# Precision Frontier at High Energies

*Future Circular Colliders kick-off meeting*
*Geneva, February 12-15, 2014*

*Christophe Grojean*

ICREA@IFAE/Barcelona

( christophe.grojean@cern.ch )

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## after the 125 GeV Higgs discovery

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# The HEP landscape after LHC

Nicely summarized by MLM@Aspen'14:

## My key message

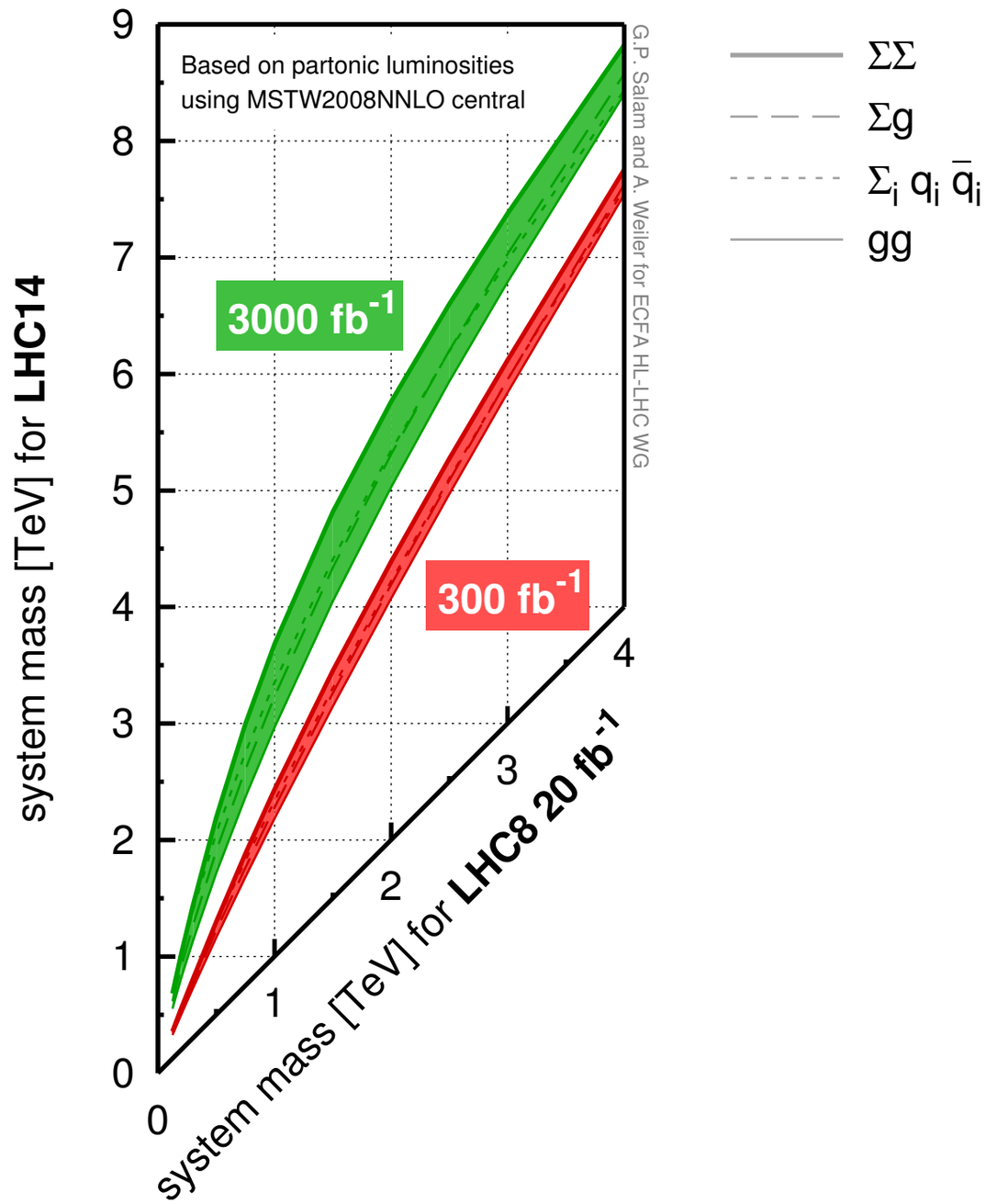
- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, .... )
- This simply implies that, more than for the past 30 years,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

I'll show on a few examples what kind of information FCC could bring and to which extend FCC could answer some of the big questions.

NB: I'll focus on Higgs physics for illustration and I'll leave out other very interesting topics

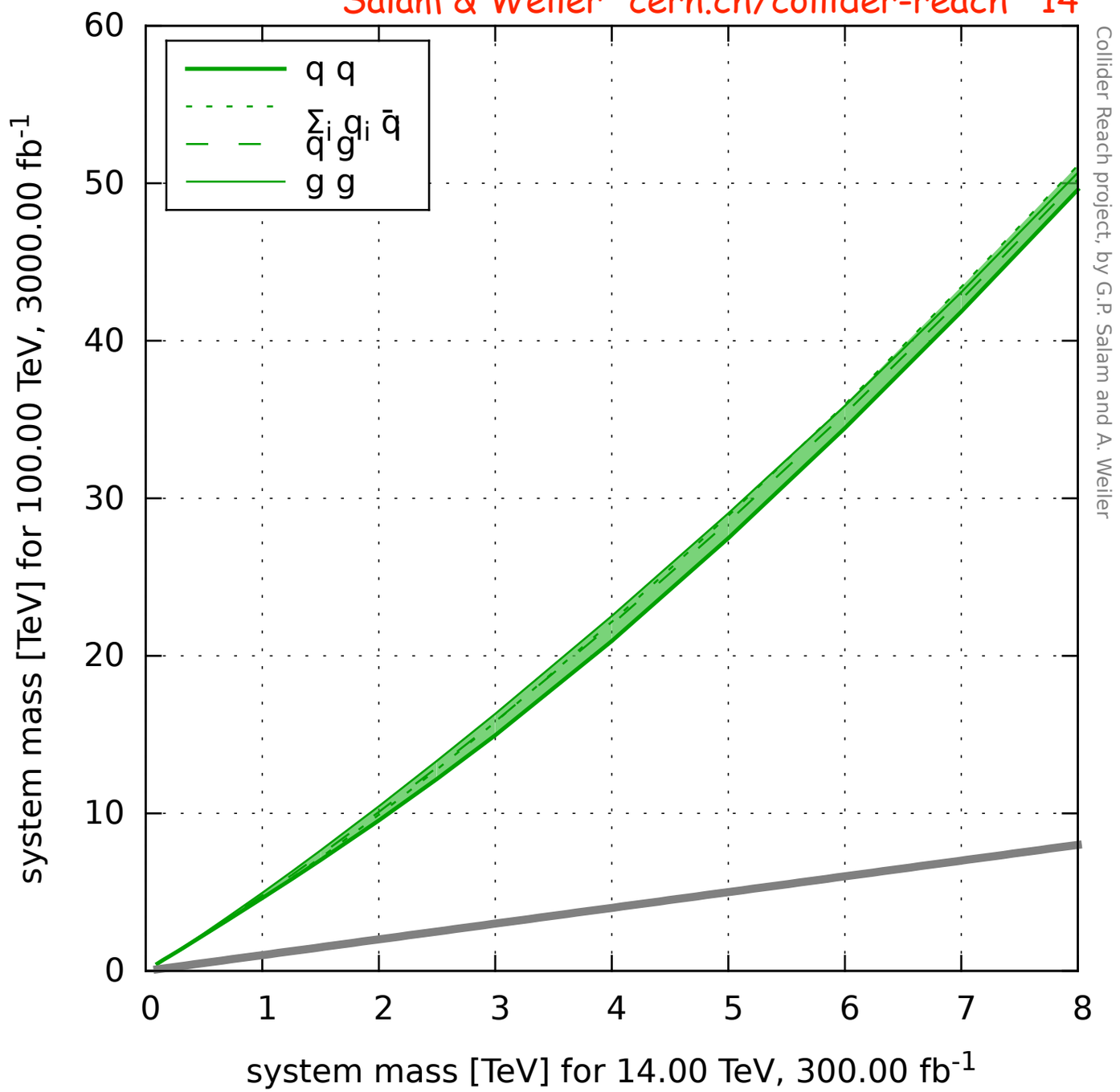
# The benefit of being energetic

## Direct exploration of an unexplored energy territory




$LHC_{14}/LHC_8$:
mass reach x O(2)

Salam & Weiler "cern.ch/collider-reach" '14




VHE-$LHC_{100}/LHC_{14}$:
mass reach x O(5)

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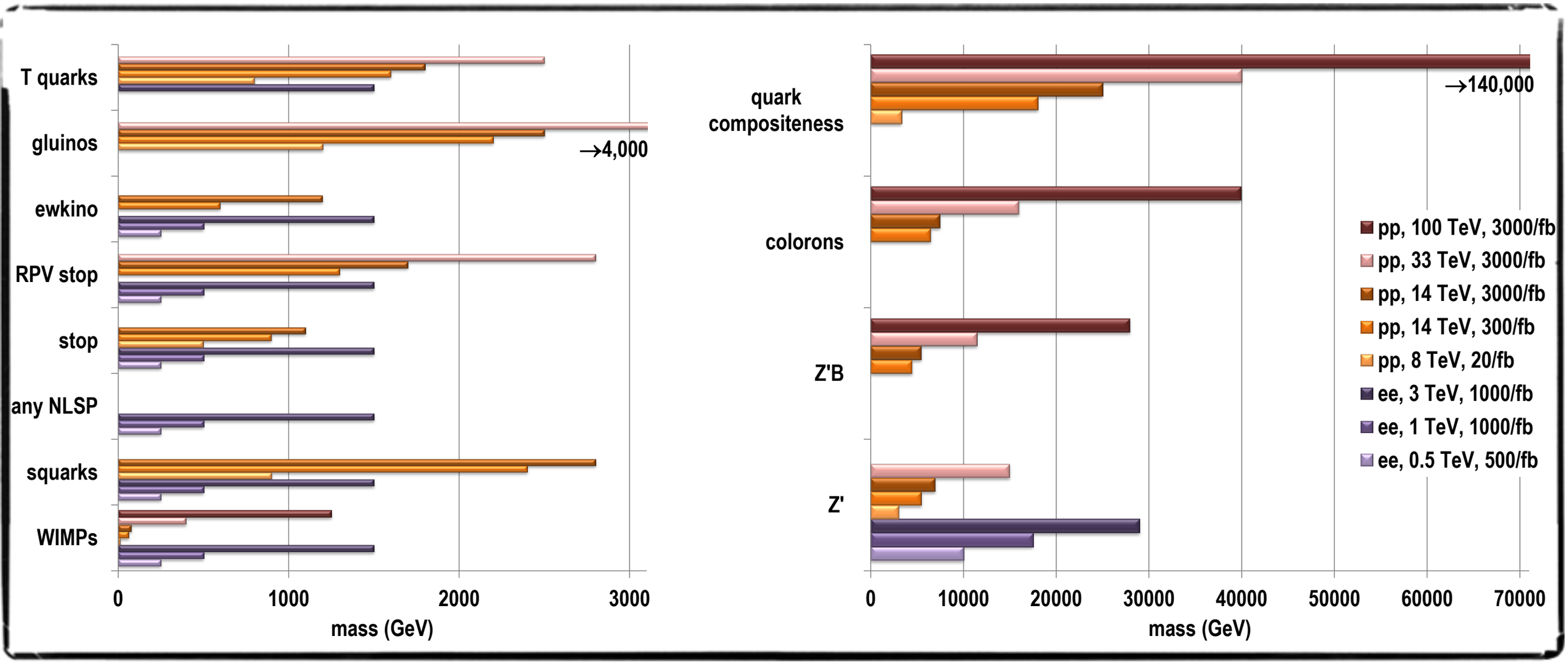


Energy Frontier Snowmass Study '13

# A Higgs: Now what? What's next?

*"The experiment worked better than expected and the analysis uncovered a very difficult to find signal"*

the words of a string theorist, Aspen '13

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Have the theorists been lying for so many years?

Have the exp's been too naive to believe the th's?

What should we still expect to see beyond the Standard Model?

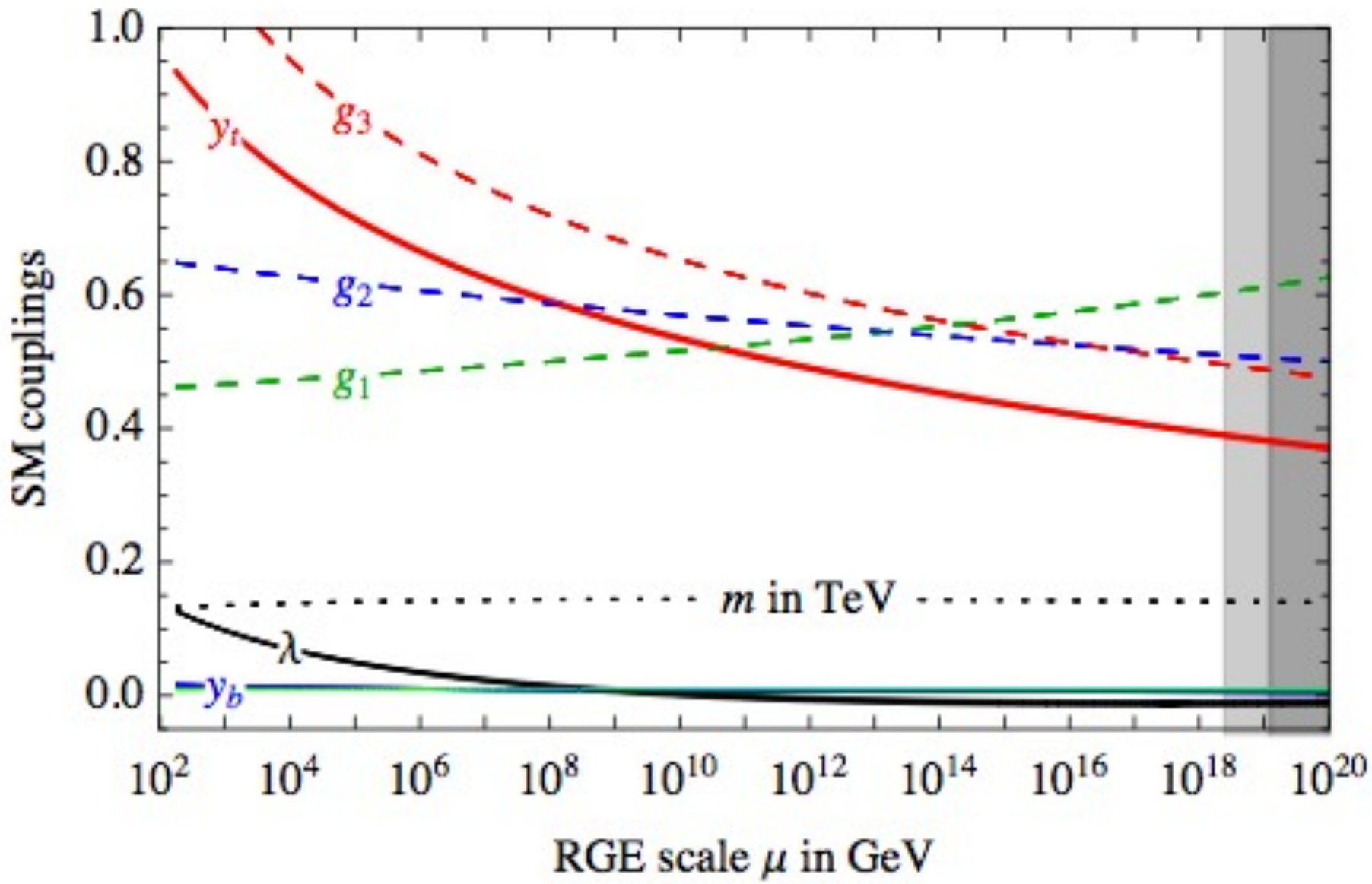
What should be our guiding principle(s)?

