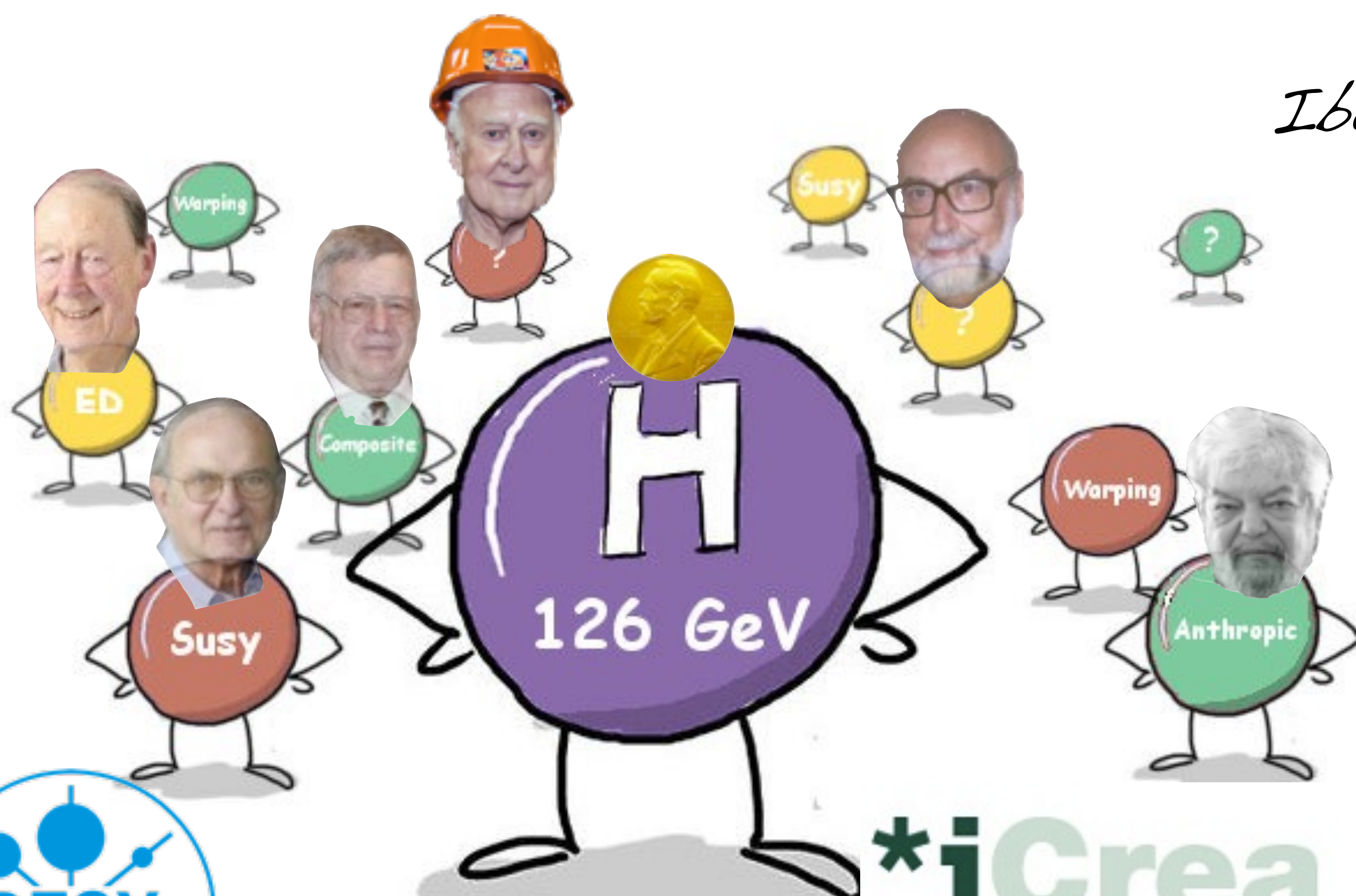
Higgs Physics

CLASHEP 2015

Ibarra, Ecuador, March 2015



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Lecture Outline

1 First Lecture ➲

- Standard Model and EW symmetry breaking ➲
- Higgs mechanism - custodial symmetry ➲
- Goldstone equivalence theorem ➲
- What is the Higgs boson the name of? ➲
- SM Higgs @ colliders ➲
- UV behavior of the Higgs boson (triviality, stability, naturality) ➲
- Symmetries for a natural EWSB ➲

2 Second Lecture ➲

- Implications for SUSY ➲
- Composite Higgs models ➲
- Precision Higgs couplings ➲
- Future Higgs channels:
  - Boosted and off-shell channels ➲
  - Multi-Higgs ➲

⇧ 1 ⇧ 2

We all have a Post higgs Depression

For the first time in the history of physics,
we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up M_{Planck}?)

My key message

MLM@Aspen'14

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Where and how does the SM break down?
Which machine(s) will reveal this breakdown?

HEP with a Higgs boson

"If you don't have the ball, you cannot score"

HEP with a Higgs boson

" If you don't have the ball, you cannot score "

Now with the Higgs boson in their hands,
particle physicists can... play as well as the Barca players

Higgs as a target

- observe it in as many channels as possible to measure its properties
- check of the coupling structure of the SM and its deformations
- interpret deviations of Higgs couplings as a sign of NP

Higgs as a tool

- a portal to New Physics
- in initial states: rare decays (BSM Higgs decays)

  e.g., $h \to \mu\tau$, $h \to J/\Psi+\gamma$

- in final states as an object that can be reconstructed and tagged (BSM Higgs productions)

  e.g., $t \to h+c$, $H \to hh$

Profound change in paradigm:
missing SM particle ⇨ tool to explore SM and venture into physics landscape beyond

1

Implications for SUSY

Is SUSY/MSSM Natural?

The Higgs mass is calculable in the MSSM

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

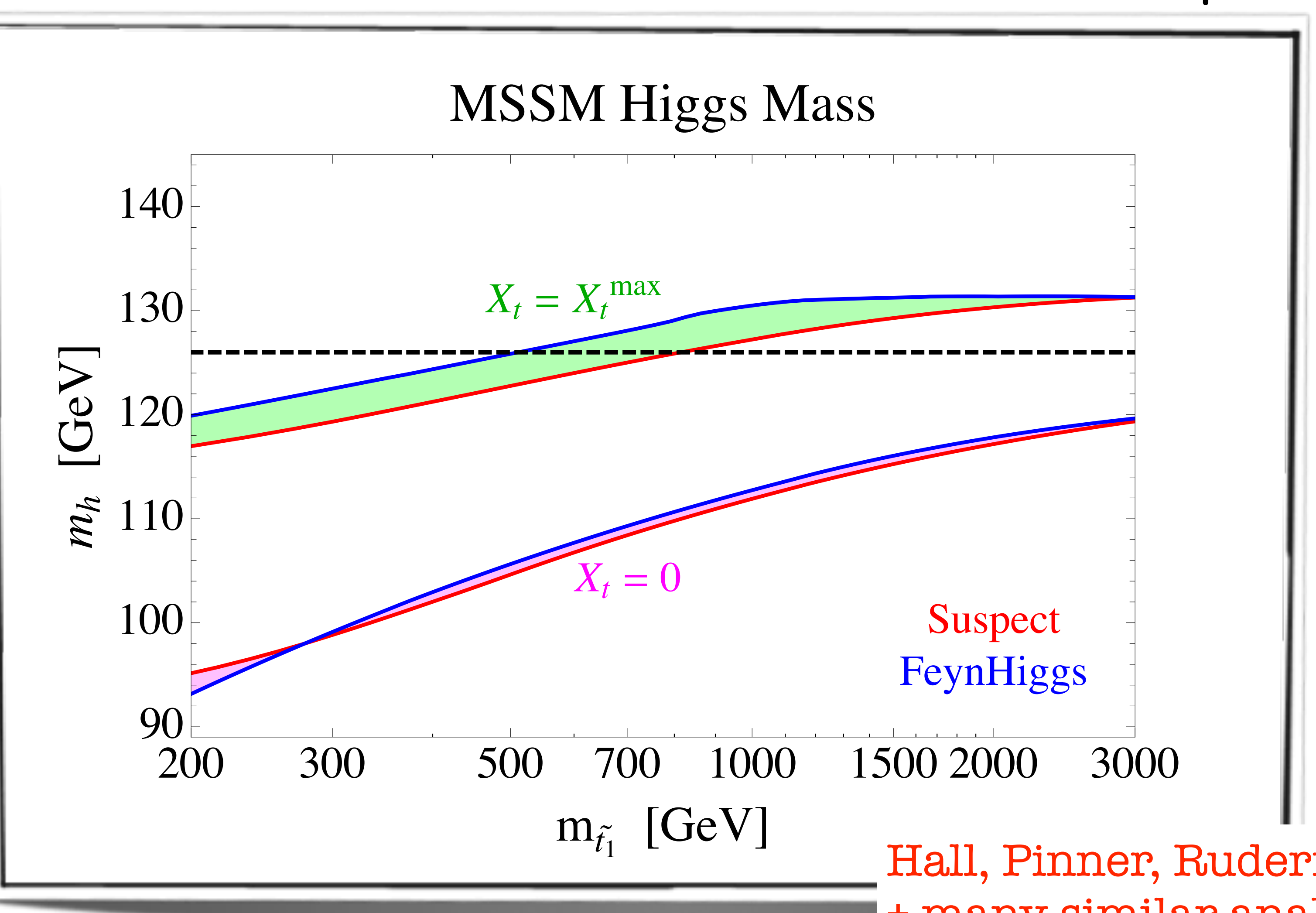
$$\delta_t^2 \approx \frac{3\sqrt{2}G_F M_t^4}{16\pi^2}\left[\log\frac{M_{\tilde{t}}^2}{M_t^2} + \frac{X_t^2}{M_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12M_{\tilde{t}}^2}\right)\right]$$

$M_{\tilde{t}}$ stop mass (degenerate)

X_t stop mixing

m_h^2: $(125\ \mathrm{GeV})^2$ δ_t^2: $(\gtrsim 87\mathrm{GeV})^2$

substantial loop contribution from stops



Hall, Pinner, Ruderman '11
+ many similar analyses

large mixing

heavy stops

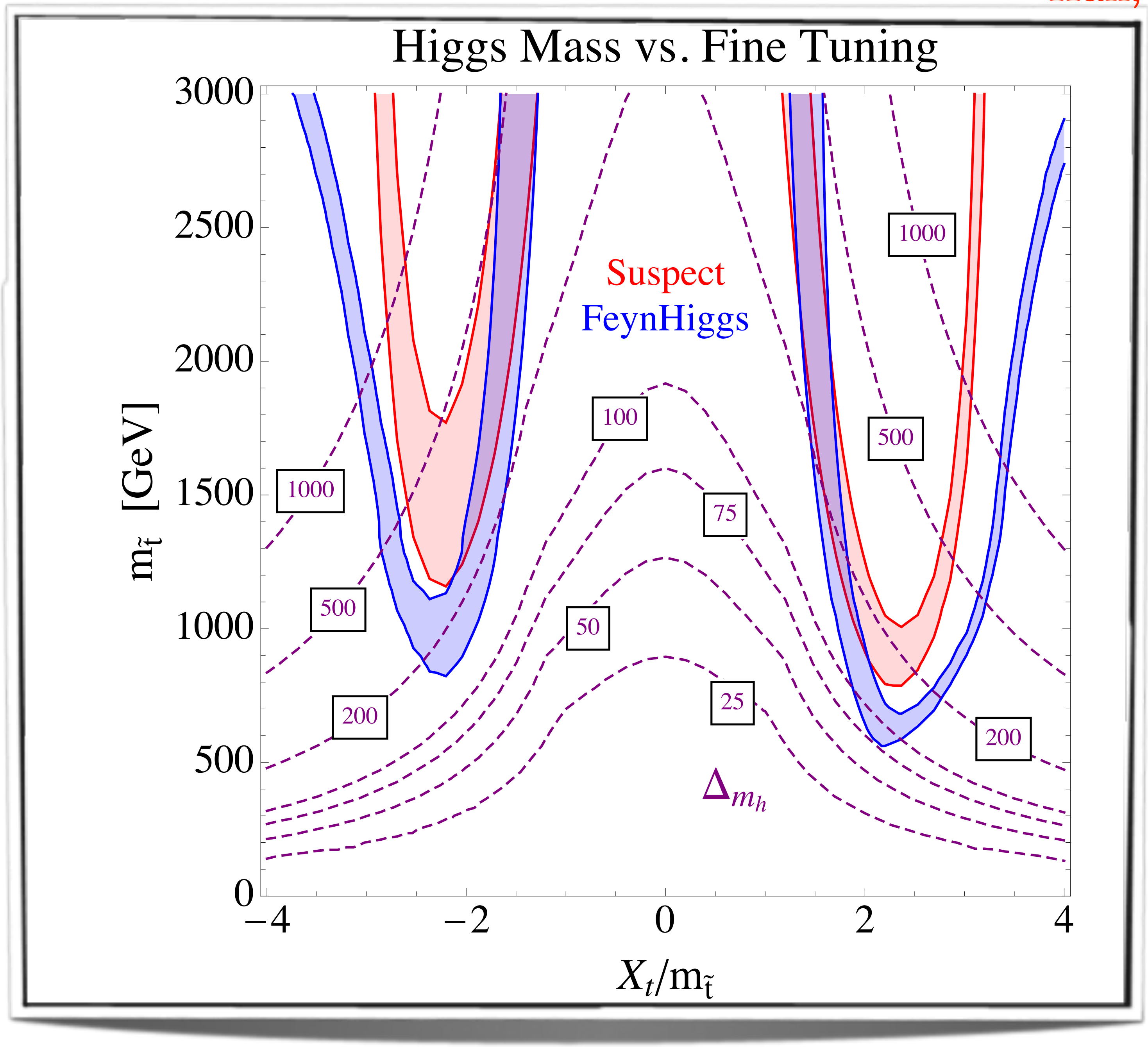
$$\sqrt{m_{Q_3} m_{u_3}} \gtrsim 700\ \mathrm{GeV}$$

⇓ ⇓

fine-tuning ≳ 1%

MSSM fine-tuning

Hall, Pinner, Ruderman '11



maximal mixing requires engineering

$$m^2_{\tilde{t}}(M_Z) \simeq 5.0 M_3^2(M_G) + 0.6 m^2_{\tilde{t}}(M_G)$$
$$A_t(M_Z) \simeq -2.3 M_3(M_G) + 0.2 A_t(M_G)$$

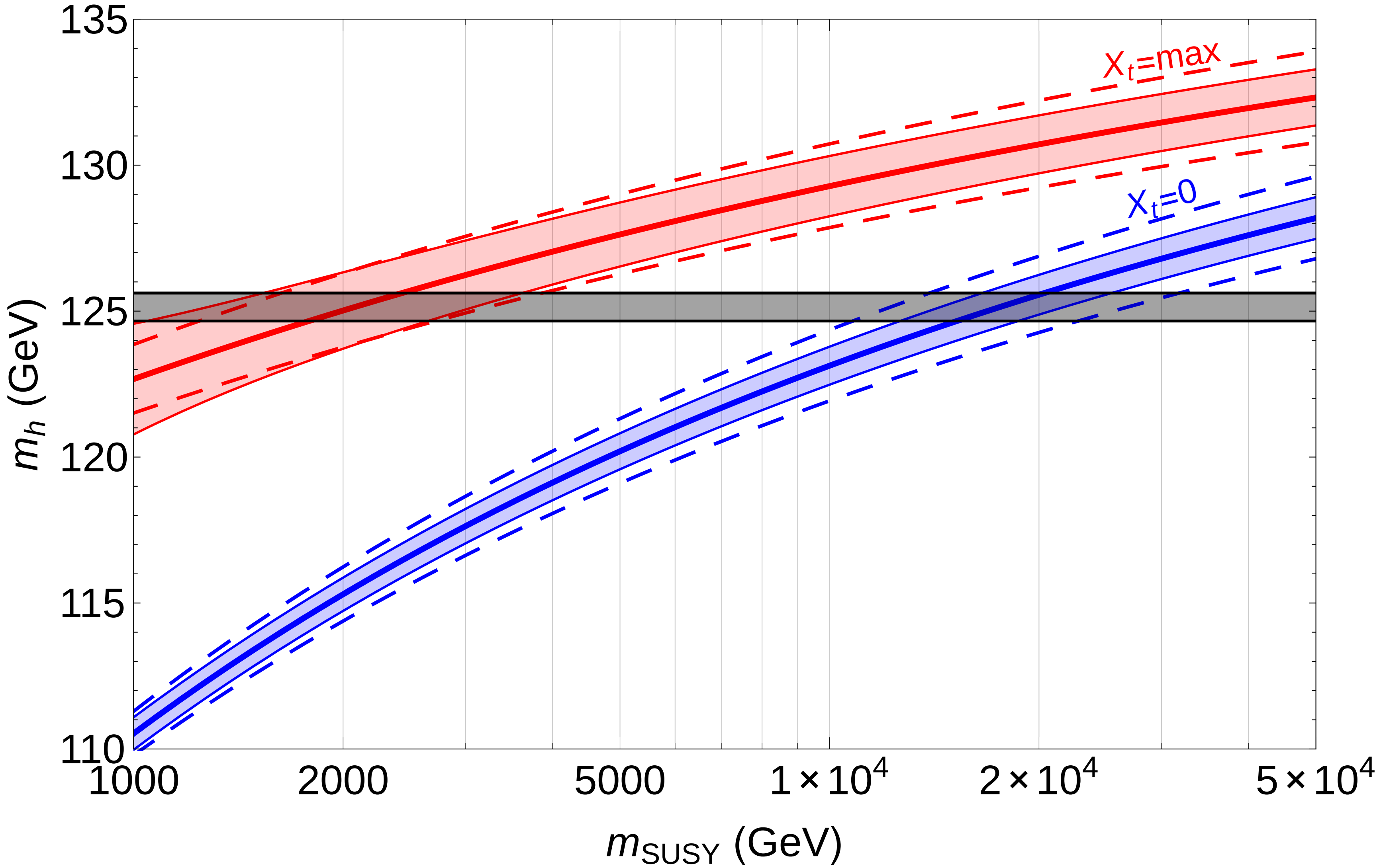
⋯▸ generically $|A_t/m_{\tilde{t}}| \leq 1$

Fermisek, Kim '06

Towards precise prediction of MSSM Higgs mass

further improved predictions (full 2-loop QCD corrections)

Bagnaschi et al '14
Degrassi et al '14
Pedro Vega, Villadoro 'to appear



requires
even heavier stops
to accommodate
a 125GeV Higgs

[plot from J. Padro Vega and G. Villadoro, 'to appear]

Saving SUSY

SUSY is Natural
but not plain vanilla

- ~~CMSSM~~
- pMSSM
- NMSSM
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families) Mahbubani et al
  - reduce MET (e.g. ~~R-parity~~, compressed spectrum) Csaki et al
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy) Fan et al

LHC$_{100fb^{-1}}$ will tell!

Good coverage of

hidden natural susy

- mono-top searches (DM, flavored naturalness - mixing among different squark flavors-, stop-higgsino mixings)
- mono-jet searches with ISR recoil (compressed spectra)
- precise tt inclusive measurement+ spin correlations (stop → top + very soft neutralino)
- multi-hard-jets (RPV, hidden valleys, long decay chains)

2

Composite Higgs models

Why should you care about compositeness?

Higgs compositeness means new fundamental interactions

Pospelov's 38 years rule...

38 years rule = new forces of nature are discovered every 38 years for the last 150 yrs

1. 1860s – first papers of Maxwell on EM. Light is EM excitation. E & M unification.
2. 1897 – Becquerel discovers radioactivity – first evidence of weak charged currents (in retrospect).
3. 1935 – Chadwick gets NP for his discovery of neutron with subsequent checks that there exists strong n-p interaction. Strong force is established.
4. 1973 – Gargamelle experiment sees the evidence for weak neutral currents in nu-N scattering
5. 2011/2012 Discovery of the Higgs, i.e. new Yukawa force.

6. Prediction: Discovery of a new dark force – 2050?

(+/- 2 years or so).

M. Pospelov, SHiP collab. meeting, Naples '15

Why should you care about compositeness?

All SM shortcomings are intimately linked to the Higgs elementary nature

$$\mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

vacuum energy
cosmological constant
$V_0 \approx (2\times 10^{-3}\ \text{eV})^4 \ll M_{\text{PL}}^4$

hierarchy problem
$m_H \approx 100\ \text{GeV} \ll M_{\text{Pl}}$

triviality/stability
of EW vacuum

mass and mixing
hierarchy

flavour & CP:
no FCNC, small CP

All these problems because the Higgs boson would be the first elementary particle whose interactions are not endowed with a gauge structure

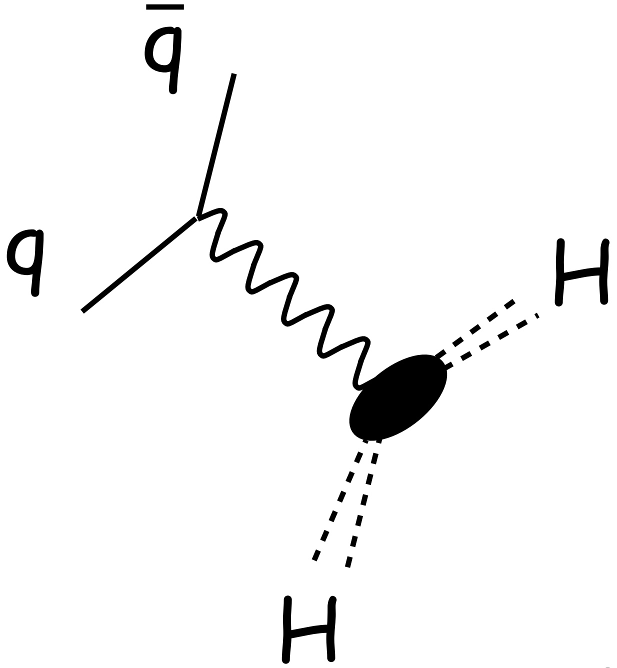
Higgs = Elementary or Composite?

