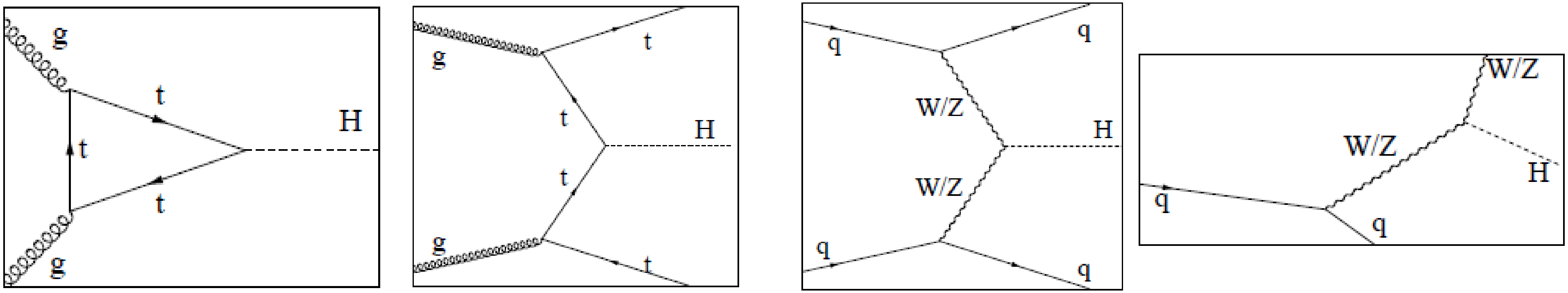
Measurements of properties of the Higgs-like Particle at 125 GeV by the CMS collaboration

Sabino Meola
On behalf of the CMS collaboration

Outline

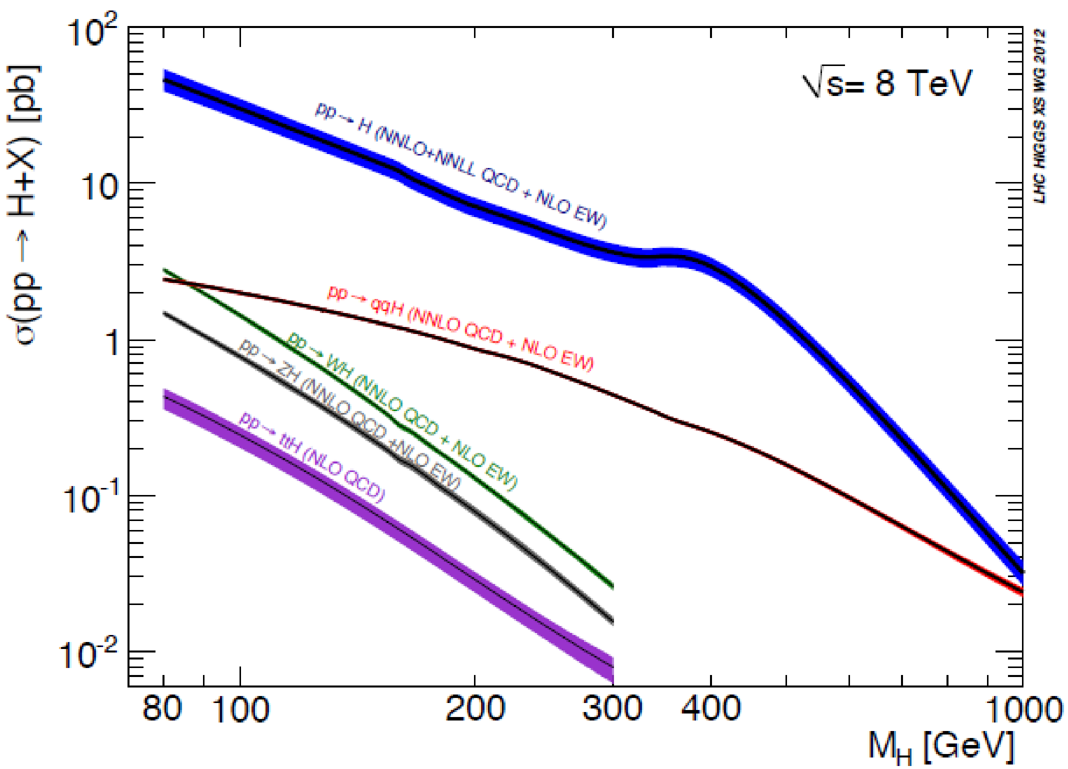
- **Higgs production and decays**
- **Combination: ingredients.**
  - Summary of the 5 channels
  - What goes in the combination
- **Combination: mass.**
- **Compatibility tests.**
  - Signal strength
  - Couplings and Custodial symmetry
  - Test of spin-parity hypotheses

Higgs Production



Fermionic

Bosonic



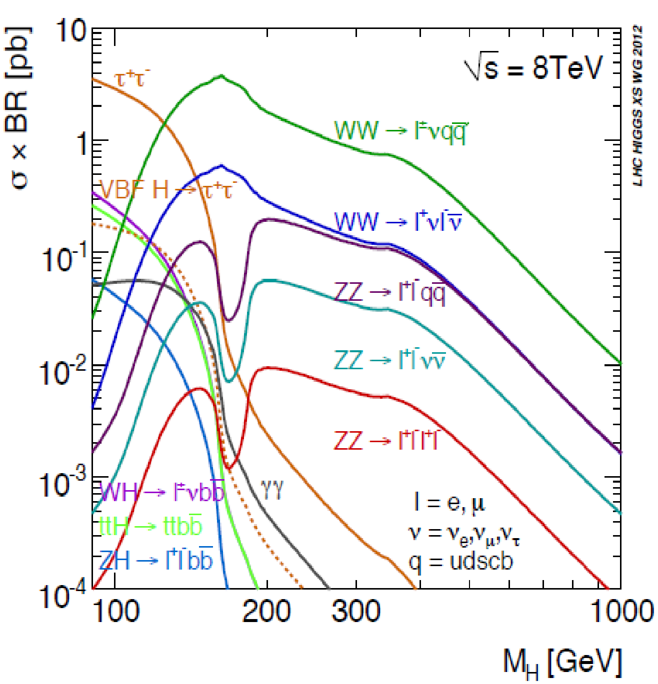
Higgs decays

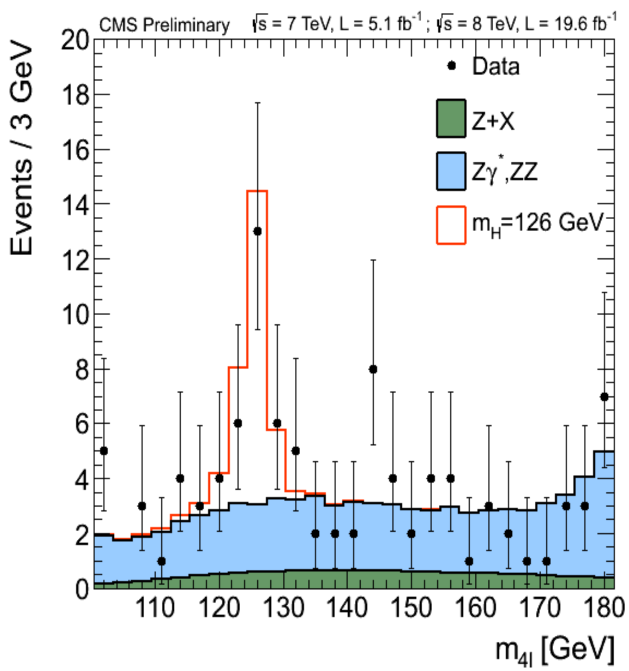
- $H \to ZZ \to 4l$ ($l = e, \mu$)
  - Clean final state
  - Small cross section
  - Most accurate mass meas.

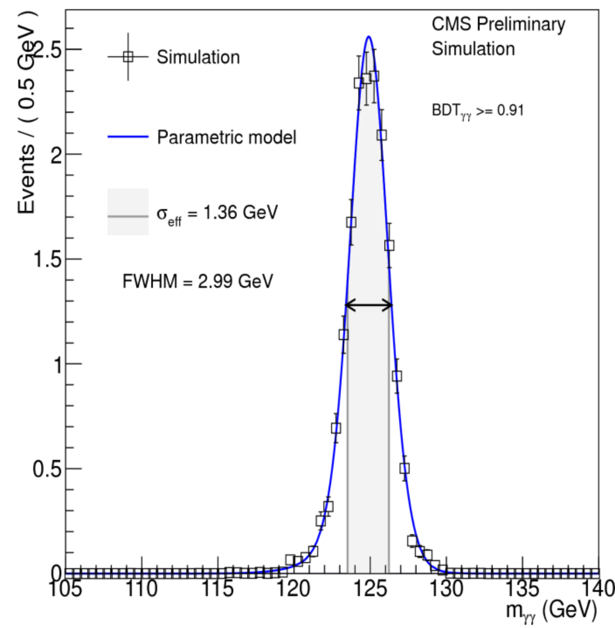
$$m_x = 125.7 \pm 0.4 \text{ GeV}$$

- $H \to \gamma\gamma$
  - 2 energetic photons in a narrow peak
  - Good detector resolution

$$m_x = 125.4 \pm 0.8 \text{ GeV}$$

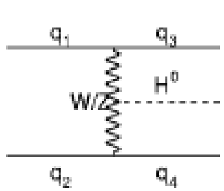


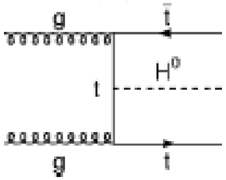


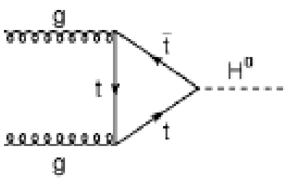


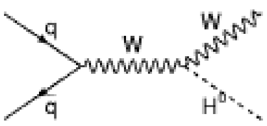
Ingredients

- High resolution final states $\gamma\gamma$ and 4l.
- WW high sensitivity, poor mass res.
- bb and $\tau\tau$ have large background.
- Evidence observed in 5 channels.









