unraveling flavor & naturalness from RUN II to 100 TeV

Amarjit Soni, HET, BNL

EW (50) Moriond 2015; mar. 14-21

03/20/15

outline

- O(1) TeV for NP was unrealistically optimistic
- Good reasons for scale around 10TeV
- An exciting possibility for RUN II [precoscious]
- 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

EXPLORATION INDIA/USA

- 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**

Feb 2012

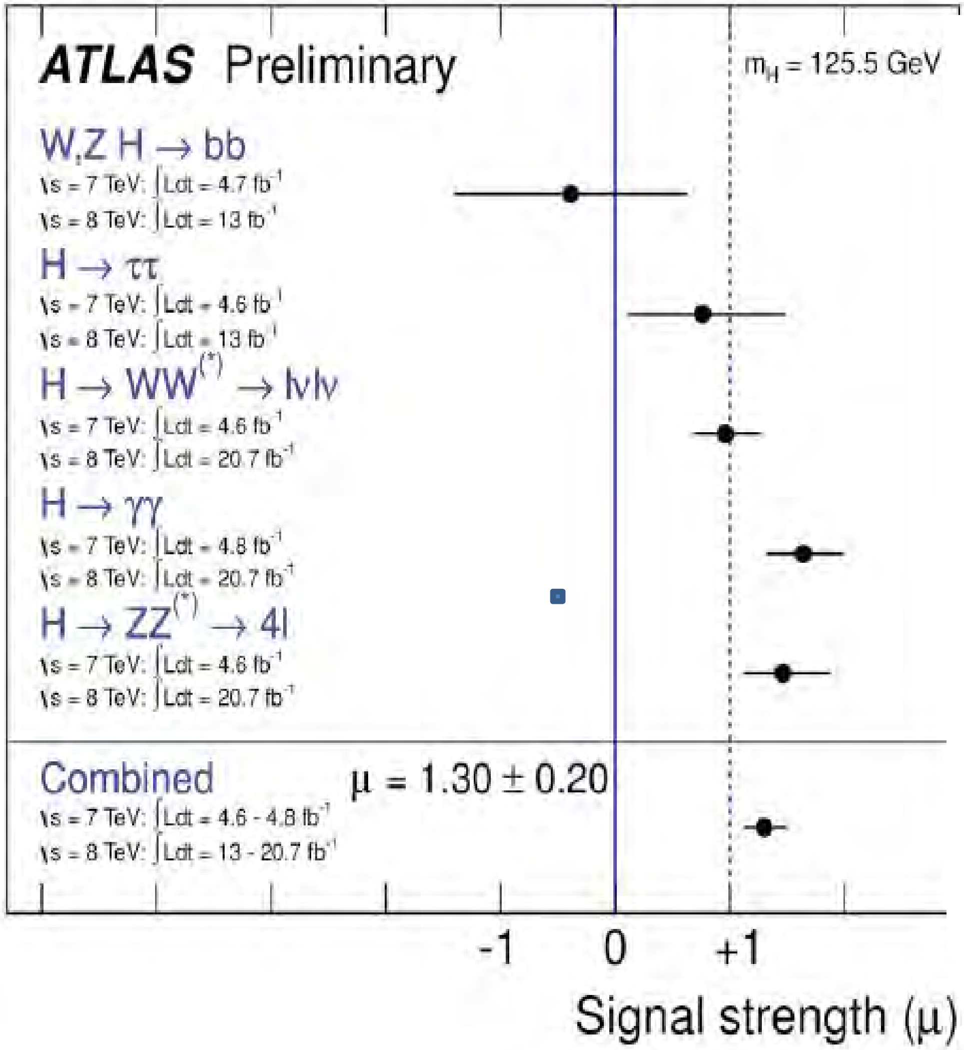
JIANGLAI LIU [INPAC, SHANGHAI]: DAYA BAY

