Effective Composite Higgs @ Colliders

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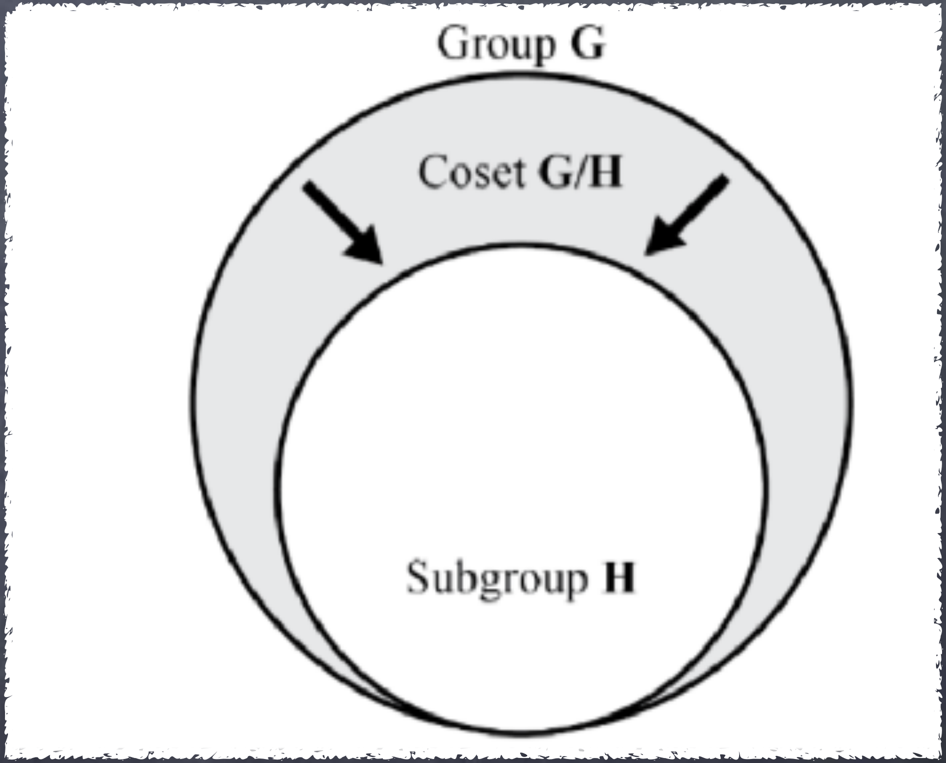
We have a Higgs!

- Is the Higgs an elementary point particle?
- Or does it have an extension in space: l_h
- Corresponding compositeness scale: $f_h \sim 1/l_h$
- Assuming the generation of this scale is natural in the UV: dimensional transmutation??
- The theory provides a resolution of the gauge hierarchy problem.
- Natural prediction: $m_h^2 \sim m_Q^2 \sim f_h^2$

Composite Higgs as pNGB

- However in generic composite models (technicolor) f_h also represent the scale where resonances of the strong sector shows up. This usually messes up things!
- A hierarchy between the cutoff scale and the Higgs mass can be induced if the Higgs is a pNGB of a strong sector.
- $m_h < f_h$: the small hierarchy in these models
- $\xi \sim \dfrac{m_h^2}{f_h^2}$ expansion parameter for EFT



Composite Higgs program

SM except the Higgs $\Longleftrightarrow$ Strong sector $G \to H \subset G$

$$\mathcal{L}_{mix} = \bar{q}_L \mathcal{O}_R + \bar{t}_R \mathcal{O}_L + A_g^\mu \mathcal{J}_\mu + \ldots$$

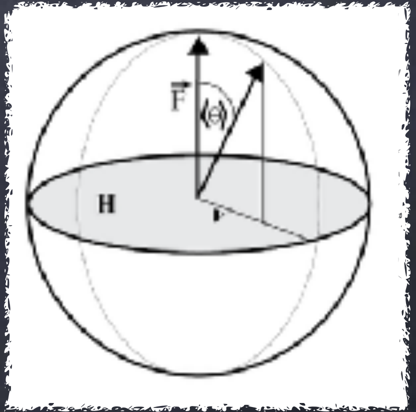
Higgs Potential @ 1-loop:

$$m_h^2 \sim \frac{N_c}{\pi^2} \frac{m_t^2 m_Q^2}{f_h^2}$$

Alex Pomarol Francesco Riva
JHEP 1208 (2012) 135

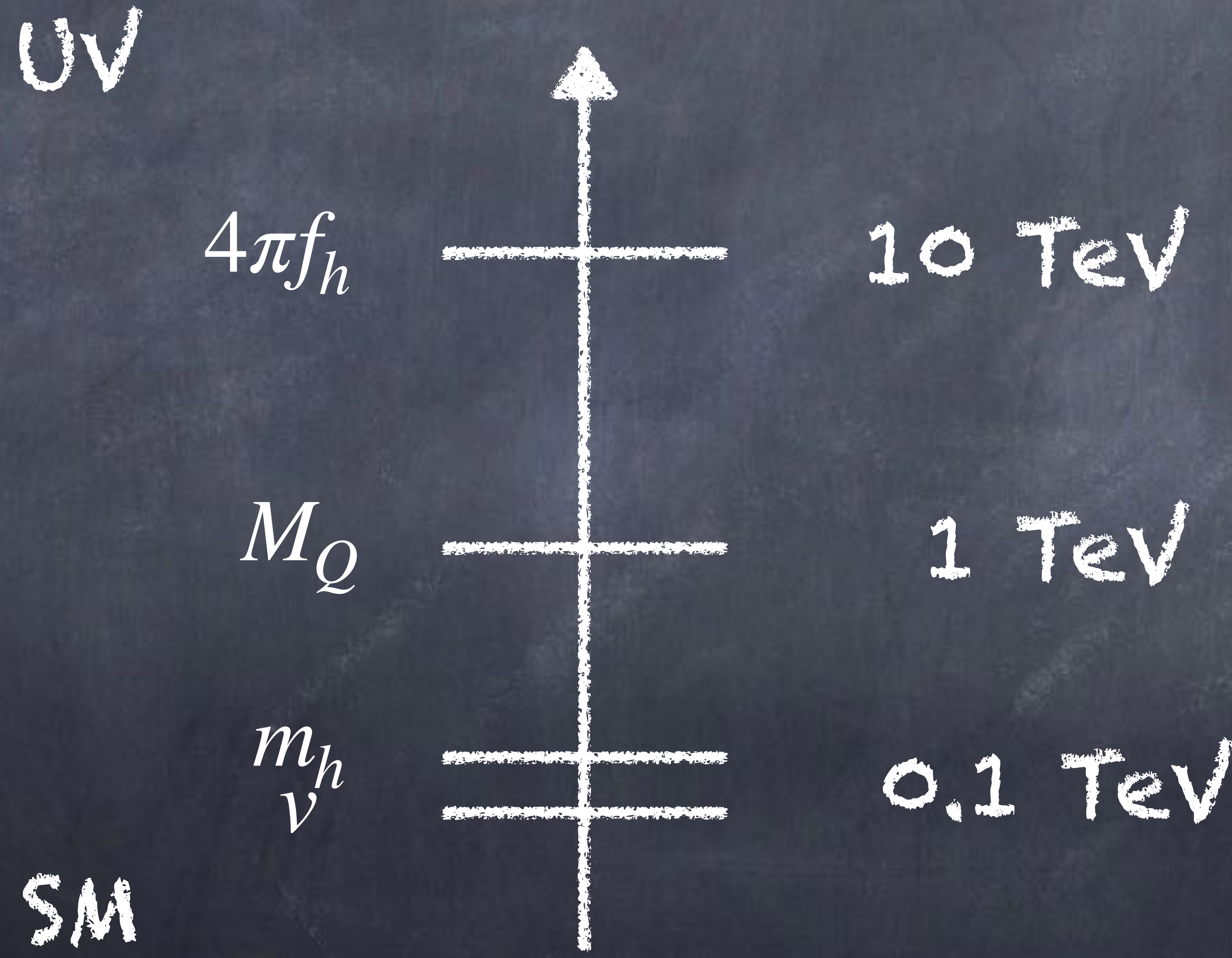
Vacuum misalignment:

$$\xi = \frac{v^2}{f_h^2}$$



Measure of
proximity to elementary Higgs

Composite Higgs EFT



Top Partners

Partial Compositeness

The linear mixing between SM top and operators of the strong sector lead to the top-Higgs Yukawa couplings. This immediately indicates that the strong sector has to have color charges and existence of $SU(3)_c$ adjoint operators of the strong sector is indicated. An effective description of the linear mixing is given by:

$$\mathscr{L}_{mix} = \bar{q}_L \mathcal{O}_R + \bar{t}_R \mathcal{O}_L + A_g^{\mu} \mathscr{J}_{\mu} + \ldots$$

Effective Lagrangian for the top partners

$t_{5/3}$ $t'_{2/3}$

Coset: SO(5)/SO(4), $\psi = (2,7/6) \in \quad (X, U)$

$$\mathscr{L}_{eff} = i\bar{\psi}D^m u\gamma_m u\psi + i\bar{q}_L D^m u\gamma_m u q_L + i\bar{\tilde{t}}_R D^m u\gamma_m u\tilde{t}_R + \bar{b}_R D^m u\gamma_m u b_R$$

$$-\tilde{m}_t \bar{\tilde{t}}_L \tilde{t}_R - x\bar{U}_L \tilde{t}_R - M\bar{U}_L U_R + M_\rho \rho^\mu \rho_\mu + h.c.$$

Top Yukawa

Mixing

Strong resonance

EFT expansion parameter: $\dfrac{M_Q}{f_h}$

@ $p \to 0$

(Talk by Naveen Gaur)

Two caveats

- The gluon partners (that should exist with top partners, 5d Models) can contribute to the production channels of top-partners

- The strong resonates (top partners/gluon partners) can be broad resonances. (Talk by Luca Panizzi)

