The Higgs boson: a portal to BSM physics

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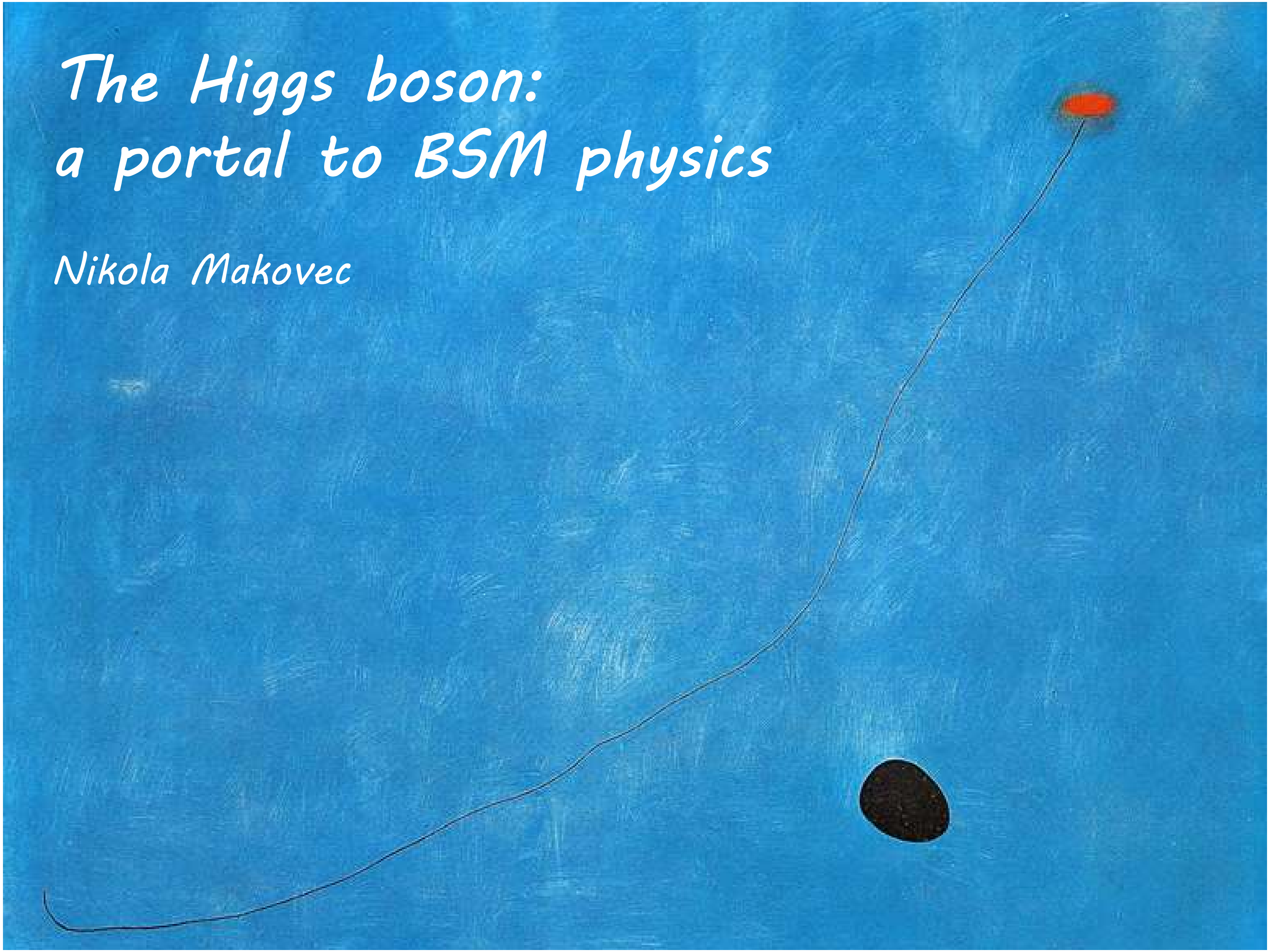


The Higgs boson: a door to new physics

Is the Higgs boson consistent with Standard Model?

- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Rare decays

Precision measurements

Is the Higgs sector minimal?

- 2 Higgs doublet models
- Additional singlet(s)
- Additional triplet(s)
- …

Tool for discovery

- Portal to Dark Matter (invisible Higgs)
- Portal to BSM physics with H in the final state

Direct searches

Outline

1. Introduction
    1. Coupling and decays
    2. Constraints on the Higgs mass

2. Higgs boson discovery at the LHC
    1. Production mechanisms
    2. Review of the various channels
    3. Combination

3. Coupling measurements

4. Constraints on new physics

References

Status of the Higgs boson:

- PDG review
- http://pdg.lbl.gov/2020/reviews/rpp2020-rev-higgs-boson.pdf

Topics in Higgs physics

- J. Ellis
- https://arxiv.org/abs/1702.05436

Implications of the Higgs discovery for the MSSM

- A. Djouadi
- https://arxiv.org/abs/1311.0720

Higgs Physics – Experiment

- Lecture at HCPSS 2018 by M. Kado
- https://indico.fnal.gov/event/15893/timetable/#all.detailed

Introduction

The Higgs mechanism

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

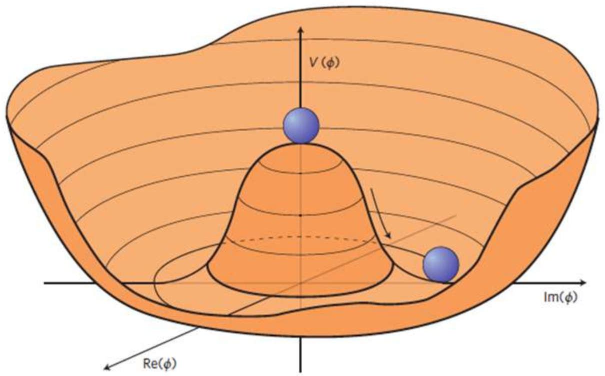
$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

The elegant gauge sector (three parameters for EWK and one parameter for QCD)
But massless gauge bosons

$$+ \bar{\Psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Provides masses to bosons and fermions
Not governed by symmetries
Flavor hierarchy problem
Gauge hierarchy problem (naturalness)

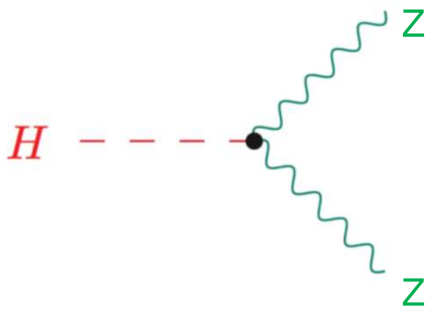


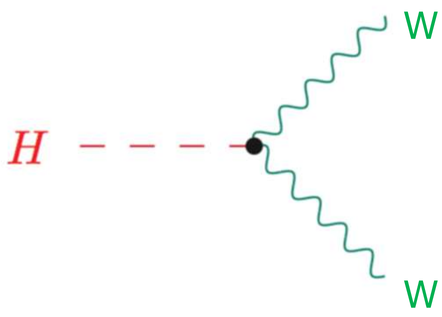
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

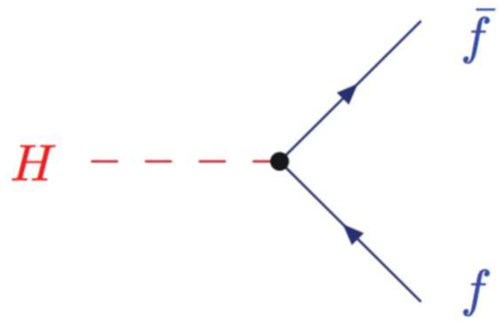
The Higgs potential has the shape of a “mexican hat”
It has a minimum which is not at $< \phi >= 0$
Known as the vacuum expectation value:

$$v = \frac{|\mu|}{\sqrt{\lambda}} = \frac{2M_W}{g} = 246\text{GeV}$$

Higgs boson couplings



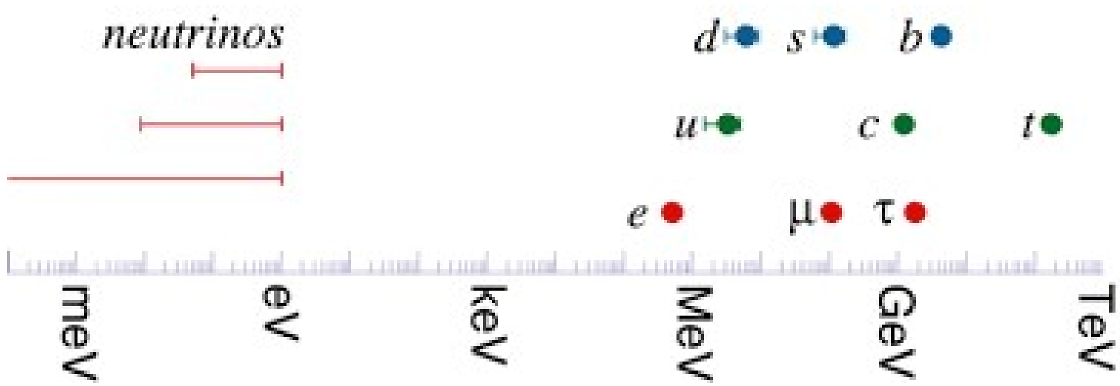




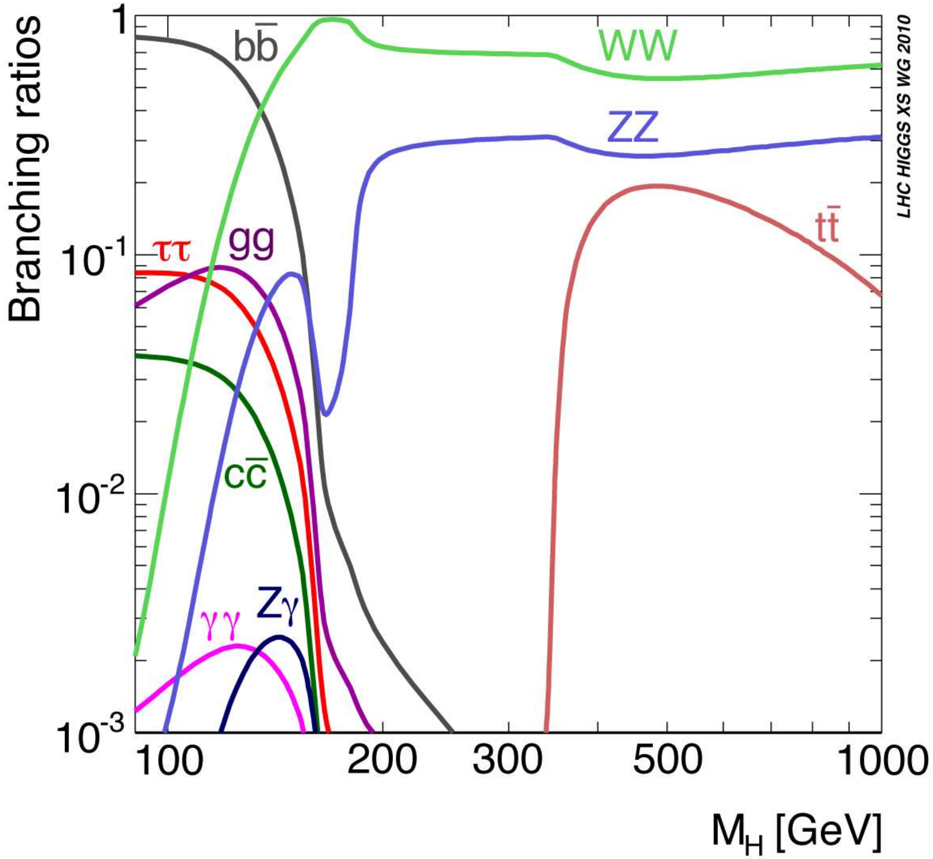
$$g_{HZZ} = \frac{2m_Z^2}{v}$$

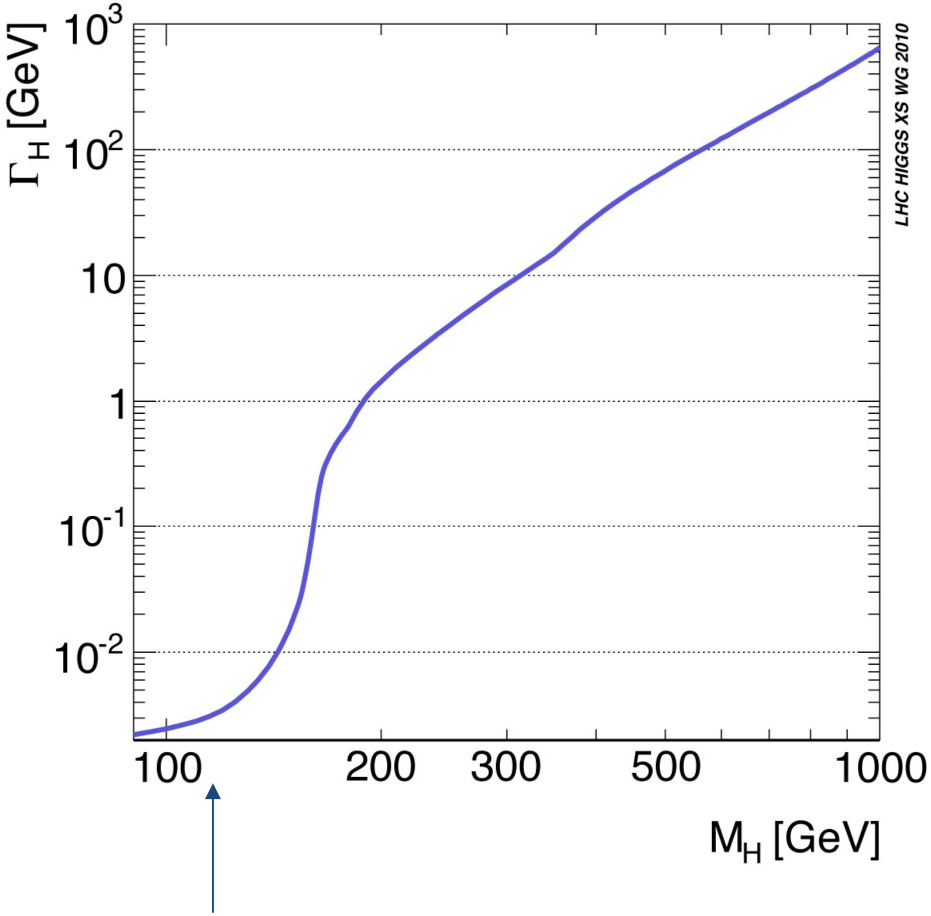
$$g_{HWW} = \frac{2m_W^2}{v}$$

$$g_{Hff} = \frac{m_f}{v}$$



Higgs boson decays

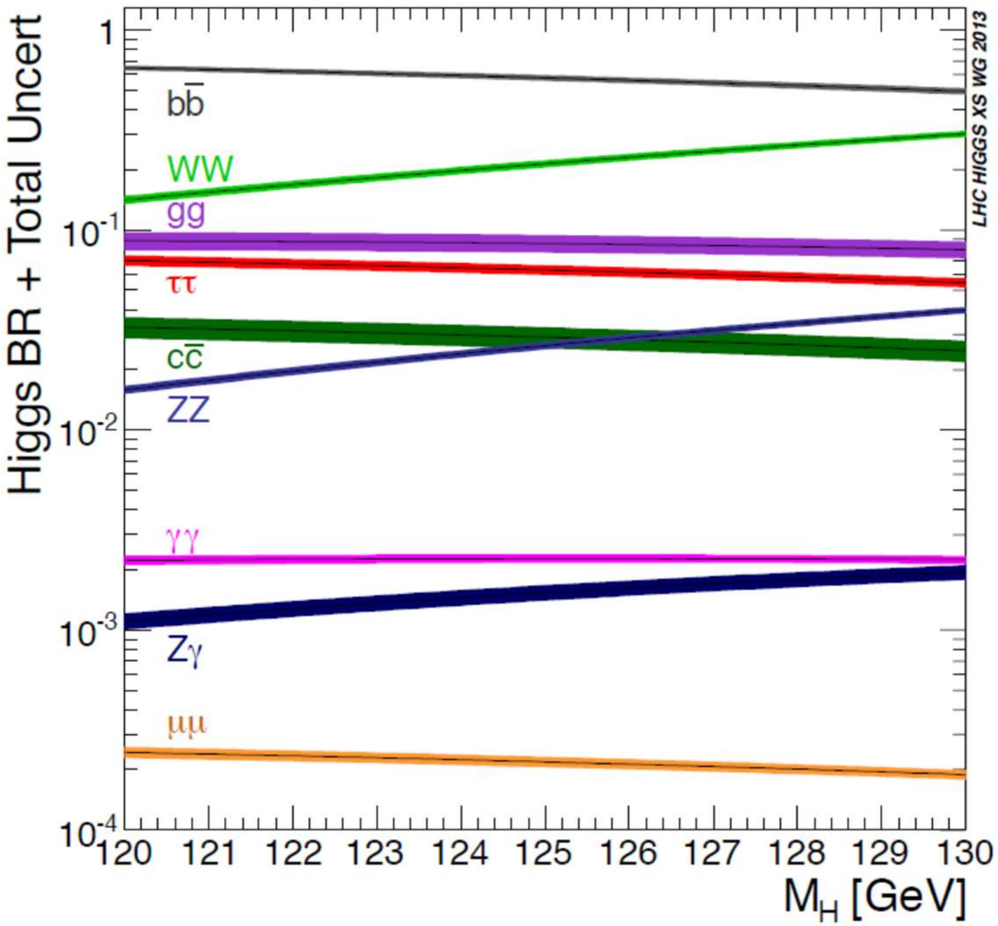




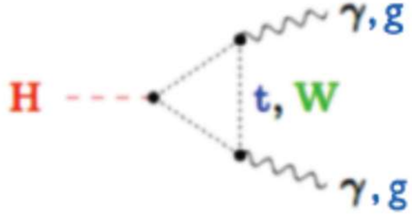
The Higgs boson is narrow

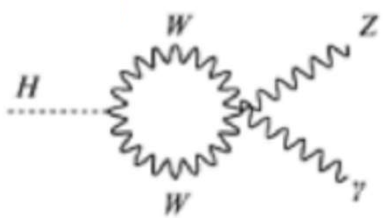
$\Gamma(125\text{GeV}) \sim 4\text{MeV}$

Higgs boson decays



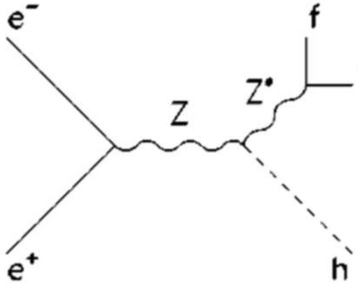
- Dominant: bb (57%)
- WW channel (22%)
- ττ channel (6.3%)
- ZZ channel (3%)
- cc channel (3%)
- The γγ channel (0.2%)
- The Zγ (0.2%)
- The μμ channel (0.02%)





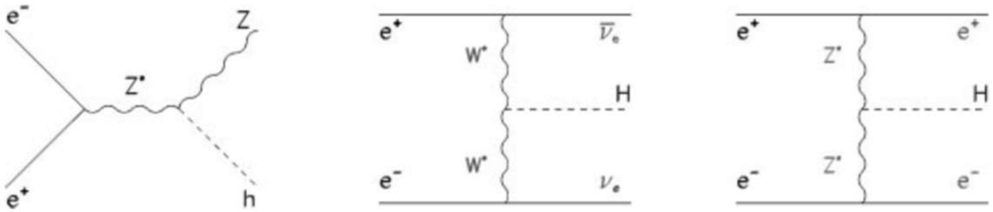
Absolute Lower Limit on the Higgs Mass at LEP

- LEP1:(1989-1995)
  - $\sqrt{s} \sim M_Z$



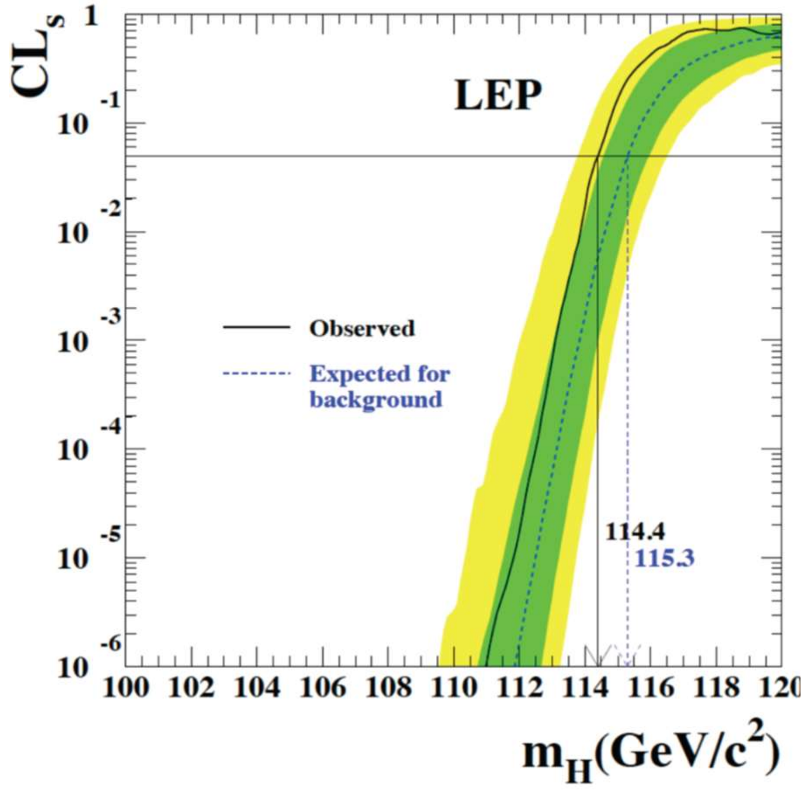
  - Exclusion: $M_H < 58$ GeV

- LEP2 (1996-2001)
  - $\sqrt{s}$ up to 209GeV



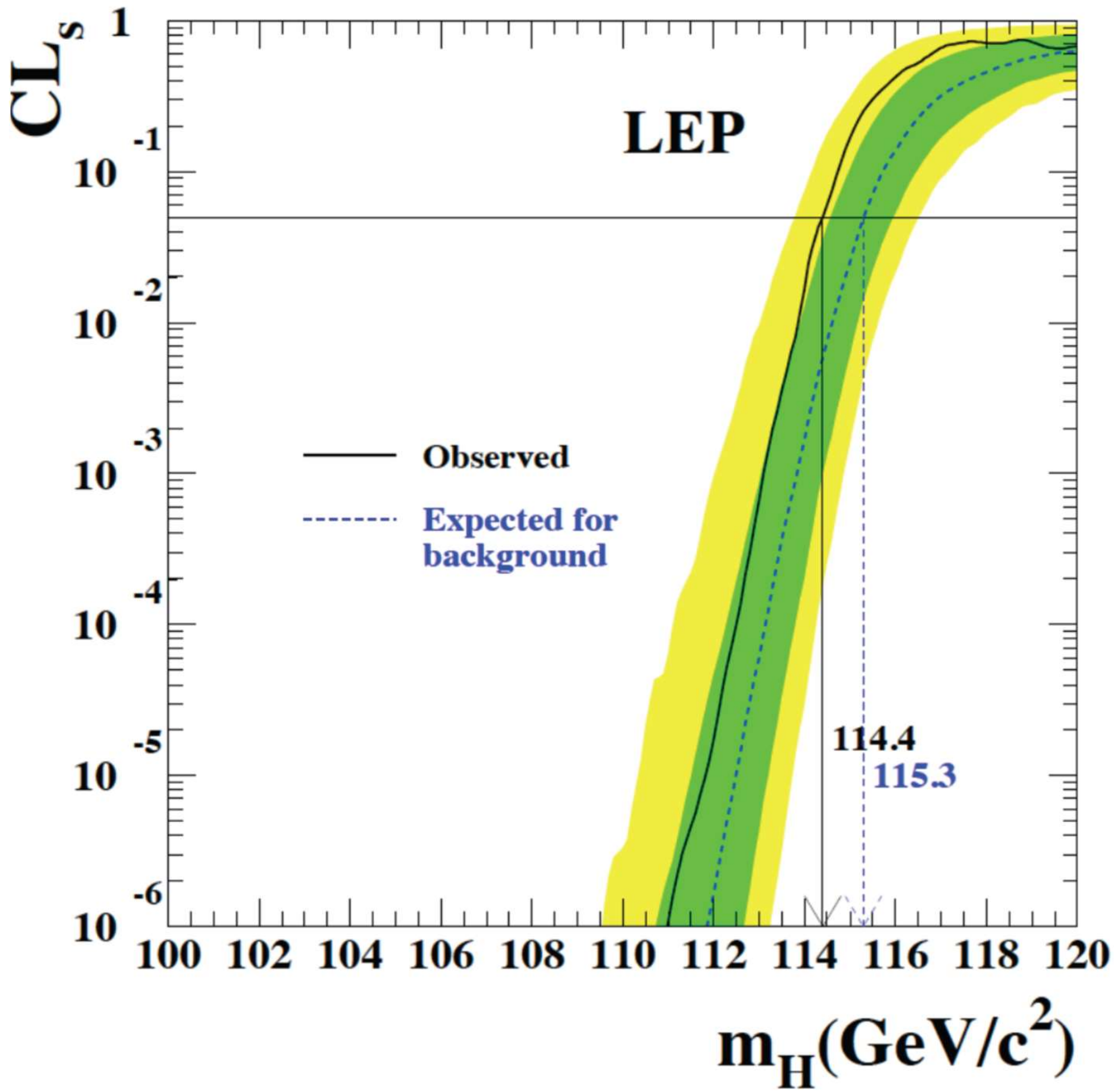
  - Mostly bb and ττ

Observed limit slightly worse than expected one



Exclusion: $M_H < 114$ GeV

Absolute Lower Limit on the Higgs Mass at LEP



Electroweak Precision Data and the Higgs Mass

The electroweak gauge sector is fully described at tree level by three parameters: g, g' and v which can be replaced by:

Fermi Constant $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ (muon lifetime)

