Lattice field theory beyond the Standard Model

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for the USQCD Collaboration
LQCD-ext III Scientific Review
July 9, 2019

Outline of talk

1. Motivation and overview
2. Background: the “theory space” of strongly-coupled gauge interactions
3. Science drivers for lattice BSM
4. USQCD science highlights
5. Conclusion

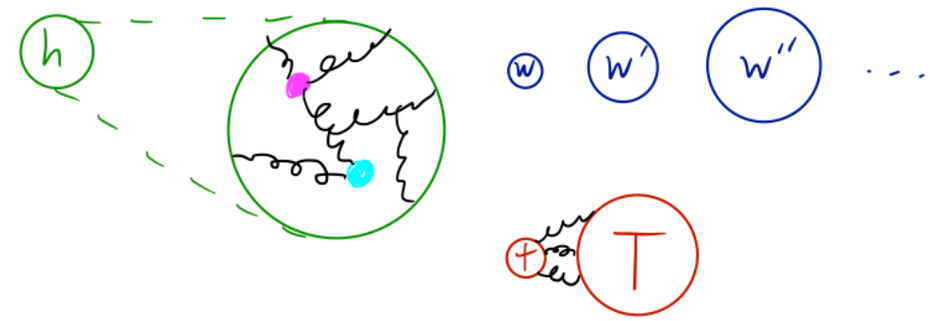
1. Motivation/overview

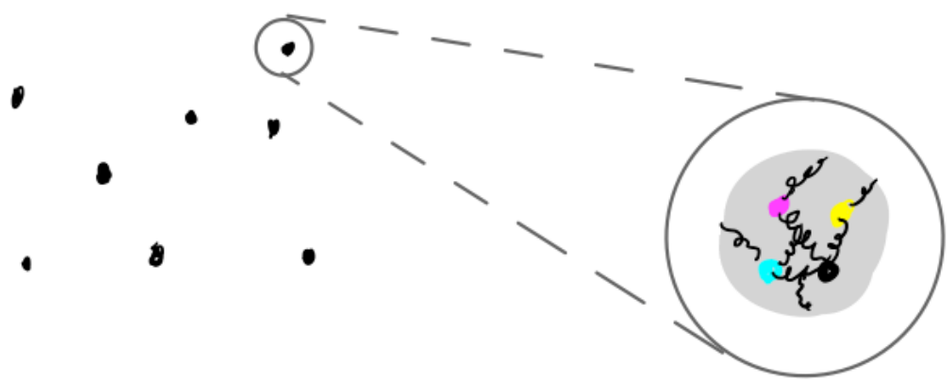
Motivation

- There are many motivations for studying models of *new physics Beyond the Standard Model* (**BSM**). Some excerpts from the P5 report:
  - "Dark matter is presumed to consist of one or more kinds of new particles…"
  - "What is the origin of neutrino mass?"
  - "…Is there one Higgs particle or many? Is the new particle really fundamental, or is it composed of others?"
- Perturbative extensions of the SM are nice for the theorist, but sometimes physics is <u>strongly coupled</u>, e.g. QCD!
- If BSM physics is strongly coupled, <u>lattice</u> can give physics information that is otherwise inaccessible.

What kinds of BSM models?

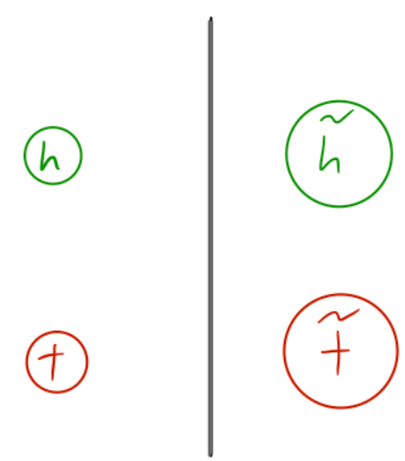
<u>Composite Higgs:</u> new strongly-coupled sector at the electroweak scale; Higgs is a composite bound state. (W/Z, top often have some composite part too.)





<u>Composite dark matter:</u> dark "hidden sector" which is strongly coupled. Can appear naturally with composite Higgs or GUT theories.

<u>Supersymmetry (SUSY):</u> hypothetical symmetry relating bosons to fermions. Supersymmetric SM requires *SUSY breaking*, where strong coupling can be relevant.



What kinds of BSM models?

Composite Higgs: new strongly-coupled sector at the electroweak

Strongly-coupled quantum field theory!

Exploring the rich dynamics of QFT at strong coupling cuts across all models; lattice is the only available non-perturbative definition

We learn about strong dynamics from lattice, even if BSM model *X* is ruled out. *(Like exploring QCD at non-physical quark mass.)*

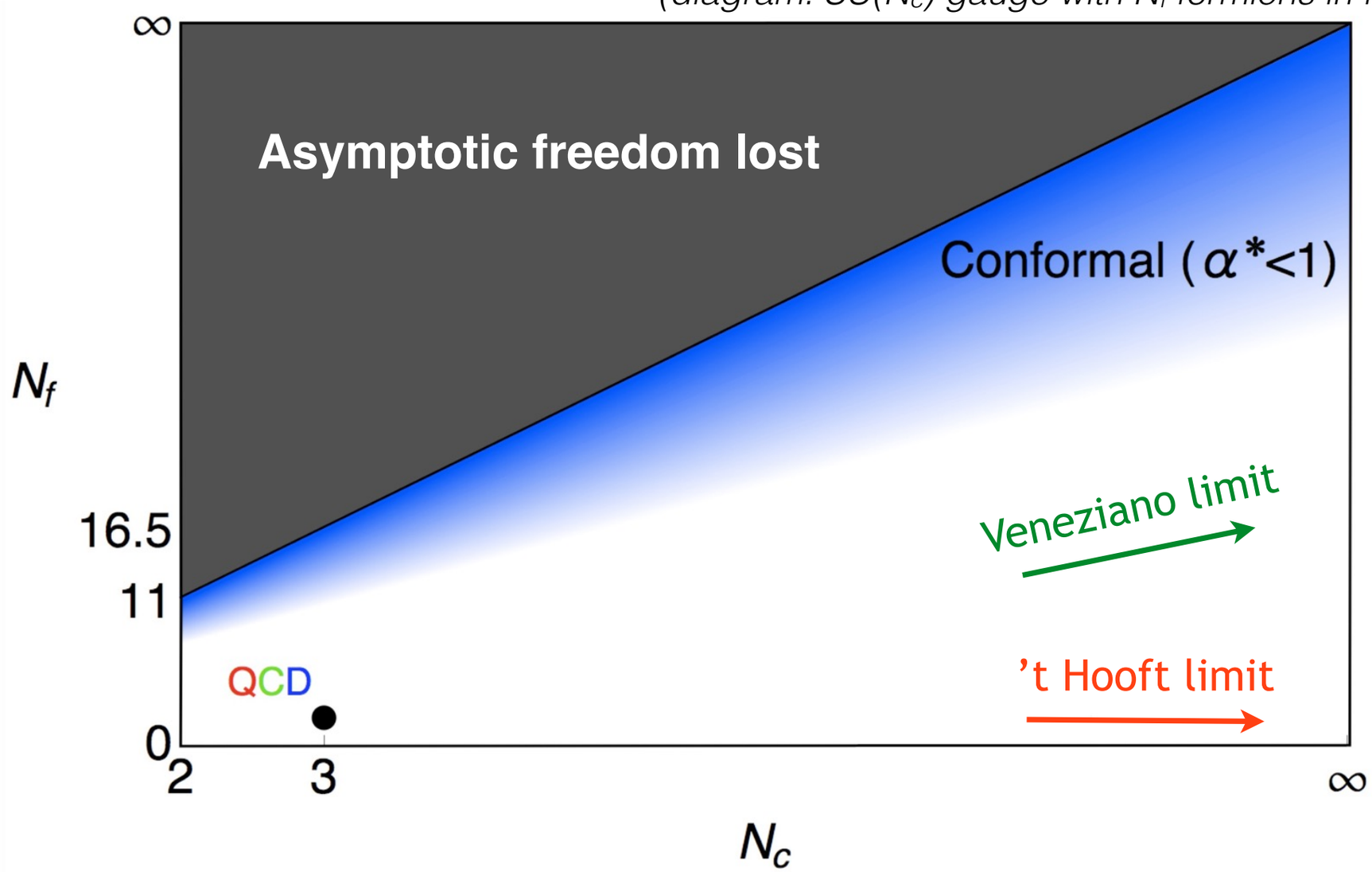
Need to develop tools for studying strongly-coupled QFT now, to be ready for possible discovery at the LHC or elsewhere!

SM requires *SUSY breaking*, where strong coupling can be relevant.

2. Background: “theory space”

Exploring the theory space

(diagram: SU(N_c) gauge with N_f fermions in fundamental irrep)

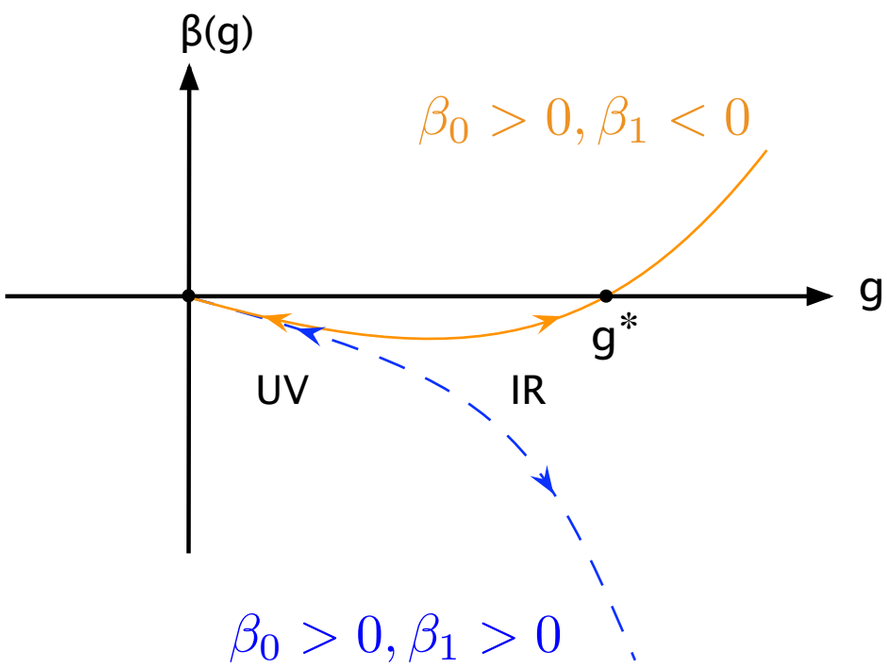


Aside from specific models, lattice can give non-perturbative insight into the broader space of gauge-fermion theories, which exhibits:

- **rich phase structure** (IR-conformal phase transition),
- **emergent dynamics** (4d conformal field theories),
- **well-established trends** (the 't Hooft and Veneziano large-N limits.)

Aside: the infrared-conformal phase

$$\beta(g) \equiv \frac{\partial g}{\partial(\log \mu)} = -\beta_0 g^3 - \beta_1 g^5 - \ldots$$



- Many theories in the space are "cousins" of QCD: color charges *confine* into a spectrum of "hadron" bound states.
- In the infrared-conformal phase, gauge coupling *g* will approach an "infrared fixed point", freezing at some *g*=*g**>0.
- This freezing *restores scale invariance* - we recover a conformal field theory (CFT). CFTs have a unique "spectrum" of operator anomalous dimensions; no confined bound states.

