Charmonium and Confinement from Lattice QCD (pn29se@SuperMUC-NG)

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FOR5269: Future methods for studying confined gluons in QCD

https://confluence.desy.de/display/for5269

Spokesperson: Francesco Knechtli

Main Goals:

- **Disconnected contributions in charmonium**
- **String breaking in hybrid potentials**
- Glueballs in full dynamical QCD
- Multilevel algorithms for glueballs
- Novel schemes for molecular dynamics
- **Connection of distillation and multi-grid**
- Multilevel Monte Carlo for trace estimation

Outline:

- Lattice Quantum Chromo Dynamics (LQCD)
- Hadron spectroscopy and Distillation
- Charmonium and potential results
- Outlook

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Dimensional Hierarchy

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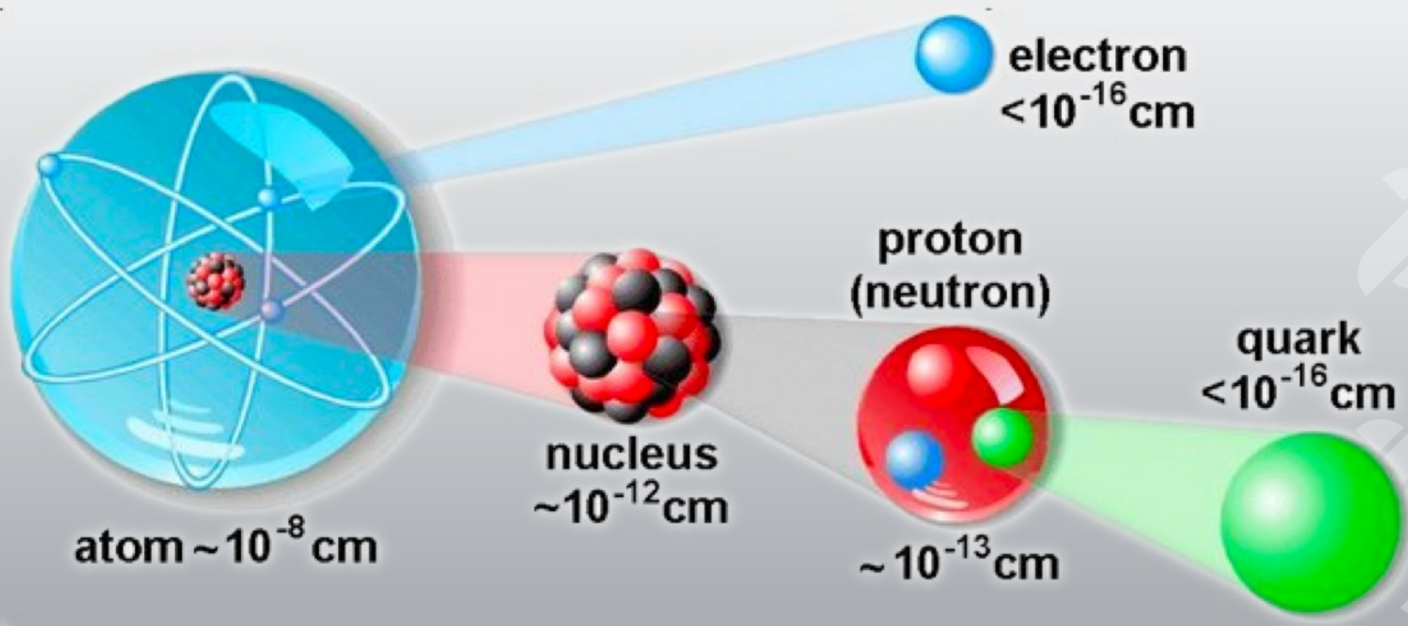

Strong force: responsible for interactions between quarks and gluons

- confines quarks into hadrons (pion, proton, neutron, etc)
- binds protons and neutrons to form nuclei of the atoms

Quantum Chromodynamics (QCD):

- fundamental theory that describes the strong interactions
- parameters: quark masses and coupling constant

