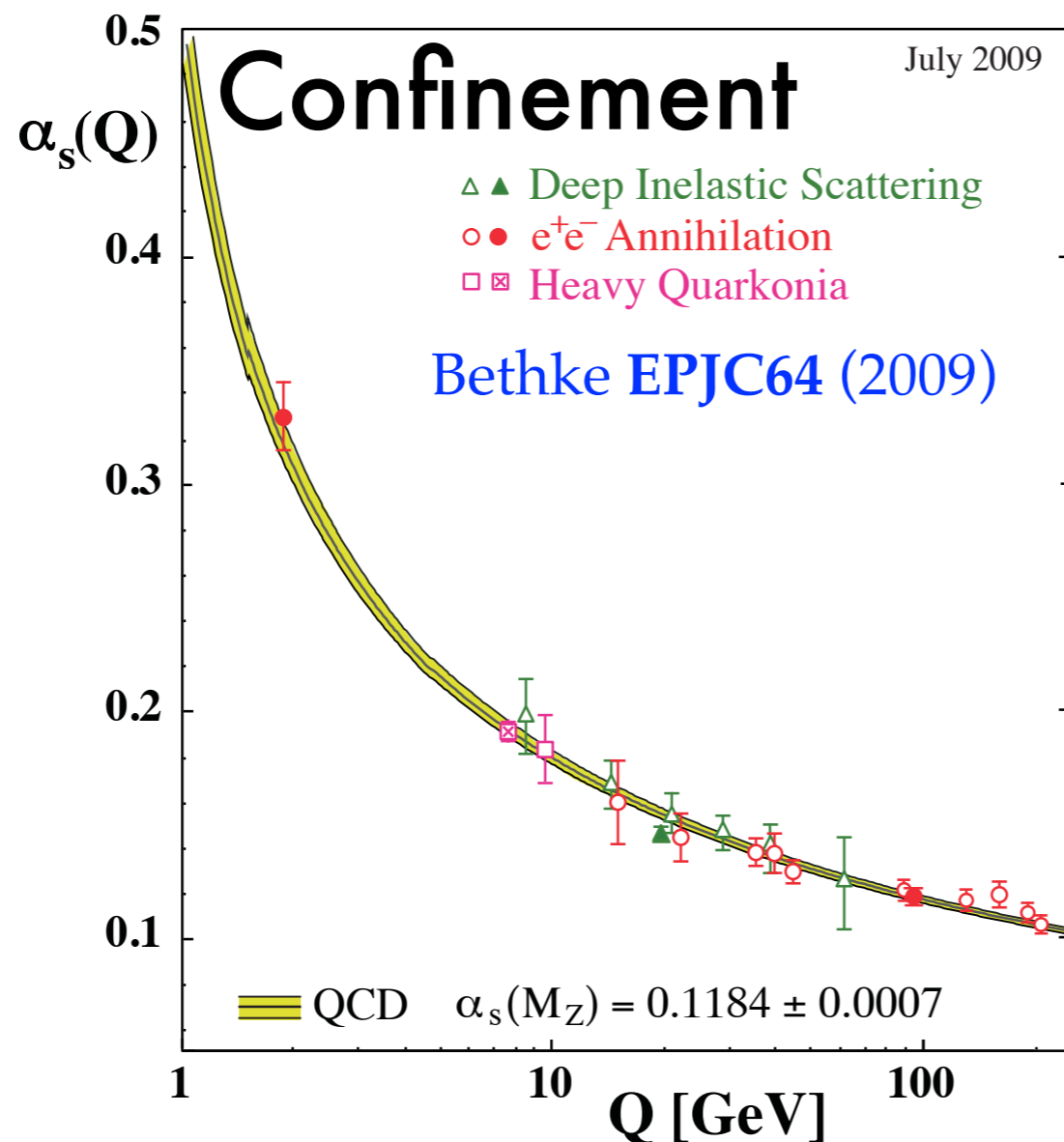
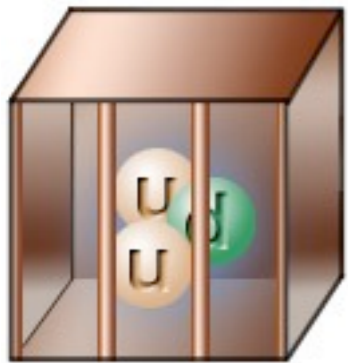
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Asymptotic freedom

Quarks and gluons: QCD

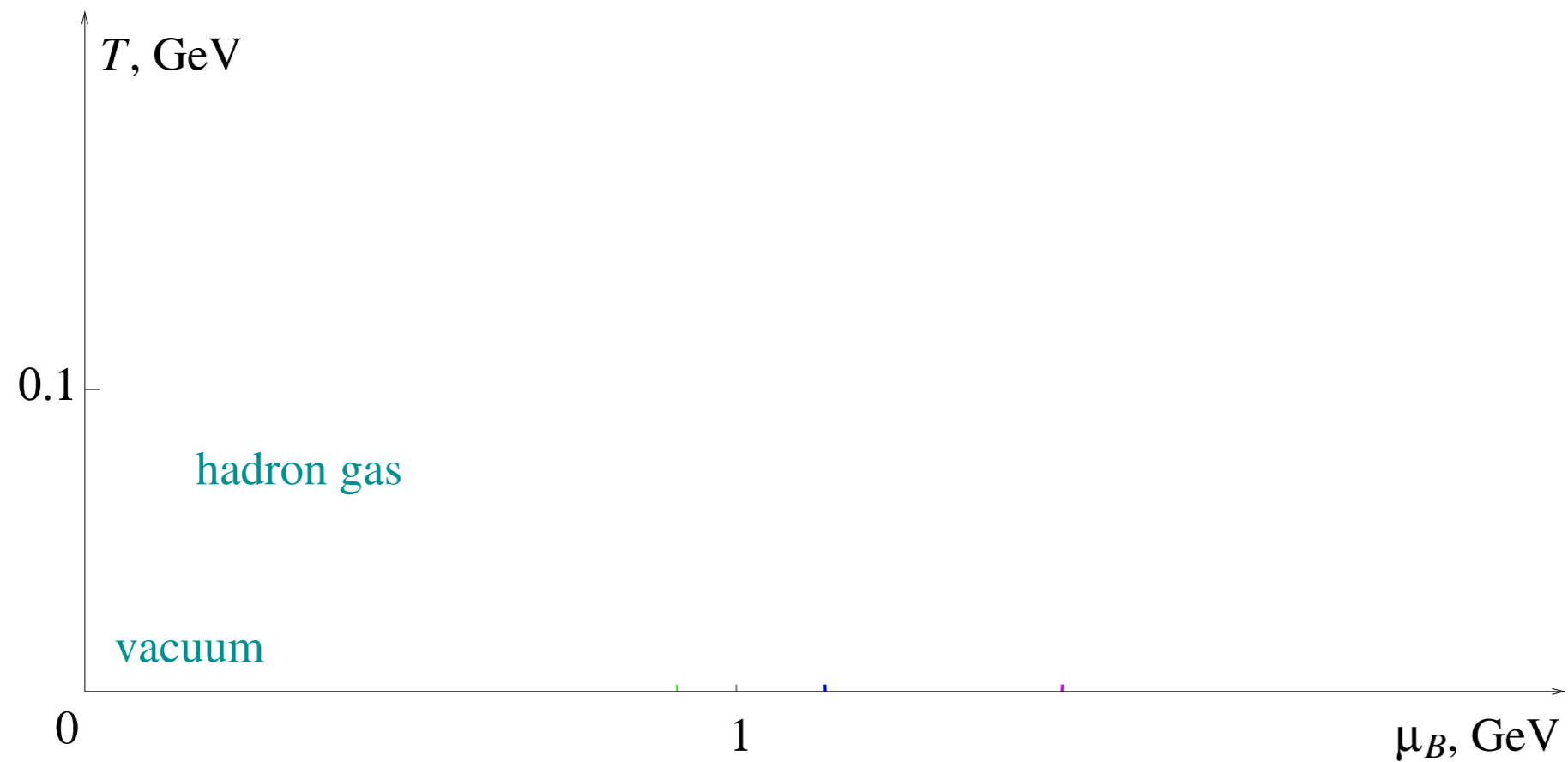
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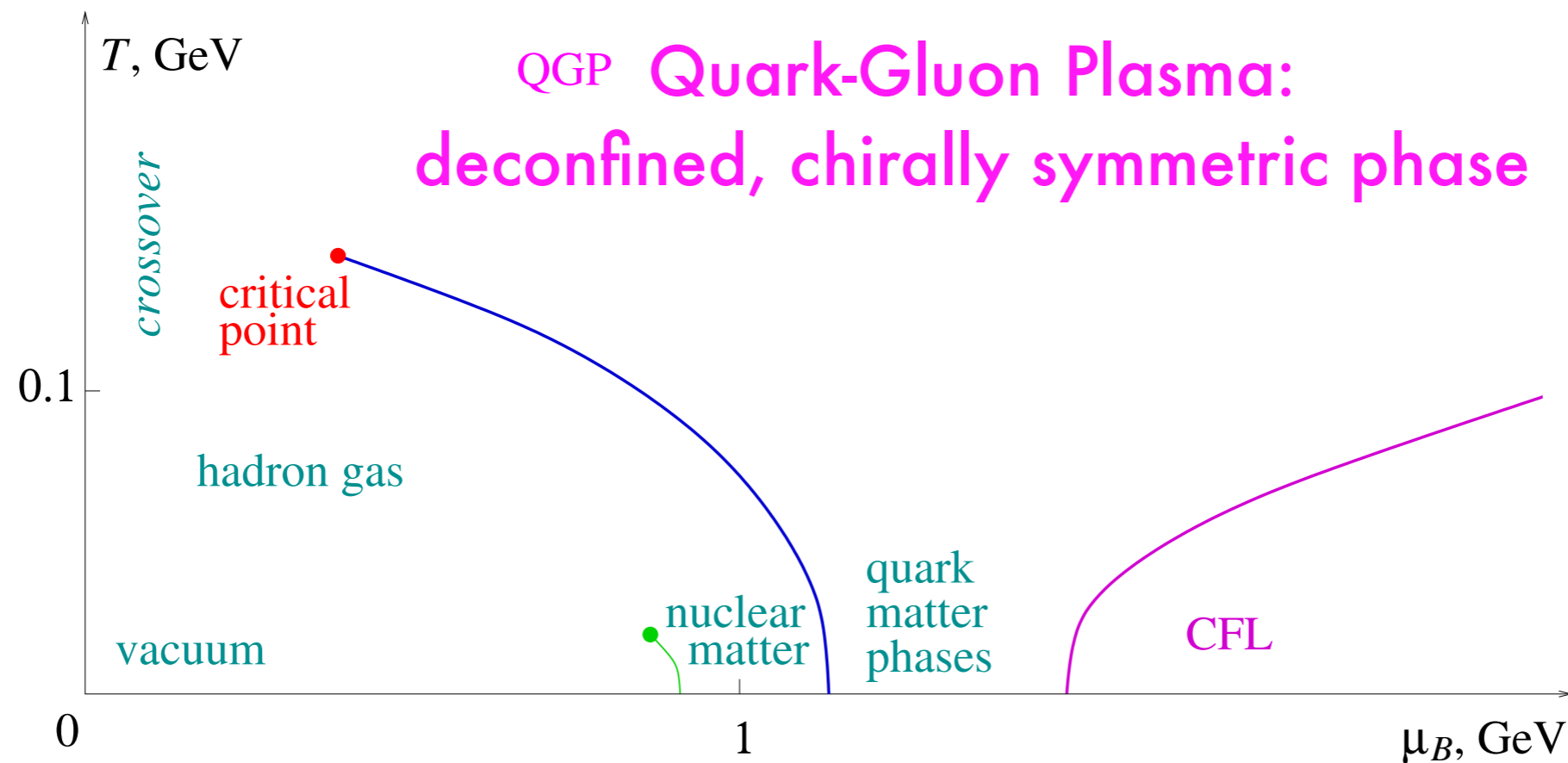
The phase diagram of QCD

- In the temperature / baryon chemical potential plane:



The phase diagram of QCD

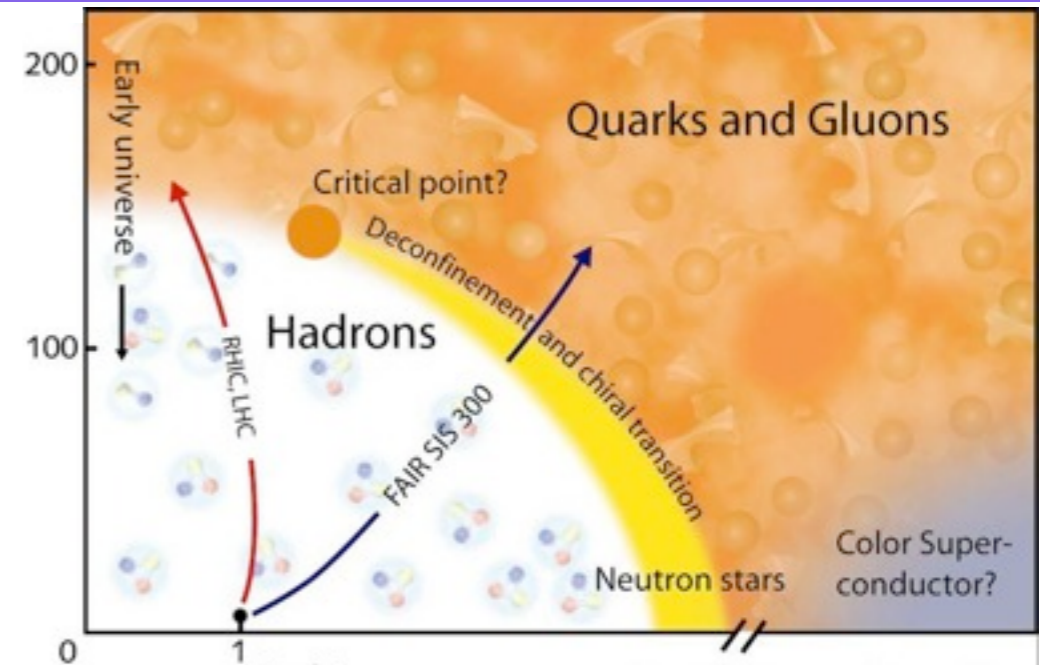
- In the temperature/baryon chemical potential plane:



