Di-Higgs Workshop at Colliders

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Why are we here ?

1922 compton effect

1983 W,Z

1979 gluons

$$\mathcal{L} = -\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a}$$
$$+\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{\ell}_i i\not{D}\ell_i$$
$$+\left(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i \ell_j H + c.c.\right)$$
$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$

?

next to come

2012 Higgs boson

The current established global picture

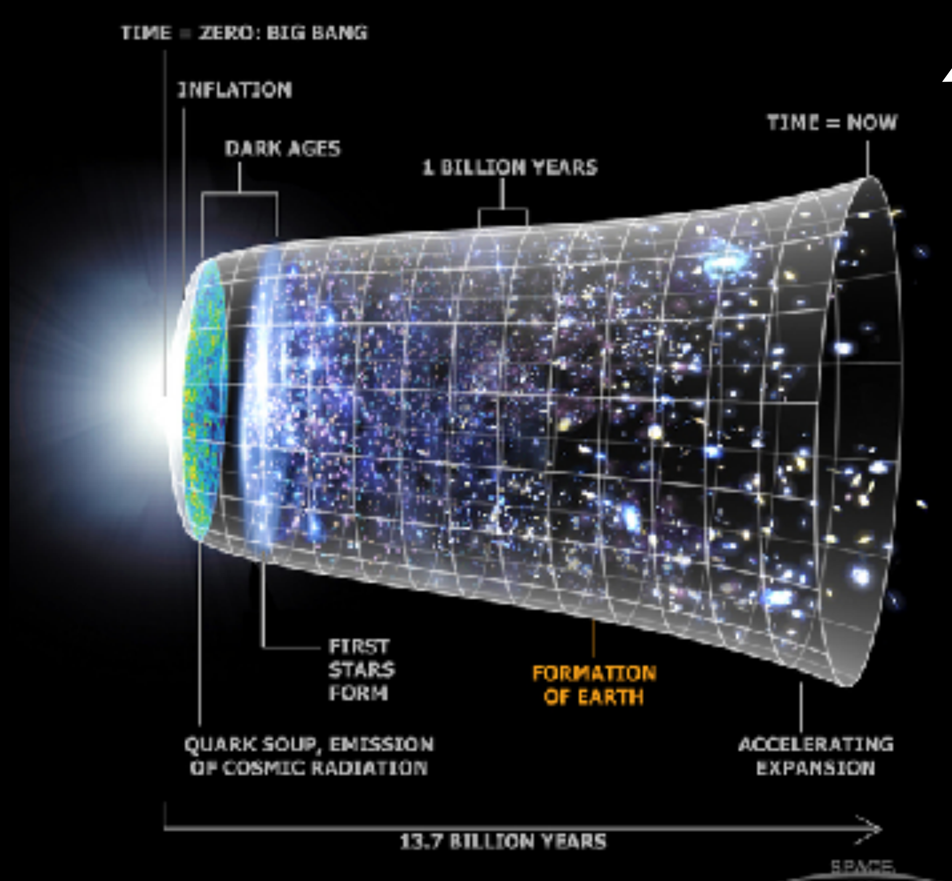
Hilbert-Einstein action (folding in gravitation)

$$S = \int \left[\frac{1}{2} M_{\mathrm{pl}}^2 R + \mathcal{L}\right] d^4x\sqrt{-g} = \int \left[\frac{1}{2} M_{\mathrm{pl}}^2 R - \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + \ldots\right] d^4x\sqrt{-g}$$

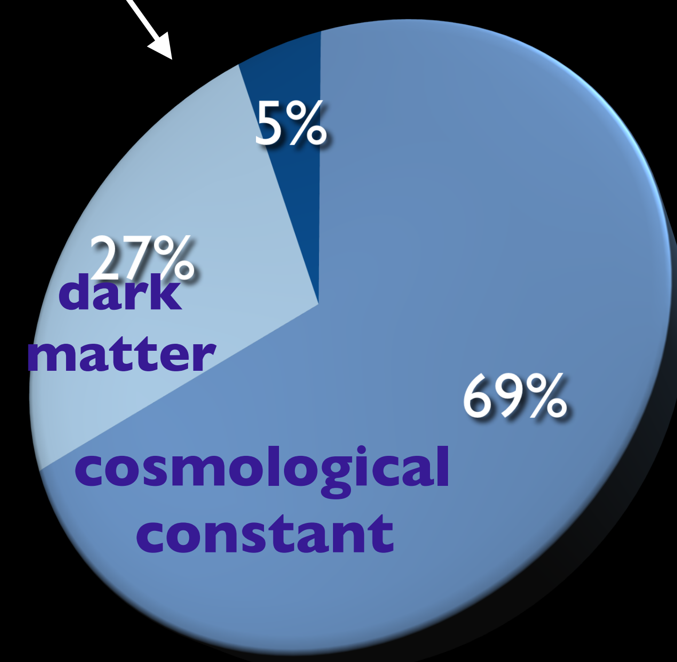
set the dynamic of the matter field interaction

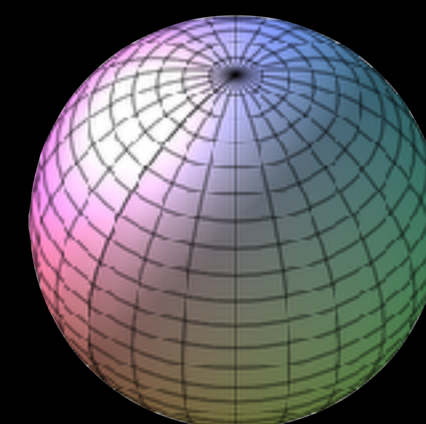
determine the evolution of the space time:
inflation cosmological constant (dark energy)

set the space-time geometry



barionic matter.





Inflation picture

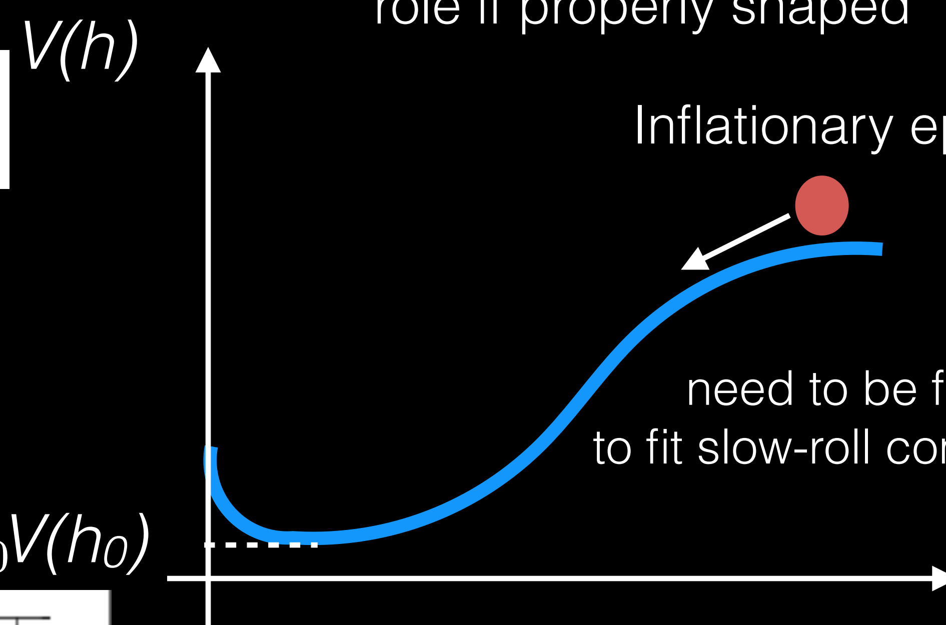
$$S = \int \left[\frac{1}{2}M_{\rm pl}^2 R + \mathcal{L}\right] d^4x\sqrt{-g} = \int \left[\frac{1}{2}M_{\rm pl}^2 R - \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + ...\right] d^4x\sqrt{-g}$$

a(t) universe radius

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \rightarrow H^2 = \frac{8\pi G}{3}V(\phi) \simeq const. \rightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a}\right)$$

universe radius, exponentially expanding during inflation

The Higgs potential could have such role if properly shaped

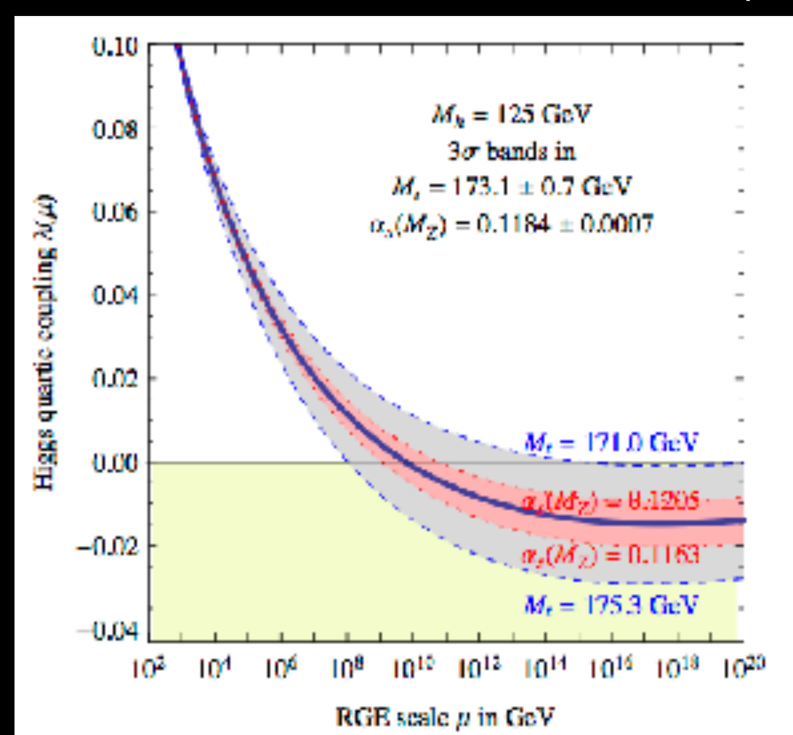


In order to make this to work $V(h) \sim \lambda h^4$ $\lambda \sim 10^{-13}$ $h >> h_0 V(h_0)$

λ determined by the Higgs boson mass ($\lambda_{mh} \sim 0.129$)

It runs with the energy scale fixed by the *h* value.

Intringuing, λ nearly vanishes for high h value with the present value of top and Higgs mass.



if λ is too large, matter fluctuations not compatible with present data (Bezrukov, Shaposhnikov arXiv:0710.3755

