Charmonia on the Lattice

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New states

Spectroscopy: $n_f = 0$ and $n_f > 0$

Radiative transitions

Quarkonium decay and mixing

Summary

IHEP Beijing, 7.6.6

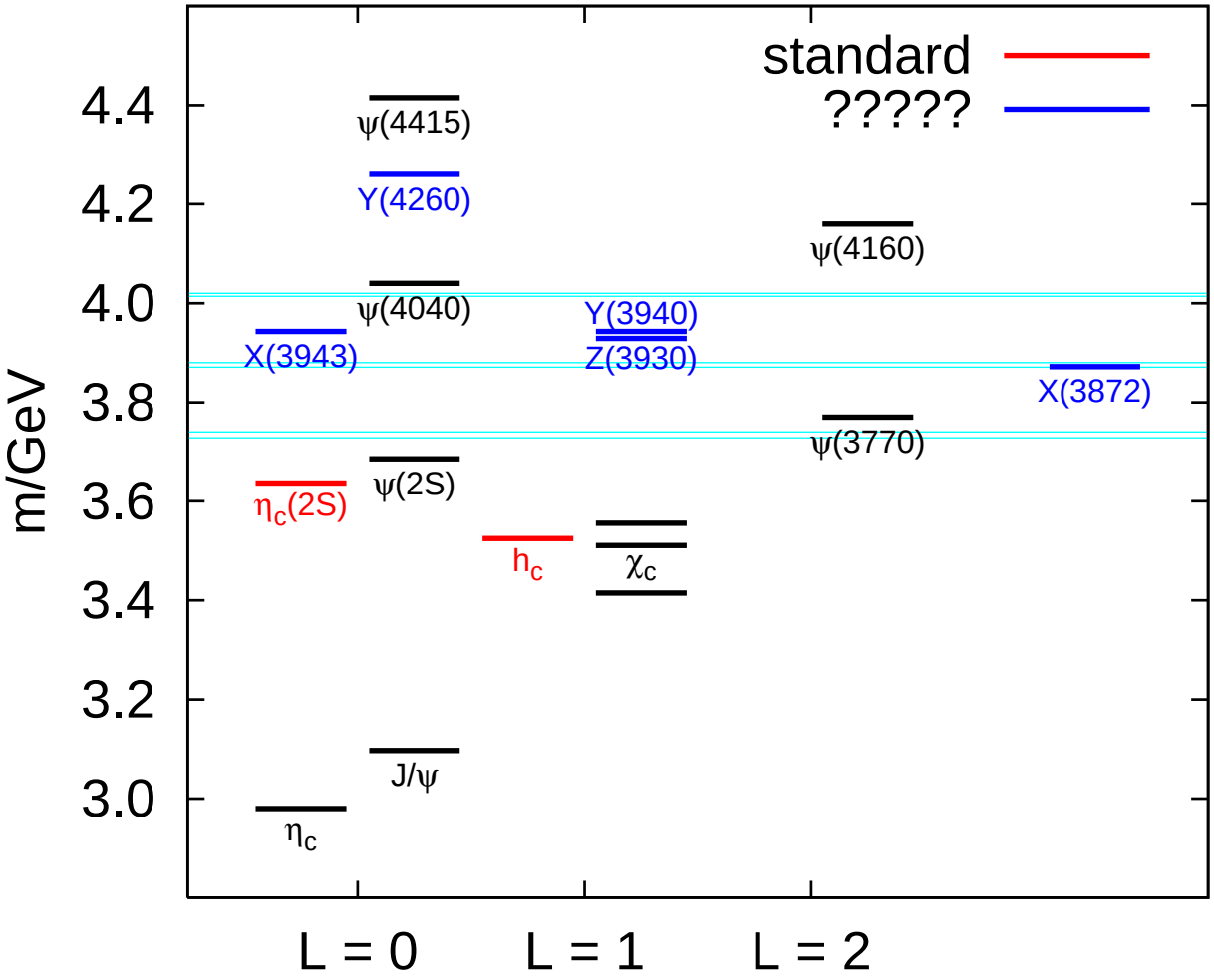
Spectroscopy: exciting times

First time in > 20 years: several new narrow < 10 MeV resonances!

- ★ Υ D wave(s)
- ★ B_c
- ★ η_c', h_c
- ★ $X(3872), X(3943)$
- ★ $D_{sJ}^*(2317)$, $D_{sJ}^*(2460)$, more D_{sJ}^*'s ???
- ★ Baryonic news

1974 – 1977: 10 $c\bar{c}$ resonances, 1978 – 2001: 0 $c\bar{c}$'s

2002 – 2005: 7 new $c\bar{c}$'s discovered by BaBar, Belle, CLEO-c, CDF, D0



new detectors

higher luminosity

new channels:

