# *geometric theory of flavor, 126 Gev scalar and the 100 TeV collider*

**Amarjit Soni; HET-BNL**

**LHC Physics Conference**

**Columbia Univ, 6/5/14**

# 4th of July 2012 Fireworks!

- **LHC makes TWO (not one) huge discoveries**

- => “Higgs” 126GeV
- => Nothing else till 1-2 TeV
- **Particle Physics in Disarray!!**

..

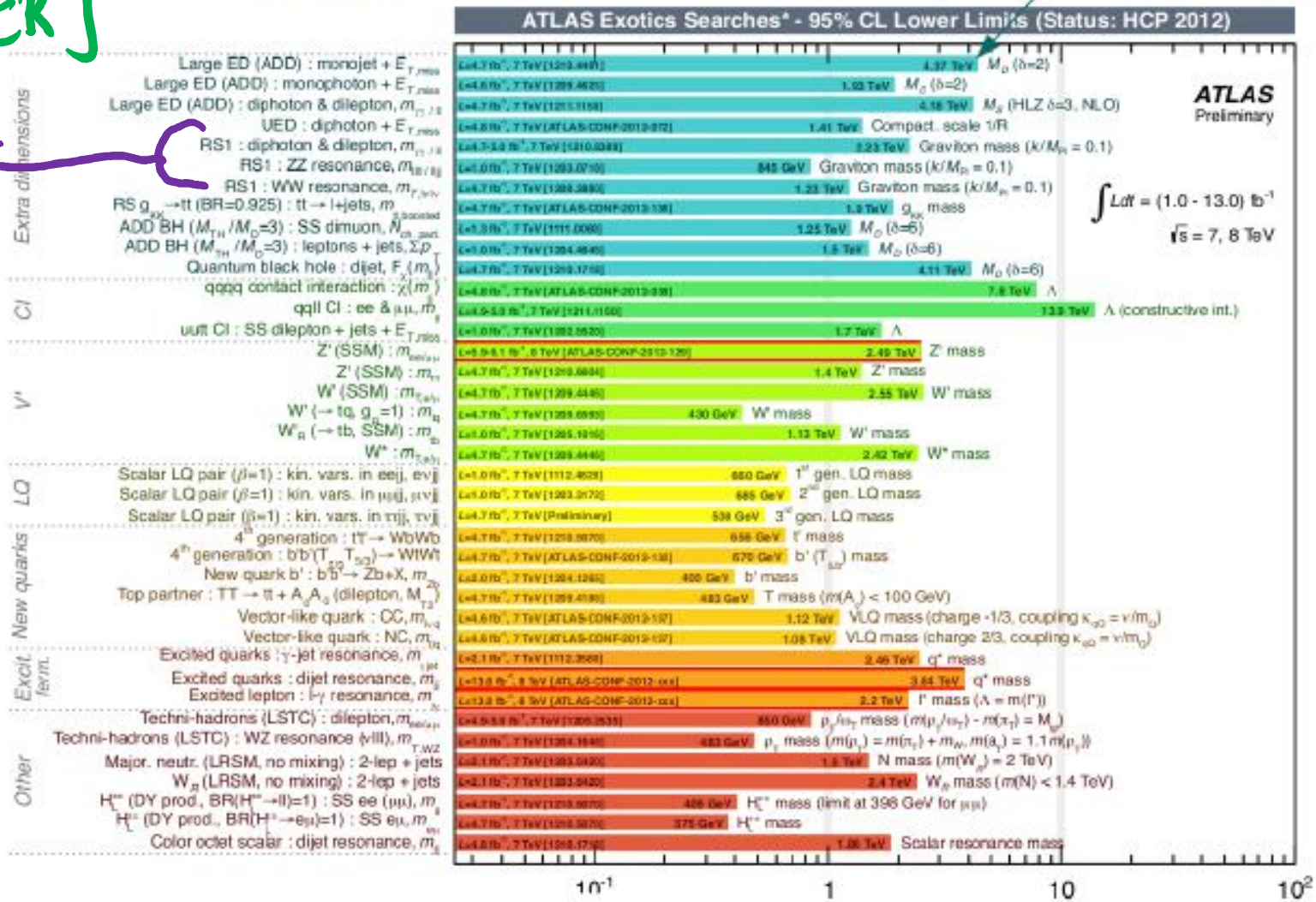
We, as "members of a curious species [that] have dedicated their lives and fortunes to the search for their origin in a dark universe" (NYT, July 4, 2012) are proud of the discovery of the Higgs boson

[BAUER]

RS

# Overview of current results

8TeV result now available




*Huge amount of results, only a selection shown above*

*Red lines along a limit indicates 8TeV data*

# For further details....

- Talk is primarily based on recent arXives:
- 1405.2924 (Bar-Shalom and Jose Wudka);
- 1312.3331 (with Michael Geller and Bar-Shalom); PRD May 2014 and
- 1303.5056
- also several talks, in particular,
- FPCP 2012, Hefei China, May 2012..[1st started talking on 100 TeV Collider..]

# Main points

- **Aftermath of 126 GeV scalar: What's the scale of NP?**
- **What are its experimental ramifications for IF & HF**

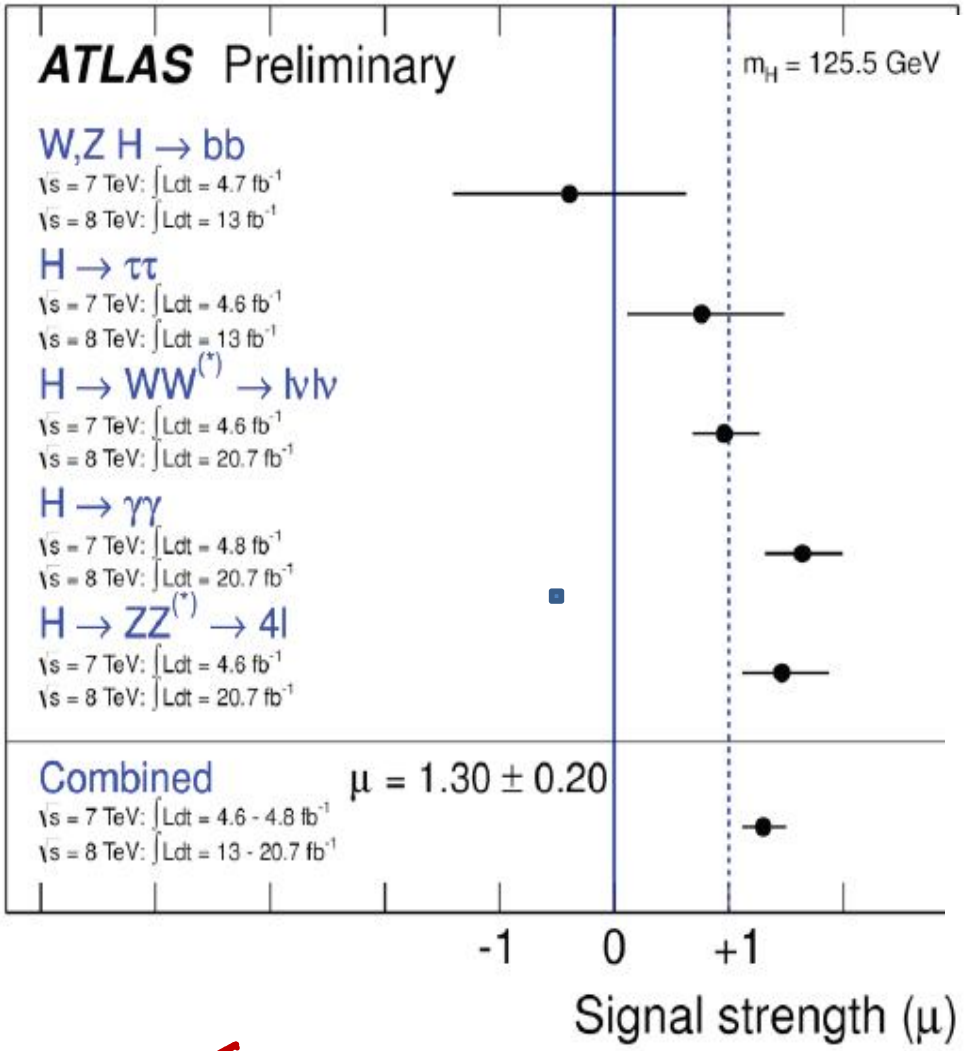
**[Most of the talk from the perspective of a *CANDIDATE* theory of flavor & then some model independent]**

