

Implications of the Higgs boson measurements at the LHC on theoretical ideas

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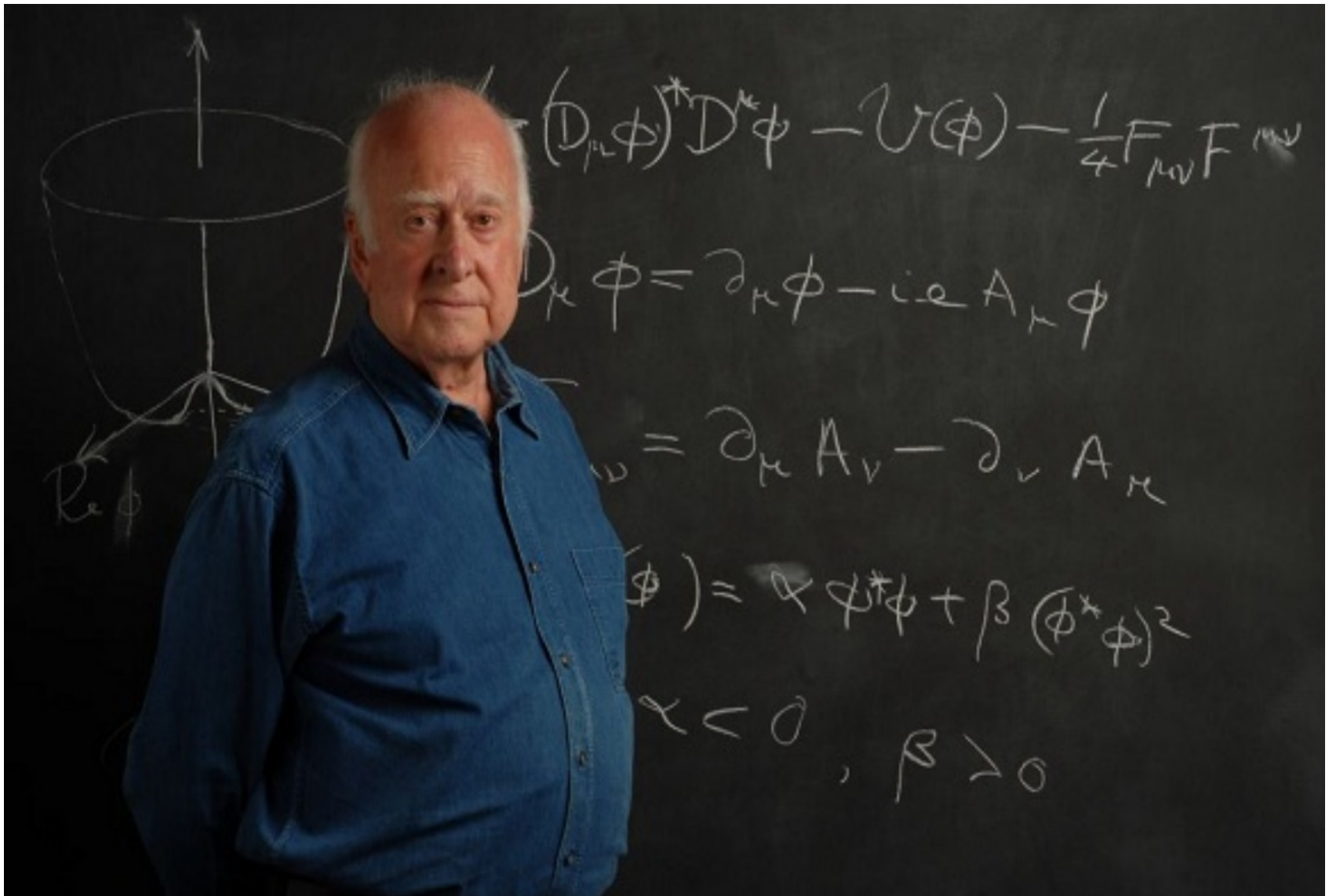
Dipartimento di Fisica, Università di Trieste, 8 Ottobre 2013

Nobel Price in Physics 2013

Outlook

- **Anatomy of the Higgs-like resonance**
- **Impact on BSM Higgs scenarios:**
 - **SUSY Higgs**
 - **Composite Higgs**
 - **Higgs Fermiophobia**
 - **Anomalous top-Higgs coupling**
 - **Higgs imposters**
- **Conclusions**

Why we need the Higgs boson ?



SM is a weakly coupled $SU(2)_L \times U(1)_Y$ gauge-theory

■ Gauge bosons: $W^{(\pm)}$ + Z + Photon

■ 3 Quark families

3 Lepton families

(u, d) (c, s) (t, b)

(ν_e, e) (ν_μ, μ) (ν_τ, τ)

■ Gauge symmetry is broken: W and Z are massive

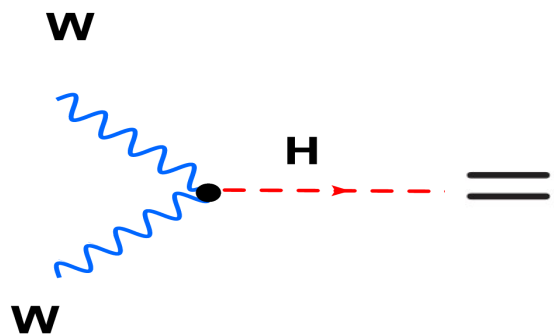
$SU(2)_L \times U(1)_Y$ is broken to $\rightarrow$ exact $U(1)_{EM} = QED$

■ If masses of W and Z are put by hand:

- SM is not renormalizable $\rightarrow$ effective theory valid up TeV scale
- unitarity broken at the TeV scale where a NP should appear to recover unitarity (i.e. new strongly interacting resonances)

Higgs boson mechanism

- Add **H** scalar **$SU(2)_L$ -doublet** minimally coupled to **$SU(2) \times U(1)_L$**
- **H** gets a non-vanishing **vacuum expectation value $\langle H \rangle = v$**
- **W, Z** masses generated in a renormalizable way, **γ massless !**
- perturbative unitarity in **$VV \rightarrow VV$** with **$V = W, Z$** is achieved
- SM perturbative up to the Planck mass energies $\sim 10^{19}$ GeV !
- main characteristic: **Higgs boson is coupled to the masses**



The diagram shows a vertex where a Higgs boson (H) is produced from two W bosons (W). The W bosons are represented by blue wavy lines, and the Higgs boson is represented by a red dashed line with an arrow. The vertex is marked with a black dot. The equation is set equal to the coupling term $\eta_{\mu\nu} g M_W$.

$$\begin{array}{c} W \\ \diagup \\ \text{blue wavy line} \\ \bullet \\ \text{red dashed line with arrow} \xrightarrow{H} \\ \diagdown \\ \text{blue wavy line} \\ W \end{array} = \eta_{\mu\nu} g M_W$$

- Fermion mass term is not $SU(2)_L$ gauge invariant
- Higgs mechanism can provide masses to SM fermions in a renormalizable and unitary way

Yukawa couplings

$$\mathcal{L} = -y \bar{f}_L \Phi f_R - y \bar{f}_R \Phi^\dagger f_L \quad \text{gauge invariant}$$

- After spontaneous symmetry breaking $\langle \Phi \rangle = v$

$$\Phi = v + h$$

$$\mathcal{L} = -m \bar{f}_L f_R - m \bar{f}_R f_L - y h \bar{f}_L f_R - y h \bar{f}_R f_L$$

- Fermion mass $m = v * Y \longrightarrow$ Main characteristic of Higgs couplings to fermions

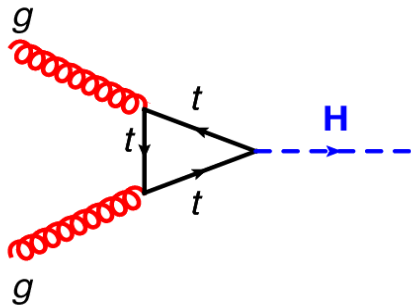
- Known W,Z and fermion masses, all Higgs couplings predicted

- Higgs quartic-coupling free param. $\rightarrow$ Higgs mass is not predicted
this is why Higgs search is very difficult !

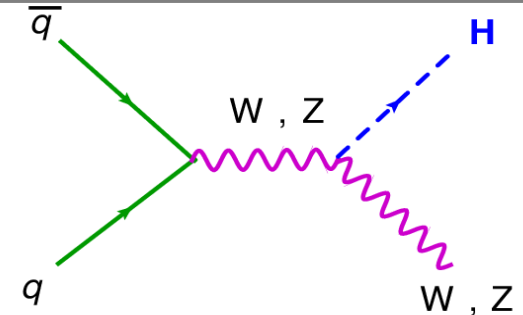
SM Higgs production mechanisms at the LHC

$$p p \rightarrow H X$$

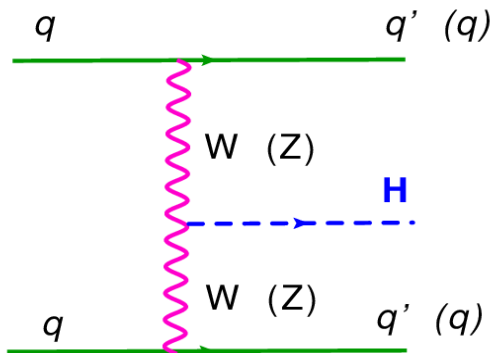
Gluon fusion



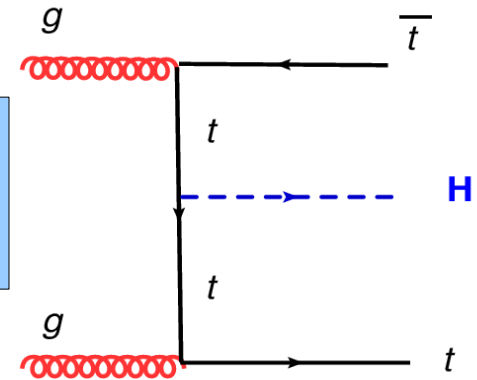
VH



VBF



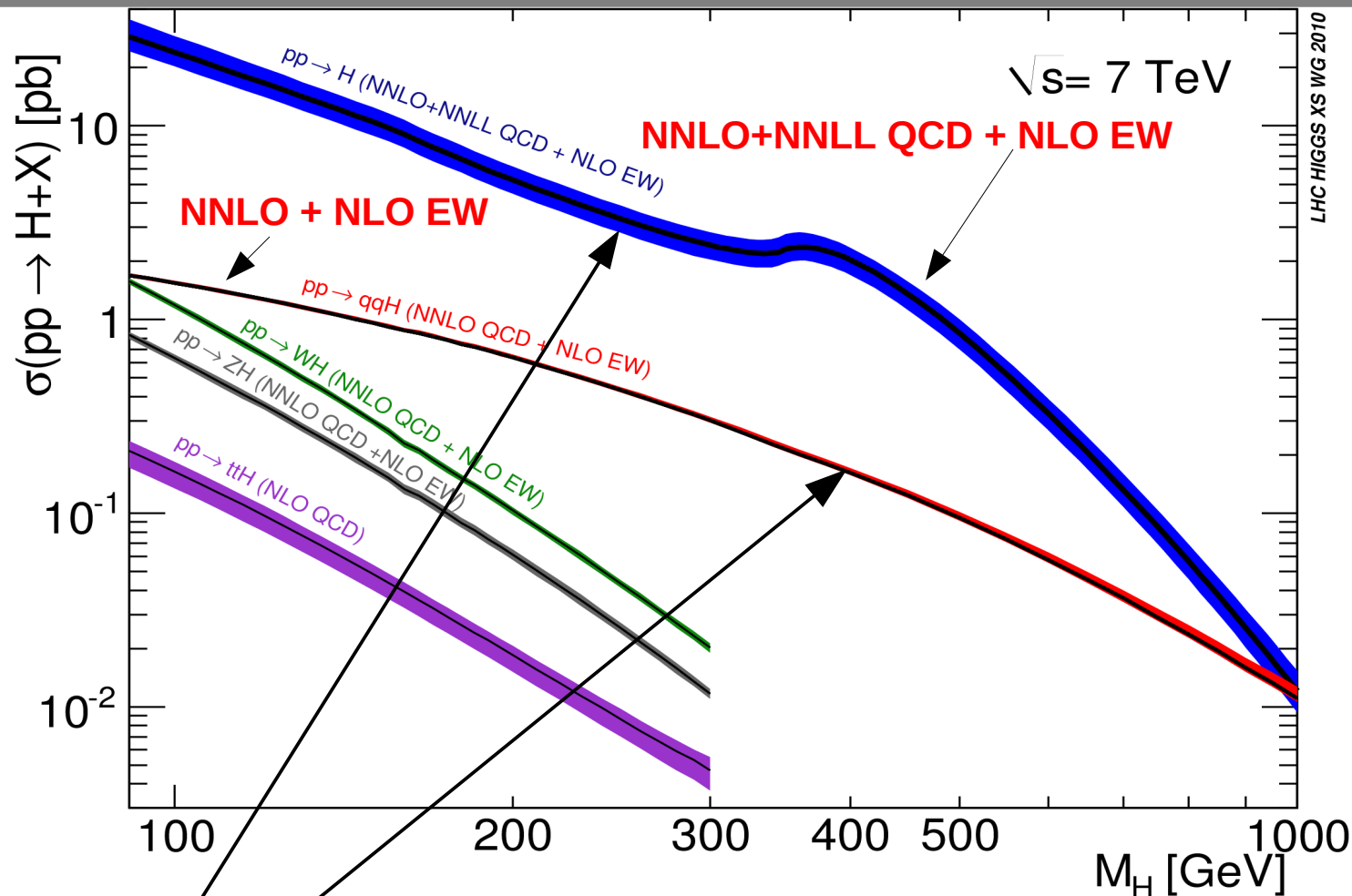
ttH



$$\sigma(pp \rightarrow HX) = \sum_{ij} \int_{(0 < x < 1)} dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}(ij \rightarrow HX)$$

$(0 < x < 1)$ PDF partonic cross-section

SM Higgs production cross sections at LHC

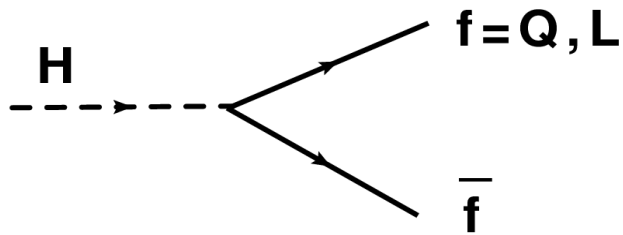


Gluon fusion : the leading production mechanism

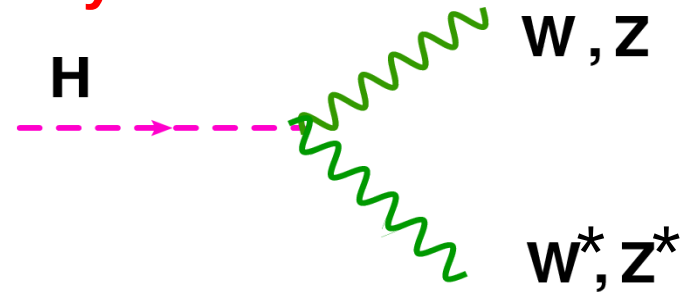
VBF : the next-to-leading mechanism

Relevant SM Higgs decay channels

Tree - level decays

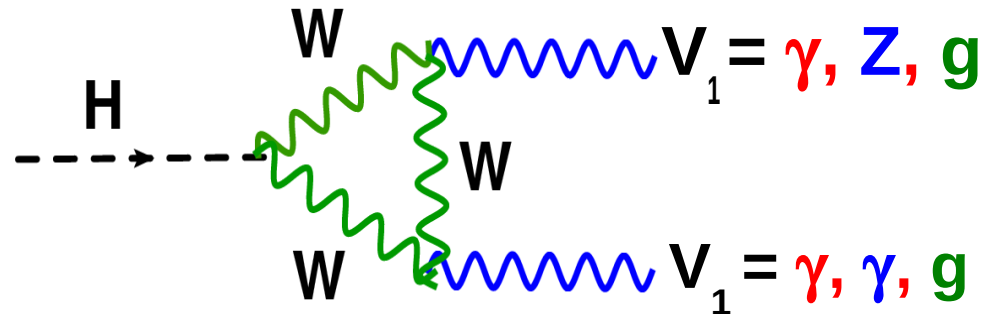
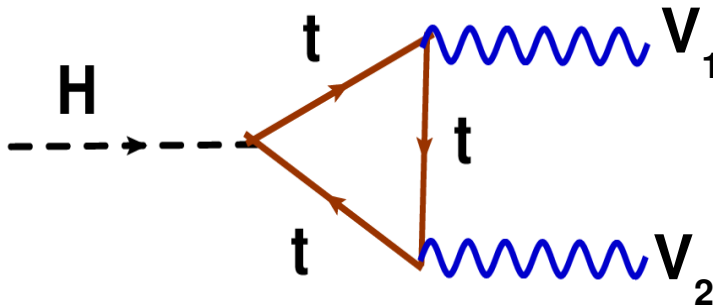


$Q = u, d, c, s, b$
 $L = e, \mu, \tau$



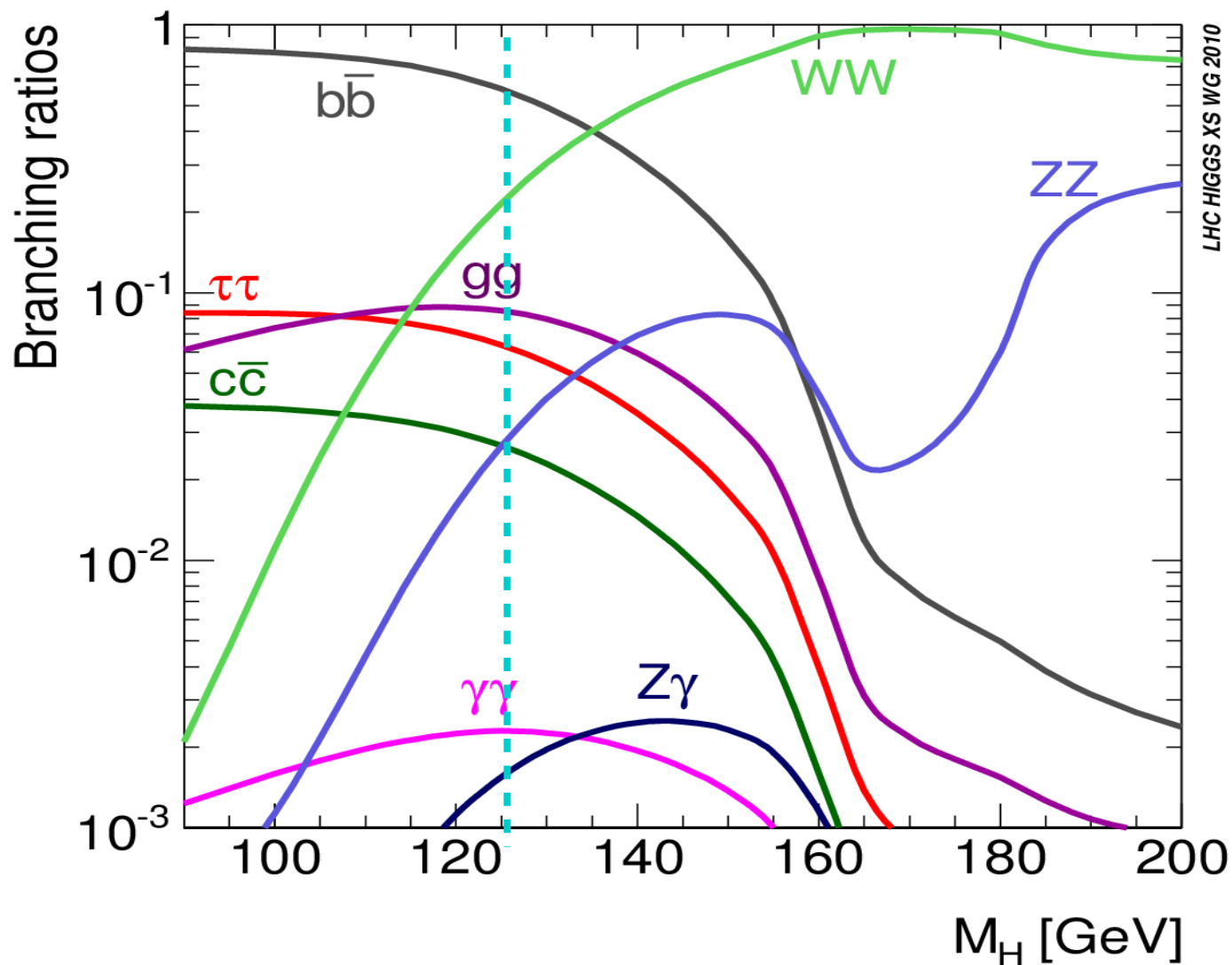
For $M_H = 125 \text{ GeV}$
 $W^*, Z^* \rightarrow \text{off-shell}$

One-loop decays



$H \rightarrow \gamma\gamma$ relevant process for Higgs discovery at low masses
 very sensitive probe of new physics

$H \rightarrow \gamma Z$ smaller, also quite sensitive to new physics



$M_H = 126$ GeV

BRs ($H \rightarrow XX$)

bb	56 %
WW*	23 %
gg	8.5 %
$\tau\tau$	6.2 %
ZZ*	2.9 %
cc	2.8 %
$\gamma\gamma$	2.3 %
$Z\gamma$	1.6 %

● $H \rightarrow bb$ dominant for $m_H < 140$ GeV, but signal difficult to detect due to the huge QCD background

● $H \rightarrow \gamma\gamma$ golden discovery channel for $M_H < 130$ GeV

125 GeV Higgs-like discovery

- **14 July 2012**, ATLAS and CMS collaborations announced the discovery of a **NEW neutral Boson** resonance with mass $\sim$ **125-126 GeV** compatible with a Higgs-like particle



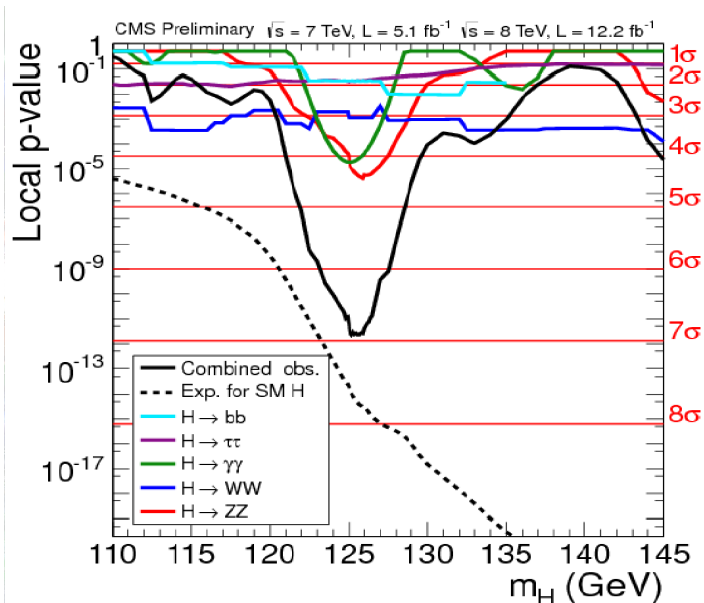
- Since then, ATLAS and CMS focussed on two main questions:
 - Is this New Boson the SM Higgs boson ?
responsible for **EW symmetry breaking**
providing masses to all the SM particles
 - Can we find signs of **Physics Beyond the SM** studying its properties ?
- addressed experimentally by **Property Measurements**

Where are we ?