Probing the Higgs compositeness

Unlikely we'll ever see the fundamental constituents of the Higgs

But we can infer that it is not an elementary particle

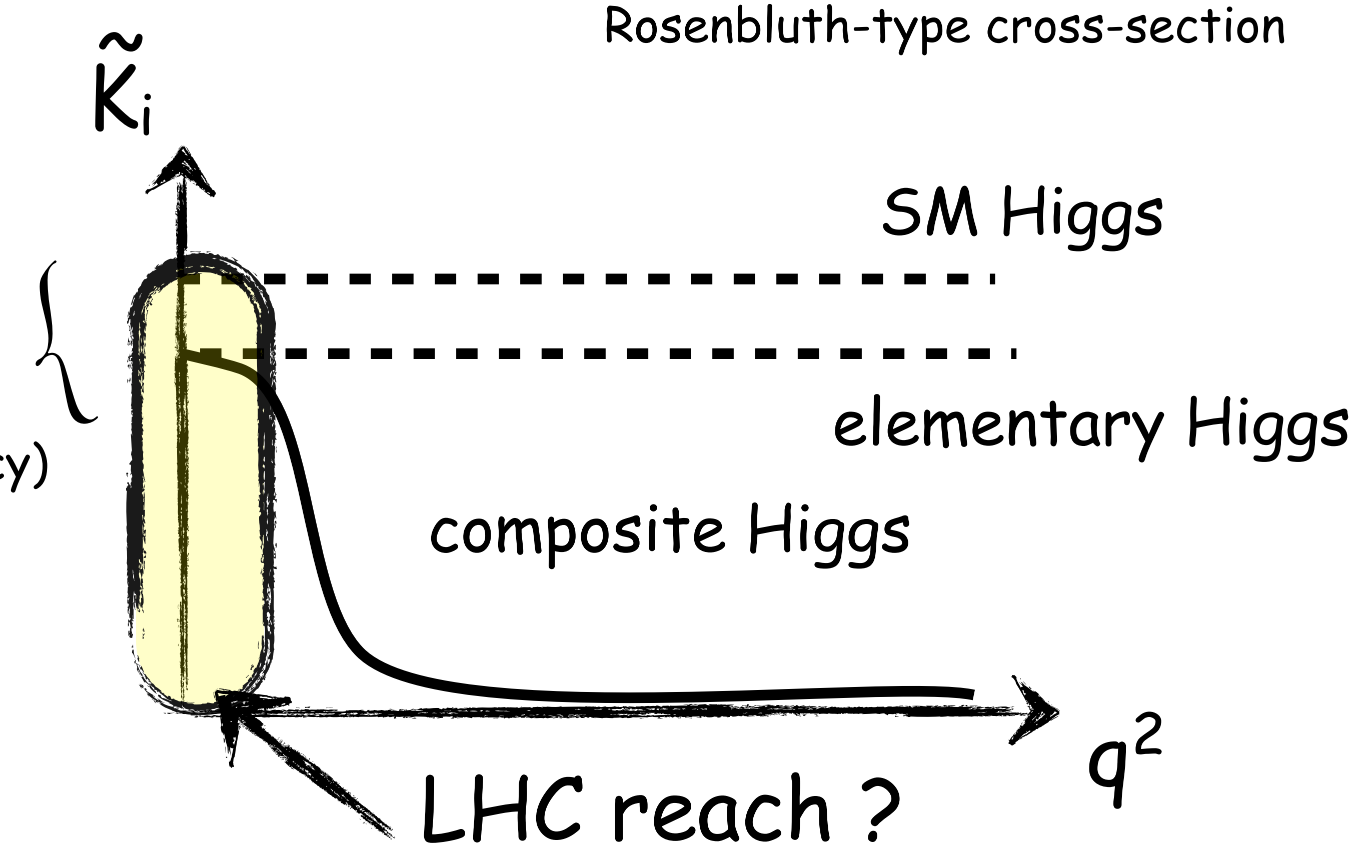
by measuring its couplings to SM particles



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2}\frac{E'}{E^3}\left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2\cos^2\theta/2\right)$$

Rosenbluth-type cross-section

anomalous couplings
(accessible @ LHC with 20-10% accuracy)



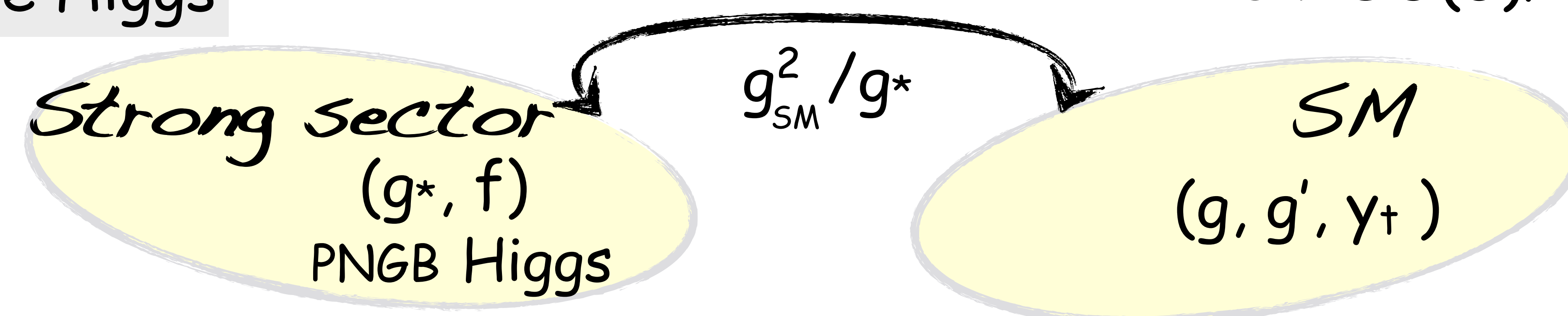
Which composite scenario?

Minimal Composite Higgs

ex: SO(5)/SO(4)

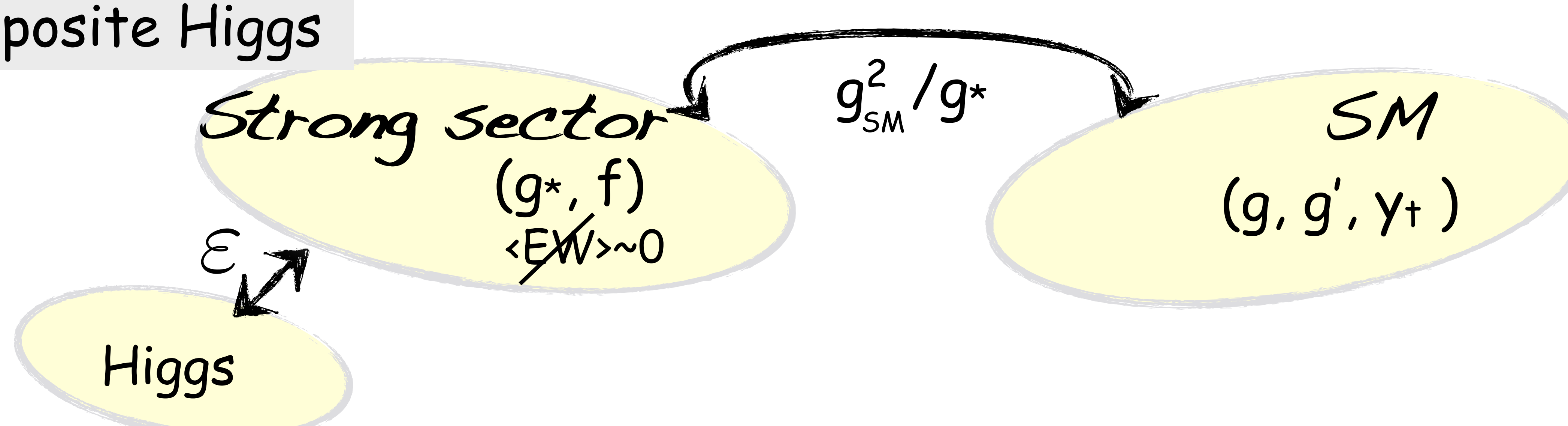
SILH

$$\xi = \frac{v^2}{f^2} \ll 1$$



Partly Composite Higgs

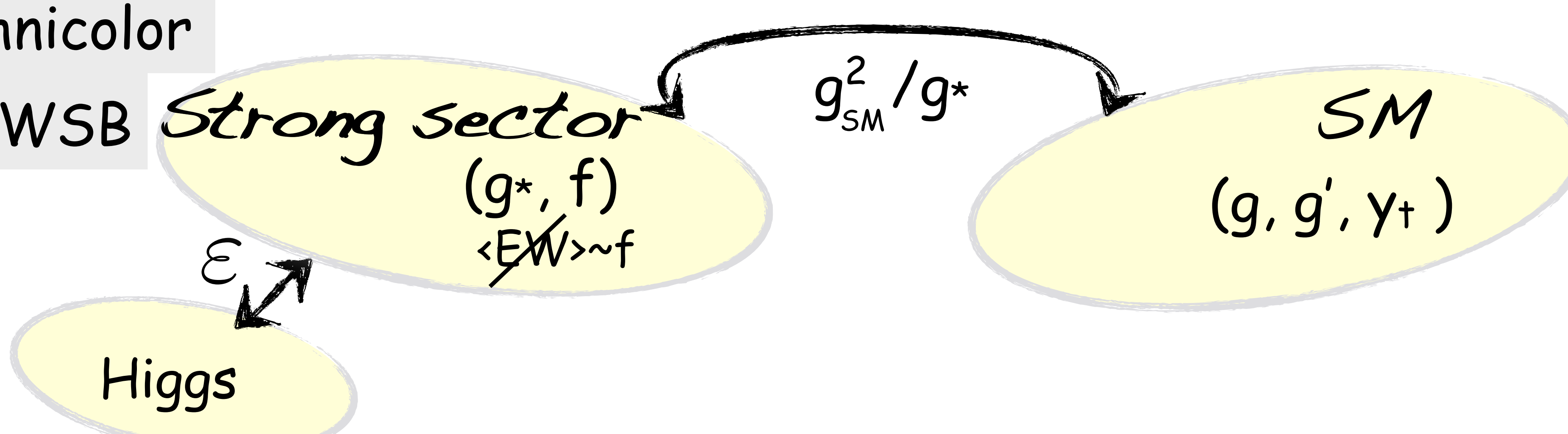
$$\xi = \frac{v^2}{f^2} \ll 1$$



Bosonic Technicolor

Induced EWSB

$$\varepsilon = \frac{f}{v} \ll 1$$



Which composite scenario?

Minimal Composite Higgs

SILH

$$\frac{1}{f^2}\left(\partial_\mu |H|^2\right)^2 \qquad \frac{\lambda_4}{f^2}|H|^6$$

$$\xi = \frac{v^2}{f^2} \ll 1$$

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\xi \qquad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\xi$$

Partly Composite Higgs

$$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2 \qquad \frac{\varepsilon^6}{f^2}|H|^6$$

$$\xi = \frac{v^2}{f^2} \ll 1$$

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\varepsilon^4\xi \qquad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\varepsilon^2\frac{g_*^2 v^2}{m_h^2}\varepsilon^4\xi$$

Bosonic Technicolor

Induced EWSB

$$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2 \qquad \frac{\varepsilon^6}{f^2}|H|^6$$

$$\varepsilon = \frac{f}{v} \ll 1$$

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\varepsilon^2 \qquad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\mathcal{O}(1)$$

Patterns of Higgs coupling deviations

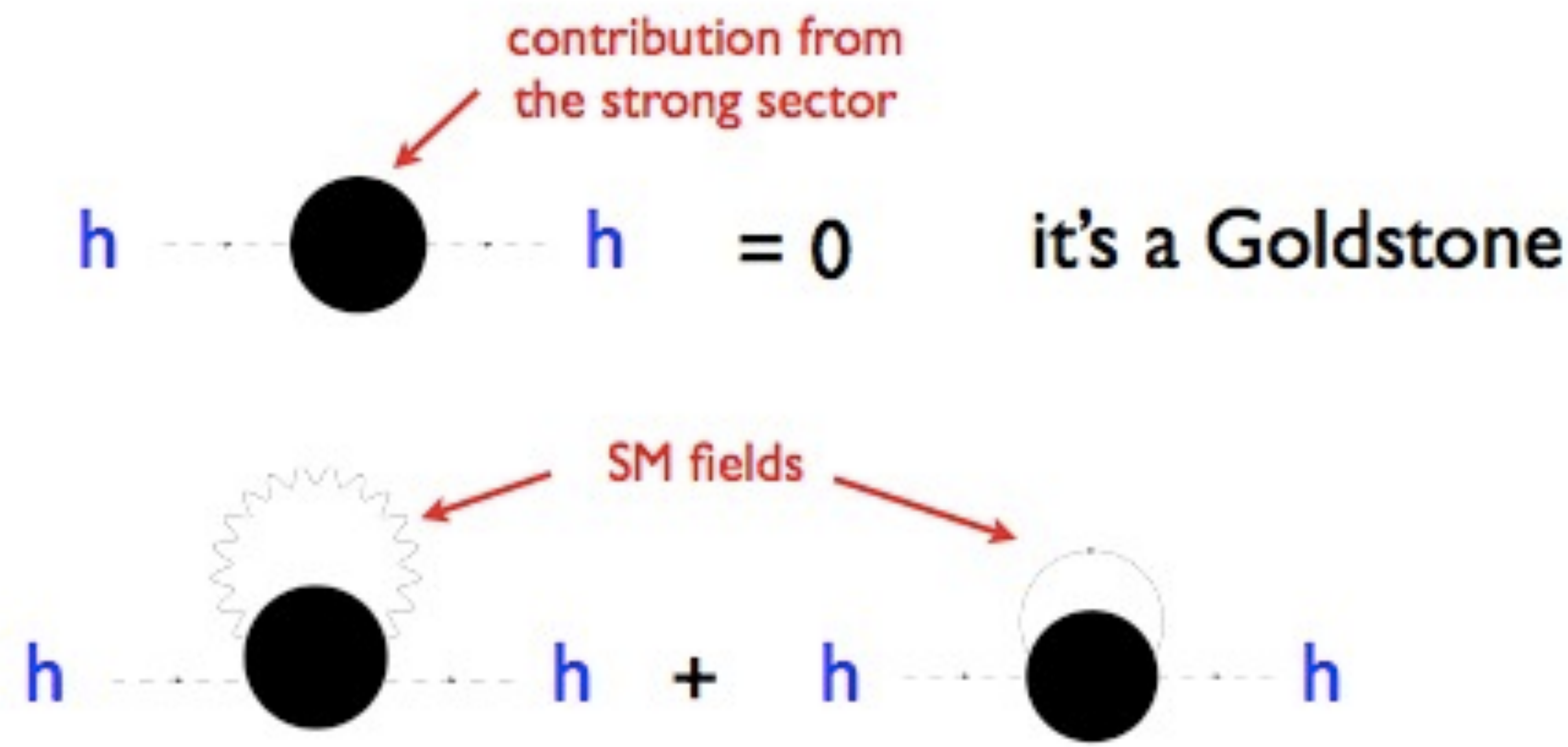
expected largest relative deviations

	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

Light composite Higgs from "light" resonances

The interactions between the strong sector and the SM generate a potential for the Higgs



Impossible to compute the details of the potential from first principles
but using general properties on the asymptotic behavior of correlators
(saturation of Weinberg sum rules with the first few lightest resonances)
it is possible to estimate the Higgs mass

Pomarol, Riva '12

Marzocca, Serone, Shu '12

$$m_h^2 \approx \frac{3}{\pi^2}\frac{m_t^2 m_Q^2}{f_{G/H}^2}$$

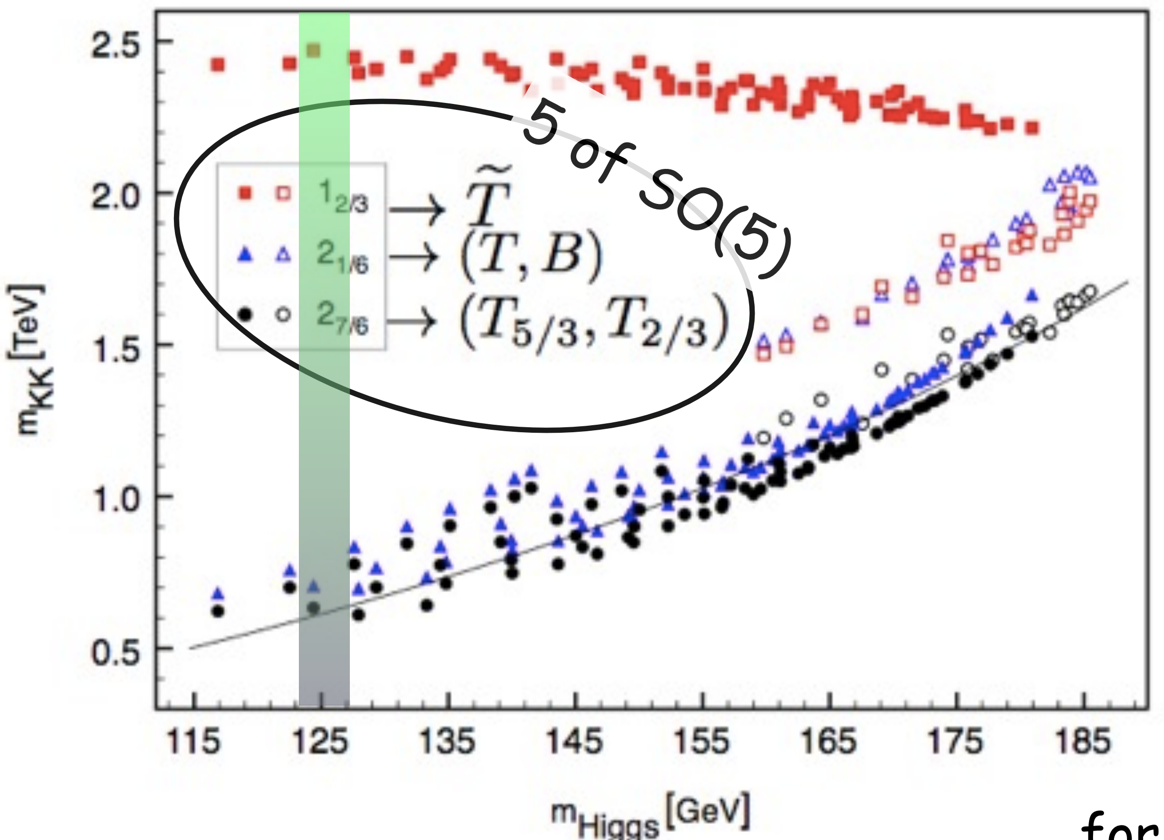
$$m_Q \lesssim 700\ \text{GeV}\left(\frac{m_h}{125\ \text{GeV}}\right)\left(\frac{160\ \text{GeV}}{m_t}\right)\left(\frac{f}{500\ \text{GeV}}\right)$$

fermionic resonances below ~ 1 TeV
vector resonances ~ few TeV (EW precision constraints)
~ for a natural (<20% fine-tuning) set-up ~

