Quo Vadis Higgs?

IFAE Colloquium

January 14, 2013

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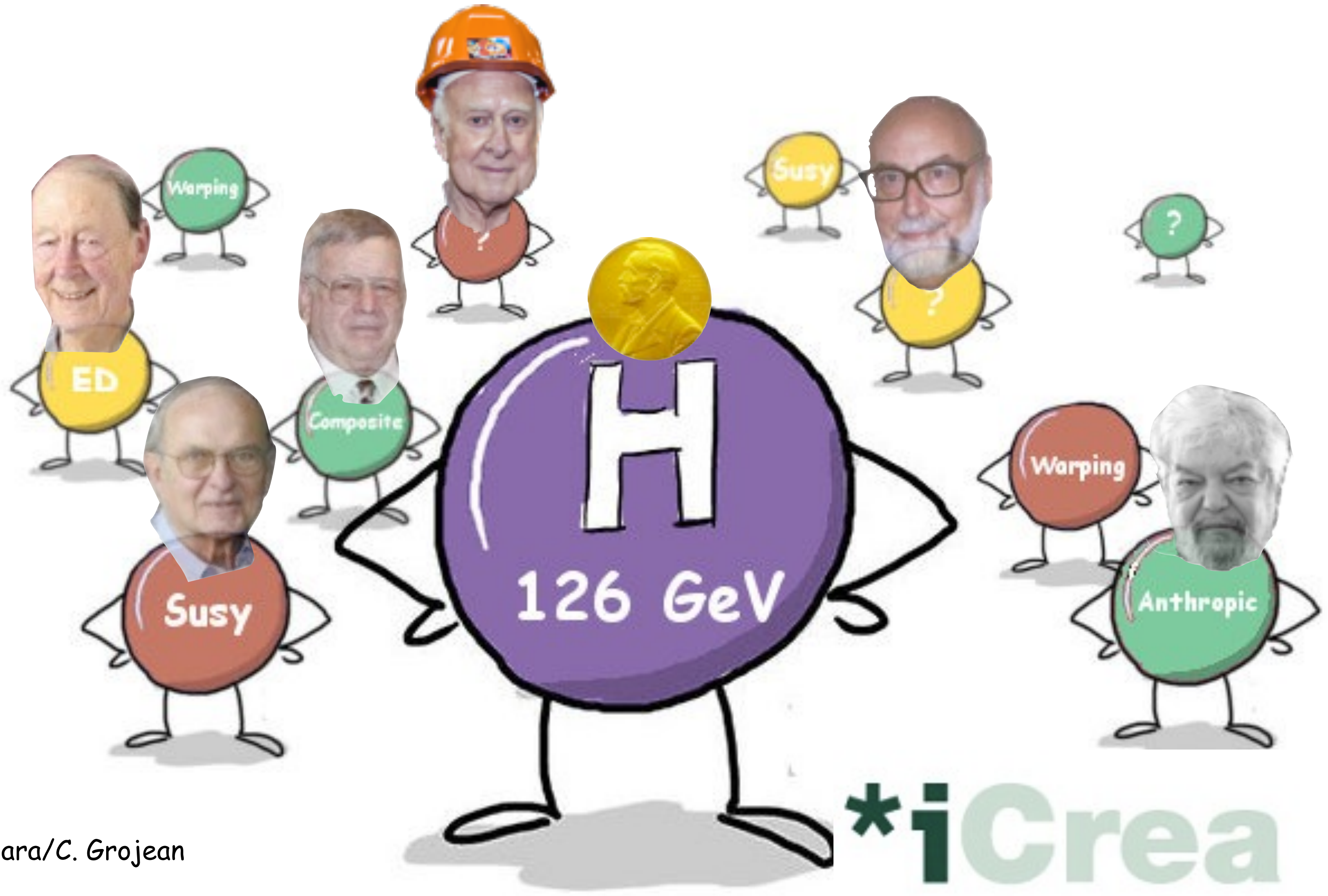
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

Vade Retro
Standard Model Higgs



P. Cámara/C. Grojean

IFAE Colloquium
October 20, 2014

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The mass conundrum

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SM = Quantum Mechanics + Special Relativity

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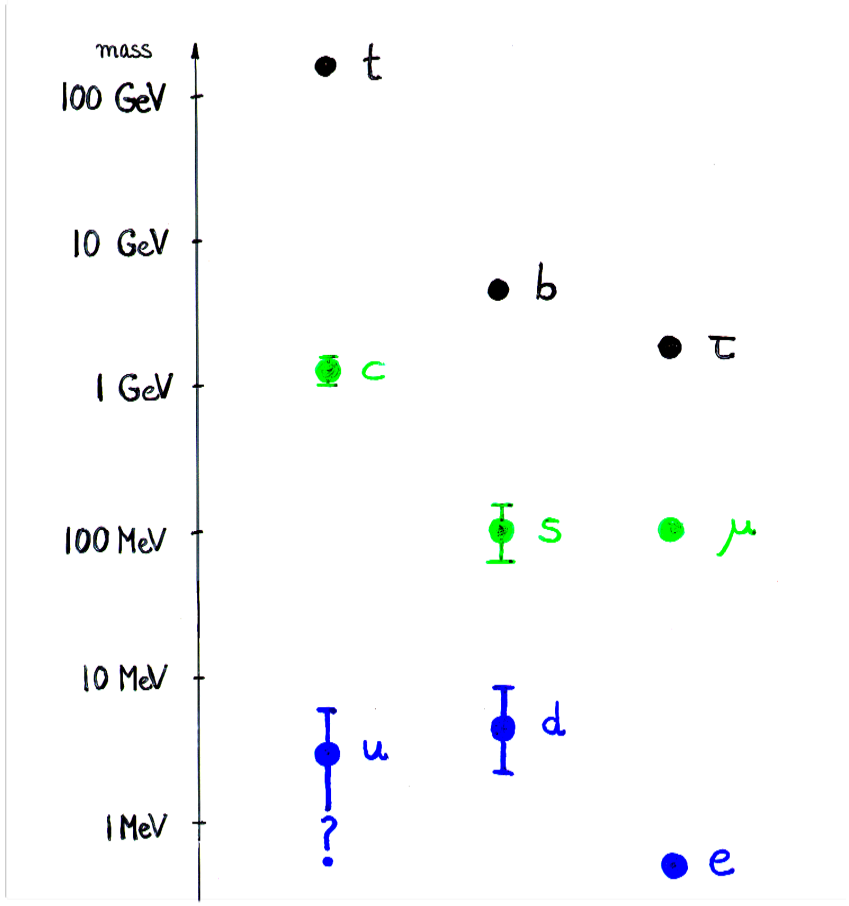

(pictures: courtesy of A. Weiler)

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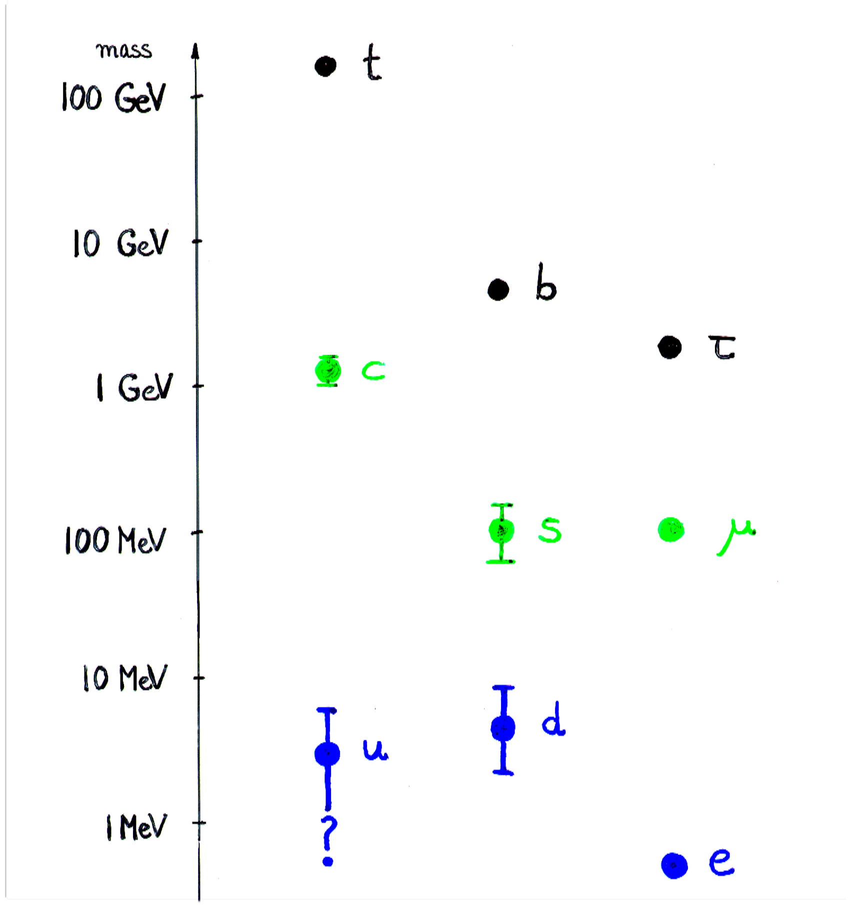

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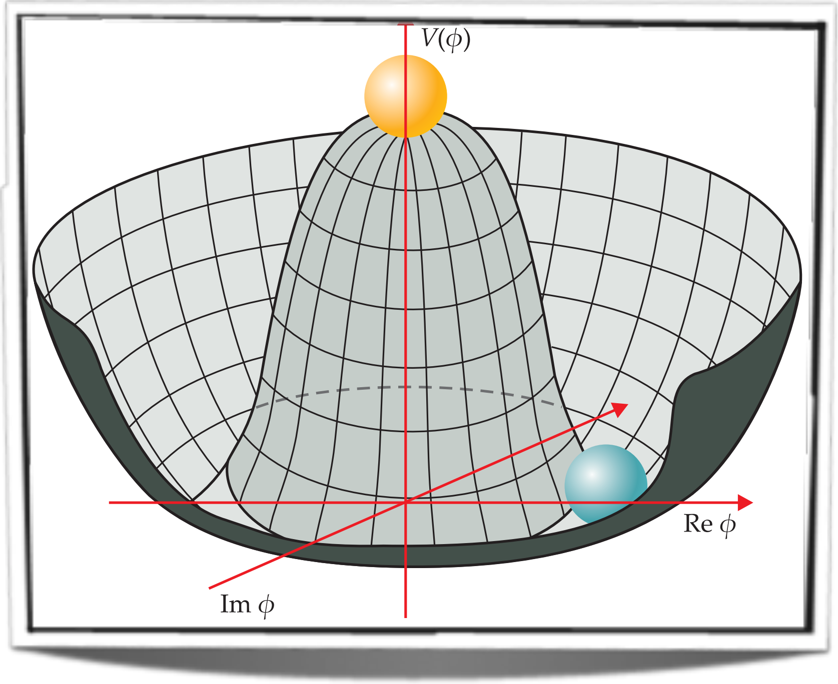
but

incompatible with gauge symmetries
chiral fermion ⇛ m=0 only
gauge boson ⇛ m=0 only

Solution: spontaneous symmetry breaking

The masses are emergent due to a non-trivial structure of the vacuum



vacuum = a space entirely devoid of matter

Oxford English

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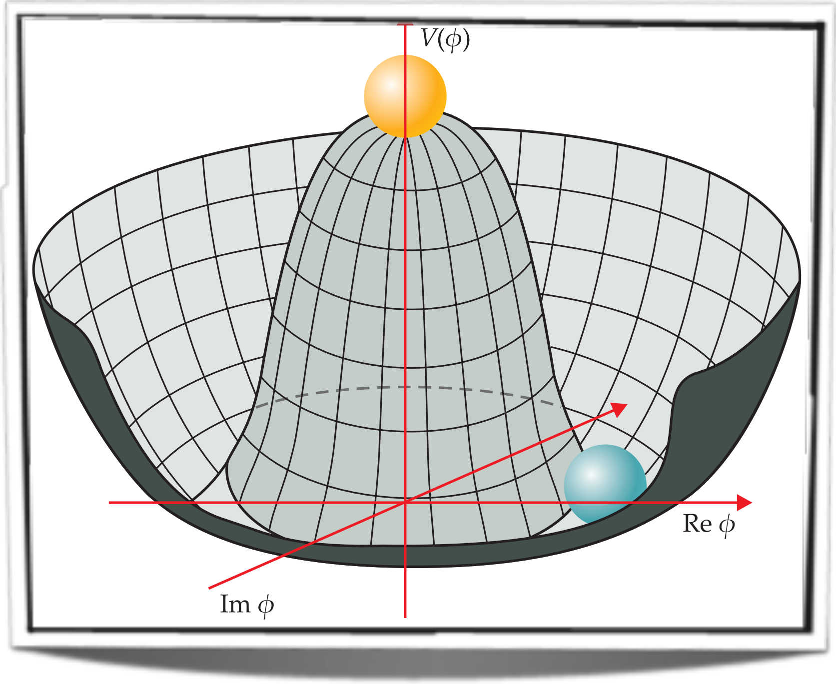

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vacuum = a space filled with Higgs substance

Physics English

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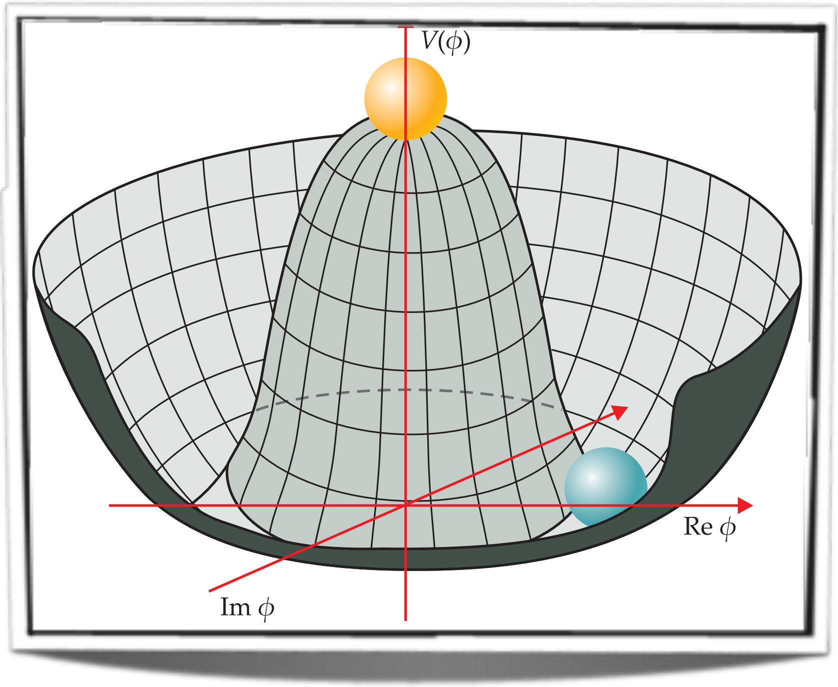

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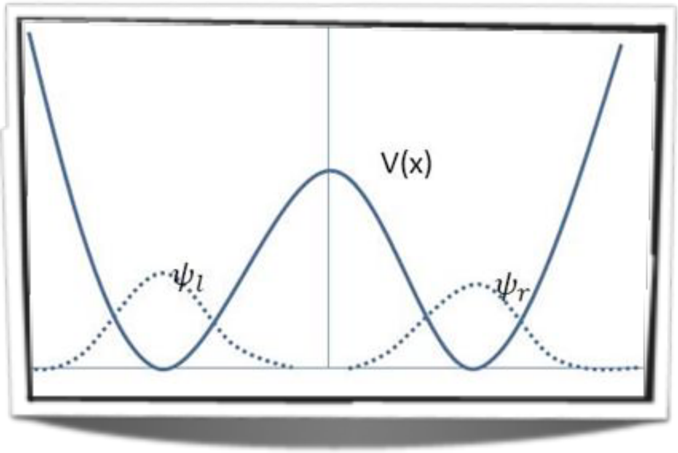
The Brout-Englert-Higgs mechanism is not a trivial thing

(courtesy of J. Lykken@Aspen2014)



ground state of QM double well potential
is a superposition of two states localized on one minimum,
and this superposition preserves the Z_2 symmetry of the potential

the vacuum of the SM breaks SU(2)xU(1) to $U(1)_{em}$

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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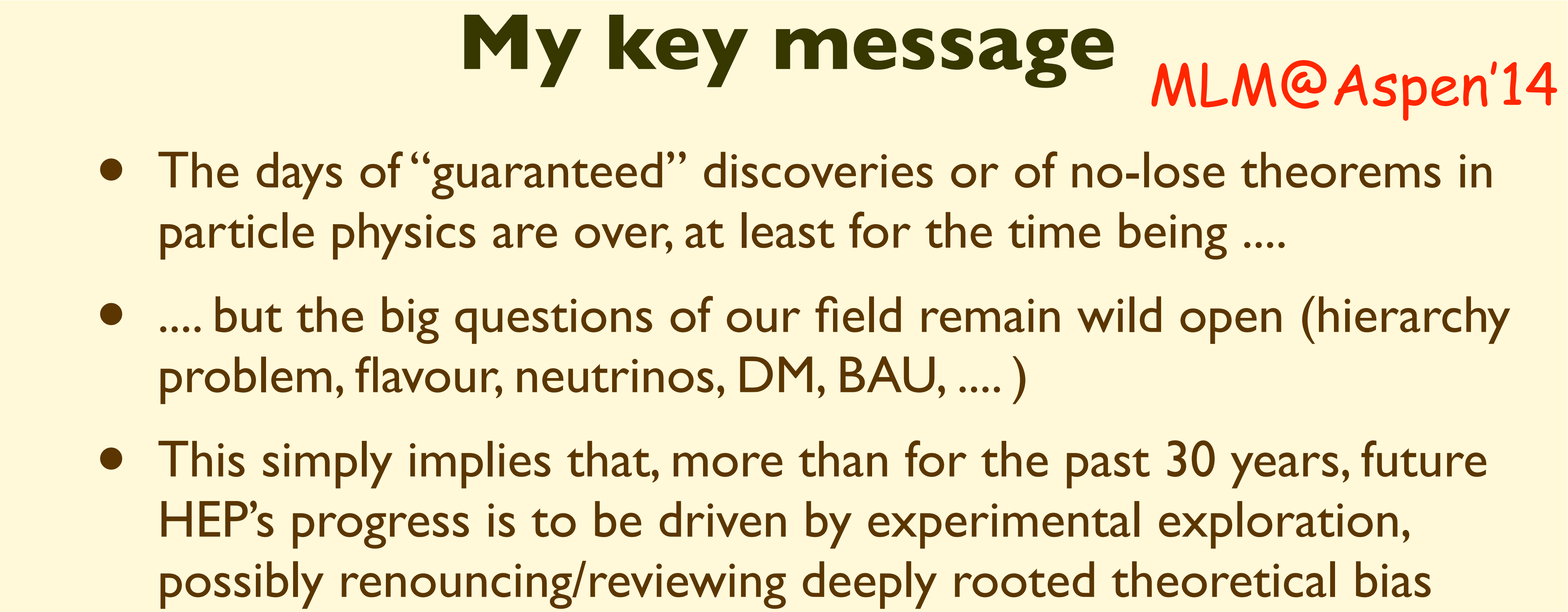

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Where and how does the SM break down?
Which machine(s) will reveal this breakdown?

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors

  (w/ optimized design)
- informs about couplings to quarks and gluons

Leptons

- S/B ~ 1
- polarized beams

  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
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Without knowing the properties of New Physics BSM,
opting for one option a delicate question

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Could have the Higgs boson been discovered
w/o 30 years of theory efforts to characterize it?

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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- Is it the SM Higgs?
- Is it an elementary/composite particle?
- Is it unique/solitary?
- Is it eternal/temporary?
- Is it natural?
- Is it the first supersymmetric particle ever observed?
- Is it really "responsible" for the masses of all the elementary particles?
- Is it mainly produced by top quarks or by new heavy vector-like quarks?
- Is it a portal to a hidden world?
- Is it at the origin of the matter-antimatter asymmetry?
- Is it responsible for the inflationary expansion of the Universe?

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- Is it responsible for the inflationary expansion of the Universe?
- ... Will it help Catalunya to become a CERN member state after the "independence ~~referendum~~"?

consultation

1

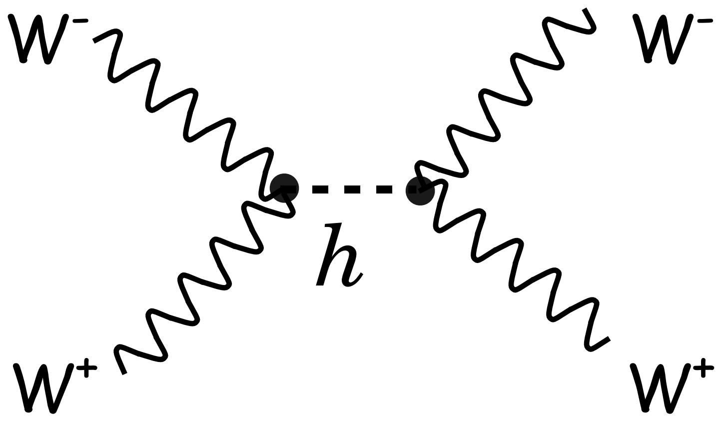
Is it the SM Higgs?

What is the Higgs the name of?

A single scalar degree of freedom neutral under SU(2)$_L$xSU(2)$_R$/SU(2)$_V$

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

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



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s-m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\Sigma = e^{i\sigma^a\pi^a/v}$$

Goldstone of SU(2)$_L$xSU(2)$_R$/SU(2)$_V$

$$D_\mu\Sigma \approx W_\mu$$

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

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

Cornwall, Levin, Tiktopoulos '73

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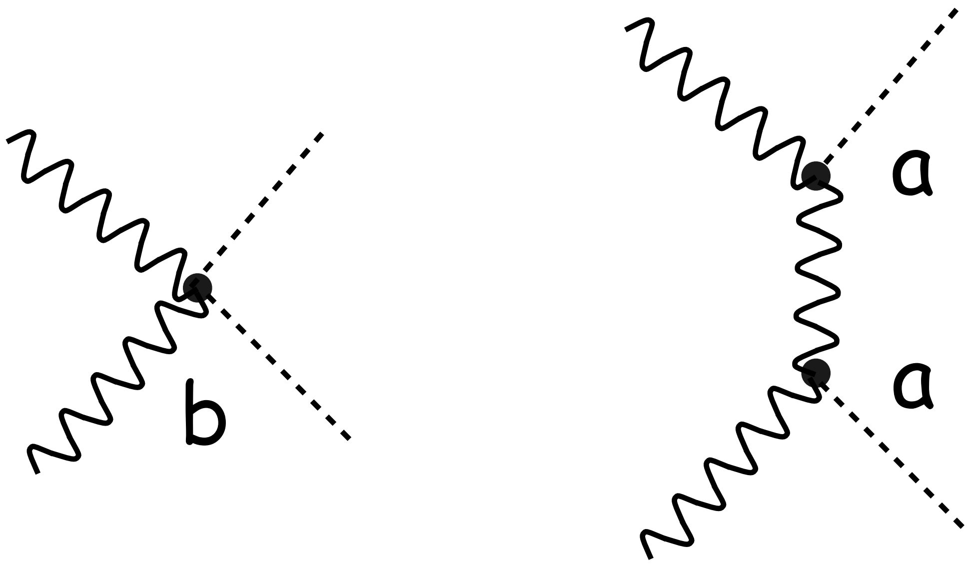

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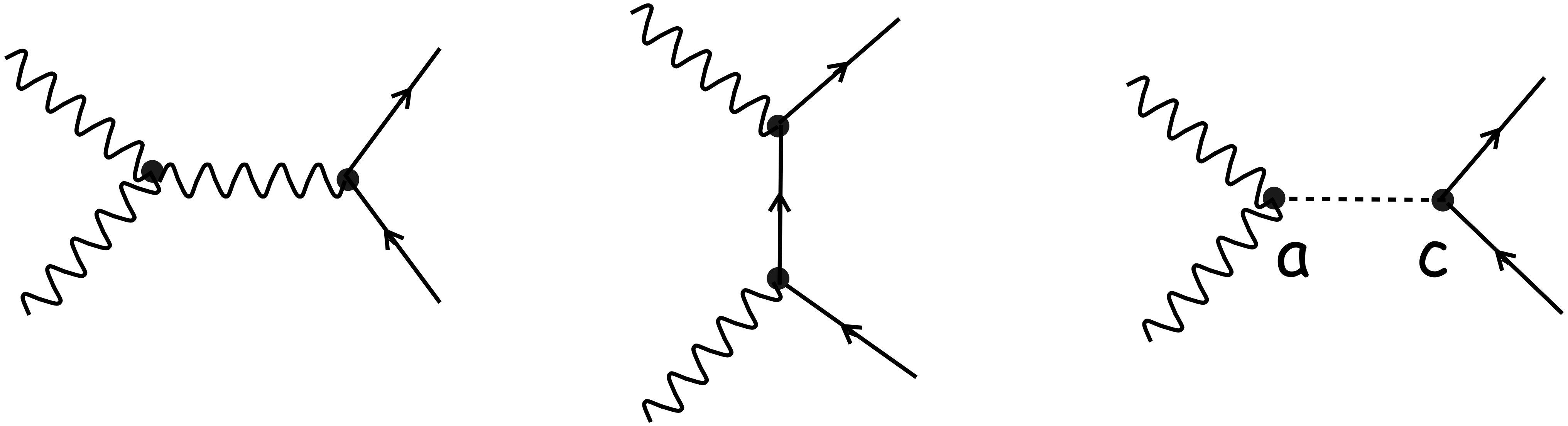

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'a=1', 'b=1' & 'c=1' define the SM Higgs

Higgs properties are fixed once all masses are known (including m_H)

$\mathcal{L}_{\mathrm{EWSB}}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

h and π^a (ie W_L and Z_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

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)$_V$ $D_\mu \Sigma = g V_\mu$

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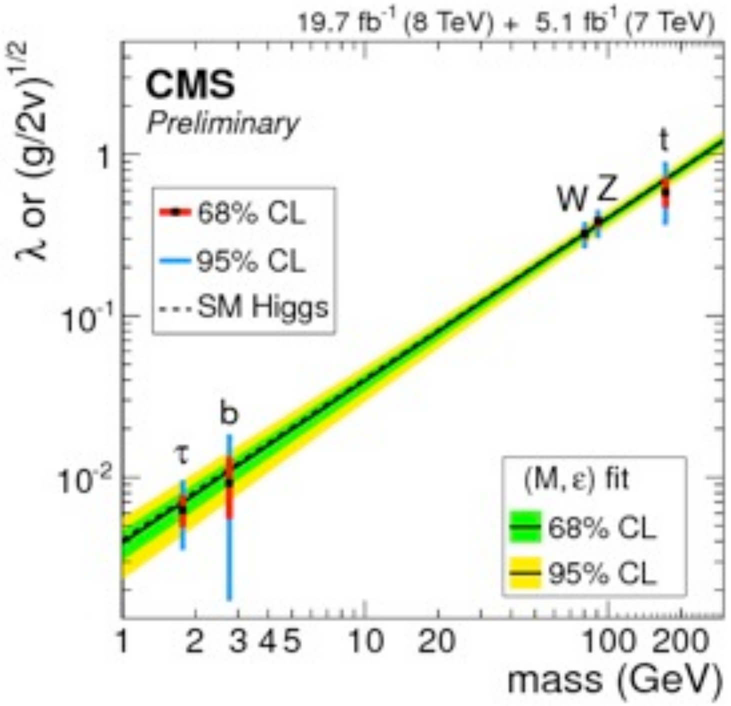

