Higgs-Dilaton Equivalence and Naturalness

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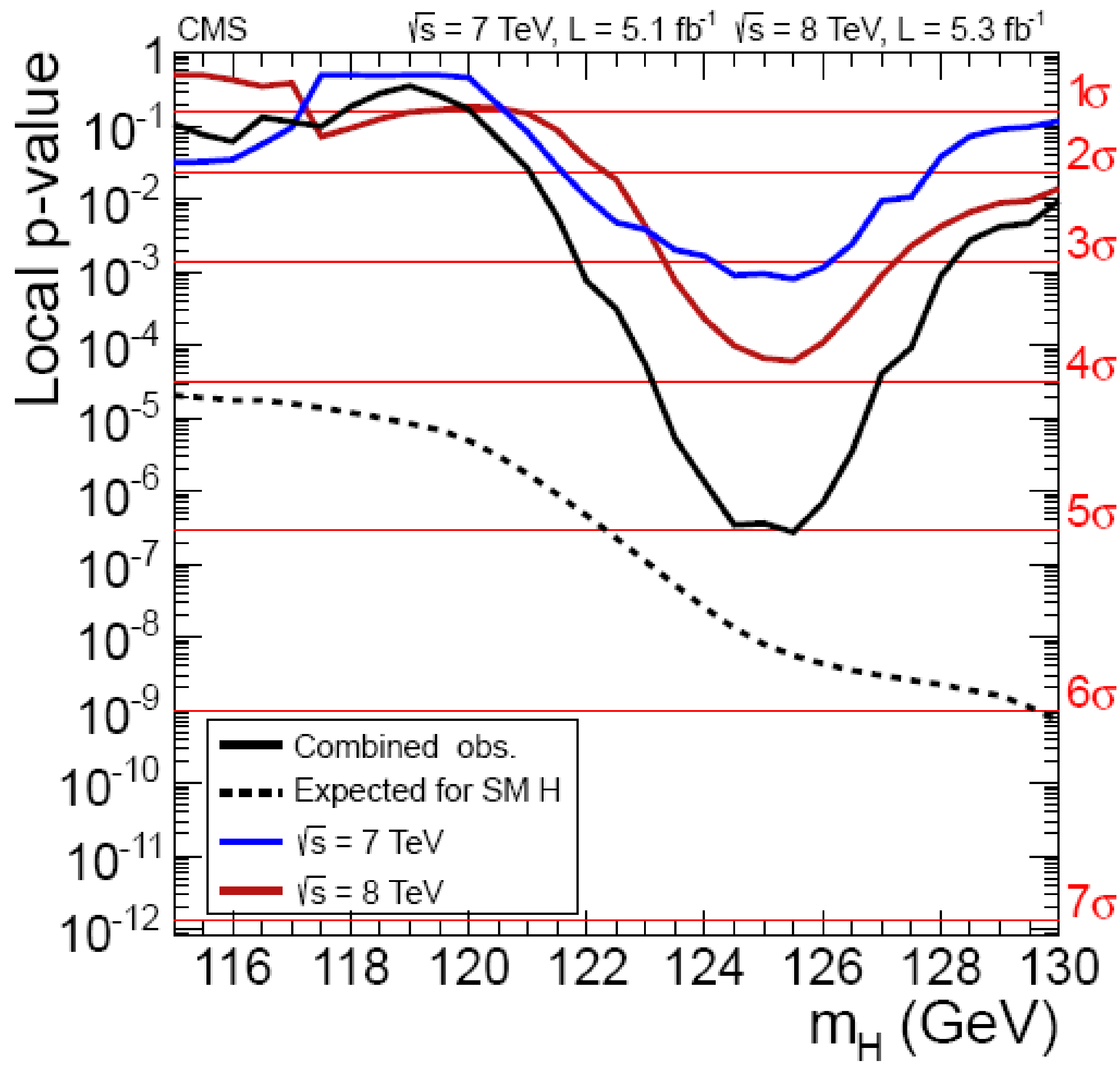
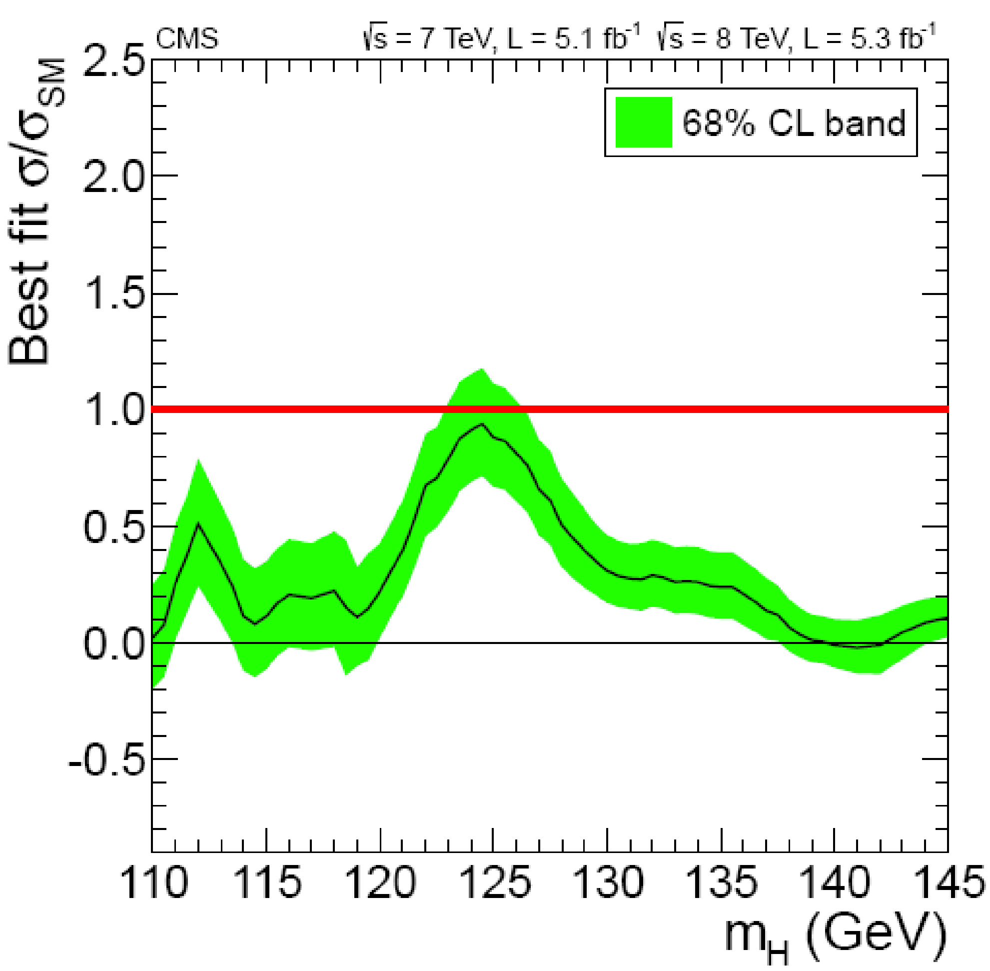
Higgs Signal

