Exploratory calculations of baryon resonances and exotic charmonia from Lattice QCD using Lüscher's method

Daniel Mohler

Hirschegg,
January 15th, 2018

Outline

1. Introduction and motivation
   - Recent progress in Lattice QCD simulations
   - Coordinated Lattice Simulations (CLS)
   - Illustrative example: ρ resonance and relevance to $(g-2)_\mu$
2. Exploratory calculations for charmonium resonances and bound states
   - Previous results for the χ'_{c0} / $X(3915)$
   - Towards charmonium resonances from coupled-channel simulations
3. Exploratory calculations for baryon resonances
   - Previous results
   - Challenges
   - Towards coupled-channel results for the $\Lambda(1405)$
4. Conclusions and Outlook

Outline

1. Introduction and motivation
   - Recent progress in Lattice QCD simulations
   - Coordinated Lattice Simulations (CLS)
   - Illustrative example: ρ resonance and relevance to $(g-2)_\mu$
2. Exploratory calculations for charmonium resonances and bound states
   - Previous results for the χ'_{c0} / $X(3915)$
   - Towards charmonium resonances from coupled-channel simulations
3. Exploratory calculations for baryon resonances
   - Previous results
   - Challenges
   - Towards coupled-channel results for the $\Lambda(1405)$
4. Conclusions and Outlook

Lattice Quantum Chromodynamics: What do we calculate?

Regularization of QCD by a 4-d Euclidean space-time lattice. (Kenneth Wilson 1974)
Provides a calculational method for QCD

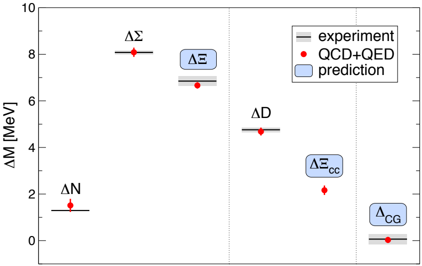
Euclidean correlator of two Hilbert-space operators $\hat{O}_1$ and $\hat{O}_2$.

$$\left\langle \hat{O}_2(t)\hat{O}_1(0) \right\rangle = \sum_n e^{-t\Delta E_n} \langle 0|\hat{O}_2|n\rangle\langle n|\hat{O}_1|0\rangle$$
$$= \frac{1}{Z}\int \mathcal{D}[\psi,\bar{\psi},U] e^{-S_E} O_2[\psi,\bar{\psi},U] O_1[\psi,\bar{\psi},U]$$

- Path integral over the Euclidean action $S_{E,QCD}[\psi,\bar{\psi},U]$; (a sum over quantum fluctuations)
- Can be evaluated with *Markov Chain Monte Carlo* (using methods well established in statistical physics)

Recent progress in Lattice QCD

- Dynamical simulations with 2+1(+1) flavors of sea quarks
- Simulations at physical pion (light-quark) masses
- Isospin splitting and QCD+QED simulations
- Improved heavy quark actions for charm



BMW Collaboration, Borsanyi et al. Science 347 1452 (2015)

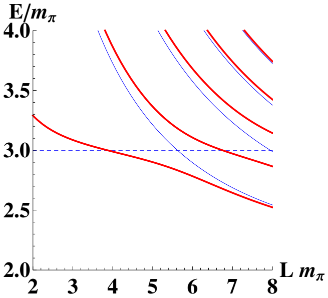
Progress from an old idea: Lüscher's finite-volume method

M. Lüscher Commun. Math. Phys. 105 (1986) 153;
Nucl. Phys. B 354 (1991) 531; Nucl. Phys. B 364 (1991) 237.

Basic observation: Finite volume, multi-particle energies are shifted with regard to the free energy levels due to the interaction

$$E = E(p_1) + E(p_2) + \Delta_E$$

- Energy shifts encode scattering amplitude(s)
- Original method: Elastic scattering in the rest-frame in multiple spatial volumes L^3
- Coupled 2-hadron channels well understood
- $2 \leftrightarrow 1$ and $2 \leftrightarrow 2$ transitions well understood (example $\pi\pi \to \pi\gamma^*$)
- significant progress for 3-particle scattering
  $\to$ see talk by Akaki Rusetsky



Fully systematic calculation vs. exploratory study

Important lattice systematics from

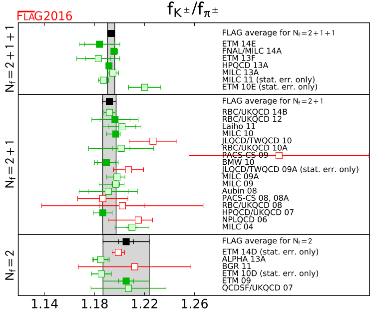
- Taking the *continuum limit*: $a(g,m) \to 0$
- Taking the *infinite volume limit*: $L \to \infty$
- Calculation at (or extrapolation to) the physical pion mass

I cover many *exploratory* results

- Should be compared only qualitatively to experiment
- Provide an outlook on future Lattice QCD results

Example for fully systematic results:

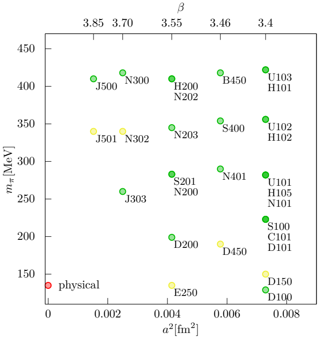
- Flavor physics results listed in the FLAG review
  http://itpwiki.unibe.ch/flag/



