BSM Prospects in Higgs Physics at the HL-LHC

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Higgs and New physics

The **Higgs** discovery completely modified our perspective on BSM

Before Higgs

After Higgs

Higgs and New physics

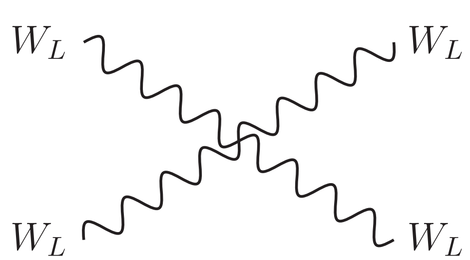
The **Higgs** discovery completely modified our perspective on BSM

<u>Before Higgs</u>

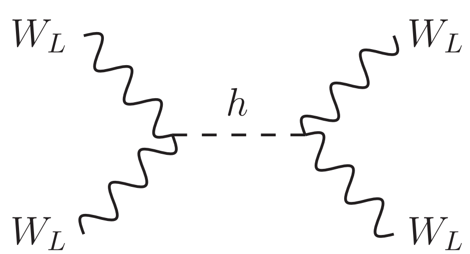
guaranteed discovery at LHC
(ensured by no-lose theorem)

- strongly coupled processes at energy scales ~*few* TeV

<u>After Higgs</u>



$+\cdots$ $\sim g_W^2 E^2/m_W^2 < 16\pi^2$ → **non-perturbative** at E ~ TeV
nearby new physics



$+\cdots$ … or cured by **light Higgs** → $m_H < 4\pi v \simeq 3$ TeV

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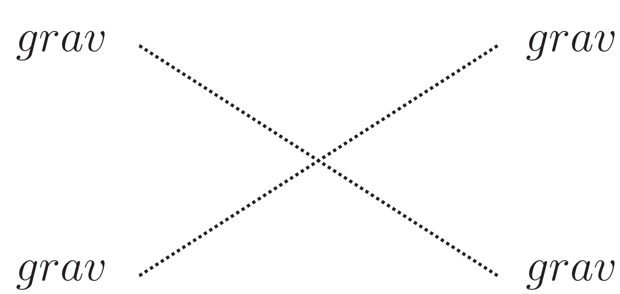
After Higgs

renormalizable theory of EW and strong interactions

- only no-lose for gravity… but new-physics could be at M_{Pl}

$$\frac{1}{G_N}\sqrt{g}R \rightarrow$$



$$\sim G_N E^2 \simeq E^2/M_{Pl}^2 < 16\pi^2$$

gravity non-perturbative at Planck scale → maximal SM cut-off $\Lambda_{\rm SM} \lesssim M_{Pl}$

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Additional considerations:

✦ there is experimental evidence for BSM (dark matter, neutrino masses) but not necessarily light and strongly-coupled enough to be detectable at LHC

What can we (still) learn from LHC?

Still many open questions we could hope to address

- ✦ **Naturalness**: explain microscopic origin of EW scale
- ✦ **Dark matter**: if WIMP, it could be tested at colliders

Natural BSM can still be discovered at LHC

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Natural BSM can still be discovered at LHC

… but also **negative answer** could provide important information

- rule out classes of BSM theories
- encourage a **paradigm shift**

What can we (still) learn from LHC?

Broad search program that could cover a large range of BSM

- **direct exploration** (high-energy frontier)
- **indirect tests** (precision frontier)

Direct Searches at LHC

Direct searches for partners

Direct searches provide the simplest way to test scale of new physics

In many cases direct connection with tuning ➜ test of Naturalness

$$\Delta \geq \left(\frac{\Lambda_{\rm SM}}{500\,{\rm GeV}} \right)^2$$

Low-energy SUSY

$\Lambda_{\rm SM} =$ **stop** mass

- current bounds ~ 1 TeV
- in minimal models (MSSM) additional tuning from gluinos $m_{gluinos} > 1$ TeV

Composite Higgs

$\Lambda_{\rm SM} =$ **top partners** mass

- current bounds ~ 1.2 TeV

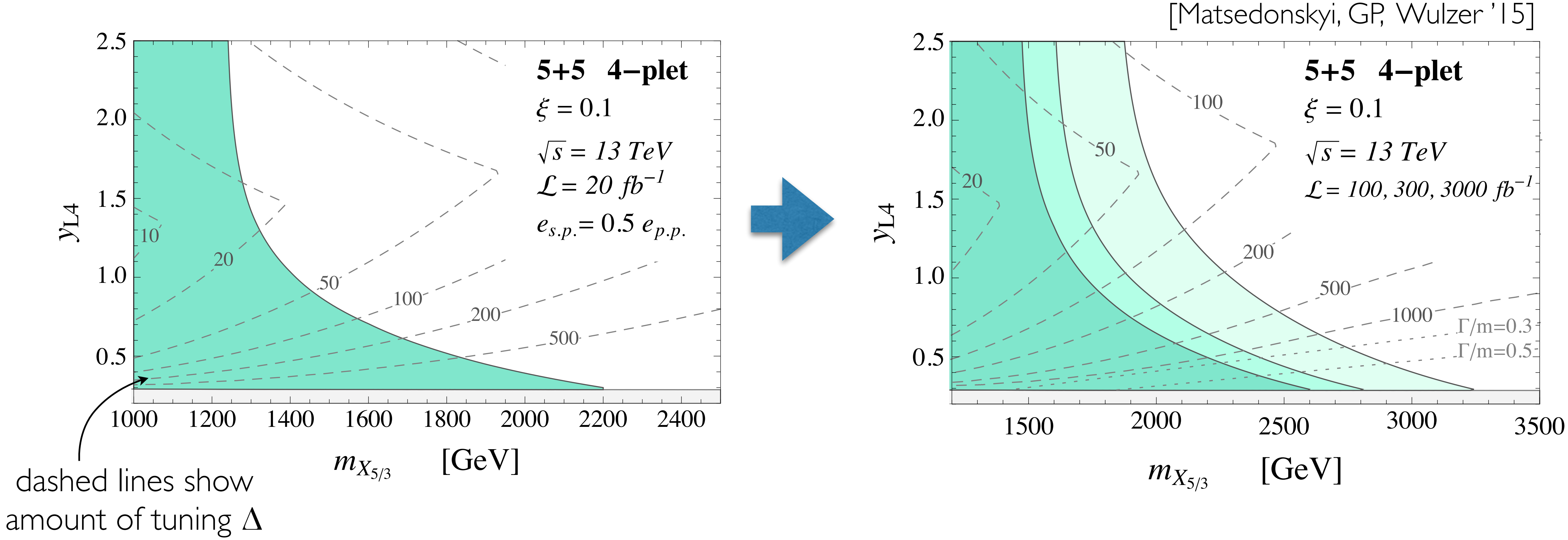
- Current bounds **still allow minimal models** with ~10% tuning!
- Fast progress with 13TeV runs, but slower at HL-LHC (saturation)

Fermionic partners

HL-LHC can push top partners scale well above the TeV, probing models with minimal tuning

<u>Example</u>: Projected bounds on **top partners**

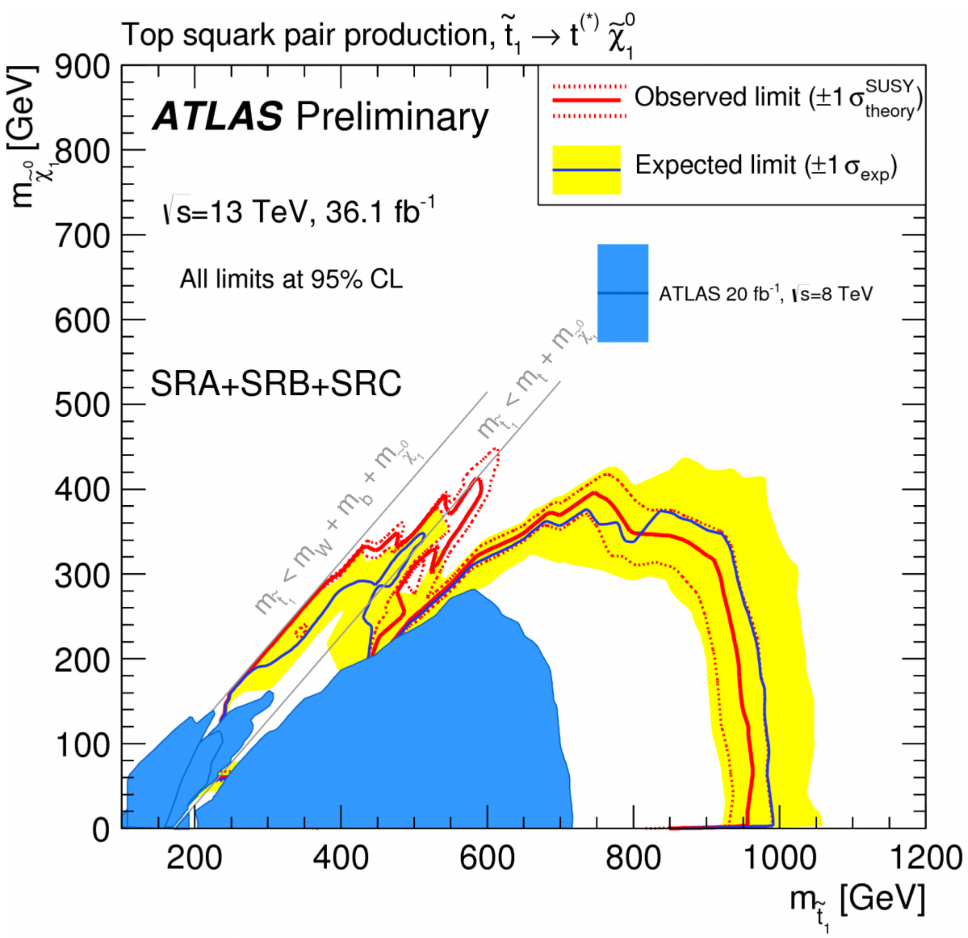
[Matsedonskyi, GP, Wulzer '15]

