BSM interpretations of Higgs measurements

20th Workshop of the LHC Higgs Working Group at CERN

November 13th 2023

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Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

The SM Higgs sector

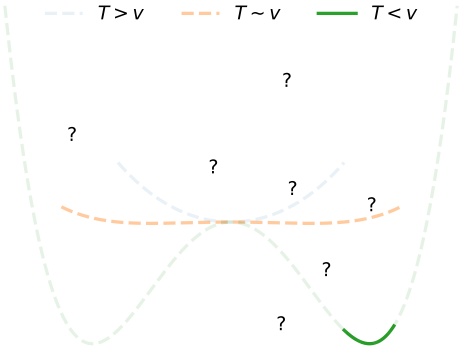
Minimal parametrization of EW symmetry breaking

Predictions:

→ One fundamental scalar particle

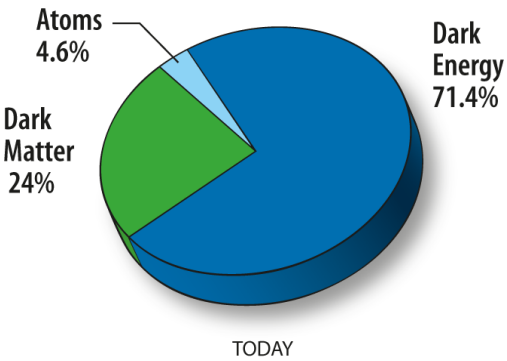
→ Couplings $\sim m_f$ or m_V^2

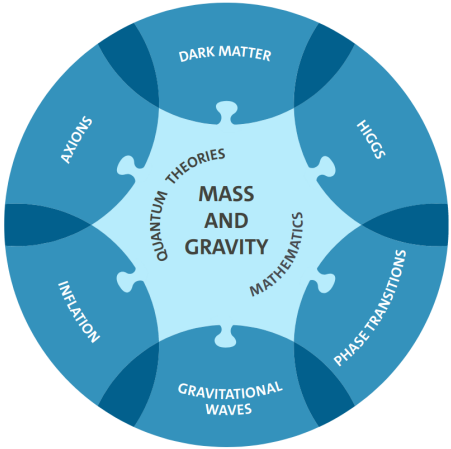
→ No CP violation in Higgs potential



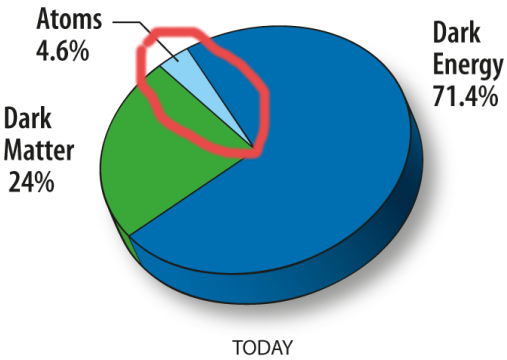
Any modifications from these predictions → BSM physics