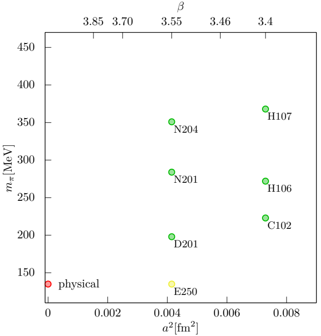
CLS 2+1 flavor ensembles: Overview

Bruno *et al.* JHEP 1502 043 (2015); Bali *et al.* PRD 94 074501 (2016)

$Tr(M) = \text{const.}$



$m_s = \text{const.}$



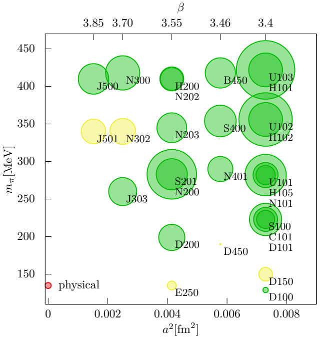
plots by Jakob Simeth, RQCD

- Letters in the name denote the aspect ratio T/L; First digit encodes β
- Ensembles at 5 lattice spacings and with a range of $M_\pi \leq 420\text{MeV}$
- Ensembles to control (or exploit) finite volume effects

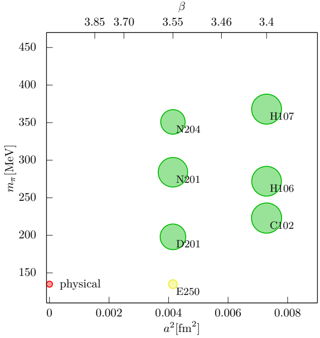
CLS 2+1 flavor ensembles: Statistics – area ∝ MDU

Bruno *et al.* JHEP 1502 043 (2015); Bali *et al.* PRD 94 074501 (2016)

$Tr(M) = \text{const.}$



$m_s = \text{const.}$



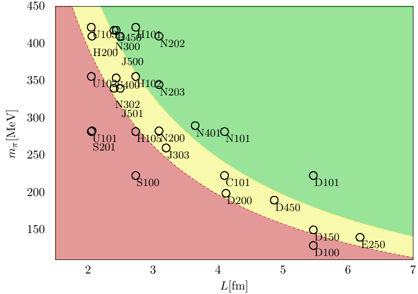
plots by Jakob Simeth, RQCD

- >4000 MDU for many ensembles
  Typically save 1 configuration every 4 MDU
- target statistics chosen considering largest τ_{int} (often YM action density)

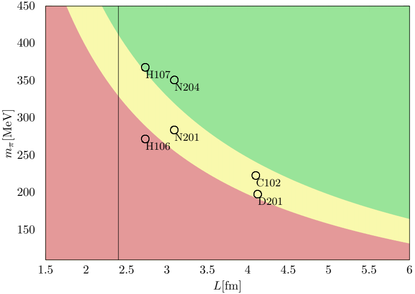
CLS 2+1 flavor ensembles: Volumes used

Bruno *et al.* JHEP 1502 043 (2015); Bali *et al.* PRD 94 074501 (2016)

$Tr(M) = \text{const.}$



$m_s = \text{const.}$



plots by Jakob Simeth, RQCD

- red: $m_\pi L \leq 4$; yellow: $4 \leq m_\pi L \leq 5$; green $5 \leq m_\pi L$
- Most ensembles with $m_\pi L \geq 4$
- Some smaller volumes to check finite size effects

A non-exotic example: The ρ meson

$\rho(770)$ [h] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 775.26 \pm 0.25$ MeV

Full width $\Gamma = 149.1 \pm 0.8$ MeV

$\rho(770)$ DECAY MODES	Fraction (Γ_i/Γ)
$\pi\pi$	$\sim$ 100

For $2m_\pi \leq m_\rho \leq 4m_\pi$ the original Lüscher formalism is applicable

Correlation matrix built from both quark-antiquark ρ and $\pi\pi$ interpolators:

$$C(t) = \begin{pmatrix} \langle \rho(t)\rho(0)^\dagger \rangle & \langle \rho(t)(\pi\pi)(0)^\dagger \rangle \\ \langle (\pi\pi)(t)\rho(0)^\dagger \rangle & \langle (\pi\pi)(t)(\pi\pi)(0)^\dagger \rangle \end{pmatrix}$$

Where we use ρ^0 and $\pi^+\pi^-$ type interpolators:

$$\rho^0(P,t) \propto \sum_{\mathbf{x}} \mathrm{e}^{-i\mathbf{P}\cdot\mathbf{x}} \left(\bar{u}\mathbf{a}\cdot\gamma u - \bar{d}\mathbf{a}\cdot\gamma d\right)(\mathbf{x},t)$$

$$(\pi\pi)(t) = \pi^+(\mathbf{p_1},t)\pi^-(\mathbf{p_2},t) - \pi^-(\mathbf{p_1},t)\pi^+(\mathbf{p_2},t)$$

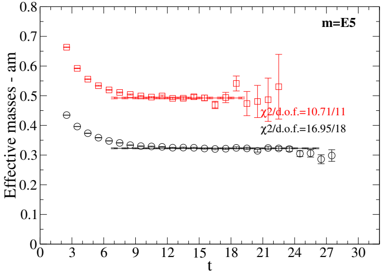
$$\pi^+(p,t) \propto \sum_{\mathbf{x}} \mathrm{e}^{-i\mathbf{p}\cdot\mathbf{x}} \bar{d}\gamma_5 u(\mathbf{x},t)$$

