The global Higgs as a signal for compositeness at the LHC

Sylvain Fichet
ICTP/SAIFR&IFT Sao Paulo

Based on 1607.03125 (JHEP) and 1608.01995 (JHEP) with
Gero von Gersdorff, Eduardo Pontón, Rogerio Rosenfeld

GDR

25/11/16

1. The composite Higgs paradigm
2. The global Higgs and its properties
3. LHC prospects
4. Outlook

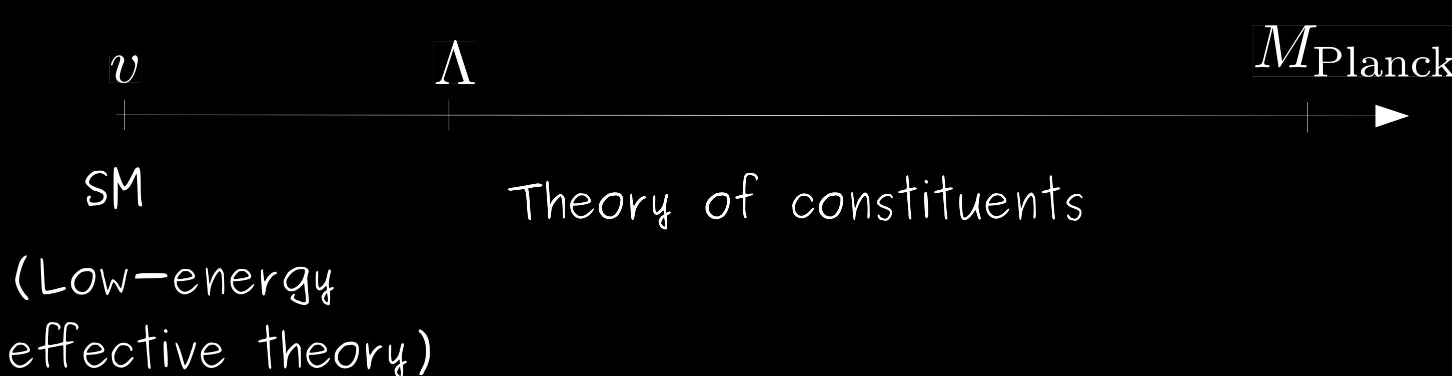
1. The composite Higgs paradigm

Is the Standard Model composite ?

Motivation 1: Why not ?

Motivation 2: $m_h \ll M_{\rm Planck}$?
Mass of spin-0 particle not protected by a symmetry. The mass of the Higgs boson is technically unnatural.

A solution: NO spin-0 particle. The Higgs is a composite state that dissolves above a scale Λ .



Is the Standard Model composite ?

LHC produced a 125 GeV very SM-like Higgs resonance without revealing any obvious substructure → Binding should be quite strong → Strongly coupled interaction

But the 125 GeV SM-like Higgs is not accompanied by nearby resonances and has a narrow width… Doesn't look like a regular hadron…

Composite pNGB Higgs

Borrow intuition from QCD: the pions are much lighter than other bound states, because they are pseudo Nambu–Goldstone bosons (pNGBs) of a spontaneously broken approximate global symmetry.

Composite pNGB Higgs

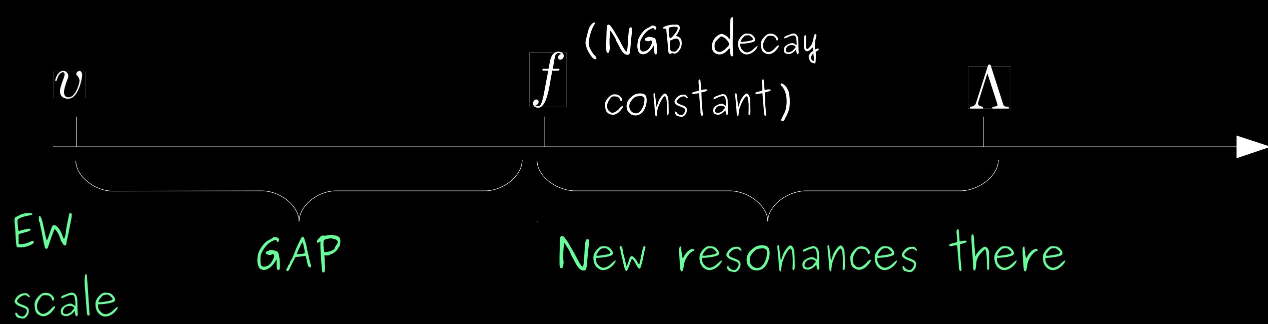
Borrow intuition from QCD: the pions are much lighter than other bound states, because they are pseudo Nambu-Goldstone bosons (pNGBs) of a spontaneously broken approximate global symmetry.

Composite pNGB Higgs

Borrow intuition from QCD: the pions are much lighter than other bound states, because they are pseudo Nambu-Goldstone bosons (pNGBs) of a spontaneously broken approximate global symmetry.

