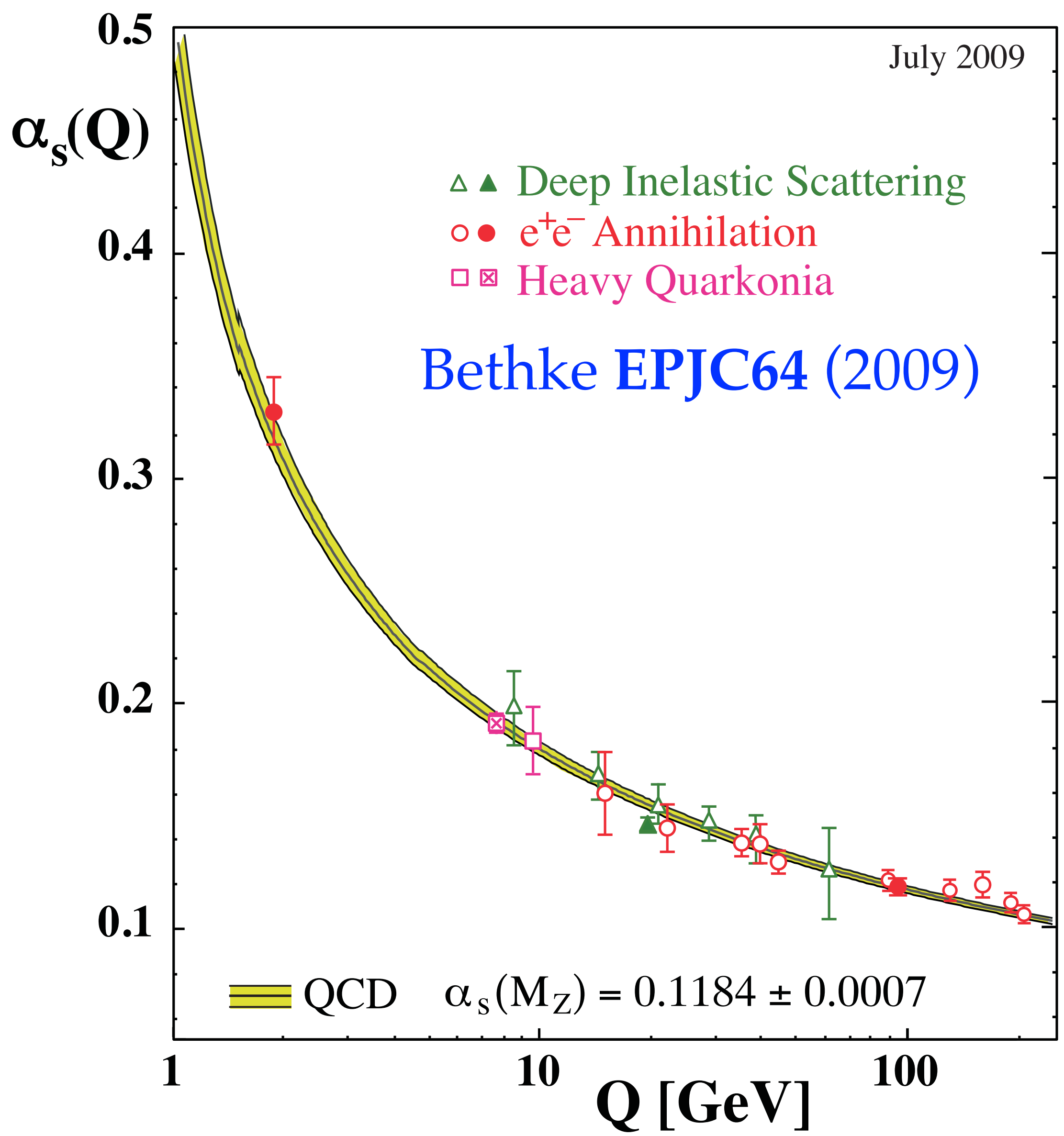
Effective Field Theories of QCD for Heavy Quarkonia at Finite Temperature

Jacopo Ghiglieri

Mündliche Doktorprüfung, 28.07.2011

Quantum Chromodynamics

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



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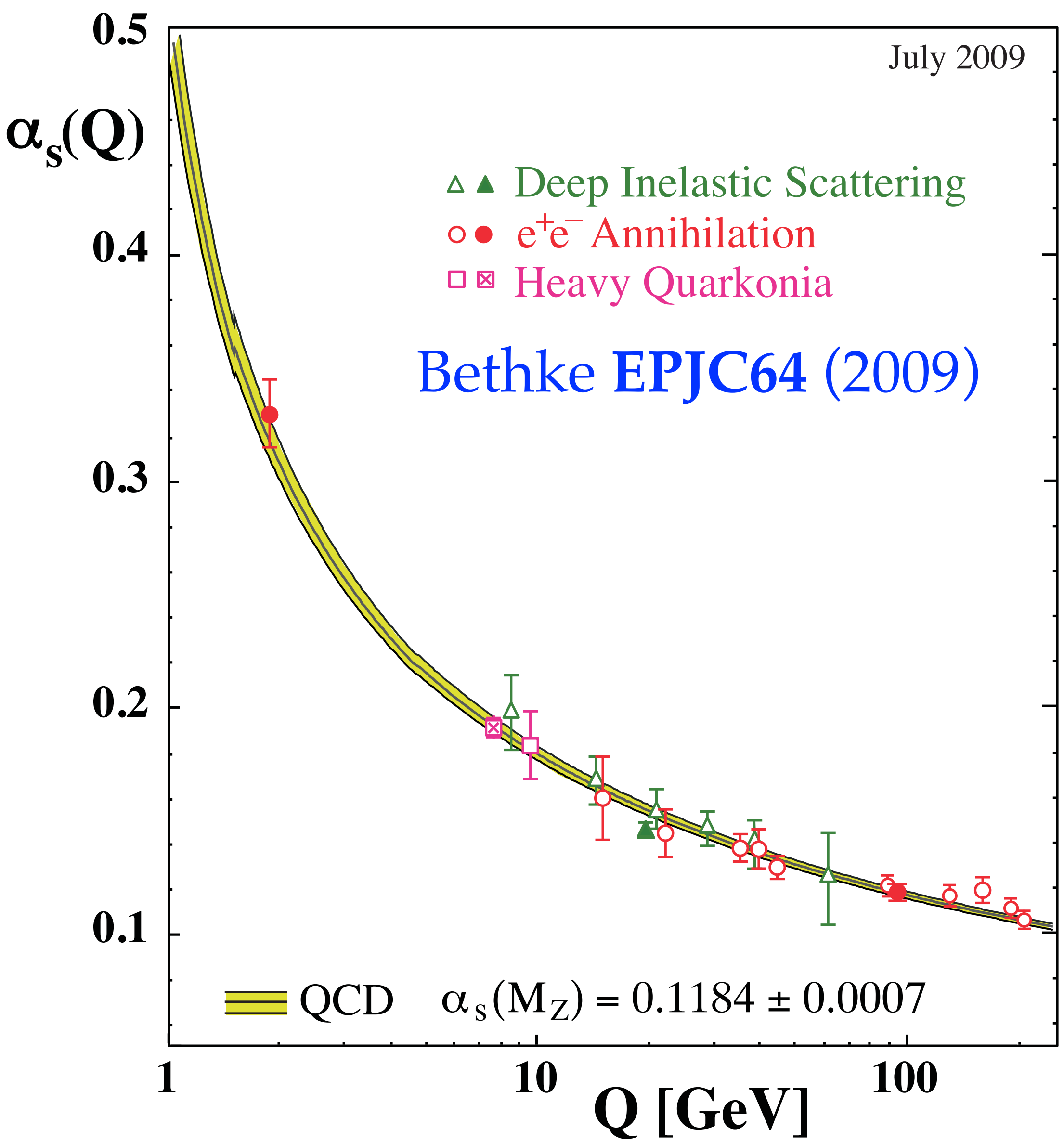

Asymptotic freedom

$$\langle O \rangle = c_0 + c_1 \alpha_s + c_2 \alpha_s^2 + \dots$$

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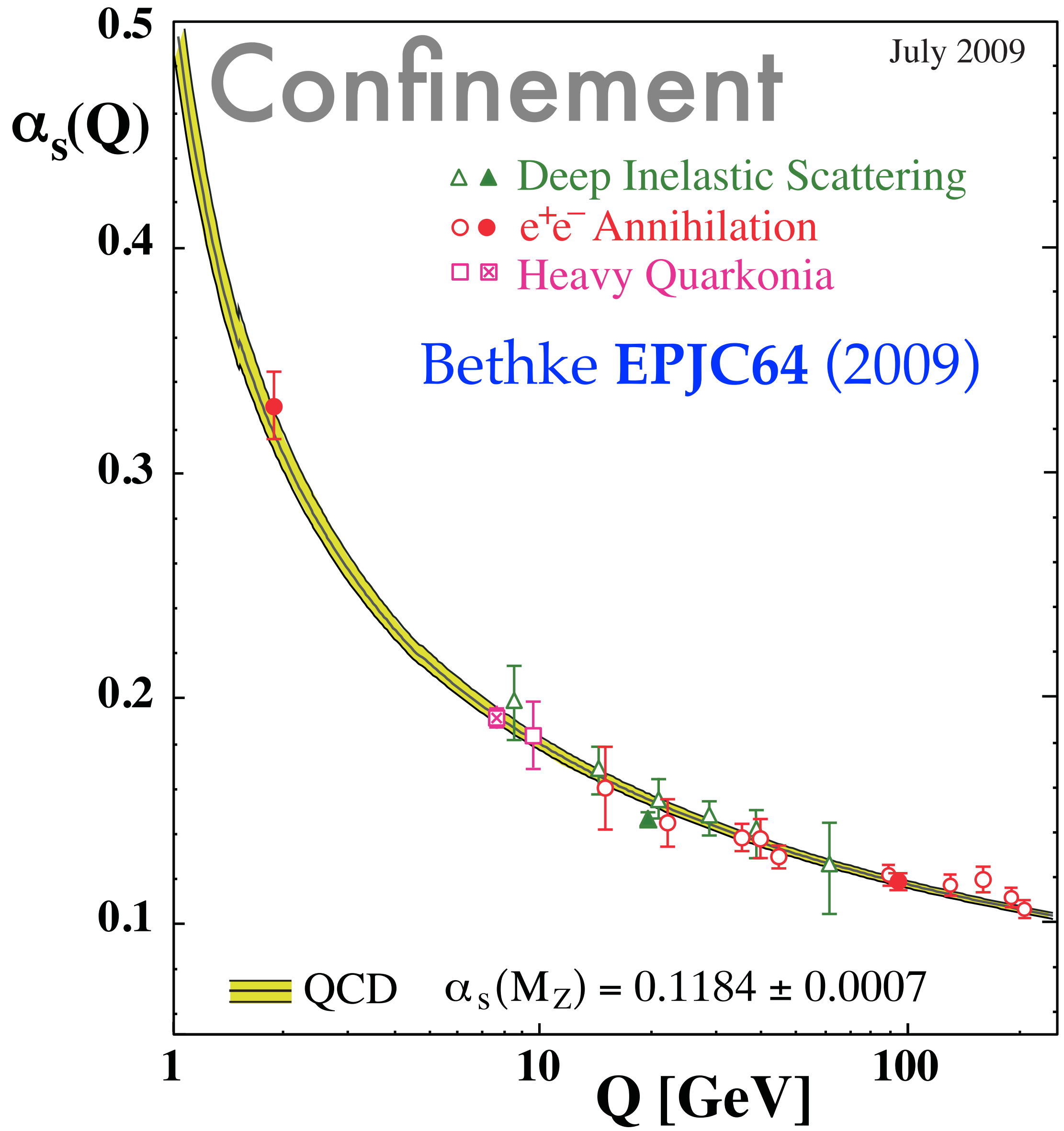

