

# What next @ LHC | 3.5 TeV ?

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# Are we done?

- ◆ Seen the Higgs
- ◆ Inflationary cosmology works (?)





# Back to the drawing board

# Points

- ◆ Degrees of naturality
- ◆ Perturbative conformal naturality
- ◆ Conformality organizes PT in SM\*
- ◆ (Lattice) composite EW dynamics



\*H. Osborn Nucl.Phys. B363 (1991)

\*Antipin, Gillioz, Mølgaard, Sannino 1303.1525, PRD

\*Antipin, Gillioz, Krog, Mølgaard, Sannino 1306.3234, JHEP

$$\ln\mathrm{formulæ}$$

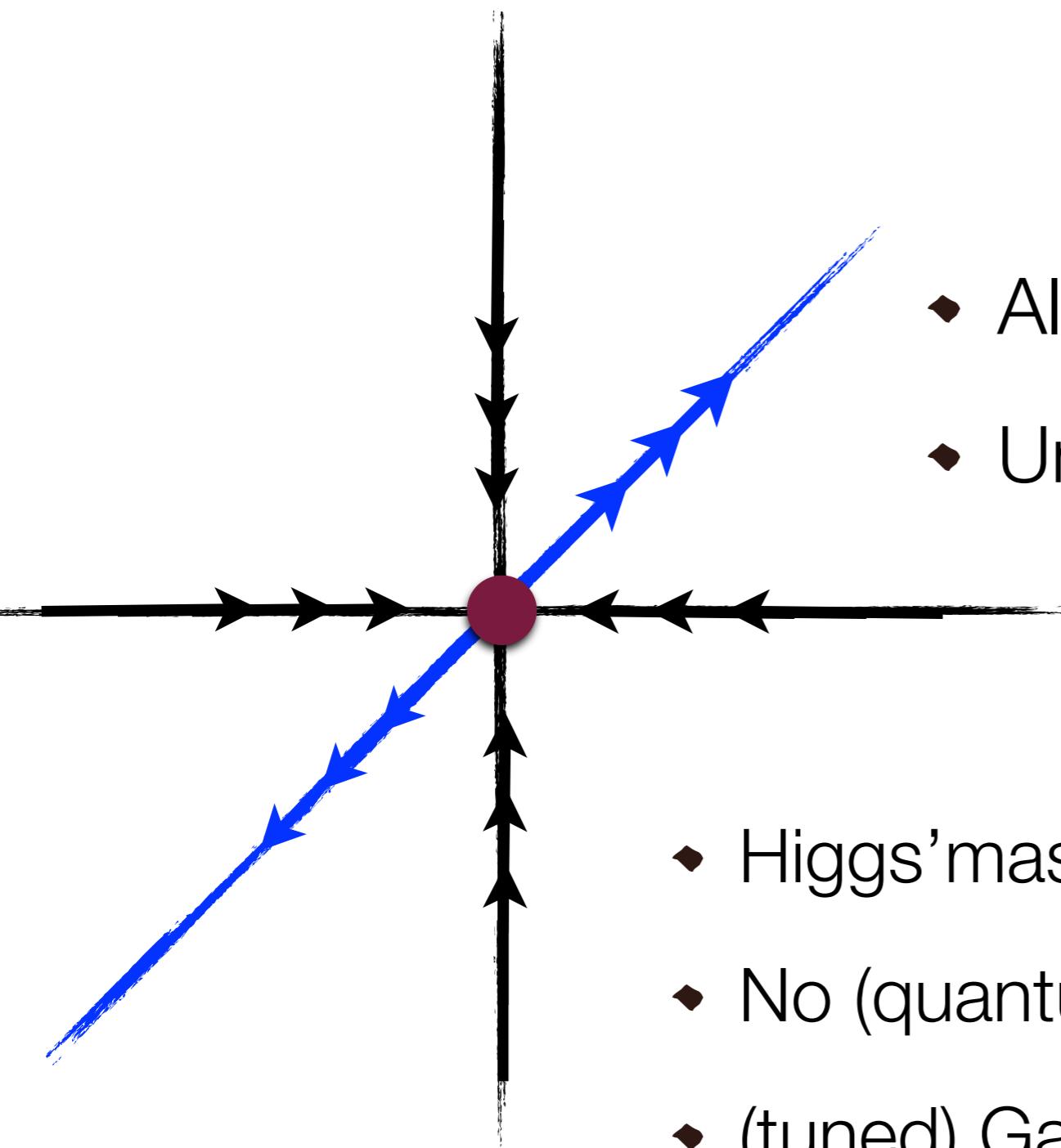
$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi_r)^2 - \frac{1}{2}m^2\phi_r^2 - \frac{\lambda}{4!}\phi_r^4 + \frac{\delta_Z}{2}(\partial_\mu \phi_r)^2 - \frac{\delta_m}{2}\phi_r^2 - \frac{\delta_\lambda}{4!}\phi_r^4$$

$$\phi_B \equiv \sqrt{Z} \phi_r \quad \delta_Z \equiv Z-1 \quad m^2 \equiv m_0^2 Z - \delta_m \quad \delta_\lambda \equiv \lambda_0 Z^2 - \lambda$$

$$Z=1+f_1(\lambda,g_i)\log\frac{\Lambda^2}{m_0^2}+\ldots\qquad\qquad\qquad\delta_m=f_2(\lambda,g_i)\Lambda^2+\ldots$$

$$m^2=m_0^2(1+f_1(\lambda,g_i)\log\frac{\Lambda^2}{m_0^2})-f_2(\lambda,g_i)\Lambda^2$$

# RG (un)naturality



- ◆ All stable directions = Fixed point
- ◆ Unstable direction = Fine-tuned FP
- ◆ Higgs' mass = unstable direction
- ◆ No (quantum) symmetry = No protection
- ◆ (tuned) Gauge - Yukawa are interesting FTs

