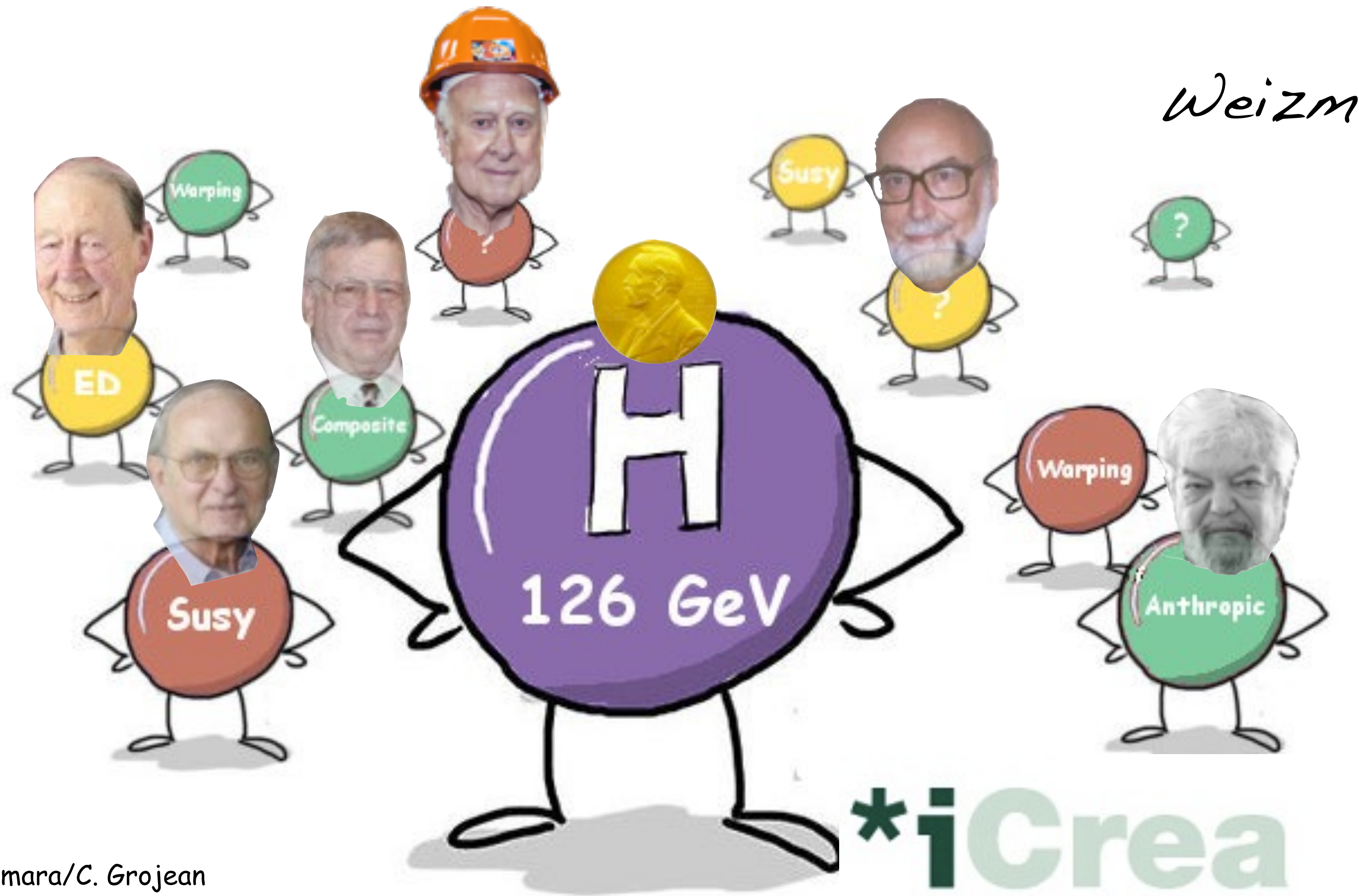
Higgs Physics and the Future

Naturalness 2014

Weizmann Inst. November 16, 2014



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*iCrea
INSTITUCIÓ CATALANA DE
RECERCA I ESTUDIS AVANÇATS

...& the future!

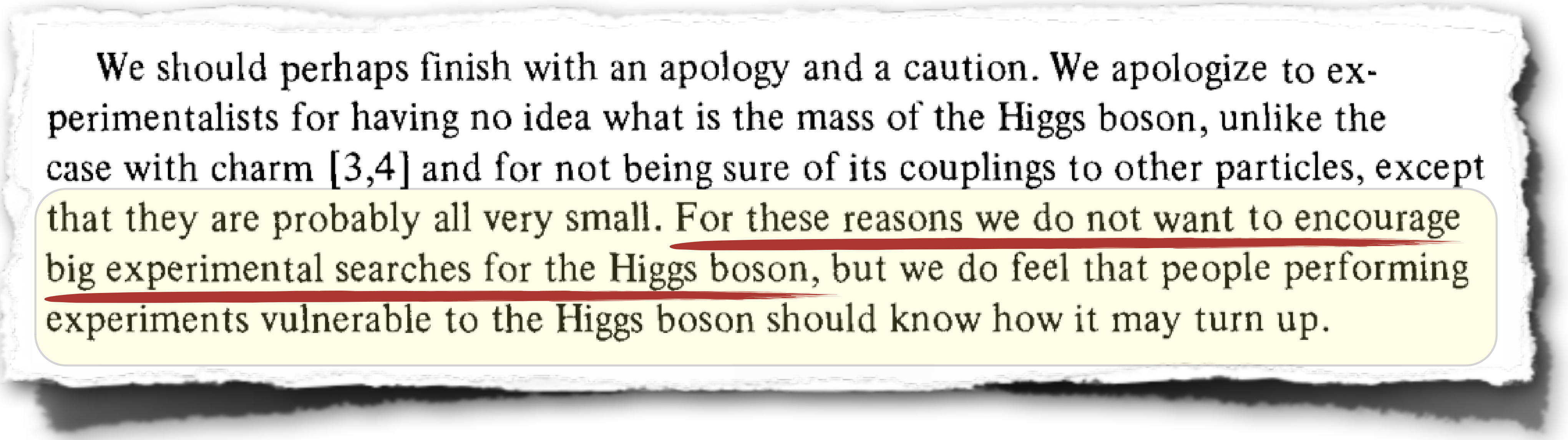
- Take all what I'll say with a grain of salt
  (remember that a few years ago, I was interested in higgsless models...)

- Even great minds can advocate the wrong directions

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

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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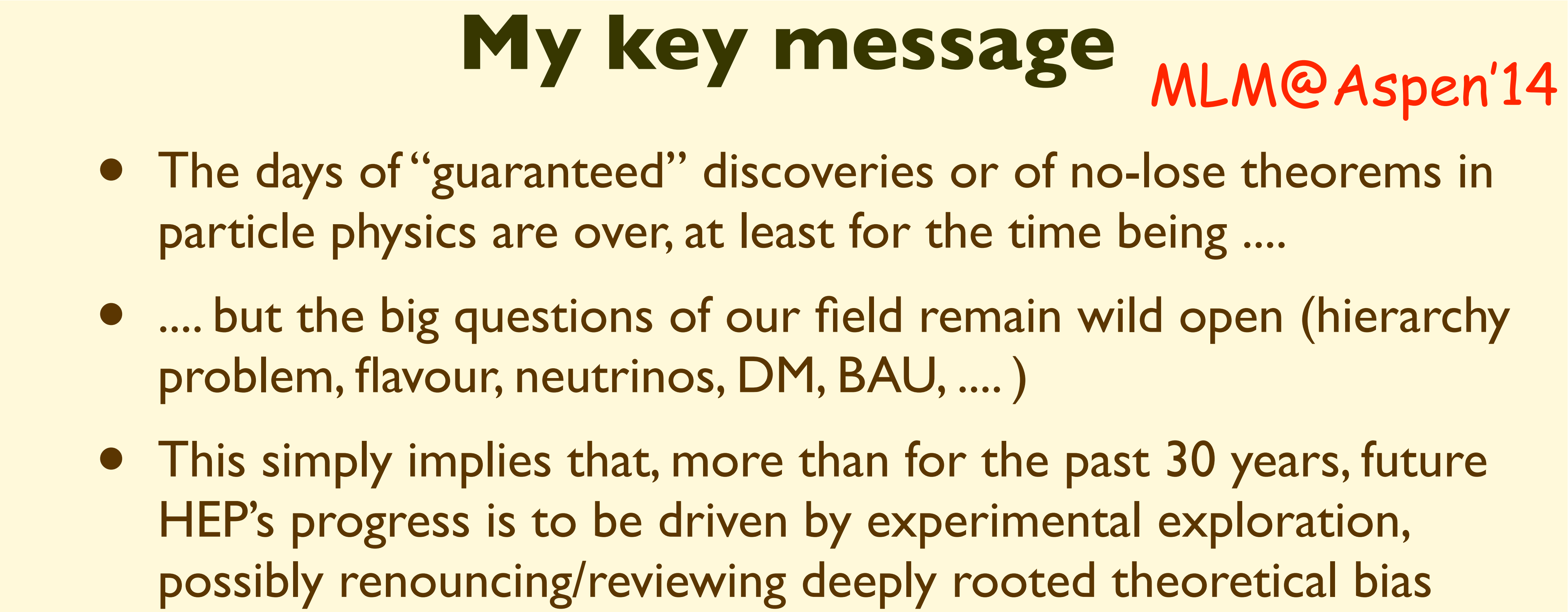

My key message

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?

HEP with a Higgs boson

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

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Now with the Higgs boson in their hands,
particle physicists can... play as well as Germans against Brazilians

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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

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)$_L$xSU(2)$_R$/SU(2)$_V$ $D_\mu \Sigma = g V_\mu$

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

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

For a=1: perturbative unitarity in elastic channels WW → WW

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

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

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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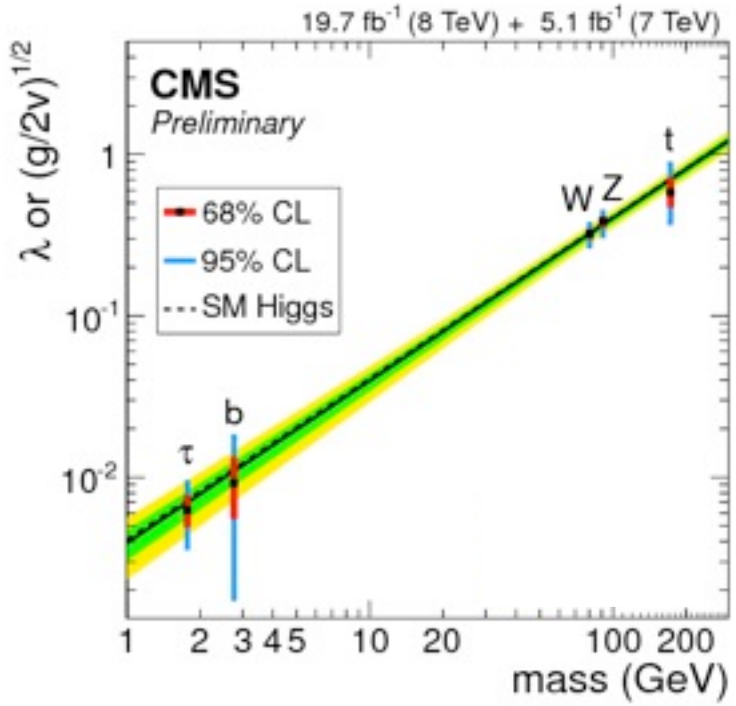

CMS PAS-HIG-14-009

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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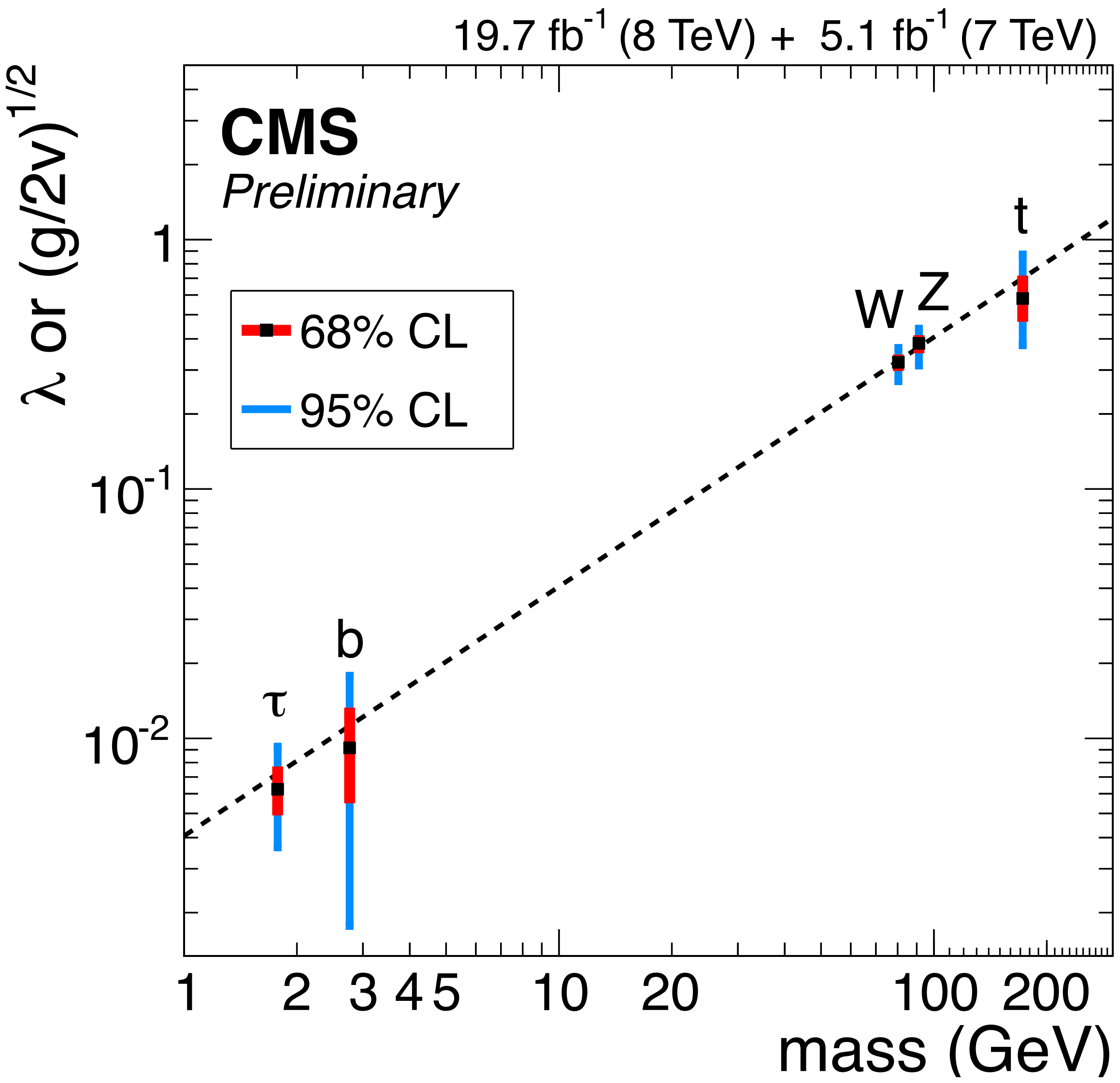

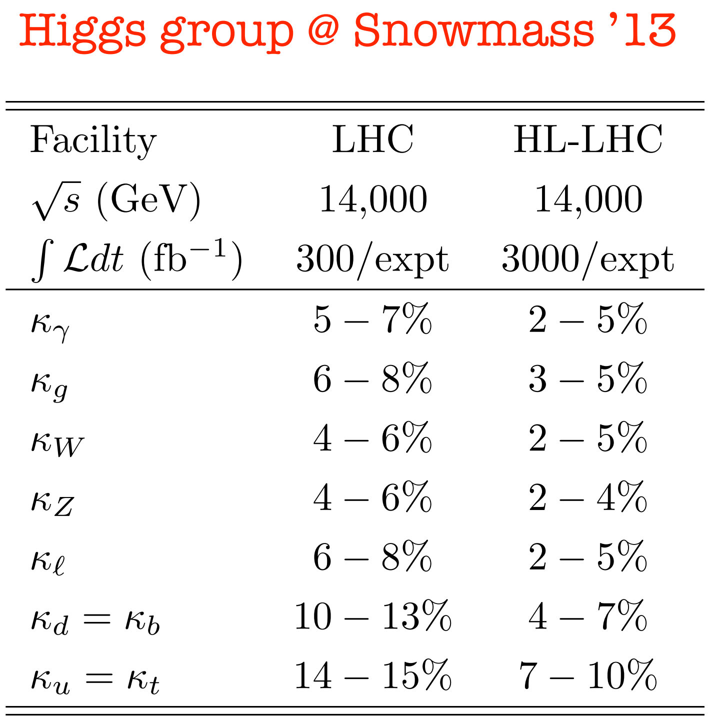

Higgs group @ Snowmass '13

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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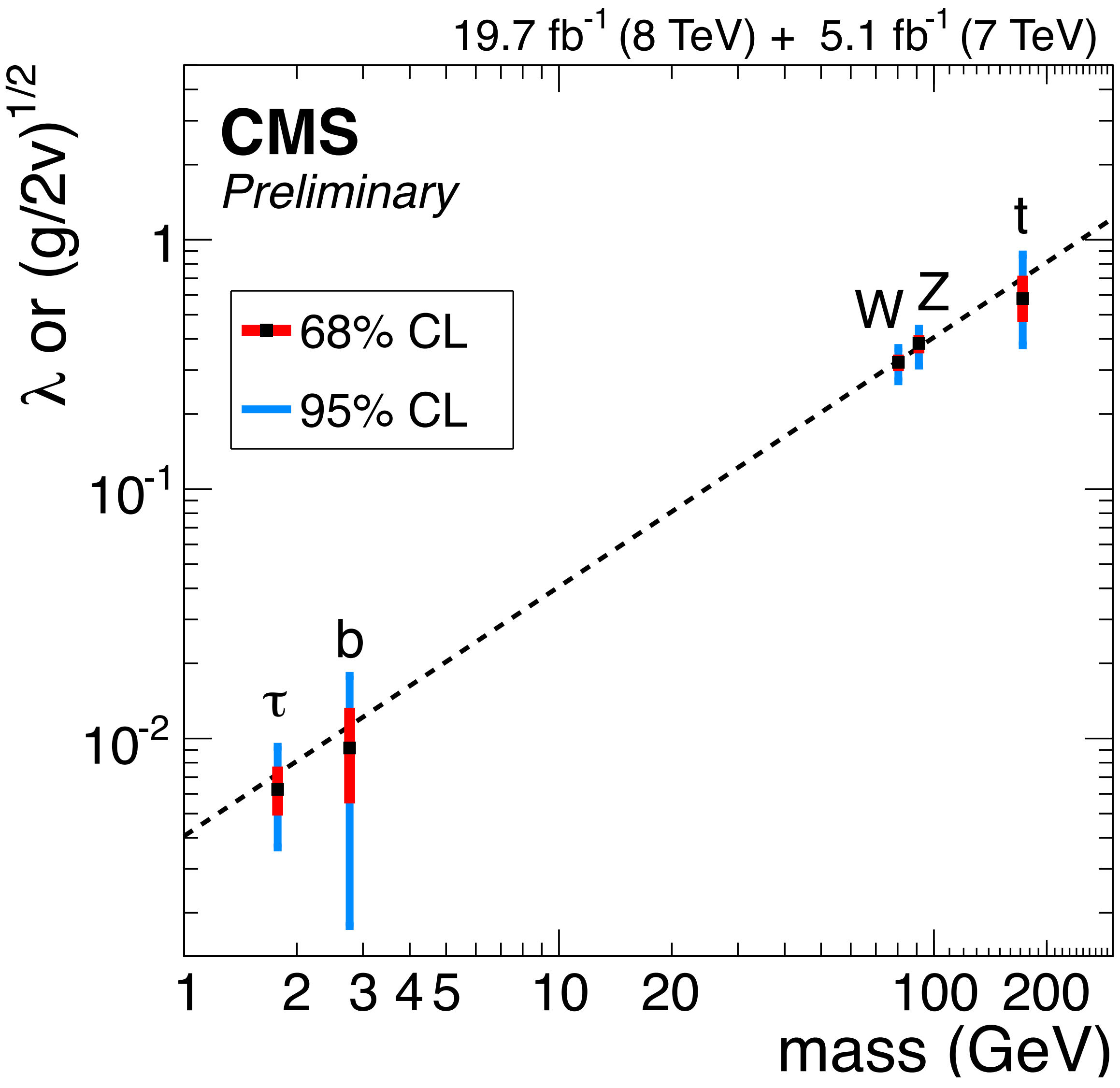

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missing information to complete the picture

° width measurement?

