Extraction of SM parameters

Nora Brambilla (U. Milano)
Extraction of SM parameters from Onia

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Onia and QCD

Onia Scales and QCD Effective Field Theories

Extraction of $\alpha_s$ and $m_Q$

Other examples

Open challenges in theory and experiments
QCD and the Onia

\[ \mathcal{L}_{QCD} = -\frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu])^2 + \bar{\psi}_f (i\not\!\!\!\!\!\!\partial - gA - m_f) \psi_f \]
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Parameters:
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Parameters:

\[ \alpha_s = \frac{g^2}{4\pi} \]
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\[ \alpha_s = -\frac{1}{\beta_0 \log \frac{Q^2}{\Lambda_{\text{QCD}}^2}} \]
QCD and the Onia

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Parameters:

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in some scheme and at some scale
QCD and the Onia

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Cross section

\[ m_Q \gg \Lambda_{\text{QCD}} \]
QCD and the Onia

\[ \mathcal{L}_{\text{QCD}} = -\frac{1}{4} \left( \partial_\mu A_\nu - \partial_\nu A_\mu - ig [A_\mu, A_\nu] \right)^2 + \bar{\psi}_f (i\partial_\mu - gA_\mu - m_f) \psi_f \]

\[ m_Q \gg \Lambda_{\text{QCD}} \]

\[ \alpha_s(m_Q) \ll 1 \]
QQ: a multiscale System

The mass scale is perturbative:
\[ m_b \approx 5 \text{ GeV}, \quad m_c \approx 1.5 \text{ GeV} \]

The system is non-relativistic:
\[ \Delta_n E \sim m v^2, \quad \Delta_{fs} E \sim m v^4 \]
\[ v_b^2 \approx 0.1, \quad v_c^2 \approx 0.3 \]

Non-relativistic bound states are characterized by at least three energy scales:
\[ m \gg m v \gg m v^2, \quad v \ll 1 \]

\[ 2S + 1 L J \]
Non-relativistic bound states

Even if $\alpha_s \ll 1$
on bound state the perturbative expansion breaks down when $\alpha_s \sim v$:

\[ \frac{1}{E - \left( \frac{p^2}{m} + V \right)} \approx \frac{1}{E - \left( \frac{p^2}{m} + V \right)} \]
Non-relativistic bound states

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\[
\begin{align*}
\frac{1}{E - \left(\frac{p^2}{m} + V\right)} & \approx \\
\end{align*}
\]
Non-relativistic bound states

Even if $\alpha_s \ll 1$
on bound state the perturbative expansion breaks down when $\alpha_s \sim v$: $p \sim m\alpha_s$

\[ p \approx \frac{1}{E - \left( \frac{p^2}{2m} + V \right)} \]
Non-relativistic bound states

Even if $\alpha_s \ll 1$, on bound state the perturbative expansion breaks down when $\alpha_s \sim \nu$:

$\frac{g^2}{p^2} \left( 1 + \frac{m\alpha_s}{p} \right)$

$p \sim m\alpha_s$
Non-relativistic bound states

- Even if $\alpha_s \ll 1$
  on bound state the perturbative expansion breaks down when $\alpha_s \sim v$: $p \sim m\alpha_s$

\[
g^2 \frac{1}{p^2} \left( 1 + \frac{m\alpha_s}{p} \right) \approx \frac{1}{E - \left( \frac{p^2}{m} + V \right)}
\]

- From $(\frac{p^2}{m} + V)\phi = E\phi \rightarrow p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$. 
Non-relativistic bound states

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\[
p \sim m\alpha_s
\]

\[
\frac{g^2}{p^2} \left(1 + \frac{m\alpha_s}{p}\right)
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Non-relativistic bound states

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\[ E \sim mv^2 \]

Difficult also for the lattice!
Disentangling scales with EFTs

QCD

perturbative matching

perturbative matching

μ

NRQCD

nonperturbative matching
(1ong-range quarkonium)

perturbative matching
(short-range quarkonium)

μ'

pNRQCD

Hard

Soft
(relative momentum)

