Lawrence Livermore National Laboratory

Strongly-Coupled Gauge Theories
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Investigation of the scalar spectrum in SU(3) with 8 flavors

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Lattice Strong Dynamics collaboration

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in collaboration with Anna Hasenfratz

Lattice Strong Dynamics Collaboration

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Outline

- Phase diagram: Finite temperature transitions
- Scale setting: Define a running coupling
- Connected spectrum: Mesons towards the chiral limit
- Flavor-singlet scalar spectrum: Disconnected diagrams and mass gap

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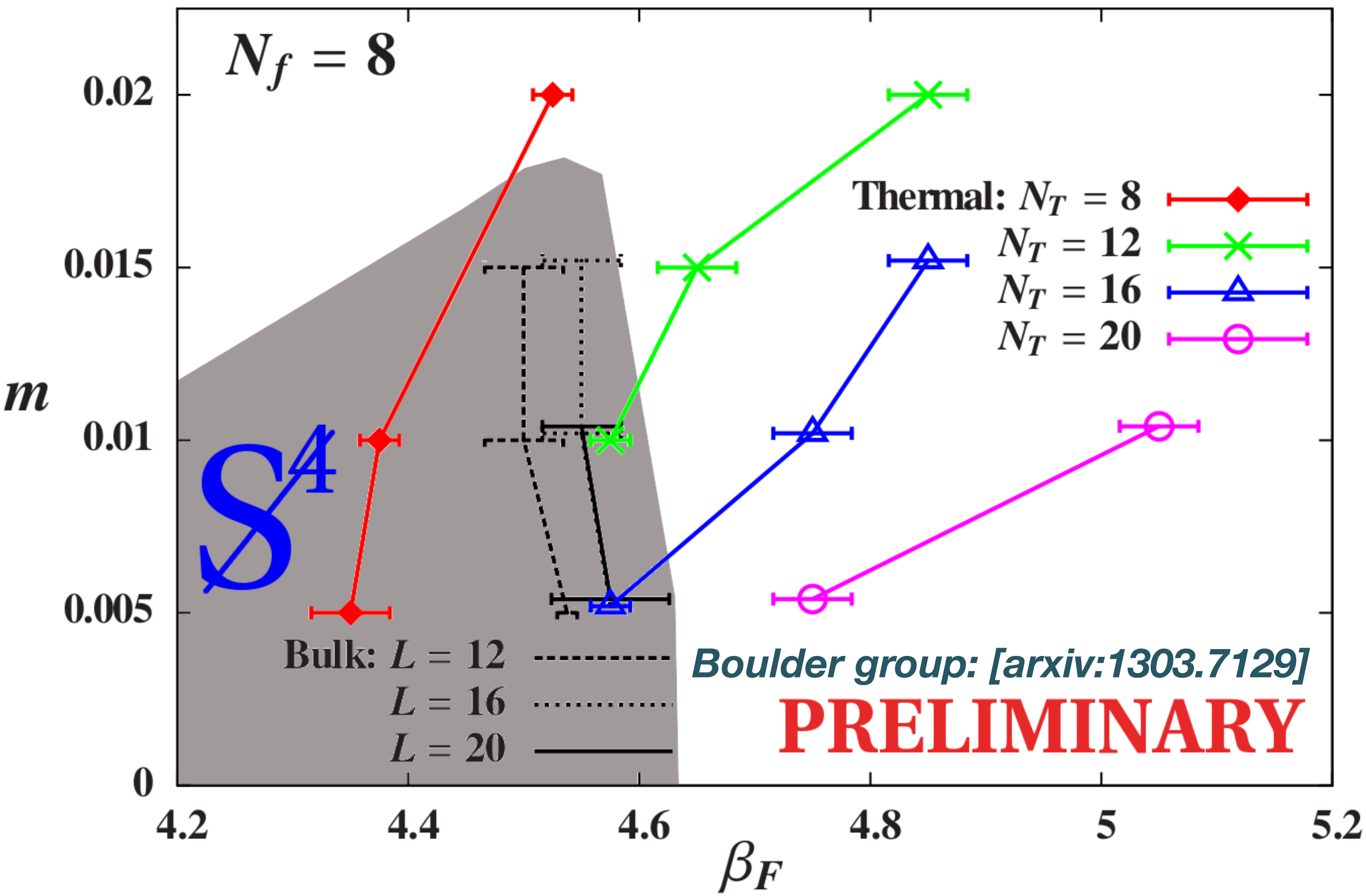
- Connected spectrum: Mesons towards the chiral limit
- Flavor-singlet scalar spectrum: Disconnected diagrams and mass gap

a still unfamiliar strongly-coupled theory

Eight flavors at finite temperature



see poster by D. Schaich
with the LSD collaboration

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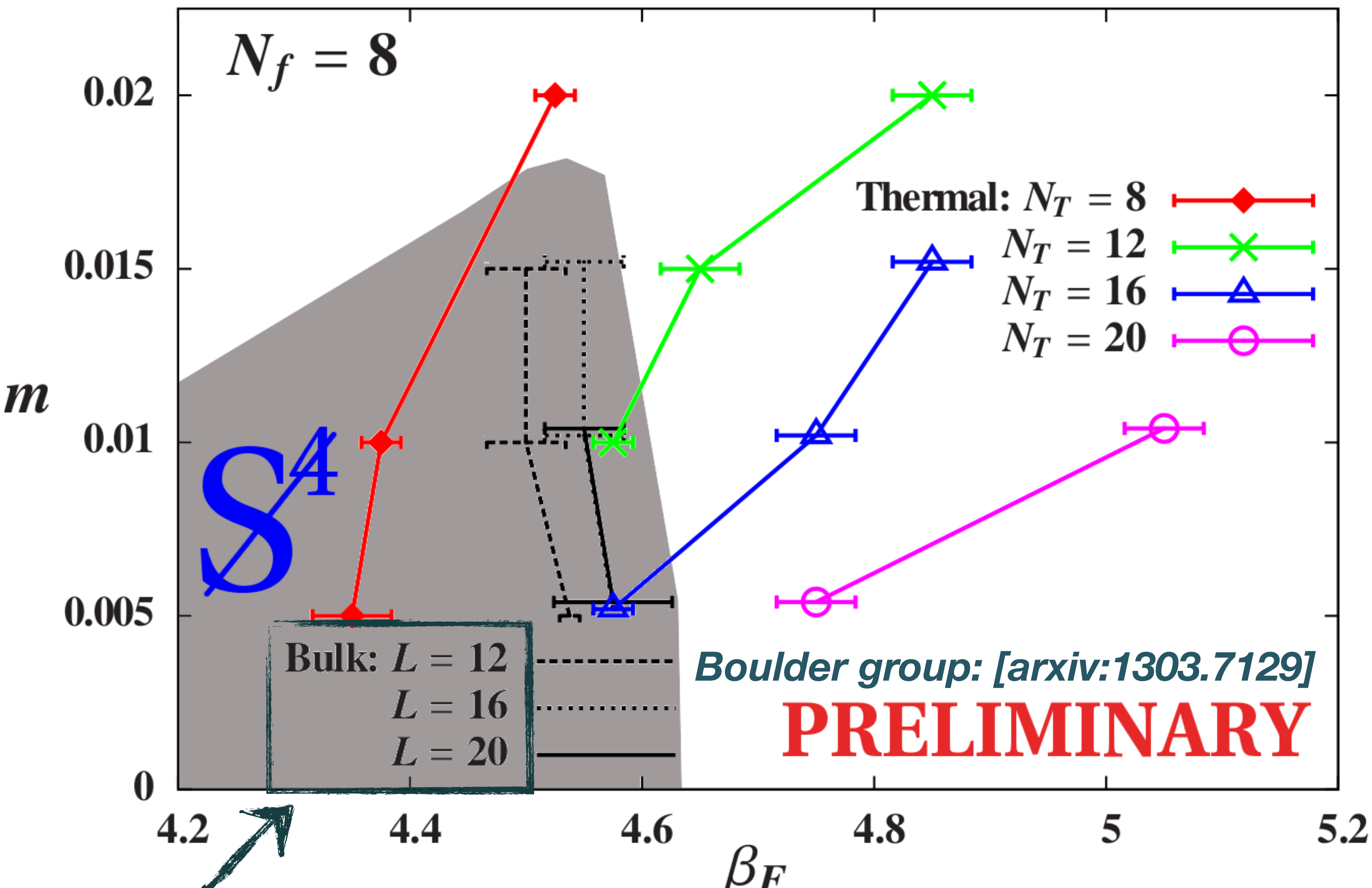
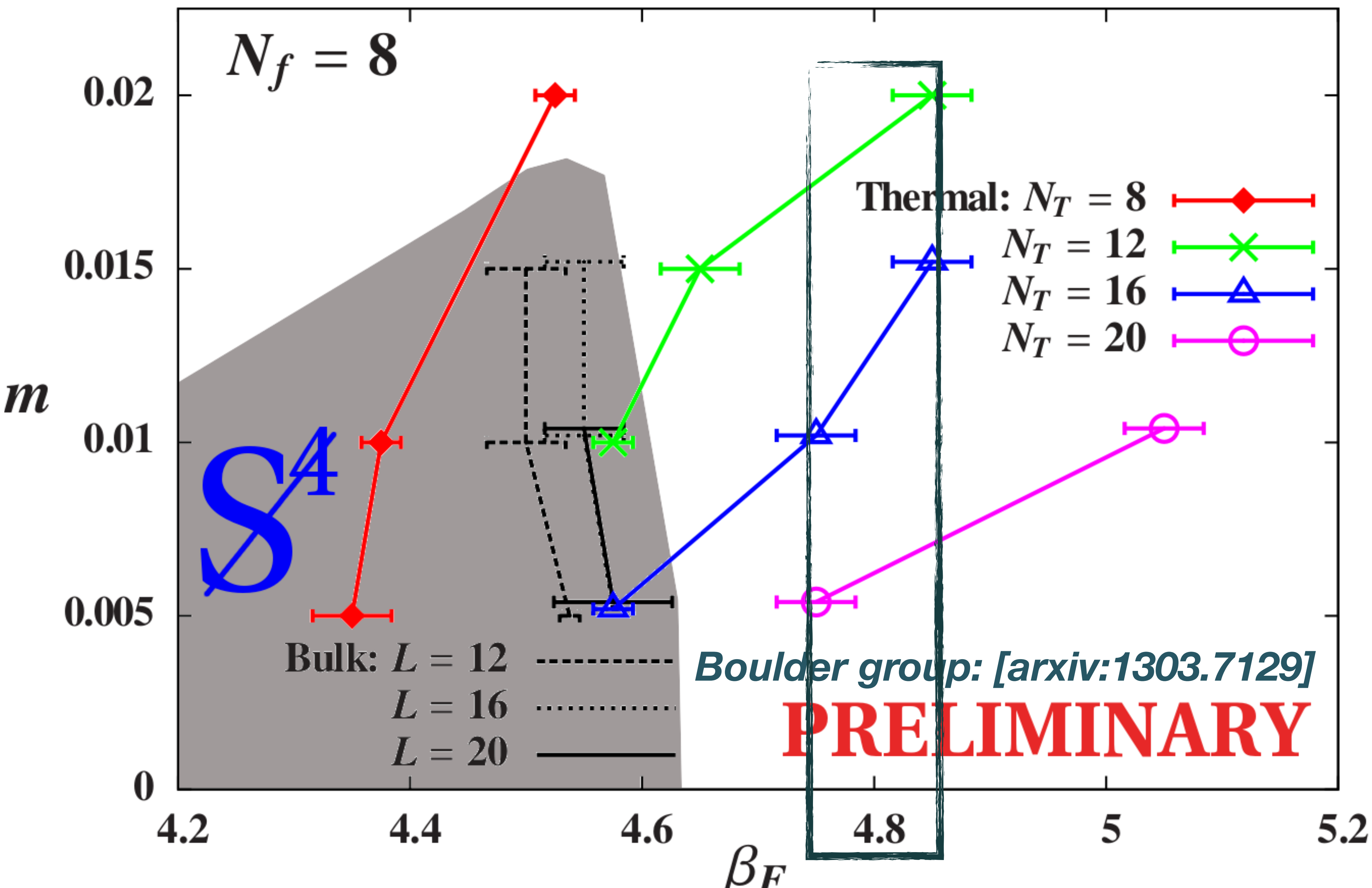


