Charmonium Spectroscopy

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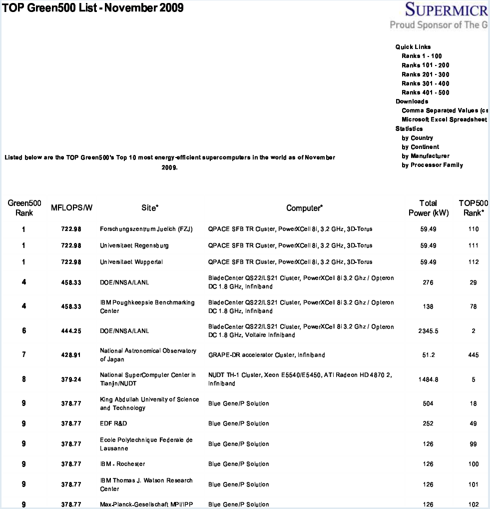
Universität Regensburg

FAIR Lattice QCD Days

GSI, 23 November 2009

Lattice QCD spin off

QPACE



TOP Green500 List - November 2009

Quick Links
- Ranks 1 - 100
- Ranks 101 - 200
- Ranks 201 - 300
- Ranks 301 - 400
- Ranks 401 - 500

Downloads
- Comma Separated Values (cs
- Microsoft Excel Spreadsheet

Statistics
- by Country
- by Continent
- by Manufacturer
- by Processor Family

Listed below are the TOP Green500's Top 10 most energy-efficient supercomputers in the world as of November 2009.

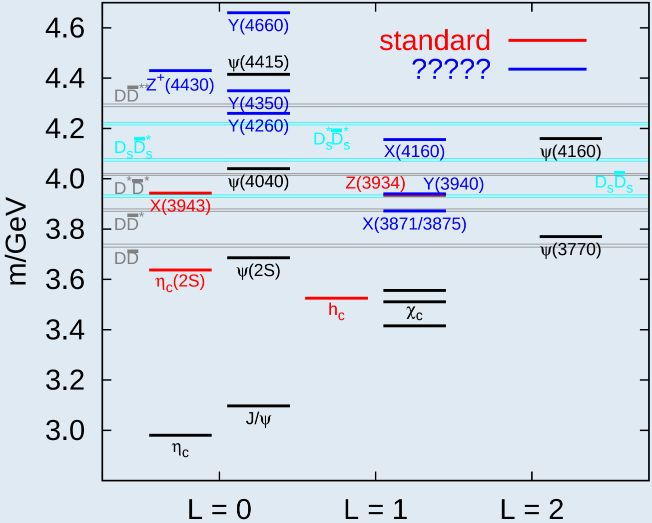
Green500 Rank	MFLOPS/W	Site*	Computer*	Total Power (kW)	TOP500 Rank*
1	722.98	Forschungszentrum Juelich (FZJ)	QPACE SFB TR Cluster, PowerXCell 8i, 3.2 GHz, 3D-Torus	59.49	110
1	722.98	Universitaet Regensburg	QPACE SFB TR Cluster, PowerXCell 8i, 3.2 GHz, 3D-Torus	59.49	111
1	722.98	Universitaet Wuppertal	QPACE SFB TR Cluster, PowerXCell 8i, 3.2 GHz, 3D-Torus	59.49	112
4	458.33	DOE/NNSA/LANL	BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 Ghz / Opteron DC 1.8 GHz, Infiniband	276	29
4	458.33	IBM Poughkeepsie Benchmarking Center	BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 Ghz / Opteron DC 1.8 GHz, Infiniband	138	78
6	444.25	DOE/NNSA/LANL	BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 Ghz / Opteron DC 1.8 GHz, Voltaire Infiniband	2345.5	2
7	428.91	National Astronomical Observatory of Japan	GRAPE-DR accelerator Cluster, Infiniband	51.2	445
8	379.24	National SuperComputer Center in Tianjin/NUDT	NUDT TH-1 Cluster, Xeon E5540/E5450, ATI Radeon HD 4870 2, Infiniband	1484.8	5
9	378.77	King Abdullah University of Science and Technology	Blue Gene/P Solution	504	18
9	378.77	EDF R&D	Blue Gene/P Solution	252	49
9	378.77	Ecole Polytechnique Federale de Lausanne	Blue Gene/P Solution	126	99
9	378.77	IBM - Rochester	Blue Gene/P Solution	126	100
9	378.77	IBM Thomas J. Watson Research Center	Blue Gene/P Solution	126	101
9	378.77	Max-Planck-Gesellschaft MPI/IPP	Blue Gene/P Solution	126	102