Ultrasoft
(binding energy)
Disentangling scales with EFTs

$$\mathcal{L}_{\text{EFT}} = \sum_n c_n \left( \frac{E_\Lambda}{\mu} \right) \frac{O_n(\mu)}{E_\Lambda}$$
Disentangling scales with EFTs

\[ \mathcal{L}_{\text{EFT}} = \sum_{n} c_n \frac{O_n(\mu)}{E_\Lambda} \]

\[ \langle O_n \rangle \sim E^n_\Lambda \]
Disentangling scales with EFTs

\[ \frac{E_\lambda}{E_\Lambda} = \frac{mv}{m} \]

\[ \mathcal{L}_{\text{EFT}} = \sum_n c_n \frac{O_n(\mu)}{E_\Lambda} \]

\[ \langle O_n \rangle \sim E_\lambda^n \]
Disentangling scales with EFTs

\[ E_\lambda \] = \frac{\mu}{m}

\[ \frac{E_\lambda}{E_\Lambda} = \frac{mv}{m} \]

\[ \frac{E_\lambda}{E_\Lambda} = \frac{mv^2}{mv} \]

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Disentangling scales with EFTs

\[ \mathcal{L}_{\text{EFT}} = \sum_n c_n \left( \frac{E_\Lambda}{\mu} \right) \frac{O_n(\mu)}{E_\Lambda} \]

Hard

Soft
(relative momentum)

Ultrasoft
(binding energy)
EFTs for Quarkonium

QCD
perturbative matching

NRQCD
nonperturbative matching (long-range quarkonium)

pNRQCD
perturbative matching (short-range quarkonium)

A potential picture arises at the level of pNRQCD:
- the potential is perturbative if $mv \gg \Lambda_{QCD}$
- the potential is non-perturbative if $mv \sim \Lambda_{QCD}$
NRQCD is the EFT that follows from QCD when $\Lambda = m$

- The matching is perturbative.
- The Lagrangian is organized as an expansion in $1/m$ and $\alpha_s(m)$:

$$\mathcal{L}_{\text{NRQCD}} = \sum_n c(\alpha_s(m/\mu)) \times O_n(\mu, \lambda)/m^n$$

Suitable to describe decay and production of quarkonium.

Caswell Lepage 86, Bodwin Braaten Lepage 95
Weakly coupled pNRQCD

pNRQCD is the EFT for heavy quarkonium that follows from NRQCD when $\Lambda = \frac{1}{r} \sim m v$

NRQCD

pNRQCD

- The Lagrangian is organized as an expansion in $1/m$, $r$, and $\alpha_s(m)$:

$$\mathcal{L}_{pNRQCD} = \sum_n c(\alpha_s(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda) r^n$$
In this framework we can obtain
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- **Precision determinations of QCD parameters**
  (of interest for SM and BSM physics)
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- **Precision determinations of QCD parameters** (of interest for SM and BSM physics)

- **Information on QCD vacuum and low energy properties** (of interest for theories beyond QCD)

- **Information on the transition region from high energy to low energy** (of interest for the behaviour of perturbative series)
Low energy (nonperturbative) effects always exist but their form depend on the size of the system.

The EFT factorizes the low energy nonperturbative part. Depending on the physical system:

- $\Lambda_{QCD} \sim t$
  - $\langle F^2(0) \rangle$  \( \Upsilon(1S) \), ...
  - $\langle F(t)F(0) \rangle$  annihilations, short range $c\bar{c}$, $b\bar{b}$, gluelumps, ...

- $\Lambda_{QCD} \sim \text{loop}$
  - $\langle e^{ig \int dx A(x)} \rangle$  long range $c\bar{c}$, $b\bar{b}$, hybrids, glueballs, ...

The more extended the physical object, the more we probe the non-perturbative vacuum.
To extract SM parameters

Consider systems or observables with suppressed nonperturbative effects (typically quarkonia with small radius)

Get under control the perturbative series and resum all large contributions
Mass determination
Mass determination

Example: mass extraction from 1S energy level (e.g. Y(1s))
Calculate QQ energies at best possible accuracy $m \alpha_s^5$

\[ E_n = 2m + \langle n \mid \frac{p^2}{m} + V_s \rangle + \langle n \mid \langle n \rangle \]
Calculate QQ energies at best possible accuracy $m\alpha_s^5$

$$E_n = 2m + \langle n\left|\frac{p^2}{m} + V_s\right|n\rangle + \langle n\mid \text{perturbative singlet potential}\mid n\rangle$$
Calculate QQ energies at best possible accuracy $m\alpha_s^5$

\[ E_n = 2m + \langle n | \frac{p^2}{m} + V_s | n \rangle + \langle n | \]
Calculate QQ energies at best possible accuracy $m\alpha_s^5$

$$E_n = 2m + \langle n | \frac{p^2}{m} + V_s | n \rangle + \langle n |$$

perturbative singlet potential

octet
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perturbative singlet potential
Calculate QQ energies at best possible accuracy $m\alpha_s^5$.

