Updated spectroscopy for SU(3) with eight fundamental flavors

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(arXiv:1601.04027, **1807.08411**)

Lattice **S**trong **D**ynamics Collaboration

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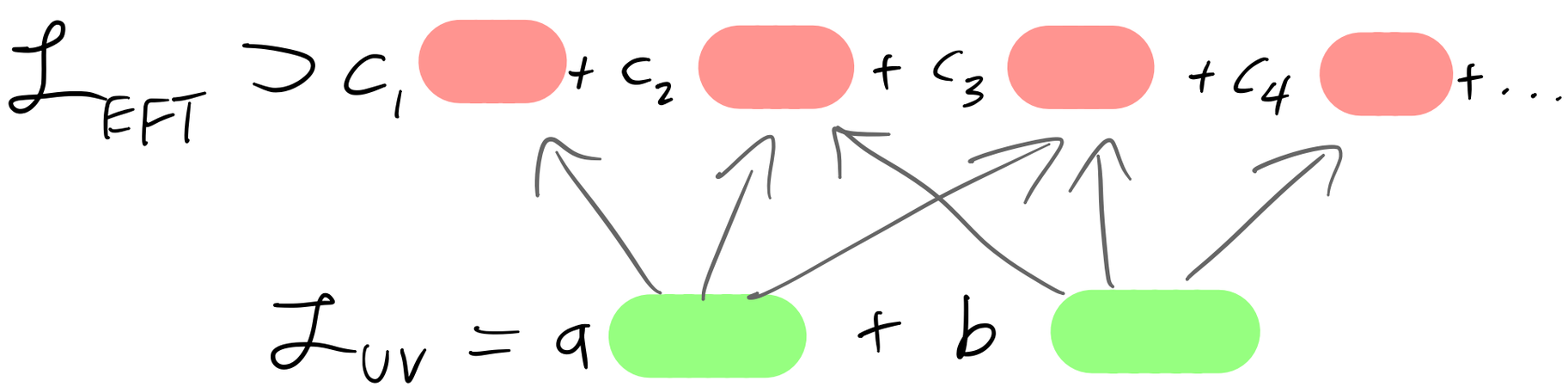
Motivation/context

- So far LHC —> Higgs and nothing else - but the Standard Model is still incomplete: ν mass, dark matter, Higgs naturalness

- <u>BSM theories with strong dynamics</u> (strongly-coupled gauge interactions) are interesting, need lattice to fully understand. Gauge group, fermion content can (and often does!) vary from QCD.

- Role of lattice here is not high precision! Main contributions from lattice are:
  - **Relating LECs** in terms of a handful of underlying parameters
  - **Revealing dynamical surprises**; LECs which are unexpectedly large/small, or possibly even that the EFT we guessed originally may not be correct



SU(3) with N_f=8

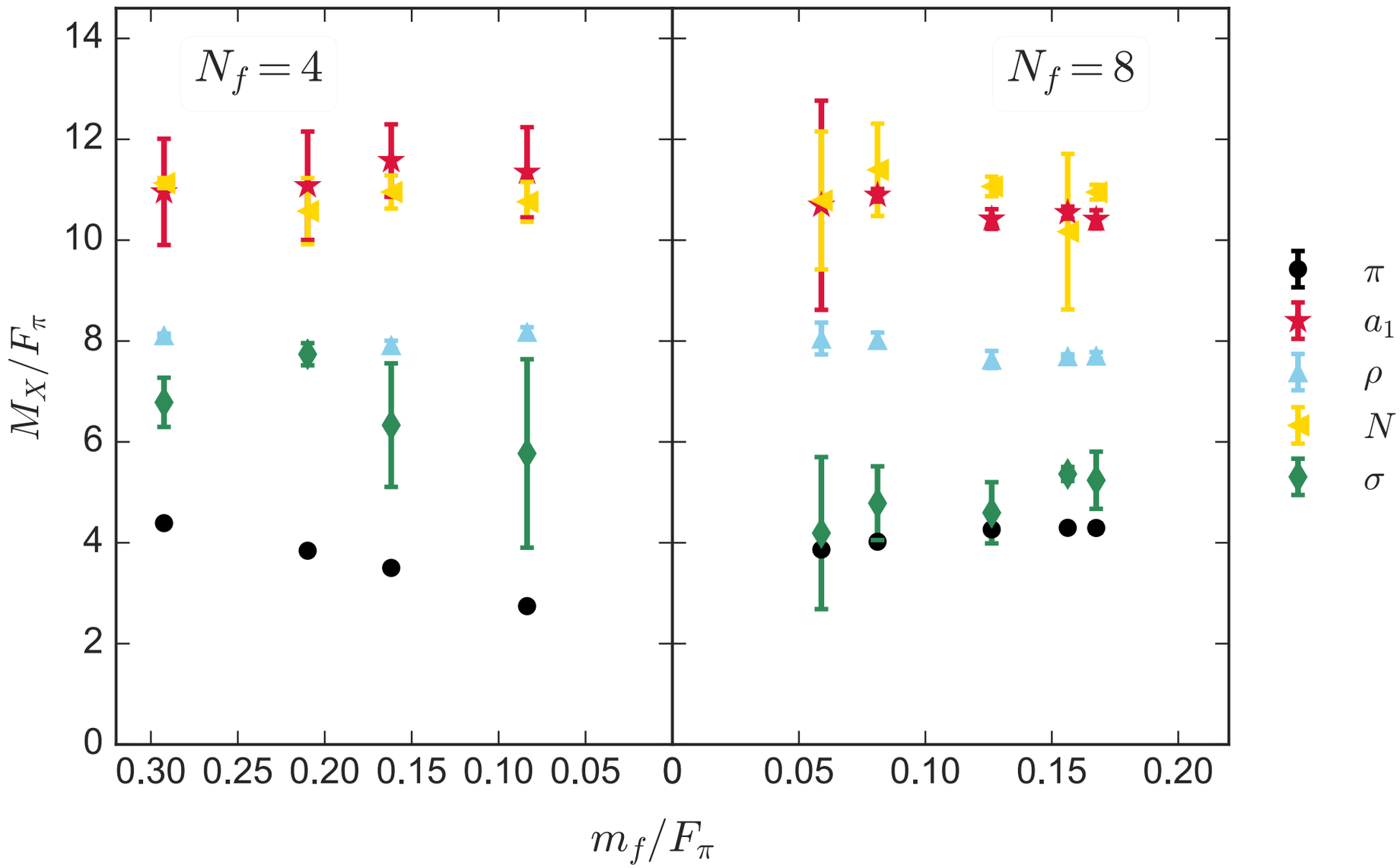
Why this theory?

- "Near-conformal": lattice results so far hint this theory is very near the conformal transition
- SU(3) + fundamental rep: can use highly optimized codes available for QCD, adjusting the number of fermions is easy
- *No particular pheno model connection in mind*, although some attempts have been made[1,2] (assumptions about low-energy EFT…)

[1] S. Matsuzaki and K. Yamawaki, arXiv:1201.4722
[2] LatKMI collaboration, arXiv:1302.6859

(note “butterfly plot” - zero for both x-axes in center.)

Spectrum results



Main result is **light σ state for N_f=8**, degenerate with pions!
(*New this analysis:* added statistics, new lightest 0++ result, refined analysis procedure.)

Lattice setup and ensembles

- nHYP staggered fermions with fundamental-adjoint plaquette action
- High statistics for disconnected diagrams - determination of 0++ scalar
- Wilson flow scale t_0 used for scale setting. (Note: strong dependence on am!)
- <u>Finite volume:</u> explicit tests show small effects, $M_\pi L$~5 or larger for all ensembles used in main analysis
- <u>No continuum extrapolation</u> of results yet; taste breaking indicates a~0.15 fm or so.

