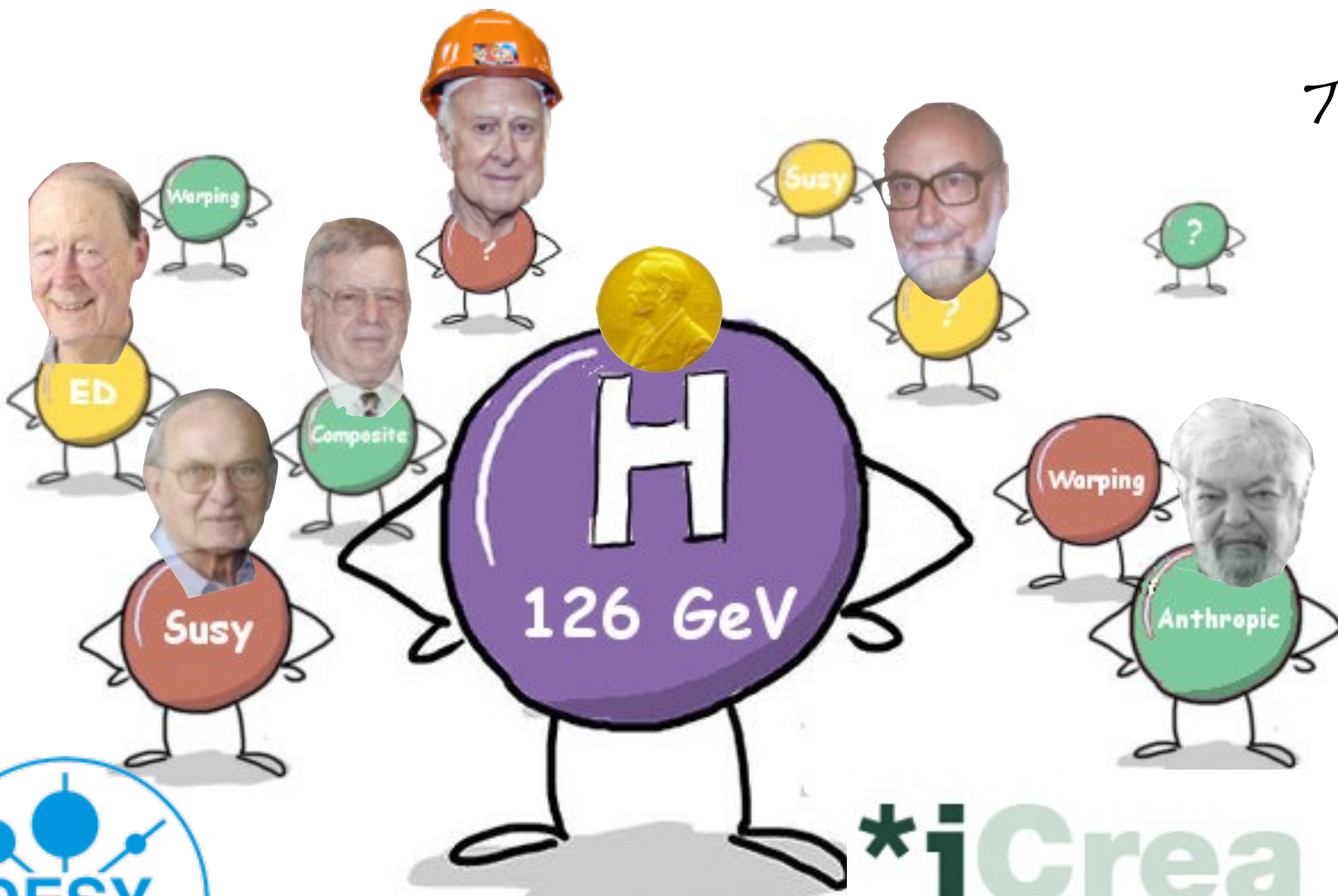
Could the Higgs be composite?

HPNP 2015

Toyama Univ. Feb. 12, 2015



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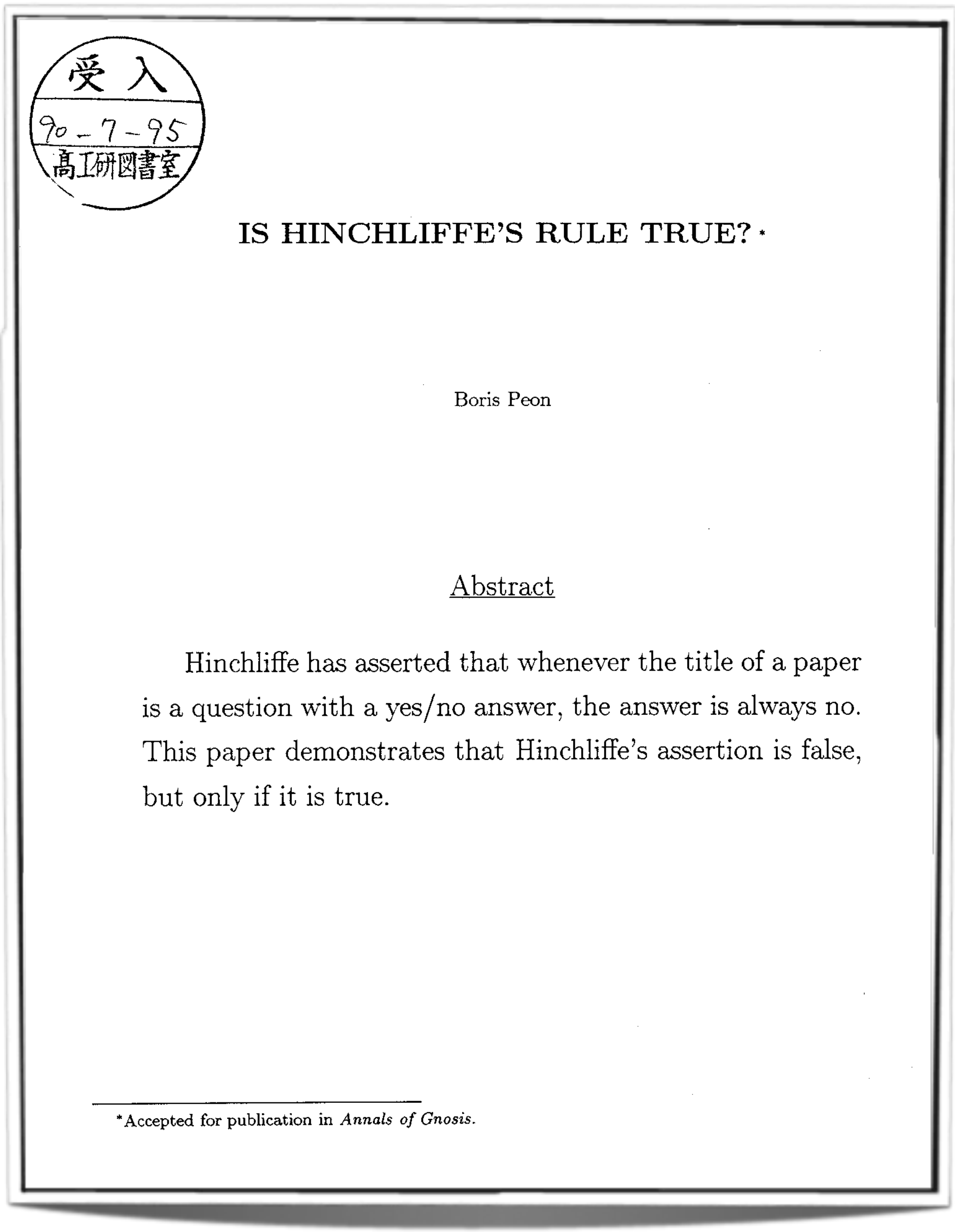
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

Remember Hinchliffe's rule...



IS HINCHLIFFE'S RULE TRUE?*

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

*Accepted for publication in *Annals of Gnosis*.

However, as physicists, we want to base our answers on experimental data and to keep challenging theoretical prejudices...

We all have a PhD

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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}?)

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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

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

Why should you care about compositeness?

Higgs compositeness means new fundamental interactions

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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

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

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cosmological constant

$V_0 \approx (2\times 10^{-3}\ {\rm eV})^4 \ll M_{\rm PL}^4$

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SUSY?
TeV New Physics?

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well described
experimentally by CKM
(up to a few exceptions: $A_{FB}^{t\bar{t}}$, ΔA_{CP}^{c}...)

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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

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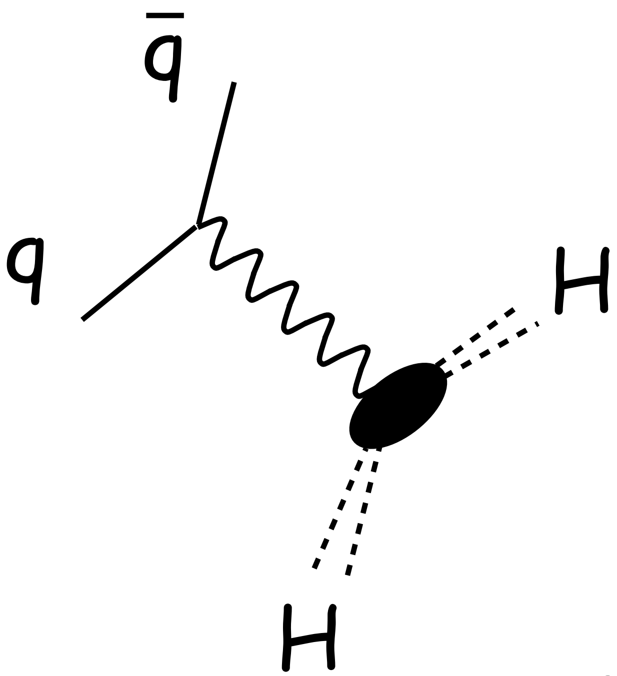
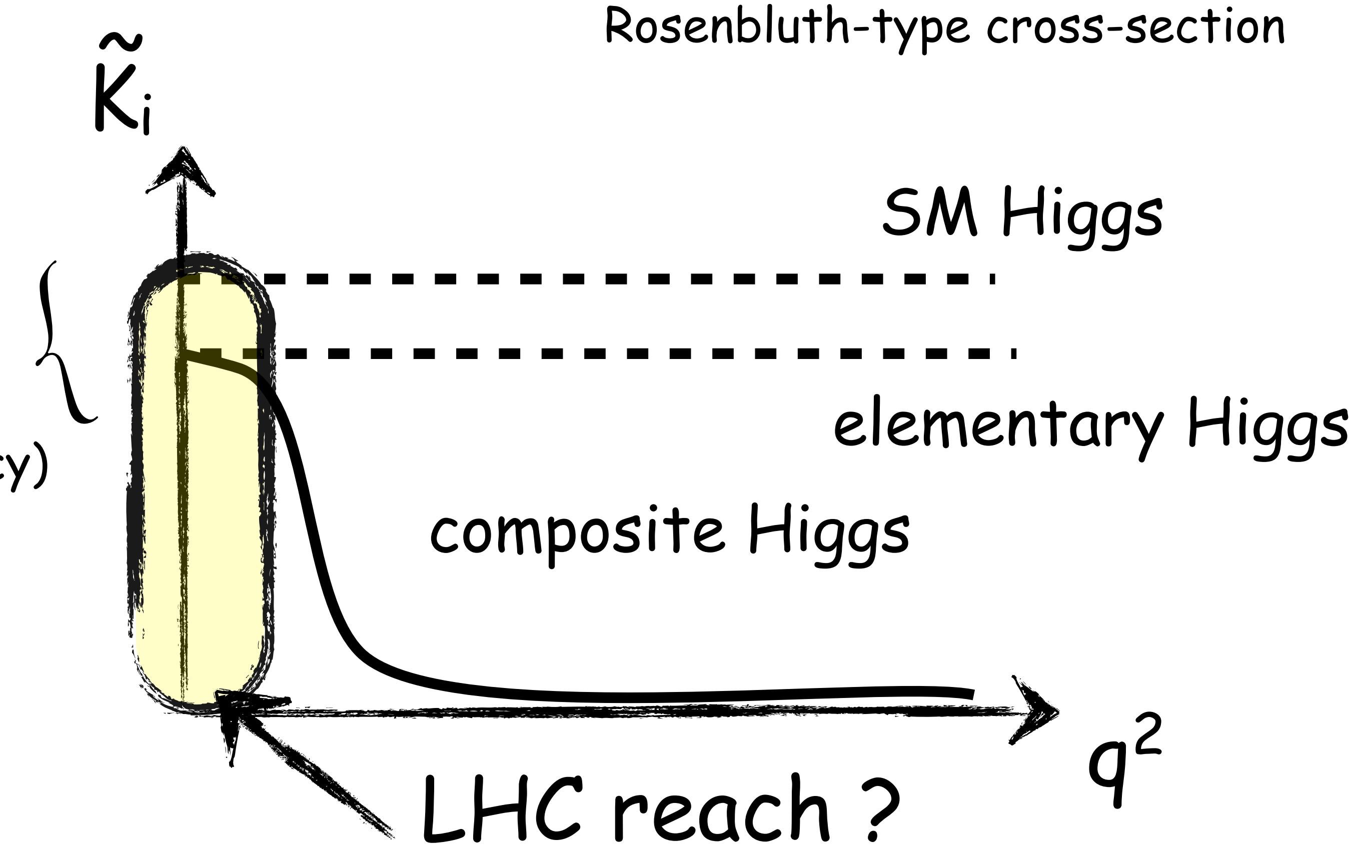


$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2} \frac{E'}{E^3} \left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2 \cos^2\theta/2 \right)$$

Rosenbluth-type cross-section



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

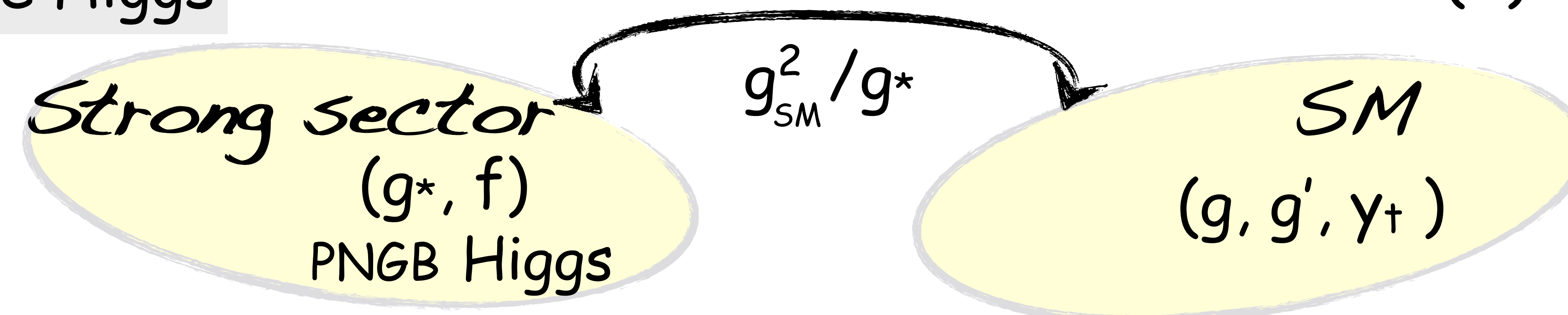
Which composite scenario?

Minimal Composite Higgs

ex: SO(5)/SO(4)

SILH

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



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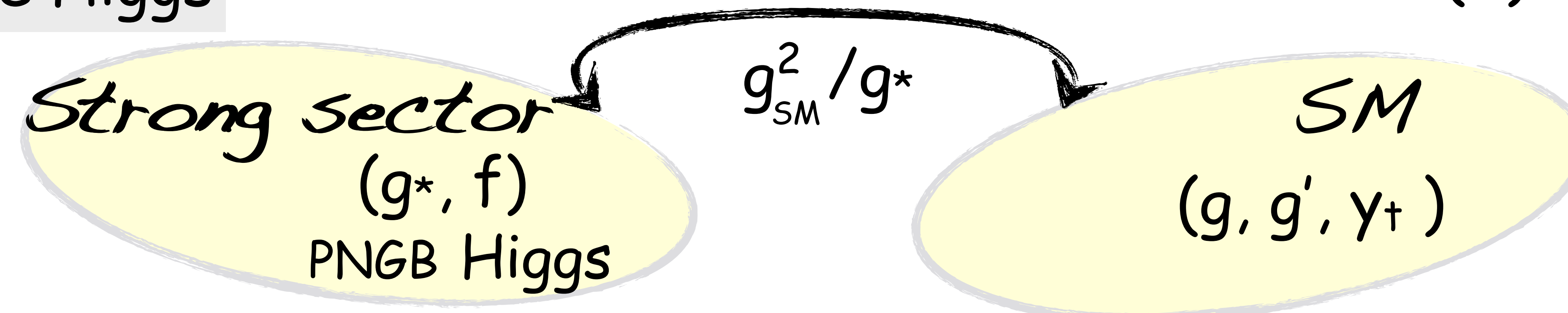

Partly Composite Higgs

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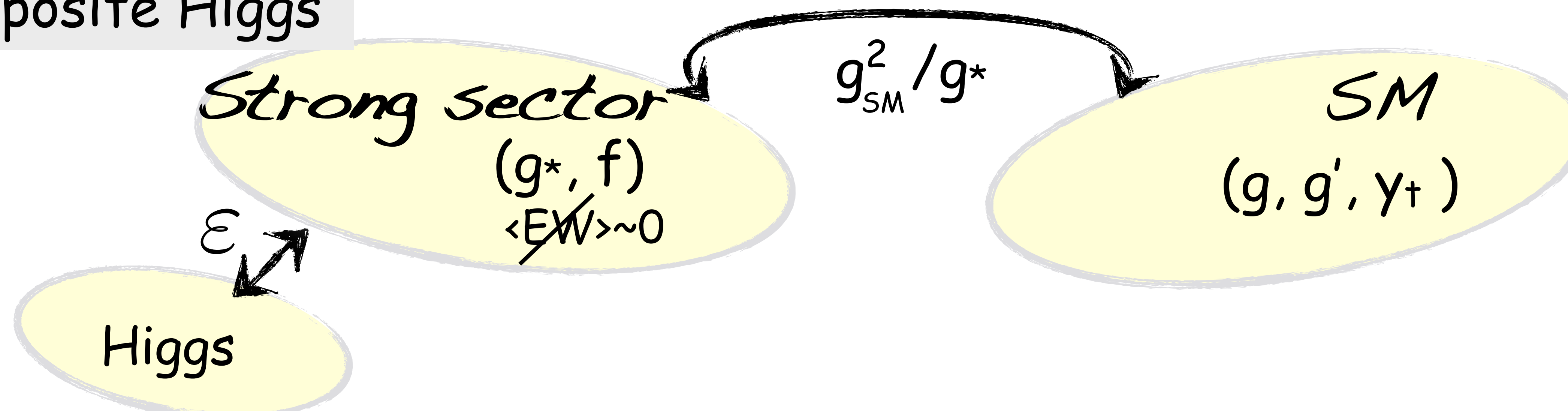

