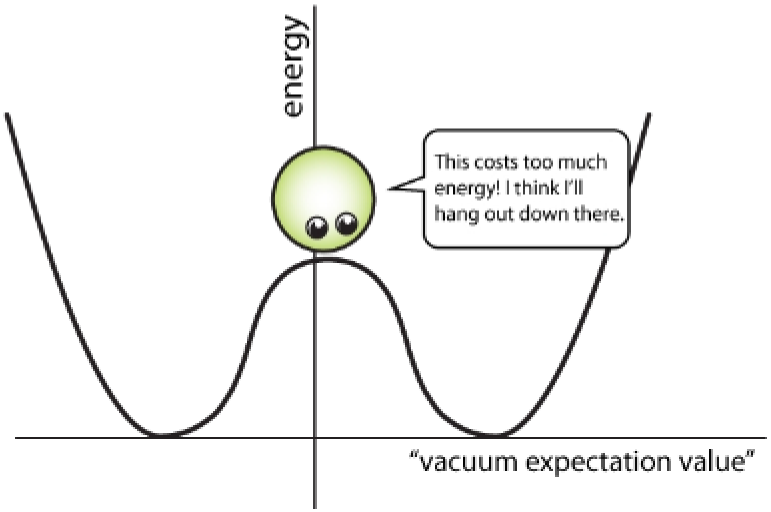
Maxime Gouzevitch

Higgs boson : discovery, study and future

1) Introduction: historical perspective
2) Situation before the LHC
3) Higgs Hunting at the LHC
4) Future colliders



Jubilee Seminar dedicated to the 85th anniversary of Prof. I. Golutvin

Introduction: Historical Perspective

Spontaneous (dynamical) symmetry breaking

L. Euler, Memoires de l'Academie des Sciences de Berlin, **13**, *252 (1759)*

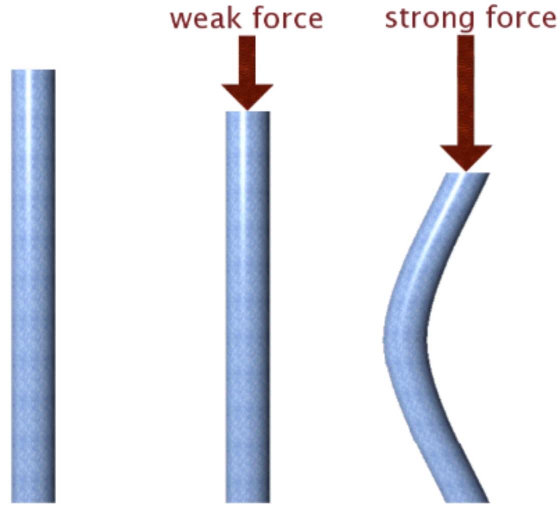


Figure: Elastic rod compressed by a force of increasing strength

1.1) A successful example

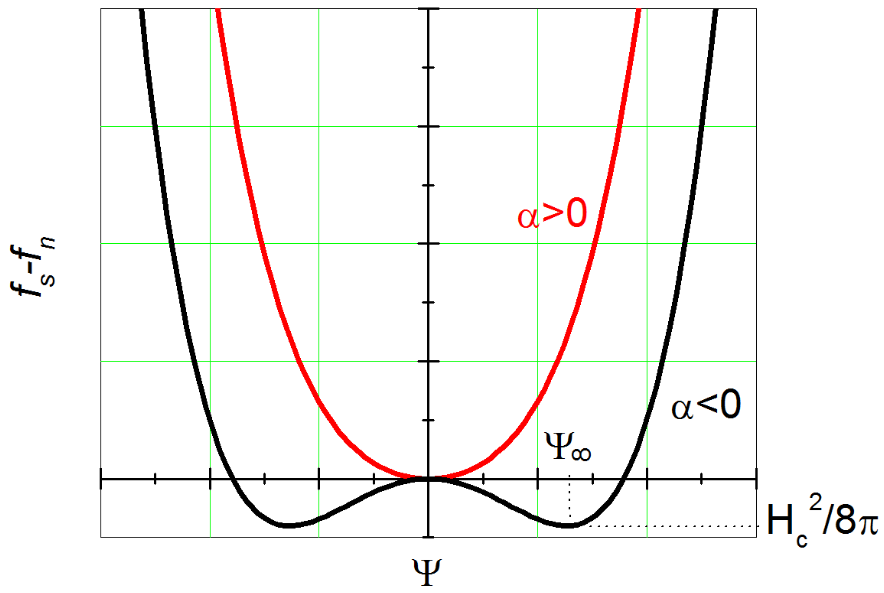
Ginzburg-Landau theory from 1950 offered a macroscopic (ie effective) theory for conventional superconductivity,

$V(\Psi) = \alpha(T)|\Psi|^2 + \beta(T)|\Psi|^4 \qquad \alpha(T) \approx a^2(T - T_c) \qquad \text{and} \qquad \beta(T) \approx b^2$

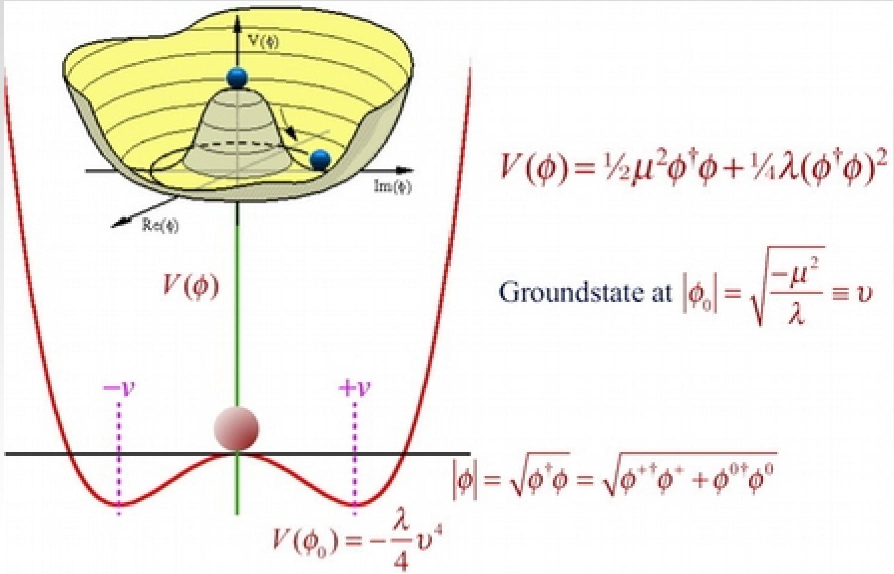
In 1957 Bardeen, Cooper and Schrieffer provided the microscopic (fundamental) theory that allows one to

1) interpret $|\Psi|$ as the number density of Cooper pairs
2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

Ian Low
Argonne/Northwestern/CERN



1.2) SM and BEH mechanism



- After EWSB the extra degrees of freedom of Higgs doublet from the potential are redefined trough a proper gauge into W±, Z mass.
- Yukawa coupling gives mass to fermions.

$$\mathscr{L}_{higgs}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi)$$

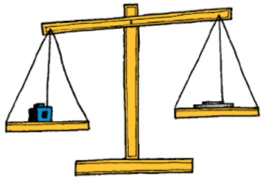
$$V(\phi) = -\mu^2\phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\psi_L^i\psi_R^j\phi$$

1.3) Potential reformulation

We can rewrite the BEH potential as with 3 fundamental parameters that are related

$\mathbf{V = - m_H^2 |H|^2 + \lambda|H|^4}$ **and** $\mathbf{\lambda = m_H^2 / 2 v^2}$

1) $\mathbf{m_H}$ can be interpreted as the mass of the Higgs field. It is directly measured once Higgs boson is discovered.

