## Roper State from Overlap Fermion

- Discrepancy in various lattice calculations
- Fitting methods: variation vs sequential empirical Bayes method
$\square$ Chiral dynamics: Multi-hadrons from single hadron interpolater - $\uparrow$ : ghost state
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## Many Facets of Roper Resonance <br> Theory:

$\square$ Quark potential model prediction is $100-200 \mathrm{MeV}$ too high (Liu and Wong, 1983, Capstick and Isgur, 1986)

- Skyrmion can accommodate it as a radial excitation
(J. Breit and C. Nappi, 1984 , Liu, Zhang, Black, 1984;
U. Kaulfuss and U. Meissner, 1985)
- Suggestion as a pentaquark (Krewald 2000);
as a member of the antidecuplet
(Jaffe, Wilczek, 2003)
- Perhaps a hybrid
(Barnes, Close, etc. 1983)
$\square \rightarrow$ Lattice calculations


$$
\begin{aligned}
& -\Theta^{+} \quad[u d]^{2} \bar{s} \\
& \text { - N } \quad[u d]^{2} \overline{\mathrm{~d}} \\
& \text { - } \mathrm{N}_{\mathrm{S}} \quad[\mathrm{ud}][\mathrm{su}] \overline{\mathrm{s}} \\
& \Lambda \Sigma \quad[u d][s u] \overline{\mathrm{d}}, \ldots \\
& {[u s]^{2} \bar{s}} \\
& \text { [su][ds] } \bar{d}, \ldots \\
& \Rightarrow \Xi^{--}[\mathrm{su}]^{2} \overline{\mathrm{~d}} \\
& \Rightarrow \Xi^{+}[\mathrm{ds}]^{2} \overline{\mathrm{u}}
\end{aligned}
$$

## Quenched Lattice Calculations of Roper



## Roper on the lattice

$\square 4$ issues about lattice calculations:

- Radial excitation or pentaquark state?
- Dynamical fermions
- Variation vs Bayesian fitting
- Chiral dynamics


## Rover <br> Radial excitation? $\mathbf{q}^{4} \mathbf{q}$ State?

- Roper is seen on the lattice with three-quark interpolation field.
- Weight :

$$
|<0| \mathrm{O}_{\mathrm{N}}\left|\mathrm{R}>\left.\right|^{2}>|<0| \mathrm{O}_{\mathrm{N}}\right| \mathrm{N}>\left.\right|^{2}>0 \text { (point source, point sink) }
$$



$$
\begin{gathered}
\text { Point sink } \quad \text { Wall source } \\
<0\left|\mathrm{O}_{\mathrm{N}}(0)\right| \mathrm{N}><\mathrm{N}\left|\sum \psi(\mathrm{x}) \sum \psi(\mathrm{y}) \sum \psi(\mathrm{z})\right| 0 \gg 0 \\
\text { However, }<0\left|\mathrm{O}_{\mathrm{N}}(0)\right| \mathbb{R}><\mathbb{R}\left|\sum \psi(\mathrm{x}) \sum \psi(\mathrm{y})\right| \sum \psi(\mathrm{z}) \mid 0><0
\end{gathered}
$$




## Roper and Nucleon Wavefunctions at $\mathrm{m}_{\mathrm{\pi}}=438 \mathrm{MeV}$

$$
\mathrm{O}_{\mathrm{RN}}=0.59
$$



## Dynamical Fermions



$$
\begin{aligned}
& \text { * Experiment } \\
& \chi \text { QCD (nucleon) } \\
& \chi \text { QCD (Roper) } \\
& \text { \& } \chi \text { QCD (overlap + SEB) } \\
& \text { \& } \chi \text { QCD (clover + SEB) } \\
& \text { \$ } \chi \text { QCD (clover + variation large) } \\
& \text { | } \chi \text { QCD (clover + variation small) } \\
& \text { \& } \chi \text { QCD (overlap + variation) } \\
& \text { BGR } \\
& \text { Cyprus (twist mass) } \\
& \text { Cyprus (clover) } \\
& \text { CSSM } \\
& \text { § JLab }
\end{aligned}
$$

## Variation on JLab anisotropic $24^{3} \times 128$ Clover lattice $\left(\mathrm{m}_{\mathrm{T}}=390 \mathrm{MeV}, \mathrm{a}=0.12 \mathrm{fm}\right)$



$$
M_{R}=1.92(6) \mathrm{GeV}
$$

4 smearing sizes, the largest $\left\langle r^{2}\right\rangle^{1 / 2}=0.86 \mathrm{fm}$


$$
M_{R}=2.19(11) \mathrm{GeV}
$$

3 smearing sizes, the largest $\left\langle\mathrm{r}^{2}\right\rangle^{1 / 2}=0.39 \mathrm{fm}$

## Variation on $24^{3} \times 64$ DWF lattice with overlap valence $\left(m_{\pi}=330 \mathrm{MeV}, \mathrm{a}=0.111 \mathrm{fm}\right)$