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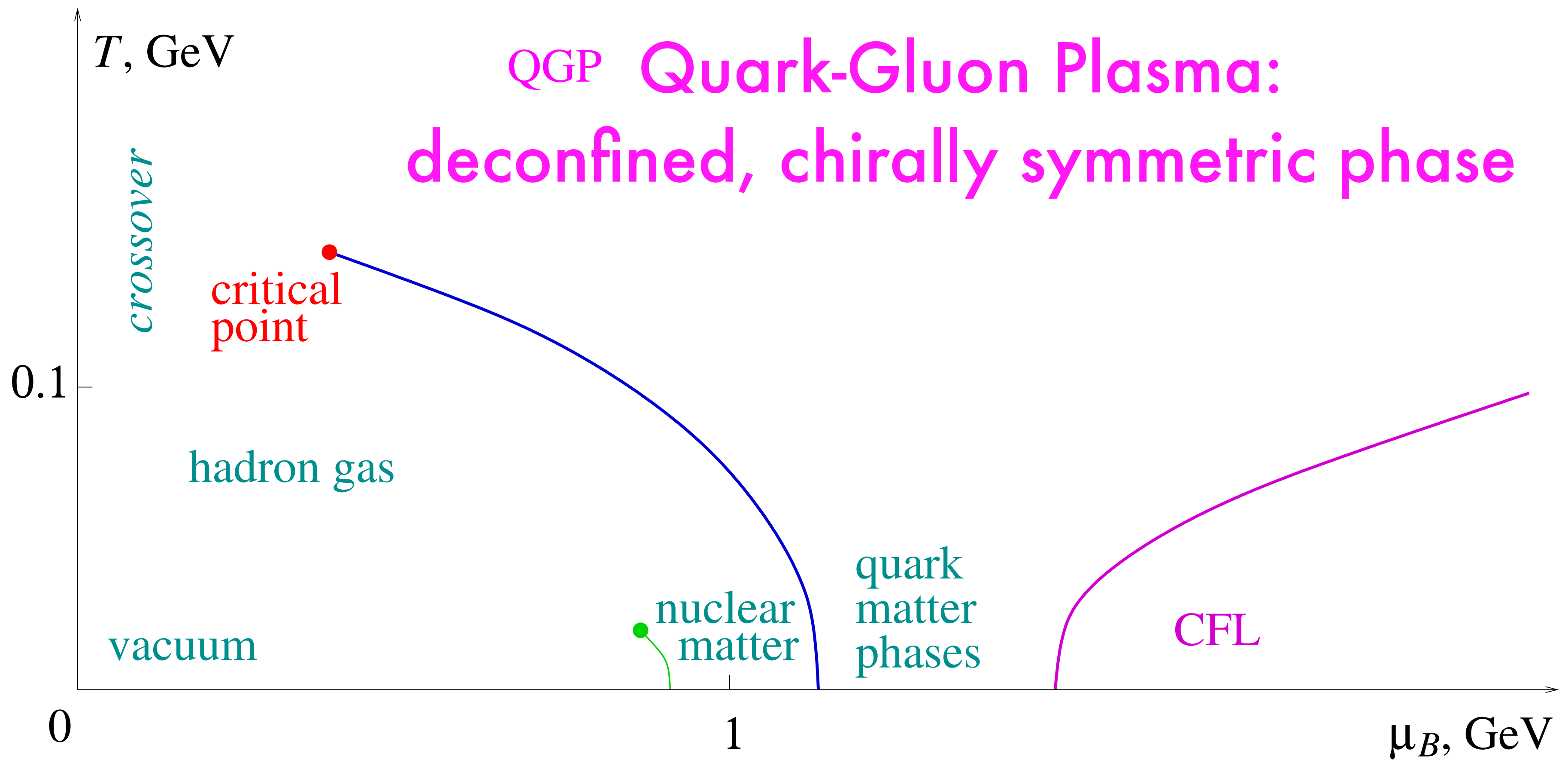
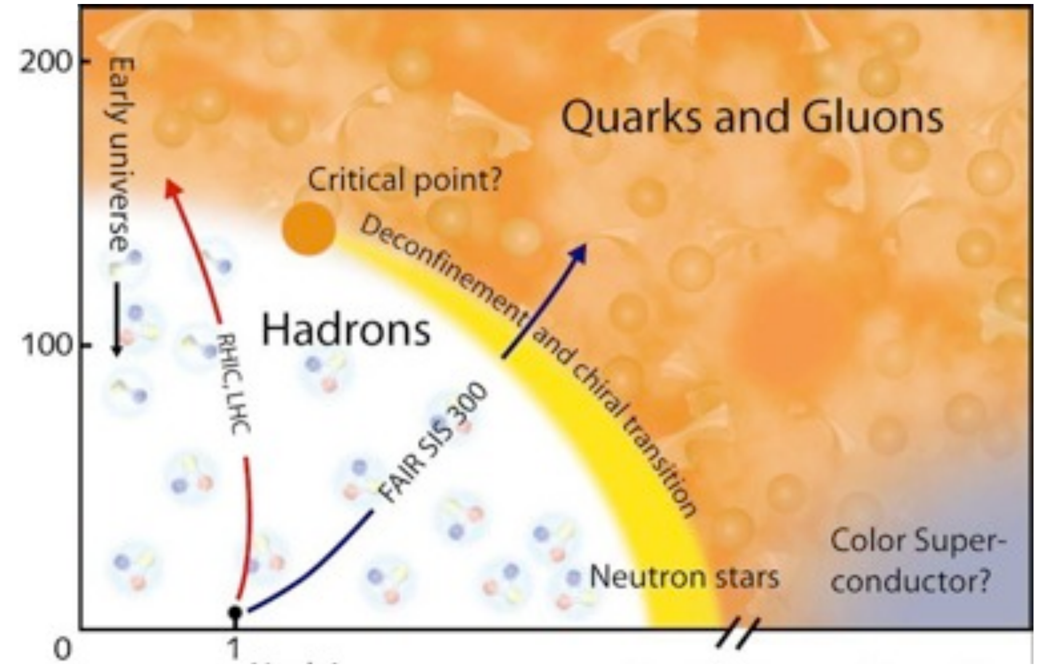
The phase diagram of QCD

- At sufficiently high temperature and/or baryon chemical potential the phase diagram of QCD exhibits new phases



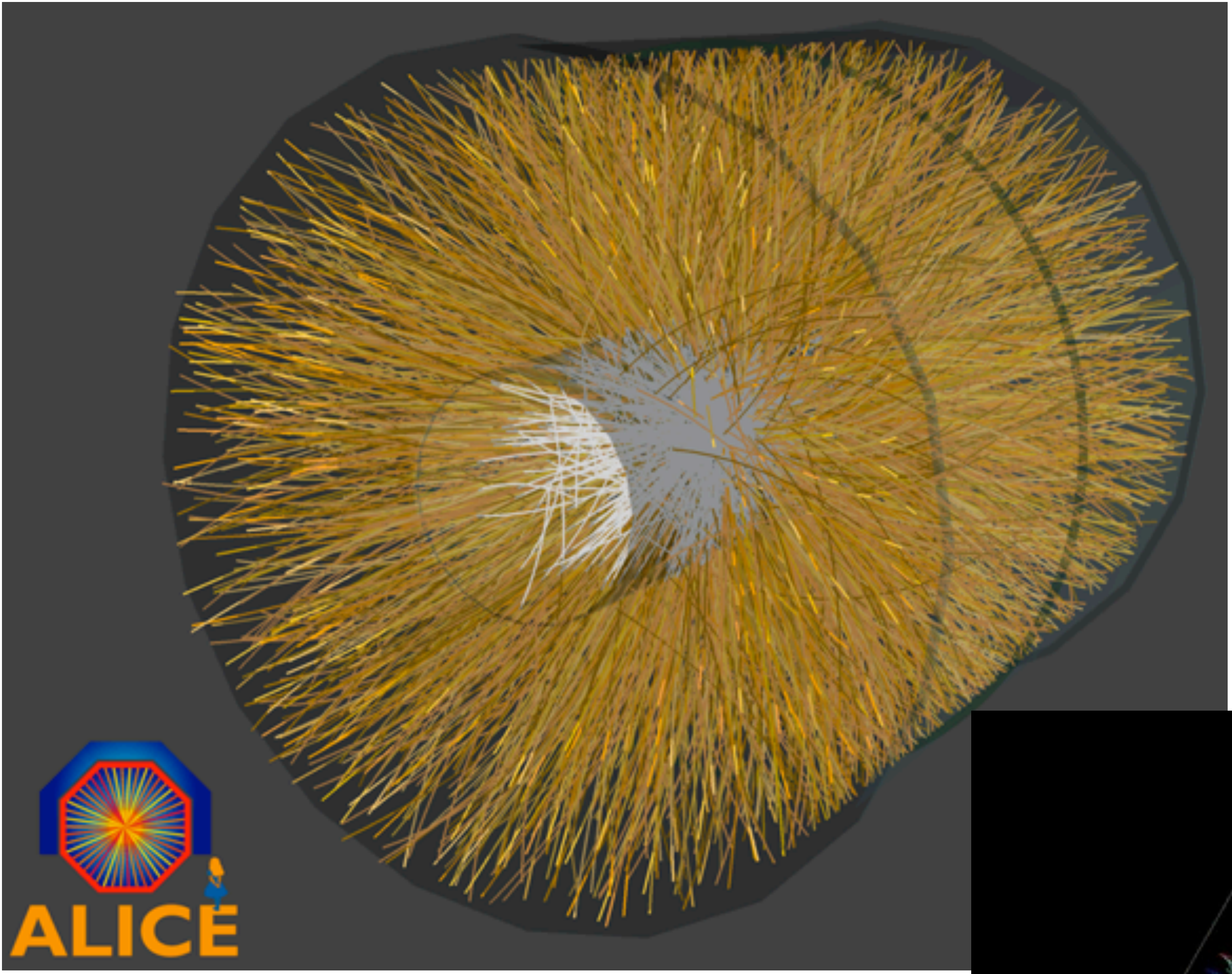
- In the upper-left region, lattice QCD indicates a (pseudo)critical temperature T_c~160 MeV ~2x10^{12} K (Budapest-Wuppertal and HotQCD collaborations)