1

# The fate of the EW vacuum: a question of precision

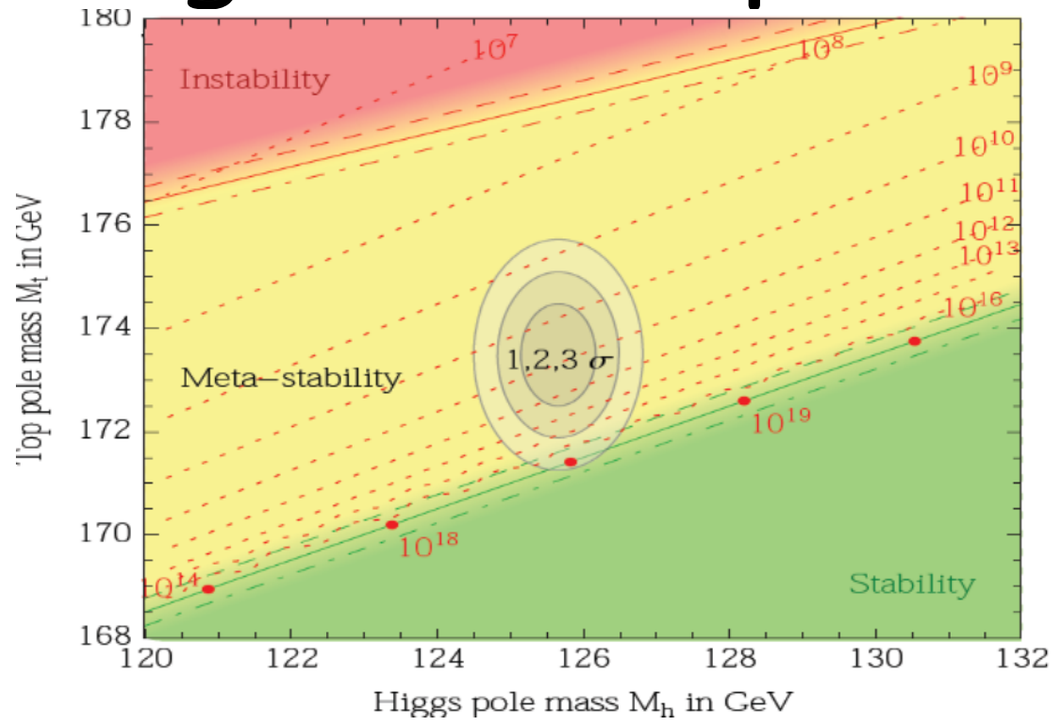
# Can we live without new physics?

Buttazzo et al '13




Can the SM (without new physics)
be valid up to $M_{Pl}$ and remain weakly coupled?

# Are we living at a edge of the phase diagram?

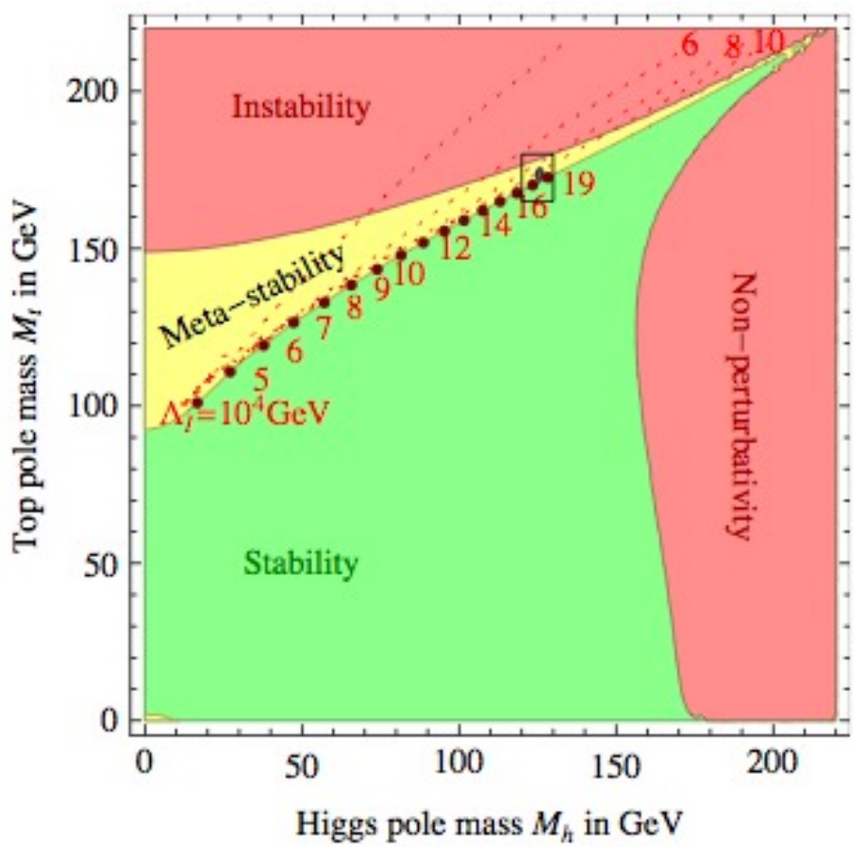


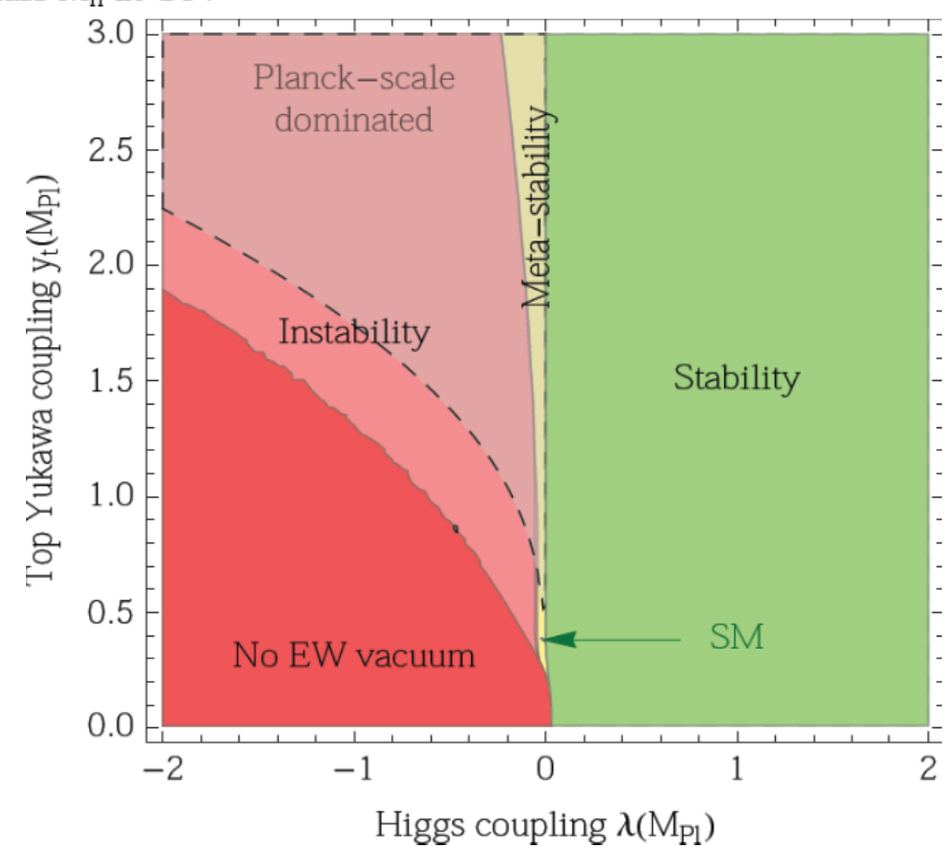

Buttazzo et al '13

see also:

Bezrukov et al '12

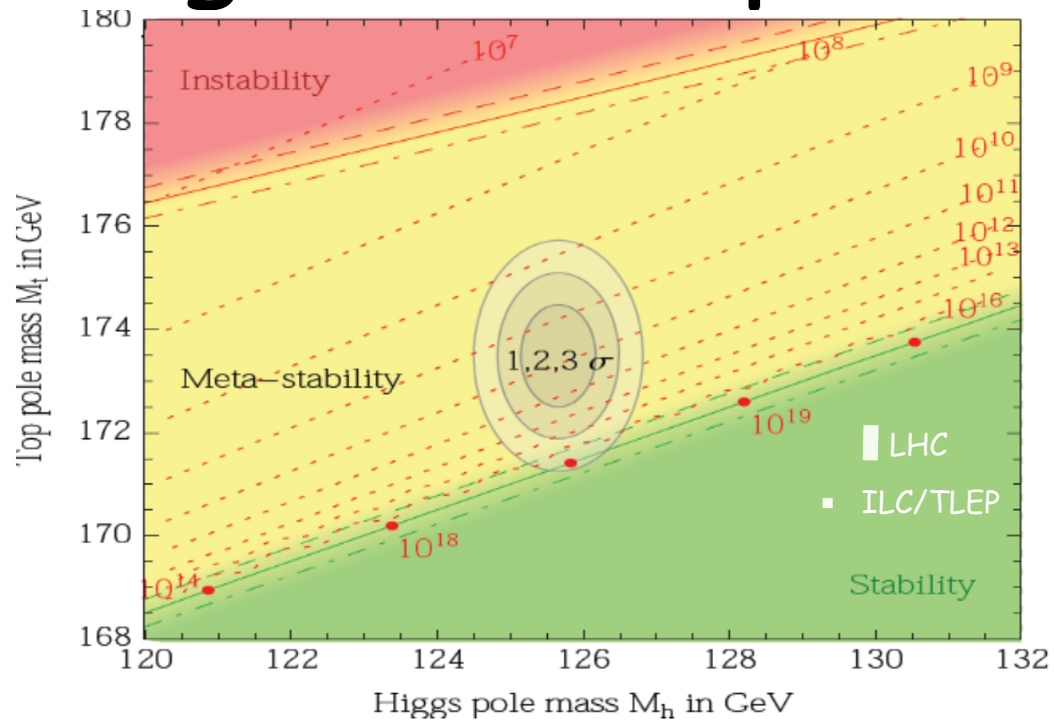
Degrassi et al '12



# Are we living at a edge of the phase diagram?

| Parameter | Present | LHC | ILC/GigaZ | TLEP |
|---|---|---|---|---|
| $M_H$ [GeV] | 0.4 | $< 0.1$ | $< 0.1$ | $< 0.1$ |
| $M_W$ [MeV] | 15 | 8 | 5 | 1.3 |
| $M_Z$ [MeV] | 2.1 | 2.1 | 2.1 | 0.1 |
| $m_t$ [GeV] | 0.9 | 0.6 | 0.1 | 0.08 |

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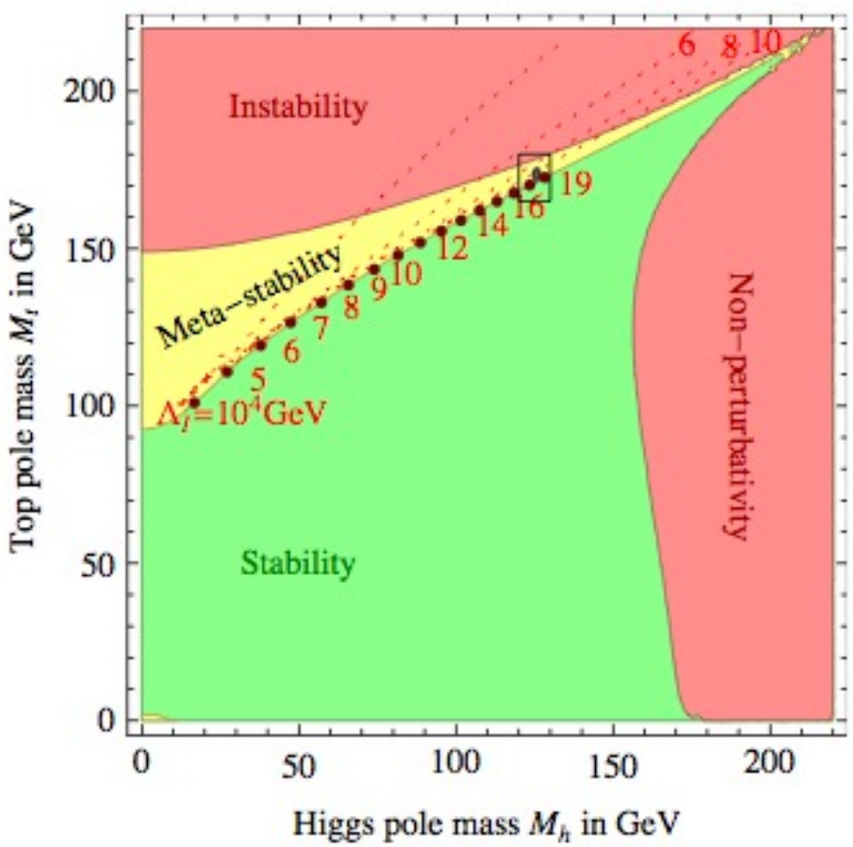


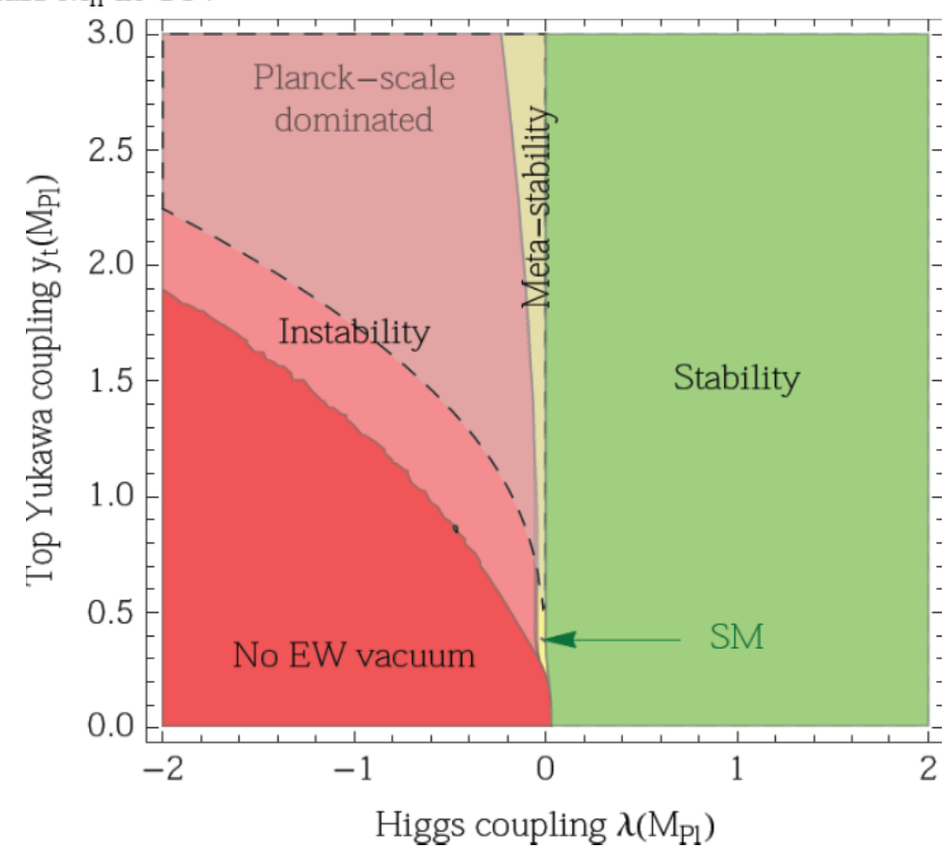


The (near) criticality of our vacuum calls for a precise measurement

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Voltaire & Spider-Man

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actually, first google hit gives a link to an article of
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1

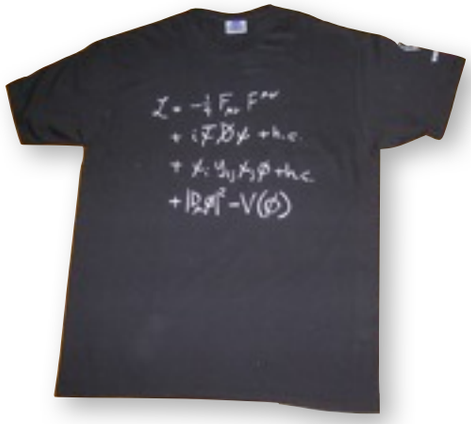
## Higgs properties

$J^{PC}$

Important & nice to see progresses but "this question carries a similar potential for surprise as a football game between Brazil and Tonga" Resonaances