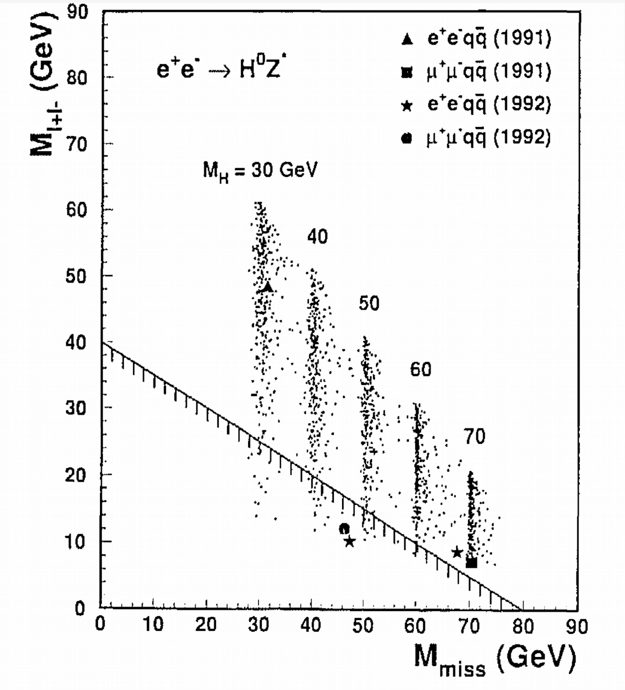


2) $\boldsymbol{\lambda}$ is the Higgs boson field self coupling constant.
It gives the intensity of $H^* \rightarrow HH$ and $HH \rightarrow HH$ interactions.
The hardest to measure.

3) **v** is the vacuum expectation value and it is measured indirectly and very precisely at low energy looking on beta decays

$$v = 2^{-1/4} \cdot G_F^{-1/2} \approx 246\ \mathrm{GeV}$$

2) Situation before the LHC



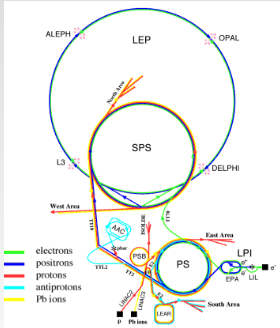
2.1) Dark age times

1) EWSB proposed in 60-ies
2) No significant constraints existed till 70-ies: only indirect through neutron stars or nuclear physics.

We should perhaps finish our paper with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, ..., 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 doing experiments vulnerable to the Higgs boson should know how it may turn up.

— John R. Ellis, Mary K. Gaillard, and Dimitri V. Nanopoulos, [8]

2.2) Higgs in accelerators era: pre-LHC

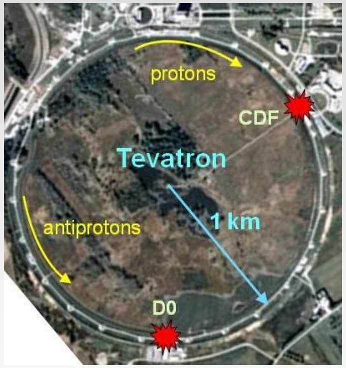


LEP e+e-
209 GeV (CERN)

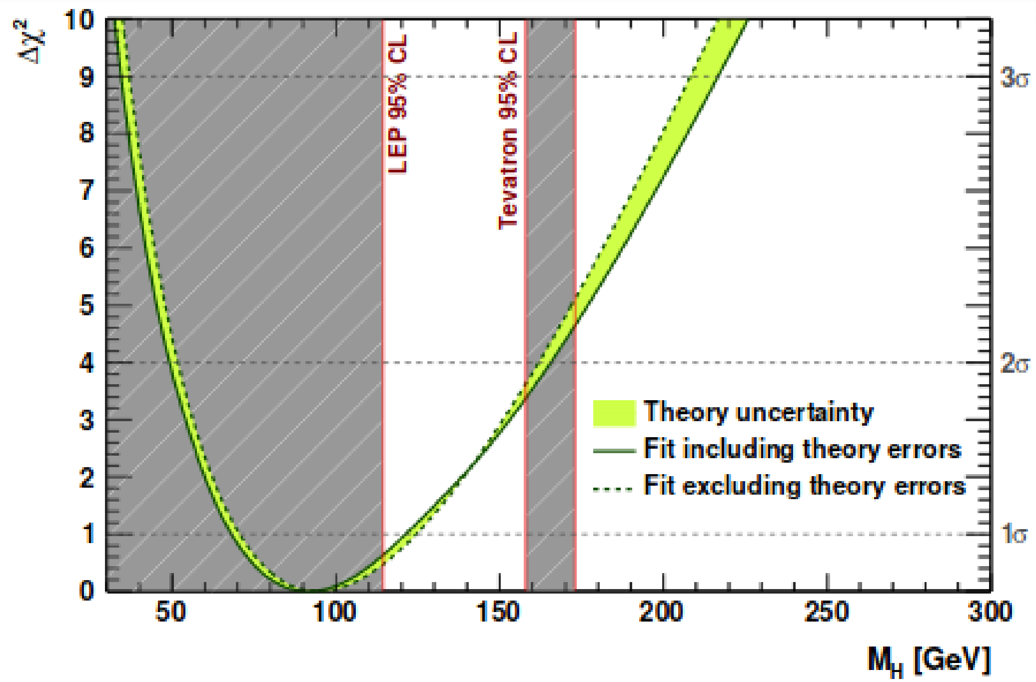
- Z factory
- $m_H > 114$ GeV

TEVATRON p+p-
1.96 TeV (USA)

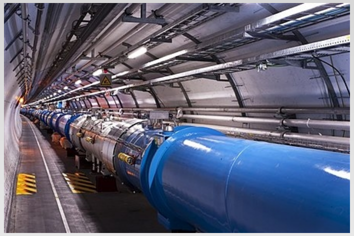
- W, Z factory
- M ~ 175 GeV
- M_H != 2 M_W

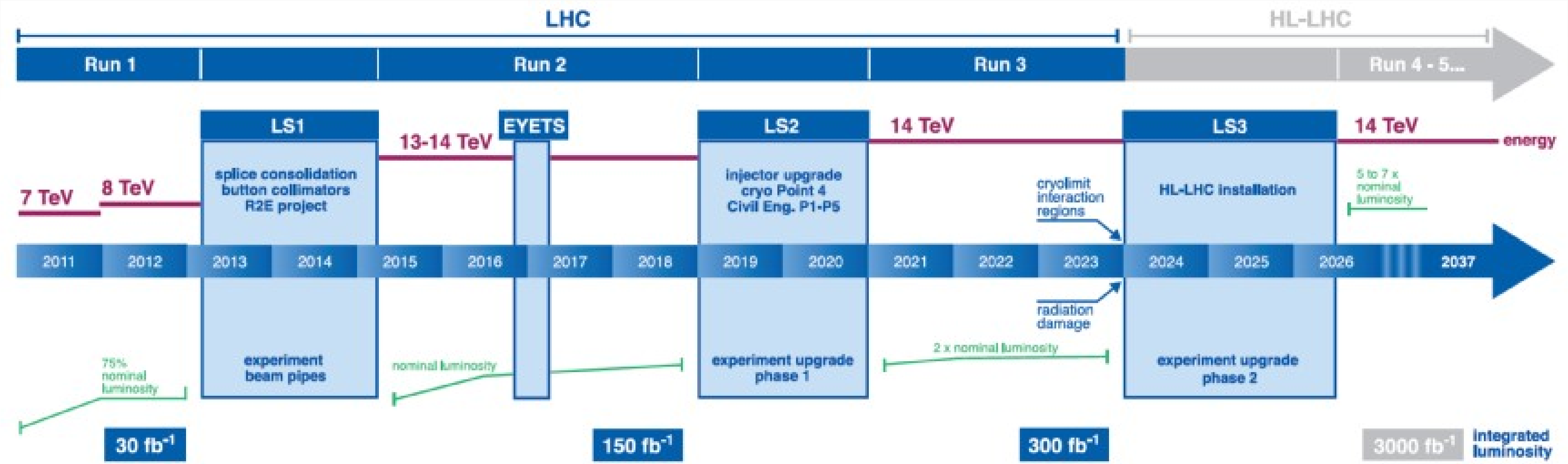


- LEP:
  e+e- → ZH
- TEVATRON:
  qqbar → ZH/WH
- Indirect constrains through the EWK corrections.