$m_H = 125.7$ GeV

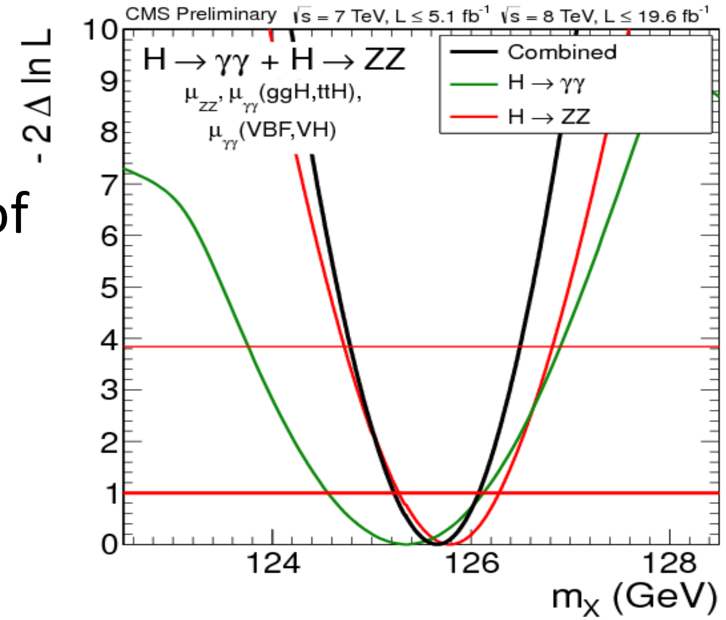
Decay	Exp.	Obs.
ZZ	7.1 σ	6.7 σ
$\gamma\gamma$	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.0 σ
$\tau\tau$	2.6 σ	2.8 σ
$\tau\tau$+bb	3.4 σ	3.4 σ

First single experiment evidence of couplings to fermions!

	ggH	VBFH	VH	ttH
$H\rightarrow\gamma\gamma$	√	√	√	
H→ZZ(4l)	√			
H→WW	√	√	√	
$H\rightarrow\tau\tau$	√	√	√	
H→bb			√	√

Mass of the observed state

- Using high resolution channels, $H \to ZZ \to 4l$ and $H \to \gamma\gamma$.
  - Small systematics from 4l (good control of the leptons scale and resolution)
  - Systematics on the extrapolation from the $Z \to ee$ to $H \to \gamma\gamma$

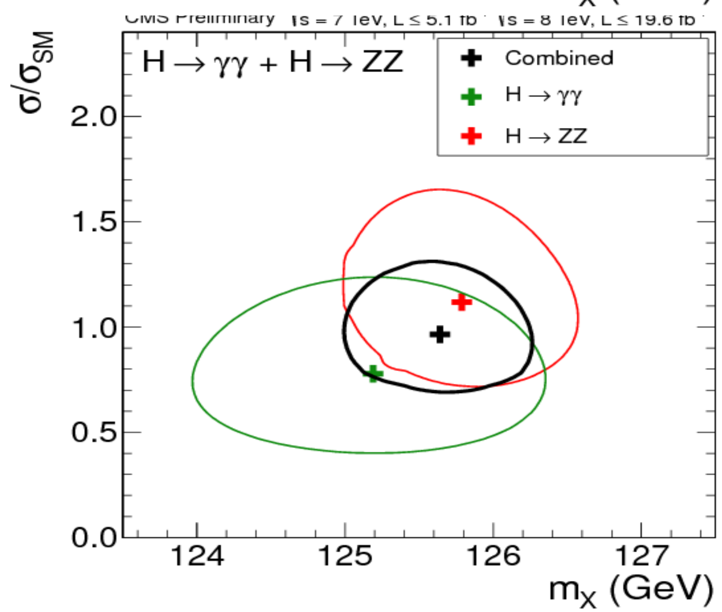


- Unique state assumption.

- Model-independent extraction.
  - $\mu = \sigma/\sigma_{SM}$ not tied to SM expectations

$$m_x = 125.7 \pm 0.3^{(stat)} \pm 0.3^{(syst)}\,\text{GeV}$$

$$m_x = 125.7 \pm 0.4\,\text{GeV}$$

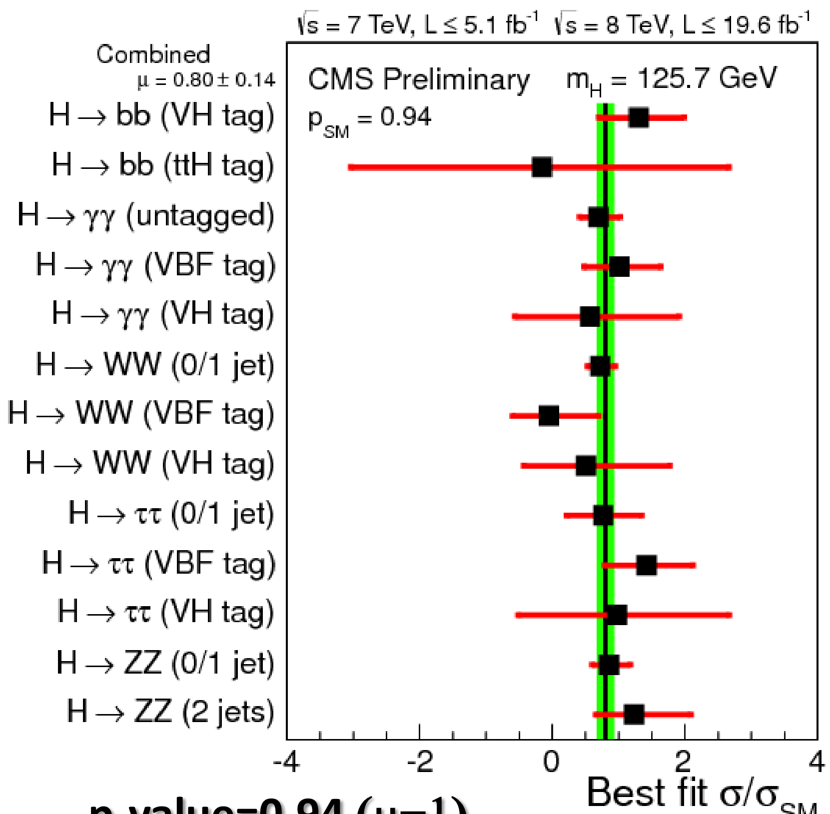


Signal strength

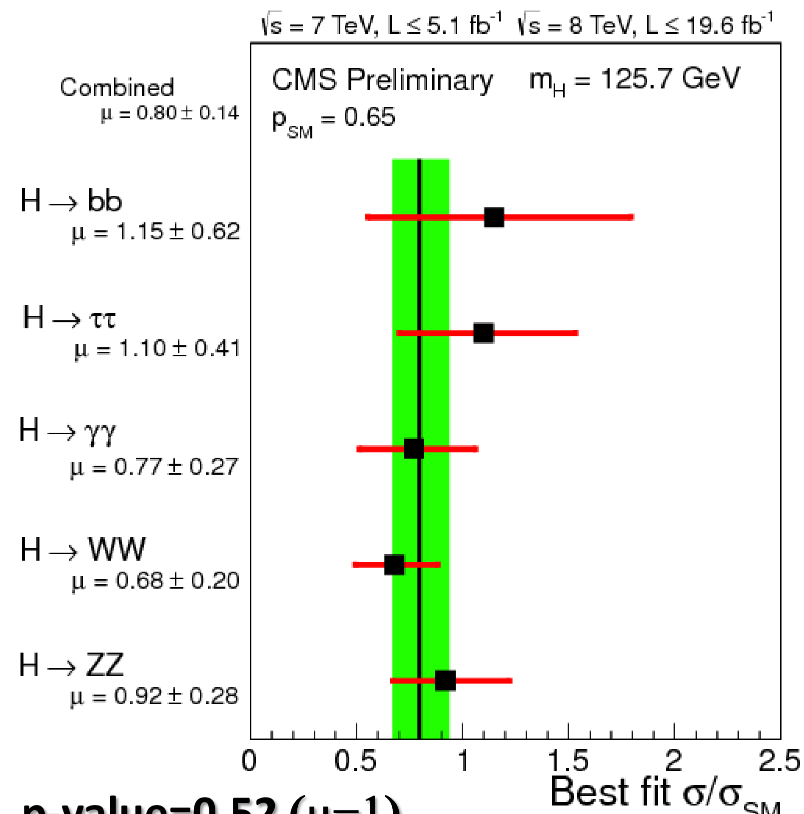
- Samples purity significantly different.
- Results consistent with SM within the errors.

Combined

$$\mu = 0.8 \pm 0.14$$



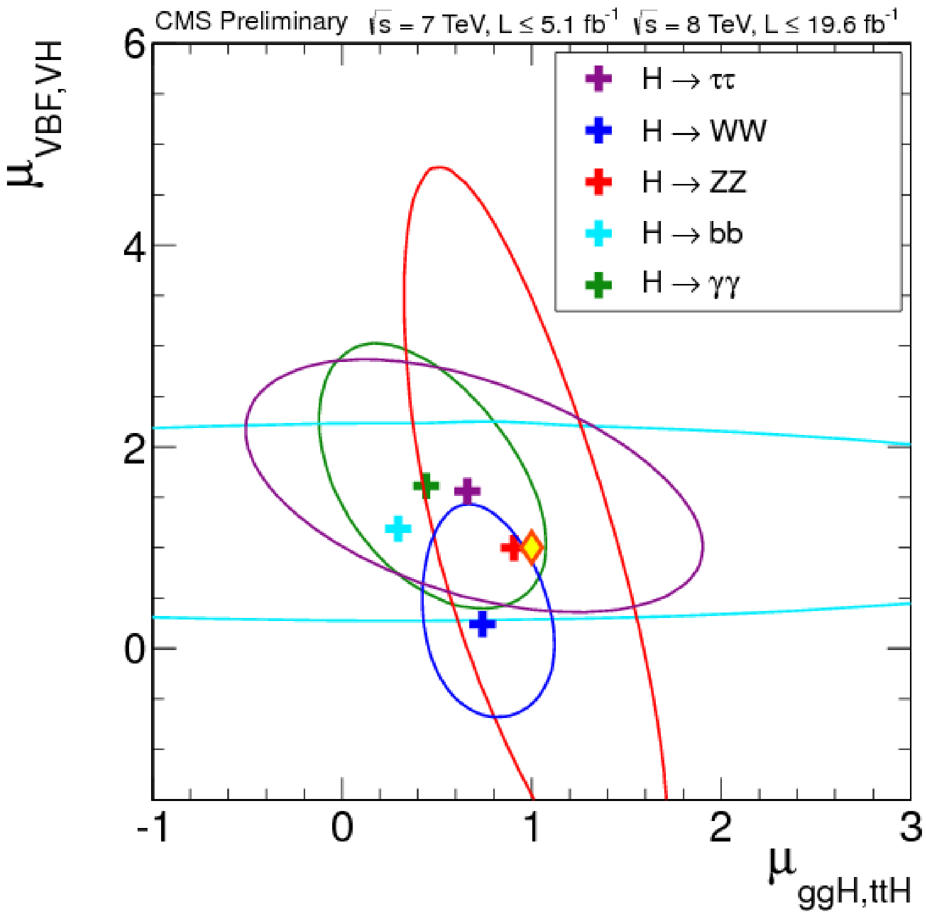
p-value=0.94 (μ=1)



p-value=0.52 (μ=1)

Signal strength: 2D

- $\mu_{ggH,tth}$ VS $\mu_{VBF,VH}$ CL intervals for the 5 decay modes.
- Test the relative strengths of the couplings to the vector bosons and the top quark.
- Contamination properly taken into account in the fit.