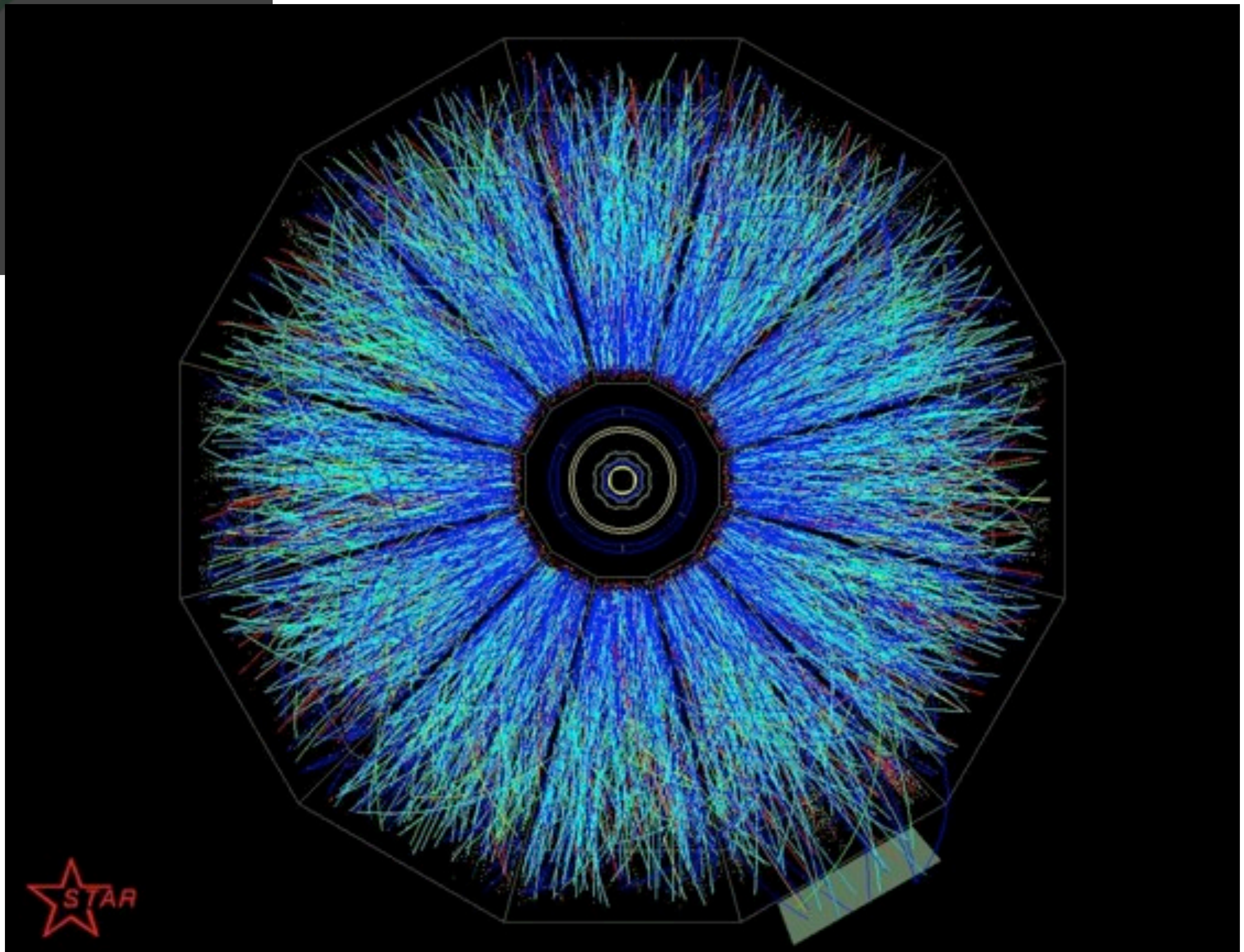
Heavy ion collision experiments

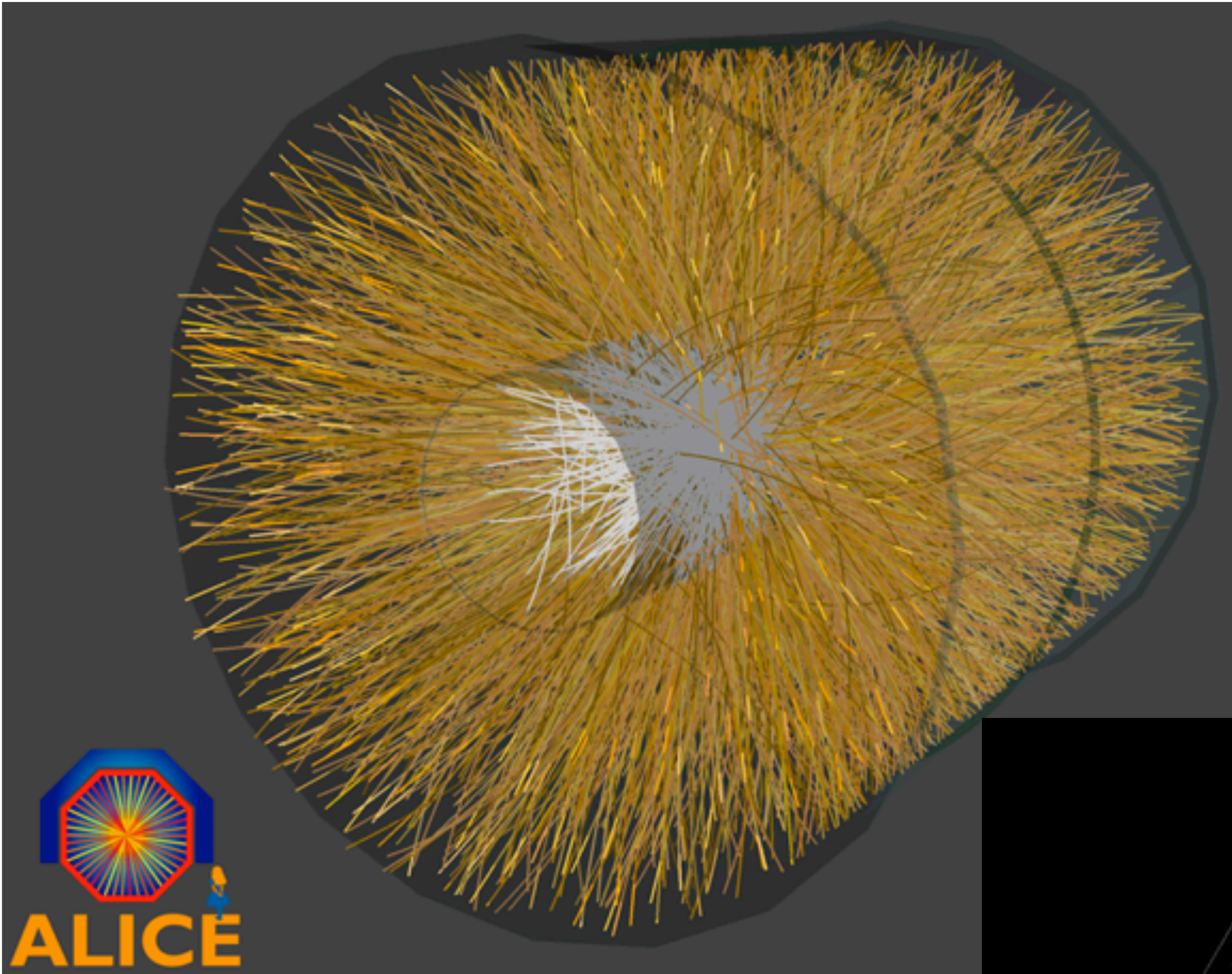


- The deconfined phase can be sought after experimentally in relativistic heavy ion collisions
- Such experiments have been performed at the CERN SPS, are being performed at the RHIC (BNL) and the LHC and will be performed at FAIR (GSI). The energies $\sqrt{s_{\mathrm{NN}}}$ are 200 GeV at RHIC and 2.76 TeV at LHC
- 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)

- Need for *hard probes*, i.e. high-energy particles not in equilibrium with the medium to perform its *tomography* and understand its properties, such as deconfinement







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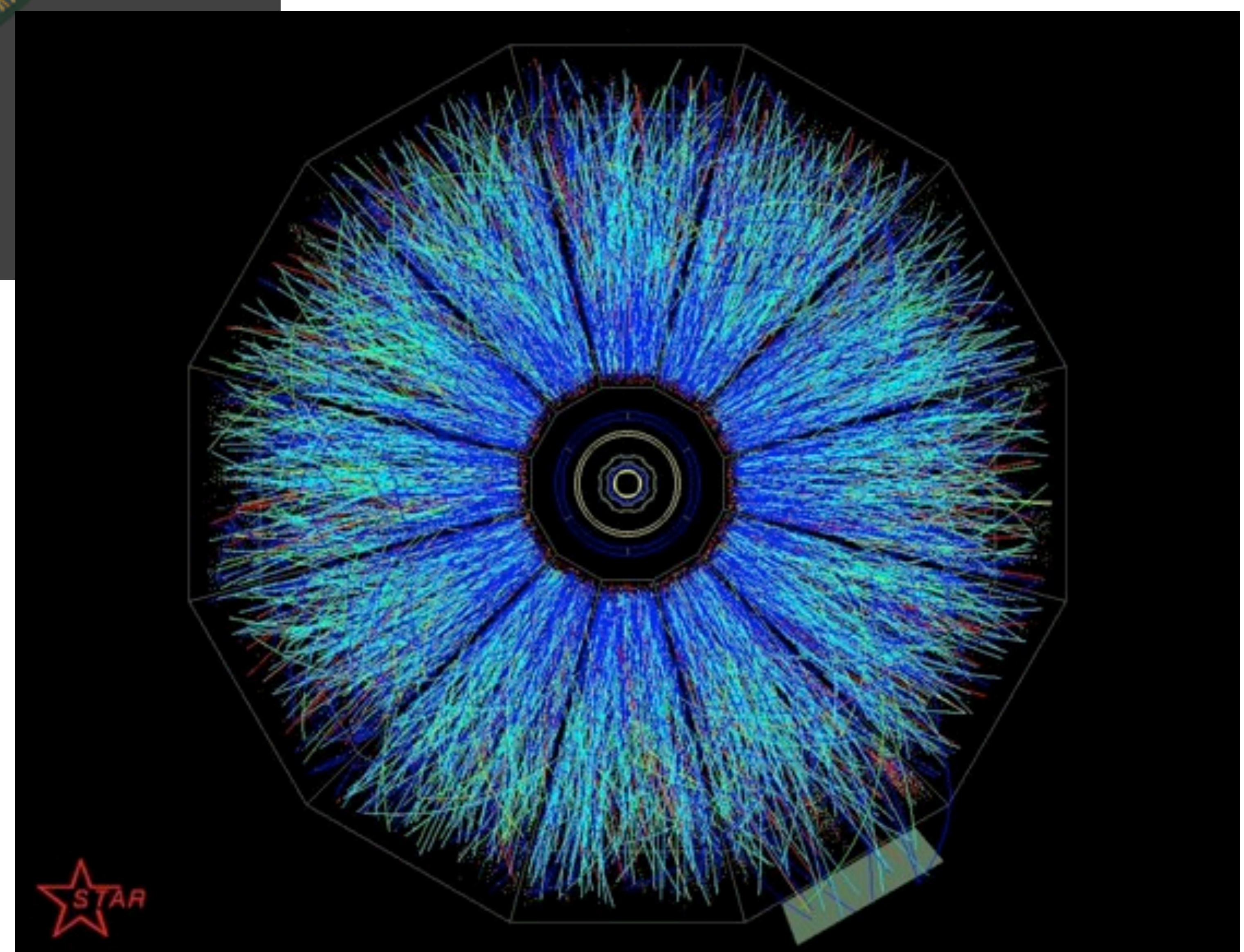
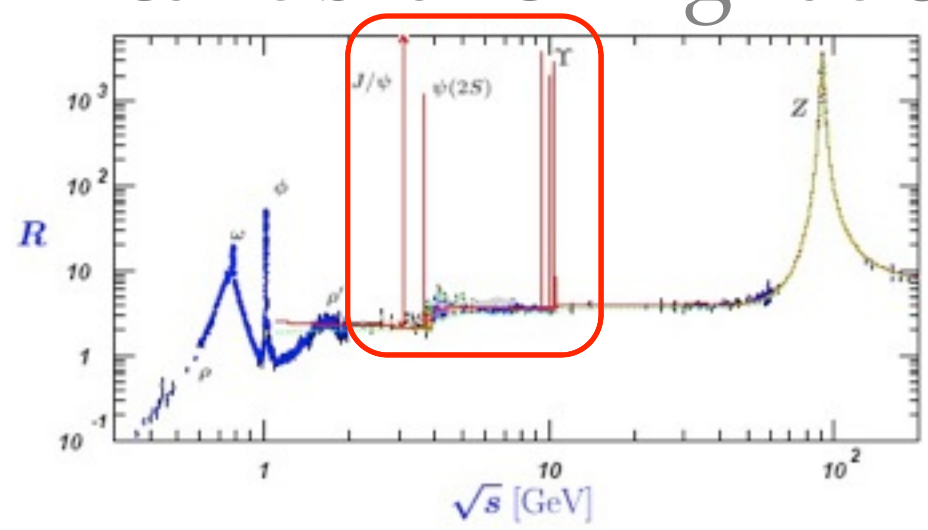


- Quarkonia represent one of the most important hard probes, together with jet-quenching, electromagnetic probes and heavy open flavour

Heavy quarkonia

- The masses of the *c* (~1.5 GeV), *b* (~4.5 GeV) and *t* (~175 GeV) are much larger than $\Lambda_{\rm QCD}$.
  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. The vector states have narrow widths and clean dileptonic decays with significant branching ratios.



Quarkonium suppression

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  - In-medium bound-state dynamics
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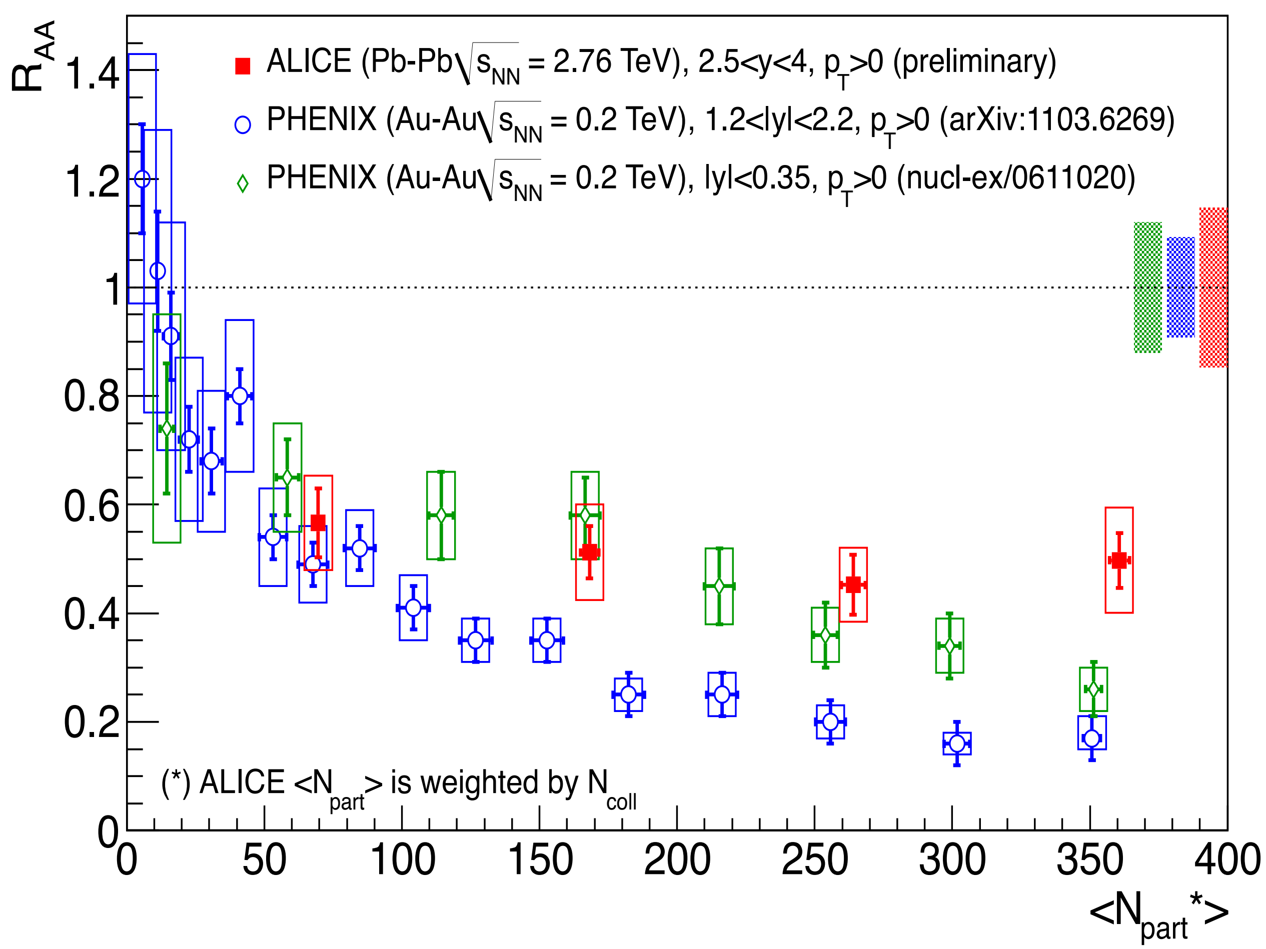
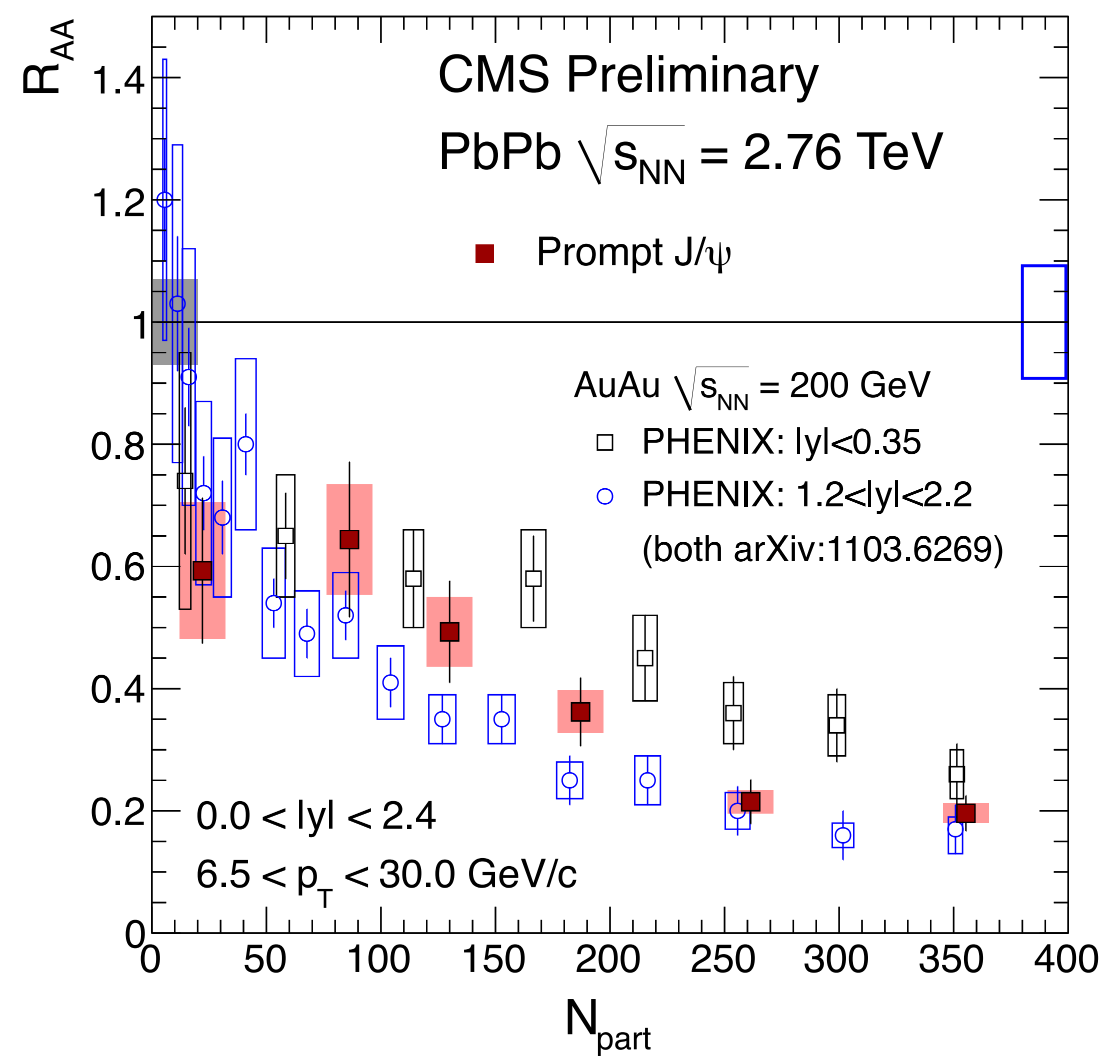
Charmonium suppression in experiments

