unraveling flavor & naturalness from RUN II to 100 TeV

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IHEP, Beijing March 3-7, 2015

[Flavor and Top Physics @ 100 TeV Workshop]

outline

- O(1) TeV for NP was unrealistically optimistic
- Good reasons for scale *at least* around 5-10TeV
- An exciting possibility for RUN II
- 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 EXPLORATION INDIA/USA
- no no lose theorem?

4^{th} 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...

- See also 1303.5056

Feb 2012

JIANGLAI LIU [INPAC, SHANGHAI]: DAYA BAY

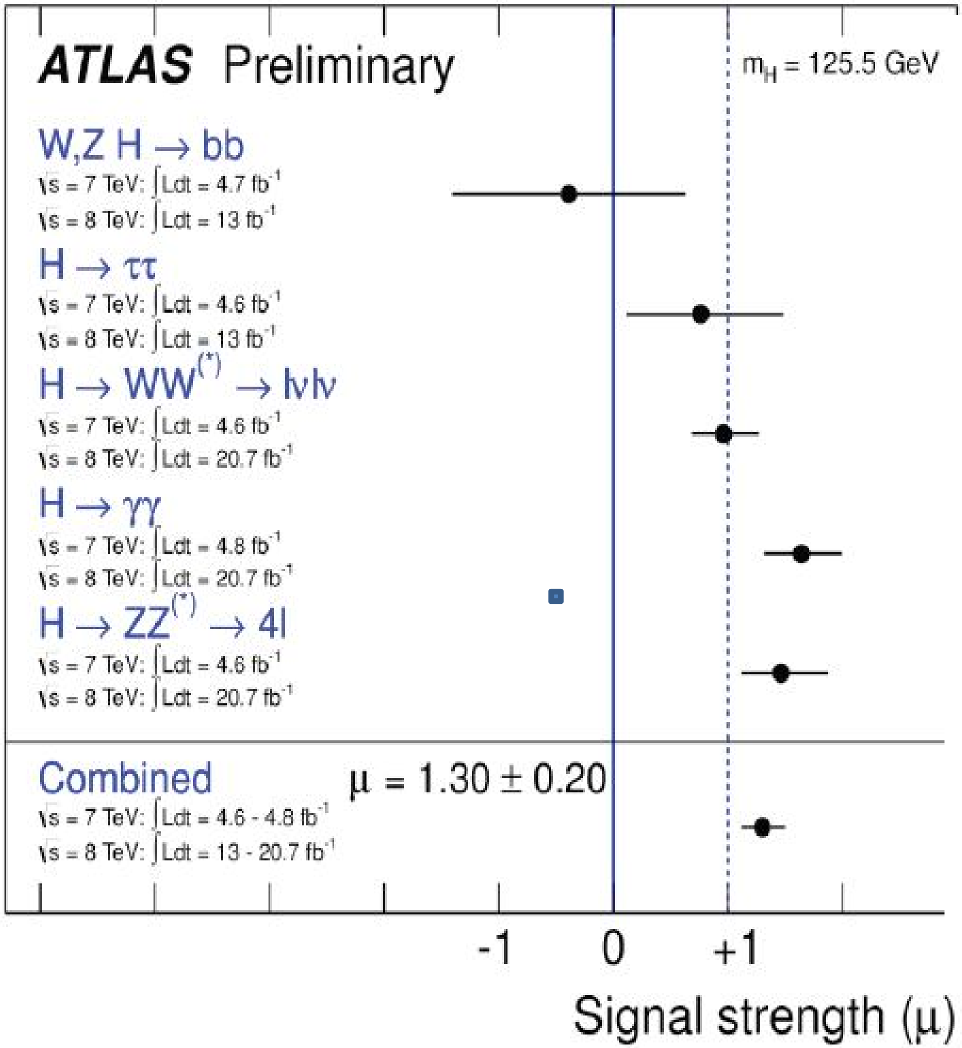
SSC 40 TeV ~ 1990

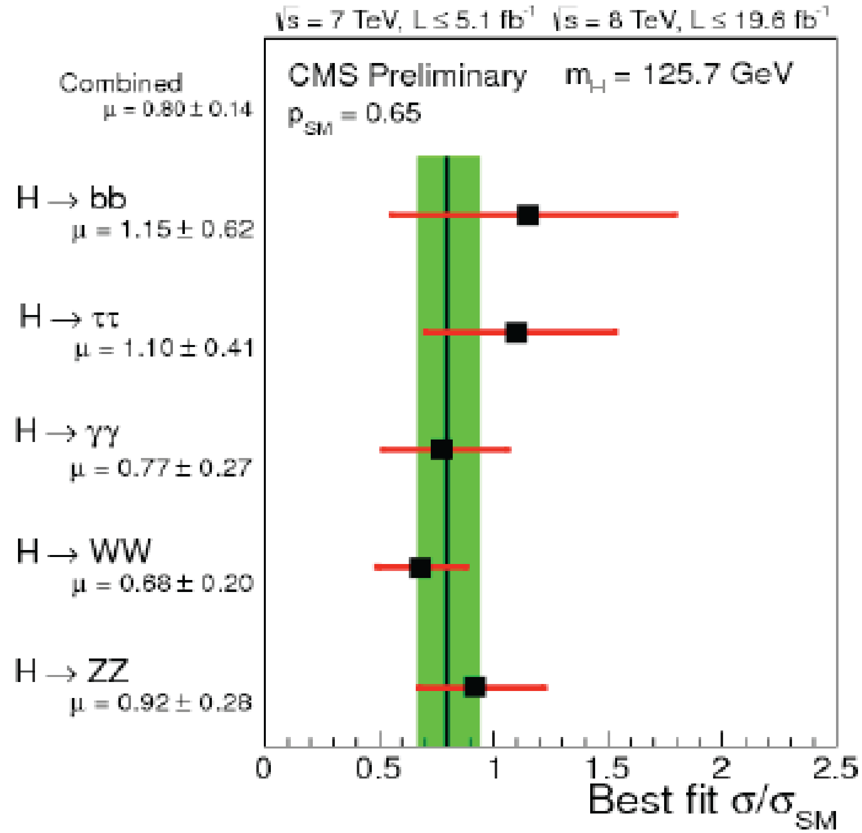
MAY WELL NEED SERIOUSLY THINKING of

GIGANTIC INTERNATIONAL HADRON COLLIDER

~ 100 TeV CM

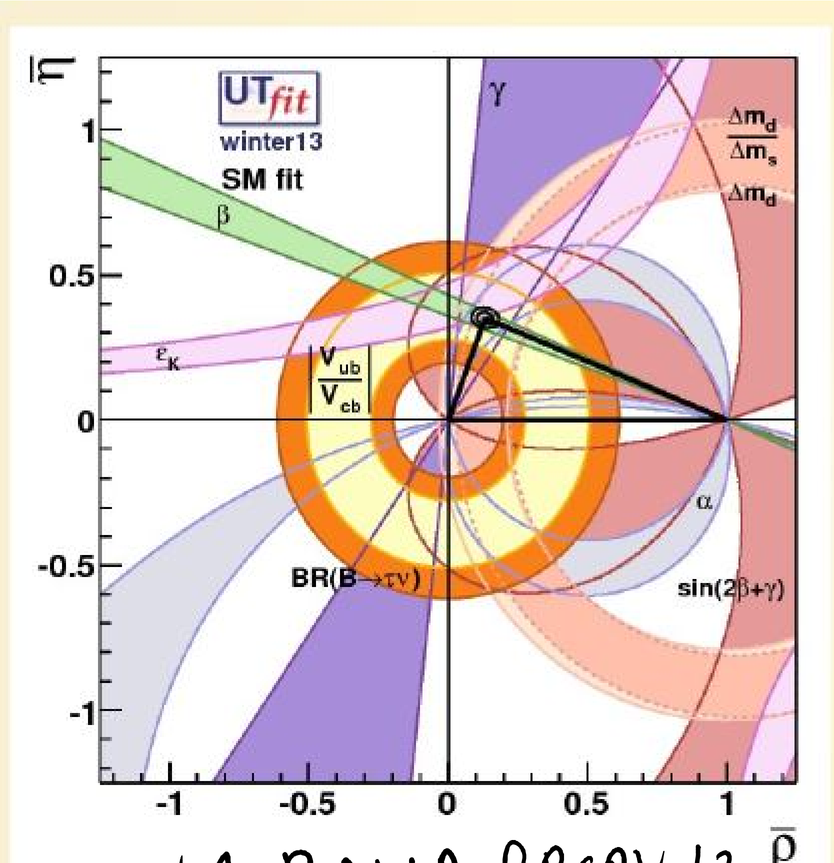
FITS LIKE A GLOVE!
[OR DOES IT?]