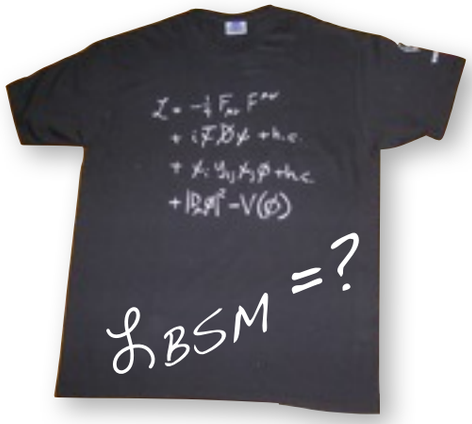
2

## Higgs couplings



3

## BSM implications



2

# Higgs and Naturalness: a question of precision

# 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
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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
  - 2208 citations (as of Feb. 11, 2014)
- CMS Higgs discovery paper: arXiv:1207.7235
  - submitted on July 31, 2012@ 13:27:18 GMT
  - 2192 citations (as of Feb. 11, 2014)

➠ fine-tuning ≈ 0.7%

# Higgs couplings = test of Naturalness?

$$\delta m_H^2 = -(125\ \mathrm{GeV})^2 \left(\frac{\Lambda}{600\ \mathrm{GeV}}\right)^2$$

charged particles

$$+$$

$$\frac{g_*^2}{16\pi^2}\Lambda^2$$

$$\sim m_H^2$$

neutral particles

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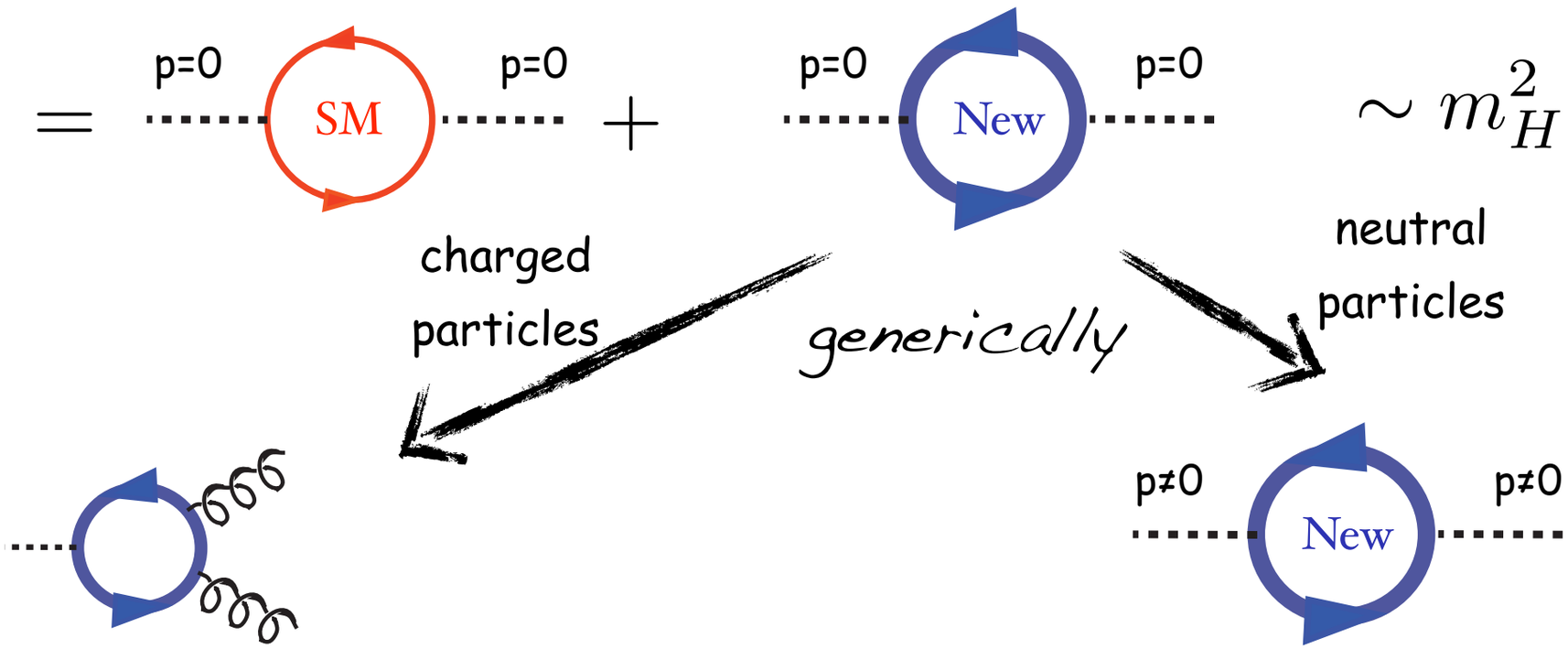
$$\delta m_H^2 = -(125\ \text{GeV})^2 \left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 + \frac{g_*^2}{16\pi^2}\Lambda^2 \sim m_H^2$$




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

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$

$$BR(h\to ii) = BR_{\text{SM}}$$

$$\Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

nice to be able to measure Γ

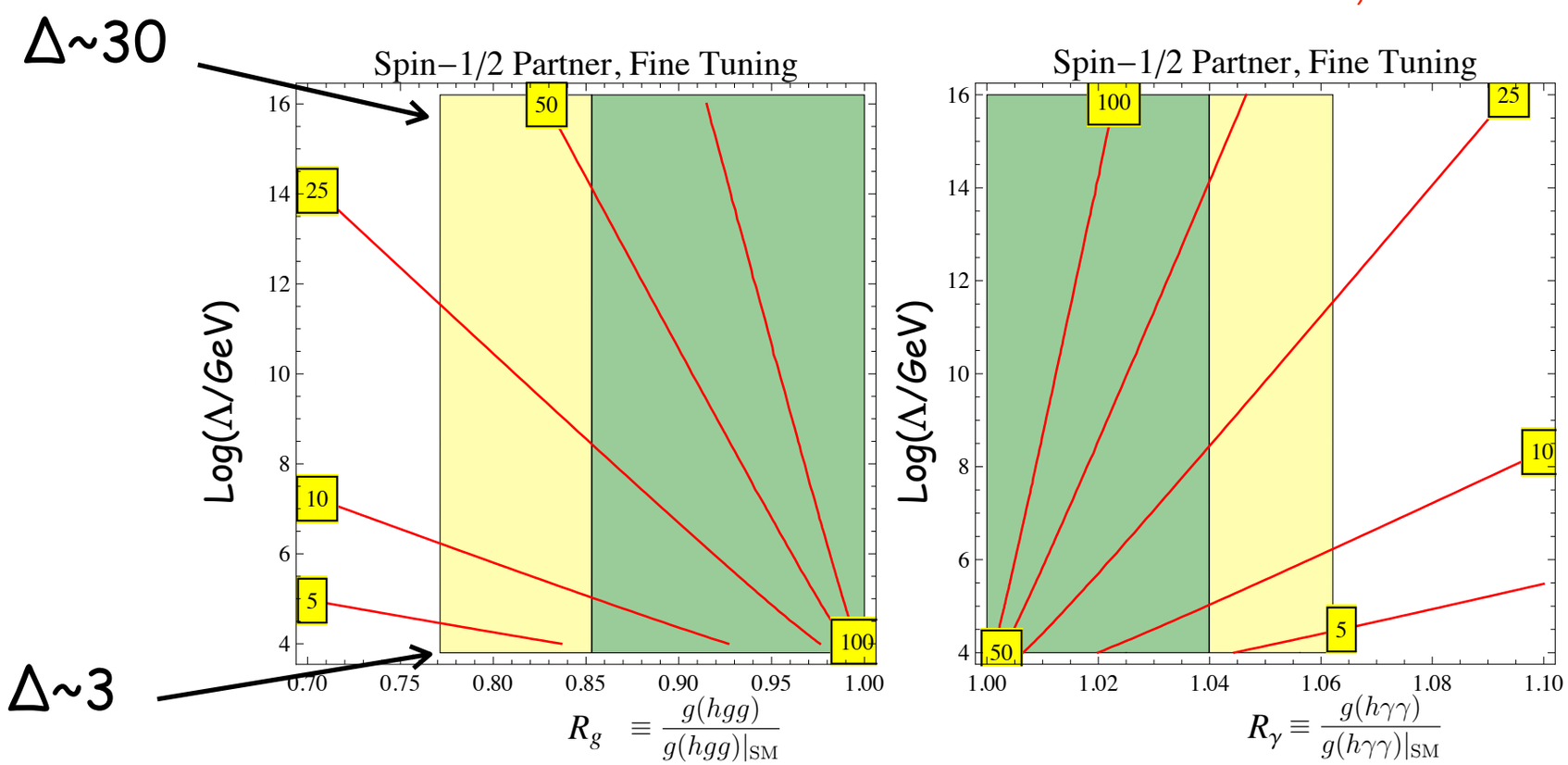
Generically, natural scenarios come with deviations of the Higgs coupling

# 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

$\Lambda$ cutoff scale of log. divergences to the Higgs mass

High scale models ($\Lambda \sim 10^{16}$GeV) come with a generic fine-tuning O(1/30)

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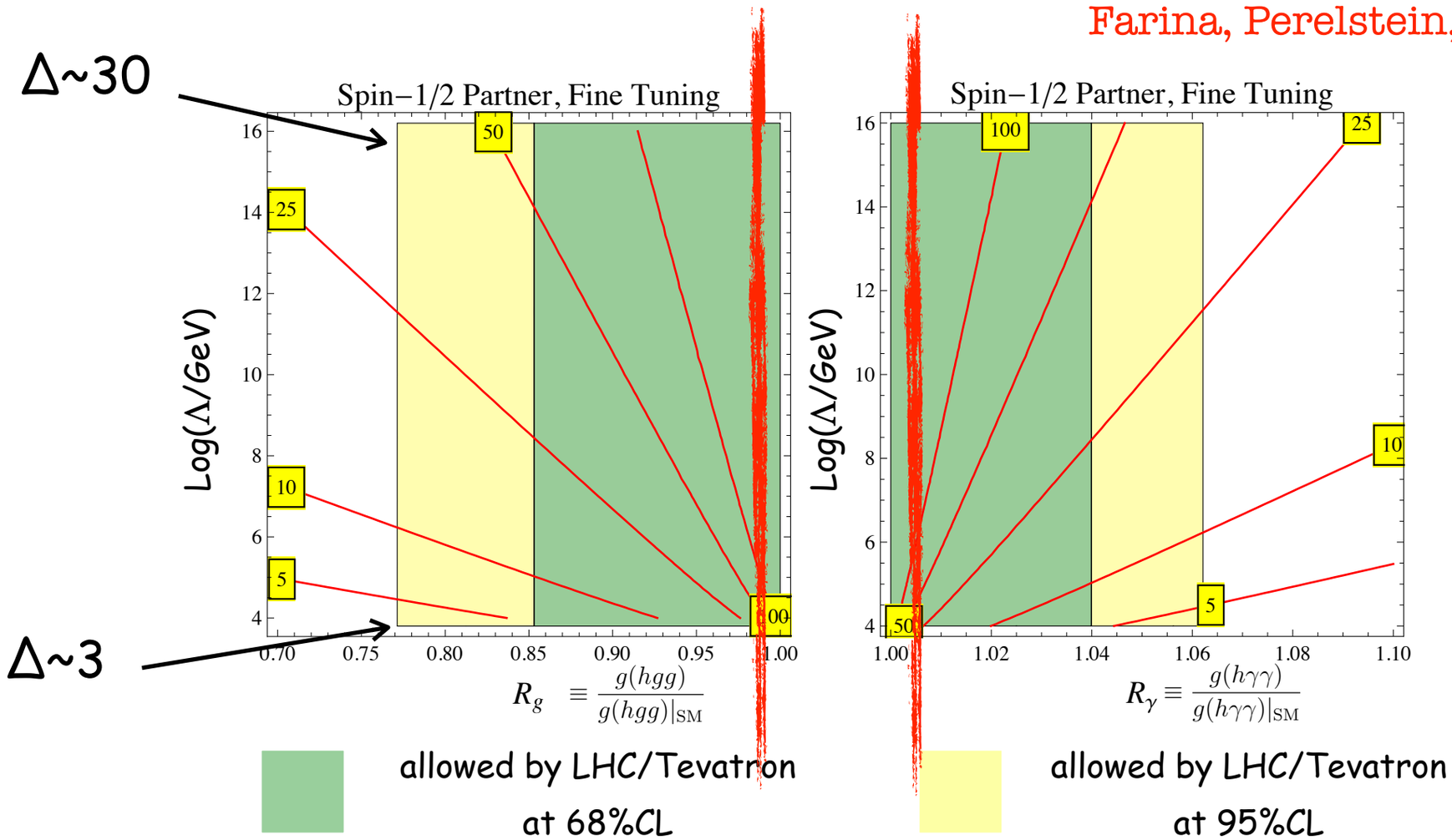


$\Lambda$ cutoff scale of log. divergences to the Higgs mass

High scale models ($\Lambda$ ~$10^{16}$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

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

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

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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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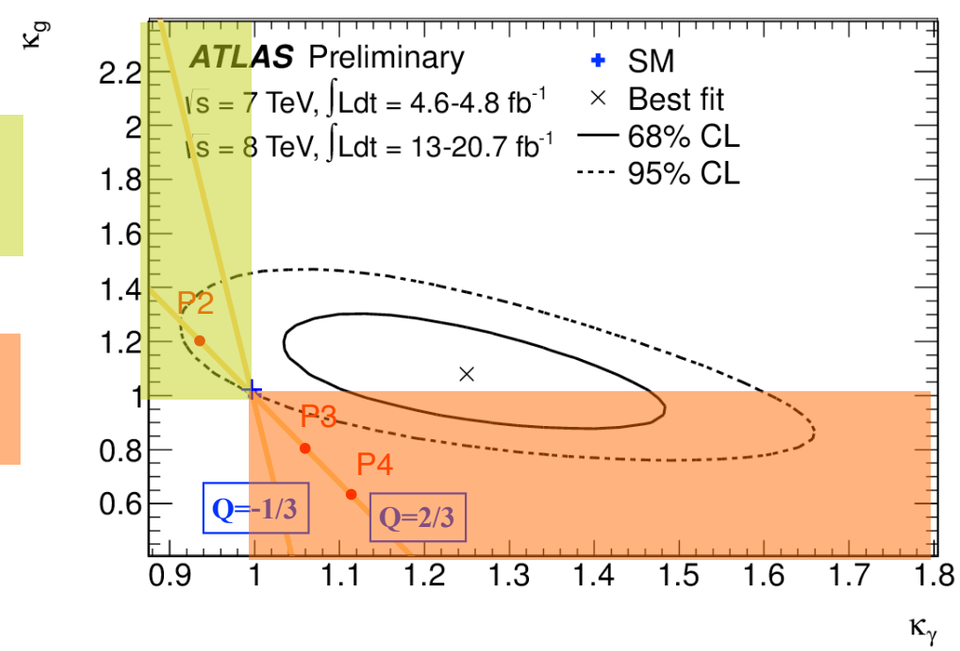
P1: $m_{\tilde{t}_1} = 100\,\mathrm{GeV},\ m_{\tilde{t}_2} = 300\,\mathrm{GeV},\ \theta_t = 0$

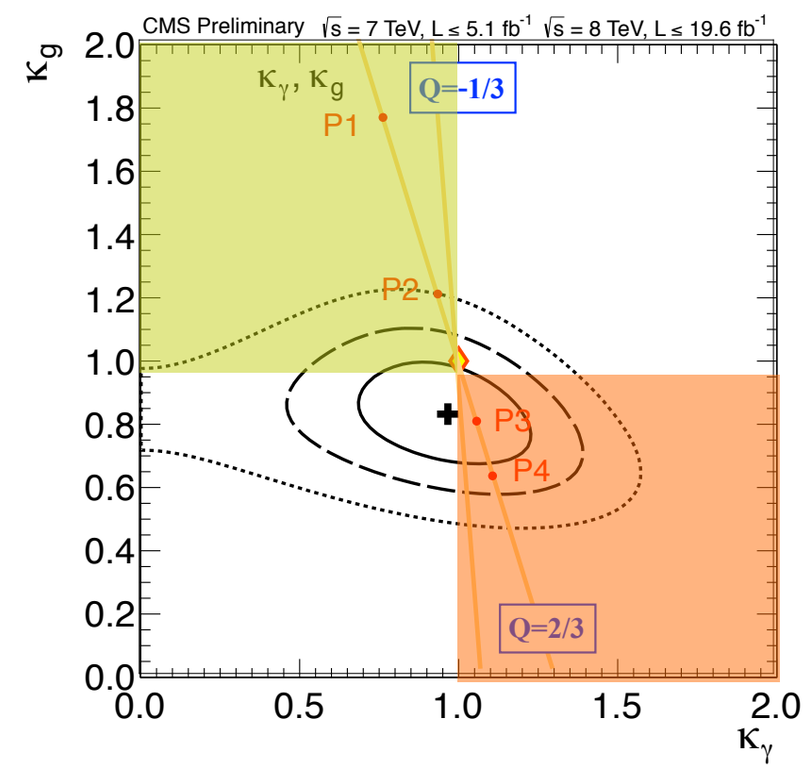
P2: $m_{\tilde{t}_1} = 200\,\mathrm{GeV},\ m_{\tilde{t}_2} = 500\,\mathrm{GeV},\ \theta_t = 0$

P3: $m_{\tilde{t}_1} = 400\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1000\,\mathrm{GeV},\ \theta_t = \pi/4$

P4: $m_{\tilde{t}_1} = 500\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1500\,\mathrm{GeV},\ \theta_t = \pi/4$

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 precision measurement

$$\frac{\Delta g}{g_{SM}} \approx \frac{g_*^2 v^2}{m_*^2} \approx ?$$

to which level of precision do we need to measure the Higgs couplings?