- The new Charmonia
- Lattice spectroscopy
- Fine structure
- Disconnected quark lines 1: $c\bar{c} \leftrightarrow \bar{q}q$
- Disconnected quark lines 2: $c\bar{c} \leftrightarrow c\bar{q}q\bar{c}$
- Outlook

Own charmonium results from GB & Christian Ehmann,
`arXiv:0710.0256`, `arXiv:0903.2947`, `arXiv:0911.1238`

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

2002 – 2008: $\leq$ 12 new $c\bar{c}$'s found by BaBar, Belle, CLEO-c, CDF, D0



new detectors

higher luminosity

new channels:

B decays

$\gamma\gamma$

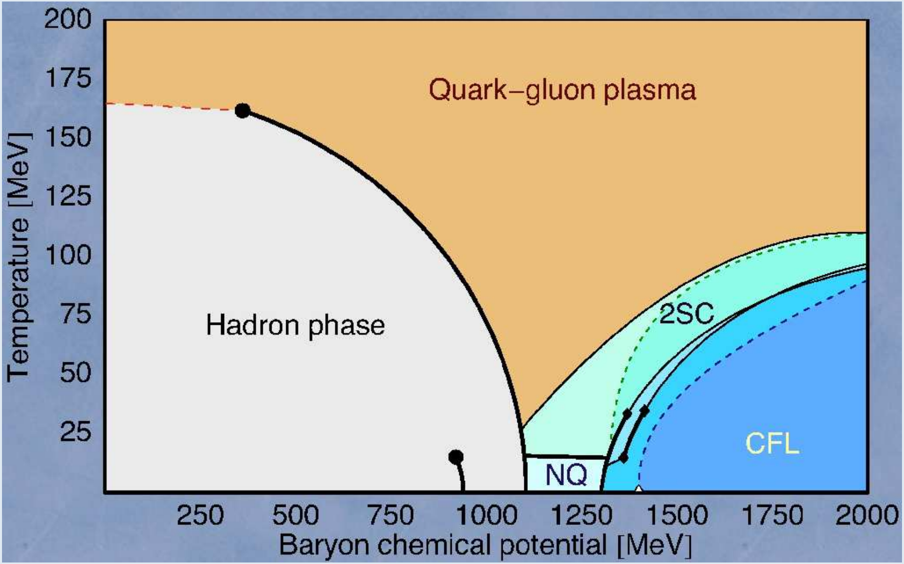
$\psi\psi$-production

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

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

$cg\bar{c}$ hybrids ?

Possible QCD phase diagram: diquarks ?

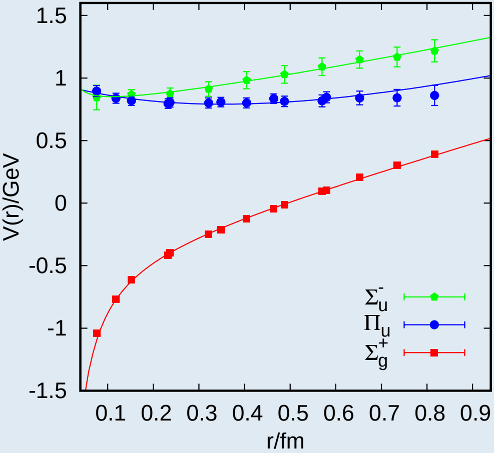


Hybrid mesons

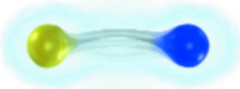
$m_c \gg \Lambda_{\rm QCD} \longrightarrow$ Adiabatic and non-relativistic approximations:

$$H\psi_{nlm} = E_{nl}\psi_{nlm} \quad , \quad H = 2m_c + \frac{p^2}{m_c} + V(r)$$

Lattice:



hybrid potential:



Input: $\mathcal{L}_{\mathcal{QCD}} = -\frac{1}{16\pi\alpha_L} FF + \bar{q}_f(\not{D} + m_f)q_f$

$$\begin{aligned} m_N^{\text{latt}} &= m_N^{\text{phys}} && \longrightarrow \quad a \\ m_\pi^{\text{latt}}/m_N^{\text{latt}} &= m_\pi^{\text{phys}}/m_N^{\text{phys}} && \longrightarrow \quad m_u \approx m_d \\ &\dots \end{aligned}$$

Output: hadron masses, matrix elements, decay constants, etc...

