# $D_s$ meson spectroscopy

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# Outline

1. $D_s$ spectrum: Experimental situation
2. Computational setup
3. Charm quark treatment
4. (Preliminary) results for $D_s$ and charmonium
5. Conclusions & outlook

# $D_s$ spectrum: What do we know from experiment?

Established states:

- $D_s$ ($J^P = 0^-$) and $D_s^*$ ($1^-$)
- $D_{s0}^*(2317)$ ($0^+$), $D_{s1}(2460)$ ($1^+$), $D_{s1}^*(2536)$ ($1^+$), $D_{s2}^*(2573)$ ($2^+$)

More recent discoveries:

- $D_{s1}^*(2710)$ seen by BaBar, Belle ($1^-$)
- $D_{sJ}^*(2860)$ seen by BaBar ($3^-$?,$0^+$?)
- $D_{sJ}^*(3040)$ seen by BaBar ($1^+$?,$2^-$?)
- $D_{sJ}^*(2632)$ seen by SELEX ($1^-$?)

There is a zoo of phenomenological models and lattice results are getting dated

# Ensembles used

- We use (publically available) Clover-Wilson ensembles generated by the PACS-CS collaboration
- (Sea) Pion masses range from 156MeV to 702MeV
- Preliminary data from a small subset of configurations

| lattice size | $\kappa_{u/d}$ | $\kappa_s$ | #configs used | #configs total |
|---|---|---|---|---|
| $32^3 \times 64$ | 0.13700 | 0.13640 | 104 | 399 |
| $32^3 \times 64$ | 0.13727 | 0.13640 | - | 400 |
| $32^3 \times 64$ | 0.13754 | 0.13640 | - | 450 |
| $32^3 \times 64$ | 0.13754 | 0.13660 | - | 400 |
| $32^3 \times 64$ | 0.13770 | 0.13640 | 66 | 800 |
| $32^3 \times 64$ | 0.13781 | 0.13640 | 104 | 198 |

- For initial tests and to check volume effects configurations by the CPPACS and JLQCD collaborations were used.

# Quark sources and sinks

- Jacobi smeared quark sources, e.g., $u_s \equiv (S\,u)_x$

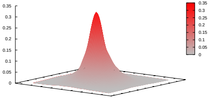
$$S = M\,S_0 \quad \text{with} \quad M = \sum_{n=0}^{N} \kappa^n H^n$$

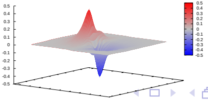
$$H(\vec{n},\vec{m}\,) = \sum_{j=1}^{3} \left( U_j\,(\vec{n},0)\,\delta\left(\vec{n}+\hat{j},\vec{m}\right) + U_j\left(\vec{n}-\hat{j},0\right)^\dagger \delta\left(\vec{n}-\hat{j},\vec{m}\right)\right).$$

- Derivative quark sources $W_{d_i}$:

$$D_i(\vec{x},\vec{y}) = U_i(\vec{x},0)\delta(\vec{x}+\hat{\imath},\vec{y}) - U_i(\vec{x}-\hat{\imath},0)^\dagger\delta(\vec{x}-\hat{\imath},\vec{y})\ ,$$
$$W_{d_i} = D_i\,S_w\ .$$

- We do not symmetrize derivatives
  $\rightarrow$ admixture of opposite charge conjugation for charmonium



# Technicalities

- We calculate propagators for 8 source timeslices on each (independent) gauge configuration
- The source location is chosen randomly within the timeslice
- We use the inverter from Lüscher's DD-HMC package
- SAP-GCR inverter to calculate the charm quark propagators and deflation version for light (strange) quark propagators
- Gaussian smeared quarks for both charm and strange and derivatives for charm only
- Per configuration 8*12*4=386 sources for the charm quark and 8*12=98 sources for the strange quark

# Charm quark treatment

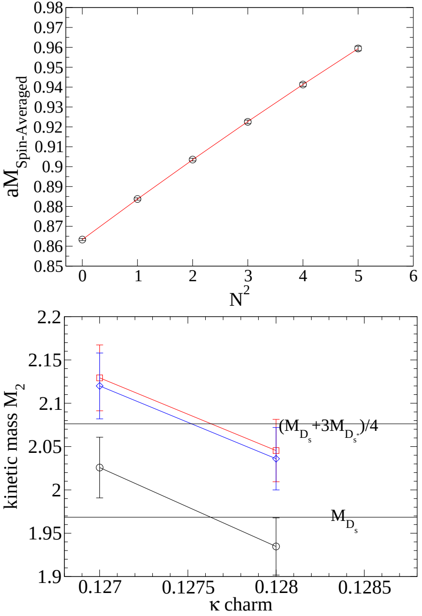
- We use the *Fermilab method* for the heavy (charm) quark
  El-Khadra et al., PRD 55, 3933
- We tune the spin averaged kinetic mass ($M_{D_s} + 3M_{D_s^*}$) to its physical value and measure mass splittings.
- For the charm quark we use the tadpole improved $c_{sw} = \frac{1}{u_0^3}$
- General form for the dispersion relation (Bernard et al. arXiv:1003.1937):