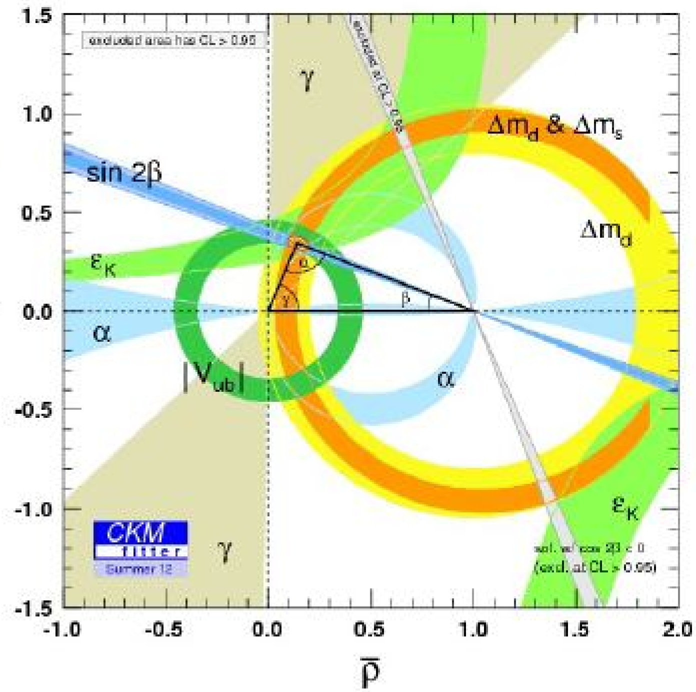
$\mu = 0.80 \pm 0.14$

Agree with SM ± 20%



M. BONA @CPV 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
$\varepsilon_K \sim 10^{-3}$!!!

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]

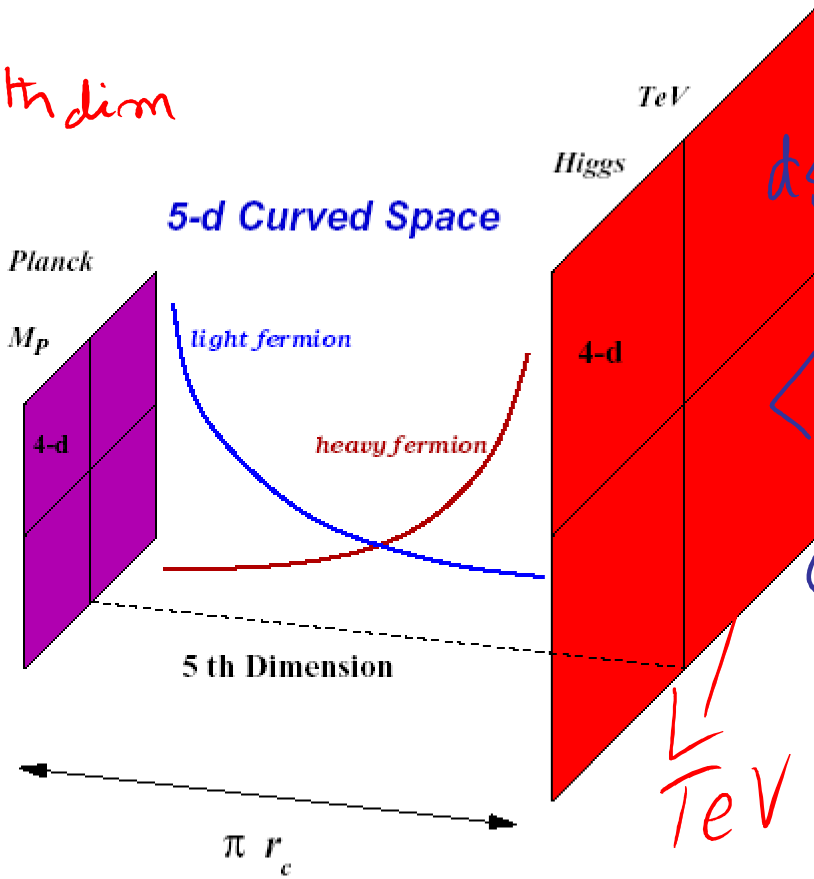
[exciting] possibility @ RUNII !!

INSIGHTS FROM A (CANDIDATE) GEOMETRIC THEORY OF HIERARCHY & FLAVOR: MANY +'S AND A WHOLE LOT OF –'S

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

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



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

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

$$\sigma = k r_c \pi$$

~ 12

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

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!
- 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 5th 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 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

- 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 5th dim.

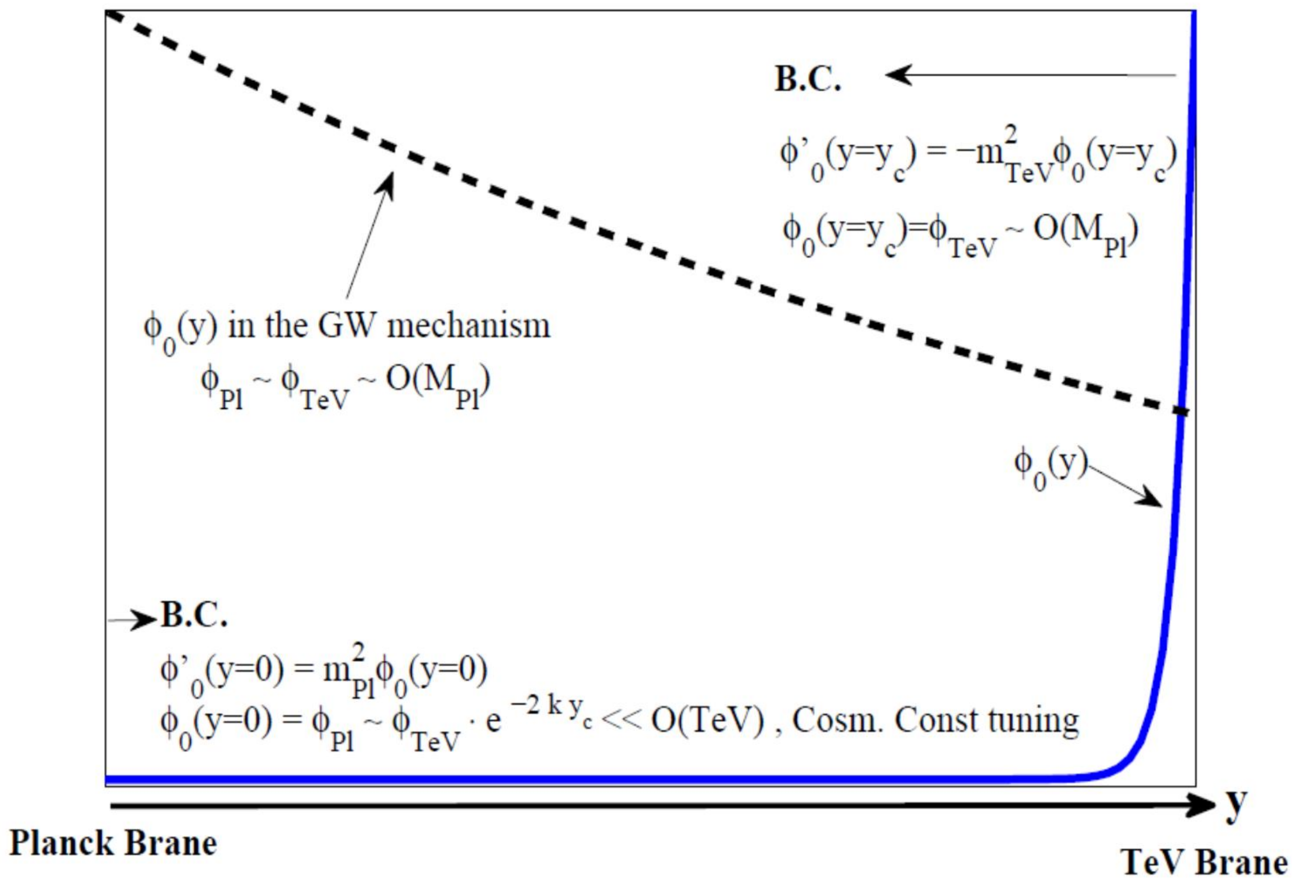
(if a solution is possible then)

2nd question: 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**
- ***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]***

	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]	$4.21 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$

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

IMPT To measure

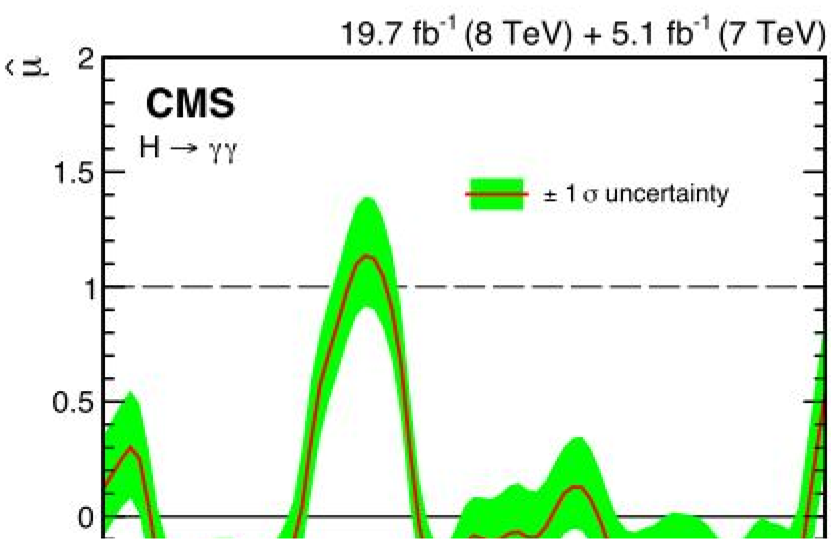
CAUTION: Effects of KK Towers not included yet ubmitted to EPJC]