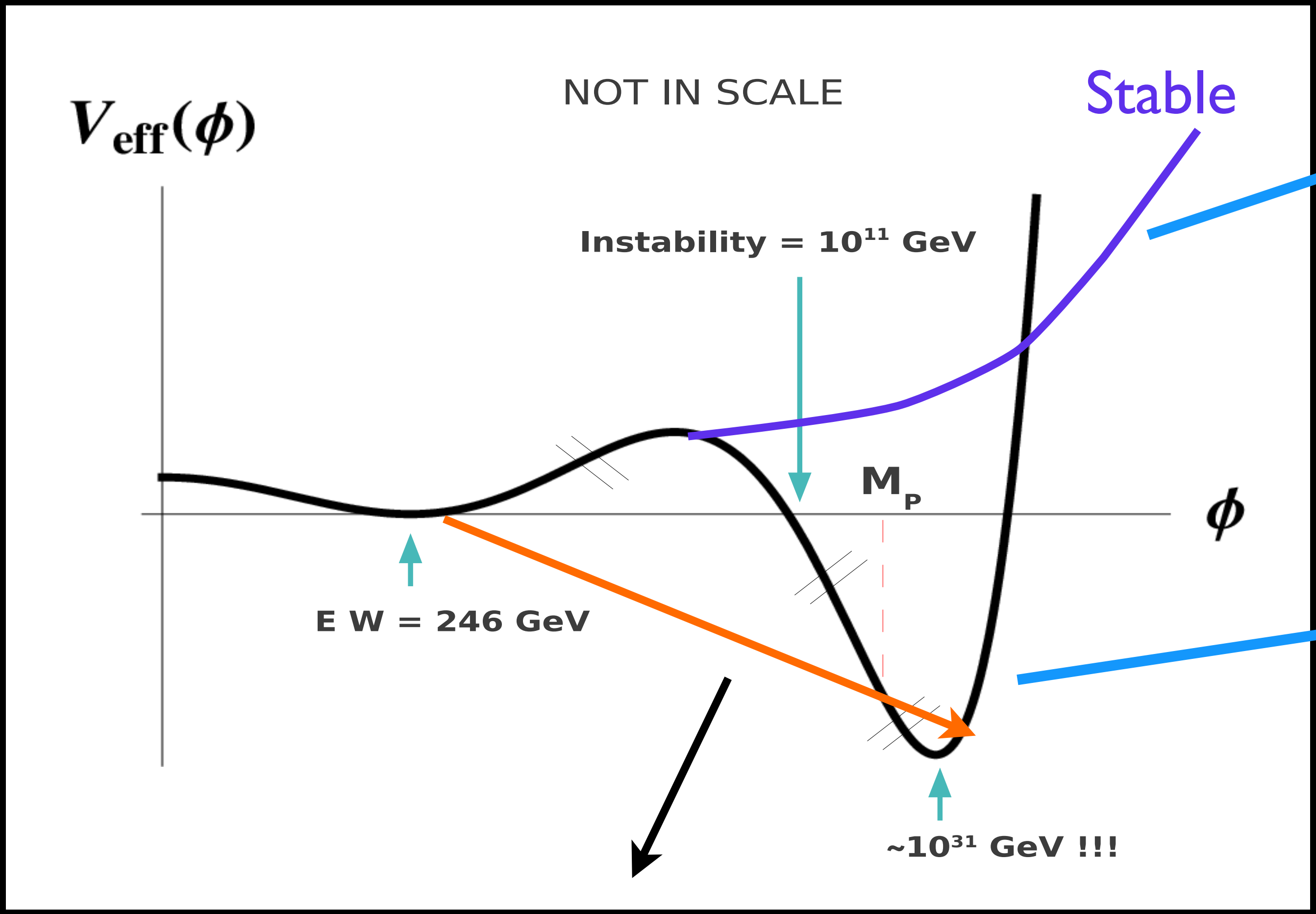
Can be fixed with minimal couplings of the Higgs boson to gravity $\frac{\xi h^2}{2}R$

$$\Delta\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHHH\,SM}} = -\frac{\xi R}{2VEV}$$

vacuum stability

The modification of λ with the energy (running due to quantum corrections) implies a dependence of it from the Higgs boson field Φ. The Higgs potential assumes a shape that is more complex than just $\lambda\Phi^4$ (also known as effective potential)

See Buttazzo *et al.* and talk from V. Branchina

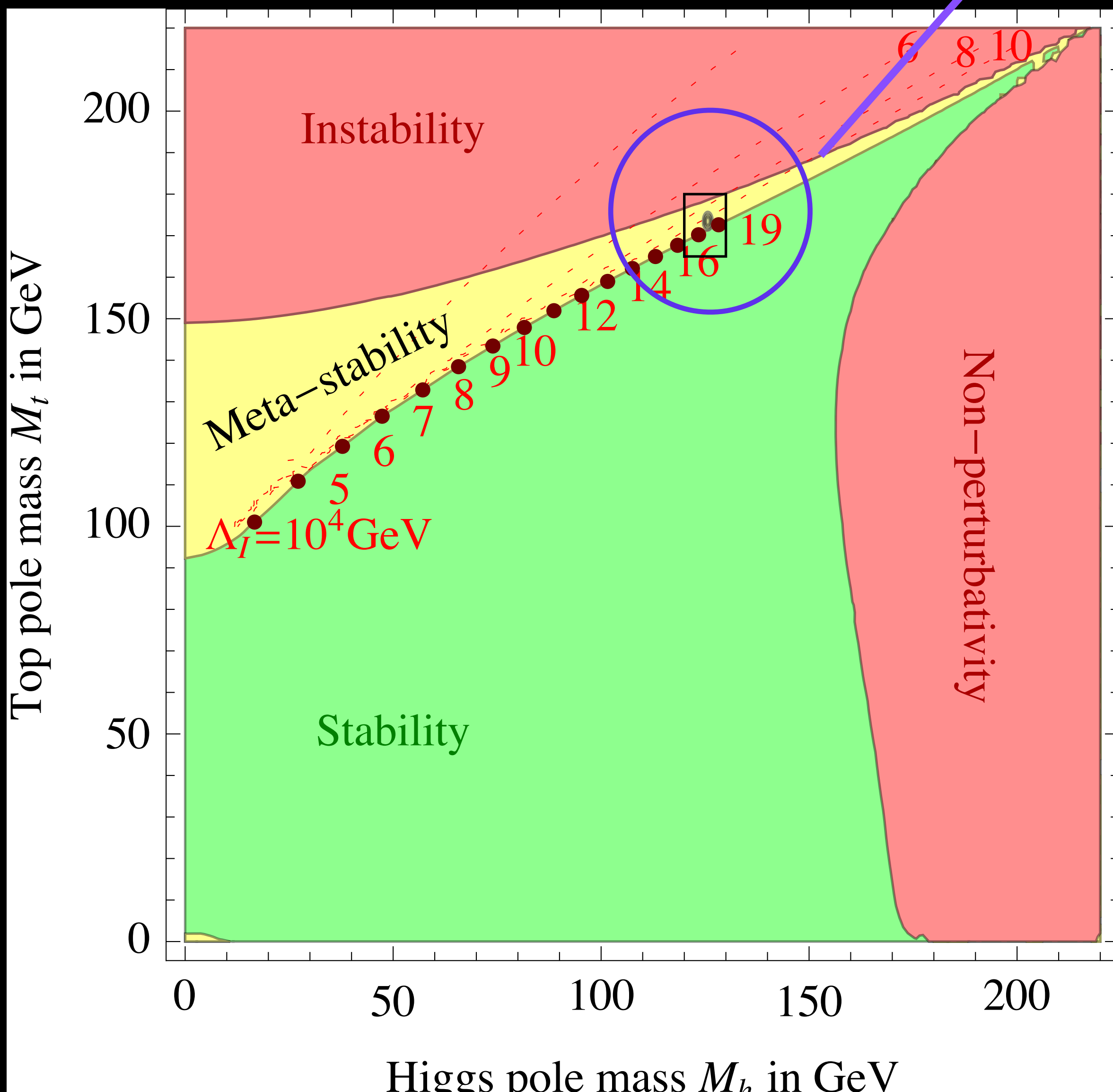


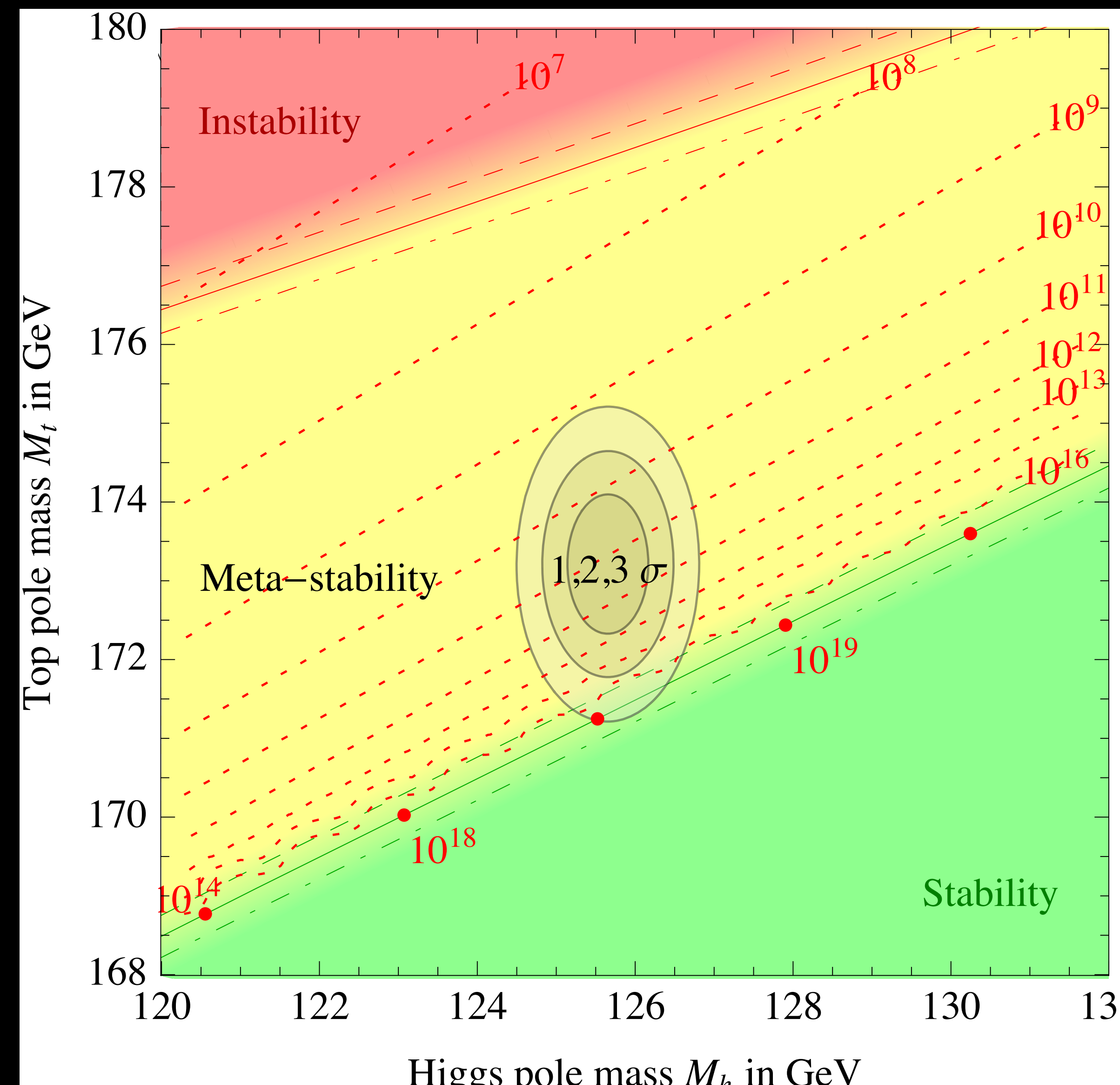
The present minimum is the absolute minimum, the Higgs field will remain in this state forever.

The present minimum is the false vacuum (the universe is trapped in it but eventually will decay to the new minimum)

Vacuum collapses.
If the lifetime is larger than the age of the universe we call it metastable otherwise it is unstable.

We are at the edge between stability and instability, in a quite narrow region of the instability region (many theoretical speculations are starting) - assuming SM fully valid (but we need to check…)



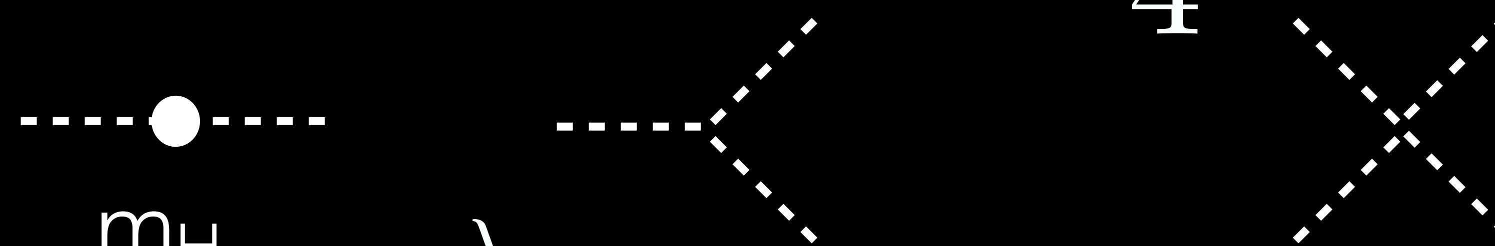


Transition time of the unstable vacuum:

with m_t = 173.1 GeV and m_H = 126 GeV,
$\tau_{transition} \sim 10^{588}\, T_{Universe}$ (if you started to be concerned I think now you can relax a bit...)

probing the potential

$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$



m_H λ_{HHH} λ_{HHHH}

SM relations

$v^2 = (2G_F)^{-1/2}$ $\lambda = \frac{m_H^2}{\sqrt{2}} G_F$ $\lambda_{HHHH} = \frac{m_H^2}{4\sqrt{2}} G_F$

G_F Fermi coupling constant

$$\lambda_{HHH} = m_H^2 \sqrt[4]{\frac{G_F^3}{4}}$$

pp → *HH* provides a first direct measure of λ_{HHH}

when is the right time to start measuring λ_{HHH} ?