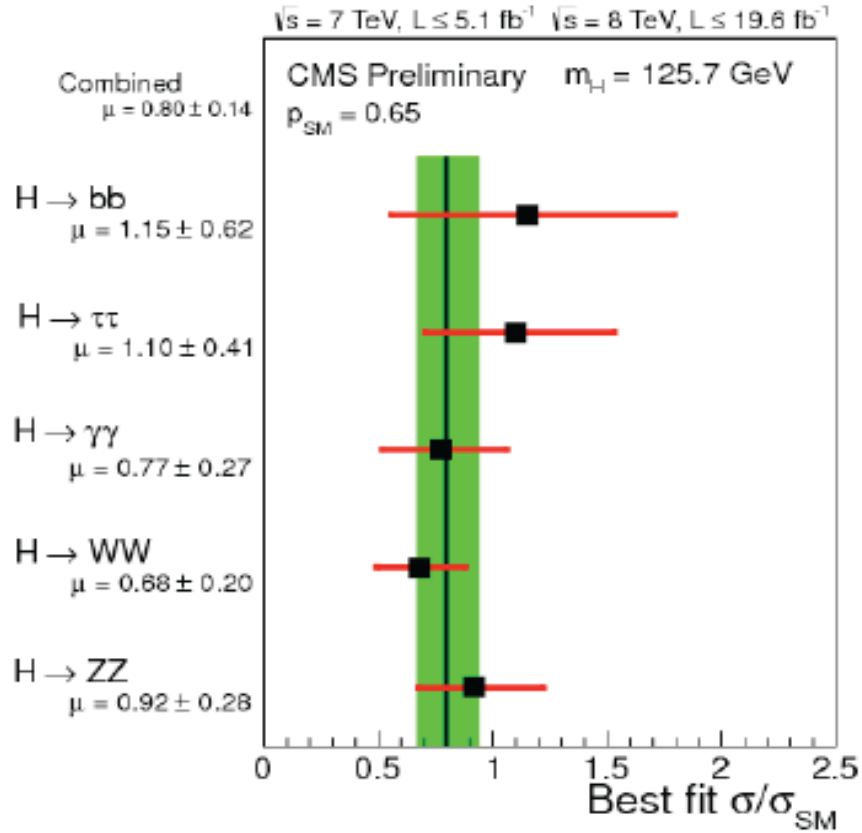
# One central message

- From the vantage point of flavor scale of NP was not expected to be ~ 1 TeV
- Its not clear what physical principle says that we need just worry about experimental constraints (say) from EWP data & disregard $K^0$ mixing, $\varepsilon_K$

Flavor is not a footprint and, in particular flavor-alignment is a serious issue

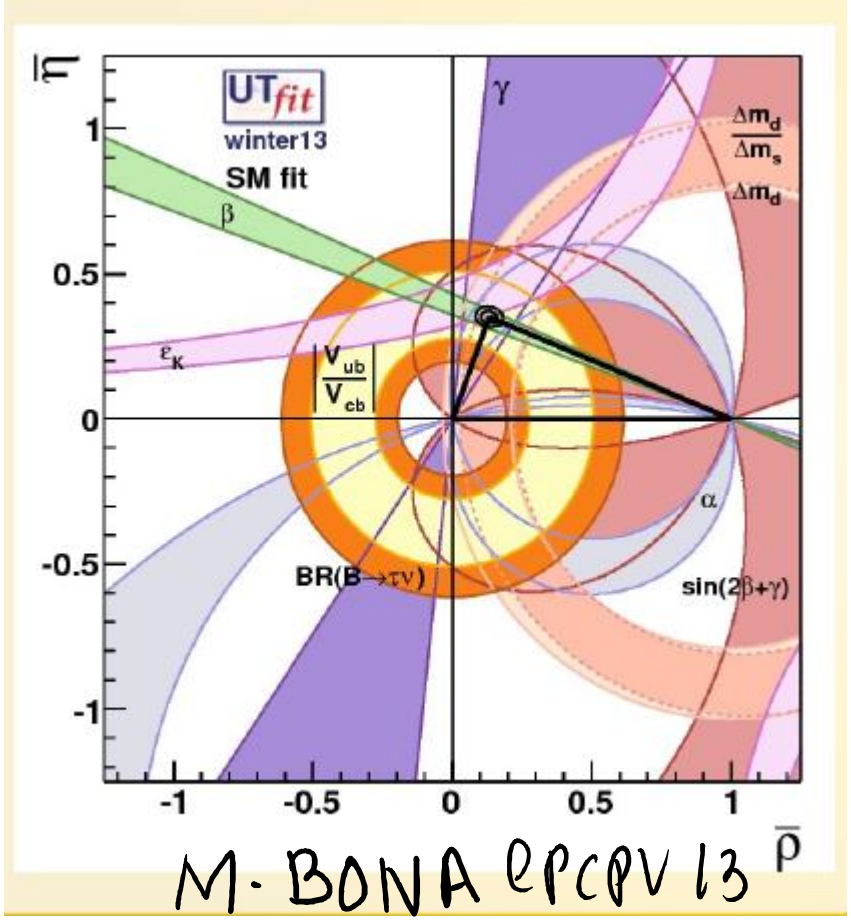
# FITS LIKE A GLOVE!
# [OR DOES IT?]



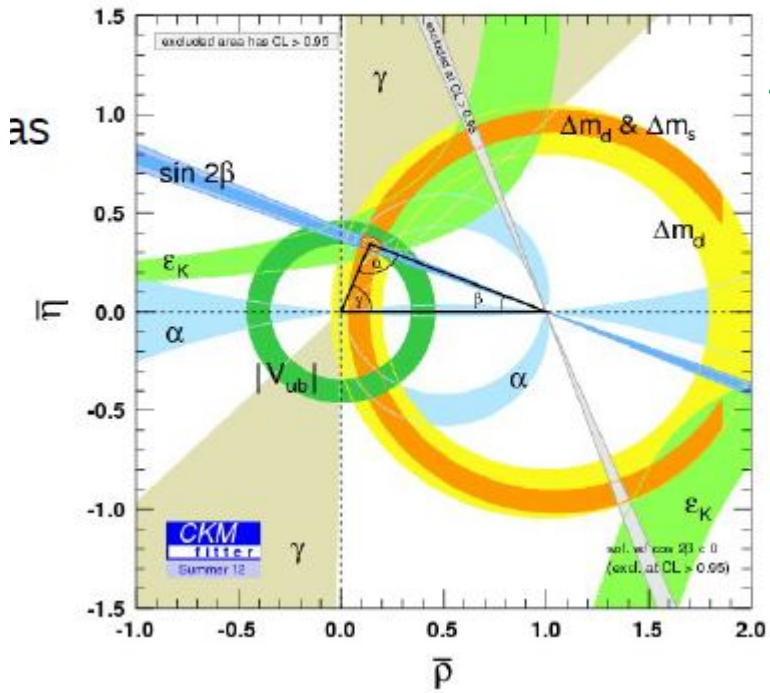

**μ=0.80±0.14**

[ERRORS Likely underestimated
Theory errors h→gg ??]




M. BONA ℓPCPV 13

http://ckmfitter.in2p3.fr
see also http://www.utfit.org




T. GERSHON @BF2013

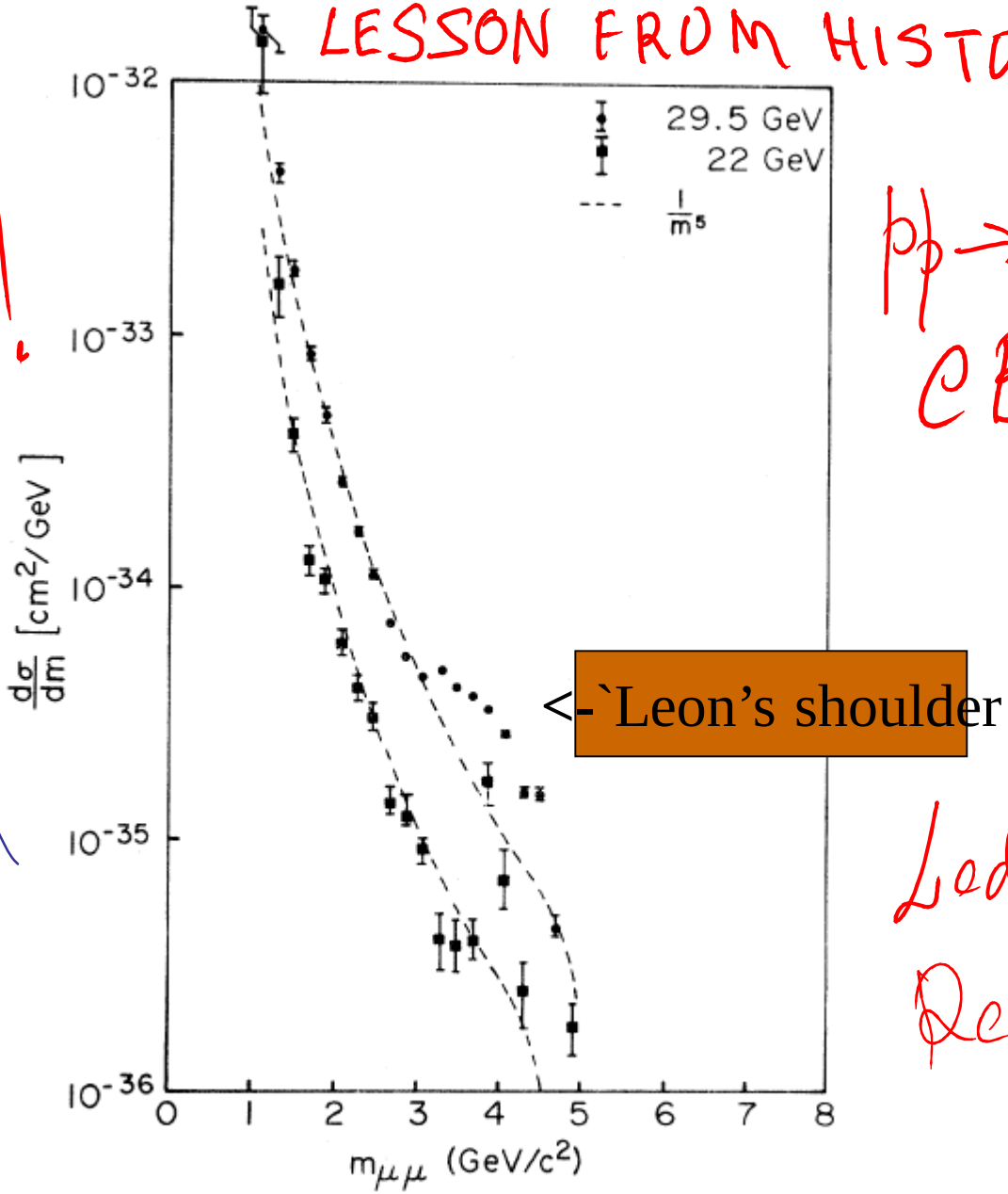
SM-CKM paradigm works rather well.
No glaring discrepancy
OTOH tests only ~ 10–15% accuracy

