COMPOSITE HIGGS FROM SU(2) WITH TWO FUNDAMENTAL FLAVORS

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IMADA / QTC

11.10.2024,
$\hbar$QTC Journal Club

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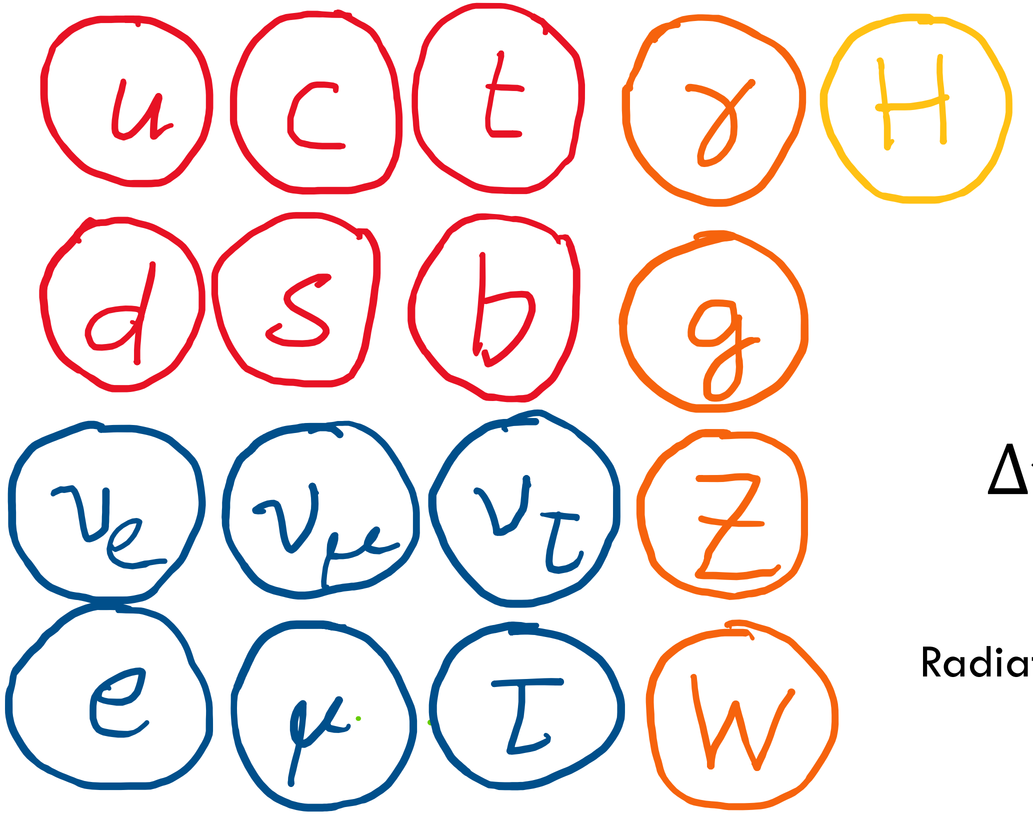
OUTLINE

1. Introduction
   1. Composite Higgs
   2. Lattice Gauge Theory
2. Standard Model Quark Mass Generation
   1. Walking Technicolor
   2. Partial Compositeness
3. Lattice Studies of CH
   1. Software
   2. SU(2) with two fundamental flavors
   3. The pseudoscalar decay constant
   4. The mass of the new Higgs
4. Outlook

INTRODUCTION

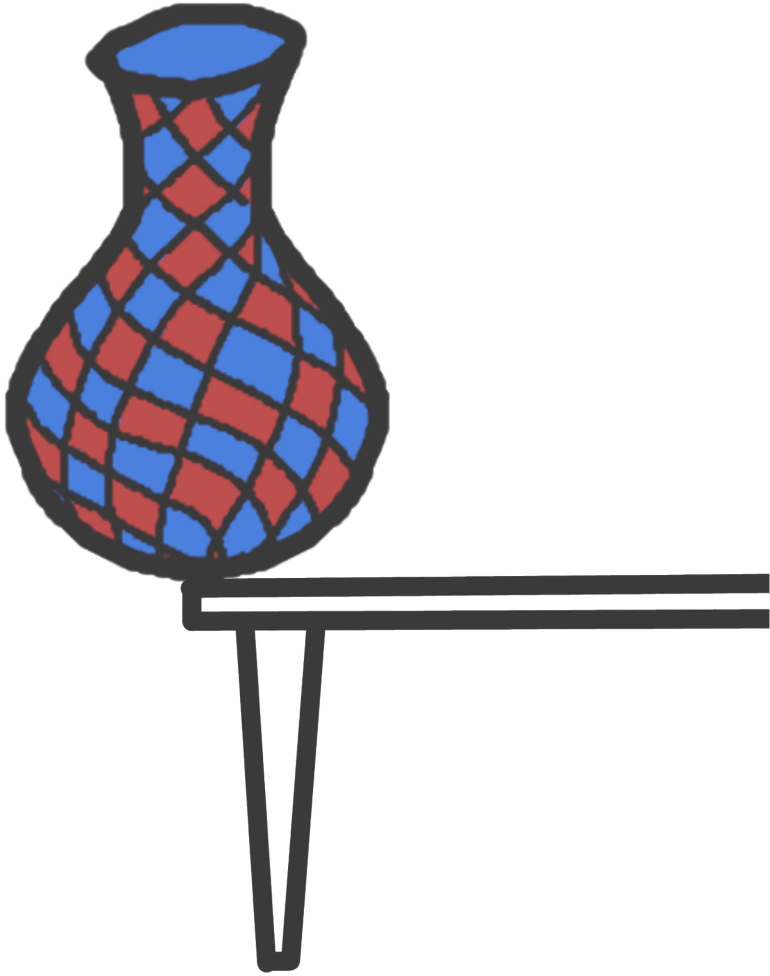
See for example the review [Cacciapaglia, Pica, Sannino, 2020, 2002.04914 , Phys. Rept.] and references therein

WHY COMPOSITE HIGGS?



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{8\pi}\Lambda_{\mathrm{UV}}^2$$

Radiative corrections to the Higgs-mass



See for example the review [Cacciapaglia, Pica, Sannino, 2020, 2002.04914 , Phys. Rept.] and references therein

WHY COMPOSITE HIGGS?

Standard Model symmetries

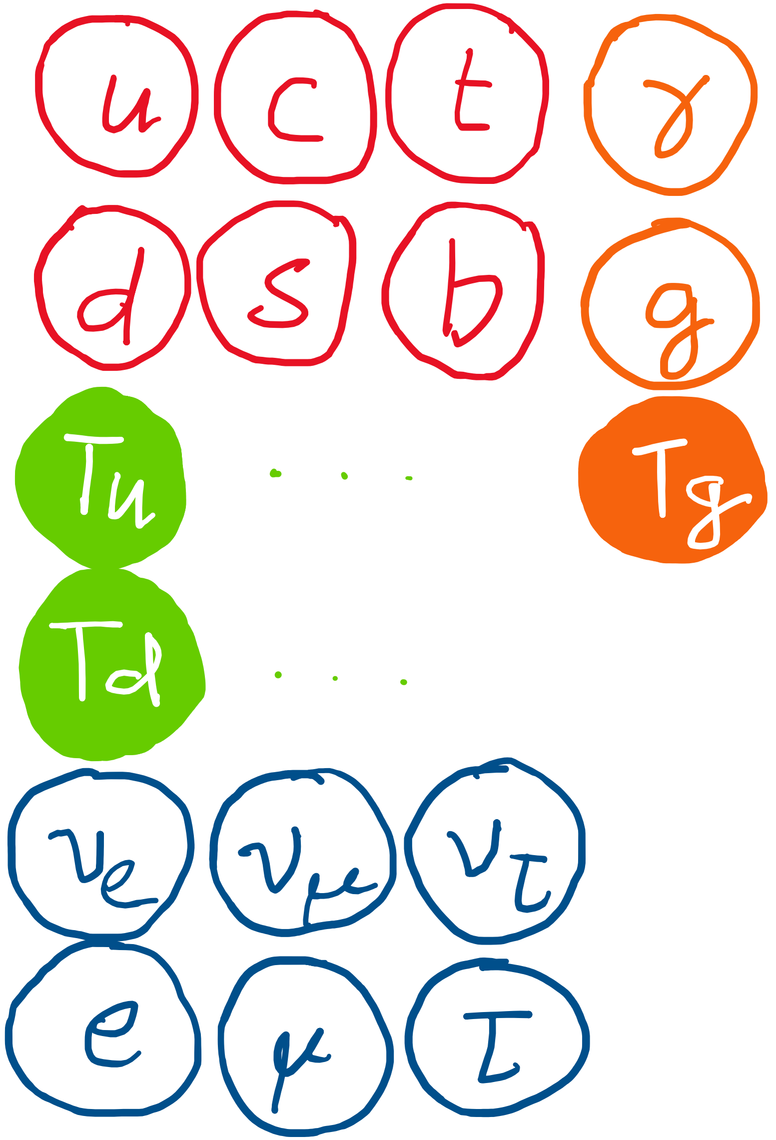
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Protect the ρ-parameter with additional custodial symmetry

$$SU(3)_c \times SU(2)_L \times U(1)_Y \\ \rightarrow \\ SU(3)_c \times U(1)_{EM}$$