B decays

$\gamma\gamma$

$\psi\psi$-production

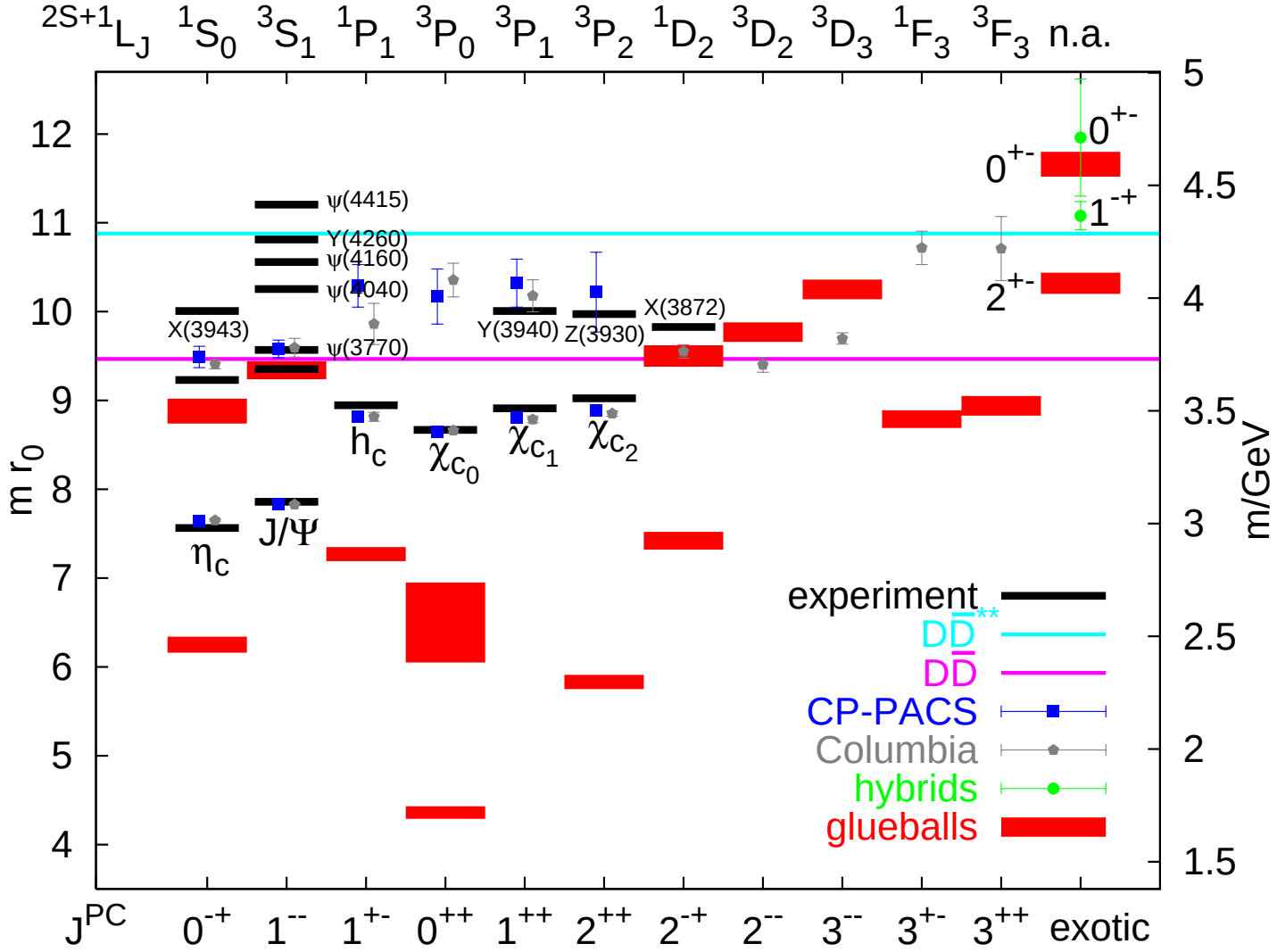
gg in $p\bar{p}$ collisions.

$c\bar{c}g$ hybrids ?

$c\bar{q}q\bar{c}$ in $c\bar{c}$?

Quenched Lattice: glueballs, charmonia and hybrids

(No "disconnected diagramms" and no sea quarks $\longrightarrow$ no mixing $G, c\bar{c}, c\bar{q}q\bar{c}$, no decay !)



quark mass: $m_c \approx 1.3$ GeV binding energies: $\bar{\Lambda} \approx 400$ MeV

$La \gg \bar{\Lambda}^{-1}, \quad a \ll m_c^{-1} \quad \Longrightarrow \quad L > 20$

one possibility: anisotropy, $a_t < a_s \quad \longrightarrow \quad L_s < L_t$

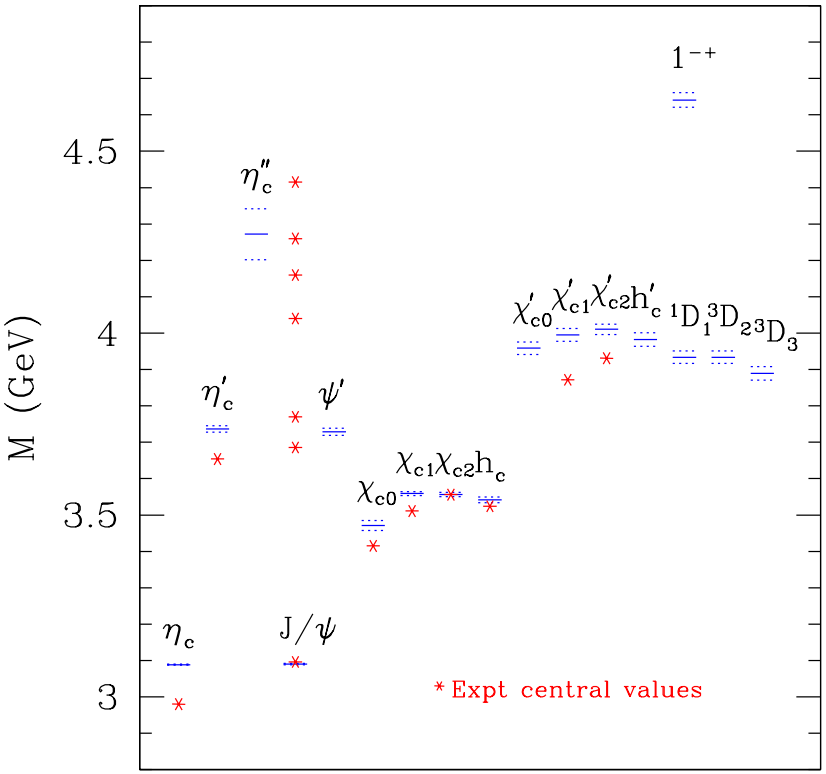
Columbia: X. Liao, T. Manke, hep-lat/0210030; P. Chen, PRD64 (01) 034509.
CP-PACS: M. Okamoto et al, PRD65 (02) 094508.
Z.-H. Mei, X.-Q. Luo, IJMP A18 (03) 5713; Y. Liu, X.-Q. Luo, PRD73 (06) 054510.

chiral fermion action and anisotropy:
S. Tamhankar et al, hep-lat/0507027.
J. Dudek, R. Edwards, D. Richards, PRD73 (06) 074507.

$a_s = a_t$:
P. Boyle, hep-lat/9903017.
QCD-Taro: S. Choe et al, JHEP 0308 (03) 022; P. de Forcrand et al, JHEP 0408 (04) 004.
UKQCD: C. McNeile et al, PRD70 (04) 034506.

