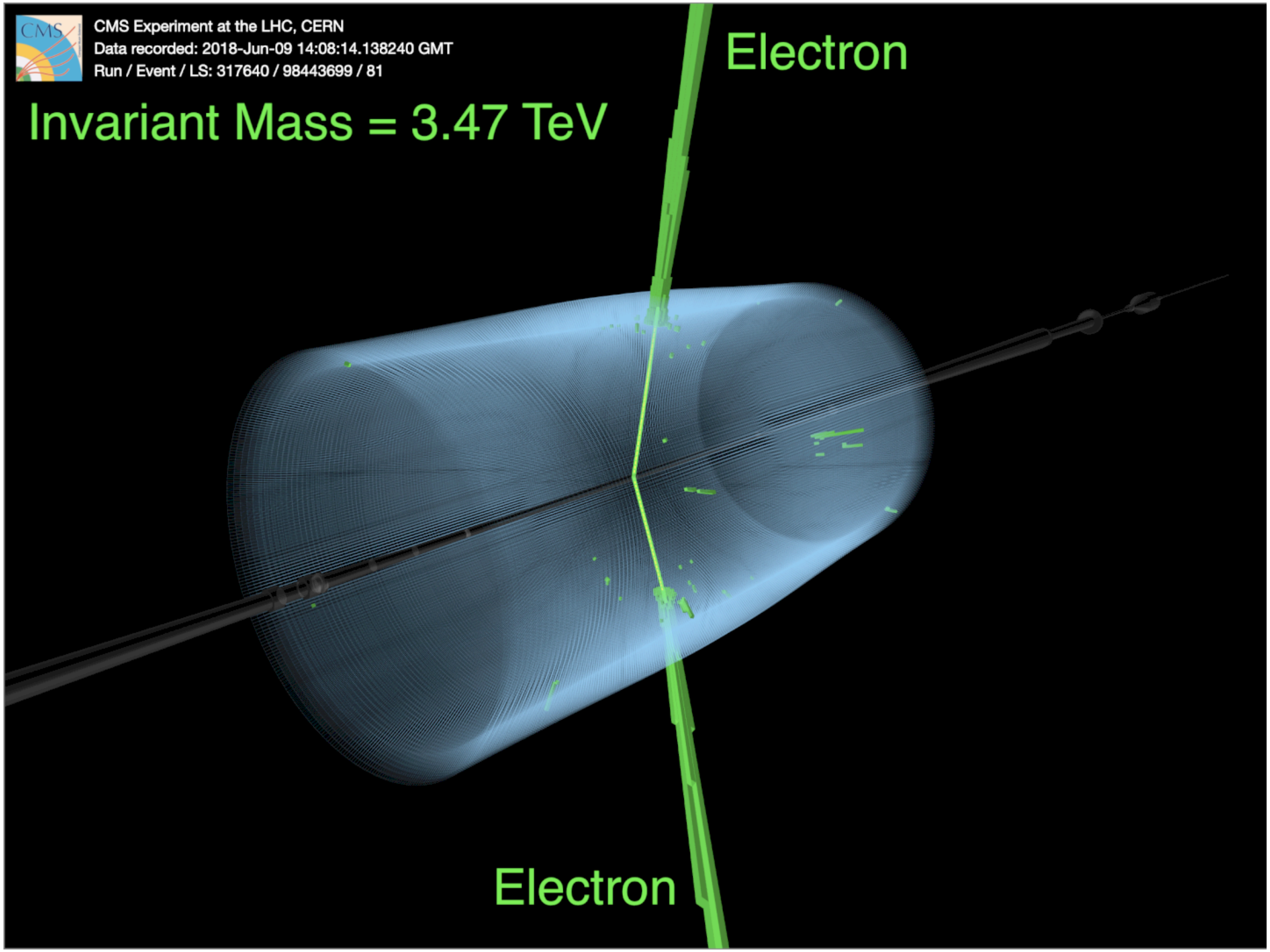
(https://cds.cern.ch/record/2758962)



Lattice for BSM exploration

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Motivation

- There are many motivations for studying models of *new physics Beyond the Standard Model* (**BSM**). Dark matter, neutrino mass, Higgs sector, flavor puzzles…

- Perturbative extensions of the SM are nice for the theorist, but sometimes physics is strongly coupled, e.g. QCD!

- If BSM physics is strongly coupled, lattice can give physics information that is otherwise inaccessible.

Approaches to lattice BSM*

- 1) “**Top-down BSM**”: pick a specific strongly-coupled model, put it on the lattice, calculate things of pheno relevance.

