Higgs properties, CMS: mass, couplings, and spin

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Higgs questionnaire

Questions

- Statistical significant?
- Is it a boson?
- Mass?
- Spin?
- Parity?
- Is it "the" Higgs boson?
- Is it "a" Higgs boson?
- Is it "the" SM Higgs boson?

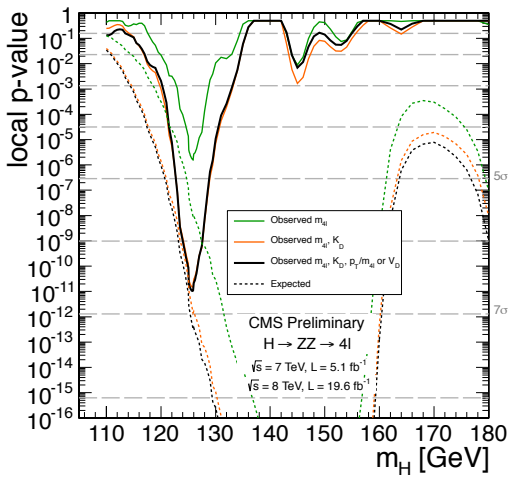
The channels

H decay	H prod	Exclusive Final States	No. of channel	m_H range [GeV]	m_H reso	Lumi (fb^{-1}) [7-8 TeV]
$H \to bb$	VH-tag	($\upsilon\upsilon$, ee, $\mu\mu$, eυ, with 2-bjets) $\otimes$ (low or high p_{TV} or low b-tag)	10 or 13	110-135	10%	5.0 -12.1
	ttH-tag	(l with 4,5,≥6 jets)$\otimes$(3,≥4 b-tags) (l with 6 jets with 2 b-tags) (ll with 2,≥3 b-tagged jets)	9	110-140	10%	5.0 - 5.1
$H \to \tau\tau$	1 jet	(eτ_h, $\mu\tau_h$, eμ, $\mu\mu$) $\otimes$ (low or high $p_{T\tau\tau}$) + $\tau_h\tau_h$	9	110-145	20%	4.9 - 19.4
	VBF-tag	(eτ_h, $\mu\tau_h$, eμ, $\mu\mu$, $\tau_h\tau_h$ with 2 jets)	5	110-145	20%	4.9 - 19.4
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, eτ_h, $\mu\tau_h$, eμ)	8	110-160	20%	4.9 - 19.4
	WH-tag	$\tau_h$ee,$\tau_h\mu\mu$,τ_heμ	3	110-140	20%	4.9 - 19.4
$H \to WW \to l\upsilon qq$	untagged	(eυ, $\mu\upsilon$)$\otimes$((jj)W with 0 or 1 jet)	4	170-600	20%	4.9 - 12.1
$H \to WW \to l\upsilon l\upsilon$	0/1 jet	(DF or SF dilep.)$\otimes$(0 or 1 jet) $l\upsilon l\upsilon$+(jj)	4	110-600	20%	4.9 - 19.5
$H \to WW \to l\upsilon l\upsilon$	VBF-tag	VBF(DF or SF dilep. 8TeV)	1 or 2	110-600	20%	4.9 - 12.1
$H \to WW \to l\upsilon l\upsilon$	WH-tag	3l3υ	1	110-200	20%	4.9 - 19.5
$H \to \gamma\gamma$	untagged	$\gamma\gamma$ (4 di-photon classes)	4	110-150	1-2%	5.1 - 19.6
	VBF-tag	$\gamma\gamma$+(jj)VBF(low/high m_{jj} for 8TeV)	1 or 2	110-150	1-2%	5.1 - 19.6
$H \to ZZ \to 4l$	$N_{jet} < 2$	4e, 4μ, 2e2μ $\otimes$ (low or high m_{4l})	6	110-1000	1-2%	5.1 - 19.6
	$N_{jet} > 2$	4e, 4μ, 2e2μ	3			
$H \to ZZ \to 2l2\tau$	inclusive	(ee, $\mu\mu$)$\otimes$($\tau_h\tau_h$, eτ_h, $\mu\tau_h$, eμ)	8	180-1000	10-15%	5.1 - 19.6

Statistical significance

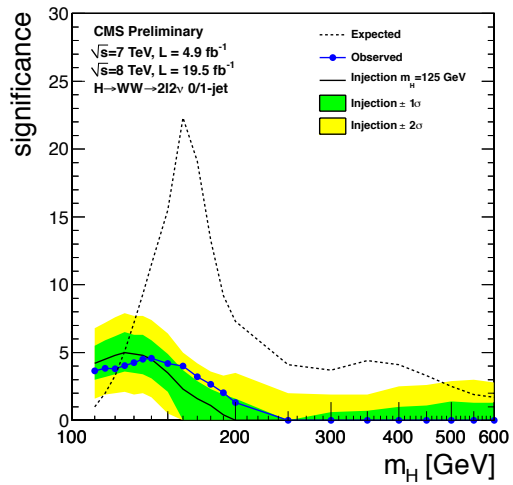
H→ZZ

m_H ~126 GeV
Expected 7.1σ
Observed 6.7σ



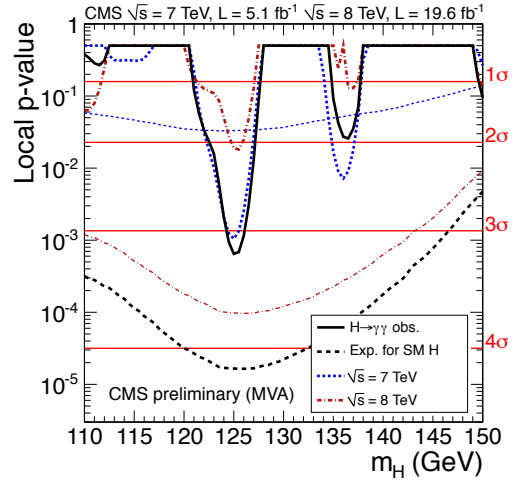
H→WW

m_H ~126 GeV
Expected 5.3σ
Observed 3.9σ



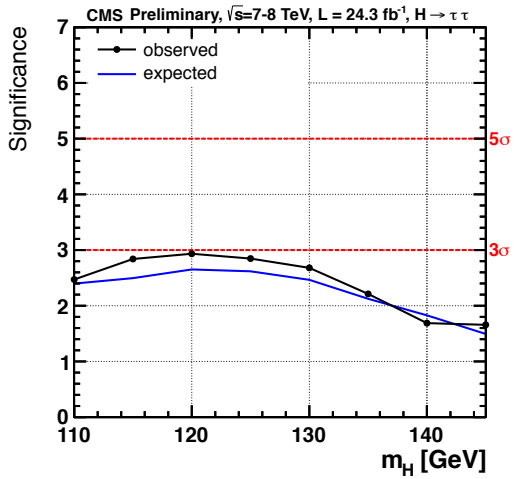
H→γγ

m_H ~126 GeV
Expected 3.9σ
Observed 3.2σ



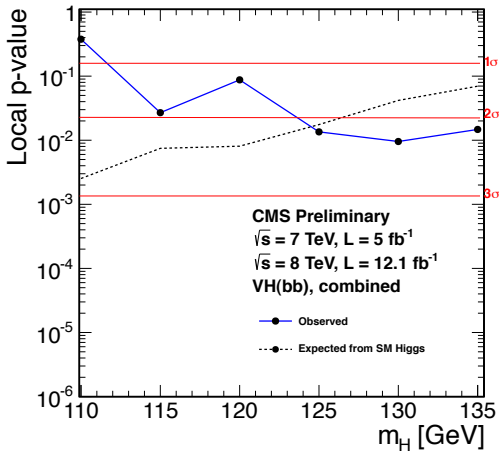
H→ττ

m_H ~126 GeV
Expected 2.6σ
Observed 2.8σ



H→bb

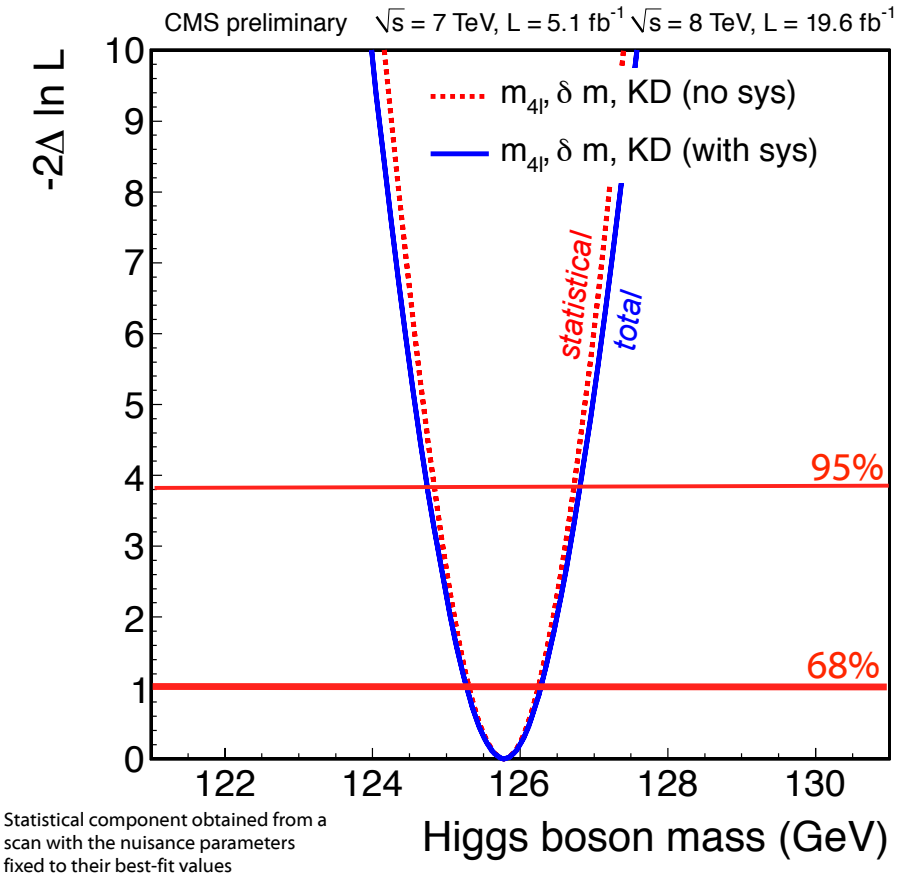
m_H ~126 GeV
Expected 2.2σ
Observed 2.0σ



Mass measurement: H→ZZ→4l

High resolution channel

Fit of the mass with freely floating signal strength modifier ($\mu=\sigma/\sigma_{SM}$)
(e.g. no assumption on individual $\sigma\cdot BR$) to minimize model dependence



Statistical component obtained from a scan with the nuisance parameters fixed to their best-fit values

