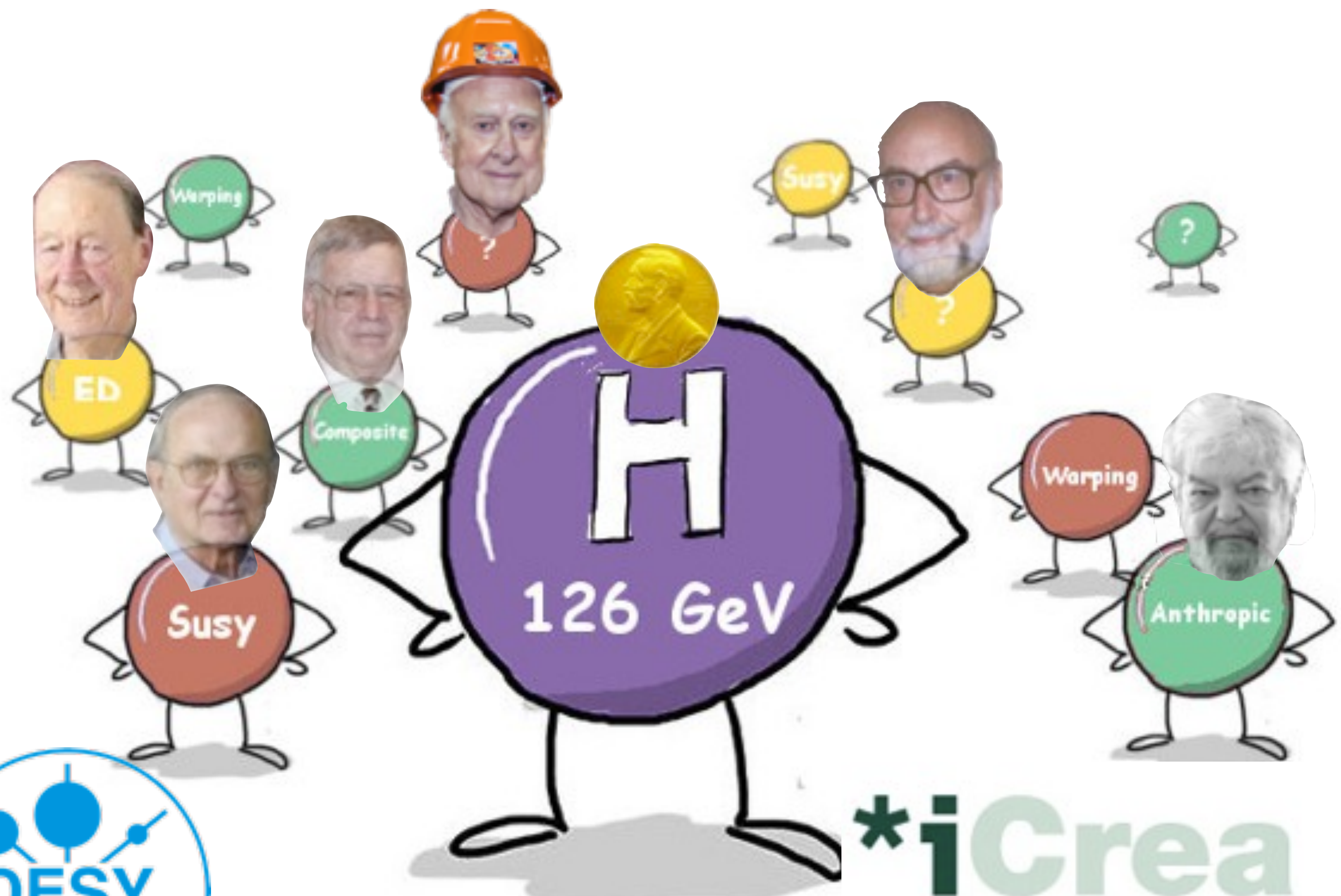
Beyond the Standard Model

CERN summer student lectures 2016



Lecture 3/4

Christophe Grojean

DESY (Hamburg)

ICREA@IFAE (Barcelona)

(christophe.grojean@cern.ch)

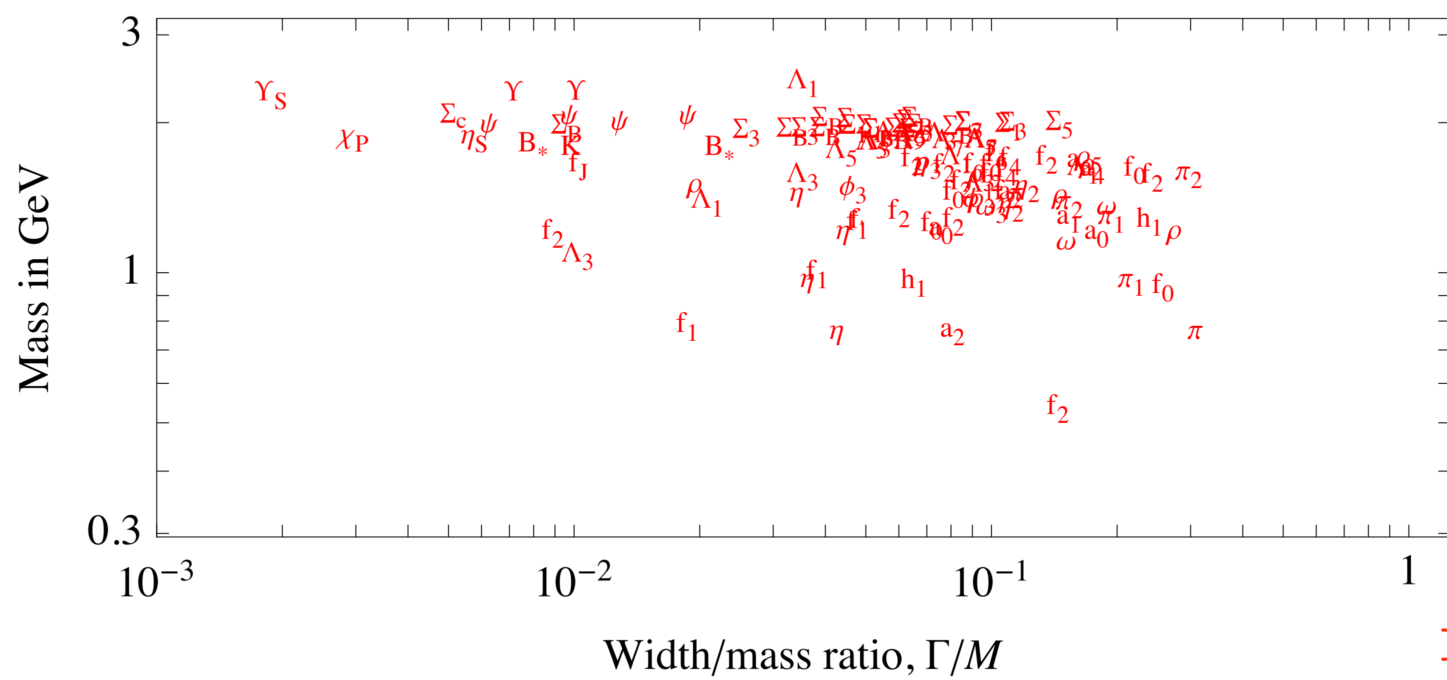
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

Outline

- Monday I
  - General introduction
  - Higgs physics as a door to BSM
- Monday II
  - Naturalness
  - Supersymmetry
  - Grand unification, proton decay
- Tuesday
  - Composite Higgs
  - Extra dimensions ↞ postponed till tomorrow
  - Effective field theory
- Wednesday
  - Cosmological relaxation
  - Quantum gravity

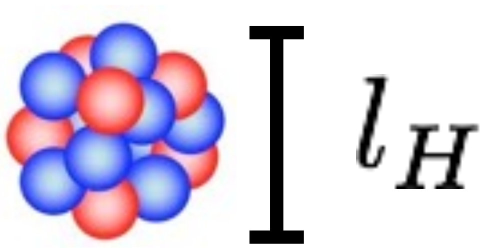
Composite Higgs

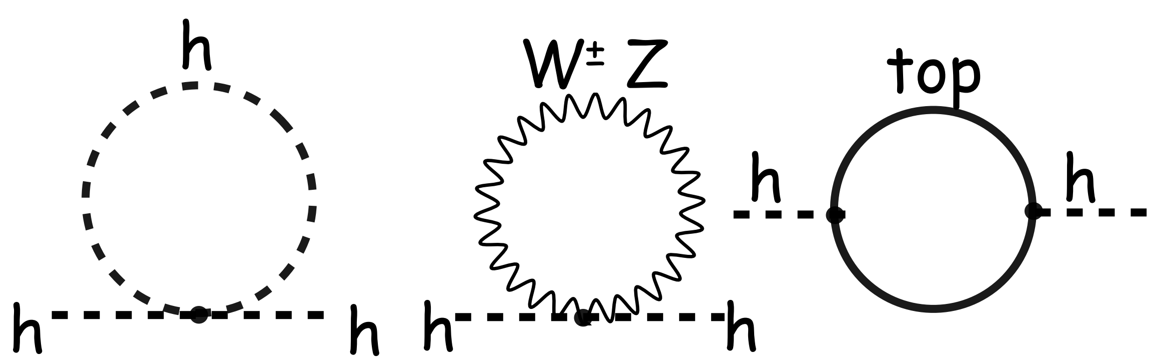
Light scalars exist in Nature but all the ones observed before the Higgs boson discovery were composite bounds states



Franceschini et al. '15

Could the Higgs be a "hadron" of a new strong force?