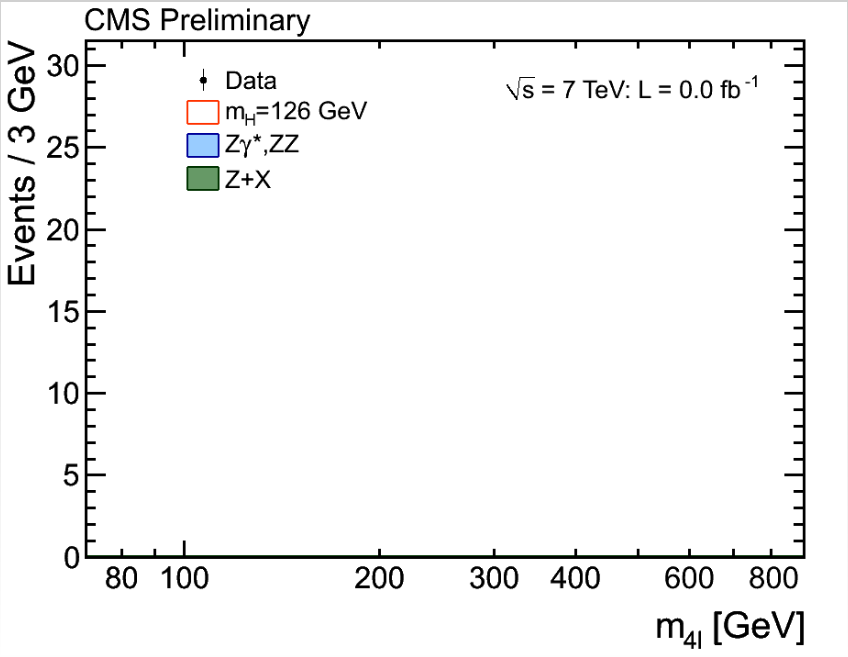
3) Higgs Hunting at the LHC

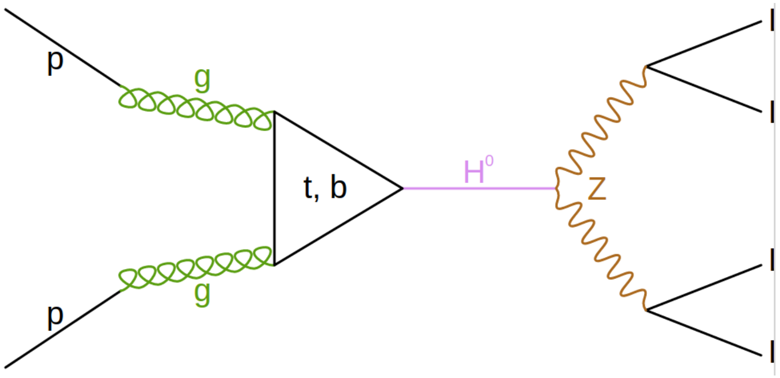




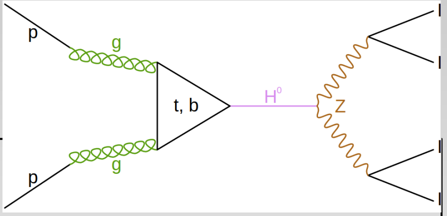
3.1) Higgs discovery

- 4 July 2012: Higgs boson discovery by ATLAS – CMS from LHC
- 2013: Nobel prize to theorist (Englert-Higgs, Brout died before) in 2013.
- 2014: Cherenkov prize of Russian Academy of Science to Igor Golutvin (CMS) and Aleksandr Zaitsev (ATLAS) for « Major contribution to CMS and ATLAS experiments at the LHC, qui ont permi la découverte du boson de Higgs »





3.2) What did we learned first



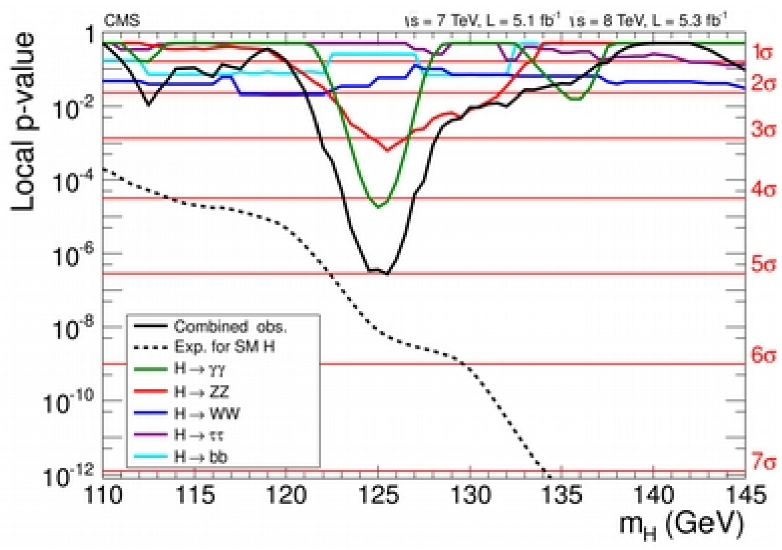
- Production mechanism: gluon-gluon fusion.

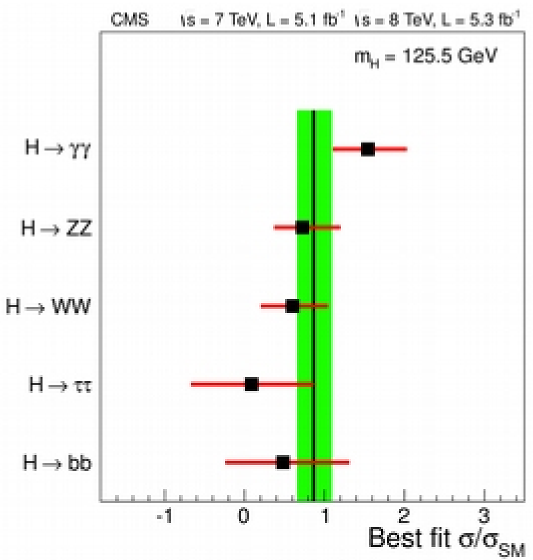
H in the only particle that was discovered through the loops!

- Higgs boson was discovered in VV channels: $H \rightarrow ZZ$, $(H \rightarrow WW)$, $H \rightarrow \gamma\gamma$.

Production and decay in these compatible with EWSB prediction from BEH mechanism:

  – Higgs boson exist with a mass compatible with EWK fits and the « scalar » hypothesis is preveledged by the data.
  – BEH mechanism is responsible of at least 70% of EWSB.
  – Indirectly we see that top quark mass is generated by Yukawa coupling.



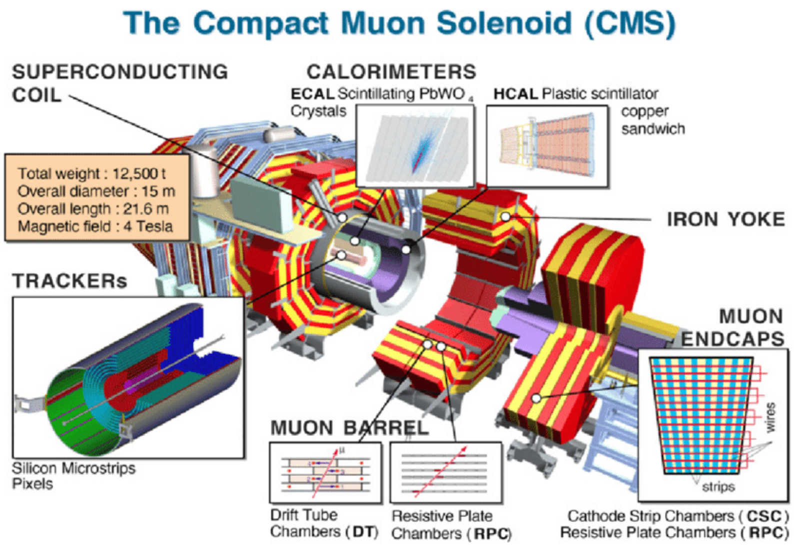


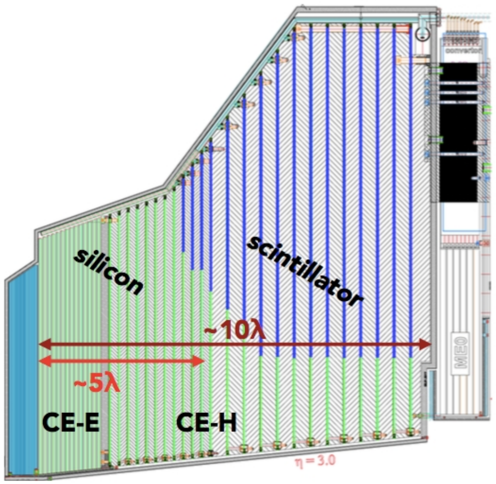
3.3) Contribution of I. G. and RDMS to H discovery

- Higgs boson discovery detectors: ECAL+tracker (photons, electrons) and Muon+Tracker system where RDMS and Igor Golutvin played a key role.