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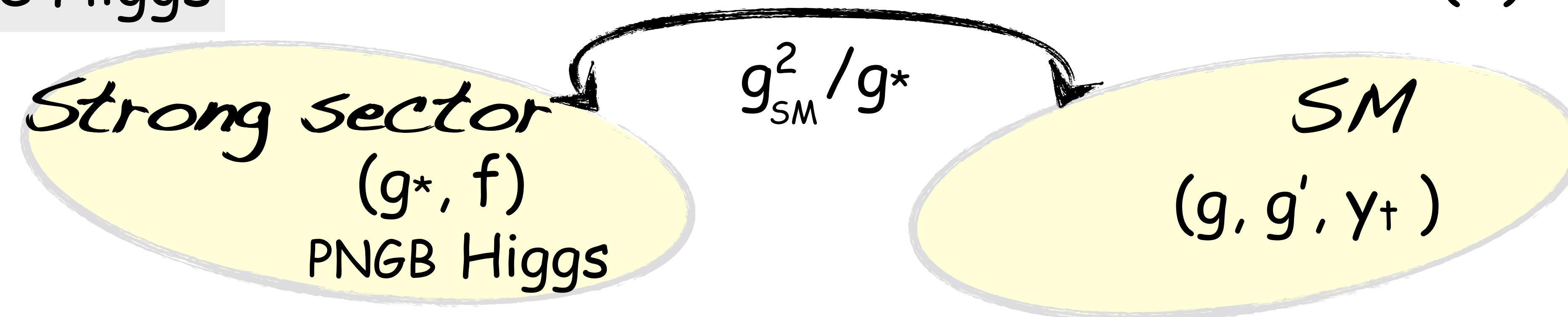

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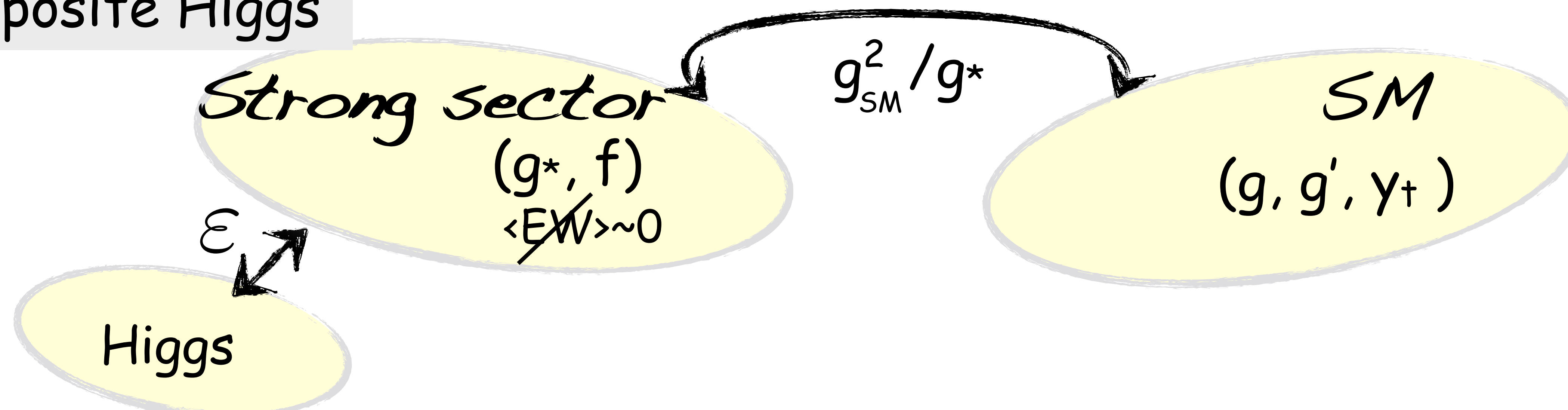
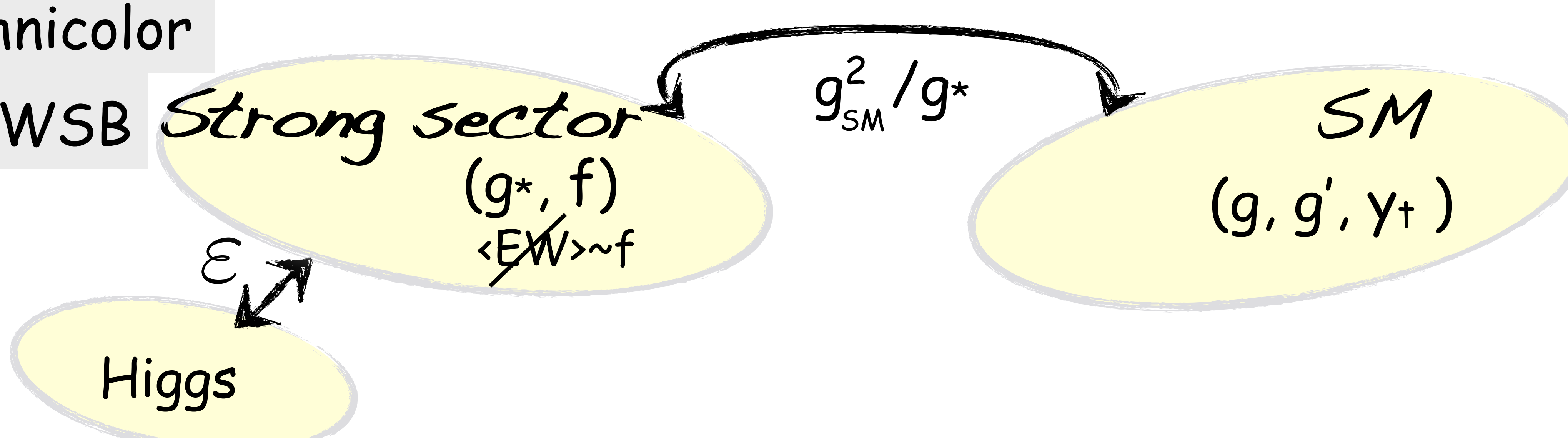


Bosonic Technicolor

Induced EWSB

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



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SILH

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

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

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

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Patterns of Higgs coupling deviations

expected largest relative deviations

	hff	hVV	hγγ	hγZ	hGG	h
MSSM	√		√	√	√	
NMSSM	√	√	√	√	√	
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

see also Muehlleitner's talk

A. Pomarol, Naturalness ’15

What is the Higgs the name of?

The SM Higgs couplings are fixed to restore unitarity with mass

$\Sigma = e^{i\sigma^a \pi^a / v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$ $D_\mu \Sigma = g V_\mu$

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

'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b=a^2: perturbative unitarity in inelastic channels WW $\to$ hh

For ac=1: perturbative unitarity in inelastic WW $\to \psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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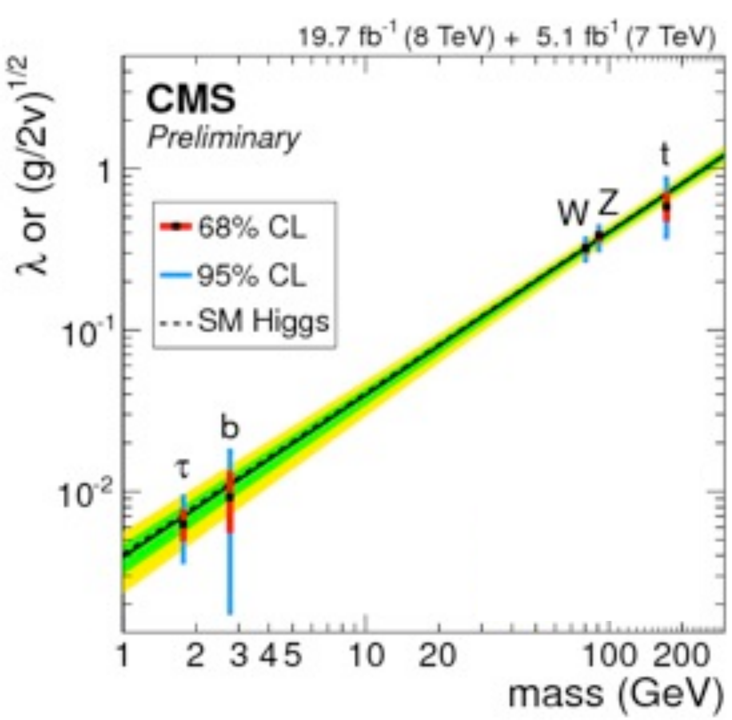

CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

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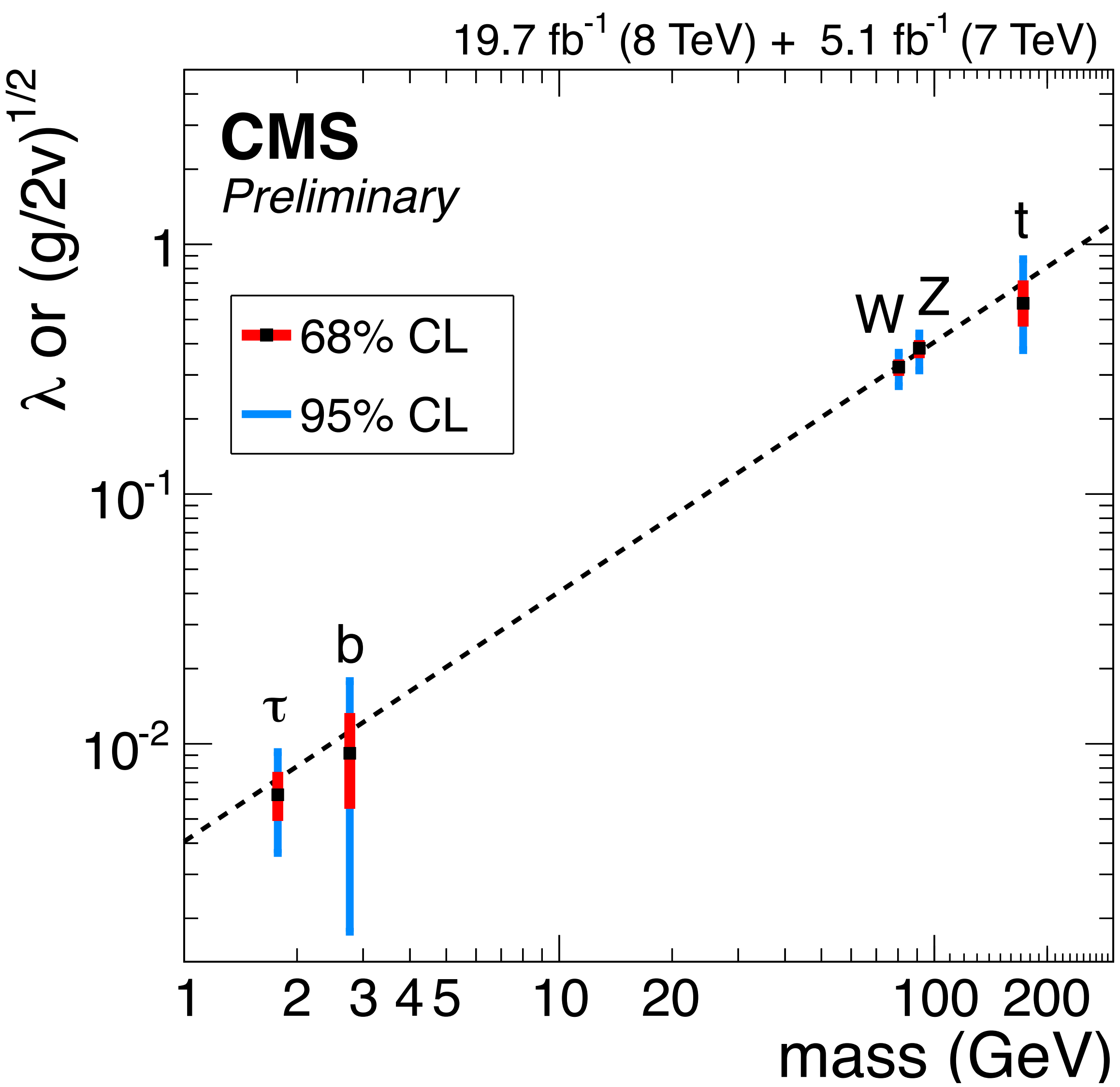

Higgs group @ Snowmass '13

Facility	LHC	HL-LHC
$\sqrt{s}$ (GeV)	14,000	14,000
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt
κ_γ	5 – 7%	2 – 5%
κ_g	6 – 8%	3 – 5%
κ_W	4 – 6%	2 – 5%
κ_Z	4 – 6%	2 – 4%
κ_ℓ	6 – 8%	2 – 5%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%

~ Is this fit theoretically consistent? ~

can you generate a 500% deviations

in the bottom coupling without generating other coupling

structures not taken into account in the fit?

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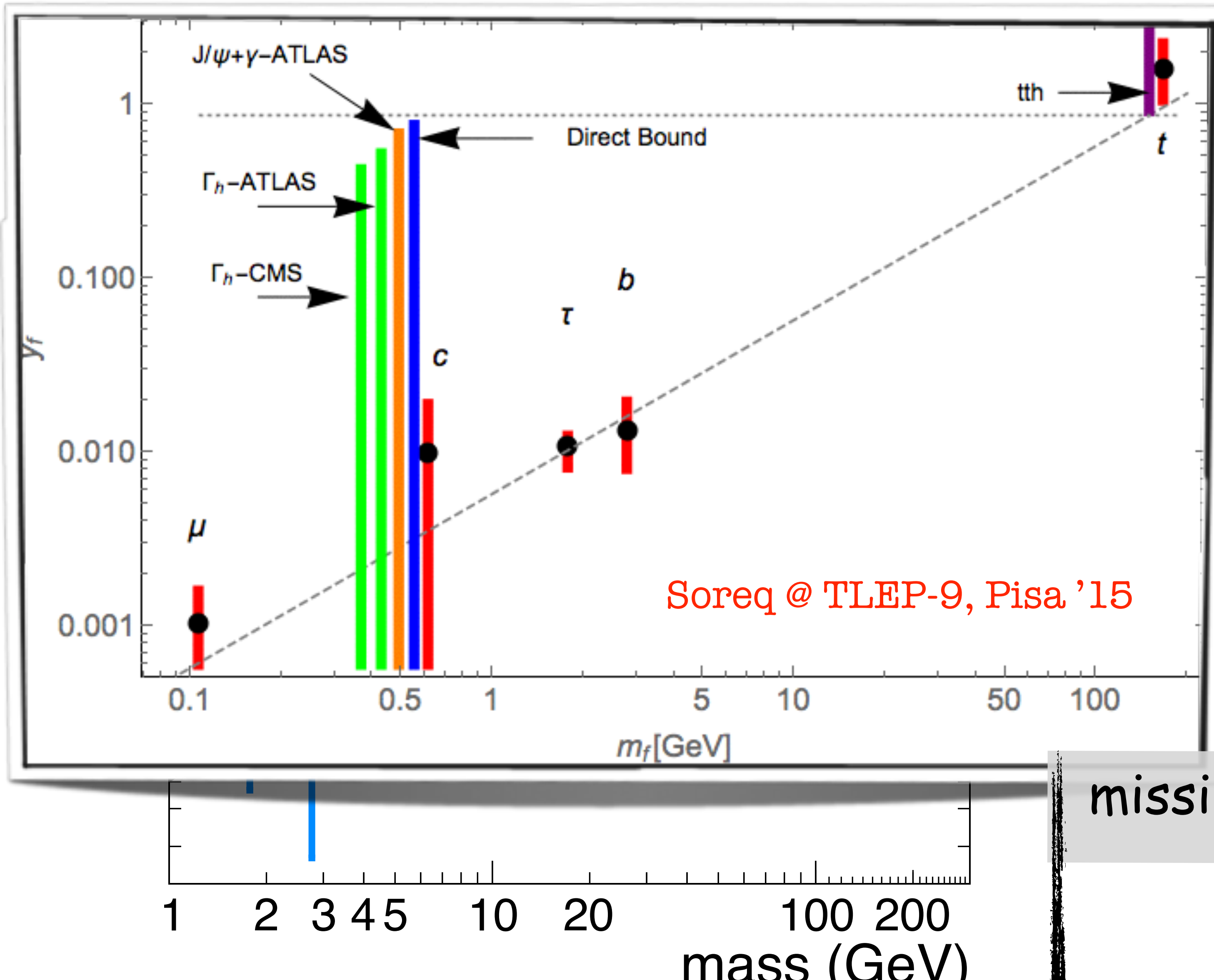

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missing information to complete the picture

° width measurement?