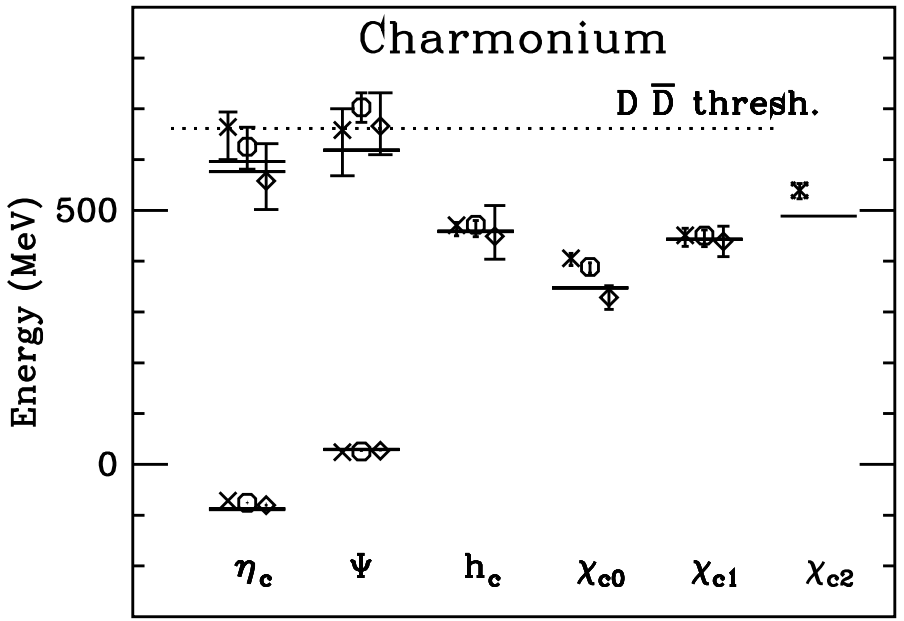
with sea quarks:
TrinLat: J. Juge et al, PoS LAT2005 (06) 029 ($n_f = 2, a_s \approx 6a_t$).
FNAL+MILC: S. Gottlieb et al, PoS LAT2005 (06) 203 ($n_f \approx 2 + 1, a_s = a_t$).

TrinLat (preliminary: $L_s = 8$!)



$a_s^{-1} \approx 1.3$ GeV

FNAL+MILC ($n_f \approx 2+1$)



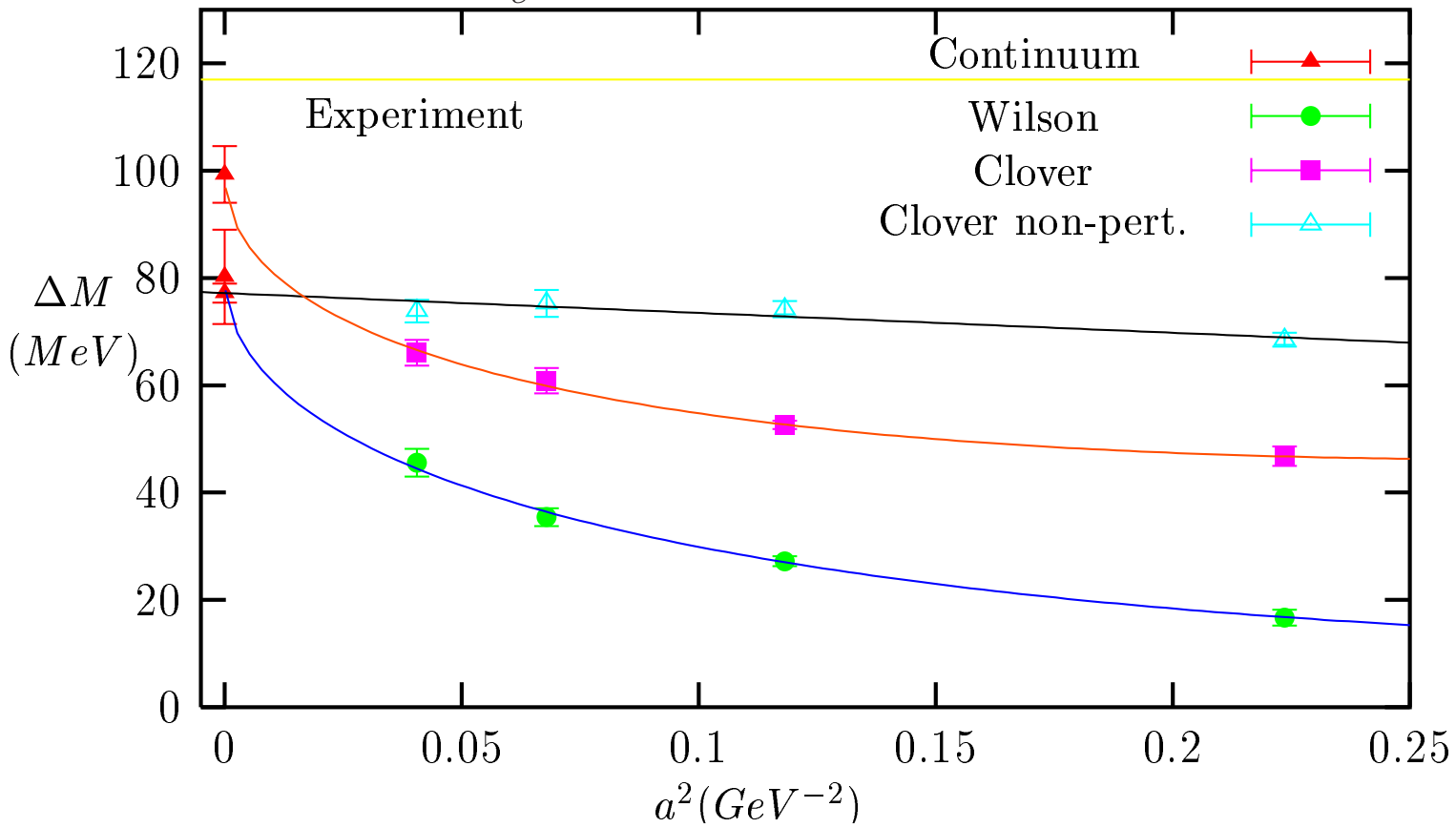
$a^{-1} \approx 1.1, 1.6, 2.3$ GeV.

TrinLat: 1^{--} $cg\bar{c}$ content of J/ψ negligible, vector $m(^3D_1) \longrightarrow m(1^3S_1)$.

T. Burch et al 03: same observation for hybrid content of Υ.

Liu & Luo 05: strong mixing with hybrid operators ????

NRQCD: $V_{FS}(r) = \frac{1}{6m_c^2}\mathbf{S}^2 V_4(r) + \cdots$. LO pQCD: $V_4 = 8\pi C_F \alpha_s \delta^3(r)$.