Avoid lattice bulk transition

see poster by D. Schaich
with the LSD collaboration

Eight flavors at finite temperature



Larger volumes are needed to stay in the confined phase as the mass decreases

see poster by D. Schaich with the LSD collaboration

Lattice simulation parameters

- **Gauge action: Fundamental + Adjoint Plaquette (two gauge coupling parameters)**

$$\beta_F \equiv \beta = 4.8,\ \ 5.0$$
$$\beta_A = -0.25\beta_F$$

- **Fermion action: Staggered quarks with nHYP smearing (one mass parameter)**

$$m_f$$
$$\alpha_{\mathrm{smear}} = \{0.5, 0.5, 0.4\}$$

- Same action used by the Boulder group and USBSM studies ***[arXiv:1303.7129][arXiv:1310.7006]***
- We use FUEL on BlueGene Q at LLNL to generate configurations and measure the spectrum ***[github.com/jcosborn/qhmc]***

M	β	L	m	MDTU
5.5	4.8	24	0.00889	~25K
6.5	4.8	32	0.00750	~25K
5.3	4.8	32	0.00500	~14K
5.3	4.8	48	0.00222	~10K
5.3	4.8	64	0.00125	~2K

we acknowledge computing time through the Grand Challenge program at LLNL and USQCD at Fermilab

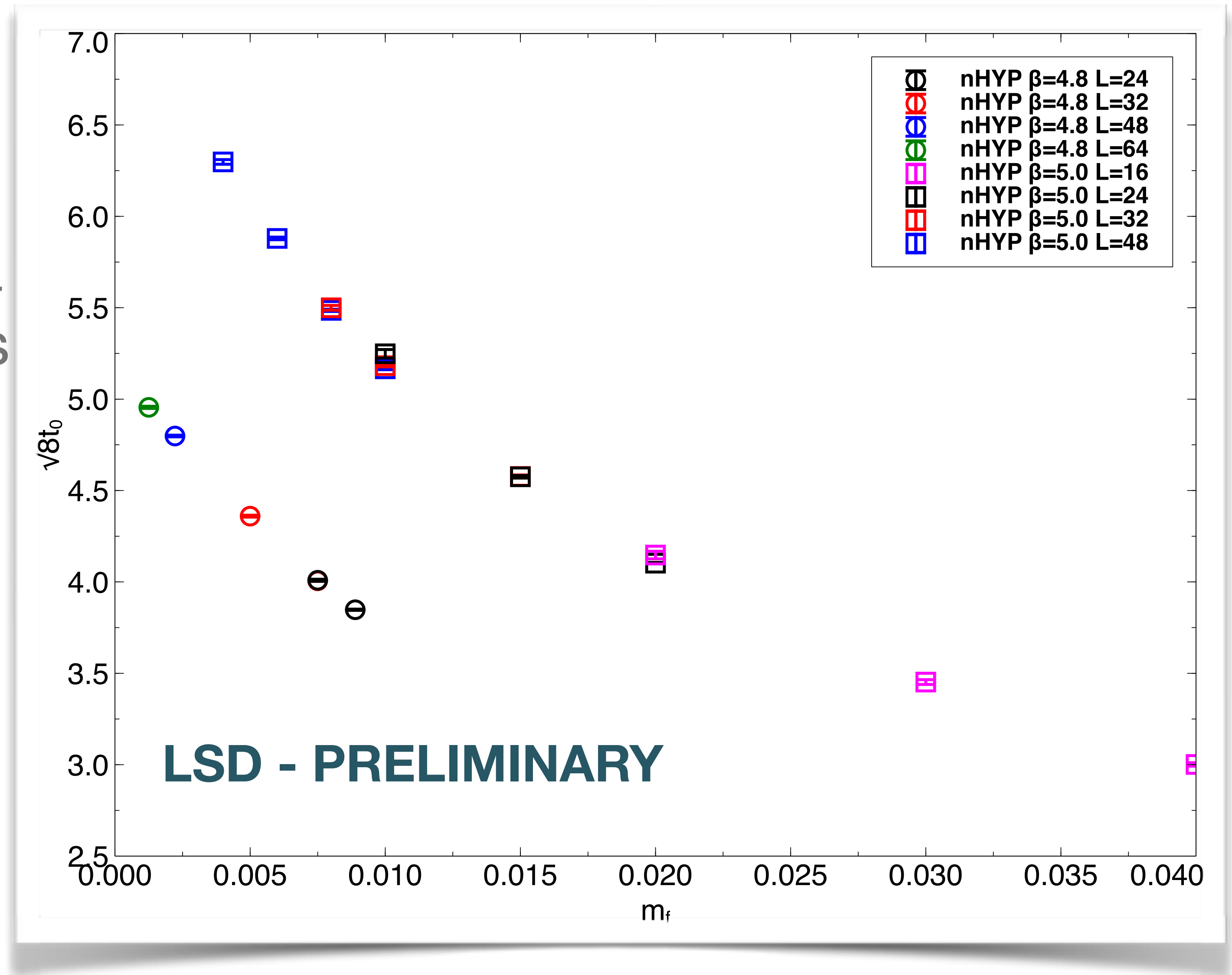
The Wilson Flow scale

- Use the Wilson Flow to define a lattice scale $\sqrt{8t_0}$

- We use it to define dimensionless quantities and compare lattice data with different couplings and actions