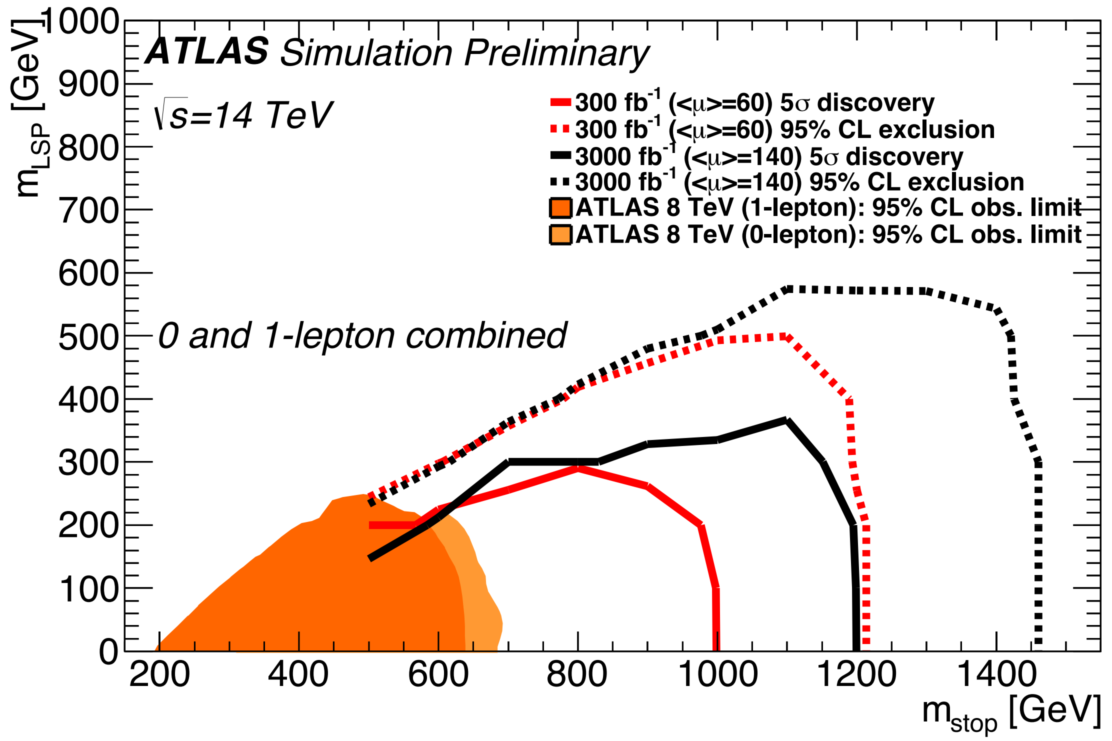


- Current bounds still allow for ~ 5-10 % tuning
- HL-LHC tests multi-TeV states and completely probes $1/\Delta > 2$ %

SUSY partners

… similar situation for SUSY partners





- Bounds on the stop at HL-LHC can reach 1.5 TeV
- but still space for discovery

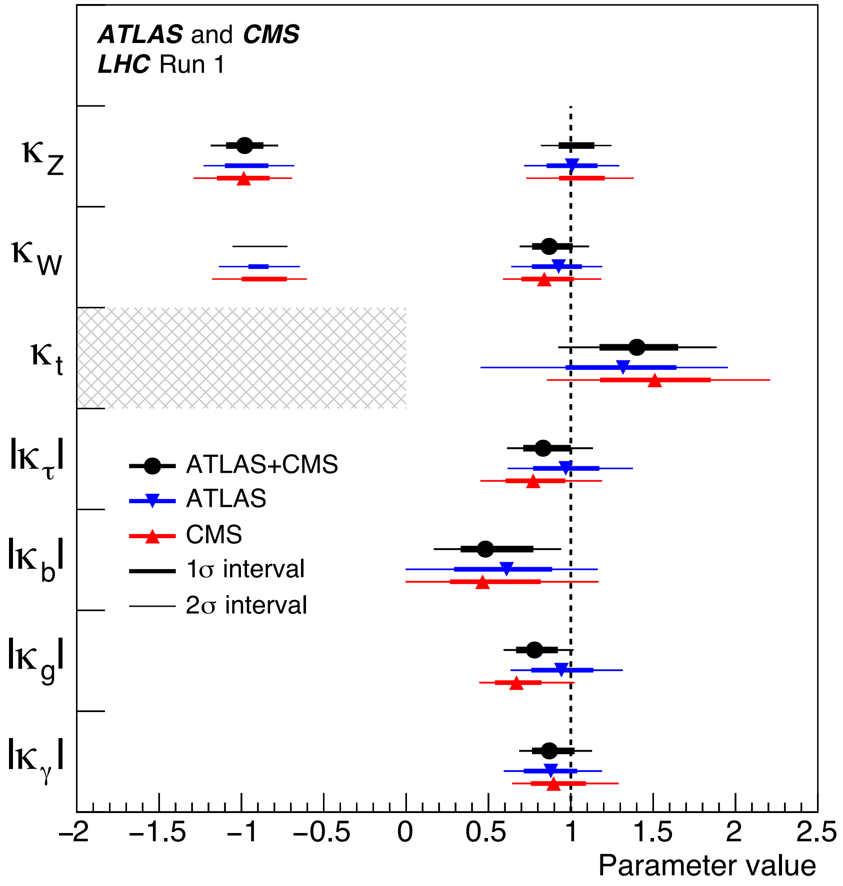
Indirect Searches at LHC

Higgs couplings

Precision measurement of **Higgs couplings** allows for test of SM and probe of BSM theories

- ✦ deviations expected in many BSM scenarios (eg. SUSY and composite Higgs)

- ✦ useful to derive bounds (can be competitive with direct searches)

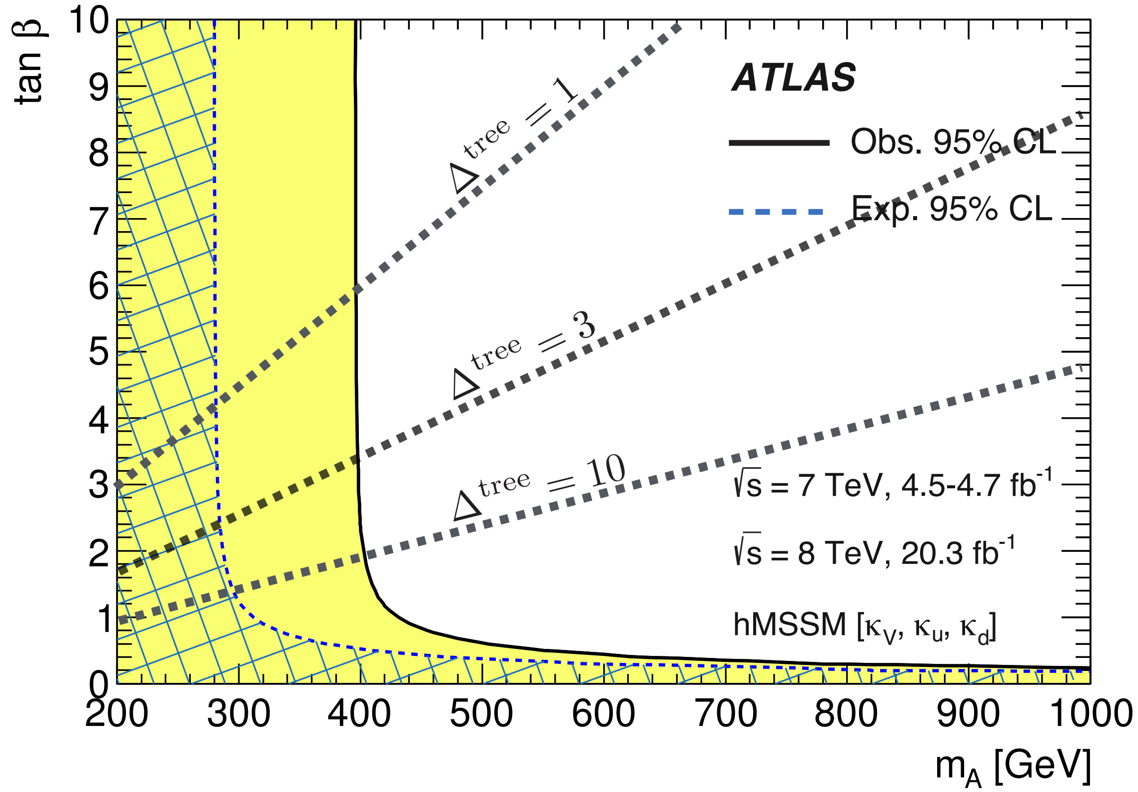


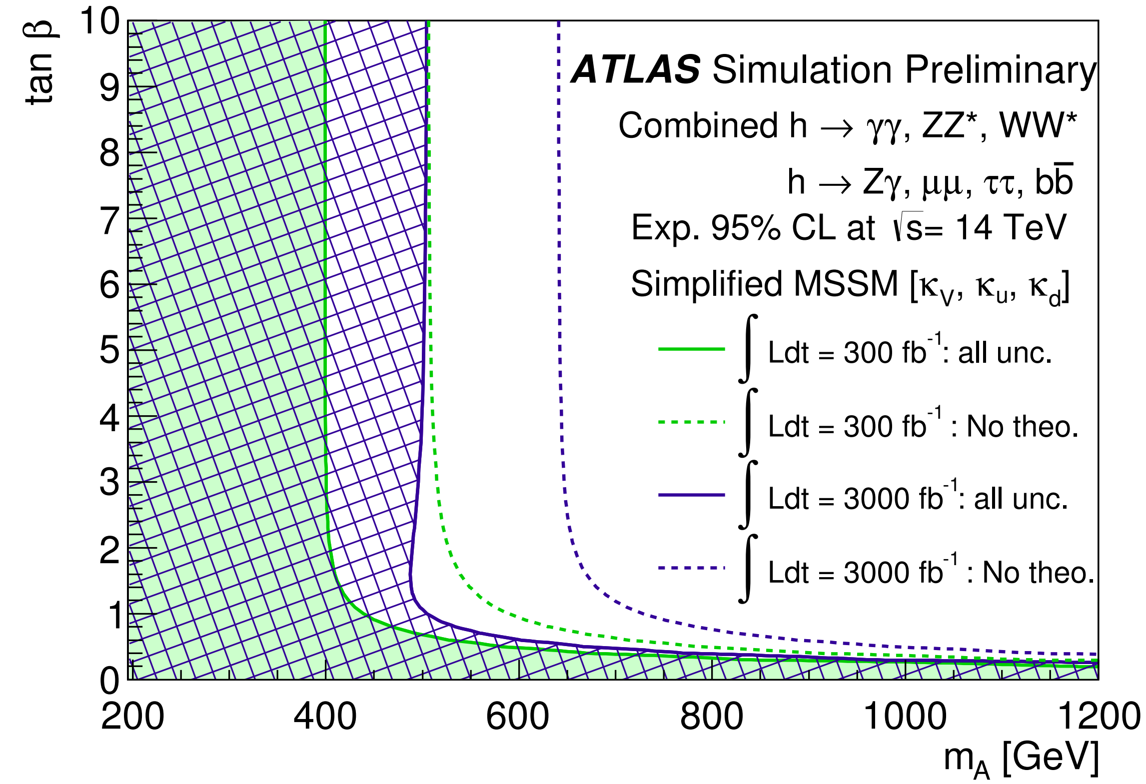
- particularly relevant if a connection with naturalness (fine-tuning) can be established

