Introduction to the Standard Model

New Horizons in Lattice Field Theory
IIP Natal, March 2013

Rogerio Rosenfeld
IFT-UNESP

Lecture 1: Motivation/QFT/Gauge Symmetries/QED/QCD
Lecture 2: QCD tests/Electroweak sector/Symmetry Breaking
Lecture 3: Successes/Shortcomings of the Standard Model
Lecture 4: Beyond the Standard Model

Beyond the Standard Model (BSM)

Three main avenues

- Supersymmetry
- Extra dimensions
- Composite models

In this lecture: broad introduction to BSM

Supersymmetry (SUSY)

- New symmetry of Nature: relates bosons and fermions
- For each SM particle it associates a SUSY partner

W-> wino, gluon-> gluino, top-> stop, ...

- Protects Higgs mass from quadratic divergences
- The Higgs mass at tree level must be lighter than the Z

tension with measurements – difference must come from loops

- Must have a second Higgs doublet: 5 physical Higgses
- Has a natural dark matter candidate – the LSP

requires R-parity; WIMP miracle

- Necessary ingredient in Superstring Theory
- Unification of coupling constants (g_s,g,g’)
- SUSY is broken in Nature!

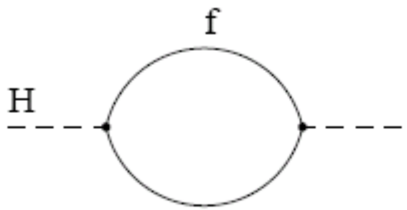
Introduces several parameters to describe “soft” breaking

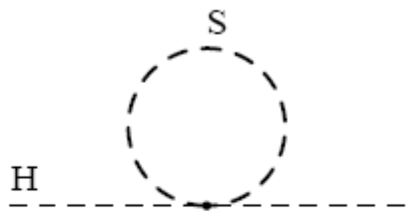
Particle content in Minimal Supersymmetric Standard Model

spin-$\frac{1}{2}$ $(\nu_L, e_L); e_R$	spin-0 $(\tilde{\nu}_L, \tilde{e}_L); \tilde{e}_R$ $\times$ generations
spin-$\frac{1}{2}$ $(u_L, d_L); e_R$	spin-0 $(\tilde{u}_L, \tilde{d}_L); \tilde{d}_R$ $\times$ generations
spin-1 $(g, \gamma, W^{\pm}, Z)$	spin-$\frac{1}{2}$$(\tilde{g}, \tilde{\gamma}, \widetilde{W}^{\pm}, \widetilde{Z})$
spin-0 Higgs bosons $(h^0, H^0, A^0, H^{\pm})$	spin-$\frac{1}{2}$ higgsinos $(\tilde{H}_u^+, \tilde{H}_u^0)$, $(\tilde{H}_d^-, \tilde{H}_d^0)$

Masses are not predicted

Higgs mass protection: cancellation of quadratic divergences





$$\Delta m_H^2 = -\frac{y_f}{16\pi^2}[2\Lambda^2 + 6m_f^2\ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2\ln(\Lambda/m_S) + ...]$$

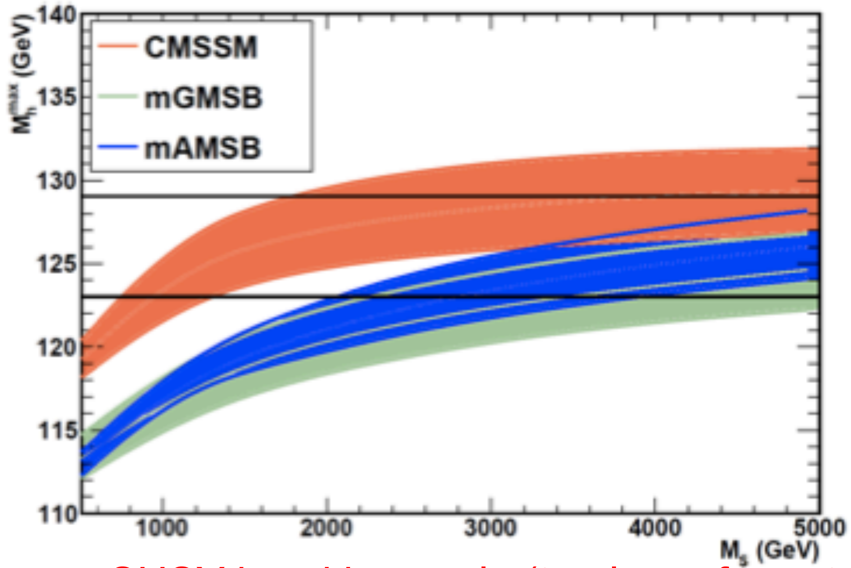
scalar (stop) mass

$$m_h^2 = \underbrace{M_Z^2\cos^2 2\beta}_{\leq M_Z^2} + \underbrace{\frac{3g^2 m_t^4}{4\pi^2 M_W^2}\log\left(\frac{\tilde{m}}{m_t}\right)}_{(86\ \mathrm{GeV})^2}$$

Same order as tree level!

Not easy to have a heavy higgs in SUSY

There are several different SUSY models



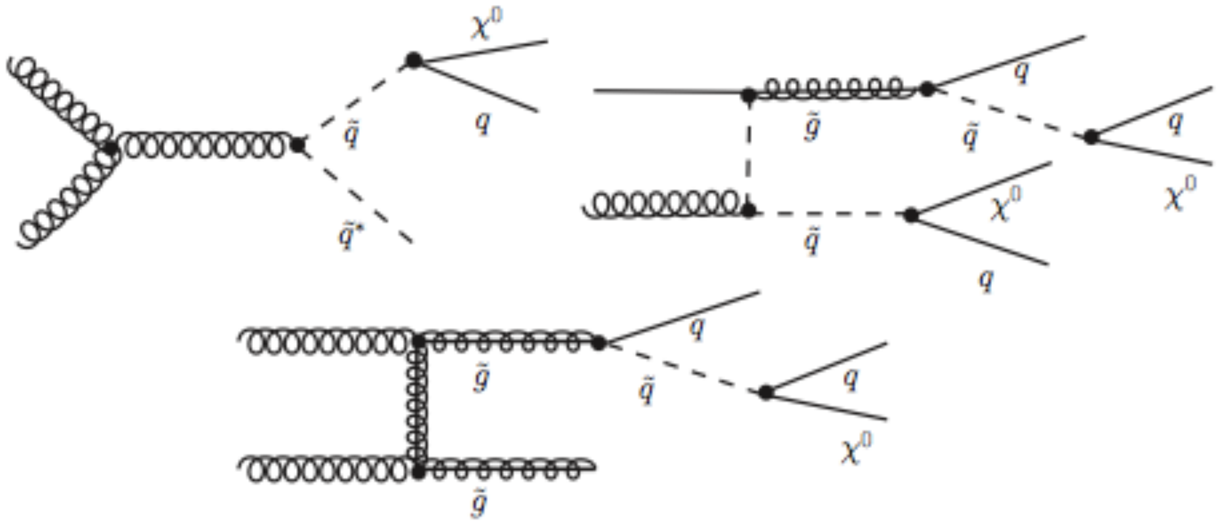
arXiv:1211.2794

SUSY breaking scale (too large for naturalness)

Figure 3: Maximal Higgs mass in mSUGRA, mAMSB and mGMSB, as a function of M_S for the top quark mass varied in the range $m_t = 170 - 176$ GeV.

SUSY is becoming unnatural!

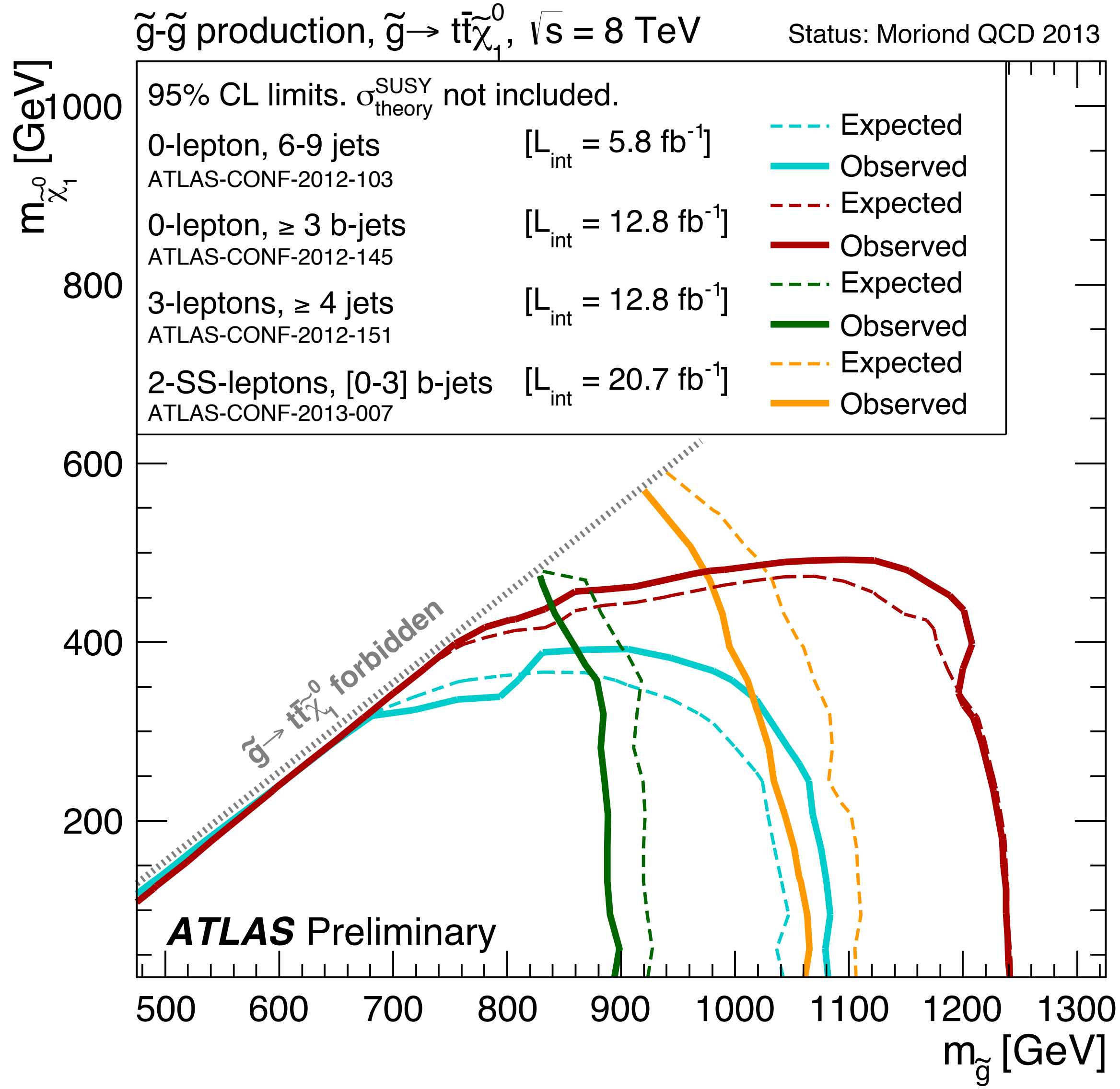
Smoking gun at the LHC: production of new colored particles squarks and gluinos



Process	LHC8	LHC 14
Total	.1b	.1 b
$b\bar{b}$ ($p_T > 30$ GeV)	.3 μb	1 μb
$t\bar{t}$	200 pb	800 pb
$gg \to h$	15 pb	50 pb
gluino ($m_{\tilde{g}} = 500$ GeV)	4 pb	30 pb
gluino ($m_{\tilde{g}} = 750$ GeV)	200 fb	3 pb
gluino ($m_{\tilde{g}} = 1$ TeV)	20 fb	400 fb

FIG. 4: Production of colored superpartners. Clockwise from upper-left are representative diagrams for squark pair production, squark-gluino associated production and gluino pair production. Their decays are shown to quarks and the lightest supersymmetric particle, here assumed to be the neutralino. The result is a final state with jets and missing energy.

arXiv:1303.1142



No signs of SUSY yet

Extra dimensions

Old idea since 1920's: Kaluza and Klein

Universe may have extra, compact dimensions (motivated by string theory)