# Degrees of (un)naturality

$$m^2 = m_0^2 \left( 1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2} \right) - f_2(\lambda, g_i) \Lambda^2$$

- ◆ Tuning = No prediction for BSM physics\*
- ◆ Tuning via “classical conformality”  $\Lambda = 0, m_0 = 0$
- ◆ Delayed naturality (Veltman)  $f_2 = 0$  Perturbatively
- ◆ **Perturbative natural conformality (PNC)**  $f_2 = 0, m_0 = 0$

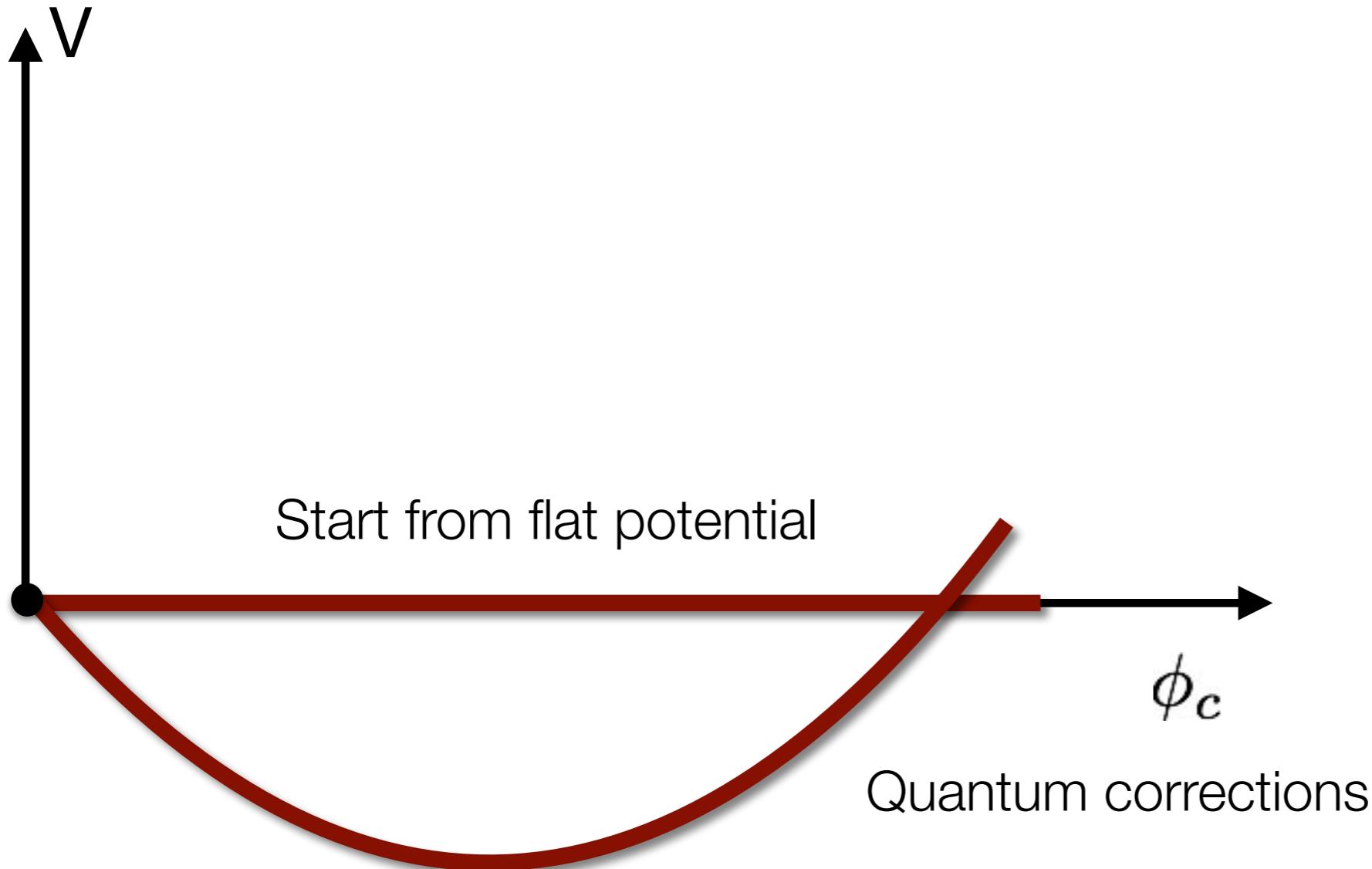
\*Vacuum stability

Antipin, Mojaza, Sannino 1310.0957, PRD

# PNC: Recipe

- ◆ Start with a Gauge - Yukawa theory
- ◆ No bare masses to scalars and fermions
- ◆ Mass generated via radiative corrections
- ◆ Coleman - E. Weinberg can condense scalars
- ◆ Forbid quadratic divergences via Veltman conditions

# Coleman & E. Weinberg



# Intriguing PNC model

- ◆ Conformal extension of the SM

Antipin, Mojaza, Sannino 1310.0957 PRD

$$V_0 = V_0^{SM} + \lambda_{HS} H^\dagger H S^2 + \frac{\lambda_S}{4} S^4 + y_\chi S(\chi\chi + \bar{\chi}\bar{\chi})$$

$$V_0^{SM} = \lambda (H^\dagger H)^2 - \frac{1}{2} \left( g^2 W_\mu^+ W^{-\mu} + \frac{g^2 + g'^2}{2} Z_\mu Z^\mu \right) H^\dagger H + y_t(\bar{t}_L, 0) (i\sigma^2 H^*) t_R + \text{h.c.}$$