- These CFTs can appear in many models of new physics, but only with *broken scale invariance*, since our world isn't conformal! Still, learning about the symmetric limit is useful and important. (Analogous to supersymmetric BSM models: SUSY must be broken, but it's still useful to describe the physics.)

Modeling the theory space

- If we have models like ’t Hooft large-N expansion available, why do we need lattice?

- Lattice gives *quantitative* information in a vast space for which we have only one real-world example (QCD). Allows us to:

  - Test and validate models of theory space

  - Search for novel phenomena that might require new models

  - Fill in details that the models don’t provide

- Analogous to the *Wigner-Eckart theorem* in quantum mechanics. Symmetry gives us a big part of the story, but we still have to calculate the reduced matrix elements to make concrete predictions!

$$\langle j', m' | \hat{T}_q^{(k)} | j, m \rangle = \langle jk; mq | jk; j'm' \rangle \langle j' || \hat{T}^{(k)} || j \rangle$$

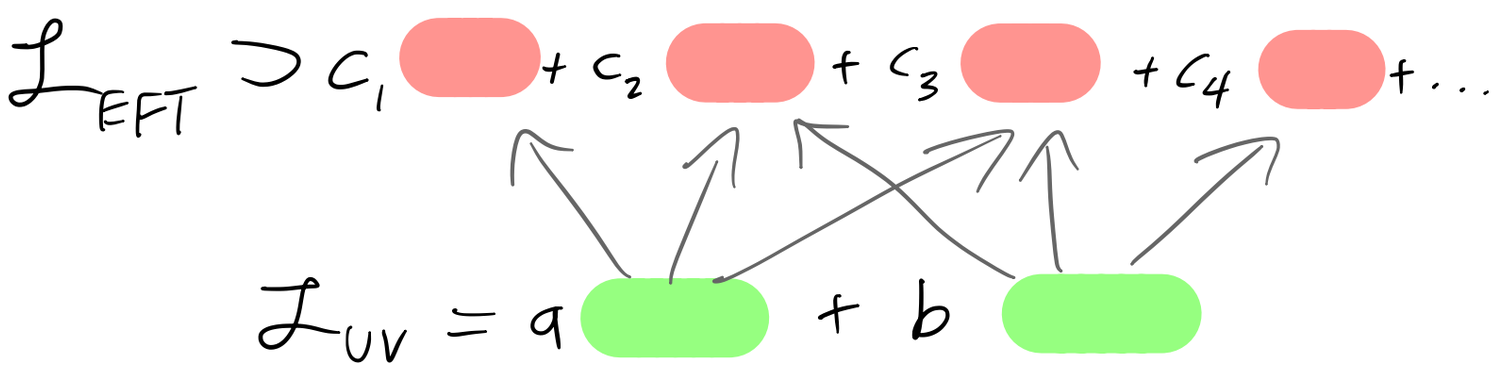
What about effective theories?

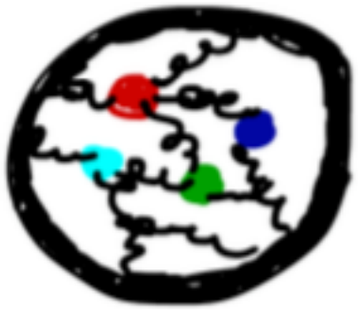
- We can take a more bottom-up approach and say: just identify the right <u>effective field theory (EFT)</u> for collider physics, dark matter detection, etc.

- Nothing wrong with this approach, but using *only* the EFT has limited predictive power: need to fix many (infinite!) low-energy constants from experiment.

- Plus, EFT comes with an <u>energy cutoff</u>: fine for working in the low-energy limit at the threshold of discovery, but many details of the full theory are out of reach.

- **EFT + lattice** allows analytic calculation but many LECs are determined from a handful of underlying UV parameters - best of both worlds!





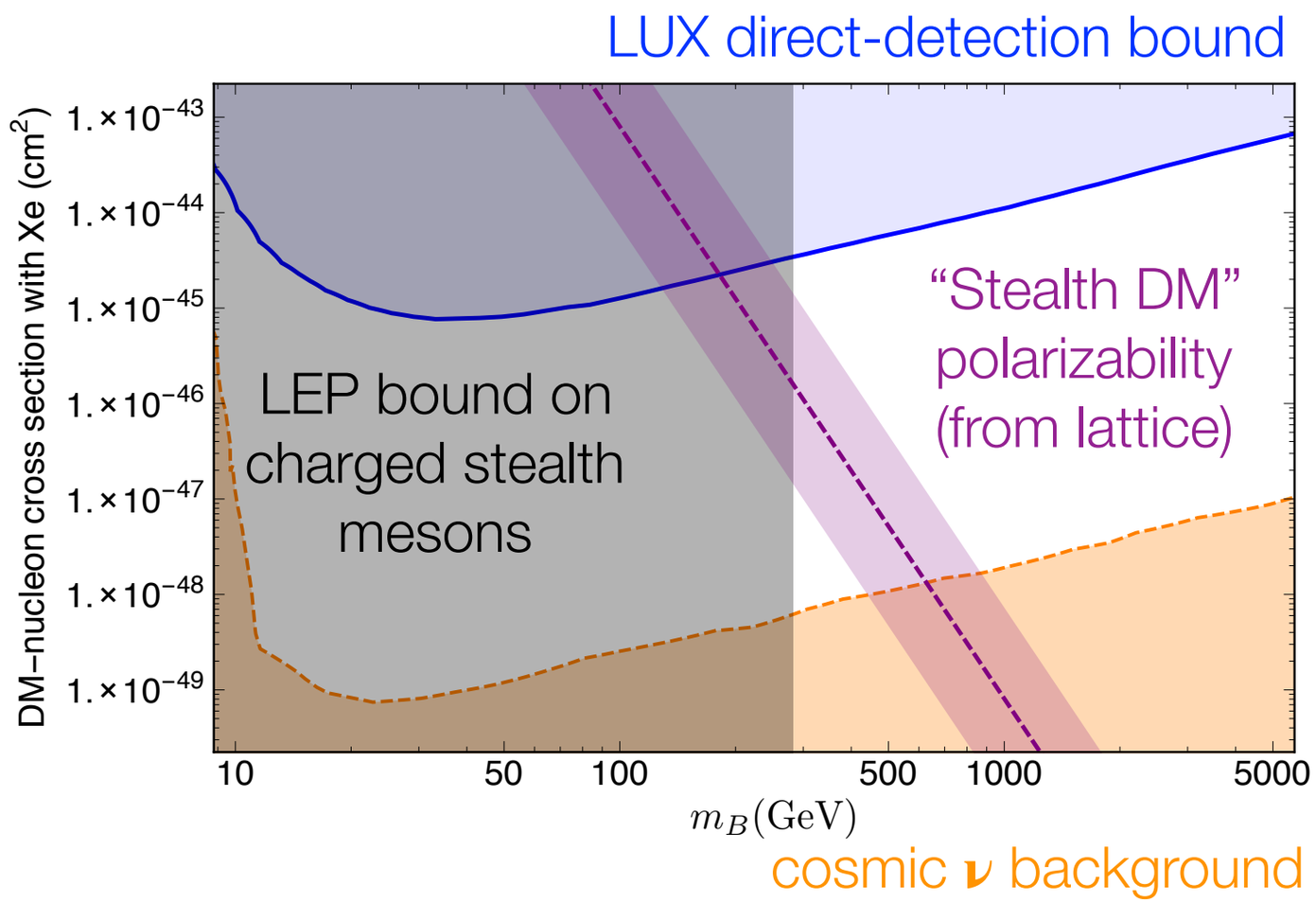
Example: electromagnetic polarizability of "dark baryons"

(LSD Collaboration, arXiv:1503.04205)

- "Stealth DM" model based on SU(4) gauge group, with lightest baryon as dark matter
- Dark quarks carry electric charge, but the baryon is net neutral; symmetry —> leading interaction is EM polarizability - EFT operator

$$\mathcal{O}_F = C_F B^* B \, F^{\mu\alpha} F^{\nu}_{\alpha} v_\mu v_\nu$$

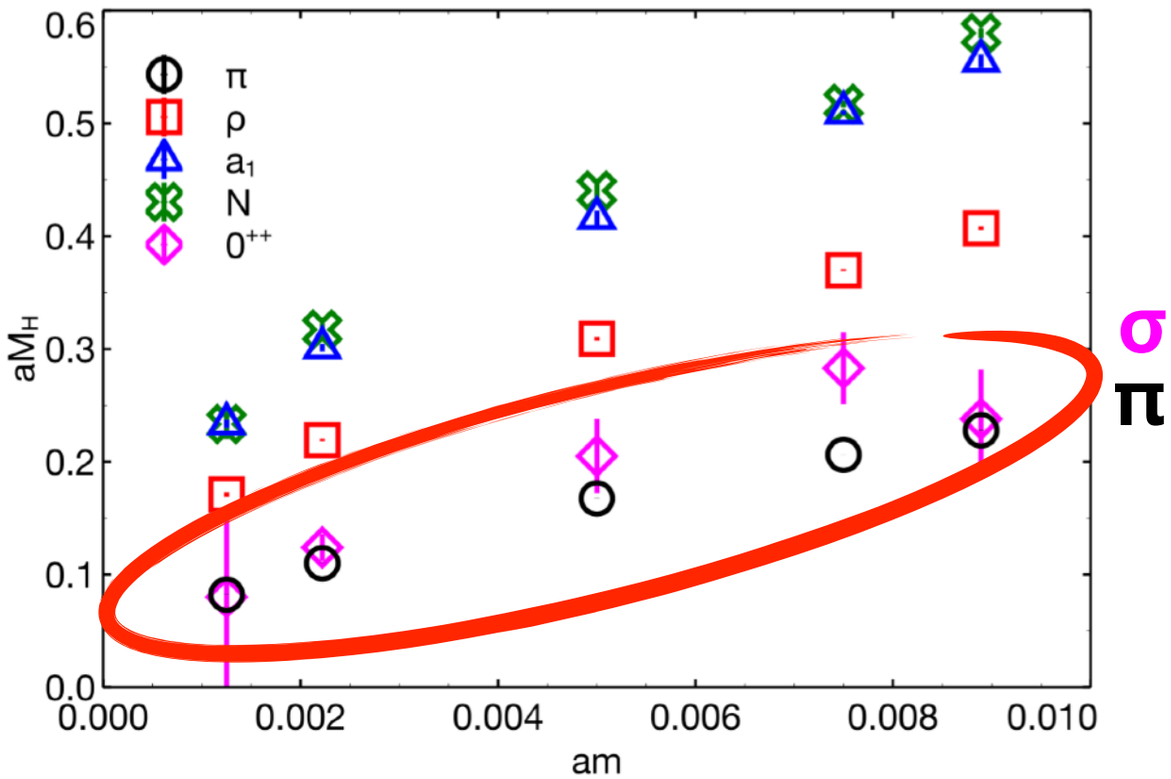
- But EFT doesn't tell us C_F… with four quarks in a baryon, C_F may be *heavily suppressed* if the quarks pair up into dipoles due to Fermi statistics.