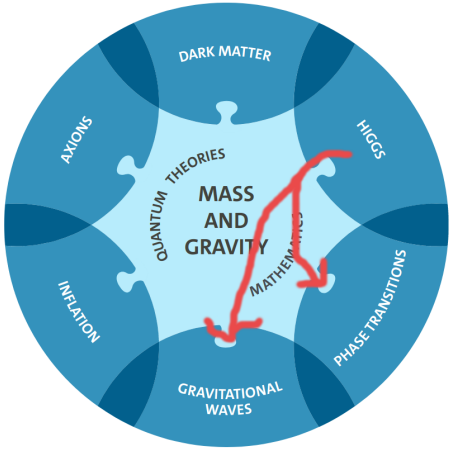
h_{125} as a probe for new physics





h_{125} as a probe for new physics





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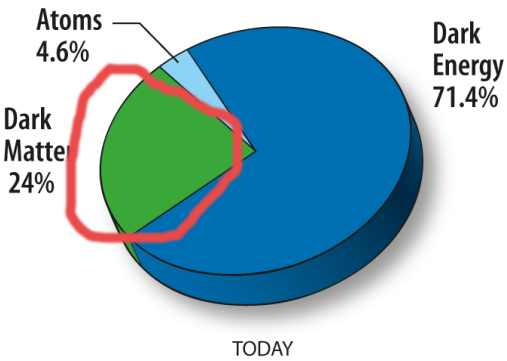
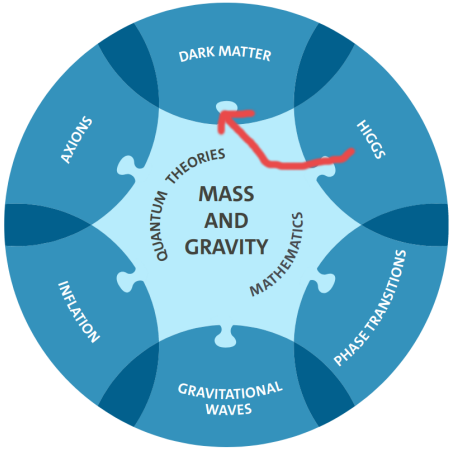
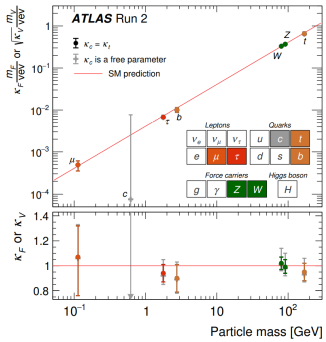




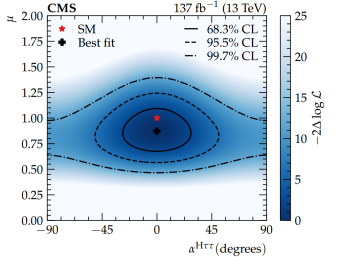
The LHC Run 2 legacy

Coupling strength?



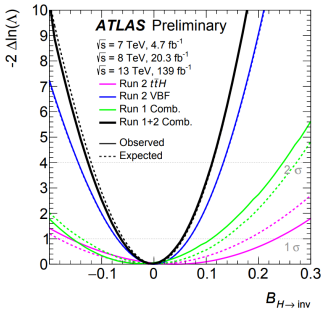
[ATLAS: 2207.00092]

CP properties?



[CMS: 2110.04836]

Coupling to hidden sectors?

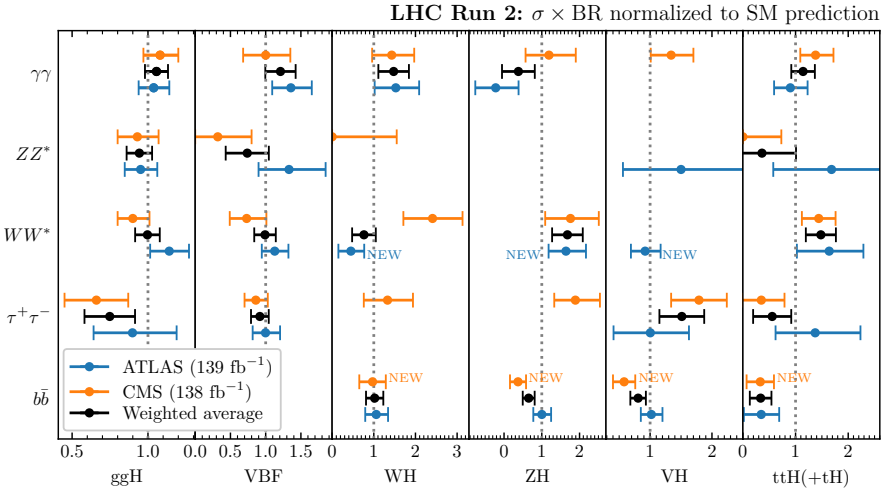


[ATLAS-CONF-2020-052]

"Nature operates in the shortest way possible." – Aristotle

"It is the simple hypotheses of which one must be most wary; because these are the ones that have the most chances of passing unnoticed." – Henri Poincaré