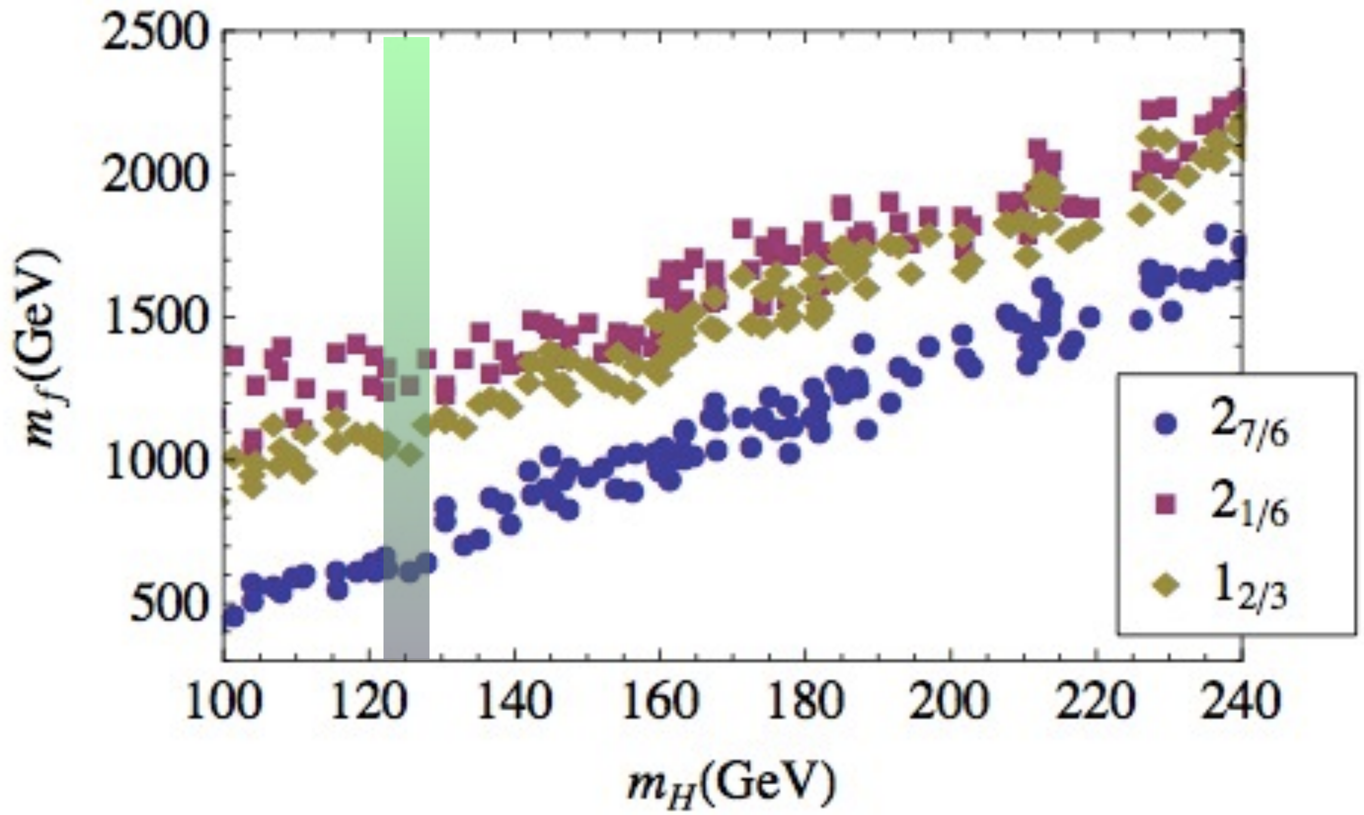
Light composite Higgs from "light" resonances

true spectrum in explicit realizations

Contino, Da Rold, Pomarol '06



De Curtis, Redi, Tesi '11



for similar results, see also

Matsedonskyi, Panico, Wulzer '12 & Marzocca, Serone, Shu '12

Nice AdS/CFT interpretation

$$\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

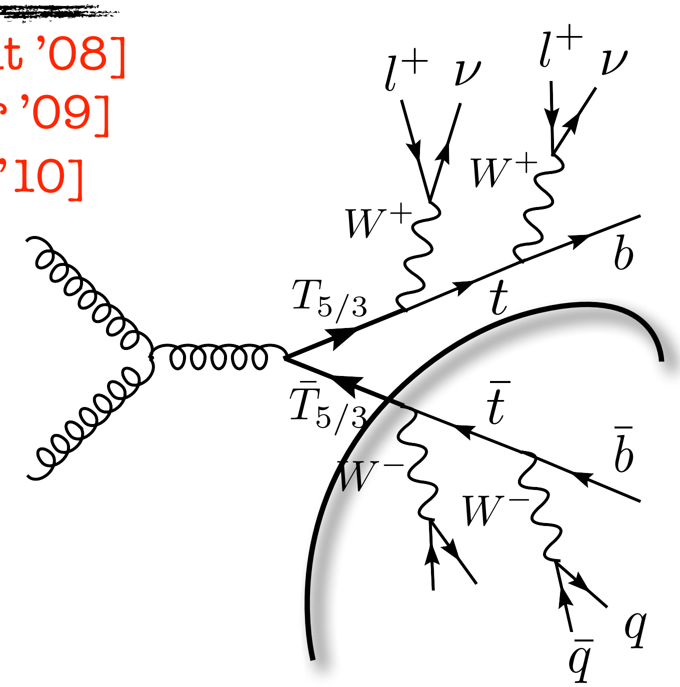
$$M_\Psi = 1/2 \leftrightarrow \dim[\mathcal{O}_\Psi] = 3/2 \leftrightarrow \text{light free field decoupled from CFT}$$

Rich phenomenology of the top partners

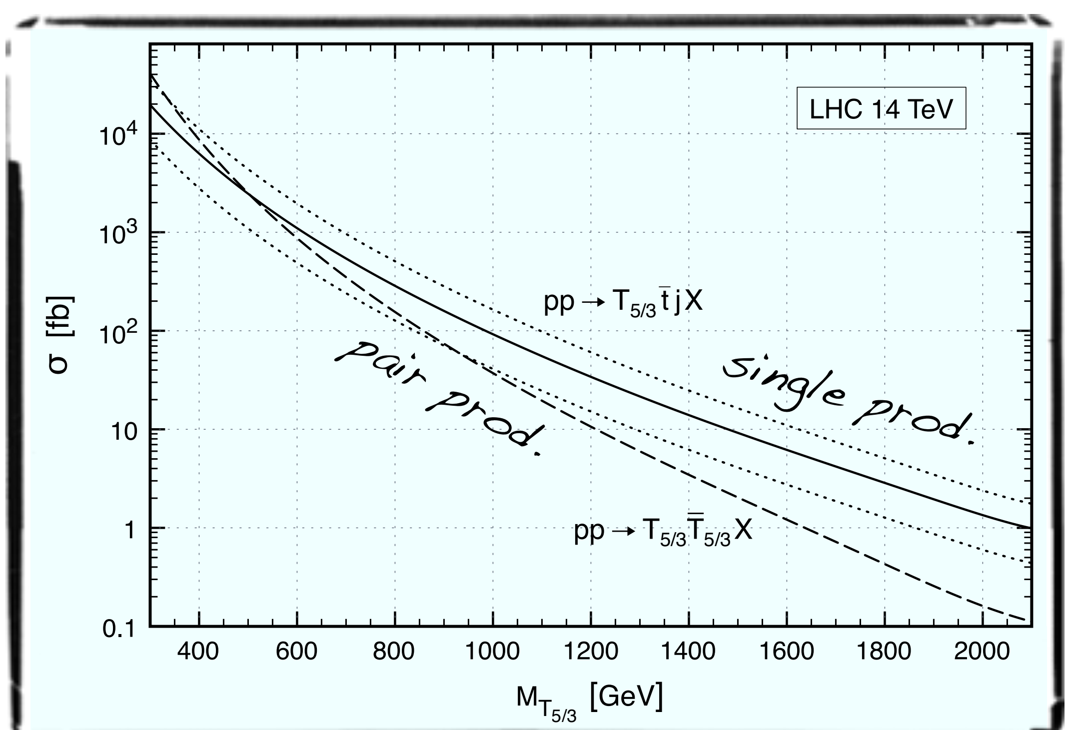
Search in same-sign di-lepton events

[Contino, Servant '08]
[Mrazek, Wulzer '09]
[Dissertori et al '10]

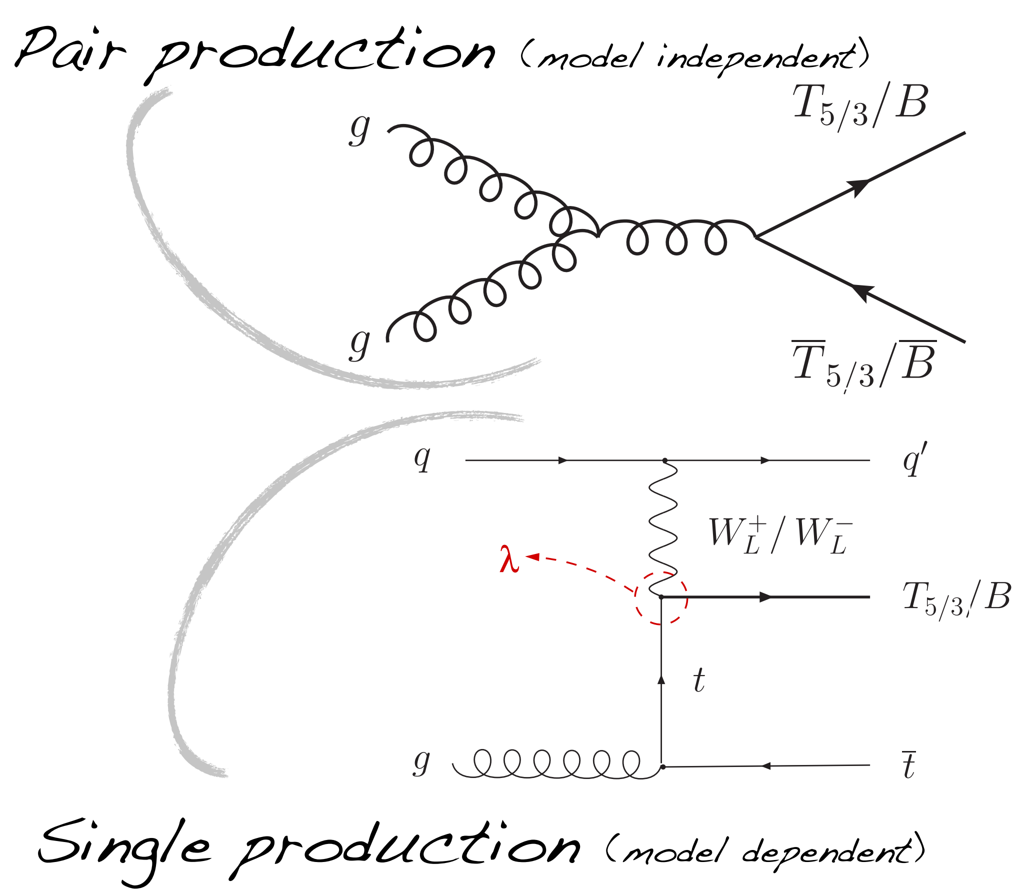
- $t\bar{t}$+jets is not a background [except for charge mis-ID and fake e$^-$]
- the resonant (tW) invariant mass can be reconstructed



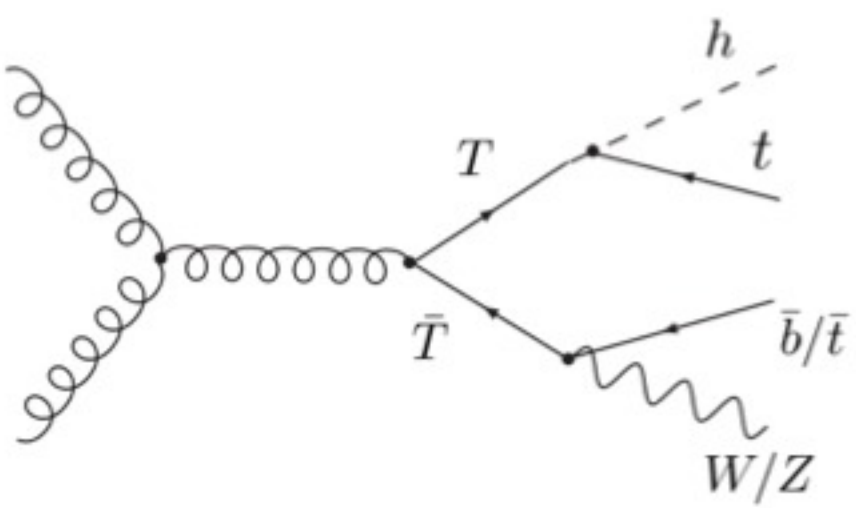
discovery potential (LHC14TeV)
$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}



[Contino, Servant '08]



Rich phenomenology of the top partners



l± + 4b final state

Aguilar-Saavedra '09

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

$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$

l± + 6b final state

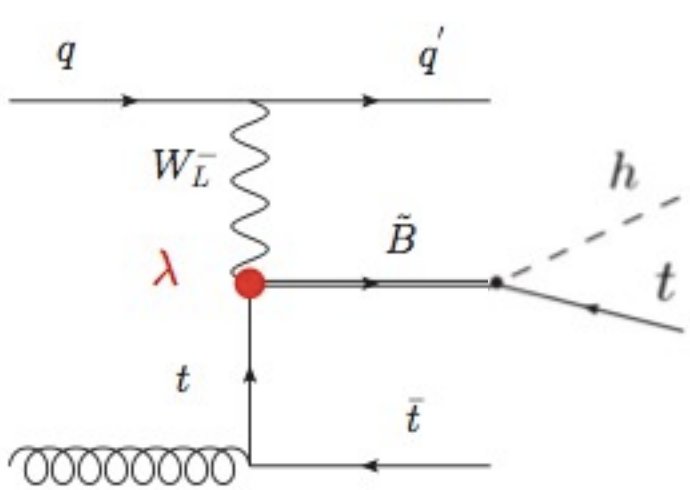
Aguilar-Saavedra '09

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

$\gamma\gamma$ final state

Azatov et al '12

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



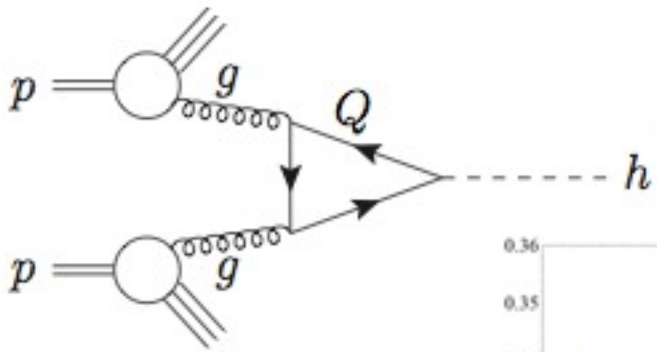
l± + 4b final state

Vignaroli '12

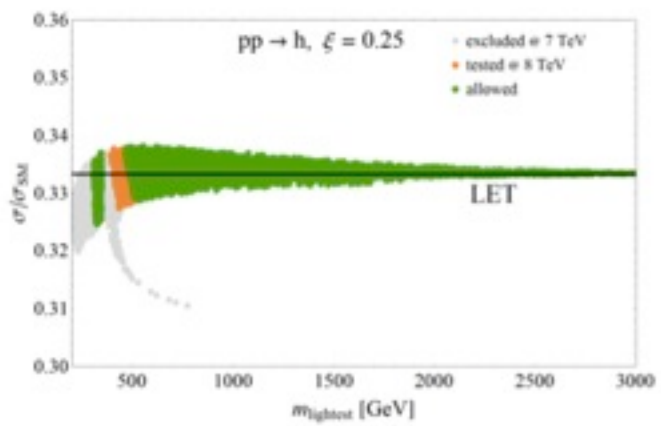
$pp \to (\tilde{B} \to (h \to bb)b)t + X$

Top partners & Higgs physics

~ current single higgs processes are insensitive to top partners ~



$\sigma^{SM}_{14\mathrm{TeV}} \approx 50$ pb



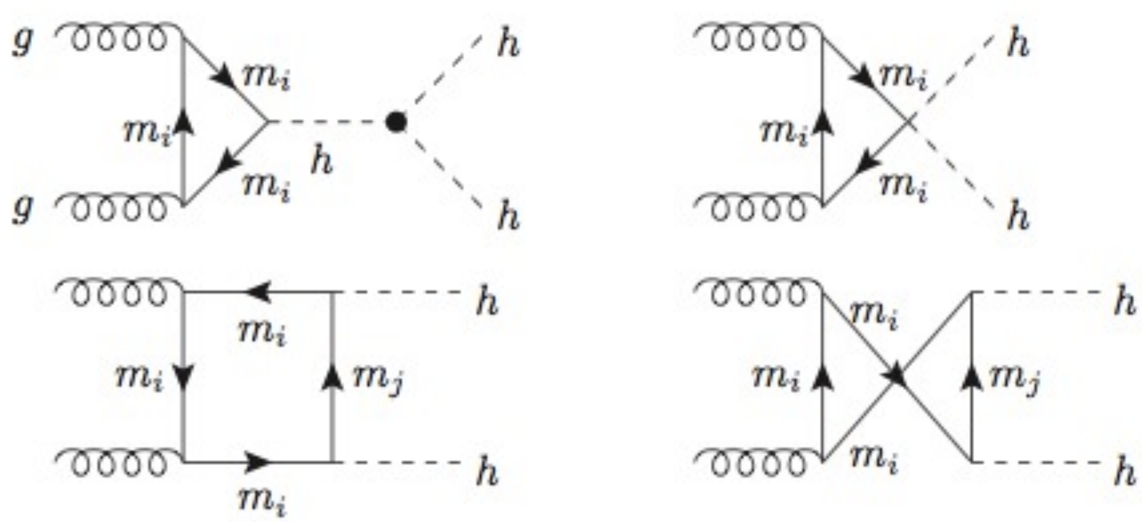
two competing effects that cancel:

- ☑ T's run in the loops
- ☑ T's modify top Yukawa coupling

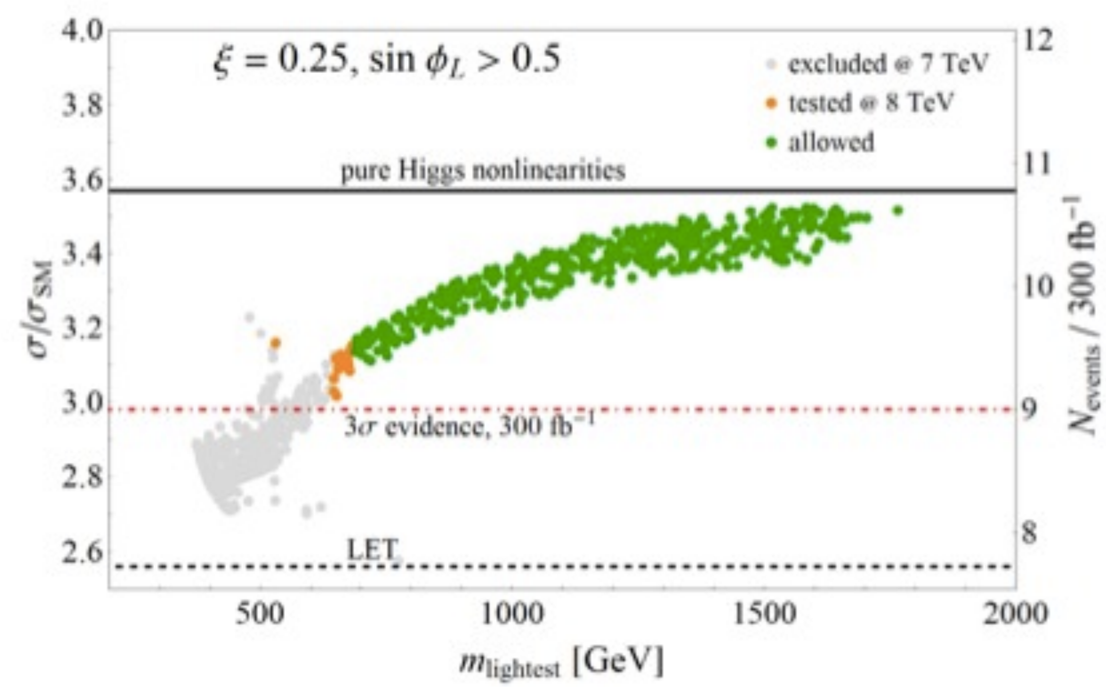
Falkowski '07
Azatov, Galloway '11
Delaunay, Grojean, Perez, '13

~ sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



$\sigma^{SM}_{14\mathrm{TeV}} = 17.9\mathrm{fb}$



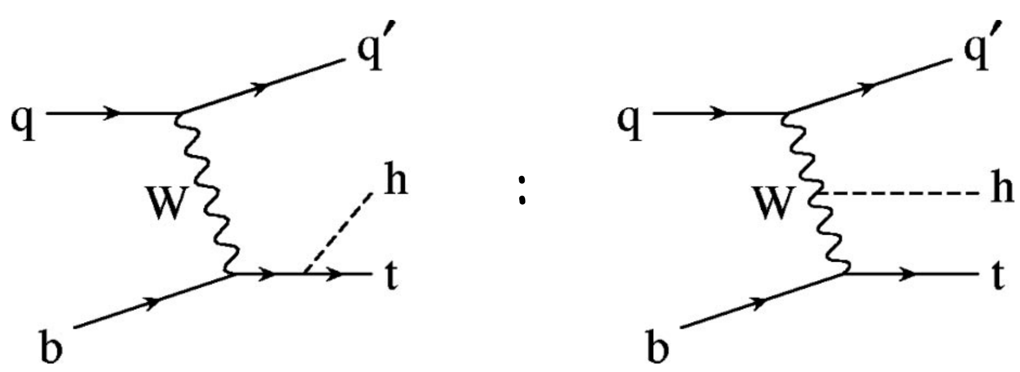
Top partners & Higgs physics

direct measurement of top-higgs coupling

htt is important but challenging channel

may be easier channel to look at

qb→q'th



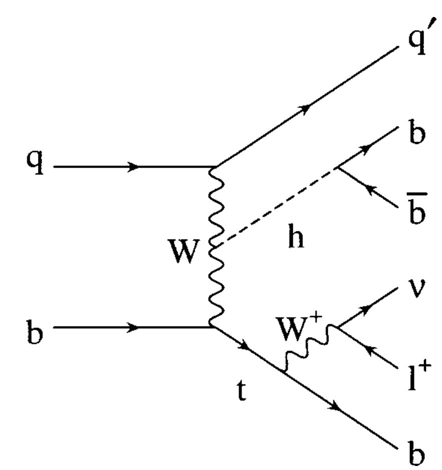
@m_H=125GeV $\quad \frac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$

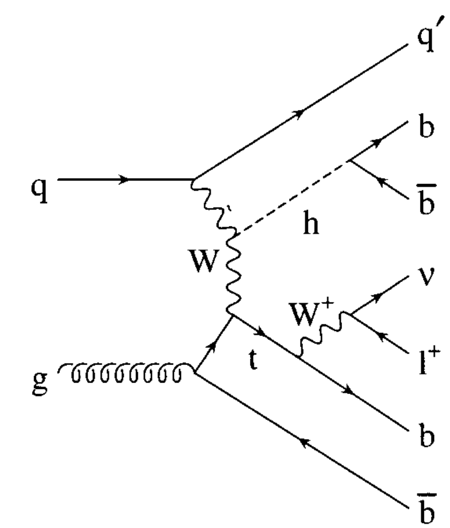
Farina, Grojean, Maltoni, Salvioni, Thamm '12

	$\sigma(pp \to tjh)$ [fb]		$\sigma(pp \to tjh\bar{b})$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.3	252.7	12.14	181.4
14 TeV	80.6	1042	59.6	828.5

look at final states:

$3\,b + 1\,\text{fwd jet} + l^\pm + \not{p}^T$. $\quad 4\,b + 1\,\text{fwd jet} + l^\pm + \not{p}^T$.