- ◆ 1-loop stability = Veltman conditions

$$f_2 = 0$$

$$\begin{aligned} \lambda_{HS}(\mu_0) &= 6y_t^2(\mu_0) - \frac{9}{4}g^2(\mu_0) - \frac{3}{4}g'^2(\mu_0) \stackrel{\mu_0 \approx v}{\approx} 4.84 , & \lambda(\mu_0) &\approx 0 \quad \text{CW flatness} \\ \lambda_S(\mu_0) &= \frac{8}{3}y_\chi^2(\mu_0) - \frac{4}{3}\lambda_{HS}(\mu_0) \stackrel{\mu_0 \approx v}{\approx} \frac{8}{3}y_\chi^2(\mu_0) - 6.45 & \mu_0 &\simeq 246 \text{ GeV} \end{aligned}$$

- ◆ Higgs mass and its self-coupling vanish at tree-level

# 2 predictions

- ◆ Coleman E. Weinberg one-loop Higgs mass

$$m_h^2 = \frac{3}{8\pi^2} \left[ \frac{1}{16} (3g^4 + 2g^2 g'^2 + g'^4) - y_t^4 + \frac{\lambda_{HS}^2}{3} \right] v^2 \quad \Rightarrow \quad m_h \approx 126 \text{ GeV ,}$$

- ◆ Tree - level induced S-mass

$$m_S^2 = \lambda_{HS} v^2 \quad \Rightarrow \quad m_S \approx 541 \text{ GeV}$$

- ◆ S must be produced in pairs
- ◆ Higgs in 2 chi fermions is helicity suppressed

# Natural theories

$$m^2 = m_0^2 \left( 1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2} \right) - f_2(\lambda, g_i) \Lambda^2$$

- ◆ A symmetry exists protecting  $f_2 = 0$
- ◆ Cutoff is physical as in composite models

# Degrees of naturality



SM

Space of 4d theories

**Delayed naturality**

Veltman\*\*

**Natural**

Susy/Technicolor

**Classical CF (SSB via CW\*)**

Higgs = pseudo-dilaton,  
With UV cutoff is unnatural

**Perturbative quantum-CF**

CW + Veltman

New physics needed @ EW!

\* CW = Coleman-Weinberg

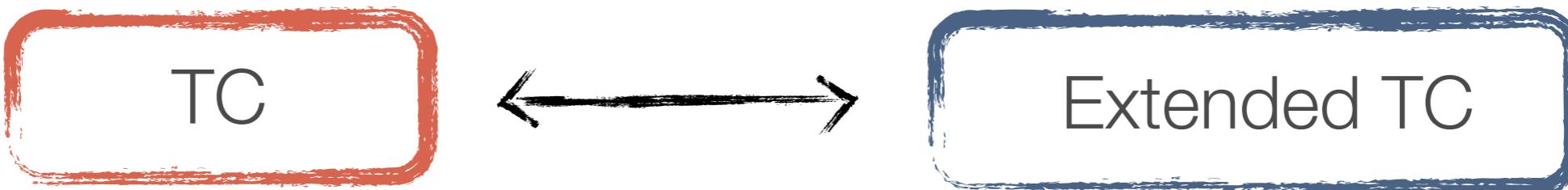
\*\*Perturbative cancellation of quadratic divergences

# Composite Higgs dynamics

$$DH^\dagger DH - V(H) + \bar{\Psi}_L H \psi_R$$

$$m_W^2 WW$$

$$m_\psi \bar{\psi}_L \psi_R$$



# Technicolor

Higgs is the lightest scalar excitation of the condensate

## Inside the box

- ◆ Break EW
- ◆ Theories available/unexplored
- ◆ Vacuum stable
- ◆ Natural

## Outside the box

- ◆ Fermion masses vs FCNC
- ◆ Electroweak precision data
- ◆ Light Higgs

# TC Higgs

TC - Higgs is the lightest spin-0 scalar made of TC-fermions

$$H \sim c_1 \bar{Q}Q + c_2 \bar{Q}QQ\bar{Q}Q + \dots$$

Will contain also a TC-glue component

QCD lightest scalar is  $f_0(500)$  with mass  $\sim 400\text{-}550$  MeV

Sannino & Schechter 95 PRD [ $'t$  Hooft 1/N, crossing, chiral, pole mass]

Harada, Sannino & Schechter 95 PRD [ $f_0(980)$ ], 96PRL

Pelaez - Confinement X - lecture

# Narrow state in strong dynamics?

Example  $f_0(980)$

$$\Gamma = 40 - 100 \text{ MeV} \quad m = 990 \pm 20 \text{ MeV}$$

Narrow because near/below 2 kaon threshold

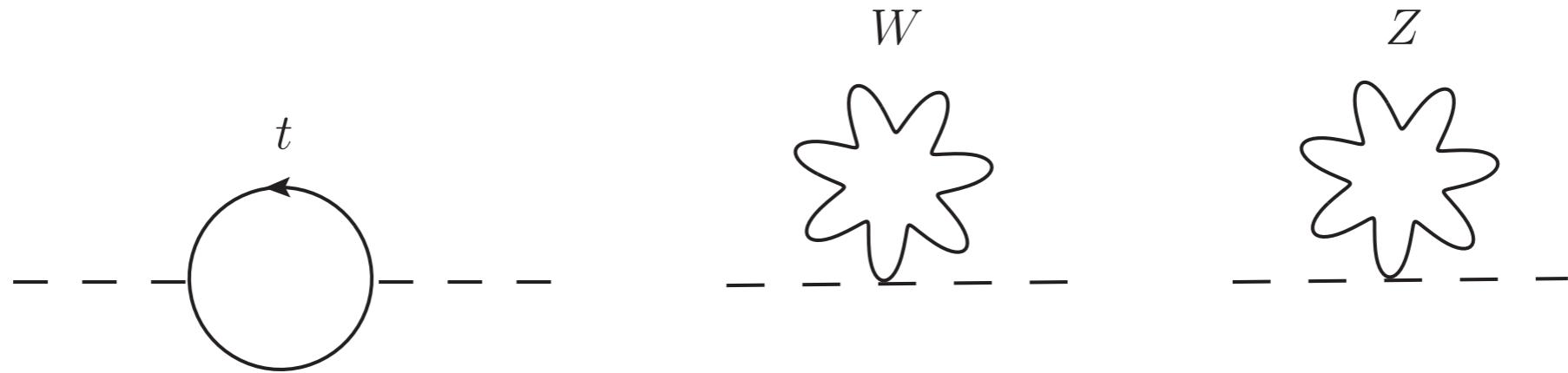
$$m_{2K\alpha\alpha} \simeq 987.4 \text{ MeV}$$

