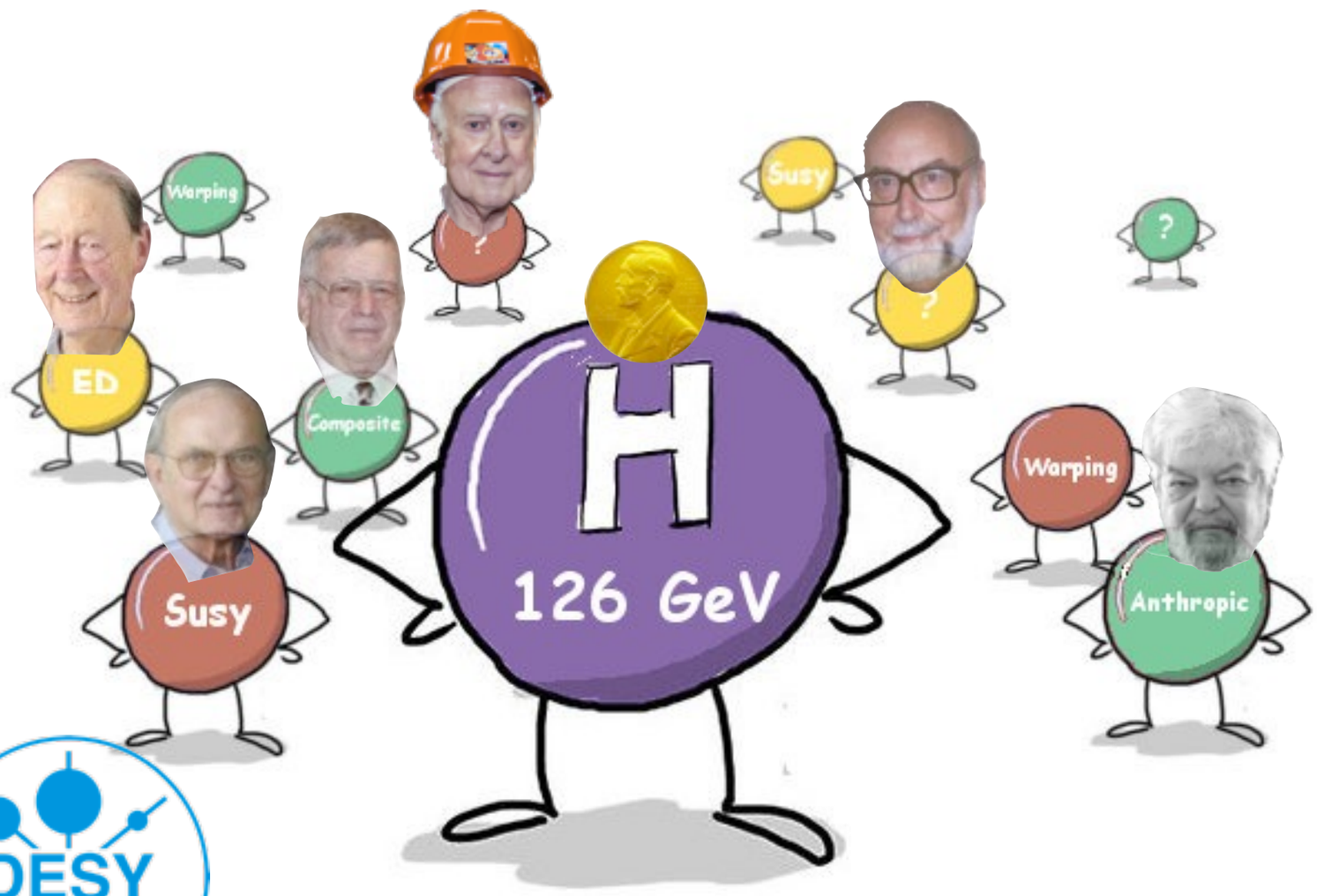
# Non-SUSY BSM Higgs

SUSY 2016

Melbourne, July 3-8, 2016




P. Cámara/C. Grojean adapted from phdcomics.com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# Happy Birthday, Higgs boson!

## As time flies, some consistency in the questions we are facing

**2012**

- Is B. Obama going to be re-elected?
- Is the € going to survive?
- Is the Higgs boson going to be discovered?

**2016**

- Is D. Trump going to be elected?
- Is UK going to leave Europe?
- Is di-gamma going to be discovered?

### Where should you invest your money?

- Greece?
- Spain/Italy?
- Poland?
- Germany?

### Which physics to expect Beyond the Standard Model?

- Technicolor/Higgsless?
- (C)MSSM?
- (Natural) SUSY? Composite Higgs?
- SM?

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# Higgs Portrait

# HEP with a Higgs boson

## The successes have been breathtaking

- in 4 years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
- some of its couplings, e.g. $\kappa_\gamma$, have been measured with 1-loop sensitivity (as EW physics at LEP)

## The meaning of the Higgs

Particle physics is not so much about particles but more about fundamental principles

- About $10^{-10}$s after the Big Bang, the Universe filled with the Higgs substance because it saved energy by doing so:

**"the vacuum is not empty"**

(even when $\hbar \to 0$, not a Casimir effect)

- The masses are emergent quantities due to a non-trivial vacuum structure
- There are only a finite number of particles (the SM ones) that acquire their mass via the Higgs vev

Profound change in paradigm:

missing SM particle ➪ tool to explore SM and venture into physics landscape beyond

# HEP with a Higgs boson

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## Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, CepC, SppC, SHiP

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

M.L. Mangano, Washington '15

- rare Higgs decays: $h\to\mu\mu$, $h\to\gamma Z$
- Higgs flavor violating couplings: $h\to\mu\tau$ and $t\to hc$
- Higgs CP violating couplings
- exclusive Higgs decays (e.g. $h\to J/\Psi+\gamma$ ) and measurement of couplings to light quarks
- exotic Higgs decay channels:

  $h\to \not{E}_T$, $h\to 4b$, $h\to 2b2\mu$, $h\to 4\tau, 2\tau 2\mu$, $h\to 4j$, $h\to 2\gamma 2j$, $h\to 4\gamma$, $h\to\gamma/2\gamma+\not{E}_T$,

  $h\to$isolated leptons$+\not{E}_T$, $h\to 2l+\not{E}_T$, $h\to$one/two lepton-jet(s)+X, $h\to bb+\not{E}_T$, $h\to\tau\tau+\not{E}_T$ ...
- searches for extended Higgs sectors (H, A, $H^\pm$,$H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

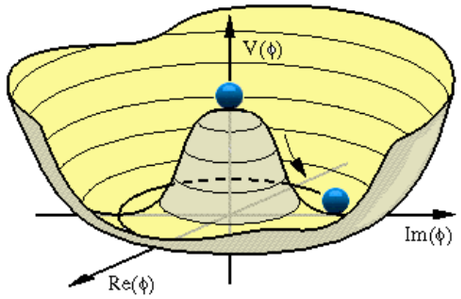
**What is the next mass scale?**

# Higgs physics vs BSM

Several deformations away from the SM affecting Higgs properties are already probed in the vacuum

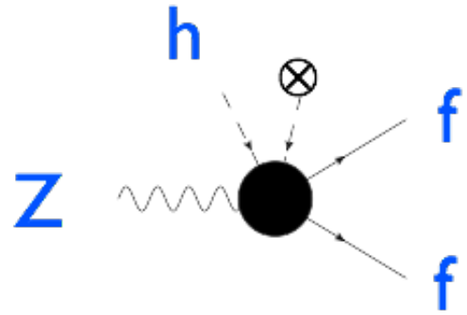
$\phi = v + h$

vacuum

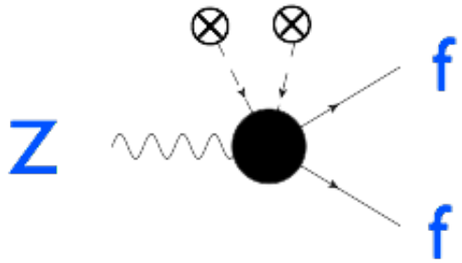



Potentially new BSM-effects in h physics could have been already tested in the vacuum

e.g.




$$= \frac{1}{2v} \times$$




$H^\dagger D_\mu H \bar{f} \gamma^\mu f$

(assuming that the Higgs boson is part of a doublet)

Modifications in $h \to Zff$ related to $Z \to ff$

consistency check not discovery mode

One can use $h \to ZZ \to 4l$ to probe this deformation but hard time to compete with LEP bounds

(courtesy of A. Pomarol@Moriond2014)

# Higgs/BSM Primaries

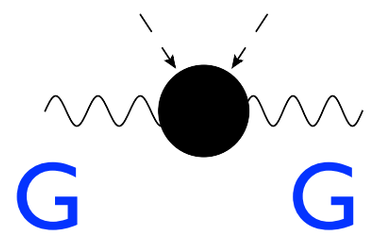
There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

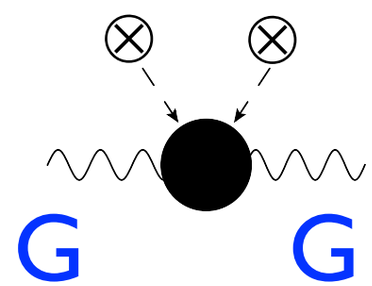
(courtesy of A. Pomarol@HiggsHunting2014)

e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

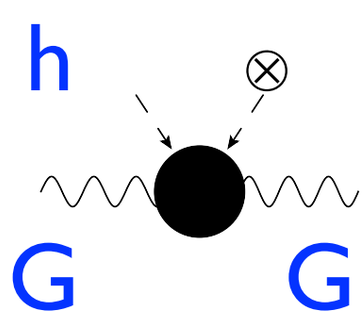
operator is not visible in the vacuum

(redefinition of input parameter)




But can affect h physics:




affects GG →h!

# Higgs/BSM Primaries

## How many of these effects can we have?

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

As many as parameters in the SM: **8**

for one family

*(assuming CP-conservation)*

(courtesy of A. Pomarol@HiggsHunting2014)

| | | |
|---|---|---|
| $g_s$ | $\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ | → GGh coupling |
| $g$ | $\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ | → hγγ coupling |
| $g'$ | $\lvert H\rvert^2 W^a_{\mu\nu} W^{\mu\nu\, a}$ | → hZγ coupling |
| $m_W$ | $\lvert H\rvert^2 \lvert D_\mu H\rvert^2$ | → hVV* (custodial invariant) |
| $m_h$ | $\lvert H\rvert^6$ | → $h^3$ coupling |
| $m_f$ (f=t,b,τ) | $\lvert H\rvert^2 \bar{f}_L H f_R + h.c.$ | → htt, hbb, hττ |

yet to be measured at the LHC

the 6 others have been measured (~15%)