- a new particle (resonance) has been discovered at the LHC
- consistent with the long-awaited **SM Higgs boson**
- **fully confirmed in all its most sensitive channels**

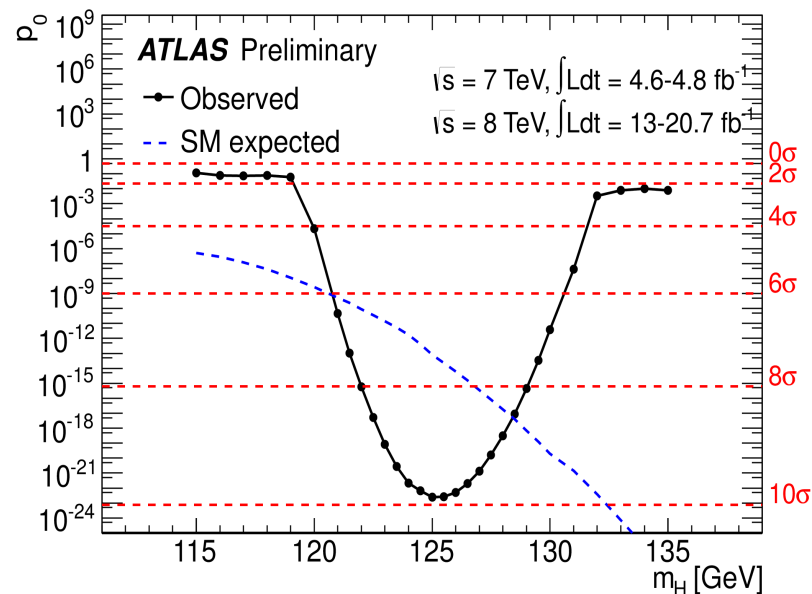
CMS-HIG-12-045

■ **CMS $m_H = 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})$ GeV**



ATLAS-CONF-2013-034

■ **ATLAS $m_H = 126 \text{ GeV} \pm 0.4(\text{stat}) \pm 0.4(\text{syst})$ GeV**



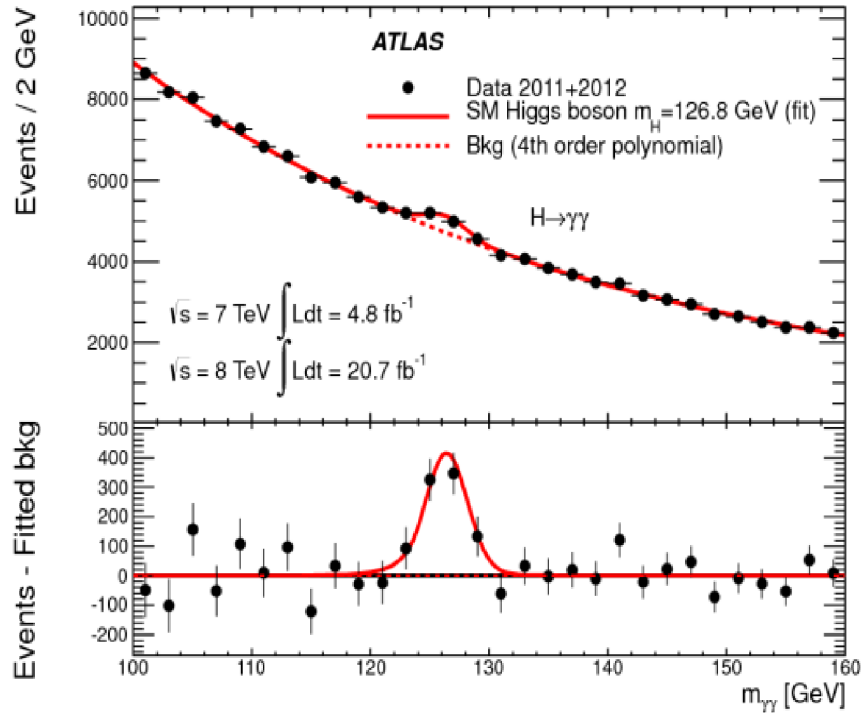
■ Local probability p for a bckg-only experiment to be more signal like than the observation versus M_H

■ **Local significance:** ATLAS $\sim 10 \sigma$
CMS $\sim 7 \sigma$

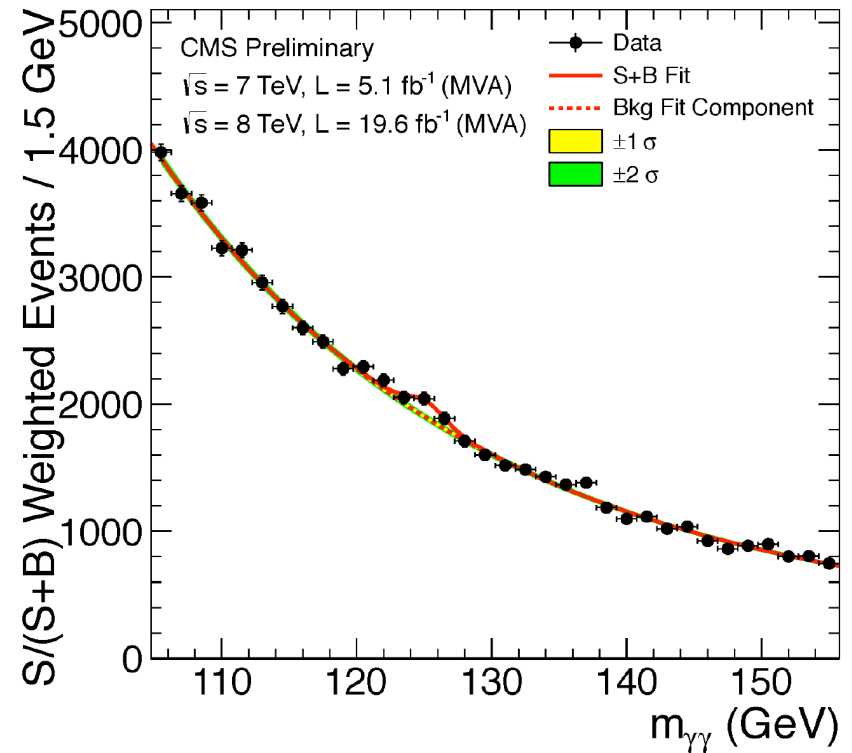
■ $H \rightarrow \gamma\gamma$ rules out spin-1. While **spin-0** and **spin-2** in principle are both viable

Mass distribution for $H \rightarrow \gamma\gamma$

ATLAS



CMS



Summary of the five main channels

Discovery level ($> 5\sigma$) reached in two channels

$\gamma\gamma$ (ATLAS) and ZZ (ATLAS & CMS)

	ATLAS		CMS	
	Observed	Expected	Observed	Expected
ZZ	6.6	4.4	6.7	7.1
$\gamma\gamma$	7.4	4.3	3.2	4.2
WW	3.8	3.8	4.0	5.1
$\tau\tau$	1.1	1.7	2.9	2.7
bb	1.	1.5	2.1	2.2

3.6 σ combined

Anatomy of the 125 GeV resonance

■ assuming this is a SM Higgs-like boson

■ the production mechanisms

● gluon-gluon fusion

$ggH \rightarrow \text{loop}$

● Vector Boson Fusion (VBF)

$qqH \rightarrow \text{tree-level}$

● W,Z associated production

$VH \rightarrow \text{tree-level}$

■ Crucial to measure Higgs couplings to W, Z, b, t, τ !

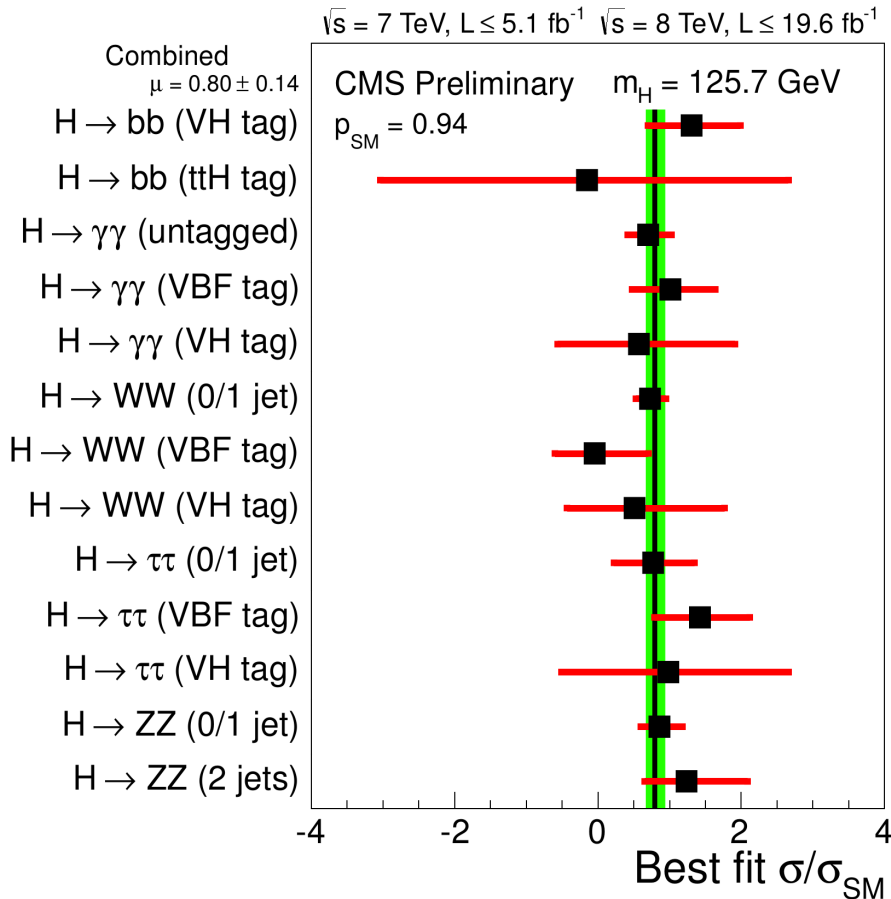
■ tags are needed to isolate the production mechanisms

● $ggH \rightarrow$ gives indirect informations on colored particles running in the loop, as well as on top-Yukawa coupling

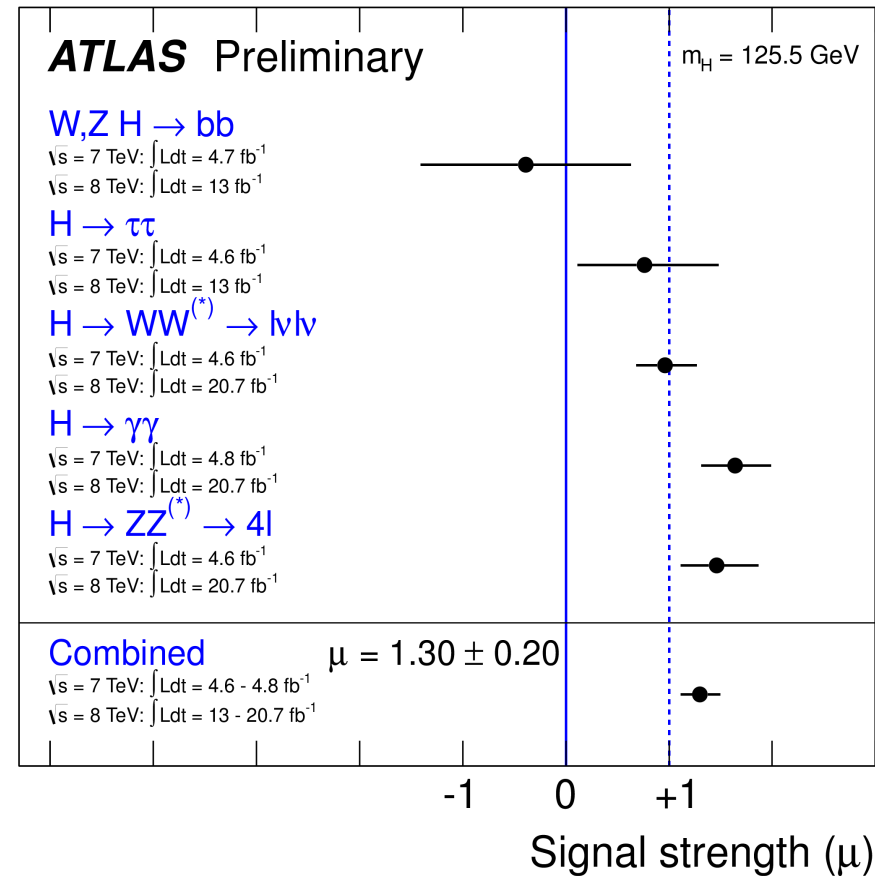
● $VBF, VH, H \rightarrow VV \rightarrow$ informations on Higgs coupling to W and Z

Compatibility with SM Higgs hypothesis

CMS-PAS-HIG-13-005



ATLAS-CONF-2013-034



■ μ = overall signal strength (normalized to SM)

CMS = 0.80 ± 0.14 ATLAS = 1.30 ± 0.20

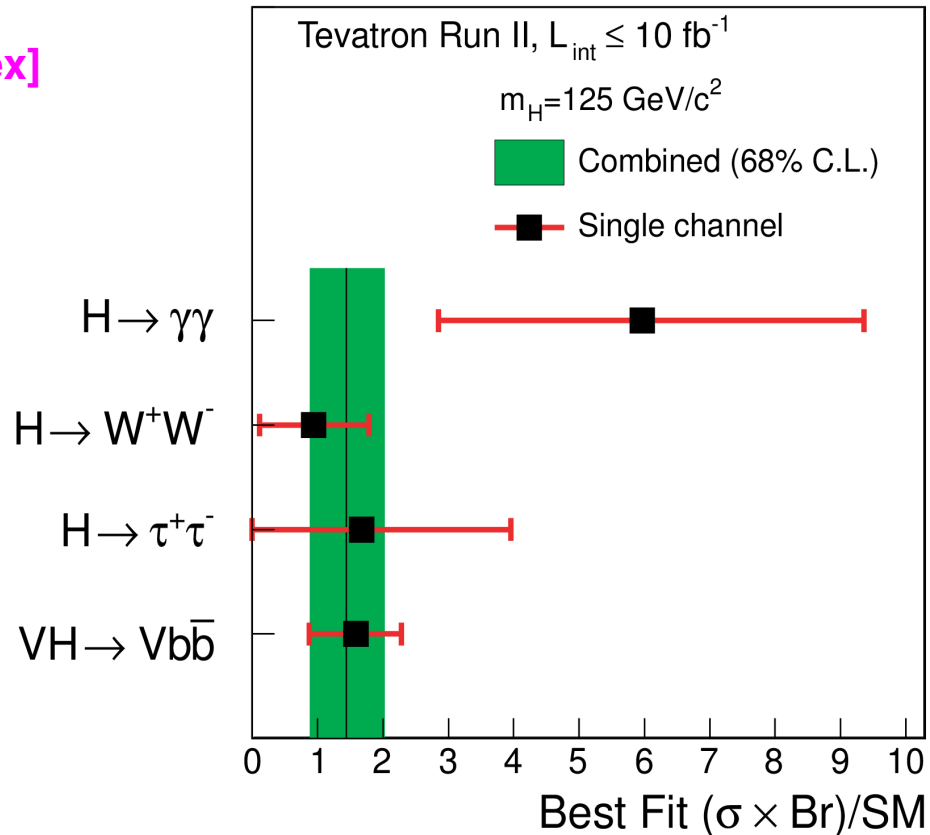
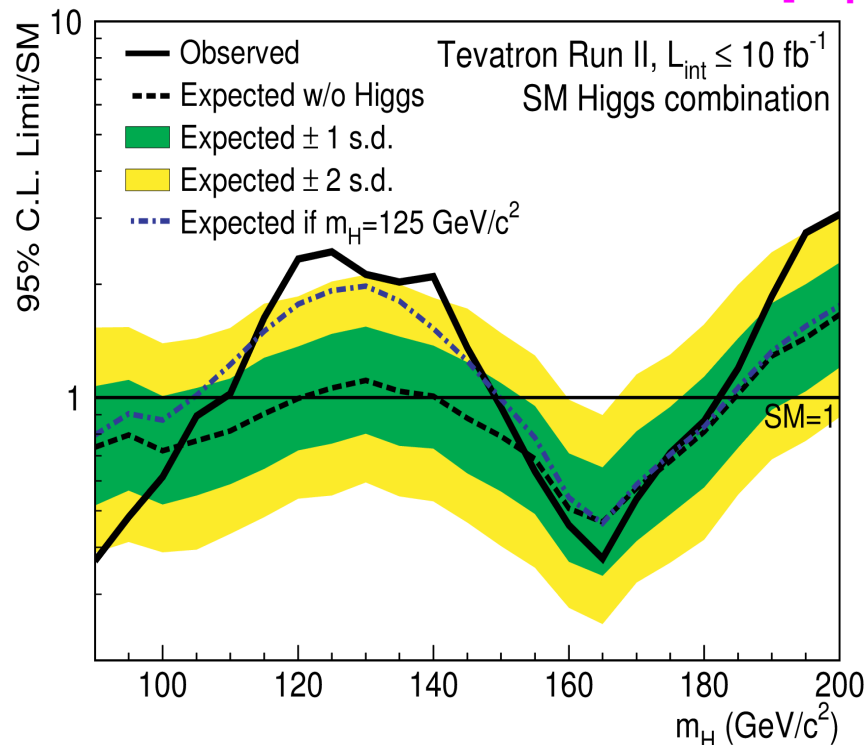
■ di-photon rate enhancement seen only in ATLAS

Higgs searches from Tevatron

■ Combination of D0 & CDF analysis for $H \rightarrow WW, ZZ$ and $H \rightarrow bb, \tau\tau, \gamma\gamma$ shows a clear excess in **115 GeV - 135 GeV** mass region

■ local significance at 125 GeV is 3σ

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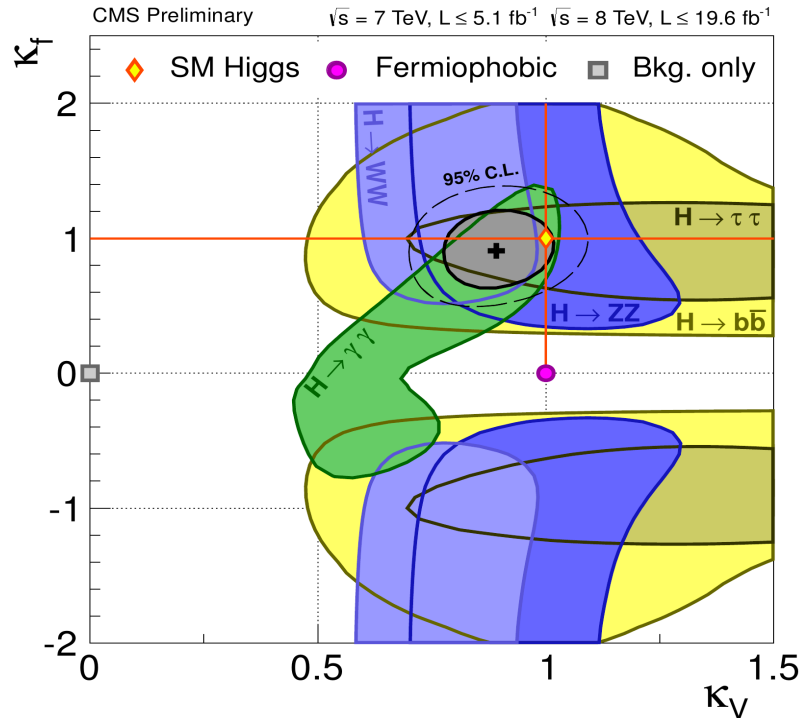
Combined production rates are consistent within 1σ with a Higgs mass of 125 GeV → **However, $\gamma\gamma$ rate appears enhanced !**

Combination of couplings: what we know ?