- Different reference scales can be used in the definition. Our choice:

$$t^2 \langle E(t) \rangle \Big|_{t=t_0} = 0.3$$



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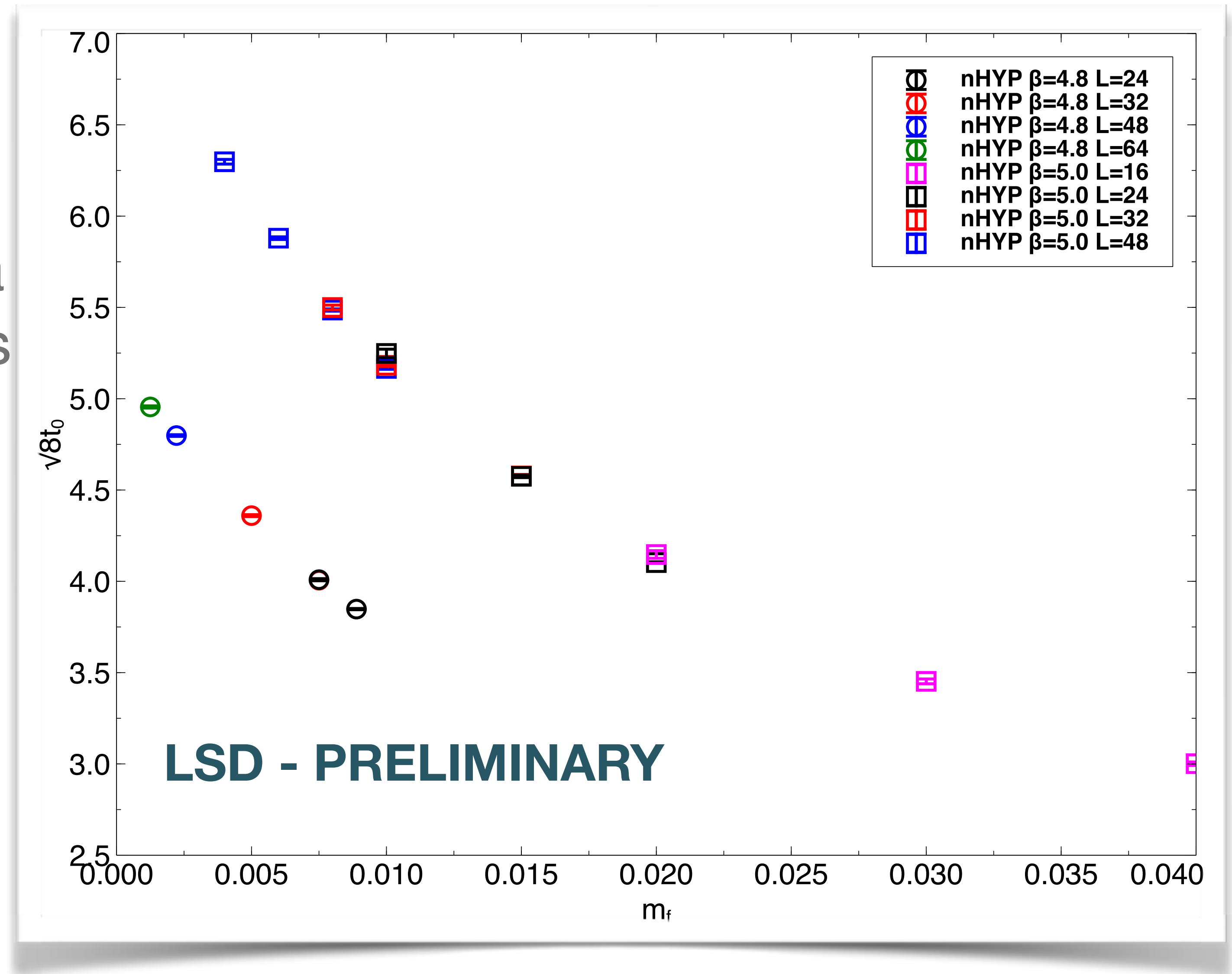
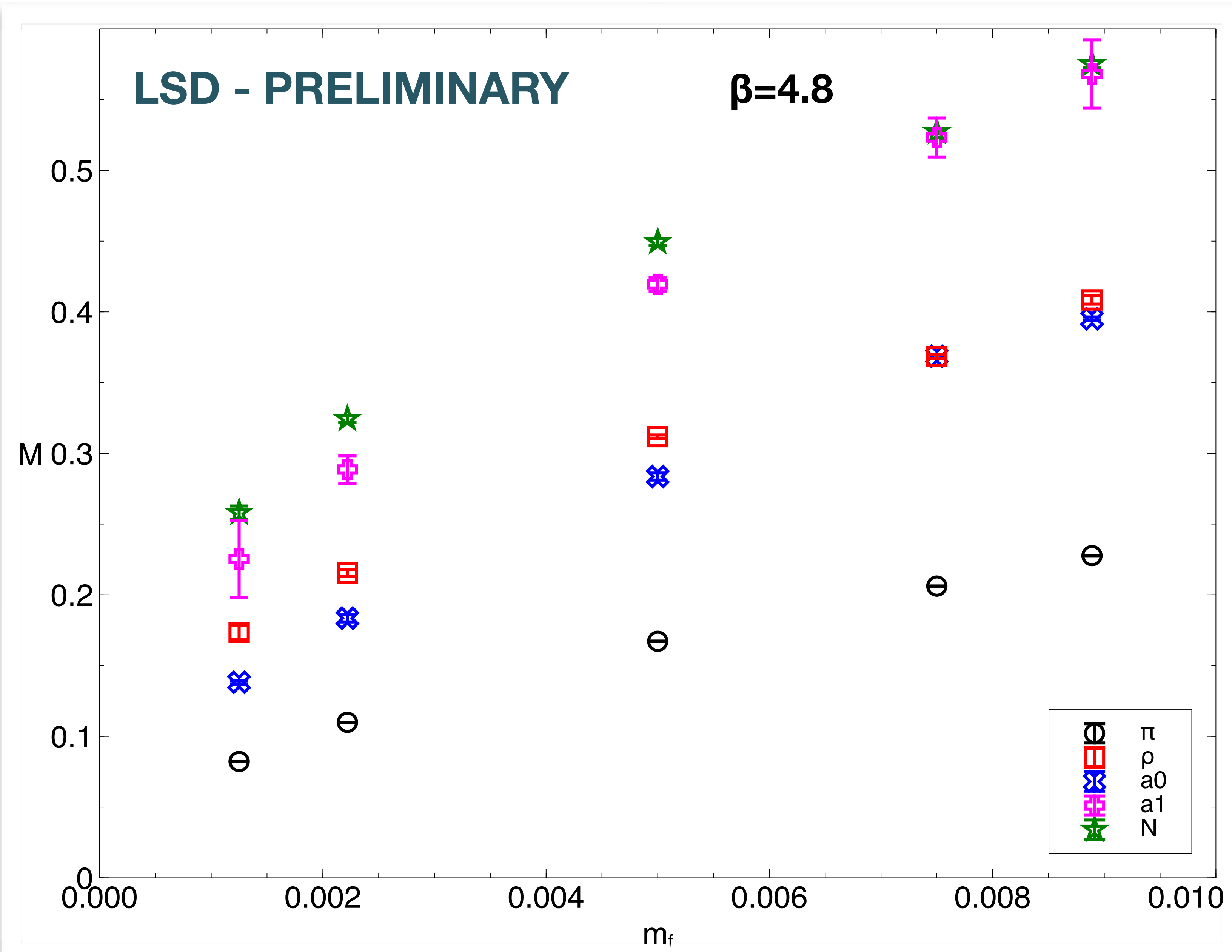
- Strong dependence on the fermion mass, contrary to QCD

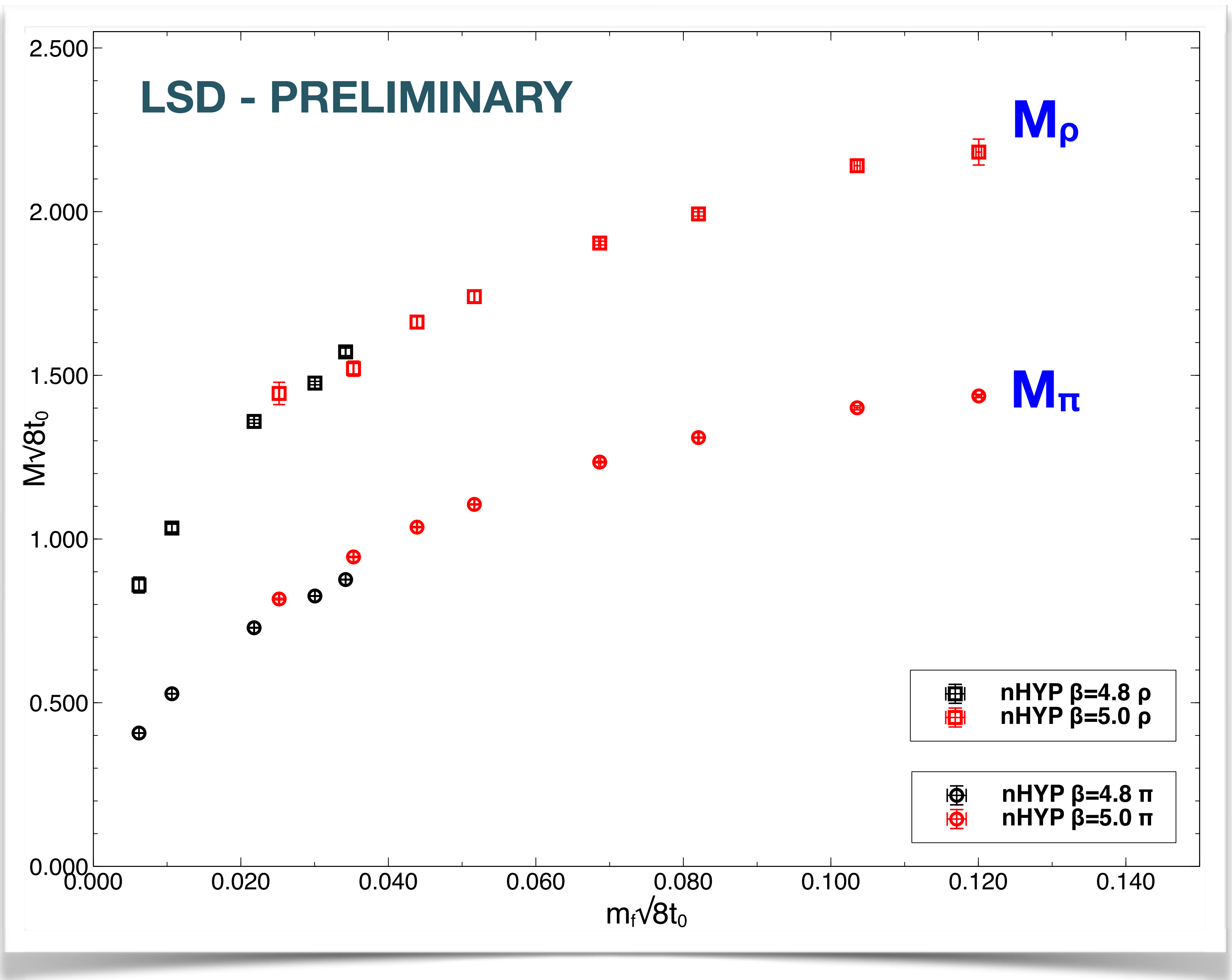


Connected spectrum towards the chiral limit



- M_π, M_ρ, F_π, M_{a0}, M_{a1}, M_N
- Increasing volume towards the chiral limit

