Karlsruhe Institute of Technology

SFB TR9

The low-energy theorem in Composite Higgs models

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INSTITUTE FOR THEORETICAL PHYSICS

Outline

Motivation

On the July, 4th: ATLAS and CMS announced the discovery of a new boson at 126 GeV/125.3 GeV.

- But is it really *the* SM Higgs? Or a SUSY Higgs, a Composite Higgs,...?
- Composite Higgs: Hierarchy problem solved $\rightarrow$ Higgs mass dynamically generated
- Higgs as a PGB from a new strongly-interacting sector [Kaplan, Georgi; Galison, Dugan; Dimopoulos, Preskill; Banks]
- Heavy top mass through large mixing of top quark with new fermionic resonances

At LHC:

- Main Higgs production channel: Loop mediated gluon fusion
- But: Found insensitive to the details of heavy spectrum [Falkowski; Low, Vichi; Azatov, Galloway]
- But what about Multi Higgs production?

An explicit model: MCHM5 with extra fermionic resonances [Contino, Da Rold, Pomarol]

- Holographic Higgs: 4d description of 5d model on AdS spacetime
- Symmetry breaking pattern $SO(5) \times U(1)_X / SO(4) \times U(1)_X$ with $SO(4) \sim SU(2)_L \times SU(2)_R$ (at scale f)
- 4 Goldstone bosons = 3 longitudinal degrees of freedom for gauge bosons + 1 Higgs boson
- Global symmetry explicitely broken: Higgs boson gets mass through loop corrections
- Introduce a new **5** of $SO(5)$ of composite fermions (called ψ)

Lagrangian:

$$\mathcal{L} = \frac{f^2}{2}(D_\mu \Sigma)^T (D^\mu \Sigma) + i\bar{q}_L \not{D} q_L + i\bar{t}_R \not{D} t_R + i\bar{b}_R \not{D} b_R + \overline{\psi}\left(i\not{D} - m_\psi\right)\psi + \\ - y\, f\left(\overline{\psi} \cdot \Sigma\right)\left(\Sigma^T \cdot \psi\right) - \left(m_L \overline{q}_L Q_R + m_R \overline{T}_L t_R\right)$$

where $\Sigma = (0, 0, \sin(H/f), 0, \cos(H/f))^T$.

Composite fermions

$$\psi = \frac{1}{\sqrt{2}} \begin{pmatrix} B - X_{5/3} \\ -i(B + X_{5/3}) \\ T + X_{2/3} \\ i(T - X_{2/3}) \\ \sqrt{2}\tilde{T} \end{pmatrix} .$$

field	T_L^3	T_R^3	Y	$Q_{el} = T_L^3 + Y$
T	$+1/2$	$-1/2$	$1/6$	$+2/3$
B	$-1/2$	$-1/2$	$1/6$	$-1/3$
$X_{5/3}$	$+1/2$	$+1/2$	$7/6$	$+5/3$
$X_{2/3}$	$-1/2$	$+1/2$	$7/6$	$+2/3$
$\tilde{T}$	0	0	$2/3$	$+2/3$

- Mixing of top quark with 2/3 charged fermions $\rightarrow$ diagonalisation of mass matrix necessary
- At LO in v/f

$$m_t = y \sin\phi_L \sin\phi_R v/\sqrt{2}$$

with $\phi_{L,R}$ mixing angles before EWSB.

- $m_H = 125$ GeV implies $m_{lightest} \lesssim 700$ GeV [Matsedonskyi, Panico, Wulzer; Marzocca, Serone, Shu; Redi, Tesi; Pomarol, Riva]

Low energy theorem

LET provides leading interactions of Higgs bosons with gluons and photons [Kniehl, Spira; Ellis, Gaillard, Nanopoulos; Shifman, Vainshtein, Voloshin, Zakharov] Expanding field-dependent masses of heavy particles around VEV

$$\mathcal{L}_{h^n gg} = \frac{g_s}{96\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \left(A_1 h + \frac{1}{2} A_2 h^2 + ... \right)$$

and

$$A_n = \left(\frac{\partial^n}{\partial H^n} \log\det \underbrace{\mathcal{M}^2(H)}_{\text{Heavy fermion mass matrix}} \right)_{\langle H \rangle}$$

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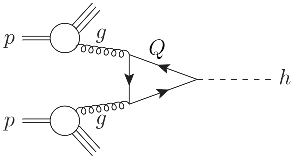
Single Higgs production:



$\Longrightarrow$

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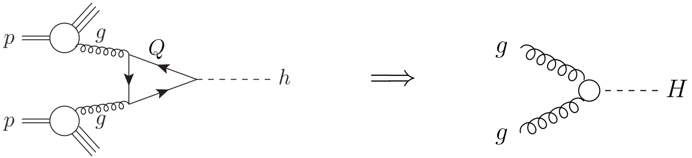