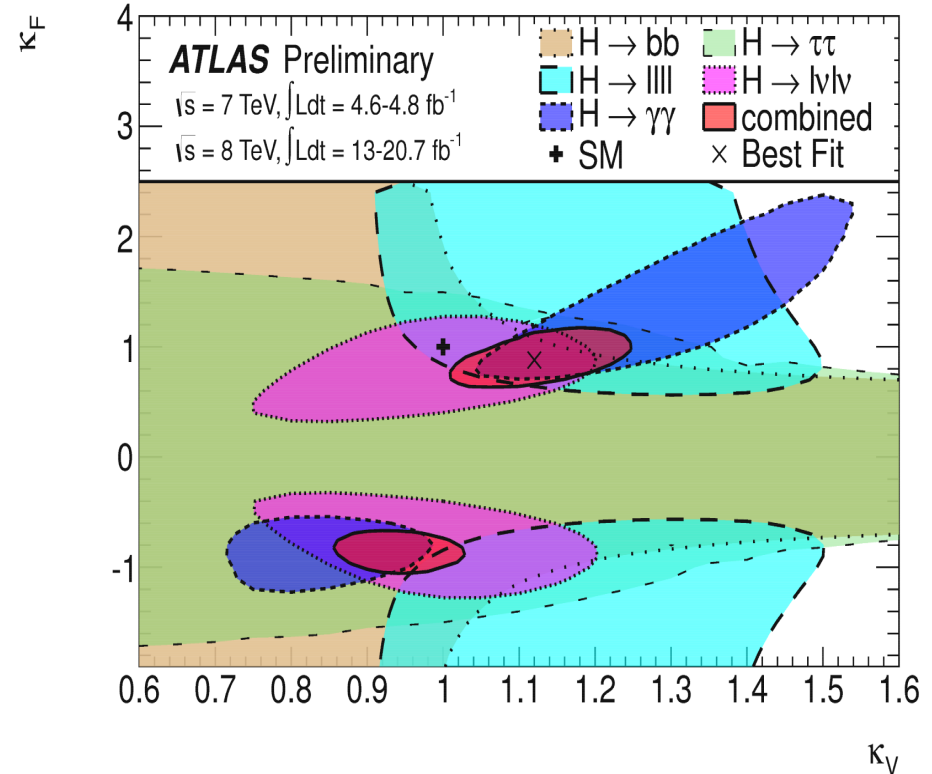
Assuming K_F and K_V universal scaling of fermions and vector bosons

Higgs couplings respectively

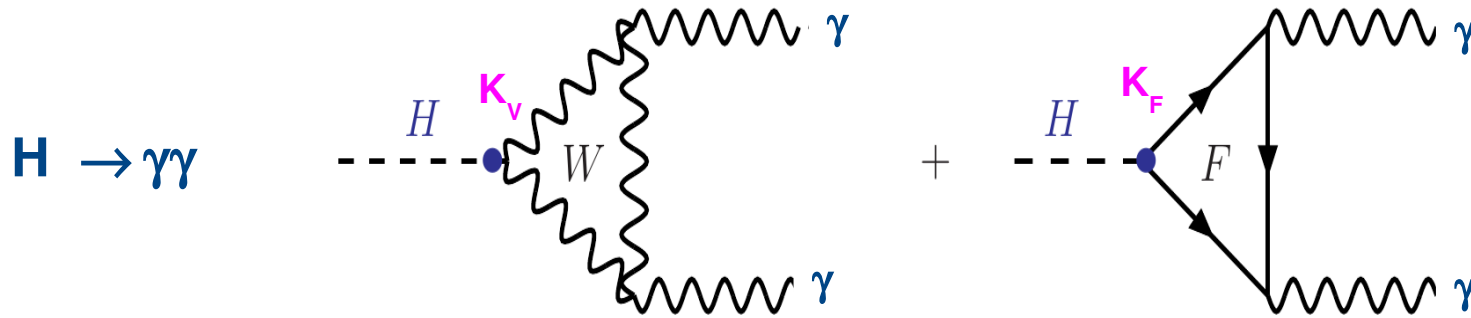
CMS-PAS-HIG-13-005



ATLAS CONF-2013-034



■ Asymmetric solutions for K_V/K_F comes from $H \rightarrow \gamma\gamma$

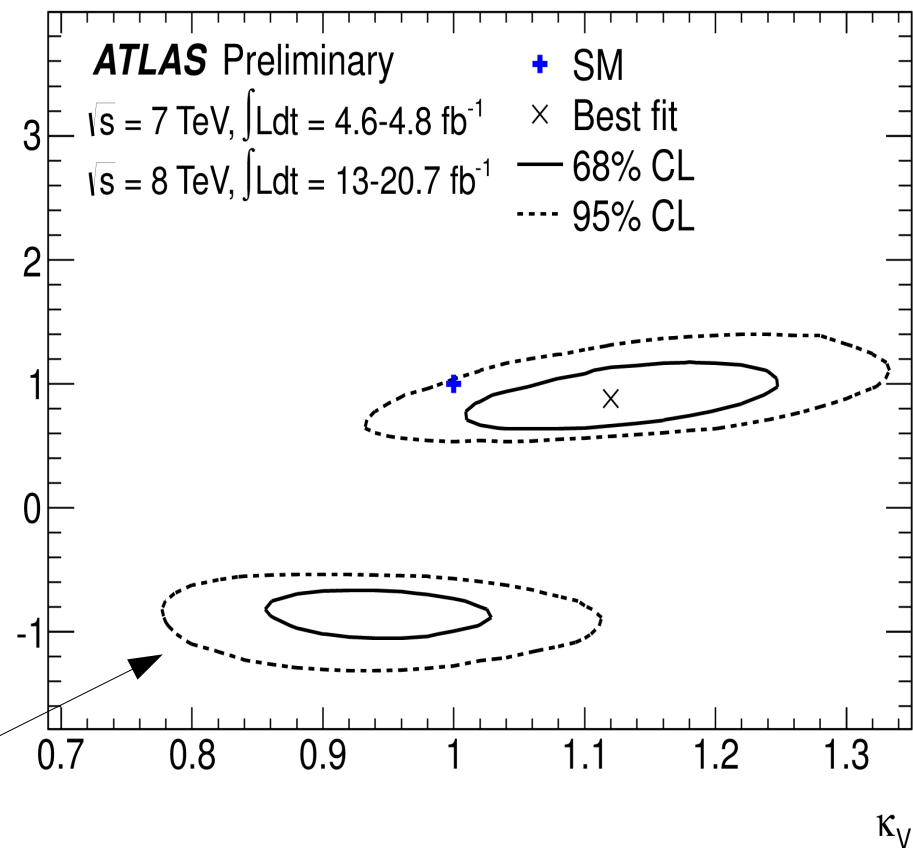
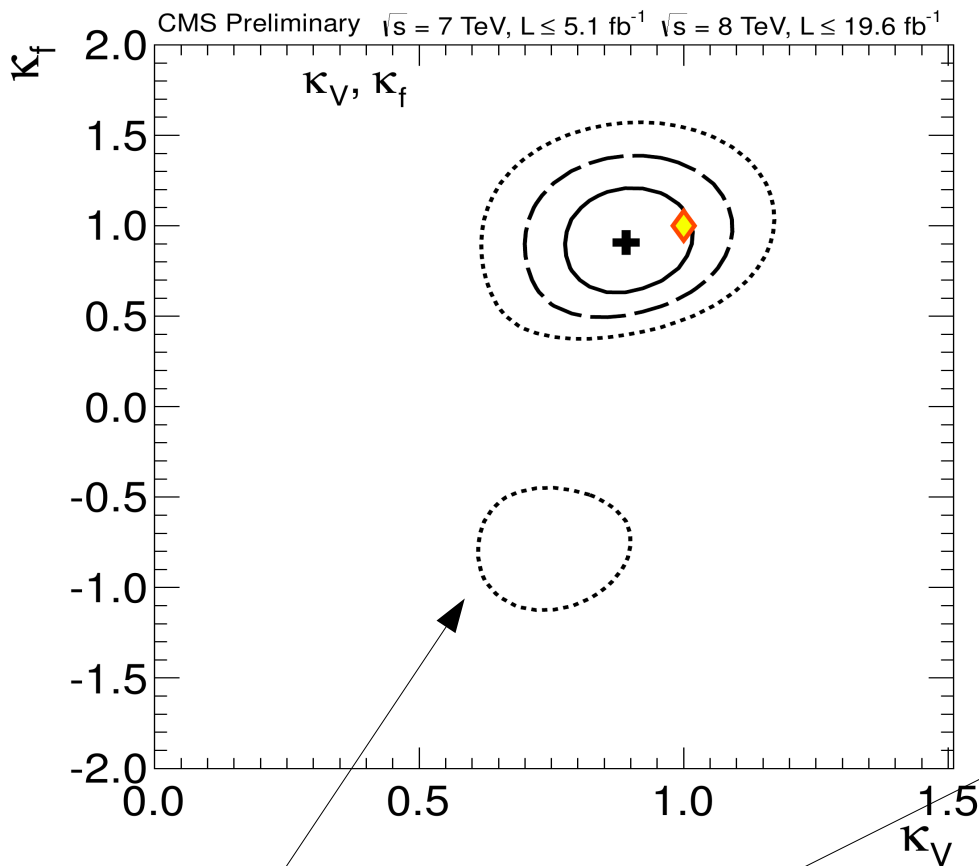


■ $\text{Sign}[A_{1/2}^H(\text{loop of top})] = -\text{Sign}[A_1^H(\text{loop of } W)]$

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_\mu \alpha^2 M_H^3}{128 \sqrt{2} \pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2 \quad \tau_i = M_H^2 / 4M_i^2$$

■ Changing the sign of top-Yukawa coupling **improves the fit**
in $H \rightarrow \gamma\gamma$: destructive interferences turn out to be constructive

■ $\sigma(H \rightarrow \gamma\gamma) \sim (5 K_V - K_F)^2 \rightarrow$ **asymmetric constraints for $K_F \rightarrow -K_F$**



- **positive Yukawa** → **SM solution is within (1 – 2) σ region**
- **negative Yukawa** → **far from SM solution → dramatic implications for EWSB (see next slides)**
- **How much data do we still need to exclude negative K_F region ? (see next slides)**

Test of Custodial Symmetry

■ parametrization $\lambda_{AB} = K_A / K_B$ scaling of vector boson couplings

$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z / \kappa_H$$

$$\sigma(gg \rightarrow H) * \text{BR}(H \rightarrow \gamma\gamma) \sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{\gamma Z}^2$$

$$\sigma(qq' \rightarrow qq' H) * \text{BR}(H \rightarrow \gamma\gamma) \sim \kappa_{\text{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{\gamma Z}^2$$

$$\sigma(gg \rightarrow H) * \text{BR}(H \rightarrow ZZ^{(*)}) \sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2$$

$$\sigma(qq' \rightarrow qq' H) * \text{BR}(H \rightarrow ZZ^{(*)}) \sim \kappa_{\text{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2$$

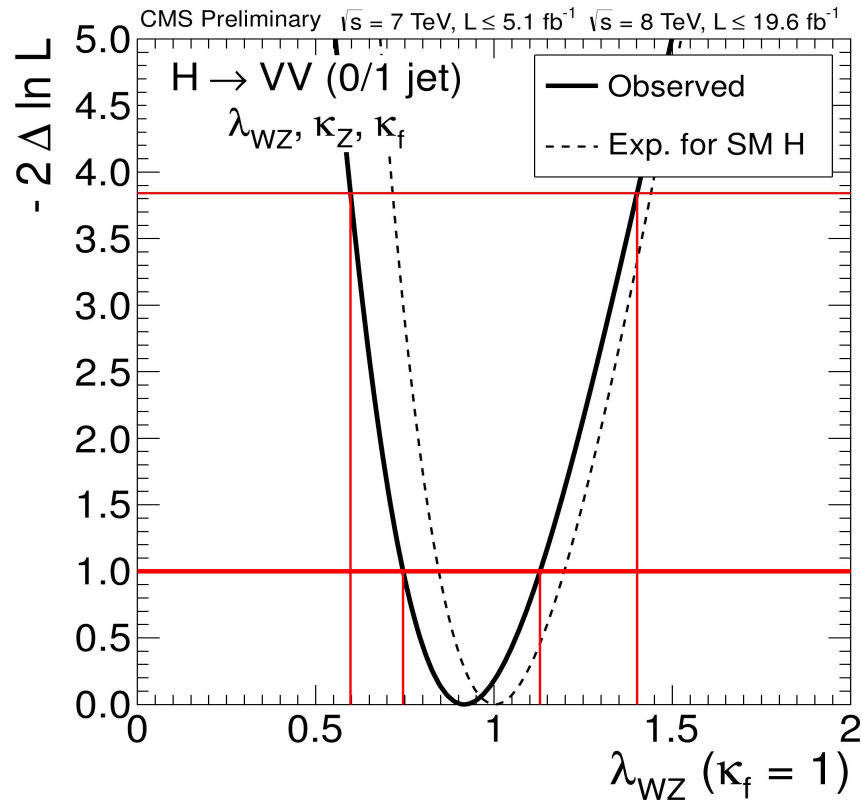
$$\sigma(gg \rightarrow H) * \text{BR}(H \rightarrow WW^{(*)}) \sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{WZ}^2$$

$$\sigma(qq' \rightarrow qq' H) * \text{BR}(H \rightarrow WW^{(*)}) \sim \kappa_{\text{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{WZ}^2$$

$$\sigma(qq' \rightarrow qq' H) * \text{BR}(H \rightarrow \tau\tau) \sim \kappa_{\text{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{FZ}^2$$

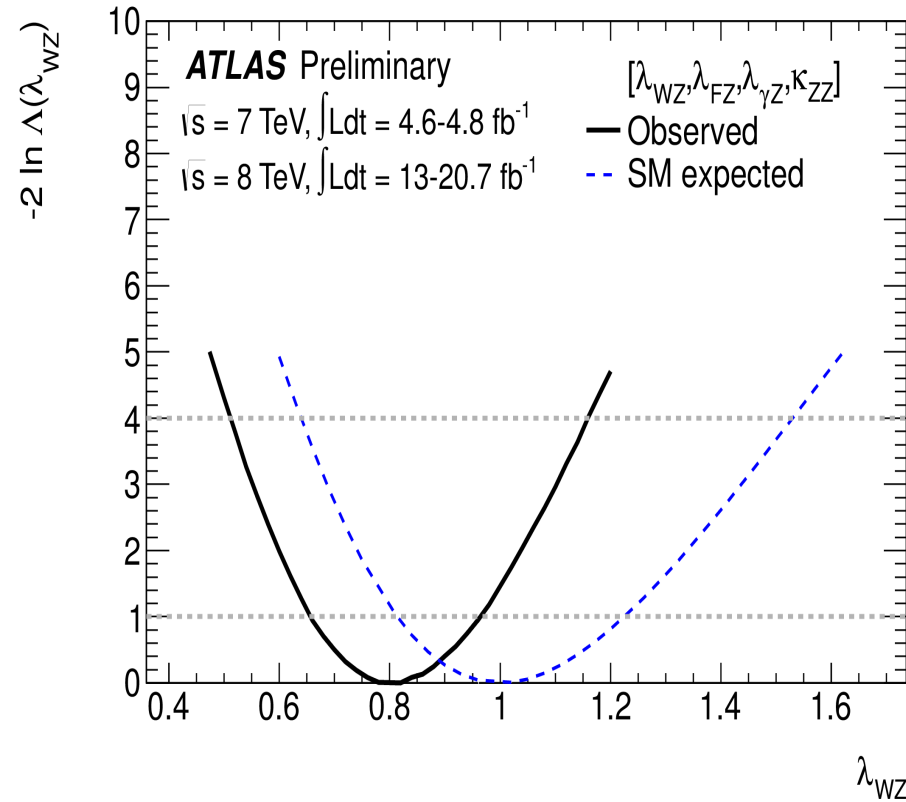
Test of Custodial Symmetry : Results

CMS-PAS-HIG-13-005



$$\lambda_{WZ} = [0.62 - 1.19] @ 95\%CL$$

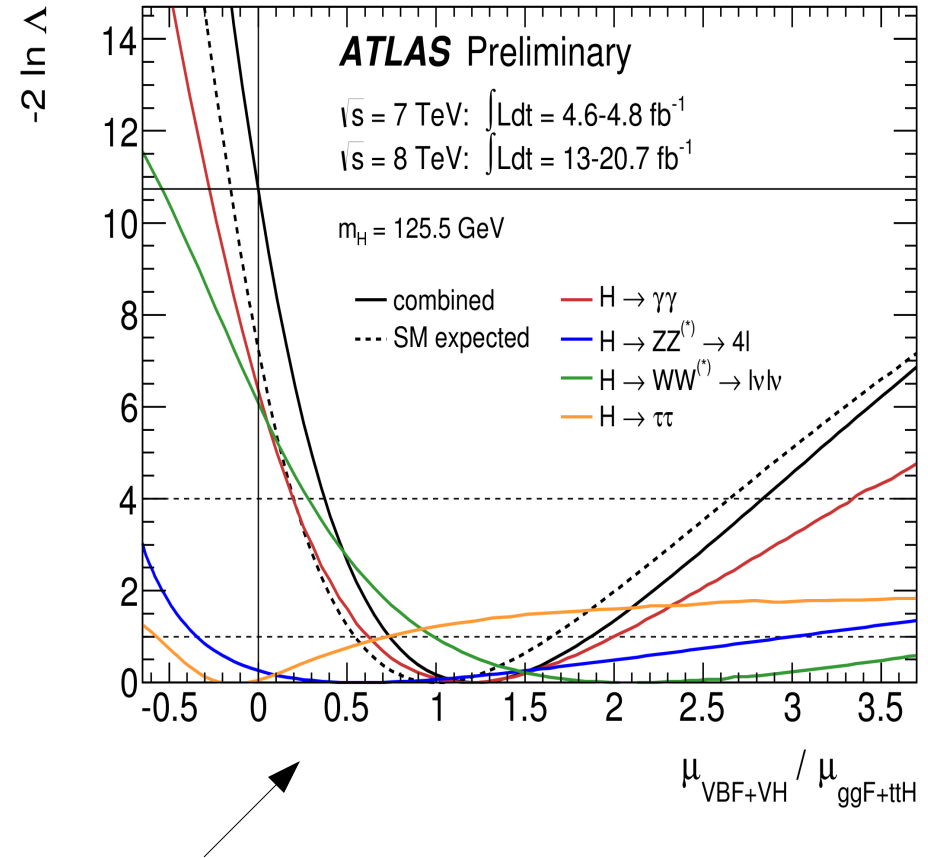
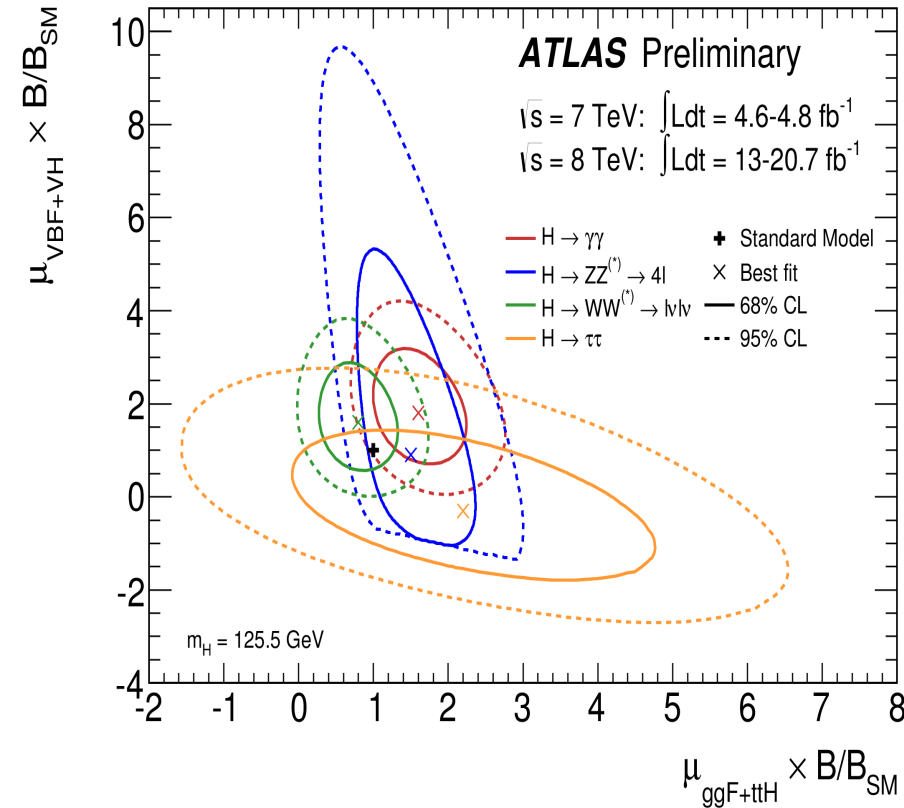
ATLAS CONF-2013-034