Harada, Sannino & Schechter 95 PRD [ $f_0(980)$ ], 96PRL [Large N apparent violation]

S. Weinberg 2013

# Top - corrections

$$\begin{aligned}\mathcal{L}_H \supset & \frac{2 m_W^2 r_\pi}{v} H W_\mu^+ W^{-\mu} + \frac{m_Z^2 r_\pi}{v} H Z_\mu Z^\mu - \frac{m_t r_t}{v} H \bar{t} t \\ & + \frac{m_W^2 s_\pi}{v^2} H^2 W_\mu^+ W^{-\mu} + \frac{m_Z^2 s_\pi}{2 v^2} H^2 Z_\mu Z^\mu\end{aligned}$$



$$M_H^2 = (M_H^{\text{TC}})^2 + \frac{3(4\pi\kappa F_\Pi)^2}{16\pi^2 v^2} \left[ -4r_t^2 m_t^2 + 2s_\pi \left( m_W^2 + \frac{m_Z^2}{2} \right) \right] + \Delta_{M_H^2}(4\pi\kappa F_\Pi)$$

Foadi, Frandsen, Sannino, 1211.1083 PRD

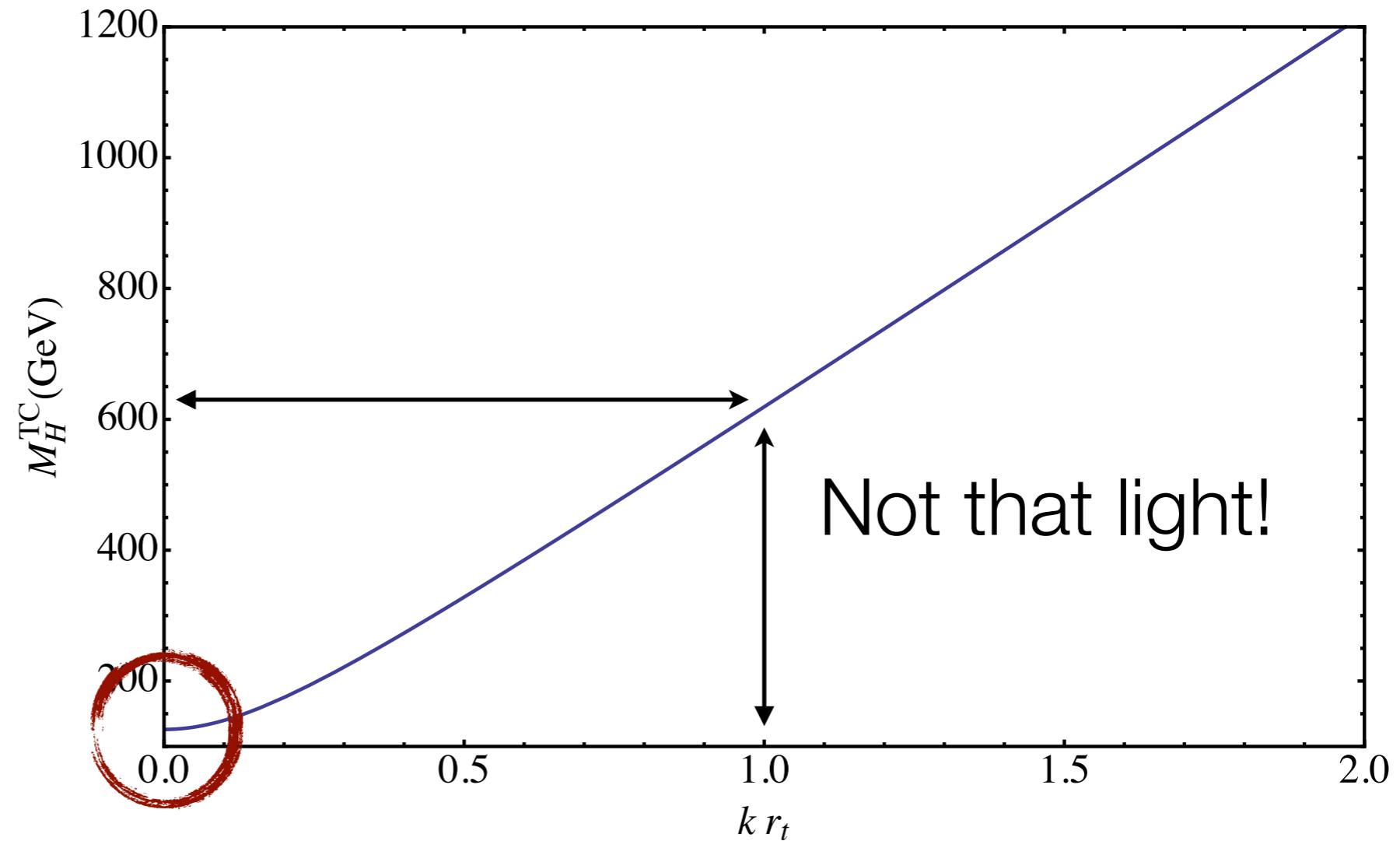
Cacciapaglia, Sannino 1402.0233 JHEP

# How light is the TC-Higgs ?

$$(M_H^{\text{TC}})^2 \simeq M_H^2 + 12 \kappa^2 r_t^2 m_t^2$$

$$\kappa r_t \sim \text{TC} \times \text{ETC}$$

$$F_\Pi = v$$



Narrow due to kinematics [Similar to  $f_0(980)$  in QCD]