Higgs couplings in SUSY

Higgs couplings modifications expected from mixing with second Higgs doublet

[ATLAS 1509.00672]



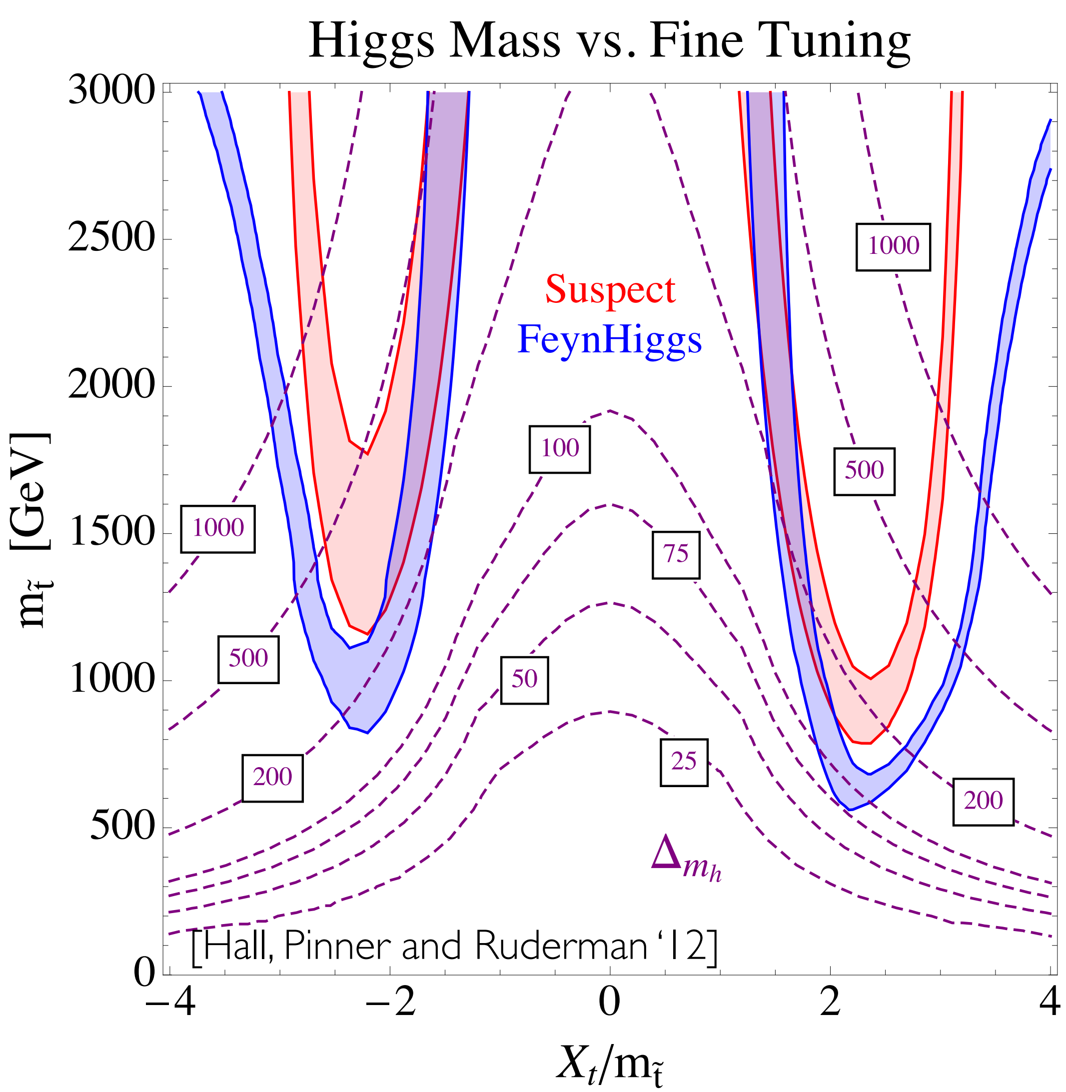


exclusions have no direct impact on fine-tuning in MSSM

Higgs couplings in SUSY

In MSSM main source of tuning from reproducing Higgs mass

- heavy stops needed to raise Higgs mass ➔ significant tuning



- minimal tuning ~ 1 %

Higgs couplings in λ-SUSY

In non-minimal SUSY models one can avoid heavy stops

<u>example</u>: adding an extra singlet [Barbieri et al. '06, Hall et al. '12, Barbieri et al. '13]

$$W_\lambda = \lambda S H_u H_d \longrightarrow m_H^2 \sim m_Z^2 \left(\frac{1-t_\beta^2}{1+t_\beta^2}\right)^2 + 4\lambda^2 v^2 \frac{t_\beta^2}{(1+t_\beta^2)^2}$$

correct Higgs mass requires sizable λ and moderate $\tan\beta$

Tuning set by mass of heavy Higgses:

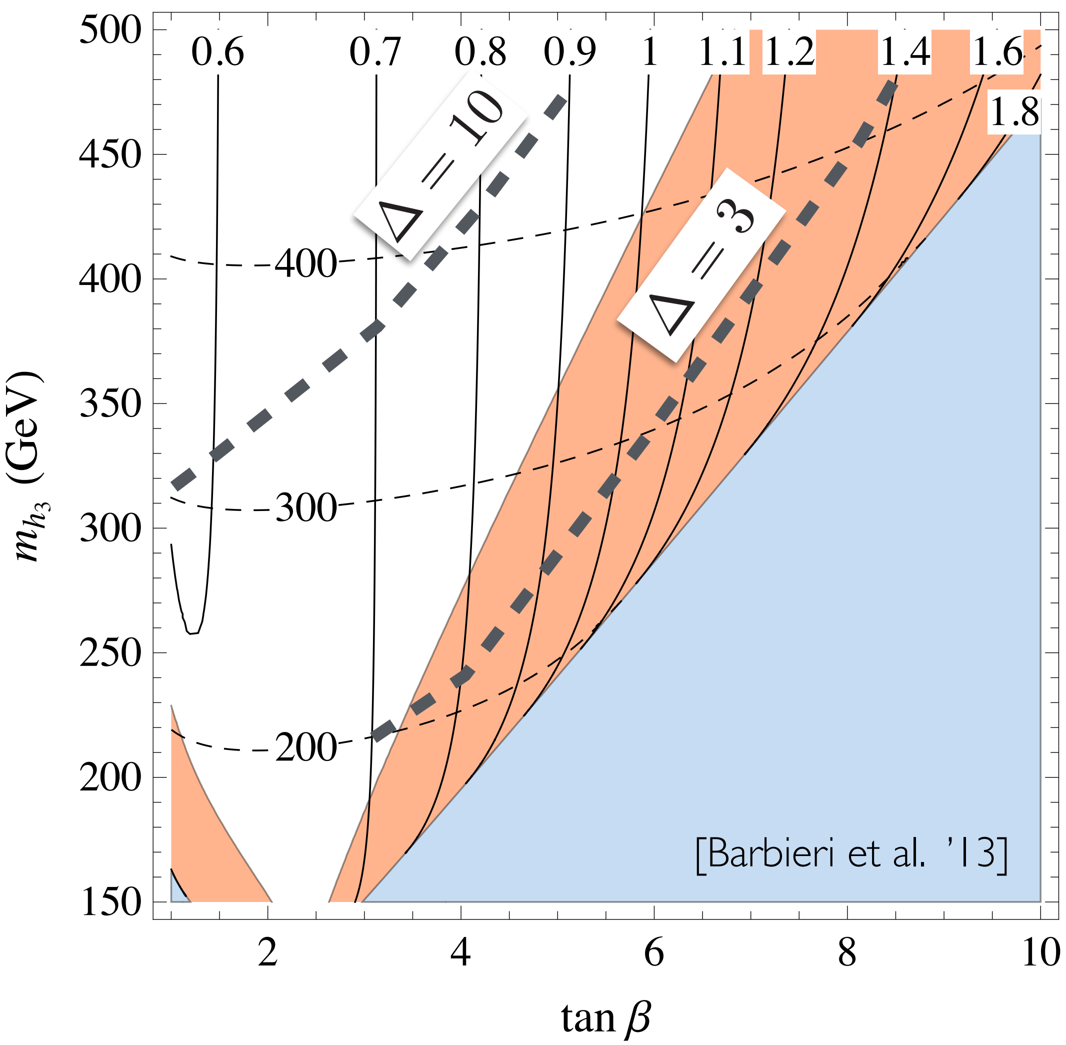
$$\Delta \gtrsim \frac{1}{\lambda^2}\left(\frac{m_{H^\pm}}{170\ \mathrm{GeV}}\right)^2$$