Basic idea

Consider a free scalar field in 5 dimensions:

$$\phi(\vec{x}, y, t)$$

Action:

$$S = \int dt\, d^3x\, dy \sqrt{-g}\, \frac{1}{2}\left(\partial_M \phi\, \partial^M \phi\right)$$

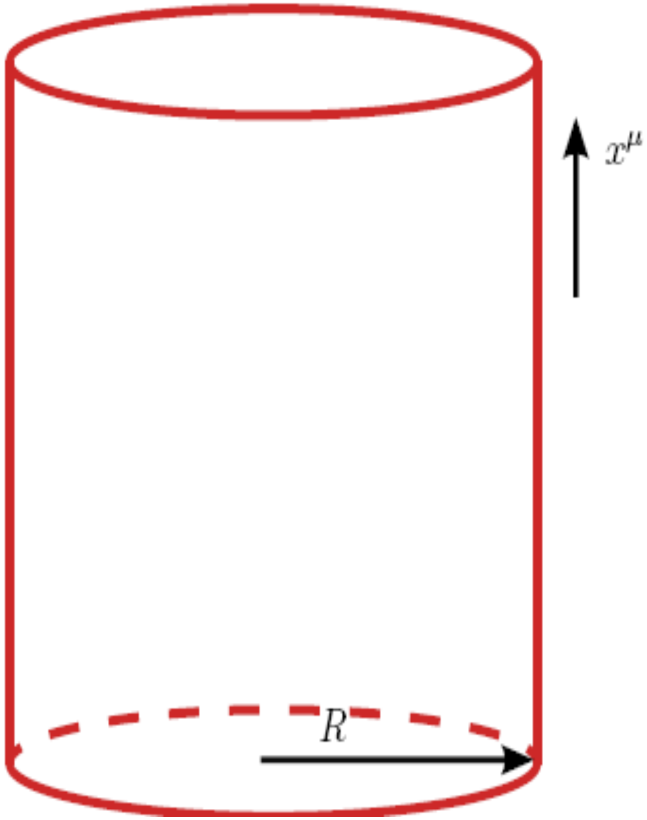
Flat metric: $g_{MN} = (-1,1,1,1,1)$

Equation of motion for free massless scalar field:

$$\Box_{M}\phi(\vec{x}, y, t) = 0 \Rightarrow$$

$$\Box\phi + \frac{\partial^2}{\partial y^2}\phi = 0$$

Compactify extra dimension in a circle of radius R:



$$\phi\left(\vec{x}, y + 2\pi R, t\right) = \phi\left(\vec{x}, y, t\right)$$

Expand in a complete basis:

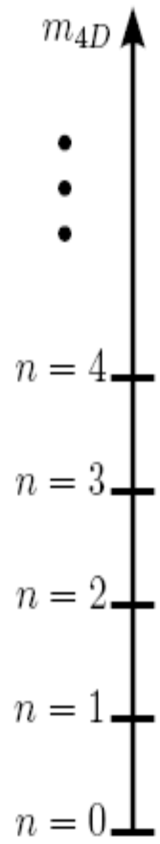
$$\phi(\vec{x}, y, t) = \sum_{n=0}^{\infty} \varphi_n(\vec{x}, t) e^{i\frac{n}{R}y}$$

Equation of motion becomes:

$$\Box\varphi_n(\vec{x}, t) - \frac{n^2}{R^2}\varphi_n(\vec{x}, t) = 0$$

5d free massless scalar field = n free scalar fields in 4d of mass

$$m_n^2 = \frac{n^2}{R^2}$$



Kaluza-Klein (KK) tower

This is a general feature:
it happens in models with scalars, fermions and gauge fields!

Zero modes are identified with SM fields.

Different models with extra dimensions

- Large extra dimensions (ADD)

only gravity propagates in the bulk

- Universal extra dimensions (UED)

All fields can propagate in flat extra dimensions

- Warped extra dimensions (RS)

can address issues of hierarchy in fermion masses with profiles of particles in the extra dimension

New ideas on EWSB from extra dimensions:

Gauge-Higgs unification: Higgs can be identified with 5th component of a gauge field
(mass protected by 5d gauge invariance)

~~Higgsless models: EW symmetry broken by boundary conditions in 5th dim~~
~~(WW scattering unitarized by exchange of KK tower)~~

~~Top quark condensate models: EW symmetry broken by condensation of top quark due to exchange of KK gluons~~
~~(Dobrescu et al.)~~

Signals @ LHC

KK recurrences of SM particles
All in the few TeV range (precision measurements)

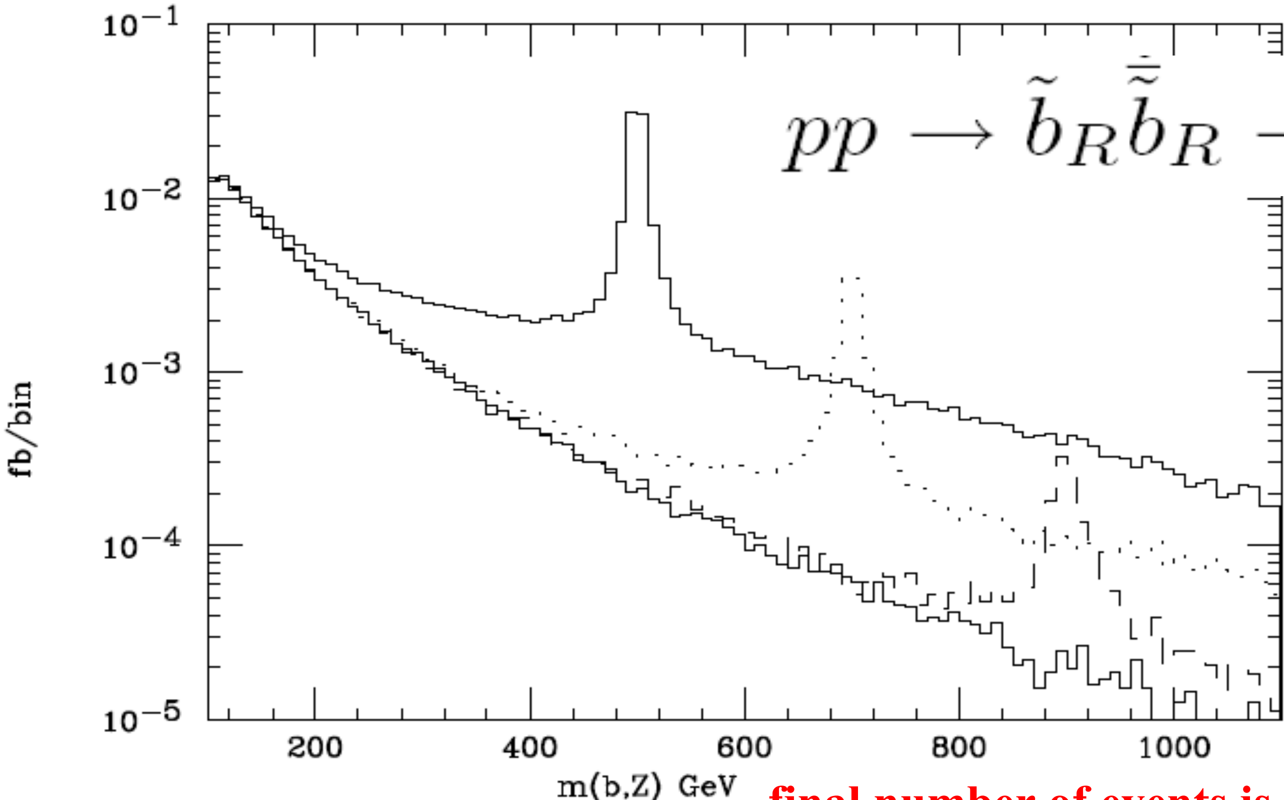
- KK gluons, KK W's and Z's
- KK fermions   No signs of KK particles yet
- Light "custodians"

EW precision tests -> needs custodial symmetry to keep T small

Light custodians @ LHC

(de Sandes & RR 2009)

$$pp \to \tilde{b}_R \bar{\tilde{b}}_R \to bZ\bar{b}Z$$



final number of events is small

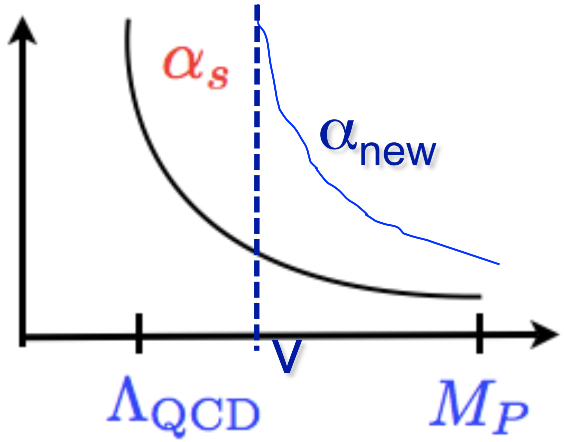
Figure 1: Cross section per 10 GeV bin of the invariant bZ pair mass for the process $pp \to \tilde{b}_R \bar{\tilde{b}}_R \to bZ\bar{b}Z$ at the LHC for $m_{\tilde{b}} = 500, 700$ and 900 GeV. Solid line is the SM irreducible background.

Composite models

Inspired by QCD: electroweak symmetry is broken by new strong interactions.

QCD can have huge hierarchy between Planck scale and QCD scale naturally: log running of coupling constant.

Could the same mechanism happen in EW?



Lightest mesons are pseudo Nambu-Goldstone bosons: mass protected by symmetry.

Massless QCD with 2 flavors: chiral symmetry is broken by quark condensate: $\langle \bar{q}q \rangle = f_\pi^3$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

3 pions are generated (3 broken generators).

Simplest technicolor model: scaled-up version of QCD by v/f_π

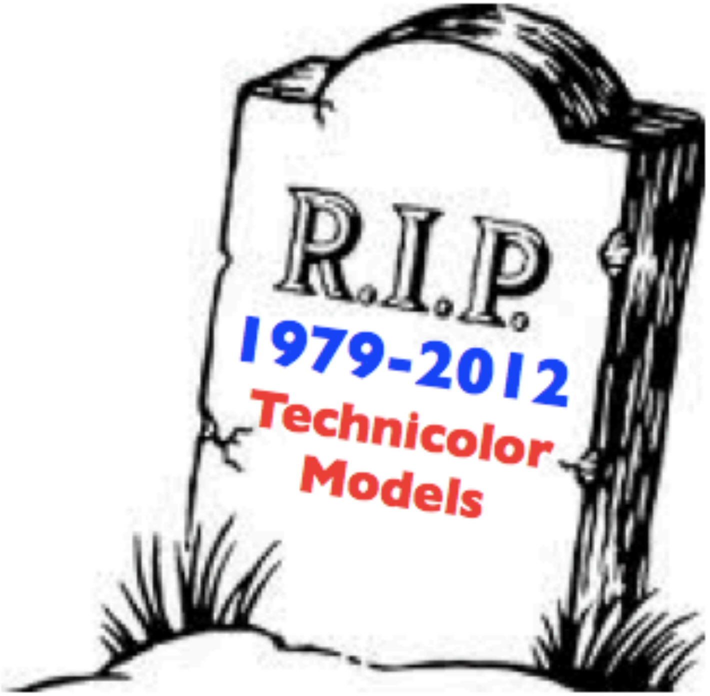
New techniquarks with a new interaction that induces chiral symmetry breaking $\langle \bar{q}_T q_T \rangle = v^3$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

3 technipions are generated and are eaten by EW gauge bosons

Higgsless model

Specially for fans of **Higgsless models:**



Pomarol – ICHEP 2012

but be careful about resurrections...