Couplings: method

- Event yields related to production cross-section, partial and total Higgs boson decay widths.

$$(\sigma \cdot BR)(x \to H \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{tot}}$$

- Modified couplings described by scale factors: $\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$ (**arxiv:1209.0040**)
  - 8 independent parameters: Γ_{ZZ}, Γ_{WW}, $\Gamma_{\tau\tau}$, Γ_{bb}, $\Gamma_{\gamma\gamma}$, Γ_{gg}, Γ_{tt}, Γ_{Tot}

- Assume SM Higgs couplings, variations w.r.t SM trough κ_i. So for $gg \to H \to \gamma\gamma$:

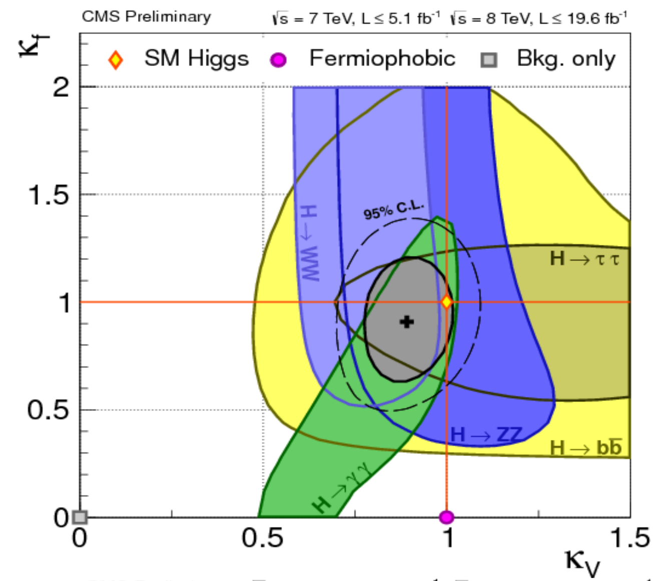
$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma^{SM}_{gg \to H} \cdot BR_{gg \to H} \cdot \kappa_g^2 \cdot \kappa_\gamma^2 / \kappa_H^2$$

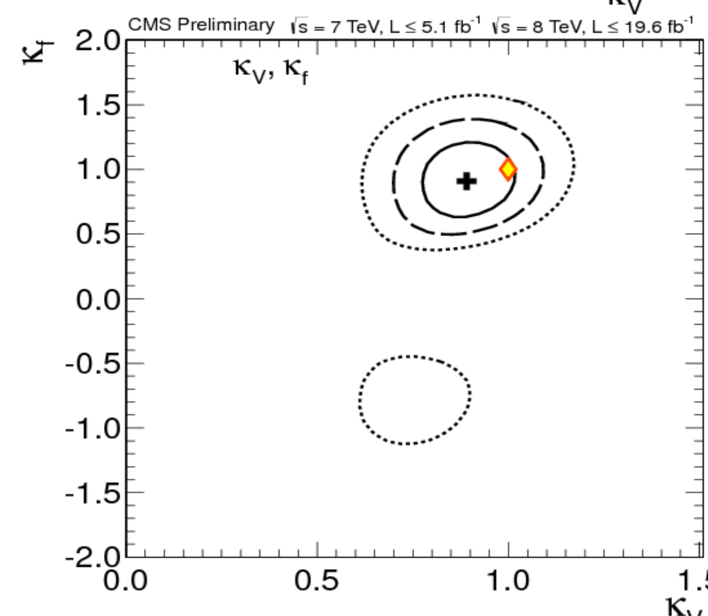
Couplings: κ_V , κ_f

- Scale factors for couplings to vectors and fermions.
- At LO almost all Γ_{ii} scale as κ_V^2 or κ_f^2

$$\Gamma_{\gamma\gamma} = |\alpha\kappa_V + \beta\kappa_f|^2$$

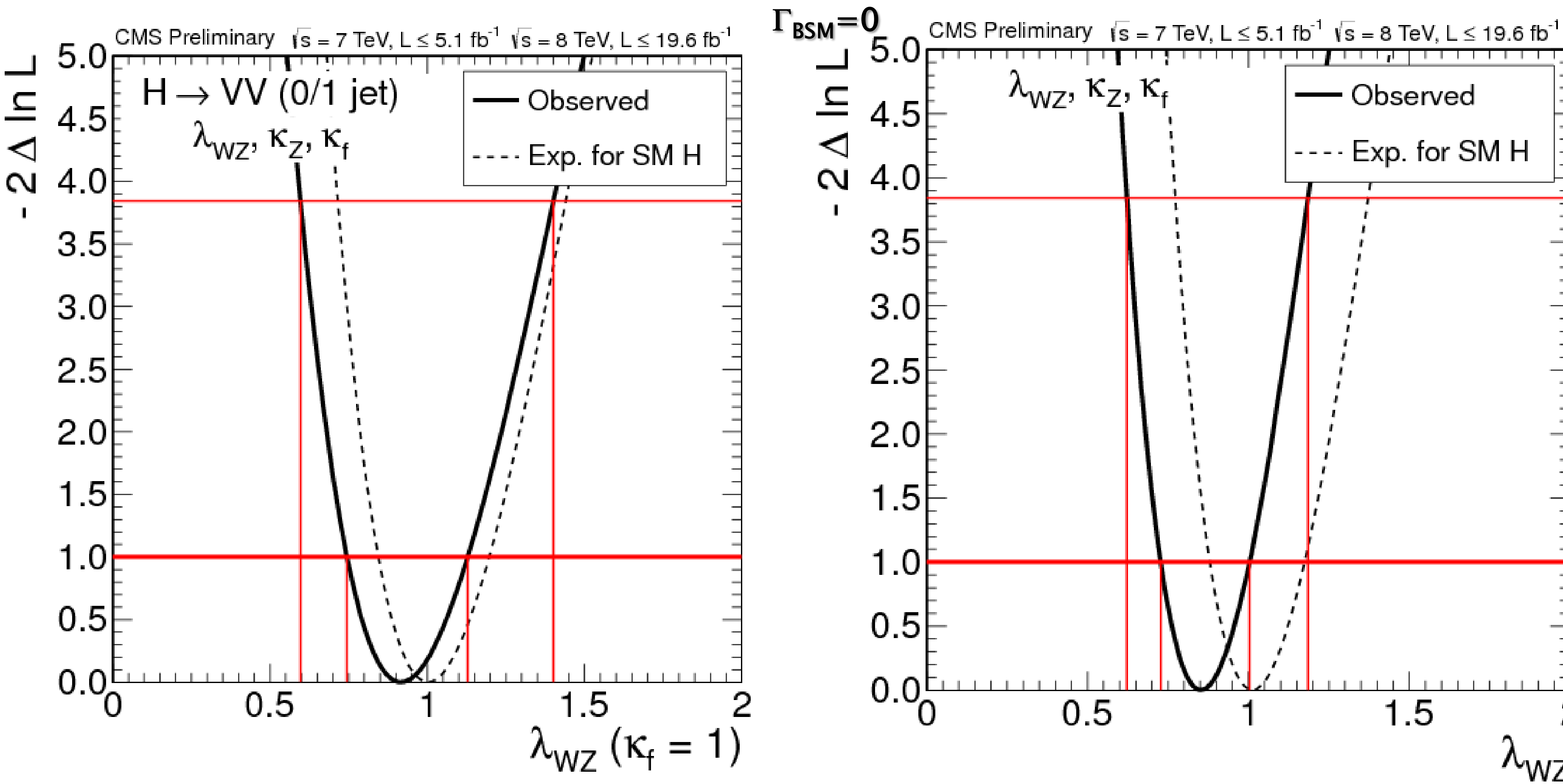
- Mass fixed to m_H=125.7 GeV.
- No new Higgs decay allowed (Γ_{BSM}=0).