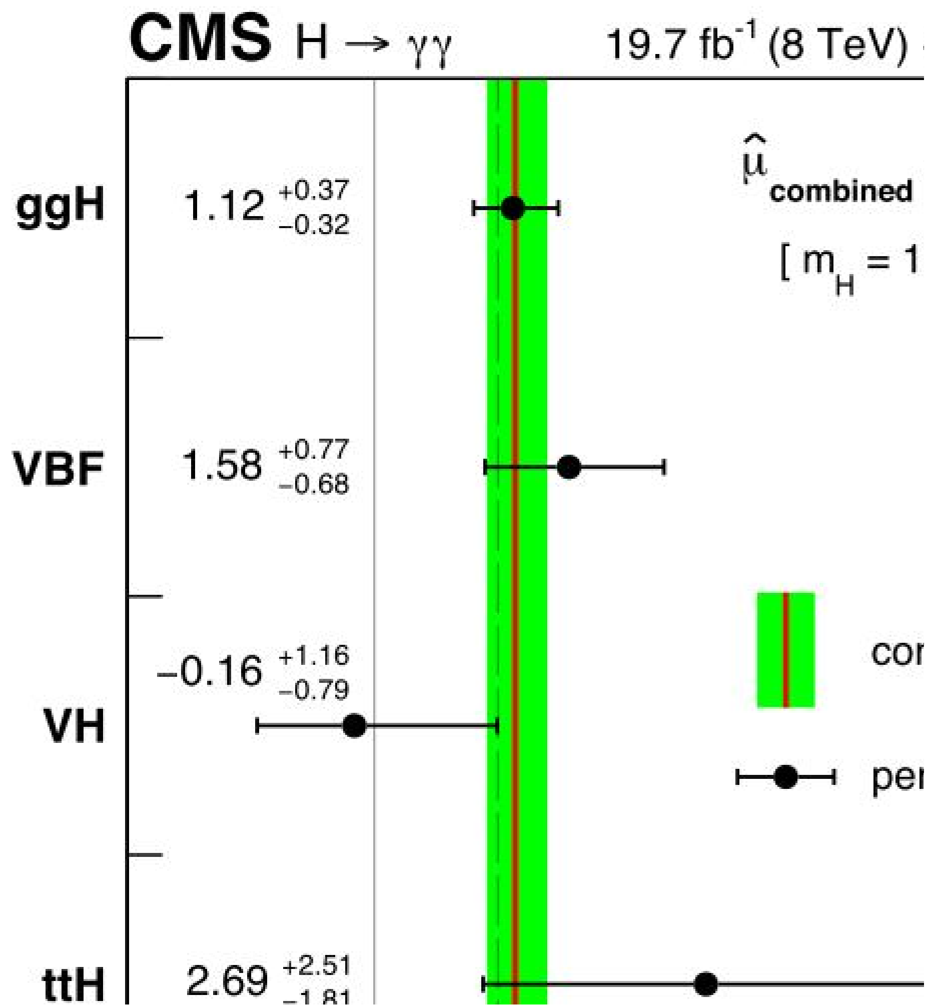
CMS ICHEP 2014

$$= 1.14^{+0.26}_{-0.23} \left[\pm 0.21(\text{stat.})^{+0.13}_{-0.09}(\text{theo.})^{+0.09}_{-0.05}(\text{s}\right.$$

Atlas ICHEP 2014

$1.57^{+.33}_{-.28}$





A promising ratio that needs special attention

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

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

In contrast, in the SM it is ~1

Summary so far

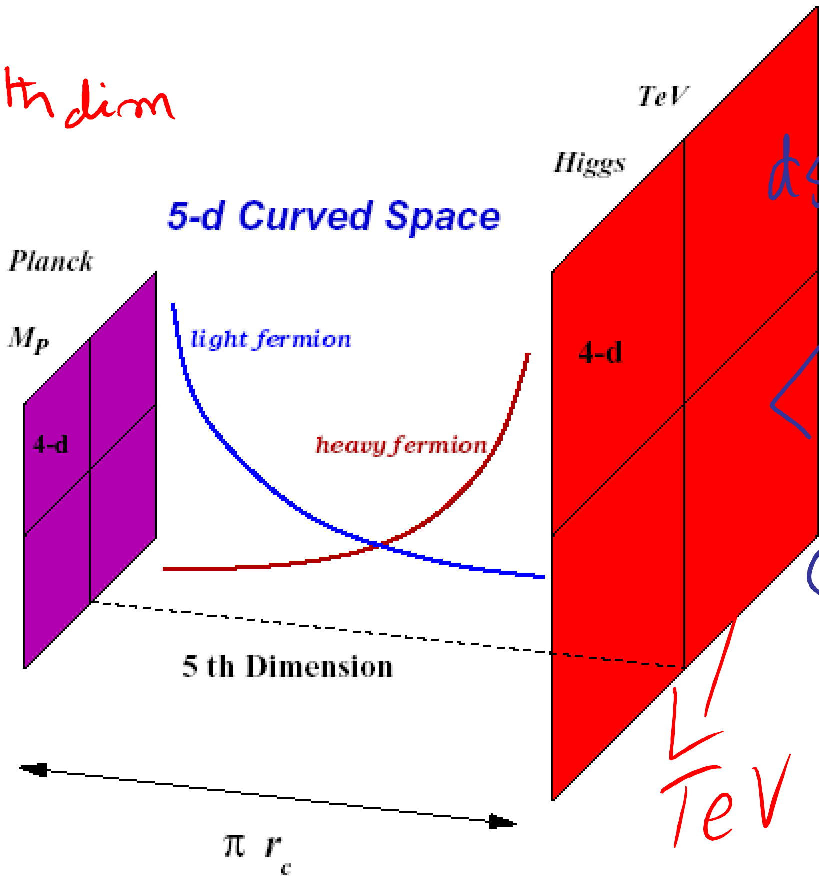
- **When examined in greater detail, we claim, that it will be found that the 126 GeV scalar is actually not the Higgs of the SM but rather a “Higgs-radion” from the RS-setup hinting of KK-zoo starting above around 5 TeV!!**

THE FLAVOR CONNECTION: PROS & CONS OF A CANDIDATE THEORY OF FLAVOR

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

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



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

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

$$\sigma = k r_c \pi \quad (k r_c \sim 12)$$

→ 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

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**

Δ flavor = 2 esp $K - \bar{K}$

HUGE TENSION $\sim \frac{g^2_{NP}}{\Lambda^2_{NP}} \Rightarrow \Lambda_{NP} \gtrsim 10^3$ TeV
to avoid constraint from Δm_K, ϵ_K

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^* $\rho\gamma$]; 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

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

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

Localization parameters of the 3-families of quarks

$c_{Q_1} = -0.579$,	$c_{Q_2} = -0.517$,	$c_{Q_3} = -0.473$
$c_{u_1} = -0.742$,	$c_{u_2} = -0.558$,	$c_{u_3} = +0.339$
$c_{d_1} = -0.711$,	$c_{d_2} = -0.666$,	$c_{d_3} = -0.553$

Table from M. Neubert @Moriond09

⇒ masses of the 6 quarks in RS!

⇒ However, (1) RS does not predict masses.

⇒ ALSO Lepton Sector needs more work as $\mu \to e\gamma$ suggest very high scale ~ O(tens of TeV)

Cons –for RS flavor [I]

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

- **Absence of BSM CP-phase in D^0 complex seems to require a very high new physics scale [Altmannshofer]**
- ..**more later (for leptonic sector)**

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**

Observable	Limit
$\mathrm{Br}(\mu \to 3e)$	$< 1.0 \times 10^{-12}$ [1]
$\mathrm{Br}(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$ [1]
$\mathrm{Br}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^-\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^+\mu^-\mu^-)$	$< 1.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu^-e^+e^-)$	$< 1.8 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu^+e^-e^-)$	$< 1.5 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$ [1]
$\mu - e$ conversion	$\Lambda \gtrsim 10^3$ TeV [5]
$e^+e^- \to e^+e^-$	$\Lambda \gtrsim 5$ TeV [3]
$e^+e^- \to \mu^+\mu^-$	$\Lambda \gtrsim 5$ TeV [3]
$e^+e^- \to \tau^+\tau^-$	$\Lambda \gtrsim 4$ TeV [3]

On the other hand

- g-2 of muon

$$\delta a_\mu \equiv a_\mu^{expt} - a_\mu^{SM} = (28.8 \pm 8.0) \times 10^{-10}$$

$$\sim 3.66$$

- New physics or under estimate of errors?
- lattice

MODELS ABOUND

Possible ways out

- Kile, Kobach and AS, arXiv:1411.1407
  Lepton flavors ⇔ DM connection

e^-, ν_e is left out

B. $SU(2)_F$ **Model**

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

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

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

, true flavor constraints

RHC in $K\bar{K}$

- 10 TeV lower bound is a crude estimate=>
- ~3TeV 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 $O(3^2)$

so

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

What physics principle?

- **In constraining new physics models, SUSY-like**

or not, people often only pay attention to EWPC and disregards flavor constraints (e.g. Kaon mixing or…), it is very difficult to give a physics justification for this strategy.