- The Vector-Boson Fusion production is the most interesting channel for EWSB understanding. It is characterized by forward jets, relying on Endcap Hadronic calorimeter that is also an RDMS and I.G. “baby”.

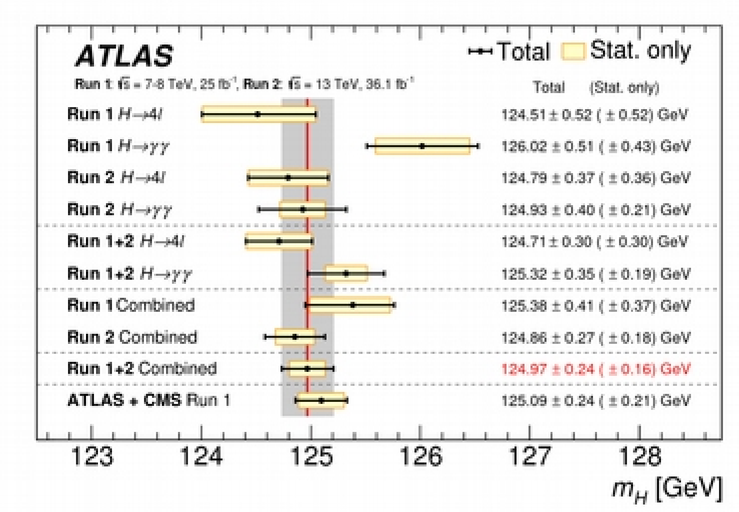
- HL-LHC forward ECAL would be fully silicon as pioneered by Dubna Silicon program (I.G. spokeperson) and RD35 program aleady in 1992-94.



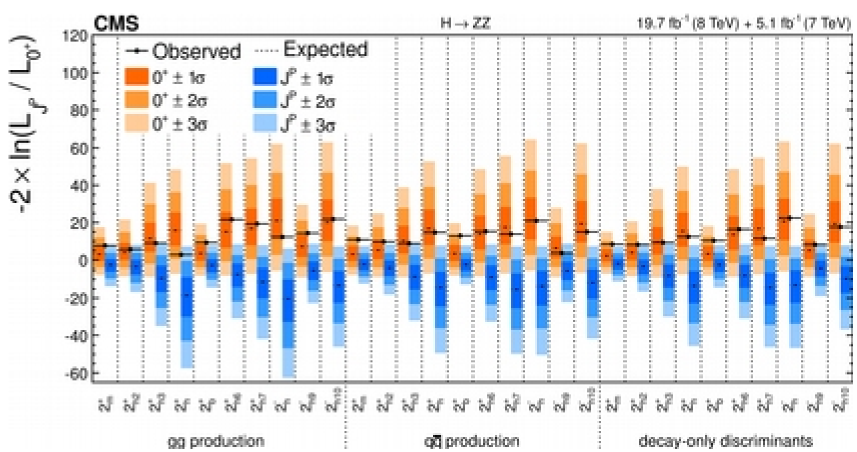


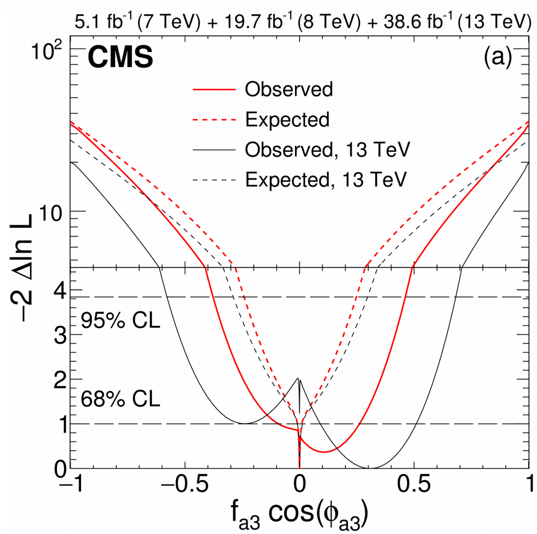
3.4) H boson properties: Run II

- Measure precisely the Higgs mass and validate its compatibility between $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ$, att 8 TeV and 13 TeV. ✓



- Validation of scalar nature of Higgs boson from angular distribution: spin-0, even parity. ✓

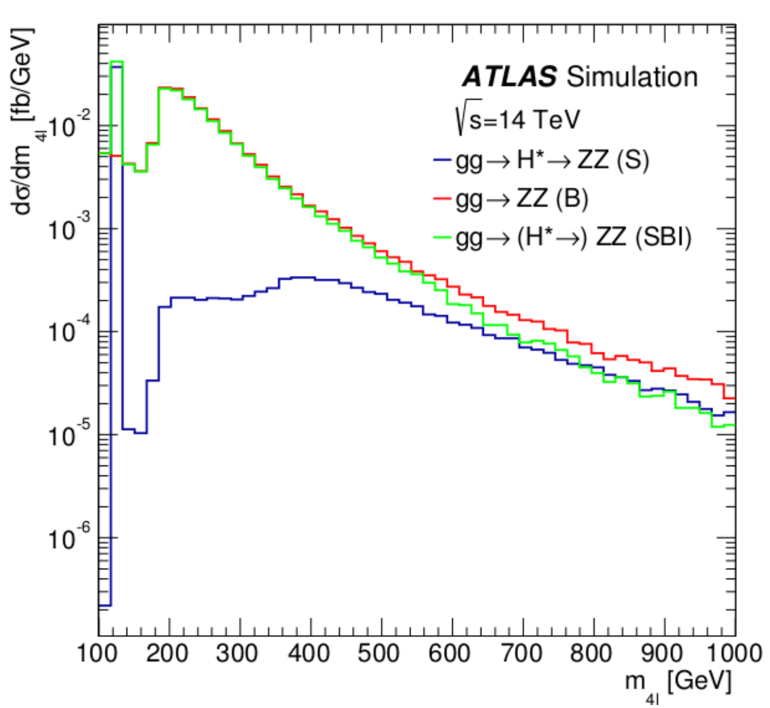


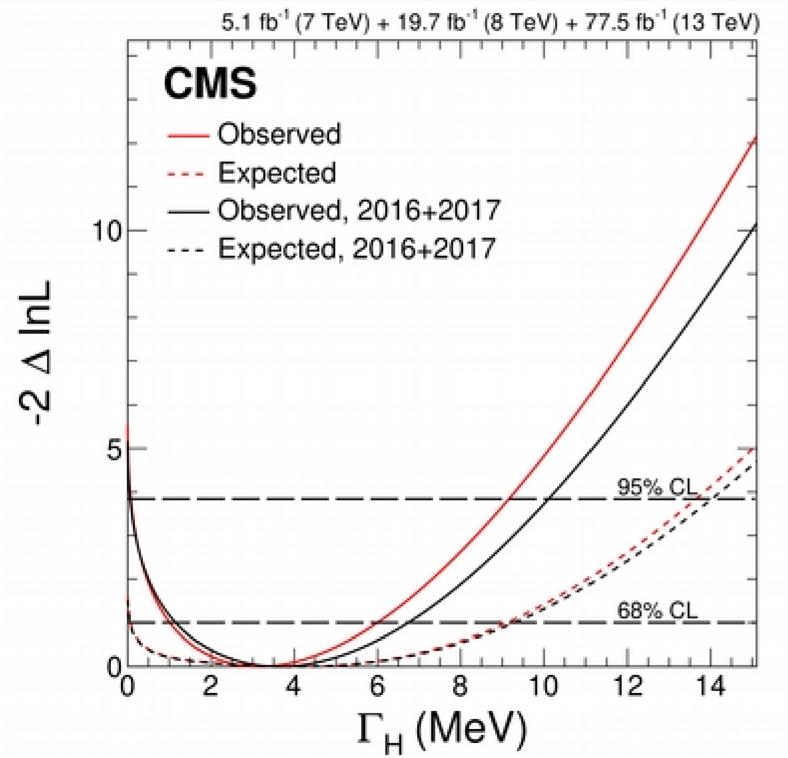


95% CL excluded pseudo-scalar contribution

3.5) H boson properties: Run II

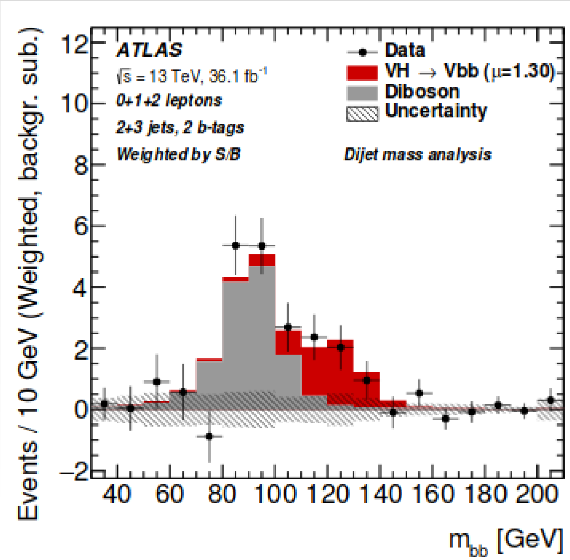
- Direct measurement of Higgs width is limited by the statistics and lepton energy scale at the LHC.
- Think-out-of-box approach: fortunately Higgs couples to the mass: when $H^* \rightarrow ZZ$ ($H^* \rightarrow WW$) off-shell channels opens there is a significant increase of the cross section. Through the interference with ZZ continuum we can constraint total on-shell Higgs width in a model dependent way.
- HL-LHC projections: $\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys).



