## BSM 3/3

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# Strong EWSB (Composite Higgs)





Supersymmetry is a weakly coupled solution to the hierarchy problem. We can extrapolate physics to the Planck scale, complete the MSSM in a GUT.

There is another way and it's already in use. Nature already employs a strongly coupled mechanism to explain why

> $\Lambda_{\rm QCD} \ll M_{\rm Planck}$  $\sim 1$  GeV  $10^{19}$  GeV









**Frank Wilczek** 

#### $\rightarrow$  exponential hierarchy generated dynamically  $\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm HIV}}=e^{-\frac{8\pi^2}{g_0^2 b}}, \ \Lambda_{\rm QCD}\leq \ {\rm GeV}$ Theory of strong interactions. Fix QCD coupling at some high scale





At strong coupling, new resonances are generated



At strong coupling, new resonances are generated

### QCD vs. EWSB

#### QCD dynamically breaks SM gauge symmetry  $\mathcal{O}(L)[L] \times \mathcal{O}(L)[R] \rightarrow \mathcal{O}(L)$  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$

 $\langle \bar{q}_L q_R \rangle \sim \Lambda_{\rm QCD}^3 \sim (GeV)^3$ 

### QCD vs. EWSB

QCD dynamically breaks SM gauge symmetry QCD dynamically breaks SM

$$
\langle \bar{q}_L q_R \rangle \simeq \Lambda_{\rm QCD}^3 \sim \langle Q_V \rangle^3
$$

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$$

 $\cos \theta = \frac{1}{2}$ The QCD masses of W/Z are small

$$
m_{\rm W,Z}\sim \frac{g}{4\pi}\Lambda_{\rm QCD}\sim 100~{\rm MeV}
$$

al compo en  $-$ s of W &  $\overline{Z}$  have till admixture of pions... Longitudinal components of W & Z have tiny

## Technicolor

#### Scaled up version of QCD mechanism Scaled un version of OCD mechanis

 $\langle \bar{q}'_L q'_R \rangle \sim \Lambda_{\rm TC}^3$ ,  $\Lambda_{\rm TC} \sim \text{TeV}$ 



 $*$  the Higgs as the dilaton as the last bastion …

# Composite Higgs

- Want to copy QCD, but extend pion  $\sf sector$  (QCD:  $\pi^0, \pi^\pm$  )
- Higgs as a (pseudo) Goldstone boson

### Need to learn about goldstone bosons…



#### Quantum Protection

Symmetries can soften quantum behaviour

$$
\mathcal{L} = |\partial_{\mu}\phi|^2 + \left[\mu^2|\phi|^2\right] - \lambda|\phi|^4 + \dots
$$

breaks susy → corrections must be proportional to susy breaking

Higgs mass term can be forbidden

$$
\mathcal{L} = |\partial_{\mu}\phi|^2 + \left[\mu^2|\phi|^2\right] - \lambda|\phi|^4 + \dots
$$

$$
\phi \to e^{i\alpha}\phi
$$

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$$
\phi \to \phi + \alpha
$$

works!

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$$

$$
\phi \to e^{i\alpha}\phi
$$

does not work

$$
\phi \to \phi + \alpha
$$

works!

Can we make the Higgs transform this way?



$$
\mathcal{L} = |\partial_{\mu}\phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \dots
$$
  
use 
$$
\phi(x) = \frac{1}{2}e^{i\pi(x)/f}(f + \sigma(x))
$$

$$
\mathcal{L} = |\partial_{\mu}\phi|^{2} + \mu^{2}|\phi|^{2} - \lambda|\phi|^{4} + \dots
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use 
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$$

$$
\partial^{\mu}\phi^{\dagger}\partial_{\mu}\phi = \frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma + \frac{1}{2}(1 + \sigma/f)^{2}\frac{1}{2}\partial^{\mu}\pi\partial_{\mu}\pi
$$

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\n
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$$
\n
$$
V(|\phi(x)|^{2}) = V(\sigma(x))
$$
\nno dependence on  $\pi(x)$ 

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\n
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$$
\n
$$
V(|\phi(x)|^{2}) = V(\sigma(x))
$$
\nno mass term\nno dependence on  $\pi(x)$ 

$$
\frac{1}{2} (1 + \sigma(x)/f)^2 \frac{1}{2} \partial^{\mu} \pi \partial_{\mu} \pi + \frac{1}{2} \partial^{\mu} \sigma \partial_{\mu} \sigma - V(\sigma(x))
$$

Using this parameterization there's a new symmetry:

$$
\pi(x) \to \pi(x) + \alpha
$$

because

$$
\partial_{\mu}(\pi(x)+\alpha)=\partial_{\mu}\pi(x)
$$

$$
\frac{1}{2} (1 + \sigma(x)/f)^2 \frac{1}{2} \partial^{\mu} \pi \partial_{\mu} \pi + \frac{1}{2} \partial^{\mu} \sigma \partial_{\mu} \sigma - V(\sigma(x))
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$$