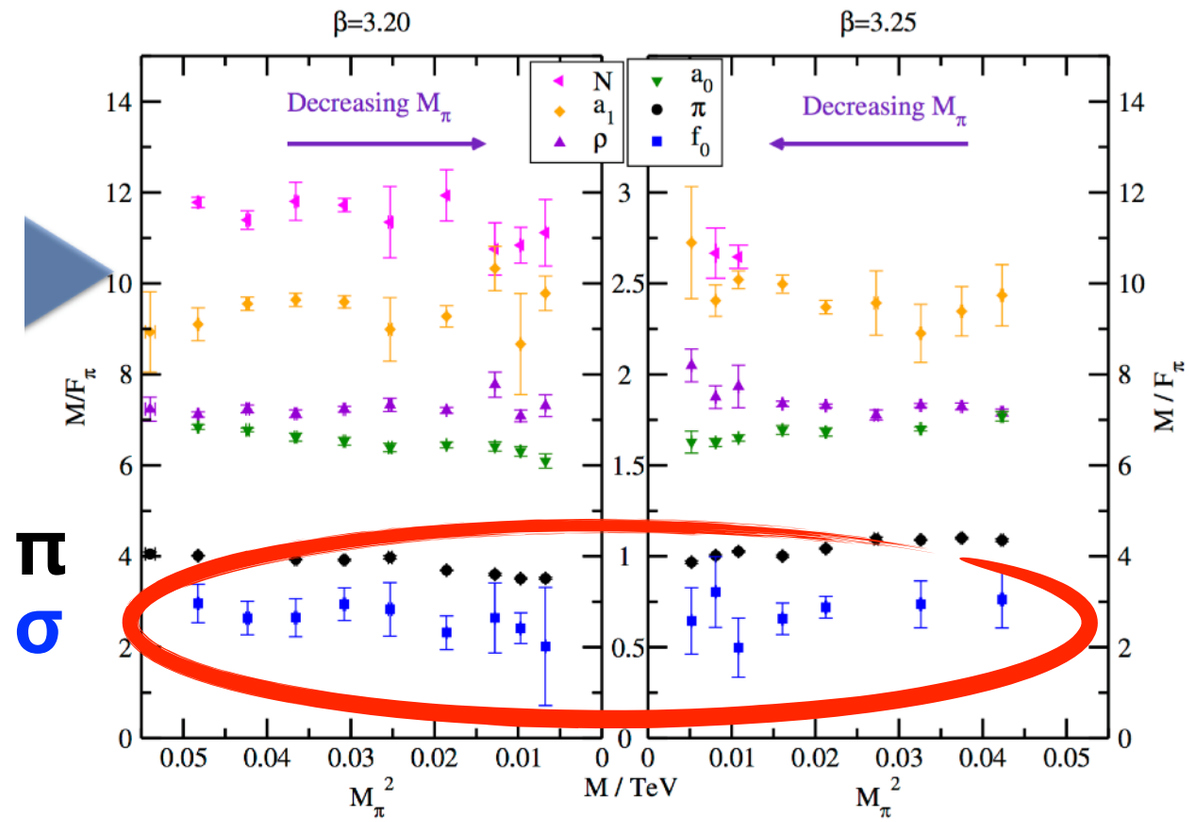
- Lattice calculation reveals <u>no suppression relative to SU(3)</u>; direct detection can probe the stealth model up to ~ TeV scale.

Example: emergence of a light scalar particle

LSD Collaboration, arXiv:1601.04027



LatHC Collaboration, arXiv:1605.08750



- In QCD (and similar theories), pions are the lightest hadronic states by far, due to their pseudo-Goldstone boson nature.
- But lattice studies in multiple theories (left: SU(3) Nf=8, right: SU(3) Nf=2 “sextet” irrep) revealed a surprising **light 0++ scalar state** as light as the pions!
- This state has the <u>same quantum numbers as the Higgs boson</u>, and has been speculated to be a <u>pseudo-dilaton</u> associated with closeness to the IR-conformal transition.

3. Science drivers for lattice BSM

Science drivers: questions for lattice model builders

Concrete science goals which are driving our lattice investigations in the near term, divided by topic area. ***:** new questions added this year.

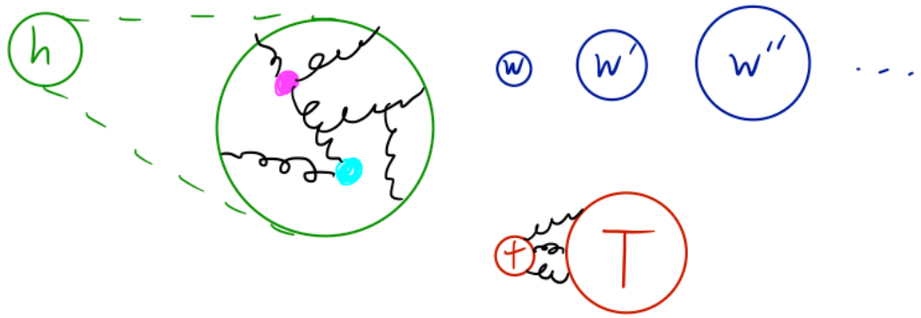
1) Composite Higgs

A. What dynamics yields a Standard Model-like **Higgs light relative to other new resonances** ("little hierarchy")?

B. How large are the non-perturbative matrix elements that determine **Standard Model fermion masses**?

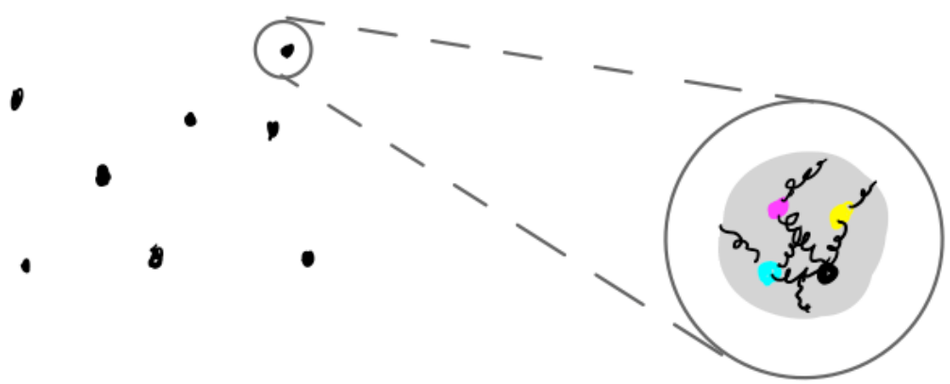
C. What are the **other lowest-energy composite states**? How can the LHC search for them?

D*. How are the **parameters of the low-energy EFT** for composite Higgs related to one another?



Science drivers: questions for lattice model builders

Concrete science goals which are driving our lattice investigations in the near term, divided by topic area. ***:** new questions added this year.



2) Composite dark matter

A. What are the "form factors" of composite dark particles that control their **interactions with SM states**?

B. Under what circumstances can stable "**dark nuclei**" form?

C. What are the properties of the **dark thermal phase transition**? Can it generate observable gravity waves?

D*. How do composite dark matter particles **interact with each another**? What implications are there for cosmology and large-scale structure?

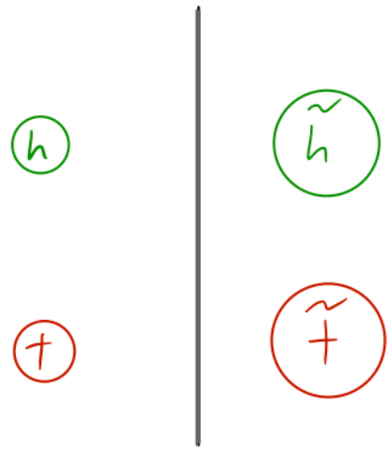
Science drivers: questions for lattice model builders

Concrete science goals which are driving our lattice investigations in the near term, divided by topic area. ***:** new questions added this year.

3) Supersymmetry

A. Can we provide **non-perturbative tests** of phenomena in supersymmetric theories, like the S-duality conjecture?

B. What can we learn about the emergence of **dynamical SUSY breaking** from strongly-coupled supersymmetric theories?



4*) Conformal field theories

A*. What is the **spectrum of anomalous dimensions** in strongly-coupled CFTs that emerge from many-flavor gauge theory?

B*. What is the order and location of the **infrared-conformal phase transition** in many-fermion gauge theories?

C*. Are there **dualities or other theoretical descriptions** that can be used to understand strongly-coupled interacting CFTs?

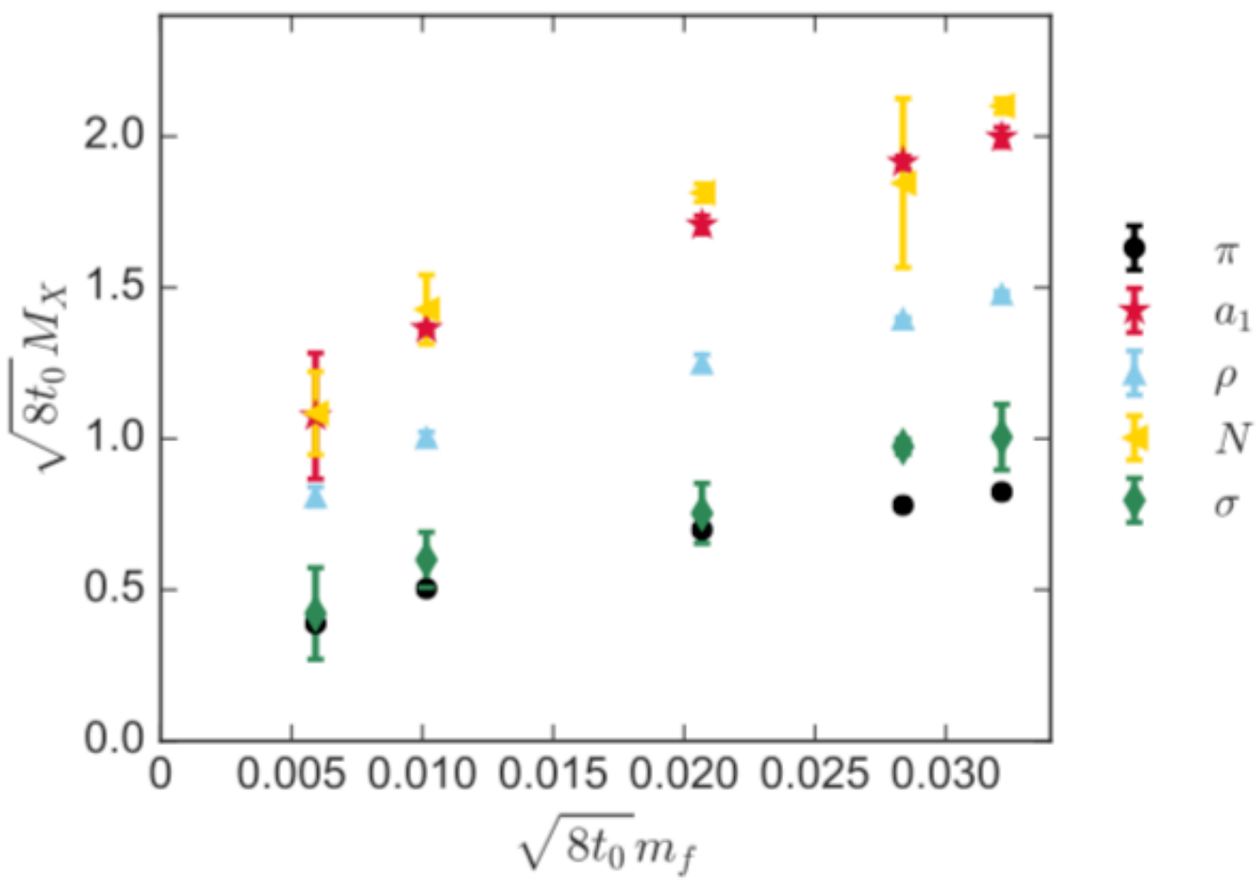
4. USQCD Science Highlights

(all science results are from USQCD, unless noted otherwise. Not an exhaustive list, just a sample.)

