Light Scalar from Conformal Symmetry

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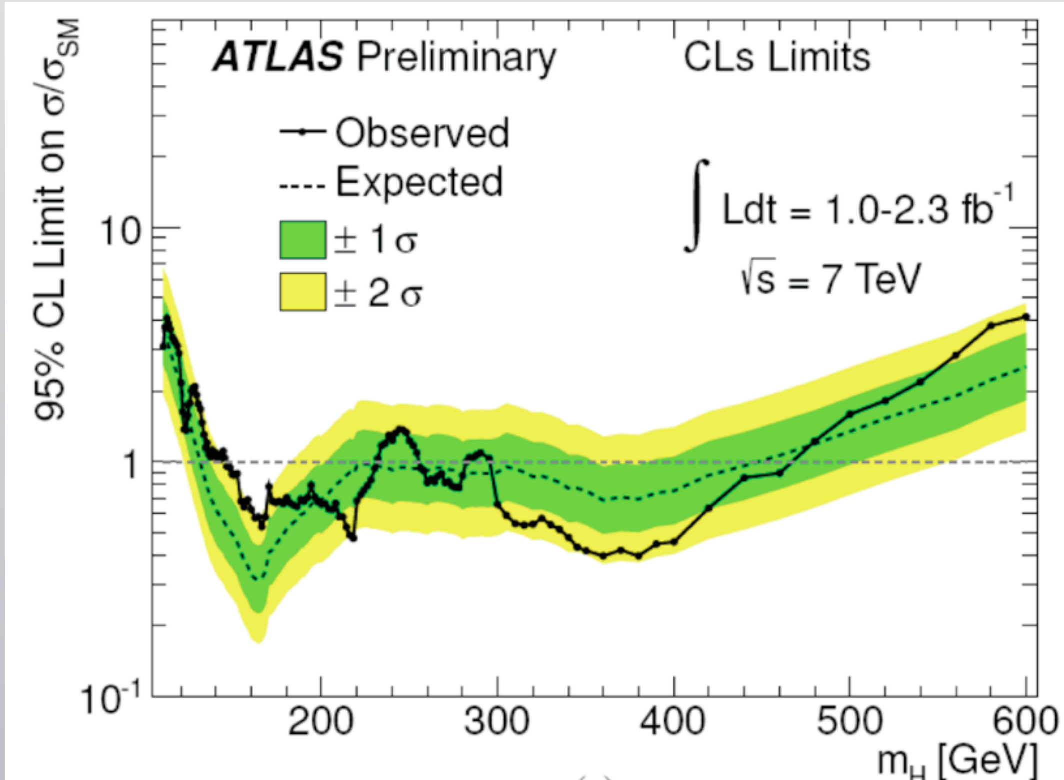
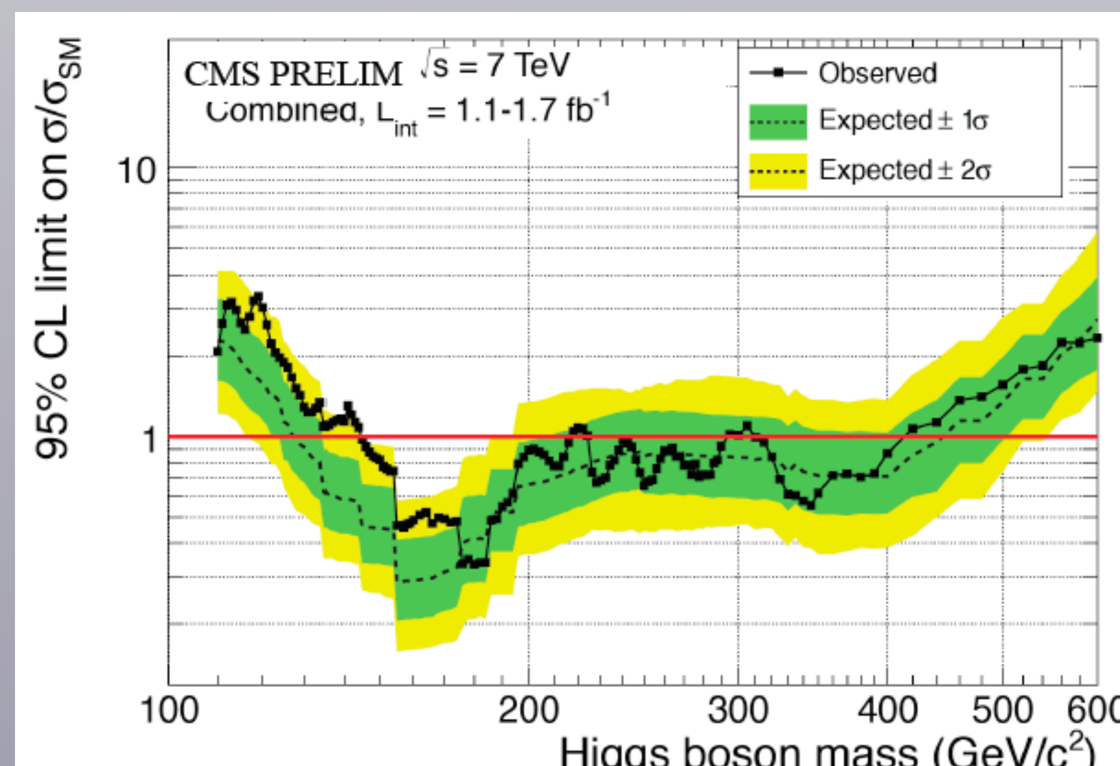
(with W. Goldberger and B. Grinstein,
and J. Fan, W. Goldberger, and A. Ross)