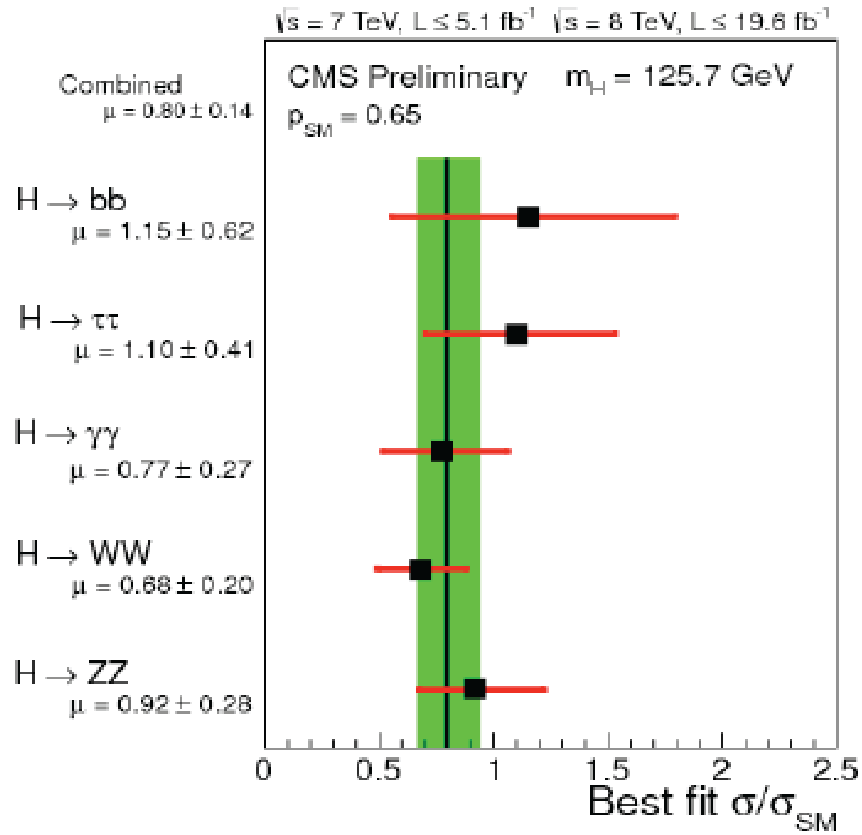
SSC 40 TeV ~ 1990

MAY WELL NEED SERIOUSLY THINKING of GIGANTIC INTERNATIONAL HADRON COLLIDER ~ 100 TeV CM

GLOBAL VILLAGE

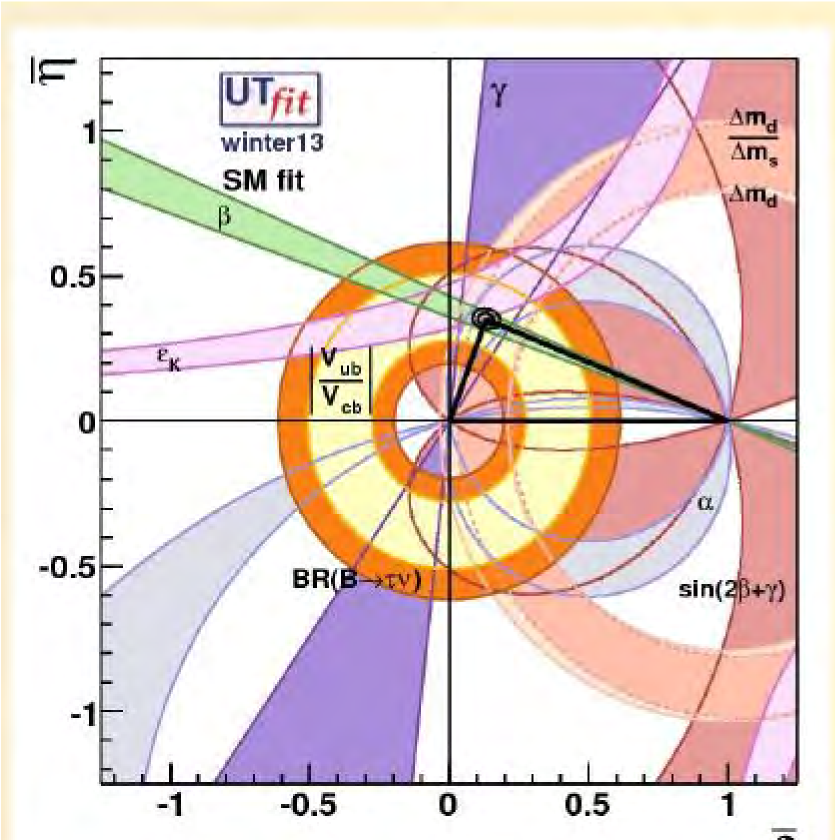
FITS LIKE A GLOVE!
[OR DOES IT?]





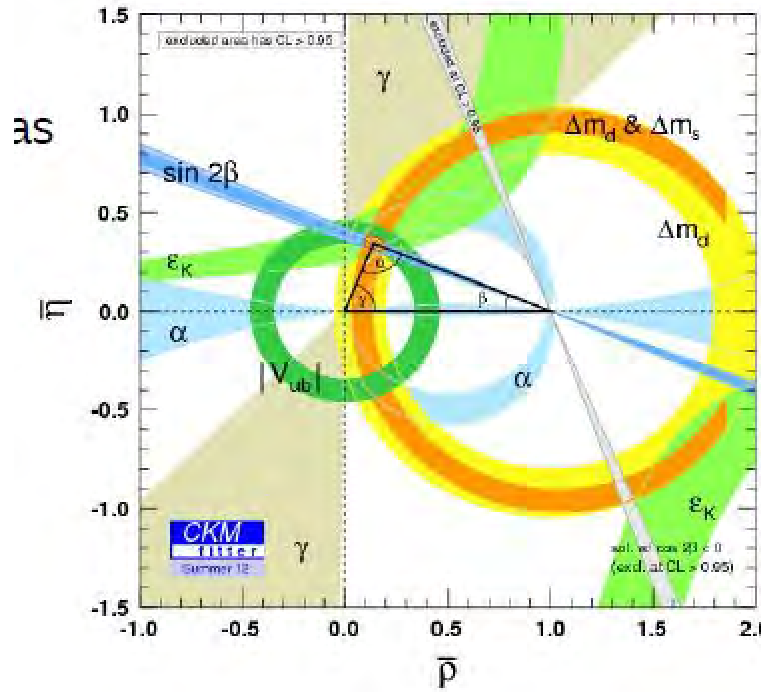
μ=0.80±0.14

Agree with SM ± 20%



M. BONA @CPCPV13

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 $\sim$ 10–15% accuracy
$\epsilon_K \sim 10^{-3}$!!!

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

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

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

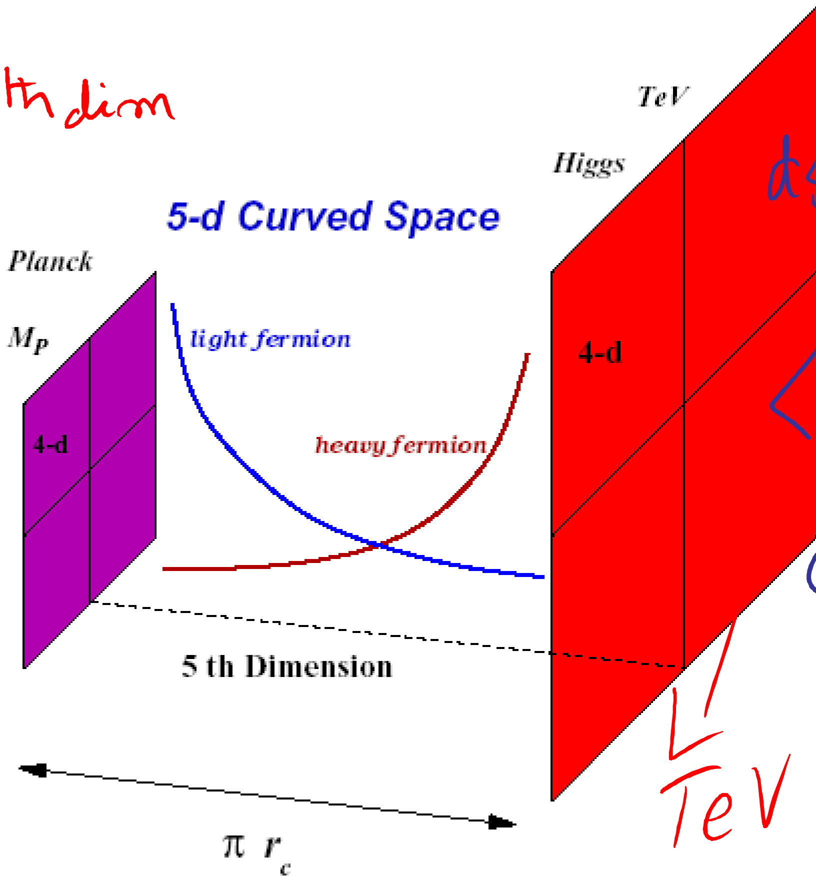


Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$.

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

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

$$\sigma = k r_c \pi$$

$k r_c \sim 12$

TeV

M_P

Simultaneous resolution to hierarchy and flavor puzzles

[125 GeV Scalar discovery]

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 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.

