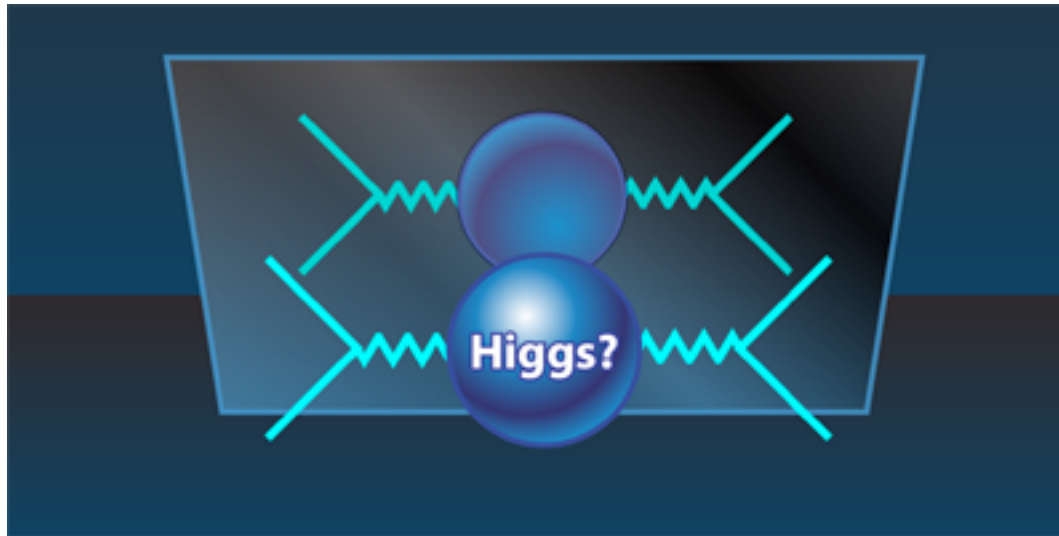




Spin-parity measurements of the 126 GeV resonance at CMS

Kalanand Mishra, *Fermilab*



WIN 2013 at Natal
Sept 17, 2013

Courtesy APS/Alan Stonebraker

Outline

- Introduction to Higgs spin-parity quantum numbers
 - Spin information from rate & coupling measurements
- Spin-parity measurements in bosonic decay modes
 - in $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, and $H \rightarrow \gamma\gamma$
- Summary

References

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG>

Phys.Lett. B 716 (Discovery)

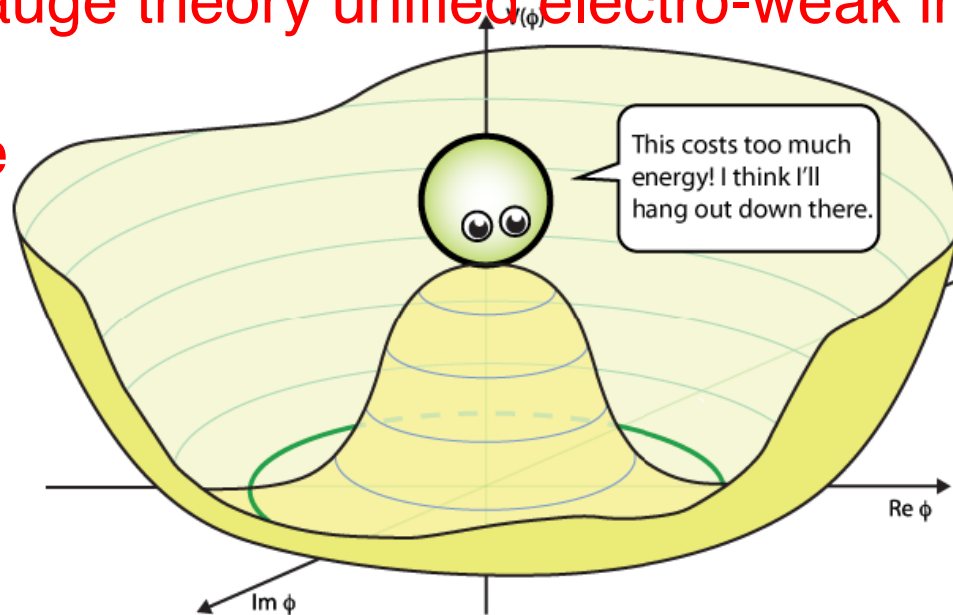
CMS-PAS-HIG-13-002 (ZZ^* , spin)

CMS-PAS-HIG-13-003 (WW^*)

CMS-PAS-HIG-13-016 (Properties $\gamma\gamma$)

Electroweak symmetry breaking

50 years ago, gauge theory unified electro-weak interactions, but could not accommodate non-zero masses for W^\pm & Z



**Predicted
a remnant
scalar
particle!**

$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2 \Phi^2 - \lambda \Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

Introduction of a doublet of complex scalar fields with peculiar potential provided masses for W^\pm & Z and left γ massless!

Higgs boson discovery and its mass, couplings

For a mass of $m_H = 125.7 \pm 0.4$ GeV

Decay	Expected	Observed
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ZZ	7.1 σ	6.7 σ
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$\gamma\gamma$	3.9 σ	3.2 σ
----------------------------------	--------------------------------	--------------------------------

WW	5.3 σ	3.9 σ
-----------	--------------------------------	--------------------------------

bb	2.2 σ	2.1 σ
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$\tau\tau$	2.6 σ	2.8 σ
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bosons

} 3.4 σ combined!
fermions

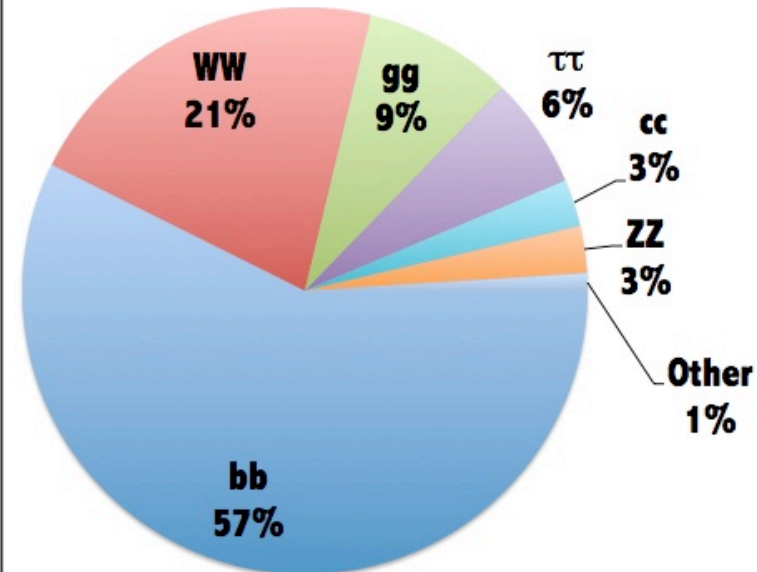
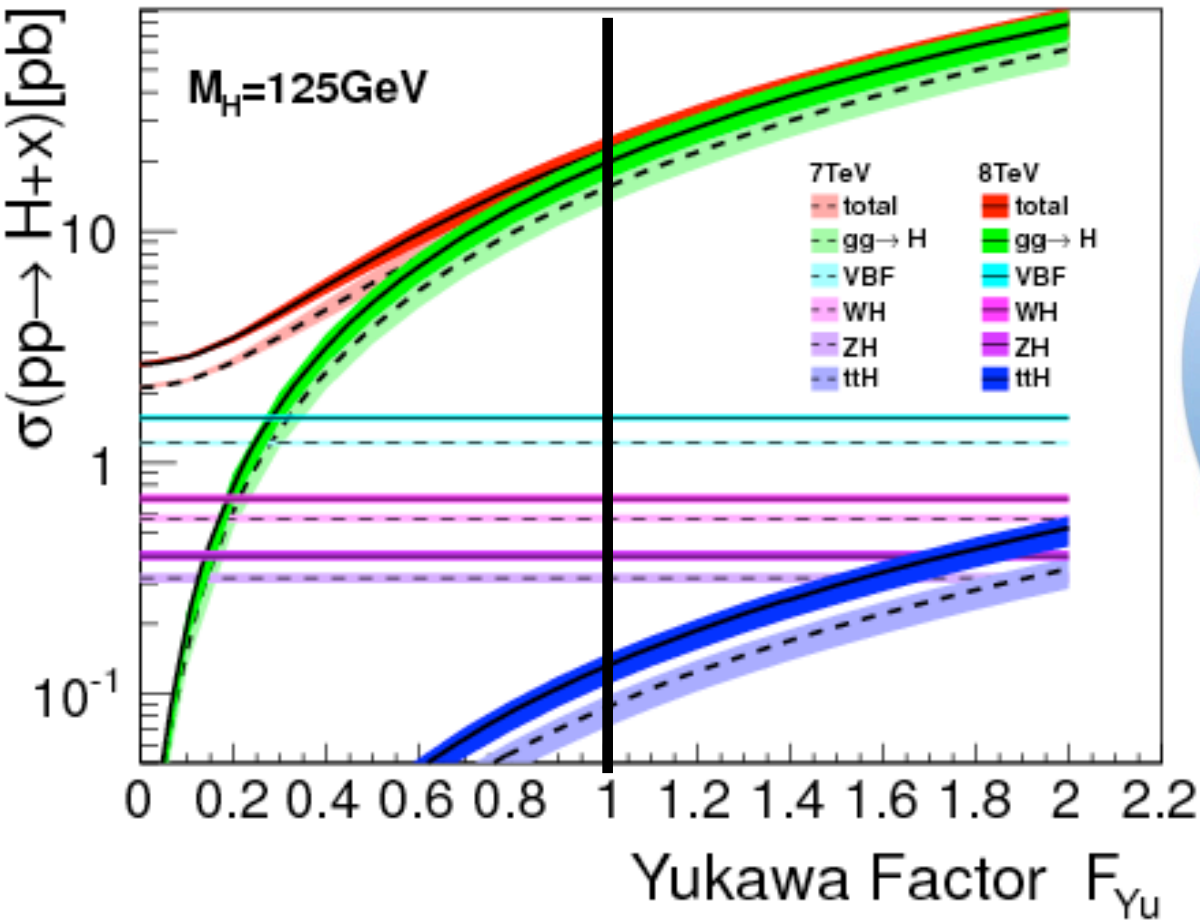


bb: includes VH and VBF
WW: includes ggF, VH, VBF

See talks by Petra Mulders and Stefano Casasso for details on these measurements

Is it **THE** Standard Model Higgs boson ?