It is *not unconceivable* that a light dilaton appears in Higgsless theories

Pomarol – ICHEP 2012

Dilaton

(Goldstone of the spontaneous breaking of scale invariance)

Couples as a Higgs up to an overall scale → **A Higgs impostor**

Interlude: Dilatons

Consider the following general lagrangian:

$$\mathcal{L} = \sum_i \underbrace{g_i(\mu)}_{\text{coupling}} \underbrace{\mathcal{O}_i(x)}_{\text{operator with scaling dimension } d_i}$$

Scale transformation (dilatations):

$$x \to e^{\alpha} x \qquad\qquad \mathcal{O}_i(x) \to e^{\alpha d_i} \mathcal{O}_i(e^{\alpha} x)$$

Associated current: $$j^\mu = x_\nu T^{\mu\nu}$$

$$\delta\mathcal{L} = \partial_\mu j^\mu = T^\mu_\mu$$

Variation of lagrangian under an infinitesimal scale transformation:

$$\delta\mathcal{L} = \sum_i \left[g_i(\mu)(d_i - 4) - \beta(g_i)\right] \mathcal{O}_i(x)$$

$$\beta(g_i) \equiv \frac{\partial g_i(\mu)}{\partial \ln \mu}$$

Two sources of scale violation: classical and quantum.

Theory is scale invariant if operators have dimension 4 (dimensionless couplings) and couplings don't run.

Broken scale invariance can be realized nonlinearly by introducing a scalar field

$$\chi(x) = f e^{\phi(x)/f} \approx f + \phi(x) + \frac{1}{2f}\phi(x)^2 + \cdots$$

symmetry breaking scale

$$\delta\phi = x^\mu \partial_\mu \phi + f$$

Nambu-Golstone boson – the dilaton

Scale invariant lagrangian (at the classical level)

$$\mathcal{L} = \sum_i g_i \left(\frac{\chi}{f}\mu\right)\left(\frac{\chi}{f}\right)^{4-d_i} \mathcal{O}_i(x) + \mathcal{L}_\chi$$

Expanding field χ in lagrangian:

$$\mathcal{L} = \mathcal{L}(\chi = f) + \left(\frac{\phi(x)}{f} + \frac{\phi^2(x)}{2f^2} + \cdots\right) \overbrace{\sum_i \left[g_i(\mu)(d_i - 4) - \beta(g_i)\right] \mathcal{O}_i}^{T^\mu_\mu} + \mathcal{L}_\chi$$

Dilaton couples to the trace of the energy-momentum tensor (which is the source of scale symmetry breaking)

Examples:

Does this look familiar??

- coupling to W's and Z's (dim=2)

$$\left(\frac{\phi(x)}{f}+\frac{\phi^2(x)}{2f^2}+\cdots\right)\left(2M_W^2 W_\mu W^\mu + M_Z^2 Z_\mu Z^\mu\right)$$

- coupling to fermions (dim=3)

$$\left(\frac{\phi(x)}{f}+\cdots\right)\left(m_f \bar{f} f\right)$$

- coupling to massless gauge bosons (dim=4)

$$\left(\frac{\phi(x)}{f}+\cdots\right)\left(\beta(g)\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right)$$

Trace anomaly

Dilaton couplings = Higgs couplings (with f=v)

Important exception: coupling to massless gauge bosons

$$\mathcal{L}_{hgg} = \frac{h}{v}\beta(g)_{\text{heavy}}\,(G_{\mu\nu})^2 \qquad \mathcal{L}_{\phi gg} = \frac{\phi}{f}\beta(g)_{\text{light}}\,(G_{\mu\nu})^2$$

$$b_0^{\text{top}} = 2/3 \qquad b_0^{\text{light}} = -11 + 2n_f/3 = -23/3$$

factor ~10

Dilaton ≠ Higgs (dilaton is singlet)

Dilaton can mimick a Higgs (Higgs impersonator)

Golberger, Grinstein and Skiba (2008); Fan, Goldberger, Ross and Skiba (2009)

Dilaton can mix with a Higgs (change “Higgs” couplings)

Higgs or dilaton?

$$\frac{\varphi}{\Lambda}T^{\mu}_{\mu} = \frac{\varphi}{\Lambda}\left(\sum_f m_f \bar{f} f - M_Z^2 Z_\mu^2 - 2M_W^2 W_\mu^2 + b_3 \frac{\alpha_3}{8\pi} G^a_{\mu\nu} G^a_{\mu\nu} + b_\gamma \frac{\alpha_{\rm em}}{8\pi} F_{\mu\nu} F_{\mu\nu}\right)$$

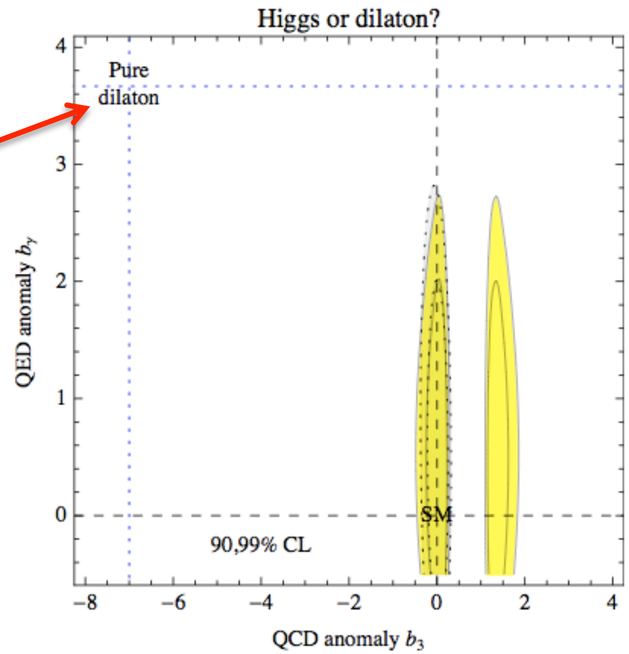
Universal fit adapted for the dilaton case

$$r \equiv r_W = r_Z = r_t = r_b = r_\tau = \frac{V}{\Lambda}, \qquad r_g \approx r(1 - 1.45 b_3), \qquad r_\gamma \approx r(1 + 0.15 b_\gamma)$$

where $V = 246\,\mathrm{GeV}$.

Pure dilaton excluded at 5 sigma

1303.3570



A dilaton-like particle also appears in models of warped extra dimensions:

Radion

Some radion phenomelogy, in particular a mixing with the Higgs was discussed in
de Sandes and RR (arXiv:1111.2006)

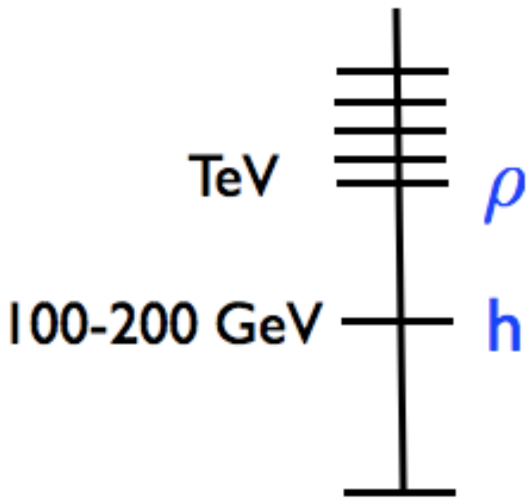
Composite Higgs idea

New symmetry breaking pattern: $SO(5) \rightarrow SO(4)$

$SO(N): \ \frac{N(N-1)}{2}$ generators

4 technipions with the quantum numbers of a Higgs doublet are generated. Three are eaten by EW gauge bosons -> physical Higgs is a NGB.

Spectrum:



Resonances (techni-rho) are a smoking gun for this model

Higgs potential generated radiatively

A TWO-STEP SYMMETRY BREAKING:

$$SO(5) \xrightarrow{f} SO(4) \xrightarrow{v} SO(3)$$

composite doublet H

EWSB

Free parameter

$$\xi = \left(\frac{v}{f}\right)^2$$

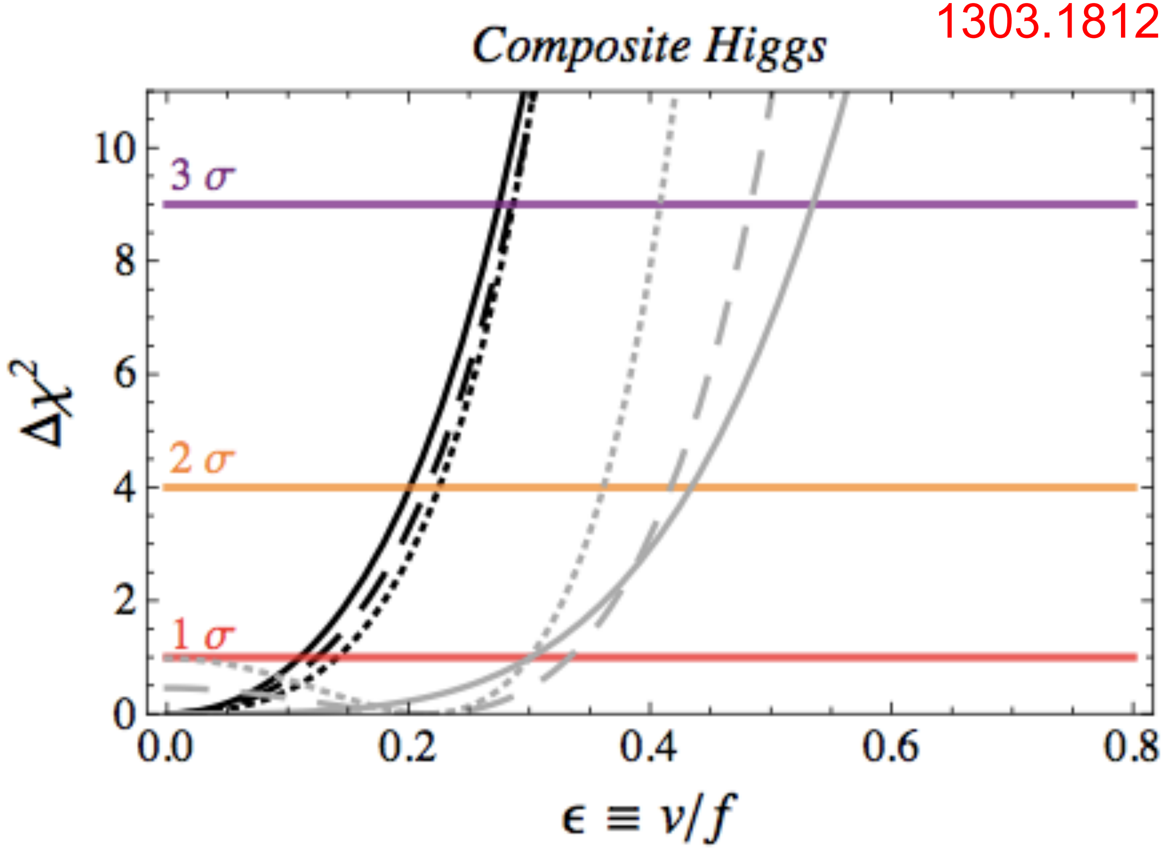
$$m_\rho \sim 4\pi f = 4\pi v/\sqrt{\xi}$$

decoupling limit:

$$\xi \to 0$$
$$v = \text{fixed}$$

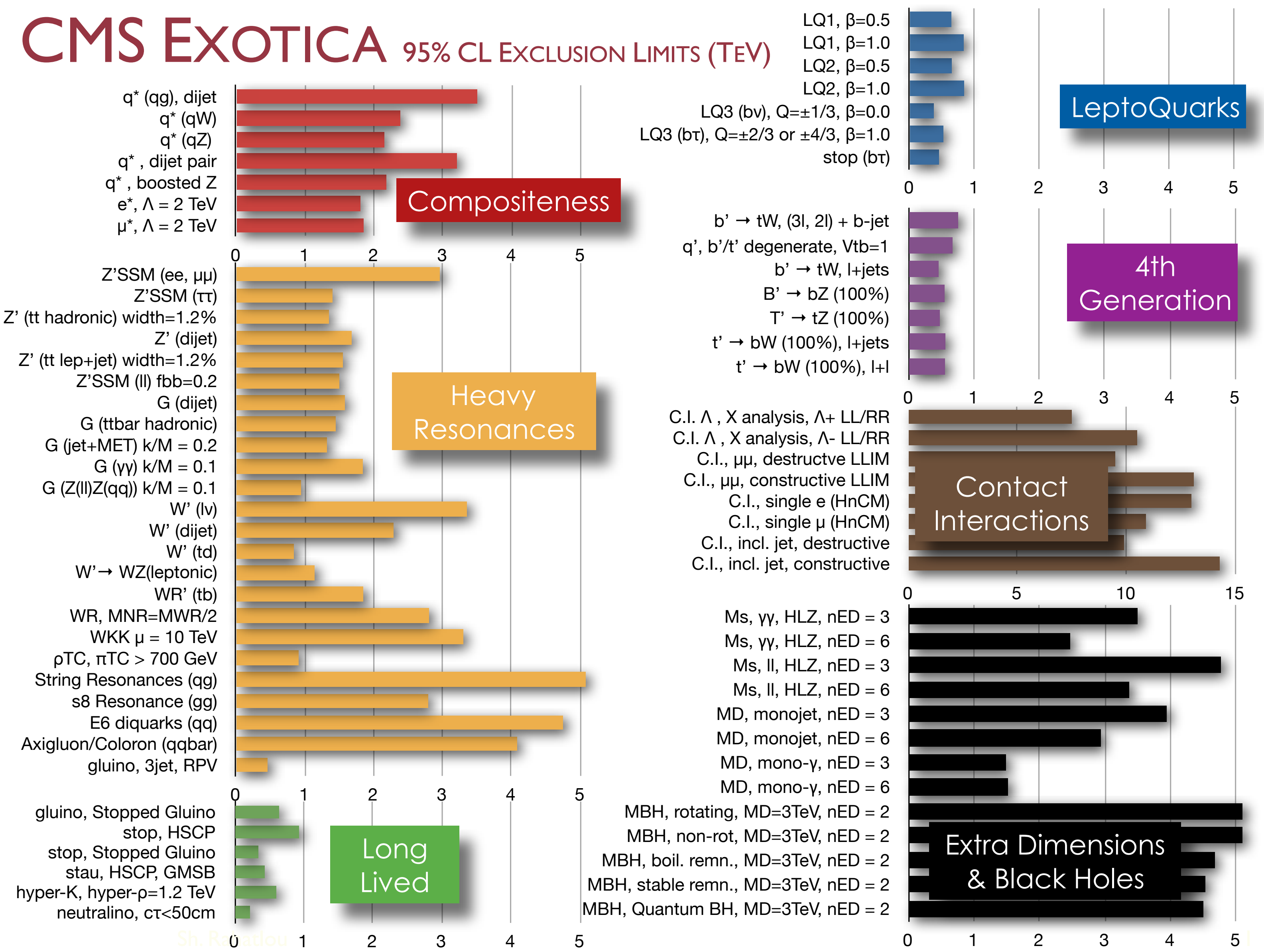
Recent fit with Higgs + EW data

1303.1812



$\epsilon = v/f$ in sample composite Higgs models with (black) and without (gray) including EW precision data. The different lines correspond to the $SO(5)/SO(4)$ coset and fermionic representations with $m = 0$ and $n = 0$ (solid), $n = 1$ (dashed) and $n = 2$ (dot-dashed)."

LHC results on searches for new particles



New signature of strongly coupled models: multiparticle production

Belyaev, Oliveira, RR, Thomas, arXiv:1212.3860

Take a nonlinear sigma model:

$$\mathcal{L}_{NL\sigma M} = \frac{v^2}{4}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right]$$

The cross section to produce n relativistic pions is:

$$\sigma(2 \to n) \sim \frac{1}{s}\left(\frac{s}{v^n}\right)^2 s^{n-2}$$

The cross section grows faster with number of pions: violates perturbative unitarity.

In the SM there must be strong cancellations in the scattering amplitudes to avoid unitarity violation.

In composite Higgs models the unitarization is only partial due to anomalous Higgs couplings.

One can have greater sensitivity to modifications of Higgs couplings in multi-particle production.

Can parametrize anomalous couplings with an effective lagrangian:

$$\mathcal{L}_{\text{eff}} = \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right)\text{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right]$$
$$+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3\lambda v h^3 - d_4\frac{\lambda}{4}h^4 + \cdots$$

SM values $a = b = d_3 = d_4 = 1$ and $b_3 = 0$

$$a = \sqrt{1-\xi},\ b = (1-2\xi)\ \cdots$$

$$\mathcal{M}_{00;+-} = \frac{s\left[(1-a^2)s - m_h^2\right]}{v^2(s-m_h^2)} \xrightarrow[s \gg m_h^2]{} (1-a^2)\frac{s}{v^2}$$

Amazing cancellations in the SM

$$\mathcal{M}_{00;00+-} \propto \tfrac{1}{v^4}\,[72s\,(13a^4 - a^2(7b+5) - 1) +$$
$$3m_h^2\,(1580a^4 - 378a^3d_3 - 3a^2(245b+131) - 74) +$$
$$\tfrac{m_h^4}{s}\,(9774a^4 - 3087a^3d_3 - a^2(4494b+1289) + 52) +$$
$$\cdots] \tag{14}$$

It grows with s, as expected. However, in the SM $(a = b = d_3 = 1)$ one obtains in the limit $s \gg m_h^2$:

$$\mathcal{M}_{00;00+-} \propto \frac{1}{s}\frac{m_h^4}{v^4} \tag{15}$$

Huge enhancements

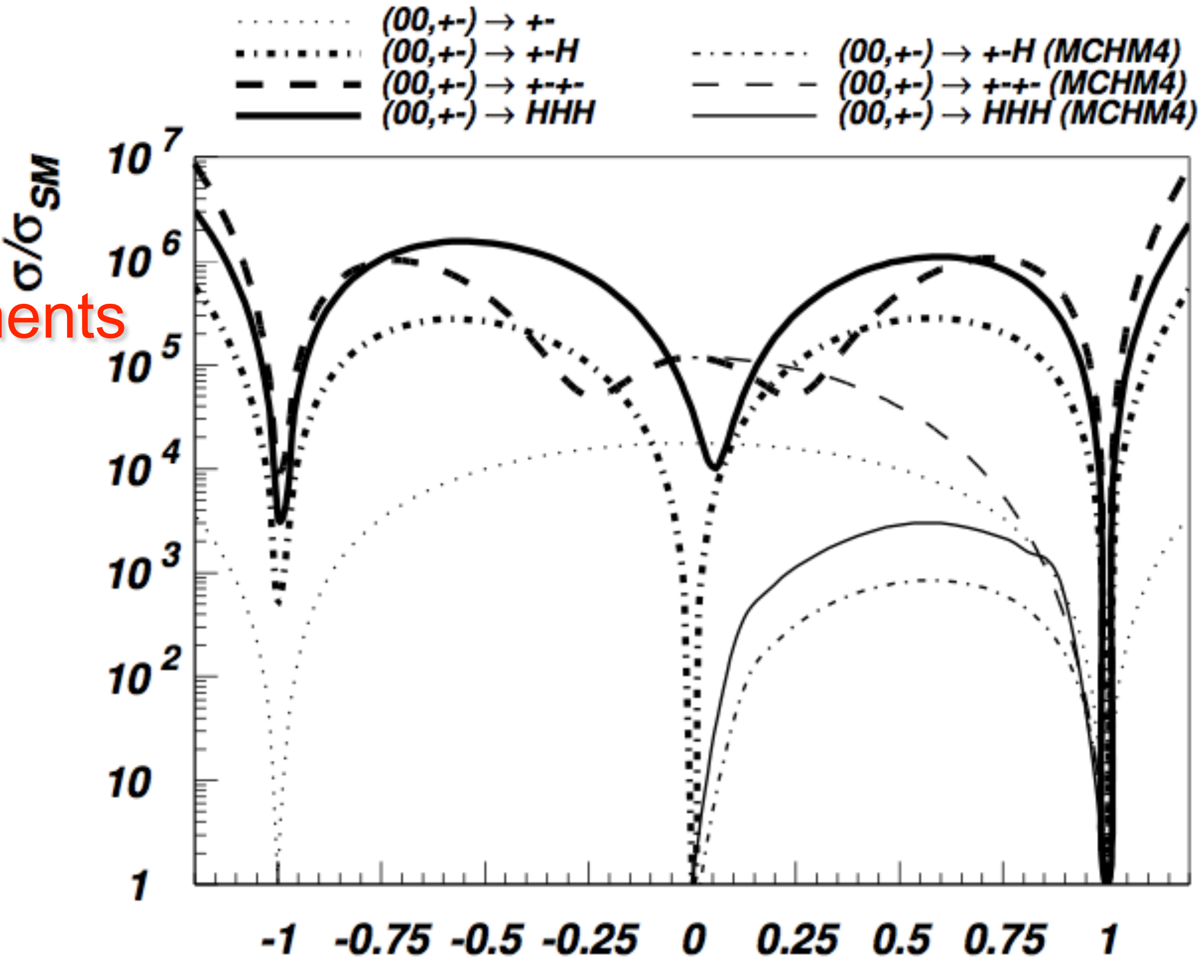


Figure 1: Ratio of the SMEFF (thin lines) and MCHM4 (thick lines) cross sections to the SM one versus a parameter at a fixed energy of $\sqrt{s} = 2$ TeV. The different channels are: $(00,+-) \to +-+-$ (dashed line), $(00,+-) \to +-h$ (dot-dashed line), $(00,+-) \to hhhh$ (solid line), and $(00,+-) \to +-$ (dotted line) for comparison. The notation $(00,+-)$ indicates that both 00 and $+-$ initial states were taken into account.

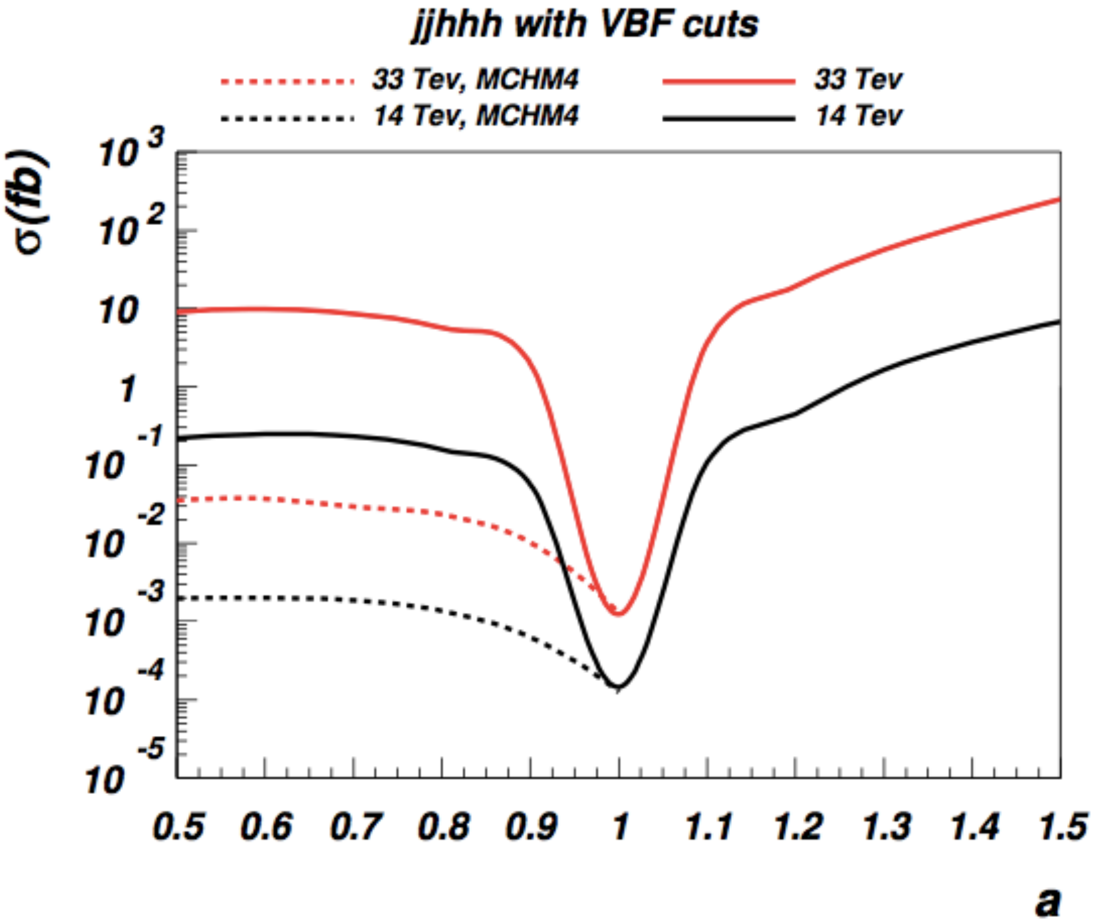
Do large enhancements persist in full calculation?