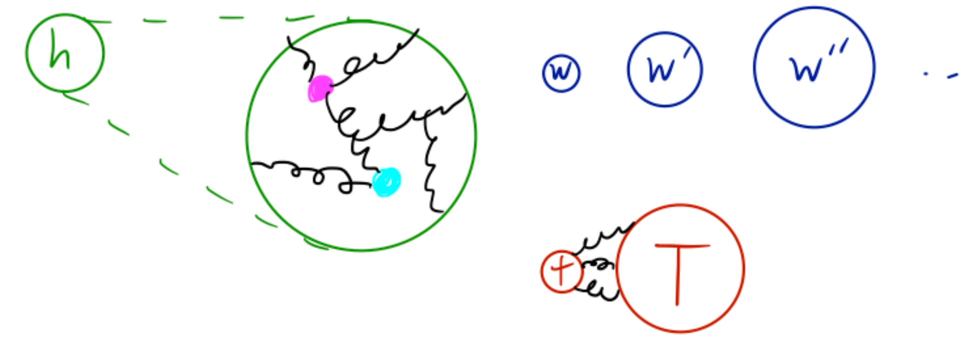
- 2) “**Bottom-up BSM**”: choose a class of theories with common properties or shared description: large-Nc expansion, near-conformal (dilaton EFT), etc. Try to study the broad

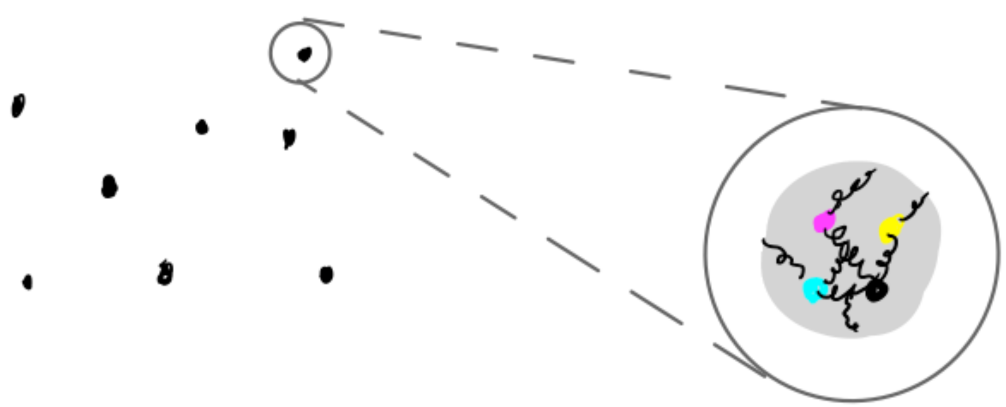
- 3) “**Pure exploration**”: studies of non-perturbative phenomena, strongly-coupled QFT purely for theory interest, with no immediate pheno connection.

*not a unique way to organize; many lattice calculations have motivation/application in more than one area. Never a “waste” even if we rule out a specific theory…

1) (Example) top-down models

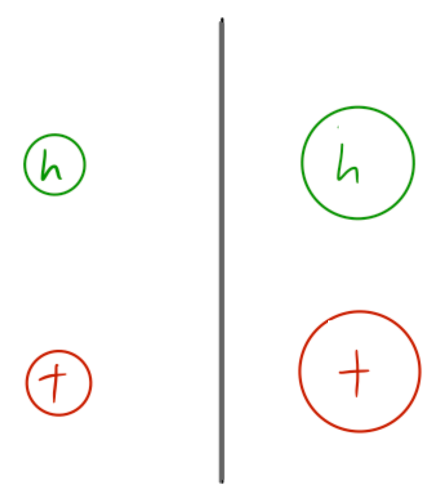
Composite Higgs: new strongly-coupled sector at the electroweak scale; Higgs is a composite bound state. (W/Z, top often have some composite part too.)





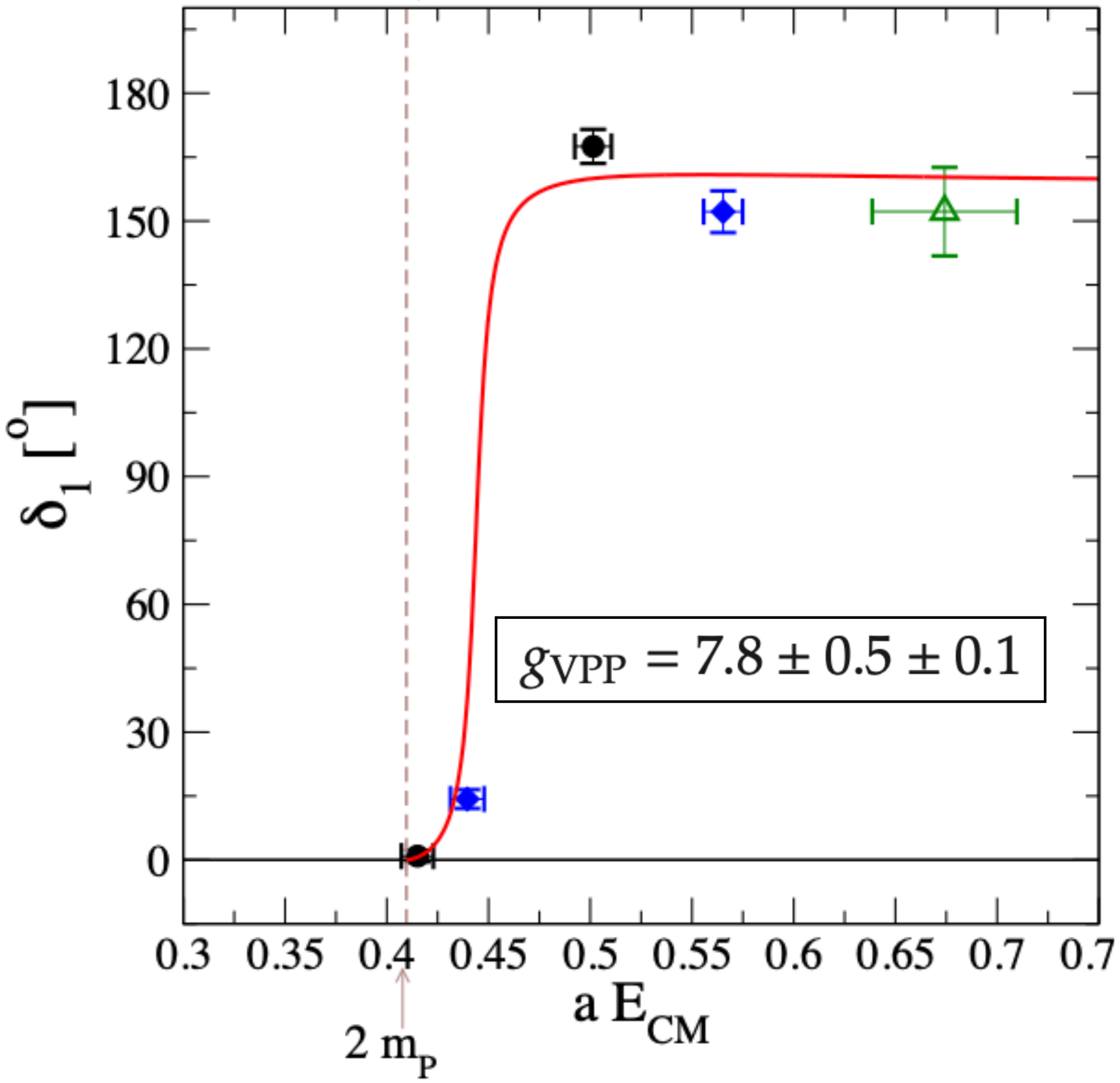
Composite dark matter: dark “hidden sector” which is strongly coupled. Rich spectrum of possible DM candidates: dark baryons, dark mesons (e.g. SIMPs), dark glueballs…