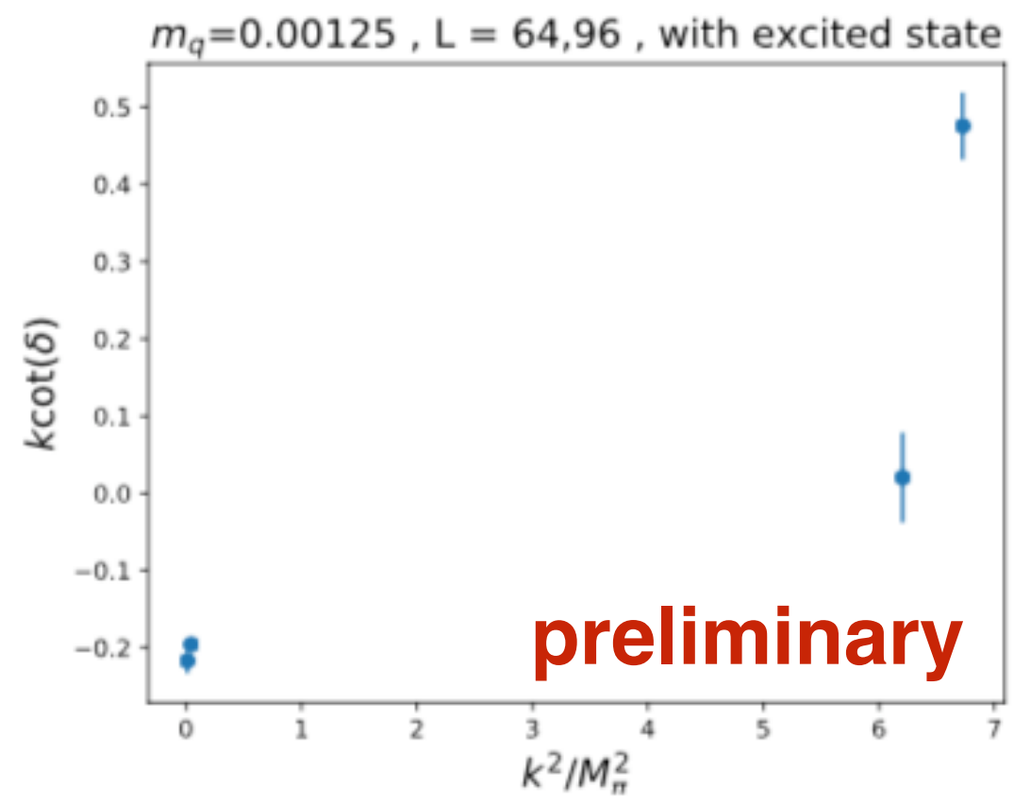
Light scalar resonance

(Composite Higgs, drivers 1A, 1C, 1D)

T. Appelquist et al (**LSD collab**), arXiv:1807.08411



George Fleming (**LSD collab**), Lattice 2019



(above: **I=2 π-π scattering** phase shift)

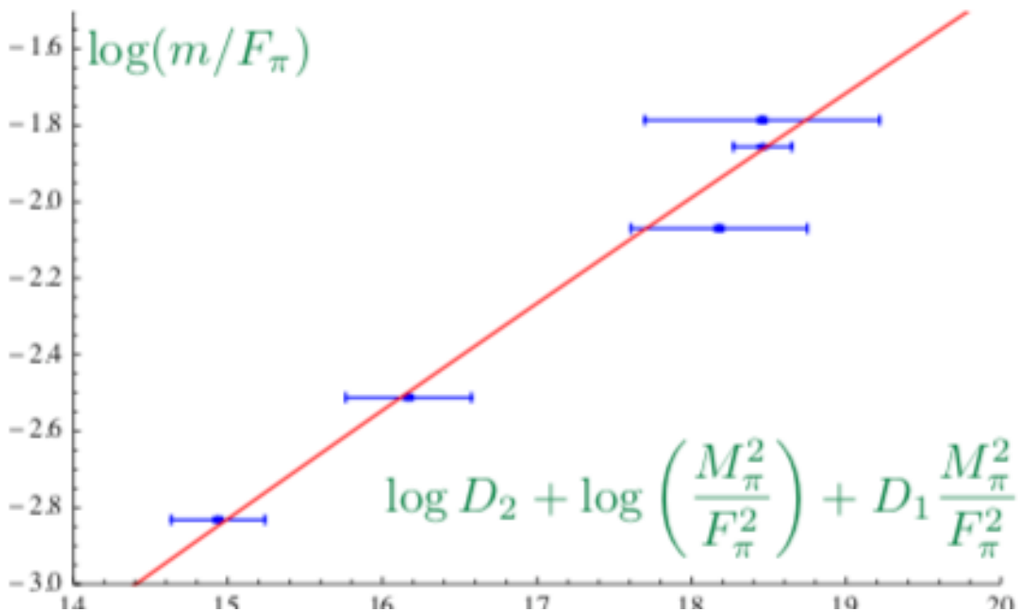
- Updated lattice results confirm the presence of a light 0++ scalar in certain theories, improve precision of spectrum (left)
- Progress is beginning on calculation of other quantities, such as scattering phase shifts (right), in order to probe low-energy EFT

Light scalar EFT?

(Composite Higgs, drivers 1A, 1C, 1D)

Maarten Golterman, Lattice 2019

(not USQCD, but fitting USQCD lattice data)

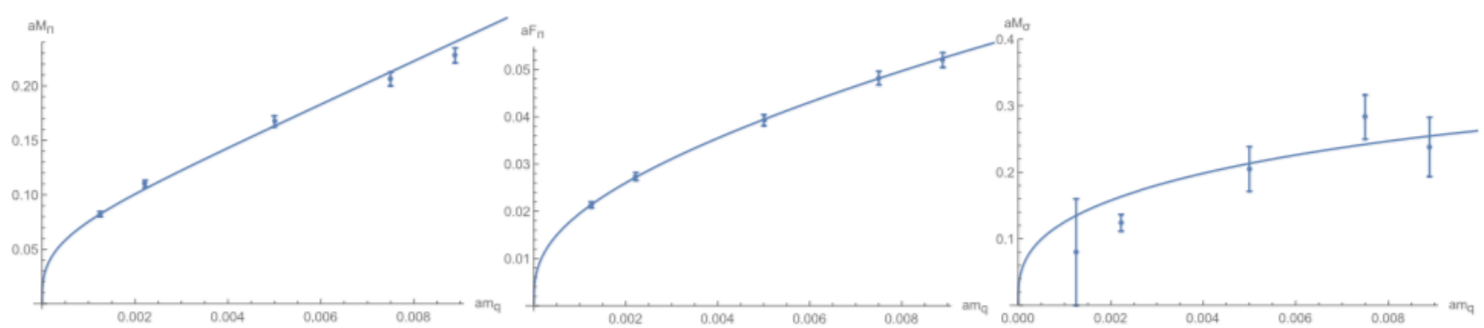


Left: "**dilaton EFT**" (Golterman and Shamir, arXiv:1603.04575) light scalar is associated with breaking of approx. scale invariance near the infrared-conformal phase transition.

Below: "**generalized linear sigma model**", (LSD collaboration, arXiv:1809.02624) scalars are added to chiral effective theory, but no association with scale symmetry

Preliminary

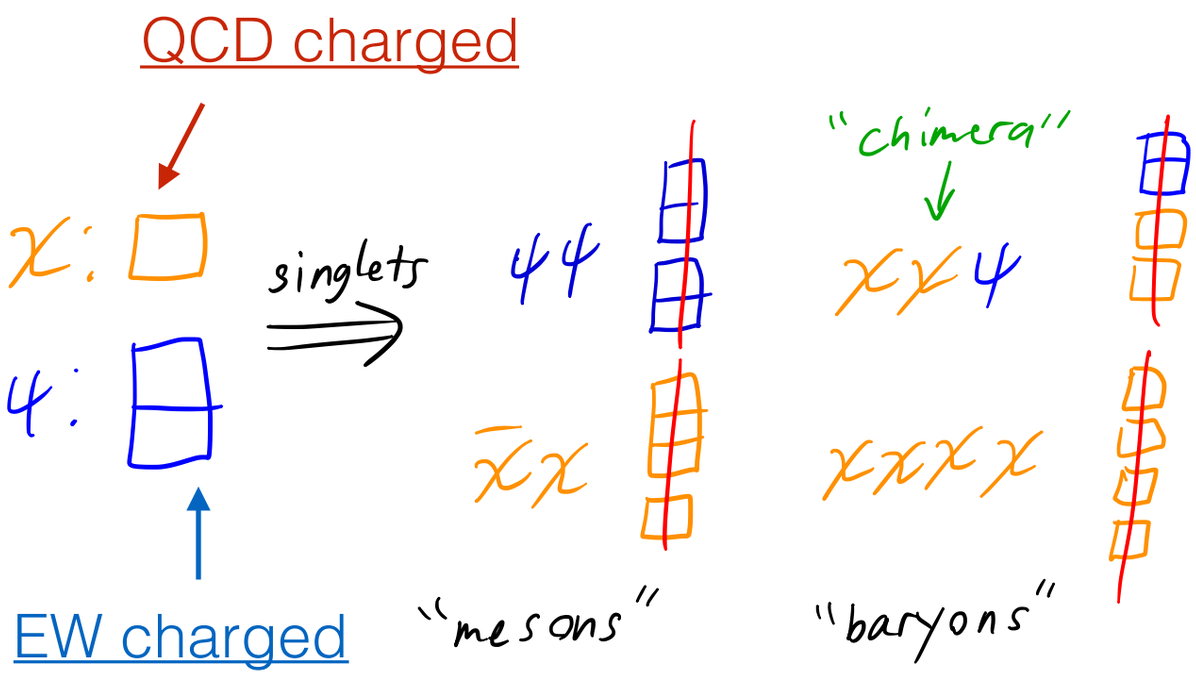
Lattice units
χ^2/dof=1.30



George Fleming (**LSD collab**), Lattice 2019

- Substantial ongoing work on developing EFT descriptions that accommodate a light 0++, and fitting them to lattice data. More work on both ends will be needed to reach firm conclusions.