But what happened to the U(1) symmetry ? Fields are real…

#### $\phi \rightarrow e^{i\alpha}\phi$ But what happened to the U(1) symmetry ?

$$
e^{i\pi(x)/f}(f+\sigma(x)) \to e^{i\alpha}e^{i\pi(x)/f}(f+\sigma(x))
$$

$$
\begin{array}{c}\n\longrightarrow \\
\begin{array}{c}\n\sigma(x) \to \sigma(x) \\
\pi(x) \to \pi(x) + \alpha\n\end{array}\n\end{array}
$$

#### Phase rotation becomes shift symmetry

#### $\phi \rightarrow e^{i\alpha}\phi$ But what happened to the U(1) symmetry ?

$$
e^{i\pi(x)/f}(f+\sigma(x)) \to e^{i\alpha}e^{i\pi(x)/f}(f+\sigma(x))
$$

$$
\begin{array}{c}\n\sigma(x) \to \sigma(x) \\
\pi(x) \to \pi(x) + \alpha\n\end{array}
$$

#### Phase rotation becomes shift symmetry

 $\pi(x)$  is massless **but** also no  $\|\cdot\|$  gauge couplings

- 
- potential
- yukawas

### Semi-realistic model



$$
\begin{array}{ll}\n\blacklozenge & \Lambda = 4\pi f & \text{UV completion} \\
\hline\nm_{\rho} = g_{\rho} f & \text{resonances} \\
v = 246 \,\text{GeV} & \text{EW scale}\n\end{array}
$$

$$
\mathbf{P} \mathbf{A} \mathbf{B} \mathbf{
$$

# Goldstone bosons = # broken generators  $H$  **u**olustone bosons –  $H$  broken  $\frac{SPI(2)}{W}$ 

$$
\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}
$$

$$
H_1 \quad (H_1) \quad \text{CFT}(\Omega)
$$

$$
\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} SU\{\frac{1}{2} + \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\partial}{\partial V} \sqrt{3} & \frac{\partial}{\partial V} \\ \frac{\partial}{\partial V} \sqrt{3} & \frac{\partial}{\partial V} \sqrt{3} \\ \frac{\partial}{\partial V} \sqrt{3} & \frac{\partial}{\partial V} \sqrt{3} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial V} & \frac{\partial}{\partial V} \\ \frac{\partial}{\partial V} \sqrt{3} & \frac{\partial}{\partial V} \sqrt{3} \end{pmatrix}
$$

$$
\begin{aligned} &\mathbf{Expa}(\mathbf{H}_1) = SU(2) \\ &\mathfrak{F}(X) = \begin{pmatrix} H_1(x) \\ H_2(x) \\ -\frac{2}{\sqrt{2}}\eta(x) \end{pmatrix} \mathfrak{F} = \frac{1}{\sqrt{2}} e^{i\mathbf{H}} \mathcal{H} + \begin{pmatrix} \mathcal{H} \\ 0 + \lambda \\ f + \sigma \end{pmatrix} + \mathbf{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathcal{H} \\ \mathcal{H} \\ \mathcal{H} + \sigma \end{pmatrix} \end{aligned}
$$

 $H =$  $H_1$  $H_2$ ⇥ Contains a Higgs:  $H = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} = SU(2)$  doublet  $SU(3)$  **H** 

 $SU(3) \rightarrow SU(2)$ 

# pGB Higgs

Unbroken gauge symmetry in global SU(2), dynamics generates 'vacuum mis-alignment' PNGB SYMMETS (CONT'd)



$$
\langle \Phi \rangle = \frac{f}{\sqrt{2}} \left( \frac{0}{\sin \theta} \right) \frac{SU(2)_L}{v}
$$
\n
$$
f \sin \theta
$$
\n
$$
f \sim \text{scale of new physics} \quad \theta
$$
\n
$$
\ll 1 \Leftrightarrow f \gg v \sin \theta \ll 1 \Leftrightarrow f \gg v \text{ (SM limit)}
$$
\n
$$
H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}
$$

## Collective Breaking

We now want to add a yukawa coupling to give mass to the top quark

$$
\lambda_t \overline{Q}_i H_i^c t_R \qquad \text{ i: sum over SU(2)}
$$

Fundamental field is a triplet

$$
\phi = \exp\left\{i \begin{pmatrix} & & & h_1 \\ & & & h_2 \\ h_1^* & h_2^* & \end{pmatrix}\right\} \begin{pmatrix} \\ & \\ f \end{pmatrix}
$$

#### Top yukawa: 1st try  $\sum \lambda_t \overline{\phi}_i H_i^c t_R$  works, gives mass to the top 2 *i*

… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:
## Top yukawa: 1st try  $\overline{\blacktriangledown}$ 2 *i*  $\lambda_t \overline{\phi}_i H_i^c t_R$  works, gives mass to the top

… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:



# Collective breaking

Example:  $SU(3) \rightarrow SU(2)$  (ignore  $U(1)_Y$  again)  $\langle \Phi_1 \rangle =$ 1  $\overline{\sqrt{2}}$  $\sqrt{ }$ ⇧⇤ 0 0 *f*1 ⇥  $\langle \Phi_2 \rangle =$ 1  $\overline{\sqrt{2}}$  $\sqrt{ }$  $\overline{\mathcal{L}}$ 0 0 2 ⇥  $\overline{\phantom{a}}$ 

Gauge full  $SU(3) \Rightarrow$  exact symmetry

$$
\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \qquad t_{1R}, \ t_{2R}, \ b_R
$$





## Collective Symmetry Breaking



*t*?*<sup>R</sup>*



#### Minimal composite Higgs The Higgs doublet H is the NG boson associated G **→** G' to the global symmetry G **→** G' of a new strong Agashe et. al

Minimal bottom up construction  $\Sigma = \exp(i\sigma^i \chi^i(x)/v)$   $\exp(2i T^{\hat{a}} \pi^{\hat{a}}(x)/f)$   $T^{\hat{a}} \in \text{Alg}(G/G')$ 

 $SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R$ SO(5) **→** SO(4)~SU(2)LxSU(2)R four real NG bosons:

$$
= \frac{f^{2}}{2} (D_{\mu}\phi)^{T} (D^{\mu}\phi)
$$
\n
$$
C = \frac{f^{2}}{2} (D_{\mu}\phi)^{T} (D^{\mu}\phi)
$$
\n
$$
C = \frac{f^{2}}{2} (D_{\mu}\phi)^{T} (D^{\mu}\phi)
$$
\n
$$
S = \frac{SO(5)}{SO(4)} = S^{4}
$$
\n
$$
\phi^{T} \phi = 1
$$
\n
$$
\phi^{T} \phi = 1
$$
\n
$$
S = \frac{S}{S}
$$
\n
$$
\phi = e^{i\pi}
$$
\n
$$
\phi = e^{i\pi^{a}T^{a}/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin(\pi/f) \times \begin{pmatrix} \hat{\pi}^{1} \\ \hat{\pi}^{2} \\ \hat{\pi}^{3} \end{pmatrix} \begin{pmatrix} \hat{\pi}^{1} \\ \sin(\theta + h(x)/f) \end{pmatrix} e^{i\chi^{i}(x)A^{i}/\pi} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}
$$
\n
$$
I = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} e^{i\pi^{a}T^{a}/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin(\pi/f) \times \begin{pmatrix} \hat{\pi}^{1} \\ \hat{\pi}^{3} \\ \hat{\pi}^{4} \end{pmatrix} \begin{pmatrix} \hat{\pi}^{1} \\ \hat{\pi}^{2} \\ \hat{\pi}^{3} \end{pmatrix} = \begin{pmatrix} \sin(\theta + h(x)/f) & e^{i\chi^{i}(x)A^{i}/\pi} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \end{pmatrix}
$$
\n
$$
I = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} \frac{\hat{\pi}^{1}}{2} \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} \frac{\hat{\pi}^{2}}{2} \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} \frac{\hat{\pi}^{3}}{2} \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} \frac{\hat{\pi}^{2}}{2} \\ 0 \\ 0 \end{pmatrix} =
$$

mym  $\blacklozenge$ 

### Linear couplings with the summer SU(3) can be said  $\sim$ EING COUPINS

 $\mathcal{L} \triangleq \exists \lambda L dL dL dR + A R^u R^d R dR d^c L + h.c.$  $\mathcal{L} = \lambda_L \bar{d}_L \partial_R + \lambda_R \bar{u}_R \partial_L + \partial_R \bar{u}_R \partial_L$ 



## Deviations from SM Higgs VIII JI I

*SO*(5) *SO*(4)  $4$  NGBs transforming as a (2,2) of  $\mathbb{R}^2$  of  $\mathbb{R}^2$  of  $S$  (2) of  $S$  (2) of  $S$  (3) of  $\mathbb{R}^2$ Goldstone boson nature

$$
f^2 \left| \partial_\mu e^{i\pi/f} \right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2} \left[ \partial_\mu (H^\dagger H) \right]^2 + \frac{c'_H}{2f^4} (H^\dagger H) \left[ \partial_\mu (H^\dagger H) \right]^2 + \dots
$$

Giudice et al. JHEP 0706 (2007) 045



## EW precision tests *W, Z*



### Higgs couplings 125*GeV). Lower plot:CMS with data taken at m<sup>h</sup>* = 125*GeV. A flat prior a* 2 [0*,* 3]*, c* 2 [3*,* 3] *is used.*