CMS PAS-HIG-14-009

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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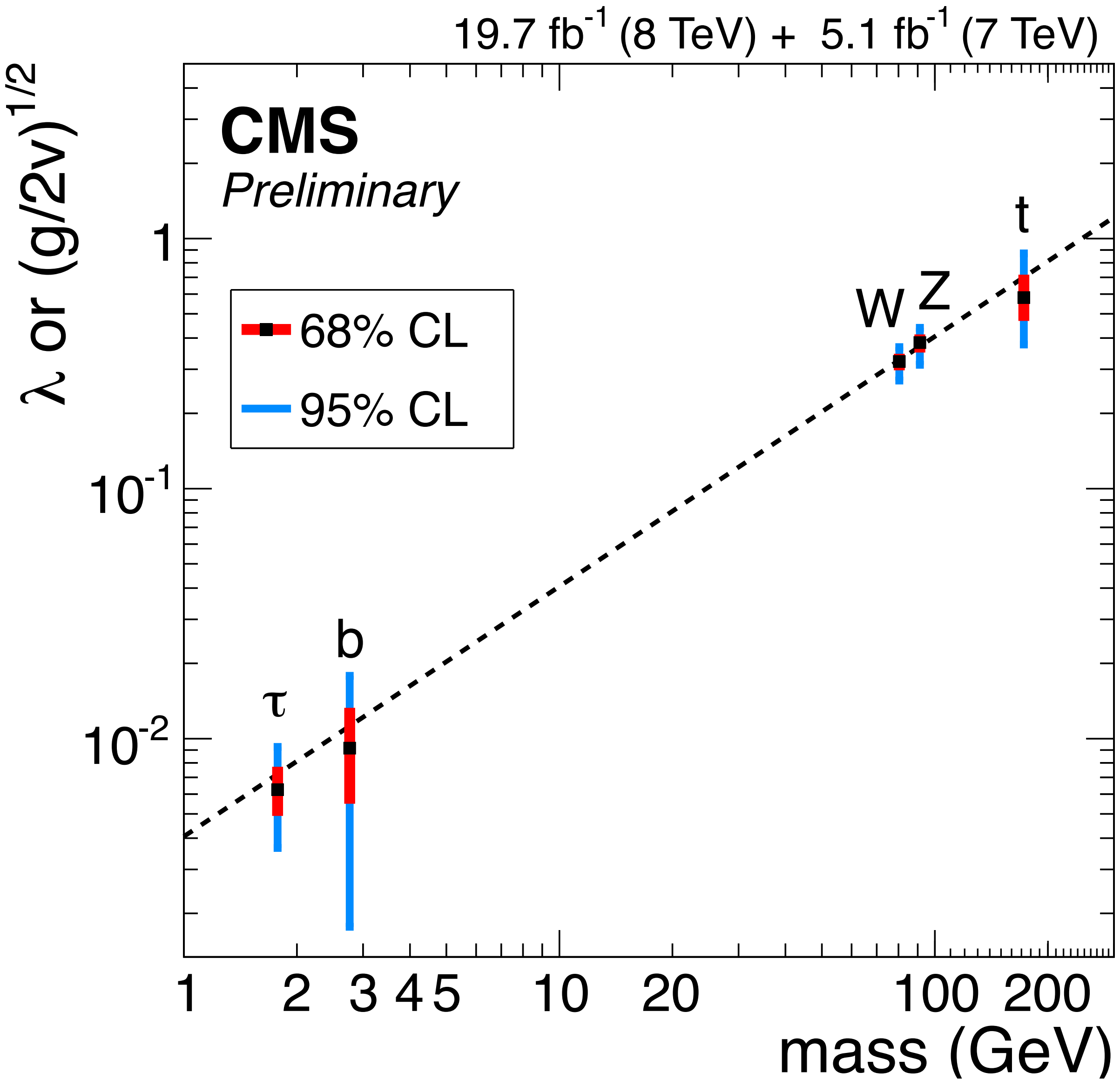
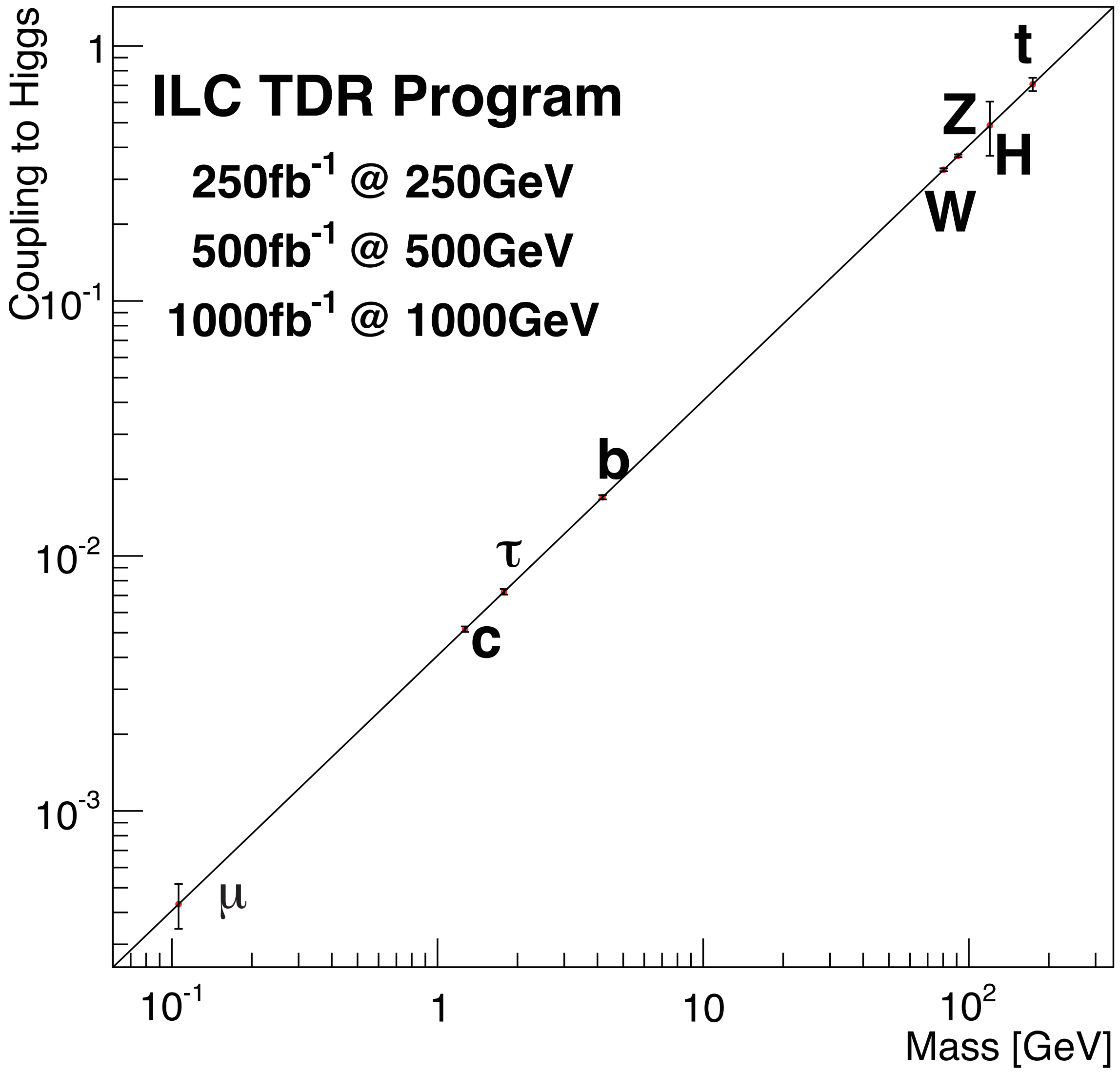




The LHC cannot fully confirm this picture

(no model-independent measurements of the couplings, no access to the couplings to light particles...)

Higgs couplings measurement projections

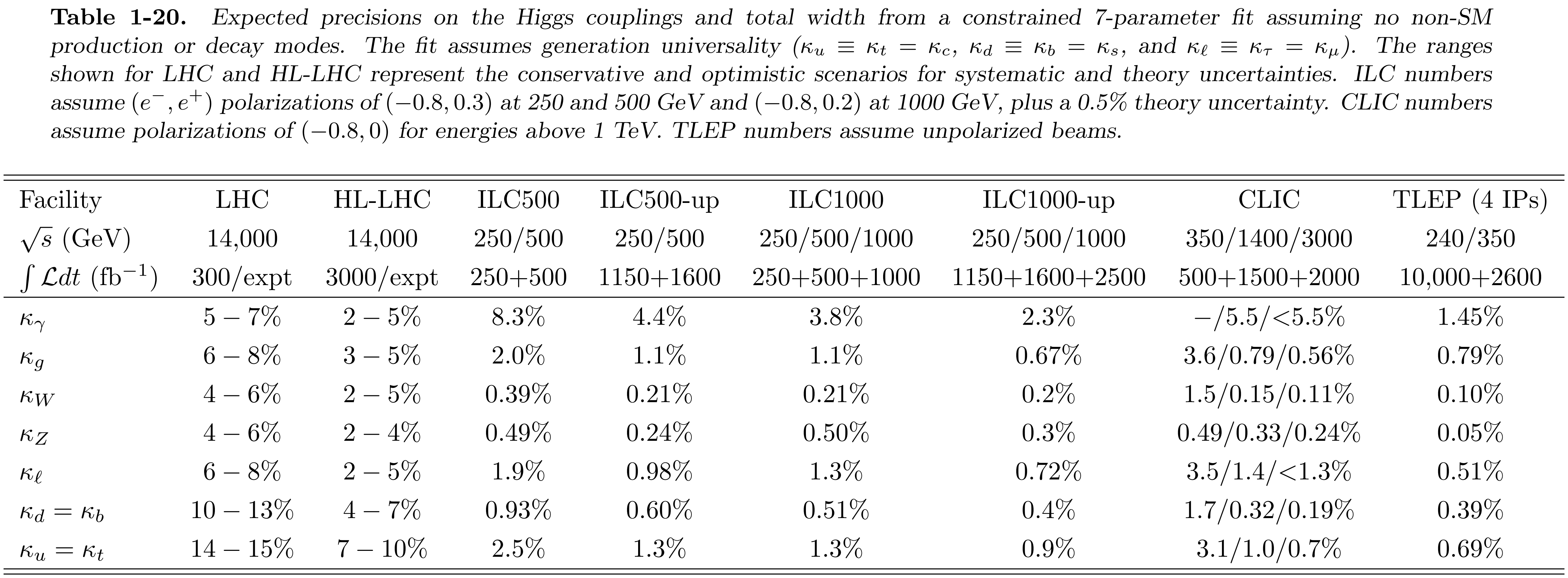
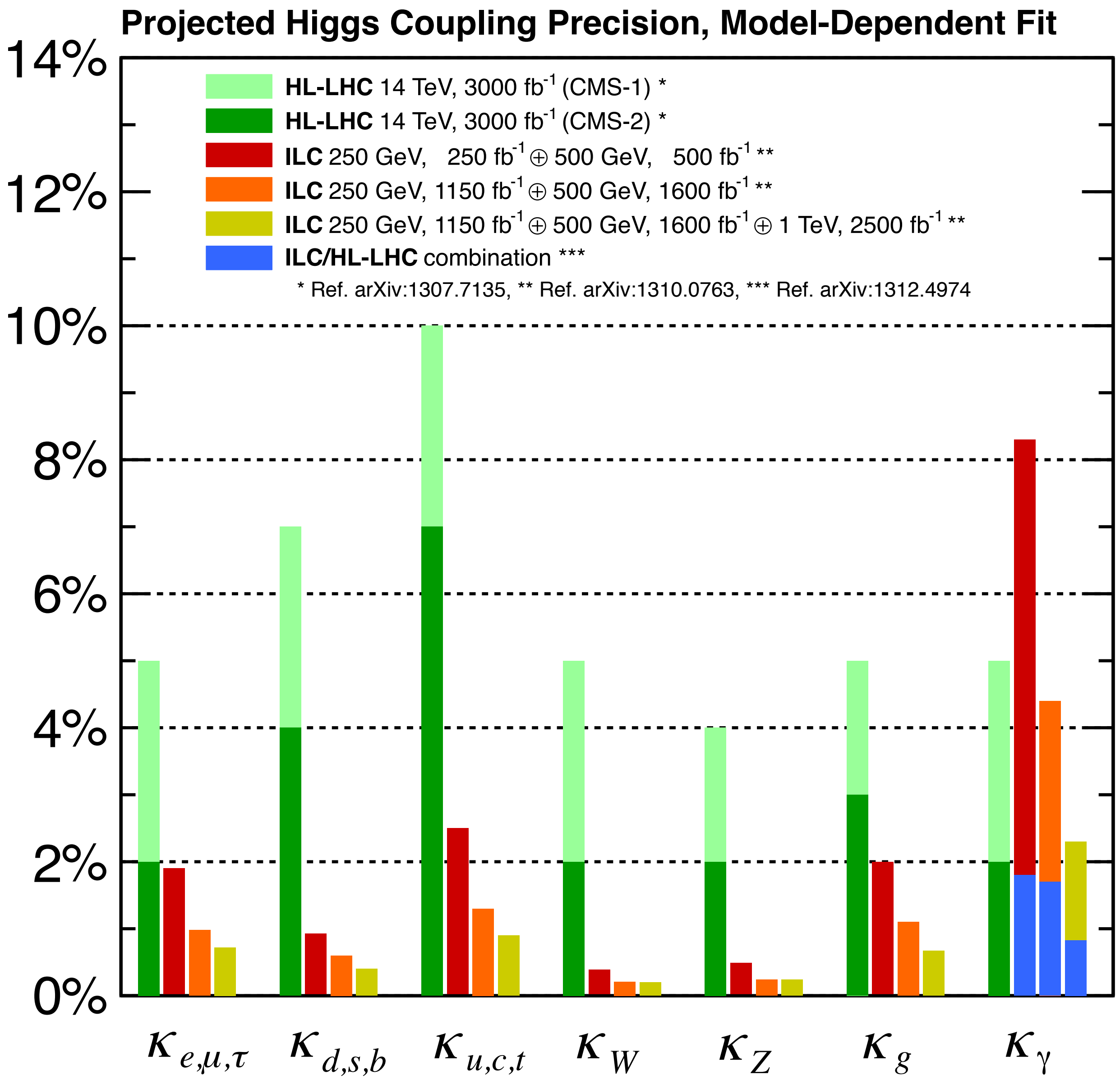


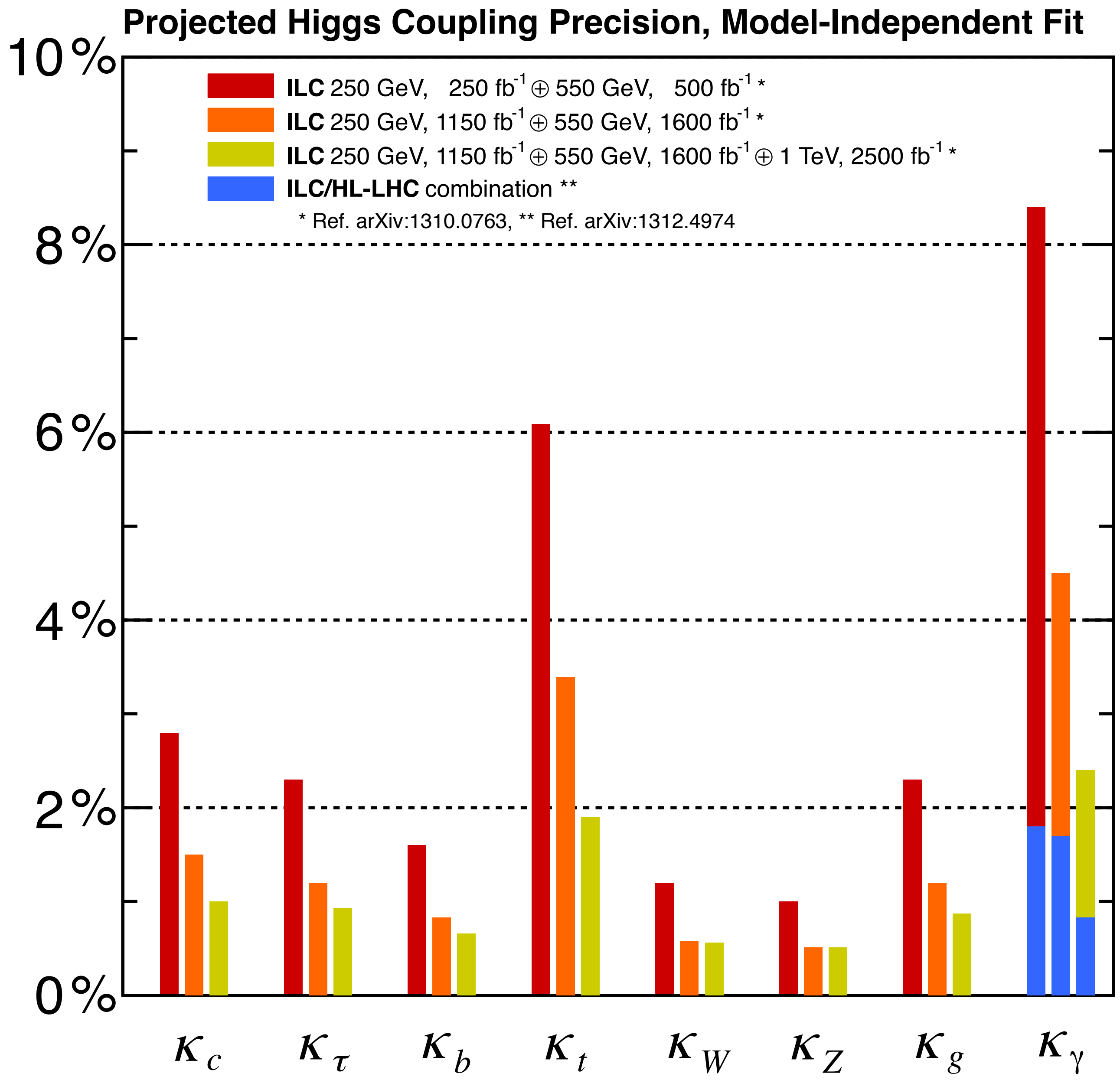
Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Rich experimental program of (sub)percent precision

Higgs couplings measurement projections





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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

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

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

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

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Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $t \to hc$

- weak indirect constrained by flavor data (e.g. $\mu \to e\gamma$): 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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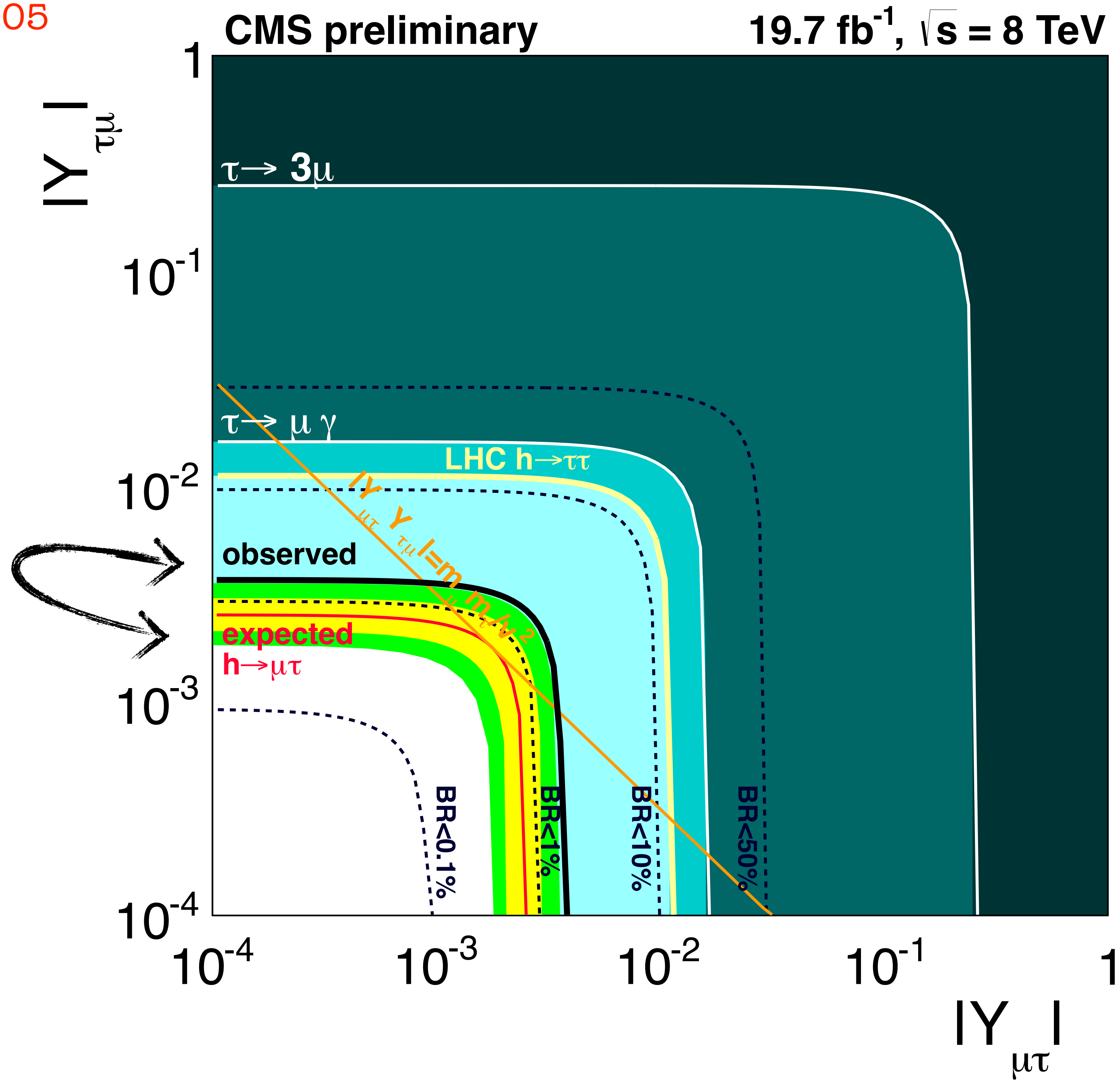
CMS-PAS-HIG-2014-005

by the way:
2.3σ excess!



Off-diagonal Higgs couplings can reveal the origin of flavor

We need to know the prospects to measure them at lepton colliders!

2

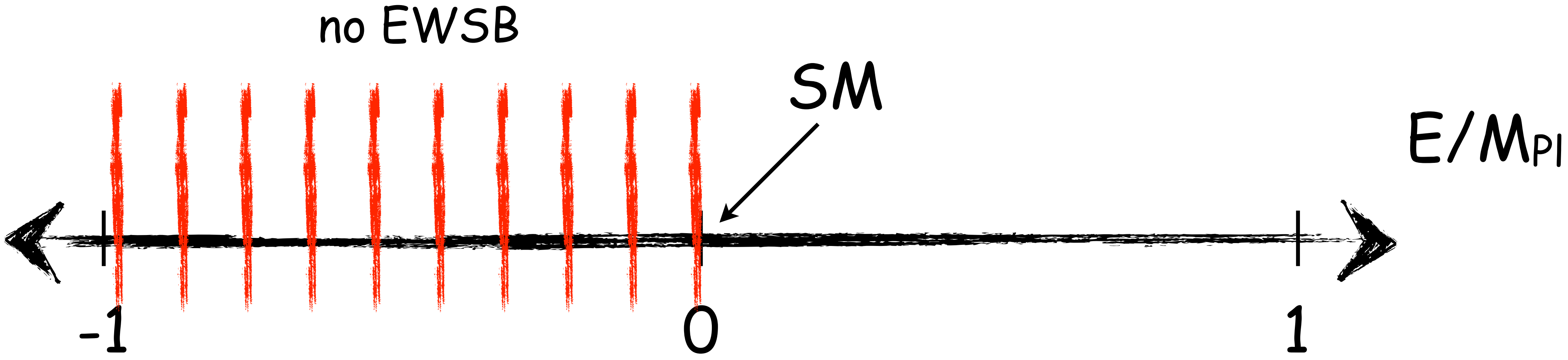
Is Higgs natural?
aka... Where is New Physics?

Higgs & Naturalness

The last unknown parameter of the SM has been measured

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

$$\mu \approx 88.8\,\mathrm{GeV} \qquad \lambda \approx 0.13$$



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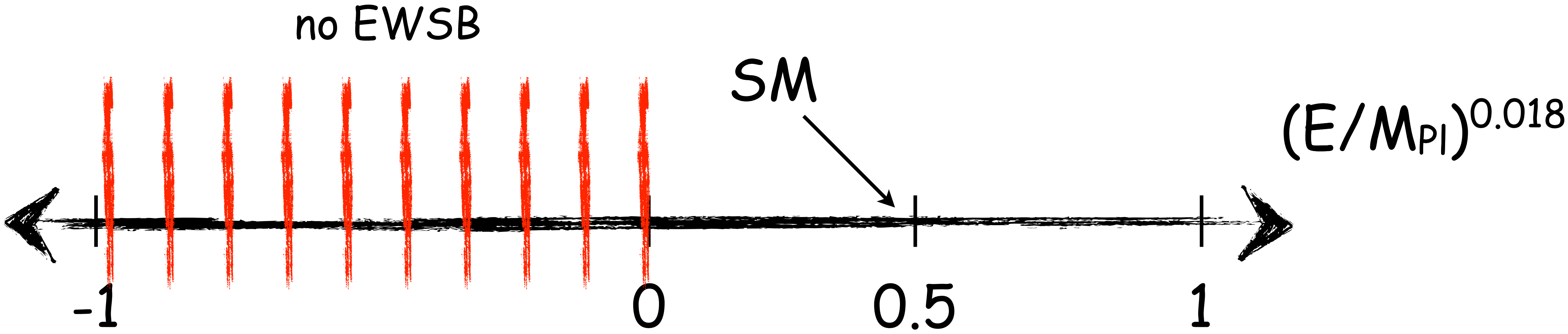

Why m_H/M_{Pl}~10^{-16}? Why m_H so close to the critical boundary?