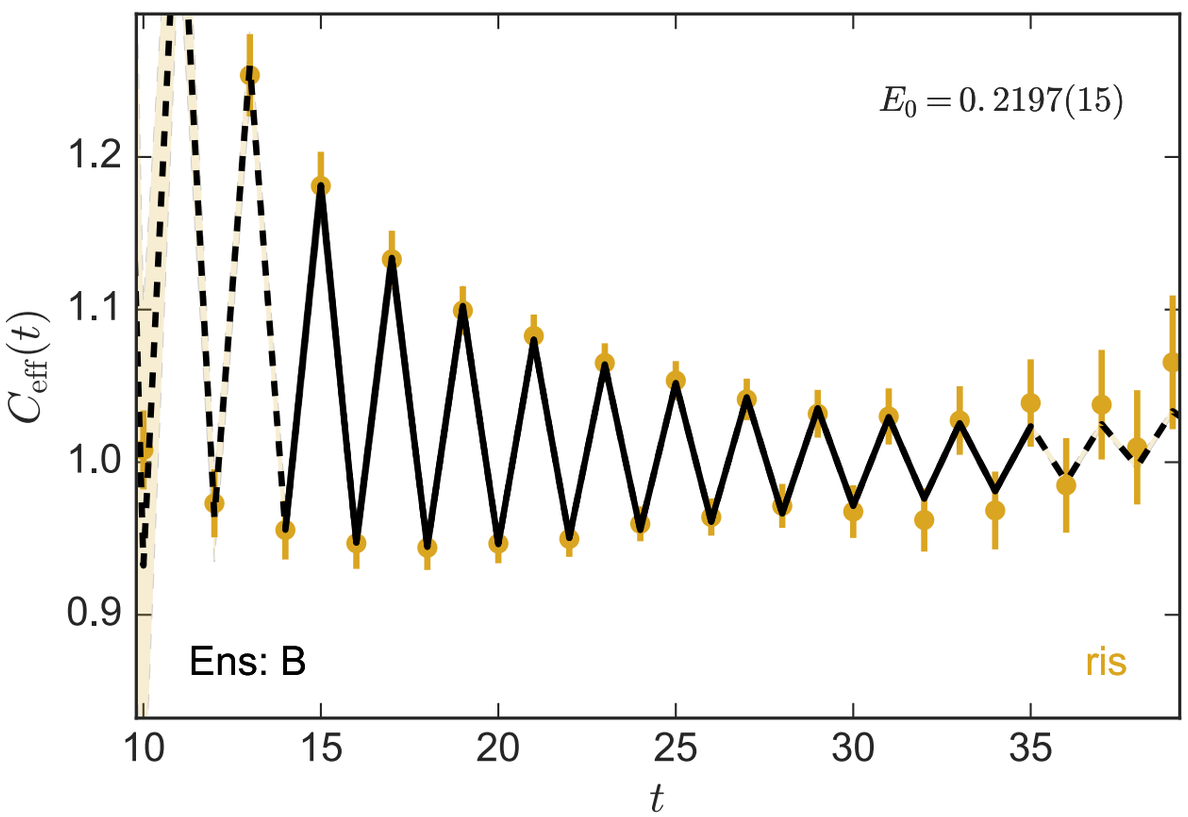
N_f	β_F	$L^3 \times N_t$	am_f	τ	MDTU	Sep.	# Est.	Bins	$\sqrt{8t_0}/a$
8	4.8	$64^3 \times 128$	0.00125	0.5	4,314	6	$720^\dagger$	72	
					4,494	6	750	75	
					5,094	6	850	85	4.7345(14)
8	4.8	$48^3 \times 96$	0.00222	1.0	10,640	16	666	111	
					8,912	16	558	93	4.5742(21)
8	4.8	$32^3 \times 64$	0.005	2.0	5,100	20	256	128	
					5,100	20	256	128	
					6,380	20	320	160	4.1371(33)
8	4.8	$32^3 \times 64$	0.0075	1.0	24,590	10	2,460	492	3.7820(19)
8	4.8	$24^3 \times 48$	0.00889	1.0	24,500	20	1,226	613	3.6152(32)
4	6.4	$24^3 \times 48$	0.0125	1.0	24,620	20	1,232	616	3.7214(13)
4	6.6	$48^3 \times 96$	0.003	2.0	20,680	40	$518^\S$	518	4.9779(10)
4	6.6	$32^3 \times 64$	0.007	2.0	15840	20	$792^\star$	198	4.8478(20)
4	6.6	$24^3 \times 48$	0.015	1.0	24,380	20	1,220	610	4.6390(22)

(4-flavor ensembles mainly as cross-check of methods; expected to be “QCD-like”.)

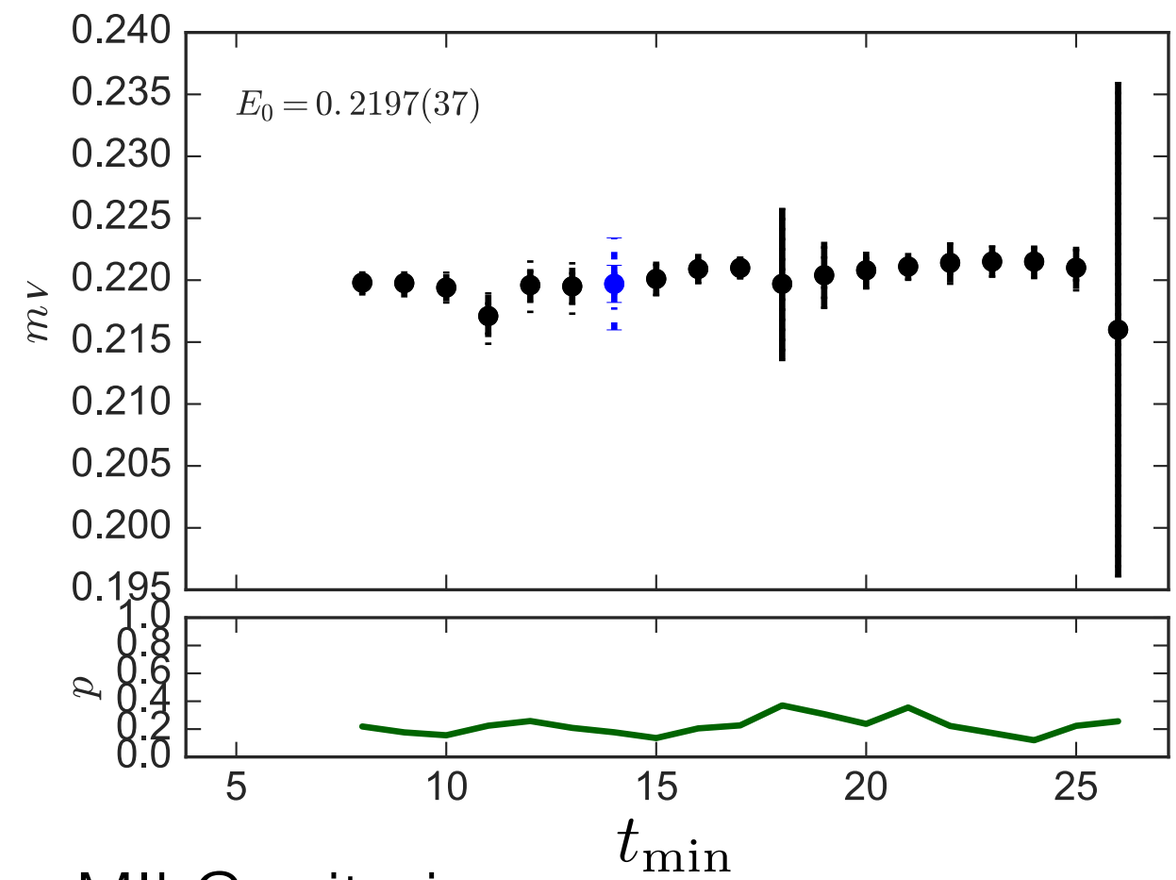
Fitting procedure

- Standard procedure for connected two-point functions; all fits use one pair of excited states ("2+2" model)

$$C_{\text{eff}}(t) \equiv C(t)e^{+E_0 t}$$



- <u>Fit-range systematic scan:</u> dotted error bars show variation with t_{max}, all fits with p>0.1 considered. Sys err from *significant* (1σ) difference of mean.



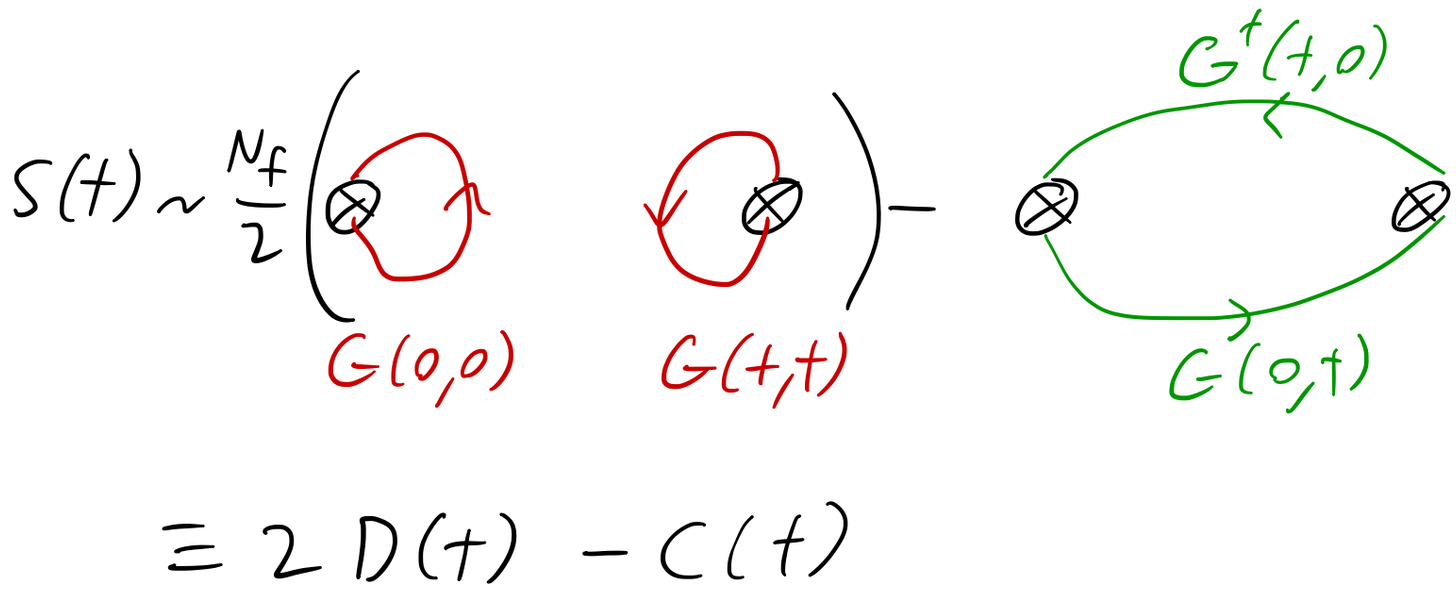
"Best fit" from variant of the MILC criterion:

$$C \equiv \frac{p \times N_{\text{dof}}}{\sum_n (\sigma_n/\mu_n)^2}.$$

Fully automated procedure with conservative error from fit range choice.