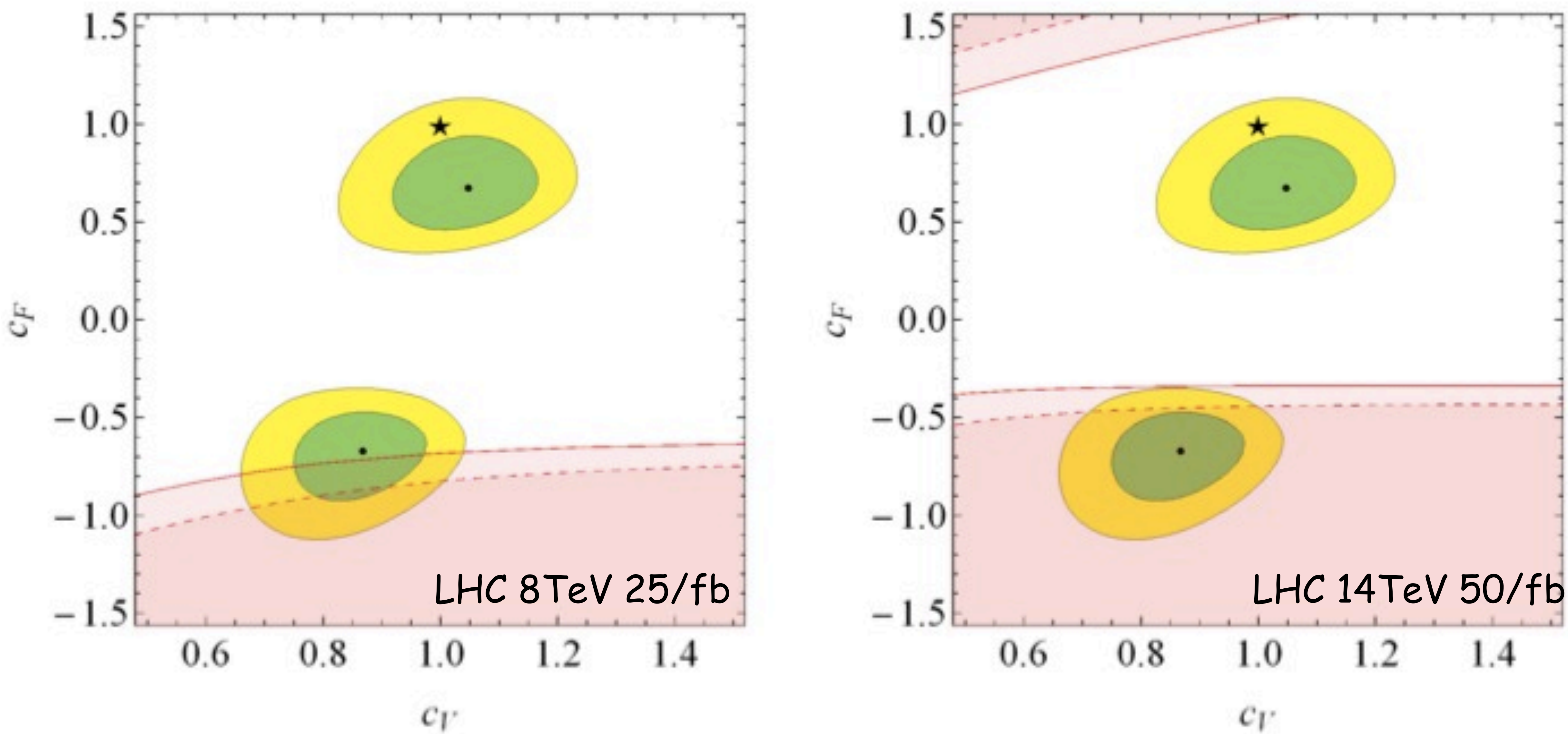




Top partners & Higgs physics

direct measurement of top-higgs coupling

single-top in association with Higgs



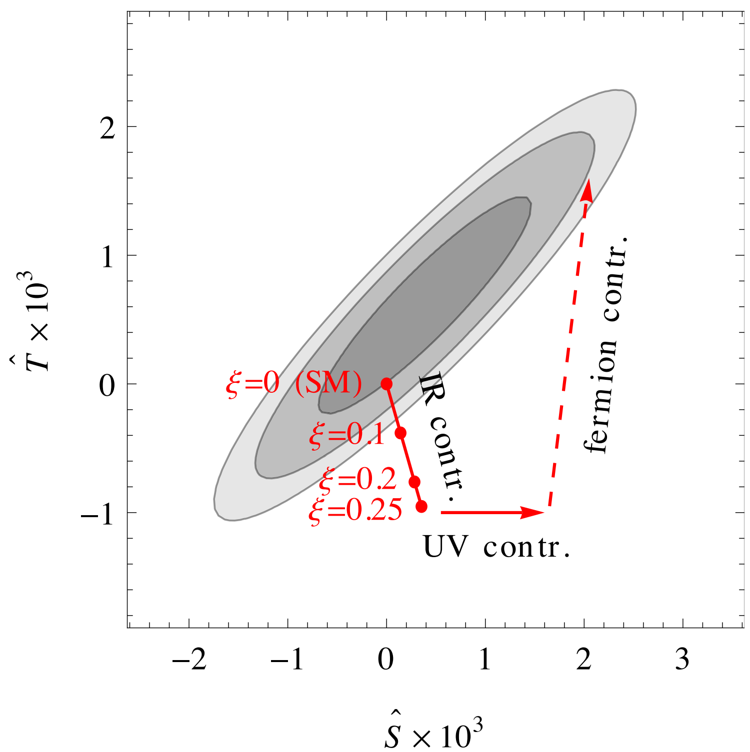
68% and 95% CL exclusion region vs current Higgs coupling fit

Farina, Grojean, Maltoni, Salvioni, Thamm '12

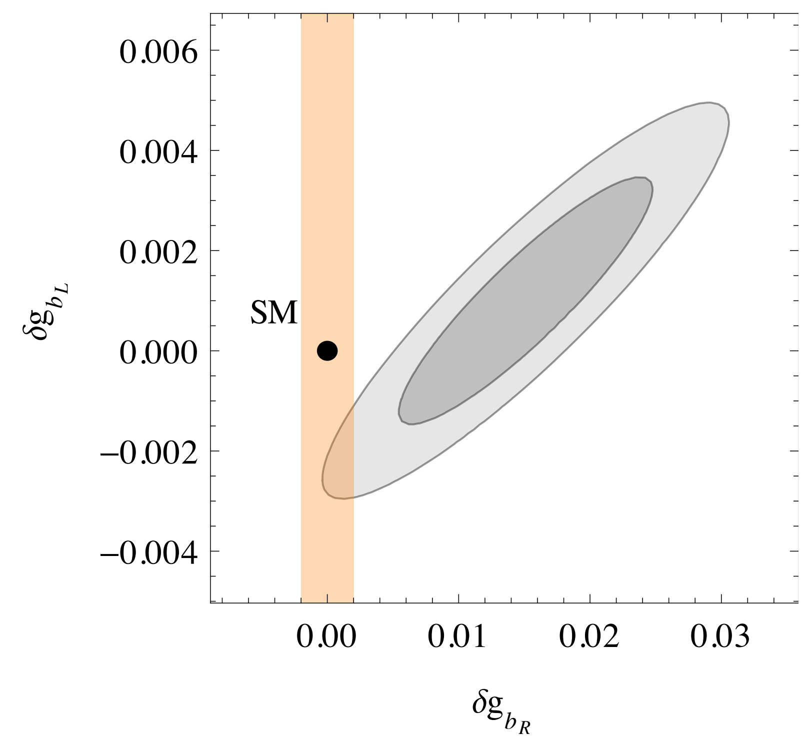
Top partners & EWPT

Grojean, Matsedonskyi, Panico '13

Oblique parameters



Zb_Lb_L



tree-level contribution

$$\Delta\widehat{S} \simeq \frac{g^2}{g_*^2}\xi \simeq \frac{m_w^2}{m_*^2}$$

Higgs loop

$$\Delta\widehat{S} = \frac{g^2}{192\pi^2}\xi \log\left(\frac{m_*^2}{m_h^2}\right) \simeq 1.4\cdot 10^{-3}\,\xi \qquad \Delta\widehat{T} = -\frac{3g'^2}{64\pi^2}\xi \log\left(\frac{m_*^2}{m_h^2}\right) \simeq -3.8\cdot 10^{-3}\,\xi$$

fermion loop

$$\Delta\widehat{S}^{div}_{ferm} = \frac{g^2}{8\pi^2}(1-2c^2)\,\xi \log\left(\frac{m_*^2}{m_4^2}\right) \qquad \Delta\widehat{T} \simeq \frac{N_c}{16\pi^2}y_t^2\,\xi \simeq 2\cdot 10^{-2}\,\xi$$

tree-level contribution

$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \sim \frac{y_L^2 f^2}{m^2}\frac{m_z^2}{m_*^2} \simeq 8\cdot 10^{-4}\,\frac{f}{m}\left(\frac{4\pi}{g_*}\right)^2\xi$$

fermion loop

$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \simeq \frac{y_t^2}{16\pi^2}\xi \log\left(\frac{m_*^2}{m_4^2}\right) \simeq 2\cdot 10^{-2}\,\xi$$

ξ<0.1 ⇨ we might have to wait LHC-HL to see any new physics in Higgs data

BSM Higgs precision era

3

Precision program in single Higgs processes

(assuming a mass gap between weak scale and new physics scale)

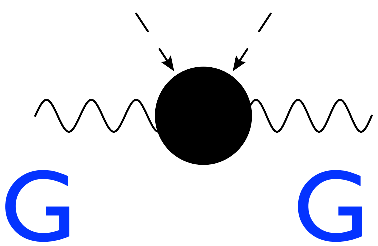
Higgs/BSM Primaries

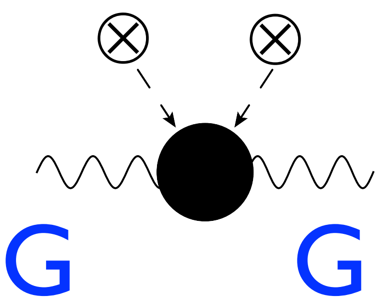
Several deformations away from the SM are harmless in the vacuum and need a Higgs field to be probed

(courtesy of A. Pomarol@HiggsHunting2014)

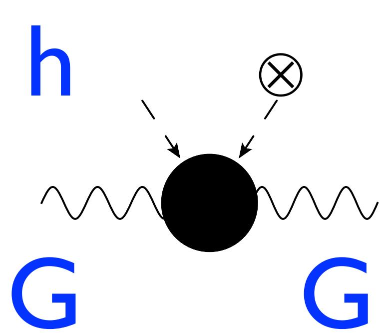
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right) G_{\mu\nu}^2$$

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

yet to be measured at the LHC (hZγ coupling, h^3 coupling)

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

Higgs/BSM Primaries

How many of these effects can we have?

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

Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit

Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	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 approximation built-in

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

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

8 for one family *(assuming CP-conservation)*

- **GGh coupling**
- **hγγ coupling**
- **hZγ coupling**
- **hVV* (custodial invariant)**
- **h^3 coupling**
- **htt, hbb, h$\tau\tau$**

yet to be measured at the LHC

Don't forget LEP!

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables

$$\mathcal{L} \supset \frac{1}{f^2}|H|^2|D_\mu H|^2$$

$$\Rightarrow a = \kappa_V = 1 + \frac{v^2}{2f^2}$$

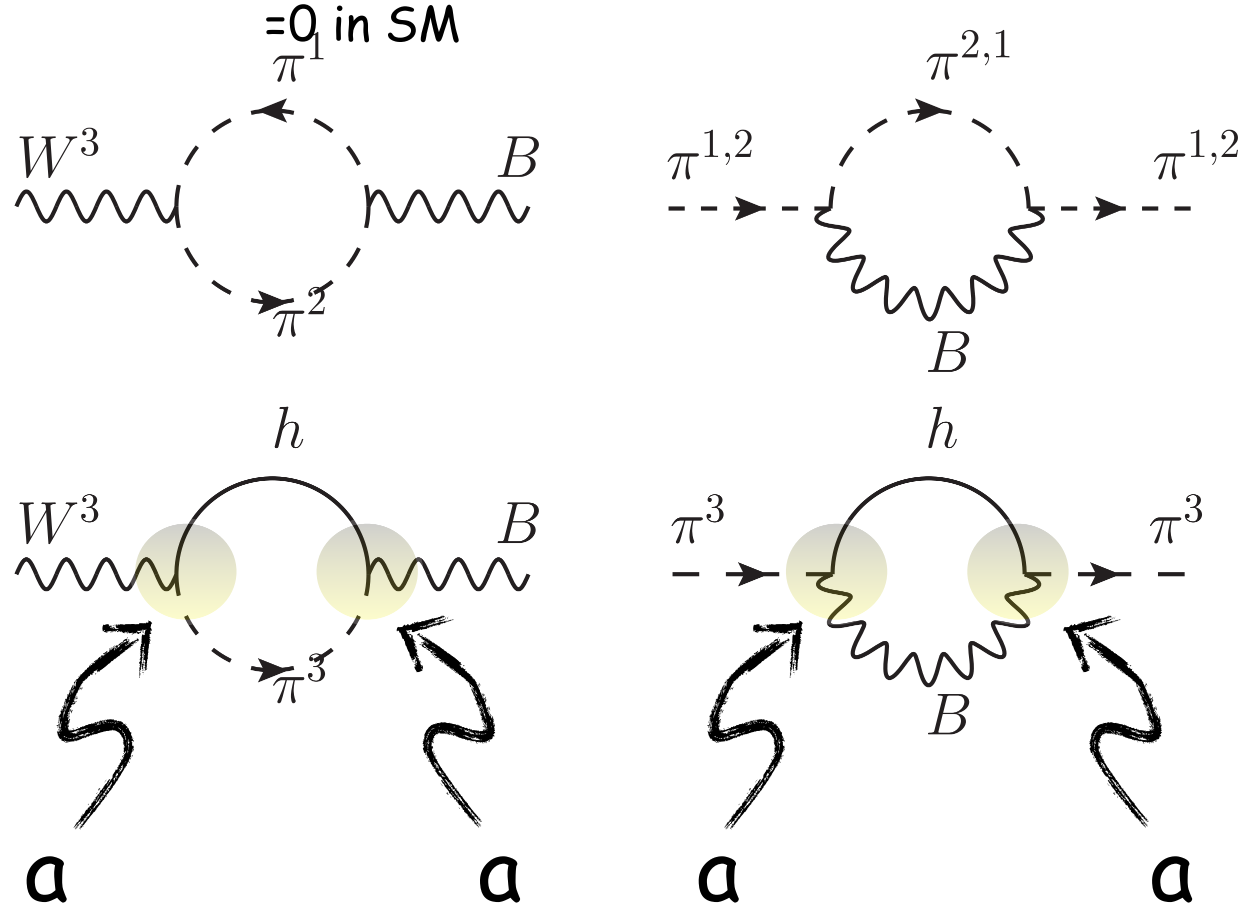
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3}(1-a^2)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

=0 in SM

$$c_1 = +\frac{3}{16\pi^2}\frac{\alpha(m_Z)}{\cos^2\theta_W} \qquad c_3 = -\frac{1}{12\pi}\frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\left(1-a^2\right)\log(m_\rho^2/m_h^2)$$

Barbieri, Bellazzini, Rychkov, Varagnolo '07



Log. div. cancel only for a=1 (SM)

a≠1 log. sensitivity on the scale of new physics

Don't forget LEP!

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Barbieri, Bellazzini, Rychkov, Varagnolo '07

EW fit:

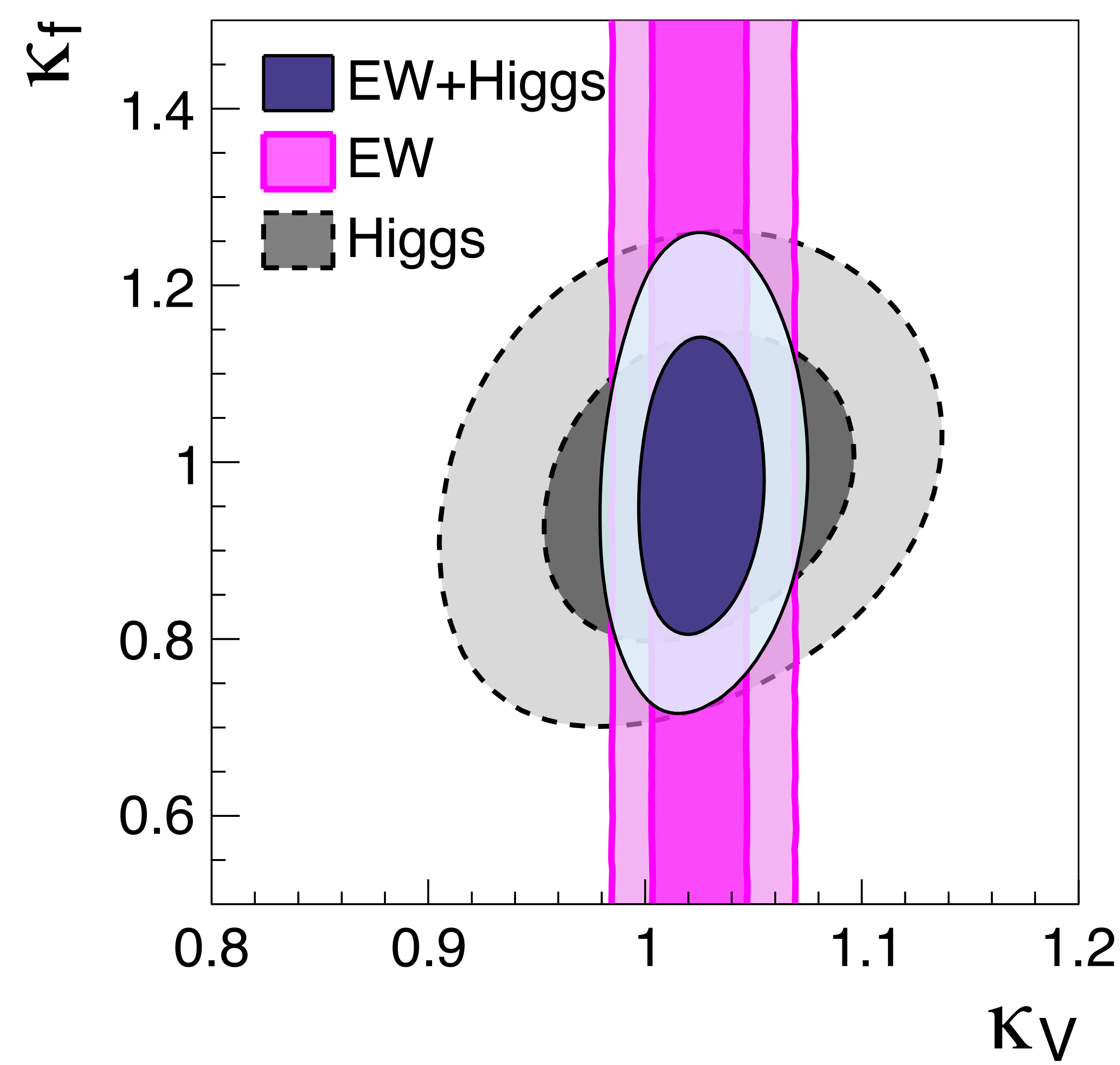
$$0.98 \le a^2 \le 1.12$$

Ciuchini et al '13

see also Grojean et al '13

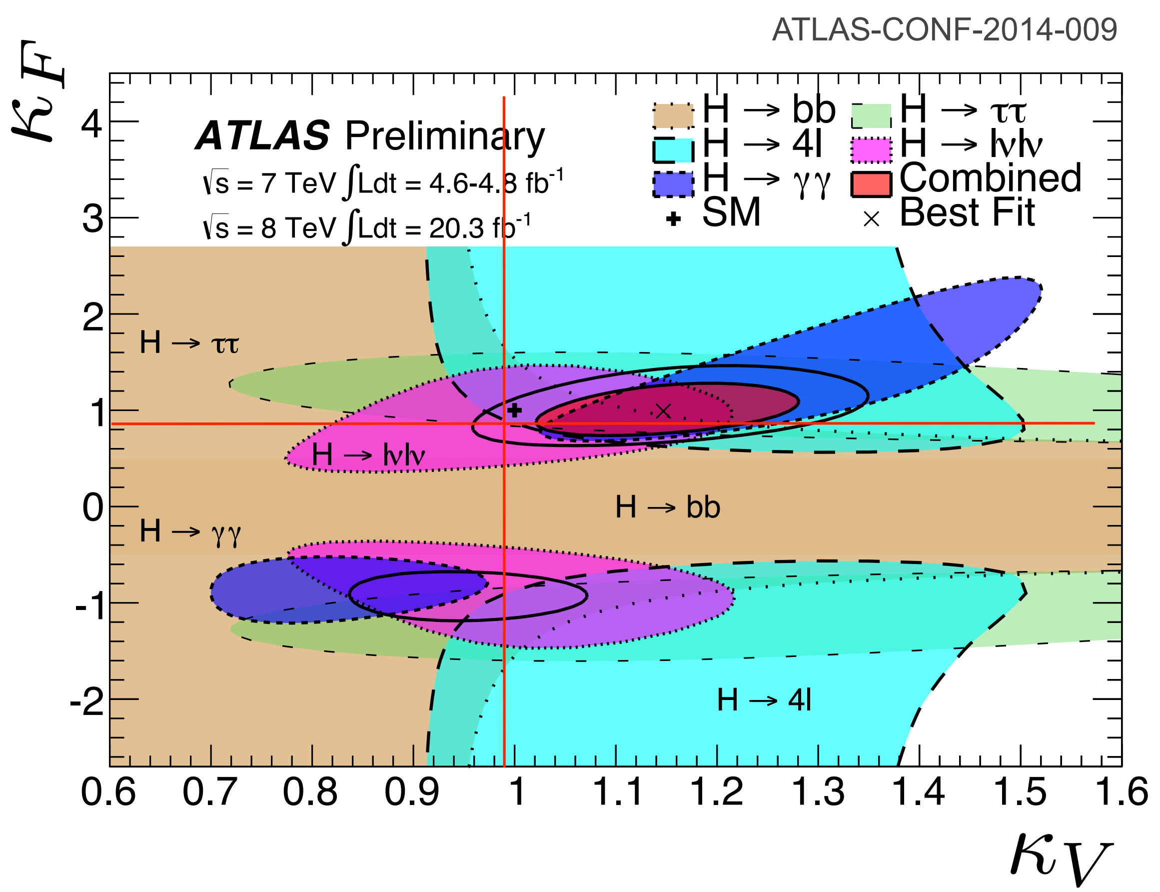
The LEP indirect constraints on the other BSM primaries are not competitive