- **Flavor constraints are very important 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
- Or 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 ~10 TeV so 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

$$\text{tuning} \sim \frac{v^2}{m^2_{KK}} \sim O(10^{-3})$$

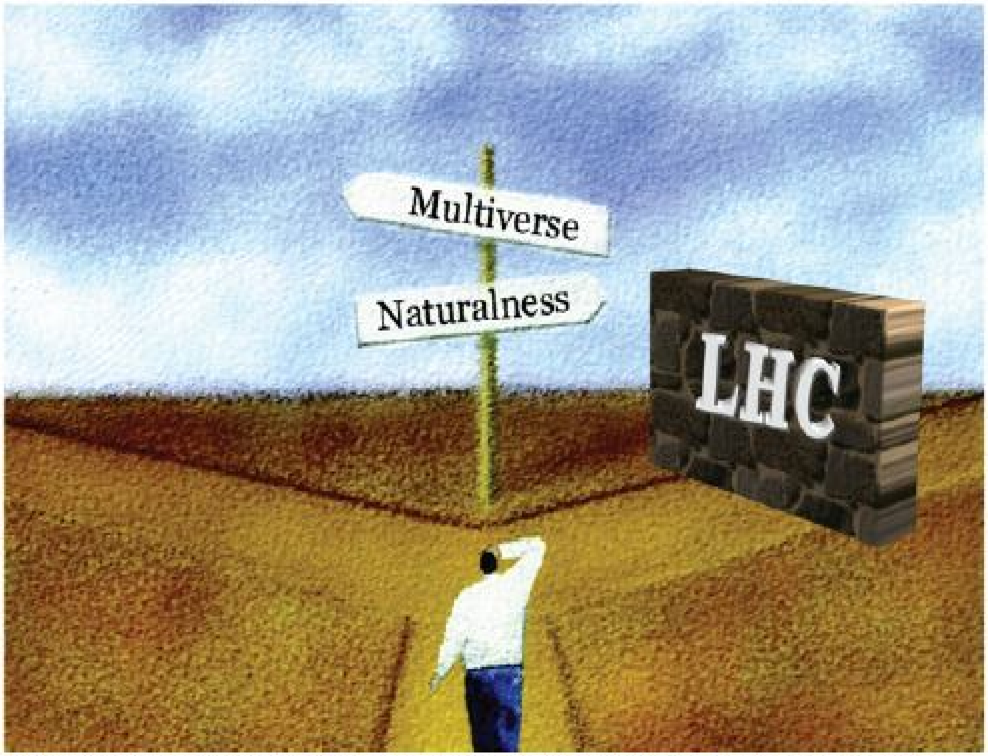
Is Nature Unnatural?

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)

Highlighted Articles

Solid or Liquid? Physicists Redefine States of Matter

Glass and other strange materials have long confounded textbook definitions of what it means to be solid. Now, two groups of physicists propose a new solution to the...

learn more

Computer Scientists Take Road Less Traveled

An infinitesimal advance in the traveling salesman problem breathes new life into the search for improved approximate...

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Science Lives

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

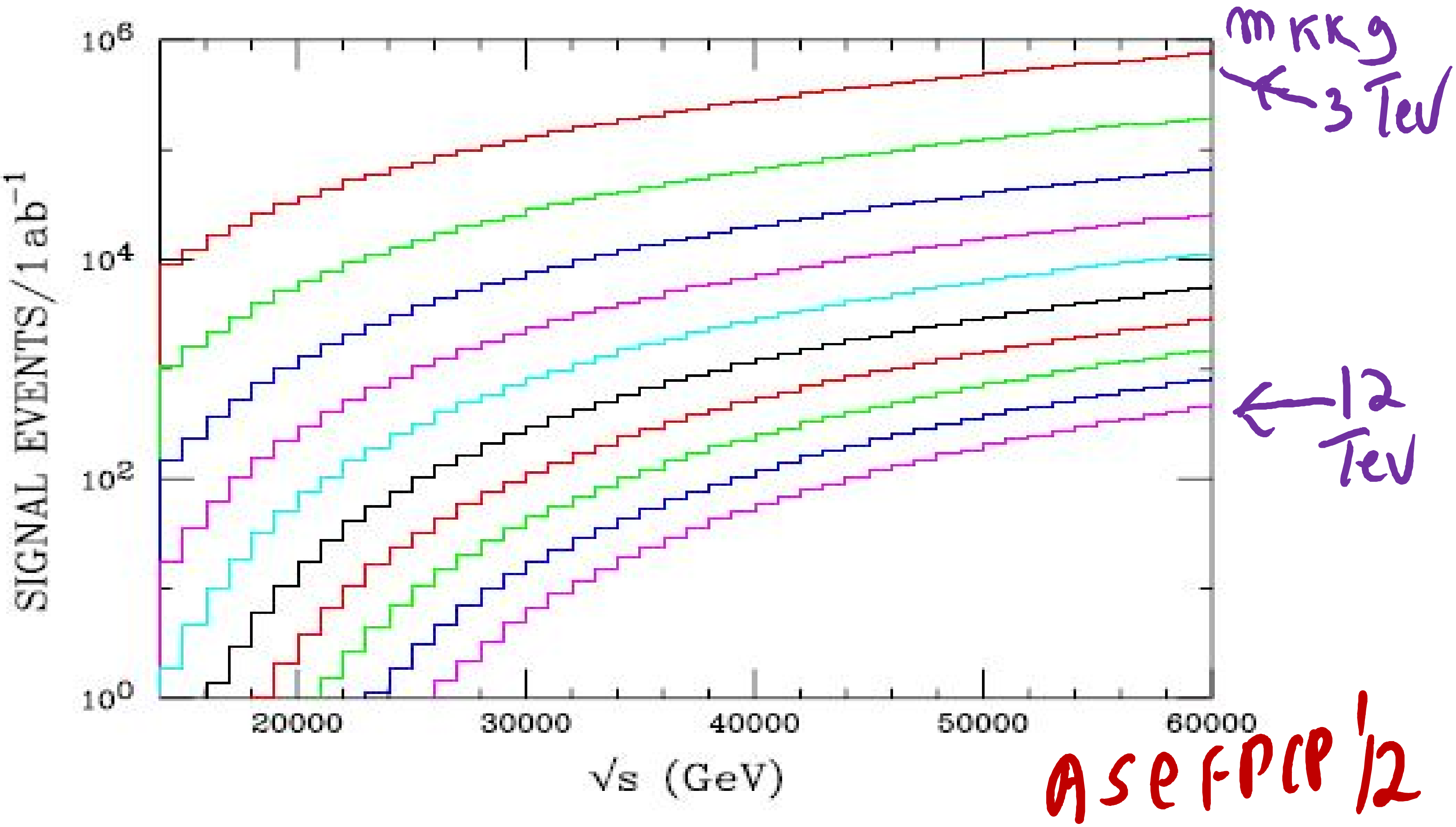


FIG. 10 (color online). Signal rate for a possible gluon KK resonance as a function of the collider energy employing the cuts described in the text. Branching fractions and efficiencies have been neglected. From top to bottom, the results are shown for gluon KK masses in the range from 3 to 12 TeV in steps of 1 TeV.

Davoudiasl,Rizzo,AS,PRD'08

SM vs BSM

- Shortcomings of SM abound:
- nu masses, DM, baryongenesis, unification……
- Unfortunately, all the BSMs "on the table" are worse…..explosion of parameters, most cases no

understanding of flavors……, many unnatural aspects

…..

- Emphasizing the need for radical ideas
- Doze of experimental reality could do wonders=>

Precisely what a 100 TeV collider can provide

金矿

e 100TeV

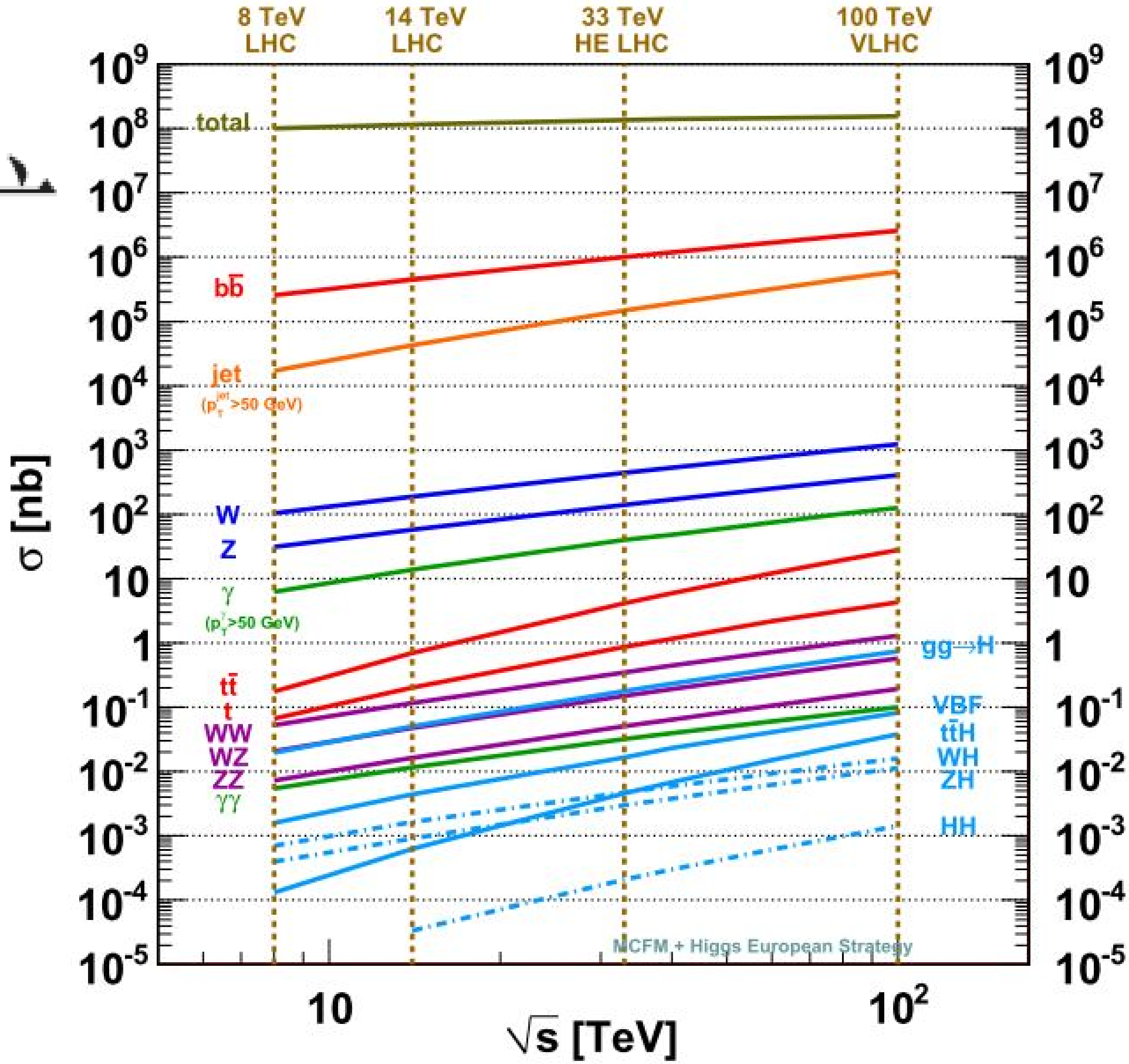


Figure 1-6. *Cross section predictions at proton-proton colliders as a function of center-of-mass operating energy,* $\sqrt{s}$.