- direct connection between scalar sector and naturalness

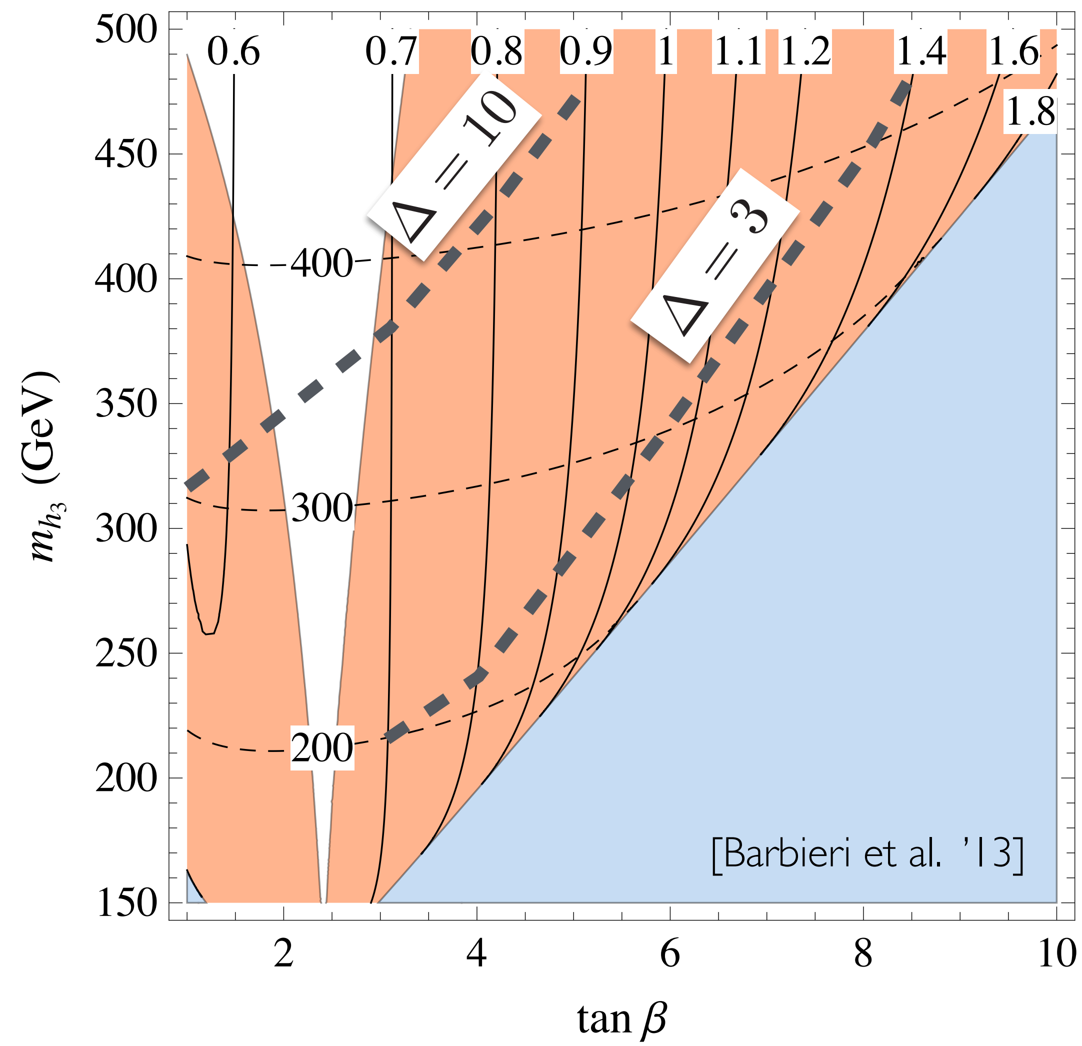
Higgs couplings in λ-SUSY

Bounds from Higgs coupling measurements

LHC 8TeV



LHC 13 TeV - 300/fb



Higgs couplings in CH

The **Higgs compositeness** induces modification of **Higgs couplings**

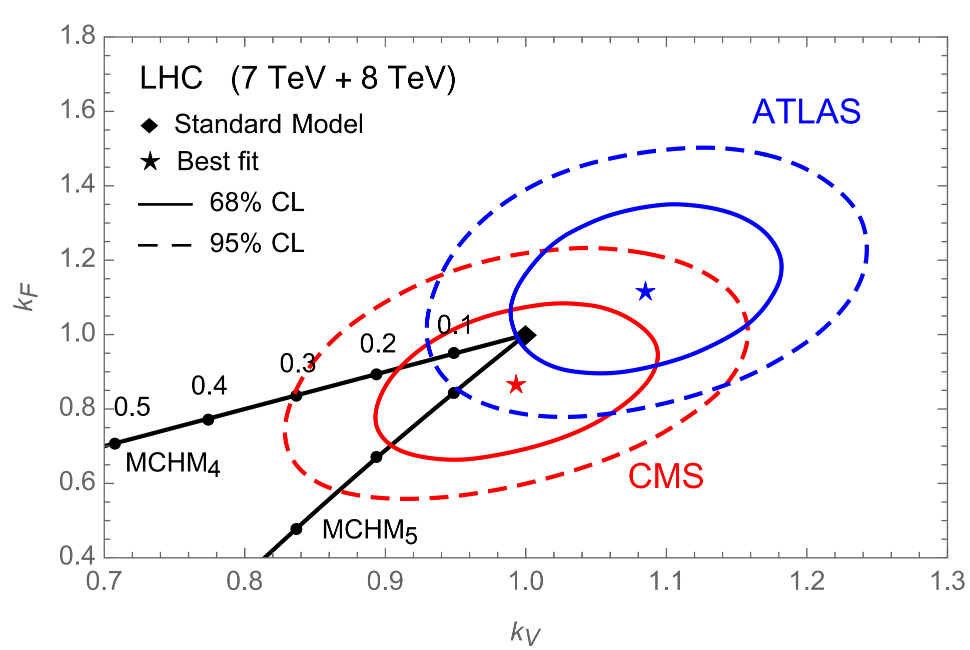
- coupling to **gauge fields**
  - universal, determined by symmetry: eg. SO(5)/SO(4) $\Rightarrow \quad k_V = \sqrt{1-\xi}$
- **Yukawa's**
  - depends on partners quantum numbers: eg. MCHM5 $\quad k_F = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

    MCHM4 $\quad k_F = \sqrt{1-\xi}$

Direct connection with tuning: $\Delta \gtrsim 1/\xi \qquad (\,\xi = v^2/f^2)$

compositeness scale

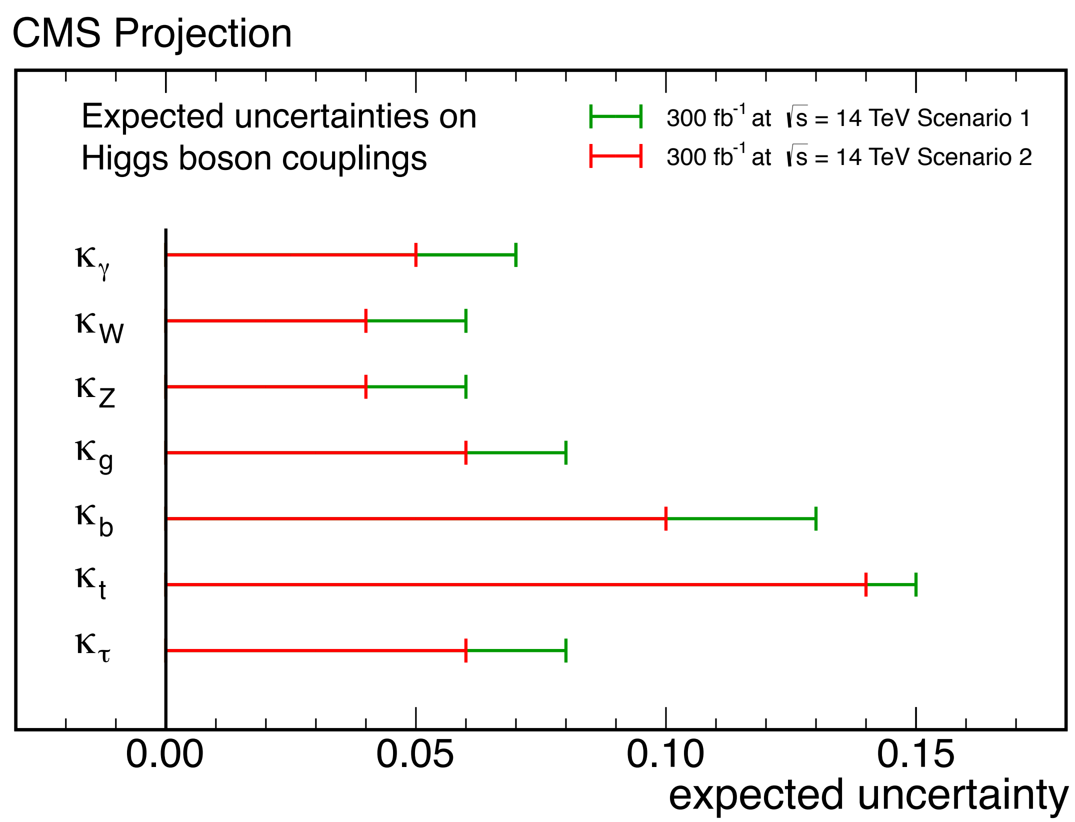
- current bounds $\quad \xi \lesssim 0.1$
  [ATLAS Collab. 1509.00672]
- space for improvement?
  crucially related to systematics… see later