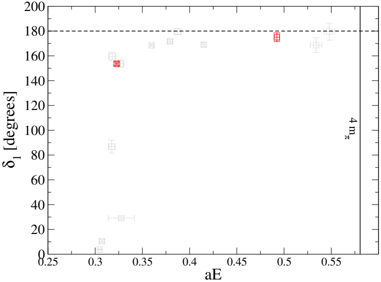
A non-exotic example: The ρ meson

- Lüscher quantization condition

$$\delta_1(k) + \phi\left(\frac{L}{2\pi}k\right) = n\pi \quad \text{with} \quad E_{cm}(k) = 2\sqrt{k^2 + m_\pi^2}$$

- In this simple case of elastic scattering:
  one phase-shift point for each energy level



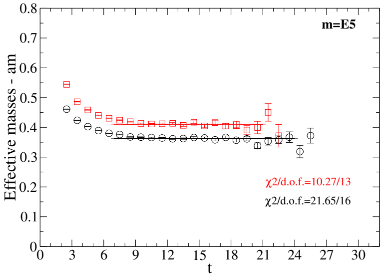


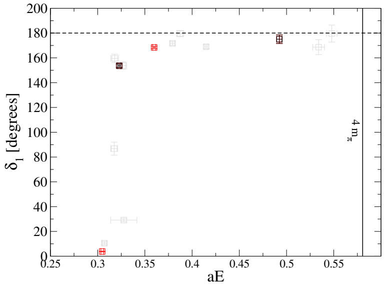
A non-exotic example: The ρ meson

- Lüscher quantization condition

$$\delta_1(k) + \phi\left(\frac{L}{2\pi}k\right) = n\pi \quad \text{with} \quad E_{cm}(k) = 2\sqrt{k^2 + m_\pi^2}$$

- In this simple case of elastic scattering:
  one phase-shift point for each energy level



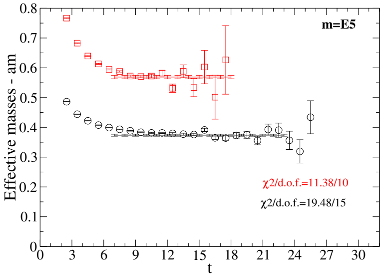


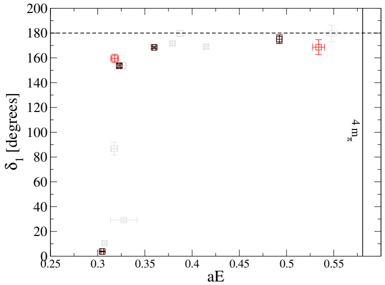
A non-exotic example: The ρ meson

- Lüscher quantization condition

$$\delta_1(k) + \phi\left(\frac{L}{2\pi}k\right) = n\pi \quad \text{with} \quad E_{cm}(k) = 2\sqrt{k^2 + m_\pi^2}$$

- In this simple case of elastic scattering:
  one phase-shift point for each energy level



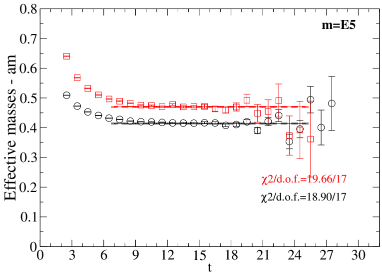


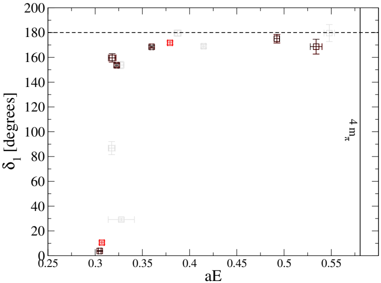
A non-exotic example: The ρ meson

- Lüscher quantization condition

$$\delta_1(k) + \phi\left(\frac{L}{2\pi}k\right) = n\pi \quad \text{with} \quad E_{cm}(k) = 2\sqrt{k^2 + m_\pi^2}$$

- In this simple case of elastic scattering: one phase-shift point for each energy level



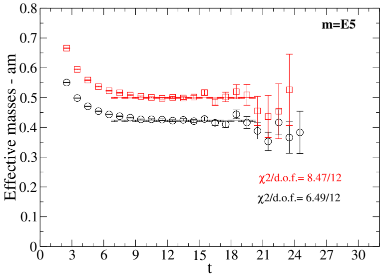


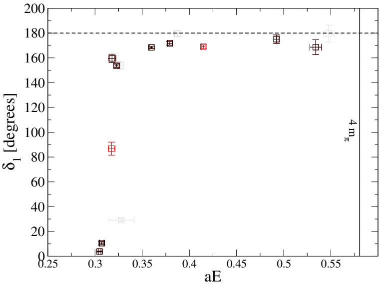
A non-exotic example: The ρ meson

- Lüscher quantization condition

$$\delta_1(k) + \phi\left(\frac{L}{2\pi}k\right) = n\pi \quad \text{with} \quad E_{cm}(k) = 2\sqrt{k^2 + m_\pi^2}$$

- In this simple case of elastic scattering:
  one phase-shift point for each energy level



