Higgs boson Couplings and Properties with CMS

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On behalf of the CMS Collaboration

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects
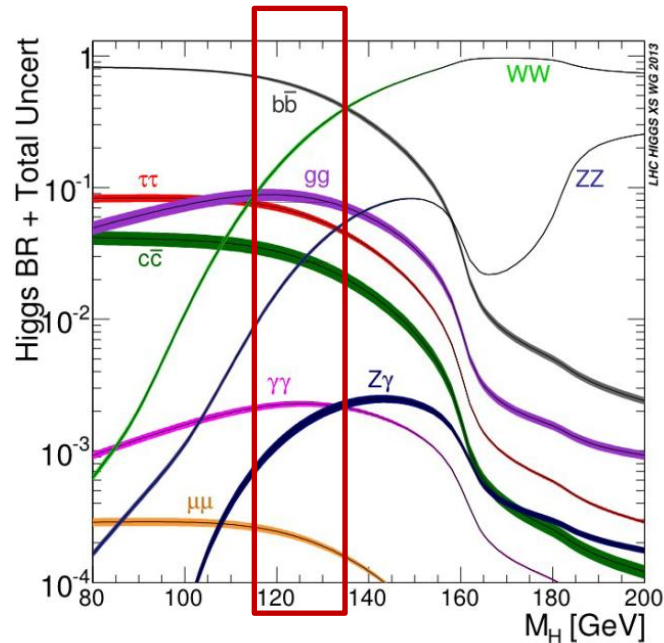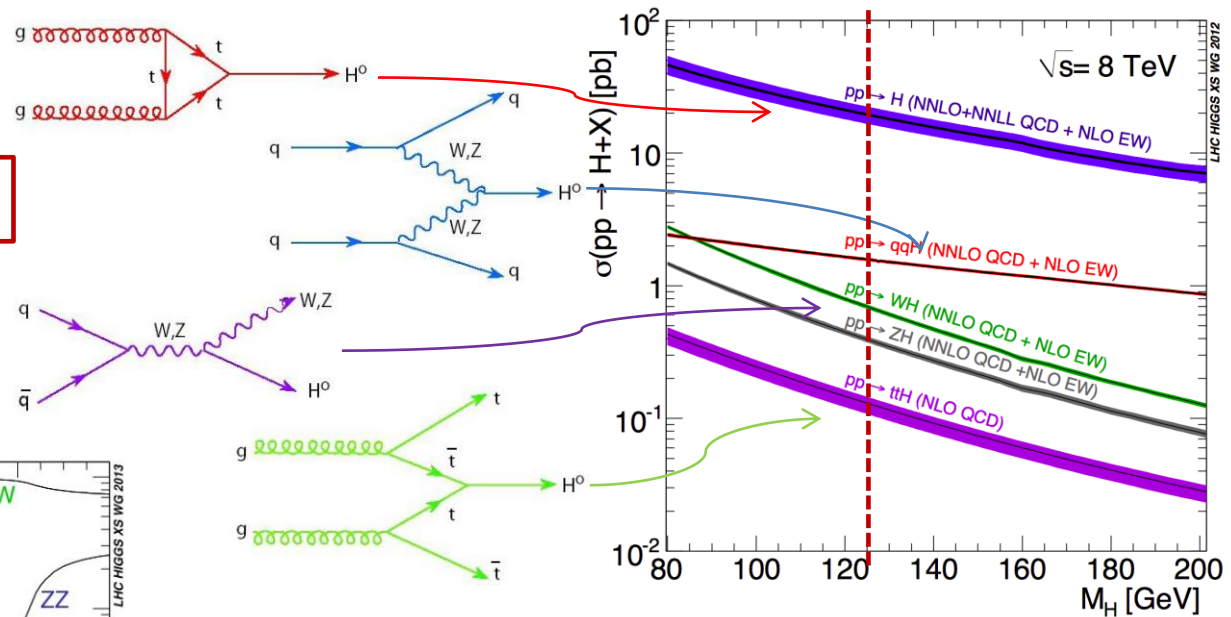
Outline

