

BSM Prospects in Higgs Physics at the 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

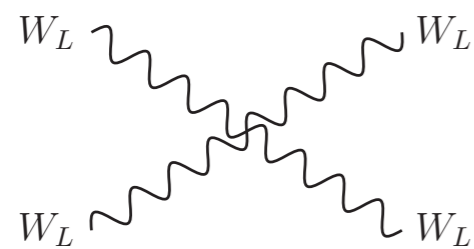
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Before Higgs

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

- strongly coupled processes at energy scales \sim few TeV

After Higgs

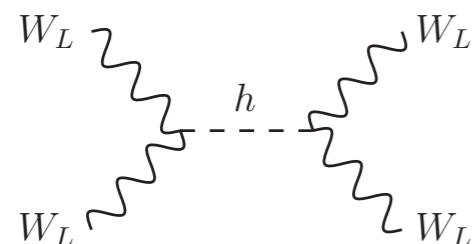


+ ...

$$\sim g_W^2 E^2 / m_W^2 < 16\pi^2$$



non-perturbative at $E \sim$ TeV
nearby new physics



+ ...

... or cured by **light Higgs**



$$m_H < 4\pi v \simeq 3 \text{ TeV}$$

Higgs and New physics

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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}



$$\frac{1}{G_N} \sqrt{g} R \quad \longrightarrow \quad \begin{array}{ccc} grav & & grav \\ & \diagdown & / \\ & & \\ & / & \diagdown \\ grav & & grav \end{array}$$

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

gravity non-perturbative at Planck scale



maximal SM cut-off $\Lambda_{SM} \lesssim M_{Pl}$

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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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- ◆ **Naturalness:** explain microscopic origin of EW scale
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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)

The Naturalness argument

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

Higgs mass sensitive to UV physics

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



SM contribution

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

UV contribution

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

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

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

The Naturalness argument

LHC and future colliders allow to **test Naturalness** by probing the scale of BSM physics

Even “discovering” **Un-Naturalness** can have strong consequences

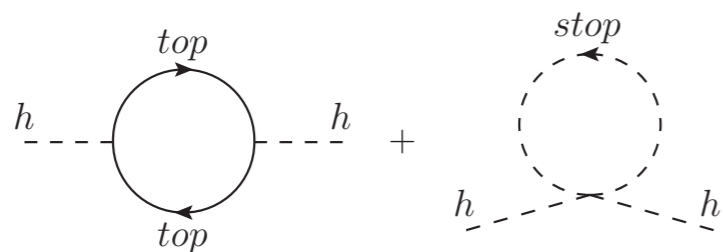
1. Standard scenarios too fine-tuned:
alternative non-minimal theories should be considered
(eg. neutral naturalness)
2. Complete change of paradigm
(eg. dynamical generation of EW scale, relaxion)
3. Higgs mass as a fundamental parameter
(anthropic selection?)

“Standard” Natural scenarios

Two “standard” approaches to the Naturalness problem

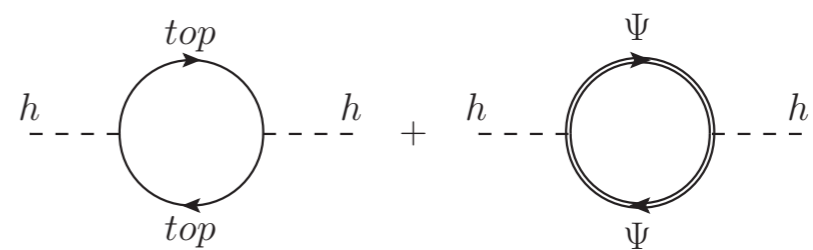
Low-energy SUSY

- **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

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 \rightarrow test of Naturalness

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

Low-energy SUSY

$\Lambda_{\text{SM}} = \text{stop mass}$

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

Composite Higgs

$\Lambda_{\text{SM}} = \text{top partners mass}$

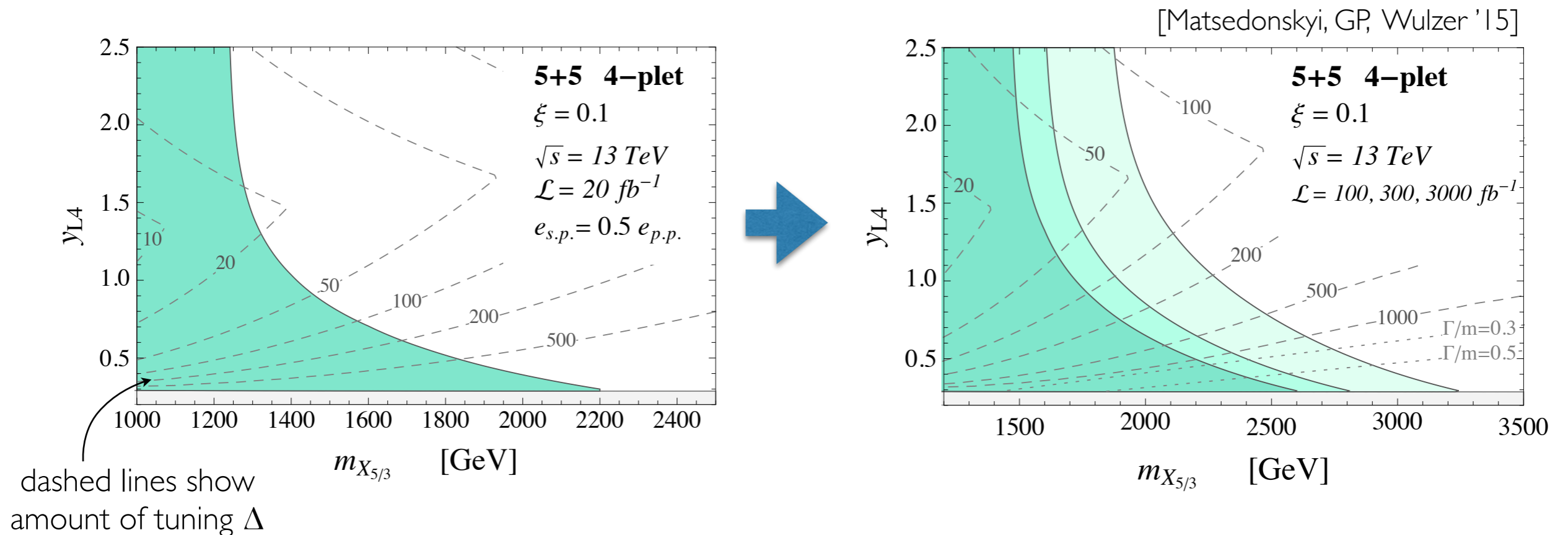
- current bounds $\sim 1.2 \text{ TeV}$

- ▶ Current bounds **still allow minimal models** with $\sim 10\%$ tuning!
- ▶ Fast progress with 13 TeV 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