Change the metric? e.g. $d=(E/M_{Pl})^{0.018}$

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In the meantime...
One more experimental evidence for a fine-tuning in the Higgs sector:

Higgs & Naturalness

Given the absence of signal of new physics
and the compatibility of the Higgs properties with the SM predictions
some doubts arose about the relevance of the naturalness argument
as an organizing principle at higher energies

In the meantime...
One more experimental evidence for a fine-tuning in the Higgs sector:

- ATLAS Higgs discovery paper: arXiv:1207.7214
  - submitted on July 31, 2012@ 11:59:59 GMT
  - 3399 citations (as of Oct. 20, 2014)
- CMS Higgs discovery paper: arXiv:1207.7235
  - submitted on July 31, 2012@ 13:27:18 GMT
  - 3343 citations (as of Oct. 20, 2014)

➠ fine-tuning ≈ 1%

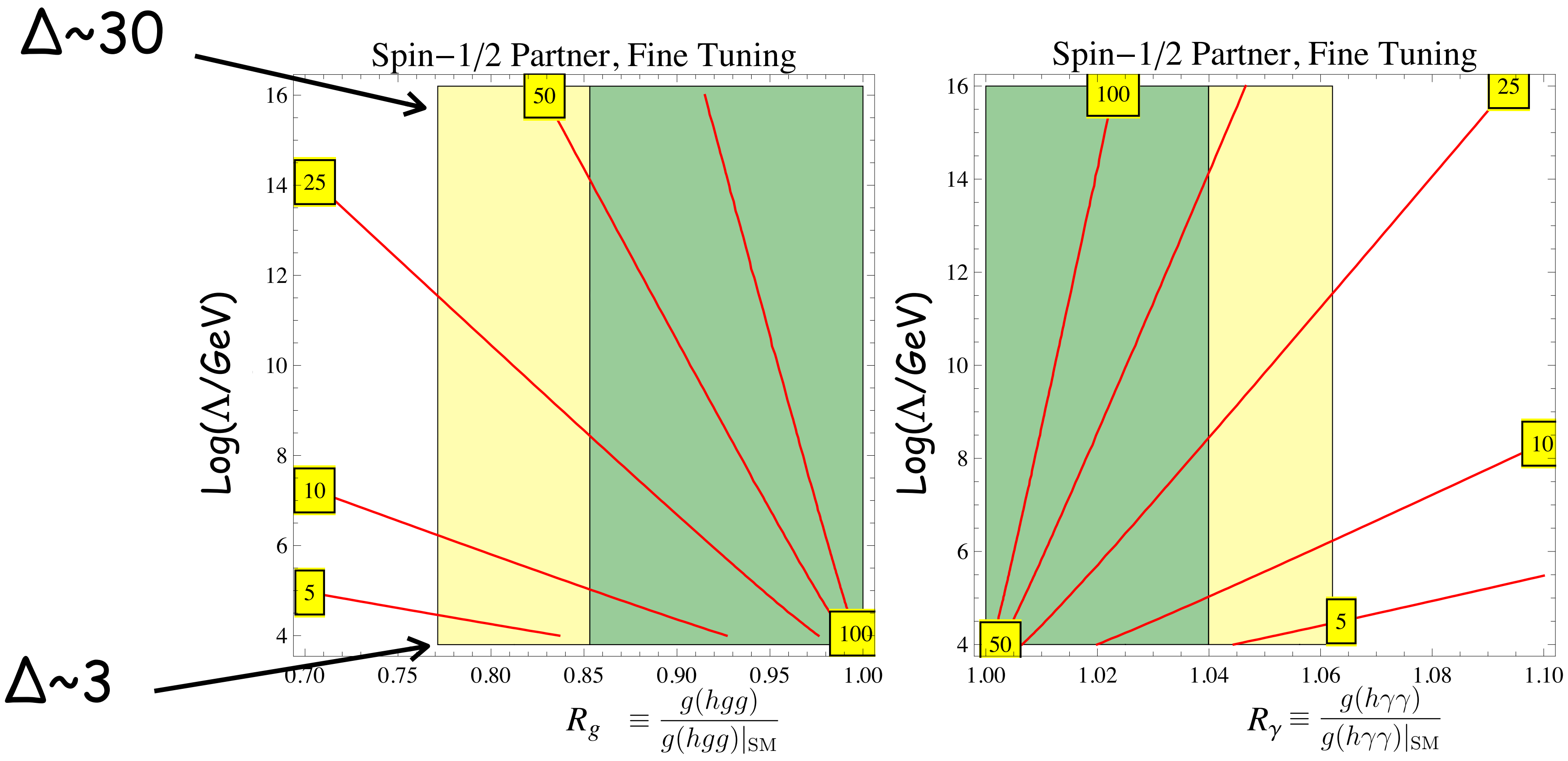
Here, we clearly have a dynamical explanation!

Higgs couplings = test of Naturalness?

simple toy model: a single spin-$\frac{1}{2}$ top partner

deviations in the couplings ⇔ amount of fine-tuning $\Delta = \delta m_H^2 / m_H^2$

Farina, Perelstein, Rey-Le Noisier, ’13



🟩 allowed by LHC/Tevatron at 68%CL

🟨 allowed by LHC/Tevatron at 95%CL

Λ cutoff scale of log. divergences to the Higgs mass

High scale models (Λ ~10^{16}GeV) come with a generic fine-tuning O(1/30)

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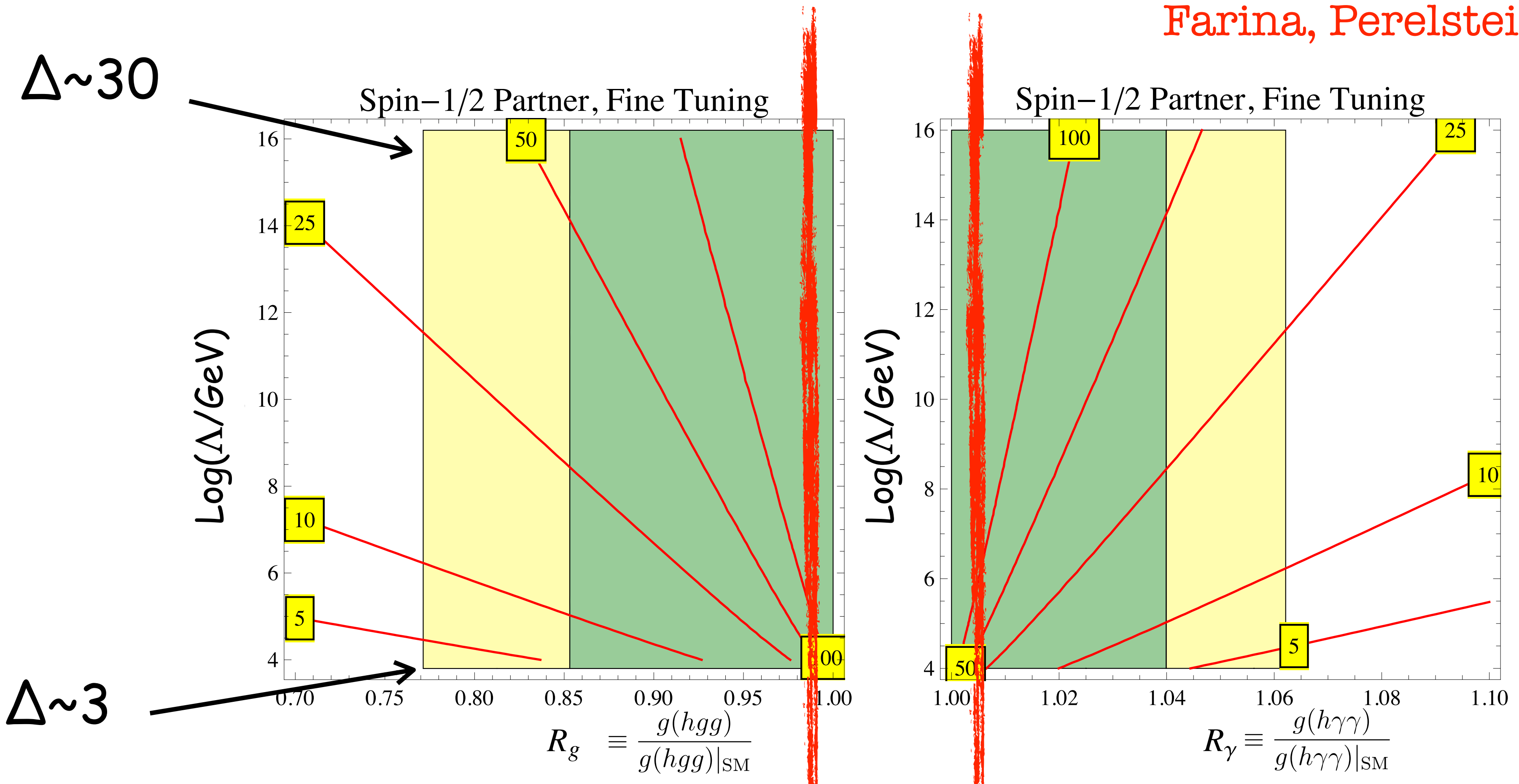

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Λ cutoff scale of log. divergences to the Higgs mass

High scale models (Λ ~10^{16}GeV) come with a generic fine-tuning O(1/30)

Increasing the couplings measurement to 1% precision will raise the fine-tuning to O(1/400)

Higgs couplings = test of Naturalness?

MSSM: more complicated situation: 2 (spin-0) stops w/ mixing

$$\frac{\sigma(gg\to h)}{\mathrm{SM}}\approx(1-0.7\,F_{\tilde t})^2 \qquad\qquad \frac{\Gamma(h\to\gamma\gamma)}{\mathrm{SM}}\approx(1+0.2\,F_{\tilde t})^2$$

$$F_{\tilde t}=-\frac{1}{3}\left[\frac{m_t^2}{m_{\tilde t_1}^2}+\frac{m_t^2}{m_{\tilde t_2}^2}-\frac{1}{4}\,\sin^2(2\,\theta_t)\,\frac{\delta m^4}{m_{\tilde t_1}^2\,m_{\tilde t_2}^2}\right].$$

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$$F_{\tilde{t}} = -\frac{1}{3}\left[\frac{m_t^2}{m_{\tilde{t}_1}^2}+\frac{m_t^2}{m_{\tilde{t}_2}^2}-\frac{1}{4}\sin^2(2\,\theta_t)\,\frac{\delta m^4}{m_{\tilde{t}_1}^2\,m_{\tilde{t}_2}^2}\right].$$

Small mixing: ➡ $\Gamma(gg\to h)$ enhanced

$F_{\tilde{t}} < 0$ $\Gamma(h\to\gamma\gamma)$ suppressed

Large mixing: ➡ $\Gamma(gg\to h)$ suppressed

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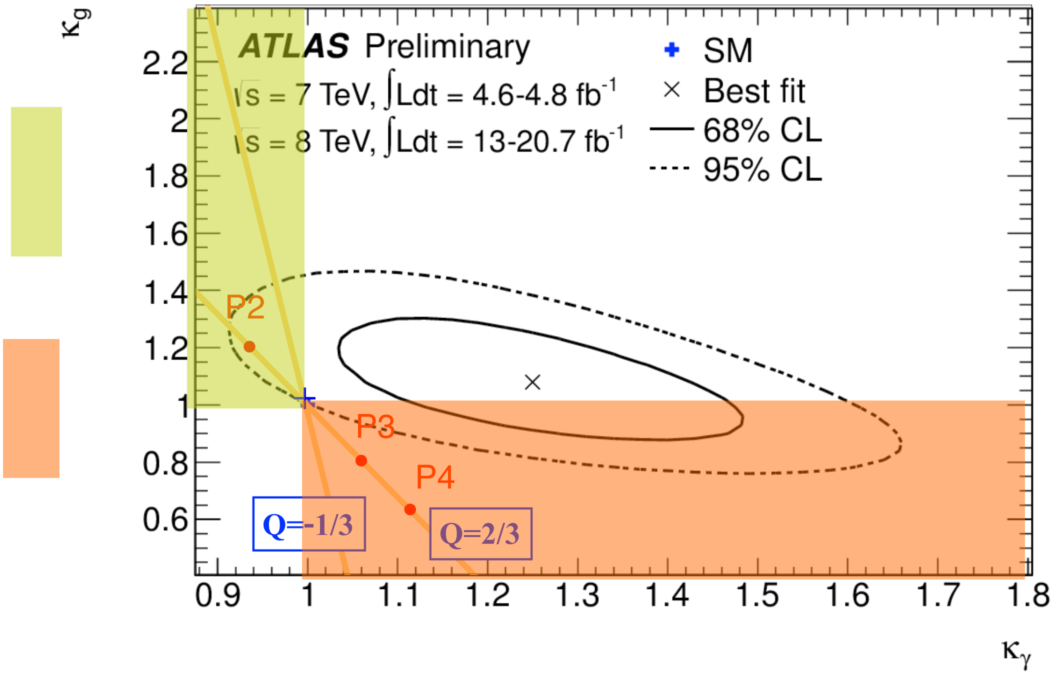
P1: $m_{\tilde t_1} = 100\,\text{GeV},\ m_{\tilde t_2} = 300\,\text{GeV},\ \theta_t = 0$

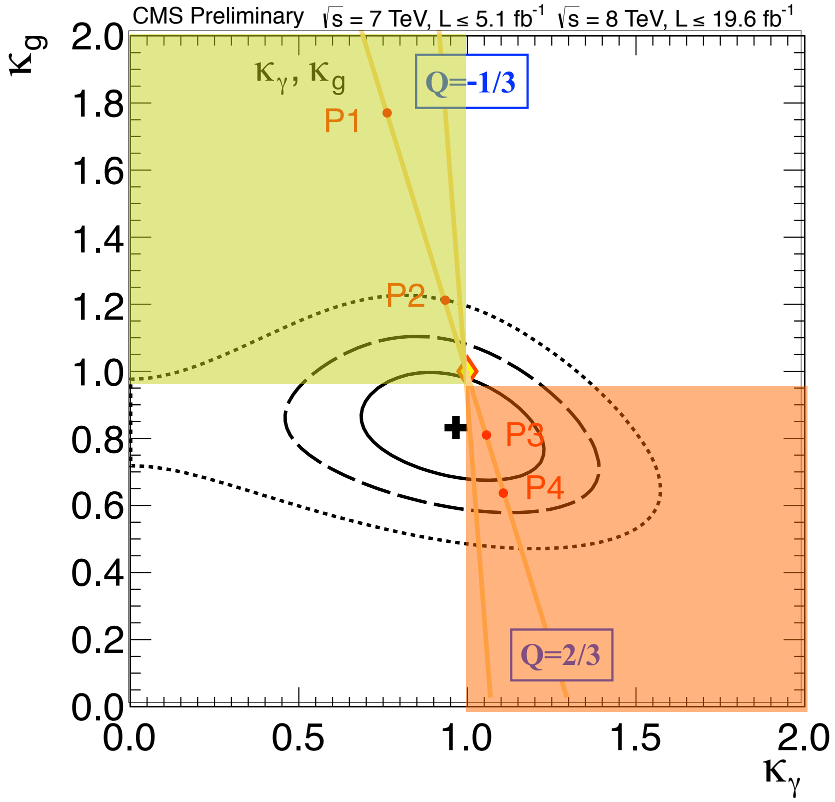
P2: $m_{\tilde t_1} = 200\,\text{GeV},\ m_{\tilde t_2} = 500\,\text{GeV},\ \theta_t = 0$

P3: $m_{\tilde t_1} = 400\,\text{GeV},\ m_{\tilde t_2} = 1000\,\text{GeV},\ \theta_t = \pi/4$

P4: $m_{\tilde t_1} = 500\,\text{GeV},\ m_{\tilde t_2} = 1500\,\text{GeV},\ \theta_t = \pi/4$

Contino, Genova '13





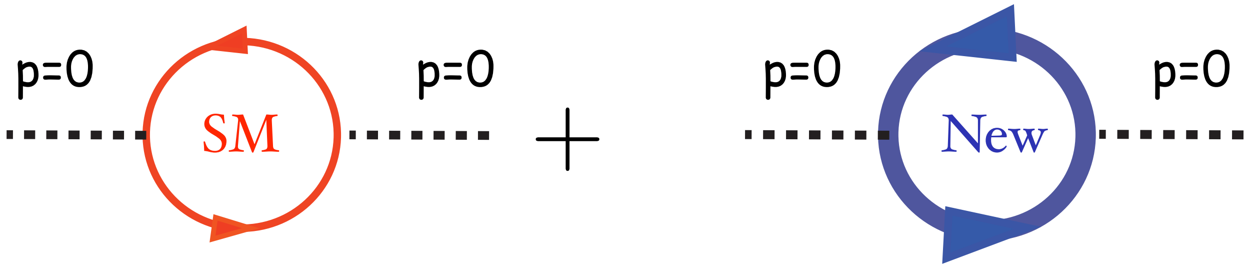
no direct measure of fine-tuning

but Higgs couplings can teach us about stops which are the key players in naturalness

Higgs couplings = test of Naturalness?

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

$$\delta m_H^2 \quad = \qquad\qquad + \qquad\qquad \sim m_H^2$$



charged particles

neutral particles

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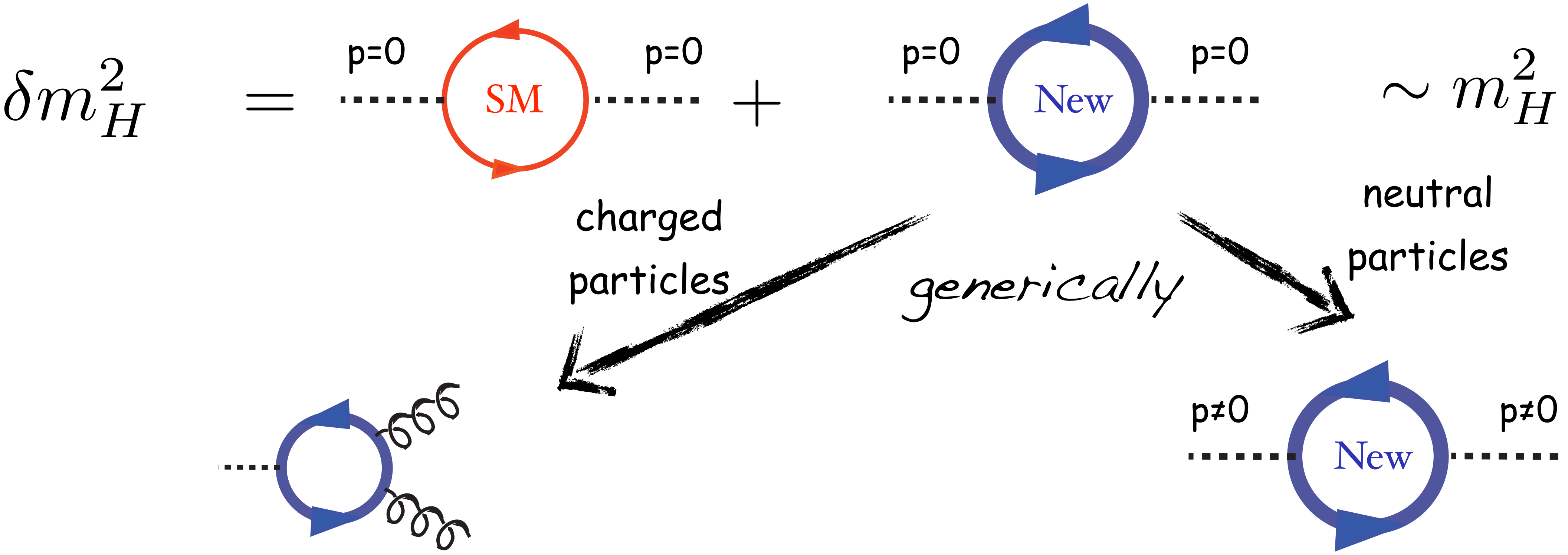


$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2 \qquad \frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

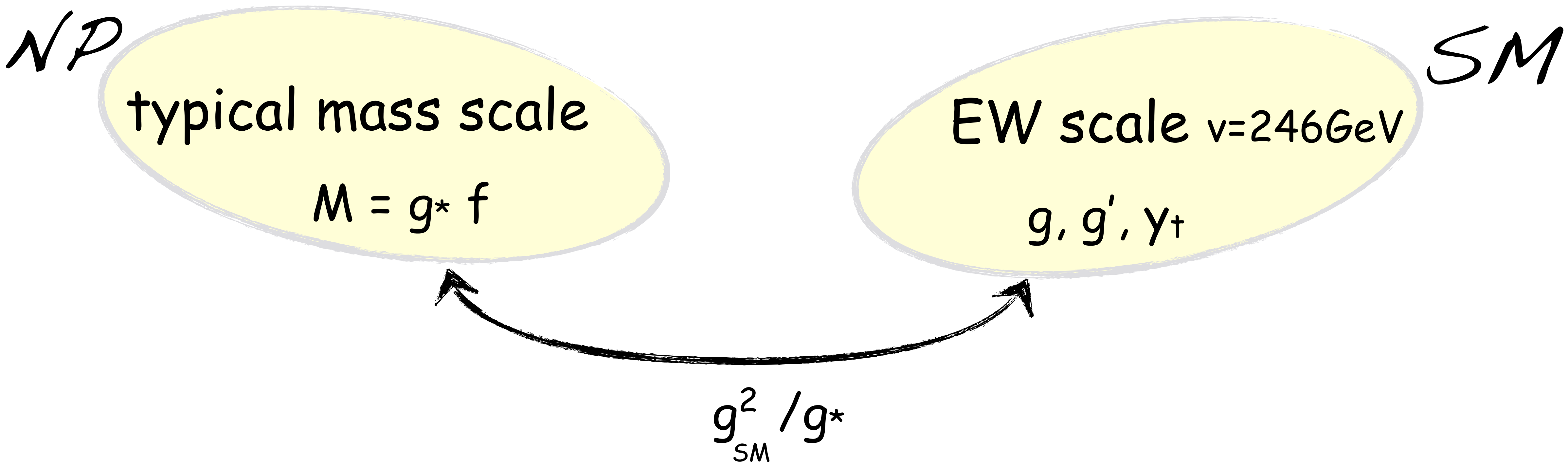
$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2} \qquad BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

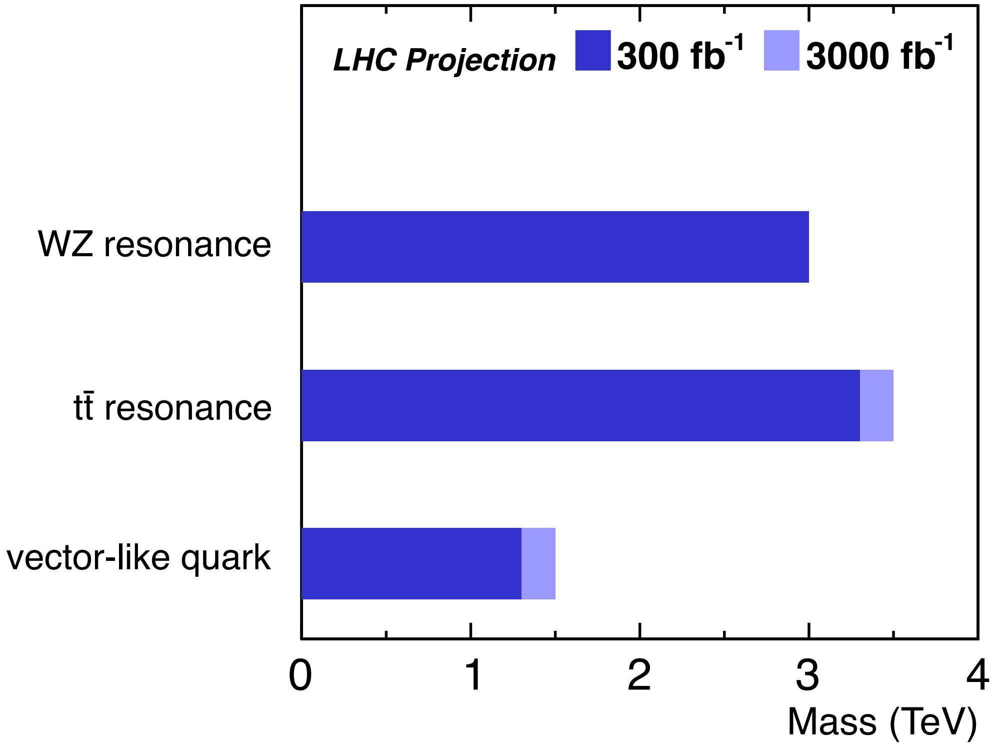
nice to be able to measure Γ

Generically, natural scenarios come with deviations of the Higgs coupling
lower bound on the size of the deviations: O(1%)

Higgs & New Physics

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





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_*

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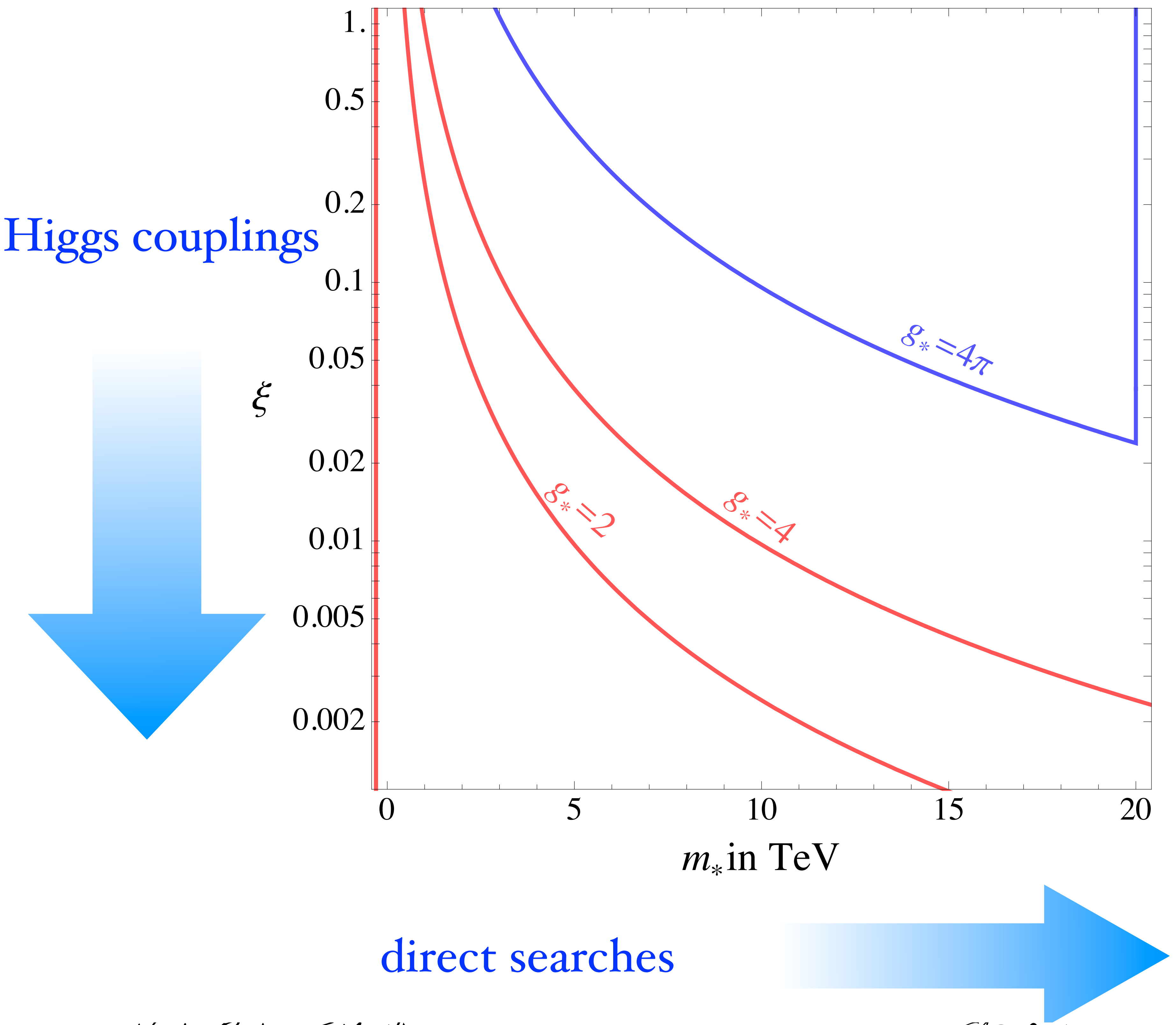
Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Mass reach:

ee machines are best to test strongly coupled NP

pp machines are best to test weakly coupled NP



Rattazzi, BSM@100TeV, CERN '14

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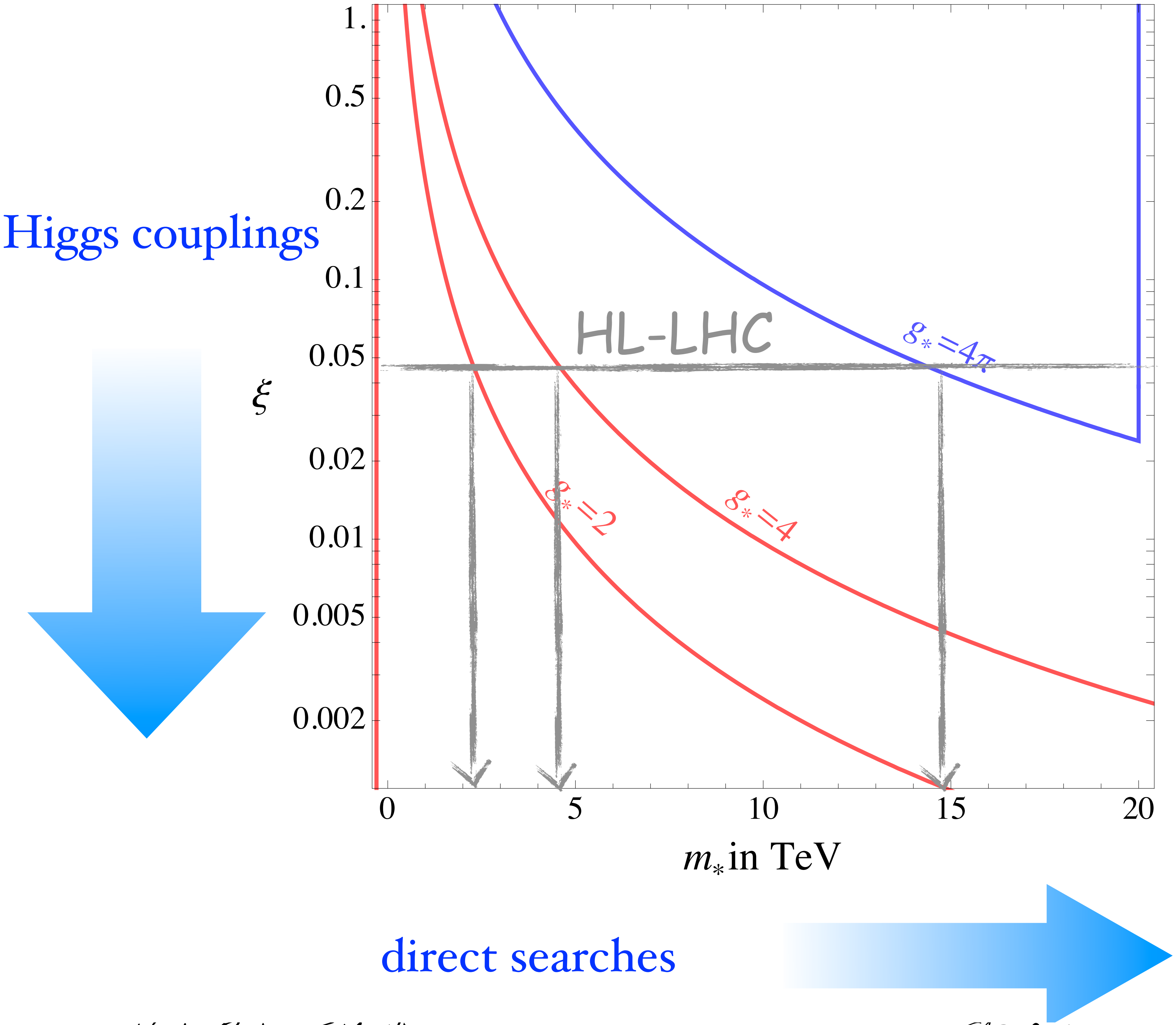