$$\lambda_{WZ} = 0.80 \pm 0.15$$

■ Results well consistent with SM

Test of production mechanisms



Ratios do not depend on BRs, so different channels can be combined

$$\mu_{\text{VBF}} / \mu_{\text{ggF+ttH}} = 1.2^{+0.7}_{-0.5}$$

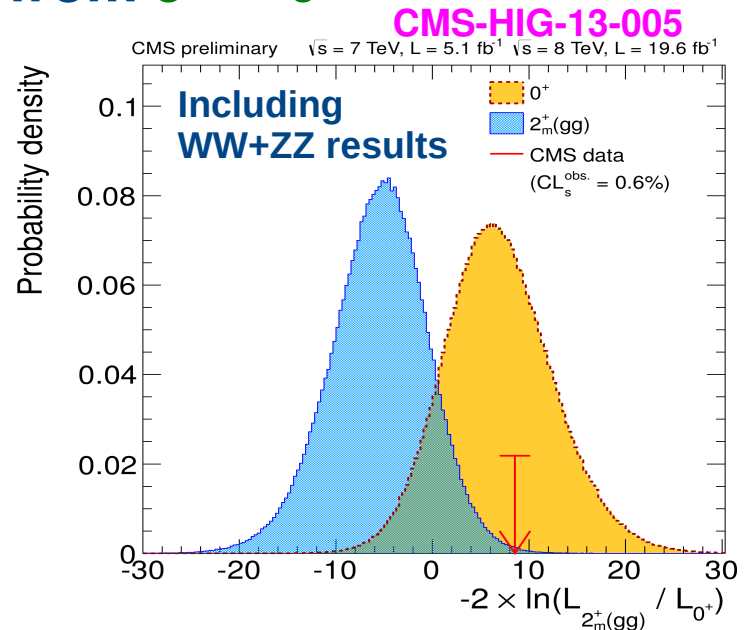
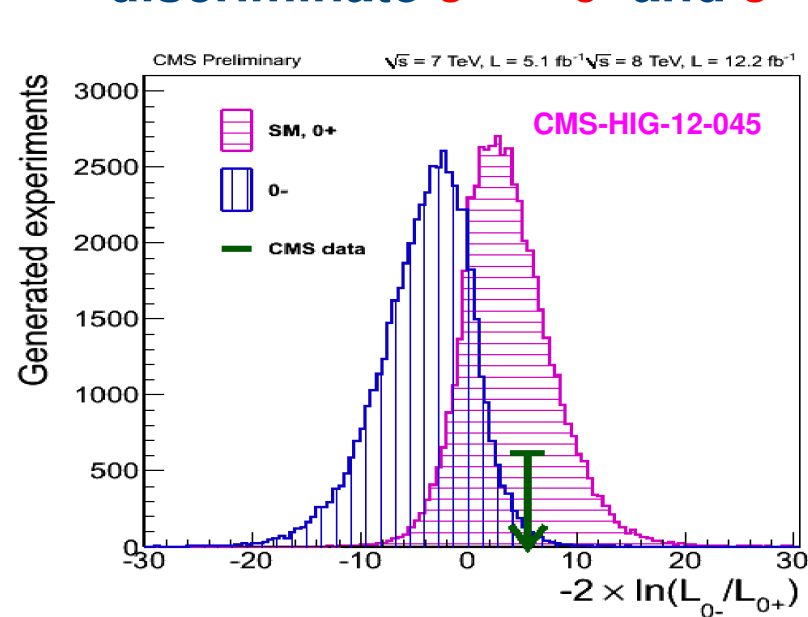
→ well consistent with SM

95% CL that there is a non-vanishing VBF component

Main properties: spin and CP

couplings to photons $\rightarrow$ spin 0 or 2

leptons kinematic distributions in $H \rightarrow ZZ \rightarrow 4l$ decay used to discriminate $J^{PC} = 0^-$ and $J^{PC} = 2^+$ from $J^{PC} = 0^+$



Expected distribution of the test statistics comparing the signal J^P hypotheses

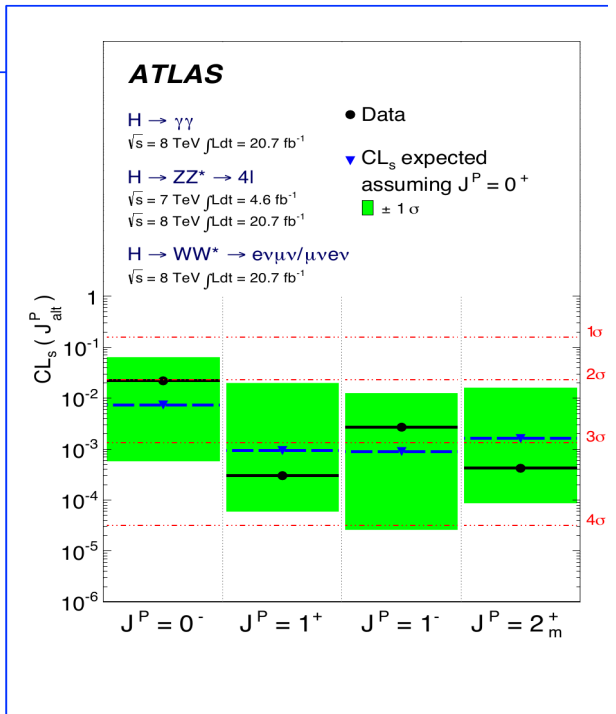
Observed value indicated by the arrow

$J=2^+$ and $J=0^+$ deviate from the median expected by 2.84σ and 0.34σ

data disfavor 0^- and 2^+ hypothesis

Combination

J^P	production	particle	ATLAS CLs	CMS CLs
0^-	$gg \rightarrow X$	pseudoscalar	2.2% ($H \rightarrow ZZ^*$)	0.16% ($H \rightarrow ZZ^*$)
1^+	$qq \rightarrow X$	exotic pseudovect.	0.030% ($H \rightarrow ZZ^*, WW^*$)	<0.1% ($H \rightarrow ZZ^*$)
1^-	$qq \rightarrow X$	exotic vector	0.27% ($H \rightarrow ZZ^*, WW^*$)	<0.1% ($H \rightarrow ZZ^*$)
2^+	$gg/qq \rightarrow X$	graviton minimal coupl	0.042% (gg) ($H \rightarrow \gamma\gamma, ZZ^*, WW^*$)	0.6% (gg) ($H \rightarrow ZZ^*, WW^*$) 60% ($H \rightarrow \gamma\gamma$)



A CL_s criterion is defined as the ratio of the probabilities to find, under each of the hypotheses, values of the test statistic equal or larger than the one observed in the data:

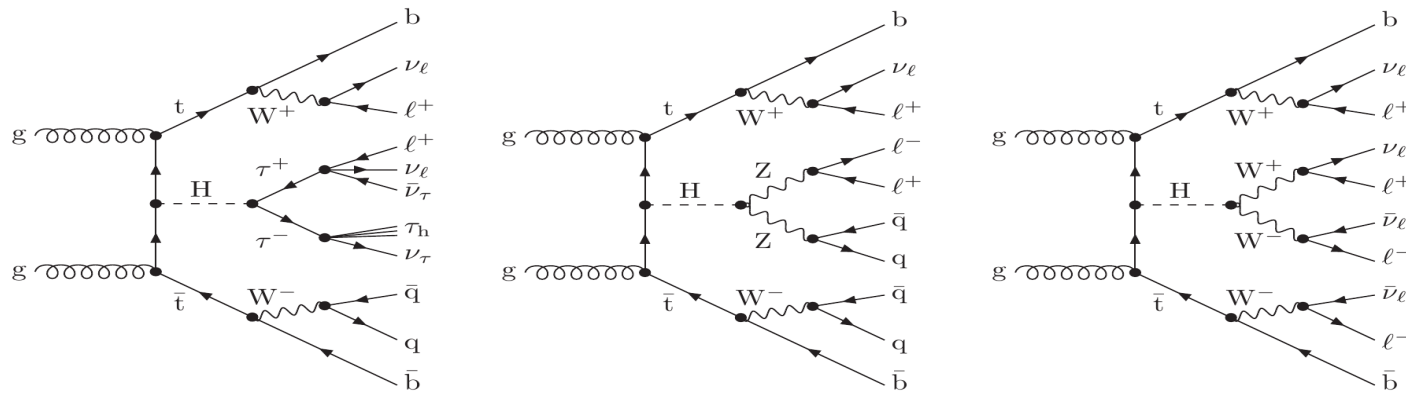
$$CL_s^{\text{obs.}} = P(q \geq q^{\text{obs.}} | 2_m^+(gg)) / P(q \geq q^{\text{obs.}} | 0^+).$$

Direct measurement of ttH coupling

$g g \rightarrow t t H$

CMS PAS HIG-13-020

Final states: $H \rightarrow WW^*, ZZ^*, \tau\tau$ + semileptonic top decay



Signal strength measured for $M_H = 125.7$ GeV

$$\mu = 3.7^{+1.6}_{-1.4}$$

Upper limit @ 95% CL on cross-section = $2.4 \times \text{SM}$

Why not being happy with SM Higgs boson?

- mass is in the favored Higgs mass range of EWPT
- $\sigma \times \text{BRs}$ well consistent with SM predictions !!!
- SM is a renormalizable theory in principle valid up to Planck mass M_p

Theoretical arguments in favor of New Physics

- quantum instability of Higgs mass $\rightarrow$ sensitivity to $(\text{UV cutoff})^2$
(cutoff scale is identified with mass of heavy particles coupled to Higgs)
- this is at the origin of what we call the fine-tuning problem
- Cosmological constant problem is similar (but worst)
- Solving the fine-tuning problem has been the guide for BSM theories
- But...maybe the fine-tuning problem is a ill-defined problem ?

Why EWSB requires new phenomena at the TeV scale

Perturbative unitarity at all energies $\rightarrow m_H \lesssim 1 \text{ TeV}$

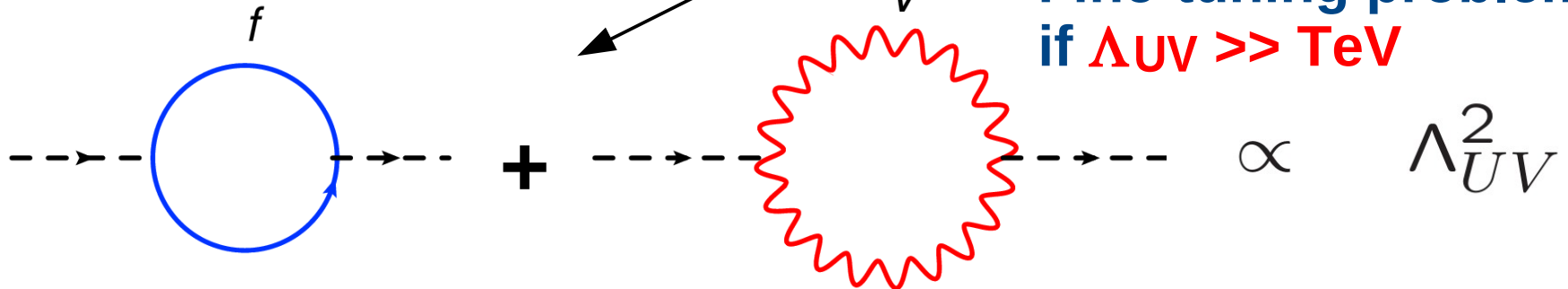
Quantum corrections

NP scale

$$\left\{ \begin{array}{l} m_f \bar{\psi}\psi \xrightarrow{\text{chiral symmetry}} 0 \Rightarrow \delta m_f \sim m_f \ln \frac{\Lambda_{UV}}{m_f} \quad \text{OK} \\ m_W^2 W_\mu W^\mu \xrightarrow{\text{gauge symmetry}} 0 \Rightarrow \delta m_W^2 \sim m_W^2 \ln \frac{\Lambda_{UV}}{m_W} \quad \text{OK} \\ m_H^2 H^2 \xrightarrow{\text{no symmetry in SM}} \Rightarrow \delta m_H^2 \sim \Lambda_{UV}^2 \end{array} \right.$$

$$\delta m_H^2 \sim \Lambda_{UV}^2$$

Fine-tuning problem
if $\Lambda_{UV} \gg \text{TeV}$



The diagram shows two Feynman diagrams representing quantum corrections to the Higgs mass. The first diagram is a fermion loop (blue circle) with external dashed lines labeled 'f'. The second diagram is a vector boson loop (red wavy circle) with external dashed lines labeled 'V'. They are added together, and the result is proportional to Λ_{UV}^2 .

$$\text{Feynman diagrams showing fermion and vector boson loops contributing to the Higgs mass correction. The result is proportional to } \Lambda_{UV}^2.$$

$$\Lambda_{UV} = \max[m_f, m_V]$$

$$m_H + \delta m_H \lesssim 1 \text{ TeV}$$

■ **Phenomenological arguments in favor of NP BSM:**

- huge hierarchy of fermion masses and mixing (origin of Yukawa couplings ?) → **flavor hierarchy problem**
- missing Dark matter candidate (as WIMP) in the SM
- not enough $\cancel{CP}$ source for matter-antimatter asymmetry of Universe

■ **BSM theories aim to solve the Higgs fine-tuning problem**

main approaches proposed so far:

- **Elementary Higgs boson** → **symmetry that cancels Λ^2 terms**
(SUSY models, Lee-Wick SM (SM replica with massive ghosts))
- **Elementary Higgs boson** → **UV scale lowered at TeV scale**
(quantum gravity models in large extra-dimensions)
- **Composite Higgs boson** → **strongly coupled NP sector,**
(Technicolor, composite Higgs boson as pNGB)

SUPERSYMMETRY



Standard particles $\longleftrightarrow$ SUSY particles

- Provides a solution to the naturalness problem without spoiling the good features of the standard model, **but SUSY spectrum below TeV !**
- It has a number of welcome side-effects:
 - **can achieve grand unification of couplings at the right scale**
 - **a natural candidate for cold dark matter**
- SUSY breaking in realistic models is still an open problem

Higgs spectrum:

- 2 neutral scalars: H (heavy), h (light),
- 2 Charged scalars: H^+ , H^- (self-conjugates)
- 1 pseudoscalar: A

$$\tan(\beta) = \langle H_U \rangle / \langle H_D \rangle$$

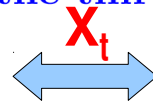
SUSY partners spectrum for Gauge and Higgs bosons:

- Charginos ($\chi^\pm$), 4-Neutralinos (χ^0), gluinos ($\tilde{g}$) $\rightarrow$ spin 1/2

SUSY partners spectrum for Quarks and Leptons

- Squarks ($\tilde{q}$) and Sleptons ($\tilde{l}$) $\rightarrow$ spin-0, carry same QN as SM quarks and leptons .

Mass matrices for squarks and sleptons in the third generation, in



**X_t responsible
for Left-Right
mixing**

$$\text{s - top : } \begin{pmatrix} \tilde{t}_L^* & \tilde{t}_R^* \end{pmatrix} \begin{pmatrix} m_Q^2 + m_t^2 + \Delta_Q & m_t(A_t - \mu \cot \beta) \\ m_t(A_t - \mu \cot \beta) & m_U^2 + m_t^2 + \Delta_U \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$\text{s - bottom : } \begin{pmatrix} \tilde{b}_L^* & \tilde{b}_R^* \end{pmatrix} \begin{pmatrix} m_Q^2 + m_b^2 + \Delta_Q & m_b(A_b - \mu \tan \beta) \\ m_b(A_b - \mu \tan \beta) & m_D^2 + m_b^2 + \Delta_D \end{pmatrix} \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \end{pmatrix}$$

$$\text{s - tau : } \begin{pmatrix} \tilde{\tau}_L^* & \tilde{\tau}_R^* \end{pmatrix} \begin{pmatrix} m_L^2 + m_\tau^2 + \Delta_L & m_\tau(A_\tau - \mu \tan \beta) \\ m_\tau(A_\tau - \mu \tan \beta) & m_E^2 + m_\tau^2 + \Delta_E \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}$$

where

$$\Delta = m_Z^2(T_3 - Q \sin^2 \theta_W) \cos 2\beta$$

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}$$

Model	e, μ , τ , γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^\pm \rightarrow q\tilde{q}W^\pm \tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV
	GGM (wino NLSP)	1 e, $\mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV
3 rd gen. $\tilde{g}$ med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^\pm$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.4 TeV
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^\pm$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^\pm$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^\pm$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV
	$\tilde{b}_2\tilde{b}_2, \tilde{b}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{b}_2$ 271-520 GeV
	$\tilde{t}_1\tilde{t}_1$	0	0	Yes	20.3	$\tilde{t}_1$ 85-315 GeV
	$\tilde{t}_1\tilde{t}_1$	0	0	Yes	20.3	$\tilde{t}_1$ 125-450 GeV
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 180-330 GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 600 GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu}), \tilde{\ell}\tilde{\nu}\tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$ (RPV)	1 μ , displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 e, $\mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e, $\mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV
	$\tilde{g} \rightarrow q\tilde{q}q$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV
	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b\tilde{s}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV
	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b\tilde{s}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV
Other	Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV
	Scalar gluon pair, sgluon $\rightarrow t\tilde{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon 800 GeV
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

Lightest neutralino

Status: SUSY 2013

$m_{\tilde{\chi}_1^0}$ [GeV]

$\tilde{t}_1\tilde{t}_1$ production

ATLAS Preliminary

— Observed limits

- - - Expected limits

All limits at 95% CL

■ CDF 2.6 fb⁻¹ [1203.4171]

- 0L, $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
- 1L, $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
- 2L, $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
- 2L, $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$
- 0L, mono-jet/c-tag, $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$
- 0L, $m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} + 5$ GeV
- 1-2L, $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm, m_{\tilde{\chi}_1^\pm} = 106$ GeV
- 1L, $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm, m_{\tilde{\chi}_1^\pm} = 150$ GeV
- 2L, $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm, m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} - 10$ GeV
- 1-2L, $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm, m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$