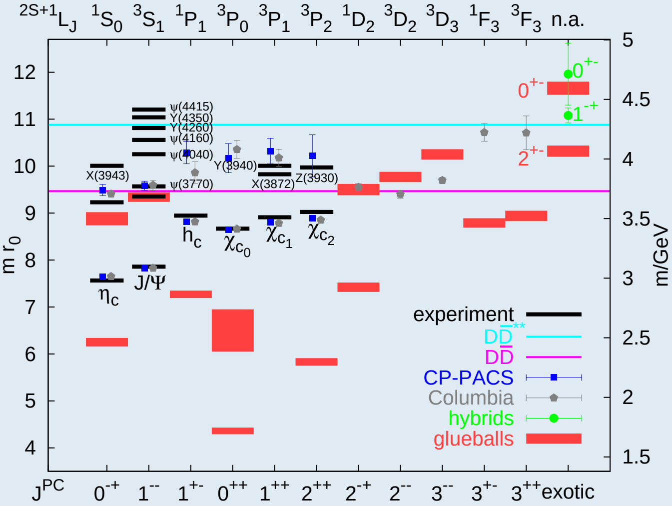
Extrapolations:

1. $a \rightarrow 0$: functional form known.
2. $L \rightarrow \infty$: harmless but often computationally expensive.
3. $m_q^{\text{latt}} \rightarrow m_q^{\text{phys}}$: chiral perturbation theory (χPT) but m_q^{latt} must be sufficiently small to start with.

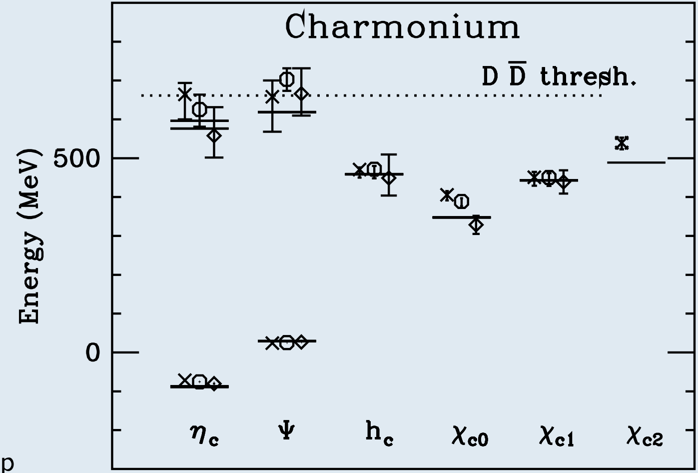
   ($m_{\text{PS}}^{\text{latt}} = m_\pi^{\text{phys}}$ has only very recently been realized.)

Quenched Lattice: glueballs, charmonia and hybrids

(No “disconnected diagrams” and no sea quarks → no mixing $G, c\bar{c}, c\bar{q}q\bar{c}$, no decay !)



First result with sea quarks 04 FNAL+MILC $(n_f \overset{?}{\approx} 2+1)$



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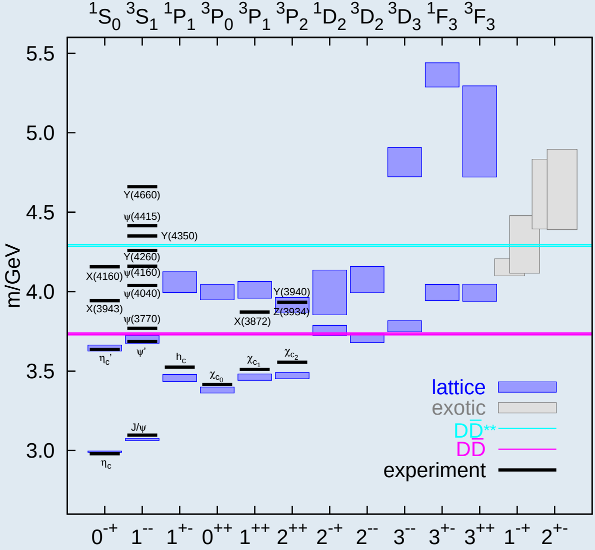
$a^{-1} \approx 1.1, 1.6, 2.3$ GeV