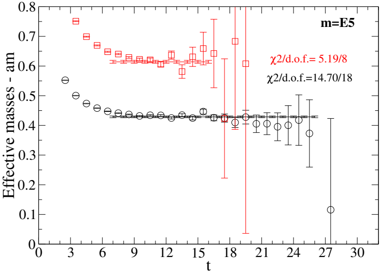


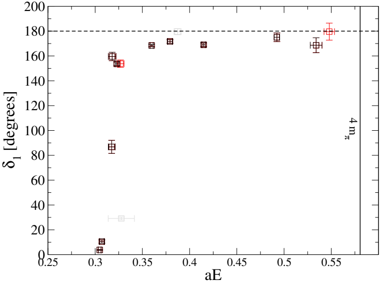
A non-exotic example: The ρ meson

- Lüscher quantization condition

$$\delta_1(k) + \phi\left(\frac{L}{2\pi}k\right) = n\pi \quad \text{with} \quad E_{cm}(k) = 2\sqrt{k^2 + m_\pi^2}$$

- In this simple case of elastic scattering:
  one phase-shift point for each energy level



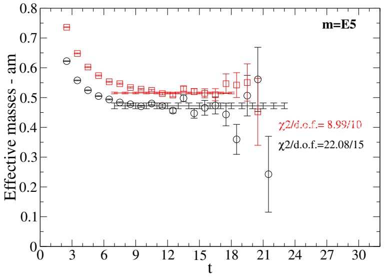


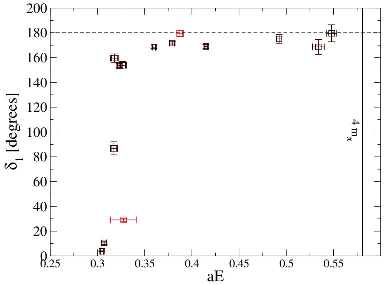
A non-exotic example: The ρ meson

- Lüscher quantization condition

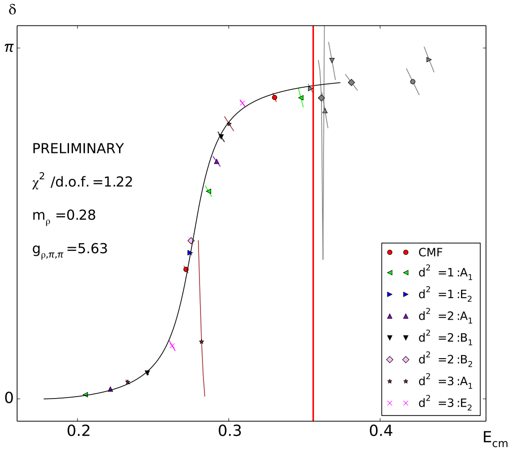
$$\delta_1(k) + \phi\left(\frac{L}{2\pi}k\right) = n\pi \quad \text{with} \quad E_{cm}(k) = 2\sqrt{k^2 + m_\pi^2}$$

- In this simple case of elastic scattering: one phase-shift point for each energy level





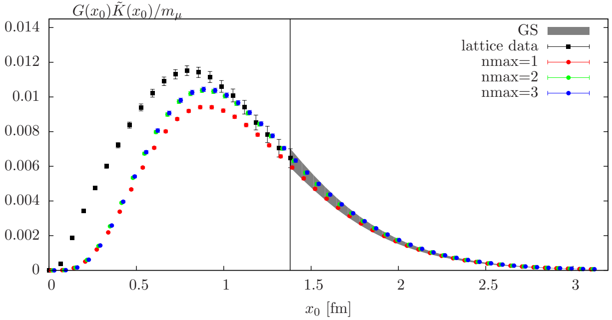
Similar results with $m_\pi \approx 265$ MeV



Data from Felix Erben, Mainz

- Treats all correlations correctly, see arXiv:1710.03529
- Different fits for final publications: Breit-Wigner, Gounaris-Sakurai, ...

$(g-2)_\mu$ and the large x_0 behavior of the vector correlator

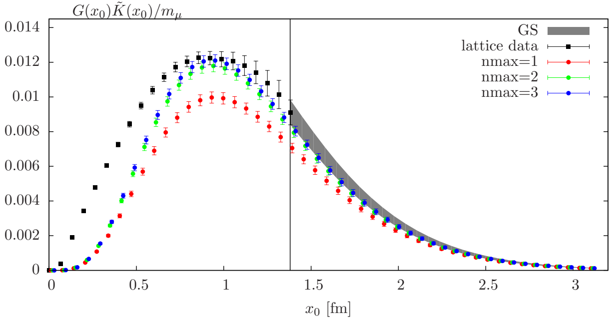


Previous determination from arXiv:1705.01775
New analysis from Felix Erben.