Given H mass, the SM predicts cross section & BR precisely.
 And its quantum numbers: **$J^P = 0^+$**

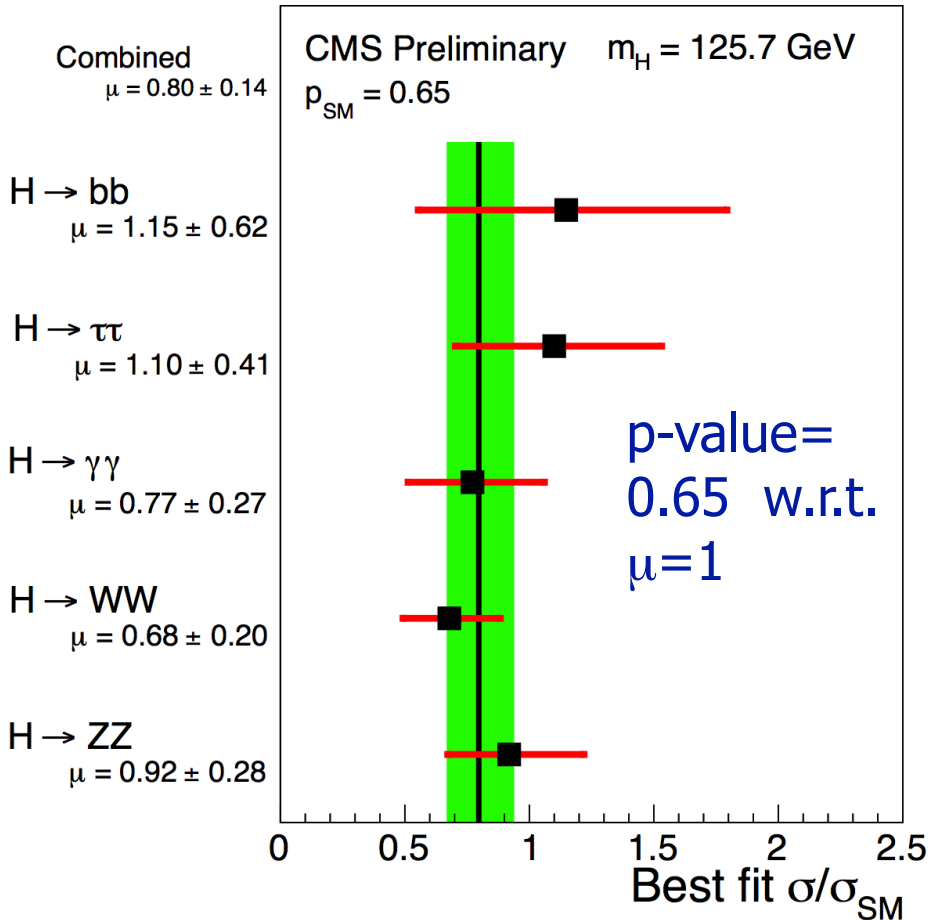


H (125) branching fraction

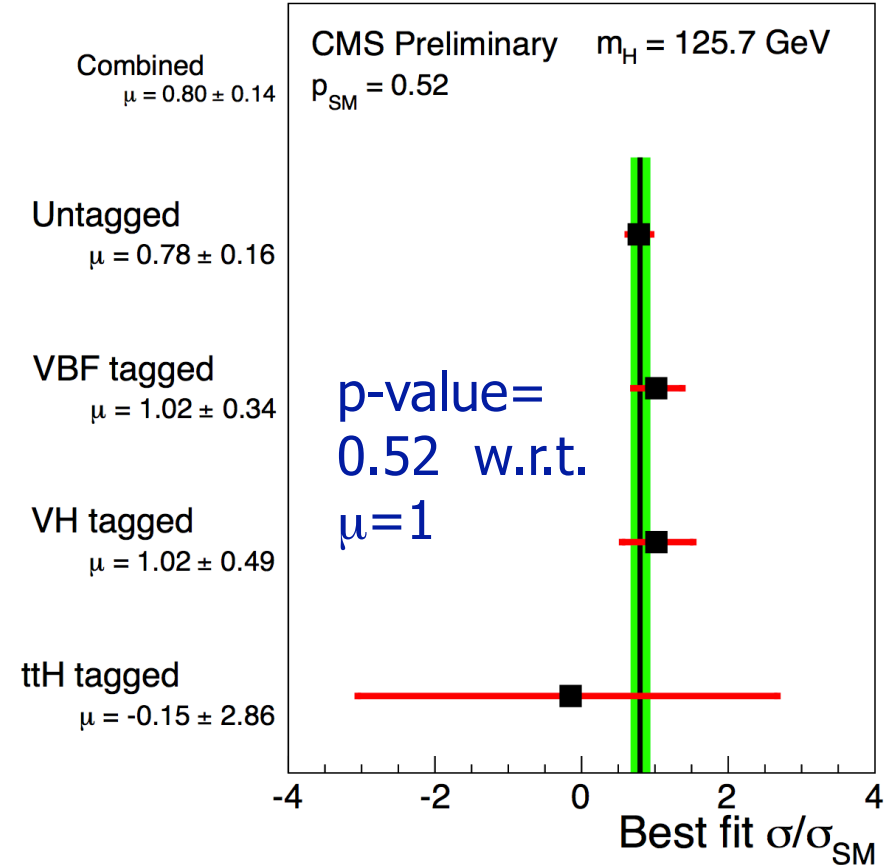
What we know from the production rate in data

Consistent with SM Higgs in all production & decay modes

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



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



Combined signal strength: $\mu = 0.80 \pm 0.14$

Spin-parity quantum numbers

Observation of Higgs signal in various decay modes already tells us something about its spin !



Spin of the decaying boson	Allowed decay channel for a boson with given spin value			
	photons	ZZ or WW	taus	b quarks
Spin 0	yes	yes	yes	yes
Spin 1	no *	yes	yes	yes
Spin 2	yes	yes	no	yes
Observed?	yes	yes	~yes	~yes

*Landau-Yang theorem → still worth testing with other decays as there are caveats

Spin-parity determination

Kinematics of production and decay of the new boson are sensitive to its spin and parity → test agreement with data for SM hypothesis and one alternative model at a time

arXiv:1208.4018

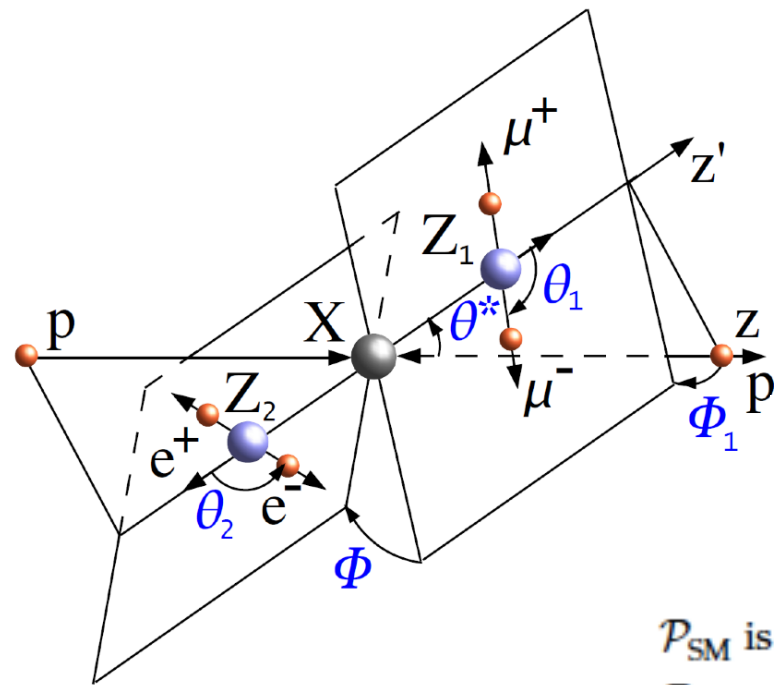
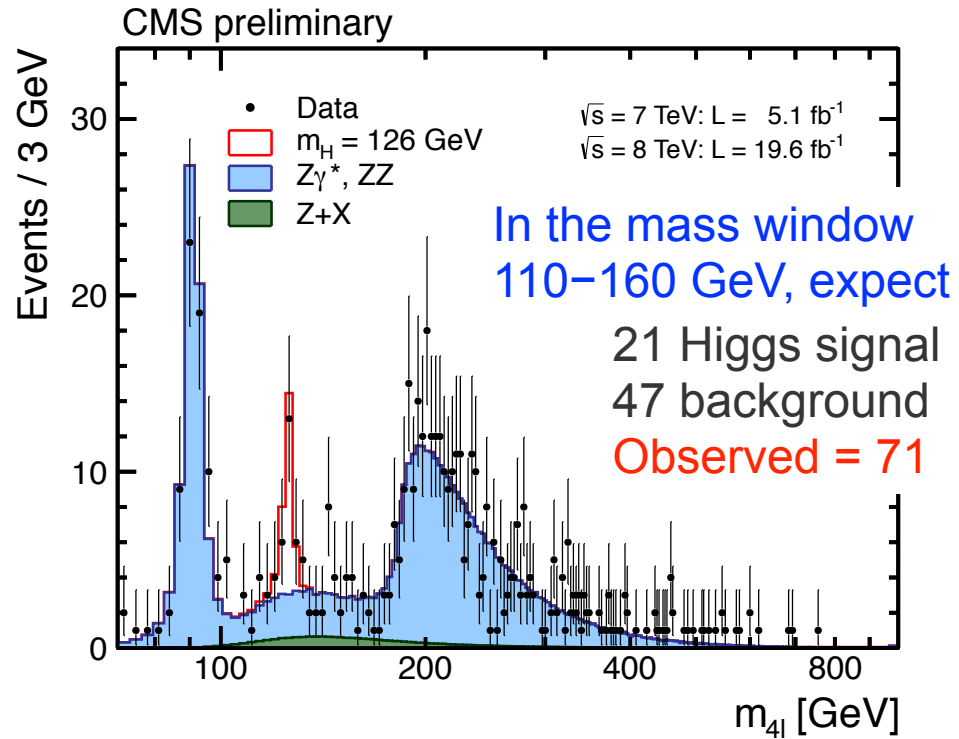
J^P	production	description
0^+	$gg \rightarrow X$	SM Higgs boson
0^-	$gg \rightarrow X$	pseudoscalar
$0^+_{h'}$	$gg \rightarrow X$	BSM scalar with higher dim operators in decay amplitude
$2^+_{m,gg}$	$gg \rightarrow X$	KK Graviton-like with minimal couplings
$2^+_{m,q\bar{q}}$	$q\bar{q} \rightarrow X$	KK Graviton-like with minimal couplings
1^-	$q\bar{q} \rightarrow X$	exotic vector
1^+	$q\bar{q} \rightarrow X$	exotic pseudovector