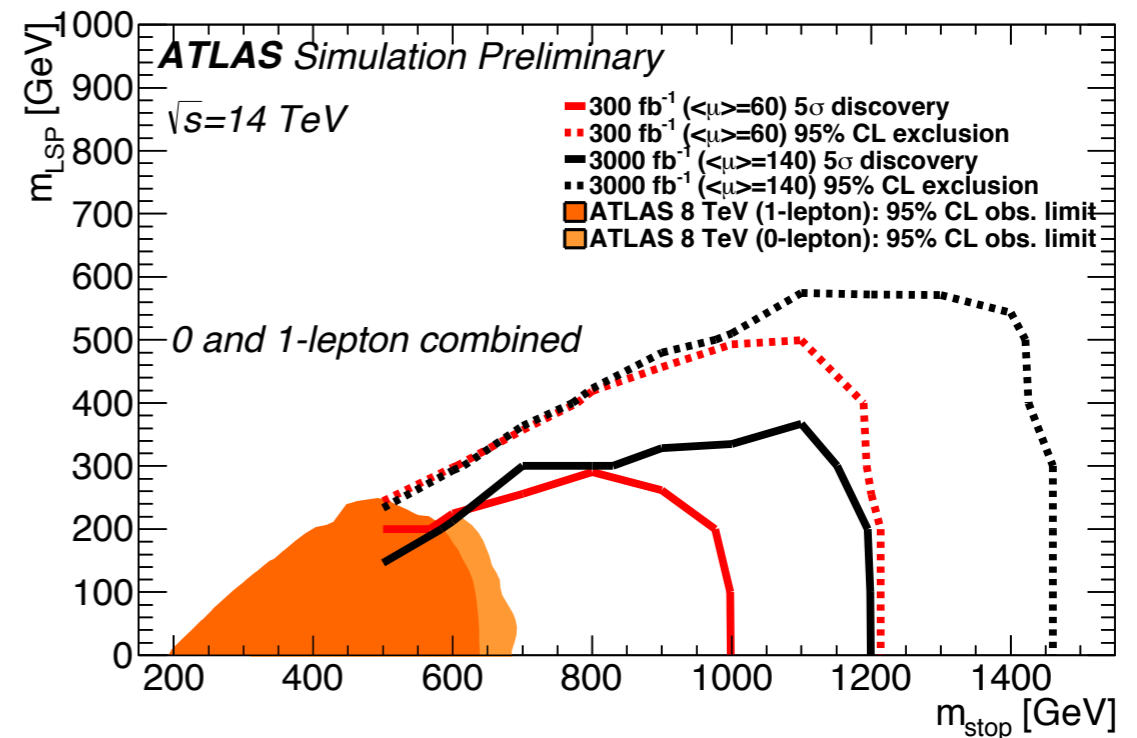
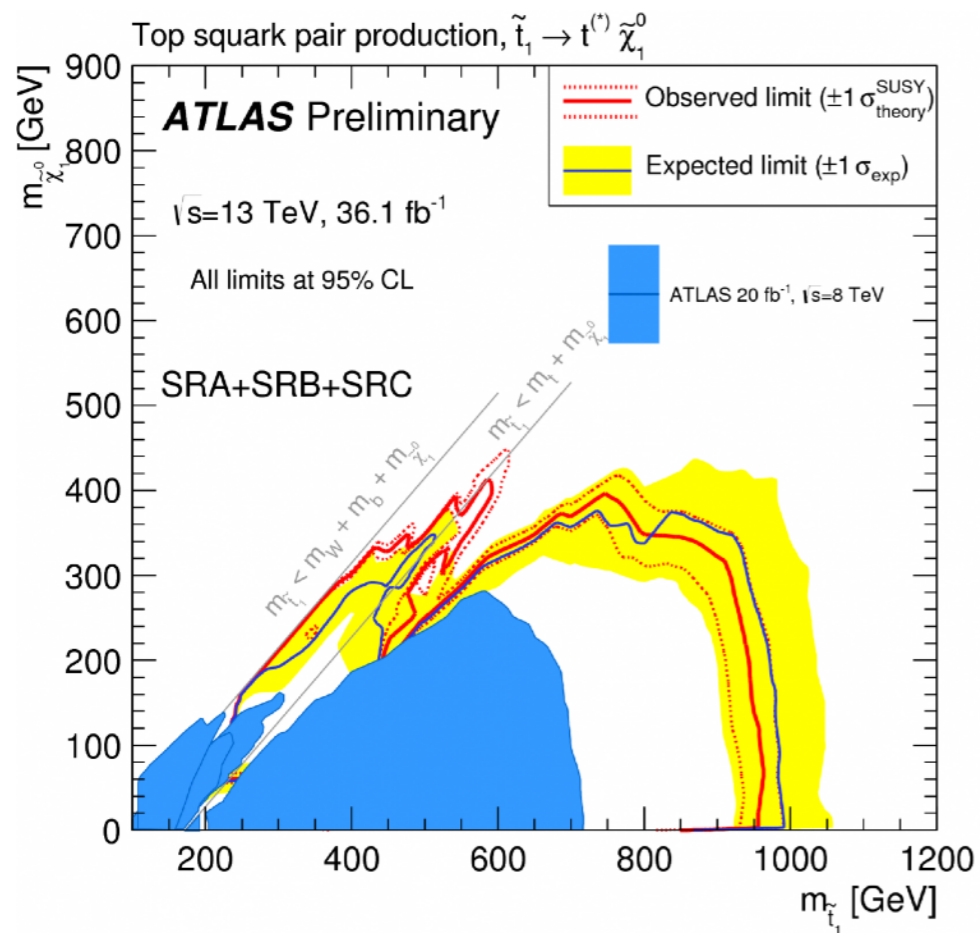
Example: Projected bounds on **top partners**



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

SUSY partners

... similar situation for SUSY partners



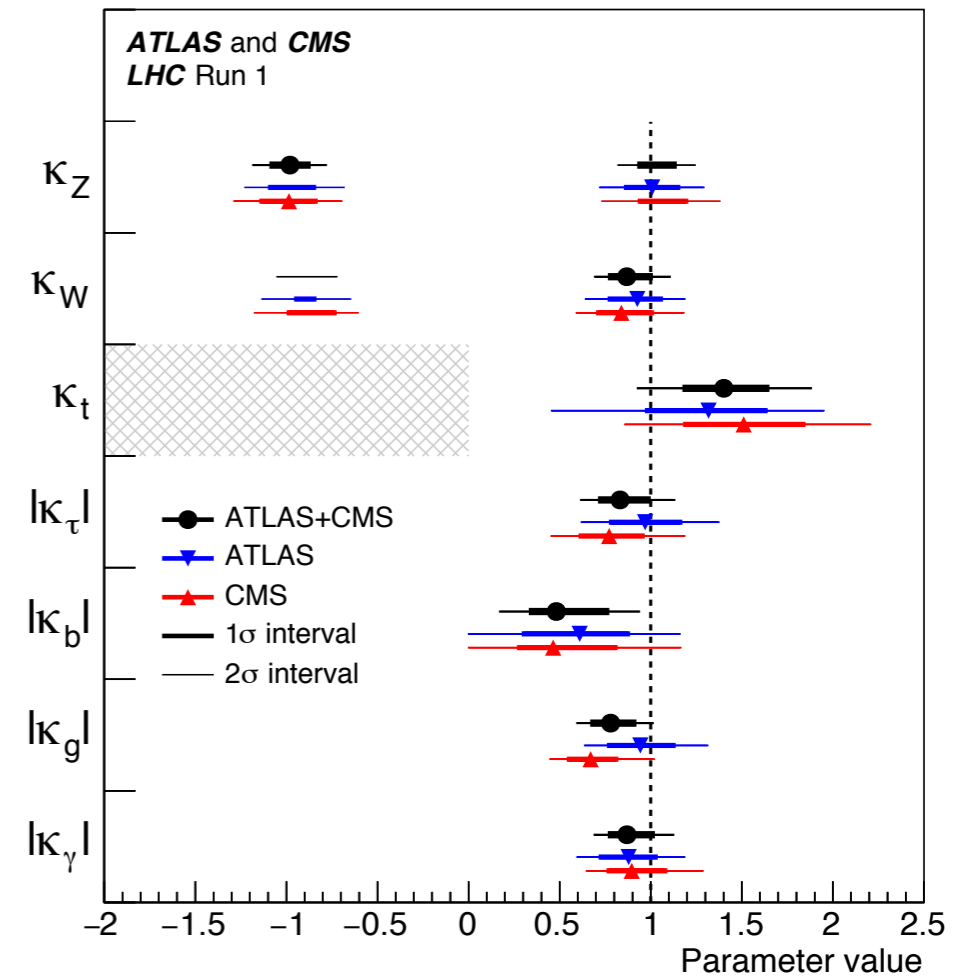
- ▶ Bounds on the stop at HL-LHC can reach 1.5 TeV
- ▶ but still space for discovery

Indirect Searches at LHC

Higgs couplings

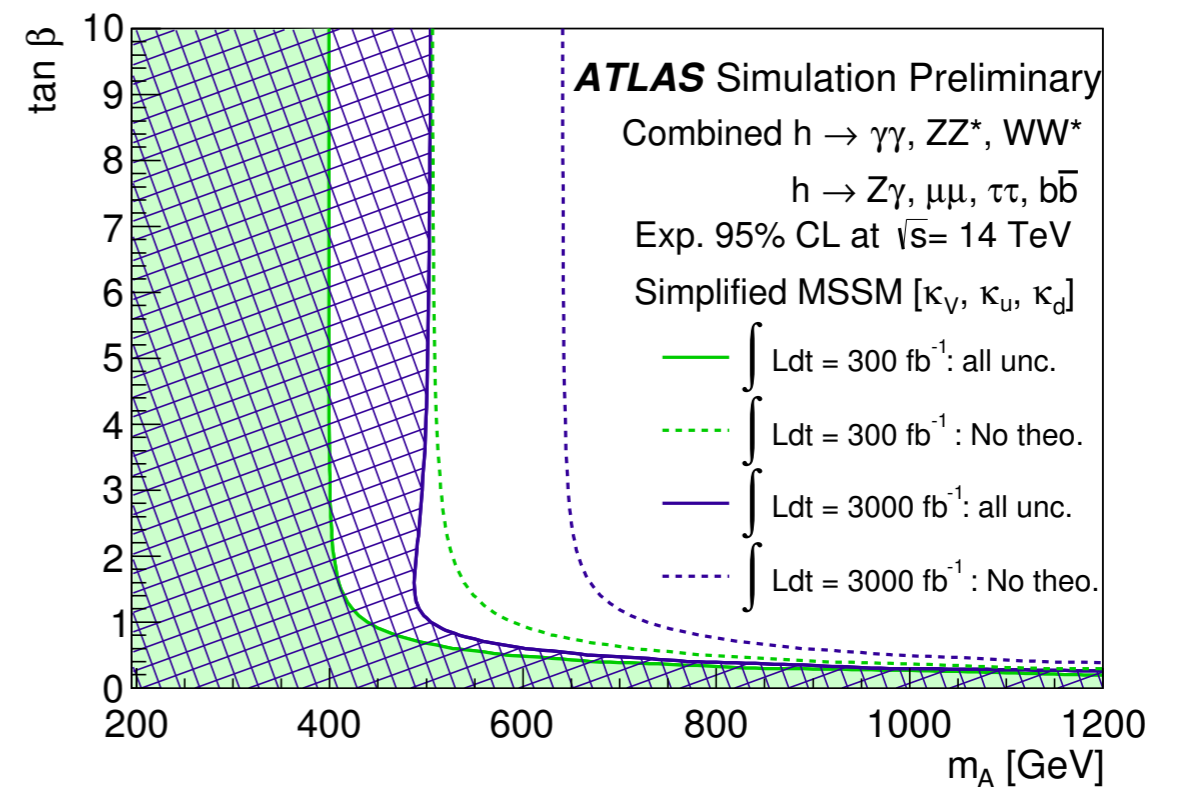
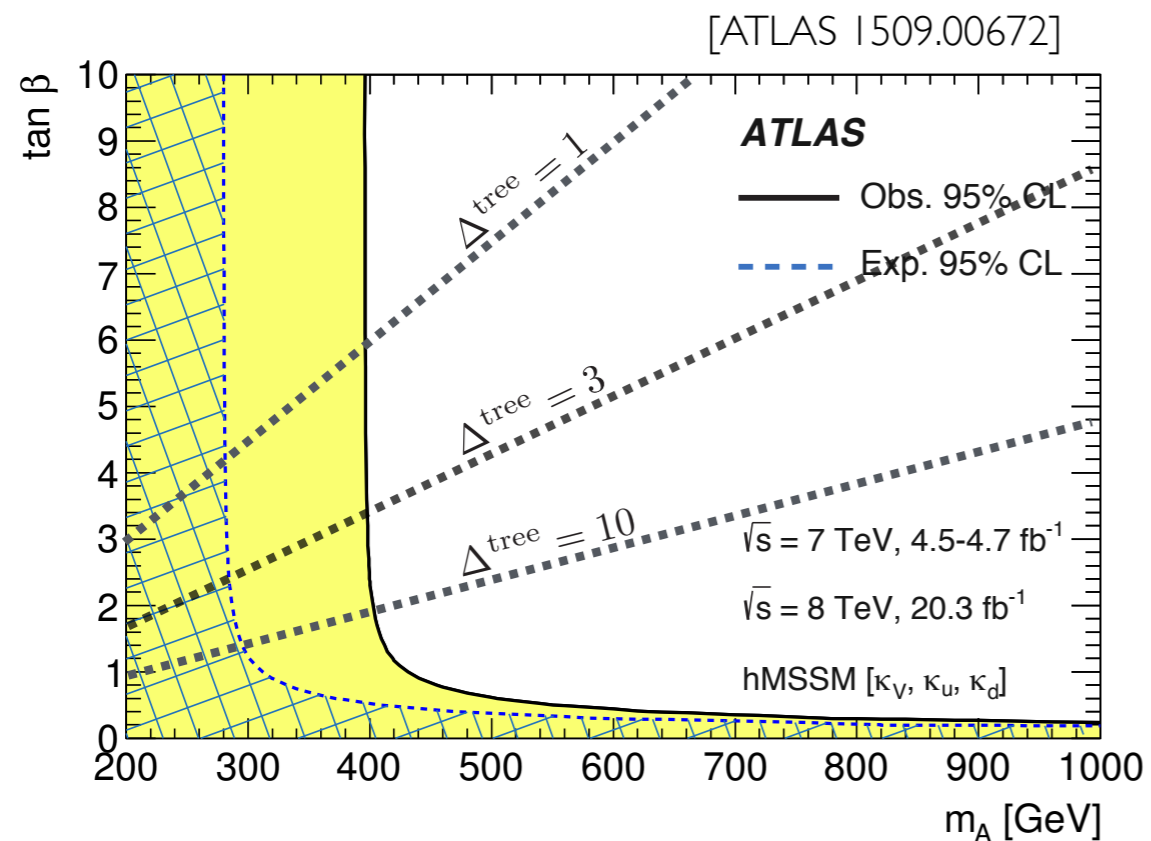
Precision measurement of **Higgs couplings** allows for test of SM and probe of BSM theories

