Beyond the Standard Model

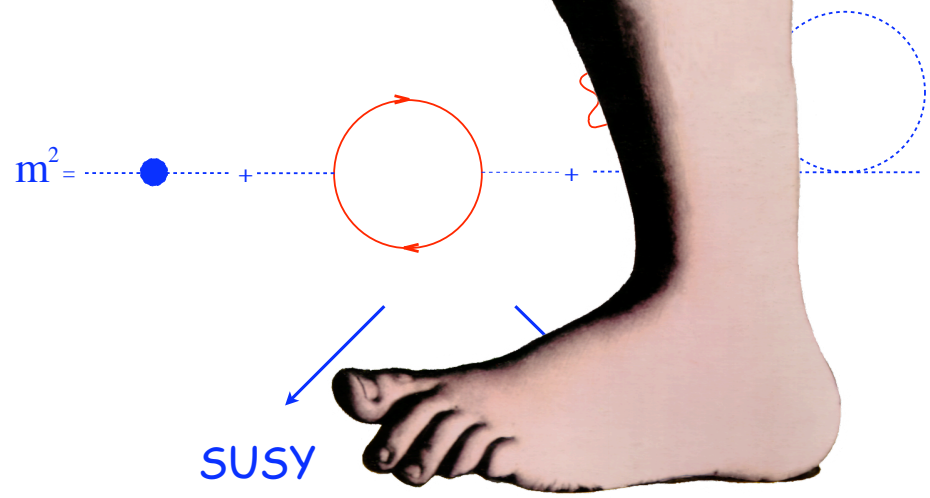
To Infinity and Beyond!

John Terning

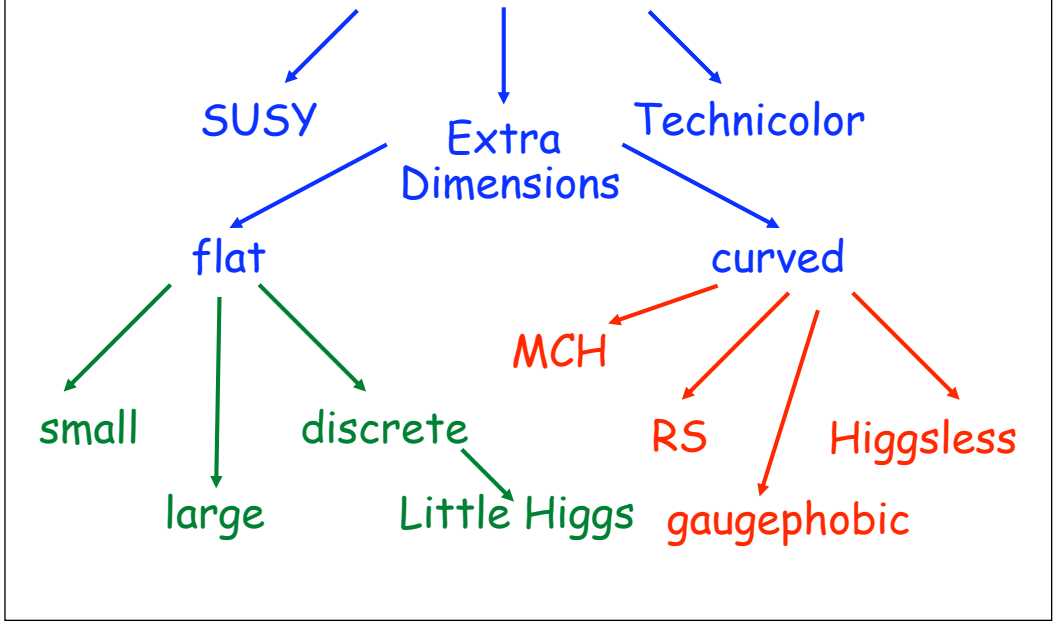
Outline

- Motivation: the Hierarchy Problem
- Good News/Bad News
- Lamppost Physics
- Conclusions