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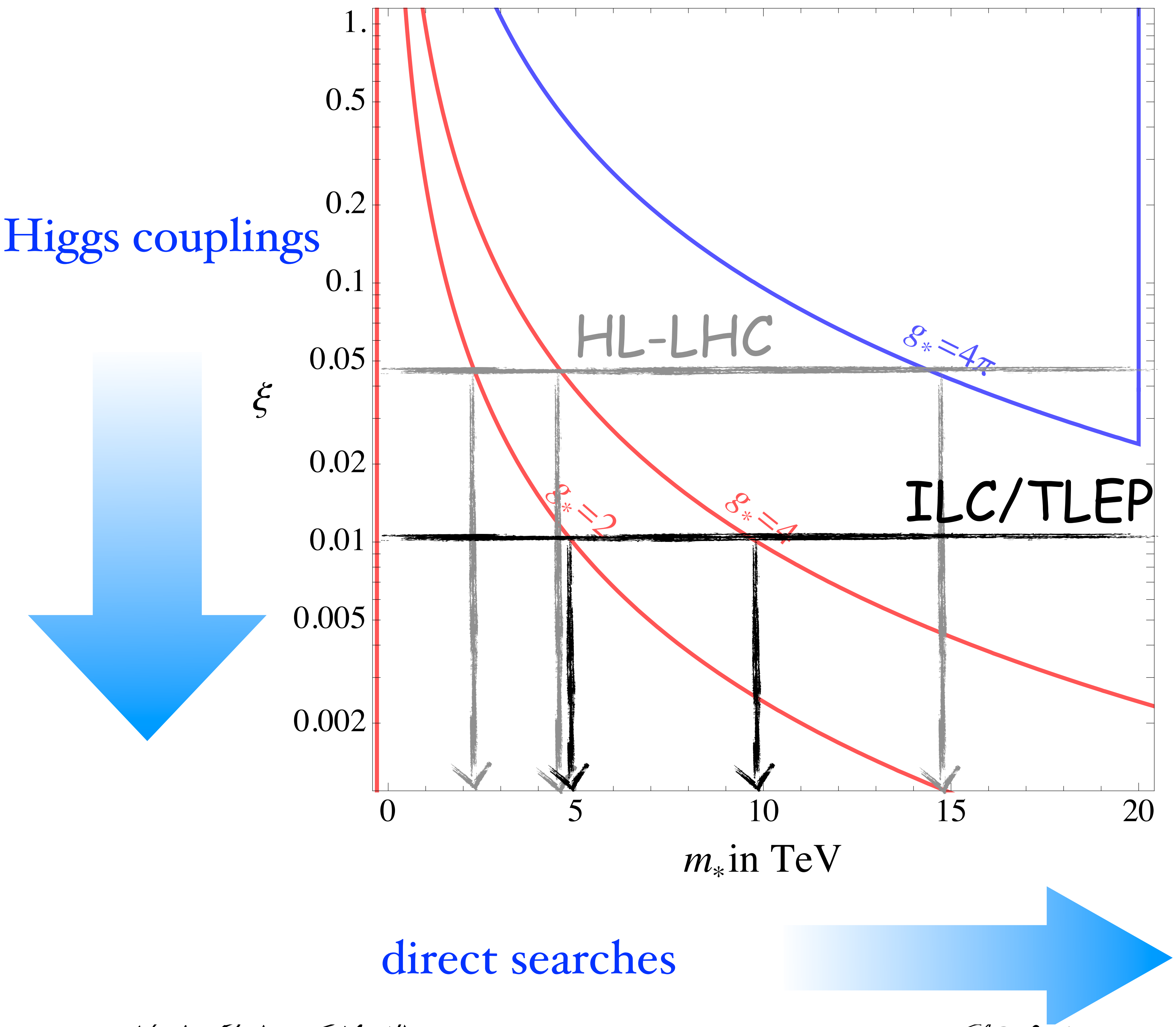

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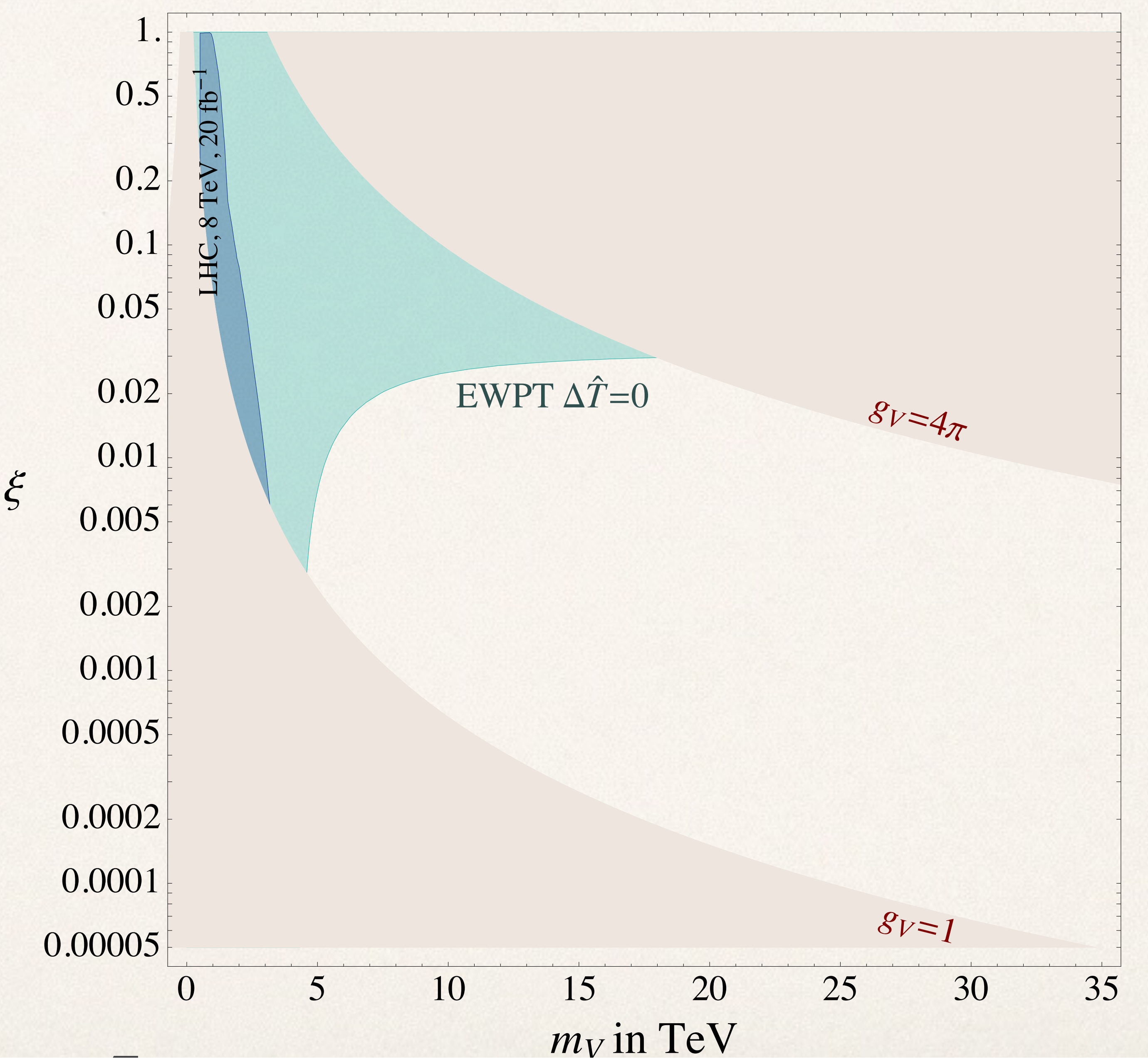
- large region of parameter space already disfavored by EW precision data

- 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

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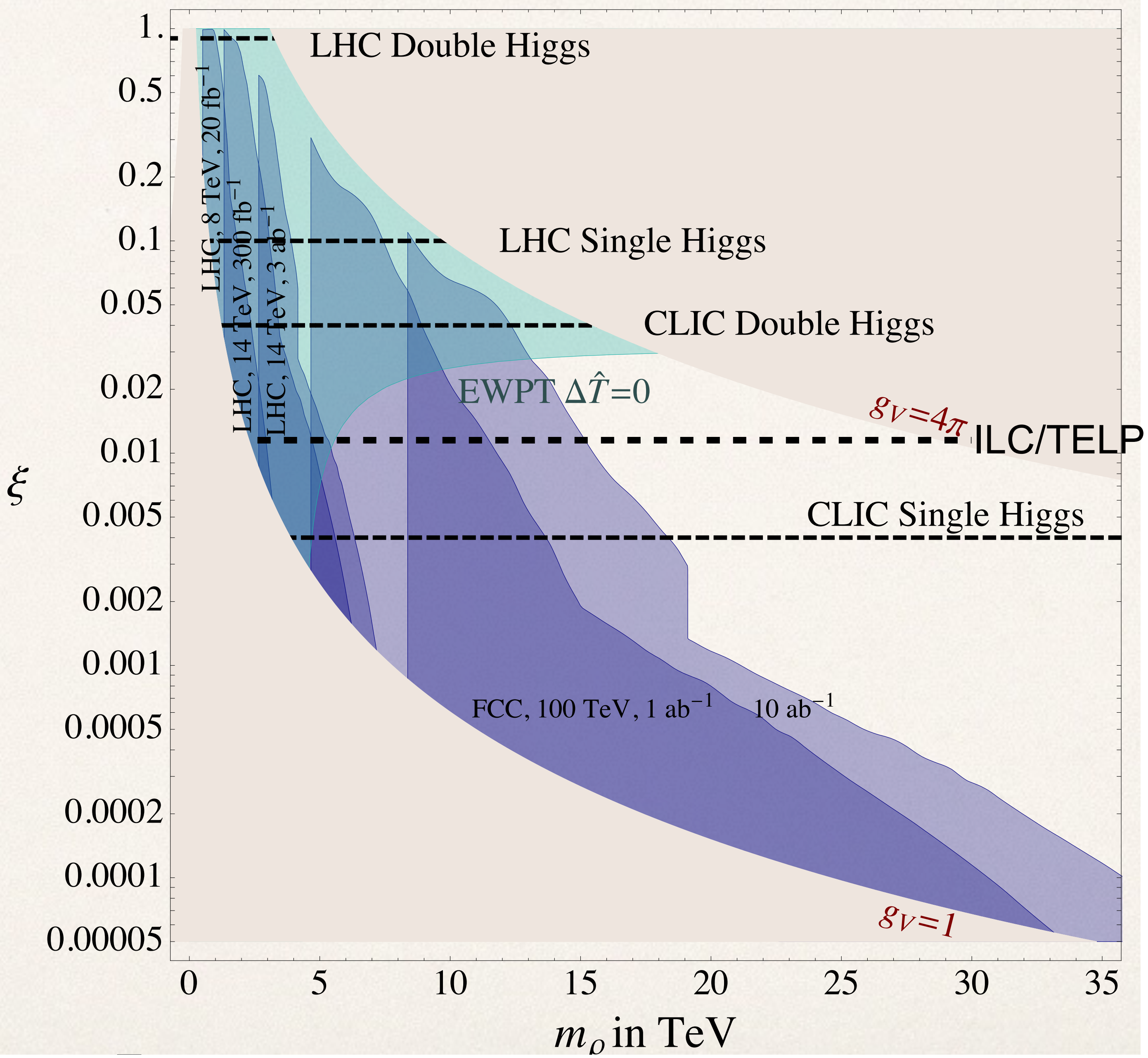

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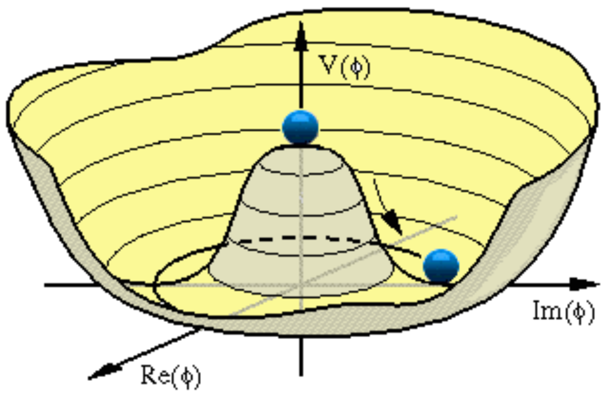
3

Is the Higgs a portal to New Physics?

Higgs physics vs BSM

$\phi = v+h$

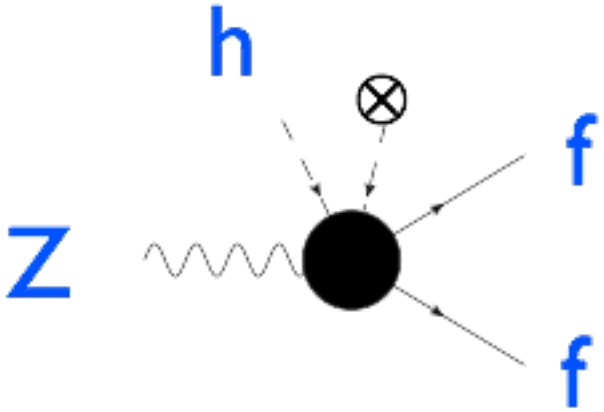
↳ vacuum



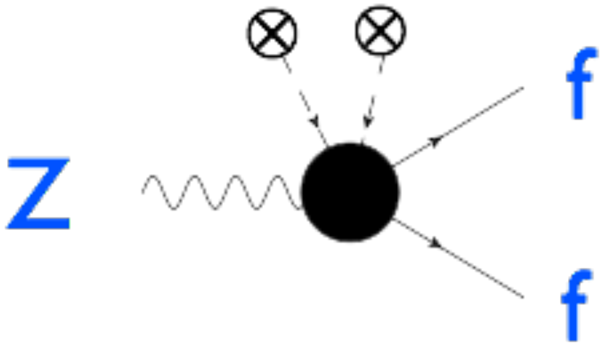
(courtesy of A. Pomarol@Moriond2014)

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

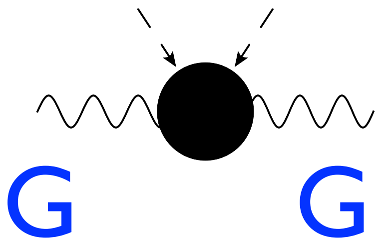
Higgs/BSM Primaries

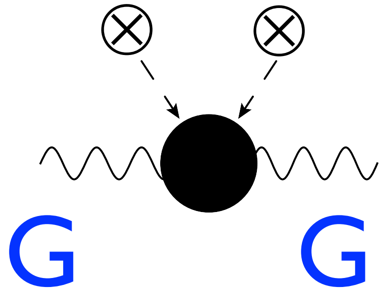
Effects that on the vacuum, **H** = v, give only
a redefinition of the SM couplings:

(courtesy of A. Pomarol@HiggsHunting2014)

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

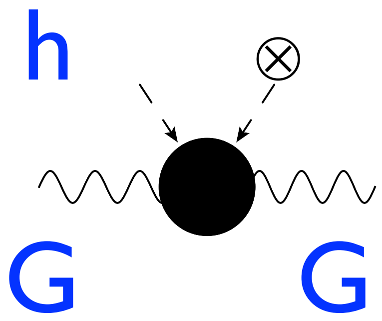
operator
is not visible in
the vacuum





Not physical!

But can affect h physics:



affects GG →h!

this BSM operator is visible only in Higgs physics!

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

(f=t,b,τ)

(courtesy of A. Pomarol@HiggsHunting2014)

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yet to be measured at the LHC

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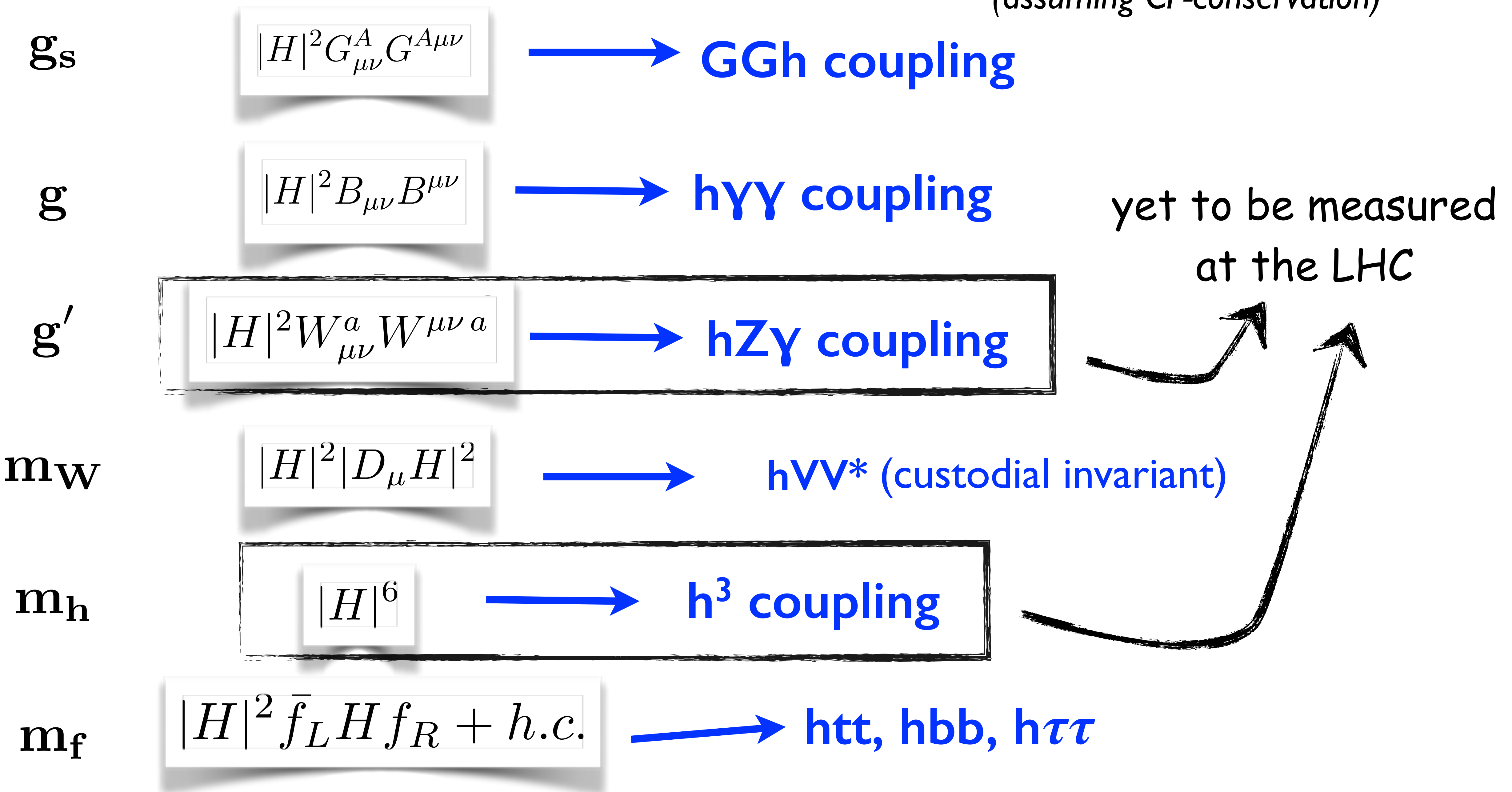

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(f=t,b,τ)

yet to be measured at the LHC

the 6 others have been measured (~10%) up to a flat direction between between the top/gluon/photon couplings

(courtesy of A. Pomarol@HiggsHunting2014)

Don't forget LEP!

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

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

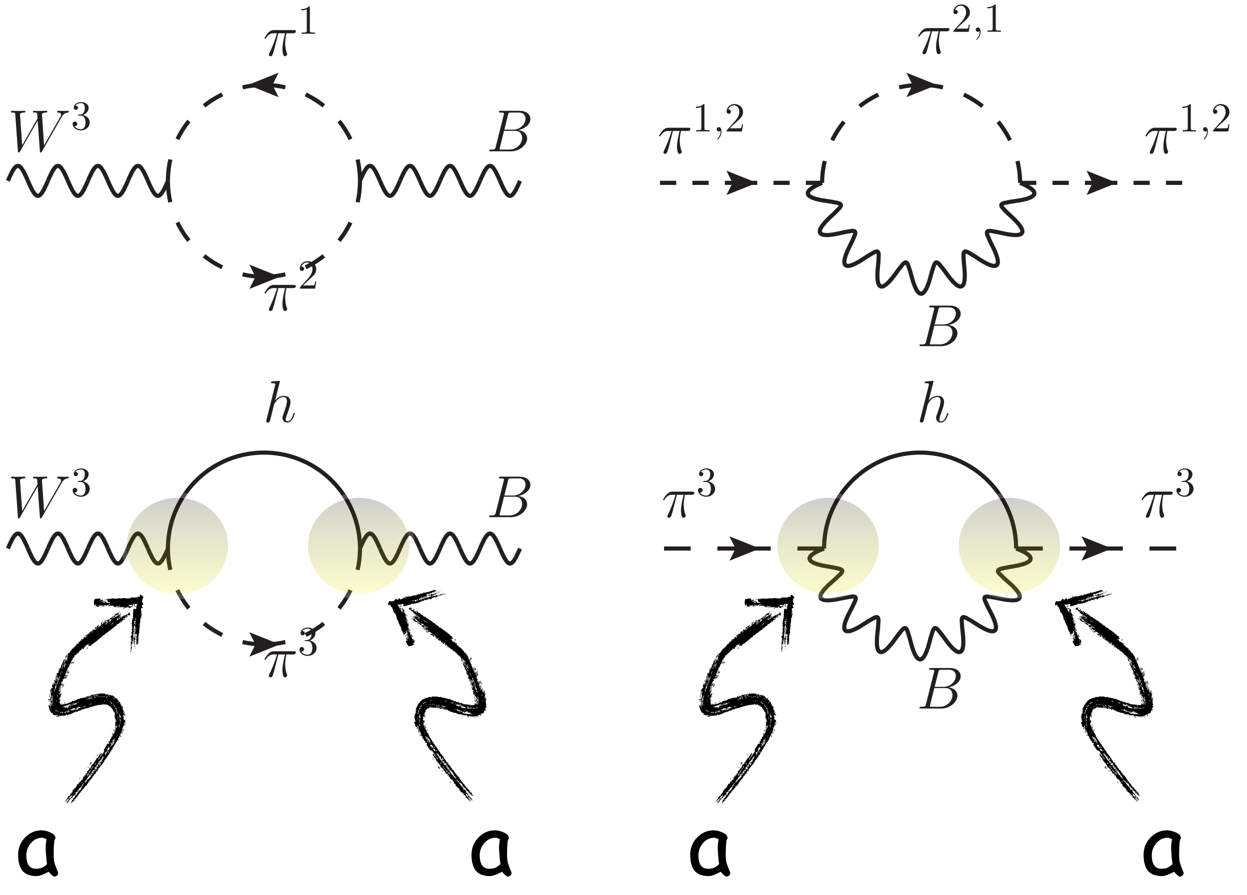
$$\Rightarrow a = \kappa_V = 1 + \frac{v^2}{2f^2}$$

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

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

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07



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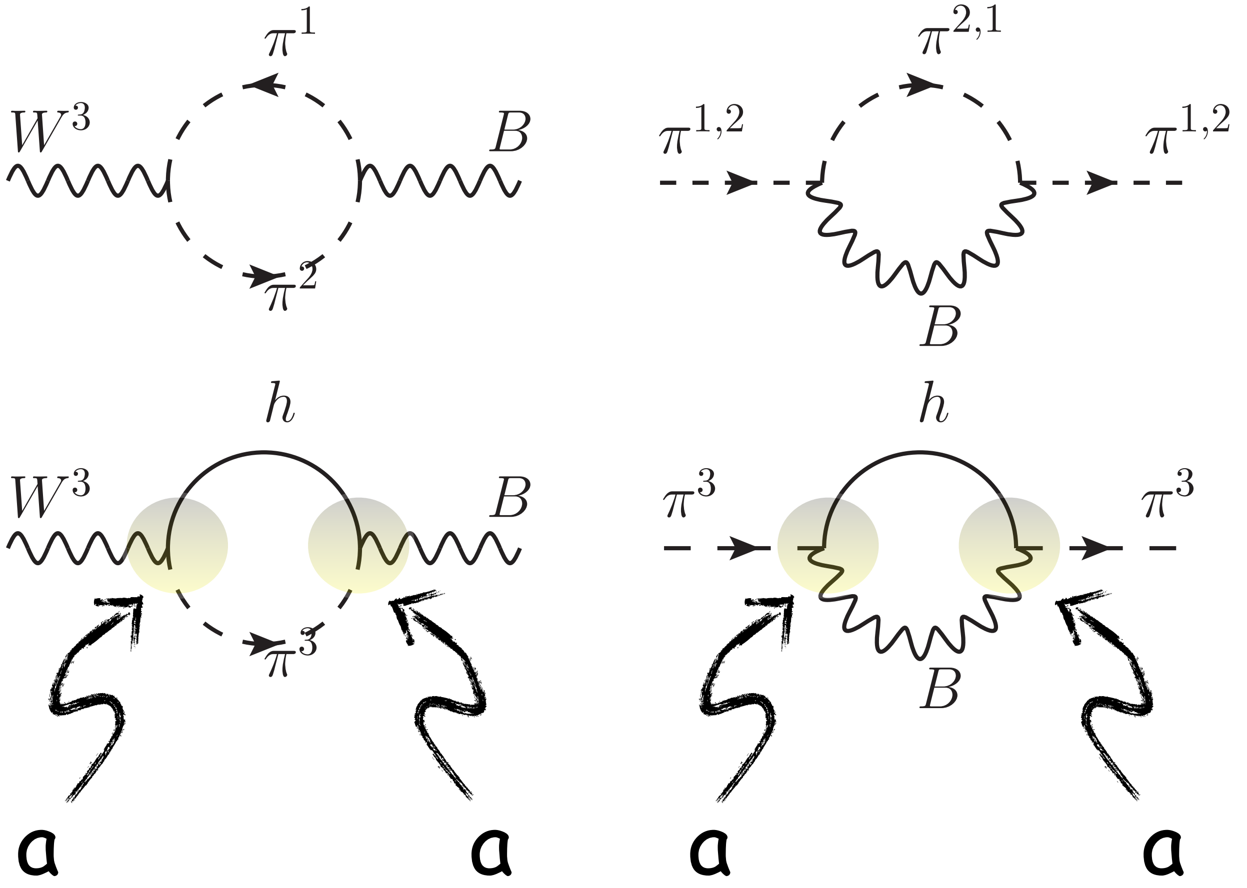