$$E(p) = M_1 + \frac{p^2}{2M_2} - \frac{a^3 W_4}{6} \sum_i p_i^4 - \frac{(p^2)^2}{8M_4^3} + \dots$$

- We compare results from two different fits:
  1. Neglect the term with coefficient $W_4$
  2. Fit $E^2(p)$ and neglect $(p^2)^2$ term from mismatch of $M_1$, $M_2$ and $M_4$

$$E^2(p) \approx M_1^2 + \frac{M_1}{M_2} p^2 - \frac{M_1 a^3 W_4}{3} \sum_i (p_i)^4 \qquad (1)$$

# Determining the charm quark mass: $\kappa$ tuning

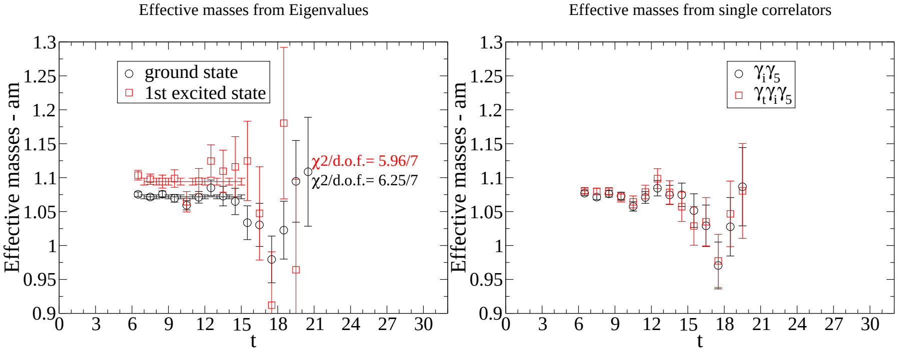



- Example for *kappa* $= 0.12800$

$$M_1 = 0.86334(50)$$
$$M_2 = 0.9337(73)$$
$$M_4 = 0.863(28)$$
$$\frac{M_2}{M_1} = 1.0815(86)$$

- Errors from second method somewhat larger but compatible
- We calculate at two values and interpolate

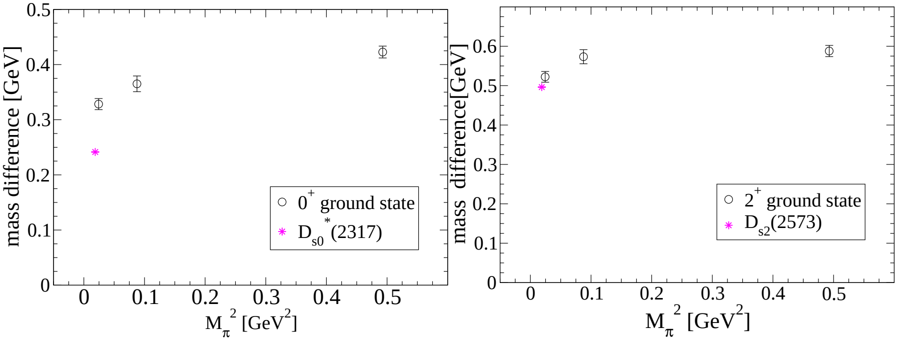
# $D_s$ mesons: Effective masses & mixing for $1^+$ states