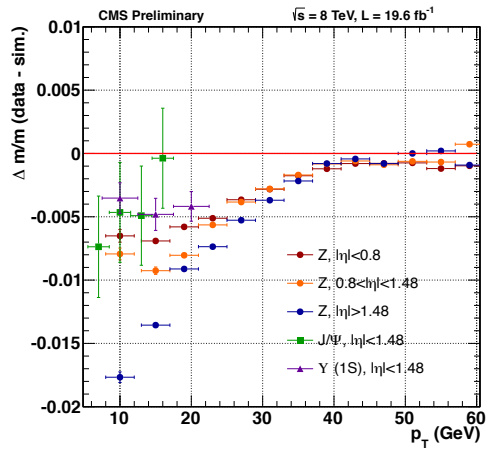
Systematics

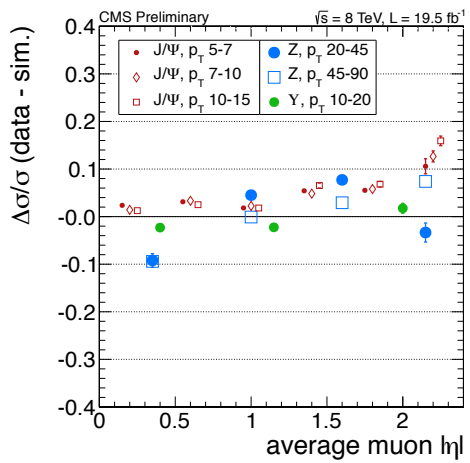
on scale

4e: 0.3%, 4μ: 0.1%, 2e2μ 0.1%(e)/0.05%(μ)

on resolution

4e/4μ/2e2μ: 20%



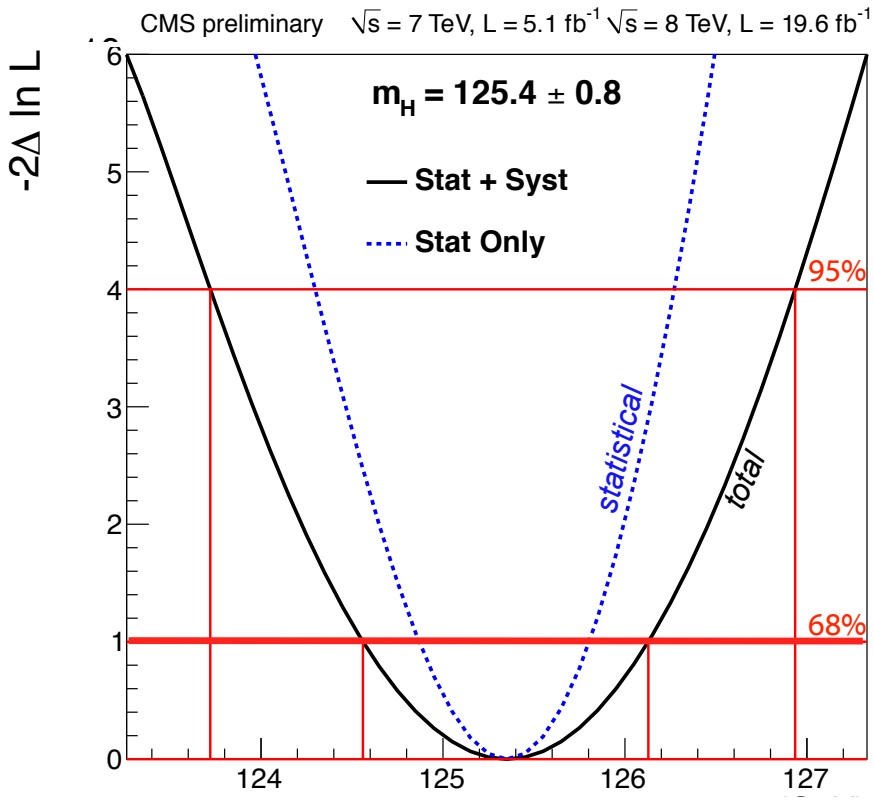


$m_H = 125.8 \pm 0.5$ (stat.) ± 0.2 (syst.) GeV

Mass measurement: H→γγ

High resolution channel

Fit of the mass with freely floating signal strength modifier ($\mu=\sigma/\sigma_{SM}$)
(e.g. no assumption on individual σ·BR) to minimize model dependence



Statistical component obtained from a scan with the nuisance parameters fixed to their best-fit values

Systematics

dominated by the overall γ energy scale

- **0.25% for the imperfect modeling by the MC of e/γ differences**
- **0.4% for possible non-linearity extrapolating from the Z-mass scale to the m_H~125 GeV**

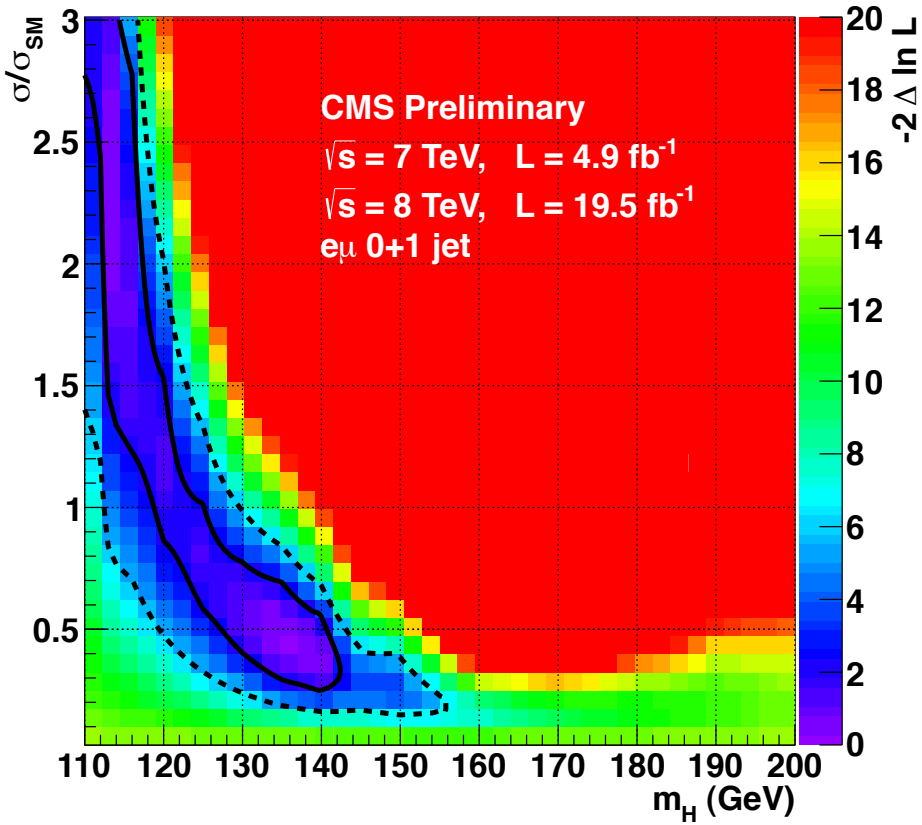
The 2 uncertainties are fully correlated between all event classes.
Summed in quadrature amount to 0.47%.

m_H = 125.4 ± 0.5 (stat.) ± 0.6 (syst.) GeV

Mass measurement: H→WW→lνlν / H→ττ

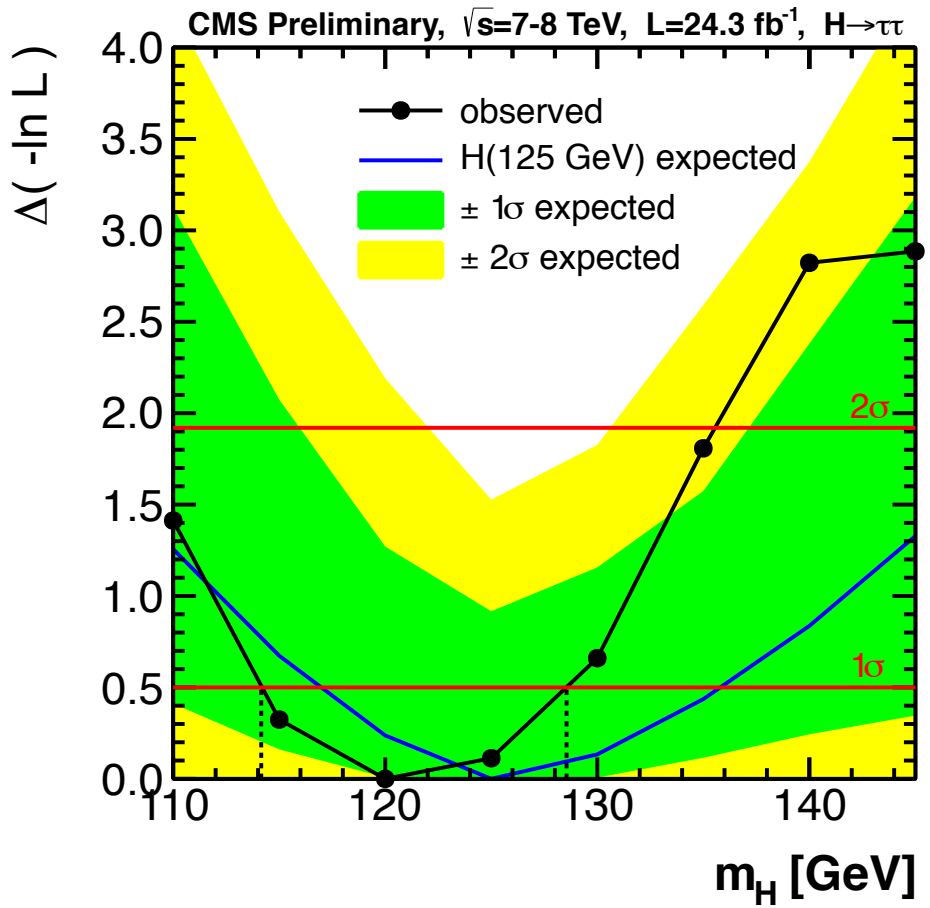
Low resolution channel

Likelihood scan for mass and signal strength modifier



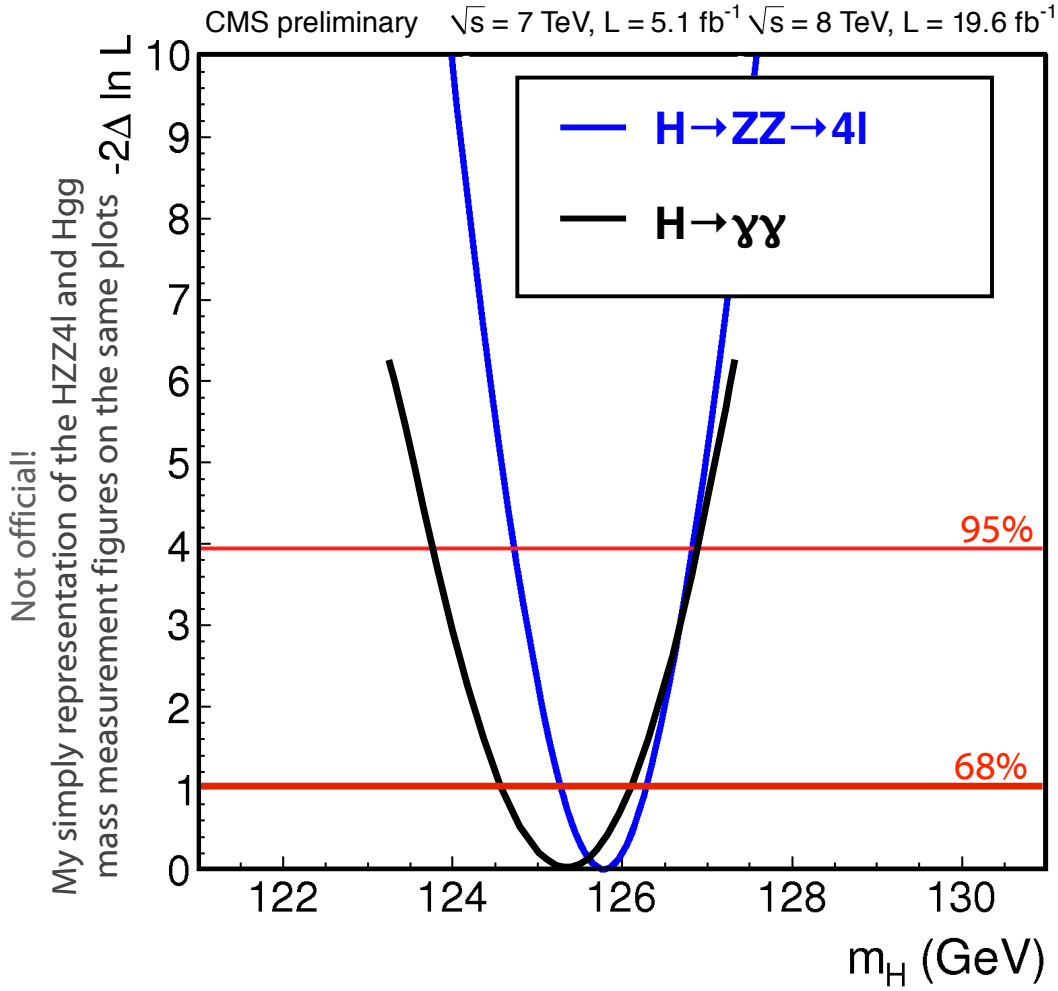
Wide spread of flat minimum compatible with the low resolution of the channel