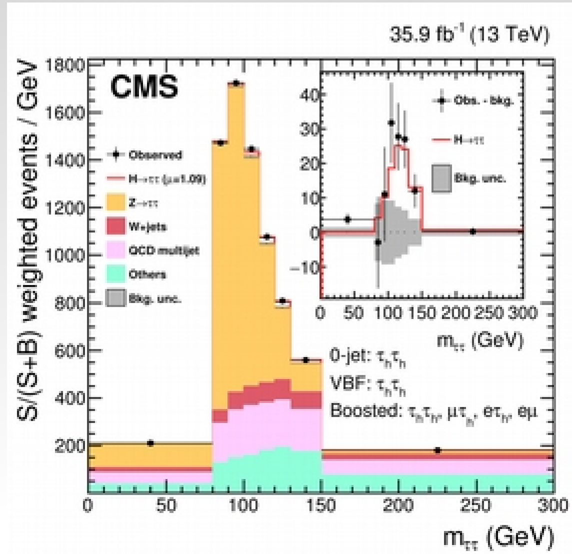


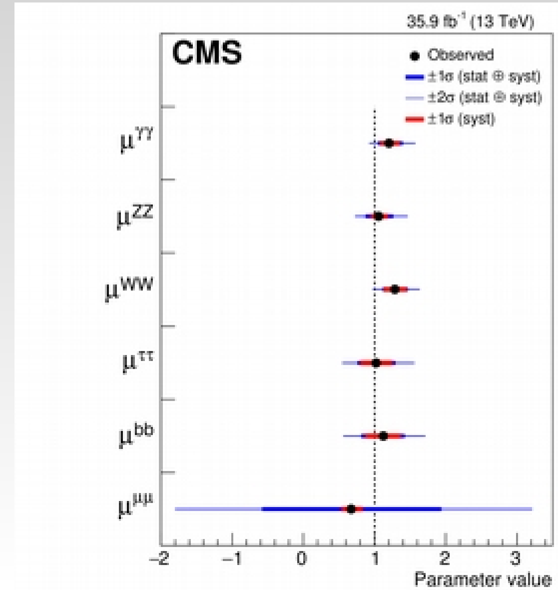
3.6) 3rd generation

VH → bb ✓

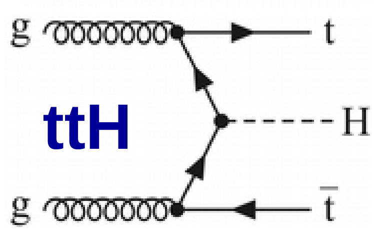


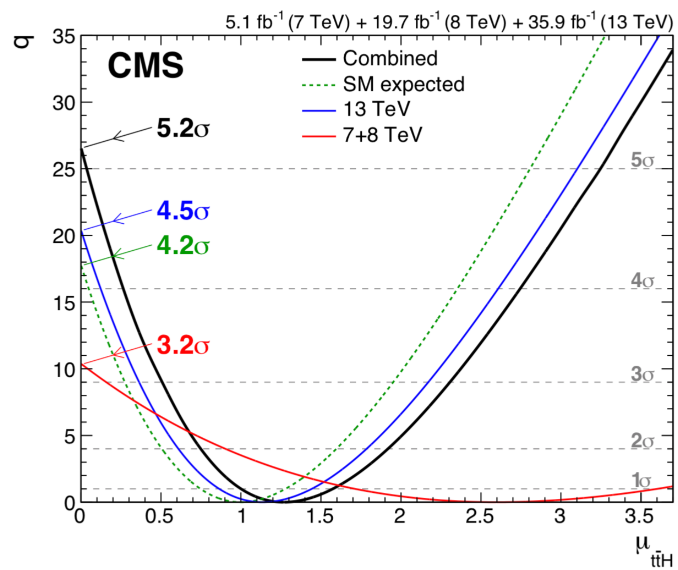
H → ττ ✓





✓ **ttH**





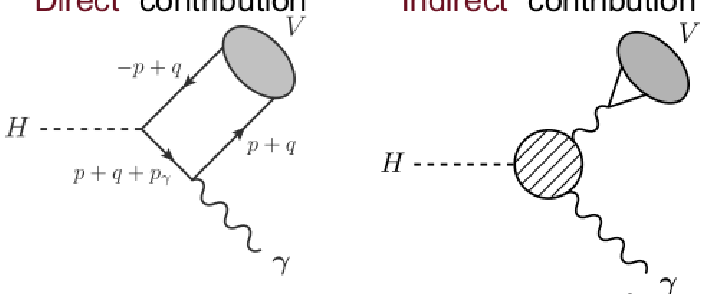
- Run II+Run I provides per experiment observation of 3rd generation Yukawa couplings.
- BEH mechanism is responsible at least at 50-70% of the 3rd generation mass.

3.7) 2nd generation

- With b-tagging H→ bb is already challenging, with c-tagging H→ cc is nearly impossible.
- Alternative idea with exclusive decays appeared to me a way more challenging than initially expected.
- Little chance to provide a « measurement » at the LHC.

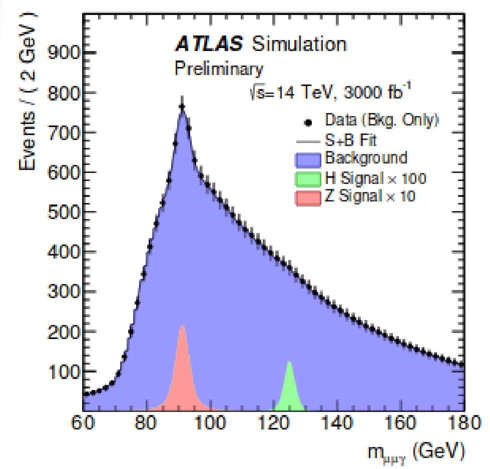
- **h→Qγ decays: clean probe** for Higgs-quark couplings for 1st/2nd generation quarks
  - Q is a vector meson or quarkonium state
- **Two contributions:** direct and indirect amplitude
  - **Direct amplitude:** provides sensitivity to Higgs-quark couplings
  - **Indirect amplitude:** insensitive to Higgs-quark couplings; larger than direct amplitude
  - **Destructive interference**