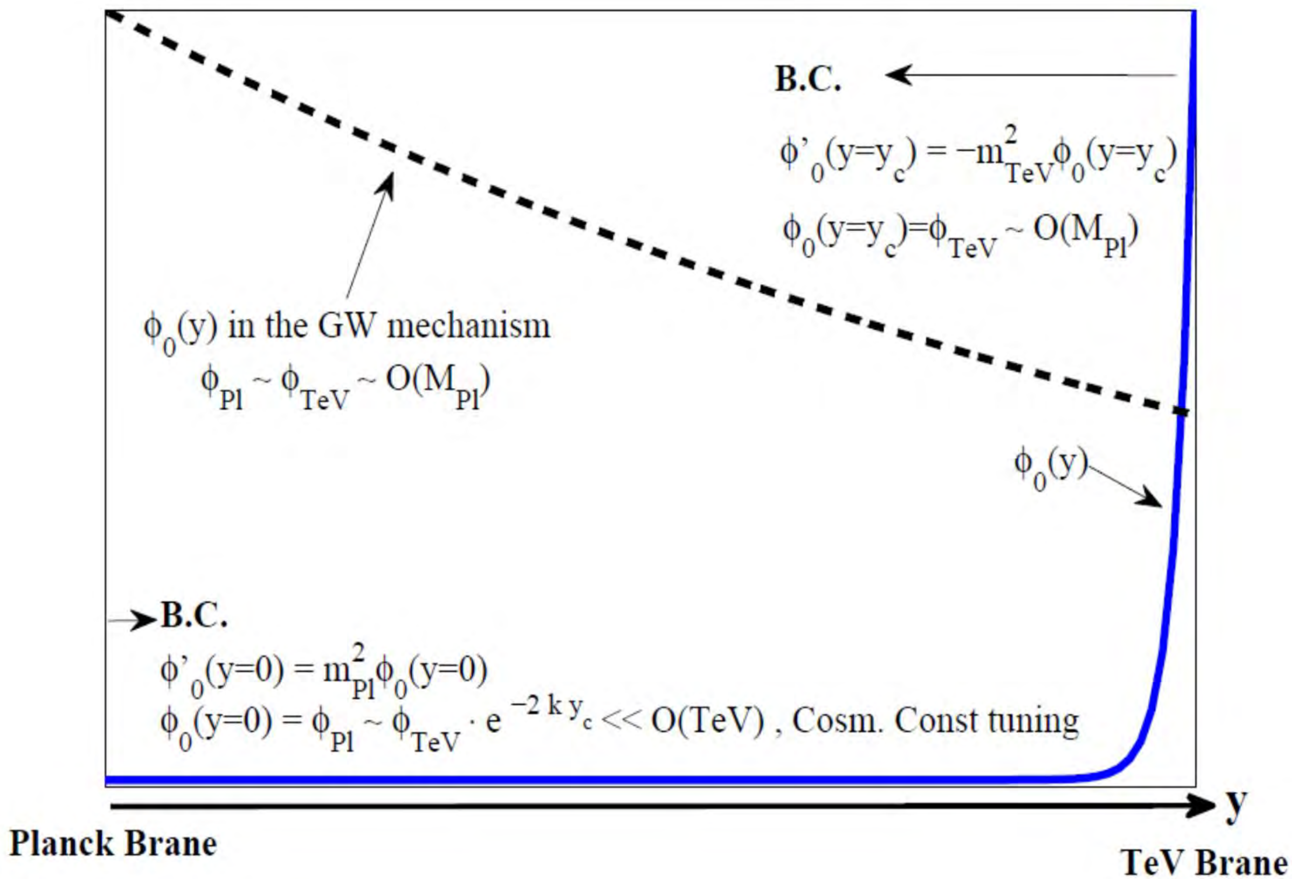
(if a solution is possible then)

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

IMPT TO measure

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

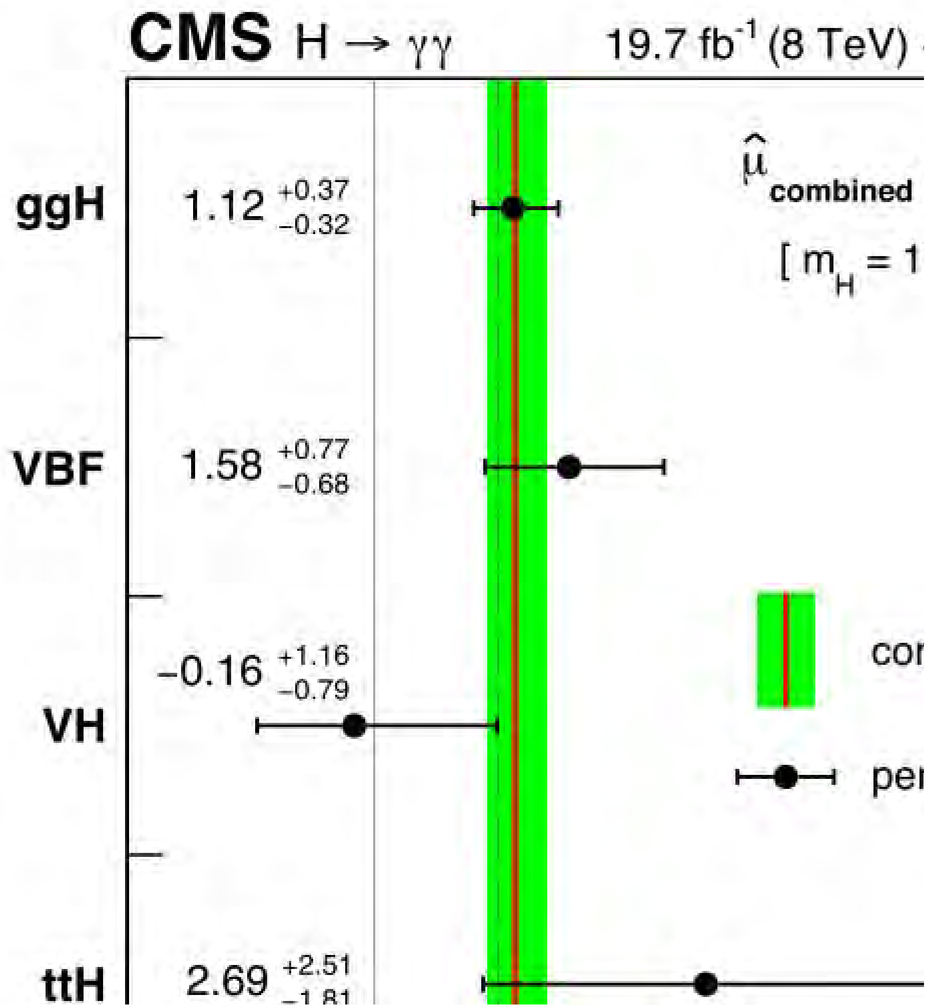
CAUTION: Effects of KK Towers not included yet ubmitted to EPJC]