- In the upper-left region, lattice QCD indicates a (pseudo)critical temperature $T_c \sim 160 \text{ MeV} \sim 2 \times 10^{12} \text{ K}$
- For comparison, sun's core: $T \sim 1.5 \times 10^7 \text{ K}$

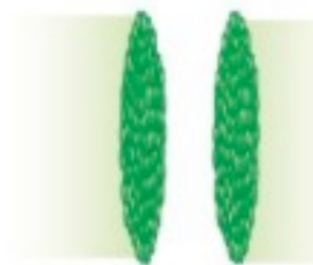
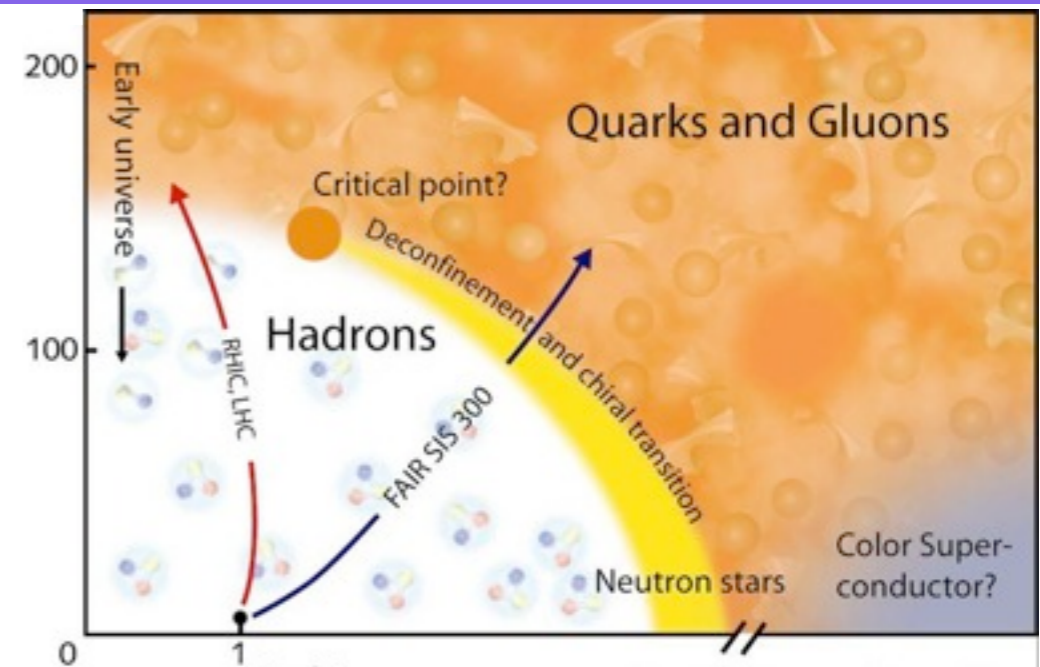
Heavy ion collision experiments

- 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



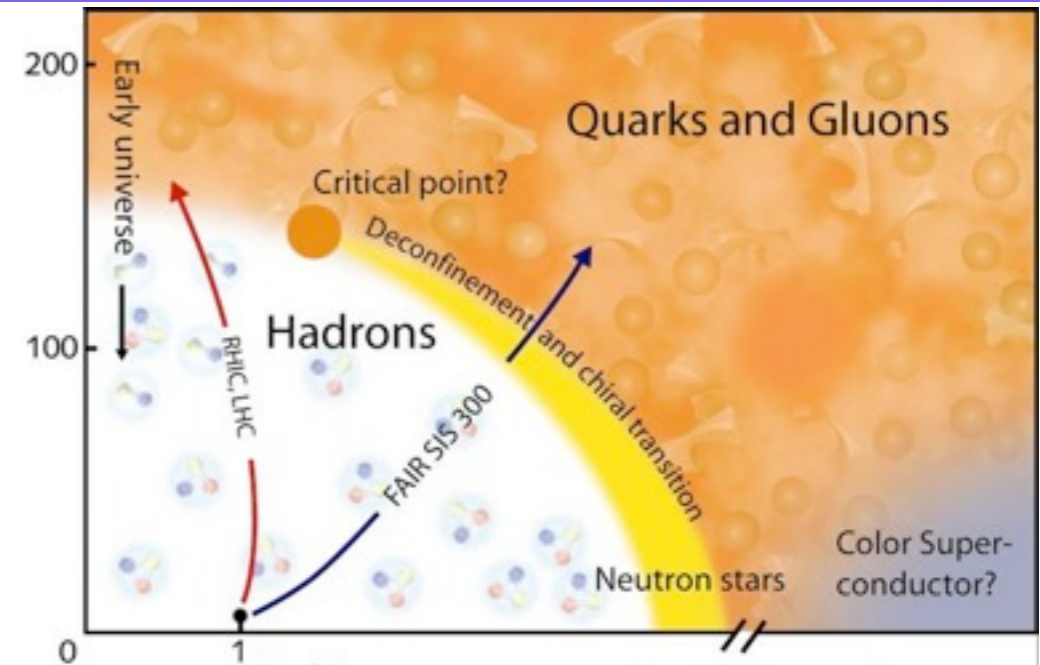
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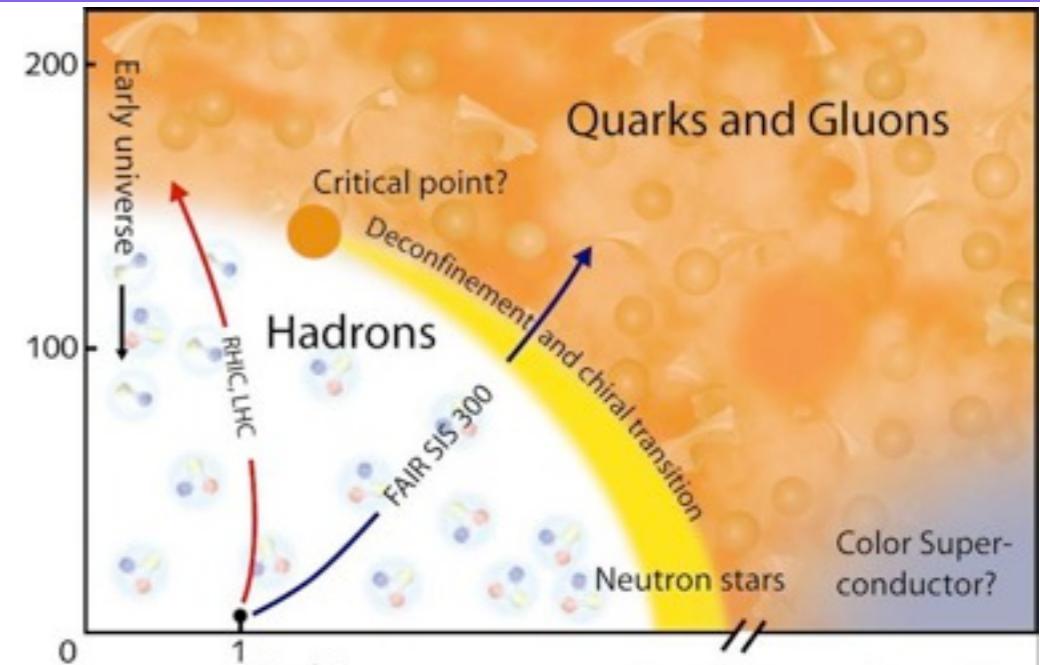
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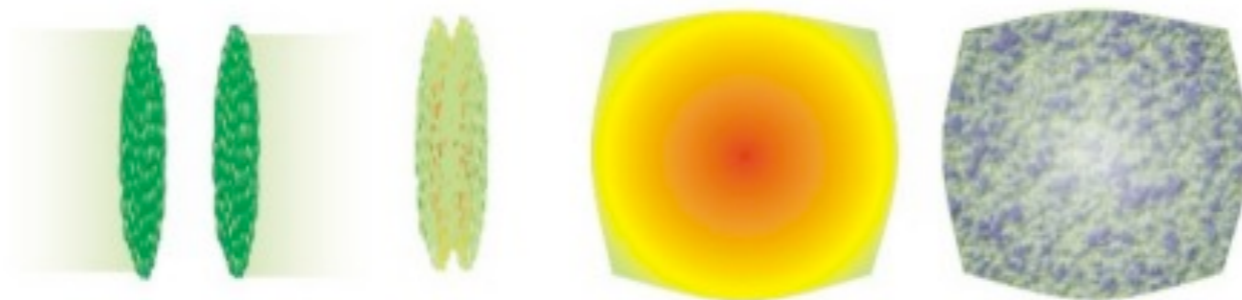
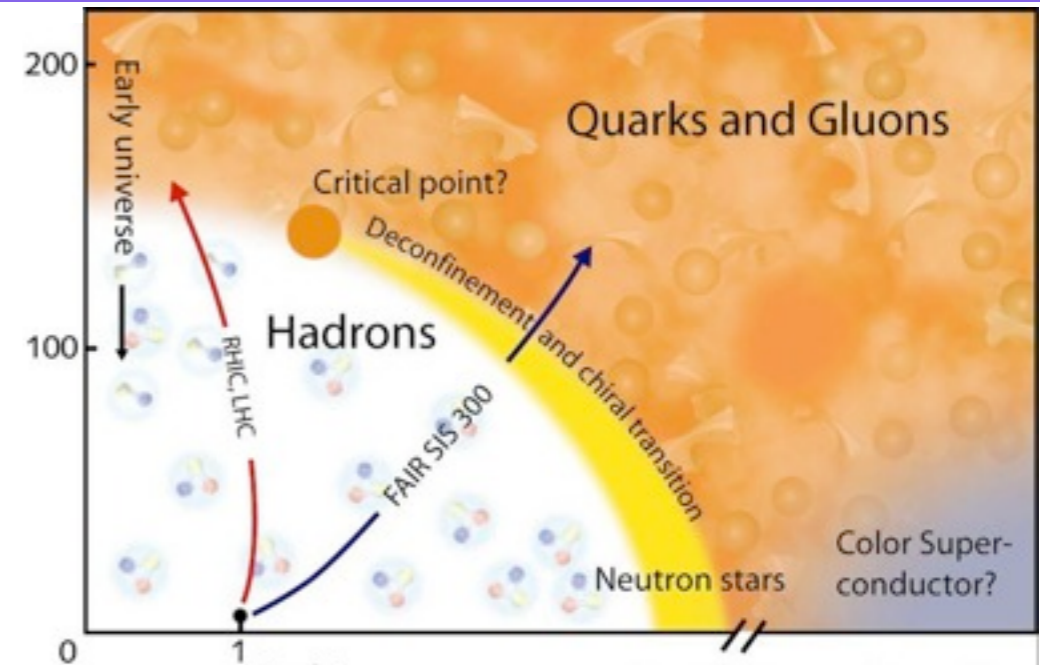
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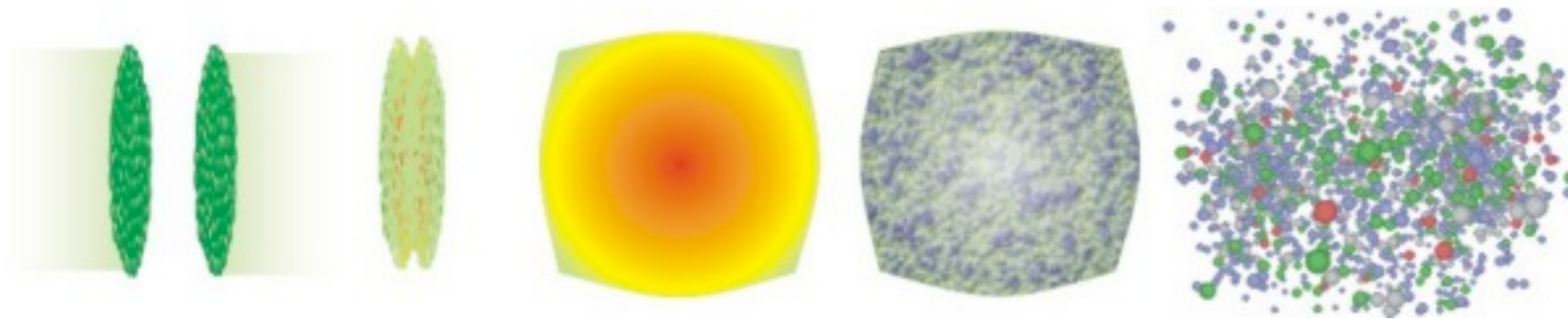
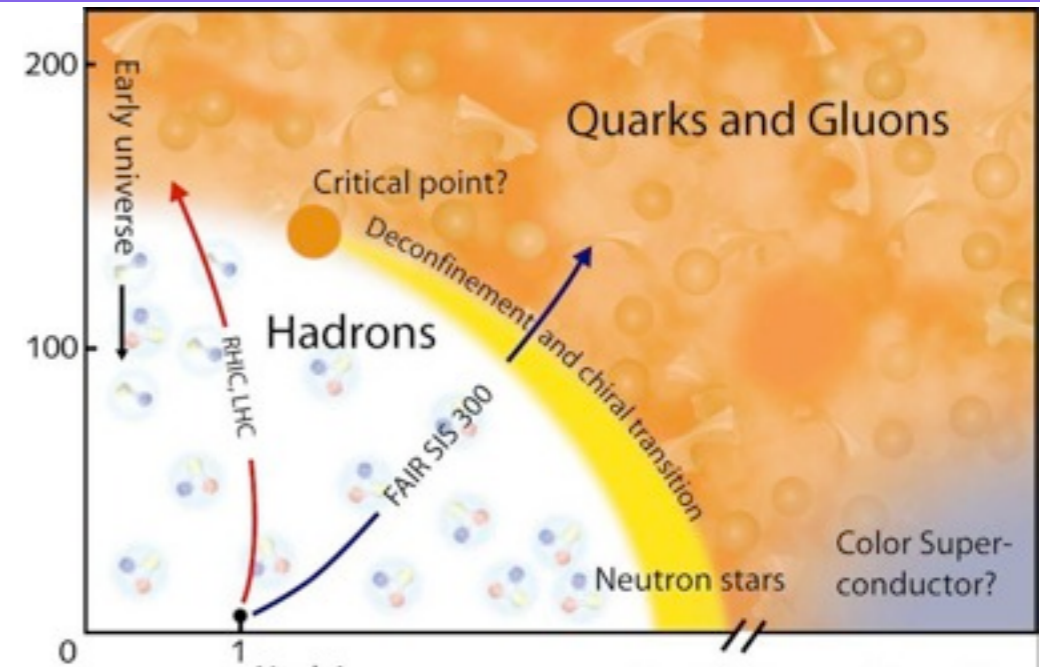
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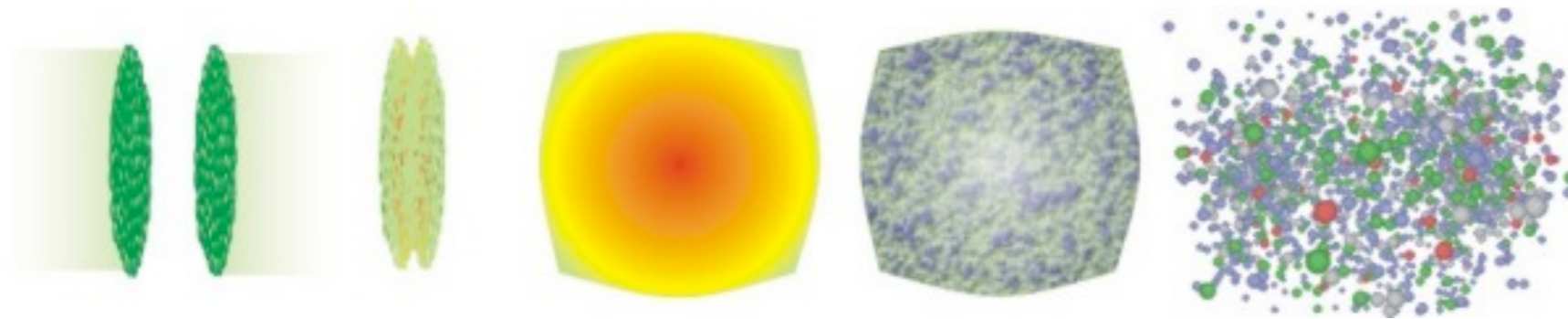
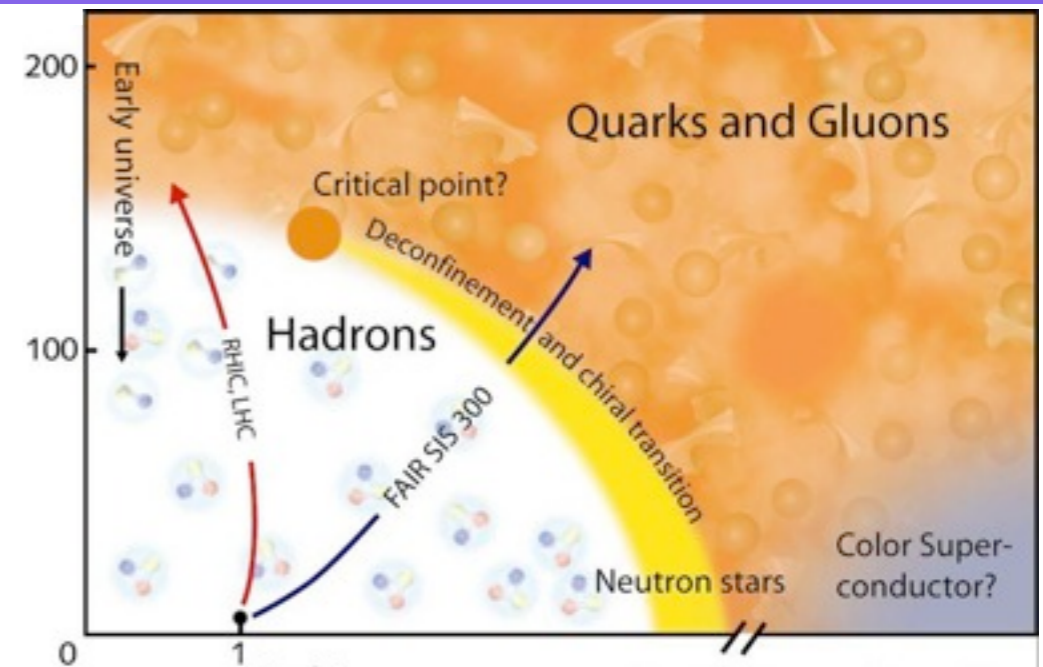
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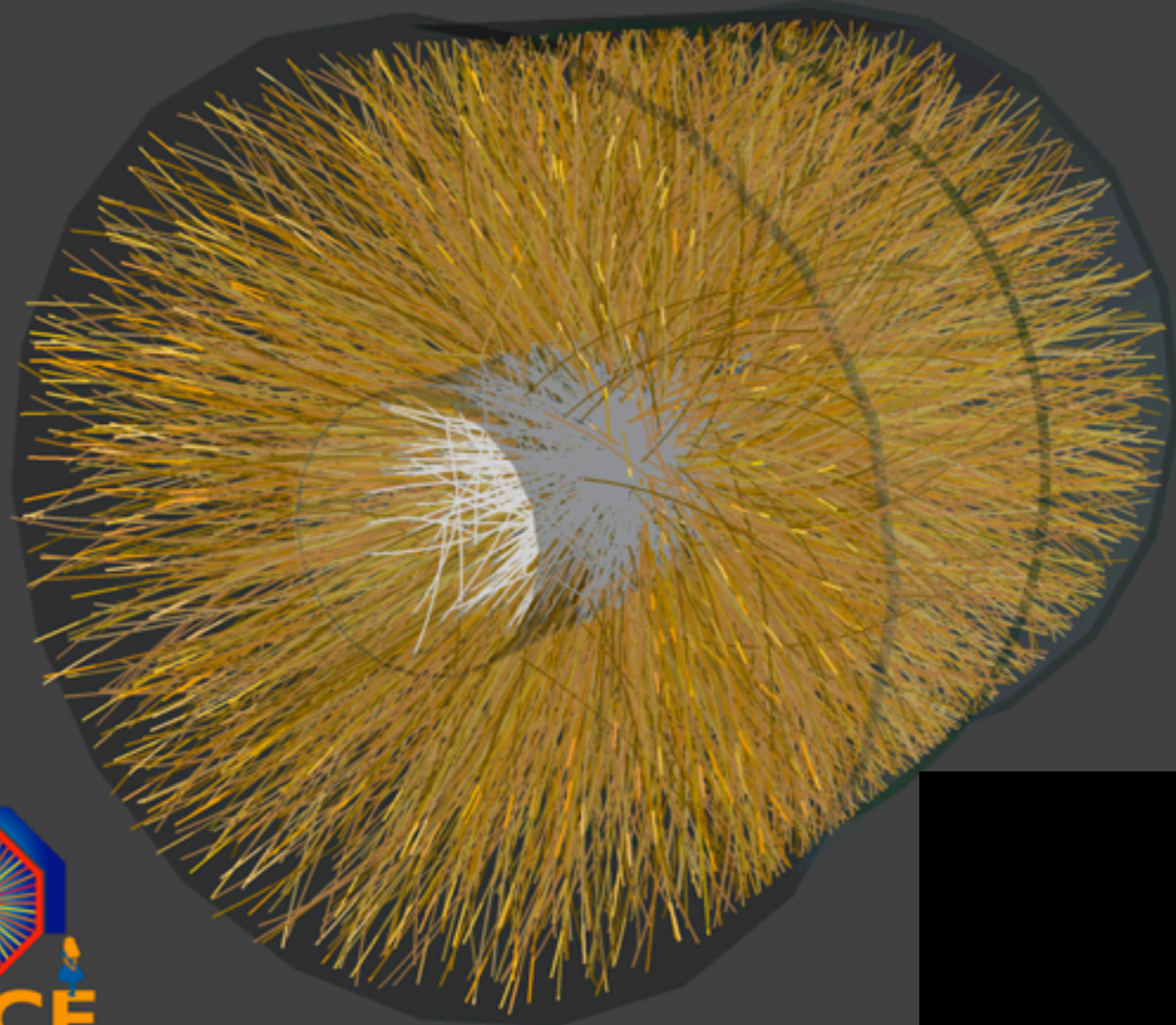