LESSON FROM HISTORY

DRELL-YAN
@ its
INFANCY!

The BIGGEST
MISNOMER

PRD '73




<-`Leon's shoulder

$pp \to \mu^+\mu^- X$
@BNL

Lederman
Reaction

FIG. 15. Experimental cross sections at two energies compared with a simple $1/m^5$ continuum.

# Drawing strong conclusions based on 20% tests is too risky!!

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

[C Later]

# SHOULD WE BE SHOCKED TO FIND THAT THE SCALE OF NEW PHYSICS IS NOT ~ 1 TEV & APPEARS TO BE HIGHER?

# Outstanding Th.puzzles of our times

- **Hierarchy puzzle**

For Radiative stability of $m_H \Rightarrow \Lambda_{NP} \lesssim$ TeV

to avoid fine tuning $m_H$

- **Flavor puzzle** $\Delta$flavor = 2 esp $K-\bar{K}$

$\sim \frac{g^2_{NP}}{\Lambda^2_{NP}} \Rightarrow \Lambda_{NP} \gtrsim 10^3$ TeV

HUGE TENSION

to avoid constraint from $\Delta m_K$, $\epsilon_K$

# INSIGHTS FROM A (CANDIDATE) GEOMETRIC THEORY OF HIERARCHY & FLAVOR

**A fascinating interpretation of the 126 GeV scalar in RS:**

**GOOD NEWS IS ACTUALLY AWESOME NEWS!!**

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

**1312.3331; PRD 2014**

# Geller, Bar-Shalom + AS (starting point)

- **Ask: Can the Higgs doublet simultaneously break EW symmetry as well as stabilize 5$^{th}$ dim-radius**
- **Answer Yes!**
- **Therefore minimal model whereas with traditional Goldberger –Wise you need to have an additional scalar ("Radion")**
- **With our set up instead there is only the Higgs doublet: "Higgs-radion" serving a dual purpose**

# 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$^{th}$ dim: needs a scalar field, "Radion"
- The mass of the radion is (may be?) parametrically suppressed compared to the KK scale; therefore radion
- Expected to be the lightest RS particle..focus of attention
- Quantum numbers identical to the higgs
- Numerous studies to see if 126 GeV object is

the GW radion: NO as then KK-scale needs to be ~ 1 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 5th dim by the Higgs doublet

- **Higgs in the bulk-**

**Can the Higgs VeV also simultaneously give mass to the radion?**

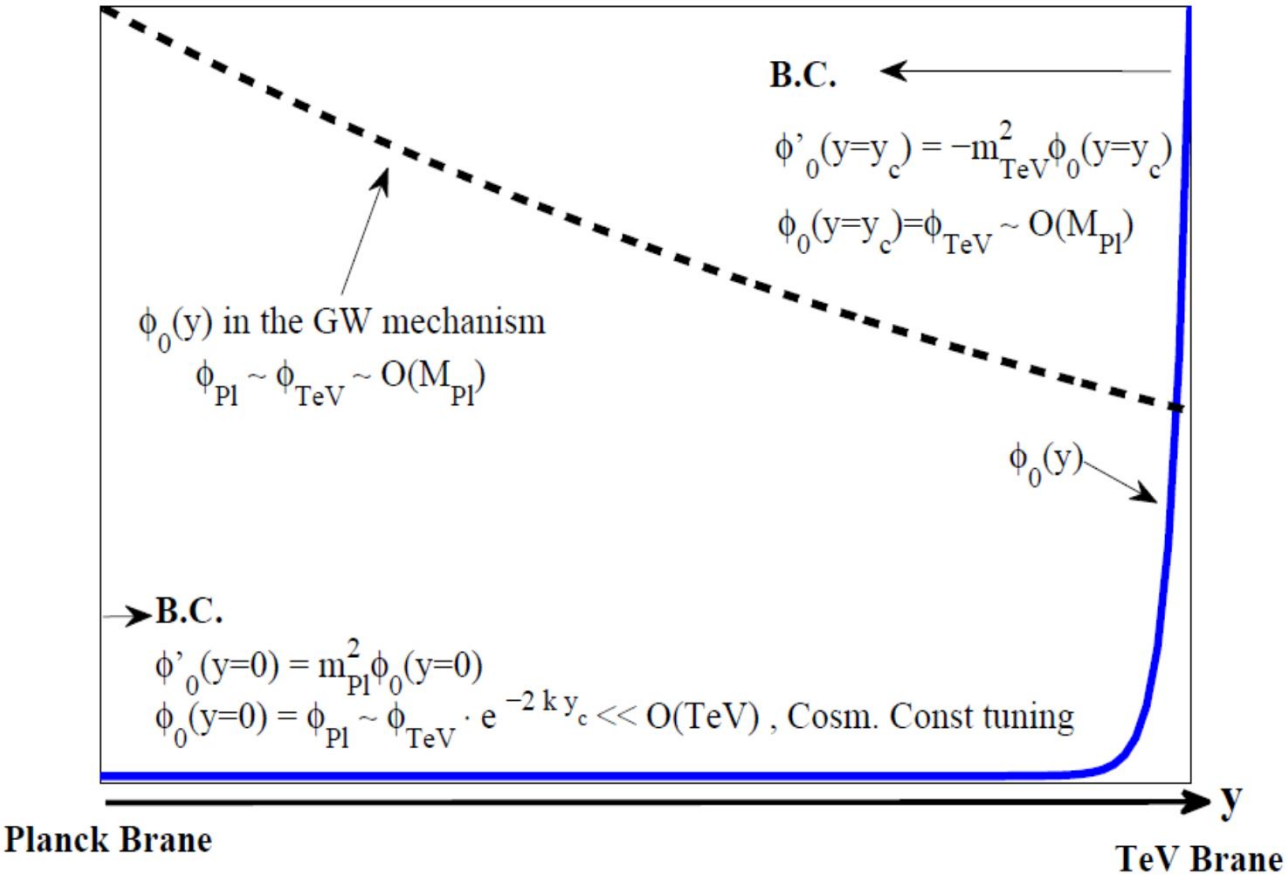
**[if so it'd be more economical]**

**Is it phenomenologically viable?**

- **Potential difficulty**

**The higgs has to be close the TeV brane (for m_EW ~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
- *Kkgluon mass lies between 4.5 and 5.4 TeV! (95%CL fit to existing data)*
- *[Note: this is completely data driven => for sure LHC13 with 100/fb will change these]*

| | SM ($m_h = 126\ GeV$) | Higgs-Radion ($m_{h_r} = 126\ GeV$) |
|---|---|---|
| $Br(h \to WW^*)$ | 0.231 | 0.204 |
| $Br(h \to ZZ^*)$ | 0.0289 | 0.0257 |
| $Br(h \to gg)$ | 0.0848 | 0.13 |
| $Br(h \to \gamma\gamma)$ | $2.28 \cdot 10^{-3}$ | $3.8 \cdot 10^{-3}$ |
| $Br(h \to b\bar{b})$ | 0.561 | 0.545 |
| $Br(h \to \tau\bar{\tau})$ | 0.0615 | 0.063 |
| $Br(h \to c\bar{c})$ | 0.0283 | 0.028 |
| Total width [GeV] | $4.21 \cdot 10^{-3}$ | $2.2 \cdot 10^{-3}$ |

IMPT to measure

E II: *The Higgs-radion and the SM Higgs branching ratios and total width. The SM values*