$$E_n = 2m + \langle n \left| \frac{p^2}{m} + V_s \right| n \rangle + |n\rangle$$

- perturbative singlet potential

Diagram:
- Singlet
- Octet
- Singlet
Calculate QQ energies at best possible accuracy $m \alpha_s^5$

\[ E_n = 2m + \langle n | \frac{p^2}{m} + V_s | n \rangle + \langle n | \]

- perturbative singlet potential
- low energy gluon

- singlet
- octet
- singlet
Calculate QQ energies at best possible accuracy $m \alpha_s^5$

$$E_n = 2m + \langle n | \frac{p^2}{m} + V_s | n \rangle + \langle n |$$

perturbative singlet potential

$$E_n = \langle n | H_s(\mu) | n \rangle - i \frac{g^2}{3N_c} \int_0^\infty dt \langle n | r e^{i t (E_n^{(0)} - H_0)} r | n \rangle \langle E(t) E(0) \rangle(\mu)$$
Calculate QQ energies at best possible accuracy \( m\alpha_s^5 \)

\[
E_n = 2m + \langle n | \frac{p^2}{m} + V_s | n \rangle + \langle n | p^2 m + V_s | n \rangle
\]

\[
E_n = \langle n | H_s(\mu) | n \rangle - i \frac{g^2}{3N_c} \int_0^\infty dt \langle n | r e^{it(E_n^{(0)} - H_0)} r | n \rangle \langle E(t) E(0) \rangle(\mu) \sim e^{i\Lambda_{QCD} t}
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low energy gluon
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$$E_n = 2m + \langle n \mid \frac{p^2}{m} + V_s \mid n \rangle + \langle n \mid \rangle$$

Take $n=1S$, to obtain a precise extraction for the mass one has to:
Calculate QQ energies at best possible accuracy $m_\alpha_s^5$

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1) Sum large beta0 (removing the renormalon of the series) Beneke et al., Hoang et al., Brambilla et al, Pineda
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2) Sum the logs of $v$ (coming from the ratio of scales) RG correlated scales Luke and Savage; Manohar and Stewart; Pineda Soto
Calculate QQ energies at best possible accuracy $m\alpha_s^5$.

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**Take n=1S, to obtain a precise extraction for the mass one has to:**

1) **Sum large beta0 (removing the renormalon of the series)** Beneke et al., Hoang et al., Brambilla et al, Pineda

2) **Sum the logs of v (coming from the ratio of scales: mv^2/mv, mv/m) RG correlated scales** Luke and Savage; Manohar and Stewart; Pineda Soto

3) **Deal with the nonperturbative corrections**
1) Bad behaviour of the perturbative series (the renormalon $O(\Lambda_{QCD})$)

**Static singlet potential**

\[
V = \left( \begin{array}{ccc}
\text{Diagram 1} & \text{Diagram 2} & \cdots \\
\text{Diagram 3} & \text{Diagram 4} & \cdots \\
\end{array} \right) + \cdots
\]

The potential is a Wilson coefficient of an EFT. In general, it undergoes renormalization, develops scale dependence and satisfies renormalization group equations, which allow to resum large logarithms.
Static singlet potential

\[ V = \left( \begin{array}{ccc}
\vdots & \vdots & \vdots \\
\vdots & \vdots & \vdots \\
\vdots & \vdots & \vdots \\
\end{array} \right) - \text{in PT, i.e. } 1/r \gg \Lambda_{\text{QCD}} \]

\[ = -\frac{4}{3} \frac{\alpha_s(1/r)}{r} \left[ 1 + a_1 \frac{\alpha_s(1/r)}{4\pi} + a_2 \left( \frac{\alpha_s(1/r)}{4\pi} \right)^2 \\
+ \left( 144 \pi^2 \ln r\mu + a_3 \right) \left( \frac{\alpha_s(1/r)}{4\pi} \right) \\
+ \left( a_4^L \ln^2 r\mu + \left( a_4^L + 48\pi^2 \beta_0(-5 + 6\ln 2) \right) \ln r\mu + a_4 \right) \left( \frac{\alpha_s(1/r)}{4\pi} \right)^4 + \ldots \right] \]

\[ a_4^L = -144\pi^2 \beta_0 \]

\[ a_4^L = 432\pi^2 \left[ a_1 + 2\gamma_E/\beta_0 + n_f \left( -\frac{20}{27} + \frac{4}{9} \ln 2 \right) + \frac{149}{9} - \frac{22}{3} \ln 2 + \frac{4}{3} \pi^2 \right] \]

