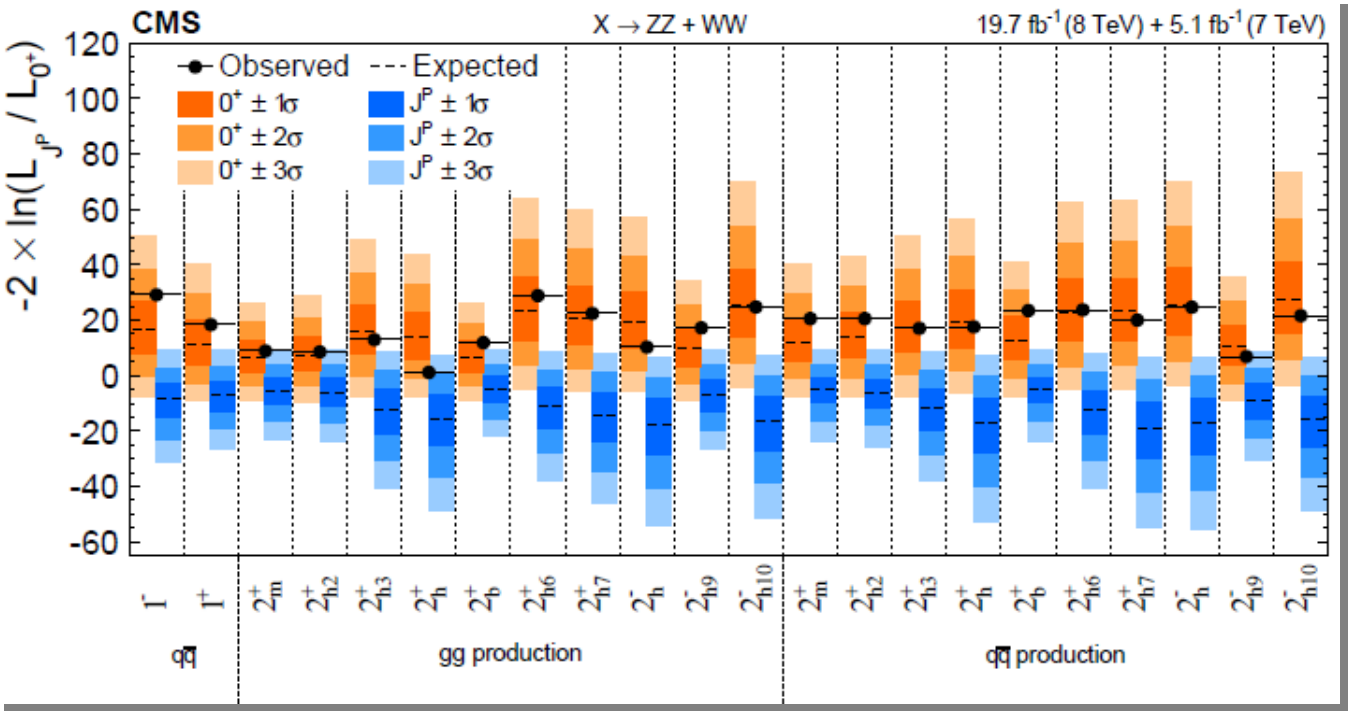
What has the Higgs taught us?

Stefania Gori
Perimeter Institute for Theoretical Physics

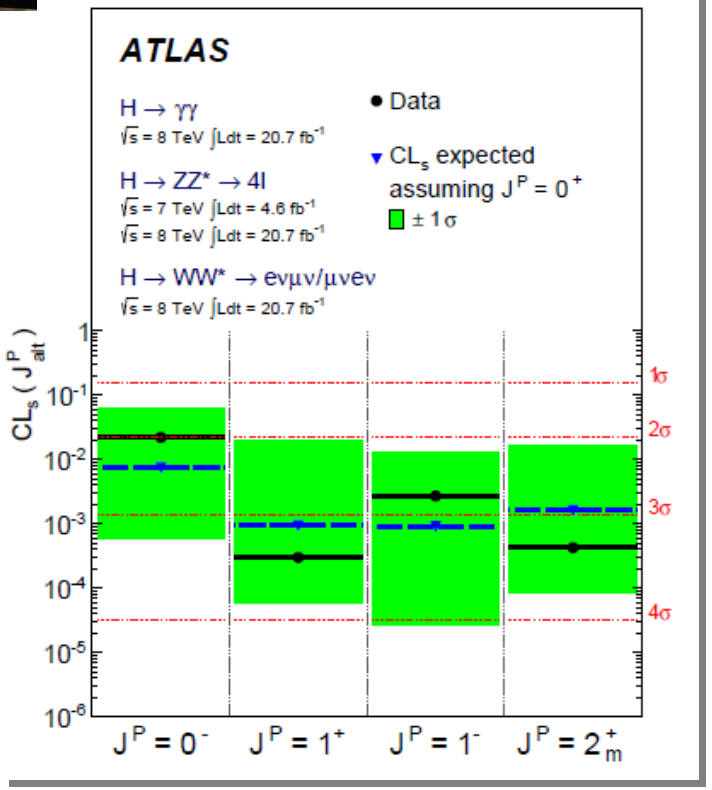
LHCP 2015 conference

St Petersburg,
September 1st 2015

It´s a Higgs!