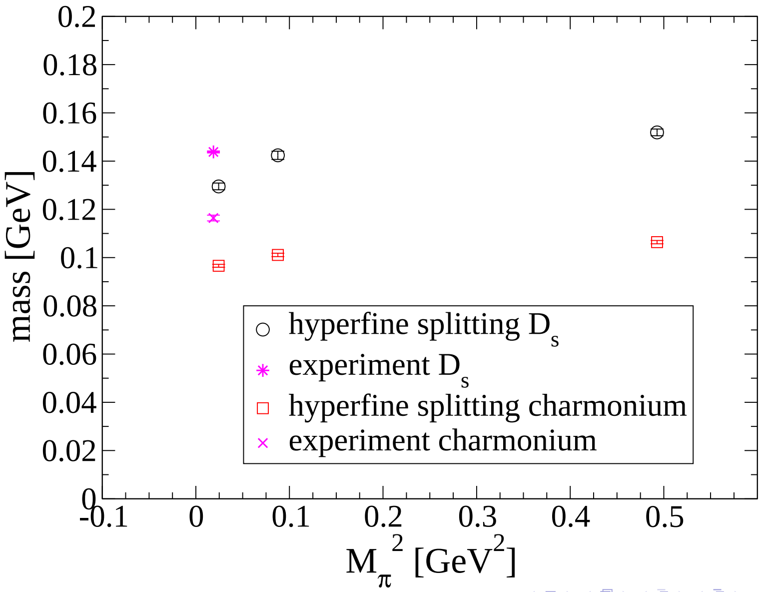

- Mixing of interpolaters corresponding to different charge conjugation in the mass degenerate case is important.
- Magnitude of observed splitting is compatible with experiment.

# $D_s$ mesons: Chiral behavior

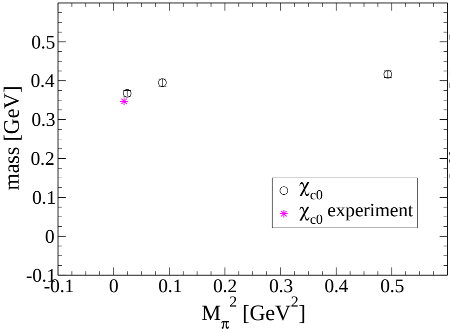
- All results are preliminary
- Throughout: Errors from statistics & uncertainty in scale setting only

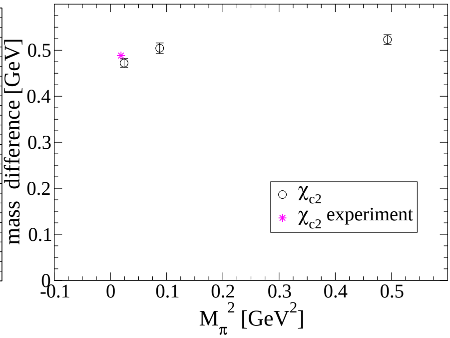


# Results III: Hyperfine Splitting

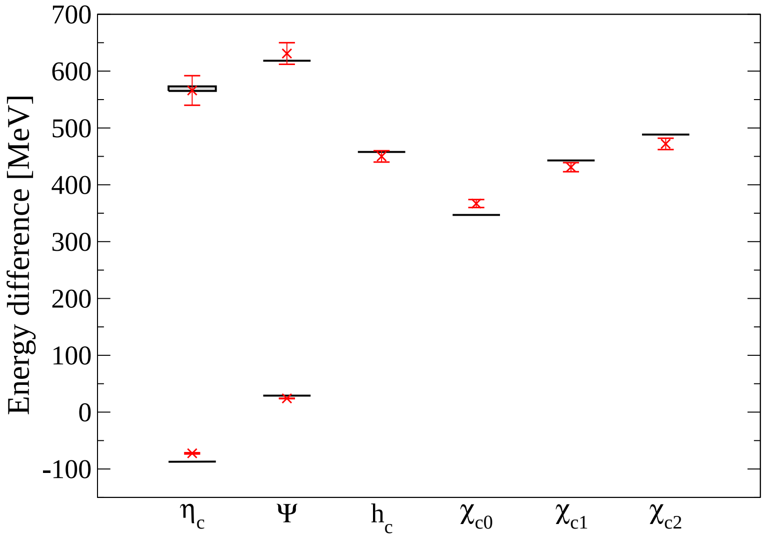


# Charmonium: Chiral behavior



# Charmonium results at the lowest sea quark mass



# What we have and what is missing

- Presented data from very limited statistics
  - Currently increasing statistics and running further ensembles
- Calculation at a single lattice spacing
- Multiple volumes are available only at large pion masses
  - Expect volume effects to be small but would like to verify this
- Investigate effects from slightly unphysical strange quark mass
- Determination of the charm quark $\kappa$ is limited by statistics/ errors on the lattice spacing *a*

- Inclusion of scattering states in the basis might be needed to reconcile data with experiment

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# Conclusions & Outlook

- Presented preliminary results for ground and excited $D_s$ and Charmonium states including Spin 2 states
- Qualitative agreement with the experimental spectrum
- Results are currently limited by the fact that we have only one lattice spacing
- Simulation would benefit greatly from newer PACS-CS configurations


**Thanks to ...**

The PACS-CS collaboration for their gauge configurations
Martin Lüscher for making his DD-HMC code available
Randy Lewis for sharing computing ressources
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