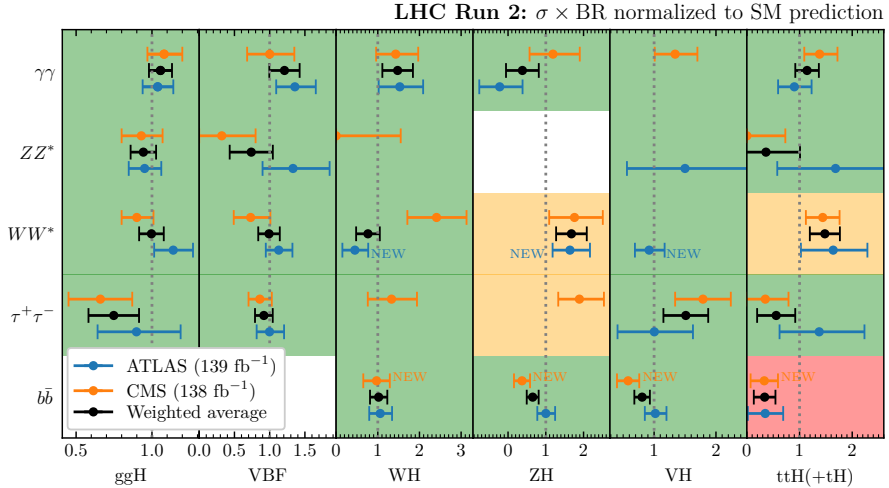
The LHC Run 2 legacy



New: After the **10 year anniversary papers**

[CMS: 2103.06956, 2204.12957, **2207.00043**, CMS-HIG-20-001, CMS-PAS-HIG-19-011; ATLAS: 2007.02873, **2207.00092**, ATLAS-CONF-2022-067]

The LHC Run 2 legacy



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h_{125} in UV-complete models

(So far) no clear pattern of coupling modifications of h_{125} pointing towards a specific BSM theory
$\Rightarrow$ A BSM interpretation is typically as good as a SM interpretation (maybe not?*)

However: Still large uncertainties that leave room for new physics

Higgs portal to hidden sectors: Constraining $\mathrm{BR}_{\mathrm{inv}}$ with global fits and direct searches
Based on [TB, M. Pierre: 2208.05505]

Odd sides of h_{125}: CP-violating couplings in 2HDMs under current exp. constraints
Based on [TB, D. Fontes, M. Mühlleitner, R. Santos, J. Romao, J. Silva: tbp]

h_{125} and the EW phase transition: Non-resonant Higgs-boson pair production
Based on [TB, S. Heinemeyer, J. No, O. Olea Romacho, G. Weiglein: 2208.14466]

* Slightly fermiphobic h_{125}: A case study in tth with $h \to b\bar{b}$
Can new physics modify only a specific channel?

For EFT interpretations, see e.g. talks by H. Bahl and A. Biekötter

HiggsTools

The new software package HiggsTools incorporates HiggsBounds and HiggsSignals

History of HiggsBounds and HiggsSignals

Former members: Philip Bechtle, Oliver Brein, Karina E. Williams, Oscar Stal, Tim Stefaniak, Daniel Dercks, Tobias Klingl, Jonas Wittbrodt

HiggsBounds confronts models with cross-section limits from collider searches

- 02/2009, v.1 LEP and Tevatron limits
- 08/2010, v.2 Added support for charged scalars
- 05/2011, v.3 LHC 7 TeV limits included
- 05/2013, v.4 LHC 8 TeV limits included
- 03/2017, v.5 LHC 13 TeV limits included
- 10/2022 Incorporation in HT

HiggsSignals confronts models with cross-section and mass measurements of h_{125}

- 05/2013, v.1 Tevatron and LHC 7/8 TeV data
- 03/2017, v.2 LHC 13 TeV data included
- 10/2022 Incorporation in HT

HiggsSignals

Karlsruher Institut für Technologie

Is my BSM theory compatible with the cross section measurements of h_{125}?
$\rightarrow$ Use `HiggsSignals` to perform global a χ^2-fit

$$\chi^2 = (\mu - \hat{\mu})^T \left[\Delta^T_{\text{obs}} \text{Corr}_{\text{obs}} \Delta_{\text{obs}} + \Delta^T_{\text{theo}} \text{Corr}_{\text{theo}} \Delta_{\text{theo}}\right]^{-1} (\mu - \hat{\mu})$$

Dataset: `gitlab.com/higgsbounds/hsdataset`

- Currently 22 measurements: 11 from ATLAS, 9 from CMS, 2 combinations from Run 1
- Mass measurement (PDG), total cross sections, STXS measurements
- NEW: many full Run 2 results, measurement of τ-Yukawa CP phase