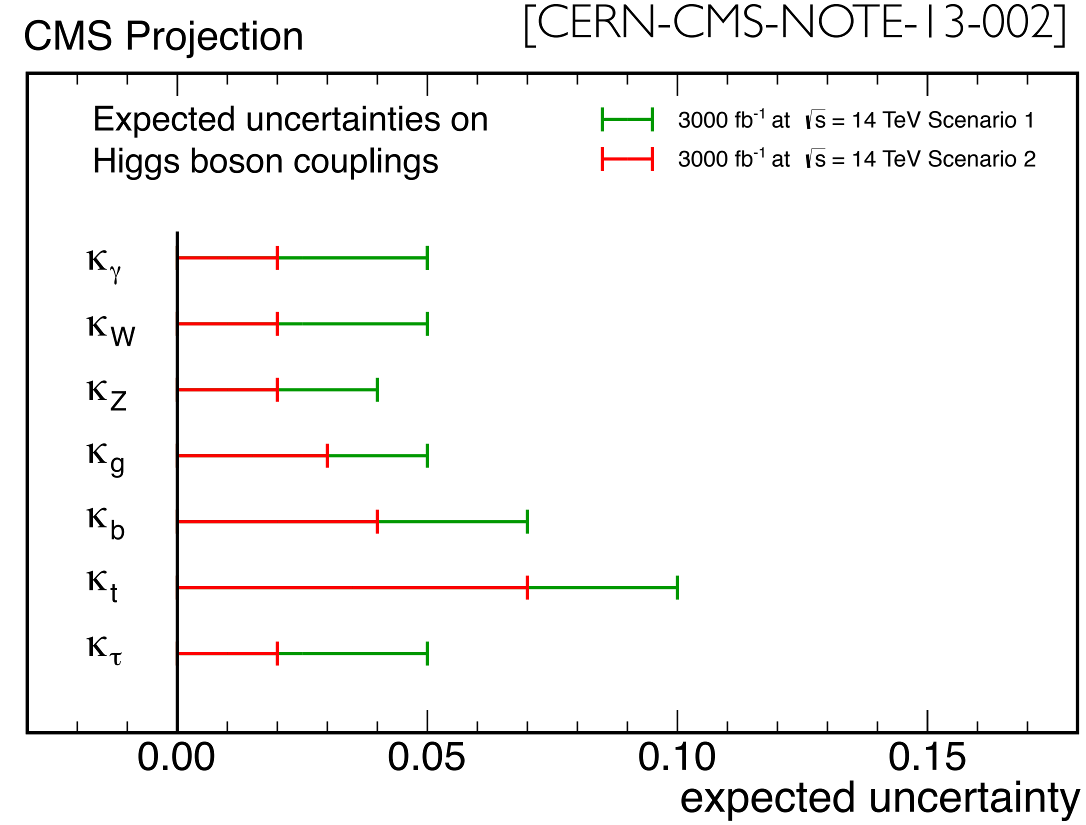


Higgs couplings at HL-LHC

Slow progress on Higgs couplings in future runs

[CERN-CMS-NOTE-13-002]



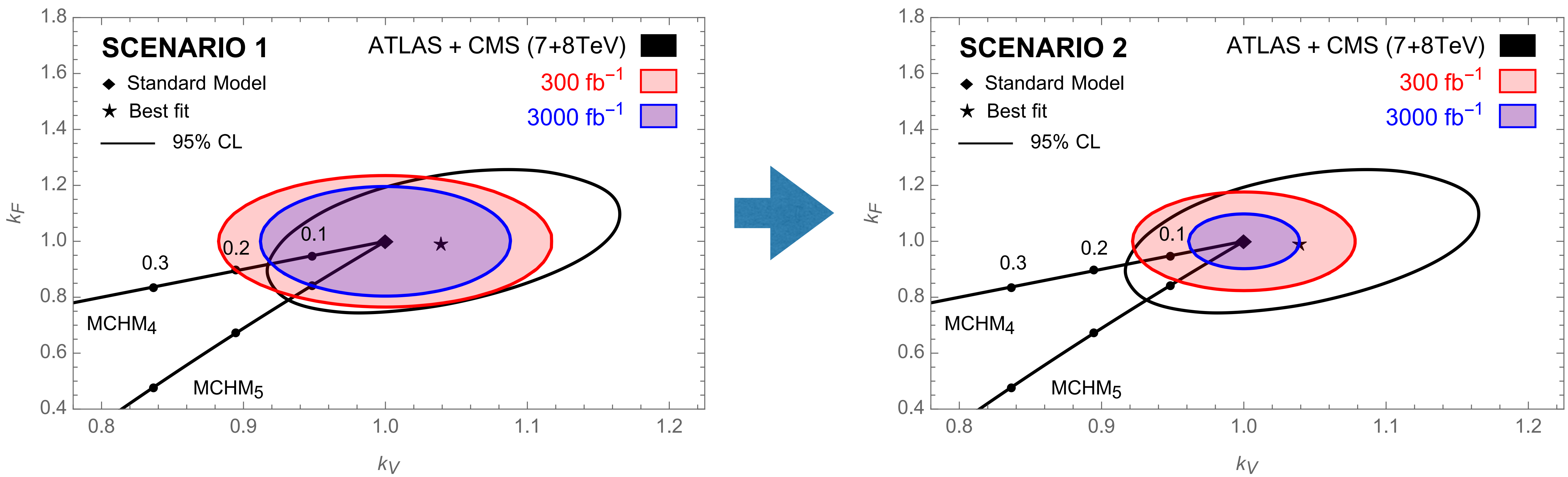


L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

- Not far from threshold due to systematics

Higgs couplings at HL-LHC

Systematics can play a crucial role for **BSM interpretation**



- Scenario I: systematics do not allow for improvement $(\xi \lesssim 0.1)$
- Scenario II: possible to probe $\xi \simeq 0.05 \longrightarrow f \simeq 1.1 \text{ TeV}$

The Higgs Self-Couplings

The Higgs self-interactions

Measuring the **Higgs self-interactions** is an essential step to understand the structure of the **Higgs potential**

$$\mathcal{L} = -\frac{m_h^2}{2} h^2 - \lambda_3 v h^3 - \lambda_4 h^4 \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

- distortions expected in many BSM scenarios

  eg. Higgs-portal models can give large corrections only in Higgs self couplings

$$\mathcal{L} = \theta g_* m_* H^\dagger H \phi - \frac{m_*^4}{g_*^4} V(g_* \phi / m_*) \quad \longrightarrow \quad \frac{\delta \kappa_\lambda}{\delta c_z} \sim \frac{\theta g_*^2}{\lambda_3^{\rm SM}} \gg 1$$

for $\theta, g_* \sim 1$

- related to properties of EW phase transition (relevant for cosmology)

The trilinear Higgs coupling

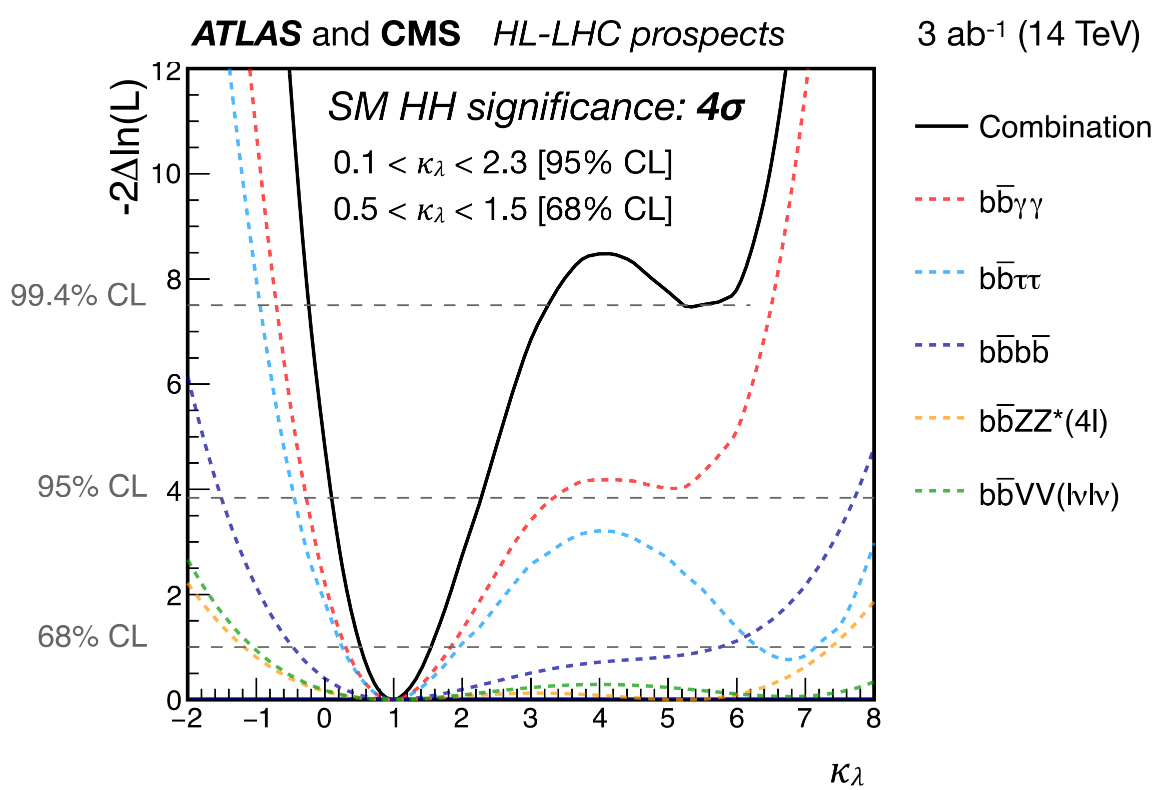
Main channel **double Higgs production** via gluon fusion