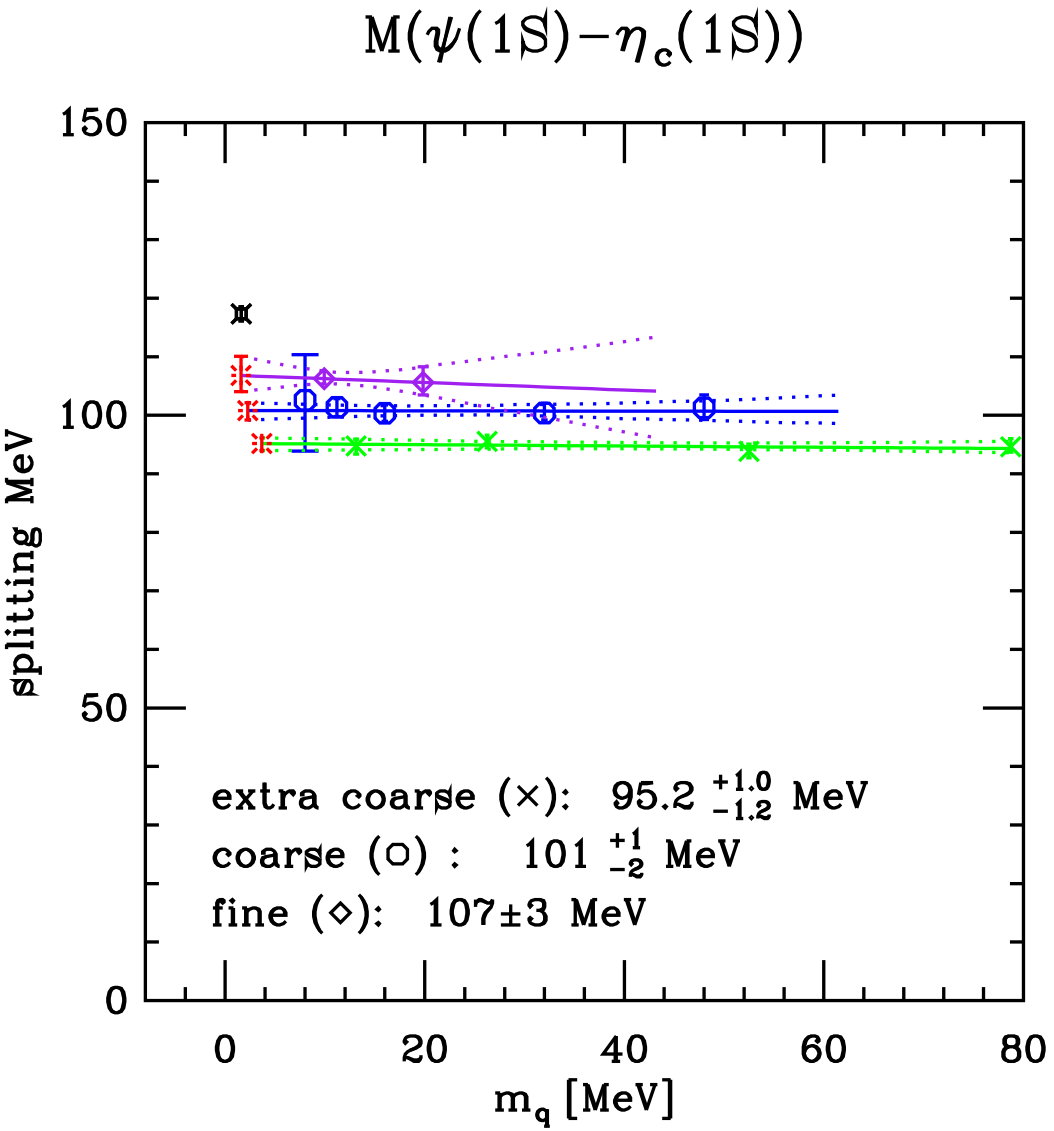
QCD-TARO: $\Delta m = m_{J/\psi} - m_{\eta_c} = 77(2)(6)$ MeV, scale from r_0.

Agrees with Columbia and CP-PACS. Scale from 1P-1S instead of r_0: $\Delta m = 89(8)$ MeV.

Tamhankar et al: $m = 88(4)$ MeV from r_0 at one lattice spacing a, small V.

Dudek et al: $\Delta m = 97(6)$ MeV but m_c 5 % too small, one a, small V.

FNAL+MILC: $n_f \approx 2+1$



$a^{-1} \approx 1.1, 1.6, 2.3$ GeV.

$\Delta M \to 117$ MeV as $a \to 0$?

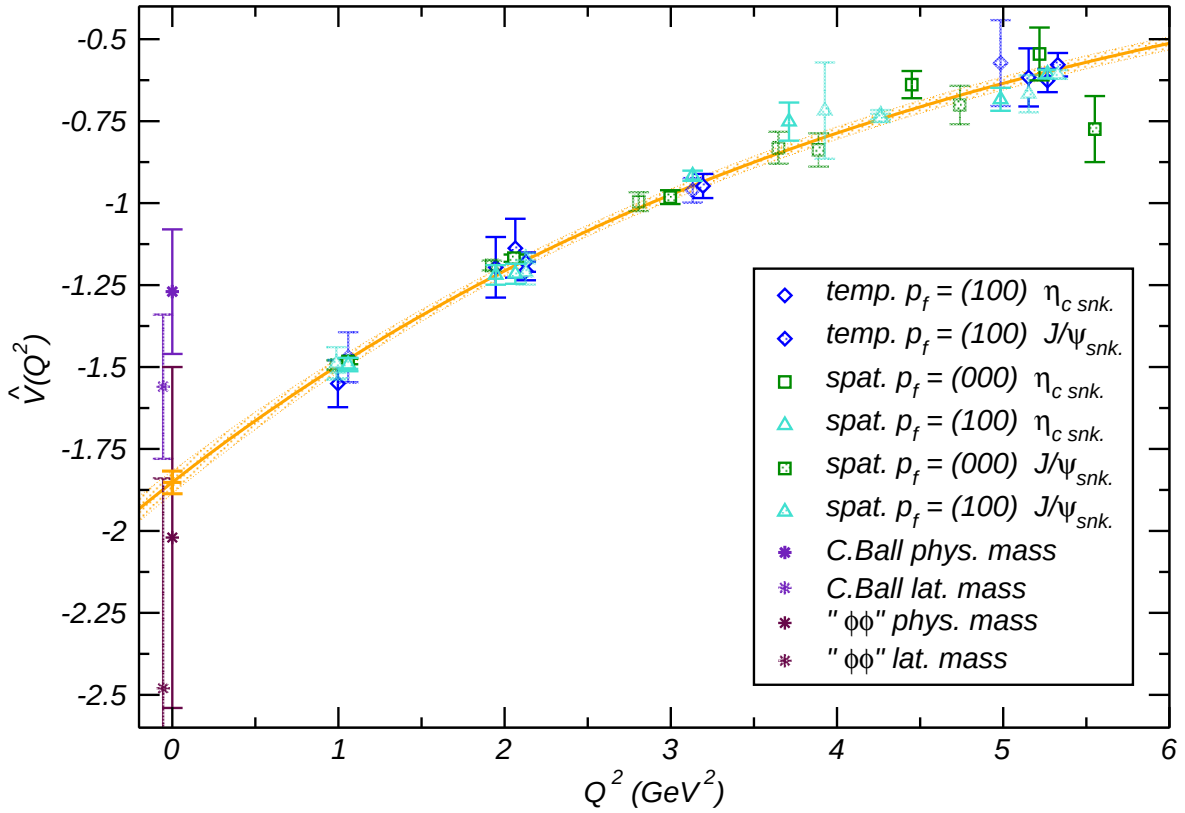
Disconnected quark line diagrams?