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

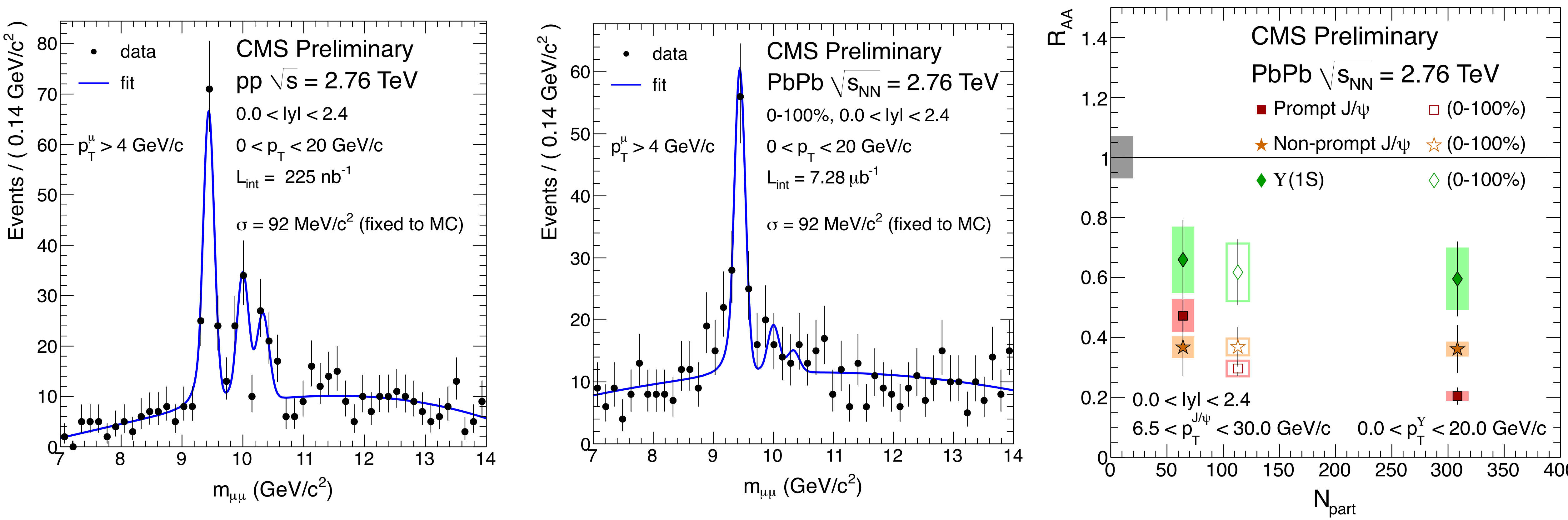




- Nuclear modification factor $R_{AA} \equiv \dfrac{\text{Yield}_{AA}}{\text{Yield}_{pp} \times N_{\text{bin}}}$

Bottomonium suppression in experiments

- First quality data on the Υ family from CMS



- Significant suppression of the Υ(2S) and Υ(3S)

CMS, **1105.4894** and CMS-PAS-HIN-10-006 (2011)

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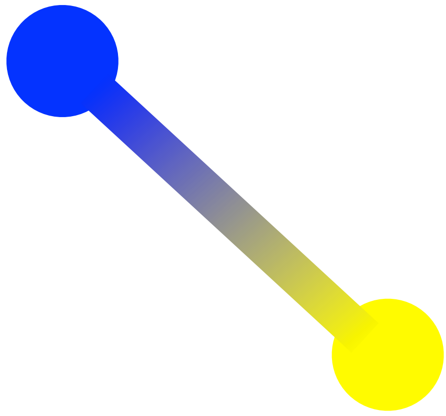

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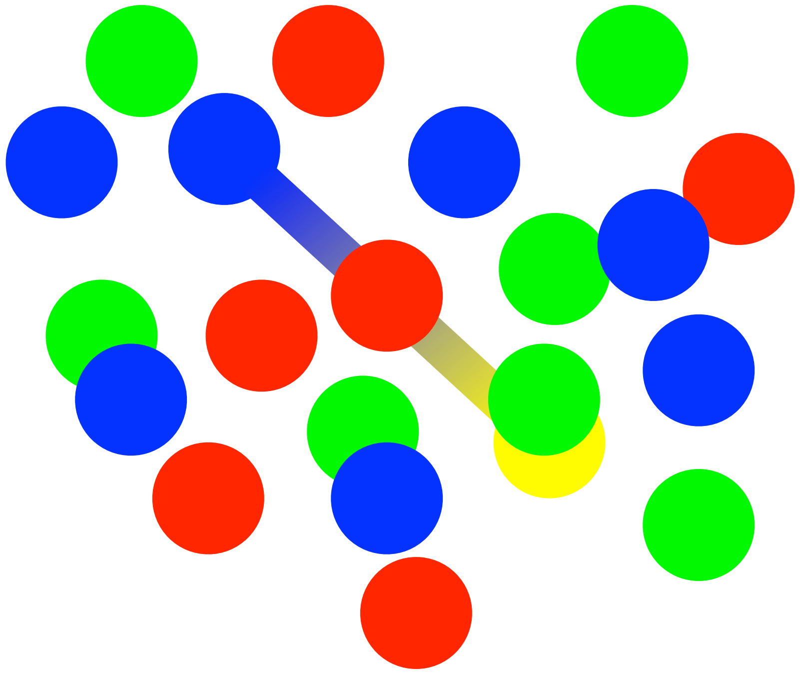

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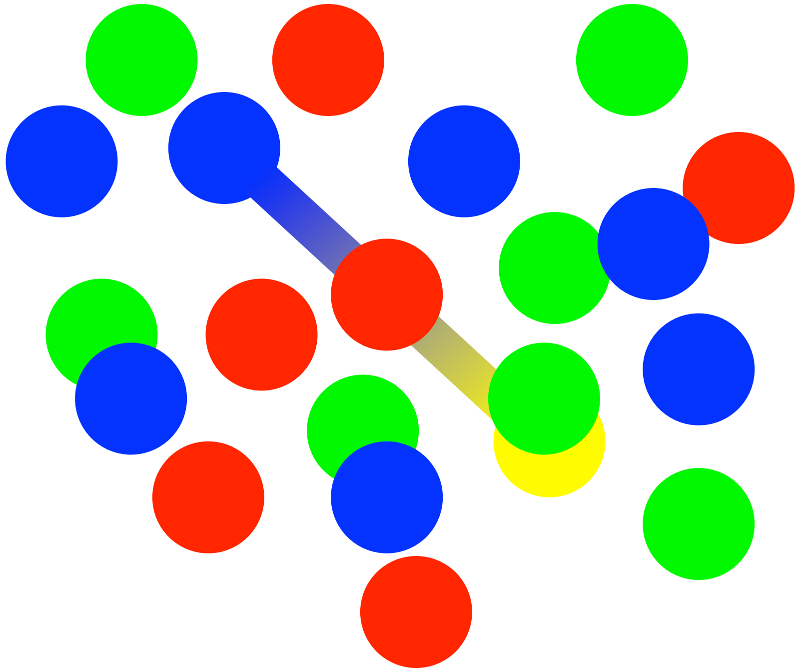

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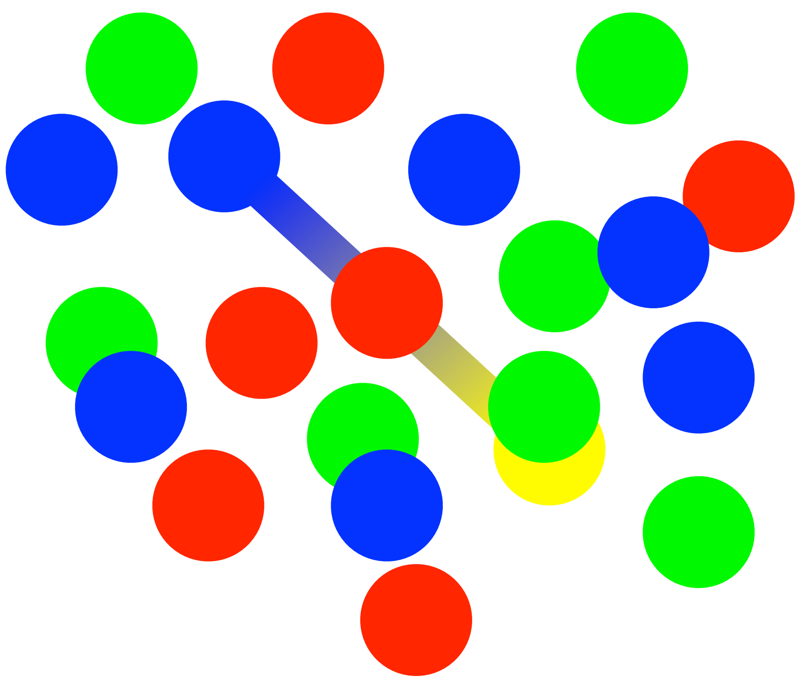