Neutral naturalness: mirror copy of SM components in hidden sector. Rich structure for e.g. dark matter. Lattice SU(3) results (particularly w/ heavy quarks) can be relevant.

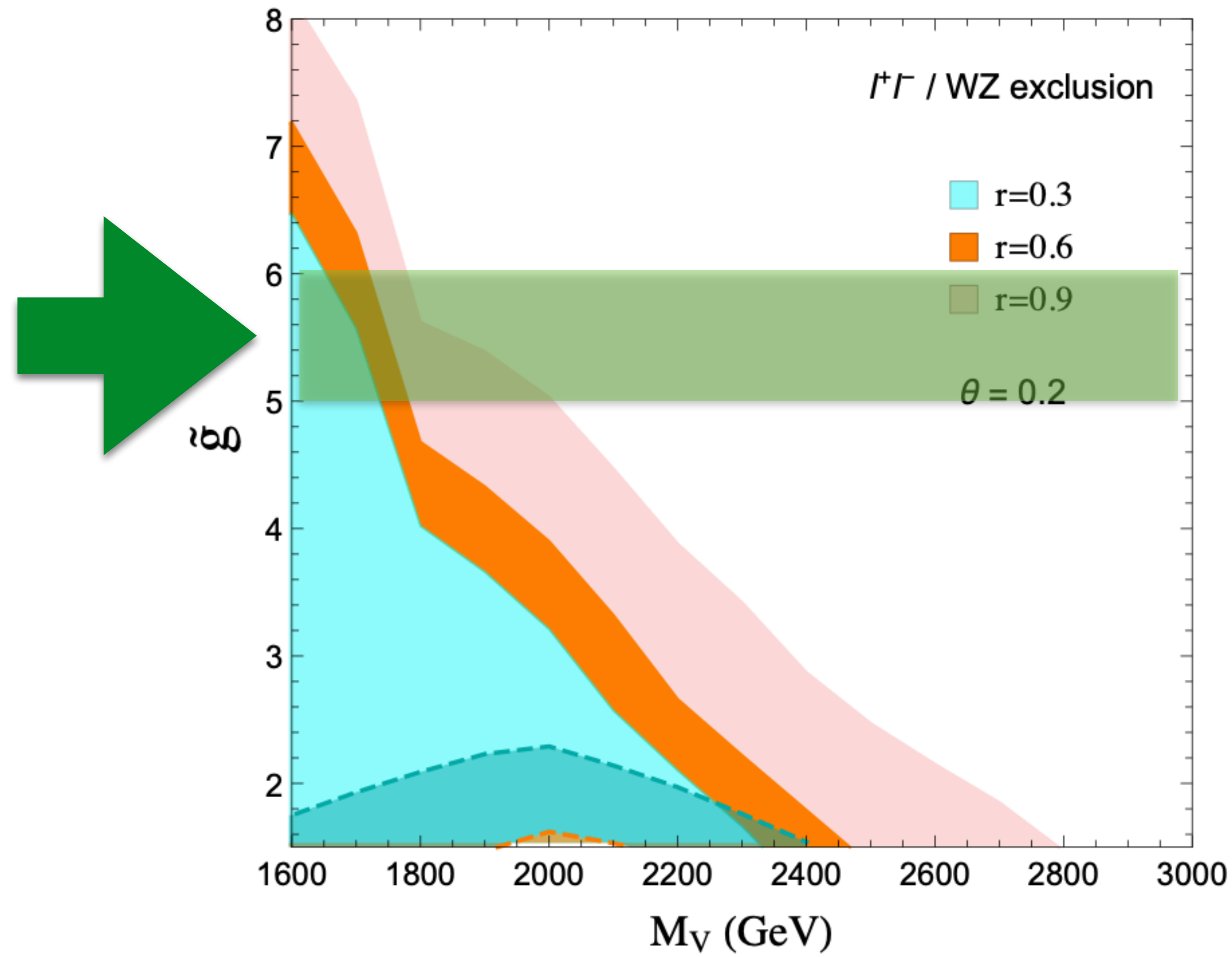


Snowmass WP: Batell, Low, EN, Verhaaren, arXiv:2203.05531