Have been measured to 20-30% precision Pseudo Nambu-Goldstone boson (PNGB) nature of







Red points at  $\xi \equiv (v/f)^2 = 0.2, 0.5, 0.8$ 



4

Table 1: Impact of the heavy-quark masses on the inclusive NLO cross sections. All results are  $\lim_{m \to \infty} \frac{\text{max}}{\text{max}}$  and the masses on the inclusive NLO cross sections. All results are  $\infty$  result.  $\frac{200}{200}$   $\frac{1.185}{200}$   $\frac{1.185}{1.134}$   $\frac{1.134}{200}$   $\frac{1.134}{200$ If the neavy-quark masses on the inclusive NLO cross sections. All results are  $m_t \to \infty$  result.  $\frac{200}{200}$   $\frac{1.185 \cdot 1.54}{200}$  1.185:154 1.134<br>
show particles running in the low of the local canonical top control to control the induce MLQ cross, sections. All recors a

 $C_{\text{C}}$   $C_{\text{C}}$  in  $\Gamma$  Chefter emphasi  $\mathcal{C}$ that the mass effects change the cross section at the few percent level, and the mass eneeds enange the eross section at the rew percent fever,  $\mathcal{P}(\mathcal{P})$  and hestally  $\mathcal{P}(\mathcal{P})$  is defined to the top-duck  $\mathcal{P}(\mathcal{P})$  and  $\mathcal{P}(\mathcal{P})$ h ishdseotwathedne<u>gat</u>ine interference with the LU [5, 97] and found its with those obtained with the numerical program HIGLU [5, 7] and fo<br>Its with those obtained with the numerical program HIGLU [5, 7] and fo We describe the impact of natural subsets of  $SM$  consider the impact of n cross  $SM$  $\Delta c$ We plot the  $p_T$  spectrum of the Higgs boson at NLO with full dependence and bottom marks and we compare it with the corresponding result in k contribution is considered. Both results are normalized to the result obtained in the right in the right limit. To better emphasize the impact of the bottom model of the right  $\ddot{4}$ **L** ross 地工作 *|H|* 2 G (CERSS) **Aceim** 2例 |**httlbution contribution**<br>
and the cross section process the cross section by a few percent. The fact of the cross of the cross sections of **2***u***<sub>1</sub>**<br>22 F*u***<sub>1</sub> G</del><sub>2</sub> Freeds (Catilical Press) Section 1, The Lefter is encent, Ic** *U***<sub>4</sub> G<sub>L</sub> H U<sub>4</sub> C<sub>4</sub> GL H U<sub>4</sub> CH U<sub>4</sub>** 2  $\frac{\partial^2 (y \partial^2 \mathbf{g} \mathbf{a})}{\partial \mathbf{g}}$  munder that program HIGLU  $[5, \frac{7}{5}]$  and ip  $\left(\frac{1}{2} \mathbf{g} + \mathbf{y} \right)$   $\left(\frac{1}{2} \mathbf{g} + \mathbf{y} \right)$  $\Delta c$  $\text{MGrisRef:}$  that the mass effects change the cross section at the few ipercent level, h ish dae ot oat hed nei<u>t at</u> it is a mutaefor emprogrikk mile to for quark op the top in we have lts with those obtained with the numerical program HIGLU  $[5, 7]$  and pump  $(\frac{1}{2} \sqrt[4]{\zeta})$  =<br>ider the impact of n<br>ider the impact of n<br> $\frac{\text{SM}}{\zeta} = (1 + (c_g - c_t)v^2)^2$  is have  $\frac{1}{\zeta} = \frac{1}{\zeta}$ early himpact of mass-effects on the  $p_T$  cross section. Such effects have  $\text{LQ}$  in earlier works  $[45, 46, 47, 13, 48, 49]$ . NLO with full december of  $\sim$ anel) we plote perekacy up the Higgs boson at NC the the manufacture he top and bottom quarks and www with the corresponding result in he top-and bottom quarks and  $\sim$  with the corresponding result in minut. To better emphasize the im  $\sim$  m quark, in the right result in p-quark contribution is conside ige- $m_t$  limit. To better emphasized the intervals of the bottom quark, in the right **L** F<u>ASS</u><br>Place **ikiB∕n** *|H|* <sup>2</sup>*G<sup>a</sup>* <sup>2</sup> *<sup>µ</sup>*⌫ + **A**<br>Quad dari |
|a*H*<br>|atao  $\mathcal{L}_{\mathbf{W}}^{\mathbf{H}}$  effect<sup>c</sup> is  $y_t c_t \bar{q}_L$ <br>in We have **pound very (6)** Degenerad ve compare it with the corresponding result in anochid



### $\left( -\right)$   $\Lambda$  ) inclusive  $\overline{I}$  radiation. The problem includes the H  $\overline{I}$  $\sigma(pp \to H + X)_{\rm inclusive}$

