Lattice field theory and BSM: the beginning of a beautiful friendship

Giacomo Cacciapaglia

IP2I Lyon, France

Lattice 2021

July 27

Strong coupling in BSM

- Composite Higgs models

- Composite Dark Matter

- SIMP
- Dark glueballs

- Composite axions
- ...

Which theory to choose?

SU(3) w.
2A

SU(3) w.
8F

SU(2) w.
2F

SU(3) w.
10F

SU(4) w.
5A + 6F

...

Sp(4) w.
4F + 6A

Which theory to choose?

SU(3) w.

SU(3)

(2) w.

F

SU(3) w.
10F

4) w.
+ 6F

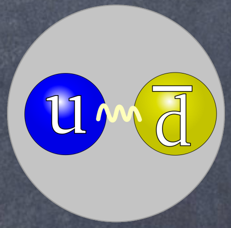
...

4F + 6A

Let's choose first the problem:
what is inside the plush?

Composite Higgs models 101

- Symmetry broken by a condensate (of TC-fermions)
- Higgs and longitudinal Z/W emerge as mesons (pions)



Scales:

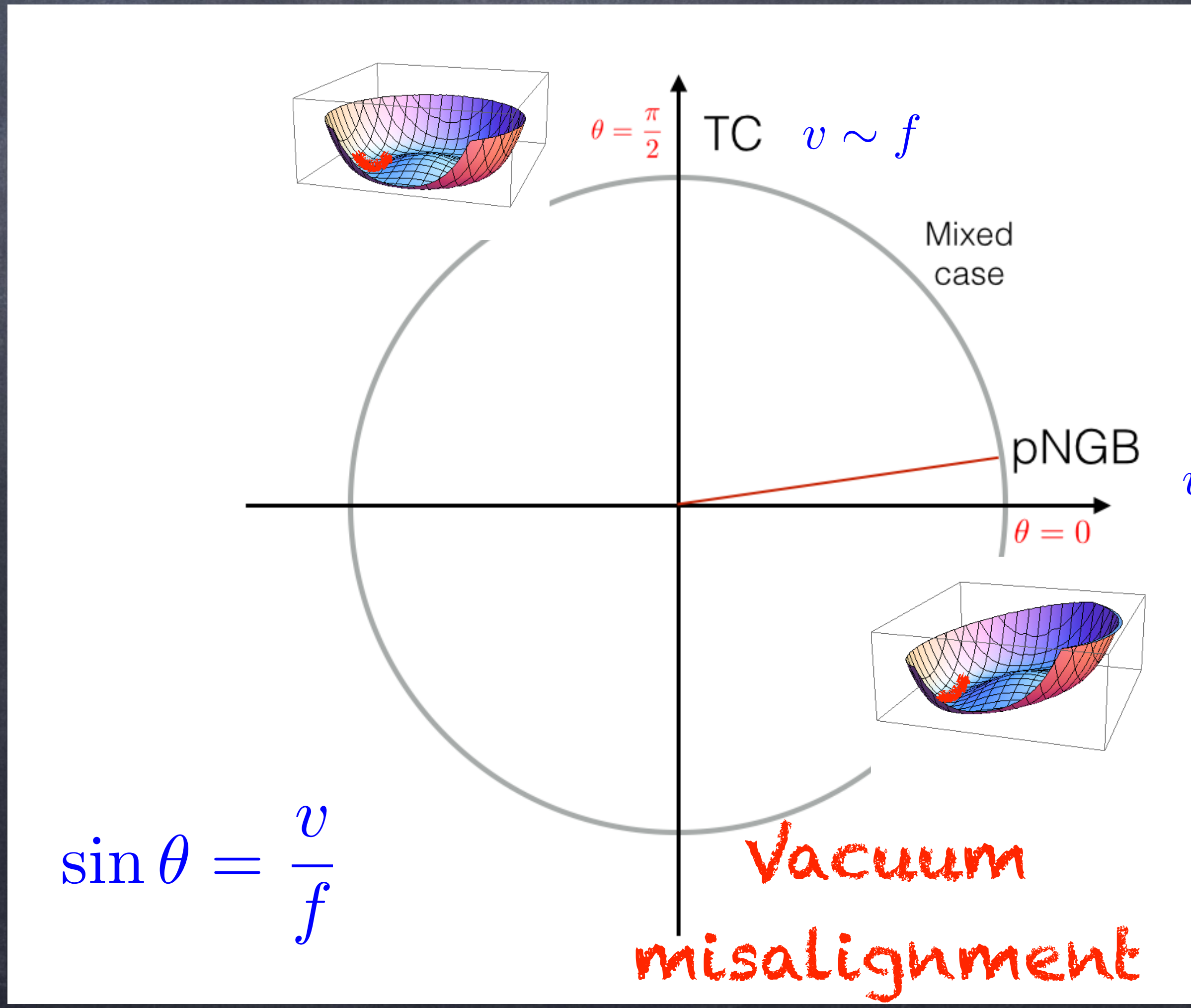
f : Higgs decay constant

v : EW scale

$m_\rho \sim 4\pi f$

EWPTs + Higgs coupl. limit:

$$f \gtrsim 4v \sim 1 \text{ TeV}$$



Composite Higgs models 101

T.Ryttov, F.Sannino 0809.0713
Galloway, Evans, Luty, Tacchi 1001.1361

	$SU(2)_{\mathrm{TC}}$	$SU(4)_\psi$	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix}\psi^1\\ \psi^2\end{pmatrix}$	□	□	**2**	0
ψ^3	□		**1**	-1/2
ψ^4	□		**1**	1/2

The EW symmetry is embedded in the global flavour symmetry SU(4) !

- The global symmetry is broken: SU(4)/Sp(4)

  Witten, Kosower

- 5 Goldstones (pions) arise:

$$\mathbf{5}_{\mathrm{Sp}(4)} \to (2,2) \oplus (1,1)$$

Higgs — additional singlet

Composite Higgs models 101

The difficult parts:

- Generate the needed misalignment (via an effective potential)
- Generate couplings for the top (and other SM fermions)
- Correct Higgs mass and couplings
- Conformal window

The partial compositeness paradigm

Kaplan Nucl.Phys. B365 (1991) 259

$$\frac{1}{\Lambda_{\text{fl.}}^{d-1}} \mathcal{O}_H q_L^c q_R \qquad \Delta m_H^2 \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-4} f^2$$

Both irrelevant if

we assume: $d_H > 1$ $\quad d_{H^2} > 4$

Let's postulate the existence of fermionic operators:

$$\frac{1}{\Lambda_{\text{fl.}}^{d_F-5/2}} (\tilde{y}_L\, q_L \mathcal{F}_L + \tilde{y}_R\, q_R \mathcal{F}_R)$$

This dimension is not related to the Higgs!

$$f(y_L\, q_L Q_L + y_R\, q_R Q_R)$$

with

$$y_{L/R} f \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_F-5/2} 4\pi f$$

Top partners as baryons

Gauge-fermion underlying theory

$$\frac{1}{\Lambda_{\text{fl.}}}\, q \underbrace{\sigma^{\mu\nu} \psi G_{\mu\nu}}_{T}$$

$$d_T^{\text{naive}} = 7/2$$

- typically loop-suppressed
- psi need to carry QCD colour and flavour quantum numbers: too many!
- too many adjoint fermions!