Fit of the mass with freely floating signal strength modifier



$m_H = 120\,^{+9}_{-7}$ (stat.+syst.) GeV

Mass measurement: all in one



$m_{H(4l)} = 125.8 \pm 0.5^{(stat.)} \pm 0.2^{(syst.)}$ GeV

$m_{H(\gamma\gamma)} = 125.4 \pm 0.5^{(stat.)} \pm 0.6^{(syst.)}$ GeV

$\mathbf{m_{H(Comb.)} = 125.7 \pm 0.5}$ **GeV** (*)

(*) My simply computation (error it is an upper limit)

Reminder CMS published results:

HCP12 - Phys. Rev. Lett. 110 (2013) 081803

$m_{H(Comb.)} = 125.8 \pm 0.4^{(stat.)} \pm 0.4^{(syst.)}$ GeV

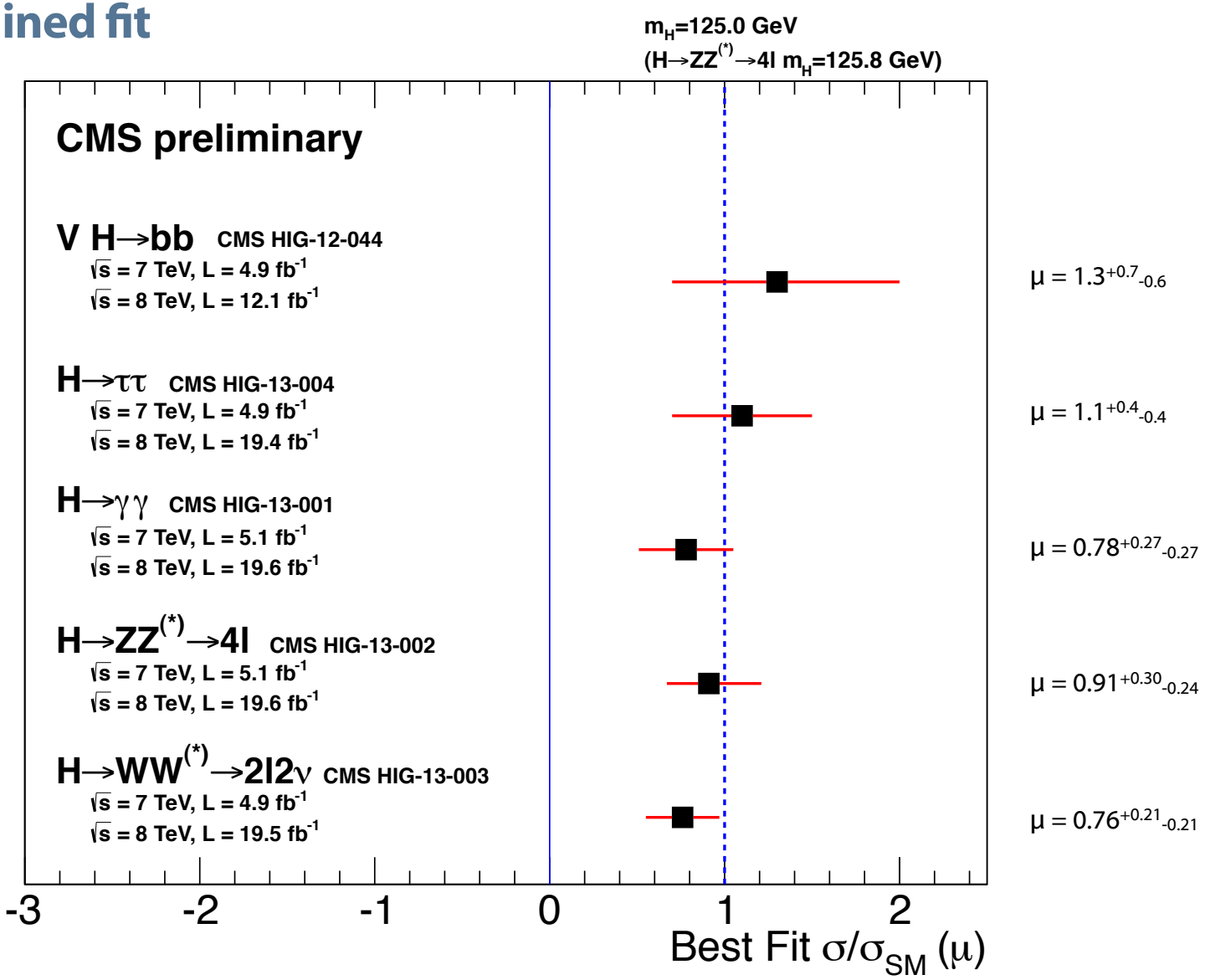
ICHEP12 - Physics Letters B 716 (2012) 30–61

$m_{H(Comb.)} = 125.3 \pm 0.4^{(stat.)} \pm 0.5^{(syst.)}$ GeV

Results are fully compatible within the uncertainties

Signal strength per channel

Unconstrained fit

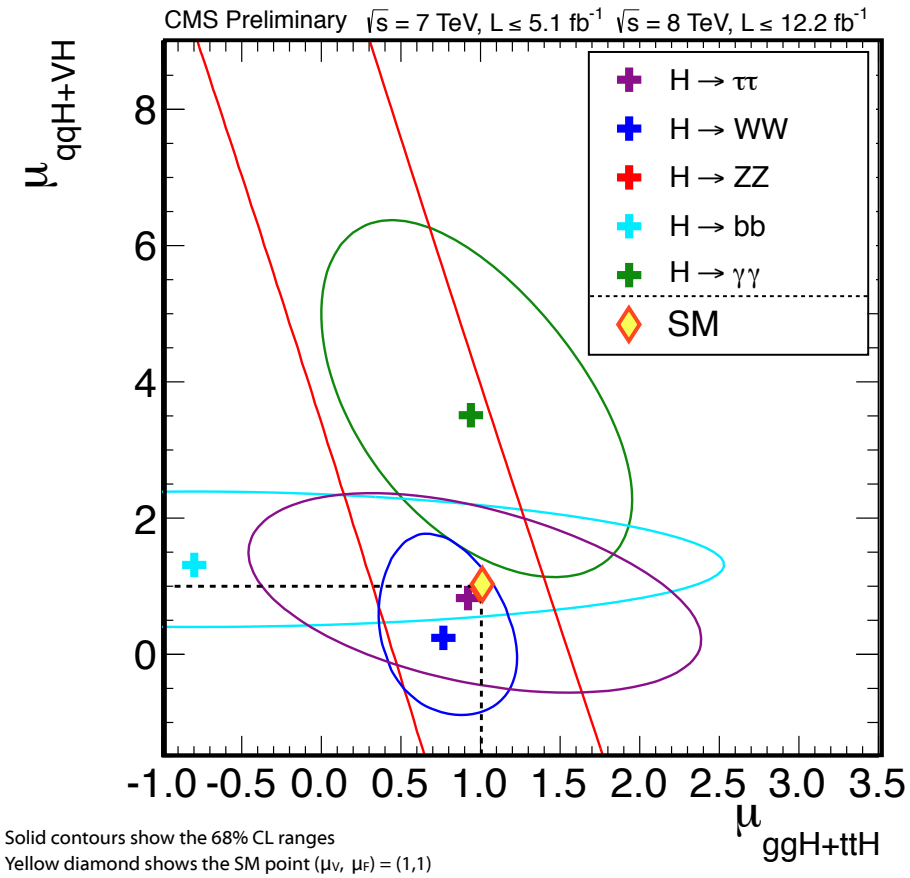


Constrained fit results within the physical region $\sigma \geq 0$ (using the Feldman-Cousin construction) give similar results and they can be interpreted as measurements of $\sigma \cdot BR$'s

Vector boson vs. Gluon fusion productions

Channels associated with a particular decay mode and explicitly targeting different production mechanisms are used to test the relative strengths of the couplings to the vector bosons [μ_{qqH+VH}] and top quarks [$\mu_{ggH+ttH}$]