The Standard Model, Elementary Particles

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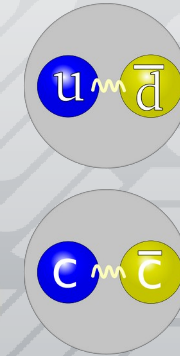
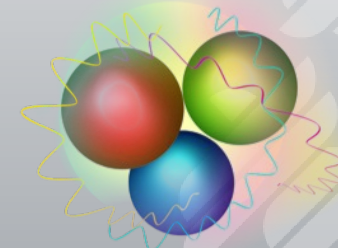
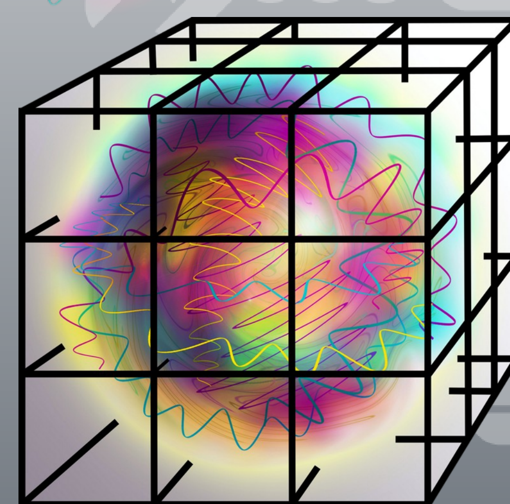
Group	Name	Symbol	mass	charge	spin
QUARKS	up	u	≈2.3 MeV/c²	2/3	1/2
QUARKS	charm	c	≈1.275 GeV/c²	2/3	1/2
QUARKS	top	t	≈173.07 GeV/c²	2/3	1/2
QUARKS	down	d	≈4.8 MeV/c²	-1/3	1/2
QUARKS	strange	s	≈95 MeV/c²	-1/3	1/2
QUARKS	bottom	b	≈4.18 GeV/c²	-1/3	1/2
LEPTONS	electron	e	0.511 MeV/c²	-1	1/2
LEPTONS	muon	μ	105.7 MeV/c²	-1	1/2
LEPTONS	tau	τ	1.777 GeV/c²	-1	1/2
LEPTONS	electron neutrino	ν_e	<2.2 eV/c²	0	1/2
LEPTONS	muon neutrino	ν_μ	<0.17 MeV/c²	0	1/2
LEPTONS	tau neutrino	ν_τ	<15.5 MeV/c²	0	1/2
GAUGE BOSONS	gluon	g	0	0	1
GAUGE BOSONS	photon	γ	0	0	1
GAUGE BOSONS	Z boson	Z	91.2 GeV/c²	0	1
GAUGE BOSONS	W boson	W	80.4 GeV/c²	±1	1
	Higgs boson	H	≈126 GeV/c²	0	0







Charmonium and confinement from Lattice QCD
Francesco Knechtli, FOR5269

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Lattice Field Theory – Lattice QCD

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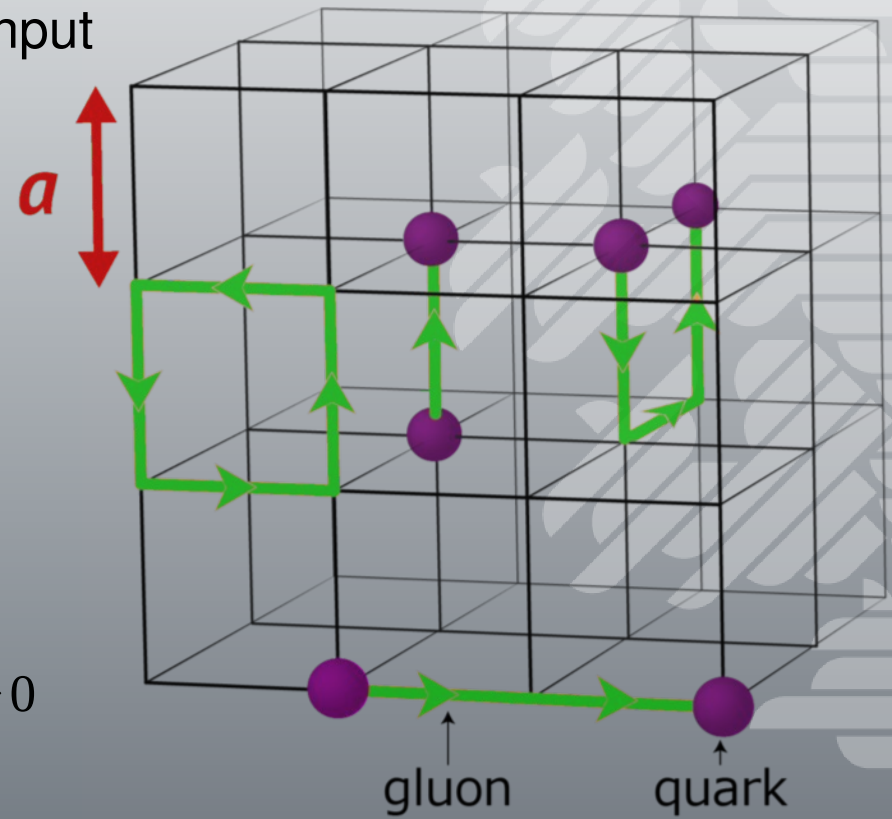
Numerical simulations of QCD using Monte Carlo methods