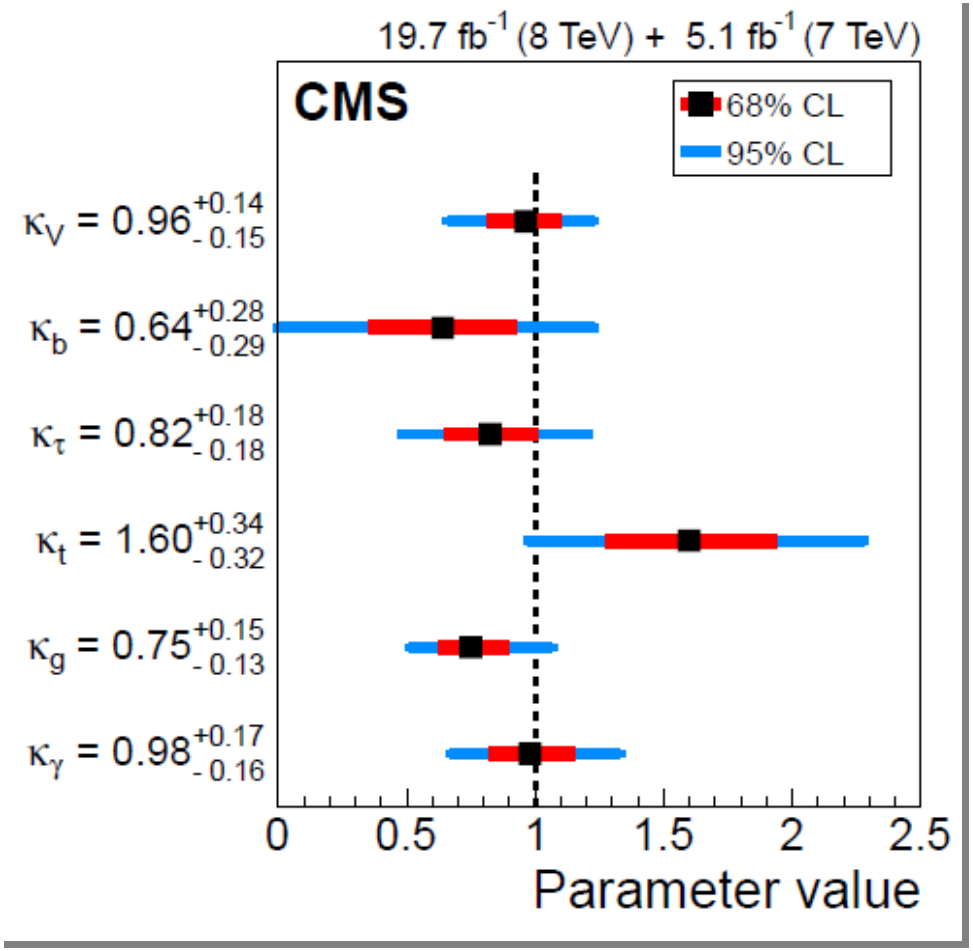
1411.3441



1307.1432

CERN-PH-EP-2015-114

It´s a SM-like Higgs



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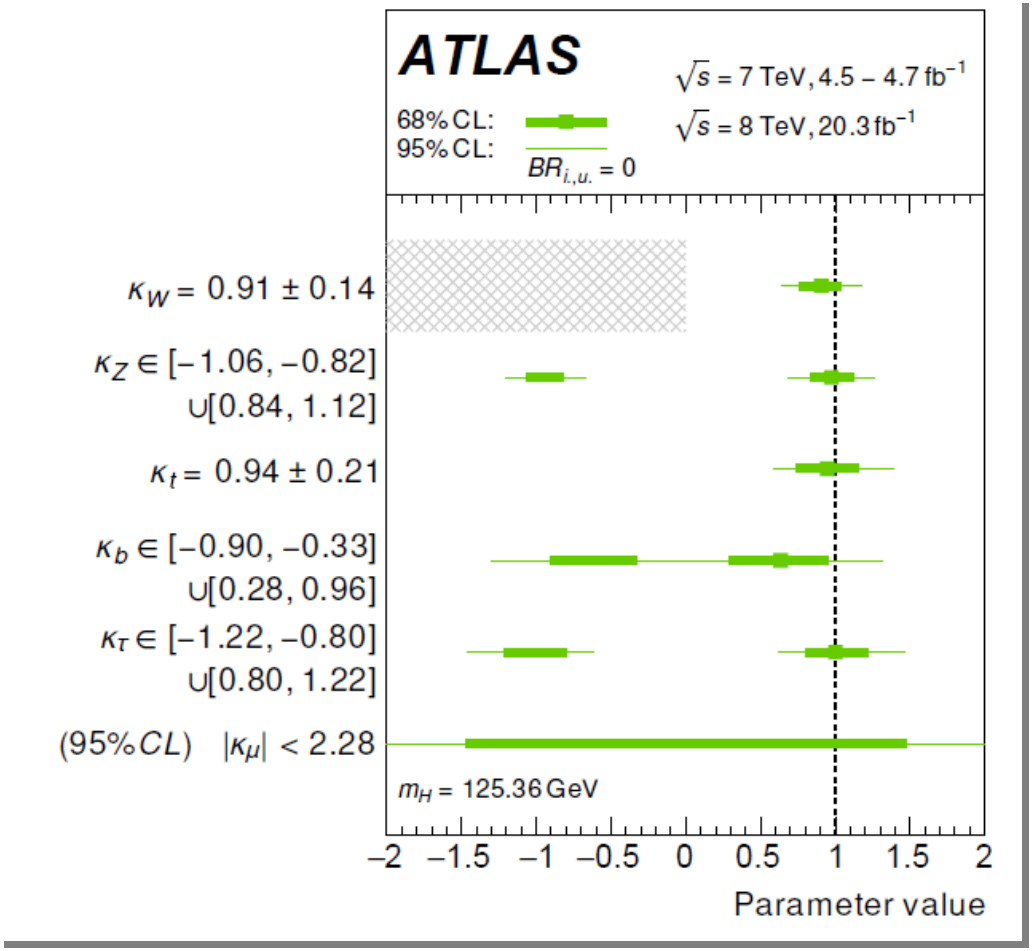
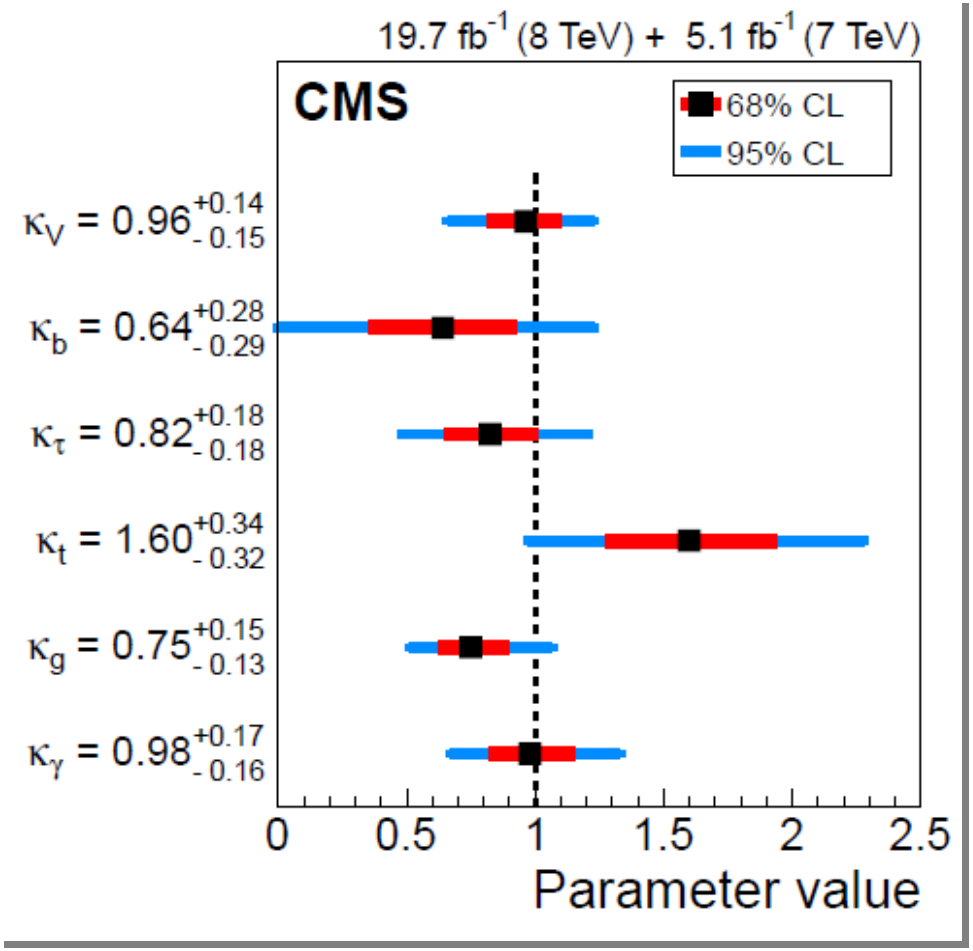


ATLAS, 1507.04548

It´s a SM-like Higgs



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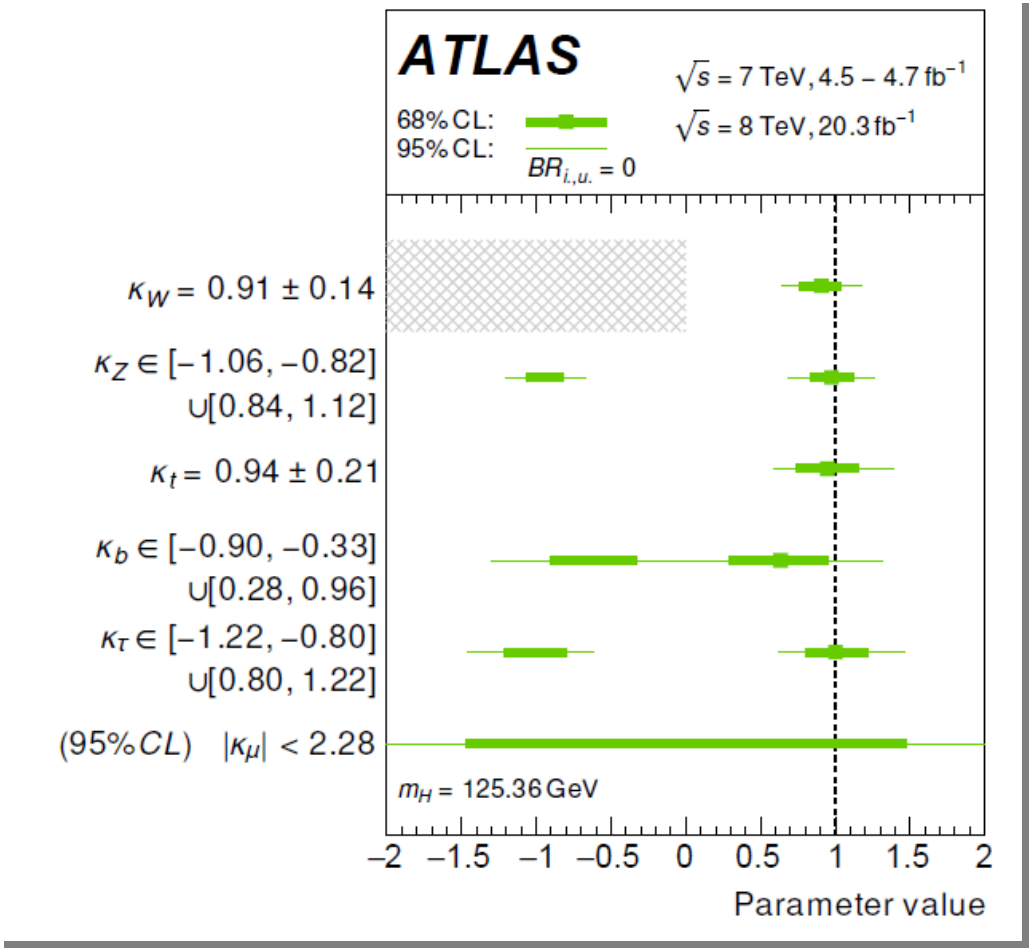

ATLAS, 1507.04548

Lesson # 1

Mechanism to give mass to (massive) quarks and gauge bosons

The Higgs and the big questions

Naturalness

Is the SM vacuum stable?