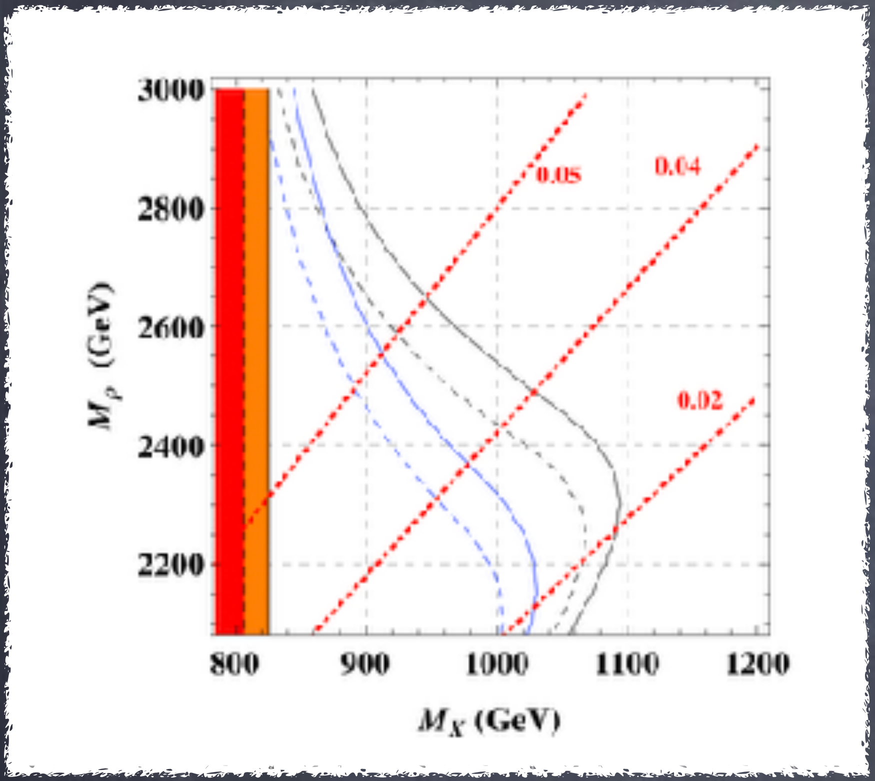
  For width: $\Gamma/m \gtrsim 20\,\%$ the Breit-Wigner form of propagators starts to fail. Safer to use 1PI summed full propagator

  Needs update of tools: CALCHEP, MADGRAPH etc.