Replace the weak sector with a **fundamental color** theory

$$SU(3)_c \times \boldsymbol{SU(2)_L} \times \boldsymbol{SU(2)_R} \times U(1)_Y \\ \rightarrow \\ SU(3)_c \times U(1)_Y \times \boldsymbol{SU(N_{FC})}$$



See for example the review [Cacciapaglia, Pica, Sannino, 2020, 2002.04914 , Phys. Rept.] and references therein

TECHNICOLOR VS COMPOSITE GOLDSTONE HIGGS

Vacuum alignment θ

0 — **Mixed realizations** — $\pi/2$

Composite Higgs → Higgs is a pNGB

Technicolor → Higgs is a light resonance

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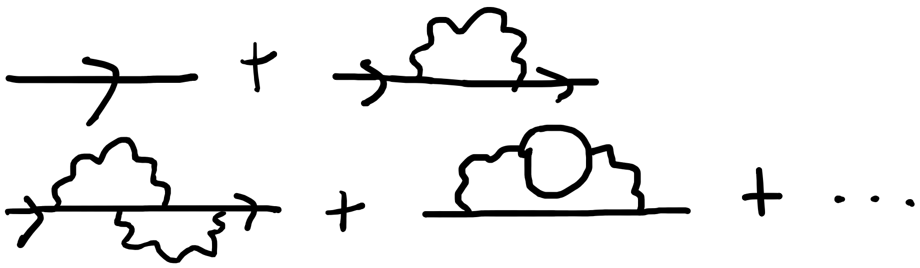
THE ROLE OF LATTICE GAUGE THEORY

Minkowskian 4D continuum physics

$$Z = \int \mathcal{D}U\mathcal{D}\Psi\mathcal{D}\bar{\Psi}e^{iS[U,\Psi,\bar{\Psi}]}$$

Generating Functional with conjugate variables

$$Z = \int \mathcal{D}U\mathcal{D}\Psi\mathcal{D}\bar{\Psi}e^{iS[U,\Psi,\bar{\Psi}]-(J,U)-(\pi,\Psi)-\overline{(\pi,\Psi)}}$$

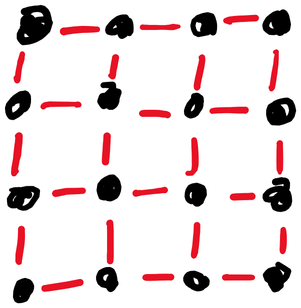


QFT on a Euclidean 4D lattice

$$Z = \int \mathcal{D}U\mathcal{D}\Psi\mathcal{D}\bar{\Psi}e^{-S[U,\Psi,\bar{\Psi}]}$$

Generate sample of gauge fields U_i, $i = 1, \dots, N$

$$\langle \widehat{O} \rangle = \frac{1}{N}\sum_{i=1}^{N} O(U_i) \pm \sqrt{\frac{var(O(U_i))}{N}}$$

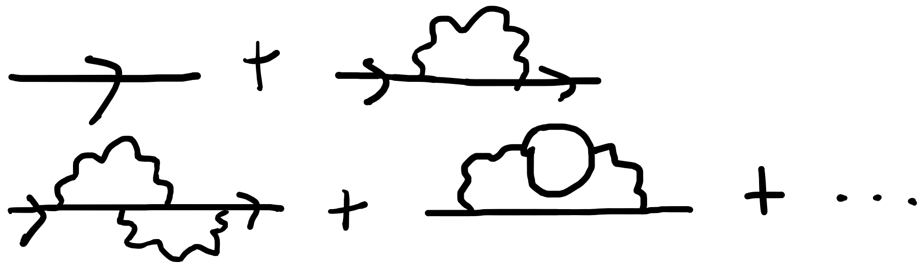


PROBLEMS WITH BOTH APPROACHES

Minkowskian 4D continuum physics

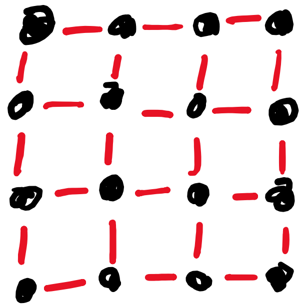
$$Z = \int \mathcal{D}U\mathcal{D}\Psi\mathcal{D}\overline{\Psi}e^{iS[U,\Psi,\overline{\Psi}]}$$

Breaks down at large couplings



QFT on a Euclidean 4D lattice

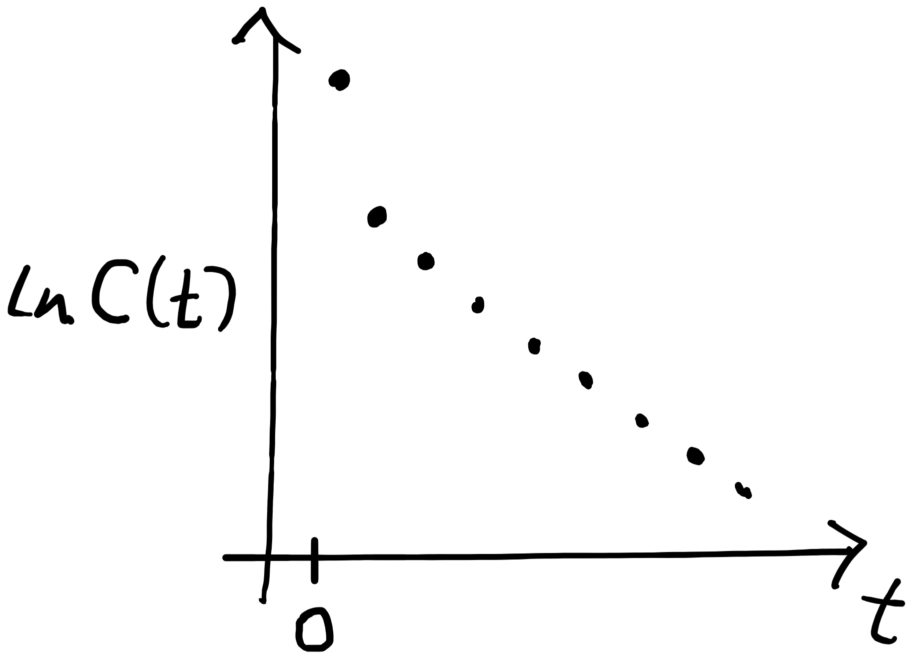
- Systematic uncertainties: Finite lattice spacing, volume and quark mass
- Statistical uncertainties: Sample size

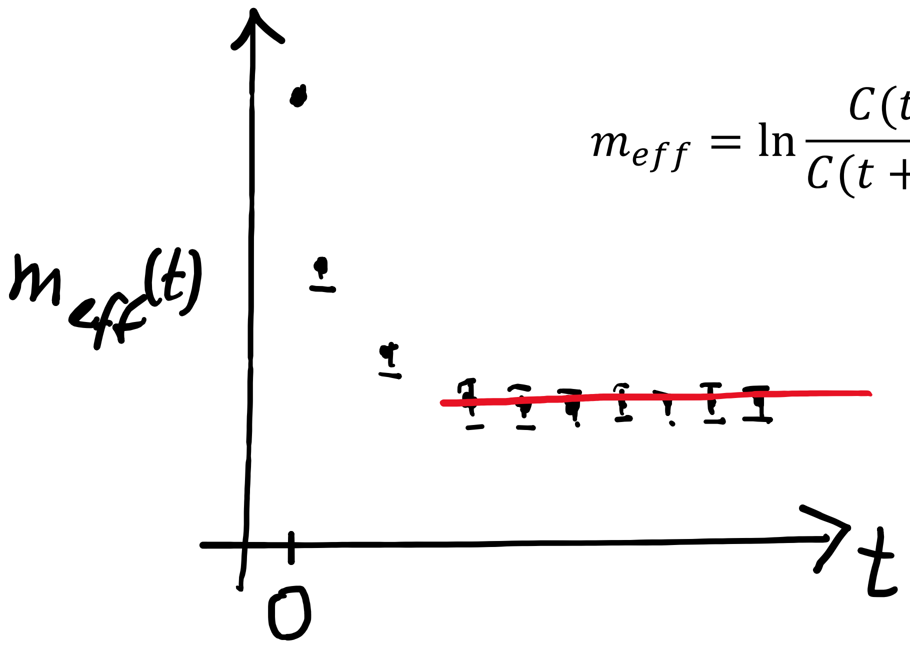


THE ROLE OF LATTICE GAUGE THEORY

Lattice gauge theory is good at **extracting masses**

$$C(t_1, t_0) = \langle O(t_1) O(t_2) \rangle = \sum_n |\langle 0|O(0)|n\rangle|^2 e^{-E_n(t_1 - t_0)} \rightarrow |\langle 0|O(0)|n\rangle|^2 e^{-m(t_1 - t_0)}$$





$$m_{eff} = \ln \frac{C(t)}{C(t+1)}$$

STANDARD MODEL QUARK MASS GENERATION

WALKING TECHNICOLOR

This is some necessary context for lattice studies on **Technicolor**

[1]Picture: [Particle Data Group, Phys. Rev. D 110, 030001 (2024)]