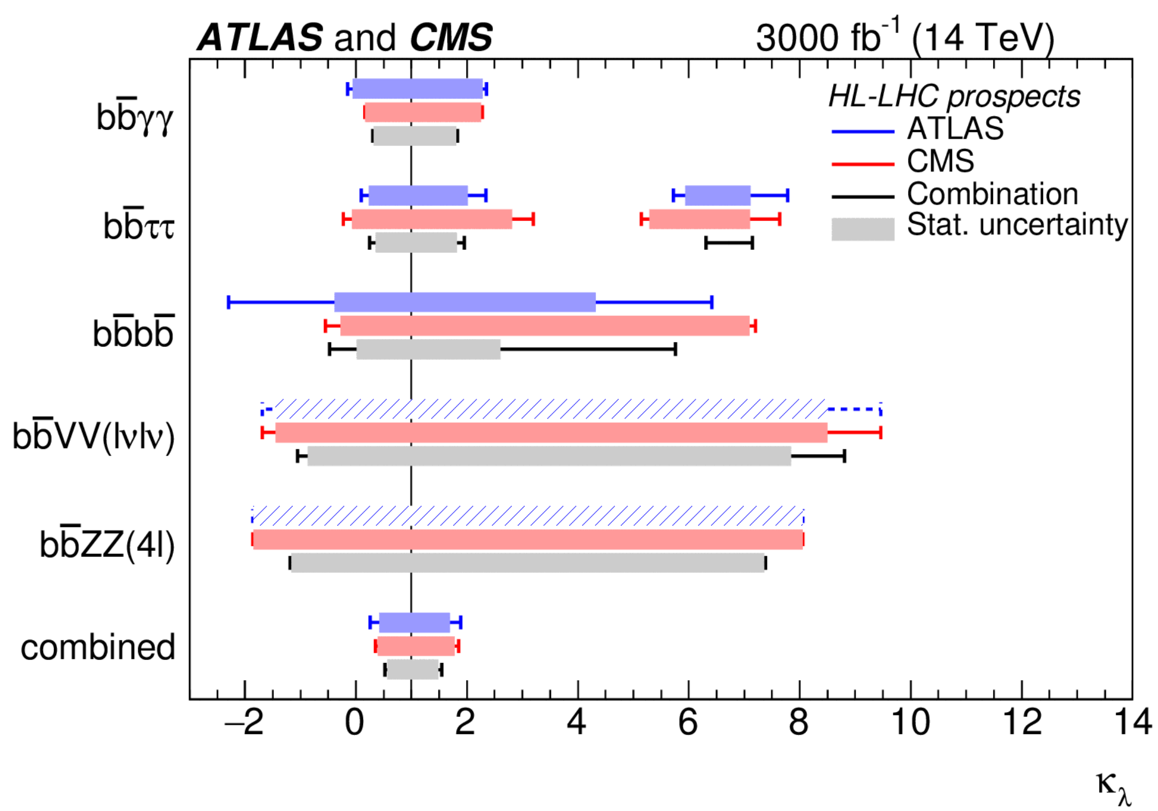
Different final states accessible:

- $\bar{b}b\gamma\gamma$: cleanest channel, but low cross section
- $\bar{b}b\tau\tau$: larger statistics, but harder analysis
- $\bar{b}b\bar{b}b, \bar{b}bWW, \bar{b}bZZ$: limited impact

Best channels

[HL- and HE-LHC Report '19]





✦ only ~50 % determination of Higgs self coupling possible at HL-LHC

The trilinear Higgs coupling

Precision determination of Higgs trilinear coupling possible at future colliders

- Hadron colliders:
  - FCC-100 could reach ~5 % precision [Contino et al., FCC report 1606.09408]
  - High-energy LHC (~28 TeV) could reach ~20 % precision [HL- and HE-LHC Report '19]
- Lepton colliders:
  - high-energy machines (CLIC) could reach ~10 % precision (directly through Higgs pair production) [CLIC Report '18]
  - low-energy machines (CEPC, FCC-ee) could reach ~40 % precision (indirectly through single Higgs processes) [Di Vita et al. '17]

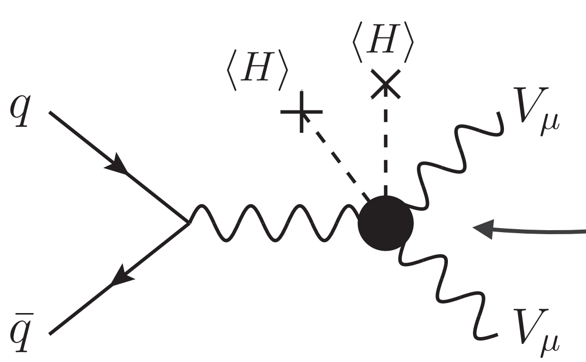
Beyond Higgs Couplings

Beyond Higgs couplings

Higgs couplings are **not the end of the story**…

… LHC can also perform **other indirect tests**, probing the EW dynamics and the Higgs at high energy

<u>example</u>: **di-boson** production can probe deviations in the Higgs dynamics



$$\mathcal{O}_W = (H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)(D^\nu W_{\mu\nu})^i$$

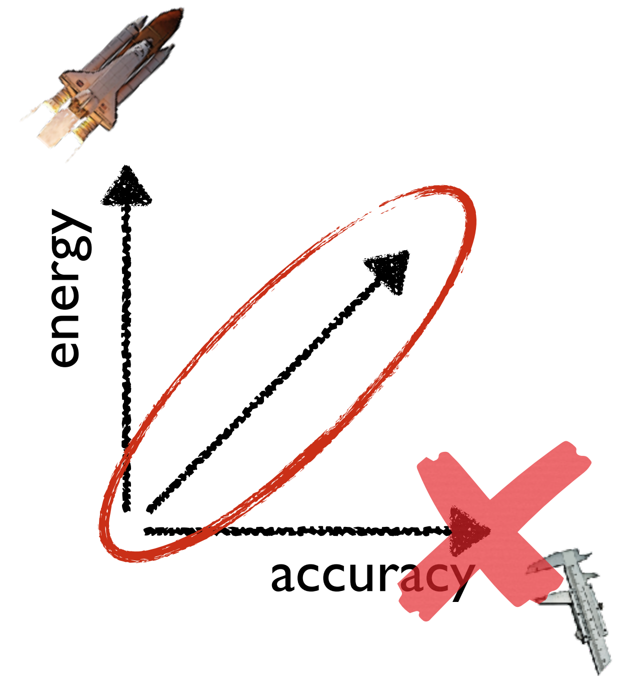
$$\mathcal{O}_{HW} = (D_\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

Beyond Higgs couplings

- ✦ sizeable systematic errors in many cases do not allow for pole (or low-energy) precision measurements

- ✦ however we can exploit the high energy reach

→ **energy helps accuracy** [Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16]



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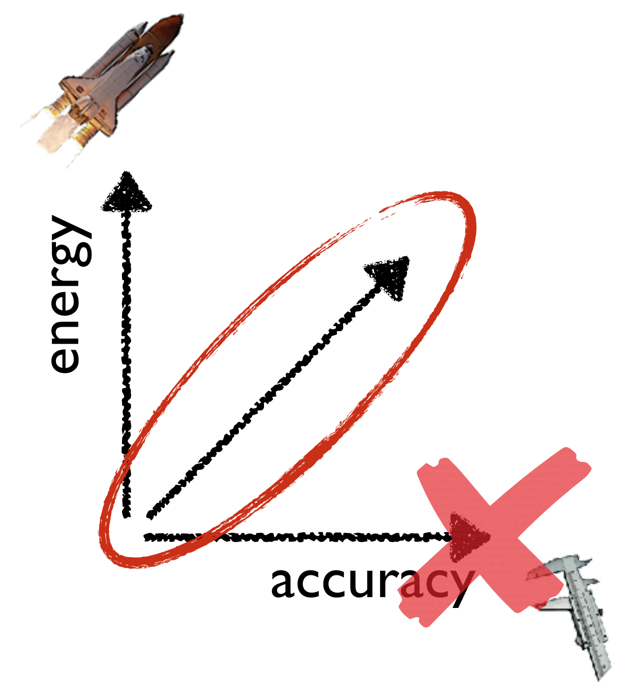


- ✦ key point: deviations from SM typically **grow with energy**

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

→ LHC can match LEP sensitivity exploiting the **high energy** reach

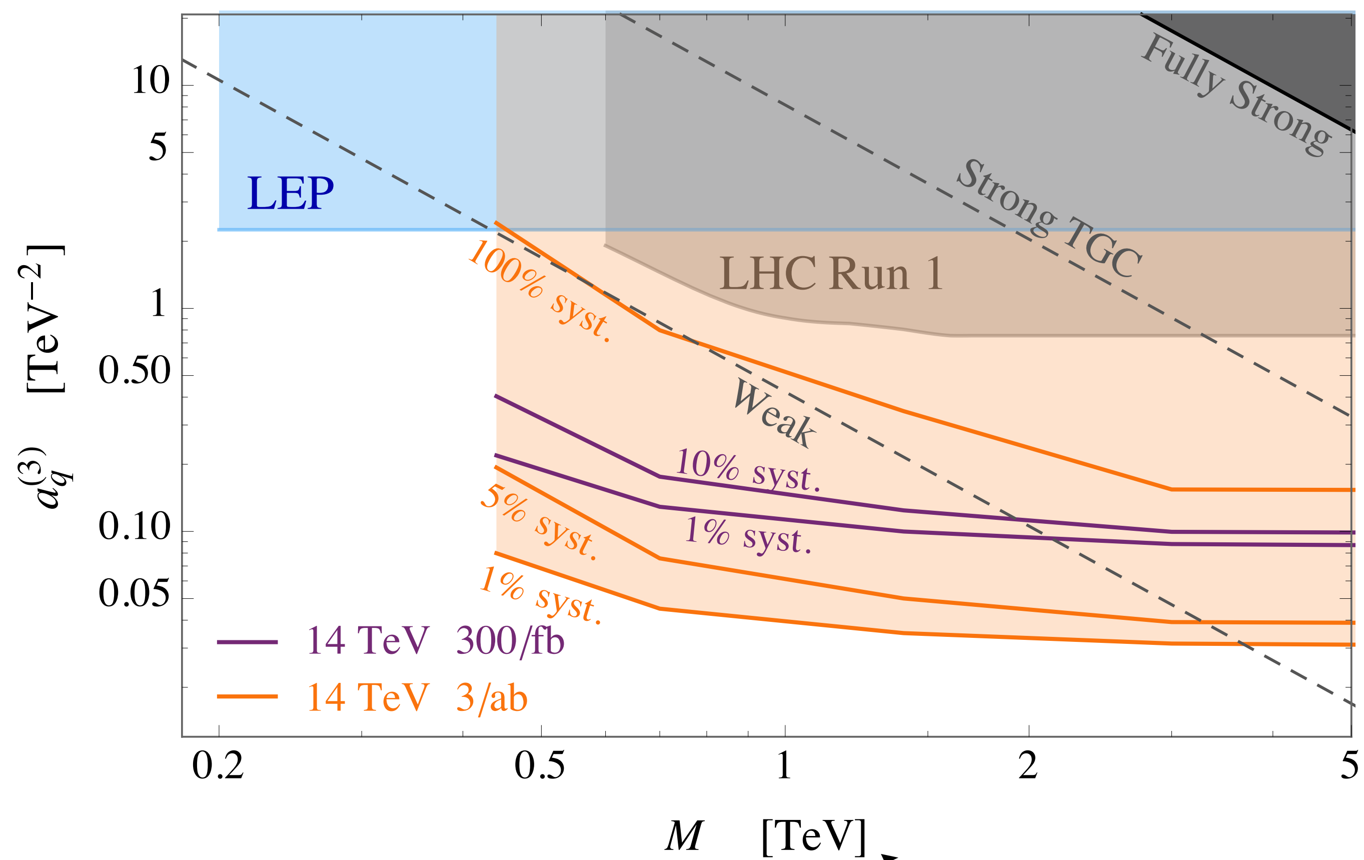
$$0.1\ \%\quad \text{at}\quad 100\ \text{GeV} \longrightarrow 10\ \%\quad \text{at}\quad 1\ \text{TeV}$$