Top partners as baryons

Gauge-fermion underlying theory

$$\frac{1}{\Lambda_{\text{fl.}}^2} \, q \underbrace{\psi\psi\psi}_{T}$$

$$d_T^{\text{naive}} = 9/2$$

- higher dimension, but easier to generate
- More freedom in choosing the fermion representations

Top partners as baryons

Gauge-fermion underlying theory

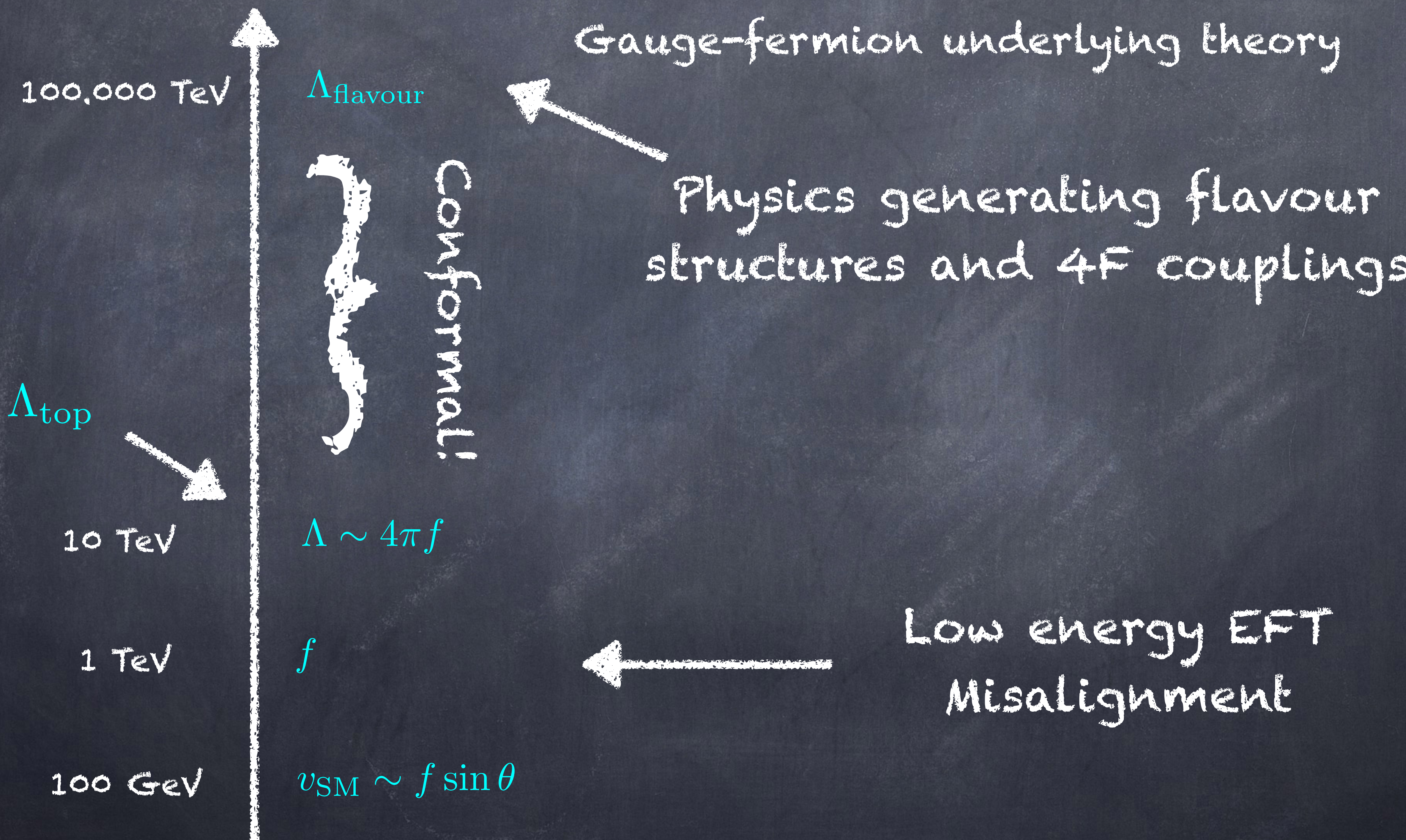
$$\frac{1}{\Lambda_{\text{fl.}}^2}\,\underbrace{q\psi\psi\psi}_{T}$$

$$d_T^{\text{naive}} = 9/2$$

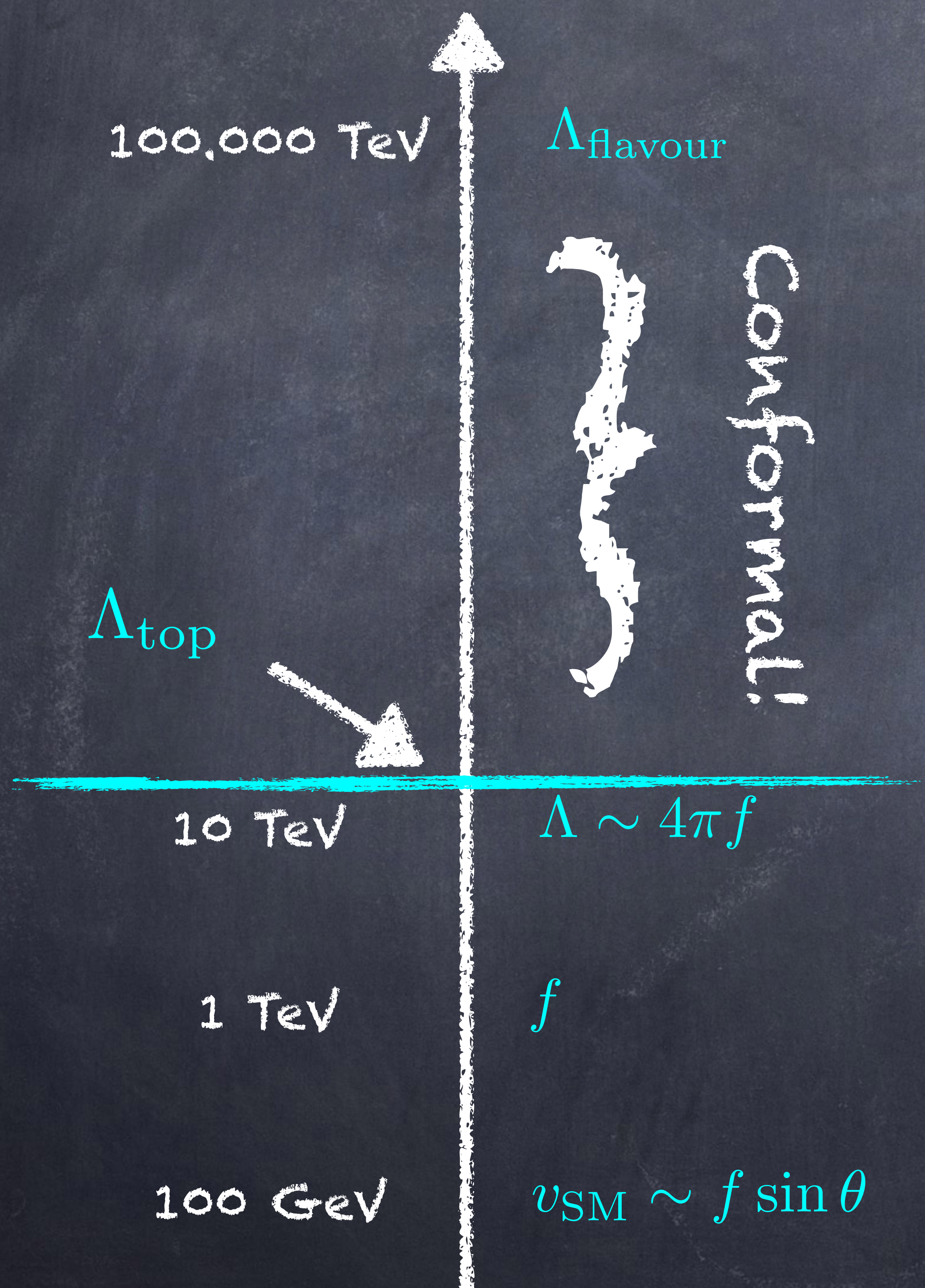
- higher dimension, but easier to generate
- More freedom in choosing the fermion representations

- What generated the 4-F interactions?
- We need large anomalous dimensions: strongly coupled conformal phase!