Some Limits

$t_{5/3}$ & $t_{-1/3}$

CMS 8 TeV,

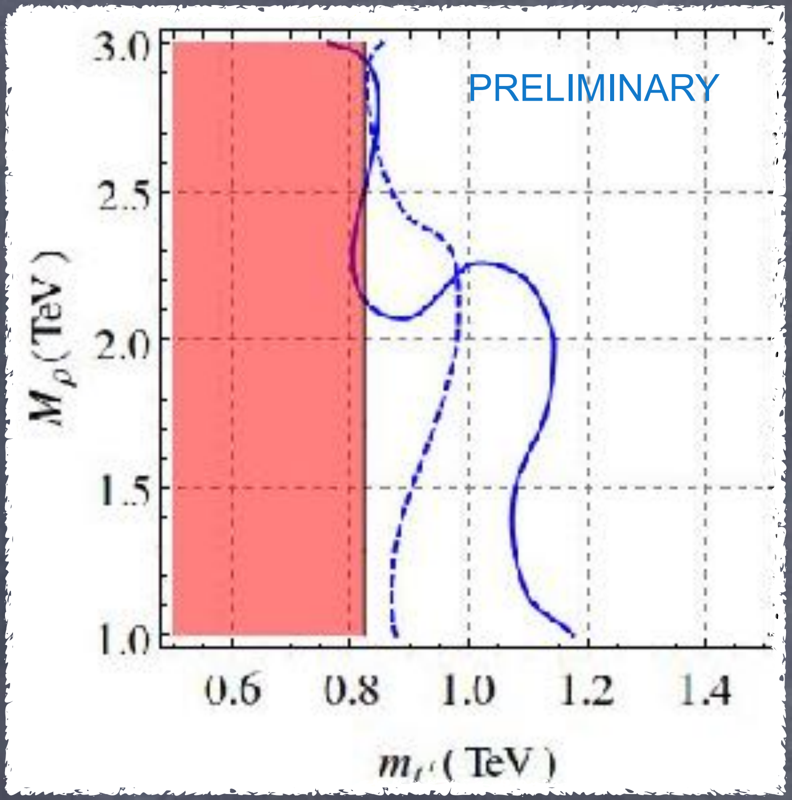


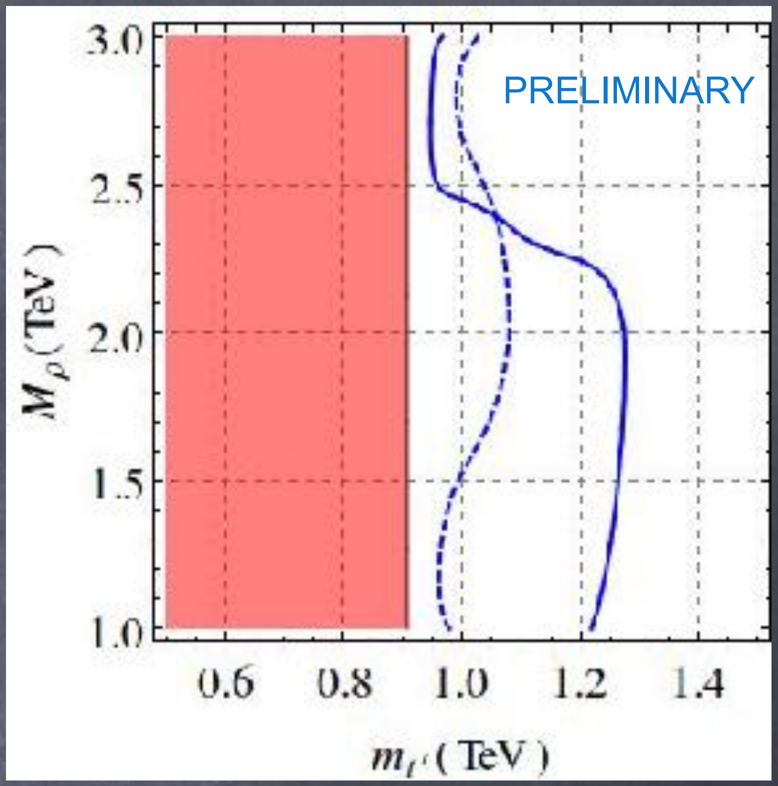
95% C.L. exclusion contours. Solid lines represent the constraints obtained from recasting the CMS study and the dashed lines correspond to the ones from the ATLAS study. The black (blue) lines correspond to the value g_*=2.5(3). The orange and red vertical bands are the constraints assuming only QCD production

S A. Azatov, D. Chowdhury, D. Ghosh, TSR JHEP 1508, 140 (2015)

$t'_{2/3}$

CMS 13 TeV, 35.8 fb- ATLAS 13 TeV, 36.1 fb-





2σ exclusion plots from CMS a single lepton & trilepton channels. Solid red line is the plot for NWA, dashed red line represents the plot for fat-width correction and the blue line is within the NRW. The red vertical bands are the constraints assuming only QCD production

S Dasgupta, S K Rai, TSR, in preparation

Note

- You can buy your way into heavy top parters by paying in fine-tuning!
- Finding top partners may not uniquely identify Higgs as an composite object (UED, RS, SM4, etc)

pNGB (Composite) Higgs couplings

Low energy effective Lagrangian for pNGB Higgs

EFT:

$$U = e^{i\Pi}, \;\; \Pi \equiv \Pi^A T^A \, .$$

$$\mathscr{L} = \frac{m_\rho^4}{g_\rho^2}\left[\mathscr{L}^{(0)}(U,\Phi,\partial/m_\rho) + \frac{g_\rho^2}{(4\pi)^2}\mathscr{L}^{(1)}(U,\Phi,\partial/m_\rho) + \frac{g_\rho^4}{(4\pi)^4}\mathscr{L}^{(2)}(U,\Phi,\partial/m_\rho) + \ldots\right]$$

SILH Basis:

Expansion parameter: v/f @ p→0

$$\begin{aligned}\mathscr{L}^{(0)}_{\text{SILH}} = {} & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\ & -\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2}H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) \\ & +\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\ & +\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\ & +\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\end{aligned}$$

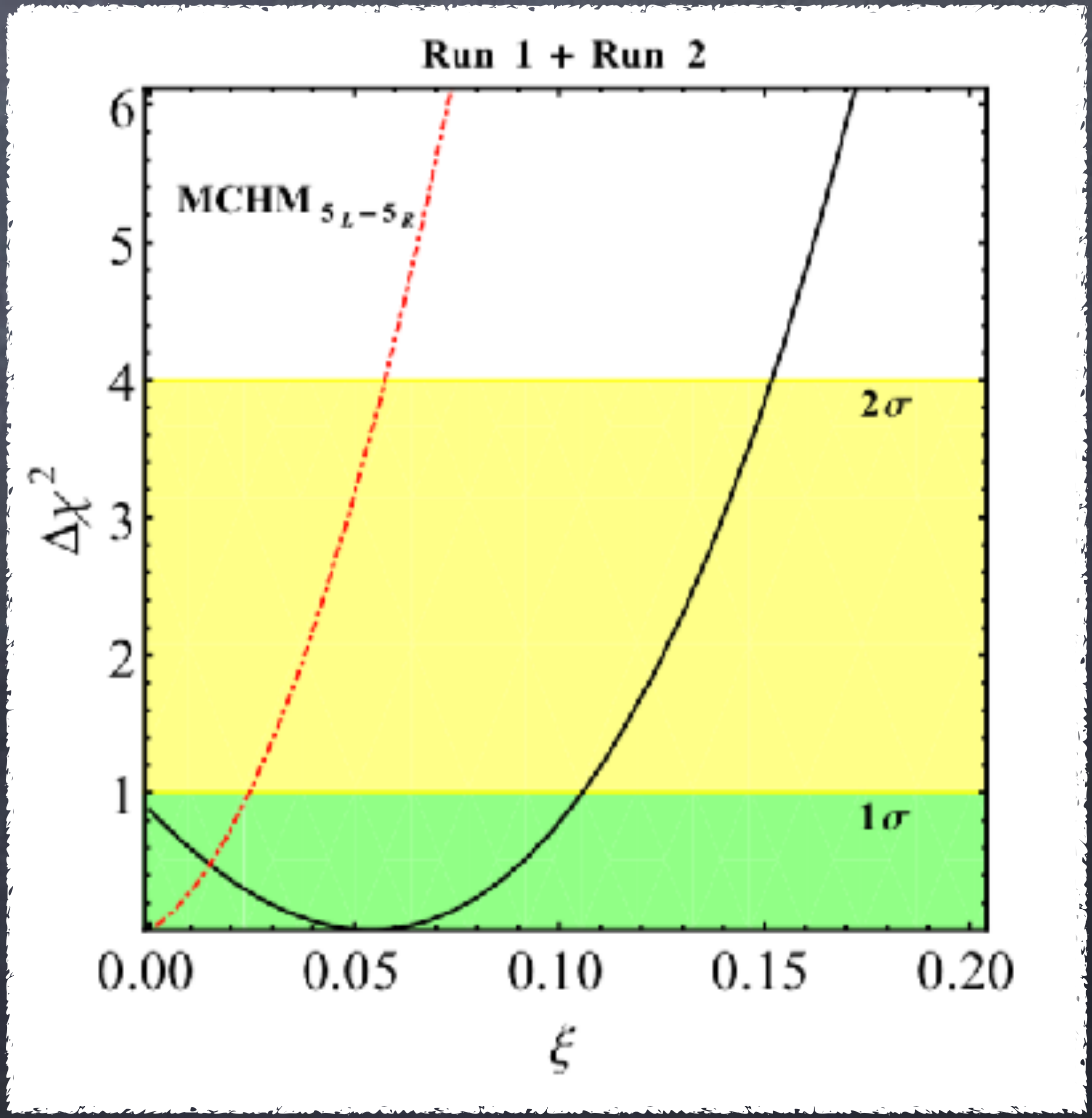
Giudice, Grojean, Pomarol, Rattazzi; JHEP 0706, 045 (2007)