- ◆ deviations expected in many BSM scenarios (eg. SUSY and composite Higgs)
- ◆ useful to derive bounds (can be competitive with direct searches)



Higgs couplings in SUSY

Higgs couplings modifications expected from mixing with second Higgs doublet

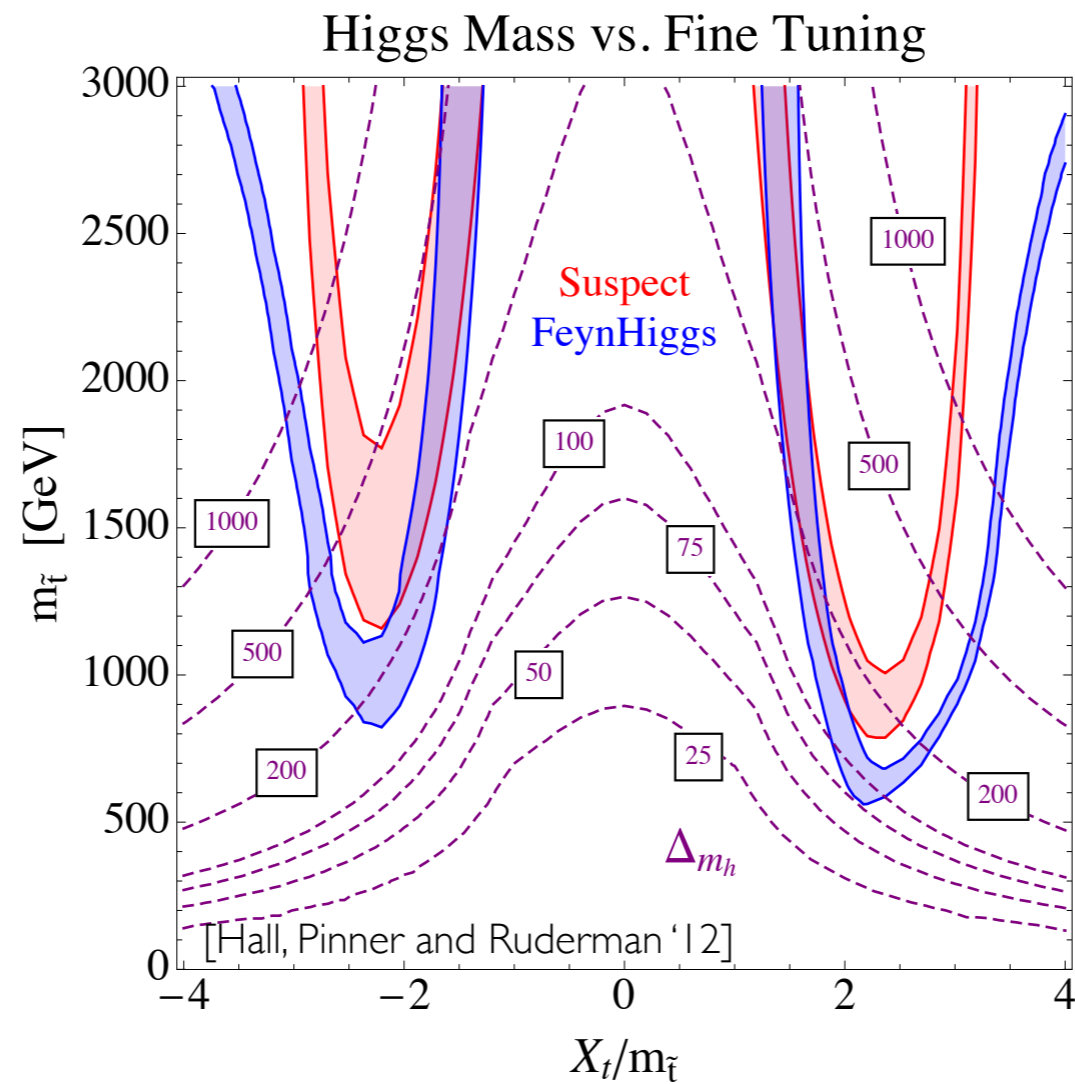


exclusions have no direct impact on fine-tuning in MSSM

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 $\sim 1\%$

Higgs couplings in λ -SUSY

In non-minimal SUSY models one can avoid heavy stops

example: 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:

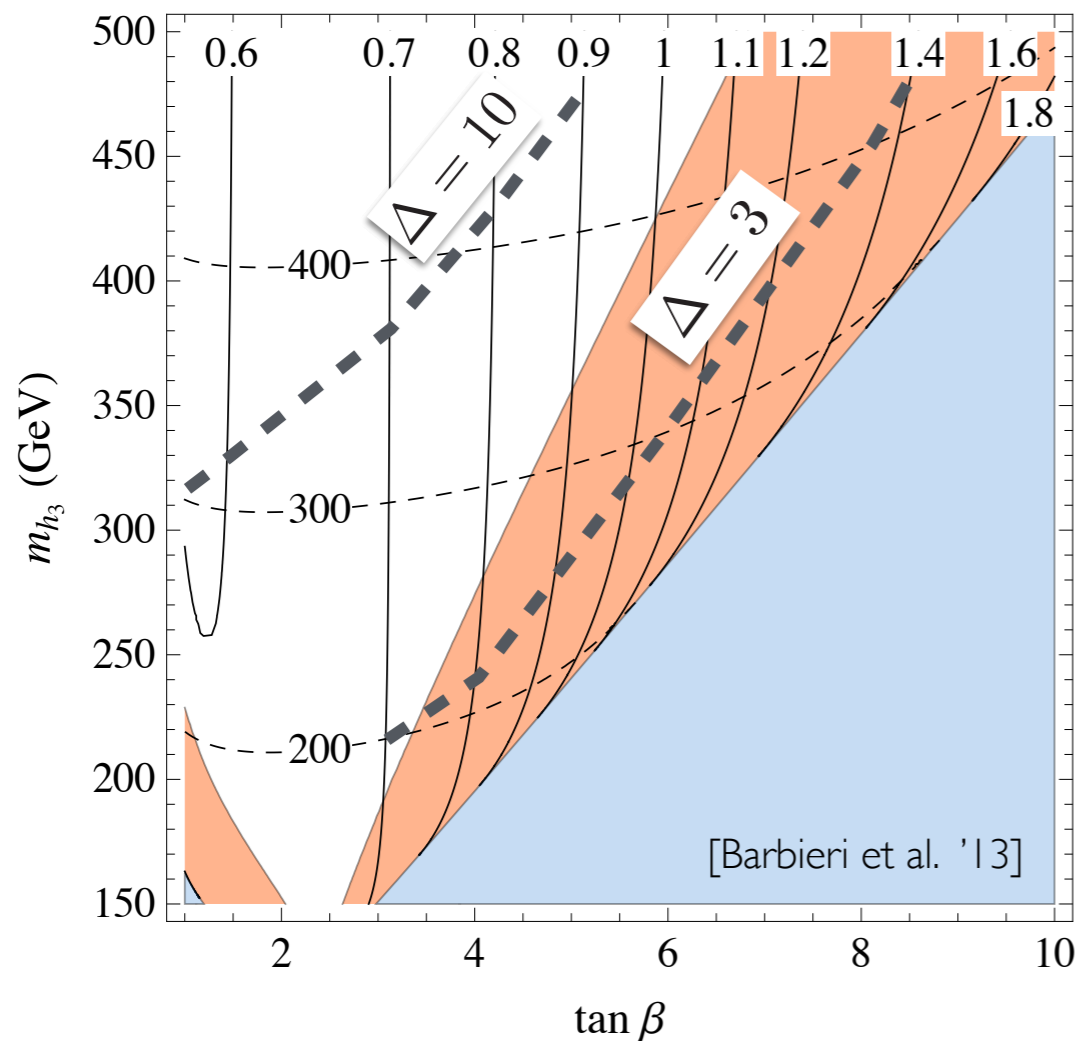
$$\Delta \gtrsim \frac{1}{\lambda^2} \left(\frac{m_{H^\pm}}{170 \text{ GeV}} \right)^2$$