*en from [33].*

CAUTION: Effects of KK towers not included yet

# A promising ratio that needs special attention

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

$$\frac{\mu_{\gamma\gamma}^{ggF}}{\mu_{bb}^{VH}} \sim 2.5.$$

In contrast in the SM it is ~1

# Summary so far

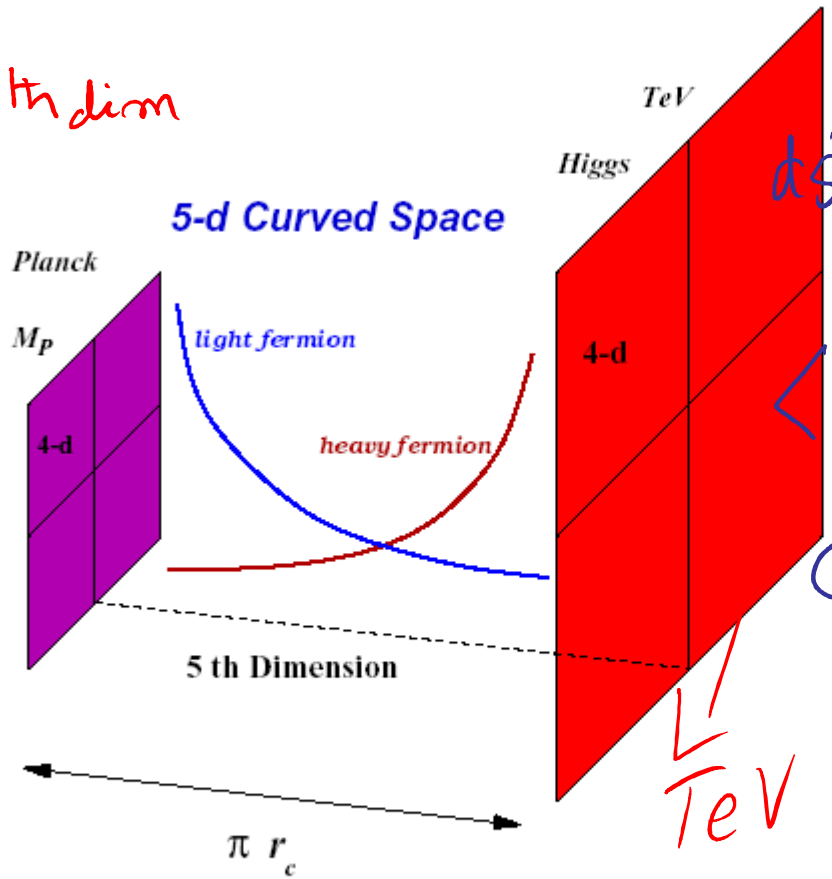
- When examined in greater detail, it may well be that the scalar at 126 GeV observed by the LHC is actually not the Higgs of the SM but rather a "Higgs-radion" from the RS-setup hinting of KK-zoo above ~5 TeV

# THE FLAVOR CONNECTION

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

Points along 5th dim correspond to diff. eff. 4d scale!




$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$$

$$\langle H_4 \rangle = e^{-\sigma}\langle H_5 \rangle$$

$$\sigma = \underbrace{k r_c}_{\sim 12}\pi$$

TeV

$M_P$

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

## Simultaneous resolution to hierarchy and flavor puzzles

## *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 [$\varepsilon'/\varepsilon$, $\gamma$, $\Delta$ACP(B=>K$\pi$),$\Delta$(Sin2$\beta$);S[B=>K$^*$ $\rho\gamma$]; $\Delta$ACP(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**

$\epsilon_K, \Delta m_K : 10^3$ TeV $\Longrightarrow RS_{Fl} \sim 10$ TeV!

**EXTENSIVE STUDIES by Blanke et al and by Cassagrande et al &.....**

# KK-scale from flavor constraints

- 10 TeV lower bound is a crude estimate
- Whereas 4-5 TeV suggested
  by ATLAS+CMS data on Higgs properties
- Both #s have considerable uncertainties
- Once KK-scale ~10 TeV custodial symm and

the particle additions it entails may not be needed.

# 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

**Bottom line is that from a variety of considerations tuning $O(10^{-3})$ may be needed but even so this is a far far cry from $10^{-34}$!**

**=> Naturalness is not at stake; at least not now**

$$\frac{v^2}{100\ \mathrm{TeV}^2} \sim 1/1600$$

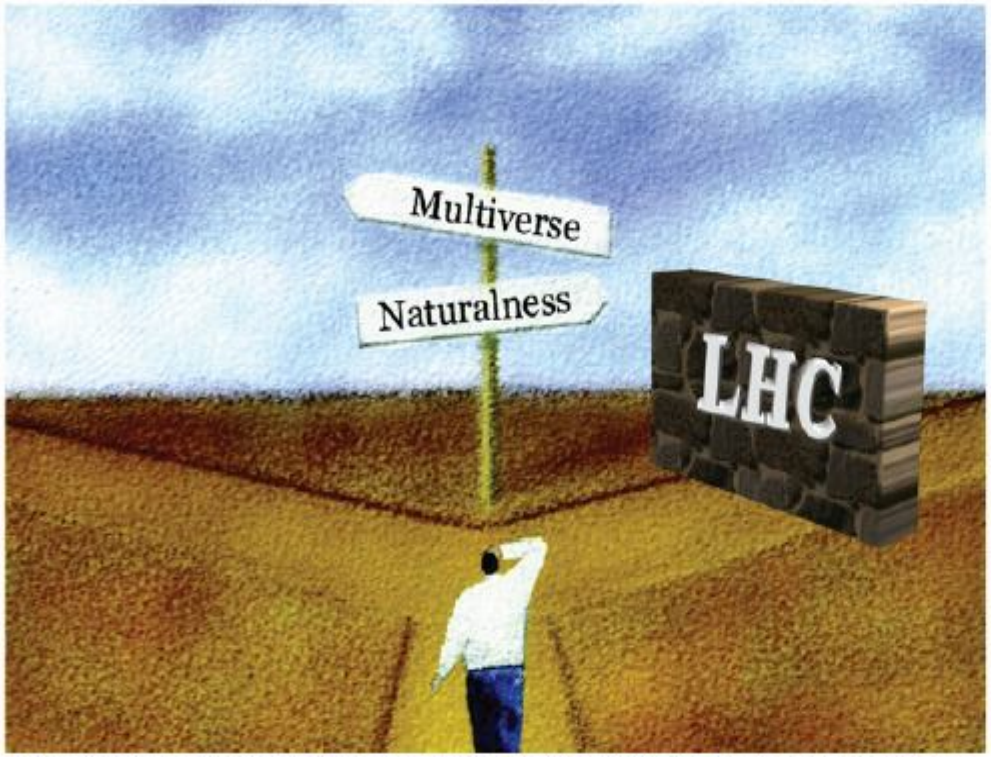
## Is Nature Unnatural?

Decades of confounding experiments have physicists considering a startling possibility: The universe might not make sense.

by: Natalie Wolchover

May 24, 2013

email print




Is the universe natural or do we live in an atypical bubble in a multiverse? Recent results at the Large Hadron Collider have forced many physicists to confront the latter possibility. (Illustration: Giovanni Villadoro)

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Science Lives

**Gee, don't see no NP signals**
**Flavor: Told you so!**

**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**

# KEY MESSAGES FROM A CANDIDATE THEORY OF FLAVOR

**1. In a candidate theory, the gigantic tension between hierarchy and flavor puzzle gets dramatically amieliorated.** ***Thus remarkably RS-leads to lowering of $\Lambda_{flavor}$ from ~1000 to ~10 TeV*** HARDER TO LOWER FURTHER

***Beat them to Death!***

**II. Due to flavor mis-alignment, O(1) BSM phases occur naturally; => direct CP is an extremely powerful probe of flavor alignment and holds the key to unlocking new physics.**

**For this purpose, RS flavor [APS '04] suggests fortunately, there are many observables : Nedm, $\varepsilon'/\varepsilon$; $\gamma$; S[B=>K* ($\rho$)$\gamma$], DCP in BSM modes....but expected signals tend to be small (for 10 TeV) necessitating high precision.**

Beat them to Death!