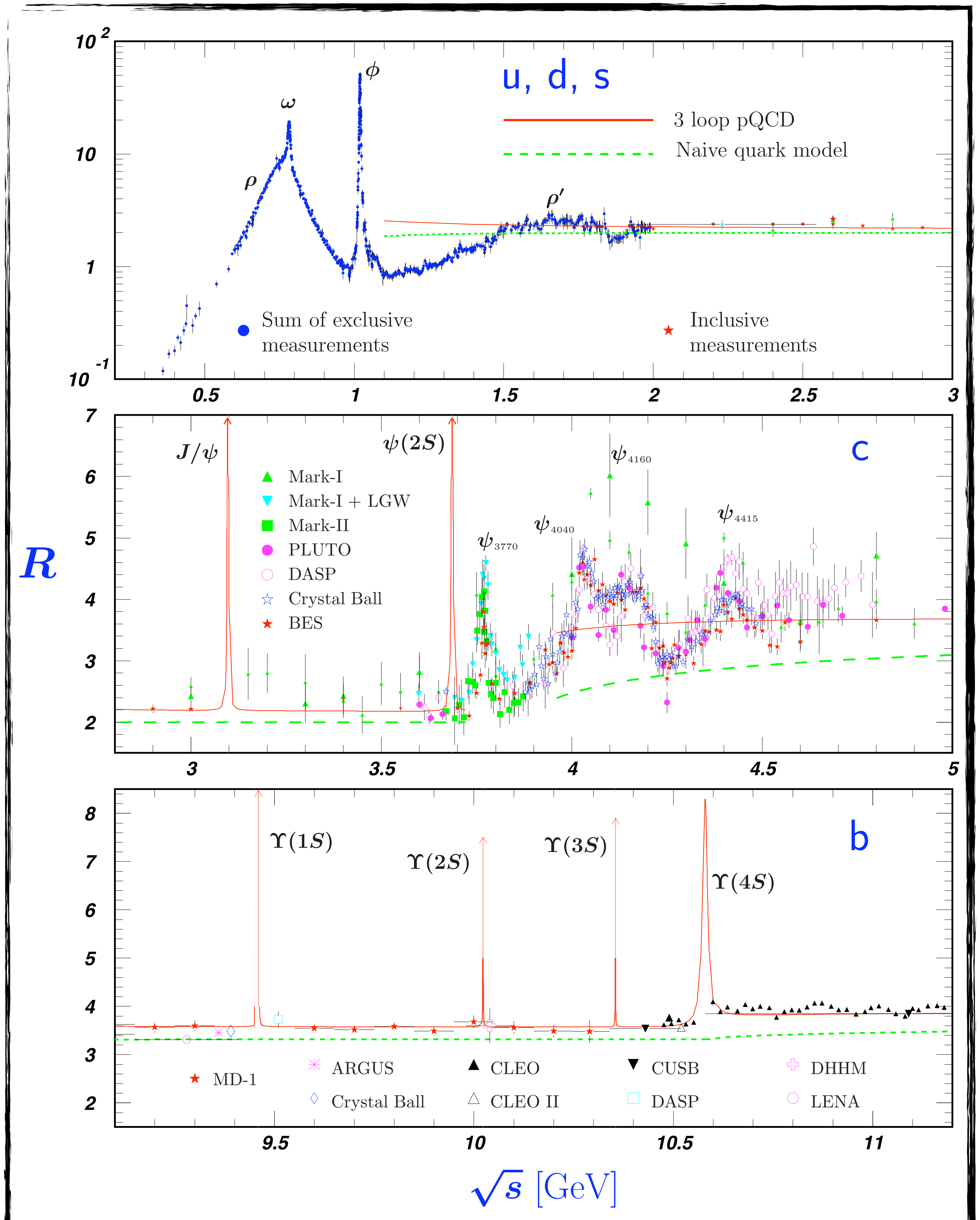




At energy above $1/\ell_H$, the Higgs dissolves, the integrals are smoothed out

$$\int \frac{d^4k}{(2\pi)^4} \mathcal{F}_H(k) \frac{1}{k^2 - m^2} \propto 1/l_H^2$$

Higgs as a bound state



The Higgs discovery would be the first step of rich physics ahead of us:

- discover a new SU(N_c) force
- access to the fundamental constituents
- rich spectrum of bound states

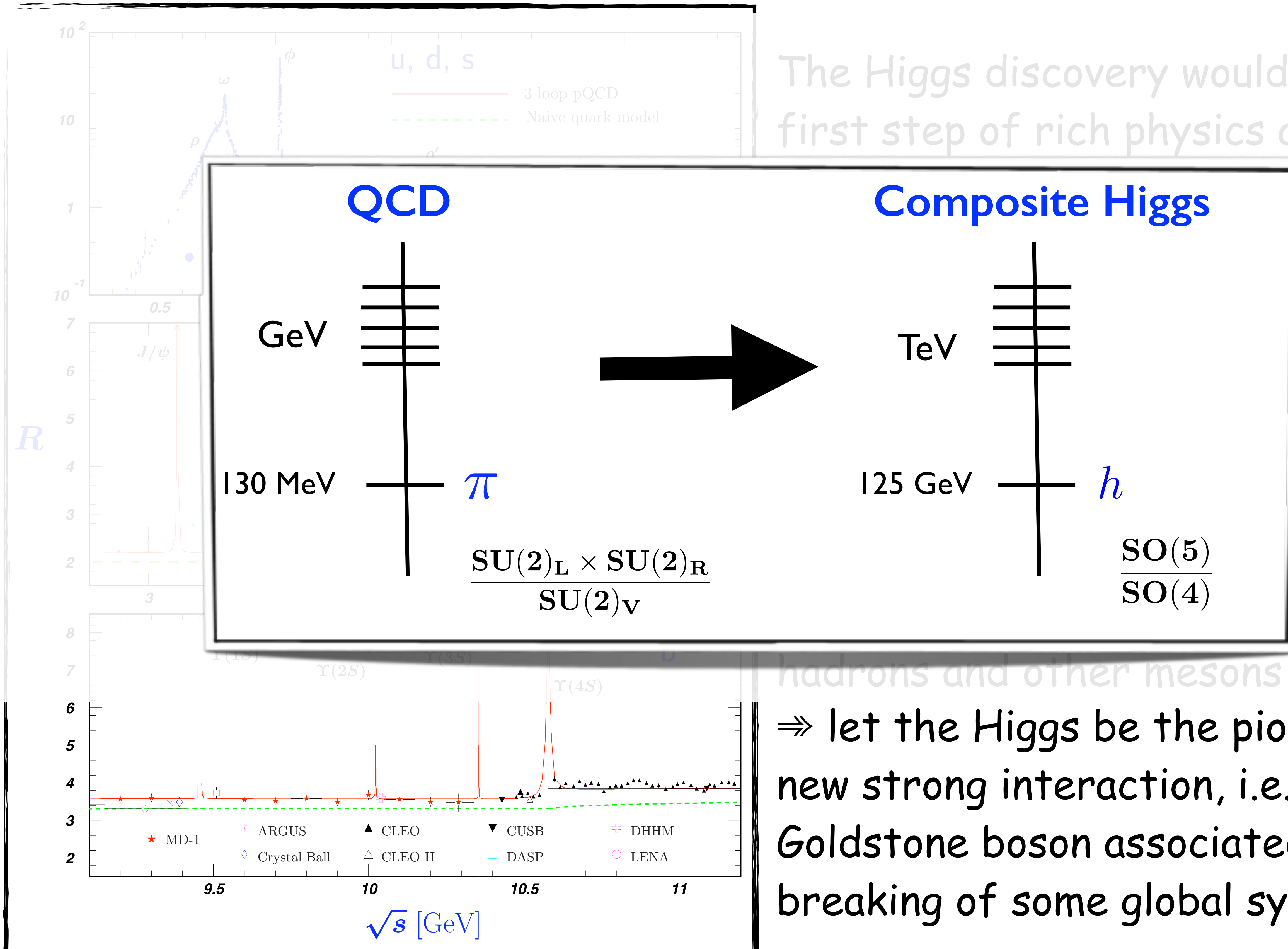
But how come we haven't seen anything of these yet?

⇛ The Higgs has to be lighter than the other bound states

⇛ pions are lighter than nucleons, hadrons and other mesons

⇛ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a bound state



The Higgs discovery would be the first step of rich physics ahead of us:

...nstituents

...s

...een

...ter than

...cleons,

hadrons and other mesons

⇛ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a Goldstone boson

SM: $SO(4)/SO(3)$ — $W^{\pm}_L$ & Z_L ⇒ G/H — $W^{\pm}_L$ & Z_L & h :BSM

Examples:

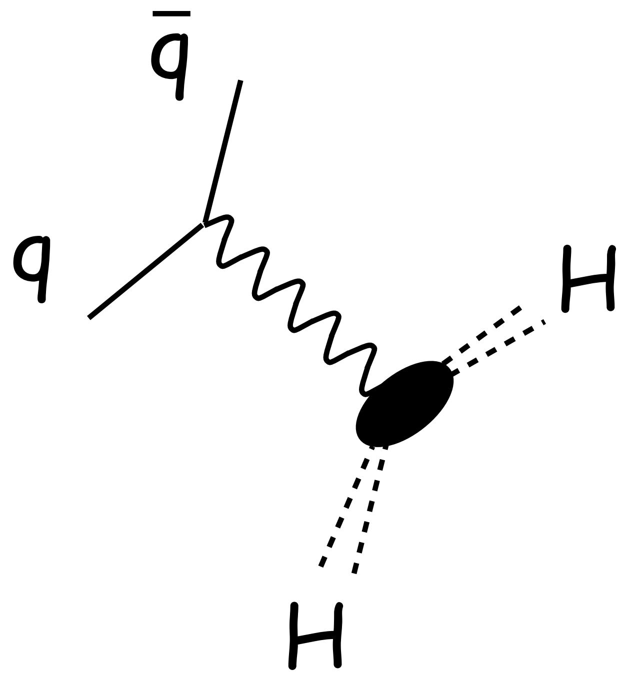
$SO(5)/SO(4)$: 4 PGBs=$W^{\pm}_L$, Z_L, h ⟷ Minimal Composite Higgs Model
Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$: 5 PGBs=H, a ⟷ Next MCHM
Gripaios, Pomarol, Riva, Serra '09

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s

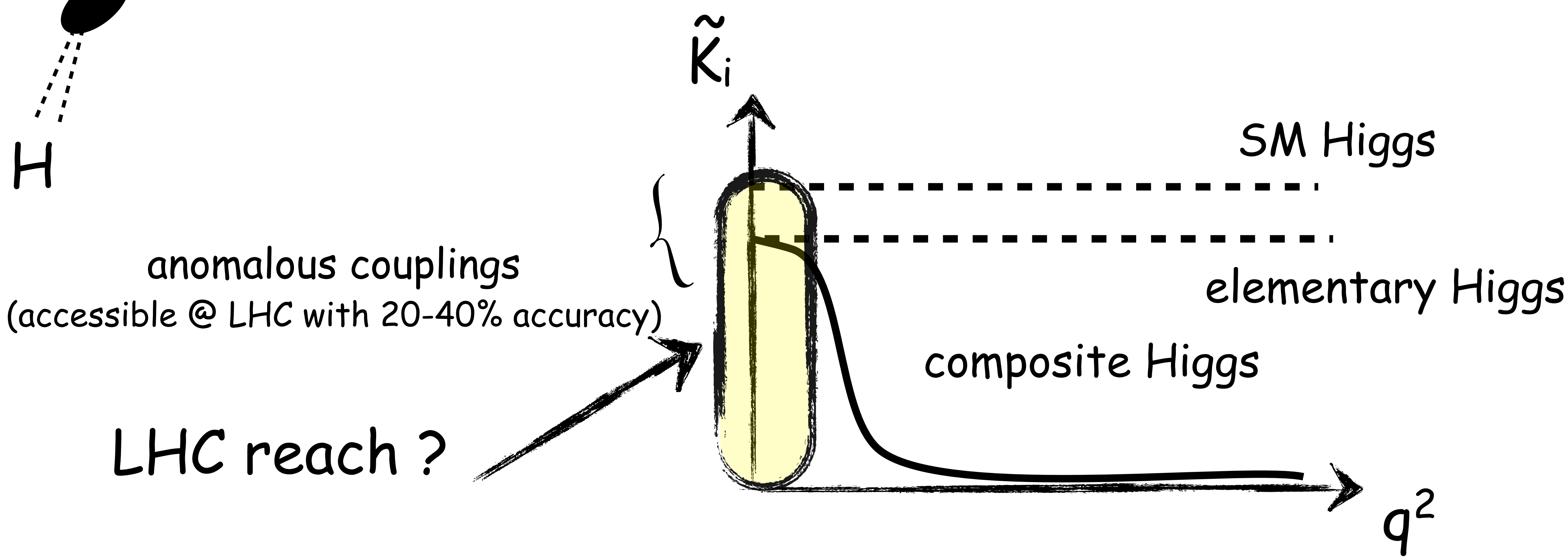
$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ⟷ Minimal Composite Two Higgs Doublets
Mrazek, Pomarol, Rattazzi, Serra, Wulzer '??

How to probe the compositeness of the Higgs?



