unraveling flavor & naturalness from RUN II to 100 TeV

Amarjit Soni, HET, BNL

EW (50) Moriond 2015; mar. 14-21
03/20/15
O(1) TeV for NP was unrealistically optimistic
Good reasons for scale around 10 TeV
An exciting possibility for RUN II [precocious]
Direct searches for such heavier states requires higher energy machines
Modern BSM-building may be seriously flawed
Doze of experimental reality from ~100 TeV collider could do wonders....
Due to legendary potential of hadron colliders, payoffs likely huge
no no lose theorem?
4th of July 2012 Fireworks!

- LHC makes TWO (not one) huge discoveries

- =>

- =>

- Particle Physics in Disarray!!
GLAD THAT IT STUCK SO WELL!....

• FPCP, Hefei China, May 2012..[“New ideas and directions in flavor physics/CP violation”]
  1st mentioned possibility of 100 TeV Collider in China...

• 100 TeV special for probing mysteries of flavor

• See also 1303.5056
SSC 40 TeV ~ 1990

May well need seriously thinking of

Gigantic International Hadron Collider ~ 100 TeV CM

Global Village

Flavor - naturalness, RUN II to 100 TeV; A. Soni
FITS LIKE A GLOVE!
[OR DOES IT?]

flavor- naturalness, RUN II to100 TeV ; A.
Soni
Agree with SM ± 20%
SM-CKM paradigm works rather well.
No glaring discrepancy
OTOH tests only \( \sim 10-15\% \) accuracy

\( \varepsilon_K \mathcal{N} 10^{-3} \! \! \! \! \! \! \)
Drawing strong conclusions based on 20% tests is too risky!!

Buried underneath the current errors in the measurements may well be gems of NP!!.

[Later]
[exciting] possibility @ RUNII !!
INSIGHTS FROM A (CANDIDATE) GEOMETRIC THEORY OF HIERARCHY & FLAVOR: MANY +’S AND A WHOLE LOT OF –’S

flavor- naturalness, RUN II to100 TeV ; A. Soni
Points along 5th dim correspond to diff. eff.
4d scale!

Simultaneous resolution to hierarchy and flavor puzzles
Good news is actually awesome news!!
A fascinating interpretation of the 126 GeV scalar in RS

**GELLER, BAR-SHALOM + A.S.**

1312.3331 => PRD 2014
Geller, Bar-Shalom + AS

• In the traditional Goldberger – Wise mechanism you need to have an additional scalar (“Radion”) to stabilize the extra dimension.

• We Ask: *Can the Higgs doublet simultaneously break EW symmetry as well as stabilize 5th dim-

• Answer Yes!

• Note: With our set up there is only the Higgs doublet: “Higgs-radion” serving a dual purpose, i.e. a more economical setup
Is the scalar 126 GeV the GW Radion?

• Recall in the RS set up the famous Goldberger-Wise mechanism (‘99) is invoked to stabilize the the 5\textsuperscript{th} dim: needs a scalar field, “Radion”; Quantum numbers identical to the higgs

• The mass of the radion is (may be?) parametrically suppressed compared to the KK scale; Since the radion is likely the lightest particle in RS-KK spectrum, it has been focus of dozens of studies…] to see if 126 GeV object is the GW radion:

  ▪ NO as then KK-scale needs to be \(~1\text{ TeV}\) to fit the data which is ruled out by direct searches [see e.g. Z. Chacko et al; Csaki et al; Low et al…….]
A new proposal: Stabilization of the 5\textsuperscript{th} dim by the Higgs doublet

• In our setup a 5D SU(2) bulk-scalar doublet is introduced, The VEV has a profile along the extra dim. Then you basically ask what conditions are necessary for this setup to simultaneously give mass to the W,Z bosons and Stabilize the 5\textsuperscript{th} dim. (if a solution is possible then)

2\textsuperscript{nd} question: is it phenomenologically viable?