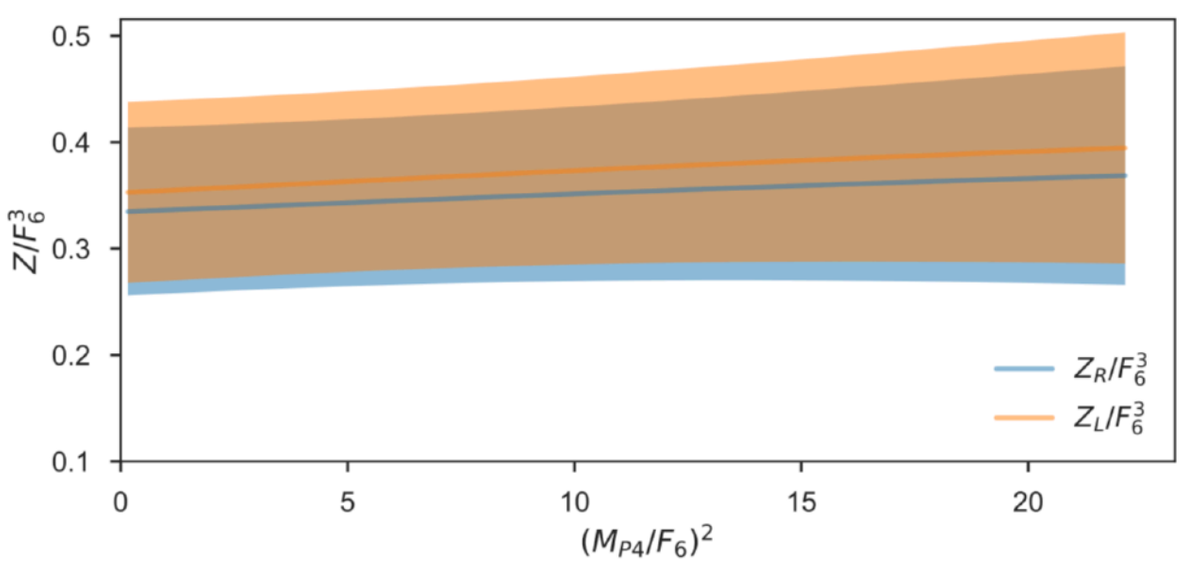
SU(4) composite Higgs



- UV-complete composite Higgs model (G. Ferretti), based on SU(4) gauge group with fermions in two irreps
- New work on "chimera" baryon Z-factor, which determines top Yukawa coupling:

$$y_t \sim \left(\frac{g_{\rm EHC} F_6}{\Lambda_{\rm EHC}}\right)^4 \left(\frac{Z}{F_6^3}\right)^2 \frac{F_6}{M_B}$$

(Tel Aviv-Colorado collaboration, 1812.02727)



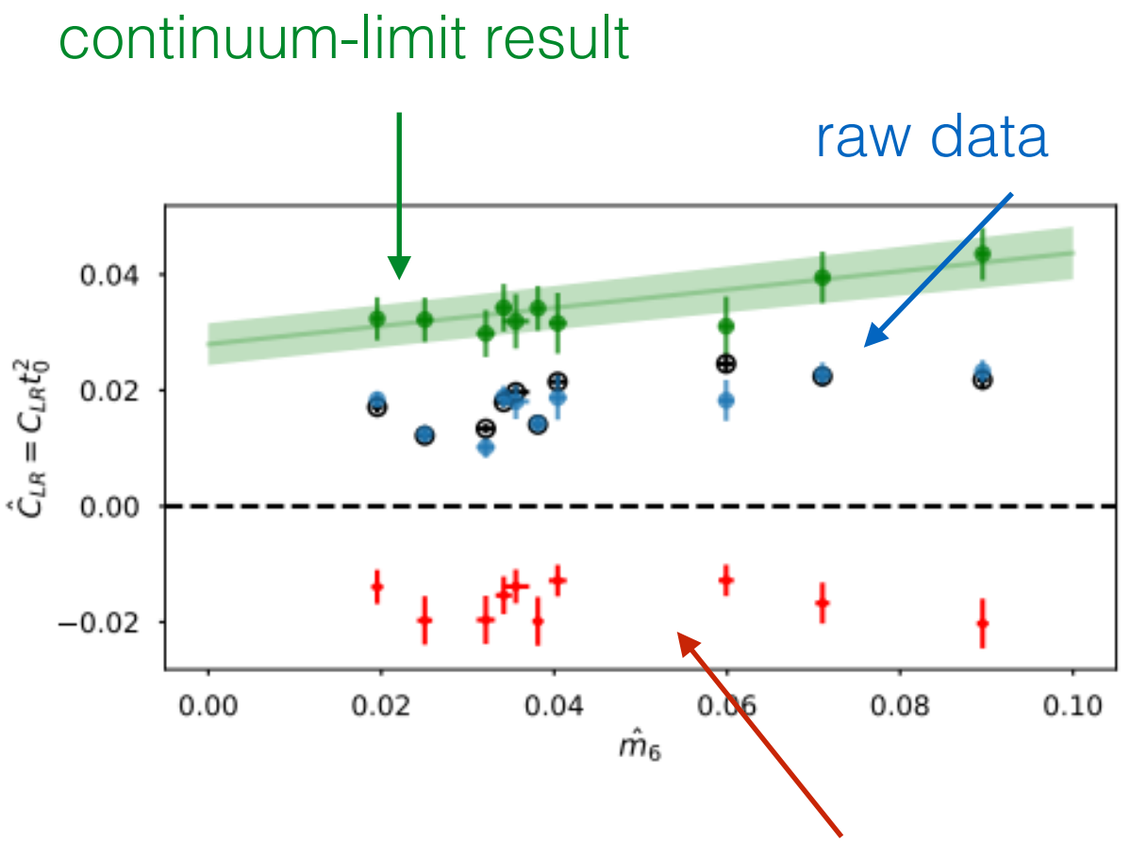
- Small size of Z/F_6^3 implies **inconsistency**: "extended hypercolor" (EHC) coupling $g_{\rm EHC}$ must be so strong that it would alter the strong dynamics.

Higgs potential from the lattice

- In composite Higgs models, can calculate Higgs potential from theory parameters + strong dynamics:

$$\hat{V}(\hat{h}) = \alpha\cos(2\hat{h}) - \beta\sin^2(2\hat{h})$$

$$\alpha = \frac{1}{2}\hat{F}_{\rm LL} - \hat{c}_{\rm LR} \qquad \beta = \frac{1}{2}\hat{F}_{\rm EW} - \frac{1}{4}\hat{F}_{\rm LL}$$



- Experiment constrains Higgs potential α,β. Calculation of strong-dynamics contribution lets us quantify fine-tuning in this model.

- Construct C_{LR} (left-right vacuum polarization) as an integrated current-current correlator:

$$C_{LR} = 16\pi^2 \int \frac{d^4q}{(2\pi)^4}\Pi_{LR}(q_\mu).$$

$$\hat{c}_{LR} = \frac{1}{2}(3g^2 + g'^2)(C_{LR}/f_6^4)$$
$$= 19(5)(3)$$

- **Much larger than physically allowed value** of α~-0.01; indicates significant fine-tuning to reproduce observed Higgs properties, although no lattice calculation of other LEC F_{LL} (very challenging four-point correlator.)

Gravitational wave signal from first-order phase transition provides intriguing way to search for composite DM!

From first-order transition to gravitational wave signal

First-order transition $\longrightarrow$ gravitational wave background will be produced

How do we predict its features?

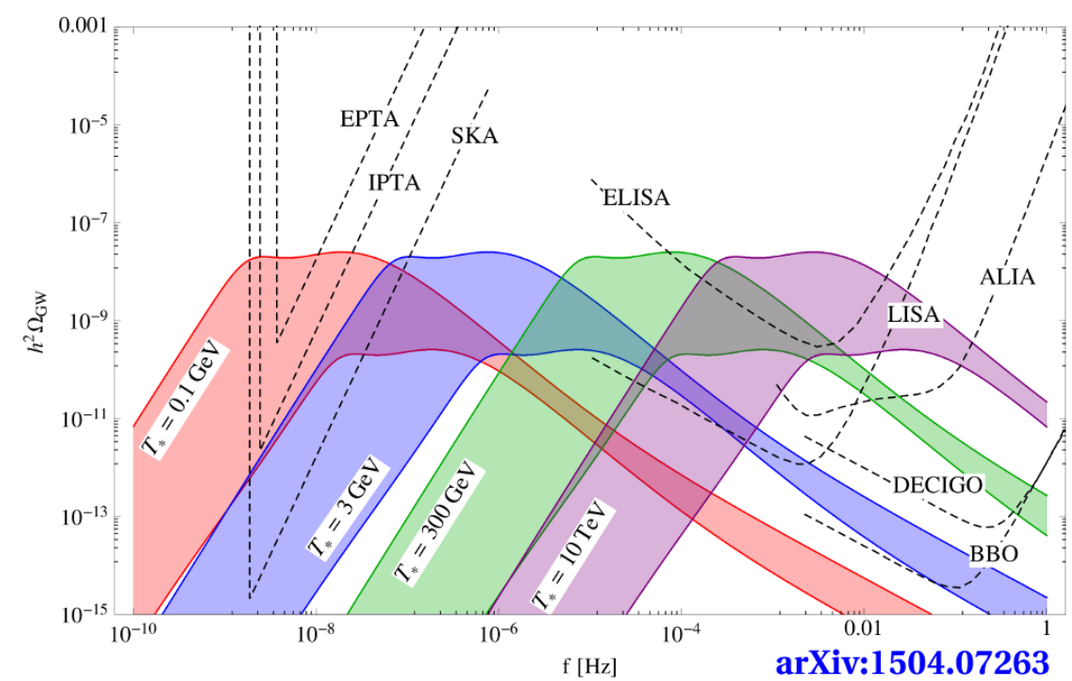
Four key parameters

Transition temperature $T_* \lesssim T_c$

Vacuum energy fraction from **latent heat**

Bubble nucleation rate (transition duration)