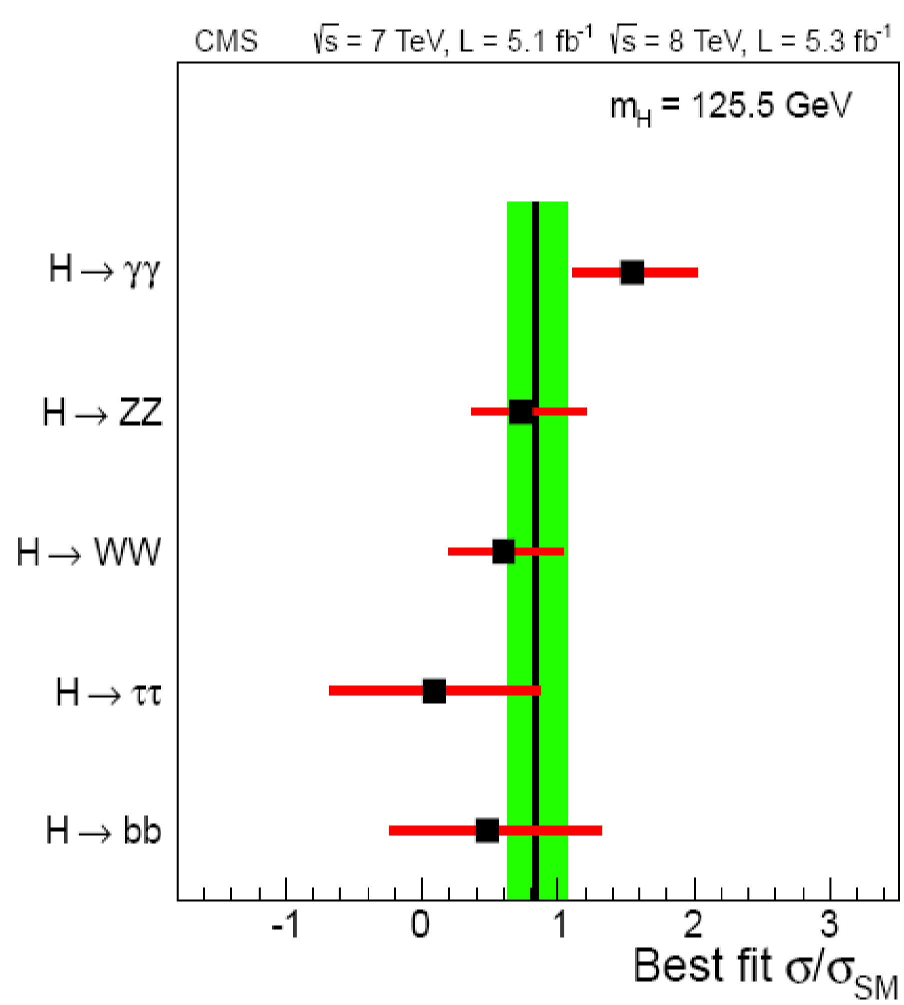
CMS Collab.
arXiv: 1207.1225 [hep-ex]



It is probably the SM Higgs ...



But ...