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a≠1 log. sensitivity on the scale of new physics

EW fit:

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

Ciuchini et al '13

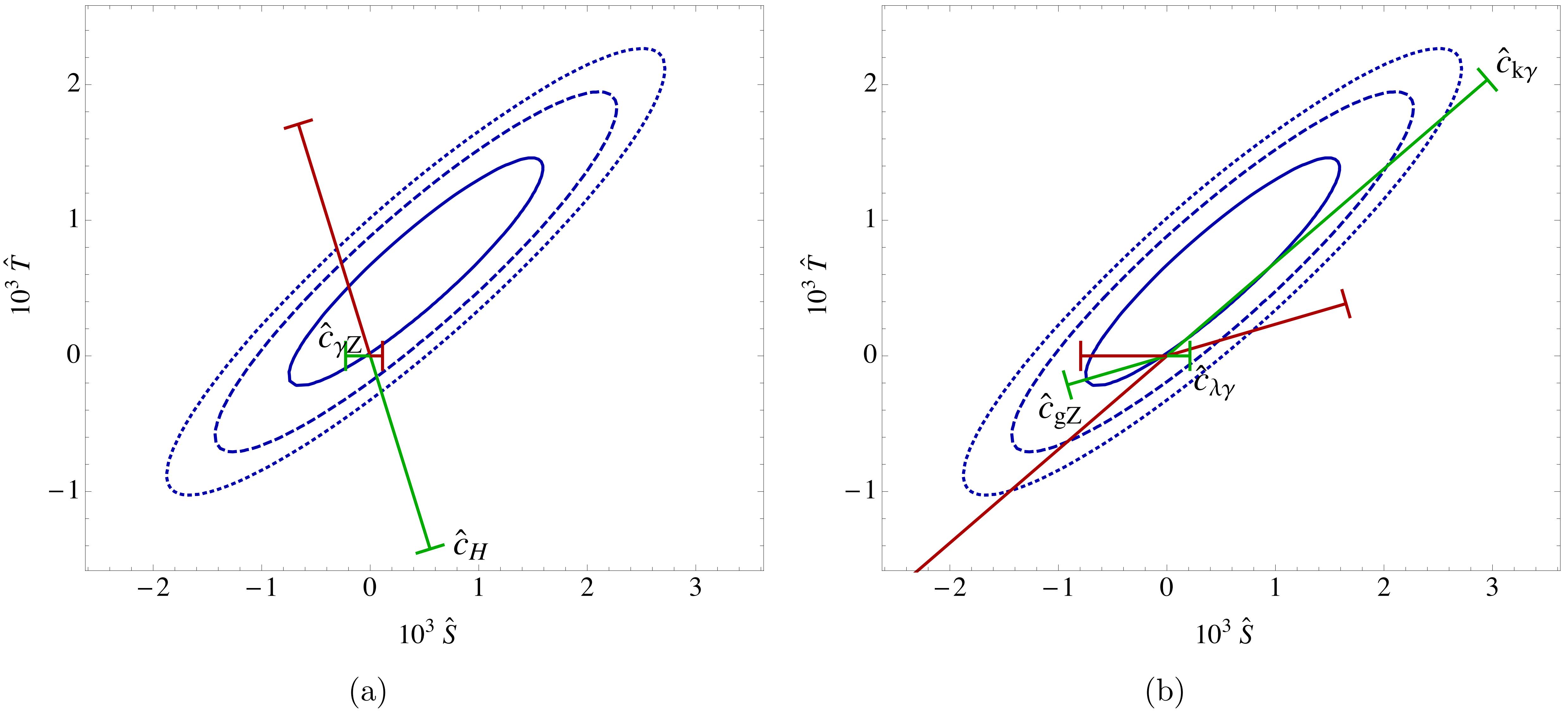
see also Grojean et al '13

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

Elias-Miro et al '13

Don't forget LEP!

Elias-Miro, Grojean, Gupta, Marzocca '14



(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	Zγ, 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.

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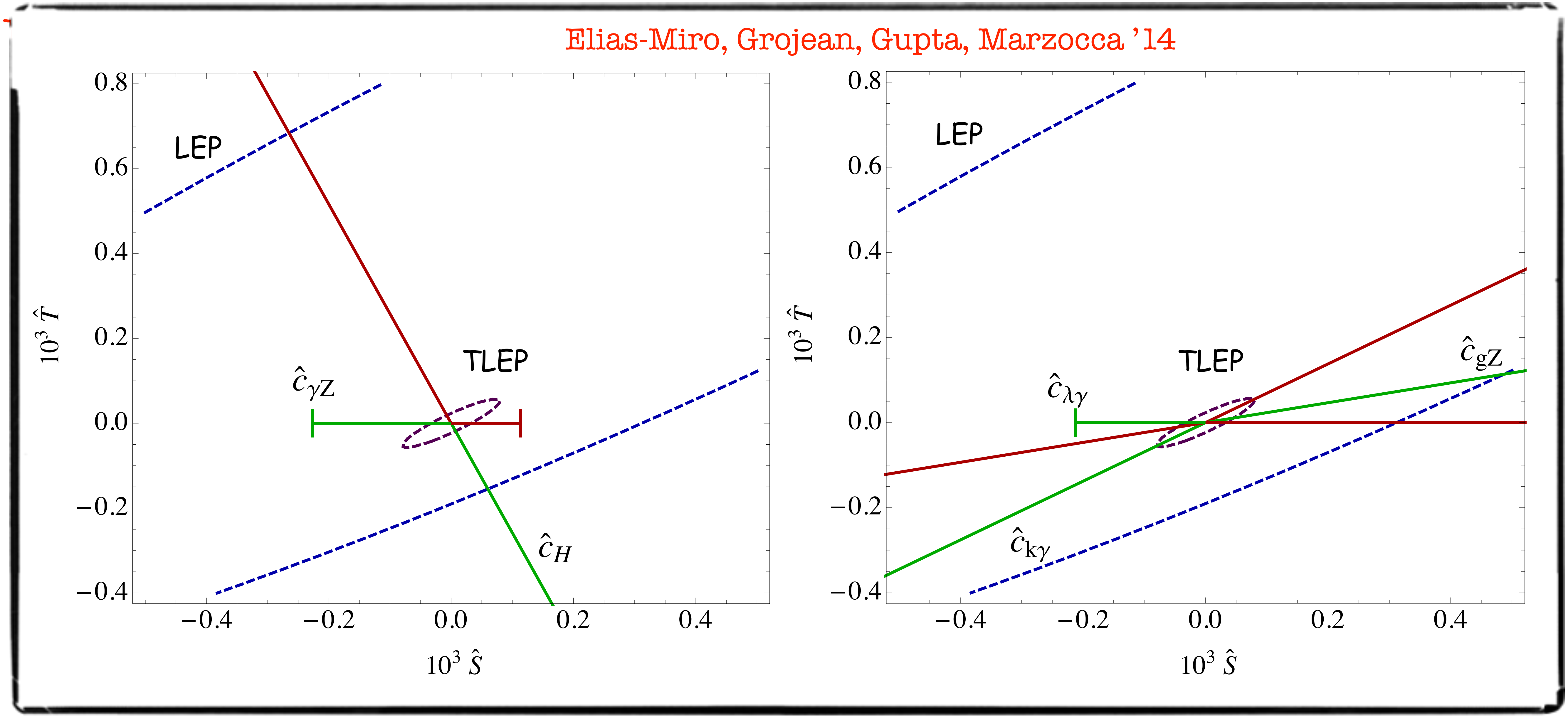
Elias-Miro, Grojean, Gupta, Marzocca '14

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

(ILC/now ≈ 2÷3 improvement only)

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}))

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

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 $\cancel{\text{C}}$P Higgs/BSM primaries

$$\begin{aligned}\Delta\mathcal{L}_{\rm BSM} = &\ i\delta\tilde{g}_{hff}\, h\bar{f}_L f_R + h.c. \\ &+\tilde{\kappa}_{GG}\frac{h}{v}G^{\mu\nu}\tilde{G}_{\mu\nu} \\ &+\tilde{\kappa}_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu} \\ &+\tilde{\kappa}_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}\end{aligned}$$

(f=b, τ, t)

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

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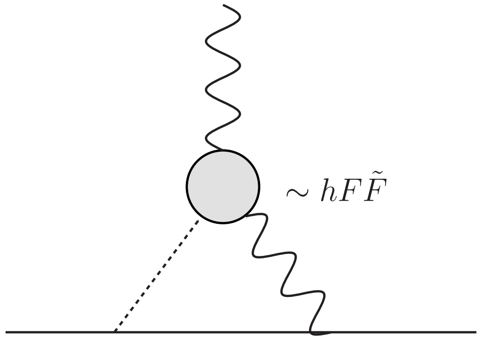
($\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$)

operators with γ:

already severely constrained by e and q EDMs

McKeen, Pospelov, Ritz '12



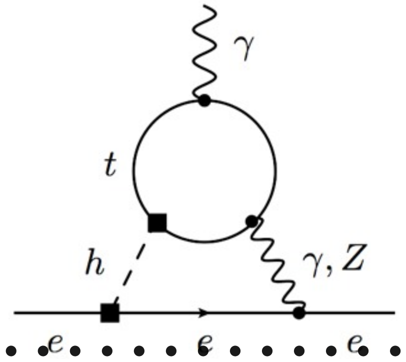
$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$

$\Lambda_{\not{C}\not{P}}$ > 25 TeV

operators with top:

already severely constrained by e and q EDMs

Brod, Haisch, Zupan '13



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

$\Lambda_{\not{C}\not{P}}$ > 2.5 TeV

Last hopes in h$\tau\tau$ or hbb?

4

Multi Higgs, boosted and off-shell 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)

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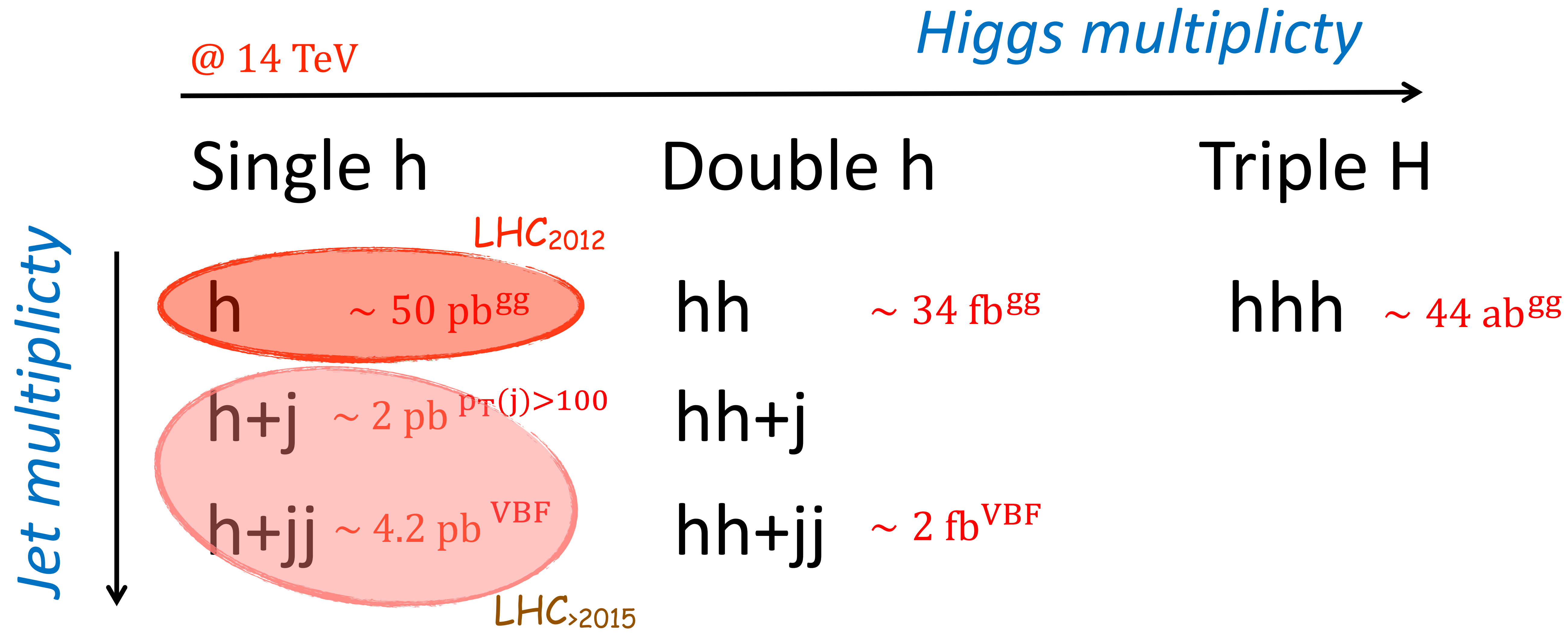

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	LHC$_{>2015}$		

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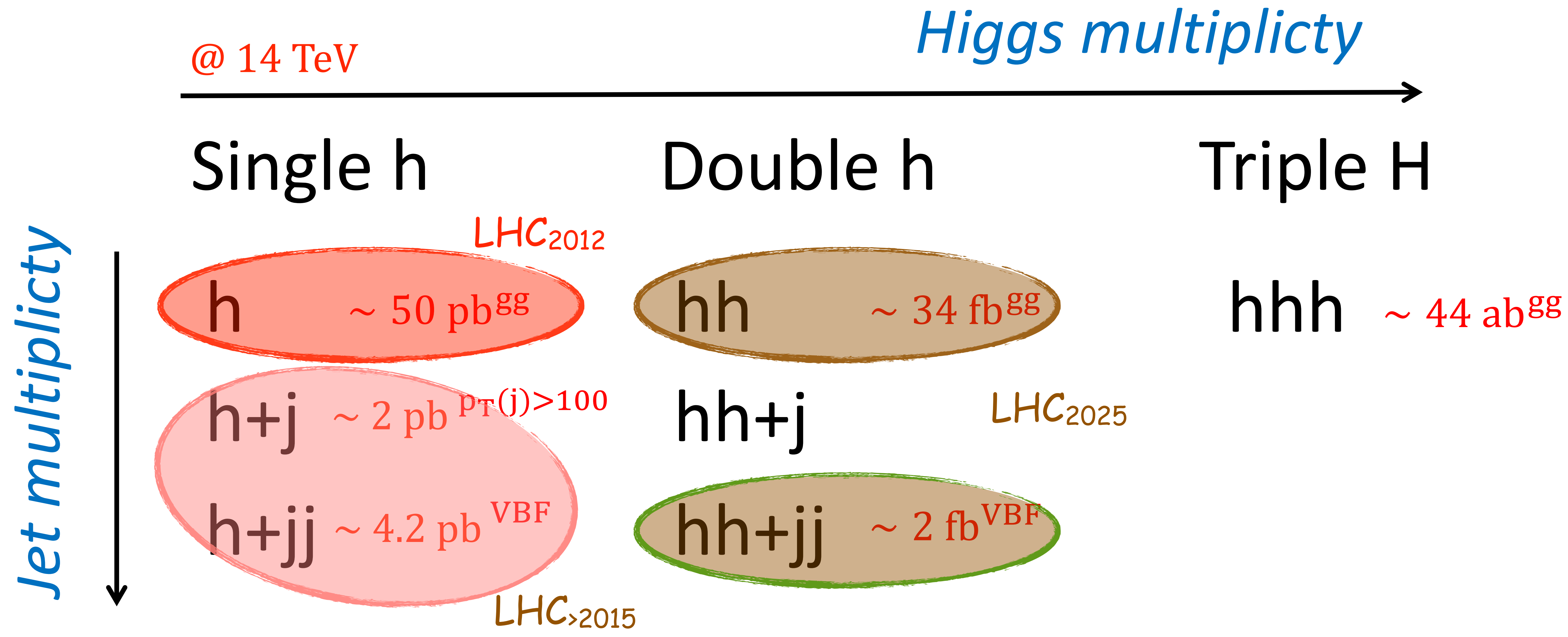

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hh+j

LHC_{2025}

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$\text{LHC}_{>2015}$

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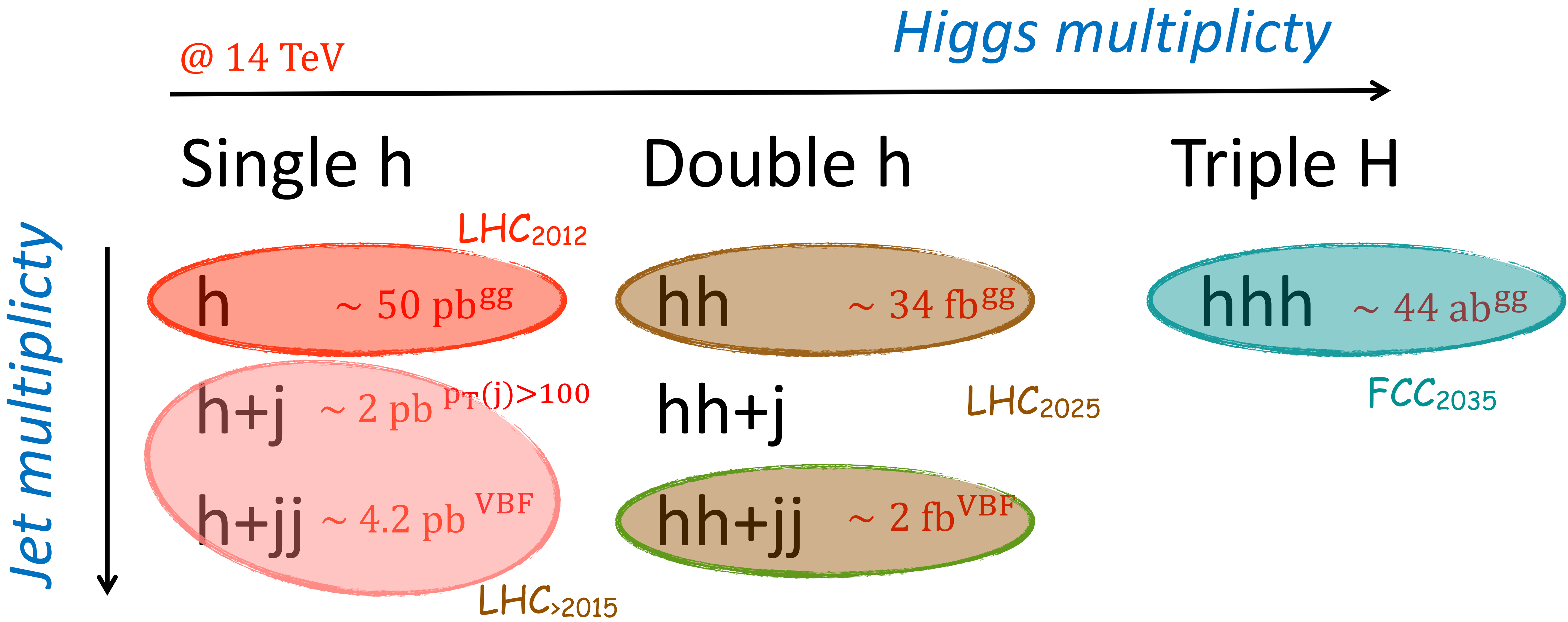

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h+j $\sim 2\ \mathrm{pb}$ $p_T(j)>100$

hh+j

LHC2025

FCC2035

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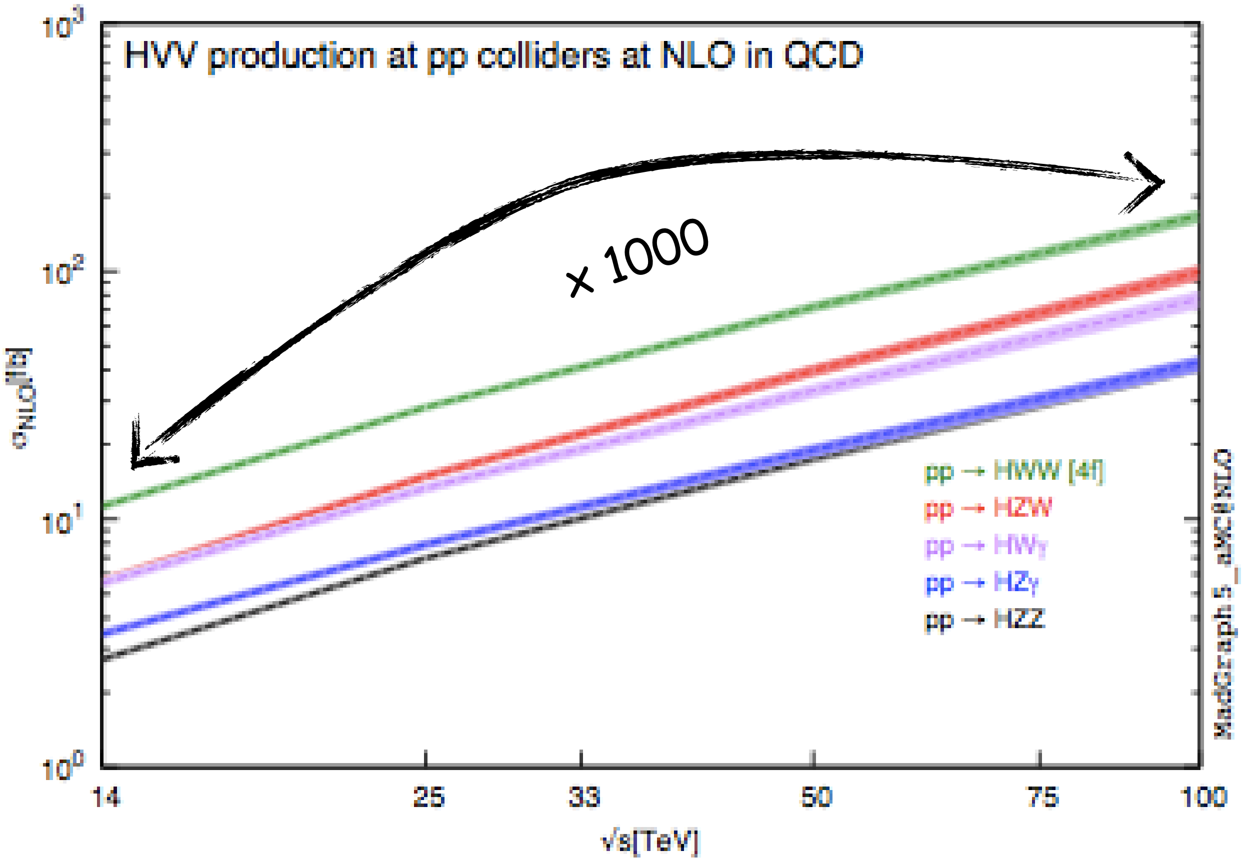
Beyond single Higgs processes

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

Higgs-diboson associated production

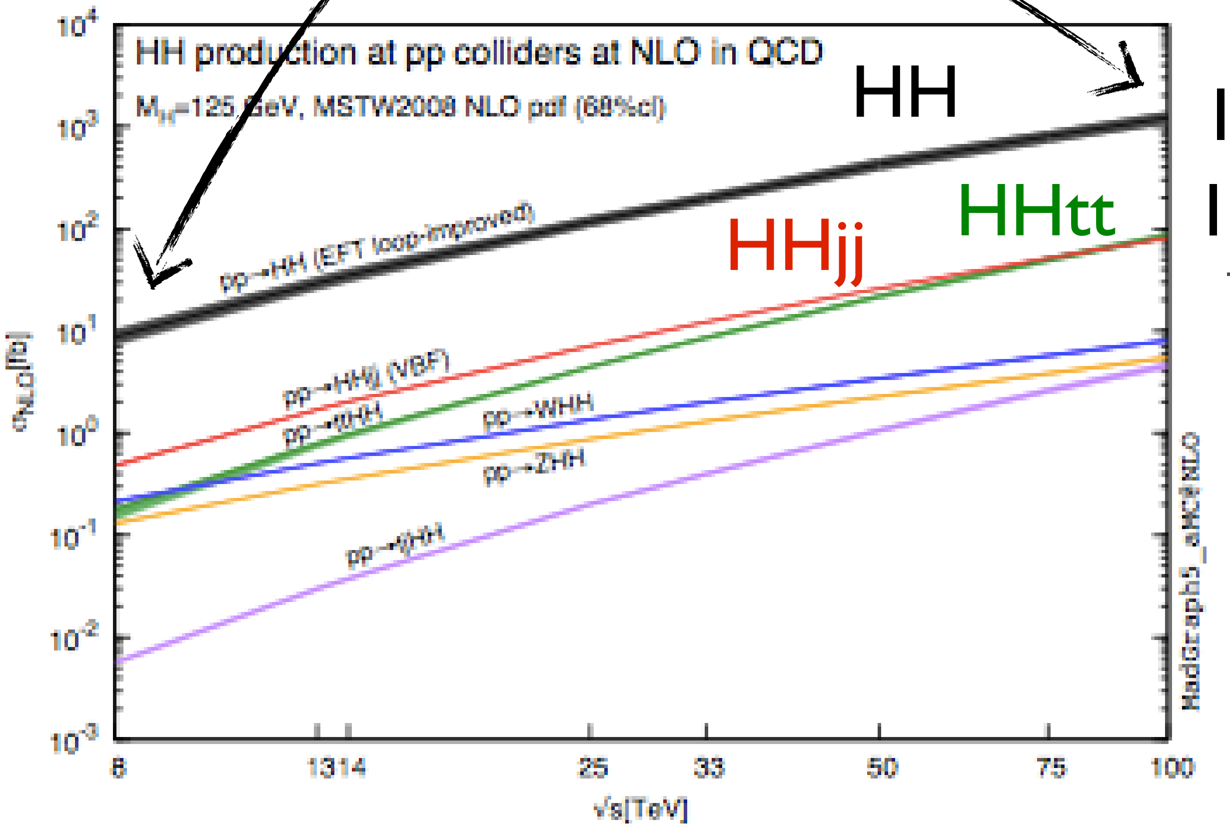


100 fb

FCC = H+X factory

× 100-1000

Higgs-pair associated production



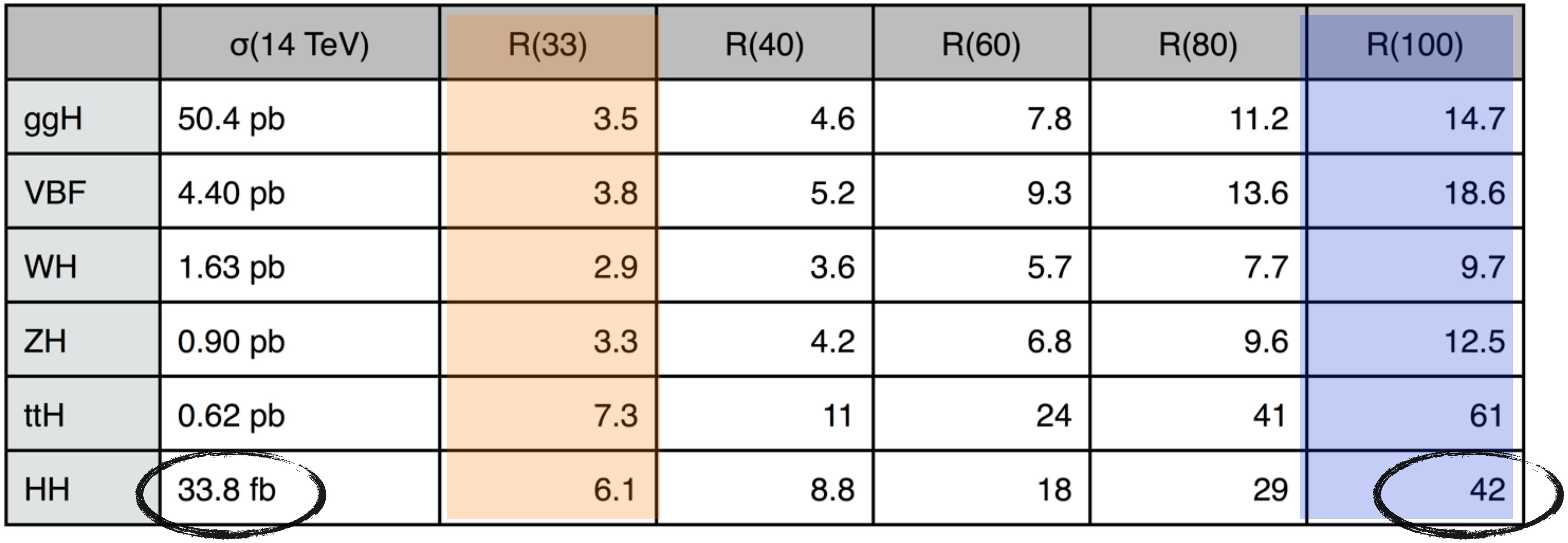
1000 fb

100 fb

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

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)

