SU(3) gauge-fermion systems with fundamental flavors

Oliver Witzel

Universität Siegen

TP1 Theoretical Particle Physics

CPPS Center for Particle Physics Siegen

SUBATOMIC HEROES

August 20, 2024

Motivation

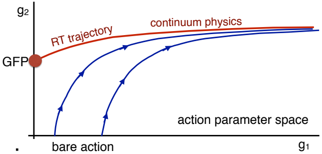
- Study properties of strongly coupled gauge-fermion systems
- Characterize nature of such systems
  $\rightarrow$ Where is the onset of the conformal window?
- Determine properties of these systems
  $\rightarrow$ Anomalous dimensions: important for BSM model building
  $\rightarrow$ New method to determine Λ parameter ($\rightsquigarrow \alpha_s$)
- Interesting signs of a new phase for SU(3) with $N_f = 8$ fundamental flavors
  $\rightarrow$ Symmetric Mass Generation (SMG)

Renormalization Group β function

$$\beta(g^2) = \mu^2 \frac{dg^2}{d\mu^2}$$

- Encodes dependence of coupling g^2 on the energy scale μ^2
- β has no explicit dependence on μ^2, only implicit through $g^2(\mu)$
- Known perturbatively up to 5-loop order in the $\overline{\text{MS}}$ scheme (1- and 2-loop are universal)
  [Baikov, Chetyrkin, Kühn PRL118(2017)082002] [Ryttov and Shrock PRD94(2016)105015]
- Known perturbatively at 3-loop order in the GF scheme [Harlander, Neumann JHEP06(2016)161]
- Perturbative predictions reliable at weak coupling,
  nonperturbative methods needed for strong coupling

Gradient flow and real-space renormalization Group (RG) flow



- RG flow: change of (bare) parameters and coarse graining (blocking)

- Gradient flow is a continuous transformation
  $\rightarrow$ Define real-space RG blocked quantities by incorporating coarse graining as part of calculating expectation values [Carosso, Hasenfratz, Neil PRL 121 (2018) 201601]

- Relate GF time t/a^2 to RG scale change $b \propto \sqrt{t/a^2}$
  $\rightarrow$ Quantities at flow time t/a^2 describe physical quantities at energy scale $\mu \propto 1/\sqrt{t}$
  $\rightarrow$ Any local operator with non-vanishing expectation value can be used to define running coupling
  $\rightsquigarrow$ Simplest choice: $t^2\langle E(t)\rangle$ [Lüscher JHEP 1008 (2010) 071]

- Continuous RG β function

$$\beta_{GF}(g_{GF}^2) = \mu^2 \frac{dg_{GF}^2}{d\mu^2} = -t\frac{dg_{GF}^2}{dt}$$

Continuous RG β function

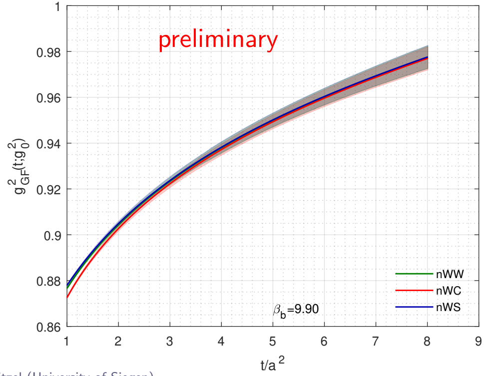
[Fodor et al. EPJ Web Conf. 175 (2018) 08027]
[Hasenfratz, OW PRD 101 (2020) 034514] [Hasenfratz, OW PoS LATTICE2019 (2019) 094]
[Wong et al. PoS LATTICE2022 (2023) 043] [Hasenfratz, Peterson, Van Sickle, OW PRD108 (2023) 014502]

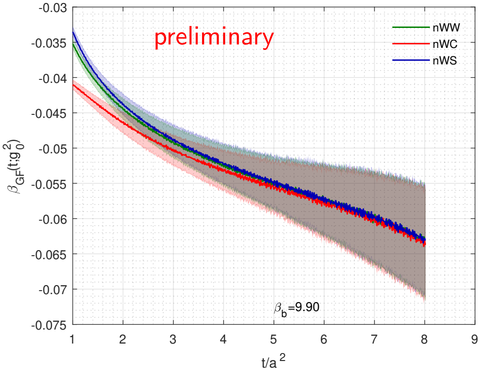
New in next FLAG edition!