(Drach et al, arXiv:2012.09761)



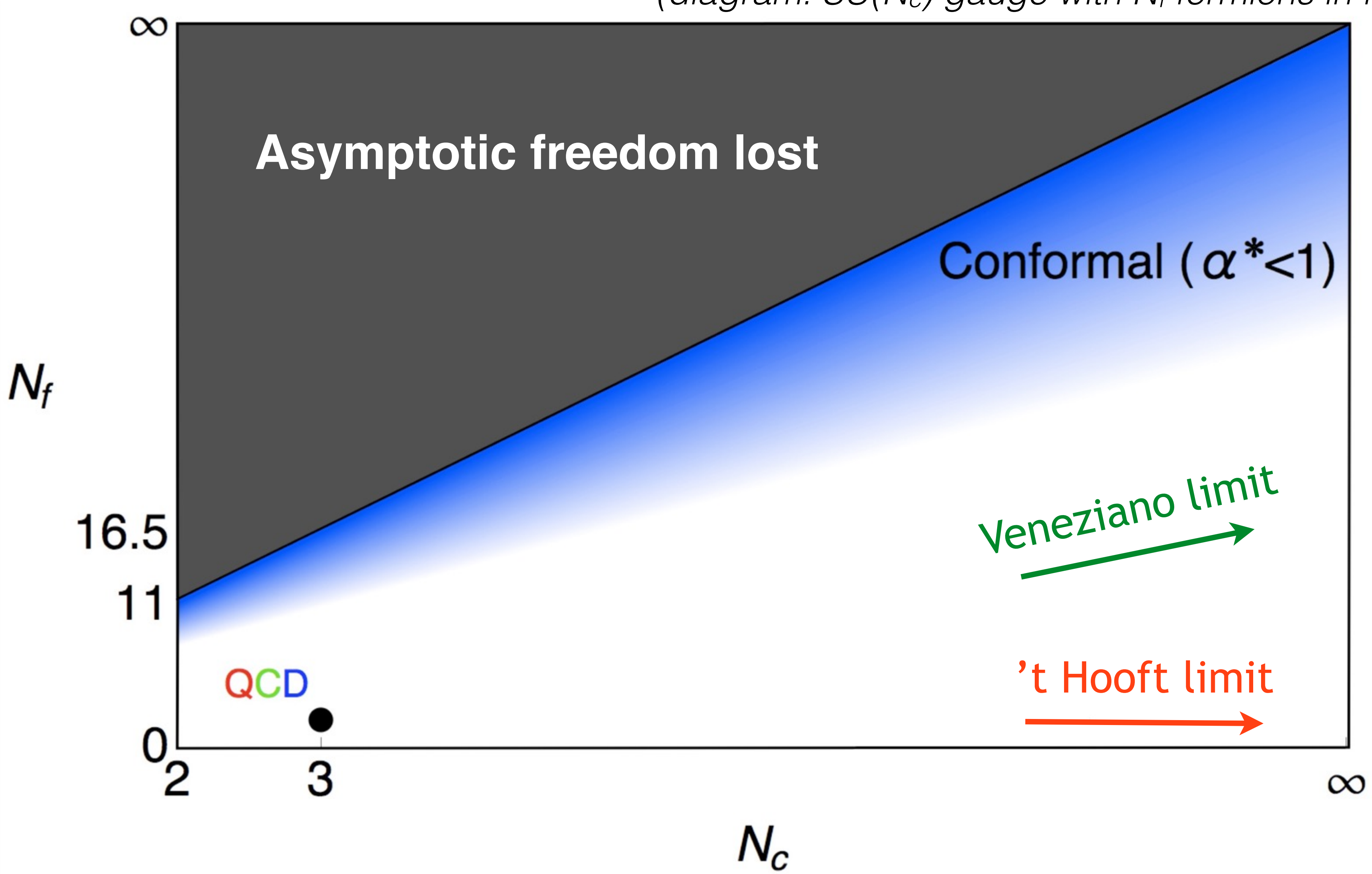
(Franzosi et al, arXiv:1605.01363)



- SU(2), Nf=2 "minimal composite Higgs". *Left*: lattice calculation of ρ-π-π resonance coupling. *Right*: ATLAS bounds from LHC run-II WZ search in mass-coupling plane.