• Potential difficulty
The higgs has to be close the TeV brane (for m\_EW \sim O(100 GeV))

• In the GW case the scalar is almost flat: \[ \phi_{UV} \sim \phi_{IR} \]
Note that tuning of the C.C is needed just as in the GW case.
“Higgs-radion”

• Confrontation with all the existing LHC data shows that properties all consistent with the SM Higgs [SMH] so far
• However BR-> 2 gamma and into 2 gluons appreciably different from SMH (see Table)
• Gives a crucial hint on the scale of NP
• Fitting to the existing data we find Kkgluon mass must lie between 4.5 and 5.4 TeV! (95%CL)
• [Note: this is completely data driven => for sure LHC13 with 100/fb will change these]
<table>
<thead>
<tr>
<th></th>
<th>SM ($m_h = 126, GeV$)</th>
<th>Higgs-Radion ($m_{hr} = 126, GeV$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Br(h \to WW^*)$</td>
<td>0.231</td>
<td>0.204</td>
</tr>
<tr>
<td>$Br(h \to ZZ^*)$</td>
<td>0.0289</td>
<td>0.0257</td>
</tr>
<tr>
<td>$Br(h \to gg)$</td>
<td>0.0848</td>
<td>0.13</td>
</tr>
<tr>
<td>$Br(h \to \gamma\gamma)$</td>
<td>$2.28 \cdot 10^{-3}$</td>
<td>$3.8 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$Br(h \to b\bar{b})$</td>
<td>0.561</td>
<td>0.545</td>
</tr>
<tr>
<td>$Br(h \to \tau\bar{\tau})$</td>
<td>0.0615</td>
<td>0.063</td>
</tr>
<tr>
<td>$Br(h \to c\bar{c})$</td>
<td>0.0283</td>
<td>0.028</td>
</tr>
<tr>
<td>Total width [GeV]</td>
<td>$4.21 \cdot 10^{-3}$</td>
<td>$2.2 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

E II: The Higgs-radion and the SM Higgs branching ratios and total width. The SM values are from [33].

**CAUTION:** Effects of KK tower not included yet.
\[ 1.14^{+0.26}_{-0.23} \left[ \pm 0.21 \text{(stat.)} \pm 0.13 \text{(theo.)} \pm 0.09 \right] \times 
\]

\[ 1.57^{+0.33}_{-0.28} \]
A promising ratio that needs special attention

• From the above BRs, a ratio that seems particularly sensitive to higgs-radion interpretation is

\[
\frac{\mu_{ggF}}{\mu_{bb}} \sim 2.5.
\]

In contrast, in the SM it is \(\sim 1\)
Summary so far

• When examined in greater detail, we claim, that it will be found that the 126 GeV scalar is actually not the Higgs of the SM but rather a “Higgs-radion” from the RS-setup hinting of KK-zoo starting above around 5 TeV!!
THE FLAVOR CONNECTION: PROS & CONS OF A CANDIDATE THEORY OF FLAVOR
Outstanding Th. puzzles of our times

• Hierarchy puzzle

For radiative stability of $m_W$ 

$\Rightarrow \Lambda_{NP} \lesssim 10^{3}$ TeV 

to avoid fine tuning $m_W$

• Flavor puzzle

$\Delta_{flav} = 2$ esp. $K - \bar{K}$

HUGE TENSION

$\sim \frac{g_{NP}^2}{m_{NP}} \Rightarrow \Lambda_{NP} \sim 10^{3}$ TeV 

to avoid constraint from $\Delta M_{K, \bar{K}}$
Simultaneous resolution to hierarchy and flavor puzzles

flavor- naturalness, RUN II to 100 TeV; A. Soni

Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$. 

$\delta^2 = e^{26} \eta dx dx - \epsilon d\phi^2$

$\langle H_4 \rangle = e^6 \langle H_5 \rangle$

$G = \frac{1}{24} \pi \frac{1}{M_P}$

Points along 5th dim correspond to diff. eff.