Fine structure Constant $\alpha = 1/137.035999679(94)$ (quantum Hall effect)

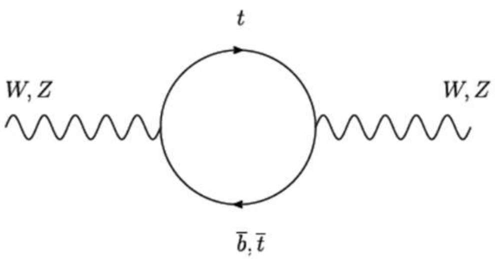
Z mass $M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$ (LEP)

At higher order, the electroweak gauge observables depend also on the additional Standard Model parameters. For instance, the W mass is given by:

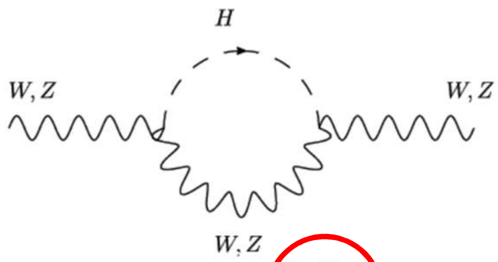
$$M_W = \frac{M_Z}{\sqrt{2}}\left[1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_z^2(1-\Delta r)}}\right]^{\frac{1}{2}}$$

Higher order corrections

With various contributions to Δr



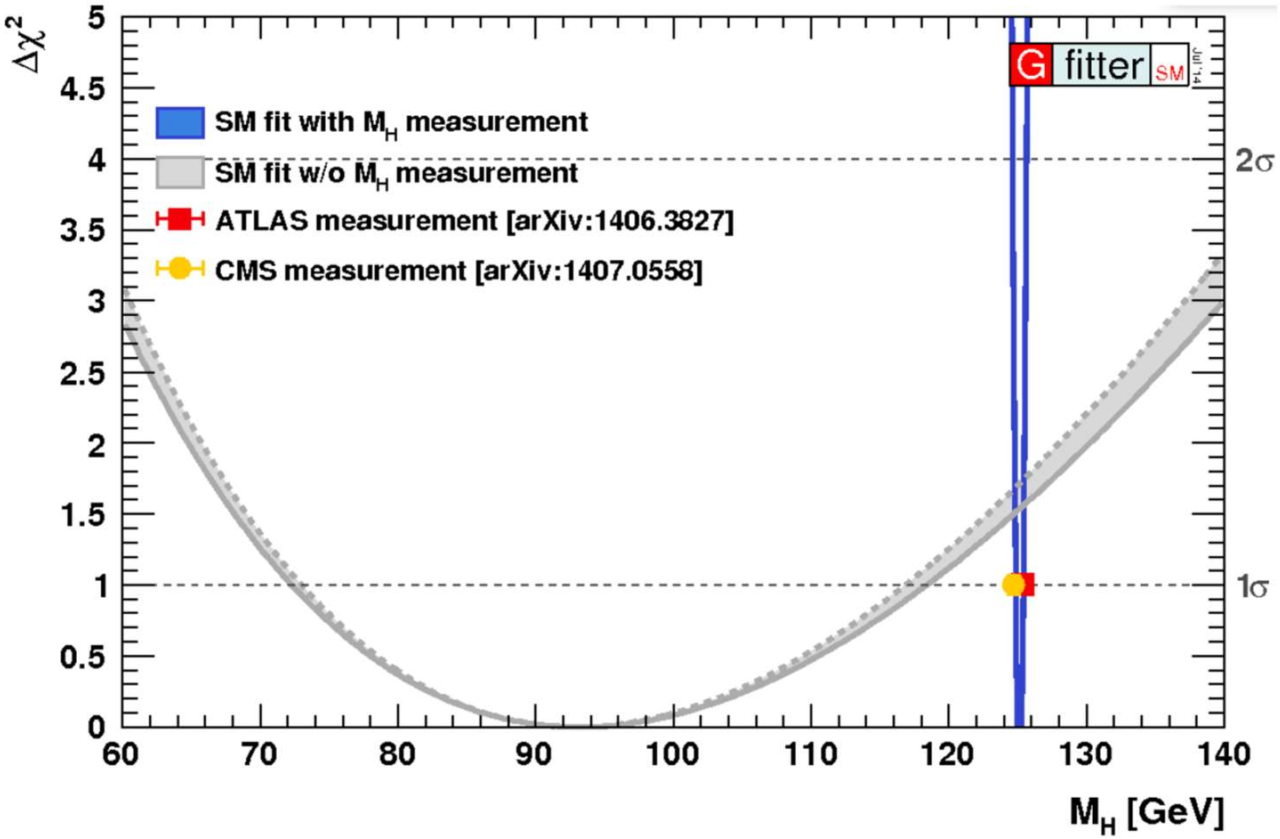
$\propto m_t^2$



$\propto \log \frac{M_H}{M_Z}$

Electroweak Precision Data and the Higgs Mass

A global fit of all relevant measurements can be then done to check the consistency of the Standard Model or **predict parameters** that are unknown

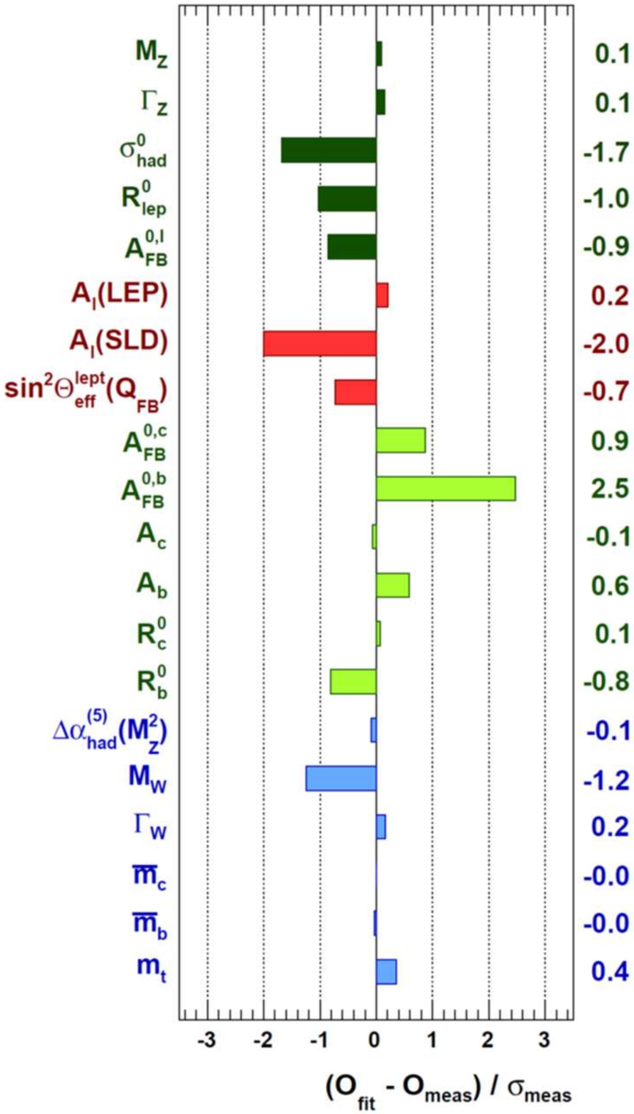


Indirect measurement of the Higgs boson mass through its quantum effect on the precision observables.

$$m_{\mathrm{H}} = 91^{+30}_{-23}\ \mathrm{GeV}$$

Electroweak Precision Data and the Higgs Mass

A global fit of all relevant measurements can be then done to **check the consistency of the Standard Model** or predict parameters that are unknown



arXiv:1107.0975

$$\chi^2_{\min} = 16.6$$

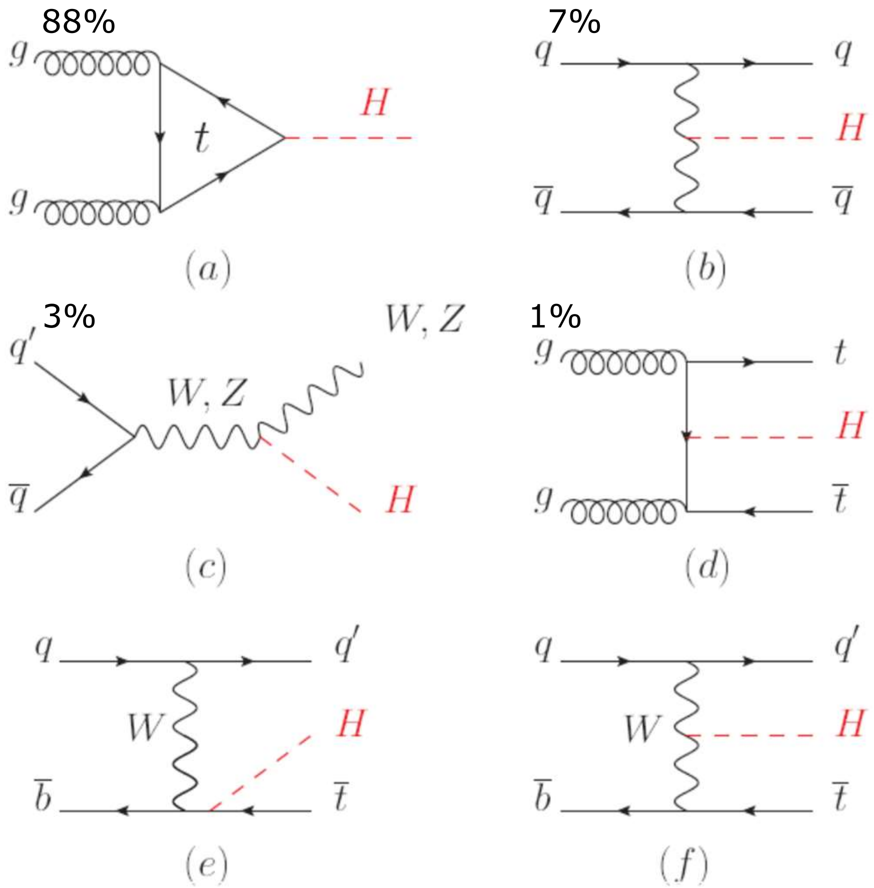
Ndf=13

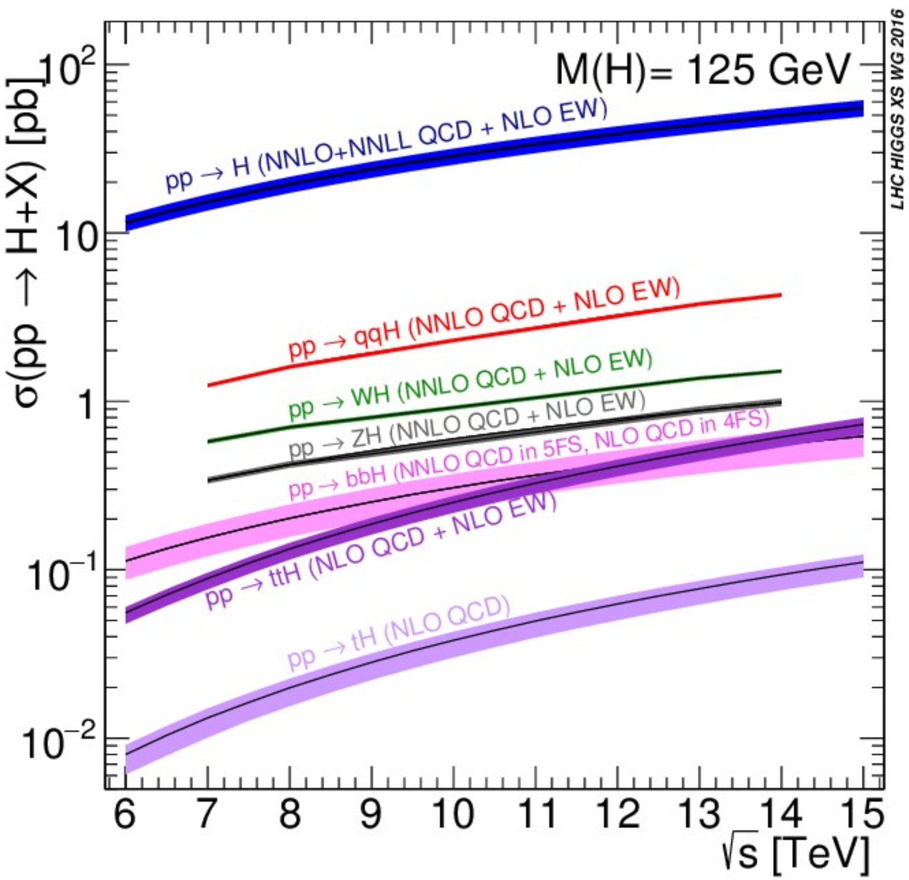
p-value=0.21

http://project-gfitter.web.cern.ch/project-gfitter/

Higgs boson searches at the LHC

Higgs production at the LHC



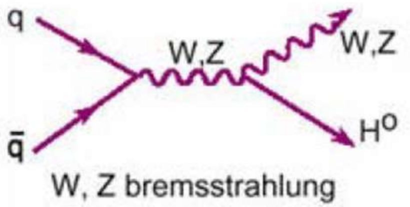


Total cross-section σ = 56 pb at 13 TeV

Cross section dependence on the centre-of-mass energy favours higher mass systems in the final state (i.e. the ttH production process)

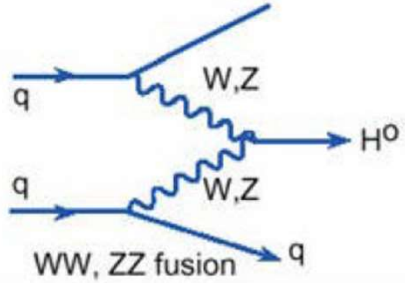
Disentangle production process

Higgs candidate events are selected from their decay signatures. Then production processes are disentangle using the production signatures.



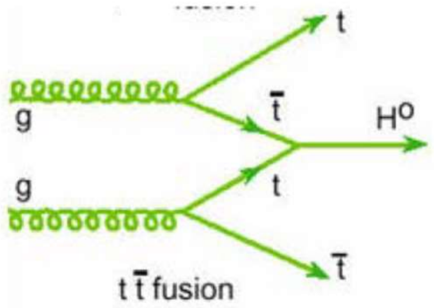
VH

Tagged by W/Z decay signatures:
leptons, missing ET or low-mass dijets
from W or Z decays



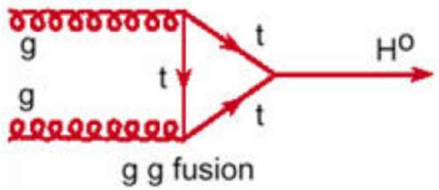
VBF

Two high pT jets with high-mass and large pseudorapidity separation



ttH

Tagged by top decay signatures:
leptons, missing ET, multijets or
b-tagged jets



ggF

Untagged: the rest
separate into 0, 1 or 2 jets

Analysis categorization: divide and conquer

Categorization help analysis to separate different production processes but also to improve the significance

Let's take a simple example with two categories:

- C1: s=12 and b=60
- C2: s=18 and b=40

Gaussian approx:

$$Z = \frac{s}{\sqrt{b}}$$

Inclusively we have a significance of 3

Separating in two categories:

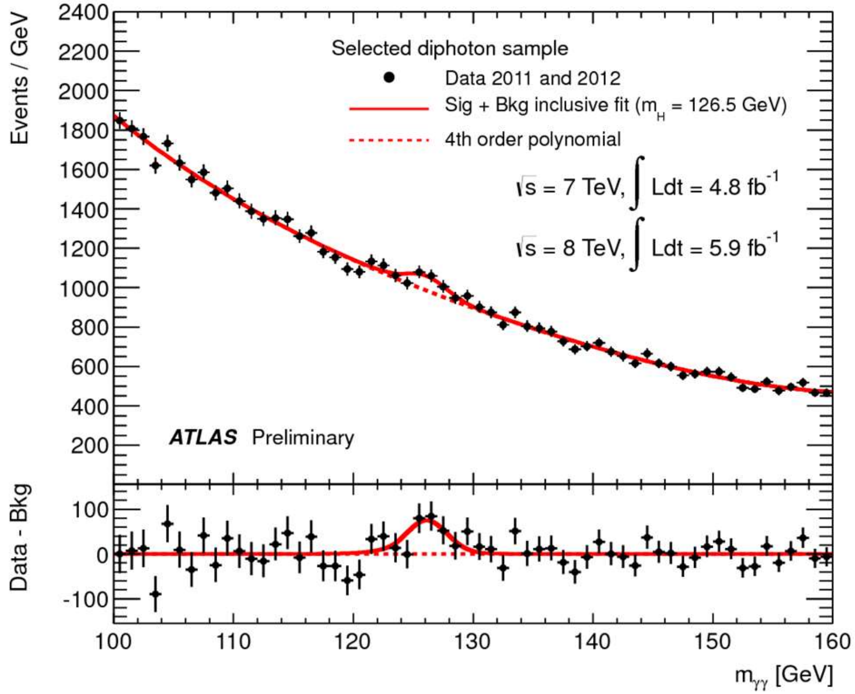
- C1: 2.85 σ
- C2: 1.55 σ
- Combined significance: 3.24

Improved only when S/B are different

$H \to \gamma\gamma$

Main production and decay processes occur through loops

→ excellent probe for new physics



Key features:

- Small S/B-ratio,
- High event yield
- di-photon mass resolution = 1-2%

Analysis strategy:

- Di-photon mass is the key observable
- Two isolated high-pT photons
- Background estimated from $m_{\gamma\gamma}$ distribution (in the sidebands)

$H \rightarrow \gamma\gamma$: likelihood without uncertainties

Observable: set of values $m_1, \ldots, m_n$

$$L(m_1,\ldots m_n \mid \mu) = P(n \mid \mu).\prod_{i=1}^{n} f(m_i \mid \mu)$$

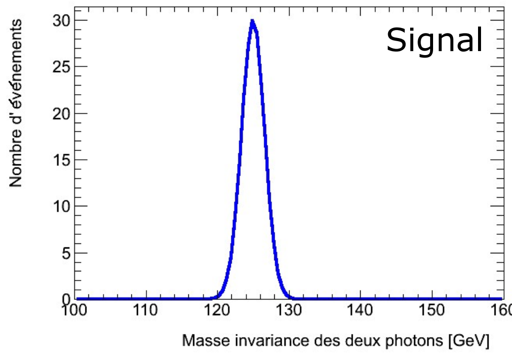
Probability to observe n events: $\dfrac{(b+\mu s)^n e^{-(b+\mu s)}}{n!}$

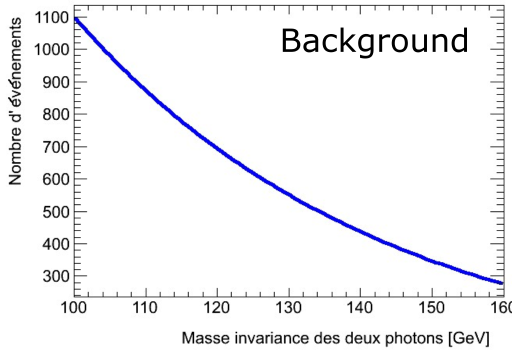
Probability to measure m_i: $\dfrac{\mu s}{\mu s + b} f_s(m_i) + \dfrac{b}{\mu s + b} f_b(m_i)$

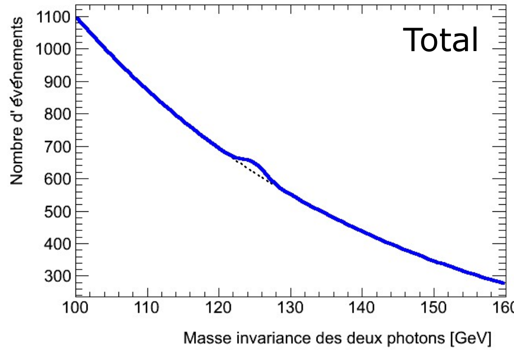
f_s: Pdf for the signal hypothesis

f_b: Pdf for the background hypothesis

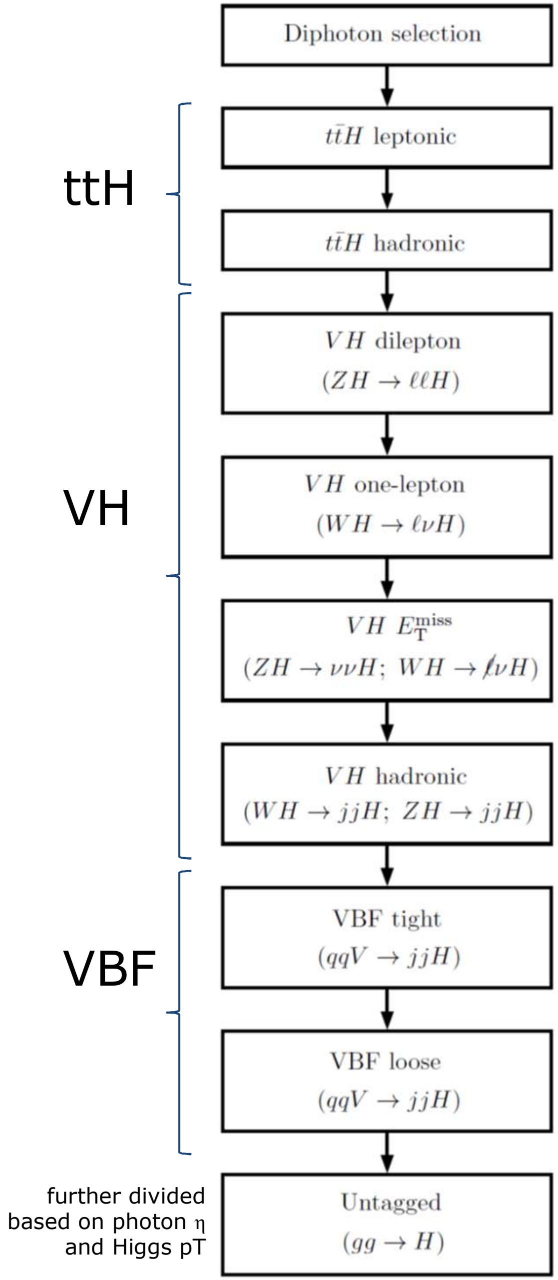
$$L(m_1,\ldots m_n \mid \mu) = \frac{(b+\mu s)^n e^{-(b+\mu s)}}{n!} \prod_{i=1}^{n} (\mu s f_s(m_i) + b f_b(m_i))$$

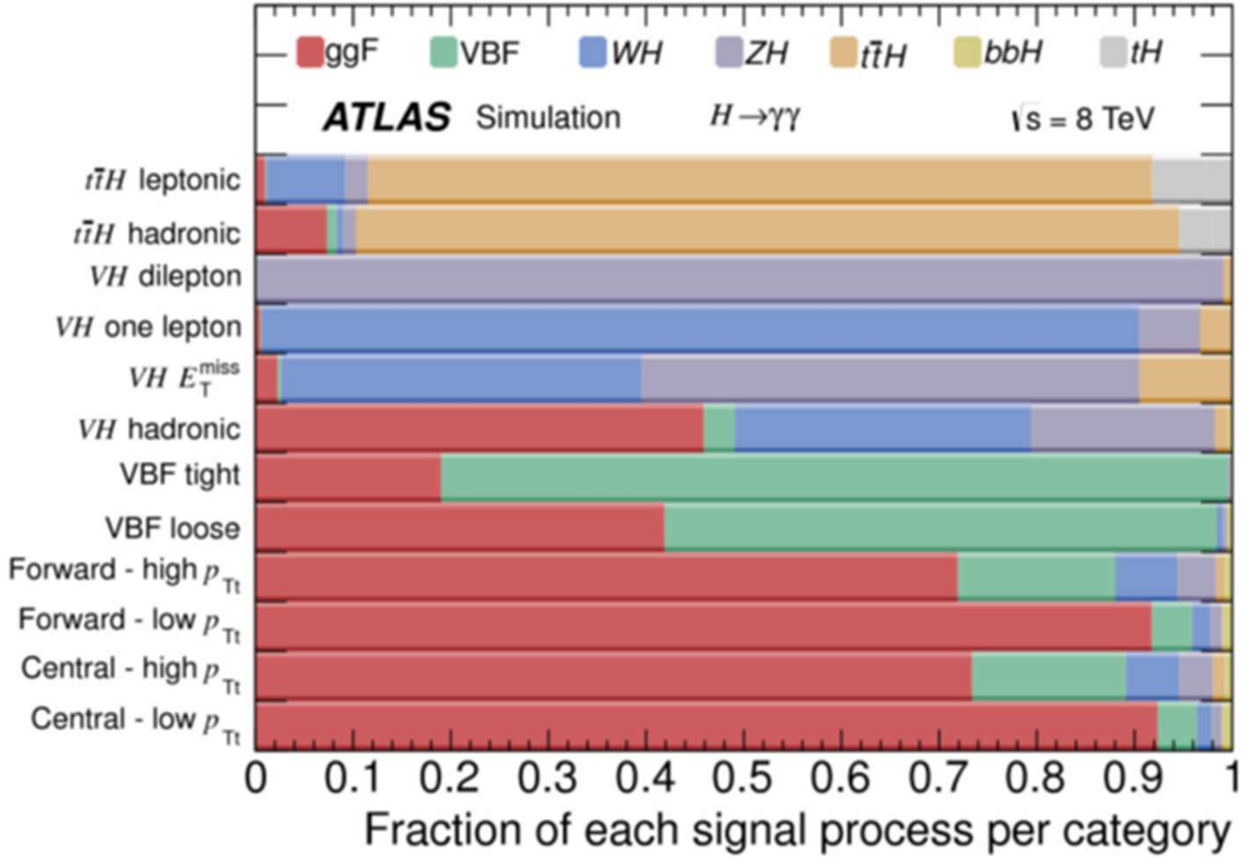






$H\to\gamma\gamma$: categories



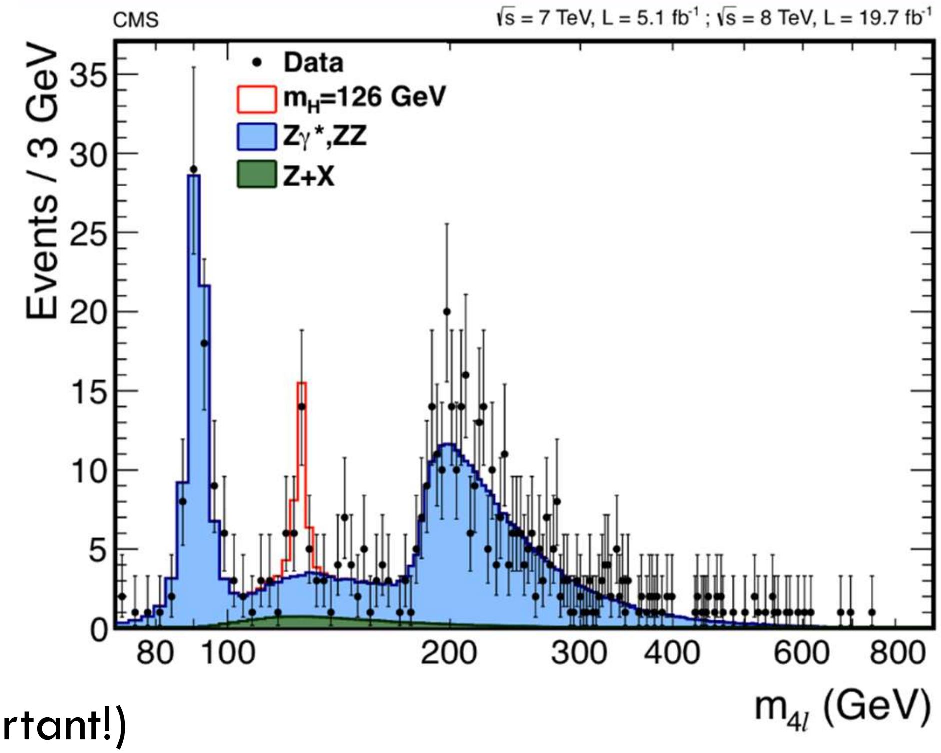


$$L(m_1,\ldots m_n \mid \mu,\theta) = \prod_{categories} L_{cat.}(m_1,\ldots m_n \mid \mu,\theta)G(\theta)$$