Top partners as baryons



Top partners as baryons



Gauge-fermion underlying theory

The theory needs to lie just below the conformal window

IR Model zoology

G_{HC}	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) × SU(6)/SO(6)				
$SO(N_{HC})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{HC}\geq 55$	$\frac{5(N_{HC}+2)}{6}$	1/3	/	
$SO(N_{HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$N_{HC}\geq 15$	$\frac{5(N_{HC}-2)}{6}$	1/3	/	
$SO(N_{HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{HC}=7,9$	$\frac{5}{6}$, $\frac{5}{12}$	1/3	$N_{HC}=7,9$	M1, M2
$SO(N_{HC})$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{HC}=7,9$	$\frac{5}{6}$, $\frac{5}{3}$	2/3	$N_{HC}=7,9$	M3, M4
	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$2N_{HC}\geq 12$	$\frac{5(N_{HC}+1)}{3}$	1/3	/	
$Sp(2N_{HC})$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$2N_{HC}\geq 4$	$\frac{5(N_{HC}-1)}{3}$	1/3	$2N_{HC}=4$	M5
$SO(N_{HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{HC}=11,13$	$\frac{5}{24}$, $\frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) × SU(3)²/SU(3)				
$SU(N_{HC})$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{HC}=4$	$\frac{5}{3}$	1/3	$N_{HC}=4$	M6
$SO(N_{HC})$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$N_{HC}=10,14$	$\frac{5}{12}$, $\frac{5}{48}$	1/3	$N_{HC}=10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{HC}\leq 36$	$\frac{1}{3(N_{HC}-1)}$	2/3	$2N_{HC}=4$	M8
$SO(N_{HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{HC}=11,13$	$\frac{8}{3}$, $\frac{16}{3}$	2/3	$N_{HC}=11$	M9
	Complex	Real	SU(4)²/SU(4) × SU(6)/SO(6)				
$SO(N_{HC})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{HC}=10$	$\frac{8}{3}$	2/3	$N_{HC}=10$	M10
$SU(N_{HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{HC}=4$	$\frac{2}{3}$	2/3	$N_{HC}=4$	M11
	Complex	Complex	SU(4)²/SU(4) × SU(3)²/SU(3)				
$SU(N_{HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{HC}\geq 5$	$\frac{4}{3(N_{HC}-2)}$	2/3	$N_{HC}=5$	M12
$SU(N_{HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{HC}\geq 5$	$\frac{4}{3(N_{HC}+2)}$	2/3	/	
$SU(N_{HC})$	$4\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{HC}=5$	4	2/3	/	

Ferretti
1604.06467

	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{HC} \geq 12$	$\frac{5(N_{HC}+1)}{3}$	1/3	/	
$Sp(2N_{HC})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{HC} \geq 4$	$\frac{5(N_{HC}-1)}{3}$	1/3	$2N_{HC} = 4$	M5
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) × SU(3)^2/SU(3)				
$SU(N_{HC})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 4$	$\frac{5}{3}$	1/3	$N_{HC} = 4$	M6
$SO(N_{HC})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{HC} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	1/3	$N_{HC} = 10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{HC} \leq 36$	$\frac{1}{3(N_{HC}-1)}$	2/3	$2N_{HC} = 4$	M8
$SO(N_{HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{HC} = 11$	M9
	Complex	Real	SU(4)^2/SU(4) × SU(6)/SO(6)				
$SO(N_{HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{HC} = 10$	$\frac{8}{3}$	2/3	$N_{HC} = 10$	M10
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{HC} = 4$	$\frac{2}{3}$	2/3	$N_{HC} = 4$	M11
	Complex	Complex	SU(4)^2/SU(4) × SU(3)^2/SU(3)				
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}-2)}$	2/3	$N_{HC} = 5$	M12
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \overline{\mathbf{S}_2})$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}+2)}$	2/3	/	
$SU(N_{HC})$	$4 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 5$	4	2/3	/	

	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{HC} \geq 12$	$\frac{5(N_{HC}+1)}{3}$	1/3	/	
$Sp(2N_{HC})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{HC} \geq 4$	$\frac{5(N_{HC}-1)}{3}$	1/3	$2N_{HC} = 4$	M5
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	1/3	/	

	Real	Complex	SU(5)/SO(5) × SU(3)²/SU(3)				
$SU(N_{HC})$	$5 \times \mathbf{A}_2$					$N_{HC} = 4$	M6
$SO(N_{HC})$	$5 \times \mathbf{F}$	3				$N_{HC} = 10$	M7

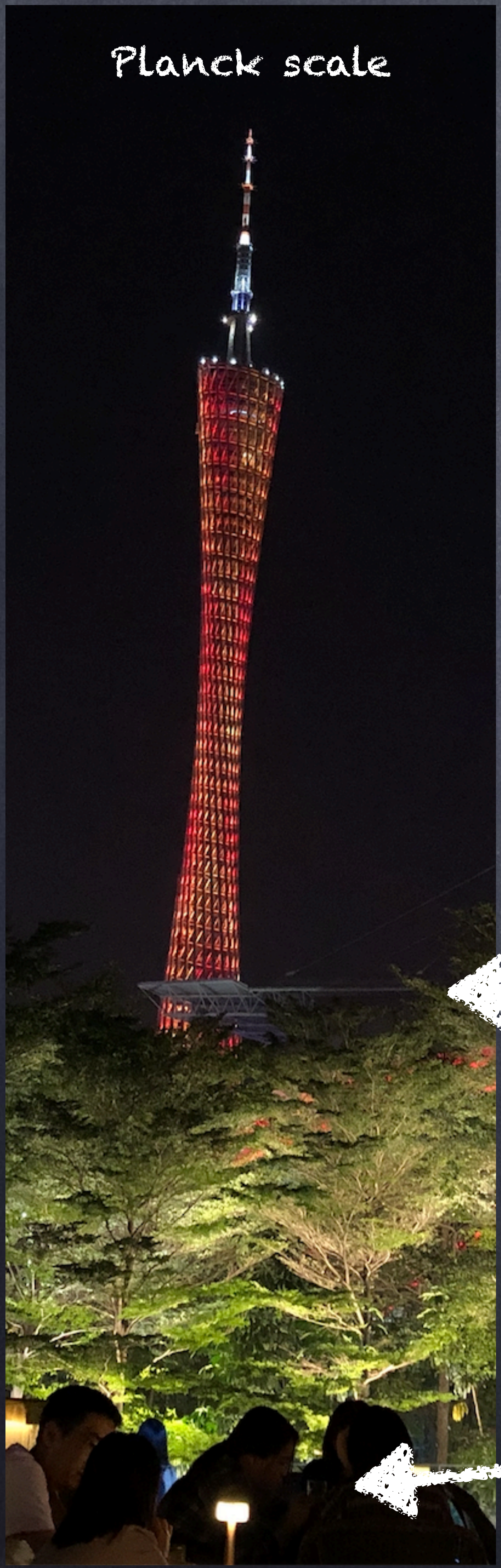
	Pseudo-Real						
$Sp(2N_{HC})$	$4 \times \mathbf{F}$					$2N_{HC} = 4$	M8
$SO(N_{HC})$	$4 \times \mathbf{Spin}$					$N_{HC} = 11$	M9