Low energy theorem – Single Higgs production

$$A_n = \left(\frac{\partial^n}{\partial H^n} \log\det \mathcal{M}^2(H) \right)_{\langle H \rangle}$$

If

$$\det \mathcal{M}^2(H) \;=\; F(H/f) \times P(\lambda_i, M_i, f) \qquad\qquad \text{with } F(0) = 0$$

$\Longrightarrow$ *hgg* vertex independent of details of heavy spectrum, only depends on $\xi = v^2/f^2$ (Higgs non-linearities)

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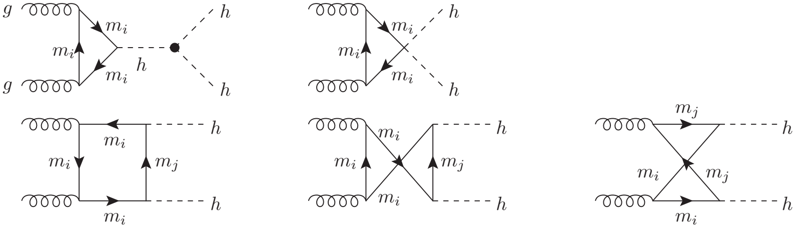
Example: MCHM5 (with $s = \sin(H/f)$ $c = \cos(H/f)$)

$$-\mathcal{L}_{mass} = \overline{\begin{pmatrix} t_L \\ Q_L^u \\ X_L^u \\ T_L \end{pmatrix}} \begin{pmatrix} 0 & m_L & 0 & 0 \\ 0 & m_\Psi + \frac{s^2}{2} f\, y & \frac{s^2}{2} f\, y & c\, v\, y \\ 0 & \frac{s^2}{2} f\, y & m_\Psi + \frac{s^2}{2} f\, y & c\, v\, y \\ m_R & cv\, y & c\, v\, y & m_\Psi + c^2 f\, y \end{pmatrix} \begin{pmatrix} t_R \\ Q_R^u \\ X_R^u \\ T_R \end{pmatrix} + h.c.$$

We find

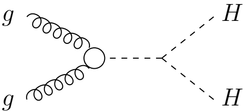
$$\det \mathcal{M}^\dagger(H)\mathcal{M}(H) = \frac{M_0^4 y^2 f^2 \sin^2\phi_L \sin^2\phi_R}{8\cos^2\phi_L \cos^2\phi_R} (M_0 + yf)^2 \sin^2\left(\frac{2H}{f}\right)$$

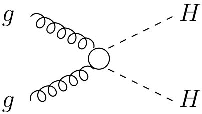
Double Higgs production



- Access to triple Higgs coupling [Djouadi, Kilian, Mühlleitner, Zerwas]
- Novel $hh\bar{f}f$ coupling [RG, Mühlleitner; Contino, Ghezzi,Moretti, Panico, Piccini, Wulzer]
- Different fermions can contribute to box diagrams

Low energy theorem – Double Higgs production

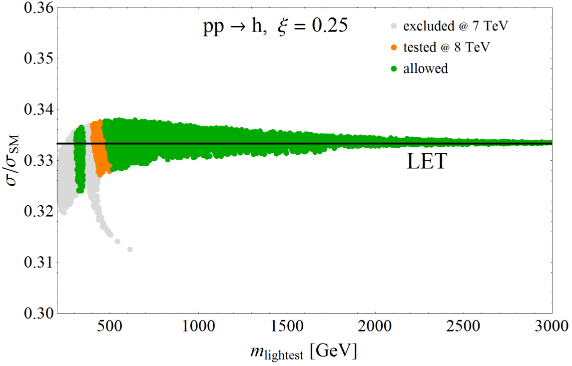




As in single Higgs production: LET independent of details of heavy spectrum
But:

- In SM: LET underestimates σ of $\mathcal{O}(20\%)$ [Glover, van der Bij; Plehn, Spira, Zerwas]
- For distributions even worse [Baur, Plehn, Rainwater]
- All fermionic resonances above cut-off: In MCHM5 for $\xi = 0.25$ LET underestimates σ of $\mathcal{O}(50\%)$