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There will always be theorists to claim that you need to measure these couplings to xx% to test his most beautiful model

# Which Higgs precision to test Naturalness?

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Models where the Higgs mass is UV insensitive

$$m_H^2 \sim \frac{N_c y_t^2}{16\pi^2} m_*^2 \quad \Rightarrow \quad \frac{\Delta g}{g_{SM}} \sim \frac{N_c g_*^2}{16\pi^2}$$

~ 1 for strongly coupled models

~ 1% for weakly coupled models

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## Models where the Higgs mass has a UV logarithmic insensitivity

e.g. high scale susy breaking

$$m_H^2 \sim \frac{N_c y_t^2}{16\pi^2} m_*^2 \log(\Lambda/m_*) \quad \Rightarrow \quad \frac{\Delta g}{g_{SM}} \sim \frac{N_c g*^2}{16\pi^2} \log(\Lambda/m_*)$$

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~ 1

O(1%) precision Higgs physics could be as important as direct searches for new physics to probe the naturalness of EWSB

# 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 |
| $\kappa_\gamma$ | $5-7\%$ | $2-5\%$ | 8.3% | 4.4% | 3.8% | 2.3% | $-$/5.5/<5.5% | 1.45% |
| $\kappa_g$ | $6-8\%$ | $3-5\%$ | 2.0% | 1.1% | 1.1% | 0.67% | 3.6/0.79/0.56% | 0.79% |
| $\kappa_W$ | $4-6\%$ | $2-5\%$ | 0.39% | 0.21% | 0.21% | 0.2% | 1.5/0.15/0.11% | 0.10% |
| $\kappa_Z$ | $4-6\%$ | $2-4\%$ | 0.49% | 0.24% | 0.50% | 0.3% | 0.49/0.33/0.24% | 0.05% |
| $\kappa_\ell$ | $6-8\%$ | $2-5\%$ | 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

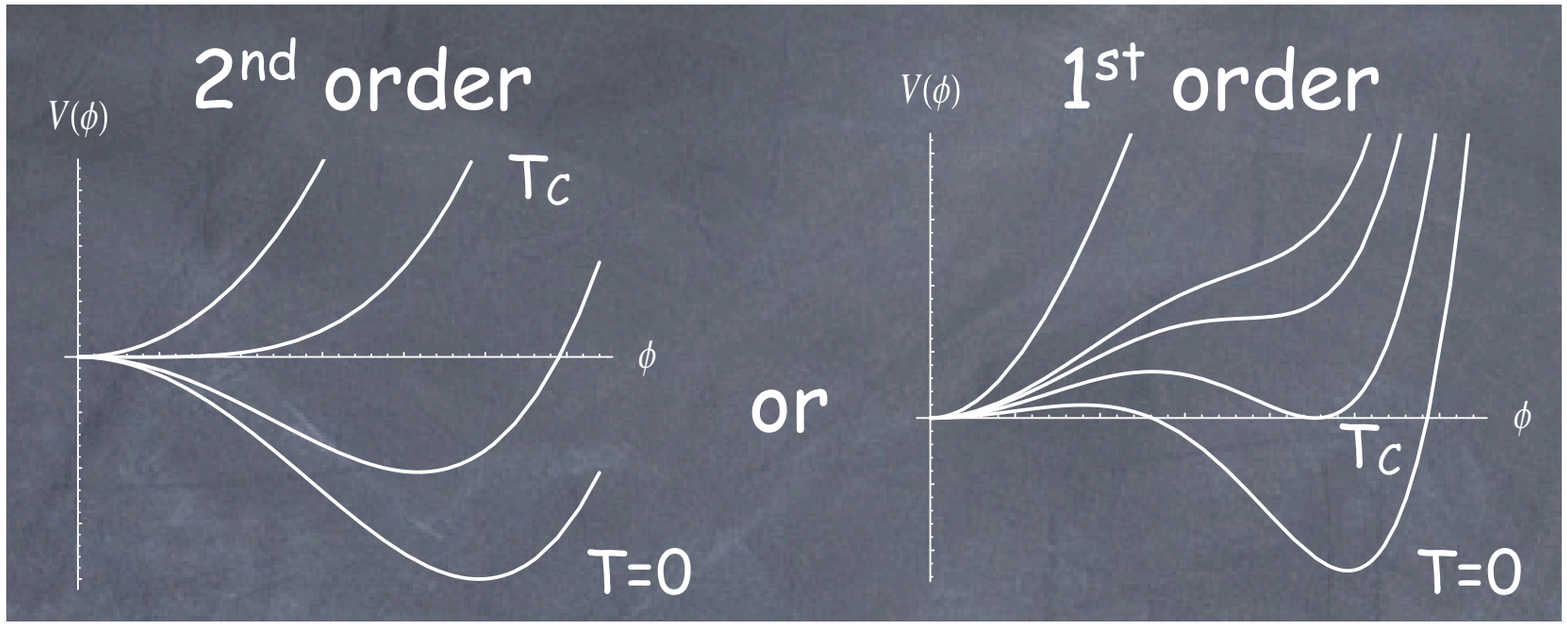
4

# EW phase transition: a question of precision

# Dynamics of EW phase transition and Cosmology

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition



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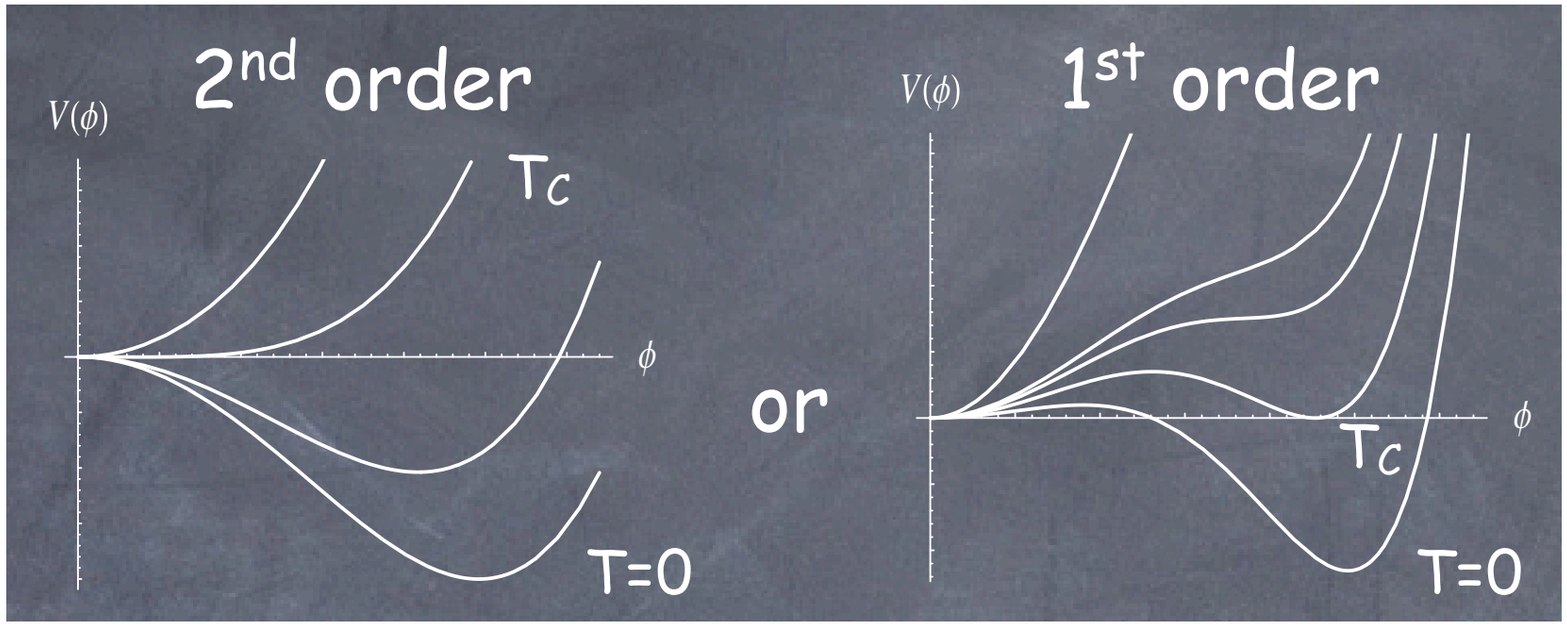


the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)

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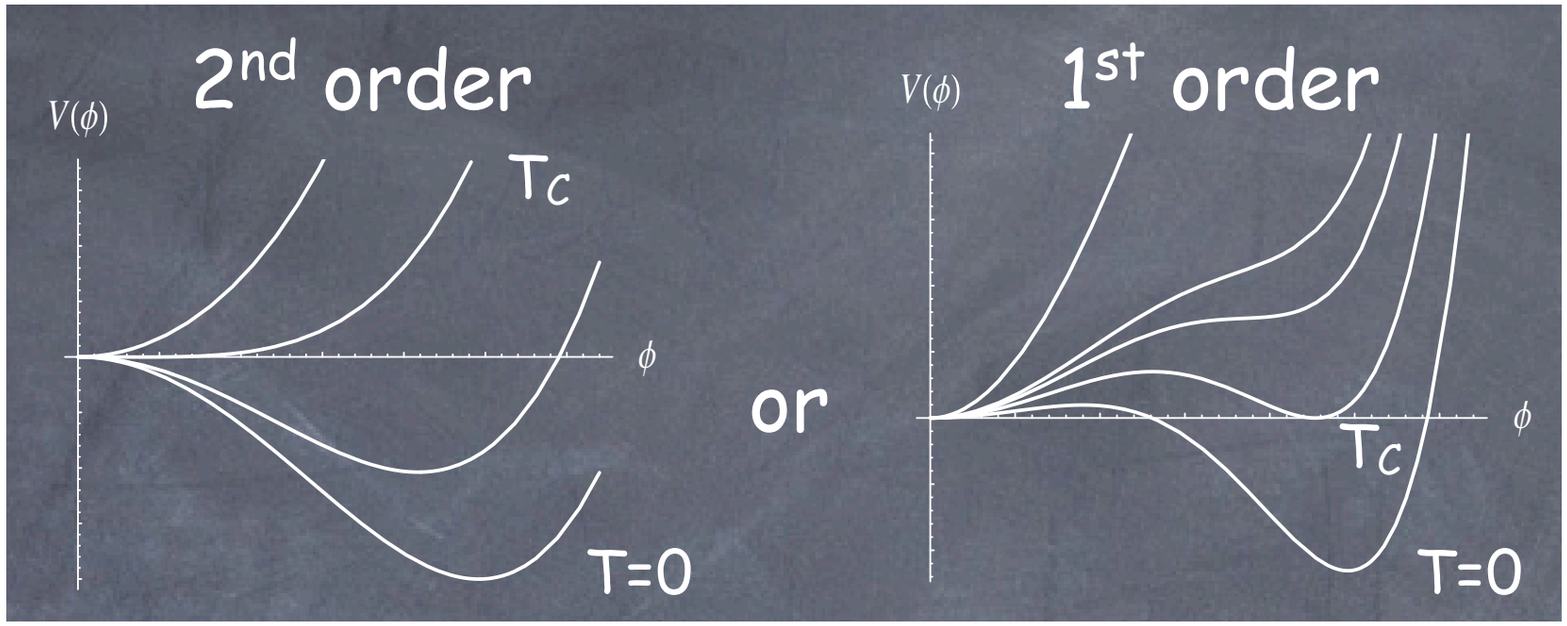


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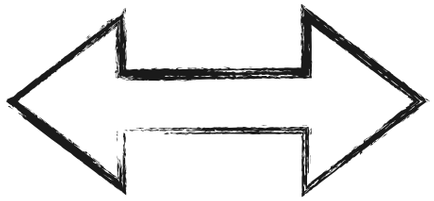
which we have no direct access at in colliders (LHC≠Big Bang machine)

finite T
Higgs potential



Higgs couplings
at T=0

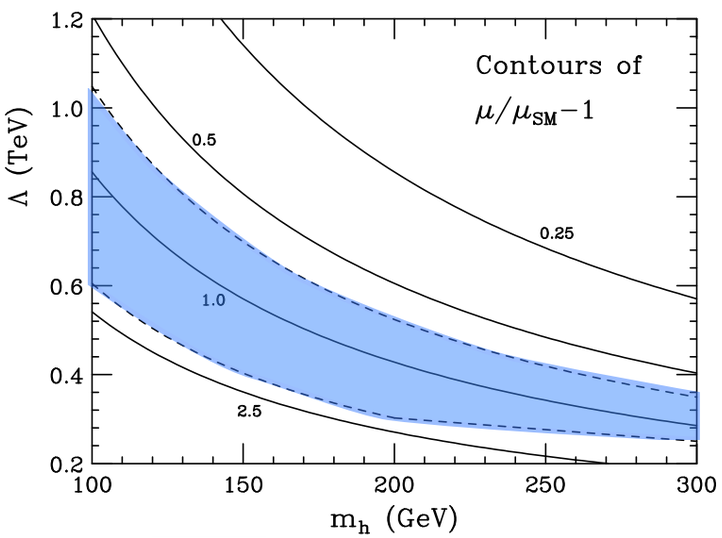
SM: first order phase transition iff mH < 47 GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

# Higgs couplings for 1st order EW phase transition

New physics @ tree-level

Grojean, Servant, Wells '04
Noble, Perelstein '07

mixing with other scalars modify the tree-level Higgs potential




first order phase transition

$$V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3$$

1st order phase transition

comes with 80-200% deviations in Higgs self-interaction

$\Downarrow$ $\Downarrow$

visible @ ILC/TLEP

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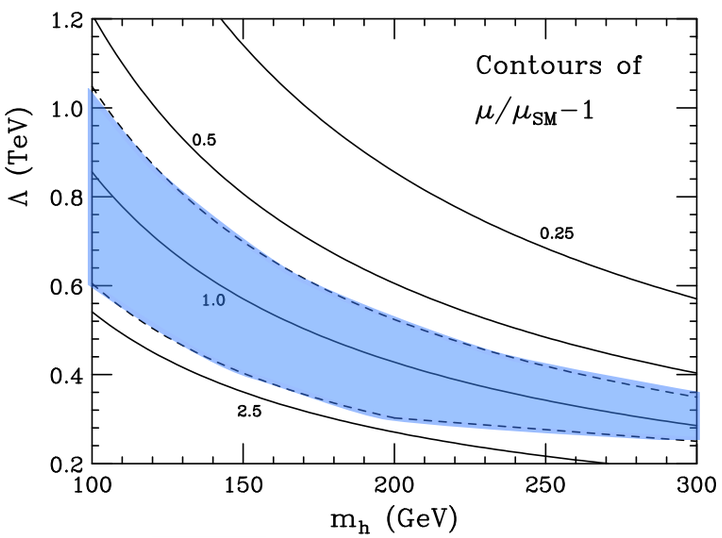


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Katz, Perelstein '14

new particles, e.g. scalars, coupled to the Higgs without affecting its tree-level potential

$$V \propto \kappa|\Phi|^2|H|^2$$

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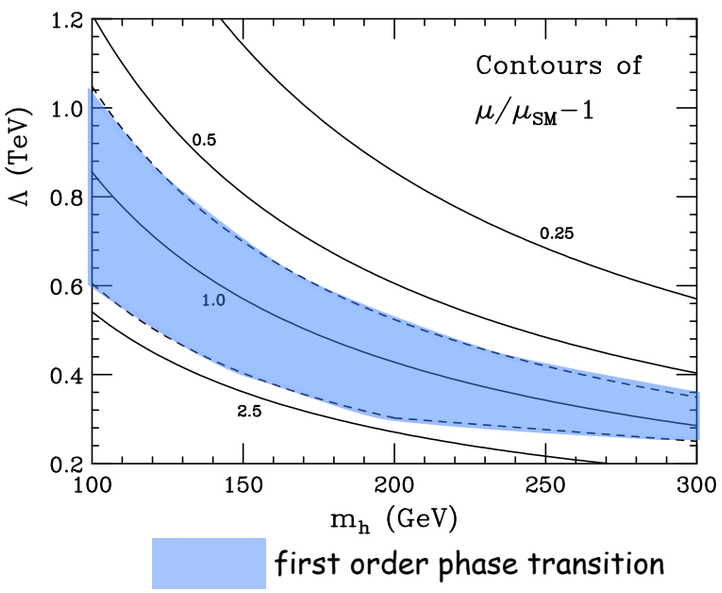