if we assume SM is correct, there is no need to make any measurement in general → no need to wait to reach SM sensitivity before starting to measure λ_{HHH}

BSM models can suggest some value for λ_{HHH} but, nowadays, no BSM model is robust enough to guide experimental searches

the only guides are:

1) enjoying doing measurements (push analysis sensitivity at the extreme)

2) use all data that are available for the already leading sensitive analyses

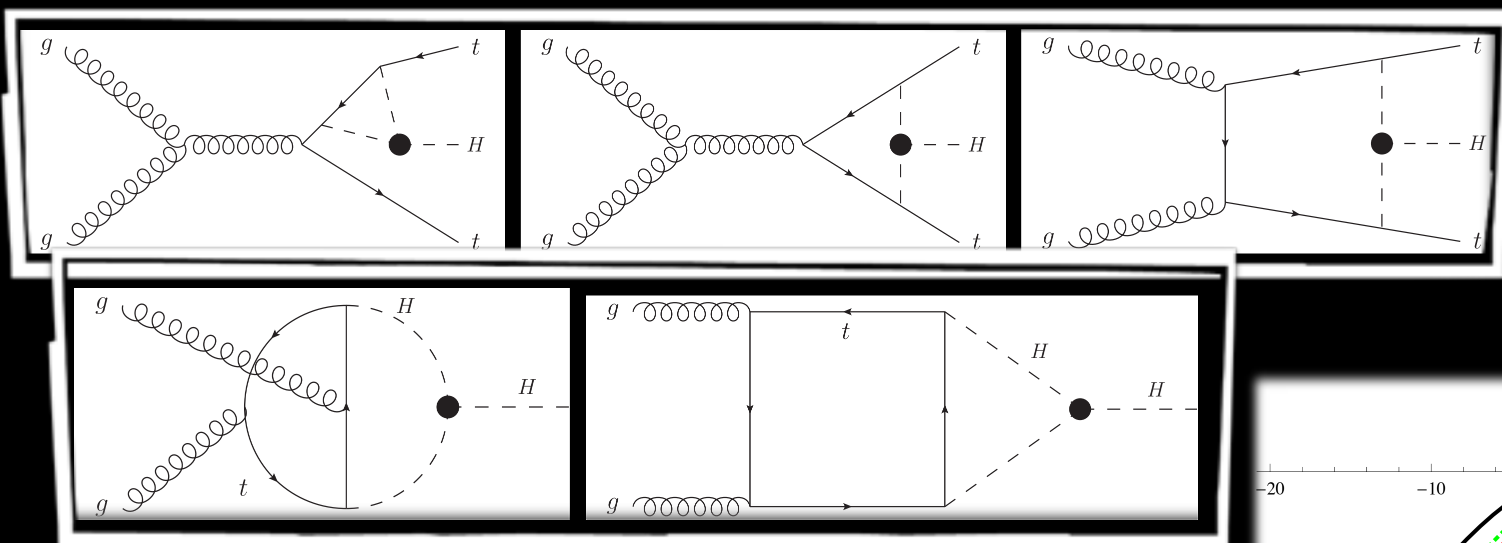
3) indirect experimental constraints from precision measurements

4) model independent theoretical arguments

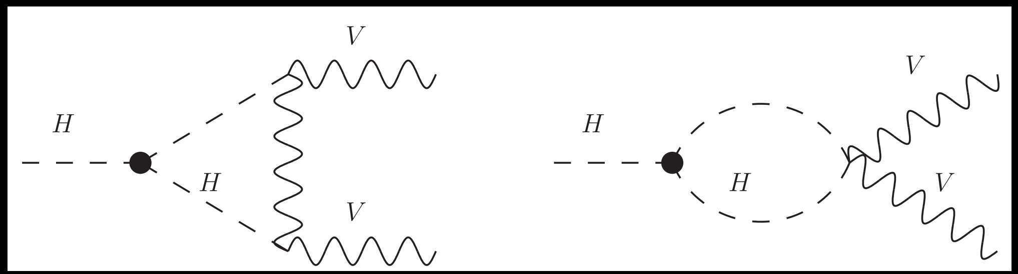
Indirect constraints: Higgs boson couplings

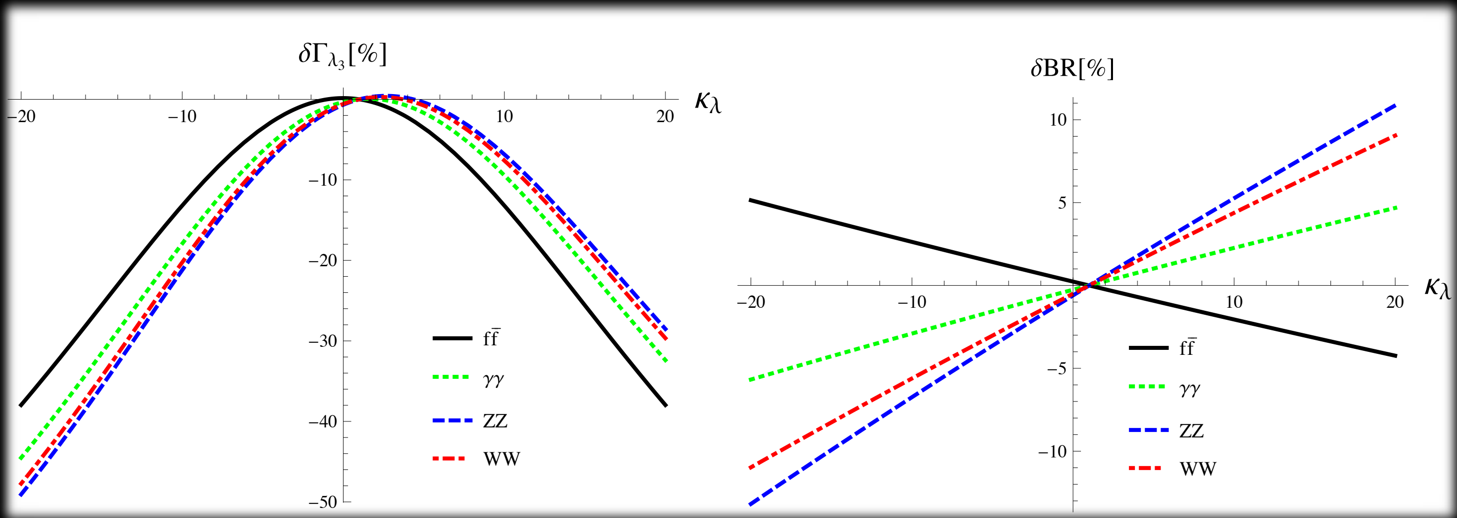
λ_{HHH} dependence in

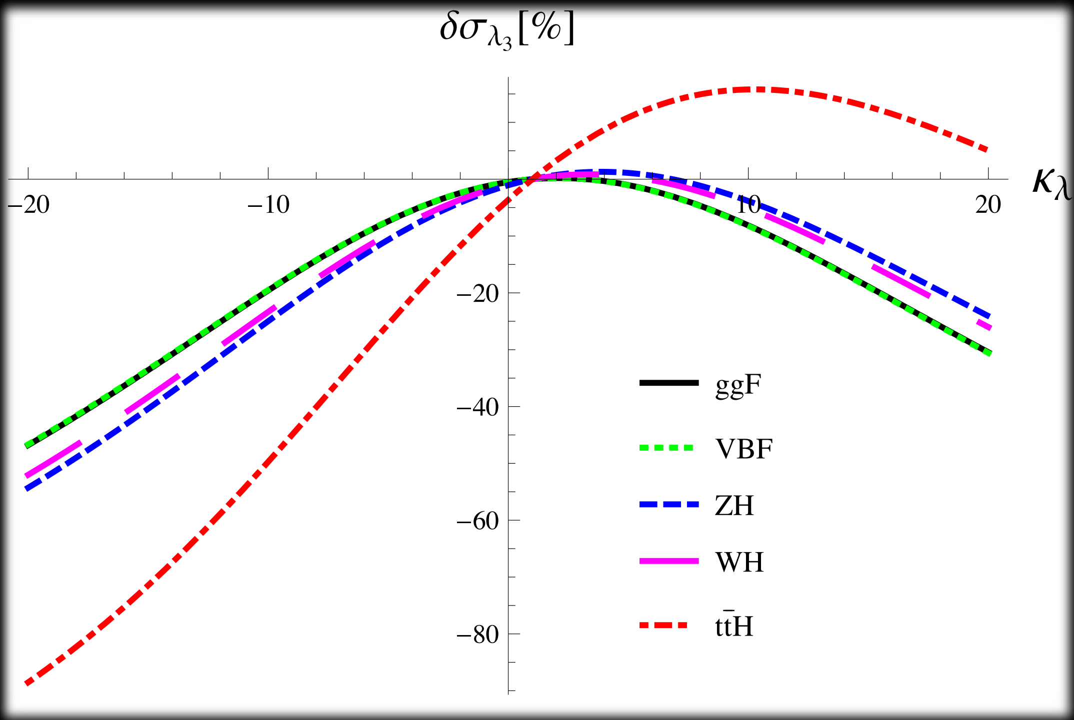
production



decay







ATLAS+CMS Run-1
ggF + VBF

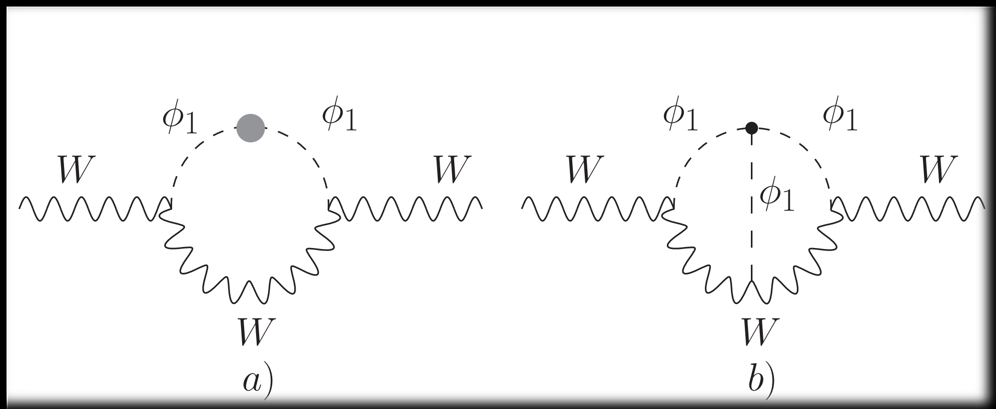
$-9.4 < \kappa_\lambda < 17.0$ @95% C.L

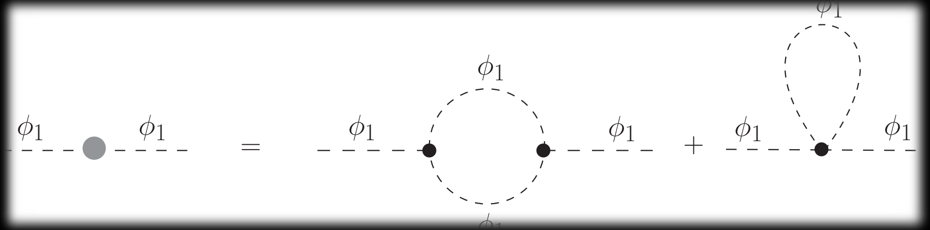
Indirect constraint: W mass and $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lep}}$