Constraining from LHC:

- Specific models maps into special choices for the coefficients of the SILH EFT
- These results in a pattern of deviation of the Higgs couplings from SM predictions leading to constraints from Higgs LHC data

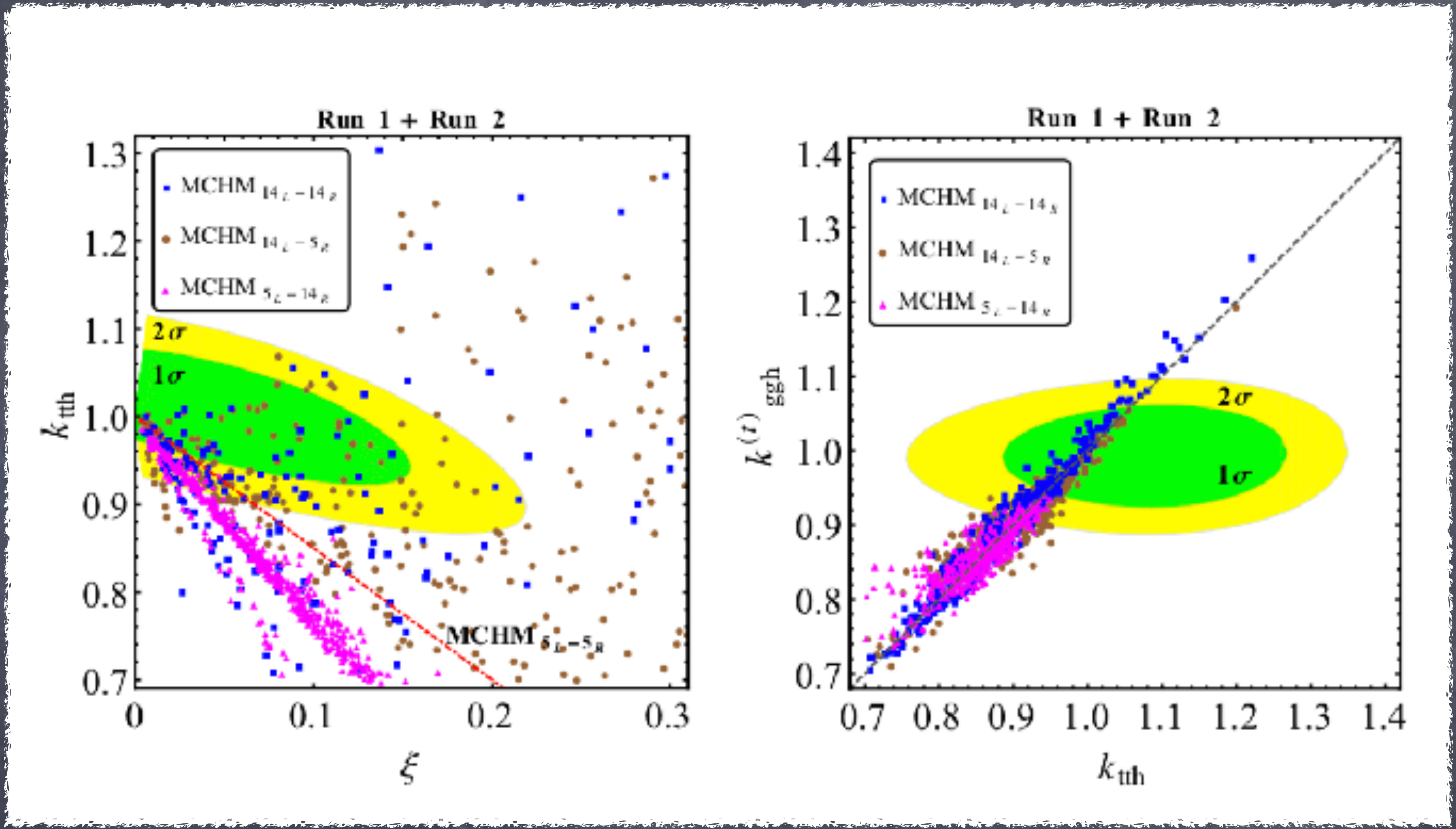
Coset: SO(5)/SO(4)