New Physics Search

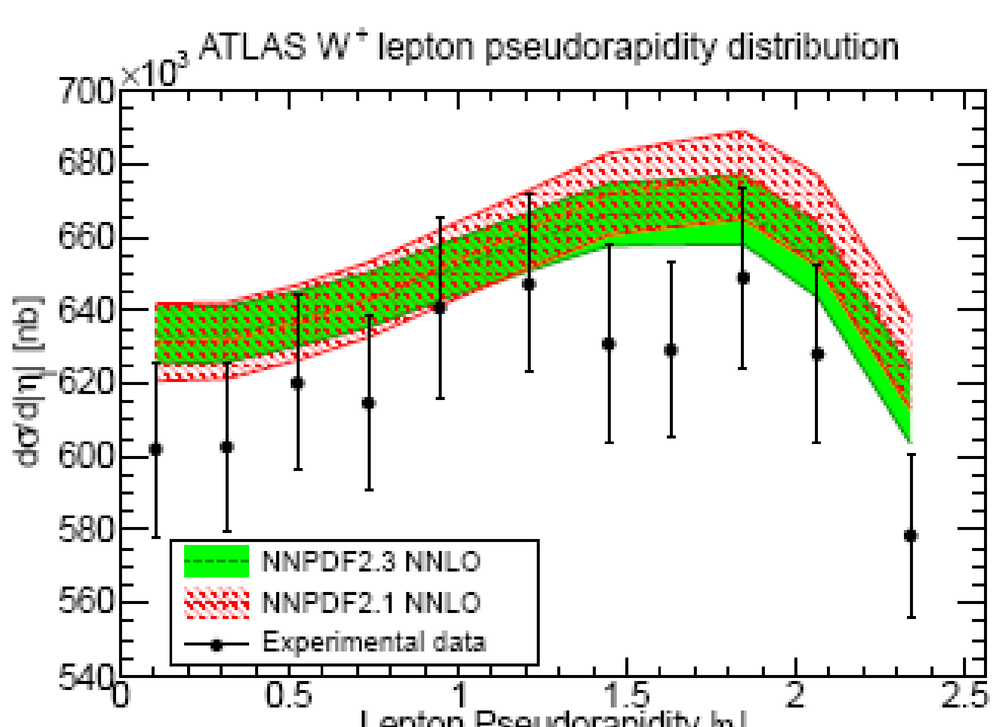
- LHC has discovered a particle whose spin = 0 (or maybe 2). Its branchings are similar to those of the SM Higgs boson.

- For the time being, the data hint in no significant deviation from the SM. Up to TeV and slightly above, no extra particle has surfaced yet.

- 2012 LHC 8-TeV data, reaching some 20/fb, can discover new particles. Several particles can hide in the data.

- Higgs couplings are crucial for naturalness (coupling to top quark) and unitarity (coupling to W boson)

- Parton Distribution Functions can cause discovery/miscovery.



Higgs Field

The SM has a single Higgs field Φ:

$$H = \frac{1}{\sqrt{2}} \mathbf{U}\left(\vec{\varphi}\right) \begin{pmatrix} 0 \\ \Phi \end{pmatrix}$$

$\mathbf{U}\left(\vec{\varphi}\right) \in SU(2)$

a real scalar field

$$\Phi(x) = v + h(x)$$

value of Φ in the ground state

Higgs boson field

Higgs Potential

The potential energy density

$$V(\Phi) = \frac{1}{2} m_H^2 \Phi^2 + \frac{1}{4} \lambda_H \Phi^4 + V_0$$

is minimized at

$m_H^2 > 0$

$\Phi = 0$

electroweak symmetry exact

massive Higgs boson

massless particles

$m_H^2 < 0$

$$\Phi^2 = \frac{-m_H^2}{\lambda_H}$$

electroweak symmetry broken

massive Higgs boson
massive particles

change in vacuum energy

Effective Action

Minimum energy configuration (vacuum state) can still be determined geometrically (by minimization) if quantum effects are incorporated into the potential energy as a correction term.

Generic Higgs interaction: $\frac{1}{2}\lambda_V \Phi^2 g^{\alpha\beta} V_\alpha V_\beta + \frac{1}{\sqrt{2}}\lambda_\Psi \Phi \overline{\Psi}\Psi$

Fast component $\in [\Lambda_{\mathtt{EW}}, \Lambda_{\mathtt{UV}}]$ in frequency.

$$\Phi = \phi + \delta\phi$$
$$V_\mu = \upsilon_\mu + \delta\upsilon_\mu$$
$$\Psi = \psi + \delta\psi$$

Slow component $\in [0, \Lambda_{\mathtt{EW}}]$ in frequency.

$$\begin{aligned} Z &= \int \mathfrak{D}\Phi\, \mathfrak{D}\overline{\Psi}\, \mathfrak{D}\Psi\, \mathfrak{D}V_\mu e^{iS_{SM}[\Phi,\Psi,V]} \\ &= \int \mathfrak{D}\phi\, \mathfrak{D}\overline{\psi}\, \mathfrak{D}\psi \mathfrak{D}\upsilon_\mu e^{iS_{SM}[\phi,\psi,\upsilon]} \\ &\times\ \mathfrak{D}\left(\delta\phi\right) \mathfrak{D}(\overline{\delta\psi}) \mathfrak{D}(\delta\psi) \mathfrak{D}\left(\delta\upsilon_\mu\right) e^{i\Delta S[\delta\phi,\delta\psi,\delta\upsilon]} \\ &= \int \mathfrak{D}\phi\, \mathfrak{D}\overline{\psi}\, \mathfrak{D}\psi\, \mathfrak{D}\upsilon_\mu e^{iS_{eff}[\phi,\psi,\upsilon;\Lambda_{\mathtt{EW}},\Lambda_{\mathtt{UV}}]} \end{aligned}$$