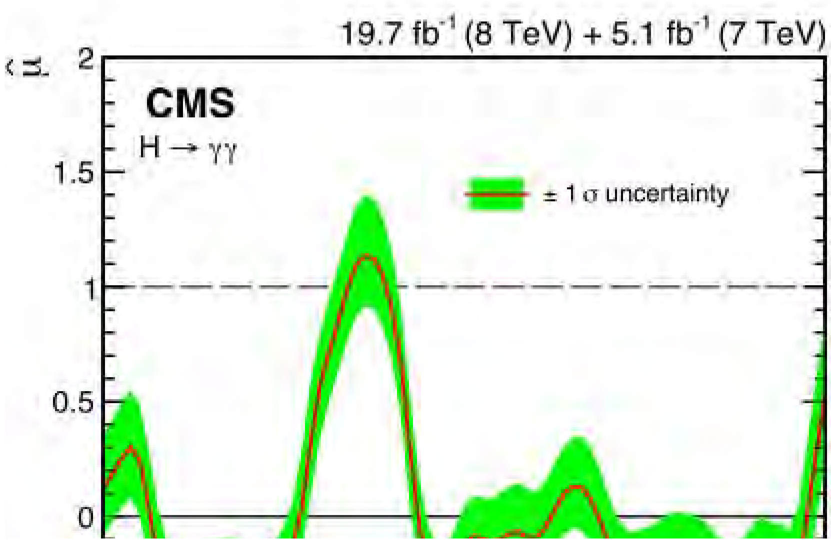
CMS ICHEP 2014

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

Atlas ICHEP 2014

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





A promising ratio that needs special attention

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

EXPERIMENTALISITS PLEASE IMPLEMENT

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

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

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

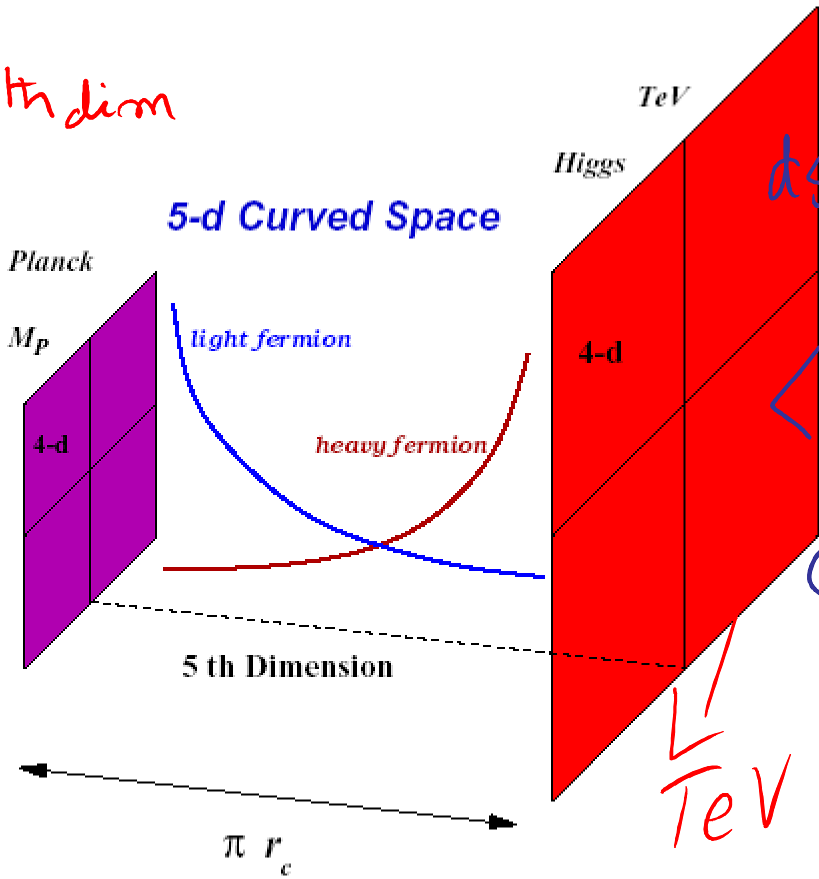
- **Flavor puzzle** Δ flavor = 2 esp $K-\bar{K}$

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

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

RANDALL+SUNDRUM '99

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



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

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

$$\sigma = k r_c \pi$$

$k r_c \sim 12$; $\langle H_5 \rangle \to M_P$; $\langle H_4 \rangle \to$ TeV

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 [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, Buras, Weiler et al and by Cassagrande, Haisch, Neubert et al &.........

Localization parameters of the 3-families of quarks

$$c_{Q_1} = -0.579\,, \qquad c_{Q_2} = -0.517\,, \qquad c_{Q_3} = -0.473$$

$$c_{u_1} = -0.742\,, \qquad c_{u_2} = -0.558\,, \qquad c_{u_3} = +0.339$$

$$c_{d_1} = -0.711\,, \qquad c_{d_2} = -0.666\,, \qquad c_{d_3} = -0.553$$

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**

Kile, Kobach,AS
arXiv:1411.1407

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

BNL E821

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

$$\sim 3.6\sigma$$

- 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

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

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

→ 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 $O(3^2)$**

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 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 ~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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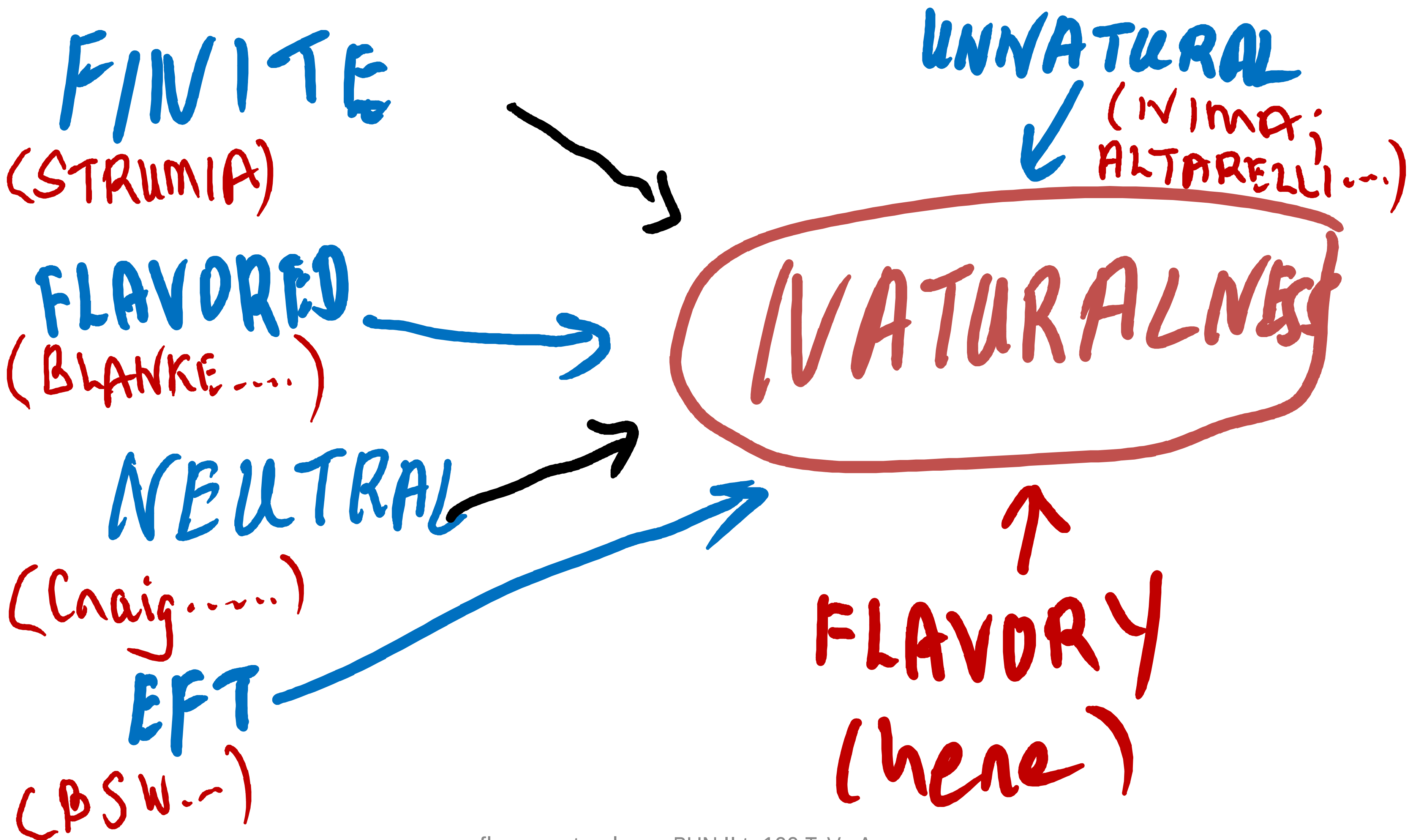
Science Lives