- ▶ direct connection between scalar sector and Naturalness

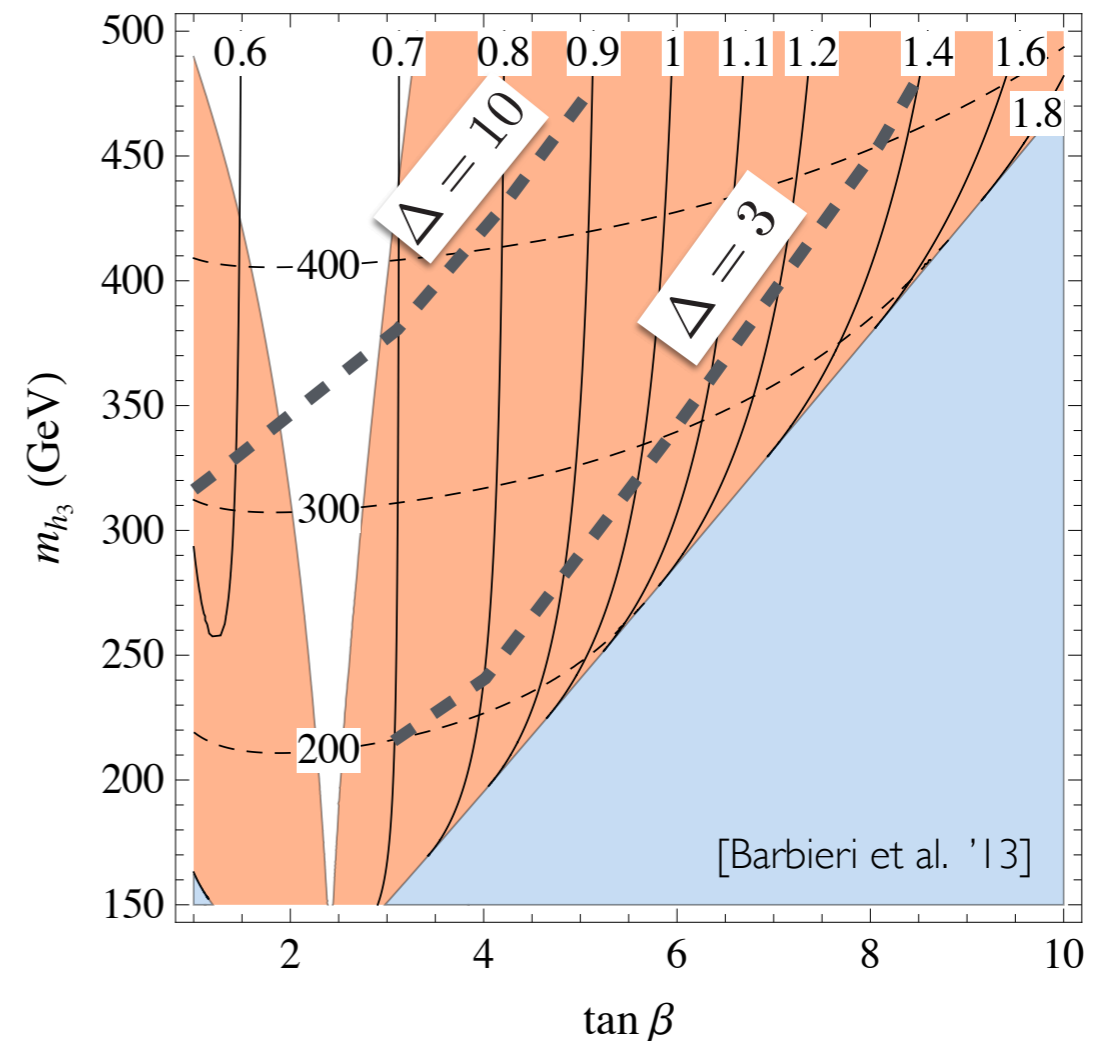
Higgs couplings in λ -SUSY

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. $SO(5)/SO(4) \Rightarrow k_V = \sqrt{1 - \xi}$

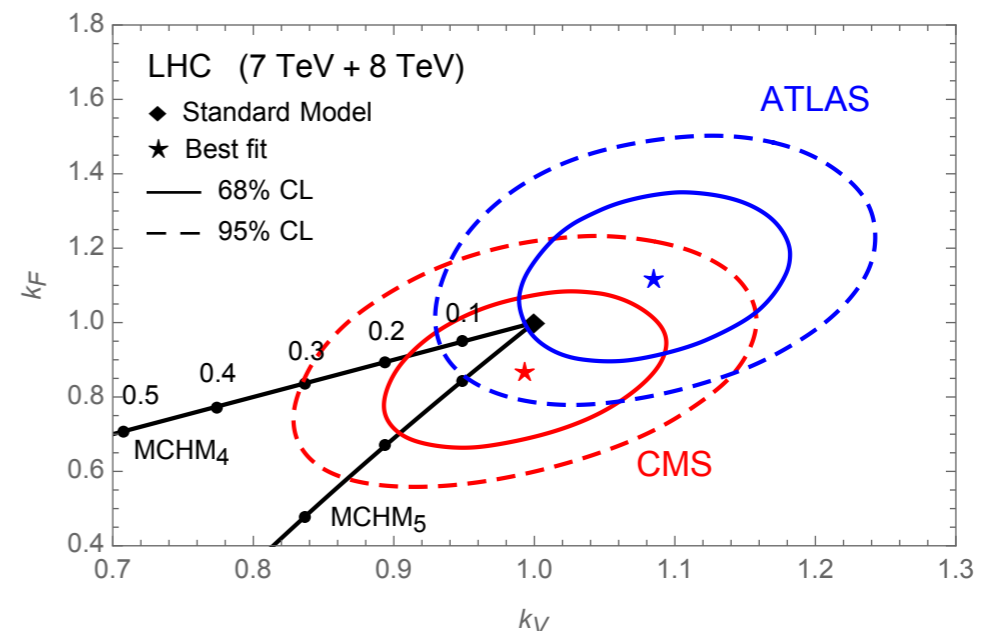
◆ **Yukawa's**

▶ depends on partners quantum numbers: eg. MCHM₅ $k_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$
MCHM₄ $k_F = \sqrt{1 - \xi}$

Direct connection with tuning: $\Delta \gtrsim 1/\xi$ ($\xi = v^2/f^2$)
↙ compositeness scale

▶ current bounds $\xi \lesssim 0.1$
[ATLAS Collab. 1509.00672]

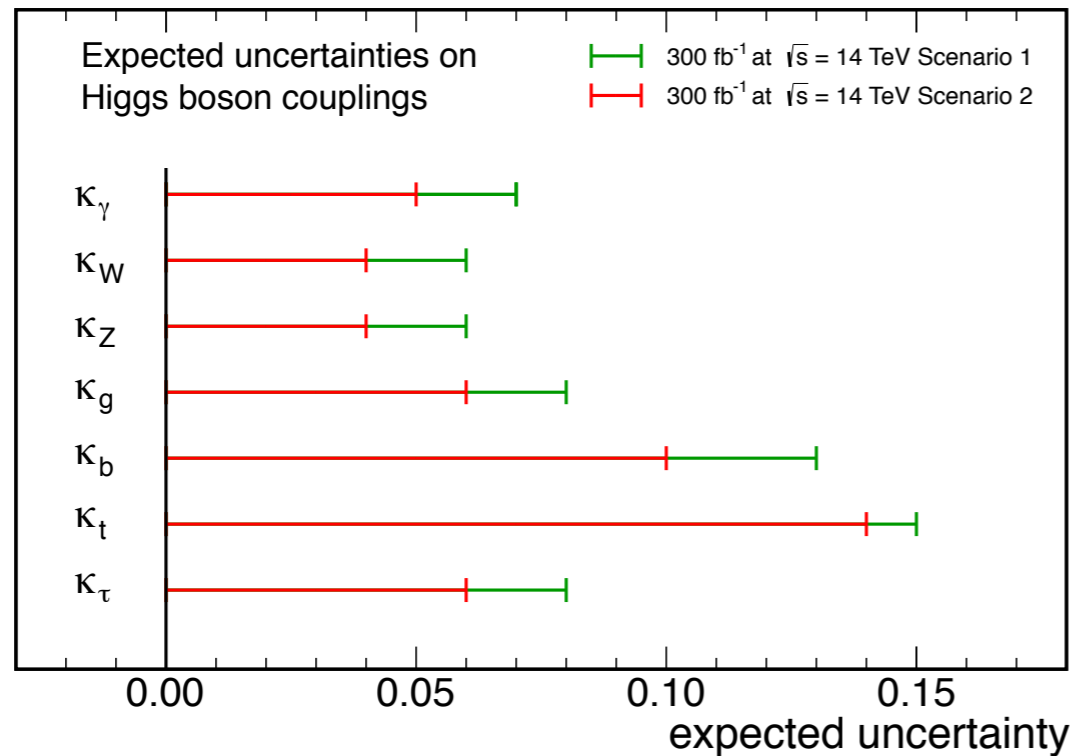
▶ space for improvement?
crucially related to systematics... see later