° couplings to light particles?

inclusive (e.g. c-tagging) or exclusive (h → J/Ψ+γ)

° coupling to top?

known indirectly (gg→h) or via difficult tth channel

Higgs and Flavor

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass

higgs-fermion interactions

both matrices are simultaneously diagonalizable

⇓ ⇓ ⇓

no tree-level Flavor Changing Current induced by the Higgs

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Not true anymore if the SM fermions mix with vector-like partners $^{(*)}$ or for non-SM Yukawa

$$y_{ij}\left(1+c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\left(1+c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i}f_{R_j} + \left(1+3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

$^{(*)}$ e.g. Buras, Grojean, Pokorski, Ziegler '11

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$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \underbrace{\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{L_i} f_{R_j}}_{\text{mass}} + \underbrace{\frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}}_{\text{higgs-fermion interactions}}$$

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Look for SM forbidden Flavor Violating decays h → μτ and t→hc

- weak indirect constrained by flavor data (e.g. μ→ eγ): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

Blankenburg, Ellis, Isidori ’12

Harnik et al ’12
Davidson, Verdier ’12
CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler ’11

Higgs and Flavor

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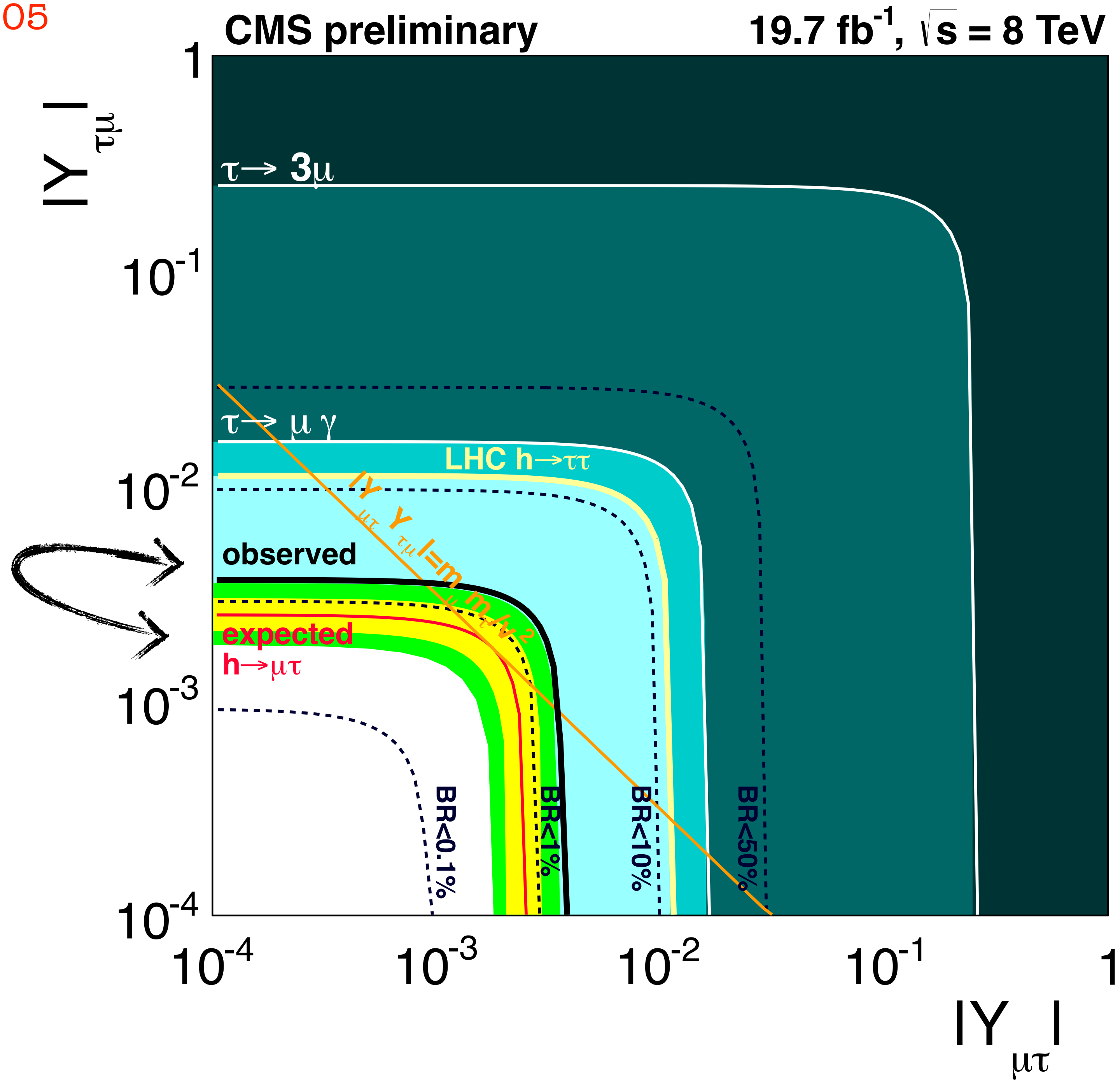
CMS-PAS-HIG-2014-005

by the way:
2.3σ excess!



Off-diagonal Higgs couplings can reveal the origin of flavor

The interesting models of flavor ($Y_{ij}\approx\sqrt{(m_i m_j/v^2)}$) start being probed by the experimental data

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

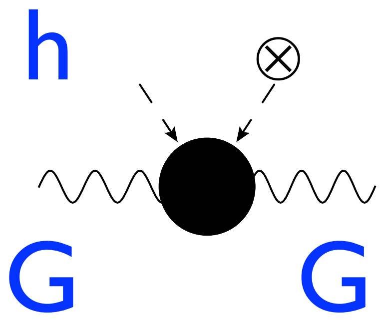
(courtesy of A. Pomarol@HiggsHunting2014)

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)

see A. Pomarol's talk

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)

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_h $|H|^6$ $\longrightarrow$ **h^3 coupling**

m_f $|H|^2 \bar{f}_L H f_R + h.c.$ $\longrightarrow$ **htt, hbb, hττ**

(f=t,b,τ)

yet to be measured at the LHC

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

(courtesy of A. Pomarol@HiggsHunting2014)

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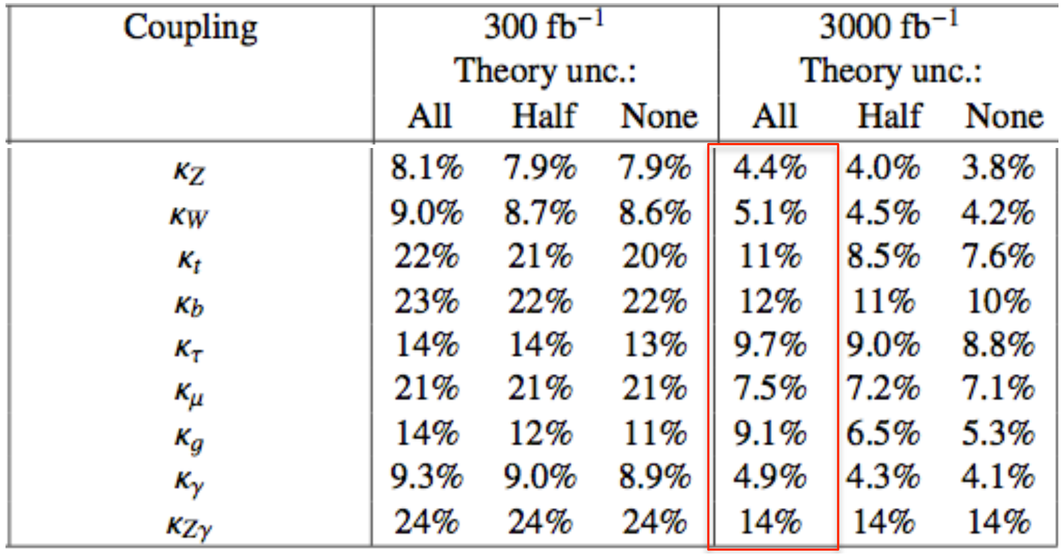
Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit



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

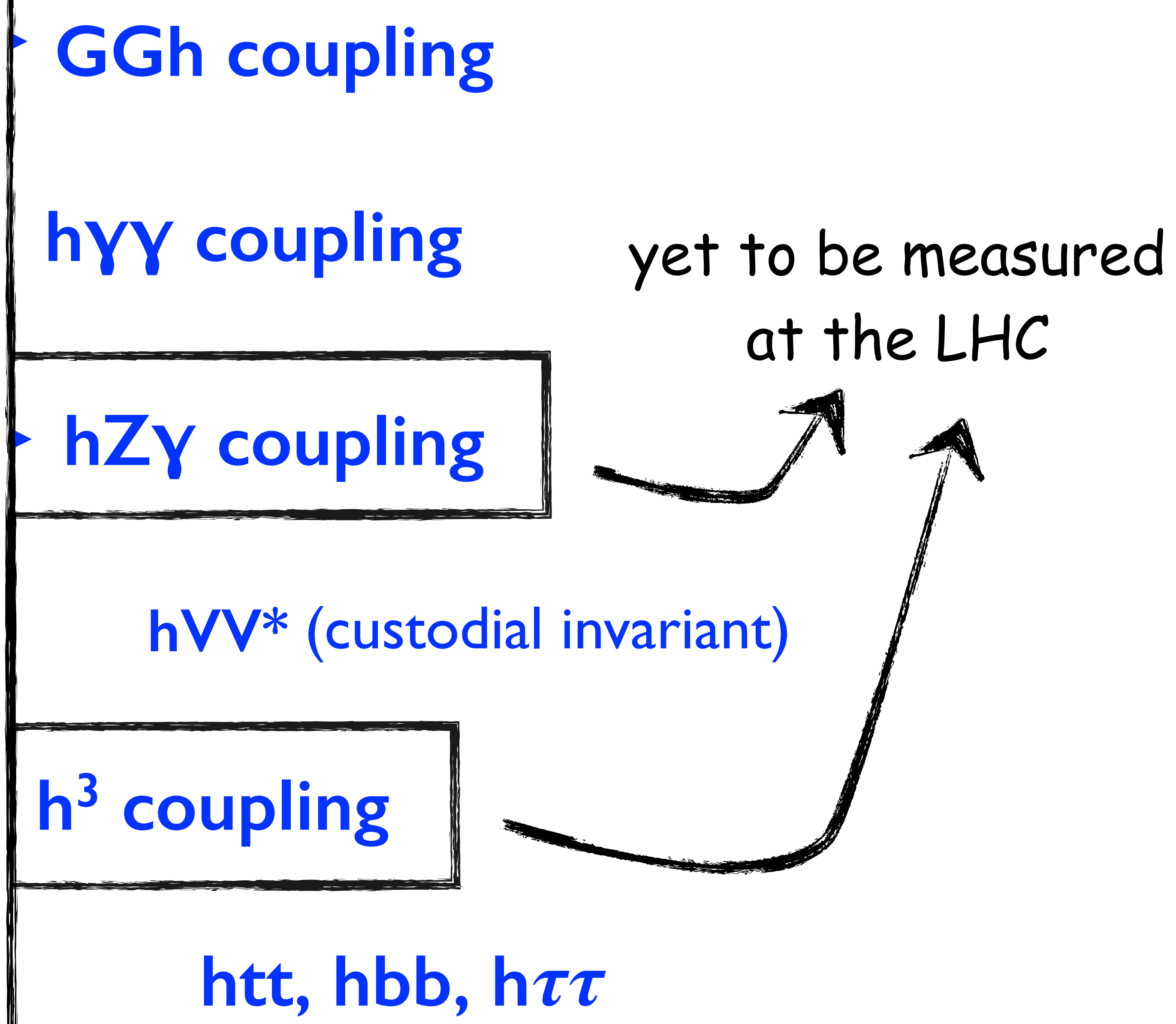
2) κ_W/κ_Z is not a primary

(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

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

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

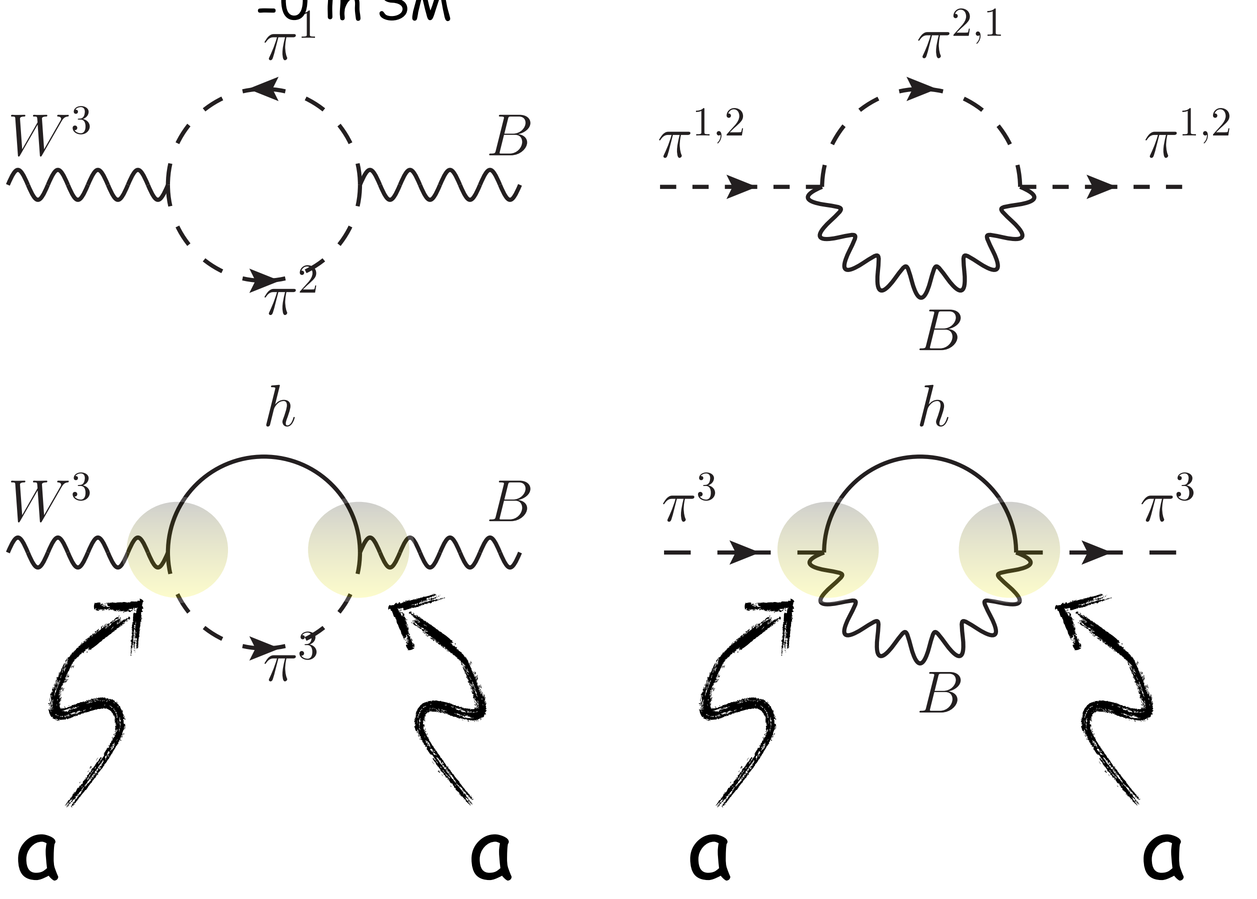
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\,a^2\log(m_h^2/\mu^2) - c_{1,3}\boxed{(1-a^2)}\log(m_\rho^2/\mu^2) + \text{finite terms}$$

=0 in SM

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

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07



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

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

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07

EW fit:

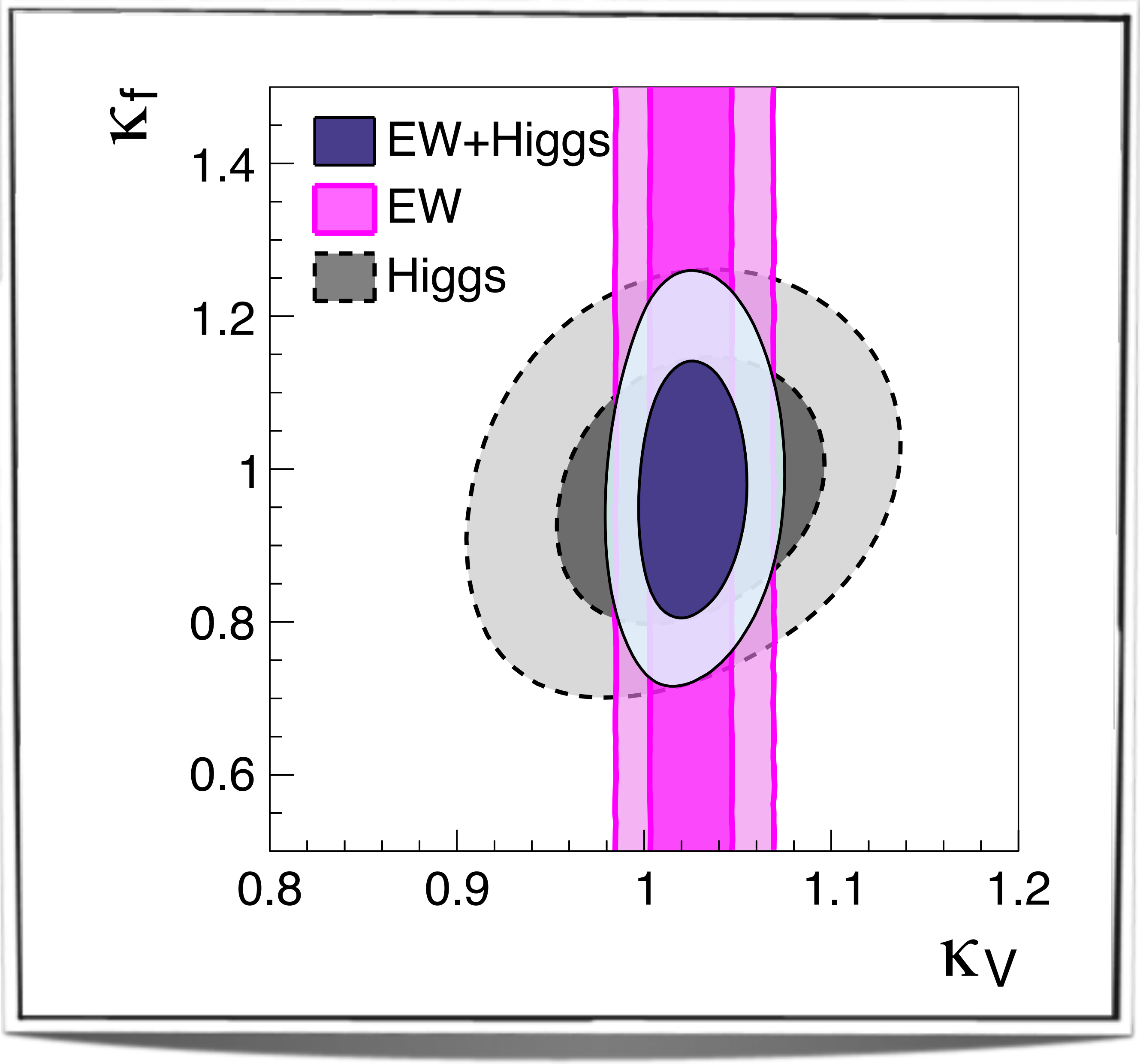
$$0.98 \leq a^2 \leq 1.12$$

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

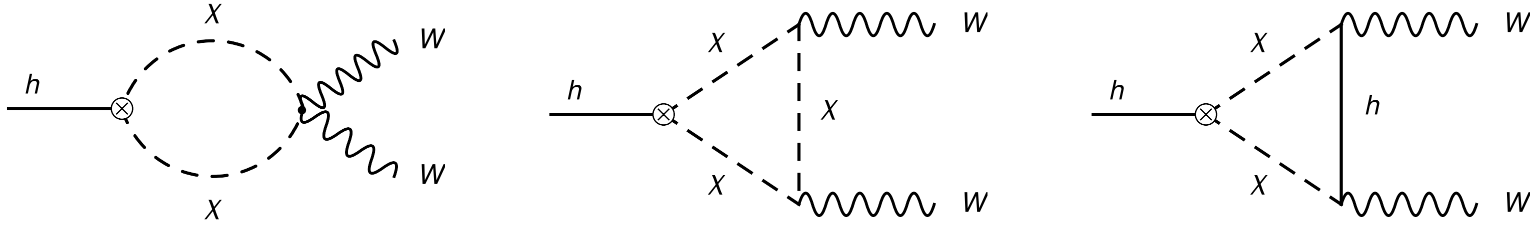


Ciuchini et al '13

LEP+LHC: an RG story

Anomalous hVV couplings (a≠1) is associated to the dimension-6 operator $(\partial_\mu |H|^2)^2$

it RG-mixes with other operators contributing to EW oblique parameters



$$\frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{i\bar{c}_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mu\frac{d}{d\mu}\left(\begin{array}{c} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{array}\right) = \frac{\alpha}{4\pi}\,\gamma\left(\begin{array}{c} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{array}\right) \quad \text{with} \quad \gamma^{(0)}_{ij} = \left(\begin{array}{ccc} 0 & 0 & 0 \\ -1/6 & 0 & 0 \\ 0 & 0 & 0 \end{array}\right)$$