Electroweak etry



Hierarchy Problem Now



Models of TeV Scale Physics

SUSY: Higgs quartic too small, fine-tuned

RS: bad precision EW, FCNC

Realistic RS: little hierarchy problem

Higgsless: bad precision EW, fine-tuned

Composite pGB Higgs: VEV fine-tuned

Little Higgs: bad precision EW, fine-tuned

T-parity Little Higgs: very complex

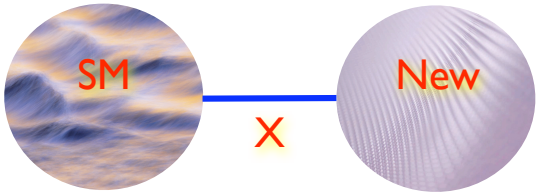
Don't have a complete model where everything just fits together

Csaki http://bit.ly/WcCAm

Looking Under the Lamppost

quirks/hidden valleys/unparticles

New Sector

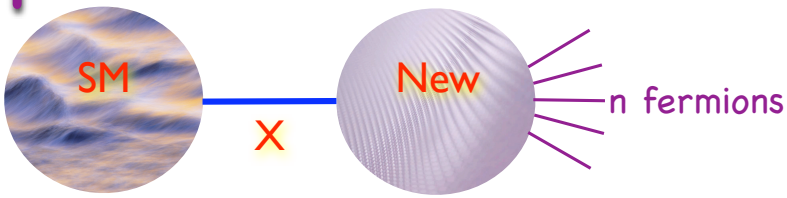


$M_X \gg \text{TeV}$ $\qquad \dfrac{\mathcal{O}_{SM}\mathcal{O}_{new}}{M_X^n}$

$M_X \sim \text{TeV}$ $\qquad gg \to X + \ldots$

$X \to Y_{new} + \ldots$

Quirk/Hidden Valley/ Unparticle Model

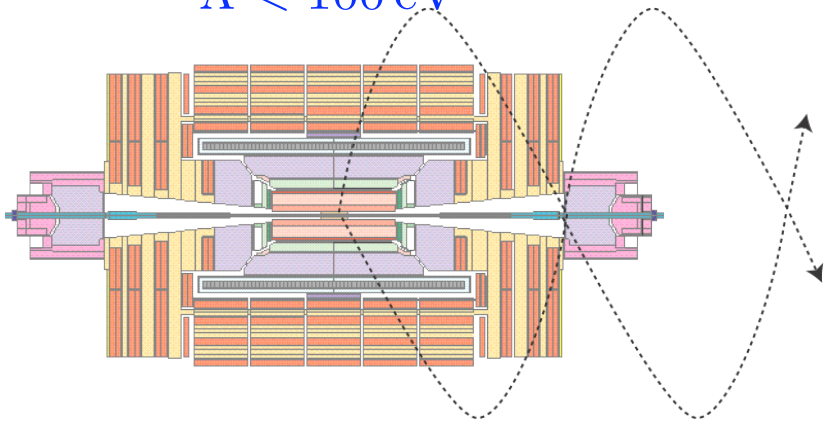


X is a heavy fermion with both SM and New gauge couplings

stringy confinement →	quirks	n=0
QCD-like confinement →	hidden valley	n=few
CFT, no confinement →	unparticles	n=many