Couplings for alternative models not known a priori → #signal events in each channel & for each test hypothesis are treated as independent

Starting with the decay $H \rightarrow ZZ^*$

Full final state reconstruction sensitive to J^P

- 2 masses (M_{Z1}, M_{Z2}), 5 angles
- Form a matrix-element based discriminant

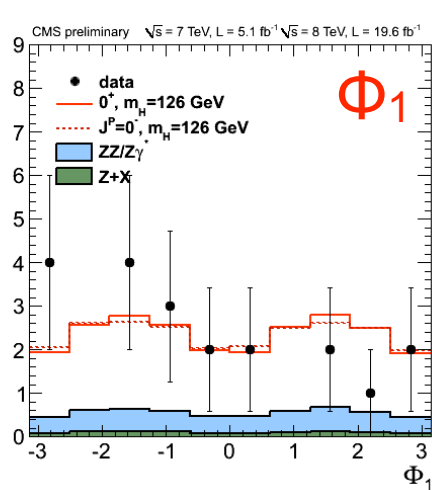
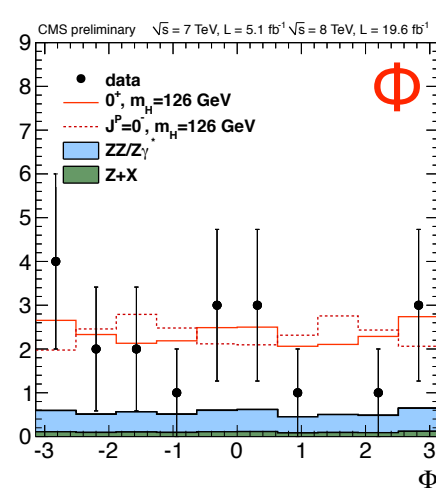
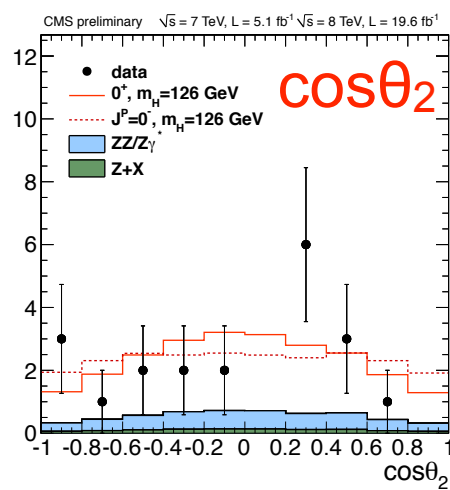
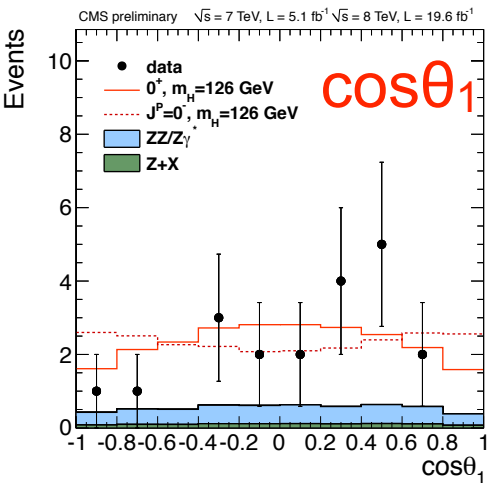
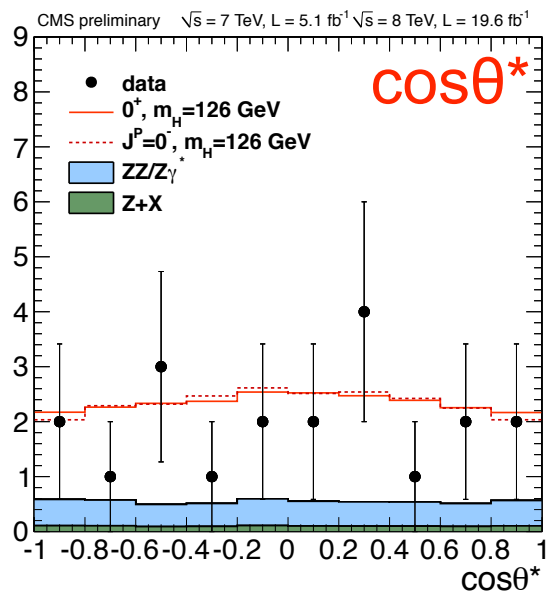
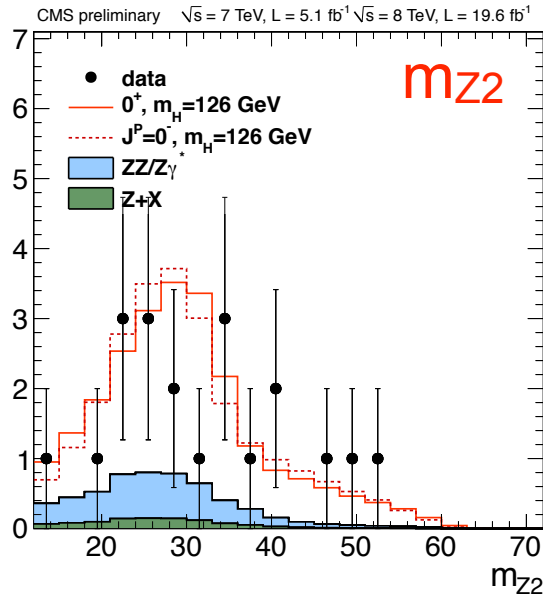
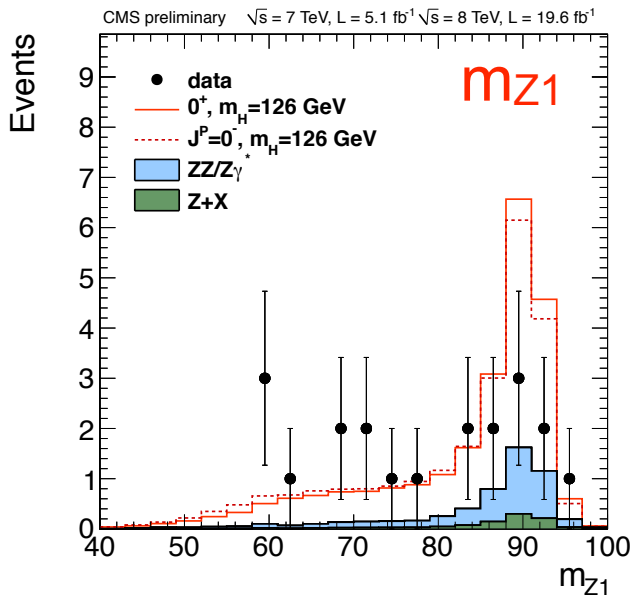


$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\text{SM}}}{\mathcal{P}_{\text{SM}} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z1}, m_{Z2}, \vec{\Omega} | m_{4l})}{\mathcal{P}_{\text{SM}}(m_{Z1}, m_{Z2}, \vec{\Omega} | m_{4l})} \right]^{-1}$$

\mathcal{P}_{SM} is the probability distribution for the SM Higgs boson hypothesis,
 \mathcal{P}_{J^P} is the probability distribution for an alternative model.

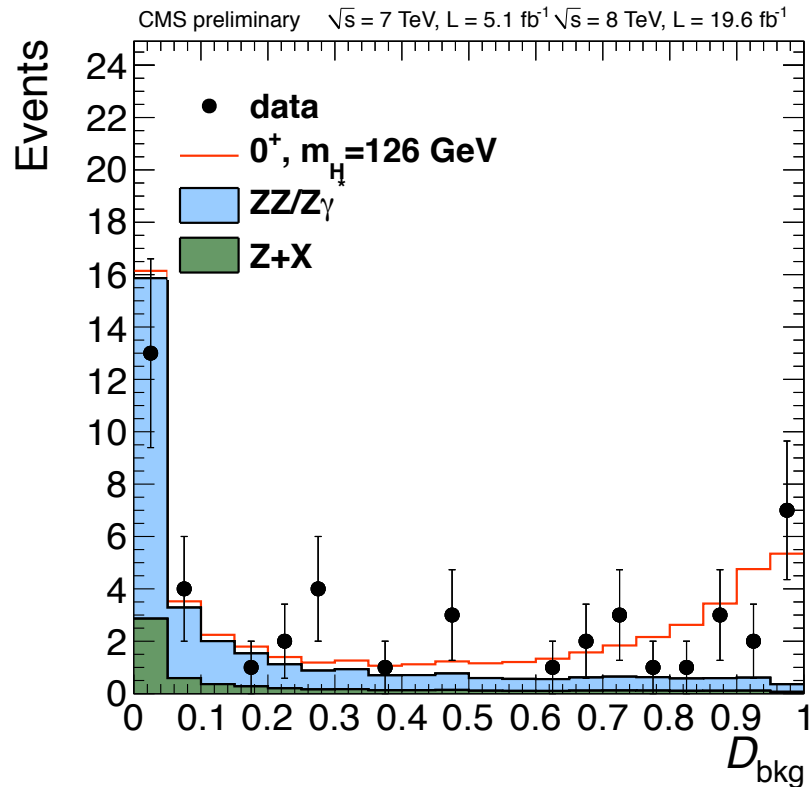
Spin-parity sensitive observables

CMS HIG-13-002



Data very consistent with $J^P = 0^+$ (i.e., SM Higgs)

