Open Issues in Charmonium Physics

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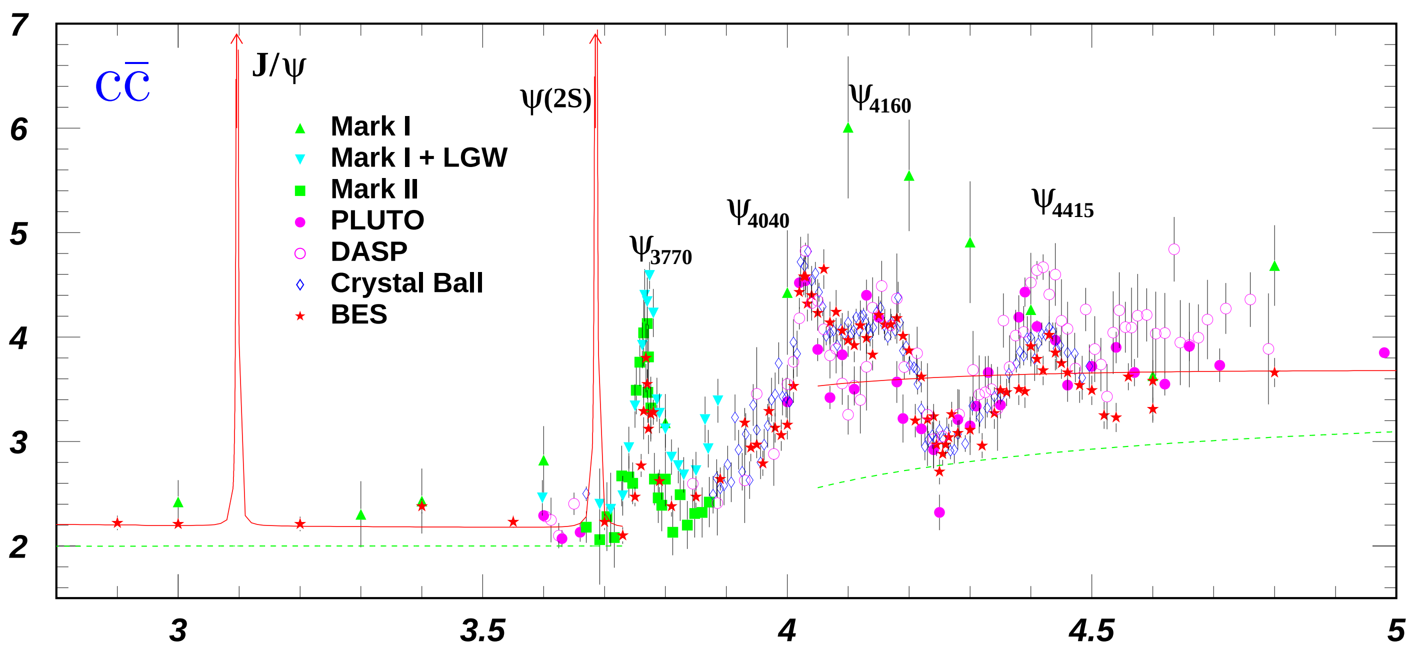
Motivation



- The system is accessible to QCD studies.
  (i) hierarchy of scales (⇒ factorizaton/effective field theories)
  (ii) some of the scales are perturbative.
- For these same reasons, charmonium (and quarkonium) are systems where low energy QCD may be studied in a systematic way (e.g. non-perturbative matrix elements, QCD vacuum, confinement, exotica, ...)

Summary

1. Effective Field Theories: NRQCD, pNRQCD

2. Annihilations

2.1 Inclusive decays

2.2 Electromagnetic decays

2.3 Exclusive decays (15% rule)

3. Production

3.1 Polarization

3.2 Double charmonium production

4. Radiative transitions

4.1 $J/\psi \to \gamma\, \eta_c$

5. New spectroscopy

5.1 Hybrids

6. Conclusion

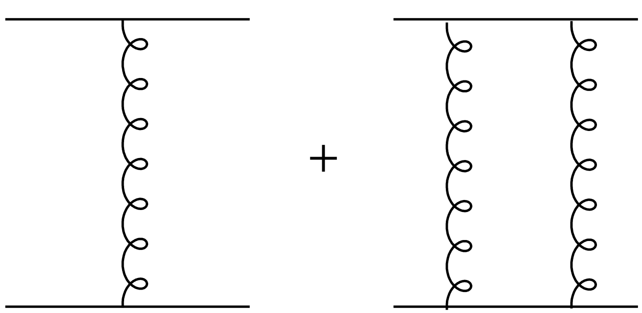
1. EFTs

Quarkonium Scales

Apart from α_s, another small parameter shows up near threshold:

$$E \approx 2m + \frac{p^2}{m} + \ldots \qquad \text{with} \quad v = \frac{p}{m} \ll 1$$

- The perturbative expansion breaks down when $\alpha_s \sim v$:



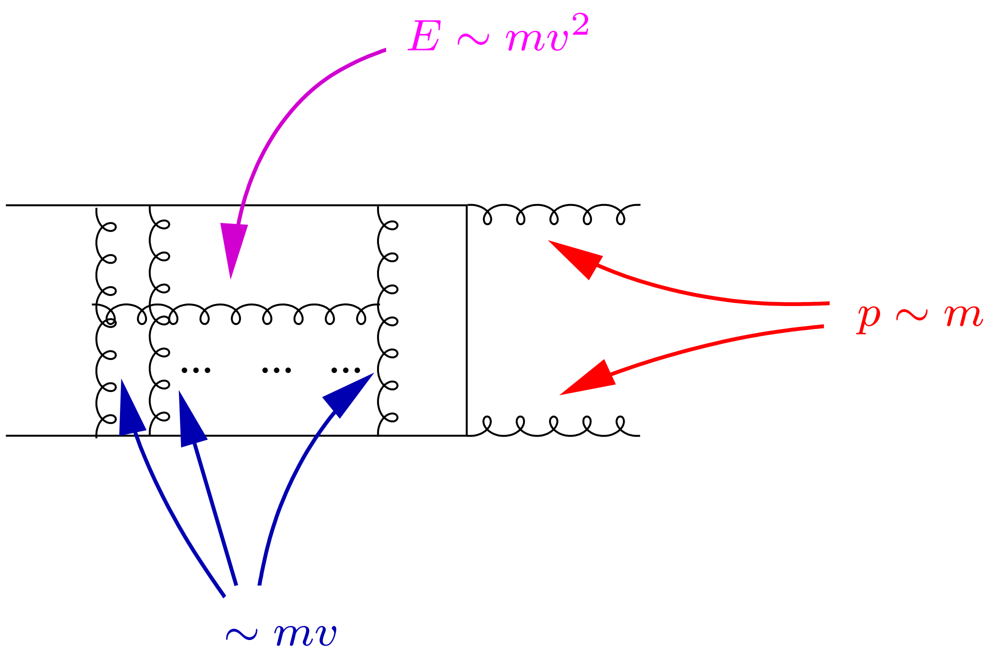
$$+ \quad \cdots \qquad \approx \frac{1}{E - \left(\frac{p^2}{m} + V\right)}$$

$$\alpha_s \left(1 + \frac{\alpha_s}{v} + \ldots\right)$$

- The system is non-relativistic : $p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.

Quarkonium Scales

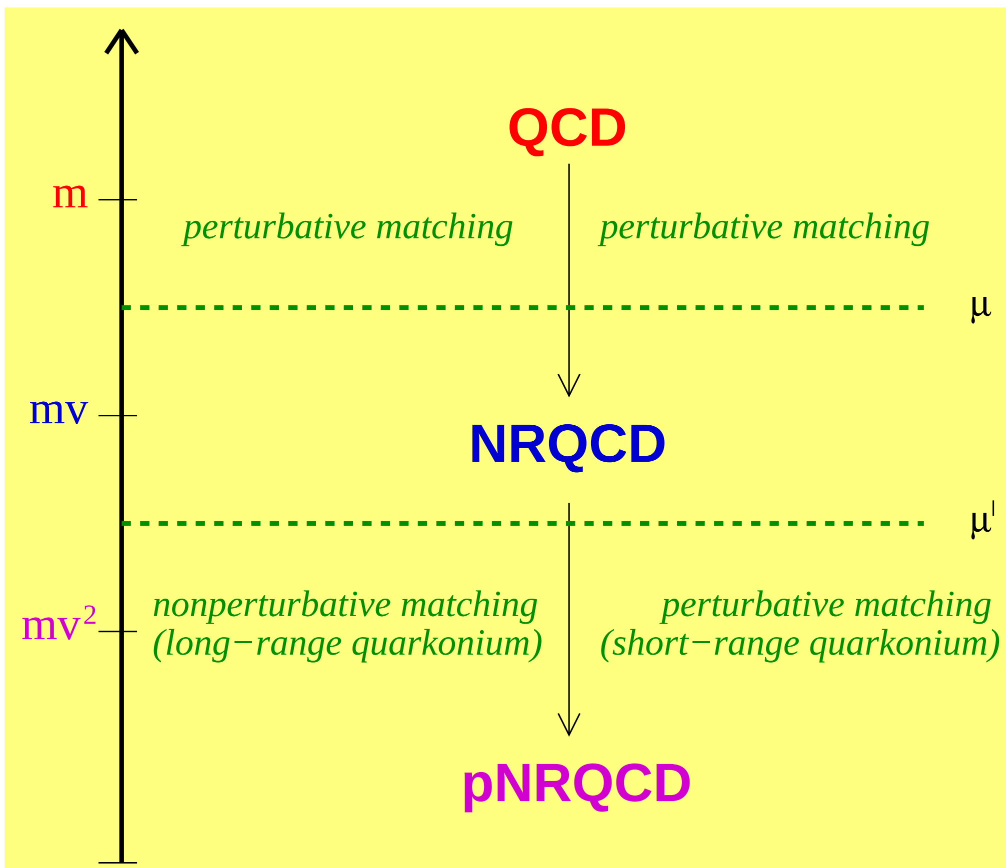
Scales get entangled.