Extracting the sigma mass

- For flavor-singlet states (like σ), propagator from source/sink to itself does not vanish —> double-trace (**disconnected**) diagrams:



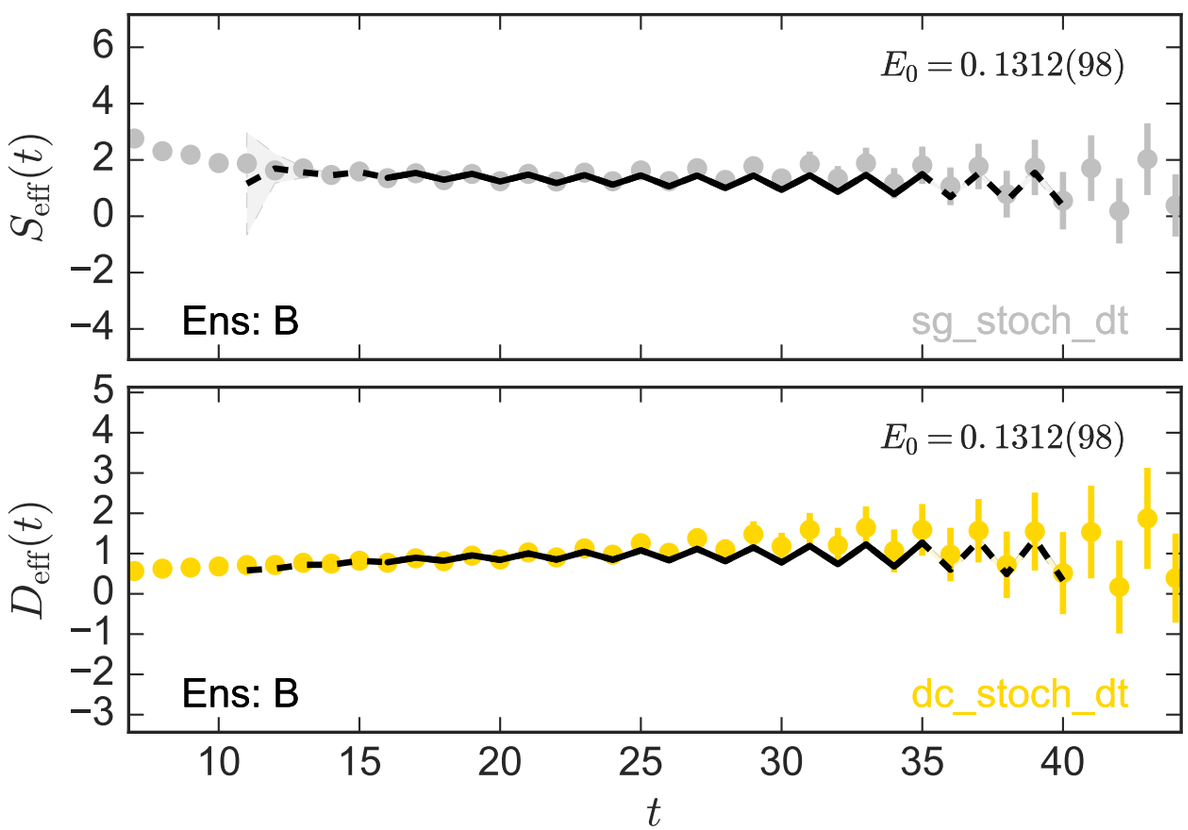
- We use **stochastic estimation** (6 U(1) wall sources/config) with **dilution** (suppresses off-diagonal noise correlations) to reduce noise in disconnected correlator. Fermionic operator only.

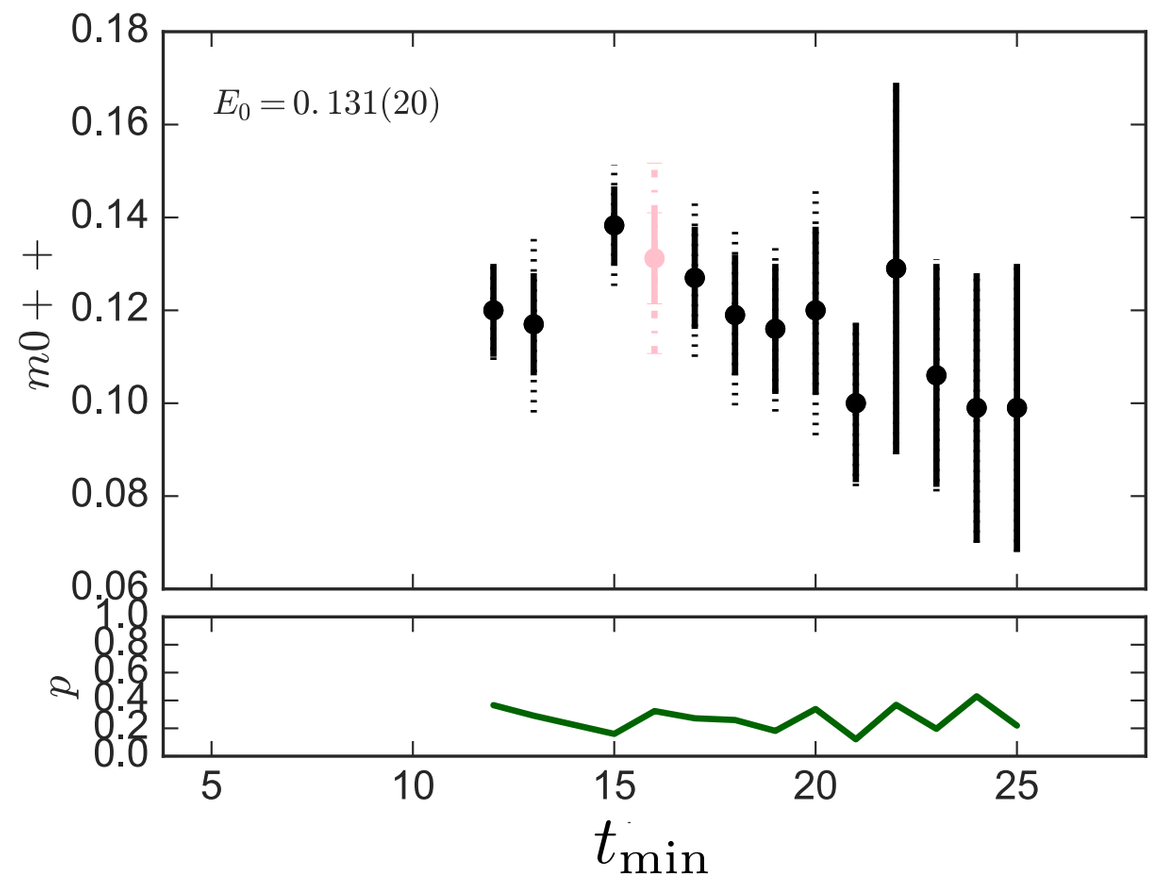
- In practice, fit *finite difference correlator* ~[D(t+1) - D(t)]. Removes t-independent constant, which is annoying to fit; also reduces autocorrelation significantly.

- <u>Joint fit</u> to S=2D-C and D, both of which contain M_{0++} but have different systematics:

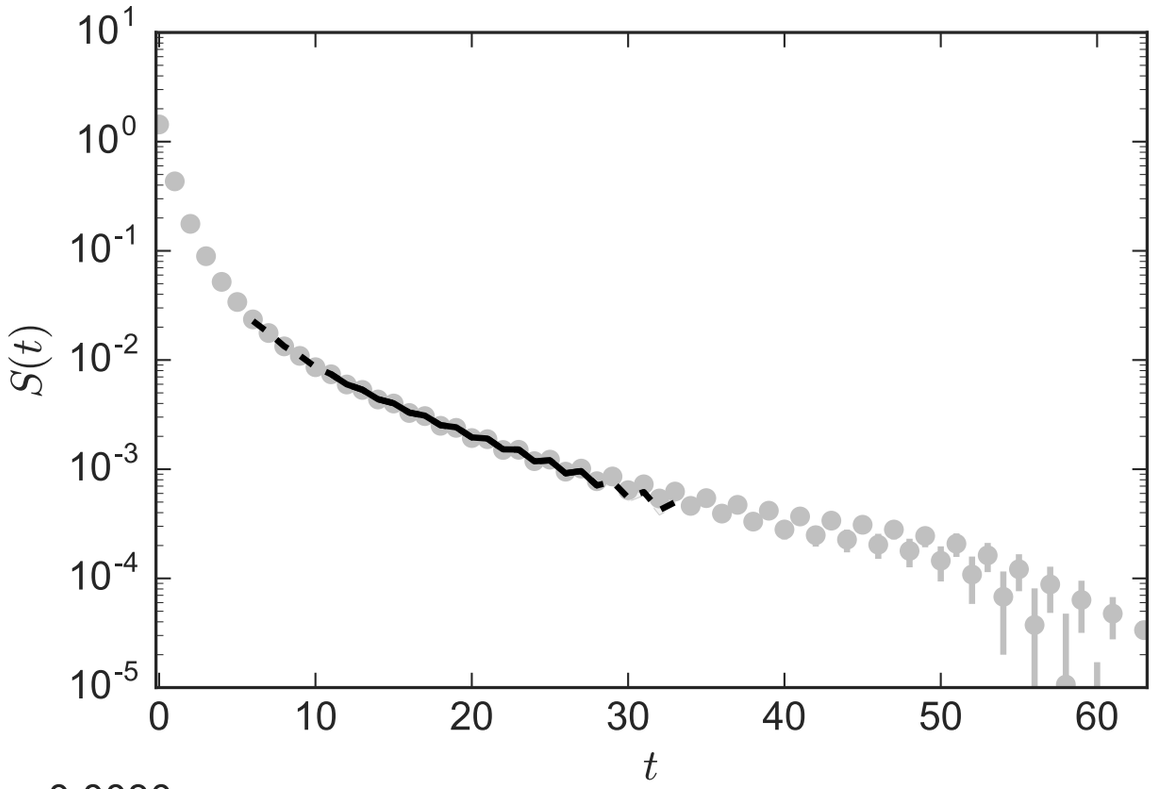
$$S(t) = a_d \cosh\left[M_{0++}(N_t/2 - t)\right] + b_d(-1)^t \cosh\left[M_{\eta_{sc}}(N_t/2 - t)\right]$$