C Ehmann, GB ($n_f = 2$, $a^{-1} \approx 1.73$ GeV from m_N)

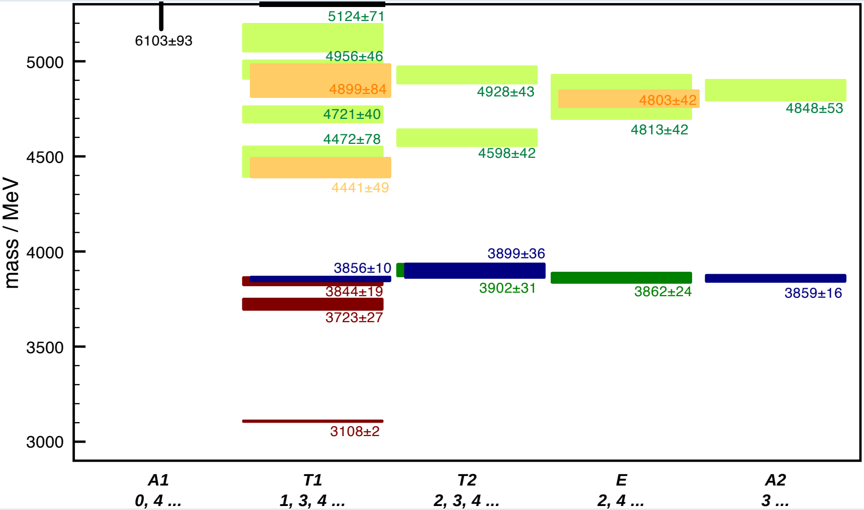


Lattice operators

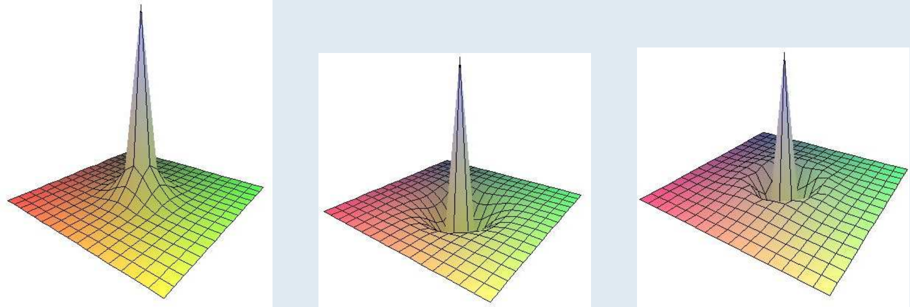
$$
\begin{aligned}
A_1 &\rightarrow J = 0, 4, \cdots \\
A_2 &\rightarrow J = 3, 6, \cdots \\
E &\rightarrow J = 2, 4, \cdots \\
T_1 &\rightarrow J = 1, 3, 4, \cdots \\
T_2 &\rightarrow J = 2, 3, 4, \cdots
\end{aligned}
$$