Results of χ^2analysis for Run 1 + Run 2 datasets. Solid black line represents $\Delta\chi^2 = \chi^2 - \chi^2_{\text{min}}$ for the extended models, while the red dashed lines represents the same for $\text{MCHM}_{5_L-5_R}$. Green and yellow regions denote the allowed range for ξ at 68\% and 95\% CL, respectively



A. Banerjee, G. Bhattacharyya, N. Kumar, TSR; JHEP 1803, 062 (2018)

Constraining from LHC:



For the minimal coset SO(5)/SO(4), we present the regions allowed at 68\% (green) and 95\% (yellow) CL using combined Run 1 and available Run 2 data. Valid 'extended model' points are observed to lie within the experimentally allowed regions.

A. Banerjee, G. Bhattacharyya, N. Kumar, TSR;
JHEP 1803, 062 (2018)

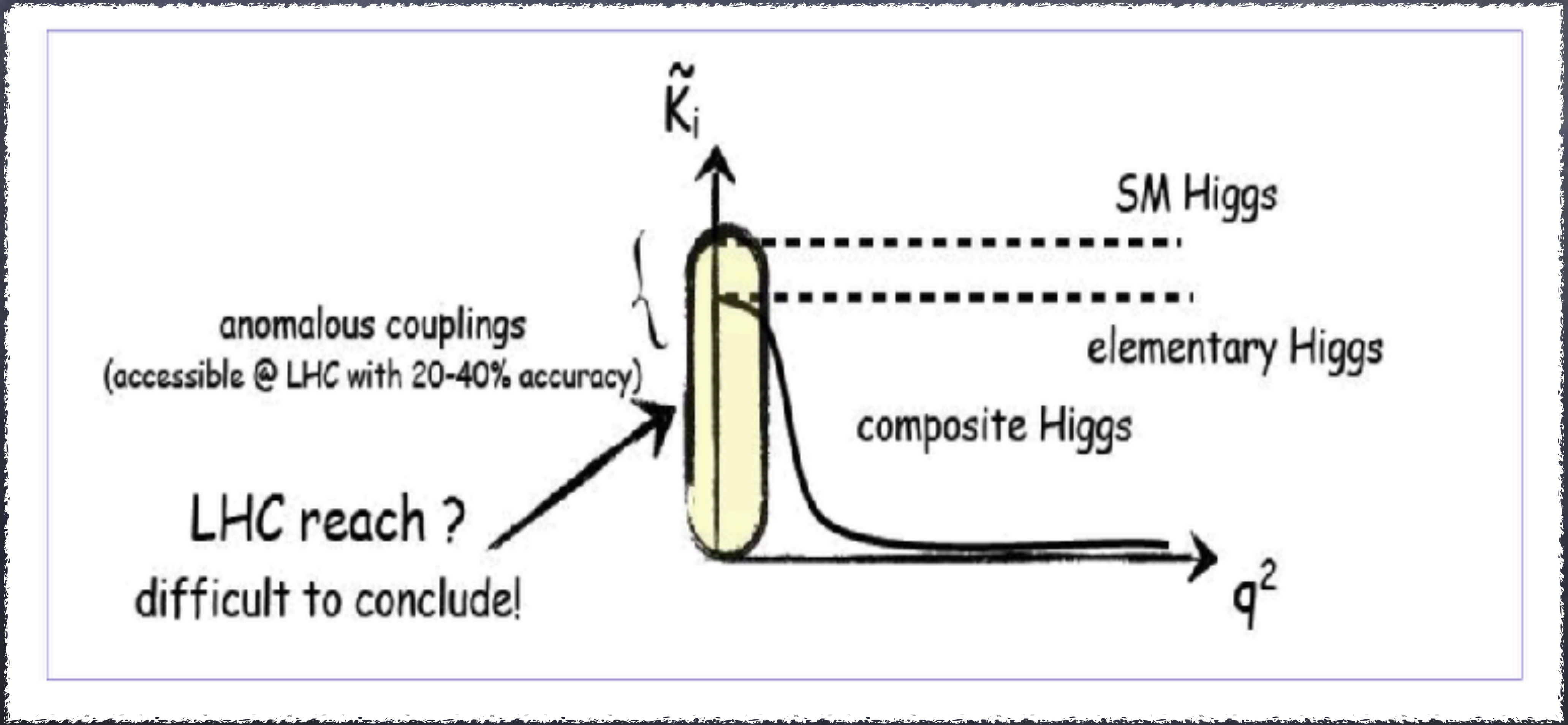
Note

- A correlated pattern of the Higgs coupling departing from SM prediction may indicate NLR of Higgs
- LHC has a limit of 10-20 % (?) for the measurement of most Higgs couplings
- Higgs factory??
- But this still does not identify a finite shape of the Higgs!