"Direct" contribution "Indirect" contribution



$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

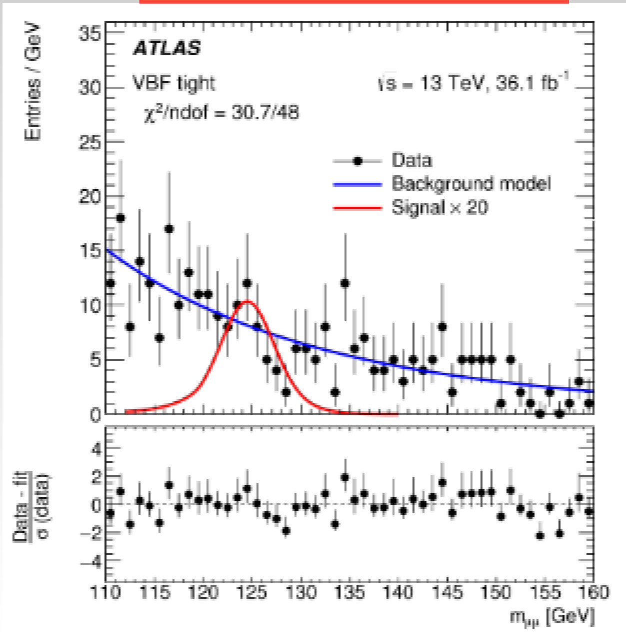
Phys.Rev. D90 (2014) 11, 113010

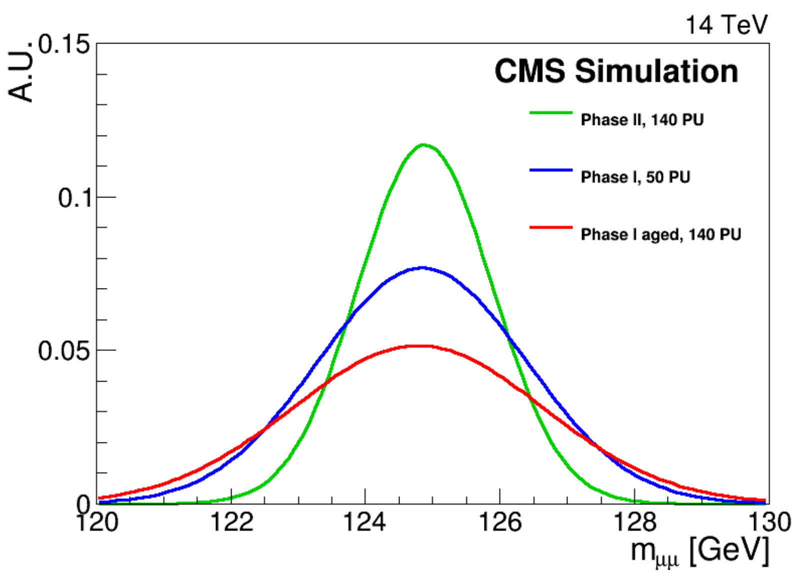


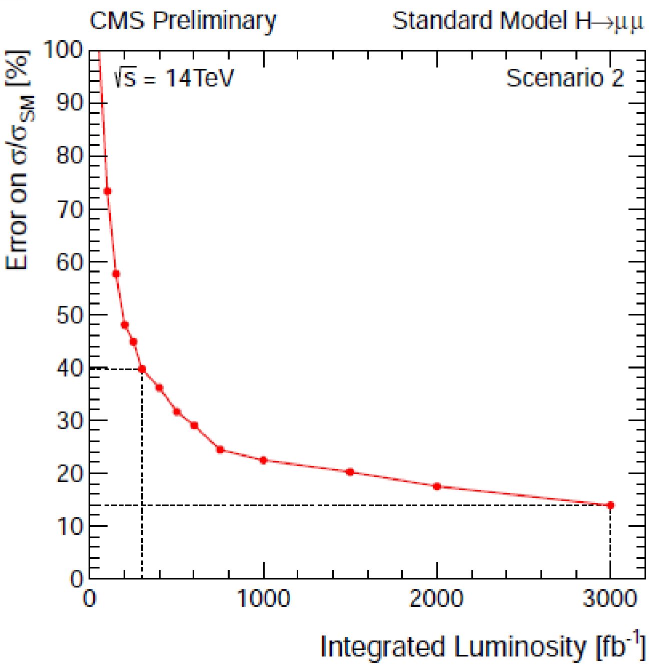
3.8) 2nd generation

arXiv:1705.04582

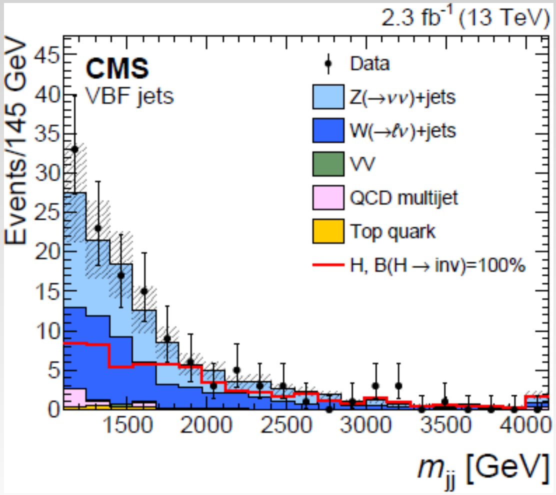
- H → μμ :
  - We have to fight against large DY background: important mass resolution.
  - We need to maximize statistics: muons acceptance is important.
- Muon system critical → Important RDMS role for forward Muon system.
- Actual situation: 2-3 times SM.
- HL-LHC: can reach 10 %.

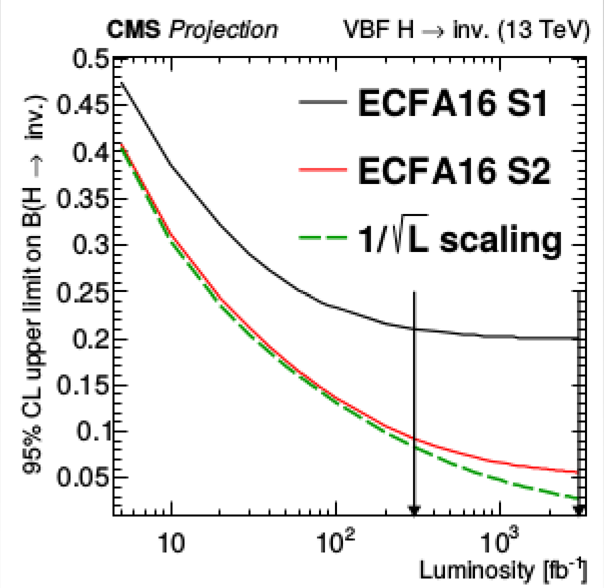




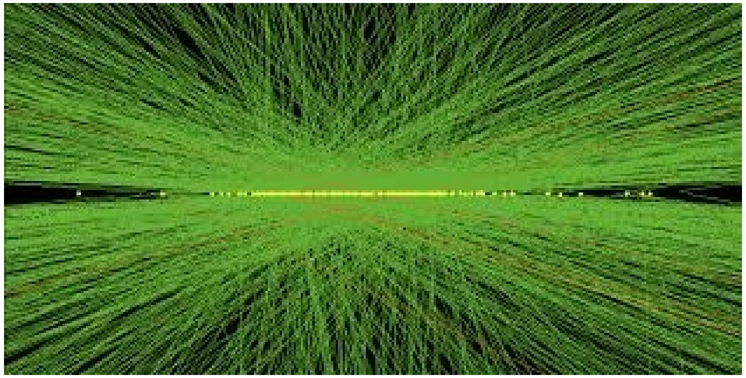


3.9) H → Invisible





- The H → invisible is measured assuming SM Higgs production cross section.
- Critical to constraint Dark Matter oriented models.



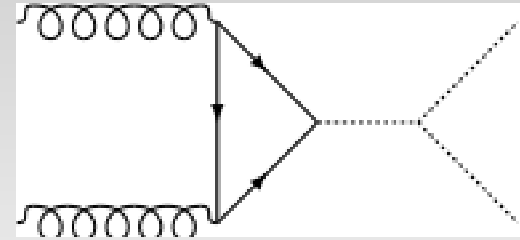
- The Run I + 2015 limit is 25%.
- HL-LHC: limit on 5-10% >> BR(SM H).

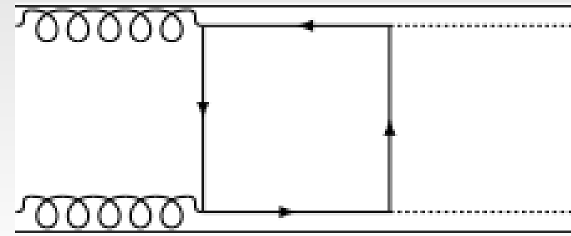
Limited by MET degradation with large pile-up (200 PU/event).