- well-established framework for non-perturbative QCD
- ab-initio calculations, action only input
- discretization of space-time,
- introduce lattice spacing *a*
- gluons, link variables
- quarks, covariant derivatives
- Dirac operator, quark propagator
- discretized forms must reduce

  to continuum form in the limit $a \to 0$



Hadron Spectroscopy and Distillation

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Monte Carlo methods: statistical treatment of the theory

- create gluon configurations using QCD action
- average over configurations, error
- we need 1000s of (statistically independent) configurations
- observables: correlation functions in terms of ‘quark propagators’
- building block of hadronic measurements on the lattice
- solution of the Dirac equation $D \cdot x_i = v_i$

  most intensive part of calculations
- very large (190Mx190M), but sparse matrix (most elements zero)
- highly optimized algorithms with good scaling behavior

Distillation: quark field smearing with Laplacian eigenmodes $v_i[t]$

- we need inversions to get ‘quark perambulators’ $v_i[t_1] \cdot D^{-1}_{\alpha\beta} v_j[t_2]$

N_f = 3 + 1 Lattice Ensembles

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3 degenerate light quarks (up, down, strange)
Sum of light quark masses same as in nature, pion mass m_π ~ 420 MeV

1 physical charm quark, m_{η_c}~ 3 GeV

Fine lattice: a = 0.043 fm @ β = 3.43

- B - light : 144 x 48^3

  R. Höllwieser et al., Eur. Phys. J. C 80 (2020) no. 4 349

- Charmonium are states made of a charm quark anti-quark pair
  Eigenstates J^{PC} of total angular momentum *J*, parity *P* and charge conjugation *C*

- measurement code based on “QCDlib”, a library written by us in C+MPI

Charm Correlators (ensemble B-light)