# (Lattice) SU(3)<sub>s</sub> MWT

Sannino & Tuominen hep-ph/0405209

Fodor, Holland, Kuti, Nogradi, Schroeder, Wong, 1209.0391 [LHC collaboration]

$$M_\rho \simeq 1754 \pm 104 \text{ GeV}$$

$$M_{A_1} \simeq 2327 \pm 121 \text{ GeV}$$

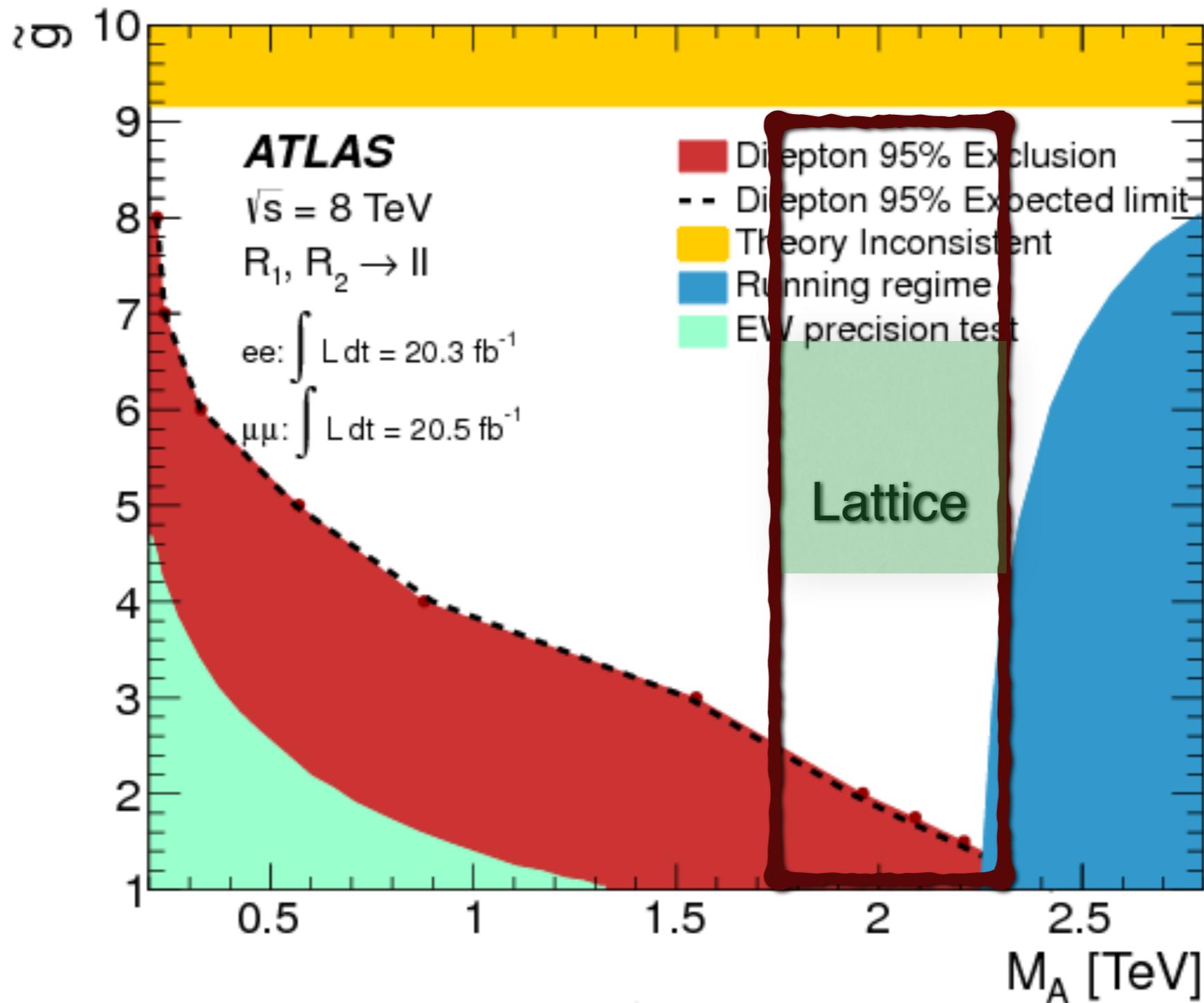
$$M_H^{TC} \approx 200 - 700 \text{ GeV}$$

Scalar mass in line with theory expectations: 1401.2176

US - Germany - Hungary collaboration



# Di-leptons -predictions for SU(3)<sub>S</sub> MWT



ATLAS arXiv:1405.4123

LHC can discover/rule-out MWT

# Composite Goldstone Higgs

D.B. Kaplan & H. Georgi, 84

Higgs is a pseudo goldstone boson

## Inside the box

- ◆ Higgs is massless
- ◆ Gauge boson couplings

Work in 4 dimensions

## Outside the box

- ◆ Underlying theory
- ◆ Higgs mass
- ◆ Fermion masses/couplings
- ◆ EW vacuum alignment