EXAMPLES OF RG TRANSFORMATIONS

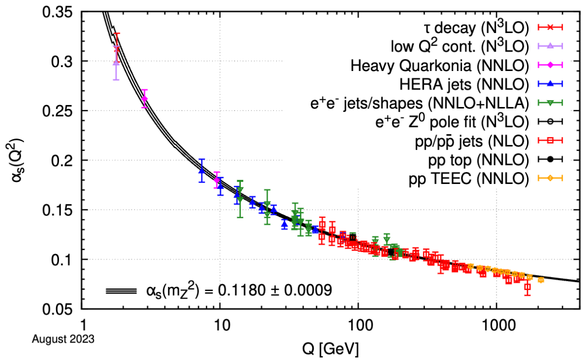
* RG = RENORMALIZATION GROUP

Infectious disease spread

Predicting the number of infections at a future time from the current time

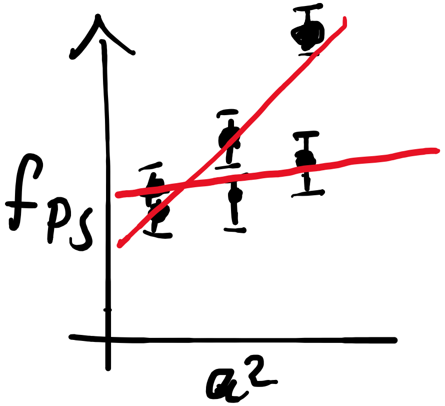
[de Hoffer, A., Vatani, S., Cot, C. et al., 2022, Nature, 0.1038/s41598-022-12442-8]

SU(N) theories



Increasing the center of mass energy[1]

Lattice Field Theory



Performing a continuum extrapolation

[1]Picture: [Particle Data Group, Phys. Rev. D 110, 030001 (2024)]

EXAMPLES OF CONFORMAL BEHAVIOR

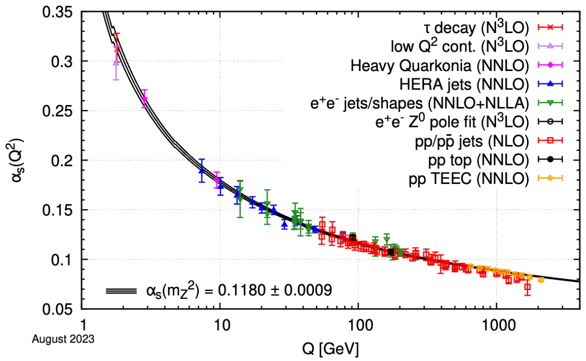
* RG = RENORMALIZATION GROUP

Infectious disease spread

The disease is endemic

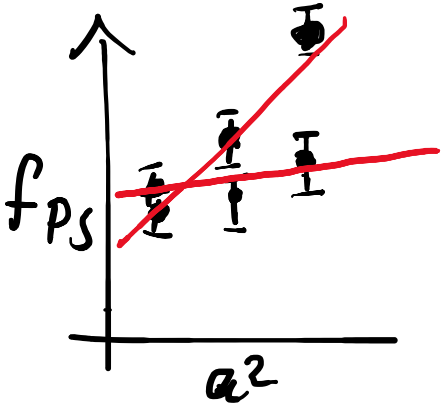
[de Hoffer, A., Vatani, S., Cot, C. et al., 2022, Nature, 0.1038/s41598-022-12442-8]

SU(N) theories



The coupling stays constant[1]

Lattice Field Theory



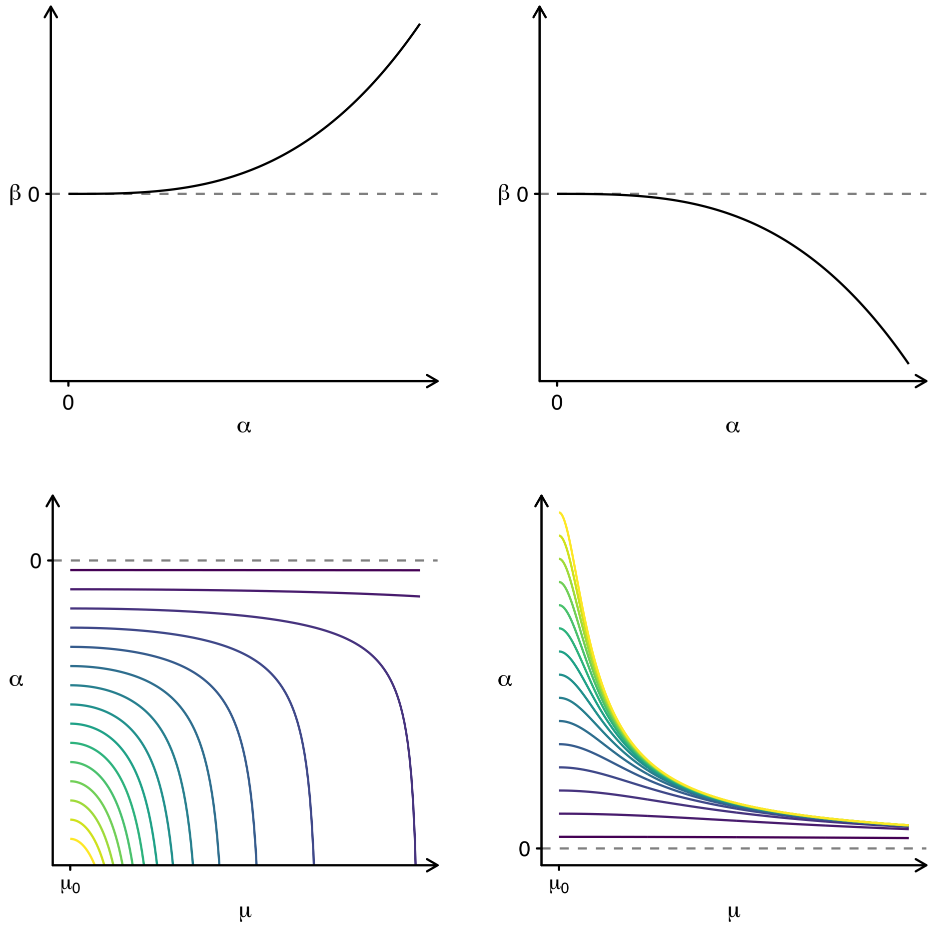
”Perfect actions”

[Hasenfratz, Niedermayer, 1993, Phys. Rev. D, hep-lat/9308004]

ANALYZING THE BETA FUNCTION – QED & QCD

$$\mu \frac{d\alpha}{d\mu} = -\beta(\alpha)$$

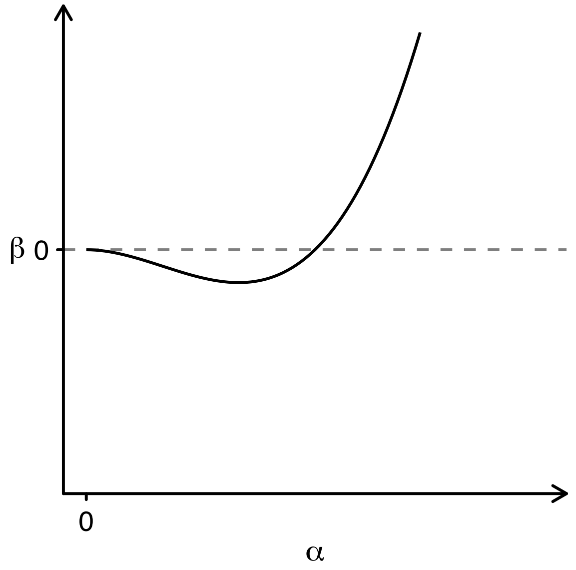
1. Trivial fixed point
2. Sign of beta function
3. Divergence of coupling

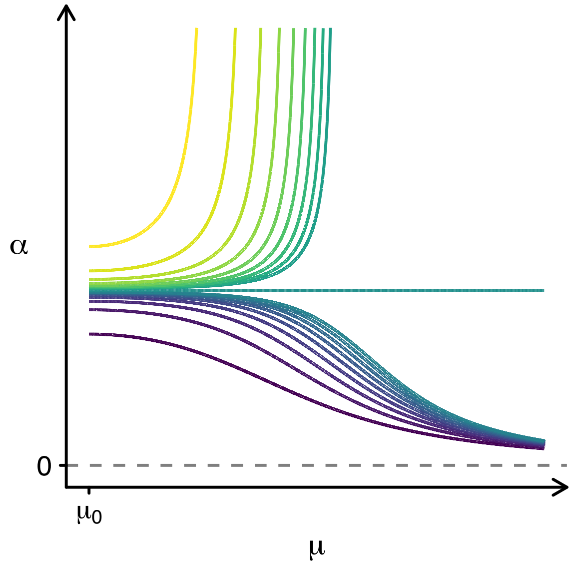


ANALYZING THE BETA FUNCTION - CFT

$$\mu \frac{d\alpha}{d\mu} = -\beta(\alpha)$$

1. **Attractive** or **repulsive** fixed points
2. **Conformal phases** with IR fixed point
3. Phase structure defined by Beta-function



