Effective Field Theories in Heavy Quarkonia

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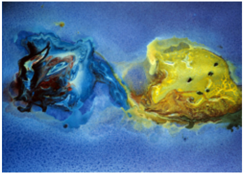
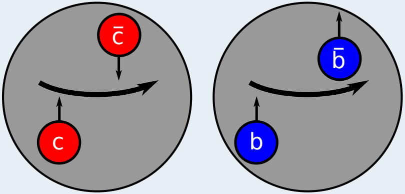


Physik-Department T30f

Outline

Definition

Heavy quarkonium is a bound state of a heavy quark with its antiparticle



It contains not only two quarks but also virtual quark and gluons.
Quark and anti-quark interact with each other by exchanging an arbitrary number of gluons.

History

1974: Discovery of J/ψ and ψ' mesons which are $c\bar{c}$-bound states.
1977: Discovery of $\Upsilon(1S)$, a $b\bar{b}$-bound state.

Challenges

The evolution of a $q\bar{q}$-pair to a $q\bar{q}$-bound state is a non-perturbative process.

Importance

The more we know about quarkonia, the better we can understand the strong force and confinement.

Quarkonium spectroscopy

states are labeled by $N^{2S+1}L_J$

- $N = n_r + 1 = n - L$
- $|L - S| \leq J \leq L + S$
- $n = 1, 2, 3, \ldots$
- $L = 0, 1, 2, \ldots < n$
- $S = 0, 1$

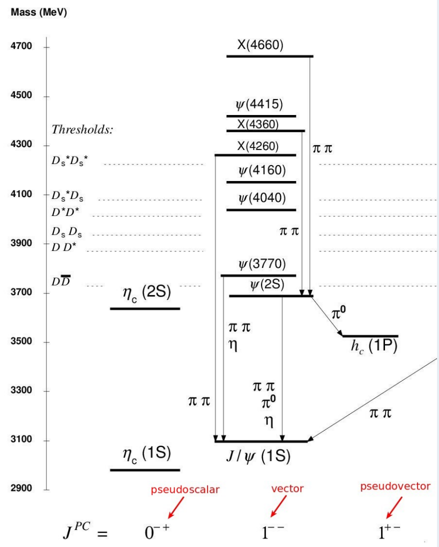
short form: NL and J^{PC}

- $P = (-1)^{L+1}$
- $C = (-1)^{L+S}$

Rich phenomenology

Spectra of heavy quarkonia contain many well separated states with different masses and quantum numbers

Part of the level scheme of $c\bar{c}$



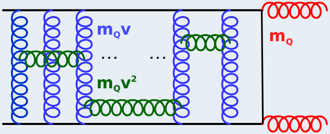
Relevant scales

$m_Q \gg m_Q v \gg m_Q v^2$, $m_Q \gg \Lambda_{\rm QCD}$
with

- $|\vec{p}_{\rm rel}| \sim m_Q v$
- $E_{\rm bind} = m_H - 2m_Q \sim m_Q v^2$
- $\Lambda_{\rm QCD} \approx 0.2\,{\rm MeV}$
- $m_c \approx 1.3\,{\rm GeV}$, $m_b \approx 4.2\,{\rm GeV}$
- $v_c \approx 0.55$, $v_b \approx 0.32$

Full QCD

Different scales are entangled, their contributions are difficult to separate



Effective Field Theory

Motivation: Let us deal only with scales we are interested in.
General Idea: To study production and annihilation we are interested in scales below m_Q.
Approach: Start with full QCD and integrate out the scale m_Q. Make sure that the resulting theory reproduces full QCD below that scale. This theory is called *Non-Relativistic QCD (NRQCD)*.
[Bodwin et al, 1995]
Advantage: In NRQCD one has to deal only with two dynamical scales which are $m_Q v$ and $m_Q v^2$. The effects of the m_Q scale on physics below $m_Q v$ are encoded in the short distance coefficients of the NRQCD operators.

Features of NRQCD

- Not a model, rigorous derivation from the full QCD.
- $\mathcal{L}_{\text{NRQCD}}$ is an expansion in v.
- Infinite number of operators with increasing mass dimension.
- Operators are compatible with QCD symmetries.
- Contributions to a process at the given accuracy estimated by velocity scaling rules.

NRQCD Lagrangian

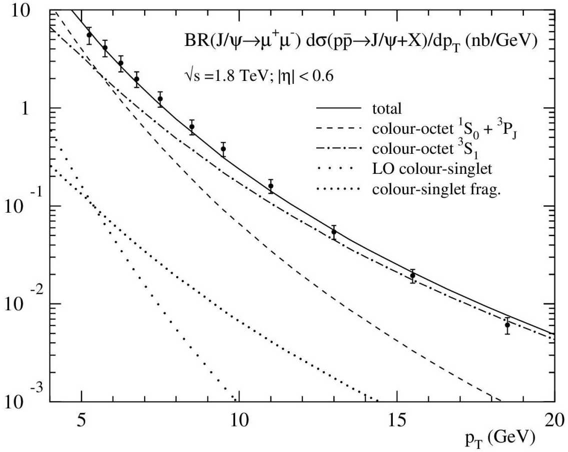
$$\mathcal{L}_{\text{NRQCD}} = \sum_n \frac{c_n(\alpha_s(m),\mu)}{m^n} O_n(\mu)$$