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

Essential that we beat many of these 2 Death!

- t=> qZ; qh; q g, q gamma, [See Eilam,Hewett, AS'91; Agashe, Perez, AS '07; Atwood, Gupta, AS'14; c also Hou et al, Durieux, Maltoni, Zhang……] ….. t=>q τμ [Kile + AS'08]
- t dm [RM Xu+AS' 92; Atwood +AS'92; Bernreuther et al '92……]

G.E

top decays are self analyzers

CP ← T_N odd, T_N even

- **tth [Atwood, Bar-Shalom, AS] PRD'96**
- **See Atwood et al Physics Reports for numerous CP Observables and tests**

ABES PR '20

Huge Menu (II)

- T_p =>t h taming higgs self energy BCS, C-R CHEN
- SST powerful diagnostic; Atwood, Gupta, AS'13; Qing-Hong Cao
- h=>mu tau, [Harnik]; Z=>>mu tau,
- h=> Z Z* =>4 l [Xu + AS'93; Harnik et al; Low..
- Z'=>mu tau, BHSS'85; Han,Lewis,Sher'00

"HORIZONTAL" Gauge bosons

Large $\nu_\mu \Leftrightarrow \nu_\tau$ mixing

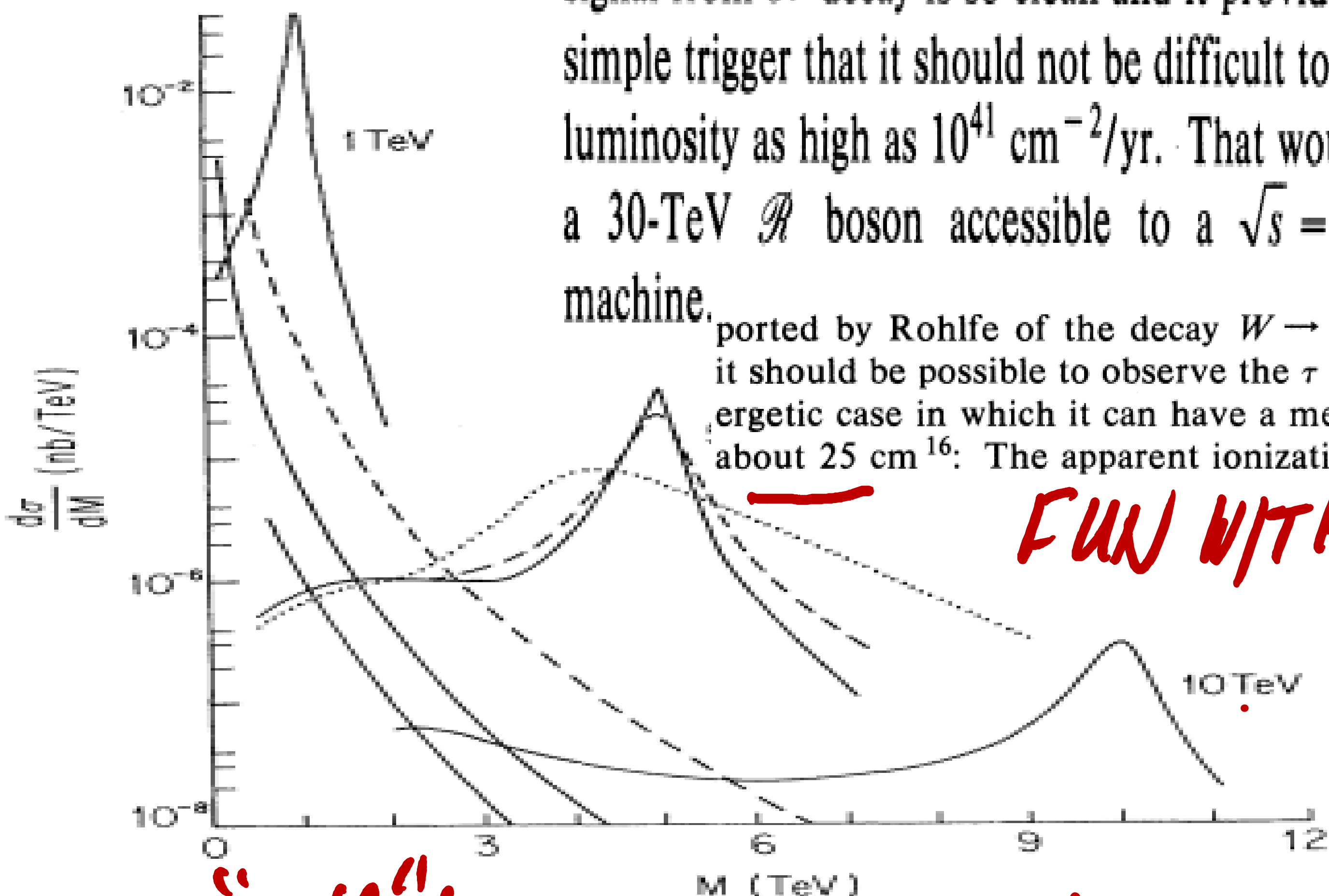
Hans-Uno Bengtsson, Wei-Shu Hou,[a] A. Soni, and D. H. Stork

PRL '85

signal from $\mathscr{R}$ 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} cm^{-2}/yr. That would make a 30-TeV $\mathscr{R}$ boson accessible to a $\sqrt{s} = 100$-TeV machine.

ported by Rohlfe of the decay $W \to \tau\bar{\nu}$.[15] Moreover, it should be possible to observe the τ decay for the energetic case in which it can have a mean decay path of about 25 cm[16]. The apparent ionization change would

FUN WITH τ'S



POSSIBLE "Double" bangs with Cascade decays of B's

Huge Menu (III)

- H^+-, H^0… a la “who ordered the muon”
- 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
- KKg, KKW, KKZ, KKG e.g.ADPS07, DRS’08
- As an important by product, powerful fixed target program ”SppCf” @ 50 TeV

- Fine tuning by (13/100)^2 => ~10^{-4} impressive achievement in itself

ADPS '07

DRS '08

PHYSICAL REVIEW D **76,** 036006 (200

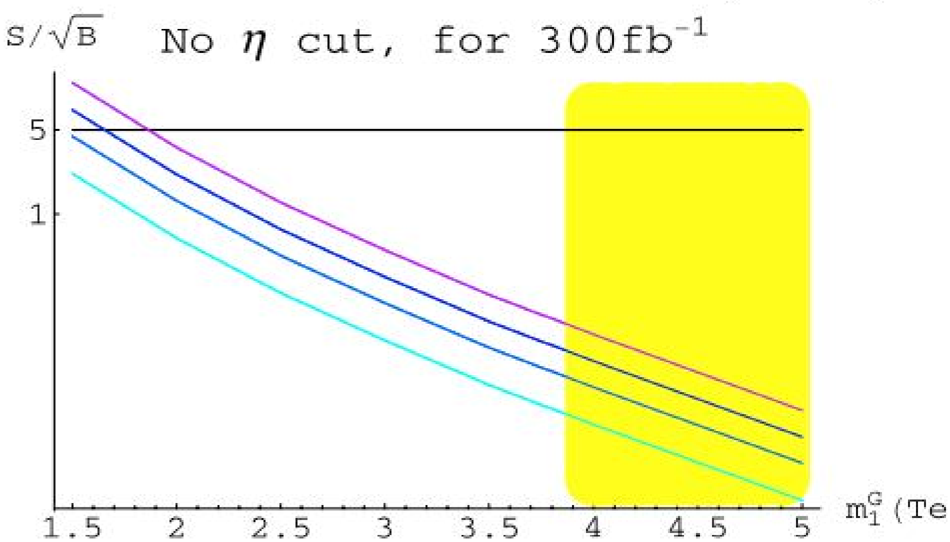


FIG. 4 (color online). Significance for the purely lepton decay mode for Z pairs from KK graviton using 300 fb^{-1}. Se also Fig. (1).