- Extract $g^2_{GF}(t; \beta_b, L/a)$ its derivative $\beta_{GF}(t; \beta_b, L/a)$ for a range of GF times on each ensembles
  $\rightarrow$ Different bare coupling β_b on different volumes $(L/a)^4$ or $(L/a)^3 \times T/a$
- Perform infinite volume extrapolation at fixed bare coupling β_b and GF time t
  $\rightarrow$ Obtain $g^2_{GF}(t; \beta_b)$ and $\beta_{GF}(t; \beta_b)$
- Interpolate discrete infinite volume values to get continuous values at fixed flow time
  $\rightarrow$ $g^2_{GF}(t)$ and $\beta_{GF}(t; g^2_{GF})$
- Take continuum limit $(a^2/t \rightarrow 0)$ for fixed g^2_{GF} and obtain $\beta_{GF}(g^2_{GF})$

Continuous RG β function ($N_f = 2$) [Hasenfratz, Monahan, Rizik, Shindler, OW in preparation]

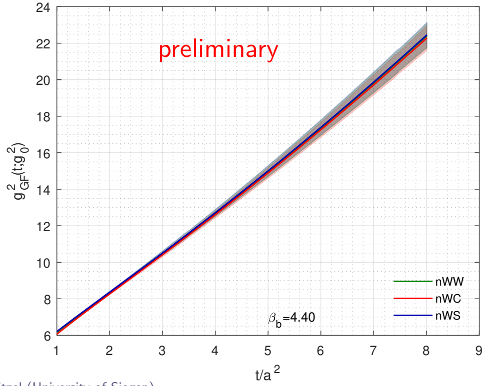
- Extract $g^2_{GF}(t; \beta_b, L/a)$ its derivative $\beta_{GF}(t; \beta_b, L/a)$ for a range of GF times on each ensembles
  - → Different bare coupling β_b on different volumes $(L/a)^4$ or $(L/a)^3 \times T/a$
- Perform infinite volume extrapolation at fixed bare coupling β_b and GF time t
  - → Obtain $g^2_{GF}(t; \beta_b)$ and $\beta_{GF}(t; \beta_b)$

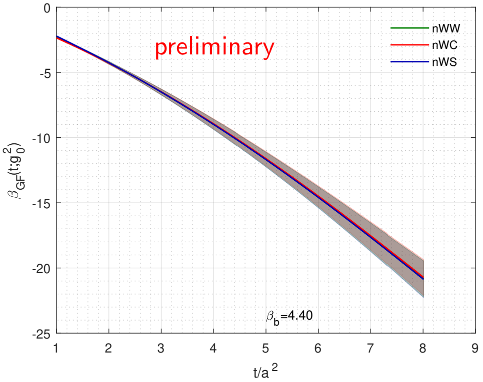




Continuous RG β function ($N_f = 2$) [Hasenfratz, Monahan, Rizik, Shindler, OW in preparation]

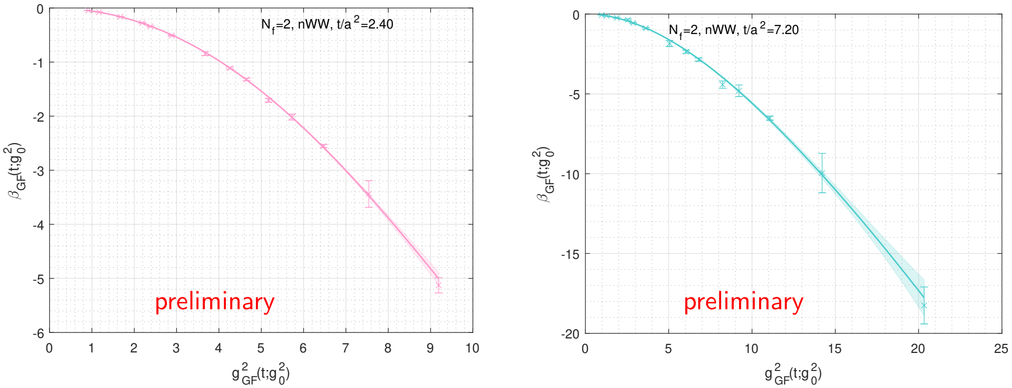
- Extract $g^2_{GF}(t; \beta_b, L/a)$ its derivative $\beta_{GF}(t; \beta_b, L/a)$ for a range of GF times on each ensembles
  - → Different bare coupling β_b on different volumes $(L/a)^4$ or $(L/a)^3 \times T/a$
- Perform infinite volume extrapolation at fixed bare coupling β_b and GF time t
  - → Obtain $g^2_{GF}(t; \beta_b)$ and $\beta_{GF}(t; \beta_b)$