$L_{\text{int}} = 20 - 21 \text{ fb}^{-1} \sqrt{s}=8 \text{ TeV}$

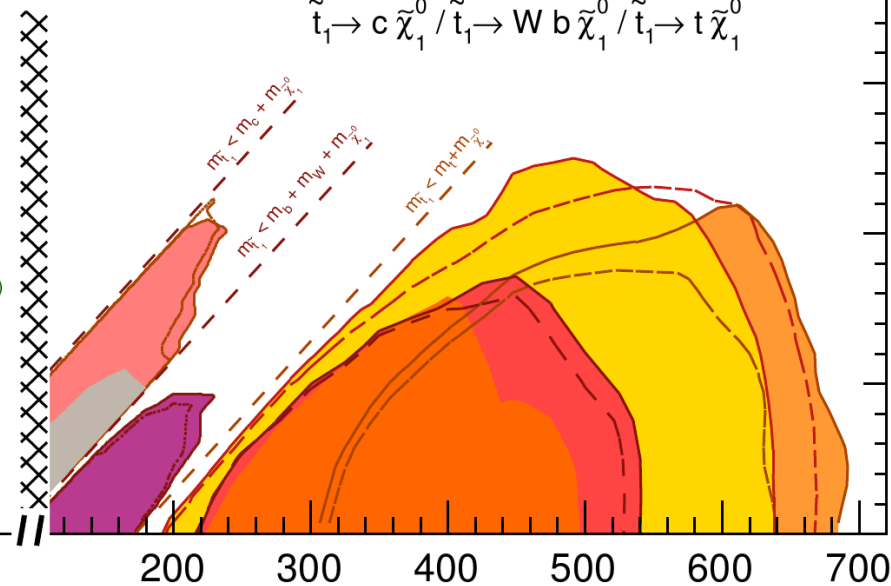
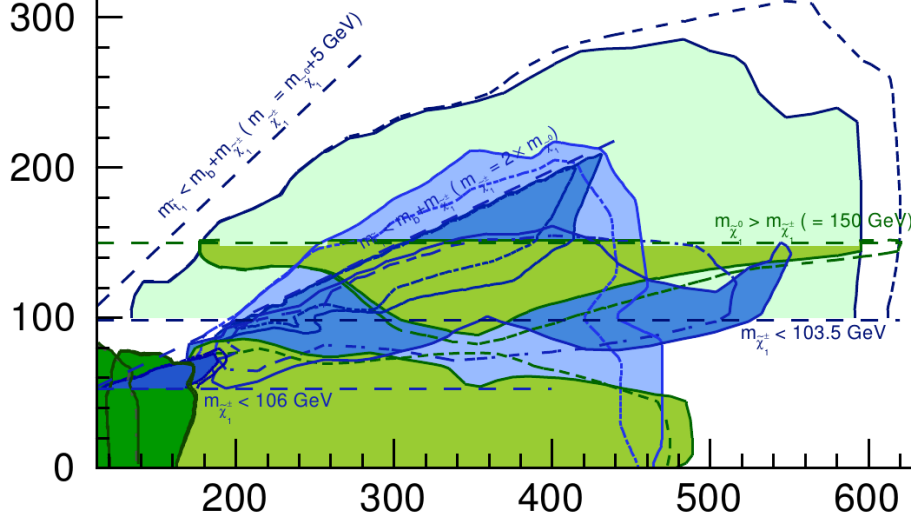
0L ATLAS-CONF-2013-024
1L ATLAS-CONF-2013-037
2L ATLAS-CONF-2013-065
2L ATLAS-CONF-2013-048
0L mono-jet/c-tag, CONF-2013-068
0L 1308.2631

$L_{\text{int}} = 4.7 \text{ fb}^{-1} \sqrt{s}=7 \text{ TeV}$

0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
-
-
-
2L [1208.4305], 1-2L [1209.2102]
-
-
1L CONF-2013-037, 0L 1308.2631
2L ATLAS-CONF-2013-048
1L CONF-2013-037, 2L CONF-2013-048 1-2L [1209.2102]

$\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W^{(*)} \tilde{\chi}_1^0$

$\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$



Lightest stop

$m_{\tilde{t}_1}$ [GeV]

Higgs mass impact on SUSY models (MSSM)

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

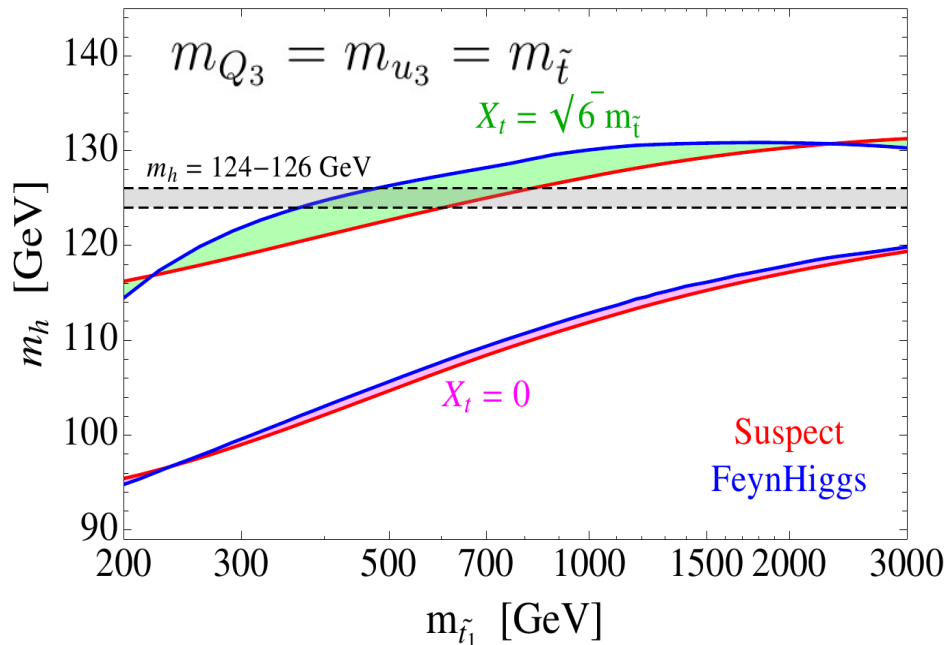
$$\sim 85 \text{ GeV}^2$$

■ large Higgs mass implies SUSY badly broken

■ at large $\tan\beta \rightarrow \delta_t \approx \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[\ln \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right]$

■ $m_h = 125 \text{ GeV}$ requires heavy squarks $X_t = A_t - \mu \cot \beta$

MSSM Higgs Mass



● Higgs mass maximized for

$$X_t^{\max} = \sqrt{6} m_{\tilde{t}}$$

● Large X_t mixing $\rightarrow$ heavy stops

$$\sqrt{m_{Q_3} m_{u_3}} \gtrsim 700 \text{ GeV}$$

● fine-tuning $O(1\%)$ on EWSB condition

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

Fine Tuning problem

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2} (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \ln \left(\frac{\Lambda}{m_{\tilde{t}}} \right)$$

$m_{H_u}^2$ is the quadratic term in the Higgs potential

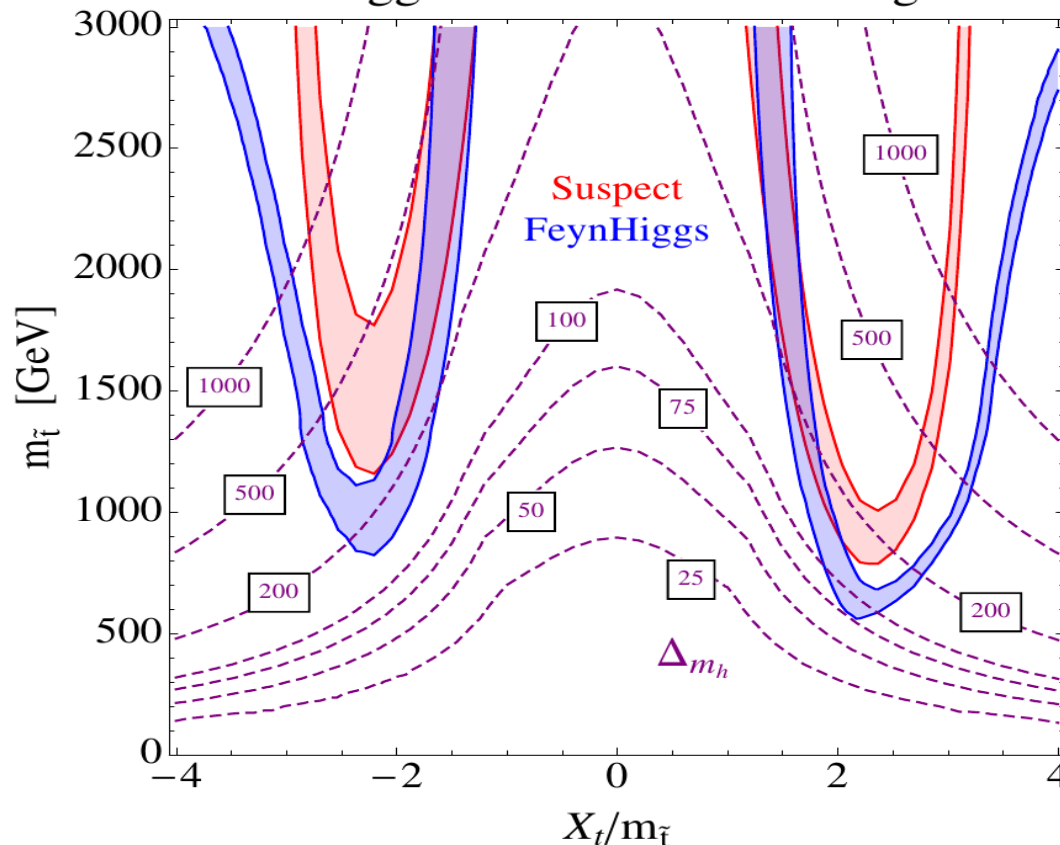
Λ scale of SUSY breaking

■ for large squarks $\delta m_{H_u}^2$ becomes too large

■ fine tuning is needed to achieve EWSB

$$\Delta_{m_h} = \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right|$$

Higgs Mass vs. Fine Tuning



■ maximal mixing required to avoid multi TeV stops

■ difficult to achieve in SUSY breaking scenarios

■ $\Delta_m > 75$ (100) in order to achieve $M_H = 124$ (126) GeV for $\Lambda = 10$ TeV

■ fine-tuning much worse for higher Λ scales

Natural SUSY with $M_H = 125$ GeV

Why SUSY should be simple MSSM ?

NMSSM → additional new singlet S → μ -term naturally generated by $\langle S \rangle$

$$\mathbf{W} \rightarrow \lambda S H_u H_d$$

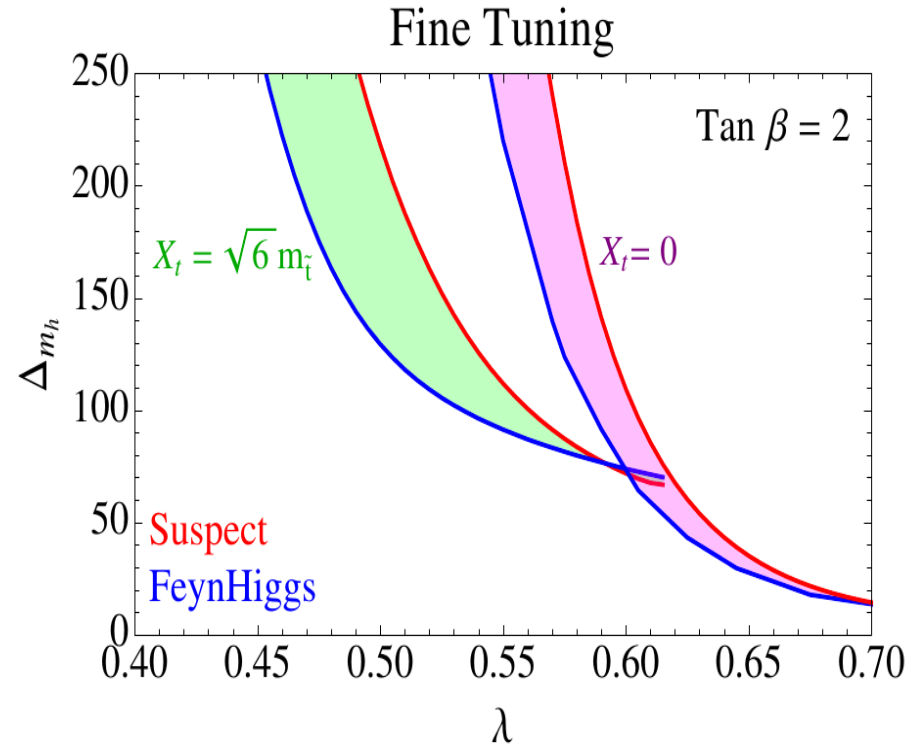
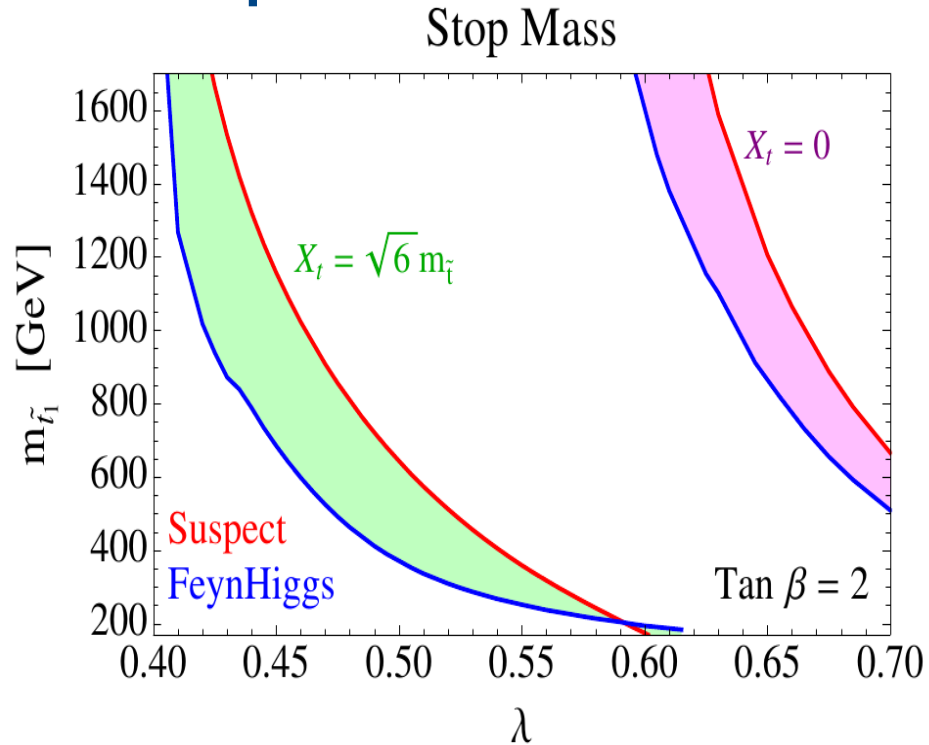
no dimensionfull terms
in the $\mathbf{W}$ superpotential

$$(m_h^2)_{\text{tree}} \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

- ◆ potentially reducing the fine-tuning problem
- ◆ however for large values of $\lambda > 0.7$ the theory becomes non-perturbative
- ◆ for $\lambda < 0.7$ theory is perturbative up to GUT scale

NMSSM perturbative

Hall, Pinner, Ruderman JHEP 1204 (2012)



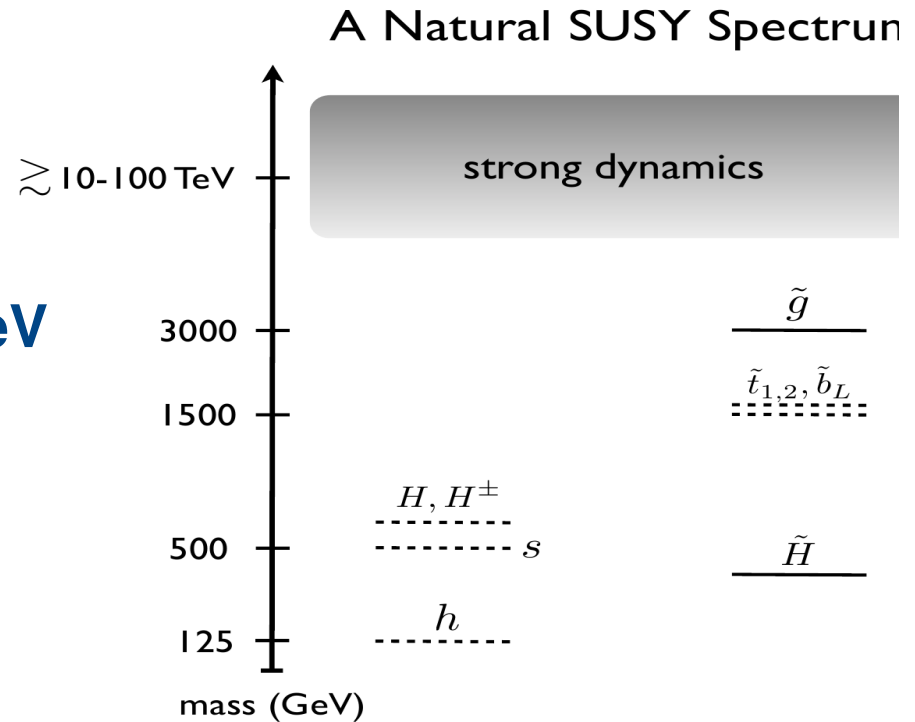
- ◆ large values of λ allow for lighter stops and much less fine tuning
- ◆ only 5 – 10 % tuning if mediation scale of SUSY breaking is low and stop mixing is non-maximal
- ◆ achieved with $\tan\beta \sim 2$ and $\lambda \sim 0.7$, but very close to the edge of perturbative regime

Naturalness in large λ -SUSY scenario

■ Higgs mass can be still **125 GeV** with $\lambda > 2$ but strong dynamics expected at **10-100 TeV**

■ stops mass can be ~ 1.5 TeV

■ gluino as heavy as 3 TeV



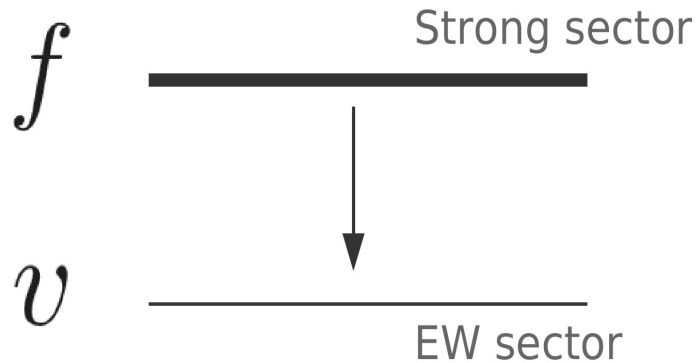
Hall, Pinner, Ruderman JHEP 1204 (2012)

■ Interesting **non-decoupling effects** among Higgs-doublets:

- suppresses the coupling of light Higgs to b-quarks
- enhancing rates of $\gamma\gamma$ and WW and depleting rates of bb and $\tau\tau$

Composite Higgs models

$$\xi = \frac{v^2}{f^2} < 1$$



Higgs boson is a bound state of a new strongly interacting sector → Pseudo Nambu-Goldstone Boson

Mass protected by its PNGB nature

Strongly Interacting Light Higgs (SILH)

- ◆ Light composite Higgs as PNGB from strongly interacting sector (SIS)
- ◆ Higgs mass is acquired by interactions of SIS with SM fields
- ◆ Various realizations in specific models (Holographic Higgs as PNGB, Little Higgs, etc) Arkani-Hamed, Cohen, Georgi (2001), Arkani-Hamed, Cohen, Katz, Nelson (2002), Contino, Nomura, Pomarol (2003)
- ◆ Low energy effective Lagrangian parametrization in terms of two parameters: coupling g_ρ and mass m_ρ of the strongly interacting sector Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007)

$$m_\rho = g_\rho f$$

Characteristic parameters
f = scale of sigma-model

$$\xi \equiv \frac{v^2}{f^2}, \quad v = \left(\sqrt{2} G_F \right)^{-1/2} = 246 \text{ GeV}$$