Dark Matter & Dark sectors

Is the SM electro-weak theory self-consistent?

Quarks and leptons beyond the SM?

Flavor puzzle

Questions for the Standard Model

Questions for beyond the Standard Model

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Questions for beyond the Standard Model

The Higgs mass in the Standard Model

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

Nucl. Phys. B 106, 292 (1976)

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

We need to measure the Higgs mass!

Vacuum structure of the Universe

The Higgs mass was the last free parameter of SM to be measured

Why is it so important? What do we learn?

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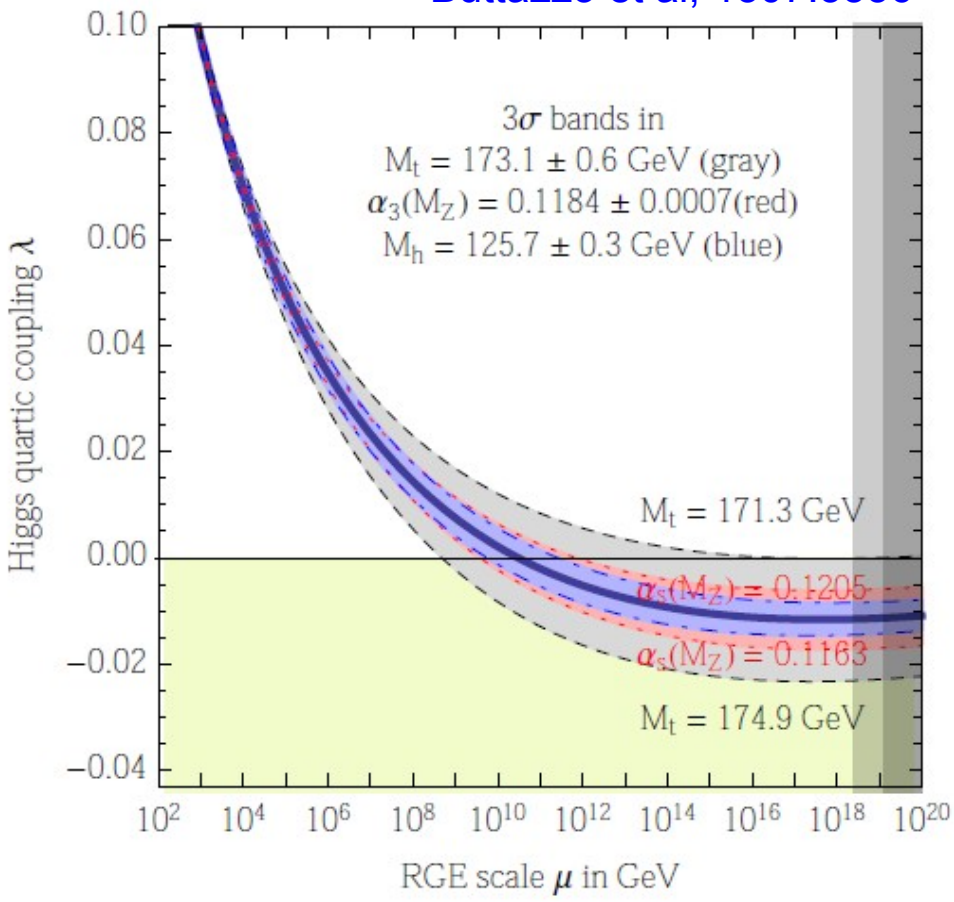
Why is it so important? What do we learn?

If the SM is the full story...

Buttazzo et al, 1307.3536



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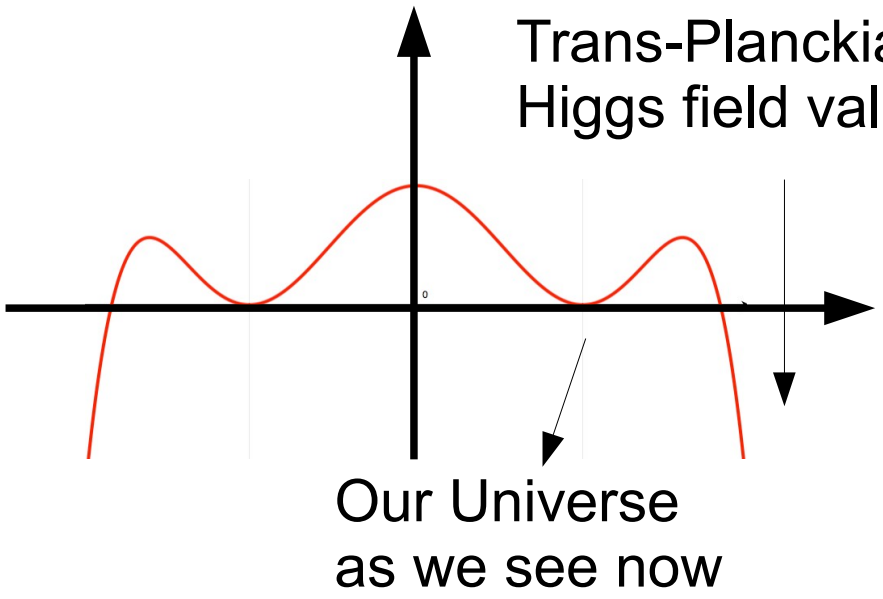

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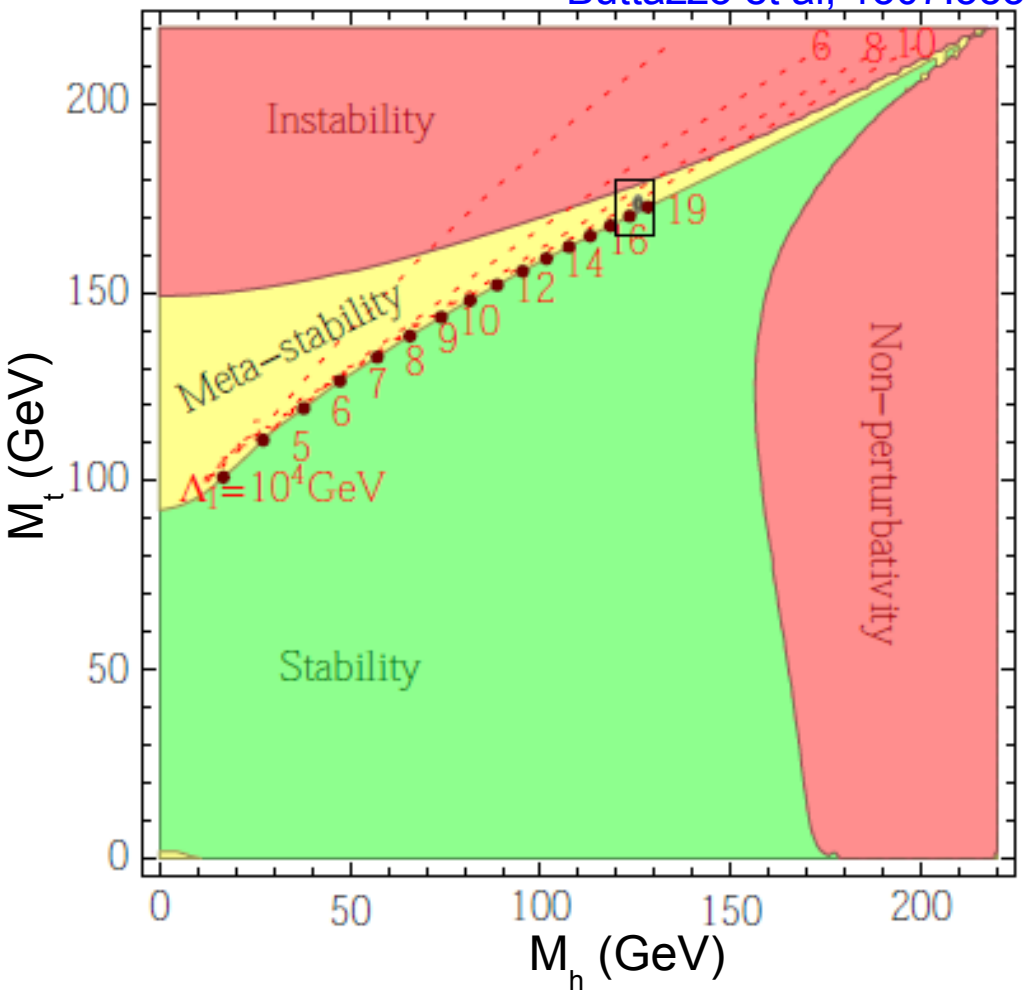