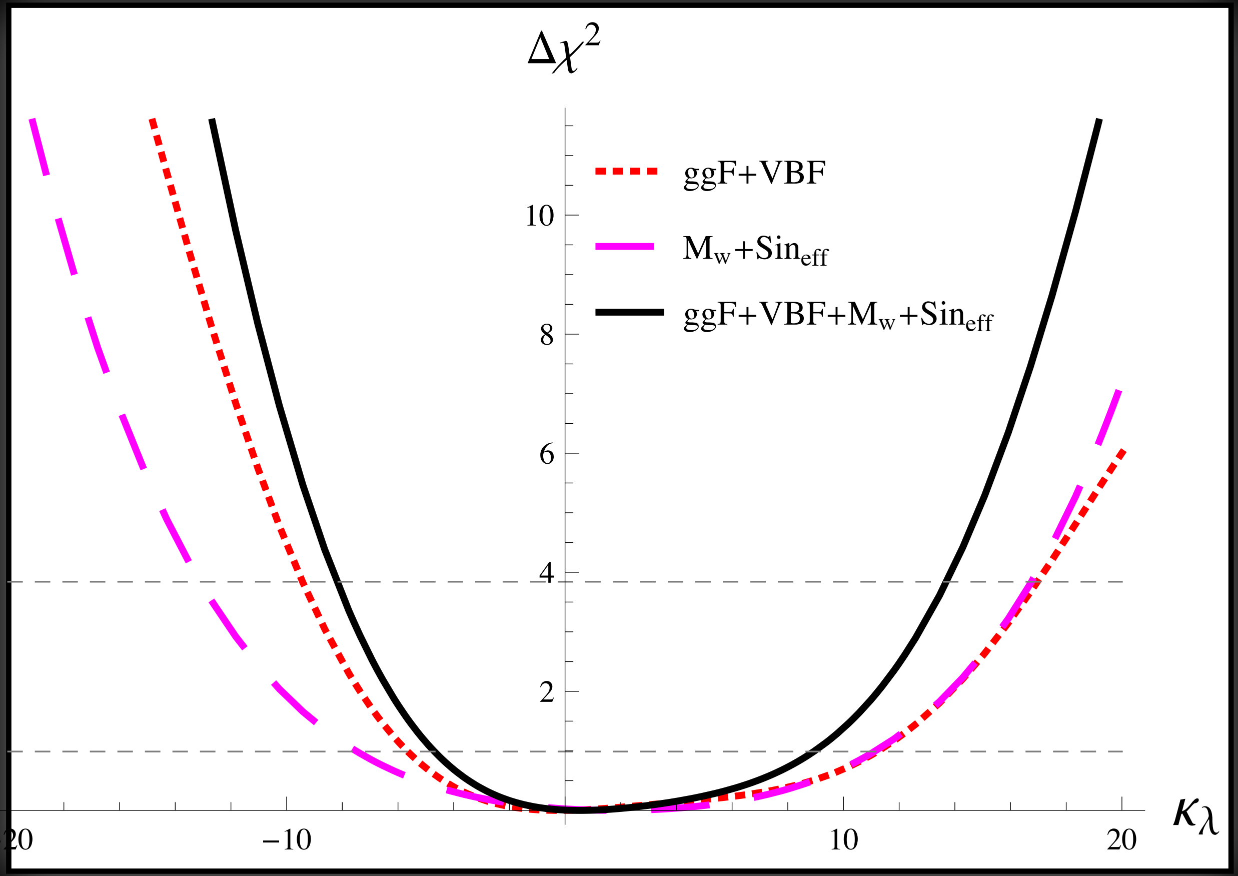
$m_W = 80.370 \pm 0.019\,\mathrm{GeV}$ ATLAS measurement

$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lep}} = 0.23185 \pm 0.00035$ CDF + D0 combination

Higgs boson couplings ATLAS+CMS Run-1







$m_W + \sin^2\theta_{\mathrm{eff}}^{\mathrm{lep}}$ $\quad -13.2 < \kappa_\lambda < 16.7$ @95% C.L.

ggF + VBF $\quad -9.4 < \kappa_\lambda < 17.0$

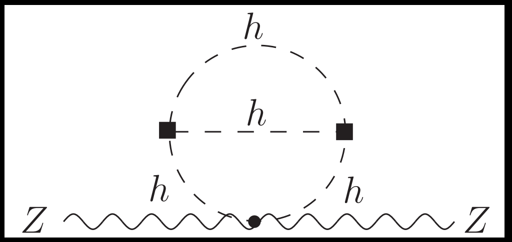
ggF + VBF + $m_W + \sin^2\theta_{\mathrm{eff}}^{\mathrm{lep}}$ $\quad -8.2 < \kappa_\lambda < 13.7$

Indirect constraints: S & T relations

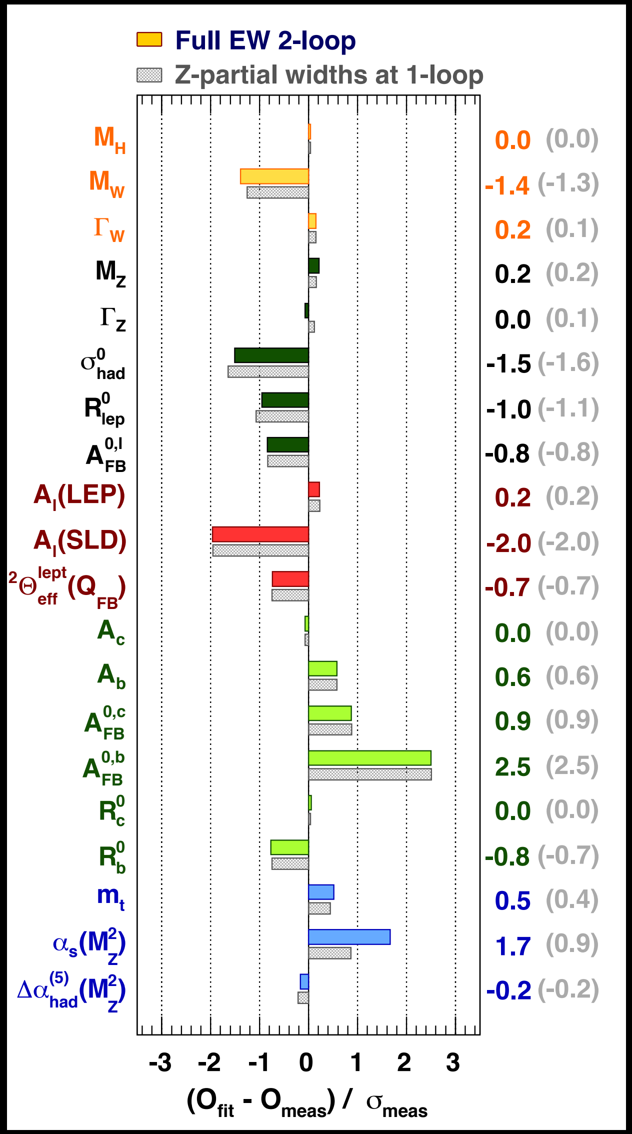
$$S = \frac{4c^2 s^2}{\alpha_e m_Z^2}\mathrm{Re}\left(\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0) - \frac{c^2 - s^2}{cs}\left[\Pi_{Z\gamma}(m_Z^2) - \Pi_{Z\gamma}(0)\right] - \Pi_{\gamma\gamma}(m_Z^2)\right)$$

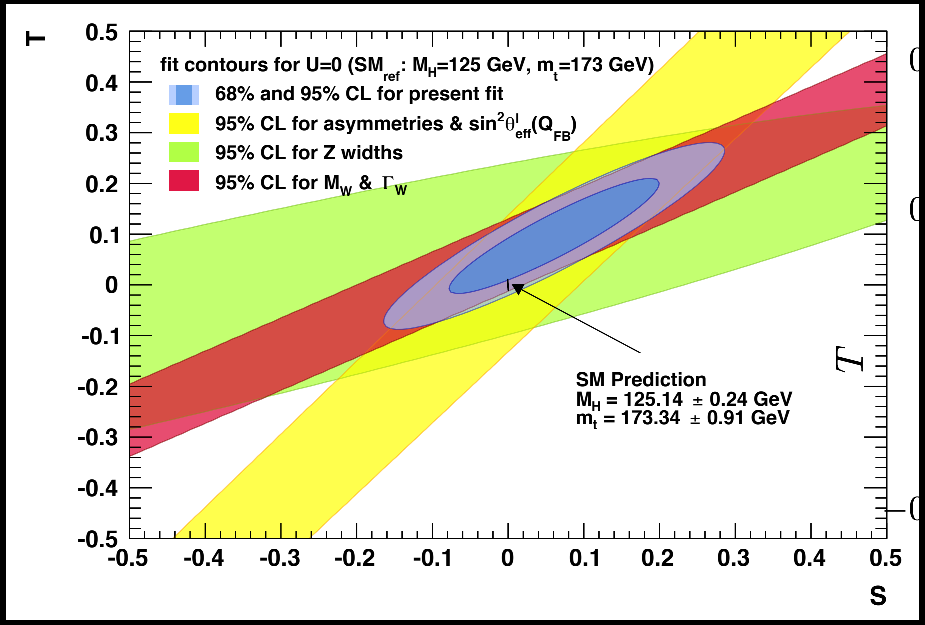
$$T = \frac{1}{\alpha_e}\left(\frac{\Pi_{WW}(0)}{m_W^2} - \frac{c^2}{m_W^2}\left[\Pi_{ZZ}(0) + \frac{2s}{c}\Pi_{Z\gamma}(0)\right]\right) .$$

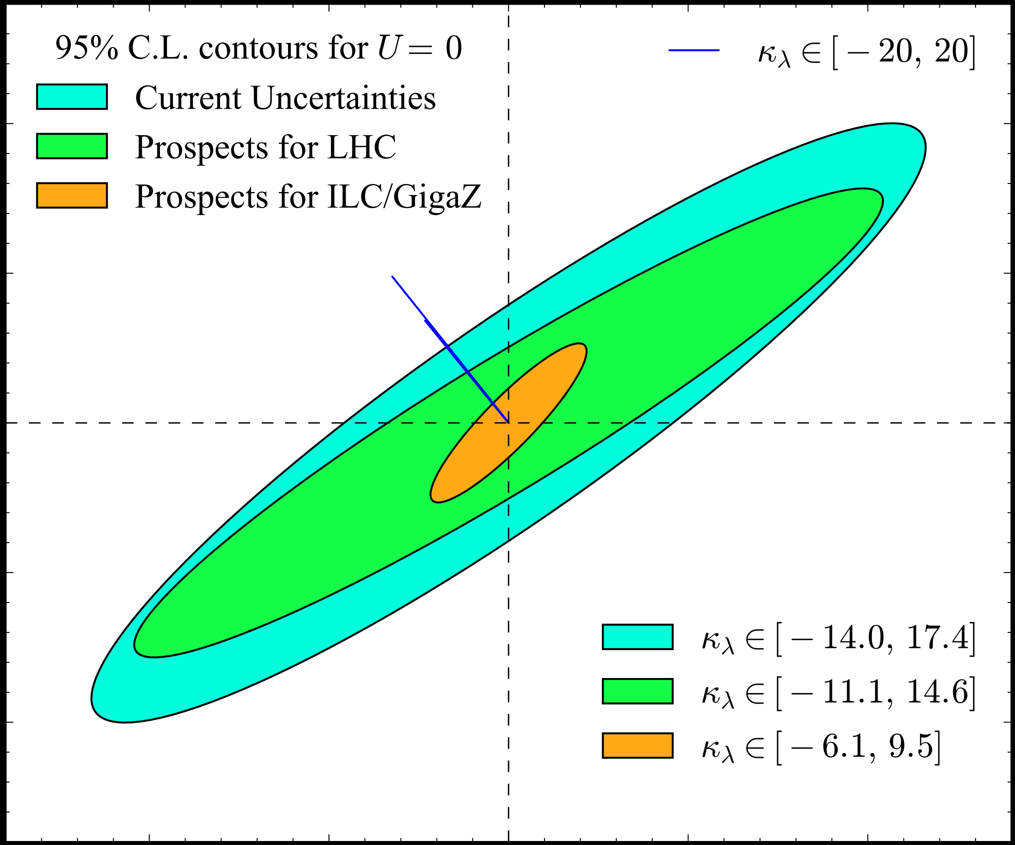
Π_{ZZ}



S&T relations are extracted from global fit to EWK observables







$-14.0 < \kappa_\lambda < 17.4$ @95% C.L.