name	O_h repr.	J^{PC}	state	operator
a_0	A_1	0^{++}	χ_{c0}	1
π	A_1	0^{-+}	η_c	γ_5
ρ	T_1	1^{--}	J/ψ	γ_i
a_1	T_1	1^{++}	χ_{c1}	$\gamma_5\gamma_i$
b_1	T_1	1^{+-}	h_c	$\gamma_i\gamma_j$
$\pi \times \nabla$	T_1	1^{+-}	h_c	$\gamma_5\nabla_i$
$a_0 \times \nabla$	T_1	1^{--}	J/ψ	∇_i
$a_0' \times \nabla$	T_1	1^{-+}	exotic	$\gamma_4\nabla_i$
$(\rho \times \nabla)_{A_1}$	A_1	0^{++}	χ_{c0}	$\gamma_i\nabla_i$
$(\rho \times \nabla)_{T_1}$	T_1	1^{++}	χ_{c1}	$\epsilon_{ijk}\gamma_j\nabla_k$
$(\rho \times \nabla)_{T_2}$	T_2	2^{++}	χ_{c2}	$s_{ijk}\gamma_j\nabla_k$
$(a_1 \times \nabla)_{A_1}$	A_1	0^{--}	exotic	$s_{ijk}\gamma_j\nabla_k$
$(a_1 \times \nabla)_{T_2}$	T_2	2^{--}		$\gamma_5 s_{ijk}\gamma_j\nabla_k$
$(b_1 \times \nabla)_{T_1}$	T_1	1^{-+}	exotic	$\gamma_4\gamma_5\epsilon_{ijk}\gamma_j\nabla_k$
$a_0' \times D$	T_2	2^{+-}	exotic	$\gamma_4 D_i$
$(a_1 \times D)_{A_2}$	A_2	3^{++}		$\gamma_5\gamma_i D_i$
$(a_1 \times D)_{T_1}$	T_1	1^{++}	χ_{c1}	$\gamma_5 s_{ijk}\gamma_j D_k$
$(a_1 \times D)_{T_2}$	T_2	2^{++}		$\gamma_5\epsilon_{ijk}\gamma_j D_k$
$(b_1 \times D)_{A_2}$	A_2	3^{+-}		$\gamma_4\gamma_5\gamma_i D_i$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$

J-assignment for $PC = --$ J Dudek et al.



Wavefunctions after variational optimization (Coulomb gauge). CE, GB



S1 2S 3S

NRQCD: $$\Delta M = \frac{1}{6m_c^2}\langle\psi|V_4|\psi\rangle + \cdots$$

Leading order perturbation theory: $V_4(r) = 8\pi C_F \alpha_s \delta^3(r)$.

ΔM	scale from $r_0 = 0.5$ fm	scale from $1\overline{P} - 1\overline{S}$
Columbia	72(2) MeV	83(??) MeV
CP-PACS	73(1)(4) MeV	85(4)(6) MeV
QCD-TARO	77(2)(6) MeV	89(??) MeV
χQCD	88(4) MeV	121(6) MeV
JLAB	97(6) MeV	???

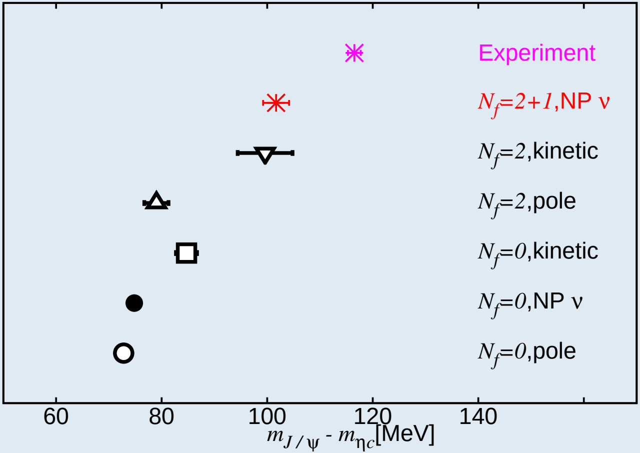
JLAB (Dudek et al): $m_c \approx 5\,\%$ too small !

χQCD (Tamhankar et al) + JLAB: only one lattice spacing a.

χQCD: $La < 0.9$ fm $\rightarrow 1\overline{P} - 1\overline{S}$ underestimated ?

Y Namekawa et al (PACS-CS, arXiv:0810.2364)

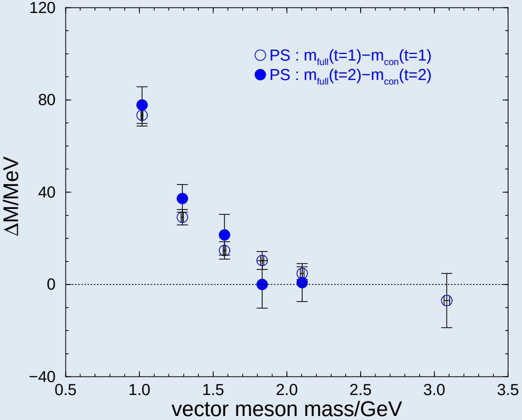
$a^{-1} \approx 2.2$ GeV from m_Ω, 310 MeV $> m_{\rm PS} \geq$ 165 MeV, $Na \approx 2.9$ fm.