- $c_n(\alpha_s(m),\mu)$ - Wilson coeffs
- $O_n(\mu)$ - NRQCD operators

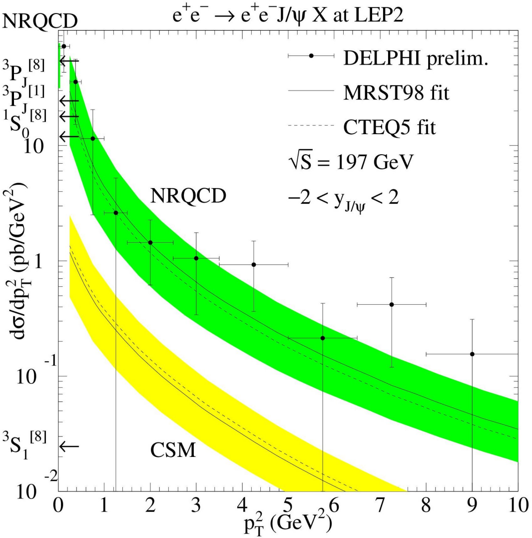
Predictions

- Predictive power of the theory relies on the knowledge of non-perturbative NRQCD matrix elements $\langle O_n(\mu)\rangle$.
- Matrix elements must be extracted from experiment but do not depend on the process.
- Since the matrix elements are universal, values extracted from one experiment can be used to make predictions for a completely different experiment.
- This description was recently successfully tested using values obtained from global fits on available data for J/ψ production [Butenschoen, Kniehl 2012].

The breakthrough of NRQCD happened in 1995, when Tevatron [CDF 1997] presented new measurements of quarkonia decays. While the previously used Color Singlet Model failed to explain the data, the predictions of NRQCD showed very good agreement with experiment.

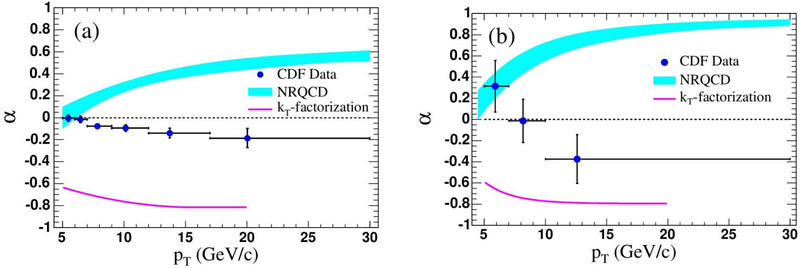


Matrix elements obtained from the Tevatron data were used to obtain predictions for other experiments, e.g. LEP2 [Klasen, Kniehl et al. 2001]



However, there are also some puzzles, one of which is J/ψ-polarization at the Tevatron [CDF 2007]

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha \cos^2\theta$$



There are hints, that higher order corrections may be very large. The addition of these corrections would then lead to a better agreement with data. Futhermore, there is some disagreement between Tevatron measurements from Run I and Run II that have not been resolved yet.

Going one step further : pNRQCD

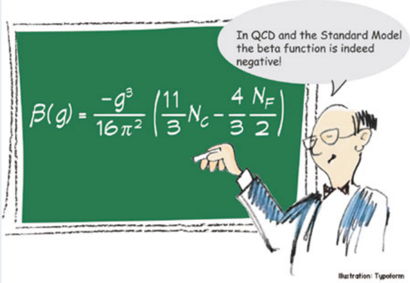
- If one is interested in studying the formation of quarkonium, NRQCD can be simplified by integrating out the scale $m_Q v$ from NRQCD. The resulting theory is called potential NRQCD (pNRQCD).
  [Brambilla et al. 1999]
- A big advantage of pNRQCD is that it allows to understand how QCD potential models emerge from the full QCD and how to compute corrections to such potentials.
- The Lagrangian of the pNRQCD is an expansion in $1/m$ and r, where r is the distance between the heavy quark and the heavy antiquark.

$$\mathcal{L}_{\mathrm{pNRQCD}} = \int d^3r \sum_n \sum_k \frac{c_n(\alpha_s(m), \mu)}{m^n} V_{n,k}(r, \mu', \mu) r^k \times O_k(\mu')$$

- pNRQCD is phenomenologically successful.

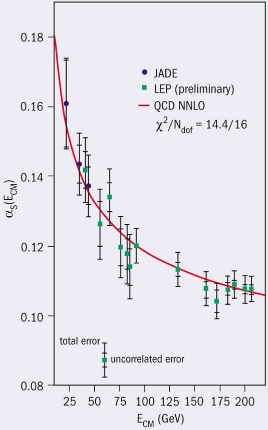
Asymptotic freedom

An important property of QCD is asymptotic freedom. At high energies (short distances) the coupling α_s becomes so small, that quarks behave like free particles.



Infrared slavery

At small energies (large distances) α_s becomes so large that quarks remain confined in colorless hadrons.