Effective Field Theories for Quarkonium

Whenever a system H, described by $\mathcal{L}_{\rm QCD}$, is characterized by 2 scales $\Lambda \gg \lambda$, observables may be calculated by expanding one scale with respect to the other.

An effective field theory makes the expansion in λ/Λ explicit at the Lagrangian level.



$$\frac{\lambda}{\Lambda} = \frac{mv}{m}$$

$$\frac{\lambda}{\Lambda} = \frac{mv^2}{mv}$$

Charmonium Scales

$$m_c \approx 1.5 \text{ GeV} \gg \Lambda_{\rm QCD}$$

$$m_c v \approx 0.8 \text{ GeV} > \Lambda_{\rm QCD} \quad \text{for } J/\psi, \eta_c$$

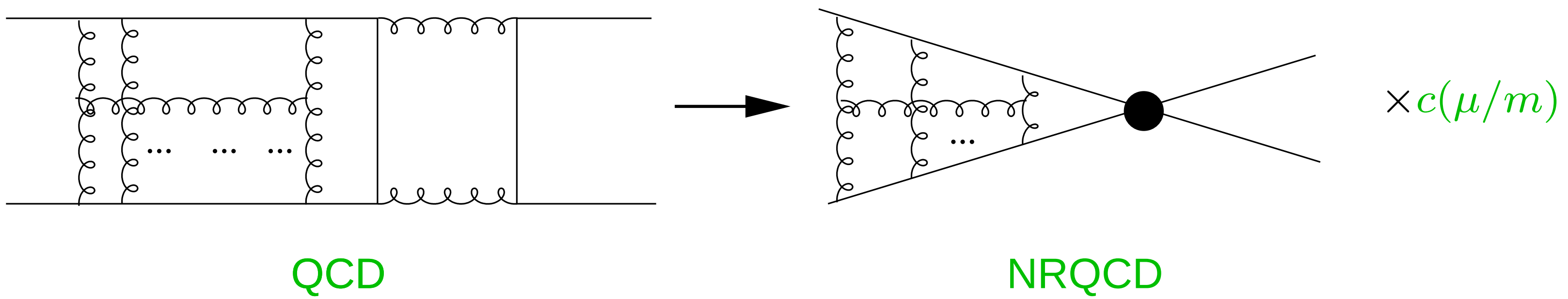
$$m_c v \sim \Lambda_{\rm QCD} \quad \text{for all higher resonances}$$

As a consequence:

- annihilation, production, hard scale processes happen at a perturbative scale;
- the bound state is perturbative (i.e. Coulombic) perhaps only for the J/ψ, η_c;
- for all other charmonium resonances the bound state is non-perturbative. It will be described by matrix elements, (confining) potentials to be determined on the lattice.

NRQCD

NRQCD is the EFT that follows from QCD when $\Lambda = m$



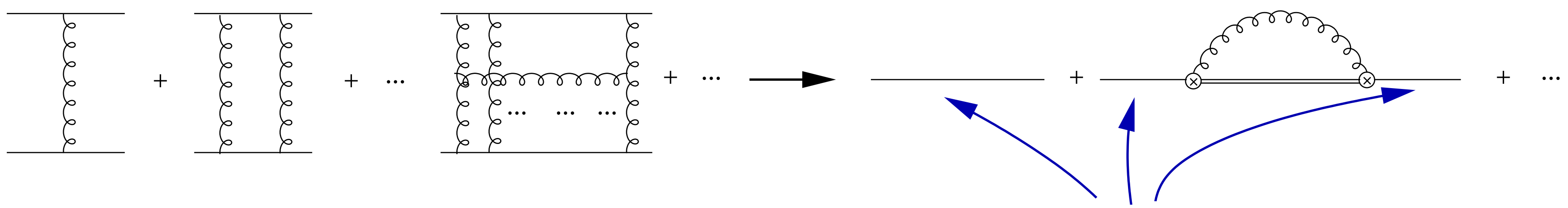
- The matching is perturbative.
- The Lagrangian is organized as an expansion in $1/m$ and $\alpha_s(m)$:

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

Suitable to describe decay and production of quarkonium.

pNRQCD

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



$$\frac{1}{E - p^2/m - V(r)}$$

NRQCD

pNRQCD

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

$$\mathcal{L}_{\mathrm{pNRQCD}} = \sum_k \sum_n \frac{1}{m^k} \times c_k(\alpha_s(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

2. Annihilations

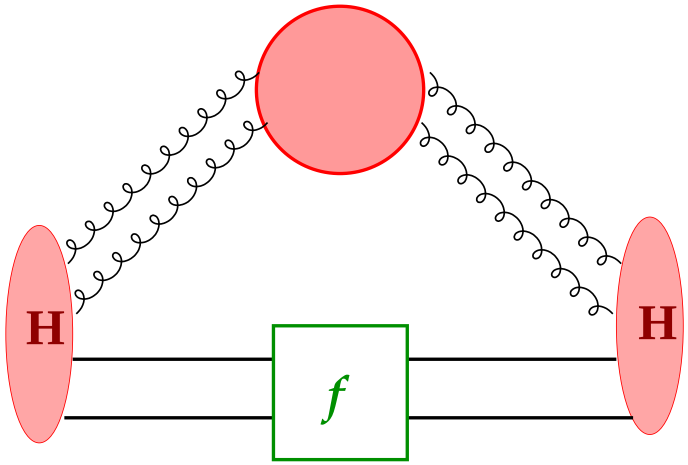
Inclusive Decays in NRQCD

$$\Gamma(H \to \mathrm{LH}) = -2\,\mathrm{Im}\,\langle H|\,\mathcal{H}\,|H\rangle$$

$$= \sum_n \frac{2\,\mathrm{Im}\,f^{(n)}}{m^{d_n-4}}\langle H|\psi^\dagger K^{(n)}\chi\chi^\dagger K'^{\,(n)}\psi|H\rangle$$

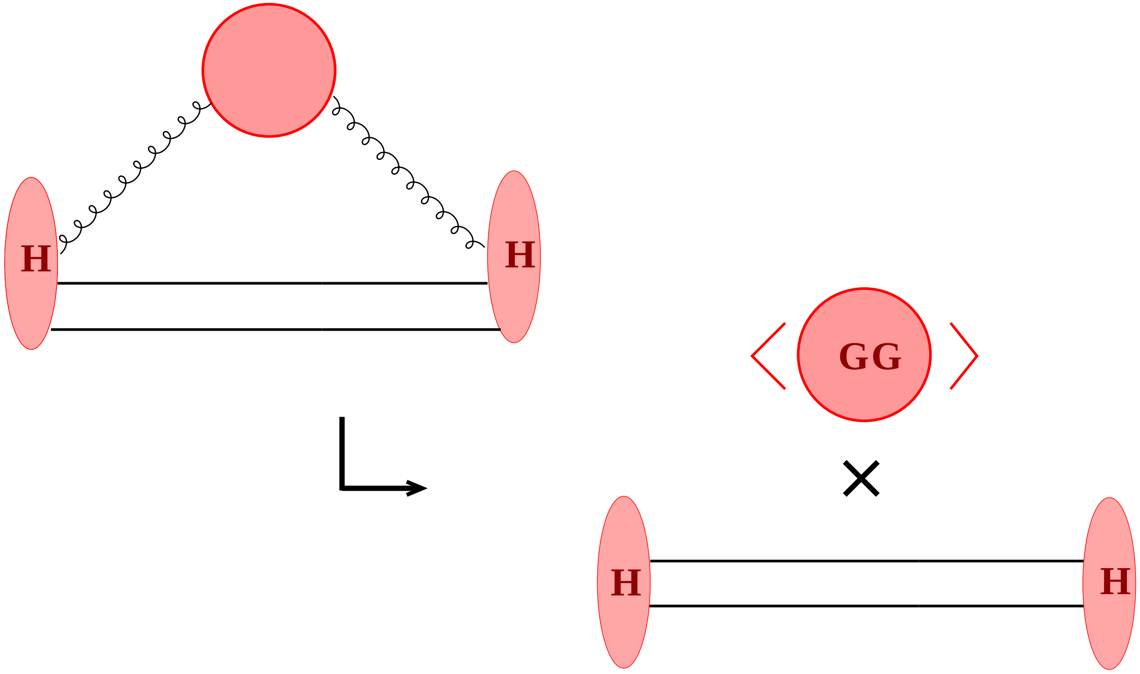
$$\Gamma(H \to \mathrm{EM}) = \sum_n \frac{2\,\mathrm{Im}\,f^{(n)}_{\mathrm{em}}}{m^{d_n-4}}\langle H|\psi^\dagger K^{(n)}\chi|\mathrm{vac}\rangle\langle \mathrm{vac}|\chi^\dagger K'^{\,(n)}\psi|H\rangle$$