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

FACETS of Naturalness



"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 ~1000TeV (due naïve Kaon mixing constraints) as exemplified in a candidate theory of flavor i.e. RS-flavor**

LOWER Bound

- **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.

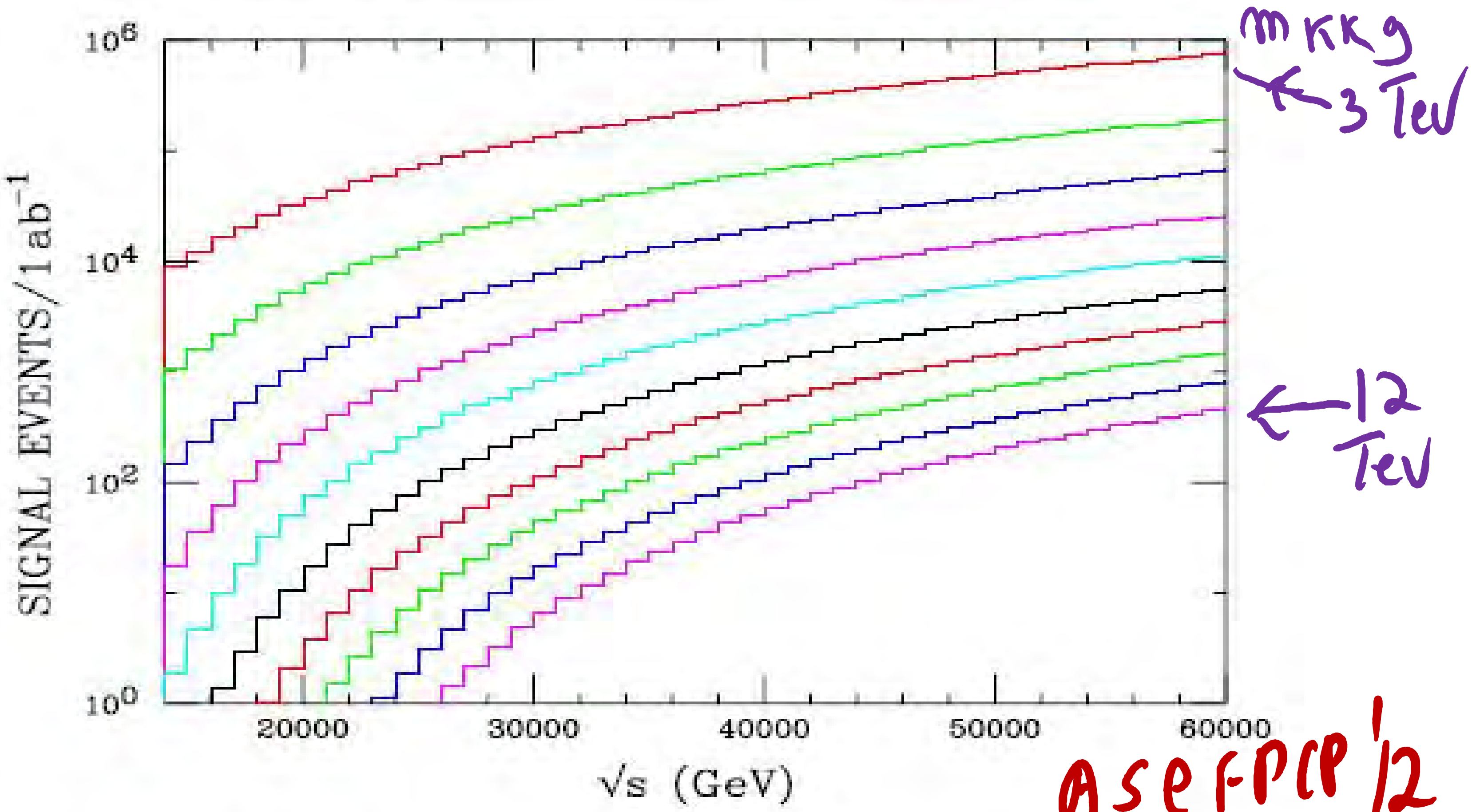


FIG. 10 (color online). Signal rate for a possible gluon KK resonance as a function of the collider energy employing the cuts described in the text. Branching fractions and efficiencies have been neglected. From top to bottom, the results are shown for gluon KK masses in the range from 3 to 12 TeV in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

Davoudiasl,Rizzo,AS,PRD'08

ADPS '07

GOLDEN Decay
$G \to ZZ$

DRS '08

60 TeV

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

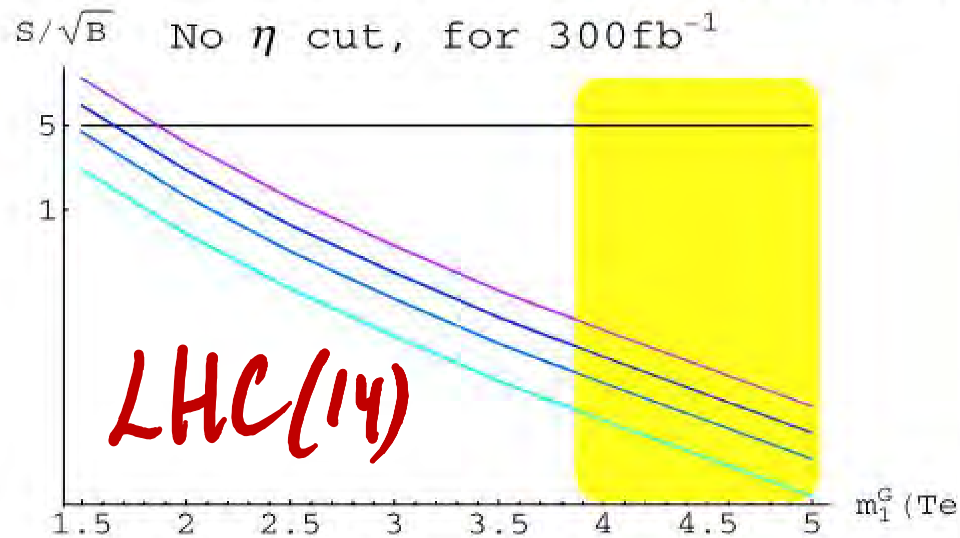


FIG. 4 (color online). Significance for the purely lepton decay mode for Z pairs from KK graviton using 300 fb^{-1}. Se also Fig. (1).