$H \to ZZ^* \to 4\ell$

Key features:

- High S/B-ratio
- Low statistics (BR(H→ZZ)~22%, BR(Z→ee or μμ)~6.7%)
- Only one Z is on-mass shell
- Mass resolution = 1-2%

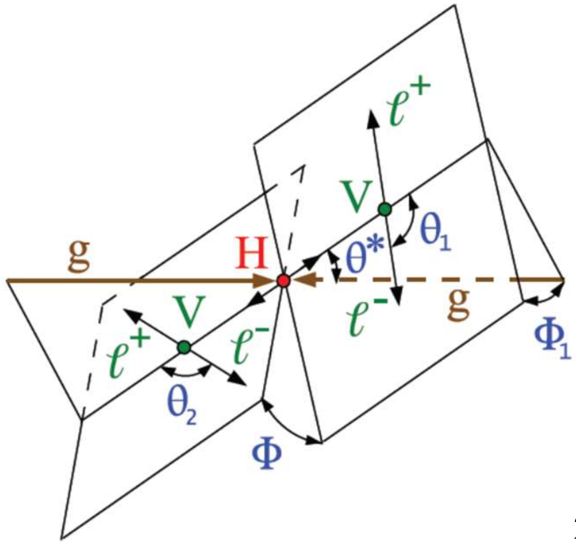


Analysis strategy:

- Four prompt leptons (low pT is important!)
- Four-lepton mass is the key observable
- Split events into 4e, 4μ, 2e2μ channels:
  - Different resolutions and S/B rates
- Complicated kinematics for 4 final states

→ advanced techniques (BDT,ME,…) can improve sensitivity significantly

- Background: pp→ZZ estimated by MC

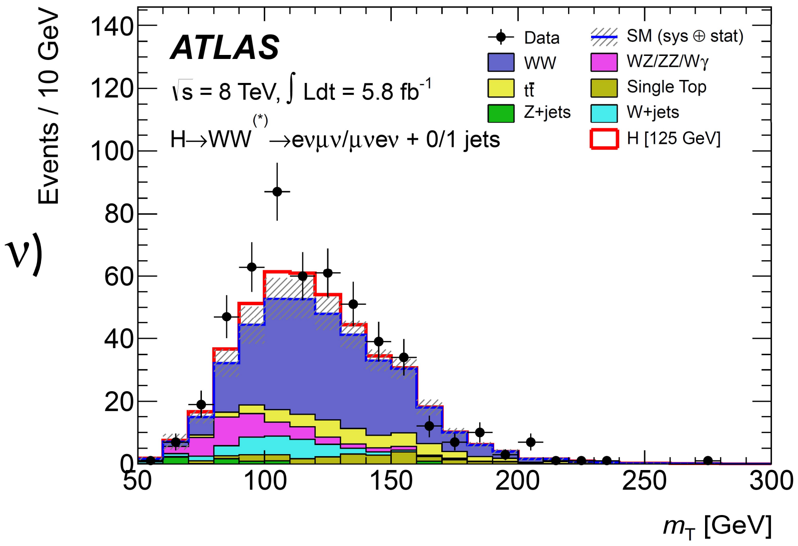


$H \to WW^* \to \ell\nu\ \ell\nu$

Key features:

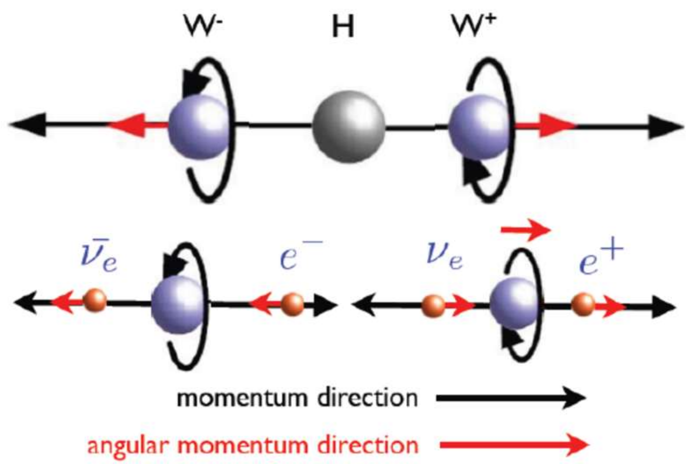
- Large signal event rate, but large background
- "Mass" resolution = ~20% (spoiled by the ν)

$$m_T^2 = \left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\vec{p_T}_{\ell\ell} + \vec{E_T^{\text{miss}}}\right|^2$$



Analysis strategy:

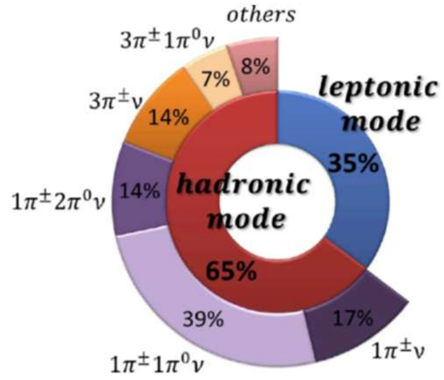
- 2l OS and missing transverse energy
- Transverse mass is the key observable
- Low $\Delta\varphi(\ell, \ell)$
- Events are separated into categories of number of jets from 0 to 2
- Dominant background is from pp→ WW production and top at larger jet multiplicity
- Requires a very good understanding of the background in simulations and with control regions



$H \rightarrow \tau\tau$

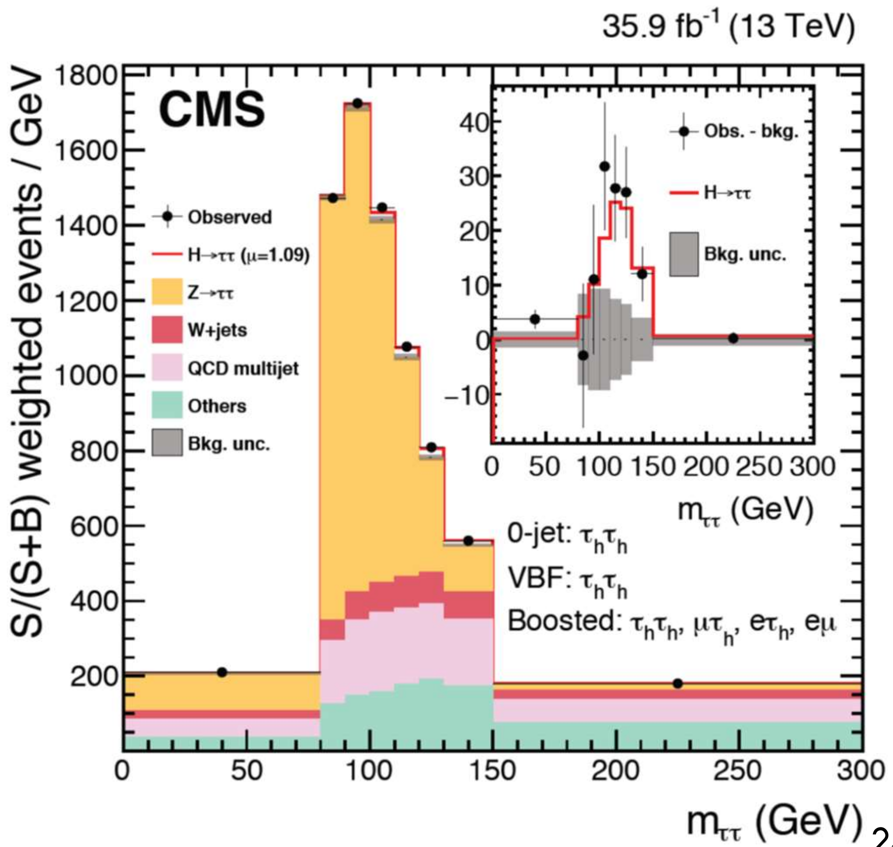
Key features:

- Low S/B
- Resolution ~15% (spoiled by the ν)
- VBF production is the most sensitive production mode



Analysis strategy:

- 3 channels: $\tau_{lep}\ \tau_{lep}$, $\tau_{lep}\ \tau_{had}$, $\tau_{had}\ \tau_{had}$
- VBF: two forward jets and a large rapidity gap between the jets
- Main discriminant variables: $m_{\tau\tau}$
- Crucial to distinguish $H \rightarrow \tau\tau$ from large $Z \rightarrow \tau\tau$ background



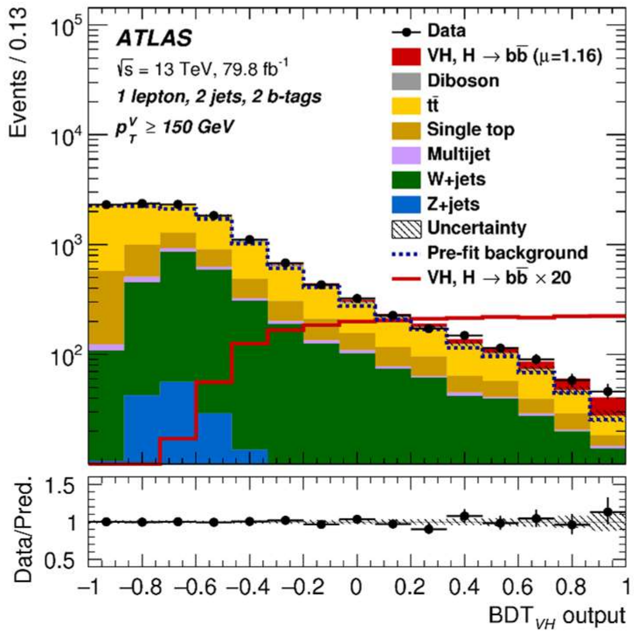
$H \rightarrow bb$

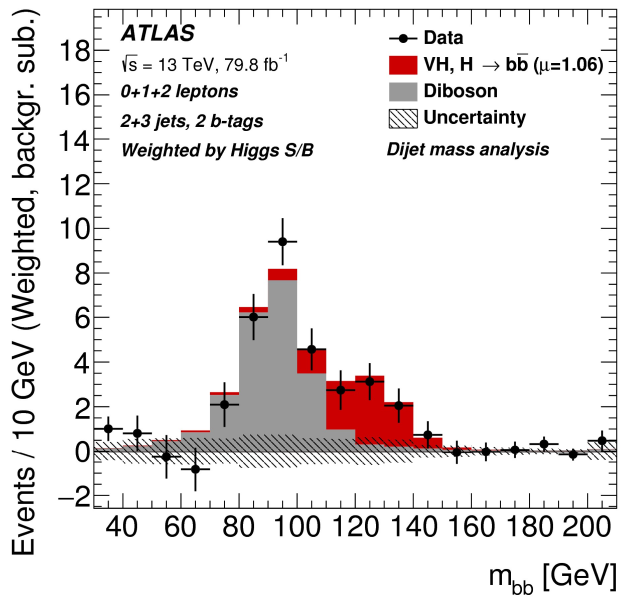
Key features:

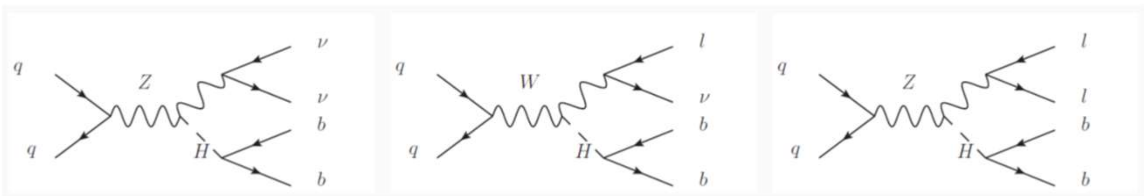
- Low S/B ~0.05
- Resolution ~10%
- VH production is the most sensitive production mode

Analysis strategy:

- Select 2 b-tagged jets
- 3 channels (0-, 1-, 2 charged leptons from V= W/Z boson)
- Main discriminant variables **m(bb)**, p_T(V) and ΔR(bb) → MVA
- Main background is V+jets controlled in the mass side-bands
- VZ with Z→bb offers validation







Combinations

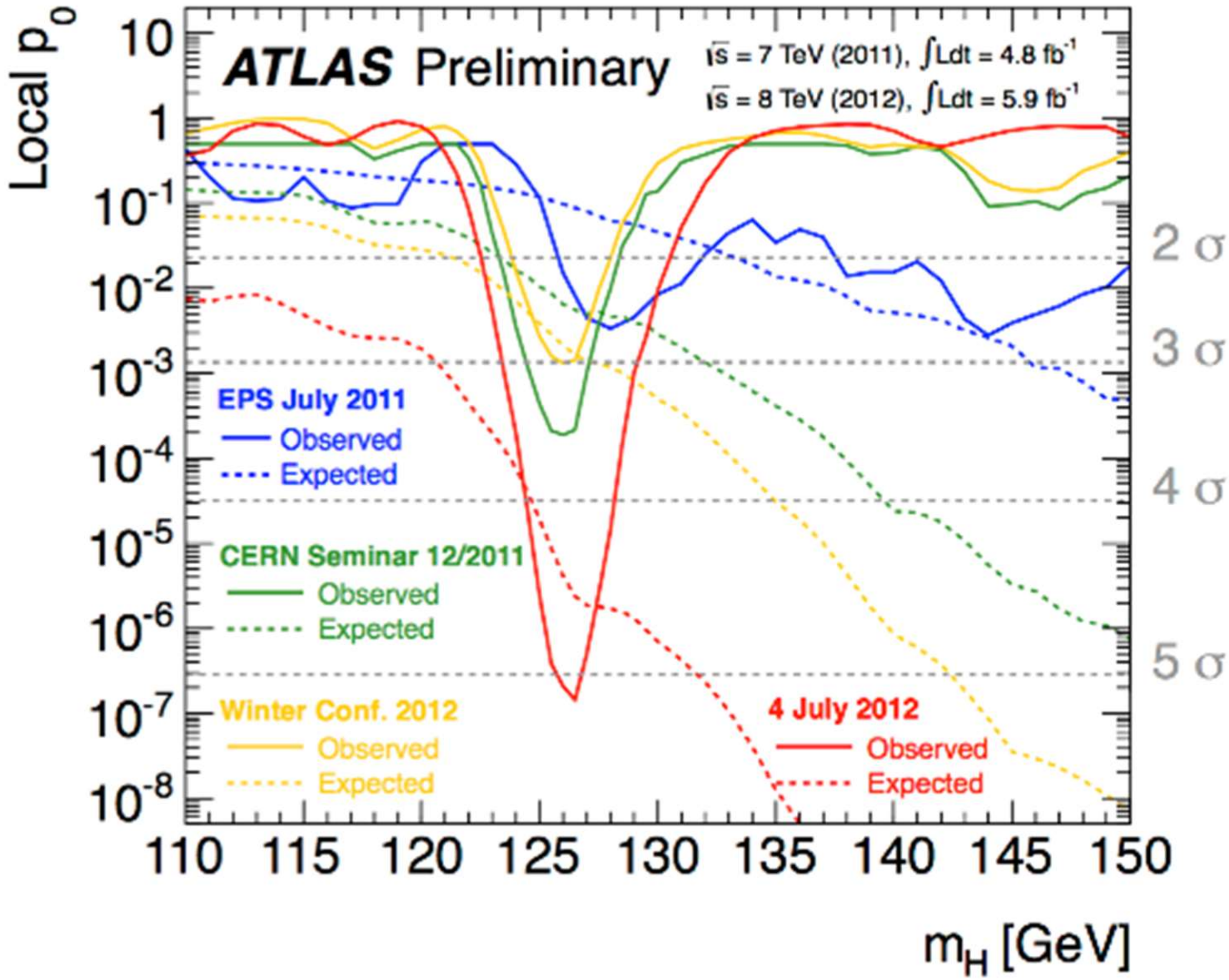
Channels combination

- Searches mainly based on the Higgs decay modes with exclusive subchannels defined according to the Higgs production processes
- Combine the analysis channels ($\gamma\gamma$,4l,…) together in order to probe further the production and decay modes of the Higgs boson and measure its coupling

Run I ATLAS+CMS combination:

- Rule of thumbs: improving by $1/\sqrt{2}$ the precision if limited by statistics
- ~600 signal regions & control regions
- Grand total of ~4200 nuisance parameters: related to (systematic) uncertainties
- Up to now, only done for run1 data

Higgs discovery



$H\to\gamma\gamma$, $H\to ZZ^*\to 4\ell$, and $H\to WW^*\to \ell\nu\,\ell\nu$ were all observed(*) with run 1 dataset separately by ATLAS and CMS

$H\to\tau\tau$: observed with run 1 data combining ATLAS (3.3σ) and CMS(3.7σ) results

$H \to bb$: observed in 2018 (Run1 and Run2 data, ATLAS and CMS separetely)

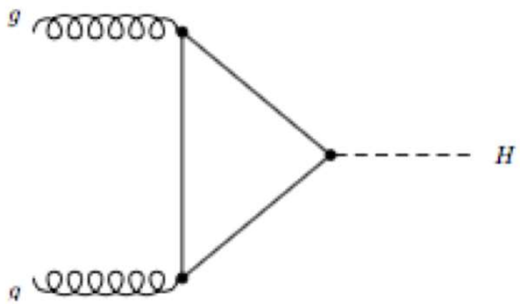
(*) CMS 4l : σ=4.6

First consequences for BSM physics

Models without Higgs boson are obviously excluded

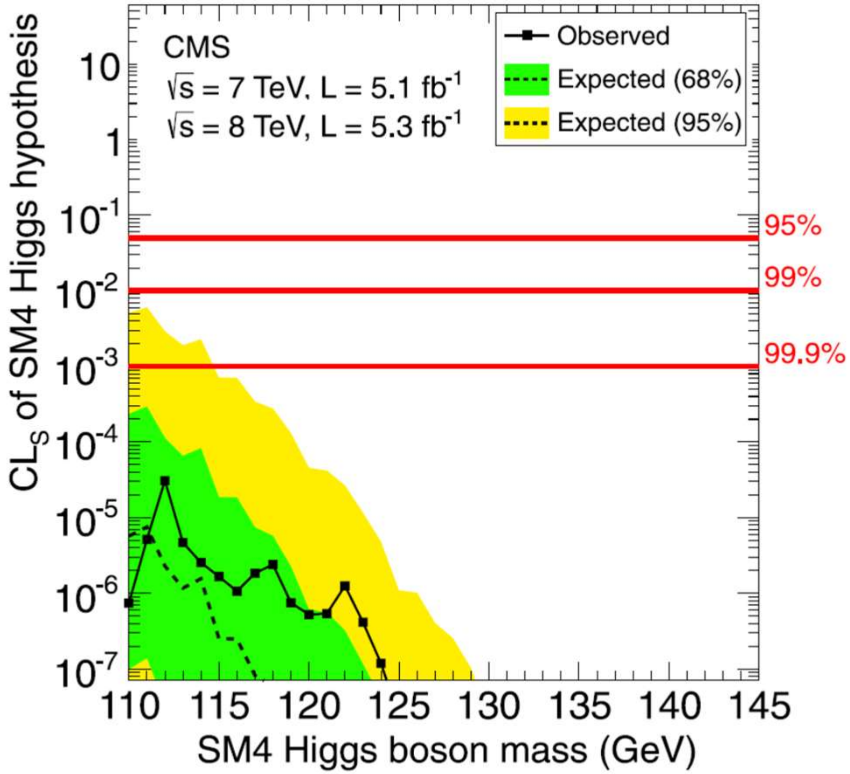
- Ex: simple technicolor models

Models with 4th generation of chiral quarks are excluded



Higgs cross-section enhancement due to 4th generation in loop

arXiv:1302.1764

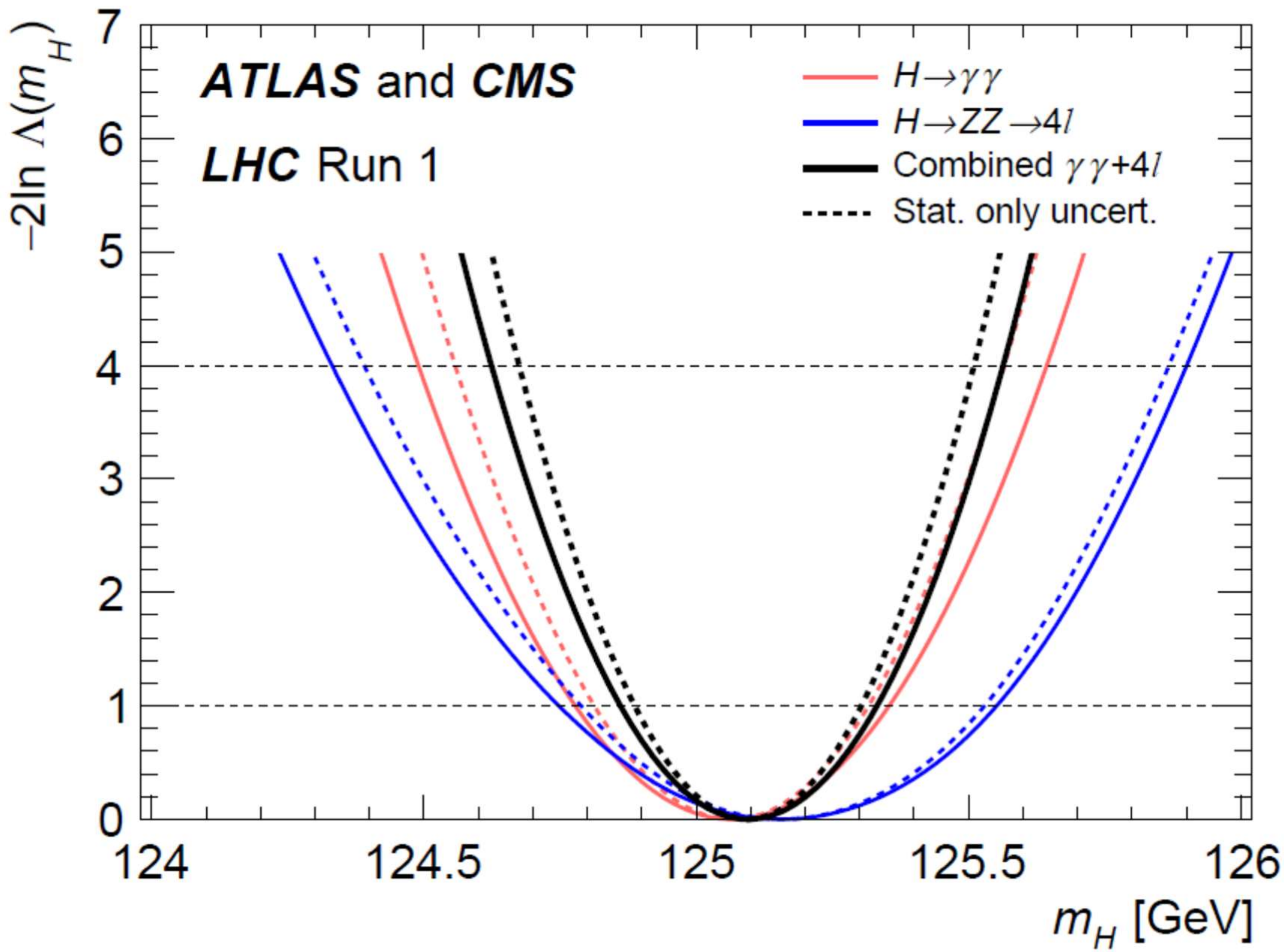


But

- A 4th generation can be compatible with two scalar doublets
- Could be viable if they are vector-like and not chiral (discussed later)

arXiv:0904.4698, arXiv:1202.3072, arXiv:1209.1101

Higgs boson mass



m_H = 125.09 ± 0.21 (stat) ± 0.11 (sys) GeV
(Run1 ATLAS+CMS combination)

Coupling measurements

Results mainly from ATLAS+CMS run 1 combination
https://arxiv.org/abs/1606.02266

Combination procedure

$$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Count number of signal events in each category (narrow width approximation)

Nb of events

$$\lambda^{cat} = \sigma^i_{SM} \times Br^f \times \mathcal{L}$$

Luminosity

Cross-section
Prod: ggH, VBF, WH, ZH, ttH

Branching ratio
Decay: γγ,WW, ZZ, bb, ττ

Combination procedure

$$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Count number of signal events in each category (narrow width approximation)