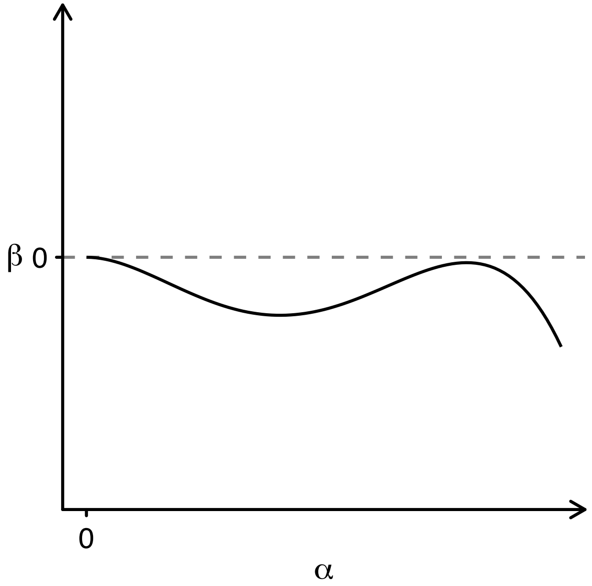


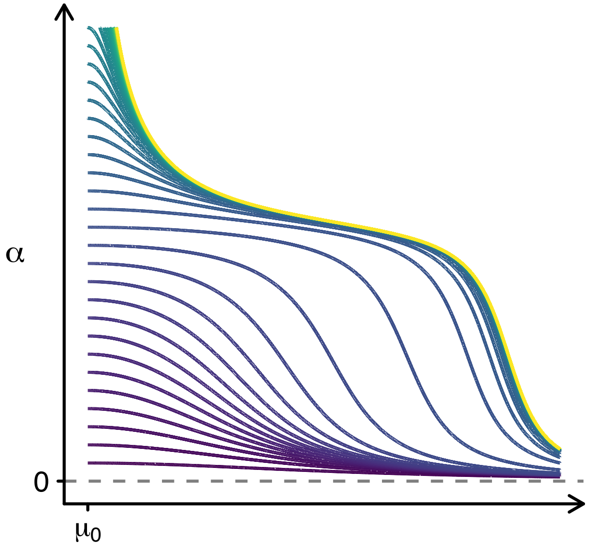
See for example the review [Cacciapaglia, Pica, Sannino, 2020, 2002.04914 , Phys. Rept.] and references therein

ANALYZING THE BETA FUNCTION – WALKING TC

$$\mu \frac{d\alpha}{d\mu} = -\beta(\alpha)$$

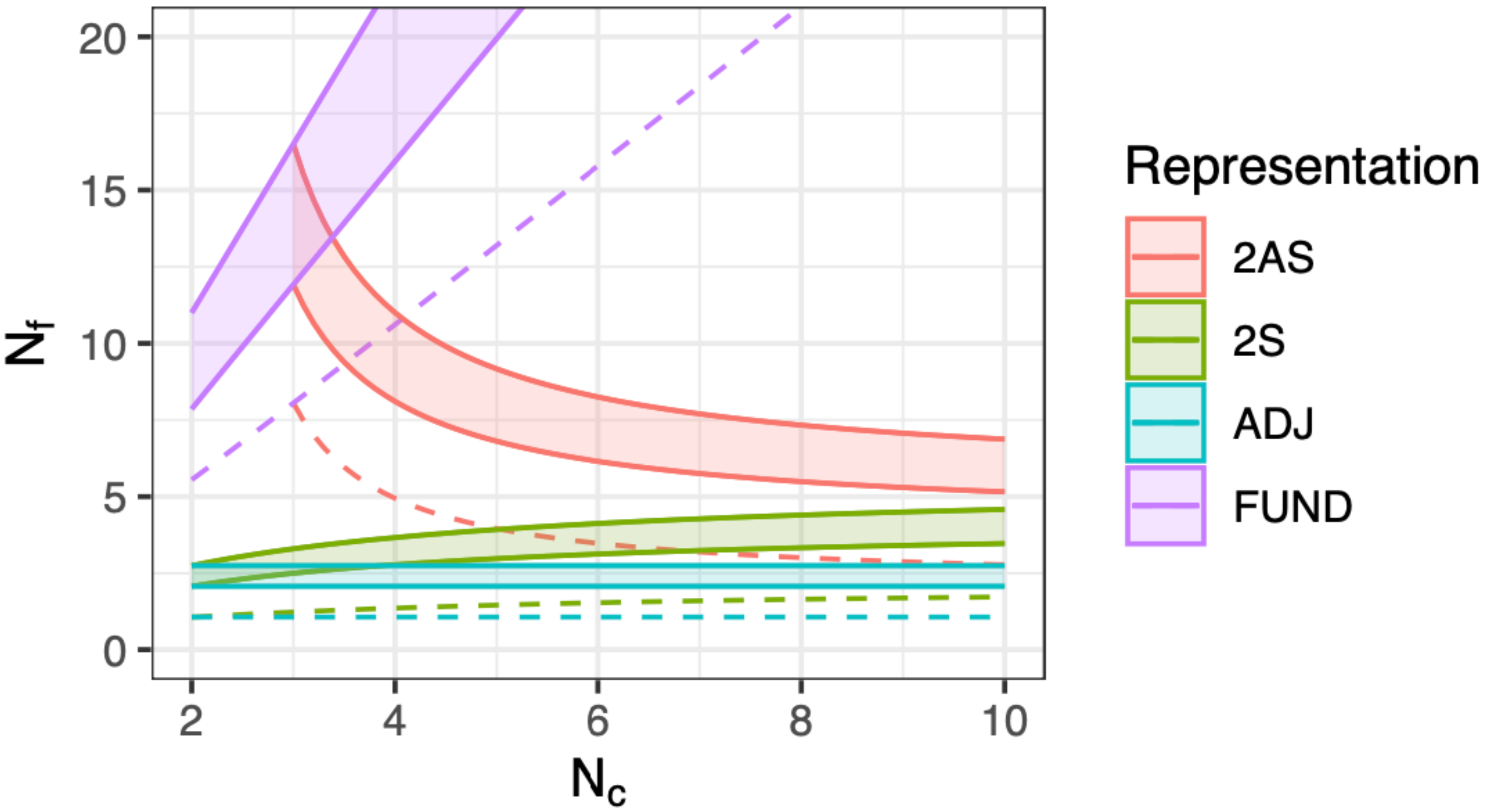
1. Near conformality = Walking TC
2. AF & ChiSB are still there, like regular QCD





[Dietrich, Sannino, 2007, Phys. Rev. D, hep-ph/0611341]

CONFORMAL WINDOW (PERTURBATIVE)



[Dimopoulos, Susskind, 1979, Nucl. Phys. B., 0.1016/0550-3213(79)90364-X]
[Eichten, Lane, 1980, Phys. Lett. B, 10.1016/0370-2693(80)90065-9]

STANDARD MODEL MASS GENERATION

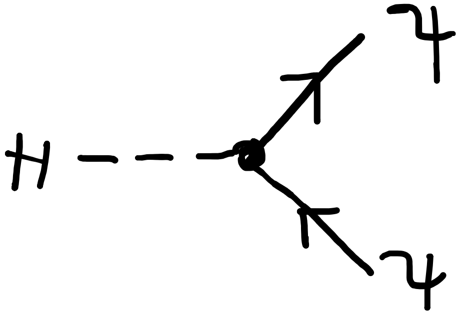
This aims to generate the masses of the Standard Model quarks.

Why is the top so heavy??

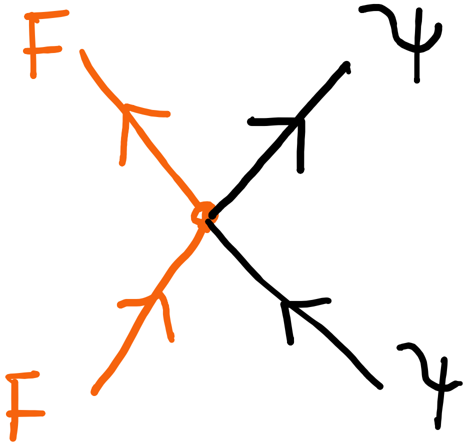
Higgs interaction with Standard Model quarks

becomes

New sector quarks F interact with Standard Model quarks



$$= gH\Psi\bar{\Psi} \quad \rightarrow \quad \alpha_{ab}\frac{\bar{F}T^aF\bar{\Psi}T^b\Psi}{\Lambda^2}$$



[Dimopoulos, Susskind, 1979, Nucl. Phys. B., 0.1016/0550-3213(79)90364-X]
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STANDARD MODEL MASS GENERATION

This aims to generate the masses of the Standard Model quarks.

Why is the top so heavy??

Electroweak symmetry breaking	*becomes*	Chiral Symmetry Breaking
$\langle H \rangle$	$\rightarrow$	$\langle \bar{F} F \rangle$

[Dimopoulos, Susskind, 1979, Nucl. Phys. B., 0.1016/0550-3213(79)90364-X]
[Eichten, Lane, 1980, Phys. Lett. B, 10.1016/0370-2693(80)90065-9]

STANDARD MODEL MASS GENERATION

This aims to generate the masses of the Standard Model quarks.

Why is the top so heavy??

$$m_q \sim \frac{\alpha}{\Lambda^2}\langle \bar{F}F \rangle \approx \frac{\alpha}{\Lambda^2}\langle \bar{F}F \rangle_{SU(N)} = \frac{\alpha}{\Lambda^2}\langle H \rangle$$

[Koichi, Masako, Ken-Iti, 1986, Phys. Rev. Lett., 10.1103/PhysRevLett.56.1335]

STANDARD MODEL MASS GENERATION

This aims to generate the masses of the Standard Model quarks.