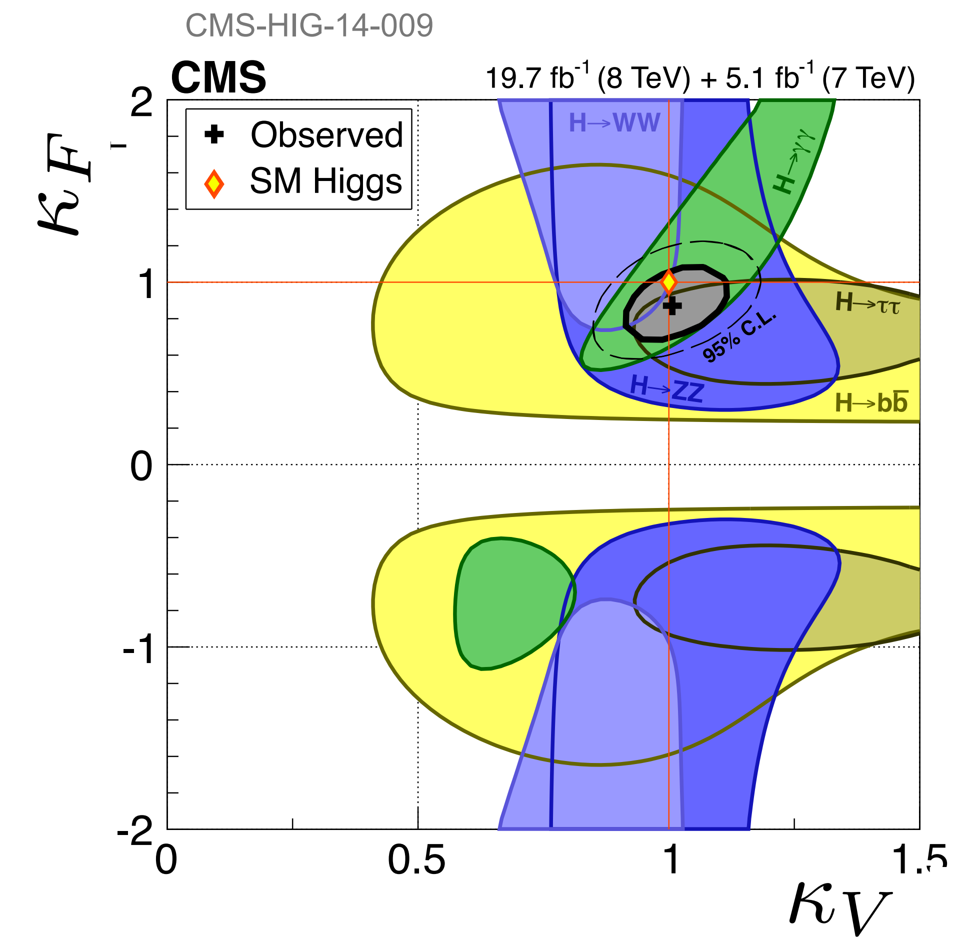
Elias-Miro et al '13



Ciuchini et al '13

Experimental results





CP violation in Higgs physics?

Is CP a good symmetry of Nature? 2 CP-violating couplings in the SM:

V_{CKM} (large, O(1)), but screened by small quark masses) and θ_{QCD} (small, $O(10^{-10})$)

Can the 0^+ SM Higgs boson have CP violating couplings?

Among the 59 irrelevant directions, 6 ~~CP~~ Higgs/BSM primaries

$$\Delta\mathcal{L}_{\rm BSM} = i\delta\tilde{g}_{hff}\, h\bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau\text{, t)}$$

$$+\tilde{\kappa}_{GG}\frac{h}{v}G^{\mu\nu}\tilde{G}_{\mu\nu} \qquad (\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma})$$

$$+\tilde{\kappa}_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu}$$

$$+\tilde{\kappa}_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}$$

CP violation in Higgs physics?

Among the 59 irrelevant directions, 6 $\not{\text{CP}}$ Higgs/BSM primaries

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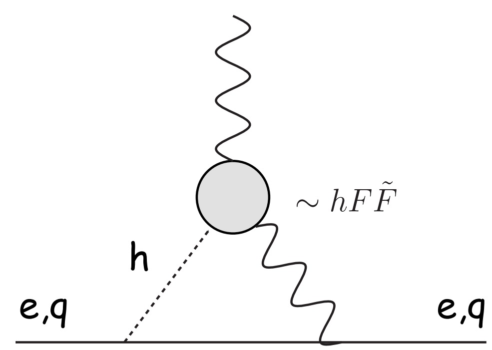
$$+\tilde{\kappa}_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}$$

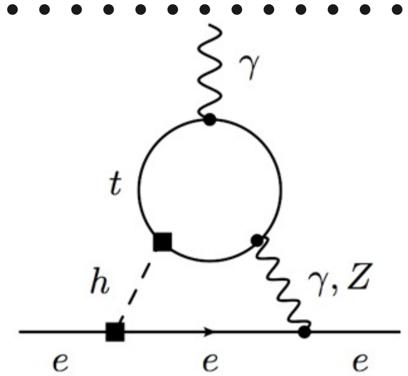
operators with γ:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

$\Lambda_{\not{\text{CP}}}$ > 25 TeV

operators with top:
already severely constrained
by e and q EDMs
Brod, Haisch, Zupan '13



$$\delta\tilde{g}_{htt} \leq 0.01$$

$\Lambda_{\not{\text{CP}}}$ > 2.5 TeV

Caveats: h couplings to light particles can be significantly reduced

4

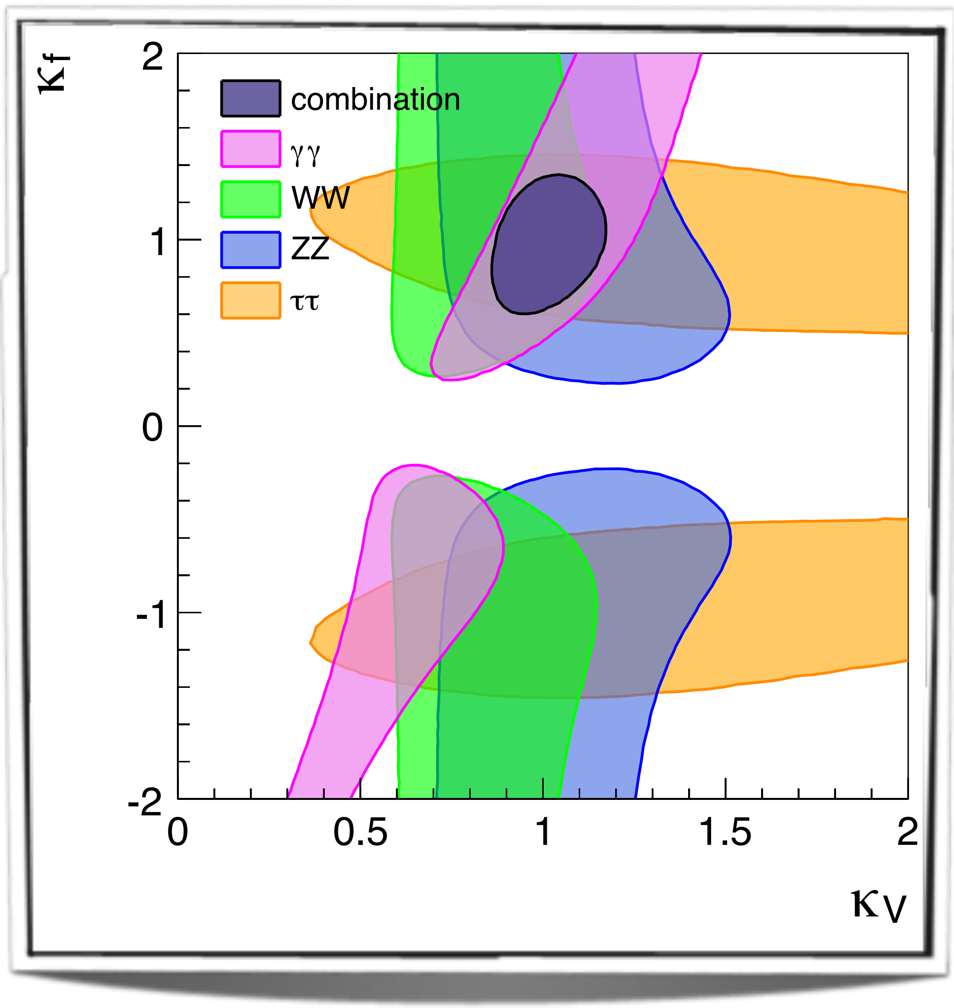
Boosted and off-shell Higgs channels

Why going beyond inclusive Higgs processes?

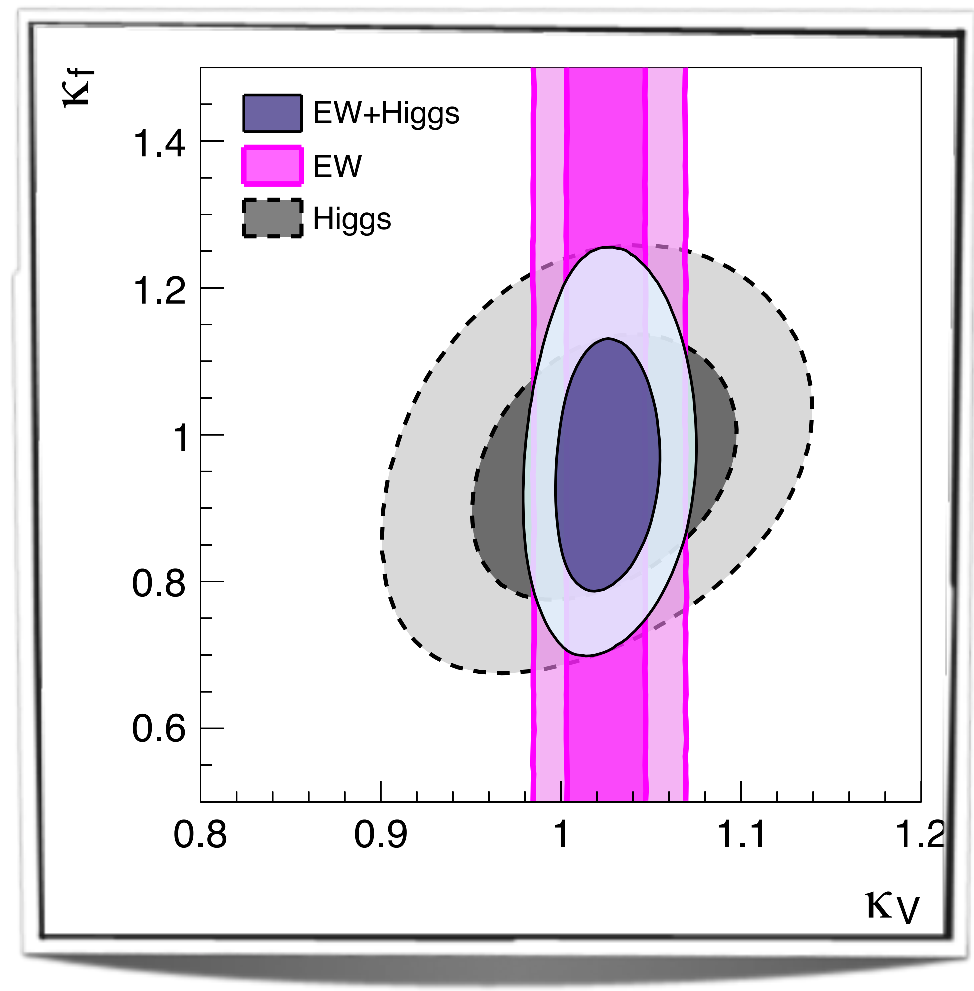
So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

⇩ ⇩

access to Higgs couplings @ m_H



Ciuchini et al '13



Ciuchini et al '13

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
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⇩ ⇩

access to Higgs couplings @ m_H

Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

Probing new corrections to the SM Lagrangian?

on-shell Z @ LEP1

constraints on
S and T oblique corrections

off-shell Z @ LEP2
constraints on
W and Y oblique corrections
(same order as S and T but cannot be probed @ LEP1)

But... off-shell Higgs data do not probe new corrections
that cannot be constrained by on-shell data

Boosted Higgs

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

(*) unless it doesn't decouple (e.g. 4th generation)

the inclusive rate doesn't "see" the finite mass of the top

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

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

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

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

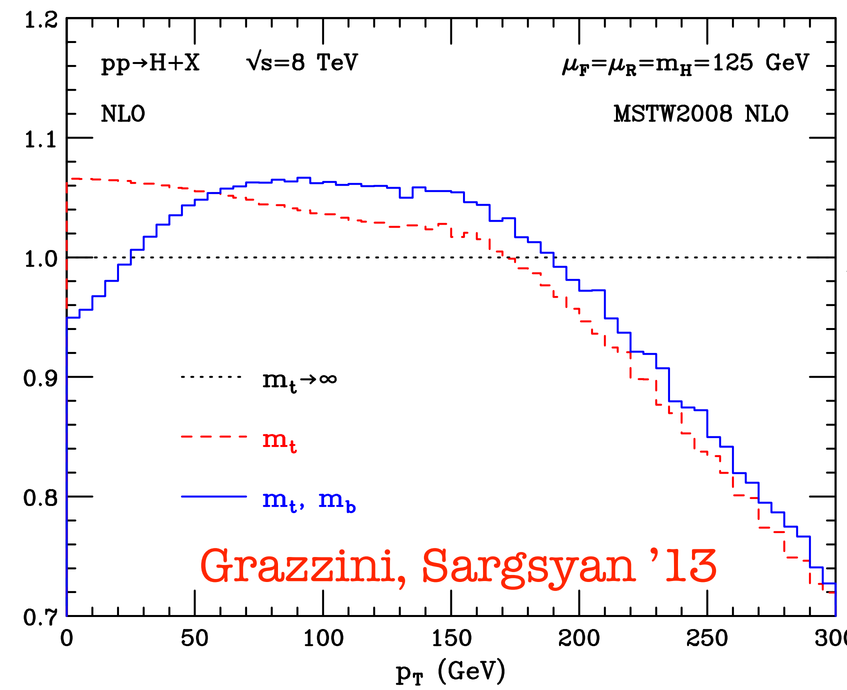
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

Resolving top loop: Boosted Higgs

cut open the top loops

high $p_T \approx$ Higgs off-shell
we "see" the details of the particles
running inside the loops

Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



Note: LO only
NLO_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

the high p_T tail
is tens' % sensitive
to the mass of top

Resolving top loop: Boosted Higgs

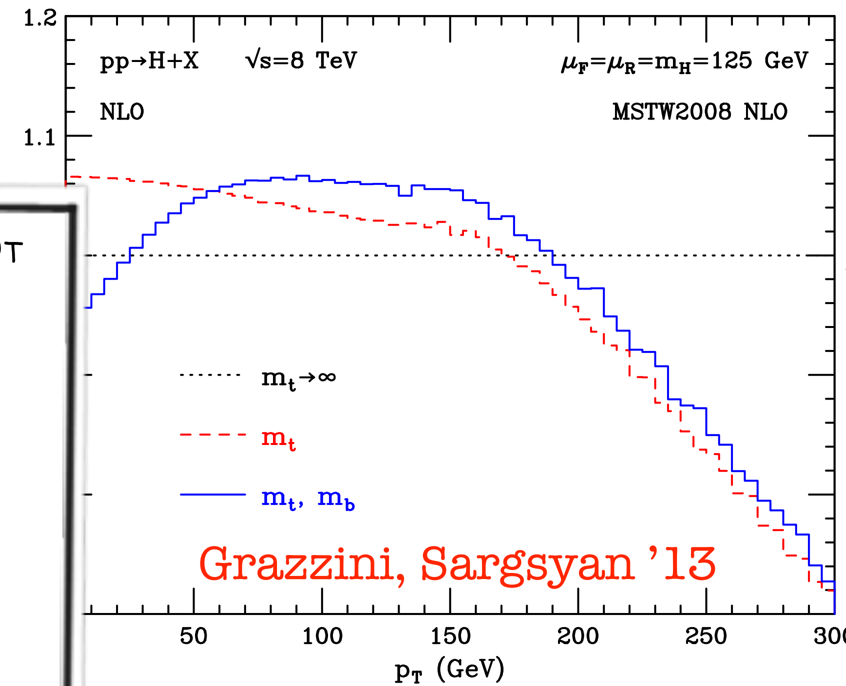
cut open the top loops

Don't think it is easy to produce a Higgs with high p_T

$\sqrt{s}$ [TeV]	p_T^{min} [GeV]	$\sigma^{SM}_{p_T^{min}}$ [fb]	δ	ϵ	gg, qg [%]
	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
14	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57

×1000 reduction

Grojean, Salvioni, Schlaffer, Weiler '13



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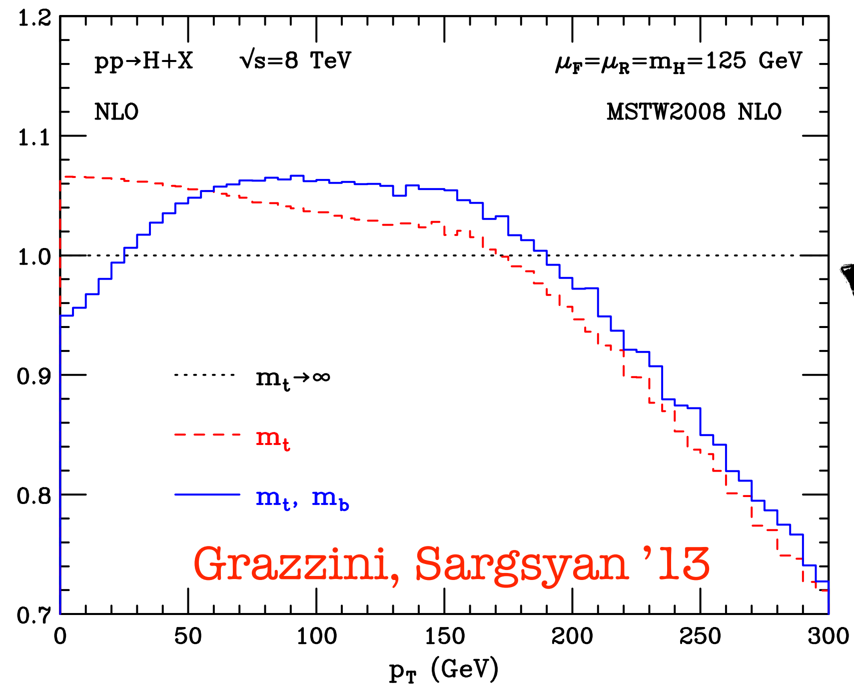

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Harlander et al '12

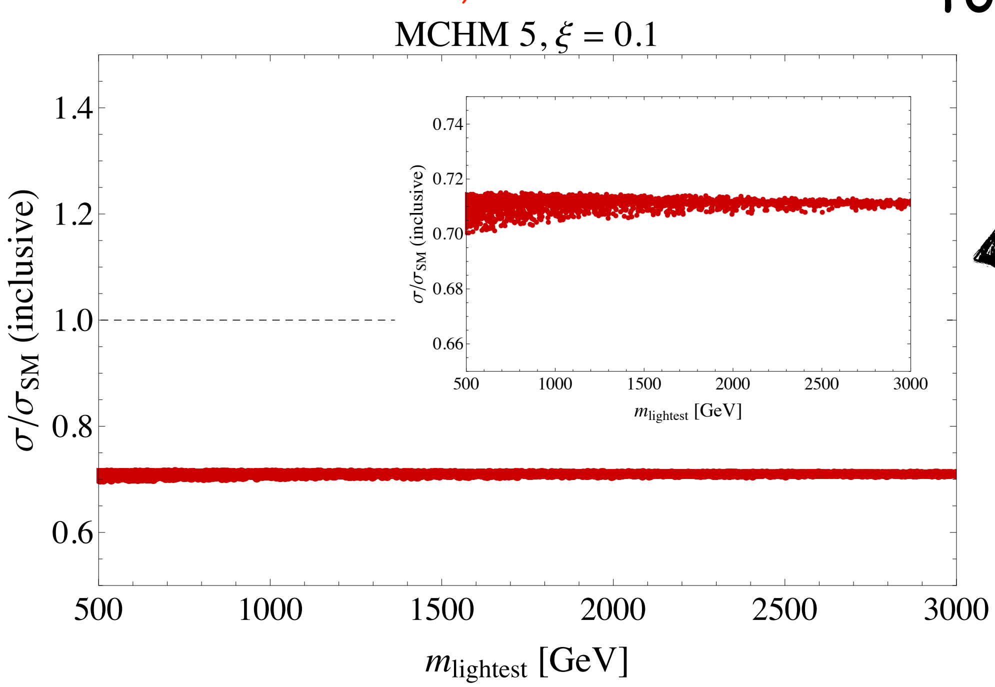
the high p_T tail is tens' % sensitive to the mass of top