Quirks

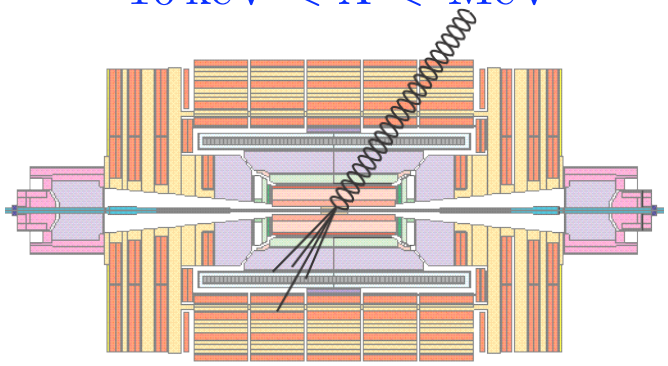
$\Lambda < 100\,\mathrm{eV}$



Luty, Kang hep-ph/0805.4642

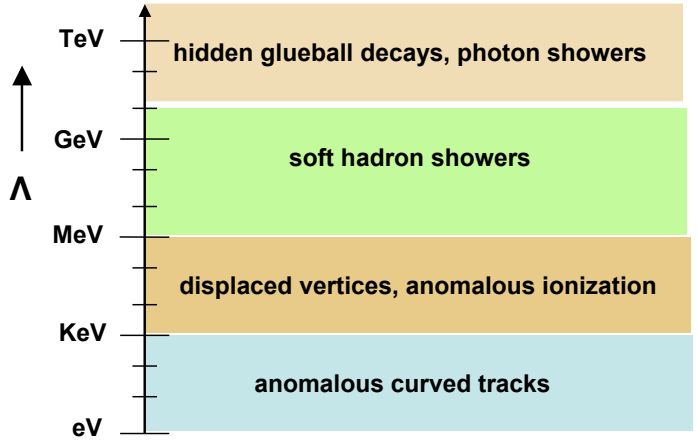
Quirks

$10\,\mathrm{keV} < \Lambda <$ MeV



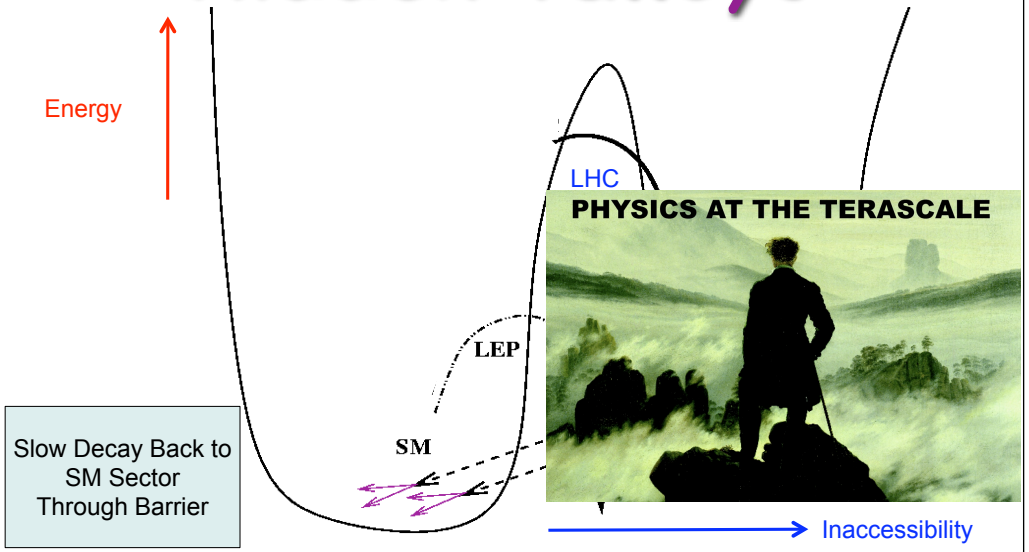
Luty, Kang hep-ph/0805.4642

Quirks



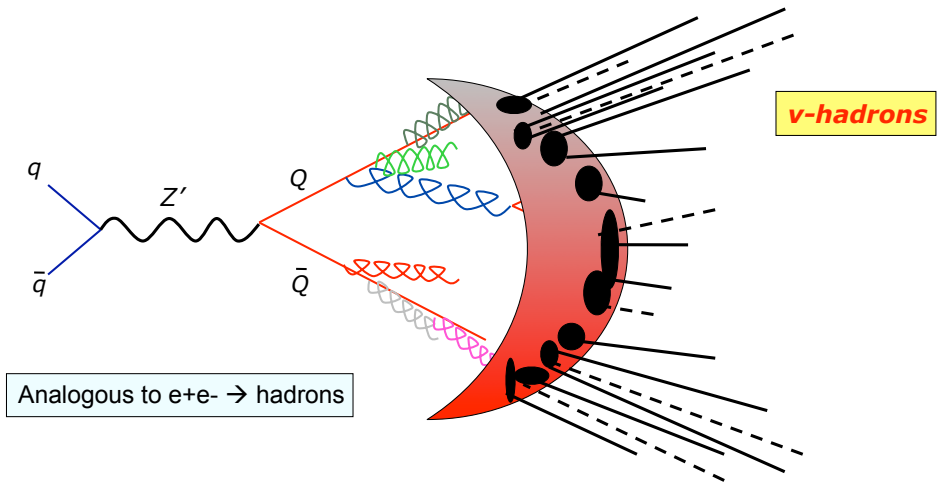
Chacko, Harnik hep-ph/0805.4667

Hidden Valleys



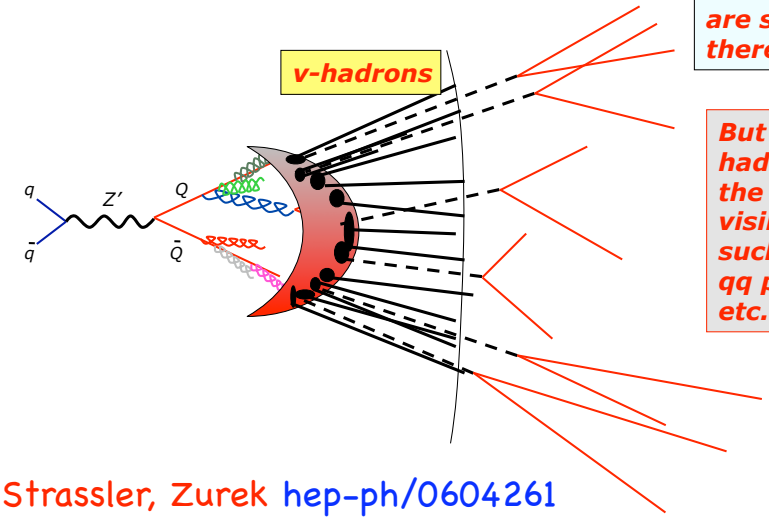
Strassler, Zurek hep-ph/0604261, 0605193

Hidden Valleys



Strassler, Zurek hep-ph/0604261

Hidden Valleys



Some v-hadrons are stable and therefore invisible

But some v-hadrons decay in the detector to visible particles, such as bb pairs, qq pairs, leptons etc.

Strassler, Zurek hep-ph/0604261

Hidden Valley Features

New neutral resonances