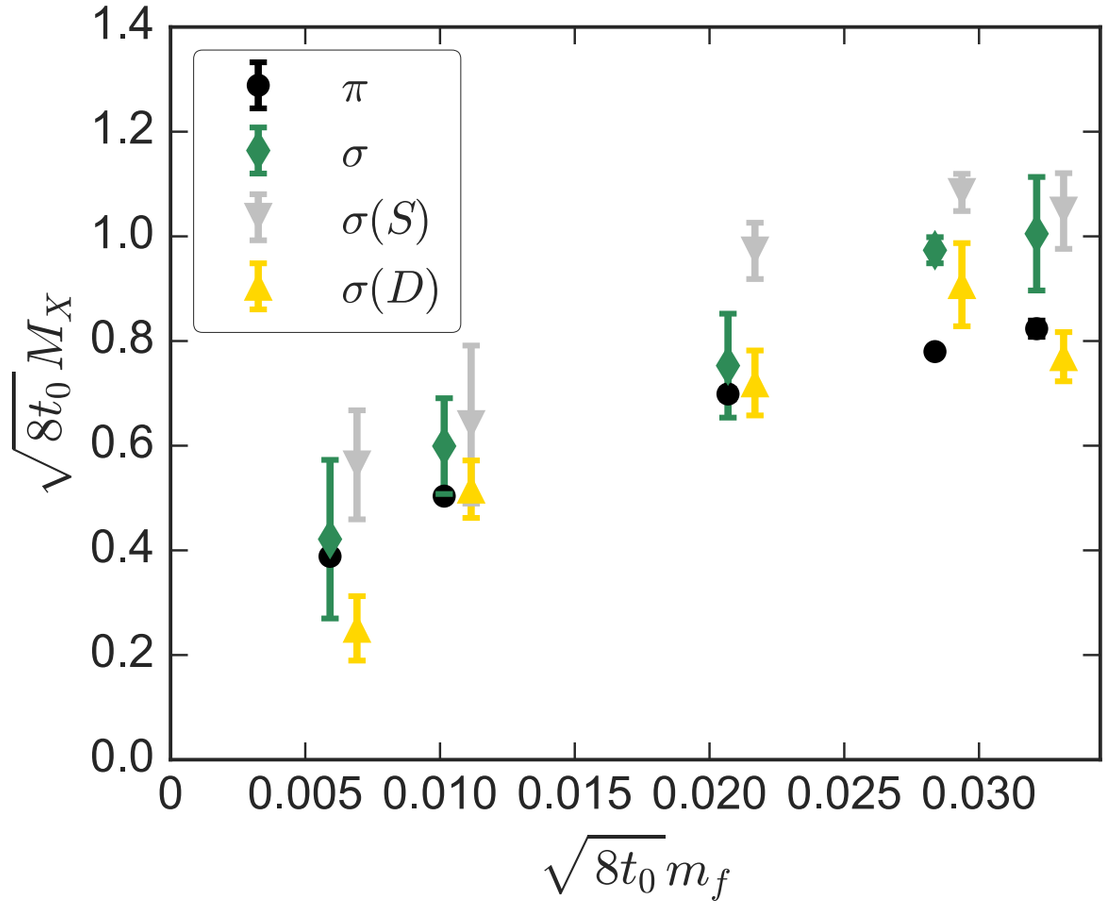
$$D(t) = \frac{4}{N_f}\left\{S(t) - (-C(t))\right\} = a_d e^{-M_{0++}t} - a_c e^{-M_{a_0}t} + (-1)^t\left\{b_d e^{-M_{\eta_{sc}}t} - b_c e^{-M_{\pi_{sc}}t}\right\}$$

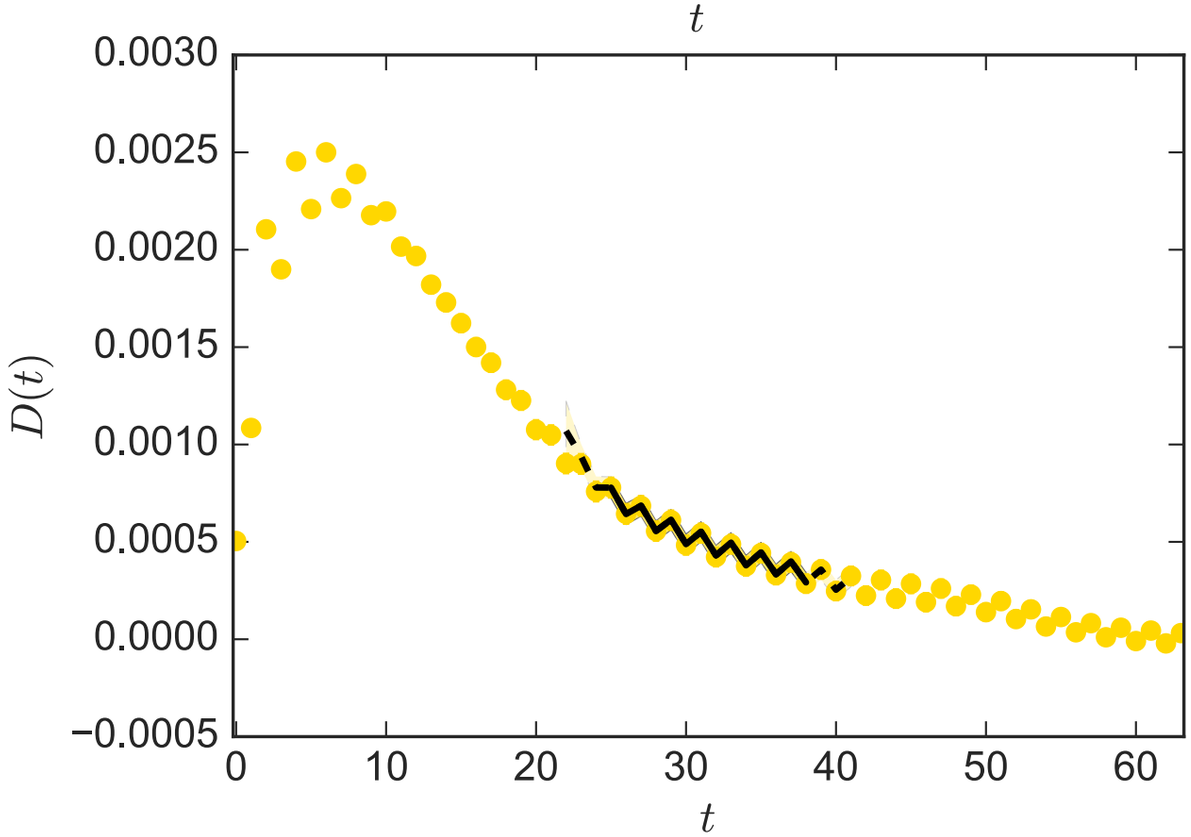




Same procedure based on MILC criterion for best-fit selection and fit-range systematic error assignment







- Joint fits tend to be **more stable** with respect to t-range. (Note opposite sign of excited states in S vs. D correlators, *left*!)
- *Above*: comparison of joint fit (green) to individual S, D fits for 0++
- Joint extraction gives **smaller error** than just taking difference between S, D results as systematic

[1]K. Kawarabayashi and M. Suzuki, Phys. Rev. Lett.16, 255 (1966); Riazuddin and Fayyazuddin, Phys. Rev. 147,1071 (1966).

Vector Meson Saturation

- Saturation of vector channel by a single resonance (ρ) gives a phenomenological model of low-energy quantities, based on rho mass and width.

- VMS works well in QCD (~10%) for some things, e.g. KSRF[1] relations:

electroweak decay →

$$F_\rho = \sqrt{2}\, F_\pi \ , \quad g_{\rho\pi\pi} = \frac{M_\rho}{\sqrt{2}\, F_\pi} \ ,$$

HC-strong decay →

$$\Gamma_\rho \approx \frac{g^2_{\rho\pi\pi}\, M_\rho}{48\pi} \approx \frac{M_\rho^3}{96\pi F_\pi^2}$$