CMS HIG-13-002



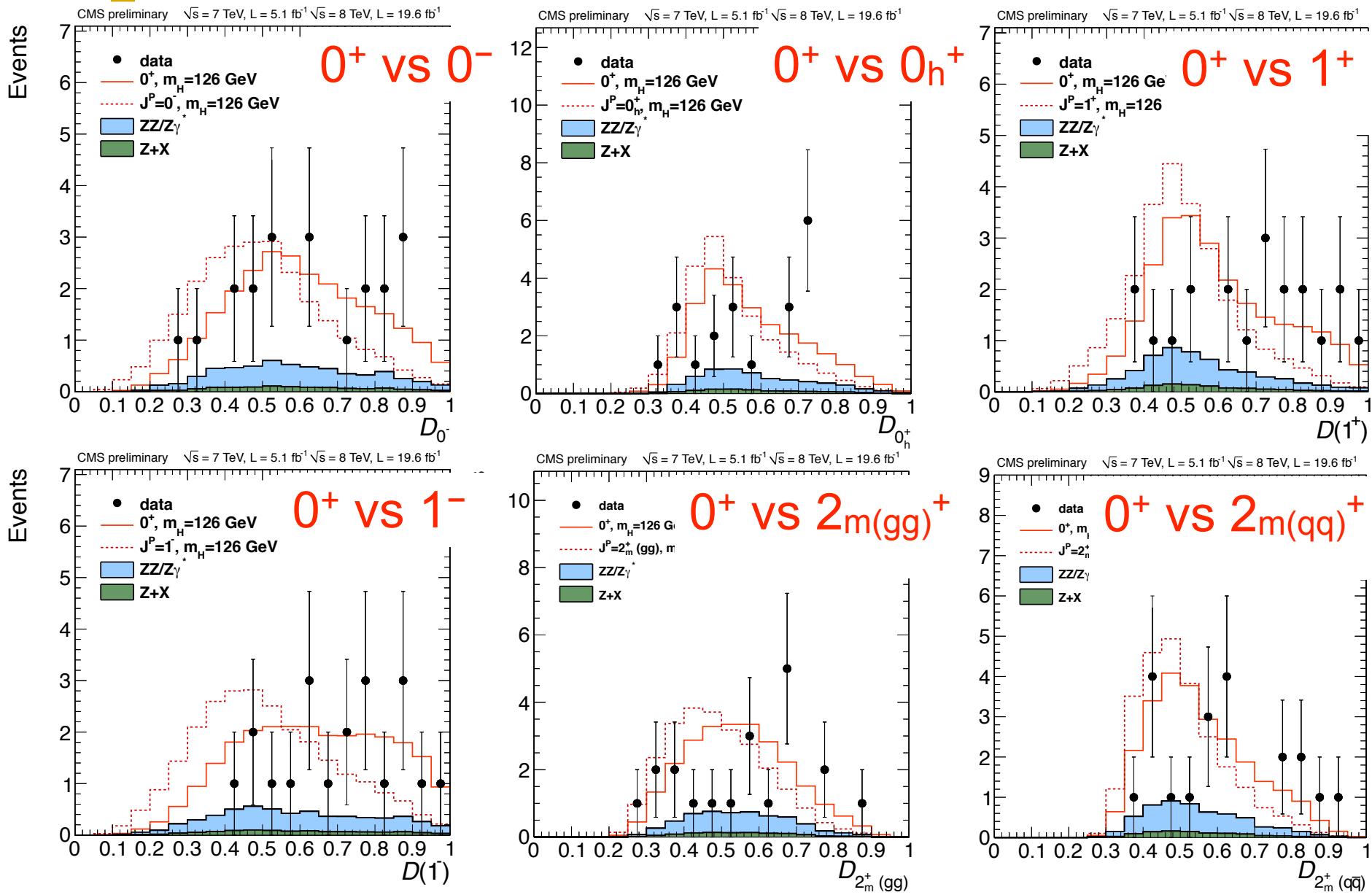
But even more interesting will be to quantify agreement with data between 0^+ and the alternative J^P .

→ Perform a 2D analysis of the $(D_{\text{bkg}}, D_{J^P})$ distributions where correlations of observables are included in the probability parameterizations.

Then examine the log-likelihood ratio $-2\ln(\mathcal{L}_{J^P} / \mathcal{L}_{\text{SM}})$ of the expected distributions, where the cross section for each type of signal is taken from a likelihood fit to data

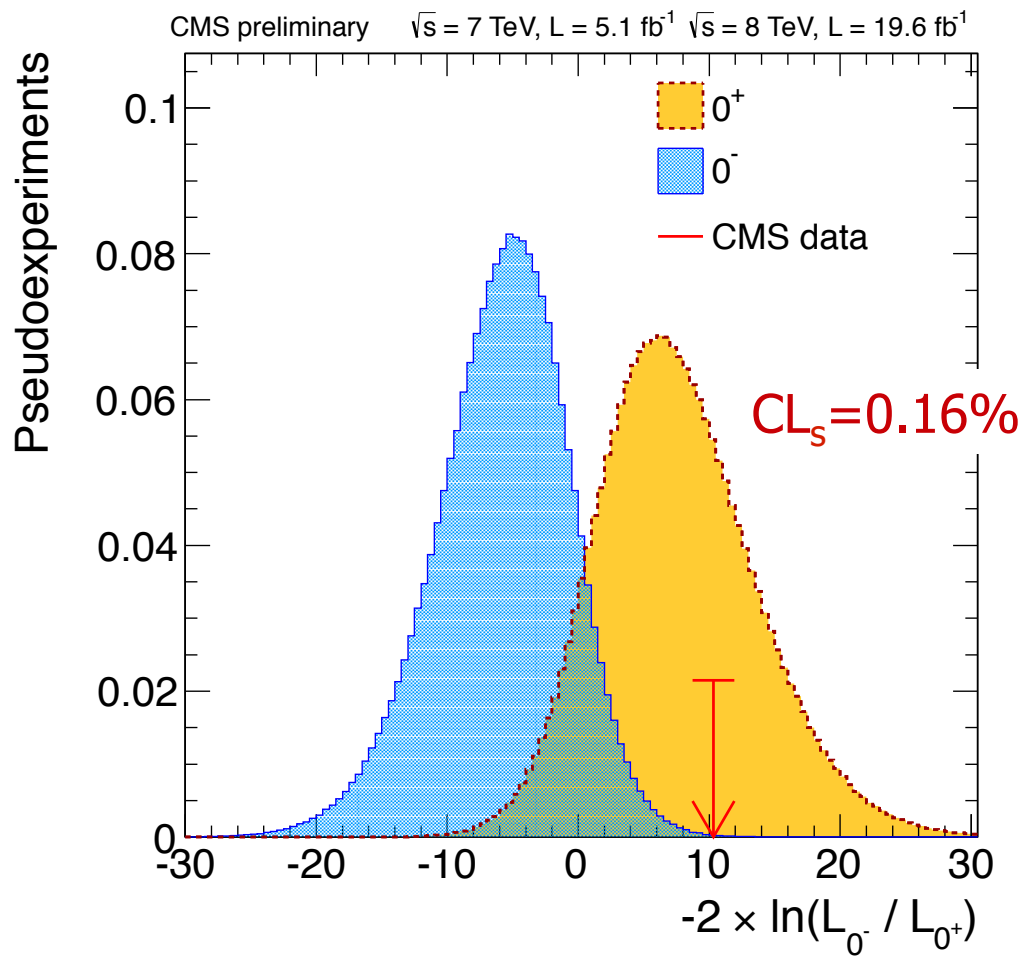
Examples of discriminant distribution

CMS HIG-13-002



Test of 0^+ versus 0^- hypotheses

CMS HIG-13-002



Data disfavor 0^- over 0^+
by CL_s value of 0.16%

More J^P hypotheses have
been tested in a similar way

J^P	CL_s
0^-	0.16%
0_h^+	8.1%
$2_{m\bar{g}g}^+$	1.5%
$2_{mq\bar{q}}^+$	<0.1%
1^-	<0.1%
1^+	<0.1%

Spin 1
disfavored
by a lot
(next three slides)

Beyond hypothesis testing: 0^+ versus 0^-

Measure **fraction of CP-violating** contribution

CMS HIG-13-002

Most general spin-0 $H \rightarrow VV$ amplitude

$$A = v^{-1} \left(\underbrace{a_1 m_Z^2 \epsilon_1^* \epsilon_2^*}_{A_1} + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \underbrace{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{A_3} \right)$$

$$= \underbrace{A_1}_{A_1} + A_2 + \underbrace{A_3}_{A_3}$$

At LO, SM $a_1 = 1$, $a_2 = a_3 = 0$

A_3 : CP odd amplitude

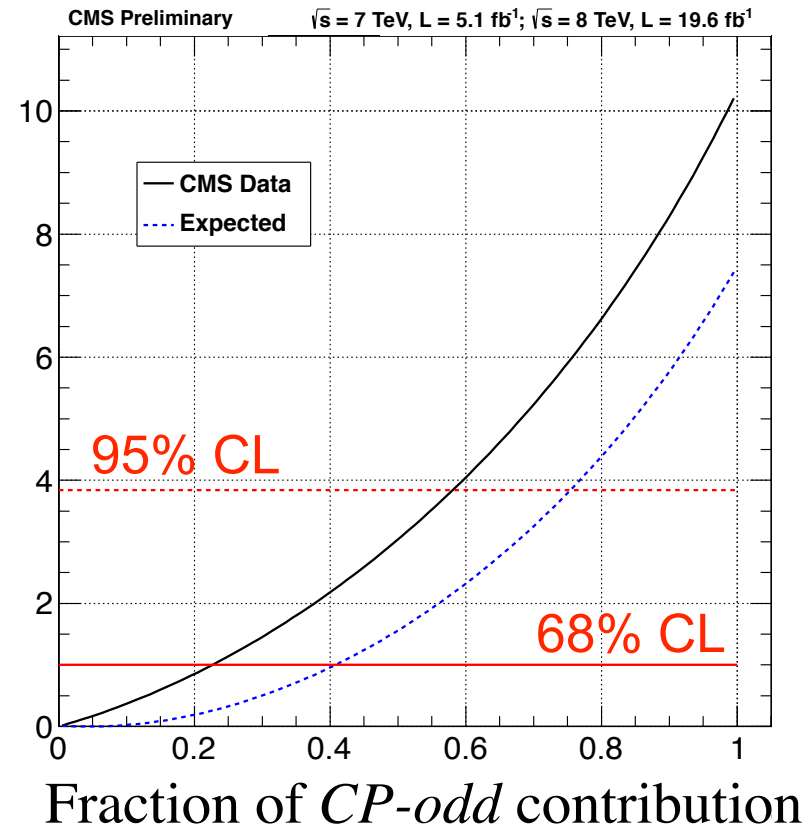
Fit for $f_{a_3} = |A_3|^2 / |A_1|^2 + |A_3|^2$