- Often boosted in production; jet substructure key observable

Long-lived resonances

- Often large missing energy
- Displaced vertices common (possibly 1 or 2, possibly >10 per event)

Multiparticle production

- 6-60 quark/lepton final states possible

Strassler, Zurek hep-ph/0604261

Unparticles

$$\Delta(p) \propto (-p^2 - i\epsilon)^{d-2}$$

$$d\Phi(p) \propto \frac{1}{\Gamma(d-1)} \theta(p^0)\theta(p^2)(p^2)^{d-2}$$

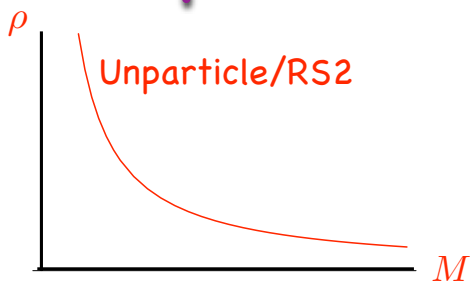
* must be equivalent to RS2

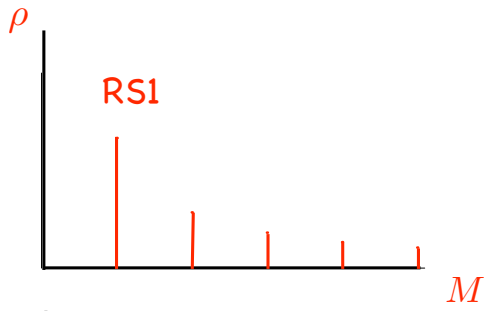
Georgi hep-ph/0703260, 0704.2457

Broken CFT's are Interesting

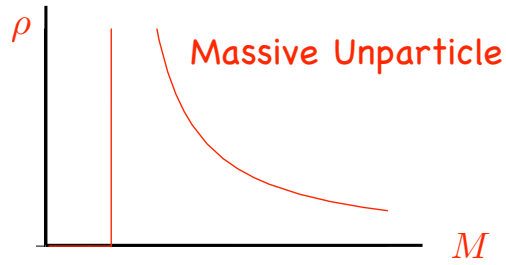
- IR cutoff at TeV turns RS2 to RS1
- address the hierarchy problem
- new phenomenology for LHC