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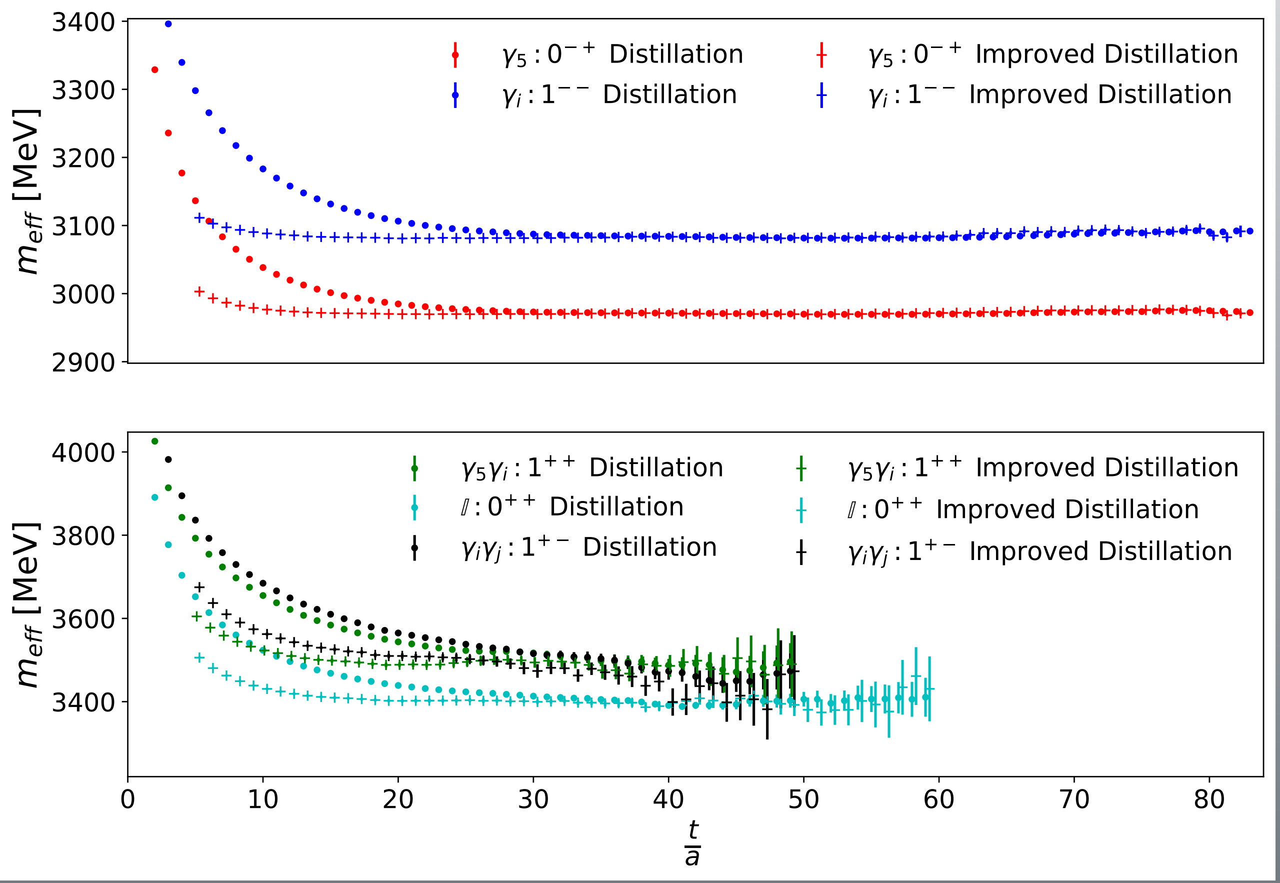
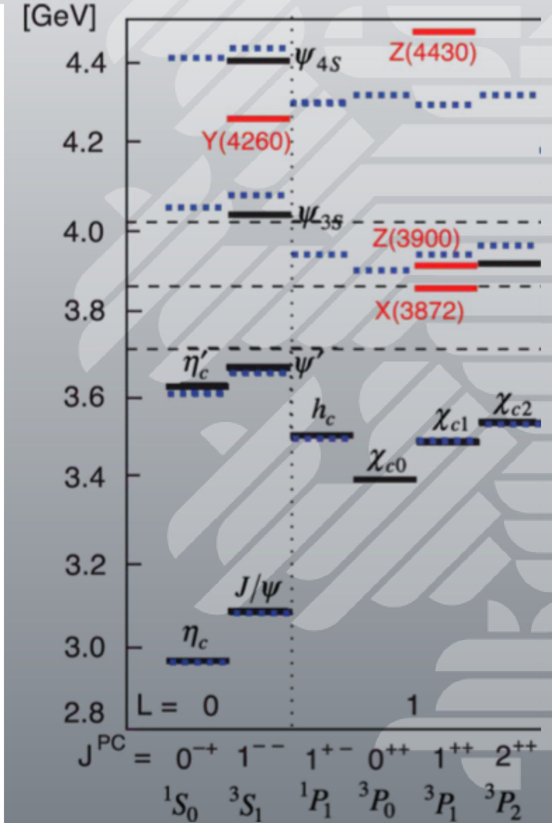
Extract charmonium masses from plateaus of effective masses

Improved distillation yields early mass plateaus

F. Knechtli et al., Phys. Rev. D 106 (2022), no. 3. 034501





Hosaka et al., PTEP 2016

Charmonium spectrum (ensemble B-light)

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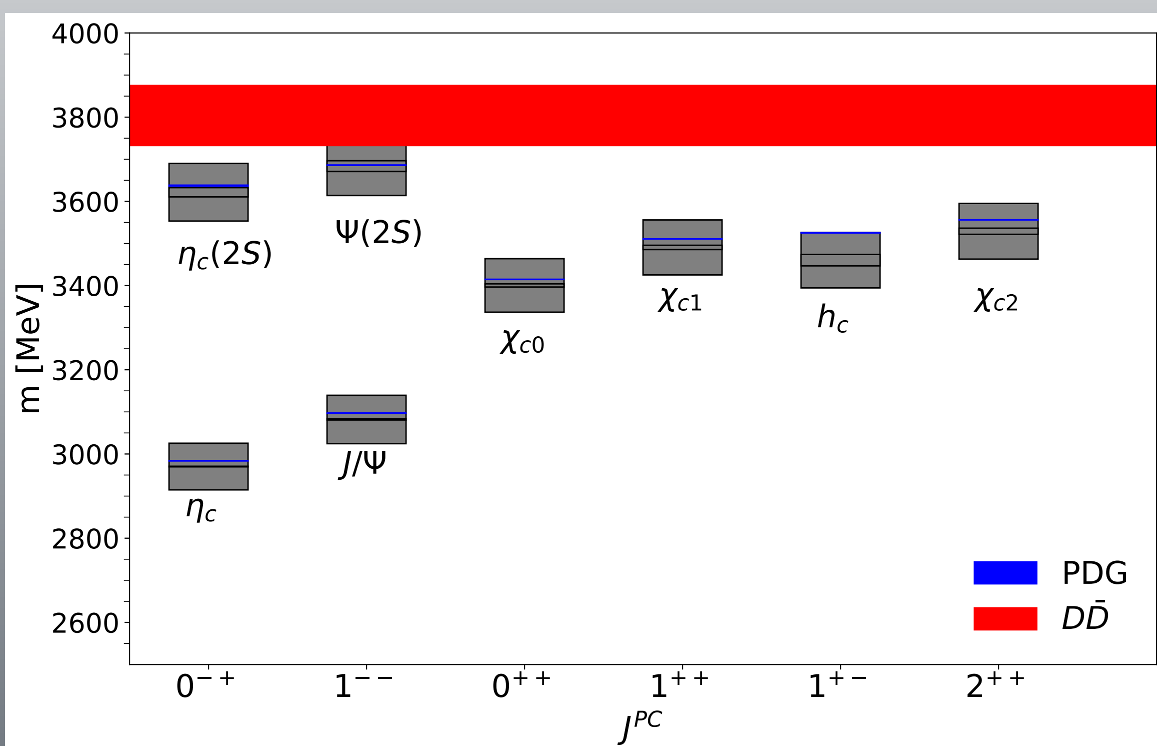