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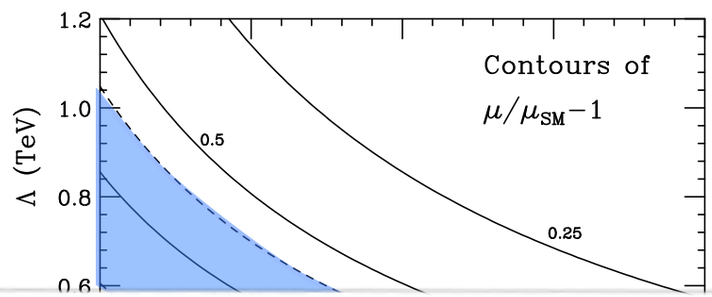


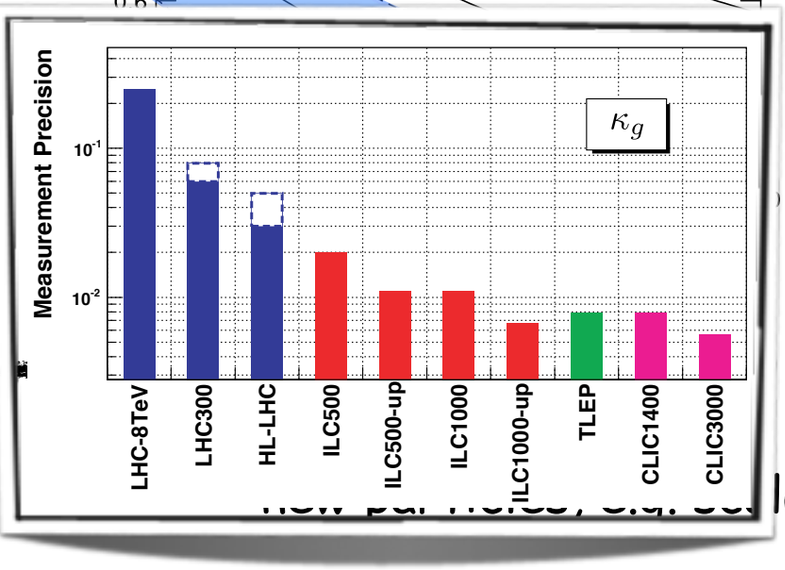


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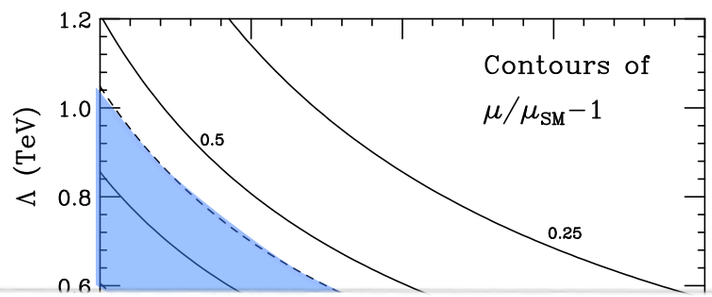


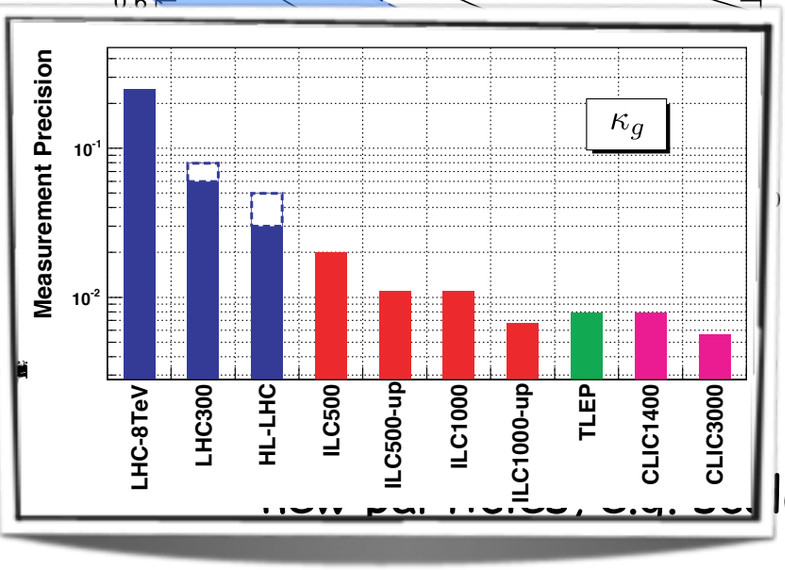


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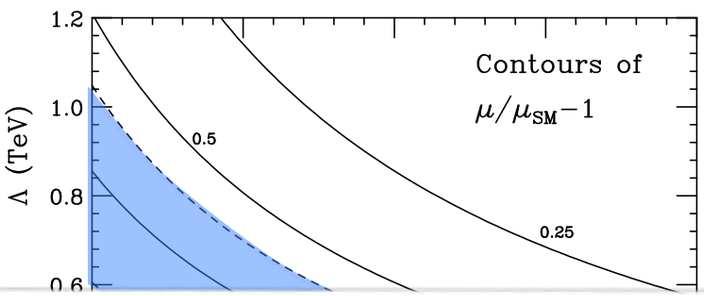


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⇓

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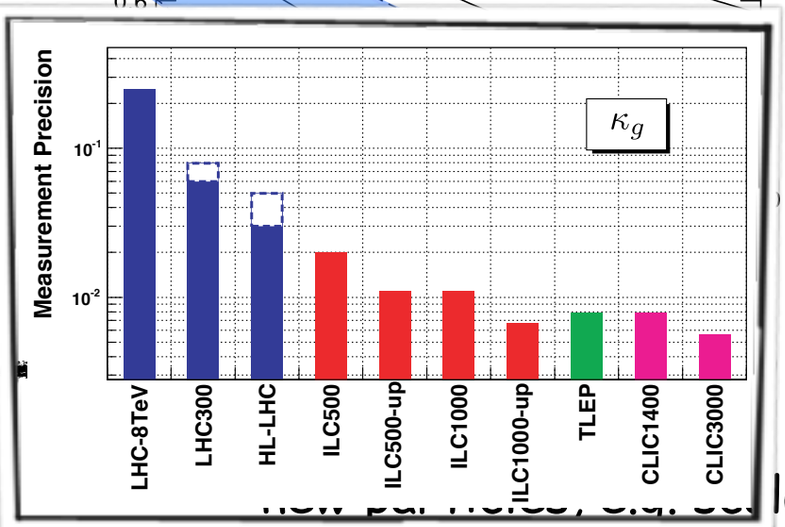


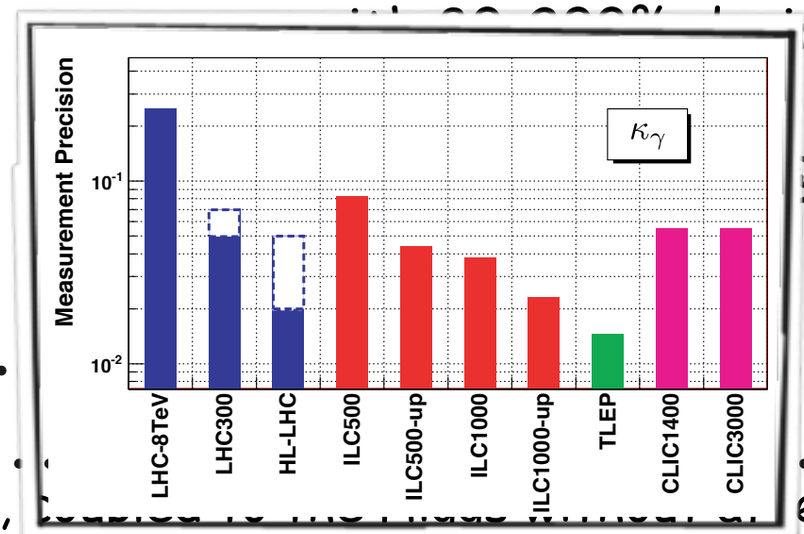


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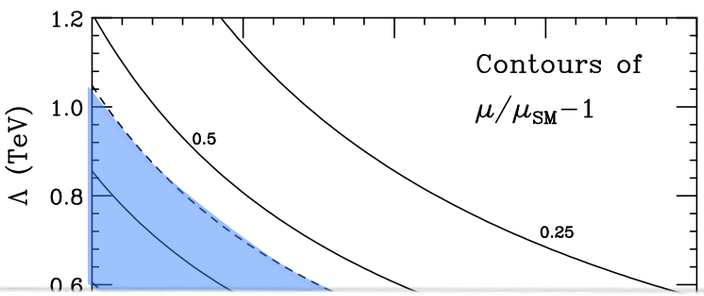


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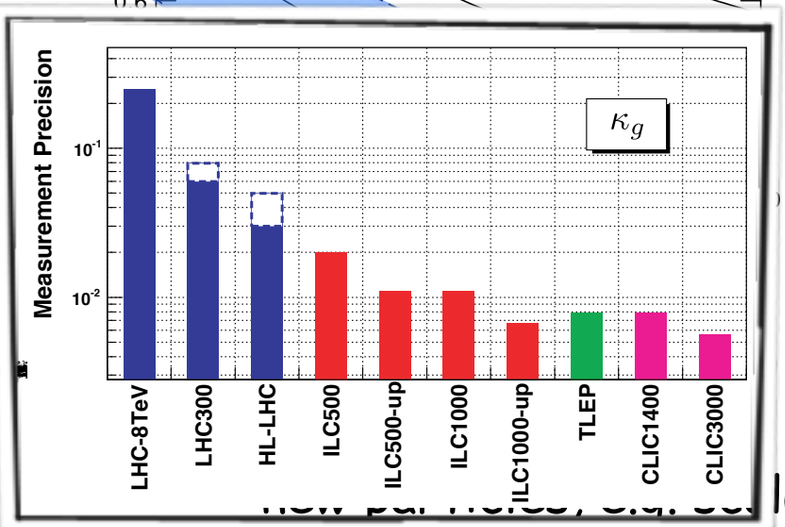


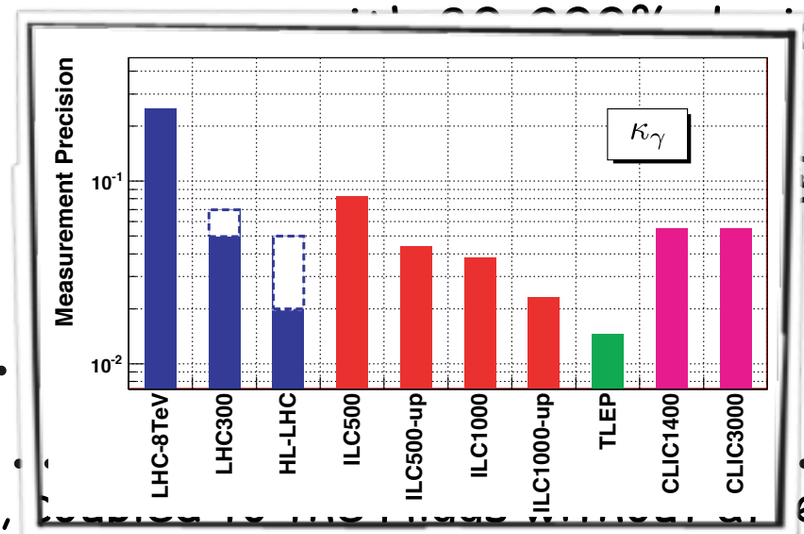


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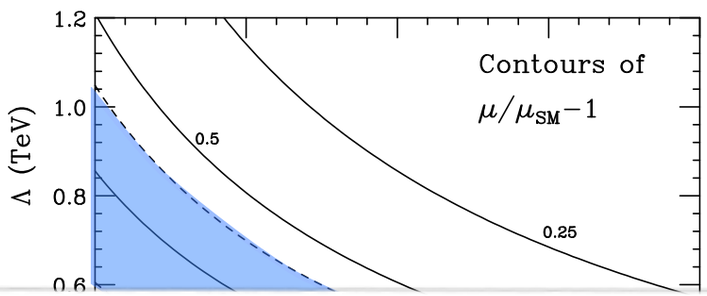


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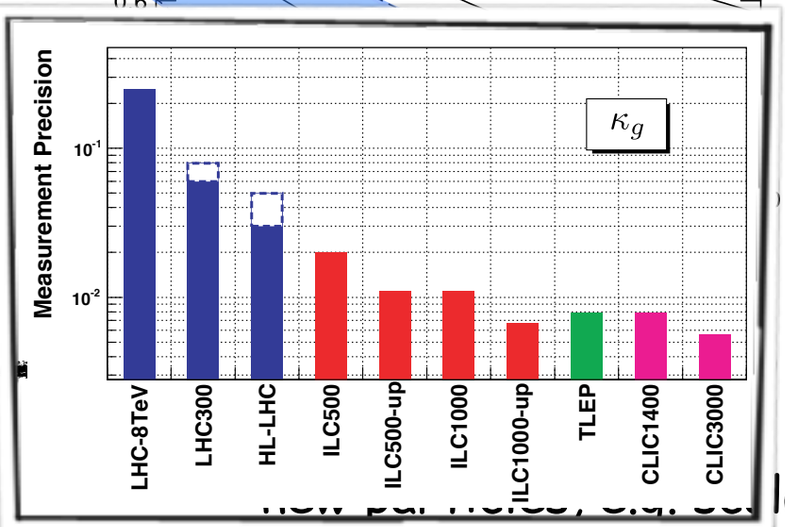