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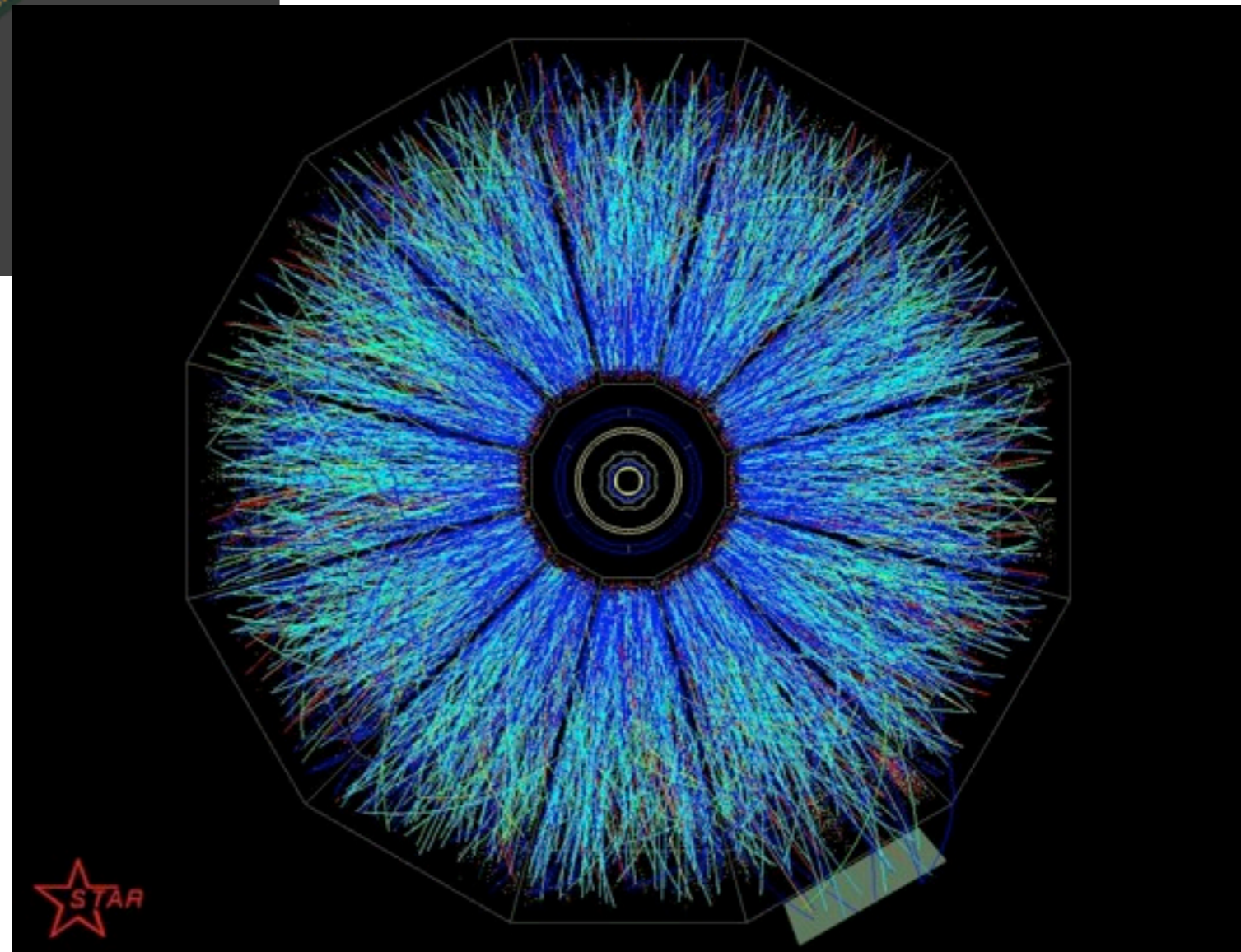
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- The highest particle multiplicities are measured in these experiments, such as $dN_{\text{ch}}/d\eta = 1584 \pm 4 (stat.) \pm 76 (sys.)$
[ALICE PRL105 \(2010\)](#)



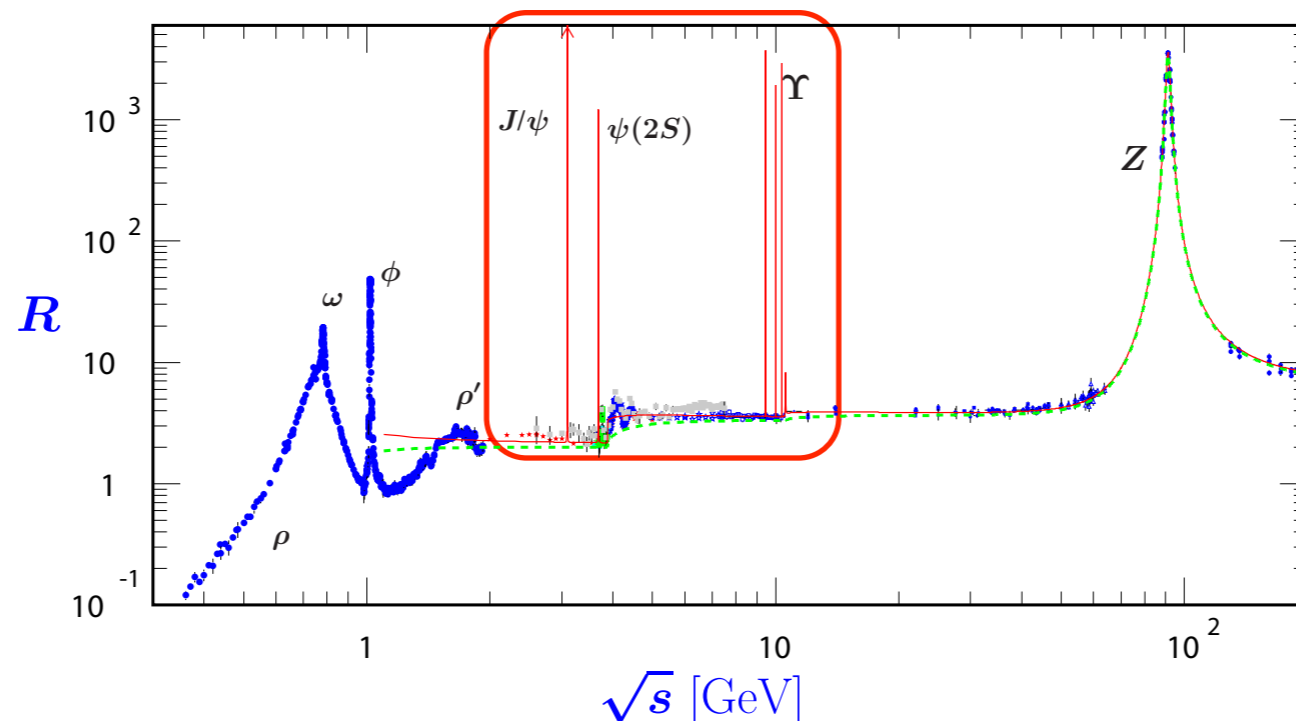
- Characterization of the medium through **two** classes of observables
- **Bulk** properties (hydro, flow, etc...)
- **Hard probes** (jets, e/m probes, quarkonia...)