Does not resolve short-distance physics Cocs not resolve shore-distance physics and  $\sim$ 





e.g. [1306.4581](http://arxiv.org/abs/1306.4581)

## Beyond current observables

Cut the loop open, recoil against hard jet



# Complementary to htt



notoriously difficult  $h \bar{t} t$ channel

Theory frontier:  $NLO_{m_t}$  not yet calculated,  $1/m_t$  known to  $\mathcal{O}(\alpha_S^4)$ : few  $%$  up to  $p_T \sim 150$  GeV

Harlander et al '12

# Top partner example



50

100

 $0.7$ 

 $\Omega$ 

Grazzini, Sargsyan '13

150

 $p_T$  (GeV)







$$
m_{\pi^+}^2 - m_{\pi^0}^2 \simeq \frac{3\alpha}{2\pi} m_\rho^2 \log 2 \simeq (37 \text{ MeV})^2
$$

#### $1$  mplications of  $m_H =$ Working in the SM gauge contribution and SU(2) we see SU(2) Loops of SU(2)  $5 \text{ GeV}$ Implications of  $m_H = 125$  GeV

Potential is fully radiatively generated Potential is fully radiatively generated

$$
V_{gauge}(h) = \frac{9}{2} \int \frac{d^4 p}{(2\pi)^4} \log \left( \Pi_0(p) + \frac{s_h^2}{4} \Pi_1(p) \right) \qquad s_h \equiv \sin h/f
$$

 $\frac{1}{2}$ 

Agashe et. al

$$
\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p) , \qquad \Pi_1(p) = 2 [\Pi_{\hat{a}}(p) - \Pi_a(p)]
$$

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$$
\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p) , \qquad \Pi_1(p) = 2 [\Pi_{\hat{a}}(p) - \Pi_a(p)]
$$

 $\int d^4p \, \Pi_1(p)/\Pi_0(p)$  <  $< \infty$ 

 $\int d^4p \, \Pi_1(p)/\Pi_0(p) \, < \infty$  Higgs dependent term momentum space,  $\alpha$   $\alpha$   $\beta$   $\beta$   $\beta$   $\alpha$   $\beta$  for the current associated to the broken generators of the broken gener in Society, Society, Society, For the precise definitions see Ref. *Assumed* and we will assume with we will assume with a society of the precise o dependent term in SO(5)/SO(4); for the precise definitions see Ref. [5]. In a large-*N* expansion, that we will assume Higgs dependent term UV finite

 $\frac{1}{2}$ 

#### $1$  mplications of  $m_H =$ Working in the SM gauge contribution and SU(2) we see SU(2) Loops of SU(2)  $5 \text{ GeV}$ Implications of  $m_H = 125$  GeV

Potential is fully radiatively generated *V*<br>*V V M*<sup>4*p*</sup> *(<sup>2</sup>*)<sup>4</sup> *× (<sup>2</sup>*)<sup>4</sup> *× s*<sup>2</sup> Potential is fully radiatively generated Potential is fully radiatively generated Agashe et. al

$$
V_{gauge}(h) = \frac{9}{2} \int \frac{d^4 p}{(2\pi)^4} \log \left( \Pi_0(p) + \frac{s_h^2}{4} \Pi_1(p) \right) \qquad \frac{s_h \equiv \sin h/f}{h^2}
$$

$$
\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p) , \qquad \Pi_1(p) = 2 [\Pi_{\hat{a}}(p) - \Pi_a(p)]
$$

where  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$  are vector resonances coming respectively in  $4$ 

 $\int d^4p \, \Pi_1(p)/\Pi_0(p)$  <  $< \infty$ 

 $\int d^4p \, \Pi_1(p)/\Pi_0(p) \, < \infty$  Higgs dependent term momentum space,  $\alpha$   $\alpha$   $\beta$   $\beta$   $\beta$   $\alpha$   $\beta$  for the current associated to the broken generators of the broken gener in Society, Society, Society, For the precise definitions see Ref. *Assumed* and we will assume with we will assume with a society of the precise o  $\int d^4p \,\Pi_1(p)/\Pi_0(p) < \infty$  Higgs dependent term This convergence is equivalent to imposing a set of requirements on  $\mathbf{v}_1$  and  $\mathbf{v}_2$ , usually known as the  $\mathbf{v}_2$ dependent term in SO(5)/SO(4); for the precise definitions see Ref. [5]. In a large-*N* expansion, that we will assume UV finite

 $\frac{1}{2}$ 

 $\rightarrow$  'Weinberg sum rules'  $\rightarrow$  '*Mainharg* cum rules' → 'Weinberg sum rules'

⇧*a*(*p*) = *<sup>p</sup>*<sup>2</sup><sup>X</sup>

$$
\lim_{p^2 \to \infty} \Pi_1(p) = 0, \qquad \lim_{p^2 \to \infty} p^2 \Pi_1(p) = 0
$$