Stability condition:

$$M_h > (129.6 \pm 1.5)\,\mathrm{GeV}$$

Self-consistency of the EW-SM theory

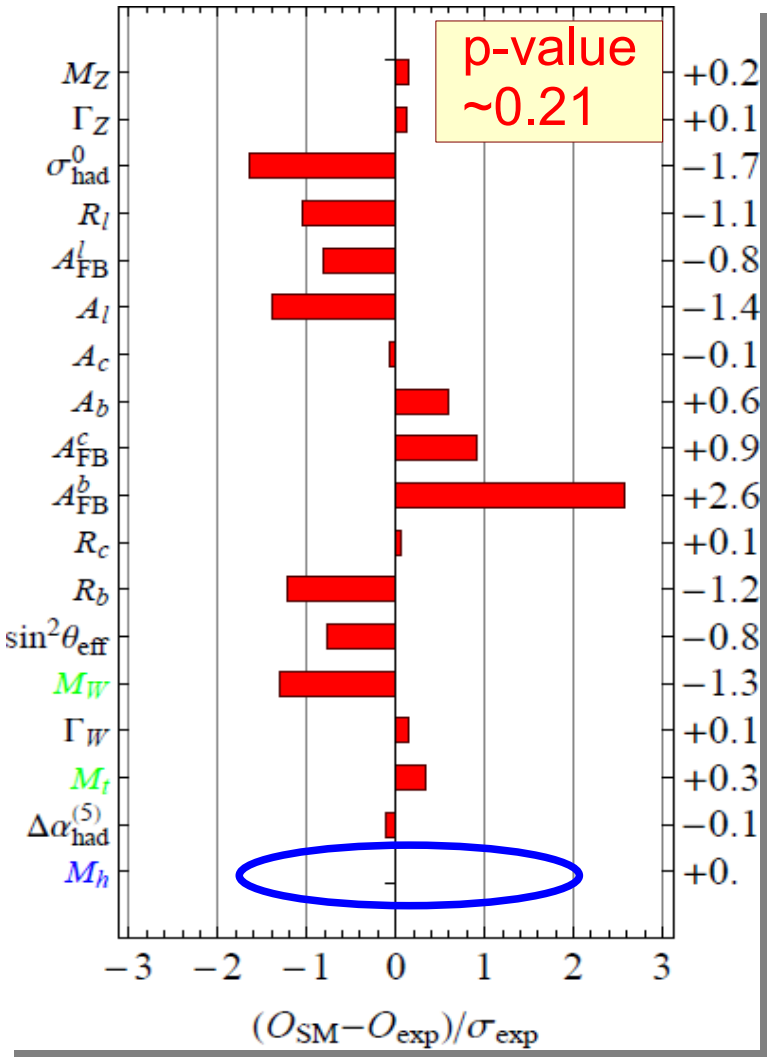
The Higgs mass was the last free parameter of SM to be measured

Why is it so important? What do we learn?

If the Higgs is the one of the SM...

For the first time we have the measurement of a self-consistent electro-weak sector

If e.g. M_h = 300 GeV ➡ $p_{value} \sim 3 \times 10^{-5}$!



Update from Batell, SG, Wang, 1209.6382

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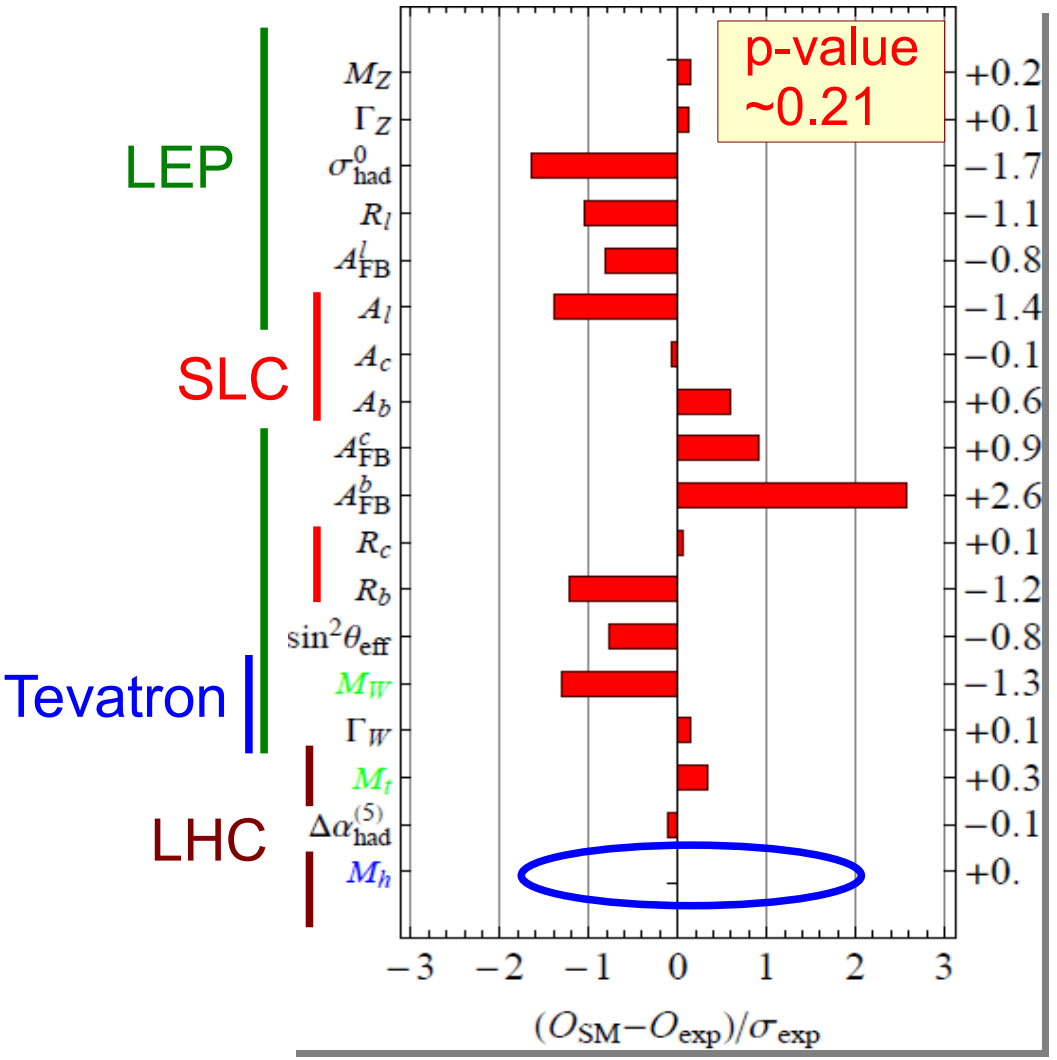
Result of decades of experimental & theory efforts



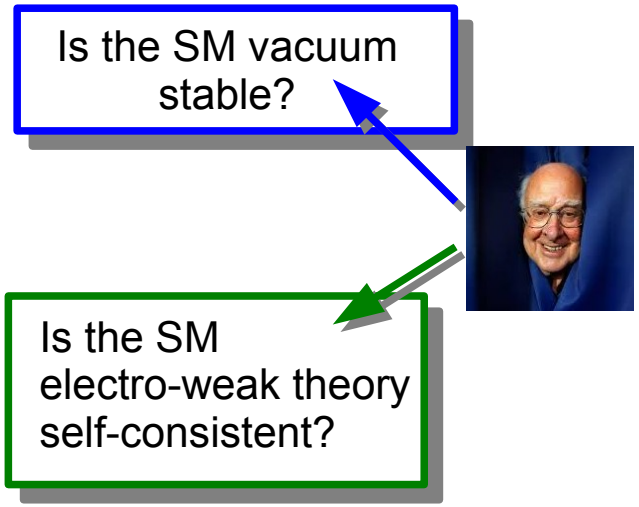
Update from Batell, SG, Wang, 1209.6382

Lesson #2

The discovery of the Higgs does not imply univocally the presence of physics beyond the Standard Model.

Nevertheless

the Higgs is an amazing tool to discover New Physics...