Higgs couplings at HL-LHC

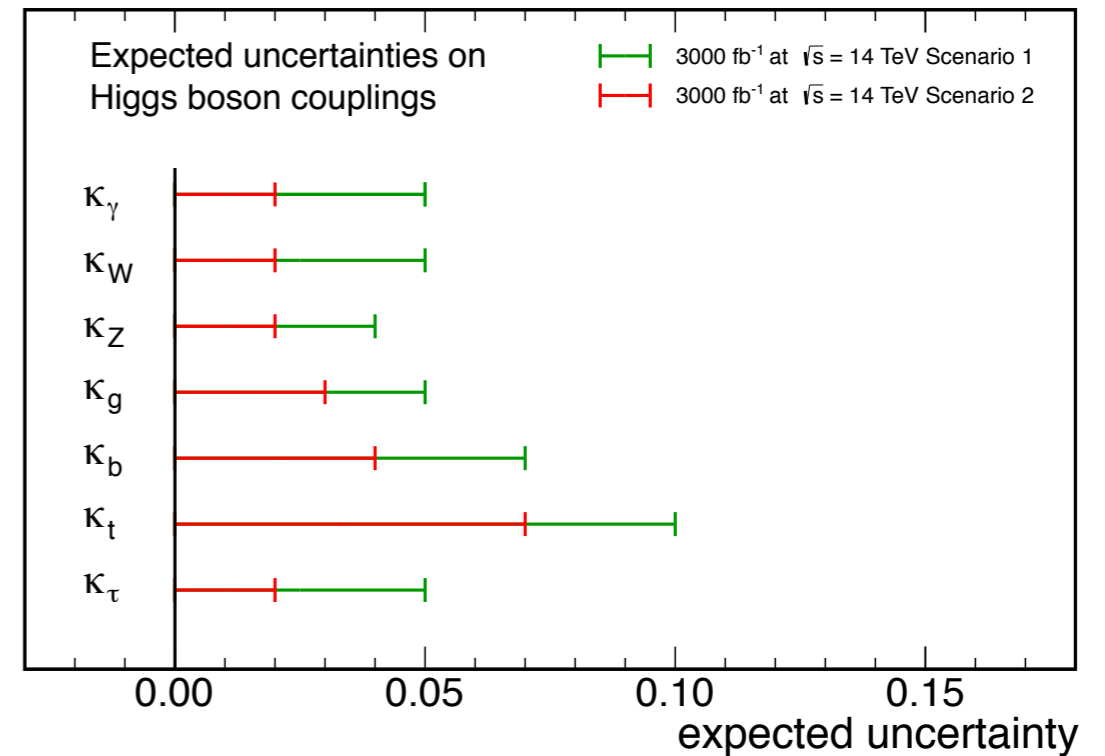
Slow progress on Higgs couplings in future runs

CMS Projection



CMS Projection

[CERN-CMS-NOTE-13-002]

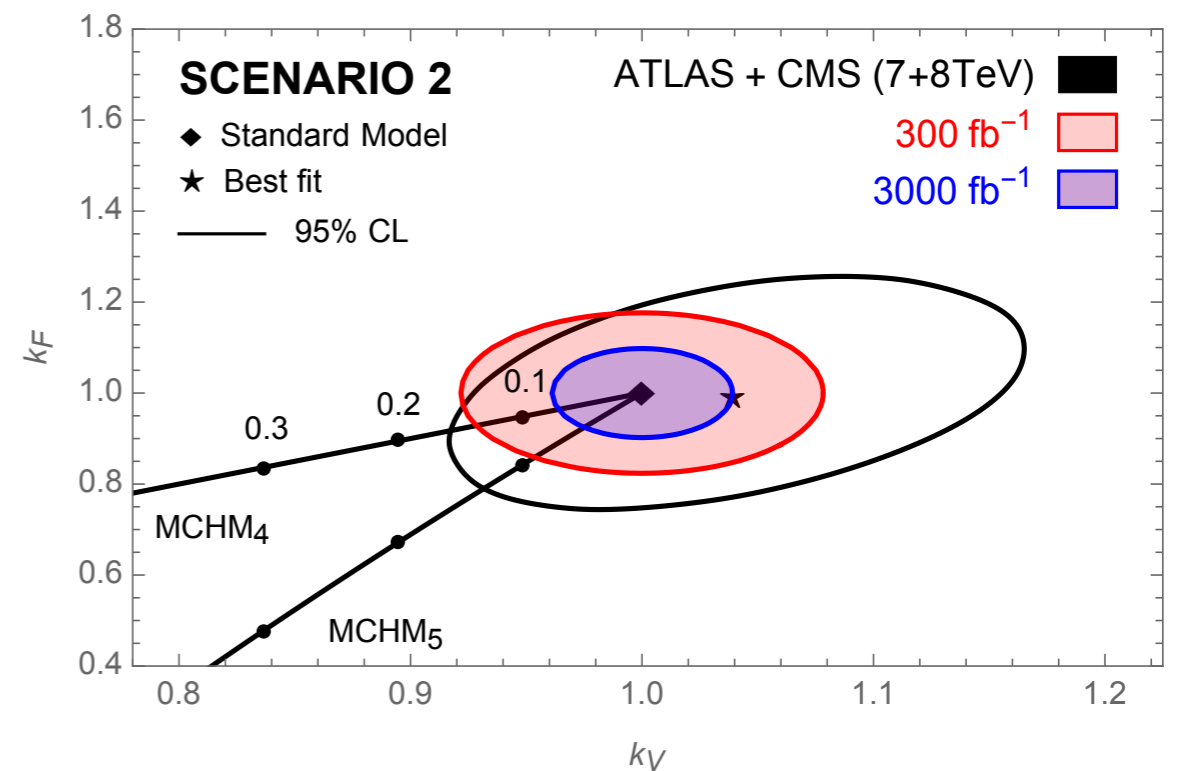
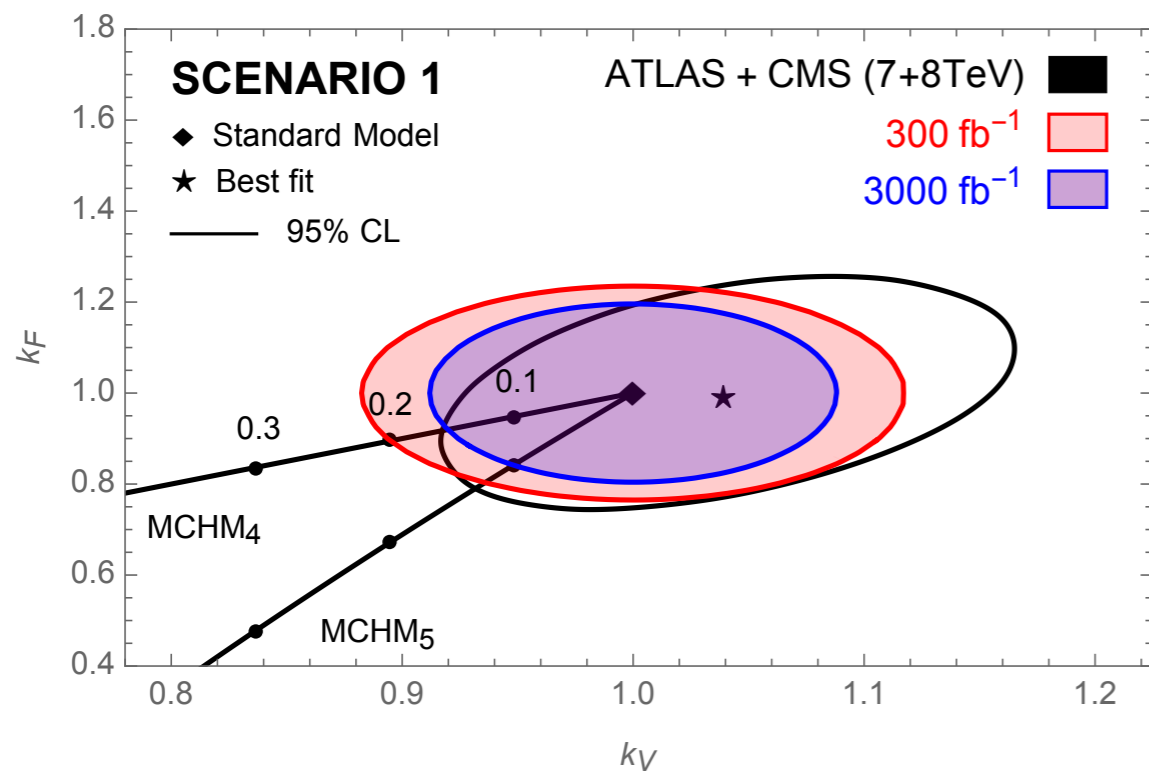