° couplings to light particles?

inclusive (e.g. c-tagging) or exclusive ($h \to J/\Psi+\gamma$)

° coupling to top?

known indirectly ($gg\to h$) or via difficult tth channel

1

Precision program in single Higgs processes

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

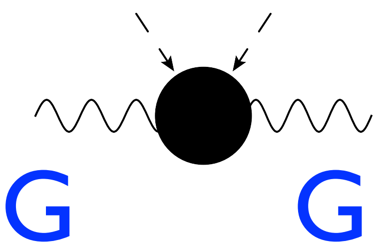
Higgs/BSM Primaries

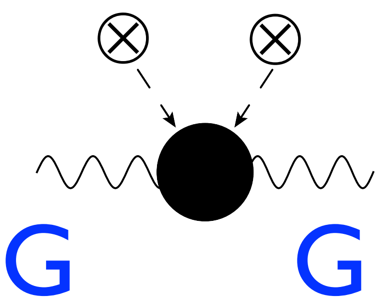
Several deformations away from the SM are harmless in the vacuum and need a Higgs field to be probed

(courtesy of A. Pomarol@HiggsHunting2014)

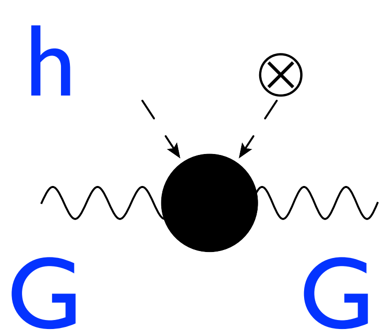
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

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

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m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$	→ 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

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8 for one family
(assuming CP-conservation)

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

- **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

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

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

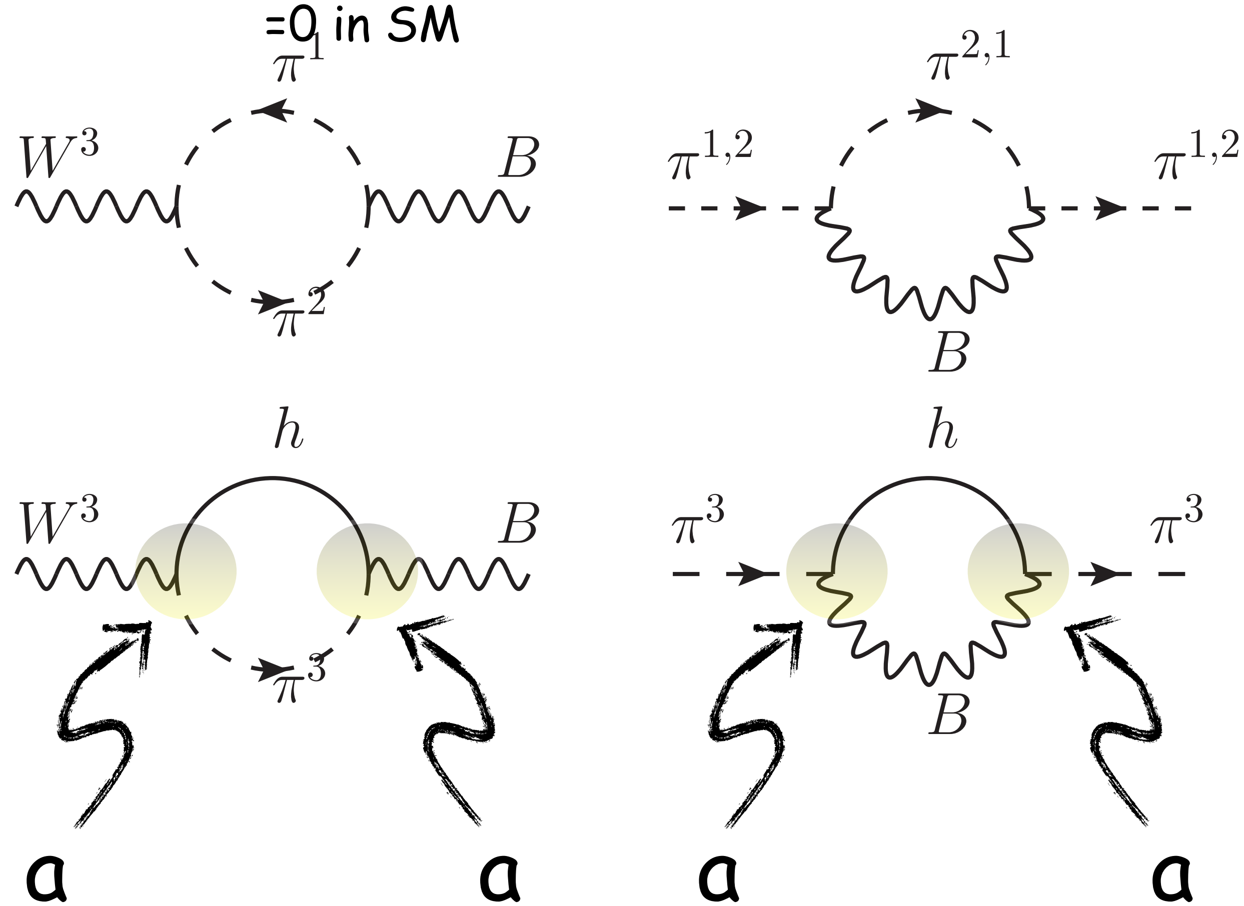
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3}(1-a^2)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

=0 in SM

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

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

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!

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

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

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

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07

EW fit:

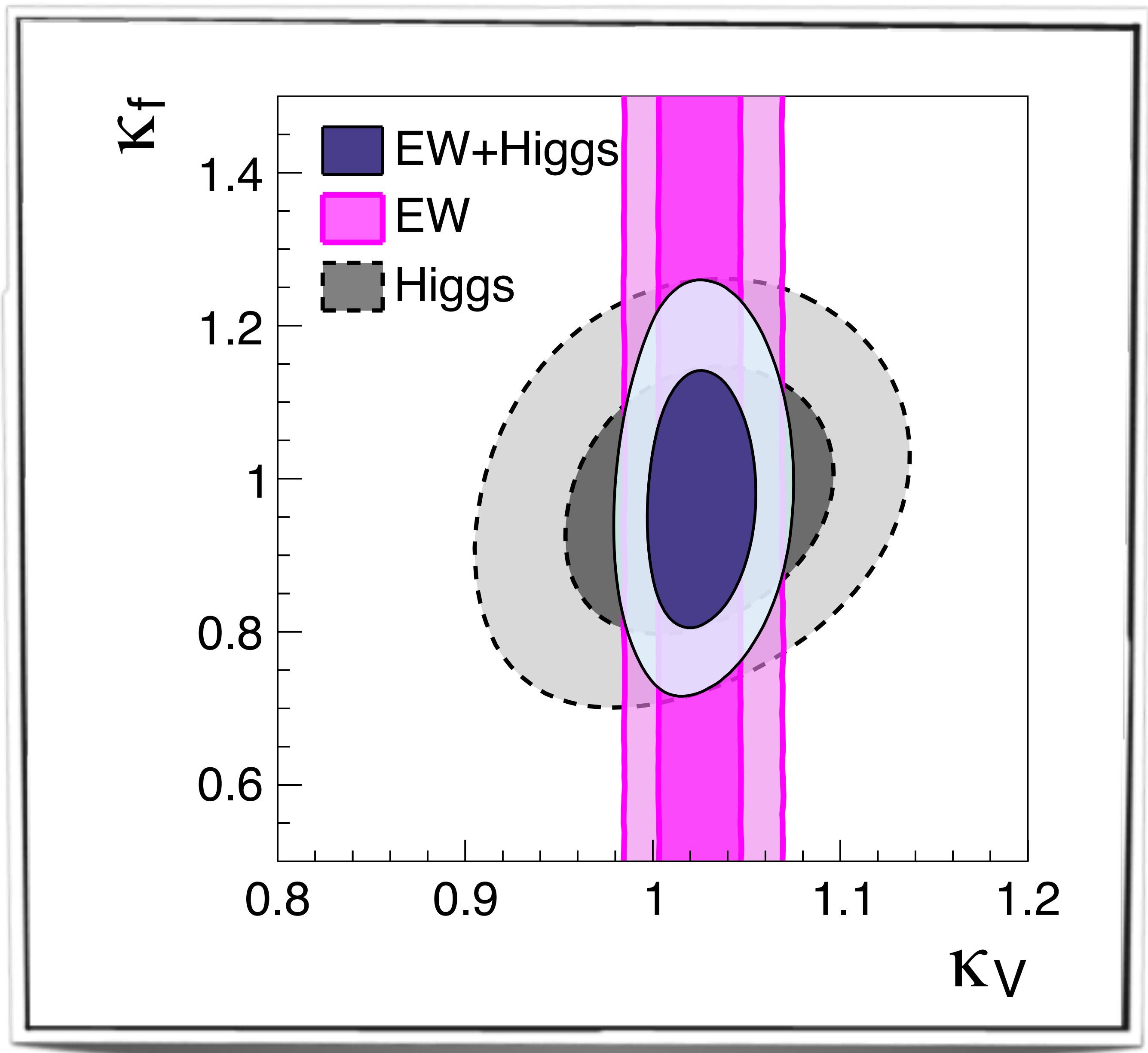
$$0.98 \le a^2 \le 1.12$$

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

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

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

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

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

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

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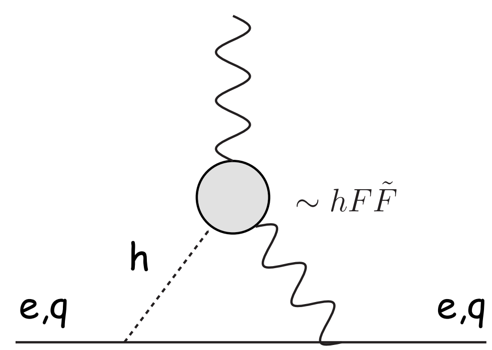
see also Boudjema's talk

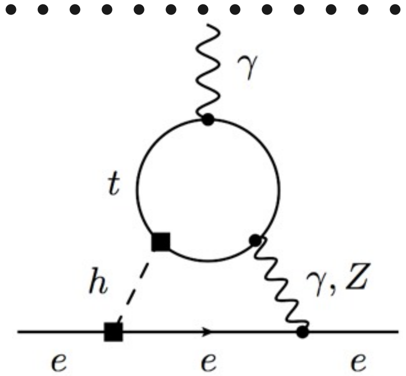
operators with γ:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



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

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

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



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

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

Caveats: h couplings to light particles can be significantly reduced

2

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 $\mu \approx m_H$

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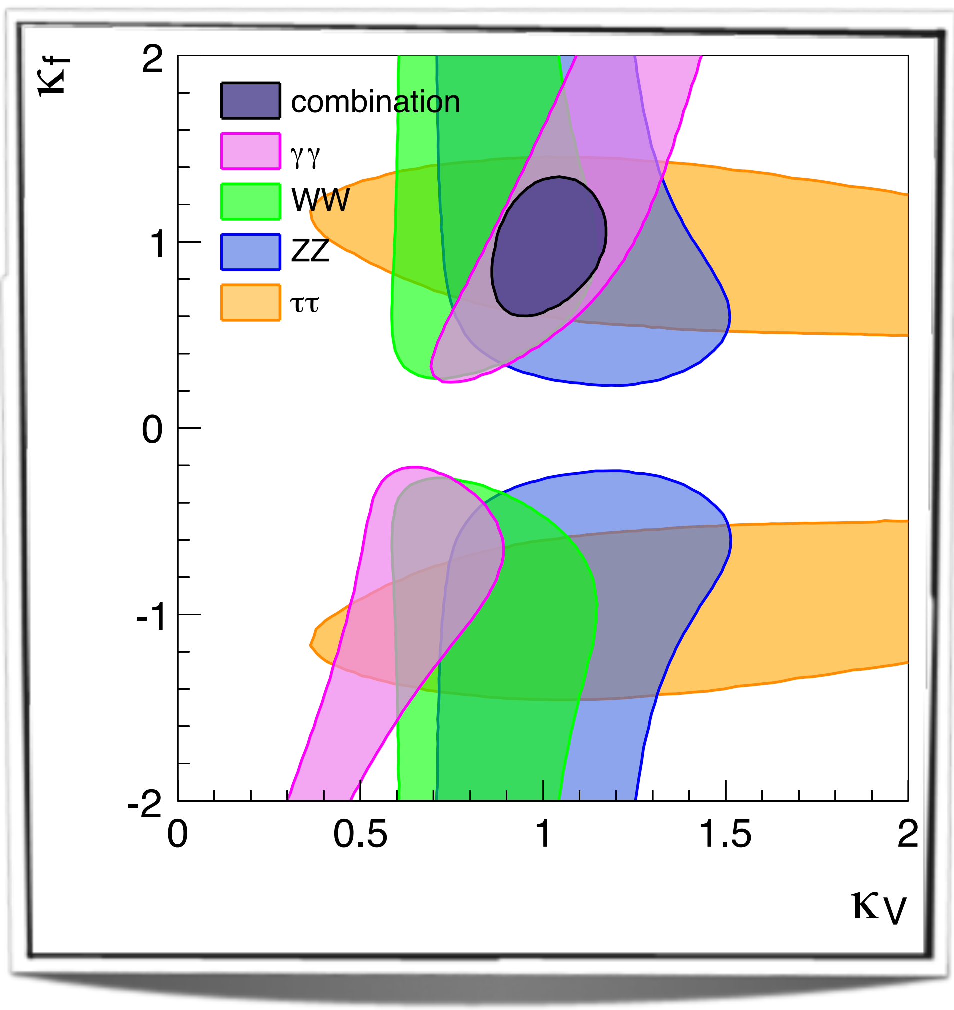
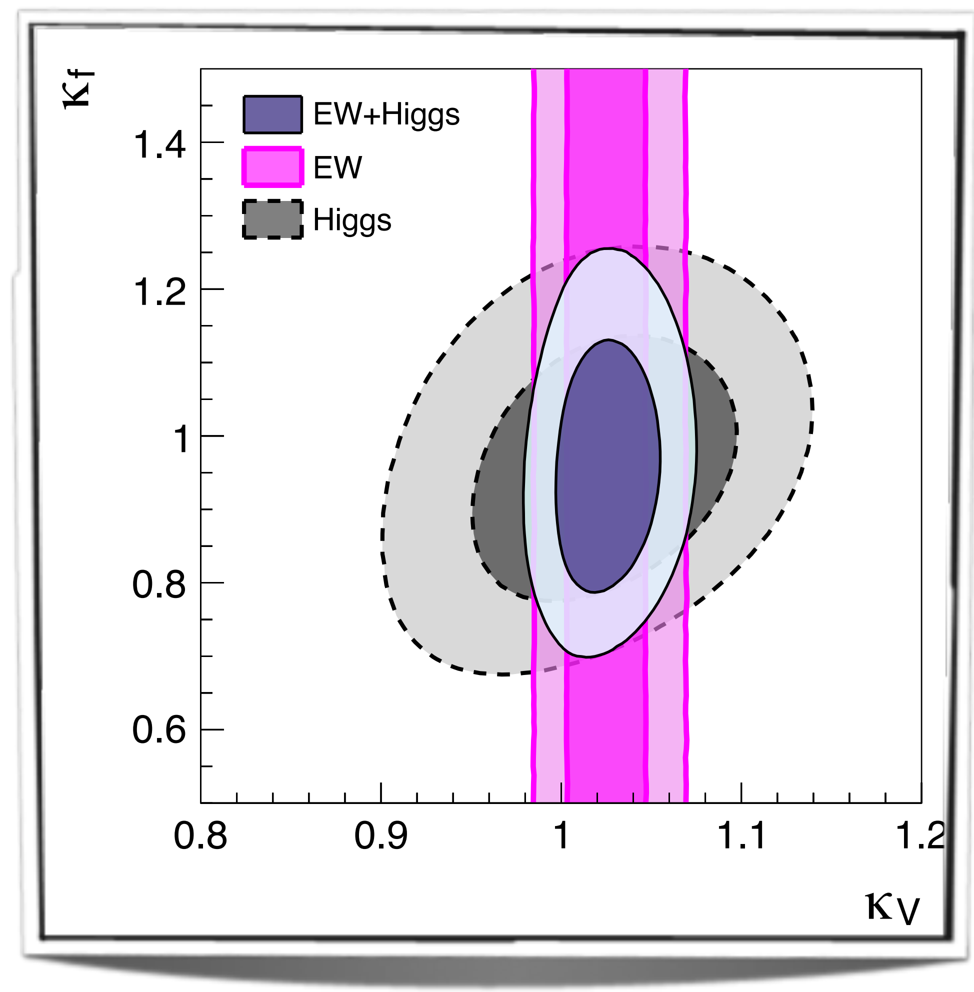


Ciuchini et al '13



Ciuchini et al '13

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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 (*)

$m_H(\mathrm{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
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

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⇛ 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 $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

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

see also Boudjema's talk

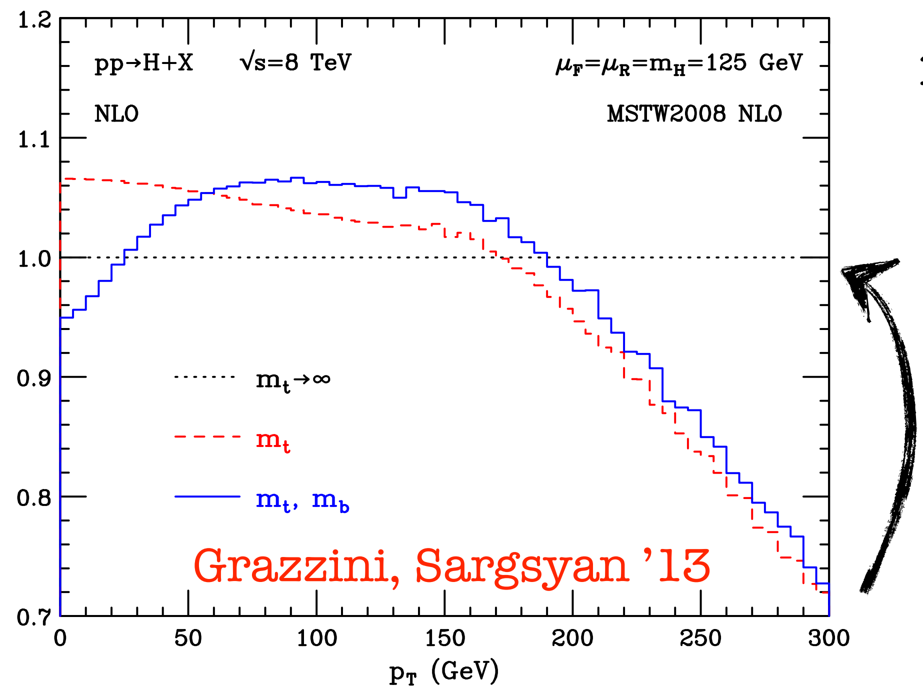
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

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_{m_t} 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