Theoretical constraints

Large values of κ_λ can induce lost of the perturbation expansion and unitarity breaking

- in the first case the theory becomes “strongly” coupled (like QCD at low energy, it would be a bit sad but it is not impossible…)

- in the second case NP needs to come in to restore unitarity (a probability cannot be larger than 1), strong historical example: Fermi theory and the discovery of the W and Z bosons

from the experimental point of view nothing changes (we would be quite happy to need new resonances to restore unitarity due to the measurement of a large κ_λ value)

- it is anyway interesting to understand what the implications of a large k_λ value could be

Unitarity violation 1

A. Folkowski (https://indico.cern.ch/event/592697)

Unitarity can be broken in several processes when playing with κ_λ

$hh \to hhh \;\; V_L V_L \to hh$

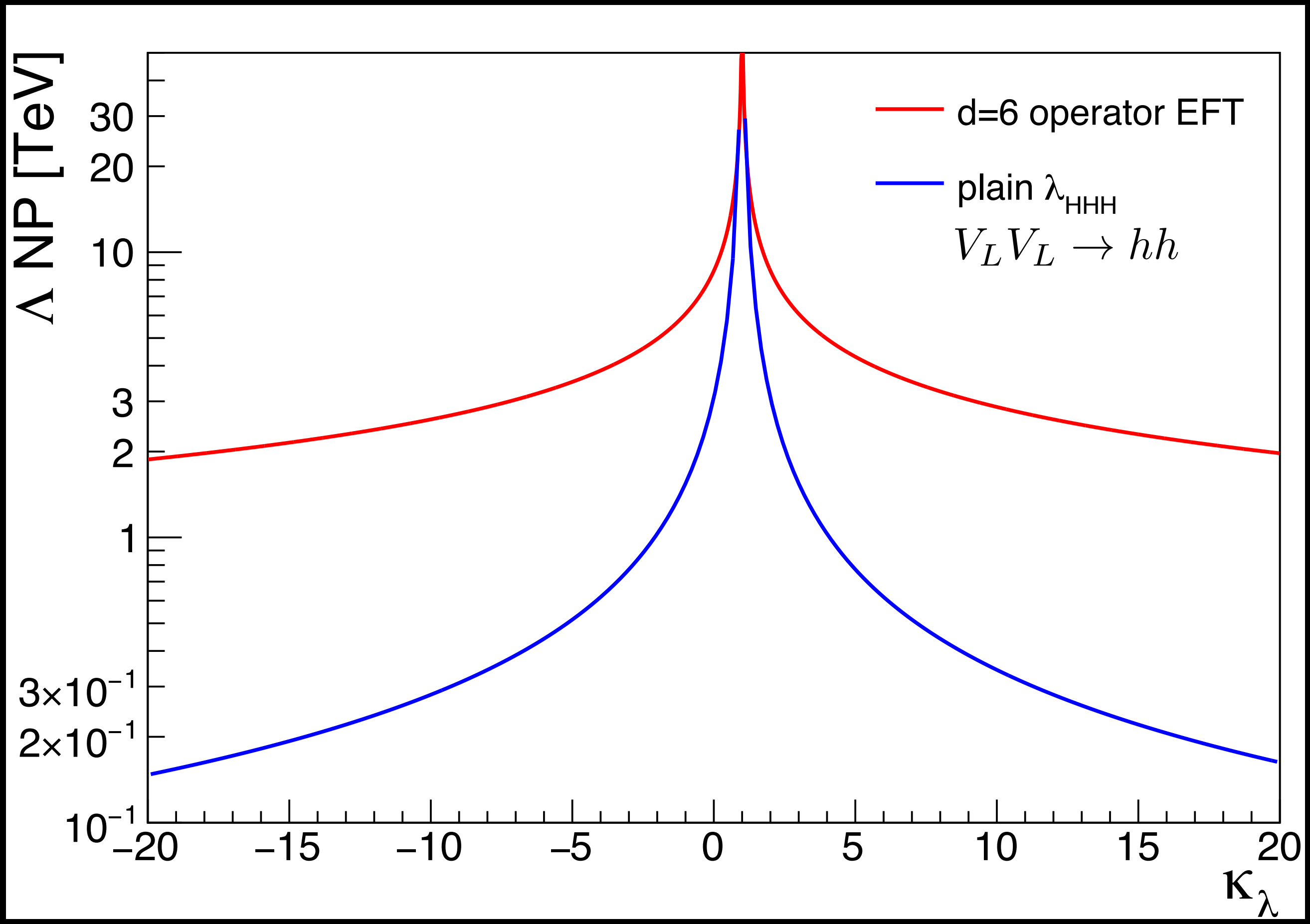
1) modify SM adding a d=6 operator $\dfrac{(H^\dagger H)^3}{M^2}$

2) modifying SM adding just modifications to κ_λ

NP needed at much lower scale in the second case

From exp. point of view: interesting to look at $V_L V_L \to hh$ i

Very similar case of the VBS scattering without Higgs (pre-Higgs boson discovery)



Unitarity violation 2

arXiv:1704.02311

unitarity breaking in *hh* → *hh* scattering amplitude

$$a^0_{hh\to hh} = -\frac{1}{2}\frac{\sqrt{s(s-4m_h^2)}}{16\pi s}\left[\lambda^2_{hhh}\left(\frac{1}{s-m_h^2} - 2\frac{\log\frac{s-3m_h^2}{m_h^2}}{s-4m_h^2}\right) + \lambda_{hhhh}\right]$$

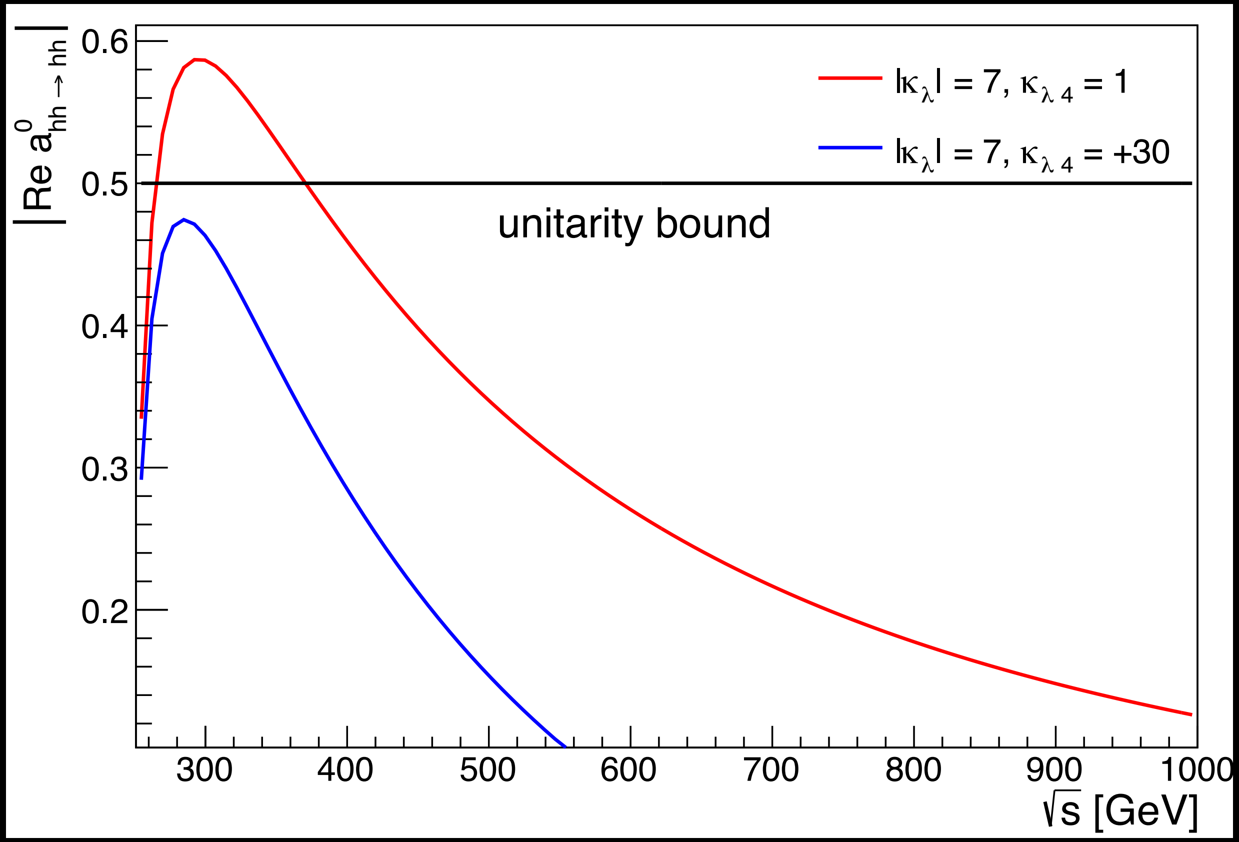
unitarity condition $\left|\mathrm{Re}\, a^0_{hh\to hh}\right| < \frac{1}{2}$

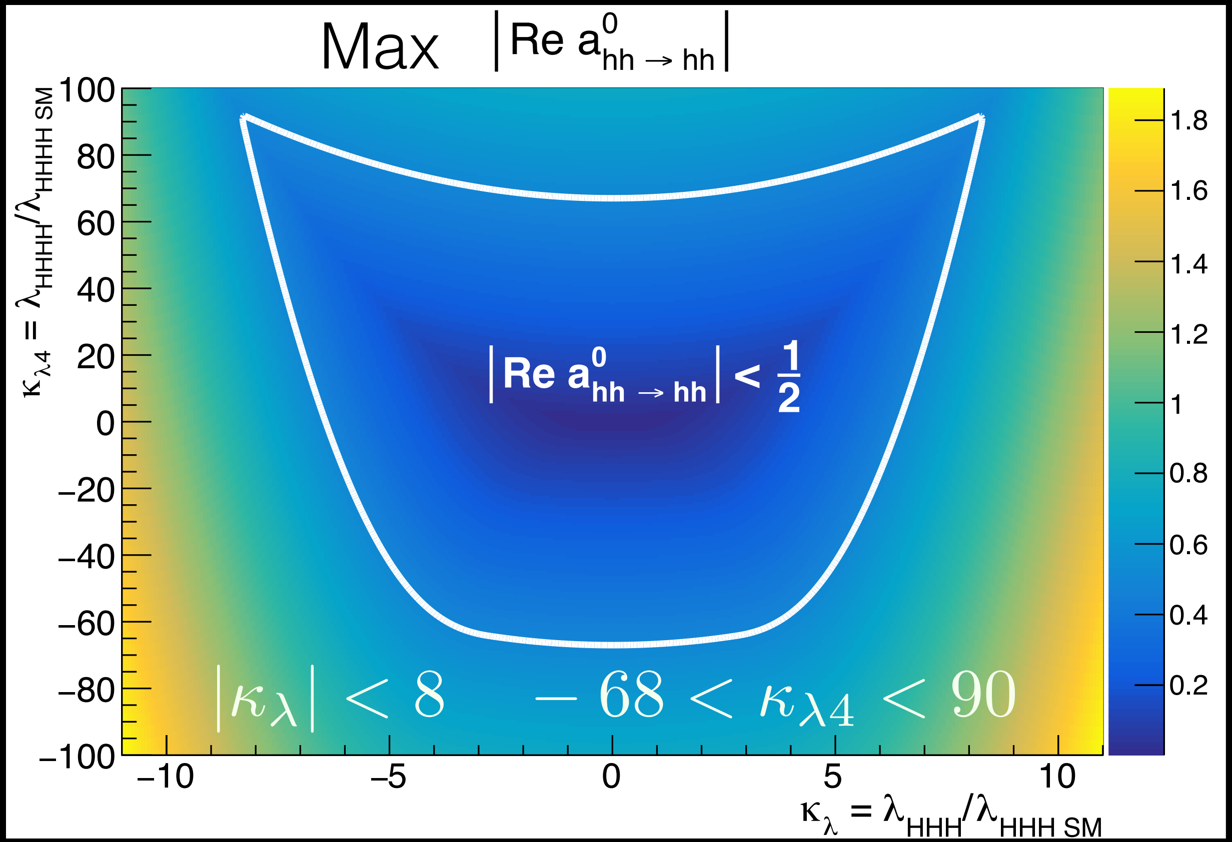
$|\kappa_\lambda| < 6.5 \quad \kappa_{\lambda 4} = \frac{\lambda_{\mathrm{HHHH}}}{\lambda_{\mathrm{HHHH\,SM}}} = 1$

$|\kappa_{\lambda 4}| < 65 \quad \kappa_\lambda = 1$

unitarity breaking at low √s, interesting to look at BSM models (typically hh resonances) that could restore it like in S-wave ππ, KK scattering with the showing up of f_0, a_0 : typically broad resonances (they can easily decay to the initial state products)

Maximised over √s [$2m_h$ - 1 TeV]