GEVP with projected correlator

$$
\begin{aligned}
& \tilde{C}(t)=U^{T} C(t) U, \quad U=\left[u_{1}, u_{2}\right] \\
& \tilde{C}(t) v_{n}\left(t, t_{0}\right)=\lambda\left(t, t_{0}\right) \tilde{C}\left(t_{0}\right) v_{n}\left(t, t_{0}\right)
\end{aligned}
$$


$M_{R}=1.55(10) \mathrm{GeV}$


## Check source size dependence

| Method | Source | Sink | $t_{0}$ | $t_{\text {pro }}$ | $t_{\text {ref }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | w0,w2,w4,w8 | w0,w2,w4,w8 | 2 | 8 | none |
| 2 | Wall,w12 | B2,B6 | 5 | none | 6 |
| 3 | Wall,w12 | $\mathrm{B} 4, \mathrm{~B} 8$ | 5 | none | 6 |
| 4 | Wall,w12 | $\mathrm{B} 8, \mathrm{~B} 12$ | 4 | none | 6 |
| 5 | Wall,w8 | $\mathrm{B} 2, \mathrm{~B} 6$ | 4 | none | 6 |
| 6 | Wall,w8 | $\mathrm{B} 4, \mathrm{~B} 8$ | 4 | none | 6 |
| 7 | Wall,w8 | $\mathrm{B} 8, \mathrm{~B} 12$ | 4 | none | 6 |
| 8 | Wall,w5.5 | $\mathrm{B} 2, \mathrm{~B} 6$ | 3 | none | 6 |
| 9 | Wall,w5.5 | $\mathrm{B} 4, \mathrm{~B} 8$ | 3 | none | 6 |
| 10 | Wall,w5.5 | $\mathrm{B} 8, \mathrm{~B} 12$ | 3 | none | 6 |




## Why such a difference between clover and overlap fermion?

$\square$ Not due to fitting algorithm -- variation agrees with SEB for both clover and overlap fermions

- Chiral dynamics?
- Dynamical coupled-channle model predicts couplings to NTt, N $\eta$ and NTाT brings down the bare N by $\sim 400 \mathrm{MeV}$.
- Higher Fock space components needed in experimental electroexcitation amplitude of Roper.
- Bethe-Salpeter wavefunctions of Roper and nuclear are less orthogonal as pion mass decreases.
- Parity reversal of Roper and $\mathrm{S}_{11}$ might be due to meson exchanges between quarks (Glozman and Riska)


## Isovector scalar correlator in quenched approximation



Ghost would-be $\eta$ пт state

$$
-W_{\eta \pi}\left(1+m_{\pi} t\right) \mathrm{e}^{-2 m_{\pi} t}
$$



Indication of the strength of coupling to multihadrons with one hadron interpolation field.

## Comparison of would-be $\eta \pi$ ghost state on quenched lattices


$\mathrm{a}=0.12 \mathrm{fm}$, pion mass $=296 \mathrm{MeV}$

$\mathrm{a}=0.09 \mathrm{fm}$, pion mass $\sim 280 \mathrm{MeV}$

## Minima of ghost state for overlap and Wilson fermions



Ratio (overlap to Wison) ~ 7.6


Ratio (overlap to Wison) ~ 3.9

## N to NT, N $\eta$, NTтT coupling



Using both $\mathrm{q}^{3}$ and $\mathrm{q}^{4} \bar{q}$ operators have not see the Roper below 1.65 GeV .
C.B. Lang et al., 1610.01422
A.L. Kiratidis et al., 1704.08816

## Summary

- SEB method and variational approach give consistent results separately for the clover and overlap fermions, but the Roper from clover fermion is $\sim 300 \mathrm{MeV}$ higher than that of overlap.
- Model and experimental electroexcitation suggest large higher Fock space in Roper.
- Compare the ghost would-be $\eta \pi$ states of Wilson and overlap fermions on quenched lattices and found large discrepancy at a $=0.12$ and 0.09 fm .
- Chiral symmetry for clover fermion may be restored below a $\sim 0.06$ or $0.04 \mathrm{fm}(?)$. Clover calculation at these small lattice spacings may be the final solution to the 'Roper Puzzle'.


## Backup

## Evidence of $\eta^{\prime} \mathrm{N}$ GHOST State in $\mathrm{S}_{11}$ (1535)

Channel







## N* spectrum in LQCD \& dynamical coupling

Lattice $\mathrm{N}^{*}$ states $\left(\mathrm{m}_{\pi}=396 \mathrm{MeV}\right)$


LQCD finds states as predicted in $\mathrm{SU}(6) \times \mathrm{O}(3)$
R. Edwards, J. Dudek, D. Richards,
S. Wallace, PRD84, 074508 (2011)

Dynamics of $\mathrm{P}_{11}$-states:
The bare state at ${ }^{\sim} 1750 \mathrm{MeV}$ through coupling to inelastic channels generates 2 poles below 1400 MeV . They are identified with the "Roper" resonance.

N. Suzuki et al. (JLab/EBAC),

Phys.Rev.Lett.104:042302,2010