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

Rosenbluth-type cross-section



Need to develop tools to understand the physics of a composite Higgs

- use effective theory approach
- rely on symmetries of the problem

} identify interesting processes

Anomalous Couplings for a Goldstone Higgs

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\partial^\mu\left(|H|^2\right)\partial_\mu\left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

f=compositeness scale of the Higgs boson

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H\frac{v^2}{f^2}\right)\left(\partial^\mu h\right)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H\frac{v^2}{f^2}}} \sim 1 - c_H\frac{v^2}{2f^2} \equiv 1 - \xi/2$

Higgs anomalous coupling: a = √1-ξ ≈ 1-ξ/2

$$\xi = v^2/f^2$$

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2$$

$$\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2}|H|^6$$

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$$

$$\frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

$$\frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

Higgs anomalous couplings

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar\psi_L \psi_R \left(1 + c\frac{h}{v}\right)$$

The Higgs couplings deviates from SM ones (a=b=c=1)
and the deviations are controlled by c_H and c_y

Anomalous couplings are related to the coset symmetry and not the spectrum of resonances

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

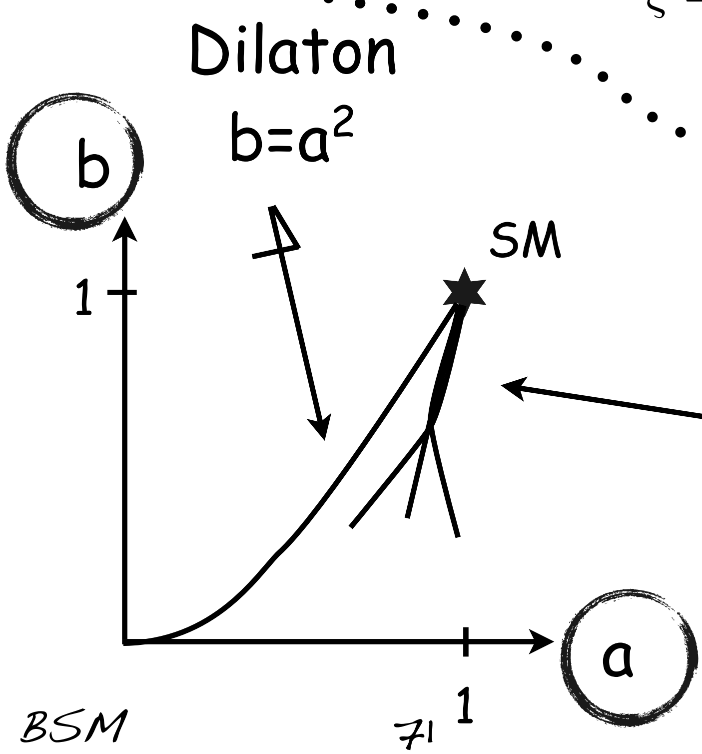
$$a = \sqrt{1-\xi} \qquad b = 1-2\xi \qquad b_3 = -\frac{4}{3}\xi\sqrt{1-\xi} \qquad c = \left(\sqrt{1-\xi}, \frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2 = -(\xi, 4\xi)$$

Uniqueness of Goldstone models in the SM vicinity

(a single operator at dimension-6 level controls the amplitudes)

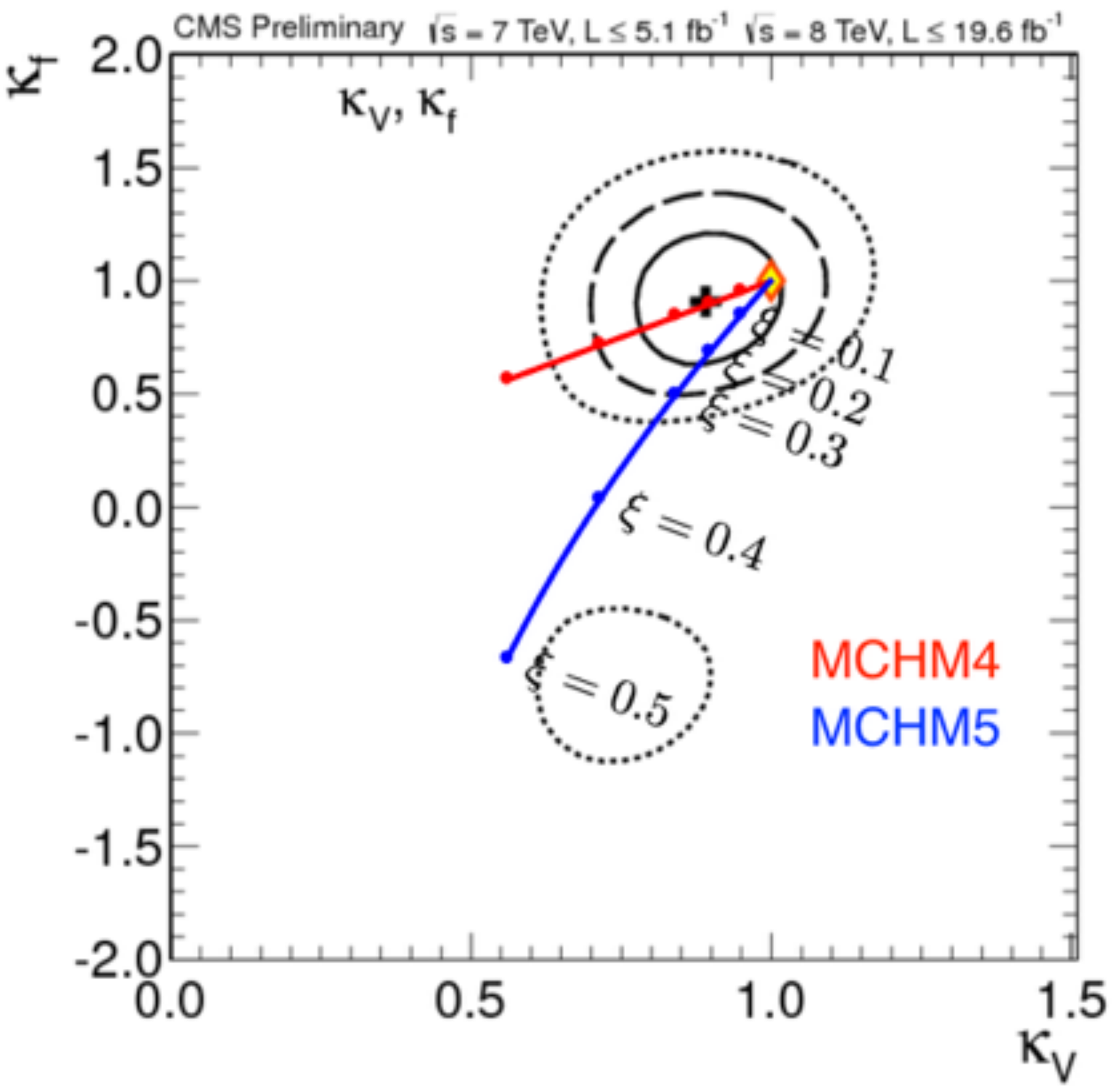
$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

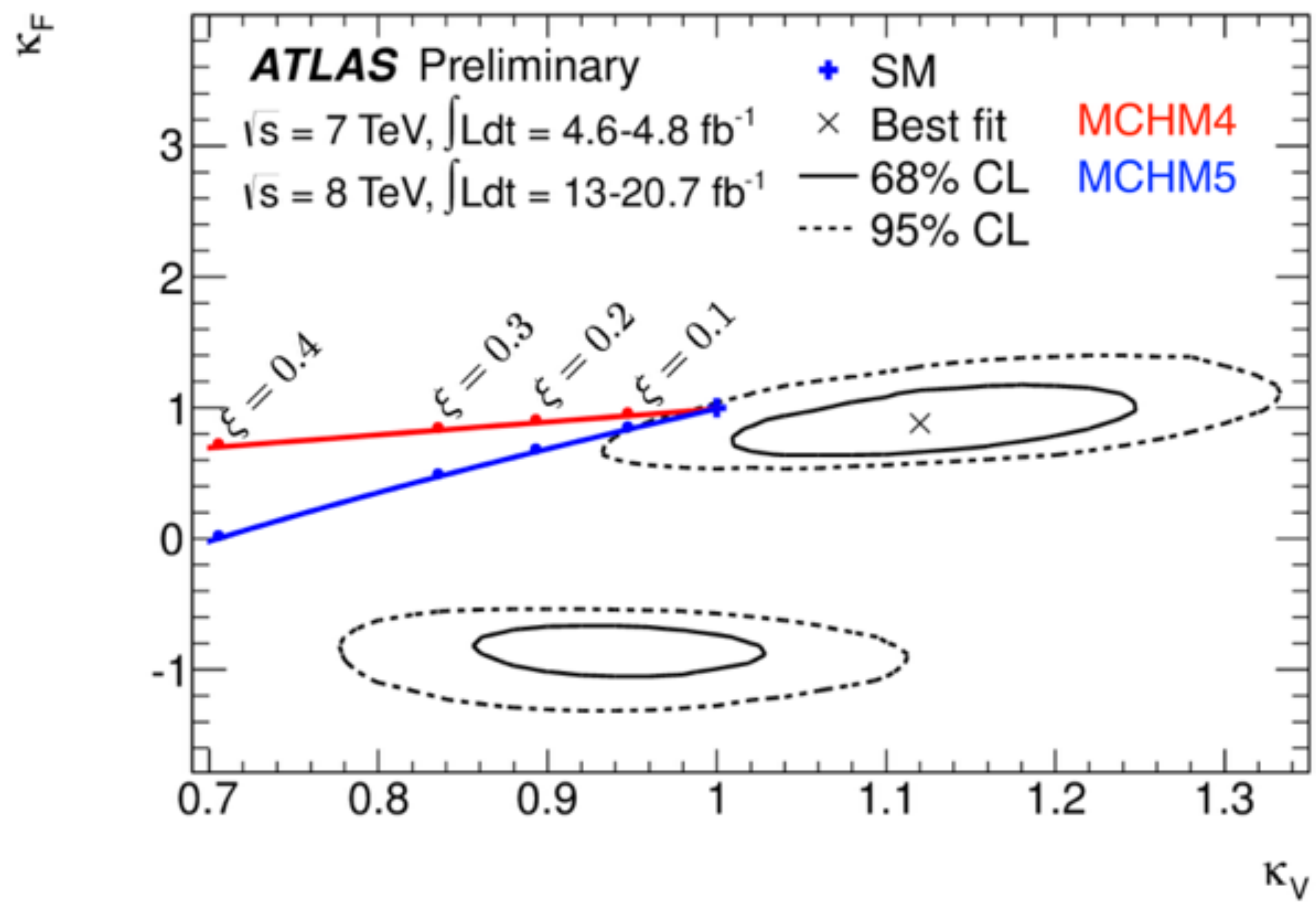
Composite Higgs
vs.
SM Higgs



Goldstone Higgs
for large f
$a=1-v^2/2f^2 \quad b=1-2\, v^2/f^2$

Higgs couplings fit





- MCHM4

$$\xi < 0.12 \quad \text{at } 95\%\text{CL}$$

- MCHM5

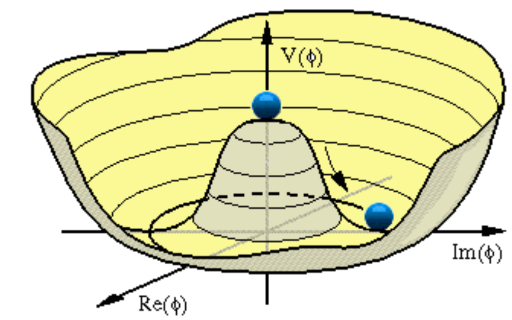
$$\xi < 0.10 \quad \text{at } 95\%\text{CL}$$

Higgs couplings vs BSM

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

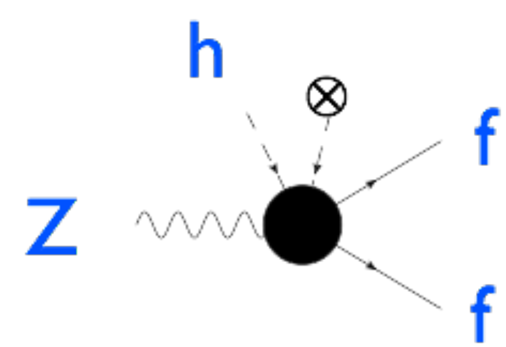
ϕ = v+h

↳ vacuum

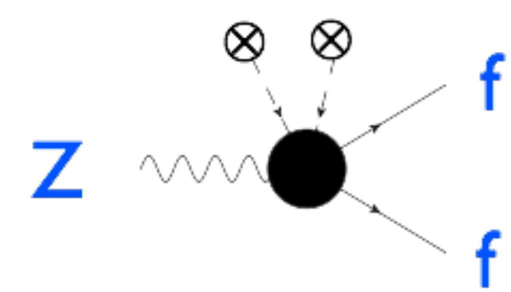


Potentially new BSM-effects in h physics could have been already tested in the vacuum