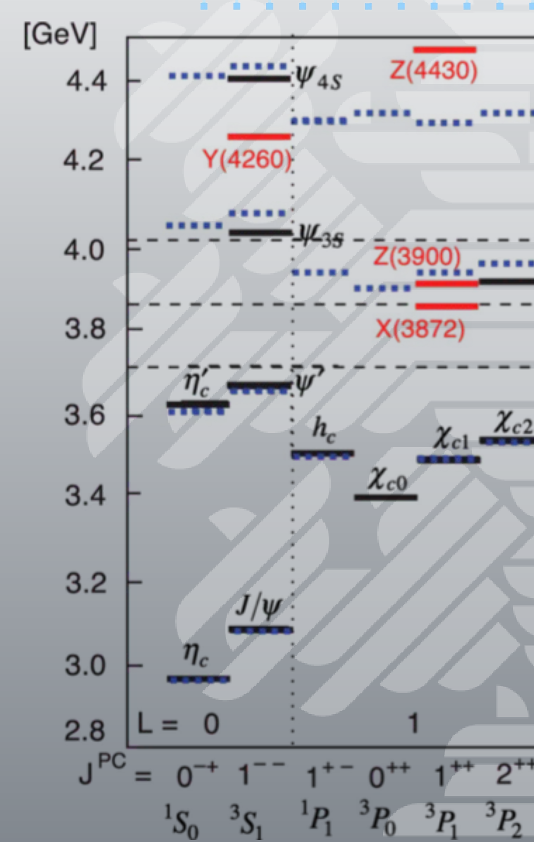

Model study of charmonium 3D spatial profiles

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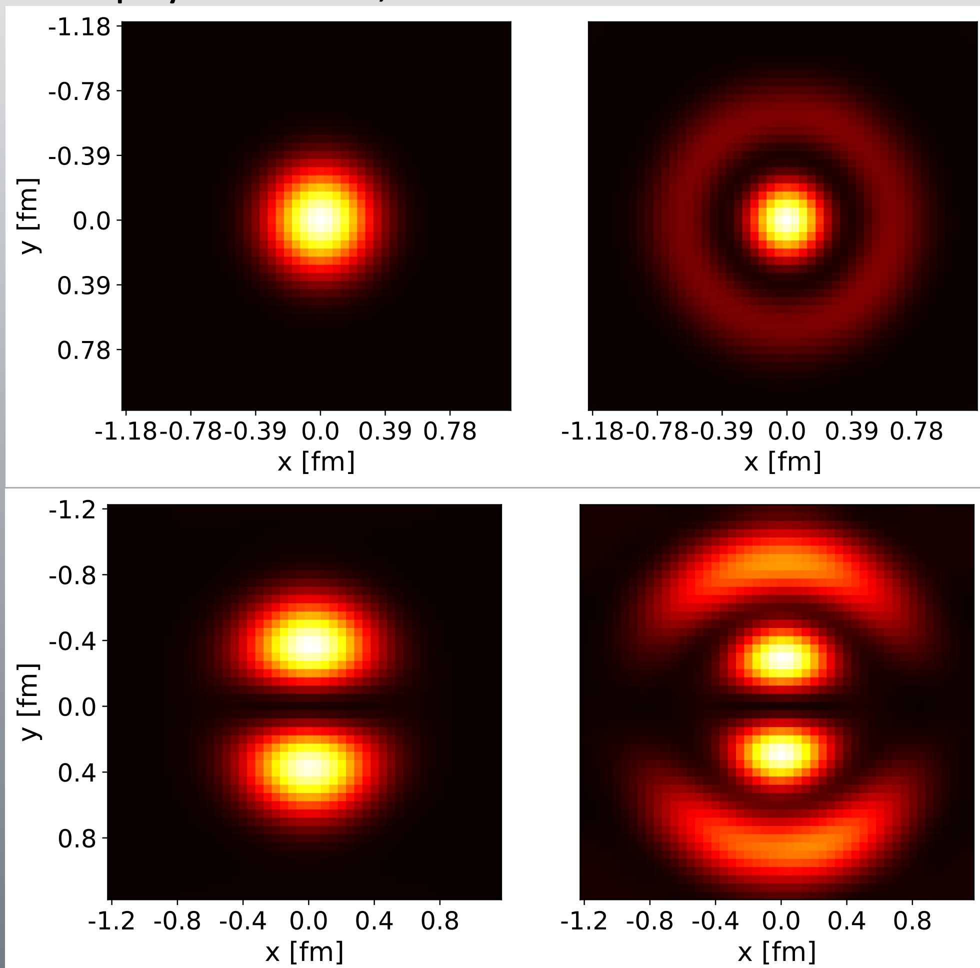
Simulation of a model with two degenerate “charm quarks” at half of their physical mass, ensemble Nm1: a = 0.049 fm, 96 x 48^3