- **III Top quark edm may be non-vanishing and its measurement deserves special attention**

Atwood et al PR'00; Kamenik et al '13

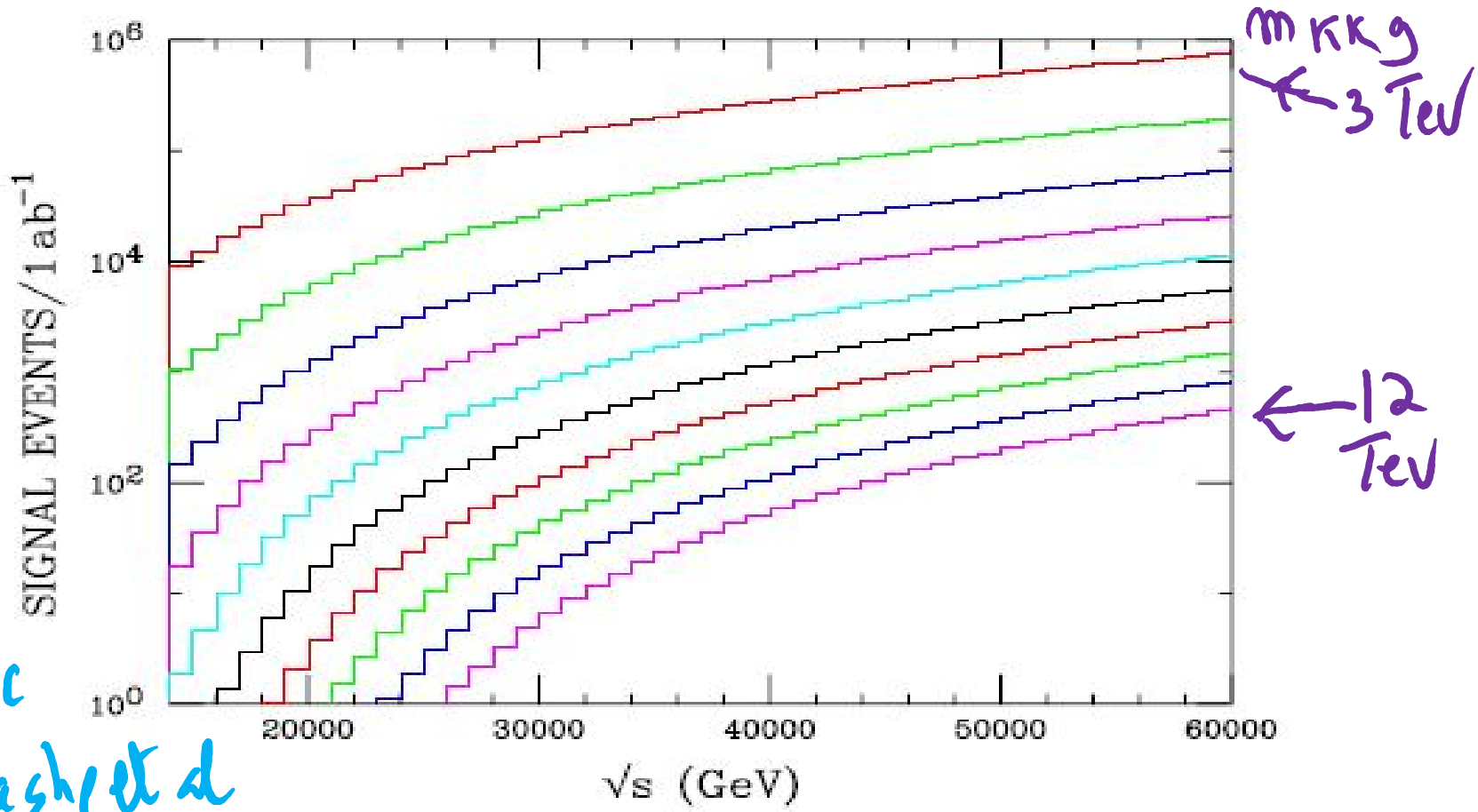
- **IV Top quark is very sensitive to flavor violation; t=>c Z; t=> c h, pp => t c h X etc need to be vigorously pursued.**

# VI. Expected size of corrections to Higgs couplings

- **Deviation from SM ~ $O(v^2/ m_{KK}^2)$ ~0.3%**
  **[assuming $m_{KK}$ > ~ 5 TeV ].**
  **Such small corrections should be a concern**

- ***VI. Once mKKg > 3 TeV, LHC14 CANNOT See KK***
  ***Or EFT Zoo***

- **VIII. For direct observation of (KK)particles of mass > ~ 10 TeV need a Gigantic International Hadron Collider (GIHC) ~ 100 TeV cm energy**




FOR LHC
See Agashe et al
06/2015

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.

**Davoudiasl,Rizzo,AS,PRD'08**



KKg → tt̄

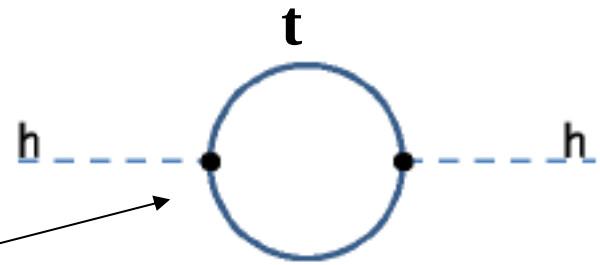
TRY a completely different line of thinking

with Shaouly Bar-Shalom [Technion]
+ Jose Wudka [UC, Riverside]

arXiv:1405.2924

# EFT APPROACH TO UNDERSTANDING HIGGS NATURALNESS

# Hierarchy/Naturalness Problem of the SM




$$\delta m_h^2(\mathrm{SM}) = \frac{\Lambda^2}{16\pi^2}\left[24x_t^2 - 6\left(2x_W^2 + x_Z^2 + x_h^2\right)\right] \sim 8.2\frac{\Lambda^2}{16\pi^2} \quad , \quad x_i \equiv \frac{m_i}{v} \quad (v \simeq 246\mathrm{GeV})$$

$$m_h^2(physical\ mass) = m_h^2(tree) + \delta m_h^2(SM) \approx 126\,GeV$$

$$\delta m_h^2(\mathrm{SM}) > m_h^2(\mathrm{tree}) \text{ when } \Lambda \gtrsim 500\,\mathrm{GeV}.$$

**driving force behind search for NP**

Assumptions:weakly coupled,Perturbative, renormalizable.....

# Set up

For subtelties, see, e.g Jenkins, Manohar & Trott, arXiv:1305.0017;1308.2627

**E**

**Heavy physics**

CONTRARIAN approach: heavy physics in curves

$\Lambda$

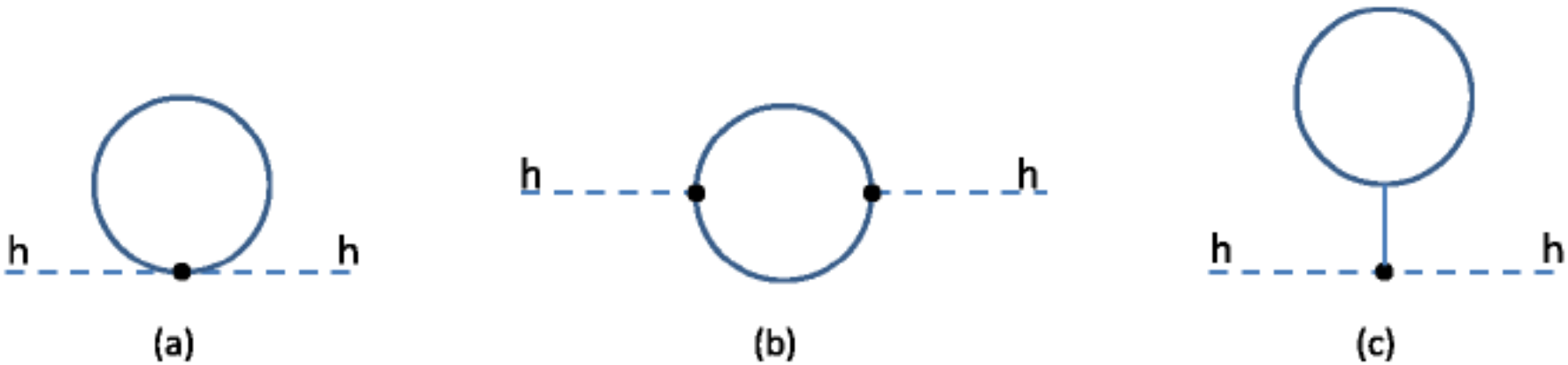
$$\text{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

(SM fields and symmetries …)

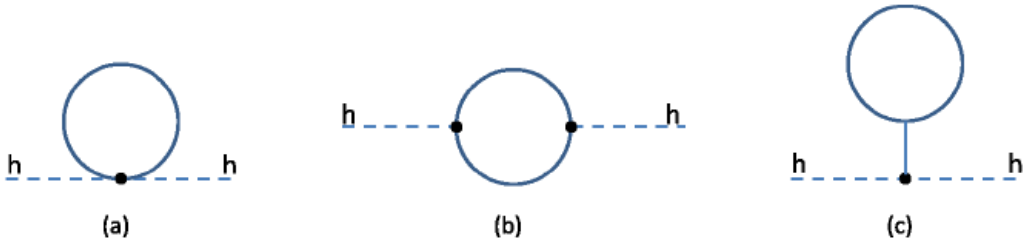
***EFT naturalness:*** conditions among $f_i$ for theory to be natural at $\Lambda$

# Sources for corrections

In general, all (**SM + NP**) 1-loop corrections to Higgs mass are from:
(internal lines are bosons or fermions from either SM or heavy NP):




Within EFT approach: useful to separate the above into 3 categories




$\delta m_h^2(\mathbf{SM})$: When all internal lines are the light SM fields.

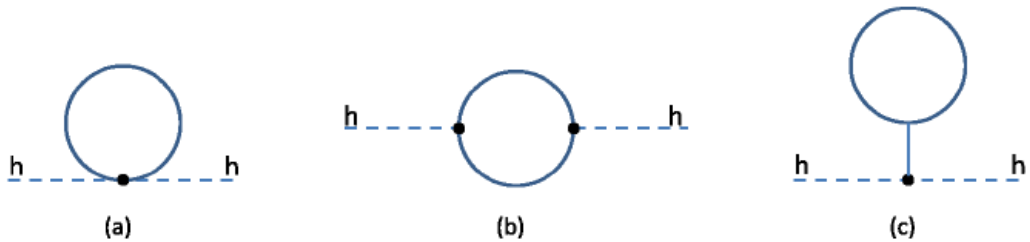
$\delta m_h^2(\mathbf{Hvy})$: When all internal lines are heavy fields of the underlying NP.