Composite Higgs Model

top partners contributions

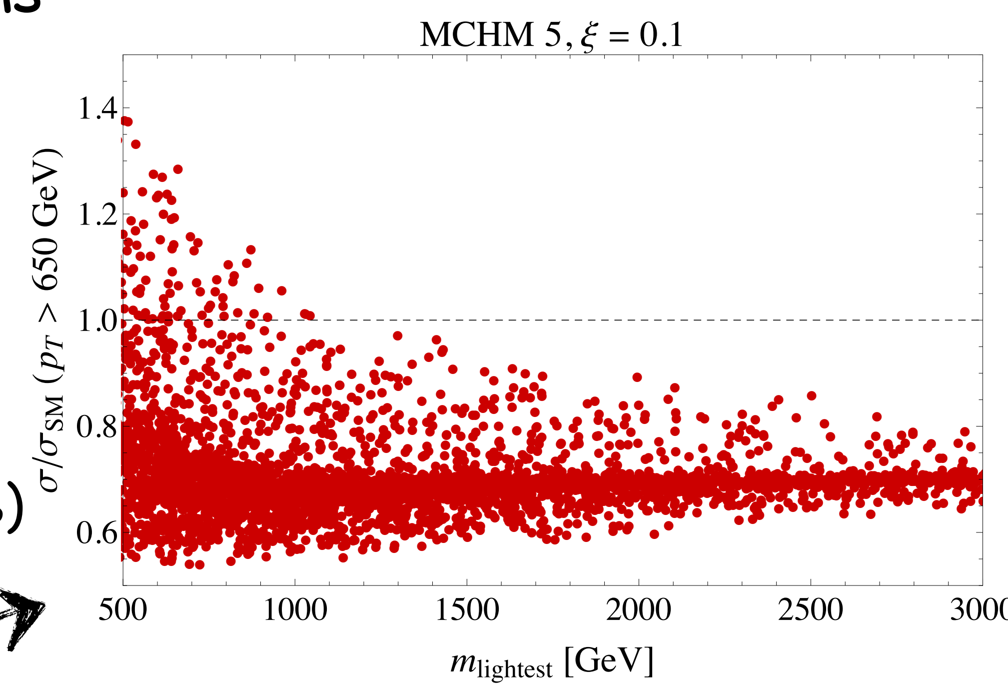
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: O(%)

with high-p_T cut: O(x10'%)



high-p_T tail "sees" the top partners that are missed by the inclusive rate

Boosted Higgs

see also Azatov, Paul '13

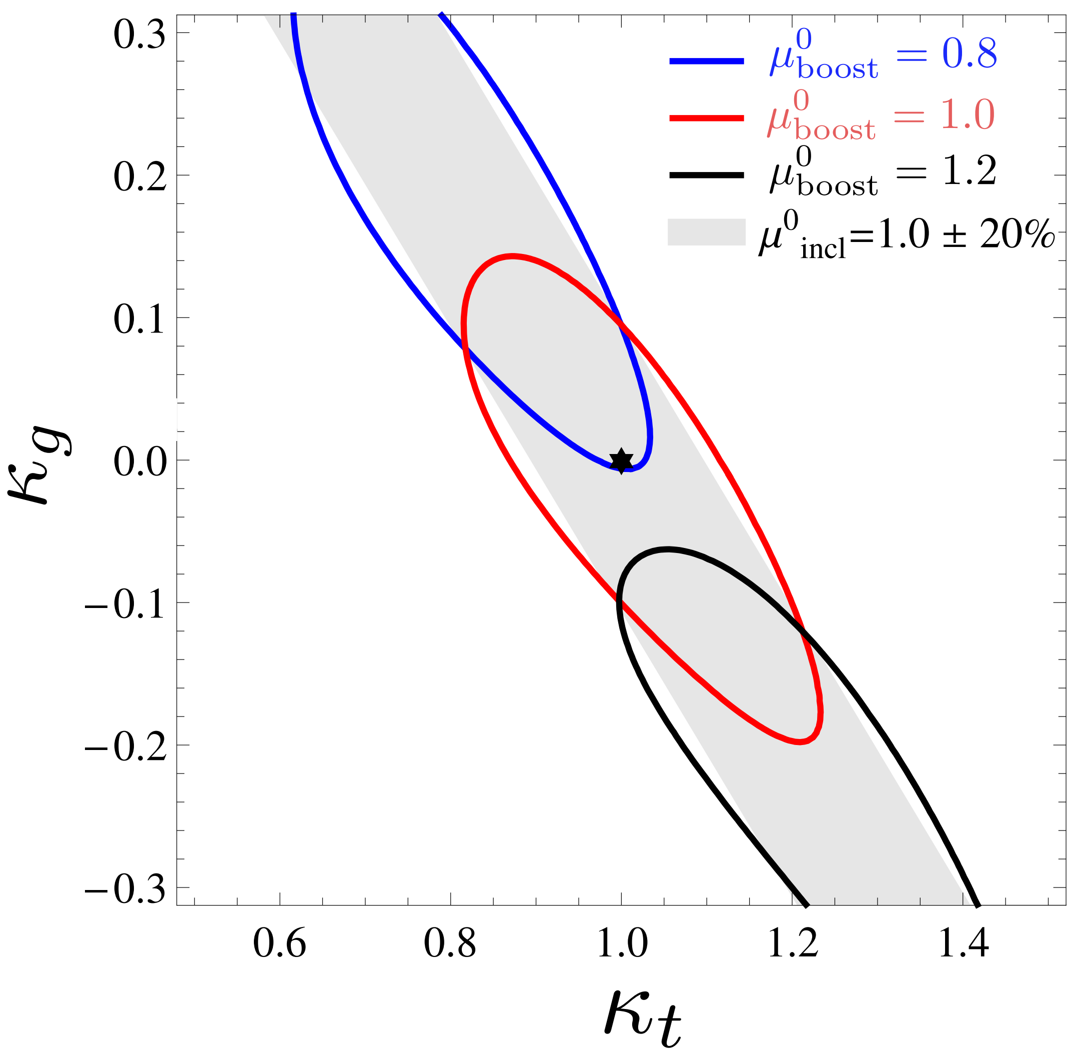
Grojean, Salvioni, Schlaffer, Weiler '13

high p_T tail discriminates short and long distance physics contribution to $gg \to h$

$$\sqrt{s} = 14 \text{ TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650 \text{ GeV}$$

(partonic analysis in the boosted "ditau-jets" channel)

see Schlaffer et al '14 for a more complete analysis including WW channel



10-20% precision on κ_t

⇓ ⇓

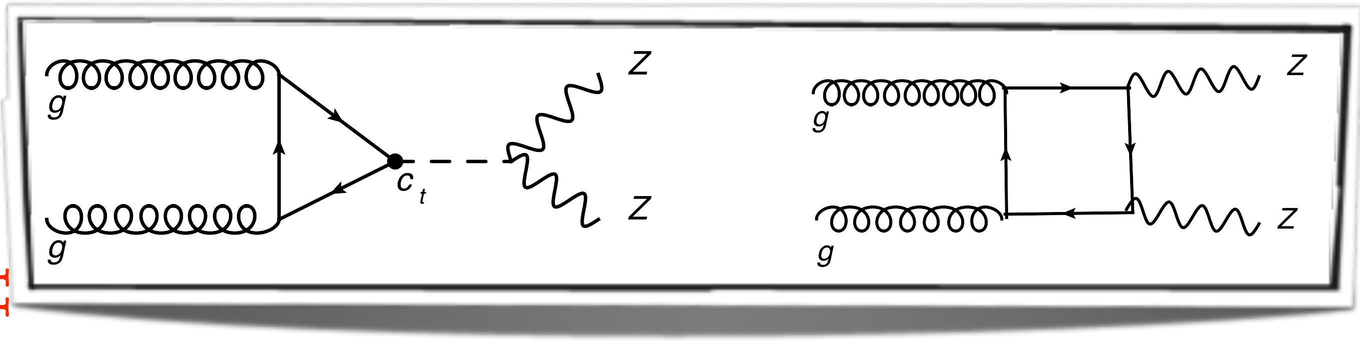
competitive/complementary to htt channel for the measure the top-Higgs coupling

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

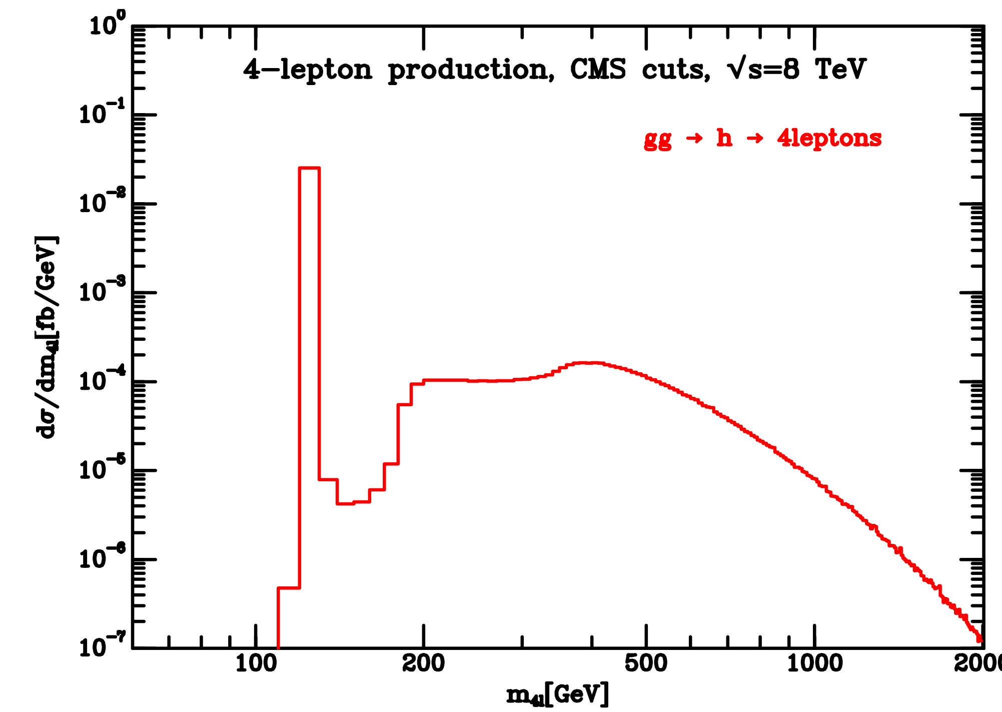
Off-shell Higgs: gg → h* → ZZ → 4l

off-shell effects enhanced by the particular couplings of H to V_L

Glover, van der Bij '89



$$\mathcal{M}^{++00}_{\rm Higgs} \sim \log^2 \frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\rm box} \sim -\log^2 \frac{\hat{s}}{m_t^2}$$



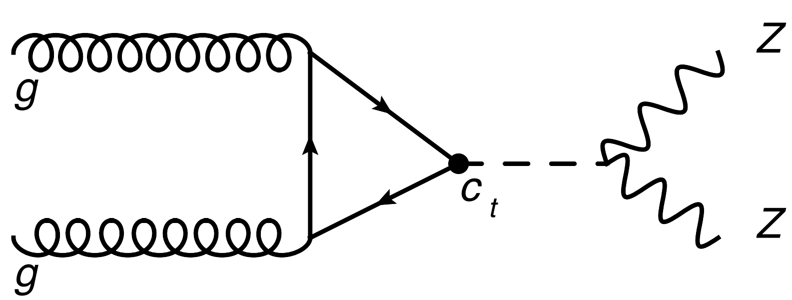
SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large s will be amplified

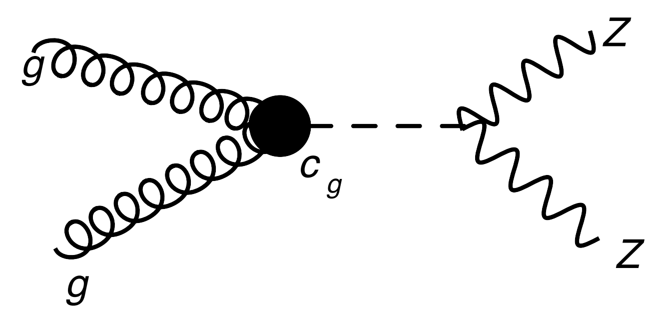
Azatov, Grojean, Paul, Salvioni '14

CMS interpretation in terms of bounds of the Higgs width is limited

data can be better used to measure the structure of the couplings at high √s



$$\mathcal{M}^{++00}_{c_t} \sim \log^2 \frac{\hat{s}}{m_t^2}$$

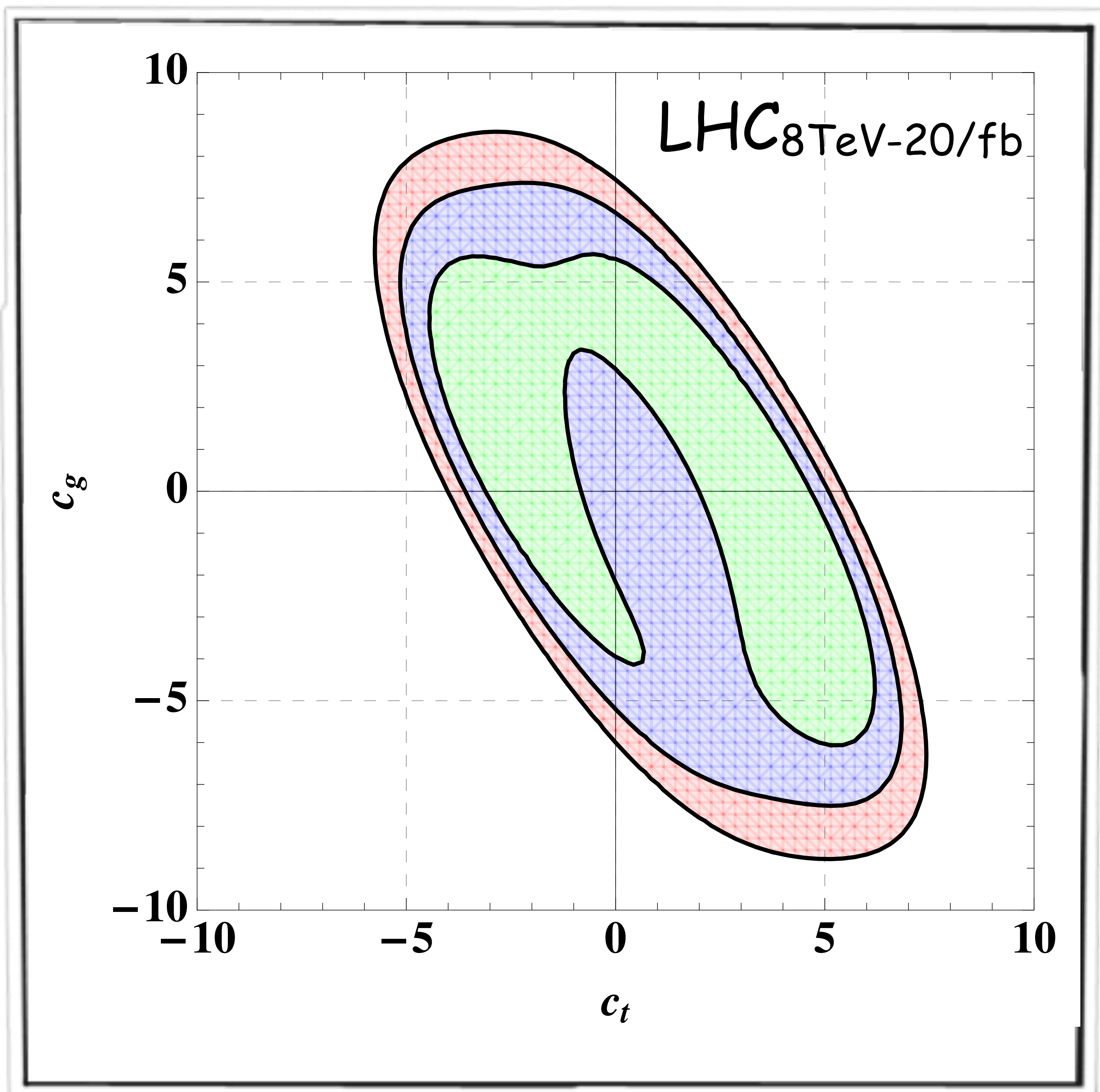


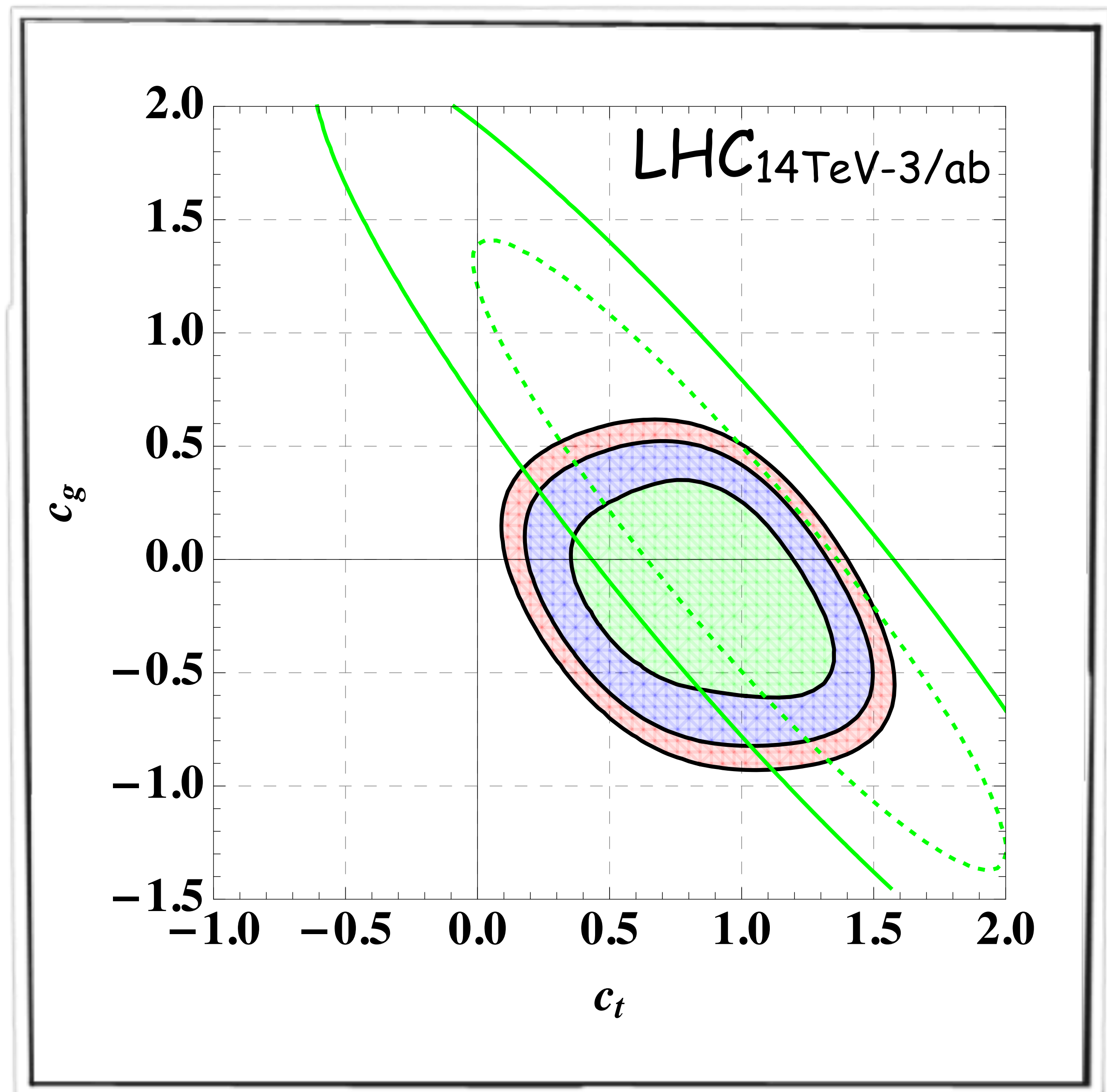
$$\mathcal{M}^{++00}_{c_g} \sim \hat{s}$$