HCP dataset

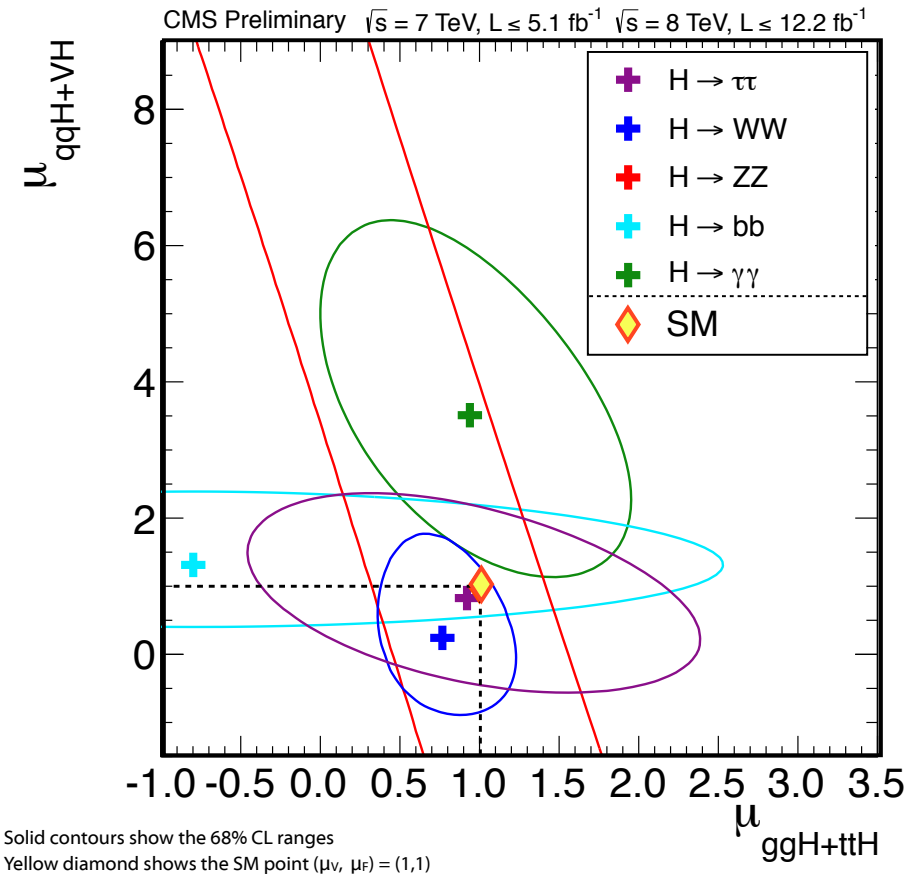


SM inside 2σ contours

Vector boson vs. Gluon fusion productions

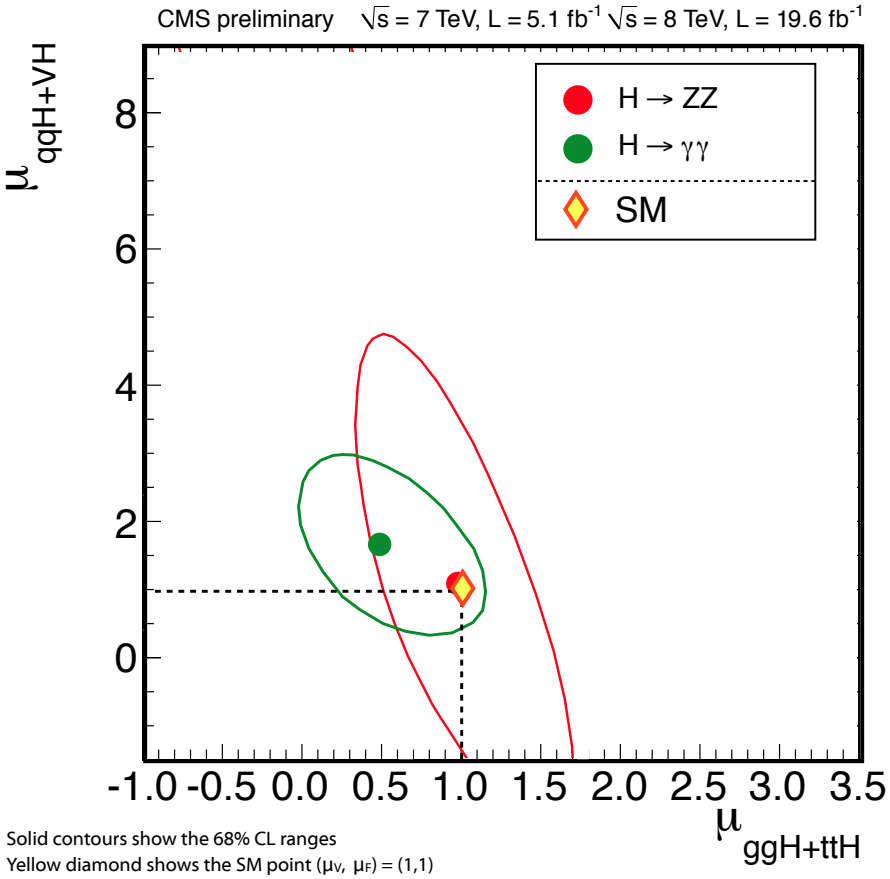
Channels associated with a particular decay mode and explicitly targeting different production mechanisms are used to test the relative strengths of the couplings to the vector bosons [μ_{qqH+VH}] and top quarks [$\mu_{ggH+ttH}$]

HCP dataset



SM inside 2σ contours

Updates with full dataset



The merged representation of the HZZ4l and Hgg μ_F -μ_V figures

Not official!

SM inside 1σ contours

Spin-Parity - H→ZZ→4l

Kinematics of the production and decay are sensitive to spin-parity

Combine mass and kinematics in a discriminant

$$D_{bkg} = \frac{P_{SM}(kin,m_{4l})}{P_{SM}(kin,m_{4l}) + P_{ZZ}(kin,m_{4l})}$$

Introduce a second discriminant to separate SM Higgs from J^P hypothesis

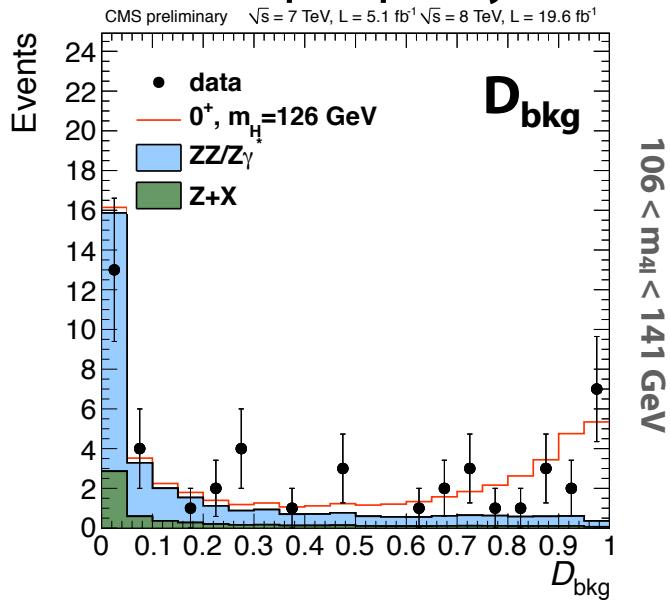
$$D_{JP} = \frac{P_{SM}(kin|m_{4l})}{P_{SM}(kin|m_{4l}) + P_{JP}(kin|m_{4l})}$$

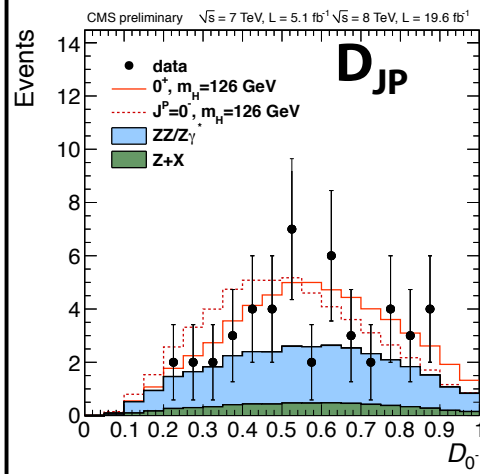
Do analysis in (D_{bkg}, D_{JP}) plane with 2D templates

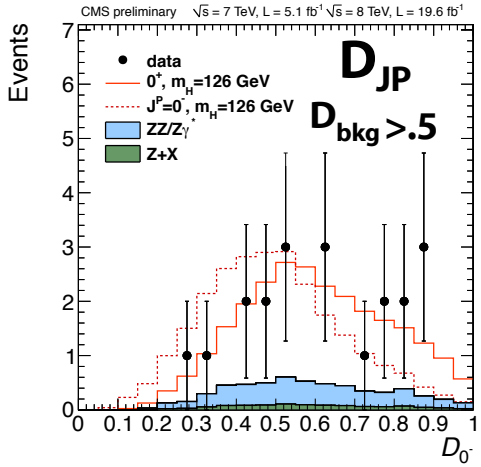
P_X is taken from **JHUGen**[1,2](signal) and **MCFM**[3](ZZ) LO ME Calculations (vector algebra)

cross-check with analytical[1,2,4] and Madgraph[5]

[1]arXiv:1208.4018, [2]arXiv:1001.3396, [3]arXiv:1105.0020, [4]arXiv:1211.1959, [5]arXiv:1210.0896





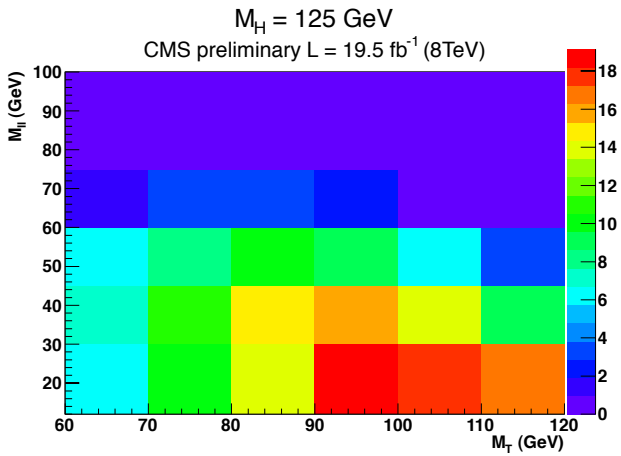


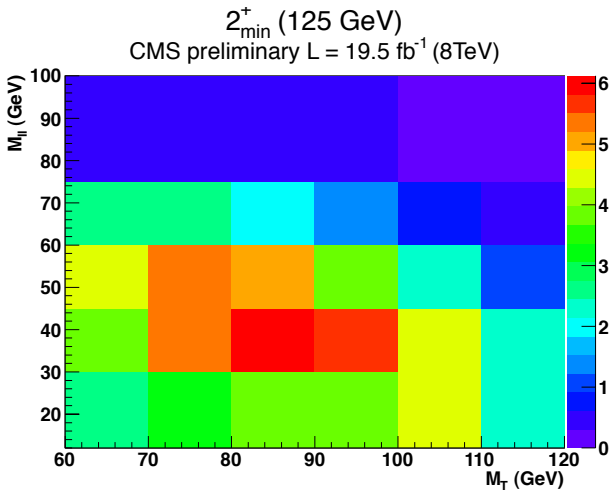
Using inclusive category to preserve model independence for the spin studies

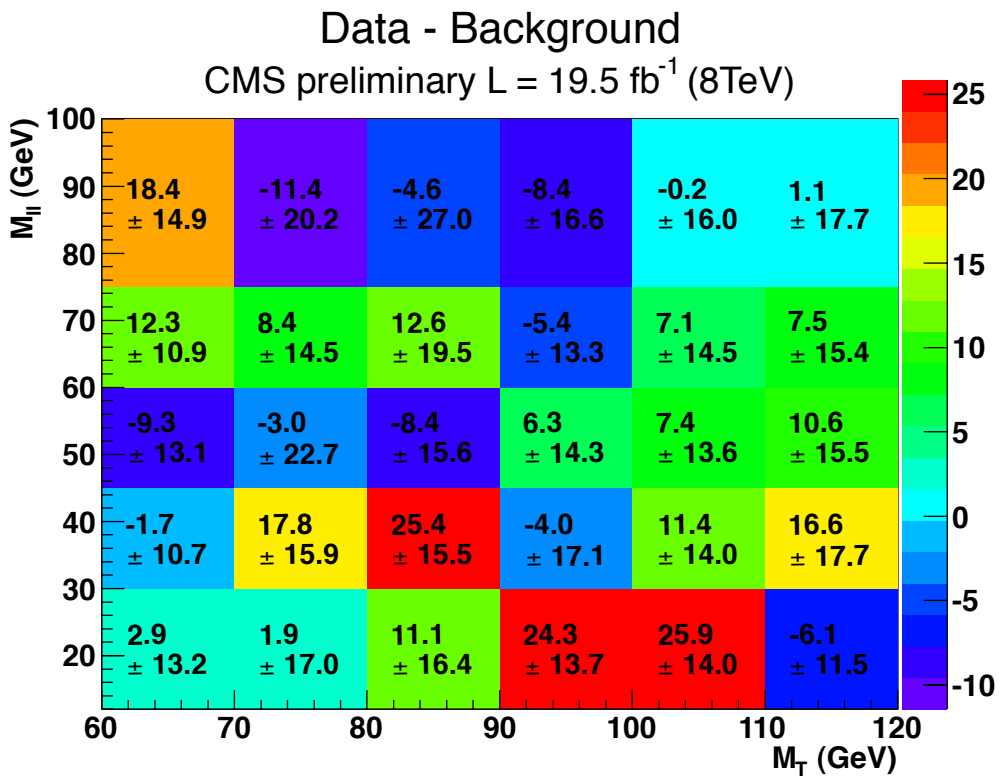
Spin-Parity - H→WW→lνlν

To distinguish between the SM Higgs and 2_m^+ hypothesis a signal plus background model in the m_{ll}-m_T plane is constructed

same background description and templates as the standard 2D analysis





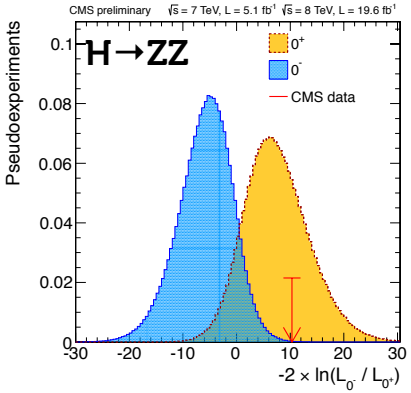


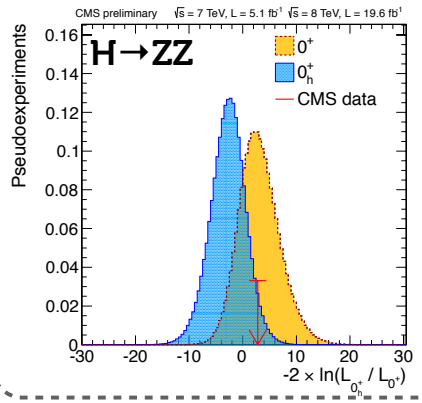
SM Higgs using POWHEG (same as the standard analysis)
2_m^+ using JHUGen