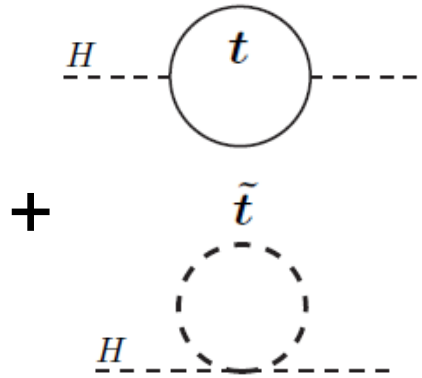
Naturalness, SUSY

Leading theoretical principle of the last decades

The SM does not seem the full story since $m_h^2 \sim \mu^2 + c\,\Lambda^2$

- This principle has lead us believe in TeV-scale SUSY

$$m_h^2 = \mu^2 + m_{\rm SUSY}^2 \left(\frac{y_t^2}{8\pi^2} \log\left(\frac{\Lambda}{m_{\rm SUSY}} \right) + \cdots \right)$$



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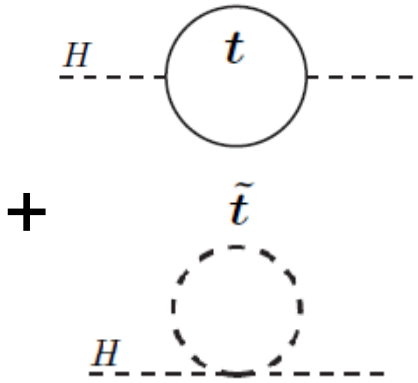

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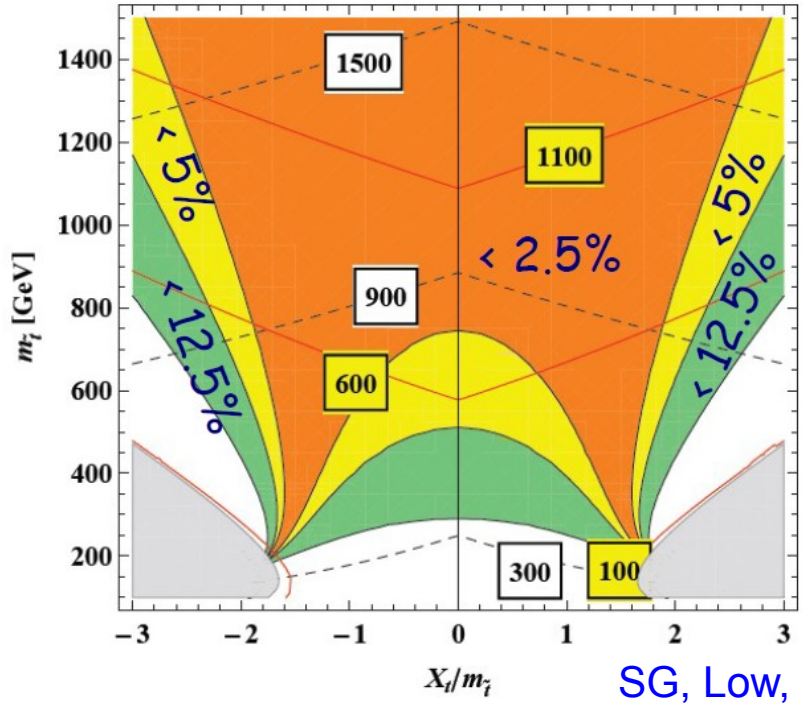
hgg coupling:



$$\mathcal{O}\left(\frac{v^2}{m_{\rm NP}^2}\right) \sim 5\%$$

SG, Low, 1307.0496

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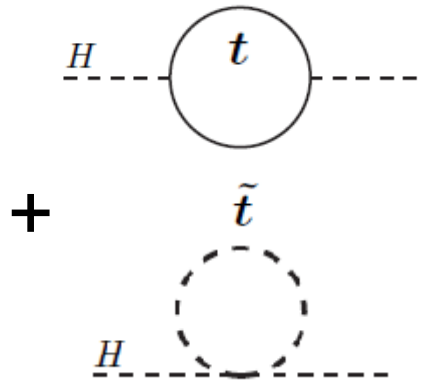

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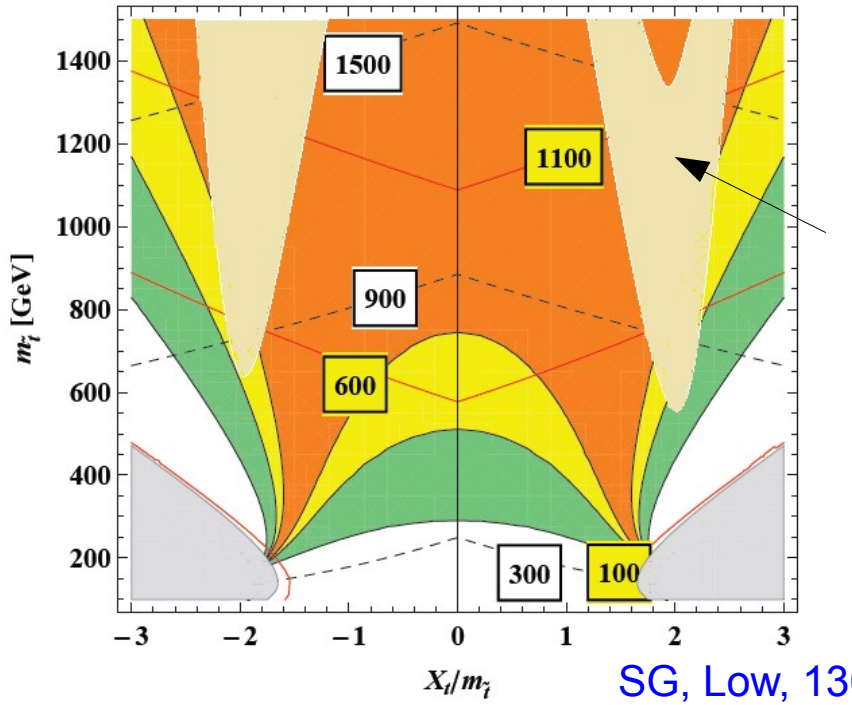


Higgs mass constraint

$$\mathcal{O}\left(\frac{v^2}{m_{\rm NP}^2}\right) \sim 5\%$$

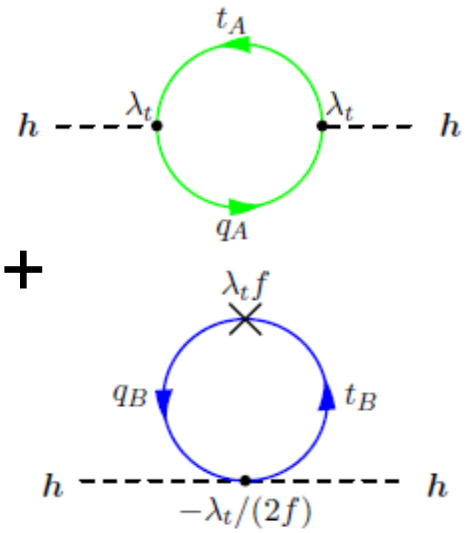
SG, Low, 1307.0496

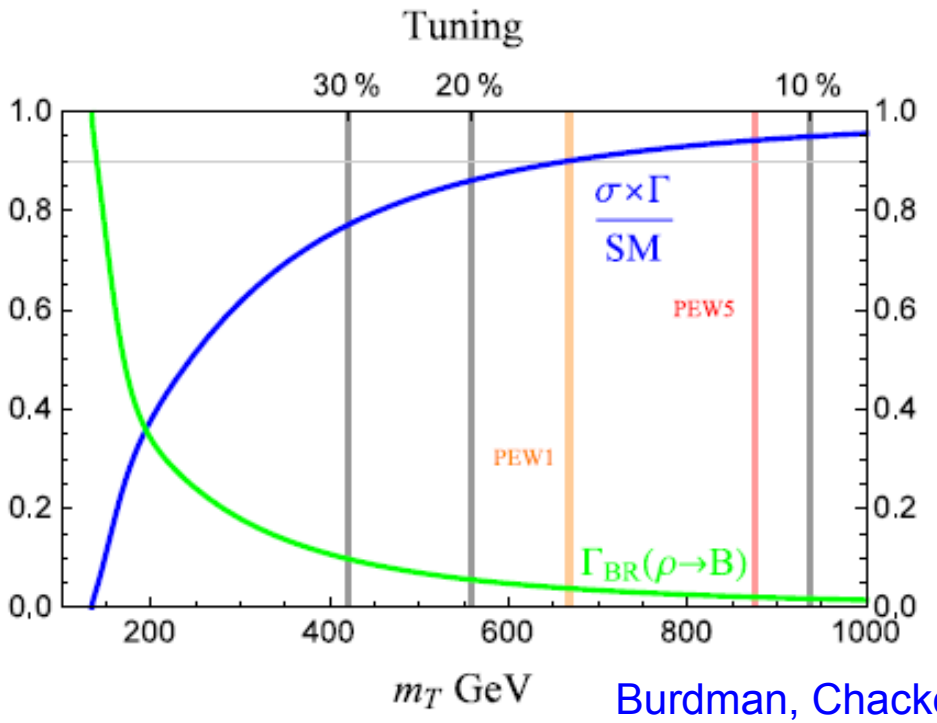
Naturalness, beyond SUSY

Leading theoretical principle of the last three decades

The SM does not seem the full story since $m_h^2 \sim \mu^2 + c\,\Lambda^2$

- Pretty general statement, valid also in theories of neutral naturalness: e.g. Twin Higgs models