- **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 $Q\bar{Q}$ 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**

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

- $R_{AA} \neq 1 \Rightarrow$ 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}

Quarkonium suppression in experiments

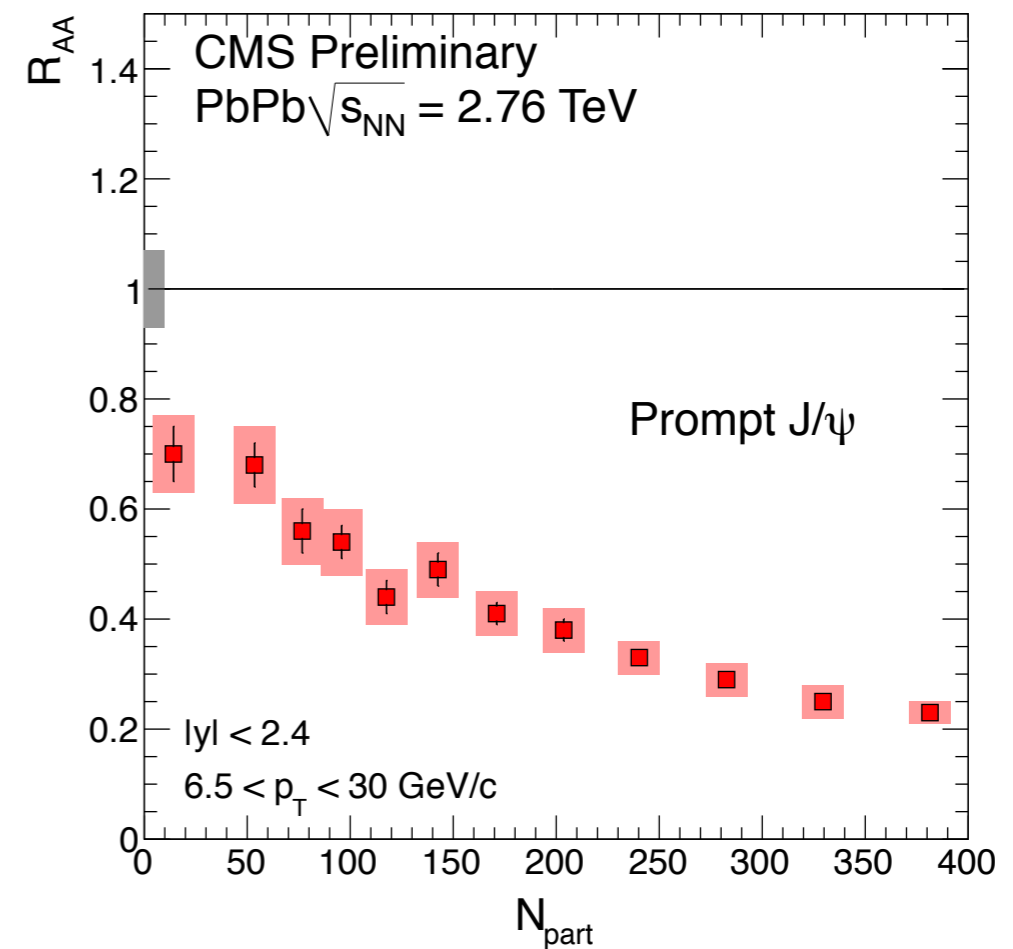
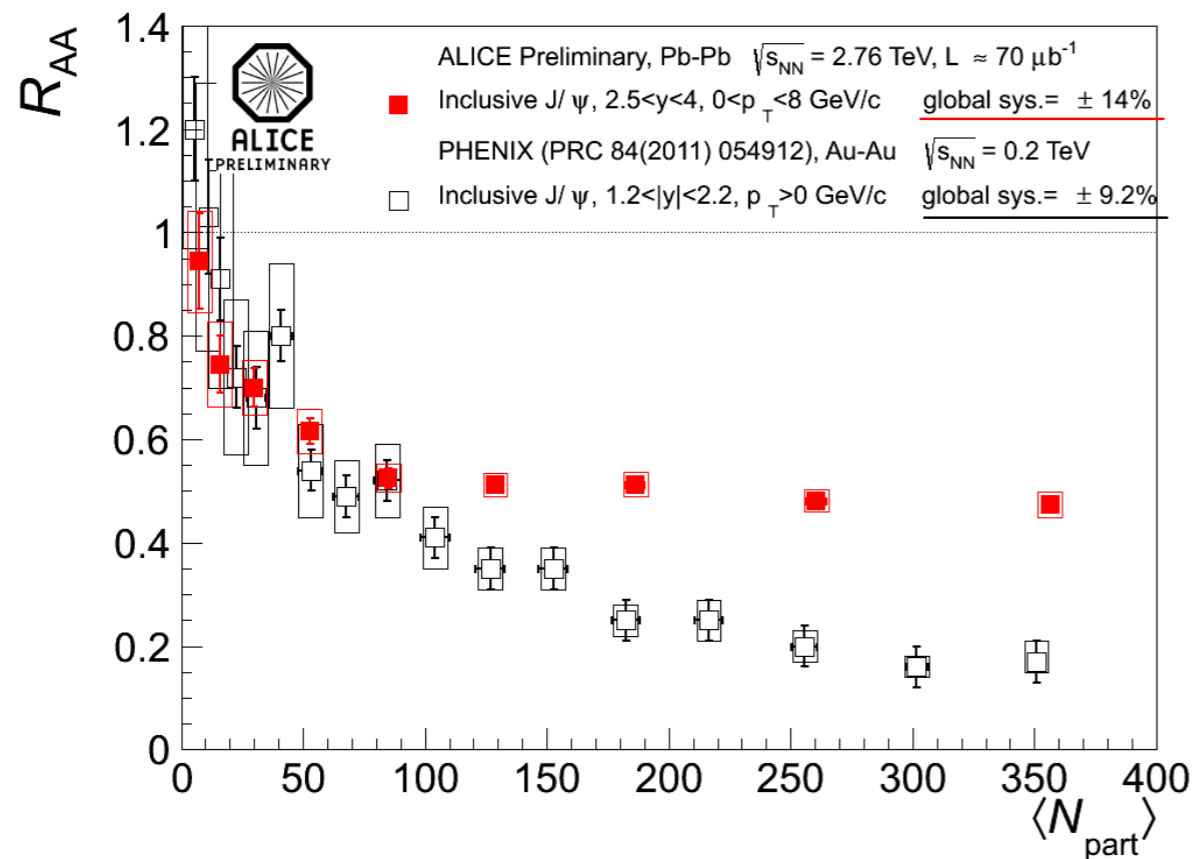
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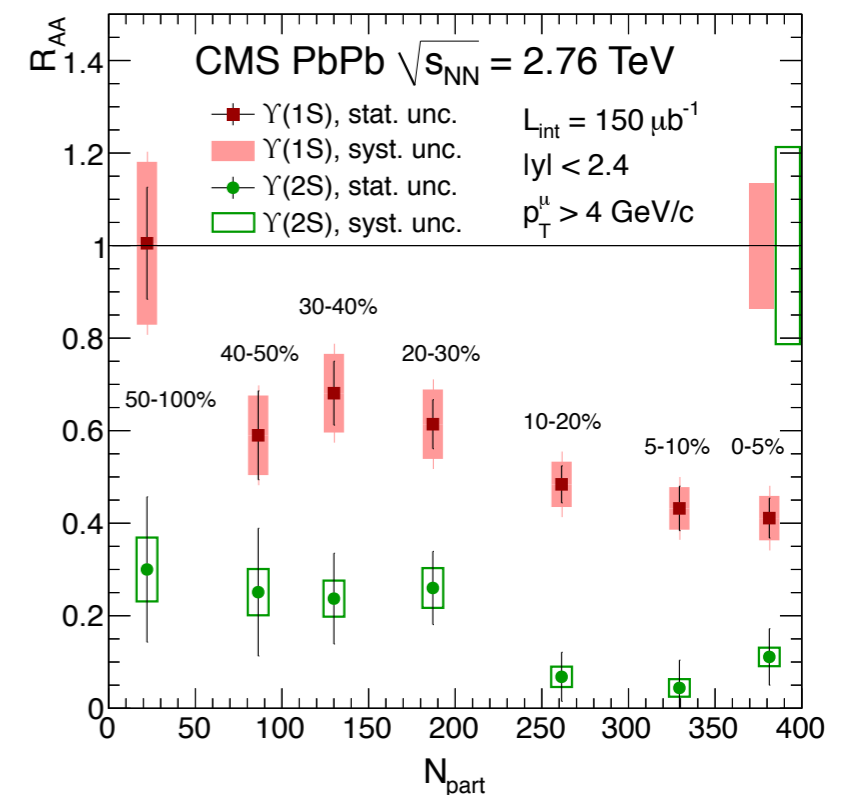
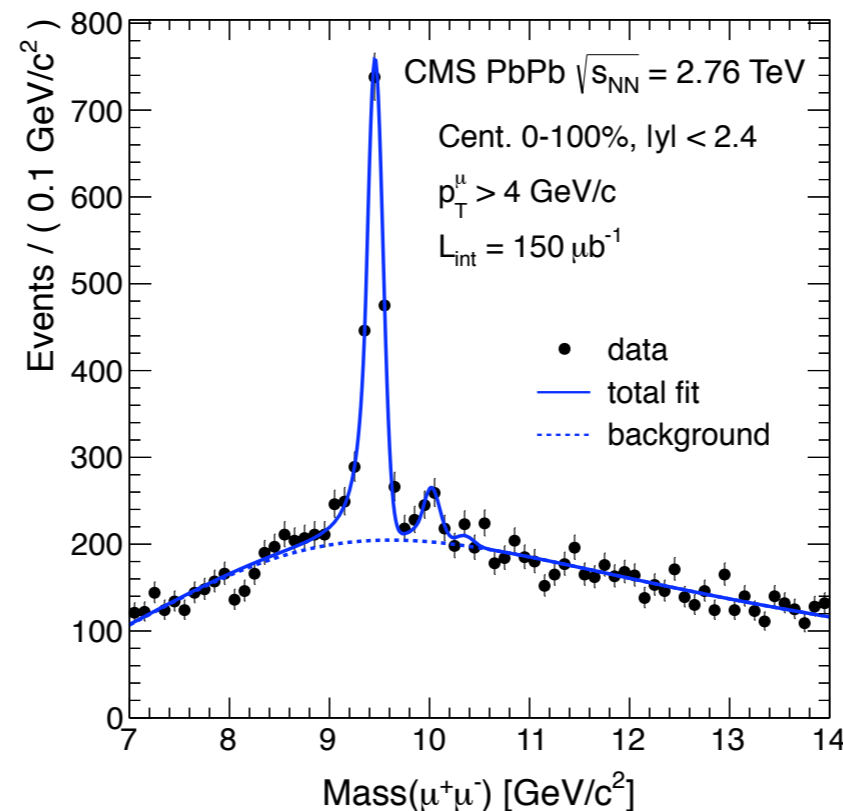
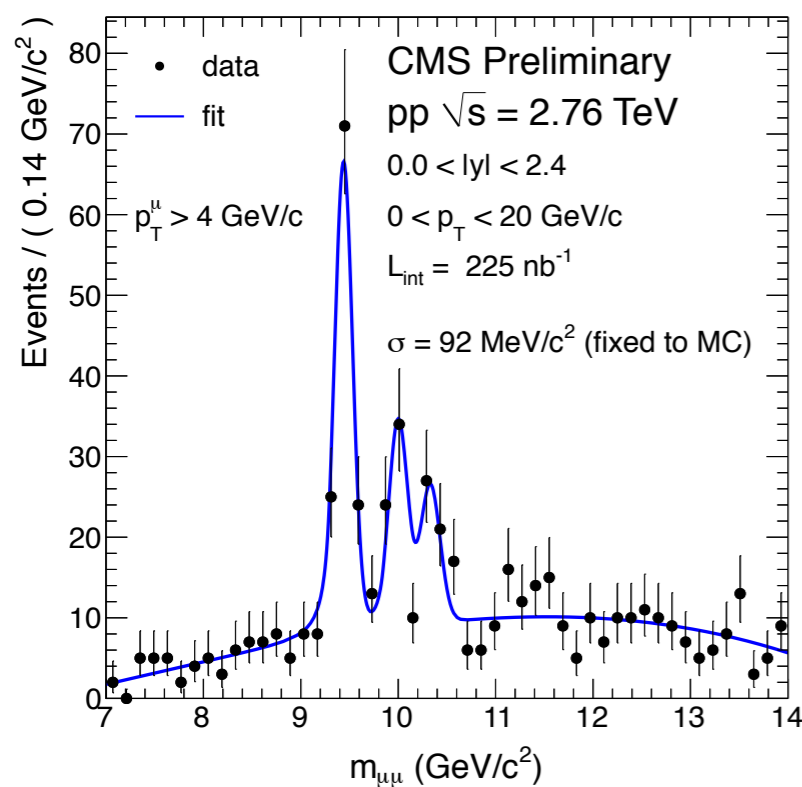
Charmonium suppression in experiments

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



Bottomonium: the new frontier

- First quality data on the Υ family from CMS

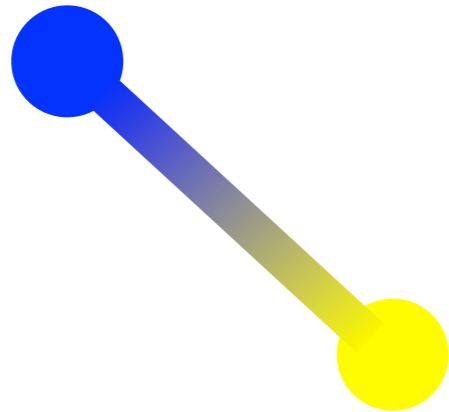


- Sequential suppression of $\Upsilon(1S)$ and $\Upsilon(2S)$
[CMS, 1208.2826](#)