#### $\frac{1}{1!}$ **Fault and** *F* and *F* and *F* and *F* and the two resonance masses in the two resonance UV finiteness requires at least two resonances

$$
\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)} \qquad \text{spin}
$$

#### $\frac{1}{1!}$ **Fault and** *F* and *F* and *F* and *F* and the two resonance masses in the two resonance UV finiteness requires at least two resonances ⇧*<sup>t</sup>L,R* <sup>1</sup> <sup>=</sup> *<sup>|</sup><sup>F</sup> L,R* UV finiteness requires at least two resonances *<sup>Q</sup>*<sup>1</sup> ) *,*

$$
\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)} \qquad \text{spin l}
$$

Similarly for SO(5) fermionic contribution  
\n
$$
m_h^2 \simeq \frac{N_c}{\pi^2} \left[ \frac{m_t^2}{f^2} \frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2} \log \left( \frac{m_{Q_1}^2}{m_{Q_4}^2} \right) \right] f
$$
\n5 = 4 + 1 with EM charges 5/3, 2/3,°-173  
\nQ4 Q<sub>1</sub>  
\n⇒ solve for  $MP_h = 125$  GeV



 $m_{Q_1}$ (GeV)



### Composite inggs parameter space Scan over composite Higgs parameter space



see e.g. ATLAS-CONF-2013-051

# Top partners









#### **[pb]** !

1

1

**Limits between 690 and 782 GeV** 

*t*



**m** = 850 GeV

## Flavor used to be a showstopper

CPV in Kaon mixing

 $|\epsilon| = 2.3 \times 10^{-3} \implies \frac{M_{ETC}}{g_{ETC} \sqrt{\text{Im}(V_{sd}^2)}} \gtrsim 16,000 \, \text{TeV}$ 

$$
m_{q,\ell,T}(M_{ETC}) \simeq \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T \rangle_{ETC} \lesssim \frac{0.1 \,\mathrm{MeV}}{|V_{sd}|^2 N^{3/2}} \quad \mathrm{VS.} \quad \mathrm{M_{top}}
$$

# "Into the Extra-dimension and back"

# Exciting journey…


## Depends on the perspective…



## Extra-dimensions





Compact Extra-dimension => momentum in ED direction is quantized:  $p_{ED} = n/(size of ED)$ 



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$$
p^2 = m^2
$$
  $p_{5D}^2 = p^2 - (n/R)^2 = m^2$   
4D



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Two pictures (n/R on LHS or RHS):

1) 5D field with quantized momentum and mass  $m^2$ 



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$$
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$$
  $p_{5D}^2 = p^2 - (n/R)^2 = m^2$   
4D

Two pictures (n/R on LHS or RHS):

1) 5D field with quantized momentum and mass  $m^2$ 2) infinite tower of 4D fields labeled by 5 momentum  $n/R$  with masses  $\frac{m}{n} = m^2 + (n/R)^2$ 

new particles: Kaluza Klein (KK) modes



## The SM flavor puzzle

 $Y_U \approx$  $\overline{1}$  $\overline{a}$  $6 \cdot 10^{-6}$   $-0.001$   $0.008 + 0.004i$  $1 \cdot 10^{-6}$  0.004  $-0.04 + 0.001$  $8 \cdot 10^{-9} + 2 \cdot 10^{-8}i$  0.0002 0.98  $\setminus$ A  $Y_D \approx \text{diag}(2 \cdot 10^{-5} \quad 0.0005 \quad 0.02)$ 

Why this structure?

Other dimensionless parameters of the SM:  $g_s$  ~ 1,  $g$  ~ 0.6,  $g'$  ~ 0.3,  $\lambda_{\text{Higgs}}$  ~ 1,  $|\theta| < 10^{-9}$ 

# Log(SM flavor puzzle)

$$
-\log|Y_D| \approx \text{diag}(11 \quad 8 \quad 4)
$$

$$
-\log|Y_U| \approx \begin{pmatrix} 12 & 7 & 5 \\ 14 & 6 & 3 \\ 18 & 9 & 0 \end{pmatrix}
$$

### If  $Y = e^{-\Delta}$  , then the  $\Delta$  don't look crazy.

### SM on thick brane & domain wall  $\Rightarrow$  chiral localization Hierarchies w/o Symmetries Simply contribution of the same scalar production of the same scalar  $\theta$ Arkani-Hamed, Schmaltz



$$
\mathcal{S} = \int d^5x \sum_{i,j} \bar{\Psi}_i[i \partial_5 + \lambda \Phi(x_5) - m]_{ij} \Psi_j
$$
  

$$
\Psi = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} = \begin{pmatrix} \psi_L^0 \\ 0 \end{pmatrix} + \text{KK modes}
$$