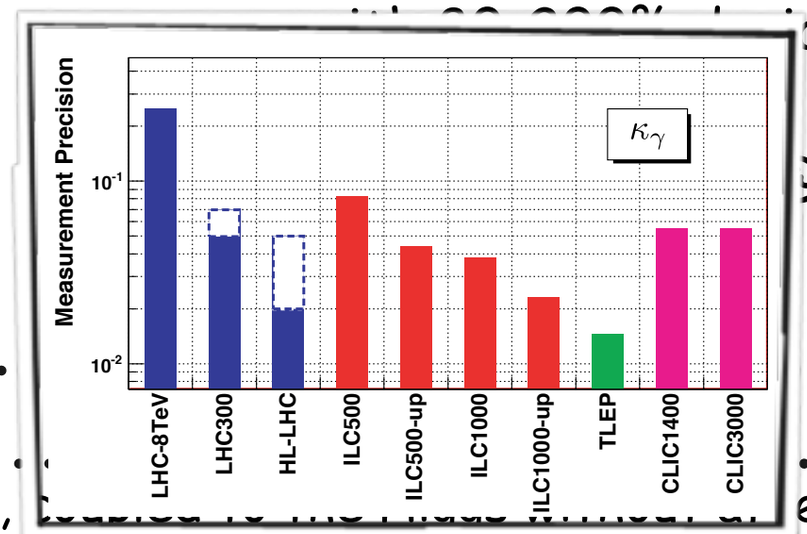


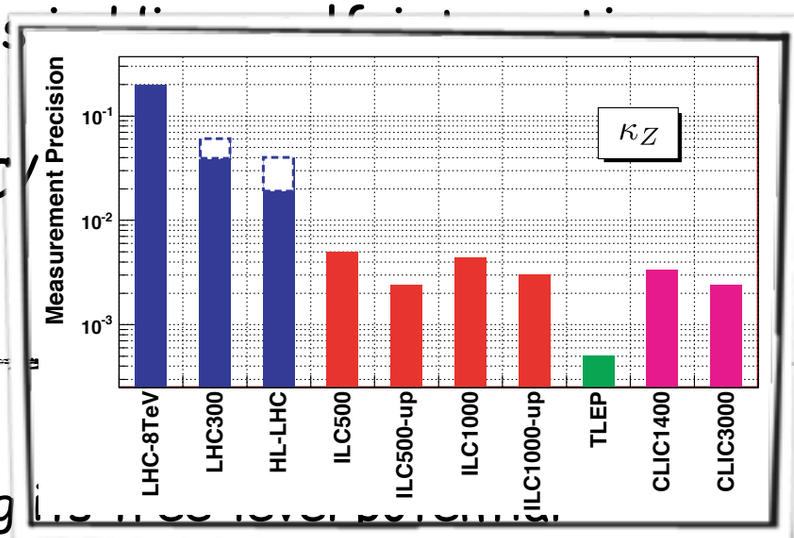


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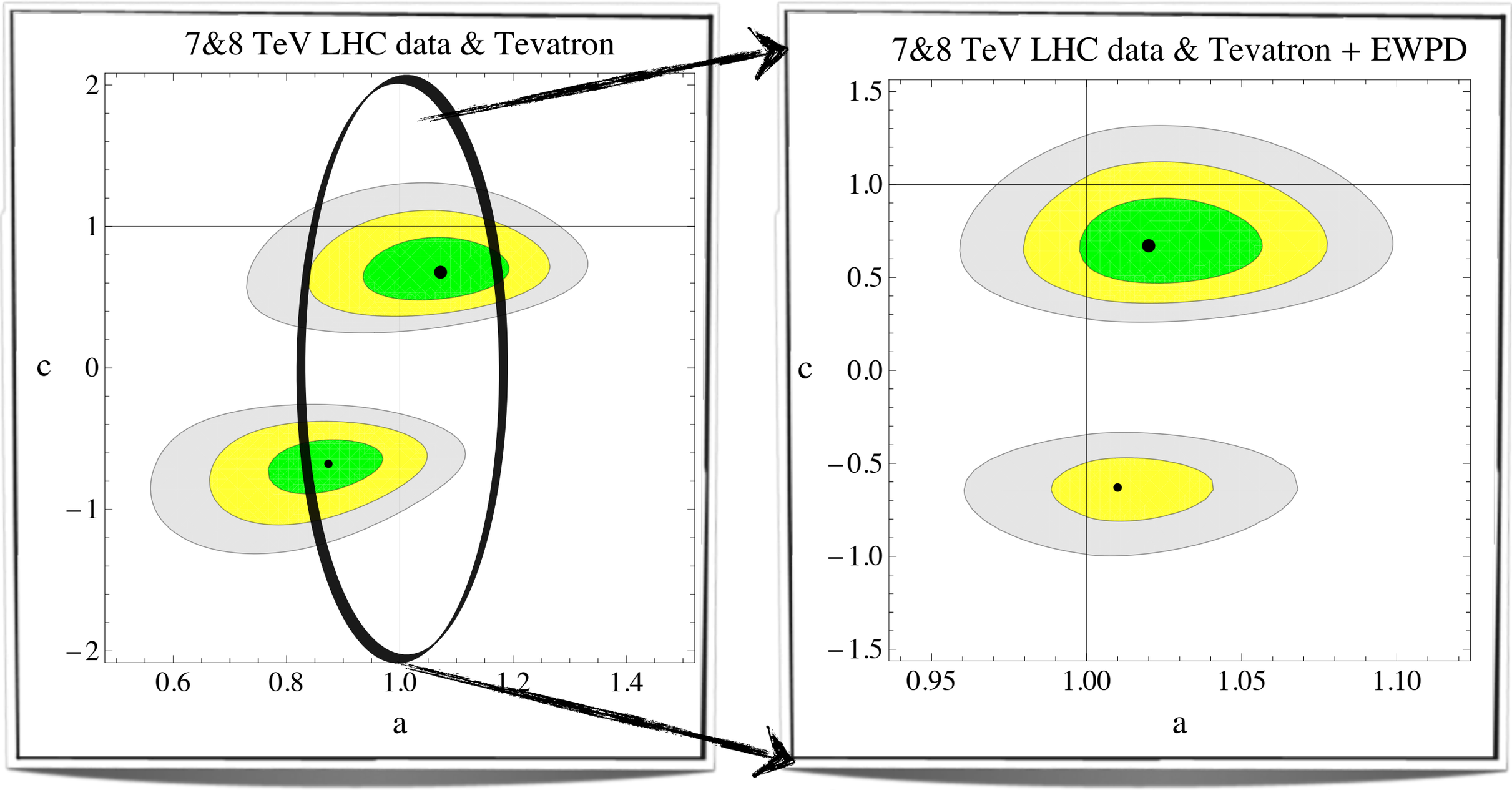
5

# Complementarity Higgs & EW precision data

# Higgs physics: Don't forget LEP!

Espinosa, Grojean, Muhlleitner, Trott '12




EW data prefer value of 'a' close to 1

a shift of the hVV coupling induce oblique corrections
that are already highly constrained by LEP data

for other more complete studies along this line, see

Falkowski, Riva, Urbano '13

Elias-Miro, Espinosa, Masso, Pomarol '13

# RG-bounds on EW/Higgs data

Elias-Miro, Grojean, Gupta, Marzocca '14

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

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 ($\Lambda$~3TeV) |

# RG-bounds on EW/Higgs data

Elias-Miro, Grojean, Gupta, Marzocca '14

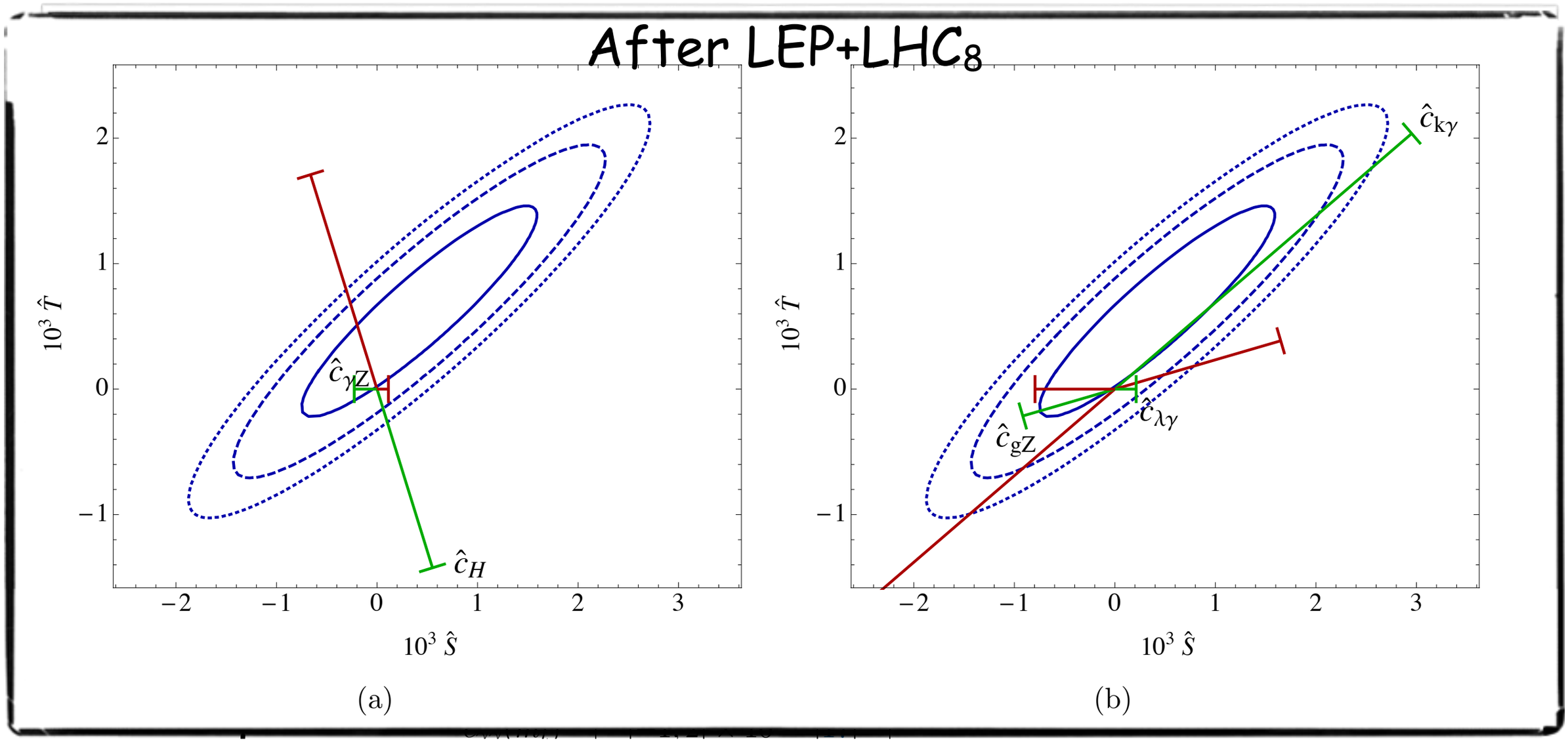
| | EW data | TGC | Higgs-only | | |
|---|---|---|---|---|---|
| # operators | 8 | 3 | 2+4+2 | | |
| tree-level constraints | O(1‰) | O(1%) | O(1%) | O(10-50%) | O(100%) |

After LEP + $LHC_8$

| Coupling | Direct Constraint | RG-induced Constraint |
|---|---|---|
| $\hat{c}_S(m_t)$ | $[-1,2]\times 10^{-3}$ [29] | - |
| $\hat{c}_T(m_t)$ | $[-1,2]\times 10^{-3}$ [29] | - |
| $\hat{c}_Y(m_t)$ | $[-3,3]\times 10^{-3}$ [21] | - |
| $\hat{c}_W(m_t)$ | $[-2,2]\times 10^{-3}$ [21] | - |
| $\hat{c}_{\gamma\gamma}(m_t)$ | $[-1,2]\times 10^{-3}$ [17] | - |
| $\hat{c}_{\gamma Z}(m_t)$ | $[-0.6,1]\times 10^{-2}$ [17] | $[-2,6]\times 10^{-2}$ |
| $\hat{c}_{\kappa\gamma}(m_t)$ | $[-10,7]\times 10^{-2}$ [27] | $[-2,5]\times 10^{-2}$ |
| $\hat{c}_{gZ}(m_t)$ | $[-5,2]\times 10^{-2}$ [27] | $[-1,3]\times 10^{-2}$ |
| $\hat{c}_{\lambda\gamma}(m_t)$ | $[-6,2]\times 10^{-2}$ [27] | $[-8,2]\times 10^{-2}$ |
| $\hat{c}_H(m_t)$ | $[-6,5]\times 10^{-1}$ [30] | $[-2,0.5]\times 10^{-1}$ |

# RG-bounds on EW/Higgs data

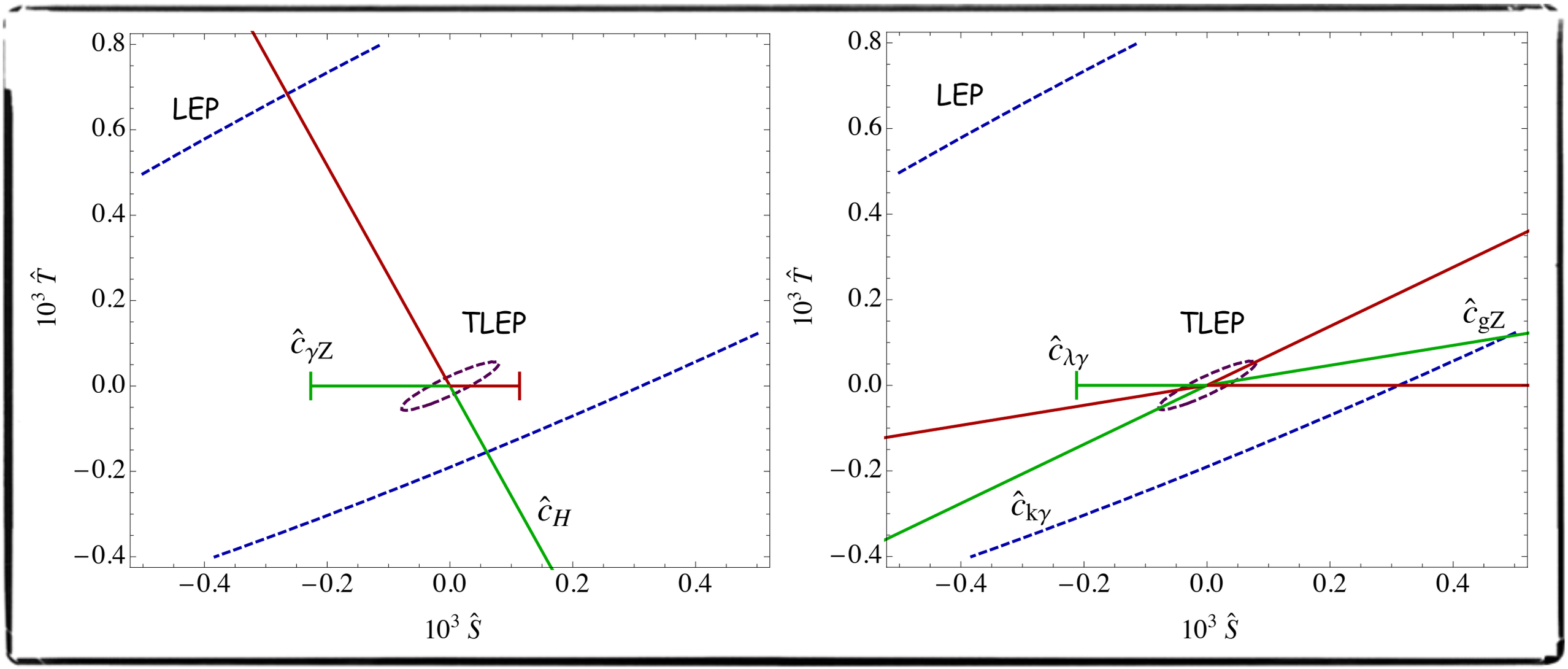
Elias-Miro, Grojean, Gupta, Marzocca '14




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




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

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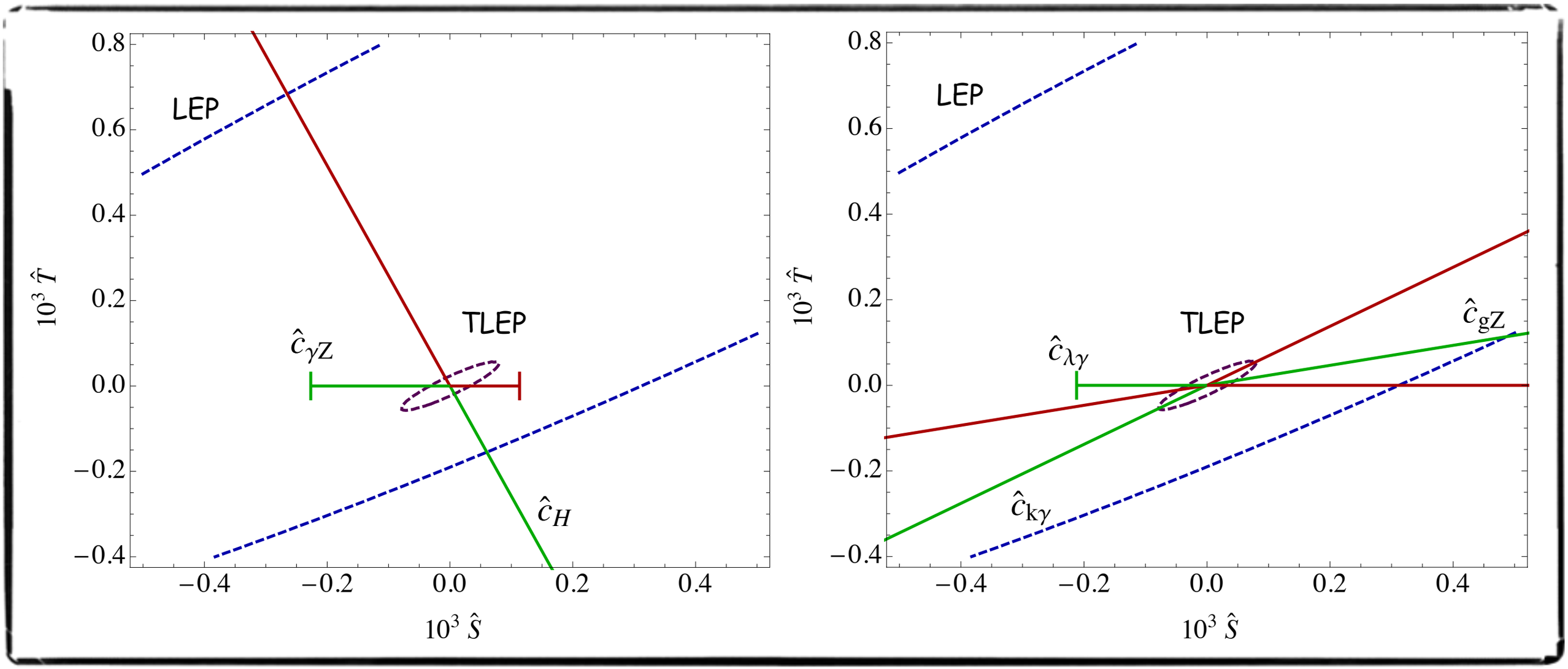



