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M_H a possible tool to measure the non-naturalness of SM

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Disclaimer: It is NOT a public result just a Lego for an educated guess. CMS is used as example, the discussion is detector independent.

Fairy tail

Once upon a time wise sages had a nightmare. They predicted a quadratic obesity crisis of the mysterious Higgs, God of all masses.


3 =


Sapients and Alchimists from  Samarkand Ivory tower

worked hard to hide the fat belly in extra dimensions,

Or to create an s-belly to cancel out the belly.

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Then we grew up, found the 

and  it:
his weight is just « normal ».

But nobody found why..

Since the we call it naturalness mystery.

Here stops the legend and starts our story in RDMS 2017 in Varna

How to measure (un-)naturalness

1.1) A bit un-natural (following Guidici)

arXiv:1307.7879v2

Destabilization of m_H in SM only for a cutoff scale Λ

$$\frac{\delta m_h^2}{m_h^2} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(\frac{4m_t^2}{m_h^2} - \frac{2m_W^2}{m_h^2} - \frac{m_Z^2}{m_h^2} - 1\right)\Lambda^2 = \left(\frac{\Lambda}{500\ \text{GeV}}\right)^2$$

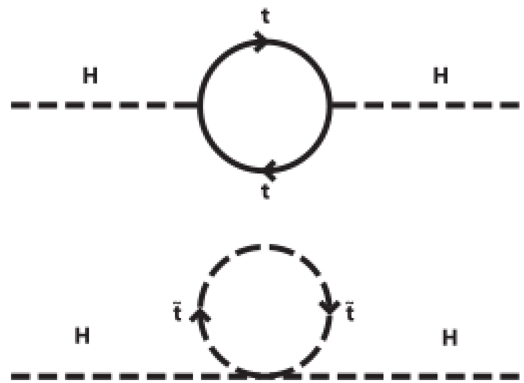
To give more sense to Λ adding a scalar with mass M >> mH mixing to Higgs

$$V = m_H^2|H|^2 + \lambda|H|^4 + \lambda_\Phi|H|^2|\Phi|^2$$

$$\delta m_H^2 \approx \frac{\lambda_\Phi}{16\pi^2}M^2 \ln\frac{M^2}{\Lambda^2} + \dots$$

In case a as heavy stop

$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2}\tilde{m}_t^2 \ln\frac{\tilde{m}_t^2}{\Lambda^2} + \dots ,$$



"In experimental science instead of calculating you can always measure if a you need an information. This is why I like it. » – I. Bagaturia, CMS Georgia

1.2) Un-natural in experimentalist language

So how can I measure it?
For that how shall I interpret experimentally this equation?

1) There is a new physics that I shall look for:

- Directly if they are within the reach of our collider: stop, WED etc…
- « Directly » if they are out-of-reach of our collider: EFT or Contact interactions. Cross section deviations.
- Indirectly in loops: rare decays of SM particles, EWK precise measurements.

Nothing on horizon….

1.3) Masses measurement: where LHC means high precision

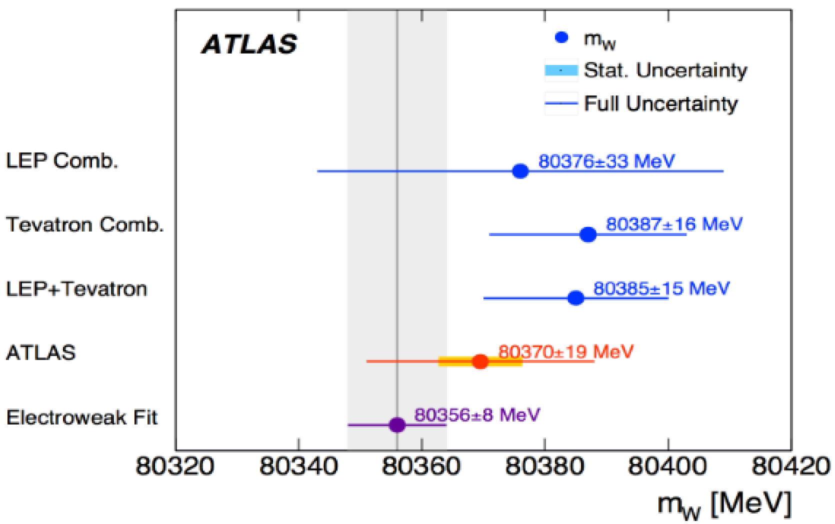
Can we change perspective?