Why going beyond single 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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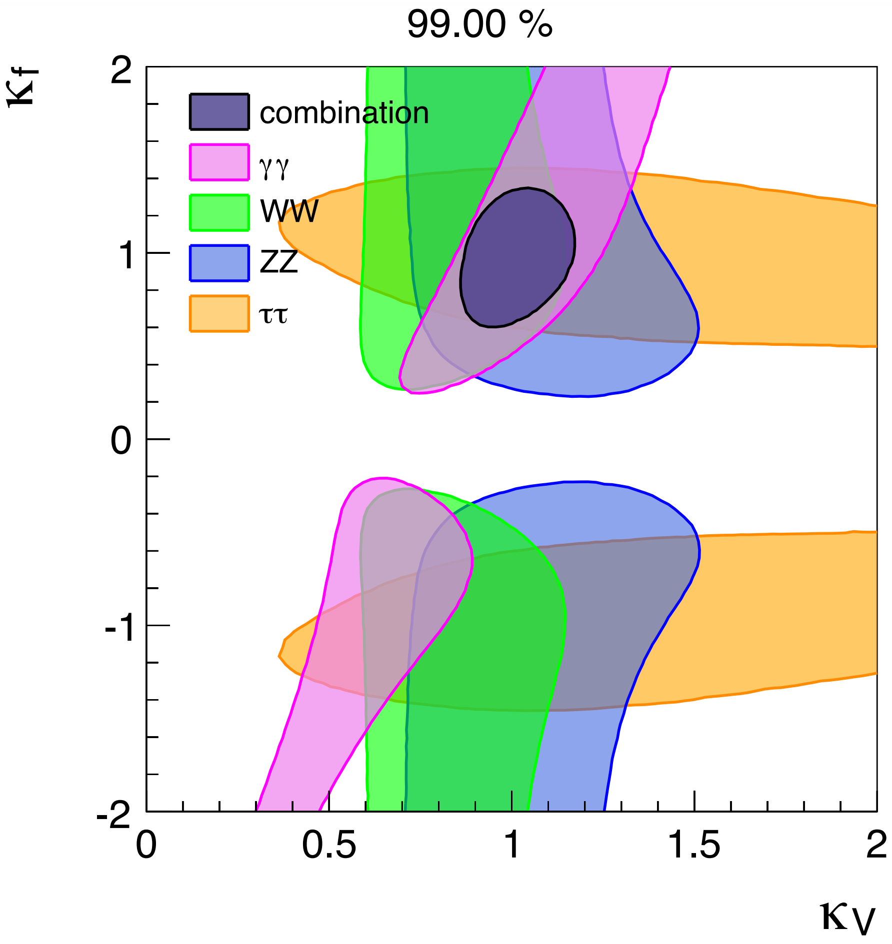

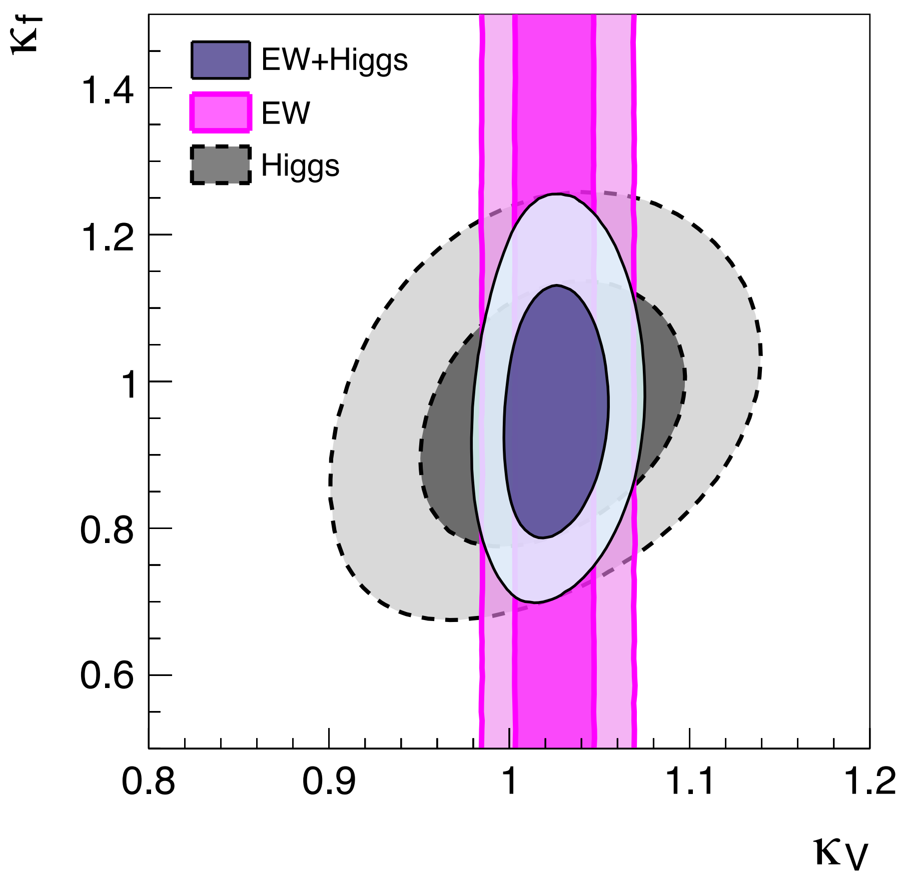

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Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

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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)

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Probing new corrections to the SM Lagrangian?

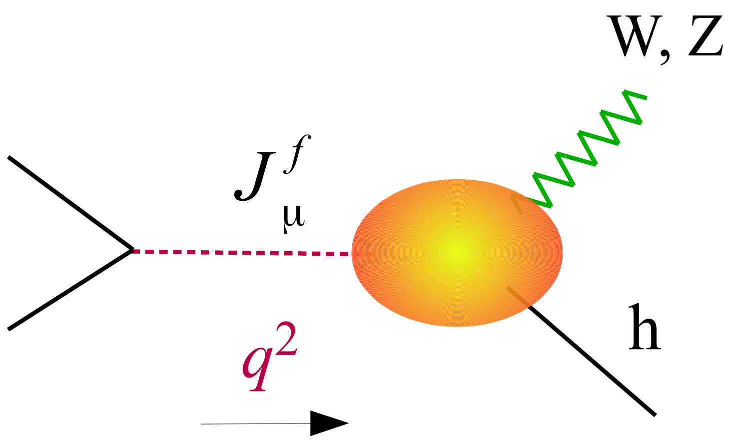
on-shell Z @ LEP1	off-shell Z @ LEP2
constraints on S and T oblique corrections	constraints on W and Y oblique corrections (same order as S and T but cannot be probed @ LEP1)

off-shell Higgs data does not probe new corrections
that are not already constrained by on-shell data

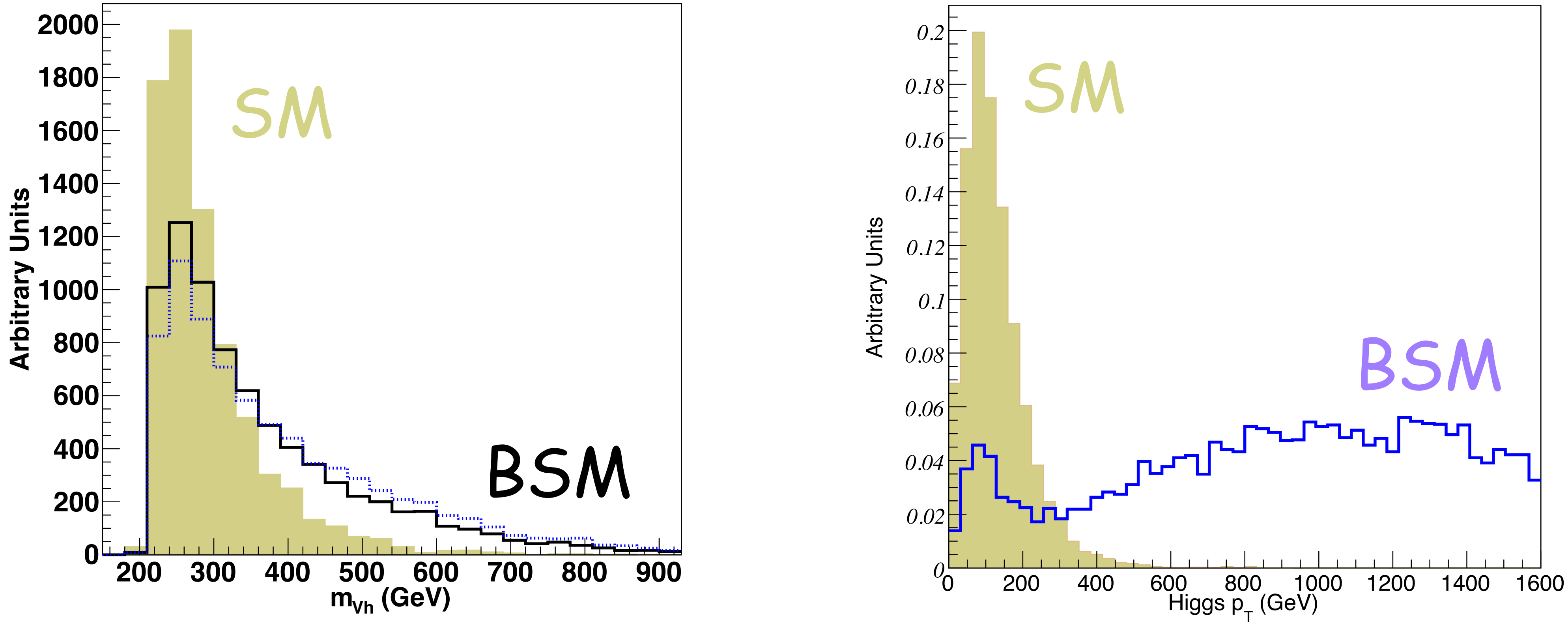
Boosted Higgs in HV production

Associate production ff→Vh probe
the high q^2 dependence of the form factors

Isidori, Trott '13



Alloul, Fuks, Sanz '13



The large effects at high p_T or m_{VH} have been used to probe higher dimensional derivative operators

Ellis, Sanz, You '13

Beneke, Boito, Wang '13

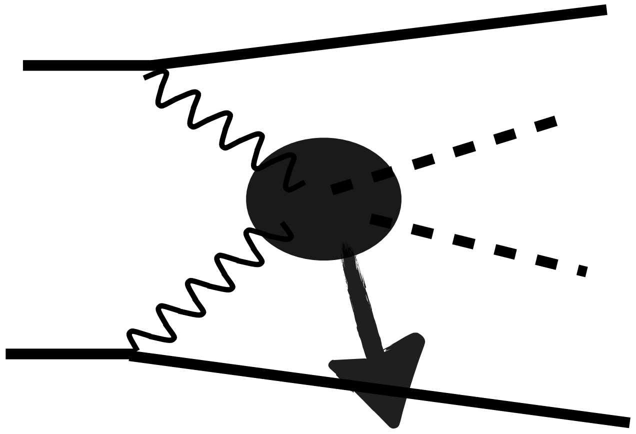
but the validity of the EFT approach is endangered

Biekoetter et al '14

Multiple Higgs interactions in WW→HH

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

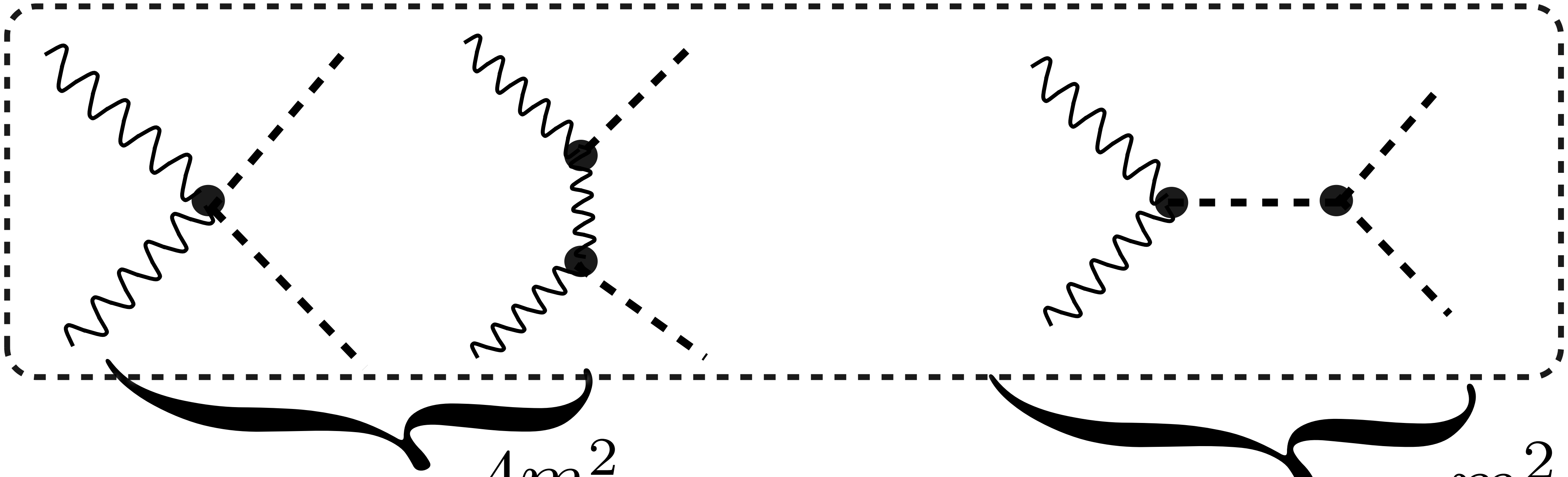
(e.g. WW scattering)



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

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

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



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

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

asymptotic behavior
sensitive to strong interaction

threshold effect
anomalous coupling'

Multiple Higgs interactions in WW→HH

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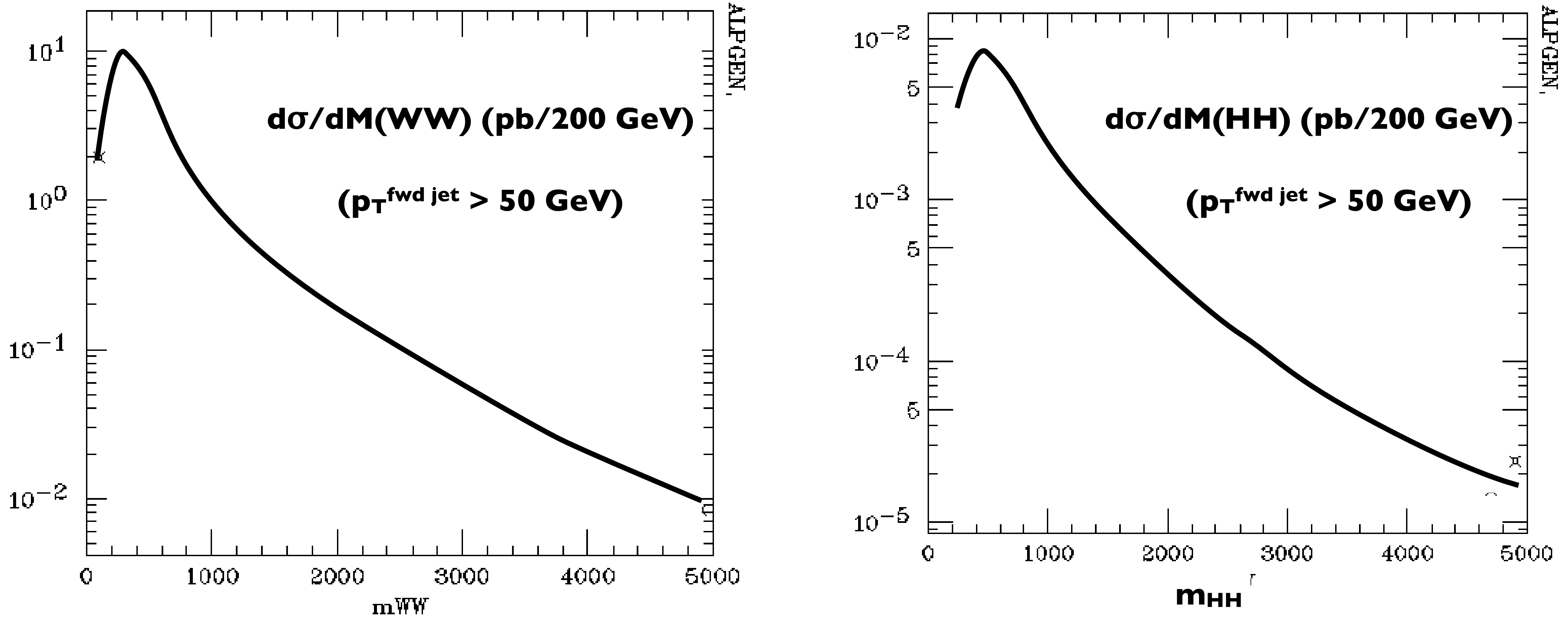
SM rates at 100 TeV

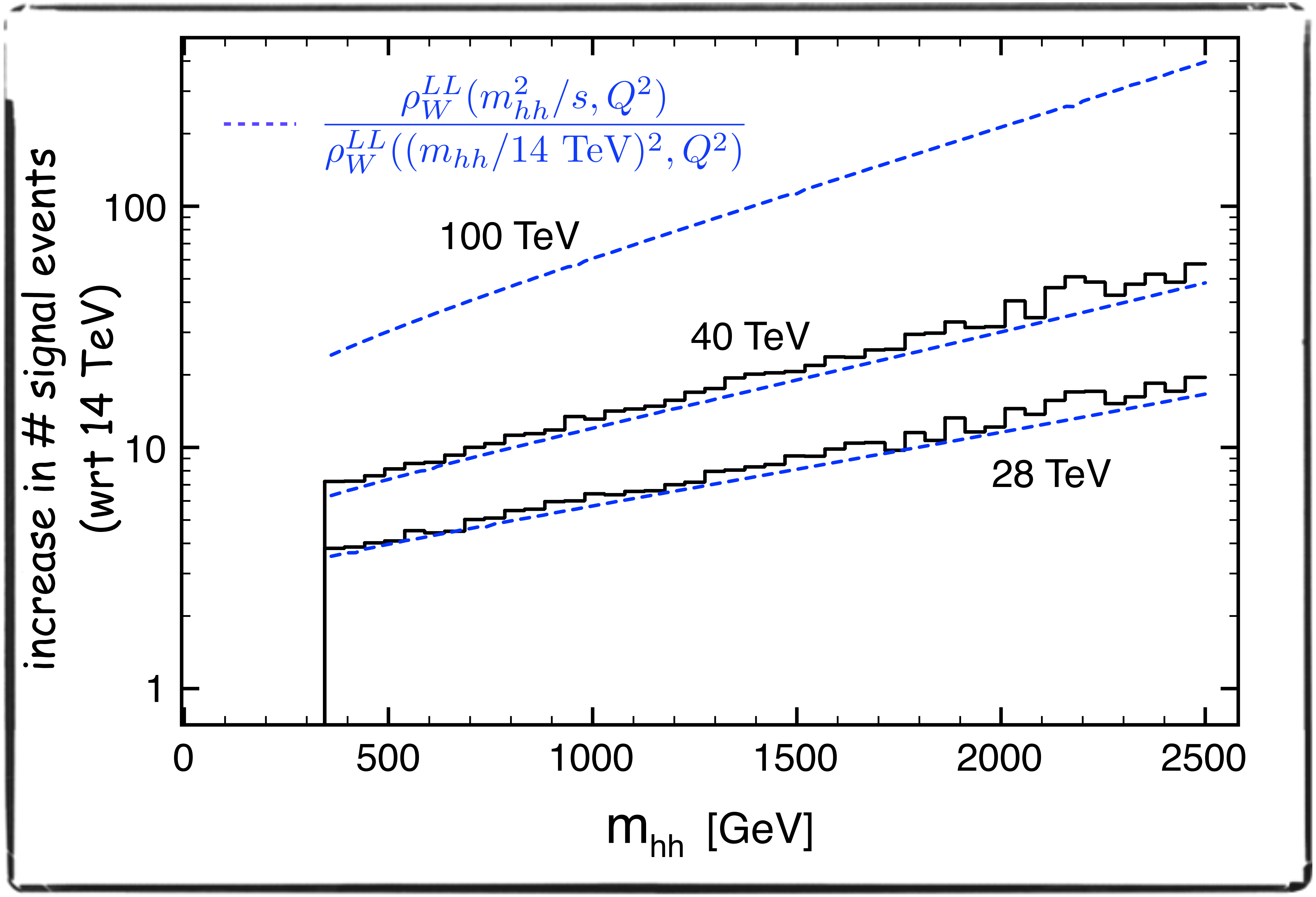


100 fb with M(WW) > ~3 TeV **1 fb with M(HH) > ~2 TeV**

M. Mangano @ Fermilab '14

Multiple Higgs interactions in WW→HH

Contino, Grojean, Moretti, Piccini, Rattazzi '10



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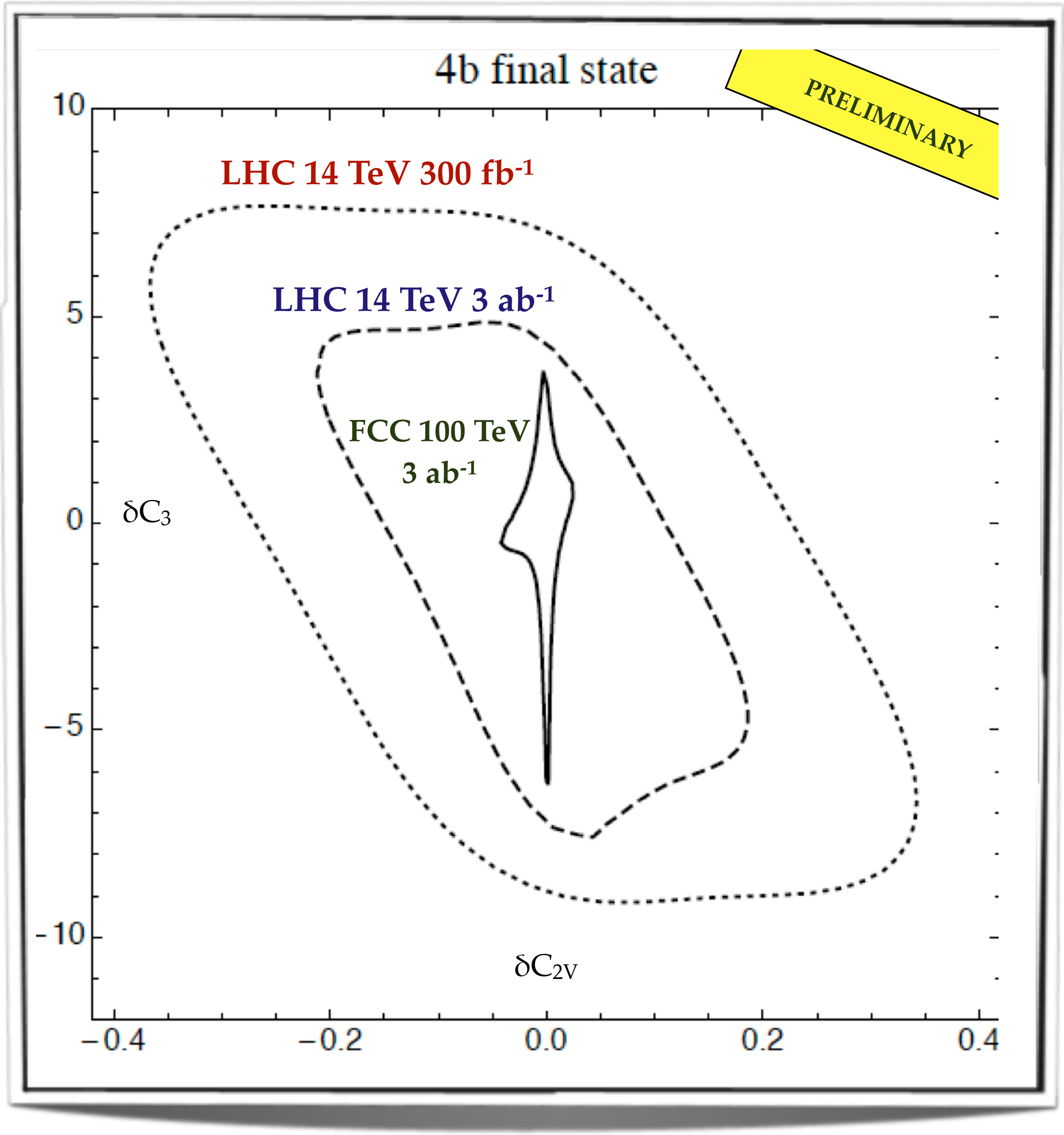
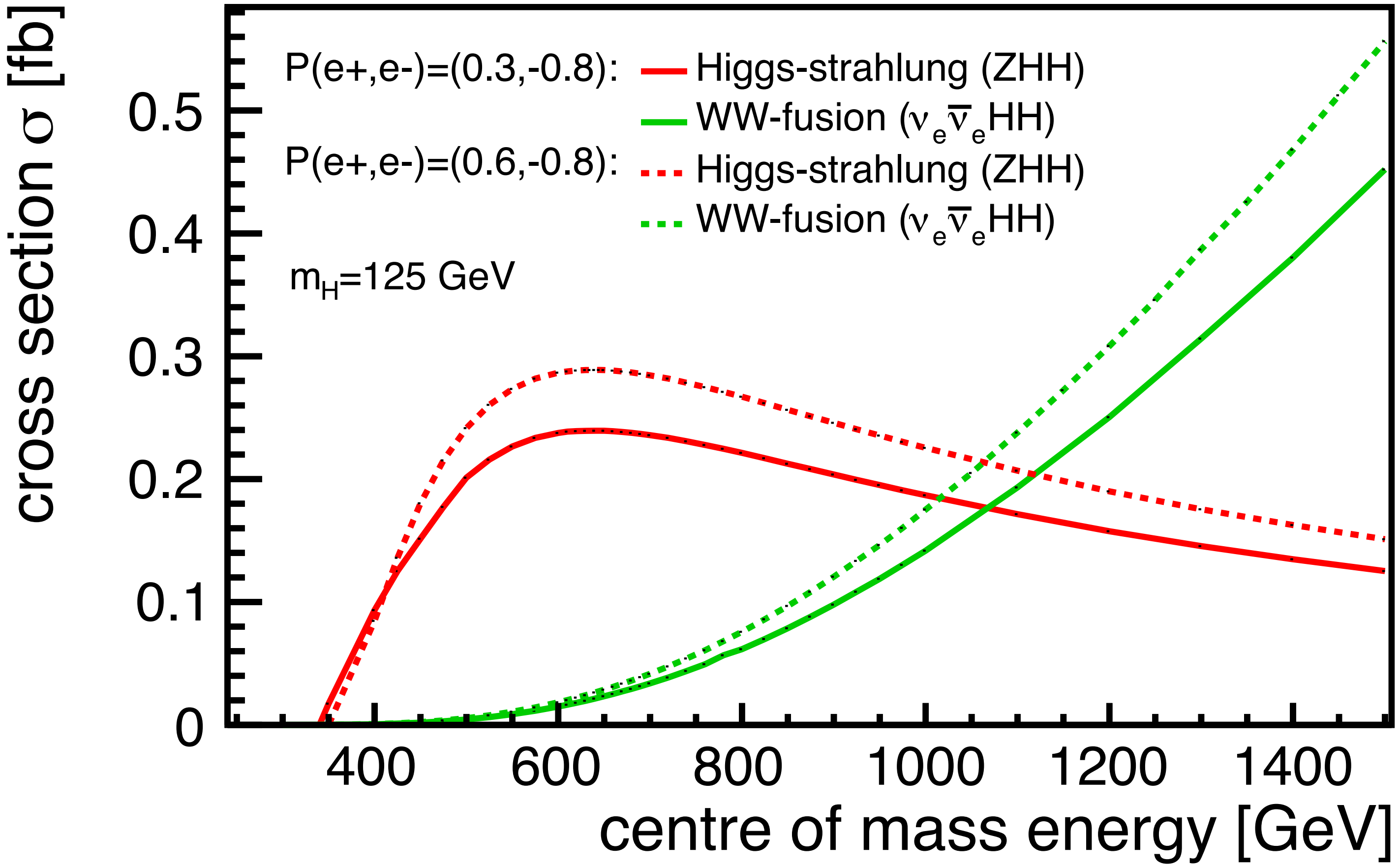