■ Expected small modifications to the SM Higgs couplings

■ New operators in Higgs self-coupling suppressed by $1/m_\rho$

■ Expected violation of unitarity in $VV \rightarrow VV$ scattering

$$g_{hWW} = gm_W \left[1 - \frac{c_H}{2} \xi \right],$$

$$g_{hff} = \frac{gm_f}{2m_W} \left[1 - \xi \left(\frac{c_H}{2} + c_y \right) \right],$$

**C_i parameters of order $O(1)$
model dependent**

$$g_{hhh} = \frac{gm_H^2}{4m_W} \left[1 + \xi \left(c_6 - \frac{3c_H}{2} \right) \right]$$

■ Higgs does not balance completely the $VV \rightarrow VV$ amplitude

■ Scale of unitarity breaking higher than in no-Higgs

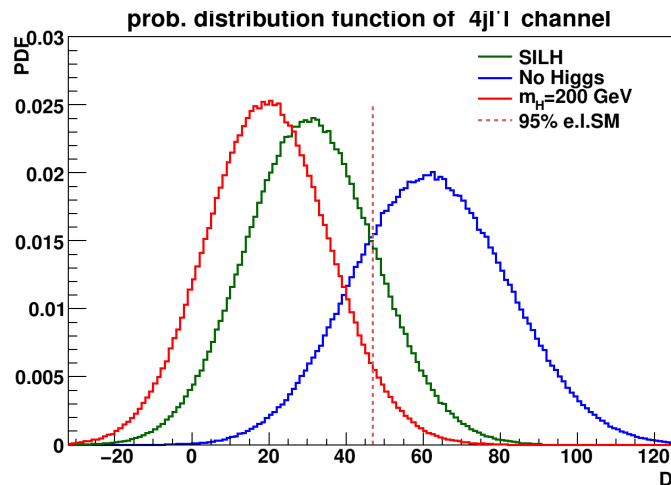
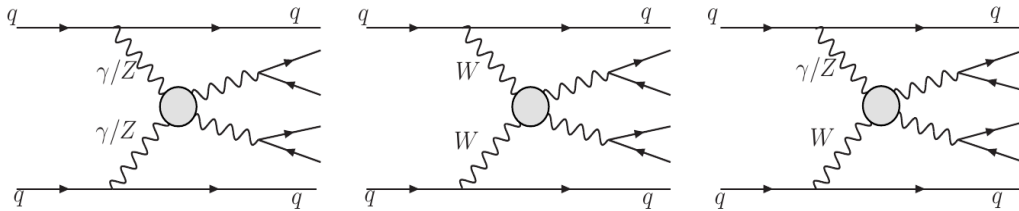
$$\sigma(pp \rightarrow V_L V_L' X)_{c_H} = (c_H \xi)^2 \sigma(pp \rightarrow V_L V_L' X)_H$$

■ Unitarity recovered by exchange of heavy resonances

◆ new resonances are predicted in Composite Higgs models → heavy vector-resonance ρ like in QCD, composite partners of top

◆ rich phenomenology expected at LHC if the scale is $O(\text{TeV})$

◆ Possible to distinguish SM Higgs from Higgsless and SILH via $VV \rightarrow VV$



$4jll$ channel

SILH with $c_H \xi = 1$

$L=200/\text{fb}$, LHC 14 TeV
sum over ee and $\mu\mu$ final states

D =actual number of events founds in the peak taking into account stat. fluct,

Ballestrero et al., JHEP 0911 (2009)

$$D = B + S - \overline{B}$$

Limits on Higgs compositeness

- Limits **from couplings measurement** of low mass Higgs h_{126}
 - > **LHC: $4\pi f > 5-7$ TeV** if no deviations observed
 - > **ILC: $4\pi f > 30$ TeV**
- Direct analysis of **VV scattering and double Higgs production at LHC:**
 - > $4\pi f > 4$ TeV (**direct probe of SILH scenarios**)
- **At LHC direct search of ρ** important at small g_ρ
 - > able to push m_ρ at 1 TeV-2 TeV, ie $4\pi f > 3-4$ TeV
but **less effective at high g_ρ**
- **At ILC the test of aTGC** can constraint $m_\rho > 7-8$ TeV

More exotic scenarios

Naive **F**ermio-**P**hobic Higgs scenario



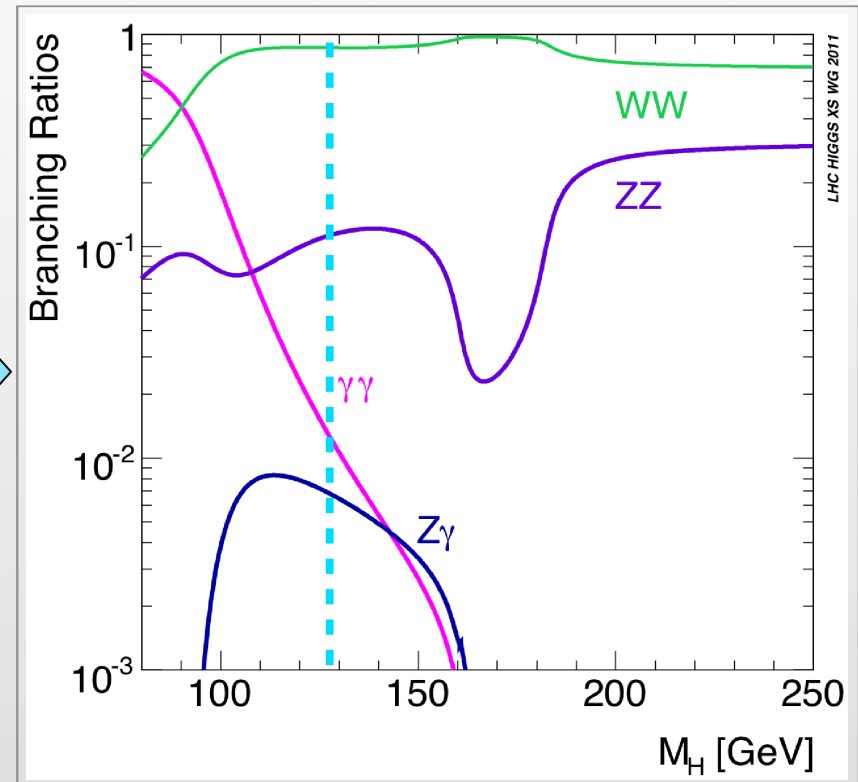
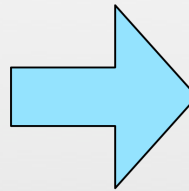
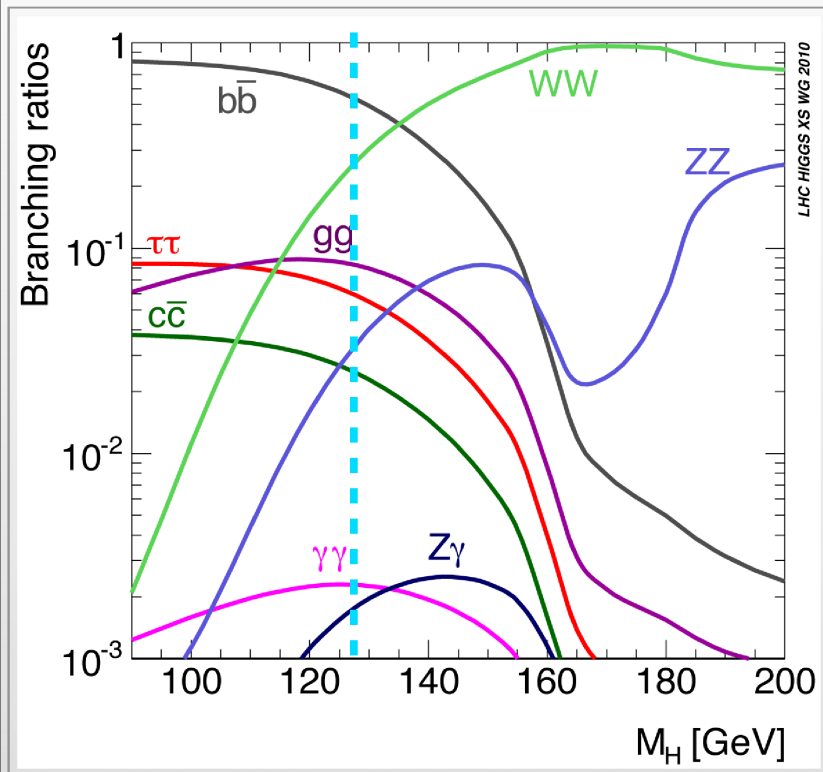
- **NO** Yukawa couplings at **tree-level**
- Higgs mechanism gives mainly rise to **EWSB** and **M_W, M_Z**
- but is **not** responsible for **ChSB** and **fermion masses**

Advantages

- Fermiophobia lowers the vacuum stability bound on Higgs
- $M_H = 125$ GeV consistent with no NP below Planck scale

Higgs decays : FP vs SM

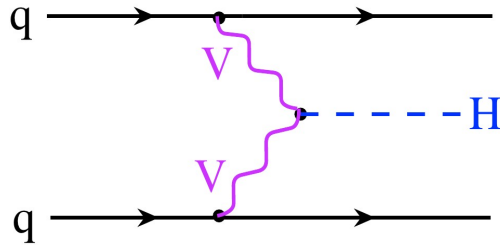
$H \rightarrow WW, ZZ, \gamma\gamma, Z\gamma$ [through W loops (no-top loops)]
 $M_H = 125 \text{ GeV}$
SM Higgs **FP Higgs**



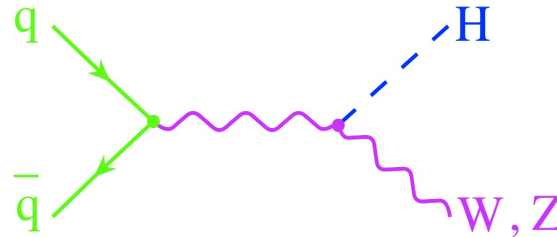
For $M_H \sim [100, 110, 125] \text{ GeV}$:
 $BR(\gamma\gamma)_{FP} \sim [110, 30, 7] \times BR(\gamma\gamma)_{SM}$

Naive Fermio-**P**hobic Higgs production mechanisms

VBF



VH

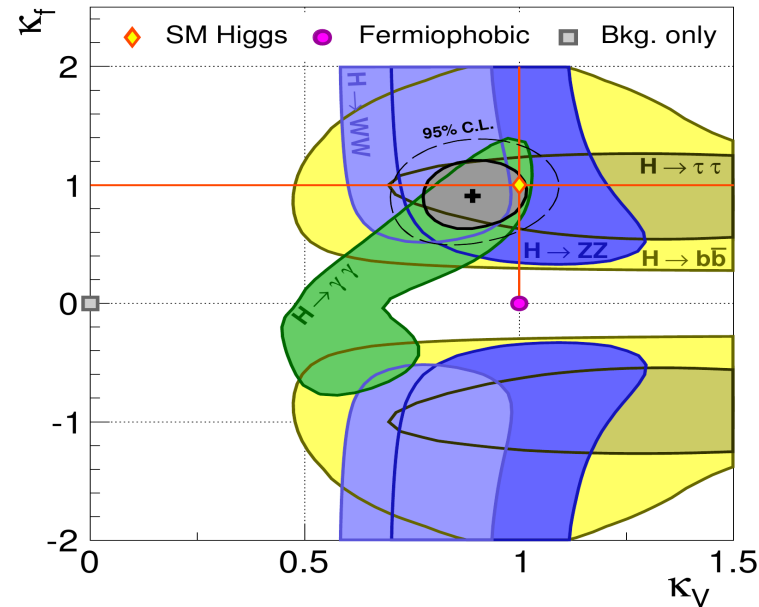


- no gluon-gluon fusion
- **VBF** fusion dominant mechanism
- harder **pT** spectrum → better **S/B** !

Naive FP Higgs with $M_H=125$ GeV excluded at 99 % CL

CMS-HIG-13-005

CMS Preliminary $\sqrt{s} = 7$ TeV, $L \leq 5.1$ fb $^{-1}$ $\sqrt{s} = 8$ TeV, $L \leq 19.6$ fb $^{-1}$



- NFP Higgs predicts $\mu=1$ @ $M_H=123$ GeV
EG, Mele, Raidal PLB 716 (2012)
- higher μ predicted in $WW, ZZ, \gamma\gamma$ when VBF and VH tagging are applied
- observed rates in VBF and VH are much smaller.

- above results do not take into account effect of **Radiative Corrections**
EG, Mele, Raidal PLB 716 (2012)
- Yukawa couplings cannot be kept vanishing at any scale
- fermion masses $\longrightarrow$ Yukawa radiatively generated EG, Mele, PRD 82 (2010)
- **RC** can suppress BRs of $H \rightarrow \gamma\gamma, WW, ZZ$ (depending on the scale Λ where Yukawa's are assumed to be vanishing)

SUSY Fermiophobia

EG, Kannike, Mele, Racioppi, Raidal, PRD 86 (2012)

- **Fermiophobic Higgs** can cure some SUSY problems

- **fine-tuning problem** of SUSY induced only by gauge couplings → fine-tuning improved by a factor

$$N_c y_t^4 / g^4 \sim 25.$$

- removes **little SUSY hierarchy problem**

- squarks and sleptons masses of **2-3 TeV** become now completely Natural

- **FCNC** and **CP problems** automatically solved

- SUSY effects in FCNC processes much suppressed

Failure of MSSM in the FP limit

Fermiophobic limit: $y_t \rightarrow 0$

$$\Delta M_h^2 = -\frac{3v^2 \sin^2 \beta}{2\pi^2} \frac{a_t^4}{48M_S^4} < 0$$

- we cannot get $m_H > m_Z$ and even more ~ 125 GeV
- $m_H < m_Z \Rightarrow$ MSSM is ruled out
- FP Higgs suggests NMSSM as a natural candidate
EG, Kannike, Mele, Racioppi, Raidal, PRD 86 (2012)
- large A-terms required to generate $H \rightarrow gg$ by squark loops
- Current SUSY analysis do not apply $\rightarrow$ dedicated analy. needed

Anomalous Yukawa couplings

BSM theories can predict $C_f < 0$!

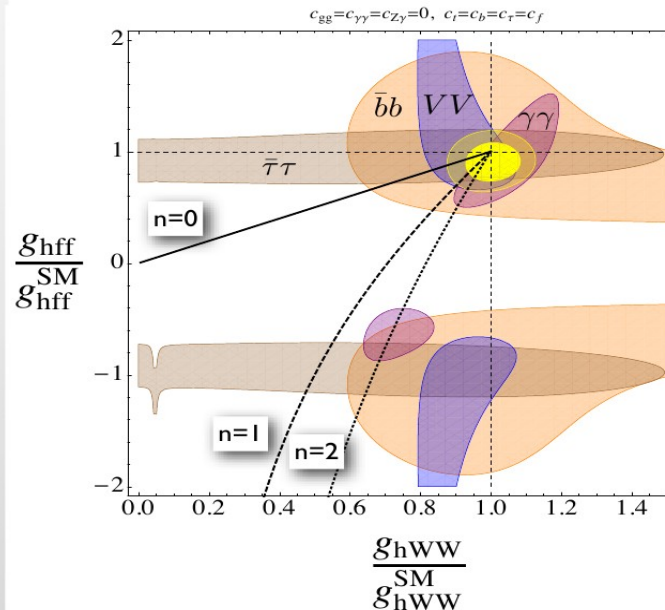
example : Minimal Composite Higgs Models $SO(5) \rightarrow SO(4)$
global symmetry in a strong sector broken at a scale $f_H > v$

Agashe, Contino, Pomarol, [hep-ph/0412089]

$$\xi = \frac{v^2}{f_H^2}$$

$$\frac{g_{hWW}}{g_{hWW}^{\text{SM}}} = \sqrt{1 - \xi} \quad \frac{g_{hff}}{g_{hff}^{\text{SM}}} = \frac{1 - (1 + n)\xi}{\sqrt{1 - \xi}} \quad n = 0, 1, 2, \dots$$

Depending on realization

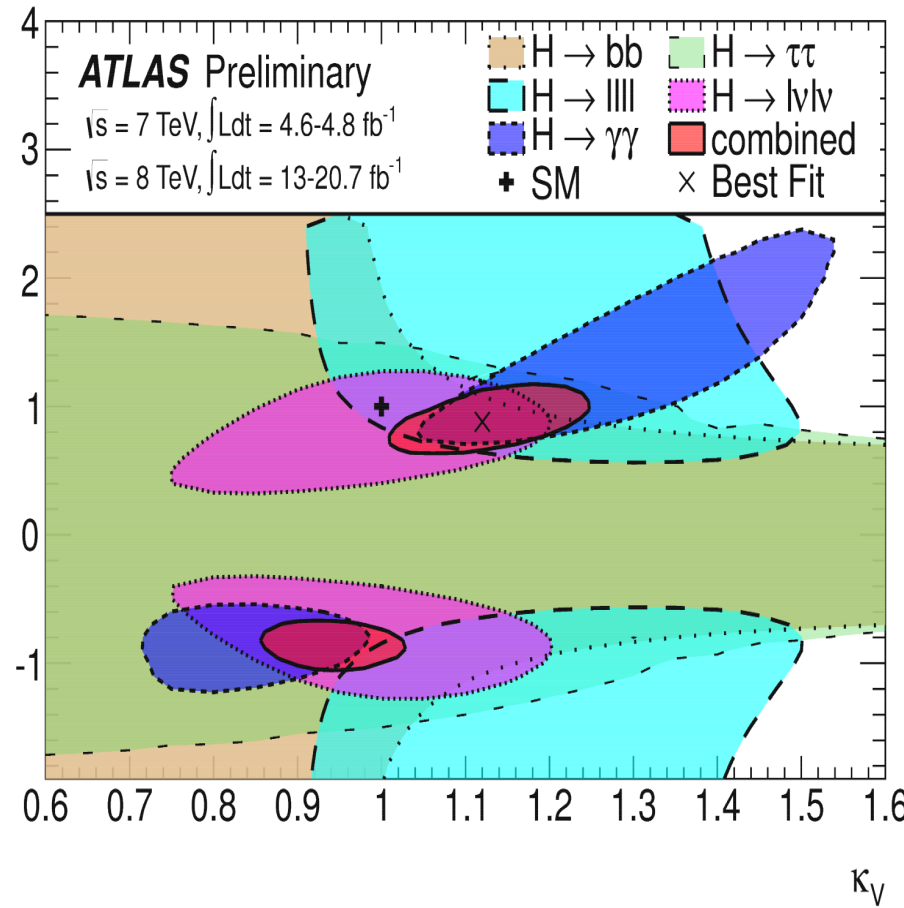
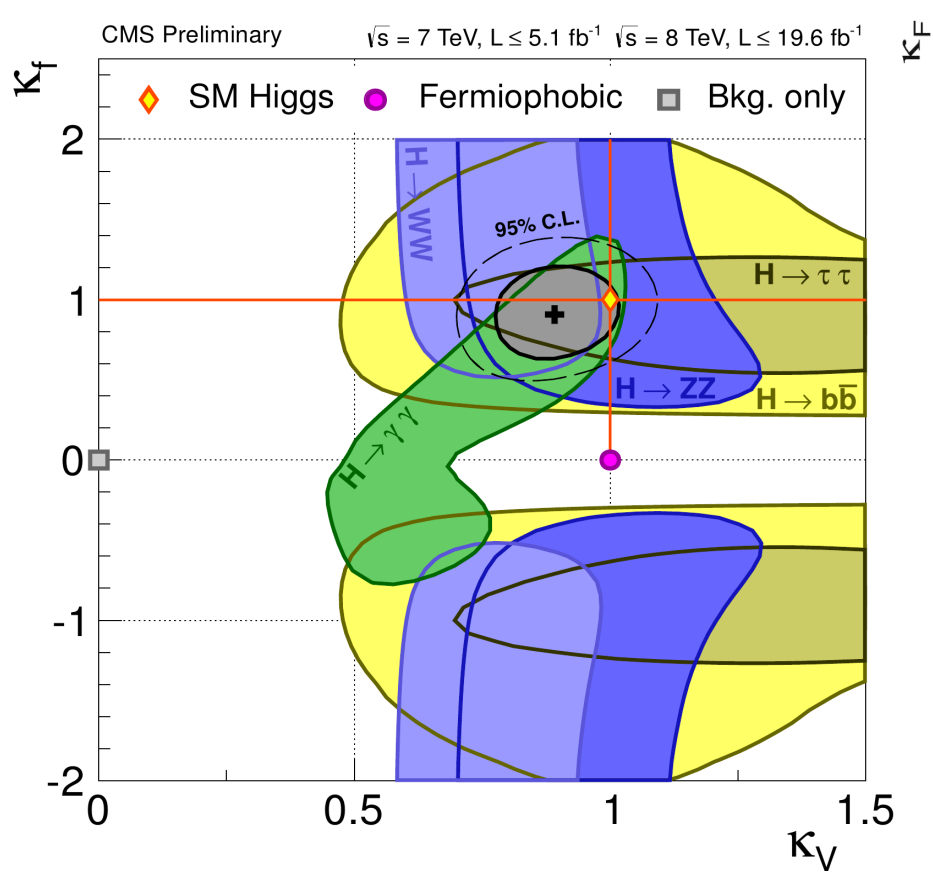


■ MCHM limit

$$\rightarrow f_H \gtrsim 700 \text{ GeV}$$

Falkowski, Riva, Urbano, [1303.1812]

How to disentangle the negative Yukawa regions ?