Spin-Parity - Test statistic distributions

0^-

pure pseudoscalar





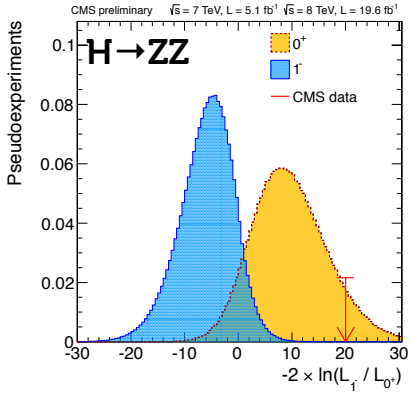
0^+_h

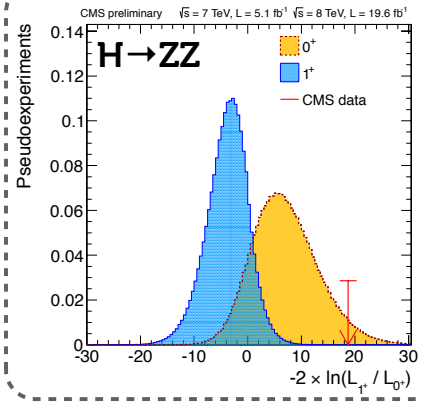
higher dim. operators

(in decay amplitude)

1^-

exotic vector



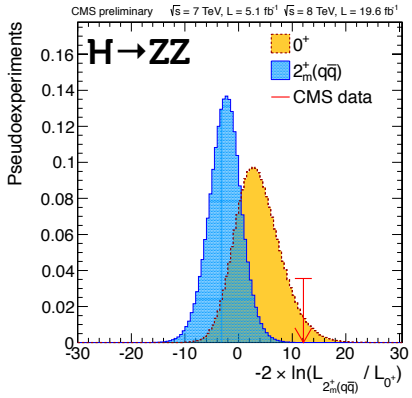


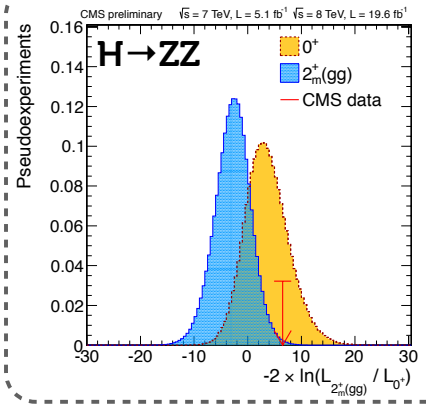
1^+

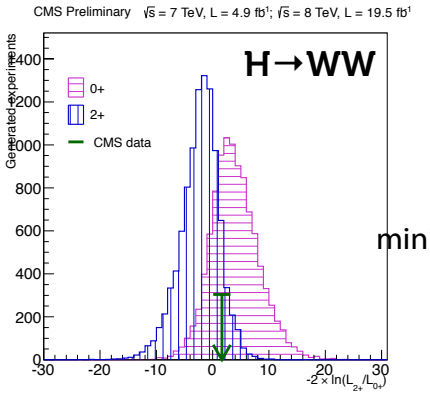
exotic axial-vector

2^+_{qq}

minimal couplings



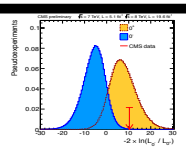
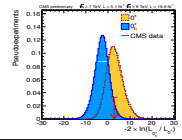
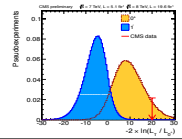
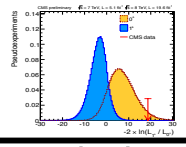
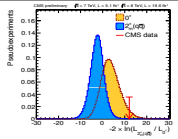
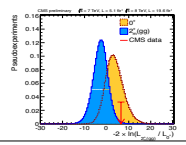
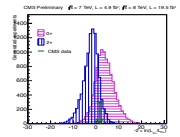




2^+_{gg}

minimal couplings

Spin-Parity - Results

J^P	Model (production)	Channel	Exp.(*) $\mu = 1$/$\mu = \mu_{obs}$	Obs. 0^+ $\mu = \mu_{obs}$	Obs. J^P $\mu = \mu_{obs}$	CL_s $\mu = \mu_{obs}$	Distr.
0^-	Pure Pseudoscalar (gg →X)	H→ZZ→4l	2.8σ / 2.6σ	0.5σ	3.3σ	0.16%	
0^+_h	Higher dim. operators (gg →X)	H→ZZ→4l	1.8σ / 1.7σ	0.0σ	1.7σ	8.1%	
1^-	Exotic vector (qq →X)	H→ZZ→4l	3.1σ / 2.8σ	1.4σ	>4.0σ	<0.1%	
1^+	Exotic axial-vector (qq →X)	H→ZZ→4l	2.6σ / 2.3σ	1.7σ	>4.0σ	<0.1%	
2^+_{qq}	Minimal couplings (qq →X)	H→ZZ→4l	1.9σ / 1.7σ	1.8σ	4.0σ	<0.1%	
2^+_{gg}	Minimal couplings (gg →X)	H→ZZ→4l	1.9σ / 1.8σ	0.8σ	2.7σ	1.5%	
		H→WW→lυlυ	2.4σ / 1.8σ	0.5σ	1.3σ	14%	

(*)The expected separation is quoted for two scenarios, when events are generated with SM expectation for the signal yield (μ=1) when the signal strength for each hypothesis is pre-determined from the fit to data (μ_{obs} : μ_{obs}^{ZZ} = 0.91 / μ_{obs}^{WW} = 0.76)

Mixed Parity - H→ZZ→4l

Fraction of a CP-violating contribution to the decay amplitude

General decay amplitude for a spin-zero boson

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right)$$
$$= A_1 + A_2 + A_3$$

We define and measure the parameter $f_{a3} = |A_3|^2/(|A_1|^2 + |A_3|^2)$

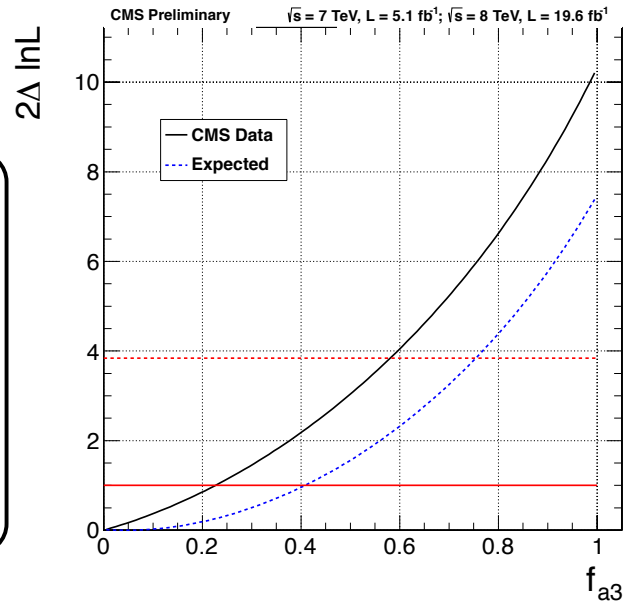
which does not define the mixture of parity-even and parity-odd states but allows to provide consistency test of the $f_{a3} = 0$ and $f_{a3} = 1$ scenarios

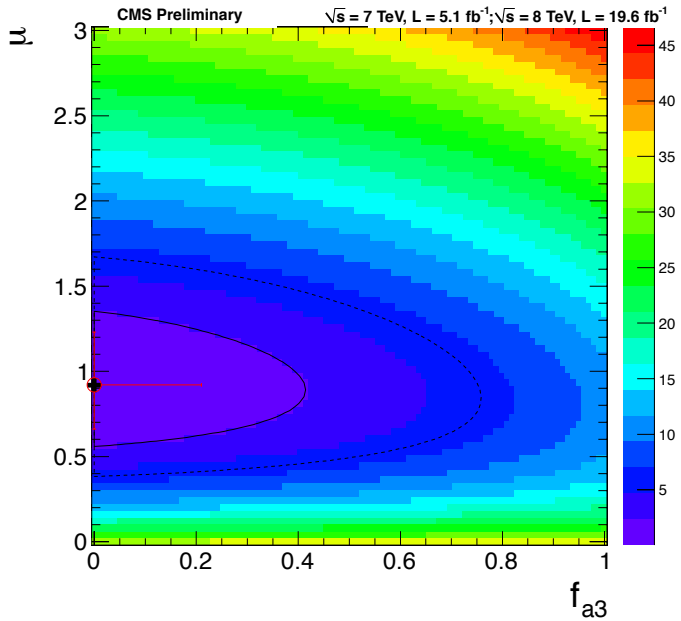
From data

$f_{a3} = 0.00^{+0.23}$

($f_{a3} < 0.58$ at 95% C.L.)

Interval checked with Feldman-Cousins and found to agree





Couplings

Assumptions

Follow the LHCWG prescriptions **arXiv:1209.0040**

- **the signals observed in the different channels originate from a single narrow resonance**
- **zero-width approximation for the state**
- **the tensor structure of the couplings is assumed to be the same as in the SM prediction (pure CP-even state)**

$$(\sigma \times BR)(ii \rightarrow H \rightarrow ff) = \sigma_{SM}(ii \rightarrow H) \times BR_{SM}(H \rightarrow ff) \times \frac{k_i^2 k_f^2}{k_H^2}$$

tested scaling factors

scaling coupling through loop defined either:

as function of scale factors for the fields in the loop (resolved at NLO accuracy)

as additional free parameter

Compatibility of the data with the SM Higgs boson couplings tested in

Fermion and vector boson couplings(*)
Custodial Symmetry(*)
Asymmetries in couplings to fermions
Search for BSM Physics in Loops and Decays

LHCWG benchmark parameterizations
simplifying assumptions to reduce free parameters

C6 model with six independent couplings

More general parameterization
better interpretation in a realistic model

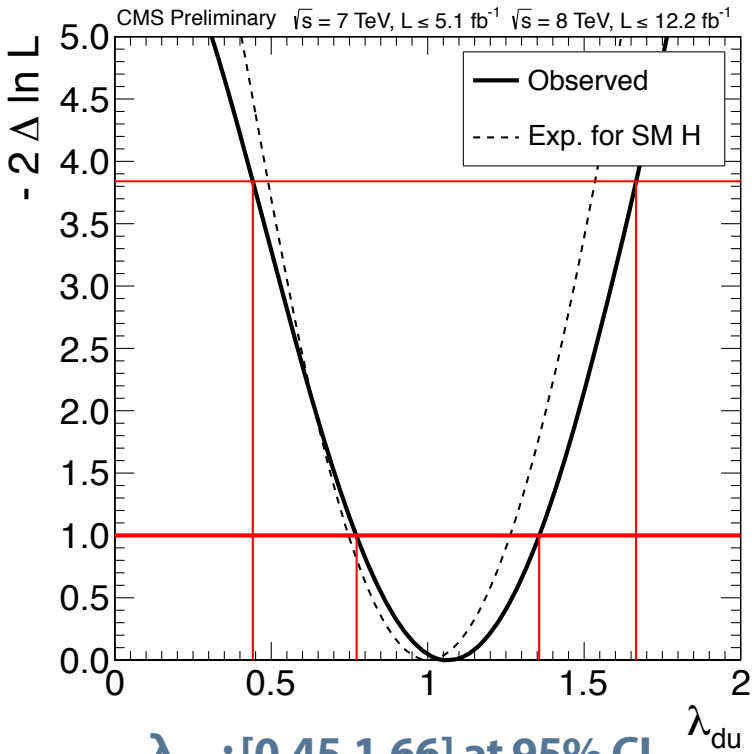
(*) in backup

Asymmetries in couplings to fermions

In 2HDM models (Type I / Type II) the couplings of the neutral Higgs bosons to fermions can be modified wrt the Yukawa couplings