Signal acceptance (MC) Efficiency

$$\lambda^{cat} = \sigma^{i}_{SM} \times Br^{f} \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Combination procedure

$$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Count number of signal events in each category (narrow width approximation)

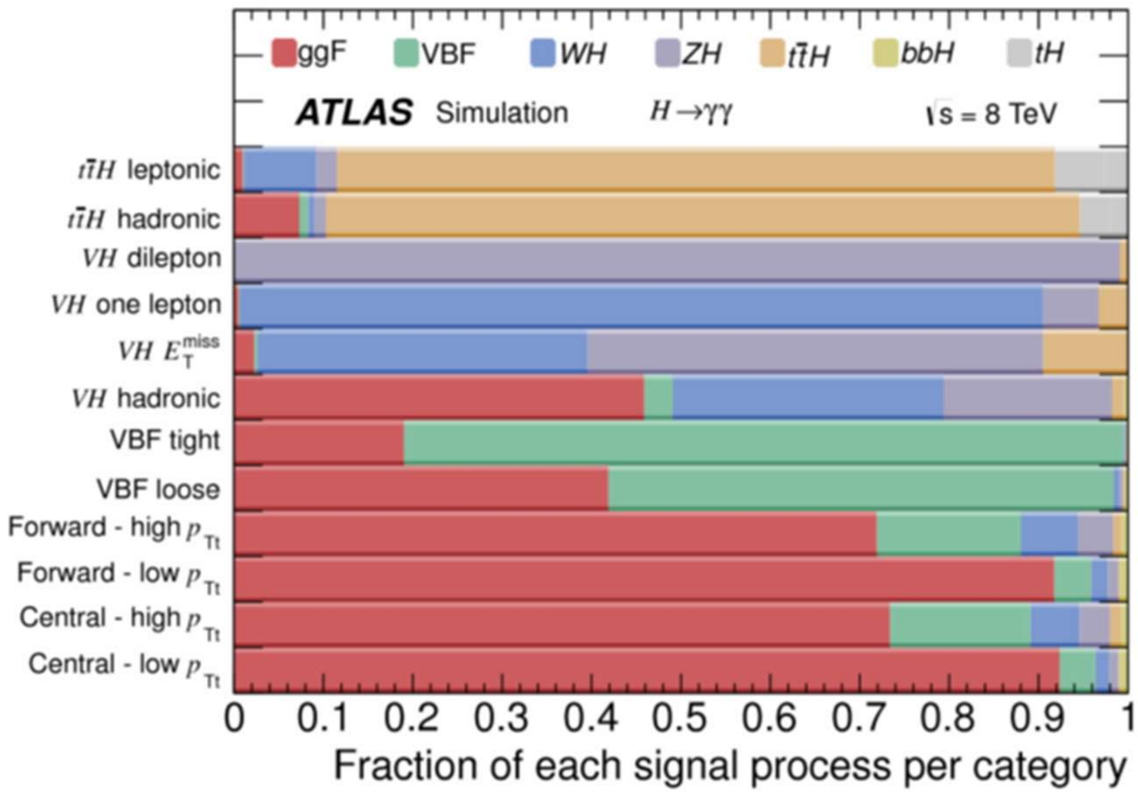
$$\lambda^{cat} = \sum_{i \subset \{\text{prod}\}} \sigma^{i}_{SM} \times Br^{f} \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Combination procedure

$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$

Count number of signal events in each category (narrow width approximation)

$$\lambda^{cat} = \sum_{i \subset \{\mathrm{prod}\}} \sum_{f \subset \{\mathrm{decay}\}} \sigma^{i}_{SM} \times Br^{f} \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$



Combination procedure

$$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Count number of signal events in each category (narrow width approximation)

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}}$$

$$\lambda^{cat.}(\mu^i, \mu^f) = \sum_{i \subset \{\mathrm{prod}\}} \sum_{f \subset \{\mathrm{decay}\}} \mu^i \sigma_{SM}^i \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

$$\mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}.$$

Cannot determine the signal strength parameters μ_i and μ_f simultaneously without assumption

Combination procedure

$$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Count number of signal events in each category (narrow width approximation)

Nb of events

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}}$$

Signal acceptance (MC)

Efficiency

$$\lambda^{cat.}(\mu^i, \mu^f) = \sum_{i \subset \{\mathrm{prod}\}} \sum_{f \subset \{\mathrm{decay}\}} \mu^i \sigma^i_{SM} \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Luminosity

Cross-section
Prod: ggH, VBF, WH, ZH, ttH

$$\mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}.$$

Branching ratio
Decay: γγ,WW, ZZ, bb, ττ

Cannot determine the signal strength parameters μ_i and μ_f simultaneously without assumption

Combination procedure

Given a set of measurements and a hypothesis, a likelihood function is defined as the probability of the data under this hypothesis

Likelihood without nuisance parameters and without shape information:

$$L(data \mid \mu_i , \mu_f) = \prod_{categories} Poisson(n_{cat}, \lambda^{cat}(\mu_i , \mu_f))$$

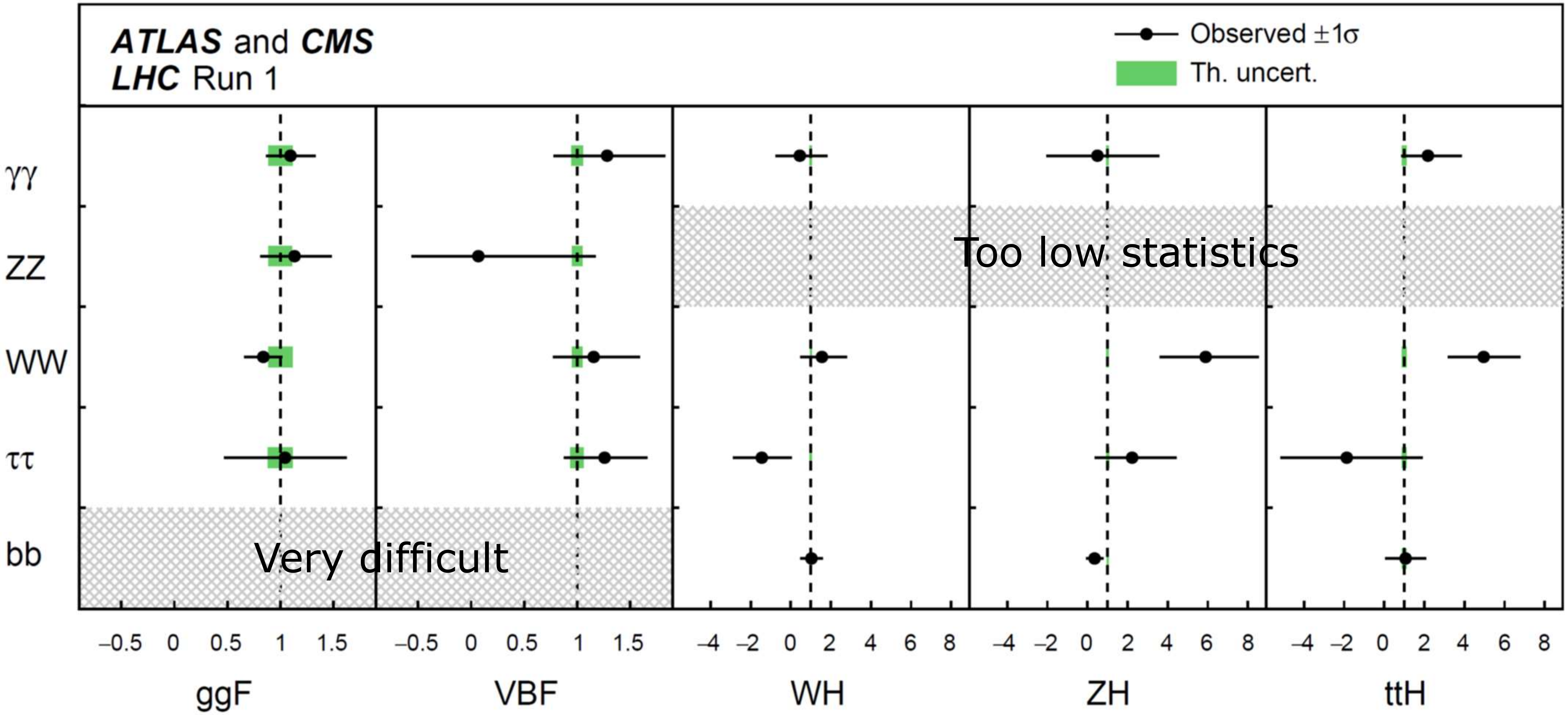
When nuisance parameters are included, their dependences are removed using a profile likelihood ratio

$$\Lambda(data \mid \mu_i , \mu_f) = \frac{L(data \mid \mu_i , \mu_f , \hat{\hat{\theta}})}{L(data \mid \hat{\mu}_i , \hat{\mu}_f , \hat{\theta})}$$

Assuming $\mu_i \mu_f = \mu =$ constant (ATLAS and CMS run 1 combination):

$$\mu = 1.09 \pm 0.07\ (\text{stat})\ \pm 0.04\ (\text{expt})\ \pm 0.03\ (\text{th. bkg})\ \pm 0.07\ (\text{th. sig})$$

$\mu_{if} = \mu_i \cdot \mu_f$ arXiv:1606.02266



20/25 measurements possible with run 1 data

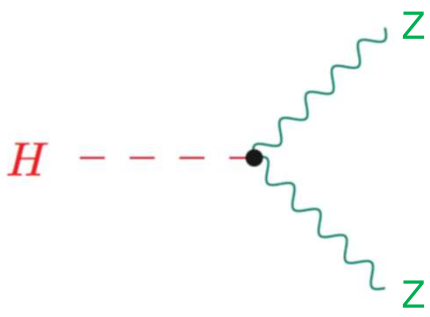
Rate consistent with Standard Model predictions within uncertainties

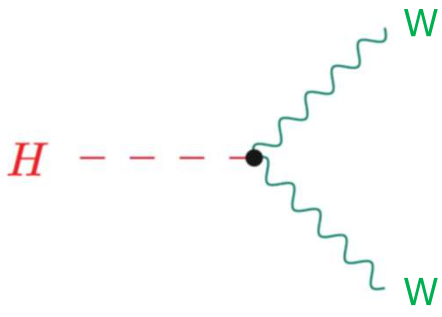
K-framework: coupling modifiers

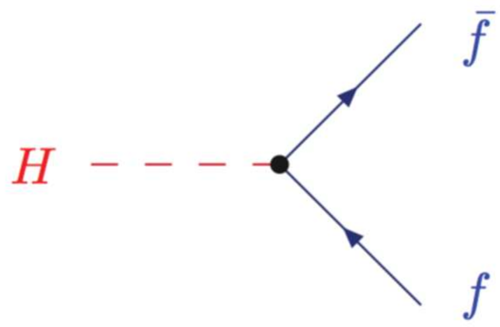
Introduce simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian (assumes that the tensor structure is that of the SM)

$$L \supset \kappa_W \frac{2m_W^2}{v} W_\mu^+ W_\mu^- H + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z_\mu H - \sum_f \kappa_f \frac{m_f}{v} f\bar{f} H$$

In the SM, $\kappa_W = \kappa_Z = \kappa_f = +1$







$$g_{HZZ} = \kappa_Z \frac{2m_Z^2}{v} \qquad g_{HZZ} = \kappa_W \frac{2m_W^2}{v} \qquad g_{Hff} = \kappa_f \frac{m_f}{v}$$

K-framework: total width

Changes in the values of the couplings will result in a variation of the Higgs width.

A new modifier is defined:

$$\kappa_H^2 = 0.57\kappa_b^2 + 0.06\kappa_\tau^2 + 0.03\kappa_c^2 + 0.22\kappa_W^2 + 0.03\kappa_Z^2 + 0.09\kappa_g^2 + 0.0023\kappa_\gamma^2$$

The total width is then given by

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

Example of BSM decays: decays into BSM particles that are invisible to the detector because they do not appreciably interact with ordinary matter

Since Γ_H can't be measured accurately at the LHC in model-independent way, one needs to:

- make assumptions on Γ_H (ex: BR_{BSM}=0)
- measure ratio of coupling modifiers (lambdas)

K-framework

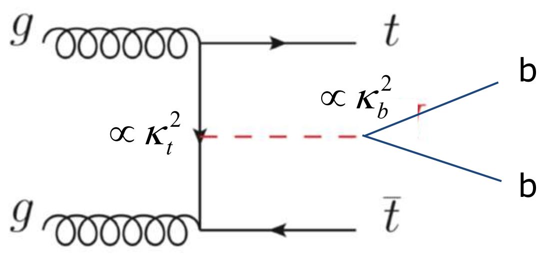
For a given production process, one define

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \qquad j \subset \{ggF, VBF, WH, ttH, \ldots\}$$

For a given decay mode, one define

$$\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}} \qquad j \subset \{bb, ZZ, \gamma\gamma, \tau\tau, \ldots\}$$

Example:



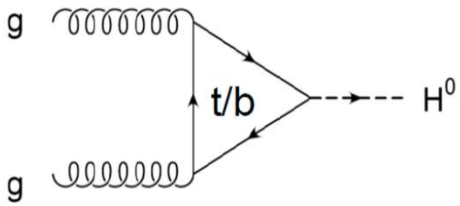
$$\sigma(gg \to tt(H \to bb)) = \sigma_{ttH} \times BR_{H \to bb} = \frac{\sigma_{ttH}\Gamma_{bb}}{\Gamma_H} = \frac{\kappa_t^2 \kappa_b^2}{\kappa_H^2} \frac{\sigma_{ttH}^{SM}\Gamma_{bb}^{SM}}{\Gamma_H^{SM}}$$

NWA

$BR_{BSM}=0$

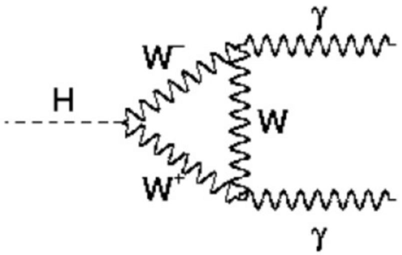
K-framework: loops

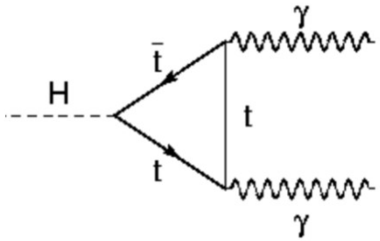
Gluon fusion:



$$\kappa_g^2 = \frac{\sigma}{\sigma_{SM}} = \frac{\kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$$

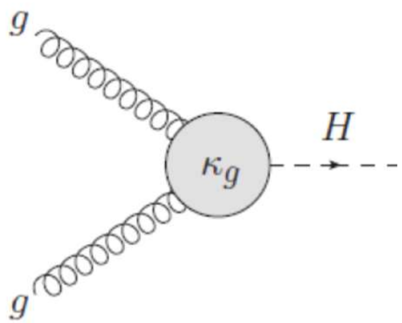
Photon decay:

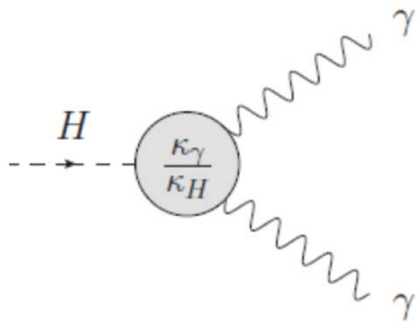




$$\kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \frac{\kappa_t^2 \Gamma_{\gamma\gamma}^{tt} + \kappa_W^2 \Gamma_{\gamma\gamma}^{WW} + \kappa_t \kappa_W \Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt} + \Gamma_{\gamma\gamma}^{WW} + \Gamma_{\gamma\gamma}^{tW}}$$

It was assumed that no new particle runs in the loops. An alternative approach is to represent loop processes with effective params (κ_g,κ_γ) → allow BSM contribution





K-framework

$\sqrt{s}$=8TeV M_H=125.09

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2

K-framework

Likelihood reparametrization

$$L(data \mid \mu_i, \mu_f) \rightarrow L(data \mid \kappa_i, \kappa_f)$$

$$\mu_i = \kappa_i^2$$

$$\mu^f = \frac{\kappa_f^2}{\kappa_H^2}$$

Fit only sensitive to products of coupling modifiers and not to their signs

The measurements of coupling modifiers is sensitive to many BSM models:

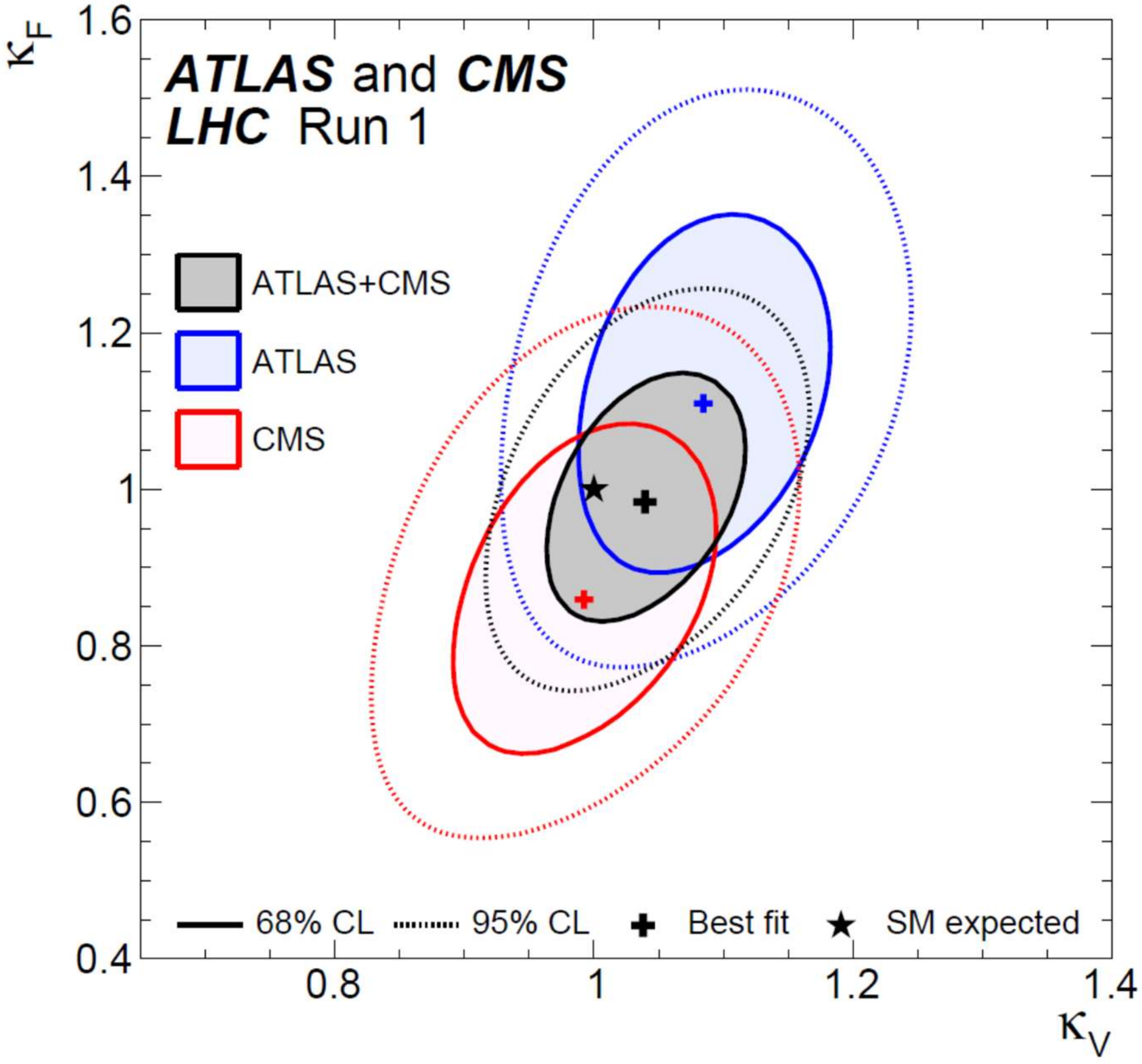
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Constraints for couplings to fermions and bosons

Fit assuming one coupling modifier for all fermions and one coupling modifier for all bosons without new particles in the loops or in the decays

$$\kappa_V = \kappa_W = \kappa_Z$$

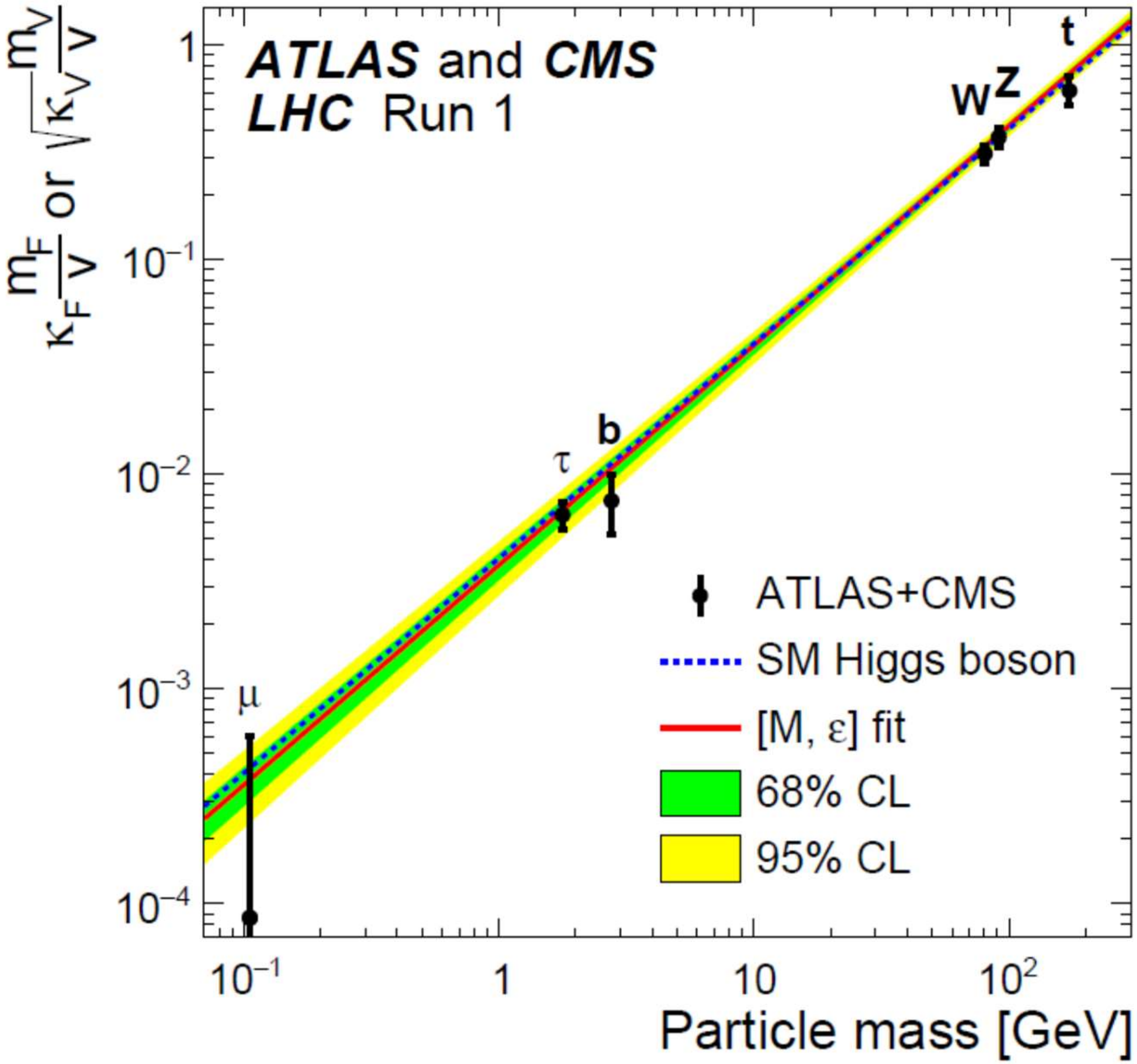
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_\mu$$



Constraints on tree-level Higgs couplings

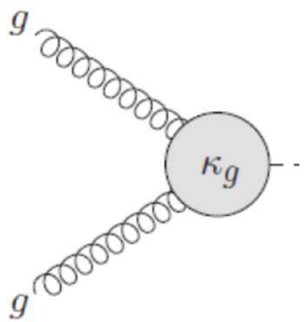
Assume only SM physics in loops, no invisible Higgs decays

