# Composite Higgs model with four light and six heavy flavors (LSD collaboration)

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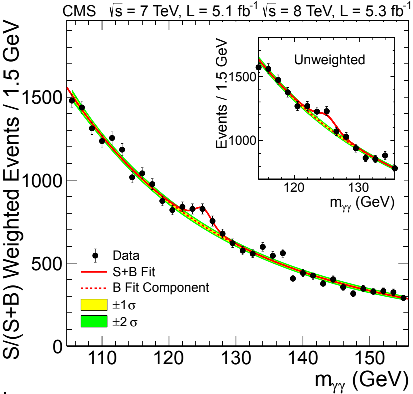
# Experimental observations

- Discovery of the Higgs boson in 2012
  [Atlas PLB 716 (2012) 1] [CMS PLB 716 (2012) 30]
- Mass of the Higgs boson is 125 GeV
- No other states found
  - $\Rightarrow$ must be much heavier, likely $> 1.5$ TeV
- Standard Model not UV complete
- What is the origin of the electro-weak sector?

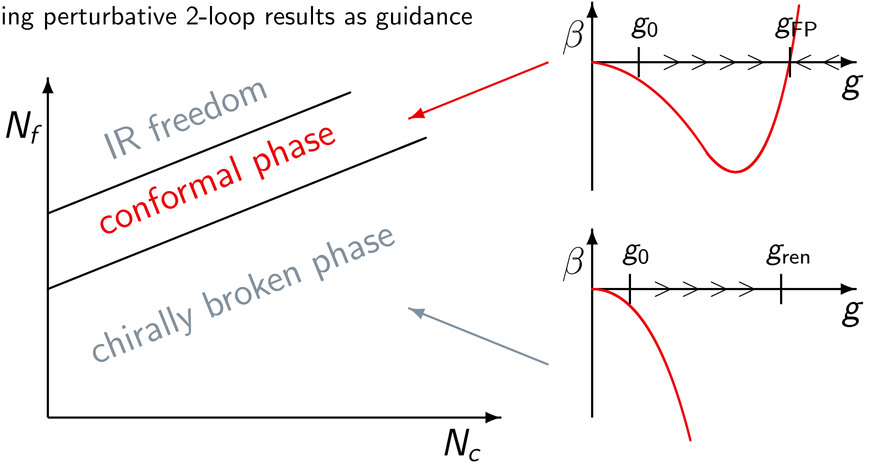
$\Rightarrow$ Seek a model exhibiting a large separation of scales

$\rightsquigarrow$ Near-conformal gauge theories / composite Higgs model



# Near-conformal gauge theories

- Gauge-fermion system with $N_c \geq 2$ colors and $N_f$ flavors in some representation
- Using perturbative 2-loop results as guidance



# Composite Higgs models

- New, strongly interacting gauge fermion system
- Effective theory describing part of the dynamics
- Coupled to the Standard Model

Higgs-less, massless SM $\rightarrow$ "full" SM

$$\mathcal{L}_{UV} \rightarrow \mathcal{L}_{SD} + \mathcal{L}_{SM_0} + \mathcal{L}_{int} \rightarrow \mathcal{L}_{SM} + \ldots$$

# Composite Higgs models

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## Add new strong dynamics coupled to SM

$$\mathcal{L}_{UV} \to \mathcal{L}_{SD} + \mathcal{L}_{SM_0} + \mathcal{L}_{int} \to \mathcal{L}_{SM} + \ldots$$

↑

Full SM + states from $\mathcal{L}_{SD}$

This construction gives mass to:

- the SM gauge fields
- the SM fermions fields: 4-fermion interaction or partial compositeness

# Composite Higgs models

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Full SM + states from $\mathcal{L}_{SD}$

This construction gives mass to:

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Does not explain mass of $\mathcal{L}_{SD}$ fermions and 4-fermion interactions: $\mathcal{L}_{UV}$

# Candidates for $\mathcal{L}_{SD}$

- Promising candidates are chirally broken in the IR but conformal in the UV
  [Luty and Okui JHEP 09(2006)070], [Dietrich and Sannino PRD75(2007)085018], [Vecchi arXiv:1506.00623], [Ferretti and Karateev JHEP 1403 (2014) 077], . . .