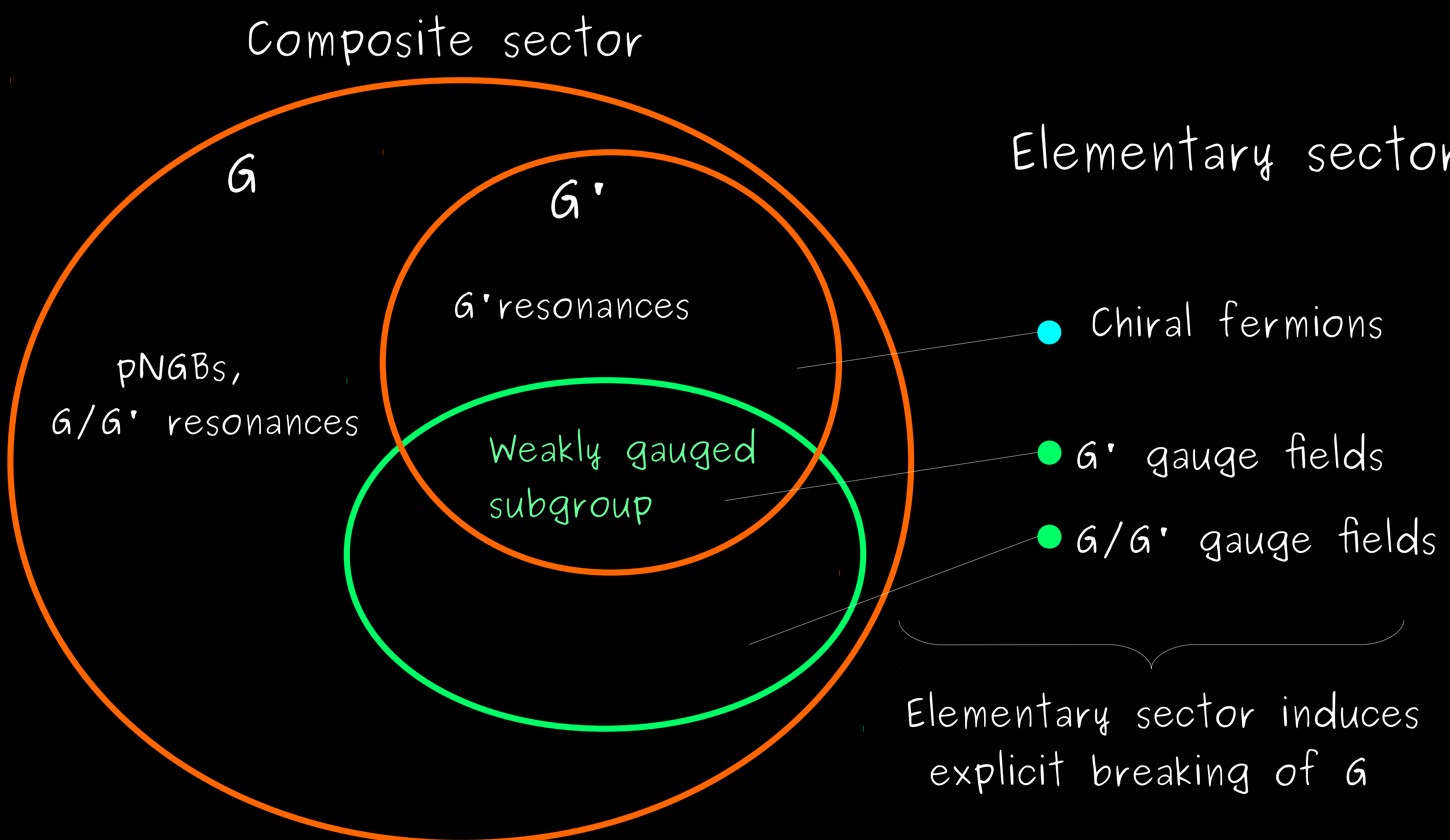
Composite pNGB Higgs

Idea: The Higgs boson and the three longitudinal polarizations of the electroweak (EW) gauge bosons are pNGBs, the 'pions' of a global group **G** broken into **G'**.



The pNGB gap is not arbitrarily large without tuning.
Hence f is expected to be O(TeV) → resonances accessible at LHC

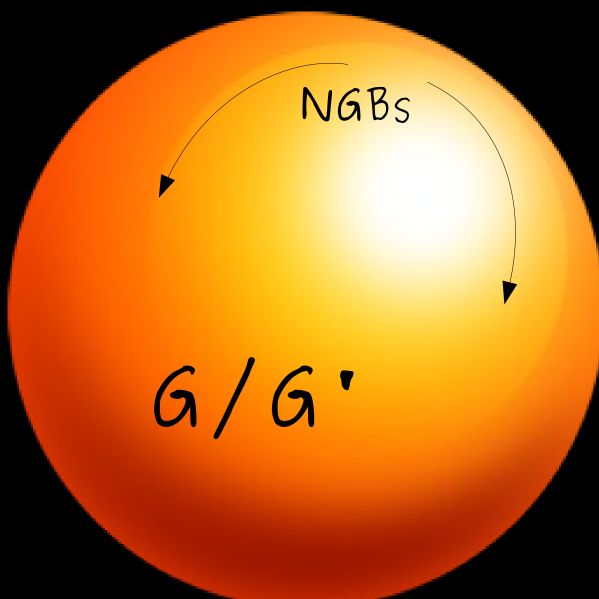
Composite Higgs paradigm



3. The global Higgs and its properties

Radius fluctuation

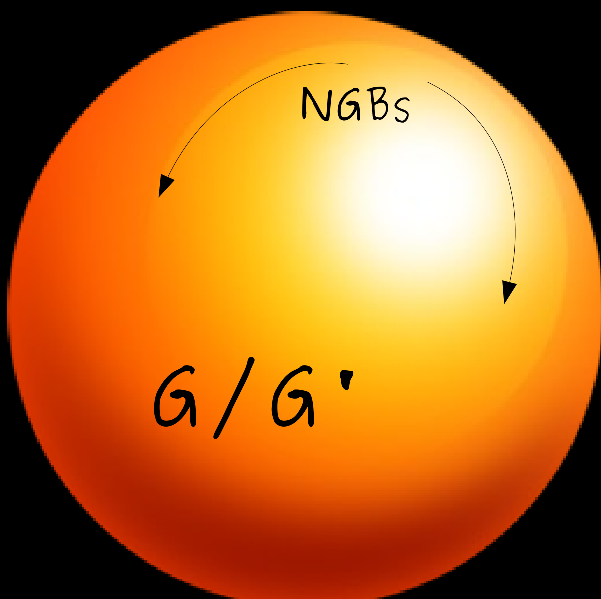
The G/G' coset has a finite radius [in most of constructions], which is assumed to be stable.



The fluctuation of this radius is a massive, CP-even scalar (just like the SM Higgs boson for the SU(2)xU(1)/U(1) coset).

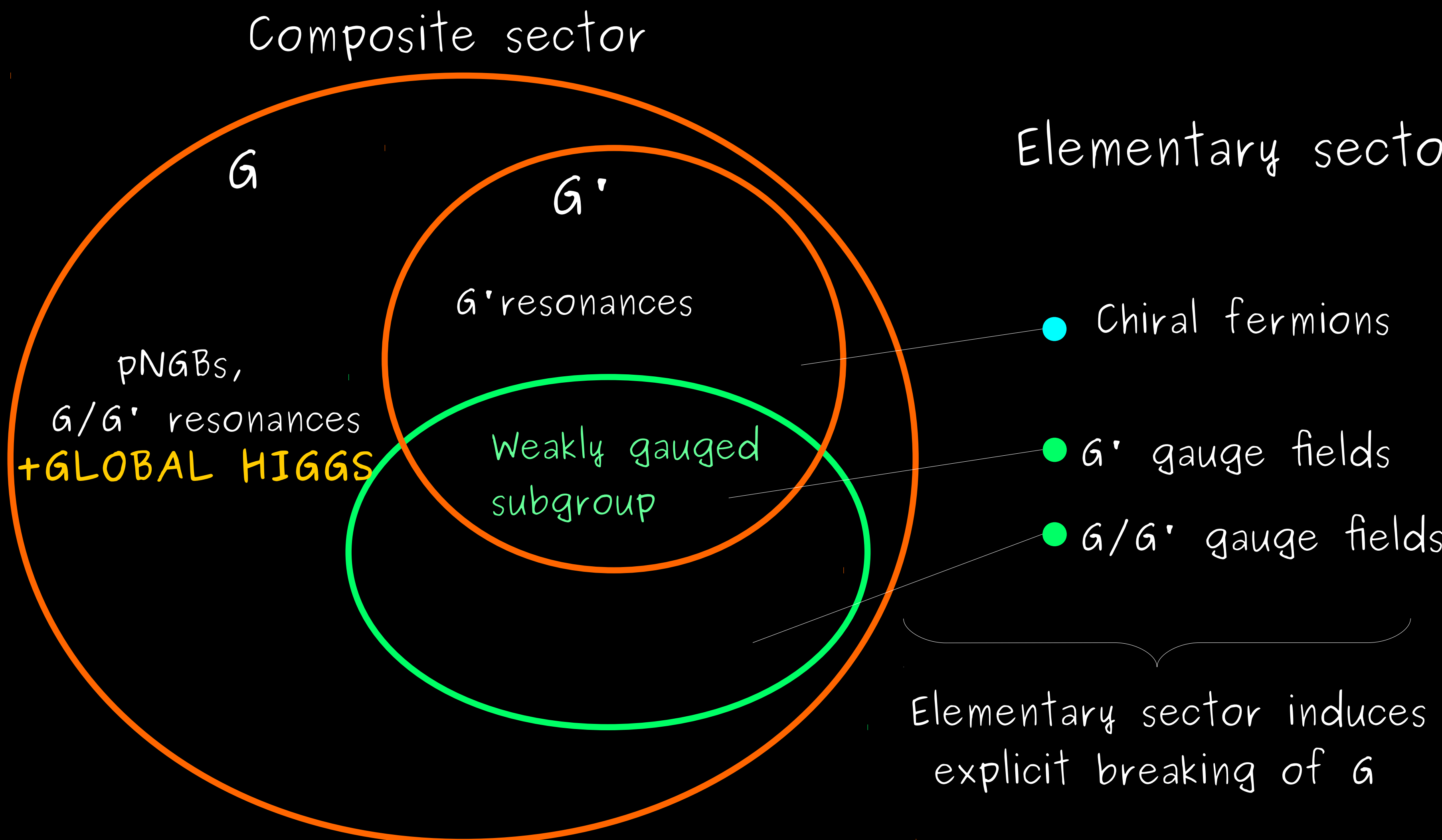
Radius fluctuation

The G/G' coset has a finite radius [in most of constructions], which is assumed to be stable.