Profiles from improved distillation and generalized eigenvalue problem (GEVP)

S-wave, “η_c” channel

Ground state (left)
First excited state (right)

P-wave, “h_c” channel

Model study of charm-quark disconnected contributions

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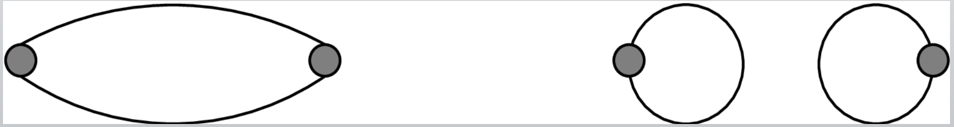
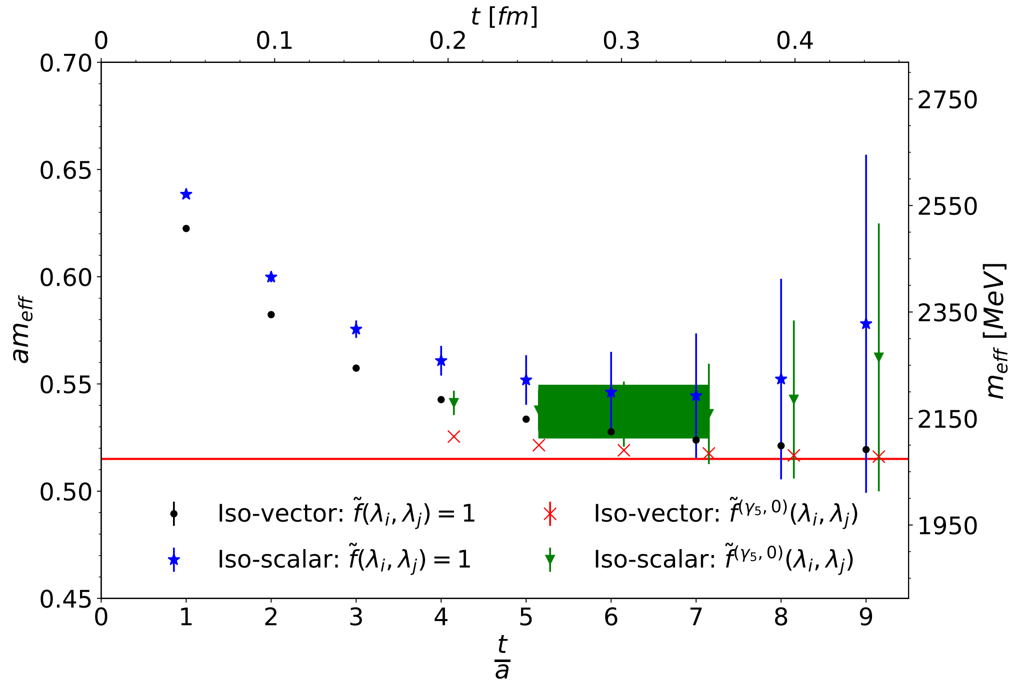
Okubo-Zweig-Iizuka (OZI) rule: suppression of quark-line diagrams with annihilation of charm-anti-charm quarks.