- check presence of CP violation (assume $a_2=0$, interference term negligible)

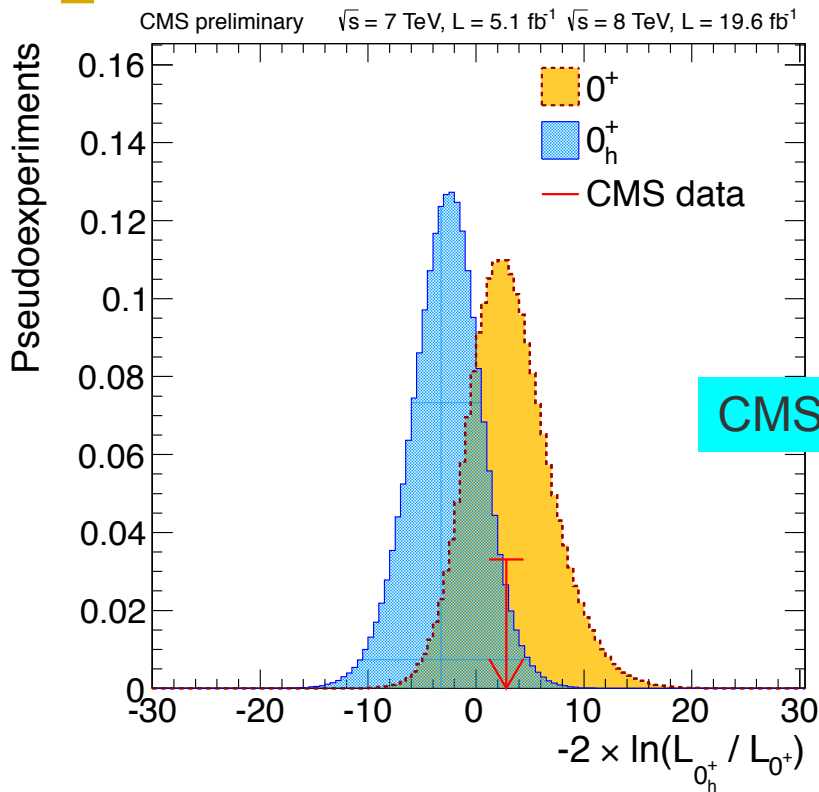
$$f_{a_3} = 0.00^{+0.23}_{-0.00}$$

$$f_{a_3} < 0.58 @ 95\%CL$$

$2\Delta \ln L$



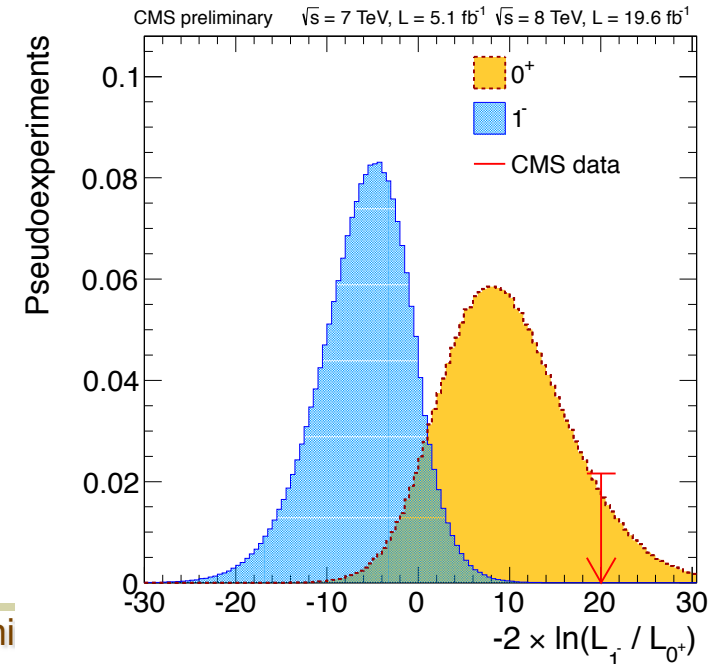
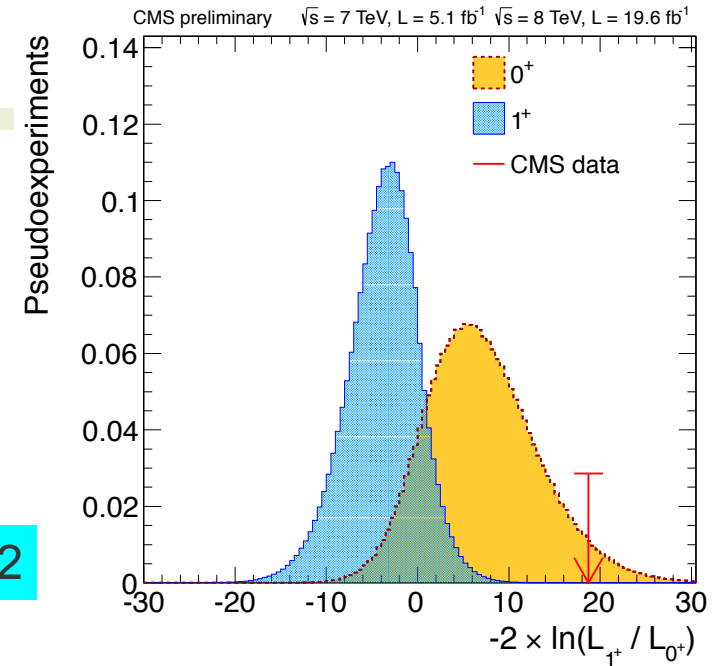
Test of 0^+ versus $[0_h^+, 1^\pm]$



CMS HIG-13-002

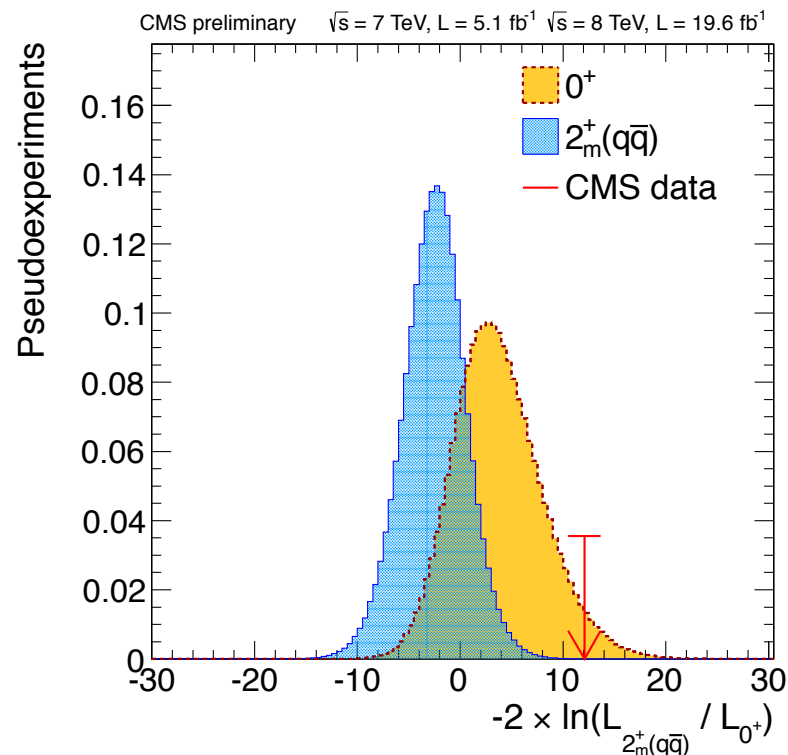
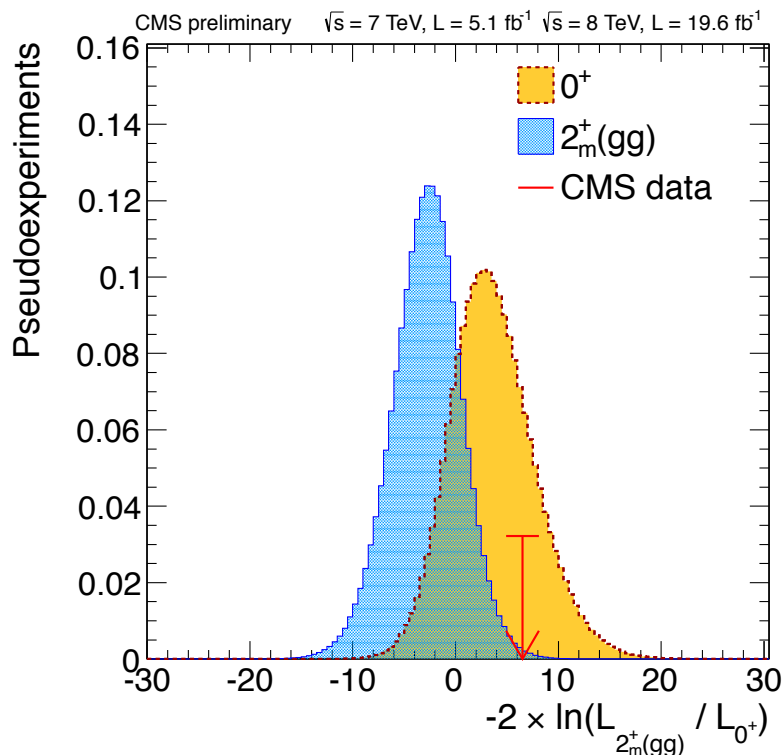
$J^P = 1^\pm$ strongly disfavored by $H \rightarrow \gamma\gamma$ decay

But if there are off-shell contributions,
Landau-Yang no longer strictly holds.
Therefore this test is more confirming.