Bodwin et al. 95



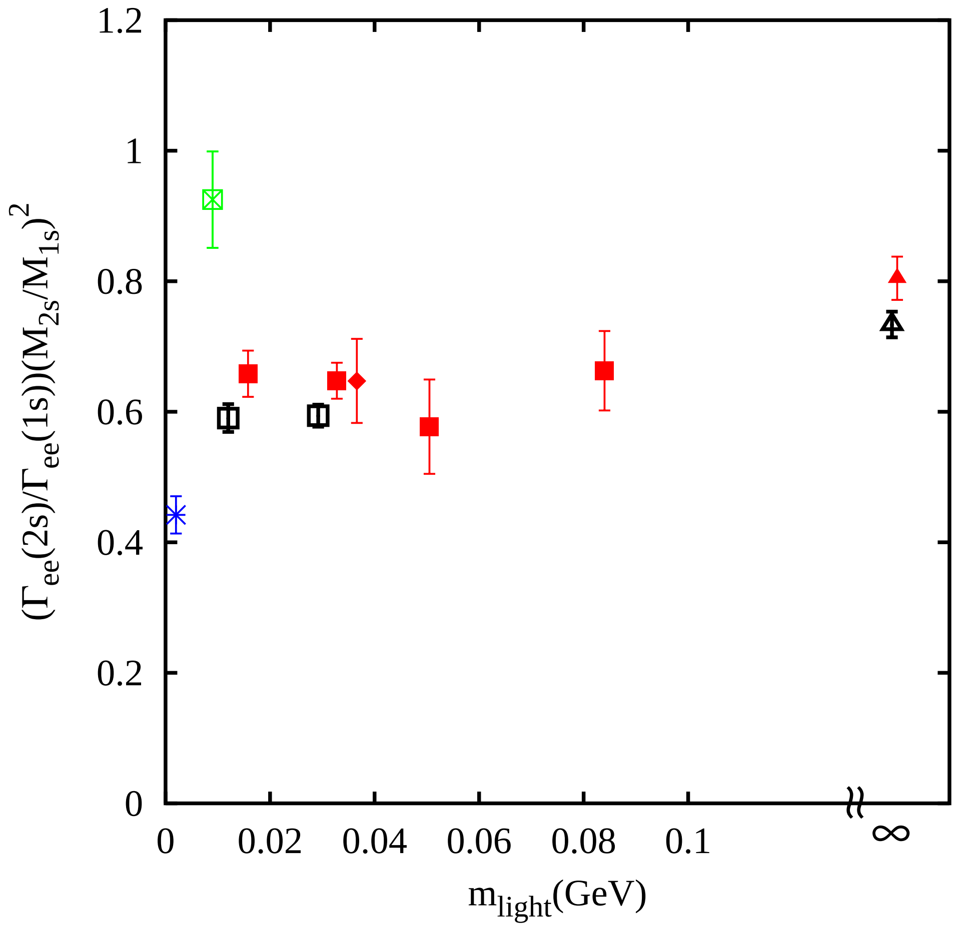
Inclusive Decays in pNRQCD

$$\langle H|\psi^\dagger K^{(n)}\chi\chi^\dagger K'^{(n)}\psi|H\rangle = |R(0)|^2 \times \int dt t^n \langle G(t)G(0)\rangle$$



Brambilla et al. 02 03

E.m. widths on the lattice



Gray et al 05

$$\Gamma(\eta_c \to LH)/\Gamma(\eta_c \to \gamma\,\gamma)$$

- Large $\beta_0 \alpha_{\rm s}$ contributions.

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} \approx (1.1 \text{ (LO)} + 1.0 \text{ (NLO)}) \times 10^3 = 2.1 \times 10^3$$

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} = (3.3 \pm 1.3) \times 10^3 \text{ (EXP)}$$

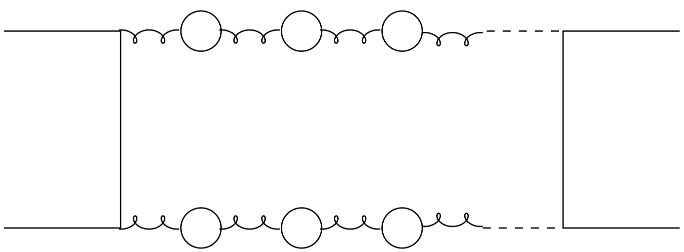
$$\Gamma(\eta_c \to LH)/\Gamma(\eta_c \to \gamma\,\gamma)$$

- Large $\beta_0 \alpha_{\rm s}$ contributions.

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} \approx (1.1 \text{ (LO)} + 1.0 \text{ (NLO)}) \times 10^3 = 2.1 \times 10^3$$

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} = (3.3 \pm 1.3) \times 10^3 \text{ (EXP)}$$

- scheme dependence
- renormalons

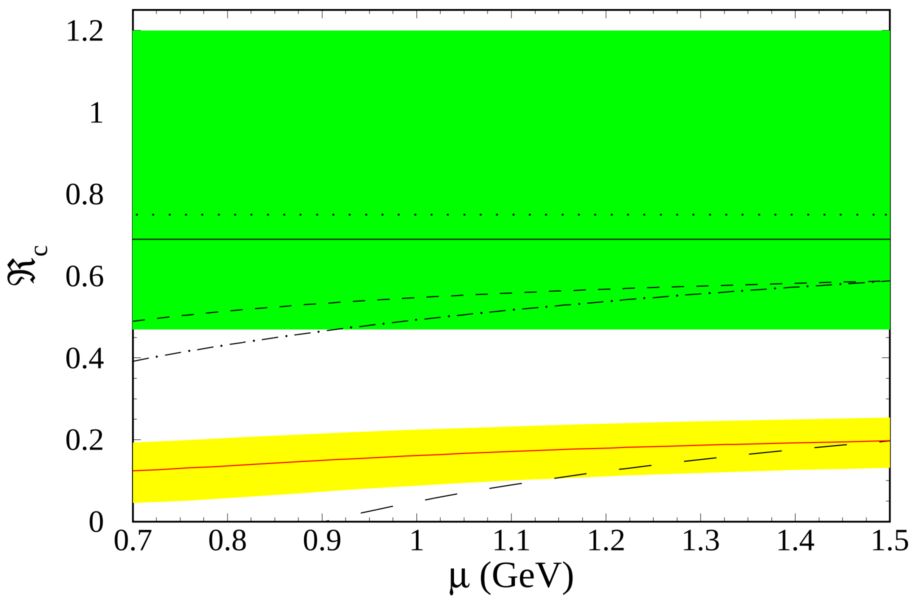


$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} = (3.01 \pm 0.30 \pm 0.34) \times 10^3$$

Bodwin Chen 01

$$\Gamma(J/\psi \to e^+e^-)/\Gamma(\eta_c \to \gamma\gamma)$$

- Large logarithms.



LO . . .

NLO _ _ _

NNLO __ __ __

NLL _ . _ .

NNLL ______

$$\mathcal{R}_c = \frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(\eta_c \to \gamma\gamma)}$$

Penin Pineda Smirnov Steinhauser 04

P-wave decays at NLO and mv^5

Ratio	PDG04	PDG00	LO	NLO
$\frac{\Gamma(\chi_{c0}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to\gamma\gamma)}$		13$\pm$10	$=$ 3.75	$\approx$ 5.43
$\frac{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$		270$\pm$200	$\approx$ 347	$\approx$ 383
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$		3500$\pm$2500	$\approx$ 1300	$\approx$ 2781
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c2}\to l.h.)}{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}$		12.1$\pm$3.2	$=$ 2.75	$\approx$ 6.63
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}$		13.1$\pm$3.3	$=$ 3.75	$\approx$ 7.63

$m_c =$ 1.5 GeV $\quad \alpha_s(2m_c) =$ 0.245

P-wave decays at NLO and mv^5

Ratio	PDG04	PDG00	LO	NLO
$\frac{\Gamma(\chi_{c0} \to \gamma\gamma)}{\Gamma(\chi_{c2} \to \gamma\gamma)}$	5.1±1.1	13±10	$=$ 3.75	$\approx$ 5.43
$\frac{\Gamma(\chi_{c2} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}{\Gamma(\chi_{c0} \to \gamma\gamma)}$	410±100	270±200	$\approx$ 347	$\approx$ 383
$\frac{\Gamma(\chi_{c0} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}{\Gamma(\chi_{c0} \to \gamma\gamma)}$	3600±700	3500±2500	$\approx$ 1300	$\approx$ 2781
$\frac{\Gamma(\chi_{c0} \to l.h.) - \Gamma(\chi_{c2} \to l.h.)}{\Gamma(\chi_{c2} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}$	7.9±1.5	12.1±3.2	$=$ 2.75	$\approx$ 6.63
$\frac{\Gamma(\chi_{c0} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}{\Gamma(\chi_{c2} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}$	8.9±1.1	13.1±3.3	$=$ 3.75	$\approx$ 7.63

$m_c =$ 1.5 GeV $\quad \alpha_s(2m_c) =$ 0.245

mainly from E835 (χ_{c0}, total width and $\gamma\gamma$)

also from Belle ($\chi_{c0} \to \gamma\gamma$) and CLEO, BES

One should notice that P-wave analyses do not include so far either

(i) subtraction of renormalons

(ii) resummation of large logs

(iii) $\mathcal{O}(v^2)$ relativistic effects (numerically of the same magnitude as NLO corrections).