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→Zff related to Z→ff

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

consistency check not discovery mode

(courtesy of A. Pomarol@Moriond2014)

Higgs/BSM Primaries

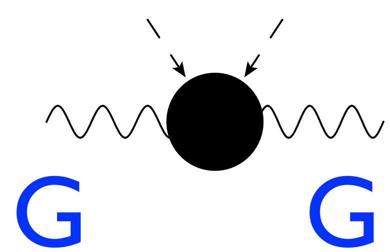
There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

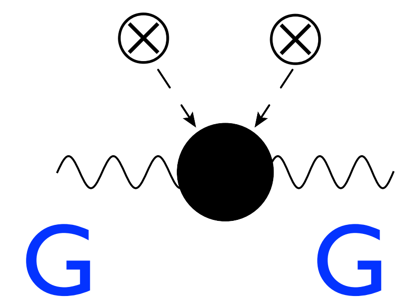
(courtesy of A. Pomarol@HiggsHunting2014)

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

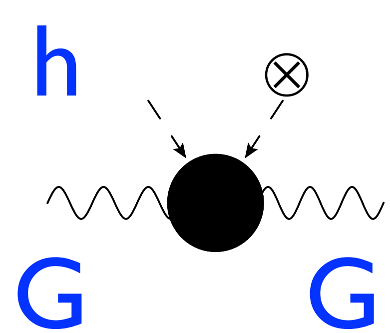
operator is not visible in the vacuum

(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	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	→	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$\tau\tau$

yet to be measured at the LHC

the 6 others have been measured (~15%)

Higgs/BSM Primaries

How many of these effects can we have?

Pomarol, Riva '13

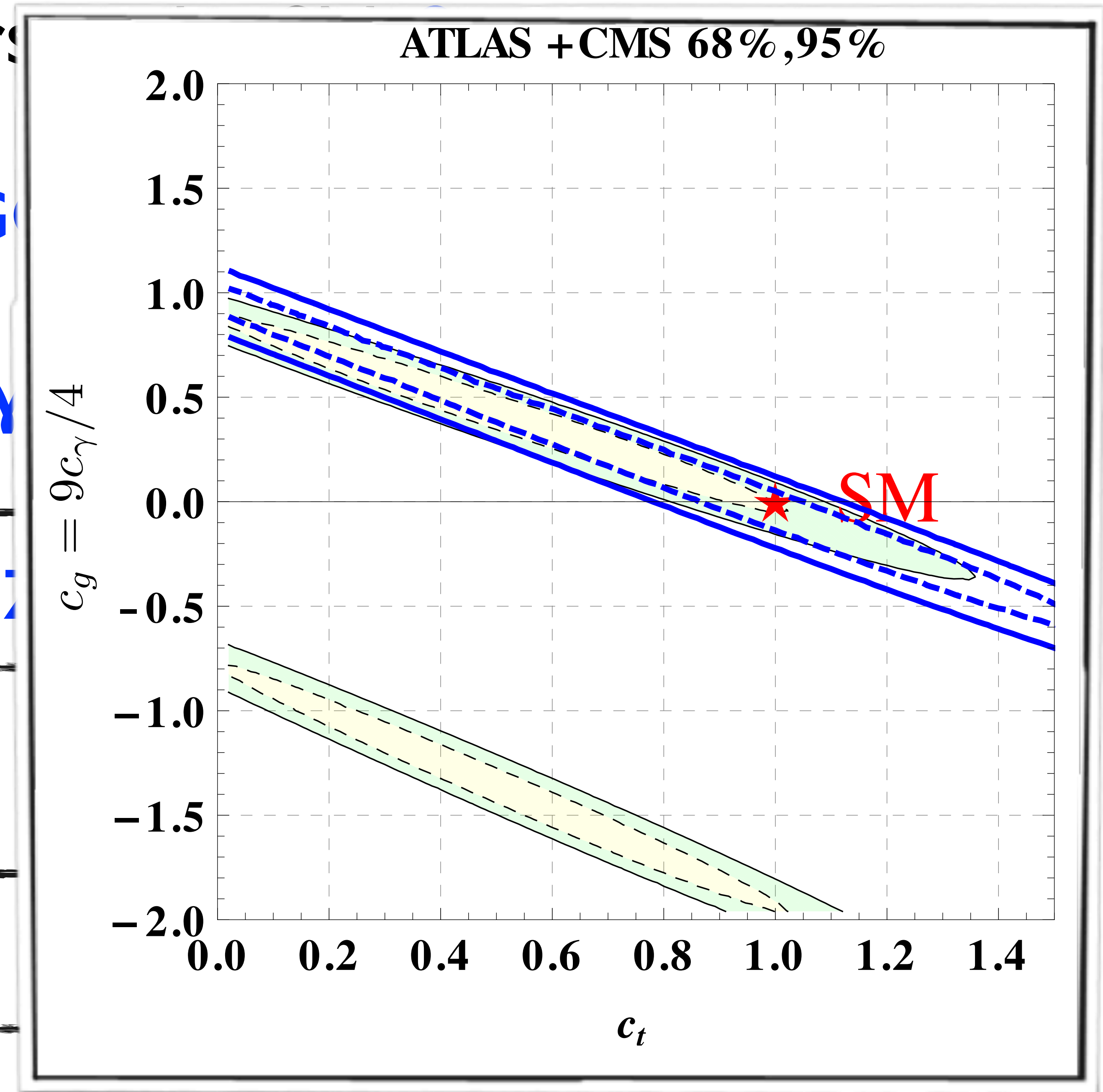
Elias-Miro et al '13

Gupta, Pomarol, Riva '14

As many as parameters

(courtesy of A. Pomarol@HiggsHunting2014)

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



Azatov '15

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

Higgs/BSM Primaries

How many of these effects can we have?

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

(courtesy of A. Pomarol@HiggsHunting2014)

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%

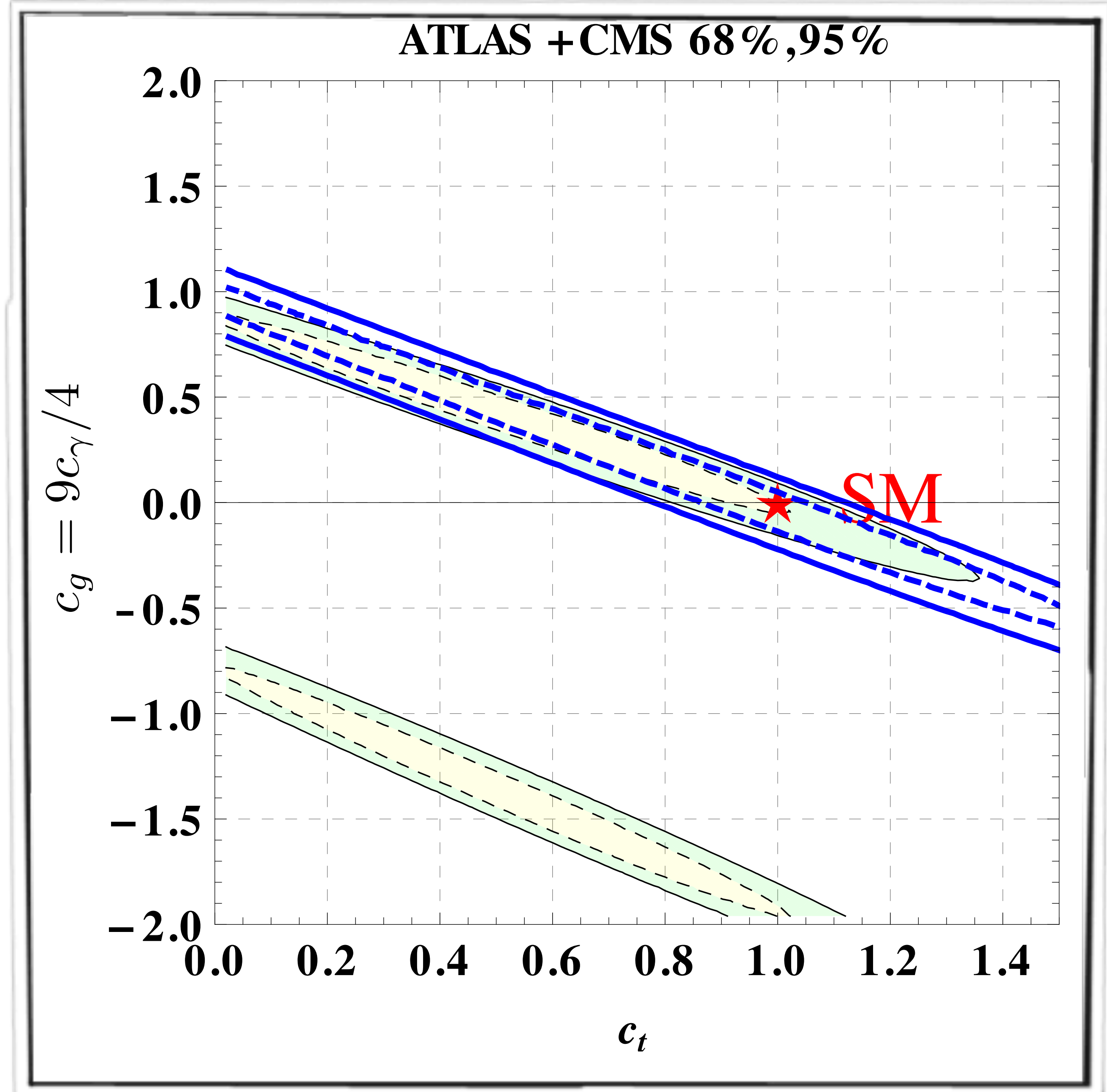
Atlas projection

With some important differences:

1) width hypothesis 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



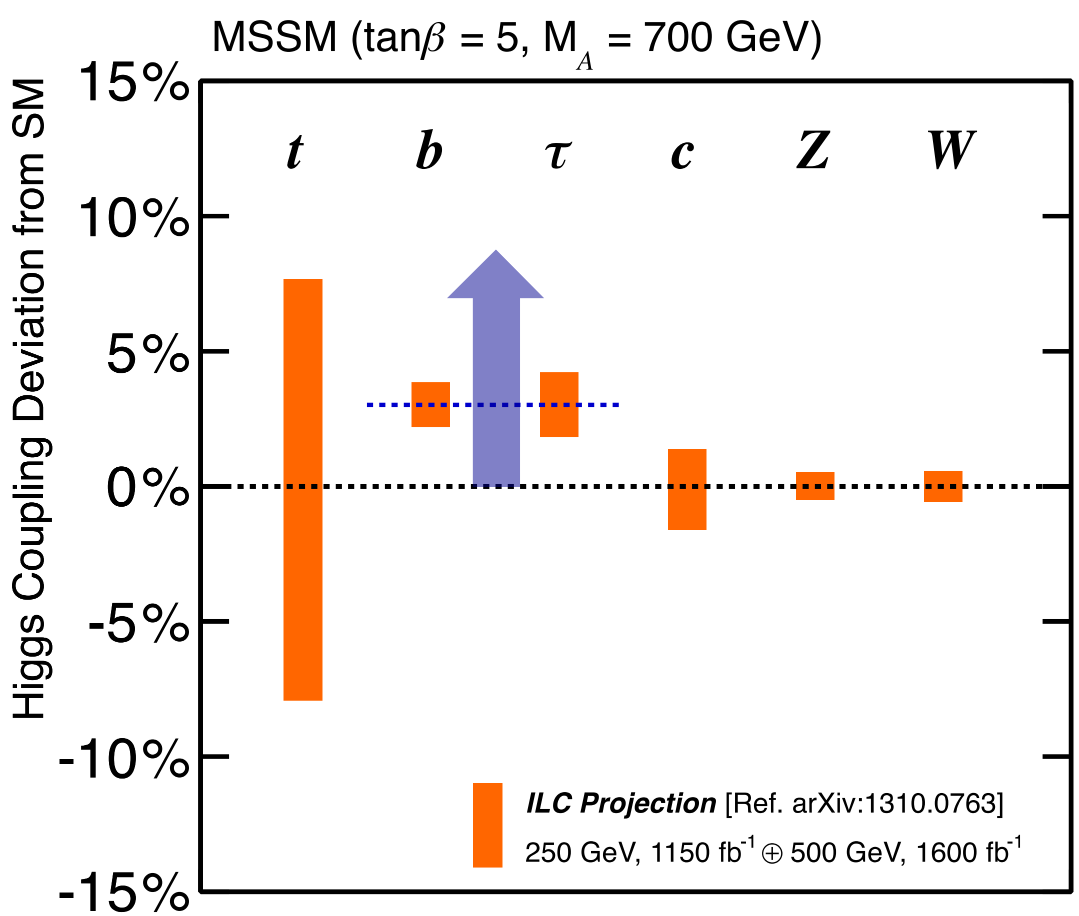
Azatov '15

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

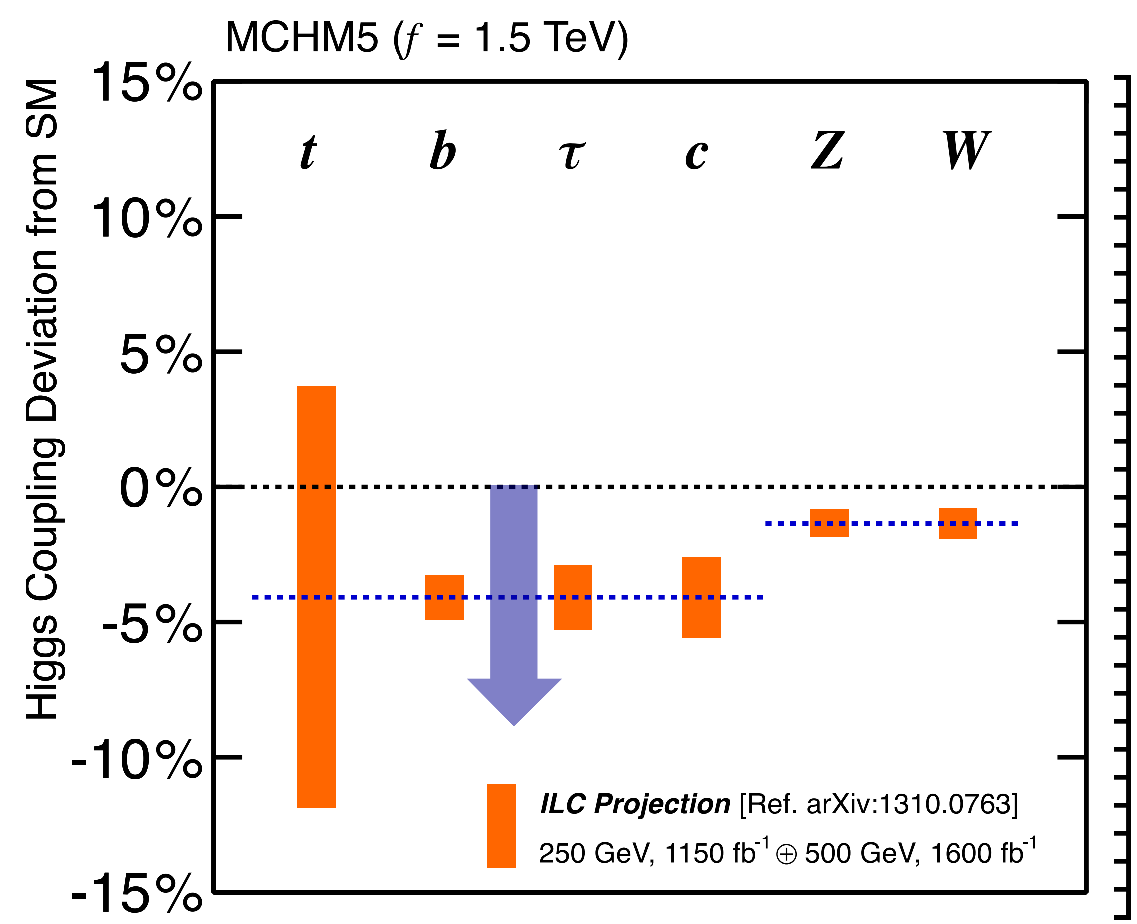
Higgs couplings and model discriminations

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

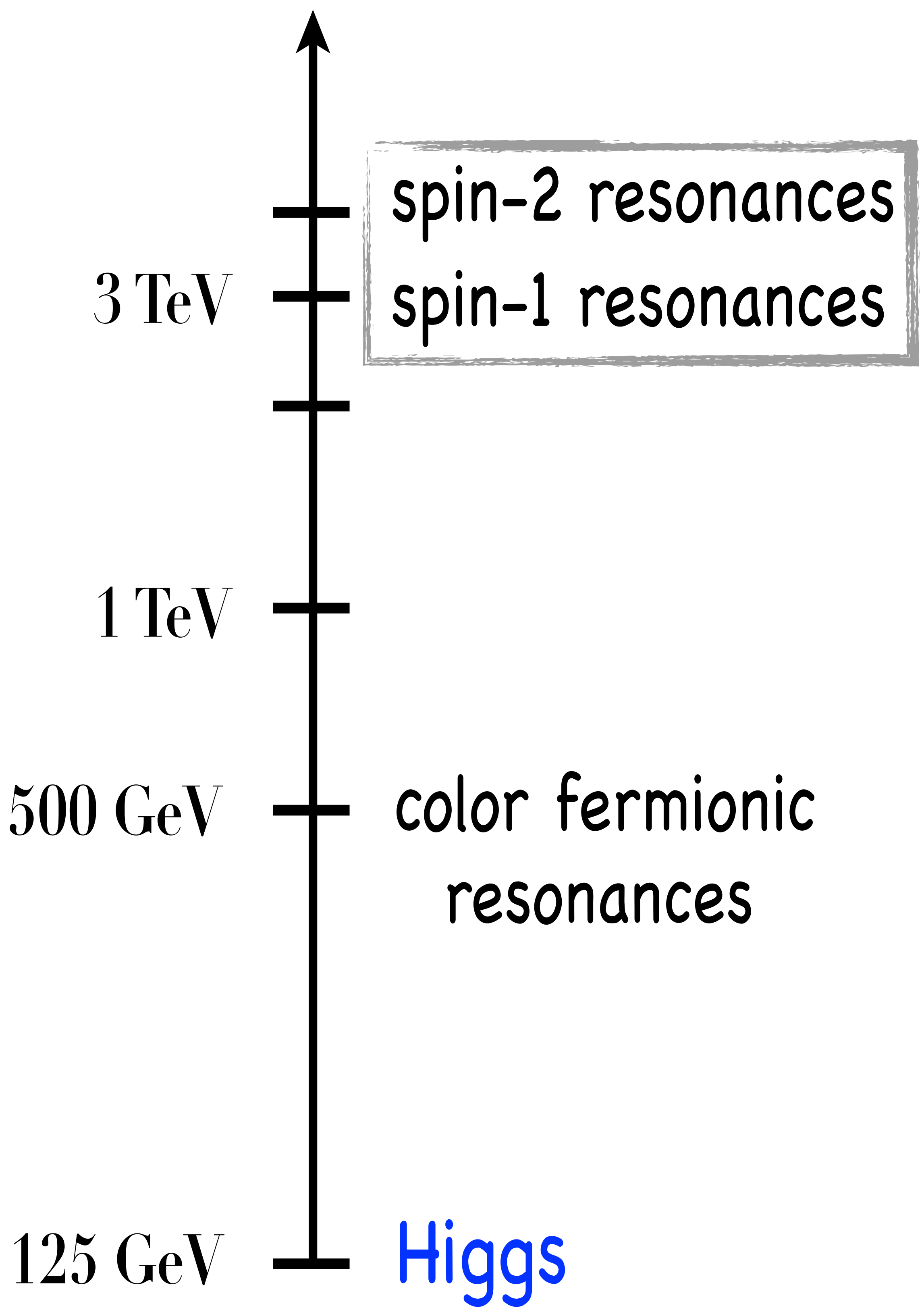
The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

~~ 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

The other resonances



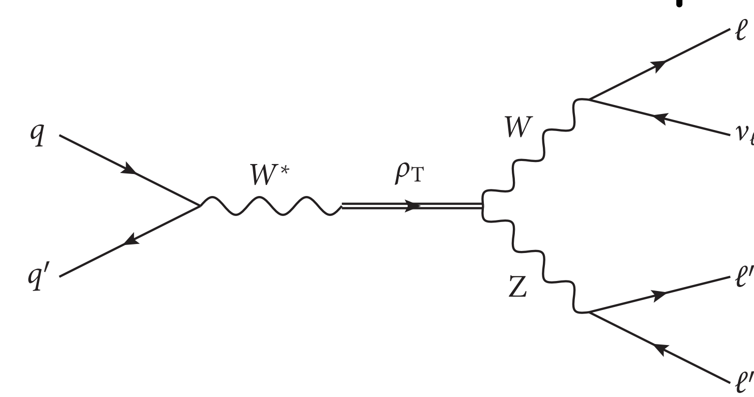
Dominant decays into longitudinal SM gauge bosons

$$\Gamma(\rho^0 \to W^+W^-) \approx \Gamma(\rho^\pm \to ZW^\pm) \approx \frac{m_\rho g^2_{\rho\pi\pi}}{48\pi} = \frac{m_\rho^5}{192\pi g_\rho^2 v^4}$$

Suppressed decays to SM quarks and leptons

$$\mathrm{Br}(\rho^\pm \to e^\pm \nu) \approx 2\mathrm{Br}(\rho^0 \to e^+e^-) \approx \frac{16 m_W^4}{m_\rho^4}$$

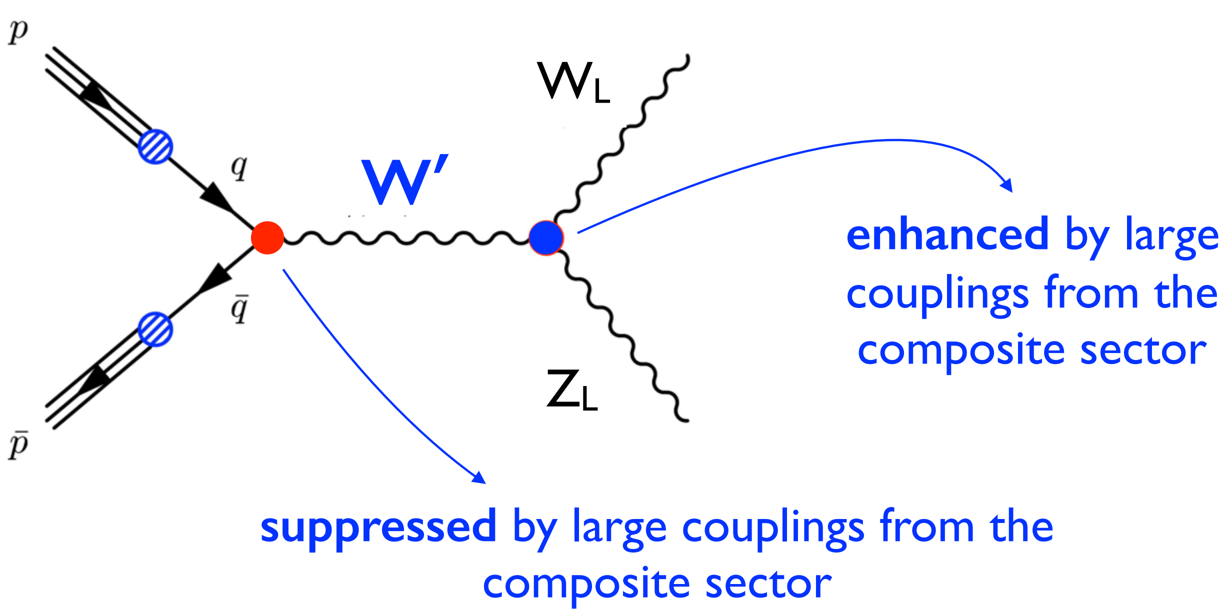
searches in WW, WZ channels in DY processes