Brambilla Pineda Soto Vairo 99, Brambilla Garcia Soto Vairo 06
1) Bad behaviour of the perturbative series (the renormalon $O(\Lambda_{QCD})$)
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\[ r_0 \left( V_{\text{os}}(r) - V_{\text{os}}(r') + E_{\text{latt}}(r') \right) \]

\[
\begin{align*}
\alpha_s &= \alpha_s \left( \frac{1}{r} \right) \\
\nu_f &= \nu_{us} = 2.5 r_0^{-1} \\
r' &= 0.15399 r_0
\end{align*}
\]

Pineda 02
1) Bad behaviour of the perturbative series (the renormalon $O(\Lambda_{QCD})$) is the main obstacle to precise extractions!
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$O(\Lambda_{QCD})$

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$$2m_{\text{pole}} + V_0$$

main obstacle to precise extractions!
1) Bad behaviour of the perturbative series (the renormalon $O(\Lambda_{QCD})$

It was found that ($\text{Hoang et al., Pineda 99}$)

$$2m_{\text{pole}} + V_0$$

Is well behaved (the renormalon cancels between the two when one eliminates $m_{\text{pole}}$ in terms of $m_{\overline{\text{MS}}}$ or threshold mass)
1) after renormalon cancellation one gets a well behaved series and good agreement with the lattice:
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2) large logs of $v$ are RG resummed --> great improvement in stability and scale independence (LL, NLL, NNLL...)
1) after renormalon cancellation one gets a well behaved series and good agreement with the lattice:

2) large logs of $v$ are RG resummed --> great improvement in stability and scale independence (LL, NLL, NNLL...)

3) nonperturbative corrections are neglected (when suppressed)
\[
\overline{m}_b(\overline{m}_b) = 4.22 \pm 0.05 \text{ GeV}
\]
Charm mass extraction from J/psi, sum rules, lattice

\[ \overline{m}_c(m_c) = 1.28 \pm 0.05 \text{ GeV} \]
More recent determinations:

**NR Sum Rules (full NLL, partial NNLL accuracy):**

\[ \bar{m}_b(\bar{m}_b) = 4.19 \pm 0.06 \text{ GeV} \]

Pineda Signer 06

**Semileptonic B decays**

\[ \bar{m}_c(\bar{m}_c) = 1.224 \pm 0.017 \pm 0.054 \text{ GeV} \]

Hoang Manohar 05

**Lattice (unquenched)**

\[ \bar{m}_b(\bar{m}_b) = 4.4 \pm 0.030 \text{ GeV} \]

Gray et al 05
alpha_s determination
$\alpha_s(M_Z)$ \textbf{FROM PDG06}

\[ \alpha_s(M_Z) = 0.1176 \pm 0.002 \]
Running of $\alpha_s$ from PDG06
Running of $\alpha_s$ from PDG06

Upsilon decay

Diagram showing the running of $\alpha_s$ with scale $\mu$ in GeV.
New extraction of $\alpha_s$ (Brambilla, Garcia, Soto, Vairo 07) from

$$R_\gamma \equiv \frac{\Gamma(\Upsilon(1S) \to \gamma X)}{\Gamma(\Upsilon(1S) \to X)}$$

based on:
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based on:

- **New data from CLEO** (**hep-ex/0512061**)**
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• **COMBINED USE OF NRQCD, pNRQCD AND SCET*
New extraction of $\alpha_s$ (Brambilla, Garcia, Soto, Vairo 07) from

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based on:

- NEW DATA FROM CLEO \texttt{(HEP-EX/0512061)}
- COMBINED USE OF NRQCD, pNRQCD AND SCET
- ACCURATE ESTIMATES OF THE OCTET CONTRIBUTIONS FROM THE LATTICE \texttt{(BODWIN, LEE, SINCLAIR 05)} AND FROM CONTINUUM \texttt{(GARCIA, SOTO 05)}
Using NRQCD decay factorization:

\[ \Gamma(H \to l.h.) = \sum_n \frac{2 \text{Im} f^{(n)}(n)}{m_{d_n}^{d_n-4}} \langle H | O_{4-\text{fermion}} | H \rangle \]