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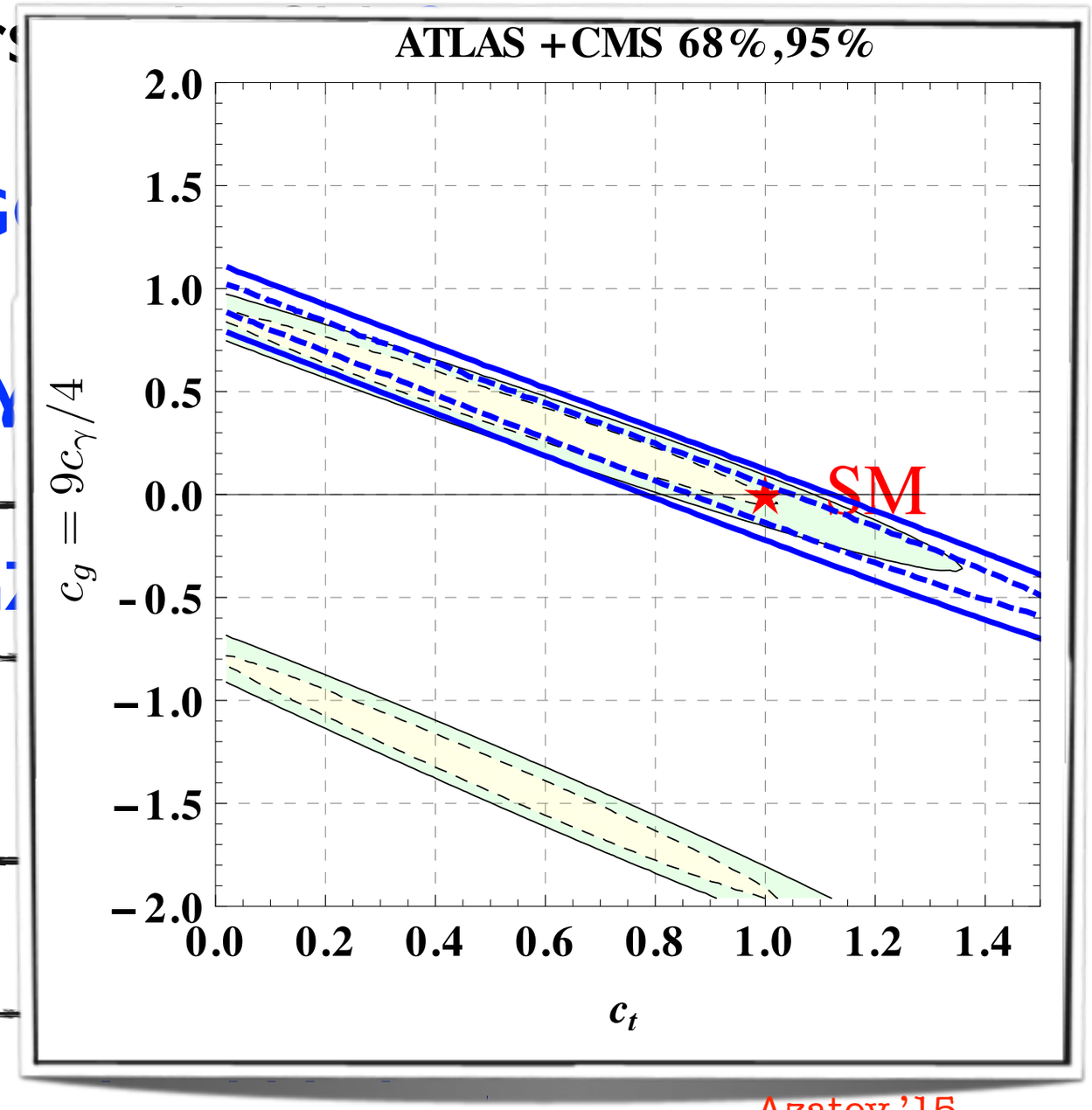
As many as parameters

| | | |
|---|---|---|
| $g_s$ | $\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ | → G |
| $g$ | $\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ | → hγ |
| $g'$ | $\lvert H\rvert^2 W^a_{\mu\nu} W^{\mu\nu\, a}$ | → hZ |
| $m_W$ | $\lvert H\rvert^2 \lvert D_\mu H\rvert^2$ | → |
| $m_h$ | $\lvert H\rvert^6$ | → $h^3$ |
| $m_f$ (f=t,b,τ) | $\lvert H\rvert^2 \bar{f}_L H f_R + h.c.$ | |




Azatov '15

the 6 others have been measured (~15%) up to a flat direction between between the top/gluon/photon couplings

(courtesy of A. Pomarol@HiggsHunting2014)

# Higgs/BSM Primaries

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(courtesy of A. Pomarol@HiggsHunting2014)

Almost a 1-to-1 correspondence with the 8 $\kappa$'s in the Higgs fit

| Coupling | 300 fb$^{-1}$ Theory unc.: All | Half | None | 3000 fb$^{-1}$ Theory unc.: All | Half | None |
|---|---|---|---|---|---|---|
| $\kappa_Z$ | 8.1% | 7.9% | 7.9% | 4.4% | 4.0% | 3.8% |
| $\kappa_W$ | 9.0% | 8.7% | 8.6% | 5.1% | 4.5% | 4.2% |
| $\kappa_t$ | 22% | 21% | 20% | 11% | 8.5% | 7.6% |
| $\kappa_b$ | 23% | 22% | 22% | 12% | 11% | 10% |
| $\kappa_\tau$ | 14% | 14% | 13% | 9.7% | 9.0% | 8.8% |
| $\kappa_\mu$ | 21% | 21% | 21% | 7.5% | 7.2% | 7.1% |
| $\kappa_g$ | 14% | 12% | 11% | 9.1% | 6.5% | 5.3% |
| $\kappa_\gamma$ | 9.3% | 9.0% | 8.9% | 4.9% | 4.3% | 4.1% |
| $\kappa_{Z\gamma}$ | 24% | 24% | 24% | 14% | 14% | 14% |

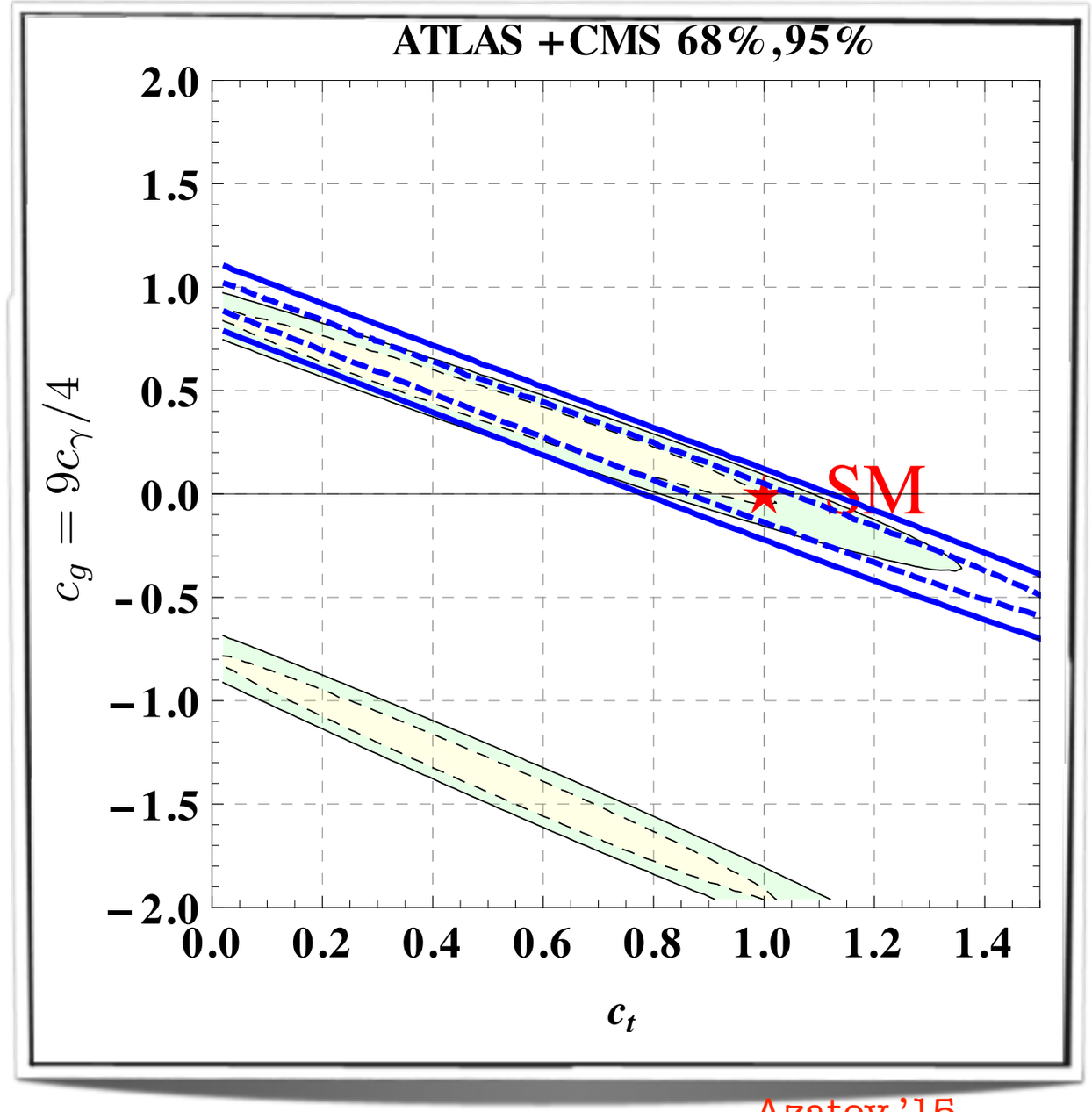
Atlas projection

With some important differences:

1) width hypothesis built-in

2) $\kappa_W/\kappa_Z$ is not a primary
(constrained by $\Delta\rho$ and TGC)

3) $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$ do not separate UV and IR contributions