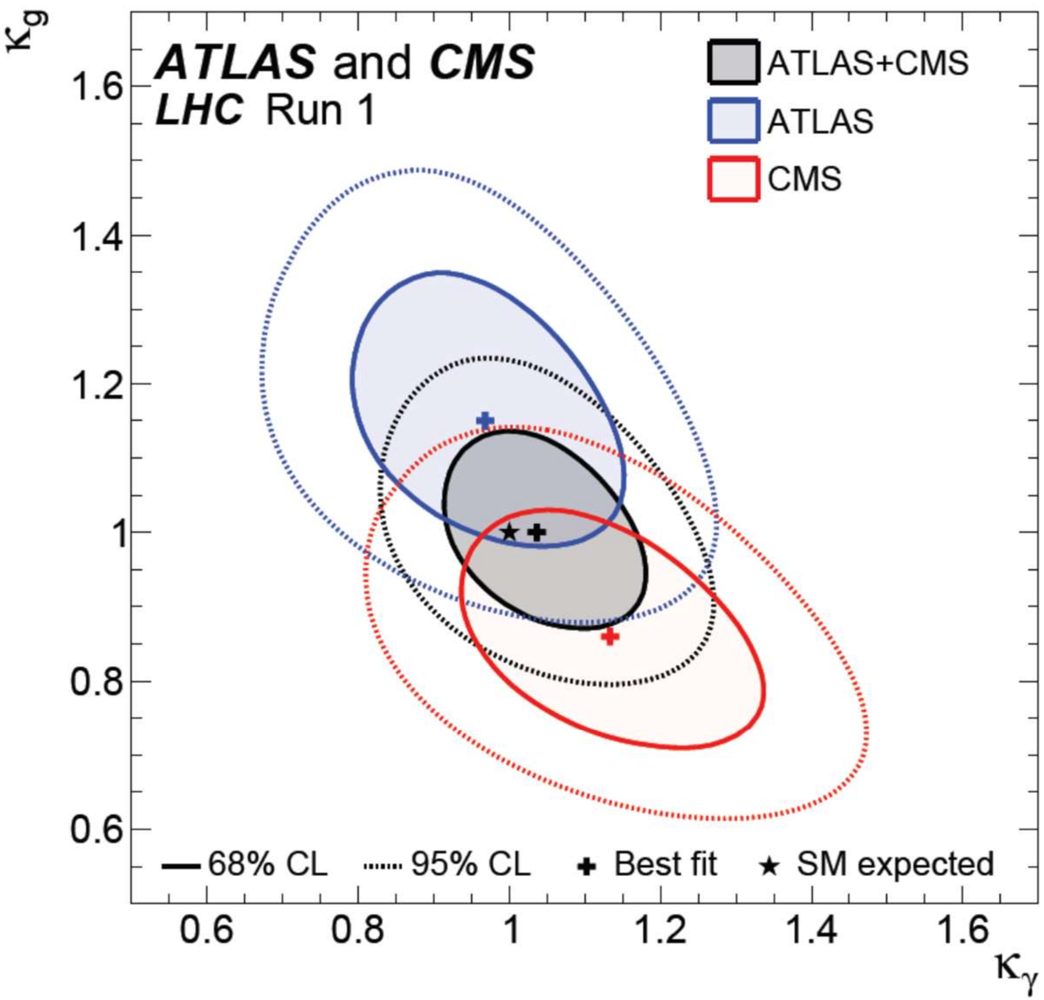
Fit for scaling parameters for Higgs couplings to W, Z, b, t, τ, μ

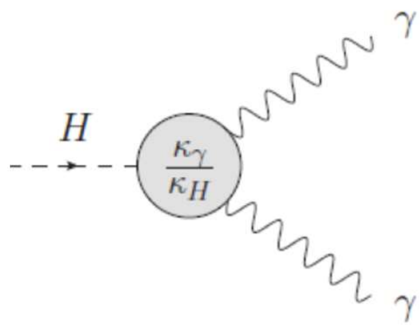


Effective photon and gluon couplings

Fit assuming that the Higgs couples to all SM according to the SM, but no assumptions made on the loops nor on the decay





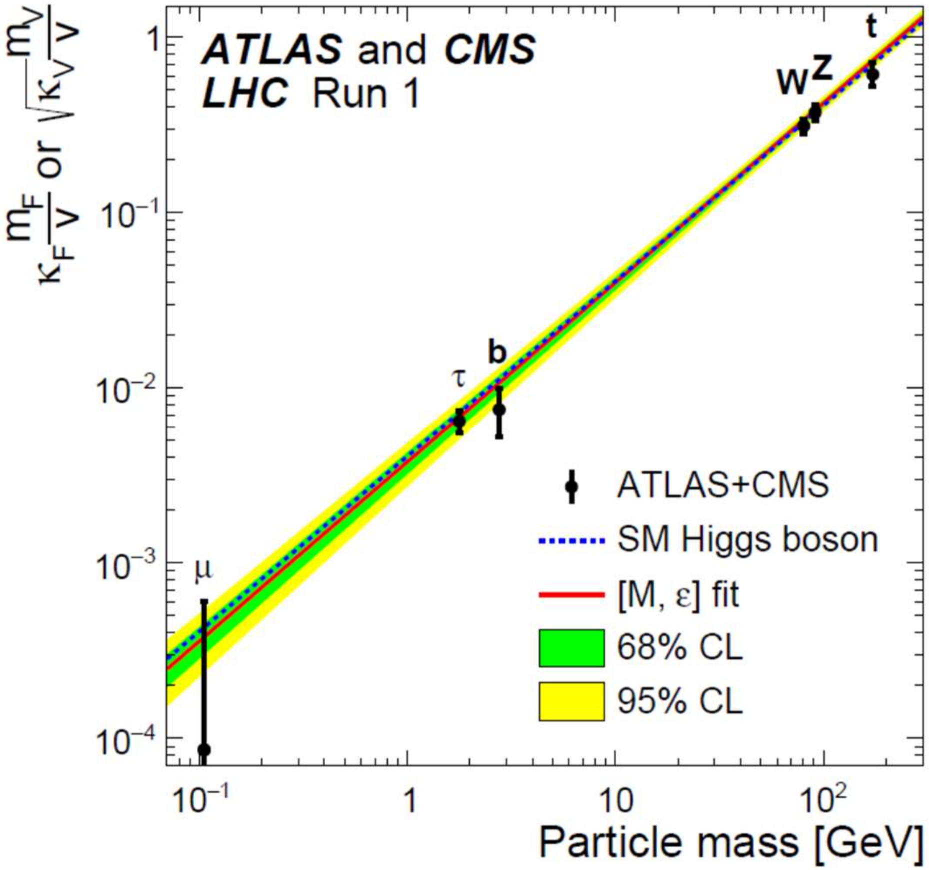


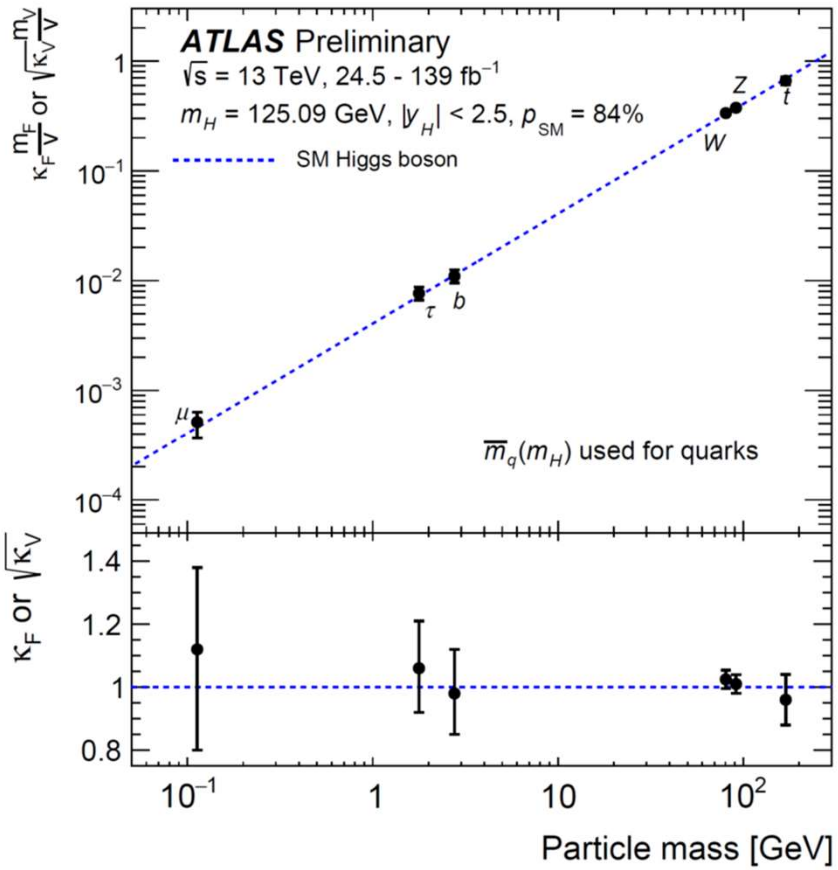
$$\kappa_W = \kappa_Z = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu = 1$$

A few words on run 2 results

The results presented in these lectures are mainly based on Run 1

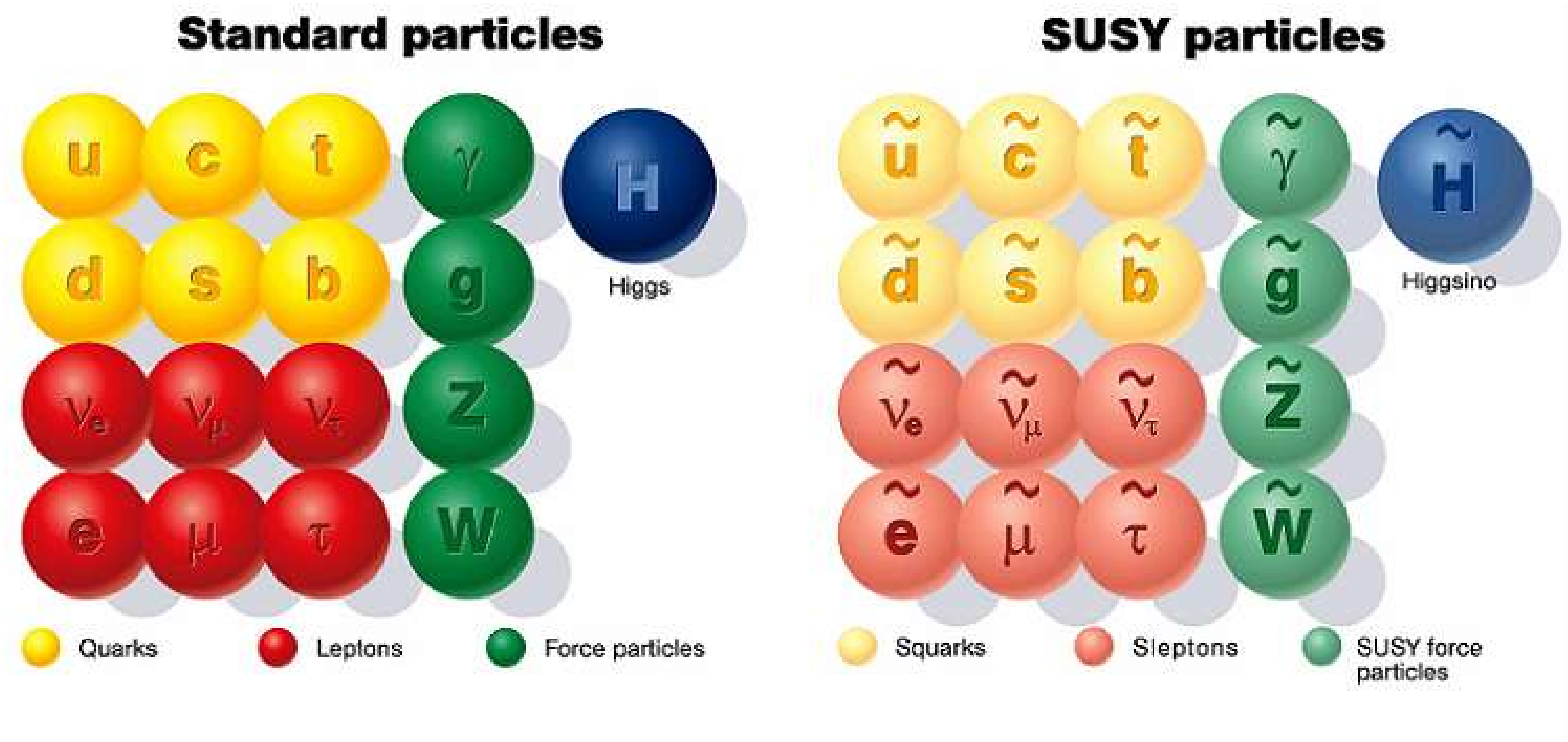
- Significant improvement with run 2 data (VHbb, ttH observed)
- Main conclusion unchanged: the Higgs boson is SM-like





Constraints on BSM physics: supersymmetry

Minimal Supersymmetric Standard Model (MSSM)



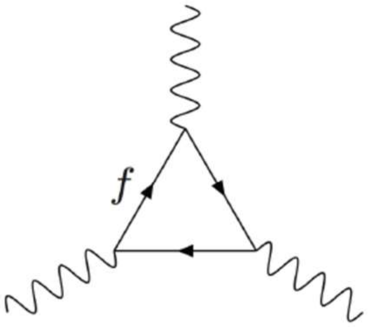
Higgs sector extended to 5 Higgs bosons: h, H, A, $H^{\pm}$

$$\tilde{H}_u^0\ \tilde{H}_d^0\ \tilde{W}^0\ \tilde{B}^0 \longrightarrow \tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$$

$$\tilde{H}_u^+\ \tilde{H}_d^-\ \tilde{W}^+\ \tilde{W}^- \xrightarrow[\text{EW symmetry breaking}]{} \tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^{\pm}$$

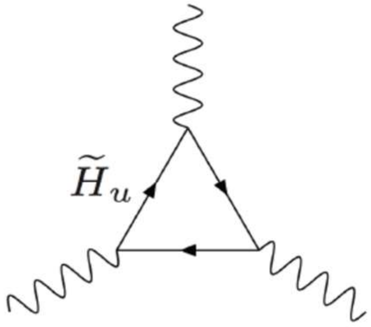
Why 2 Higgs doublets?

How Many Higgs Supermultiplets?



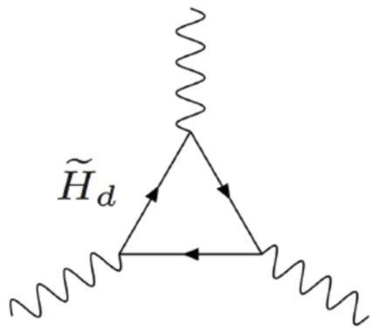
$$\sum_{SM\ fermions} Y_f^3 = 0$$

anomaly cancellation
Miracle of the standard model



$$\left(\frac{1}{2}\right)^3$$

Now in SUSY we got at least one new fermion, the Higgsino



$$\left(-\frac{1}{2}\right)^3$$

Need a Higgsino with Y=-1/2 to avoid anomalies

This new anomaly cancels if and only if both the $\tilde{H}_u$ and $\tilde{H}_d$ Higgsinos exist.

The masses of the up-quarks (u,c,t) arise from coupling with H_u
The masses of the down-quarks (d,s,b) arise from coupling with H_d

2 Higgs doublets needed!

MSSM Higgs sector

Higgs sector in SUSY contains two scalar doublets ⇒ 5 Higgs

- neutral, CP-even: h, H
- neutral, CP-odd: A
- charged H^+, H^-

$$v^2 = v_u^2 + v_d^2 \qquad \tan\beta = \frac{v_u}{v_d}$$

At tree level two free parameters: m_A and $\tan\beta$

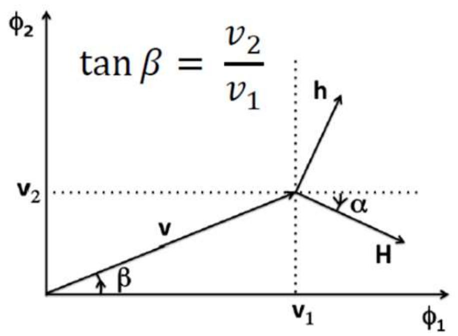
$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{H,\,h}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right)$$

$$\tan\alpha = \frac{-(m_A^2 + m_Z^2)\sin 2\beta}{(m_Z^2 - m_A^2)\cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}}$$

mixing angle of neutral CP-even Higgs boson

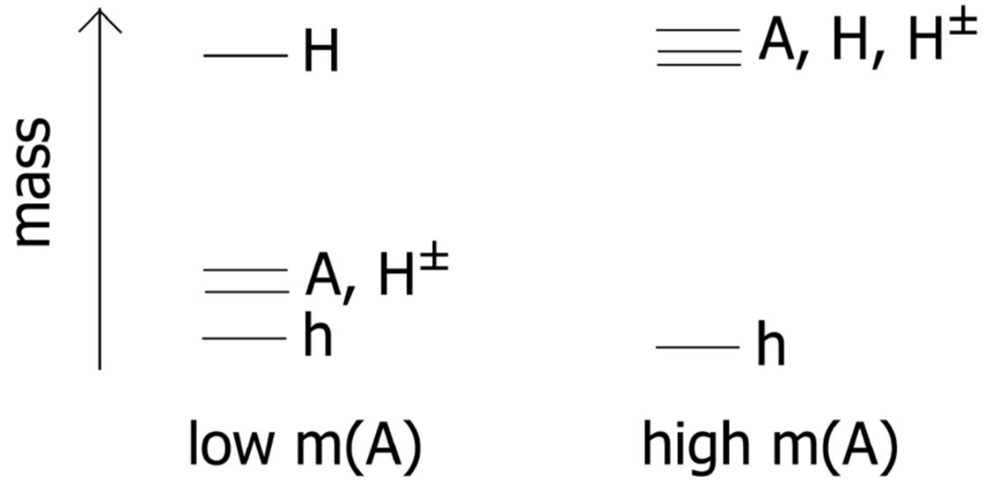
$$H^0 = \mathrm{Re}(H_d^2)\cos\alpha + \mathrm{Re}(H_u^1)\sin\alpha,$$
$$h^0 = -\mathrm{Re}(H_d^2)\sin\alpha + \mathrm{Re}(H_u^1)\cos\alpha,$$
$$A^0 = \mathrm{Im}(H_d^2)\sin\beta + \mathrm{Im}(H_u^1)\cos\beta,$$



MSSM Higgs sector: decoupling limit

Decoupling limit ($m_A >> m_z$):

- h SM-like
- H/A/H± nearly equal mass



At tree level:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta \,,$$

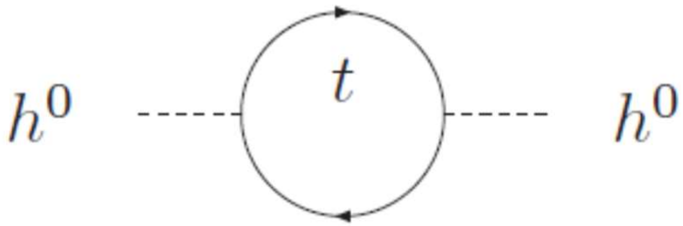
$$m_H^2 \simeq m_A^2 + m_Z^2 \sin^2 2\beta \,,$$

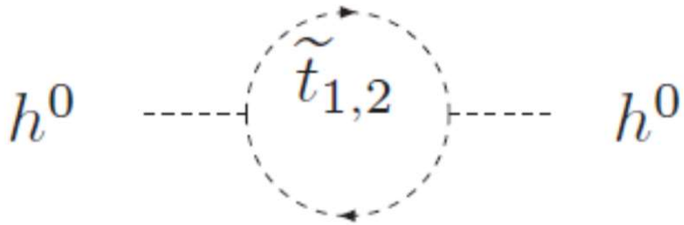
$$m_{H^\pm}^2 = m_A^2 + m_W^2 \,,$$

$$\cos^2(\beta - \alpha) \simeq \frac{m_Z^4 \sin^2 4\beta}{4 m_A^4} \,.$$

Higgs boson mass and supersymmetry

At tree level the lighter CP-even Higgs boson should be lighter than the Z boson but radiative corrections push its mass upward beyond the tree level bound





Incomplete cancellation which would have been exact if supersymmetry were unbroken

$$m_h^2 \sim M_Z^2 \cos^2 2\beta + \Delta\, m_h^2$$

(decoupling limit)

Large corrections through large stop mixing X_t and/or large M_{SUSY}

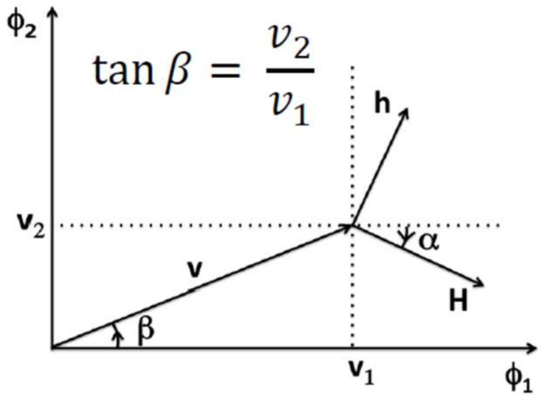
Taking into account radiative correction: $m_H < 135 GeV$

Tension between m_h = 125 GeV and Naturalness

hMSSM

Supersymmetry modifies the couplings of the Higgs boson:

- $k_V = \sin(\beta - \alpha)$
- $k_d = -\sin\alpha / \cos\beta$
- $k_u = \cos\alpha / \sin\beta$



With the following angular parameters:

- α: mixing parameter of two CP-even Higgs scalars
- tan β: ratio of V.E.V. of the two Higgs doublets

From constraints coupling measurements, limits in the MSSM parameter space can be set.

The MSSM Higgs sector at tree level is governed by only two parameters (m_A and $\tan\beta$) but is sensitive to other parameters at the loop level

hMSSM:

- Simplified MSSM model: limited validity for tan $\beta \ll 1$ or large A_t/μ
- Corrections to mass matrix of Higgs bosons from top and stop only
- Lightest Higgs *h* identified with the observed one: SM-like couplings
- Couplings κ_V, κ_u, κ_d depend only on tan β and m_A

hMSSM

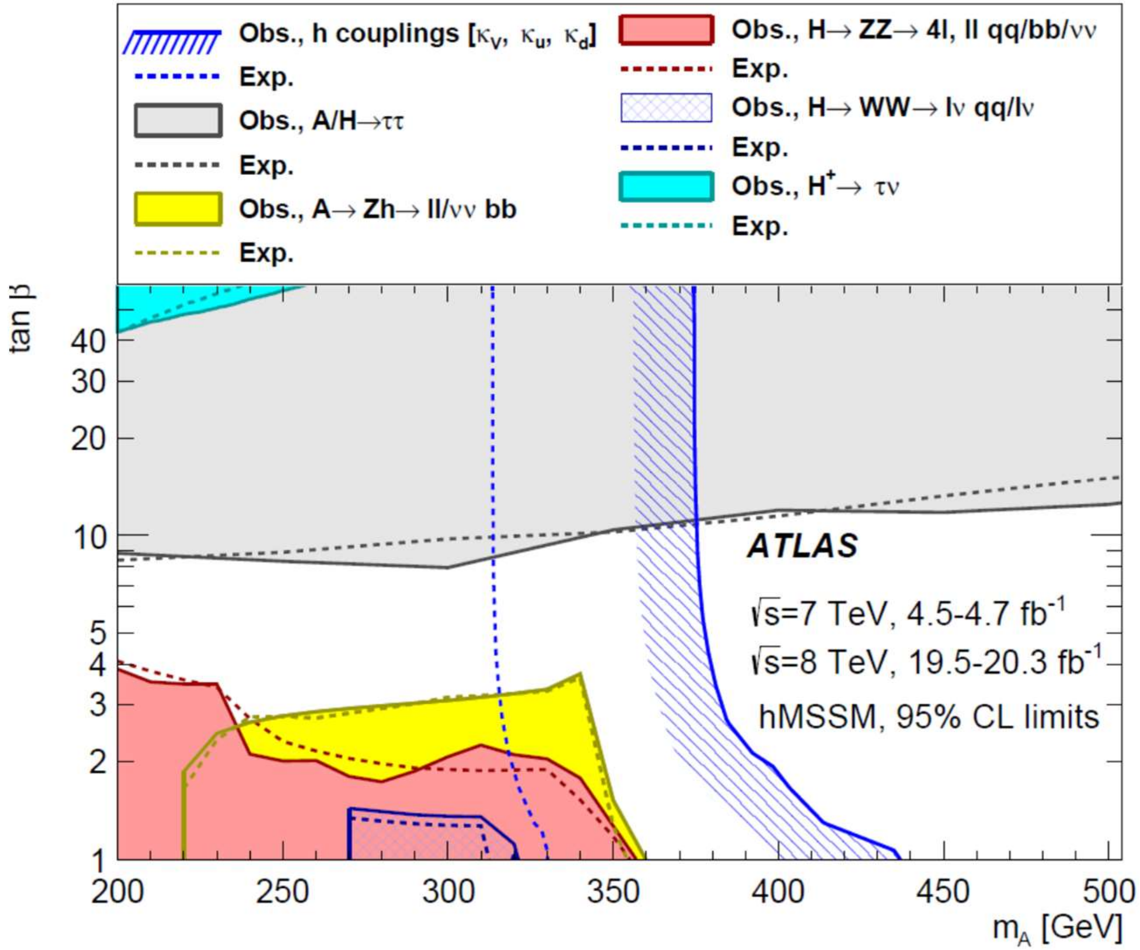
$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta} \quad ,$$

$$s_u = \frac{1}{\sqrt{1+\frac{\left(m_A^2+m_Z^2\right)^2\tan^2\beta}{\left(m_Z^2+m_A^2\tan^2\beta-m_h^2\left(1+\tan^2\beta\right)\right)^2}}}$$

$$s_d = \frac{\left(m_A^2+m_Z^2\right)\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_h^2\left(1+\tan^2\beta\right)}\, s_u$$



Data consistent with the decoupling limit ($m_A >> m_h$)
Complementary with direct searches

Constraints on BSM physics: composite Higgs

Composite pseudo-Goldstone-boson Higgs

In composite Higgs models, the Higgs boson is a bound state of a new dynamics becoming strong around the weak scale

- The Higgs boson can be made significantly lighter than the other resonances of the strong sector if it appears as a pseudo-Golsdone boson