Up-type vs down-type fermions

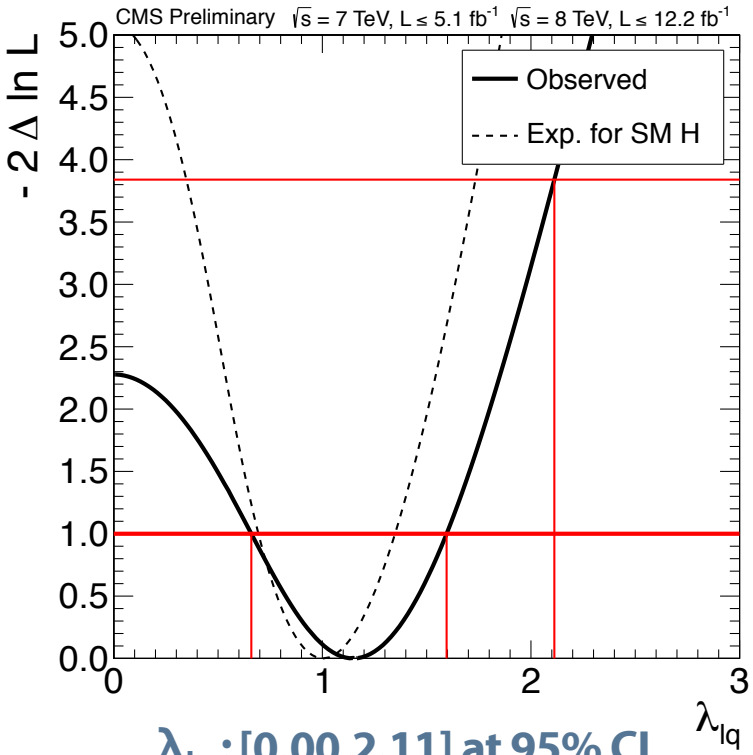
Assuming no invisible or undetectable widths
Free parameters κ_V, κ_u, and $\lambda_{du}=\kappa_d/\kappa_u$



λ_{du} : [0.45,1.66] at 95% CL
[0.78,1.35] at 68% CL

Quarks vs Leptons

Assuming no invisible or undetectable widths
Free parameters κ_V, κ_q, and $\lambda_{lq}=\kappa_l/\kappa_q$



λ_{lq} : [0.00,2.11] at 95% CL
[0.66,1.60] at 68% CL

Room to improve with the new combination using τ and b measurements

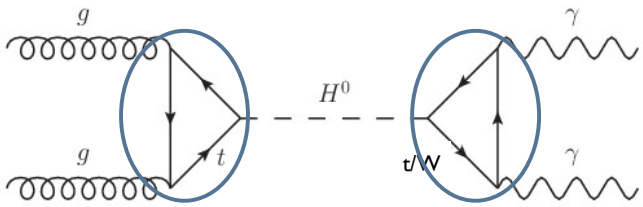
Search for BSM physics in loops and decays

Loops

Assuming no invisible or undetectable widths

Free parameters k_γ and k_g

the scaling factor mainly affected by the presence of BSM particles

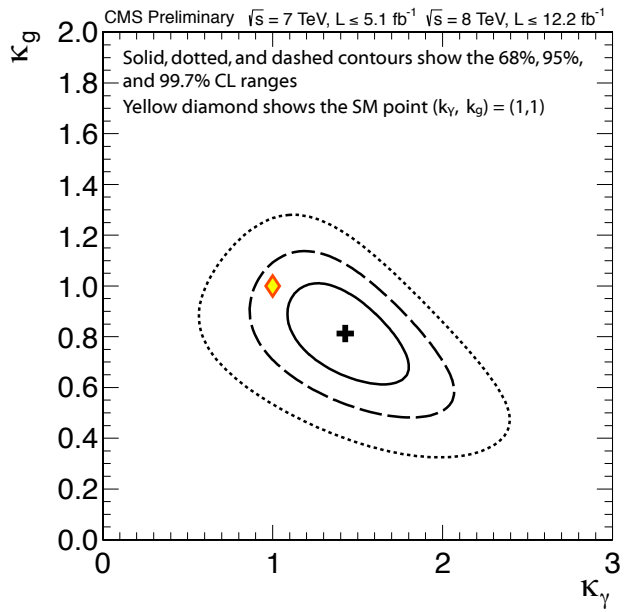


Stop Stop/Chargino

k_γ = [0.98,1.92] at 95% CL

k_g = [0.55,1.07] at 95% CL

obtained form a 1D-scan



Decays

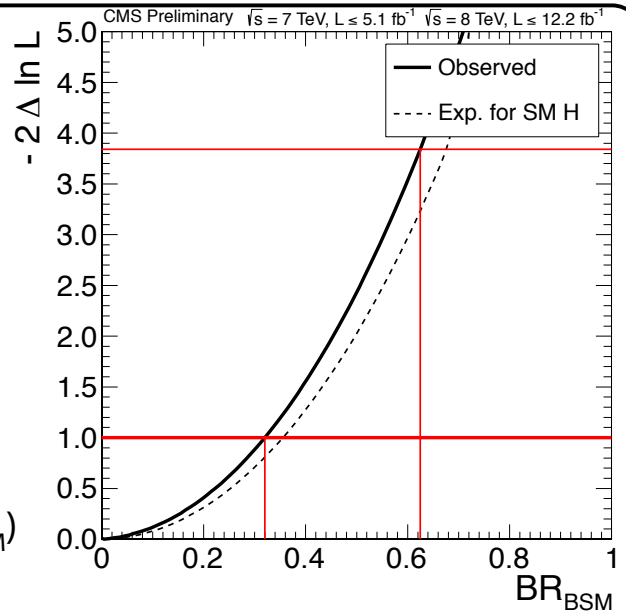
Allowing for invisible or undetectable widths

Free parameters k_γ, k_g, and BR_{BSM}

BR_{BSM} = [0.00,0.62] at 95% CL

[0.00,0.32] at 68% CL

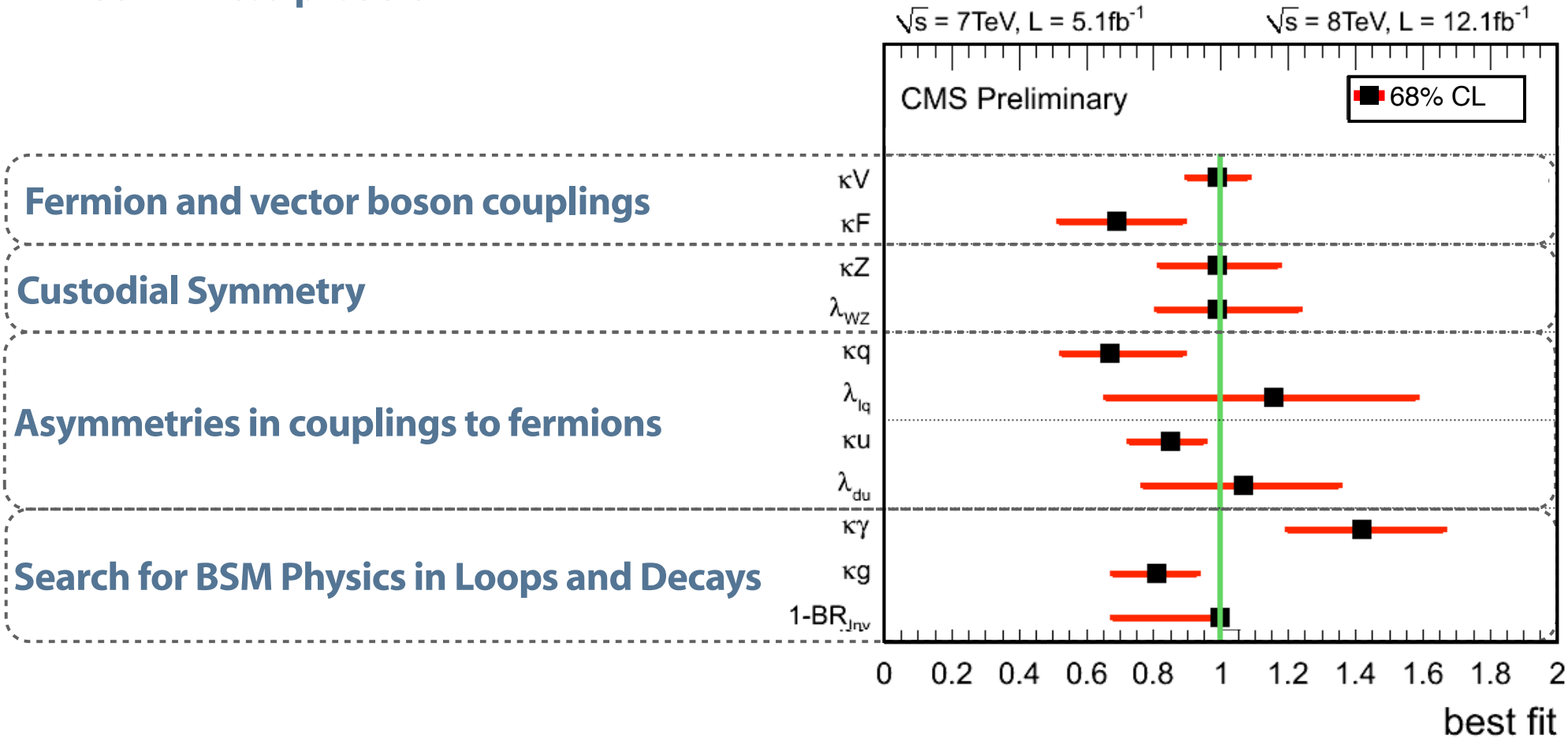
Allow total width to scale as $1/(1-BR_{BSM})$



Benchmark parameterizations: summary

No significant deviations are found

- **Overall good compatibility with SM predictions**
- **Still limited precision**



C6 model: six independent couplings

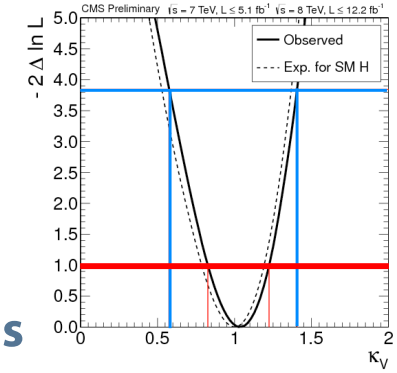
Assess individual couplings assuming:

- custodial symmetry
- couplings to the 3rd generation scaled independently
- couplings to the 1st and 2nd generations equal to those for the 3rd
- without resolving the loops structure
- partial width Γ_{BSM} is zero

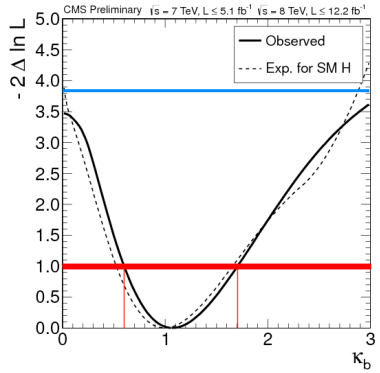
Model with six independent parameters:

κ_V κ_b κ_τ κ_t κ_g κ_γ

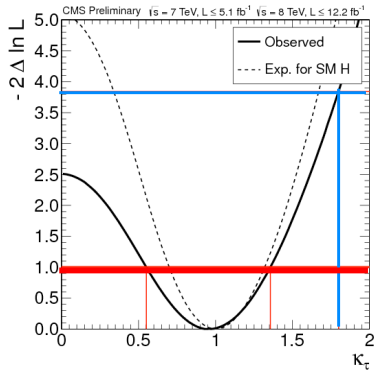
fit each one of these while profiling the others