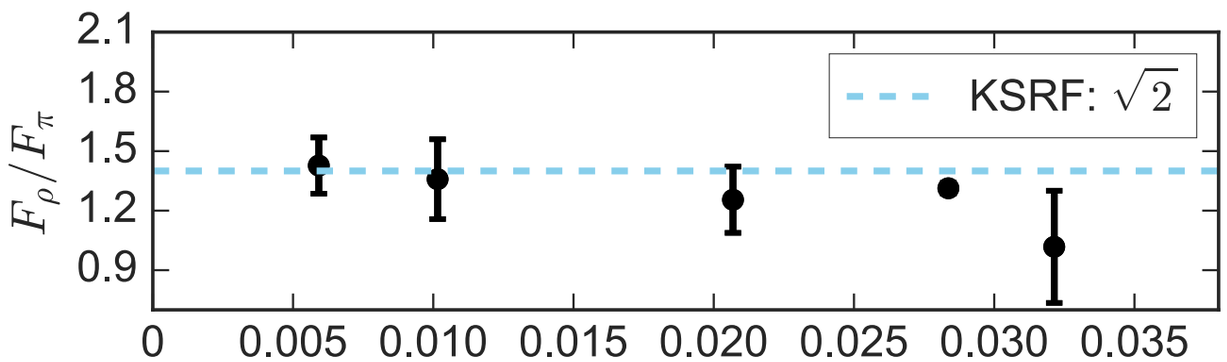
<u>large-N_c:</u>

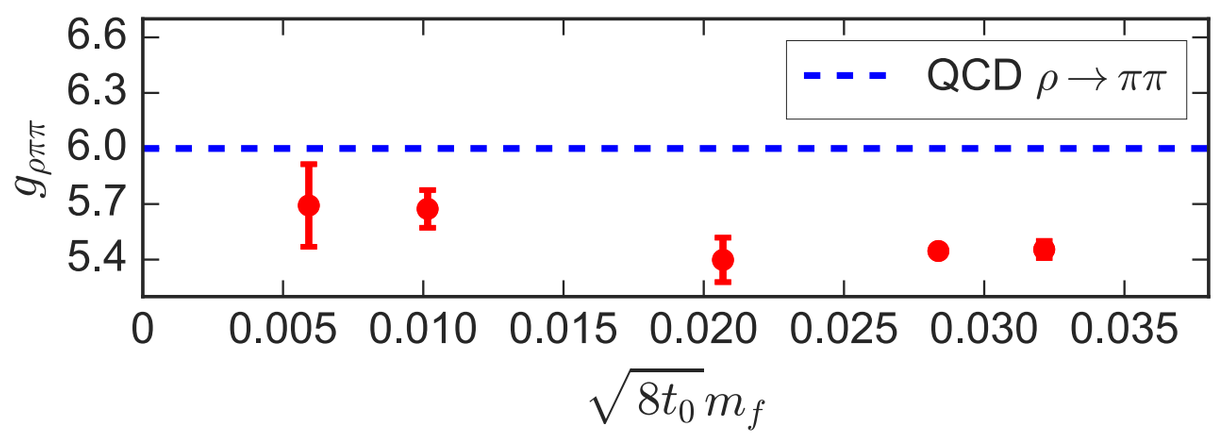
$$\frac{M_\rho}{F_\pi} \sim \frac{1}{\sqrt{N_c}}$$

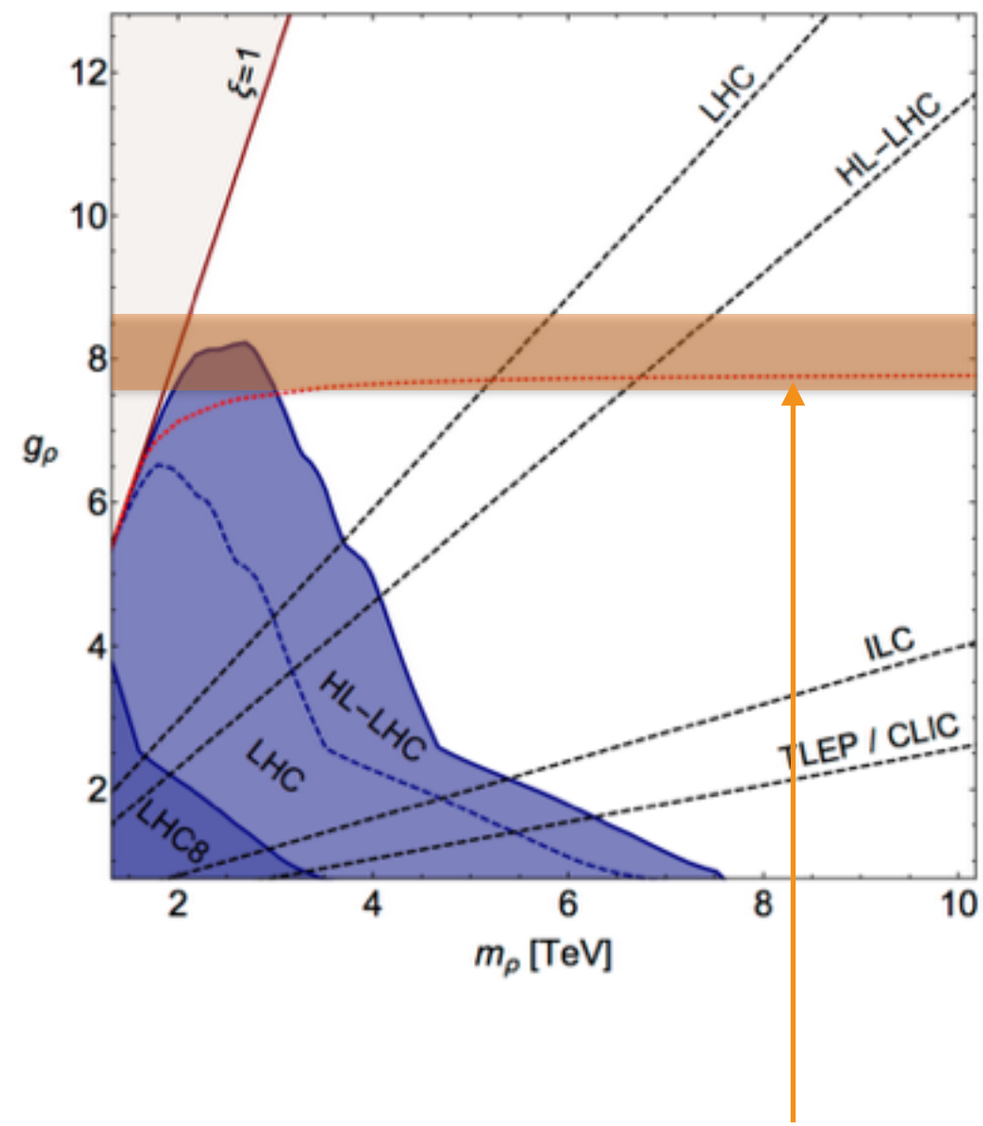
- What happens in other strongly-coupled models?

- Left: Test of one KSRF relation (F_ρ/F_π), nice agreement, little mass dependence. Other relation gives $g_{\rho\pi\pi}$ from M_ρ/F_π (convention: F_π~93 MeV in QCD.)

(Thamm, Torre and Wulzer, 1502.01701)







- Right: $g_{\rho\pi\pi}$ leads directly to collider constraints on ρ production in composite Higgs models. Lattice greatly reduces the available parameter space!

band using rough $g_{\rho\pi\pi}$ from QCD/lattice

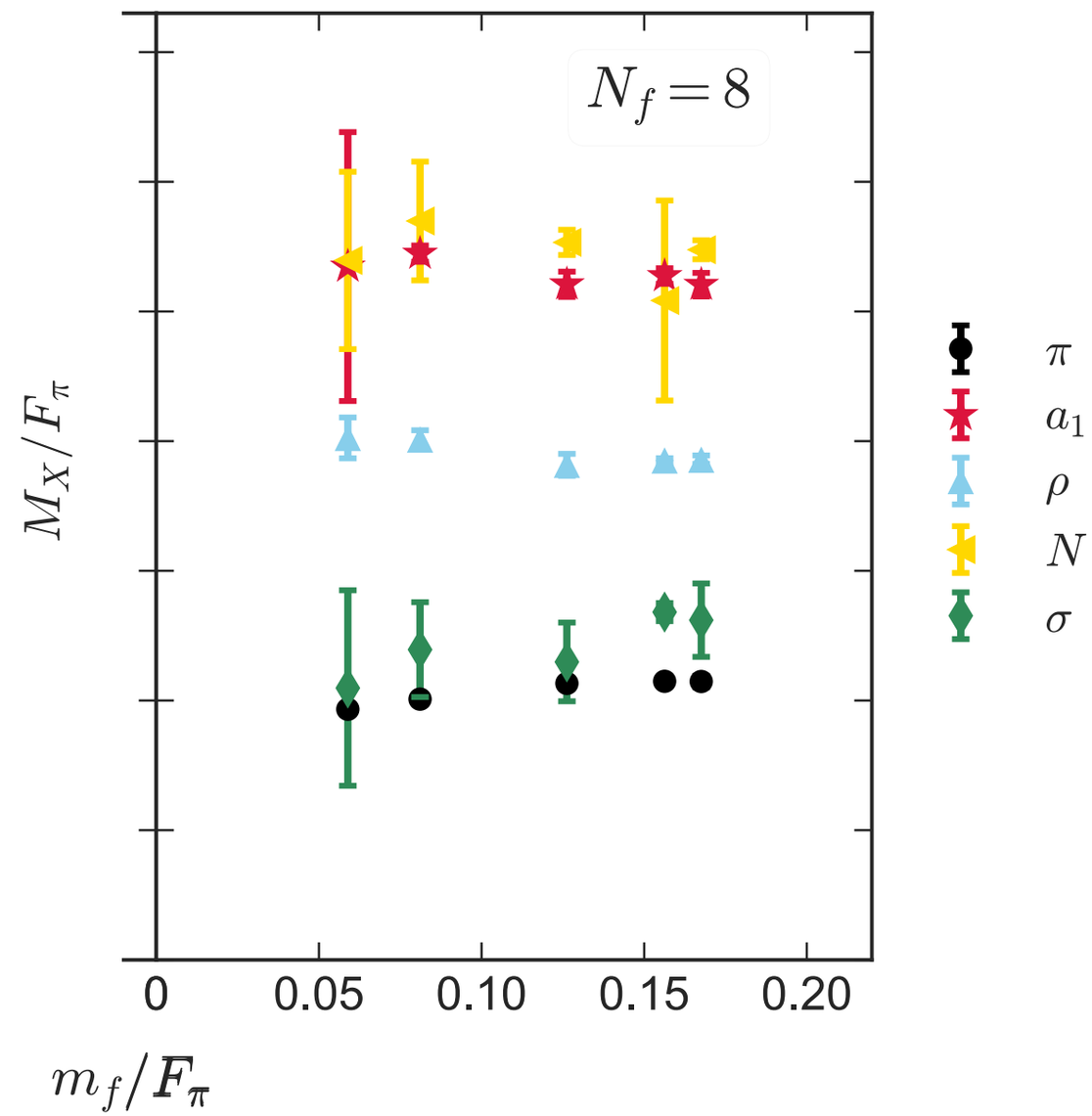
(note different convention:) $M_\rho = g_\rho f$