	Complex						
$SO(N_{HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$					$N_{HC} = 10$	M10
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{HC} = 4$	$\frac{2}{3}$	2/3	$N_{HC} = 4$	M11

	Complex	Complex	SU(4)²/SU(4) × SU(3)²/SU(3)				
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}-2)}$	2/3	$N_{HC} = 5$	M12
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \overline{\mathbf{S}}_2)$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}+2)}$	2/3	/	
$SU(N_{HC})$	$4 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 5$	4	2/3	/	

Partially Unified Partial Compositeness (PUPC)

G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302



Condensation scale

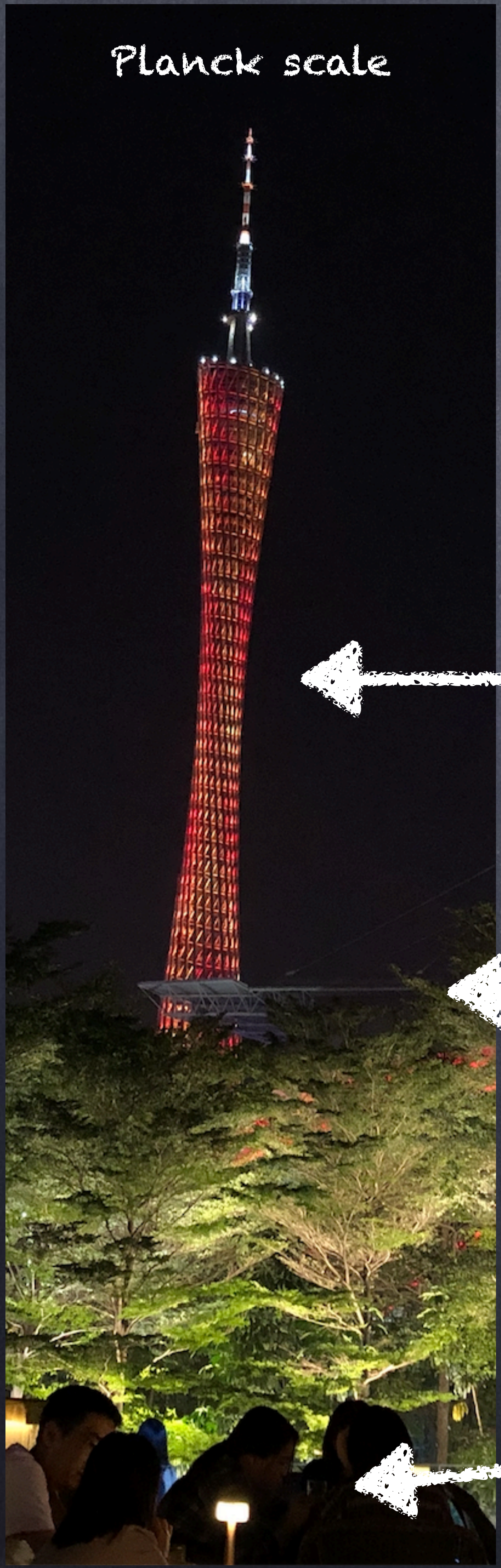
Usual low energy description
of composite Higgs models

Standard Model

One of Ferretti
models

Partially Unified Partial Compositeness (PUPC)

G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302



Conformal window
(large scaling dimensions)

One of Ferretti models + additional fermions

Condensation scale

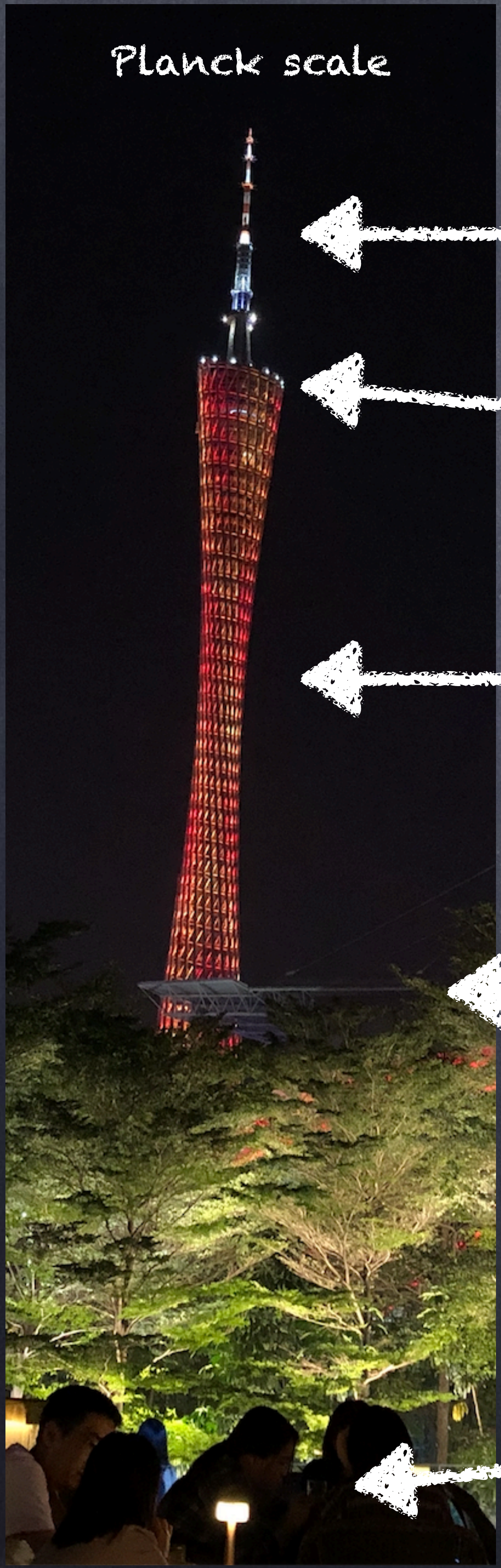
Usual low energy description of composite Higgs models

One of Ferretti models

Standard Model

Partially Unified Partial Compositeness (PUPC)

G.C., S.Vatani, C.Zhang
1911.05454, 2006.12302



HC and SM gauge groups partially unified

Symmetry breaking by scalars — 4-fermion Ops generated!