L (fb ⁻¹)	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR _{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

- 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 $\xi \simeq 0.05 \rightarrow f \simeq 1.1 \text{ TeV}$

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**

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

- ▶ distortions expected in many BSM scenarios

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

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

for $\theta, g_* \sim 1$

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

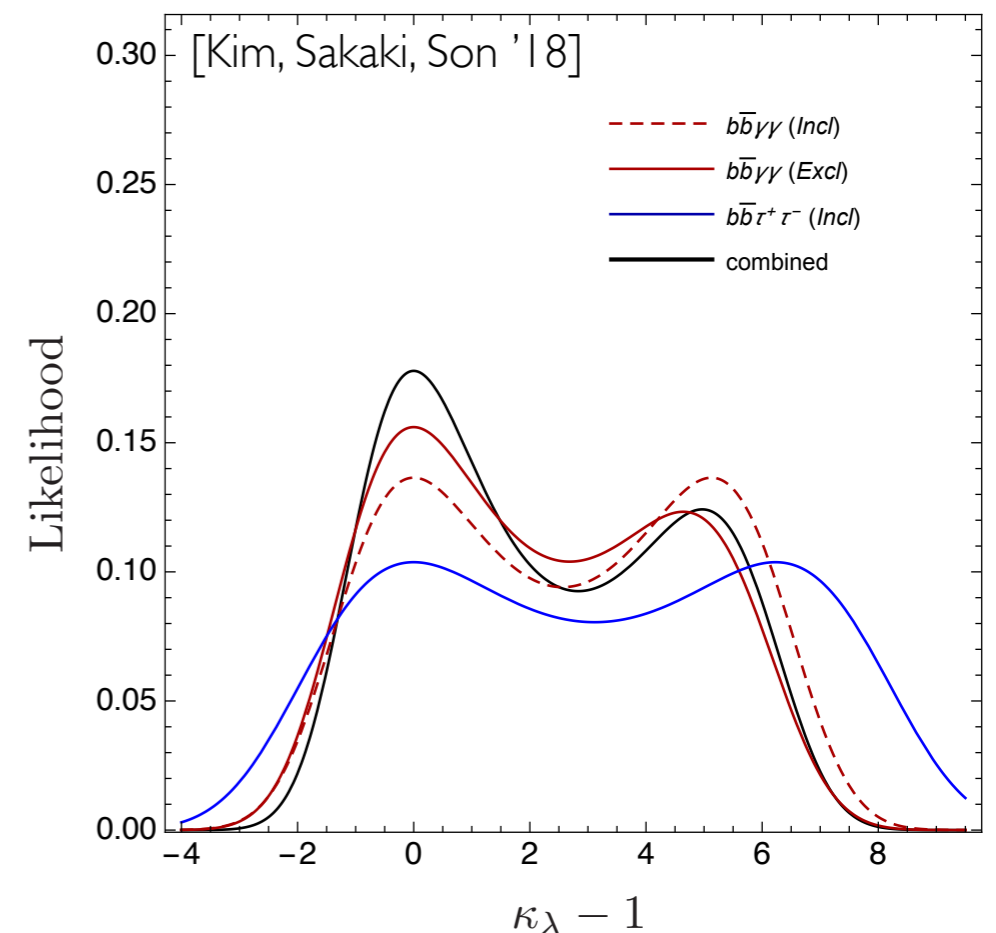
The trilinear Higgs coupling

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

Different final states accessible:

- ▶ $\bar{b}b\gamma\gamma$: cleanest channel with highest sensitivity, but low cross section
- ▶ $\bar{b}b\tau\tau$: larger statistics, but hard analysis
- ▶ $\bar{b}bWW, \bar{b}b\bar{b}b$: limited impact

HL-LHC (3 ab^{-1})	Allowed region on $\kappa_\lambda - 1$	
	68% probability	95% probability
Cut-based analysis		
$\bar{b}b\gamma\gamma$ (exclusive)	$[-0.98, 2.2] \cup [3.1, 5.3]$	$[-1.8, 6.6]$
$\bar{b}b\tau^+\tau^-$	$[-0.87, 6.1]$	$[-2.5, 8.8]$
Combined	$[-0.91, 2.3] \cup [3.4, 5.3]$	$[-1.6, 6.5]$



◆ only $\mathcal{O}(1)$ determination possible at HL-LHC

The trilinear Higgs coupling

Precision determination of Higgs trilinear coupling possible at future colliders

◆ Hadron colliders:

- ▶ FCC-100 could reach $\sim 5\%$ precision [Contino et al., FCC report 1606.09408]
- ▶ High-energy LHC (~ 28 TeV) could reach $\sim 30\%$ precision [Gonçalves et al. '18]

◆ Lepton colliders:

- ▶ high-energy machines (ILC, CLIC) could reach $\sim 20\%$ precision (directly through Higgs pair production) [see for instance: Barklow et al. '17; Di Vita et al. '17]
- ▶ low-energy machines (CEPC, FCC-ee) could reach $\sim 40\%$ precision (indirectly through single Higgs processes) [Di Vita et al. '17]

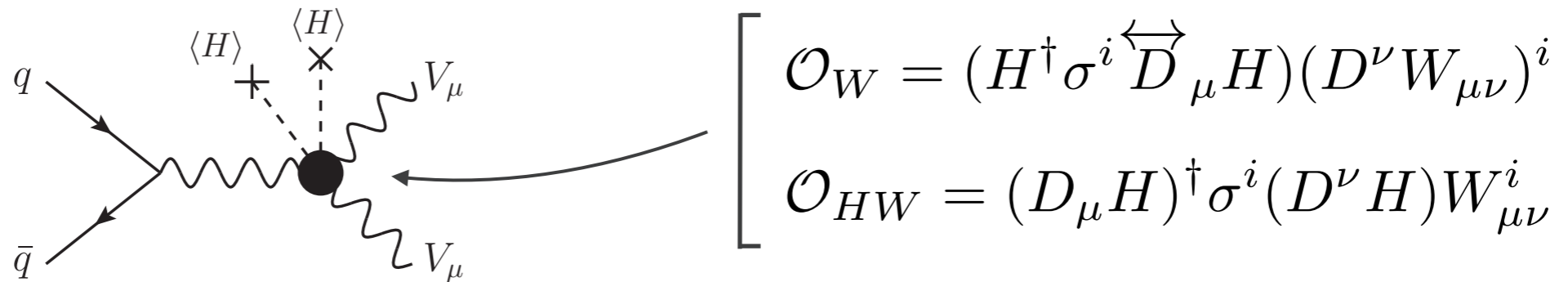
Beyond Higgs Couplings

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

example: **di-boson** production can probe deviations in the Higgs dynamics

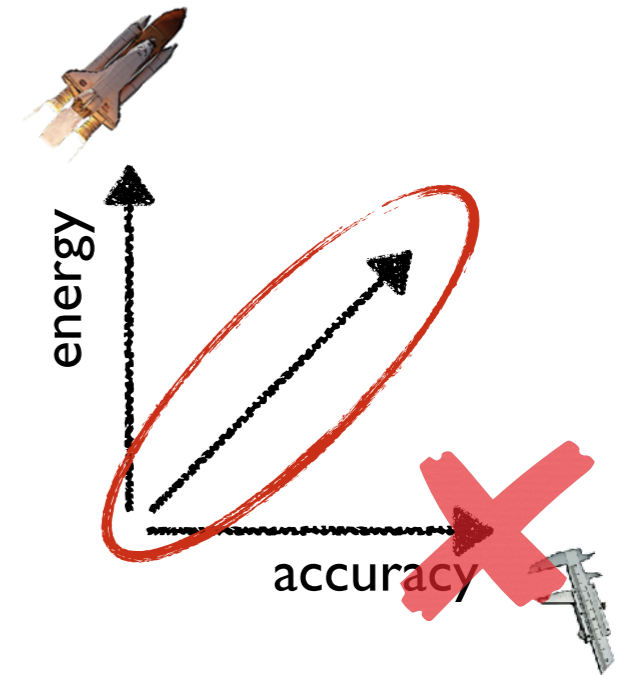


Beyond Higgs couplings

- ◆ 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]

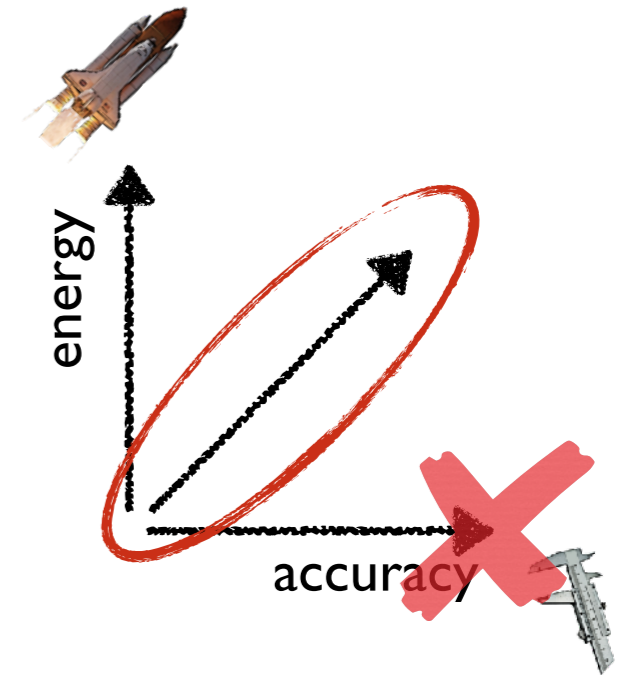


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- ◆ key point: deviations from SM typically **grow with energy**