Yes, in triple higgs production!

Process	14 TeV		33 TeV	
	with (without) VBF cuts		with (without) VBF cuts	
	a=1.0 b=1.0	a=0.9 b=1.0	a=1.0 b=1.0	a=0.9 b=1.0
$pp \to jjW^+W^-$	95.2 (1820)	99.3 (1700)	512 (5120)	540 (5790)
$pp \to jjW^+W^-h$	0.011 (0.206)	0.0088 (0.172)	0.0765 (0.914)	0.0626 (0.758)
$pp \to jjhhh$	1.16×10^{-4} (3.01×10^{-4})	0.0566 (0.0613)	0.00115 (0.00165)	1.85 (1.46)

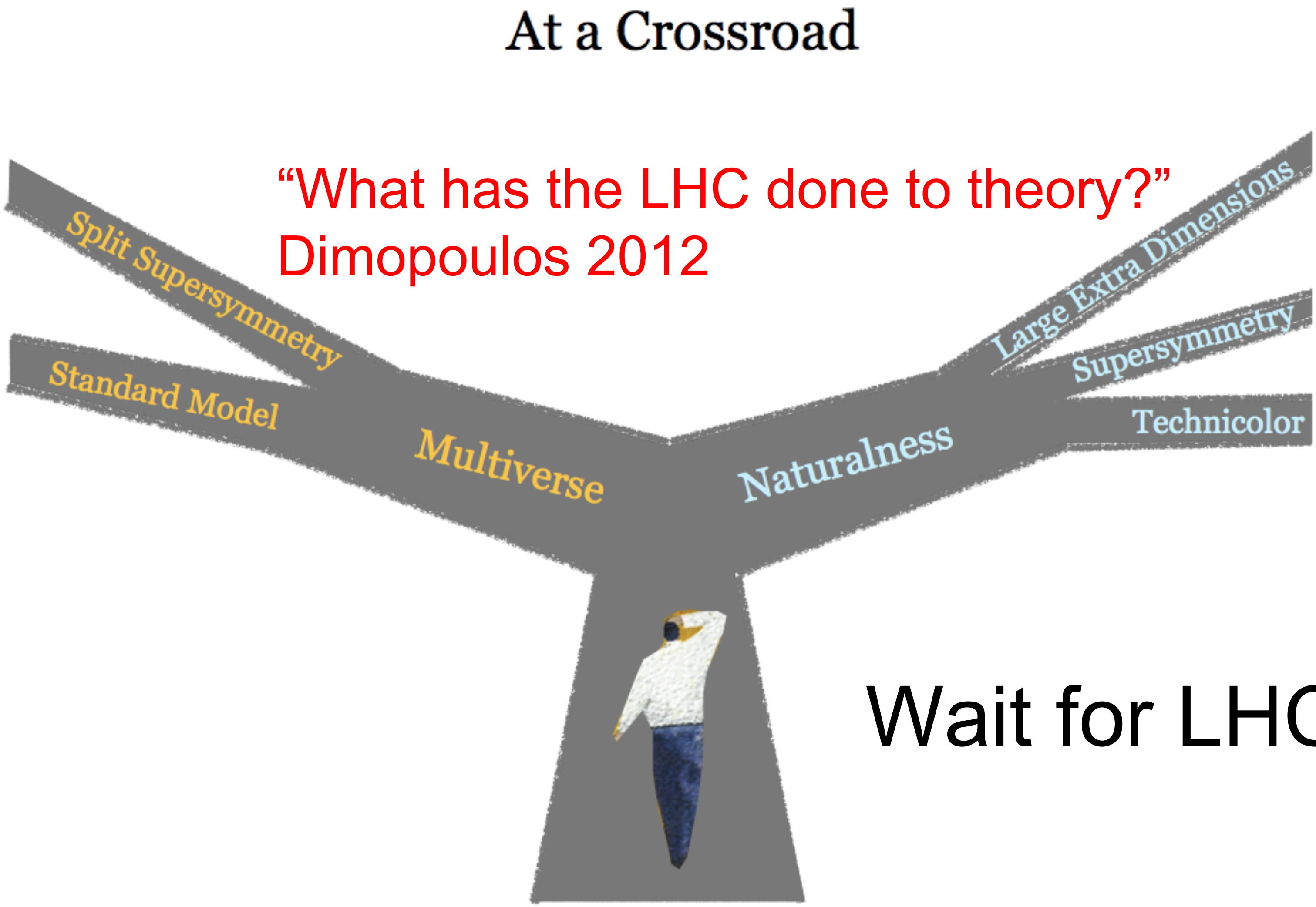
Table 2: Cross section (in fb) for $pp \to jjW^+W^-$, $pp \to jjW^+W^-h$ and $pp \to jjhhh$ processes evaluated with Madgraph5.

Triple higgs production



Too small to be seen

Conclusion



"What has the LHC done to theory?"
Dimopoulos 2012

Wait for LHC14

- Large extra dimensions (ADD, 98)

Only gravity feels extra dimensions

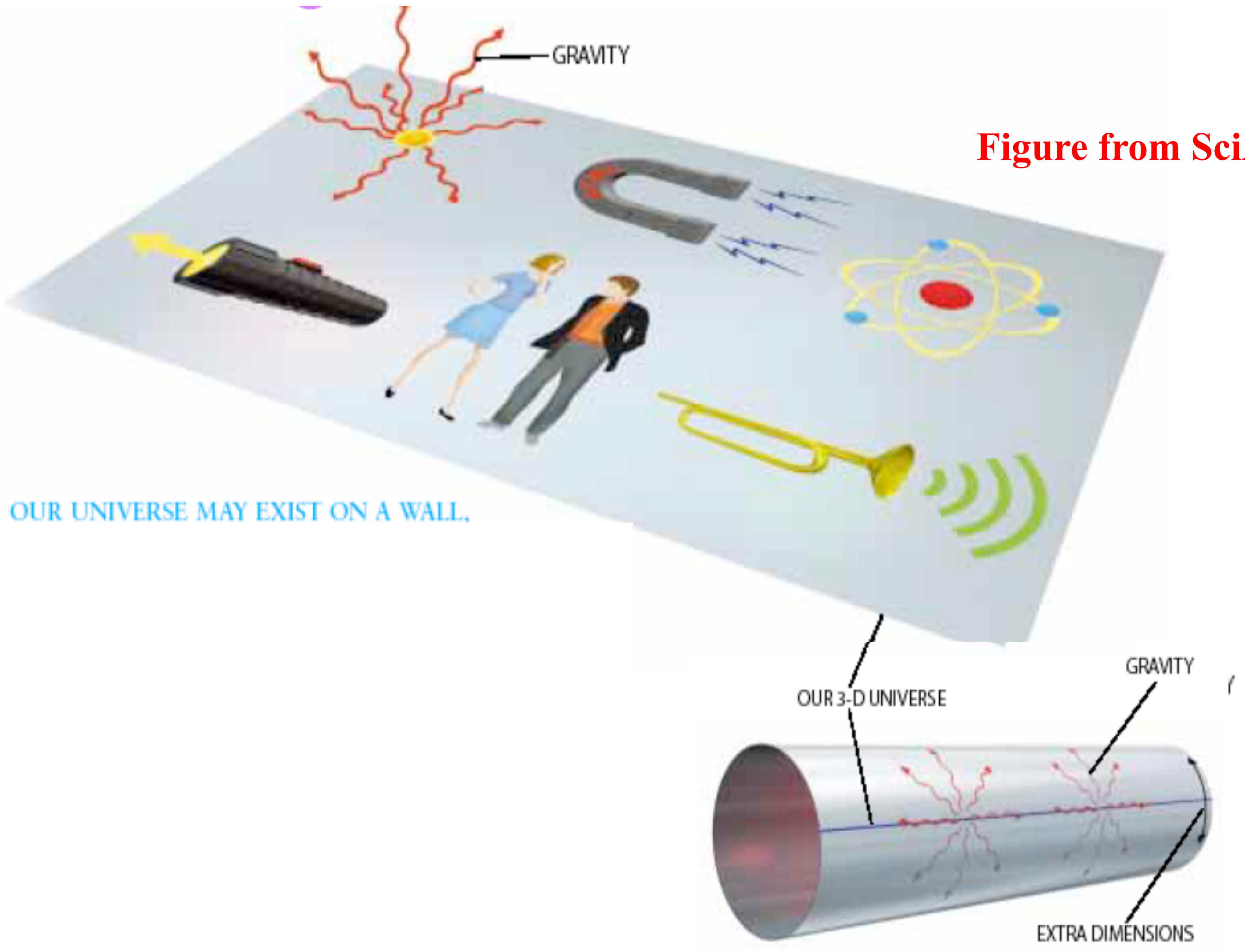
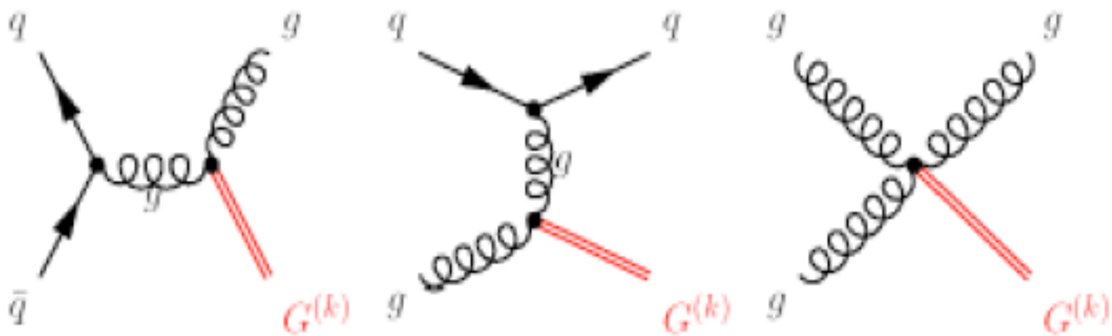


Figure from SciAm

• Large extra dimensions (ADD, 98)

Solves the hierarchy problem by lowering the real d-dimensional Planck mass: gravity in 4d is weak because it is diluted...

Collider signatures: missing energy (monojets)



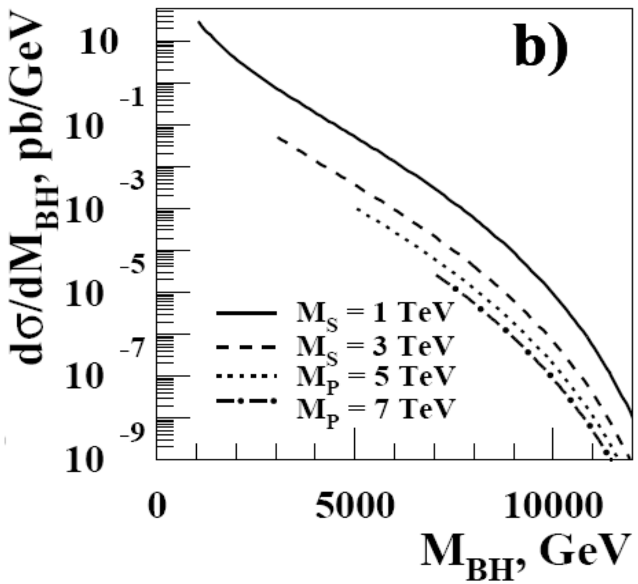
Main constraints are astrophysical (SN cooling)

• Large extra dimensions (ADD, 98)

Striking signature:

Black hole production at the LHC?

$$\sigma_{BH}(M > M_{min}) = \sum_{ij} \int_{\tau_{min}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_i(x) f_j(\tau/x) \hat{\sigma}(\sqrt{\hat{s}})$$



10^7 BH/year at the LHC
(Dimopoulos & Landsberg, PRL 01)

- Universal extra dimensions (Appelquist et al, 01)

All SM particles allowed to propagate in the extra dimension: KK towers

KK parity allows for R~1 TeV^{-1}

Dark matter candidate (LKK)

Indirect effect (e.g., Higgs pair production in gg fusion [Sandes & RR, PLB08])

- Warped extra dimensions (Randall & Sundrum, 99)