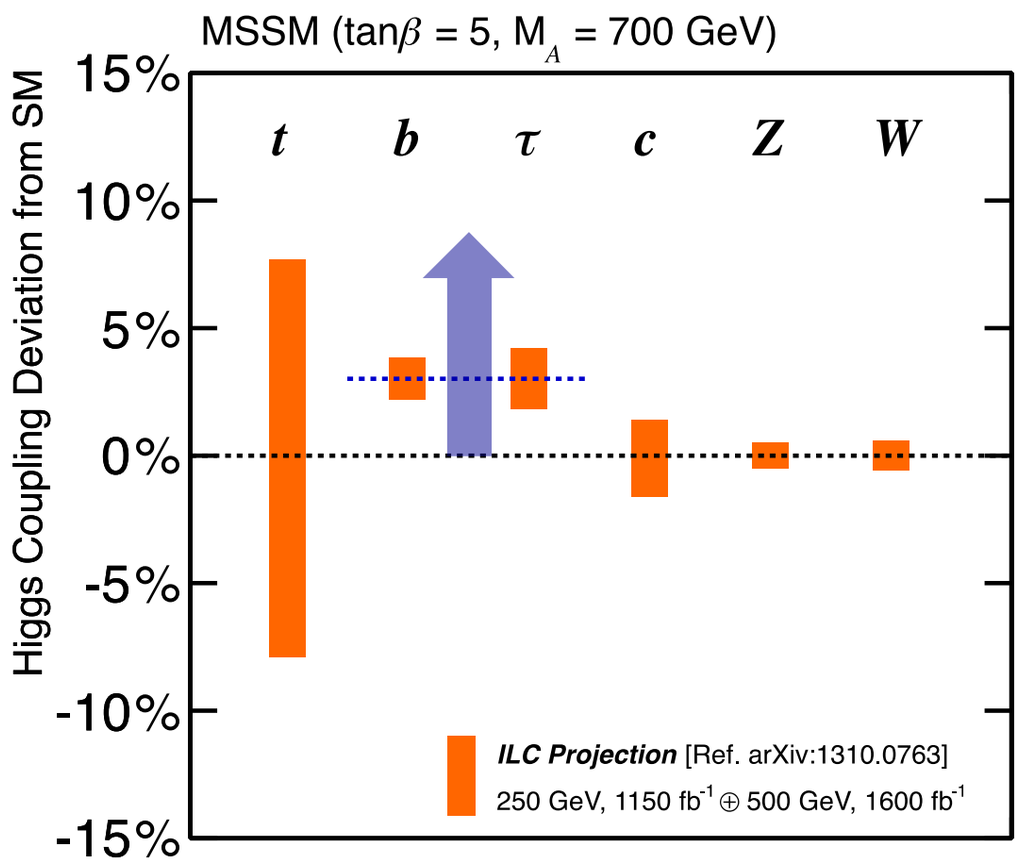

Azatov '15

up to a flat direction between between the top/gluon/photon couplings

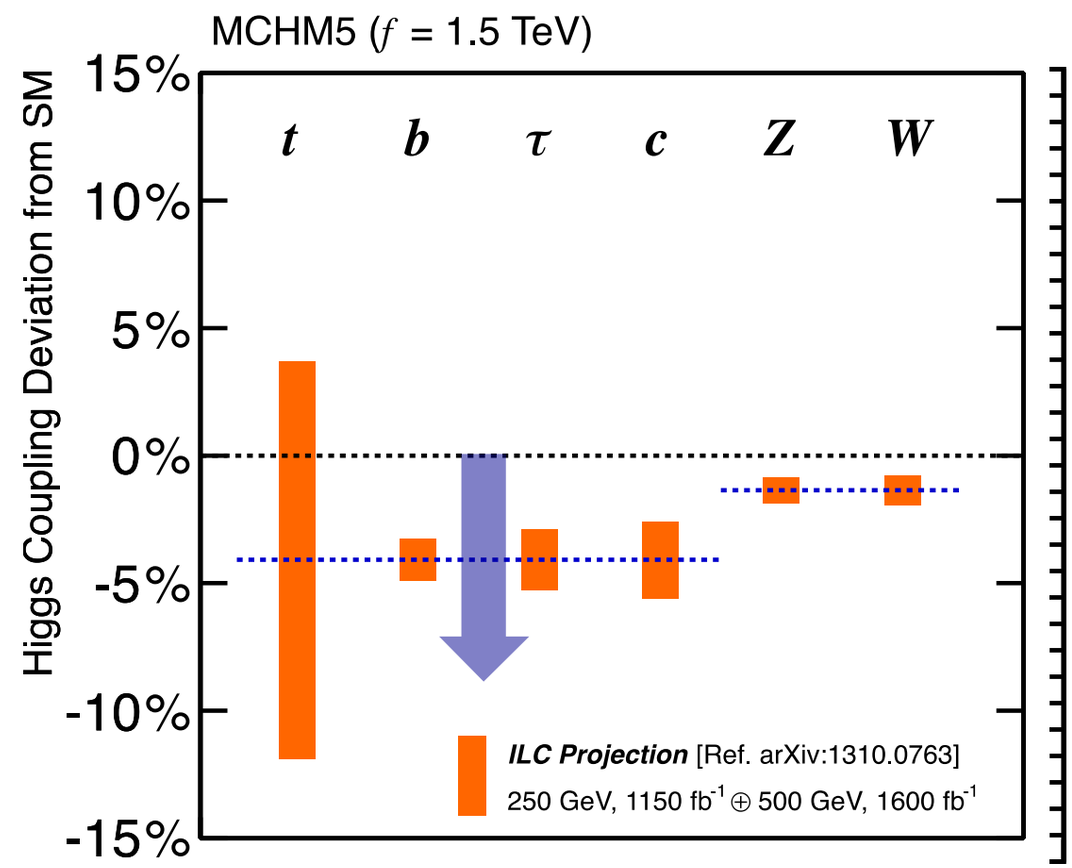
# Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

**Supersymmetry**
**(MSSM)**




**Composite Higgs**
**(MCHM5)**




ILC Physics WG, '15

# Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

~~ expected largest relative deviations ~~

| | hff | hVV | hγγ | hγZ | hGG | $h^3$ |
|---|---|---|---|---|---|---|
| **MSSM** | √ | | √ | √ | √ | |
| **NMSSM** | √ | √ | √ | √ | √ | |
| **PGB Composite** | √ | √ | | √ | | √ |
| **SUSY Composite** | √ | √ | √ | √ | √ | √ |
| **SUSY partly-composite** | | | √ | √ | √ | √ |
| **"Bosonic TC"** | | | | | | √ |
| **Higgs as a dilaton** | | | √ | √ | √ | √ |

A. Pomarol, Naturalness '15

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The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

~~ expected largest relative deviations ~~

| | hff | hVV | hγγ | hγZ | hGG | $h^3$ |
|---|---|---|---|---|---|---|
| **MSSM** | √ | | √ | √ | √ | |
| **NMSSM** | √ | √ | √ | | √ | |
| **PGB Composite** | | | | | | √ |
| | | | | √ | √ | √ |
| **SUS** | | | √ | √ | √ | √ |
| | | | | | | √ |
| **Higgs as a dilaton** | | | √ | √ | √ | √ |

There exist some physics scenarios where high energy thresholds are important and complementary to physics near Higgs threshold (HH & ttH productions)

A. Pomarol, Naturalness '15

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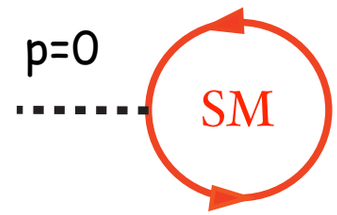
# BSM Higgs: Naturalness aka where is everybody else?

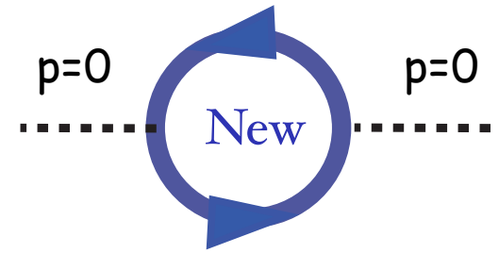
# Higgs couplings as a test of naturalness

$$-(125\ \text{GeV})^2\left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$$\delta m_H^2 =$$




$$+$$

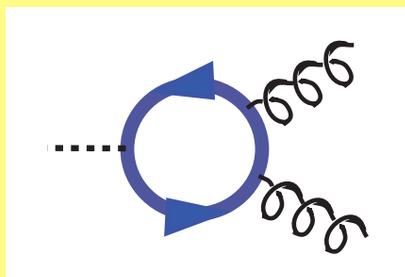



$$\sim m_H^2$$

charged particles

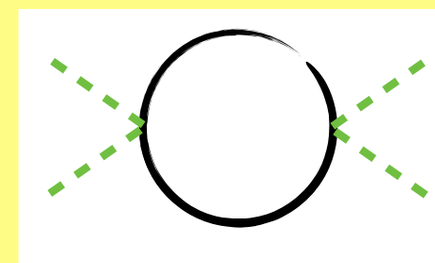
generically

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu|H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

# Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

NP

typical mass scale

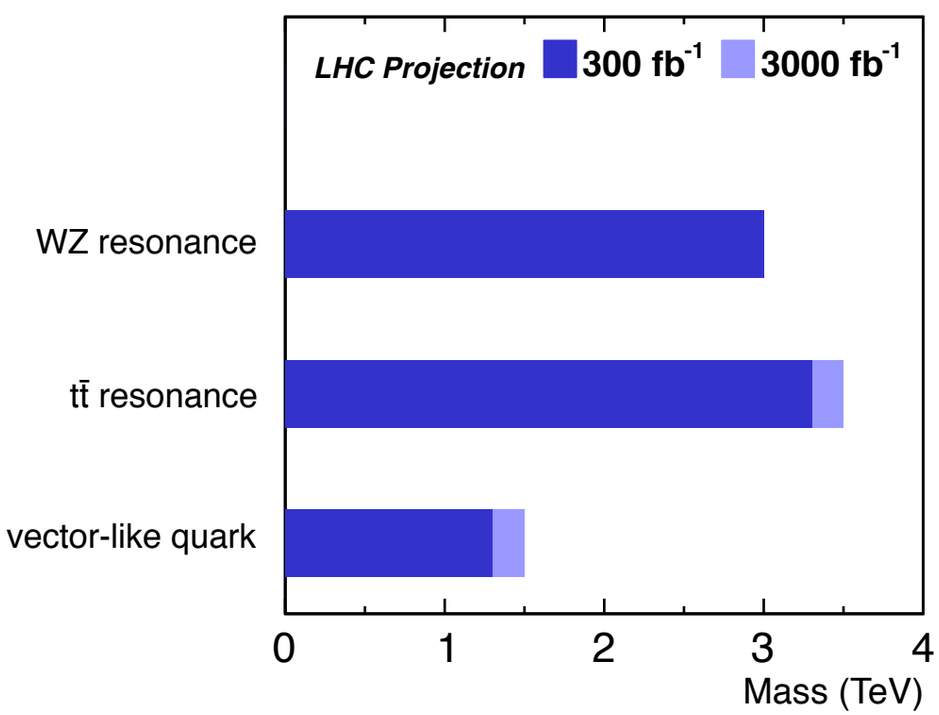
$M = g_* f$

SM

EW scale v=246GeV

$g, g', y_t$

$g^2_{SM} / g_*$




**LHC direct search**

- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$

Which one is doing best?
it depends on value of $g_*$

# Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

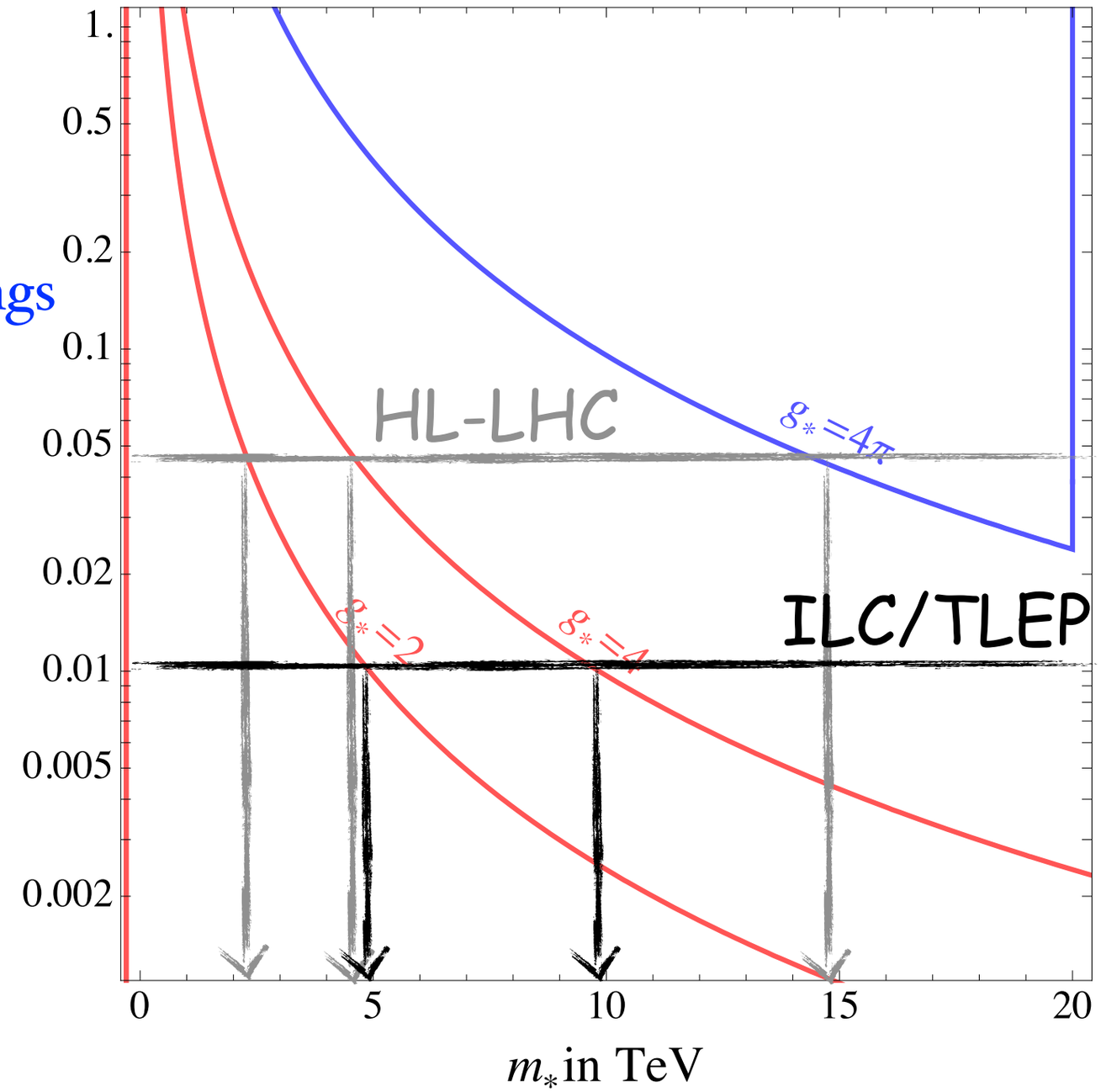
**Mass reach:**

a deviation in Higgs couplings also teaches us on the maximum mass scale to search for!