4d scale!
**Fermion “geography” (localization) naturally explains:**

Grossman & Neubert; Gherghetta & Pomarol; Davoudiasl, Hewett & Rizzo

- Why they are light (or heavy)
- FCNC for light quarks are severely suppressed automatically
- RS-GIM MECHANISM (Agashe, Perez, AS’04) flavor changing transitions though at the tree level (resulting from rotation from interaction to mass basis) are suppressed roughly to the same level as the loop in SM=> CKM mixings (& mass) hierarchy.

- O(1) CP ubiquitous; .....nedm, in fact ALL DIR-CP [ε'/ε, γ, ΔACP(B=>Kπ), Δ(Sin2β); S[B=>K* ργ]; ΔACP(D) ...] are an exceedingly important path to BSM-phase and new physics
- Most flavor violations are driven by the top

-> ENHANCED t-> cZ(h) ....A VERY IMPORTANT “GENERIC” PREDICTION ...Agashe, Perez, AS’06

ε_K, Δm_K : 10^3 TeV ⇒ RS_Fe ≈ 10 TeV !

EXTENSIVE STUDIES by Blanke, Buras, Weiler et al and by Cassagrande, Haisch, Neubert et al &............
Localization parameters of the 3-families of quarks

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{Q_1}$</td>
<td>$c_{Q_2}$</td>
<td>$c_{Q_3}$</td>
</tr>
<tr>
<td>-0.579</td>
<td>-0.517</td>
<td>-0.473</td>
</tr>
<tr>
<td>$c_{u_1}$</td>
<td>$c_{u_2}$</td>
<td>$c_{u_3}$</td>
</tr>
<tr>
<td>-0.742</td>
<td>-0.558</td>
<td>+0.339</td>
</tr>
<tr>
<td>$c_{d_1}$</td>
<td>$c_{d_2}$</td>
<td>$c_{d_3}$</td>
</tr>
<tr>
<td>-0.711</td>
<td>-0.666</td>
<td>-0.553</td>
</tr>
</tbody>
</table>

Table from M. Neubert @Moriond09

- = masses of the 6 quarks in RS!
Cons – for RS flavor [I]

- Simple (anarchical) geometric construction of course does NOT explain fermion masses [Who does?]

- Absence signal of BSM CP-phase in $D^0$ complex seems to require a very high new physics scale [Altmannshofer]

- .. for now leptonic sector is problematic
LEPTON SECTOR: AN ENIGMA FOR RS [II]
Challenges of the lepton sector for a (strictly) geometric theory of flavor

- Simple model(s) of flavor based purely on geometry and localization face serious difficulties

<table>
<thead>
<tr>
<th>Observable</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(\mu \to 3e)$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\text{Br}(\mu \to e\gamma)$</td>
<td>$&lt; 5.7 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to 3e)$</td>
<td>$&lt; 2.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to e^-\mu^+\mu^-)$</td>
<td>$&lt; 2.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to e^+\mu^-\mu^-)$</td>
<td>$&lt; 1.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to \mu^-e^+e^-)$</td>
<td>$&lt; 1.8 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to \mu^+e^-e^-)$</td>
<td>$&lt; 1.5 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to 3\mu)$</td>
<td>$&lt; 2.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to \mu\gamma)$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{Br}(\tau \to e\gamma)$</td>
<td>$&lt; 3.3 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\mu - e$ conversion</td>
<td>$\Lambda \gtrsim 10^3\ \text{TeV}$</td>
</tr>
<tr>
<td>$e^+e^- \to e^+e^-$</td>
<td>$\Lambda \gtrsim 5\ \text{TeV}$</td>
</tr>
<tr>
<td>$e^+e^- \to \mu^+\mu^-$</td>
<td>$\Lambda \gtrsim 5\ \text{TeV}$</td>
</tr>
<tr>
<td>$e^+e^- \to \tau^+\tau^-$</td>
<td>$\Lambda &gt; 4\ \text{TeV}$</td>
</tr>
</tbody>
</table>
On the other hand