RG-bounds on EW/Higgs data

Elias-Miro, Grojean, Gupta, Marzocca '13

$$\mathcal{O}^{\rm obs}_{i|{\rm EW}} = \mathcal{O}^{\rm obs}_{i|{\rm UV}} + \Delta\mathcal{O}^{\rm obs}_{i|{\rm RG}}\left(\mathcal{O}^{\rm obs}_{j|{\rm EW}}, \Lambda\right)$$

absence of fine-tuning:

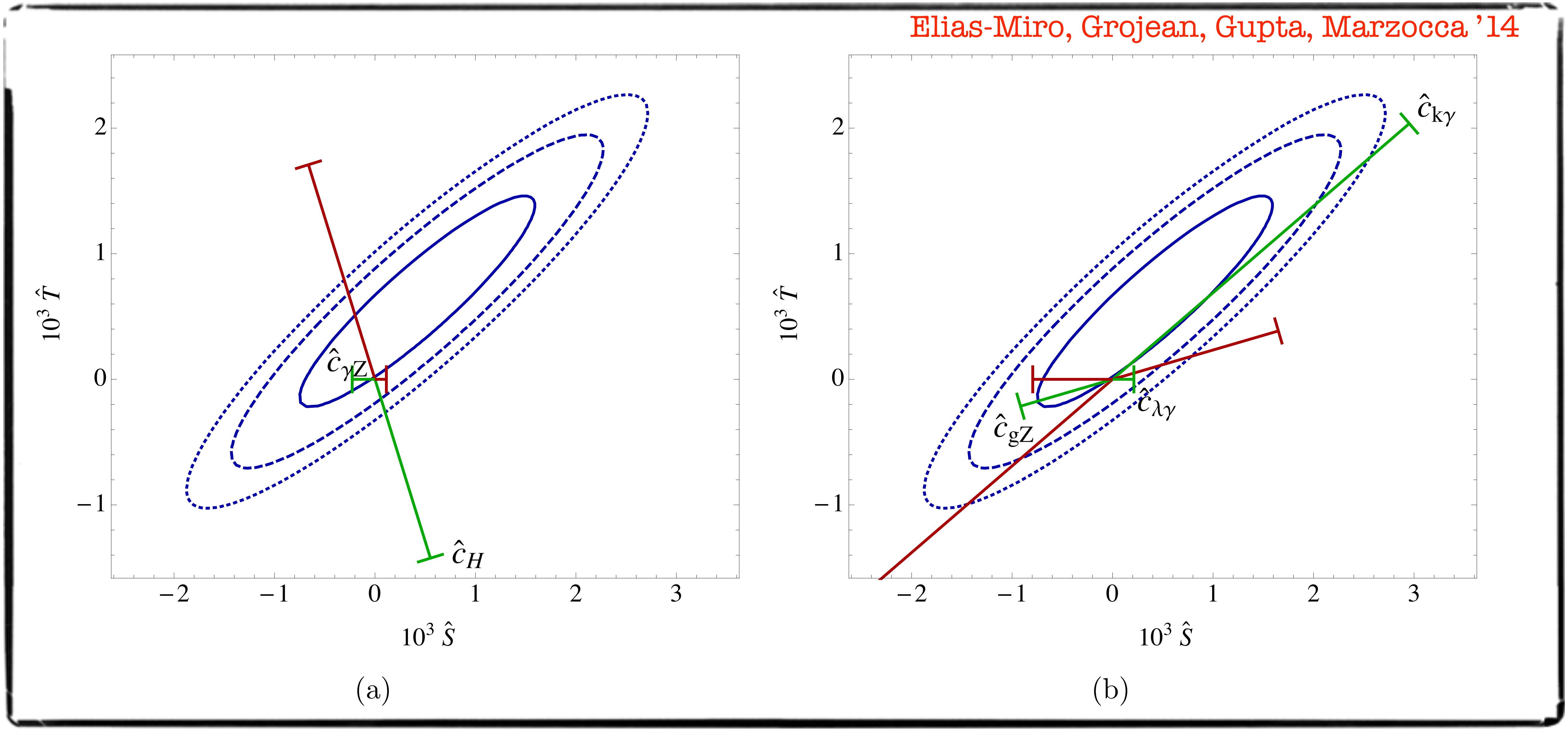
$$\left|\mathcal{O}^{\rm obs}_{i|{\rm UV}} - \mathcal{O}^{\rm SM}_{i|{\rm EW}}\right| < \epsilon_i^{\rm exp}$$

$$\left|\Delta\mathcal{O}^{\rm obs}_{i|{\rm RG}} - \mathcal{O}^{\rm SM}_{i|{\rm EW}}\right| < \epsilon_i^{\rm exp} \quad \Leftrightarrow \quad \mathcal{O}^{\rm obs}_{i|{\rm EW}} < \mathcal{E}_i\left(\epsilon_j^{\rm exp}, \Lambda\right)$$

Particularly relevant to bound the operators "poorly constrained" at tree-level through their mixing with operators "strongly constrained" at tree-level

	hVV ⇄	S, T	
tree-level constraints	O(20%)	O(1‰)	
	O(5%)	O(1‰)	one-loop constraints (Λ~3TeV)

RG-bounds on EW/Higgs data



(a) (b)

The blue ellipses represent the 68% (solid), 95% (dashed) and 99% (dotted) CL bounds on S and T.
The straight lines represent the RG-induced contribution to the oblique parameters
from the weakly constrained observable couplings, divided in Higgs couplings (a) and TGC couplings (b).
The length of the lines corresponds to their present 95% CL direct bounds.

EW/Higgs data: the TLEP improvement

LEP: 10^6 Z's ➠ TLEP: 10^{12} Z's

TLEP (physics case) '13

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Ratio TLEP/LEP
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6)	< 100	20
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{\rm had}$)	2495200 ± 2300	Z Line shape scan	8 (10)	< 100	20
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	25
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004	
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	10
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{\rm had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	100
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{\rm had}$	80385 ± 15	WW threshold scan	0.3 (0.4)	< 0.5	3
$m_{\rm top}$ (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12)	< 10	100

Table 9. Selected set of precision measurements at TLEP. The statistical errors have been determined with *(i)* a one-year scan of the Z resonance with 50% data at the peak, leading to 7×10^{11} Z visible decays, with resonant depolarization of single bunches for energy calibration at O(20min) intervals; *(ii)* one year at the Z peak with 40% longitudinally-polarized beams and a luminosity reduced to 20% of the nominal luminosity; *(iii)* a one-year scan of the WW threshold (around 161 GeV), with resonant depolarization of single bunches for energy calibration at O(20min) intervals; and *(iv)* a five-years scan of the $t\bar{t}$ threshold (around 346 GeV). The statistical errors expected with two detectors instead of four are indicated between brackets. The systematic uncertainties indicated below are only a "first look" estimate and will be revisited in the course of the design study.

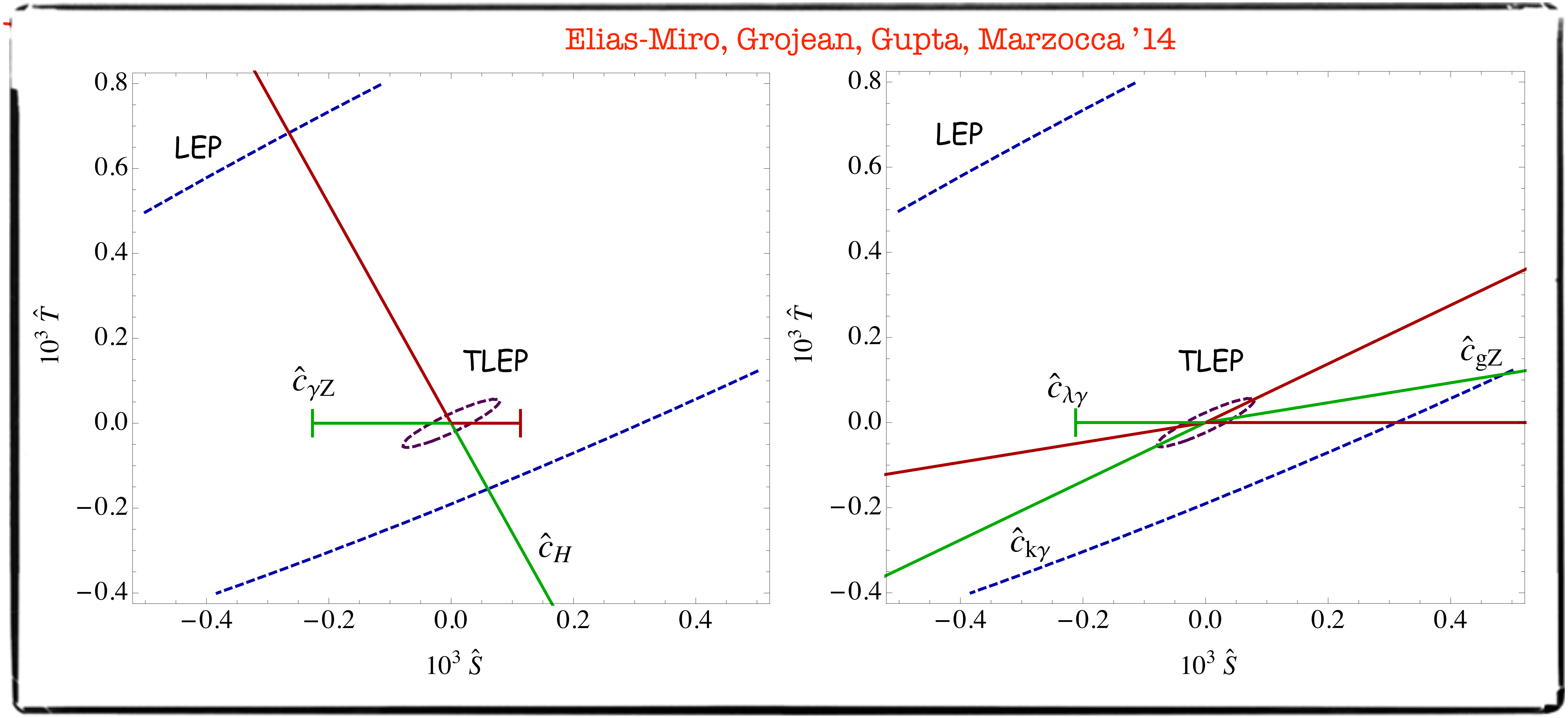
1 order of magnitude in TGC
1-2 orders of magnitude in Higgs couplings

⇨

can probe tuning/correlations
between various contributions

EW/Higgs data: the TLEP improvement

LEP: 10^6 Z's ➠ TLEP: 10^{12} Z's



O(20-30) improvement in EW oblique parameters measurement

1 order of magnitude in TGC
1-2 orders of magnitude in Higgs couplings ⇨ can probe tuning/correlations between various contributions

CP violation in Higgs physics?

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

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

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

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

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} = \; & i\delta\tilde{g}_{hff}\, h\bar{f}_L f_R + h.c. && \text{(f=b, }\tau\text{, t)} \\
& + \tilde{\kappa}_{GG}\frac{h}{v} G^{\mu\nu}\tilde{G}_{\mu\nu} && (\, \tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma} \,) \\
& + \tilde{\kappa}_{\gamma\gamma}\frac{h}{v} F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu} \\
& + \tilde{\kappa}_{\gamma Z}\frac{h}{v} F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}
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$$

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(f=b, τ, t)

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($\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$)

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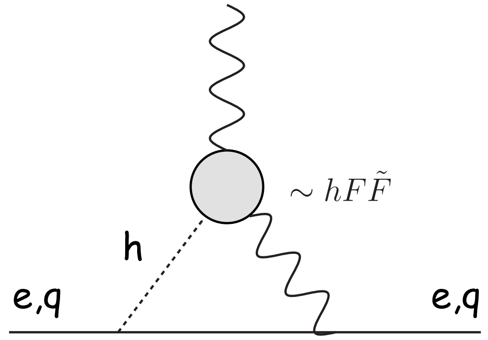
operators with γ:

already severely constrained by e and q EDMs

McKeen, Pospelov, Ritz '12



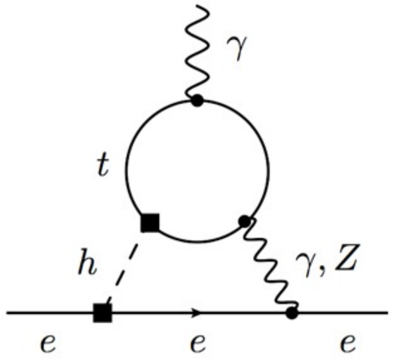
$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

$\Lambda_{\cancel{\text{C}}\text{P}}$ > 25 TeV

operators with top:

already severely constrained by e and q EDMs

Brod, Haisch, Zupan '13



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

$\Lambda_{\cancel{\text{C}}\text{P}}$ > 2.5 TeV

Caveats: h couplings to light particles can be significantly reduced

Higgs Priorities

① *Better measurements of Higgs primaries*

- in inclusive measurements
- in differential distributions

② *Going beyond the κ's? What for?*

- to compete with other (EW, TGC...) measurements?
- to check the correlations imposed by SM structure?

    e.g. doublet nature of the Higgs,
        accidental custodial symmetry @ dim-6 level

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~ fully establishing the SM will require checking correlations among different vertices ~

0-Higgs vertices ↔ 1-Higgs vertices ↔ 2-Higgs vertices

(with and beyond the κ's)

Higgs Regge's plot is a prime example
Need to look at the correlations with TGC

test of the Ginzburg-Landau's model
test of PGB nature of the Higgs

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Questions not fully addressed yet:
what is the precision that you need in Higgs physics?
will the LHC reach this required sensitivity?

Example of Correlation 1-H & 2-H vertices

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm '13

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \quad \mathcal{A} = \left(1-a^2\right)\frac{s}{v^2}$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \left(W_L^+ W_L^- \to hh\right) = \left(b-a^2\right)\frac{s}{v^2}$$

if the Higgs is part of a doublet and custodial symmetry is at work

$$\boxed{1-a^2 \simeq -\left(b-a^2\right)}$$

a single operator of dimension-6 controls these 2 processes: $\frac{c_H}{2f^2}\left(\partial^\mu \left|H\right|^2\right)^2$

$$\boxed{\Delta b = 2\Delta a^2\left(1+O(\Delta a^2)\right)}$$

$$\Delta b \equiv 1-b$$

$$\Delta a^2 \equiv 1-a^2$$

a dimension-8 operator controls the deviations to this universal relation

$$O'_H = \frac{c'_H}{2f^4}|H|^2\partial_\mu|H|^2\partial^\mu|H|^2$$

$$a = 1 - \frac{c_H}{2}\frac{v^2}{f^2} + \left(\frac{3c_H^2}{8} - \frac{c'_H}{4}\right)\frac{v^4}{f^4}$$

$$b = 1 - 2c_H\frac{v^2}{f^2} + \left(3c_H^2 - \frac{3c'_H}{2}\right)\frac{v^4}{f^4}$$

if the Higgs is a Goldstone

then non-linear symmetry relates operators of different dimensions

Example of Correlation 1-H & 2-H vertices

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm '13

Scenario 1: 10% deviations are observed

$\Delta a^2 \sim \Delta b \sim 10\%$

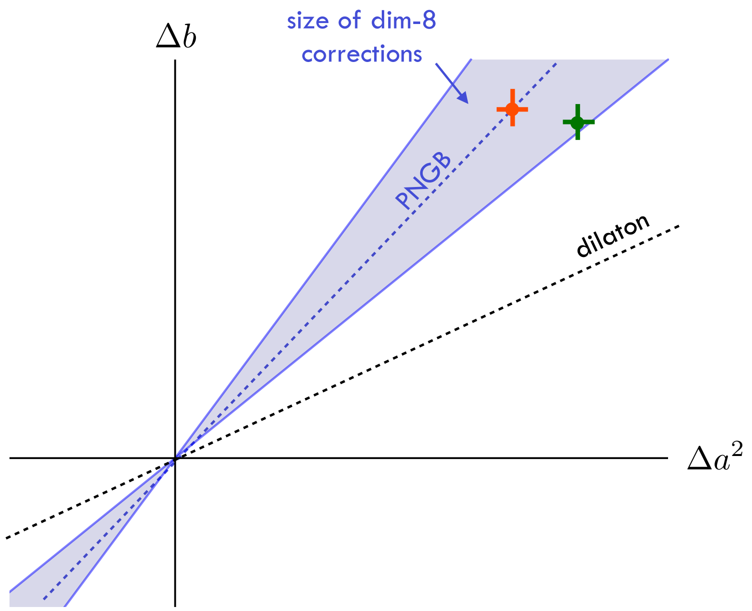
$\text{Exp. precision} \sim 1\%$

→ Test dim-8 operators

the corrections to the universal relation between 'a' and 'b' are O(1%)

1. PNGB (and specific coset) proved

2. SILH proved, PNGB disproved



can distinguish a PNGB from a non PNGB resonance

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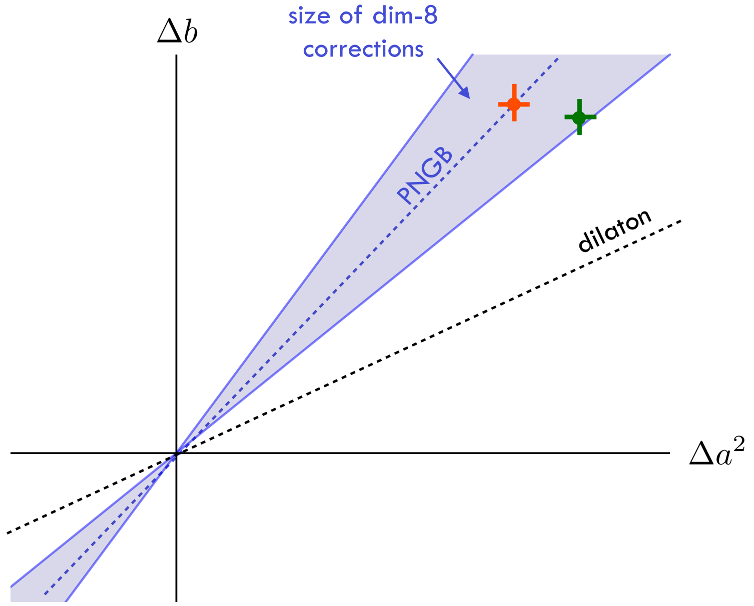