Unitarity violation with d=6 operator EFT

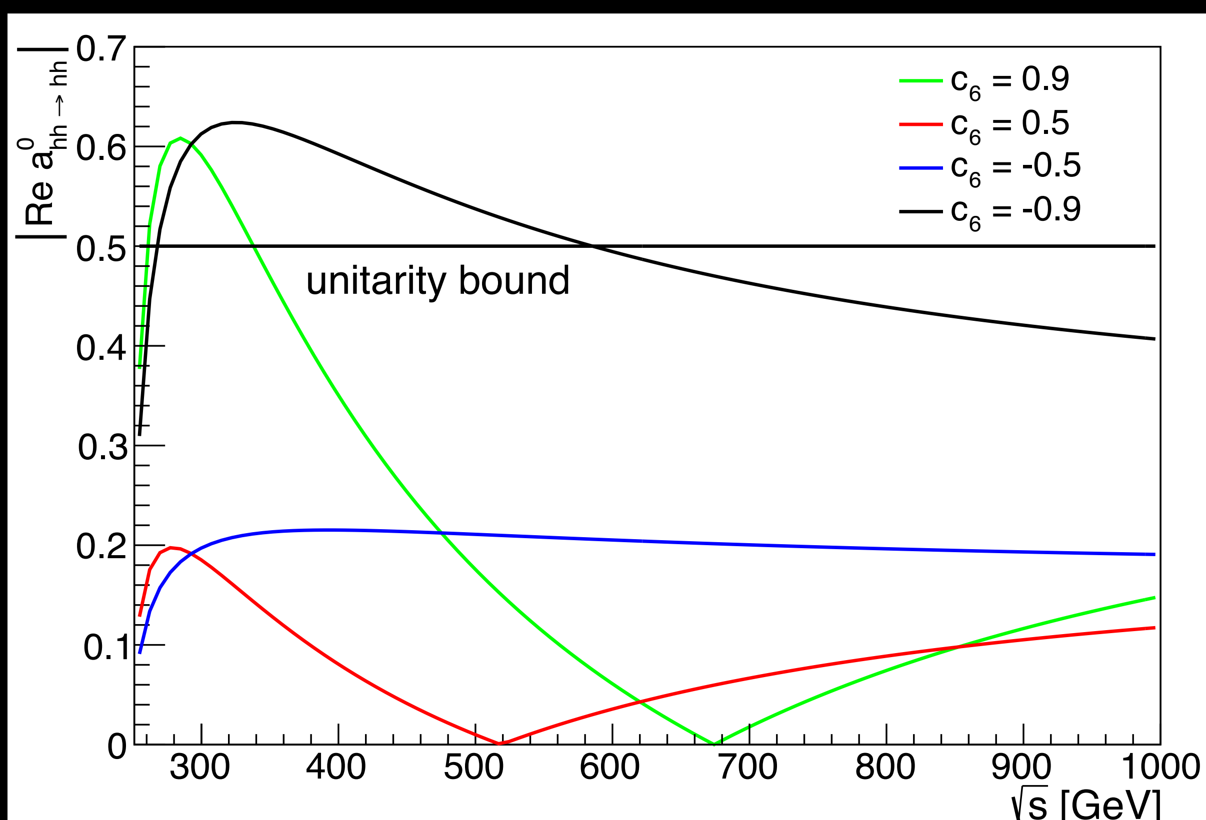
arXiv:1704.02311

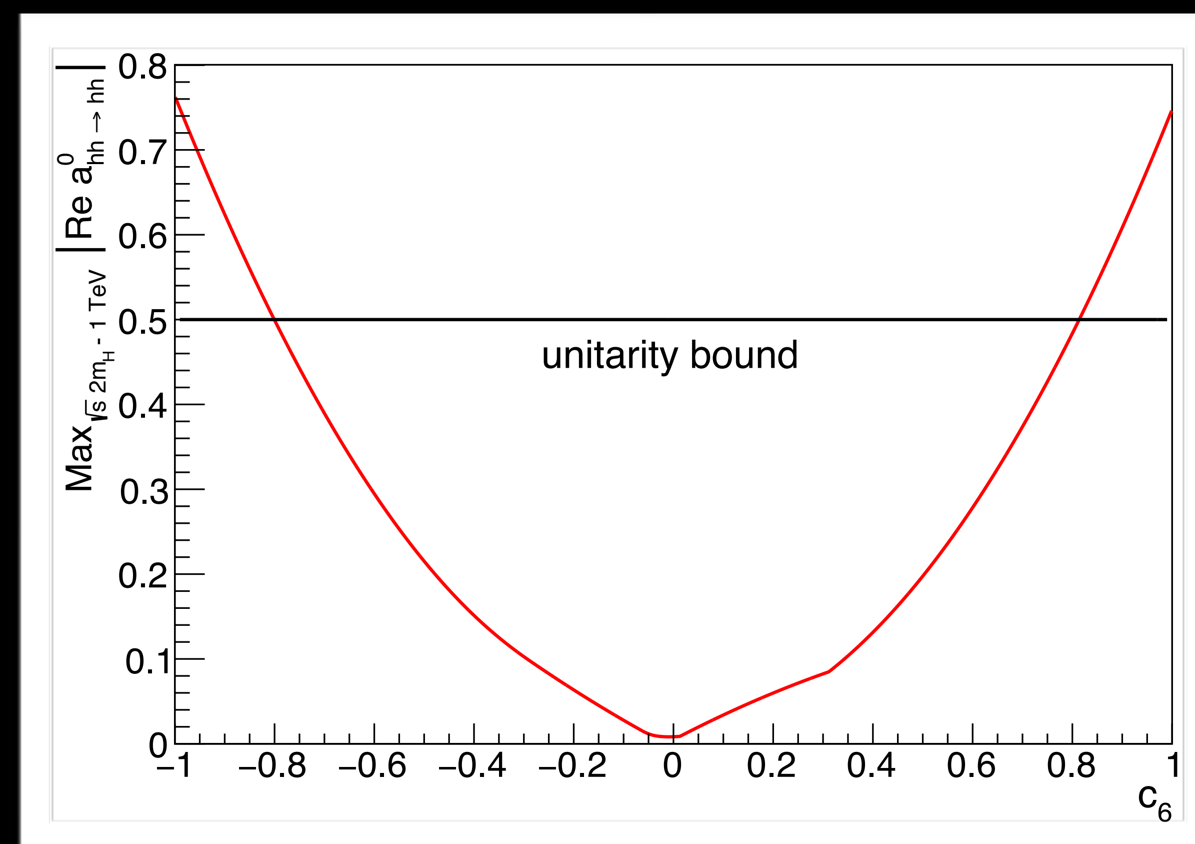
$$V^{(6)}(H) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{c_6}{v^2} |H|^6$$

addition of d=6 operator

relation valid for $c_6 << 1$

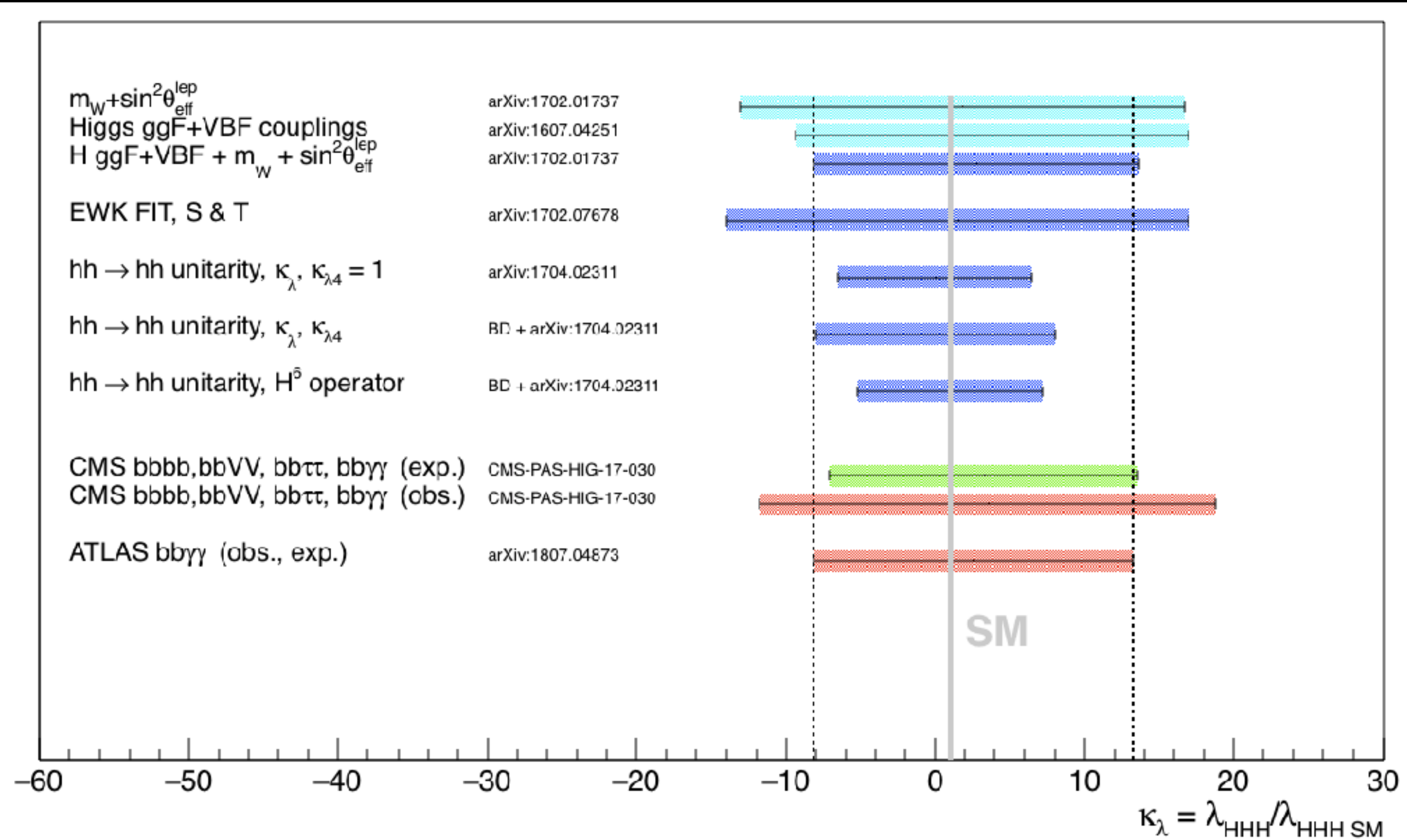
$$\kappa_\lambda = 1 + 7.8 c_6 \qquad \kappa_{\lambda 4} = 1 + 47 c_6$$





$$|c_6| < 0.8 \rightarrow -5.2 < \kappa_\lambda < 7.2 \qquad -37 < \kappa_{\lambda 4} < 39$$

Summary



$m_W+\sin^2\theta_{eff}^{lep}$
arXiv:1702.01737
Higgs ggF+VBF couplings
arXiv:1607.04251
H ggF+VBF + m_W + $\sin^2\theta_{eff}^{lep}$
arXiv:1702.01737
EWK FIT, S & T
arXiv:1702.07678
$hh \to hh$ unitarity, κ_λ, $\kappa_{\lambda 4} = 1$
arXiv:1704.02311
$hh \to hh$ unitarity, κ_λ, $\kappa_{\lambda 4}$
BD + arXiv:1704.02311
$hh \to hh$ unitarity, H^6 operator
BD + arXiv:1704.02311
CMS bbbb,bbVV, $bb\tau\tau$, $bb\gamma\gamma$ (exp.)
CMS-PAS-HIG-17-030
CMS bbbb,bbVV, $bb\tau\tau$, $bb\gamma\gamma$ (obs.)
CMS-PAS-HIG-17-030
ATLAS $bb\gamma\gamma$ (obs., exp.)
arXiv:1807.04873
SM
−60
−50
−40
−30
−20
−10
0
10
20
30
$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH\ SM}$

What to do in the next days?