- $g$-2 of muon
  
  $\Delta a_\mu = a_\mu^{\text{expt}} - a_\mu^{\text{SM}} = \left( 28.8 \pm 80 \right) \times 10^{-10} \approx 3.66$

- New physics or under estimate of errors?
- lattice
MODELS ABOUND
Possible ways out

- Kile, Kobach and AS, arXiv:1411.1407

Lepton flavors $\Leftrightarrow$ DM connection

B. $SU(2)_F$ Model

Our second toy model has an $SU(2)_F$ flavor symmetry, with the $SU(2)_F$ doublets denoted as

$$L = \begin{pmatrix} L_\mu \\ L_\tau \end{pmatrix}, \quad \ell = \begin{pmatrix} \mu_R \\ \tau_R \end{pmatrix}, \quad \nu = \begin{pmatrix} \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}, \quad \phi_F = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}. \quad (15)$$

10's of models such as this
Simple (anarchical) geometry not enough
=> Some symmetry may need be invoked

• In RS, e.g. Perez & Randall, arXiv:0805.4652; JHEP

• Also Agashe arXiv:0902.2400; PRD

• Agashe, Geller, AS; WIP
KK-scale from quark-flavor constraints

• 10 TeV lower bound is a crude estimate =>
• ~3 TeV from EWPC only is overly optimistic…
• Whereas 4-5 TeV suggested by ATLAS+CMS data on Higgs properties using the Higgs-radian interpretation.
• Note ~10 TeV KK scale has an added advantage, EWPC may be automatically satisfied, w/o imposing custodial symmetry => setup then is more economical though tuning is worse by O(3^2 )
SHOULD WE BE^ SHOCKED TO FIND THAT THE SCALE OF NEW PHYSICS IS NOT ~ 1 TeV & APPEARS TO BE HIGHER?

flavor- naturalness, RUN II to 100 TeV ; A. Soni
What physics principle?

• In constraining new physics models, SUSY-like or not, people often only pay attention to EWPC and disregard flavor constraints (e.g. Kaon mixing or...), it is very difficult to give a physics justification for this strategy.

• **Existence of flavors is a reality; flavor constraints are profound experimental statements on flavor-alignment and should not be disregarded**

• **Absence of new physics signals at LHC(8) of less than around 3 TeV may well be a gentle reminder from nature of this (obvious) fact**
Why no NP signals at ~1TeV

• Thus, from the perspective of RS, the absence of signals so far may well be because RS comes with flavor; after all geometrical understanding of flavor is the key attraction of RS

• Stated another way, an optimistic interpretation of absence of NP signals at 1-2 TeV is because RS scale is around ~10 TeV as dictated by flavor constraints
Bottom line is that from a variety of considerations new physics scale may be $\sim 10$ TeV so tuning $O(10^{-3})$ may be needed but even so this is a far far cry from $10^{-34}$!

$\Rightarrow$ Naturalness is not at stake; at least not now

$$tuning \omega \frac{v^2}{m^2_{KK}} \sim O(10^{-3})$$
Gee, don’t see no NP signals
Flavor: Told you so!
**FACETS OF NATURALNESS**

- **FINITE** (Strumia)
- **FLAVORED** (Blanke)
- **NEUTRAL** (Craig)
- **EFT** (BSW)

**UNNATURAL** (Albrezzi, Altarelli)

**NATURALNESS**

**FLAVORY** (here)
“Flavory Naturalness”

• The scale of NP must satisfy experimental constraints from flavor physics

• In a genuine theory of flavor, this scale is likely to be much less than $\sim 1000\text{TeV}$ (due naïve Kaon mixing constraints) as exemplified in a candidate theory of flavor i.e. RS-flavor

• Due to naturalness (to minimize fine-tuning) the scale of NP is likely to be (just above) the scale where flavor constraints are satisfied. (Close to the lower bound)
What is special of 100 TeV?