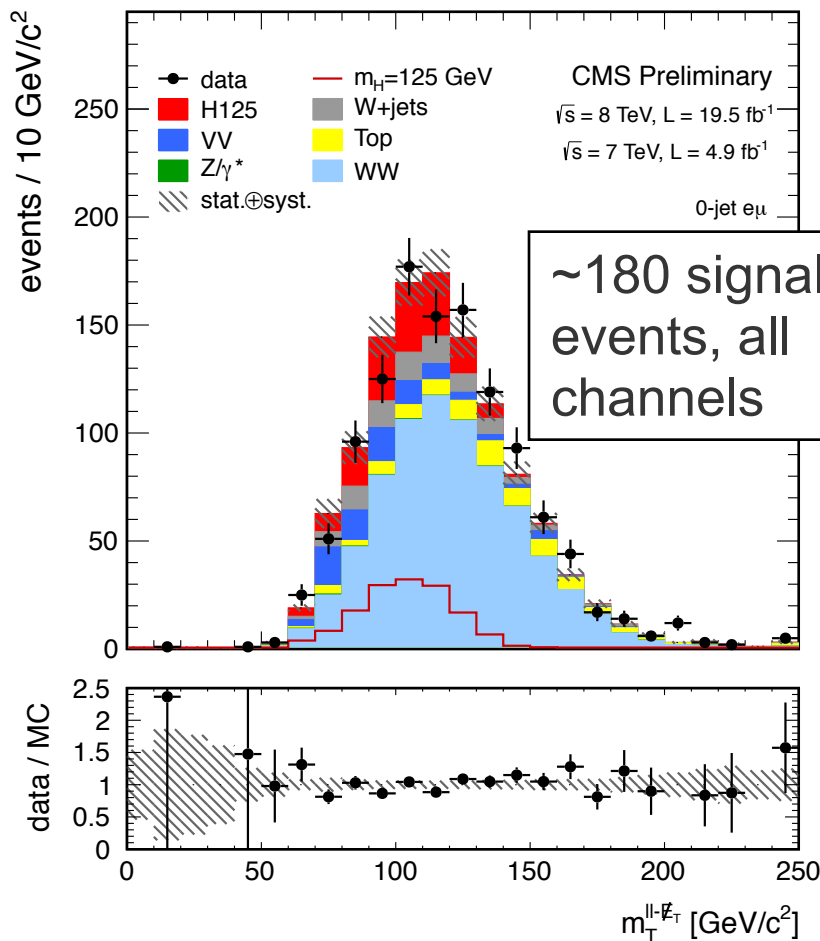


$2^+ \rightarrow$ graviton inspired models with minimal couplings

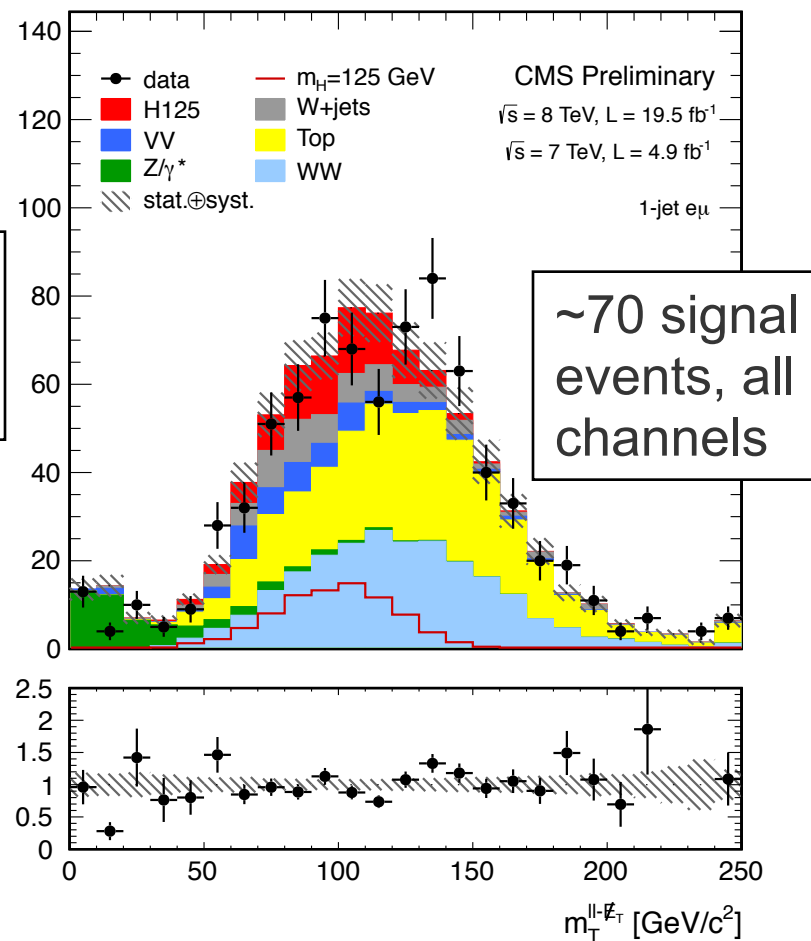
Dominant production mechanism is gluon fusion, but 4% contribution from $q\bar{q}$ at LO. Higher-order corrections can change this ratio. Therefore, consider models with different production modes admixture ($f_{q\bar{q}} \in [0, 1]$).



Can't reconstruct full event information because of two ν 's.



No additional jet



1 additional jet

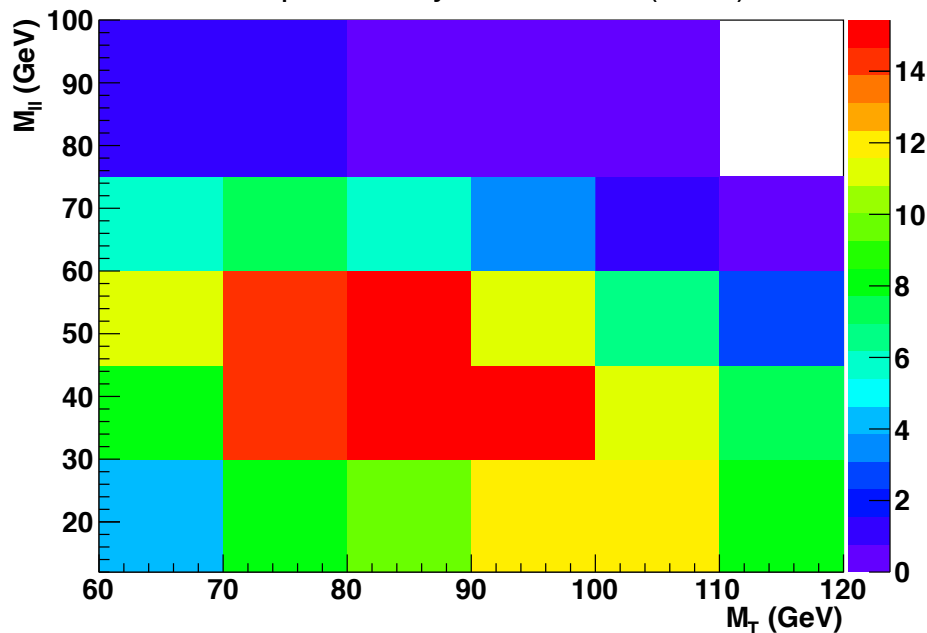
H → WW* spin analysis observables

CMS HIG-13-003

Left with essentially 2 useful variables → use 2-dimensional $m_{ll} : m_T$ distribution as the observable

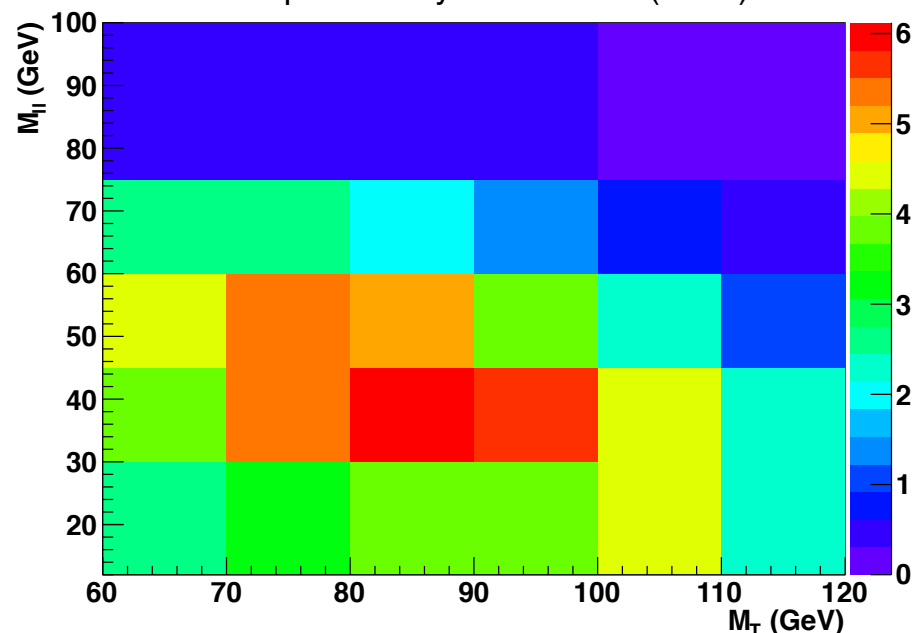
Use events in the signal region to test 0^+ vs 2^+ hypothesis

2^+_{\min} (125 GeV)
CMS preliminary L = 19.5 fb⁻¹ (8TeV)