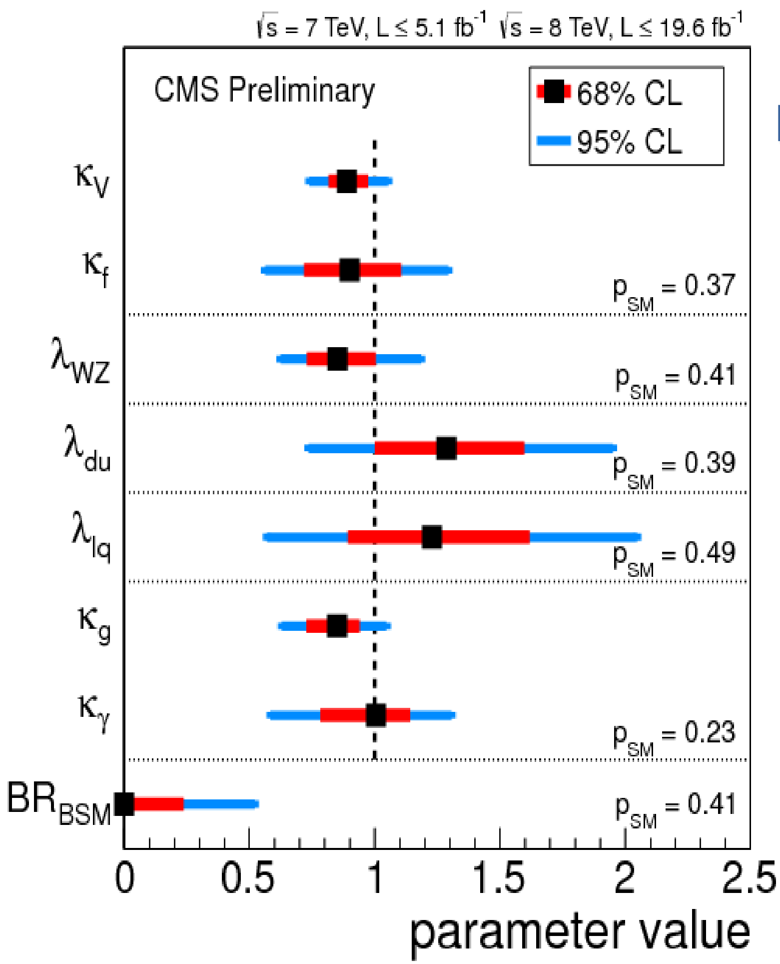
Test of Custodial Symmetry

- In SM, the ratio of couplings to W and Z bosons is protected from radiative corrections
  - Custodial symmetry tested by $\lambda_{WZ} = \kappa_W/\kappa_Z$



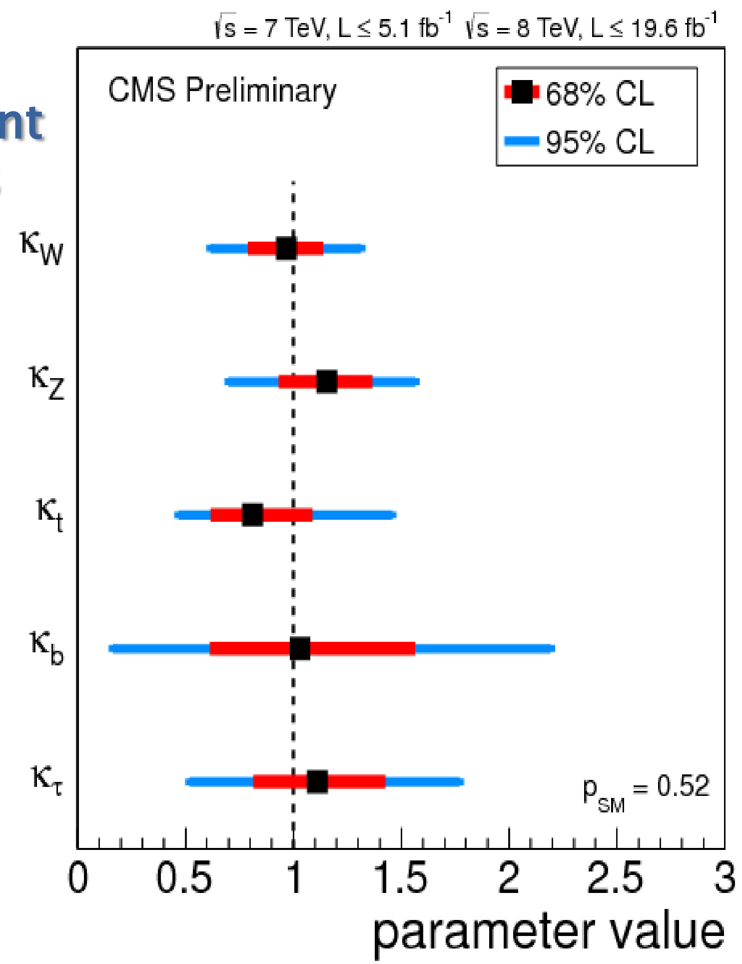
Couplings: summary

- Fermions universality tested by $\lambda_{du} = \kappa_d / \kappa_u$ and $\lambda_{lq} = \kappa_l / \kappa_q$.
- κ_γ and κ_g sensible to BSM physics in loops ($H \to \gamma\gamma$, $gg \to H$).



$\Gamma_{BSM}=0$

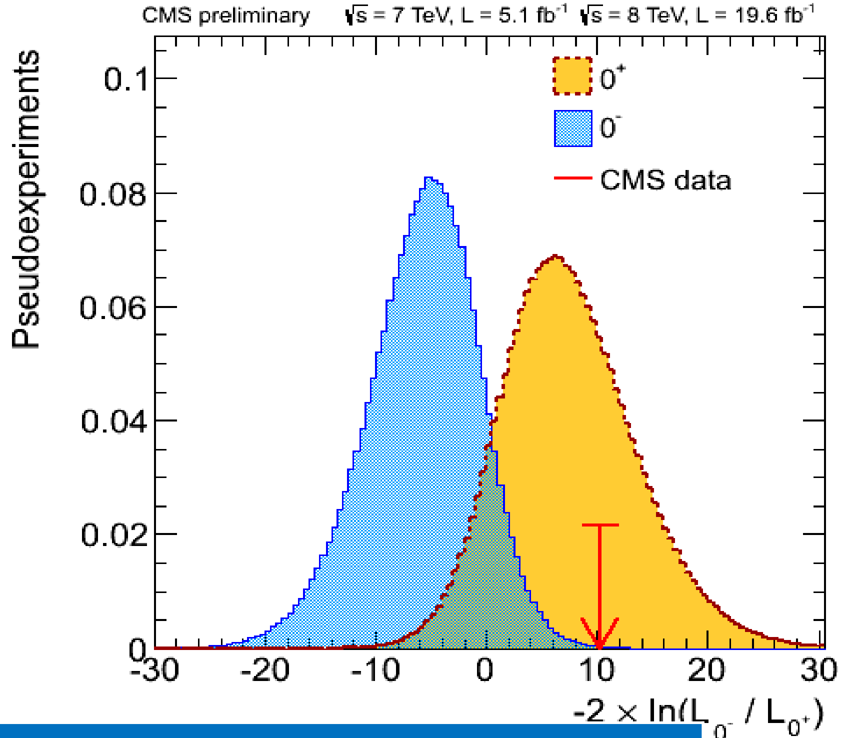
No significant anomalies



Spin-parity

- The newly observed particle is a boson and can't have spin 1 (decays to γγ - Lang-Yang Theorem).
- Tests in $ZZ \rightarrow 4l$[1] and $WW \rightarrow l\nu l\nu$[2] channels disfavor $J^P=0^-$ (CLs 0.16%).

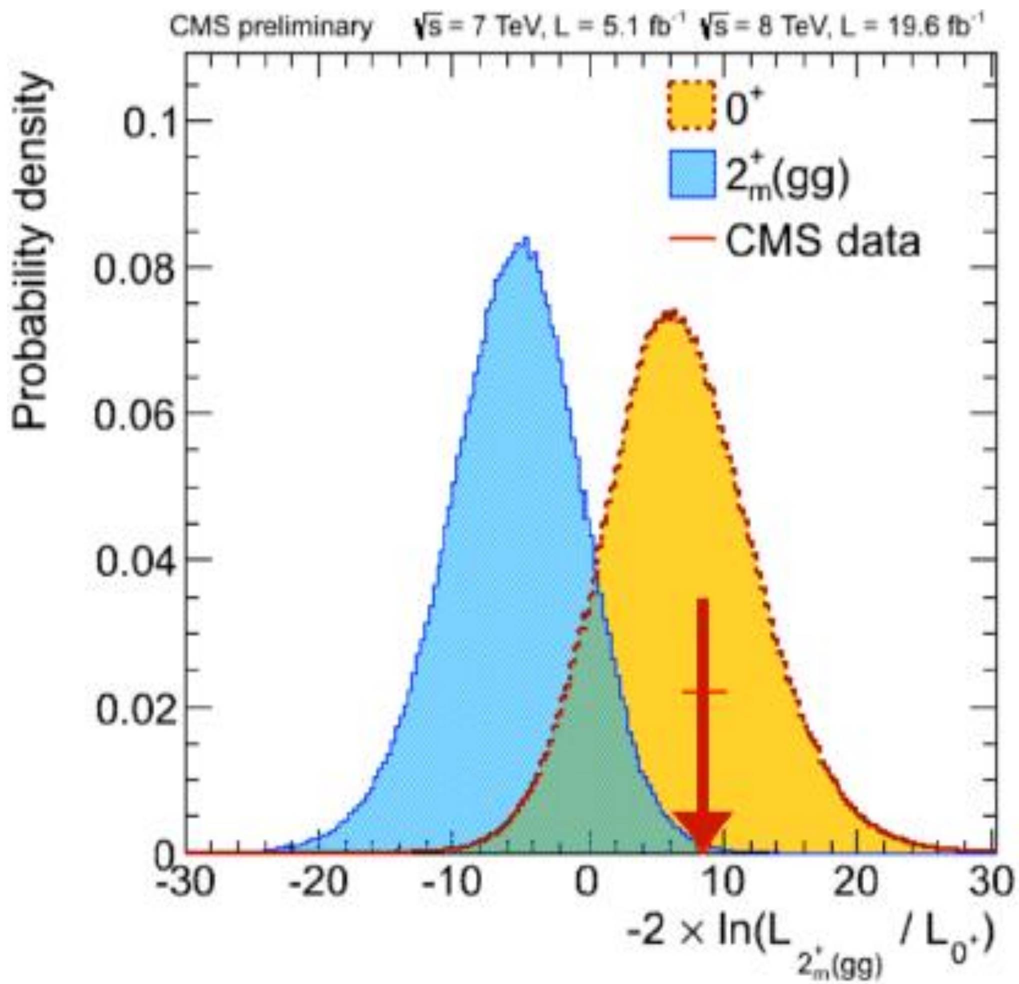
[1] CMS-PAS-HIG-13-002
[2] CMS-PAS-HIG-13-003



J^P	Production	Description
0^+	$gg \rightarrow X$	SM Higgs boson
0^-	$gg \rightarrow X$	pseudoscalar
0^+_h	$gg \rightarrow X$	BSM scalar with higher dim. operators
2^+_{mgg}	$gg \rightarrow X$	KK Graviton-like with minimal couplings
2^+_{mqq}	$qq \rightarrow X$	KK Graviton-like with minimal couplings

Spin-parity: 0^+ vs 2^+

- Improved sensitivity on 0^+ vs 2^+_{mgg} combining $ZZ\rightarrow 4l$ and $WW\rightarrow l\nu l\nu$ channels only.
- Data consistent with $J^P=0^+$ within 0.34 σ.
- Assuming Higgs boson, data disfavor $J^P=2^+$ with a CLs of 0.6%.