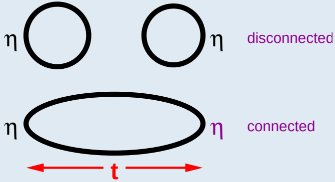
$\Delta M \to 117$ MeV as $a \to 0$?

"$I = 0$" vs. "$I = 1$" ???

Disconnected quark lines? ($n_f = 0$: P de Forcrand et al (QCD-TARO 04))



$$\Delta M = m_{``\eta"} - m_{``\pi"}$$



Disconnected diagrams $\curvearrowright$ $m_\eta > m_\pi$ $\curvearrowright$ $m_\omega - m_\eta < m_\rho - m_\pi$

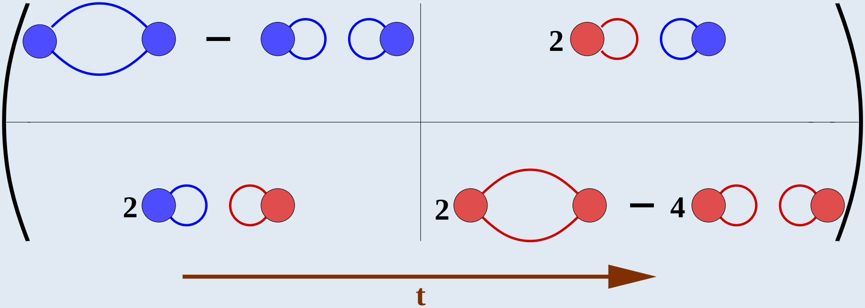
C McNeile & C Michael 04: sign change for heavy quarks ??

L Levkova & C DeTar 08: $\Delta M \approx 3 - 4$ MeV ($n_f = 0$).

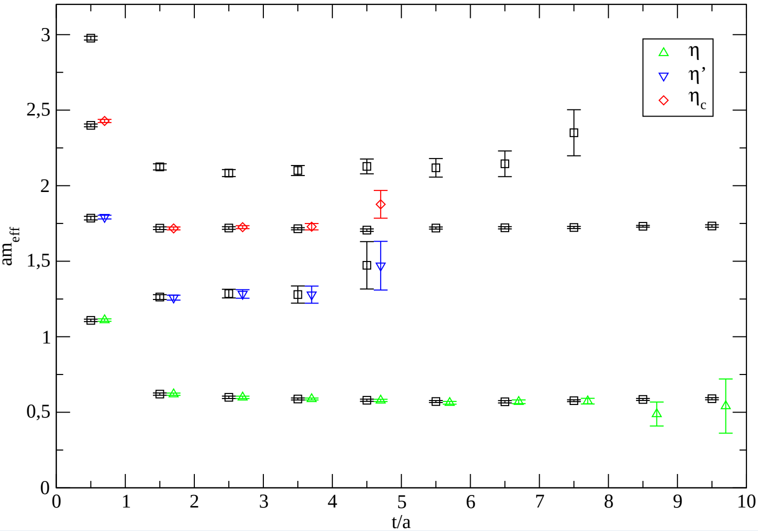
Obviously, disconnected diagrams are important, e.g.: $\psi'^{(\prime)} \leftrightarrow D\overline{D}$.

What about mixing with other $I = 0$ states?