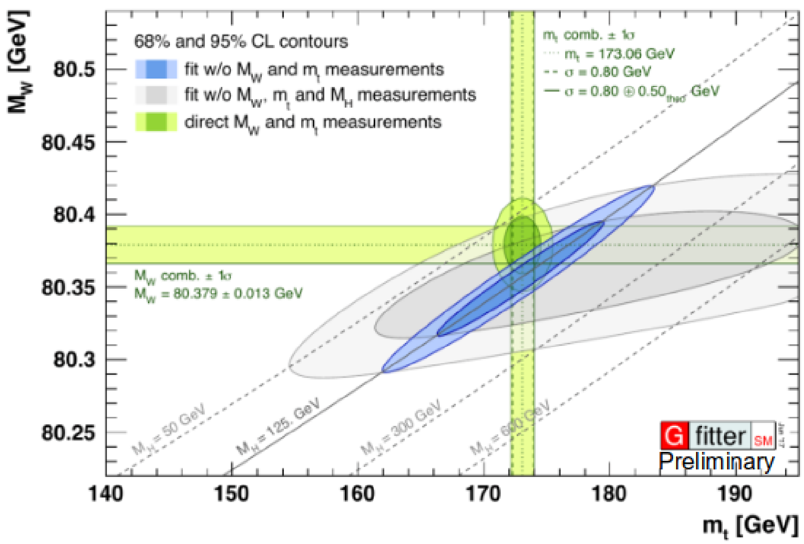
If Higgs have a problem with its mass and BSM scales why not to measure how severe is « the problem »?

$$\frac{\delta m_h^2}{m_h^2} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(\frac{4m_t^2}{m_h^2} - \frac{2m_W^2}{m_h^2} - \frac{m_Z^2}{m_h^2} - 1\right)\Lambda^2 = \left(\frac{\Lambda}{500\ \text{GeV}}\right)^2$$

1) Masses are the most precise quantities we measure at the LHC, a (way better than any cross section even relative >> 1% precision)

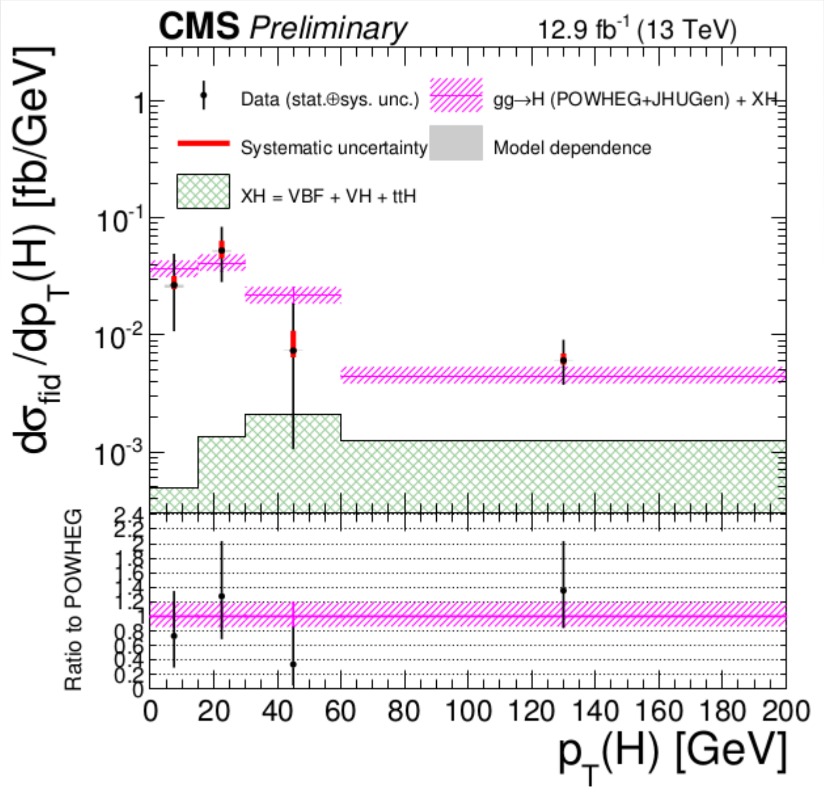
$\Delta m_t \sim 0.3\ \%$; $\Delta m_W \sim 0.025\%$; $\Delta m_H \sim 0.2\%$