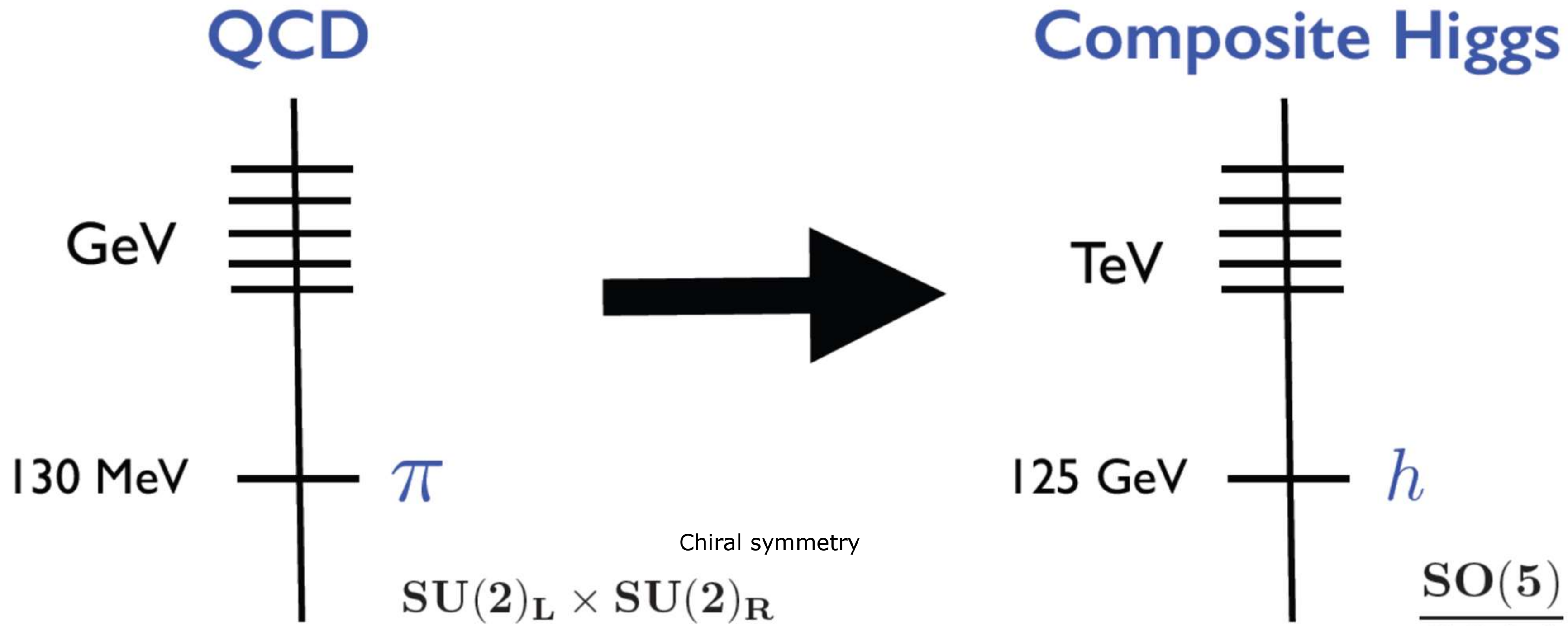
Nature contains a sector that breaks to an approximate global symmetry at a scale f: G→H

The subgroup H should contain $SU(2)_L x U(1)_Y$. As a result we have Goldstone bosons along G=H generators and some of them are identified with the SM Higgs doublet

The Higgs potential is generated radiatively by the coupling of the SM fields to the strong sector and then it triggers EWSB at lower energy

More information in arXiv:1005.4269

Composite pseudo-Goldstone-boson Higgs



Chiral symmetry

$$\frac{\mathbf{SU(2)_L \times SU(2)_R}}{\mathbf{SU(2)_V}}$$

Custiodal symmetry

$$\frac{\mathbf{SO(5)}}{\mathbf{SO(4)}}$$

Pions are the pseudo Goldstone bosons of the chiral symmetry breaking

Higgs is a "hadron" of a new strong force

Minimal Composite Higgs models

SO(5) global symmetry is spontaneously broken to SO(4)

Unbroken SO(4) is isomorphic to $SU(2)_L$ x$SU(2)_R$ in which SM electroweak symmetry $SU(2)_L$x$U(1)_Y$ can be embedded

SO(5)=10 generators, SO(4)=6 generators, thus 4 Goldstone bosons corresponding to 1 Higgs doublet (minimal Higgs sector)

MCH4: quarks and leptons are embedded into spinorial representations of SO(5)

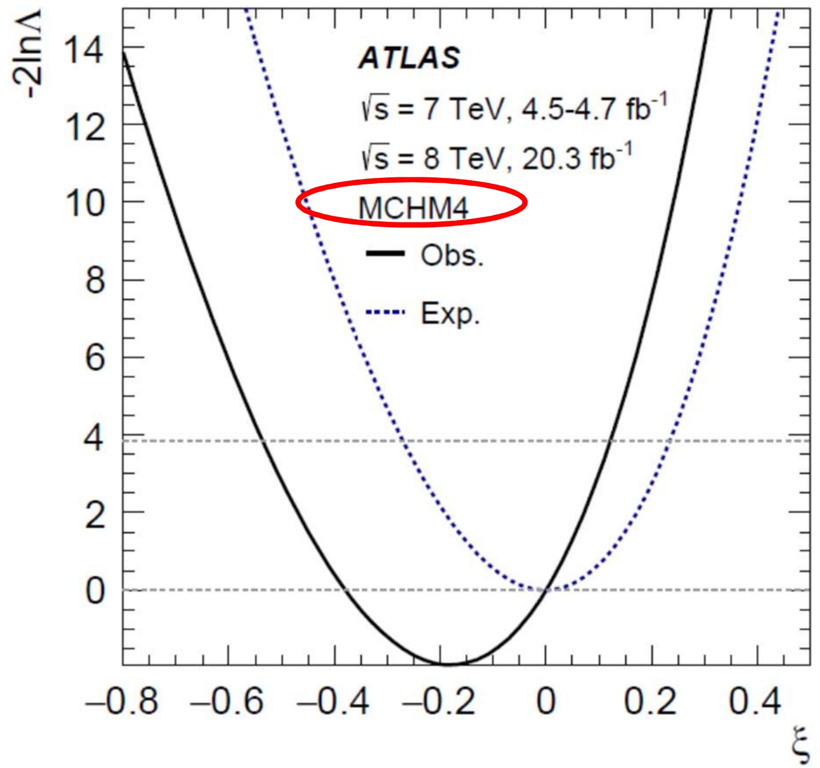
MCH5: quarks and leptons are embedded into fundamental representations of SO(5)

Minimal Composite Higgs Models

Couplings of the Higgs boson modified by amounts of order **$\xi = v^2/f^2$**

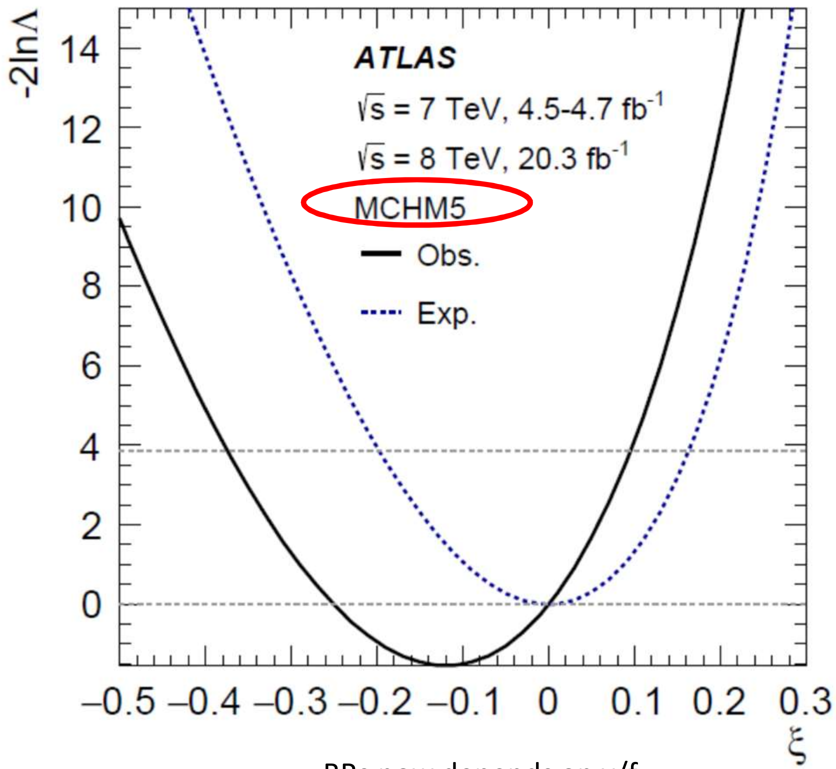
f: G→H breaking scale and ξ: degree of compositness

If $\xi \to 0$ (f →∞), the Standard Model is recovered



universal shift of the couplings
no modifications of BRs

$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$$

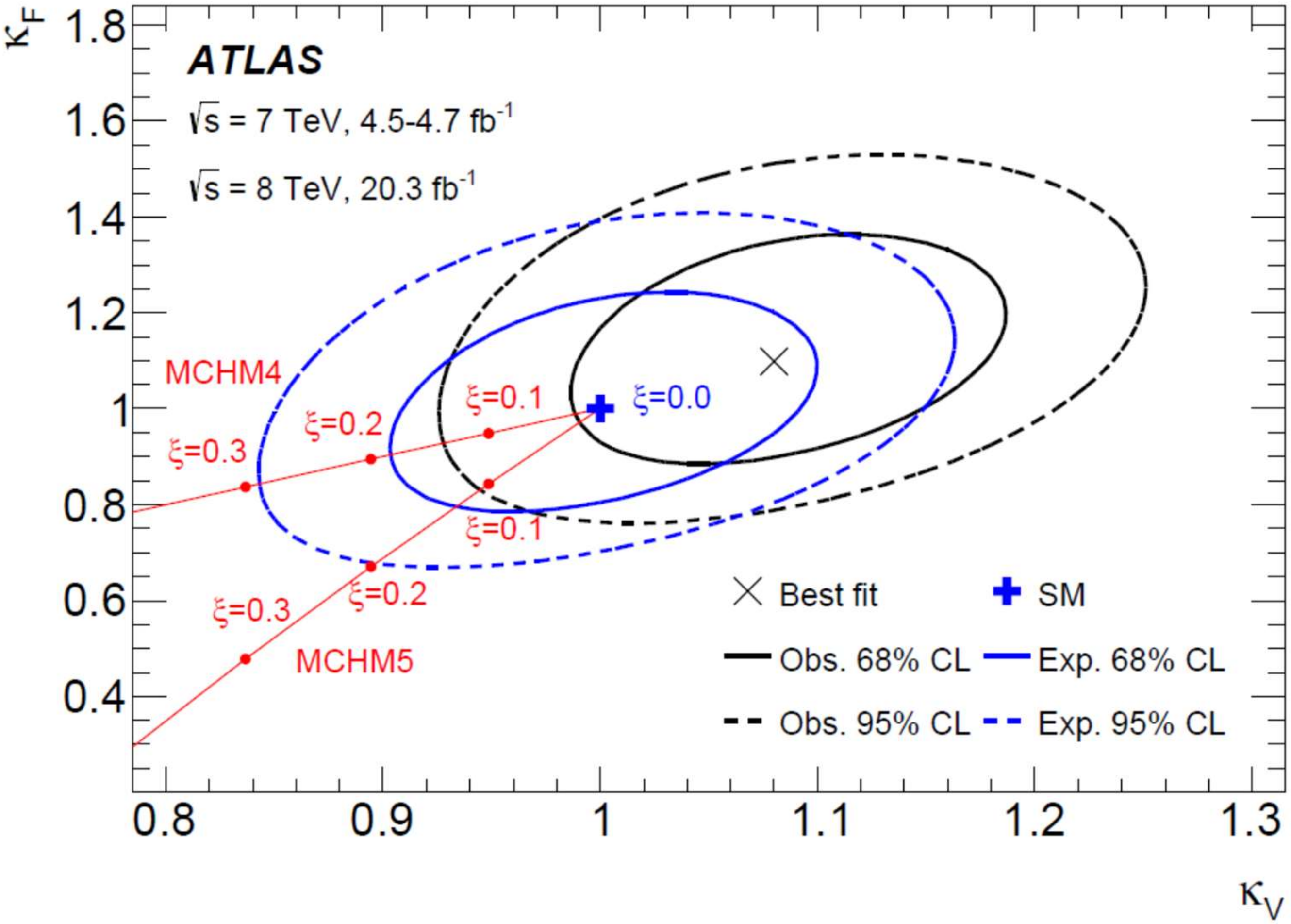


BRs now depends on v/f

$$\kappa_V = \sqrt{1-\xi}$$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Minimal Composite Higgs Models



Bound on compositeness scale of the Higgs boson:

$\xi = v^2/f^2$

Model	Lower limit on f	
	Obs.	Exp.
MCHM4	710 GeV	510 GeV
MCHM5	780 GeV	600 GeV

Conclusion

The five main Higgs decay channels has been observed

The four dominant production modes has been established

Mass measured at the few per mill level

Spin and CP: $J^P=0^+$

Coupling analysis: consistency with Standard Model with a precision of 15-30%

No sign of BSM physics in the Higgs sector

→ allows provide experimental constraints on BSM models


That's all Folks!

The Standard Model of particle physics

Most general renormalizable lagrangian including all SM fields with $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge groups:

$$\mathcal{L}_{SM} = -\frac{1}{4g'^2} B_{\mu\nu}B^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{2g_s^2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu})$$
$$+\bar{Q}_i i\not{D} Q_i + \bar{L}_i i\not{D} L_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{e}_i i\not{D} e_i$$
$$+(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + \mathrm{h.c.})$$
$$+(D_\mu H)^\dagger (D^\mu H) - \lambda(H^\dagger H)^2 - \mu^2 H^\dagger H$$
$$+\frac{\theta}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}(G_{\mu\nu}G_{\rho\sigma})$$

19 parameters:

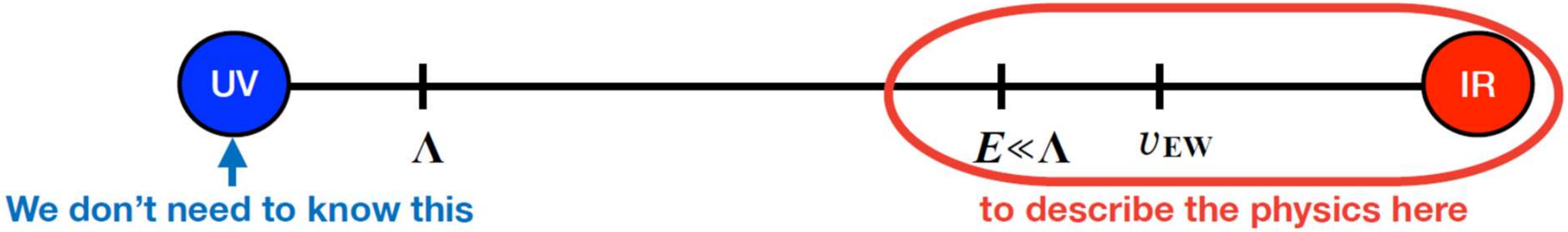
- 3 gauge coupling constants
- 9 fermion Yukawa couplings
- 3 CKM mixing angles + 1 phase
- μ, λ or m_Z, m_H
- θ_{strong}

Interpretation using Effective Field Theory

In spite of its great success and simplicity, the kappa-framework has two distinct problems:

- It only describes modifications of total rates and cannot be used to interpret kinematic distributions
- It does not allow us to combine Higgs measurements with other precision measurements

→ Interpretation with Effective Field Theory (arXiv:1712.07232)

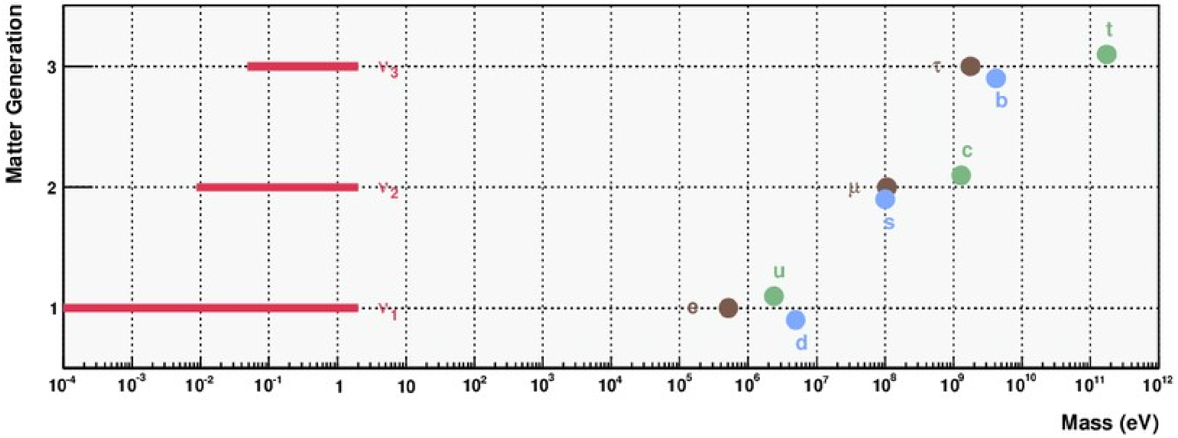


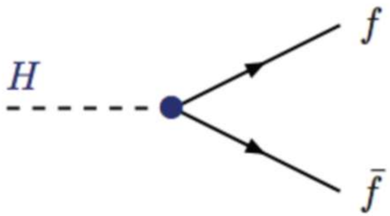
$$L_{EFT} = L_{SM} + \Sigma_i \frac{c_i^5}{\Lambda} O_i^5 + \Sigma_i \frac{c_i^6}{\Lambda^2} O_i^6 + \ldots\ldots$$

O: dimension-n operator constructed from SM fields
→ constraints on the Wilson coefficient which encodes BSM physics
dimension-5 operator violates lepton number conservation → neglected Higgs physics

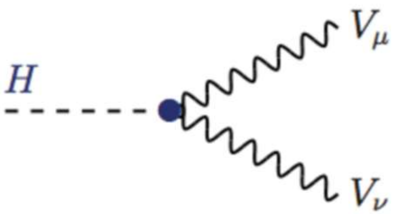
Higgs boson couplings

All the couplings of the Higgs boson to Standard Model particles (except itself) were known before the discovery of the Higgs boson!

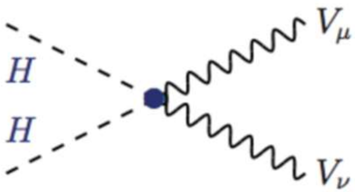




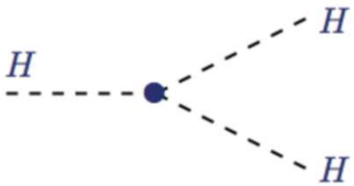
$$g_{Hff} = m_f/v$$



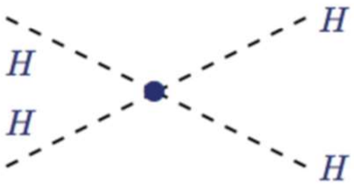
$$g_{HVV} = 2M_V^2/v$$



$$g_{HHVV} = 2M_V^2/v^2$$



$$g_{HHH} = 3M_H^2/v$$



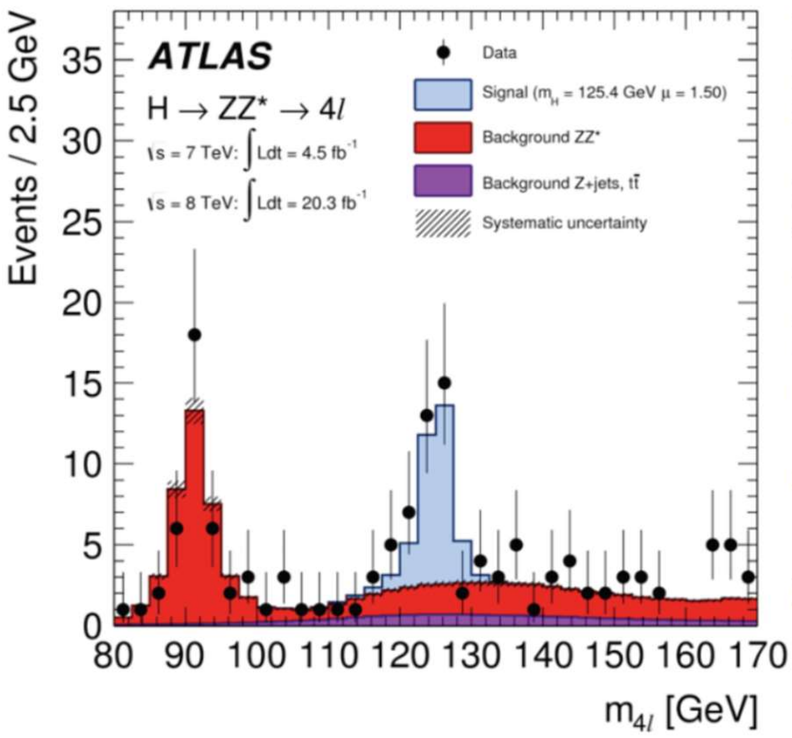
$$g_{HHHH} = 3M_H^2/v^2$$

$$m_W^2 = \frac{g^2v^2}{4} \qquad m_Z^2 = (g^2+g'^2)v^2/4 \qquad M_H^2 = 2\lambda v^2$$

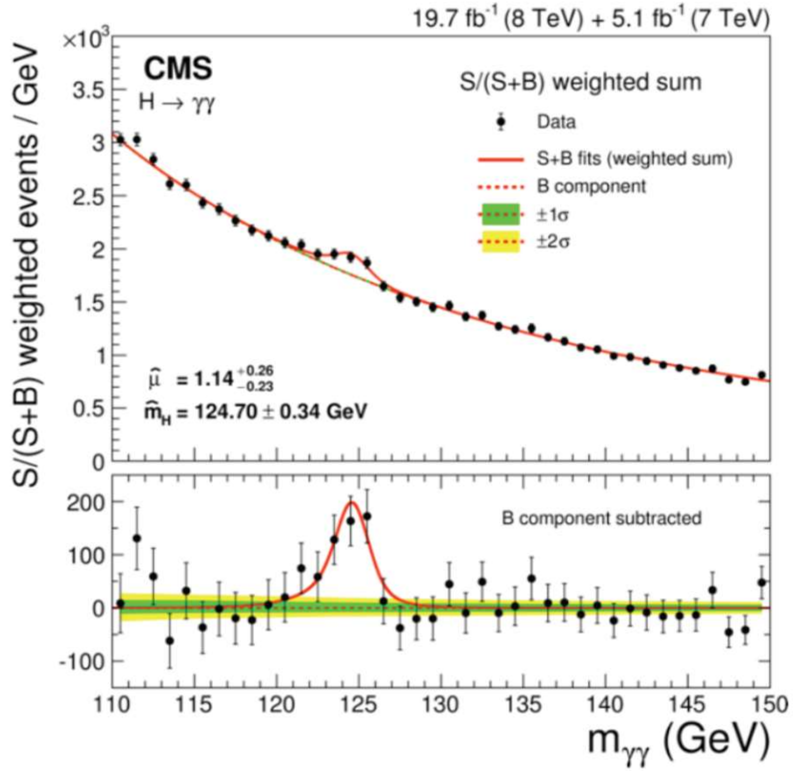
Property measurements

Higgs boson mass

Measurement based on H→ZZ*→4l and H→γγ final states, for which invariant mass can be reconstructed with high precision



Phys. Rev. D 90, 052004 (2014)