Overview of dissociation

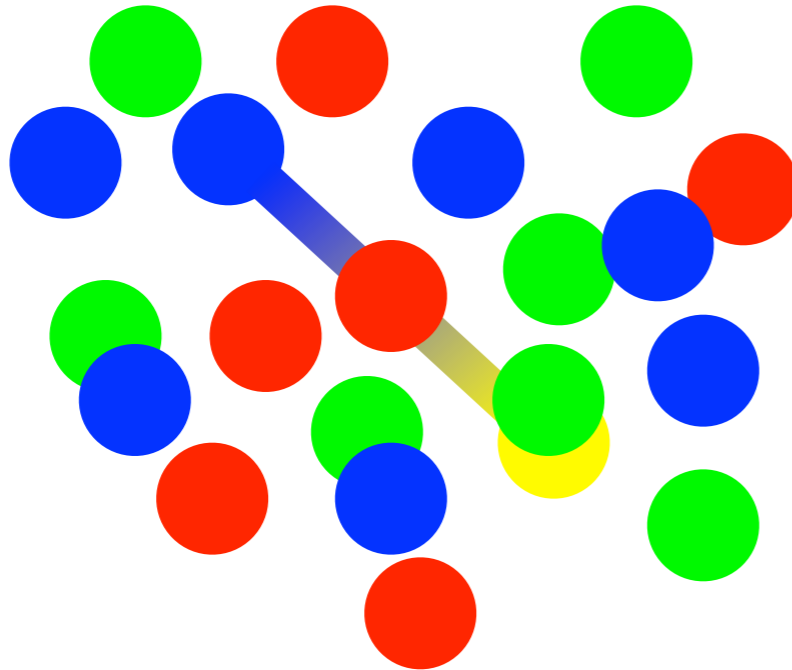
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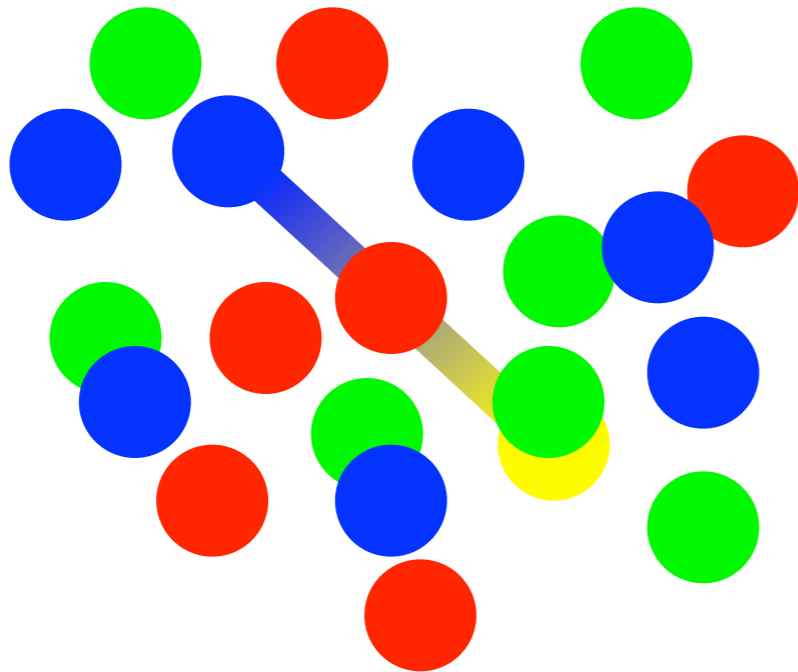


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$$r \sim \frac{1}{m_D} \longrightarrow \text{Bound state dissolves}$$

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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

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

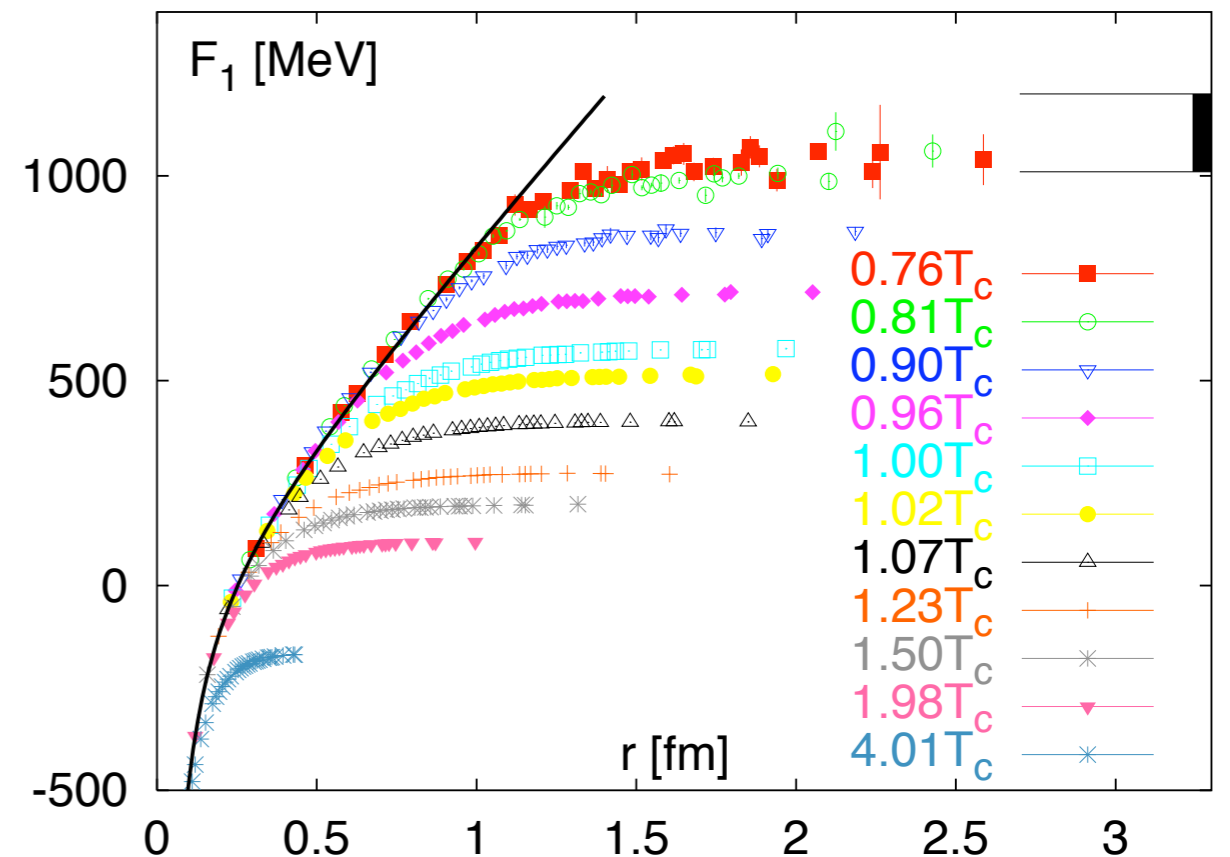
- Assume

$$V = F_1$$

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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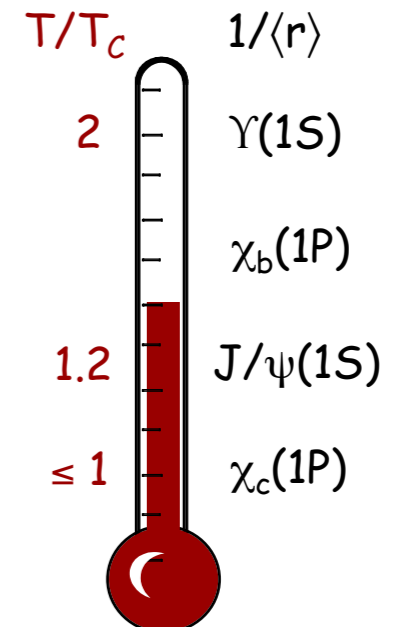
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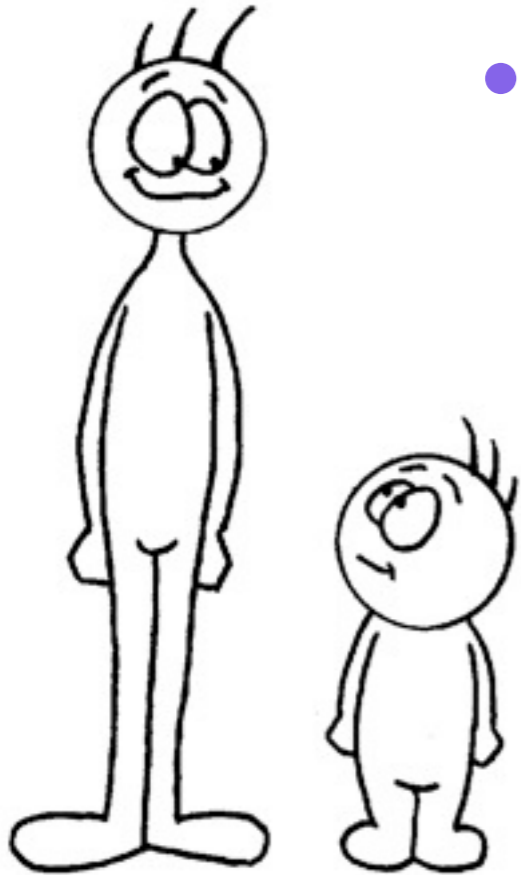
internal energy measured on the lattice

- 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



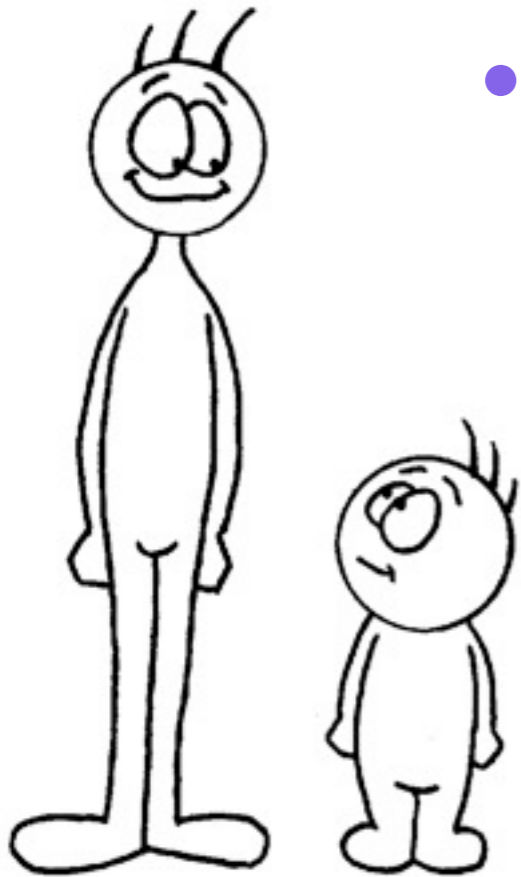
Effective Field Theories

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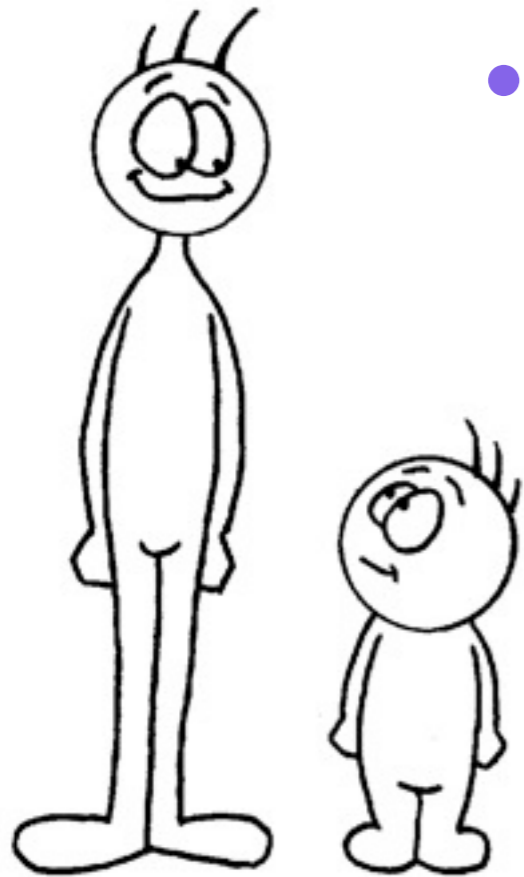


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$$\mathcal{L}_{\text{EFT}} = \sum_n c_n(\mu/\Lambda) \frac{O_n}{\Lambda^{d_n-4}}$$