There is another scalar in the composite Higgs picture: the GLOBAL HIGGS, noted ϕ.
[SF, Gersdorff, Ponton, Rosenfeld]

The fluctuation of this radius is a massive, CP-even scalar (just like the SM Higgs boson for the SU(2)xU(1)/U(1) coset).



Conceptual step : Global Higgs and pNGBs could be embedded into a multiplet of the unbroken group G (noted Φ).

Qualitative features

- The global Higgs is expected to couple to the NGB's parametrising the coset. Couplings should be derivative by NGB shift saymmetry
  → One expects a coupling $\phi(\partial_\mu h)^2$, and thus $\phi(Z_\mu)^2$ and $\phi W^+_\mu W^{\mu -}$ (by gauge invariance)

- Should couple to fermion resonances, as one needs to write proto-Yukawa operators of the form

$$-\xi_{u_i}\mathcal{O}_u(\Phi)\bar{Q}_i U_i - \xi_{d_i}\mathcal{O}_d(\Phi)\bar{Q}_i D_i - \xi_{l_i}\mathcal{O}_l(\Phi)\bar{L}_i E_i + \mathrm{h.c.}$$

- May couple to SM fermions proportionally to their mass,

$$\phi\, m_\psi(\psi_{\mathrm{SM}}\psi'_{\mathrm{SM}} + \mathrm{h.c.})$$

The SO(5)/SO(4) Higgs

- The G=SO(5), G'=SO(4), choose $\Phi \sim \mathbf{5}$ of SO(5).

$$\underbrace{\Phi = U_5 \mathcal{H}}_{\text{pNGBs} \quad \text{radius}} \qquad \underbrace{\mathcal{H} = (\hat{f} + \phi) e_5}_{\text{VEV} \quad \text{global Higgs}}$$

- Consider quartic expansion of the radius potential:

$$V(\mathcal{H}) = \frac{1}{4}\lambda \left(\mathcal{H}^2 - \hat{f}^2\right)^2 \rightarrow m_\phi = \sqrt{2\lambda}\hat{f}$$

- General bosonic Lagrangian:

$$\mathcal{L}_{\text{bos}} = \frac{1}{2}(\nabla_\mu \mathcal{H})^2 - V(\mathcal{H}) + \frac{1}{4} f_\rho^2 \left(\mathcal{A}_\mu^A - i[U_5^\dagger D_\mu U_5]^A\right)^2 + \ldots$$

The pNGBs mix with the coset resonances, $f^{-2} = \hat{f}^{-2} + f_\rho^{-2}$

Global Higgs interactions

- Bosonic couplings:
  - SM Higgs and EW gauge bosons: $2\frac{f^2}{\hat{f}^3}\phi\,(D_\mu H)^2$
  - Spin-1 (coset) resonances: $\frac{2}{\hat{f}}\phi\mathcal{A}_\mu^{\hat{a}\,2}$
- Fermionic couplings:
  - SM fermions: $-\frac{m_\psi}{\hat{f}}\phi\bar{\psi}\psi$
  - fermion resonances: completely model dependent

Only two free parameters !

And f should be minimized to reduce EW fine-tuning.

Complete realizations

To learn further about the global Higgs properties, one needs to define full realizations of the fermion sector.

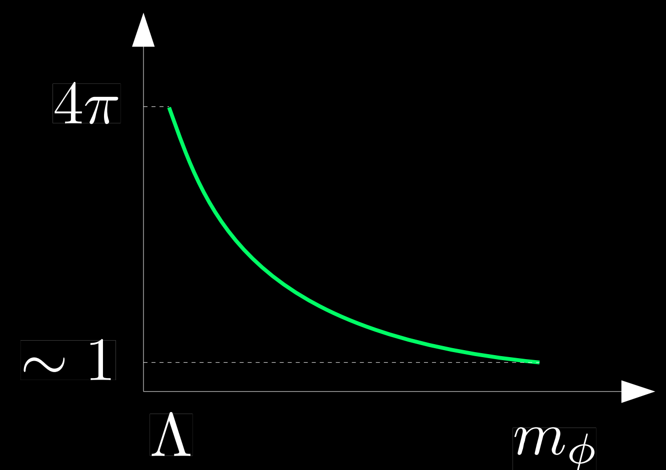
We consider four typical models, $MCHM_{Q,U,D}$, with

$$
\begin{aligned}
(Q,\ U,\ D) = \ & (5_{2/3},\ 1_{2/3},\ 10_{2/3}) \\
& (5_{2/3},\ 14_{2/3},\ 10_{2/3}) \\
& (14_{2/3},\ 14_{2/3},\ 10_{2/3}) && \leftarrow \text{Higgs in the 14 of } SO(5) \\
& (5_{2/3},\ 1_{2/3},\ x) && \leftarrow \text{No partial compositeness}
\end{aligned}
$$

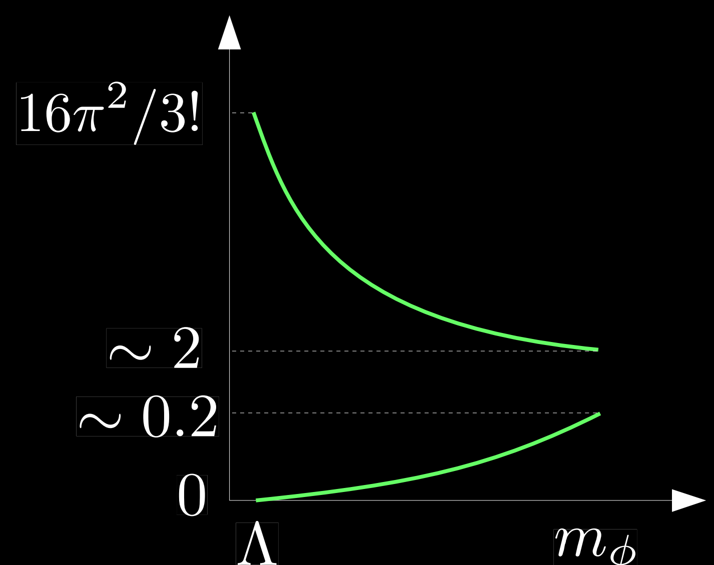
IN SHORT: Yukawa operators and thus couplings of the global Higgs to fermion resonances differ in each scenario (multiplicities, group theoretical factors…)

Renormalization (in short)

- Yukawa couplings ξ :

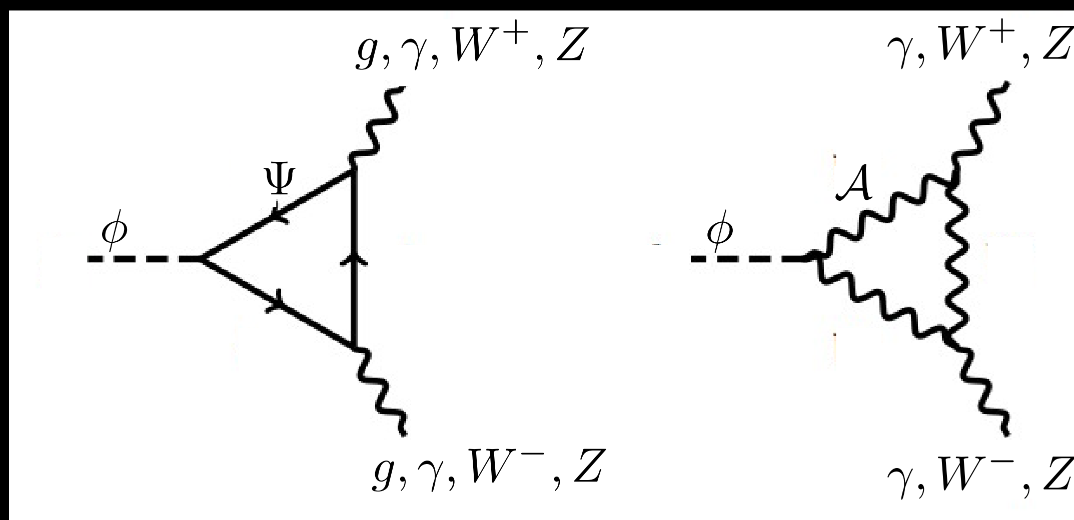


- Global Higgs quartic λ :



One-loop effective couplings

We can now go ahead: The global Higgs couples to many non SM-singlet fermion and vector resonances, which induce loop couplings to SM gauge bosons.