Charm annihilation is so far omitted in lattice QCD calculations.



With 2 charm quarks:
iso-vector vs. iso-scalar



Upward shift of the "η_c" mass

In the model: 89(53) MeV

In nature: only estimate ~7 MeV

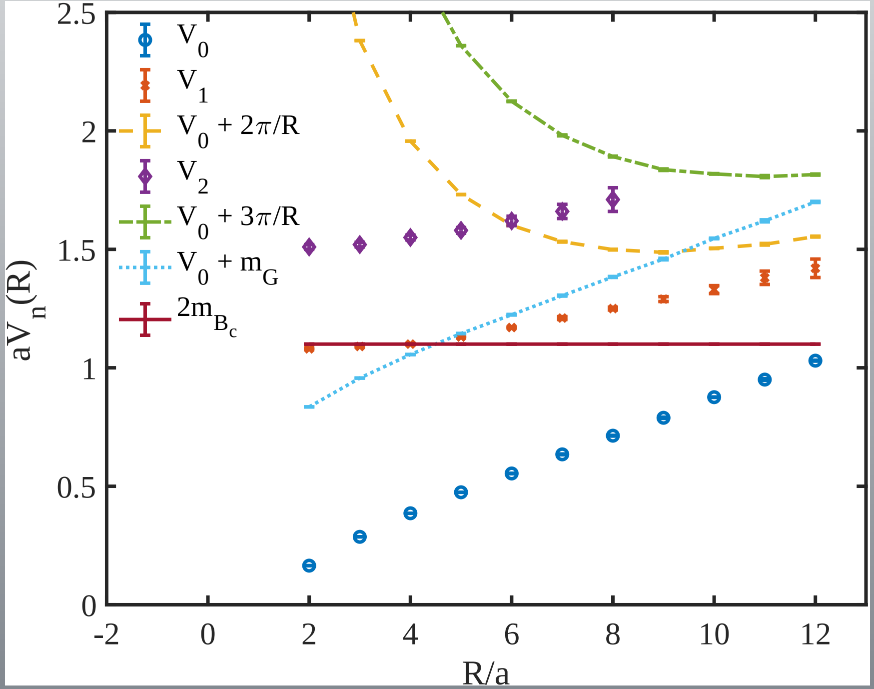
Difference due to model assumptions (no light quarks, two charm quarks)

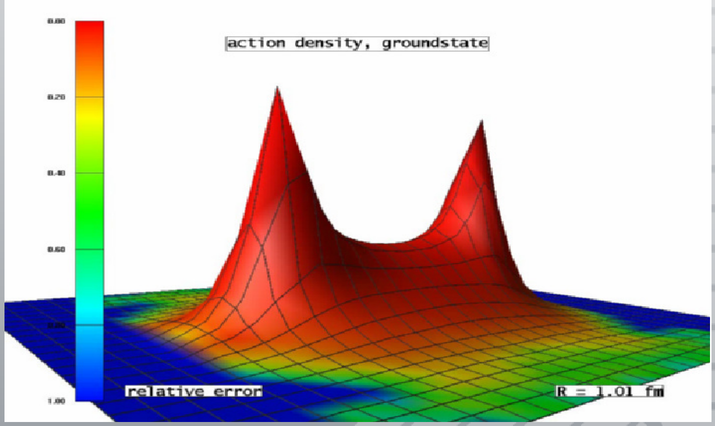
Static quark anti-quark potential

Born-Oppenheimer approximation: charmonium levels can be computed from the Schrödinger equation with the static quark anti-quark potential

We extract the potential from correlators of Laplacian trial states

R. Höllwieser et al., Phys. Rev. D 107 (2023) 3, 034511





Bali et al., PoS LAT2005 (2006)