QCD Factorization theorem

Quarkonium production includes formation of a quarkonium out of a $q\bar{q}$-pair (hadronization) which is non-perturbative. Nevertheless, it was shown [Nayak, Qiu, Sterman 2005] that if the differential cross-section is expanded in m_H/p_T, perturbative and non-perturbative contributions factorize at leading power

$$d\sigma_{A+B\to H+X}(p_T) = \sum_i d\tilde{\sigma}_{A+B\to i+X}(p_T/z,\mu) \otimes D_{H/i}(z,m,\mu) + \mathcal{O}(m_H^2/p_T^2)\,.$$

- $d\sigma_{A+B\to H+X}(p_T)$ - x-section to produce an arbitrary final state that contains a quarkonium H out of scattering of A and B.
- $d\tilde{\sigma}_{A+B\to i+X}(p_T/z,\mu)$ - inclusive production x-section to produce a state with parton i. Must be convoluted with PDFs if A or B is a hadron.
- $D_{H/i}(z,m,\mu)$ - fragmentation function (non-perturbative). Describes probability for the off-shell parton i to evolve into the quarkonium H.

Limitation

Expansion in m_H/p_T makes sense only for sufficiently high transverse momenta.

Fragmentation functions in NRQCD

Since fragmentation functions are non-perturbative, they must be extracted from experimental measurements. In the framework of NRQCD it is believed that fragmentation functions can be related to the NRQCD production operators through [Nayak, Qiu, Sterman 2005]

$$D_{H/i}(z, m, \mu) = \sum_n d_{i \to q\bar{q}[n]}(z, \mu, m) \langle 0|\mathcal{O}_n^H|0\rangle \,,$$

- $d_{i \to q\bar{q}[n]}(z, \mu, m)$ - short distance coefficient function, describes the evolution of an off-shell parton i into a $q\bar{q}$-pair with the quantum numbers $[n]$
- $\langle 0|\mathcal{O}_n^H|0\rangle$ - matrix elements of NRQCD operators $\mathcal{O}_n^H$, that describe production of the quarkonium with the same quantum numbers

Benefits of the NRQCD approach

- Fragmentation functions can be expressed through products of perturbative coefficient functions and non-perturbative NRQCD matrix elements (c-numbers).
- These matrix elements depend only on the quantum numbers of the quarkonium but not on the process in which it is produced and can be extracted from experiment.
- Hence, one needs only a finite number of experimental parameters to treat different modes of quarkonium production at a given accuracy.

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Does this formula really hold???

NRQCD Factorization

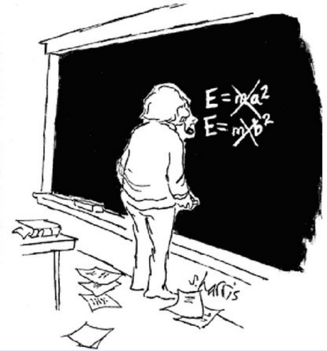
The validity of the NRQCD approach to fragmentation functions depends on the validity of the NRQCD factorization theorem

$$d\sigma_{A+B\to H+X}(p_T) = \sum_n d\hat{\sigma}_{A+B\to c\bar{c}[n]+X}(p_T)\,\langle \mathcal{O}_n^H \rangle$$

which should hold to all orders in α_s.

- A proof of this formula to all orders in perturbation theory is still lacking, the validity has been demonstrated explicitly in the context of quarkonium production only up to next-to-next-to leading order [Nayak, Qiu, Sterman 2005].
- Most of the theoretical predictions derived using NRQCD factorization are in good agreement with experiments.

Our research interests



- Understand processes that can potentially violate NRQCD factorization in quarkonium production.
- Study production in pNRQCD.
- Obtain better field theoretical definition of NRQCD production matrix elements, including $|H + X\rangle$.

Conclusions

- Study of heavy quarkonia is very important for our understanding of the strong force.
- Effective field theories are the state of the art to treat production, decay and properties of $q\bar{q}$-bound states.
- NRQCD and pNRQCD are two effective field theories that can be rigorously derived from QCD.
- They are phenomenologically successful, but some puzzles remain.
- NRQCD factorization theorem suggests a very appealing relation between non-perturbative QCD fragmentation functions and NRQCD matrix elements.
- No general proof for the NRQCD factorization is available yet. A full proof will have to consider all the contributions that might jeopardize the factorization.

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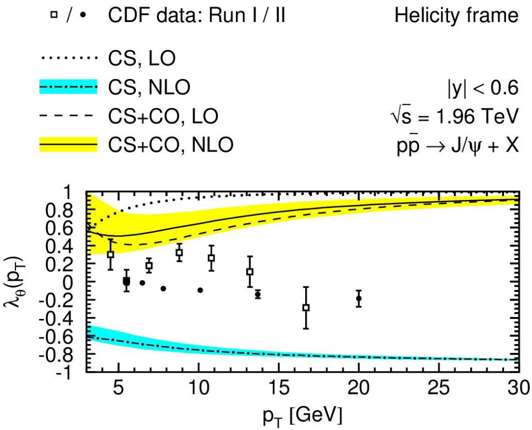

[Butenschoen, Kniehl 2012]