Connected spectrum towards the chiral limit



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- *Rescaling with WF scale to compare β=4.8 and β=5.0 results*

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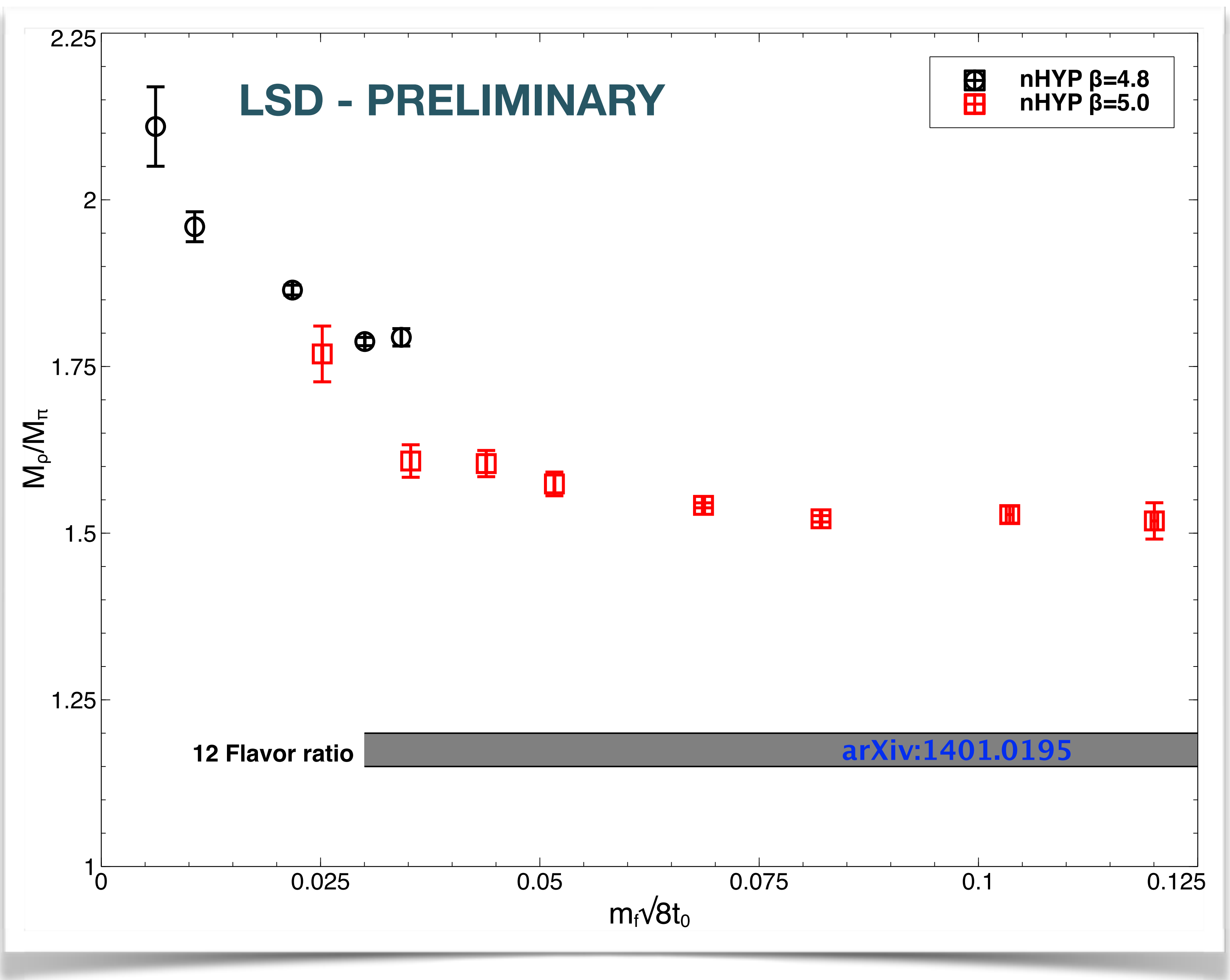

- M_π, M_ρ, F_π, M_{a0}, M_{a1}, M_N
- Increasing volume towards the chiral limit
- *Rescaling with WF scale to compare β=4.8 and β=5.0 results*
- **Ratio M_ρ/M_π indicate approach to the chiral regime**

Measuring disconnected contributions

- Measurement of flavor-singlet scalars requires extra care due to the coupling to the vacuum channel and the presence of disconnected diagrams
- Disconnected diagrams are noisy and it is difficult to extract a signal using the same techniques of the connected diagrams
- The cure is usually the following:
  - high statistics to reduce the gauge field fluctuations
  - improved stochastic estimators for the fermion trace

Techniques for the scalar channel

- Measurement techniques developed by E. Weinberg at BU:
  1. 6 U(1) stochastic wall sources
  2. dilution scheme in time, color and E/O space indices
  3. local scalar fermion bilinear with variance reduction for the trace estimator $\mathcal{O}_\sigma(t) = \langle \bar{\psi}\psi \rangle (t)$

- Combine propagators to form connected and disconnected correlators:

$D(t) \to$ vacuum subtracted disconnected correlator

$C(t) \to$ connected correlator

- Fitting is performed on two different correlators separately:

$$S(t) = 2D(t) - C(t)$$

$$2D(t)$$

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Full flavor-singlet scalar correlator

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Full flavor-singlet scalar correlator

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no connected diagrams

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- Fitting is performed on two different correlators separately:

$$\lim_{t\to\infty} S(t) \sim c_{0^{++}}\, e^{-\boxed{M_{0^{++}}}t}$$

$$\lim_{t\to\infty} 2D(t) \sim c_{0^{++}}\, e^{-\boxed{M_{0^{++}}}t}$$

if the flavor-singlet scalar state is the lightest, it will appear in both correlators at large enough time

Extracting the scalar mass

- It is hard to resolve the vacuum expectation value of the scalar operator

- Statistical fluctuations are much larger than the number we would like to resolve: we add a new free parameter to the fit

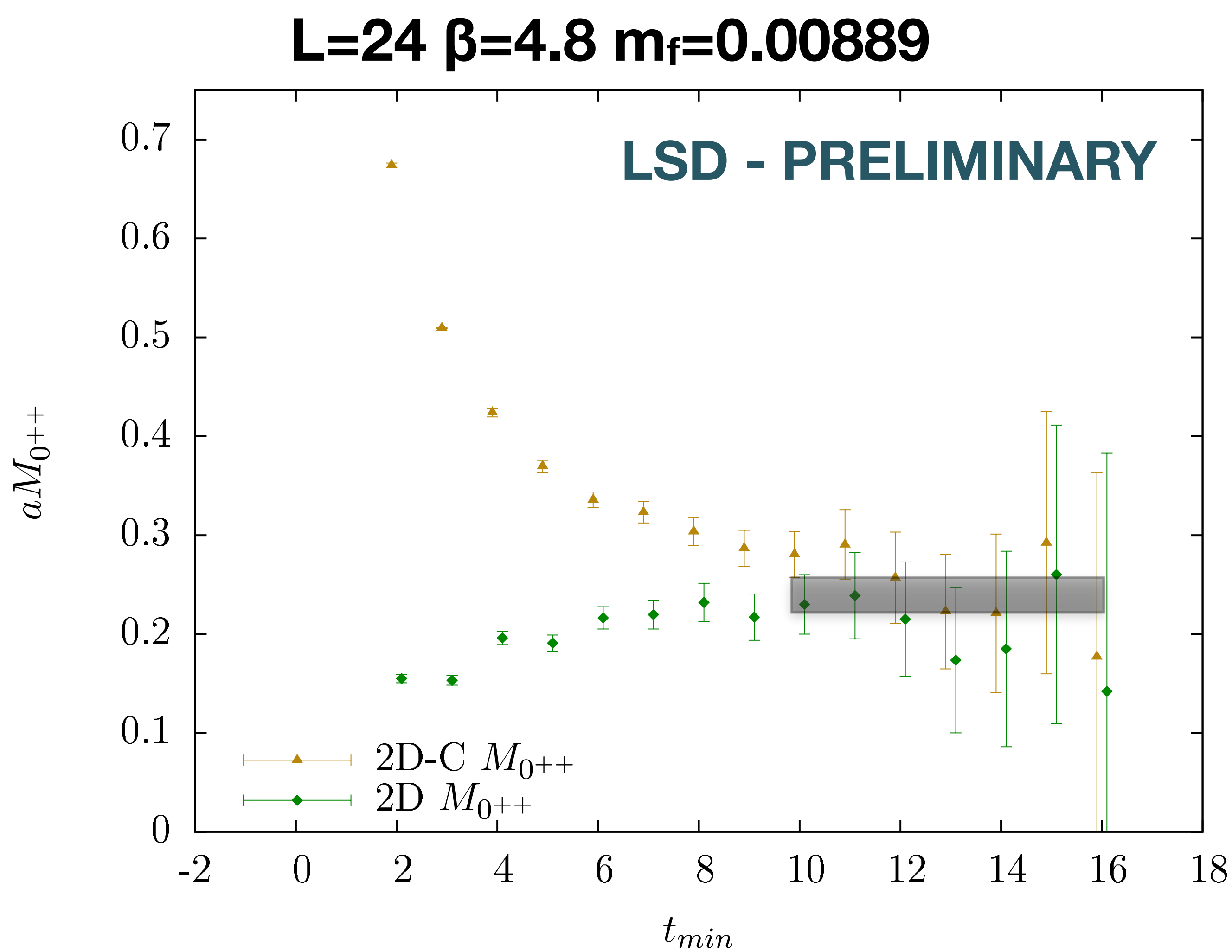
$$C_{\text{fit}}(t) = c_0 \cosh(M_0(t - T/2)) + (-1)^t c_1 \cosh(M_1(t - T/2)) \boxed{+ v}$$