- Higgs production and decay modes

- **Properties**

    - Mass measurement

    - Spin-parity measurements

    - Width measurement

- **Couplings**

    - Production and decay mechanisms

    - Tests of the Standard Model

- Conclusions

Production and Decay Modes

4 production mechanisms

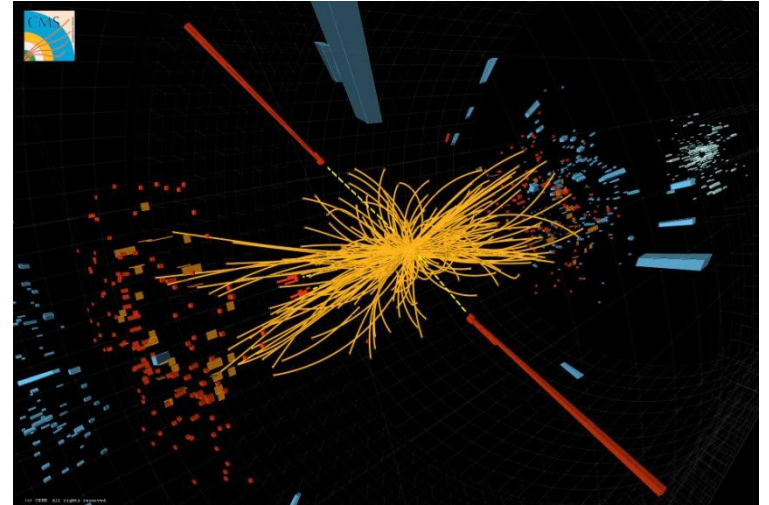**5 decay modes exploited (*WW, ZZ, γγ , bb* and *ττ*)**

MASS

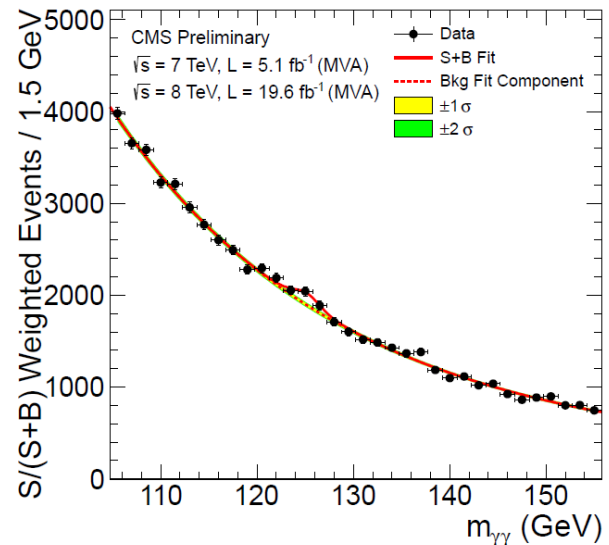# $H \rightarrow \gamma\gamma$ Decay Channel

Channel features

- Modest branching fraction
- Clear signature
    - 2 isolated and energetic γ
- Large background from QCD
- Excellent mass resolution
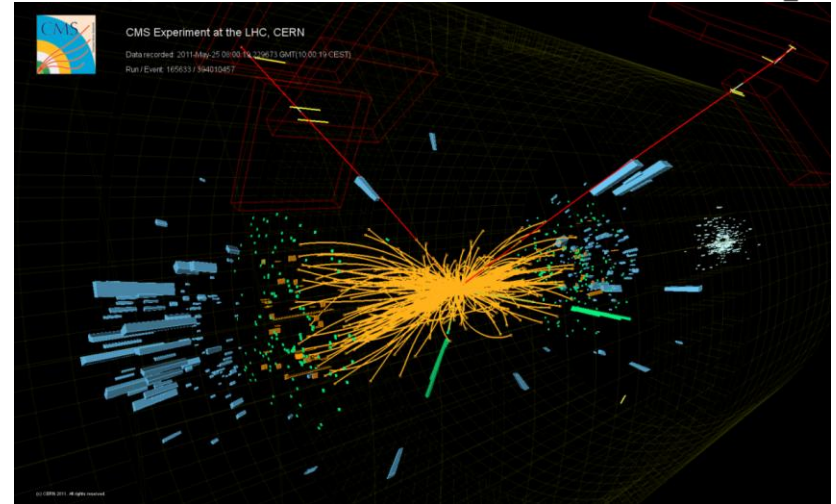
Analysis strategy