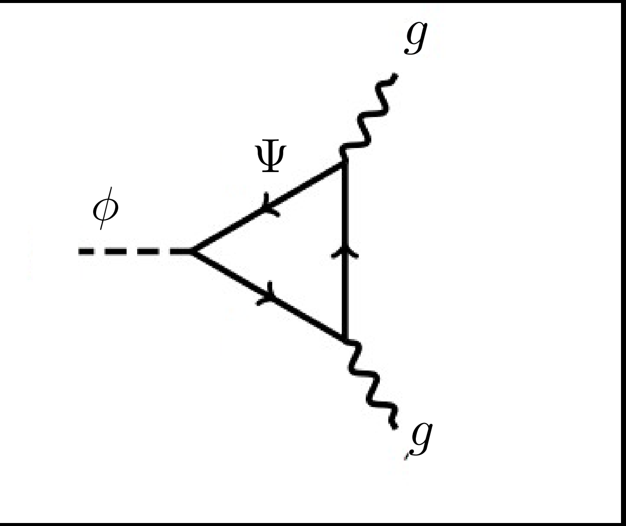
The fermion loops completely depend on the fermion sector (representation, loops, mass matrices). However, for heavy enough vector like masses, compact expressions are obtained.

One-loop effective couplings

For example : gluon coupling

$$\mathcal{L} \supset -\phi \frac{a_{gg}}{\hat{f}} \left(G^a_{\mu\nu}\right)^2$$

$$a_{gg} = c_{gg} \frac{\hat{f}^2}{M_\psi^2} A_{1/2}\left(\frac{m_\phi^2}{4M_\psi^2}\right)$$



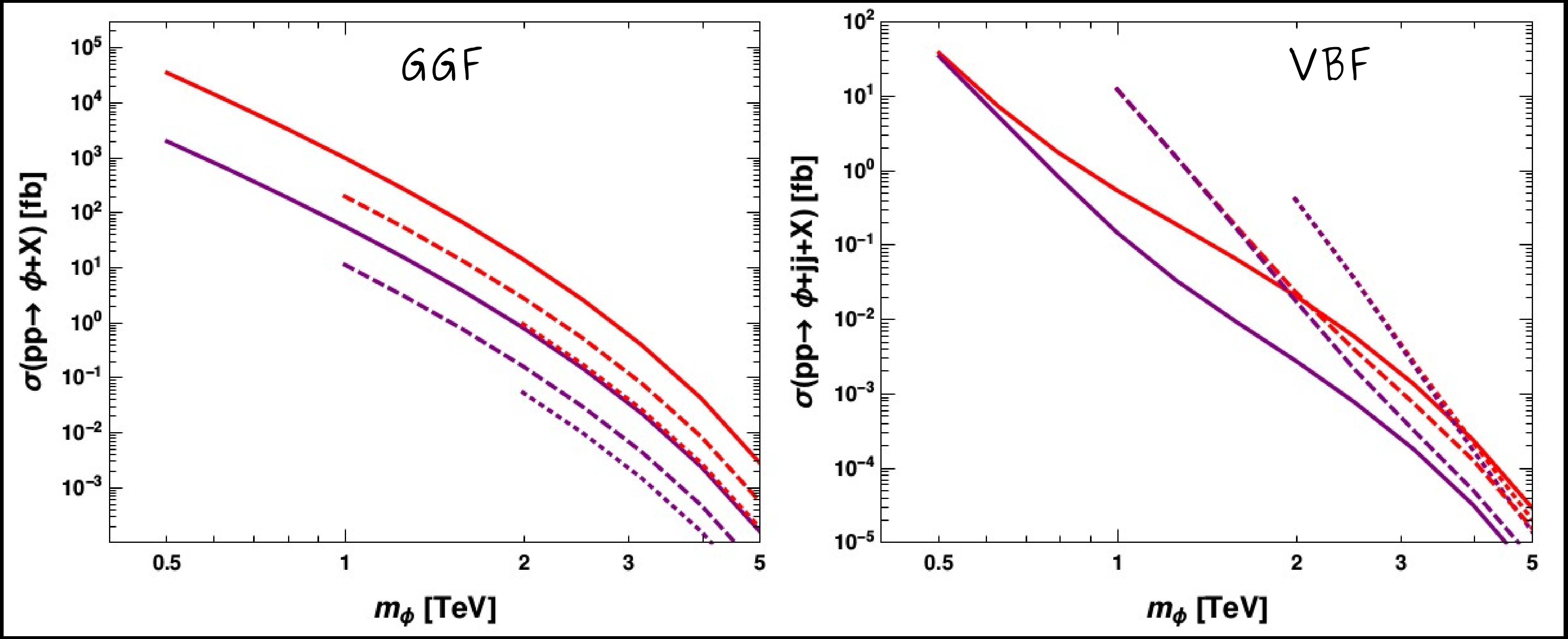
$$c_{gg} = \begin{pmatrix} 0.013 \\ 0.014 \\ 0.011 \\ 0.01 \end{pmatrix} \begin{array}{l} \mathrm{MCHM}_{5,1,10} \\ \mathrm{MCHM}_{5,14,10} \\ \mathrm{MCHM}_{14,14,10} \\ \mathrm{MCHM}_{5,1} \end{array}$$

Very similar for each scenario !

3. Some LHC prospects

Production at the 13 TeV LHC

I



Red and purple : $M_\psi = m_\phi$, $M_\psi = 2m_\phi$
Plain, dashed, dotted : $\lambda = 0.2,\, 1,\, 3$