e.g. 10% deviation ⇒ $m_V$ < 10TeV

i.e. resonance within the reach of FCC-hh

Higgs couplings



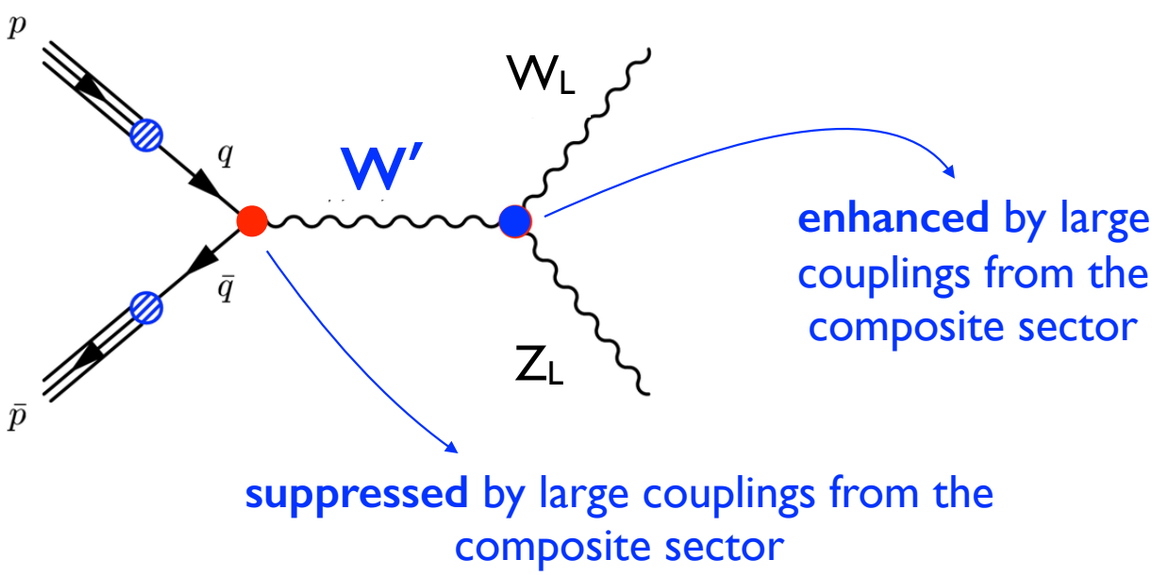

Rattazzi, BSM@100TeV, CERN '14

direct searches

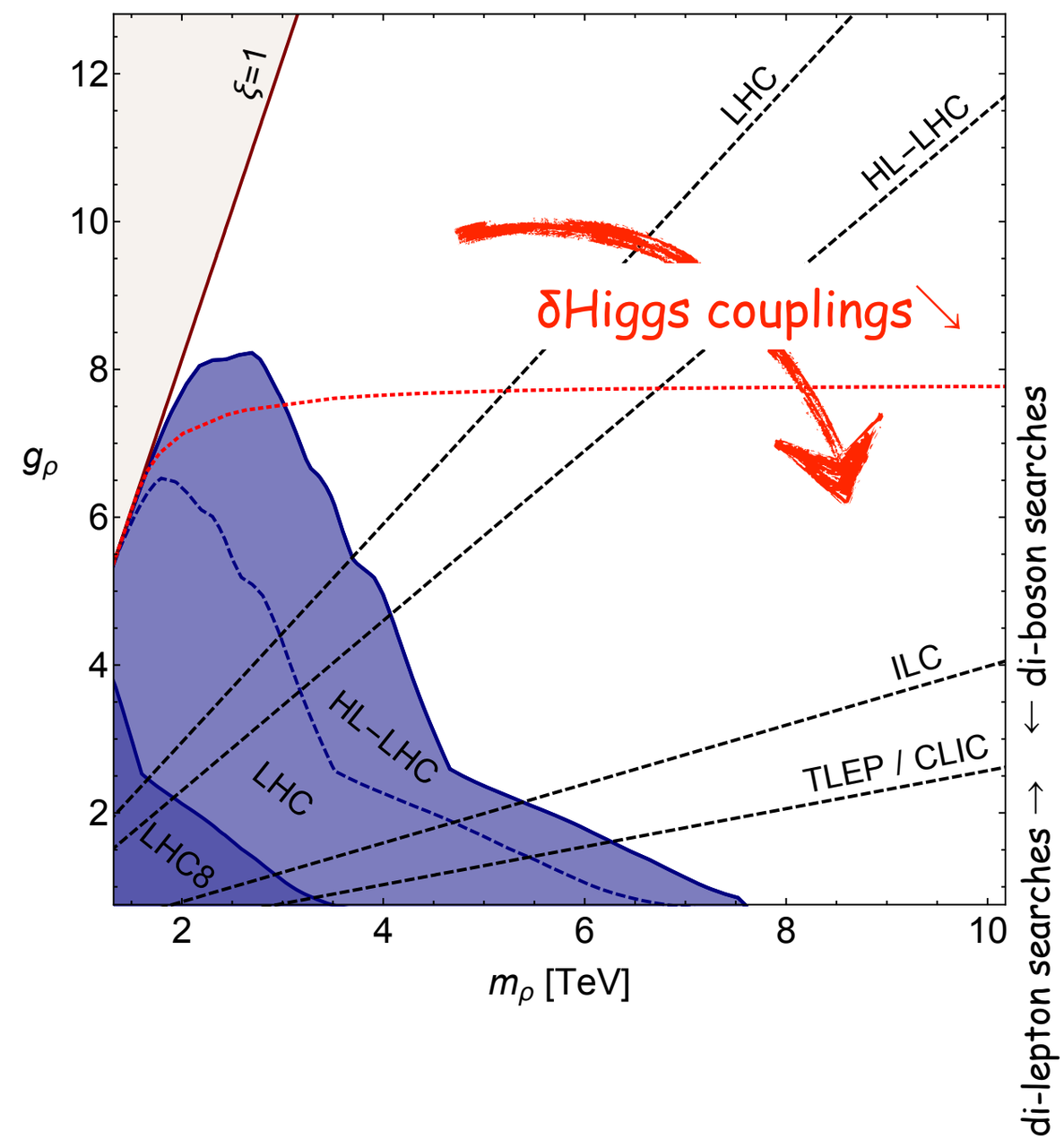
# Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15




DY production xs of resonances decreases as $1/g_\rho^2$



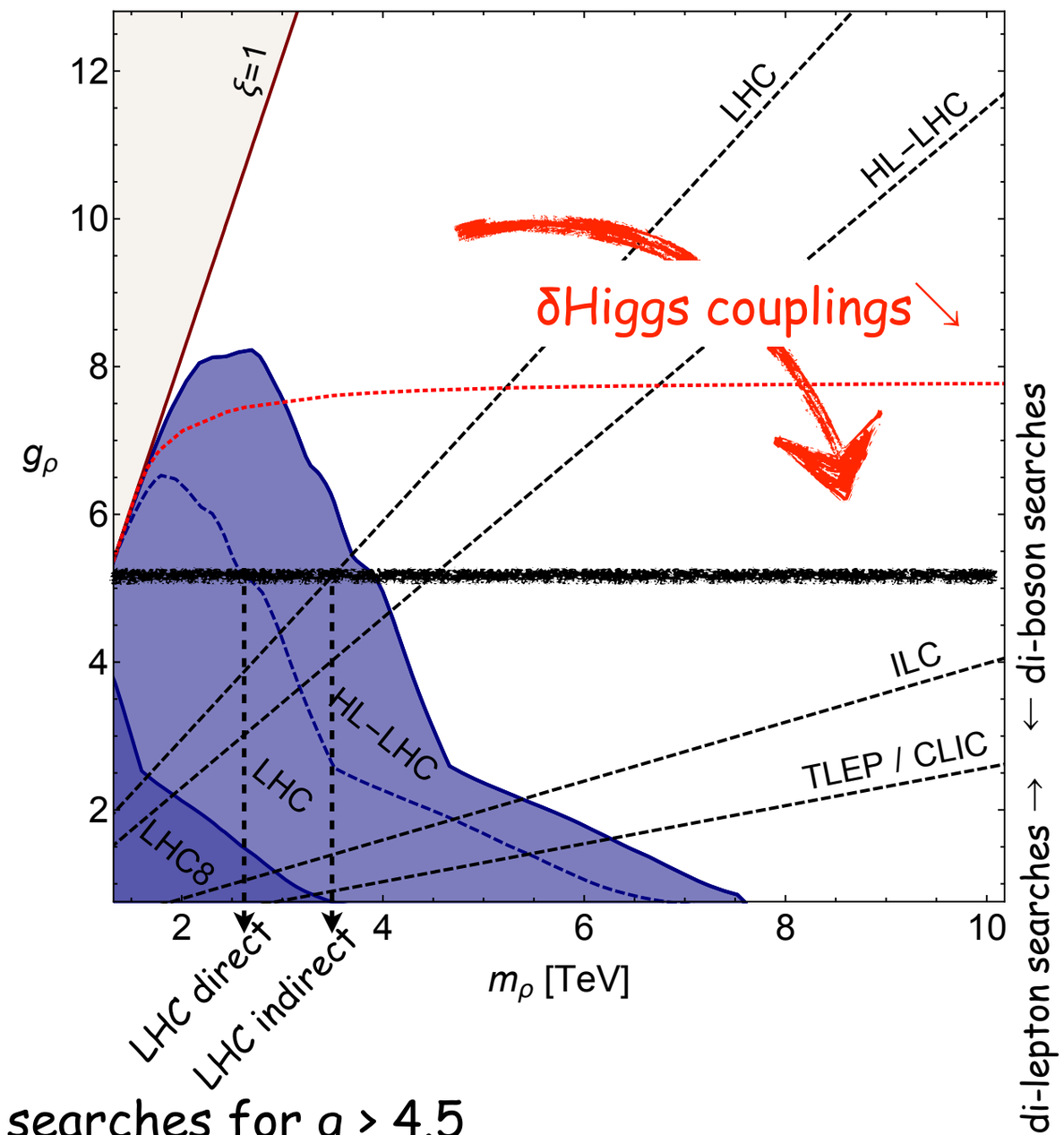
# Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15

| Collider | Energy | Luminosity | $\xi$ [$1\sigma$] |
|---|---|---|---|
| LHC | 14 TeV | $300\,\mathrm{fb}^{-1}$ | $6.6 - 11.4 \times 10^{-2}$ |
| LHC | 14 TeV | $3\,\mathrm{ab}^{-1}$ | $4 - 10 \times 10^{-2}$ |
| ILC | 250 GeV<br>+ 500 GeV | $250\,\mathrm{fb}^{-1}$<br>$500\,\mathrm{fb}^{-1}$ | 4.8-7.8 $\times 10^{-3}$ |
| CLIC | 350 GeV<br>+ 1.4 TeV<br>+ 3.0 TeV | $500\,\mathrm{fb}^{-1}$<br>$1.5\,\mathrm{ab}^{-1}$<br>$2\,\mathrm{ab}^{-1}$ | 2.2 $\times 10^{-3}$ |
| TLEP | 240 GeV<br>+ 350 GeV | $10\,\mathrm{ab}^{-1}$<br>$2.6\,\mathrm{ab}^{-1}$ | $2 \times 10^{-3}$ |

DY production xs of resonances decreases as $1/g_\rho^2$




- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

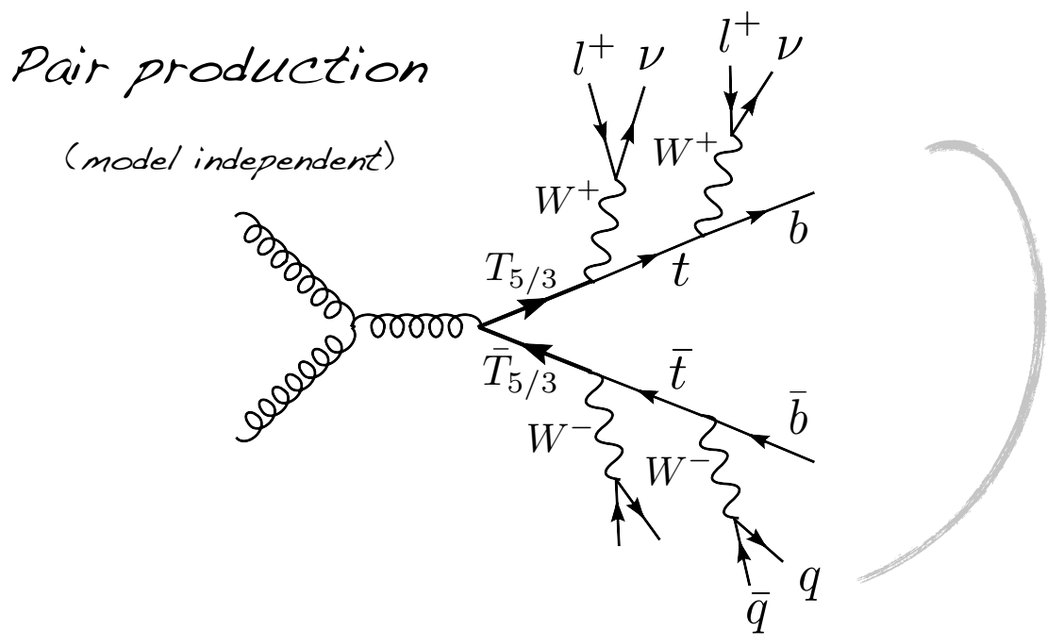
indirect searches at LHC over-perform direct searches for g > 4.5