Effective potential $V_{eff}(\phi)$

Effective Potential

Effective potential: $V_{eff}(\phi) = \frac{1}{2}\overline{m_H^2}\phi^2 + \frac{1}{4}\overline{\lambda_H}\phi^4 + \overline{V_0}$

$$\overline{\lambda_H} = \lambda_H + \frac{1}{(4\pi)^2}\left(9\lambda_H^2 + 3\lambda_V^2 - \lambda_\Psi^4\right)\log\frac{\Lambda_{\mathtt{EW}}^2}{\Lambda_{\mathtt{UV}}^2}$$

logarithmic: $\overline{\lambda_H}$ under control

$$\overline{m_H^2} = m_H^2 + \frac{1}{(4\pi)^2}\left[\left(3\lambda_H + 3\lambda_V - 2\lambda_\Psi^2\right)\Lambda_{\mathtt{UV}}^2 + 3\lambda_H m_H^2 \log\frac{\Lambda_{\mathtt{EW}}^2}{\Lambda_{\mathtt{UV}}^2}\right]$$

gauge-gravity hierarchy problem

quadratic: $\overline{m_H^2} \propto \Lambda_{\mathtt{UV}}^2$ at large $\Lambda_{\mathtt{UV}}$

$$\overline{V_0} = V_0 + \frac{1}{(4\pi)^2}\left[\frac{1}{4}(n_F - n_B)\Lambda_{\mathtt{UV}}^4 + \frac{1}{2}m_H^2\Lambda_{\mathtt{UV}}^2 + \frac{1}{4}(m_H^2)^2\log\frac{\Lambda_{\mathtt{EW}}^2}{\Lambda_{\mathtt{UV}}^2}\right]$$

cosmological constant problem

quartic: $\overline{V_0} \propto \Lambda_{\mathtt{UV}}^4$ at large $\Lambda_{\mathtt{UV}}$

New Physics -SUSY

Achieving Higgs mass naturalness by Fermi-Bose symmetry.

$\Lambda_{\mathtt{UV}} \lesssim M_{Pl}$

softly-broken SUSY above $\Lambda_{\mathtt{EW}}$

$\Lambda_{\mathtt{EW}} \gtrsim m_H$ $\qquad$ $\Lambda_{\mathtt{EW}} \simeq m_{soft}$

Typical Higgs interaction: $\frac{1}{\sqrt{2}}\lambda_\Psi \Phi \overline{\Psi} \Psi + \left(m_{soft}^2 + \frac{1}{2}\lambda_\Psi^2 \Phi^2\right) \tilde{\Psi}^\dagger \tilde{\Psi}$

$$\overline{m_H^2} = m_H^2 + \frac{1}{(4\pi)^2}\, \lambda_\Psi^2 m_{soft}^2 \log \frac{\Lambda_{\mathtt{EW}}^2}{\Lambda_{\mathtt{UV}}^2}$$

no quadratic divergence !

$$\overline{V_0} = V_0 + \frac{1}{(4\pi)^2} \left[\frac{1}{2} m_{soft}^2 \Lambda_{\mathtt{UV}}^2 + \frac{1}{4} m_{soft}^4 \log \frac{\Lambda_{\mathtt{EW}}^2}{\Lambda_{\mathtt{UV}}^2}\right]$$

no quartic divergence !

Main Experimental Signature: Observation of massive partners of the SM particles: (top, stop), (gluon, gluino), (W boson, wino), ...

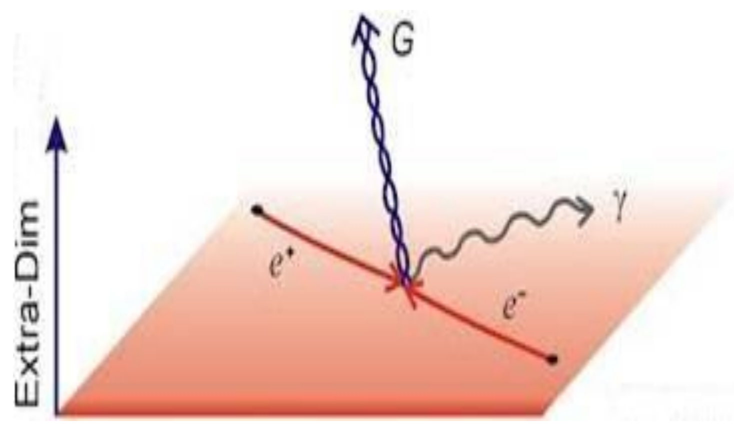
New Physics –Extra Dims.

Achieving Higgs mass naturalness by a 3-brane embedded in a D-dimensional spacetime.

D-dimensional spacetime above $\Lambda_{\mathtt{EW}}$

$\Lambda_{\mathtt{UV}} \simeq \Lambda_{\mathtt{EW}}$ $\qquad$ $\Lambda_{UV} \equiv (2\pi R M_{Pl})^{-\frac{D-4}{D-2}} M_{Pl}$

There are $D-4$ extra dimensions of size R.



$$\overline{m_H^2} \simeq m_H^2 + \frac{1}{(4\pi)^2}\left[\left(3\lambda_H + 3\lambda_V - 2\lambda_\Psi^2\right)\Lambda_{\mathtt{EW}}^2\right]$$

small wrt m_H^2

$$\overline{V_0} \simeq V_0 + \frac{1}{(4\pi)^2}\left[\frac{1}{4}(n_F - n_B)\Lambda_{\mathtt{EW}}^4 + \frac{1}{2}m_H^2\Lambda_{\mathtt{EW}}^2\right]$$

small wrt $V_0 \sim \Lambda_{\mathtt{EW}}^4$

Main Experimental Signature: Observation of monojet events, anomalous SM rates. (individual KK levels hard to observe)