Scenarios

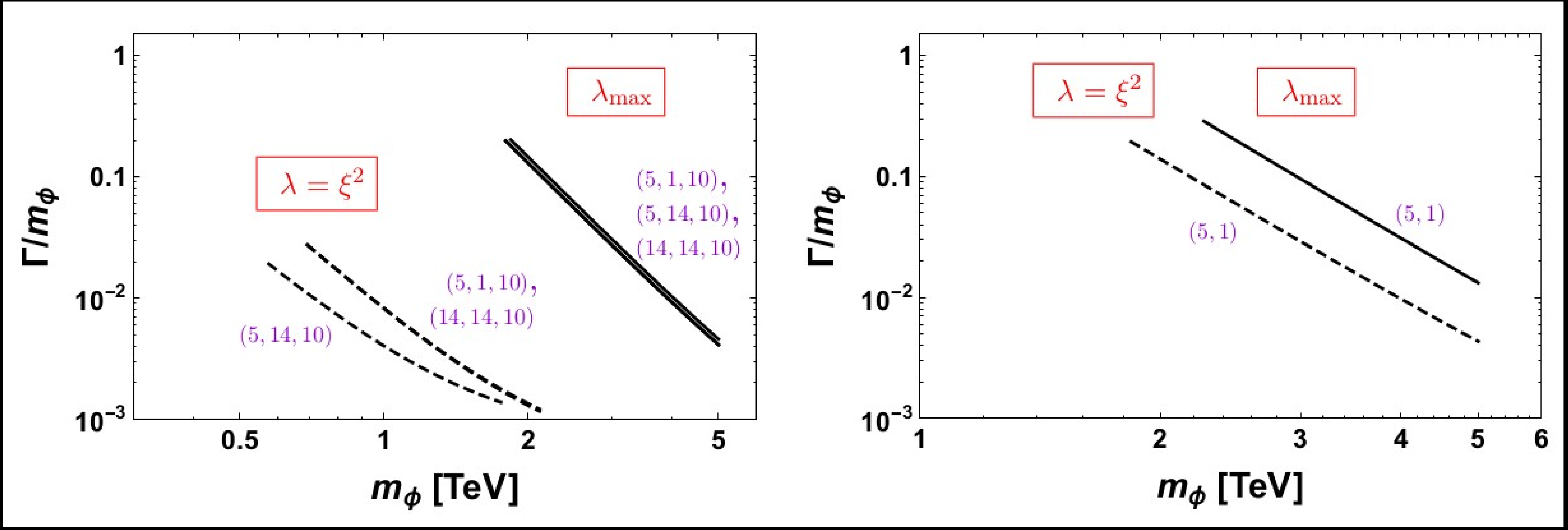
The LHC signals of the global Higgs can be split into two broad cases:

- Case I: All decays involving fermion resonances are closed. The phenomenology is then largely independent of the details of the heavy fermion sector.
  Leading decays are $\phi \to \mathrm{pNGBs}$ $\phi \to t\bar{t}$
- Case II: Some decays involving fermion resonances $\phi \to \bar{\psi}\psi'$ are also open. The phenomenology depends strongly on the realization of the fermion sector.

Case I

Decays

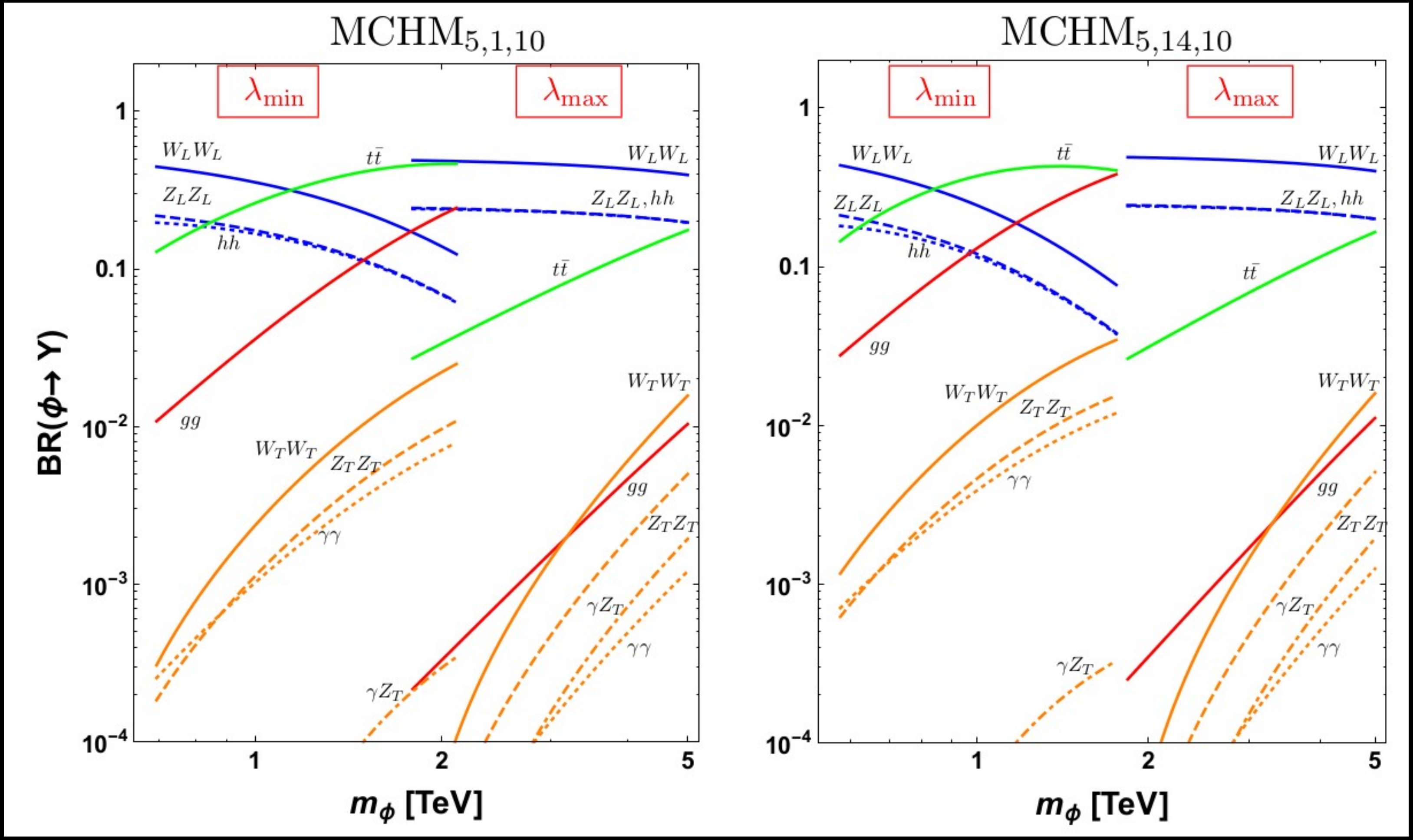
If no decays to fermion resonances are allowed, the global Higgs mainly decays into Higgs, EW bosons and top quarks.



Total width doesn't exceed $\Gamma/m_\phi \sim 0.1$, the global Higgs is a narrow state and NWA applies.