Conclusions

- New boson mass updated: m_H = 125.7±0.4 GeV.
- First evidence of coupling to fermions.
- Tests on couplings and event yields show no deviations from SM predictions:
  - Custodial symmetry
  - Couplings
  - Spin-parity
- Data consistent with SM $J^P=0^+$ and disfavoring pseudo-scalar, vector, pseudo-vector and spin-2 resonances.

"I don't know anyone, beside scientists, who is thrilled when discovering that he is wrong, and disappointed when everything works as expected"

Thank you

CMS-PAS-HIG-13-001
CMS-PAS-HIG-13-002
CMS-PAS-HIG-13-003
CMS-PAS-HIG-13-004
CMS-PAS-HIG-13-005
CMS-PAS-HIG-12-045

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13005TWiki

Mass from 4l and $\gamma\gamma$

- H→ZZ →4l
  - Mass estimation with m4l, KD and σ(m4l)
  - Very small systematics due the very good control of the leptons scale and resolution

$$m_x = 125.8 \pm 0.5^{(stat)} \pm 0.2^{(syst)}\,\mathrm{GeV}$$

- H →γγ
  - Systematics on the extrapolation from the Z→ee to H→γγ

(0.25% from e to γ, 0.4% from Z to H)

$$m_x = 125.4 \pm 0.5^{(stat)} \pm 0.6^{(syst)}\,\mathrm{GeV}$$

- Combined

$$m_x = 125.7 \pm 0.3^{(stat)} \pm 0.3^{(syst)}\,\mathrm{GeV}$$

Combination methodology

- The combination requires analysis of all channels accounting for statistical and systematic uncertainties (more details on the methodology at [1,2]).

- Test statistic defined as (profile likelihood ratio):

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{obs} \,|\, b, \hat{\theta}_0)}{\mathcal{L}(\text{obs} \,|\, \hat{\mu} \cdot s + b, \hat{\theta})}$$

- Signal model parameter derived scanning the profile likelihood ratio: best-fit parameters are those that maximize the likelihood.

$$q(a) = -2 \ln \frac{\mathcal{L}(\text{obs} \,|\, s(a) + b, \hat{\theta}_a)}{\mathcal{L}(\text{obs} \,|\, s(\hat{a}) + b, \hat{\theta})}.$$

- The p-value is the probability to obtain a q_0 at least as large as the one observed:

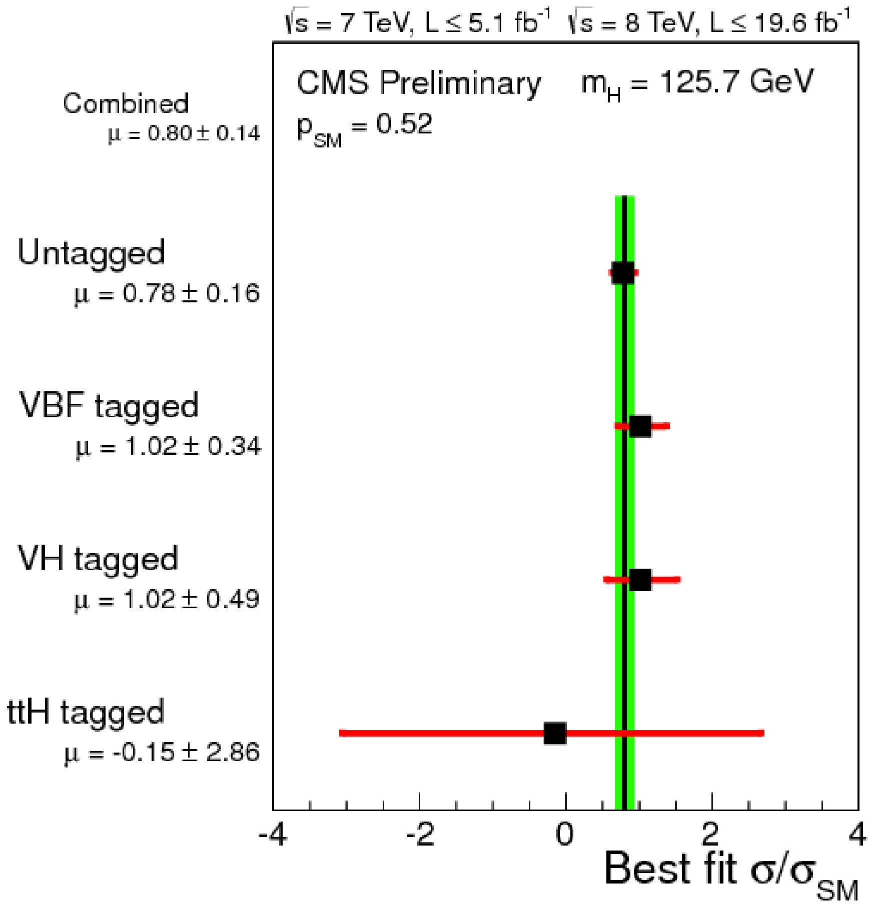
$$p_0 = \mathrm{P}(q_0 \geq q_0^{obs} \,|\, \mathrm{b})$$

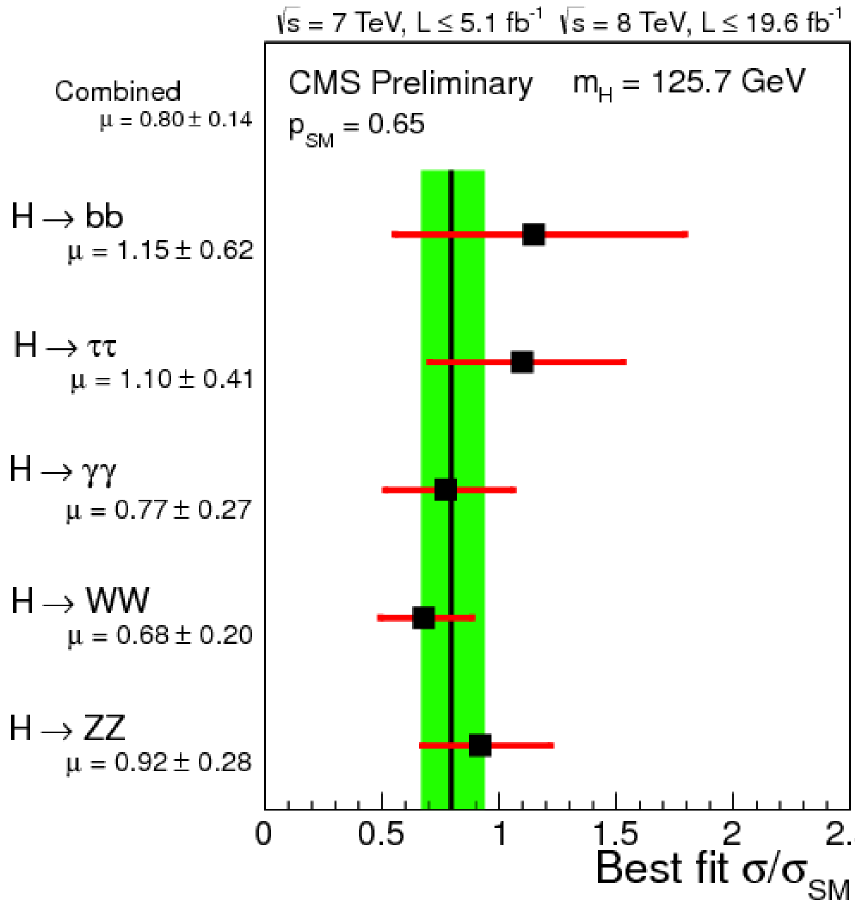
[1] arXiv:1202.1488

[2] CMS NOTE 2011/005

Signal strength

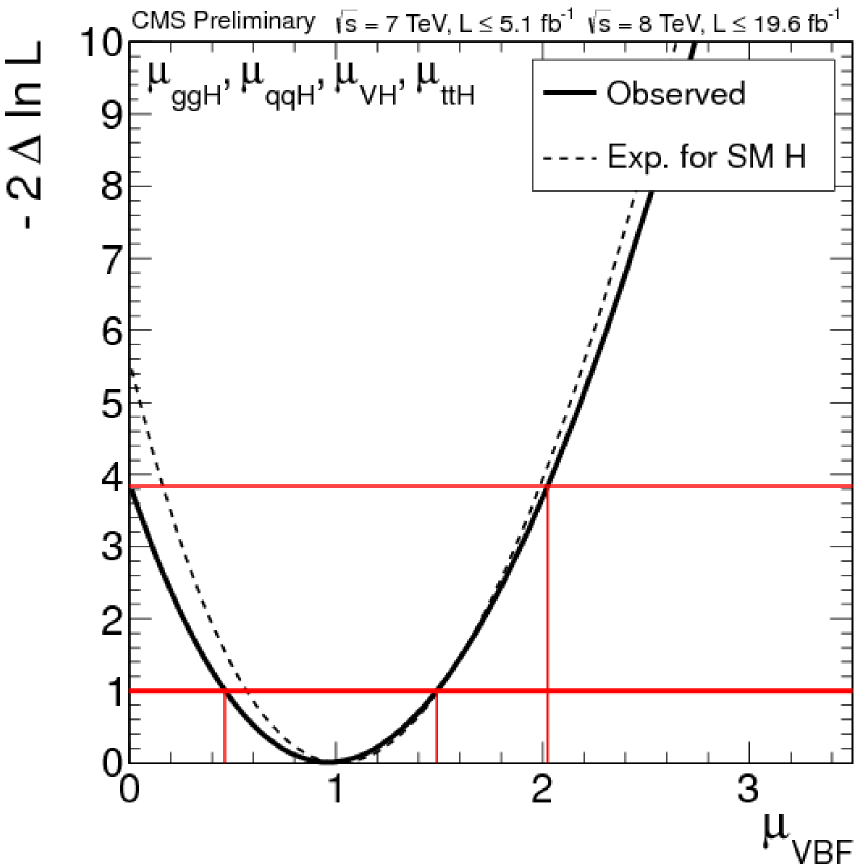
- All sub-combinations compatible with SM Higgs hypothesis.