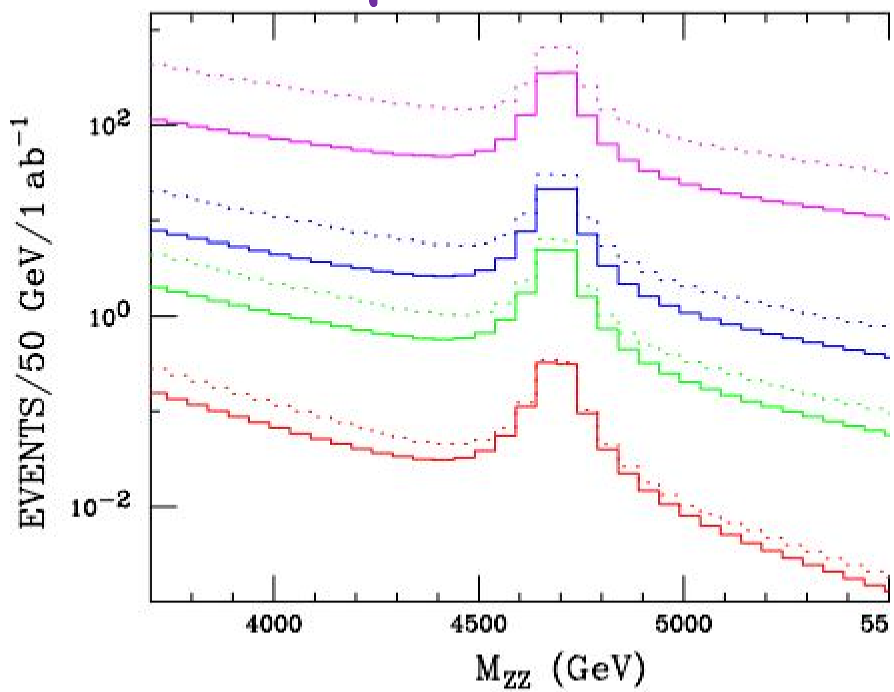


FIG. 5 (color online). Production rate for the first gravito excitation decaying into two Z bosons, assuming a rapidit $|y| < 2(1)$ on the Z's corresponding to the dotted (solid) grams. The histograms correspond, from bottom to to collider energies of $\sqrt{s} = 14$, 21, 28, and 60 TeV, respect Z branching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

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

“EFT Naturalness” approach

A modest goal:

acquire insight regarding the underlying new physics which can potentially alleviate the hierarchy problem in the SM Higgs sector

→ Contrarian

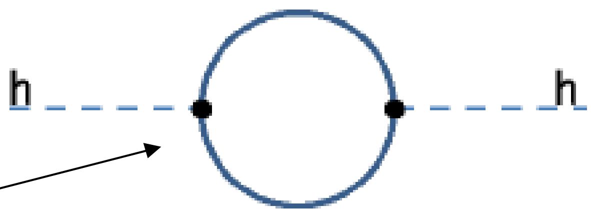
Assume: underlying Physics lies *above Λ*!

Exploit: EFT techniques

Ask: can we arrive at some conditions?

⇒ the conditions for the physics above Lambda that can soften 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

Λ

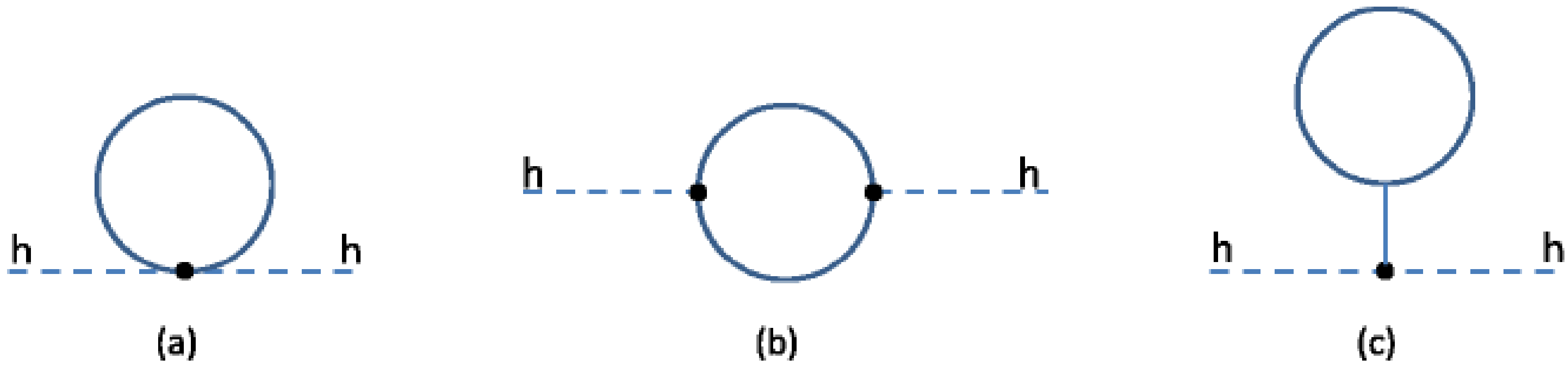
$$\text{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

(SM fields and symmetries …)

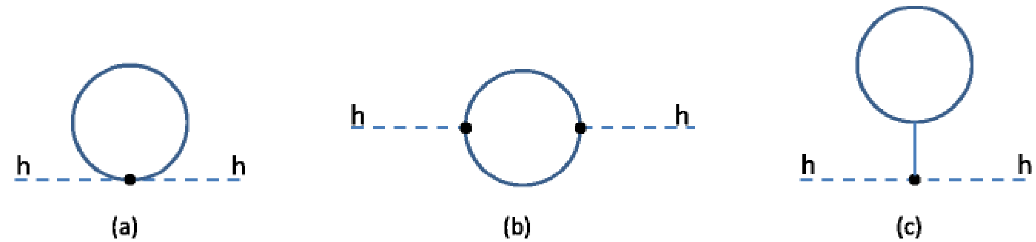
EFT naturalness: conditions among f_i for theory to be natural at Λ

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.

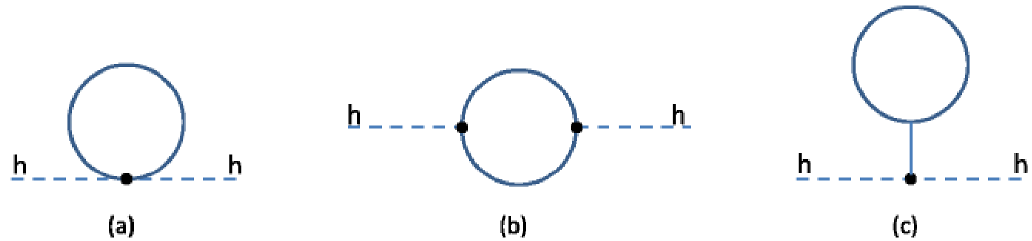
$\delta m_h^2(\mathbf{Hvy})$: When all internal lines are heavy fields of the underlying NP.

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

not of SM

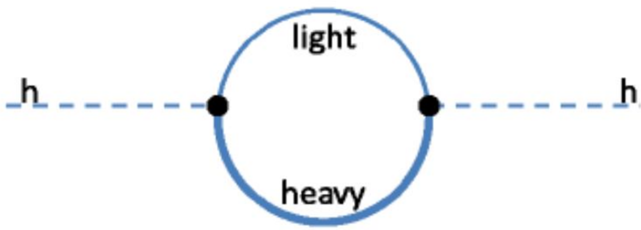
$\delta m_h^2(\mathbf{eff})$: When one line is heavy and the other is light

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

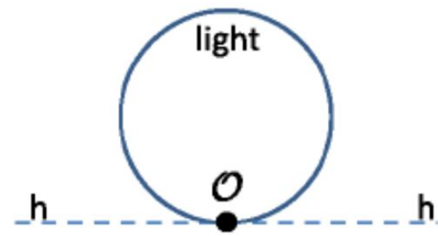


Expanding the heavy propagators in powers of its large mass, one generates an infinite series of vertices suppressed by inverse powers of this mass (Λ)

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



$= \sum$



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

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

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

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.

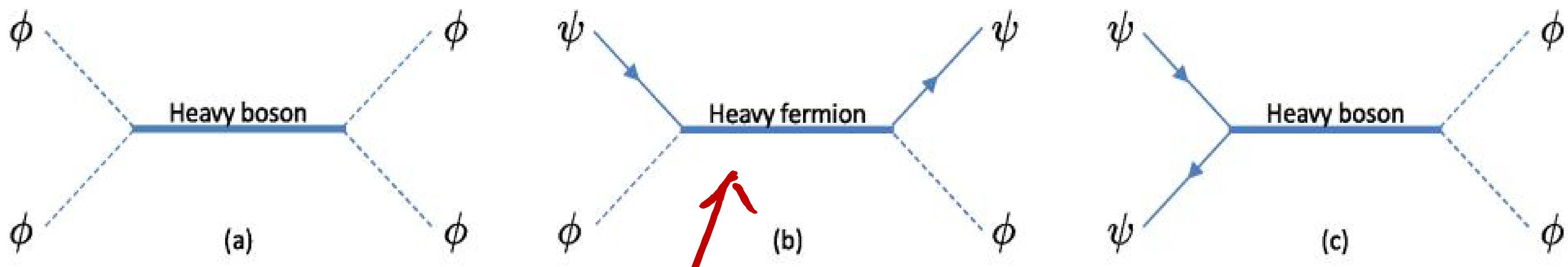


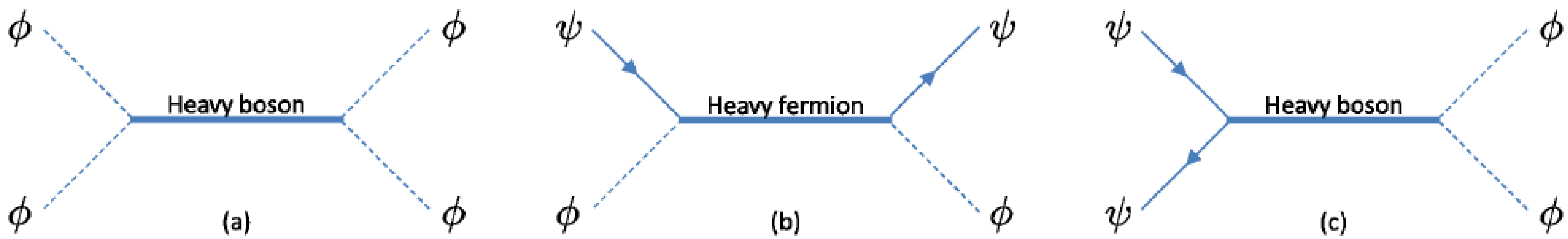
FIG. 3: *Tree-level graphs that generate the effective operators of type I (diagram a) and II (diagrams b and c), that can produce leading corrections to δm_h^2. ϕ and ψ denote the SM scalar doublet and fermions, respectively and all vertices are understood to be invariant under SM gauge transformations.*