LEP energy *LHC energy*

WZ: Reach at HL-LHC

Estimate of the bounds on $a_q^{(3)}(\overline{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$

[Franceschini, GP, Pomarol, Riva, Wulzer '17]



~ mass of new states

✦ Big improvement with respect to LEP

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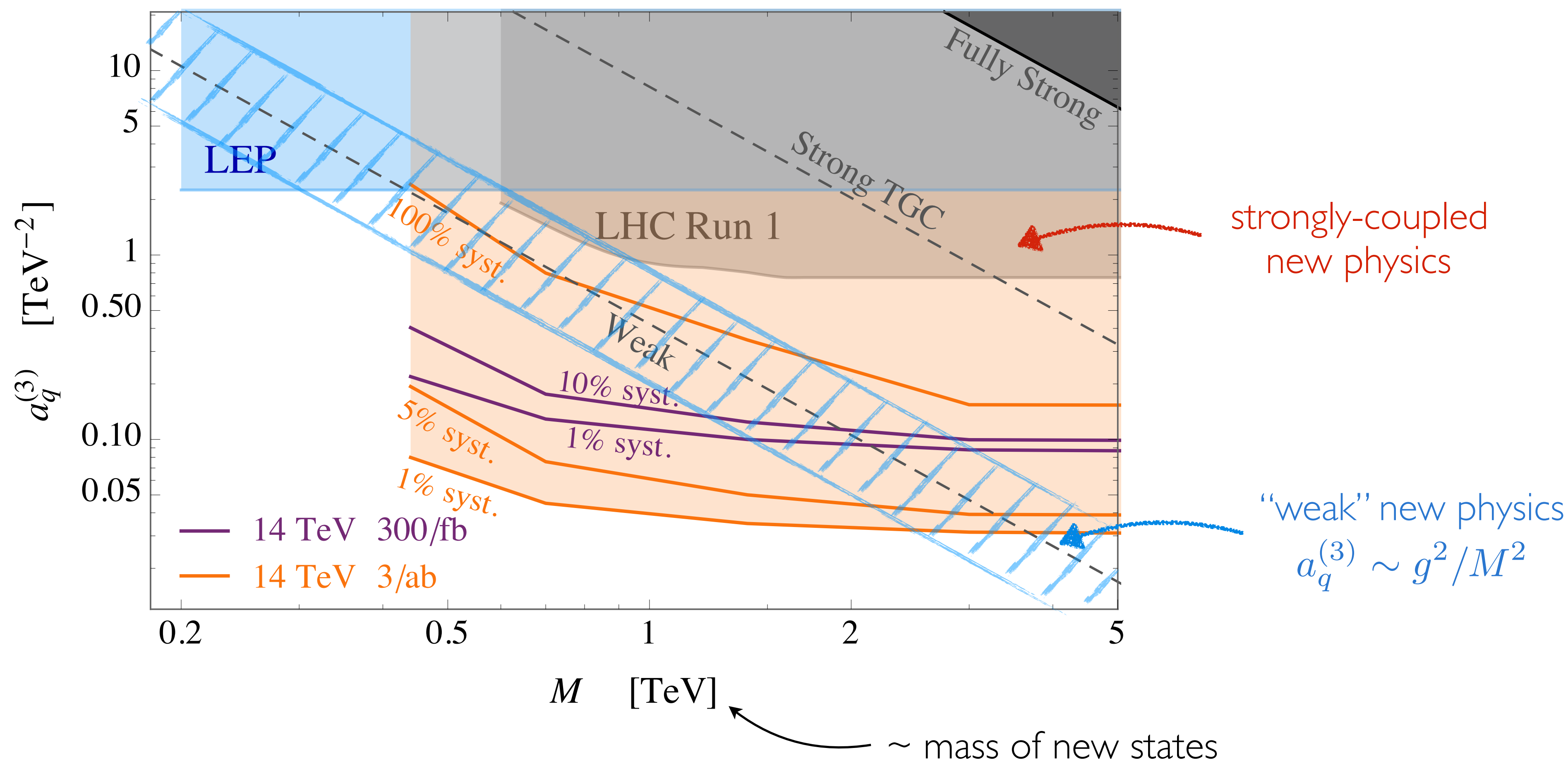


- ✦ Big improvement with respect to LEP
- ✦ **Accuracy** plays an important role for the BSM reach
  - weakly coupled new physics only accessible with low systematics (<<100%)

Conclusions

Conclusions

The **discovery of a SM-like Higgs boson** changed our perspectives

1. **confirmation** of SM theory predictions (overall understanding of EWSB)
2. **no more guaranteed discovery** at colliders
   … but still plenty of room for discovery/learning

Two main **directions for HL-LHC:**

- ✦ direct exploration
  - probe new resonances (eg. partners of the top) ⟶ test tuning ~ *few* %
- ✦ indirect tests
  - Higgs couplings (single Higgs couplings and Higgs self-interactions)
  - precision measurements of EW processes (can indirectly test Higgs dynamics)

Backup

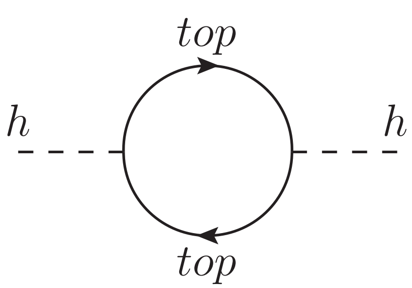
The Naturalness argument

Although not a theorem, **Naturalness** provides a **guideline** for BSM

Higgs mass sensitive to UV physics

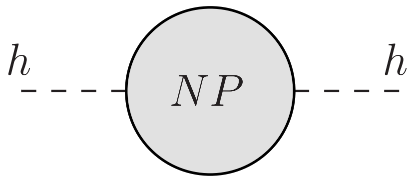
$$m_H^2 = \delta_{\rm SM} m_H^2 + \delta_{\rm BSM} m_H^2$$

SM contribution



$$\delta_{\rm SM} m_H^2 \simeq \frac{3 y_{top}^2}{8\pi^2} \Lambda_{\rm SM}^2$$

UV contribution



$$\delta_{\rm BSM} m_H^2 \sim c\, \Lambda_{\rm SM}^2$$

A large SM cut-off (i.e. a high new-physics scale) implies a significant amount of **fine-tuning**

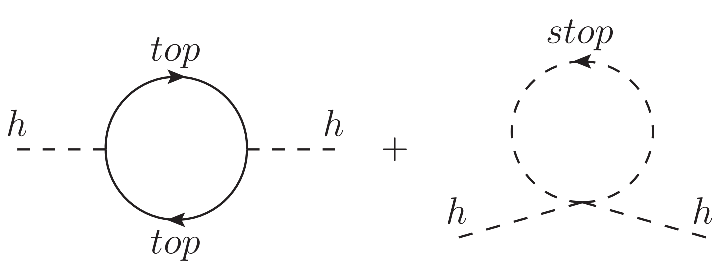
$$\Delta \geq \frac{\delta_{\rm SM} m_H^2}{m_H^2} \simeq \left(\frac{125\,{\rm GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\rm SM}}{500\,{\rm GeV}}\right)^2$$

"Standard" Natural scenarios

Two "standard" approaches to the Naturalness problem

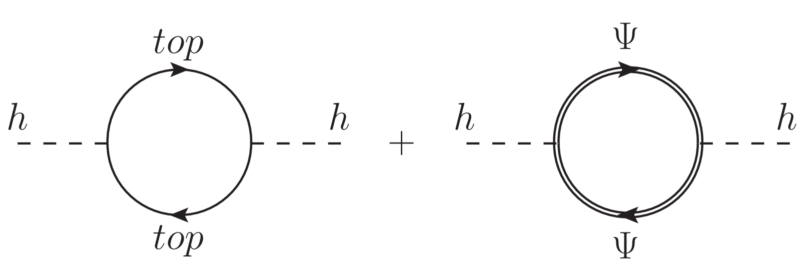
Low-energy SUSY

- **Elementary Higgs**
- SUSY partners with opposite statistics
- **Bosonic partners** of the top (stops) stabilise Higgs mass