Summary

- Vector-meson saturation seems to work well beyond QCD, and $g_{\rho\pi\pi}$~6 (in my convention) is fairly insensitive to fermion mass/number

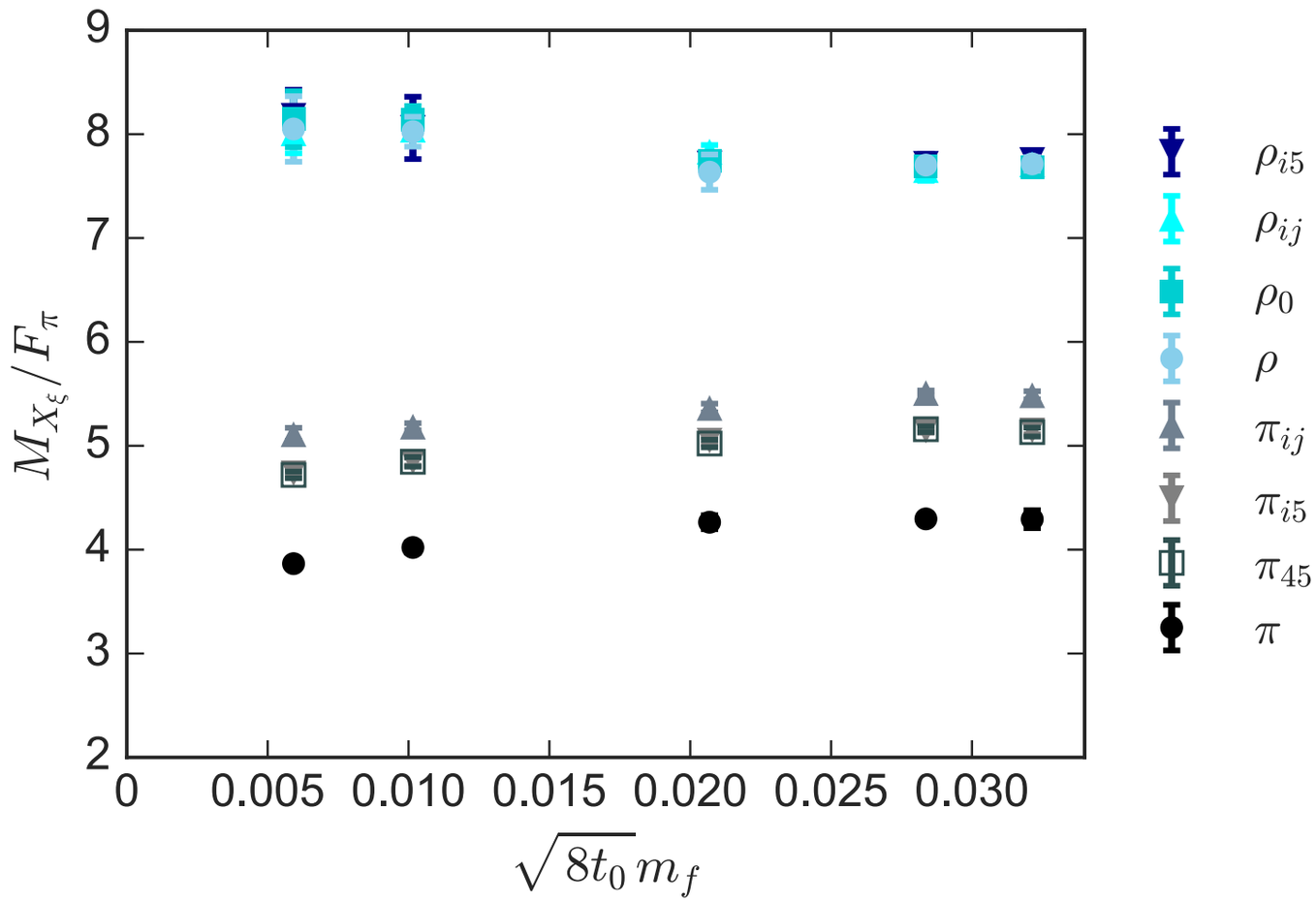
- Light 0++ scalar, degenerate with pions, reliably established; comparison to Nf=4 helps. Joint S/D fit and marginalizing over fit range improve extraction of 0++ mass.

- *What is the low-energy EFT*? Adding more mass points, observables to discriminate, future work will compare model predictions.



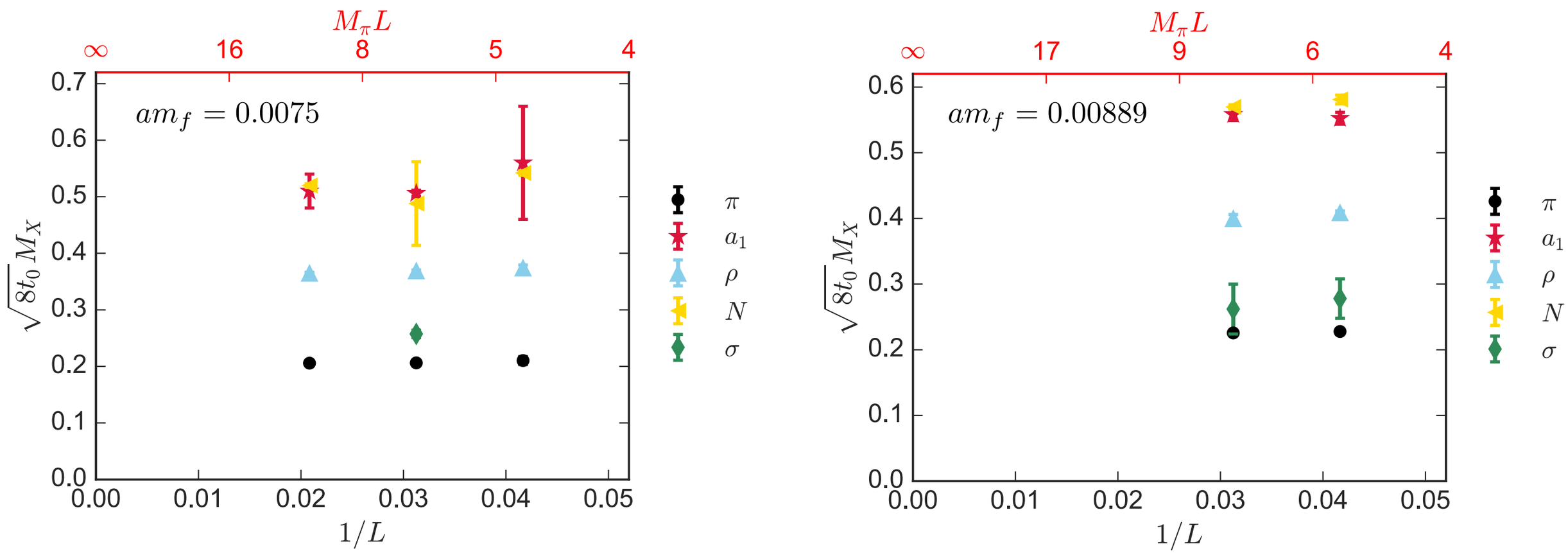
Backup

Staggered taste breaking



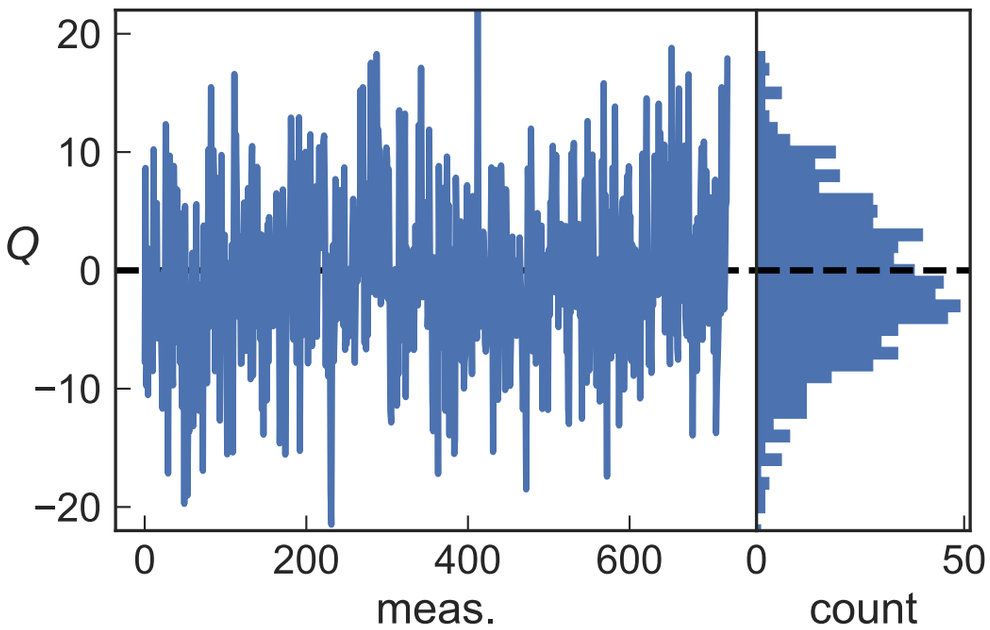
- N_f=8 shown; N_f=4 looks similar, but somewhat smaller splitting.
- Pion taste splitting is on the order of 20%-30%; compare to 15%-20% splittings seen by the MILC collaboration for a~0.12fm in QCD.