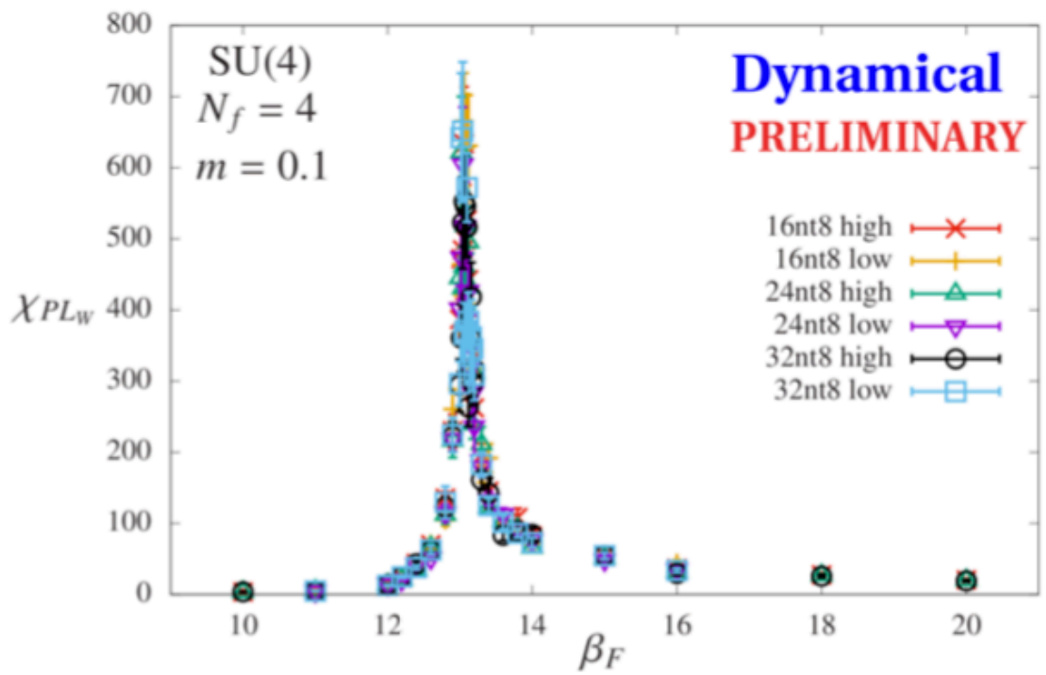
Bubble wall speed

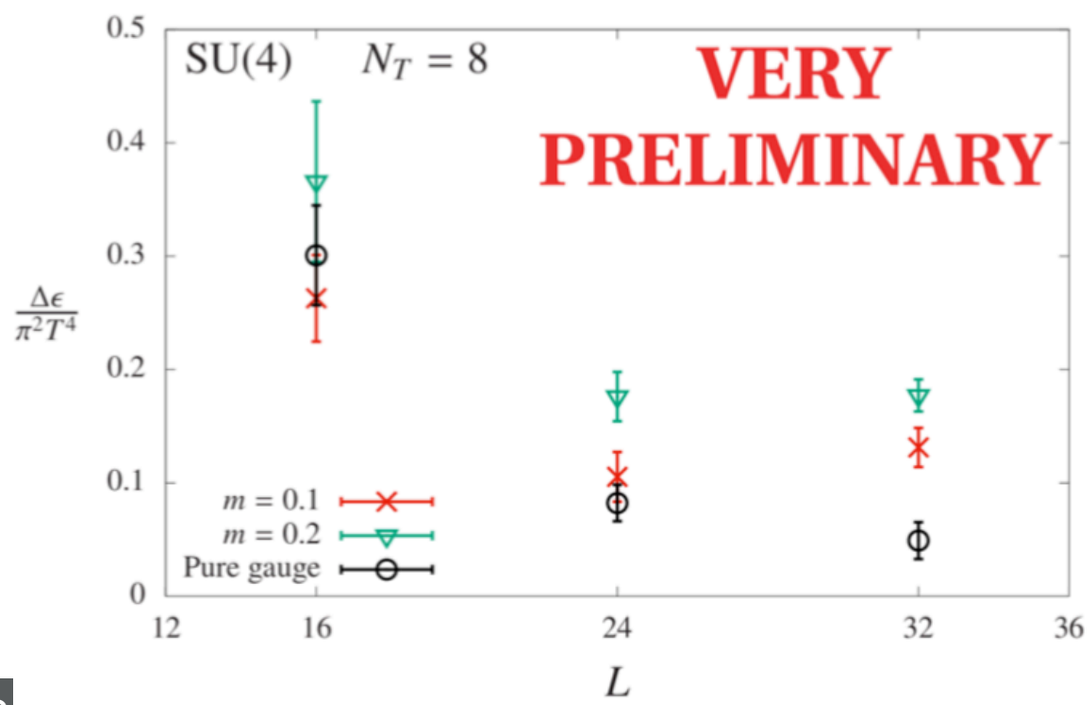


(slide from David Schaich; plot from Pedro Schwaller)

Thermal phase transitions and dark cosmology

David Schaich (**LSD collab)**, Lattice 2019



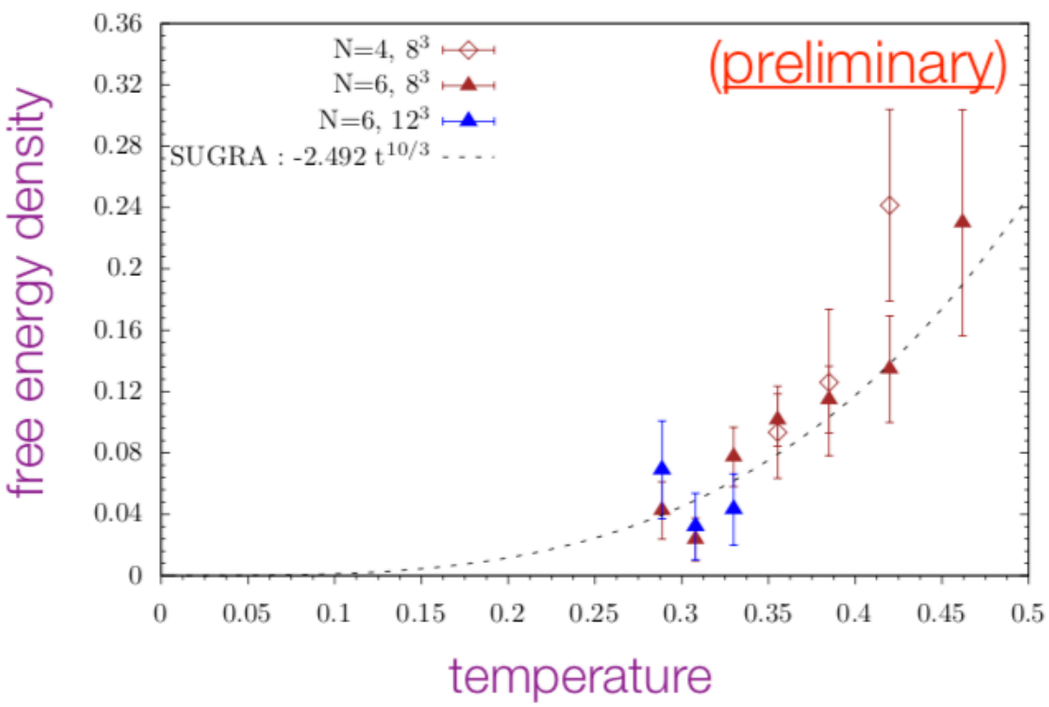


- Only theories with a first-order thermal phase transition can give stochastic gravity waves
- Investigate phase transition in “stealth DM” theory: SU(4), four flavors. Preliminary results indicate strong first-order transition!
- Starting to calculate quantities relevant for GW spectrum from lattice. <u>Left: latent heat</u> of transition ΔE.

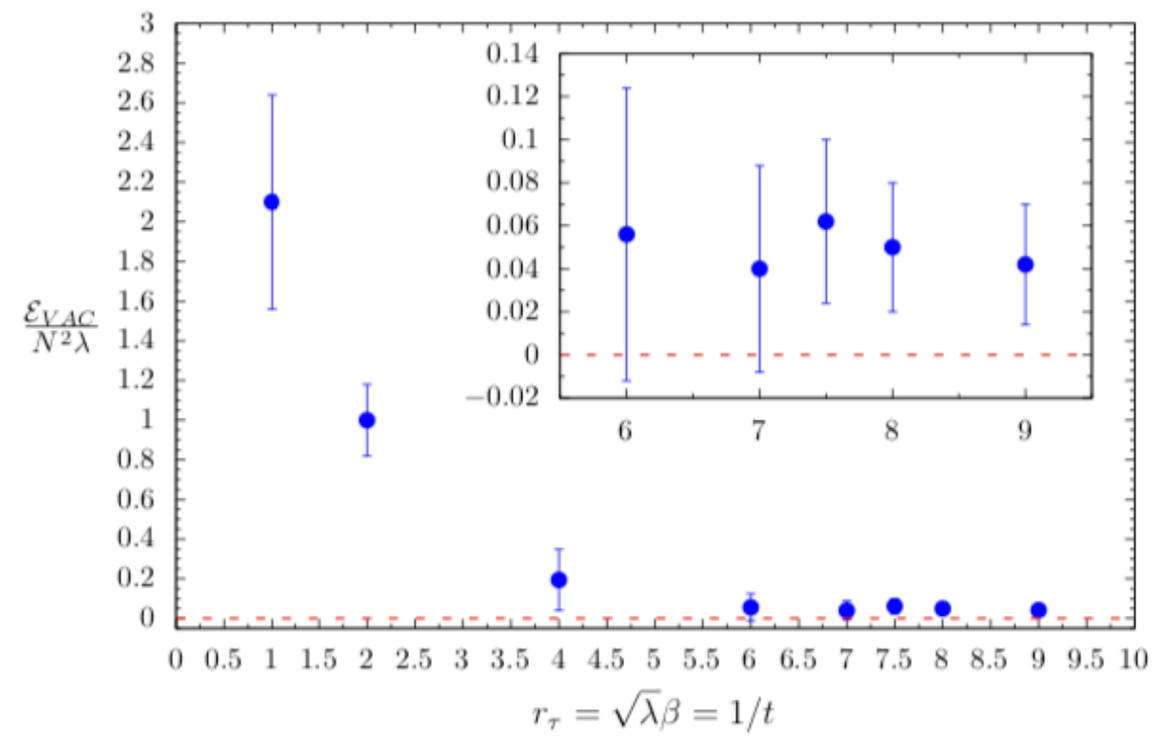
Supersymmetry on the lattice

(SUSY, drivers 3A and 3B)

Raghav Jha, Lattice for BSM Physics 2018 workshop



Catterall, Jha, and Joseph, arXiv:1801.00012



- Ongoing progress on simulating supersymmetric theories; difficult to preserve SUSY on the lattice, most work so far is in lower-dimensional systems which are more numerically tractable.
- Left: non-perturbative simulation of maximally supersymmetric super-Yang-Mills in d=3. Numerical results confirm prediction from *gauge-gravity duality* (dashed line). Higher precision can eventually reveal string corrections!
- Right: test of dynamical supersymmetry breaking in two-dimensional N=(2,2) SYM. Continuum extrapolation reveals vacuum energy density consistent with zero —> no spontaneous SUSY breaking in this model.