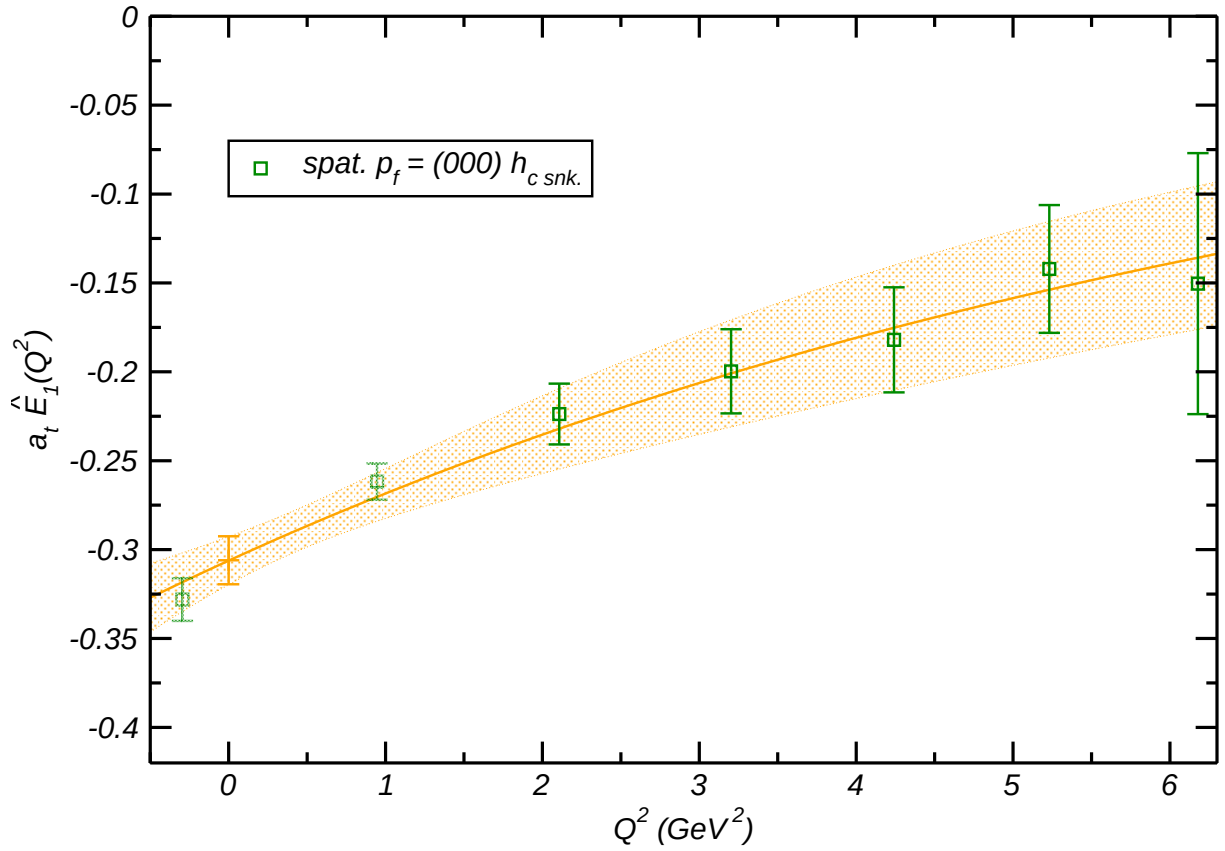
UKQCD, QCD-TARO: up to 20 MeV effect.

EM decay constants and transition rates Dudek et al 06

$$\Gamma(J/\psi \to \eta_c \gamma_{M1}) = \frac{\mathbf{q}^3}{(m_{\eta_c} + m_{J/\psi})^2} \frac{64}{27} \alpha_{\text{fs}} |\hat{V}(0)|^2$$

where $\hat{V}(Q^2)$ times kinematic factor $\propto \langle \eta_c(\mathbf{p}')|j^\mu(0)|J/\psi(\mathbf{p})\rangle$.