- Event categorization on photon resolution and kinematic properties
- Additional event classes according to production mechanism
- Signal extracted from background by fitting the observed diphoton mass distributions in each class
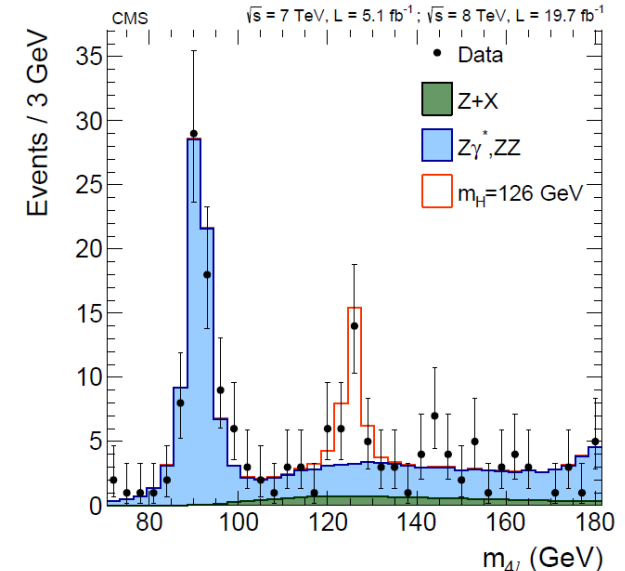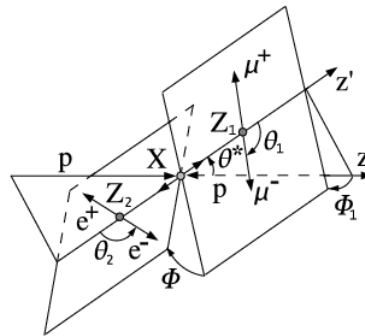
H→ZZ→4l Decay Channel