Wilson coefficient
Low-energy operator/
large scale

Effective Field Theories



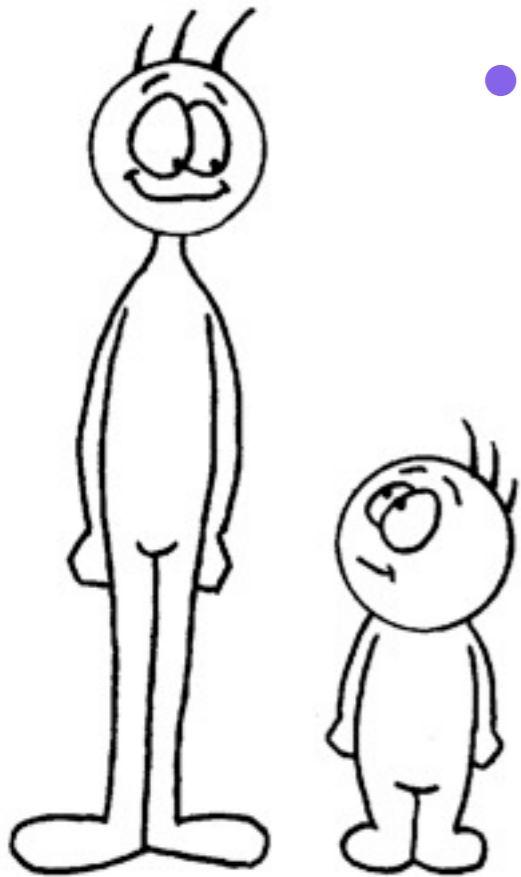
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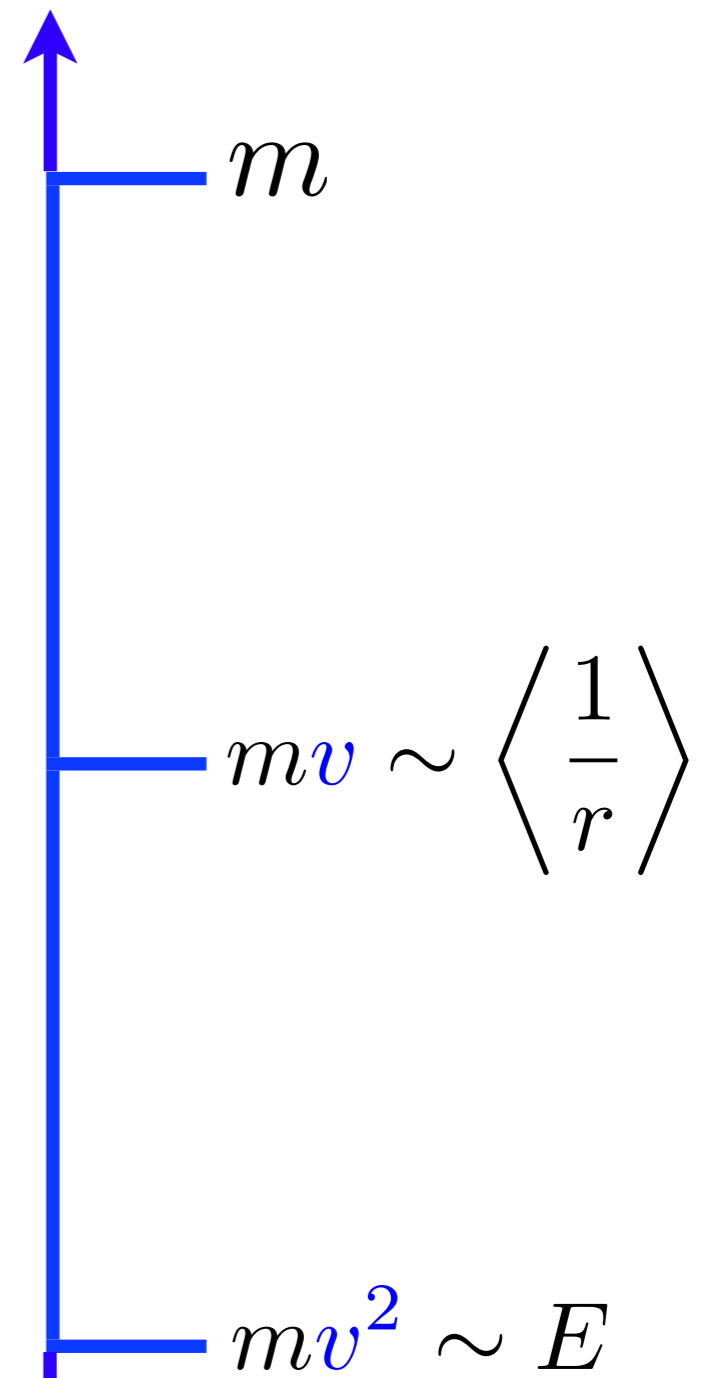
Wilson coefficient Low-energy operator/
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- The Wilson coefficient are obtained by matching Green's functions in the two theories
- The procedure can be iterated $\dots \ll \mu_2 \ll \Lambda_2 \ll \mu_1 \ll \Lambda_1$

At zero temperature

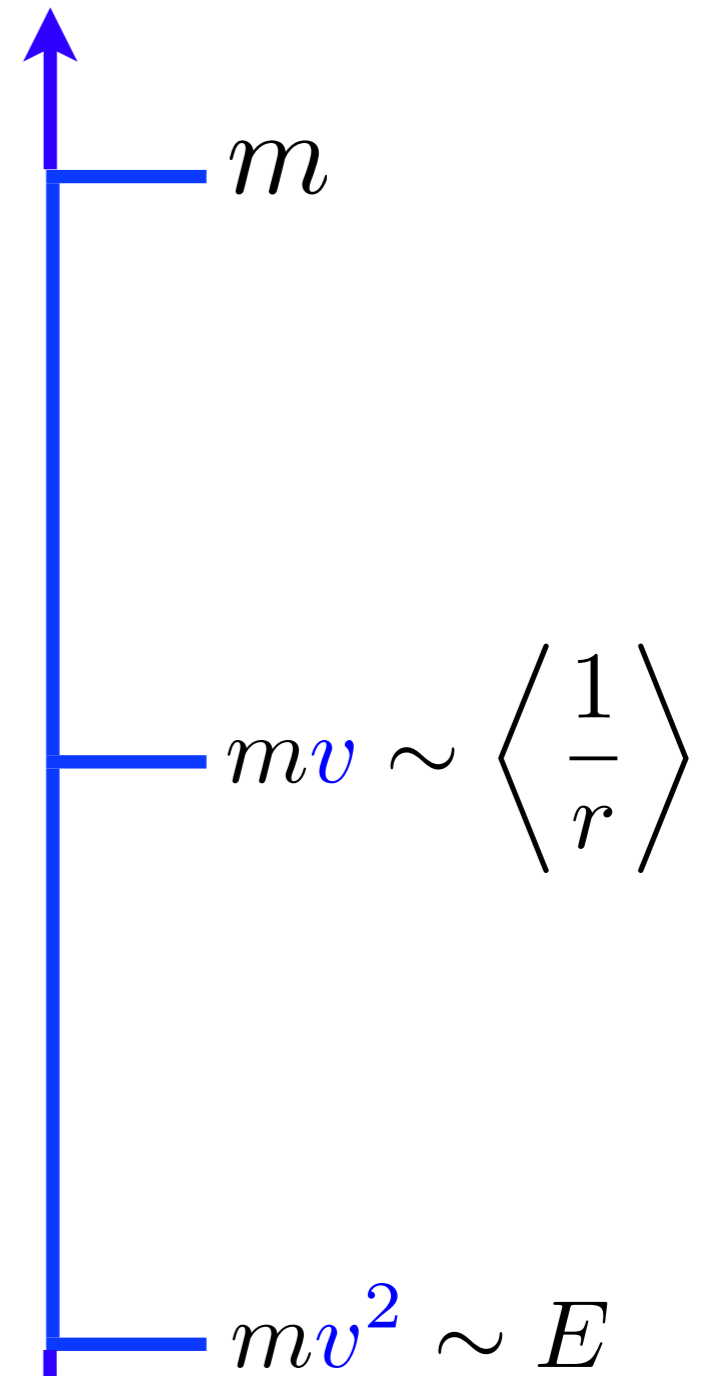
At zero temperature

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



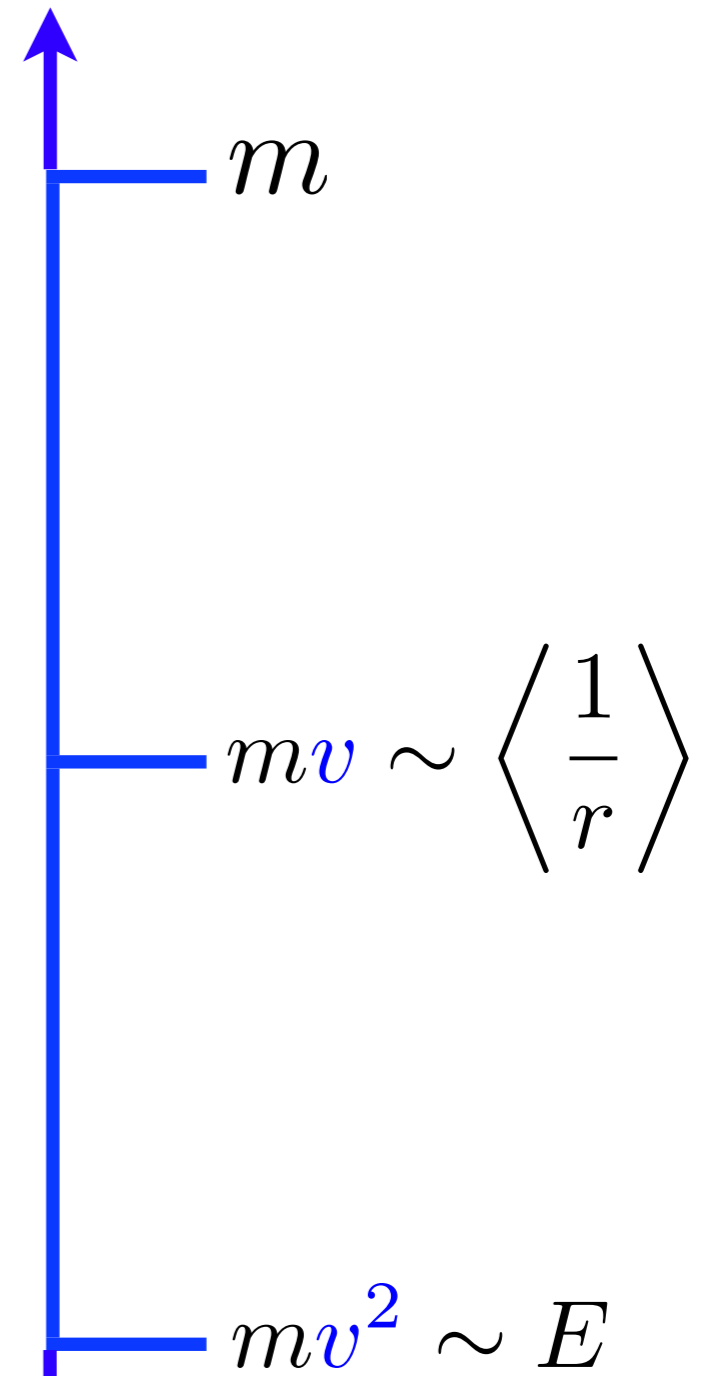
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At zero temperature

- *Non-relativistic $Q\bar{Q}$ 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



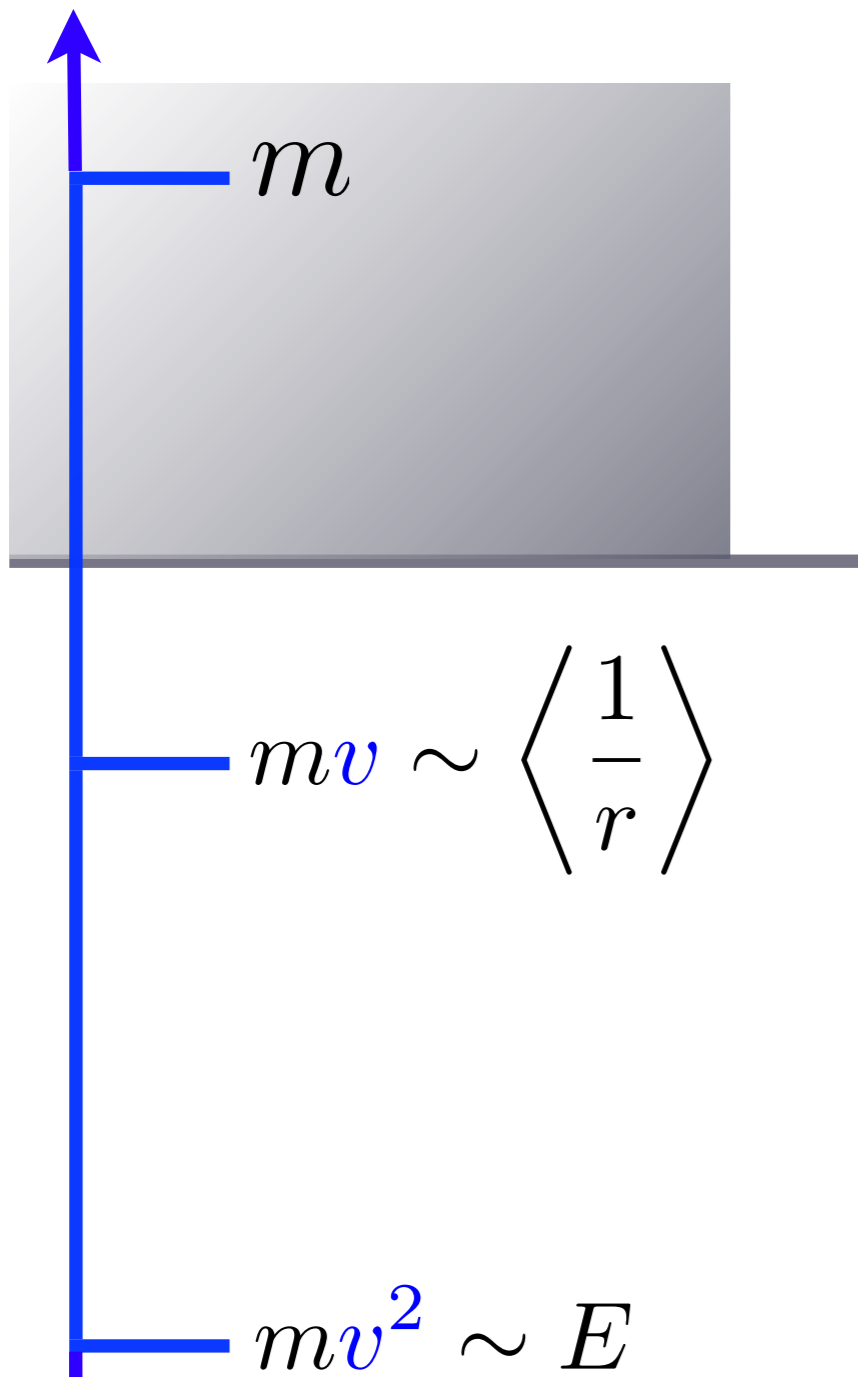
Integrating out the mass scale: Non-Relativistic QCD (NRQCD)