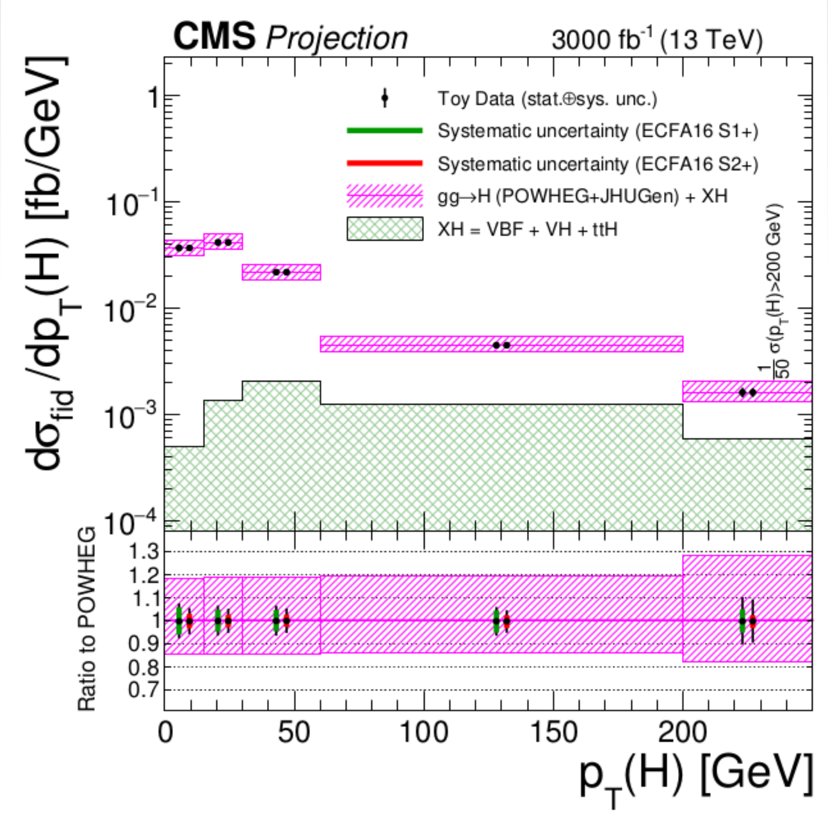


1.3) Where LHC means high precision

2) LHC provides us with energetic Higgses:
- Run II: at scales up to 0.5 TeV (4 times the mass).
- HL-LHC: thousands of boosted Higgses and going up to 1 TeV.



Now



HL-LHC

1.4) Measure the (un)-naturalness

So if we measure $m_H = f(p_{T,H} \sim \Lambda)$ could we measure that?

$$\frac{\delta m_h^2}{m_h^2} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(\frac{4m_t^2}{m_h^2} - \frac{2m_W^2}{m_h^2} - \frac{m_Z^2}{m_h^2} - 1\right)\Lambda^2 = \left(\frac{\Lambda}{500\ \text{GeV}}\right)^2$$

Sounds very attractive:

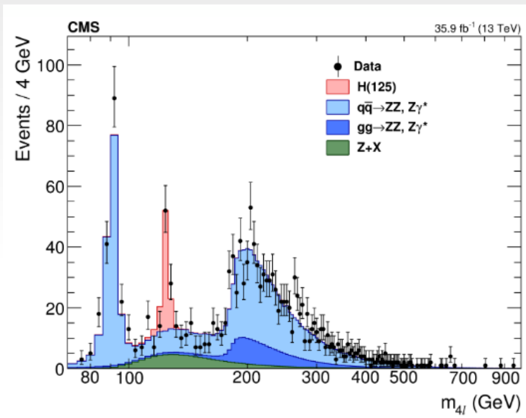
- We can be fully « BSM agnostic ».
- We make a tantalizing physics case for any hadronic machine that provide us with high pT H samples (HL/HE-LHC; FCC).
- Seems to meet the “QCD experience”: running of quark masses and running of couplings in Msbar scheme.