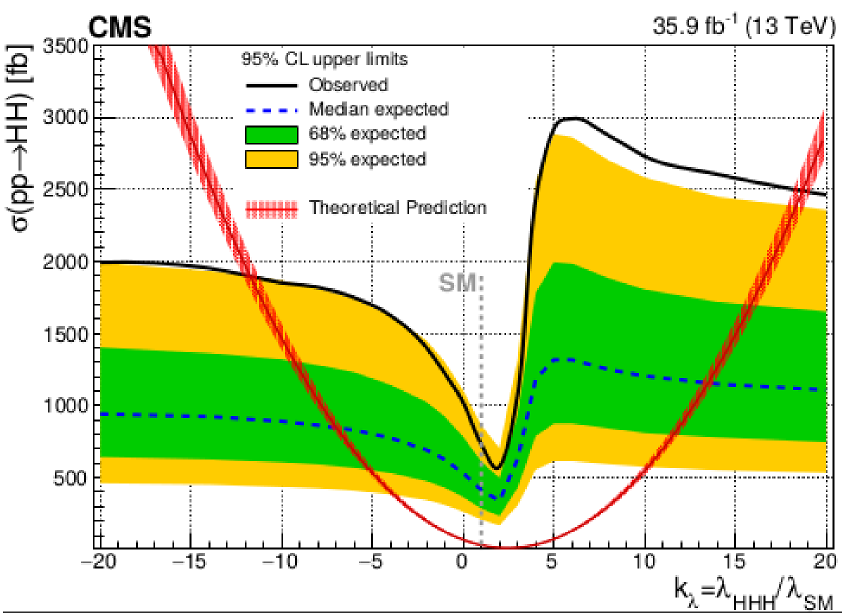
3.10) BEH potential

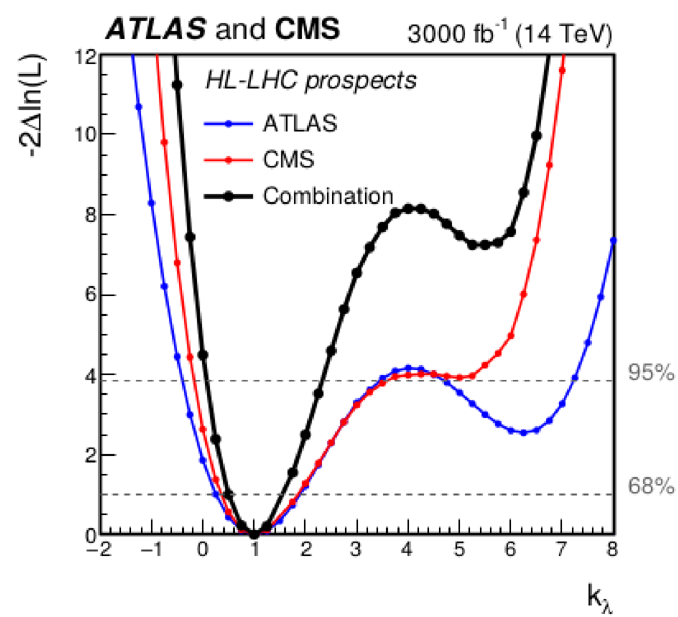
$$V = -m_H^2 |H|^2 + \lambda |H|^4$$

- Direct constraint on the potential theoretically possible through HH production:
  - The cross section 1000 times smaller than SM H.
  - Cross section dominated by top box digram, the sensitivity to Higgs self coupling is reduced.



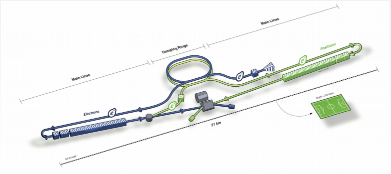


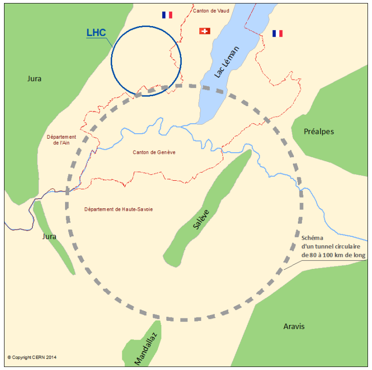




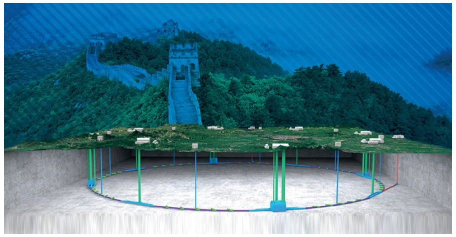
4) Future colliders

e+e- linear
ILC 250, 350, 500 GeV (JAPAN)
CLIC 380-3000 GeV (CERN)





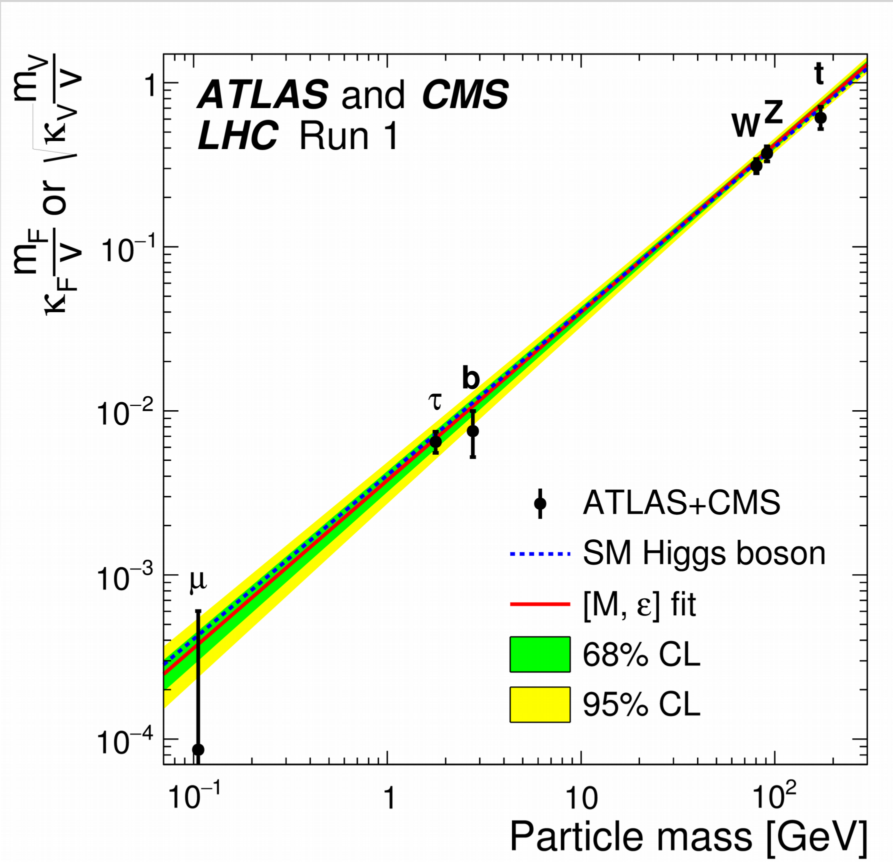
e+e- circular
CEPC 240 GeV (CHINE)
FCC-ee 90-350 GeV (CERN)

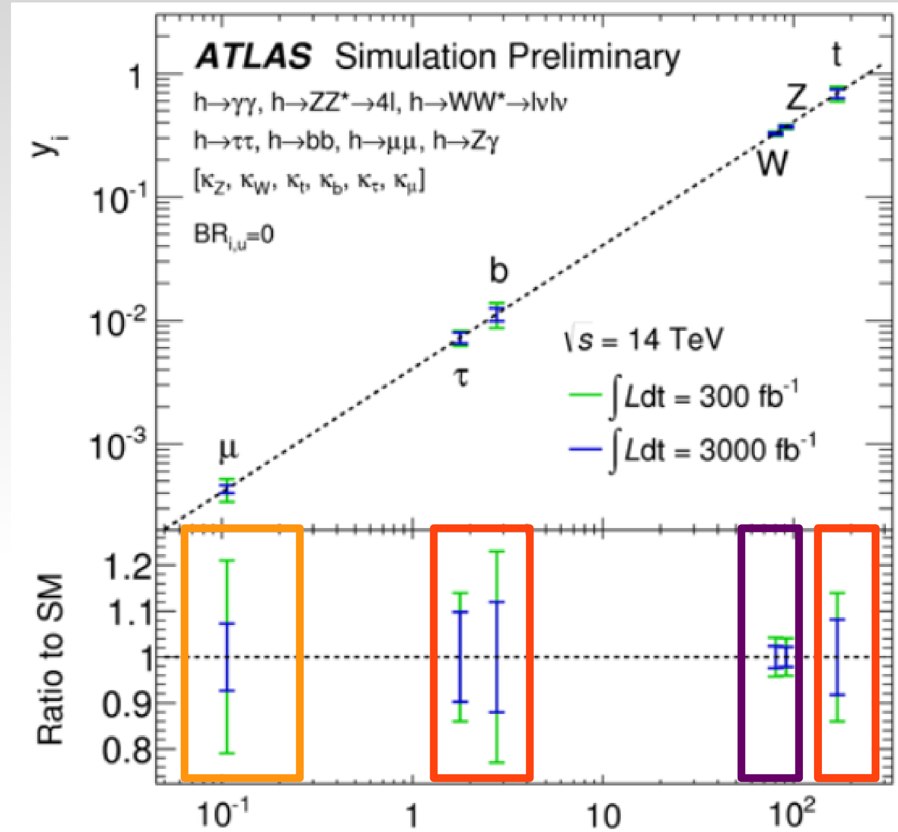


p+p+
CEPC ~ 50-70 TeV (CHINE)
HE-LHC ~ 30 TeV (CERN)
FCC-pp ~ 100 TeV (CERN)