Potentially P-wave decays may provide a competitive source of m_c and $\alpha_{\rm s}(m_c)$.

Mangano Petrelli 95, Maltoni 00, Mussa 03

Exclusive Decay Modes

$$\kappa[h_1 h_2] = \frac{\mathcal{B}(\psi(2S) \to h_1 h_2)}{\mathcal{B}(J/\psi \to h_1 h_2)} \, \frac{\mathcal{B}(J/\psi \to e^+ e^-)}{\mathcal{B}(\psi(2S) \to e^+ e^-)} \, \frac{\varrho[J/\psi h_1 h_2]}{\varrho[\psi(2S) h_1 h_2]},$$

- The phase-space factor $\rho \approx 1$.
- If $\Gamma(J/\psi \to h_1 h_2) \approx \left|\psi_{J/\psi}(\mathbf{r}=0)\right|^2 \left|\mathcal{A}(c(\mathbf{0})\bar{c}(\mathbf{0}) \to h_1 h_2)\right|^2 \frac{\varrho[J/\psi h_1 h_2]}{16\pi M_{J/\psi}}$

  and analogously for the $\psi(2S)$.

Then

$$\kappa[h_1 h_2] \approx 1$$

Also known as 15% rule.

Exclusive Decay Modes

Decay mode $h_1 h_2$ PDG 03	$\mathcal{B}[J/\psi \to h_1 h_2]$ $(\times 10^4)$	$\mathcal{B}[\psi' \to h_1 h_2]$ $(\times 10^4)$	$\kappa[h_1 h_2]$
$\varrho\pi$	127 ± 9	< 0.83 (< 0.28)	< 0.054 (< 0.18)
$\omega\pi^0$	4.2 ± 0.6	$0.38 \pm 0.17 \pm 0.11$	0.7 ± 0.4
$\varrho\eta$	1.93 ± 0.23		
$\omega\eta$	15.8 ± 1.6	< 0.33	< 0.17
$\phi\eta$	6.5 ± 0.7		
$\varrho\eta'(958)$	1.05 ± 0.18		
$\omega\eta'(958)$	1.67 ± 0.25		
$\phi\eta'(958)$	3.3 ± 0.4		
$K^*(892)^{\mp} K^{\pm}$	50 ± 4	< 0.54(< 0.30)	< 0.089 (< 0.049)
$\bar{K}^*(892)^0 K^0$+c.c.	42 ± 4	$0.81 \pm 0.24 \pm 0.16$	0.15 ± 0.05
$\pi^{\pm} b_1(1235)^{\mp}$	30 ± 5	3.2 ± 0.8	0.79 ± 0.24
$\pi^0 b_1(1235)^0$	23 ± 6		
$K^{\pm} K_1(1270)^{\mp}$	< 30	10.0 ± 2.8	> 1.7
$K^{\pm} K_1(1400)^{\mp}$	38 ± 14	< 3.1	< 0.78

Exclusive Decay Modes

Decay mode $h_1 h_2$ PDG 04, BES 04, CLEO 04	$\mathcal{B}(J/\psi \to h_1 h_2)$ $(\times 10^4)$	$\mathcal{B}(\psi' \to h_1 h_2)$ $(\times 10^4)$	$\kappa[h_1 h_2]$
$\varrho\pi$	127 ± 9	0.46 ± 0.09	0.028 ± 0.006
$\omega\pi^0$	4.2 ± 0.6	0.22 ± 0.09	0.40 ± 0.17
$\varrho\eta$	1.93 ± 0.23	0.23 ± 0.12	0.9 ± 0.5
$\omega\eta$	15.8 ± 1.6	< 0.11	< 0.06
$\phi\eta$	6.5 ± 0.7	0.35 ± 0.11	0.40 ± 0.13
$\varrho\eta'(958)$	1.05 ± 0.18	$0.19^{+0.16}_{-0.11} \pm 0.03$	2.5 ± 0.9
$\omega\eta'(958)$	1.67 ± 0.25	< 0.81	< 4.3
$\phi\eta'(958)$	3.3 ± 0.4	$0.33 \pm 0.13 \pm 0.07$	0.71 ± 0.33
$K^*(892)^\mp K^\pm$	50 ± 4	0.26 ± 0.11	0.039 ± 0.017
$\bar{K}^*(892)^0 K^0$+c.c.	42 ± 4	1.55 ± 0.25	0.28 ± 0.05
$\pi^\pm b_1(1235)^\mp$	30 ± 5	3.9 ± 1.6	1.0 ± 0.4
$\pi^0 b_1(1235)^0$	23 ± 6	$4.0^{+0.9}_{-0.8} \pm 0.6$	1.3 ± 0.5
$K^\pm K_1(1270)^\mp$	< 30	10.0 ± 2.8	> 1.7
$K^\pm K_1(1400)^\mp$	38 ± 14	< 3.1	< 0.8

Exclusive Decay Modes

Possible explanations include:

- *suppression of the $c\bar{c}$ wave function at the origin for a component of $\psi(2S)$ in which the $c\bar{c}$ is in a color-octet ${}^3S_1$ state.*
- *suppression of the $\omega\phi$ component of $\psi(2S)$.*
- *cancellation between $c\bar{c}$ and $D\bar{D}$ components of $\psi(2S)$.*
- *cancellation between $c\bar{c}$ and glueball components of $\psi(2S)$.*
- *cancellation between S-wave $c\bar{c}$ and D-wave $c\bar{c}$ components of $\psi(2S)$.*
- *cancellation between the amplitudes for the resonant process $e^+e^- \longrightarrow \psi(2S) \longrightarrow \rho\pi$ and the direct process $e^+e^- \longrightarrow \rho\pi$.*

3. Production

Quarkonium Production

- There is no formal proof of the NRQCD factorization yet.
- The relevant 4-fermion operators are

$$\psi^\dagger K^{(n)} \chi \, a_H^\dagger a_H \, \chi^\dagger K'^{(n)} \psi$$

Recently it has been proved that the cancellation of the IR divergences at NNLO requires the modification of the 4 fermion operators into

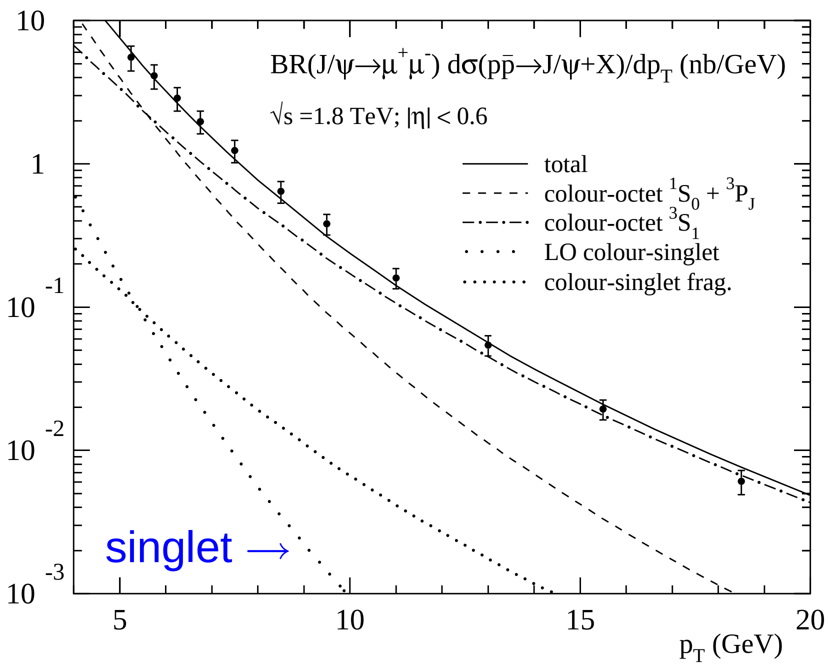
$$\psi^\dagger K^{(n)} \chi \, \phi_l^\dagger(0,\infty) \, a_H^\dagger a_H \, \phi_l(0,\infty) \, \chi^\dagger K'^{(n)} \psi$$