can distinguish a PNGB from a non PNGB resonance

Scenario 2: 1% deviations are observed

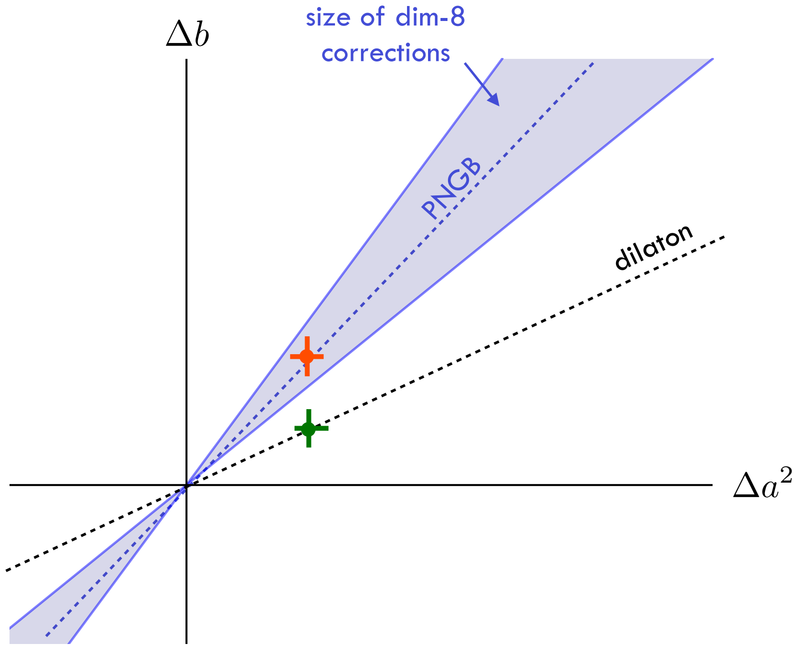
$\Delta a^2 \sim \Delta b \sim 1\%$

$\text{Exp. precision} \sim 1\%$

the corrections to the universal relation are beyond any future sensitivity

1. SILH proved

2. SILH (i.e. Higgs doublet) disproved



can distinguish a doublet from a non-doublet resonance

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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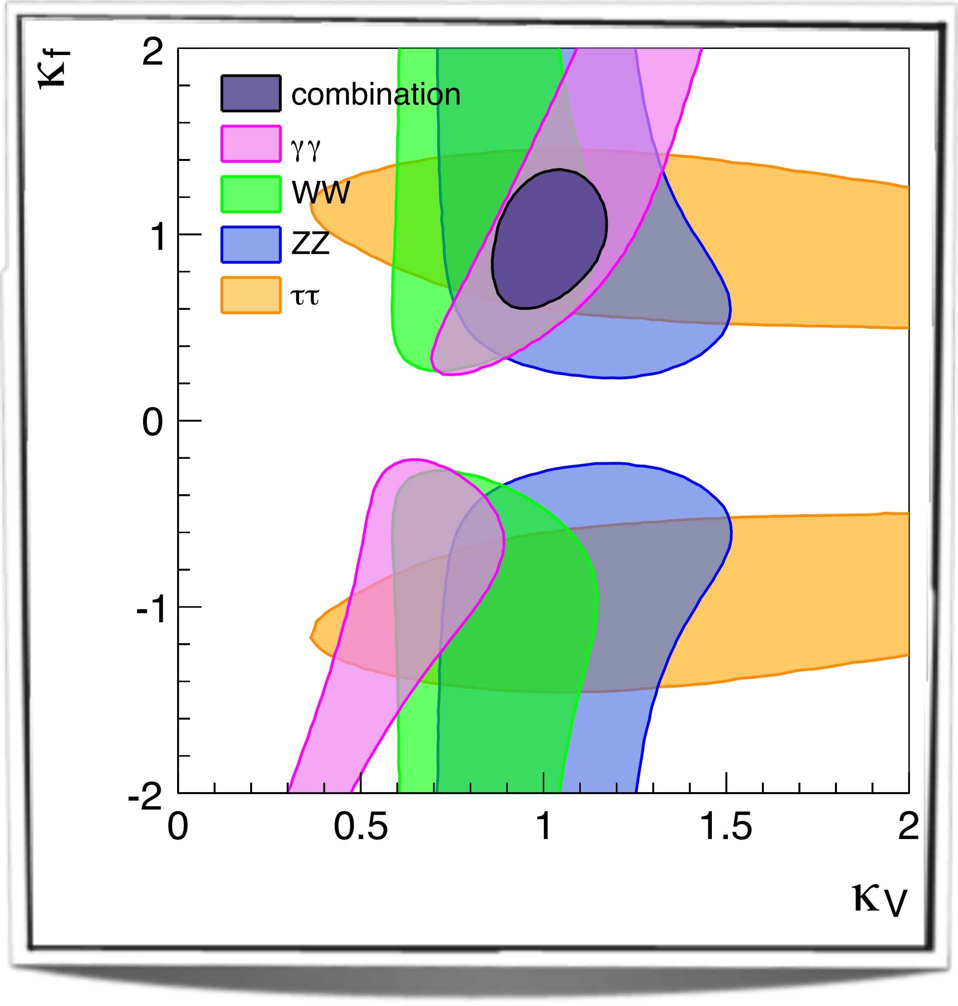
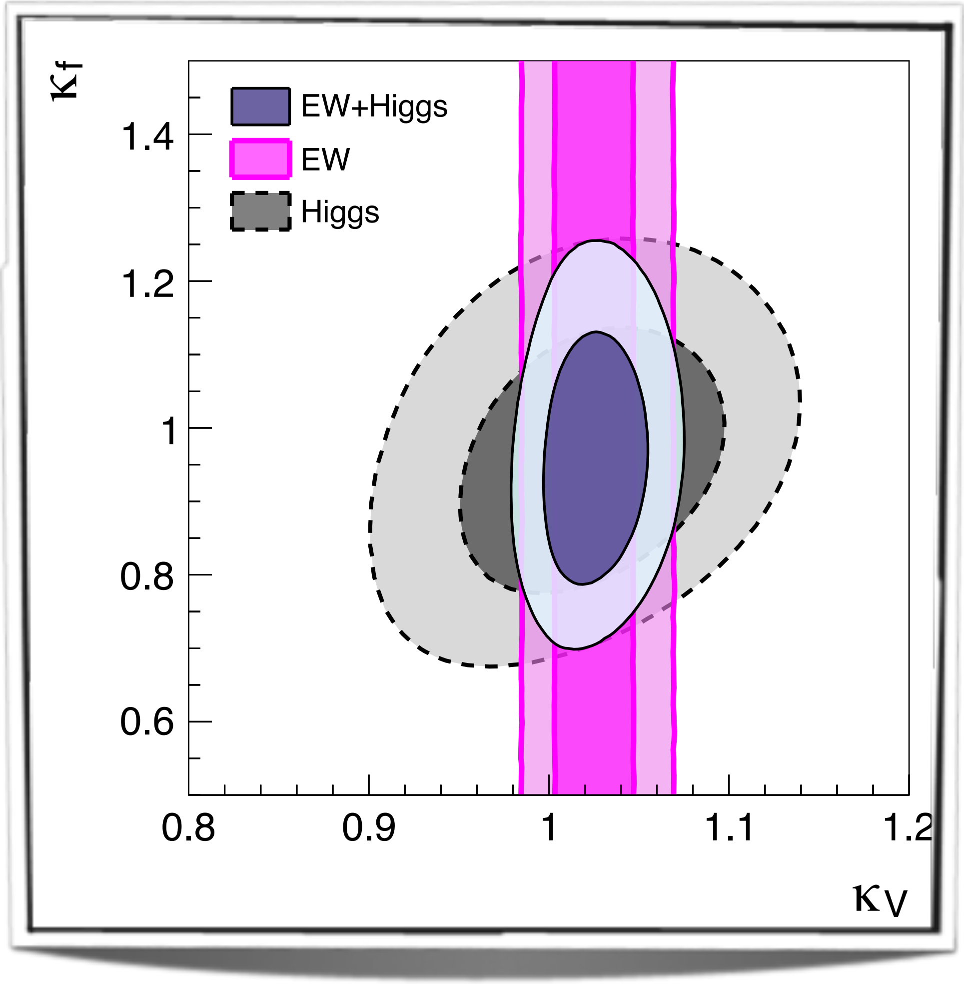


Ciuchini et al ’13



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in processes with a characteristic scale $\mu \approx m_H$

⇩ ⇩

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

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

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

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$\Rrightarrow$ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop) $\Lleftarrow$

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

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

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

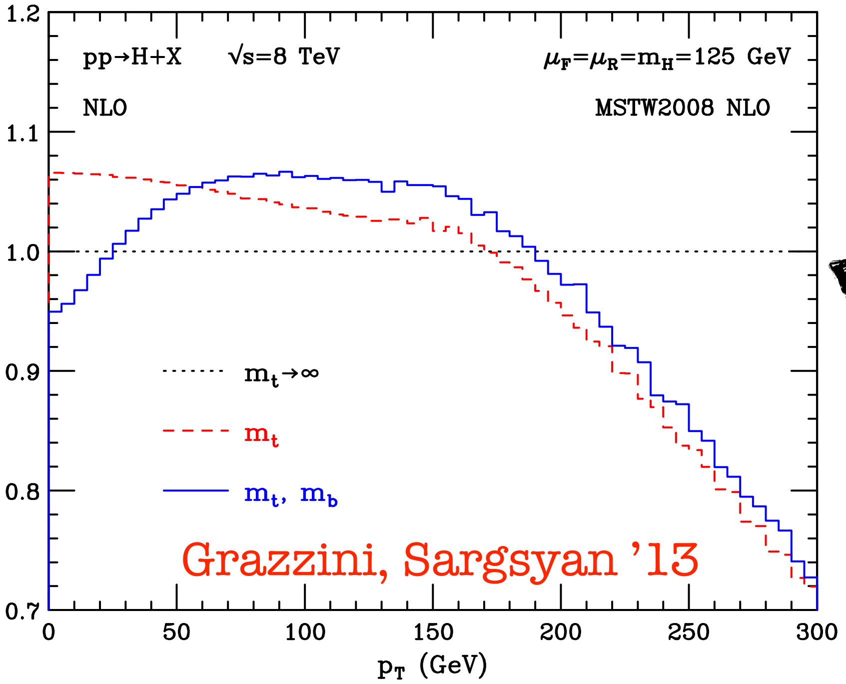
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

Resolving top loop: Boosted Higgs

cut open the top loops

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

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



Grazzini, Sargsyan '13

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

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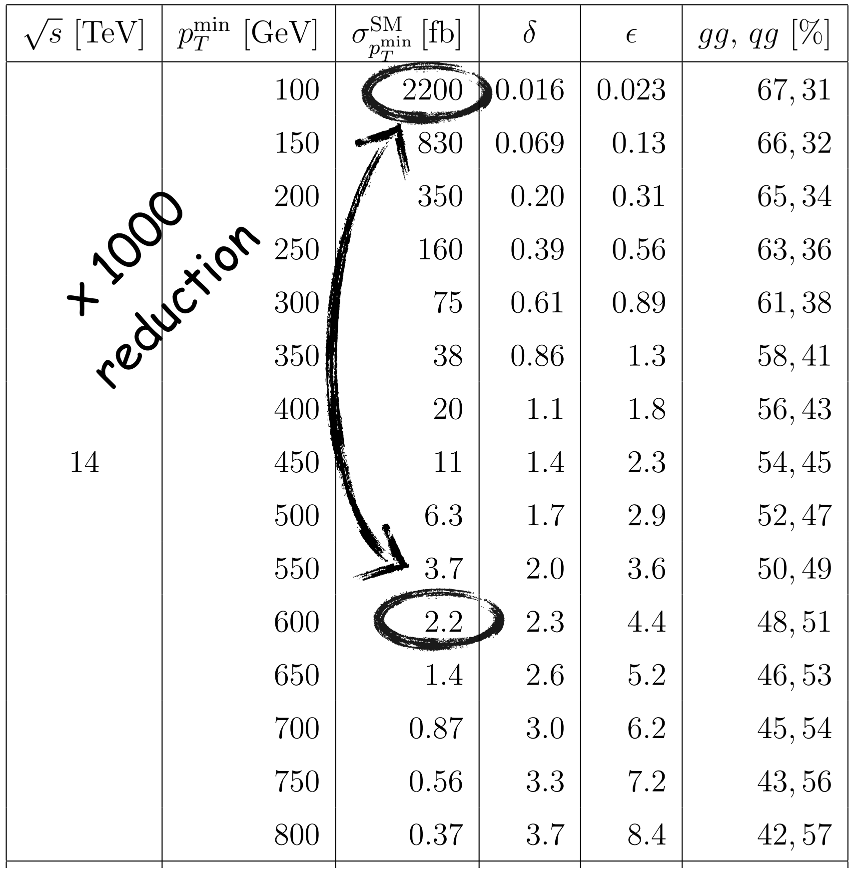
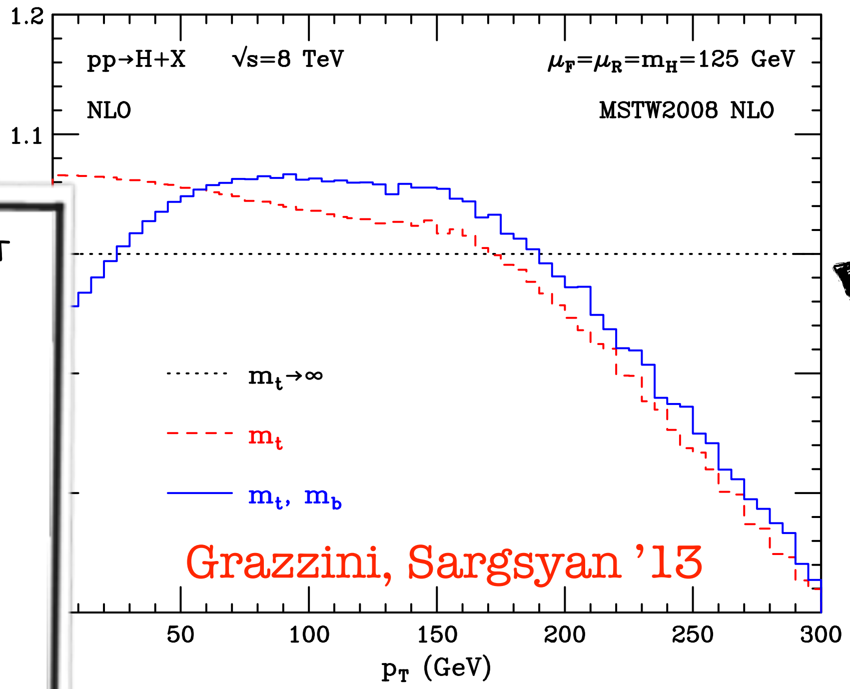
Don't think it is easy to produce a Higgs with high p_T



$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ	gg, qg [%]
14	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
	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

x 1000 reduction

Grojean, Salvioni, Schlaffer, Weiler '13



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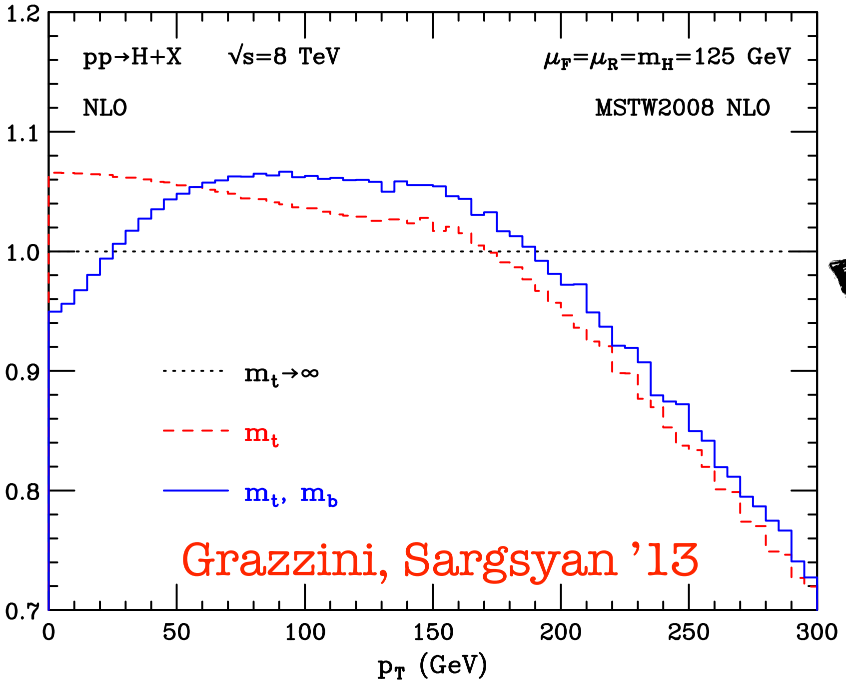

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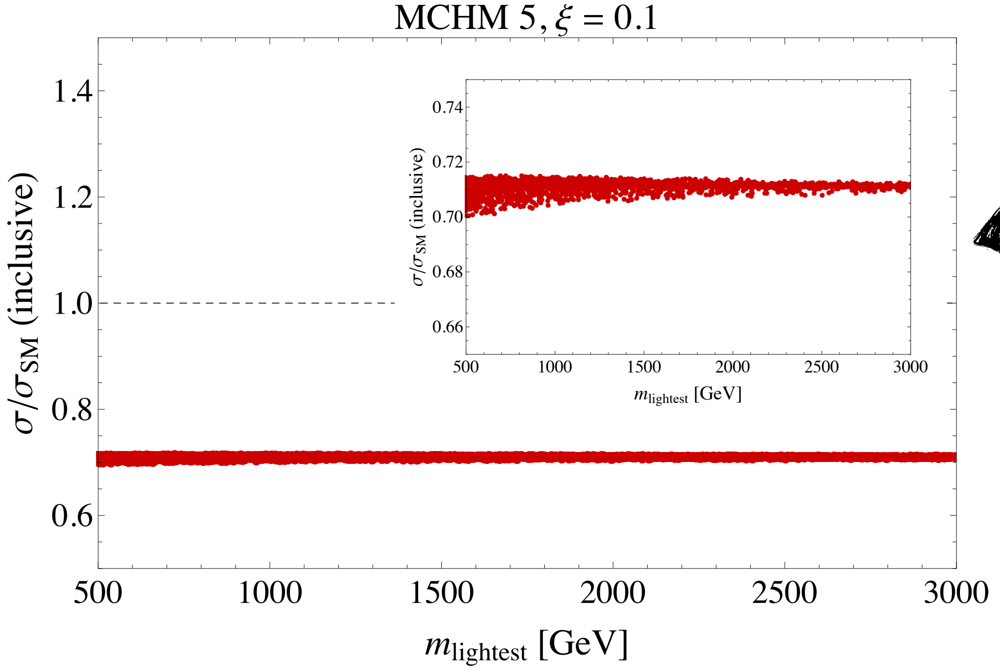
Composite Higgs Model

top partners contributions

see also Banfi, Martin, Sanz '13

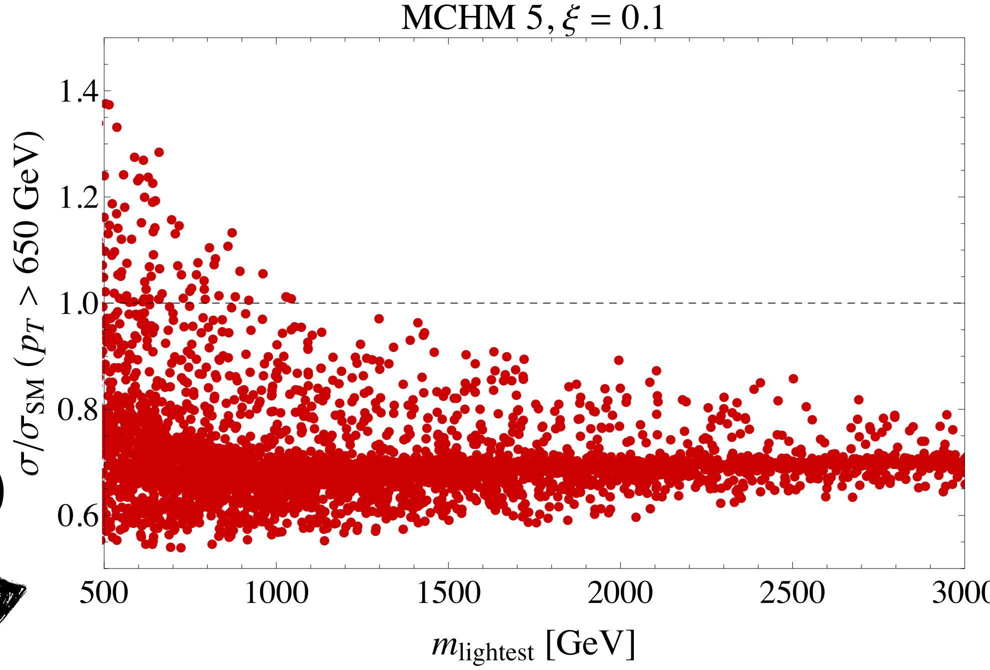
see also Azatov, Paul '13

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

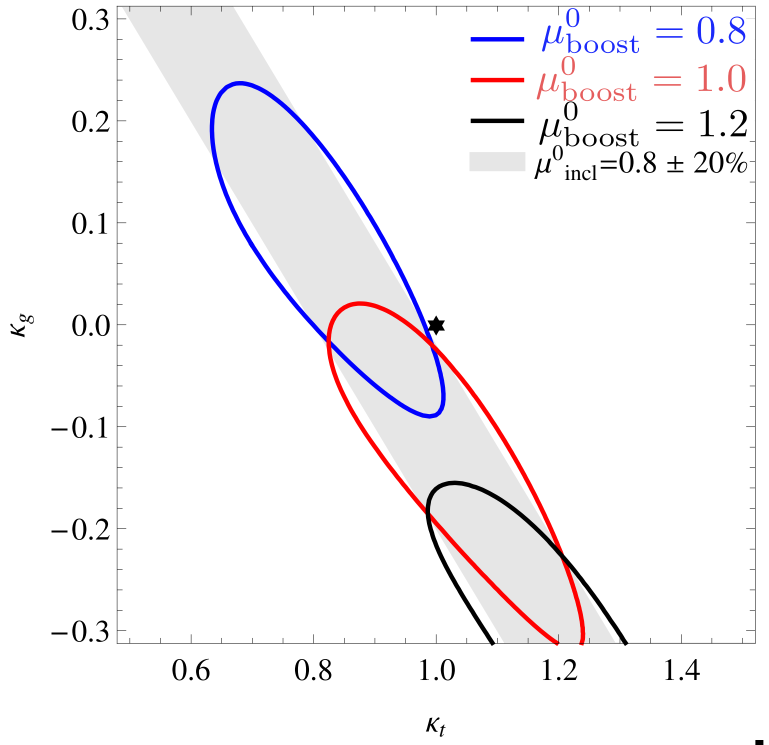
Grojean, Salvioni, Schlaffer, Weiler '13