Bodwin et al 95

we obtain
Using NRQCD decay factorization:

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\[ \Gamma(\Upsilon(1S) \to \gamma X) = 36 \frac{e_b^2 \alpha N}{5 \alpha_s D} \]

we obtain

\[ R_\gamma \equiv \frac{\Gamma(\Upsilon(1S) \to \gamma X)}{\Gamma(\Upsilon(1S) \to X)} = \frac{36 e_b^2 \alpha N}{5 \alpha_s D} \]

\text{Bodwin et al 95}
Using NRQCD decay factorization:

\[ \Gamma(H \rightarrow l.h.) = \sum_n \frac{2 \text{Im} f^{(n)}_m}{m^{d_n-4}} \langle H | O_{4-\text{fermion}} | H \rangle \]

Bodwin et al 95

we obtain

\[ R_\gamma \equiv \frac{\Gamma(\Upsilon(1S) \rightarrow \gamma X)}{\Gamma(\Upsilon(1S) \rightarrow X)} = \frac{36}{5} \frac{e_b^2 \alpha N}{\alpha_s D} \]

\[ N = 1 + C_{gg\gamma} \frac{\alpha_s}{\pi} + C_{P_1(3S_1)} R_{P_1(3S_1)} + \]
Using NRQCD decay factorization:

\[
\Gamma(H \rightarrow l.h.) = \sum_n \frac{2 \text{Im} f^{(n)}}{m^d n - 4} \langle H | O_{4-\text{fermion}} | H \rangle
\]

Bodwin et al 95

we obtain

\[
R_\gamma \equiv \frac{\Gamma(\Upsilon(1S) \rightarrow \gamma X)}{\Gamma(\Upsilon(1S) \rightarrow X)} = \frac{36}{5} \frac{e_b^2 \alpha}{\alpha_s D} N
\]

\[
N = 1 + C_{gg \gamma} \frac{\alpha_s}{\pi} + C_{P_1(3S_1)} \mathcal{R}_{P_1(3S_1)} + \frac{\pi}{\alpha_s} C_{\gamma O_8(1S_0)} \mathcal{R}_{O_8(1S_0)} + \frac{\pi}{\alpha_s} C_{\gamma O_8(1P_1)} \mathcal{R}_{O_8(1P_1)} + \mathcal{O}_N(v^3)
\]
Using NRQCD decay factorization:

\[ \Gamma(H \to l.h.) = \sum_n \frac{2 \text{Im} f^{(n)}}{m_{d_n - 4}^4} (H|O_{4\text{-fermion}}|H) \]

\[ \text{Bodwin et al } 95 \]

we obtain

\[ R_\gamma \equiv \frac{\Gamma(\Upsilon(1S) \to \gamma X)}{\Gamma(\Upsilon(1S) \to X)} = \frac{36}{5} \frac{e_b^2 \alpha}{\alpha_s} \frac{N}{D} \]

\[ N = 1 + C_{gg\gamma} \frac{\alpha_s}{\pi} + C_{P_1(3S_1)} \mathcal{R}_{P_1(3S_1)} + \frac{\pi}{\alpha_s} C_{\gamma O_8(1S_0)} \mathcal{R}_{O_8(1S_0)} + \frac{\pi}{\alpha_s} C_{\gamma O_8(1P_1)} \mathcal{R}_{O_8(1P_1)} + \mathcal{O}_N(v^3) \]

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Using NRQCD decay factorization:

\[
\Gamma(H \rightarrow l.h.) = \sum_n \frac{2 \text{Im} f^{(n)}}{m^{d-4}_n} \langle H | O_4 \text{fermion} | H \rangle
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Bodwin et al 95

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\]

accurate at NLO in \( \alpha_s \) and \( v \)
We obtain

\[ \alpha_s(M_{\Upsilon(1S)}) = 0.184^{+0.015}_{-0.014} \]
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discussion of previous determinations CLEO/PDG
Average
Hadronic Jets
\(e^+e^-\) rates
Photo-production
Fragmentation
Z width
ep event shapes
Polarized DIS
Deep Inelastic Scattering (DIS)
\(\tau\) decays
Spectroscopy (Lattice)
Y decay

\(\alpha_s(M_Z)\)
The $\alpha_s$ from quarkonium is now consistent with the other determinations.
The new determination of $\alpha_s$ will move up the $\alpha_s$ average!