from ATLAS Higgs talk at Lepton-Photon 2011



from CMS Higgs talk at Lepton-Photon 2011

Outline

- Why is the dilaton so similar to the Higgs?
- Dilaton couplings:
  Higgs-like: fermions and W/Z
  Higgs-unlike: massless gauge bosons, self couplings
- Precision electroweak results
  and strongly-interacting theories
- Dilaton mass
- Models with similar signatures

Why is the dilaton so similar to the Higgs?

Because the dilaton couples to $T^{\mu}_{\mu} = \sum_i m_i \overline{\psi}\psi + \ldots$

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Because a light Higgs can be thought of as a dilaton

- SM couplings above the EWSB are dimensionless, except for the Higgs mass term, and the beta functions are small due to the perturbativity
- Higgs mass term - explicit breaking
- Higgs VEV - spontaneous breaking

In the limit of small Higgs mass, its couplings are given by "soft Higgs theorems"

$$\mathcal{L} = \frac{h}{v} T^{\mu}_{\mu} \qquad T^{\mu}_{\mu} = \sum_i m_i \overline{\psi}_i \psi_i + \ldots$$

Shifman, Vainstein, Voloshin, Zakharov '79-80

This result is a consequence of Ward identities for the scale current applied to the electroweak singlet dilaton

$$\chi(x) = \sqrt{H^\dagger H(x)}$$

In general, conformal invariance can be broken at a higher scale than the EW symmetry

$$\Lambda_{CFT} \sim 4\pi f$$

The breaking of conformal invariance triggers EWSB

$$\Lambda_{EW} \sim 4\pi v \leq \Lambda_{CFT}$$

The scales v and *f* are not the same, except for the Higgs

Dilaton couplings

Given the Lagrangian $\mathcal{L} = \sum_i g_i(\mu)\mathcal{O}_i(x)$,

the divergence of the scale current is:

$$\partial_\mu S^\mu = \sum_i g_i(\mu)(d_i - 4)\mathcal{O}_i(x) + \sum_i \beta_i(g)\frac{\partial}{\partial g_i}\mathcal{L}$$

Including the dilaton field, $\chi(x)$, makes the Lagrangian formally scale invariant

$$g_i(\mu) \to g_i\left(\mu\frac{\chi}{f}\right)\left(\frac{\chi}{f}\right)^{4-d_i}$$