free parameter

- the extra fit parameter should be consistent with the flavor-singlet scalar amplitude by construction because we subtract the correlator value at t=T/2

$$v \approx -c_0$$

Extracting the scalar mass

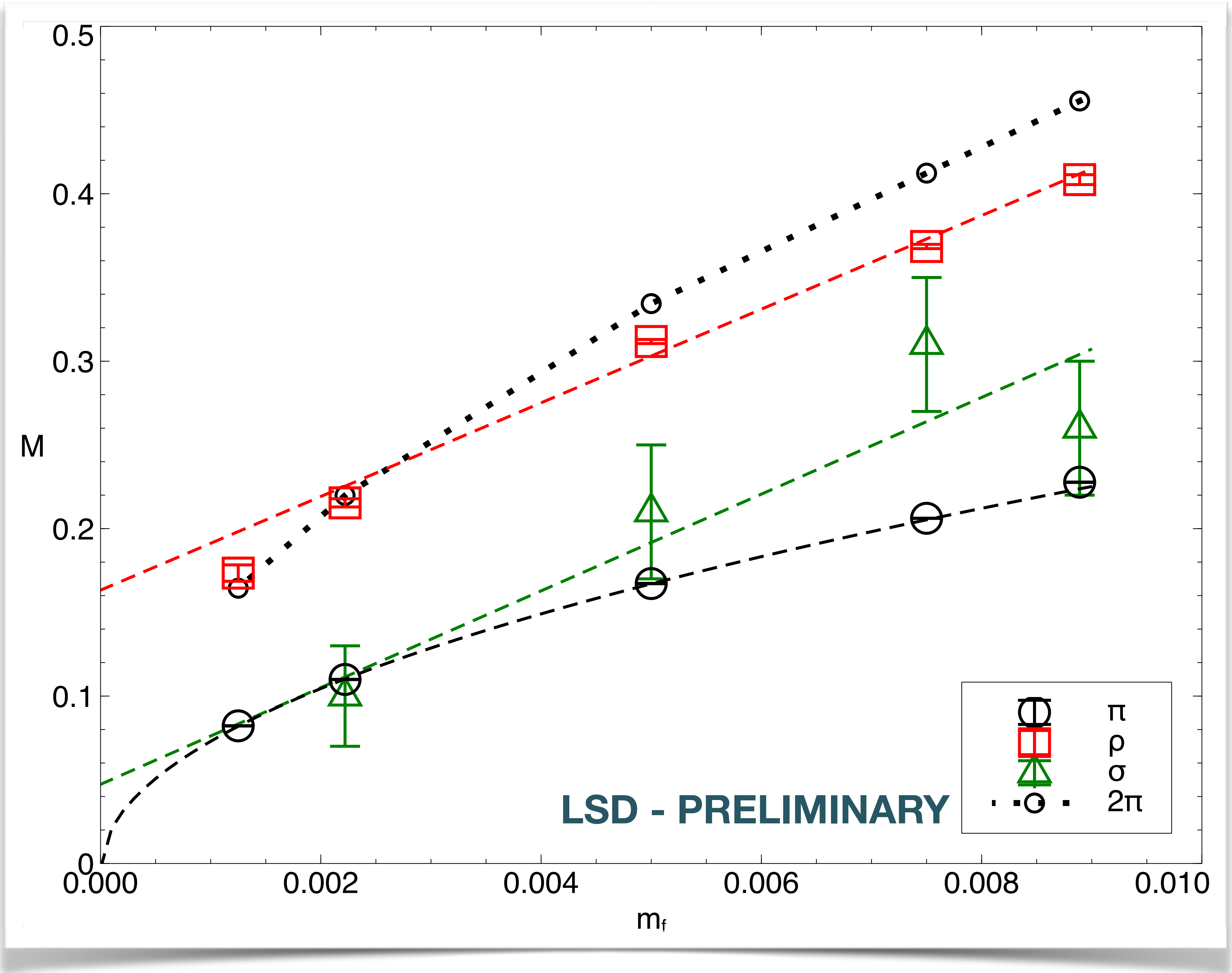


Fitted mass in the range $[t_{min}, t_{max} = T/2]$

- always compare fitted masses from the two correlators ➜ S(t) and 2D(t)
- agreement within statistical errors with no excited states ➜ fix t_{min}
- correctness of the fit form ➜ $v \approx -c_0$

criteria for robustness of result

The flavor-singlet scalar



lines are to guide the eyes

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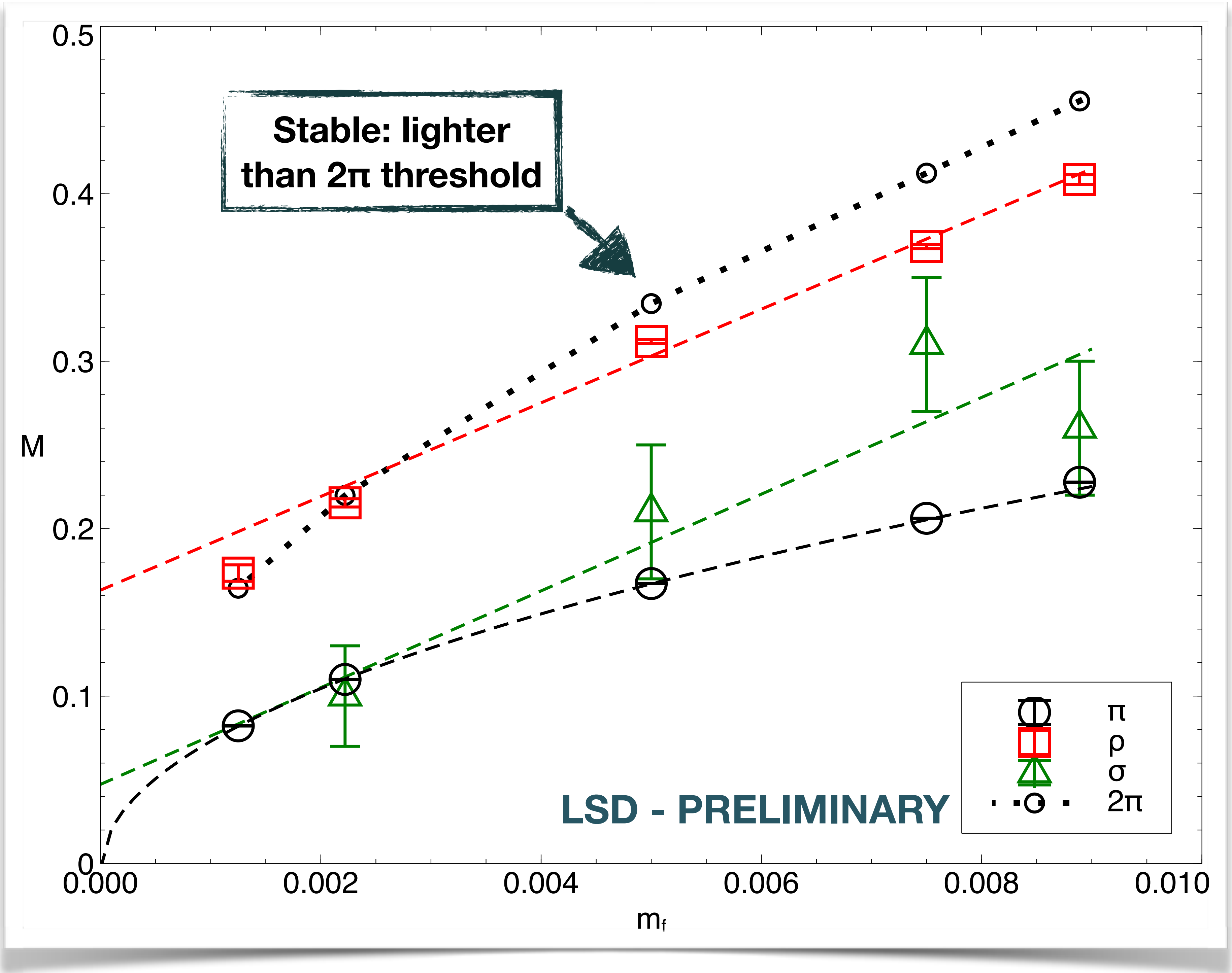