- Data from Lüscher analysis → more accurate determination of the large x_0 behavior
- Reduces uncertainty of lattice determination of the HVP contribution
- Lellouch-Lüscher yields timelike pion form factor

H.B. Meyer, PRL **107**, 072002 (2011)

$(g-2)_\mu$ and the large x_0 behavior of the vector correlator



`Previous determination from arXiv:1705.01775`
`New analysis from Felix Erben.`

- Data from Lüscher analysis → more accurate determination of the large x_0 behavior
- Reduces uncertainty of lattice determination of the HVP contribution
- Lellouch-Lüscher yields timelike pion form factor

`H.B. Meyer, PRL` **`107`**`, 072002 (2011)`

Outline

1. Introduction and motivation
   - Recent progress in Lattice QCD simulations
   - Coordinated Lattice Simulations (CLS)
   - Illustrative example: ρ resonance and relevance to $(g-2)_\mu$
2. Exploratory calculations for charmonium resonances and bound states
   - Previous results for the χ'_{c0} / $X(3915)$
   - Towards charmonium resonances from coupled-channel simulations
3. Exploratory calculations for baryon resonances
   - Previous results
   - Challenges
   - Towards coupled-channel results for the $\Lambda(1405)$
4. Conclusions and Outlook

χ'_{c0} and $X/Y(3915)$

$X(3915)$
was $\chi_{c0}(3915)$

$I^G(J^{PC}) = 0^+(0 \text{ or } 2^{++})$

Mass $m = 3918.4 \pm 1.9$ MeV
Full width $\Gamma = 20 \pm 5$ MeV (S = 1.1)

PDG interpreted $X(3915)$ as a regular charmonium (χ'_{c0})

- Some of the reasons to doubt this assignment:

  `Guo, Meissner Phys. Rev. D86, 091501 (2012)`

  `Olsen, PRD 91 057501 (2015)`

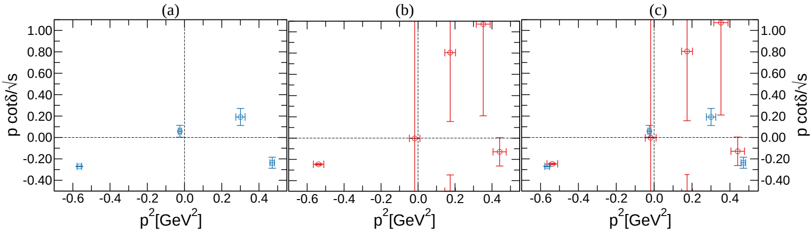
  - No evidence for fall-apart mode $X(3915) \to \bar{D}D$
  - Spin splitting $m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)}$ too small
  - Large OZI suppressed $X(3915) \to \omega J/\psi$
  - Width should be significantly larger than $\Gamma_{\chi_{c2}(2P)}$
- Zhou *et al.* (PRL 115 2, 022001 (2015)) argue that what is dubbed X(3915) is the spin 2 state already known and suggests that a broader state is hiding in the experiment data.
- Observation of an alternative $\chi_{c0}(2P)$ by Belle:

  `Chilikin et al. PRD 95 112003 (2017)`

$$M = 3862^{+26+40}_{-32-13}\ \text{MeV} \qquad \Gamma = 201^{+154+88}_{-067-82}\ \text{MeV}$$

χ'_{c0}: Exploratory lattice calculation

Lang, Leskovec, DM, Prelovsek, JHEP 1509 089 (2015)



- Assumes only $\bar{D}D$ is relevant
- Lattice data suggests a fairly narrow resonance with $3.9\text{GeV} < M < 4.0\text{GeV}$ and $\Gamma < 100\text{MeV}$
- Future experiment and lattice QCD results needed to clarify the situation

χ'_{c0}: Improvements and challenges

with G. Bali, S. Collins, M. Padmanath, S. Piemonte, S. Prelovsek

Improvements:

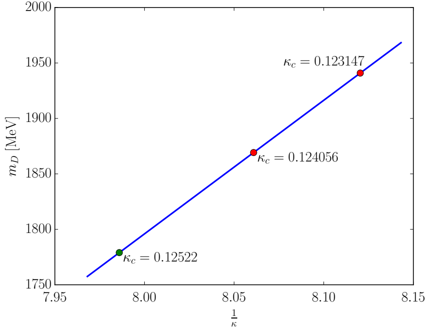
- High-precision determinations of the energy splittings needed
  $\rightarrow$ significantly improve statistics by using CLS ensembles
- Bigger density of energy level needed
  $\rightarrow$ Calculation in multiple volumes: CLS ensembles U101, H105, N101
  $\rightarrow$ Add information from moving frames
- Treatment as a single-channel problem only sensible if $X(3915)$ is indeed a spin-2 state
  $\rightarrow$ consider coupled channel $D\bar{D}$, $J/\psi\omega$ and $D_s\bar{D}_s$

Challenges:

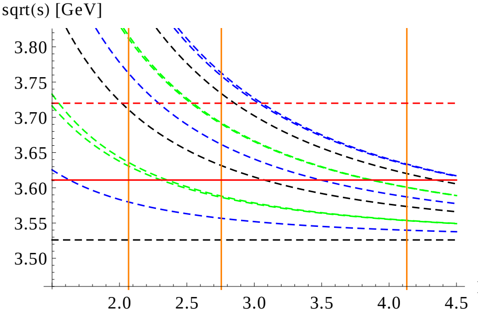
- Need strategy for dealing with (largish) discretization effects
- $Tr(M) =$ const. trajectory means $D_s\bar{D}_s$ threshold lower

Charm-quark mass tuning and expected energy levels

D-meson mass as a function of the charm-quark hopping parameter κ_c



Expected energy levels: CLS-ensembles U101, H105, N101

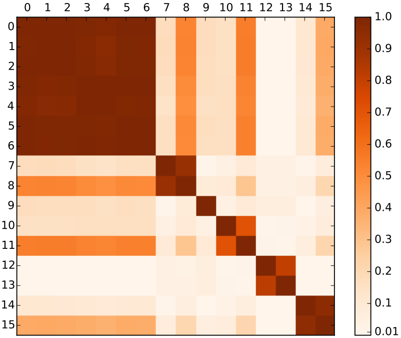


- Currently: Low statistics results on U101
- For these results: Charm quark tuning by RQCD
- Will add further charm-quark masses if needed