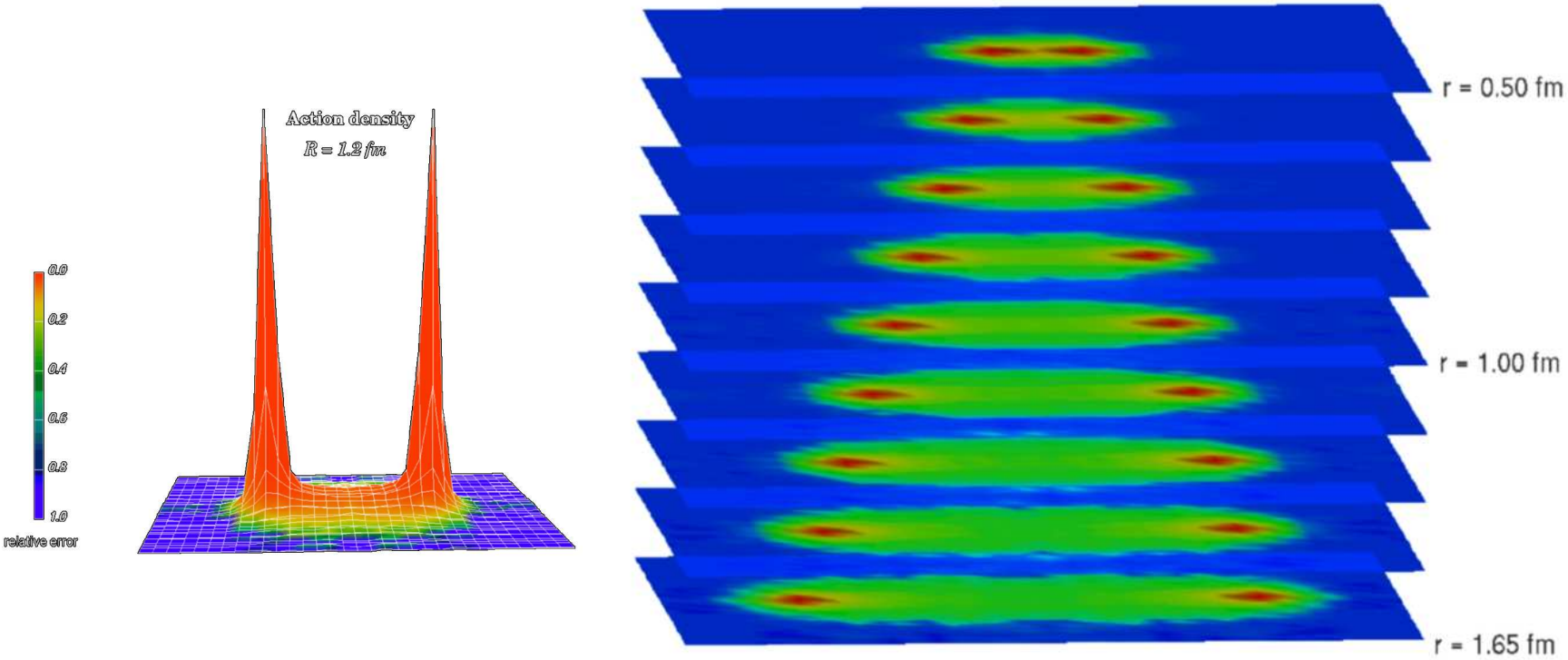




$\curvearrowright\ \Gamma(h_1 \to \eta_c \gamma_{E1,C1}) = \begin{matrix} 663(132) \\ 601(63) \end{matrix}$ keV. CLEO: $\psi' \to \pi^0 h_c$, $h_c \to \eta_c \gamma$.

Also have obtained $\chi_{c0} \to J/\psi \gamma_{E1,C1}$ and $\chi_{c1} \to J/\psi \gamma_{E1,M2,C1}$, $f_{J/\psi}, f_{\eta_c}, f_{\psi'}, f_{\eta_c'}$.

The QCD "string" 1995 GB, K. Schilling, C. Schlichter



No sea quarks !!!

String breaking: GB, H. Neff, T. Düssel, T. Lippert, Z. Prkacin, K. Schilling 04-06

Eigenstates:

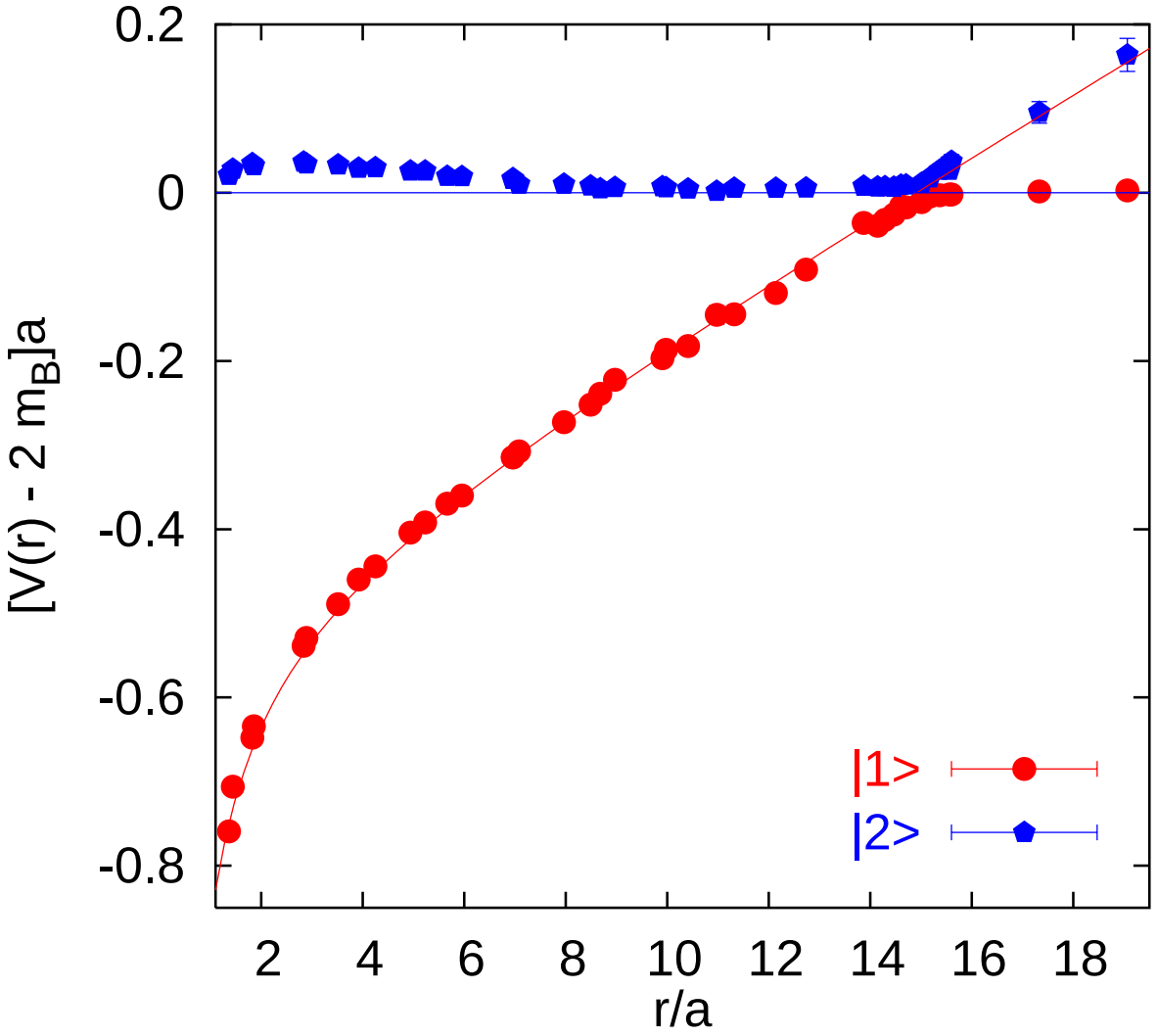
$$
\begin{aligned}
|1\rangle &= \cos\theta\,|\overline{Q}Q\rangle + \sin\theta\,|B\overline{B}\rangle \\
|2\rangle &= -\sin\theta\,|\overline{Q}Q\rangle + \cos\theta\,|B\overline{B}\rangle
\end{aligned}
$$

with $B = \overline{Q}q$.