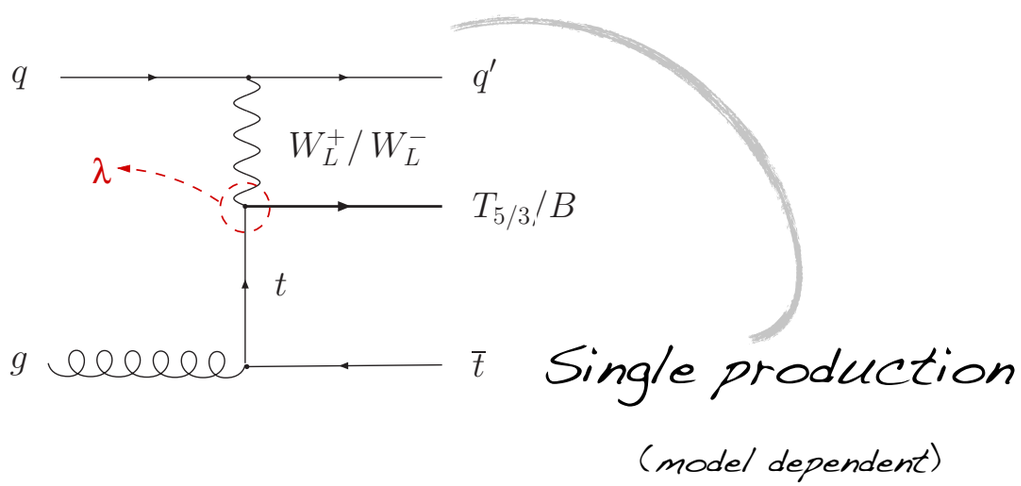
indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

# Searching for the top partners

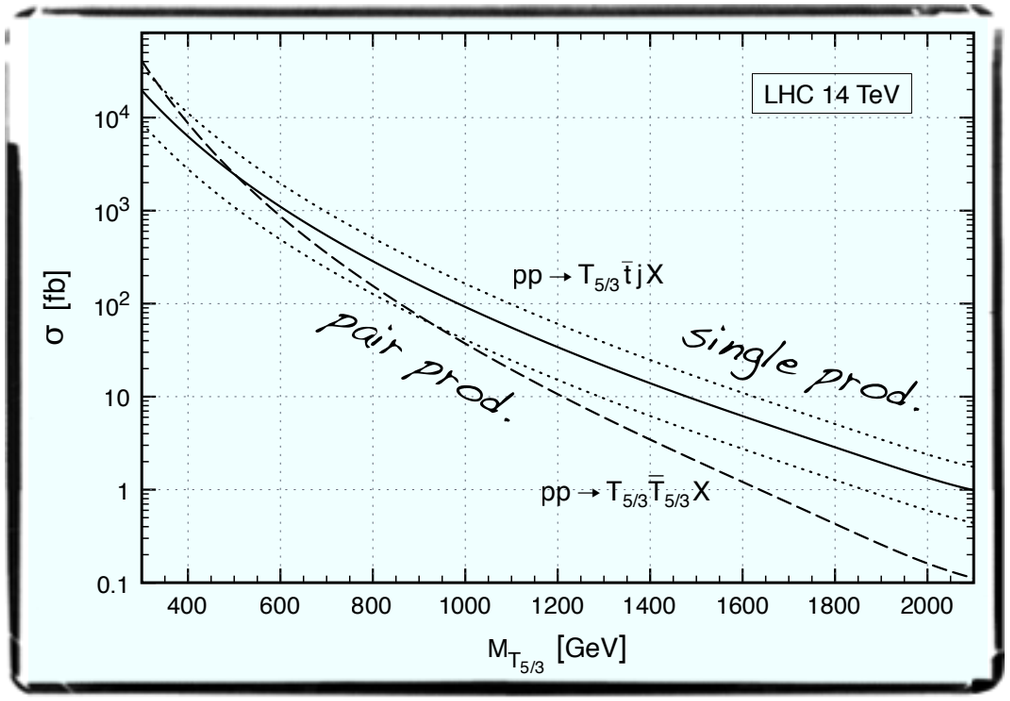
## top partners searches in composite models:

Search in same-sign dilepton events



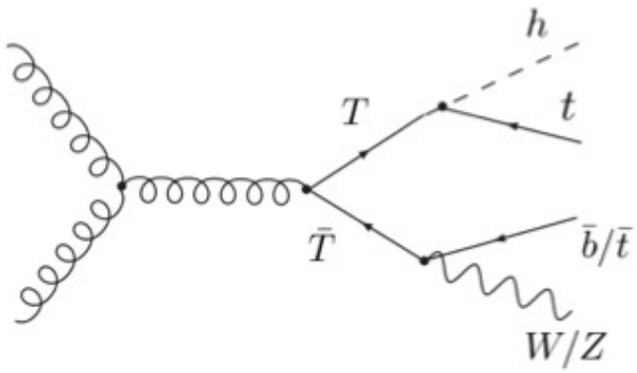




- $tt$+jets is not a background [except for charge mis-ID and fake $e^-$]
- the resonant ($tW$) invariant mass can be reconstructed




[Contino, Servant '08]

# Searching for the top partners




- $\ell^\pm$ + 4b final state Aguilar-Saavedra '09

$$T\bar{T} \to Ht\,W^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$

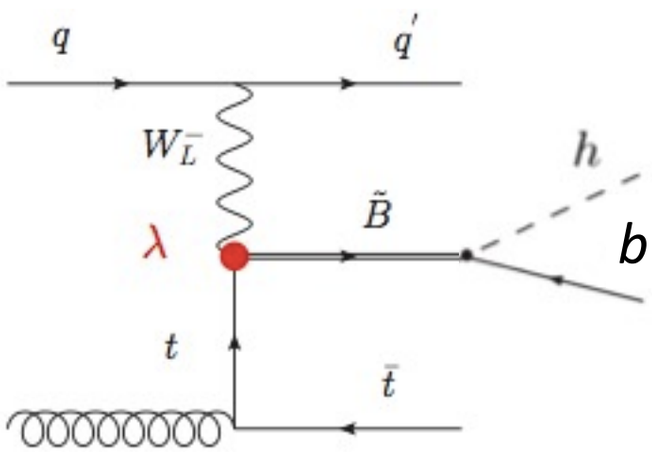
$$T\bar{T} \to Ht\,V\bar{t} \to HW^+b\,VW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^\pm$ + 6b final state Aguilar-Saavedra '09

$$T\bar{T} \to Ht\,H\bar{t} \to HW^+b\,HW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$$

- $\gamma\gamma$ final state Azatov et al '12

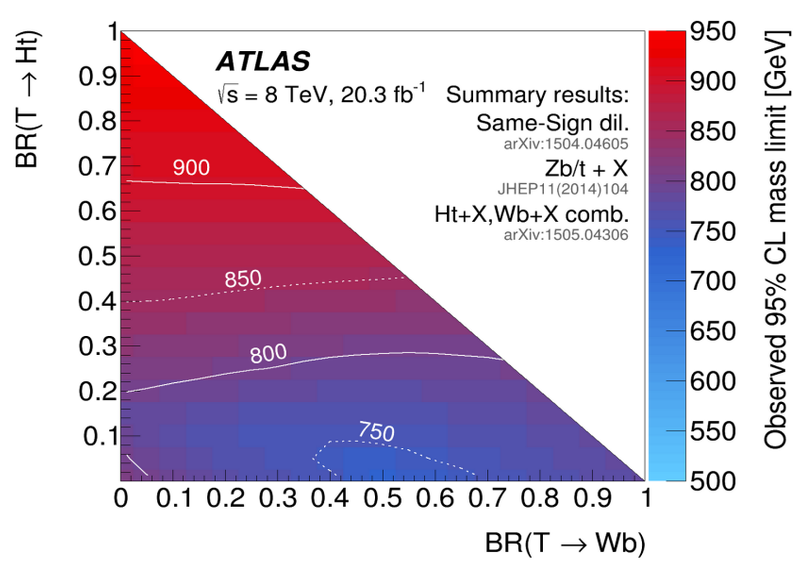
$$thbW/thtZ/thth,\ h \to \gamma\gamma$$




- $\ell^\pm$ + 4b final state Vignaroli '12

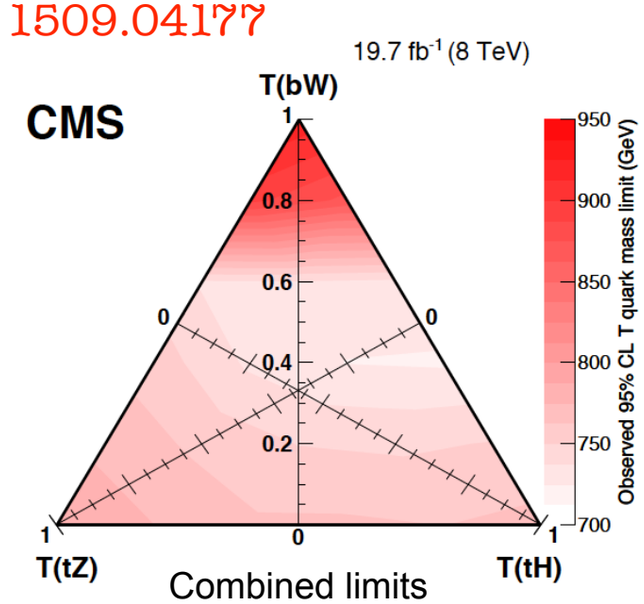
$$pp \to (\tilde{B} \to (h \to bb)b)t + X$$

1505.04306




(*) Not a combination. Only most restrictive individual bounds shown.

1509.04177



# Other searches of the missing top partners

*" Looking and not finding is different than not looking "*

giving the null search results, the top partners should either be

- **heavy** (harder to produce because of phase space)
- **stealthy** (easy to produce but hard to distinguish from background, e.g. $m_{stop} \sim m_{top}$)
- **colorless** (hard to produce, unusual decay)

| | Scalar Top Partner | Fermion Top Partner |
|---|---|---|
| All SM Charges | SUSY | pNGB/RS |
| EW Charges | Folded SUSY | Quirky Little Higgs |
| No SM Charges | ??? | Twin Higgs |

need to go beyond traditional searches

require **hidden QCD** with a higher confining scale:

⇒ 1) hidden glueball ($0^{++}$) that can mix with Higgs

$h \to G_0 G_0 \to 4l$ with displaced vertices

Curtin, Verhaaren '15

⇒ 2) emerging jets

Schwaller, Stolarski, Weiler '15

(C. Verhaaren @NKPT'16)

# Searching for the top partners with Higgs

In Higgs measurements, top partners easily hide themselves

lightness of the Higgs makes it impossible to resolve the top-loop

top partners run in the loop and modify top Yukawa couplings ⇒ net effect=0

⇛ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

⇚

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

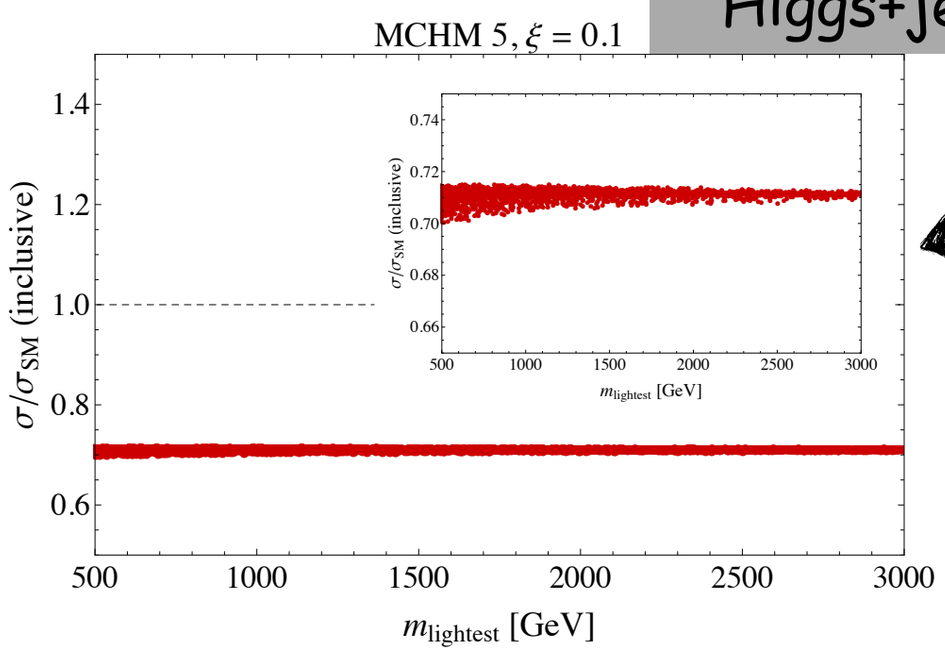
$$\frac{\sigma(gg\to h)}{\mathrm{SM}} = (1+(c_g-c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\mathrm{SM}} = (1+(c_\gamma-4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$ .