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

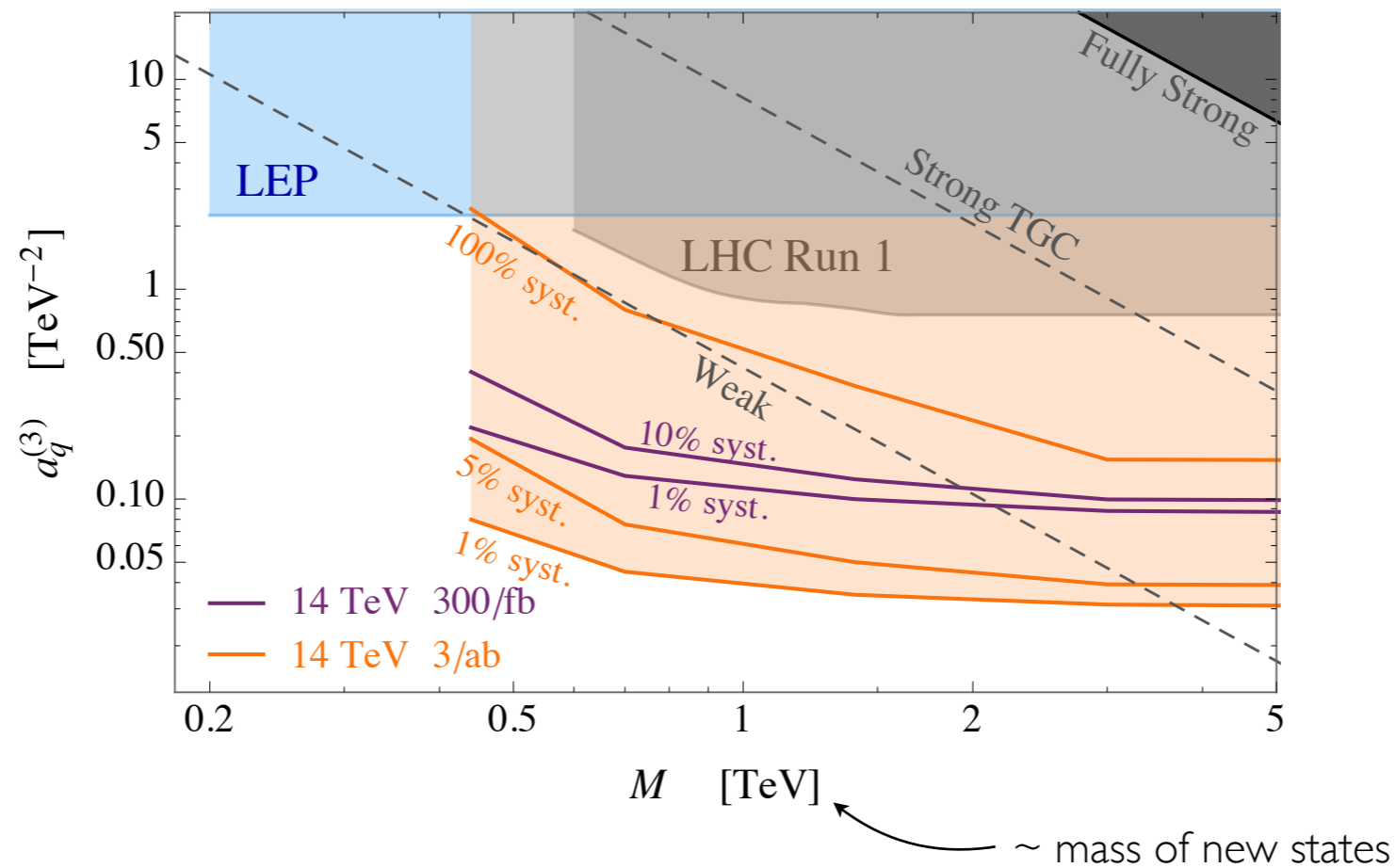
→ LHC can match LEP sensitivity exploiting the **high energy** reach

0.1 % at 100 GeV → 10 % at 1 TeV
LEP energy *LHC energy*

WZ: Reach at LHC

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

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

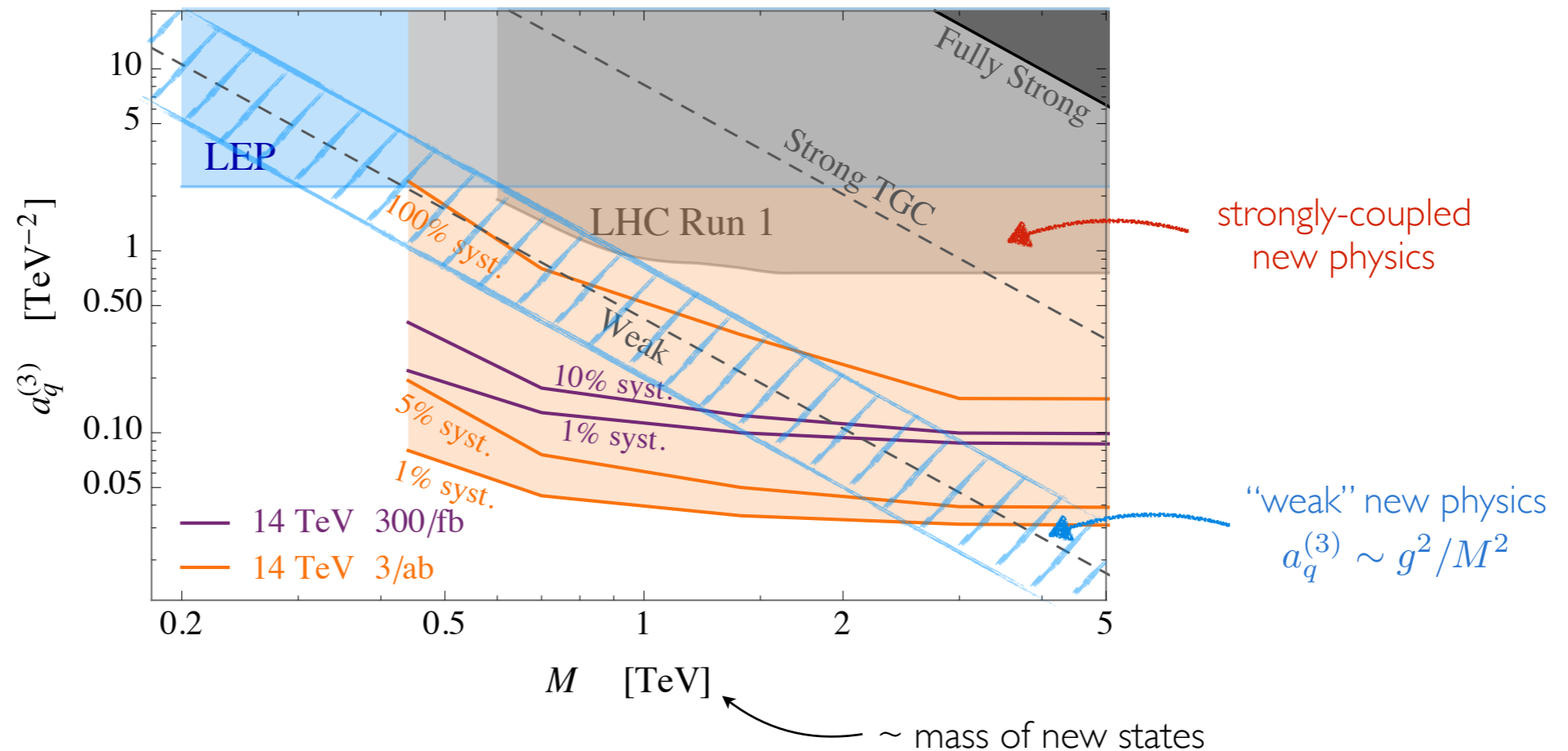


◆ Big improvement with respect to LEP

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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 ($\ll 100\%$)