2) Understanding the larger space

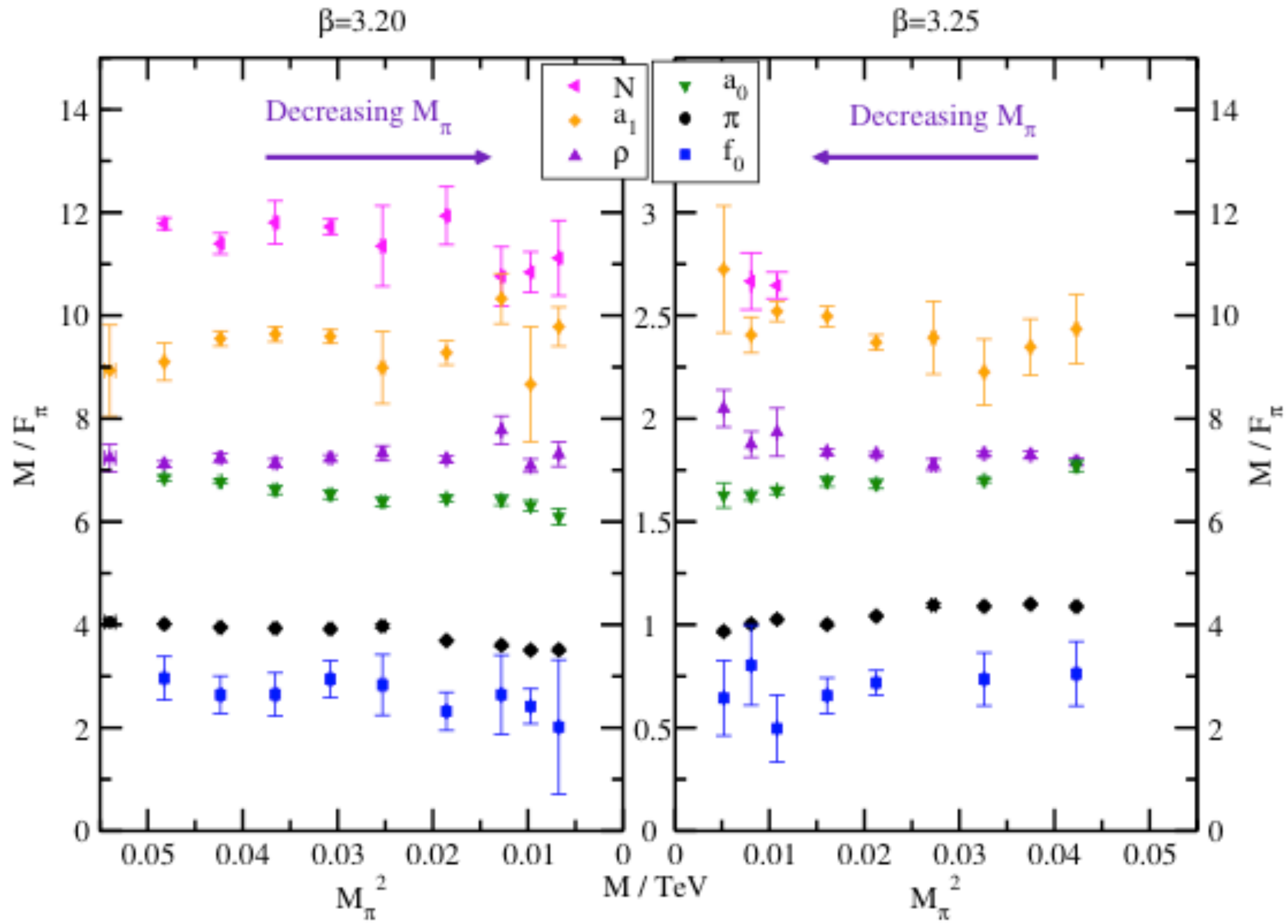
(diagram: $SU(N_c)$ gauge with N_f fermions in fundamental irrep)



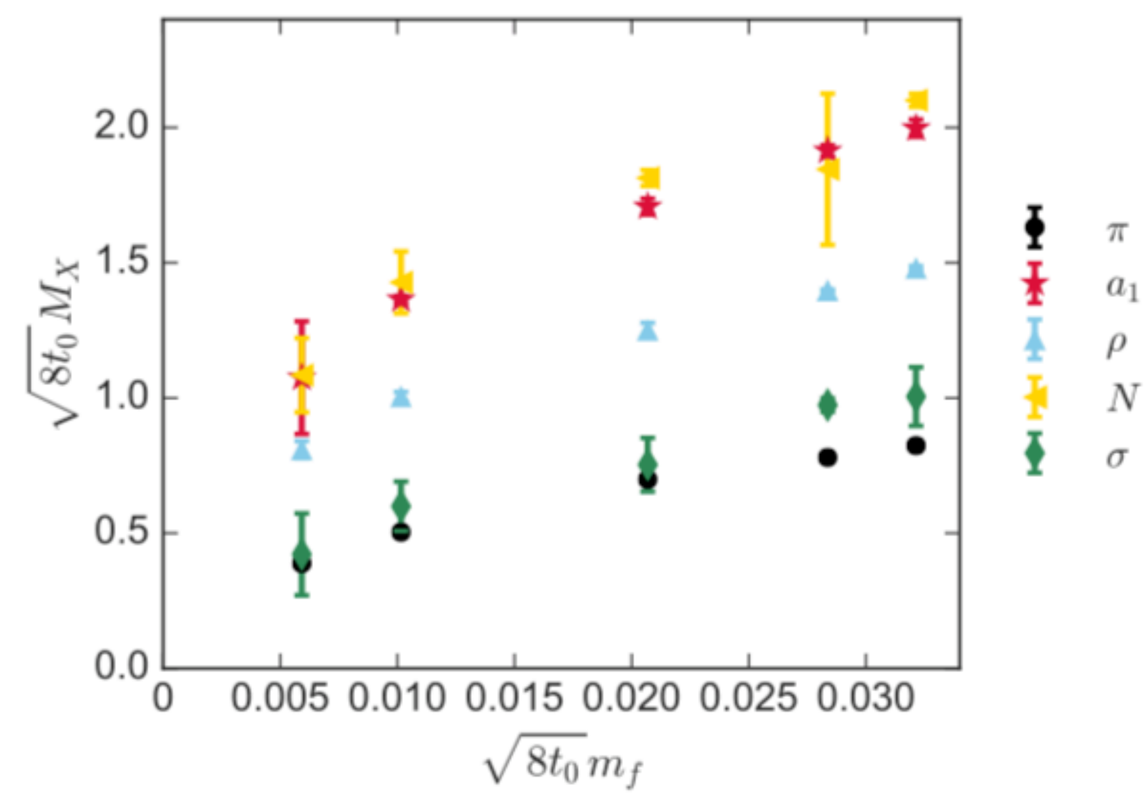
Large-N limit(s) provide analytic structure for predictions; lattice can **test** these analytic expansion and **compute** numerical values for expansion coefficients.