How to disentangle the sign of C_t

- Flipping the sign of Yukawa couplings has dramatic consequences for EWSB
- relative sign of Hff and HWW couplings is physical
- unitarity and renormalizability are spoiled
- unitarity in $V_L V_L \rightarrow f f \rightarrow$ recovered by adding new weakly interacting resonances (Higgs-boson-like) or by infinite tower of strongly coupled resonances
- If the scale of unitarity violation is high enough then the low energy processes should be insensitive to UV-completion
- Promising process: single top production in association to a Higgs

$$q b \rightarrow t H q'$$

Main references on tHq sensitivity to C_f sign

S. Biswas, E.G., B. Mele

$(H \rightarrow \gamma\gamma + \text{top (had)})$

“Single top and Higgs associated production as a probe of the Htt coupling sign at the LHC”, JHEP 01 (2013) 088 [arXiv:1211.0499]

(BGM)

M. Farina, C.Grojean, F.Maltoni, E.Salvioni, A.Thamm

$(H \rightarrow b\bar{b} + \text{top (lep)})$

“Lifting degeneracies in Higgs couplings using single top production in association with a Higgs boson”, JHEP 05 (2013) 022 [arXiv:1211.3736]

(FGMST)

S.Biswas, E. Gabrielli, F. Margaroli, B. Mele,

$(H \rightarrow \gamma\gamma, WW, \tau\tau)$

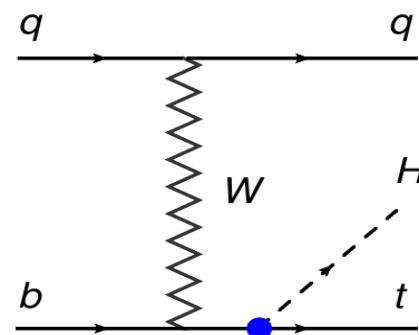
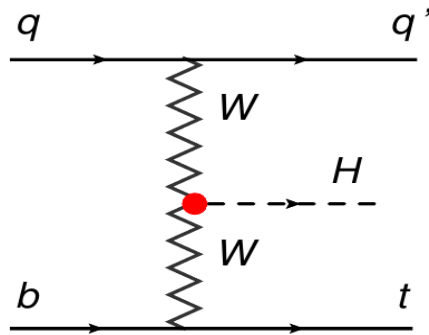
“Direct constraints on the Htt coupling from the 8 TeV LHC data”

JHEP 07 (2013) 073 [arXiv:1304.1822]

(BGM)

Sensitivity to C_t sign of the present 7 + 8 TeV data

Sensitive process to the sign of top-Yukawa



BGM

$q b \rightarrow t q' H \rightarrow t q' \gamma \gamma$ with signature of $H \rightarrow \gamma \gamma$

- SM cross-section is very small : not yet observable
- Changing sign between HWW and ffH $\rightarrow$ unitarity breaking
- unitarity breaking implies larger cross-sections

SM total σ x BR ($\gamma\gamma$)

$$\sigma(q b \rightarrow t q' H)^{SM} \simeq 15.2 \text{ fb} \quad \text{at } \sqrt{s} = 8 \text{ TeV}$$

$$\sigma(q b \rightarrow t q' H)^{SM} \simeq 71.8 \text{ fb} \quad \text{at } \sqrt{s} = 14 \text{ TeV}$$

$$BR_{\gamma\gamma}^{SM} \simeq 2.29 \cdot 10^{-3}$$

■ For $C_F < 0 \rightarrow \sigma$ expected to grow up due to unitarity breaking

■ $BR(\gamma\gamma)$ mostly sensitive to a reduction of magnitude $|C_F|$

scale of unitarity breaking

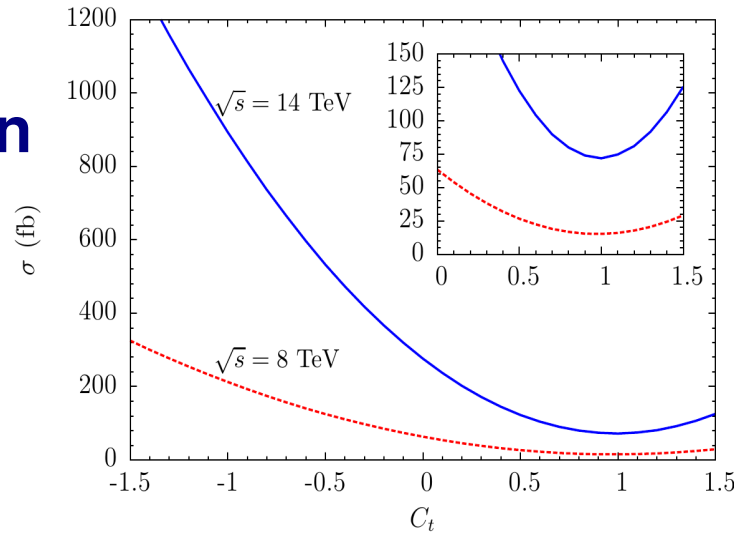
$H \rightarrow b\bar{b}$

$$\Lambda = 12\sqrt{2}\pi \frac{v^2}{m_t |c_F - c_V|} \sim 9.3 \text{ TeV}$$

FGMST

Enhancement factors versus C_t

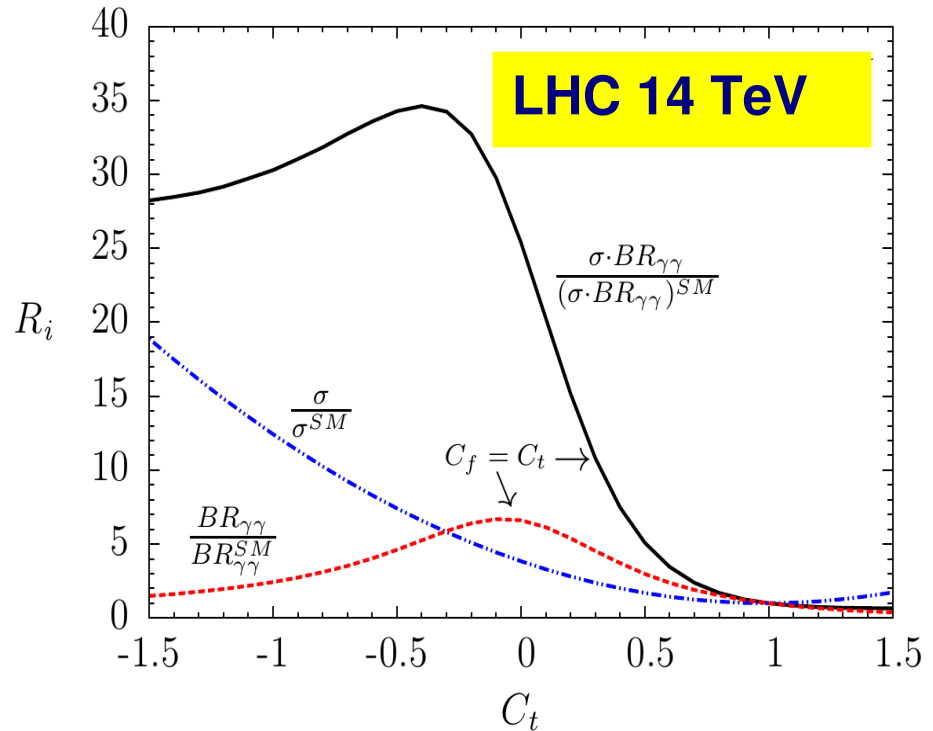
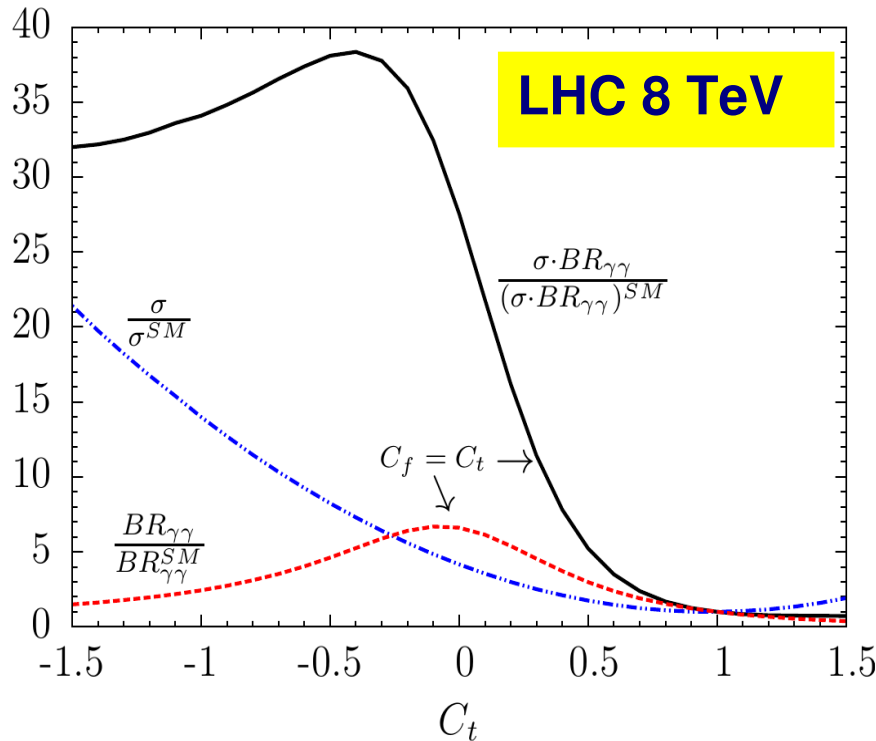
**Total cross section
 $pp \rightarrow t q H$**



SM $\rightarrow C_t = 1$

PDF = CTEQ6L1

R_i = Ratios



Irreducible backgrounds for $pp \rightarrow t \, q \, H (\rightarrow \gamma\gamma)$

■ we are looking for top decaying hadronically $t \rightarrow b \, q \, q'$

■ final state bckg consists of $\rightarrow 2 \, \gamma + b + (\geq 3 \, j)$

■ irreducibles bckg processes

$$pp \rightarrow 2 \, \gamma + t + j ,$$

$$pp \rightarrow 2 \, \gamma + \bar{t} t ,$$

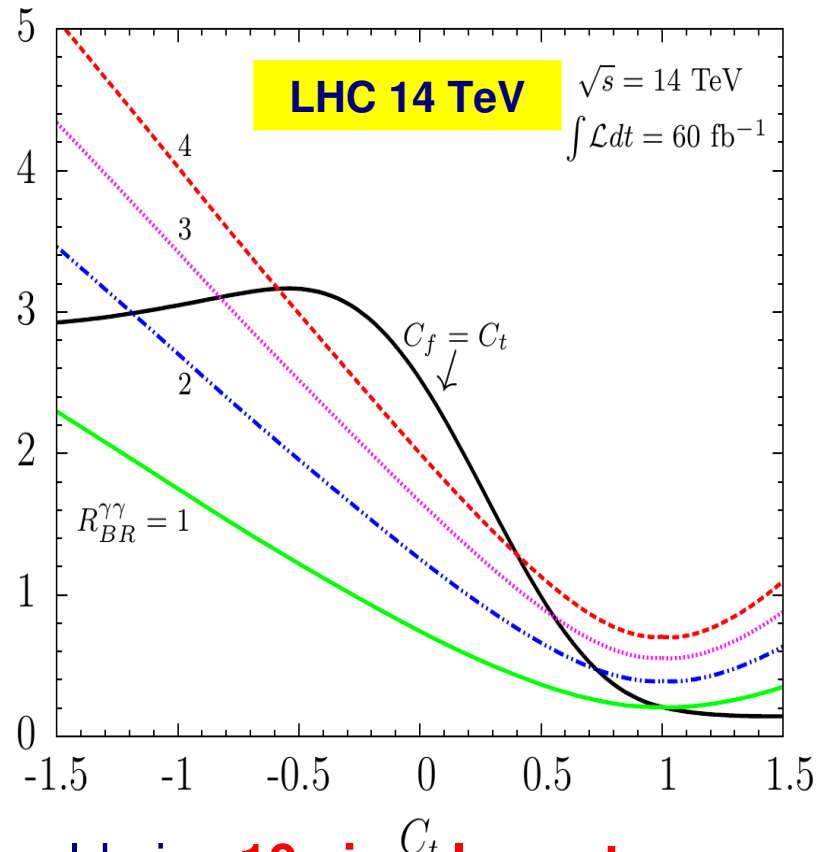
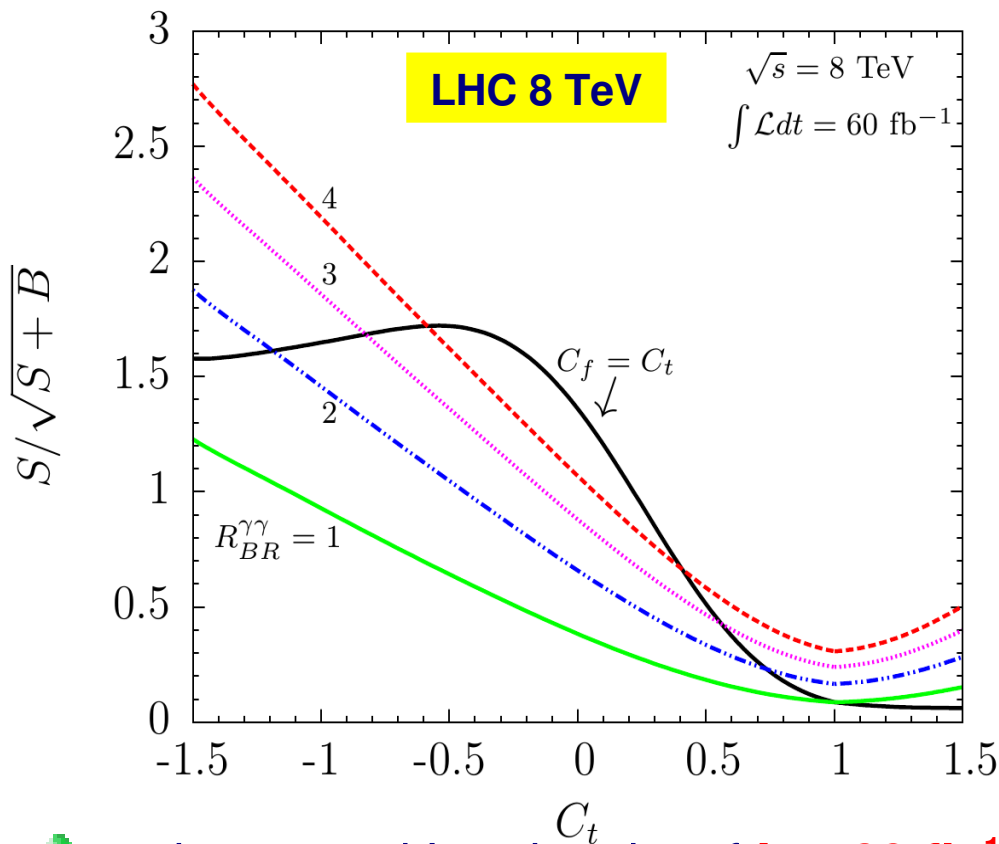
$$pp \rightarrow 2 \, \gamma + b + 3 \, j$$

■ optimized selection cuts

$$p_T^{\gamma_1} > 40 \, \text{GeV}, \quad p_T^{\gamma_2} > 30 \, \text{GeV}, \quad p_T^{j,b} > 25 \, \text{GeV}, \quad |\eta_{\gamma,b}| < 2.5, \quad |\eta_j| < 4.5$$

$$\Delta R_{i,j} = \sqrt{\Delta\eta_{i,j}^2 + \Delta\phi_{i,j}^2} > 0.4$$

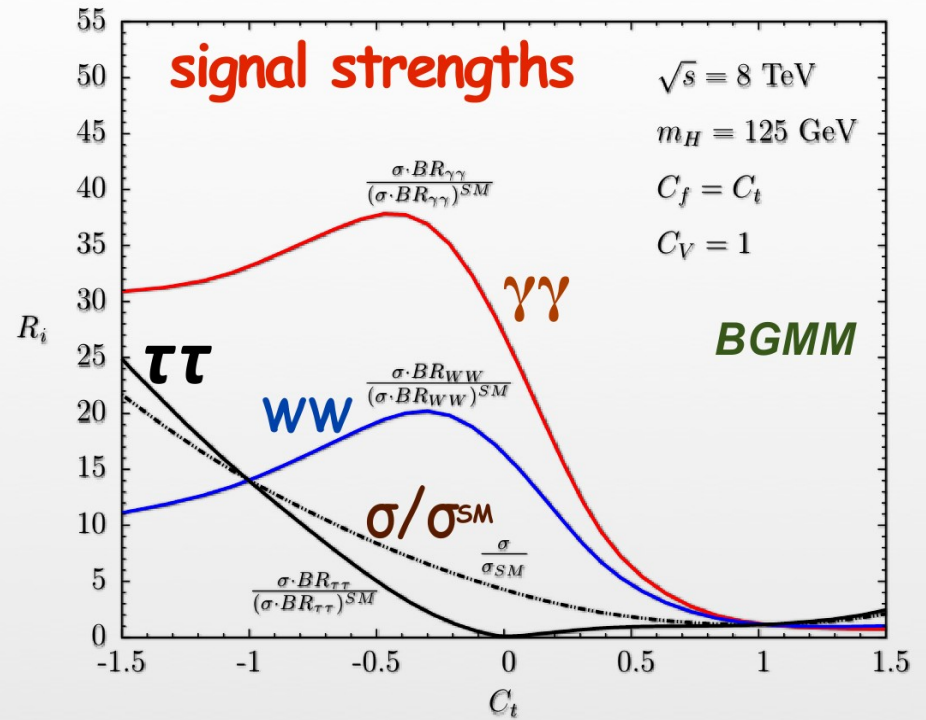
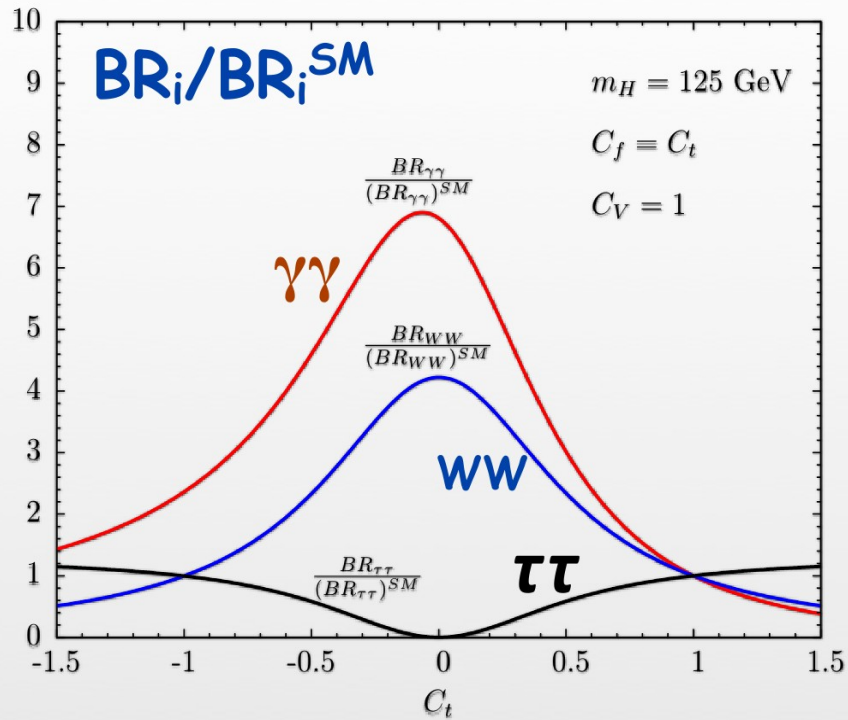
◆ bckg well under control