Ground state potential and radial excitations

Technique can be extended to hybrid (excited) potentials

Scaling on SuperMUC-NG and development of multi-grid

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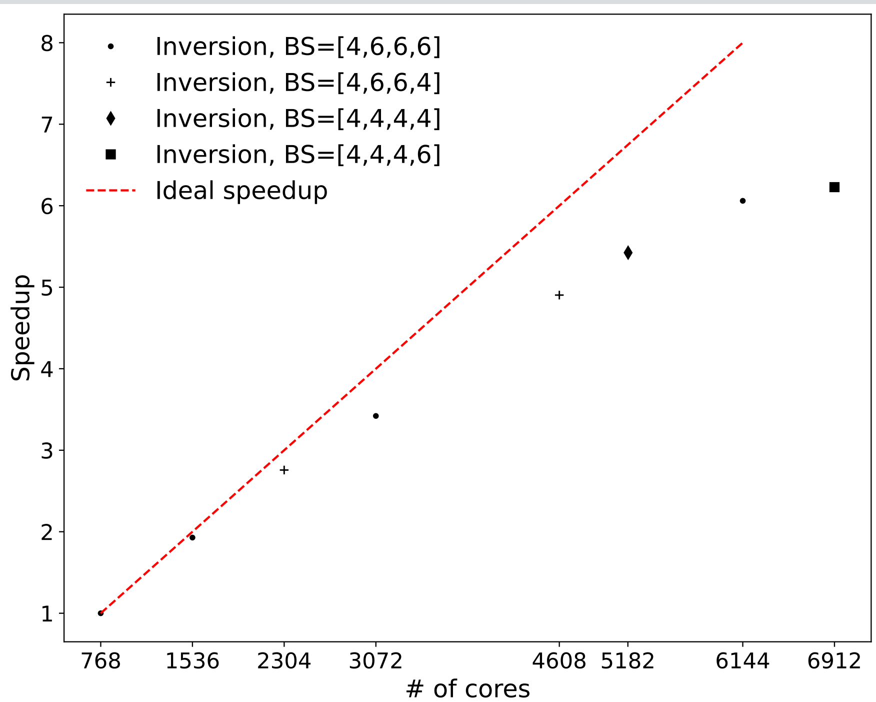

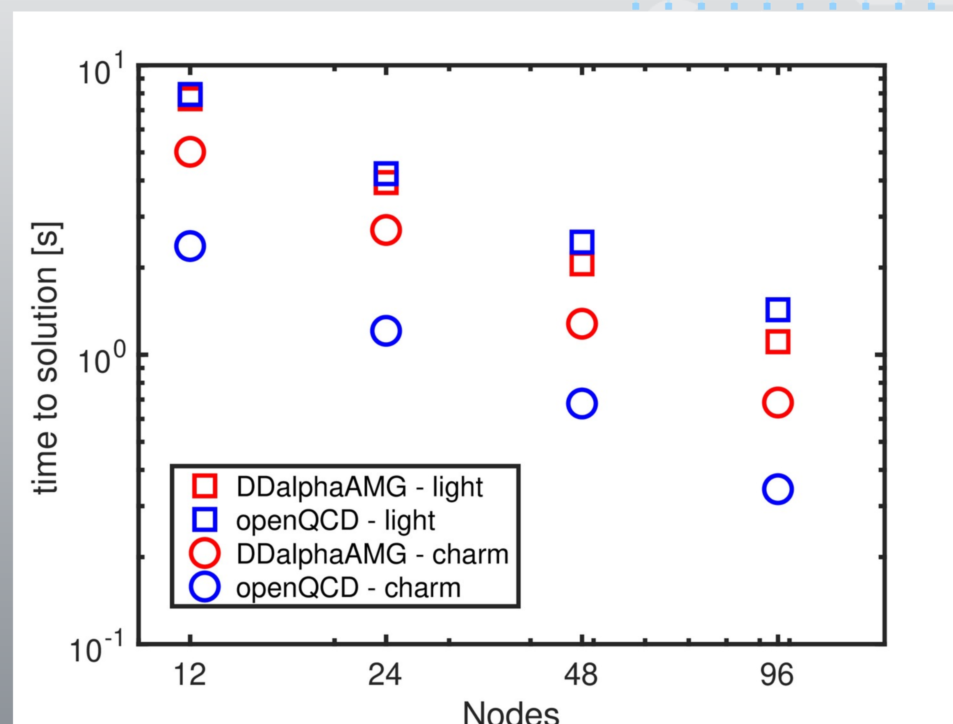

two-level SAP GCR solver with AVX instructions (96 x 48^3) of openQCD (https://luscher.web.cern.ch/luscher/openQCD/)

Three-level multi-grid solver with SSE4 and compiler-auto vectorization on the coarse grids of DDalphaAMG (https://github.com/mrottmann/DDalphaAMG)

Conclusions

Improved charmonium spectrum

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- a=0.043 fm, 144 x 48^3
- pion mass m_π ~ 420 MeV, physical charm
- 250 configurations
- charm-quark perambulators of size 325 (eigenmode) x 85 (time) x 4 (spin)
- improved distillation

Outlook

- light-quark perambulators (inversions are more expensive)
- smaller lattice a=0.054 fm, 96 x 32^3 , larger statistics
- study mixing of charmonium with light hadrons and glueballs
- D-mesons, static-light (hybrid) mesons, hybrid static potentials
- working on multi-grid and GPU codes

Thank you for your attention!

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