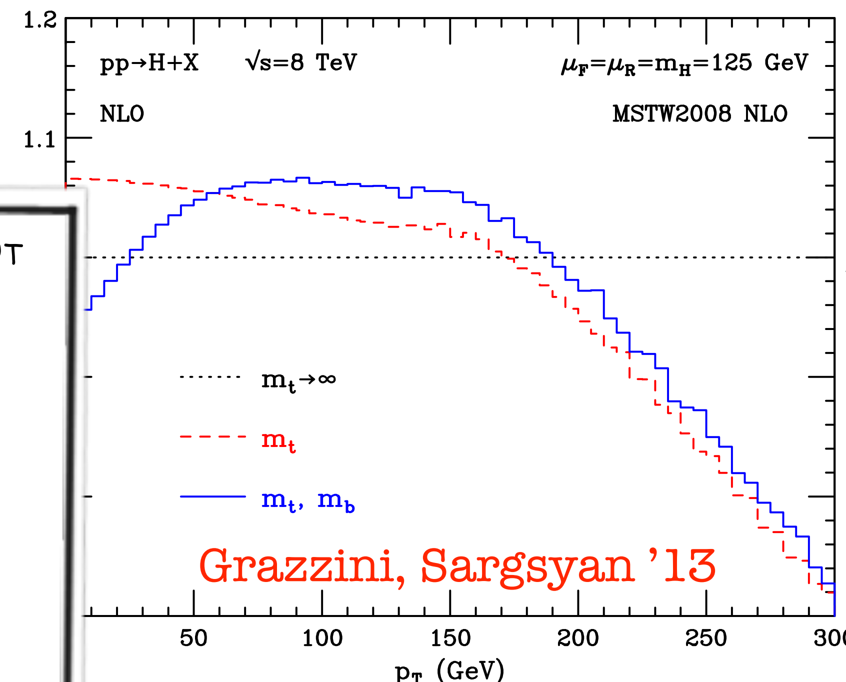
cut open the top loops

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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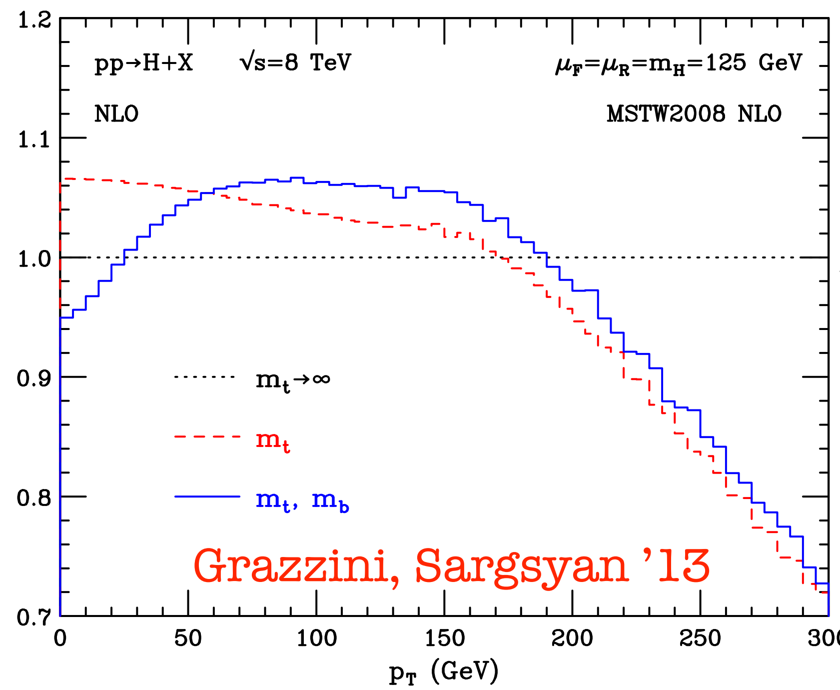


Note: LO only
NLO_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV
Harlander et al '12

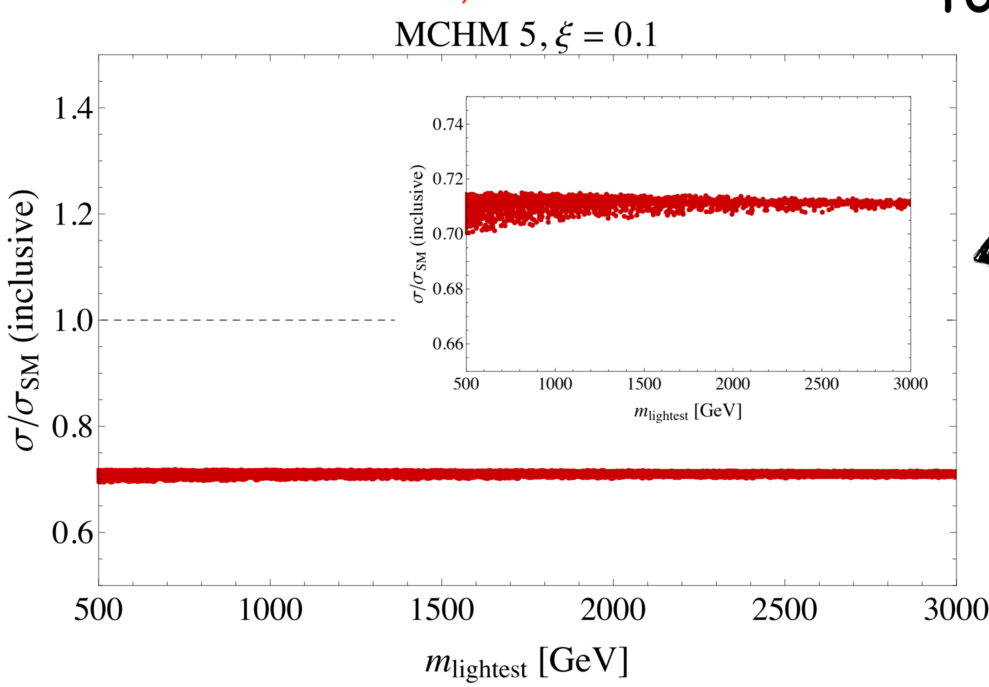
the high p_T tail is tens' % sensitive to the mass of top

Composite Higgs Model

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

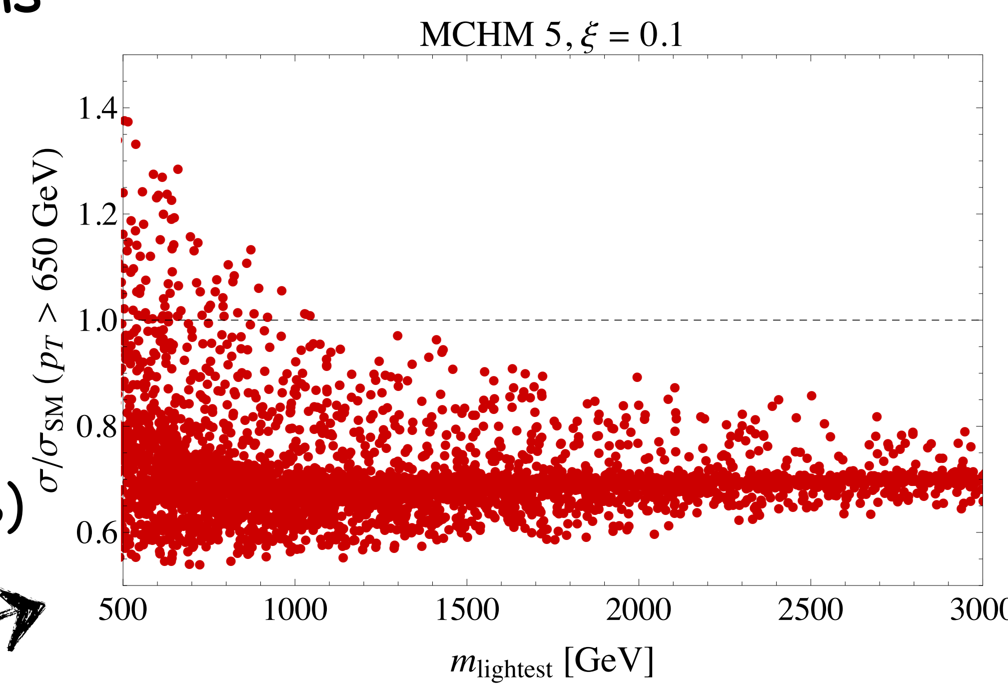
top partners contributions

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

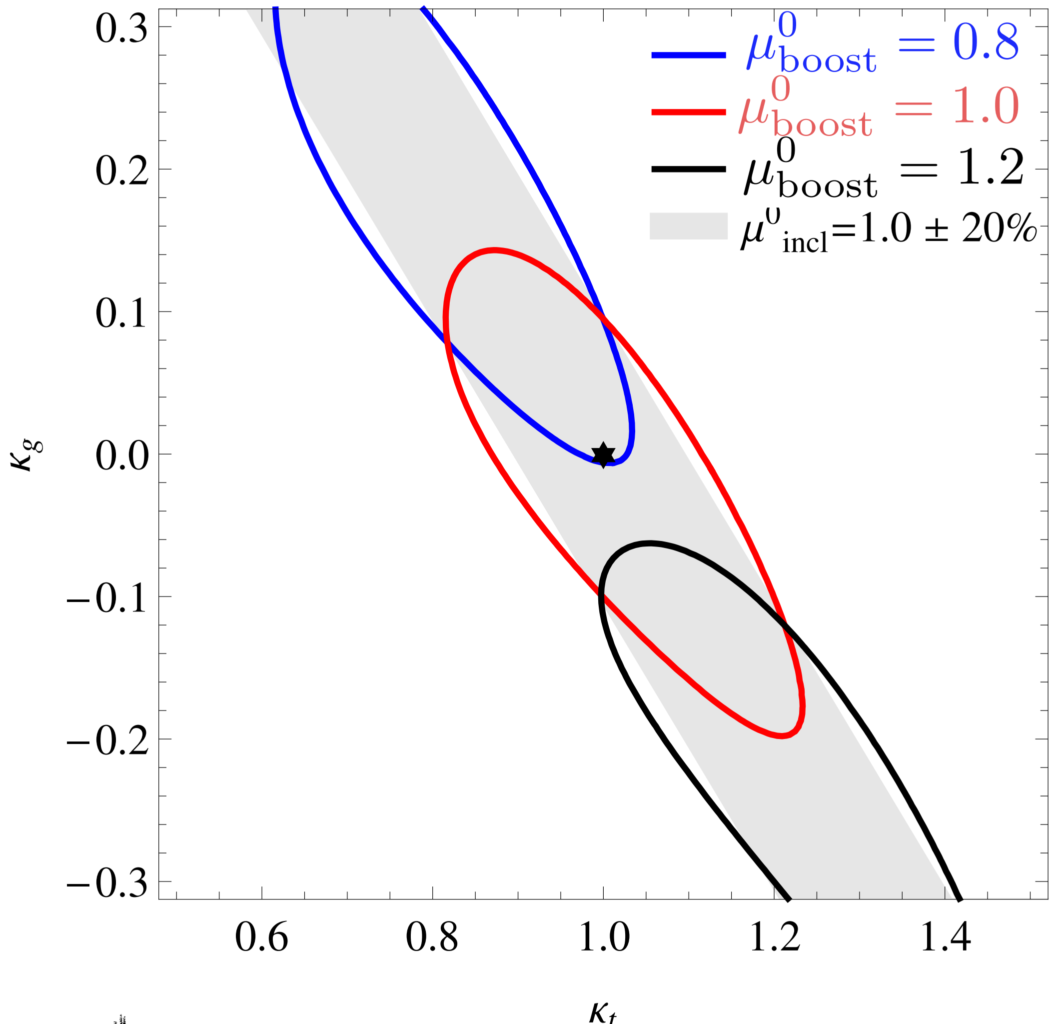
Grojean, Salvioni, Schlaffer, Weiler '13

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

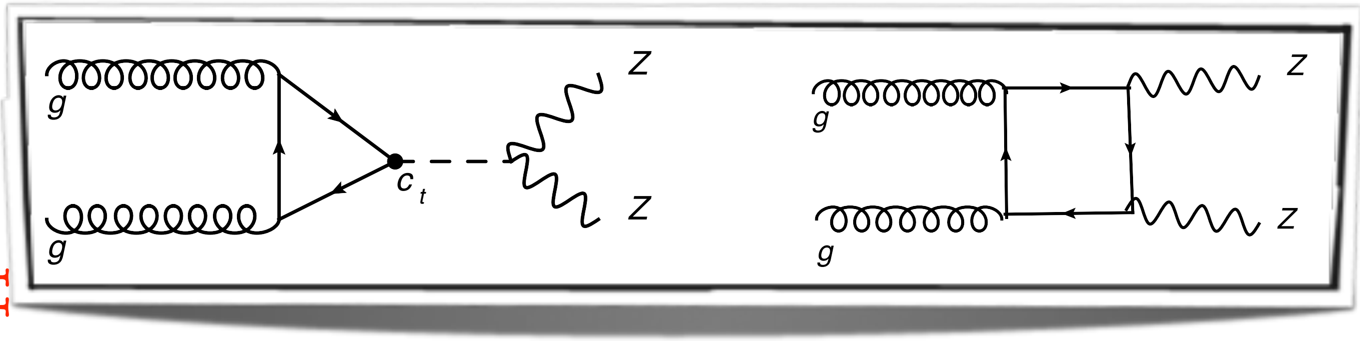
Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: $\text{N}^3\text{LO}_\infty$ for inclusive xs or NLO_{mt} for pT spectrum?

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

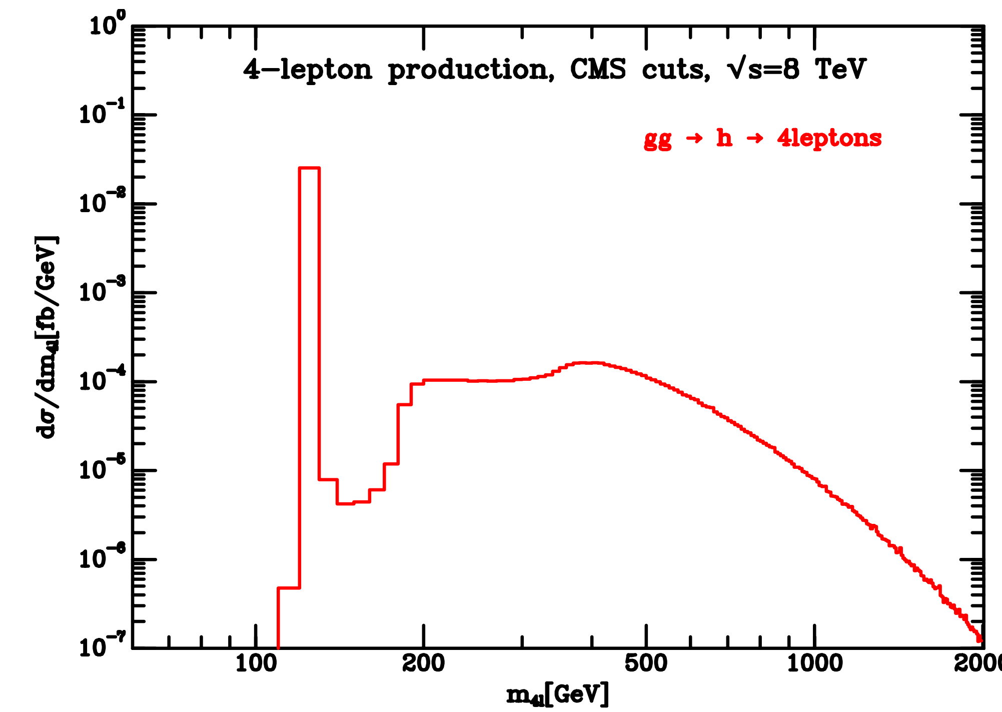
off-shell effects enhanced by the particular couplings of H to V_L

Glover, van der Bij '89

Azatov, Grojean, Paul, Salvioni '14



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

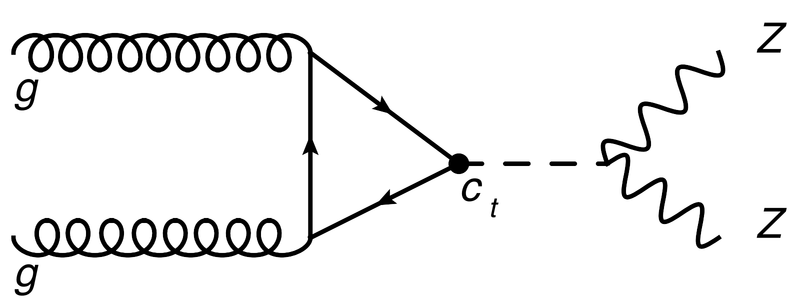


SM: cancelation forced by unitarity

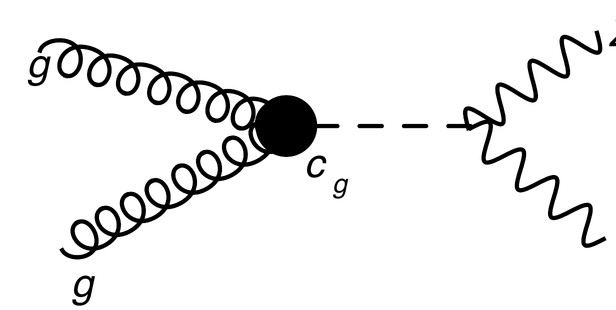
BSM: deviations of Higgs couplings at large s will be amplified