Conformal window (large scaling dimensions) — One of Ferretti models + additional fermions

Condensation scale

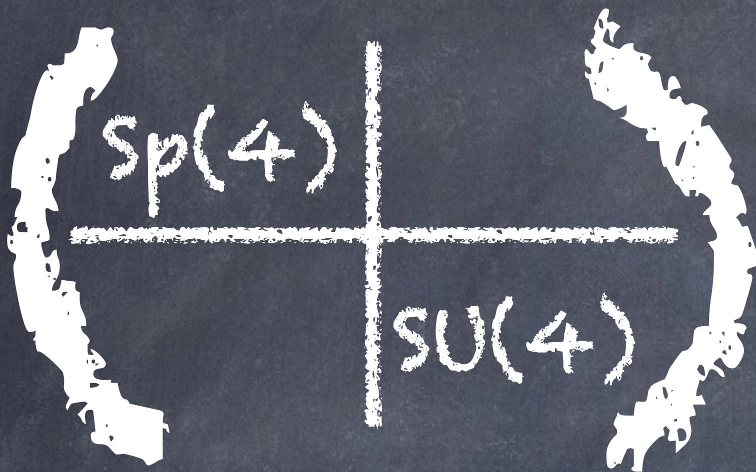
Usual low energy description of composite Higgs models

Standard Model

(Condensation scale to Standard Model:) One of Ferretti models

Techni-Pati-Salam

Parallel talk: Friday



- Simplest model embeds an Sp(4) TC with SU(4) Pati-Salam in SU(8)

$$\Omega = \begin{pmatrix} \psi_d \\ q \\ l \end{pmatrix}$$

Techni-Pati-Salam

Parallel talk: Thursday

$$\begin{pmatrix} Sp(4) & \\ & SU(4) \end{pmatrix}$$

- Simplest model embeds an Sp(4) TC with SU(4) Pati-Salam in SU(8)

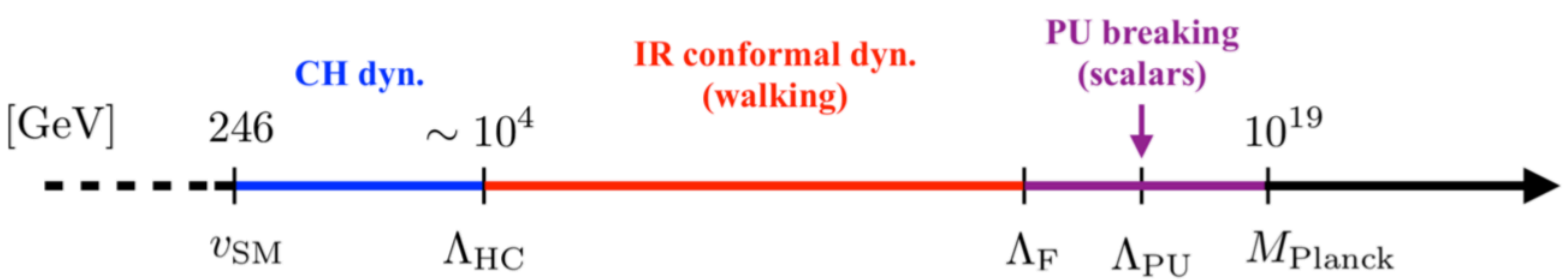
$$\Omega = \begin{pmatrix} \psi_d \\ q \\ l \end{pmatrix}$$

Sp(4) strong interactions emerge

2 or 3F + 3A

6F + 3A

- Is this theory conformal?
- What are the anomalous dimensions?