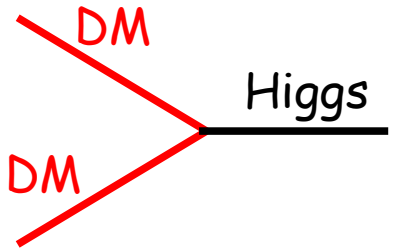


Burdman, Chacko, Harnik,
De Lima, Verhaaren, 1411.3310

Dark Matter

We know only a little about the nature of Dark Matter (DM)

- DM can thermalize thanks to its interactions with the Higgs



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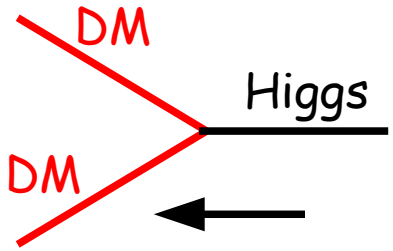

If DM is light, limits from searches for a Higgs decaying invisibly:

$$\mathrm{BR}(h \to \mathrm{inv}) \lesssim$$

VBF: 0.57 (0.40) CMS-PAS-HIG-14-038
Zh,Z⟶ll: 0.75 (0.62) ATLAS, 1402.3244
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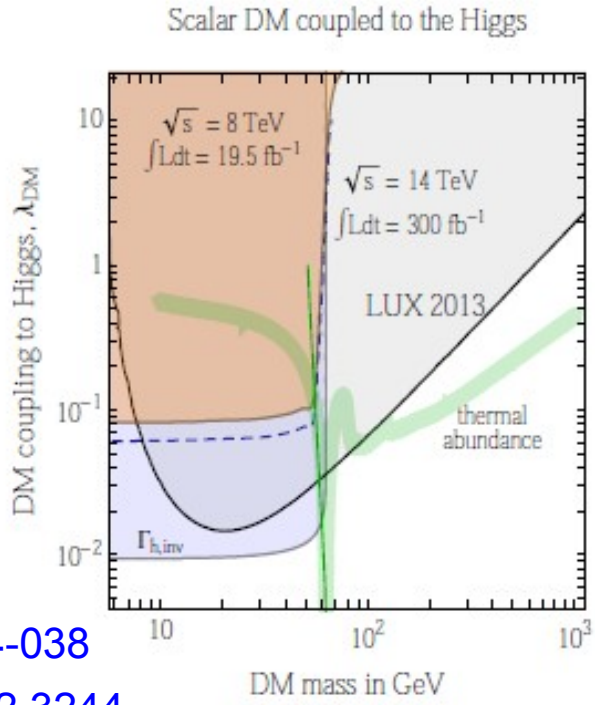
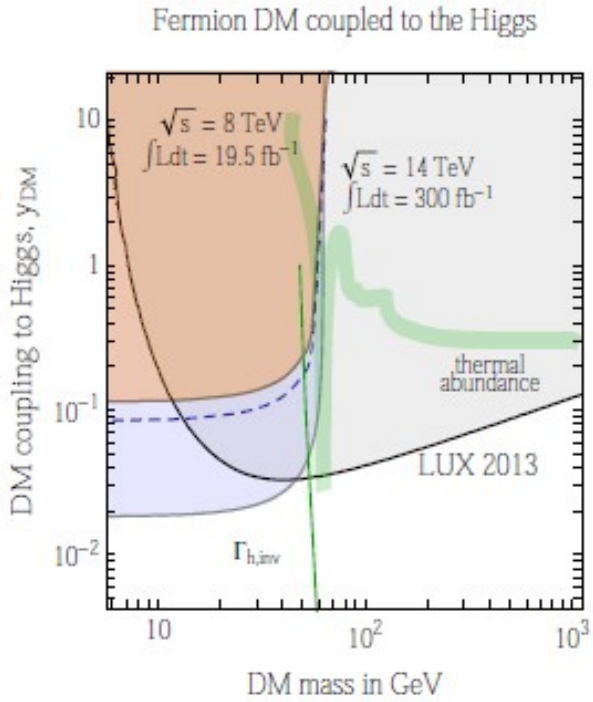
and also bounds from Higgs coupling fits





De Simone, Giudice, Strumia,1402.6287

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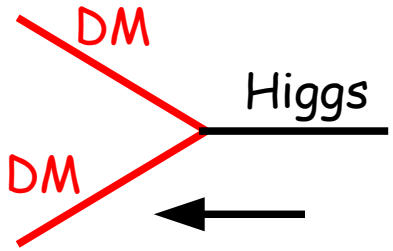

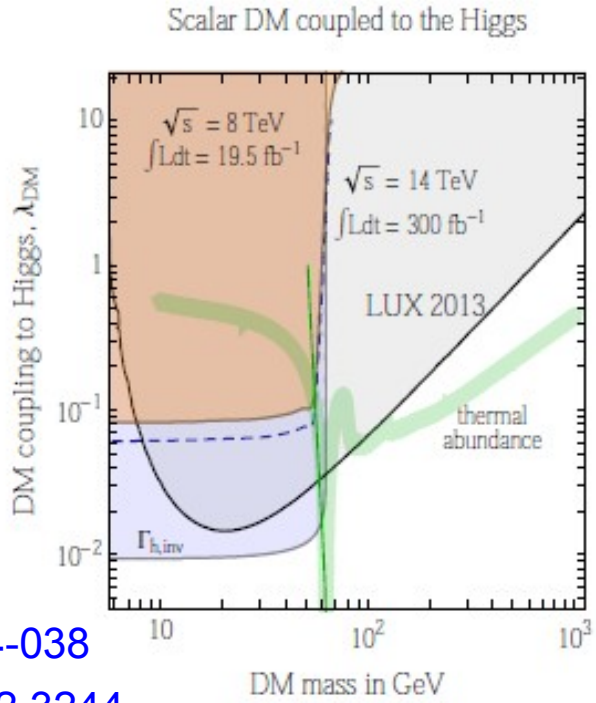

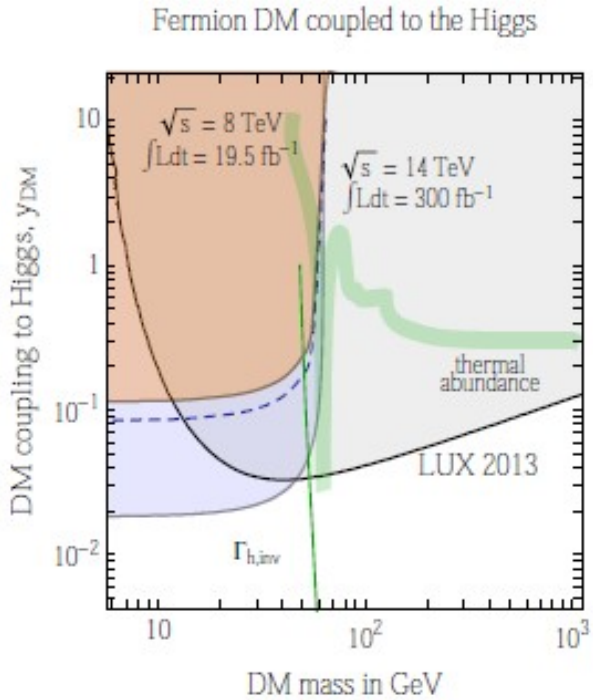

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Lesson #3

In minimal models, if the Higgs is the particle responsible of DM annihilation, then DM cannot be too light

Dark Sectors

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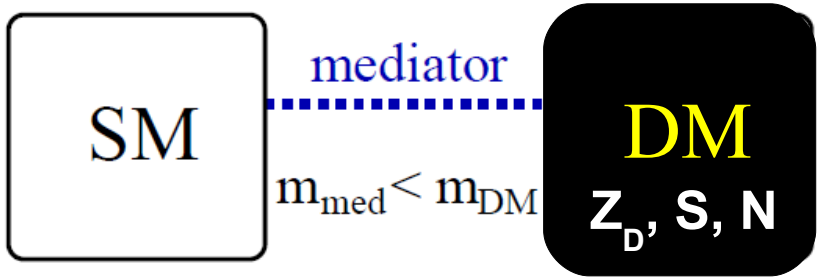