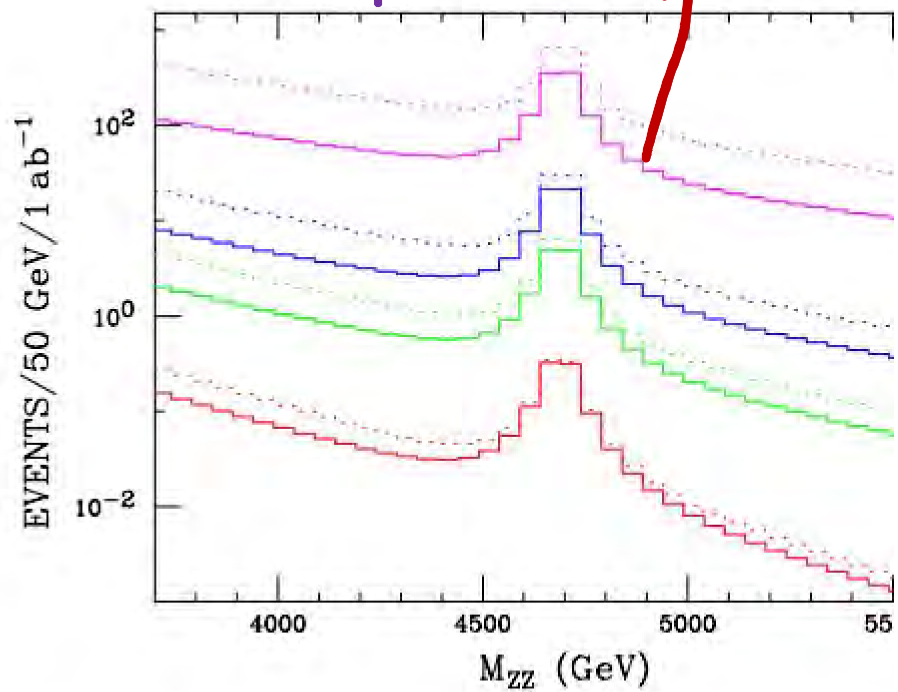


FIG. 5 (color online). Production rate for the first gravito excitation decaying into two Z bosons, assuming a rapidi $|y| < 2(1)$ on the Z's corresponding to the dotted (solid) grams. The histograms correspond, from bottom to to collider energies of $\sqrt{s} = 14$, 21, 28, and 60 TeV, respect Z branching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

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

…..

- ***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

Andersen et al, arXiv:2013.5189

GOLDMINE

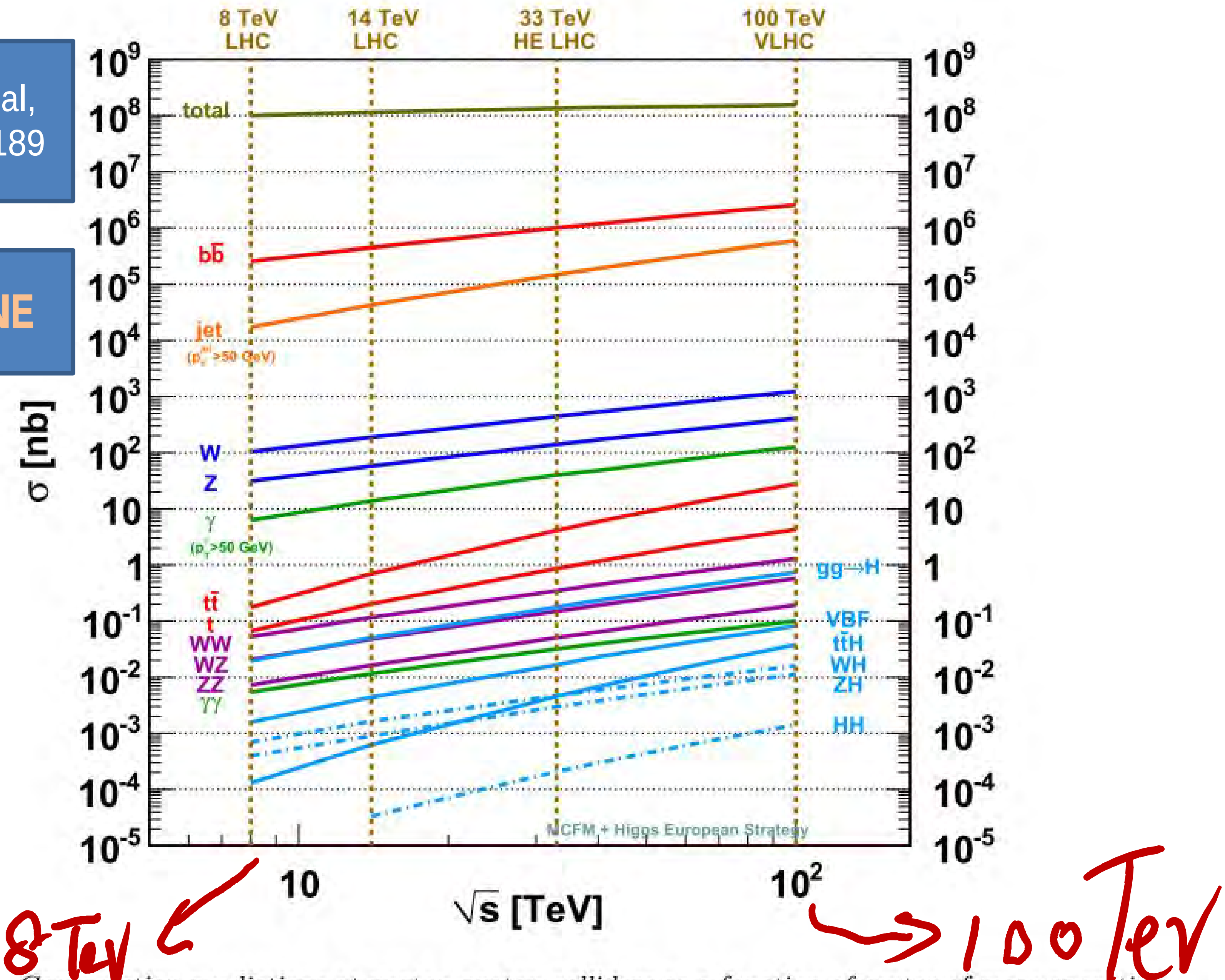


Figure 1-6. *Cross section predictions at proton-proton colliders as a function of center-of-mass operating energy,* $\sqrt{s}$.