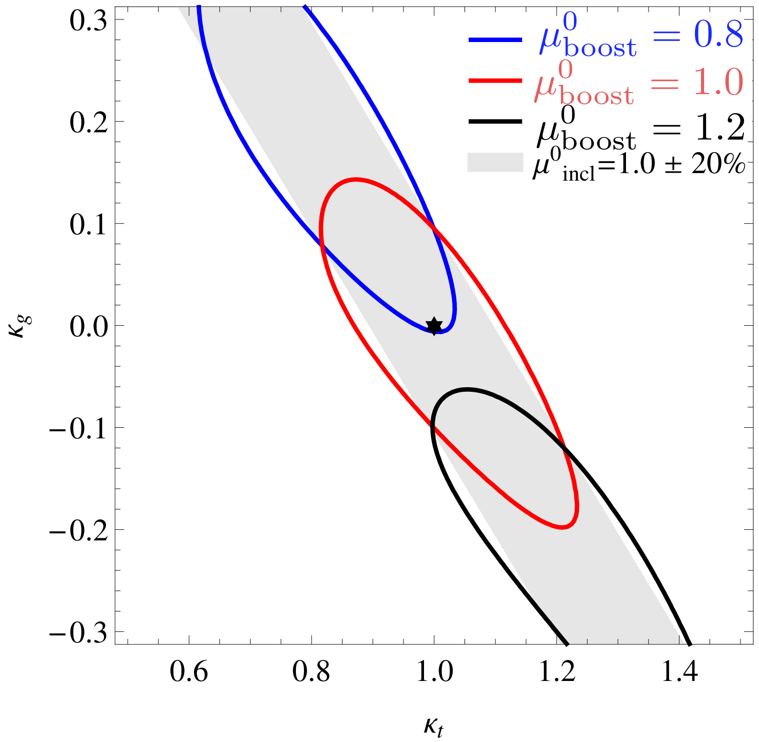
high p_T tail discriminates short and long distance physics contribution to gg → h

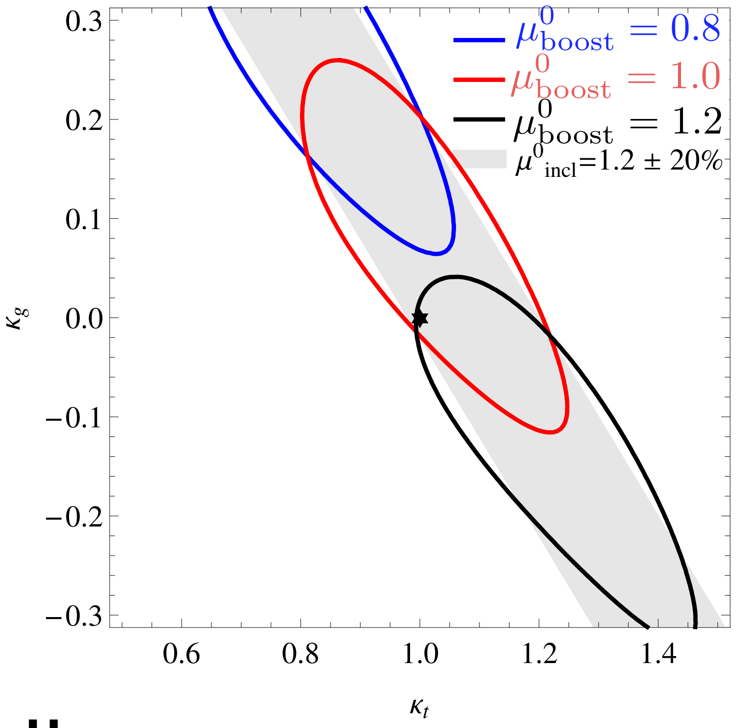
$$\sqrt{s} = 14\ \text{TeV}, \int dt\,\mathcal{L} = 3\text{ab}^{-1}, p_T > 650\ \text{GeV}$$

(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 to 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

Off-shell Higgs effects

naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs

but enhancement due to the particular couplings of H to V_L

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Recent analysis of gg→H*→ZZ→4l

CMS PAS HIG-14-002
ATLAS-CONF-2014-042

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

$$\frac{d\sigma_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}}}{dm^2_{\mathrm{ZZ}}} \propto g_{\mathrm{ggH}}g_{\mathrm{HZZ}}\frac{F(m_{\mathrm{ZZ}})}{(m^2_{\mathrm{ZZ}}-m^2_{\mathrm{H}})^2+m^2_{\mathrm{H}}\Gamma^2_{\mathrm{H}}}$$

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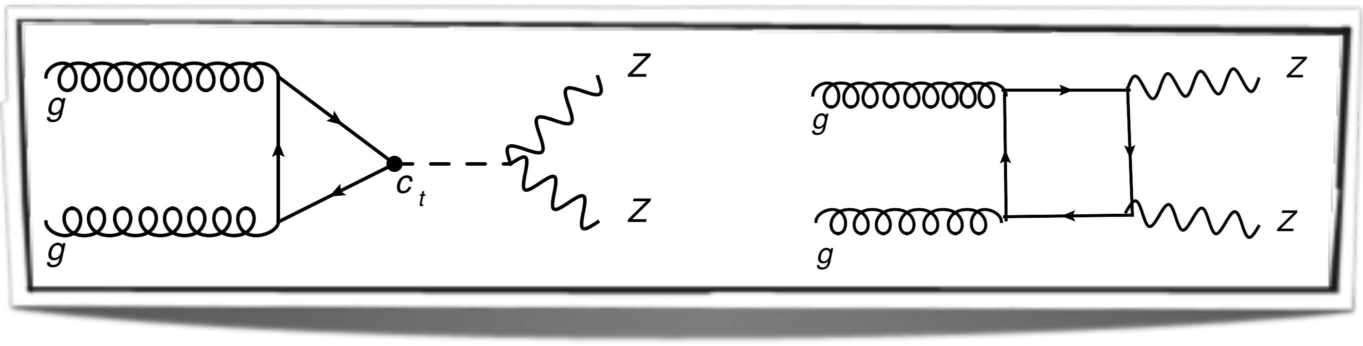
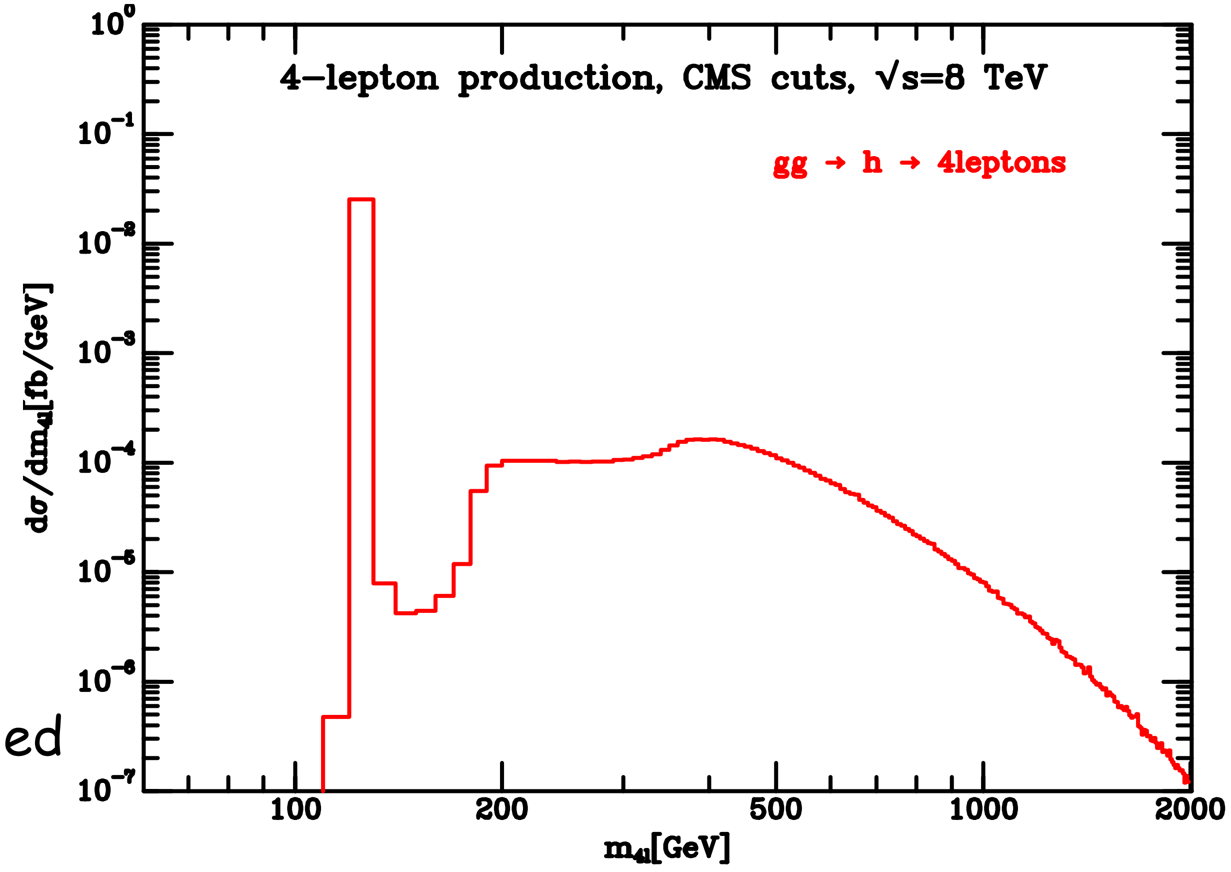
Glover, van der Bij '89



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

SM: cancelation forced by unitarity
BSM: deviations of Higgs couplings at large ŝ will be amplified



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Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via off-shell measurements or via the mass shift in gg→h→$\gamma\gamma$

Narrow Width Approx.: on-shell

ratios of κ only

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

no direct access to the width itself

(upper bound if $\kappa_V < 1$ is assumed
e.g. Dobrescu, Lykken '12)

off-shell

different width dependence

Γ_H can be fitted w/o assumption

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

Kauer, Passarino '12
Caola, Melnikov '13
Campbell et al '13

Off-shell Higgs

Off-shell Higgs effects

naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs

but enhancement due to the particular couplings of H to V_L

Recent analysis of gg→H*→ZZ→4l

CMS PAS HIG-14-002
ATLAS-CONF-2014-042

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via off-shell measurements or via the mass shift in gg→h→$\gamma\gamma$

Narrow Width Approx.: on-shell

ratios of κ only

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma_H}$$

no direct access to the width itself

(upper bound if κ_V < 1 is assumed
e.g. Dobrescu, Lykken '12)

off-shell

different width dependence

Γ_H can be fitted w/o assumption

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH}g^2_{HZZ}$$

What do we learn? BR_{inv} <85%?

Not competitive with global fits on BR_{inv}! BR_{inv} < 20%

Kauer, Passarino '12
Caola, Melnikov '13
Campbell et al '13

Model independent analysis might not be robust because of unitarity issues

($g_i(m_h)$) might be quite different than $g_i(m_{4l})$)

Englert, Spannowski '14

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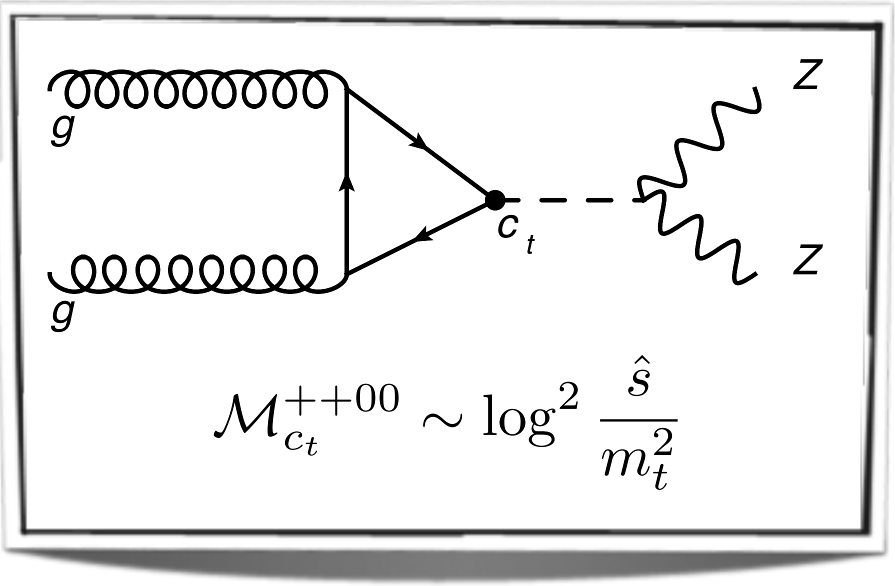
CMS PAS HIG-14-002
ATLAS-CONF-2014-042

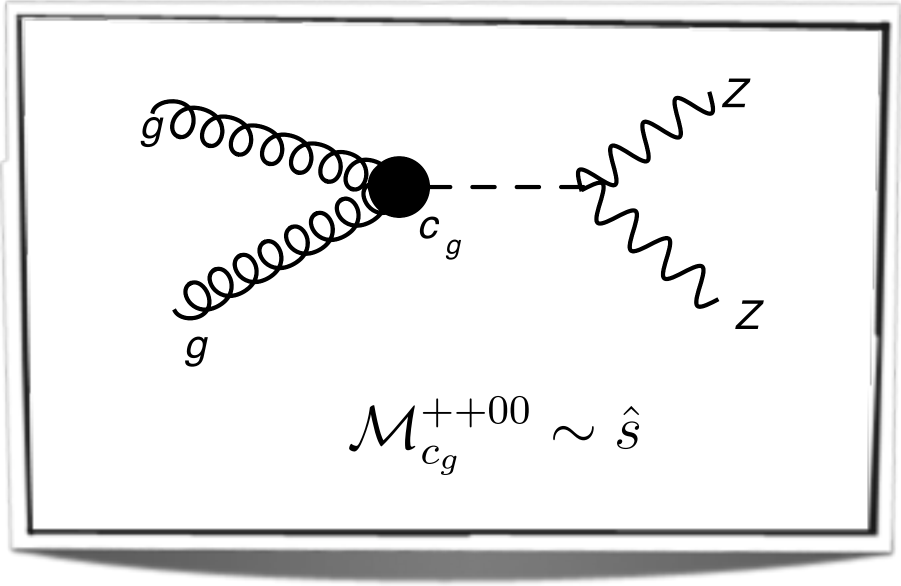
Access to top Yukawa coupling?

strong departure of the Higgs low energy theorem in the far off-shell region

can distinguish c_t from c_g



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



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

Cacciapaglia et al. ’14

Azatov, Grojean, Paul, Salvioni ’14

Off-shell Higgs

Off-shell Higgs effects

naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs

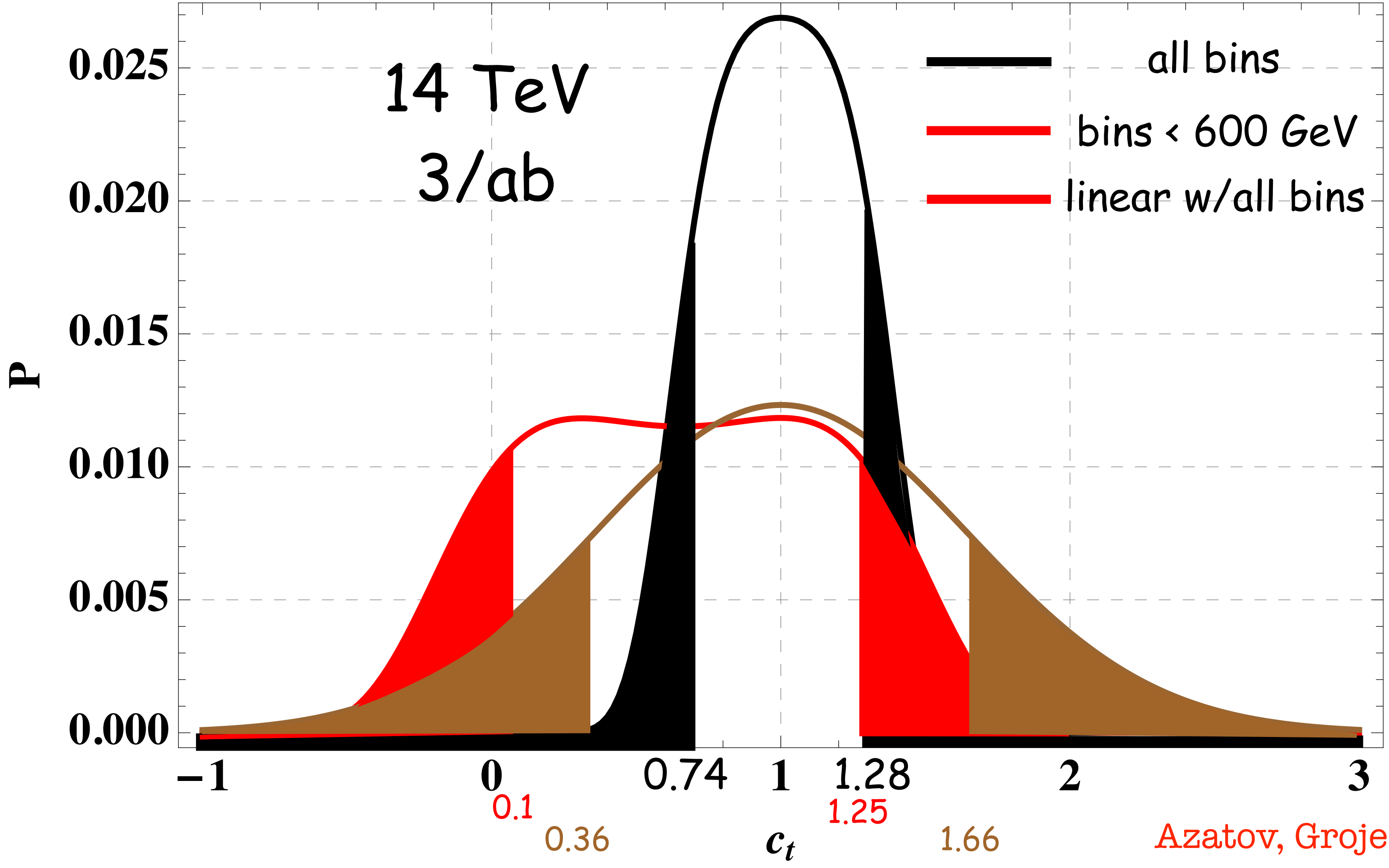
but enhancement due to the particular couplings of H to V_L

Recent analysis of gg→H*→ZZ→4l

CMS PAS HIG-14-002
ATLAS-CONF-2014-042

Access to top Yukawa coupling?