New Physics – DHE

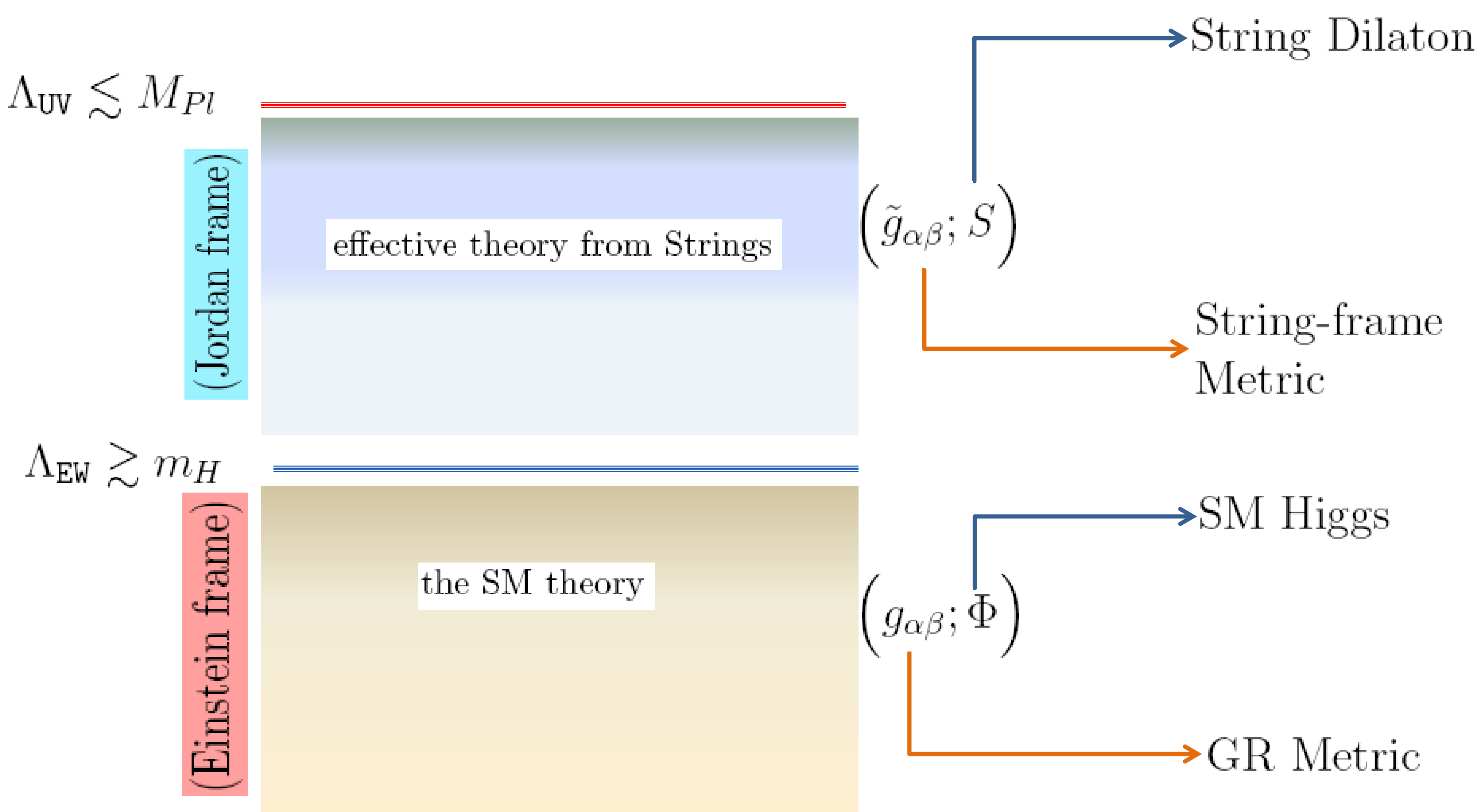
- Effective theories from strings involve Dilaton.

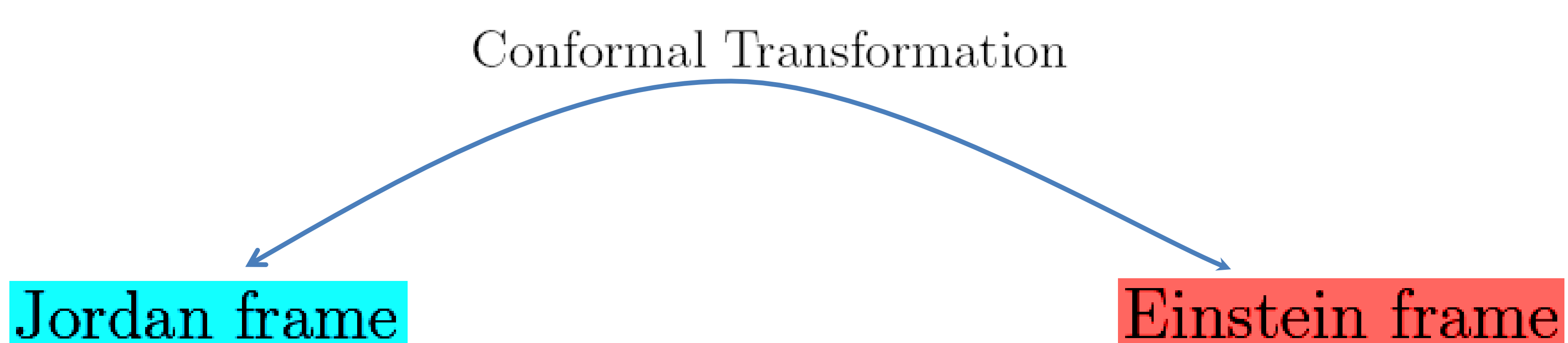
- SM involves Higgs field.