Spectral Densities



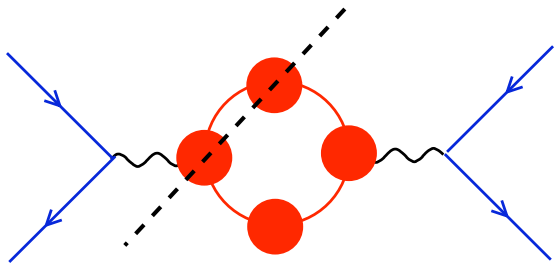


$$\Delta(p) \sim (\mu^2 - p^2 - i\epsilon)^{d-2}$$



Fox, Rajaraman, Shirman hep-ph/0705.3092

Colored Unproduction



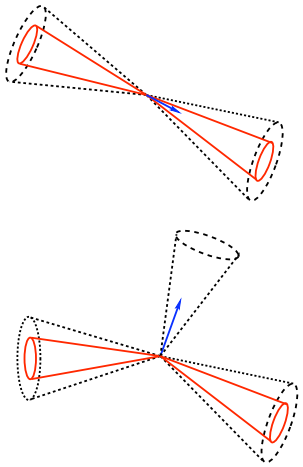
$$\sigma_{unparticle} = (2-d)\sigma_{particle} \qquad d < 2$$

R-Hadrons, anomalous jets/E loss

Cacciapaglia, Marandella, JT hep-ph/0708.0005

Anomalous Jets

2 jets + $\not{p}_T$



Pair production

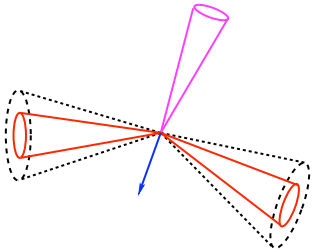
$\not{p}_T$ is aligned to visible p_T

CFT stuff radiation

$\not{p}_T$ not aligned

Anomalous Jets

QCD radiation



Hard jet + 2 jets + $\not{p}_T$

$\not{p}_T$ in opposite direction to the hard jet

Detailed calculation and simulation needed (background)

Unhiggs Model

$$S = -\int d^4x\, H^\dagger (\partial^2 + \mu^2)^{2-d} H$$

Unhiggs Model

$$S = -\int d^4x\, H^\dagger (D^2 + \mu^2)^{2-d} H + \lambda_t \bar{t}_R \frac{H}{\Lambda^{d-1}} \begin{pmatrix} t \\ b \end{pmatrix}_L + h.c.$$

Unhiggs Model

$$S = -\int d^4x\, H^\dagger (D^2+\mu^2)^{2-d} H + \lambda_t \bar{t}_R \frac{H}{\Lambda^{d-1}} \begin{pmatrix} t \\ b \end{pmatrix}_L + h.c.$$
$$-\int d^4x\, \lambda \left(\frac{H^\dagger H}{\Lambda^{2d-2}} - \frac{V^2}{2} \right)^2$$

$$H = \frac{1}{\sqrt{2}} e^{iT^a \pi^a / v^d} \begin{pmatrix} 0 \\ v^d + h \end{pmatrix}$$