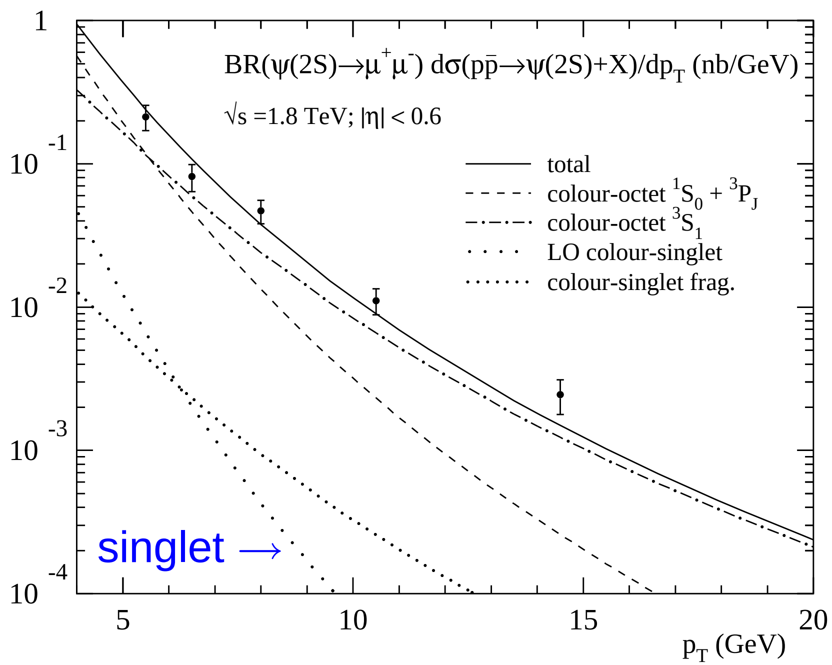
$$\phi_l(0,\infty) = \mathrm{P} \, \exp\left(-ig \int_0^\infty d\lambda \, l \cdot A(\lambda \, l)\right), \qquad l^2 = 1$$

Nayak Qiu Sterman 05

Charmonium Production at the Tevatron

Octet contributions dominate in production at high p_T.



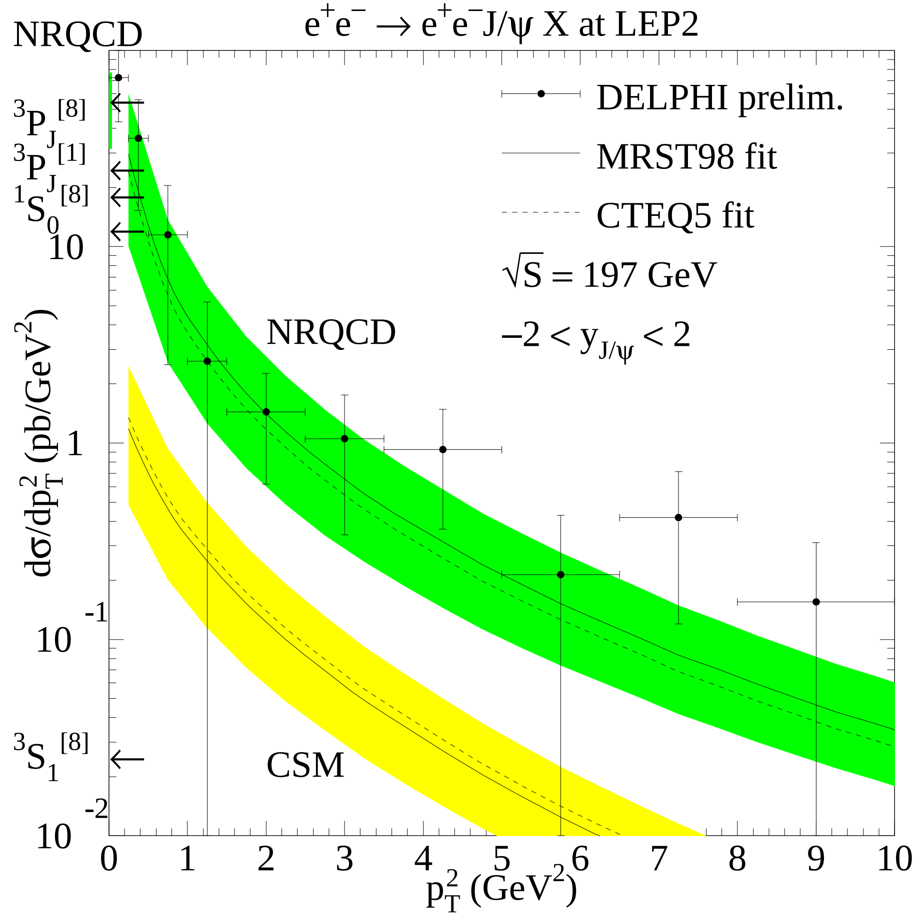


$pp \rightarrow J/\psi + X$

$pp \rightarrow \psi(2S) + X$

Krämer 01, CDF 97

$$e^+e^- \to e^+e^- \, J/\psi \, X$$



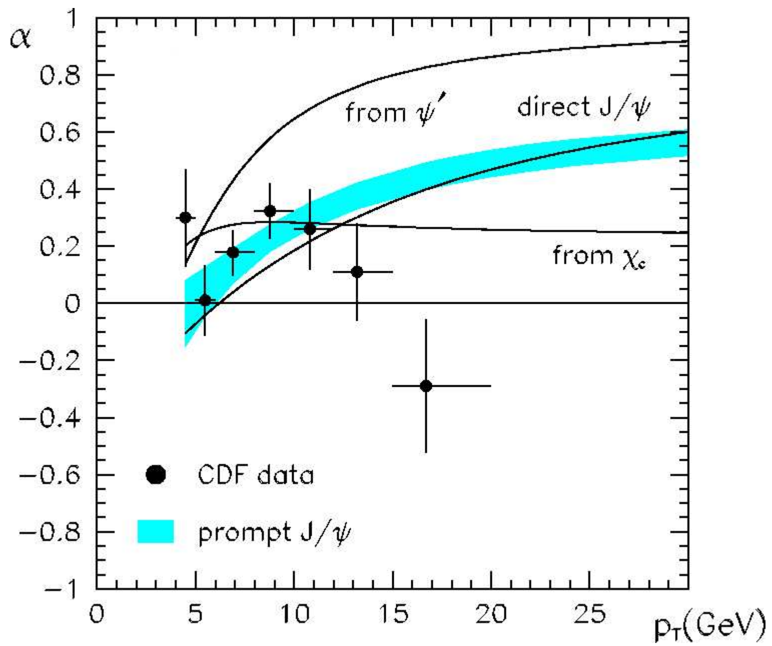
Klasen Kniehl Mihaila Steinhauser 02

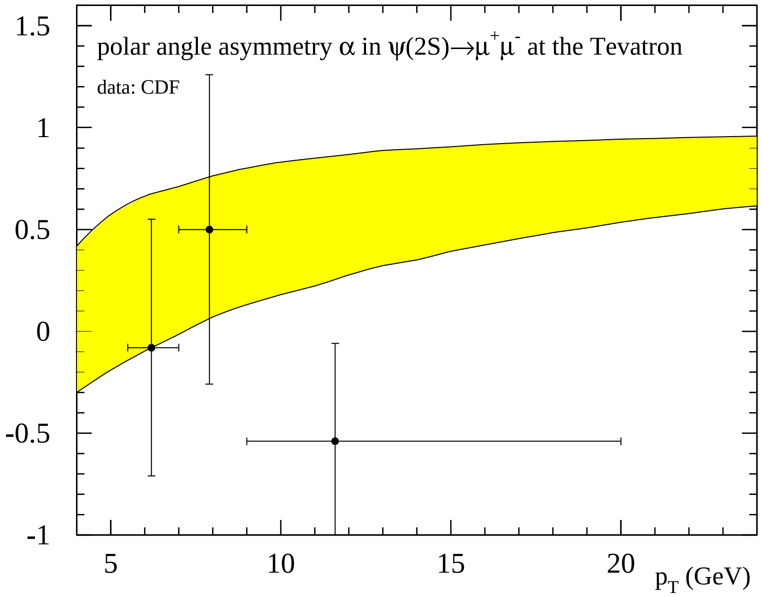
Charmonium Polarization at the Tevatron

- For large p_T quarkonium production, gluon fragmentation via the color-octet mechanism dominates: $\langle O_8^{J/\psi}(^3S_1)\rangle$.
- At large p_T the gluon is nearly on mass shell and so is transversely polarized.
- In color octet gluon fragmentation, most of the gluon's polarization is transferred to the J/ψ.
- Radiative corretions, color singlet production dilute this.
- In the case of the J/ψ feeddown is important:
  feeddown from χ_c states is about 30% of the J/ψ sample and dilutes the polarization.
- feeddown from $\psi(2S)$ is about 10% of the J/ψ sample and is largely transversely polarized.

- *Spin-flippling terms are assumed suppressed. But This stricly depends on the power counting.*
  If they are not, polarization may dilute at high p_T.