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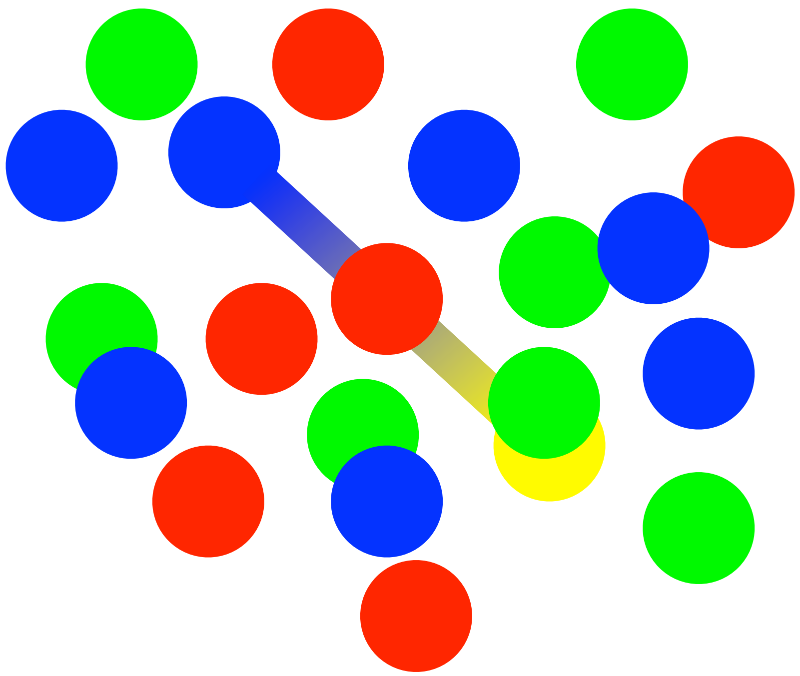

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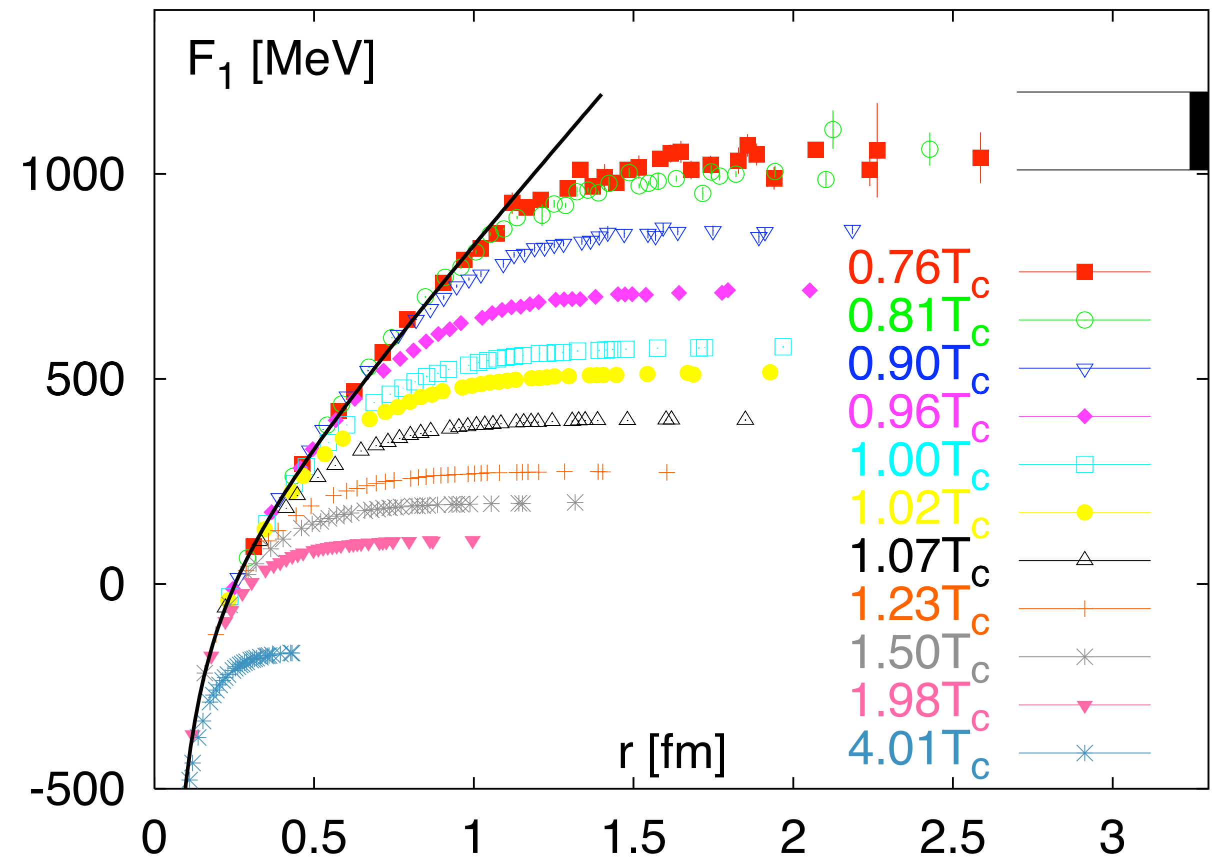
- Studied with potential models, lattice spectral functions, AdS/CFT and now with EFTs

Potential models

- Schrödinger equation with all medium effects encoded in *T*-dependent potential
- Potential extracted from lattice measurements of thermodynamical free energies (Polyakov-loop correlators)



Kaczmarek Zantow 2005

Digal, Petreczky, Satz 01
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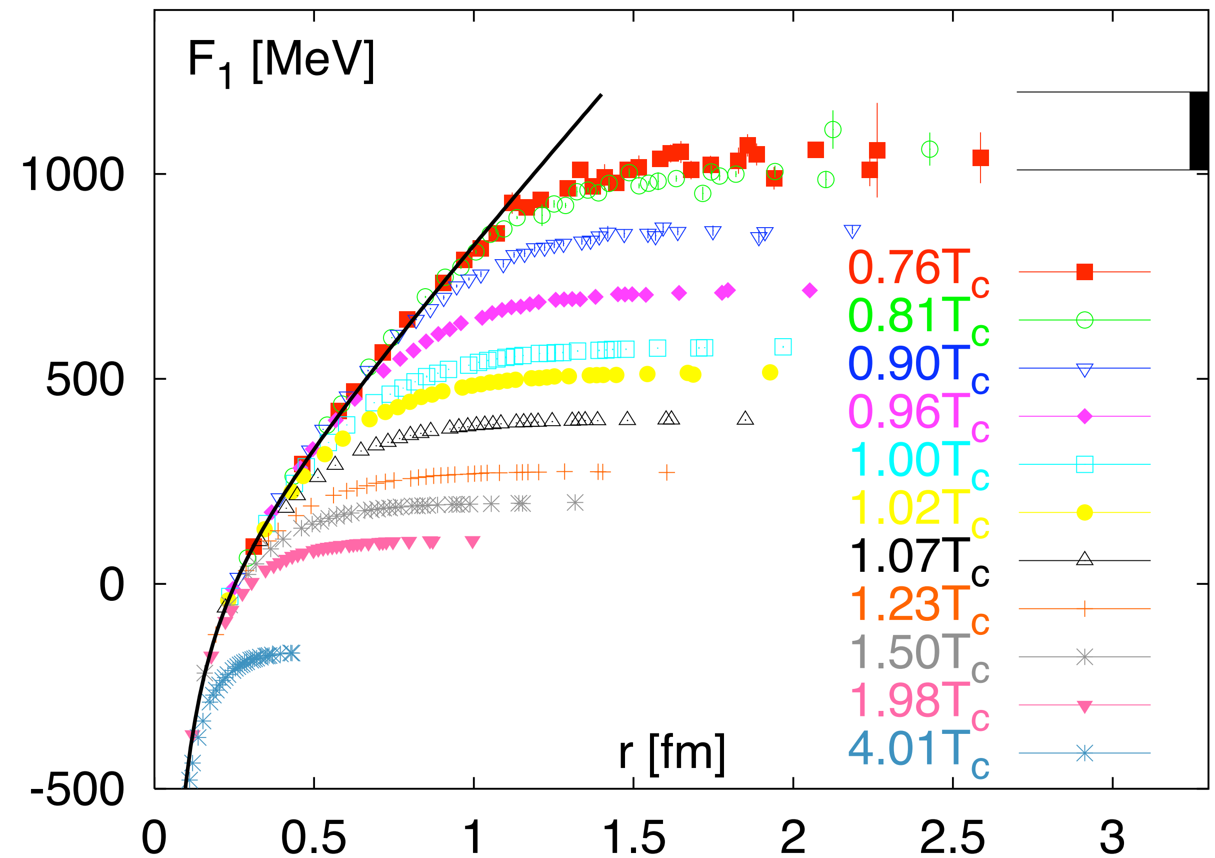

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- Schrödinger equation with all medium effects encoded in T-dependent potential
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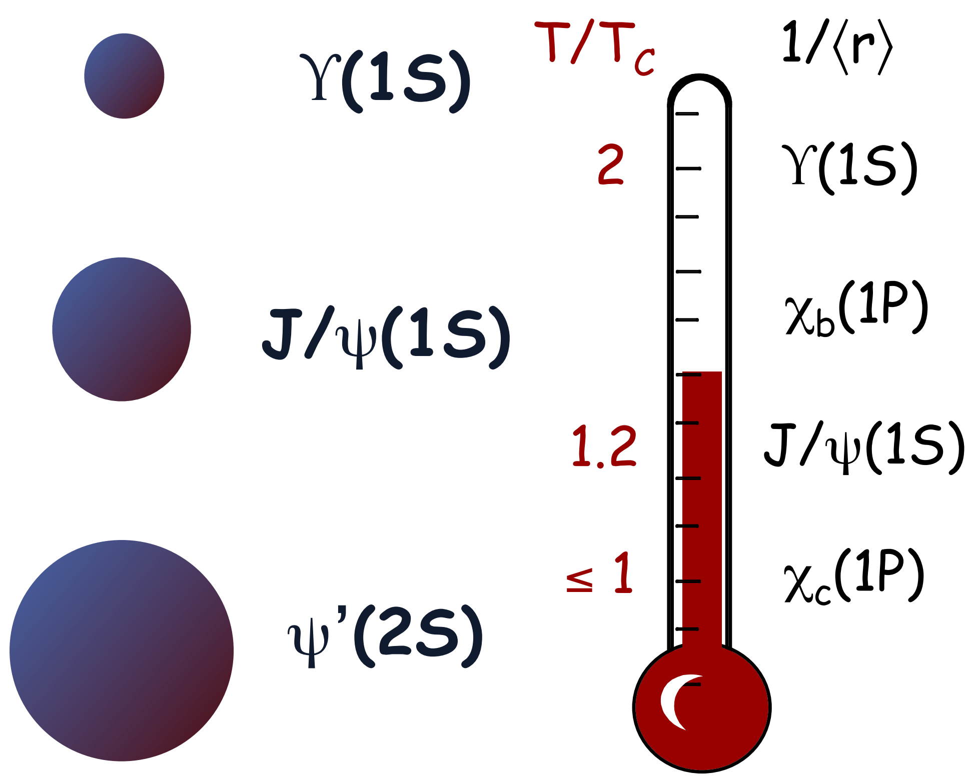
- No QCD derivation of these models and no clear relation between the free energies and the potential
- All models agree on a qualitative picture of sequential dissociation



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Wilson coefficient

Low-energy operator/large scale

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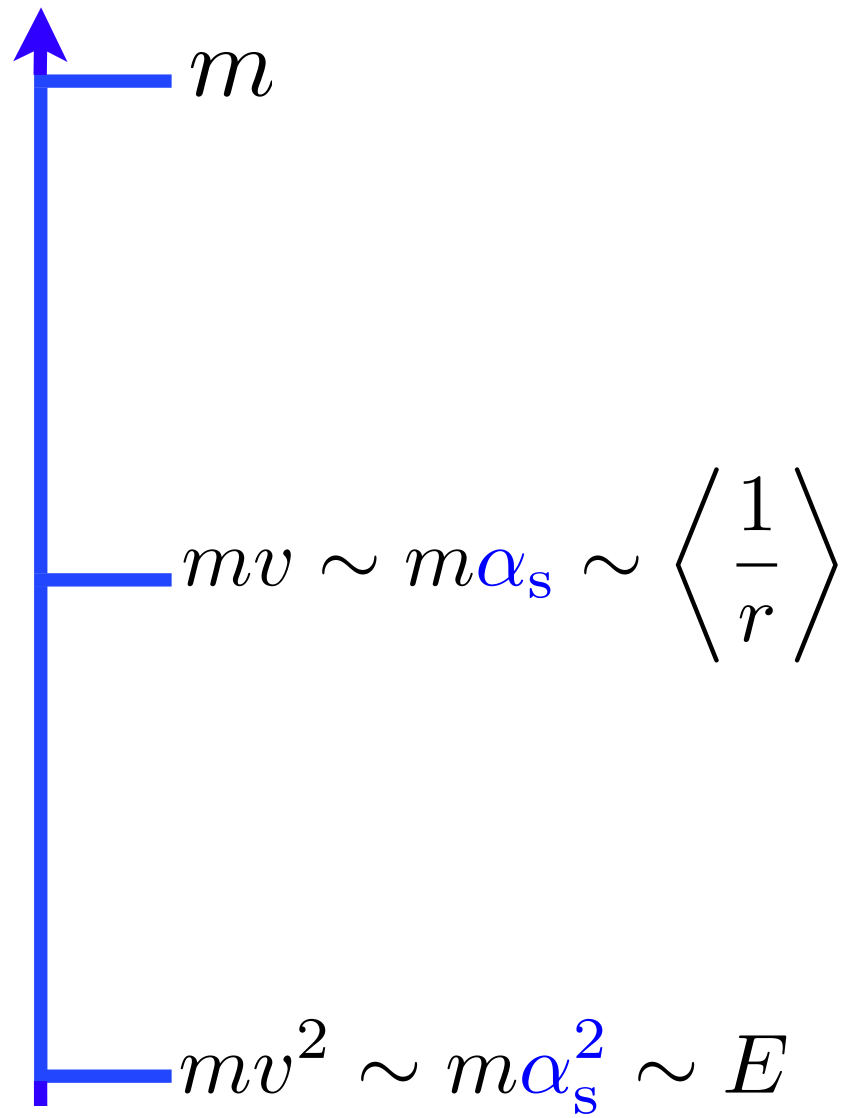
- The procedure can be iterated $\ldots \ll \mu_2 \ll \Lambda_2 \ll \mu_1 \ll \Lambda_1$