• Seen from the above (flavor) perspective and keeping in mind what may be experimentally realistic in the near future it’d be best to focus on ~100 TeV.
FIG. 10 (color online). Signal rate for a possible gluon KK resonance as a function of the collider energy employing the cuts described in the text. Branching fractions and efficiencies have been neglected. From top to bottom, the results are shown for gluon KK masses in the range from 3 to 12 TeV in steps of 1 TeV.
FIG. 4 (color online). Significance for the purely lepton decay mode for $Z$ pairs from KK graviton using 300 fb$^{-1}$. See also Fig. (1).

FIG. 5 (color online). Production rate for the first gravito excitation decaying into two $Z$ bosons, assuming a rapidity $|y| < 2(1)$ on the $Z$’s corresponding to the dotted (solid) histograms. The histograms correspond, from bottom to top, to collider energies of $\sqrt{s} = 14$, 21, 28, and 60 TeV, respectively. $Z$ branching fractions are not included, and $k/\mathcal{M}_p = 0$ has been assumed.
SM vs BSM

• Shortcomings of SM abound:
• nu masses, DM, baryogenesis, unification......
• Unfortunately, all the BSMs “on the table” are worse.....explosion of parameters, most cases no understanding of flavors......, many unnatural aspects

• This means there is a dire need for radical ideas
• Doze of experimental reality could do wonders=>

Precisely what a 100 TeV collider can provide
Figure 1-6. Cross section predictions at proton-proton colliders as a function of center-of-mass operating energy, $\sqrt{s}$. 


GOLDMINE
Moving the ball a long long way, significantly improve tens of bounds!

- \( t \Rightarrow qZ; qh; qg, q\gamma, \) [See Eilam, Hewett, AS’91; Agashe, Perez, AS ’07; Atwood, Gupta, AS’14; also Hou et al, Durieux, Maltoni, Zhang......] ..... \( t \Rightarrow q\tau\mu \) [Kile + AS’08]
- \( t \ dm \) [RM Xu+AS’ 92; Atwood +AS’92; Bernreuther et al ‘92......]
- \( tth \) [Atwood, Bar-Shalom, AS] PRD’96
- See Atwood et al Physics Reports for numerous CP Observables and tests

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Huge Menu (II)

- $T_p \Rightarrow t h$  
  - taming higgs self energy
- SST  
  - powerful diagnostic; Atwood, Gupta, AS’13; Qing-Hong Cao
- $h \Rightarrow \mu \tau$, [Harnik]; $Z \Rightarrow \mu \tau$,
- $h \Rightarrow Z Z^* \Rightarrow 4l$ [Xu + AS’93; Harnik et al; Low..]
- $Z' \Rightarrow \mu \tau$, BHSS’85; Han, Lewis, Sher’08

"Horizontal" lessons

Large $\Delta \mu - \Delta \tau$ mixing

flavor- naturalness, RUN II to100 TeV ; A. Soni
signal from $R$ decay is so clean and it provides such a simple trigger that it should not be difficult to handle a luminosity as high as $10^{41} \text{cm}^{-2}\text{yr}$. That would make a 30-TeV $R$ boson accessible to a $\sqrt{s} = 100$-TeV machine, as reported by Rohlfe of the decay $W \rightarrow \tau \bar{\nu}$. Moreover, it should be possible to observe the $\tau$ decay for the energetic case in which it can have a mean decay path of about 25 cm: The apparent ionization change would make for 'fun with $\tau$'s.'
Huge Menu (III)