Manual: [H. Bahl, TB, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein, J. Wittbrodt: 2210.09332]

Limits on $\mathrm{BR}_{\mathrm{inv}}$ from global fit

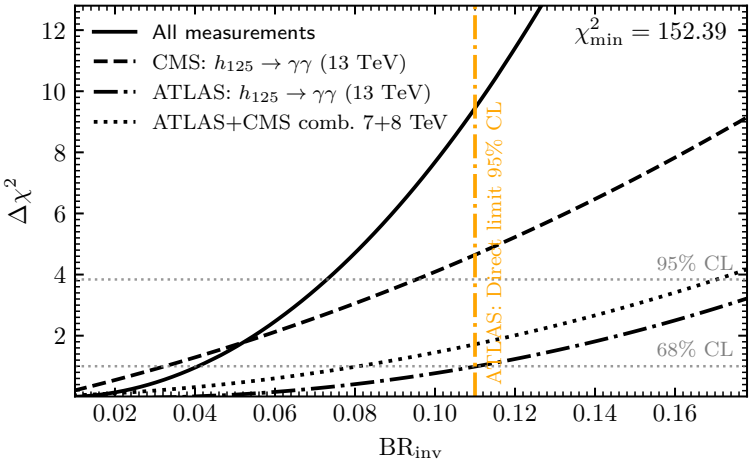
An update of
[TB, M. Pierre: 2208.05505]

Only BSM effect:
$\mathrm{BR}(h_{125} \to \mathrm{inv})$

Indirect limit at 95% CL:

$$\mathrm{BR}_{\mathbf{inv}} < \mathbf{7.3}\%$$

CMS meas. of $h_{125} \to \gamma\gamma$ alone gives rise to an indirect limit stronger than the direct limit on $\mathrm{BR}_{\mathrm{inv}}$ [2103.06956]



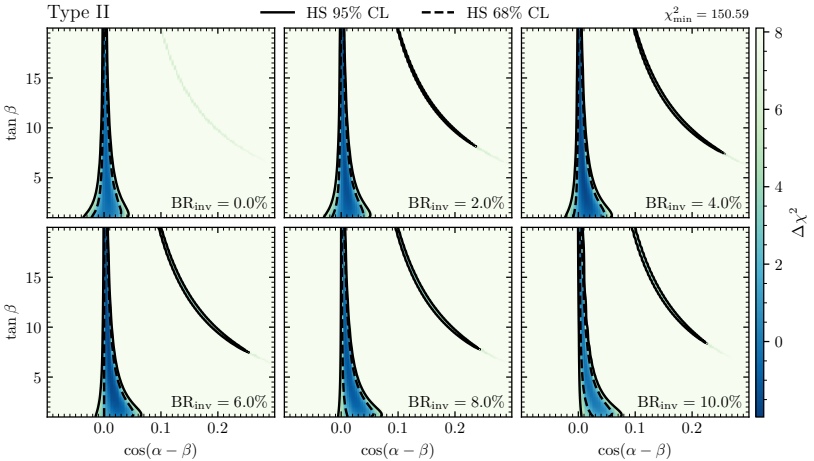
Direct limit: [ATLAS-CONF-2020-052]

$\mathrm{BR}_{\mathrm{inv}}$ and a 2nd Higgs doublet

An update of
[TB, M. Pierre: 2208.05505]

Common LHC benchmark scenario: 2HDM Type II

Complementarity of direct and indirect constrains on $\mathrm{BR}_{\mathrm{inv}}$ in models with non-minimal Higgs sectors



$\cos(\alpha-\beta) = 0$: Alignment Limit

CP-violating couplings

The matter-antimatter asymmetry can be generated dynamically in the early Universe via **EW baryogenesis**

→ requires additional sources of **CP violation**

But: Electric Dipole Moments (EDMs)

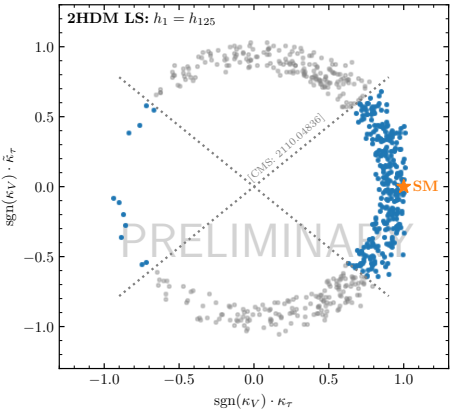
$$d_f \sim \sin\theta_{\rm CP} \frac{m_f}{\rm MeV} \left(\frac{\rm TeV}{M}\right)^2 \cdot 10^{-26}\ e \cdot {\rm cm}$$