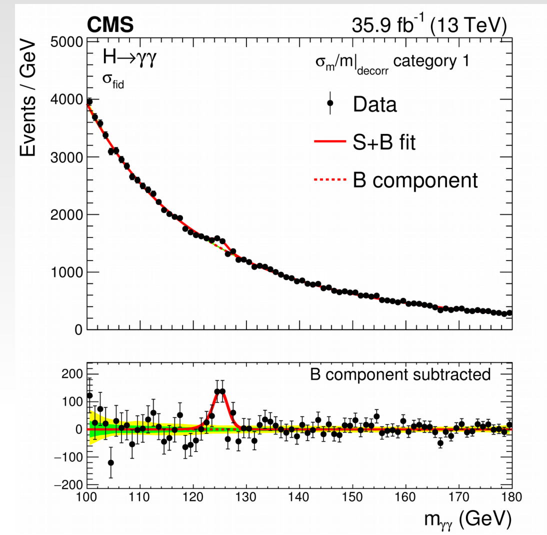
But does my naive picture make theoretically sense?
I pulled many theorists and I must confess got even more confused…
Looks like we dive deep into the fundamentals of the QFT.
In the next I explain what we measure exactly.

Principle of the measurement

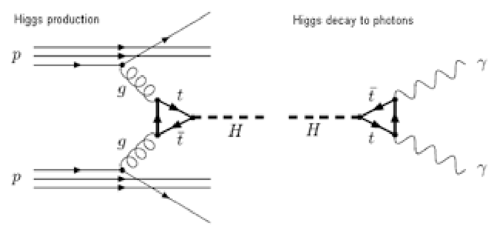
2.1) The observable

Experimentally the Higgs line shape $d\sigma/m_N$ is defined at the invariant mass of N objects from Higgs decay:
The 2 most precises : $H \rightarrow ZZ^* \rightarrow 4l$ or $H \rightarrow \gamma\gamma$.





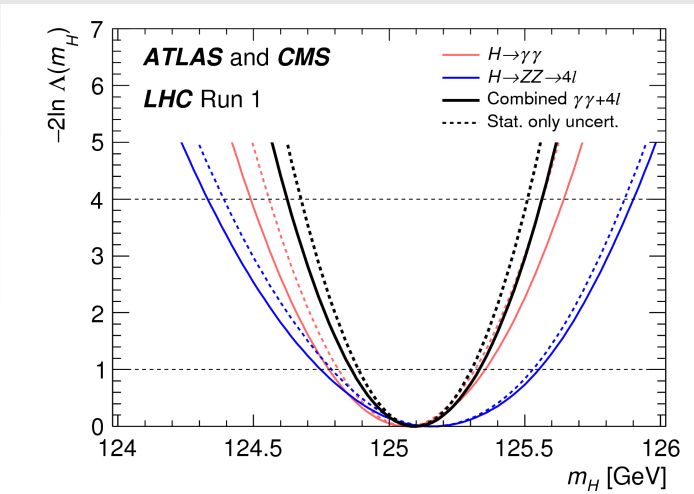
The m_H is the bare mass from the Lagrangian that appears in the H propagator. Lets concentrate on $gg \rightarrow H \rightarrow ZZ^* / \gamma\gamma$.



In a given renormalization scheme: for example “pole mass” scheme we connect roughly $m_H \sim \langle d\sigma/dm_N \rangle$.

2.2) How could we measure it?

Mixing 2 already known analyses.