Stancato JT, hep-ph/0807.3961

Mass Divergence

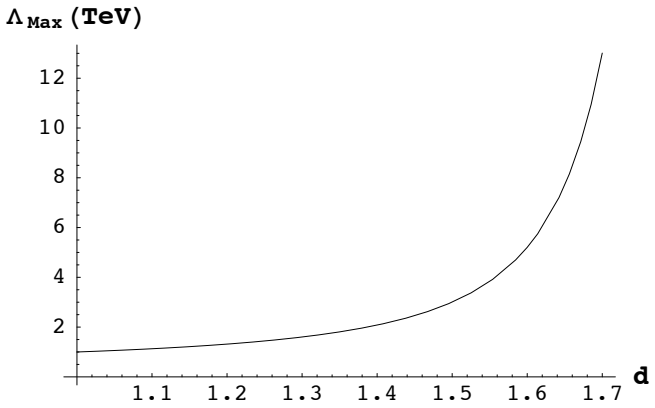
$$m_h^2 \sim \frac{\Lambda^{4-2d}}{16\pi^2}$$

$$\mathcal{L}_Y = \lambda_t \, \bar{t}_R \frac{H}{\Lambda^{d-1}} \begin{pmatrix} t \\ b \end{pmatrix}_L$$

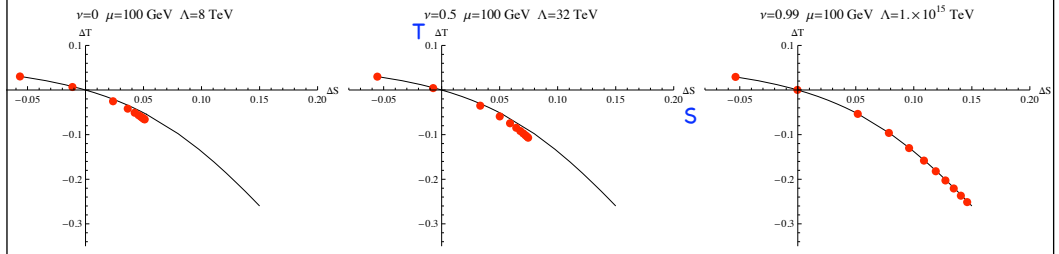
$$m_h^2 = 3 \left(\frac{\lambda_t}{\Lambda^{d-1}} \right)^2 \frac{\Lambda^2}{16\pi^2} = 3 \left(\frac{m_t}{V} \right)^2 \frac{\Lambda^{4-2d}}{16\pi^2}$$

Solve the little hierarchy problem?

loop < tree



Precision Measurements

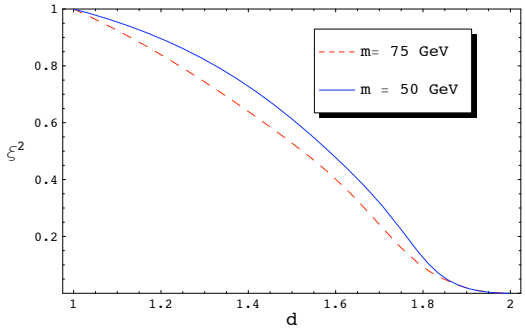


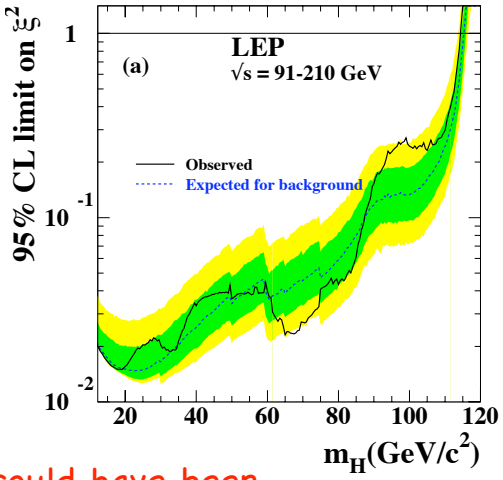
d=2 d=1.5 d=1.01

Falkowski & Perez-Victoria, hep-ph/0901.3777

Unhiggs at LEP

$$\xi^2 \equiv \frac{\sigma(e^+e^- \to HZ)}{\sigma_{SM}}$$





a light Unhiggs could have been missed at LEP

Unhiggs at LHC

generically a light Unhiggs would be missed
at the LHC using current search strategies

Conclusions

no compelling non-SUSY model

probably other ways to
address the hierarchy problem

luckily Nature is smarter
than us, and will soon tell
us the answer

if we are able to ask the right questions!