Charmonium Polarization at the Tevatron



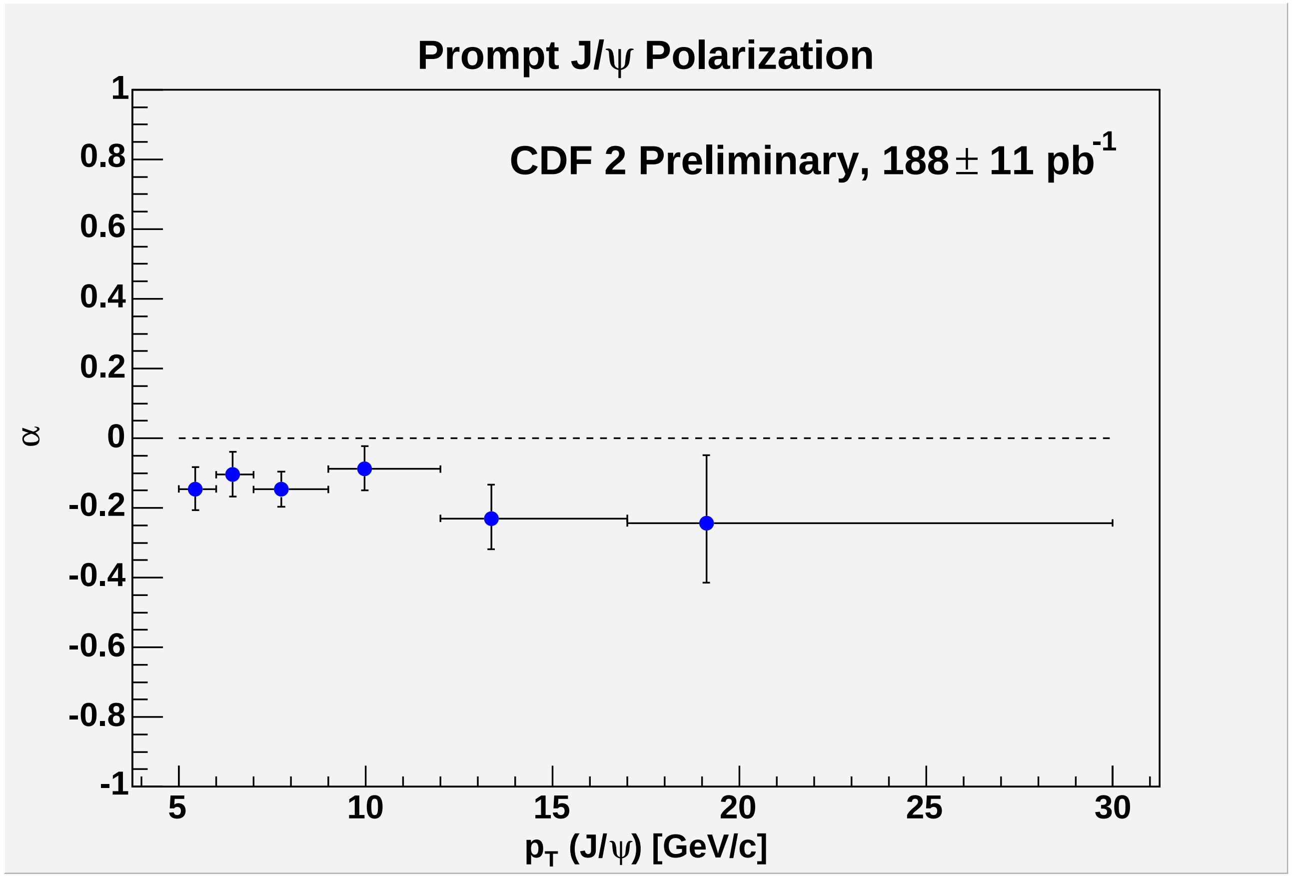


$$\frac{d\sigma}{d\cos\theta} \propto 1 + \alpha \cos^2\theta$$

$\alpha = 1$ is completely transverse $\alpha = -1$ is completely longitudinal.

Krämer 01, Braaten et al 01, CDF 97

Charmonium Polarization at the Tevatron



CDF (preliminary) 05

Double Charmonium Production

$$\sigma(e^+e^- \to J/\psi + \eta_c) \gtrsim 25.6 \pm 2.8 \pm 3.4 \text{ fb} \quad \texttt{Belle 04}$$

$$\sigma(e^+e^- \to J/\psi + \eta_c) \gtrsim 17.6 \pm 2.8^{+1.5}_{-2.1} \text{ fb} \quad \texttt{BaBar 05}$$

$$\sigma(e^+e^- \to J/\psi + \eta_c) = 3.78 \pm 1.26 \text{ fb} \quad \texttt{NRQCD}$$

- Includes QED interference corrections (-21%)
- Includes uncertainties from h.o. in α_s, v and matrix elements
- In Belle 04 $\sigma(e^+e^- \to J/\psi + J/\psi) < 9.1$ fb
- In Brodsky et al 03 $\sigma(e^+e^- \to J/\psi + \mathcal{G}_J) \approx 1.4$ fb where $\mathcal{G}_J$ is a J^{++} glueball, $J = 0$,2

Double Charmonium Production

$$\frac{\sigma(e^+e^- \longrightarrow J/\psi + c\bar{c})}{\sigma(e^+e^- \longrightarrow J/\psi + X)} = 0.82 \pm 0.15 \pm 0.14$$

Belle 03

$$\frac{\sigma(e^+e^- \longrightarrow J/\psi + c\bar{c})}{\sigma(e^+e^- \longrightarrow J/\psi + X)} \approx 0.1$$

Cho Leibovich 96, Baek et al 96, Yuan et al 96

Double Charmonium Production

$$\sigma(e^+e^- \to J/\psi + J/\psi) < 9.1 \text{ fb}$$

Belle 04

$$\sigma(e^+e^- \to J/\psi + J/\psi) = 8.70 \pm 2.94 \text{ fb}$$

Bodwin et al 03

4. Radiative Transitions

$J/\psi \to \gamma\, \eta_c$

Only one direct experimental measure:

$$\Gamma(J/\psi \to \eta_c \gamma) = (1.14 \pm 0.23)\,\text{keV} \qquad \texttt{Crystal Ball 86}$$

Moreover, there are several measurements of the BR $J/\psi \to \eta_c \gamma \to \phi\phi\gamma$ and one independent measurement of $\eta_c \to \phi\phi$ (Belle 03). From them one obtains

$$\Gamma(J/\psi \to \eta_c \gamma) = (2.9 \pm 1.5)\,\text{keV}$$

Combining both

$$\Gamma(J/\psi \to \eta_c \gamma) = (1.18 \pm 0.36)\,\text{keV} \qquad \texttt{PDG 04}$$

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

$J/\psi \to \gamma\,\eta_c$

$$\frac{\Gamma(J/\psi \to \eta_c\gamma)}{\Gamma(J/\psi)} = 0.013 \pm 0.004 \Rightarrow \frac{1+\kappa_c}{m_c}|M_{i:f}| = 0.40 \pm 0.05 \text{ GeV}$$

if $|M_{i:f}| = 1$ this implies:

- $\kappa_c = 0$, $m_c = 2.3 \pm 0.3$ GeV
- $\kappa_c = -0.28 \pm 0.09$, $m_c = 1.8$ GeV
- large relativistic corrections to the S-state wave functions

Eichten/QWG 02

M1 operator at $\mathcal{O}(1)$

$$-c_{\boldsymbol{\sigma}\cdot\mathbf{B}} \left\{ S^\dagger, \frac{\boldsymbol{\sigma}\cdot e\mathbf{B}^{em}}{2m} \right\} S$$

- $\boldsymbol{\sigma}\cdot e\mathbf{B}^{em}(\mathbf{R})$ behaves like the identity operator.
- to all orders $c_{\boldsymbol{\sigma}\cdot\mathbf{B}}$ does not get soft contributions.
- hard contributions are known:

$$c_{\boldsymbol{\sigma}\cdot\mathbf{B}} \equiv 1 + \kappa_c = 1 + \frac{2\alpha_s(m_c)}{3\pi} + \cdots$$

- No large quarkonium anomalous magnetic moment!