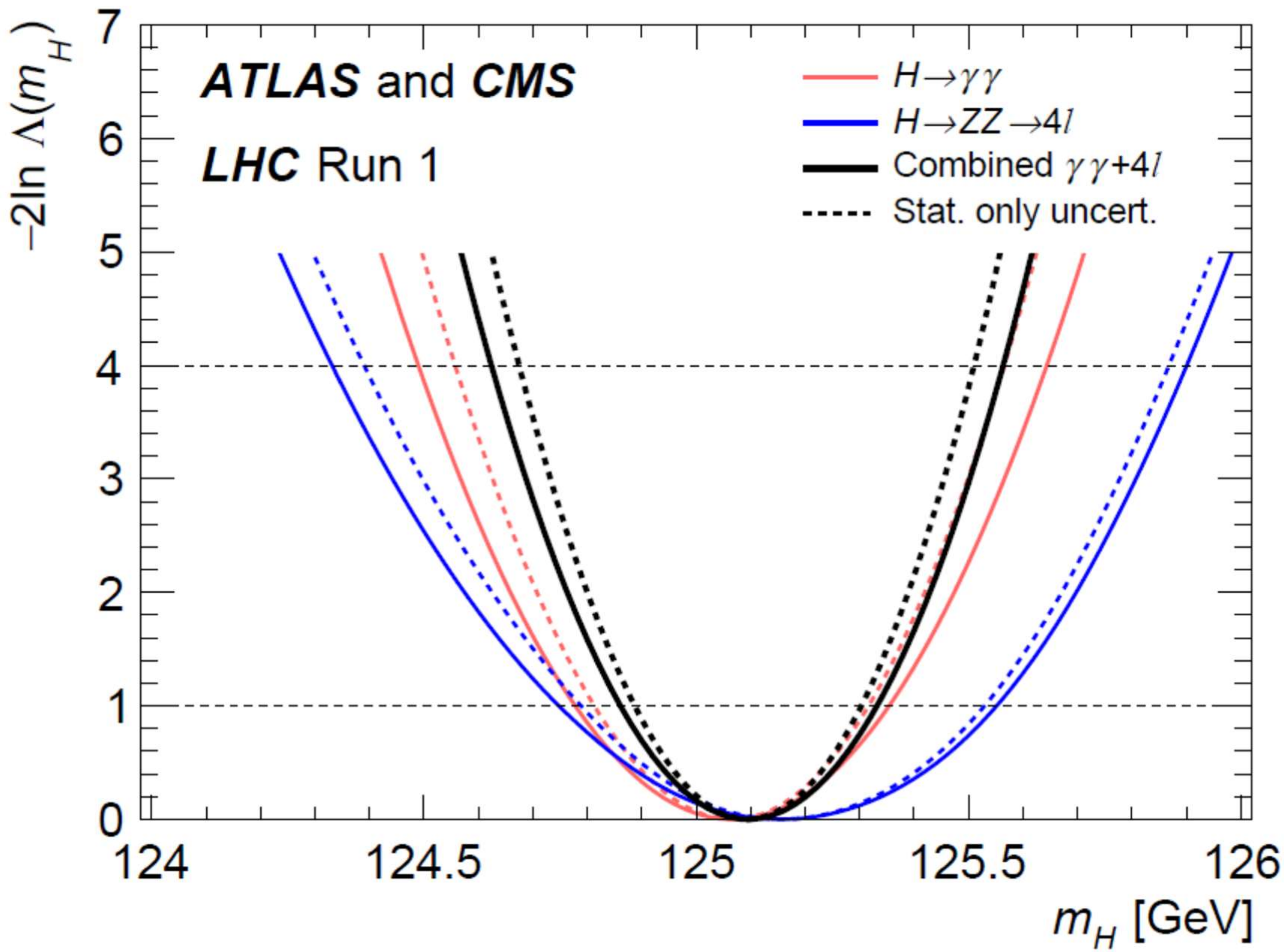


Eur. Phys. J. C 74 (2014) 3076

Mass of Higgs boson measured with <0.2% precision

Dominant systematics: energy or momentum scale and resolution for γ,e,μ

Higgs boson mass

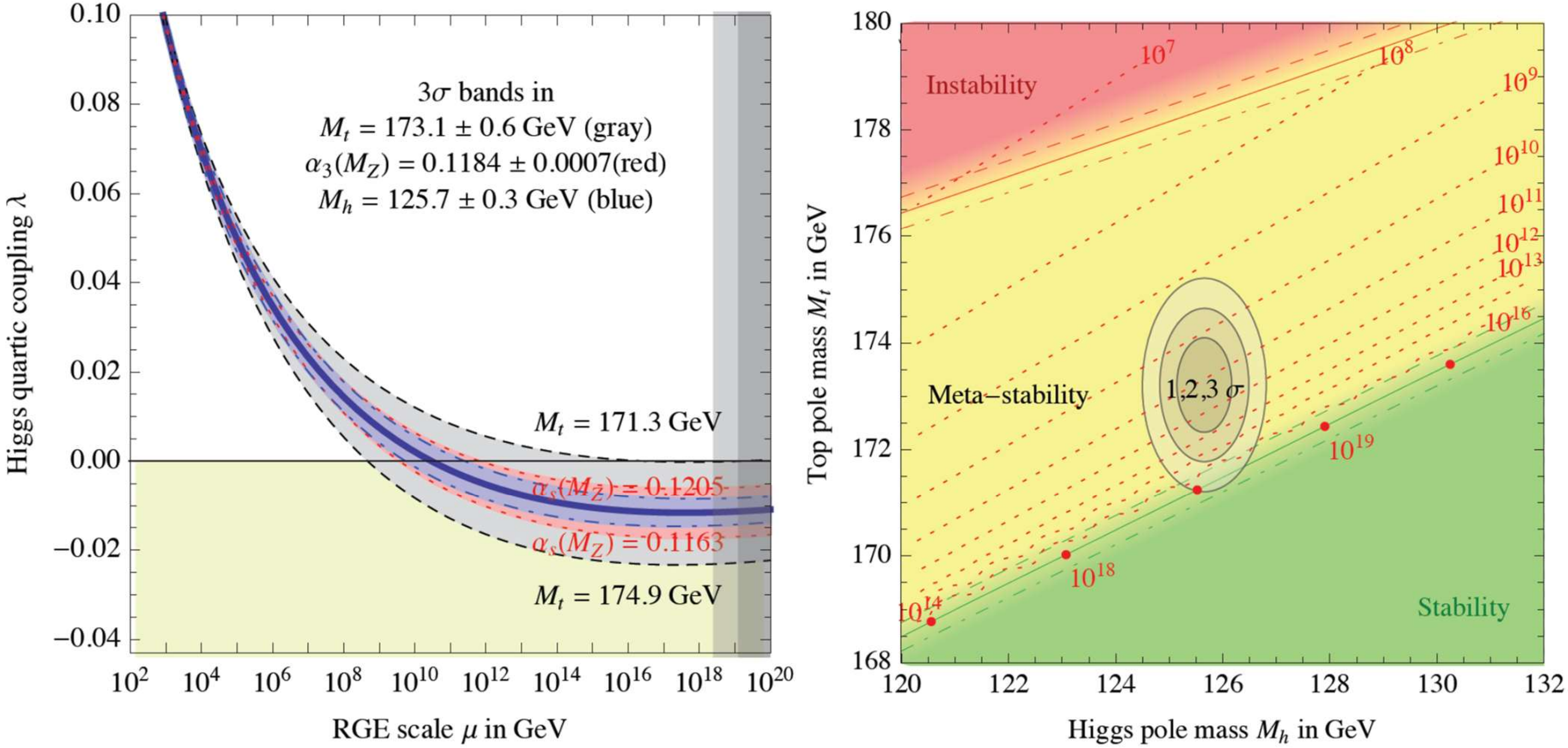


m_H = 125.09 ± 0.21 (stat) ± 0.11 (sys) GeV
(Run1 ATLAS+CMS combination)

Higgs boson mass: vacuum instability

Higgs self coupling is perturbative: $\lambda=0.13$ at the weak scale but the negative renormalization by the top quark drives $\lambda<0$ at high energy scale

→ Higgs potential unbounded from below



Hint of new physics at the 10^9GeV scale !?

Higgs boson width

Narrow resonance: Γ_H~4 MeV →BSM contributions may increase it significantly

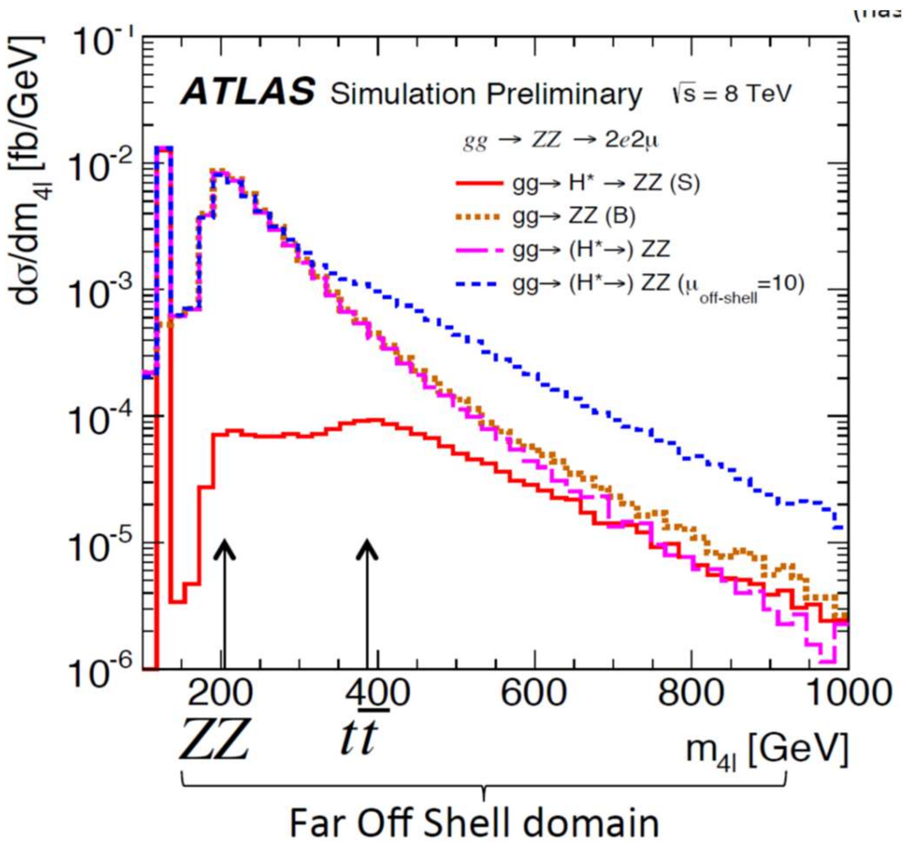
The Higgs width can be in principle extracted from the invariant mass distribution (4l or γγ) However, the direct determination is limited by the detector resolution: ~1 GeV

An alternative idea is to measure the Higgs boson off-shell production:

$$\frac{d\sigma}{dm^2} \sim \frac{g_i^2 g_f^2}{\left(m^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$$

On-peak: $$\frac{d\sigma}{dm^2} \sim \frac{g_i^2 g_f^2}{m_H^2 \Gamma_H^2}$$

Off-peak: $$\frac{d\sigma}{dm^2} \sim \frac{g_i^2 g_f^2}{\left(m^2 - m_H^2\right)^2}$$

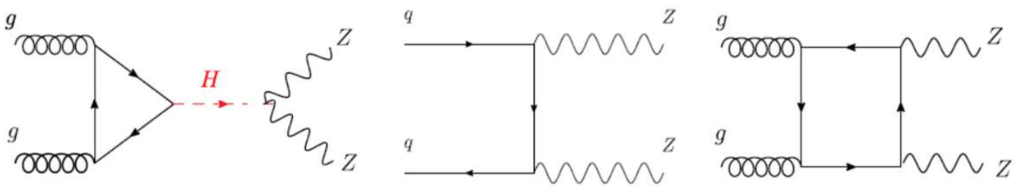


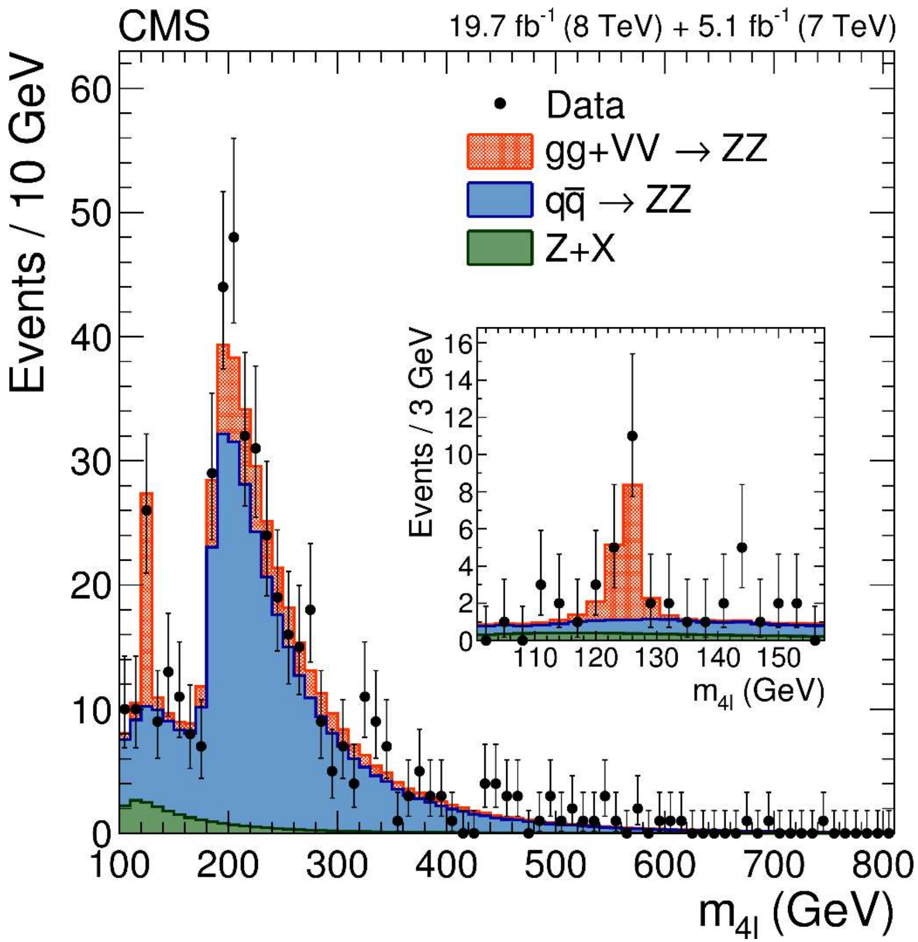
Assuming identical coupling, the ratio gives sensitivity to Higgs boson width

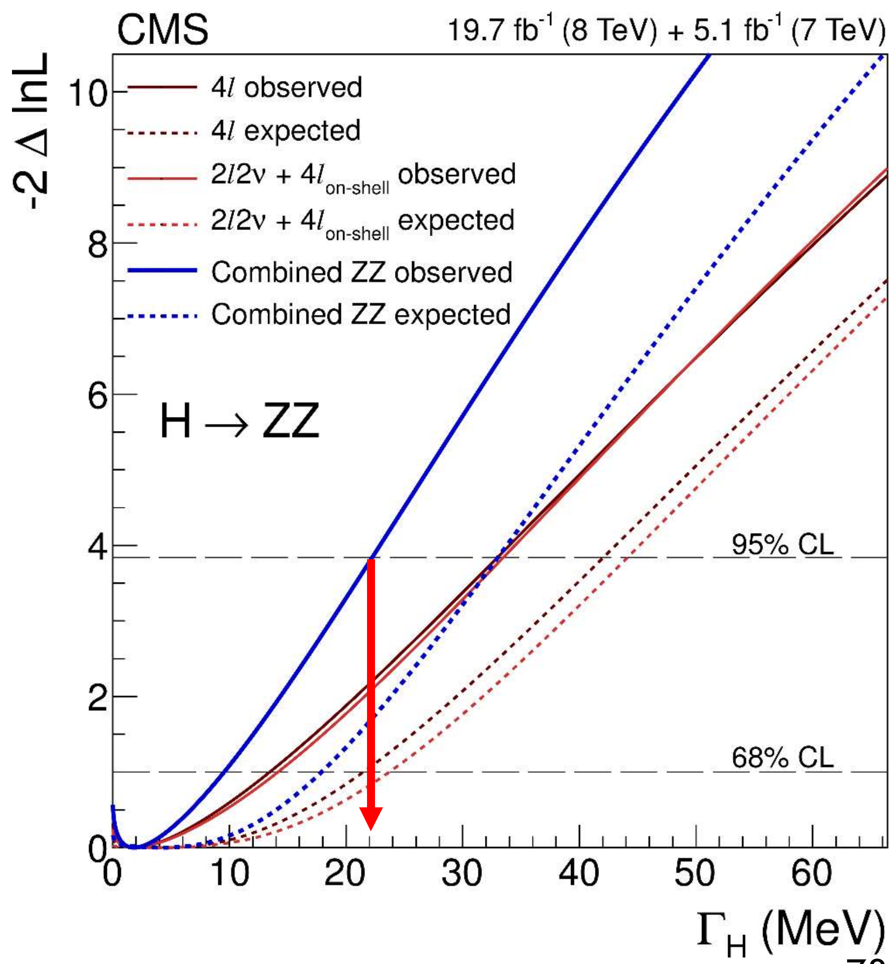
Higgs boson width

Highly non trivial due to:

- The negative interference
- The large other backgrounds





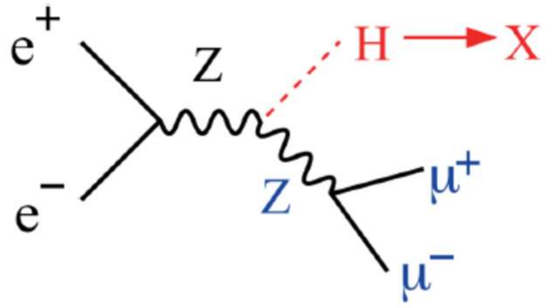


Higgs boson width: recoil mass at lepton colliders

leptonic: J. Yan, et al., Phys. Rev. D **94**, 113002 (2016)
hadronic: M. A. Thomson, Eur. Phys. J. C (2016) 76:72

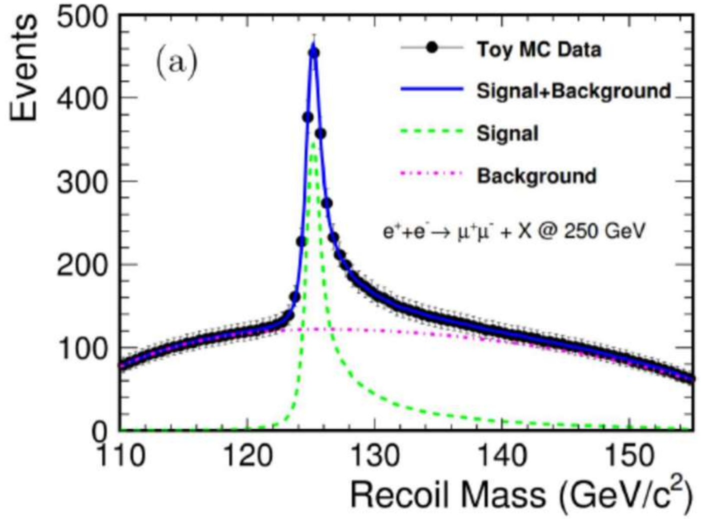
Key Measurement: σ_{Zh}

Unique measurement at lepton colliders



leptonic & hadronic

$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$



- well-defined initial states
- without looking Higgs (recoil mass technique)

ILC250, 2 ab^{-1}

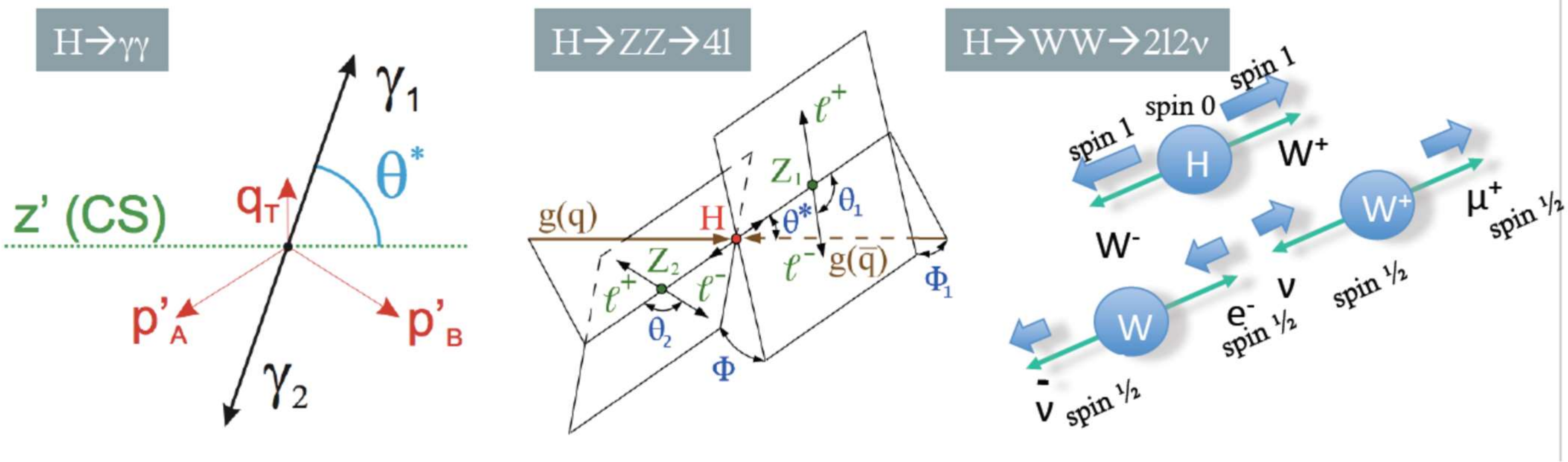
Δm_h = **14 MeV**, $\frac{\Delta\sigma_{Zh}}{\sigma_{Zh}}$ = **0.7%**

6

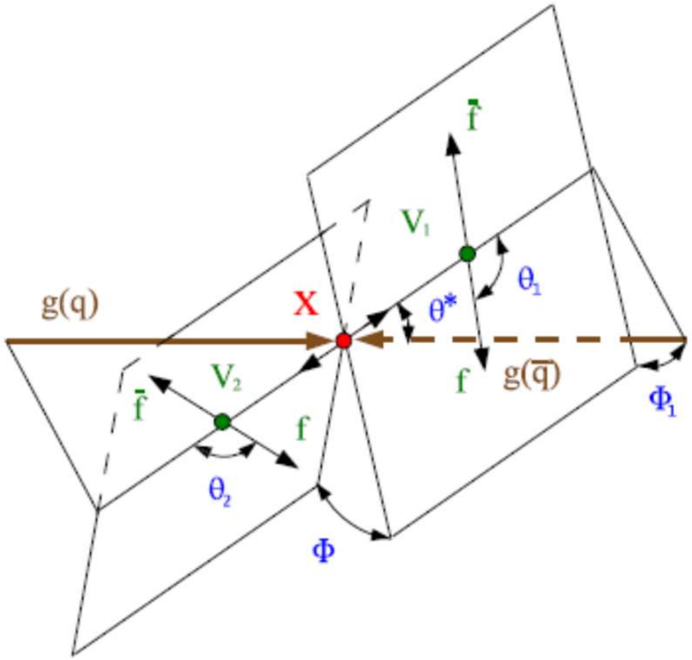
Higgs boson quantum numbers: spin and parity

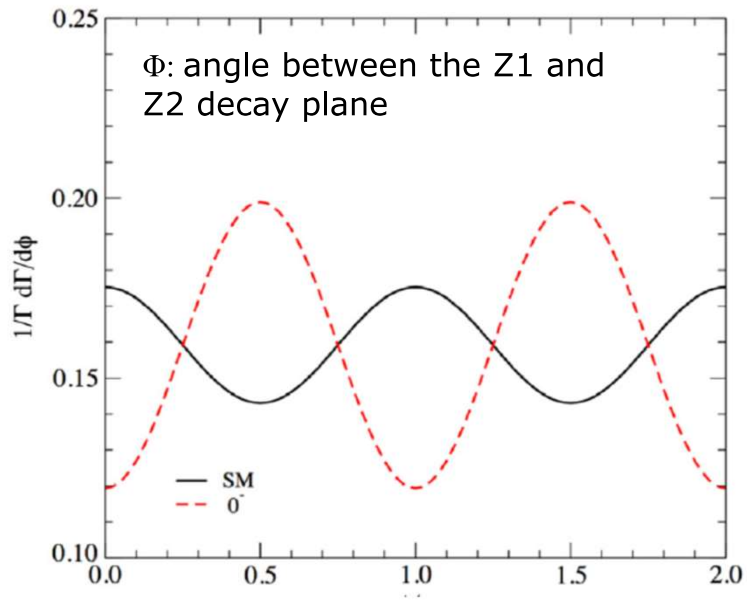
In the Standard Model, the Higgs boson is scalar: $J^P=0^+$

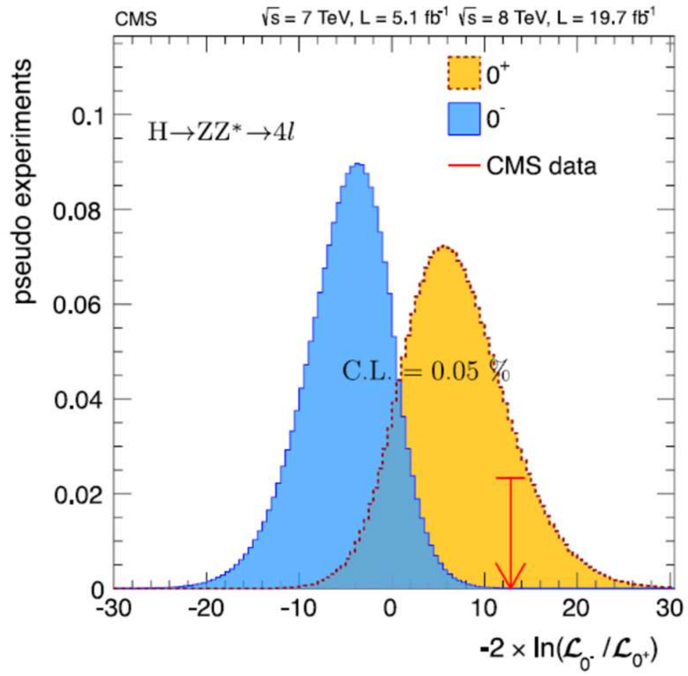
- The observation of the $H\to\gamma\gamma$ decay:
  - Excludes a spin-1 state through the Landau-Yang theorem.
  - Implies that C=+1 (assuming C and P separately conserved)
- Measure angular distributions to discriminate between different spin-parity hypotheses and check the compatibility with SM expectation.