C Ehmann, GB: $\eta_c \leftrightarrow \eta$ mixing ($n_f = 2$):

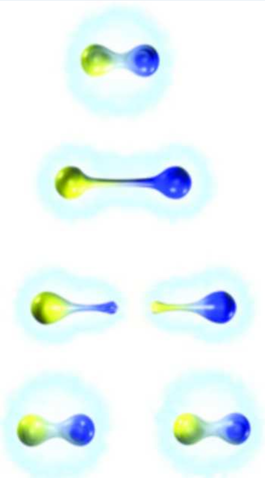


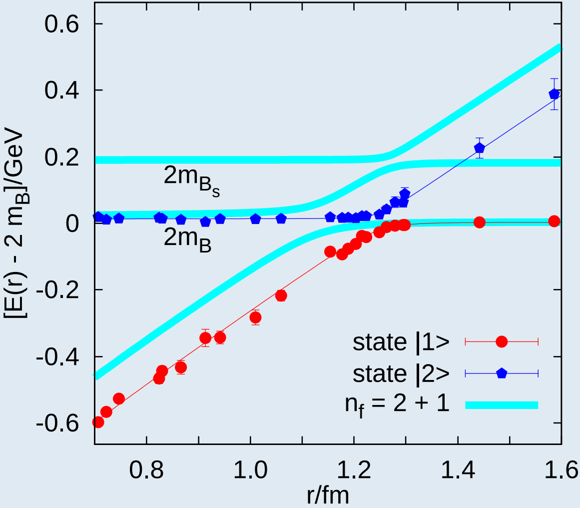
Mixing vs. no mixing:



Two state potentials

GB, H Neff, T Düssel, T Lippert, Z Prkacin, K Schilling





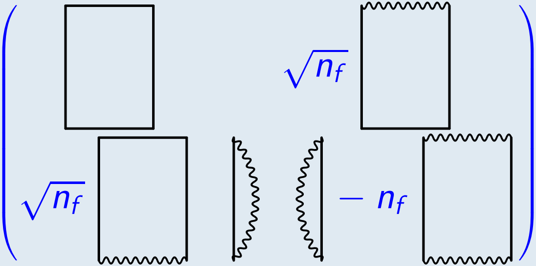
Two state system:

Eigenstates:

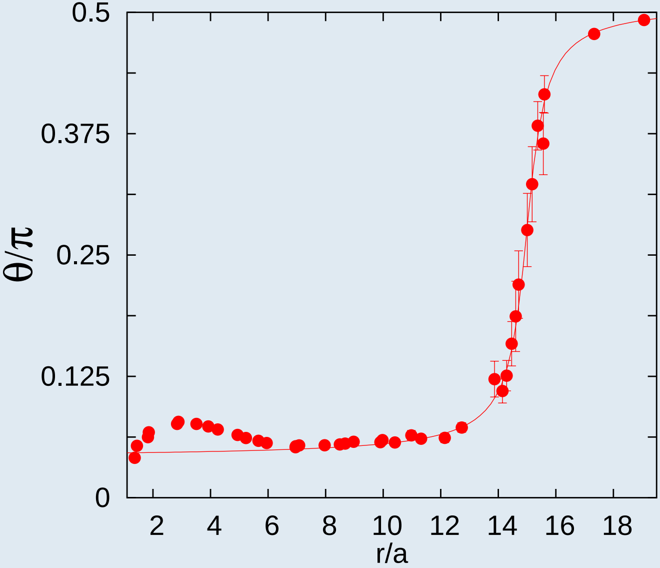
$$\begin{aligned} |1\rangle &= \cos\theta\,|\overline{Q}Q\rangle + \sin\theta\,|B\overline{B}\rangle \\ |2\rangle &= -\sin\theta\,|\overline{Q}Q\rangle + \cos\theta\,|B\overline{B}\rangle \end{aligned}$$

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

Correlation matrix:



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



$a \approx 0.083\,\mathrm{fm}$

Coupled channel potential model for threshold effects ?

Many channels ($D\overline{D}, D^*\overline{D}, D_s\overline{D}_s, D^*\overline{D}^*, \cdots$) $\Rightarrow$ many parameters!