4.1) HL-LHC impact

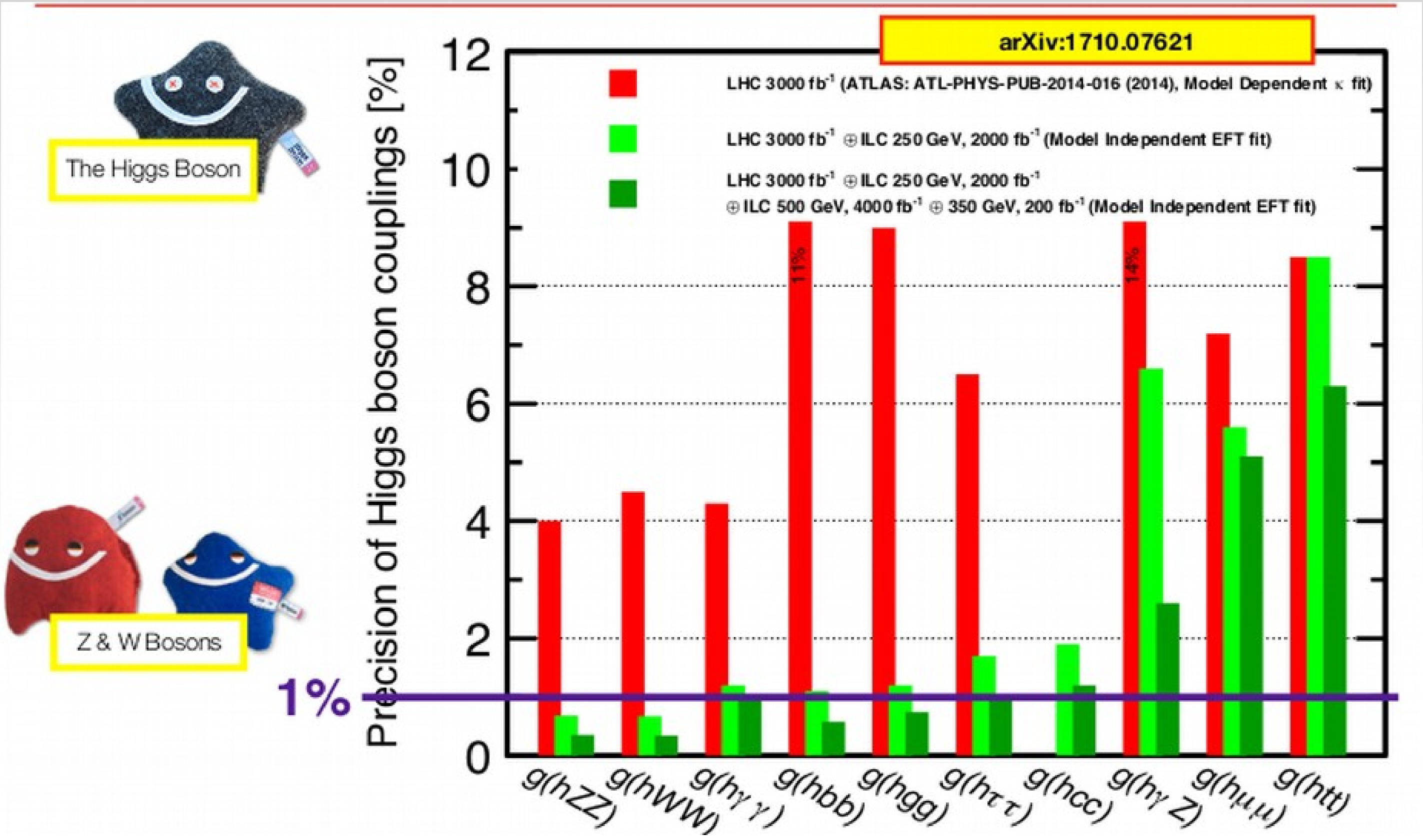
300, 3000 fb^{-1}
$\langle\mu_{PU}\rangle = 140$





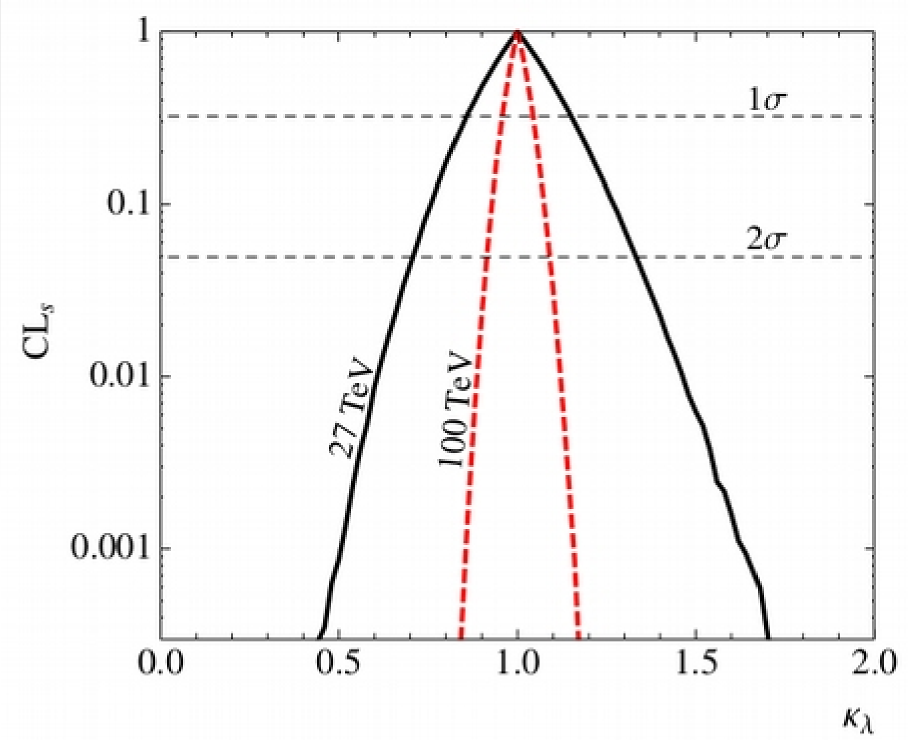
- Assuming no new physics in Γ_{tot}. $(\sigma \cdot \mathrm{BR})(x \to \mathrm{H} \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{tot}}$
- W/Z sector and 3rd generation: most of the improvement comes from Phase I. Phase II limited by systematics (experimental and theory).
- 2nd generation (μ): Phase II opens the gate (Carlo R. would be happy).

4.2) Lepton colliders



- Measure the couplings Bosons, 3rd generation with 1 % precision necessary to exclude weak BSM physics below 1 TeV.
- Measure 2nd generation with 5% precision.
- Measure in a model independent way: total width, total production / decay fractions.

4.3) High energy hadron colliders: Higgs physics



- Measure the Higgs potential parameters.
- High p_T probes: Measure the longitudinal vector boson scattering – unitarisation with BEH mechanism.

CONCLUSION

- The LHC discovery opened a door to the understanding of the BEH mechanism.

- Despite what one can think we doesn't know it so well yet. There is a huge program to be performed before claiming:
"BEH is THE EWSB mechanism and is THE origin of fermion masses and is / is not the portal to Dark Matter»
  – 2^{nd} generation Yukawa
  – Shape of BEH potential
  – Unitarization of longitudinal scattering
  – Invisible and rare decays.
  – 1^{st} generation!
  – Branchings with 1% precision at least.

- All the projects of future colliders position themselves at least partially as Higgs factories.

- RDMS and I. Golutvin played a key role since 30 years in this adventure and a lot remains to be done.