- 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

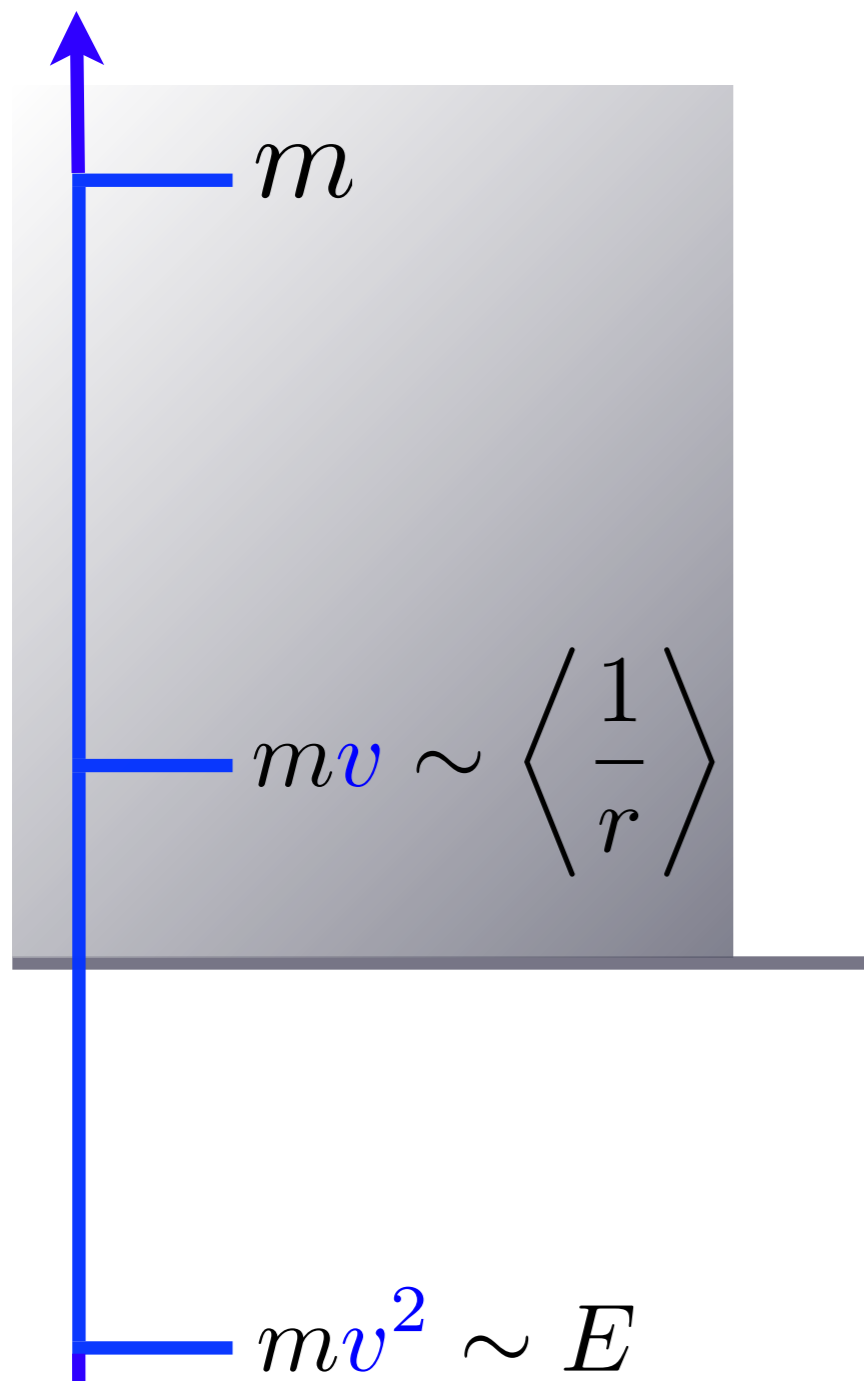
$$\mathcal{L}_{\text{NRQCD}} = \sum_n c_n(\mu/m) \frac{O_n}{m^{d_n-4}}$$

Caswell Lepage **PLB167** (1986)

Bodwin Braaten Lepage **PRD51** (1995)

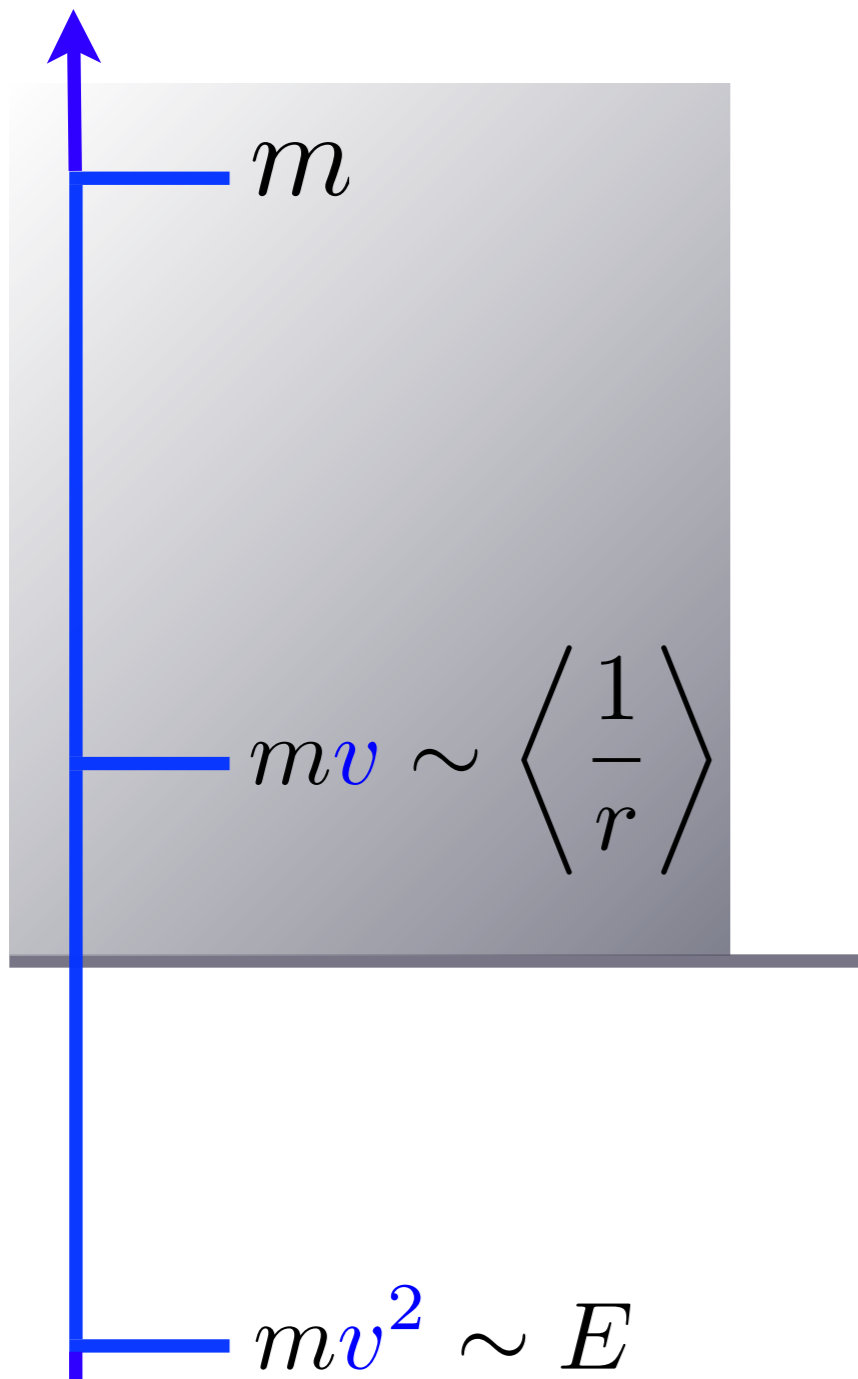


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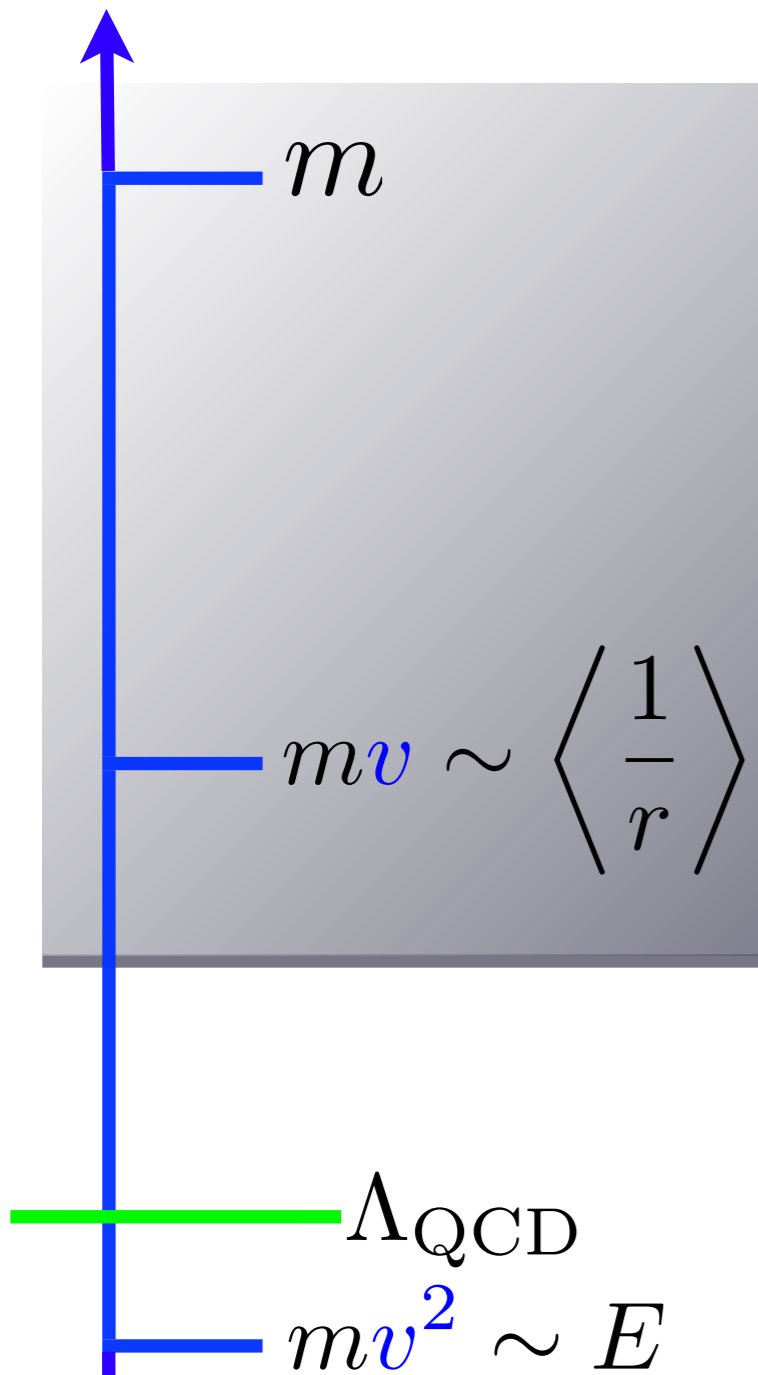
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$$\mathcal{L} = \mathcal{L}_{\text{light}} + \text{Tr} \left\{ \mathbf{S}^\dagger \left[i\partial_0 + \frac{\nabla^2}{m} - V_s \right] \mathbf{S} + \mathbf{O}^\dagger \left[iD_0 + \frac{\nabla^2}{m} - V_o \right] \mathbf{O} \right\} \\ + \text{Tr}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

Pineda Soto **NPPS64** (1998)

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



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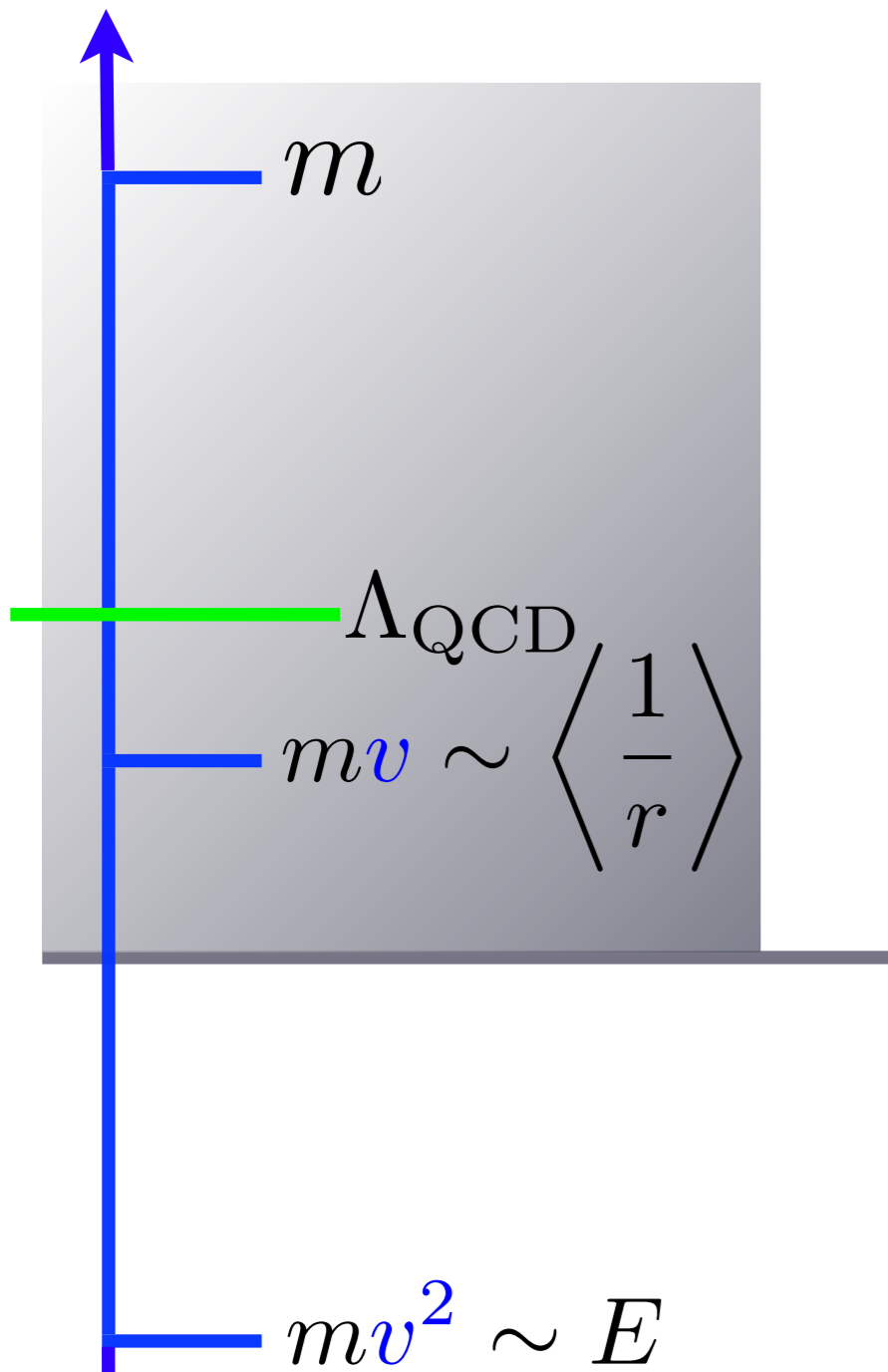
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$$+ \text{Tr} \{ \mathbf{O}^\dagger \mathbf{r} \cdot g\mathbf{E} \mathbf{S} + \mathbf{S}^\dagger \mathbf{r} \cdot g\mathbf{E} \mathbf{O} \} + \frac{1}{2} \text{Tr} \{ \mathbf{O}^\dagger \mathbf{r} \cdot g\mathbf{E} \mathbf{O} + \mathbf{O}^\dagger \mathbf{O} \mathbf{r} \cdot g\mathbf{E} \} + \dots$$