# Composite Dynamics 2014<sup>+</sup>

Cacciapaglia and Sannino arXiv:1402.0233 JHEP

- ◆ Unified TC and CH framework
- ◆ Fund 4D underlying theory
- ◆ Spectrum via lattice

## Fundamental Composite (Goldstone) Higgs Dynamics

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<sup>1</sup>*Université de Lyon, F-69622 Lyon, France: Université Lyon 1, Villeurbanne*

*CNRS/IN2P3, UMR5822, Institut de Physique Nucléaire de Lyon.*

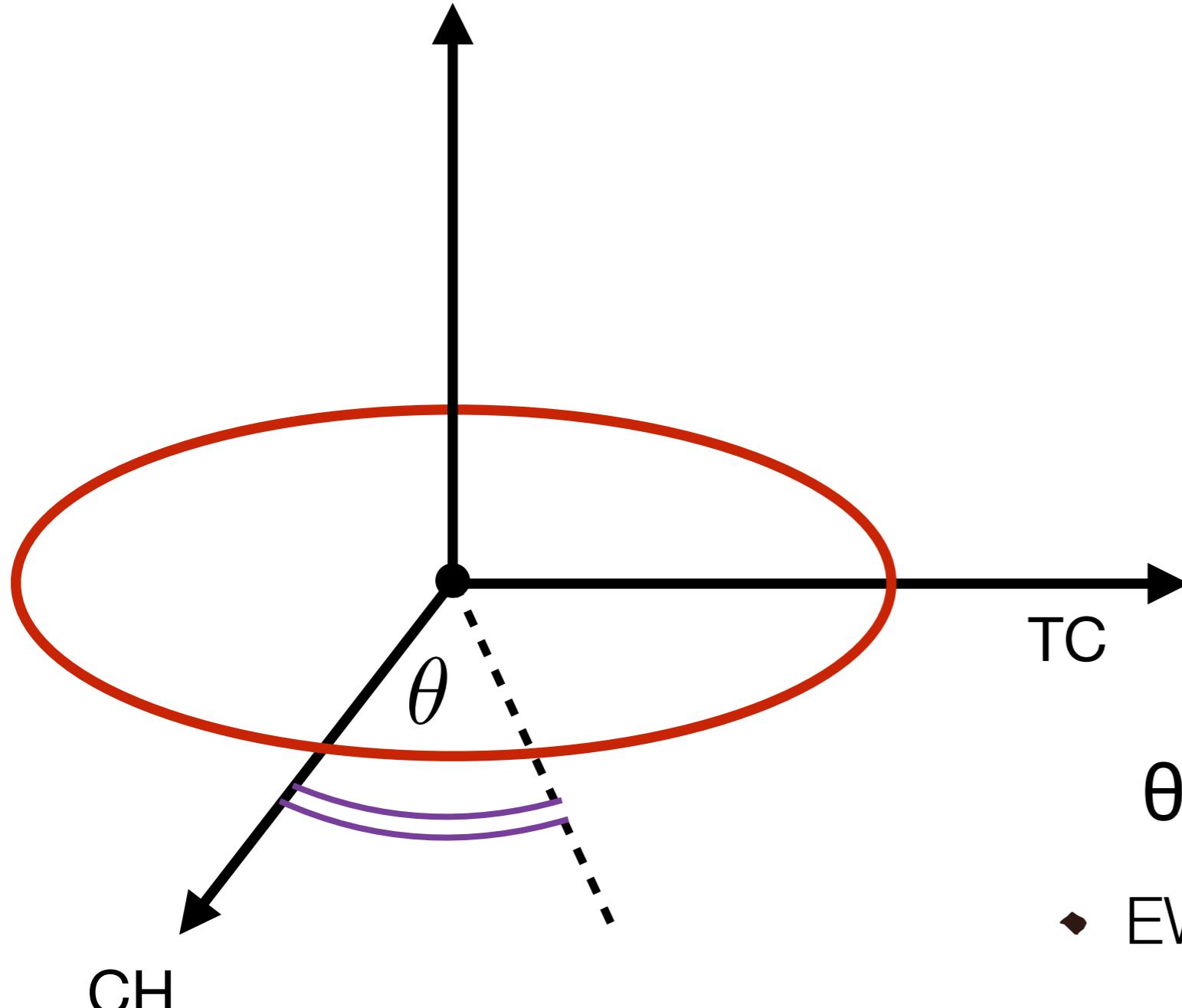
<sup>2</sup>*CP<sup>3</sup>-Origins & Danish Institute for Advanced Study DIAS,  
University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark*

### Abstract

We provide a unified description, both at the effective and fundamental Lagrangian level, of models of composite Higgs dynamics where the Higgs itself can emerge, depending on the way the electroweak symmetry is embedded, either as a pseudo-Goldstone boson or as a massive excitation of the condensate. We show that, in general, these states mix with repercussions on the electroweak physics and phenomenology. Our results will help clarify the main differences, similarities, benefits