- One possible implementation: mass-split models
  → Example: SU(3) gauge theory with "heavy" and "light" (massless) fundamental flavors
    - Add heavy flavors to push the system near an IRFP of a conformal theory
    - 4 light flavors are chirally broken in the IR

- Composite Higgs can emerge as dilaton or pseudo-Nambu Goldstone boson

# Two possibilities for a composite Higgs (IR sector)

- Spontaneous breaking of scale symmetry: Higgs is a dilaton
  - → Possibly light $0^{++}$ scalar
  - → $F_\pi$ = SM vev $\sim 246$ GeV
  - → ideal 2 massless flavors in the IR
  - → closer to old technicolor ideas

- Spontaneous breaking of flavor symmetry: Higgs is a pNGB
  - → Mass emerges from its interactions
  - → Non-trivial vacuum alignment $F_\pi = (\text{SM vev})/\sin(\chi) > 246$ GeV
  - → ideal 4 massless flavors in the IR
  - → Vecchi: UV-complete models requiring at least two types of fermions in two different gauge group representations [arXiv:1506.00623]
  - → Ferretti: Classification of models with custodial symmetry and partial compositeness [JHEP 1403 (2014) 077] [JHEP 1606 (2016) 107]
  - → Ma and Cacciapaglia: Fundamental composite 2HDM with 4 flavors in SU(3) gauge [JHEP 03 (2016) 211]

# Mass-split models

- Constructed to exhibit large scale separation ("walking coupling")
  - → Tunable by the mass $m_h$ of the heavy flavors
- Highly predictive: inherit hyperscaling from the IRFP
  - → dilaton-like Higgs (2+N): no free parameter
  - → pNGB Higgs (4+N): only angle of vacuum alignment to be fixed
- Anomalous dimensions correspond to the conformal IRFP
  - → Total number of flavors should be inside but close to the lower edge of the conformal window
- Strongly coupled, chirally broken but not QCD-like

- Examples
  - → four light and eight heavy flavors (4+8)
  - → four light and six heavy flavors (4+6) — exploratory

# Request to generate 4+6 flavor MDWF ensembles

| $L$ | $T$ | $L_s$ | $m_h$ | $m_\ell$ | $m_\ell/m_h$ | #trajectories | costs per trajectory [jpsi core-hours] | Total costs [jpsi core-hours] |
|---|---|---|---|---|---|---|---|---|
| 24 | 64 | 16 | 0.200 | 0.030 | 0.150 | 1000 | 3.3 k | 3.3 M |
| 24 | 64 | 16 | 0.200 | 0.020 | 0.100 | 1000 | 4.5 k | 4.5 M |
| 32 | 64 | 16 | 0.200 | 0.015 | 0.075 | 750 | 12.3 k | 9.2 M |
| *48* | *96* | *24* | *0.200* | *0.010* | *0.050* | — | — | — |
| 24 | 64 | 16 | 0.175 | 0.035 | 0.200 | 1000 | 3.2 k | 3.2 M |
| 24 | 64 | 16 | 0.175 | 0.026 | 0.149 | 1000 | 4.3 k | 4.3 M |
| *32* | *64* | *16* | *0.175* | *0.018* | *0.103* | — | — | — |
| 24 | 64 | 16 | 0.150 | 0.033 | 0.200 | 1000 | 3.1 k | 3.1 M |
| 24 | 64 | 16 | 0.150 | 0.023 | 0.153 | 1000 | 4.2 k | 4.2 M |
| *32* | *64* | *16* | *0.150* | *0.015* | *0.100* | — | — | — |
| **Total costs for ensemble generation** | | | | | | | | **31.8 M** |
| **Costs to carry our simple spectrum and flow measurements** | | | | | | | | **2.5 M** |
| **Cost for 15 TB disk space** | | | | | | | | **0.6 M** |
| **Total request** (skylake or KNL) | | | | | | | | **34.9 M** |

# (Non-technical) SPC questions

b) How do you determine if the model you study is indeed exhibiting hyperscaling and how precise do the data need to be?