Why is the top so heavy??

$$m_q \sim \frac{\alpha}{\Lambda^2}\langle \bar{F}F\rangle \approx \frac{\alpha}{\Lambda^2}\left(\frac{\Lambda^2}{\Lambda^2_{SU(N)}}\right)^{\gamma(\alpha^\star)} \langle \bar{F}F\rangle_{SU(N)}$$

QUICK SUMMARY

1. SU(N) gauge theories can exhibit chiral symmetry breaking or a conformal phase in the IR
2. Theories that are close to conformal have chiSB & AF but also a region where the coupling stays close to constant
3. All of these phenomena are non-perturbative and need lattice gauge theory for proof

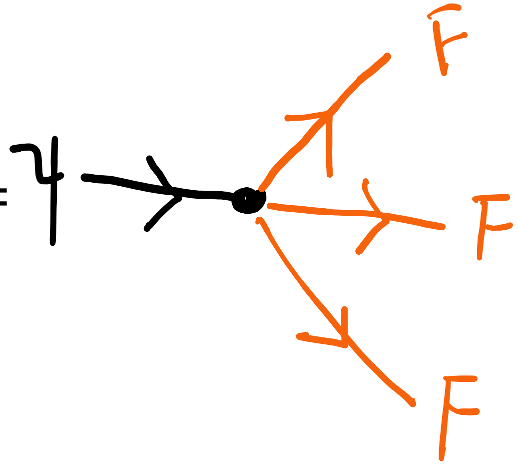
PARTIAL COMPOSITENESS

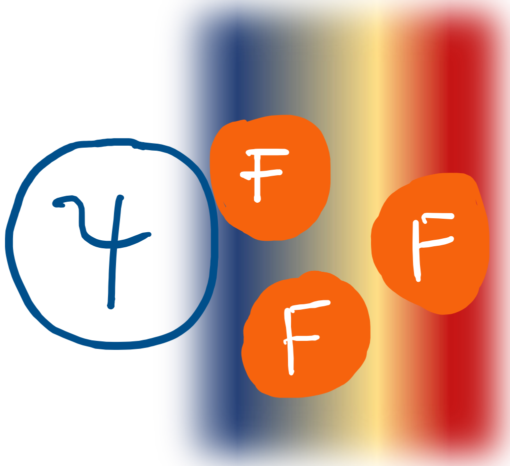
This is some necessary context for lattice studies on **Composite Higgs**

[Kaplan, 1991, Nucl. Phys. B., 10.1016/S0550-3213(05)80021-5]

SM QUARKS MIX WITH QUARKS FROM THE NEW SECTOR

$$\frac{4\pi}{M^2}\left(\kappa\Psi FFF + \kappa^{\star}\overline{\Psi}\overline{F}\overline{F}\overline{F}\right) =$$

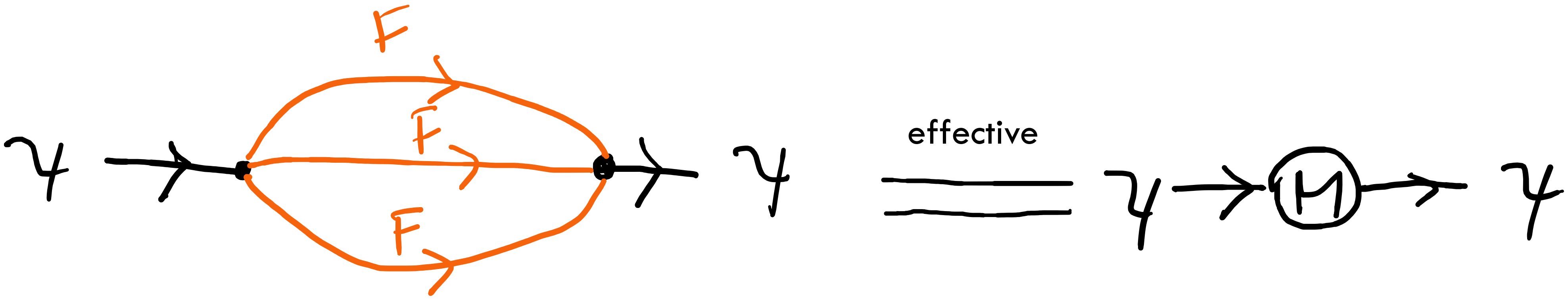




FFF must have the same quantum numbers as Ψ.

[Kaplan, 1991, Nucl. Phys. B., 10.1016/S0550-3213(05)80021-5]

SM QUARKS MIX WITH QUARKS FROM THE NEW SECTOR



Mass generation is linked to new sector quark mixing and not the condensate

QUICK SUMMARY

1. Another mass generation mechanism is partial compositeness, mixing of standard model quarks with fundamental color quarks
2. In this case one avoids coupling the Standard Model masses to the fundamental color quark condensate

See for example the review [Cacciapaglia, Pica, Sannino, 2020, 2002.04914 , Phys. Rept.] and references therein

SUMMARY

1. Walking behavior due to near conformality can explain large/different quark masses
2. Partial compositeness can explain large/different quark masses
3. To understand the workings of technicolor/Goldstone Higgs theory we need to have an estimate of $\boldsymbol{f_{PS}}$ **and** $\boldsymbol{m_H}$ from the new sector
4. This is very feasible on the lattice

LATTICE STUDIES OF CH

SOFTWARE

HiRep

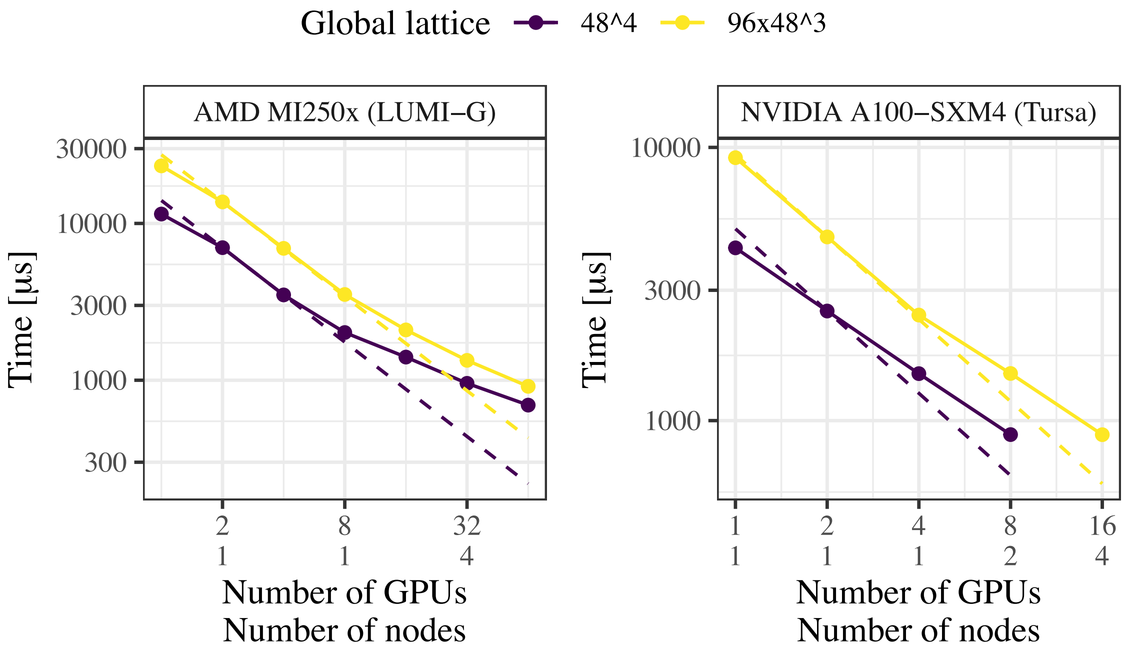
[Del Debbio, Patella, Pica, 2010, 0805.2058, Phys. Rev. D]