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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

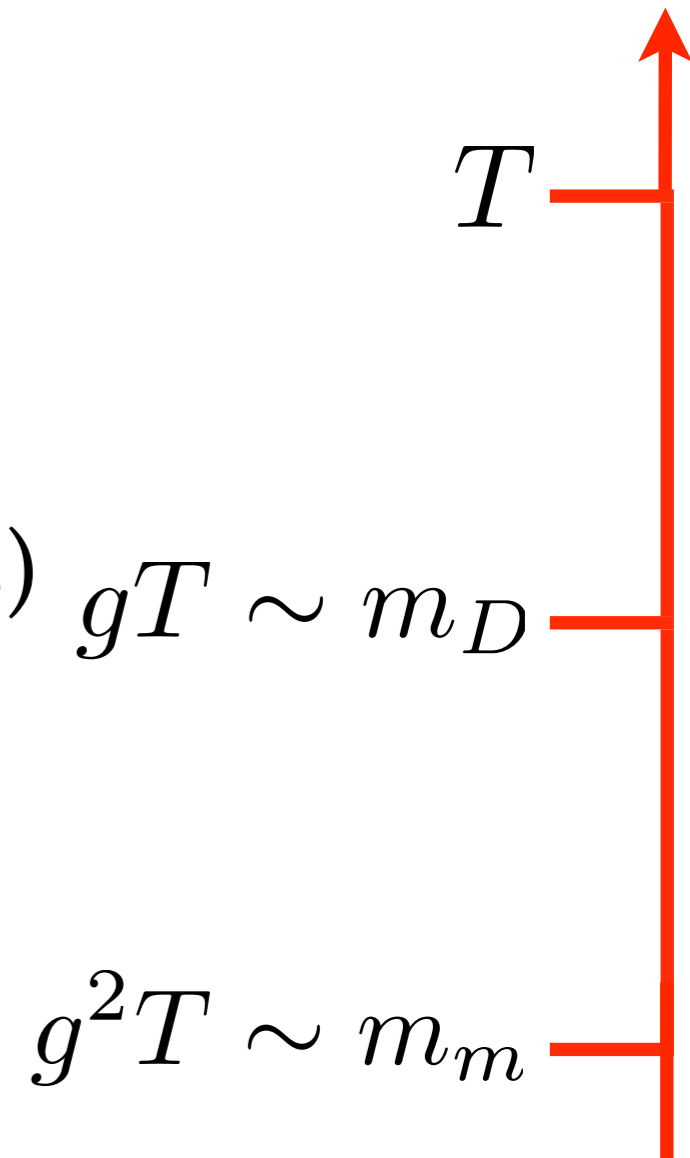
The thermodynamical scales

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- The thermal medium introduces new scales in the physical problem
 - The temperature
 - The electric screening scale (Debye mass)
 - The magnetic screening scale (magnetic mass)
- In the weak coupling assumption these scales develop a hierarchy

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Finite-temperature NR EFT how-to

$$m \gg mv \sim m\alpha_s \sim \langle 1/r \rangle \gg mv^2 \sim m\alpha_s^2 \sim E$$

?

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

- 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 $T \gg 1/r \sim m_D$ we provide an EFT derivation and rigorous definition of the potential first obtained by Laine *et al.*

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

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

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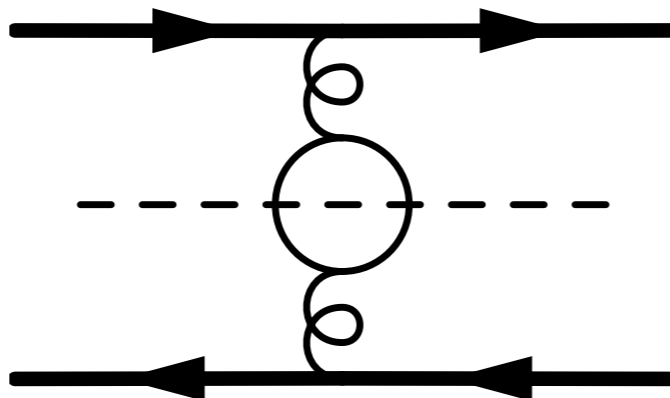
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Laine Philipsen Romatschke Tassler [JHEP0703 \(2007\)](#)

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

Landau Damping



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

- When $T \sim m\alpha_s^{2/3} \Rightarrow \text{Im}V \sim \text{Re}V$

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 $mv \gg T \gg mv^2$ the thermal medium acts as a perturbation to the potential.

Relevant for the ground states of bottomonium:

$$mv \sim 1.5 \text{ GeV}, T < 1 \text{ GeV}$$

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

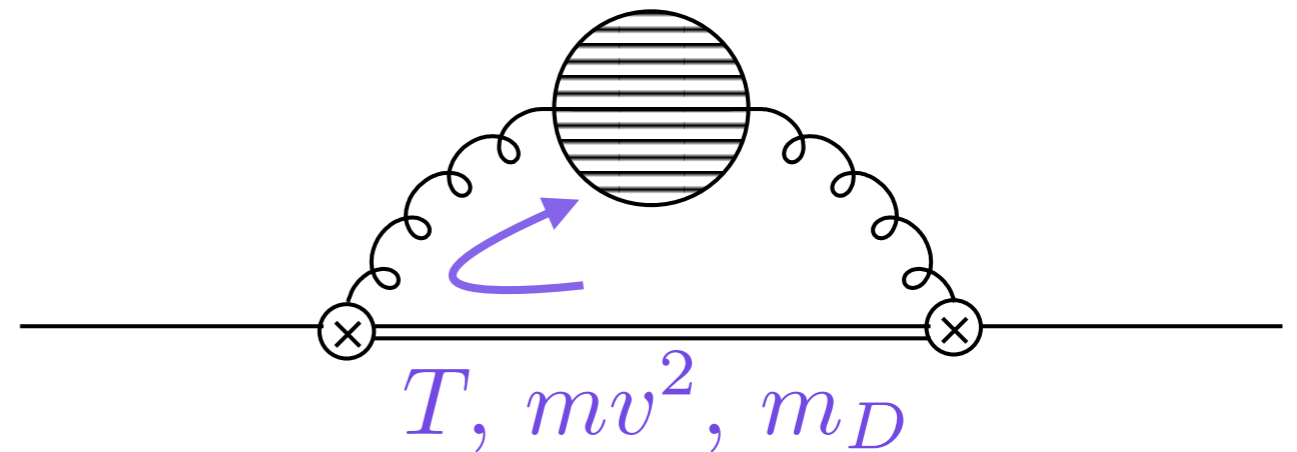
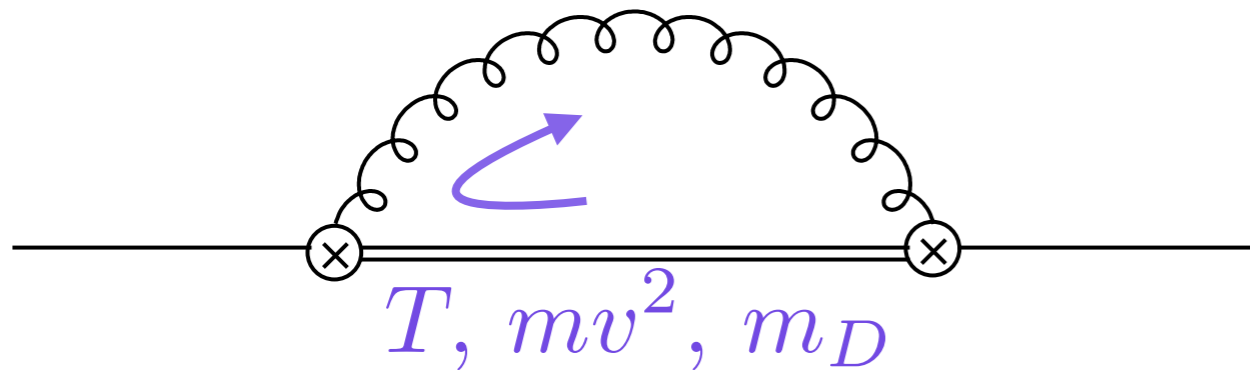
$$\mathcal{L}_{\text{pNRQCD}_{\text{HTL}}} = \mathcal{L}_{\text{HTL}} + \text{Tr} \left\{ \mathbf{S}^\dagger [i\partial_0 - h_s - \delta V_s] \mathbf{S} + \mathbf{O}^\dagger [iD_0 - h_o - \delta V_o] \mathbf{O} \right\} \\ + \text{Tr} \{ \mathbf{O}^\dagger \mathbf{r} \cdot g\mathbf{E} \mathbf{S} + \mathbf{S}^\dagger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

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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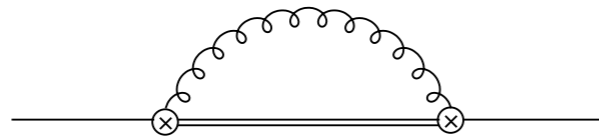
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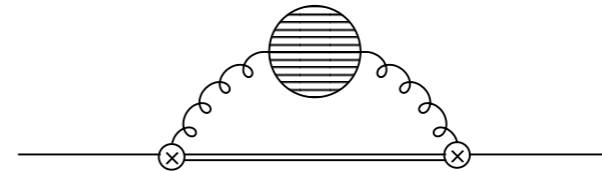
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The p



Singlet-to-octet



Landau Damping

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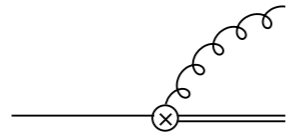
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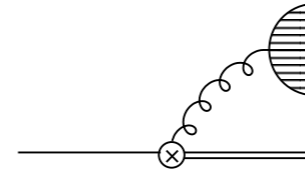
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Potentials and free energies

- 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 $Q\bar{Q}$ pair**.

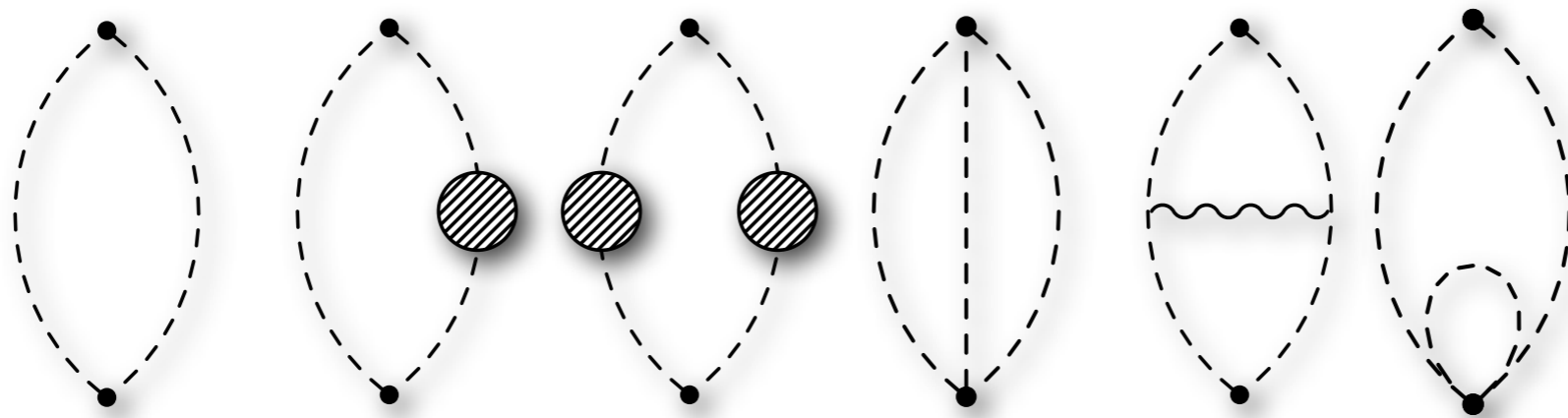
$$\langle L \rangle \equiv 1/N_c \left\langle \text{Tr P exp} \left(-ig \int_0^{1/T} d\tau A_0(\mathbf{x}, \tau) \right) \right\rangle = e^{-\frac{F_Q(T)}{T}} \quad \langle L^\dagger(\mathbf{0})L(\mathbf{r}) \rangle = e^{-\frac{F_{Q\bar{Q}}(r,T)}{T}}$$

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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)

Potentials and free energies

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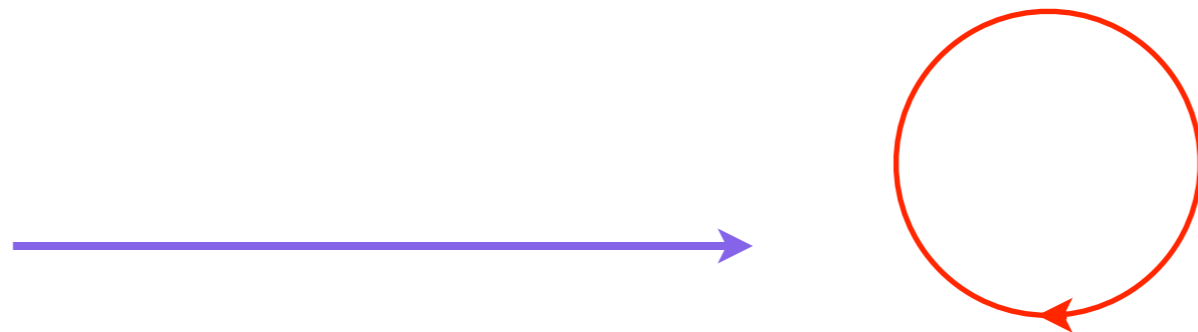
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$$\text{Im}(F) = 0, \text{Im}(V) \neq 0 \quad \text{Re}(F) \neq \text{Re}(V)$$

- Intuitively $t \rightarrow \infty \neq it = \frac{1}{T}$



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)