[D. Morrissey, M. Ramsey-Musolf: 1206.2942]

$$d_e^{\rm obs} < 4.1 \cdot 10^{-30}\ e \cdot {\rm cm}$$ [JILA: 2212.11841]

2HDM: In fine-tuned region of parameter space the LHC is able to exclude sizable CP-odd coupling components allowed by eEDM limits

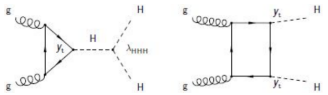
CP-violation in $h_{125} \to \tau^+\tau^-$ decays



[TB, D. Fontes, M. Mühlleitner, J. Romao, R. Santos, J. Silva, to be published]

Non-res. h_{125} pair production

EW baryogenesis requires a 1st-order EW PT
→ **Enhanced self-coupling** of h_{125} (typically)
→ Primoridal stochastic **GW background**

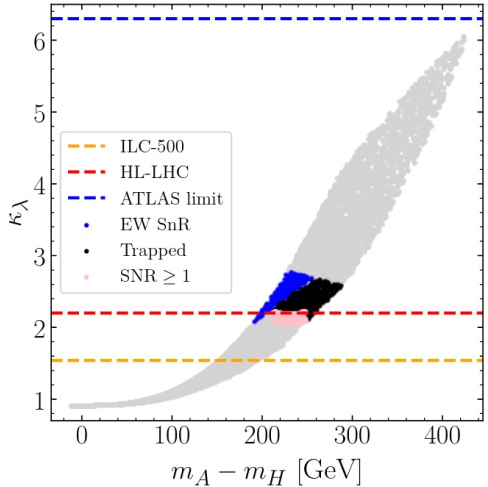


$$\kappa_\lambda = \frac{(\lambda_{hhh}^{\rm 2HDM})^{(1)}}{(\lambda_{hhh}^{\rm SM})^{(0)}}$$

Expectations at LISA will be shaped by (HL-)LHC results

Potentially detectable GW signals in **2HDM**:

$\kappa_\lambda \sim 2 \sim$ exp. HL-LHC 95% CL limits

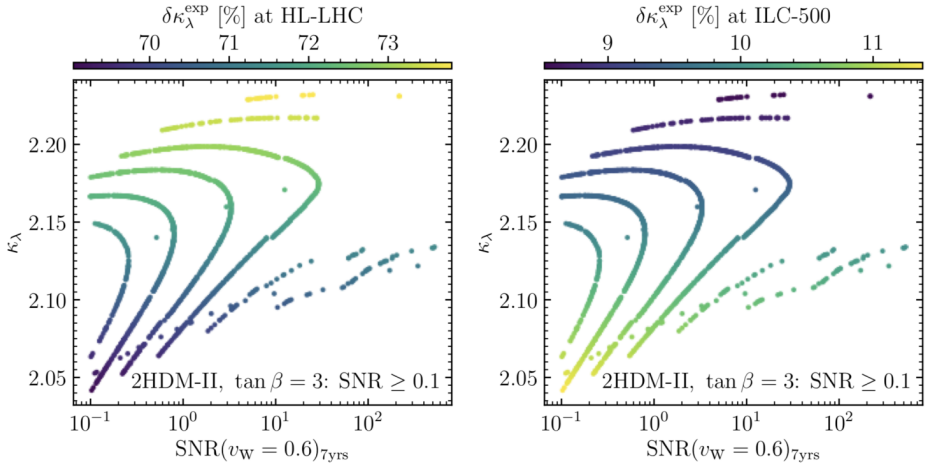


[TB, S. Heinemeyer, O. Olea Romacho, J. No, G. Weiglein: 2208.14466]