1) today dedicated to “general” review talk, plus talk on future collider facilities that look at us to make solid projections for their projects

3) discussion sessions every day (can be parallel), first one today to discuss the discussion topics and define discussion conveners - if you have ideas please show up, don’t be shy and bring them at today discussion session

4) review all the work done up to now

Tuesday, 4 September 2018

Time	Session
08:00	
09:00	
09:40	LHC status
10:30	Coffee break
11:00	
12:30	Future colliders
13:00	Lunch break
14:00	Future Colliders
15:00	Combination of single and double Higgs measurements
16:00	Coffee break
16:30	Discussion
18:00	Welcome Reception

Wednesday, 5 September 2018

Time	Session
08:30	
09:40	b-jets
10:45	
11:00	Coffee break
11:30	H(bb)H(gammagamma)
13:00	Lunch break
14:00	H(bb)H(bb)
16:00	Coffee break
16:30	Discussion

Thursday, 6 September 2018

Time	Session
09:00	H(bb)H(tautau)
10:30	Coffee break
11:00	H(bb)H(tautau)
12:20	
13:00	Lunch break
14:00	Fermilab director's welcom...
14:10	
14:40	H(bb)H(VV)
16:00	Coffee break
16:30	H(bb)H(VV)
17:00	Discussion
19:00	Workshop dinner

Friday, 7 September 2018

Time	Session
09:00	jets and boosted techniques
10:00	
10:30	Coffee break
11:00	Theory
11:30	Other signatures
13:00	Lunch break
14:00	Combination and other common topics
15:30	Wine and Cheese
17:30	Discussion

Saturday, 8 September 2018

Time	Session
09:00	Summary
10:30	Coffee break
11:00	Discussion Summary, White Paper and Follow-Ups
12:30	Lunch break
13:00	FNAL visit

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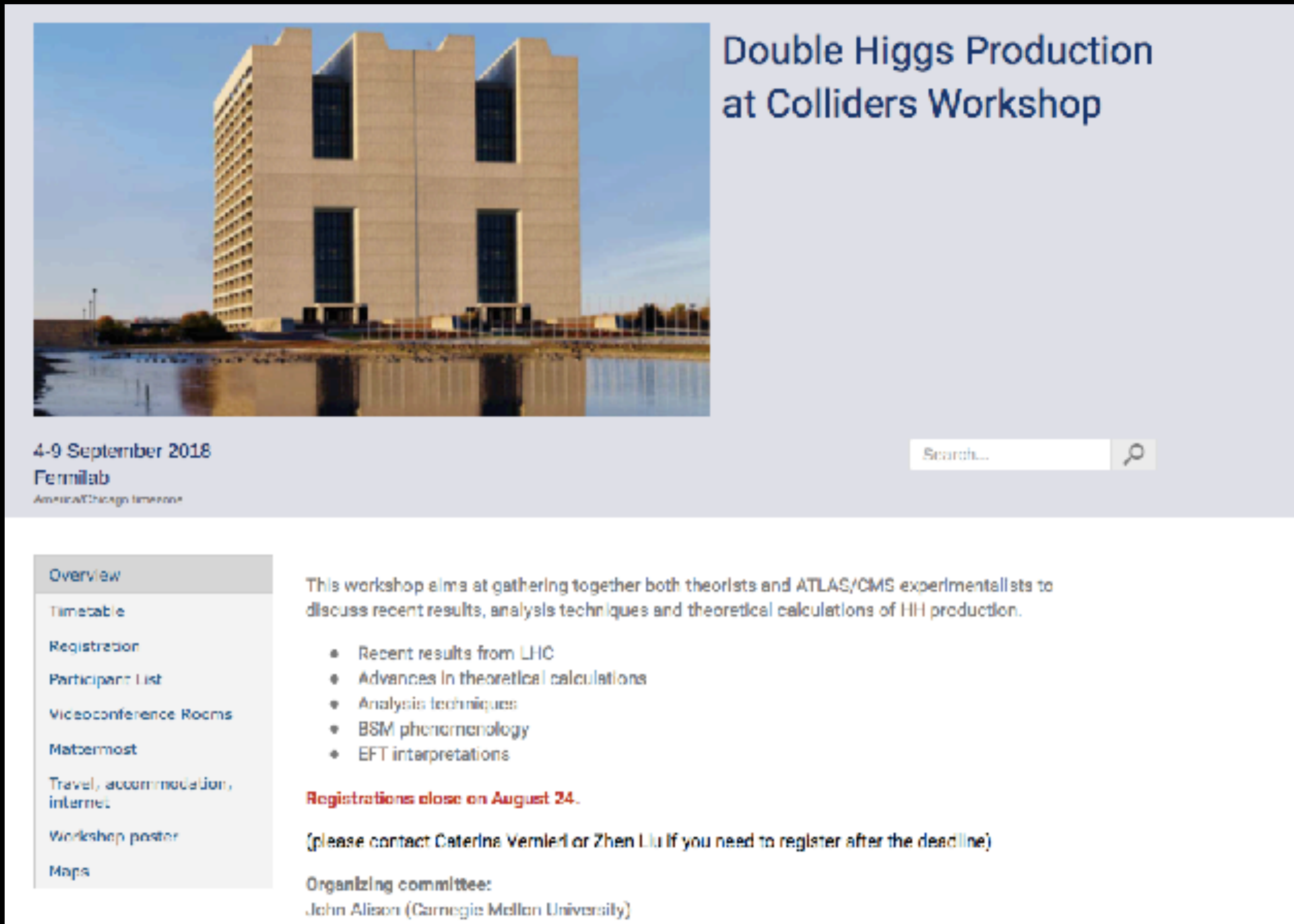
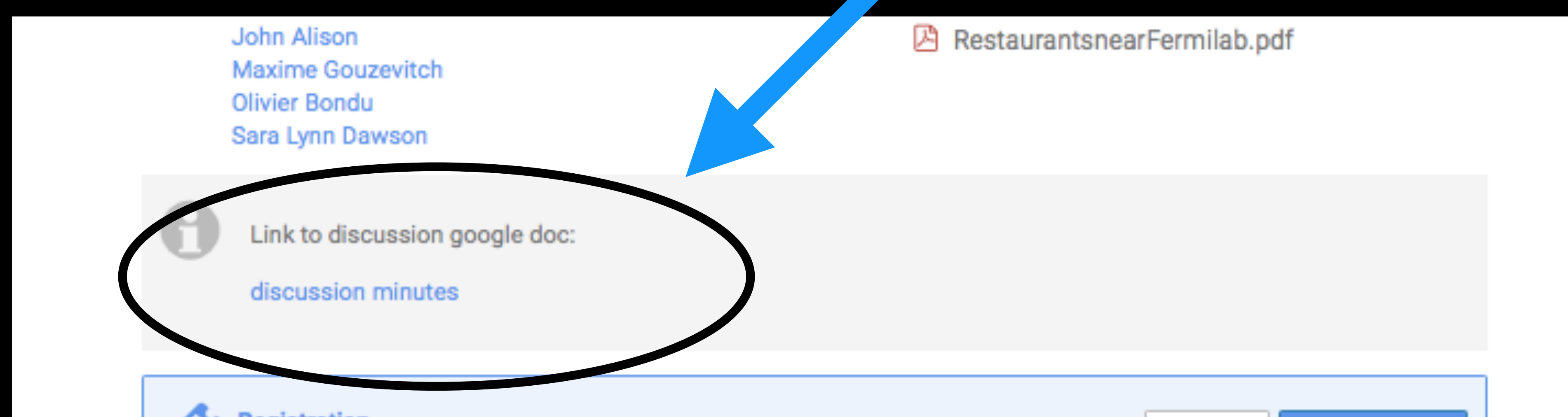
5) write minutes for each session: you can add comments for the discussion points you want to make at the link on the agenda





at the bottom part of the main page

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6) rump up with a plan for the future by this Saturday

7) Saturday we will have the summary of the discussions and we will make the point for the next steps: uniform MC generators, model interppratations, ATLAS/CMS combination, timeline

8) write down a white paper of the workshop (try to define as much as common strategies as possible)

Have a nice workshop!!

Do we really know everything about the Higgs boson?

We know:

- couplings to vectors, the heaviest lepton and quark families
- mass

Will HL-LHC give more striking information about the Higgs boson ?

- it will observe $h \to \mu^+\mu^-$
- nothing else if we are unlucky… :-(

Testing the last untested piece of the SM lagrangian is a must for fundamental physics, giving up on it means giving up in understanding the foundation of nature

On going project proposals

CepC, FCC-ee:

- can test Higgs couplings at the best possible accuracy
- some sensitivity to Higgs boson self-coupling through 1-loop EWK correction to Zh production
- can be extended in energy to make other interesting SM high precision test (Tera-LEP, W mass, top mass)
- have a nice (far?) future development as a pp collider for direct Higgs self coupling measurement

ILC, CLIC (@low energy):

- can test Higgs couplings at ~% level accuracy
- some sensitivity to Higgs boson self-coupling through 1-loop EWK correction to Zh production
- can be extended in energy to make other interesting SM high precision test (top mass), higgs self-coupling
  - but it needs $\sqrt{s} > 1\mathrm{TeV}$
- have a nice (far?) future development as linear collider hosting new high gradient lepton acceleration (plasma acceleration)

SppC, FCC-hh:

- they look more and more the next to the next step, need to wait high intensity magnet development (16T magnet at least)

CEPC Schedule (ideal)

design issues
R&D items
preCDR

design, funding
R&D program
Intl. collaboration
site study

seek approval, site decision
construction during 14th 5-year plan
commissioning

- **CEPC data-taking starts before the LHC program ends**
- **Possibly con-current with the ILC program**

European strategy timeline

December 2018:

- deadline for submission of inputs from the community

2019: Community discussion

- Open Symposium (~ September 2019, and one early 2019)
- Preparatory group summaries community feedback in Briefing Books

Early 2020: Strategy Group discussion and preparation of the draft (1 week meeting, inspired by briefing books)

Inputs: ~10 pages documents can be provided by individuals, groups, institutions

could an e^+e^- option enter as a single document (in Europe or in Cina?), could we propose an explicit input for CepC given the time schedule?

CepC project development

Conceptual Design Report: done

Technical Design Report:

what model of collaboration ?

what timeline ?

when is it the right time for formal agreement?

are formal agreements between IHEP and EU institutions useful?

agreements can include:

- exchange programs for students and researcher
- formal commitments on TDR tasks
- collaboration on specific task from the funding point of view

FCC-ee, CepC collaboration: obvious from the physics point of view, possible in practice?

What about China ?

Are deadline set by the government or scientific institutions for the project development ?

Werner Rigler
CERN

FCC-hh physics and detector coordinator

王贻芳 (Yifang Wang)
China

IHEP director

Imad Laktineh
France

working on semi digital hardronic calorimeter for ILC and CEPC

Daniela Bortoletto
UK

vertex detectors/depleted cmos and Higgs physics

Franco Bedeschi
Italy

coordinator of the INFN group on Research and Development for Future Accelerators

Marcel Vos
Spain

co-leader of the ATLAS/future collider project at IFIC Valencia

Alain Blondel
Switzerland

member of the coordination group of FCC, and co-coordinator of FCC-ee 'physics and experiments'

We will take note
Ruan Monqui

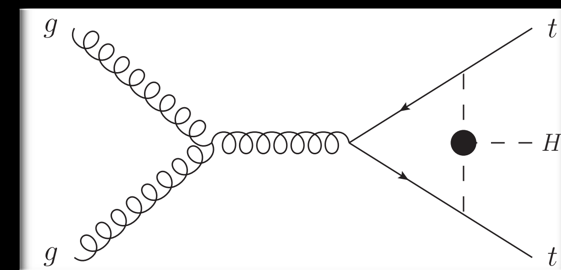
He won the competition as fastest summary talk writer than ever and he will be together with us the editor of a document summarising the discussion