Need to look at differential distributions

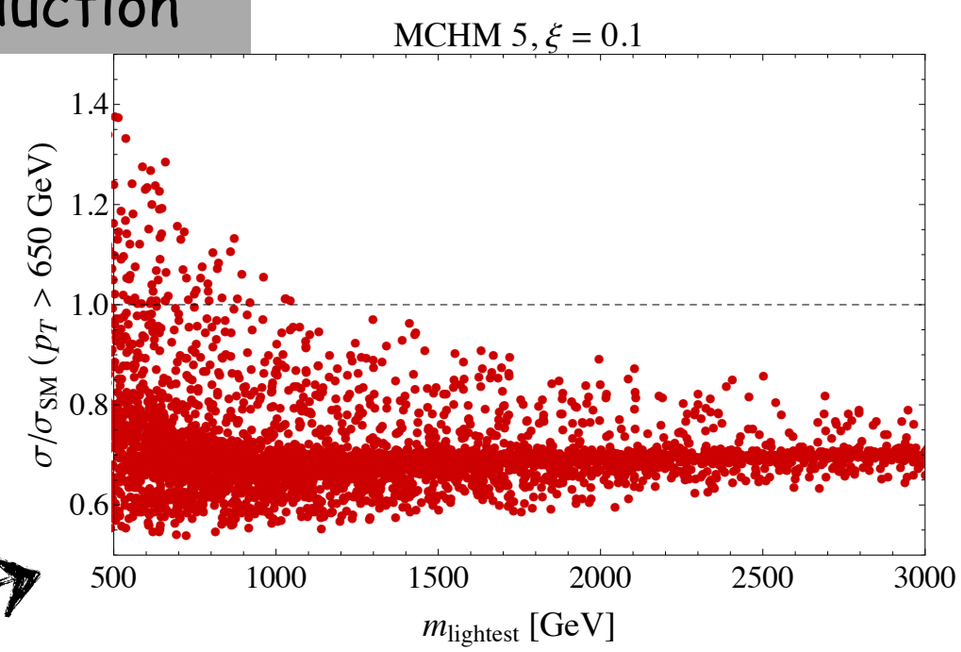
Higgs+jet, off-shell Higgs production

Grojean et al '13




inclusive rate

Higgs w/ $p_T$>500 GeV



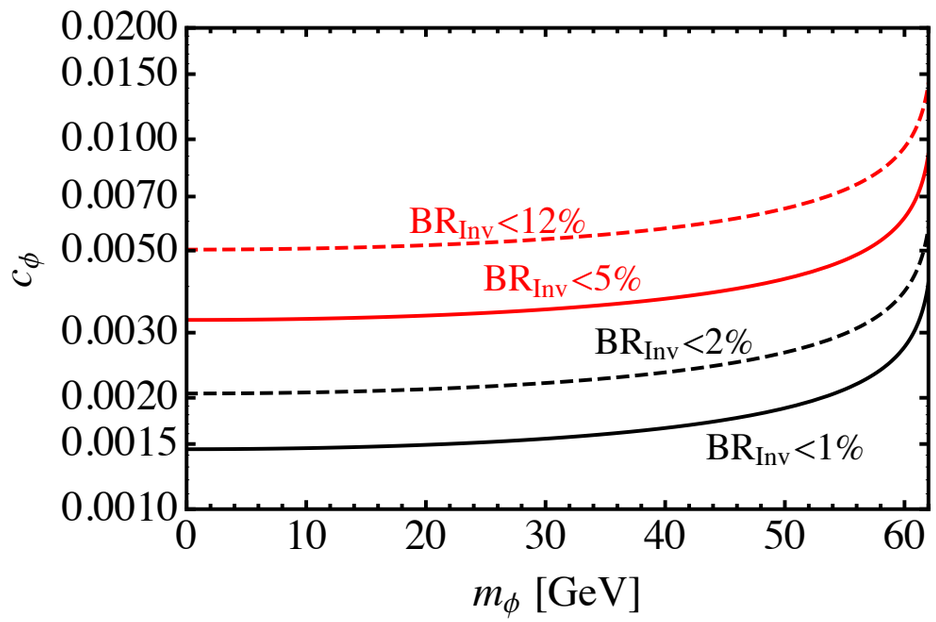
3

# BSM Higgs: Dark Matter

# Higgs portals and Higgs exotic decays

## $|H|^2$ and HL are SM-singlet of low dimension

they can have large (renormalizable) couplings to hidden/dark sector
that could make up the DM relic abundance




$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

# Higgs portals and Higgs exotic decays

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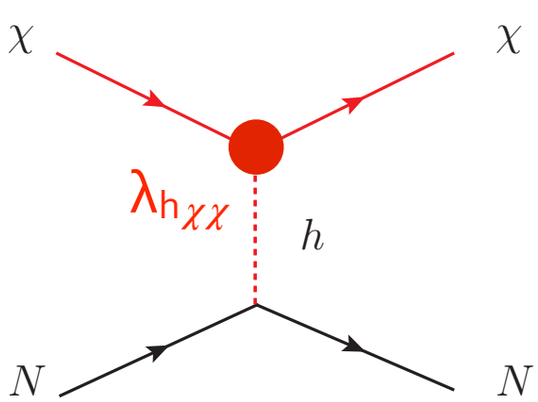
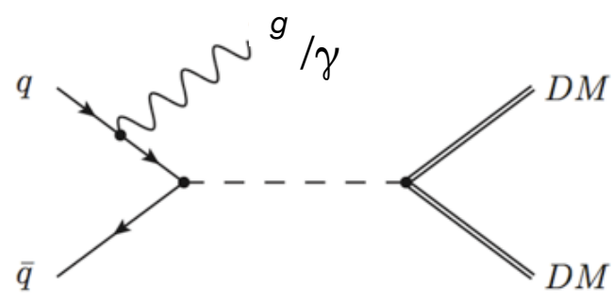
### DM direct search



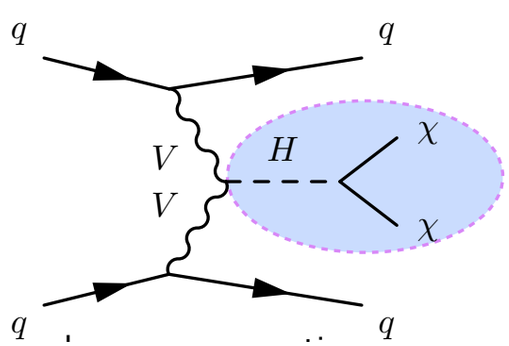

### LHC direct search

- MET + mono $\gamma$/jet

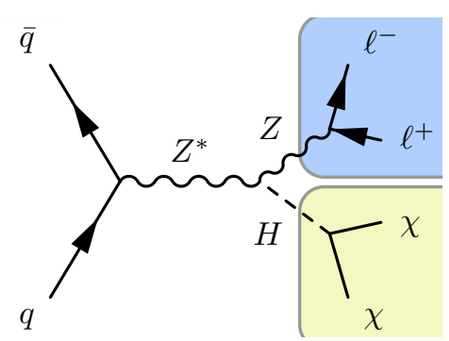



subdominant for Higgs portals

- VBF & ZH searches




CMS
PAS HIG-13-030




ATLAS
CONF-2013-011

### LHC indirect search

$BR_{inv}$
from Higgs coupling fits

$$\Gamma_{tot} = \Gamma_{tot}^{SM} \cdot \frac{\sum_X \kappa_X^2 \cdot BR_X^{SM}}{1 - BR_{BSM}}$$

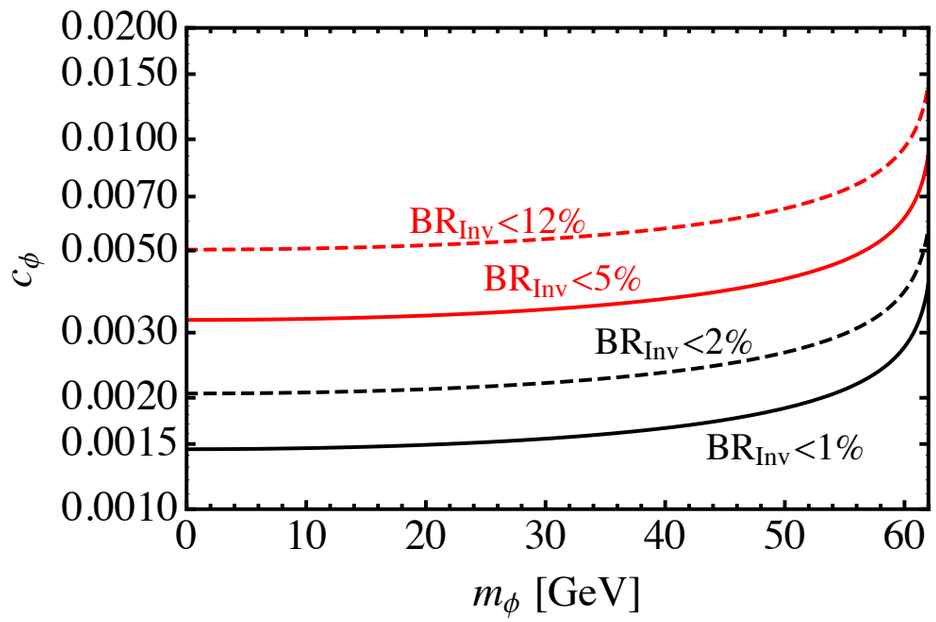
CMS
PAS HIG-13-005

ATLAS
CONF-2014-009

# Higgs portals and Higgs exotic decays

## $|H|^2$ and HL are SM-singlet of low dimension

they can have large (renormalizable) couplings to hidden/dark sector that could make up the DM relic abundance




$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

**new exotic/invisible decay modes**

**HL-LHC sensitivity: $BR_{exo}$<10% vs. ee sensitivity: $BR_{exo}$<1%**

(if $m_{NP} < m_H/2$, possible production via off-shell Higgs but limited reach Craig et al '14 )

| $Z_{\mu\nu}Z_D^{\mu\nu}$ | $\|H\|^2\|S\|^2$ | $HLN$ |
|---|---|---|
| $H \to ZZ_D$ | $H \to ss$ | $H \to LN$ |
| new force | new Higgses | new matter |