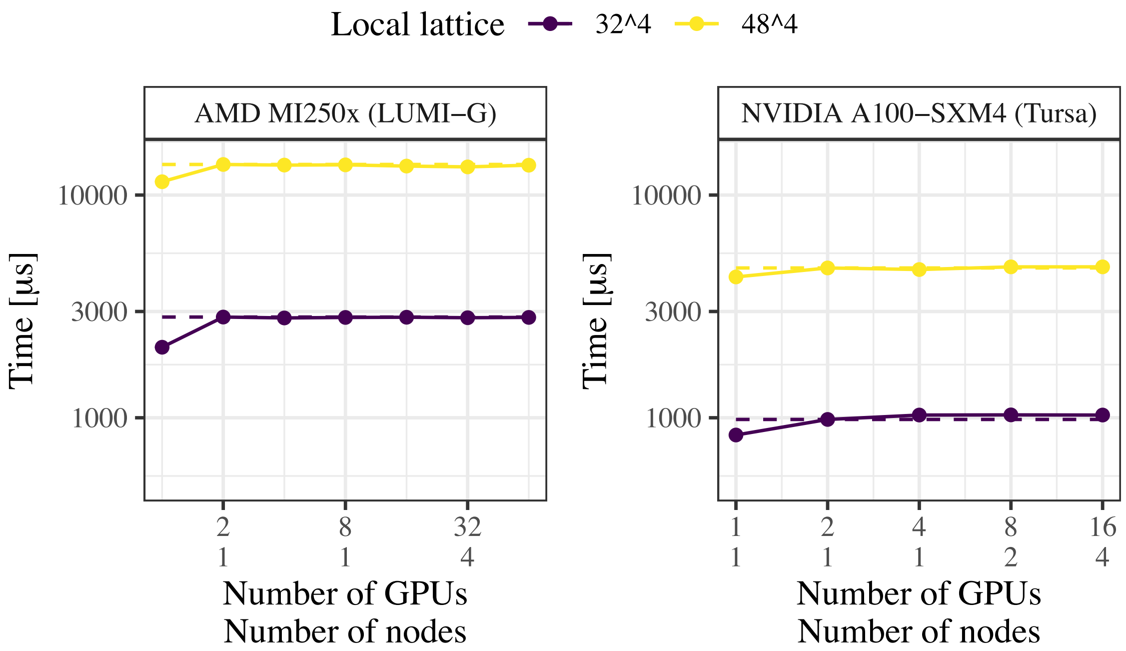
[SM et. al., 2024, PoS]

github.com/claudiopica/HiRep

A HIGH PERFORMANCE WILSON DIRAC OPERATOR

1. The software runs on **multiple architectures**
2. It achieves **peak bandwidth** on NVIDIA GPUs





1. We can reduce execution time by using more processors for the same lattice (**strong scaling**)
2. If we increase the volume together with the processors, the execution time stays the same (**weak scaling**)

[Del Debbio, Patella, Pica, 2010, 0805.2058, Phys. Rev. D]

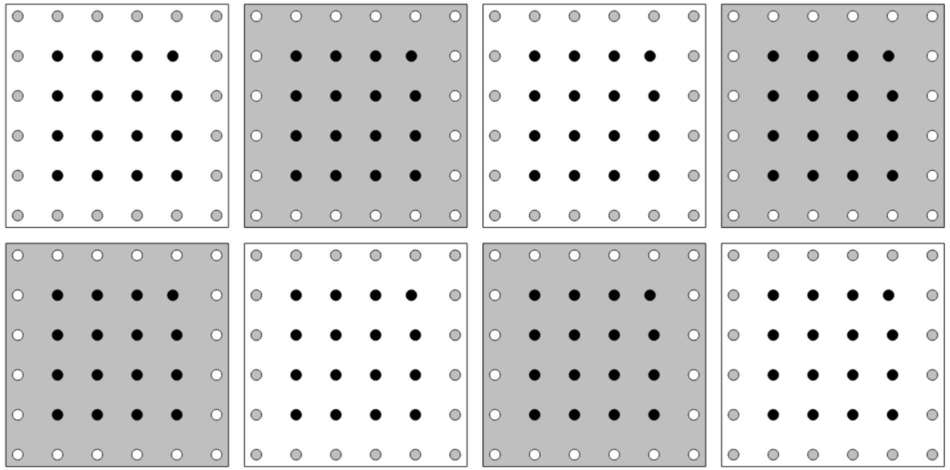
github.com/claudiopica/HiRep

[SM et. al., 2024, PoS]

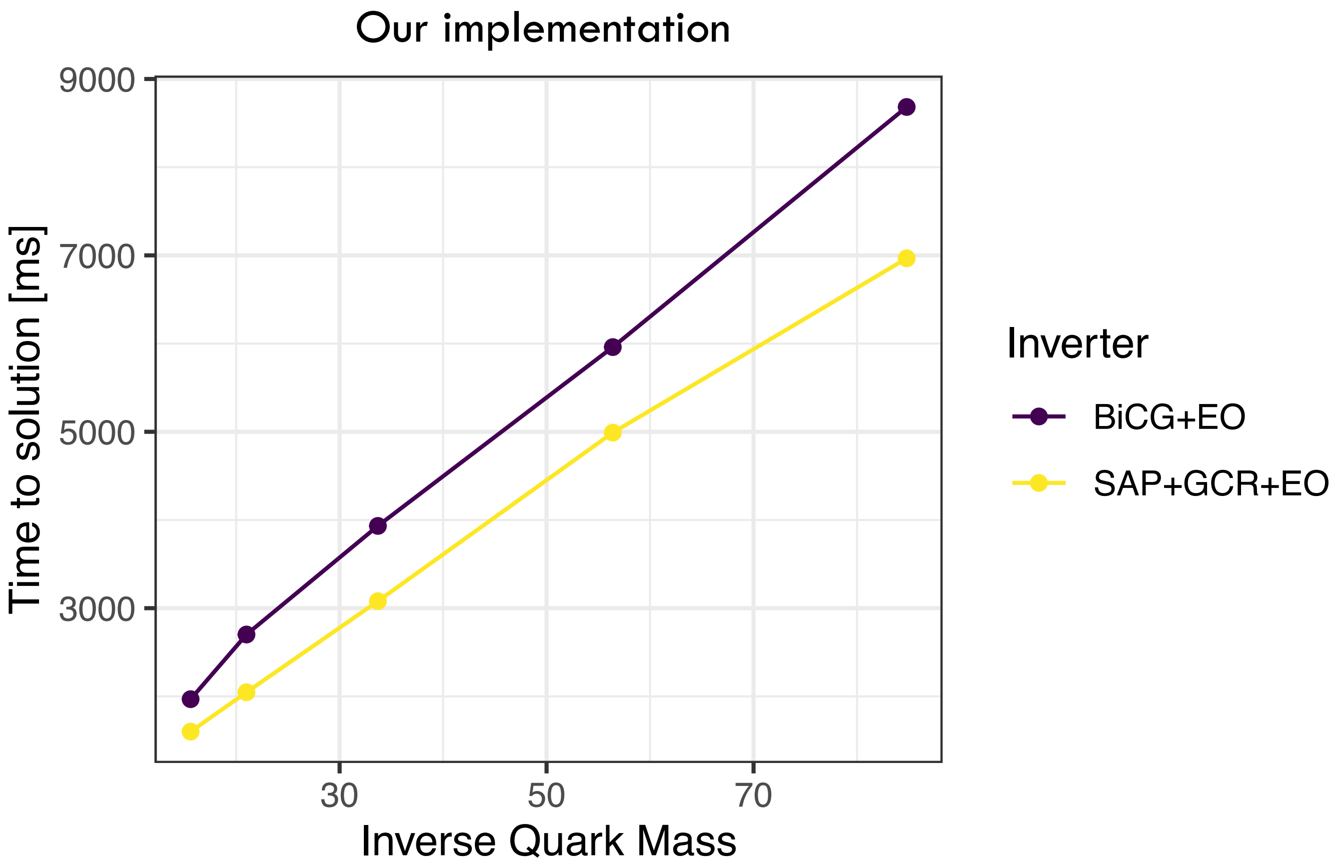
DOMAIN DECOMPOSITION FOR HIGHER REPRESENTATIONS

WORK IN PROGRESS

1. GPU kernels are executed **block by block**
2. We should perform inversions on the lattice block by block



Picture and idea: [Luscher, 2003, Comput. Phys. Commun., hep-lat/0310048]



SU(2) WITH FUNDAMENTAL FLAVORS

The minimal composite higgs scenario

See for example the review [Cacciapaglia, Pica, Sannino, 2020, 2002.04914 , Phys. Rept.] and references therein

THE MINIMAL SCENARIO

Two massless fermions and a two-color gauge boson, solves a few problems

$$\mathcal{L} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + \bar{u}\left(i\gamma^{\mu}D_{\mu} - m\right)u + \bar{d}\left(i\gamma^{\mu}D_{\mu} - m\right)d$$

Preservation of custodial symmetry

Minimal = cheap on the lattice

No hierarchy problem

DETERMINATION OF THE PSEUDOSCALAR DECAY CONSTANT

This is needed for deriving a valid low-energy theory and that has to correspond with the current weak sector

RECIPE:
FROM THE LATTICE TO A PHENO PREDICTION

1. **Extrapolate to a line of constant physics**
2. **Continuum extrapolation = extrapolating to vanishing lattice spacing**
3. **Chiral extrapolation = extrapolation to vanishing quark mass**

[A. Francis et. al., 2020, 1911.04533, Comput. Phys. Commun.]
[Ramos, Catumba, 2022, PoS, 10.22323/1.430.0383]