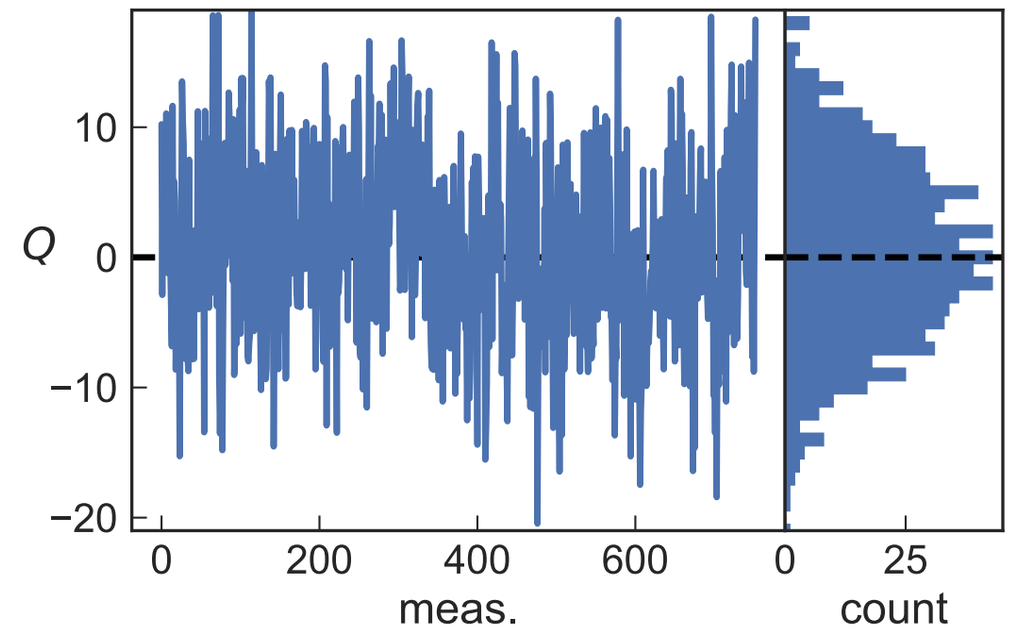
Finite-volume effects?



- Explicit tests for volume dependence on heavier masses reveal no large effects for any of the states we consider
- No explicit tests available at lighter fermion mass, but all results shown in our central analysis satisfy $M_\pi L > 5.3$

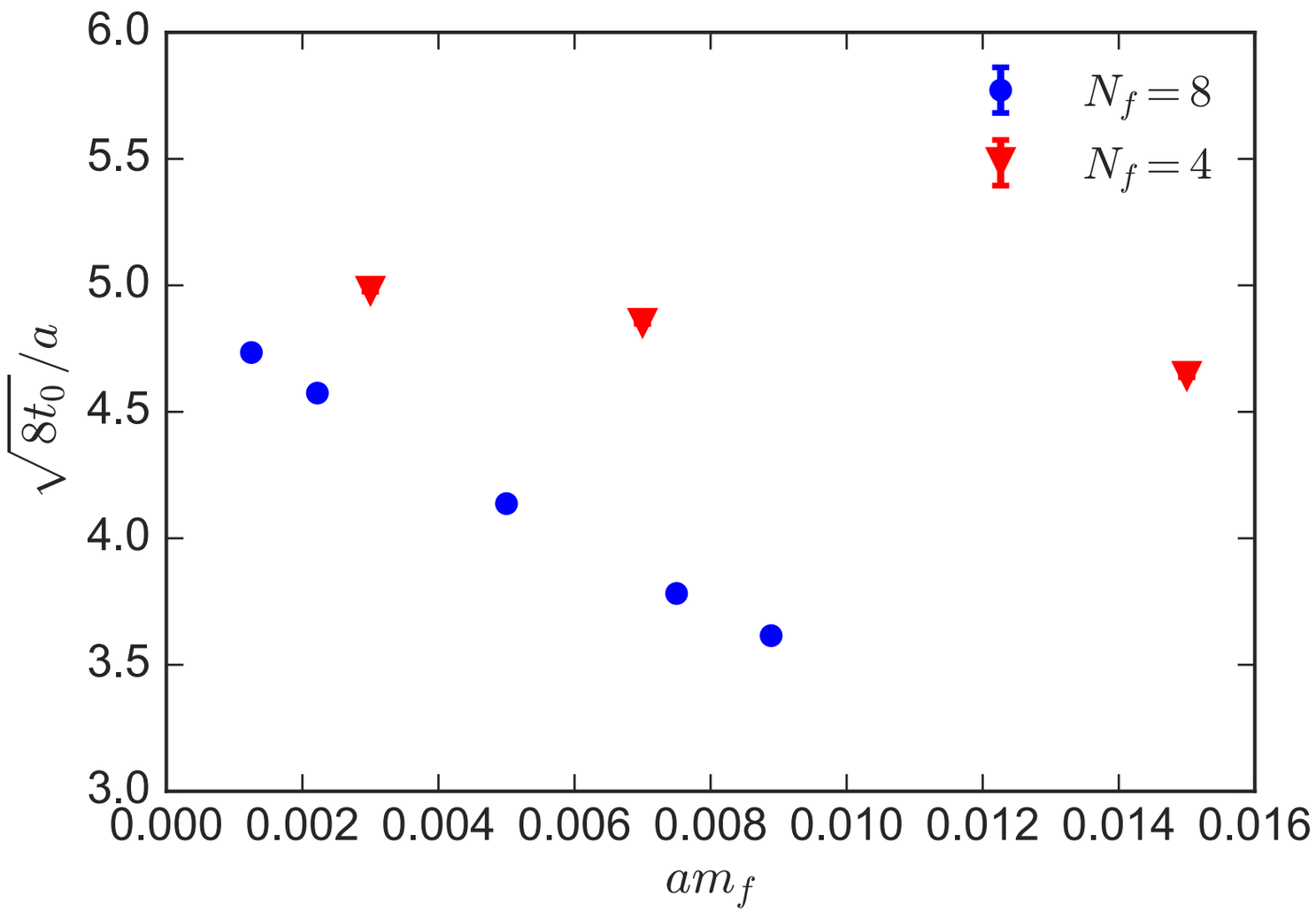
Topological charge





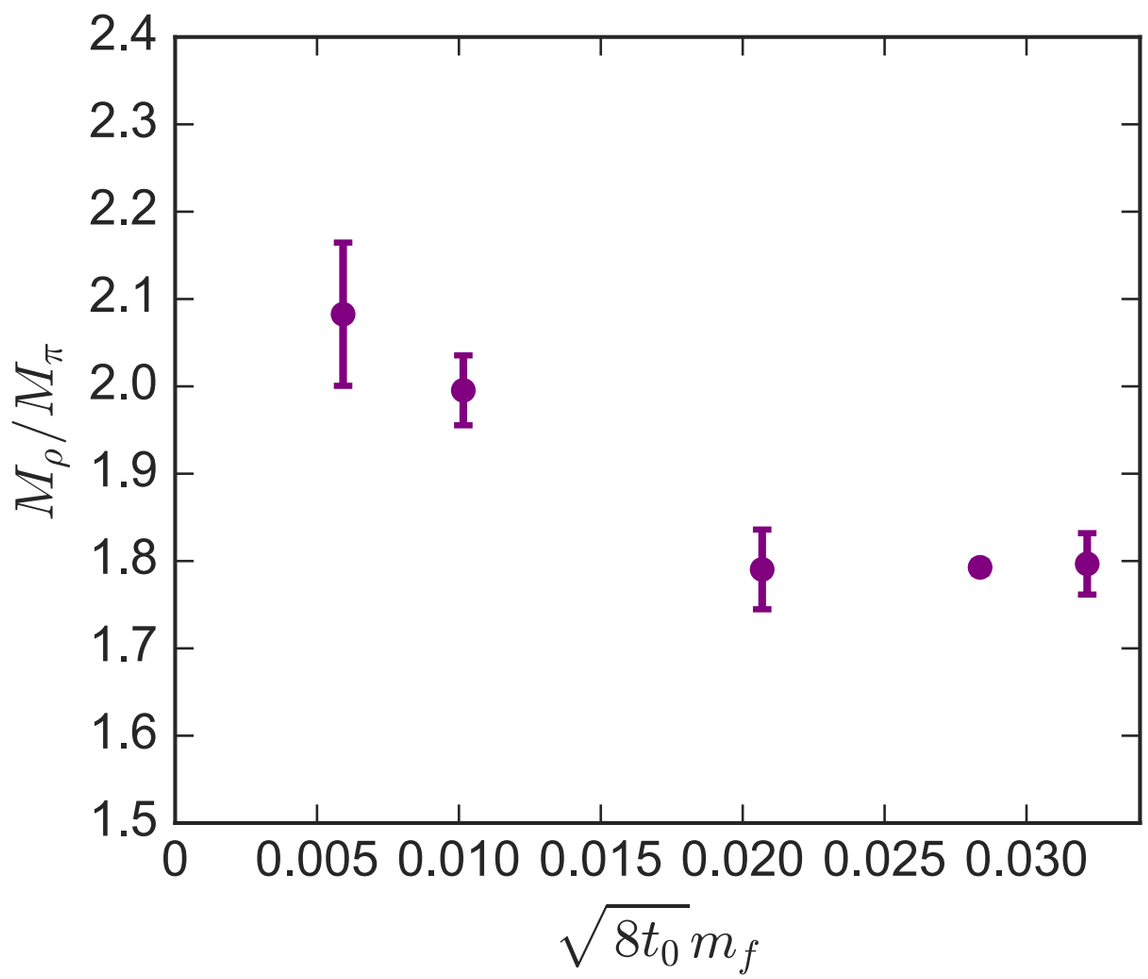
- Good evolution of topological charge seen on all ensembles, even the largest L=64 (shown above, two streams.)