Composite Higgs

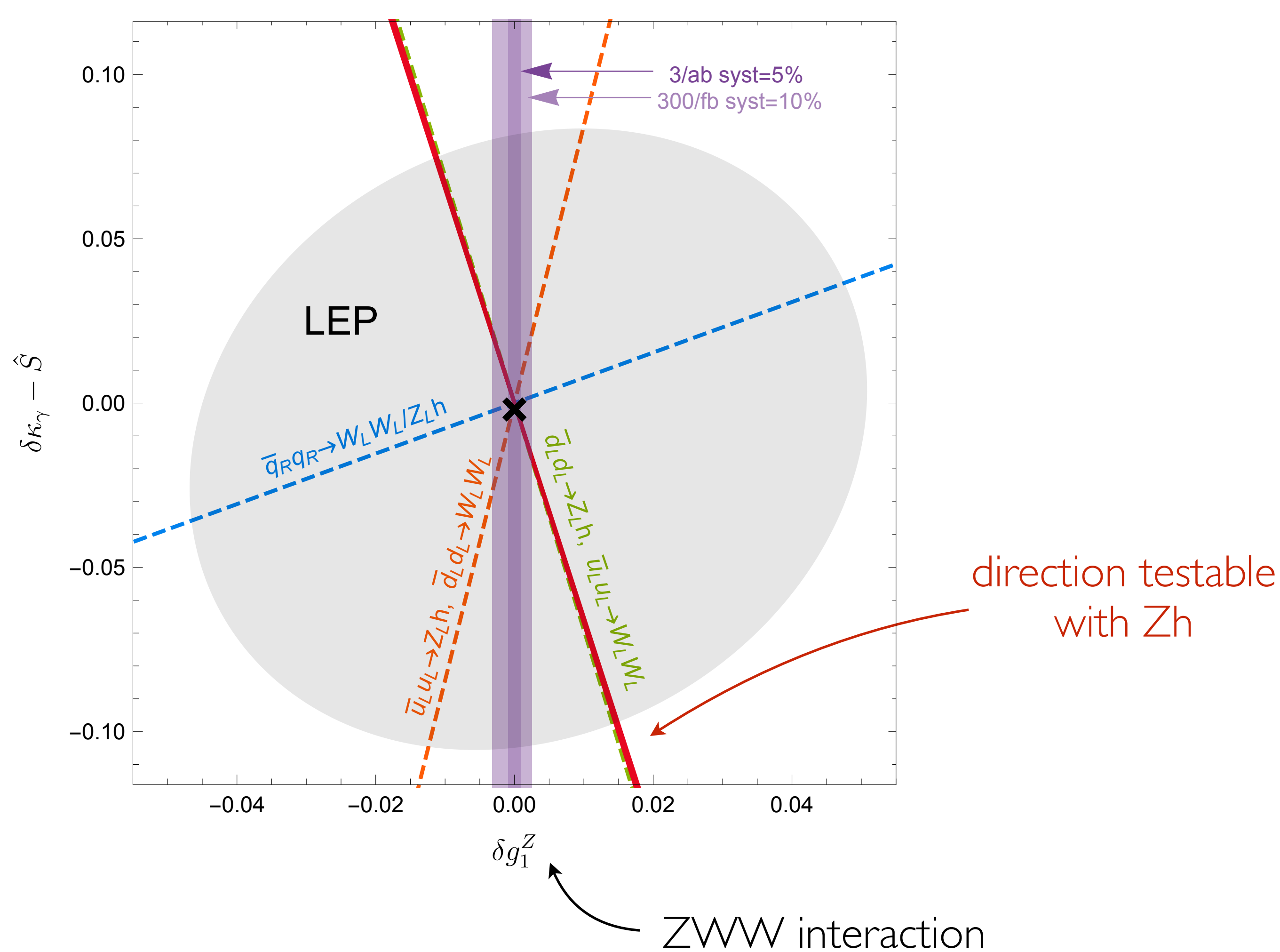
- **Higgs as a bound state** (Goldstone) of a new strong sector
- **Fermionic partners** of the top stabilize Higgs mass



‣ Natural frameworks to discuss LHC implications for Naturalness

Beyond Higgs couplings

Test universal theories in **WZ production channel** [Franceschini, GP, Pomarol, Riva, Wulzer '17]



- better determination on trilinear gauge couplings (δg_1^Z) with respect to global fit at LEP

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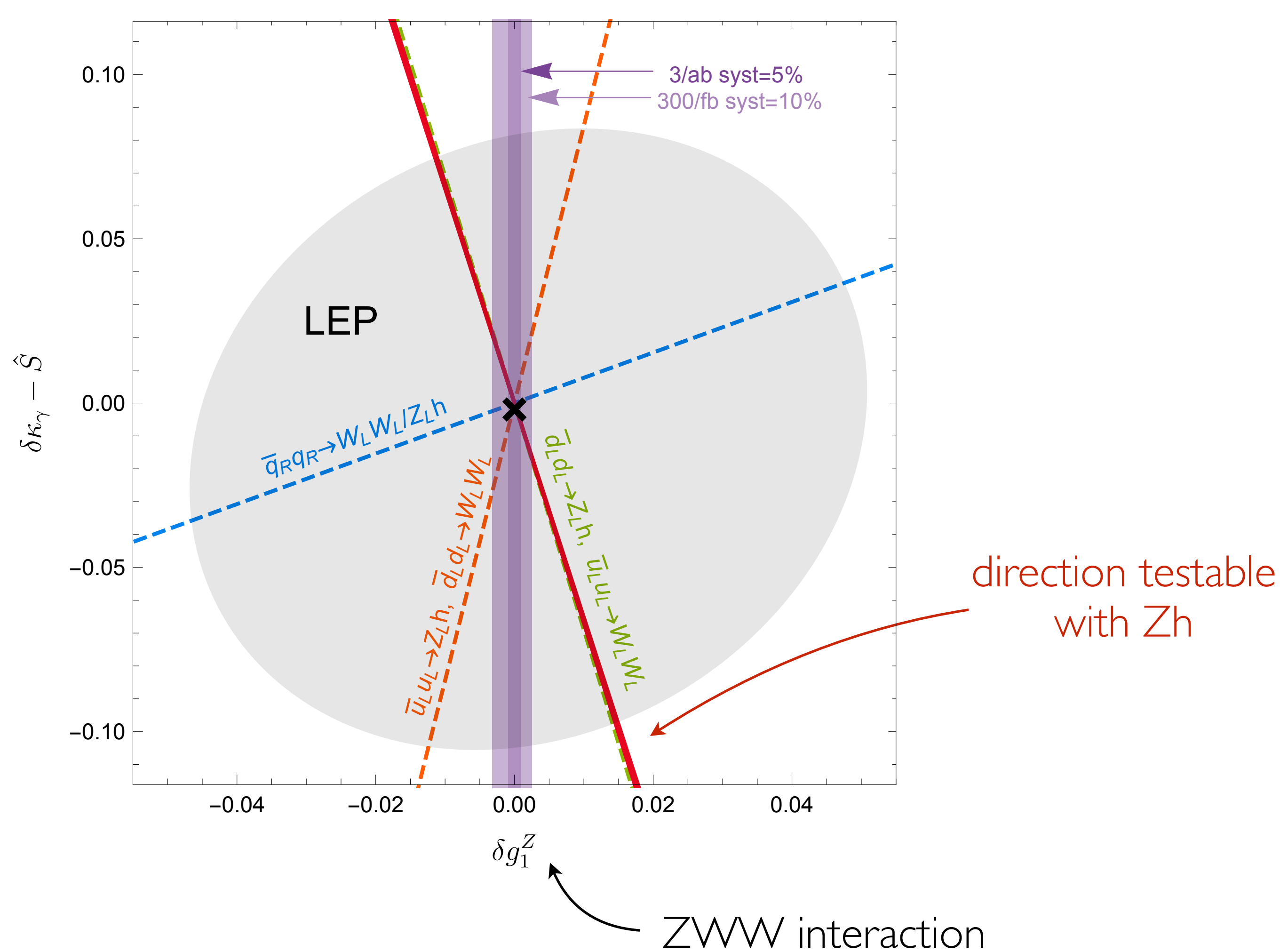

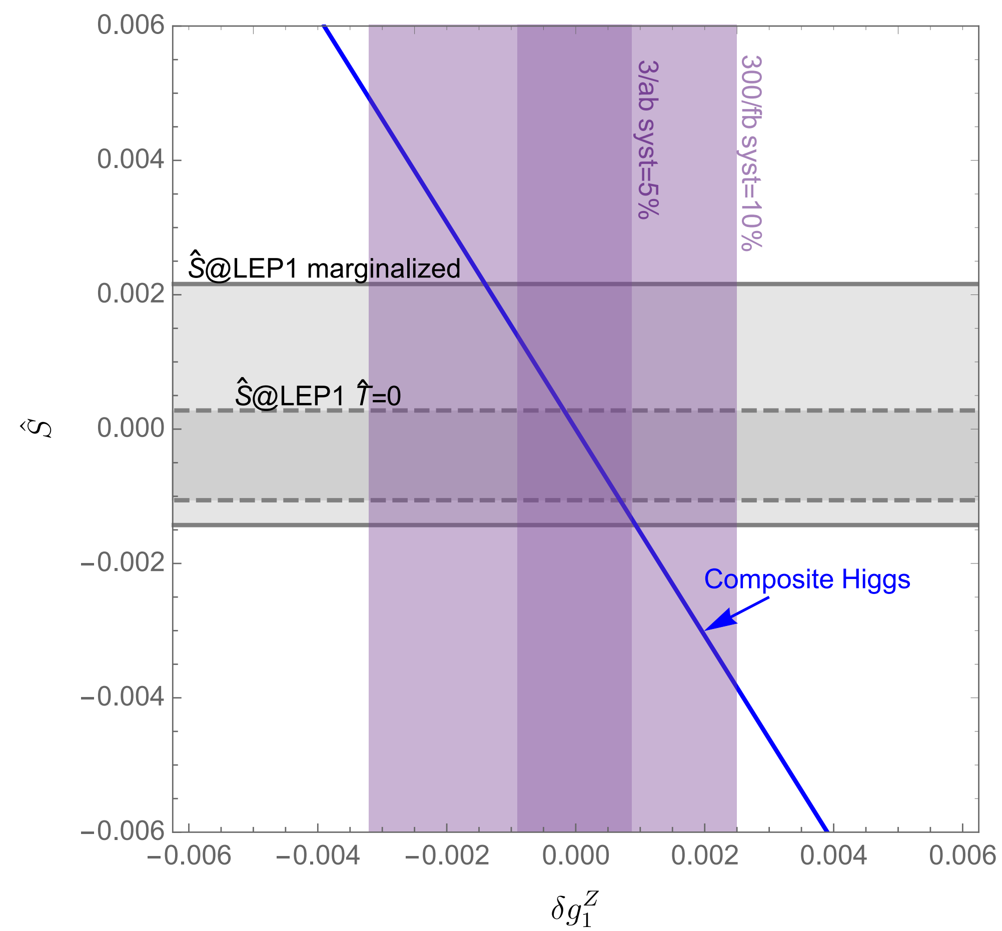

- ✦ better determination on trilinear gauge couplings (δg_1^Z) with respect to global fit at LEP
- ✦ LHC and LEP probe **independent operators**
  - correlations can exist in specific theories (eg. composite Higgs $\widehat{S} \simeq -\delta g_1^Z$)