Conformal phase transition cuts across the parameter space; low-energy theory near the edge (**dilaton EFT**) can be tested and probed by lattice.

Fodor, Holland, Kuti, Wong (**LatHC collab**), arXiv:1901.06324)



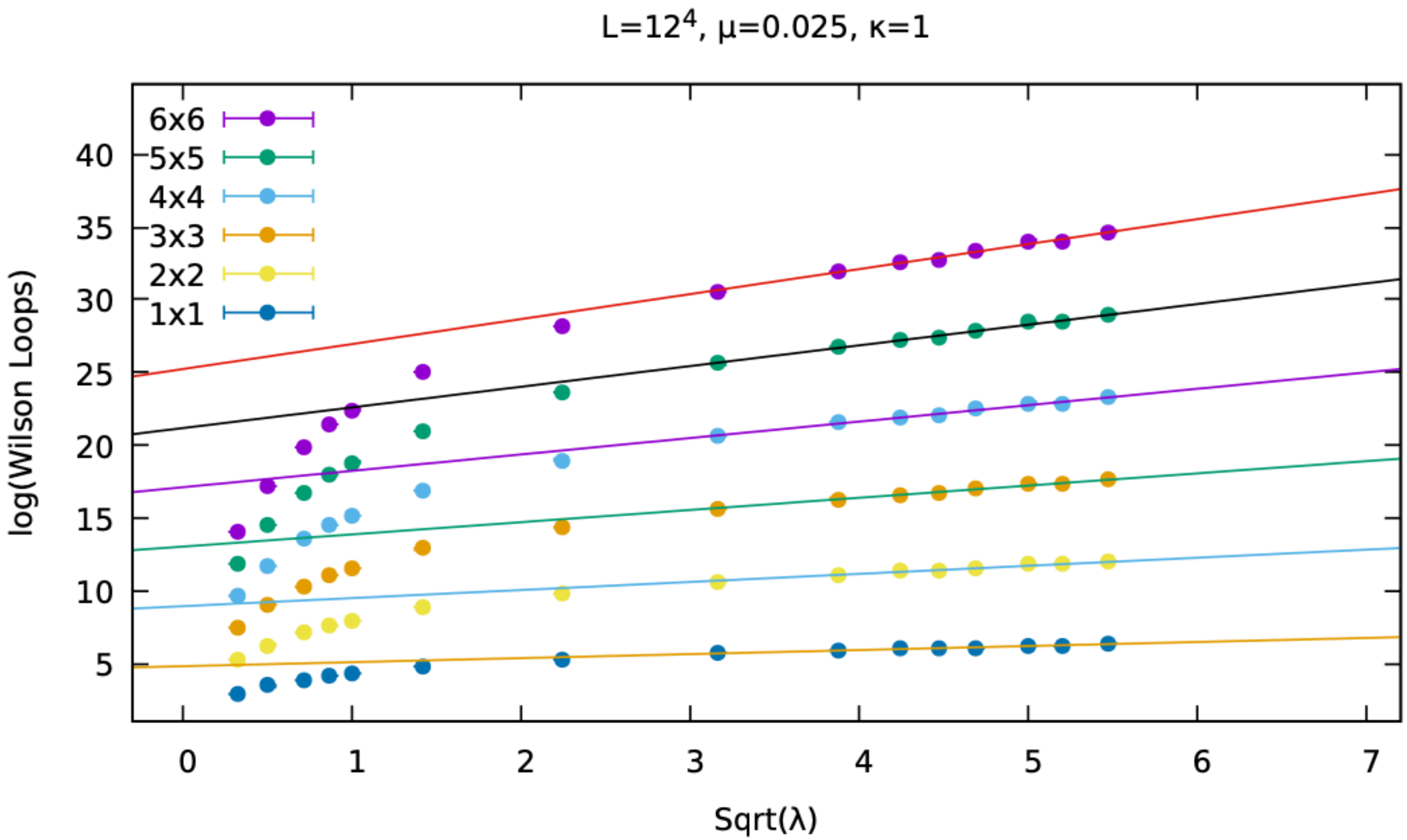
T. Appelquist et al (**LSD collab**), arXiv:1807.08411



- Emergence of light 0++ state near conformal transition - “pseudo-dilaton” - in multiple theories. Above: SU(3) Nf=2 sextet (left), SU(3) Nf=8 fundamental (right). Dynamical surprise (although speculation in literature earlier) - first indications from lattice!