- Can the Dilaton and Higgs fields be put in relation?

    - What are the consequences for Higgs mass naturalness?

DHE: Statement





$$\tilde{g}_{\alpha\beta}(x) = \Omega^2(x)\, g_{\alpha\beta}(x)$$

The quadratic divergence of the Higgs boson mass can be fully controlled if the Dilaton is to match the SM Higgs field via conformal rescalings.

DHE: Top-Down

Effective field theory from strings may be written as:

$$S_{st}\left[\tilde{g}, S\right] = \int d^4x \, \sqrt{-\tilde{g}} \left\{ \frac{1}{2}\zeta_c \left(\tilde{\Phi}^2 - M_c^2\right) \tilde{R}(\tilde{g}) + \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\tilde{\Phi}\partial_\nu\tilde{\Phi} - \left(\frac{1}{2}\tilde{m}^2\tilde{\Phi}^2 + \frac{1}{4}\tilde{\lambda}\tilde{\Phi}^4 + \tilde{V}_0\right) \right\}$$

scalar ghost !

$$\tilde{\Phi} = \frac{M_{Pl}}{\sqrt{\zeta_c}} e^{-S}$$

Conformal transformation: $\tilde{g}_{\alpha\beta} = \left(\frac{\Phi}{M_c}\right)^2 g_{\alpha\beta} = e^{2S} g_{\alpha\beta}$

scalar field !

$$S_{st}\left[g, S\right] = \int d^4x \, \sqrt{-g} \left\{ \frac{1}{2}\left(M_{Pl}^2 - \zeta_c\Phi^2\right) R(g) - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - \left(\frac{1}{2}\tilde{m}^2\left(\frac{M_{Pl}^2}{\zeta_c M_c^2}\right)\Phi^2 + \frac{1}{4}\left(\frac{4\tilde{V}_0}{M_c^4}\right)\Phi^4 + \tilde{\lambda}\left(\frac{M_{Pl}^4}{4\zeta_c^2}\right)\right) \right\}$$

$$\Phi = M_c e^S$$

DHE: Bottom-Up

SM Higgs field (excluding vectors and fermions):

$\Phi^2 = H^\dagger H$

$$S_{SM}[g,\Phi] = \int d^4x\,\sqrt{-g}\left\{\frac{1}{2}\left(M_{Pl}^2 - \zeta_c\Phi^2\right)R(g) - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - \left(\frac{1}{2}m_H^2\Phi^2 + \frac{1}{4}\lambda_H\Phi^4 + V_0\right)\right\}$$

scalar field !

Conformal transformation: $$g_{\alpha\beta} = \left(\frac{\Phi}{M_c}\right)^{-2}\tilde{g}_{\alpha\beta}$$

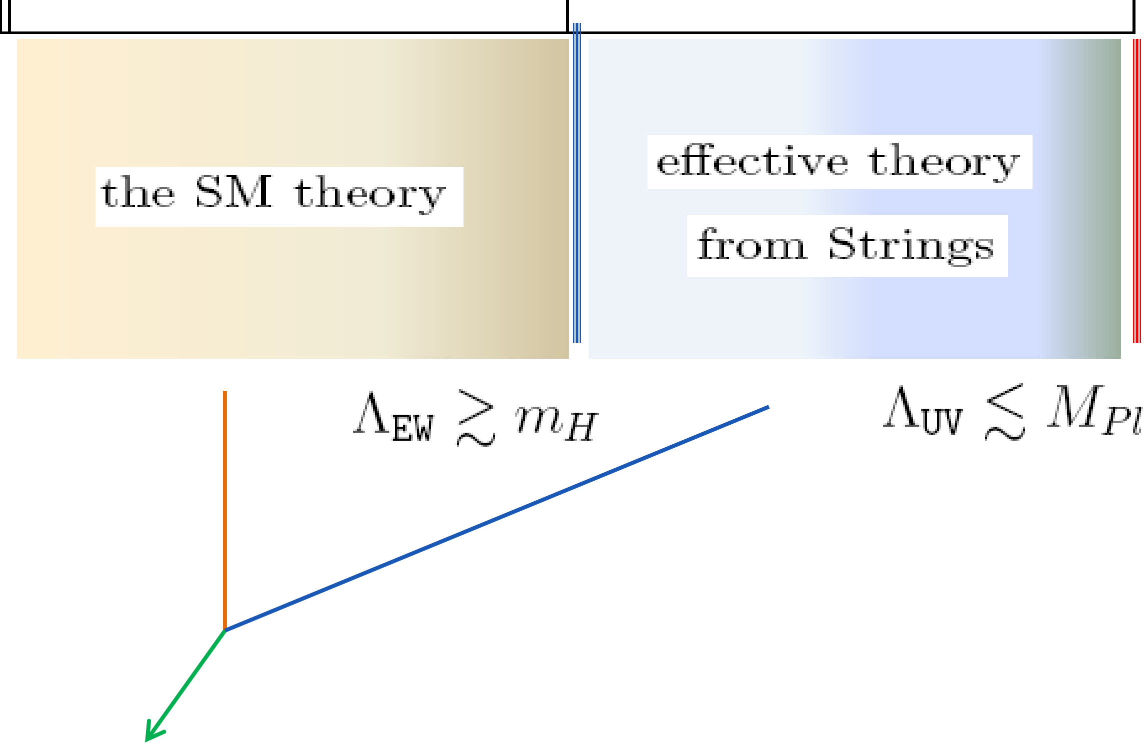
scalar ghost !