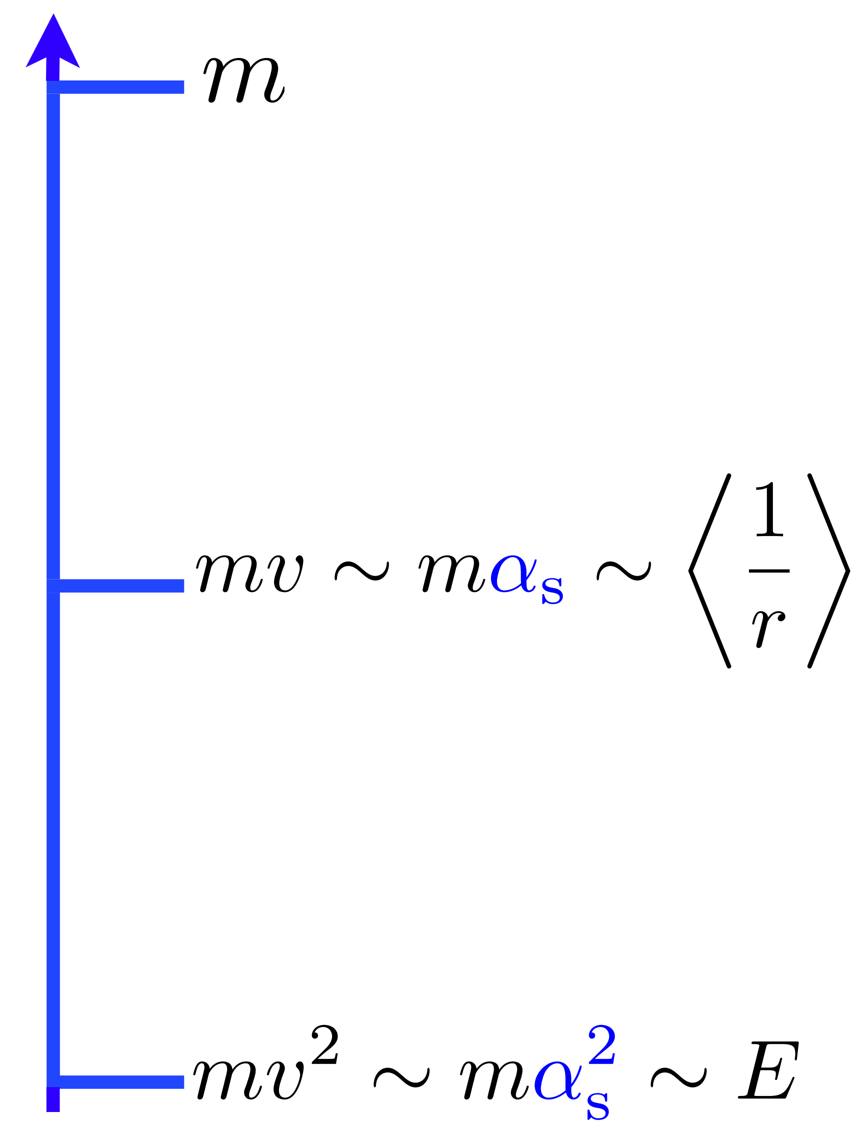
Non-Relativistic Scales

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



Non-Relativistic Scales

- Non-relativistic $Q\overline{Q}$ bound states are characterized by the hierarchy of the mass, momentum transfer and kinetic/binding energy scales
- One can then expand observables in terms of the ratio of the scales and construct a *hierarchy of EFTs* that are equivalent to QCD order-by-order in the expansion parameter



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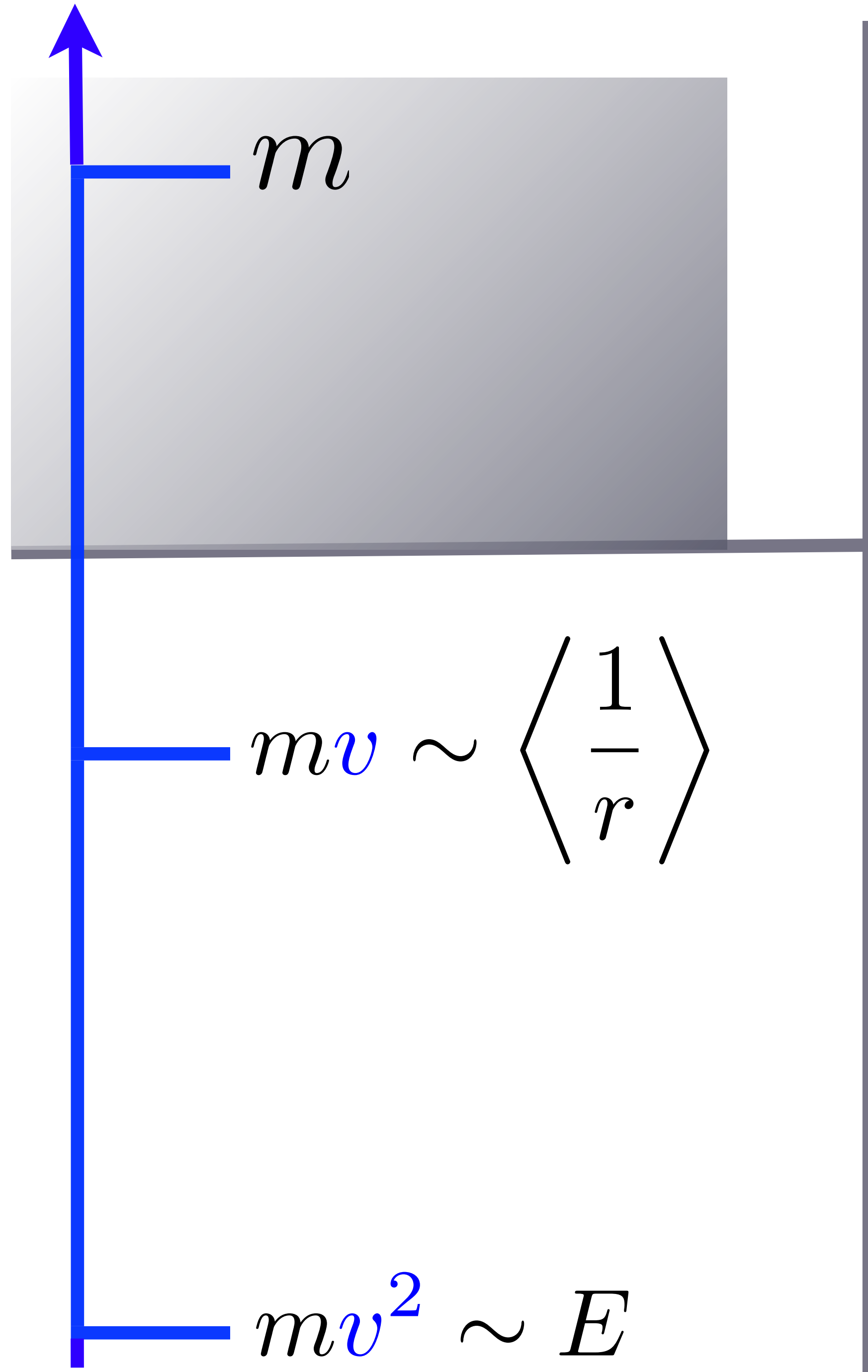
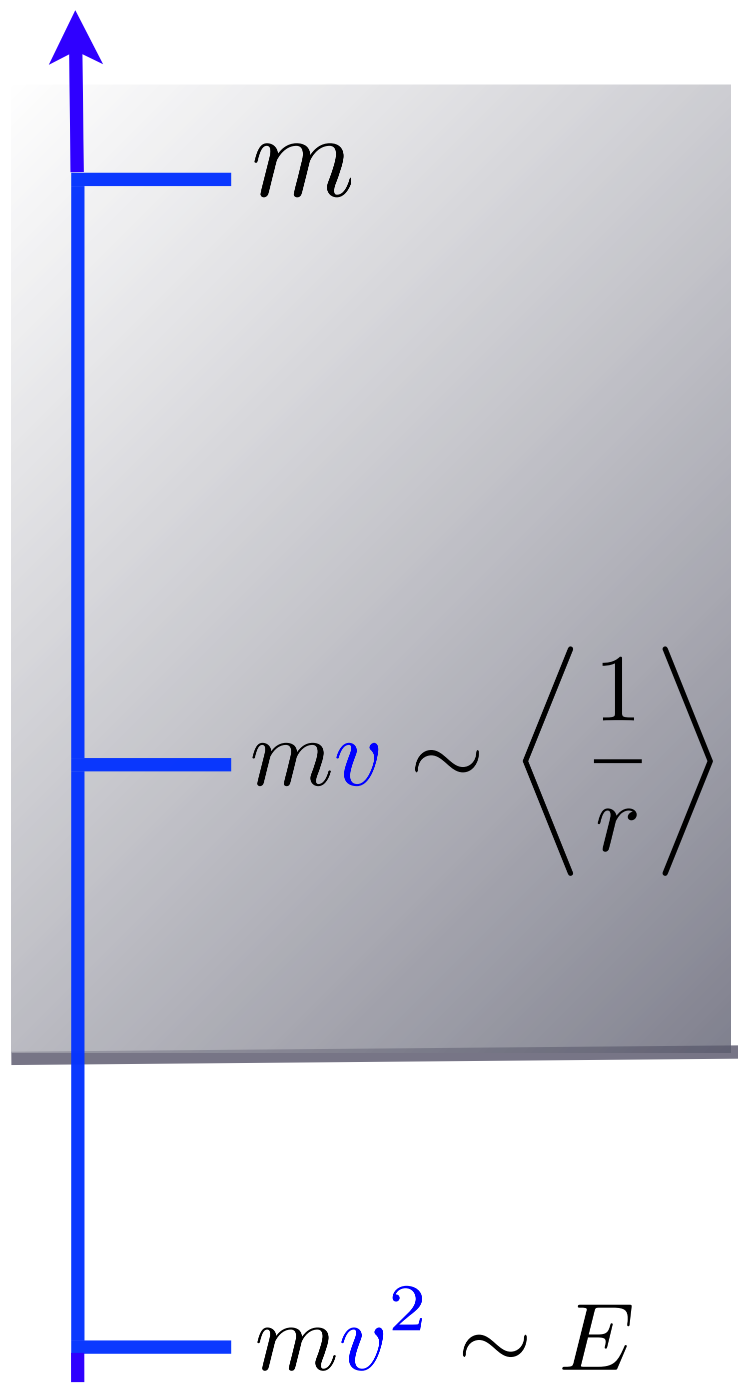


Integration of the mass scale: Non-Relativistic QCD (NRQCD)