Channel features

- Very small branching fraction
- Very clean signature
  - 2 pairs of high p_T and isolated μ or e
  - full reconstructed event topology
- Small background contribution
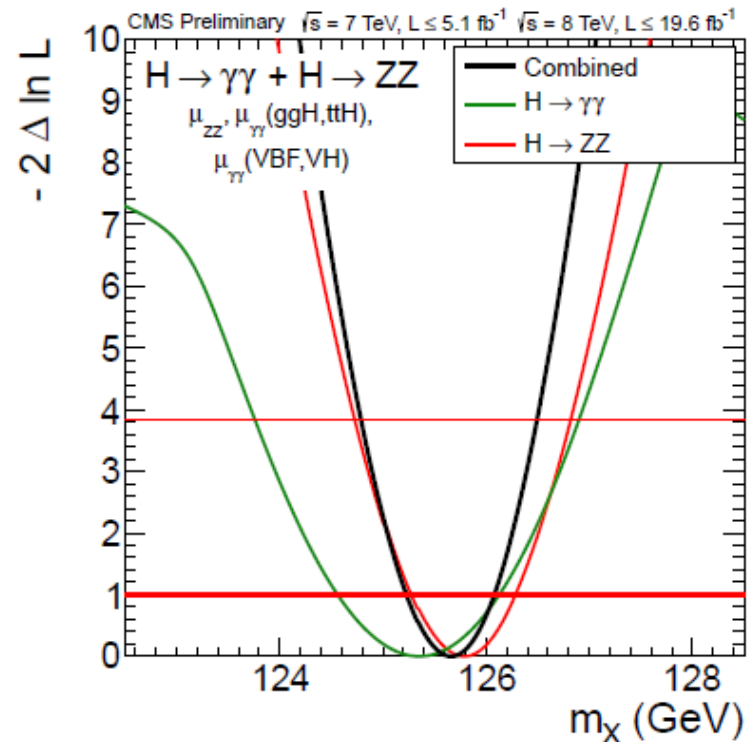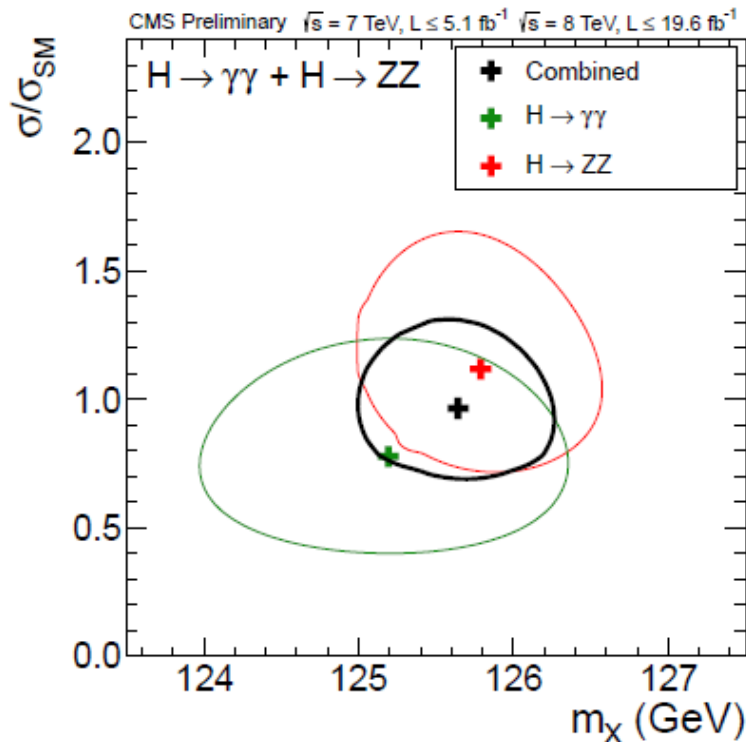- Excellent mass resolution

Analysis strategy

- Event categorization according to lepton flavor
- Mass measurement performed using 3D fit with (m_{4l}, δm_{4l}, $\mathcal{D}_{bkg}^{kin}$)

$$\mathcal{D}_{bkg}^{kin} = \frac{\mathcal{P}_{sig}^{kin}}{\mathcal{P}_{sig}^{kin} + \mathcal{P}_{bkg}^{kin}}$$

Combination

Combination of the results obtained from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ measurements, thanks to their excellent resolution