Off-shell Higgs: $gg \to h^* \to ZZ \to 4l$

off-shell effects enhanced by the particular couplings of H to V_L

Azatov, Grojean, Paul, Salvioni '14



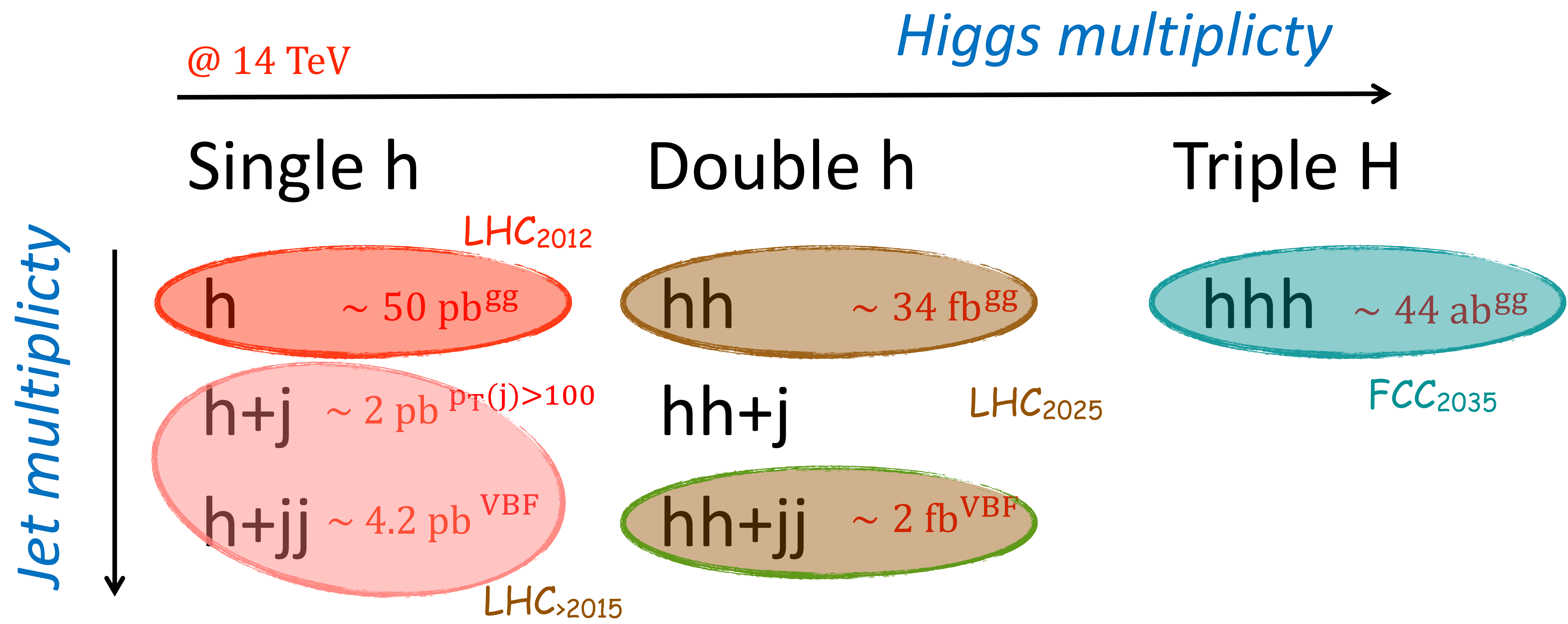


5

Multi-Higgs channels

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better



- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

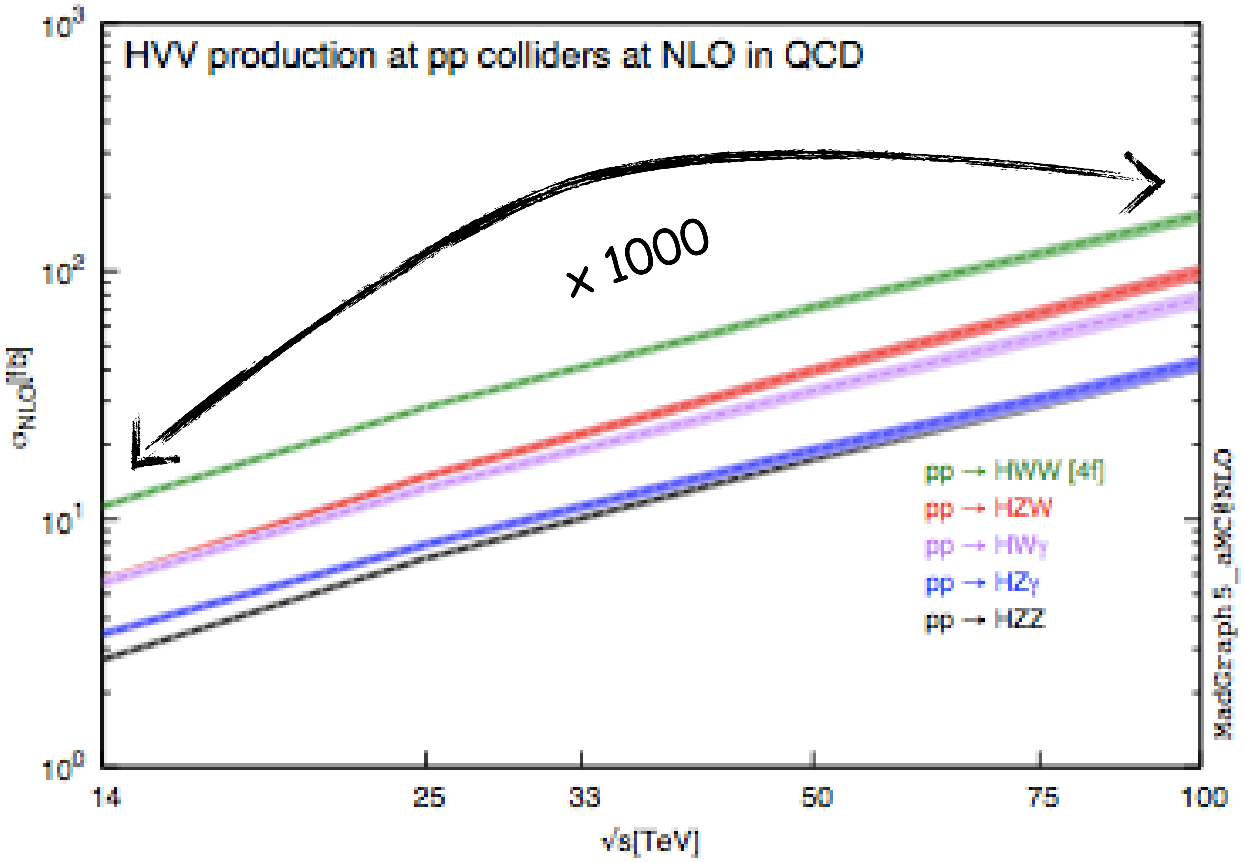
(adapted from M. Son@Planck2014)

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better

A long term plan?

Higgs-diboson associated production

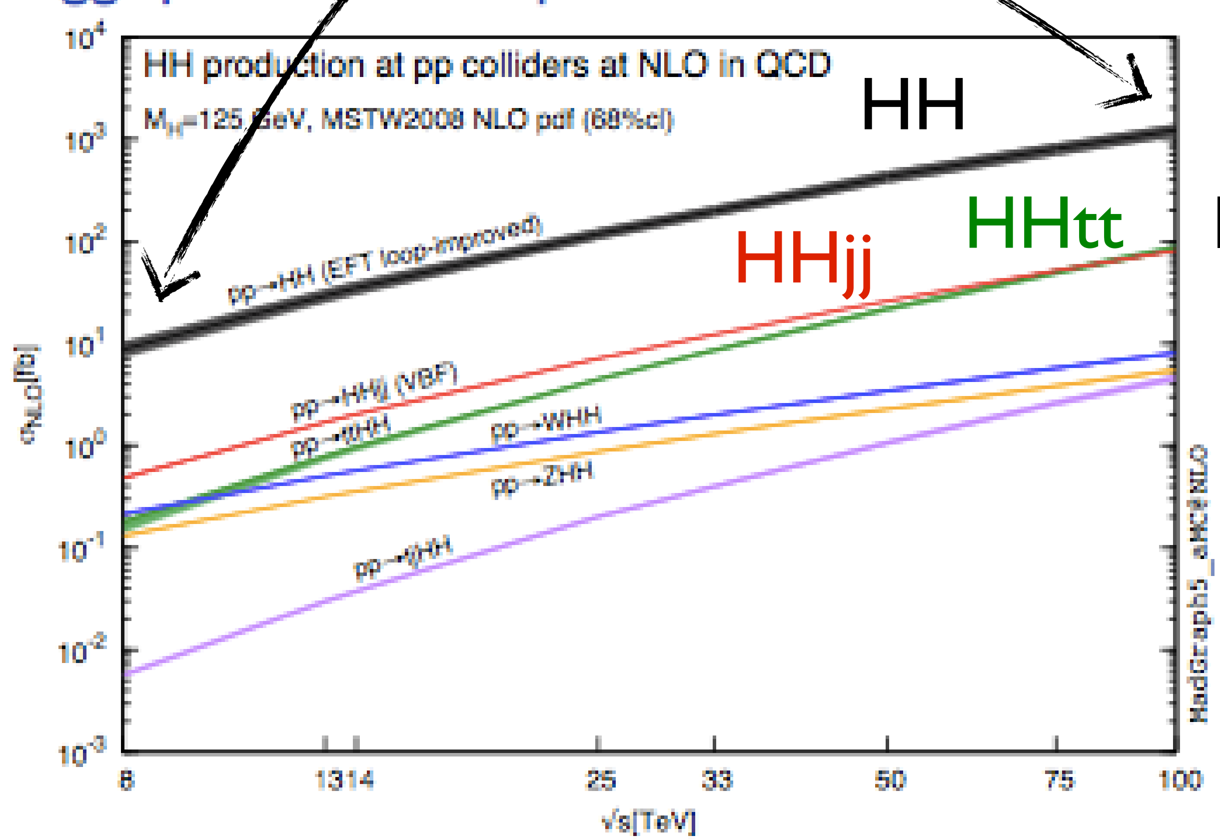


100 fb

FCC = H+X factory

× 100-1000

Higgs-pair associated production



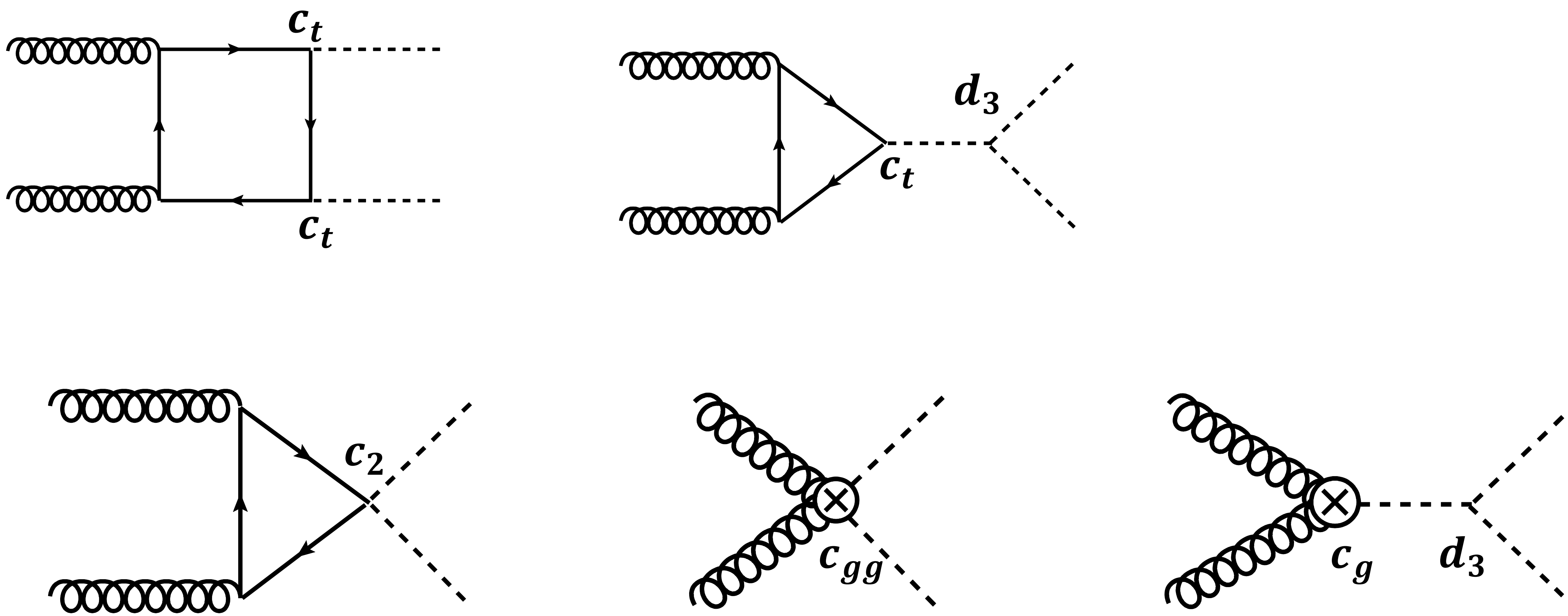
1000 fb

100 fb

(Plots from P. Torrielli and MLM, CERN'14)

What do we learn from gg→HH?

in principle gg→HH gives access to many new couplings, including non-linear couplings

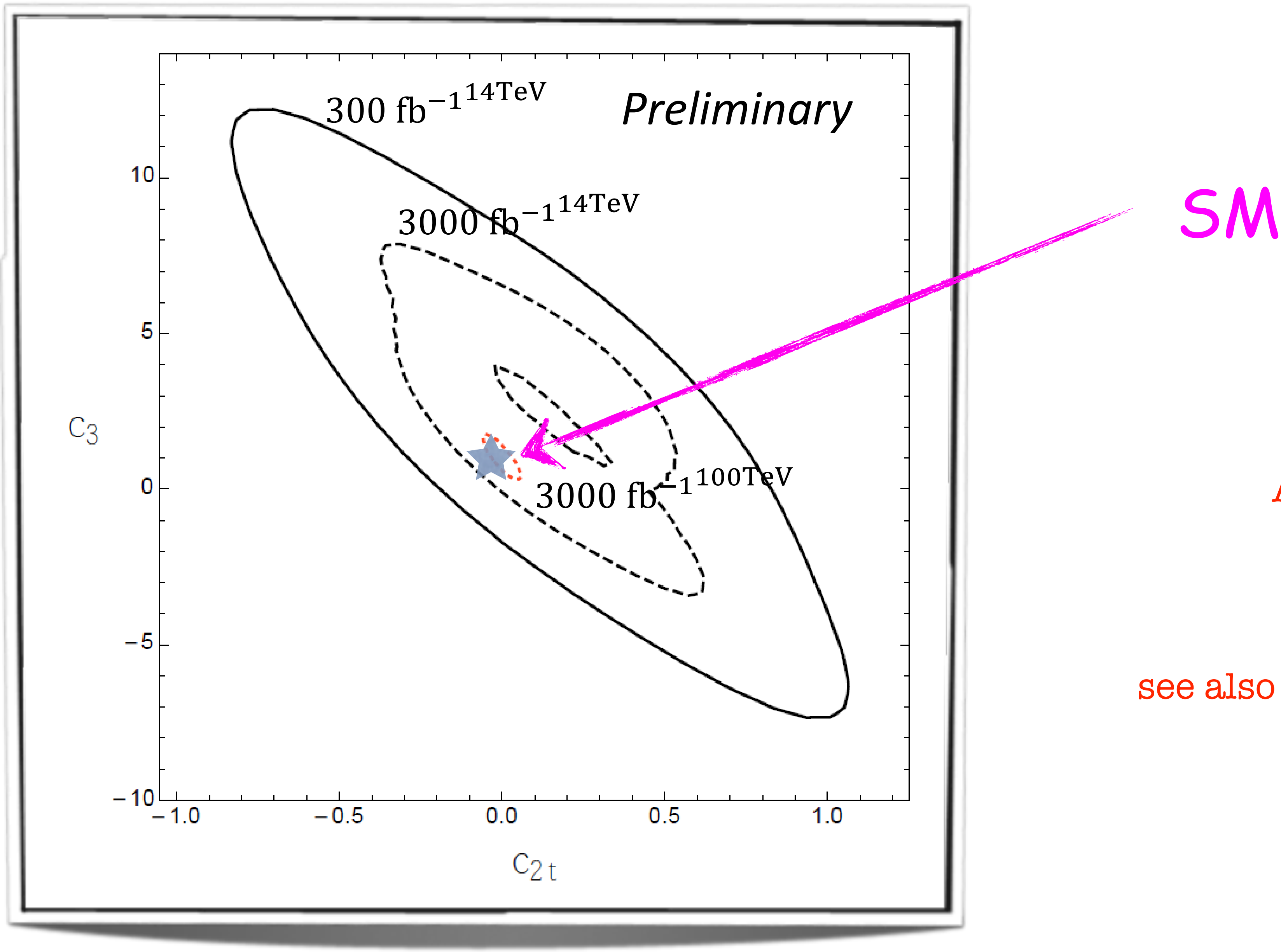


In practice, if the Higgs is part of an EW doublet,
these new couplings are related to single-Higgs couplings

$$c_{2t} = 3(c_t - 1) \qquad\qquad c_{gg} = c_g$$

Examples of connection between 1-Higgs and 2-Higgs vertices
Important to measure independently these vertices
and check the relations imposed by structure/symmetries/dynamics of the theory

What do we learn from gg→HH?



Azatov, Contino, Panico, Son ’15

see also Goertz, Papaefstathiou, Yang, Zurita ’14

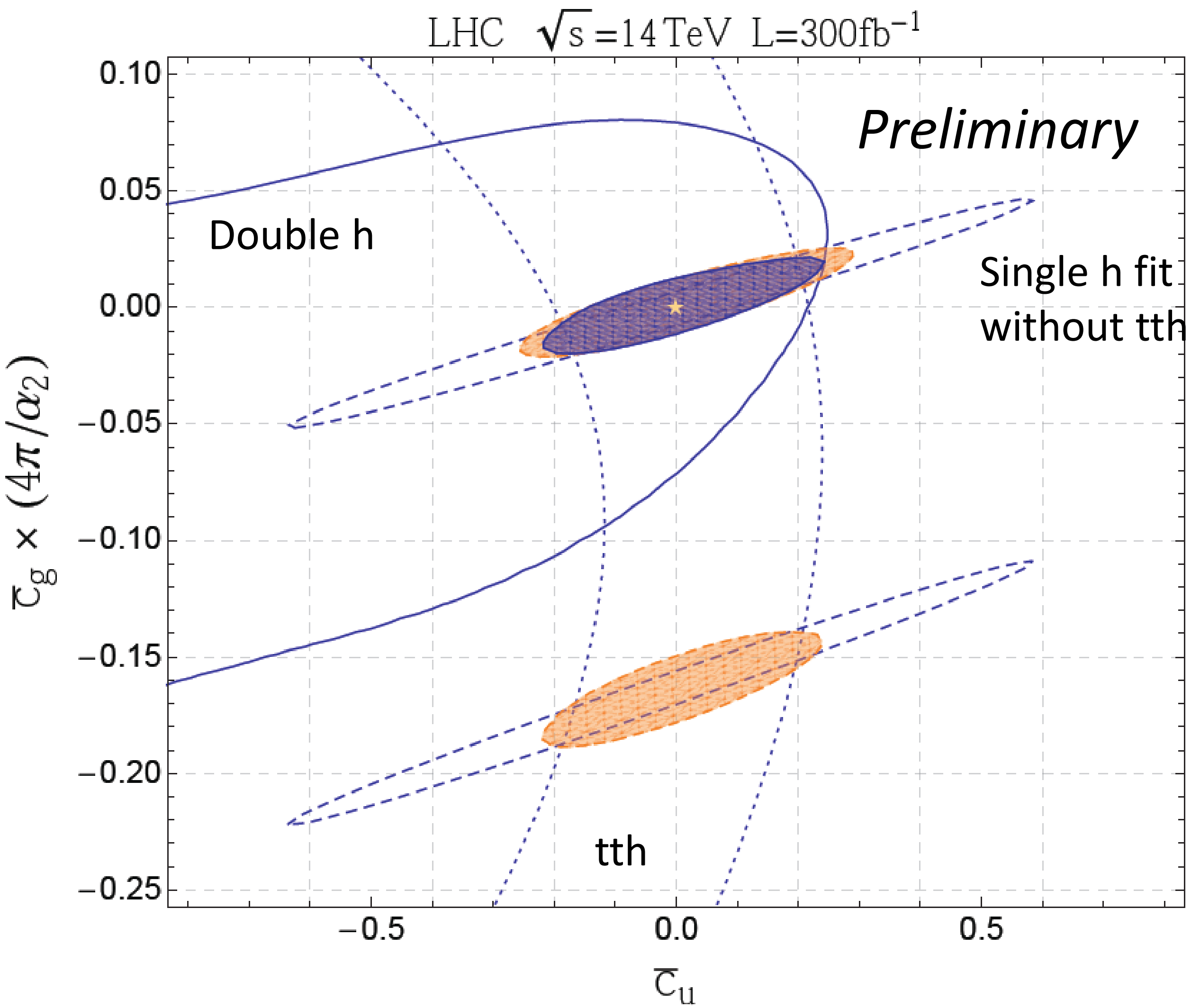
Remarks:

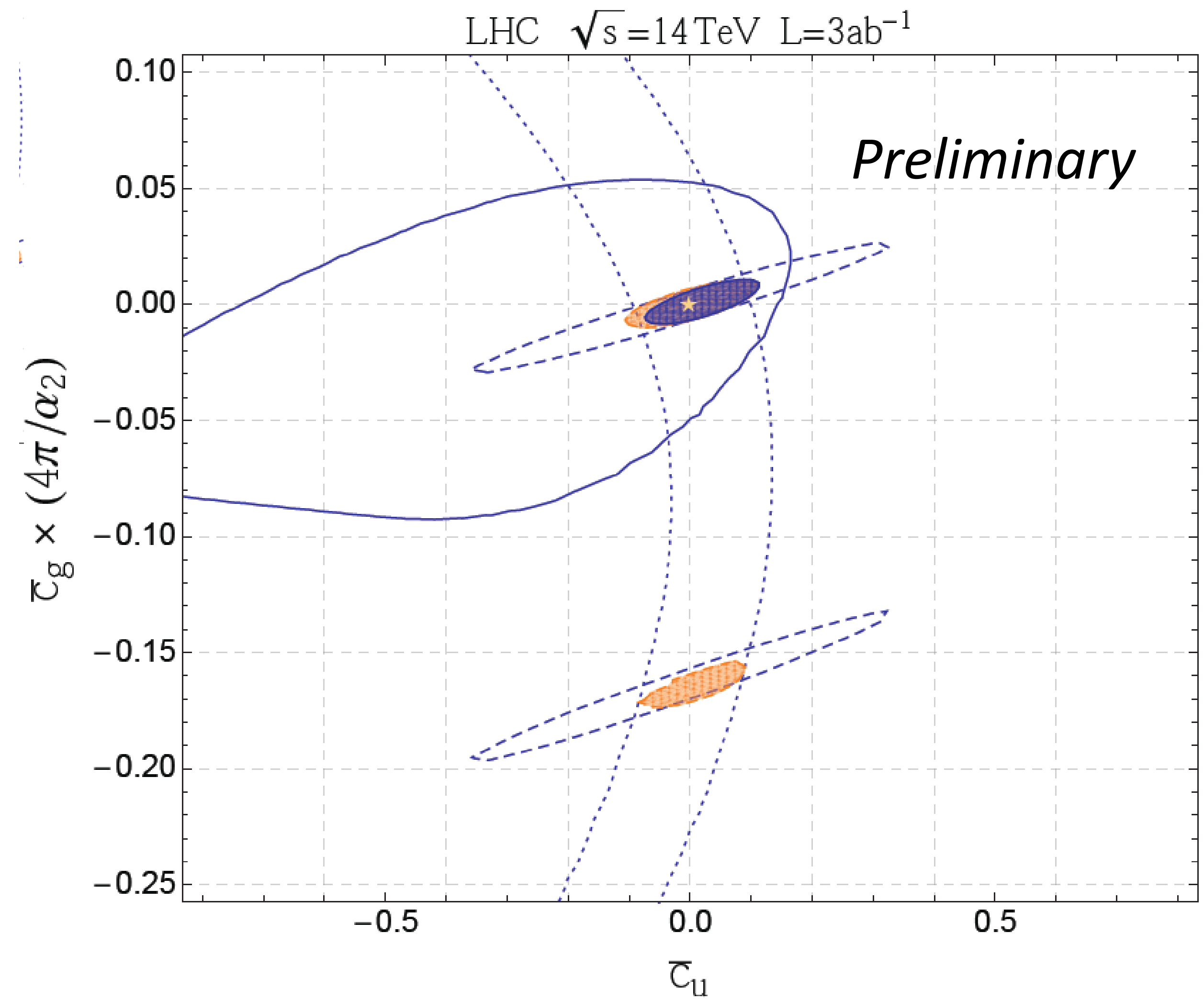
- unique access to c_3 but sensitivity is limited (within the validity of EFT?).
- statistically limited, with more luminosity
  - ⇛ access to distribution
  - ⇛ discriminating power c_3 vs. c_{2t} vs c_g