provides an alternative to ttH to measure the top Yukawa coupling



Azatov, Grojean, Paul, Salvioni '14

3

Multi-Higgs channels

Beyond single Higgs processes

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

@ 14 TeV

Higgs multiplicty →

Jet multiplicty ↓

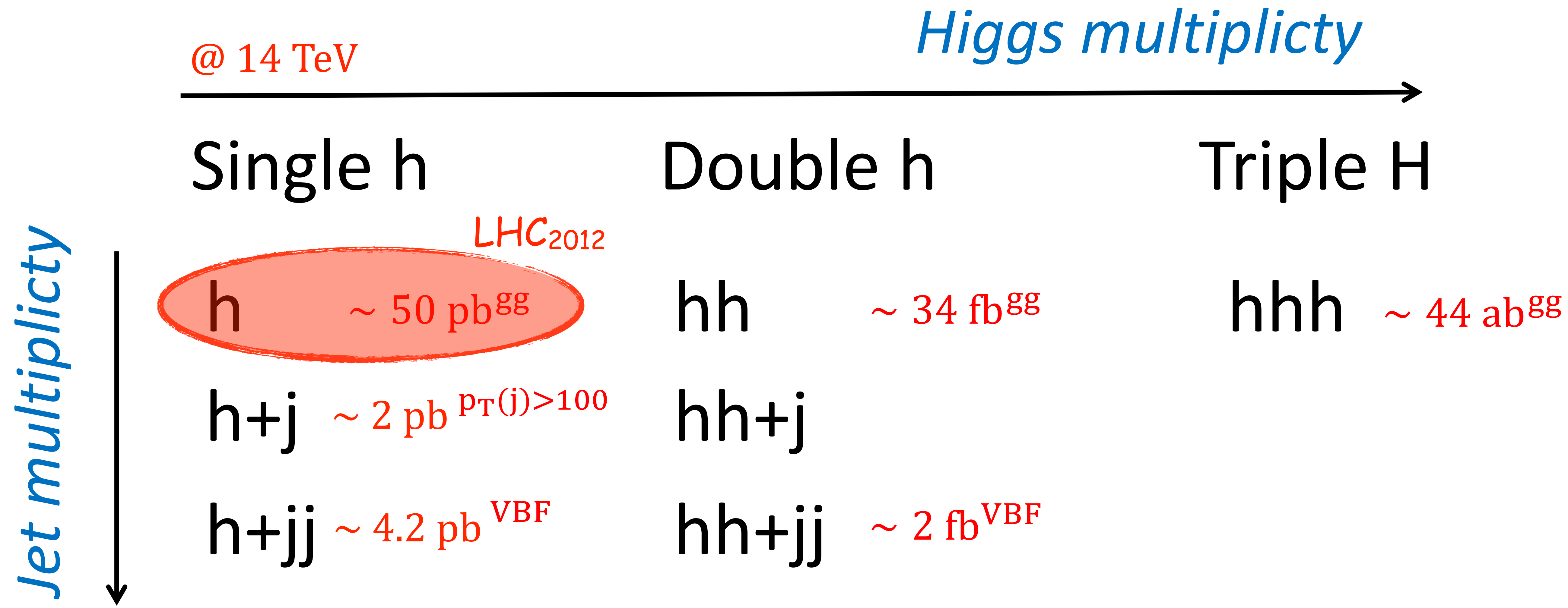
Single h		Double h		Triple H	
h	$\sim 50\ \mathrm{pb}^{gg}$	hh	$\sim 34\ \mathrm{fb}^{gg}$	hhh	$\sim 44\ \mathrm{ab}^{gg}$
h+j	$\sim 2\ \mathrm{pb}^{\ p_T(j)>100}$	hh+j			
h+jj	$\sim 4.2\ \mathrm{pb}^{\ VBF}$	hh+jj	$\sim 2\ \mathrm{fb}^{VBF}$		

- 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



@ 14 TeV

Higgs multiplicty

Jet multiplicty

LHC2012

Single h	Double h	Triple H
h $\sim 50\ \text{pb}^{gg}$	hh $\sim 34\ \text{fb}^{gg}$	hhh $\sim 44\ \text{ab}^{gg}$
h+j $\sim 2\ \text{pb}\ ^{p_T(j)>100}$	hh+j	
h+jj $\sim 4.2\ \text{pb}\ ^{VBF}$	hh+jj $\sim 2\ \text{fb}^{VBF}$	

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Beyond single Higgs processes

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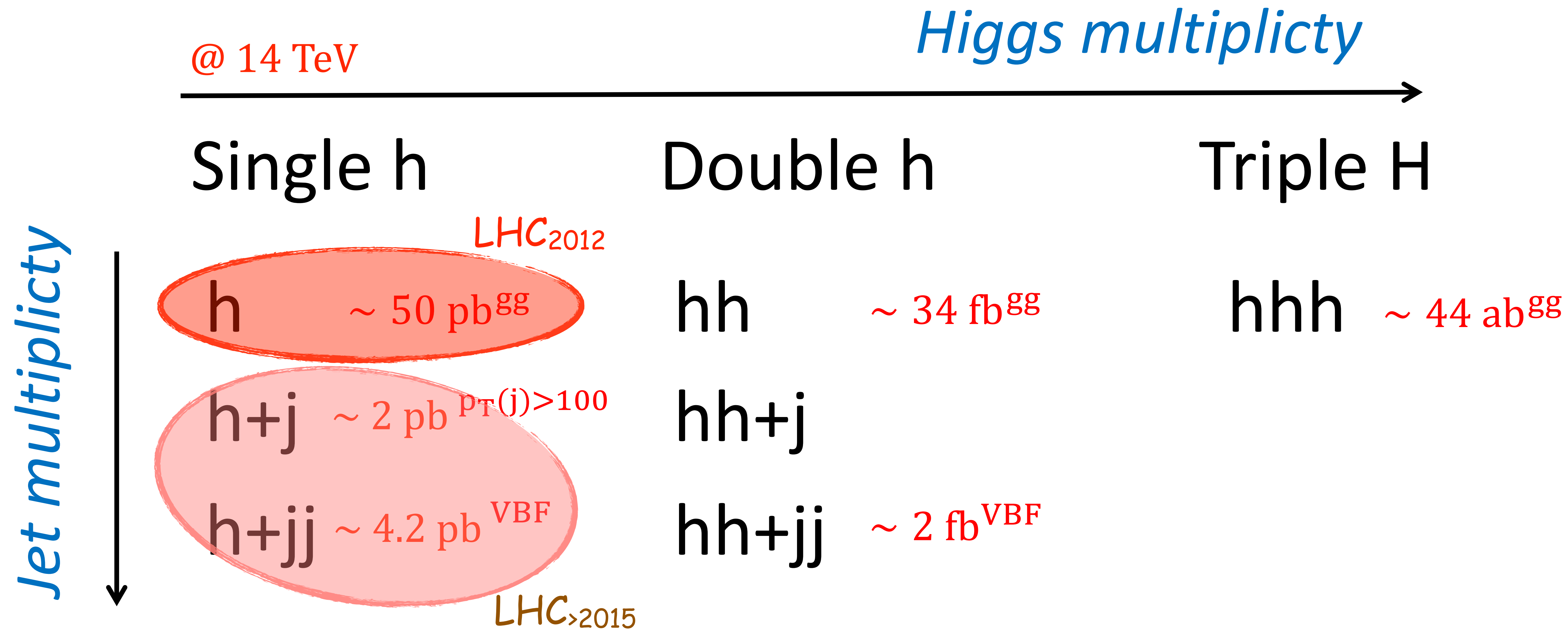

@ 14 TeV

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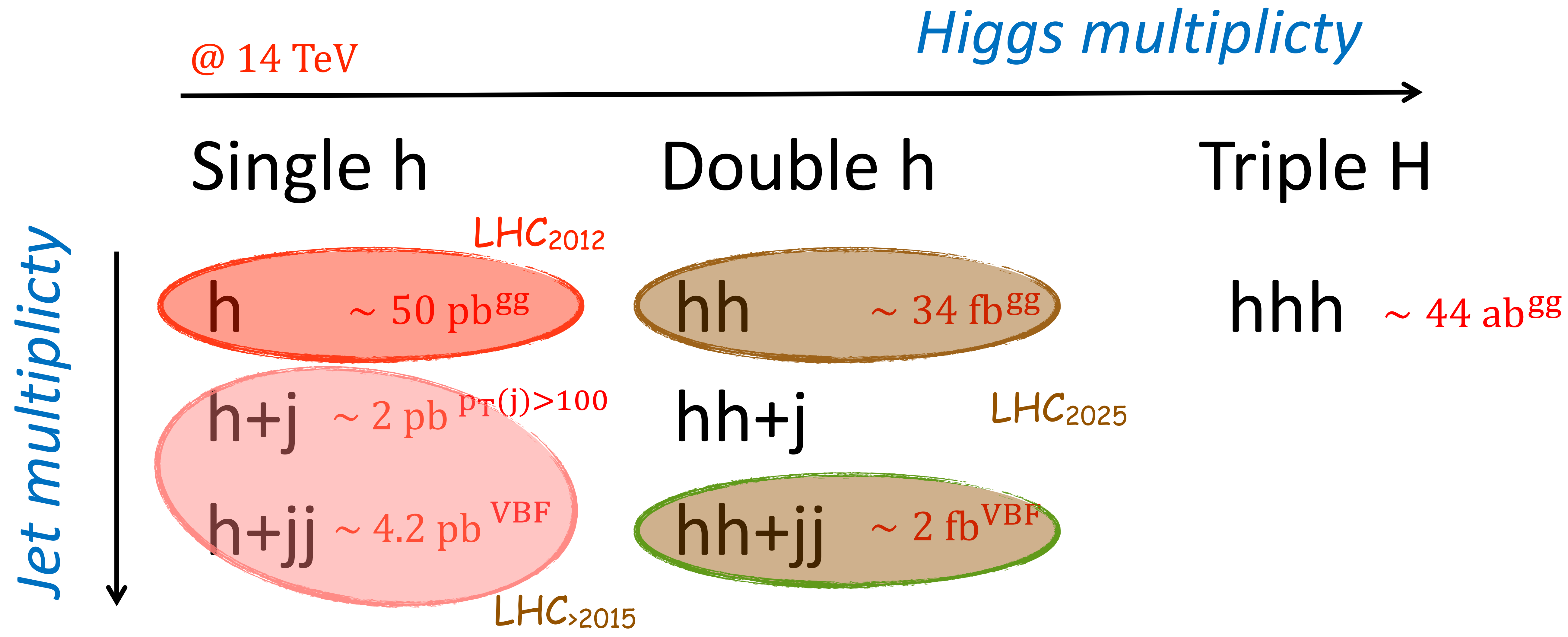
Beyond single Higgs processes

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



@ 14 TeV

Higgs multiplicty

Jet multiplicty

Single h

Double h

Triple H

LHC$_{2012}$

h $\sim 50\ \mathrm{pb}^{gg}$

hh $\sim 34\ \mathrm{fb}^{gg}$

hhh $\sim 44\ \mathrm{ab}^{gg}$

h+j $\sim 2\ \mathrm{pb}$ $p_T(j)>100$

hh+j

LHC$_{2025}$

h+jj $\sim 4.2\ \mathrm{pb}^{\mathrm{VBF}}$

hh+jj $\sim 2\ \mathrm{fb}^{\mathrm{VBF}}$

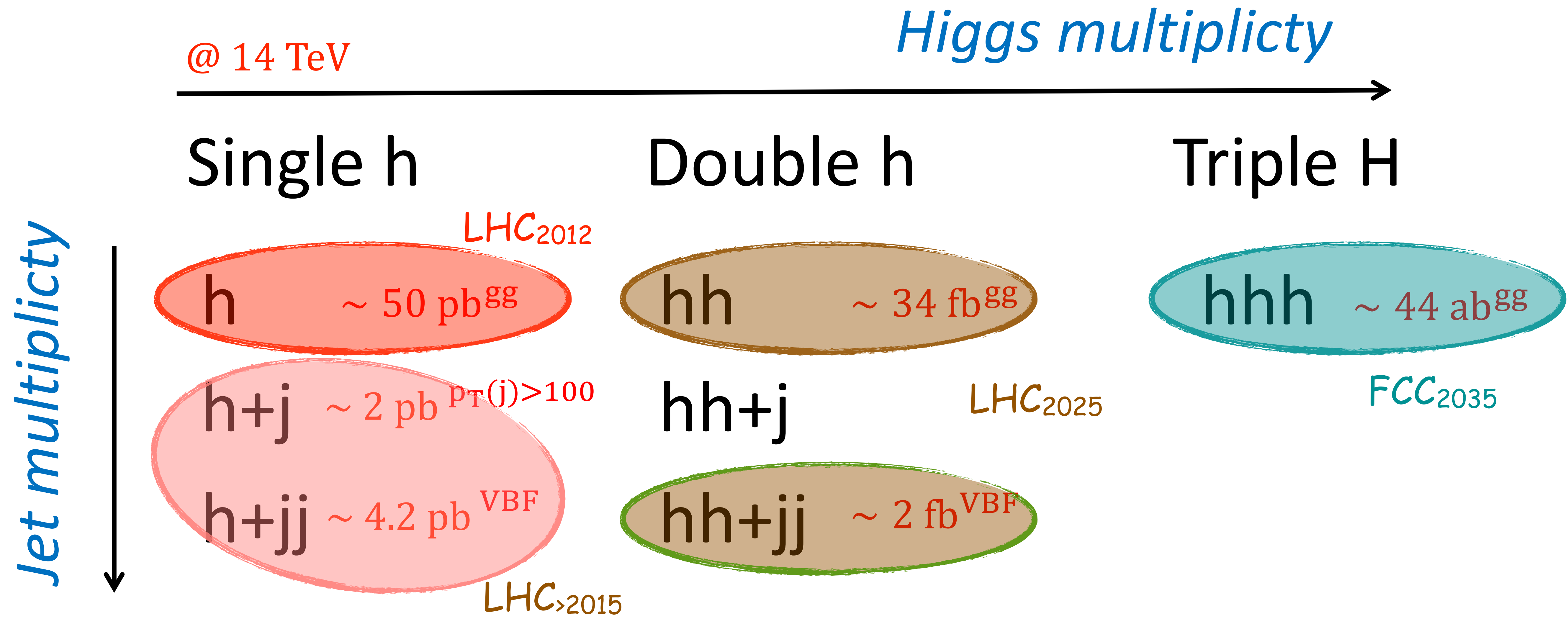
LHC$_{>2015}$

- 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



@ 14 TeV

Higgs multiplicty

Jet multiplicty

Single h

Double h

Triple H

LHC2012

h $\sim$ 50 pb^{gg}

hh $\sim$ 34 fb^{gg}

hhh $\sim$ 44 ab^{gg}

h+j $\sim$ 2 pb $p_T(j)>100$

hh+j

LHC2025

FCC2035

h+jj $\sim$ 4.2 pb ^{VBF}

hh+jj $\sim$ 2 fb^{VBF}

LHC>2015

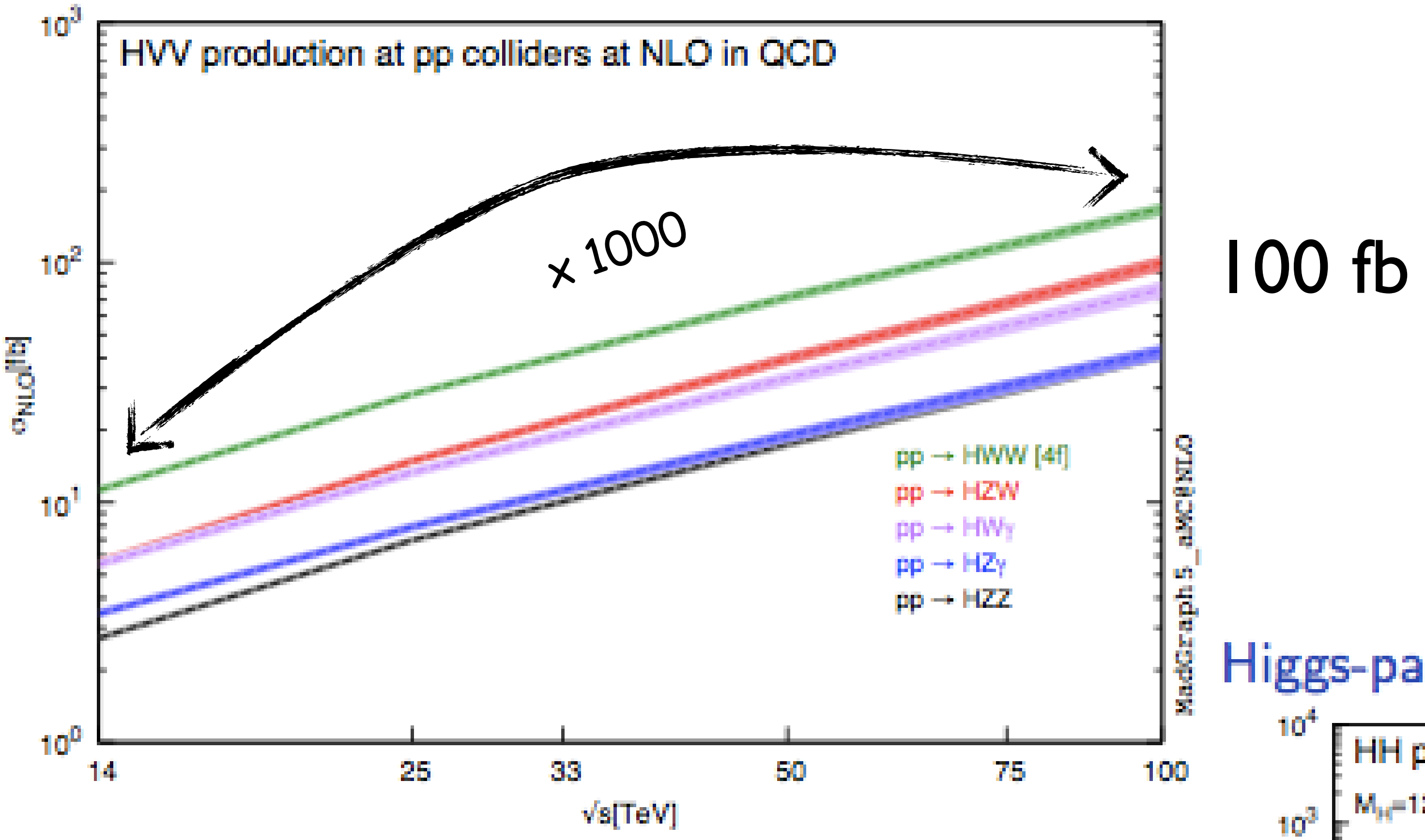
- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

(adapted from M. Son@Planck2014)

Beyond single Higgs processes

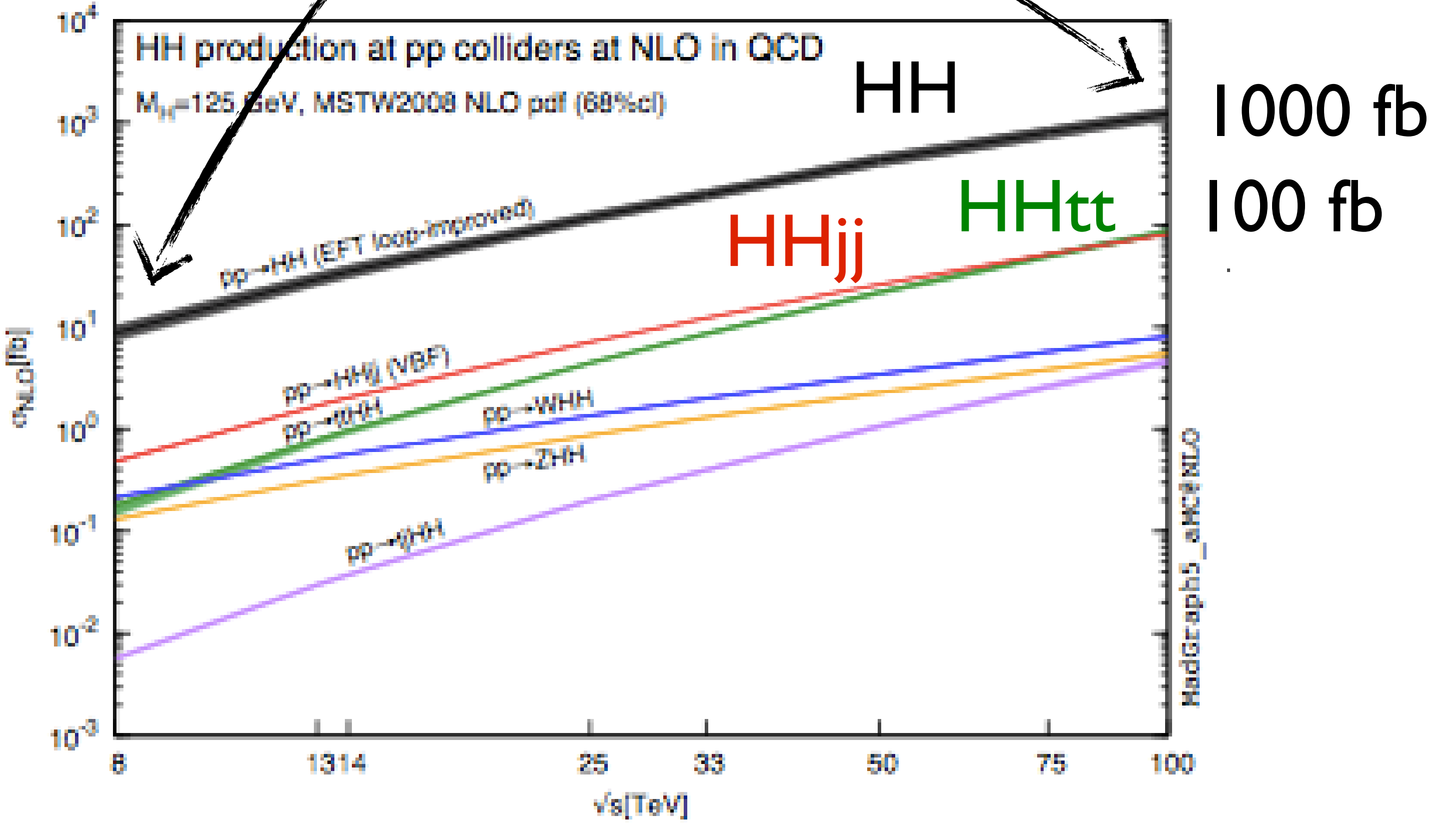
Producing one Higgs is good. Producing H+X is better
A long term plan?