$\Rightarrow$ renorm. of "tree-level" Higgs mass:

not of SM

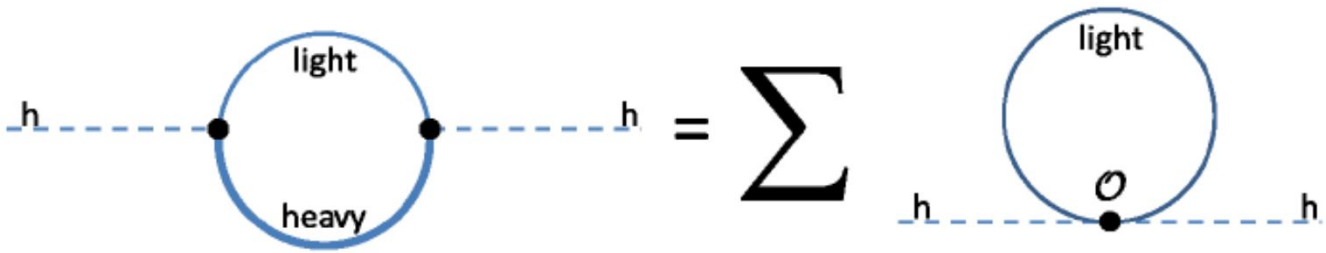
$\delta m_h^2(\mathbf{eff})$: When one line is heavy and the other is light

Generated by $L_{eff}$ – the ones we are interested in




Expanding the heavy propagators in powers of its large mass, one generates an infinite series of vertices suppressed by inverse powers of this mass ($\Lambda$)

$\delta m_h^2(\text{eff})$:




$$\sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

Different types of NP can generate the *same* operators, but, in general, with *different* coefficients.

$$\boxed{\delta m_h^2(\text{SM}) + \delta m_h^2(\text{eff}) \lesssim m_h^2 \text{ when } \Lambda \gg m_h}$$

**It ends up that there are only two types of relevant ops.**

- Type I: $\mathcal{O}$ contains 4 scalar fields, any number of derivatives and is not LG.
- Type II: $\mathcal{O}$ contains 2 fermions and 2 scalar fields, any number of derivatives and is not LG.

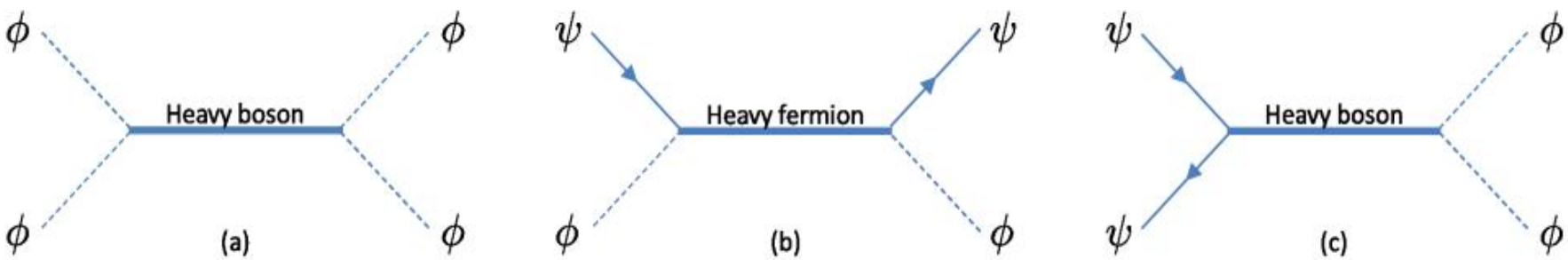
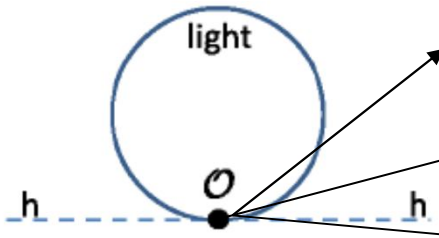



FIG. 3: *Tree-level graphs that generate the effective operators of type I (diagram a) and II (diagrams b and c), that can produce leading corrections to $\delta m_h^2$. $\phi$ and $\psi$ denote the SM scalar doublet and fermions, respectively and all vertices are understood to be invariant under SM gauge transformations.*

# EFT corrections to Higgs mass

$$\sum$$




$$\mathcal{O}_S^{(2k+4)} = \frac{1}{2}|\phi|^2\Box^k|\phi|^2 \ , \quad \mathcal{O}_{\mathbf{X}}^{(2k+4)} = \frac{1}{2}(\phi^\dagger\tau_I\phi)D^{2k}(\phi^\dagger\tau_I\phi) \ , \quad \mathcal{O}_{\tilde{\mathbf{X}}}^{(2k+4)} = \frac{1}{4}(\phi^\dagger\tau_I\tilde{\phi})D^{2k}(\tilde{\phi}^\dagger\tau_I\phi)$$

$$\mathcal{O}_v^{(2k+6)} = \frac{1}{2}j_\mu\Box^k j^\mu \ , \quad \mathcal{O}_{\tilde{v}}^{(2k+6)} = \tilde{j}_\mu^\dagger\Box^k\tilde{j}^\mu \ , \quad \mathcal{O}_{\mathbf{V}}^{(2k+6)} = \frac{1}{6}J_{I\mu}D^{2k}J_I^\mu$$

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

$$\mathcal{O}_{\Psi-\psi}^{(2k+4)} = |\phi|^2\,\bar{\psi}\,(i\,\not{D})^{2k-1}\,\psi.$$

**Fine-tuning measure:** $\Delta_h \equiv \dfrac{|\delta m_h^2|}{m_h^2}$

$\delta m_h^2 = \delta m_h^2(SM) + \delta m_h^2(eff)$

$m_h^2(tree) + \delta m_h^2$

$$\Delta_h = \frac{\Lambda^2}{16\pi^2 m_h^2}\left|F^{(\mathrm{eff})} - 8.2\right|$$

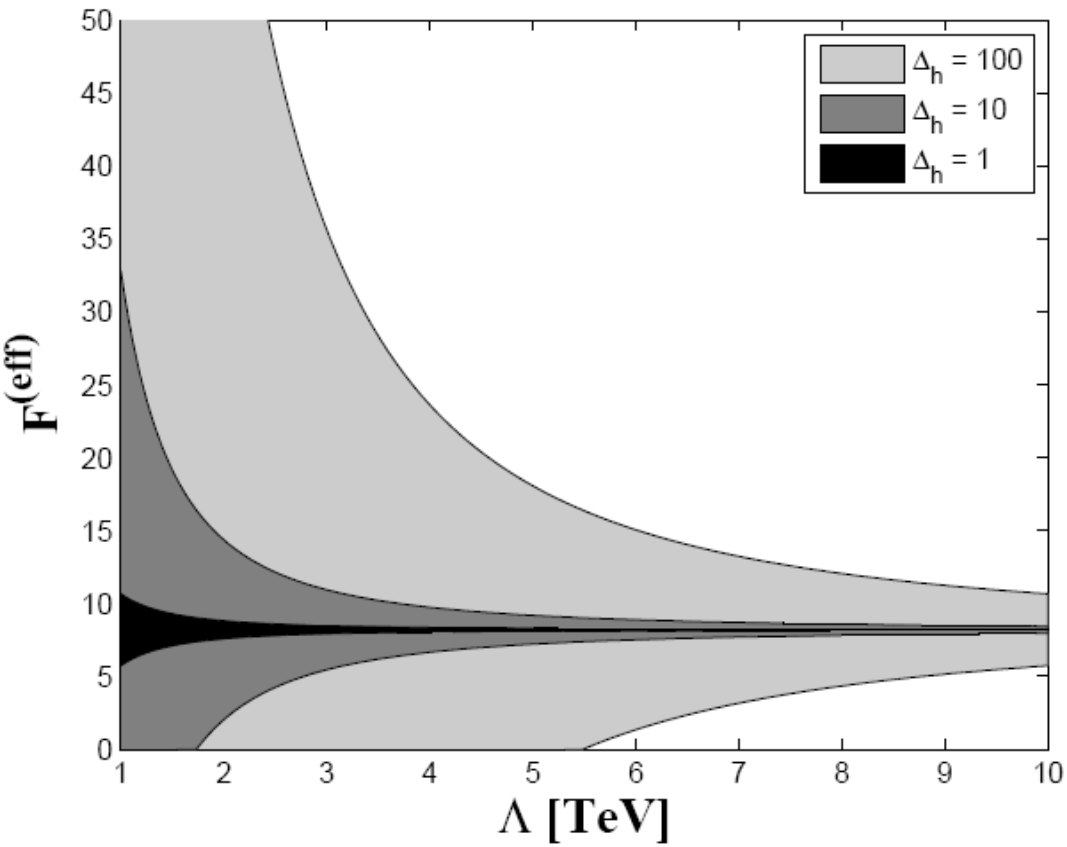
$$\left[\frac{m_h^2(tree)}{\delta m_h^2} + 1\right] = \frac{1}{\Delta_h}$$