### SM on thick brane & domain wall  $\Rightarrow$  chiral localization Hierarchies w/o Symmetries Arkani-Hamed, Schmaltz

Φ  $X_5$  $\mathbf{u}$ 

$$
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$$
  

$$
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$$

grangian. In the case that we will even use the case that we will even use the standard standard in  $\mathcal{L}_{\mathcal{A}}$ 

Simply contracted all 5-d Directions to the same scalar  $\frac{1}{2}$ 

## Hierarchies w/o Symmetries Arkani-Hamed, Schmaltz

SM on thick brane & domain wall  $\Rightarrow$  chiral localization Simply contracted all 5-d Directions to the same scalar  $\frac{1}{2}$ 



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SM on thick brane & domain wall  $\Rightarrow$  chiral localization Simply contracted all 5-d Directions to the same scalar  $\frac{1}{2}$ 

 $\Psi_R$ 



$$
\mathcal{S} = \int d^5x \sum_{i,j} \bar{\Psi}_i[i \partial_5 + \lambda \Phi(x_5) - m]_{ij} \Psi_j
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\n
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### SM on thick brane & domain wall  $\Rightarrow$  chiral localization Hierarchies w/o Symmetries  $L$ iq was defined in  $L$ ,  $\int_{0}^{1}$   $C_{\lambda}$  was defined in the previous sections, find a left-handed massless fermions l from L localized at x<sup>5</sup> = 0 and e<sup>c</sup> from EC Arkani-Hamed, Schmaltz<br>CN4 = re= ± localized at a research and the simplicity of simplicity, we will assume the that the that the th  $\mathcal{F}$  is definition in side the wall. We wall  $\Rightarrow$  chiral localization Arkani-Hamed, Schmaltz



A chiral zero mode fermion is localized at the zero of Φ.

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$$



d4

x k h(x)l(x)ecc

$$
\int dx_5 \; \phi_l(x_5) \; \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int dx_5 \; e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5 - r)^2} = e^{-\mu^2 r^2/2}
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### Warped Extra Dimensions



# AdS/CFT dictionary

$$
ds^2 = \left(\frac{R}{z}\right)^2 \left(dx_\mu dx_\nu - dz^2\right)
$$

Randall, Sundrum

 $\overline{m_W}$ 

IR

Anti-de-Sitter (AdS) (Conformal (CFT) Compactification Compactification Red-shifting of scales **Communist Communist Communis** The mutation  $m_W = \sqrt{\frac{g(11v)}{g(UV)}}\,M_P \ll M_P \qquad \qquad m_W \sim e^{-4\pi/\alpha}M_P$  $\overline{\phantom{a}}$ *g*(*IR*)  $g(UV)$  $M_P \ll M_P$ 

Text

UV

*M<sup>P</sup>*

Grossman, Neubert; Gherghetta, Pomarol; Huber;



Grossman, Neubert; Gherghetta, Pomarol; Huber;



Grossman, Neubert; Gherghetta, Pomarol; Huber;



almost universal!

Grossman, Neubert; Gherghetta, Pomarol; Huber;



### Fermion zero mode on the IR brane

$$
F(c) \sim \begin{cases} (\text{TeV/Plank})^{c-\frac{1}{2}} & c > 1/2 \\ \sqrt{1-2c} & c < 1/2 \end{cases}
$$



### Fermion zero mode on the IR brane

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# RS GIM - partial compositeness



Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;

Flavor hierarchy from hierarchy in  $F_i$ 

 $m_d \sim v F_{d_L} Y^* F_{d_R}$ 

# RS GIM - partial compositeness



Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;

Fall Flavor hierarchy from hierarchy in Fi

$$
m_d \sim v F_{d_L} Y^* F_{d_R}
$$



KK gluon FCNCs proportional to the same small Fi :

$$
\sim \frac{(g^*)^2}{M_{KK}^2} F_{d_L} F_{d_R} F_{s_L} F_{s_R}
$$

 $\sim$  $(g^*)^2$  $M^2_{\boldsymbol{\mathsf{K}}}$ *KK*  $m_d m_s$  $(vY^*)^2$ 

# Back to 4D …



\*for RS realization: Csaki,AW et al; Delaunay et al; da Rold; see also Barbieri et al



Composite *u,d* quarks, very large cross-sections

 $\sin \theta_R \gtrsim$  $\tilde{\sim}$ 1  $g_{\rho}$  $\sim$ 1 8 *mtop* :

> \*for RS realization: Csaki,AW et al; Delaunay et al; da Rold; see also Barbieri et al

...similar plot using ATLAS results

## LHC8 limits de Vries, Redi, Sanz, AW, 13



**Vector mass**

...similar plot using ATLAS results

### LHC8 limits de Vries, Redi, Sanz, AW, 13



Strong Signatures Strong Signatures CMS dijet angular searches

$$
\left| \mathcal{L} = \frac{2\pi}{\Lambda^2} \left( \bar{q}_{L,R} \gamma^\mu q_{L,R} \right)^2 \right|
$$