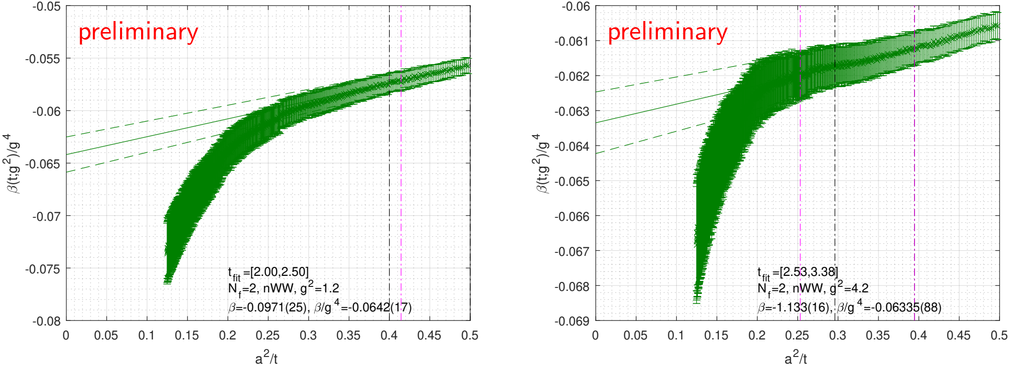
Continuous RG β function $(N_f = 2)$ [Hasenfratz, Monahan, Rizik, Shindler, OW in preparation]

- Interpolate discrete infinite volume values to get continuous values at fixed flow time $\rightarrow g^2_{GF}(t)$ and $\beta_{GF}(t; g^2_{GF})$

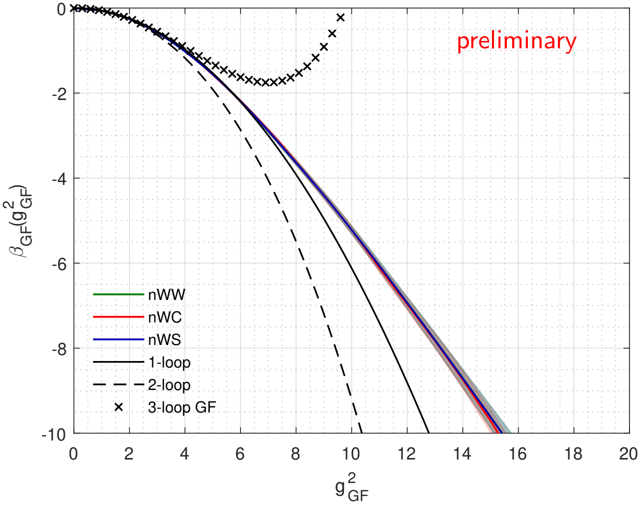


Continuous RG β function ($N_f = 2$) [Hasenfratz, Monahan, Rizik, Shindler, OW in preparation]

- Take continuum limit ($a^2/t \to 0$) for fixed g^2_{GF} and obtain $\beta_{GF}(g^2_{GF})$