- 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

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

Non-Relativistic Effective Field Theories



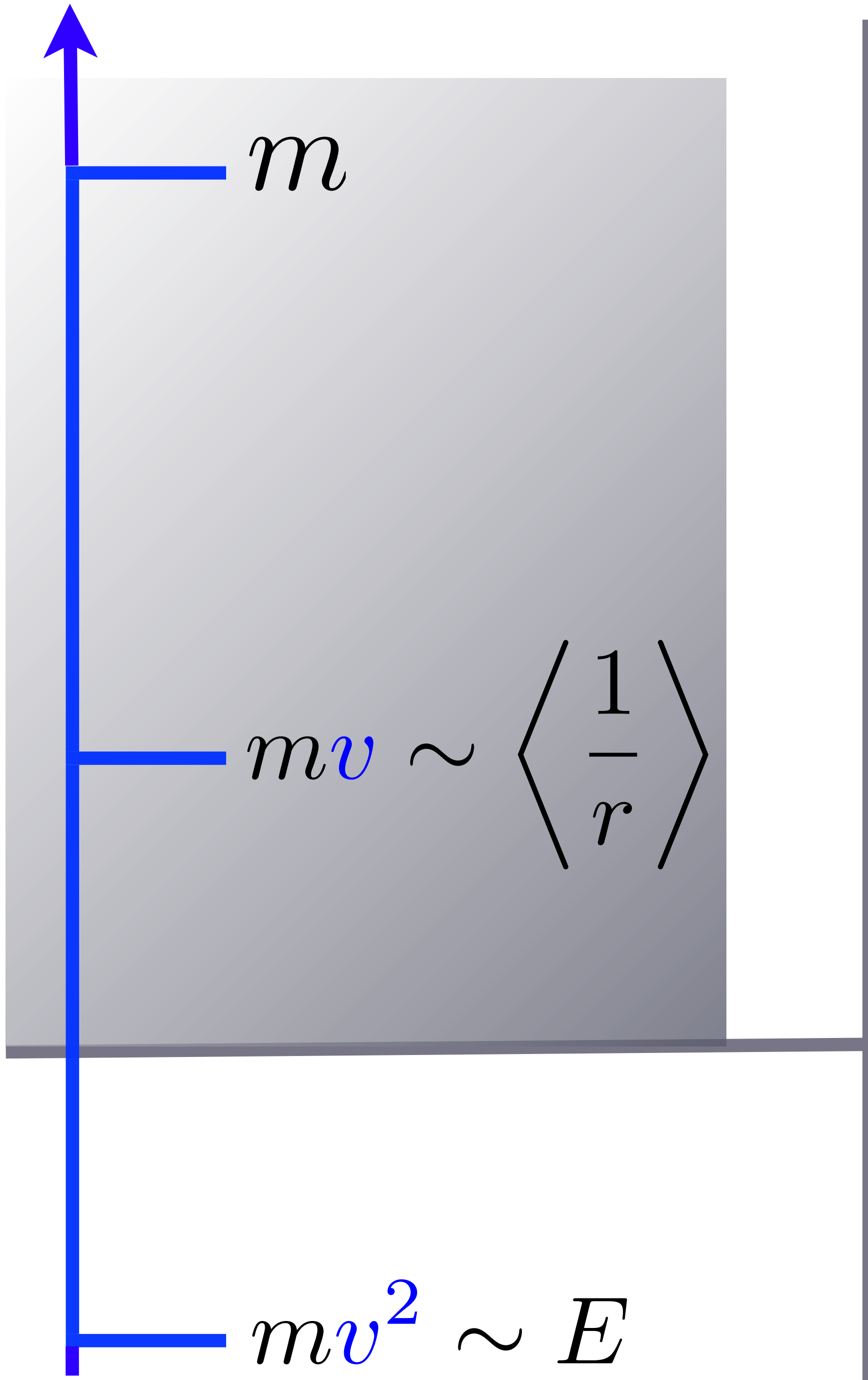
Integration of the scale *mv*: Potential NRQCD (pNRQCD)

- Integrating out the momentum transfer scale causes the appearance of non-local four-fermion operators, whose Wilson coefficients are the potentials

- Modern, rigorous definition and derivation from QCD of the potential

- Ideal for spectroscopy, decays and radiative transitions
  Pineda Soto **NPPS64** (1998)
  Brambilla Pineda Soto Vairo **NPB566** (2000)

Non-Relativistic Effective Field Theories



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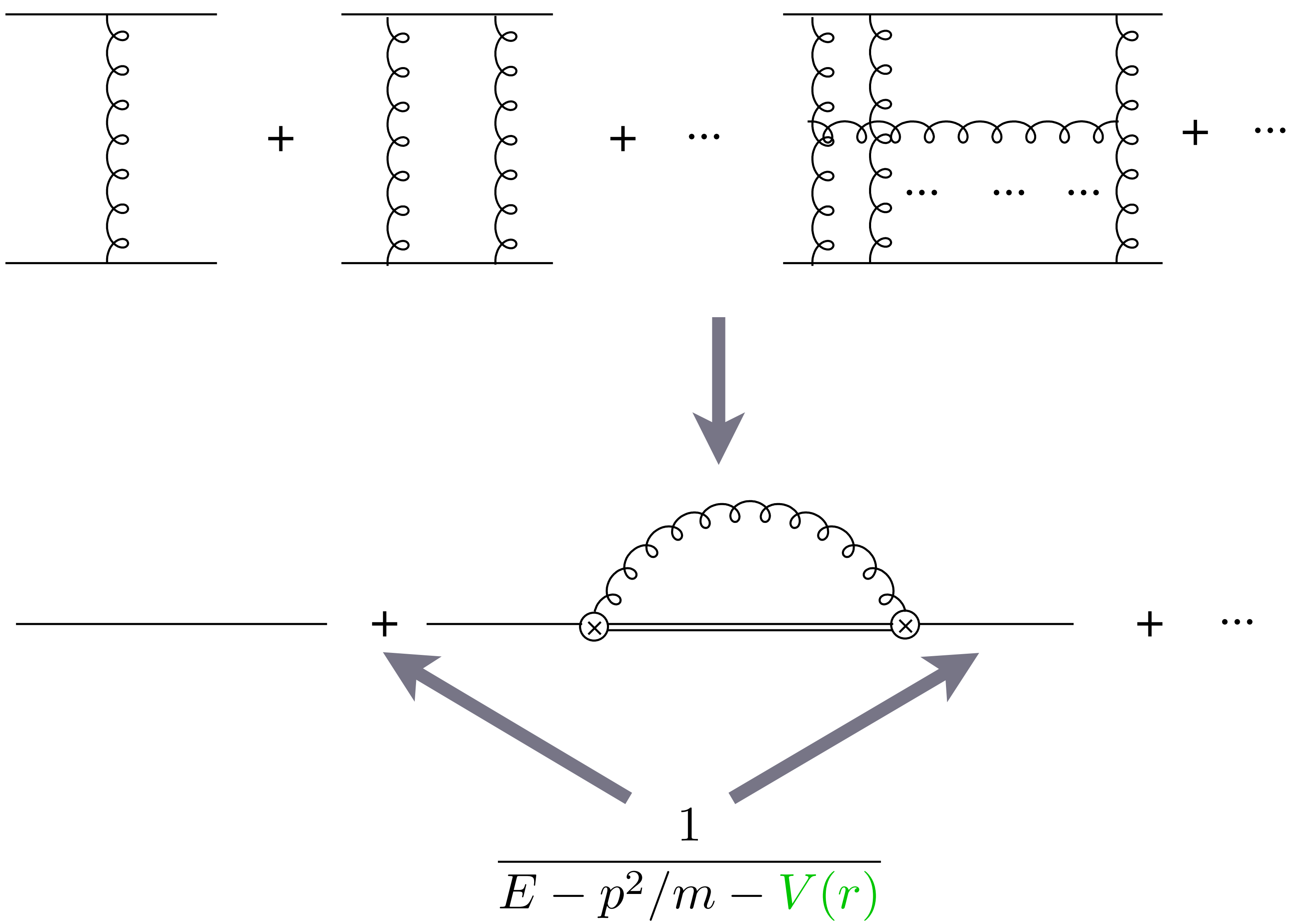

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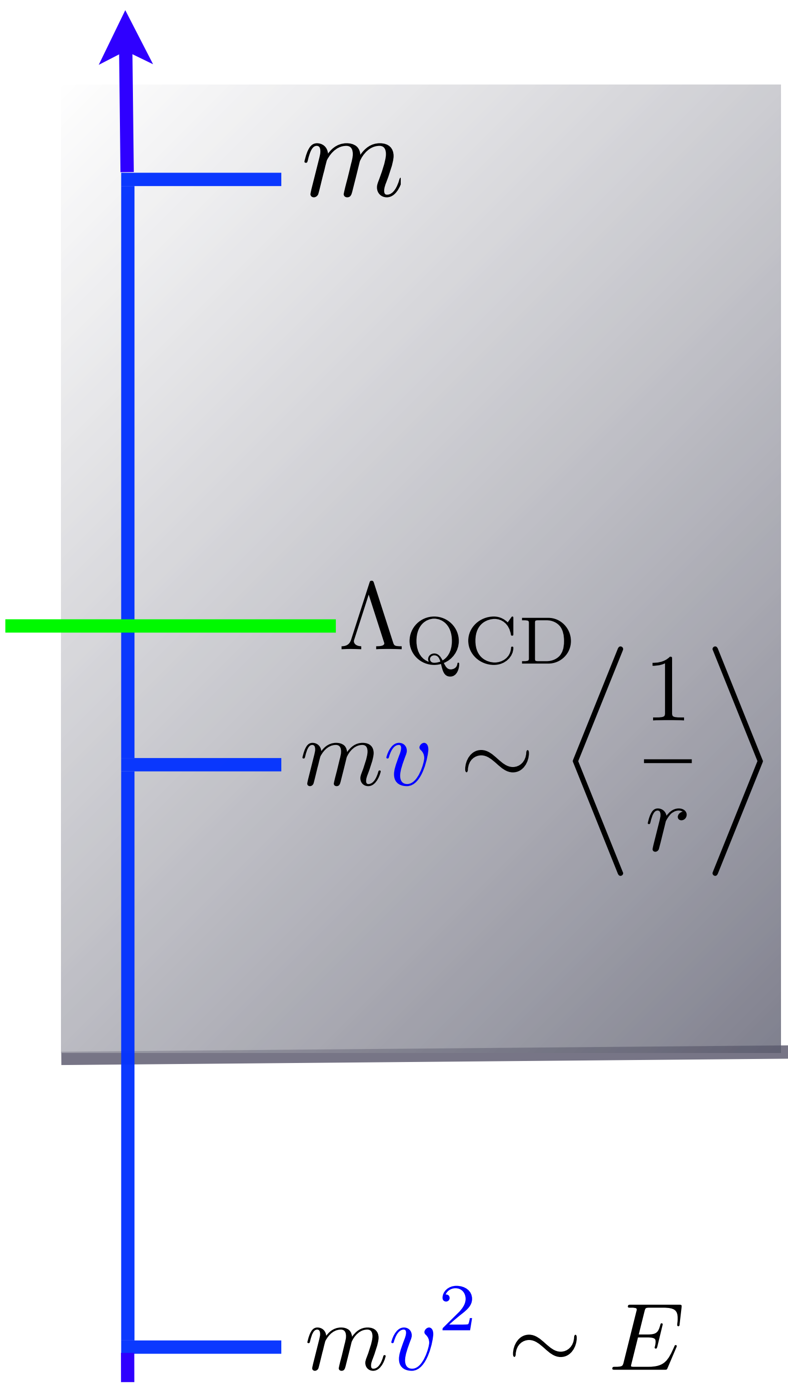

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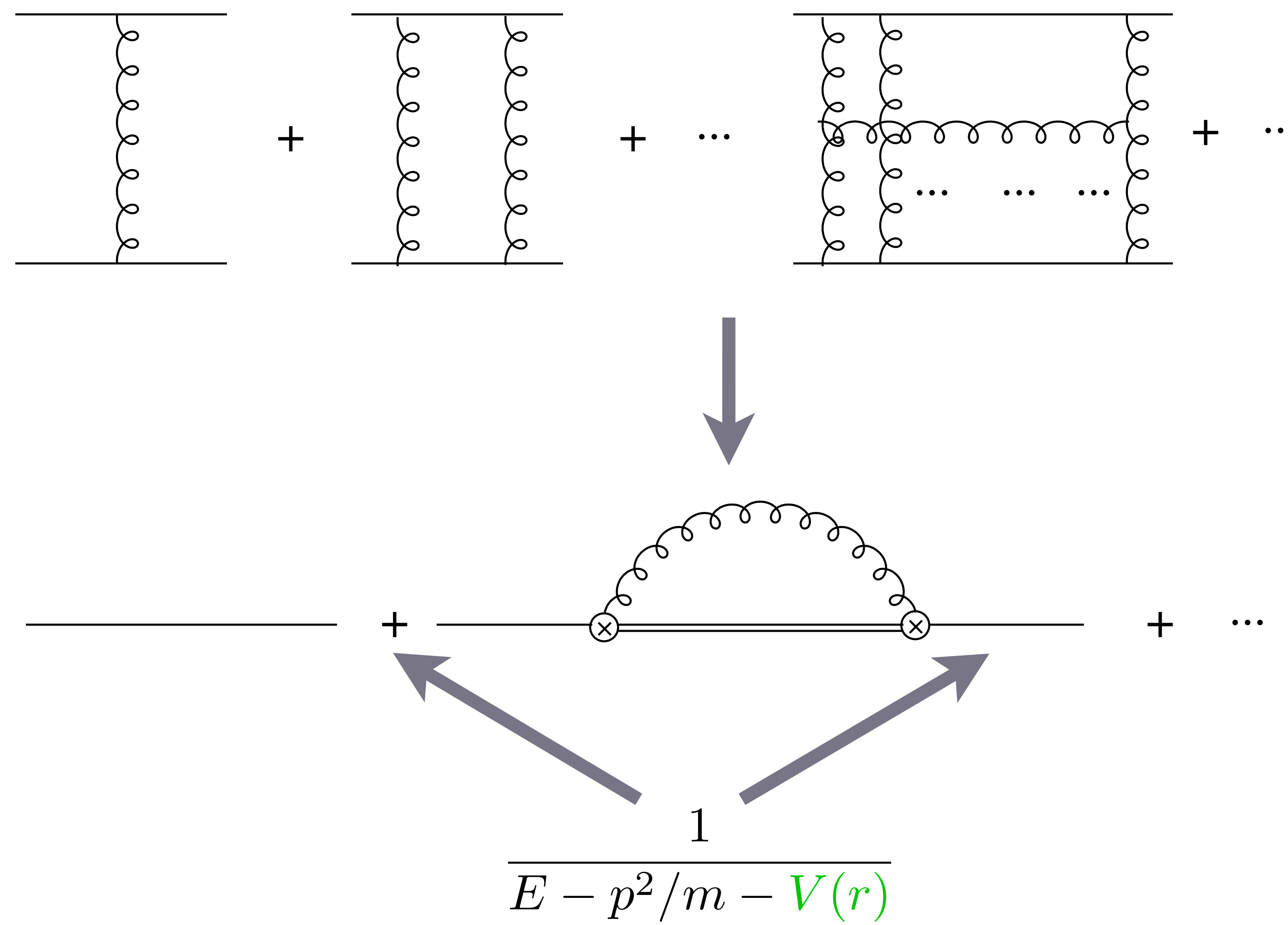