Interpolator basis

A_1^{++} $(J^{PC} = 0^{++}, 4^{++}, \ldots)$

Label n	Operator
0	$\bar{q}\, q$
1	$\bar{q}\, \gamma_i \overrightarrow{\nabla}_i\, q$
2	$\bar{q}\, \gamma_i \gamma_t \overrightarrow{\nabla}_i\, q$
3	$\bar{q}\, \overleftarrow{\nabla}_i \overrightarrow{\nabla}_i\, q$
4	$\bar{q}\, \overleftarrow{\Delta} \overrightarrow{\Delta}\, q$
5	$\bar{q}\, \overleftarrow{\Delta} \gamma_i \overrightarrow{\nabla}_i\, q$
6	$\bar{q}\, \overleftarrow{\Delta} \gamma_i \gamma_t \overrightarrow{\nabla}_i\, q$
7	$O^{\bar{D}(0)D(0)} \sim \bar{c}\gamma_5 l\; \bar{l}\gamma_5 c$
8	$O^{\bar{D}(0)D(0)} \sim \bar{c}\gamma_5\gamma_t l\; \bar{l}\gamma_5\gamma_t c$
9	$O^{\bar{D}(p)D(-p)} \sim \bar{c}\gamma_5 l\; \bar{l}\gamma_5 c$
10	$O^{\bar{D}^*(0)D^*(0)} \sim \bar{c}\gamma_i l\; \bar{l}\gamma_i c$
11	$O^{\bar{D}^*(0)D^*(0)} \sim \bar{c}\gamma_i\gamma_t l\; \bar{l}\gamma_i\gamma_t c$
12	$O^{J/\psi(0)\omega(0)} \sim \bar{c}\gamma_i c\; \bar{l}\gamma_i l$
13	$O^{J/\psi(0)\omega(0)} \sim \bar{c}\gamma_i\gamma_t c\; \bar{l}\gamma_i\gamma_t l$
14	$O^{\bar{D}_s(0)D_s(0)} \sim \bar{c}\gamma_5 s\; \bar{s}\gamma_5 c$
15	$O^{\bar{D}_s(0)D_s(0)} \sim \bar{c}\gamma_5\gamma_t s\; \bar{s}\gamma_5\gamma_t c$



A first look at mass splittings

Preliminary results: Energy splittings from 120 configurations of U101

	$\kappa_c = 0.12522$	$\kappa_c = 0.12315$	Experiment
$m_{J/\Psi} - m_{\eta_c}$	106.9(0.6)(1.1)	98.0(0.5)(1.1)	113.2(0.7)
$m_{D_s^*} - m_{D_s}$	131.3(1.9)(1.4)	118.4(2.0)(1.3)	143.8(0.4)
$m_{D^*} - m_D$	127.8(3.9)(1.4)	115.1(4.1)(1.2)	140.66(10)
$2m_{\overline{D}} - m_{\overline{c}c}$	912.0(7.6)(9.8)	939.7(8.1)(10.1)	882.4(0.3)
$2M_{\overline{D_s}} - m_{\overline{c}c}$	1011.7(4.2)(10.9)	1036.0(4.5)(11.1)	1084.8(0.6)
$m_{D_s} - m_D$	47.2(2.1)(0.5)	45.7(2.2)(0.5)	98.87(29)

- Unphysical $m_{D_s} - m_D$ creates a special challenge!

Outline

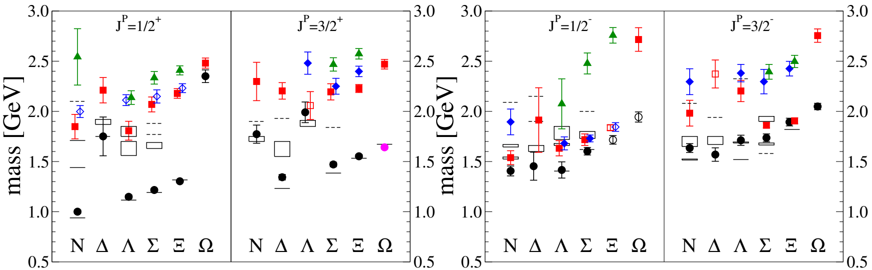
1. Introduction and motivation
   - Recent progress in Lattice QCD simulations
   - Coordinated Lattice Simulations (CLS)
   - Illustrative example: ρ resonance and relevance to $(g-2)_\mu$
2. Exploratory calculations for charmonium resonances and bound states
   - Previous results for the χ'_{c0} / $X(3915)$
   - Towards charmonium resonances from coupled-channel simulations
3. Exploratory calculations for baryon resonances
   - Previous results
   - Challenges
   - Towards coupled-channel results for the $\Lambda(1405)$
4. Conclusions and Outlook

Results from 3-quark interpolating fields

- Many older results from 3-quark interpolators

  `Example: Engel, Lang, DM, Schäfer, PRD 87 074504 (2013)`

  `Λ's in Engel et al. PRD 87 034502 (2013)`



- OK at heavy quark masses where states are stable
- Typically no indications of close-by scattering thresholds
- Experience from meson sector: Spectrum not only incomplete but wrong!