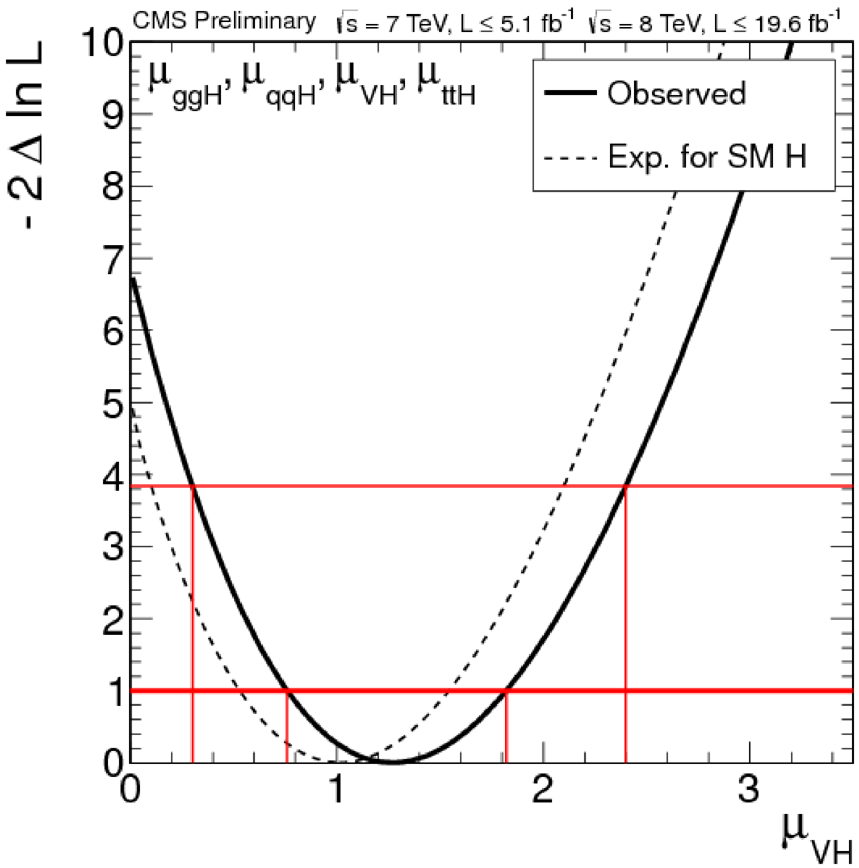




EWK production mechanism

- μ_{VH} VS μ_{VBF} comparison probes EWK production mechanism

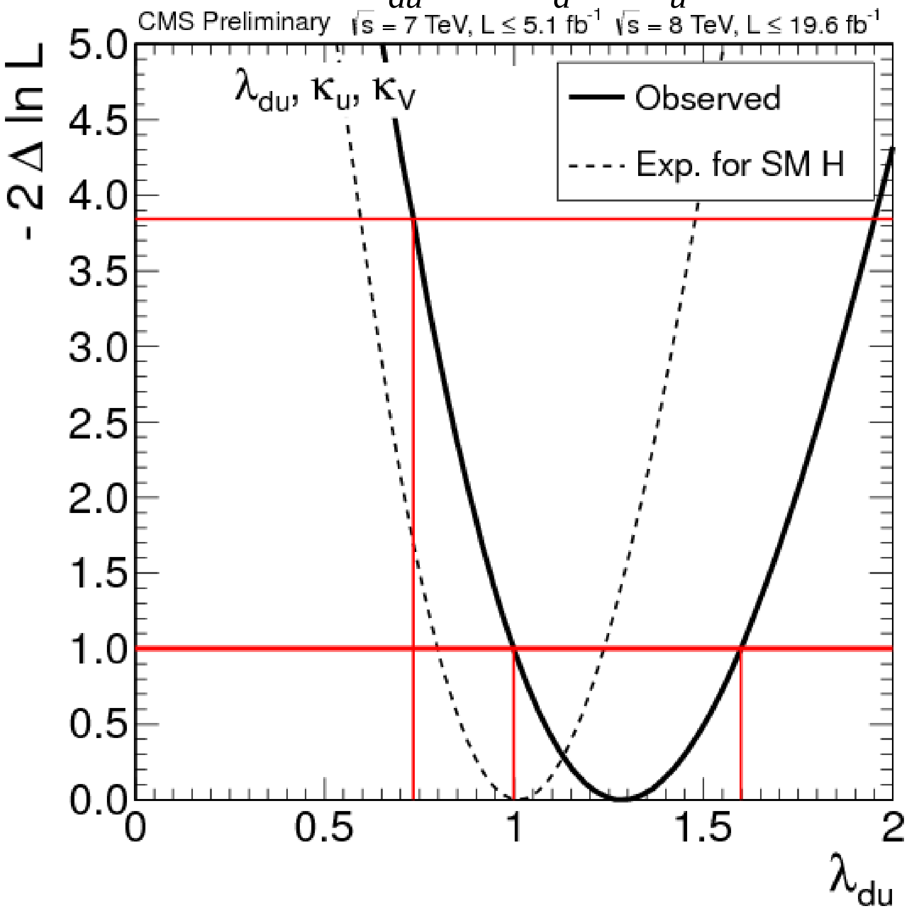




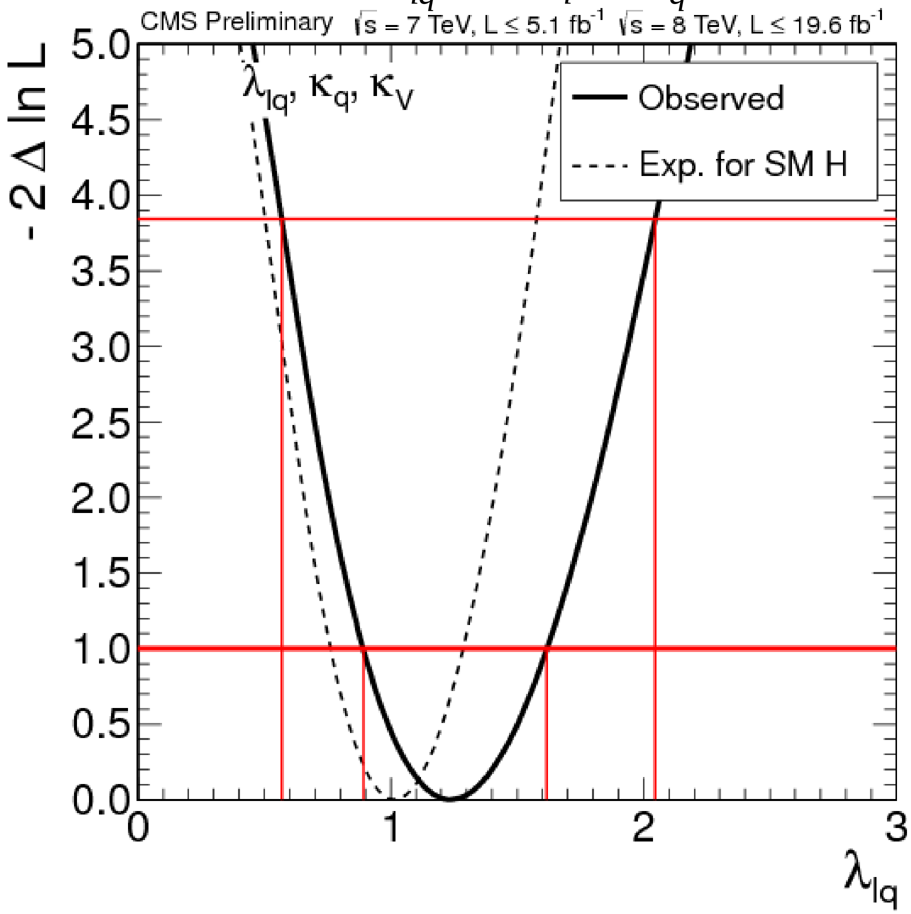
Fermion universality

- In MSSM couplings to up/down fermions are modified.
- In 2HDMs couplings to leptons and quark altered.