The electroweak sector:

$$\mathcal{L}_{EW} = \mathcal{L}_{\chi EW} + \mathcal{L}_{\psi} + \mathcal{L}_{Y}$$

EW chiral Lagragian → $\mathcal{L}_{\chi EW}$

kinetic terms for fermions → $\mathcal{L}_{\psi}$

fermion masses → $\mathcal{L}_{Y}$

After replacing $\chi(x) \to f + \bar{\chi}(x)$

$$\mathcal{L} = \left(\frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2}\right)\left[m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right] + \frac{\bar{\chi}}{f}\sum_\psi m_\psi \bar{\psi}\psi$$

(The usual Higgs couplings rescaled by $\frac{v}{f}$. Note only partial restoration of unitarity if $f > v$.)

Violation of unitarity in the gauge boson scattering is partially restored by the dilaton couplings to the massive gauge bosons

Even with a light dilaton the scattering amplitude grows proportionally to

$$E^2\left(1-\frac{v^2}{f^2}\right)$$

However, other states, for example vector resonances, can contribute to the scattering amplitudes and further delay the onset of strong coupling. (See Higgsless)

Dilaton cubic self coupling

Suppose CS is explicitly broken: $\mathcal{L}_{CFT} + \lambda_{\mathcal{O}} \mathcal{O}(x)$

Usual spurion analysis gives

$$V(\chi) = \chi^4 \sum_{n=0}^{\infty} c_n(\Delta_{\mathcal{O}}) \left(\frac{\chi}{f} \right)^{n(\Delta_{\mathcal{O}} - 4)}$$

$dim(\mathcal{O})$

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$$V(\bar{\chi}) = \frac{1}{2} m^2 \bar{\chi}^2 + \frac{\lambda}{3!} \frac{m^2}{f} \bar{\chi}^3 + \cdots$$

$$\lambda = \begin{cases} (\Delta_{\mathcal{O}} + 1) + \mathcal{O}(\lambda_{\mathcal{O}}) & \text{case (a)} \\ 5 + \mathcal{O}(|\Delta_{\mathcal{O}} - 4|) & \text{case (b)} \end{cases}$$

$$\lambda = \begin{cases} (\Delta_{\mathcal{O}} + 1) + \mathcal{O}(\lambda_{\mathcal{O}}) & \text{when } \lambda_{\mathcal{O}} \ll 1 \\ 5 + \mathcal{O}\left(|\Delta_{\mathcal{O}} - 4|\right) & \text{when } |\Delta_{\mathcal{O}} - 4| \ll 1 \end{cases}$$

The Higgs case, $\Delta_{\mathcal{O}} = 2$, checks out $\lambda = 3$

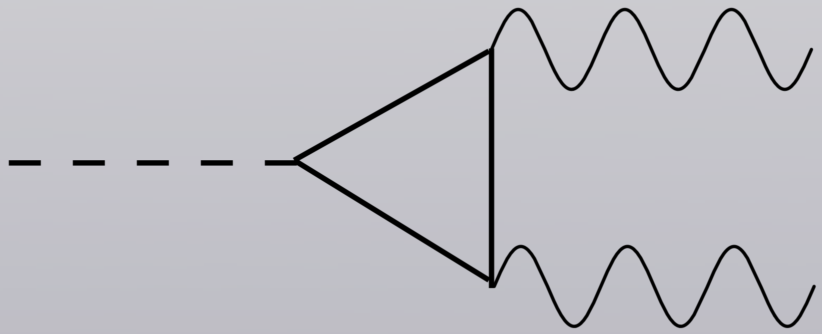
Irrelevant perturbations should not break conformal symmetry which implies an upper bound on the cubic

$$\lambda \leq 5$$

saturated for nearly marginal operators

Couplings to massless gauge bosons

At zero momentum the Higgs/dilaton couplings are related to the conformal anomaly



$$\mathcal{L}_{hGG} = \frac{\alpha_s}{8\pi} \sum_{\text{heavy}} b_0^i \frac{h}{v} (G^a_{\mu\nu})^2$$

The magnitudes of the couplings to the gluons/photons are obviously crucial for the production/detection. A possible deviation from the SM values would not provide a clean dilaton signature since the Higgs couplings can be altered by heavy particles as well.