$$S_{SM}\left[\tilde{g},\tilde{\Phi}\right] = \int d^4x\,\sqrt{-\tilde{g}}\left\{\frac{1}{2}\zeta_c\left(\tilde{\Phi}^2 - M_c^2\right)\tilde{R}(\tilde{g}) + \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\tilde{\Phi}\partial_\nu\tilde{\Phi} - \left(\frac{1}{2}m_H^2\left(\frac{M_c^2}{6M_{Pl}^2}\right)\tilde{\Phi}^2 + \frac{1}{4}\left(\frac{V_0}{9M_{Pl}^4}\right)\tilde{\Phi}^4 + \frac{1}{4}\lambda_H M_c^4\right)\right\}$$

$$\tilde{\Phi} = \frac{M_{Pl}M_c}{\sqrt{\zeta_c}\Phi}$$

DHE: Two Frames

Quantity	GR Frame (**Low Energies**)	String Frame (**High Energies**)
Higgs field (canonical)	Φ	$\tilde{\Phi} \equiv \sqrt{6} M_c M_{Pl} \Phi^{-1}$
Higgs kinetic term	$-\frac{1}{2} g^{\alpha\beta} \partial_\alpha \Phi \partial_\beta \Phi$	$\frac{1}{2} \tilde{g}^{\alpha\beta} \partial_\alpha \tilde{\Phi} \partial_\beta \tilde{\Phi}$
Higgs quartic interaction	$-\frac{1}{4} \lambda_H \Phi^4$	$-\frac{1}{4} \left(\frac{V_0}{9 M_{Pl}^4} \right) \tilde{\Phi}^4$
Higgs quadratic interaction	$-\frac{1}{2} m_H^2 \Phi^2$	$-\frac{1}{2} m_H^2 \left(\frac{M_c^2}{6 M_{Pl}^2} \right) \tilde{\Phi}^2$
Vacuum energy	V_0	$\frac{1}{4} \lambda_H M_c^4$
Gravitational interaction	$\frac{1}{2} \left(M_{Pl}^2 - \zeta_c \Phi^2 \right) R(g)$	$\frac{1}{2} \zeta_c \left(\tilde{\Phi}^2 - M_c^2 \right) \tilde{R}(\tilde{g})$



semi-classical approach:

- Metric is classical
- Higgs and matter are quantal

DHE: Effective Action

$$m_{\tilde{\phi}}^2 = -m_H^2\left(\frac{M_c^2}{6M_{Pl}^2}\right) - \left(\frac{V_0}{3M_{Pl}^4}\right)\tilde{\phi}^2$$

$$
\begin{aligned}
Z \quad &= \int \left[\mathfrak{D}\tilde{\Phi}\right]_{\tilde{g}} e^{iS_{SM}\left[\tilde{\Phi},\tilde{g}\right]} \\
&= \int \left[\mathfrak{D}\tilde{\phi}\right]_{\tilde{g}} \left[\mathfrak{D}\delta\tilde{\phi}\right]_{\tilde{g}} e^{iS_{SM}\left[\tilde{\phi},\tilde{g}\right]} e^{\frac{i}{2}\int d^4x\,\delta\tilde{\phi}\left[-\tilde{\Box}+m_{\tilde{\phi}}^2+\zeta_c\tilde{R}(\tilde{g})\right]\delta\tilde{\phi}} \\
&= \int \left[\mathfrak{D}\tilde{\phi}\right]_{\tilde{g}} e^{iS_{eff}\left[\tilde{\phi},\tilde{g}\right]} \\
&\xrightarrow{\tilde{g}_{\mu\nu}=\left(\frac{\sqrt{\zeta_c}\tilde{\phi}}{M_{Pl}}\right)^{-2} g_{\mu\nu}} \int \left[\mathfrak{D}\tilde{\phi}\right]_{g} e^{i\left\{S_{eff}\left[\tilde{\phi},g\right]+\Delta S_{\tilde{g}\to g}\left[\tilde{\phi},g;\Lambda_{\mathtt{EW}}\right]\right\}} \\
&\xrightarrow{\tilde{\phi}=\frac{M_{Pl}M_c}{\sqrt{\zeta_c}\phi}} \int \left[\mathfrak{D}\phi\right]_{g} e^{i\left\{S_{eff}[\phi,g]+\Delta S_{\tilde{g}\to g}[\phi,g;\Lambda_{\mathtt{EW}}]+\Delta S_{\tilde{\phi}\to\phi}[\phi,g;\Lambda_{\mathtt{EW}}]\right\}}
\end{aligned}
$$

$$\frac{1}{(4\pi)^2}\Lambda_{\mathtt{EW}}^4 \log\left(\frac{M_{Pl}}{M_c}\right)$$

DHE: Divergences Controlled

The effective action in GR frame:

$$S^{tot}_{eff}[g,\phi] = \int d^4x\,\sqrt{-g}\left\{\frac{1}{2}\left(M_{Pl}^2 - \zeta_c\phi^2\right)R(g) - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \left(\frac{1}{2}\overline{m_H}^2\phi^2 + \frac{1}{4}\overline{\lambda_H}\phi^4 + \overline{V_0}\right)\right\}$$

$$\overline{\lambda_H} = \lambda_H + \frac{1}{(4\pi)^2}\left[\frac{\Lambda_{\tt UV}^4}{M_c^4} + \frac{m_H^2}{3M_{Pl}^2}\frac{\Lambda_{\tt UV}^2}{M_c^2} + \left(\frac{m_H^2}{6M_{Pl}^2}\right)^2\log\frac{\Lambda_{\tt UV}^2}{\Lambda_{\tt EW}^2}\right]$$