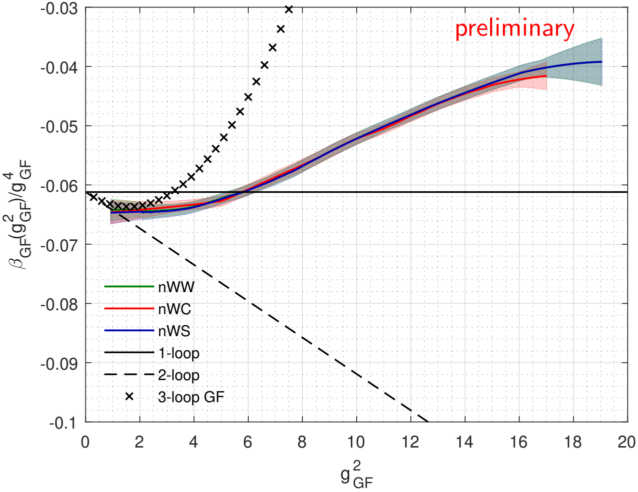
Continuum limit of continuous RG β function for $N_f = 2$



[Hasenfratz, Monahan, Rizik, Shindler, OW in preparation]

- Weak coupling well described by PT 3-loop GF result
  [Harlander, Neumann JHEP06(2016)161]
- Qualitatively more similar to 1-loop result at strong coupling
  → Very different to 3-loop GF
- Apparently linear β_{GF} function at strong coupling
  → Nonperturbative phenomenon

Continuum limit of continuous RG β function for $N_f = 2$



[Hasenfratz, Monahan, Rizik, Shindler, OW in preparation]

- Weak coupling well described by PT 3-loop GF result
  [Harlander, Neumann JHEP06(2016)161]
- Qualitatively more similar to 1-loop result at strong coupling
- Simulations at very weak coupling are challenging (critical slowing down)

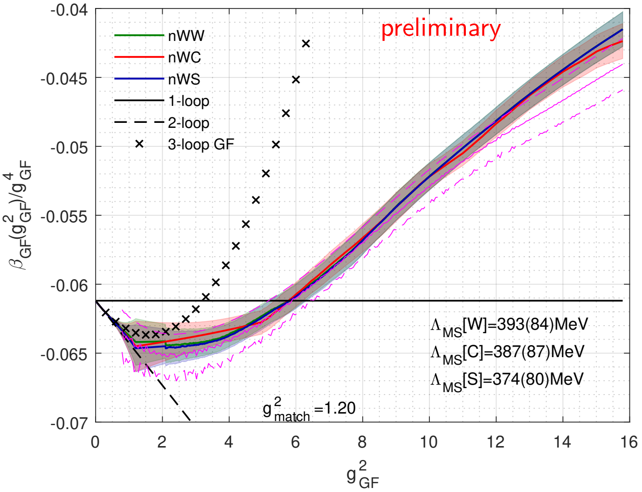
Λ parameter

- Integrate inverse β function to obtain Λ_{GF}
  - $\rightarrow$ g_m^2 GF renormalized coupling at energy scale $\mu = 1/\sqrt{8t_0}$
  - $\rightarrow$ Only need t_0 lattice scale ($\rightsquigarrow$ FLAG)
  - $\rightarrow$ b_0, b_1 universal 1-loop coefficients

$$\Lambda_{GF} = \mu\left(b_0 g_m^2\right)^{-\frac{b_1}{2b_0^2}} \exp\left(-\frac{1}{2b_0 g_m^2}\right) \exp\left[-\int_0^{g_m^2} \mathrm{d}g^2 \left(\frac{1}{\beta(g^2)} + \frac{1}{b_0 g^4} - \frac{b_1}{b_0^2 g^2}\right)\right]$$

Λ parameter

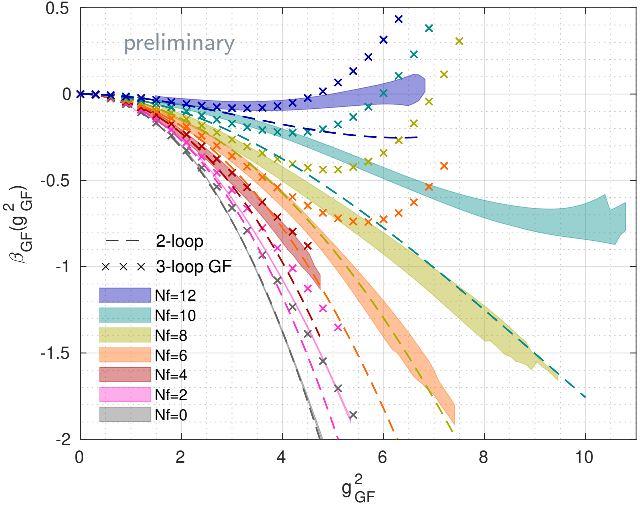
[Hasenfratz, Monahan, Rizik, Shindler, OW in preparation]