Couplings to massless gauge bosons

Even in the Standard Model, the Higgs coupling can differ from the classic result

$$\mathcal{L}_{hgg} = \frac{\alpha_s}{16\pi} \sum_{i=\text{heavy}} b_0^i \ln\left(\frac{H^\dagger H}{v^2}\right) (G^a_{\mu\nu})^2$$

Heavy particles with vector-like masses generate other higher-dimensional operators, for example

$$\mathcal{L}_{\rm h-dim} = \frac{\alpha_s}{4\pi}\frac{c}{\Lambda^2} H^\dagger H (G^a_{\mu\nu})^2$$

which can compete with the SM result.

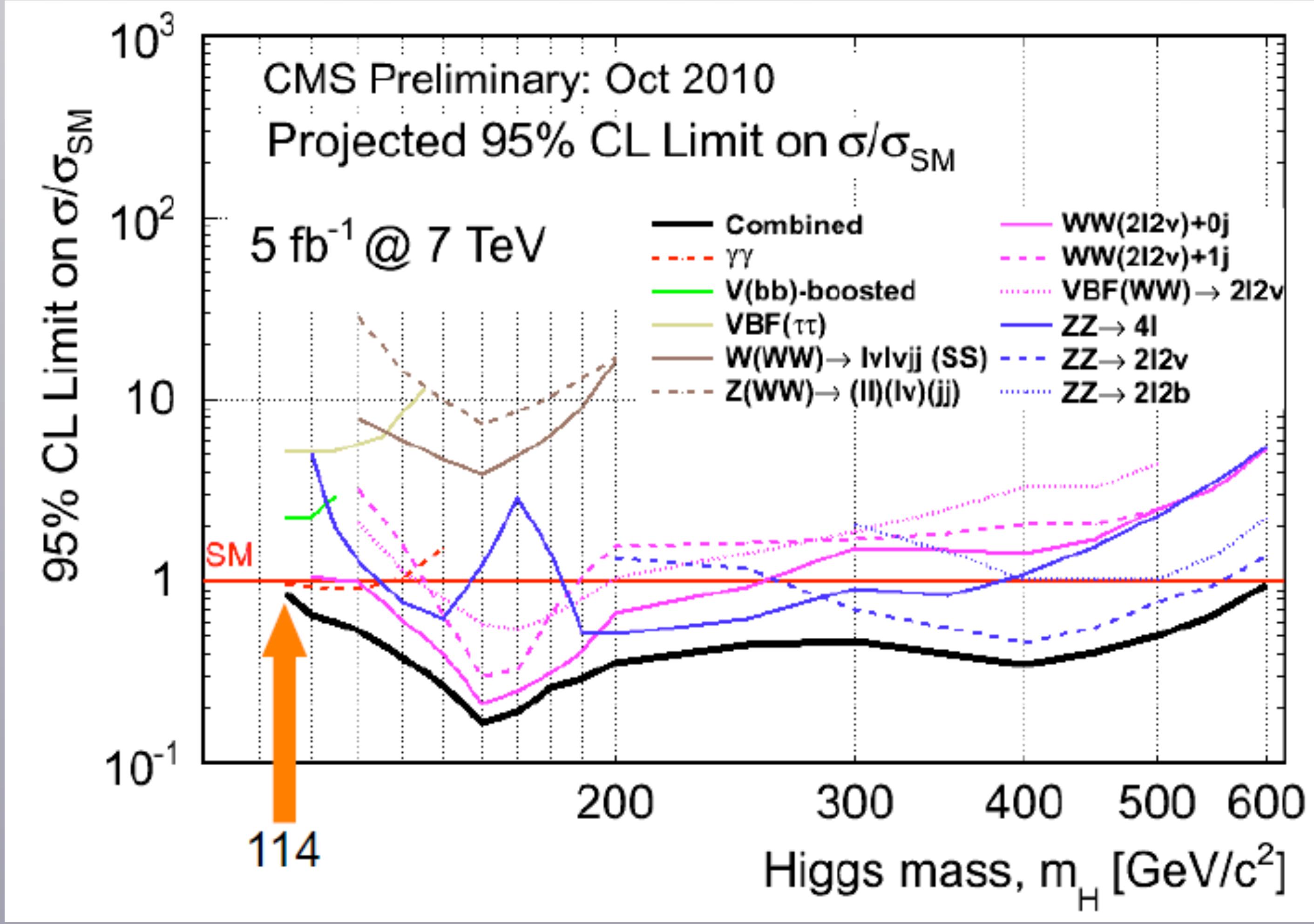
The dilaton at colliders

Branching ratios to fermions and WW, ZZ same as Higgs

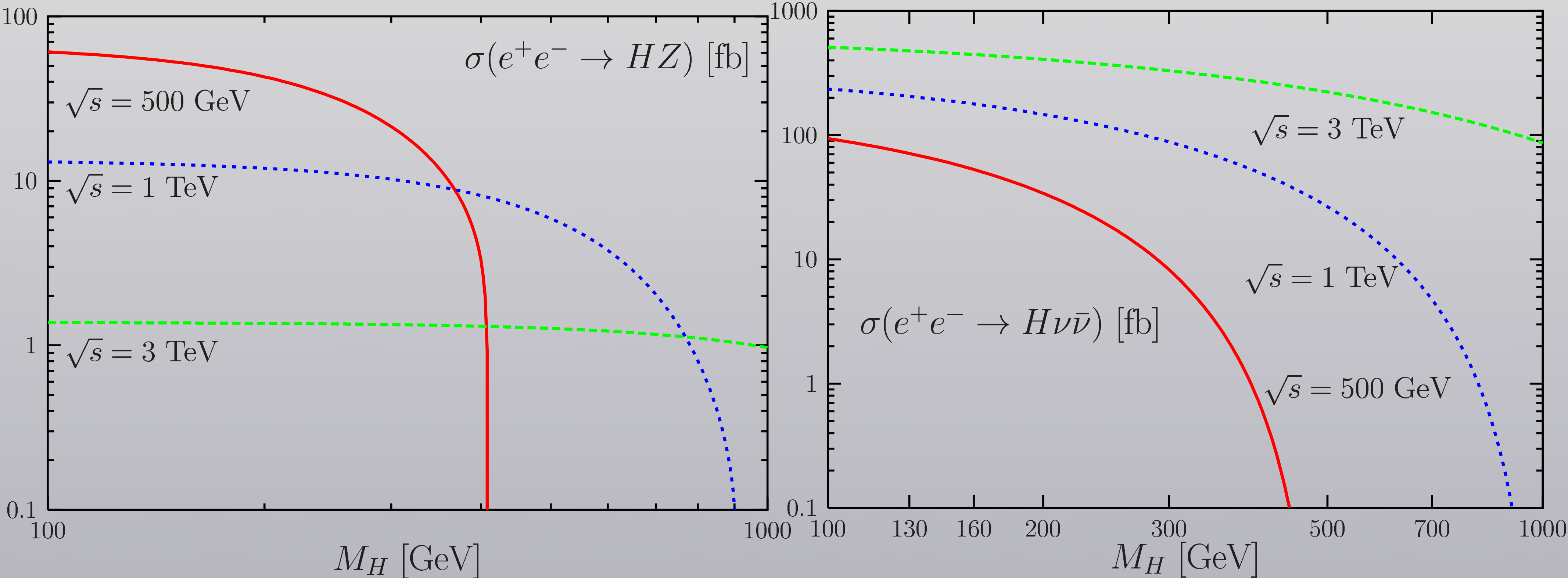
The crucial parameters are *f* and *m*

complete Lagrangian also has three couplings: $\lambda,\ c_G,\ c_{EM}$

CMS projection:



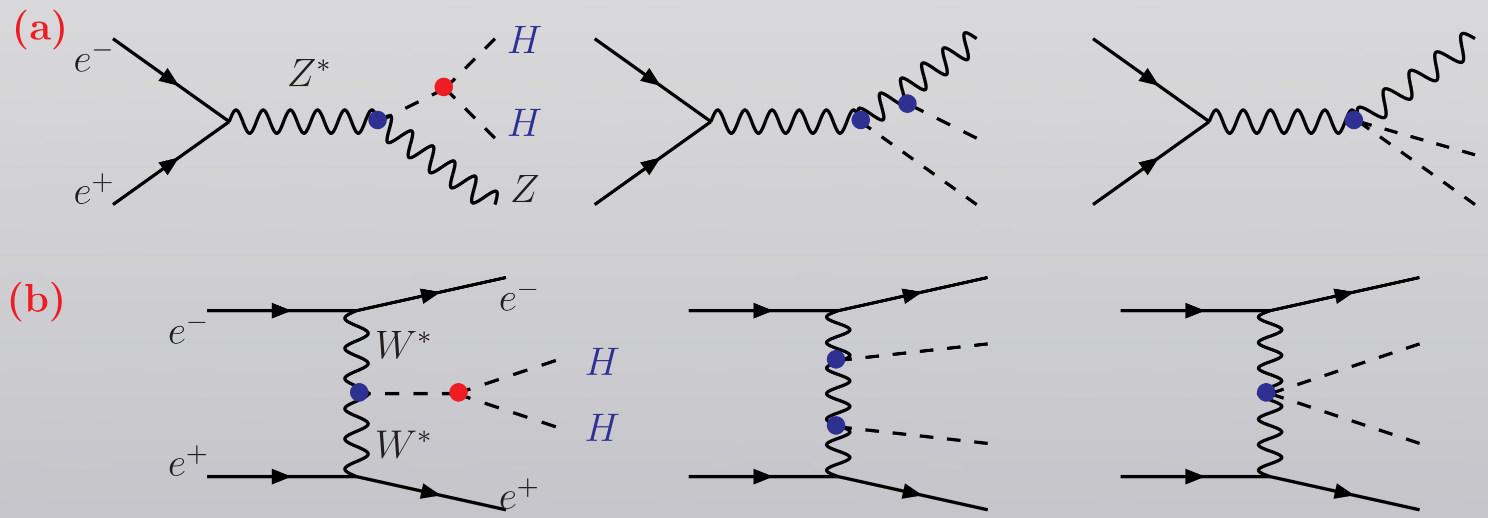
ILC Higgs production

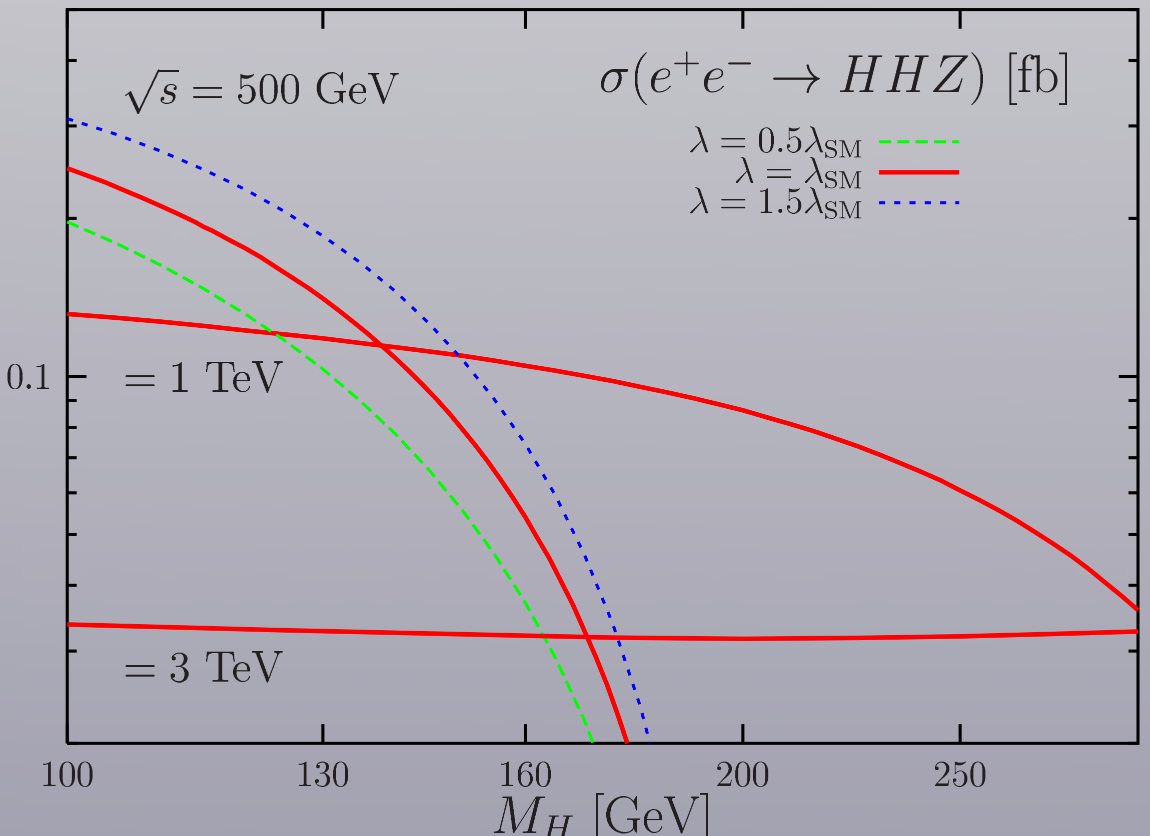


(For the dilaton rescale by v^2/f^2)

A. Djouadi
hep-ph/0503172

ILC 2 Higgs production





relative accuracy (500@500)

Quantity	$M_H = 120$ GeV	$M_H = 140$ GeV
ΔM_H	$\pm$ 0.00033	$\pm$ 0.0005
Γ_H	$\pm$ 0.061	$\pm$ 0.045
ΔCP	$\pm$ 0.038	–
λ_{HHH}	$\pm$ 0.22	$\pm$ 0.30
g_{HWW}	$\pm$ 0.012	$\pm$ 0.020
g_{HZZ}	$\pm$ 0.012	$\pm$ 0.013
g_{Htt}	$\pm$ 0.030	$\pm$ 0.061
g_{Hbb}	$\pm$ 0.022	$\pm$ 0.022
g_{Hcc}	$\pm$ 0.037	$\pm$ 0.102
$g_{H\tau\tau}$	$\pm$ 0.033	$\pm$ 0.048

Strongly-interacting theories and precision electroweak results

Conformal theories at the TeV scale

Classic example: walking technicolor
(it is not known if the dilaton is light in such theories)

Things changed with AdS/CFT and RS model,
where there are plenty of examples of CFT's
that are spontaneously broken

The usual problem with technicolor is the S parameter, which in QCD-like theories tends to be too large:

$$S \approx \frac{N_{TF} N_{TC}}{12\pi}$$

There is no reason to expect this estimate to hold in theories with dynamics that does not resemble QCD. Arguments based on parity-doubling suggest smaller values of S are possible

$$\begin{aligned} S &= 2\pi N_{TF} [\Pi'_{VV}(0) - \Pi'_{AA}(0)] \\ &= \frac{N_T F}{6\pi} \int_0^\infty \frac{ds}{s} [R_V(s) - R_A(s)] \end{aligned}$$