Structure functions

Proof of Pudding!

Without beating around the bush the tell-tale sign of compositeness would be to probe the momentum dependent structure of the Higgs couplings



Taken from a talk by Grojean, Planck 2011

Effective Higgs-top Lagrangian

$$\mathscr{L} = \bar{t}_L p^\mu \gamma_\mu \left[\Pi_0^{t_L}(p_L) + \frac{\tilde{\Pi}_1^{t_L}(p_L)}{2} C_h^2 \right] t_L + \bar{t}_R p^\mu \gamma_\mu \left[\Pi_0^{t_R}(p_R) + \tilde{\Pi}_1^{t_R}(p_R) S_h^2 \right] t_R$$

$$+ \bar{t}_L \left[\frac{M^t(p_L, p_R)}{\sqrt{2}} S_h C_h \right] t_R + \mathrm{h.c.}$$

The structure functions:

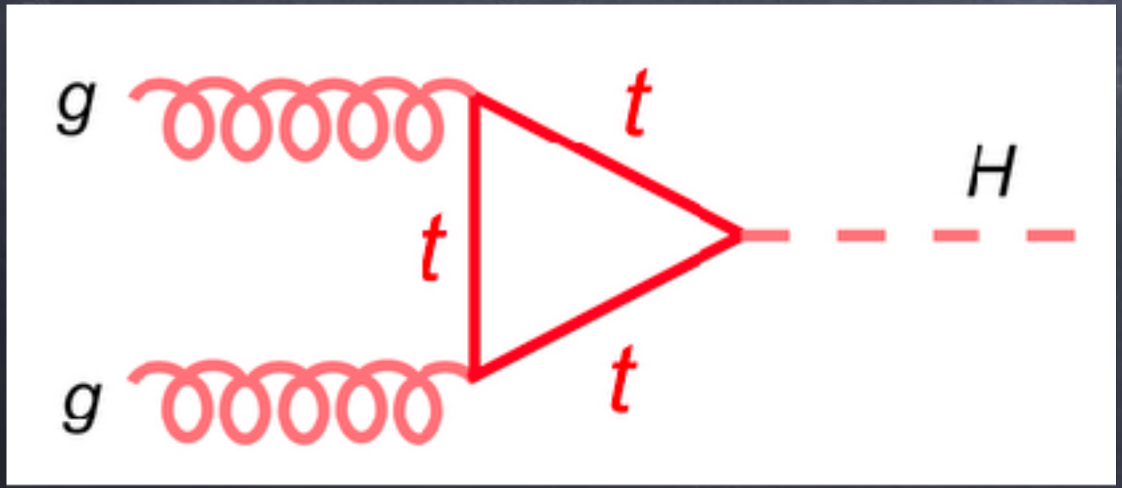
- Weinberg sum-rules
- 5d duality
- Lattice

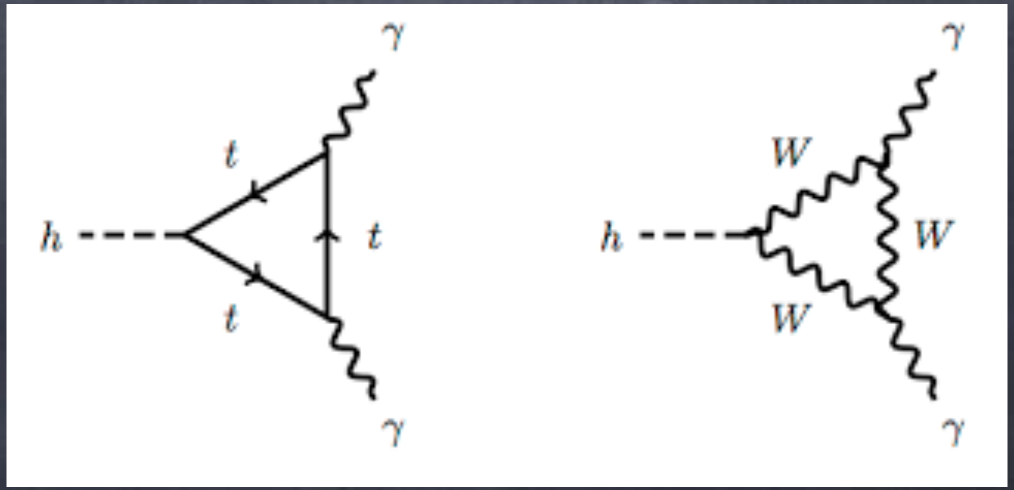
  (Talk by Anna Hasenfratz)

$\boxed{\text{Expansion: } m_h/M_Q \quad @\ p \neq 0}$

Loop Driven Higgs Couplings

The loop integrals in principle scan all momentum and naive expectation is that these Higgs couplings should be sensitive to any momentum dependence of the Higgs couplings!