- **KK-ZOO**: KKg, KKW, KKZ, KKG e.g. ADPS07, DRS’08

- **WR**.... From SU(2)XSU(2)XU(1)... KL-KS mass bound ~1.6 TeV [BBS’82]; update [Kiers et al ‘02] WR~2TeV, FCH ~7TeV .......direct search can be moved to way above 10 – 15 TeV

- **H^+-, H^0**... a la “who ordered the muon”

- **Fine tuning by (13/100)^2 => ~10^{-4}** impressive achievement in itself
MULTI PRONG ATTACK IS ESSENTIAL

ASSUMING SCALE OF NP IS ~10 TEV
WHAT ARE THE EXPERIMENTAL RAMIFICATIONS

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Important observables & some expectations

• For The Intensity Frontier

  • nedm within factors of $O(\text{few})$ close to Expt bound $< 6 \times 10^{-26}$ e-cm

  • Time dependent CP $B_d \Rightarrow K(\pi)\pi \gamma$; $B_s \Rightarrow \phi \gamma \sim O(10\%)$

  • $\Delta \gamma \sim O(2\times 10^{-3})$ comparable to theory uncertainties

Precise direct determination of $K$ form “B$\rightarrow$DK” is a Key Target of LHCb.
(More) For The Intensity Frontier

- Charm CP esp. modes where SM predicts 0...e.g. $D \rightarrow KKX$, $\phi \pi^+$, $\pi^+ \pi^0$...
- $K_L \rightarrow \pi^0 \nu \nu$
- Theory in bad shape
- Unfortunately
- $\Sigma M[2.8 \pm 0.4] \times 10^{11}$
- A unique rare gem!!

Desperate search for BSM-CP phase(s)

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For the Energy Frontier

• $t \rightarrow c \ Z, \ ch \ \text{Br} \ O(10^{-7}); \ t \rightarrow c \ g \ O(10^{-10}); \ t \rightarrow c \ \gamma \ O(10^{-11})$...many orders of magnitude bigger than SM

• $\text{tedm} \sim O(10^{-20} \ e\text{-cm})$ AtwoodAS/92; 
• Triple correlation in $ee \rightarrow tth$;
• Energy assy in top pair @ LHC

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CP violation in top pair production at hadron colliders

- Transverse energy asymmetry of charged leptons:

\[ A_T = \frac{\sigma(E_T^- > E_T^+) - \sigma(E_T^+ > E_T^-)}{\sigma(E_T^- > E_T^+) + \sigma(E_T^+ > E_T^-)} \]

\[ \Rightarrow CP\text{-}odd, \quad T_N\text{-}even \Rightarrow \text{needs abs. part} \]

flavor- naturalness, RUN II to100 TeV ; A. Soni
Perhaps feasible as 750 GeV ILC

See also Guzdzalkowski et al.

FIG. 3: Number of events, \( N_{\text{events}} \) (\( N_{\text{tag}} \)), required (expected yearly), as a function of total beam energy for set II of the parameters and for \( \mu = 100 \) and 100 GeV with unpolarized electron and positron beams.
Because the scale of NP ~ 10 TeV, expected deviations tend to be very small, strongly suggesting we need to strengthen both our computational AND measurement infrastructure.

“SHUT UP & COMPUTE and MEASURE” slightly miss quoting a famous young Italian Physicist.
Summary & Outlook (I – III)

- No NP signals ~ 1-3 TeV may just be because “flavory naturalness” requires NP to be above ~10 TeV [as e.g. in RS- flavor]
- This means no profound challenge to our notion of naturalness except instead of $O(0.01)$ tuning, its a bit worse $O(0.001-0.0001)$ but still a far cry from $10^{-32}$
- And in fact (some) theoretical scenarios become simpler to counteract FT
- 2nd good news: 125 GeV object is NOT SM Higgs, It’s a “Higgs-radion”; Run II should see appreciable deviations in 2 gamma and in 2 glu modes
- However, explicit verification will require a much higher collider energy than LHC
- For that reason & many many more, going after a ~100 TeV collider is a

**NO BRAINER**
Summary & Outlook (II)

• This is so because:

• Theoretical disarray, confusion, at a loss=> Doze of experimental reality exceedingly useful

• Move plethora of bounds by ~factors O10-100 ..