Non-res. h_{125} pair production

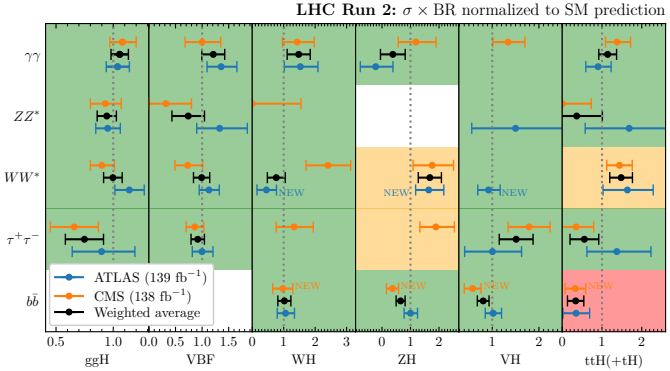
Interplay between **LHC and GW astronomy (LISA)**

For $\kappa_\lambda = 1 : \delta\kappa_\lambda^{\rm exp} = 60\%/27\%$ at HL-LHC/ILC-500



[TB, S. Heinemeyer, O. Olea Romacho, J. No, G. Weiglein: 2208.14466]

Discrepancies in ttH(bb)



Full Run 2 results:

ATLAS: $\mu_{ttH}^{b\bar{b}} = 0.35^{+0.36}_{-0.34}$

[ATLAS: 2111.06712]

CMS: $\mu_{ttH}^{b\bar{b}} = 0.33^{+0.26}_{-0.26}$

[CMS-PAS-HIG-19-011]

Disclaimer: I don't want to put forward that this is BSM physics.

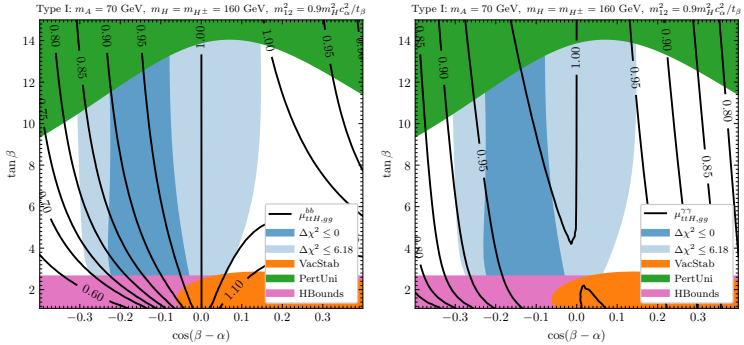
But one can raise a **general question**: Are there models in which you could realize modified signal rates of h_{125} only in one or a small number of channels?

Discrepancies in ttH(bb)

The **2HDM type I** can realize $\kappa_f < 1$ with $\kappa_V \approx 1$ for $\cos(\beta - \alpha) < 0$.

$\rightarrow$ Strong suppression in $\mu_{ttH}^{bb} \sim \kappa_f^4$ while $\mu_{ggH}^{\gamma\gamma, ZZ^*, WW^*}$ stay close to SM prediction

But large deviations from the alignment limit are strongly constrained if there is a sizable mass gap between h_{125} and the BSM scalars $\rightarrow$ Need to hide light BSM scalars



Possible in 2HDM:

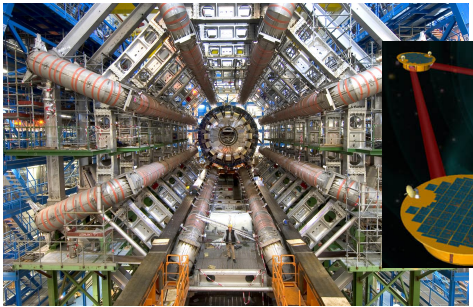
$$\mu_{ttH}^{b\bar{b}} \approx 0.7$$
$$\mu_{ggH}^{\gamma\gamma} \approx 0.9$$

Suppression in "fermionic" channels could be a hint for the 2HDM type I, but $\mu_{ttH}^{b\bar{b}} \approx 0.3 \pm 0.3$ is out of reach.

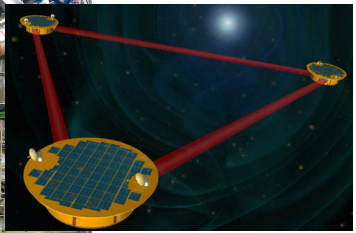
The end

LHC Higgs measurements provide vital information about possible new physics and shape expectations for future experiments

LHC



LISA



Higgs factory (?)

Thanks!