Higgs Low Energy Theorem & "Cancellations"

The light Higgs theorem is based on the fact that in the ggh or $\gamma\gamma h$ couplings are loop driven but once the Higgs is replaced by its vev they become contribution to the corresponding β functions!

$$\sigma_{hgg/\gamma\gamma} \propto \frac{\partial \log \det M}{\partial v}$$

The momentum dependence of the Higgs couplings and anomalous dimension of the partially composite top do not effect the hgg coupling!

Montull, Riva, Salvioni, Torre; PRD 88, 095006 (2013)
Azatov, Galloway; PRD 85, 055013 (2012)
Falkowski, PRD 77, 055018 (2008)

Off-Shell Higgs?

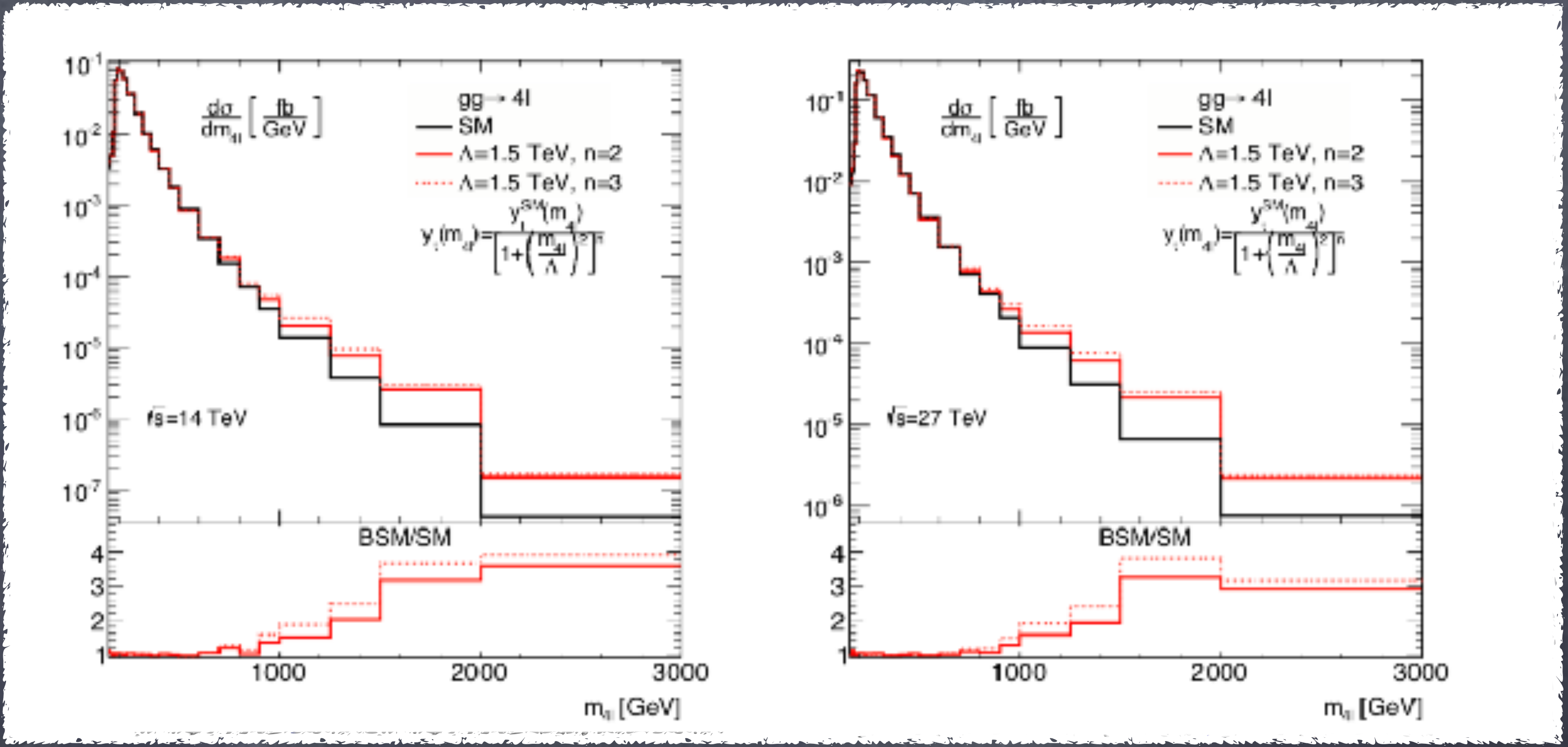
Assuming a phenomenological form factor:

$$V_{hZZ}(p^\mu, \bar{p}^\mu) = \frac{\sqrt{2}m_t}{v}\Gamma(p^2/\Lambda, \bar{p}^2/\Lambda, q^2/\Lambda)$$

One can see significant deviation in kinematic parameters in the :

pp->h* -> ZZ->4l

Gonçalves, Han, Mukhopadhyay; PRD 98 (2018) no.1, 015023



Can study of Off-shell Higgs couplings at colliders tell us about compositeness of Higgs?

Note

- Study of extremely off-shell Higgs may be useful to probe momentum scaling of Higgs couplings
- Departure from usual log scaling can manifest in kinematic distribution of final-states
- 100+ TeV collider??

Thanks