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 '00

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'08

"HORIZONTAL" Gauge bosons

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

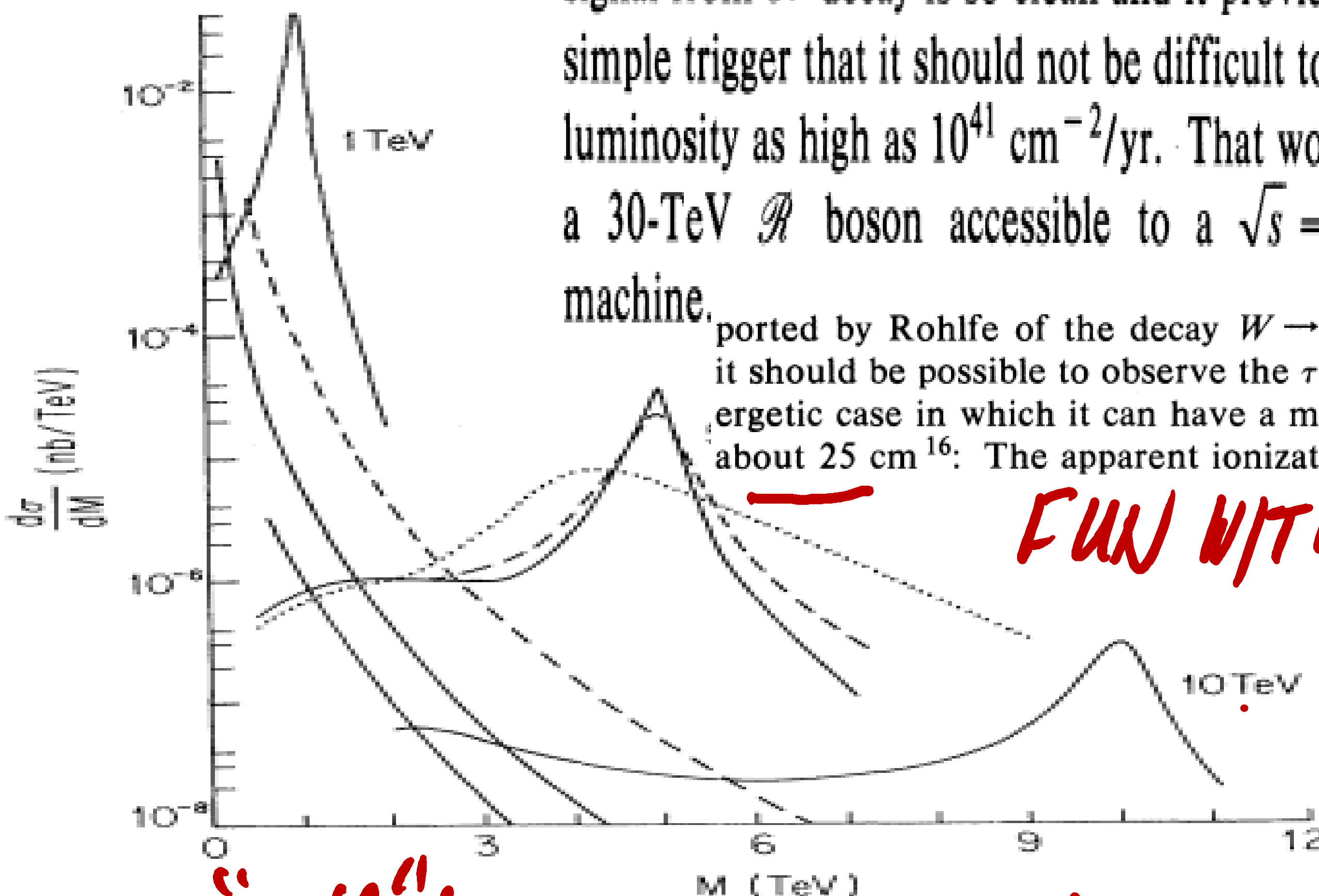
Hans-Uno Bengtsson, Wei-Shu Hou,[a] A. Soni, and D. H. Stork

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)

- **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 => $\sim 10^{-4}$ impressive achievement in itself**

MULTIPRONG ATTACK is essential

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

for precision [LE] Frontier

Important observables & some expectations

- **For The Intensity Frontier** with $m_{KK} \sim 10$ Te

- **nedm within factors of O(few) close to Expt bound < 6 X 10^{-26} e-cm**
  Agashe, Perez AS '04

- **Time dependent CP Bd=> K(π)π γ ; Bs => ϕ γ ~ O(10%)**
  ATWOOD, GRONAU, AS '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, $\phi\pi^+$, $\pi^+\pi^0$..... unfortunately theory in bad shape
- KL->$\pi^0 \nu\nu$ SM $[2.8 \pm .4] \times 10^{-11}$

↖ a unique & rare gem!!

Desperate search for BSM-CP phase(s)

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

- tedm ~ O(10^{-20} e-cm) Atwood+AS '92; Kamenik etal '11
- Triple correlation in ee=> tth ;
- Energy assy in top pair @ LHC