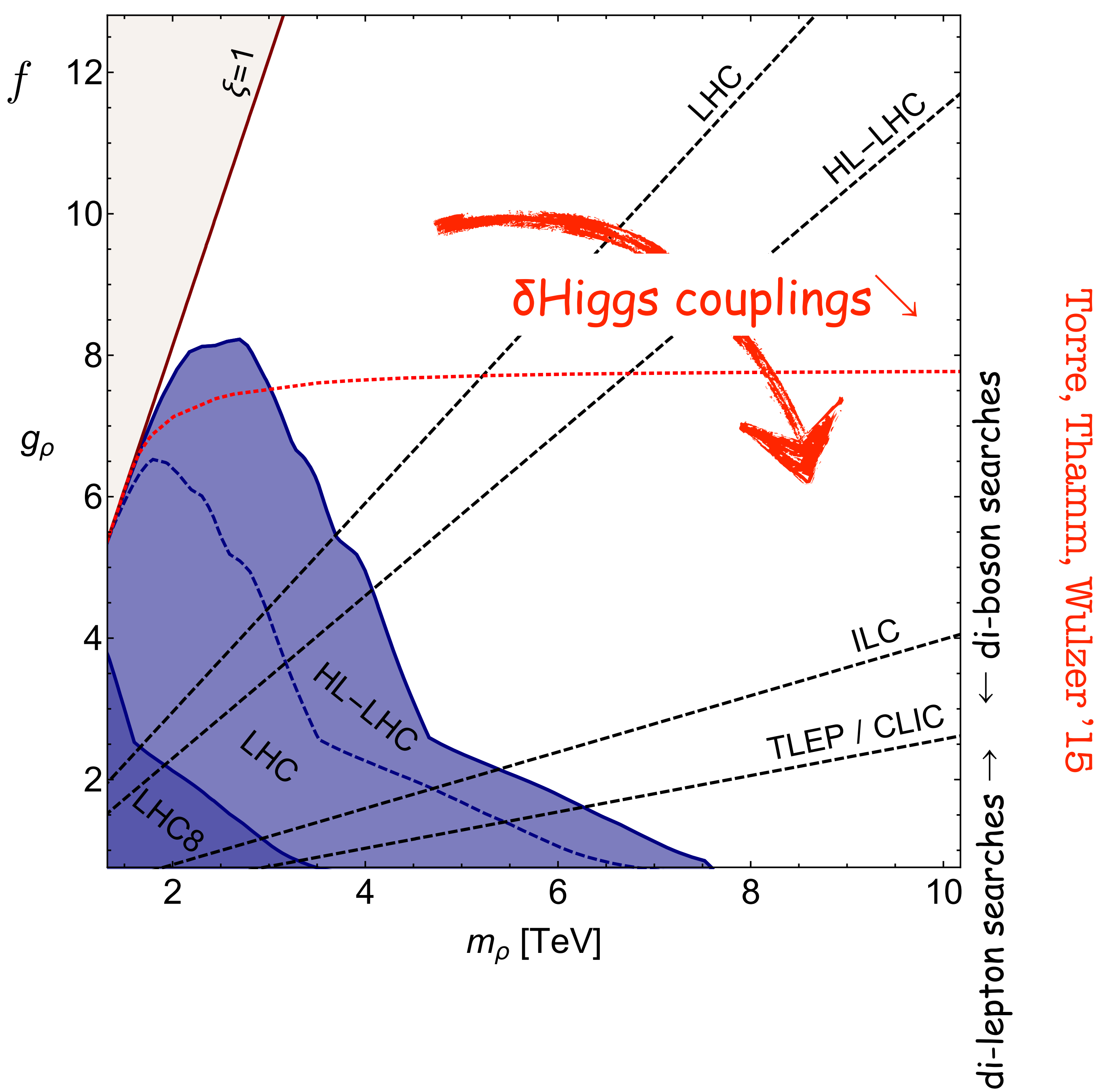
Higgs couplings vs searches for W',Z'

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

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



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



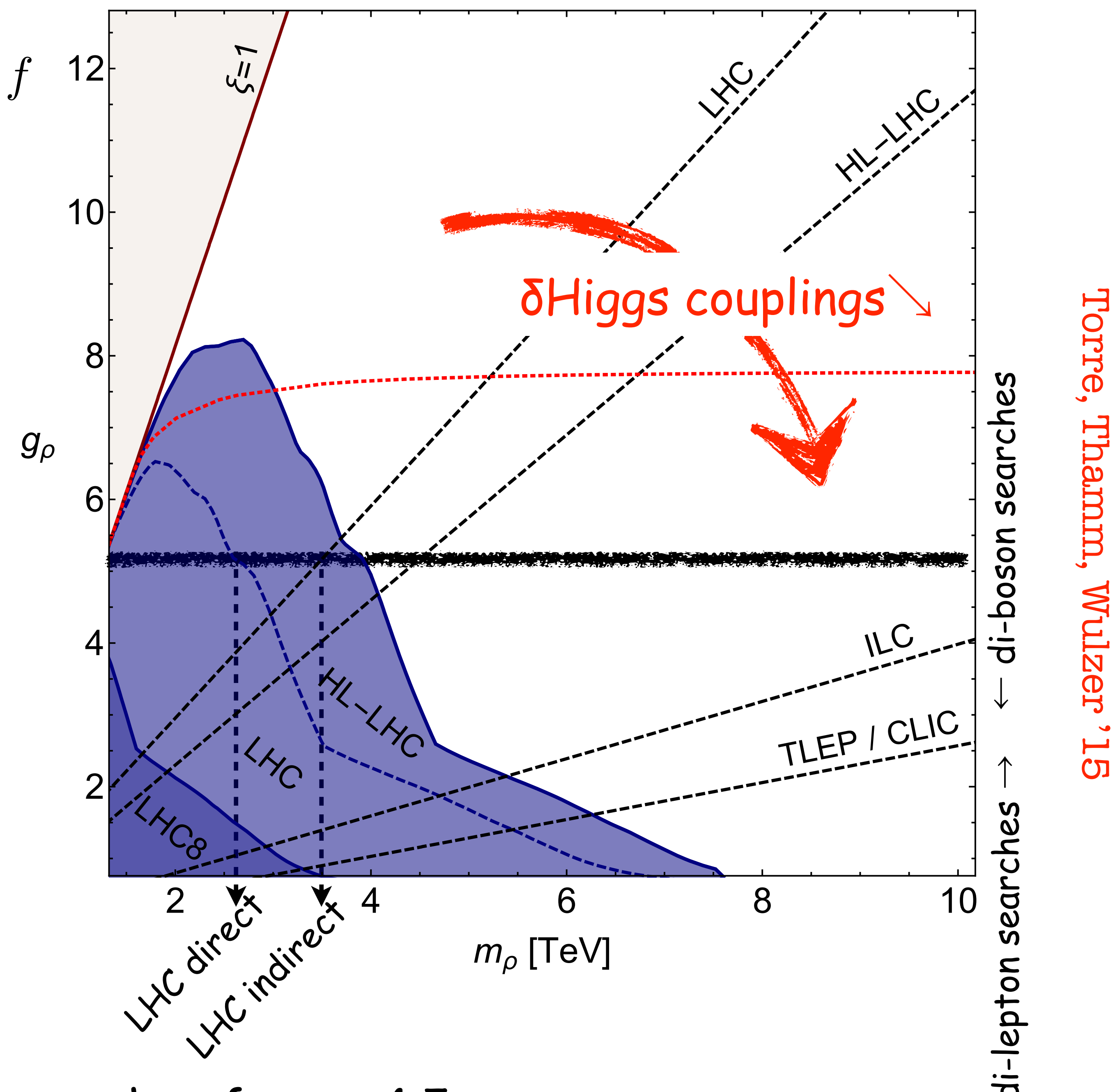
Higgs couplings vs searches for W',Z'

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

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

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

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



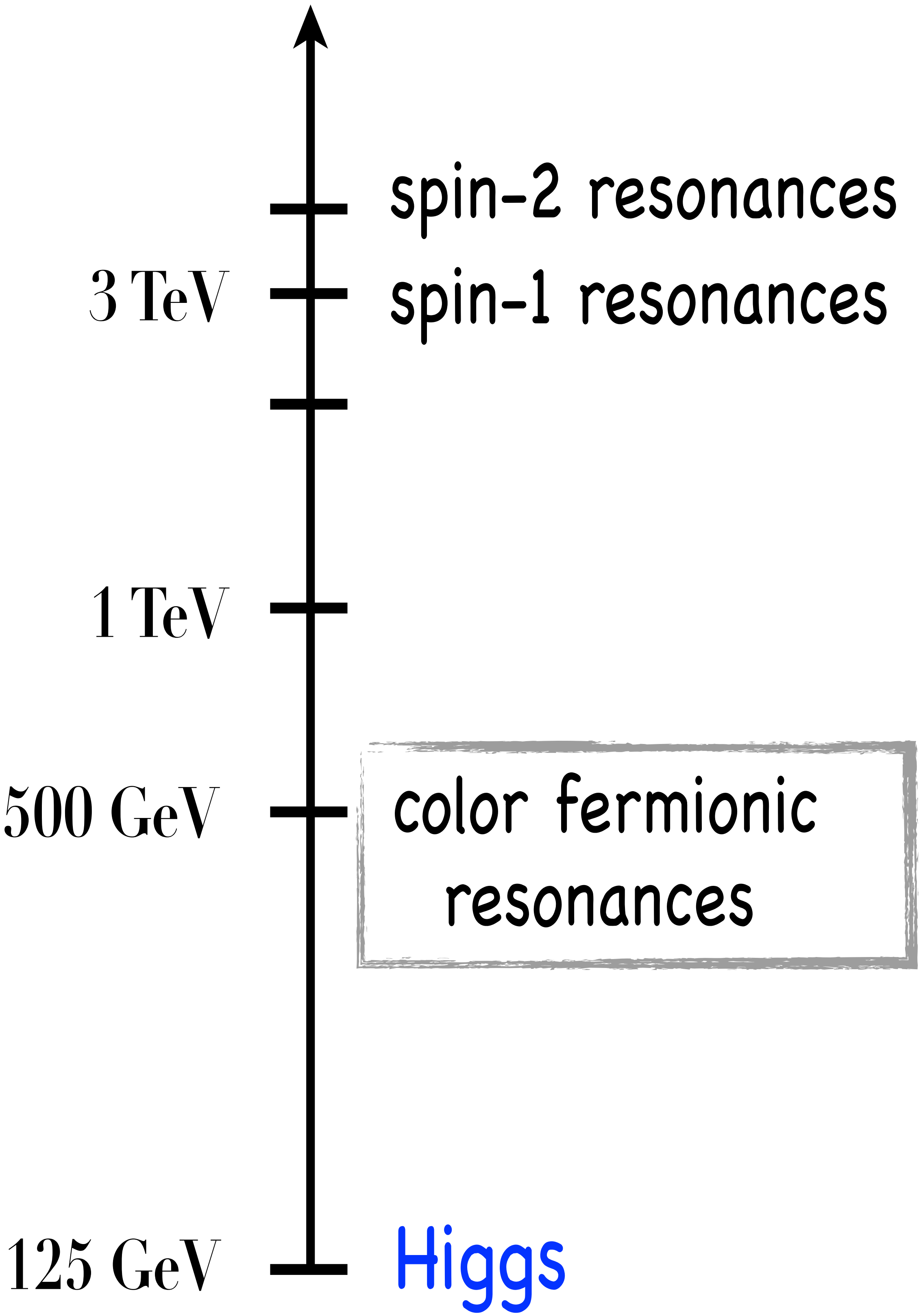
- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