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



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

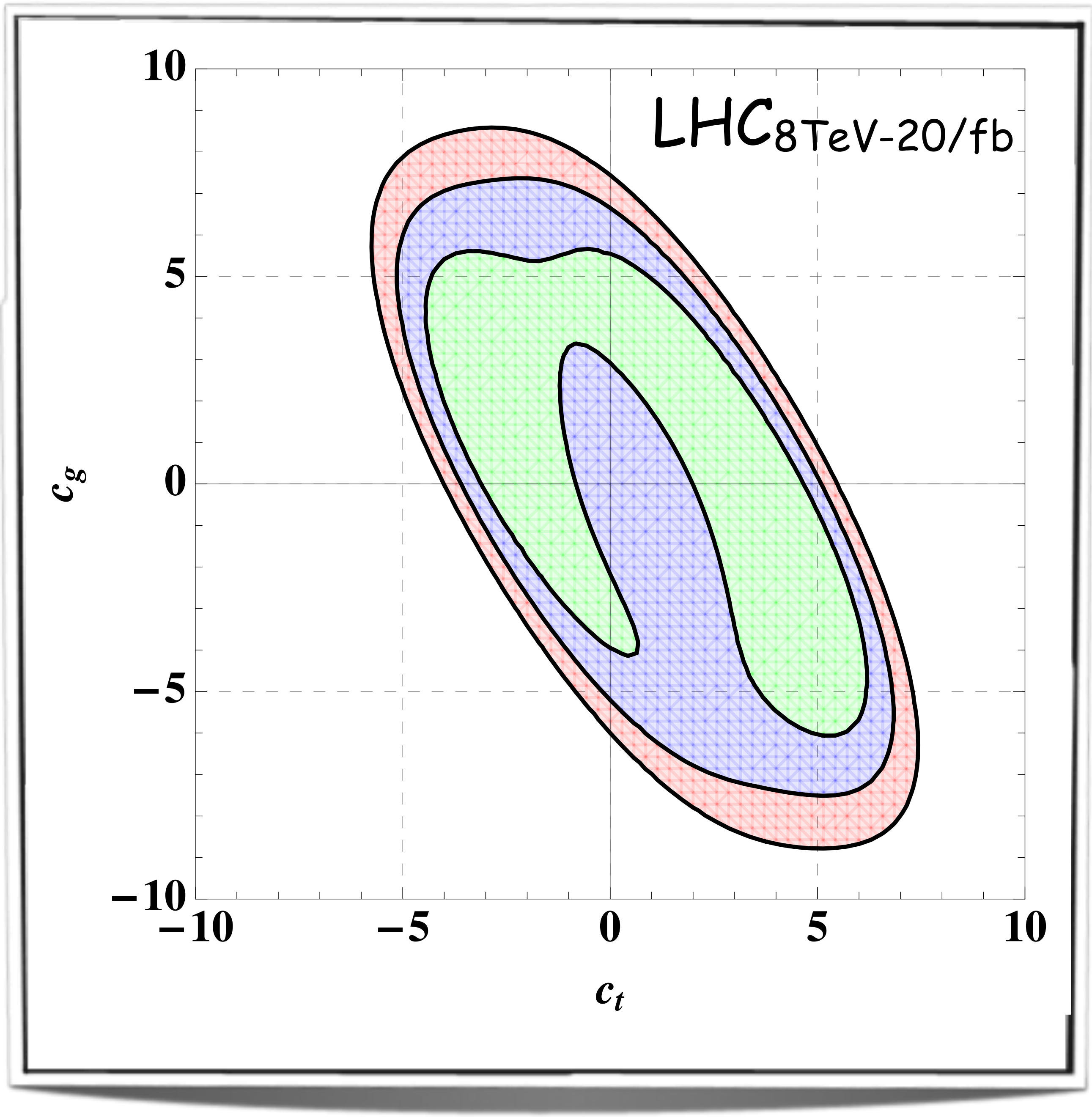


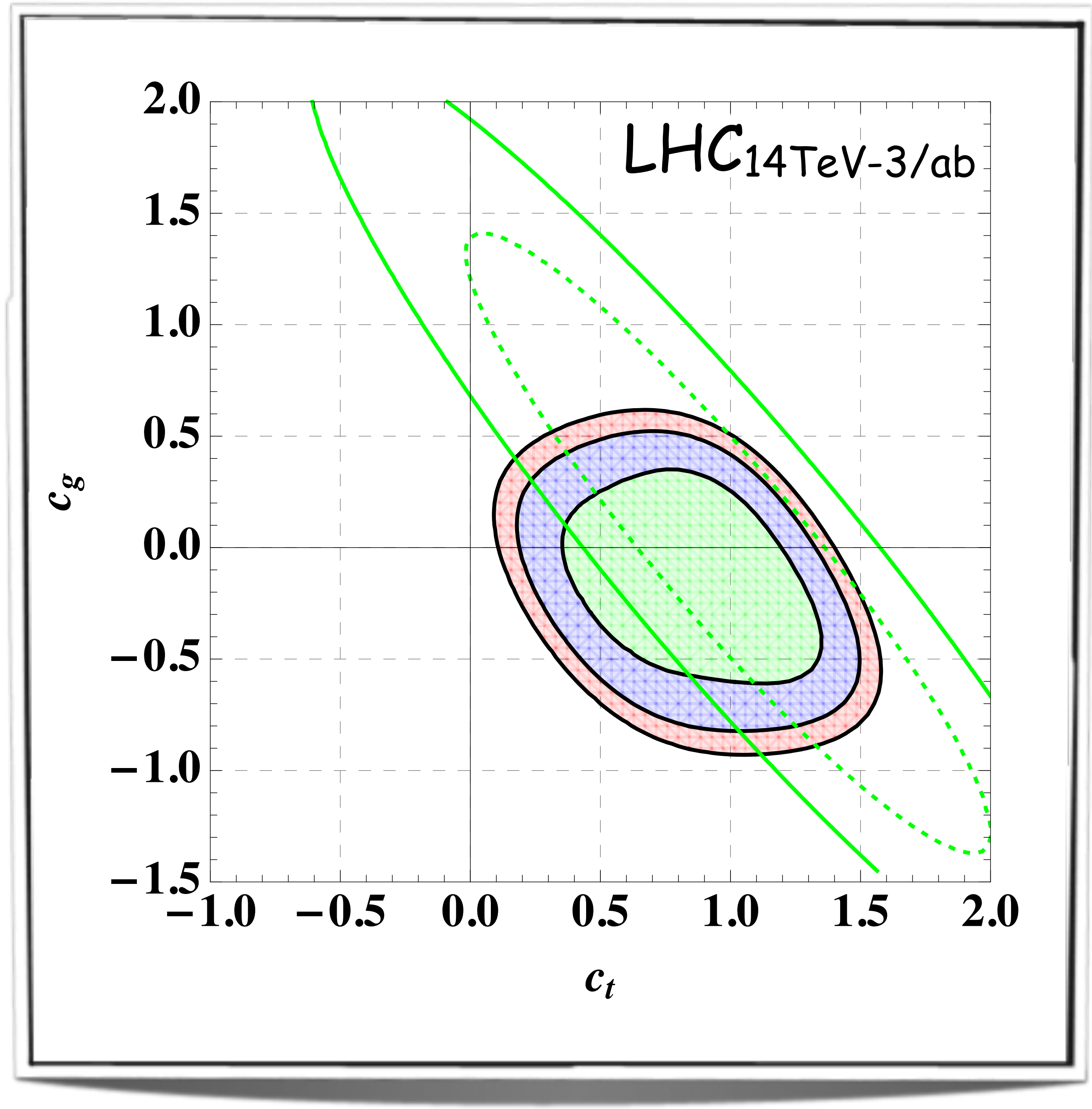
$$\mathcal{M}^{++00}_{c_g} \sim \hat{s}$$

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





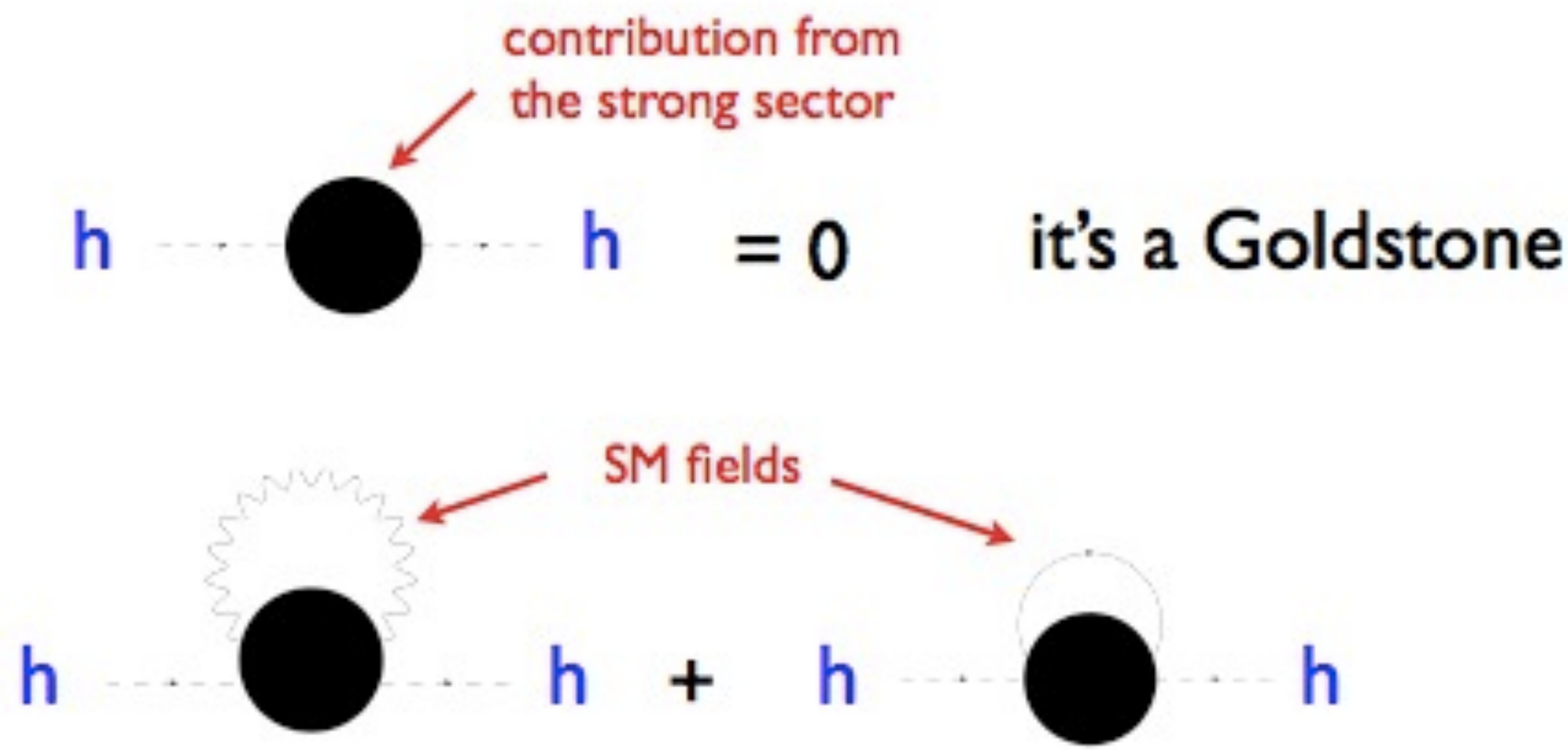
3

Direct searches of top partners

see also
De Curtis' talk

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

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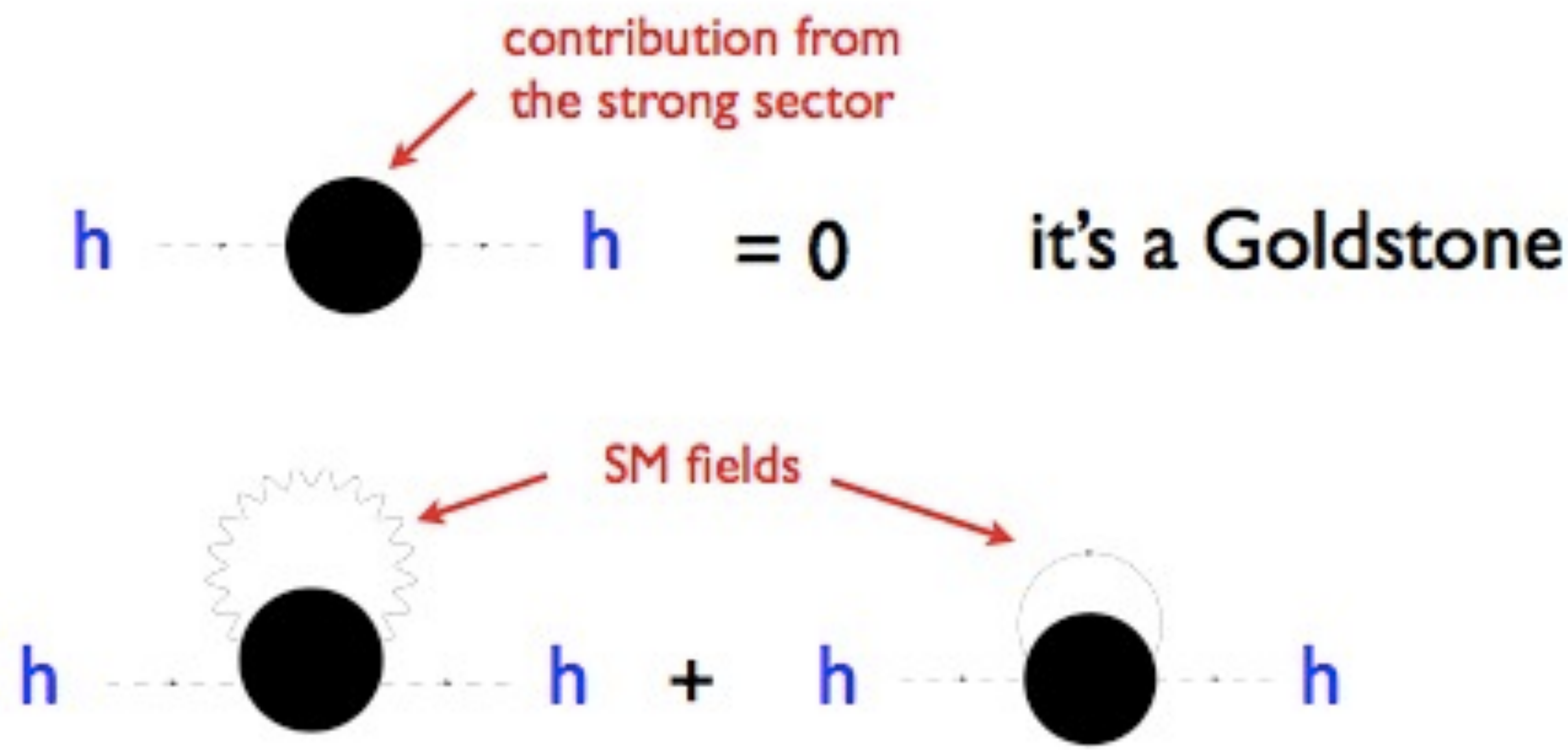

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Pomarol, Riva '12

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

Marzocca, Serone, Shu '12

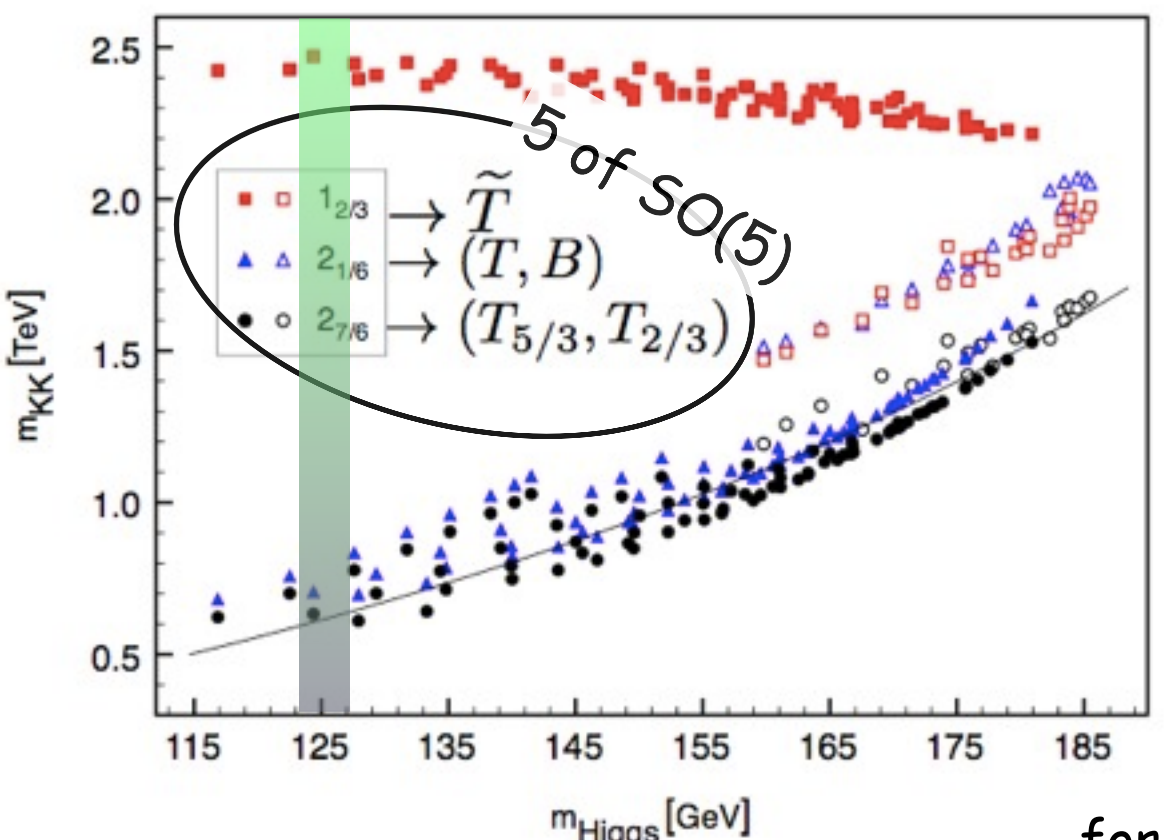
$$m_Q \lesssim 700\ \text{GeV}\left(\frac{m_h}{125\ \text{GeV}}\right)\left(\frac{160\ \text{GeV}}{m_t}\right)\left(\frac{f}{500\ \text{GeV}}\right)$$