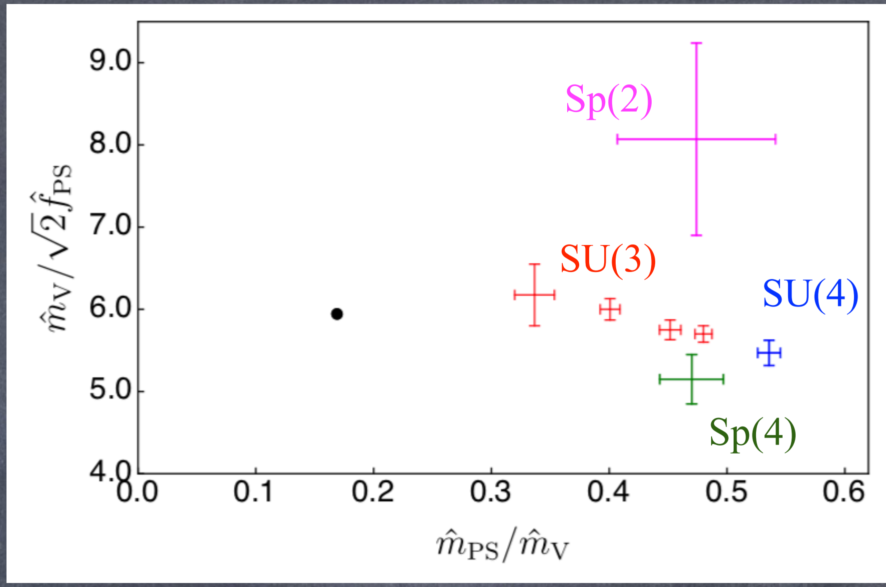
Sp(4) on the lattice

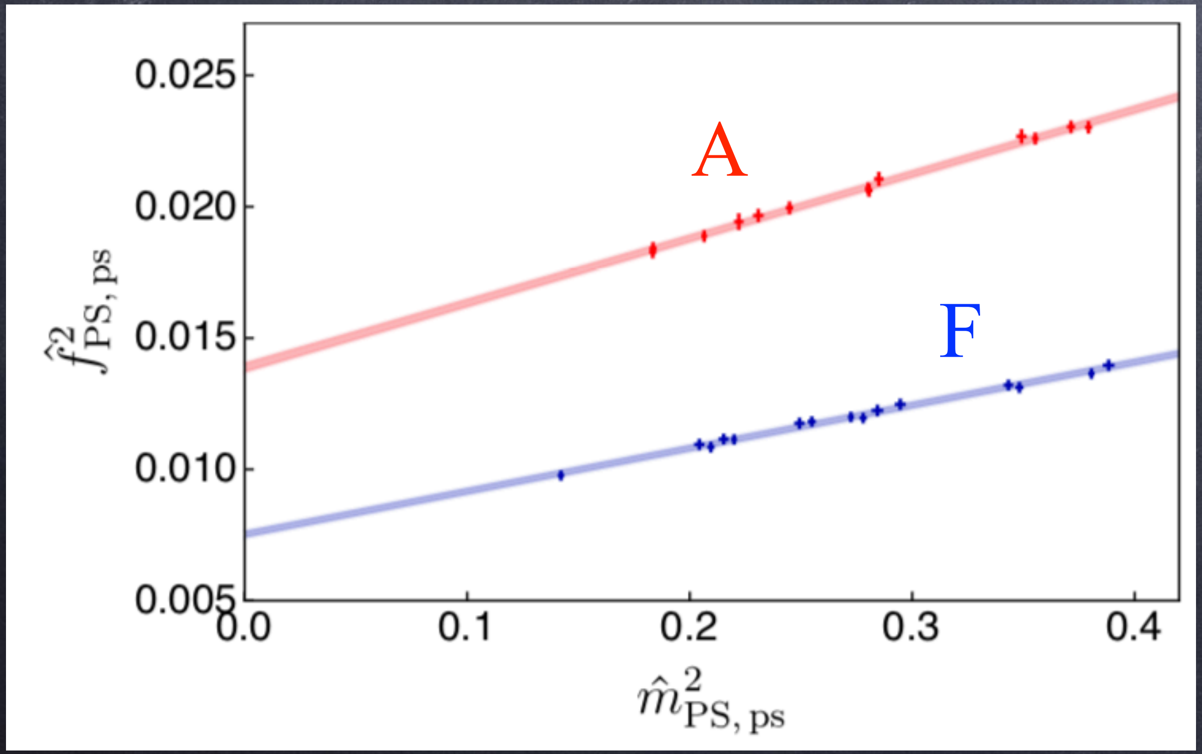
E.Bennet et al
1911.00437, 1912.06505

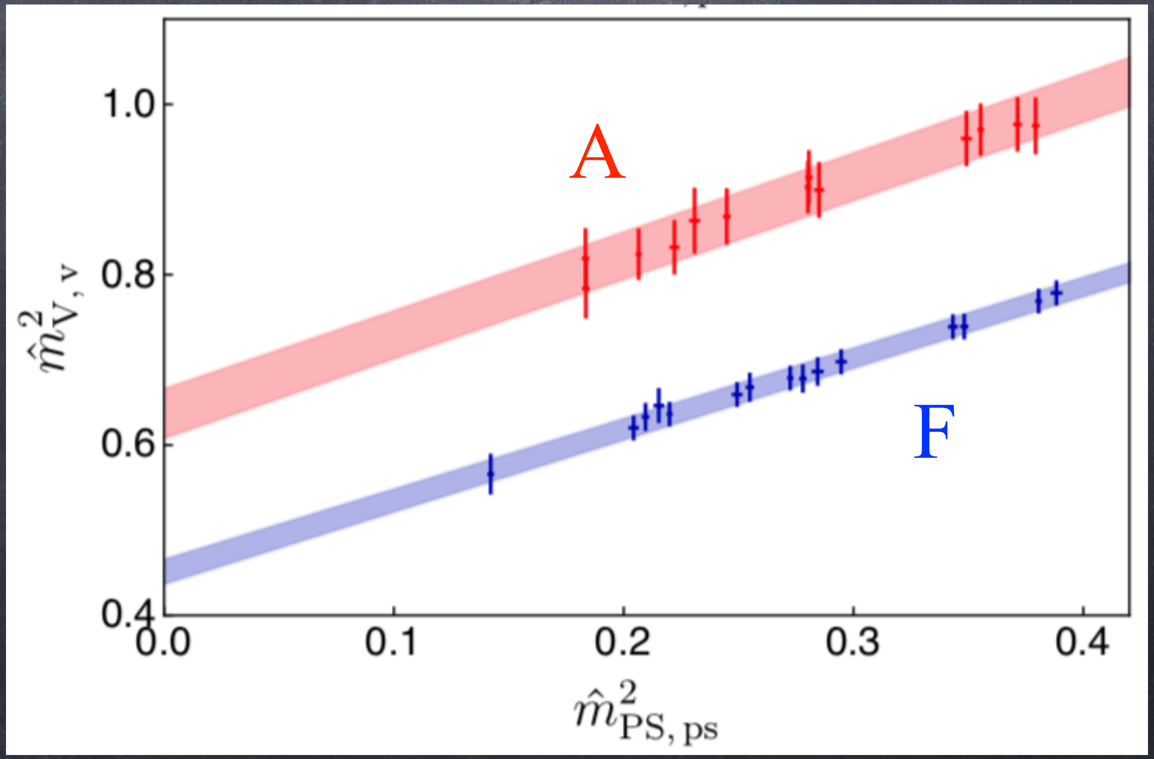
- This slide: 2F + 3A with quenched fermions (M8)

- Thursday parallel talks will give more updates

- Biagio Lucini, Jong-Wan Lee, Ho Hsiao, Jack Holligan







Other theories

- SU(4) w. 2A + 2F (rel. for models M6 and M11)

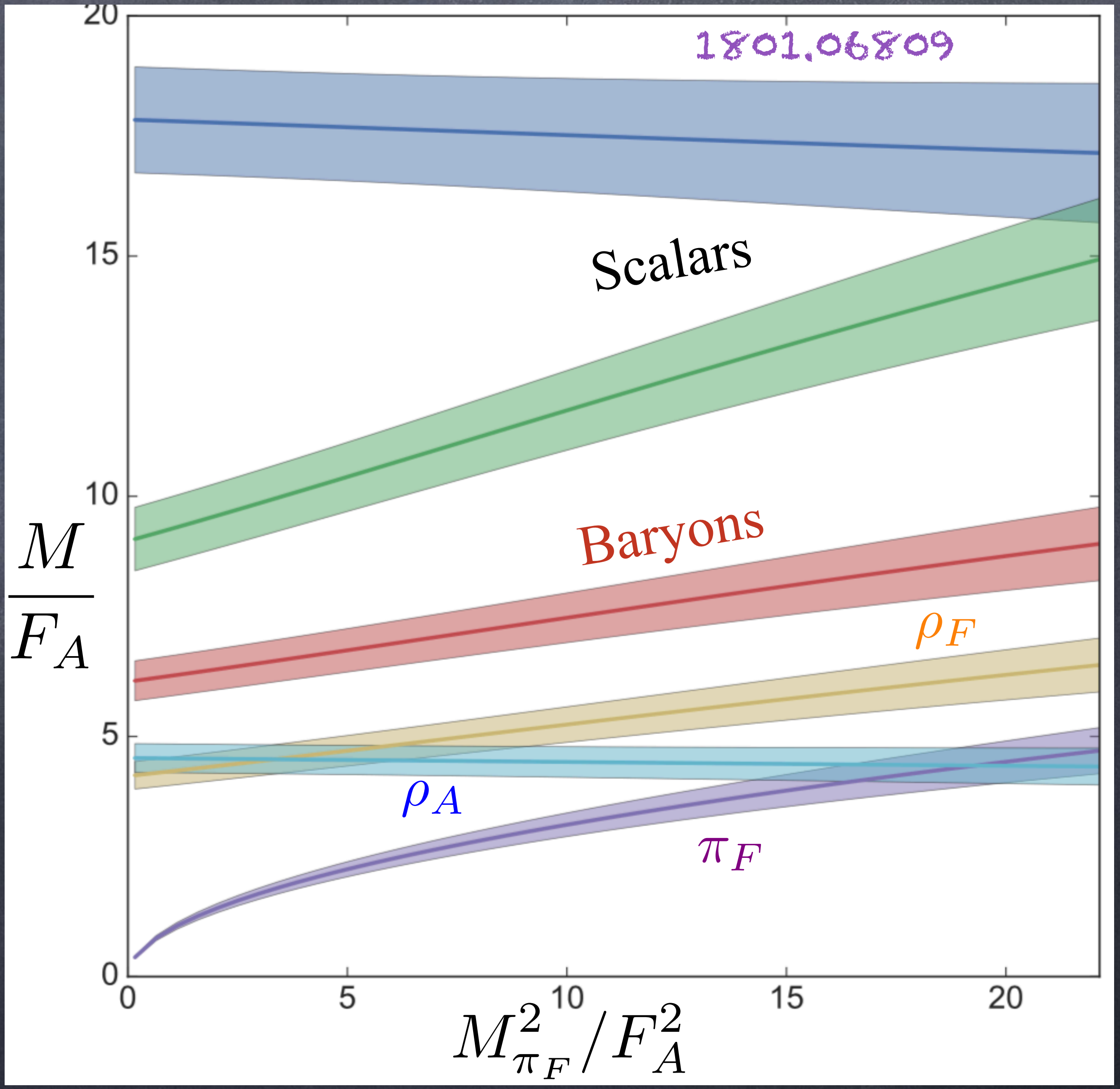
Thursday: Yigal Shamir
Friday: Alessandro Lupo

First computation of baryon masses!