Spin and parity: $H \to ZZ^* \to 4\ell$





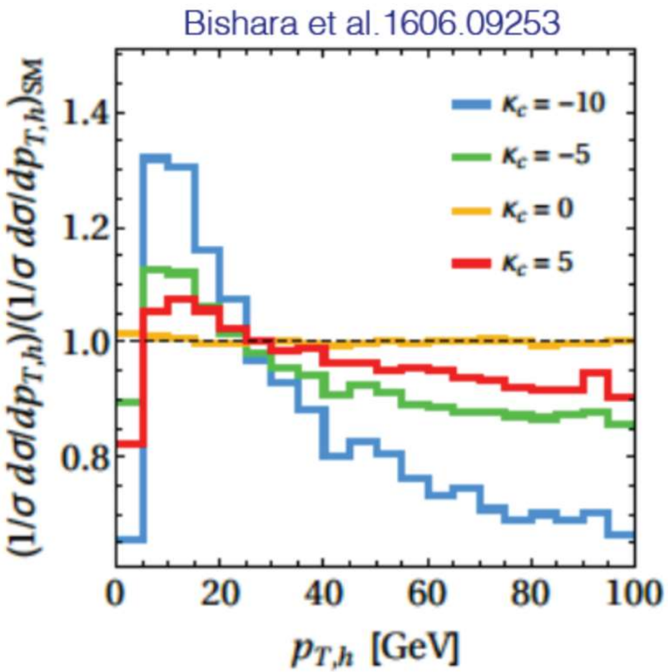


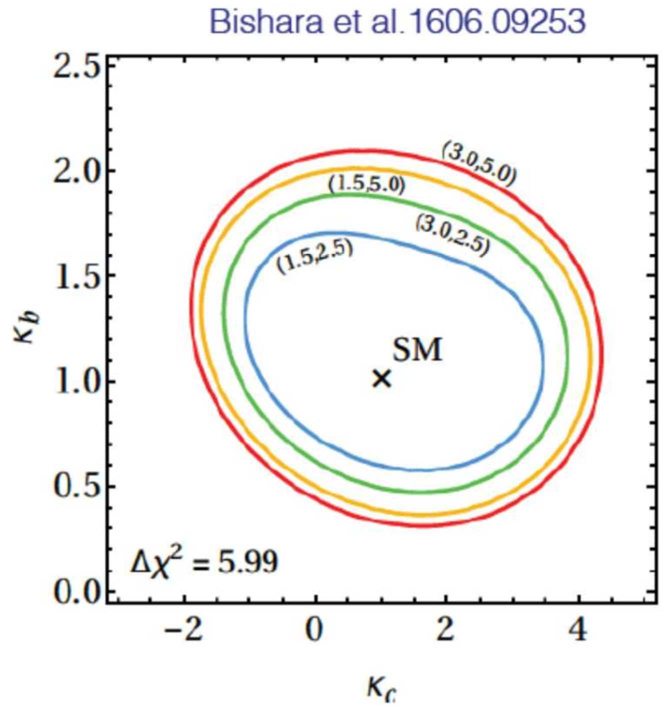
Using distributions of kinematic variables to test alternative hypothesis with log likelihood ratio as the test statistic

SM prediction of $J_P=0_+$ is strongly favored, most alternatives studied are excluded @ 95% CL or higher

Second generation

Using kinematic distributions i.e. the Higgs pT

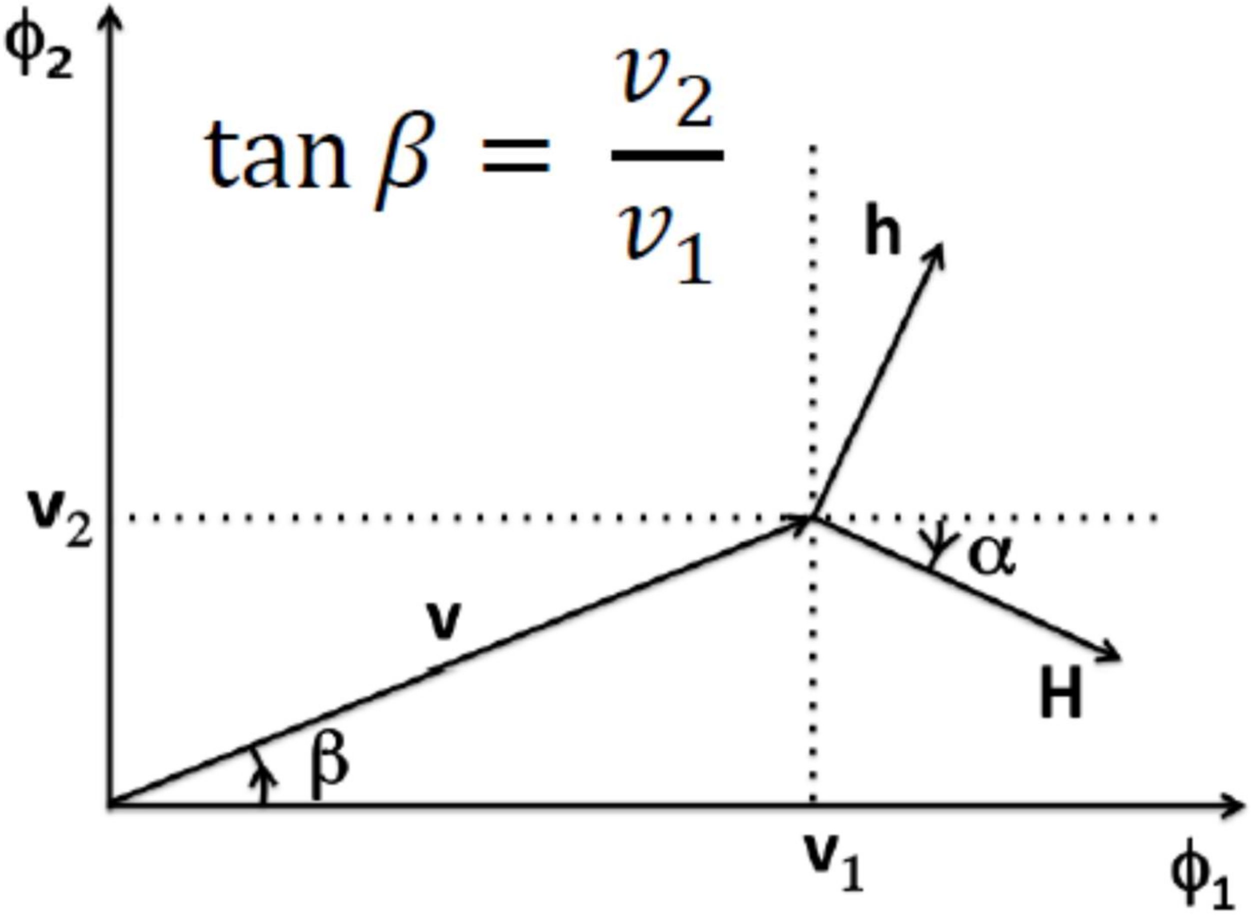




Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging) gives a limit of 110 x SM expectation
(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)

$ZH(H \to c\bar{c})$

MSSM Higgs sector



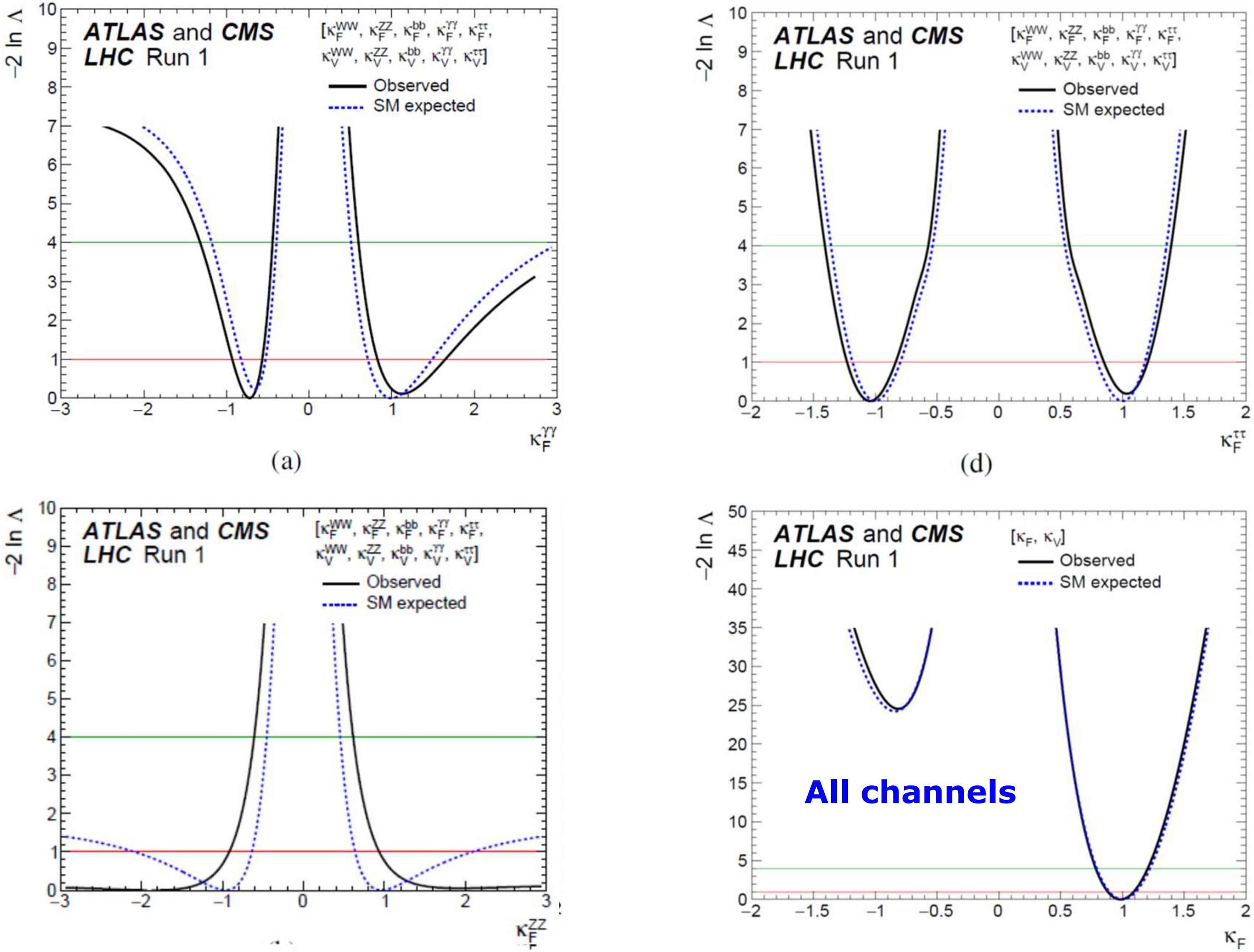
α: mixing parameter of two CP-even Higgs scalars;
tan β: ratio of V.E.V. of the two Higgs doublets

Constraints for couplings to fermions

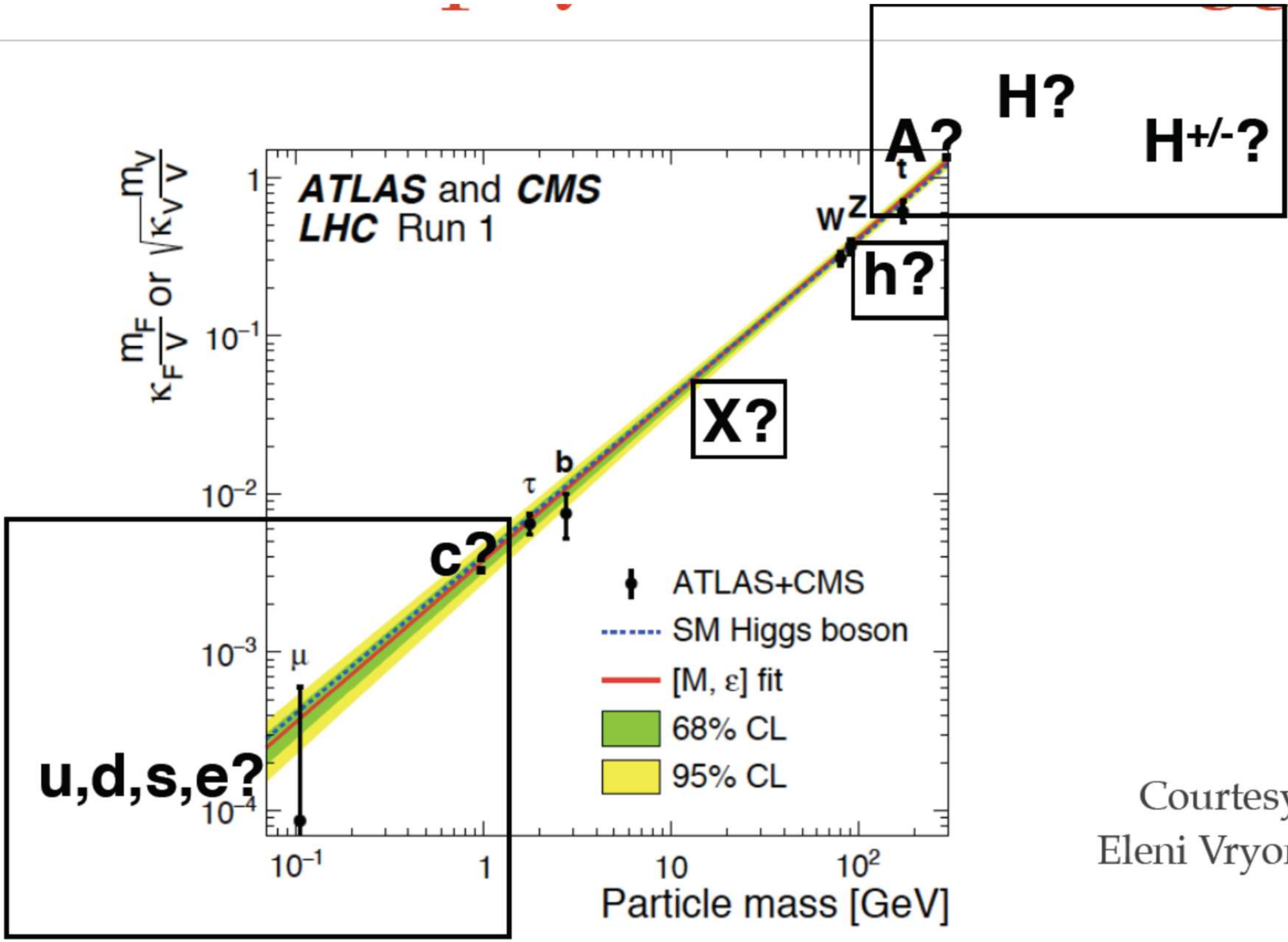
Fit assuming one coupling modifier for all fermions and one coupling modifier for all bosons without new particles in the loops or in the decays

$$\kappa_V = \kappa_W = \kappa_Z$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_\mu$$



Search for new physics via the Higgs

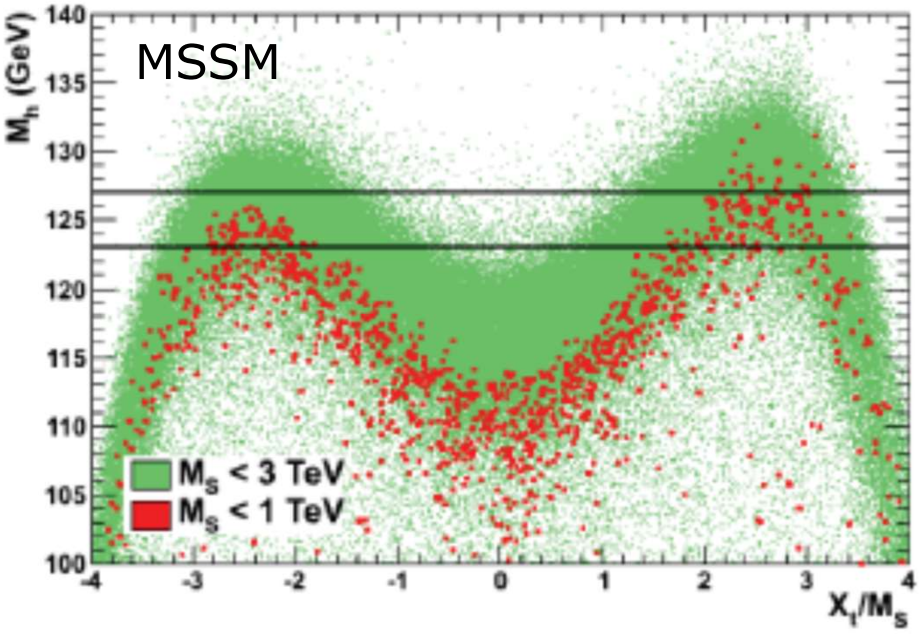


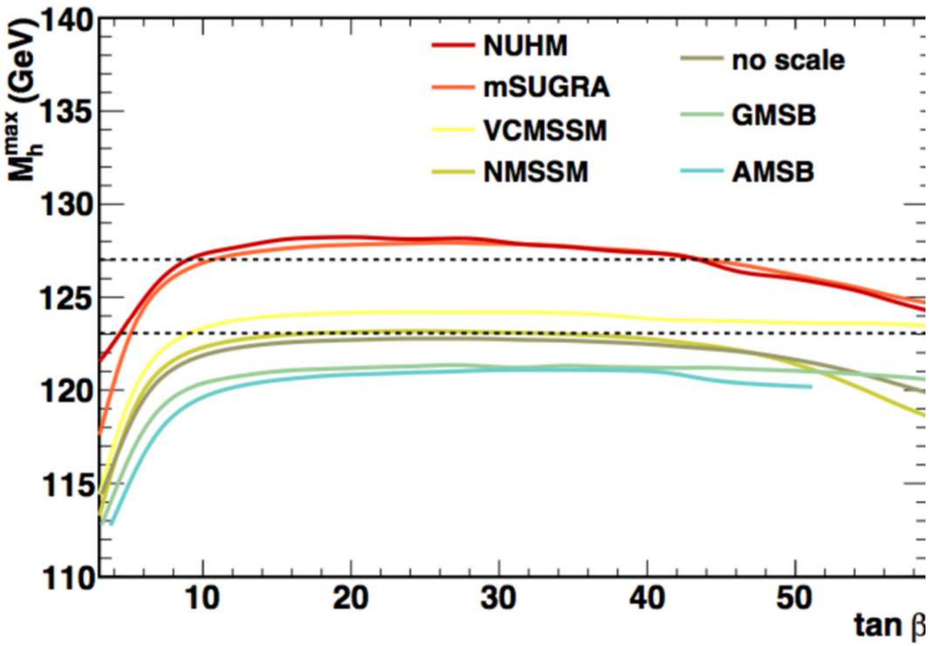
Courtesy of
Eleni Vryonidou

Higgs boson mass and supersymmetry

$$M_h^2 \simeq M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta \right] + \frac{3 m_t^4}{2\pi^2 v^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12 M_S^2} \right) \right]$$

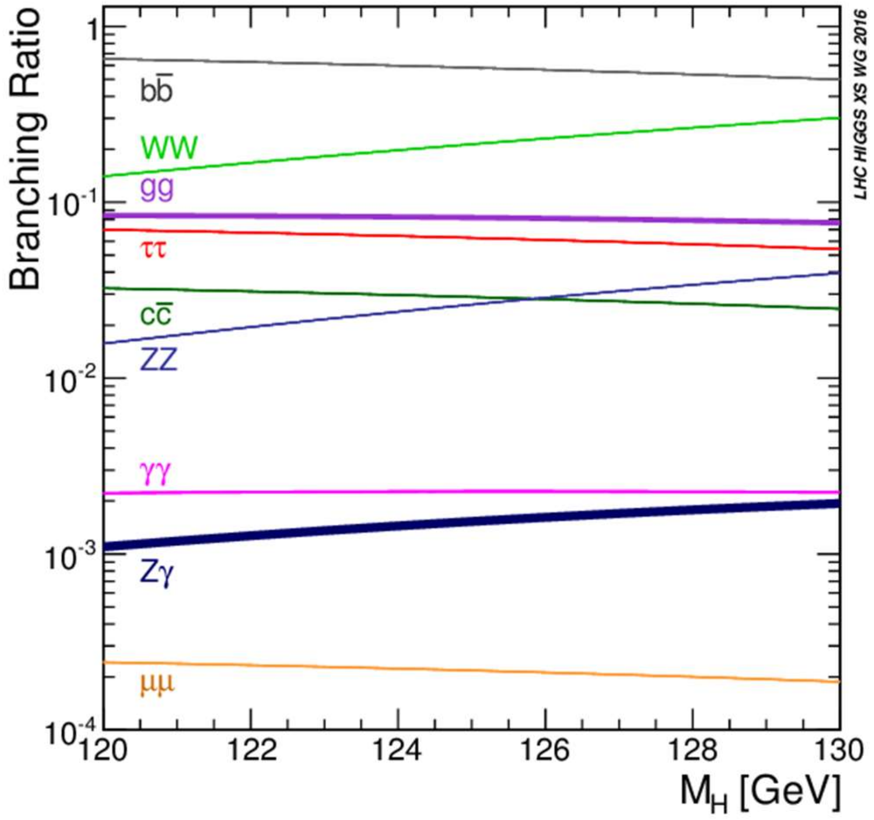
$$\boldsymbol{M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}} \qquad X_t = A_t - \mu \cot\beta$$





A 125 GeV Higgs boson is challenging to accommodate in (over)constrained versions of SUSY, particularly for "natural" values of superpartner masses

Detector requirements



γγ: identification and measurement of **photons**

ZZ,WW: identifications and measurement of **muons, electrons**

WW,ττ: measurement of **missing transverse energy** (requiring energy measurement up to very forward - |η|~5)

bb,ττ, efficient and pure **b-tagging** and **τ identification**

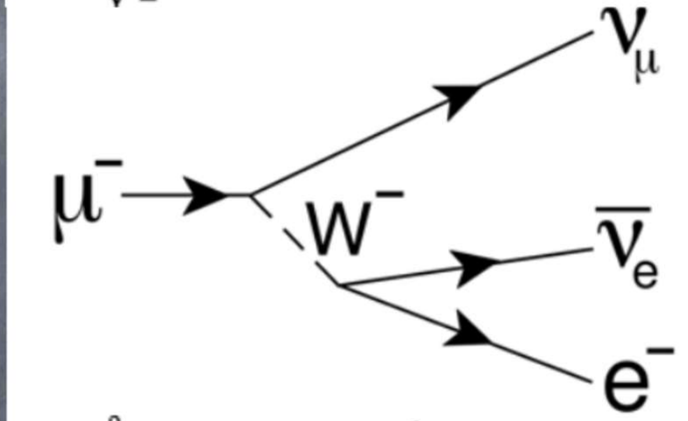
VBF: Capability to detect **forward jets** (for vector boson fusion processes)

EFT example 1

Fermi Theory of weak interactions

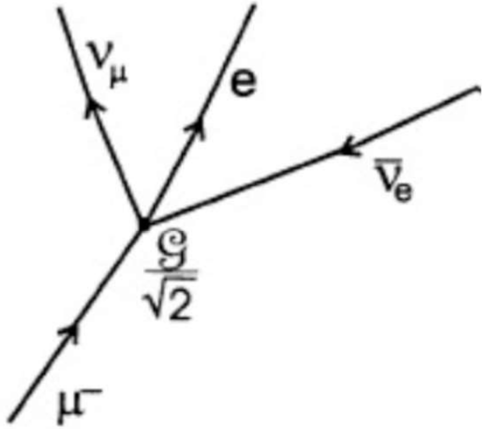
- In SM, charged current interactions mediating weak decays are mediated by W bosons
- At low energies below W mass, W boson can be integrated out, leading to effective theory with 4-fermion interactions
- In particular, muon decay can be described by effective theory with 4-fermion interactions between muon, electron, and 2 neutrinos

$$\mathcal{L} = \frac{g_L}{\sqrt{2}} \left(\bar{\nu}_\mu \bar{\sigma}_\rho \mu + \bar{\nu}_e \bar{\sigma}_\rho e\right) W^+_\rho + \text{h.c.}$$



$$\mathcal{M} = \frac{g_L^2}{2} \bar{x}(k_{\nu_\mu}) \bar{\sigma}_\rho x(k_\mu) \frac{1}{q^2 - m_W^2} \bar{x}(k_e) \bar{\sigma}_\rho y(k_{\nu_e})$$

$$q = k_\mu - k_{\nu_\mu}$$



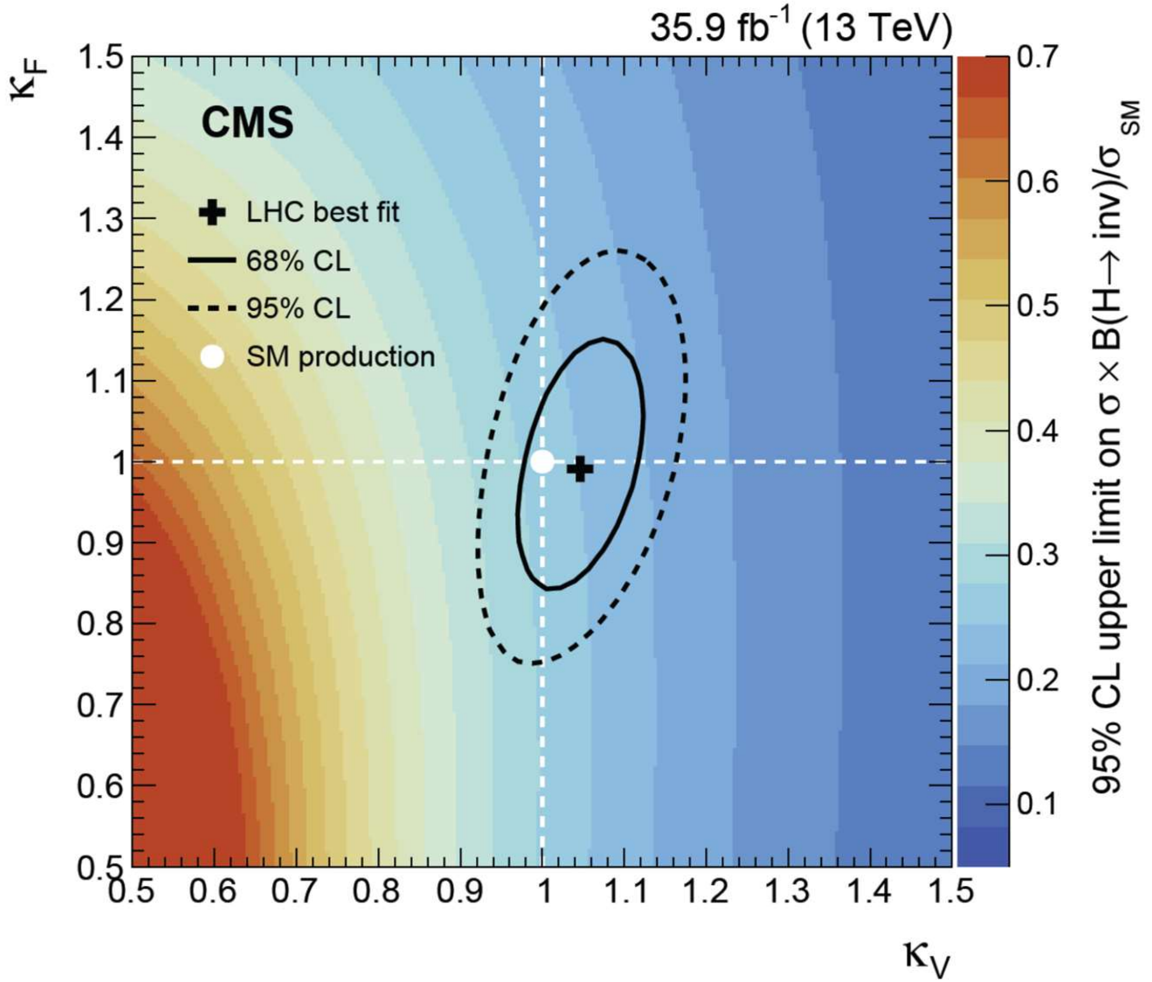
$$\mathcal{M} \approx -\frac{1}{\Lambda^2} \bar{x}(k_{\nu_\mu}) \bar{\sigma}_\rho x(k_\mu) \bar{x}(k_e) \bar{\sigma}_\rho y(k_{\nu_e})$$

$$\Lambda = \frac{\sqrt{2} m_W}{g_L} = \frac{v}{\sqrt{2}}$$

$$\mathcal{L}_{\text{eff}} = -\frac{1}{\Lambda^2} (\bar{\nu}_\mu \bar{\sigma}_\rho \mu) \bar{e} \bar{\sigma}_\rho \nu_e + \text{h.c.}$$

Combination

The relative sensitivity of each search considered in the combination depends on the assumed SM production rates. The cross sections for the ggH, VBF and VH production modes are parameterized in terms of coupling strength modifiers κ_V and κ_F



Within the 95% CL region, the

observed (expected) upper limit varies between 0.19 (0.15) and 0.31 (0.24).

Higgs discovery