PRECISION SCALE SETTING THROUGH f_{PS}

Controlling statistical uncertainties

Large lattices + High statistics on GPUs

Hasenbusch Acceleration

Controlling systematic uncertainties

Non-perturbative Exponential-Clover Improvement

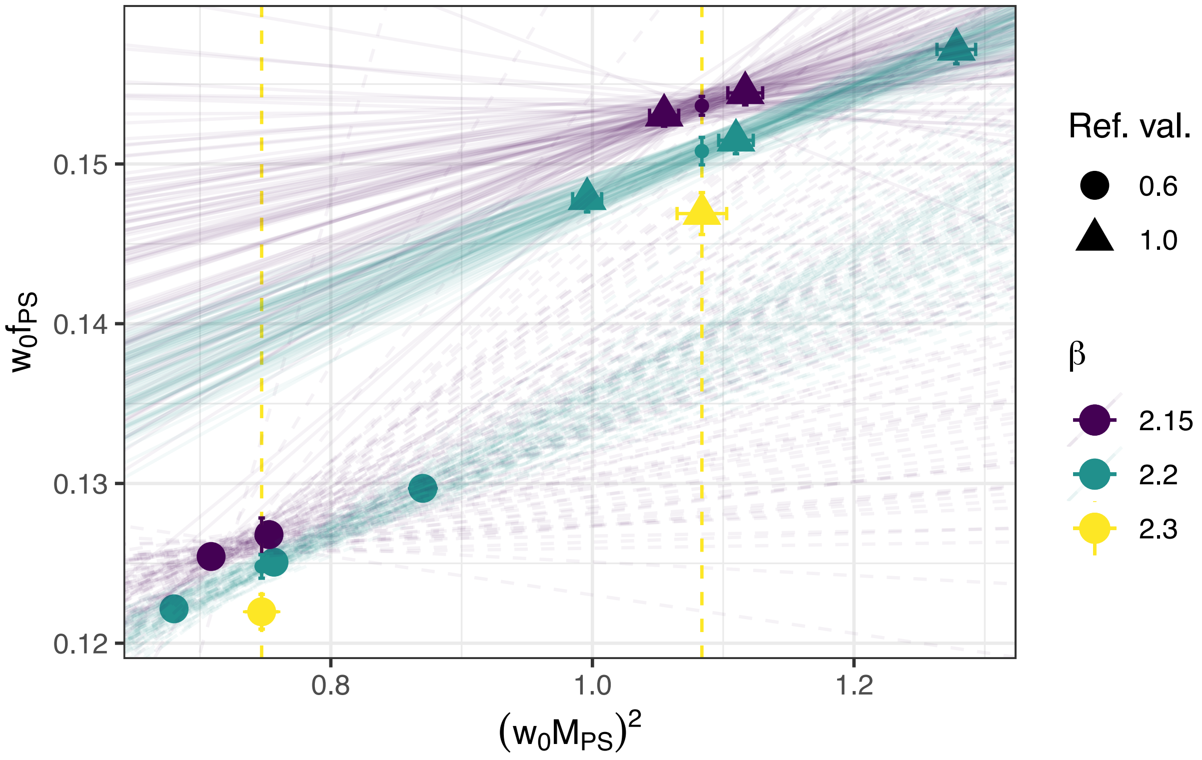
Twisted-Mass Mixed Action Measurements

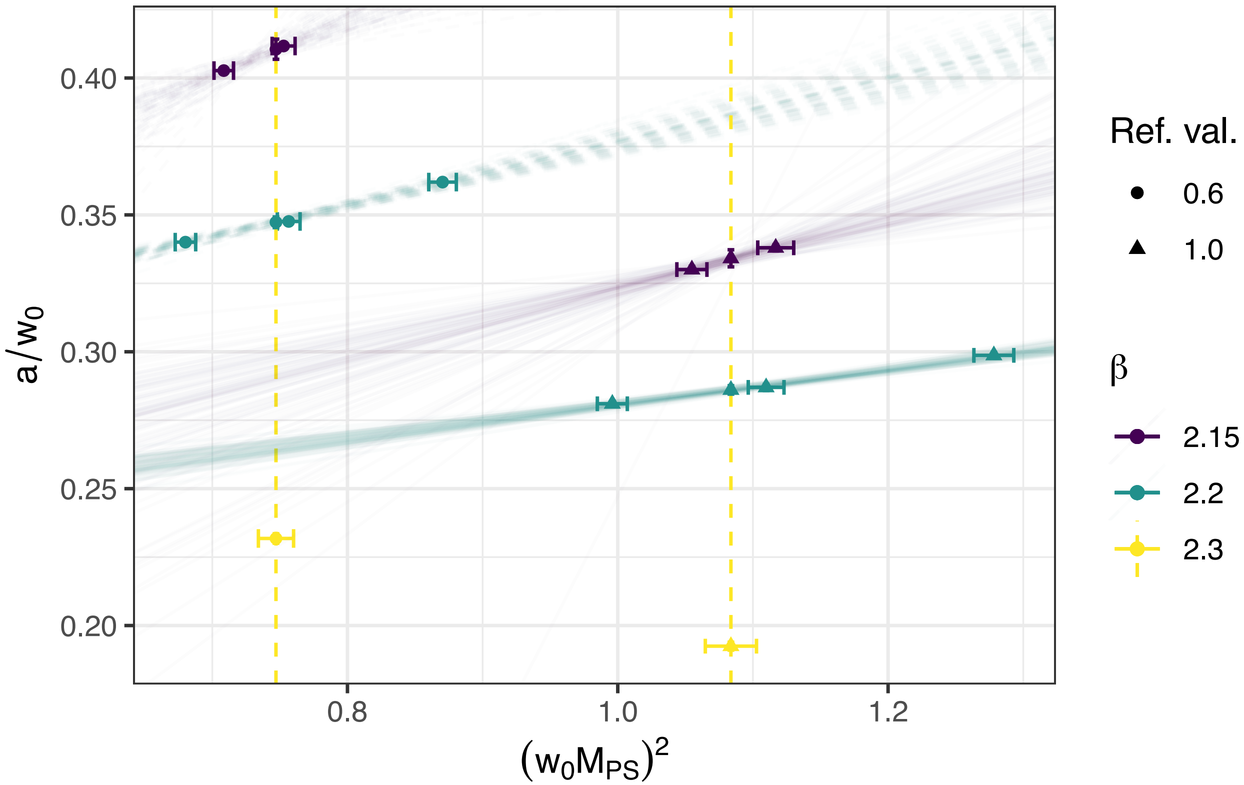
Continuum extrapolation scale setting, compare scales w_1/w_0

[SM, et. al., Talk at Lattice 2024]

LINE OF CONSTANT PHYSICS

1. **Simulate at different quark masses, then extrapolate to a line of constant physics:**
   1. Find the prediction, for example f_{PS}, for a fixed mass of the pseudoscalar
   2. Find the mass of the pseudoscalar m_{PS}
   3. Extrapolate the f_{PS} to a common fixed m_{PS}, the line of constant physics