$$\frac{M_{\mathcal{B}}}{F_A} \approx 6$$

Note: $\frac{F_F}{F_A} \approx 0.67$

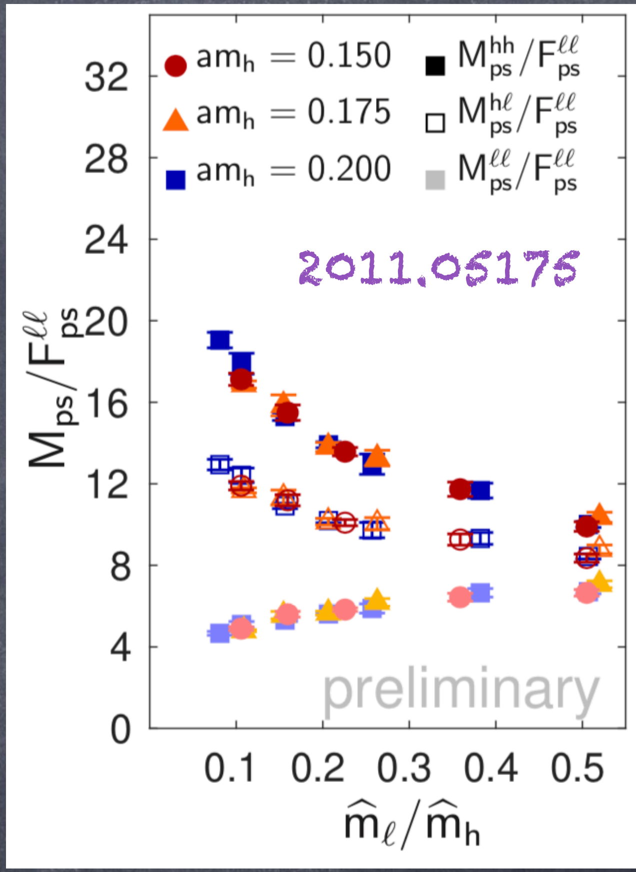
Tension reduced for M11



Other theories

- SU(4) w. 2A + 2F (rel. for models M5 and M11)

Thursday: Yigal Shamir
Friday: Alessandro Lupo



- SU(3) w. 8F or 4+6F

Thursday: Oliver Witzel,
James Ingolby

- SU(2) w. 2F (minimal template without PC)

Friday: Vincent Drach

Other theories

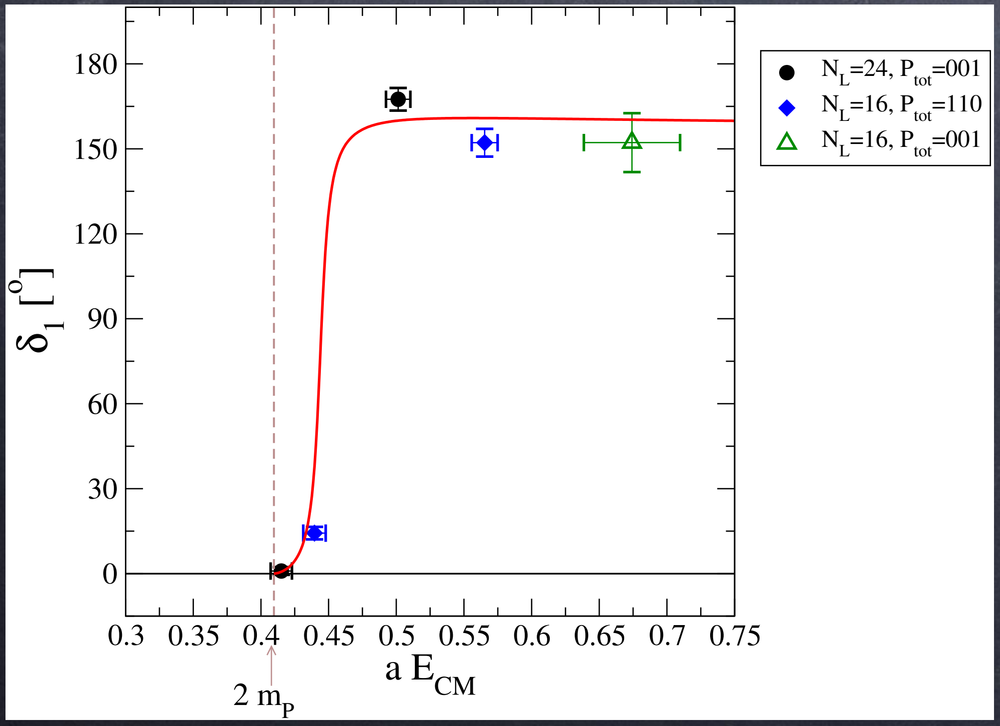
- SU(2) w. 2F (minimal template without PC) [see slide 4]

Friday: Vincent Drach

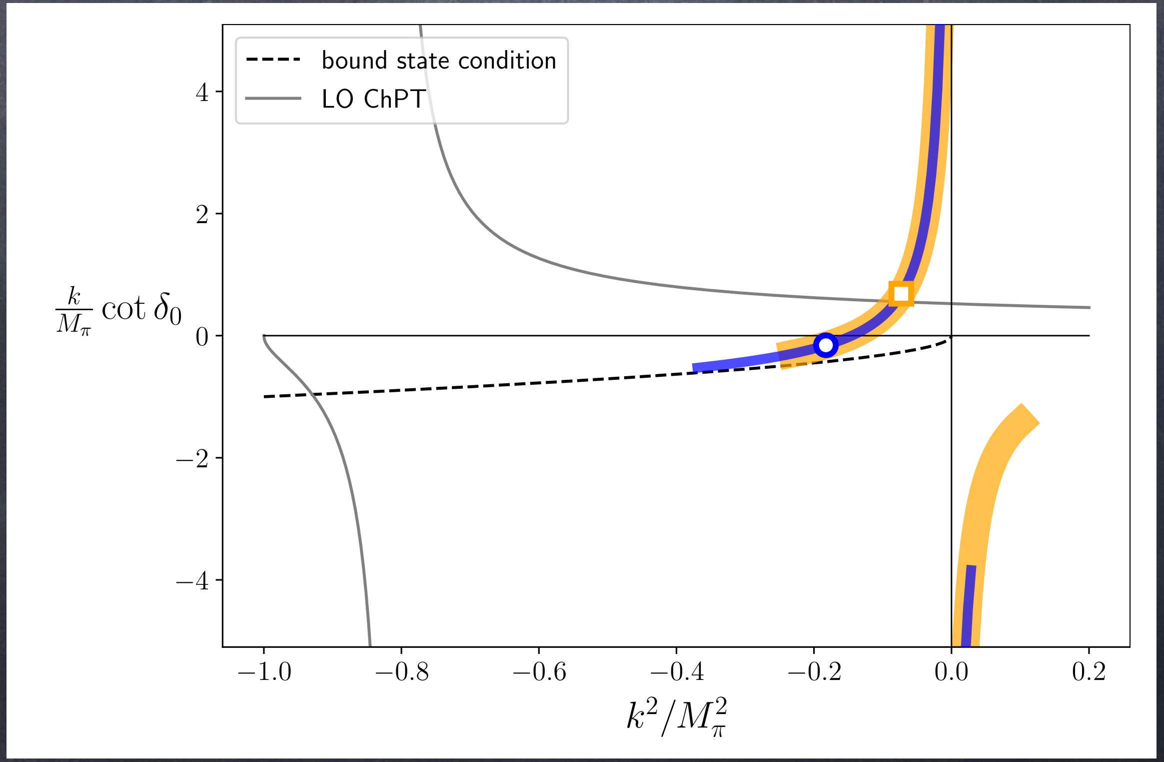
Scalar channel (0^{++}) :

- Determination of the flavour singlet coupling: the 0^{++} mixes with the would be Higgs boson altering its physical properties (see 1809.09146) and can be produced at the LHC.
- Results strongly suggest that in the explored region of fermion masses the sigma is a bound state, however more phenomenologically relevant regions (non stable sigma) will be soon investigated

Phase-shift in the vector channel - from 2012.09761



Phase-shift in the flavour singlet channel - from 2107.09974



A closer look at the top and Higgs masses

- At the EFT level, the computation can be done in two ways:
  1) Integrating out the massive Baryons that mix with the top quark.
  2) Introducing EFT operators in terms of the spurion couplings of the top to the composite operators (that generate Baryons)

- Are they equivalent?