Recent results from the Lattice Strong Dynamics collaboration indicate slower scaling than

$$S \propto N_{TF}$$

in theories near the critical number of flavors

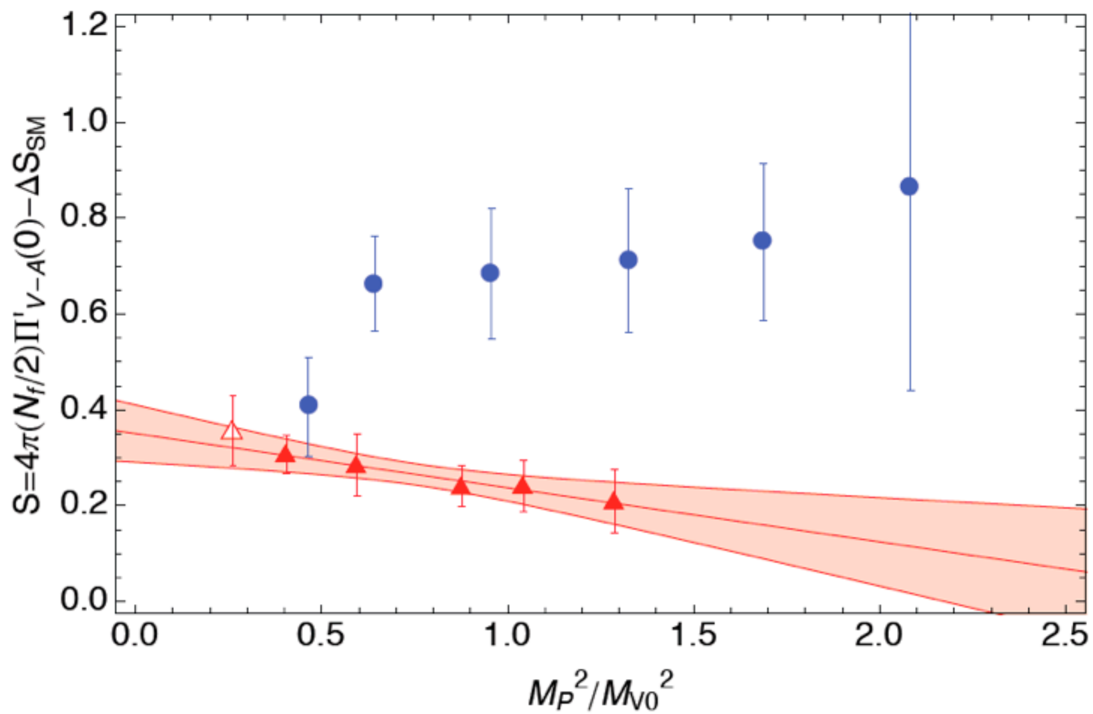


FIG. 3: S parameter for $N_f = 2$ (red diamonds) and $N_f = 6$ (blue circles). For each of the solid points, $M_P L > 4$.

LSD collab, PRL 106 (2011) 231601

Dilaton mass

We don’t have tools to compute the dilaton mass in strongly interacting theories. For years, people have argued both for and against a light dilaton in walking technicolor theories.

It is clear based on the RS setup that a light dilaton can exist, but may require some fine tuning of parameters. It is an open question.

Some recent work:

Appelquist, Bai (**Phys.Rev. D82, 2010, 071701**): a proposal for computing dilaton mass on the lattice

Grinstein, Uttayarat (1105.2370): a perturbative model with scalars near the Banks-Zaks fixed point.

Models with similar signatures

Many recent proposals with scalars with Higgs-like decays and branching ratios, for example

Electroweak singlet scalar mixing with the Higgs
Fox, Tucker-Smith, Weiner, 1104.5450 "Higgs counterfeits"
Low, Lykken, Shaughnessy, 1105.4587 "Higgs imposters"

Models with more complicated Higgs sectors.

Conclusions

- Light dilaton could be present in theories in which EWSB is triggered by a nearly conformal sector
- Dominant features are governed by few parameters
- One can make different assumptions about the UV physics and introduce model-dependent variations
- LHC can discover the dilaton, but unlikely to test its properties in any meaningful detail
- ILC is the best place to distinguish Higgs/dilaton scenarios

The end.