- Model-building work is ongoing to understand the effective theory of pions + light scalar (“dilaton EFT”). Some work on pheno-viable composite Higgs models based on such theories, e.g. arXiv:2205.03320.

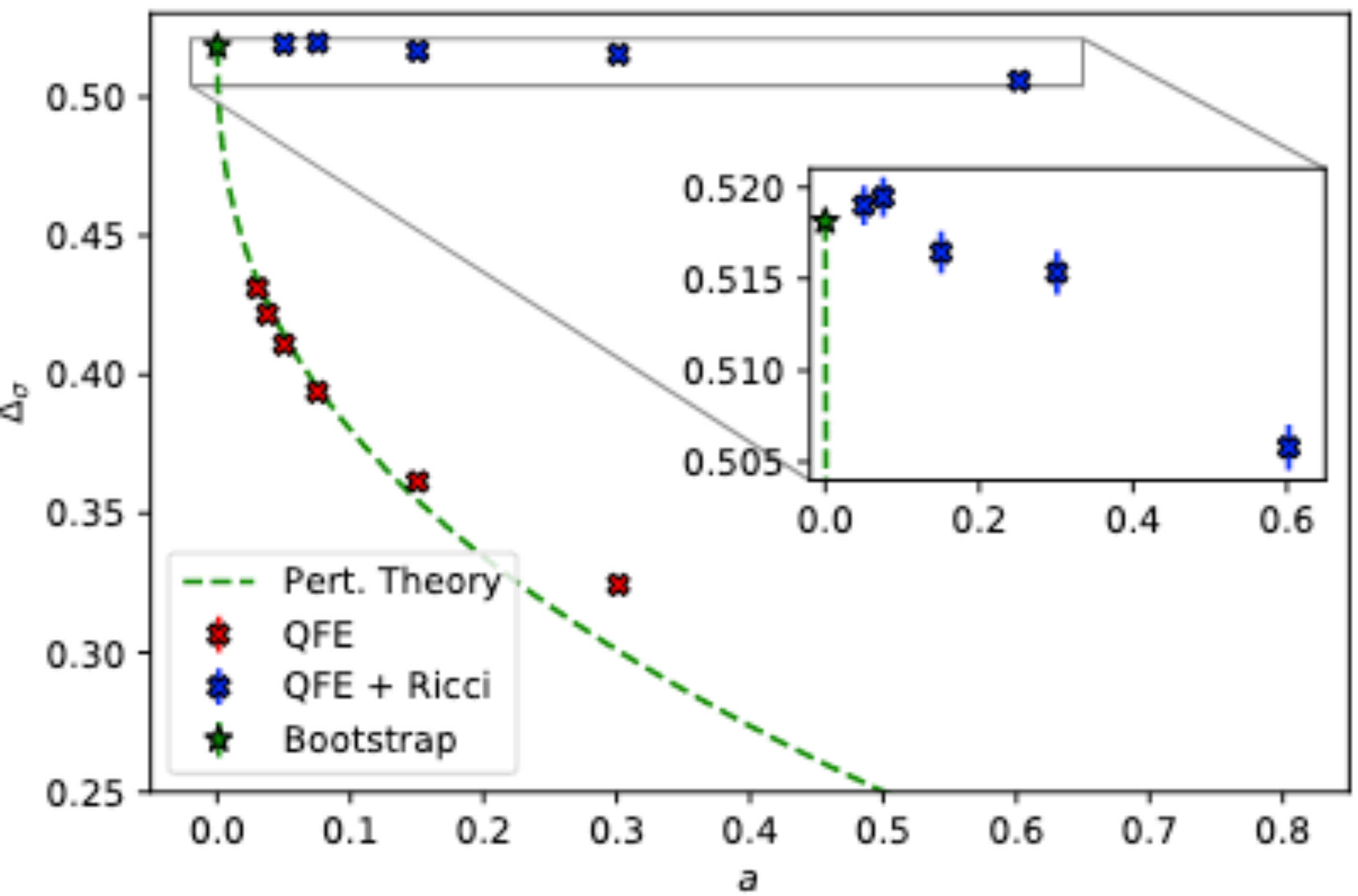
(Snowmass WP on lattice SUSY, Catterall and Giedt, arXiv:2202.08154)



- **3) Pure exploration** has the most variety. One example is lattice calculation in N=4 SYM. (Building SUSY into lattice is quite difficult - current projects are culmination of many years of work on theory and algorithms!)