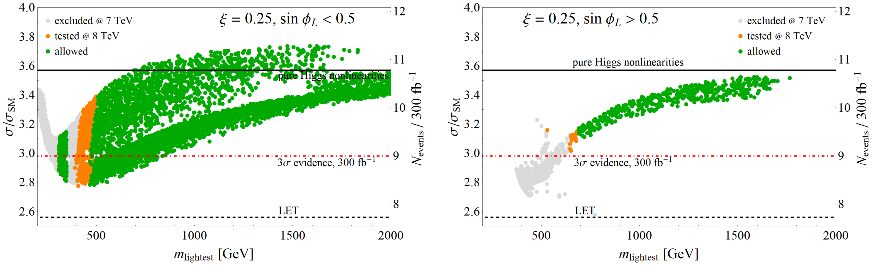
Single Higgs production



- Green: Allowed by EWPT and collider constraints
- Gray: Excluded by direct searches
- Orange: Projected exclusion by 8 TeV

LET works very good
Reason: Cancellation between loops of new fermions and modification of top Yukawa coupling

Double Higgs production



- Enhancement of cross section compared to SM
- Sizeable dependence on spectrum of heavy fermions
- Keeping full mass dependence on m_{top} only overestimates σ/σ_{SM} for $m_{lightest} \lesssim 1.5$ TeV
- LET underestimates σ/σ_{SM} drastically

Conclusion

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<u>Single Higgs Production:</u>

- LET very good approximation for full result
- σ does not depend on details of heavy spectrum
- Cancellation between contribution of heavy fermions in loop and modification of top Yukawa coupling

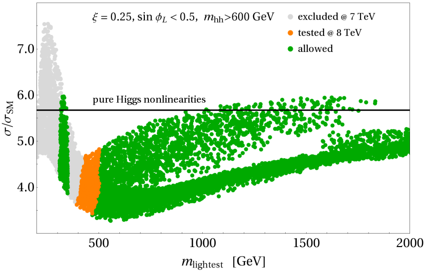
<u>Double Higgs Production:</u>

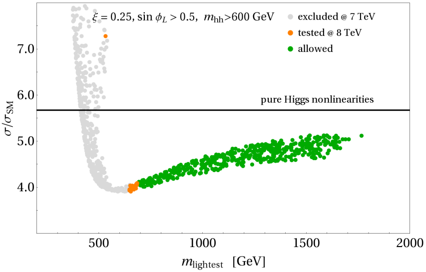
- LET not reliable
- Dependence on spectrum of heavy fermions

For more examples on LET/ model-independent way see [arXiv:1206.7120]

Thanks for your attention!

Double Higgs production – Invariant mass cut





- After invariant mass cut: LET gets worse
- σ/σ_{SM} increases with invariant mass cut

Electroweak precision tests [Barbieri, Bellazzini, Rychkov, Varagnolo; Gillioz; Anastasiou, Furlan, Santiago; Lodone; Pomarol, Serra]

Strong experimental constraints from precise measurements of Z pole mass at LEP $\rightarrow$ can be theoretically expressed in $\epsilon_1, \; \epsilon_2, \; \epsilon_3, \; \epsilon_b,$ [Altarelli, Barbieri, Caravaglios] (equivalent to $S, \; T, \; U$ parameters [Peskin, Takeuchi])
Additional effects in Composite Higgs models:

- Modified HZZ and HWW couplings lead to logarithmically divergent contributions to S and T

$$\Delta\epsilon_1^{\rm IR} = -\frac{3\,\alpha(M_Z)}{16\pi\cos^2\theta_W}\xi\log\left(\frac{m_\rho^2}{m_h^2}\right), \qquad \Delta\epsilon_3^{\rm IR} = \frac{\alpha(M_Z)}{48\pi\sin^2\theta_W}\xi\log\left(\frac{m_\rho^2}{m_h^2}\right)$$

- Direct contribution of vector ρ or axial-vector a resonance to S parameter

$$\Delta\epsilon_3^{\rm UV} = \frac{m_W^2}{m_\rho^2}\left(1+\frac{m_\rho^2}{m_a^2}\right) \cong 1.36\,\frac{m_W^2}{m_\rho^2}\,.$$

- Contributions from new fermions to T and $Zb\bar{b}$

$$\Delta\epsilon_1^{fermions} = f_1\left(\xi, \phi_L, \phi_R, R\right), \qquad \Delta\epsilon_b^{fermions} = f_b\left(\xi, \phi_L, \phi_R, R\right),$$

Constraints from direct searches

Different searches by CMS, ATLAS und CDF in pp, $p\bar{p} \to \psi\bar{\psi}$ with final states $WbWb$, $WtWt$ and $ZtZt$.
$\to$ Roughly a mass range of 180 GeV und 650 GeV is excluded (assuming $BR(\psi \to \text{final state}) = 1$.
<u>Constraint from direct searches:</u>

$$\sigma_{QCD}(pp \to \psi\overline{\psi}) \times \mathrm{BR}(\psi \to Wb)^2 \le \sigma_{exp}$$