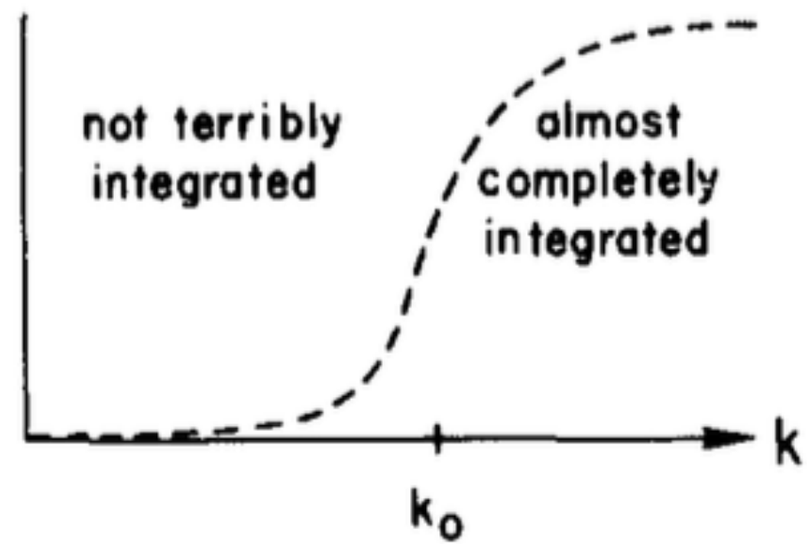
Operator anomalous dimensions with gradient flow

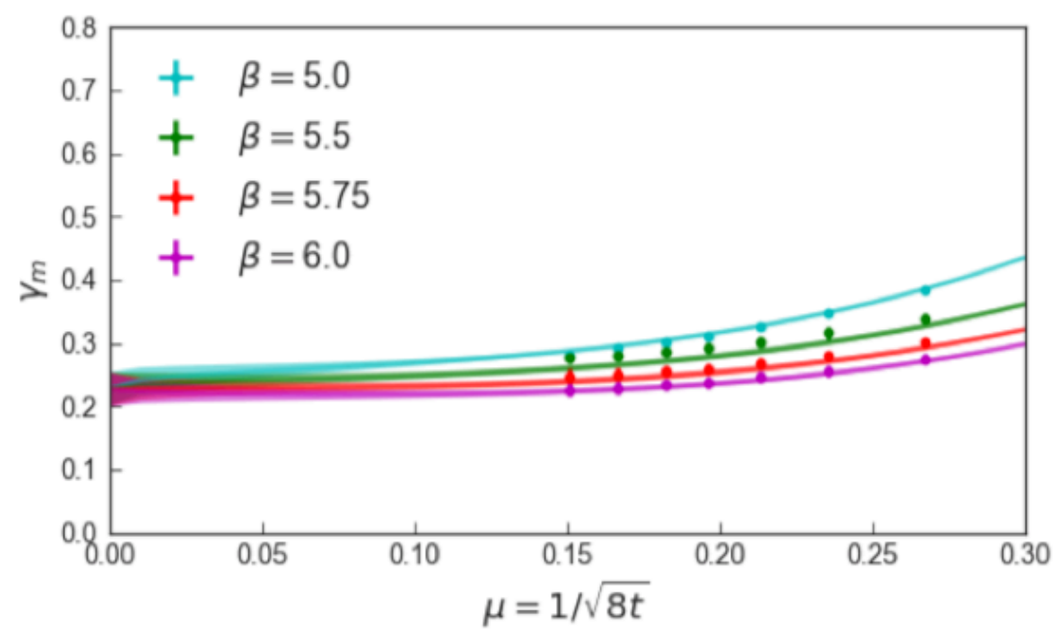
- To measure operator anomalous dimensions (spectrum of CFT), take "renormalization group" steps: integrate out high-momentum modes ("block") + rescale.

- Gradient flow cuts off high-momentum modes in a continuous way; smooth lattice cutoff allows *continuous RG* on a single gauge ensemble!

- Pilot study for N_f=12 finds mass γ consistent with perturbative estimates and other lattice, first result for nucleon γ_N~0.05(5)

(excerpted from J. Kogut and K. G. Wilson, Phys. Rept. 12 (1974), 75-200)

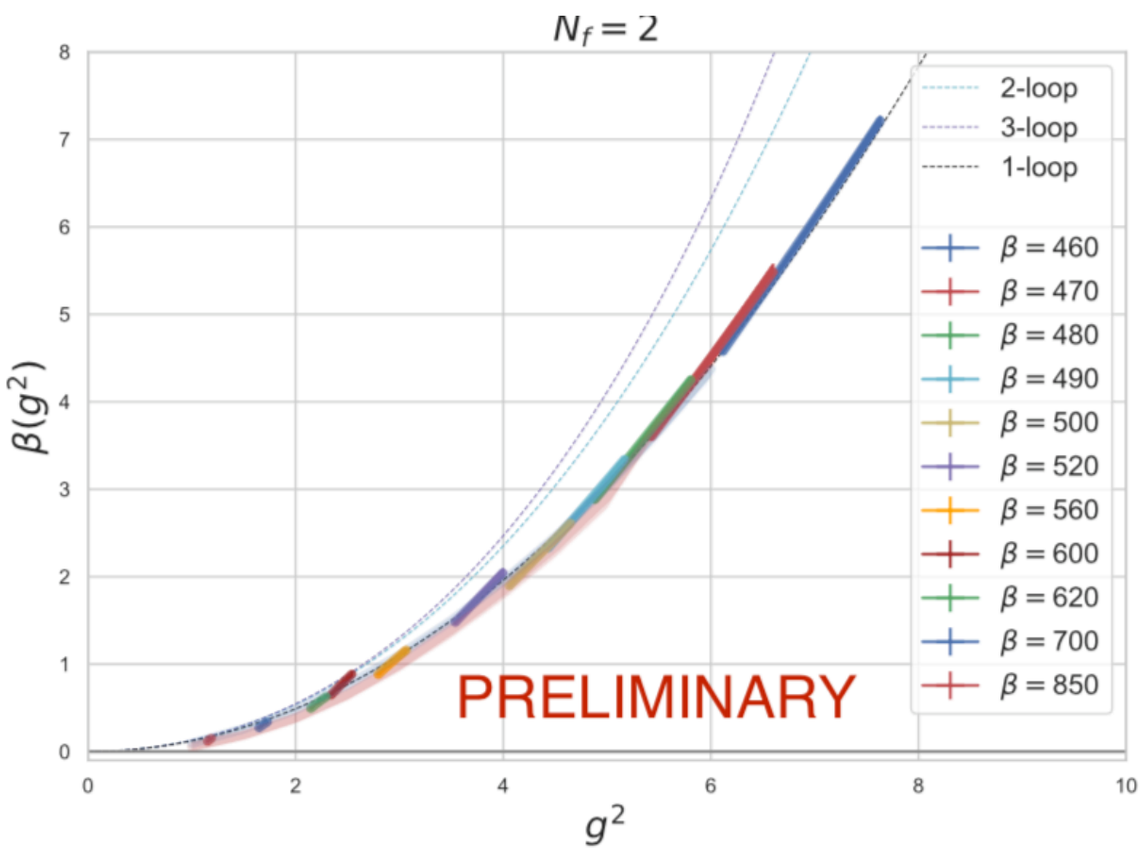


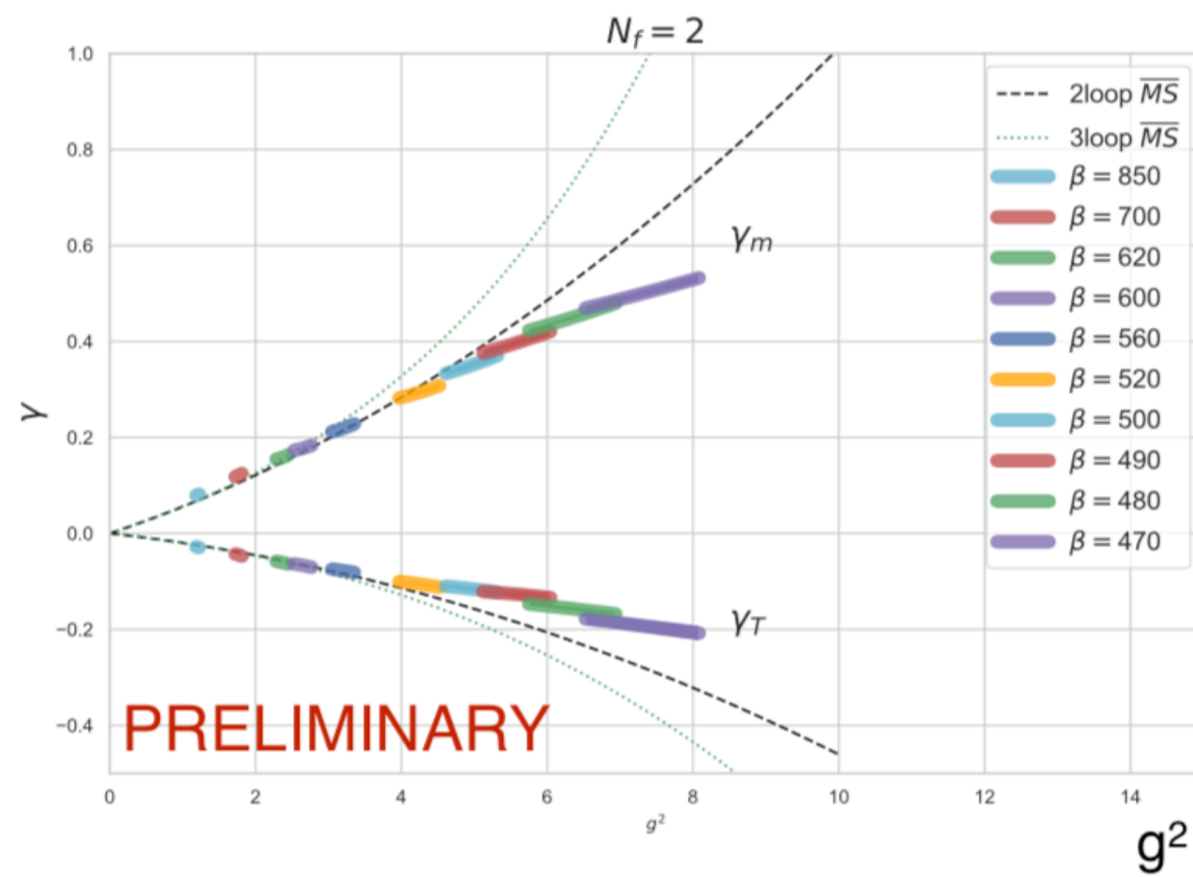


(Carosso, Hasenfratz, Neil,1806.01385)

Continuous beta-functions with gradient flow

Anna Hasenfratz and Oliver Witzel, Lattice 2019





- New work by Anna Hasenfratz and Oliver Witzel on extending the gradient flow/renormalization group formalism to compute continuous beta functions (left) and running anomalous dimensions (right)

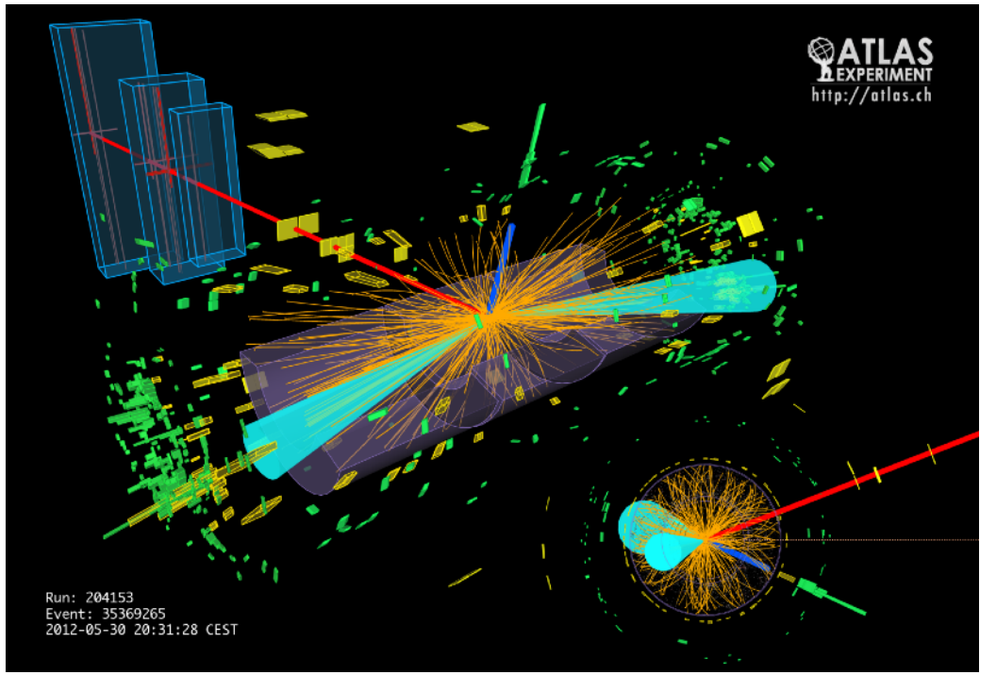
- Interesting cutting-edge technique for studying conformal phase transition. Might also be useful in lattice QCD for renormalization?