- Match to 3-loop GF β function at small g^2_{GF}
- Presently large uncertainty in Λ due to matching at weak coupling
- $g^2_m \approx 15.8$
- In principal could relate Λ to α_s
  - $\rightarrow$ $N_f = 2$ requires running "through" strange quark threshold
  - $\rightarrow$ Better repeat with $N_f = 3$ or 4

Landscape of SU(3)

- Plot: Lattice 2023 [Hasenfratz, OW in preparation]



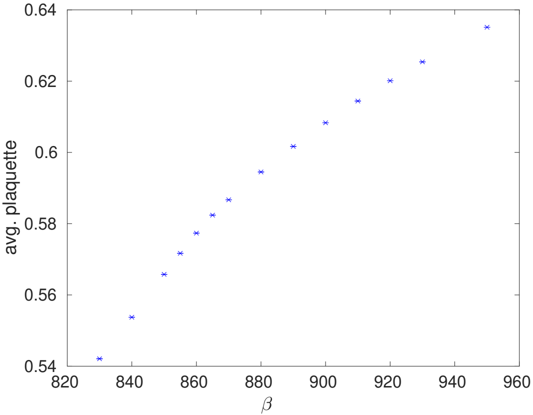
- Simulations with stout-smeared Möbius DWF and Symanzik gauge action
- Systematic effects for $N_f = 10$ likely underestimated
- Reach in g^2 limited by 1st order bulk phase transition (lattice artifact)
  - $\rightarrow N_f = 12$ sign of IRFP
  - $\rightarrow N_f = 10$ likely turning around
  - $\rightarrow N_f = 10$ Wilson+PV: conformal
    [Hasenfratz et al. PRD 108 (2023) L071503]
- Qualitative behavior captured by 2-loop PT prediction
- 3-loop GF prediction tracks nonperturbative result longer, but turns away showing different qualitative behavior
  [Harlander, Neumann JHEP06(2016)161]

What is the nature of $N_f = 8$?

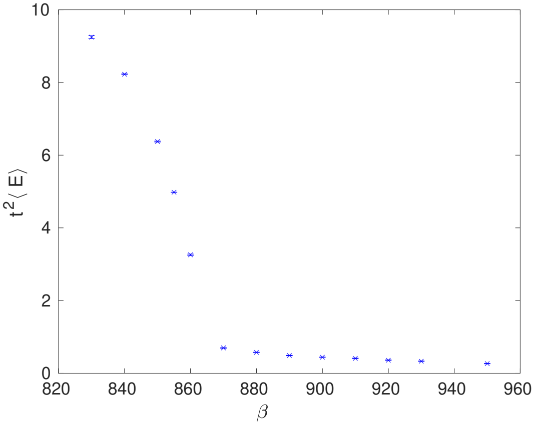
- Signs that $N_f = 8$ is special [Hasenfratz PRD 106 (2022) 014513]
  - → Small volume simulations favor finite size scaling fit with ansatz for Berezinskii-Kosterlitz-Thouless (BKT) transition
- New phase of symmetric mass generation (SMG)
  - → No chiral symmetry breaking, no massless Goldstone bosons
  - → Bilinear condensate $\langle\psi\bar{\psi}\rangle = 0$, $\langle\psi\psi\psi\psi\rangle \neq 0$
  - → All bound states are gapped
  - → 't Hooft anomalies must cancel
- Simulations: LSD collaboration [Anna Hasenfratz, Ethan Neil, OW work in progress]
  - → nHYP-smeared staggered fermions with additional Pauli-Villars fields
  - → Plaquette gauge action with adjoint term on $16^3 \times 32$, $24^3 \times 64$, $32^3 \times 64$, $48^3 \times 96$ volumes
  - → $\beta_b = 8.10, 8.20, 8.30, 8.40, 8.50, 8.60, 8.70, 8.80, 8.90, 9.10, 9.20, 9.30, 9.50$
  - → Simulations cross from weak coupling to possible SMG phase