Brambilla Jia Vairo 05

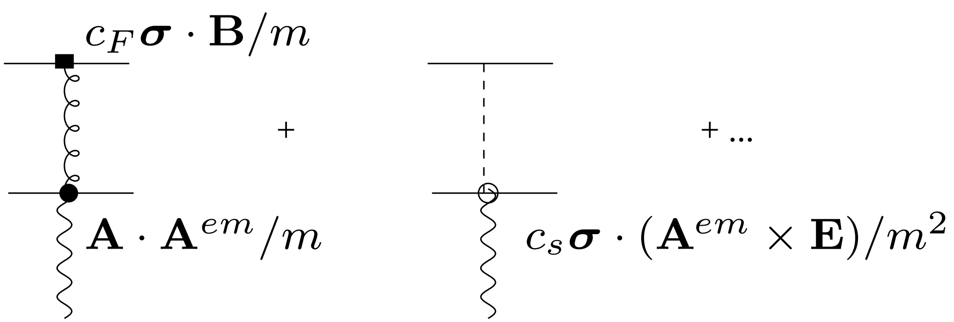
M1 operators at $\mathcal{O}(v^2)$

$$-c_{p^2\boldsymbol{\sigma}\cdot\mathbf{B}} \left\{ S^\dagger, \frac{\boldsymbol{\sigma}\cdot e\mathbf{B}^{em}}{4m^3} \right\} \boldsymbol{\nabla}_r^2 S$$

- $c_{p^2\boldsymbol{\sigma}\cdot\mathbf{B}} = -1 - \frac{2\alpha_{\rm s}(m_c)}{9\pi} + \cdots$

M1 operators at $\mathcal{O}(v^2)$

$$-c_{r\boldsymbol{\sigma}\cdot\mathbf{B}} \left\{ S^\dagger, \frac{\boldsymbol{\sigma}\cdot e\mathbf{B}^{em}}{12m^2} \right\} S$$



= (hard) $\times$ (soft)

- to all orders (hard) $= 2c_F - c_s = 1$; (soft) $= -rV_s'$
  (due to reparametrization/Poincaré invariance)
- Therefore $c_{r\boldsymbol{\sigma}\cdot\mathbf{B}} = -rV_s'$
- No scalar interaction!

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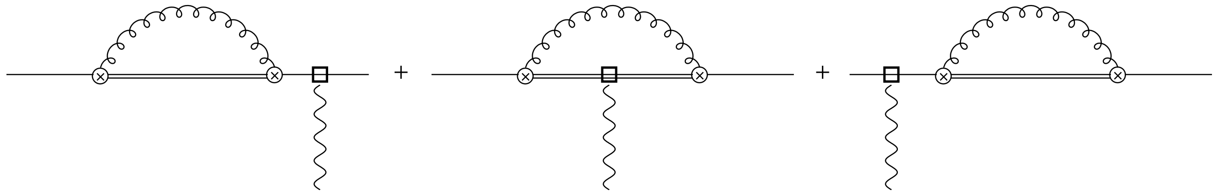
M1 operators at $\mathcal{O}(v^2)$

Coupling of photons with octets: $-c_{\boldsymbol{\sigma}\cdot\mathbf{B}} \left\{ O^\dagger, \frac{\boldsymbol{\sigma} \cdot e\mathbf{B}^{em}}{2m} \right\} O$



= 0

- If $mv^2 \sim \Lambda_{\rm QCD}$ the above graphs are potentially of order $\Lambda_{\rm QCD}^2/(mv)^2 \sim v^2$.
- The contribution vanishes because $\boldsymbol{\sigma} \cdot e\mathbf{B}^{em}(\mathbf{R})$ behaves like the identity operator.

- There are no non-perturbative contributions at $\mathcal{O}(v^2)$!

$J/\psi \to \gamma\,\eta_c$

Up to order v^2 the transition $J/\psi \to \gamma\eta_c$ is completely accessible by perturbation theory.

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

The normalization scale for the α_s inherited from κ_c is the charm mass ($\alpha_s(M_{J/\psi}/2) \approx 0.35 \sim v^2$), and for the α_s, which comes from the Coulomb potential, is the typical momentum transfer $p_{J/\psi} \approx mC_F\alpha_s(p_{J/\psi})/2 \approx 0.8$ GeV $\sim mv$.

$\Gamma(J/\psi \to \eta_c\gamma) = (1.5 \pm 1.0)$ keV.

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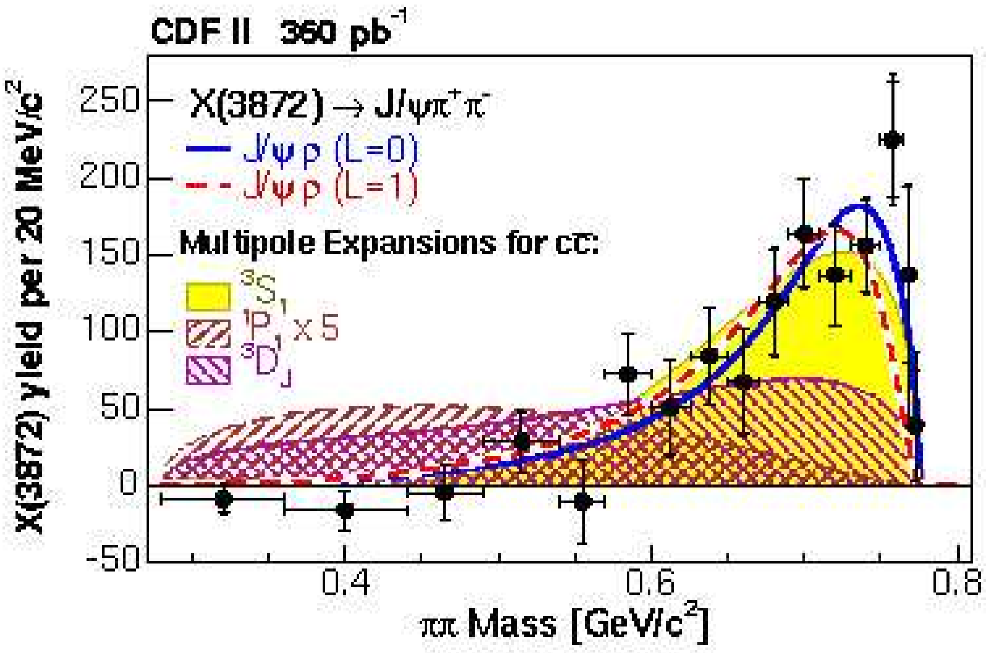
M1 (hindered and allowed) transitions between higher charmonium states and all E1 transitions involve strongly coupled bound states. The treatment has to be non-perturbative, but may go along the lines outlined before. The matching coefficients will involve Wilson loop amplitudes eventually to be calculated on the lattice.

A first QCD (quenched) lattice study of charmonium radiative transitions has been published 3 days ago. It confirms that there are no large contributions to the charmonium anomalous magnetic moment.

Dudek Edwards Richards 06

Hadronic Transitions

Hadronic transitions have been very useful to discriminate the nature of the new charmonium resonances.



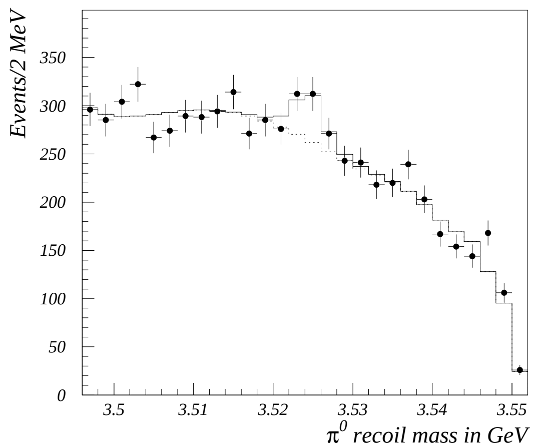
CDF 05

Relativistic corrections have been studied so far only in phenomenological models:

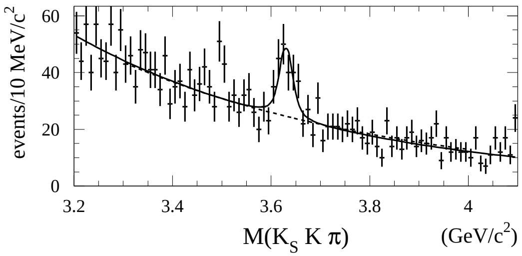
(i) QCD multipole expansion;

(ii) Chiral Lagrangian for heavy mesons.

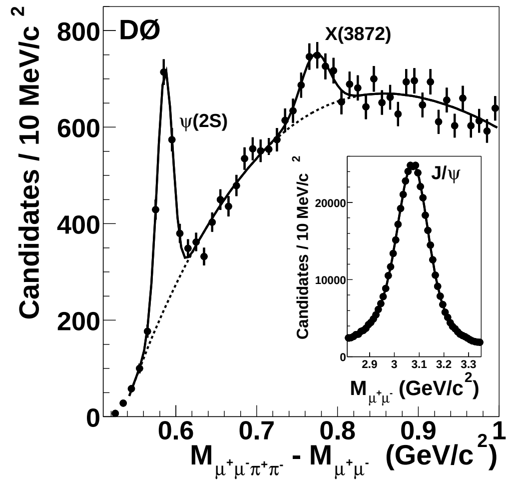
5. New Spectroscopy



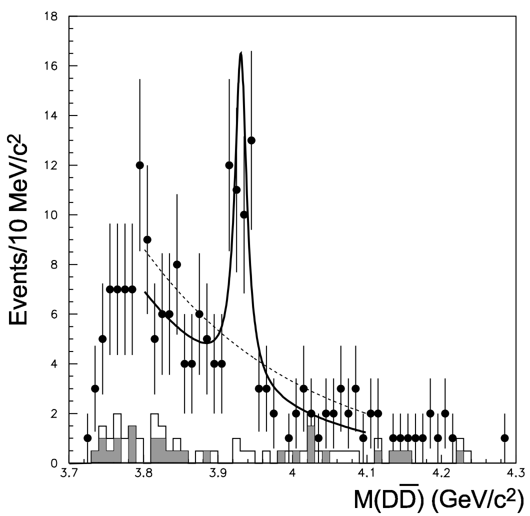
$h_c(3523)$ CLEO 05 E835 05



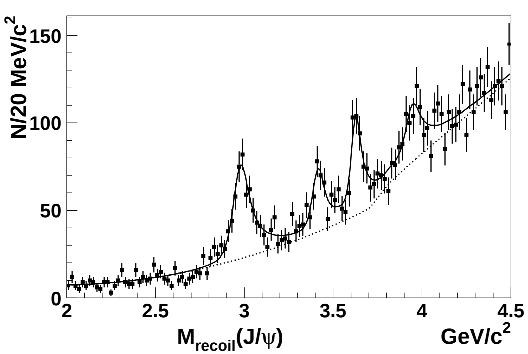
$\eta_c(2S)(3630)$ BaBar 04 CLEO 04 Belle 02