*CoDyCE project: Unified pheno + Lattice @ LHC13.5 underway*

# How does it work?



$$\theta = 0$$

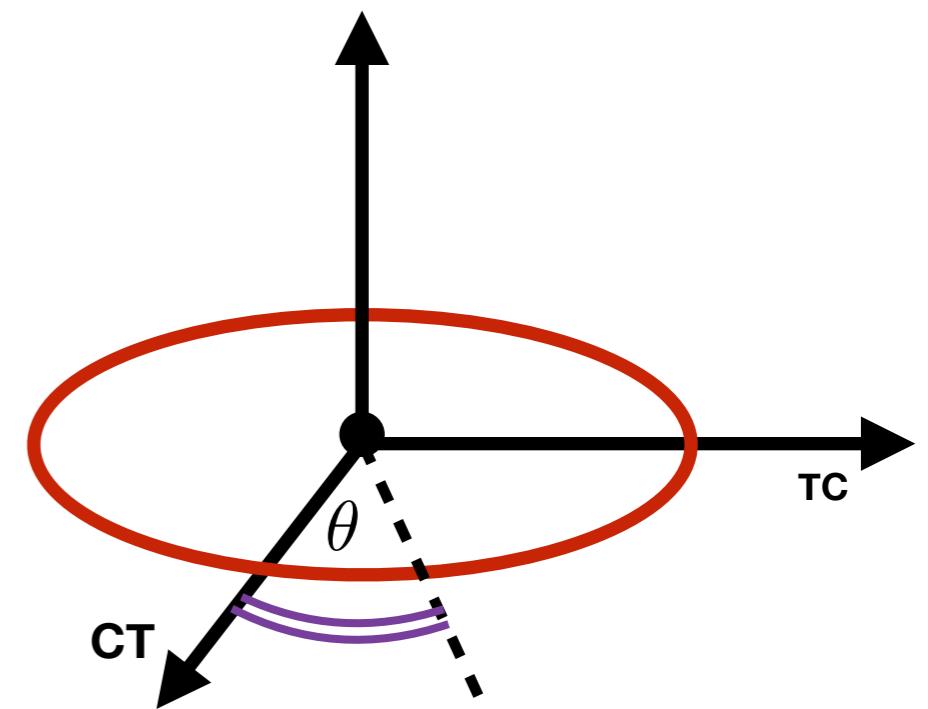
- ◆ EW does not break
- ◆ Higgs is exact GB

$$\theta = \pi/2$$

- ◆ EW breaks
- ◆ Higgs is massive excitation

# What fixes $\theta$ ?

- ◆ Gauge bosons quantum corrections
- ◆ Top corrections
- ◆ Explicit breaking of global symmetry

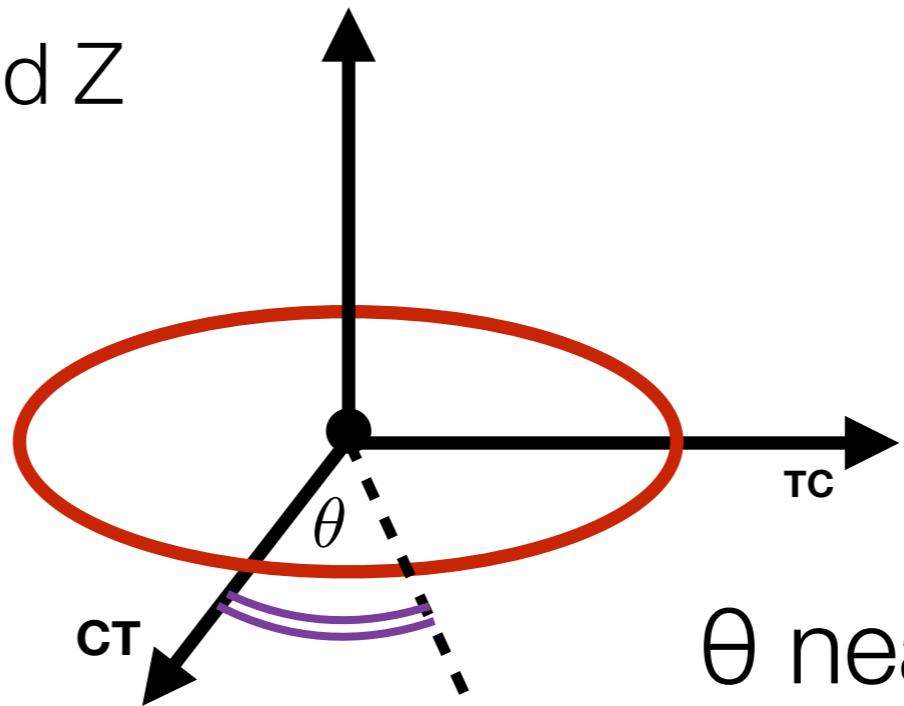


Mixed case is natural:  $0 < \theta < \pi/2$

# A pattern $SU(4) \rightarrow Sp(4) \sim SO(5)$

- ◆ Fundam. underlying 4d dynamics
- ◆ 5 Goldstone Bosons
- ◆ 3 eaten by  $W^+$ ,  $W^-$  and  $Z$

Appelquist, Sannino, 98, 99  
Ryttov, Sannino, 2008  
Katz, Nelson Walker, 2005  
Gripaios, Pomarol, Riva, Serra, 2009  
Galloway, Evans, Luty, Tacchi, 2010