Decays

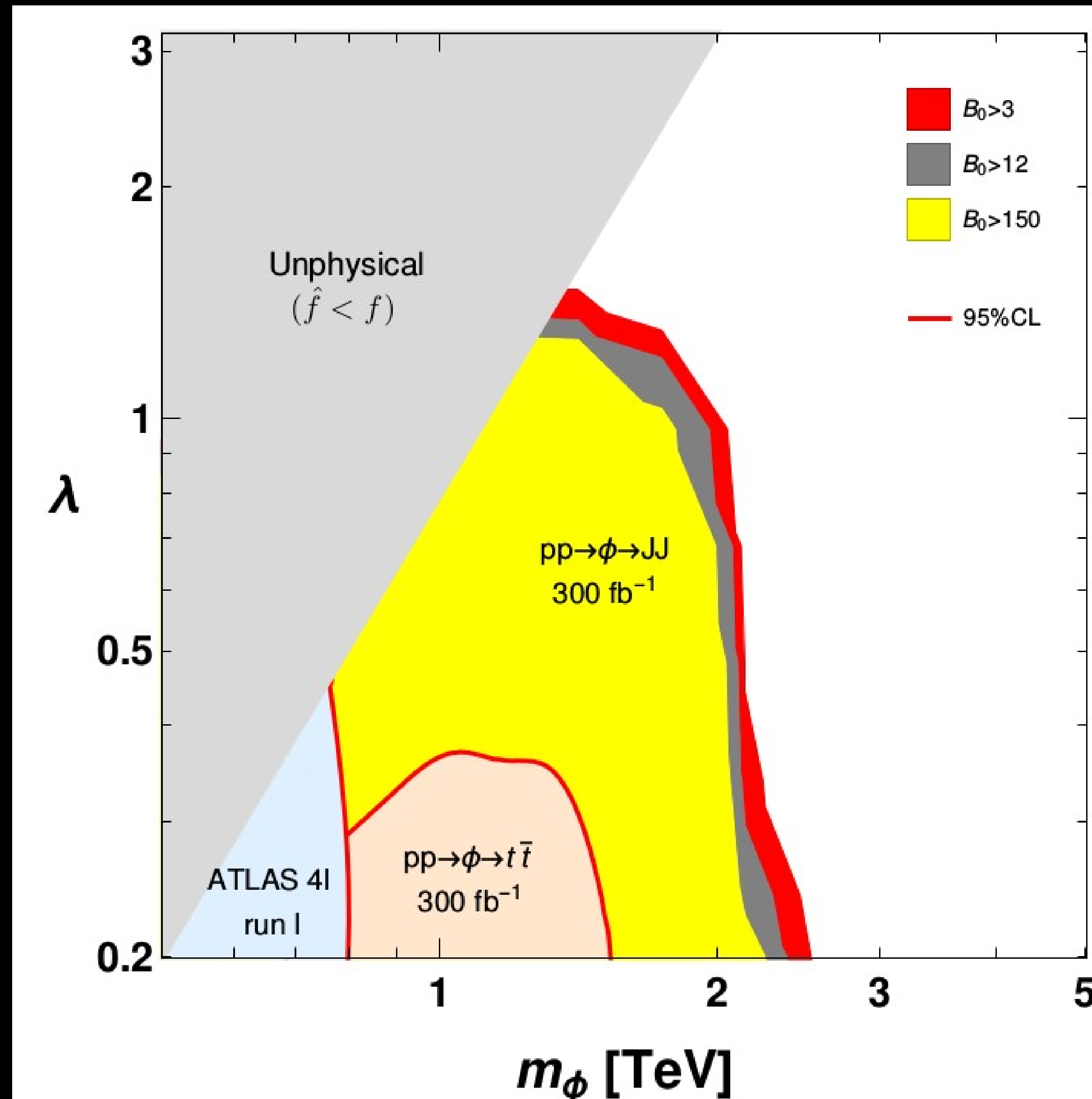
If no decays to fermion resonances, the branching ratios are



Prospects for decays into SM particles

Sensitivities :

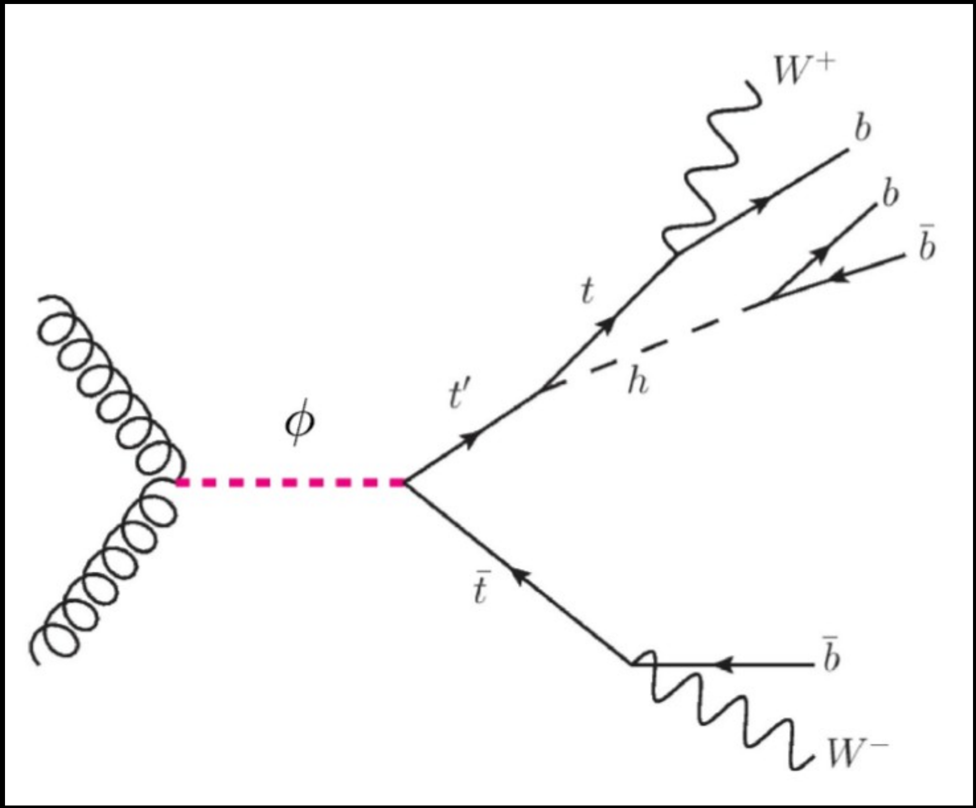
- 4l, ttbar directly obtained from exp. sensitivity
- JJ obtained by extrapolating a 8 TeV JJ background from ATLAS



Case II

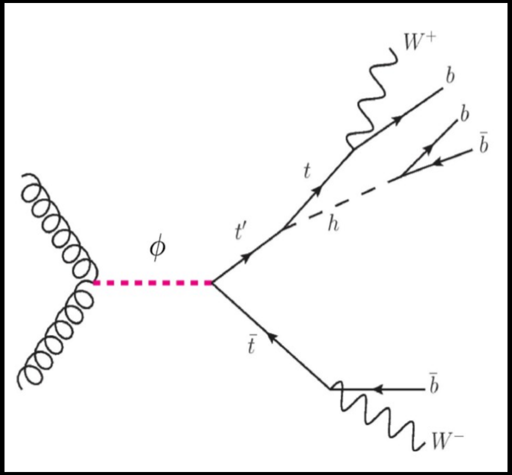
Decays into top partners

When the global Higgs decays into fermion partners, there is a larger model-dependence. We consider the case of decays into top partners (t') only, like



Decays into top partners

When the global Higgs decays into fermion partners, there is a larger model-dependence. We consider the case of decays into top partners (t') only, like



→ A new production mode for t'

→ Resonant topology is very useful to reject background

→ If hadronic decays, boosted t' may produce large-radius jets

4. Conclusions

Summary

- Composite Higgs models contain another scalar: the radial mode of the global-symmetry breaking vaccum -dubbed the global Higgs

- We considered complete fermion sector realizations, taking into account renormalization of the composite sector. Sizeable couplings to gluons arise from resonance loops.

- We evaluated the LHC sensitivity to global-Higgs resonant production.

  – If the global Higgs decays mostly into NGBs and top quarks, sensitivity in boosted hadronic channels gives a reach up to $m \sim 2$–2.5 TeV for 300 fb^{-1}. This case is very predictive.

  – If the global Higgs also decay into t', such channel can compete with standard t' production. Moreover these boosted t' have a sizeable probability to produce t'-jets.