 $\begin{array}{cc} \hline \end{array}$  and  $\begin{array}{cc} \hline \end{array}$  and

 $\overline{q}$   $\qquad$   $\qquad$   $\overline{q}$ 

 $\lambda$ 

...similar plot using ATLAS results

### LHC8 limits de Vries, Redi, Sanz, AW, 13







QCD

vs. Composite Partners

bump in sub-leading jets<br>





QCD

vs. Composite Partners

### respectively. The signal cross section can be read in figure 9 for specific values of *g*⇢, sin *Ru,d* , and it typically varies between 1 to 10 pb for *m*⇢ . 2.5 TeV. To achieve *S/B* ⇠ 1, one would need to have a Dedicated search

deVries, Redi, Sanz, AW, '13

$Cut$ -flow	$m_Q = 600 \text{ GeV}$		$m_Q = 1200 \text{ GeV}$		
	signal	QCD	signal	QCD	
$p_T$ leading jet > 450 GeV	0.51	0.0067	0.90	0.0067	
$H_T > m_Q$	0.51	0.0067	0.80	0.0015	
$ m_{ij} - m_Q  < (30, 50)$ GeV	0.15	0.00037	0.11	$2.5 \times 10^{-5}$	
$\Delta\phi_{ij} > 1.5$	0.045	$9.9 \times 10^{-5}$	0.060	$2.1 \times 10^{-7}$	

### respectively. The signal cross section can be read in figure 9 for specific values of *g*⇢, sin *Ru,d* , and it typically varies between 1 to 10 pb for *m*⇢ . 2.5 TeV. To achieve *S/B* ⇠ 1, one would need to have a Dedicated search

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 $\mathcal{U} \sim \mathcal{V}(\mathcal{P}T)_{\text{min}}$   $\mathcal{U} \sim 4(\mathcal{P}T)_{\text{min}}$ *sented in the text. The numbers correspond to the eciency to specified set of cumulative cuts. Here jj is the combination of the two subleading jets. For the background, the final numbers represent the cut-flow with either m<sup>Q</sup>* = 600 *GeV or m<sup>Q</sup>* = 1200 *GeV.* To produce this cut-flow, we took two benchmark masses, *mQ*= 600 and 1200 GeV, and the 2+1 signature. We chose the 2+1 topology, as it su↵ers from the largest background, still interesting *S/B* can be achieved using these cuts. Note that we have not truly optimized the cuts to a specific signal, we have and the table is to show that is to show that a background reduction in the required range is possible. vs  $M \sim 3(p_T)_{\text{min}}$   $M \sim 4(p_T)_{\text{min}}$ 1+1  $\sqrt{2}$ 1 1

Note also that we have not made use of the *gap* variables in this cut-flow, which could improve the

### Discovery potential of a dedicated search

deVries, Redi, Sanz, AW, '13



# Composite Higgsals

*v*

- was Higgs bosons Higgs books and the SM-like' light Higgs • 'SM-like' light Higgs<br>  $g_{hVV} = g_{hVV}^{(s)}$   $\cos \theta$  ( $v^2 = W, Z$ )
- $\cos \theta$   $(v w, z)$ <br> $\sin \theta = \frac{v}{f}$  $g_{hVV} = g$ (SM)  $N_V^{\text{(OM)}}$   $\cos \theta$   $(V = W, Z)$  $\bm{w}$   $\bm{\beta}$   $\bm{\beta}$   $\bm{\beta}$   $\bm{\beta}$  $\sin \theta =$ *f*  $\mathsf{suplines}_i \mathsf{g}_i \mathsf{g}_{hVV} = g_{hVV}^{(2,1)} \cos \theta$  ( • Correlated deviations in Higgs couplings, e.g.
- g*ho* ductý (SM)  $\mathbf{\hat{p}}$  $\mathbf{\hat{p}}$  sprok  $(\mathbf{C}\mathbf{N})$  $\alpha$ uhla Higge Ntordu · Double Higgs phoduction smoking gun



- $\mathsf{on}\,\mathsf{W}_{\mathsf{I}}\,\mathsf{W}_{\mathsf{I}}\,\to\mathsf{W}_{\mathsf{I}}\,\mathsf{W}_{\mathsf{I}}$ • Keep an eye on  $\mathsf{W}_{\mathsf{L}}\mathsf{W}_{\mathsf{L}} \to \mathsf{W}_{\mathsf{L}}\mathsf{W}_{\mathsf{L}}$
- *h h W W* • Top partners (Q = 5/3, 2/3, **-**1/3)

 $\sin$ 

## Conclusion



Bellazzini

# Conclusions

The battle for a natural resolution of the hierarchy problem goes on

Where is everybody?

LHC14 will be decisive