**Cancellations must occur to a precision of $1/\Delta_h$ !**
**$\Rightarrow$ a larger $\Delta_h$ corresponds to a less natural theory**

**Either** cancellation among 1-loop contributions $\Rightarrow$ **$m_h(tree) \sim m_W$ is natural**

**Or** cancellation between $m_h(tree)$ and $\delta m_h$ $\Rightarrow$ **$m_h(tree) \sim m_W$ requires fine-tuning**

**A theory [ $F^{(eff)}$ ] for which $\Delta_h \sim 1$ is natural, while one with $\Delta_h \sim 10(100)$ suffers from fine-tuning of (no more than) 10%(1%)**




**Λ~10 TeV:**

Natural theories: $8.17 \lesssim F^{(\mathrm{eff})} \lesssim 8.23$ **⇒ accidental, symmetry ???**

Theories with 10% fine-tuning (at most): $7.95 \lesssim F^{(\mathrm{eff})} \lesssim 8.45$

Theories with 1% fine-tuning (at most): $5.73 \lesssim F^{(\mathrm{eff})} \lesssim 10.67$

# Bottom line from EFT considerations

- **At the expense of 1% - 0.1% level of tuning,**

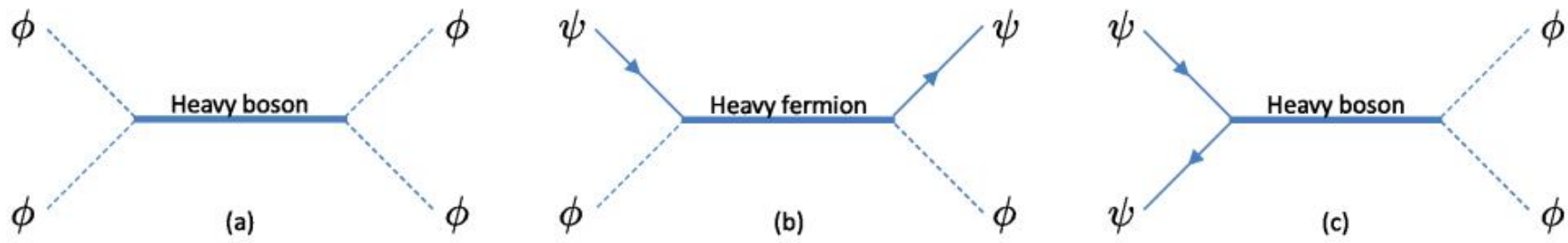
**heavy new physics ~5 TeV-10 TeV [in the guise of relatively simple (numerous) constructions] can alleviate SM-Higgs radiative stability issue**

[e.g. a singlet heavy scalar studied extensively ....

PRUNA + ROBENS PRD '13 -----

# *Experimental signals of NP that can potentially cure the fine-tuning problem in the SM-Higgs sector*

Bar-Shalom, Wudka+ AS, 1405.2924




$S \to hh$ ; $VV \to hh$ ; $\bar{\psi}_N \psi_N \to hh$ ;

$\psi_N \to h + \ell(\nu)$ ; $\psi_N \to h + q$ etc....

# RS OR EFT central message

- There is no strong reason at present for any radical revision of our ideas on naturalness
- [unless one regards ~0.1% tuning

to be a serious issue; doubt if this should be the case]

# Y BORDERS?

Recall SSC ~40 TeV ~1990 technologically completely feasible.

We should be SERIOUSLY THINKING of

GIGANTIC INTERNATIONAL HADRON COLLIDER [GIHC]

~ 100 TeV CM

"GEEK"

# Summary & Outlook (p1 of 2)

- After the 126 GeV discovery, key question for our field is the scale of new physics [NP]
- Specifically RS-flavor (which gives a nice geometric understanding of flavor & simultaneously of EW-Plank hierarchy ) strongly suggests scale is most likely bigger than ~1 TeV and more likely ~10 TeV.
- Moreover, for RS, our new "Higgs-radion" idea wherein the scalar double doublet simultaneously stabilizes the modulus as well as break EWS, provides an interesting and viable interpretation of the 126 GeV scalar. Most properties very similar to SMH except glue-glue and 2 photon BR. Requires KK-gluon mass of 4.5 to 5.5 TeV....flavor constraints may need mild tuning...
- EFT analysis also suggests heavy NP ~5 – 10 TeV with moderate tuning may well alleviate higgs radiative stability
- Unfortunately scale is out of reach of LHC14

# Summary & Outlook (p.2)

- Specifically from the perspective of warped theory the following deserve attention
- Dir CP probes [e.g. nedm, S[B=>K $\rho\gamma$]; $\gamma$; Null Tests,
- t-dm; top FV via e.g. t=>c Z; t=> c h; pp => t c h; $e^+ e^-$ => t c
- Expected deviation to higgs couplings ~O(0.3%) may be a concern for some experiments
- Precise measurements & precise computations deserve high priority.
- It is essential to have high sensitivity CP-flavor experiments; BUT we should also be seriously thinking of a GIHC (~100 TeV) as the next step in our adventure.

# XTRA

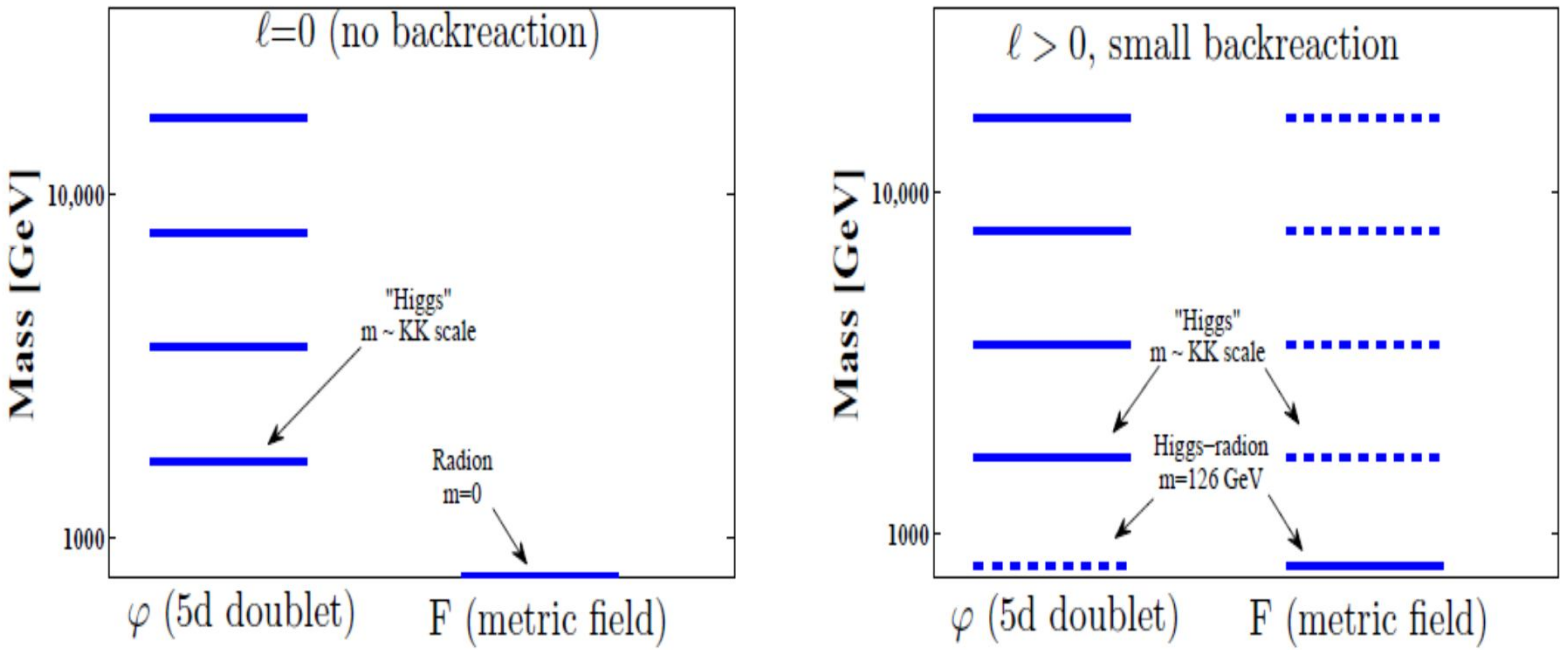



FIG. 2: *A graphic illustration of the particle/KK spectrum in our setup with (right) and without (left) backreaction.*