Meson-baryon scattering – challenges

- Nucleon noise to signal
  - For the nucleon we have (argument by Parisi, Lepage)

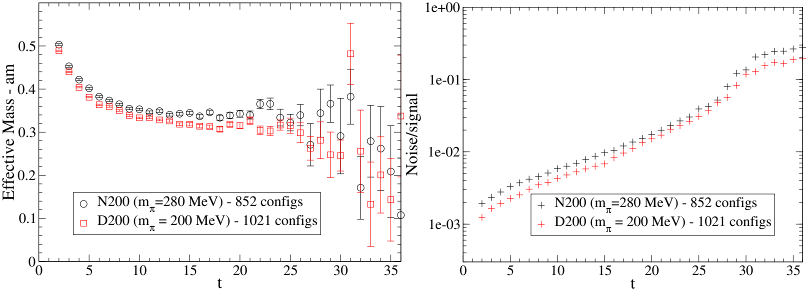
$$N\sigma^2_{N,\mathbf{p}=0} = \left\langle C_N(\mathbf{p}=0,t;m)^2\right\rangle - \langle C_N(\mathbf{p}=0,t;m)\rangle^2$$
$$\propto Z_{3\pi}\mathrm{e}^{-3m_\pi t} + Z_N^2\mathrm{e}^{-2m_N t}$$

  - The noise to signal ratio therefore degrades exponentially

$$\frac{\sigma_N(t)}{\langle C_N(t)\rangle} \simeq \frac{1}{\sqrt{N}}\mathrm{e}^{\left(m_N - \frac{3}{2}m_\pi\right)t}$$

- Contractions are more complicated
- Less cases where 3-particle scattering can be ignored (in a first step)

Nucleon noise/signal



Data from Tim Harris, Konstantin Ottnad, Mainz

- Slope in (most of) plateau region does not reach asymptotic value (given by $m_N - \frac{3}{2}m_\pi$)
- Suggests that in practice noise/signal scaling is not as severe
- Exponential growth qualitatively observed

Meson-baryon scattering – previous results

- S-wave pion-nucleon scattering with $J^P = \frac{1}{2}^-$

  `Lang, Verduci, PRD 87 054502 (2013)`

  - CMF spectrum qualitatively in agreement with negative parity spectrum

- Pion-nucleon scattering in the Roper channel

  `Lang *et al.* PRD 95 014510 (2017)`

  - CMF spectrum from 3-quark, $N(p)\pi(-p)$, and $N\sigma$ interpolators
  - No finite volume state seen for the $N^*(1440)$
  - Results compatible with models with a dynamically generated Roper resonance from coupled channel $N\pi$, $N\sigma$, $\Delta\pi$

- $I = \frac{3}{2}$ p-wave nucleon pion scattering and the $\Delta(1232)$

  `Andersen, Bulava, Hörz, Morningstar arXiv:1710.01557`

  - At $m_\pi = 280$ MeV, observe a near threshold resonance
  - Coupling $g_{\Delta N\pi}$ similar to experiment
  - Should be quite feasible at lighter pion masses

Exploratory study: $\Lambda(1405)$, $J^P = \frac{1}{2}^-$

- PDG (4 star resonance)

$$M_\Lambda = 1405^{+1.3}_{-1.0} MeV \qquad\qquad \Gamma_\Lambda = 50.5 \pm 2.0$$

- However
  - Unitarized χPT + Model input yields 2 poles with $\Re \approx 1400$MeV
  - CLAS observes different line shapes for $\Sigma^-\pi^+$, $\Sigma^+\pi^-$ and $\Sigma^0\pi^0$
    Interference between $I = 0$ and $I = 1$ amplitudes is the likely reason
  - Even the $\Sigma^0\pi^0$ is badly described by a single Breit-Wigner
  - CLAS data consistent with popular 2-pole picture
  - No satisfactory lattice results (although claims exist)
- Relevant channels: $\Sigma\pi$, $N\bar{K}$ (and maybe $\Lambda\eta$); simulation in isospin limit
- Goal: Explore coupled channel problem and extract scattering amplitudes from the low-lying energy spectrum

together with J. Bulava, M. Hansen, B. Hörz, C. Morningstar

Ensemble and group theory

Current data on CLS Ensemble N200

a [fm]	$T \times L^3$	m_π [MeV]	m_K [MeV]	$m_\pi L$	N_{cnfg}
0.0644	128×48^3	280	460	4.3	427

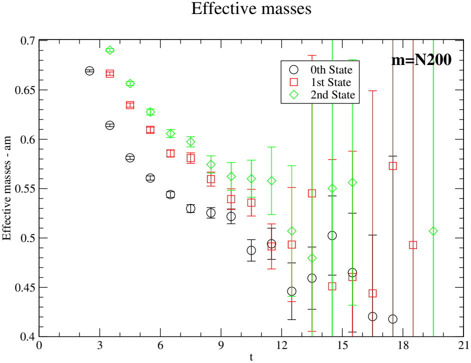
Lattice irreducible representations for a given J^P