$\theta$  near zero

$\theta$  near  $\pi/2$

- ◆ One GB is Higgs-like
- ◆ Other GB is SM neutral

- ◆ Complex GB, SM-neutral
- ◆ Natural DM candidate

# Generic properties

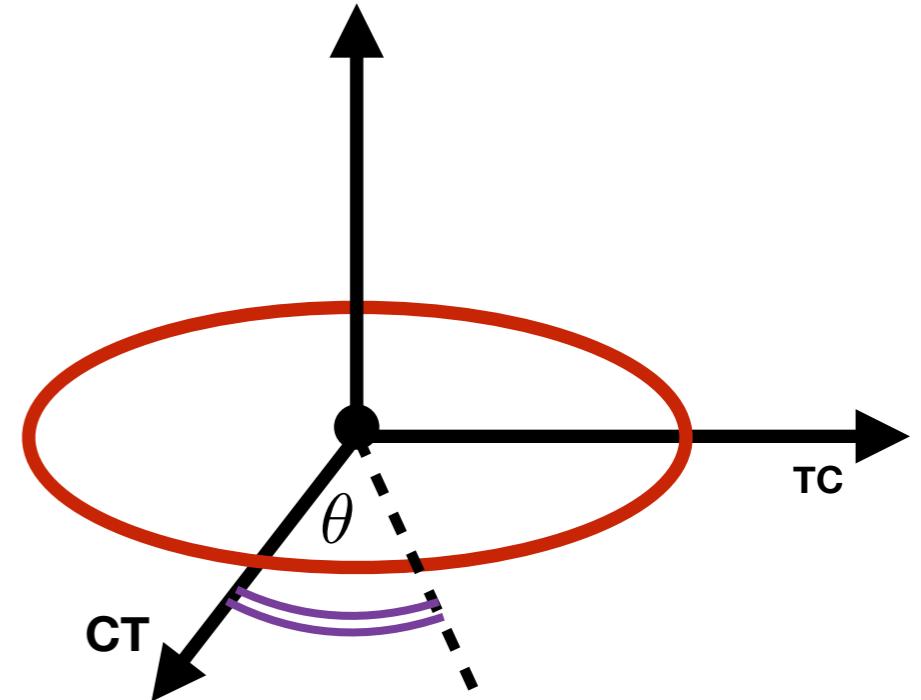
- ◆ TC-Higgs and PGB Higgs mix
- ◆ Top reduces TC-Higgs mass
- ◆ Top contributes PGB Higgs mass

@  $\theta$  near zero

$$\frac{g_{WW h_1}}{g_{WW h}^{SM}} = 1 + C_{h_2 h_1} \theta + \mathcal{O}(\theta^2)$$

$$\frac{g_{t\bar{t} h_1}}{g_{t\bar{t} h}^{SM}} = 1 + D_{h_2 h_1} \theta + \mathcal{O}(\theta^2)$$

- ◆  $h_1$  and  $h_2$  are eigenstates
- ◆ C & D vanish for large  $m_{h_2}$  mass
- ◆ Modified higgs phenomenology
- ◆ A new TeV scalar before vectors?



# Spin one resonances

- ◆ Simply rescale TC limit by  $\sin\theta$
- ◆ Small coupling to SM fermions via GB mixing

$$m_\rho = \frac{m_\rho^{TC}}{\sin \theta} \quad m_A = \frac{m_A^{TC}}{\sin \theta}$$

# Minimal Fund. Gauge Theory

$SU(2) = Sp(2)$  - Template

Appelquist, Sannino, 98, 99

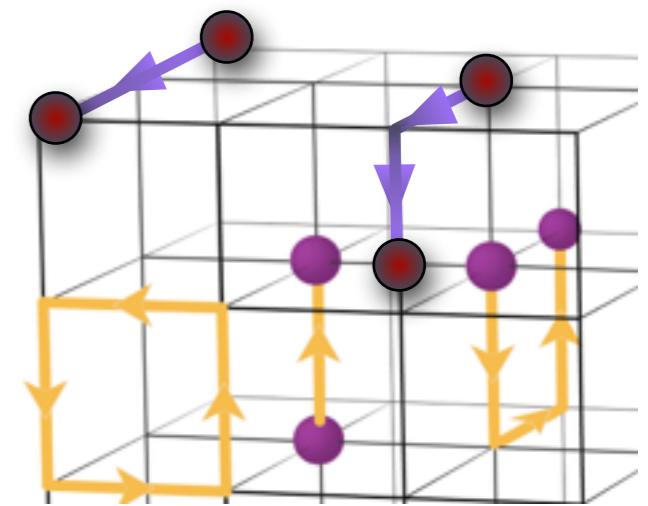
Ryttov, Sannino, 2008

Järvinen, Ryttov, Sannino, 2009

Lewis, Pica, Sannino 2012

Hietanen, Lewis, Pica, Sannino 2013

# Lattice for LHC



- ◆ SU(4) breaks to Sp(4)
- ◆ 5 Goldstone bosons
- ◆ Goldstone form factors

Lewis, Pica, Sannino 2012

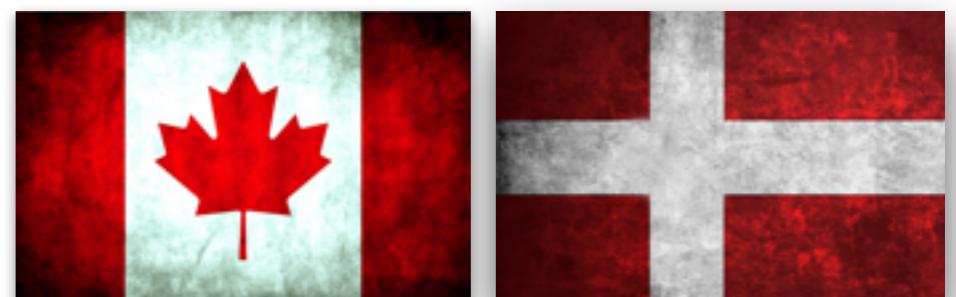
Hietanen, Lewis, Pica, Sannino 2013, 2014

Unified spin one spectrum predictions:

$$m_\rho = 2.5 \pm 0.5 \text{ TeV}/\sin \theta \quad m_A = 3.3 \pm 0.7 \text{ TeV}/\sin \theta$$

Canadian-Danish

Hietanen, Lewis, Pica, Sannino 1404.2794



# Summary

PNC: A state @ 500 GeV & derive Higgs mass

Minimal TC is testable + Intro to PGB Higgs

Unified description of TC & PGB Higgs

Next 0<sup>+</sup> and 1 states in TeV (multi-TeV) region

Fermion sector more model dependent

Unified pheno @ LHC 13.5 underway [CoDyCE project]

Lattice first important predictions!

# We are just not there yet!



Any shade of naturality implies new TeV physics