$$\lambda_{du} = \kappa_d / \kappa_u$$



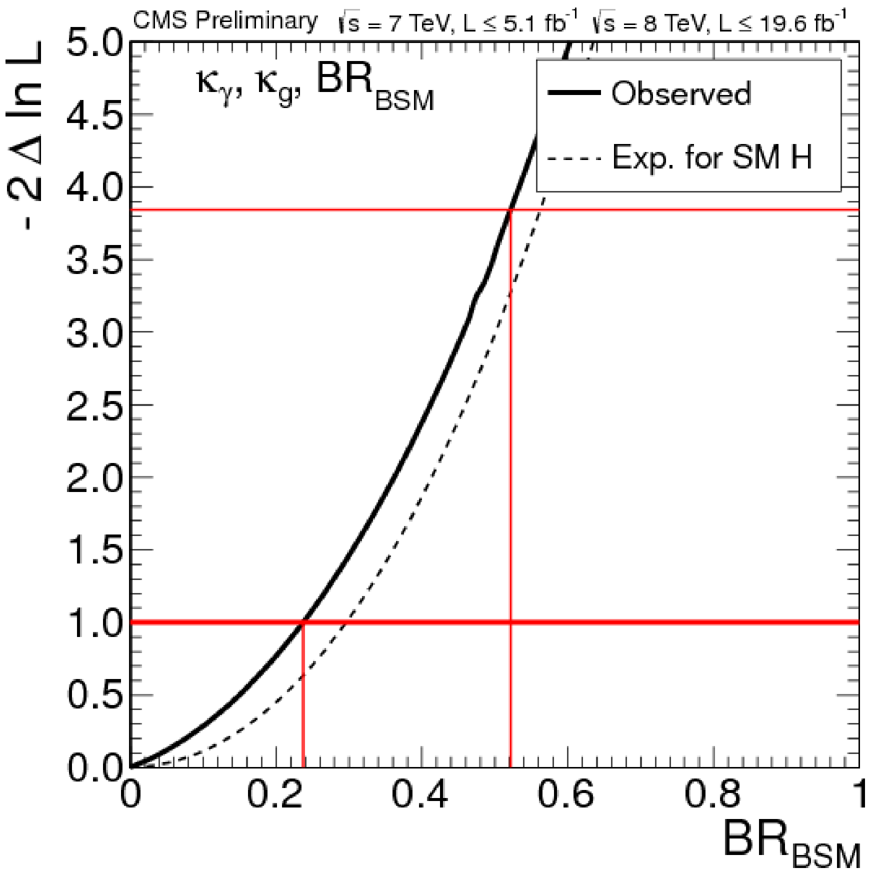
$$\lambda_{lq} = \kappa_l / \kappa_q$$



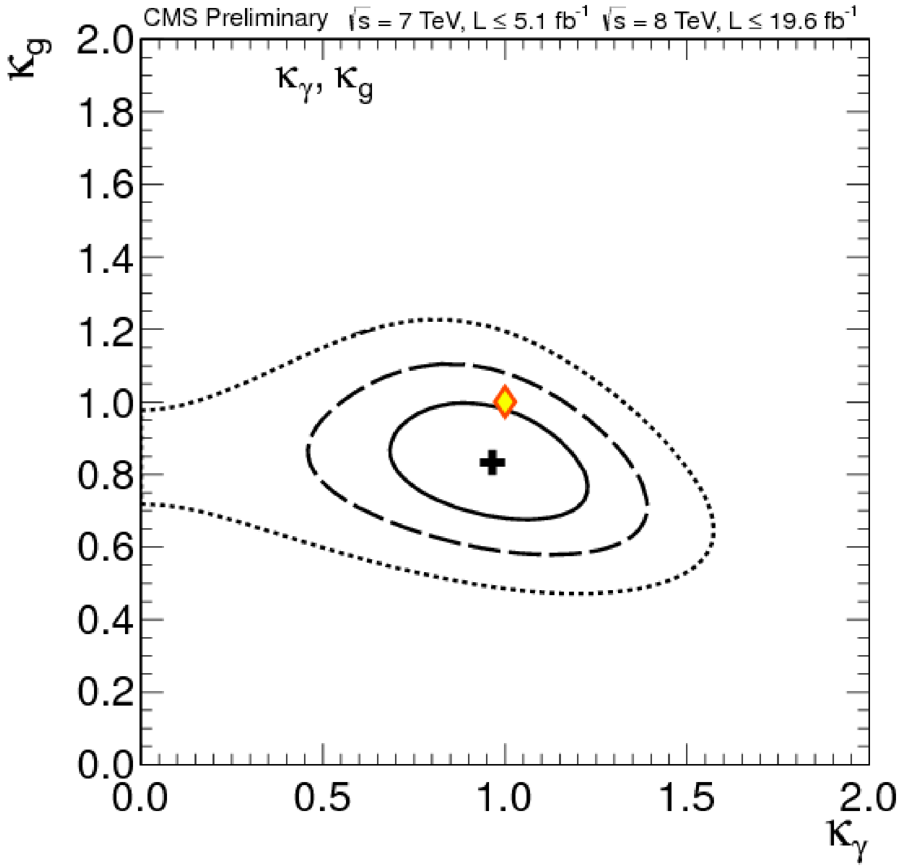
New physics in loops and decays

- New physics can appear in loops ($H\rightarrow\gamma\gamma$, $gg\rightarrow H$).
- κ_γ and κ_g sensible to BSM physics.

BR_{BSM}<0.52 @ 95% CL

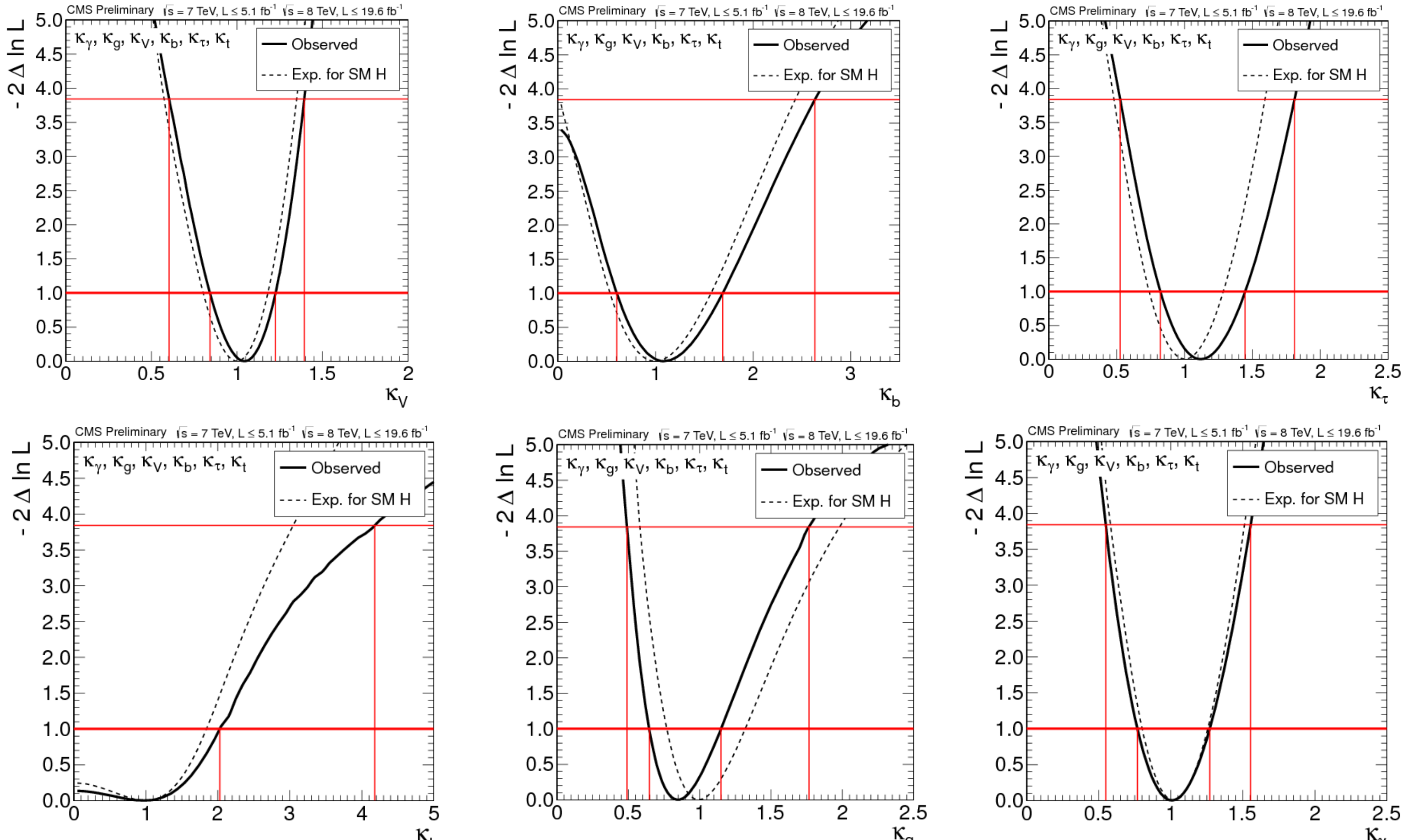


Γ_{BSM}=0



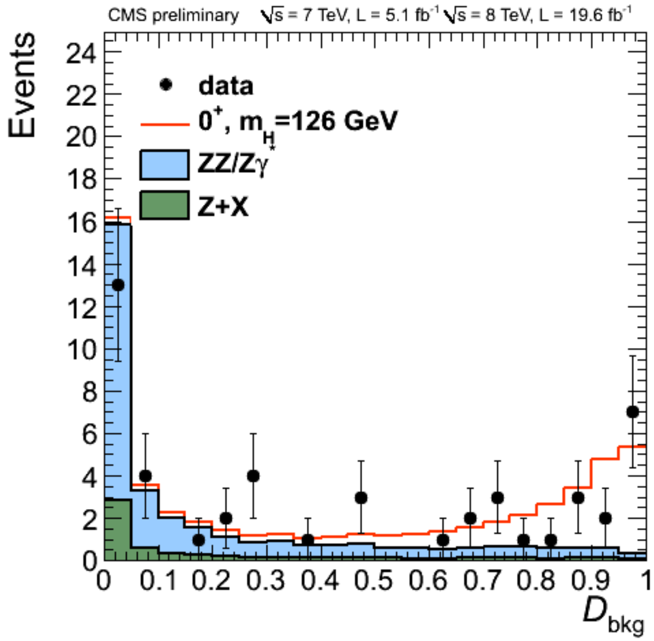
C6 model

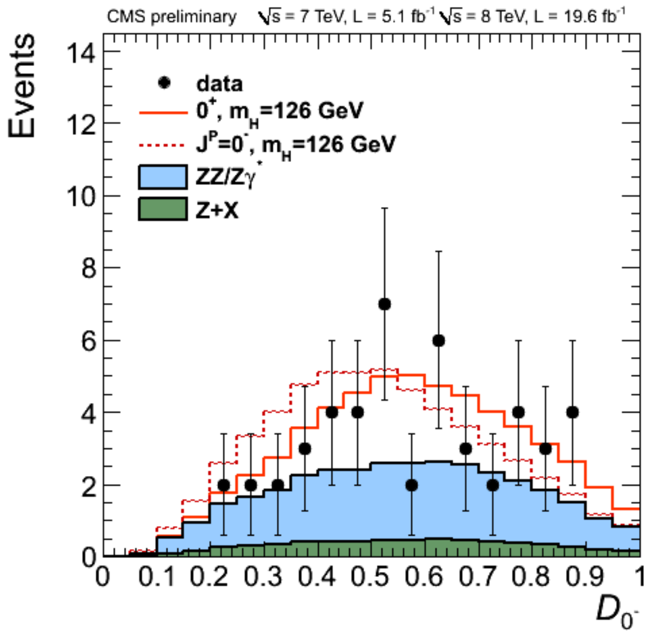
- Custodial symmetry and BR_{BSM}=0 assumed.
- Fit 6 scale factors individually, profiling the others.