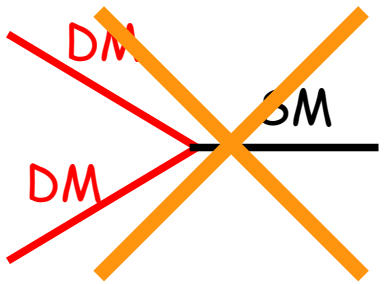

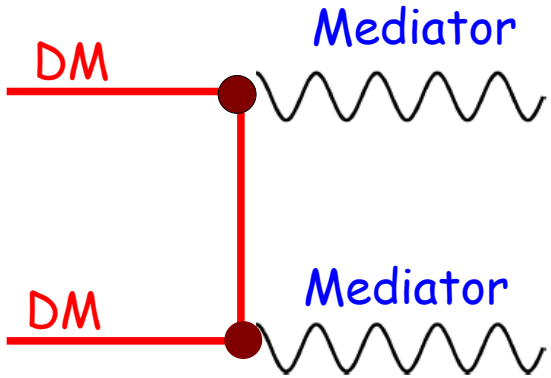

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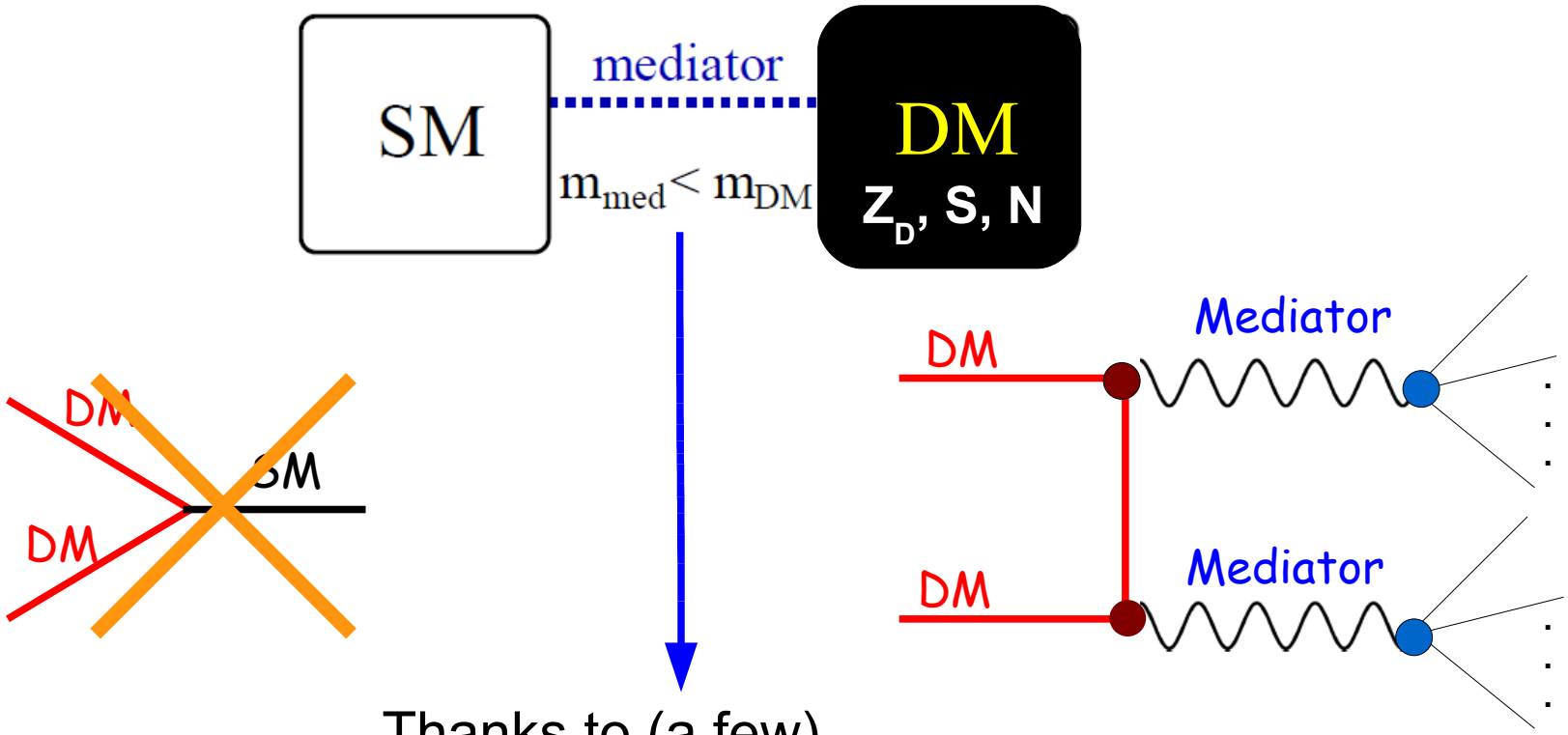

Thanks to (a few)
renormalizable "portals"

$B_{\mu\nu}F'_{\mu\nu}$, $|H|^2|S|^2$, HLN

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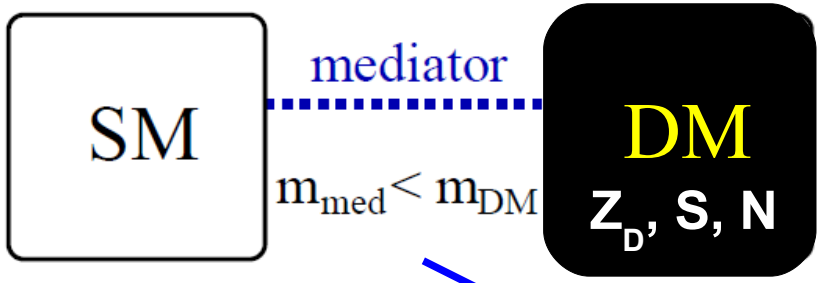


Survey paper Curtin et.al. 1312.4992

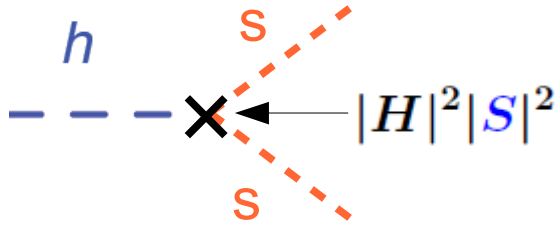
$B_{\mu\nu}F'_{\mu\nu}$, $|H|^2|S|^2$, HLN

The role of the Higgs:

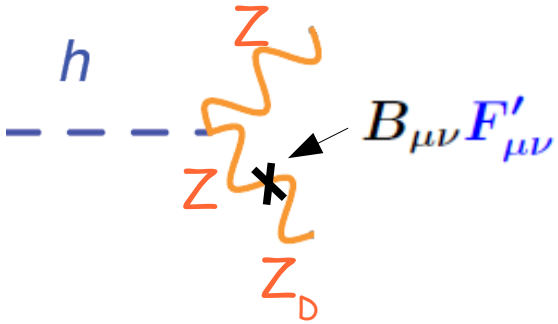
Probing these operators through "Exotic Higgs decays"

New signatures!

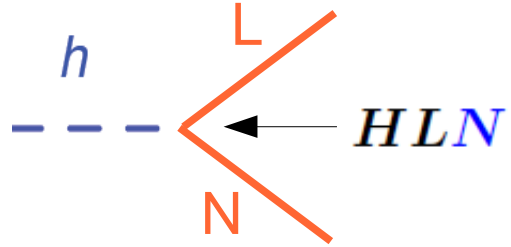
$h \to ss$



$h \to ZZ_D$

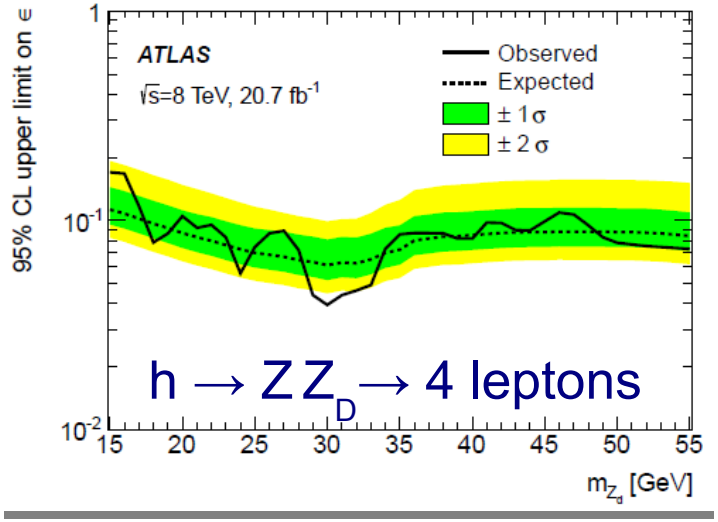


$h \to LN$

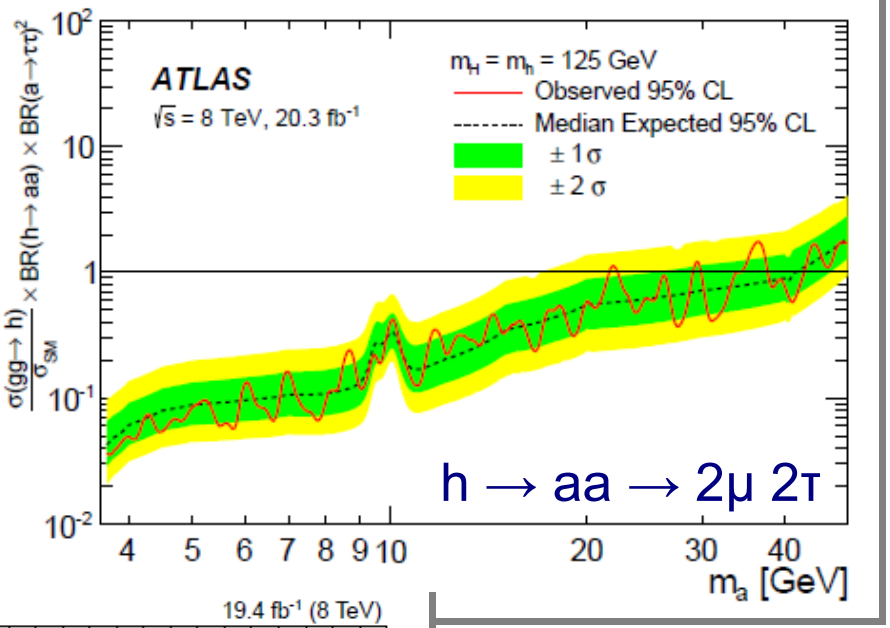


Dark Sectors: a few bounds from the Higgs

Some recent analyses...