What do we learn from gg→HH?

in principle gg→HH gives access to many new couplings, including non-linear couplings

after marginalizing over c_3, HH channel provides additional infos on single Higgs couplings





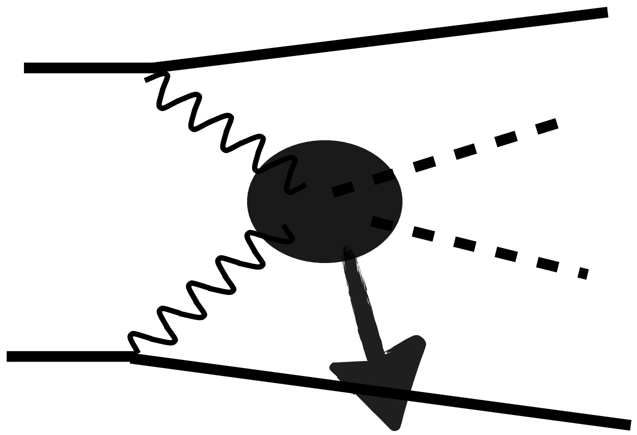
Azatov, Contino, Panico, Son 'to appear

HH channel is useful to break the degeneracy between 2 minima in the fit of single Higgs processes

Multiple Higgs interactions in WW→HH

in the SM, the Higgs is essential to prevent strong interactions in EWSB sector

(e.g. WW scattering) Contino, Grojean, Moretti, Piccini, Rattazzi '10



SM: $a=b=d_3=d_4=1$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right)$$

$$V(h)=\frac{1}{2}m_h^2h^2+d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3+d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4+\ldots$$

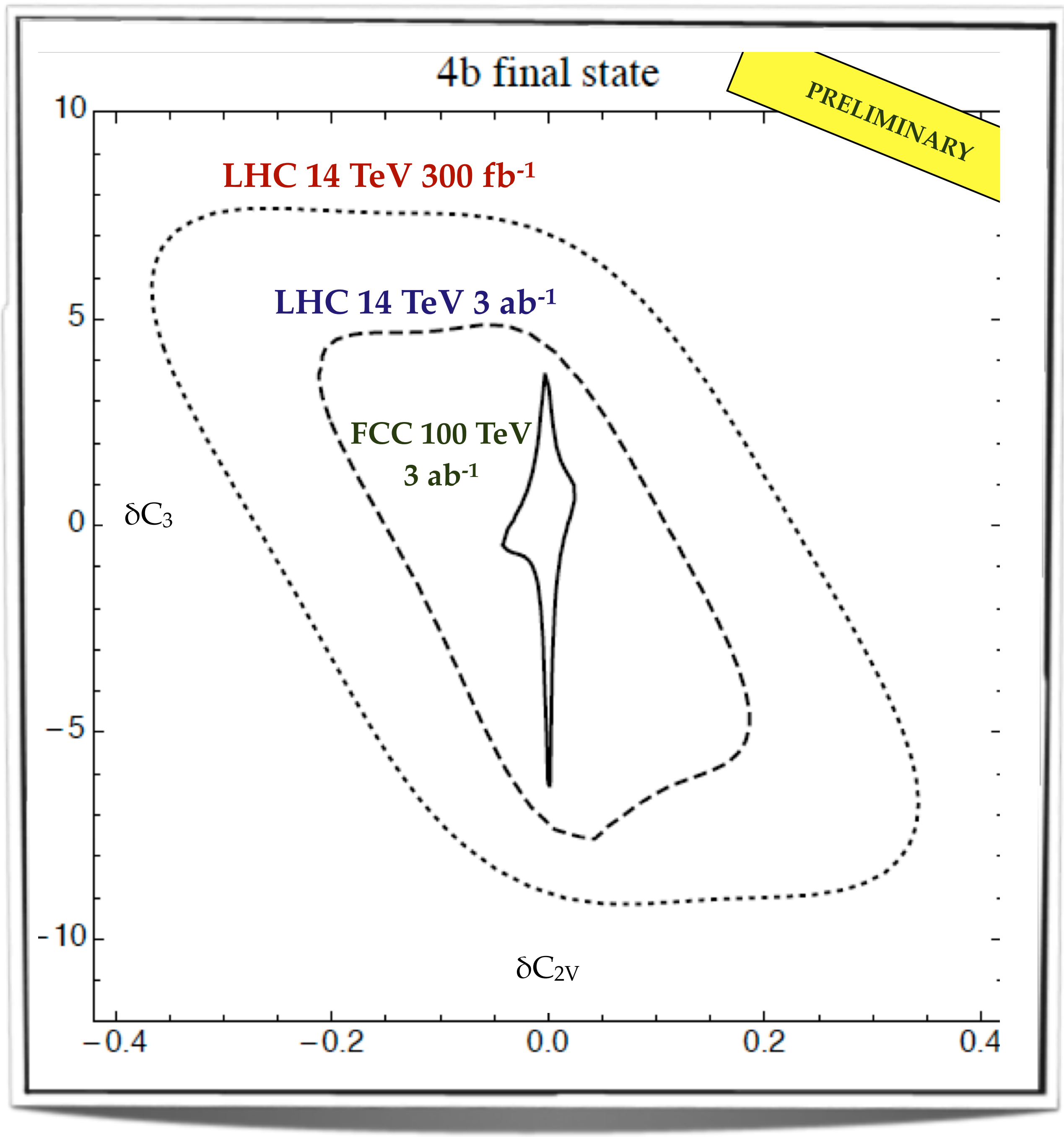
$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b-a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} {\rm cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

Multiple Higgs interactions in WW→HH



Bondu, Contino, Massironi, Rojo 'to appear

Conclusions: Higgs & New Physics

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

Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13

NP

typical mass scale

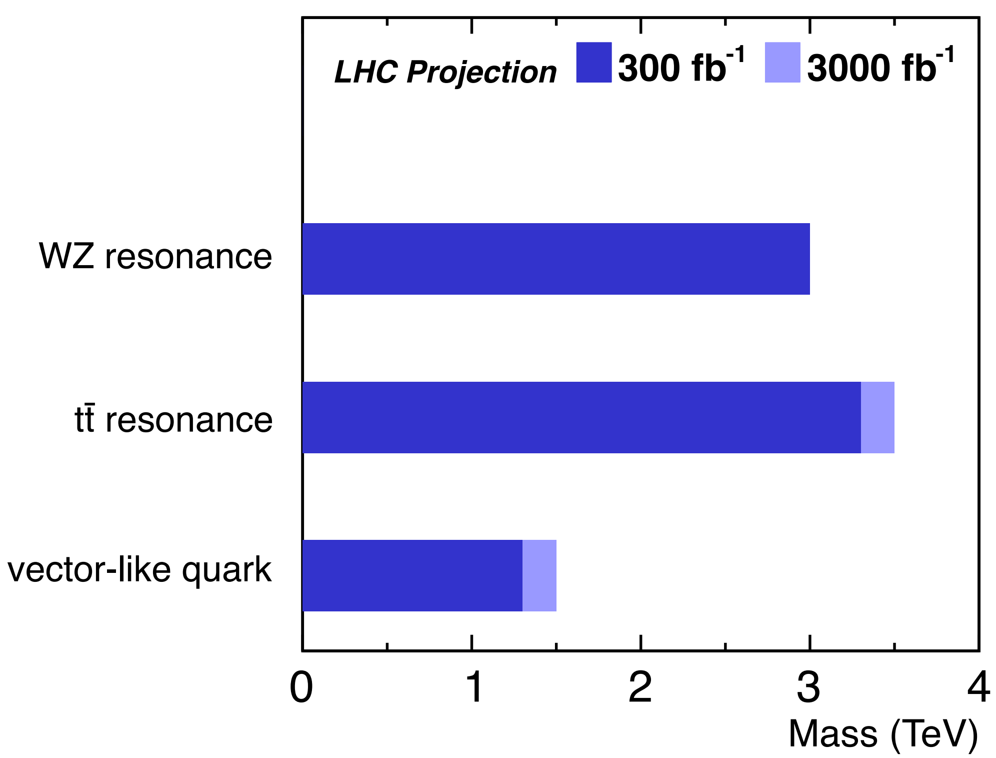
$M = g_* f$

SM

EW scale v=246GeV

g, g', y_t

g_{SM}^2 / 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_*

Conclusions: Higgs & New Physics

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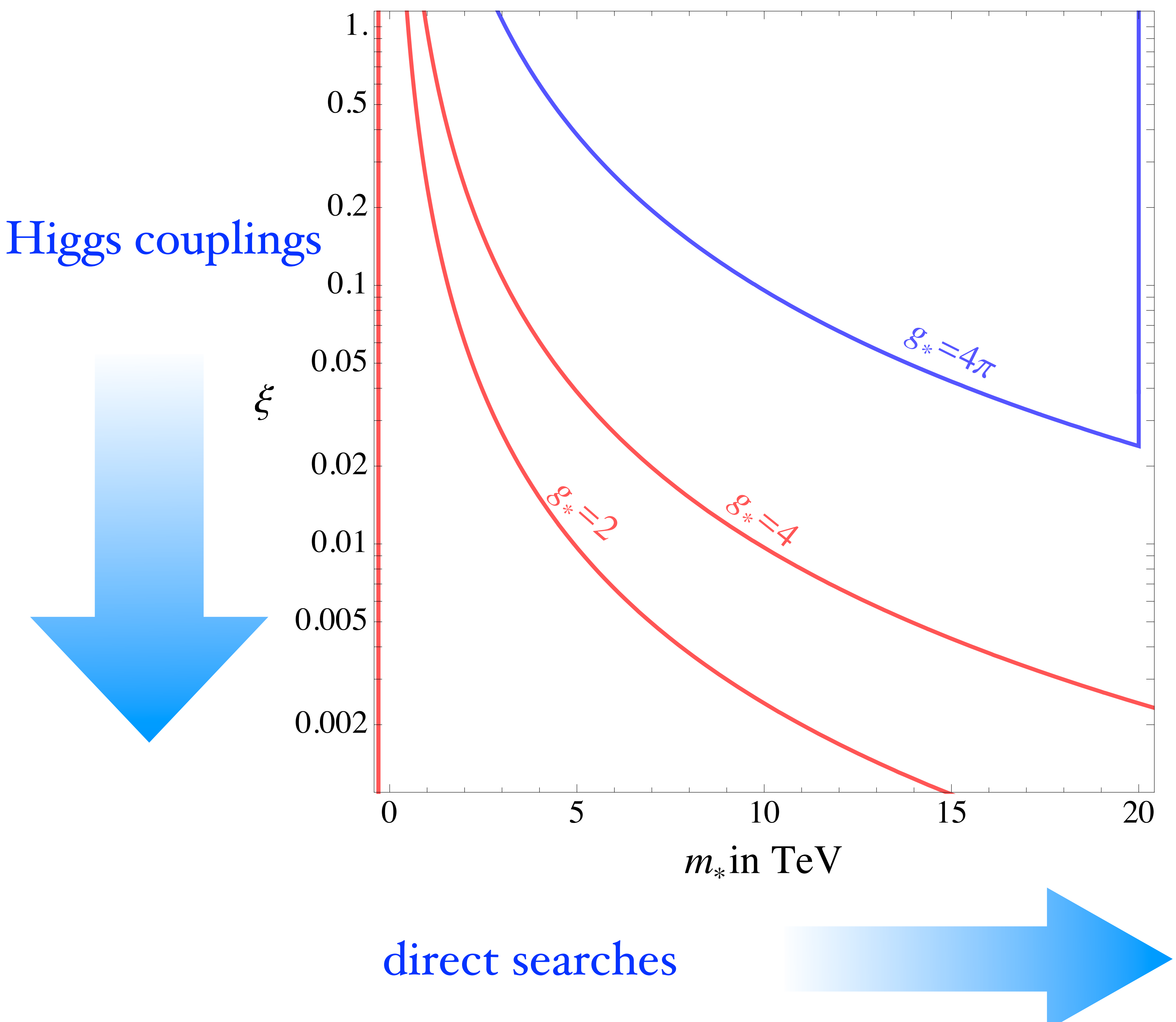

Rattazzi, BSM@100TeV, CERN '14

Conclusions: Higgs & New Physics

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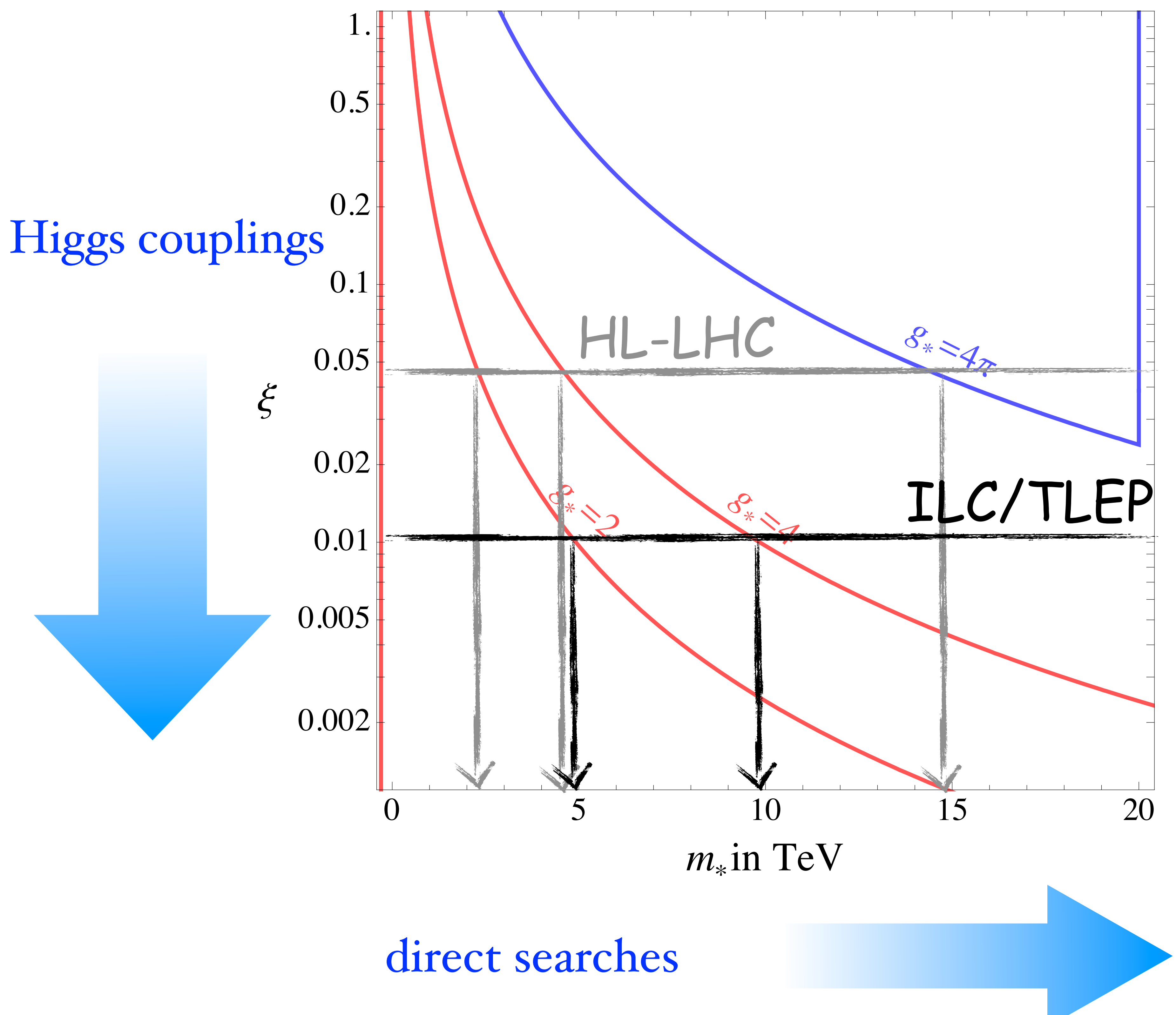


- nice complementarity between direct searches and precision Higgs physics

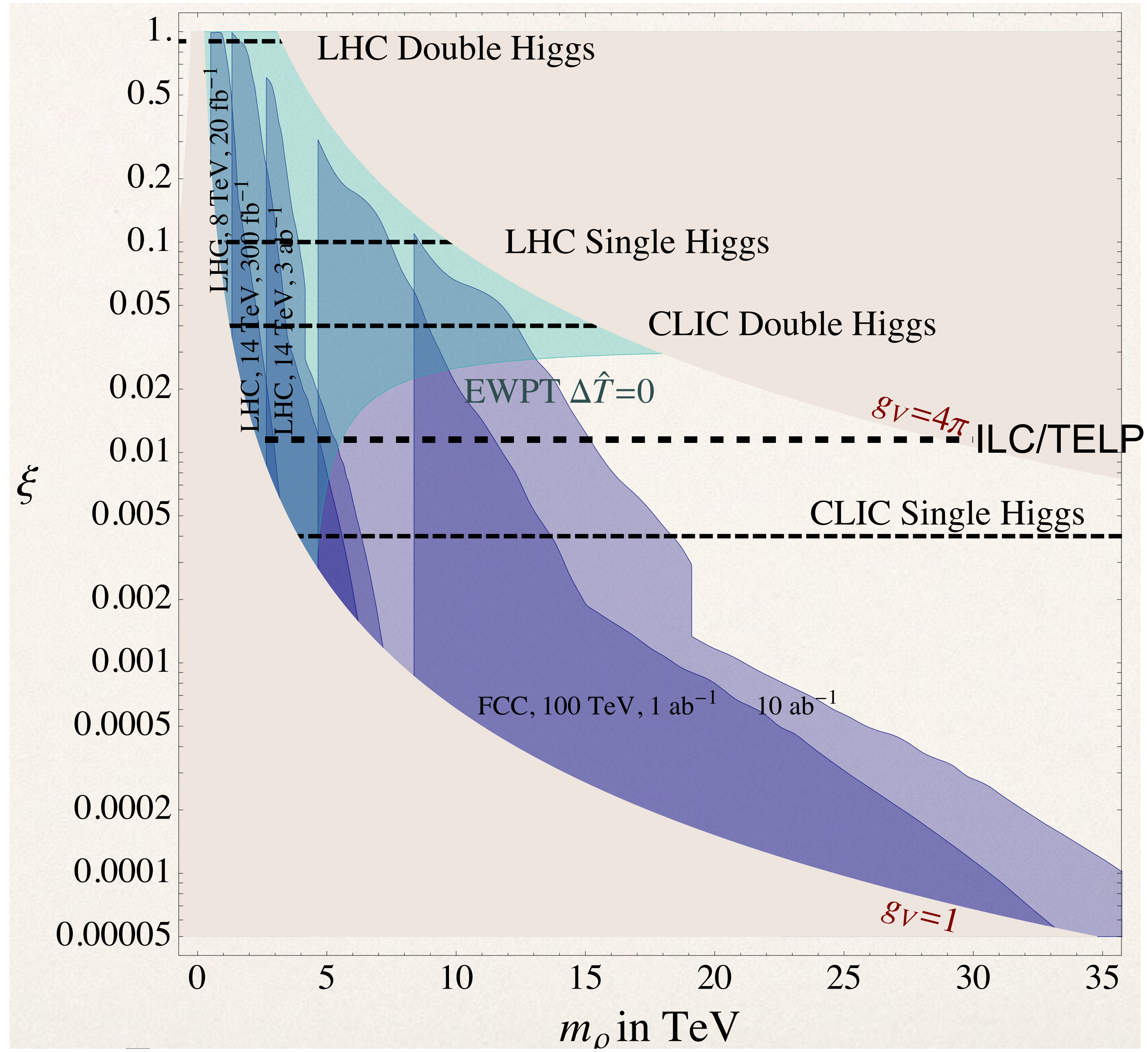
Rattazzi, BSM@100TeV, CERN '14

Conclusions: Higgs & New Physics

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

- large region of parameter space already disfavored by EW precision data

- complementarity between direct searches @ hadron machine and indirect higgs measurements @ lepton machine



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Torre, Thamm, Wulzer ’14

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