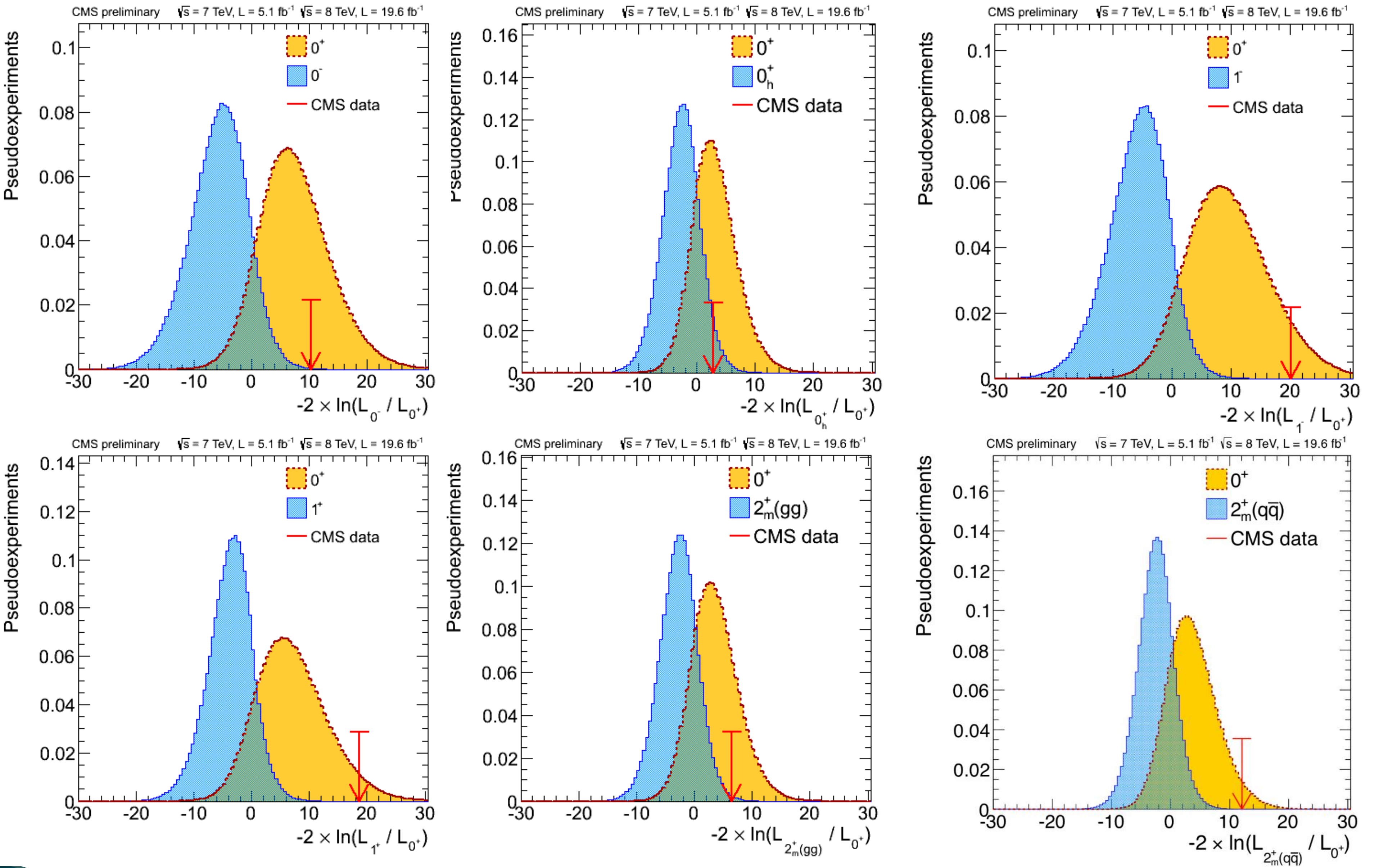
Spin-parity in 4l

- Using kinematic distributions to distinguish different signal models
  - D_{JP} distinguishes SM Higgs from other J^P hypotheses
  - D_{BKG} distinguishes signal from background
- Test compatibility of data with distinct models (Neyman-Pearson hypothesis testing with null Hypothesis always SM Higgs)





Spin-parity in 4l



Spin-parity:method

- A CLs is defined as the ratio of the probabilities to find values of the test statistic q equal or larger than the observed in data:

$$\mathrm{CL_s}^{\mathrm{obs.}} = P(\,q \geq q^{\mathrm{obs.}}\,|\,2^+_{\mathrm{m}}(\mathrm{gg})\,)\,/\,P(\,q \geq q^{\mathrm{obs.}}\,|\,0^+\,)$$

- Some to quantify the expected result.

Table 4: Results of the hypothesis test between the $J^P = 0^+$ and $2^+_{\mathrm{m}}(\mathrm{gg})$ signal hypotheses for $m_{\mathrm{H}} = 125.7$ GeV. Tail probabilities P are converted into significance Z (in σ) using the one-sided Gaussian tail convention of Eq. 3. The $2^+_{\mathrm{m}}(\mathrm{gg})$ signal hypothesis is disfavoured by the data with a $\mathrm{CL_s}$ value of 0.60%.

Pre-fit model ($\mu_i = 1$)	$ZZ \to 4\ell$	$WW \to \ell\nu\ell\nu$	Combined
Separation	81.6%	87.1%	92.4%
$P(\,q \leq q^{\mathrm{exp.}}_{2^+_{\mathrm{m}}(\mathrm{gg})}\,|\,0^+\,)$	1.8σ	1.9σ	2.6σ
$P(\,q \geq q^{\mathrm{exp.}}_{0^+}\,|\,2^+_{\mathrm{m}}(\mathrm{gg})\,)$	1.8σ	2.5σ	3.0σ
$1 - \mathrm{CL_s}^{\mathrm{exp.}}$	93.2%	98.6%	99.8%
Post-fit model (μ_i profiled)	**$ZZ \to 4\ell$**	**$WW \to \ell\nu\ell\nu$**	**Combined**
Separation	80.7%	80.9%	88.8%
$P(\,q \leq q^{\mathrm{exp.}}_{2^+_{\mathrm{m}}(\mathrm{gg})}\,|\,0^+\,)$	1.6σ	1.6σ	2.3σ
$P(\,q \geq q^{\mathrm{exp.}}_{0^+}\,|\,2^+_{\mathrm{m}}(\mathrm{gg})\,)$	1.8σ	1.7σ	2.5σ
$1 - \mathrm{CL_s}^{\mathrm{exp.}}$	93.1%	91.9%	98.8%
$P(\,q \leq q^{\mathrm{obs.}}\,|\,0^+\,)$	-0.90σ	0.44σ	-0.34σ
$P(\,q \geq q^{\mathrm{obs.}}\,|\,2^+_{\mathrm{m}}(\mathrm{gg}))$	2.81σ	1.32σ	2.84σ
$1 - \mathrm{CL_s}^{\mathrm{obs.}}$	98.6%	86.0%	99.4%

Analyses summary

Table 1: Summary of the information on the analyses included in this combination. All final states are exclusive. Notations used are: $(jj)_{\rm VBF}$ stands for a jet pair consistent with the VBF topology (VBF-tag); SF are same flavour dileptons, i.e., ee or $\mu\mu$ pairs; DF are different flavour dileptons, i.e., $e\mu$ pairs. The column "Prod. tag" indicates which production mechanism is targeted by an analysis; it does not imply 100% purity (e.g., analyses targeting VBF are expected to have 20%–50% of their signal events coming from gluon-gluon fusion). The main contribution in the untagged and inclusive categories is always gluon-gluon fusion.

Analyses			No. of	m_H	Lumi (fb^{-1})		Ref.
H decay	Prod. tag	Exclusive final states	channels	resolution	7 TeV	8 TeV	
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4 + 4	1-2%	5.1	19.6	[63]
	VBF-tag	$\gamma\gamma + (jj)_{\rm VBF}$ (two dijet classes for 8 TeV)	1 + 2	<1.5%	5.1	19.6	
	VH-tag	$\gamma\gamma$ + (e, μ, MET)	3	<1.5%		19.6	
$ZZ \to 4\ell$	$N_{\rm jet} < 2$	$4e$, 4μ, $2e2\mu$	3 + 3	1-2%	5.1	19.6	[64]
	$N_{\rm jet} \geq 2$		3 + 3				
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) × (0 or 1 jets)	4 + 4	20%	4.9	19.5	[65]
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\rm VBF}$ (DF or SF dileptons for 8 TeV)	1 + 2	20%	4.9	12.1	[66]
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2 + 2		4.9	19.5	[67]
$\tau\tau$	0/1-jet	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) × (low or high p_T^τ)	16 + 16				
	1-jet	$\tau_h\tau_h$	1 + 1	15%	4.9	19.6	[68]
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$) + $(jj)_{\rm VBF}$	5 + 5				
	ZH-tag	(ee, $\mu\mu$) × ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8 + 8		5.0	19.5	[69]
	WH-tag	$\tau_h\mu\mu$, $\tau_h e\mu$, $e\tau_h\tau_h$, $\mu\tau_h\tau_h$	4 + 4				
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets) × (low or high $p_T(V)$ or loose b-tag)	10 + 13	10%	5.0	12.1	[70]
	ttH-tag	(ℓ with 4,5 or ≥6 jets) × (3 or ≥ 4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or ≥3 b-tagged jets)	6 + 6 3 + 3		5.0	5.1	[71]