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

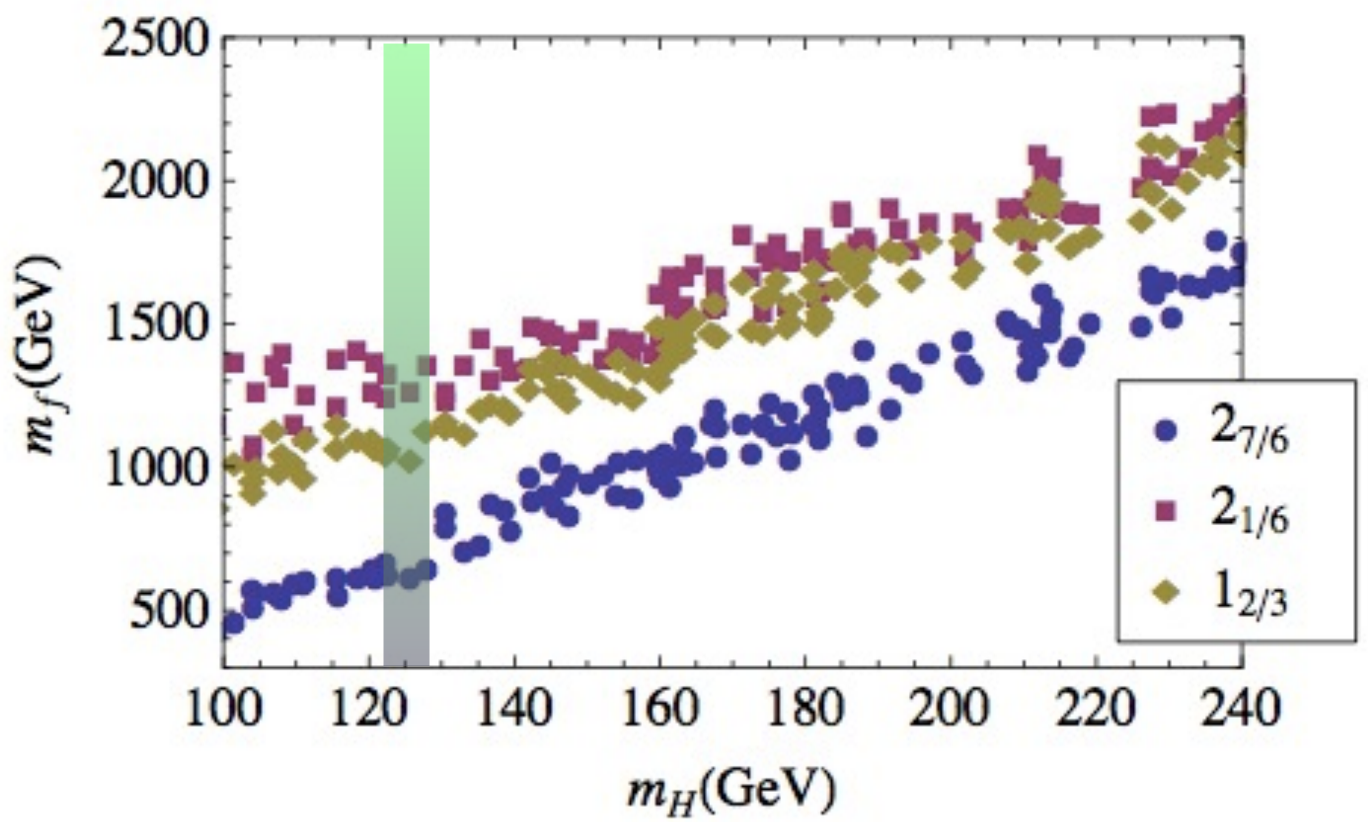
Light composite Higgs from "light" resonances

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

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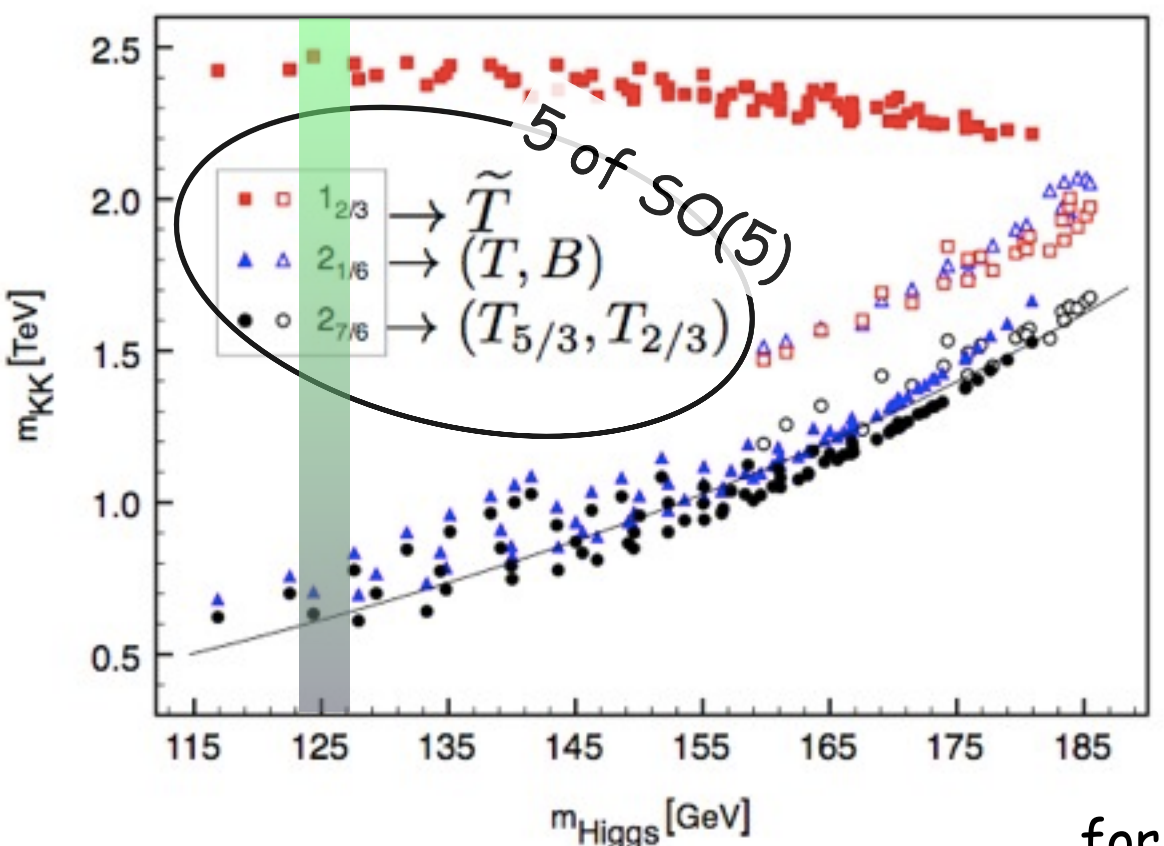
Contino, Da Rold, Pomarol '06



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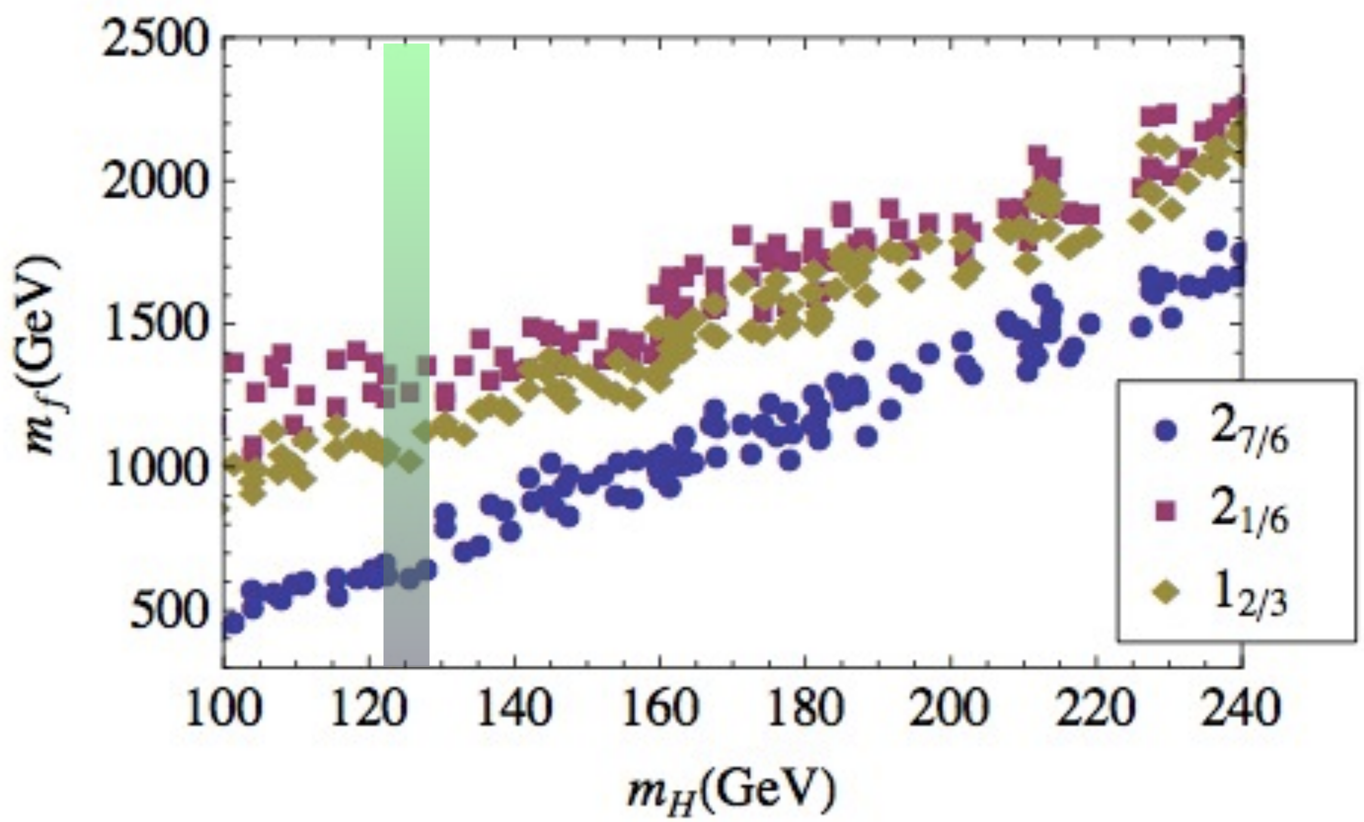

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Nice AdS/CFT interpretation

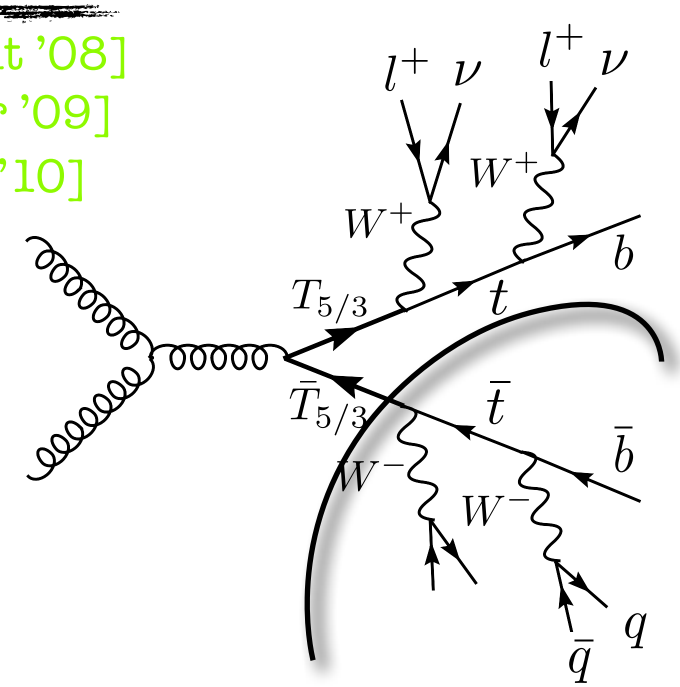
$$\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

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

Rich phenomenology of the top partners

Search in same-sign di-lepton events

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



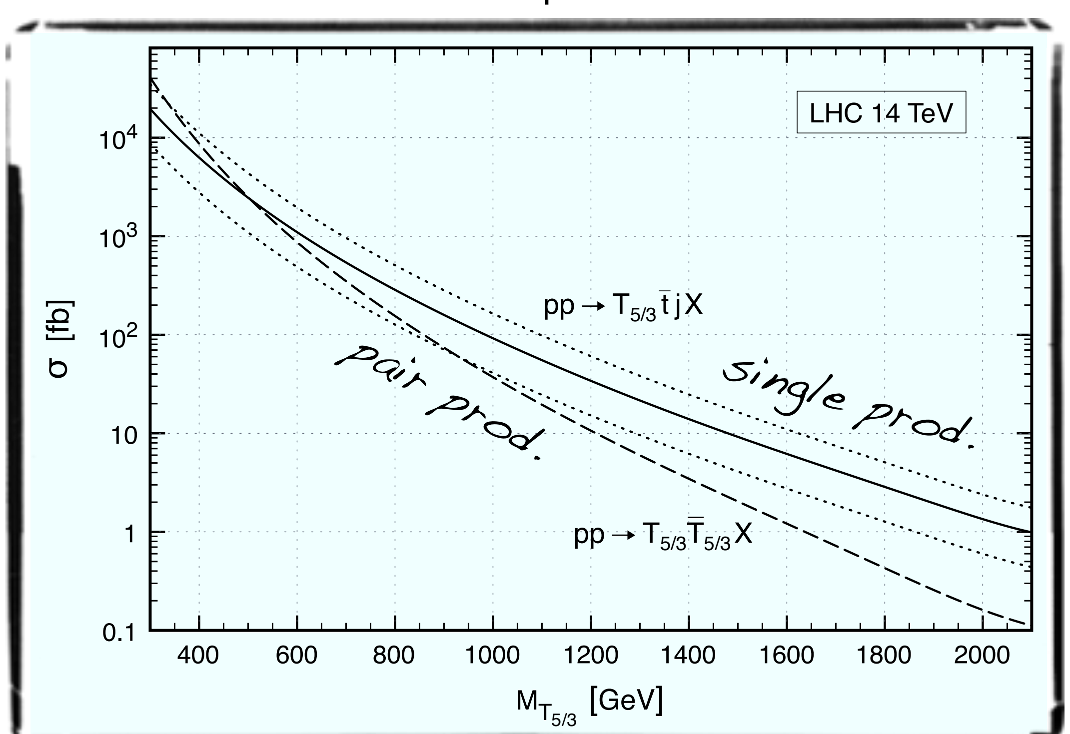
- *tt+jets* is not a background [except for charge mis-ID and fake e⁻]
- the resonant (*tW*) invariant mass can be reconstructed

discovery potential ($LHC_{14 TeV}$)

$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}

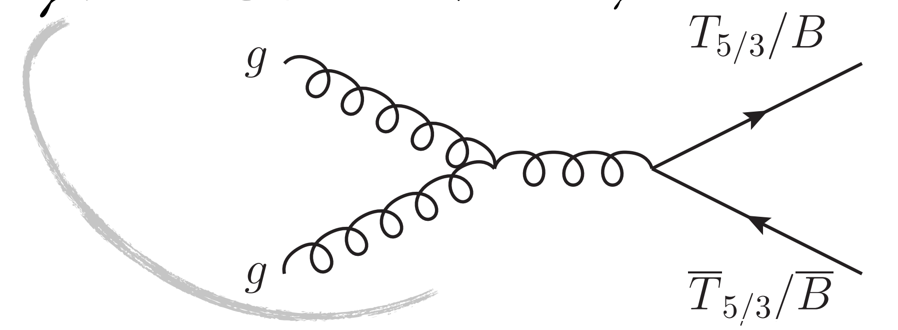
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

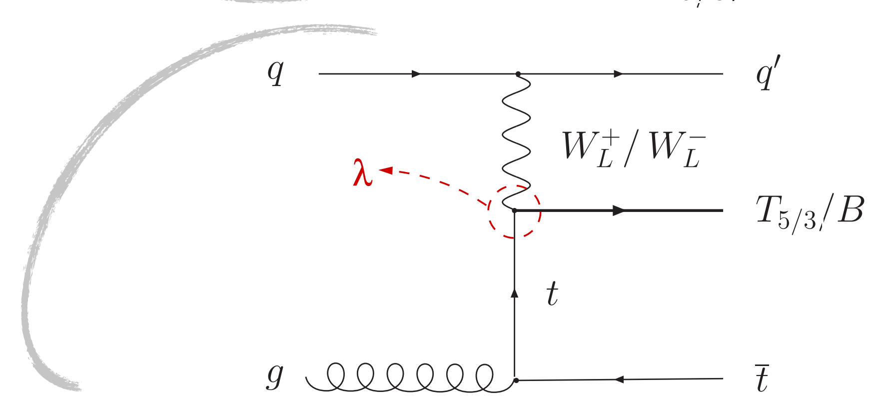
Dissertori, Furlan, Moortgat, Nef '09]
4



[Contino, Servant '08]

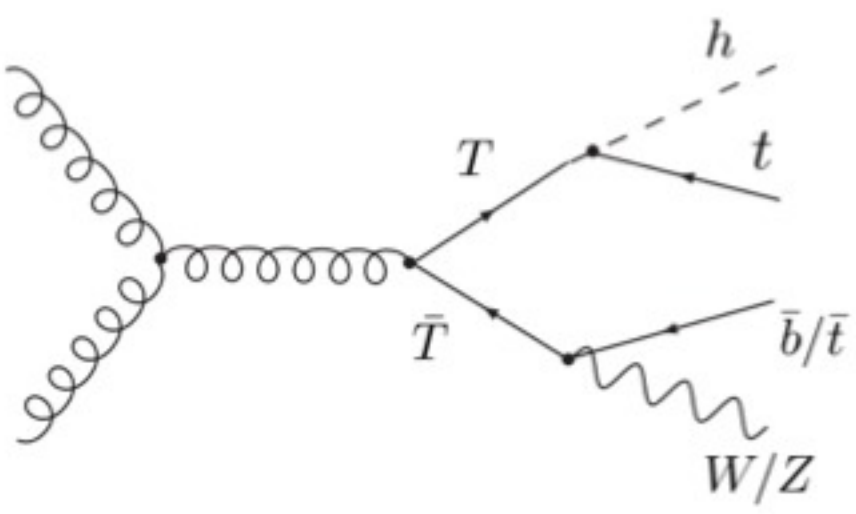
Pair production (model independent)





Single production (model dependent)