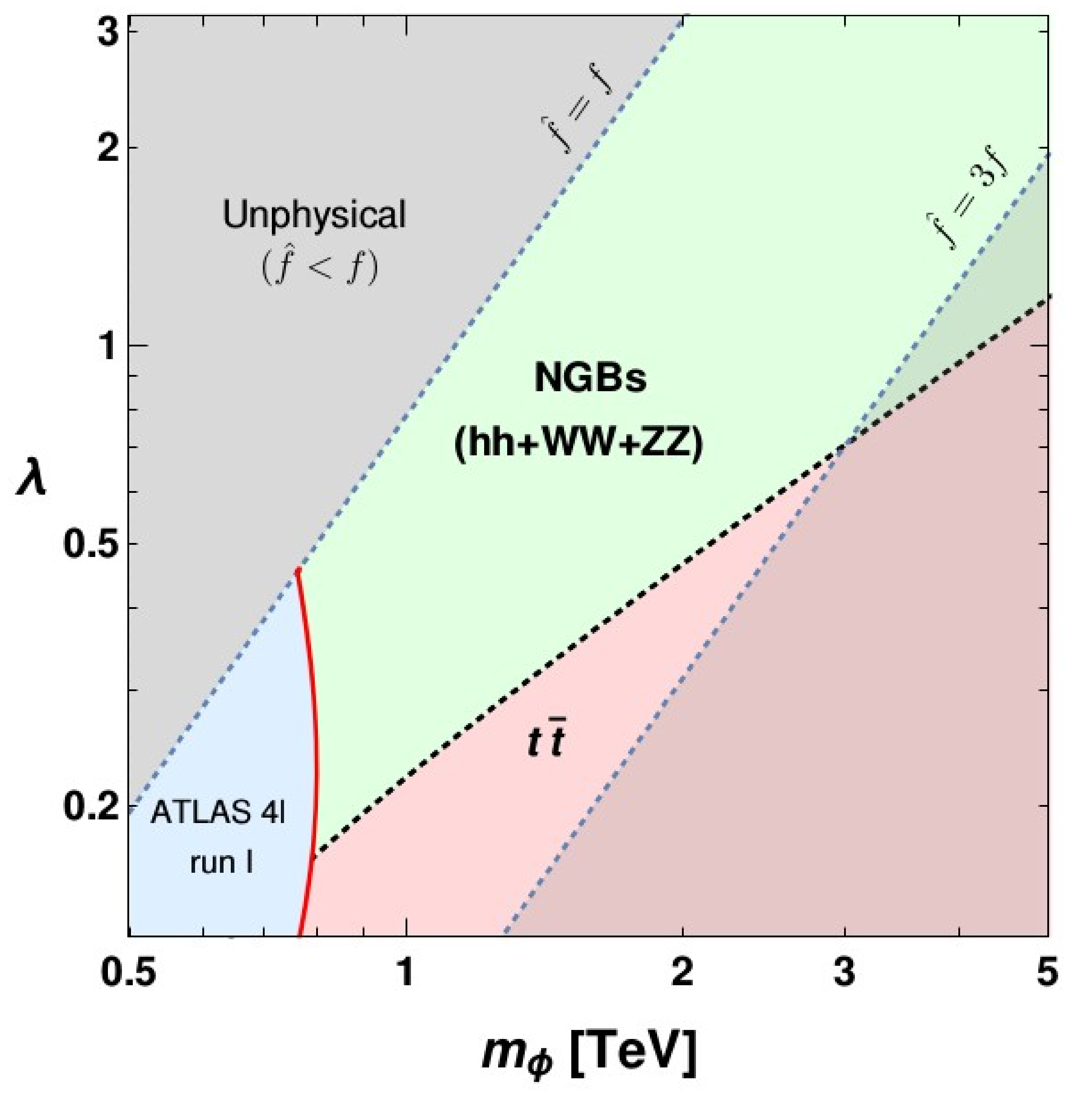
Thanks!

Prospects for decays into SM particles

When $\phi \to \bar{\psi}\psi$ closed,

(leading decays are $\phi \to \mathrm{pNGBs}$ $\phi \to t\bar{t}$)

Decays depends on 2 parameters, chosen to be the global Higgs mass and quartic.



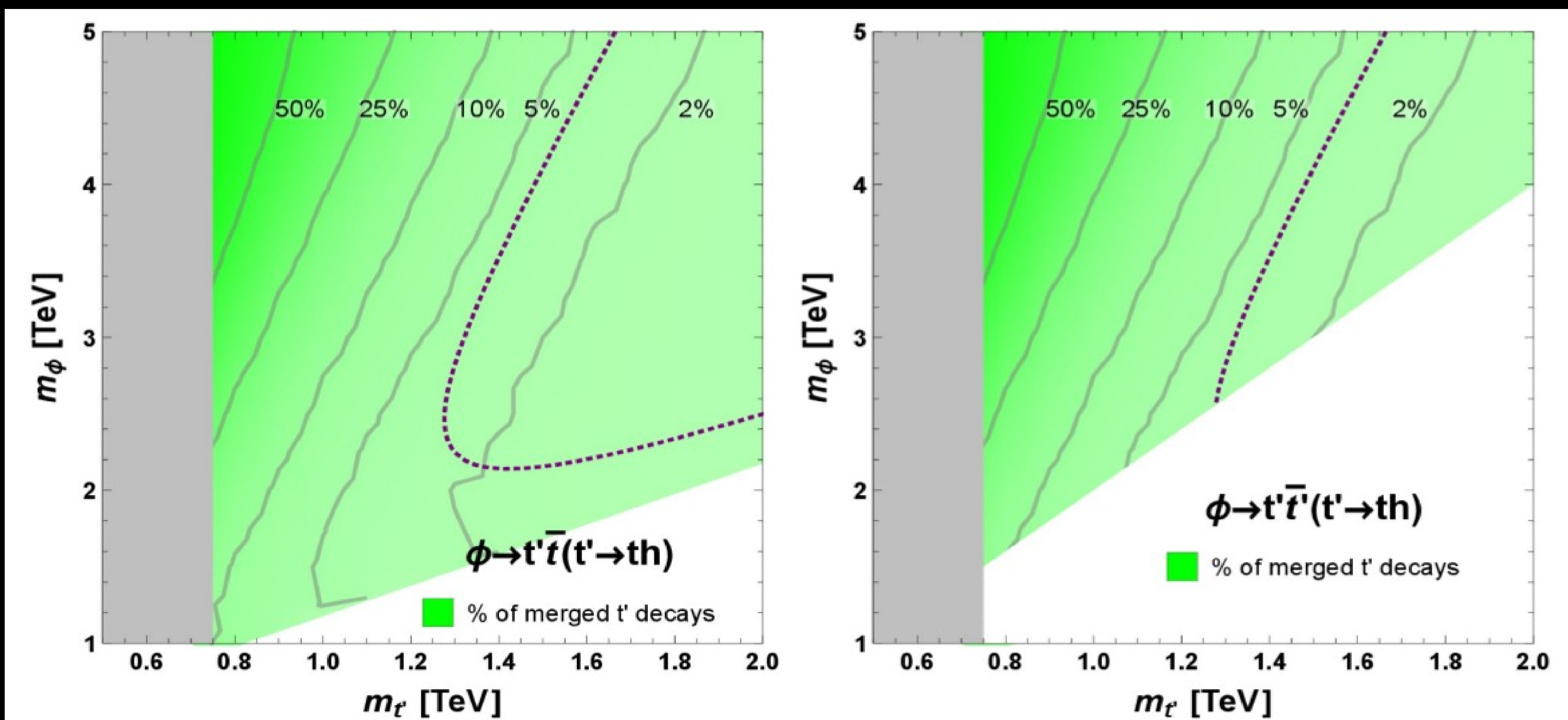
Decays

If decays to fermion resonances are open, the global Higgs width grows. In the extreme limit were all decays are open and masses negligible, one has simply

$$\frac{\Gamma_{\phi\to\bar{\psi}\psi}}{m_\phi} = \begin{pmatrix} 27/4\pi \\ 54/5\pi \\ 117/20\pi \\ 3/4\pi \end{pmatrix} |\xi|^2 \approx \begin{pmatrix} 0.8 \\ 0.9 \\ 0.7 \\ 0.6 \end{pmatrix}, \qquad \begin{matrix} \mathrm{MCHM}_{5,1,10} \\ \mathrm{MCHM}_{5,14,10} \\ \mathrm{MCHM}_{14,14,10} \\ \mathrm{MCHM}_{5,1} \end{matrix}$$