O(20-30) improvement in EW oblique parameters measurement

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

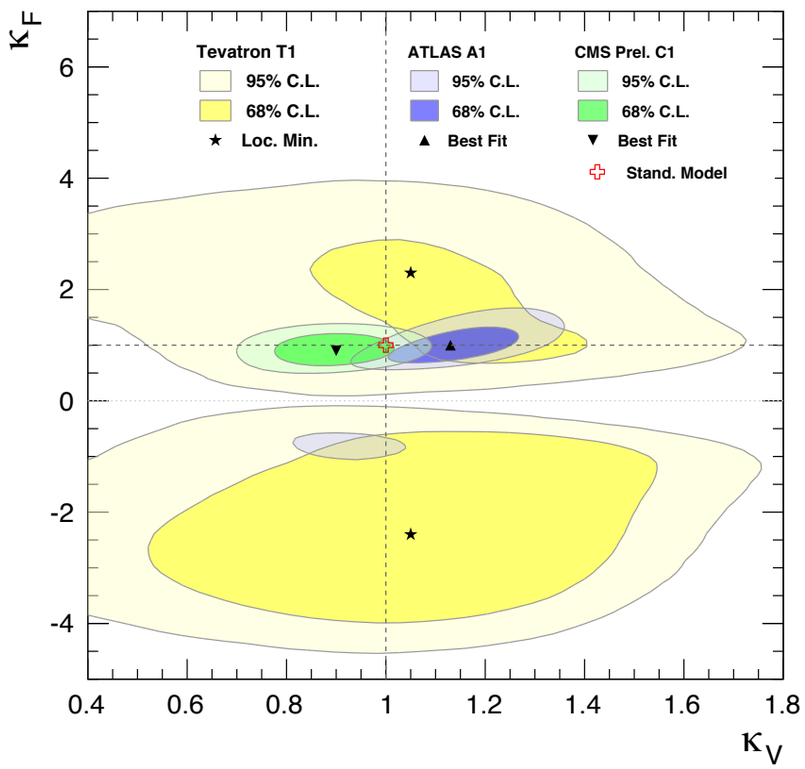
⇨

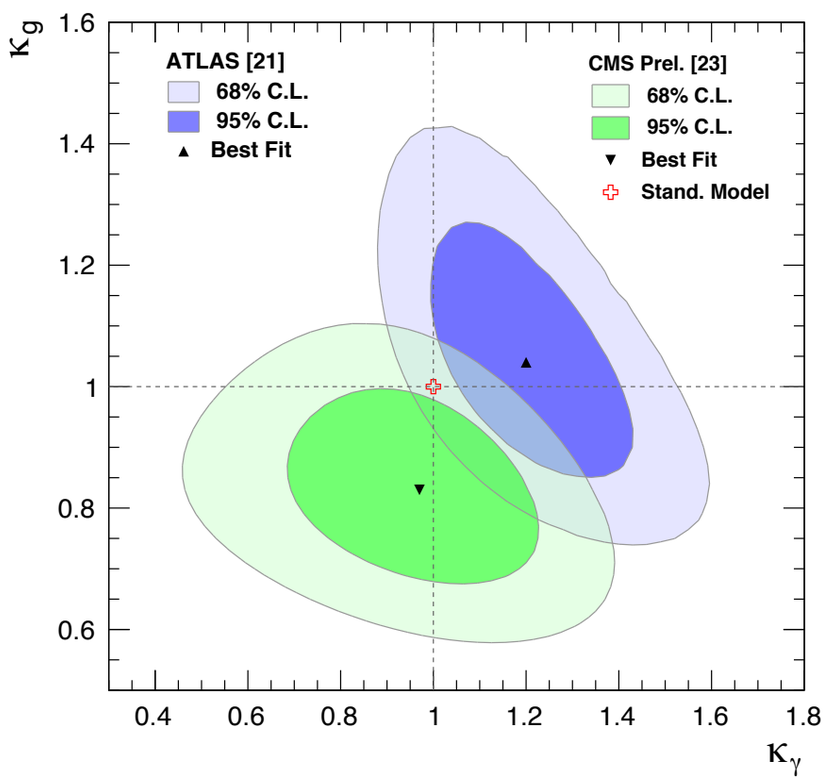
can probe tuning
between UV and RG contributions

6

# Beyond LHC Higgs measurements

# Higgs coupling fits




Current (and future) LHC fits of Higgs data: are based on rescaled SM couplings

| | ATLAS | CMS |
|---|---|---|
| $\kappa_F$ | $[0.76, 1.18]$ | $[0.71, 1.11]$ |
| $\kappa_V$ | $[1.05, 1.22]$ | $[0.81, 0.97]$ |
| $\lambda_{FV}$ | $[0.70, 1.01]$ | – |
| $\lambda_{WZ}$ | $[0.67, 0.97]$ | $[0.73, 1.00]$ |
| $\lambda^*_{WZ}$ | – | $[0.75, 1.13]$ |
| $\lambda^\circ_{WZ}$ | $[0.66, 0.97]$ | – |
| $\lambda^\ddagger_{WZ}$ | $[0.61, 1.04]$ | – |
| $\kappa_g$ | $[0.90, 1.18]$ | $[0.73, 0.94]$ |
| $\kappa_\gamma$ | $[1.05, 1.35]$ | $[0.79, 1.14]$ |
| $\mathrm{BR}_{inv,und}$ | $< 60\%^*$ at 95% CL | $< 64\%$ at 95% CL |
| $\kappa_V$ | – | $[0.84, 1.23]$ |
| $\kappa_b$ | – | $[0.61, 1.69]$ |
| $\kappa_\tau$ | – | $[0.82, 1.45]$ |
| $\kappa_t$ | – | $[0.00, 2.03]$ |
| $\kappa_g$ | – | $[0.65, 1.15]$ |
| $\kappa_\gamma$ | – | $[0.77, 1.27]$ |

e.g. Carena, Grojean, Kado, Sharma PDG'14

# More Higgs couplings

Assume heavy new physics and organize the effective Lagrangian in powers of momentum
e.g. $hV^{(*)}V^{(*)}$ @ $O(p^4)$ with EW bosons

$$hV_\mu(p_1)V_\nu(p_2): \ \left(\# + \#(p_1^2+p_2^2) + \#p_1p_2\right)\eta^{\mu\nu} + \#\left(p_1^\mu p_1^\nu + p_2^\mu p_2^\nu\right) + \#\left(p_1^\nu p_2^\mu\right) + \#\left(p_1^\mu p_2^\nu\right)$$

in general: 6 coefficients

if $V_1$ and $V_2$ are coupled to conserved currents: 3 coefficients

Contino, Ghezzi, Grojean, Muhlleitner, Spira '13

see also: Isidori, Manohar, Trott '13
Elias-Miro, Espinosa, Masso, Pomarol '13
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| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| hWW | 6 | | | 3 | | | | | |
| hZZ | 6 | = 15 | ⇨ | 3 | = 9 | ⇨ | 6 | ⇨ | 3 = $\kappa_V$, $\kappa_{\gamma\gamma}$, $\kappa_{\gamma Z}$ |
| $hZ\gamma$ | 2 | | | 2 | | | | | |
| $h\gamma\gamma$ | 1 | | | 1 | | | | | |

V couple to conserved currents ( ∝ fermion masses, decay constant of pseudo scalar)

custodial symmetry
3 relations, e.g. $c_W=c_Z$
(note: only one relation probed by LHC )

for a EW doublet Higgs
1 coupling ➟ S oblique parameter
2 couplings ➟ anomalous gauge couplings

# More Higgs couplings

Assume heavy new physics and organize the effective Lagrangian in powers of momentum
e.g. $hV^{(*)}V^{(*)}$ @ $O(p^4)$ with EW bosons

$$hV_\mu(p_1)V_\nu(p_2): \ \left(\# + \#(p_1^2+p_2^2) + \#p_1p_2\right)\eta^{\mu\nu} + \#\left(p_1^\mu p_1^\nu + p_2^\mu p_2^\nu\right) + \#\left(p_1^\nu p_2^\mu\right) + \#\left(p_1^\mu p_2^\nu\right)$$

in general: 6 coefficients
if $V_1$ and $V_2$ are coupled to conserved currents: 3 coefficients

Contino, Ghezzi, Grojean, Muhlleitner, Spira '13

see also: Isidori, Manohar, Trott '13
Elias-Miro, Espinosa, Masso, Pomarol '13
Brivio et al '13

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
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for a EW doublet Higgs
1 coupling ➟ S oblique parameter
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A Higgs factory should give access to the additional couplings not probed @ LHC
- confirm that Higgs belongs to a doublet
- test custodial symmetry/measure its breaking

(similar story for CP-odd couplings)

7

# Multi Higgs and boosted Higgs processes

# Multi Higgs processes

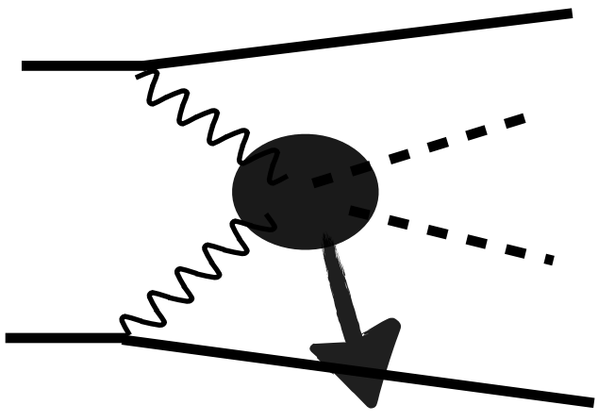
Producing one Higgs is good. Producing more Higgses is better

| | 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)

# WW→HH: probing Higgs strong interactions

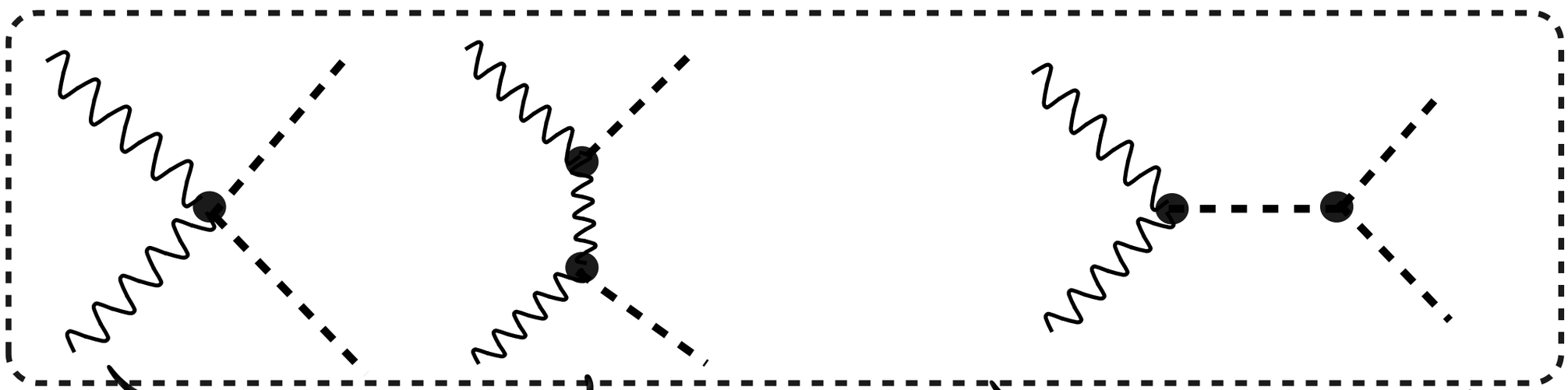
in the SM, the Higgs is essential to prevent strong interactions in EWSB sector
(e.g. WW scattering)



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

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

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



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

asymptotic behavior
sensitive to strong interaction

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

threshold effect
anomalous coupling'

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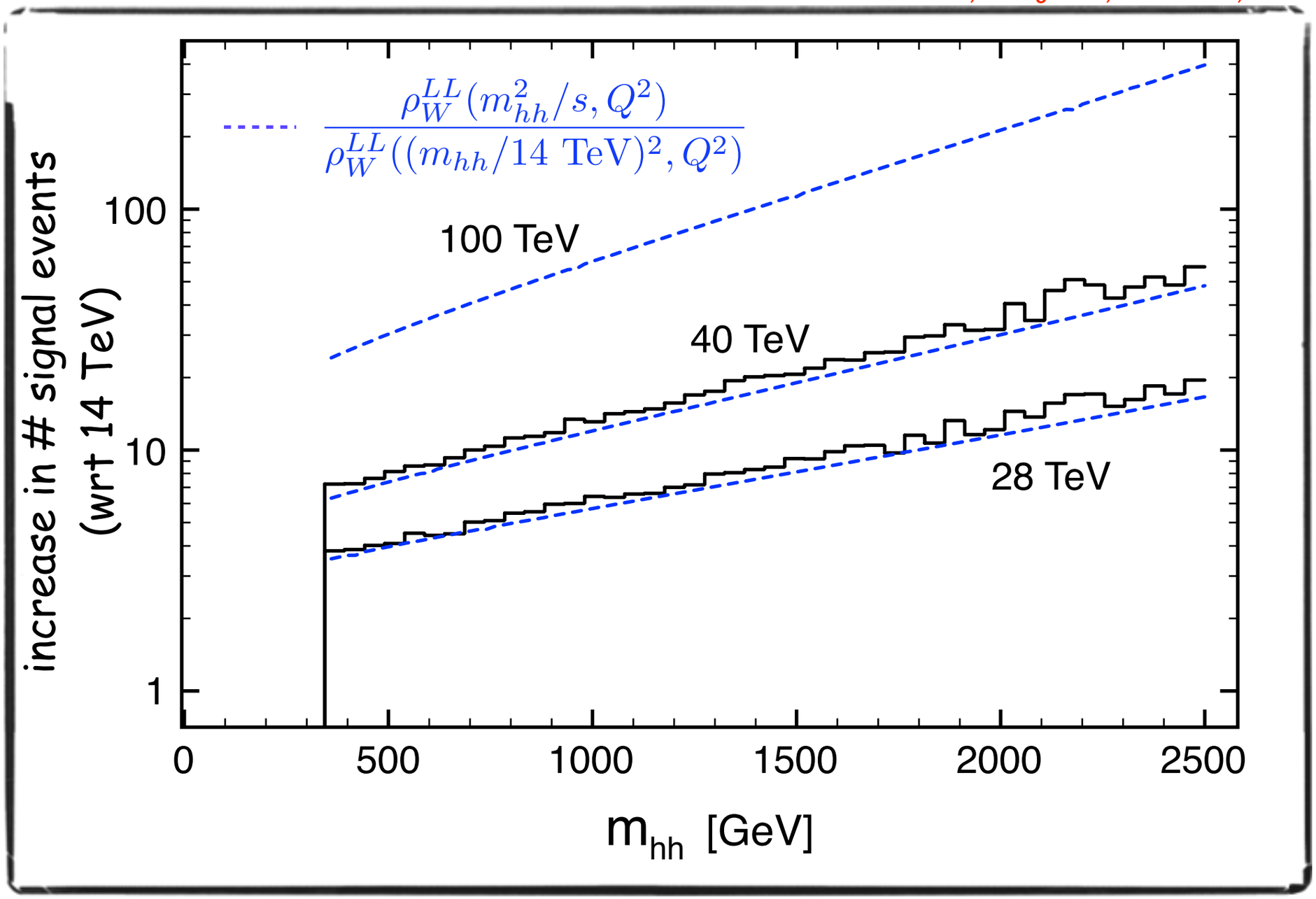
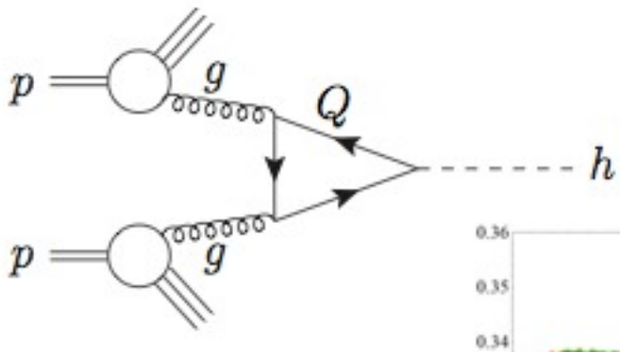
Contino, Grojean, Moretti, Piccinii, Rattazzi '10