Higgs-diboson associated production



FCC = H+X factory

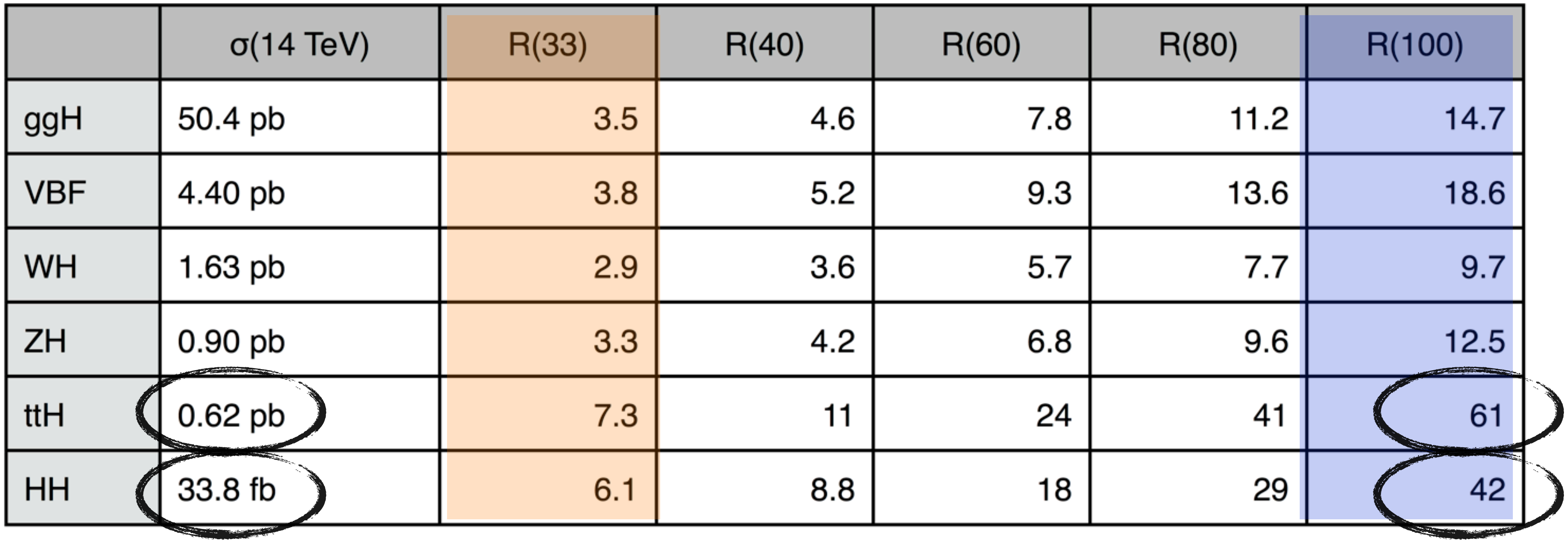
Higgs-pair associated production



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

Multi Higgs processes

Producing one Higgs is good. Producing more Higgses is better

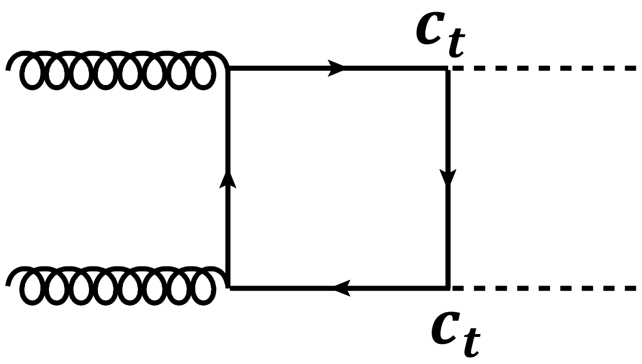


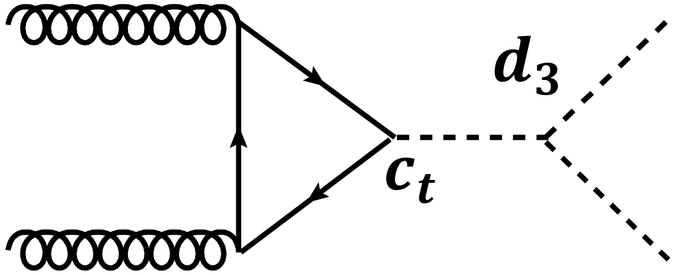
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

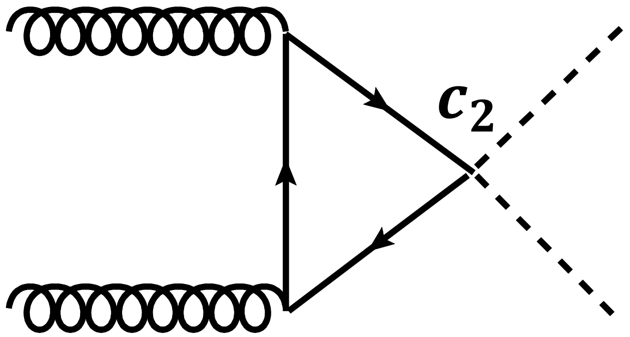
The two difficult processes @ LHC (tth and hh) are the real winners of the energy boost
(these 2 processes have to do with the top Yukawa coupling
one of the most promising probe of new physics)

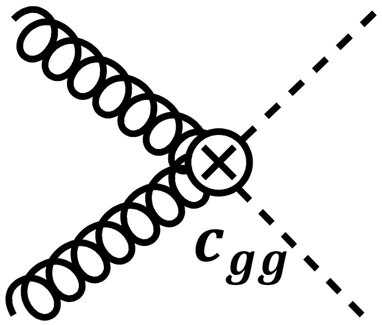
What do we learn from gg→HH?

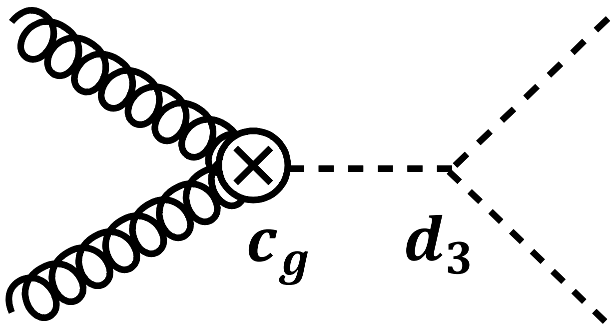
in principle gg→HH gives access to many new couplings, including non-linear couplings









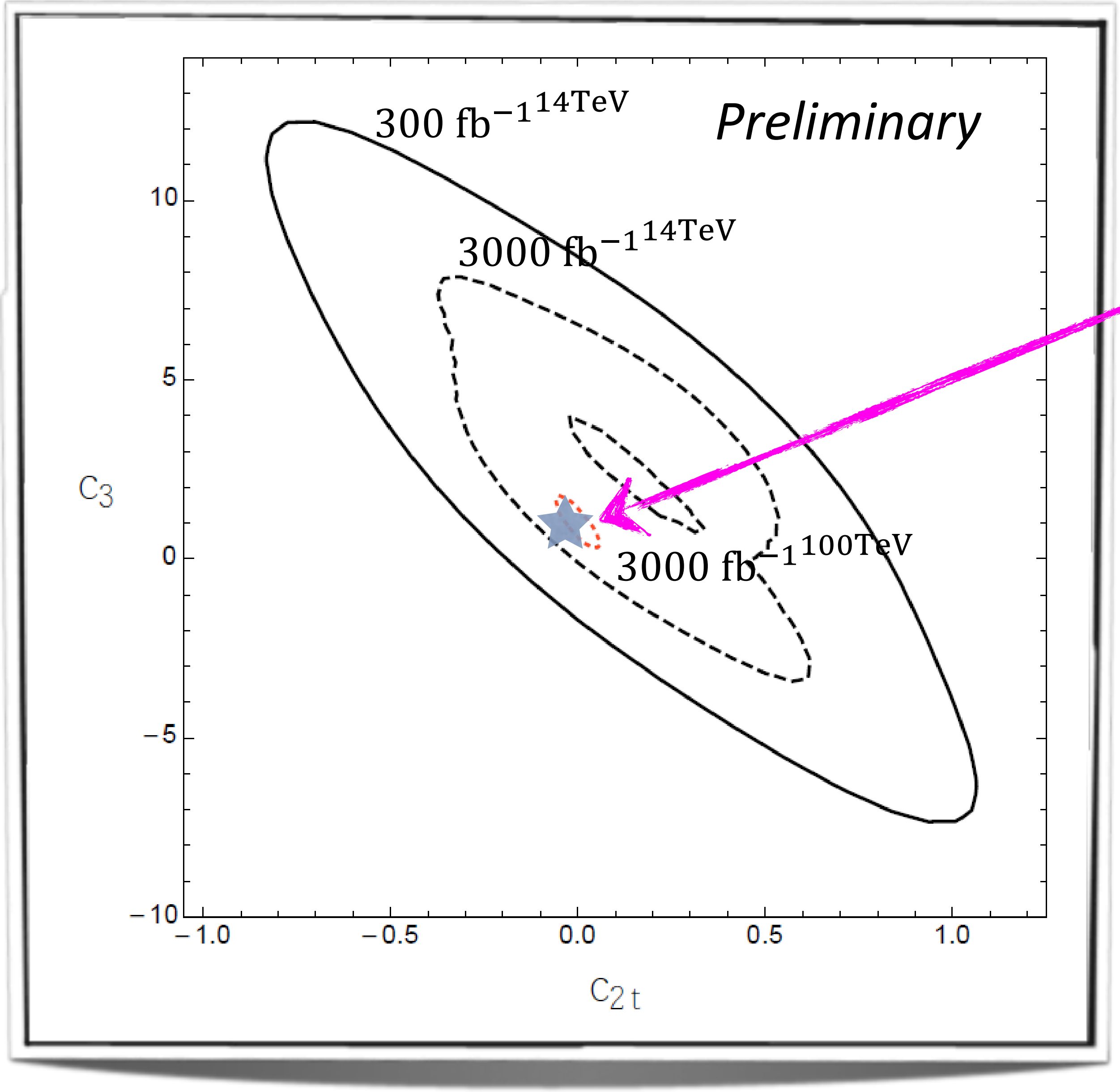


In practice, if the Higgs is part of an EW doublet, these new couplings are related to single-Higgs couplings

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

Example 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 ‘to appear

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

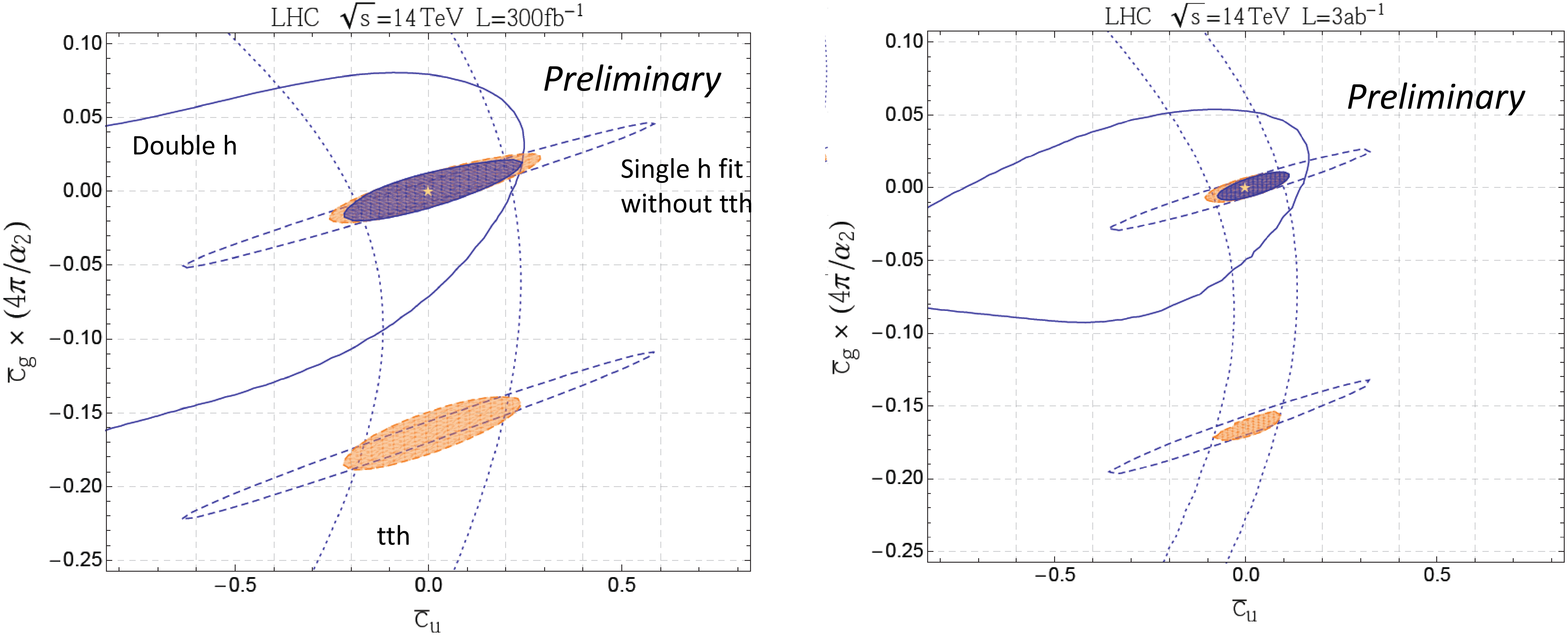
⇛ access to distribution

⇛ 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



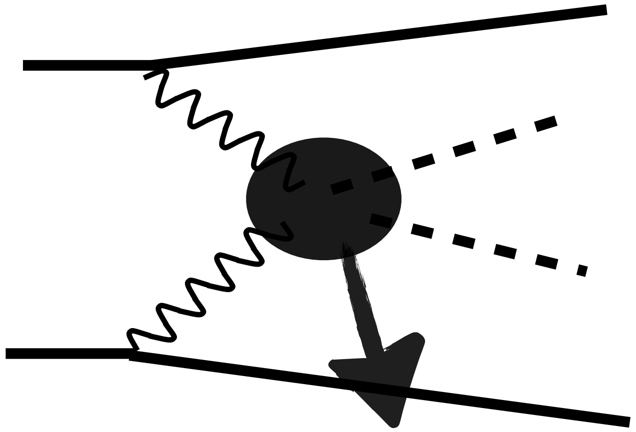
Azatov, Contino, Panico, Son ‘to appear

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

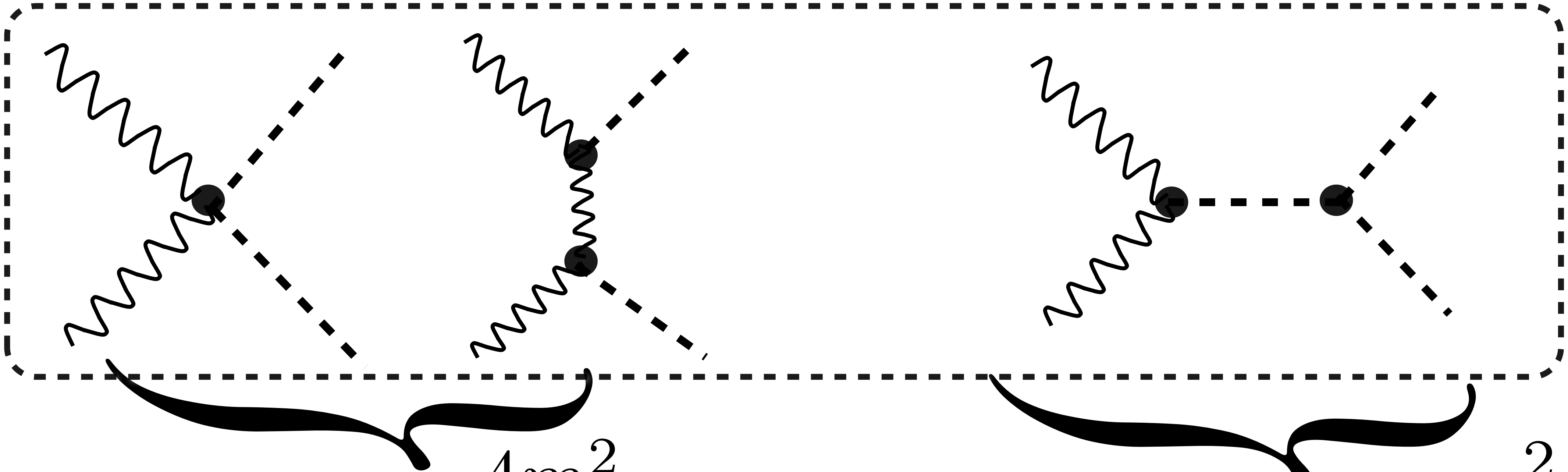
(e.g. WW scattering) Contino, Grojean, Moretti, Piccini, Rattazzi '10



SM: a=b=d_3=d_4=1

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

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



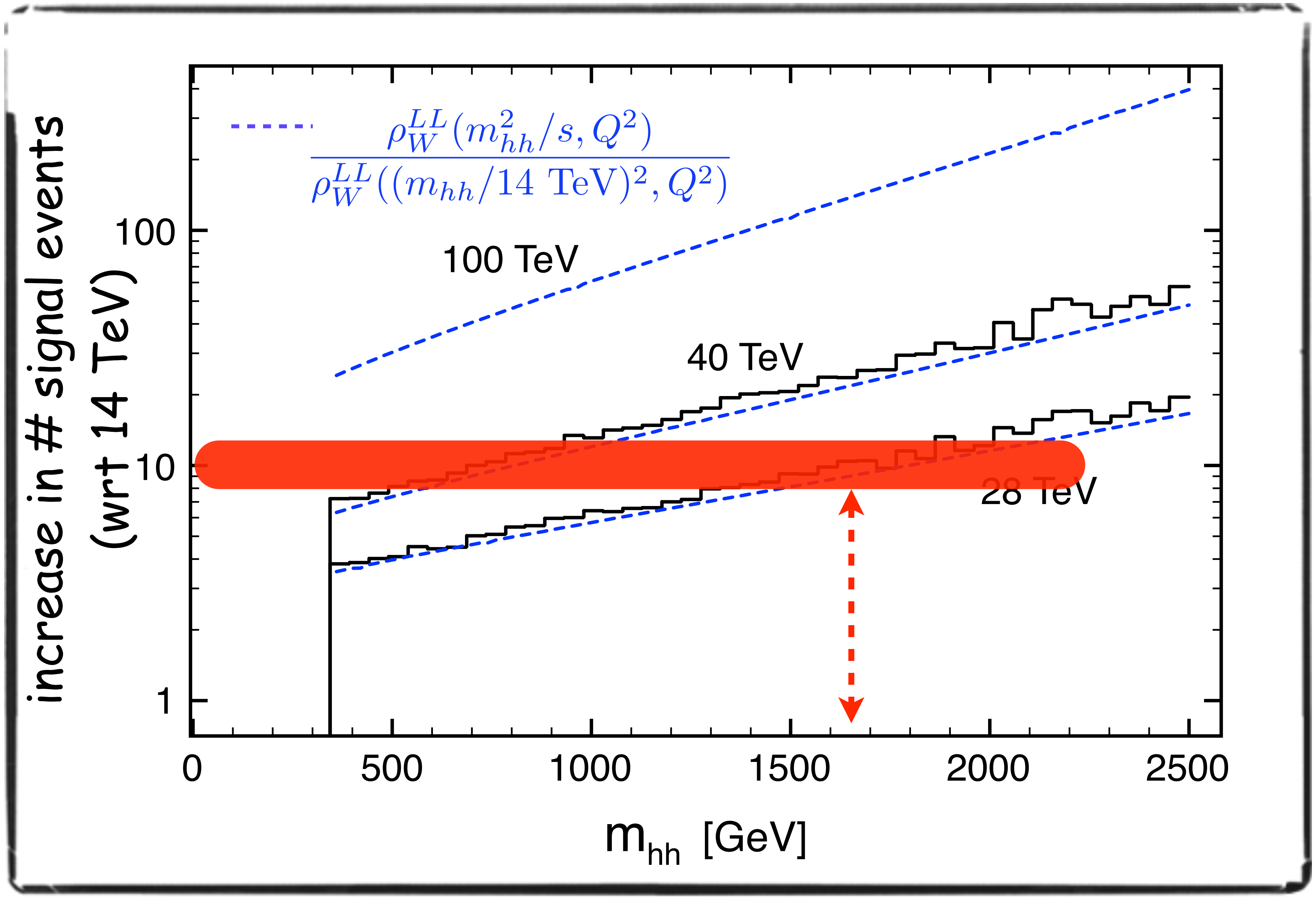
$$\mathcal{A} \underset{m_{hh}^2\gg m_W^2}{\sim} (b-a^2)\,\frac{4m_{hh}^2}{v^2}$$