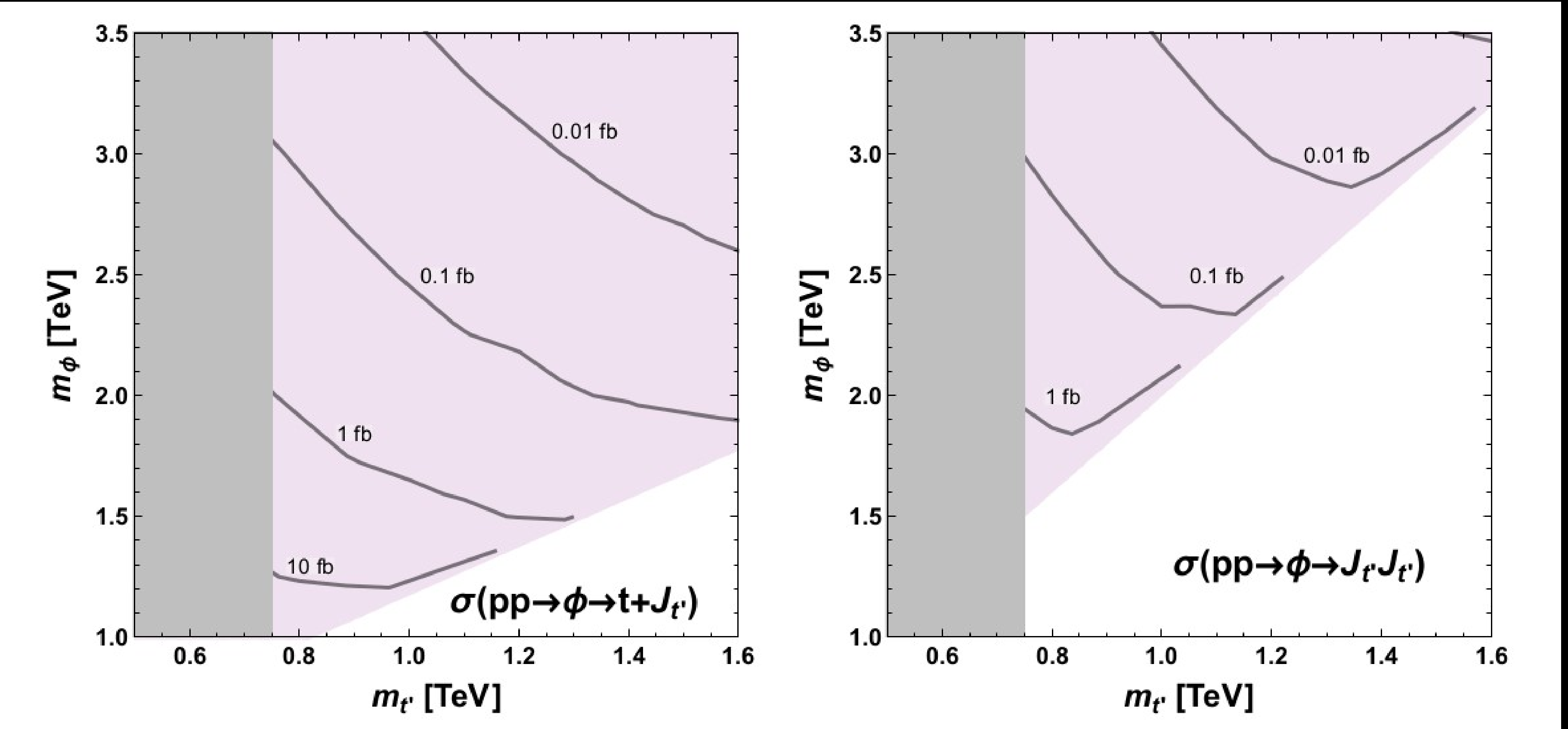
Decays into top partners

If h, t decay hadronically, jet substructure analyses are useful. However, the t' itself might be boosted enough so that its decay products merge. Can this actually happen ?
(If so, it could then be relevant to develop dedicated t'-jets substructure analyses)



Decays into top partners

If h, t decay hadronically, jet substructure analyses are useful. However, the t' itself might be boosted enough so that its decay products merge. Can this actually happen ?
(If so, it could then be relevant to develop dedicated t'-jets substructure analyses)

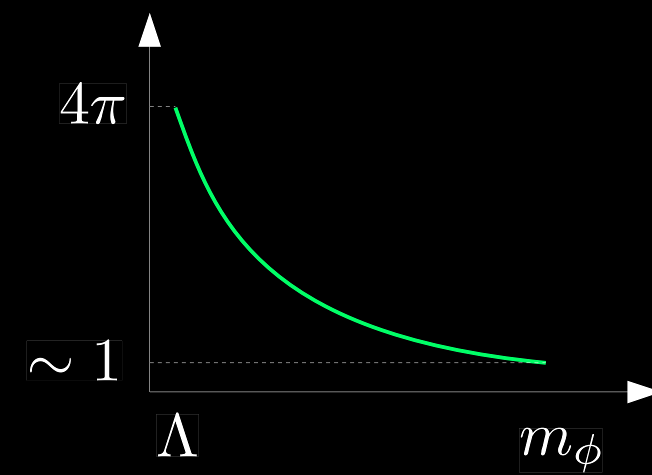


Renormalization

- Yukawa couplings ξ:

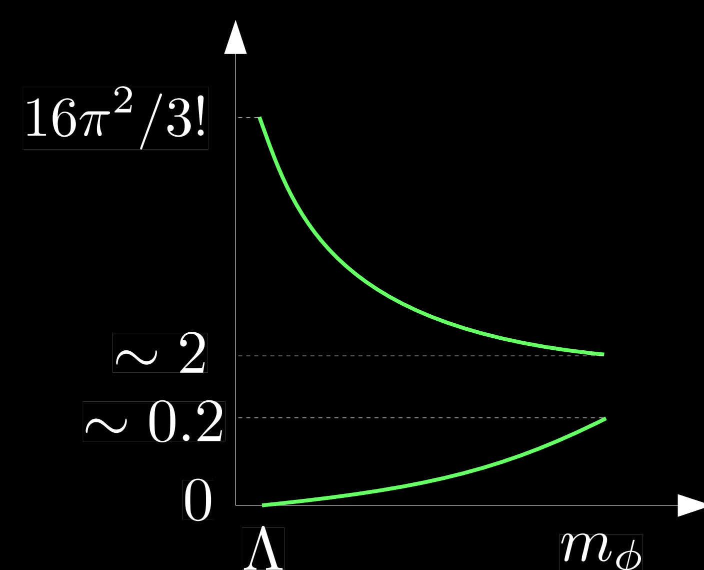
$$\xi_{\text{eff}}^2 = 4N_c\left(N^U\left[\xi_U\xi_U^T + \xi'_U\xi'^T_U\right] + N^D\left[\xi_D\xi_D^T + \xi'_D\xi'^T_D\right]\right)$$

$$\mu\frac{d\xi_{\text{eff}}^2}{d\mu} \approx \frac{\xi_{\text{eff}}^4}{16\pi^2}$$



- Global Higgs quartic λ:

$$\mu\frac{d\lambda}{d\mu} \approx \frac{1}{16\pi^2}\left(26\lambda^2 + 2\lambda\xi_{\text{eff}}^2 - \epsilon\,\xi_{\text{eff}}^4\right)$$



Outlook

A number of exciting directions can be pursued, including:

- Complete analyses including jet substructures for the resonantly produced, boosted t' channels
- Resonant pair-production of the pNGBs from Giacomo et al. via the global Higgs channel
- Investigating possible charged partners of the global Higgs. For ex, if global Higgs embedded in the 14 of SO(5), a heavy 9 of SO(4) is also present.