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

The other resonances



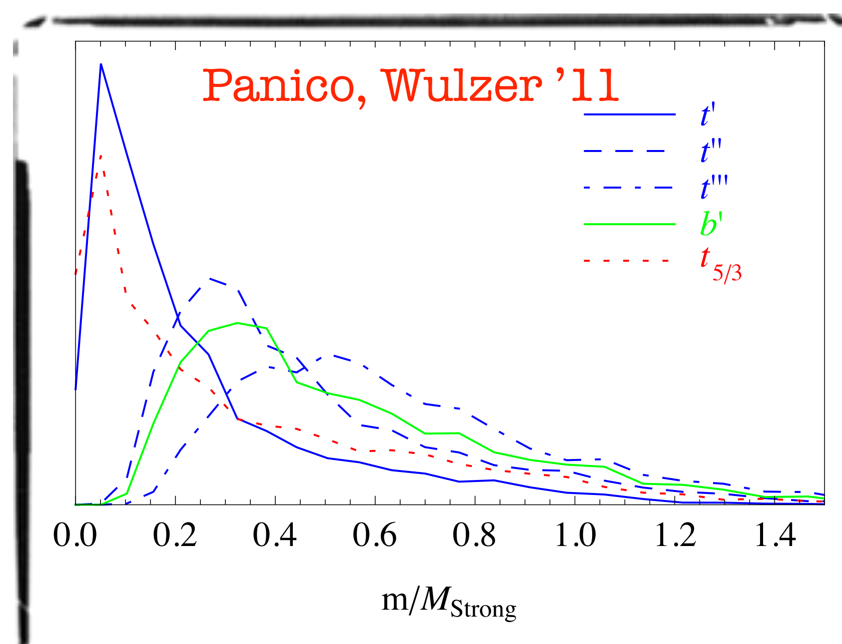
Top partners

SO(4)~SU(2)$_L$xSU(2)$_R$ embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2, \bar{2})_{2/3}$$

$$t_R \equiv (1,1)_{2/3}$$

$$b_R \equiv (1,1)_{-1/3}$$



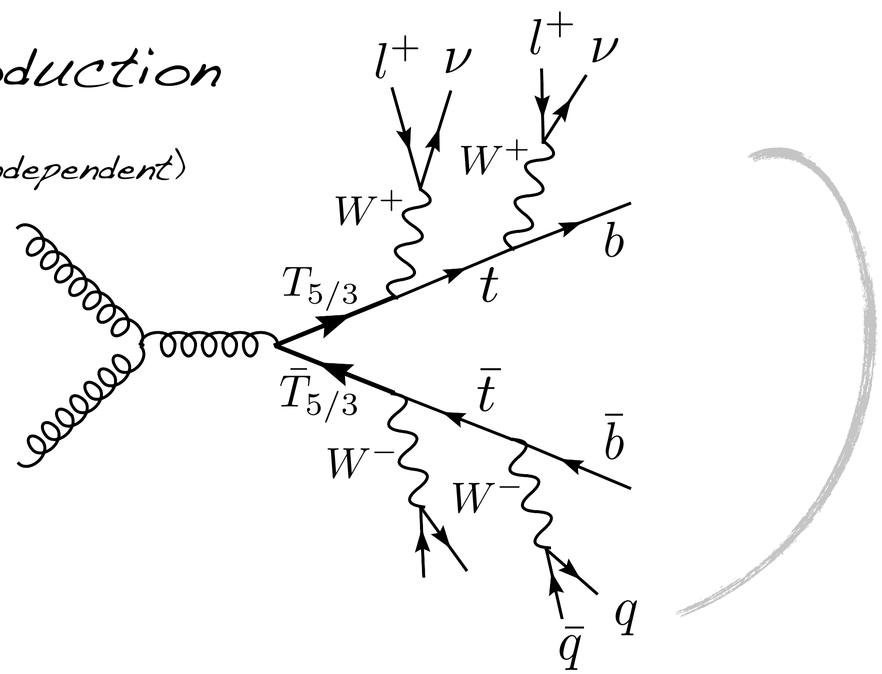
Searching for the top partners

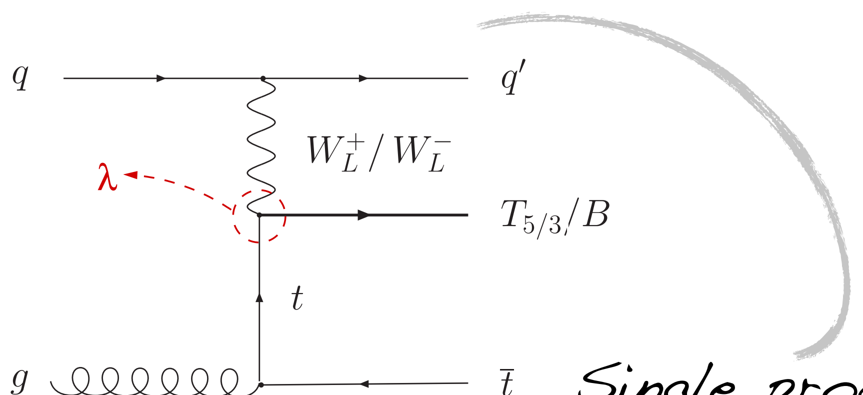
Search in same-sign dilepton events

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

Pair production

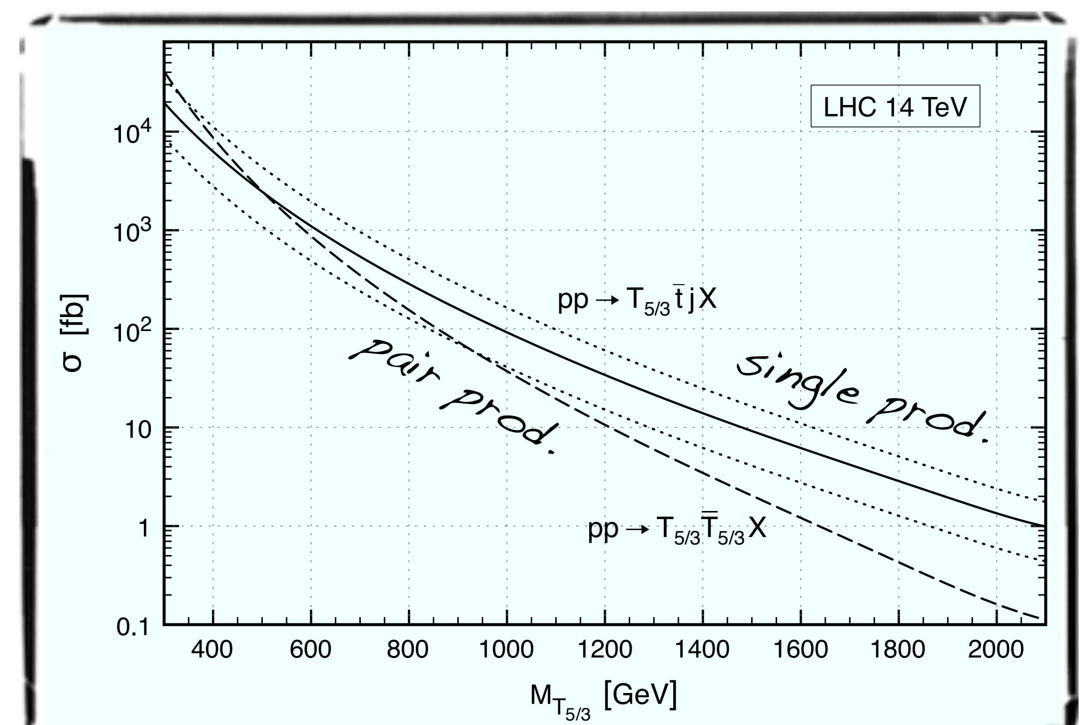
(model independent)





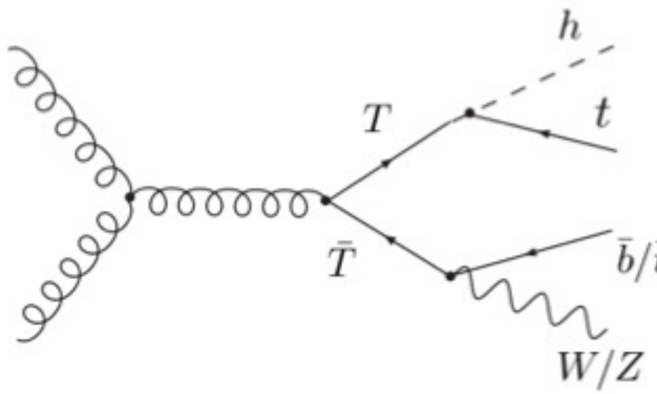
Single production

(model dependent)



[Contino, Servant '08]

Searching for the top partners



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

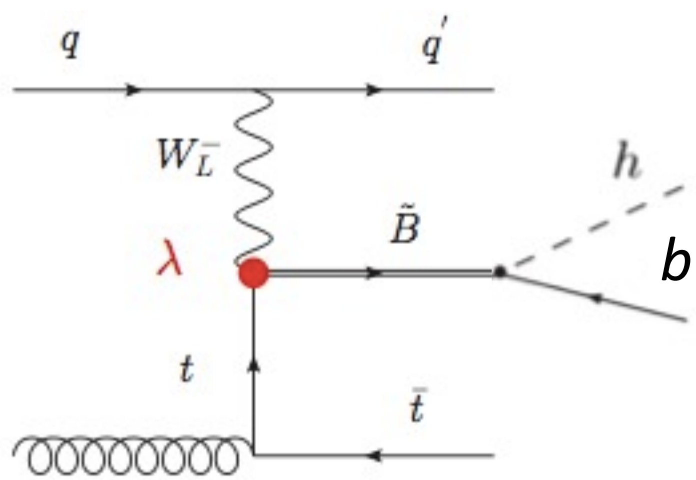
$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^\pm$ + 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