`see Morningstar et al. arXiv:1303.6816`

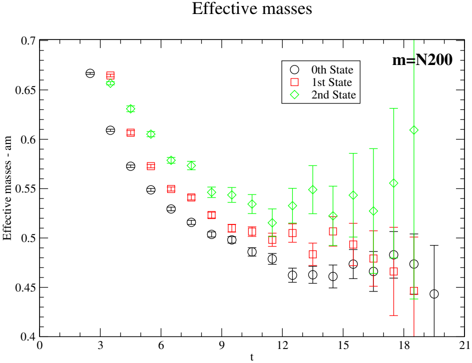
J^P	[000]	[00n]	[0nn]	[nnn]	
$\frac{1}{2}^+$	G_{1g}	G_1	G	G	$\Lambda, \Lambda(1600)$
$\frac{1}{2}^-$	G_{1u}	G_1	G	G	$\Lambda(1405), \Lambda(1670)$
$\frac{3}{2}^+$	H_g	G_1, G_2	$2G$	F_1, F_2, G	$\Lambda(1690)$
$\frac{3}{2}^-$	H_u	G_1, G_2	$2G$	F_1, F_2, G	$\Lambda(1520), \Lambda(1690)$

A first look at some data: Truncating the basis

3-quark interpolators alone

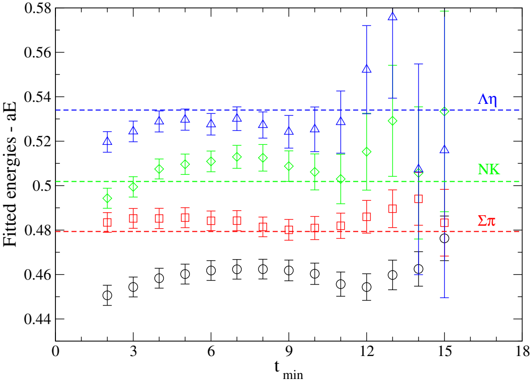


basis including $N\bar{K}$ and $\Sigma\pi$



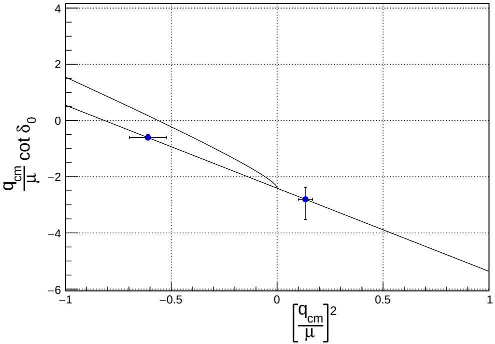
- Plot from an older dataset on 427 configurations
- Basis including meson-meson states starts to yield usable plateaus
- Even a diverse 3-quark basis does not yield the correct spectrum!

Rest frame calculation: Fit stability



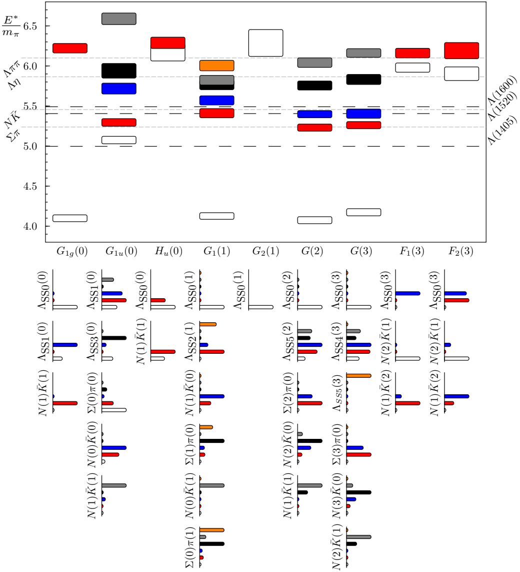
- Results for fits from t_{min} to 20
- Non-interacting levels indicated by their central value
- Correlated differences start to become significant

Rest frame calculation: effective range approximation



- Cannot rule out the simplest scenario of one bound state below $\Sigma\pi$
- Makes no statement about more complicated scenarios or physical m_π

Adding moving frames: Pattern of energy levels



- With $Tr(M) = \text{const.}$, expect mild chiral extrapolation of *uds* states
- Our $G_1(1)$ data does not have a large enough basis (caution)
- The Λ ground state is seen where expected
- No indication of levels close to $\Lambda(1600)$ in G_{1g} irrep
- No indication of levels close to $\Lambda(1520)$ in any irrep
- Apparent absence of FV states should constrain models

Next steps: What to expect

- Currently doubling N200 statistics ($\approx$ 400 configs $\rightarrow \approx$ 800 configs)
- Still enlarging the basis somewhat (include more 3-quark interpolators; include some $\Lambda\eta$)
- We plan to run more ensembles (will likely add a lighter pion mass next)
- We may add data at different lattice spacings
- Once we have bigger dataset:
  Check for consistency with model-inspired K-matrix parameterizations

Outline

1. Introduction and motivation
   - Recent progress in Lattice QCD simulations
   - Coordinated Lattice Simulations (CLS)
   - Illustrative example: ρ resonance and relevance to $(g-2)_\mu$
2. Exploratory calculations for charmonium resonances and bound states
   - Previous results for the χ'_{c0} / $X(3915)$
   - Towards charmonium resonances from coupled-channel simulations
3. Exploratory calculations for baryon resonances
   - Previous results
   - Challenges
   - Towards coupled-channel results for the $\Lambda(1405)$
4. Conclusions and Outlook

Conclusions

- Lüscher studies of meson-baryon scattering and for exotic charmonium-like states are very challenging
  - they require large statistics
  - coupled-channel formalism needed for even the simplest systems
- Making contact with experiment requires a variety of gauge ensembles
- Expect to see many new results over the next years
- Large potential to solve some of the puzzles surrounding hadrons with exotic properties (Roper, $\Lambda(1405)$, low mass charmonium-like states, ...)

Thank you!