Non-flat extra dimension: introduce geometry

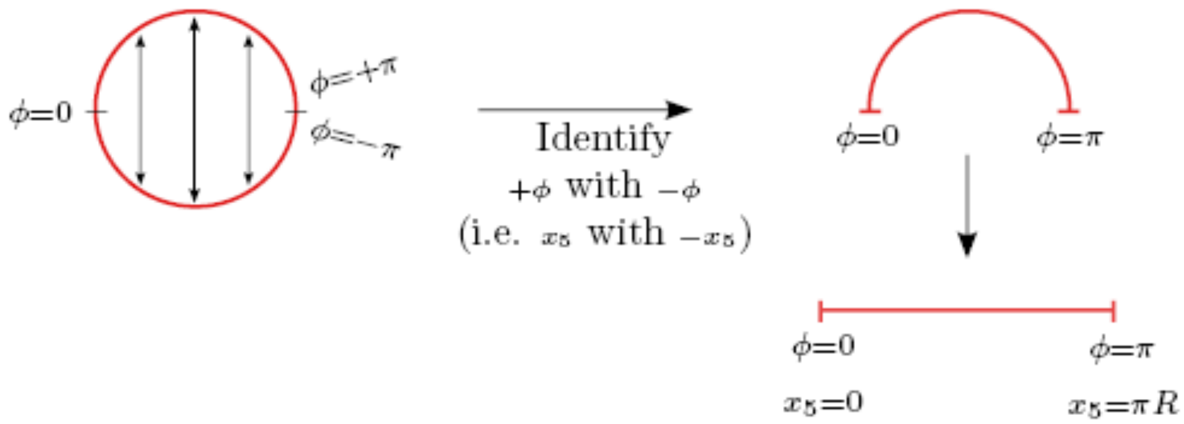
Non-factorizable metric (AdS_5):

$$ds^2 = e^{-2ky}\eta^{\mu\nu}dx_\mu dx_\nu + dy^2$$

$k \sim M_{Pl}$ is the AdS curvature

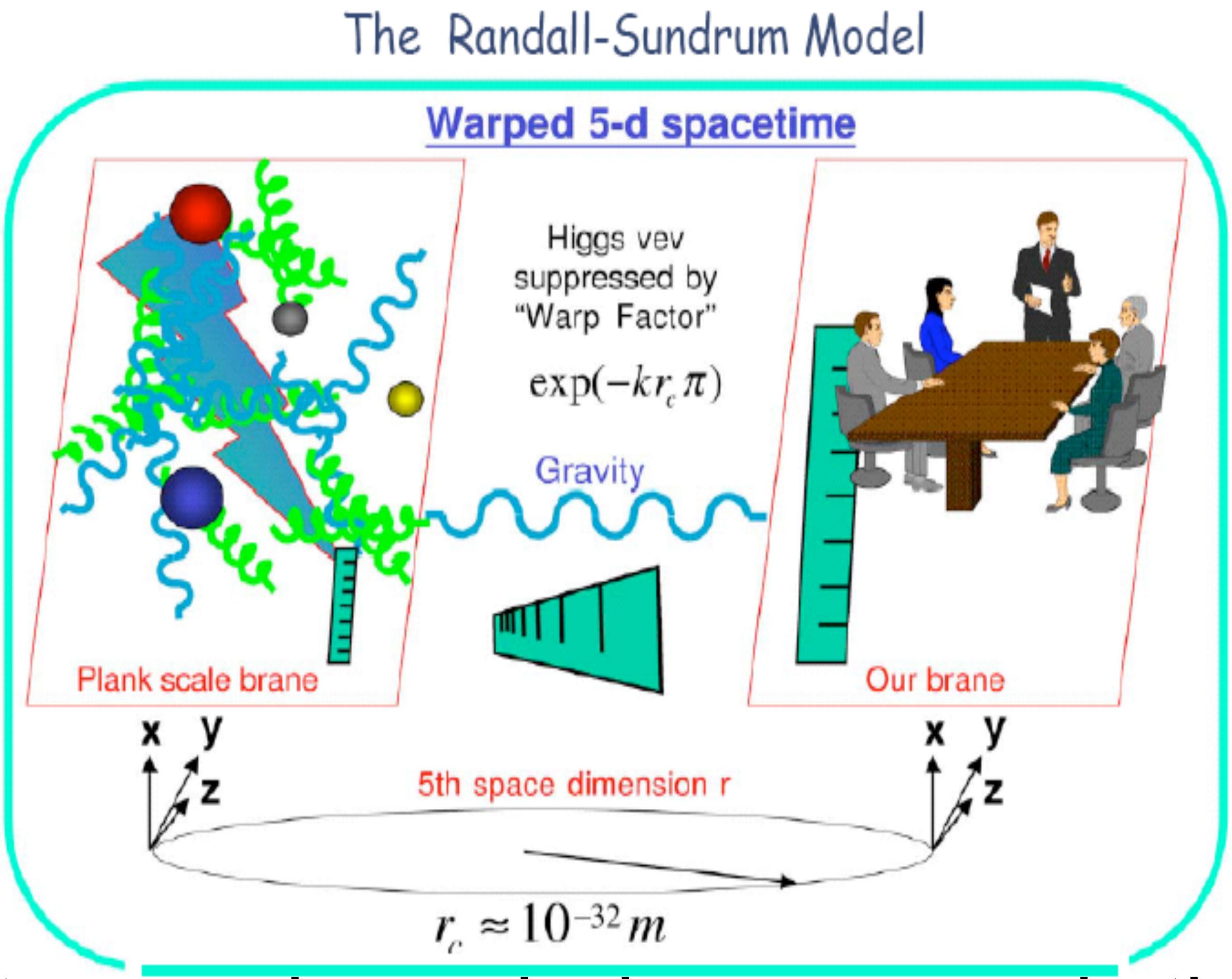
• Warped extra dimensions

Orbifold compactification:
circle becomes an interval $y \in [0, \pi R]$



The 5th dimension ends in branes (fixed points):
UV (Planck) brane at $y=0$
IR (TeV) brane at $y=\pi R$

- Warped extra dimensions



4d distances depend where we are in the extra dimension! "Warp factor".

• Warped extra dimensions

Solution to hierarchy problem if Higgs is localized in the TeV brane:

$$S = \int d^4x \int_0^{\pi R} dy \sqrt{-g}\,\delta(y-\pi R)\left[g^{MN}\partial_M H^+ \partial_N H - \lambda\left(|H|^2 - \mathrm{v}_0^2\right)^2\right]$$

naturally O(k)

$$= \int d^4x \left[\eta^{\mu\nu}\partial_\mu H^+ \partial_\nu H - \lambda\left(|H|^2 - \mathrm{v}^2\right)^2\right]$$

where $\mathrm{v} = e^{-k\pi R}\mathrm{v}_0$

Higgs vev is "warped down" to weak scale if kR~10

Introduction

Consider the following general lagrangian:

$$\mathcal{L} = \sum_i g_i(\mu)\mathcal{O}_i(x)$$

coupling   operator with scaling dimension d_i

Scale transformation (dilatations):

$$x \to e^\alpha x \qquad\qquad \mathcal{O}_i(x) \to e^{\alpha d_i}\mathcal{O}_i(e^\alpha x)$$

Associated current: $$j^\mu = x_\nu T^{\mu\nu}$$

$$\delta\mathcal{L} = \partial_\mu j^\mu = T^\mu_\mu$$

Variation of lagrangian under an infinitesimal scale transformation:

$$\delta\mathcal{L} = \sum_i \left[g_i(\mu)(d_i - 4) - \beta(g_i)\right] \mathcal{O}_i(x)$$

$$\beta(g_i) \equiv \frac{\partial g_i(\mu)}{\partial \ln \mu}$$

Two sources of scale violation: classical and quantum.

Theory is scale invariant if operators have dimension 4 (dimensionless couplings) and couplings don't run.

Broken scale invariance can be realized nonlinearly by introducing a scalar field

$$\chi(x) = f e^{\phi(x)/f} \approx f + \phi(x) + \frac{1}{2f}\phi(x)^2 + \cdots$$

symmetry breaking scale

$$\delta\phi = x^\mu \partial_\mu \phi + f$$

Nambu-Golstone boson – the dilaton

Scale invariant lagrangian (at the classical level)

$$\mathcal{L} = \sum_i g_i \left(\frac{\chi}{f}\mu\right) \left(\frac{\chi}{f}\right)^{4-d_i} \mathcal{O}_i(x) + \mathcal{L}_\chi$$

Expanding field χ in lagrangian:

$$\mathcal{L} = \mathcal{L}(\chi = f) + \left(\frac{\phi(x)}{f} + \frac{\phi^2(x)}{2f^2} + \cdots\right) \overbrace{\sum_i \left[g_i(\mu)(d_i - 4) - \beta(g_i)\right] \mathcal{O}_i}^{T^\mu_\mu} + \mathcal{L}_\chi$$

Dilaton couples to the trace of the energy-momentum tensor (which is the source of scale symmetry breaking)

Examples:

Does this look familiar??

- coupling to W's and Z's (dim=2)

$$\left(\frac{\phi(x)}{f}+\frac{\phi^2(x)}{2f^2}+\cdots\right)\left(2M_W^2W_\mu W^\mu+M_Z^2Z_\mu Z^\mu\right)$$

- coupling to fermions (dim=3)

$$\left(\frac{\phi(x)}{f}+\cdots\right)\left(m_f\bar{f}f\right)$$

- coupling to massless gauge bosons (dim=4)

$$\left(\frac{\phi(x)}{f}+\cdots\right)\left(\beta(g)\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right)$$

Trace anomaly

Dilaton couplings = Higgs couplings (with f=v)

Important exception: coupling to massless gauge bosons

$$\mathcal{L}_{hgg} = \frac{h}{v}\beta(g)_{\text{heavy}}\left(G_{\mu\nu}\right)^2 \qquad \mathcal{L}_{\phi gg} = \frac{\phi}{f}\beta(g)_{\text{light}}\left(G_{\mu\nu}\right)^2$$

$$b_0^{\text{top}} = 2/3 \qquad b_0^{\text{light}} = -11 + 2n_f/3 = -23/3$$

factor ~10

Dilaton ≠ Higgs (dilaton is singlet)

Dilaton can mimick a Higgs (Higgs impersonator)

Golberger, Grinstein and Skiba (2008); Fan, Goldberger, Ross and Skiba (2009)

Dilaton can mix with a Higgs (change “Higgs” couplings)

EWSB

Idea: EWSB (or maybe whole SM) is embedded in a conformally invariant, strongly interacting sector.

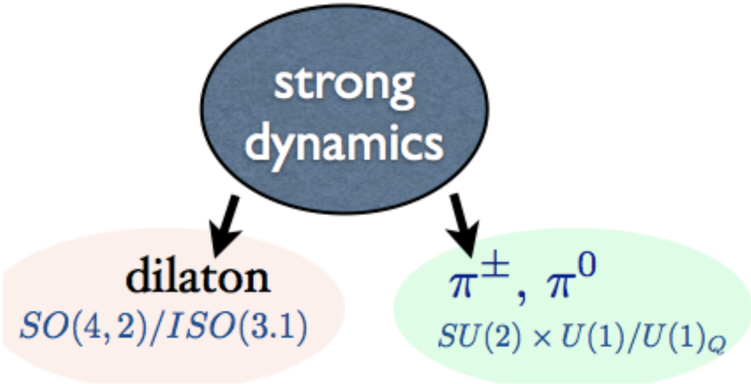
At some high energy scale f there is a breaking of scale invariance that triggers EWSB at a lower energy scale v.

A dilaton is generated at f and a Higgs doublet (PNGB) is generated at scale v.