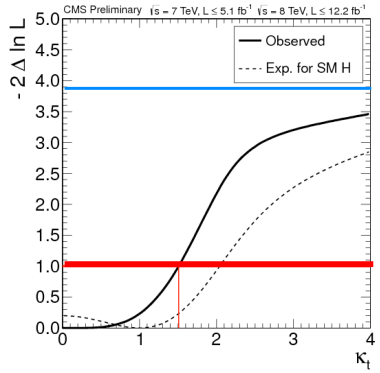
κ_V



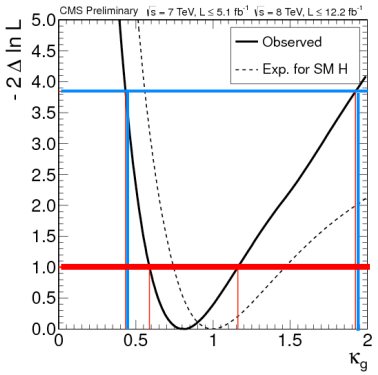
κ_b



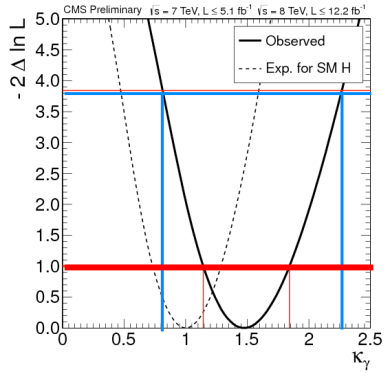
κ_τ



κ_t



κ_g



κ_γ

C6 model: six independent couplings

Assess individual couplings assuming:

- custodial symmetry
- couplings to the 3rd generation scaled independently
- couplings to the 1st and 2nd generations equal to those for the 3rd
- without resolving the loops structure
- partial width Γ_{BSM} is zero

Model with six independent parameters:

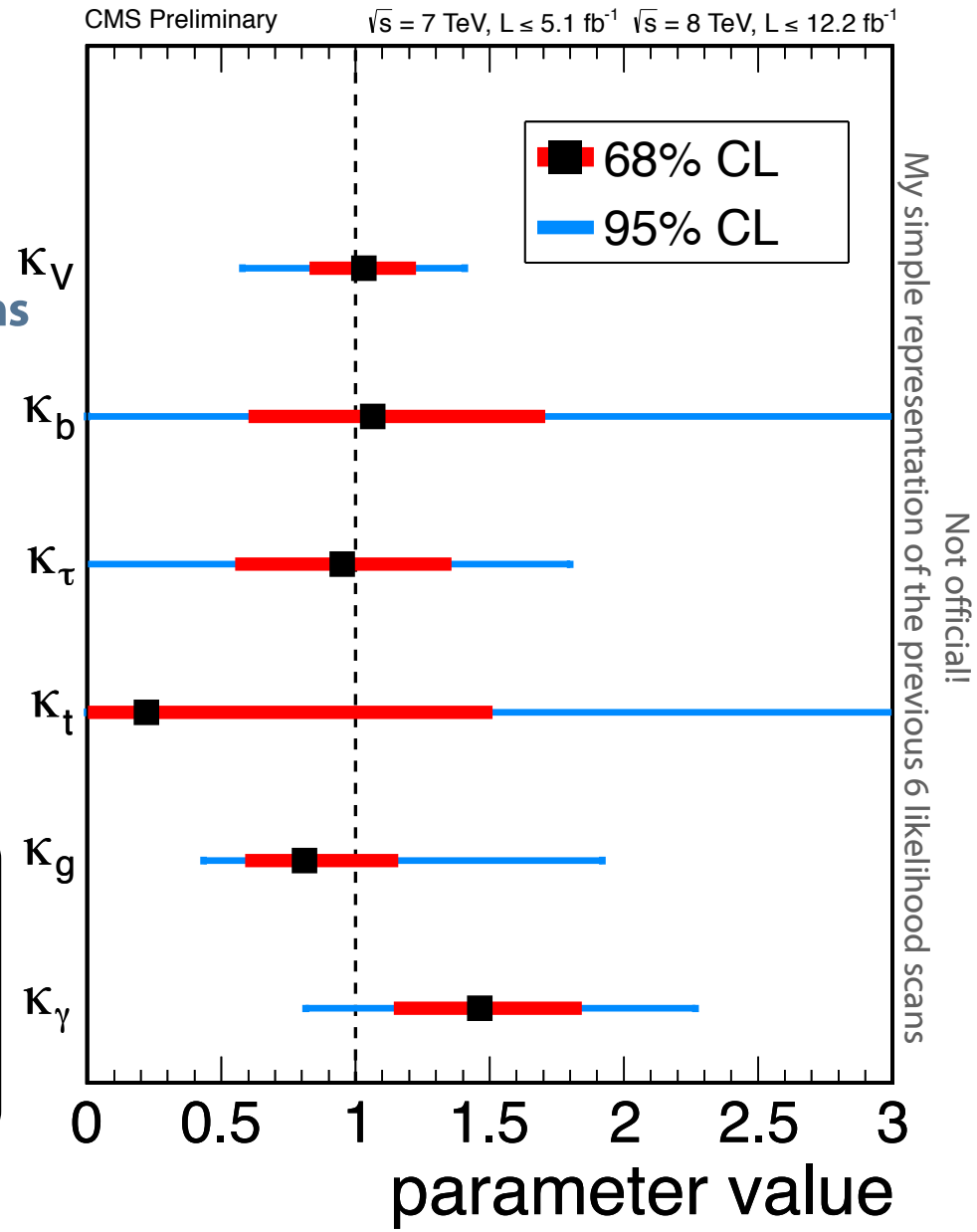
$\kappa_V \quad \kappa_b \quad \kappa_\tau \quad \kappa_t \quad \kappa_g \quad \kappa_\gamma$

fit each one of these while profiling the others

Goodness-of-fit between the parameters measured and the SM prediction

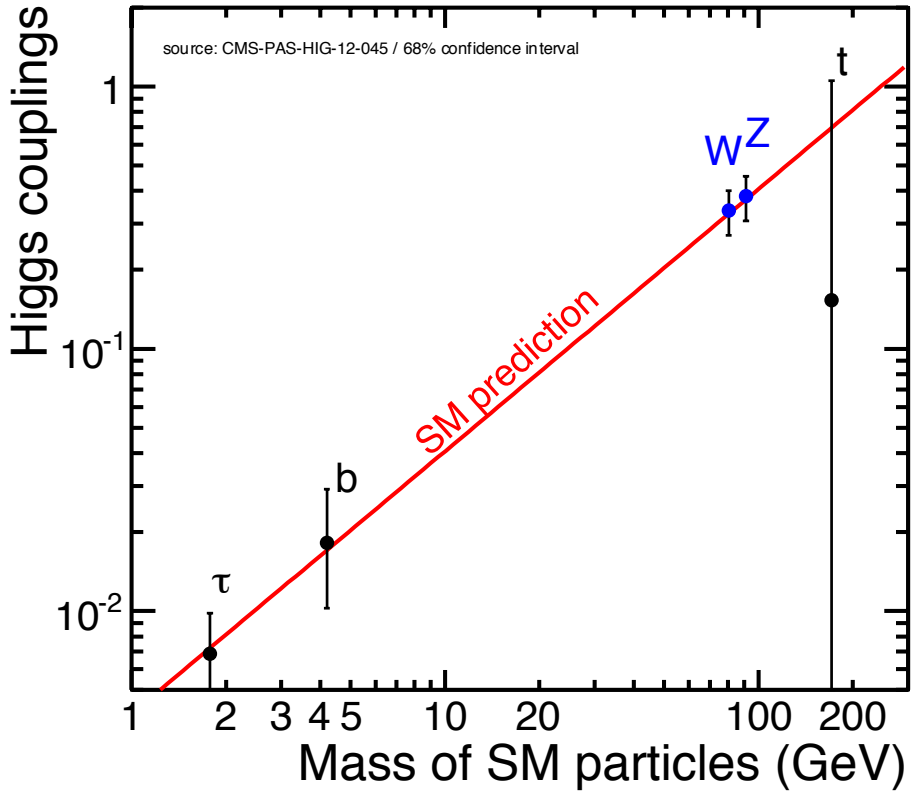
X^2/n.d.f. = 4.7/5

p-value = 0.58

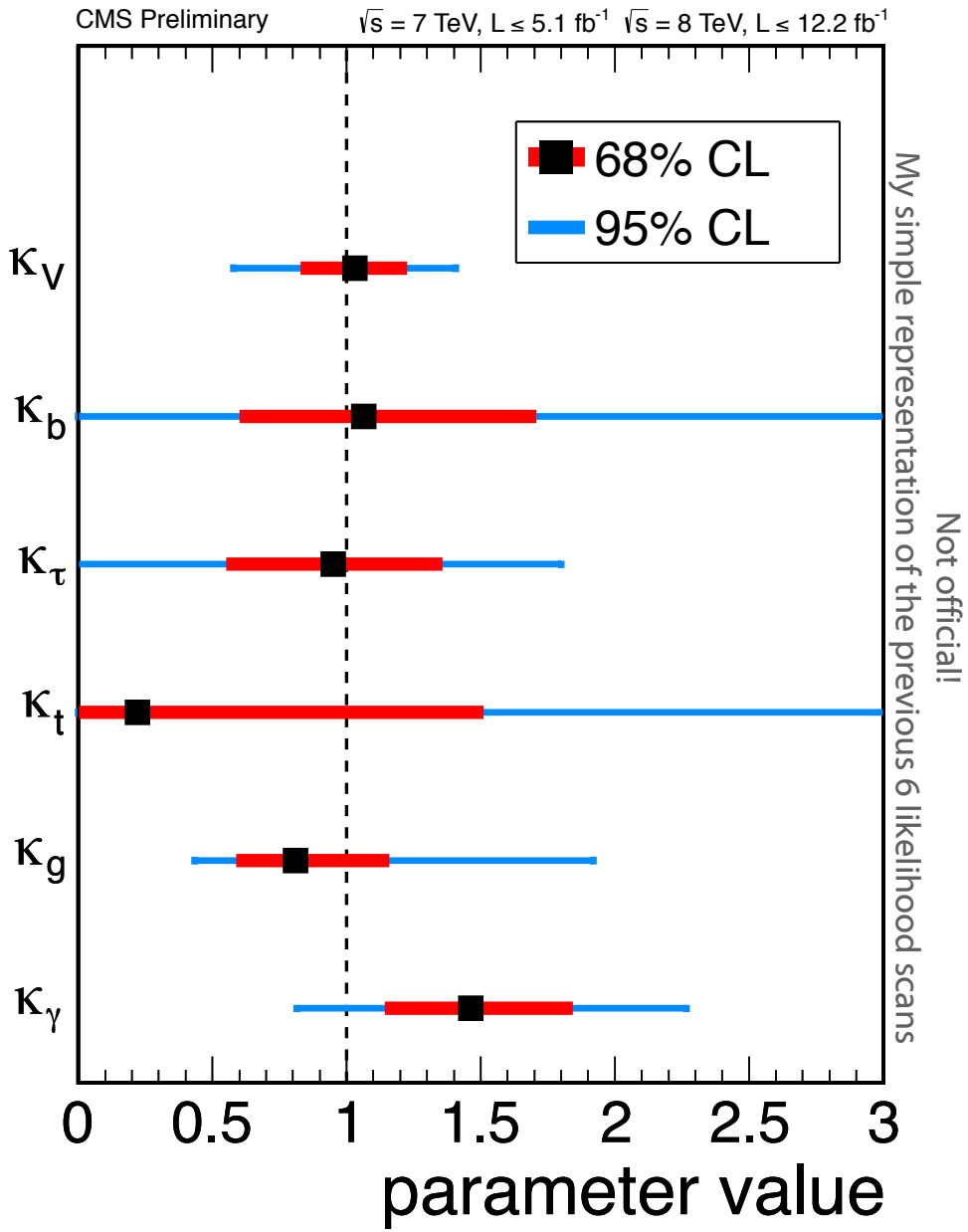


C6 model: six independent couplings

Higgs couplings vs Mass of the SM particles



Not official, a representation of fermions/bosons scaling factors



My simple representation of the previous 6 likelihood scans

Not official!