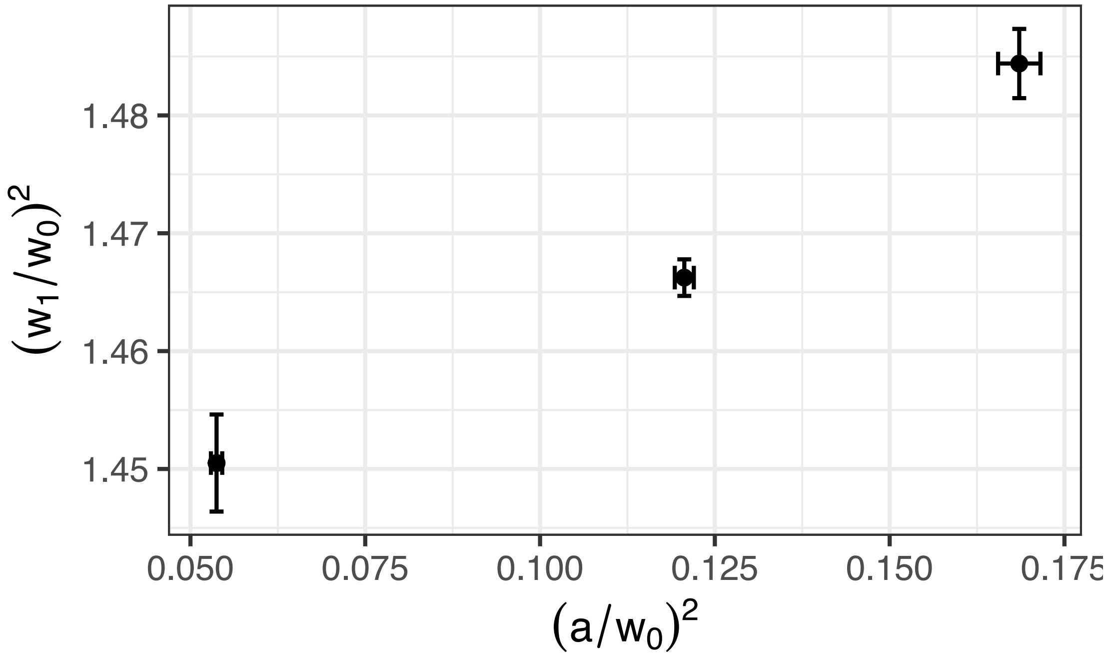


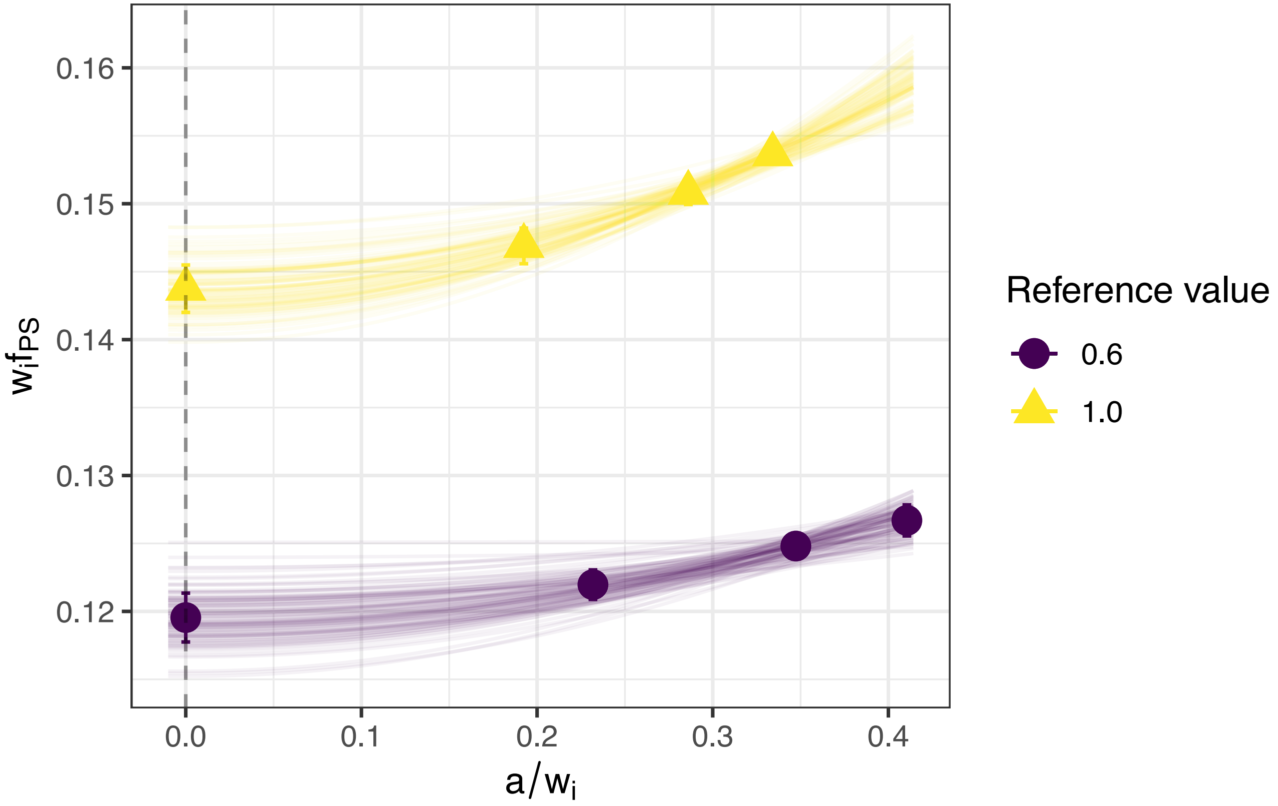


[SM, et. al., Talk at Lattice 2024]

CONTINUUM EXTRAPOLATION

1. **Continuum extrapolation**
   1. Determine the lattice spacing of the ensemble
   2. Extrapolate to the continuum





We have at most 10% discretization effects. This is quite precise!

THE MASS OF THE NEW HIGGS

Spectroscopy

DISCONNECTED CONTRIBUTIONS TO THE SINGLET

Calculate propagator

$$\langle\bar{\Psi}(x_0)\Psi(\mathrm{x}_1)\rangle = D^{-1}(x_0|x_1) = S(x_0, x_1)$$

Consider all Wick-contractions:

$$\langle O(t_0)O(t_1)\rangle = -\frac{1}{2}tr[\Gamma S(t_0|t_1)\Gamma S(t_0|t_1)] + \frac{1}{2}tr[\Gamma S(t_0|t_0)]\ tr[\Gamma S(t_1|t_1)]$$

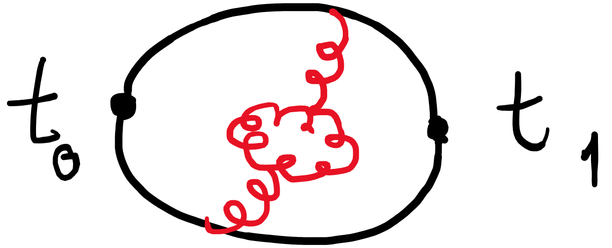
THIS IS NOT PERTURBATION THEORY

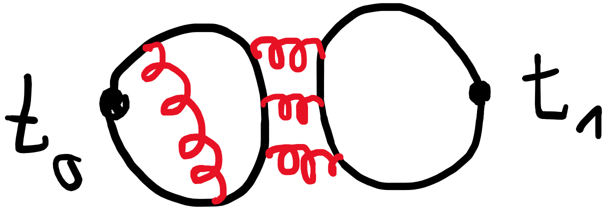
Calculate propagator

$$\langle\overline{\Psi}(x_0)\Psi(\mathrm{x}_1)\rangle = D^{-1}(x_0|x_1) = S(x_0, x_1)$$

Consider all Wick-contractions:

$$\langle O(t_0)O(t_1)\rangle = -\frac{1}{2}tr[\Gamma S(t_0|t_1)\Gamma S(t_0|t_1)] + \frac{1}{2}tr[\Gamma S(t_0|t_0)]\ tr[\Gamma S(t_1|t_1)]$$

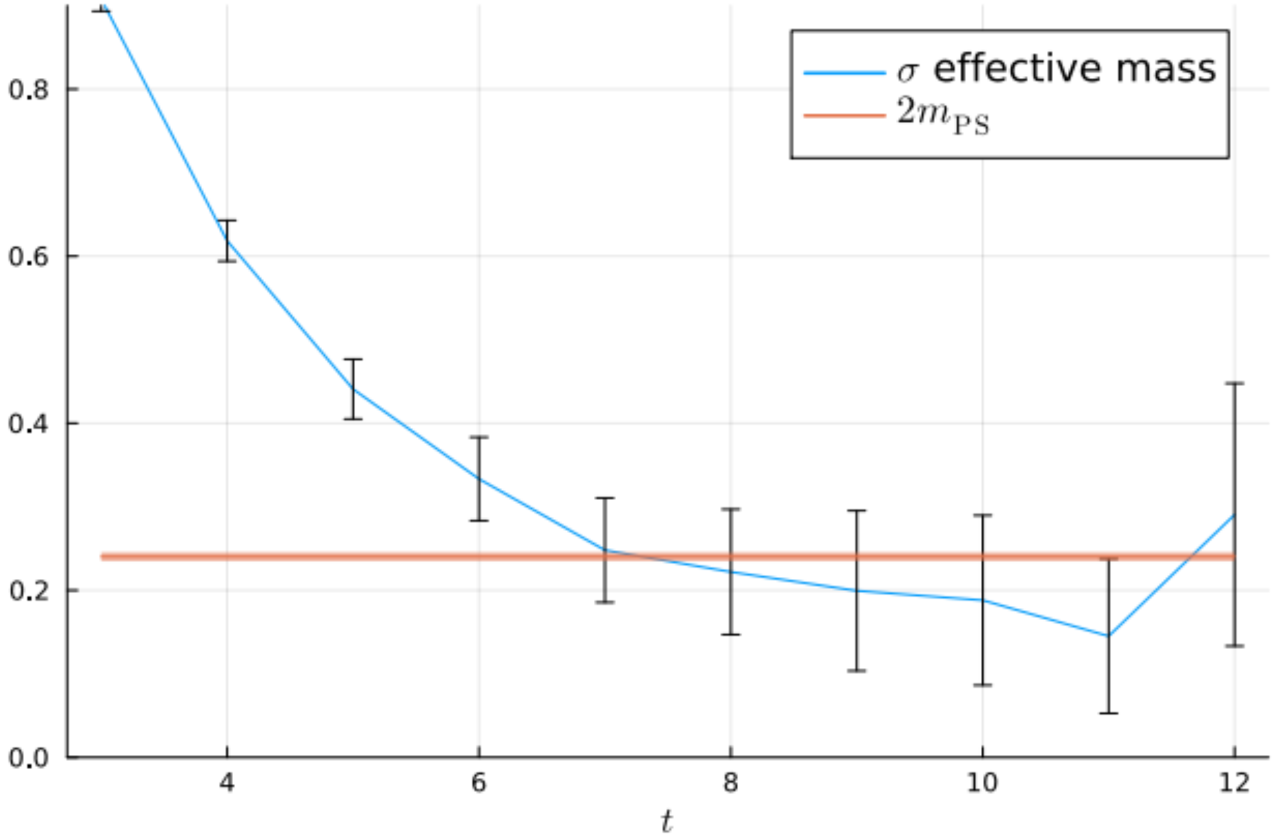




[Laurence Bowes, SM, et. al., Talk at Lattice 2024]

SINGLET & TWO-PION STATE

1. We see a plateau
2. Is this the singlet or the two-pion state?



CONCLUSION & OUTLOOK

SUMMARY

1. Composite Higgs theories are a promising candidate for BSM physics because of good phenomenological properties
2. We are examining SU(2) with two fundamental-color quarks on the lattice
3. We have managed to use state-of-the-art techniques to evaluate the pseudoscalar decay constant and Higgs mass on the lattice with very few lattice artifacts
4. A chiral extrapolation remains to be done

PRECISION PREDICTIONS FOR BSM PHYSICS

1. The GPU porting of HiRep allows the generation of high statistics on modern supercomputers
2. We were able to reach exceptionally high precisions for BSM physics

The lattice is becoming able to produce high-precision results for BSM theories