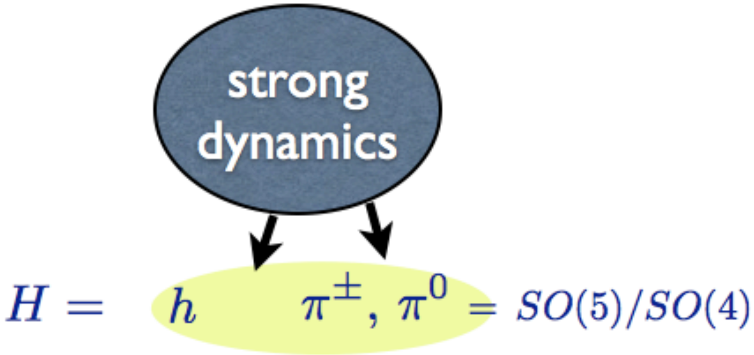
Rattazzi, Planck 2010

Agashe, Contino, Pomarol '04

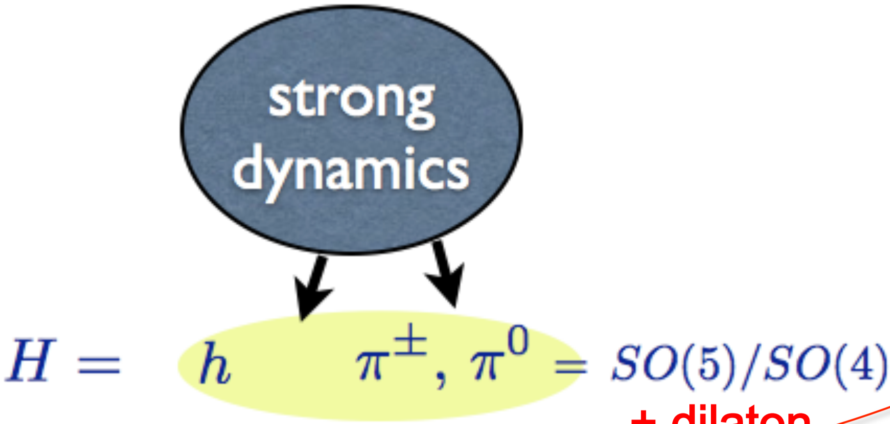
Higgsless with
Light dilaton



Pseudo-Goldstone
Higgs doublet



Pseudo-Goldstone
Higgs doublet + dilaton



+ dilaton

Higgs-dilaton mixing

Scalar fields contribution to the canonical $T^{\mu\nu}$ violate scale invariance even at the classical level.

Example: free scalar field $$\mathcal{L} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m^2 h^2$$

$$T_{\mu\nu} = \partial_\mu h \partial_\nu h - g_{\mu\nu}\mathcal{L} \Longrightarrow T^\mu_\mu = -(\partial_\mu h)^2 + m^2 h^2$$

Nonzero in the conformal m=0 limit!

Need to “improve” definition of energy-momentum tensor

Callan, Coleman and Jackiw (1970)

$$\Theta_{\mu\nu} = T_{\mu\nu} - \xi\left(\partial_\mu \partial_\nu - g_{\mu\nu}\Box\right) h^2$$

$$(\Theta^\mu_\mu = m^2 h^2 \;\; \text{for} \;\; \xi = 1/6)$$

Higgs coupling to dilaton:

$$\mathcal{L}_{h-d} = \frac{\phi}{f}\Theta^{\mu}_{\mu}$$

$$\Theta_{\mu\nu} = T_{\mu\nu} - \xi\left(\partial_\mu\partial_\nu - g_{\mu\nu}\Box\right)\underbrace{H^\dagger H}_{\frac{(h+v)^2}{2}}$$

SSB + improved $T^{\mu\nu}$: Higgs-dilaton kinetic mixing

$$\mathcal{L}_{h-d} \sim \frac{v}{f}\phi\Box h$$

Schematic Higgs-dilaton mixing:

$$\mathcal{L} = -\frac{1}{2}\tilde{\phi}\left[(1+\kappa)\Box + m^2_{\tilde{\phi}}\right]\tilde{\phi} - \frac{1}{2}\tilde{h}\left[\Box + m^2_{\tilde{h}}\right]\tilde{h} - \mu^2\tilde{\phi}\tilde{h} - \zeta\tilde{\phi}\Box\tilde{h}$$

$$\begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix} = \begin{pmatrix} 1 & \alpha \\ 0 & \beta \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

re-scaling the kinetic terms
to their canonical forms

Physical fields are obtained from a <u>non-orthogonal </u>transformation

Does a dilaton exist?

Theories can be scale invariant at the classical level but symmetry is broken at the quantum level:

- Spontaneous breaking (1-loop effective potential)
- Explicit breaking (non-zero beta functions)

It is not clear whether a dilaton exists in quasi-conformal walking technicolor models

Yamawaki et al (1986, ..., 2012); Holdom and Terning (1986,87), Appelquist and Bai (2010),...

Radion in WED models

Warped extra dimensions (Randall&Sundrum 99) is a concrete implementation of a scale invariant model. Scale invariance is broken by the presence of the IR and UV branes in the extra 5th dimension.

Radion is the scalar mode of the metric fluctuation. It may be the lightest new particle in these models (depends on the stabilization mechanism).

We follow the realistic implementation of WED by Csáki, Hubisz and Lee (2007) –fermions and gauge fields in the bulk.

WED is possible solution to the hierarchy problem

$$m_h \ll m_{Pl}$$

Fermion masses are more natural in WED – their values arise from the fermion localization in the 5th dimension

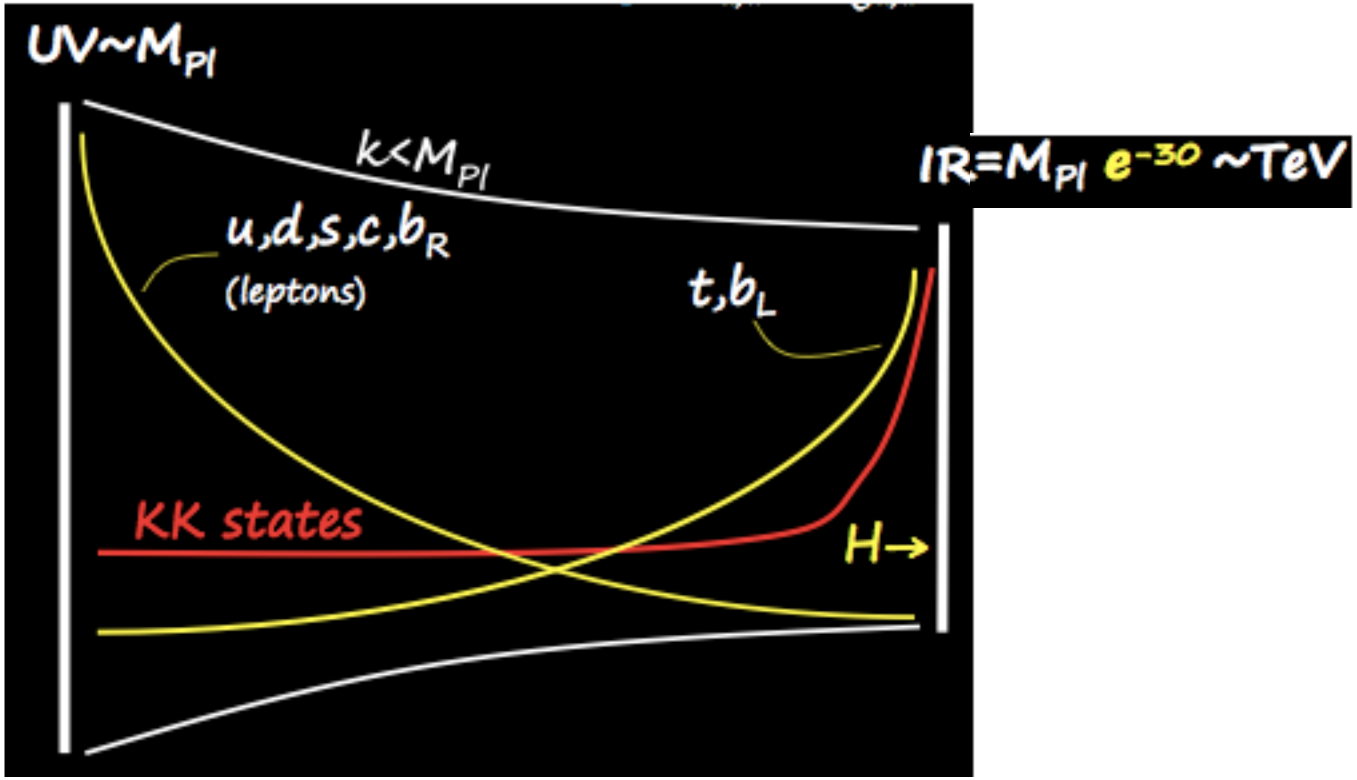
Warped metric is (y is the 5th dimension):

$$ds^2 = e^{-2ky} \underbrace{\eta_{\mu\nu} dx^\mu dx^\nu}_{\text{Flat 4d metric at each y- position}} - dy^2$$

"warp" factor –
energy ruler depends on 5d position

Introduce two (3d) branes: Planck brane at y=0 and TeV brane at y=R. Hierarchy problem becomes

$$v = m_{Pl} e^{-kR}$$



Drawing by C. Delaunay

What fixes the size of extra dimension such that

$$kR = \ln\left(\frac{m_{Pl}}{v}\right) \sim \mathcal{O}(50)$$

Need a mechanism that stabilizes the extra dimension – Goldberger & Wise (99) – add bulk scalar field with brane-localized interactions – Mass and vev are model dependent but expected to be O(TeV).

Radion is possibly the lightest new particle in WED.

Radion is a gravitational degree of freedom associated with scalar perturbations of the metric:

$$ds^2 = e^{-2(ky+F(x,y))}\eta_{\mu\nu}dx^\mu dx^\nu - (1+2F(x,y))^2 dy^2$$

$$F(x,y) = \frac{r(x)}{\Lambda_r} R(y)$$

Canonically normalized radion field

Radion profile

Radion vev – fixes the size of the extra dimension

Stabilization mechanism fixes radion vev and mass – model dependent.

Radion r(x) couplings are set by small variation in the metric due to radion field:

$$S_r = -\frac{1}{2}\int d^5x\sqrt{G}\,T^{MN}\delta G_{MN}$$
$$= \int d^5x\sqrt{G}\,\left[T^M_M - 3T^{55}G_{55}\right] F(x,y)$$

If all fields are localized in the TeV brane:

$$\mathcal{L} = \frac{r(x)}{\Lambda_r}T^\mu_\mu$$

Hardly surprising...

Radion has couplings similar to dilaton

If fermions and gauge bosons are localized in the TeV brane there are problems with FCNC and EWPT.

Hence, only Higgs is kept in the TeV brane. Profiles suppress FCNC and EWPT corrections.

Higgs-radion mixing due to a non-minimal Higgs coupling to gravity

$$\mathcal{L}_\xi \sim \xi \mathcal{R} H^\dagger H$$

Ricci scalar

changes definition of energy-momentum tensor – "improved" definition.

Radion phenomenology

Radion production and decay has same experimental efficiency and acceptance as the SM higgs of same mass. Production cross section- gluon fusion dominates:

$$\sigma(pp \stackrel{gg}{\to} r \to X)(s) = \int d\tau \mathcal{L}_{gg}(\tau)\hat{\sigma}(\tau s)$$

In the narrow width approximation

$$\frac{\sigma(pp \stackrel{gg}{\to} r \to X)}{\sigma(pp \stackrel{gg}{\to} h \to X)_{SM}} = \frac{\Gamma_h^{SM}}{\Gamma_r} \frac{\Gamma(r \to gg)}{\Gamma(h \to gg)_{SM}} \frac{\Gamma(r \to X)}{\Gamma(h \to X)_{SM}}$$

$$X = VV^*, \bar{f}f, \gamma\gamma$$

Phenomenology is determined by radion couplings and the mixing matrix (non-orthogonal)

Giudice et al (2001); Csáki et al (2001); Dominici et al (2003), ...

$$r = a\, r^{\rm phys} + b\, h^{\rm phys}$$
$$h = c\, r^{\rm phys} + d\, h^{\rm phys}$$

The physical masses of radion and Higgs, radion vev and mixing parameter determine a,b,c and d.