Colored or not

[Chacko + Harnik...; GELLER + Telem '14

Recall:

type I & II operators are generated at tree-level in the underlying heavy physics:



Relevant O's obtained by expanding internal heavy propagators in inverse powers of their mass

& neglecting O(m_{light}/Λ) contributions

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

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

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

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

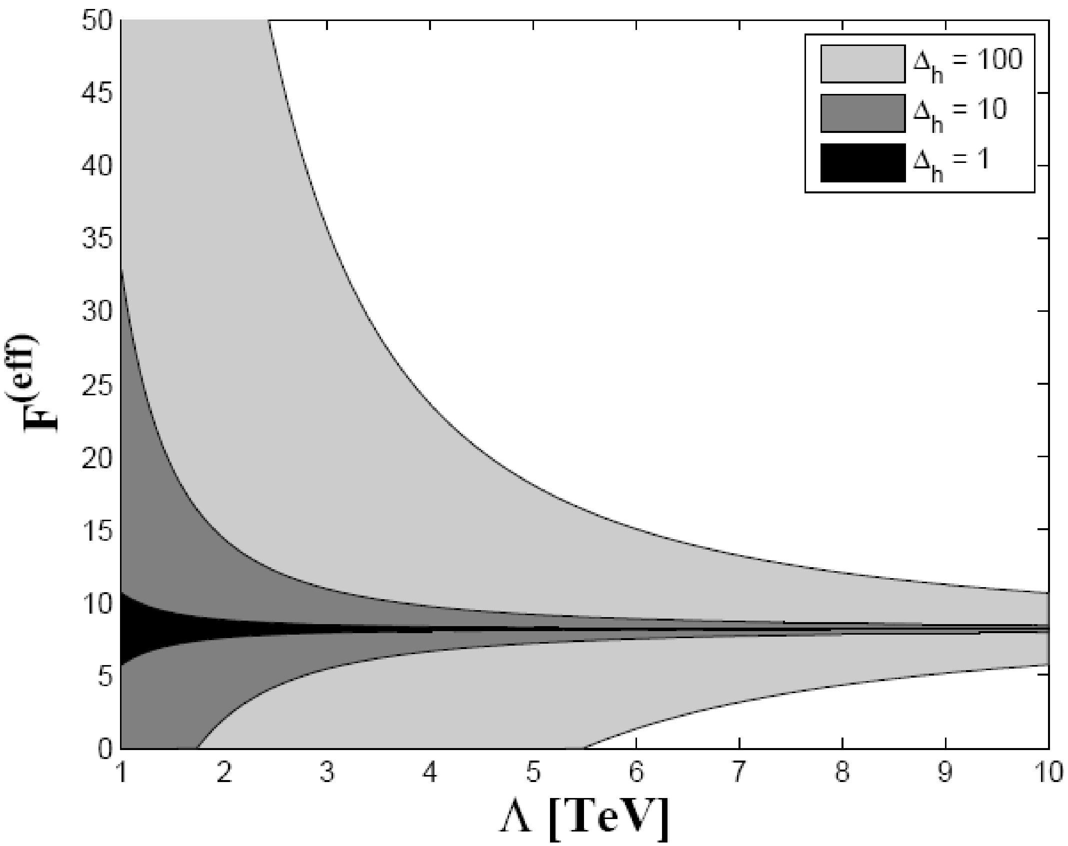
$$\left[\frac{m_h^2(tree)}{\delta m_h^2} + 1\right] = \frac{1}{\Delta_h}$$

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

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

Or cancellation between $m_h(tree)$ and δm_h ⇒ **$m_h(tree) \sim m_W$ 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

central message from two radically different approaches

- **From the perspective of RS-flavor or EFT approach conclusions are similar**
- **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]

Experimental searches

- Fig a, b, c explicitly show where the experimental signals for the mechanism(s) of restoring Higgs naturalness should be looked for

Examples: look for deviations in: VV=>hh; ψψ=>hh; production of h + q (jet) or h + lepton etc

XS marginal @ LHC; 100 TeV would be great

Operator	h^3	h^4	hWW	h^2W^2	h^3W^2	h^4W^2	hZZ	h^2Z^2	h^3Z^2	h^4Z^2	$h\psi\psi$	$h^2\psi^2$
$\mathcal{O}_S^{(2k+4)}$	✓	✓										
$\mathcal{O}_{\boldsymbol{\chi}}^{(2k+4)}$	✓	✓	✓	✓	✓	✓						
$\mathcal{O}_{\tilde{\boldsymbol{\chi}}}^{(2k+4)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{v}^{(2k+6)}$							✓	✓	✓	✓		
$\mathcal{O}_{\tilde{v}}^{(2k+6)}$			✓	✓	✓	✓						
$\mathcal{O}_{\mathbf{V}}^{(2k+6)}$			✓	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{\Psi-\psi}^{(2k+4)}$											✓	✓

TABLE I: Vertices involving the Higgs, gauge-bosons and fermions which are generated by the operators in Eqs. 3, 4 and 6. A check mark is used to indicate that the vertex is affected by the specific operator.

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

Important observables & some expectations

- **For The Intensity Frontier** (assuming $m_{KK} \sim 10$ TeV)
- nedm within factors of O(few) close to Expt bound < 6 X 10^{-26} e-cm → APS '04
-] → Atwood, Gronau, AS PRL 97
- Time dependent CP Bd=> $K(\pi)\pi\,\gamma$; Bs => $\phi\,\gamma$ ~ O(10%)
- $\Delta\sin 2\beta$(penguins) ~ O(few %) i.e. comparable to QCD uncertainties..... → London + AS PLB 97
- $\Delta\gamma$ ~ O($2X10^{-3}$) comparable to theory uncertainties

Precise direct determination of γ from "B→DK" is a Key Target of LHCb.

(More) For The Intensity Frontier

- Charm CP esp. modes where SM predicts 0...e,g D=>KKX, $\phi\pi^+$, $\pi^+\pi^0$.....
- ε'/ε : Hadronic matrix elements still a huge challenge ..... 4 THEORISTS
- KL->$\pi^0 \nu\nu$ → SM $(2.8 \pm .4) \times 10^{-11}$

Desperate search for deviations from SM

For the Energy Frontier

Agashe, P, S '06

- t=> c Z, ch   Br O(10 $^{-7}$); t=>c g O(10^{-10}); t=>c γ O(10^{-11})....many orders of magnitude bigger than SM BASED on $m_{KK} \sim 10$ TeV
- ee=> tc; R_{tc} ~ 10^{-6} - 10^{-5} Atwood, Reina+AS/95
- tedm   ~ O(10^{-20} e-cm) Atwood+AS/92; Kamenik etal/11
- Triple correlation in ee=> tth ;
- Energy assy in top pair @ LHC
- Δ SM in h=> bb

CP violation in top pair production at hadron colliders

SCHMIDT + PESKIN, PRL/92

- Transverse energy asymmetry of charged leptons:

See Atwood, Bar-Shalom, Eilam + AS PR '01

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

⇒ CP-odd, T_N-even ⇒ needs abs. part

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

$e^+e^- \to t\bar{t}h$ Triple Correlations

See also Gunion, Grzadkowski & He, PRL 96

Atwood et al PRD 96

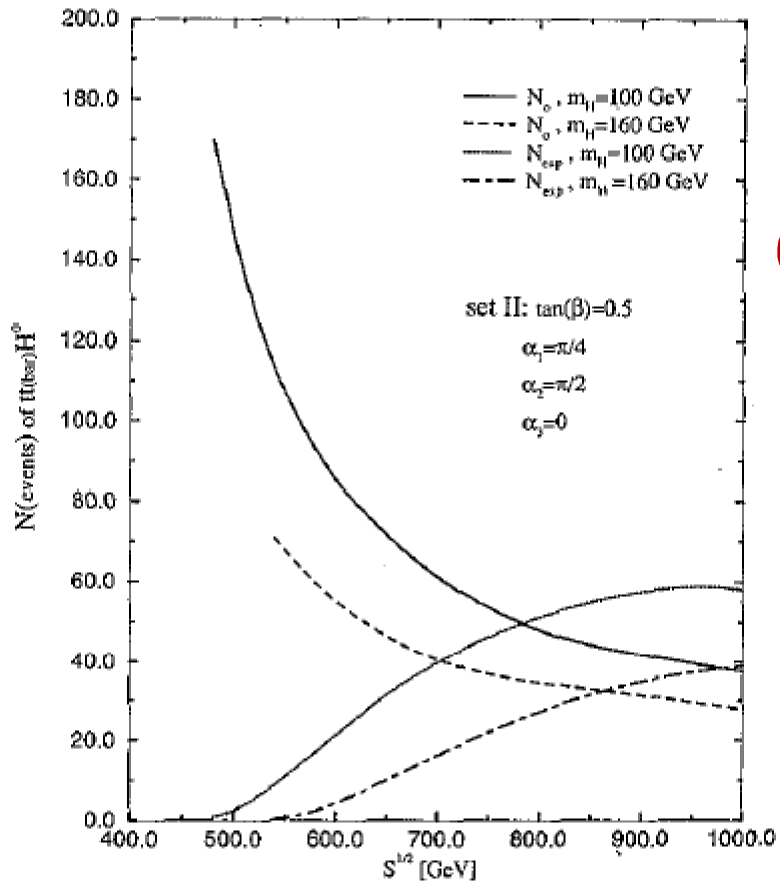


FIG. 3. Number of events, N_O ($N_{\rm exp}$) required (expected yearly), as a function of total beam energy for set II of the parameters and for $m_{H^0} = 100$ and 160 GeV with unpolarized electron and positron beams.