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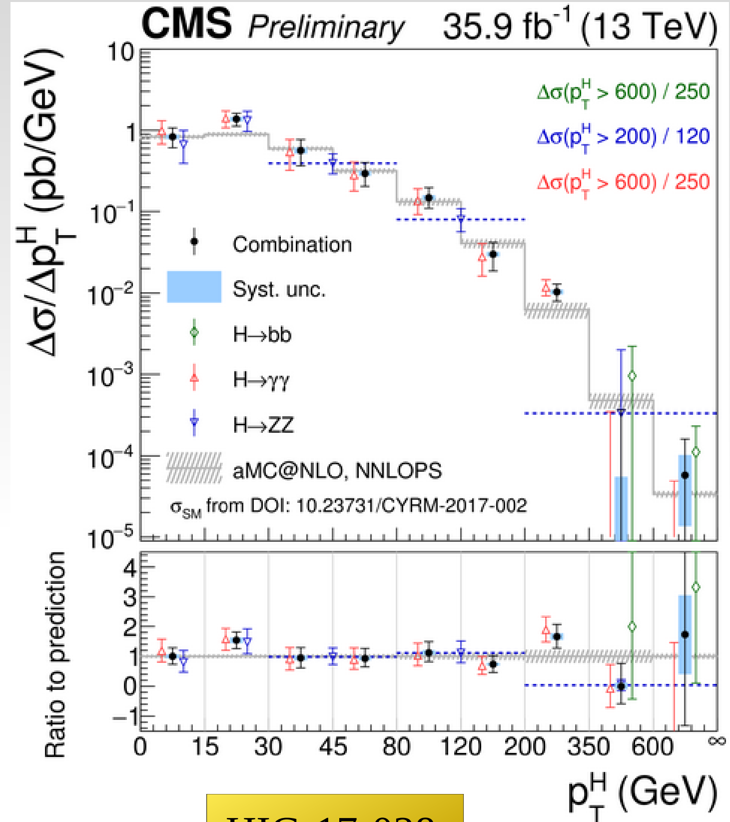


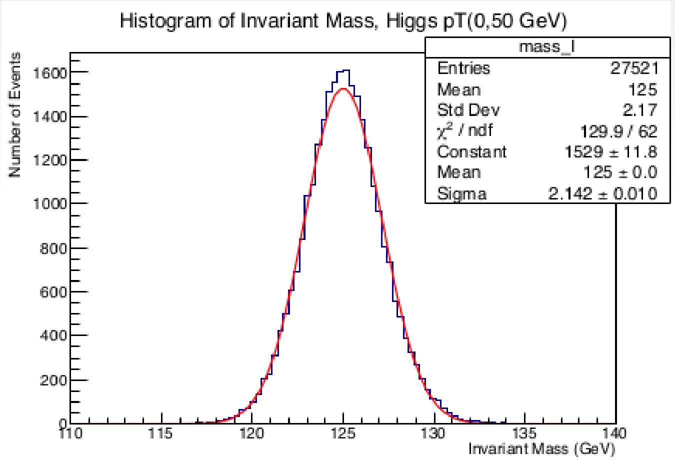
HIG-17-028

IPNL (M. Gouzevitch + L3 student M. Bourgade) + Minesotta (R. Chatterjee) + KU (A. Kropivnitskaya, P. Baringer + M2 students N. Johnson and E. Gibson),
We designed a simplified projection for $H \rightarrow \gamma\gamma$ case to get an order of magnitude.

2.3) H → γγ projection: ingredients

We generate gg → H → γγ signal using MadGraph+Delphes with HL-LHC configuration:

- We check that Mγγ resolution is compatible with HL-LHC expectations.



- We checked that the simulation is compatible with expectations.
- $\sigma_{\gamma\gamma}$ = O(2 GeV) slowly improving with p_{TH}.

- Background is estimated from public plots for different measurement. Cross check with a small sample of MG+Delphes events for γγ QCD production.

2.3) H → γγ projection: results

1) Max p_{TH} = f(Lumi) what is the maximal value reachable. Rule: at least 10 Higgs fiducial events expected / bin.

150 fb^{-1}

$p_T(H)$(GeV)	[200;300]	[300;450]	[450;750]
Number of events	128.7	42.38	10.12

300 fb^{-1}

$p_T(H)$(GeV)	[350;500]	[500;800]
Number of events	47.97	12.46

3000 fb^{-1}

$p_T(H)$(GeV)	[350;450]	[450;550]	[550;750]	[750;1050]
Number of events	398	133	68.96	11.13

2) What is the significance expected:
use simple S/√B, 123 < $M_{\gamma\gamma}$ < 127. Full analysis would be better.