Rich phenomenology of the top partners



l± + 4b final state

Aguilar-Saavedra '09

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

l± + 6b final state

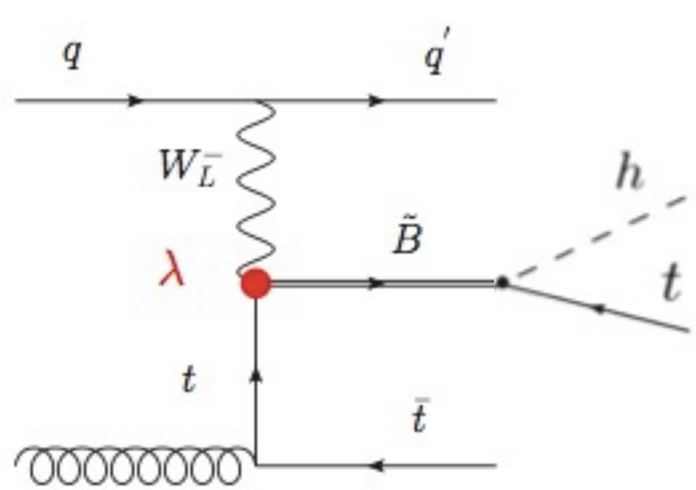
Aguilar-Saavedra '09

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

$\gamma\gamma$ final state

Azatov et al '12

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



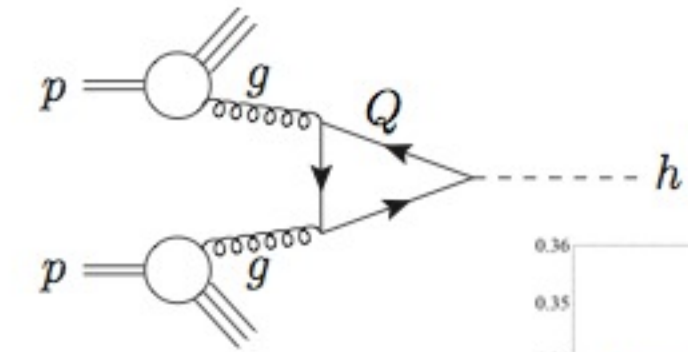
l± + 4b final state

Vignaroli '12

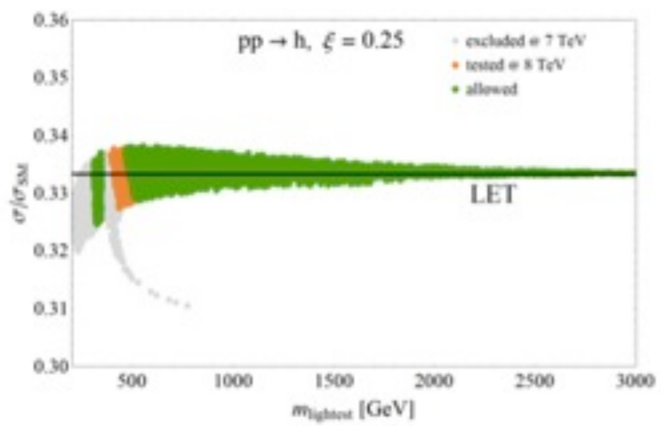
$$pp \to (\tilde{B} \to (h \to bb)b)t + X$$

Top partners & Higgs physics

~ current single higgs processes are insensitive to top partners ~



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



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

Top partners & Higgs physics

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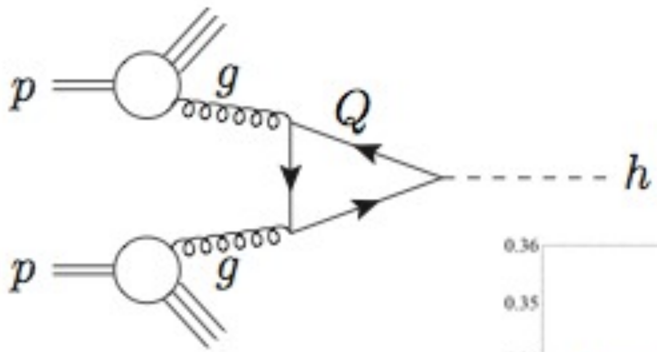

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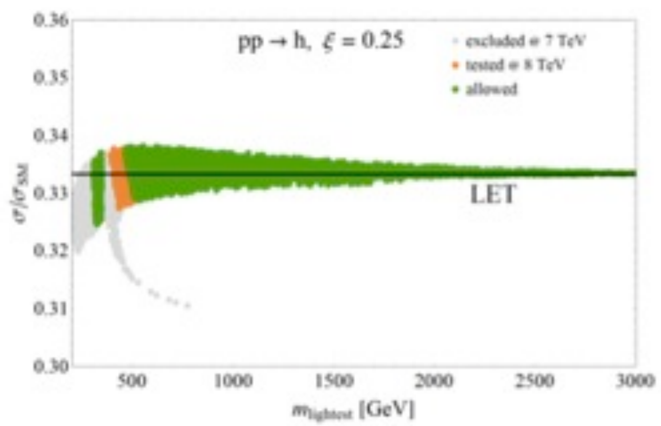

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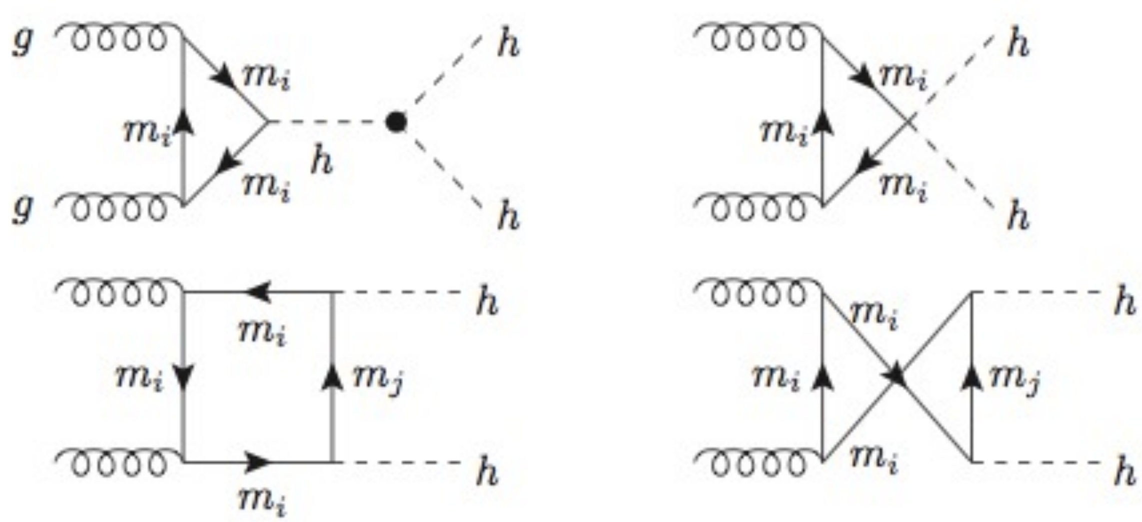
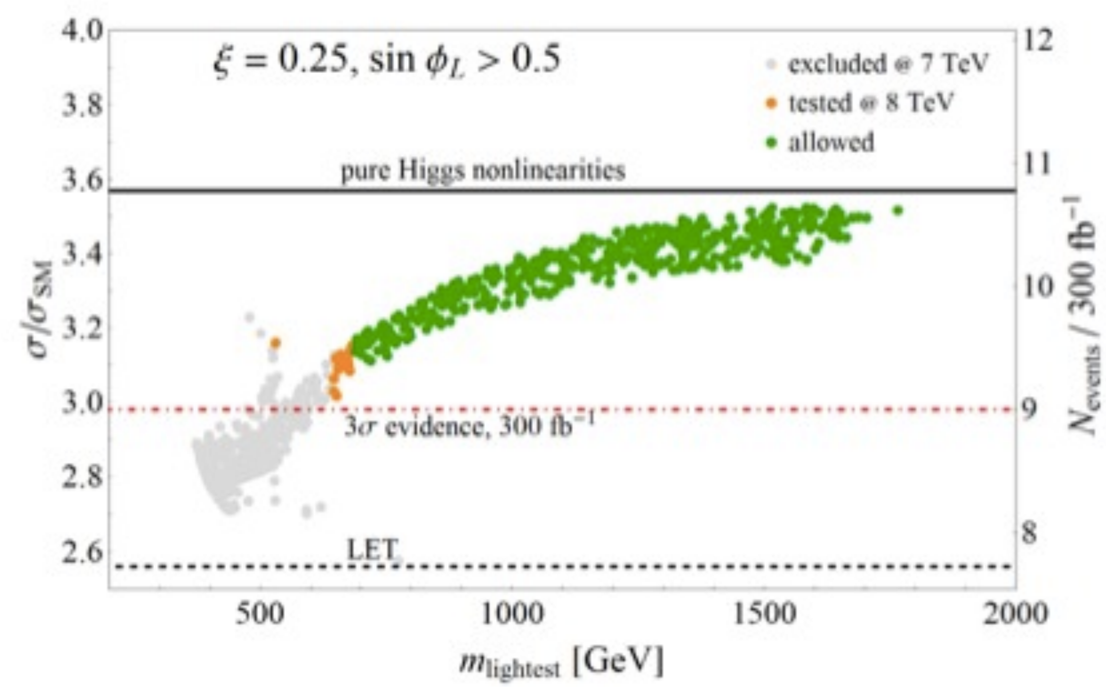
~ sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



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



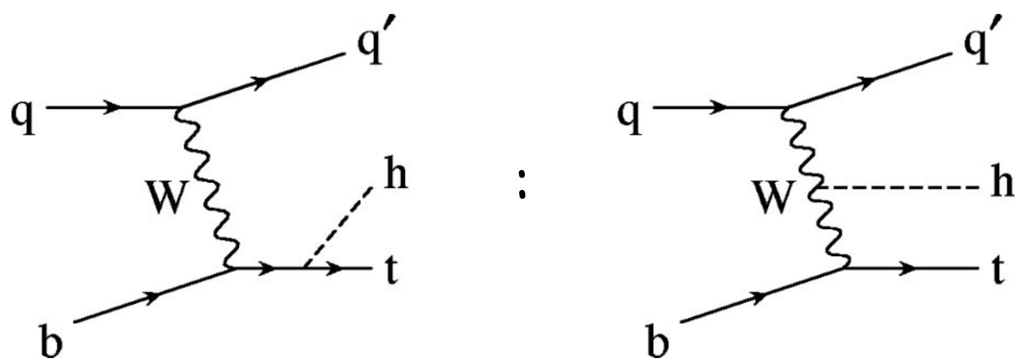
Top partners & Higgs physics

direct measurement of top-higgs coupling

htt is important but challenging channel

may be easier channel to look at

qb→q'th



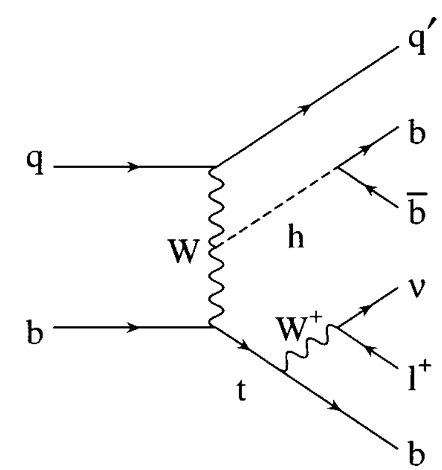
@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$

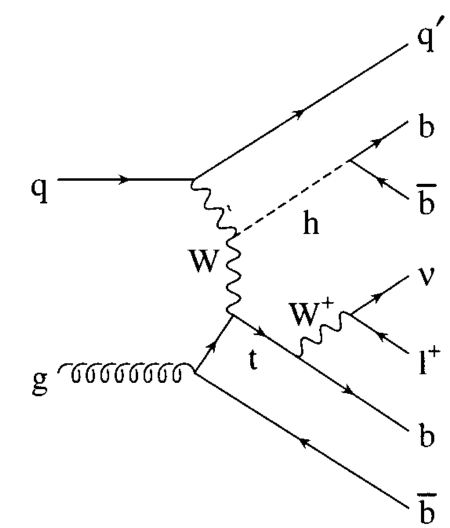
Farina, Grojean, Maltoni, Salvioni, Thamm '12

	$\sigma(pp \to tjh)$ [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:

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

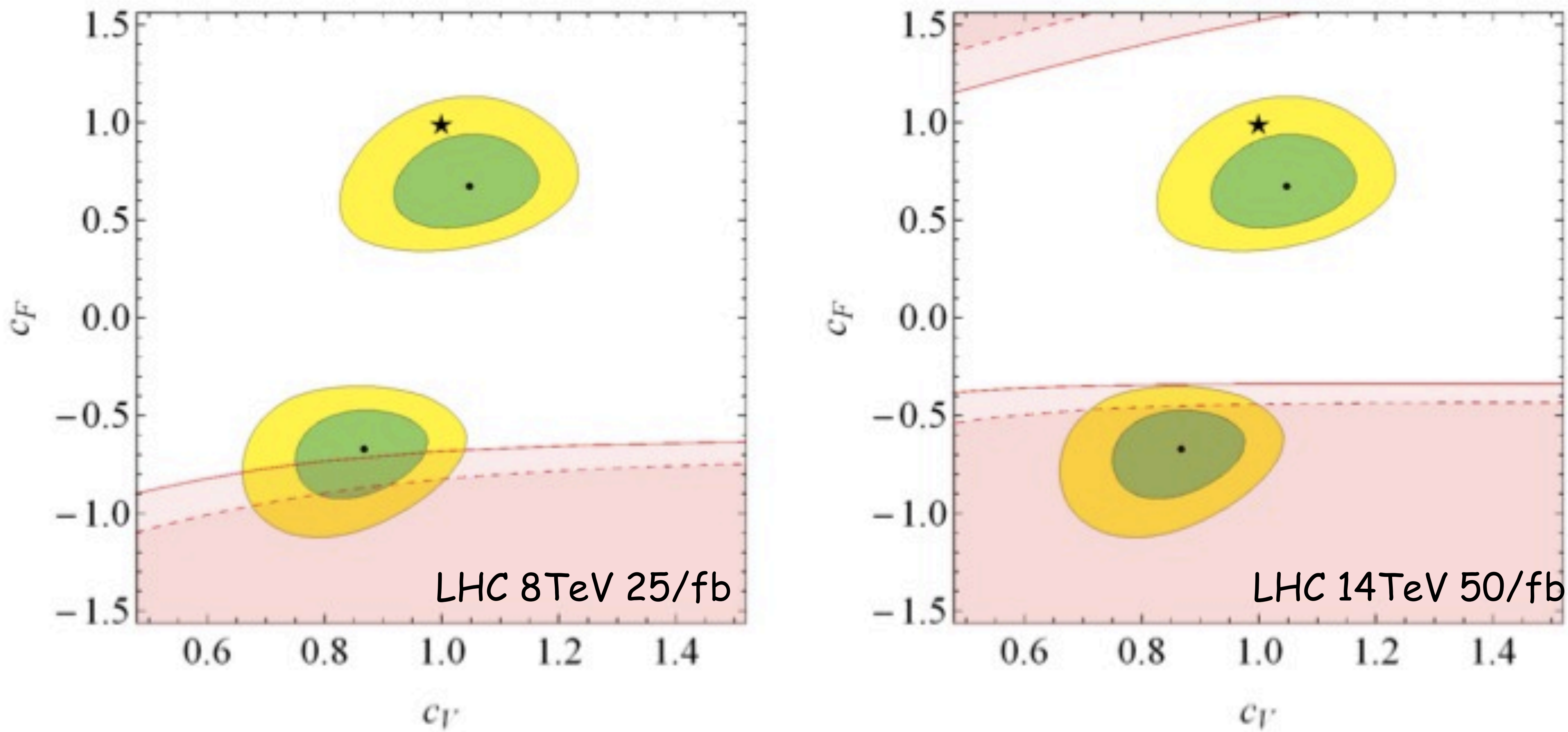




Top partners & Higgs physics

direct measurement of top-higgs coupling

single-top in association with Higgs



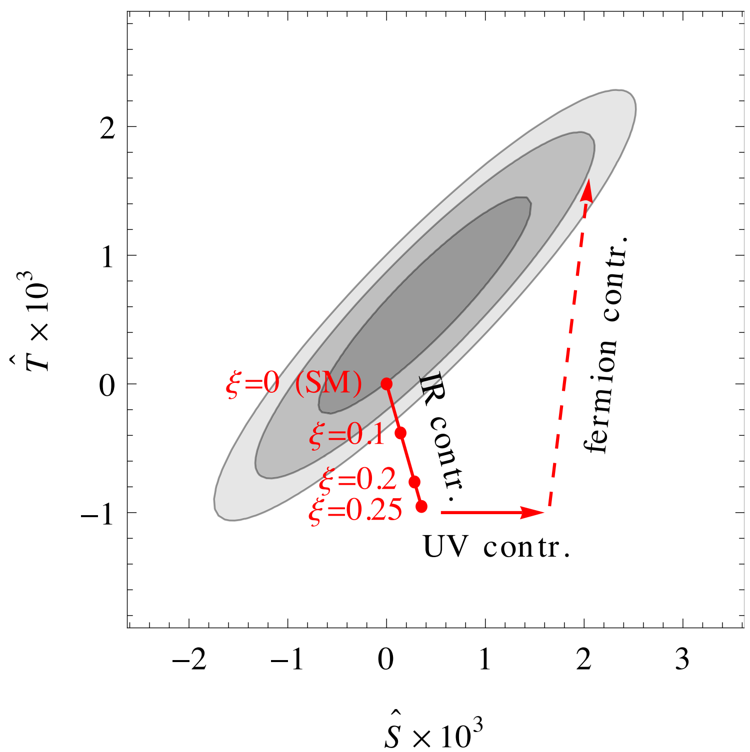
68% and 95% CL exclusion region vs current Higgs coupling fit