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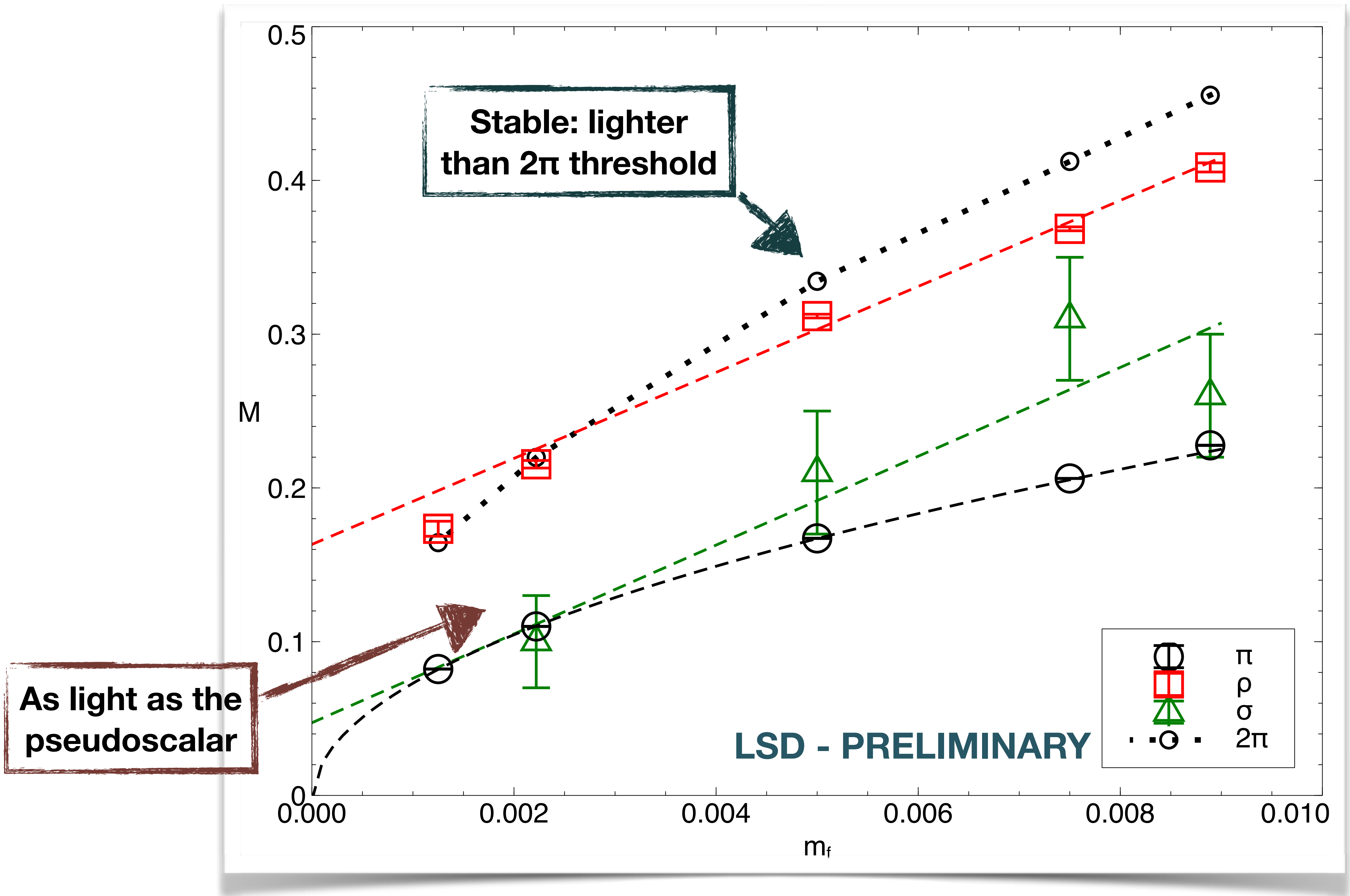

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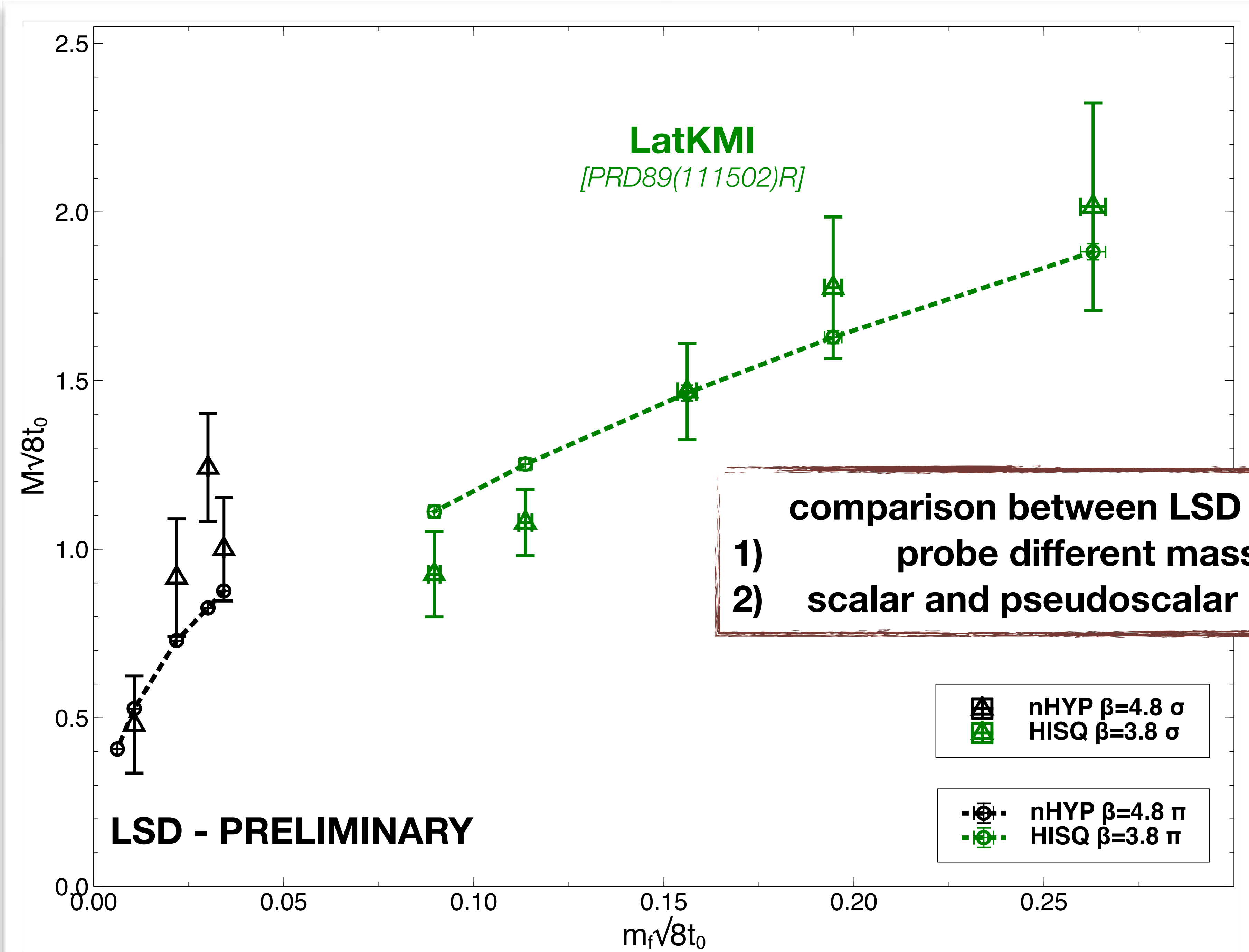
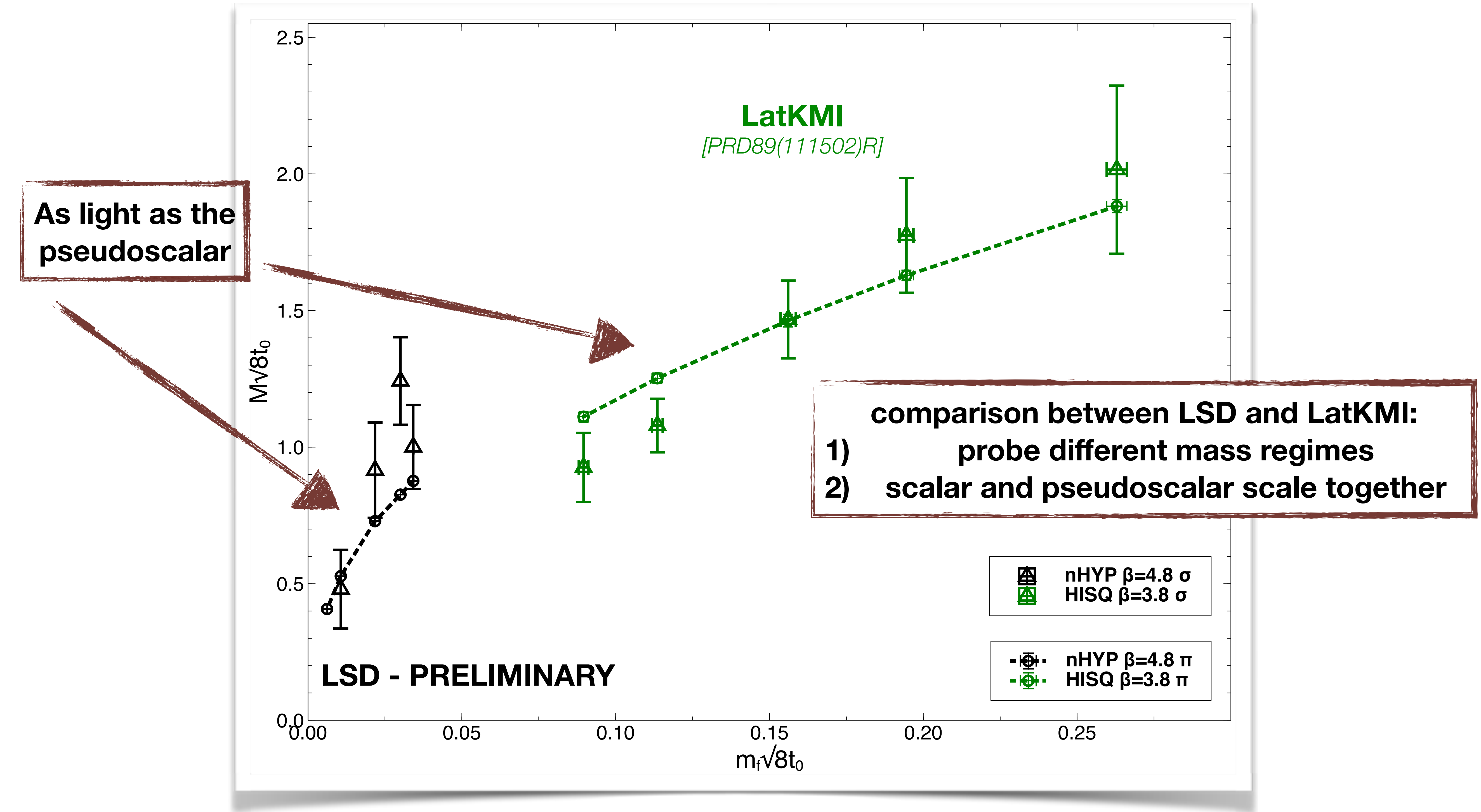