150 fb^{-1}

$p_T(H)$(GeV)	[300;450]	[450;750]
Signal	33.3	7.6
Background	610	65
Significance	1.35	0.94

3000 fb^{-1}

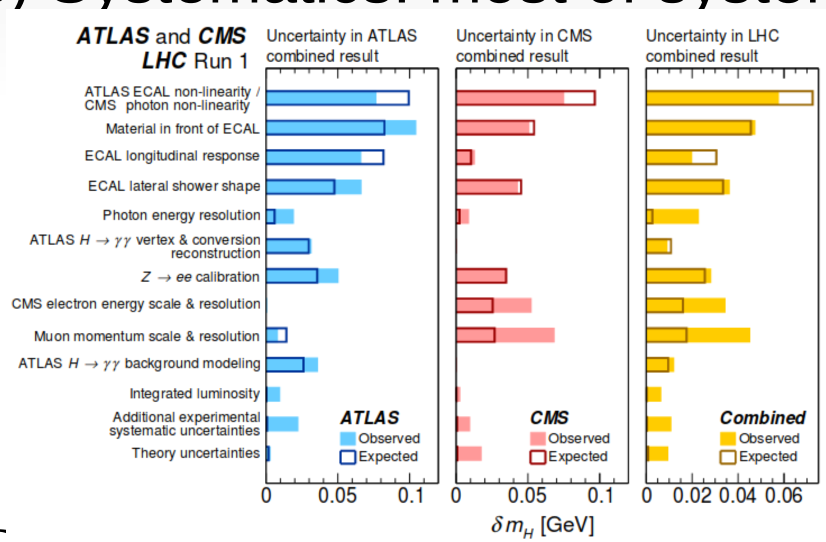
$p_T(H)$(GeV)	[550;750]	[550;750]
Signal	49.7	8.14
Background	340	67
Significance	2.70	0.99

2.4) What about mass measurement?

1) If Sig > 2-3 background impact marginal in precision. Precision can be estimated with central limit theorem: $\sigma_{\gamma\gamma}/\sqrt{N_H}$

2) For N >= 50 events $\sigma_{\gamma\gamma}$ ~< 1 GeV .

3) Systematics: most of systematics go smaller with $p_{T\gamma}$.



We can do even better with a reduced variable to cancel systematics

$$\Delta m_H = m_H(p_{TH}) - m_H(p_{TH} = 0)$$

<u>Conclusion</u>: as soon as we have a handful of H bosons we can measure its mass with precision below 1 GeV (<1%).

Discussion and worries

3.1) Interpretation of Λ

The naturalness problem in 1 loop approximation looks like

$$m^2 = m_0^2 + \Lambda^2 P(\lambda_0, g).$$

- m0 is base parameter of the Lagrangian.
- m the « measured » Higgs mass: mH
- Λ the scale of new Physics.
- P polynomial in couplings.

See G. Pivovarov, V. Kim

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If P = 0, this is a « natural solution » like softly broken SUSY.

If P != 0, we need fine tuning: m << m0 ~ - Λ P

3.2) Devil advocate opinion (J. Baglio)

At least this is my interpretation:

1) The pole mass scheme with $m = m_H$ is the right one to use since m_H can be measured with a well defined observable. Consequence:

- m_H is always the same for whatever p_{TH} is.
- The relation is “frozen” by the BSM Lagrangian and m_H value cannot be used to know m0, Λ and P

$$m_0^2 + \Lambda^2 P(\lambda_0, g).$$

2) In QCD things are different because of the confinement: quarks are not directly observables.

Conclusion: There are better ways to search for m0, Λ and P

3.3) Supportive opinion (V. Kim, G. Pivovarov)

1) This is the first time we see an elementary scalar.
There might be large quadratic and logarithmic corrections to the propagator of the Higgs, since Veltman relation doesn't hold.

2) Pole mass scheme is just one of the schemes of the renorm. group.

2) Loop corrections induce the cross dependence of the mass and couplings and inject the scale dependence into the mass:

$$m_0^2 = m^2 - \Lambda^2 P(\lambda, g),$$

$$\lambda_0 = \lambda + \log\left(\frac{\Lambda^2}{m^2}\right)\frac{\beta(\lambda, g)}{2},$$

Conclusion: there might be a lot to discover, but need to quantify the effects.

Conclusion

1) We may have found 1 out-of-box way of measuring the real naturalness problem in SM.

2) Higgs mass running It is experimentally measurable with a precision better than 1% and provides a wonderful physics case for HL-LHC.

3) We just need to know if there is really an expected effect and how big is it… Homework to our theory colleagues.

From an other hand it may be by construction an interesting measurement whatever we expect….

BACKUP