Bondu, Contino, Massironi, Rojo 'to appear

VVHH @ e^+e^-

VV→HH is difficult (impossible) at FCC-ee/ILC$_{500GeV}$

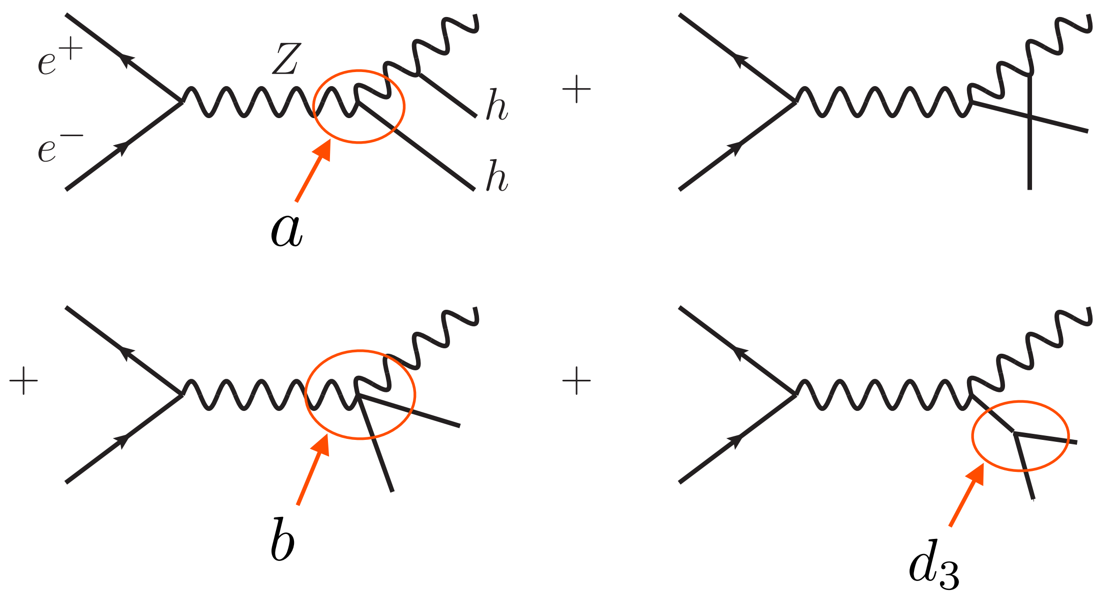


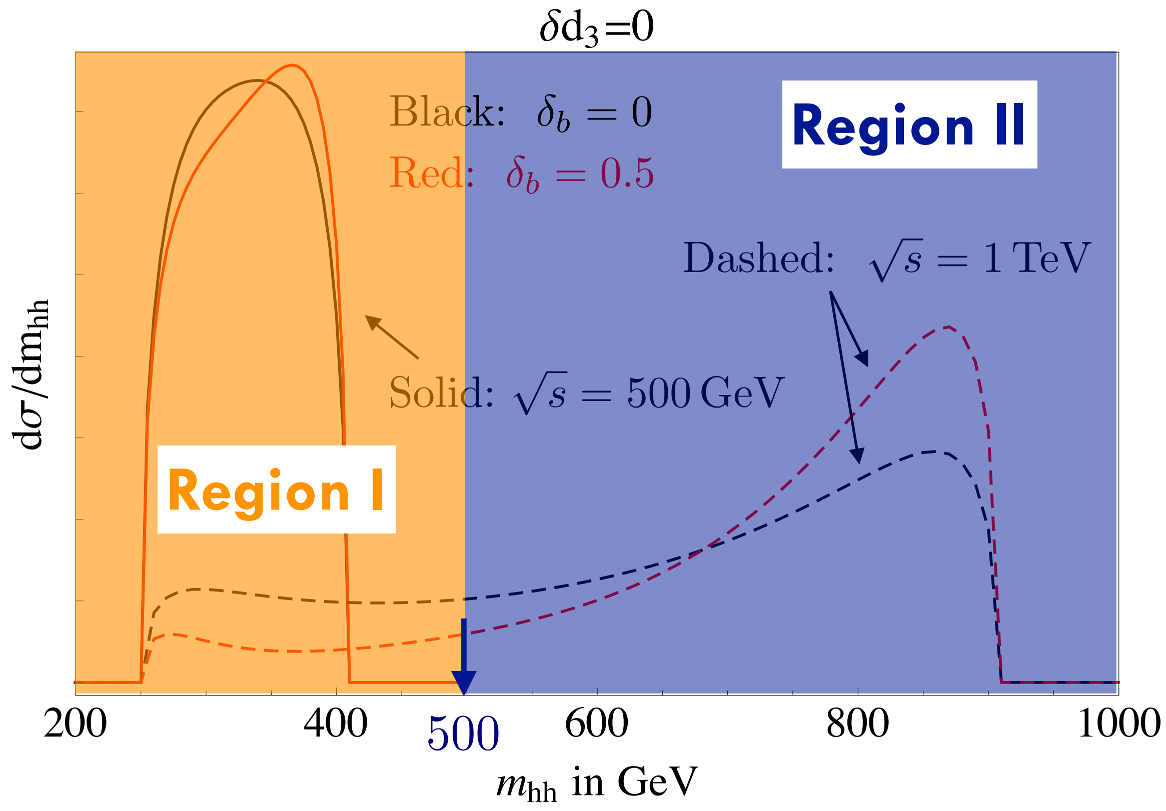
We could also access VVHH coupling through ZHH

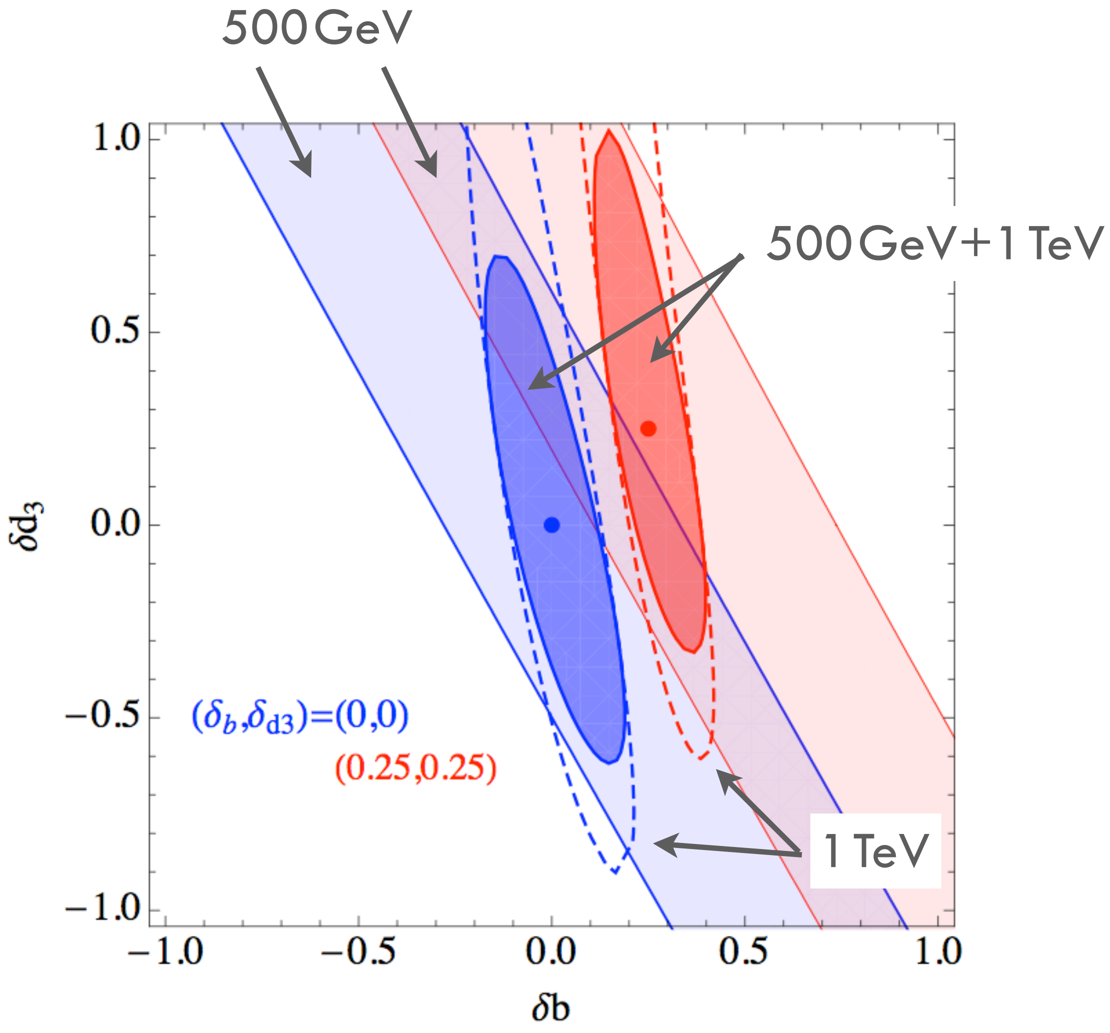
VVHH @ e^+e^-

An e^+e^- collider with $\sqrt{s} = 500\,\mathrm{GeV} - 1\,\mathrm{TeV}$ can reach a precision of ~20% on b through the double Higgsstrahlung process

Contino, Grojean, Pappadopulo, Rattazzi, Thamm ’13



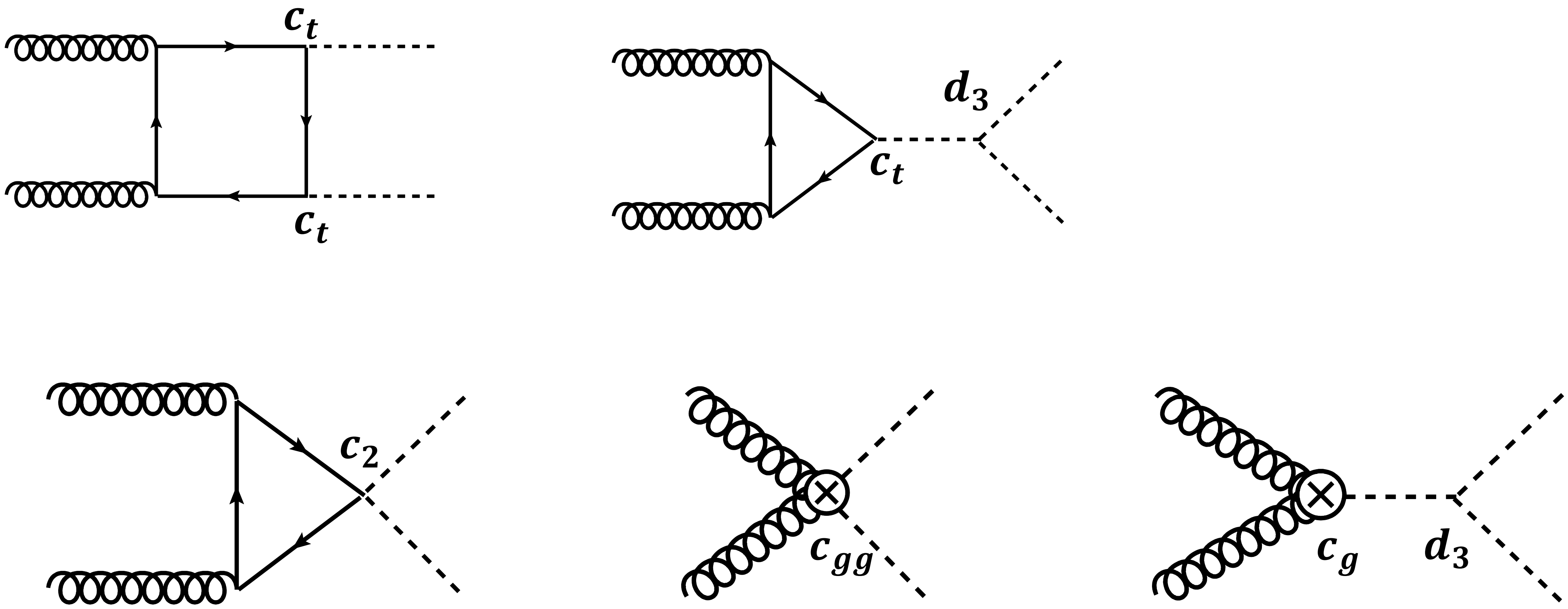




Cut on m_{hh} useful at $\sqrt{s} = 1\,\mathrm{TeV}$

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

$$c_2 = 3(c_t - 1) \qquad\qquad c_{gg} = c_g$$

In reality single-Higgs processes is unable to differentiate c_t from c_g

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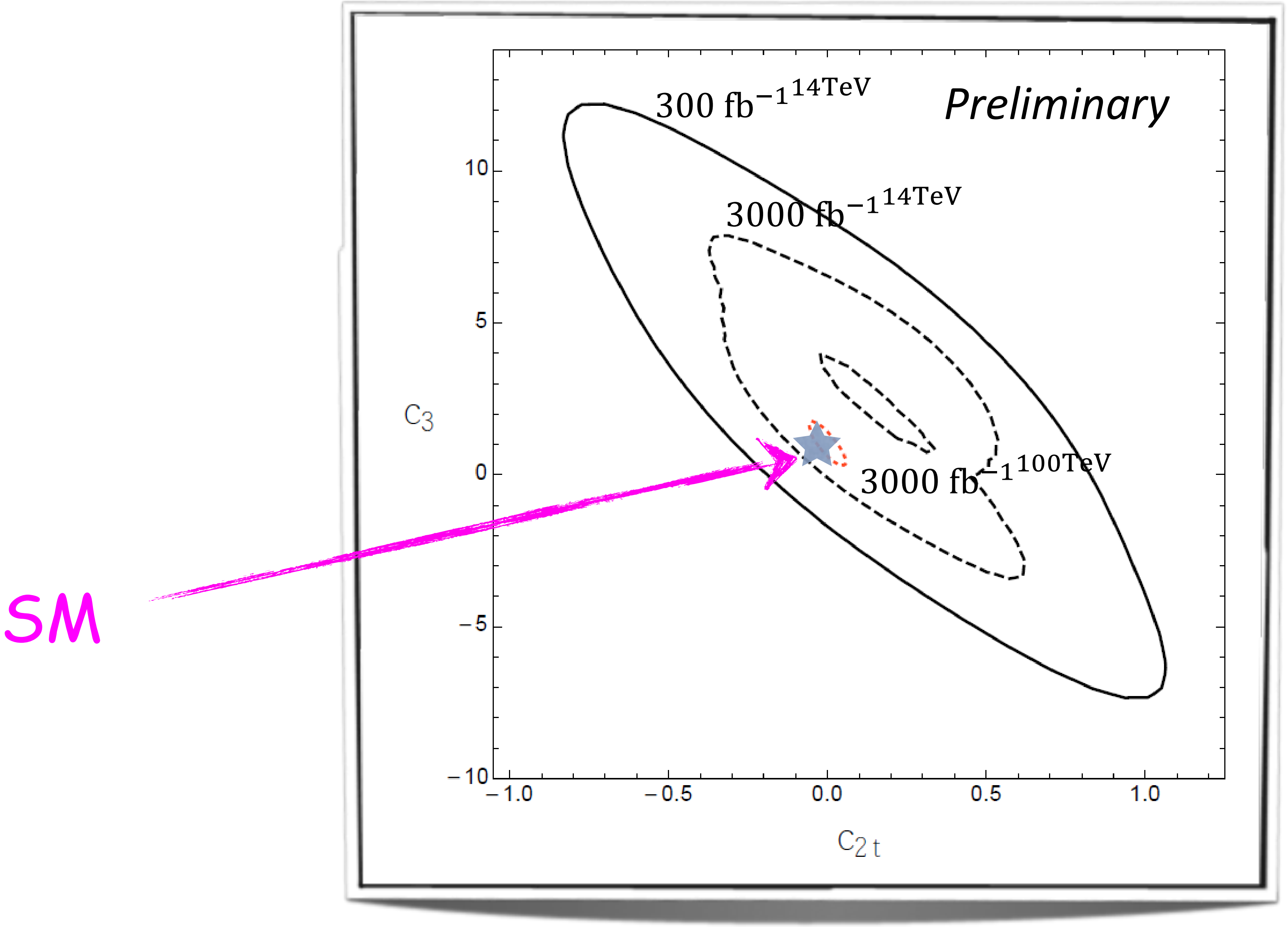

Azatov, Contino, DelRe, Meridiani, Micheli, Panico, Son 'to appear

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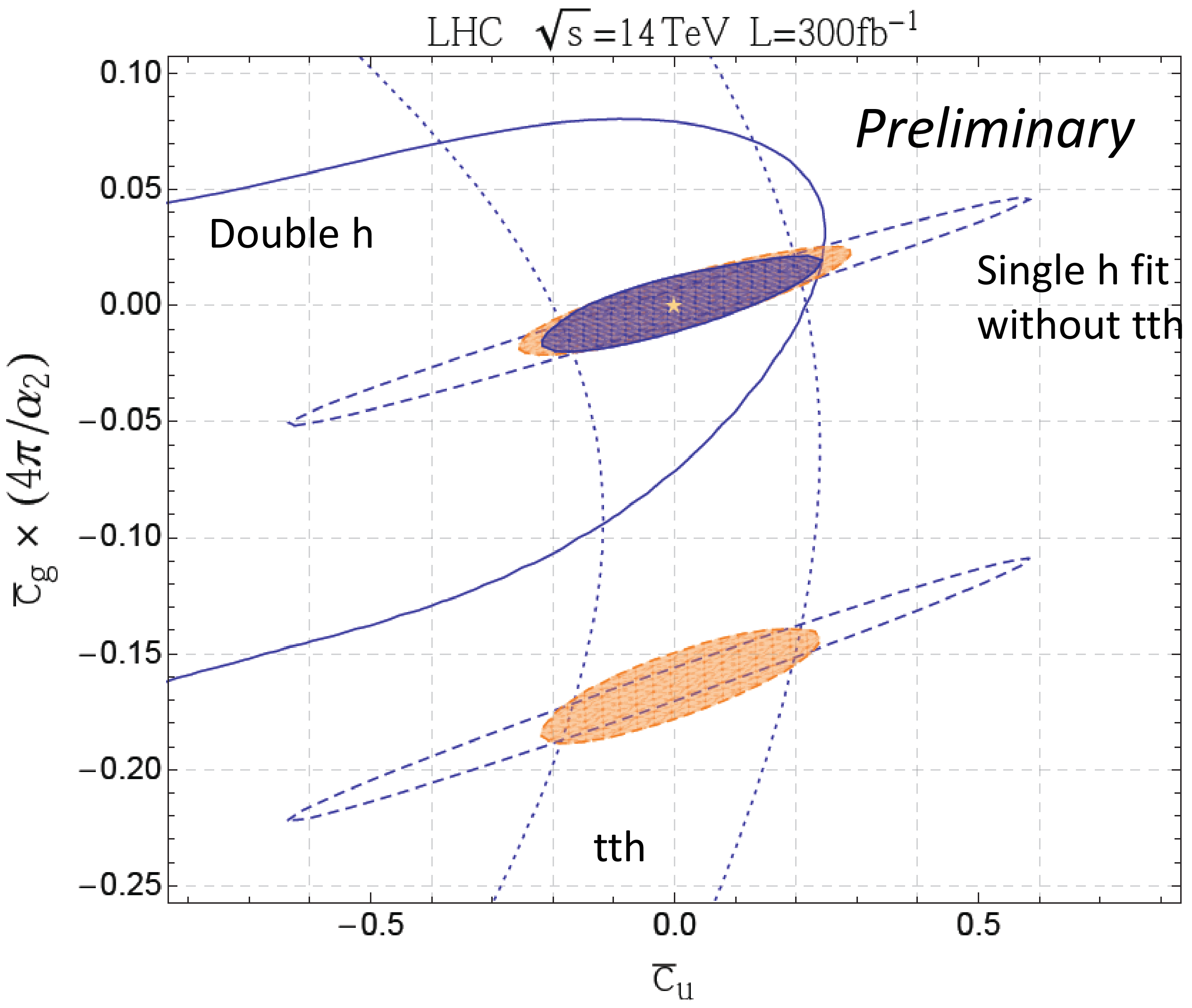
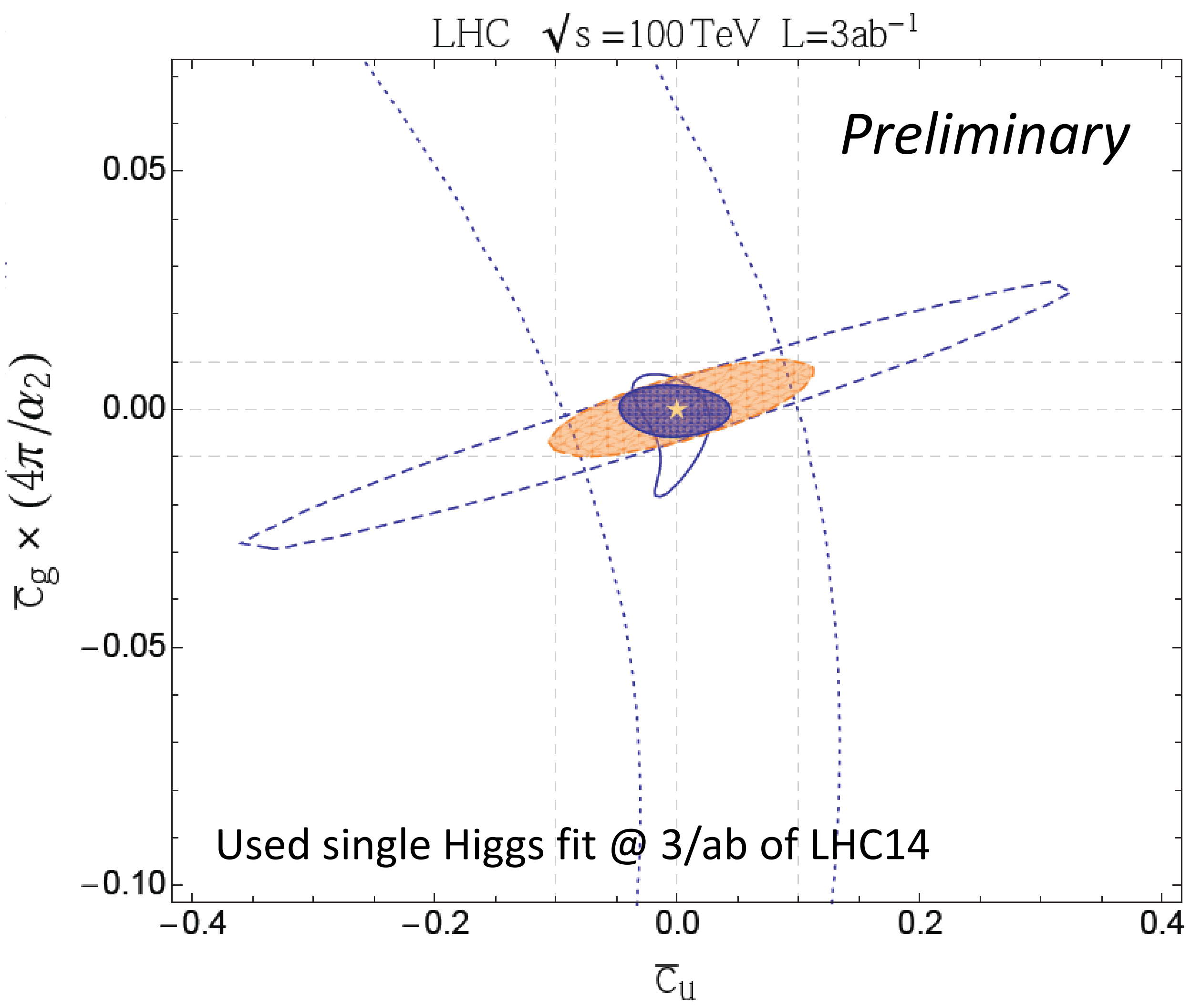
after marginalizing over c_3, hh channel provides additional info on single Higgs couplings





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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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⇛ cannot disentangle ⇚

- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

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

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

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

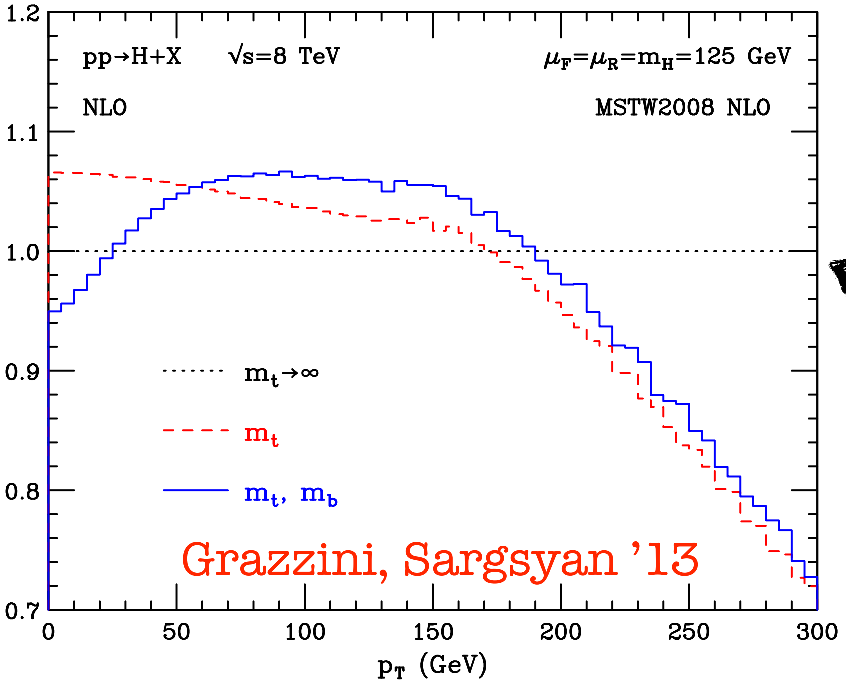
having access to h$t\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC$^{14}_{300}$-LHC$^{14}_{3000}$ vs 10%-4% @ ILC$^{500}_{500}$-ILC$^{1000}_{1000}$