Scale setting



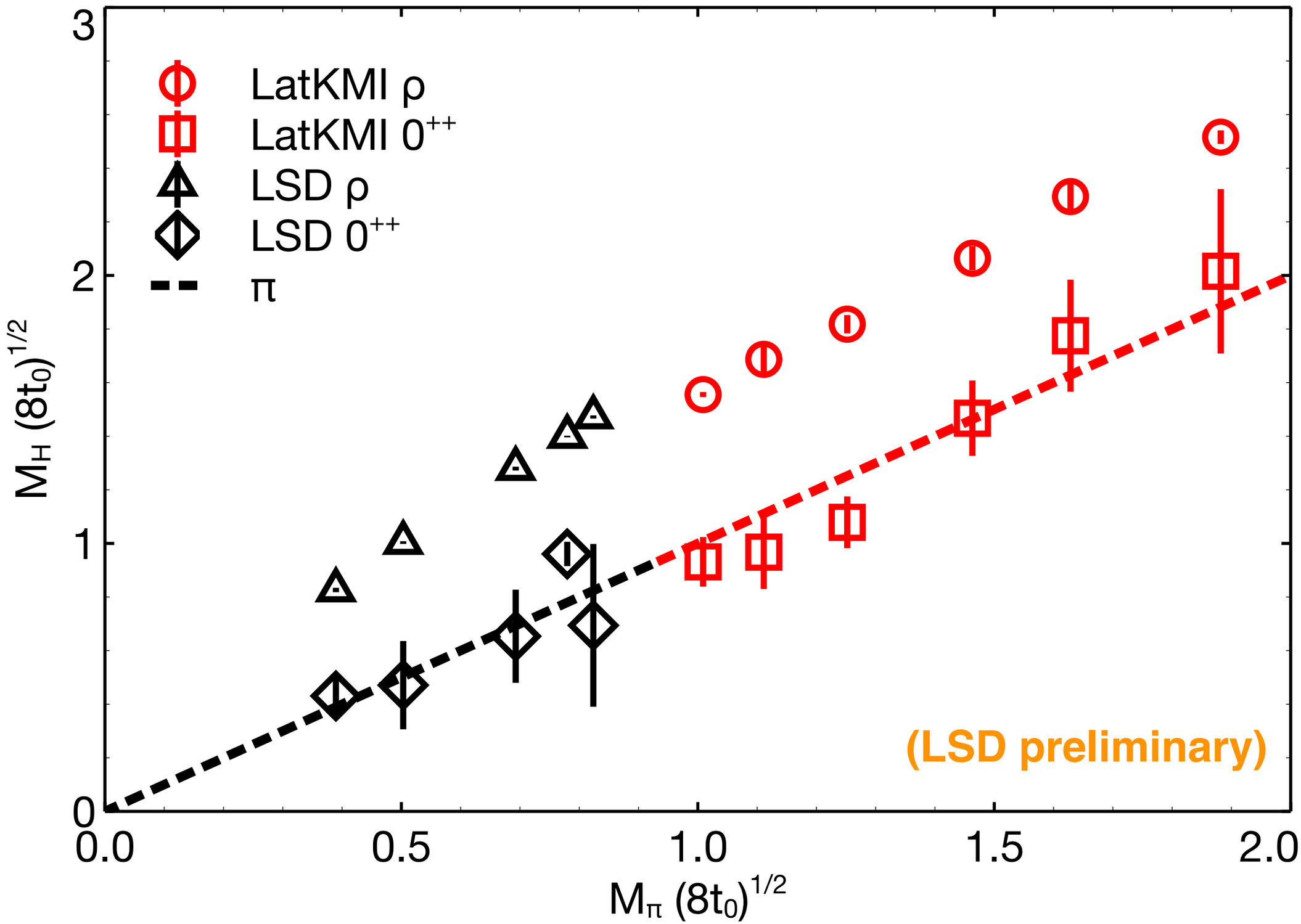
- Wilson flow + clover operator ("WWC") to determine t_0
- Dependence of flow scale on bare parameters much stronger for N_f=8 (left: fixed bare coupling β)
- Mass-dependent scale setting could leverage this for continuum extrapolation, but requires good understanding of t_0 in appropriate EFT…

Hyperscaling spectrum?



- Ratios of spectrum results are fairly constant for Nf=8; does that indicate infrared conformality —> “hyperscaling”?
- “Hyperscaling” predicts all states scale with same power-law dependence on mf, so ratios are constant.
- Closer look at more precise ratios reveals some movement: left, M_ρ/M_π shows some hint of expected behavior as m_f—>0.
- Larger question: what is the right chiral effective theory that describes our results? Subject of future work.

Scalar (σ, 0^{++}) meson



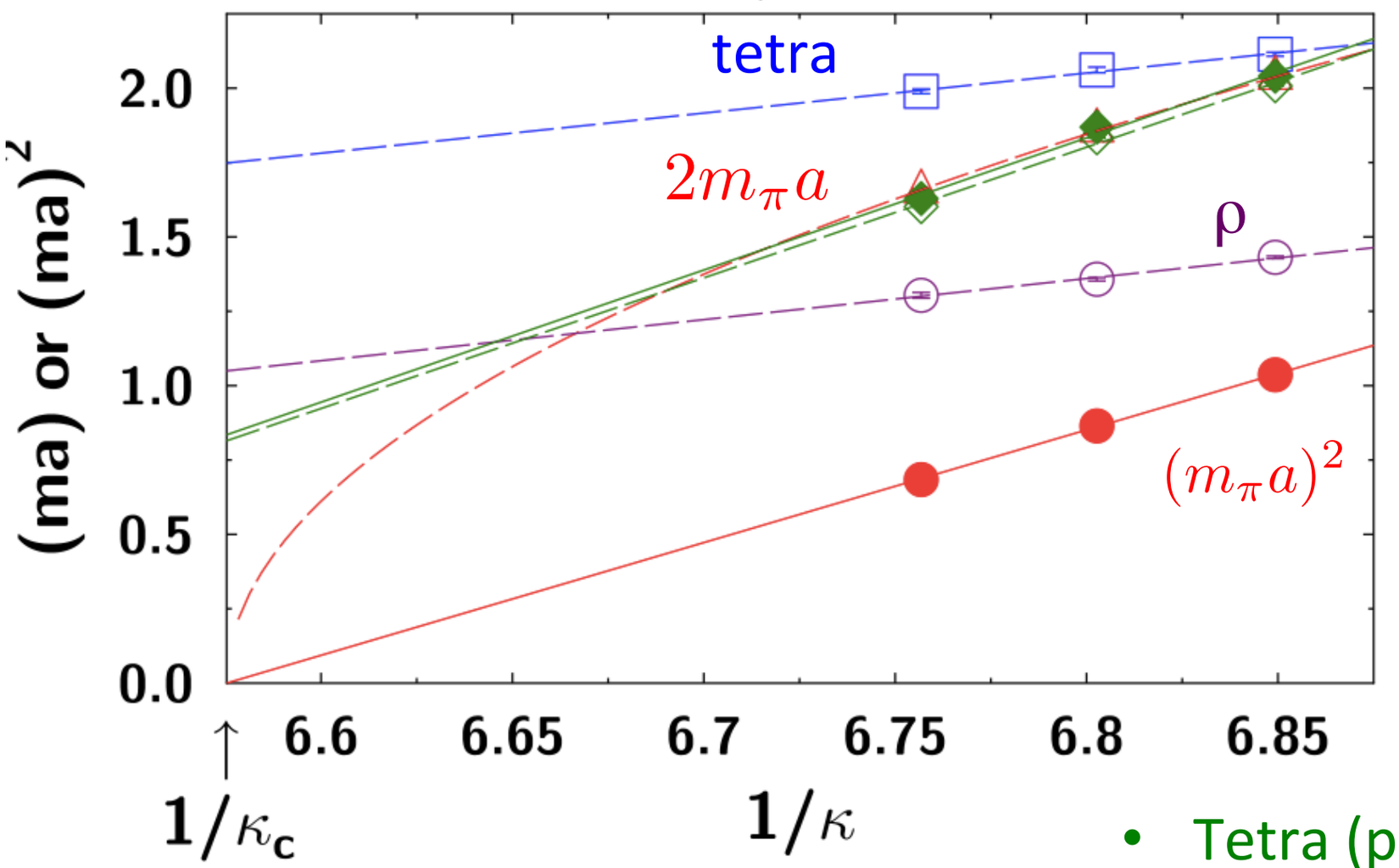
(slide from C. Nonaka)

- **QCD looks very different at heavy mass!**

κ Dependence of Effective Masses

SCGT15

arXiv1412.3909[hep-lat]



with disconnected diagram

◆ m^{molec} a

◇ m^{molec}_{con} a

connected diagram

- Molecule
  - Small effect of disconnected diagram
  - π-π scattering state?

- Tetra (plateau ?)
  - Disconnected diagram is important.
  - small overlap to ground state of molecule

0++ on lightest 4f ensemble

Large error dominated by systematics (left plot).

Possible contamination by 2π state may be allowed by light π mass + relatively heavy 0++? To be investigated in future work.