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

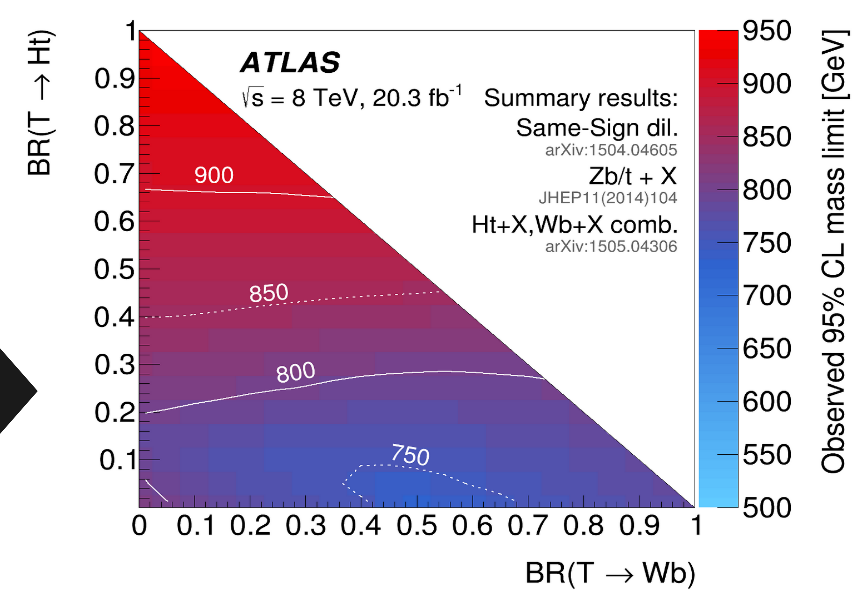


- $\ell^\pm$ + 4b final state Vignaroli '12

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

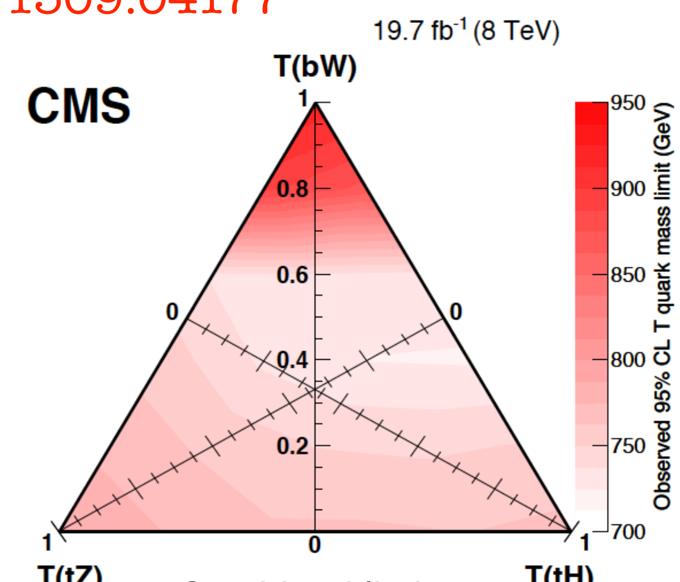
bounds on charge 2/3 states from pair production

1505.04306



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

1509.04177

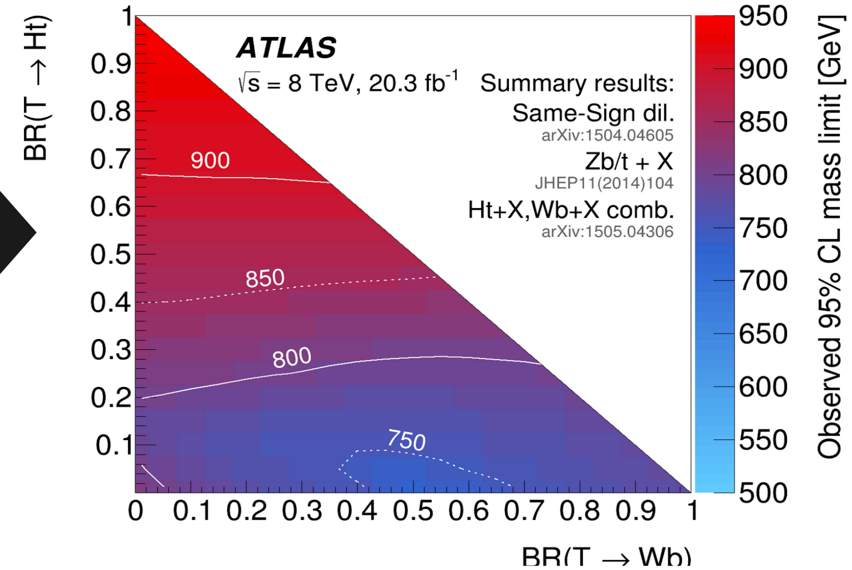


Combined limits

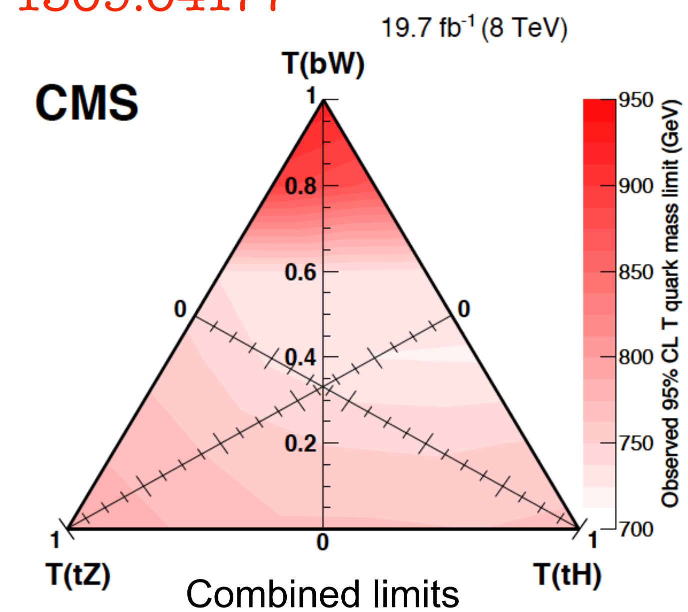
Searching for the top partners

bounds on
charge 2/3 states
from pair production

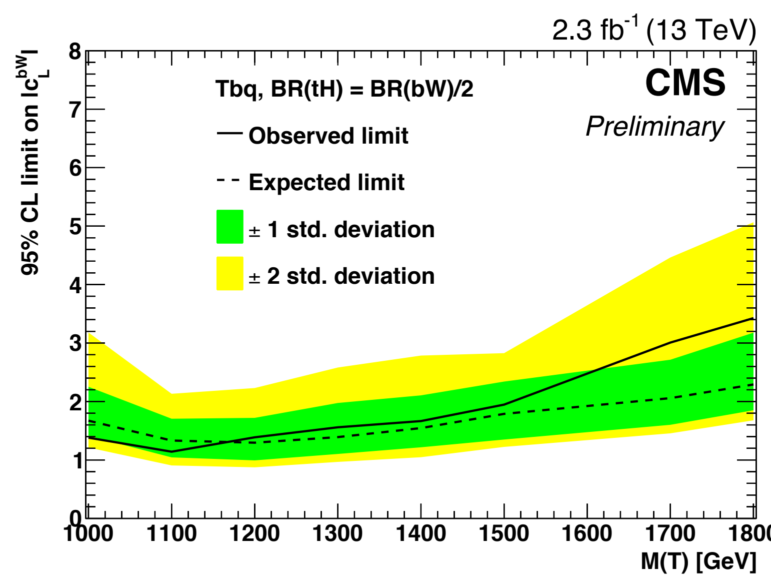
1505.04306

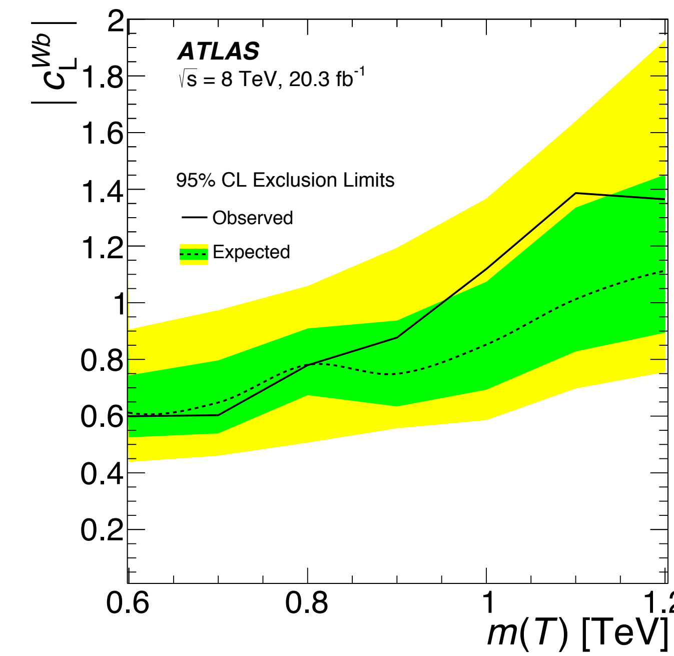


1509.04177

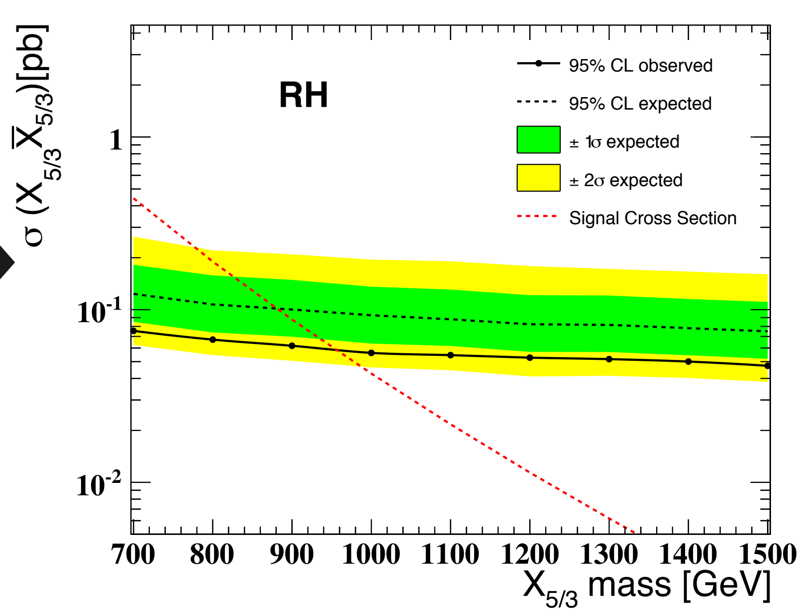


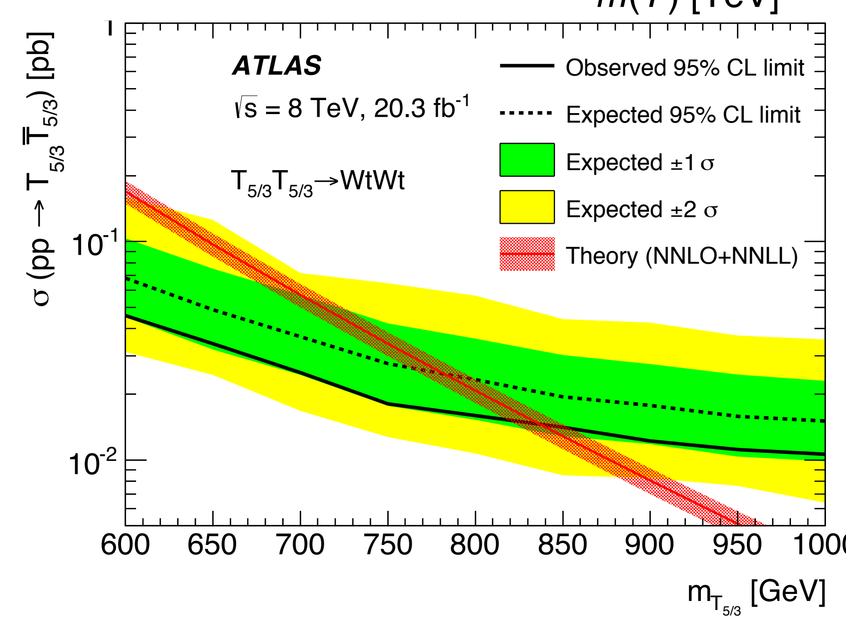
bounds on
charge 2/3 states
from single production





bounds on
charge 5/3 states
from single production





Christophe Grojean