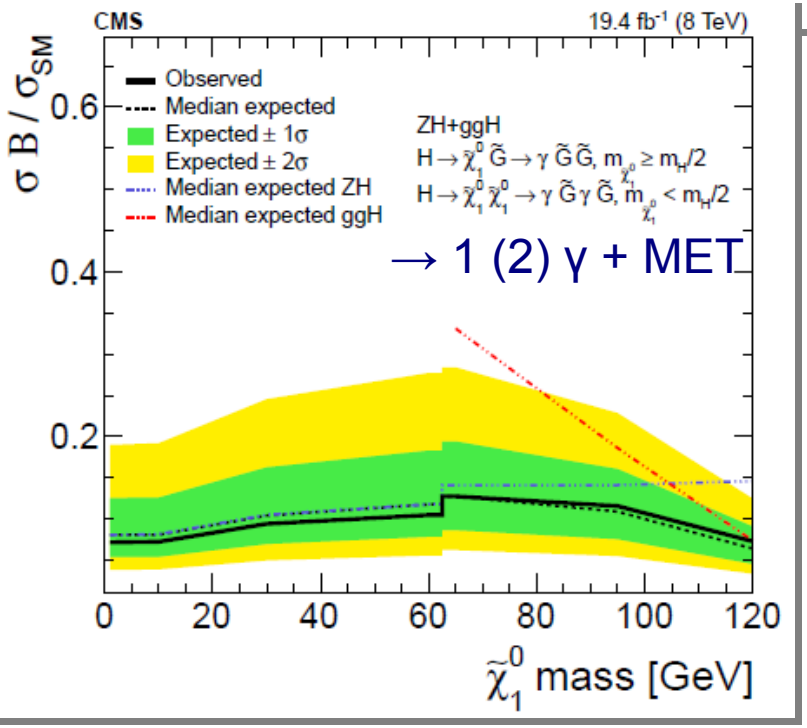


ATLAS-CONF-2015-003



ATLAS, 1505.01609

First limits on dark sectors from the LHC!



CMS, 1507.00359

Flavor Physics

1. SM flavor puzzle: - Are there 3 generations? If yes, why?
   - Why so large hierarchies between quark (and lepton) masses and mixing angles?

2. NP flavor puzzle: If NP is present at around the TeV scale, how can the theory be consistent with low energy measurements?

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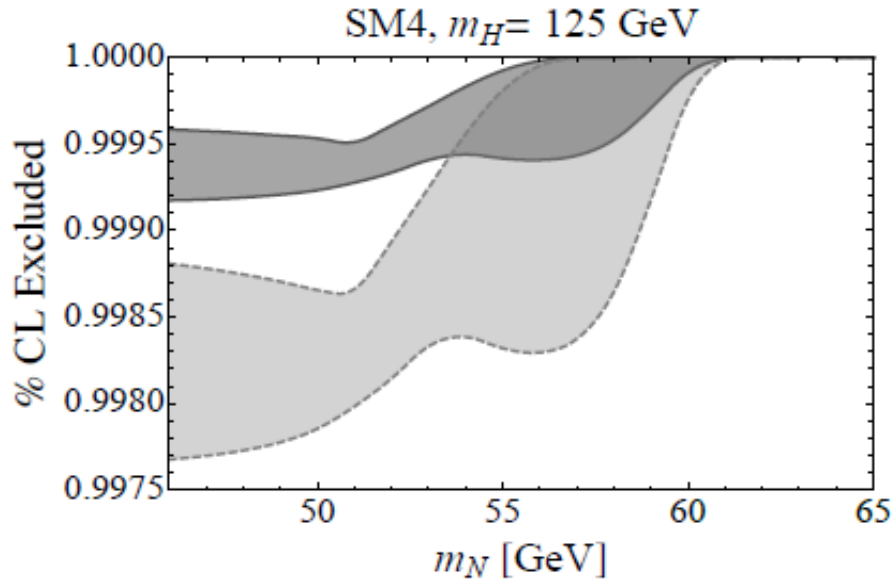
1. Fourth generation

In the presence of a 4th generation, the gluon fusion Higgs rate is enhanced by a factor of ~10; the diphoton width is decreased by a factor of about ~100.



Kuflik, Nir, Volansky, 1204.1975

Lesson #4

We have (only) three generations of quarks and leptons

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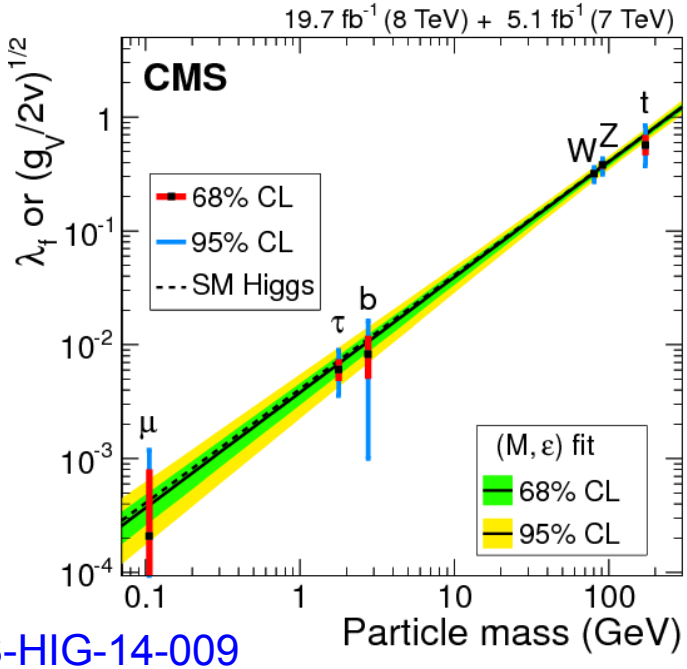
   - Why so large hierarchies between quark (and lepton) masses and mixing angles?

2. NP flavor puzzle: If NP is present at around the TeV scale, how can the theory be consistent with low energy measurements?

1. First confirmations of the <u>hierarchies of the Higgs Yukawa couplings</u>



CMS-HIG-14-009

What about 1st and 2nd generation quarks
See e.g.
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan, 1406.1722;
Perez, Soreq, Stamou, Tobioka, 1505.06689

What about 1st generation leptons?
See Altmannshofer, Brod, Schmaltz, 1503.04830

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2. NP flavor puzzle: If NP is present at around the TeV scale how can the theory be consistent with low energy measurements?

2. The Higgs can mediate <u>new flavor violation</u>

   e.g. h → μτ

Tantalizing hints from ATLAS and CMS?

- CMS, 1502.07400

$$\mathrm{BR}(h \to \mu\tau) < 1.51\%, \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

- ATLAS, 1508.03372

$$\mathrm{BR}(h \to \mu\tau) < 1.85\%, \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) = (0.77 \pm 0.62)\%$$

If this is true, how to reconcile it with low energy measurements? e.g. τ → μγ

Promising approach: second source of EWSB responsible for 1st and 2nd generation masses
Altmannshofer, SG, Kagan, Zupan, Silvestrini, 1507.07927

Conclusions

With the discovery of the Higgs and the first measurements of its properties, we have learned many lessons

- Mechanism to give mass to the (more) massive SM particles
- Vacuum stability
- Self-consistency of the SM electro-weak theory
- Exclusion of minimal Dark Matter models
- No 4th generation quarks and leptons

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- Exclusion of minimal Dark Matter models
- No 4th generation quarks and leptons

Many open questions for the coming LHC run
some highlight...

- Probing NP theories from precision H coupling measurements
- Probing non-minimal dark sectors
- Probing the flavor structure of the Higgs
- ...