Hyperscaling: ratios of masses or masses over amplitudes are independent of $m_h$

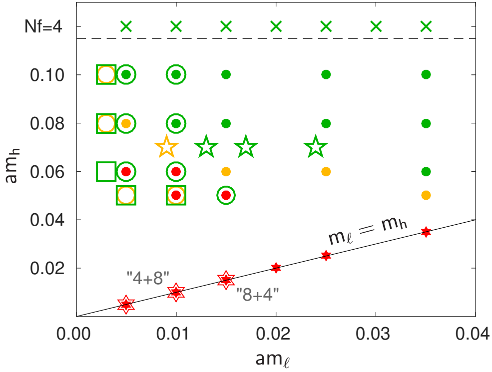
c) Do you need to calculate $\pi - \pi$ scattering to determine the scalar meson mass or the spectrum from two-fermion-two-antifermion will be enough for the first step?

Expect iso-singlet scalar ($0^{++}$) to be light $< M_\rho \to$ conn. + disc. 2-pt functions;
multiplet-scalar ($a_0$) likely requires scattering calculation for small $m_\ell$
because 2 pion (bound) state can contribute

# Hyperscaling in mass-split systems

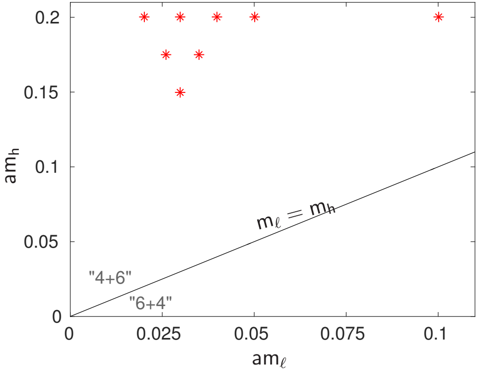
## 4+8

- $24^3 \times 48$, $32^3 \times 64$, $36^3 \times 64$, $48^3 \times 96$
- [JETP 120 (2015) 3, 423] [PRD 93 (2016) 075028] [PLB 773C (2017) 86-90]



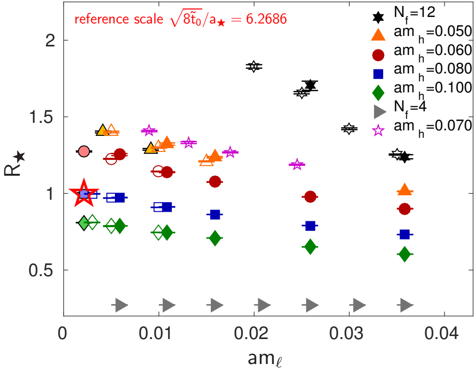

## 4+6 — PRELIMINARY!

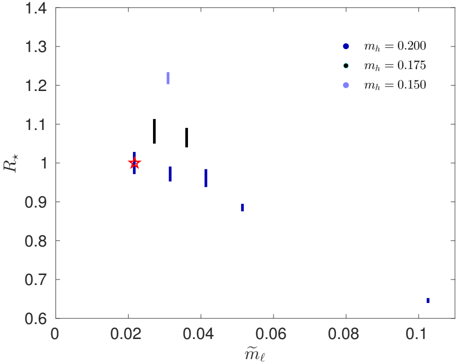
- Only $16^3 \times 32$
- Exploratory: maybe significant systematic effects ⇒ no data points



# Relative gradient flow scale

- Use gradient flow ($\sqrt{8\tilde{t}_0}$) to define a relative lattice spacing: $R_\star = \left[\sqrt{8\tilde{t}_0}/a\right] / \left[\sqrt{8\tilde{t}_0}/a_\star\right]$