# EWPC

- Unless KK-masses are heavy enough, T-parameter tends to come out large $\gtrsim$ 10 TeV Csaki et al [103] - - - -
- Since tuning goes as ~ [<v>/m_KK]^2 this tends to make the set up more unnatural compared to ~3 TeV
- Agashe, Delgado, May & Sundrum, JHEP'03 proposed an interesting way out. Impose "Custodial Symmetry" => extend the gauge group to SU(2)XSU(2)XU(1) which requires introducing additional fermions

$$Q_L^3 = \left(q_L^3 \quad q_L'^3\right) = \begin{pmatrix} t_L & \chi_L \\ b_L & T_L \end{pmatrix} \rightarrow (2,2)_{2/3}$$

Thereby EWPC and Z=> bb allow m_KK to be ~ 3 TeV =Tuning is around ~10^-2. However, since kaon mixings etc require around 10TeV, its not clear if CS is needed any more.

fermion $\Psi$ has left- and right-handed components $\Psi_{L,R}$ which can be expanded in KK modes

$$\Psi_{L,R}(x,\phi) = \sum_{n=0}^{\infty} \psi_{L,R}^{(n)}(x) \frac{e^{2\sigma}}{\sqrt{r_c}} f_{L,R}^{(n)}(\phi). \tag{5}$$

The KK wave functions $f_{L,R}^{(n)}$ are orthonormalized

$$\int d\phi e^{\sigma} f_{L,R}^{(m)} f_{L,R}^{(n)} = \delta_{mn}. \tag{6}$$

One can then show that the $n \neq 0$ modes are given by $f_{L,R}^{(n)} \propto e^{\sigma/2} Z_{1/2\pm c}(z_n^{L,R})$ [2], where $Z_a = J_a + b_n Y_a$ is a linear combination of Bessel functions of order $a$, $z_n \equiv (m_n/k)e^{\sigma}$ and $m_n$ is the KK mass. The zero-mode wave function is given by

$$f_{L,R}^{(0)} = \frac{e^{\mp c\sigma}}{N_0^{L,R}}, \tag{7}$$

with the normalization

$$N_0^{L,R} = \left[\frac{e^{kr_c\pi(1\mp 2c)} - 1}{kr_c(1/2 \mp c)}\right]^{1/2}. \tag{8}$$

In the SM, all $SU(2)$ doublets are left handed, while the singlets are right handed. Hence, one has to impose a $\mathbb{Z}_2$ parity on bulk fermion fields so that only the doublets have

tively. The scale $\Lambda_4$ can be much higher t
scale for light SM fermions.

The above fermion profiles also lead to a n
for SM fermion masses [2,3]. To see this,
examine the Yukawa interactions between
the Higgs field. We will assume that the Higg
brane; this is a very good approximation si
must be highly IR localized. Then, a typical
in the 5D action will take the form

$$S_Y^5 = \int d^4x d\phi \sqrt{-g} \frac{\lambda_5}{k} H(x) \Psi_L^D \Psi_R^S \delta(\phi$$

where $\lambda_5 \sim 1$ is a dimensionless 5D Yukawa
$\Psi^{D,S}$ are doublet left- and singlet right-hanc
ons, respectively. After the rescaling $H \to e$
action resulting from Eq. (12) is

$$S_Y^4 = \int d^4x \sqrt{-g} \lambda_4 H(x) \psi_L^{(D,0)} \psi_R^{(S,0)} +$$

where the 4D Yukawa coupling for the corres
mode SM fermion is given by [3]

$$\lambda_4 = \frac{\lambda_5}{kr_c}\left[\frac{e^{(1-c^D+c^S)kr_c\pi}}{N_0^{D,L} N_0^{S,R}}\right],$$

with $c^{D,S}$ denoting the 5D mass parameters fc
in the quark sector, there are, in general, 9 di

The bulk profile of a fermionic zero mode depends strongly on its bulk mass parameter $c_\Psi$. In case of a left-handed zero mode $\Psi_L^{(0)}$ it is given by [2, 4]

$$f_L^{(0)}(y, c_\Psi) = \sqrt{\frac{(1-2c_\Psi)kL}{e^{(1-2c_\Psi)kL}-1}}\, e^{-c_\Psi ky} \tag{2.6}$$

with respect to the warped metric. Therefore, for $c_\Psi > 1/2$ the fermion $\Psi_L^{(0)}$ is localised towards the UV brane and exponentially suppressed on the IR brane, while for $c_\Psi < 1/2$

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# KK gluon [Agashe et al Snowmass 2013 Benchmarks; arXiV:1309.7847]

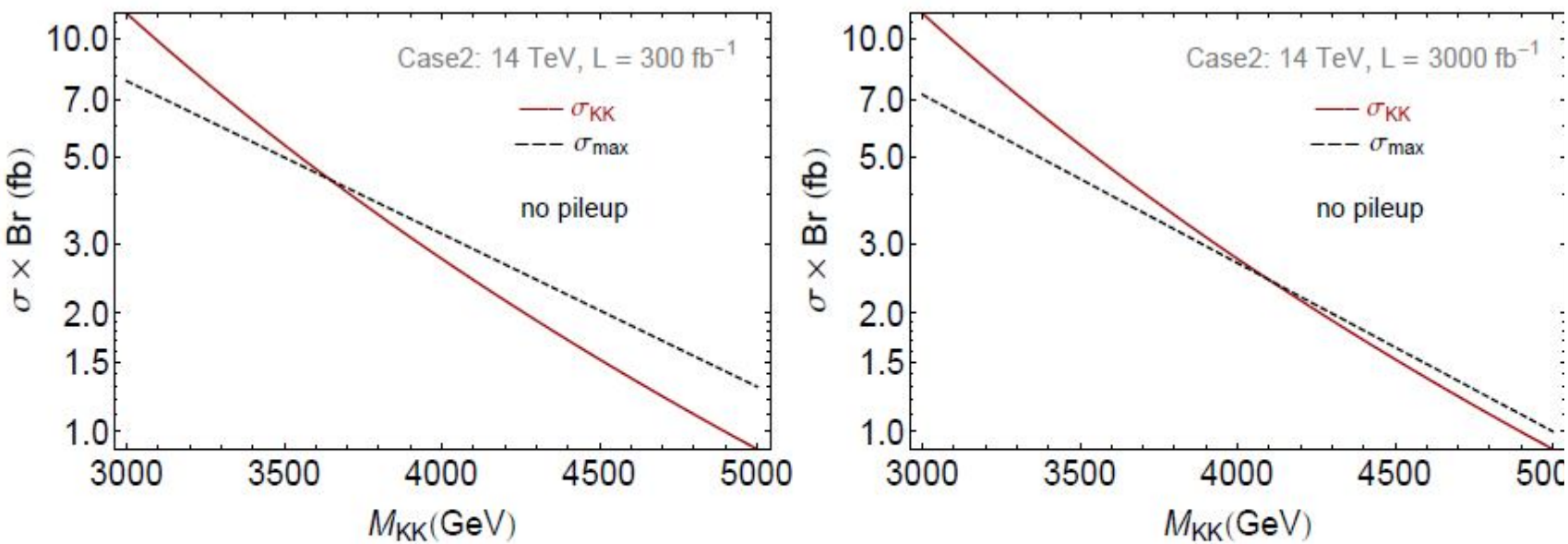


Figure 6: 95 % confidence level reach for the Case 2 KK gluon search at $\sqrt{s} = 14$ TeV $L = 300, 3000\,\text{fb}^{-1}$. The dashed line represents the upper limit on the cross section whereas solid line is the leading order KK gluon cross section.

"Semileptonic" Decays of KKZ → W W → lν, → jets.

⇒ HIGHLY COLLIMATED jets.

Table 3: $pp \to \ell^{\pm}\not{E}_T + 1$ jet cross-section (in fb) for $M_{Z'}$ =2 and 3 TeV, and background, with cuts applied successively. The number of events is shown for $\mathcal{L} = 100$ fb$^{-1}$ for 2 TeV, and 1000 fb$^{-1}$ for 3 TeV.

| $M_{Z'} = 2$ TeV | $p_T$ | $\eta_{\ell,j}$ | $M_{eff}$ | $M_{T_{WW}}$ | $M_{jet}$ | # Evts | $S/B$ | $S/\sqrt{B}$ |
|---|---|---|---|---|---|---|---|---|
| Signal | 4.5 | 2.40 | 2.37 | 1.6 | 1.25 | 125 | 0.39 | 6.9 |
| W+1j | $1.5 \times 10^5$ | $3.1 \times 10^4$ | 223.6 | 10.5 | 3.15 | 315 | | |
| WW | $1.2 \times 10^3$ | 226 | 2.9 | 0.13 | 0.1 | 10 | | |
| $M_{Z'} = 3$ TeV | | | | | | | | |
| Signal | 0.37 | 0.24 | 0.24 | 0.12 | - | 120 | 0.17 | 4.6 |
| W+1j | $1.5 \times 10^5$ | $3.1 \times 10^4$ | 88.5 | 0.68 | - | 680 | | |
| WW | $1.2 \times 10^3$ | 226 | 1.3 | 0.01 | - | 10 | | |

Shrihari Gopalakrishina et al;arXiv:0709.0007

# Singlet widely studied


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TABLE I. A summary of the most notable differences between our setup and the GW mechanism.

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

Tree level couplings to gg & γγ!