$m_H = 125.7 \pm 0.3(\text{stat.}) \pm 0.3(\text{syst.}) \text{ GeV}$

SPIN and PARITY
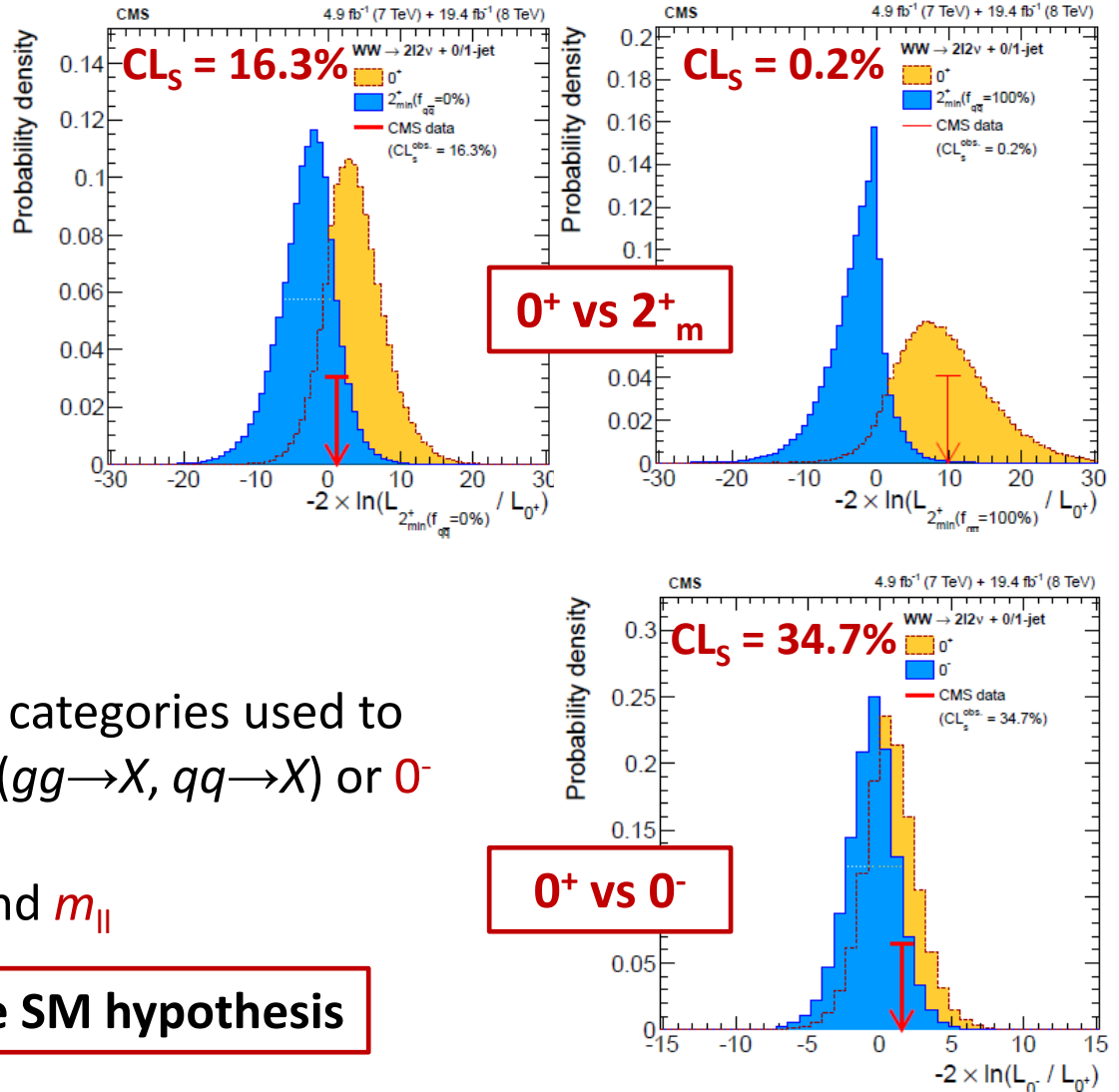
H→WW Decay Channel

Channel features

- Distinct signature
  - 2 isolated and high p_T leptons
  - small opening angle
  - missing transverse energy
- Very poor mass resolution
- Large background

CL_S = 16.3%

CL_S = 0.2%

0^+ vs 2^+_m

Analysis strategy

- Different-flavor 0-jet and 1-jet categories used to distinguish between 0^+ and 2^+_m ($gg{\to}X$, $qq{\to}X$) or 0^- ($gg{\to}X$) hypotheses
- Discriminating variables: m_T and m_{ll}