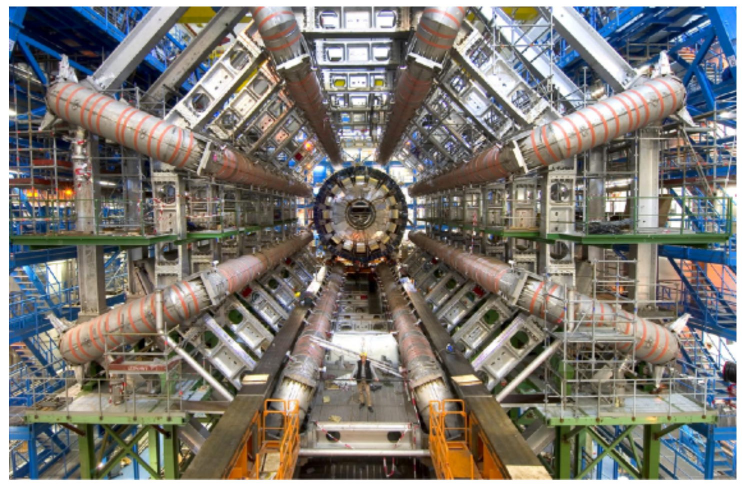
- <u>Points</u> above: scaling of Wilson loops vs. ’t Hooft coupling λ, from lattice; <u>lines</u> show holography-predicted, *non-perturbative* scaling behavior.

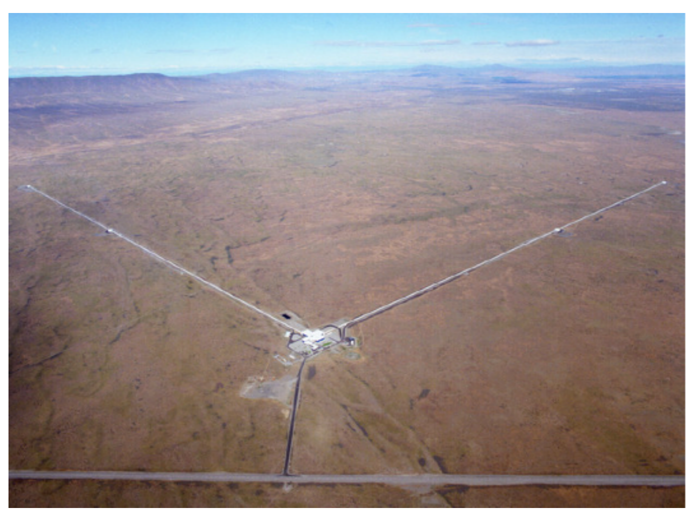
(Brower, Fleming, Gasbarro, Howarth, Raben, Tan, Weinberg, arXiv:2006.15636)



- Another example: <u>quantum finite elements (QFE)</u> approach generalizes ordinary finite element method for use in lattice QFT
- Enables simulation of QFT on <u>curved manifolds</u>, allowing radial quantization to study CFT w/ exponential scale separations
- Results for ϕ^4 theory in 3d show excellent convergence to known results from conformal bootstrap (left), particularly w/irrelevant Ricci term included

Conclusion



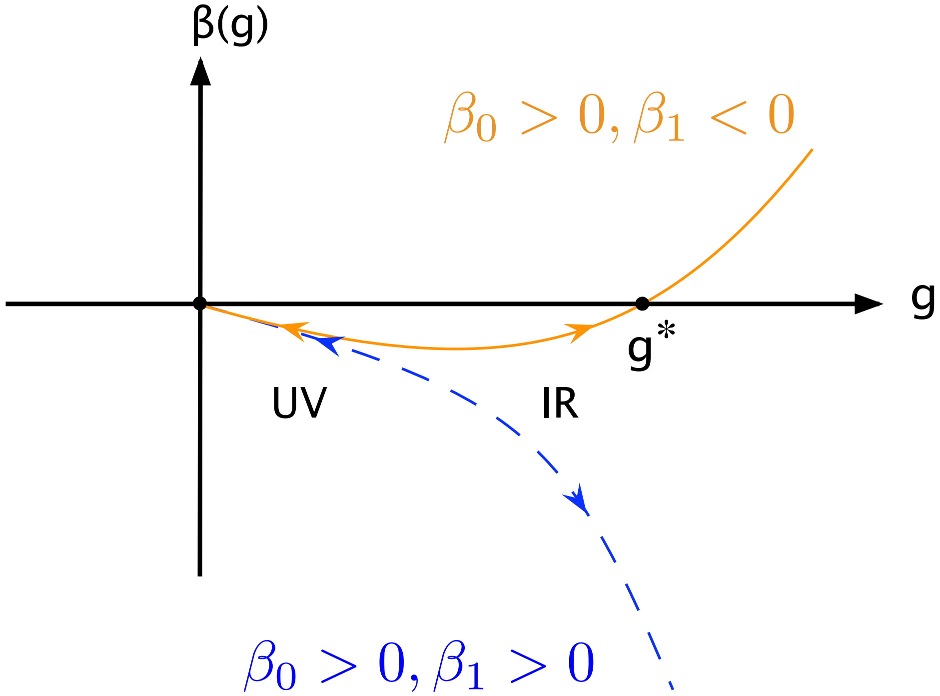


- Lattice is often used as a source of high-precision results for QCD
- But lattice is also very useful as a "numerical laboratory" to gain qualitative insights about other new theories!
- Study specific strongly-coupled theories; look at general properties of classes of theories; learn new things about QFT.

Backup

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.)

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!