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

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

See also Gunion, Grzadkowski & He, PRL 96

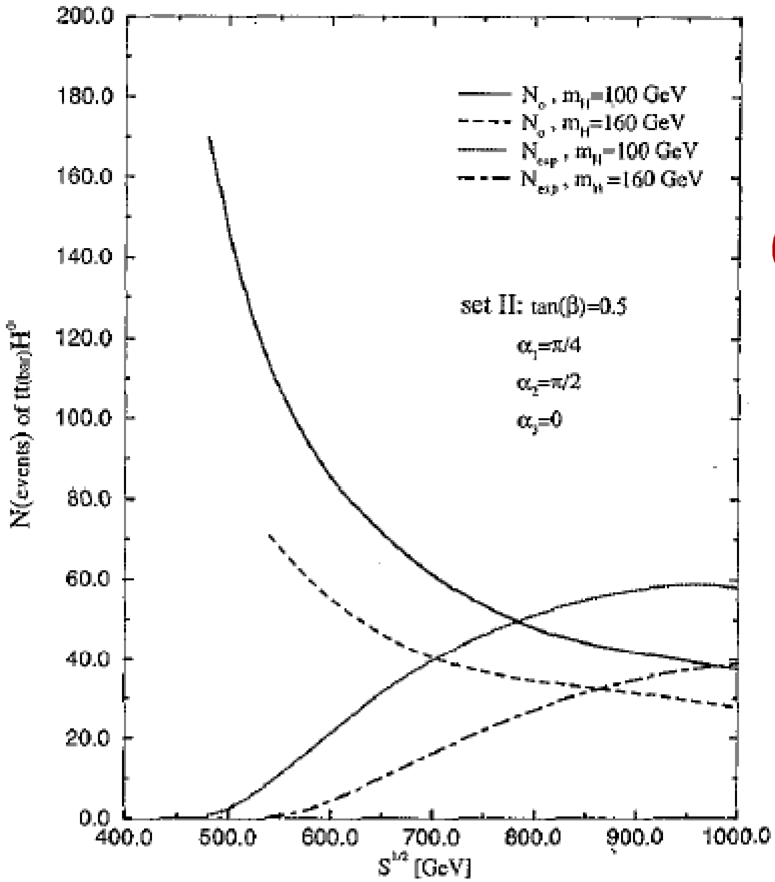


FIG. 3. Number of events, N_O ($N_{\rm exp}$) required (expected yearly), as a function of total beam energy for set II of the parameters and for $m_{H^0} = 100$ and 160 GeV with unpolarized electron and positron beams.

Atwood et al PRD 96

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

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

ddddd

"SHUT UP & COMPUTE and MEASURE"
slightly miss quoting a famous young Italian Physicist *is*

Summary & Outlook (I – III)

- **No NP signals ~ 1-3 TeV may just be because "flavory naturalness" requires NP to be above ~10TeV [as e.g. in RS- flavor]**
- **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 & 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=>q h(z,γ,g….); tdm, tca…
- Exploit richness of h=ZZ* =>4 l; CP of Higgs & much more
- WR; H^+-, H^0, FCH……
- @100 TeV exciting potential for cracking flavor mystery

LFV: t=>q μ τ; h=>μ τ; Z(')=>μ τ

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} ; $^{-5}$) ...

- **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?**

$\Rightarrow$***Promises an enticing menu & an exciting future & should be vigorously pursued***

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, $\phi_{\mathrm{TeV}} \equiv \phi_0(y = y_c)$	$\phi_{\mathrm{TeV}} \sim \mathcal{O}(M_{Pl})$	$\phi_{\mathrm{TeV}} \sim \mathcal{O}(M_{Pl})$
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!

Soni

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

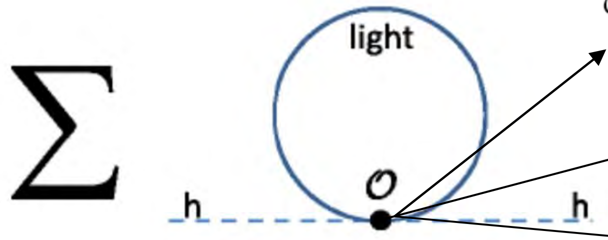
EWPC

- **Unless KK-masses are heavy enough, T-parameter tends to come out large** ≳ 10 TeV (Sakai 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**

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

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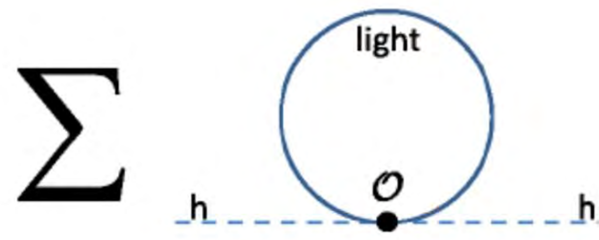
[17] J. Cao, Y. He, P. Wu, M. Zhang and J. Zhu, JHEP **1401**, 150 (2014).

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.

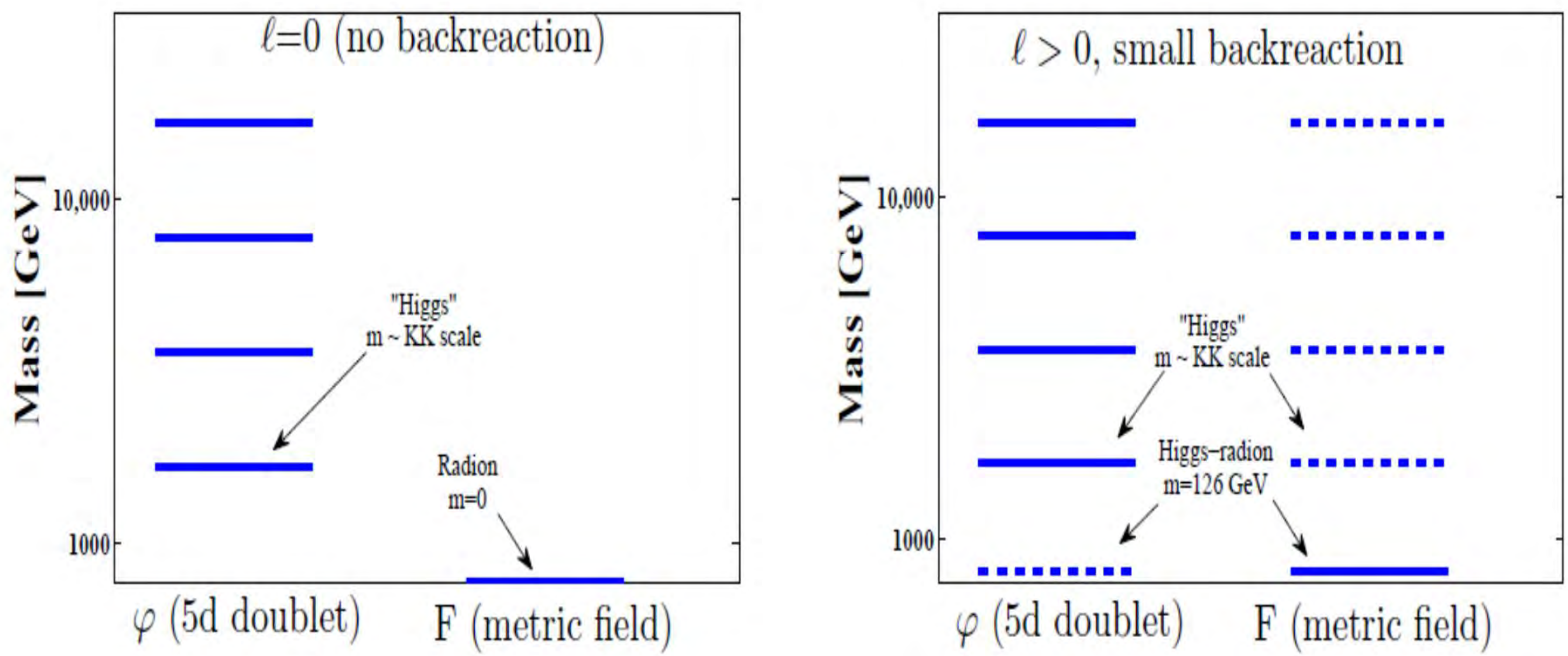


FIG. 2: *A graphic illustration of the particle/KK spectrum in our setup with (right) and without (left) backreaction.*