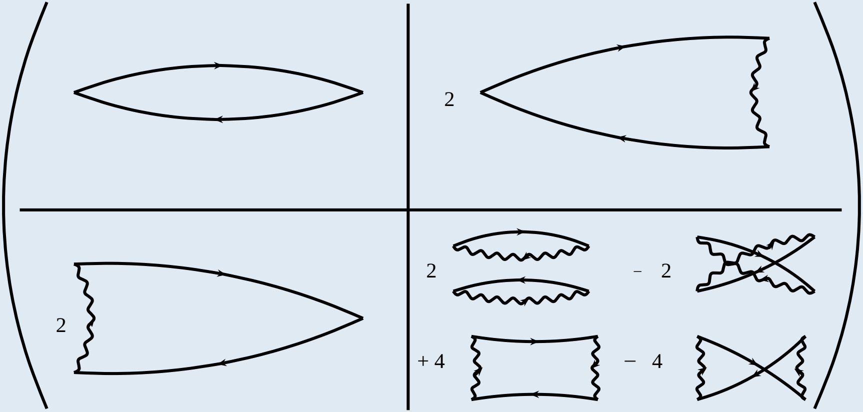
“Direct” calculation of the spectrum ?

We have to be able to resolve radial excitations!

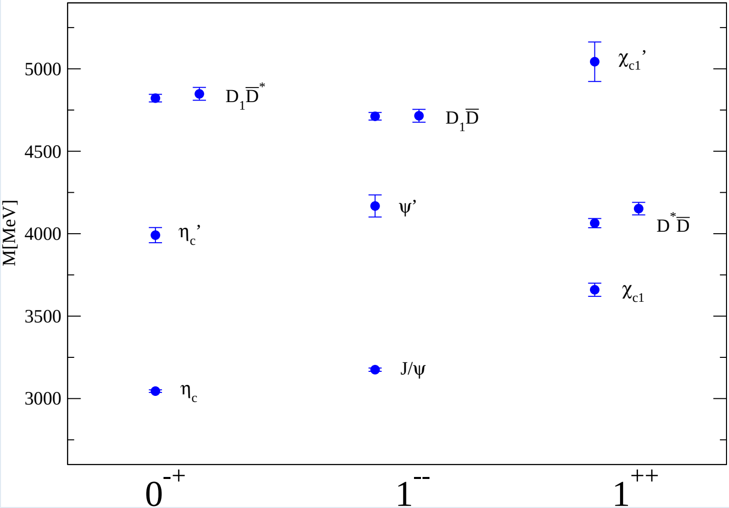
(remember e.g. the very dense 1^{--} sector.)

Required: large basis of test wavefunctions including $c\bar{c}$, $c\bar{q}q\bar{c}$ and $cg\bar{c}$ operators and good statistics.

$c\bar{c} \leftrightarrow \overline{D}D$ mixing (for $n_f = 2$):

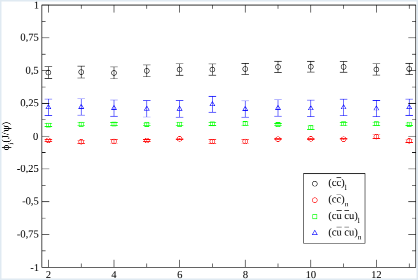


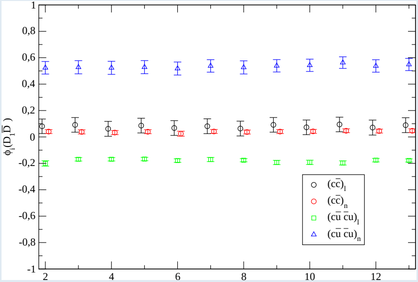
$n_f = 2,\ a^{-1} \approx 2.59\,\text{GeV},\ La \approx 1.83\,\text{fm},\ m_{\text{PS}} \approx 290\,\text{MeV}$



So far only S-waves $D\overline{D}$s ! Next step: mixing with $D_{(1)}^{(*)}\overline{D}$ P-waves.

Eigenvector components of the J/ψ. Components of the $D_1\overline{D}$.





Outlook

- $\exists$ first simulations near the physical m_π at $a^{-1} \approx 2$ GeV.
- $\exists$ first precision calculations of annihilation and mixing diagrams.
- Study of $c\bar{c} \leftrightarrow c\bar{q}q\bar{c}$ is well on its way.
- The continuum limit is important, in particular for the fine structure.
- There will be a lot of progress in charmonium spectroscopy below and above decay thresholds in the next years.
- Forces between pairs of static-light mesons for different S and I are being studied, to qualitatively understand 4-quark binding ($X(3872)$, $Z^+(4430)$ etc.).