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

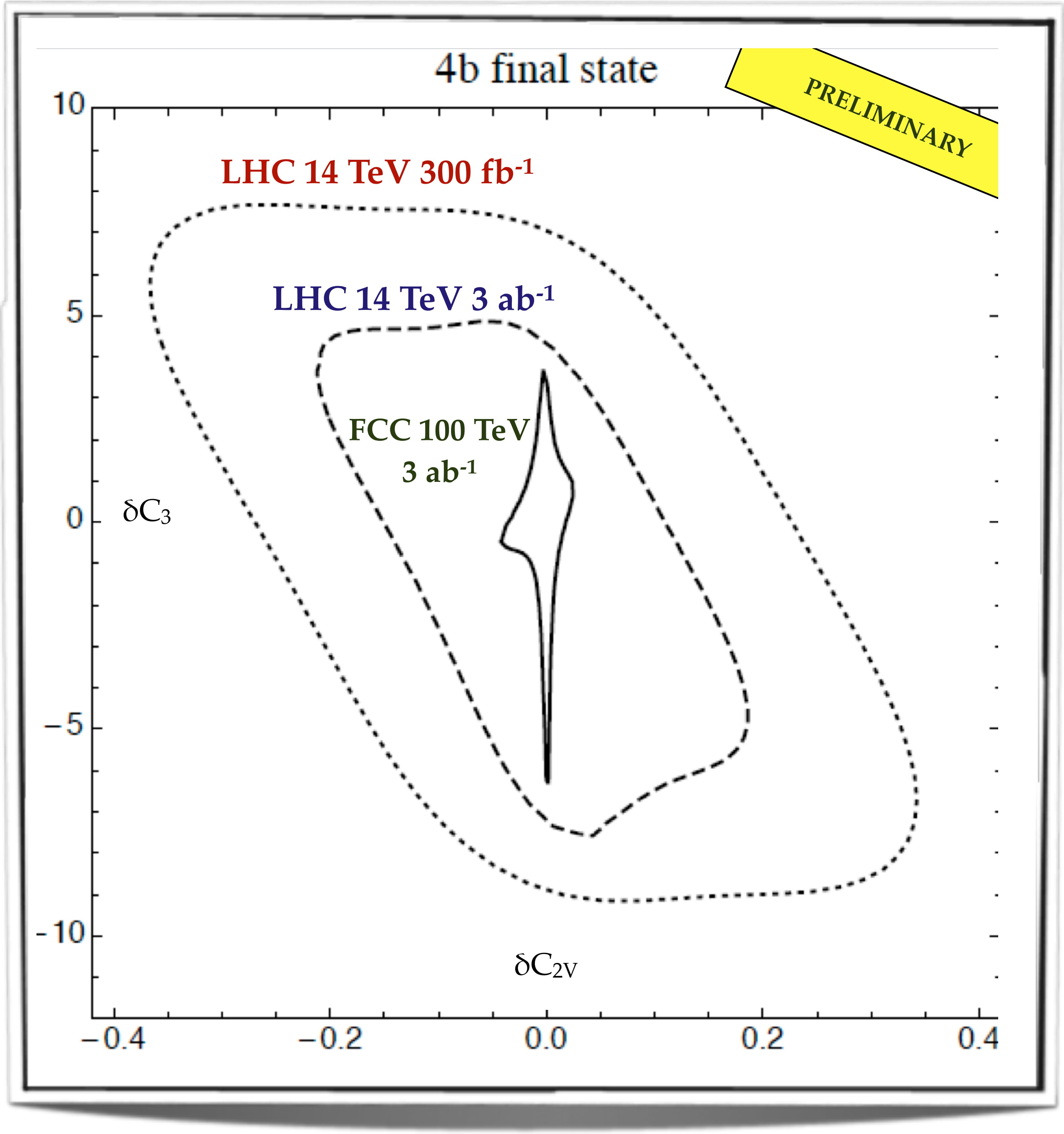


HL-LHC vs. HE-VLHC

10 x lum ≈ 10 x events

2 x √s = 10 x events
iif m_{hh} > 1.6TeV

Multiple Higgs interactions in WW→HH

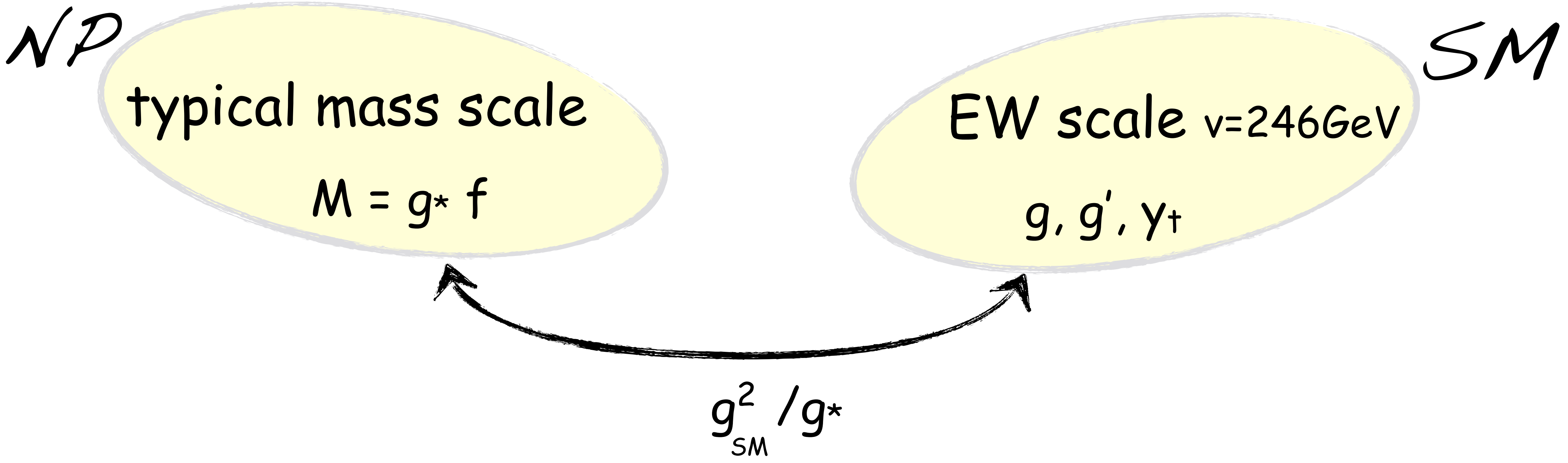


Bondu, Contino, Massironi, Rojo ‘to appear

Conclusions: Higgs & New Physics

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

Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13



NP

typical mass scale

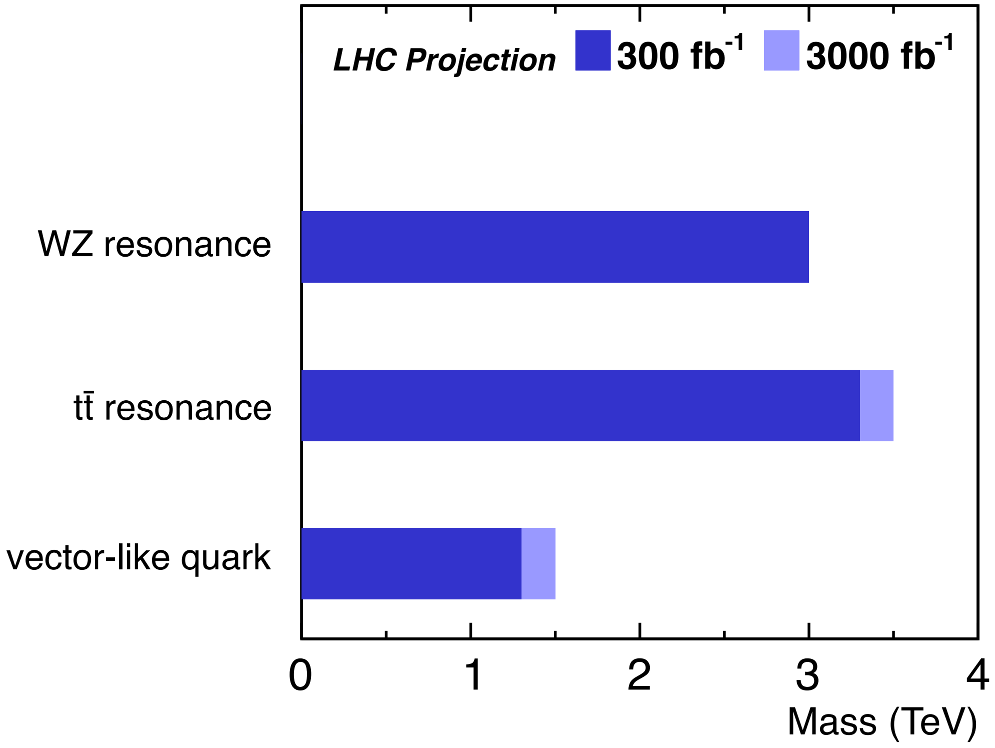
$M = g_* f$

SM

EW scale v=246GeV

g, g', y_t

g^2_{SM} / g_*



LHC direct search

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

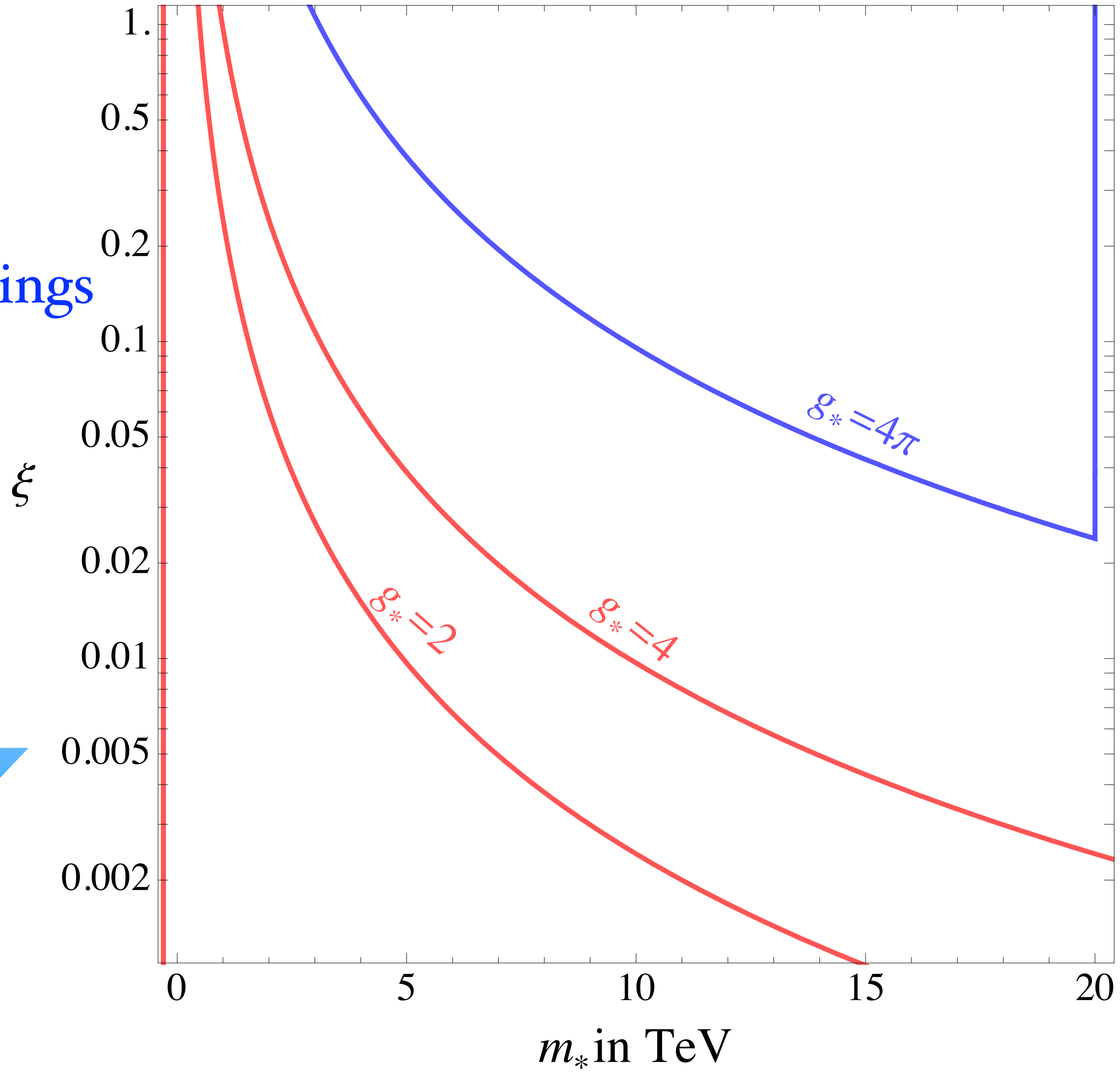
Which one is doing best?
it depends on value of g_*

Conclusions: Higgs & New Physics

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

Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13

Higgs couplings



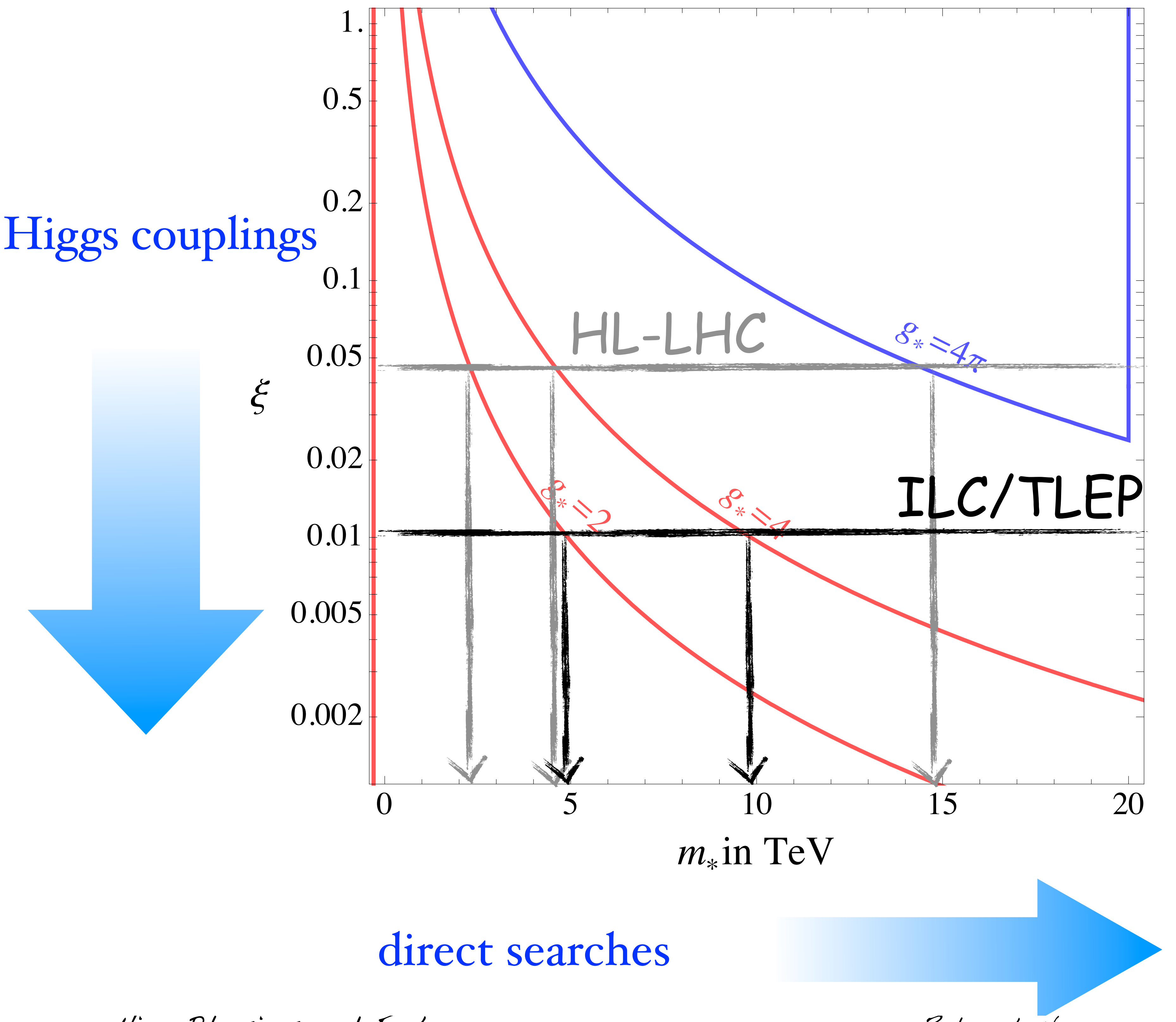
Rattazzi, BSM@100TeV, CERN '14

direct searches

Conclusions: Higgs & New Physics

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

Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13



- nice complementarity between direct searches and precision Higgs physics

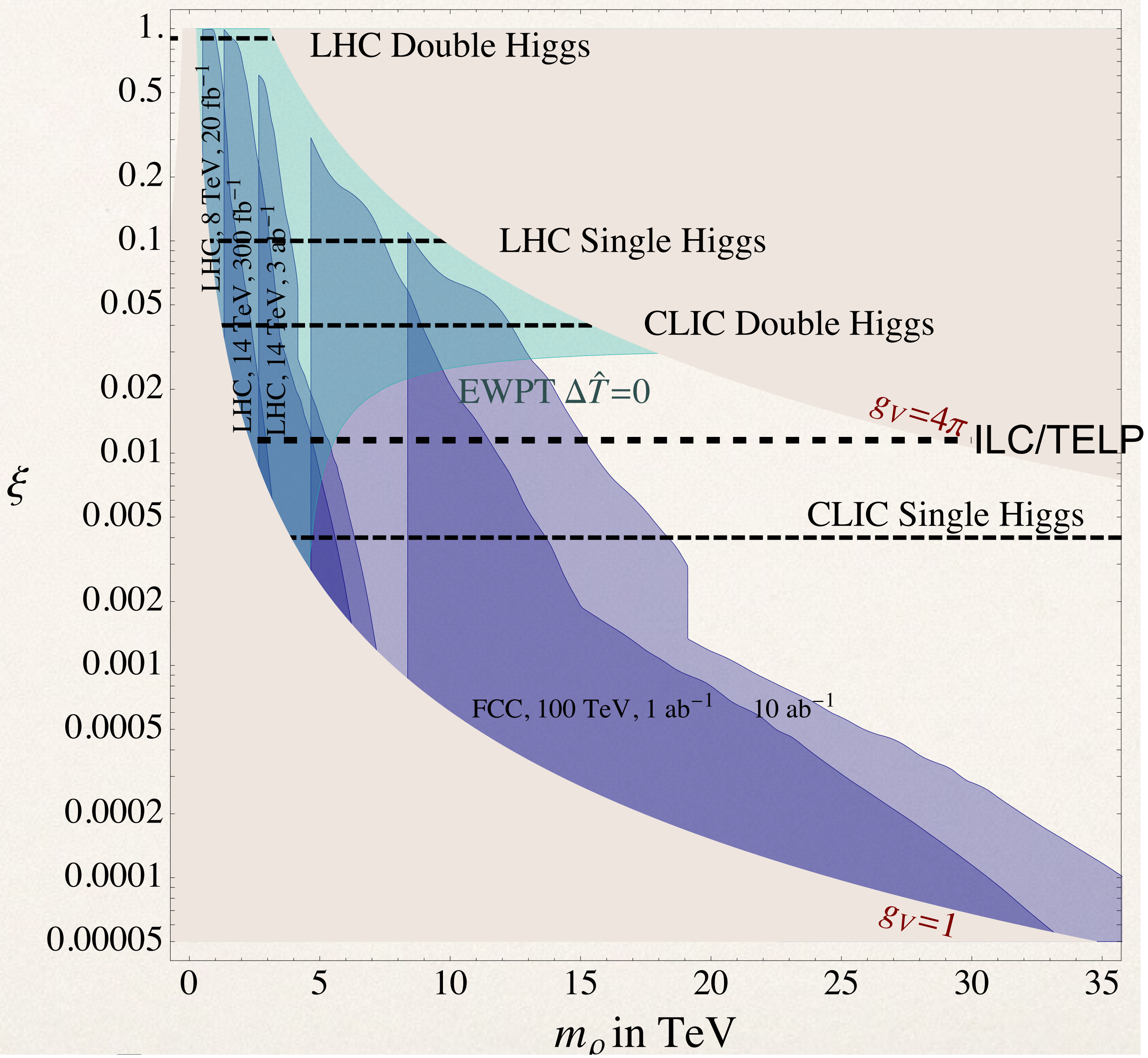
Rattazzi, BSM@100TeV, CERN '14

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 ⇛ $m_V < 10$TeV i.e. resonance within the reach of FCC-hh