$\Lambda_{\tt UV} \lesssim M_c \simeq M_{Pl}$

$$\overline{m_H^2} = m_H^2\left[1 + \frac{1}{(4\pi)^2}\frac{V_0}{3M_{Pl}^4}\log\frac{\Lambda_{\tt UV}^2}{\Lambda_{\tt EW}^2}\right] + \frac{2}{(4\pi)^2}\frac{V_0}{M_{Pl}^2}\frac{\Lambda_{\tt UV}^2}{M_c^2}$$

$V_0 < \Lambda_{\tt EW}^2 M_{Pl}^2 \simeq \left(10^{10}\ \mathrm{GeV}\right)^4$

$$\overline{V_0} = V_0\left[1 + \frac{1}{(4\pi)^2}\frac{V_0}{3M_{Pl}^4}\log\frac{\Lambda_{\tt UV}^2}{\Lambda_{\tt EW}^2}\right] + \frac{1}{(4\pi)^2}\Lambda_{\tt EW}^4\log\frac{M_{Pl}}{M_c}$$

No quadratic and quartic divergences!

DHE: Yet more…

How about fermion and gauge boson loops?

They are completely harmless for naturalness because they do not couple to Higgs field in String frame:

$$\sqrt{-g}g^{\alpha\beta}\left(D_\alpha H\right)^\dagger\left(D_\beta H\right)\xrightarrow{g_{\alpha\beta}=\left(\frac{\Phi}{M_c}\right)^{-2}\tilde{g}_{\alpha\beta}}\sqrt{-\tilde{g}}\left[M_{W_c}^2\tilde{g}^{\alpha\beta}W_\alpha^+W_\beta^-+\frac{1}{2}M_{Z_c}^2\tilde{g}^{\alpha\beta}Z_\alpha Z_\beta\right]$$

$$M_{W_c}^2=\tfrac{1}{4}g_2^2M_c^2$$

$$M_{Z_c}^2=\tfrac{1}{4}(g_2^2+g_1^2)M_c^2$$

$$\sqrt{-g}h_\Psi\overline{\Psi_R}H^\dagger\begin{pmatrix}\tilde{\Psi}'_L\\ \tilde{\Psi}_R\end{pmatrix}\xrightarrow[\Psi=\left(\frac{\Phi}{M_c}\right)^{3/2}\tilde{\Psi}]{g_{\alpha\beta}=\left(\frac{\Phi}{M_c}\right)^{-2}\tilde{g}_{\alpha\beta}}\sqrt{-\tilde{g}}M_{\Psi_c}\overline{\tilde{\Psi}_R}\Phi^{-1}H^\dagger\begin{pmatrix}\tilde{\Psi}'_L\\ \tilde{\Psi}_R\end{pmatrix}$$

$$M_{\Psi_c}=h_{\Psi_c}M_c$$

DHE: Yet more...

With hard masses for vector bosons, how about unitarity?

Unitarity is preserved for the entire field-theoretic range if $M_c \simeq M_{Pl}$.

The regions of super-Planckian momenta are described by string dynamics.

$M_c \simeq M_{Pl}$ is consistent with suppressed radiative effects in Higgs sector.

With hard masses for vector bosons, how about renormalizability?

All the way up to M_{Pl}, Higgs and massless fields (photon, gluon, ...) form a renormalizable QFT.

Massive vectors and fermions induce higher-dimensional terms (like Fermi theory of Weak Int.).

Is the ghost (phantom) disastrous? Can it be avoided?

With classical gravity, ghost is OK if it does not couple to matter.

The SM with Dirac neutrinos is all OK.

Ghost is a perfect $w < -1$ Dark Energy candidate.

If the non-minimal coupling parameter ζ_c is taken

large enough ghosts can be eliminated from the spectrum.

DHE: Yet more...

How about flavor?

With $M_c \simeq M_{Pl}$, Yukawas are linked to strings.

Flavor symmetries and Weyl invariance are both broken at $M_c \sim M_{Pl}$.

What 'new physics' can arise?

Allowed are all kinds of (massless) fields which couple conformally to the SM fields.

(For example: extra fermion generations, extra (massless) Higgs doublets, extra (massless) singlets)

Extra fields acquire their masses from the SM Higgs hence new particles, if any, should weigh at the weak scale or below (weakly coupled).

How about CP violation?

Extra CP-violating phases can arise from new fermion generations or additional scalars (*e. g.* two Higgs doublet model)

Discussions and Conclusion

- ▶ Dilaton-Higgs Equivalence can naturalize the Higgs boson without resorting to extra matter species.
- ▶ Vacuum energy plays an important role in naturalness, and closer it to existing bounds more natural the Higgs.
- ▶ New particles, if any, must weigh at the weak scale or below.

- ⊖ The Dilaton model arising here needs to be derived by taking into account the string loop effects.
- ⊖ Baryogenesis, Dark matter (scalar or vector singlets), Dark Energy (Dilaton itself ?) need to be studied.
- ⊖ Possibility of Dirac neutrinos needs to be analyzed.

THANK YOU !