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M1 Transitions
RADIATIVE TRANSITIONS

Magnetic Dipole transitions

\[ \Gamma(J/\psi \rightarrow \eta_c \gamma) = (1.18 \pm 0.36) \text{keV} \]

- \( \Gamma(J/\psi \rightarrow \eta_c \gamma) \) enters into many charmonium BR. Its 30% uncertainty sets typically their experimental errors.

In potential models

At leading order \( \Gamma(J/\psi \rightarrow \eta_c \gamma) \sim 2.83 \text{KeV} \)

this implies:
- large value of the charm mass
- large anomalous magnetic moment of the quark
- large relativistic corrections to the S-state wave functions

Eichten QWG 02
**Effective Theory of Radiative Transitions**

**pNRQCD with singlet, octet, US gluons and photons**

- No nonperturbative physics at order $\nu^2$
- Exact relations from Poincare invariance
- No large anomalous magnetic moment

\[
\Gamma(J/\psi \to \gamma \eta_c) = \frac{16}{3} \alpha e^2 \frac{k_\gamma^3}{M_{J/\psi}^2} \left[ 1 + C_F \frac{\alpha_s(M_{J/\psi}/2)}{\pi} - \frac{2}{3} (C_F \alpha_s(p_{J/\psi}))^2 \right]
\]

\[
\Gamma(J/\psi \to \eta_c \gamma) = (1.5 \pm 1.0) \text{ keV}.
\]

\[
\Gamma\gamma(1S)\to\eta_b \gamma = \left( \frac{k_\gamma}{39} \right)^3 (2.50 \pm 0.25) \text{ eV}
\]

\[
\Gamma\gamma(2S)\to\eta_b(2S) \gamma (\text{eV})
\]
Outlook: Bottom and Charm Masses

QWG extraction of c and b mass (2005)

\[ \overline{m}_b(\overline{m}_b) = 4.22 \pm 0.05 \text{ GeV} \quad \overline{m}_c(\overline{m}_c) = 1.28 \pm 0.05 \text{ GeV} \]
Outlook: bottom and charm masses

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For 1S mass extraction: Lattice calculation of \( <E E(t)> \) (full NNNLO and LL in pert)
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In NRSM: -NNLL and NNNLO; for low moments SR, from experiments: R for bb above threshold, new R for cc is good input
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In NRSM: -NNLL and NNNLO; for low moments SR, from experiments: \( R \) for $bb$ above threshold, new \( R \) for $cc$ is good input

For lattice: th error in lattice -->MS conversion, need 2 loop matching in NRQCD and Fermilab; nonperturbative matching desirable
Outlook: Top Mass and Alphas
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ttbar system: extraction of $m_t$ at the ILC. Present undetermination around 100 MeV. Needed: complete NNLL and complete NNNNLO; EW and non fact.; EFT for unstable particles
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alphas from etab
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From hyperfine separation calculated at NLL:

$$M(\eta_b) = 9.421 \pm 11^{+9}_{-8}\text{Gev}$$
Outlook: Top Mass and Alphas

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from a measurement of \( \eta_b \) with few Mev accuracy
get \( \alpha_s(M_z) \) with 0.003 error!
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*ttbar system: extraction of m_t at the ILC.*
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alphas da j/psi -> gamma X
need both theory calculations and experimental measurement
Effective field theories provide a systematic tool to investigate a wide range of heavy quark observables inside QCD.
Outlook

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They need to be complemented by lattice calculations.
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These theory tools can match some of the intense experimental progress of the last few years and of the near future, but more has to be done.
Outlook

**Effective field theories provide a systematic tool to investigate a wide range of heavy quark observables inside QCD**

They need to be complemented by lattice calculations. These theory tools can match some of the intense experimental progress of the last few years and of the near future, but *more has to be done:*

- **Perturbative calculations at higher order** (fixed order and logs summation)
- **Lattice calculations of local and nonlocal condensates** (or equivalently NRQCD matrix elements)
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Heavy quark bound states are a unique lab for the study of the strong interactions from the high energy scales where precision studies can be made to the low energy region where confinement and nonperturbative physics are dominant.
$$E_{\text{hfs}}(bb)$$

LO...
NLO___
LL____
NLL_____

$$M(\eta_b) = 9421 \pm 10 \, \text{(th)} \, ^{+9}_{-8} (\delta \alpha_s) \, \text{MeV}$$

Kniehl Penin Pineda Smirnov Steinhauser
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Under search at Fermilab and CLEO