Data favor the SM hypothesis

CL_S = 34.7%

0^+ vs 0^-
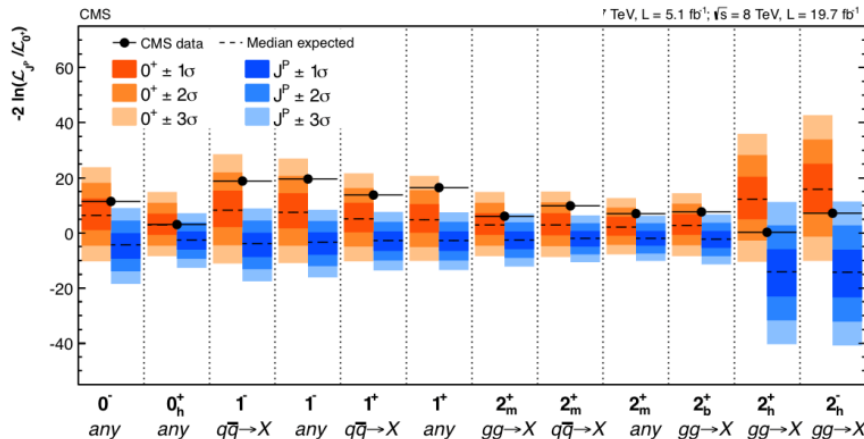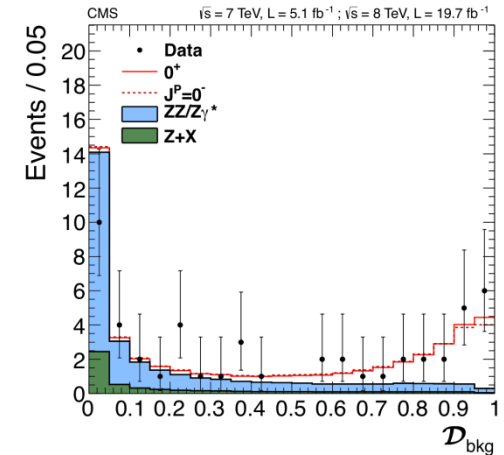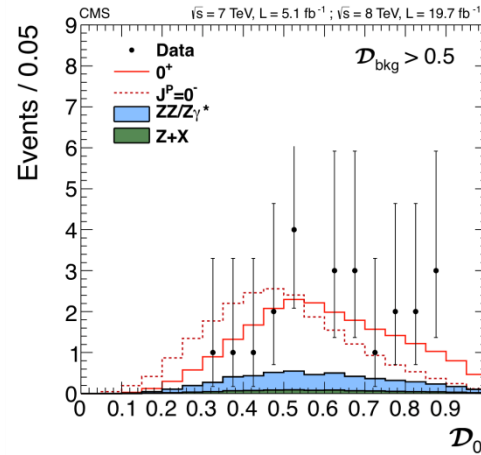
H→ZZ→4l Decay Channel

- 2D fit using $\mathcal{D}_{bkg}$ and $\mathcal{D}_{JP}$ kinematic discriminants based on angular information
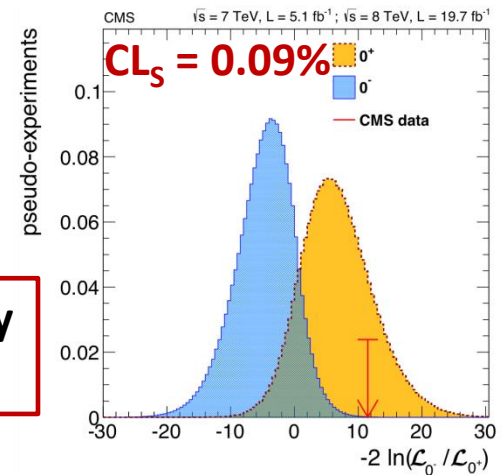
  $\mathcal{D}_{bkg}$ separates SM Higgs from background