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



Grazzini, Sargsyan ’13

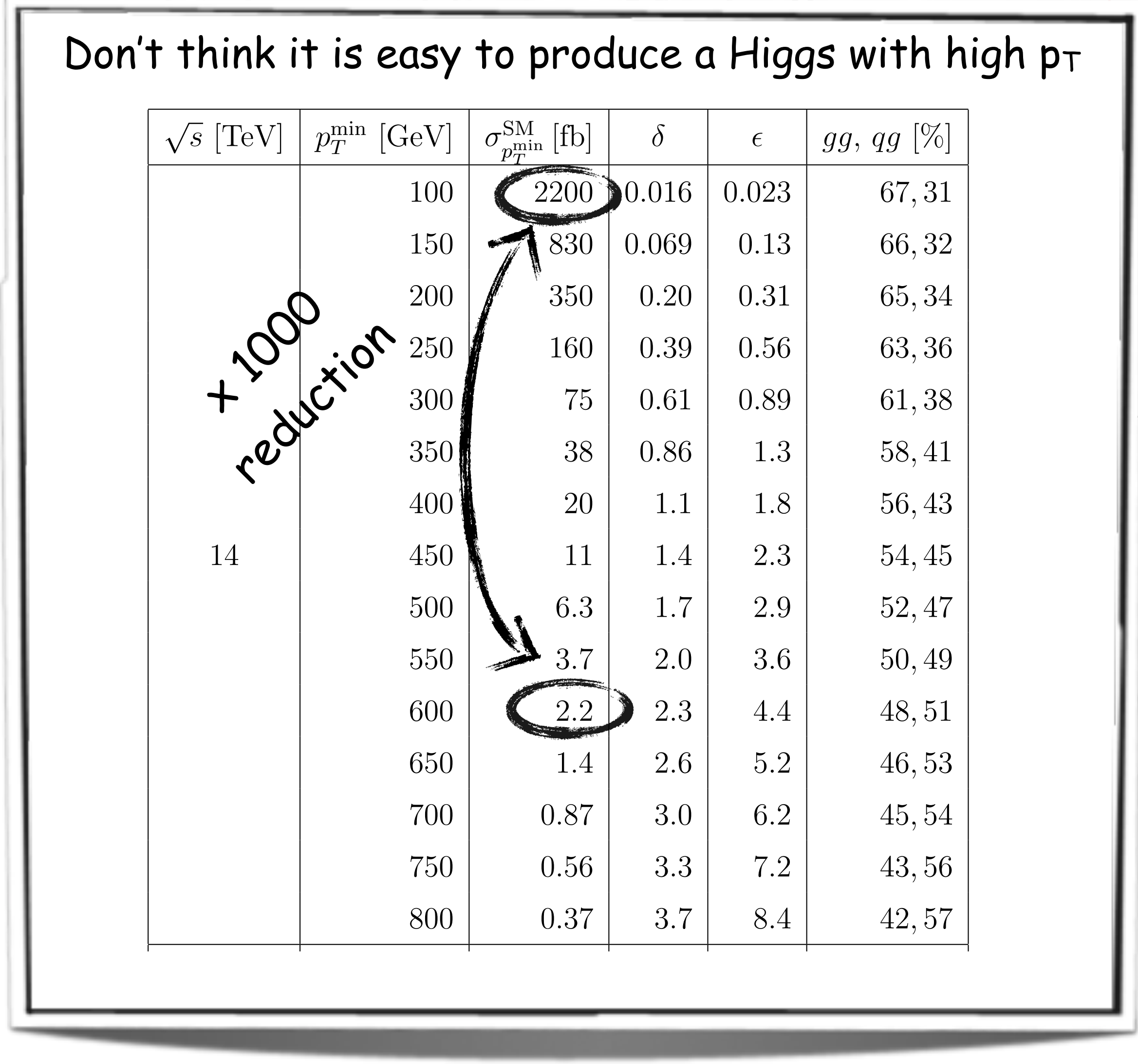
Note: LO only
NLO$_{m_t}$ is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al ’12

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

Resolving top loop: Boosted Higgs

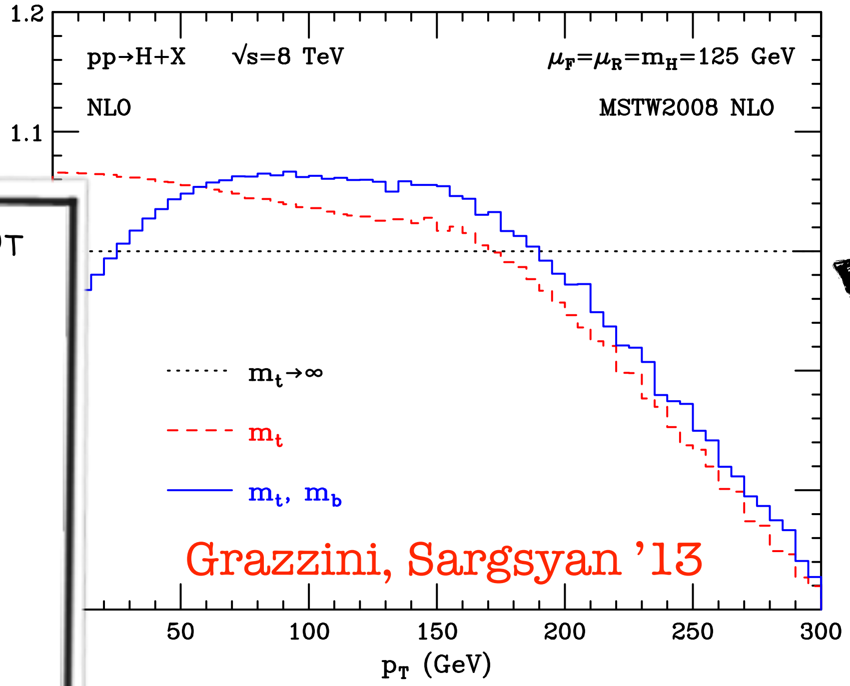
cut open the top loops



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

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [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

×1000 reduction



Grazzini, Sargsyan '13

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

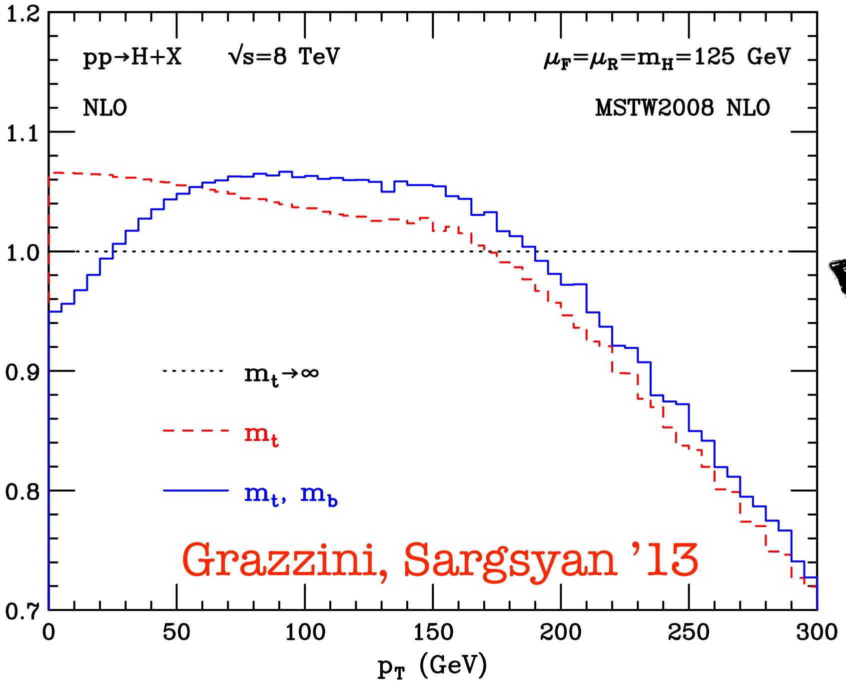
to the mass of top

Resolving top loop: Boosted Higgs

cut open the top loops

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



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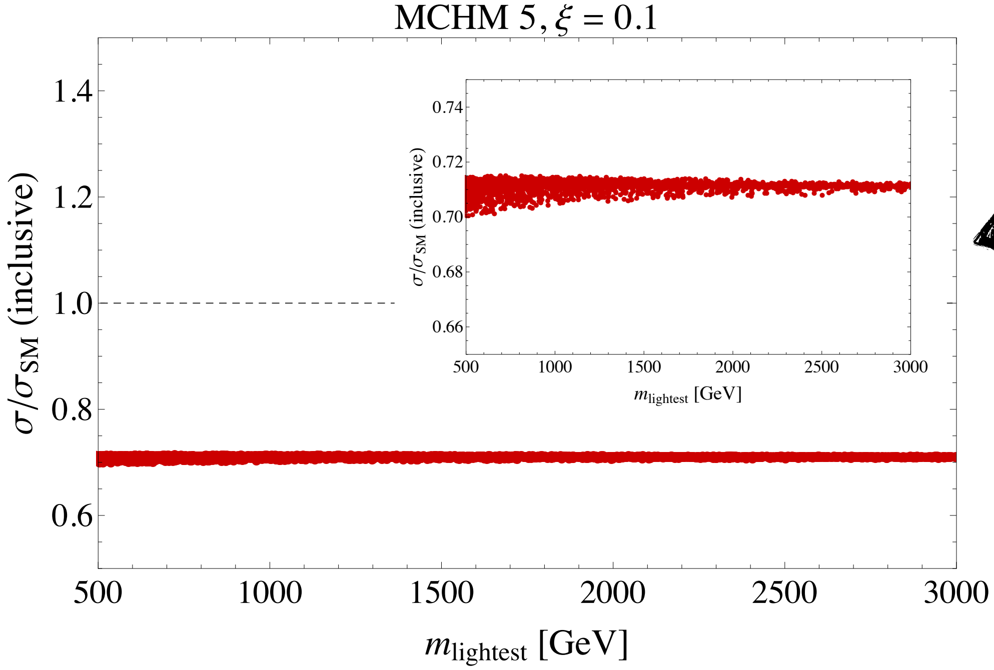
Composite Higgs Model

top partners contributions

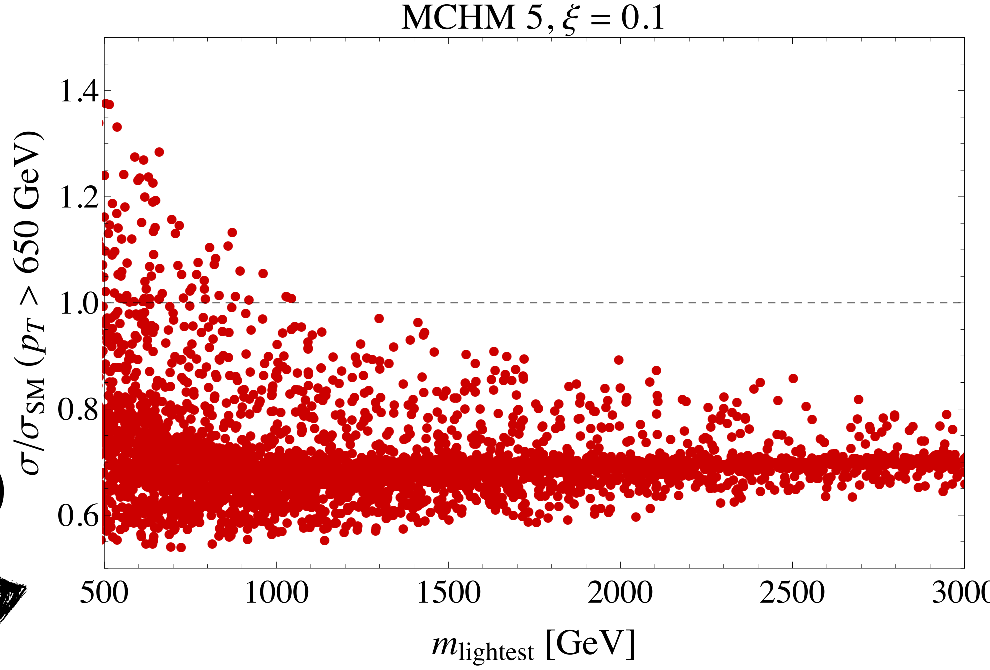
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

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

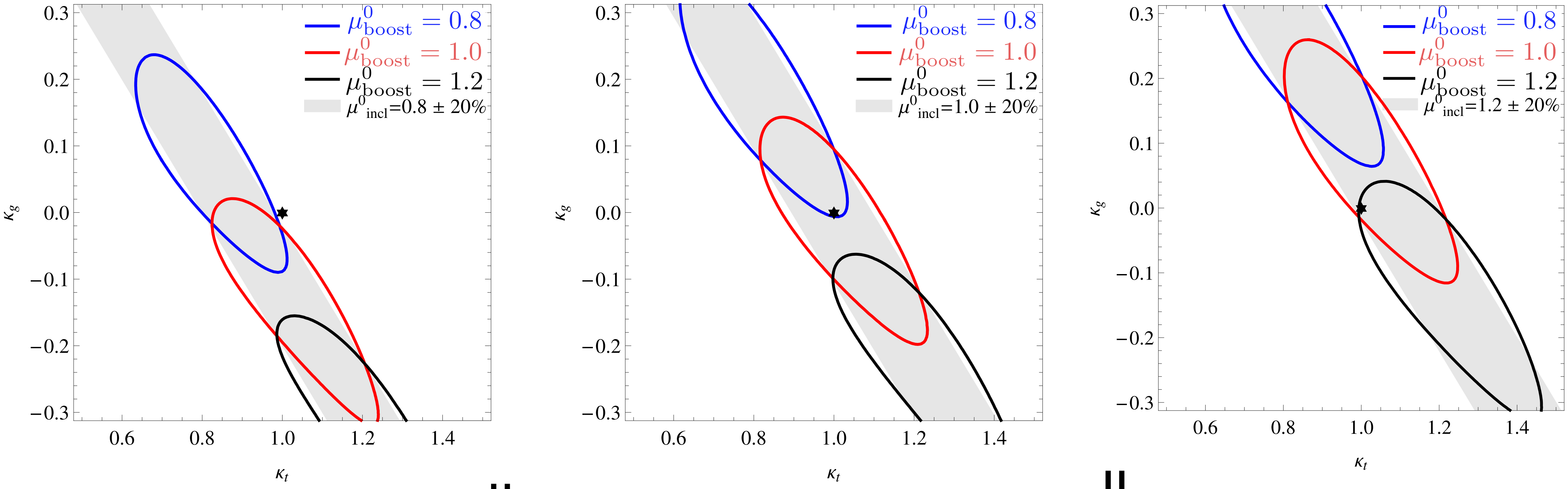
cut open the top loops

Grojean, Salvioni, Schlaffer, Weiler ‘13

see also Azatov, Paul ’13

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

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



⇓ ⇓

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^{3}LO$_\infty$ 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)

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

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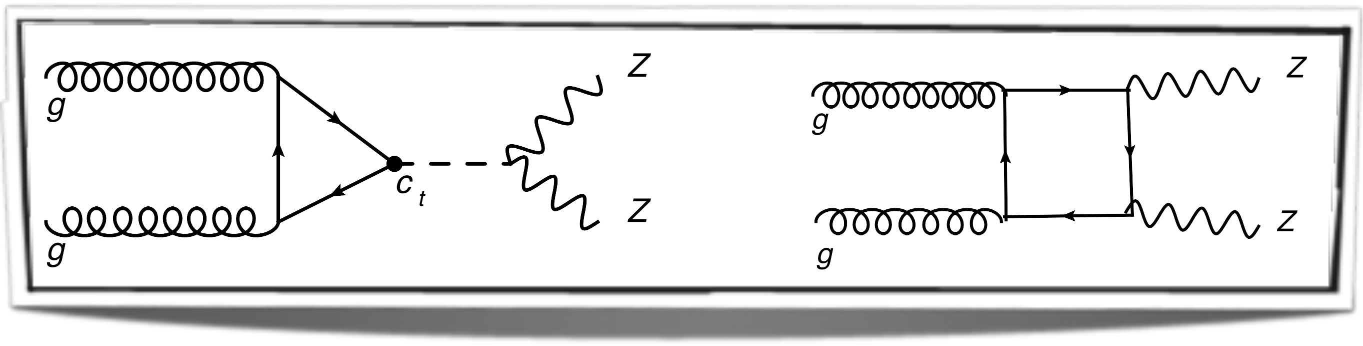
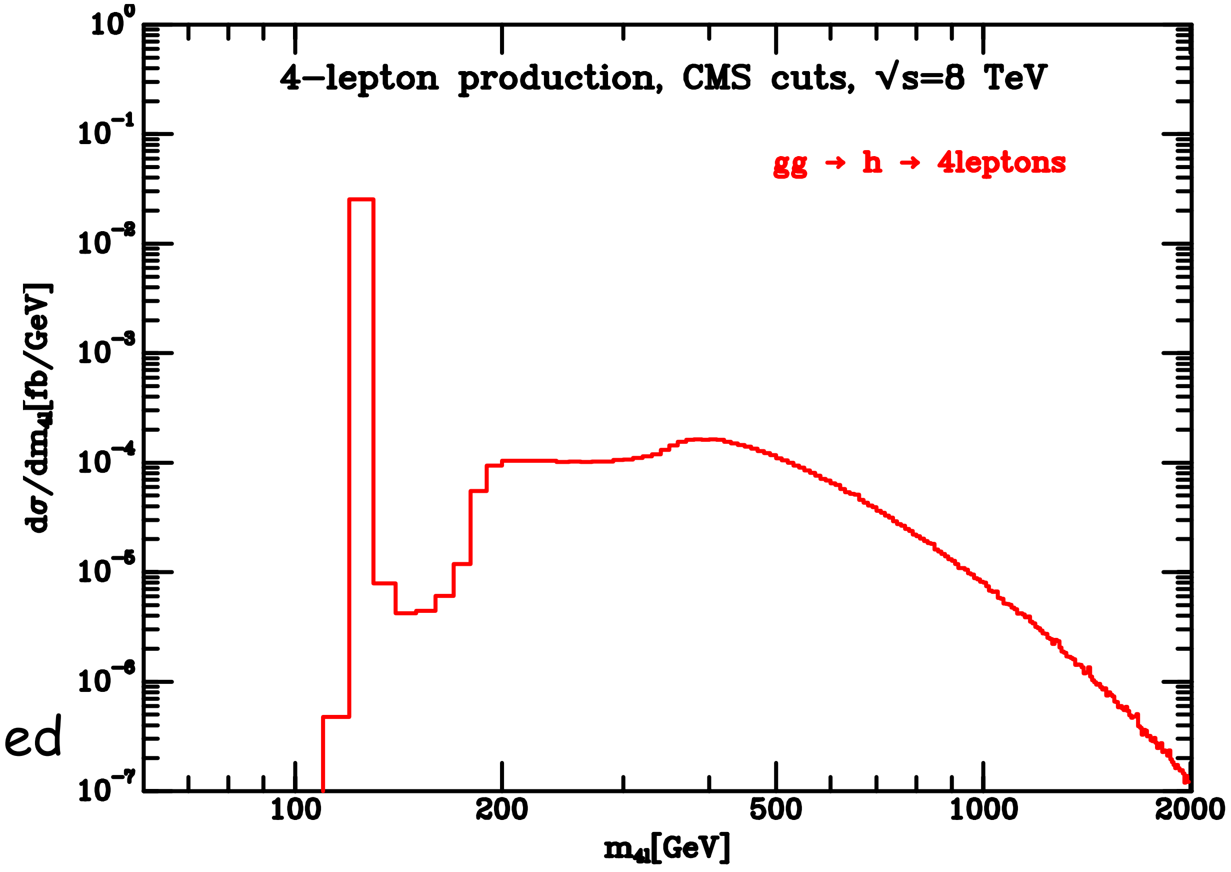
Glover, van der Bij '89



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

SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large $\hat{s}$ 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

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

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

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

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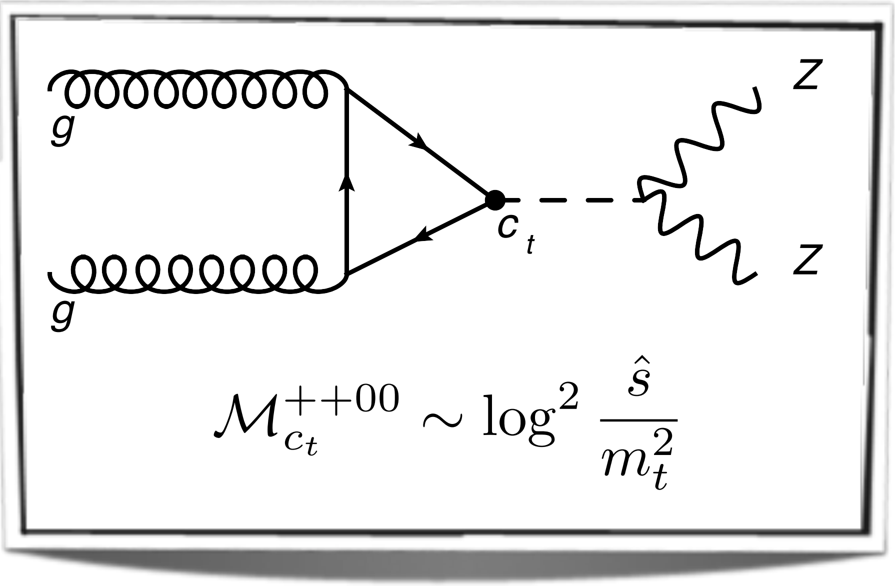
CMS PAS HIG-14-002
ATLAS-CONF-2014-042

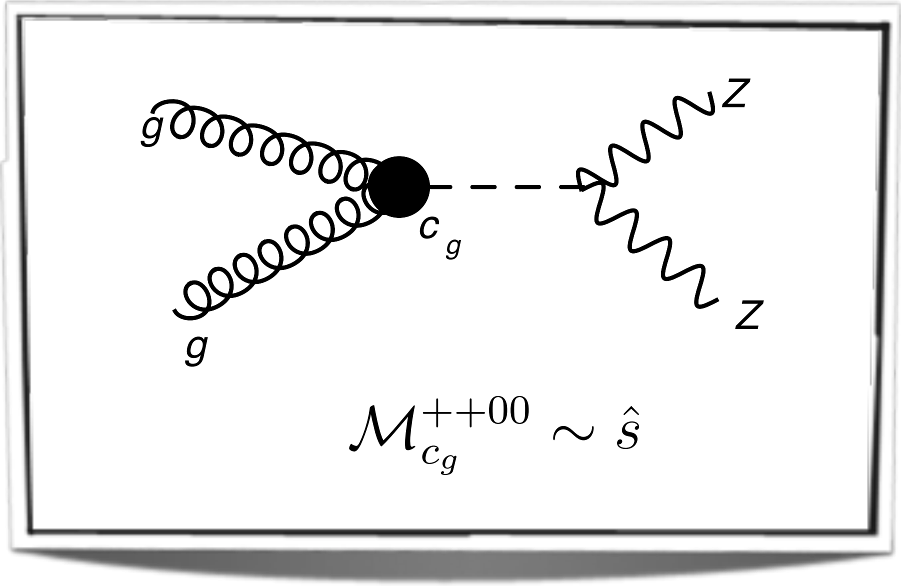
Access to top Yukawa coupling?

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

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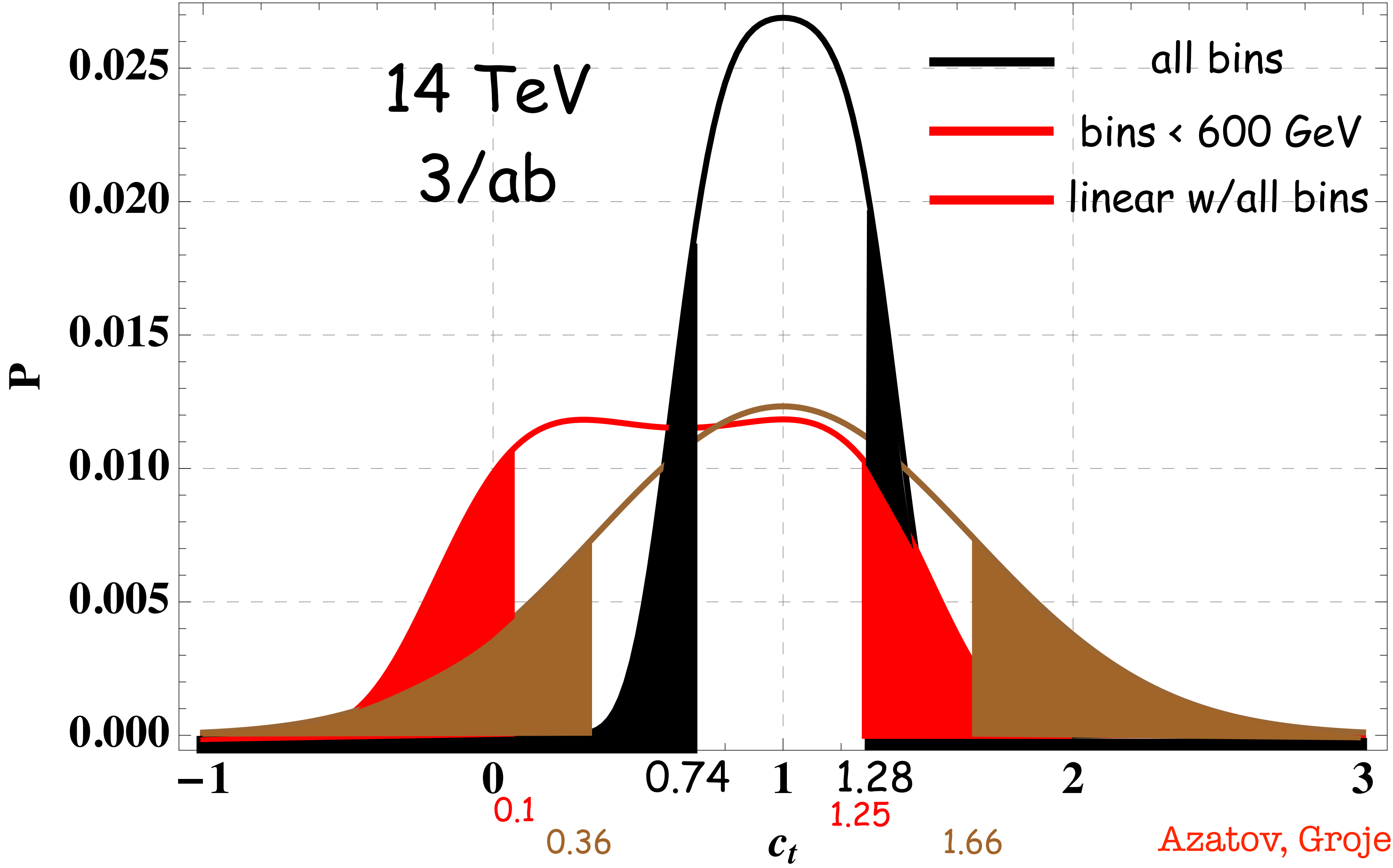
ATLAS-CONF-2014-042

Access to top Yukawa coupling?

provides an alternative to ttH to measure the top Yukawa coupling



Azatov, Grojean, Paul, Salvioni ’14

Conclusions: Executive Summary

The LHC leaves us with the deepest mathematical pb:

Dissertori, ECFA '13

$$\infty \cdot 0 = ?$$

number of already performed BSM searches

number of significant/ interesting/exciting deviations from SM predictions

general state of (our) mind (?)

Understanding the scalar sector of the SM
will help us grasping what lays beyond the SM

Conclusions

HEP program should aim at providing answers to fundamental questions like

- stability of the EW vacuum
- naturalness of EW symmetry breaking
- matter-antimatter asymmetry
- dynamics behind EW symmetry breaking (weak vs strong forces)
- is the Higgs boson responsible for the masses of all elementary particles?
- flavor structure via the access to rare processes
- nature of dark matter
- exotic new physics
- ...

Our understanding of the SM has reached an
unprecedented level of sophistication/precision
that paves the way to a discovery of New Physics

We have a rich EXP program to achieve this roadmap
Let us do it!