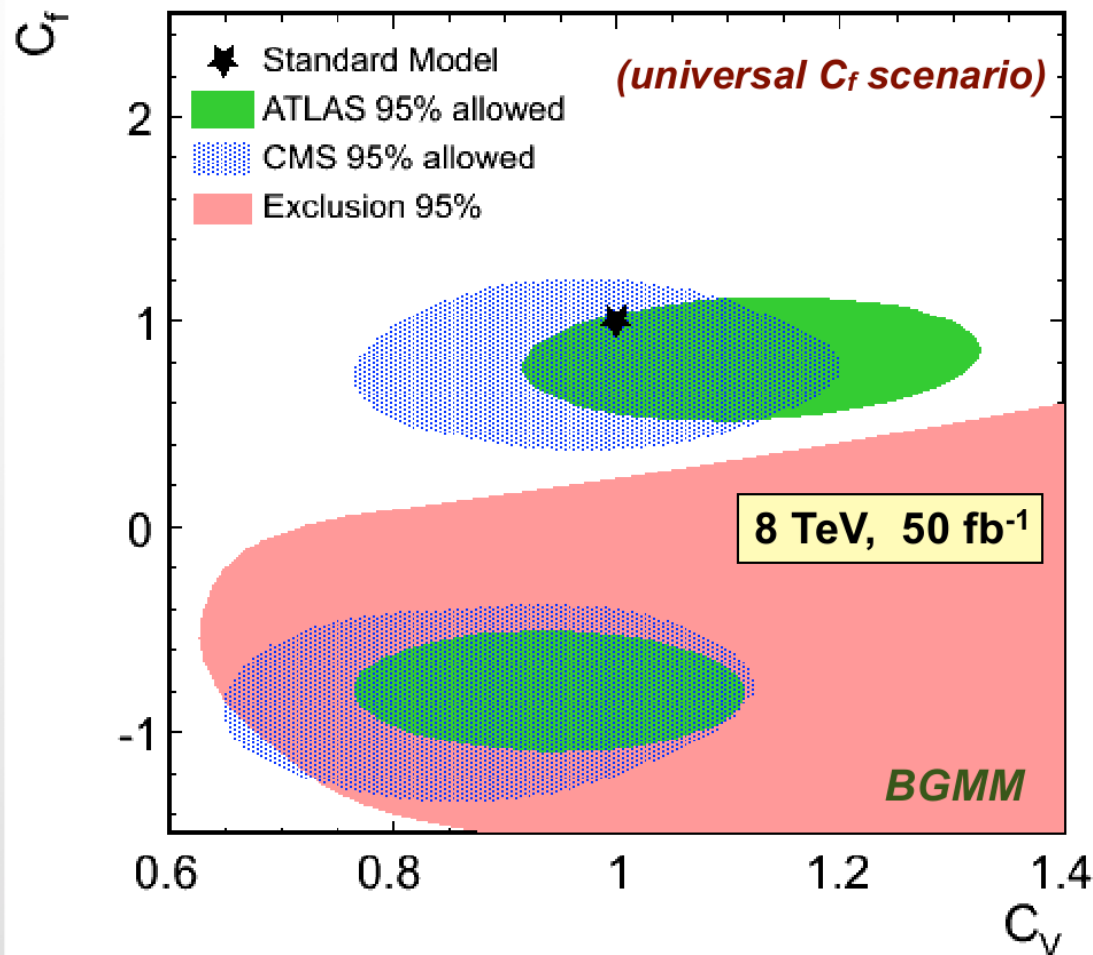
- ◆ an integrated Luminosity of **$L = 60 \text{ fb}^{-1}$** would give **10 signal events** versus **0.3 of bckg** overall the negative range **$-1.5 < C_t < 0$**
- ◆ **SM would require HL-LHC to reach an observable event statistics**
- ◆ Including different decay channels can dramatically improve the significance already with data at 8 TeV

Signal strengths for $H \rightarrow \gamma\gamma, \tau\tau, WW$

(BGMM)



exclusion potential in (C_v, C_+) plane



BGMM

$H \rightarrow \gamma\gamma, WW, \tau\tau$

covers all critical
 $C_f < 0$ region !

ATLAS-CONF-2013-034

CMS PAS HIG-12-045

**Can be the 125 GeV resonance an
Higgs-boson imposter?**

- ◆ **Spin-1 is ruled out** by $H \rightarrow \gamma\gamma$ + Yang theorem
- ◆ Pseudoscalar and spin-2 are **strongly disfavored**
- ◆ Let's focus on the case of a scalar-like imposter

Low, Lykken, Shaughnessy PRD 86 (2012)

■ **EW singlet and a custodial singlet**



**strongly
disfavored**



coupled to operator of dimension 4 (like dilaton, or graviscalar) i.e. to the trace of EMT $T_{\mu}^{\mu} \sim$ masses



Coupled to operators of dim. 5, as $\phi F_{\mu\nu} F^{\mu\nu} / \Lambda$

■ **Not an EW singlet but a custodial singlet and neutral member of a custodial 5-plet**

→ could belong to an EW triplet of SU(2) (triplet imposter)

Dilaton imposter (χ) $\rightarrow$ same couplings as SM

$$\mathcal{L}_{\chi V_1 V_2} = c_{\chi V} \left(\frac{2m_W^2}{v} \chi W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v} \chi Z_\mu Z^\mu \right) \\ + c_{\chi g} \frac{\alpha_s}{12\pi v} \chi G_{\mu\nu}^a G^{a\mu\nu} + c_{\chi\gamma} \frac{\alpha}{8\pi v} \chi F_{\mu\nu} F^{\mu\nu} + c_{\chi Z\gamma} \frac{\alpha}{8\pi v s_w} \chi F_{\mu\nu} Z^{\mu\nu}$$

EW singlet imposter (s)

$$\mathcal{L}_{sV_1 V_2} = \kappa_W \frac{\alpha}{8\pi m_s s_w^2} s W_{\mu\nu}^+ W^{-\mu\nu} + \left(\kappa_W \frac{c_w^2}{s_w^2} + \kappa_B \frac{s_w^2}{c_w^2} \right) \frac{\alpha}{16\pi m_s} s Z_{\mu\nu} Z^{\mu\nu} \\ + \kappa_g \frac{\alpha_s}{16\pi m_s} s G_{\mu\nu}^a G^{a\mu\nu} + (\kappa_W + \kappa_B) \frac{\alpha}{16\pi m_s} s F_{\mu\nu} F^{\mu\nu} \\ + \left(\kappa_W \frac{c_w}{s_w} - \kappa_B \frac{s_w}{c_w} \right) \frac{\alpha}{8\pi m_s} s F_{\mu\nu} Z^{\mu\nu},$$

SZ γ coefficient of same order of **SZZ** and **SWW**

$$\Gamma_{gg} \gtrsim \Gamma_{\gamma\gamma} \gtrsim \Gamma_{Z\gamma} \gtrsim \Gamma_{WW} \gtrsim \Gamma_{ZZ}$$

$$\Gamma_{WW}^{(\text{SM})} > \Gamma_{gg}^{(\text{SM})} > \Gamma_{ZZ}^{(\text{SM})} > \Gamma_{\gamma\gamma}^{(\text{SM})} > \Gamma_{Z\gamma}^{(\text{SM})}$$

$\rightarrow$ @ $M_H = 125$ GeV

Model independent fits

Useful to consider the ratios

$$D_{W/Z} \equiv \frac{B\sigma_{gg}(WW)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \rightarrow WW)}{\Gamma(S \rightarrow ZZ)}$$

$$D_{\gamma/Z} \equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \rightarrow \gamma\gamma)}{\Gamma(S \rightarrow ZZ)},$$

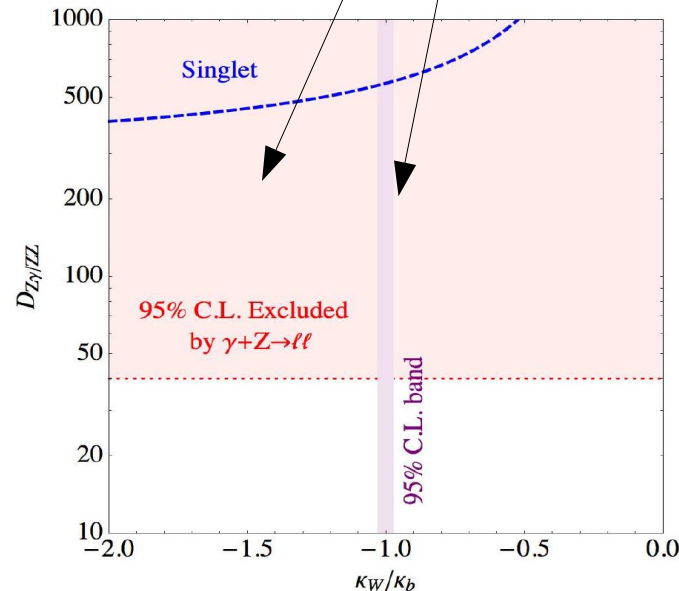
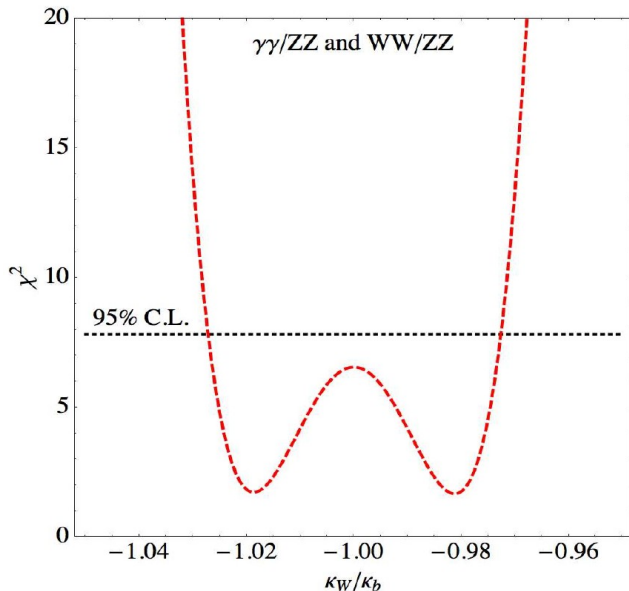
$$D_{Z\gamma/Z} \equiv \frac{B\sigma_{gg}(Z\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \rightarrow Z\gamma)}{\Gamma(S \rightarrow ZZ)}.$$

Predicted ratio

$$D_{Z\gamma/Z} \sim 500$$

95% CL excluded by $H \rightarrow Z\gamma$

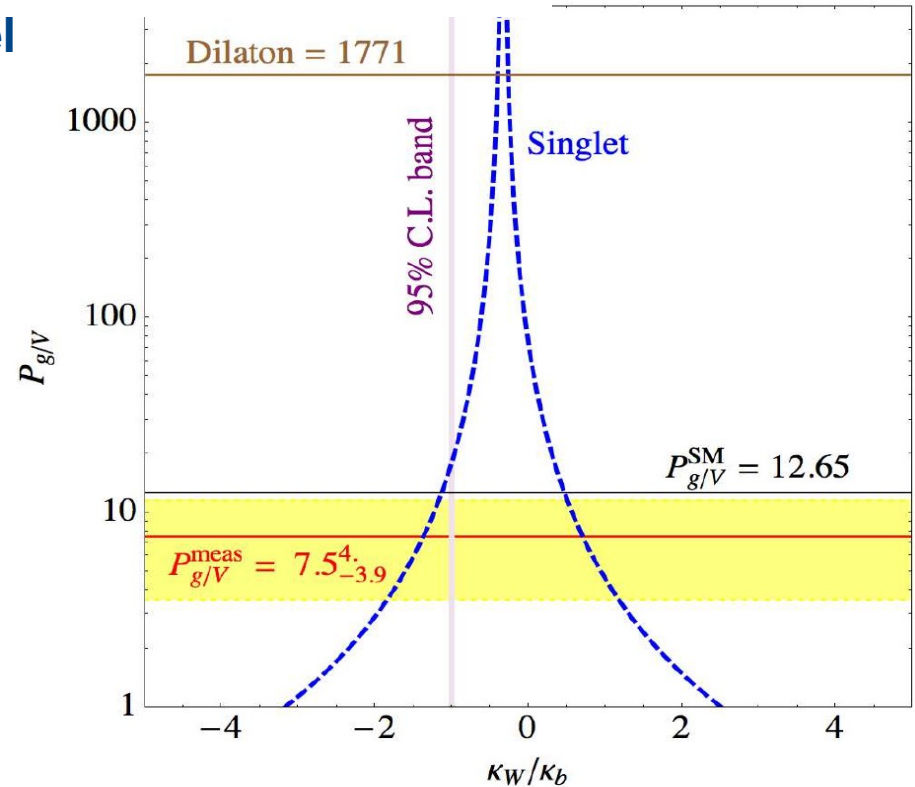
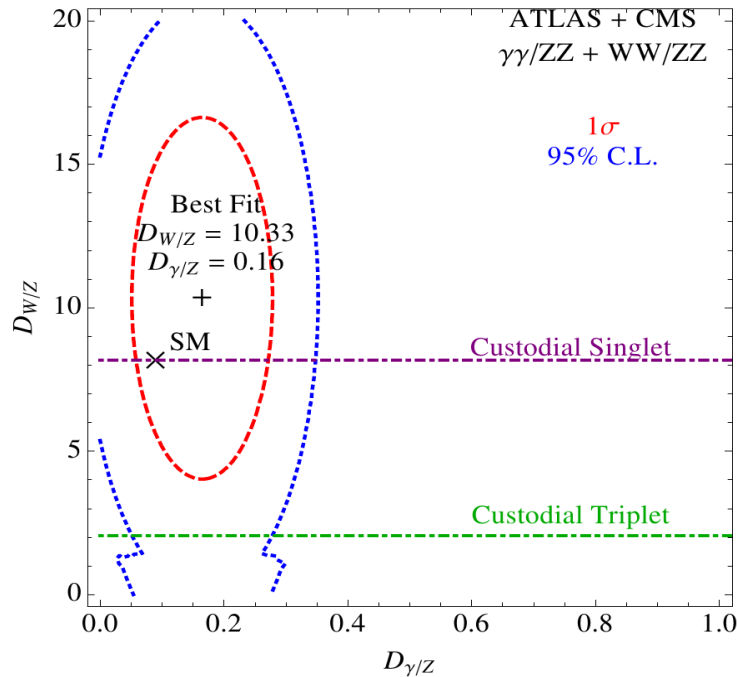
95%CL band comes from
best fit of χ^2



Predictions for **NOT EW-singlet** but a custodial singlet and 5-plet

$$D_{W/Z}^{(h)} = 8.16, \quad D_{W/Z}^{(h_5)} = \frac{1}{4} D_{W/Z}^{(h)} = 2.04$$

- custodial singlet consistent at 1σ level
- custodial triplet consistent at 2σ level



- **EW-singlet** like Dilaton (including RS radion) imposters are disfavored (observed $P_{g/V}$ is in agreement with SM)

$$P_{g/V} \equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{\text{VBF}}(\gamma\gamma)}$$

$$P_{g/V}^{(\text{D})} = 140 \times P_{g/V}^{(\text{SM})} \sim 1700$$

Conclusions

- A Higgs-like signal has been observed with 125 GeV mass
- Good consistency with SM Higgs → but fine-tuning problem is more pressing
- no signal of NP has been found at the LHC 8 TeV to account for a light Higgs
- MSSM is disfavored → new scenarios like NMSSM seems viable, but large λ couplings needed to ameliorate the SUSY little fine-tuning problem
- A composite PNGB Higgs has almost same coupling as SM, more statistics is needed to test this scenario (HL- LHC) or ILC
- Precise measurements of Higgs couplings to fermions are crucial for understanding the origin of flavor problem and fermion masses
- Fermiophobic naïve Higgs is ruled out for $m_H=125$ GeV
- sign of Yukawa of top can be disentangled at LHC via $pp \rightarrow H t q$ process → dramatic implications if a wrong sign or some anomaly would be confirmed
- EW singlet Higgs imposters are ruled out, including dilaton and RS radion. NOT-EW singlet Higgs imposters are still viable → more statistics required

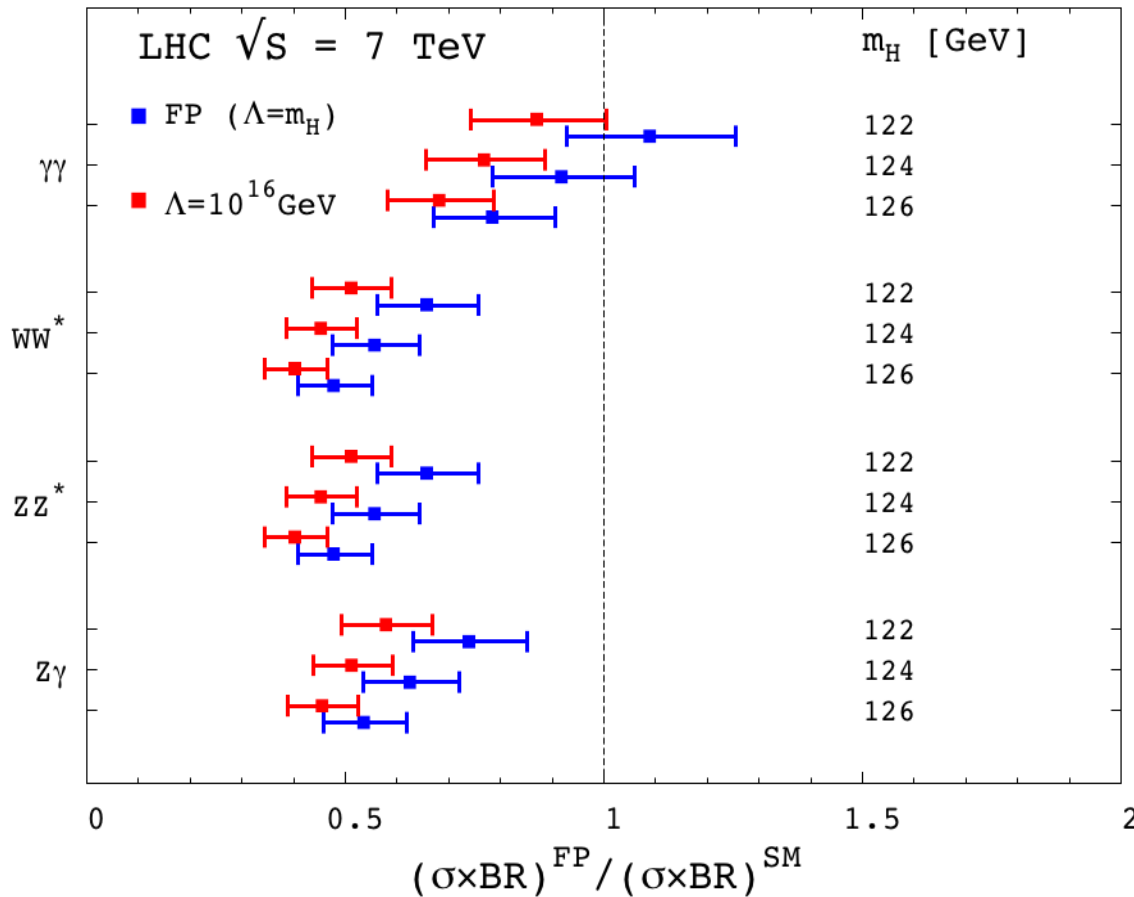
Congratulations again to

Francois Englert and Peter Higgs

**.....stay tuned for
new discoveries at
LHC !**

Backup slides

Inclusive production Signal strength for FP model



EG, B. Mele, M. Raidal PLB 716 (2012)

Naïve FP predicts $\mu = 1$ @ $M_H = 123$ GeV, while RC can reduce it

$\Lambda \rightarrow$ scale where Yukawa couplings are vanishing

+Hq signal ($H \rightarrow \gamma\gamma, WW, \tau\tau$) vs bckgr

- parton level study (MadGraph 5) BGMM
- includes mostly irreducible bckgr's
 - fair approx. for multi-photon / multi-lepton final states
- list of included signal final states :
 - 2 photons + jet (forward) + b-jet + jets
 - 2 photons + lepton + jet (forward) + b-jet + jet
 - 3 leptons + jet (forward) + b-jet
 - 2 Same-Sign leptons + jet (forward) + b-jet + jets
- always requires a forward light-jet and a b-jet tagging
- no requirement on E_T^{miss} from neutrinos
- studies (combined) $S/\sqrt{(S+B)}$ versus (C_V, C_+)
at $\sqrt{S} = 8 \text{ TeV}$ for 50 fb^{-1} (~ present ATLAS + CMS data set)