5. Conclusion

Computing resources and scientific output

(Fermilab USQCD cluster)

(ATLAS Higgs—>ττ candidate)



- Since Jan. 2018, **22** papers published or posted to arXiv from USQCD lattice BSM program, **12** journal publications (not proceedings). (List in backup slides.)

- Substantial scientific output for small proportion (~5-10%) of resources! Reasonable investment for future-looking, curiosity-driven research that stress-tests lattice machinery.

Lattice BSM in the pheno literature: (a small sample)

(gravity waves)

PRL 115, 181101 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Gravitational Waves from a Dark Phase Transition

Pedro Schwaller
CERN, Theory Division, CH-1211 Geneva 23, Switzerland
(Received 1 June 2015; revised manuscript received 2 September 2015; published 26 October 2015)

A shortcoming of the present work is a lack of precise quantitative predictions. The bubble velocity v as well as the time scale of the phase transition β^{-1} and the energy fraction Ω_{S*} are currently unknown, and are set to optimistic (but not unrealistic) values. Two approaches seem possible to improve upon this situation: On one side, lattice simulations could be used to measure quantities like the latent heat and the surface tension, which are related to the above parameters and can be used to obtain a more quantitative prediction for the GW spectra. Alternatively, one could attempt to construct a holographic dual for some of these theories, and analyse the PT in that setup.

(astrophysics)

Astrophysical Signatures of Asymmetric Dark Matter Bound States

Moira I. Gresham,[1] Hou Keong Lou,[2,3] and Kathryn M. Zurek[2,3,4]
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[3] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720*
[4] *Theoretical Physics Department, CERN, Geneva, Switzerland*

To definitively answer the question of the small-N structure of bottlenecks requires detailed numerical calculations (see e.g. [51–56]), though given how close the $A = 5$ and $A = 8$ nuclei in the SM totter towards stability, it is not hard to imagine that a dark sector with a different structure could provide for the absence of low-N bottlenecks.

(collider searches)

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Di-boson signatures as standard candles for partial compositeness

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there is no underlying reason why $f_\chi = f_\psi$. The decay constants in the two sectors can, in principle, be different. We checked that, varying this ratio, our numerical result do not change qualitatively but there are $\mathcal{O}(1)$ changes in the numerical values of the bound on f_ψ, due to the change in the couplings. This ambiguity can, however, be fixed if the models under study is studied on the Lattice: in this case, the ratios between the various decay

(flavor physics)

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***B* decay anomalies and dark matter from vectorlike confinement**

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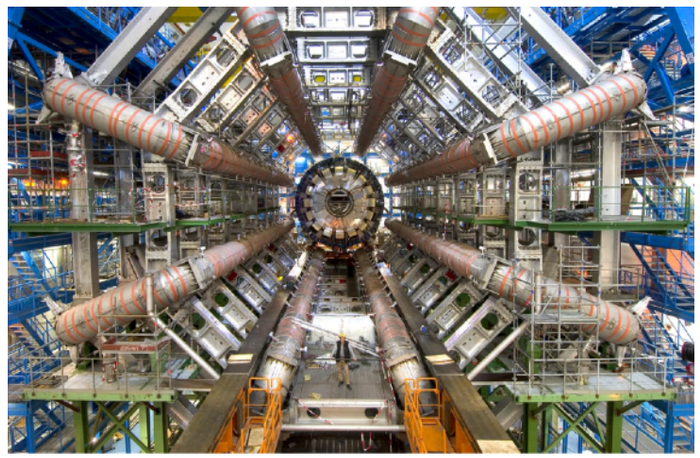
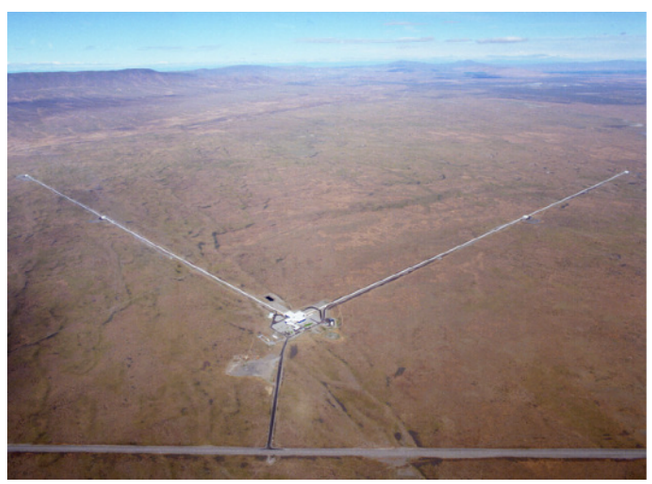
cannot be produced at LHC). For $N_{HC} = 3$, the potential model predicts that the kinetic energy of the constituent is 0.3 of its mass energy, so the nonrelativistic approximation is not very bad. Ultimately, lattice calculations should be done to make more quantitative predictions.

Conclusion





- Experiments are running with unprecedented energy and precision; now is the time to develop tools for BSM theory!
- Lattice can handle strong coupling, which appears in many interesting BSM models; studies can give general insight into strongly-coupled QFT.
- Small proportion of USQCD resources go to lattice BSM, but this is big relative to university resources - USQCD support is crucial!

Backup/info slides

http://www-hep.colorado.edu/~eneil/lbsm19/

- Tenth workshop in a series, connecting lattice BSM community to phenomenologists and other non-lattice theorists.

- Significant focus on connections between *lattice simulations and quantum computing* this time, as well as various BSM models.

Organizing Committee:

- Simon Catterall (Syracuse)
- Jay Hubisz (Syracuse)
- Jack Laiho (Syracuse)
- Ethan Neil (Colorado)
- Judah Unmuth-Yockey (Syracuse)
- Pavlos Vranas (LLNL)
- Scott Watson (Syracuse)

USQCD Lattice BSM papers/preprints since Jan 2018:

Proceedings:

1809.00073
1809.03473
1810.01850
1810.05176
1811.05024
1811.01015
1811.03182
1812.03972
1901.06324

Preprints:

1905.13061

Journal Pubs:

1801.00012 (Phys. Rev. D)
1801.05809 (Phys. Rev. D)
1802.09644 (Phys. Rev. D)
1806.01385 (Phys. Rev. Lett.)
1807.08411 (Phys. Rev. D)
1808.04735 (Phys. Rev. D)
1810.00853 (Phys. Rev. D)
1810.06117 (Phys. Rev. D)
1810.10626 (Phys. Rev. D)
1812.02727 (Phys. Rev. D)
1901.11443 (Phys. Rev. D)
1903.02535 (Phys. Rev. D)

Comparison w/international efforts

Lattice BSM is very international! Many leading collaborations are centered at institutions in different areas: Lattice Higgs Collaboration (U.S./Europe), Tel Aviv/Colorado, Canada/Denmark…(counting only faculty members, many collaborations have postdocs in other regions.)

Overall, size of lattice efforts in USA vs. Europe is comparable. In Japan, support for the largest collaboration (LatKMI) through the Kobayashi-Maskawa Institute has ended, so productivity has slowed somewhat

Of top 200 most-cited hep-lat papers since 2014, lattice BSM represents:

- **1** from Japan
- **4** from Europe/UK
  (*2 joint w/U.S., 1 joint w/Canada*)
- **4** from U.S.
  (2 *joint w/Europe*)

Lattice BSM in top 200 hep-lat, since 2014:

39. **Light composite scalar in eight-flavor QCD on the lattice**
(99) LatKMI Collaboration (Yasumichi Aoki (KMI, Nagoya) *et al.*). Mar 19, 2014. 5 pp.
Published in **Phys.Rev. D89 (2014) 111502**
KEK-PREPRINT-2013-68, LLNL-JRNL-651959
DOI: 10.1103/PhysRevD.89.111502
e-Print: **arXiv:1403.5000 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 99 records 50+

62. **Fundamental Composite Higgs Dynamics on the Lattice: SU(2) with Two Flavors**
(77) Ari Hietanen (Southern Denmark U., CP3-Origins & U. Southern Denmark, Odense, DIAS), Randy Lewis (York U., Canada), Claudio Pica, Francesco Sannino
Published in **JHEP 1407 (2014) 116**
CP3-ORIGINS-2014-012, DIAS-2014-12
DOI: 10.1007/JHEP07(2014)116
e-Print: **arXiv:1404.2794 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 77 records 50+

70. **The conformal window on the lattice**
(75) Luigi Del Debbio (Edinburgh U.). 2010. 23 pp.
Published in **PoS Lattice2010 (2014) 004**
DOI: 10.22323/1.105.0004
Conference: C10-06-14.10, Prepared for Conference: C10-06-14.10 Proceedings
e-Print: **arXiv:1102.4066 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Proceedings of Science Server; Link to Fulltext
Detailed record - Cited by 75 records 50+

81. **Strongly interacting dynamics and the search for new physics at the LHC**
(70) Thomas Appelquist (Yale U.) *et al.*. Jan 15, 2016. 6 pp.
Published in **Phys.Rev. D93 (2016) no.11, 114514**
EDINBURGH-2016-01, LLNL-JRNL-680732, NSF-KITP-16-004
DOI: 10.1103/PhysRevD.93.114514
e-Print: **arXiv:1601.04027 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 70 records 50+

Lattice BSM in top 200 hep-lat, since 2014:

151. **Can a light Higgs impostor hide in composite gauge models?**
(52) Zoltan Fodor (Wuppertal U.), Kieran Holland (U. Pacific, Stockton & U. Bern, AEC), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U.), Chik Him Wong (UC, San Diego). Jan 9, 2014. 7 pp.
Published in **PoS LATTICE2013 (2014) 062**
DOI: 10.22323/1.187.0062
Conference: C13-07-29.1 Proceedings
e-Print: **arXiv:1401.2176 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Proceedings of Science Server
Detailed record - Cited by 52 records 50+

156. **Improving the continuum limit of gradient flow step scaling**
(51) Anqi Cheng, Anna Hasenfratz, Yuzhi Liu, Gregory Petropoulos (Colorado U.), David Schaich (Colorado U. & Syracuse U.). Apr 3, 2014. 13 pp.
Published in **JHEP 1405 (2014) 137**
DOI: 10.1007/JHEP05(2014)137
e-Print: **arXiv:1404.0984 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 51 records 50+

169. **Dark nuclei. II. Nuclear spectroscopy in two-color QCD**
(48) William Detmold, Matthew McCullough, Andrew Pochinsky (MIT, Cambridge, CTP). Jun 16, 2014. 28 pp.
Published in **Phys.Rev. D90 (2014) no.11, 114506**
MIT-CTP-4555
DOI: 10.1103/PhysRevD.90.114506
e-Print: **arXiv:1406.4116 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 48 records