A closer look at the top and Higgs masses

- Are they equivalent? No!

Consider a generic Ferretti model, with a light ALP coming from the spontaneous breaking of a global U(1) symmetry.

Baryon mixing, Q and S

$$-\mathcal{L}_{\rm PC} = y_L f e^{i\xi_Q \frac{a}{f_a}}\ \bar{Q} P_L q + y_R f e^{i\xi_S \frac{a}{f_a}}\ \bar{t} P_L S - y'_L H e^{-i\xi_S \frac{a}{f_a}}\ \bar{S} P_L q - y'_R H e^{-i\xi_Q \frac{a}{f_a}}\ \bar{t} P_L Q$$

$$-i\frac{m_t}{f_a}\left(\xi_Q \frac{y_L^2 f^2}{M_Q^2} + \xi_S \frac{y_R^2 f^2}{M_S^2}\right) \sim \mathcal{O}(y^4)$$

Top mass operator

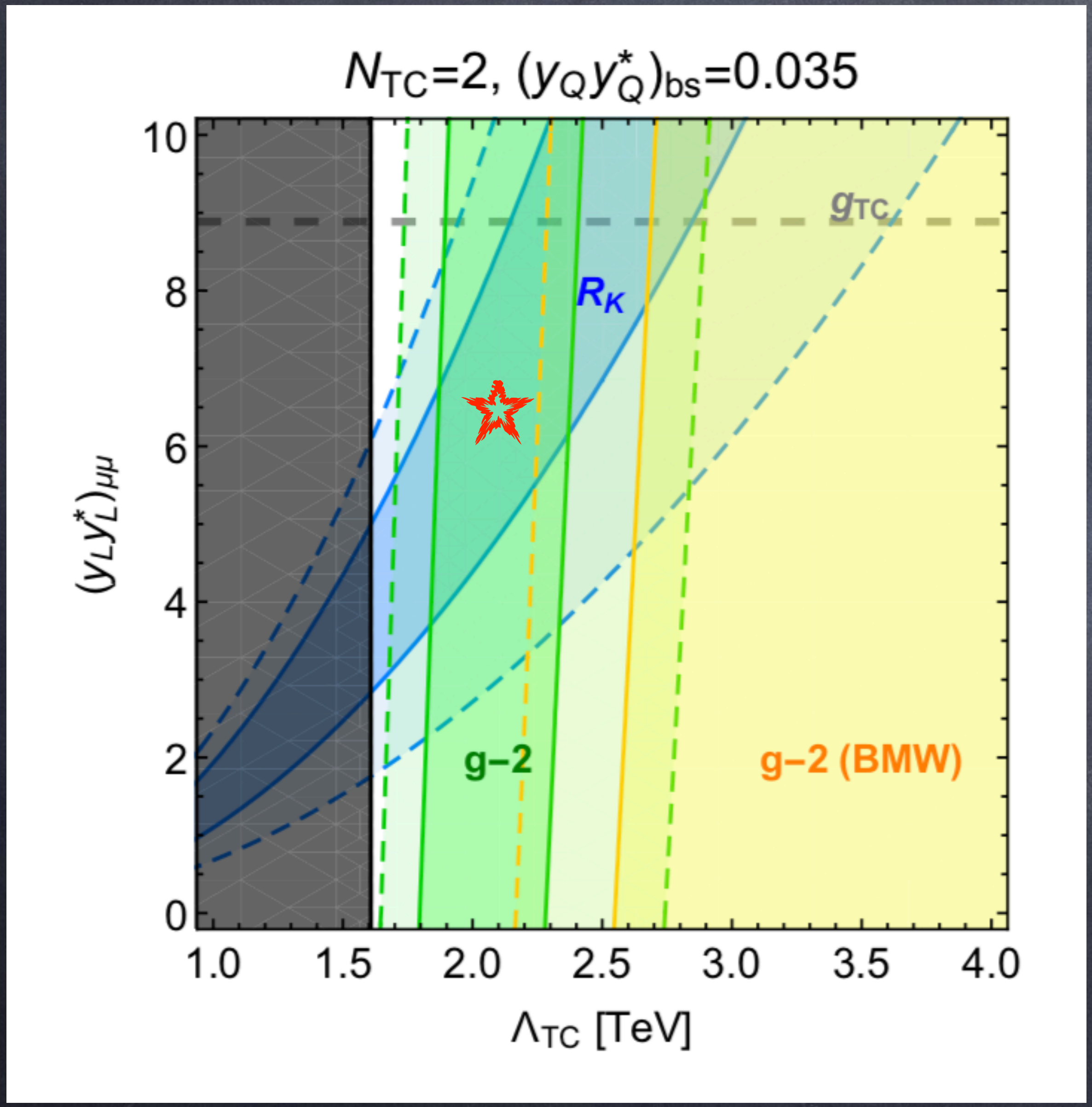
$$-\mathcal{L}_{m_t} = y_L y_R H e^{i(\xi_Q+\xi_S)\frac{a}{f_a}}\ \bar{t} P_L q$$

$$-i\frac{m_t}{f_a}(\xi_Q + \xi_S) \sim \mathcal{O}(y^2)$$

The results are parametrically different.
What is the impact on the Higgs mass calculation?
Heavy Baryons may not be disfavoured!

There's something about Muons

Technicolor strikes back?



$$R_K = \frac{\mathrm{BR}\,(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}\,(B^+ \to K^+e^+e^-)} = 0.846^{+0.044}_{-0.041}$$

- g-2 fixes the scale of new physics
- natural values for TC-like theories!

$$\Delta a_\mu|_{BSM} \approx \frac{m_\mu^2}{\Lambda^2}$$

$$\Lambda \approx 2 \text{ TeV} \approx 4\pi v$$

- RK requires large muon couplings (attainable in strong dynamics)

G.Cacciapaglia, C.Cot, F.Sannino
2104.08818

There's something about Muons

Technicolor strikes back?

- If this scenario is confirmed by the anomalies, the Higgs must be a dilaton-like light scalar.
- Lattice crucial in computing its mass and couplings!
- Which theory? [Back to slide 10]

Thursday parallel session:
Maarten Golterman, Chih Him Wong

Outlook

- Composite (Higgs or Dark Matter or...) models are a feasible route for New Physics
- Lattice input is dearly needed to establish the feasibility of these scenarios
- Intriguing hint: muon g-2 and R_K explainable via TC-like theories!
- Lots of useful results already available, and much more to come (stay tuned to the parallel sessions)