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

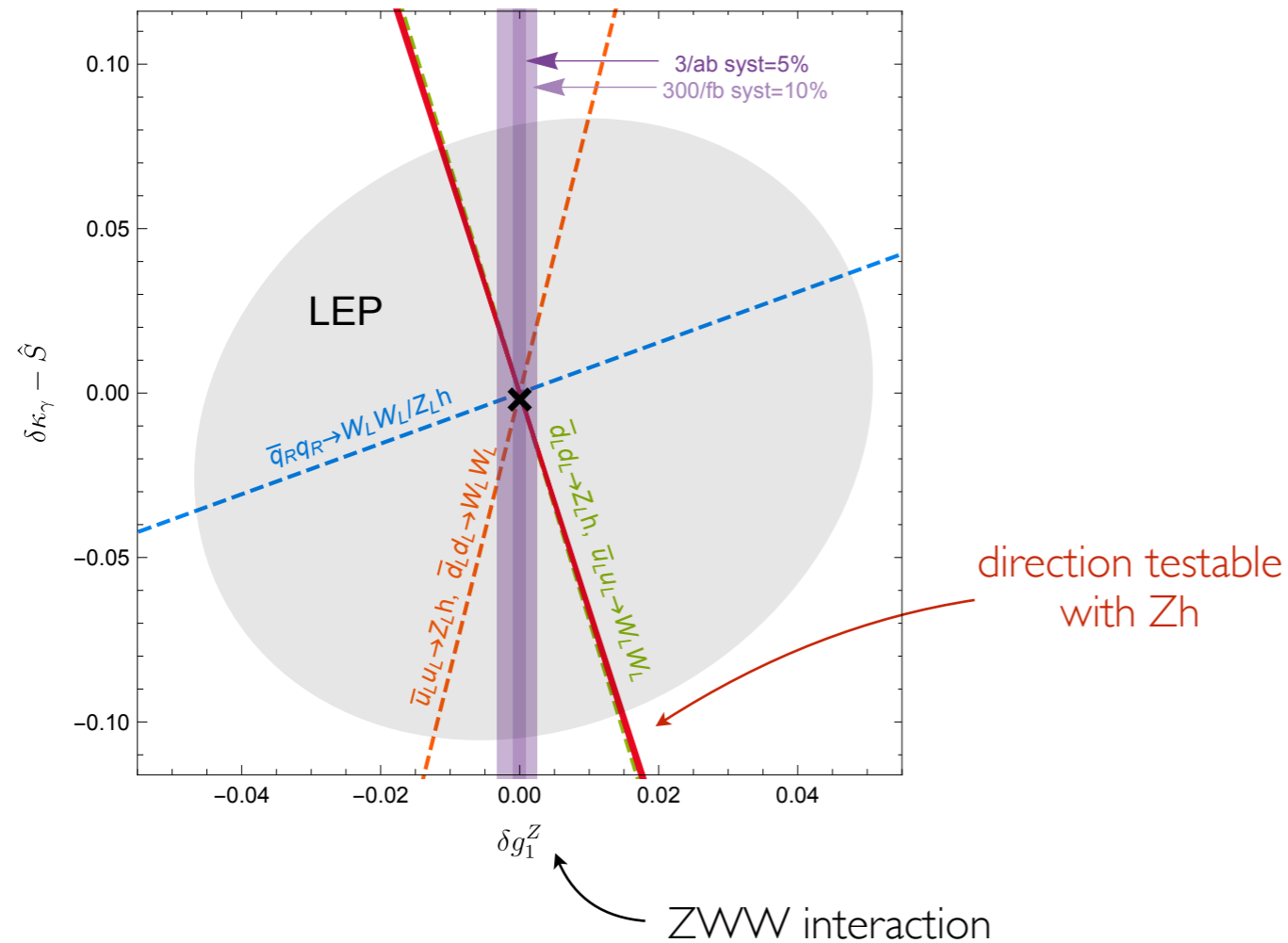
Two main **directions for HL-LHC:**

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

Backup

Beyond Higgs couplings

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

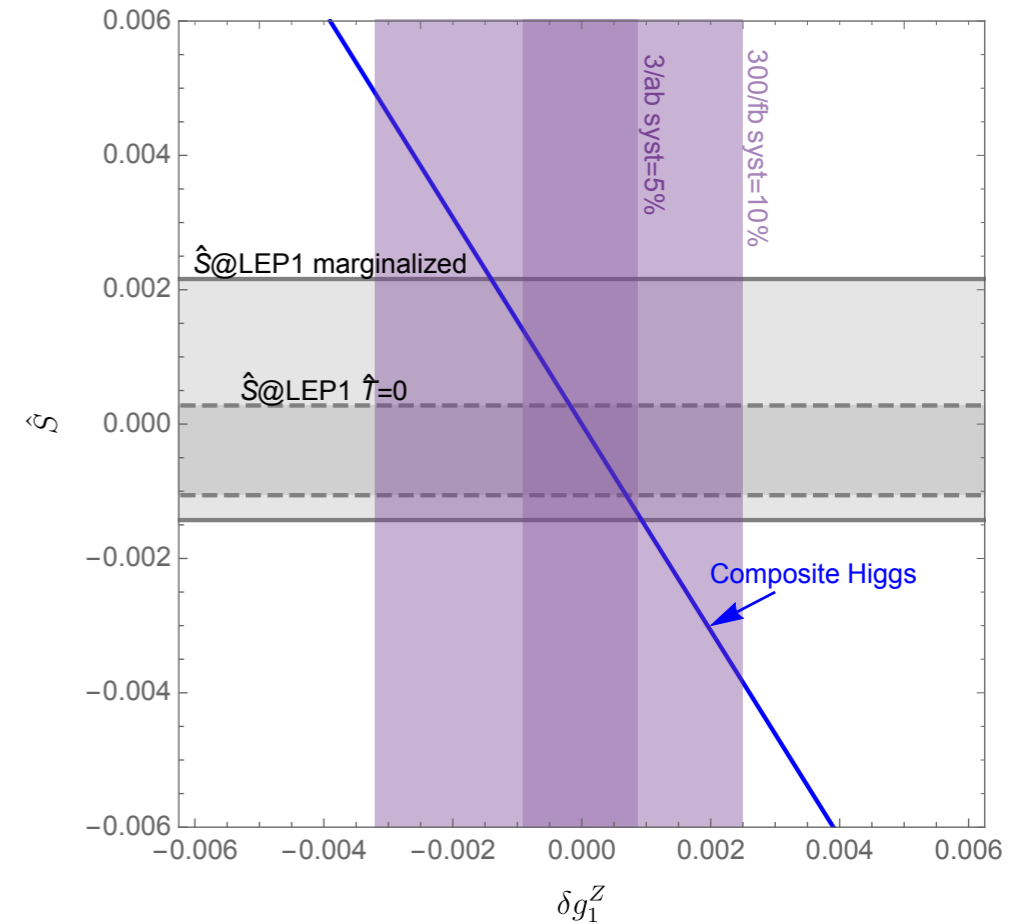
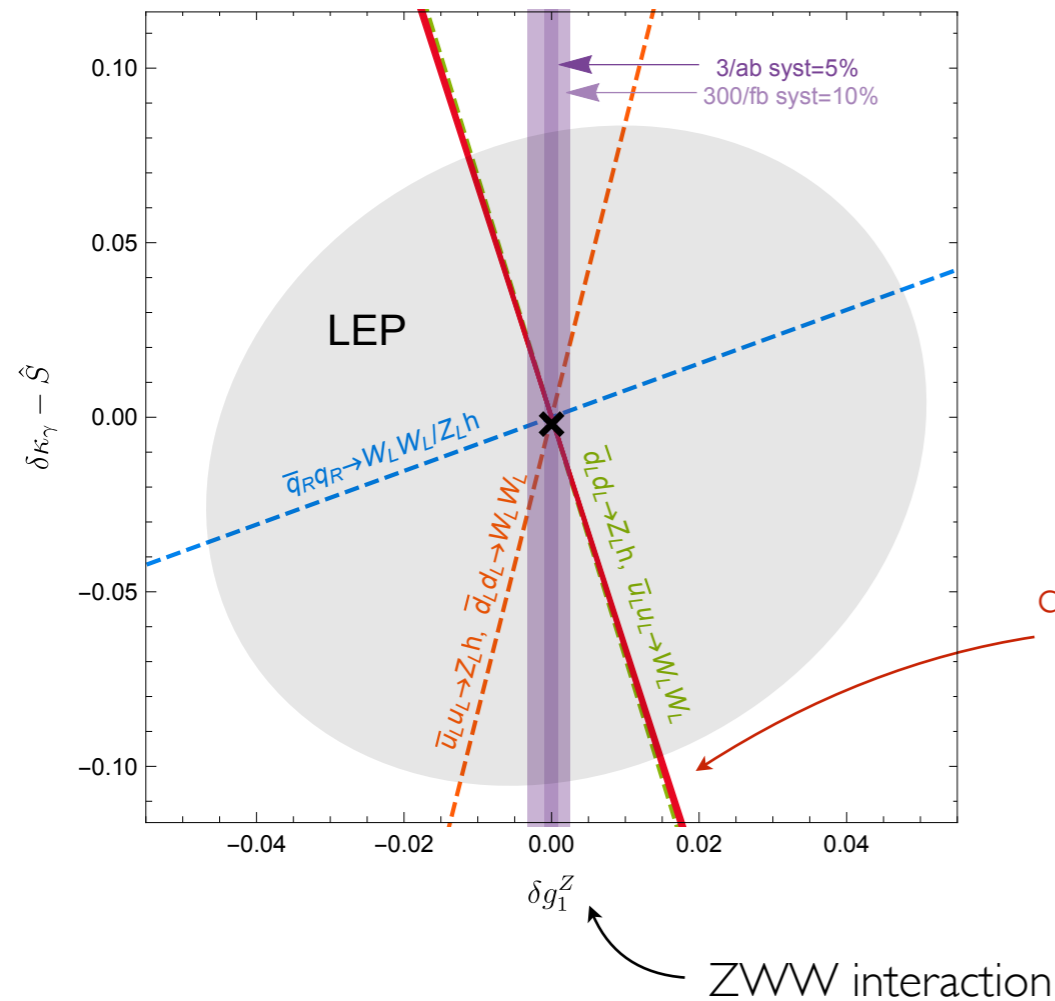


- ◆ better determination on trilinear gauge couplings (δg_1^Z) with respect to global fit at LEP

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
- ♦ LHC and LEP probe **independent operators**
 - correlations can exist in specific theories (eg. composite Higgs $\hat{S} \simeq -\delta g_1^Z$)