comparison between LSD and LatKMI:

1) **probe different mass regimes**
2) **scalar and pseudoscalar scale together**

lines are to guide the eyes

The flavor-singlet scalar



lines are to guide the eyes

Conclusions

- New simulations on larger lattices, safe from bulk phase transitions
- Closer to chiral limit in terms of fermion masses
- Complement previous studies with different couplings and actions
- Reliable singlet scalar results from high statistics runs and improved methods with multiple consistency checks
- The singlet scalar follows the pion at large and small quark masses: for how long?

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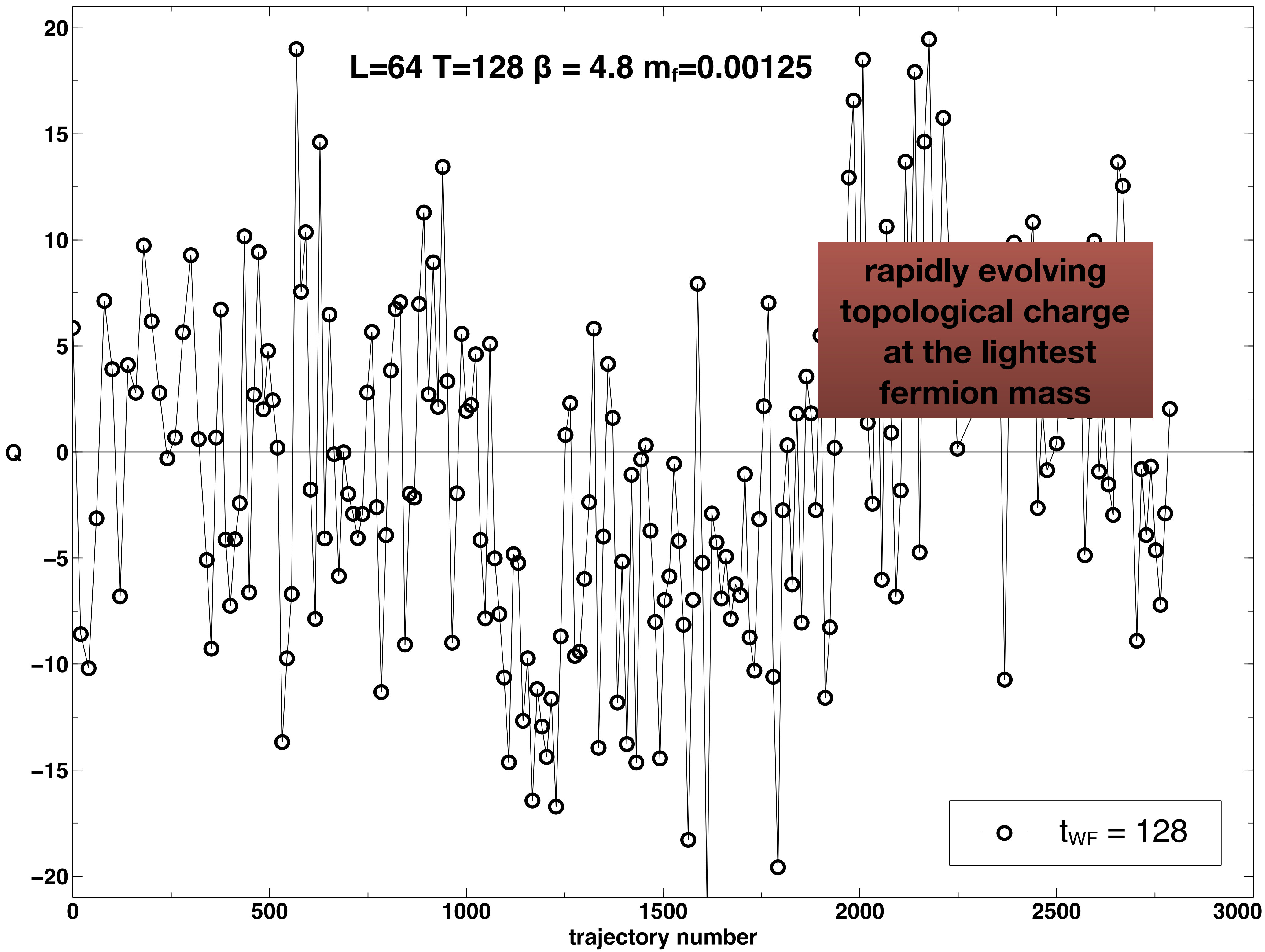
still need theoretical understanding for the lightness of the scalar in strongly-coupled theories