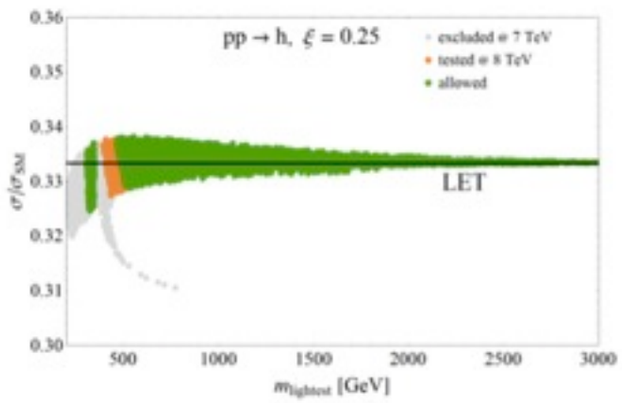

VHE-LHC can probe the high invariant-mass distribution with high statistics

# gg→HH: seeing the top partners

~ current single higgs processes are insensitive to top partners ~




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



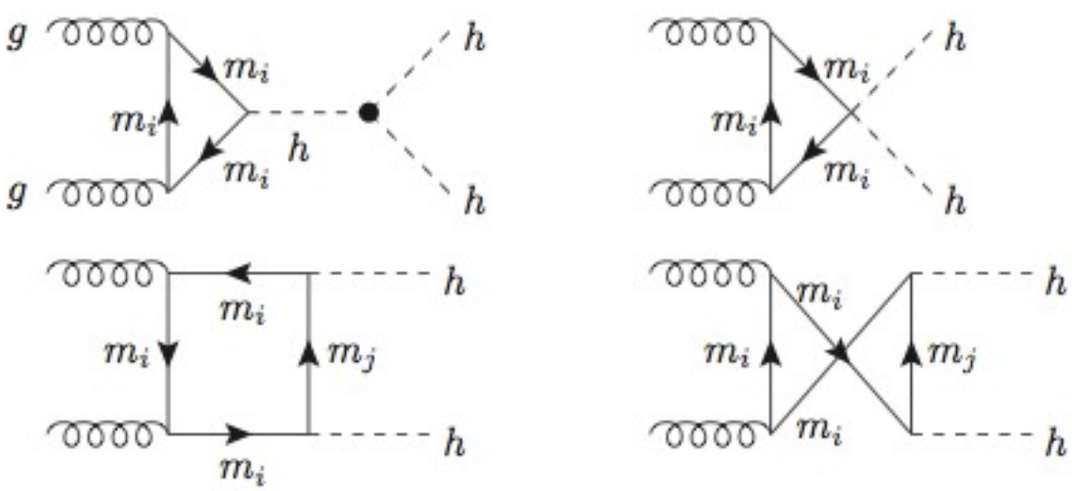

two competing effects that cancel:

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

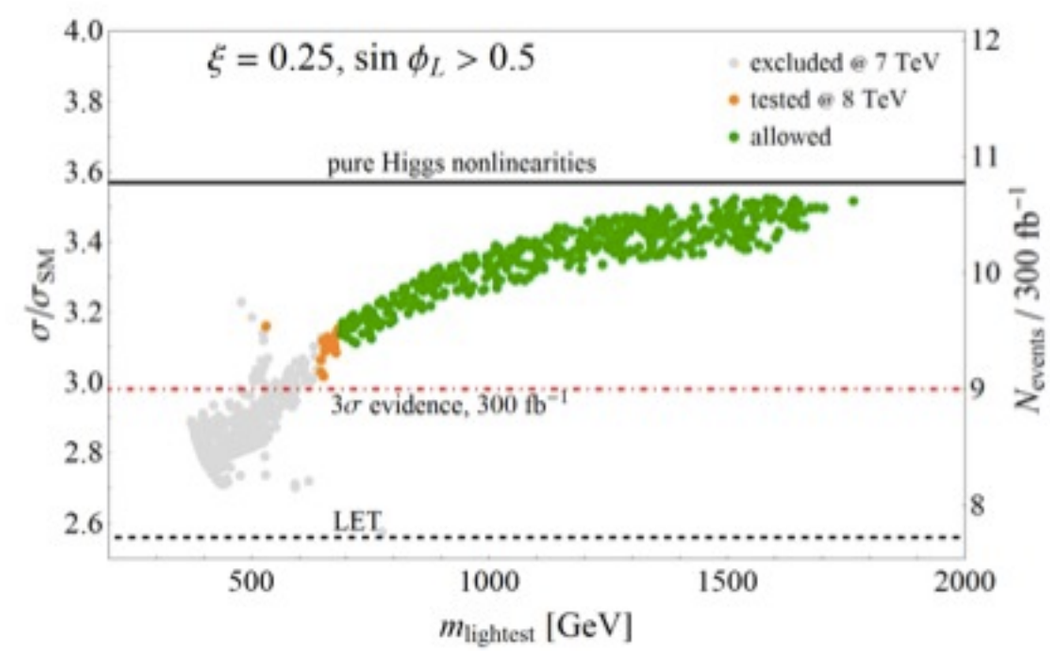
Falkowski '07
Azatov, Galloway '11
Delaunay, Grojean, Perez, '13

~ sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12




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




competitive to top-partner direct searches

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

⋘

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

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

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

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

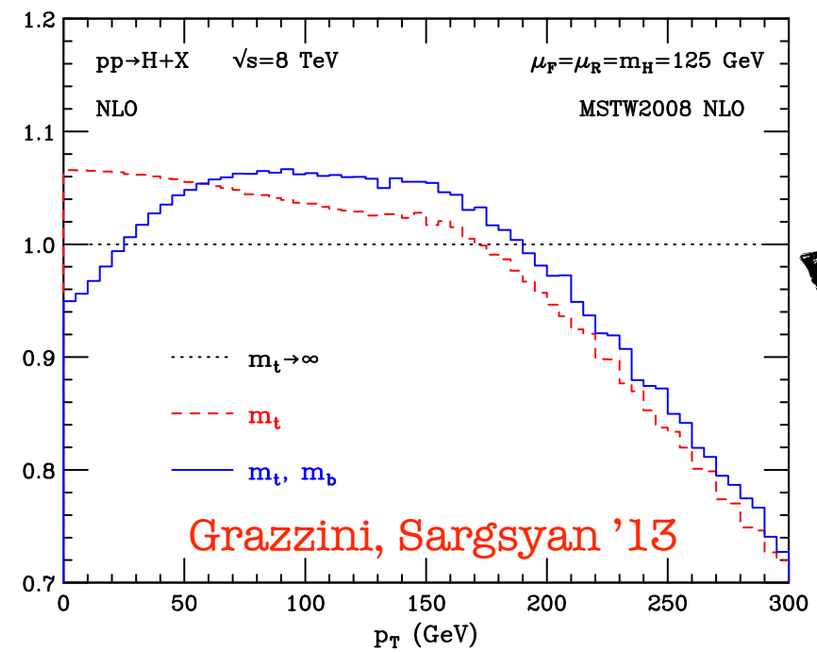
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ $\mathrm{LHC}^{14}_{300}$-$\mathrm{LHC}^{14}_{3000}$ vs 10%-4% @ $\mathrm{ILC}^{500}_{500}$-$\mathrm{ILC}^{1000}_{1000}$

# Beyond inclusive channels: Boosted Higgs

## cut open the top loops

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

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




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

Harlander et al '12

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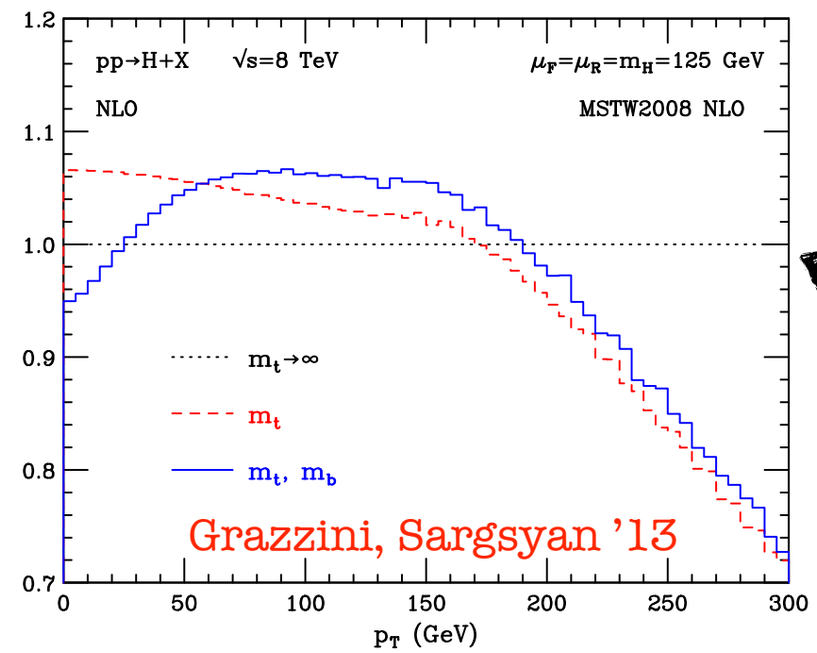


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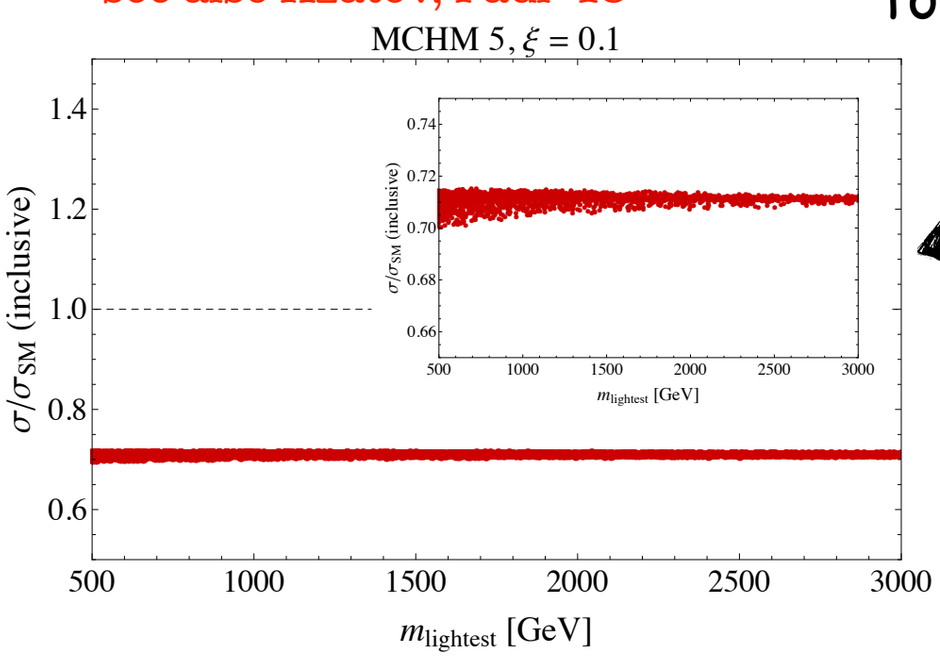
## Composite Higgs Model

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

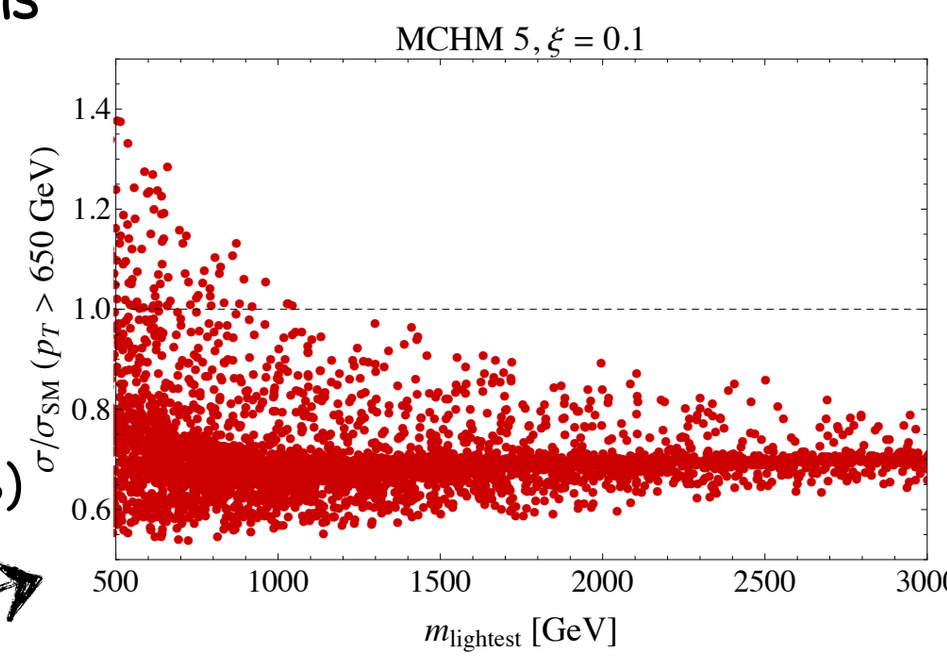
Grojean, Salvioni, Schlaffer, Weiler '13

top partners contributions




inclusive rate: O(%)

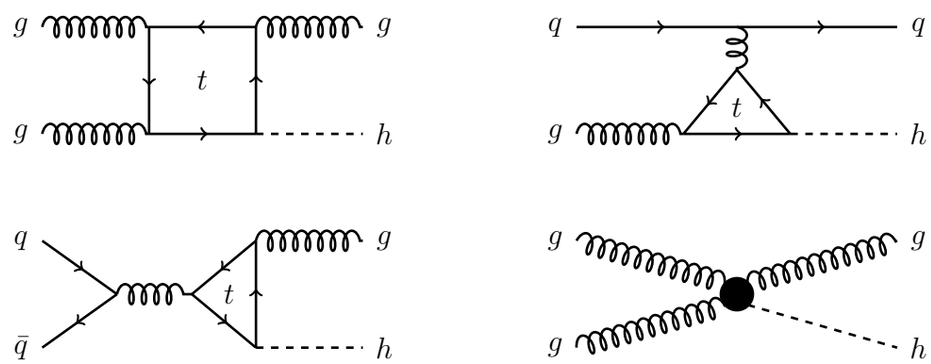
with high-$p_T$ cut: O(x10'%)




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

# Boosted Higgs

Grojean, Salvioni, Schlaffer, Weiler '13




$$\frac{\sigma_{p_T^{\min}}(\kappa_t, \kappa_g)}{\sigma^{\rm SM}_{p_T^{\min}}} = (\kappa_t + \kappa_g)^2 + \delta\, \kappa_t\, \kappa_g + \epsilon\, \kappa_g^2$$

large pT, small rates
need to focus on dominant decay modes

$$h \to b\bar{b}, WW, \tau\tau$$

non-isolated "ditau-jets"
(separation between the 2 tau's: $\Delta R \sim 2m_h/p_T \lesssim 0.5$ )

$$\epsilon_{\rm tot} = {\rm BR}(h \to \tau\tau) \left( \sum_{i = \tau_\ell\tau_\ell, \tau_\ell\tau_h, \tau_h\tau_h} {\rm BR}(\tau\tau \to i)\, \epsilon_i \right) \simeq 2 \times 10^{-2}$$

| $\sqrt{s}$ [TeV] | $p_T^{\min}$ [GeV] | $\sigma^{\rm SM}_{p_T^{\min}}$ [fb] | $\delta$ | $\epsilon$ | $gg$, $qg$ [%] |
|---|---|---|---|---|---|
| 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 |
| 100 | 500 | 970 | 1.8 | 3.1 | 72, 28 |
| | 2000 | 1.0 | 14 | 78 | 56, 43 |

x 150 enhancement

VHE-LHC is the machine
to decipher the gg→h process

# Conclusions

- FCC offer an access to a rich list processes measured with high accuracy
- FCC program has enough precision to provide 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)
  - flavor structure via the access to rare processes (not covered in this talk)
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