$24^3 \times 64$ ensembles

- Average plaquette



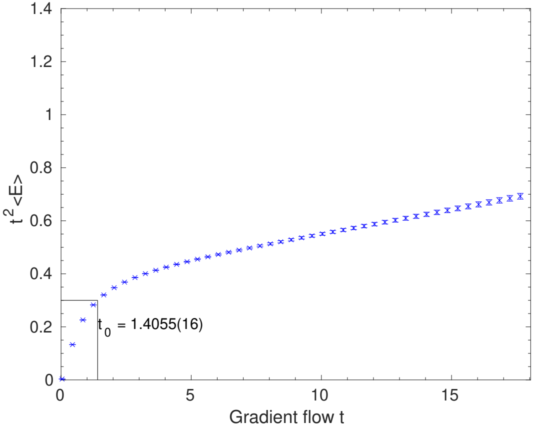
- $t^2\langle E(t)\rangle$ at $t = L^2/32 = 18$



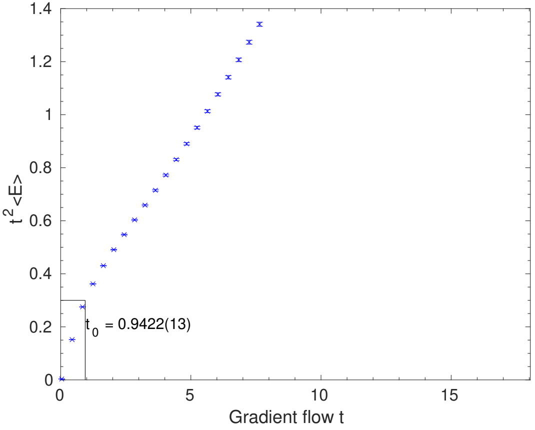
- Something interesting is happening

$t^2\langle E(t)\rangle$ vs. t

- $\beta_b = 8.70$

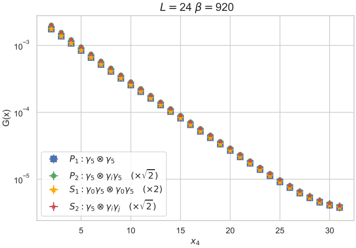


- $\beta_b = 8.60$



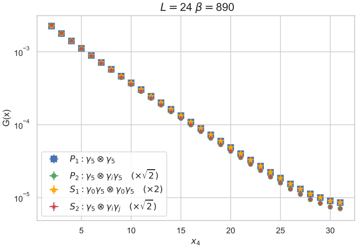
Pseudoscalar correlator

- Weak coupling
  $\beta_b = 9.20$ (conformal)



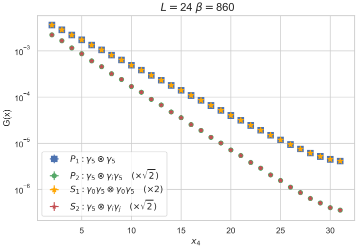
- Degenerate pseudoscalar and scalar (parity doubling)
- No taste splitting

- $\beta_b = 8.90$



- Degenerate pseudoscalar and scalar (parity doubling)

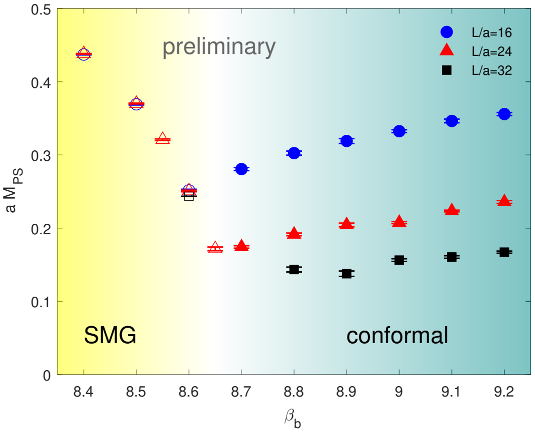
- Strong coupling
  $\beta_b = 8.60$ (SMG)