Thank you for you attention!!!

Higgs questionnaire

Questions	How	Answers
- Statistical significant?	Estimate p-values	Yes!
- Is it a boson?	It decays in $\gamma\gamma$	Yes!
- Mass?	Using $\gamma\gamma$ and 4l channels	~125.7 GeV
- Spin?	Using kinematics of decay products	0
- Parity?	Using kinematics of decay products	+
- Is it "the" Higgs boson?	Measure BR and couplings	Yes!
- Is it "a" Higgs boson?	Measure couplings, looking at different mass regions, VV scattering, and self coupling	Improving
- Is it "the" SM Higgs boson?		

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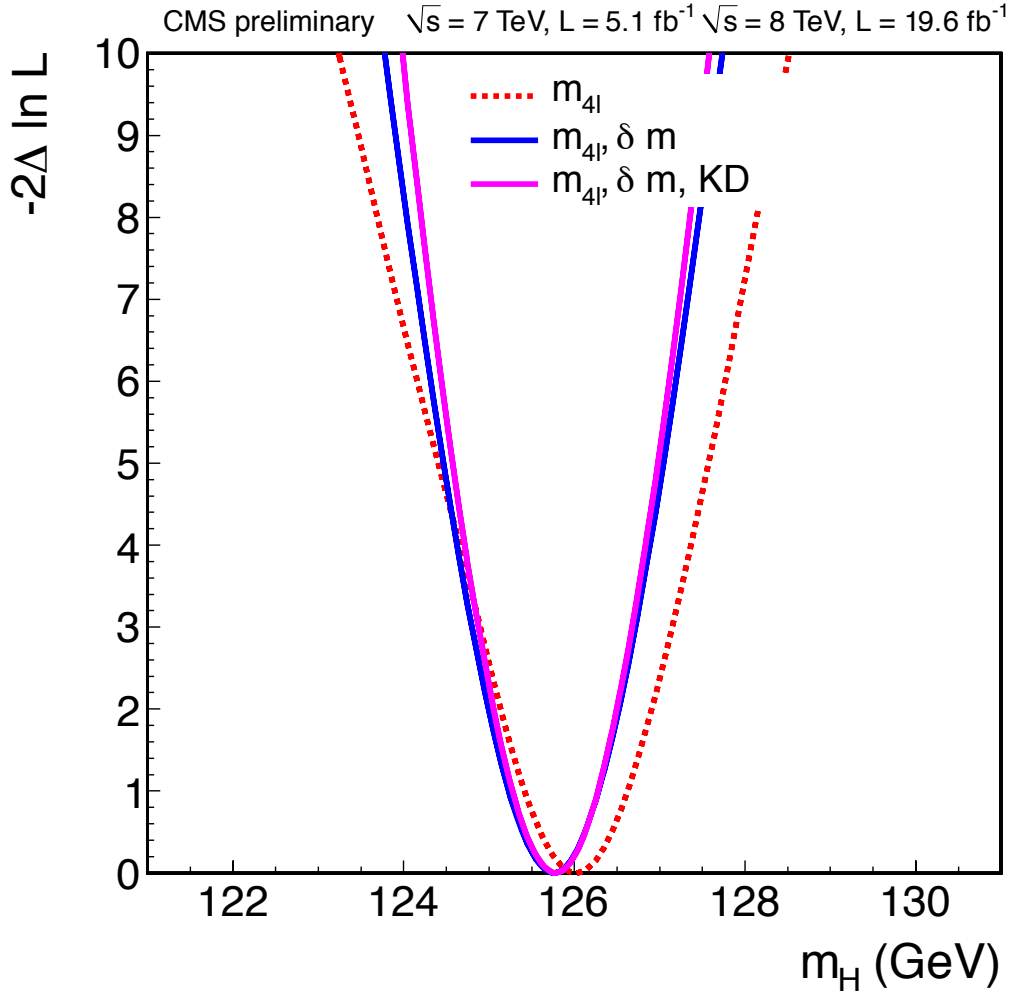
Backup

Mass measurement: H→ZZ→4l - 3 models

	Model	Mass
3D	$m_{4l}, \delta m_{4l}, K_D$	$125.80^{+0.50}_{-0.50}$
2D	$m_{4l}, \delta m_{4l}$	$125.76^{+0.52}_{-0.53}$
1D	m_{4l}	$126.02^{+0.60}_{-0.60}$



Fermions and vector bosons couplings

Assuming no invisible or undetectable widths

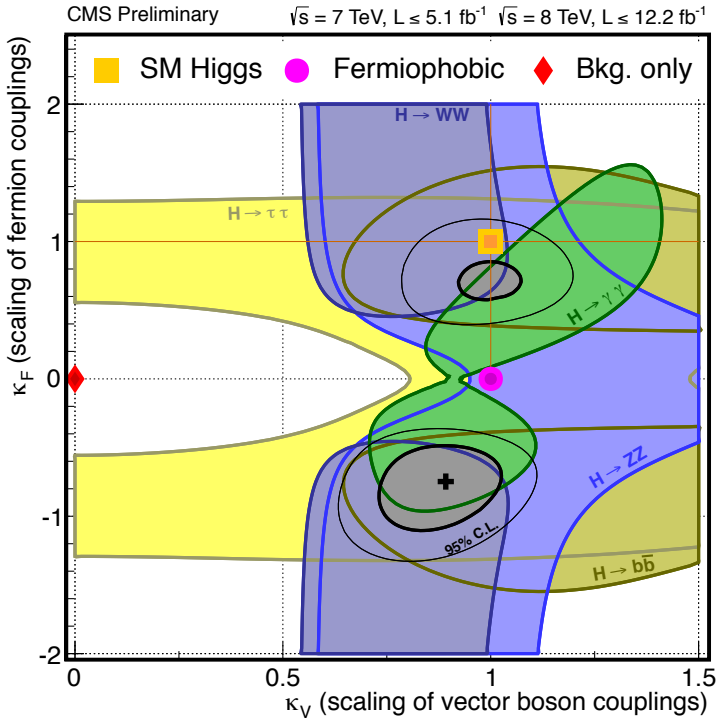
Free parameters k_V ($= k_W = k_Z$) and k_F ($= k_t = k_b = k_\tau$)

At LO $\Gamma_{\gamma\gamma}$ the partial width $|\alpha k_V + \beta k_F|^2$

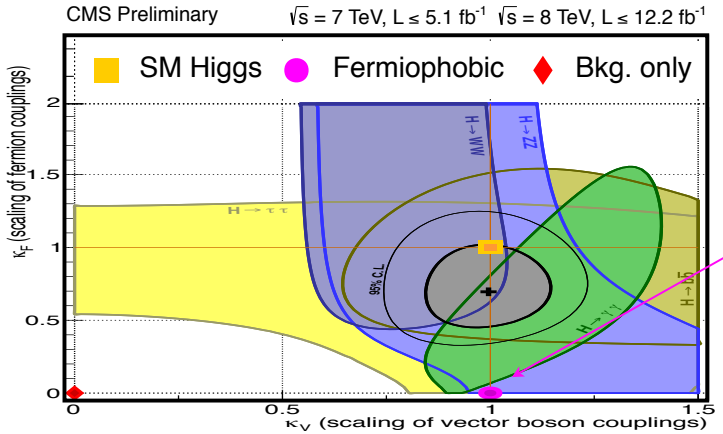
α and β are taken from predictions for the SM Higgs @ 125.8 GeV ($\alpha/\beta \sim -0.22$)

$\gamma\gamma$ only channel sensitive to the relative sign of k_f and k_v

All quadrants



SM quadrant only



Fermiophobic scenario exclude at >4σ level

Interplay of different decay modes

H→bb	H→ττ
H→ZZ	H→γγ
H→WW	**Combined**

The 95% CL intervals for k_V and k_F, obtained form a 1D-scan, are:

k_V = [0.78,1.19] k_F = [0.40,1.12]

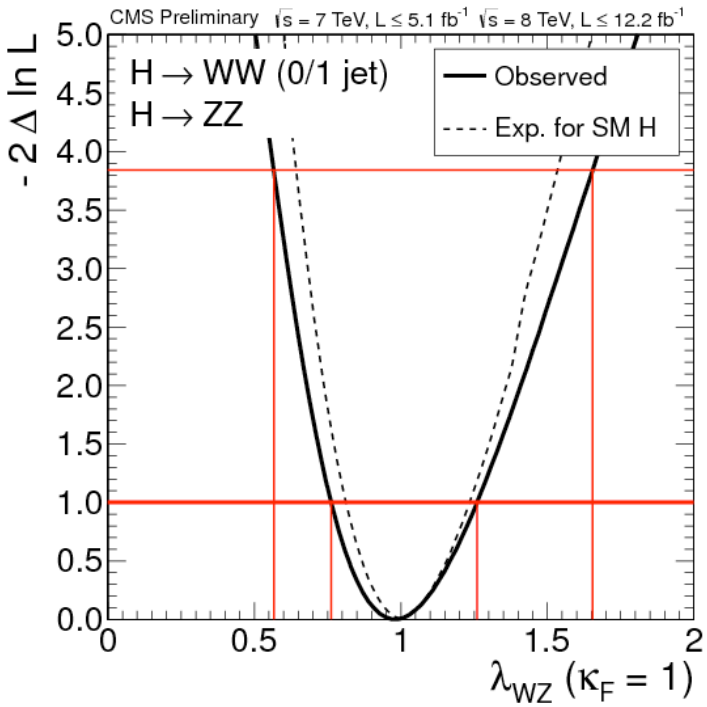
Custodial symmetry

Assuming no invisible or undetectable widths

Free parameters k_F $(= k_t = k_b = k_\tau)$, k_Z, and $\lambda_{WZ} = k_W/k_Z$

$WW_{(untagged\ 0/1\ jet)}$ and ZZ events

k_V is profile and $k_F = 1$



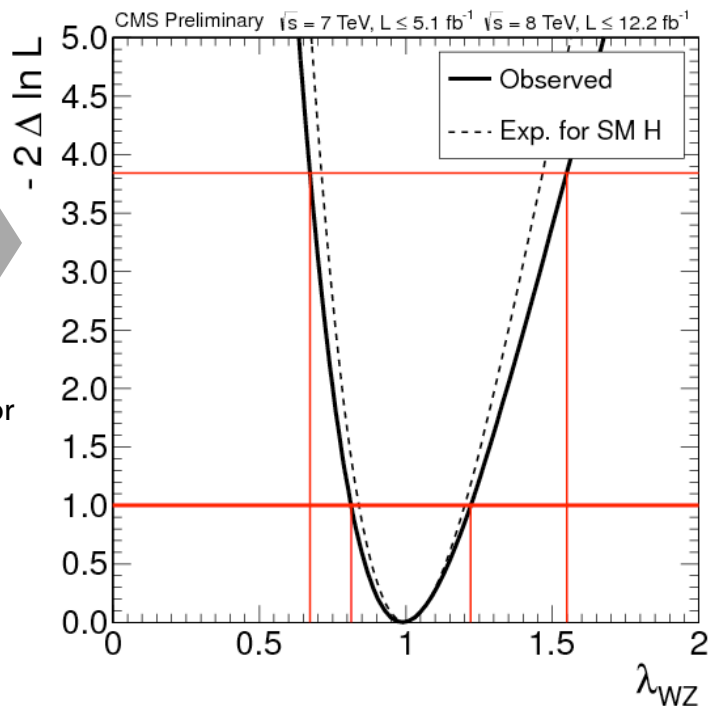
The 95% CL intervals for λ_{WZ} is:

λ_{WZ} **= [0.57,1.65]**

one common scaling factor for all fermions but greater statistical power

All channels

k_V and k_F are profile



The 95% CL intervals for λ_{WZ} is:

λ_{WZ} **= [0.67,1.55]**