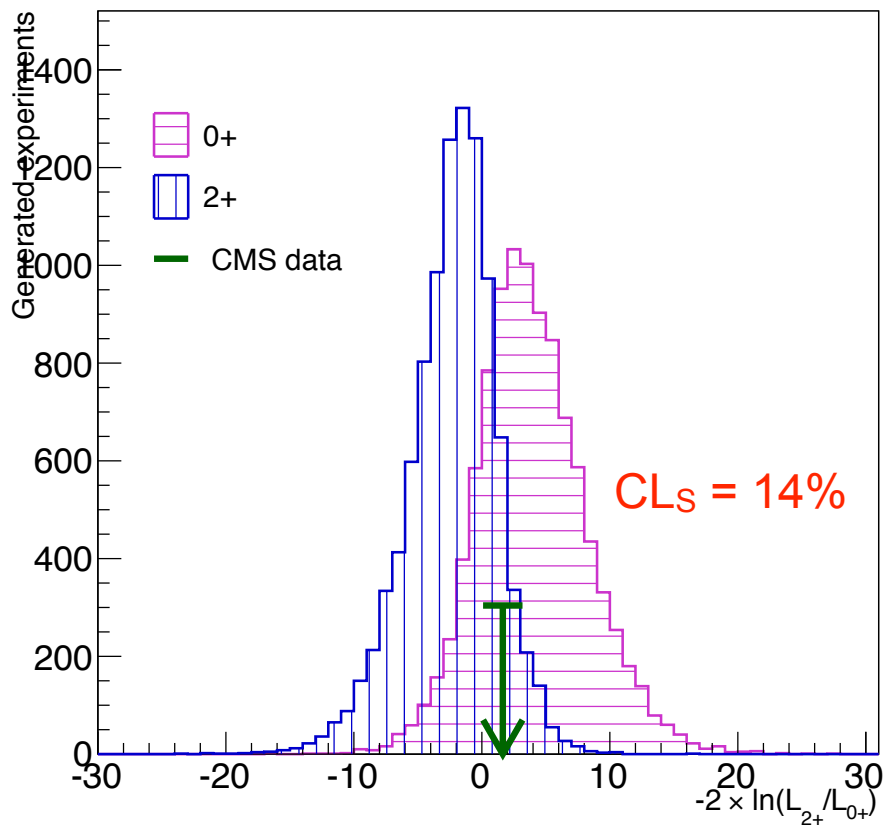
No additional jet

2^+_{\min} (125 GeV)
CMS preliminary L = 19.5 fb⁻¹ (8TeV)



1 additional jet

CMS Preliminary $\sqrt{s} = 7 \text{ TeV}, L = 4.9 \text{ fb}^{-1}; \sqrt{s} = 8 \text{ TeV}, L = 19.5 \text{ fb}^{-1}$



Combining results from WW and ZZ channels:

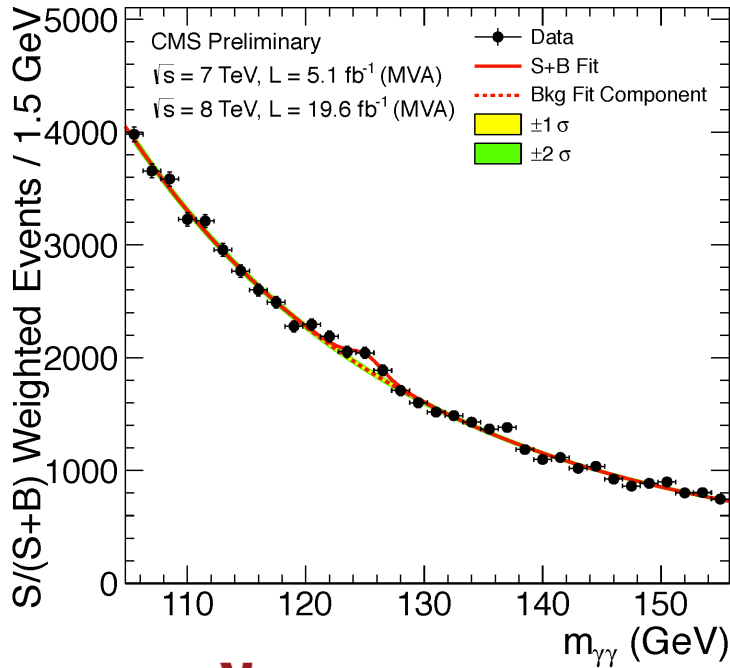
- Expected results with $\mu=1$

ZZ	WW	Comb
6.8%	1.4%	0.2%
- Observed results at measured μ

ZZ	WW	Comb
1.4%	14%	0.6%

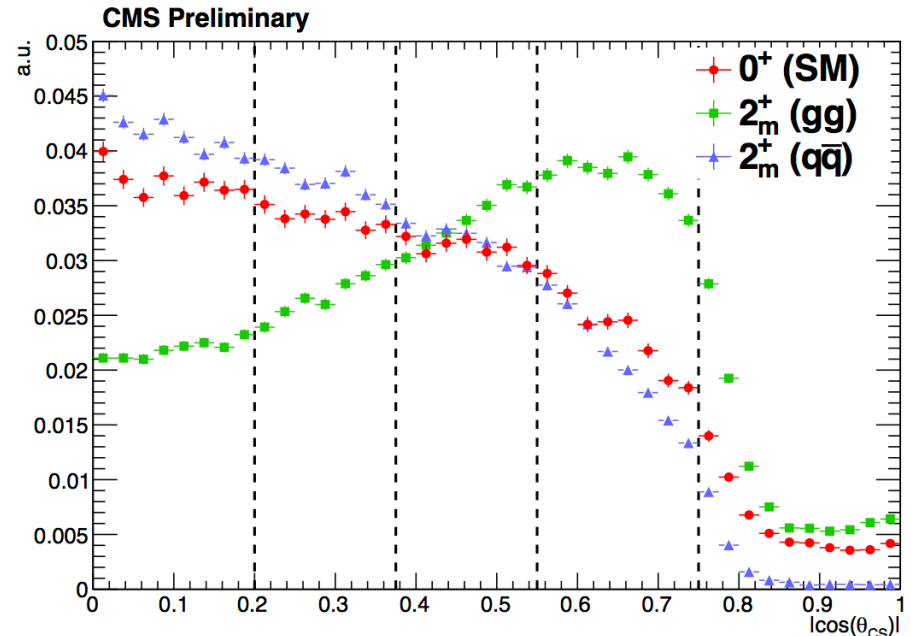
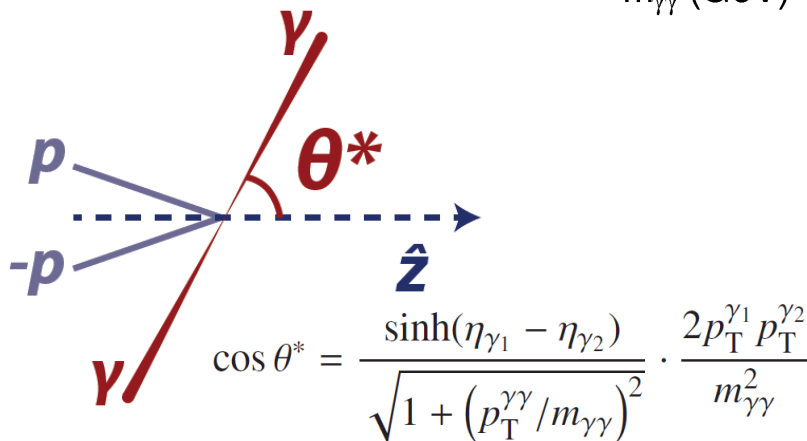
Very compatible with the SM Higgs expectations of 0^+ . **Data disfavor the $2^+_m(gg)$ hypothesis with a CL_s value of 0.6%.**

Spin analysis using the decay $H \rightarrow \gamma\gamma$

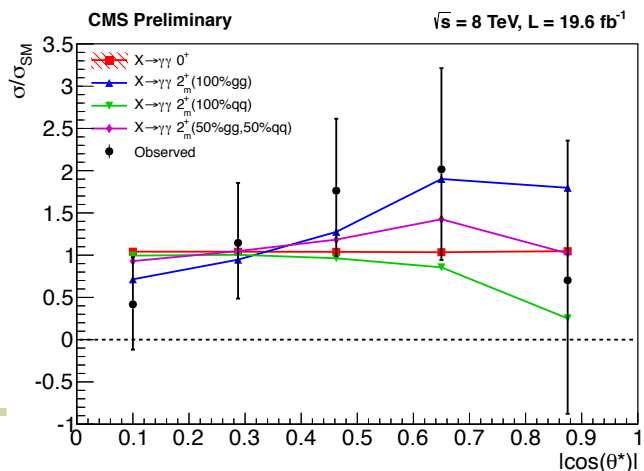
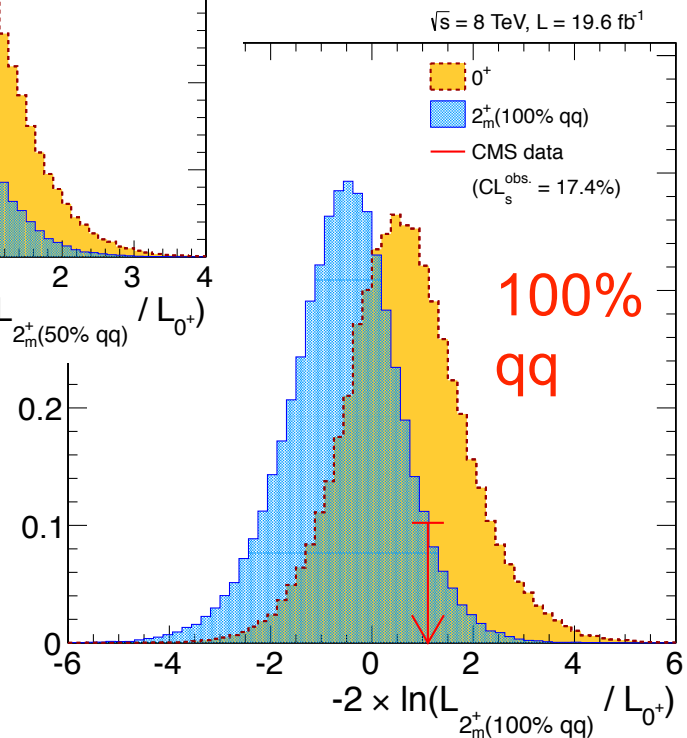
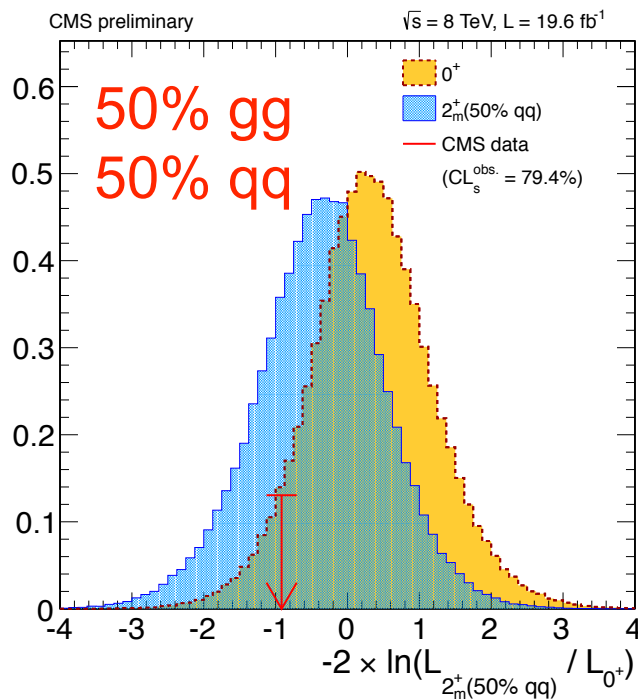
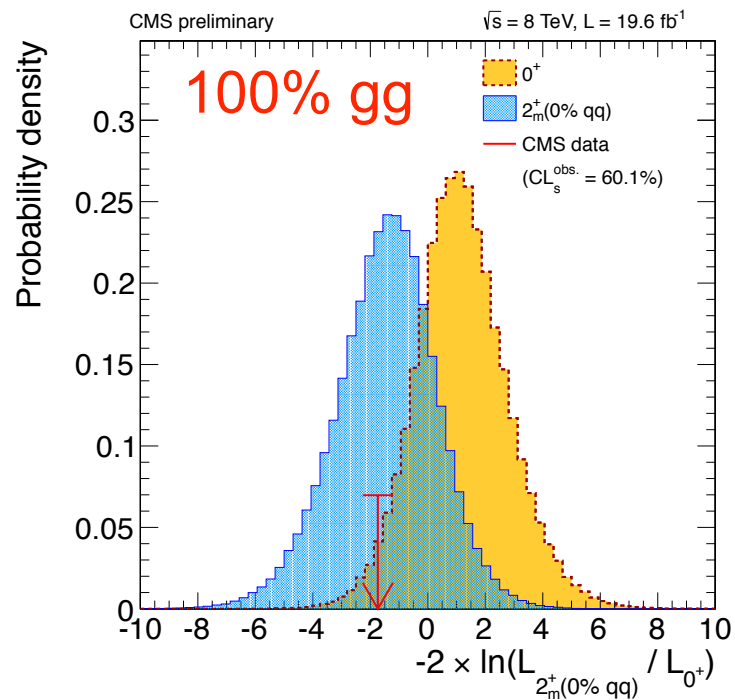