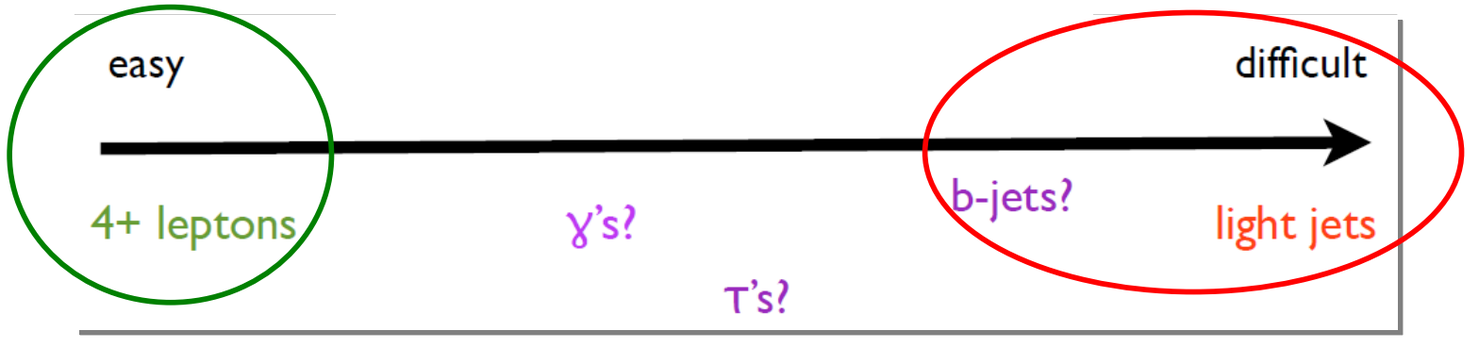
# Higgs portals and Higgs exotic decays

## $|H|^2$ and HL are SM-singlet of low dimension

they can have large (renormalizable) couplings to hidden/dark sector

that could make up the DM relic abundance

Gori @ LCWS'15




Example:
$h \longrightarrow ZZ_D \longrightarrow 4l$
**These can be seen by the LHC pretty easily:**
BRs ~ $10^{-6}$ – $10^{-7}$ can be probed by the HL-LHC

Curtin, Essig, SG, Shelton 1412.0018

See Liu, Potter, 1309.0021 for a ILC analysis
$h \longrightarrow 4\tau$

Example: (as in the NMSSM)
$h \longrightarrow ss \longrightarrow 4b$
**Background limited at the LHC.**
Theory studies show that BRs ~ 0.1 might be reached Cao et al, 1309.4939

**new exotic/invisible decay modes**

**HL-LHC sensitivity: $BR_{exo}$<10% vs. ee sensitivity: $BR_{exo}$<1%**

(if $m_{NP} < m_H/2$, possible production via off-shell Higgs but limited reach Craig et al '14 )

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|---|---|---|
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| new force | new Higgses | new matter |

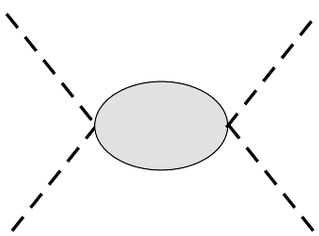
# Higgs portals power-counting

$$\Delta\mathcal{L}_{SILH} = \frac{\bar{c}_H}{2v^2}\,\partial^\mu\big(H^\dagger H\big)\,\partial_\mu\big(H^\dagger H\big) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3$$

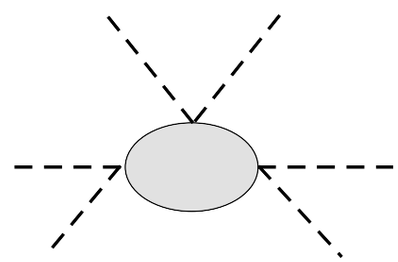
assumptions:

- UV theory = SM (including elementary Higgs doublet) + strong sector characterized by 1 scale ($m_*$) and 1 coupling strength ( $g_*$ )
- Higgs-portal interaction between the two sectors:

$$\mathcal{L}_{mix} = \lambda\, H^\dagger H O \qquad (\ \lambda \sim \text{coupling}^2\ )$$



$$\bar{c}_H \sim \frac{v^2}{f^2}\,\frac{\lambda^2}{g_*^4}$$

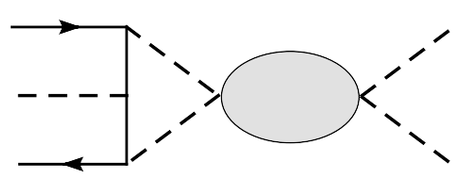


$$\bar{c}_6 \sim \frac{v^2}{f^2}\,\frac{\lambda^3}{g_*^4\lambda_{SM}} \sim \frac{\lambda}{\lambda_{SM}}\,\bar{c}_H$$

enhanced w.r.t. $\bar{c}_H$ for $\lambda > \lambda_{SM} = m_h^2/(2v^2)$

$$\bar{c}_u \sim \frac{y_t^2}{16\pi^2}\,\bar{c}_H$$

$\bar{c}_u$ generated only at 1-loop



$$g_* = 4\pi$$
$$\lambda = 4\pi\sqrt{\lambda_{SM}} \simeq 4.5$$
$$m_* = 500\,\text{GeV}$$

$$\bar{c}_6 \sim 1$$
$$\bar{c}_H \sim 0.03$$

dominant effect in Higgs self-interactions

Contino FCC@Rome '16

4

# BSM Higgs: Baryogenesis

# EW scale flavons for EW baryogenesis

Baldes, Konstandin, Servant '16

**Electroweak baryogenesis requires:**

- A strong first order phase transition
- Sufficient CP violation

**However in the SM:**

- The Higgs mass is too large
- Quark masses are too small

This negative result is tied to the fact that
Yukawa couplings during EW phase transition are identical the ones afterwards
What if they were larger?
E.g. flavor structure emerges during the EW transition

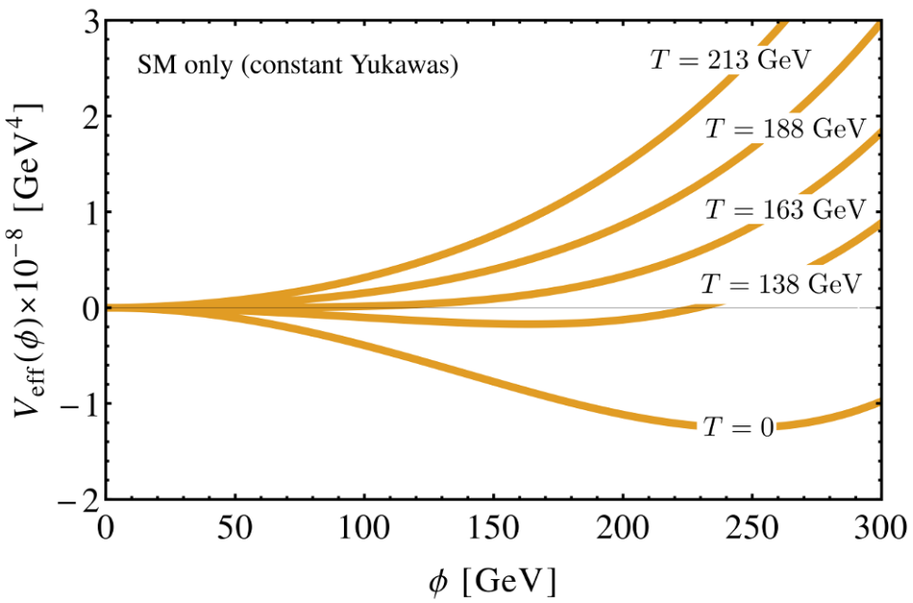
$$y_{ij}\,\bar{f}_L^i H f_R^j \qquad \Rrightarrow \qquad y_{ij}\left(\frac{\chi}{M}\right)^{q_H+q_j-q_i}\bar{f}_L^i H f_R^j$$

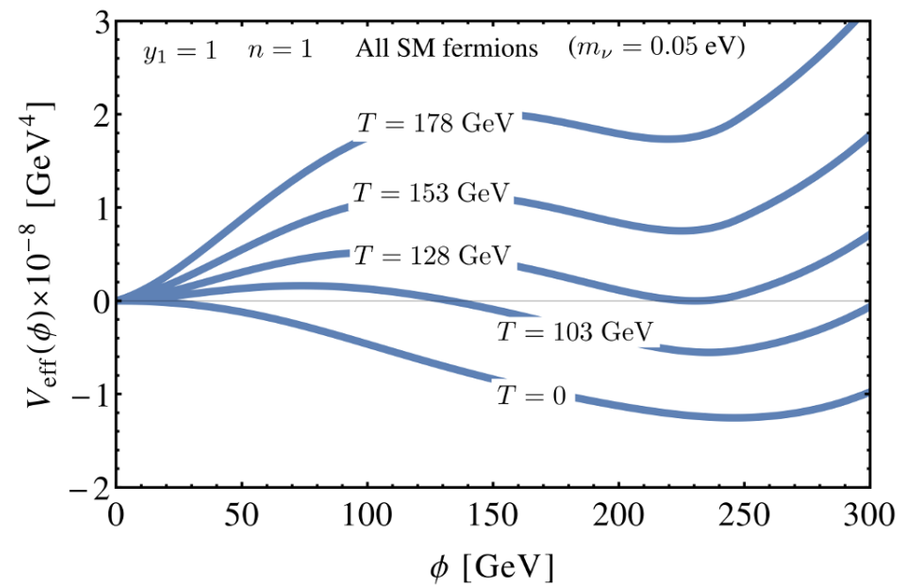
traditionally, M >> v and $\chi$ is frozen during EWSB
lowering M and allowing $\chi$ to vary leads to totally different phenomenology

# EW scale flavons for EW baryogenesis

Baldes, Konstandin, Servant '16

$$y(\phi) = \begin{cases} y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for} \quad \phi \leq v, \\ y_0 & \text{for} \quad \phi \geq v. \end{cases}$$




The evolution of the effective potential with temperature in the SM (left) and with varying Yukawas (right) The varying Yukawa calculation includes all SM fermions with y1=1, n=1 and their respective y0, chosen to return the observed fermion masses today (the neutrinos are assumed to have a Dirac m=0.05eV).

In the varying Yukawa case, there is a first-order phase transition with $\phi_c$=230GeV and Tc=128GeV (vs. second order transition at Tc=163GeV for the constant Yukawa case).

1st order phase transition + enhanced source of CP

5

# Naturalness without TeV-scale New Physics: relax!

THE 750 MAY BE DEAD!

ACCORDING TO THE RUMORS*..

* THE SPEAKER DOES NOT APPROVE OF NOR ENCOURAGES RUMOR SPREADING. BUT PLEASE LET HIM** KNOW IF YOU KNOW ANYTHING ELSE...

**and STRUMIA

(T. volansky@NKPI'16)

**Don't desperate and go relaxed!**

# The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

Espinosa et al '15

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe and scans a vast range of Higgs mass
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-evolution of the dynamical system

**Self-organized criticality**

dynamical evolution of a system is stopped at a critical point due to back-reaction

**hierarchies** result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

# Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

$\phi$ slowly rolling field (inflation provides friction) that scans the Higgs mass

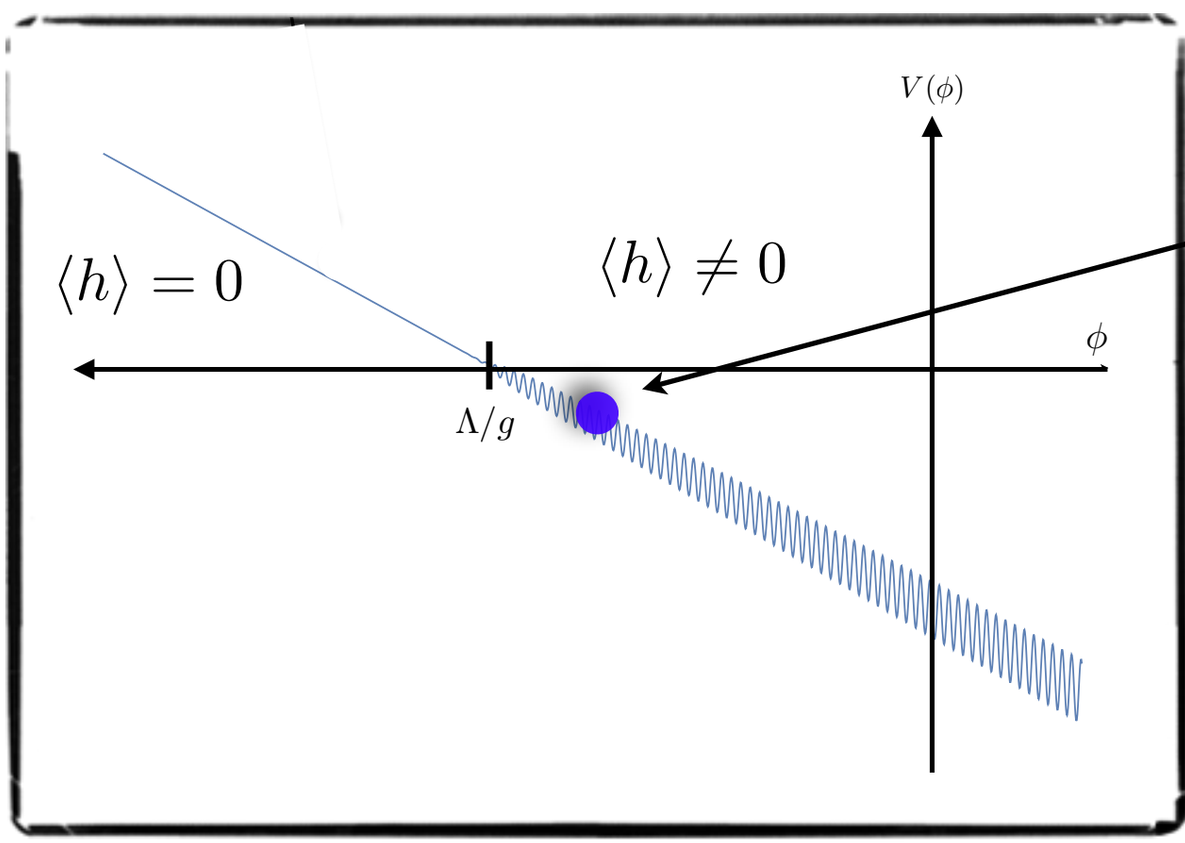
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on $\phi$