Perhaps feasible at $E_{cm} \gtrsim 750$ GeV ILC

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 Λ_{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; ε'/ε; γ; S[B=>K* (ρ)γ]; ΔSin 2 β from Bd=> eta' Ks, phi Ks, 3 Ks....; ACP(B=>Kπ), 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**

- **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 [see e.g.arXiv:0709.0007(Z'); 0810.1497(W')]

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

Summary & Outlook (I – III)

- No NP signals ~ 1-3 TeV may just be because (RS) flavor constraints require NP to be above ~10TeV.
- This means no profound challenge to our notion of naturalness except instead of O(.01) tuning, its a bit worse O(.001- .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 & a many many more, ~100 TeV collider is a NO BRAINER

没有道理

Summary & Outlook (II)

- This is so because:
- Theoretical disarray, confusion, at a loss=> Dose of experimental reality exceedingly useful
- Move plethora of bounds by ~factors O10-100 ..
- Exceedingly valuable: t=>q h(z,γ,g….); tdm, tca…
- CP of higgs: h=ZZ* =>4 l
- LFV: t=>q μ τ; h=>μ τ; Z(')=>μ τ
- WR
- H^+-, H^0, FCH……

Summary& Outlook (III)

- At 100 TeV, either we'll see new physics

(most likely not in any line we are thinking off) or tuning is needed to $O(10^{-4} ; ^{-5}$) ...

⇒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?

⇒Opens up an enticing menu & an exciting future!

Summary & Outlook (p1 of 2)

- After the 126 GeV discovery, key question for our field is the scale of new physics
- Flavor-alignment places specific constraints…has been telling us for long that scale of NP >1 TeV
- 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.
- 126 GeV scalar is not the MH but rather it is "Higgs-radion". 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 there are many avenues to alleviate higgs radiative stability
- Unfortunately scale is out of reach of LHC14 for direct observation of heavy NP

Summary & Outlook (p.2)

- Specifically from the perspective of warped theory the following deserve attention
- Dir CP probes [e.g. nedm, S[B=>K ργ]; γ; 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), which has a far reaching potential,

  as the next step in our adventure

XTRA

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!

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

$$\mu_{\gamma\gamma}^{ggF}(\Lambda_r = 3.0 \text{ TeV}) = 1.45, \tag{74}$$

$$\mu_{\gamma\gamma}^{VBF}(\Lambda_r = 3.0 \text{ TeV}) = 0.95, \tag{75}$$

$m_{KKG} = \frac{k}{m_{PL}} \Lambda_r$ 1.6

$$\mu_{VV}^{ggF}(\Lambda_r = 3.0 \text{ TeV}) = 0.87, \tag{76}$$

$$\mu_{VV}^{VBF}(\Lambda_r = 3.0 \text{ TeV}) = 0.57, \tag{77}$$

$$\mu_{bb}^{VH}(\Lambda_r = 3.0 \text{ TeV}) = 0.57, \tag{78}$$

$$\mu_{\tau\tau}^{ggF}(\Lambda_r = 3.0 \text{ TeV}) = 0.87, \tag{79}$$

$$\mu_{\tau\tau}^{VBF}(\Lambda_r = 3.0 \text{ TeV}) = 0.57, \tag{80}$$

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

EWPC

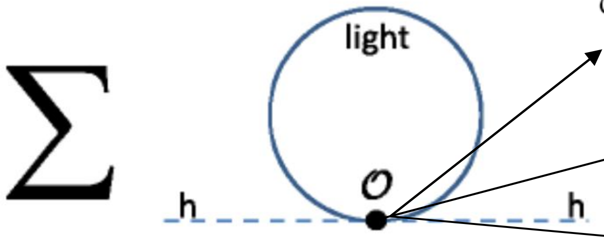
- Unless KK-masses are heavy enough, T-parameter tends to come out large ≳ 10 TeV (Csaki et al ['03] - - - -
- Since tuning goes as ~ [<v>/m_KK]^2 this tends to make the set up more unnatural compared to ~3 TeV
- Agashe, Delgado, May & Sundrum, JHEP'03 proposed an interesting way out. Impose "Custodial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

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

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.

EFT corrections to Higgs mass



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

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

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

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

Singlet widely studied

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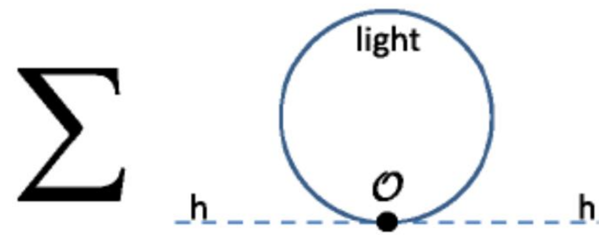
[17] J. Cao, Y. He, P. Wu, M. Zhang and J. Zhu, JHEP **1401**, 150 (2014).

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 δm_h suppressed by powers of v/Λ …)

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: $\mathcal{O}$ 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.

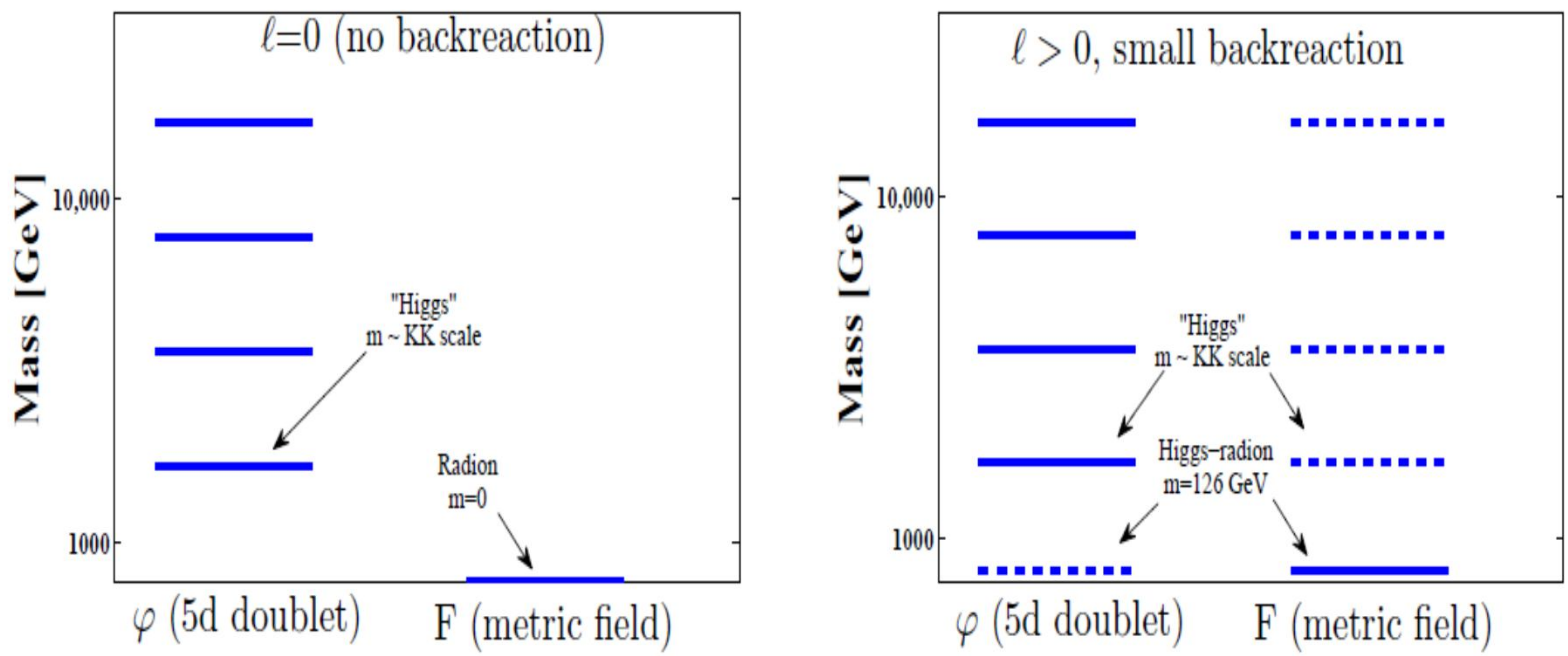


FIG. 2: *A graphic illustration of the particle/KK spectrum in our setup with (right) and without (left) backreaction.*