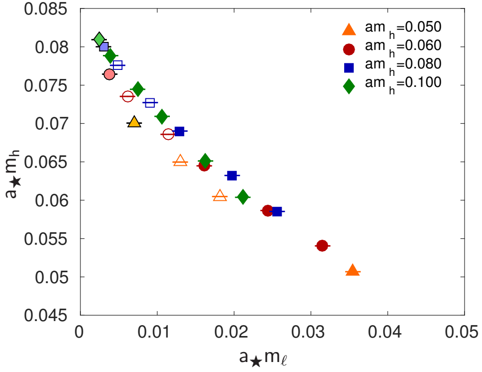


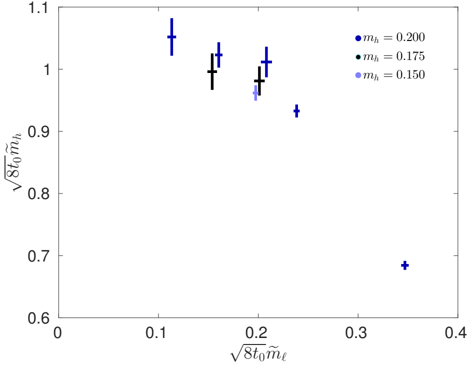

- $N_f = 12$ (conformal): scale breaks down for $m_\ell = m_h \to 0$
- 4+8a and 4+6: scale exhibits strong dependence on $m_\ell$ and $m_h$
- QCD: scale largely independent of $m_\ell$ $\to$ define scale in the chiral limit

# "Naive conversion" of bare input quark masses to physical units

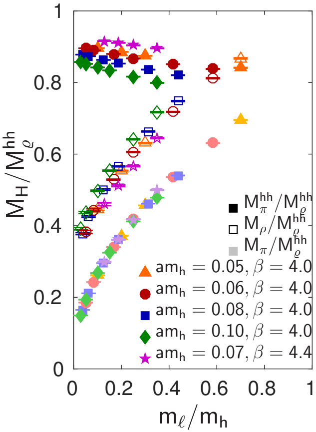
- Hyperscaling predicts quark masses scale according to the anomalous dimension
- QCD: scale largely independent of $m_\ell$ and $m_h$

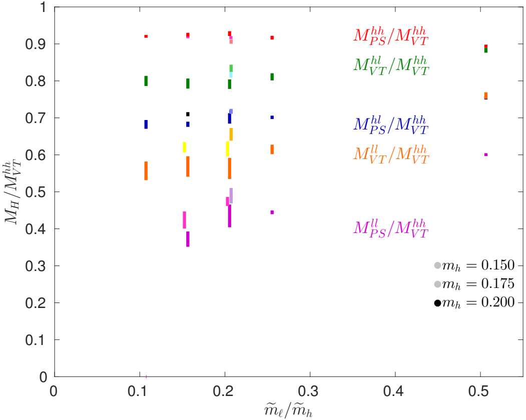



- $\widetilde{m}_q = m_q + m_{\text{res}}$



# Spectrum in units of $M_{VT}$



# Why moving to 4+6?

- 4+8 is built on IRFP of the conformal system with 12 fundamental flavors
  - → 12 flavors has a small anomalous dimension (∼0.25)
  - → Phenomenologically not that attractive

- Indications of conformality of 10-flavors [Chiu 1603.08854][PoS LATTICE2016 (2017) 228]
  - → Closer to the lower edge of the conformal window
    - ⇒ larger anomalous dimension
  - → Further investigations needed (Step-scaling proposal PI Claudi Rebbi)

- Domain-wall fermions feature continuum-like symmetries and expressions
  - → Simplifies to investigate mass generation of SM fermions
    - ⇝ partial compositeness or four-fermion interactions
  - → Easier to calculate the Higgs potential, $S$-parameter, scattering processes, ...
  - → Avoids issues of rooting or fermion universality near an IRFP [arXiv:1710.08970]