• Exceedingly valuable: $t \rightarrow q \ h(z, \gamma, g, ...) ; \ tdm, \ tca\ldots$

• Exploit richness of $h=ZZ^* \rightarrow 4 \ l$; CP of Higgs & much more

• WR; $H^{+-}, \ H^0, \ FCH\ldots$

• @100 TeV exciting potential for cracking flavor mystery

LFV: $t \rightarrow q \ \mu\ \tau; \ h \rightarrow \mu\ \tau; \ Z'(\prime) \rightarrow \mu\ \tau$

flavor- naturalness, RUN II to100 TeV ; A. Soni
Summary & Outlook (III)

- At 100 TeV, either we’ll see new physics (most likely not anything like we are thinking off) or tuning is needed to $O(10^{-4}; 10^{-5})$ …

- If no NP => Nature is not “natural” according to our current notion.....a very valuable lesson in by itself.......Why doesn’t this serve as a “No-lose” Theorem?

⇒ Promises an enticing menu & an exciting future & should be vigorously pursued
### TABLE I. A summary of the most notable differences between our setup and the GW mechanism.

<table>
<thead>
<tr>
<th>Stabilizing field</th>
<th>GW mechanism</th>
<th>Our setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>The bulk mass parameter $[V(\Phi) = m^2 \Phi^2]$</td>
<td>Scalar singlet $m^2 \ll 1$</td>
<td>SU(2) scalar doublet $m^2 \to -4k^2$</td>
</tr>
<tr>
<td>VEV profile, $\phi_0(y)$</td>
<td>Nearly flat</td>
<td>Steep, peaked on the TeV brane</td>
</tr>
<tr>
<td>TeV brane VEV, $\phi_{\text{TeV}} \equiv \phi_0(y = y_c)$</td>
<td>$\phi_{\text{TeV}} \sim \mathcal{O}(M_{\text{Pl}})$</td>
<td>$\phi_{\text{TeV}} \sim \mathcal{O}(M_{\text{Pl}})$</td>
</tr>
<tr>
<td>Planck brane VEV, $\phi_{\text{Pl}} \equiv \phi_0(y = 0)$</td>
<td>$\phi_{\text{Pl}} \sim \mathcal{O}(M_{\text{Pl}})$</td>
<td>$\phi_{\text{Pl}} \sim M_{\text{Pl}} e^{-2k y_c} \ll \mathcal{O} , (\text{eV})$</td>
</tr>
<tr>
<td>Lowest scalar excitation</td>
<td>Radion</td>
<td>Higgs radion</td>
</tr>
<tr>
<td>(Higgs-)radion couplings</td>
<td>Purely metric couplings</td>
<td>Both metric couplings and Yukawa/gauge couplings of the doublet</td>
</tr>
</tbody>
</table>

*Tree level couplings to $gg \to \gamma \gamma$!*
is $\Lambda_r = 3.0$ TeV. In particular, for $\Lambda_r = 3.0$ TeV the resulting values of the signal strengths in the various channels are

$$\mu_{\gamma\gamma}^{ggF}(\Lambda_r = 3.0 \text{ TeV}) = 1.45,$$

(74)

$$\mu_{\gamma\gamma}^{VBF}(\Lambda_r = 3.0 \text{ TeV}) = 0.95,$$

(75)

$$\mu_{VV}^{ggF}(\Lambda_r = 3.0 \text{ TeV}) = 0.87,$$

(76)

$$\mu_{VV}^{VBF}(\Lambda_r = 3.0 \text{ TeV}) = 0.57,$$

(77)