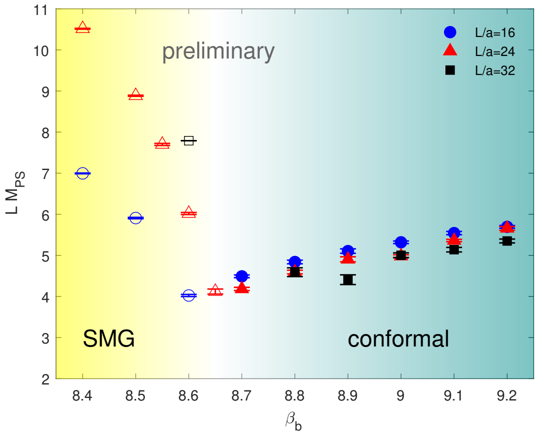
- Degenerate pseudoscalar and scalar (parity doubling)
- No chiral symmetry breaking

Pseudoscalar correlator

- aM_{PS}



- LM_{PS}



- Conformal scaling for $\beta_b > 8.6$

Summary

- Gradient flow is a very powerful tool
  - $\rightarrow$ Exploiting relation to RG flow leads to continuous β function
  - $\rightarrow$ Up to overall scale setting of t_0 and PT matching at weak coupling entirely nonperturbative method to obtain Λ and α_s

- Signs of an infrared fixed point for SU(3) with $N_f = 10$ or 12 fundamental flavors
  - $\rightarrow$ Is $N_f = 8$ the onset of the conformal window for SU(3) with fundamental flavors?

- Large scale simulations to test SU(3) with $N_f = 8$ fundamental flavors
  - $\rightarrow$ Additional Pauli-Villars fields allow investigation at strong coupling
  - $\rightarrow$ Preliminary findings support picture of a conformal and an SMG phase
  - $\rightarrow$ No chiral symmetry breaking
  - $\rightarrow$ Further simulations on larger volumes needed/planned

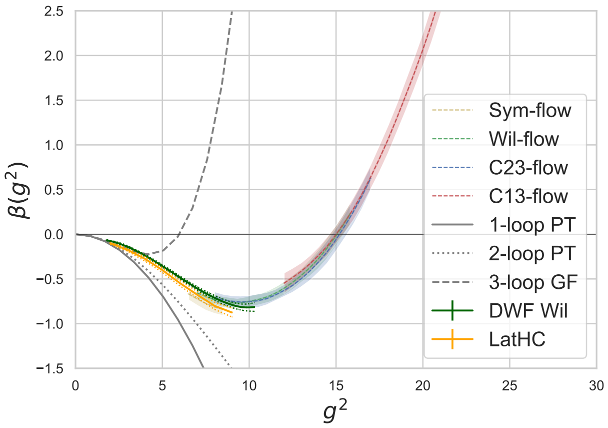
Acknowledgment

- stout-smeared Möbius domain-wall fermion simulations with $N_f = 2, 4, 6, 8, 10, 12$
  - → HMC: GRID (Boyle, Cossou, Portelli, Yamaguchi et al.)
  - → Gauge flow, spectrum: QLUA (Pochinsky et al.)
- nHYP smeared staggered $N_f = 8 +$ PV simulations
  - → HMC: QEX (Osborn, Jin, Peterson)
  - → Spectrum: MILC (DeTar et al., . . . , Schaich, Hasenfratz)
  - → Gauge flow: QLUA (Pochinsky et al.)
- Special thanks to Amitoj Singh and his team at Jefferson Lab for granting us access and early science time on the new 24s cluster critical for first results on $N_f = 8 +$ PV

extra

$N_f = 10$ at strong coupling

[Hasenfratz, Neil, Shamir, Svetitsky, OW PRD 108 (2023) L071503]



- Simulating $N_f = 10$ with Wilson fermions and additional Pauli-Villars fields allows simulations at much stronger coupling
- Clear IRFP
  $\rightarrow$ $N_f = 10$ is conformal
  $\rightarrow$ Confirms $N_f = 12$ is conformal