Farina, Grojean, Maltoni, Salvioni, Thamm '12

Top partners & EWPT

Grojean, Matsedonskyi, Panico '13

Oblique parameters



tree-level contribution

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

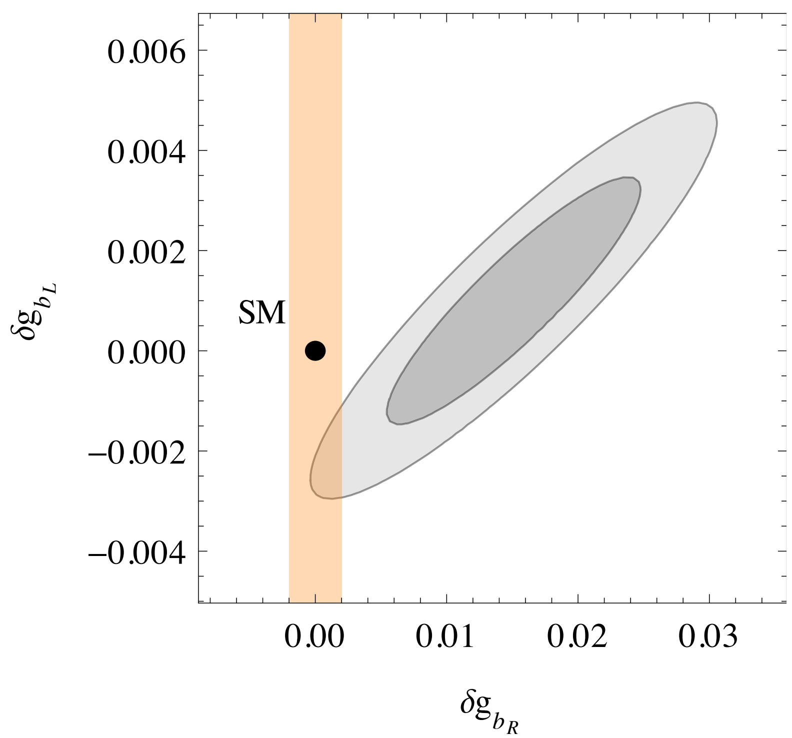
Higgs loop

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

fermion loop

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

Zb_Lb_L



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

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

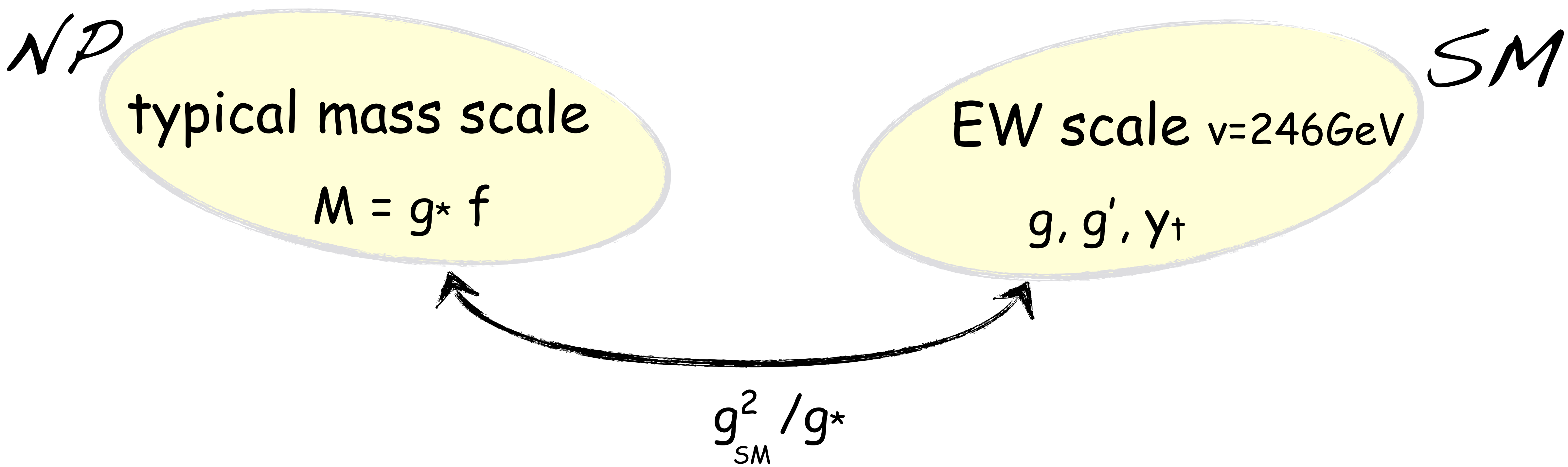
ξ<0.1 ⇨ we might have to wait LHC-HL to see any new physics in Higgs data

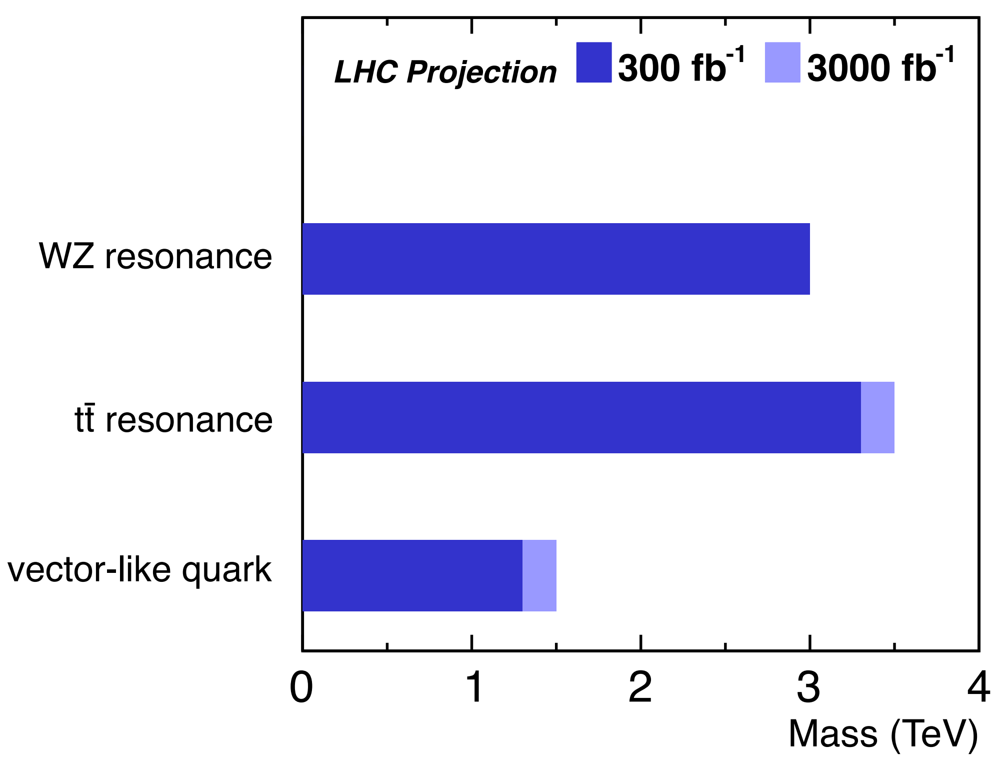
BSM Higgs precision era

Conclusions: Higgs & New Physics

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

Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13





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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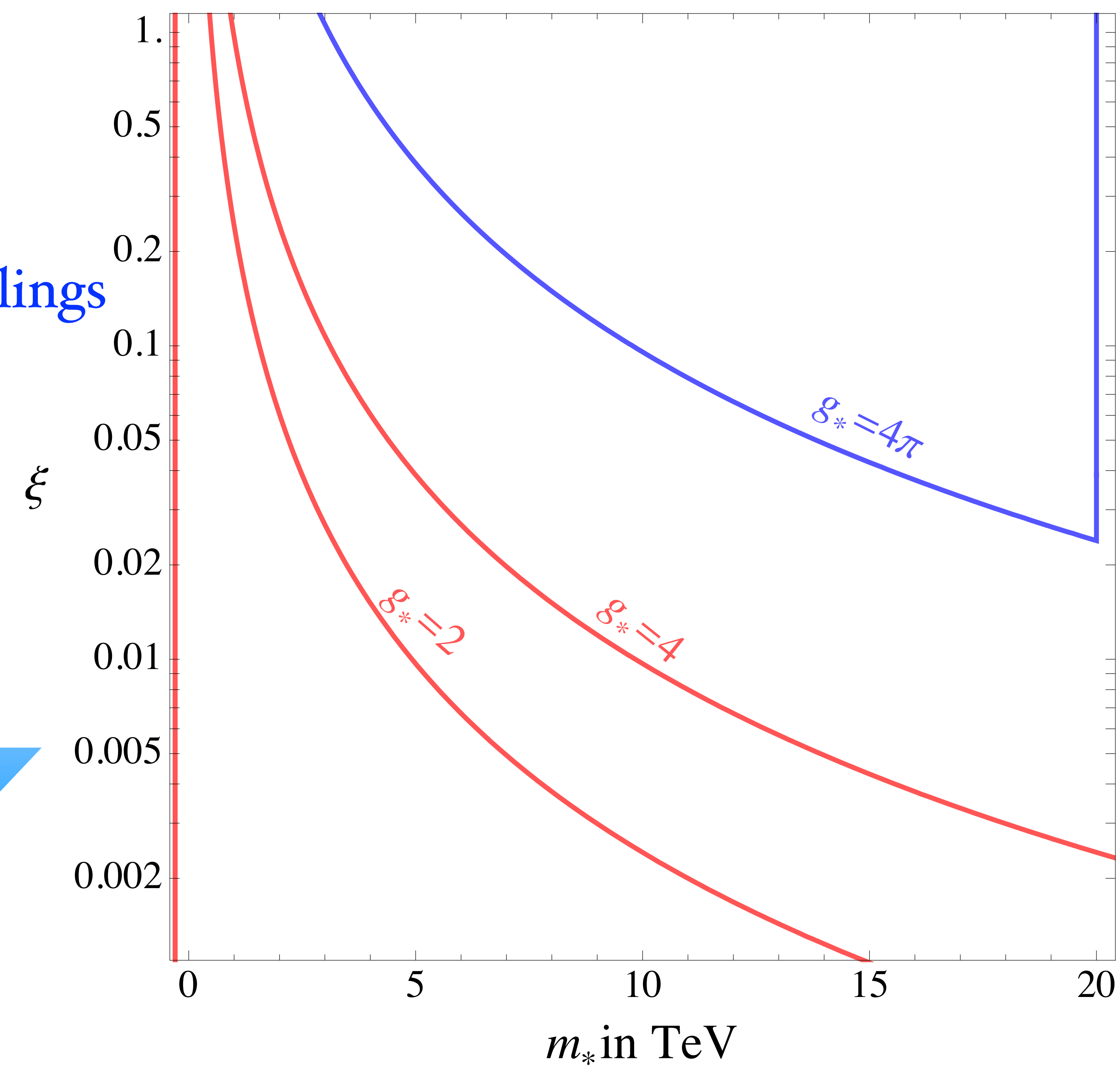
Higgs couplings



Rattazzi, BSM@100TeV, CERN '14

direct searches

Conclusions: Higgs & New Physics

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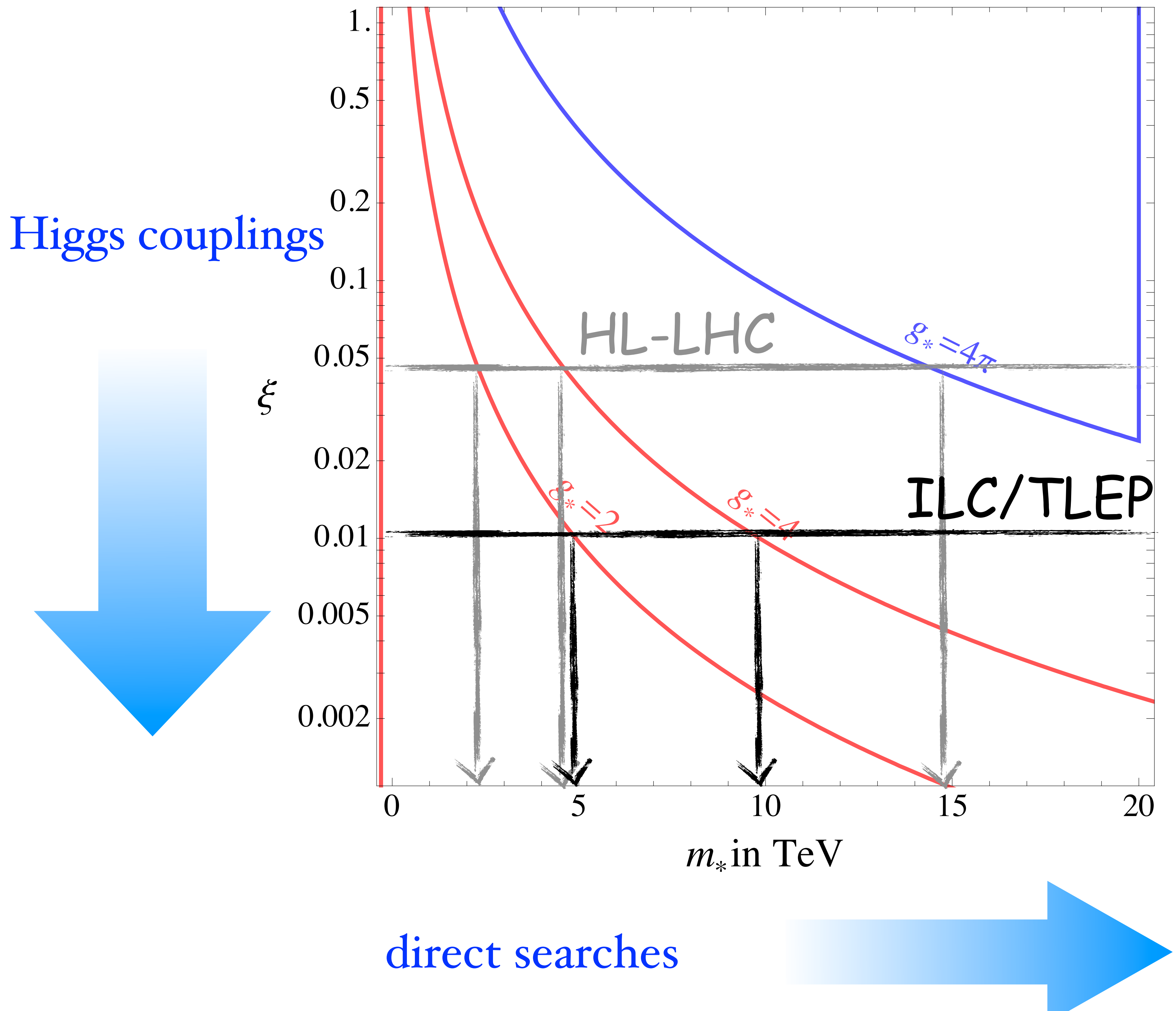


- nice complementarity between direct searches and precision Higgs physics

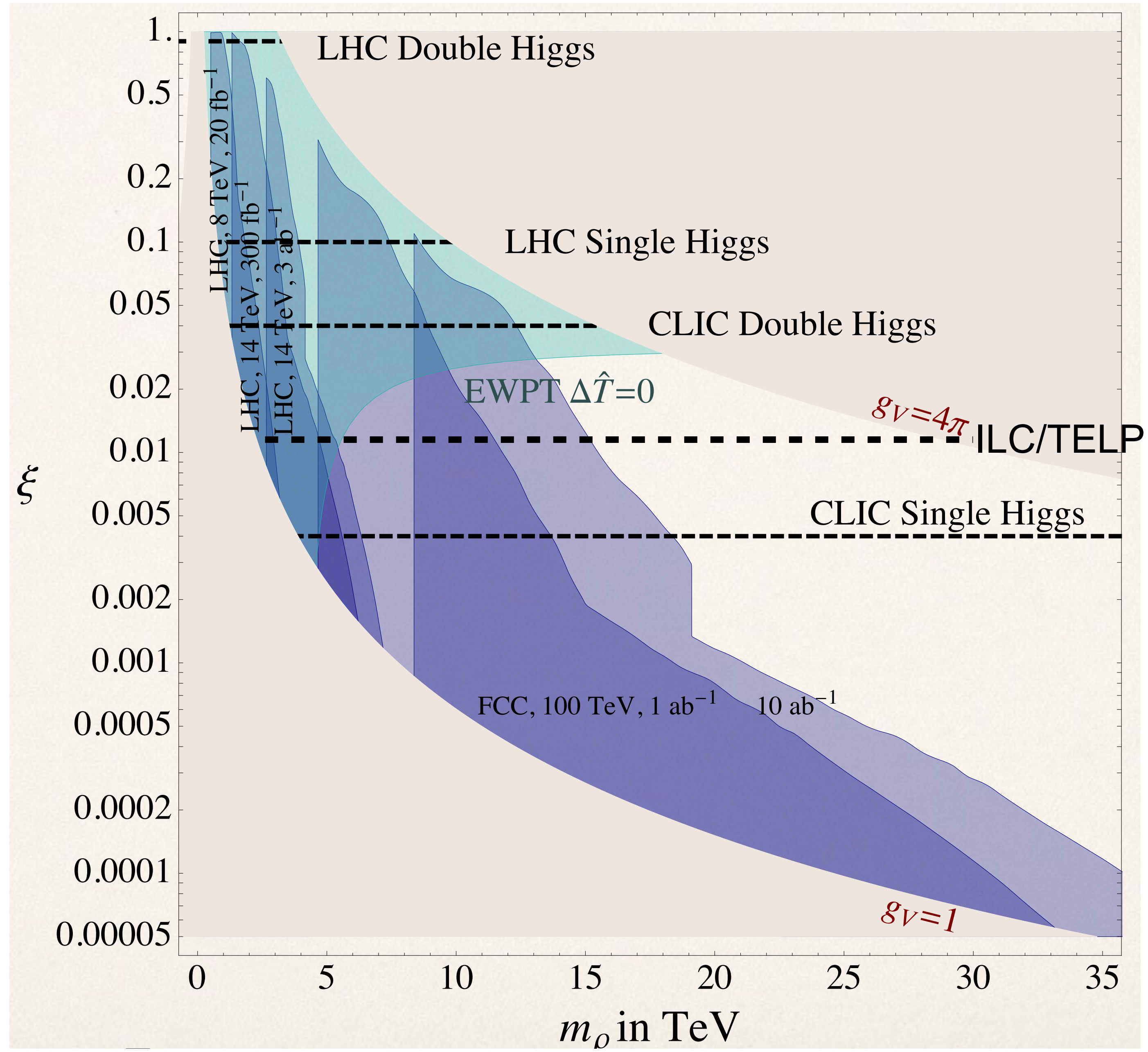
Rattazzi, BSM@100TeV, CERN '14

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



Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13

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