potential needed to force $\phi$ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

$$\Lambda^3_{\rm QCD}\, h\, \cos\frac{\phi}{f}$$



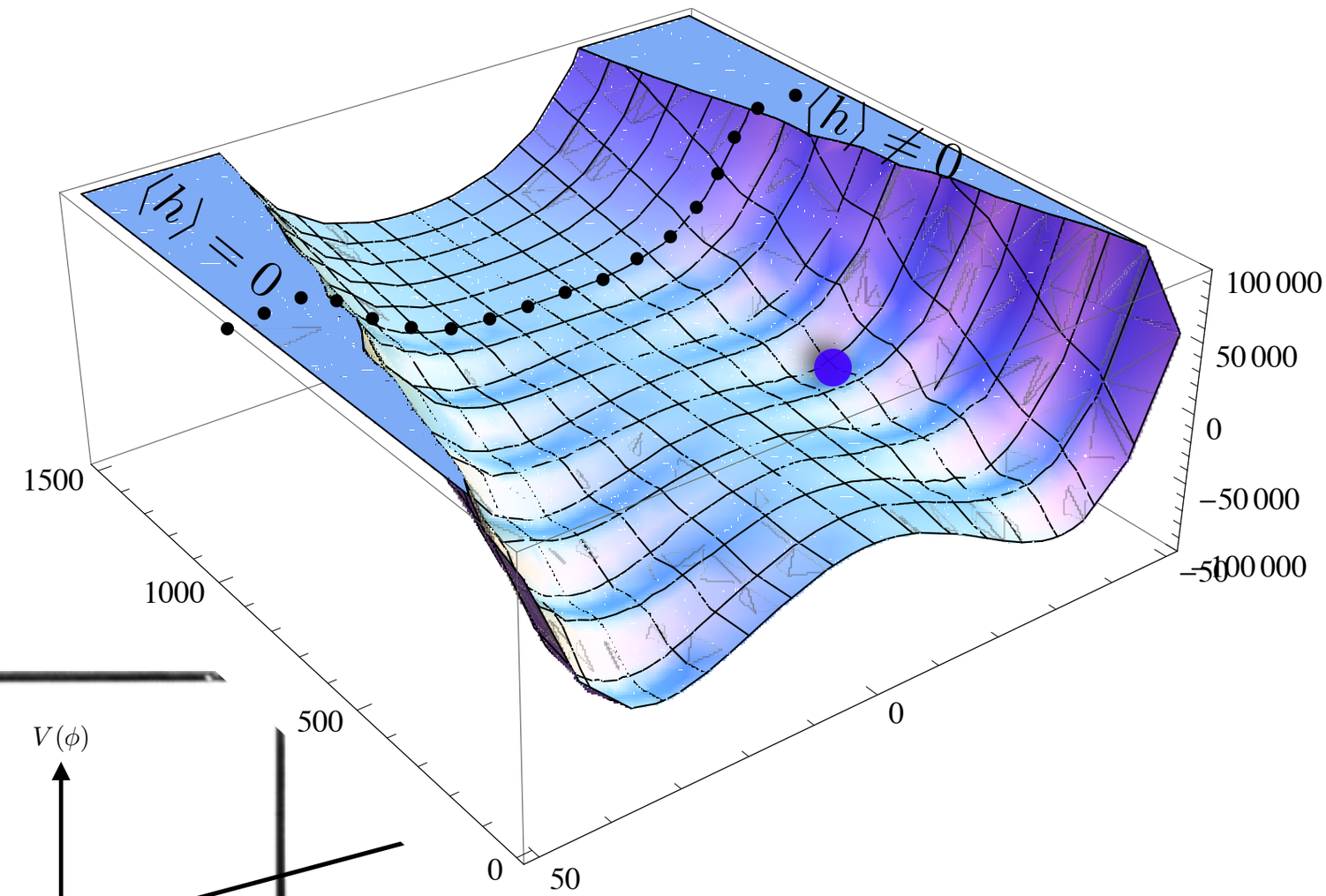
# Higgs-axion cosmological relaxation

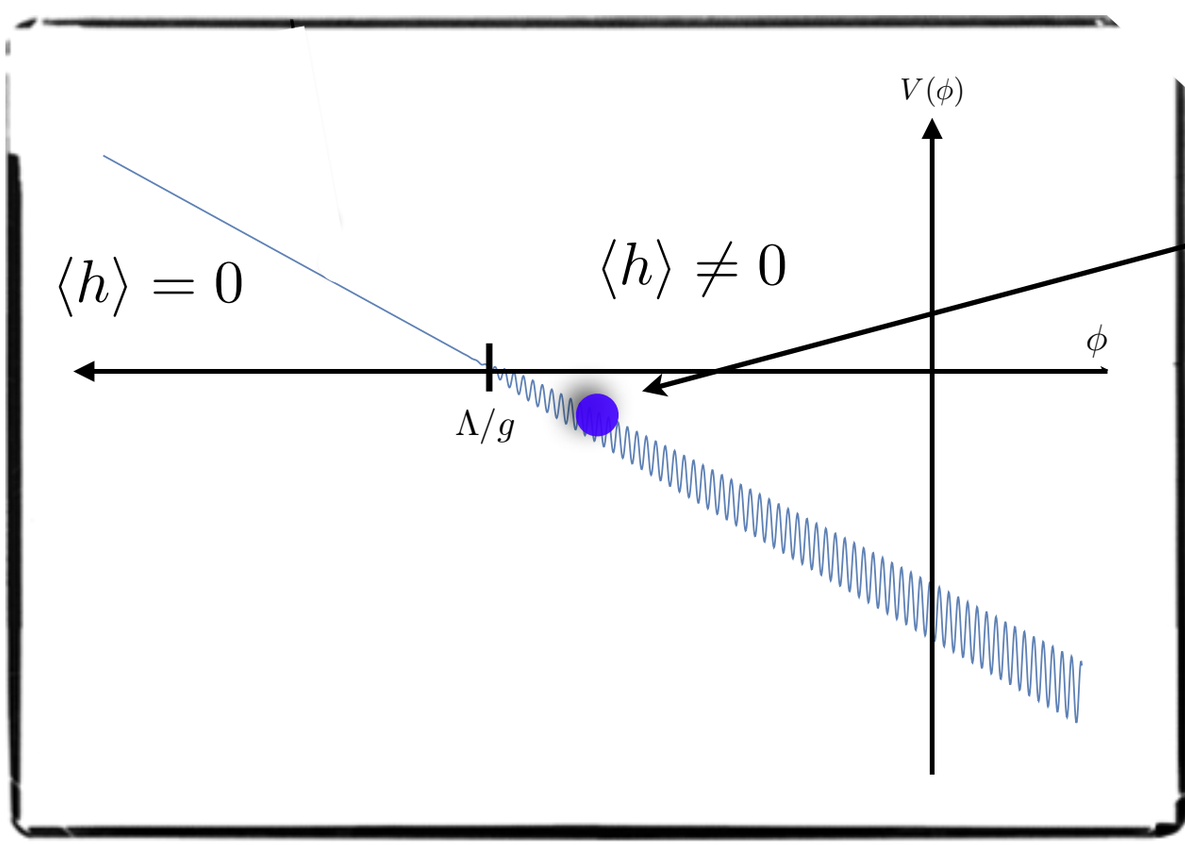
Graham, Kaplan, Rajendran '15

$$\phi$$

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)$$

Higgs mass depends on $\phi$



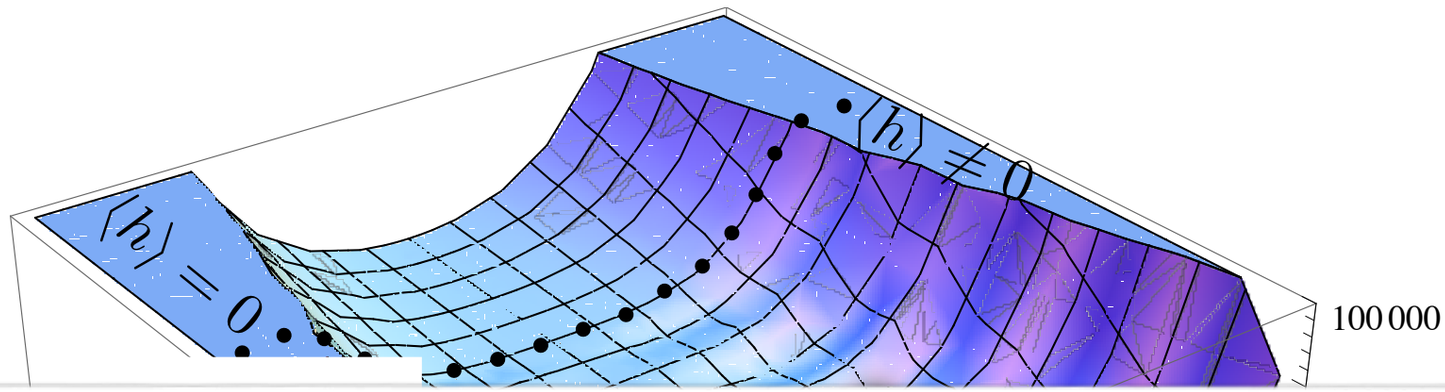

If $\phi$ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents $\phi$ from rolling down further

# Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

$$\phi$$

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)$$




Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

**~interesting cosmology signatures~**

- BBN constraints
- decaying DM signs in $\gamma$-rays background
- ALPs
- superradiance

**~interesting signatures @ SHiP~**

- production of light scalars by B and K decays

# Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

interesting signatures in cosmology

# Some open questions

- large field excursions ↪ monodromy? McAllister, Schwaller, Servant, Westphal 'in progress
  Ibanez, Montero, Uranga, Valenzuela '15
- non-periodic potential for an axion-like particle? Gupta, Komargodski, Perez, Ubaldi '15
- hierarchy of decay constants: F>>f is ≈ to non-periodid potential Choi, Im '15 Kaplan, Rattazzi '15
- eternal inflation vs classical evolution? Arvanitaki, Dimopoulos, Villadoro 'private communication
- long period of inflation? Riotto et al 'in progress
- other source of friction to prevent over-shooting the EW scale? Hardy '15
- UV completion?
- weak gravity conjecture? Heidenreich, Reece, Rudelius '15 Hebercker, Rompineve, Westphal '15
- can other scales be relaxed too? SUSY breaking scale? Batell, Giudice, McCullough '15
- signatures in atomic physics? Evans, Gherghetta, Nagata, Thomas '16

**A new playground for model builders**
**at the cross-road between exp/cosmo/pheno/strings**
**Joined forces needed**

# Conclusions

**At 4, the Higgs has certainly entered the age of precision**

- advanced QCD calculations for rates and distributions
- dedicated experimental program
- direct searches for BSM physics

**BSM in the Higgs sector can provide answers to the burning questions in HEP**

- what is DM?
- what is the origin of matter-antimatter?
- what explain the smallness of neutrino masses?
- what stabilize the weak scale?
- what drives inflation?
- is there a stochastic gravitational background?

**LHC data force to go beyond standard paradigms explored for 4 decades**

Let us continue the exploration of the unkown
that will become the SM of tomorrow