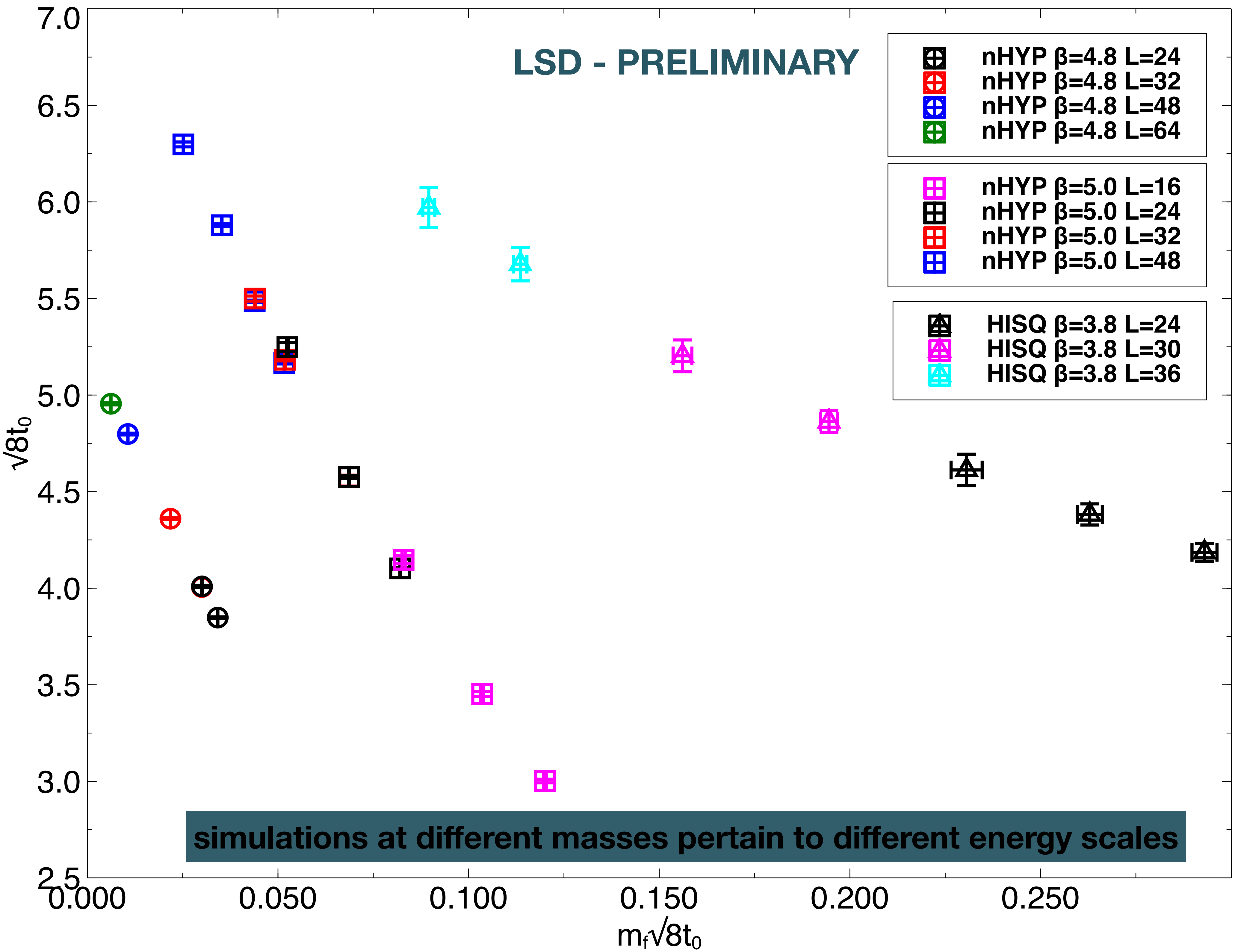
Thank you

Backup slides



Topology evolution

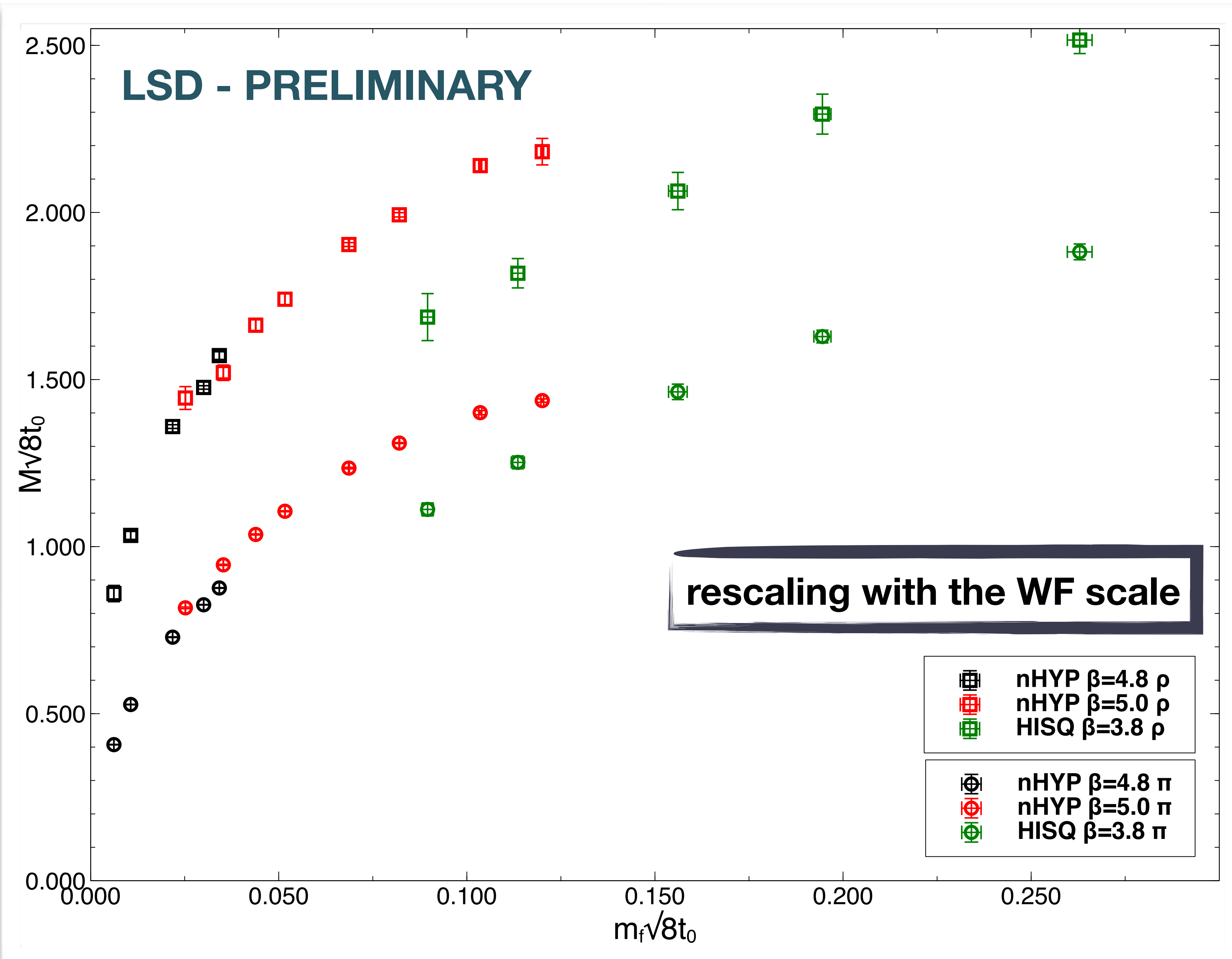
defined at $\sqrt{8t} = \frac{L}{2}$



Strong mass dependence

for different actions and lattice spacing

Comparison with other actions



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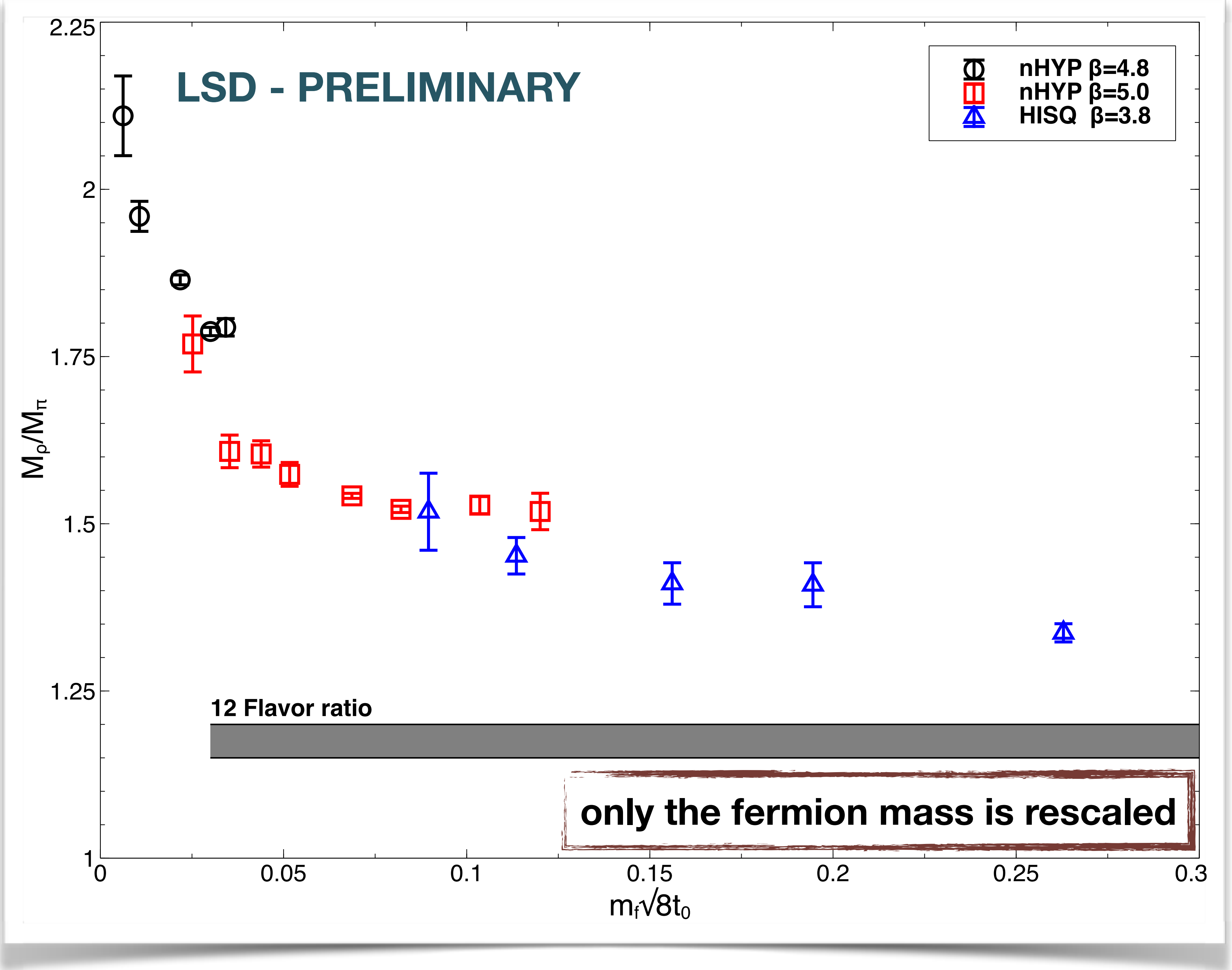

The flavor-singlet scalar