100's of Higgs signal events, but on top of a large background

Decay angle $\cos(\theta^*)$ of the photons in Collins-Soper frame sensitive to J

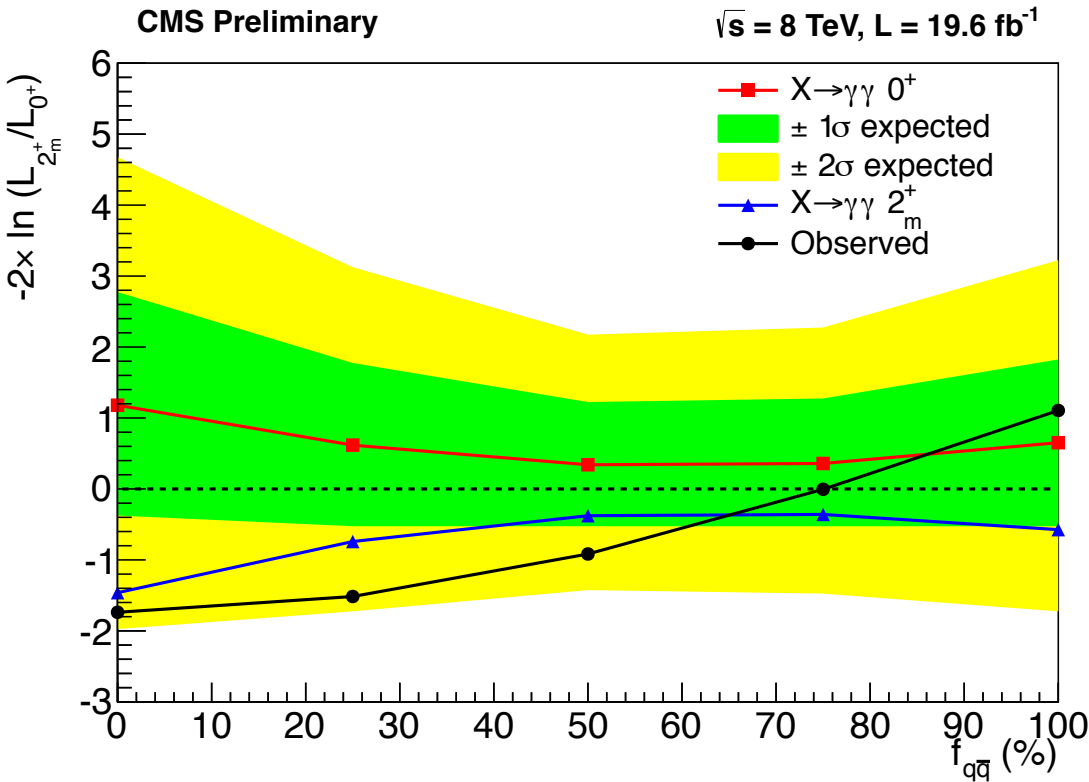


Test of 0^+ vs 2^+



As a function of the fraction of qq vs gg production

CMS HIG-13-016



Compatibility	
Source	$\chi^2 p$ -value
Data vs. 0^+	0.68
Data vs. 2_m^+ (100% gg)	0.91
Data vs. 2_m^+ (100% $q\bar{q}$)	0.51
Data vs. 2_m^+ (50% gg , 50% $q\bar{q}$)	0.81

The present $\gamma\gamma$ data do not have the power for a significant hypothesis test

Putting all channels together

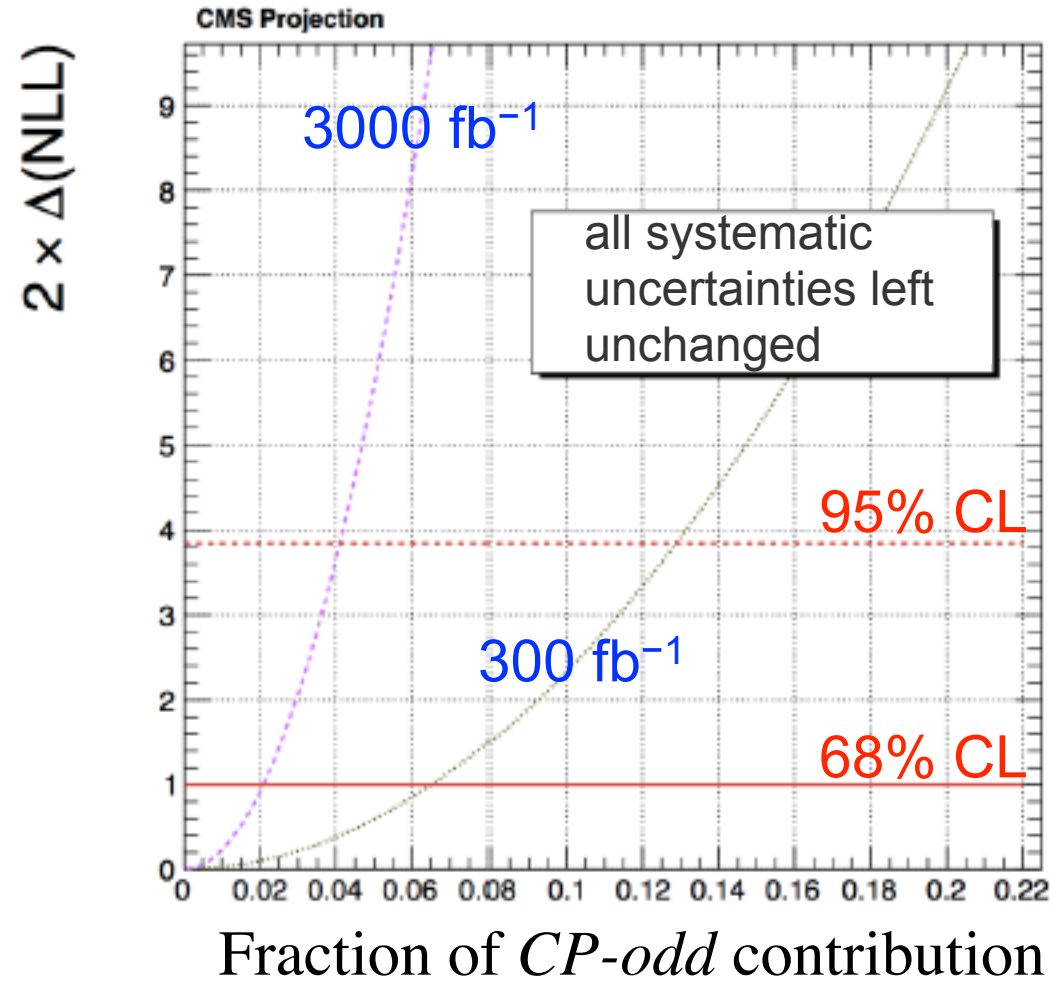
	$H \rightarrow ZZ^*$	$H \rightarrow WW^*$	Comb ZZ^* , WW^*	$H \rightarrow \gamma\gamma$
0^-	0.16%	–	–	–
0_{h^+}	8.1%	–	–	–
1^\pm	< 0.1%	–	–	N/A
$2_{m^+} (gg)$	1.5%	14%	0.6%	60.9%
$2_{m^+} (qq)$	< 0.1%	–	–	16.9%

Evidence for scalar nature 0^+ but CP admixture not completely excluded

Projection for $\sqrt{s} = 14$ TeV using $H \rightarrow ZZ^*$

CMS Submission to Snowmass

CMS-NOTE-2013-002



A 68% (95%) CL limit on CP-odd contribution can be achieved at the level of 0.07 (0.13) with 300 fb^{-1} and 0.02 (0.04) with 3000 fb^{-1} .

Summary

It has been just a year since a new boson was discovered. Thanks to the outstanding performance of the LHC, we now know a great deal more about the nature of this Higgs boson.

- ☑ Higgs quantum numbers for spin-parity tested in bosonic modes
 - Data strongly favor Standard Model 0^+ hypothesis
 - But CP admixture is not completely excluded
 - Many alternative models tested → Most excluded at 95% CL

- ☑ 2015 LHC run with higher energy/luminosity will improve the precision of these measurements
 - CP violation measurement down to 1–10% accessible

Thank you for your attention.

BACKUP SLIDES

H → γγ : Acceptance × efficiency ratio 2⁺_{m(gg)} vs 0⁺