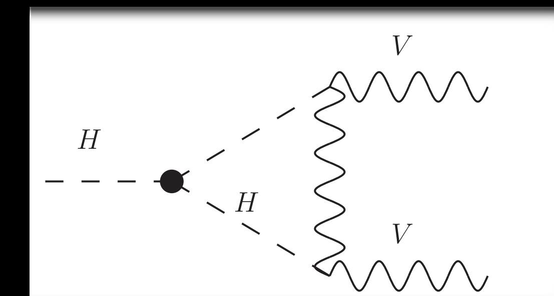
Panel discussion starts

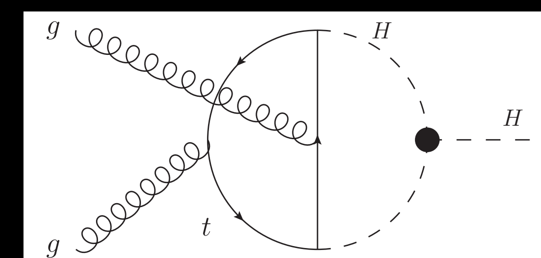
Particle physics

Experimental constraints

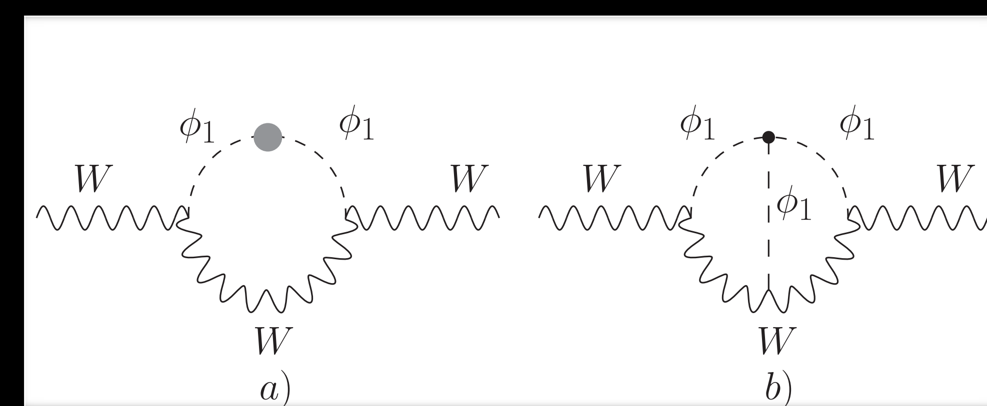
Higgs boson couplings
arXiv: 1607.04251

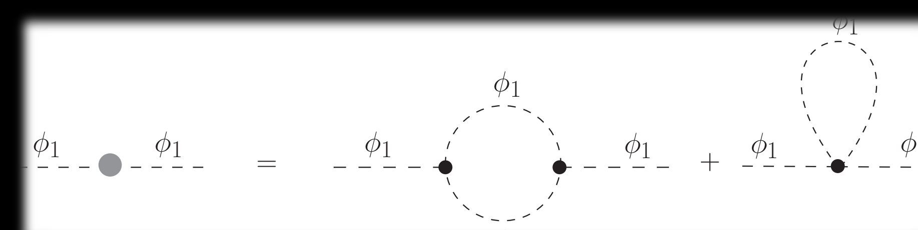




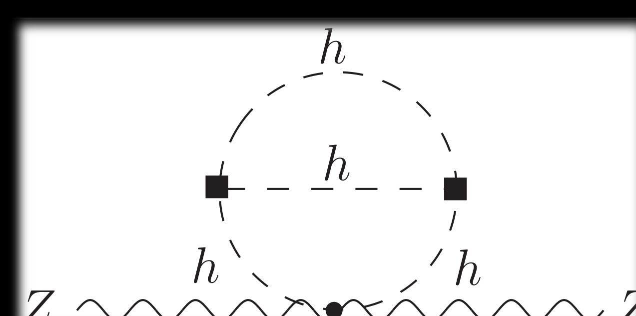


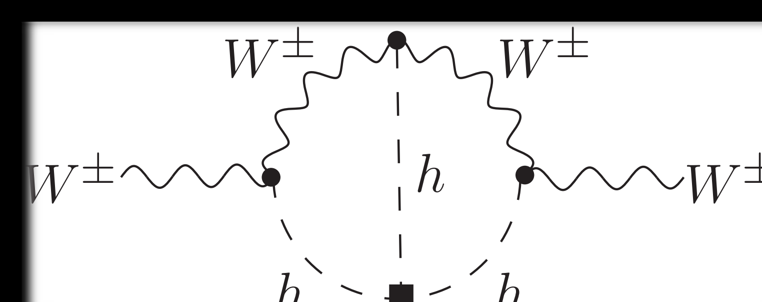
W mass and $\sin^2\theta^{\mathrm{lep}}_{\mathrm{eff}}$
arXiv: 1702.01737





S and T relations
arXiv: 1702.07678





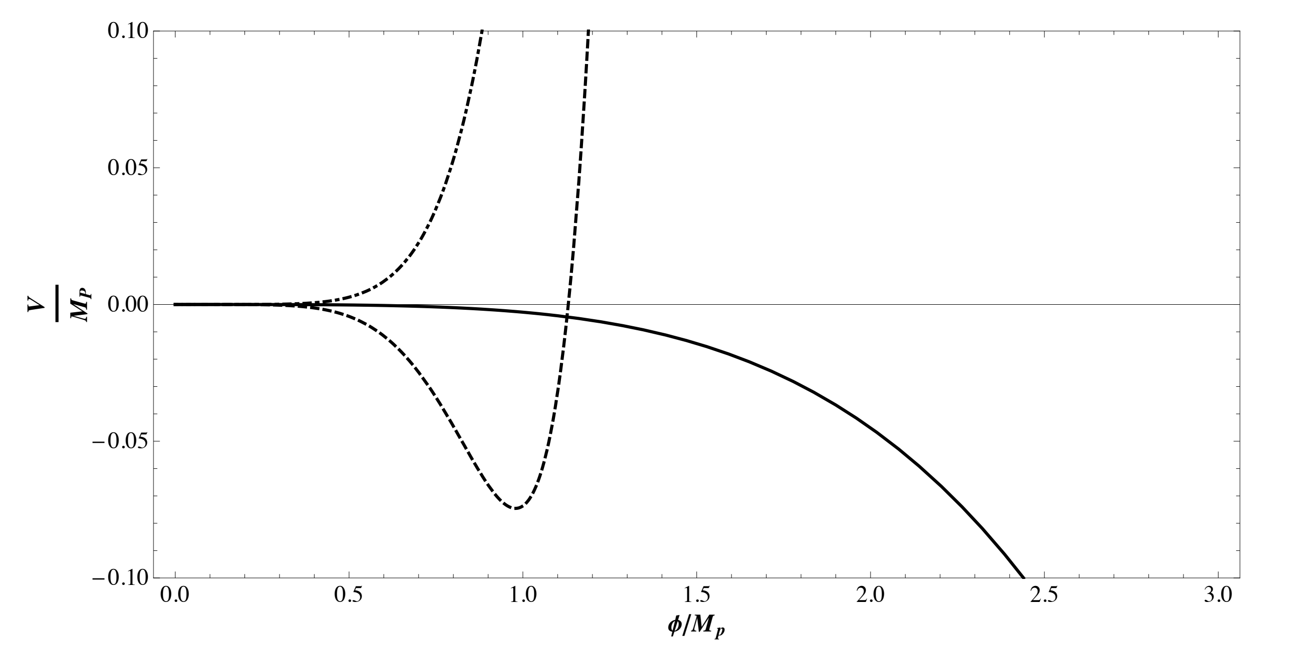
stability and new physics

New physics at the Planck scale can strongly affect the transition time [V. Branchina, E. Messina **Phys. Rev. Lett. 111 (2013) 241801**]

$$V(\phi) = \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

M_P suppressed

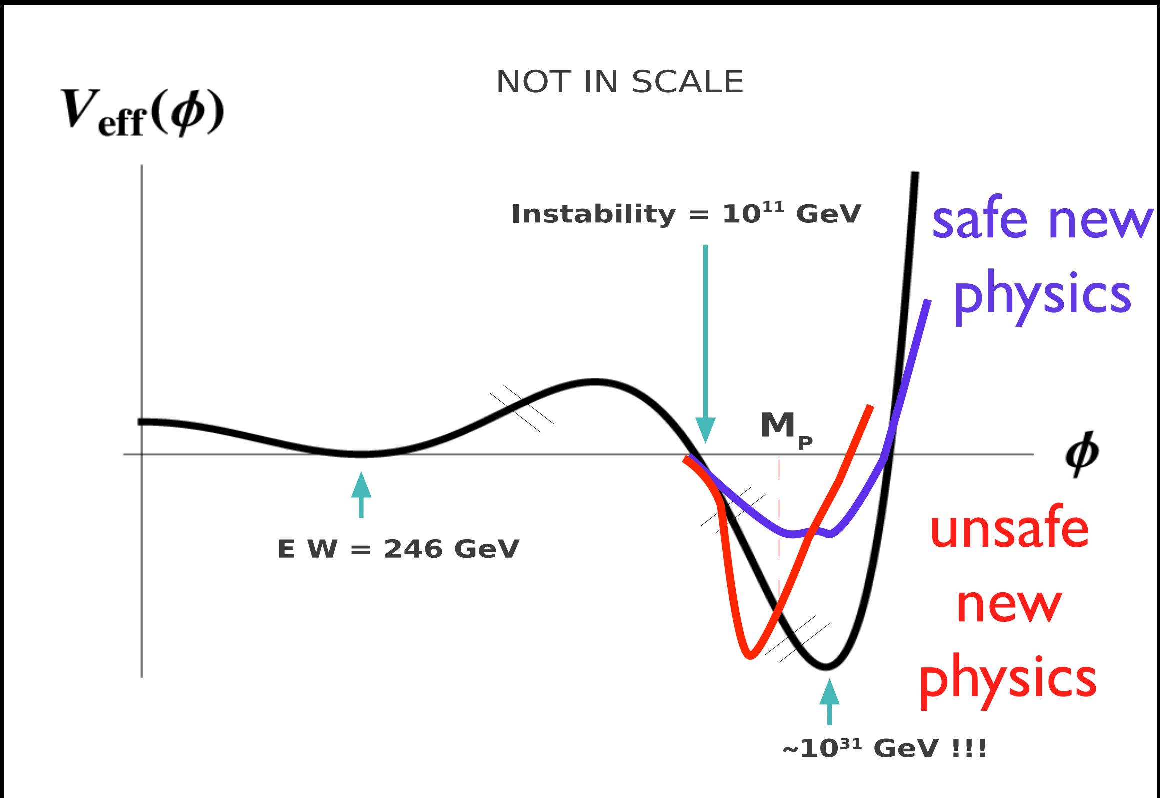
new potential around M_{pl}



The universe gets destroyed in a shot...

New physics at the Plank scale must be carefully tuned...

In general, stability considerations are preserved if new physics doesn't decrease the derivative of the potential at the turning point.



cosmological constant

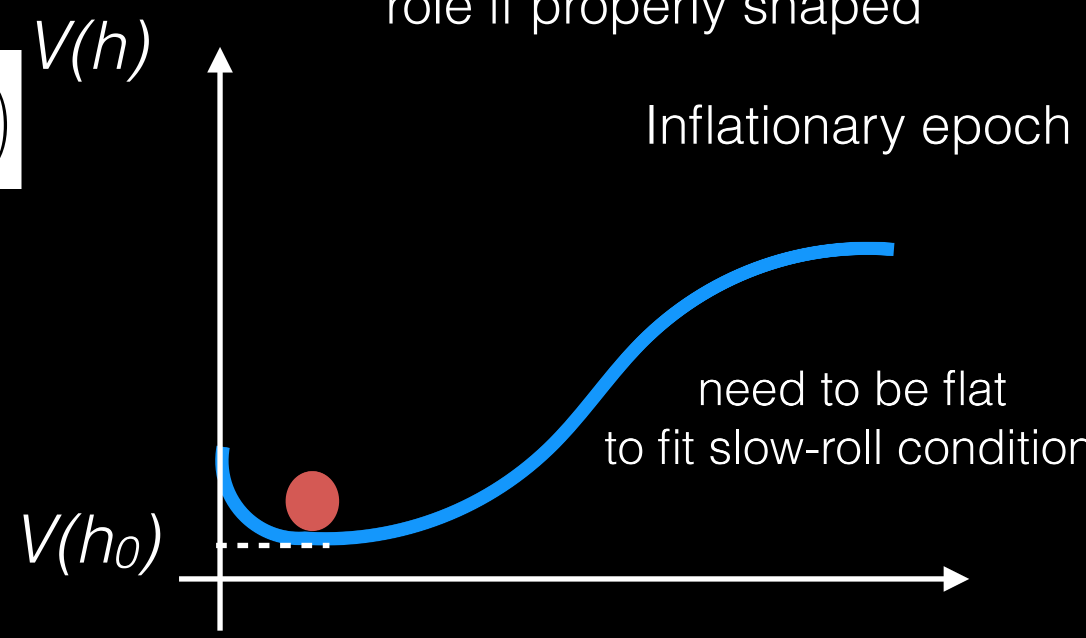
$$S = \int \left[\frac{1}{2} M_{\rm pl}^2 R + \mathcal{L} \right] d^4x \sqrt{-g} = \int \left[\frac{1}{2} M_{\rm pl}^2 R - \frac{1}{2} \partial_\mu h \partial^\mu h + V(h) + ... \right] d^4x \sqrt{-g}$$

a(t) universe radius

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3} V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a} \right)$$

universe radius, exponentially expanding during inflation

The Higgs potential could have such role if properly shaped



$h_0 = \langle 0 | \, h \, | 0 \rangle$ Higgs VEV

The value of the potential at its minimum sets the cosmological constant (i.e. the amount of dark energy)

$$\frac{\Lambda c^4}{8\pi G} = V(h_0)$$