Correlation matrix:

$$
\begin{pmatrix}
\square & \sqrt{n_f}\;\square \\
\sqrt{n_f}\;\square & -\,n_f\;\square
\end{pmatrix}
$$

Static potentials



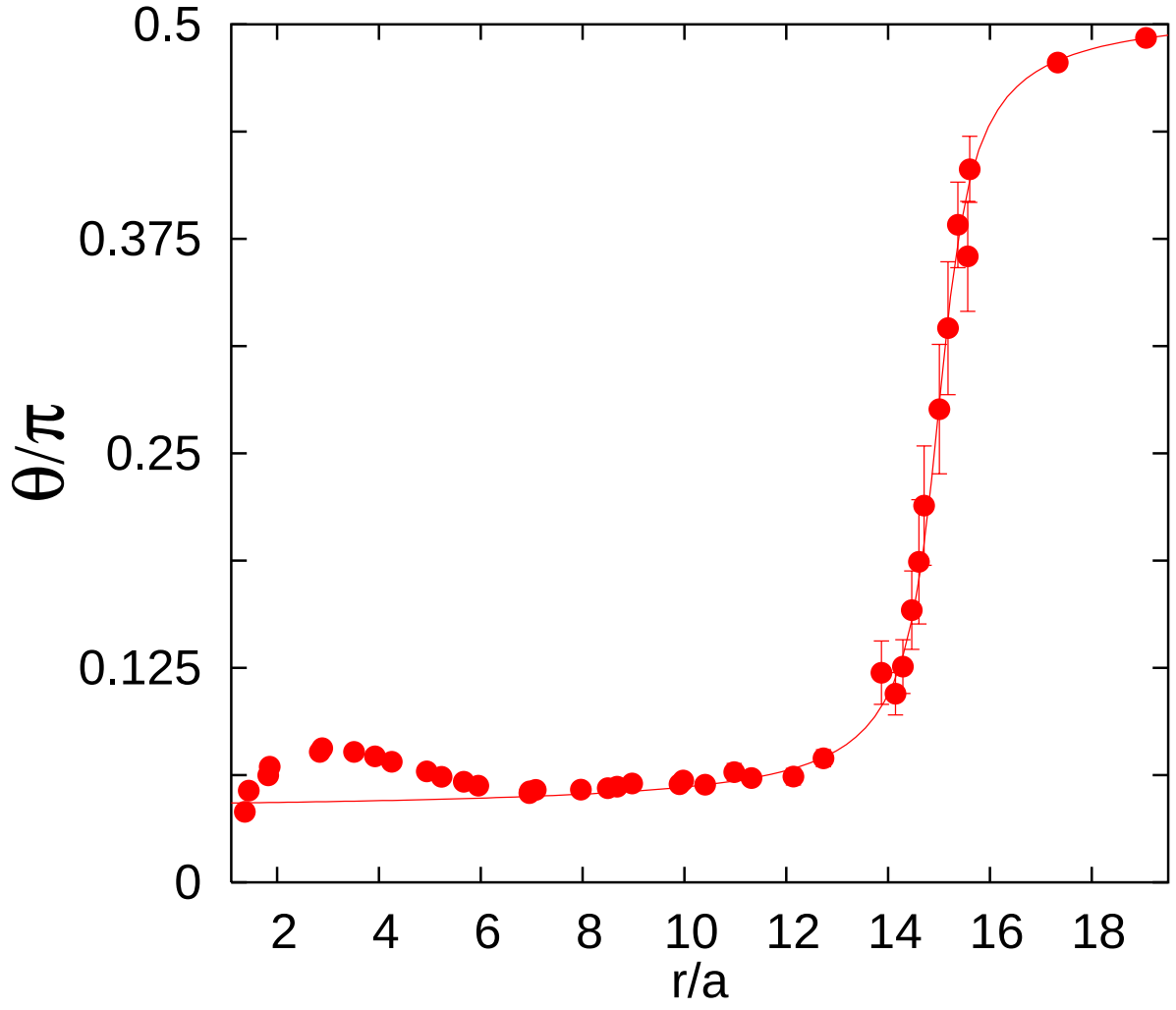
$n_f = 2$ Wilson

$m_q \approx m_s$

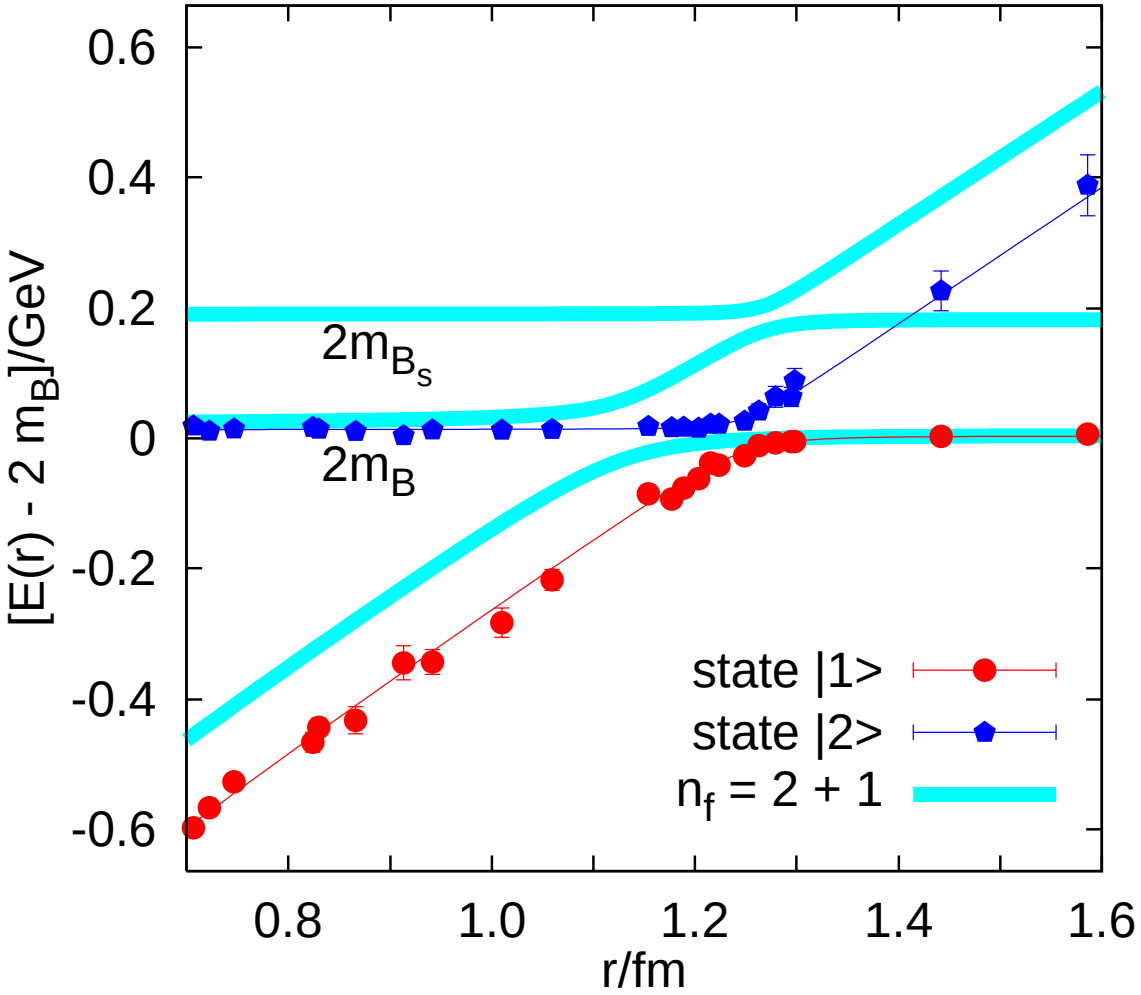
$a \approx 0.083$ fm

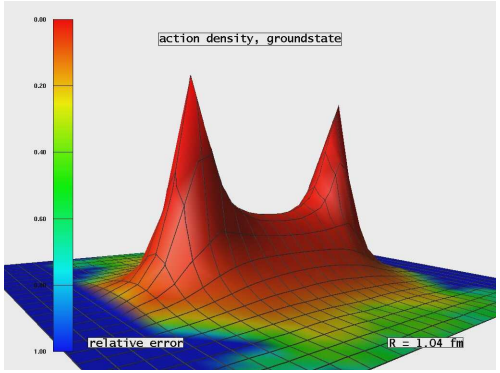
$a^{-1} \approx 2.37$ GeV

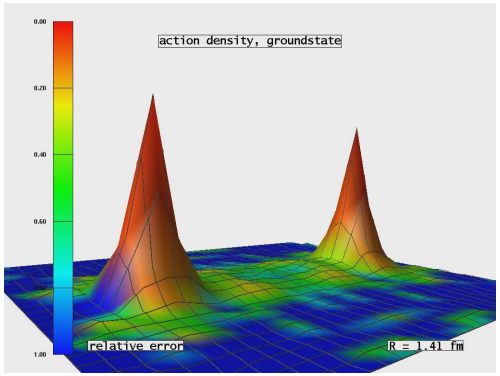
Mixing angle: $B\overline{B}$ content of ground state



String breaking in detail







Next steps:

$$c\bar{q}q\bar{c} \longleftrightarrow c\bar{c} \longleftrightarrow cg\bar{c}.$$

Sea quark mass dependence.

Quarkonium decay

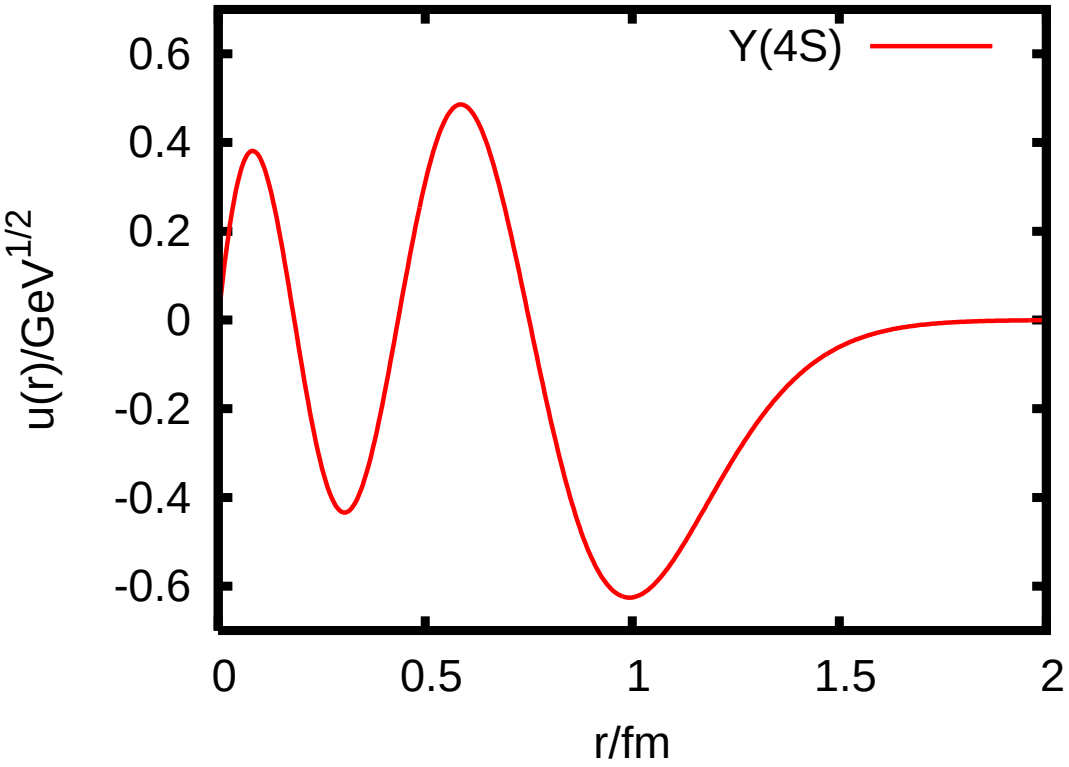
Coupled channel system: $H\psi(\mathbf{r}) = E\psi(\mathbf{r})$ with

$$H = \begin{pmatrix} \frac{1}{m_Q} & 0 \\ 0 & \frac{1}{m_B} \end{pmatrix} \mathbf{p}^2 + V(r) \quad , \quad \psi(\mathbf{r}) = \begin{pmatrix} \psi_{\overline{Q}Q}(\mathbf{r}) \\ \psi_{B\overline{B}}(\mathbf{r}) \end{pmatrix}$$

$$\begin{aligned} V(r) &= \begin{pmatrix} V_{\overline{Q}Q}(r) & g(r) \\ g(r) & V_{B\overline{B}}(r) \end{pmatrix} \\ &= \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} V_1(r) & 0 \\ 0 & V_2(r) \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \end{aligned}$$

$V_{B\overline{B}}(r) \approx 2M_B, \quad \theta = \theta(r)$

Decay rate: $\Gamma = 2\pi \sum_{i,k} \rho(k) |\langle \mathbf{k}, i|g|\psi_{\overline{Q}Q}\rangle|^2$



$\Gamma(\Upsilon(4S) \to B\overline{B}) \approx 5\,\text{MeV} \approx \text{experiment}/2.$

Summary

$n_F = 0$ charmonium spectrum including hybrids under control.

Is L a good quantum number? D wave vs. S wave J/ψ!

Is c "light"? $m_c/\overline{\Lambda} \approx 3, v > 0.5$, overlap with glueball spectrum.

Disconnected diagrams have 0–20 MeV effect. First calculations.

First steps towards $n_F = 2 + 1$.

Promising studies of EM decay and transition rates.

Results with full $c\bar{c}$, $cg\bar{c}$, $c\bar{q}q\bar{c}$ basis at Charm 2008?