Example:
Couplings to fermions and massive vector bosons:

$$\mathcal{L}_{r,h(VV,\bar{\psi}\psi)} = \left(2M_W^2 W^2 + M_Z^2 Z^2 - m\bar{\psi}\psi\right)\left[h + \frac{v}{\Lambda_r} r\right]$$

$$\mathcal{L}_{h^{\text{phys}}(VV,\bar{\psi}\psi)} = \left(2M_W^2 W^2 + M_Z^2 Z^2 - m\bar{\psi}\psi\right)\left[d + \frac{v}{\Lambda_r} b\right] h$$

Constants!

$$\mathcal{L}_{r^{\text{phys}}(VV,\bar{\psi}\psi)} = \left(2M_W^2 W^2 + M_Z^2 Z^2 - m\bar{\psi}\psi\right)\left[c + \frac{v}{\Lambda_r} a\right] r$$

Hence, modifications on widths are just constants (same for ff, WW and ZZ widths). Since these are dominant decay modes, the BR's in these modes are unchanged to a good approximation.

For instance,

radion component

Higgs component

$$\frac{\Gamma(r \to VV^*, \bar{f}f)}{\Gamma(h \to VV^*, \bar{f}f)_{SM}} = (c + \gamma a)^2$$

$$\gamma \equiv \frac{v}{\Lambda_r}$$

Similarly we can compute

If kinematically allowed

$$\frac{\Gamma(r \to gg)}{\Gamma(h \to gg)_{SM}} \qquad \frac{\Gamma(r \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \qquad \Gamma(r \to hh)$$

Free parameters: radion mass, mixing and scale

$$m_r, \ \xi, \ \Lambda_r$$

Not all values of mixing are allowed – too large values lead to imaginary masses

Branching ratios can change significantly when parameters are chosen such that

$$c + \gamma a \approx 0$$

Radion becomes phobic to both fermions and massive gauge bosons.

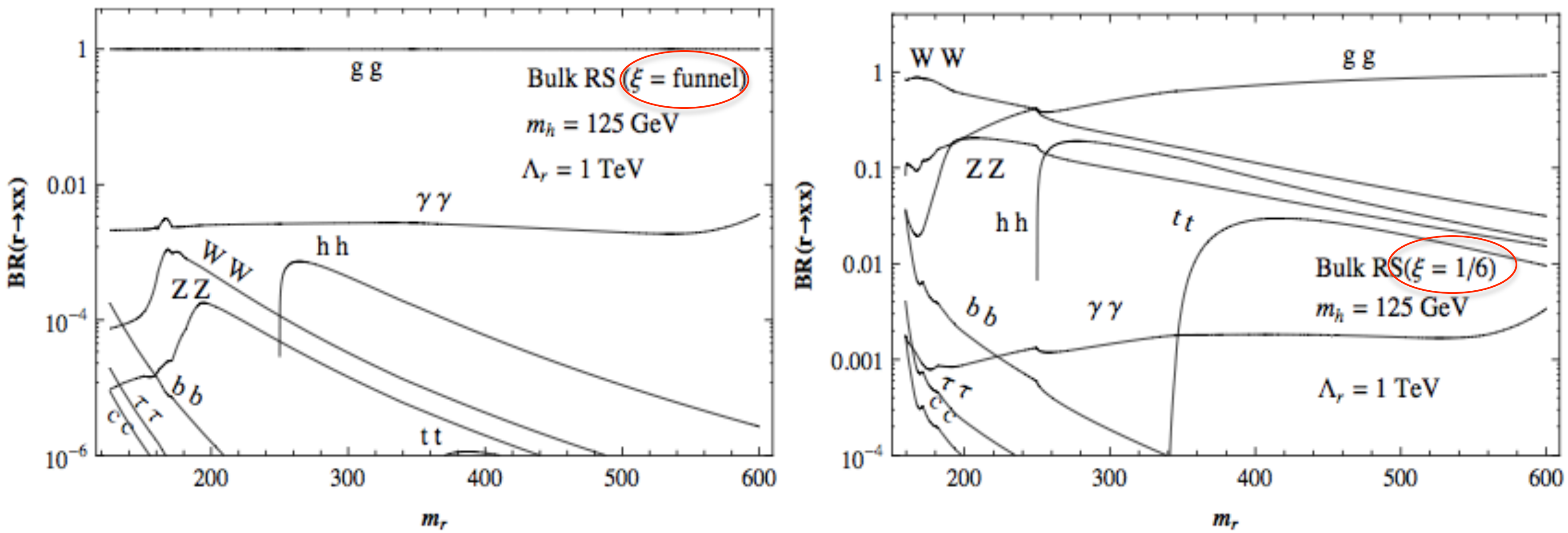


FIG. 4: Radion branching ratios for $\xi = \xi_{funnel}$(left) and $\xi = 1/6$(right). We fixed $m_r = 125$ GeV and $\Lambda_r = 1$ TeV.

Results

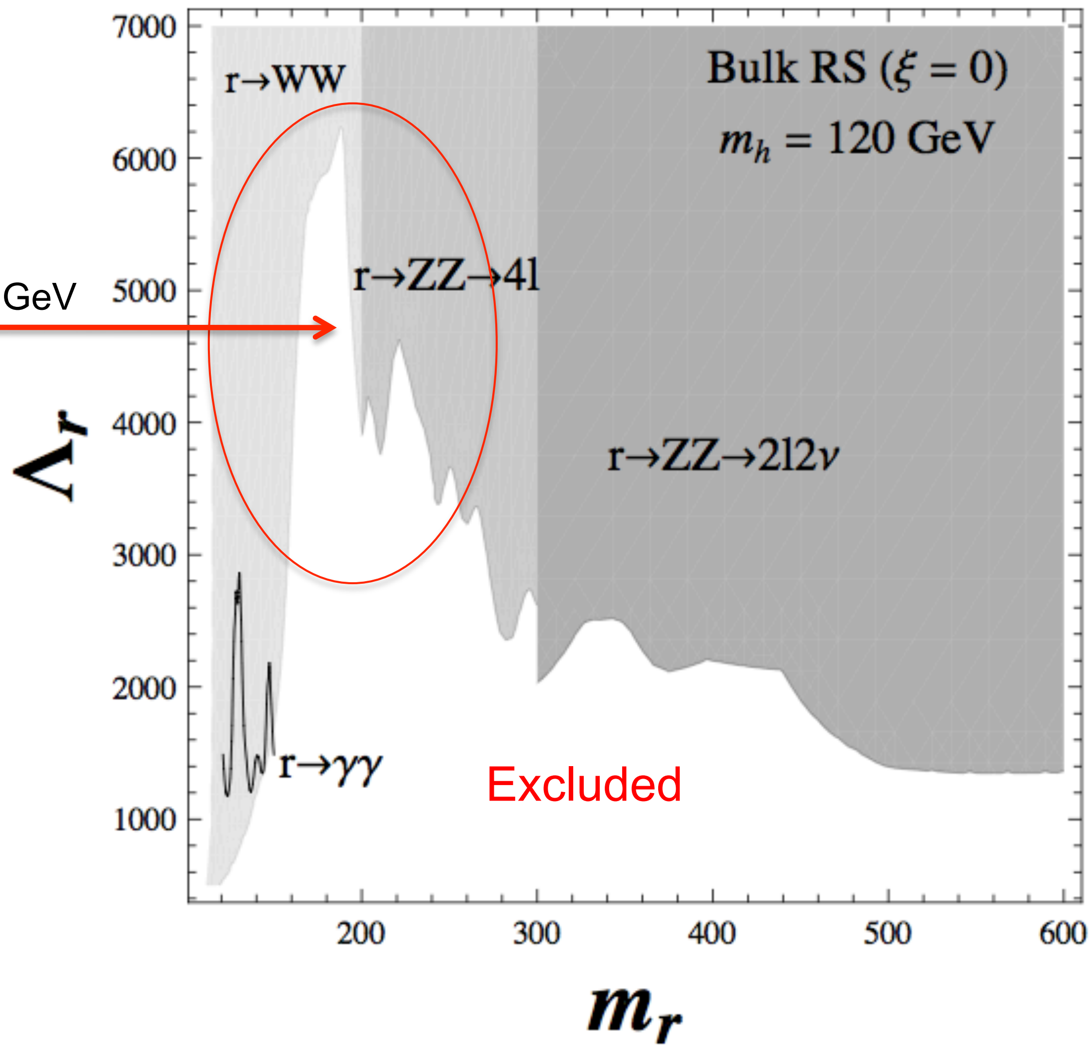
We used CMS data with “signal strength modifier”

$$\mu = \frac{\sigma(pp \stackrel{gg}{\to} r \to X)}{\sigma(pp \stackrel{gg}{\to} h \to X)_{SM}}$$

to constrain radion models using Higgs search data (before Moriond).

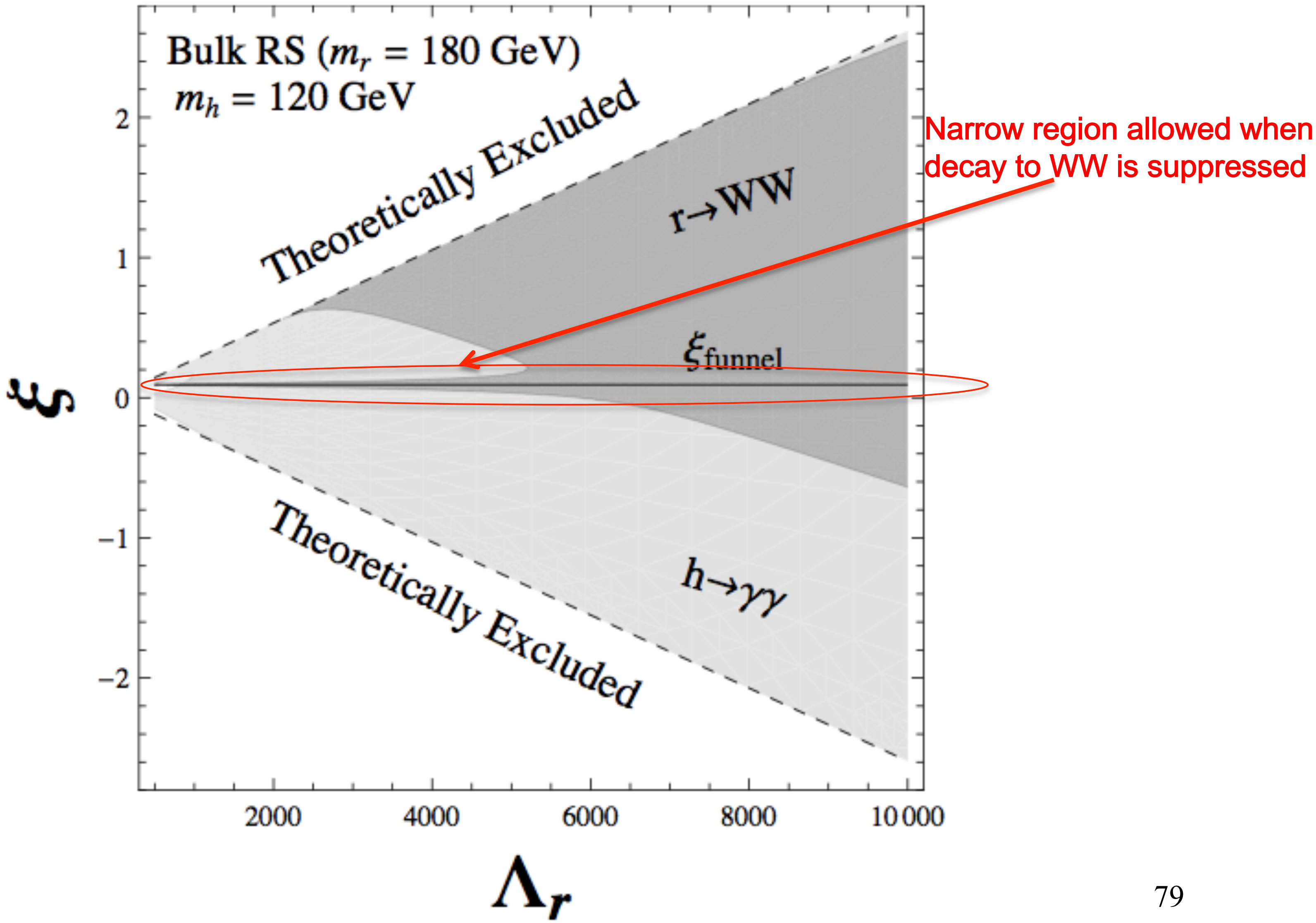
Exclusion plots

Large sensitivity at ~180 GeV



Mh< 131 GeV was allowed then

Effect of mixing: bounds are loosened



Only regions near the “funnel”are allowed – challenging!