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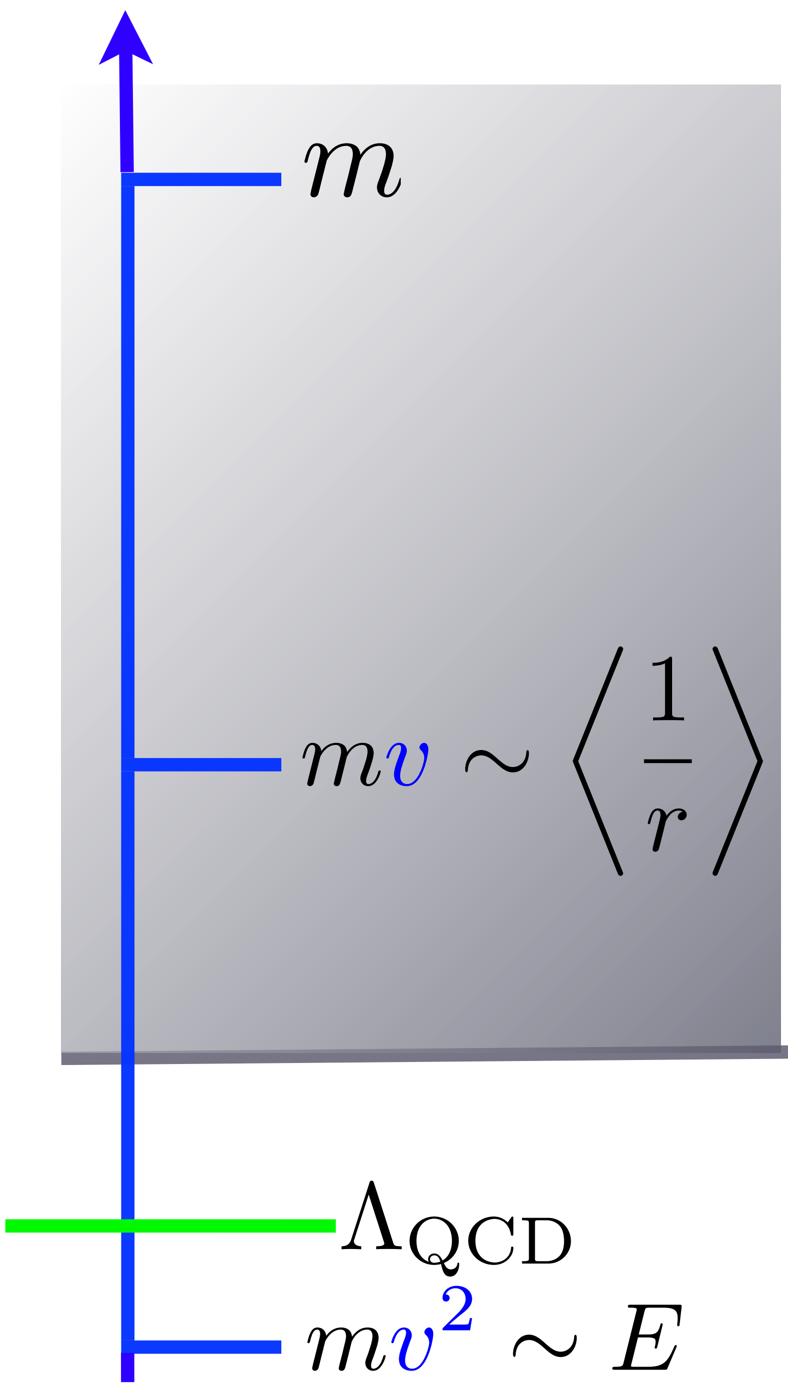

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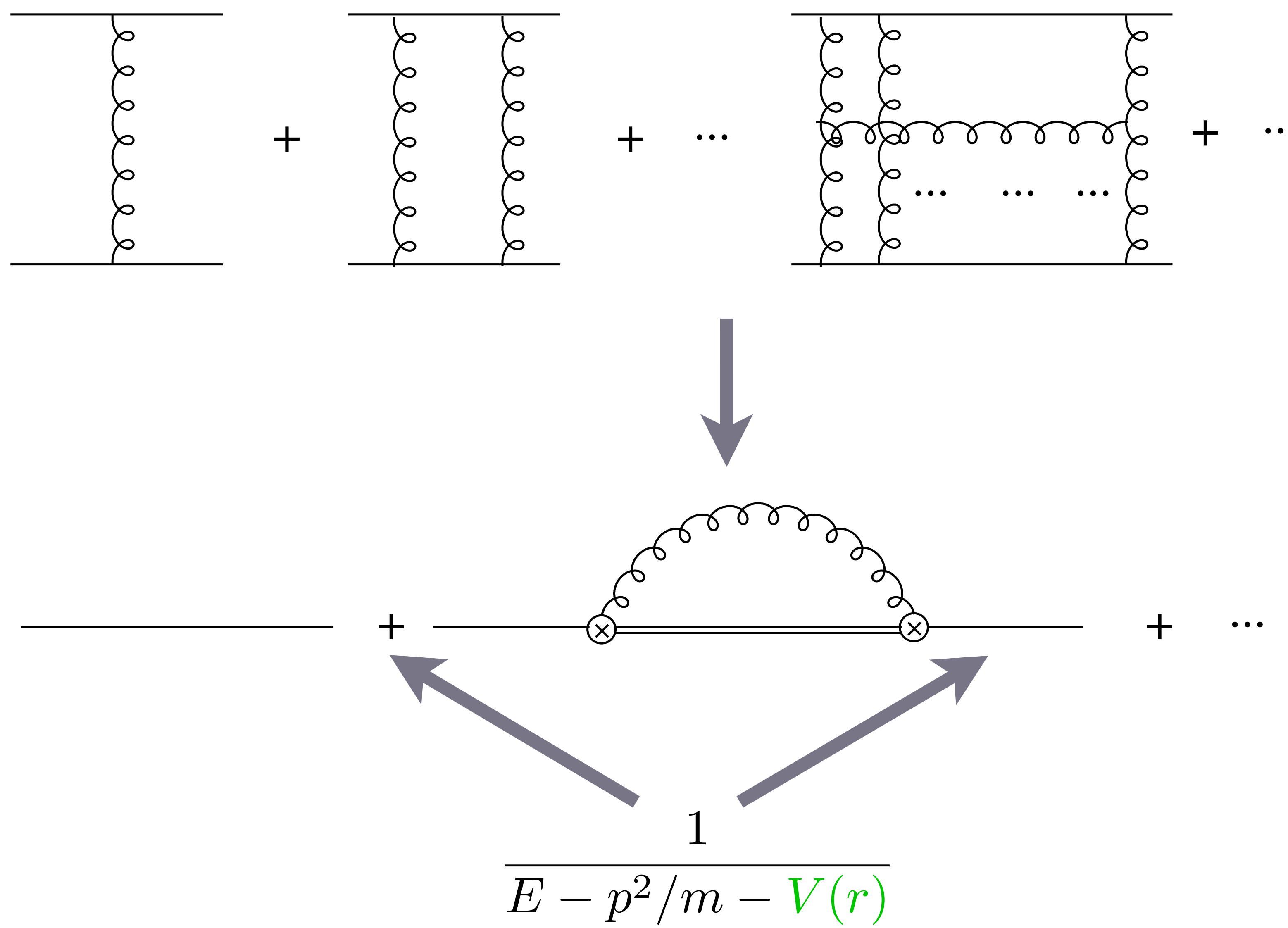

Goals of the thesis

- Main goal: extend the well-established $T=0$ NR EFT framework to finite temperatures to address systematically heavy quarkonia in the medium
- In real time:
  - 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
- In imaginary time:
  - Clarification of the relation between the thermodynamical free energies and the EFT potentials

The thermodynamical scales

- In both cases we have to take into account that 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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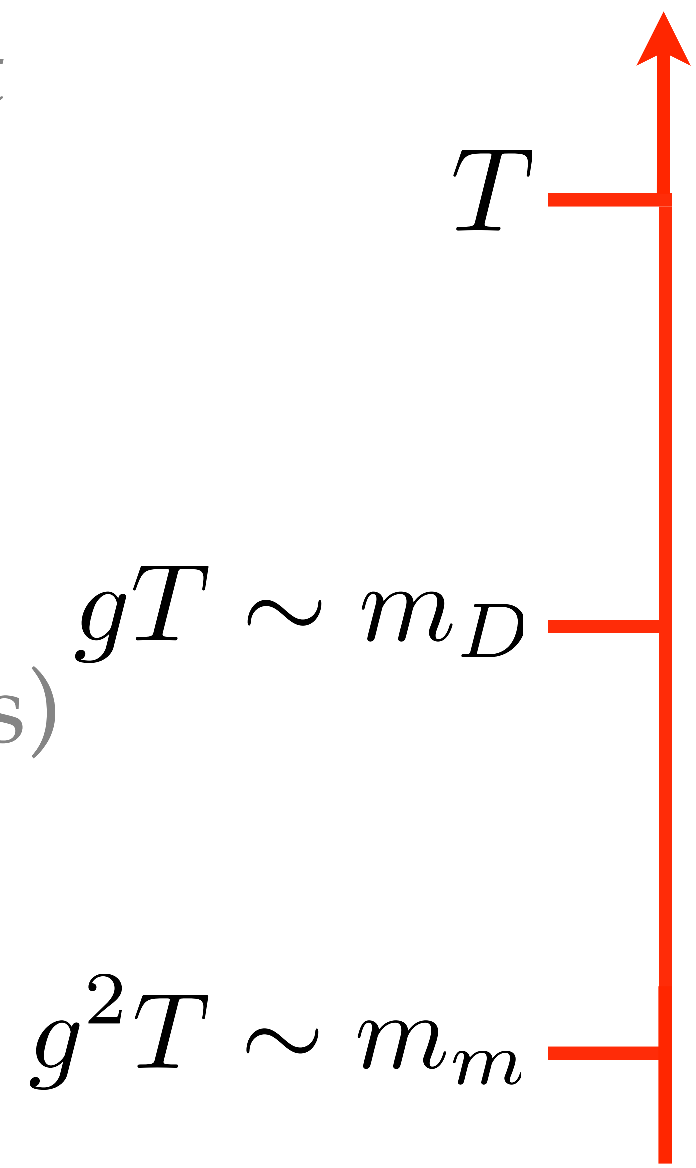

Finite-temperature NR EFT how-to

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

$$?$$

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

- Assume a global hierarchy between the bound-state and thermodynamical scales

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

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

When $r \sim \frac{1}{m_D} \Rightarrow {\rm Im}V \gg {\rm Re}V$ Landau Damping

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

Advantages of the realtime calculation

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

Advantages of the realtime calculation

- For $T>>1/r>>m_D$ we obtain new results:

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

When $T \sim m\alpha_{\rm s}^{2/3} \Rightarrow \mathrm{Im}V \sim \mathrm{Re}V$ 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. This region is particularly relevant for the ground states of bottomonium: $m\alpha_s \sim 1.5$ GeV, $T < 1$ GeV

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

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

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 to order $m\alpha_s^5$ in the power counting of the EFT

$$\Gamma_{n,l} = \frac{1}{3} C_F \alpha_s^3 T \left[N_c^2 + \frac{4}{n^2}(C_F + N_c) \right]$$

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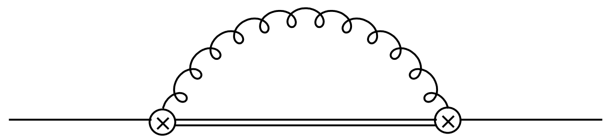
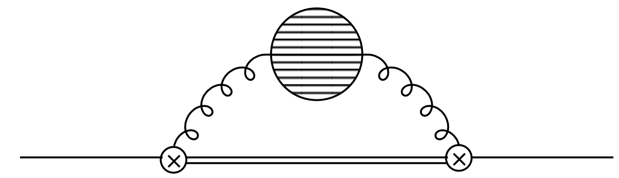


Singlet-to-octet



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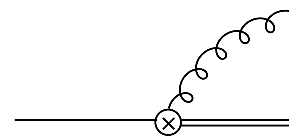

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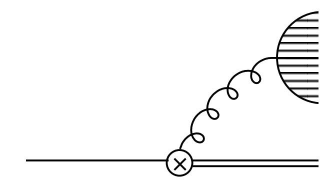

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- The Polyakov loop (PL) and the Polyakov-loop correlator (PLC) are related to the thermodynamical free energies of a static quark and of a static $Q\overline{Q}$ pair. Order parameter in pure gauge

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- Our re-analysis of the PLC within pNRQCD in imaginary time shows that the singlet free energy differs from the real-time singlet potential not only in the very important imaginary part, completely missing here, but also in the real part
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, work in progress
- Application of the methodology to other problems, such as heavy quark energy loss