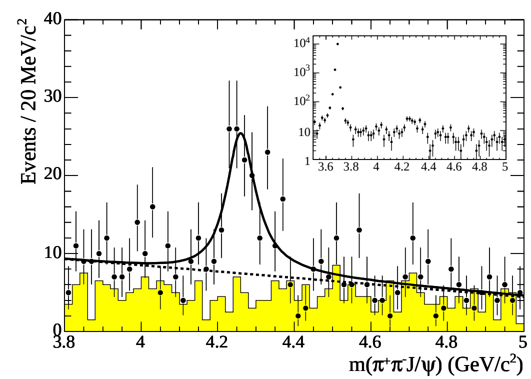
X(3872) CDF D0 04 Belle 02 BaBar 05



Z(3930) Belle 05



X(3940) Belle 05



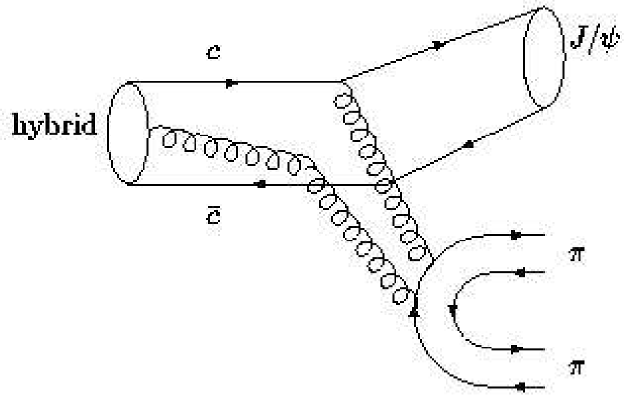
Y(4260) BaBar 05

Many interpretations have been proposed for the X, Y, Z: ordinary quarkonium states, hybrid mesons, $D\bar{D}^*$ molecules, four-quark states, ...

Even if some of the states are exotic states, like hybrids, due to the heavy mass of the quarks, factorization and analytic approaches may provide insights.

As an example, we consider the Y(4260) case and a possible hybrid interpretation of it.

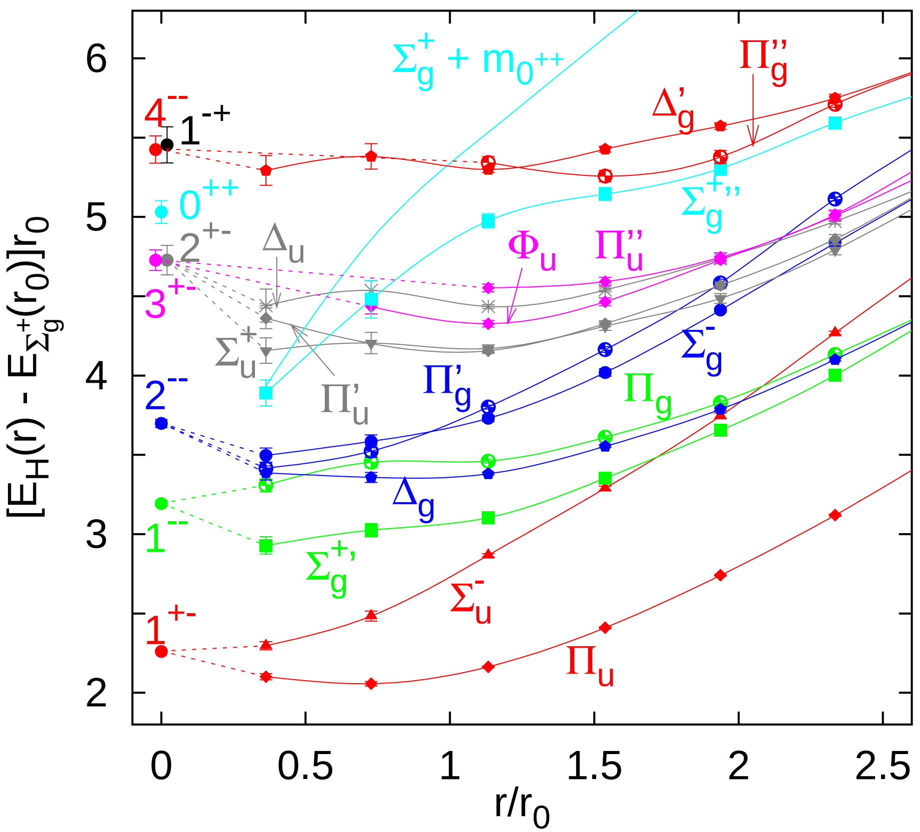
Kou Pene 05



Y(4260) is generated from initial state radiation in $e^+e^- \to \gamma\, J/\psi\, \pi^+\pi^- \Rightarrow J^{PC} = 1^{--}$

$$|Y\rangle = |\Pi_u\rangle \otimes |\phi\rangle$$

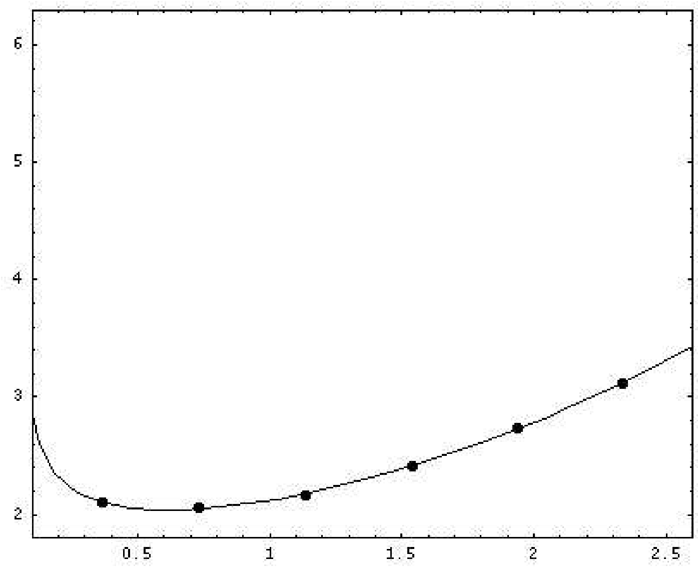
- $|\Pi_u\rangle$ is a 1^{+-} static hybrid state.
- $|\phi\rangle$ $(P = -1)$ is the solution of the Schrödinger equation whose potential is the static energy of $|\Pi_u\rangle$.



Juge Kuti Morningstar 00, 03

J^{PC}	H	$\Lambda_H^{\mathrm{RS}} r_0$	Λ_H^{RS}/GeV
1^{+-}	B_i	2.25(39)	0.87(15)
1^{--}	E_i	3.18(41)	1.25(16)
2^{--}	$D_{\{i}B_{j\}}$	3.69(42)	1.45(17)
2^{+-}	$D_{\{i}E_{j\}}$	4.72(48)	1.86(19)
3^{+-}	$D_{\{i}D_jB_{k\}}$	4.72(45)	1.86(18)
0^{++}	$\mathbf{B}^2$	5.02(46)	1.98(18)
4^{--}	$D_{\{i}D_jD_kB_{l\}}$	5.41(46)	2.13(18)
1^{-+}	$(\mathbf{B}\wedge\mathbf{E})_i$	5.45(51)	2.15(20)

Foster Michael 99, Bali Pineda 03



Fitting the Π_u curve, $E_{\Pi_u} = (0.87 + 0.11/r + 0.24\,r^2)$ GeV
and solving the Schrödinger equation, one gets

$$M(Y) = 2 \times 1.48 + 0.87 + 0.53 = 4.36 \quad \text{GeV}$$

- Solving the Schrödinger equation provides the wave function, making, in principle, possible the calculation of decay and transition widths.
- However, to do a full analysis this is not sufficient. An EFT for states over threshold is needed.

Conclusion

Charmonium physics provides a place where low-energy QCD and its rich structure may be studied in a controlled and systematic way, combining perturbative QCD, lattice calculations, and effective field theory analytical methods.