$$\mu_{bb}^{VH}(\Lambda_r = 3.0 \text{ TeV}) = 0.57,$$

(78)

$$\mu_{\tau\tau}^{ggF}(\Lambda_r = 3.0 \text{ TeV}) = 0.87,$$

(79)

$$\mu_{\tau\tau}^{VBF}(\Lambda_r = 3.0 \text{ TeV}) = 0.57,$$

(80)

where the superscripts denote the production mechanism and the subscripts denote the decay channel. The agreement with the measured data is at the level of 1σ, i.e., we obtain $\chi^2_{\text{min}} \approx 5$ for 5 d.o.f. Notice the increased sensitivity that can
• Unless KK-masses are heavy enough, T-parameter tends to come out large

\[ \sim 10 \text{ TeV} \quad \text{Csaki et al. [103]} \]

• Since tuning goes as \( \sim \left[ \frac{v}{m_{KK}} \right]^2 \) this tends to make the setup more unnatural

\text{compared to } \sim 3 \text{ TeV}

• Agashe, Delgado, May & Sundrum, JHEP’03 proposed an interesting way out. Impose “Custodial Symmetry” \( \Rightarrow \) extend the gauge group to \( \text{SU(2)} \times \text{SU(2)} \times \text{U(1)} \) which requires introducing additional fermions

\[ Q^3_L = (q^3_L, q'^3_L) = (t_L, \chi_L) \rightarrow (2, 2)_{2/3}. \]

Thereby EWPC and Z\( \rightarrow \) bb allow \( m_{KK} \) to be \( \sim 3 \) TeV = Tuning is around \( \sim 10^{-2} \). However, since kaon mixings etc require around 10 TeV, it’s not clear if CS is needed any more.
EFT corrections to Higgs mass

\[ O^{(2k+4)}_S = \frac{1}{2} |\phi|^2 \Box^k |\phi|^2, \quad O^{(2k+4)}_X = \frac{1}{2} (\phi^\dagger \tau I \phi) D^{2k} (\phi^\dagger \tau I \phi), \quad O^{(2k+4)}_X = \frac{1}{4} (\phi^\dagger \tau I \phi) D^{2k} (\phi^\dagger \tau I \phi) \]

\[ O^{(2k+6)}_\nu = \frac{1}{2} j^{\mu} \Box^k j^{\mu}, \quad O^{(2k+6)}_\nu = j^{\mu} \Box^k j^{\mu}, \quad O^{(2k+6)}_\nu = \frac{1}{6} J^{\mu} D^{2k} J^{\mu} \]

\[ j^{\mu} = i \phi^\dagger D^{\mu} \phi + \text{H.c.}, \quad j^{\mu} = i \tilde{\phi}^\dagger D^{\mu} \phi + \text{H.c.}, \quad J^{\mu} = i \phi^\dagger \tau I D^{\mu} \phi + \text{H.c.} \]

\[ O^{(2k+4)}_{\Psi-\bar{\Psi}} = |\phi|^2 \bar{\Psi} (i \not{D})^{2k-1} \Psi. \]
Singlet widely studied
Finding the eff. operators

If O’s are LG, then 2-loop effect ⇒ only PTG operators

Internal lines can be either the SM scalar, fermions or vectors

**SM scalar:** leading effect from O’s which contain **exactly** 4 SM Higgs doublets
(if it contains more than 4, then contribution to $\delta m_h$ suppressed by powers of $v/\Lambda$ …)

**SM fermions or vectors:** O’s must contain 2 SM Higgs doublets
But: operators with 2 scalar doublets, NO fermions and ANY # of vectors are LG!

Only 2 types of O’s

- Type I: $O$ contains 4 scalar fields, any number of derivatives and is not LG.
- Type II: $O$ contains 2 fermions and 2 scalar fields, any number of derivatives and is not LG.
FIG. 2: A graphic illustration of the particle/KK spectrum in our setup with (right) and without (left) backreaction.