  $\mathcal{D}_{JP}$ discriminates alternative J^P hypothesis from SM Higgs

- Twelve models tested

0⁺ vs 0⁻

0⁺ hypothesis highly favored
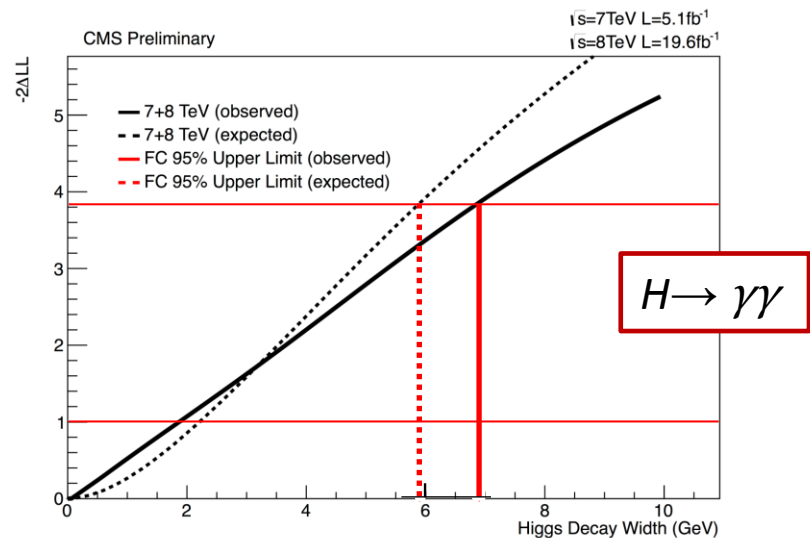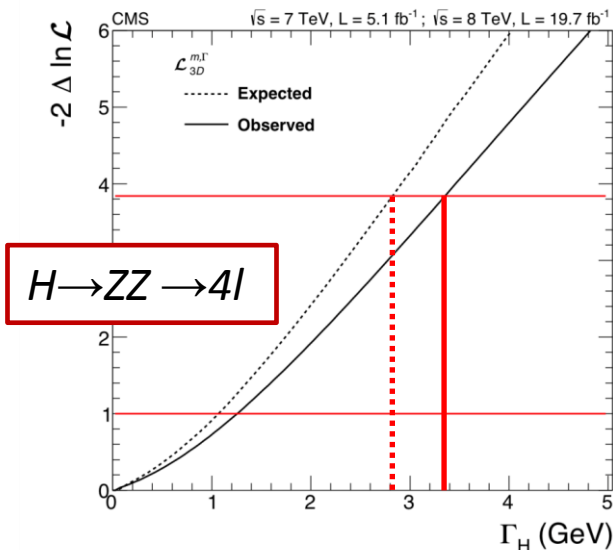
CL_S = 0.09%

WIDTH

Width Measurement

- Standard Model prediction at m_H = 125.7 GeV is **Γ ~ 4 MeV**
- Direct measurement strongly limited by experimental resolution
- Current upper limit of 3.4 (6.9) GeV at 95% C.L. in the $H{\rightarrow}ZZ{\rightarrow}4l$ ($H{\rightarrow}\gamma\gamma$) channel

Sensitivity at the resonance peak far beyond the expected width

$H{\rightarrow}ZZ{\rightarrow}4l$

$H{\rightarrow}\gamma\gamma$

Width Measurement

Goal: to constrain the Higgs boson width using the Higgs boson production and decay away from the resonance

Channels: $H\rightarrow ZZ$ decay in *4l* and *2l2v* final states

$$\sigma^{\text{on-peak}}_{\text{gg}\rightarrow\text{H}\rightarrow\text{ZZ}} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot\mathcal{B})_{\text{SM}} \equiv \boxed{\mu}(\sigma\cdot\mathcal{B})_{\text{SM}}$$

$$\kappa_g = g_{\text{ggH}}/g_{\text{ggH}}^{\text{SM}}$$

$$\kappa_Z = g_{\text{HZZ}}/g_{\text{HZZ}}^{\text{SM}}$$

$$\frac{d\sigma^{\text{off-peak}}_{\text{gg}\rightarrow\text{H}\rightarrow\text{ZZ}}}{dm_{\text{ZZ}}} = \kappa_g^2\kappa_Z^2 \cdot \frac{d\sigma^{\text{off-peak,SM}}_{\text{gg}\rightarrow\text{H}\rightarrow\text{ZZ}}}{dm_{\text{ZZ}}} = \boxed{\mu r}\frac{d\sigma^{\text{off-peak,SM}}_{\text{gg}\rightarrow\text{H}\rightarrow\text{ZZ}}}{dm_{\text{ZZ}}}$$

$$\boxed{r = \Gamma_{\text{H}}/\Gamma_{\text{H}}^{\text{SM}}}$$

- Signal strength μ provided by the measurement of the on-shell production
- r value (and Γ_{H}) can be obtained by measuring the ratio of the production in the off-shell and on-shell region

Warning: the destructive interference with continuum $gg \rightarrow ZZ$ is not negligible at high m_{ZZ}
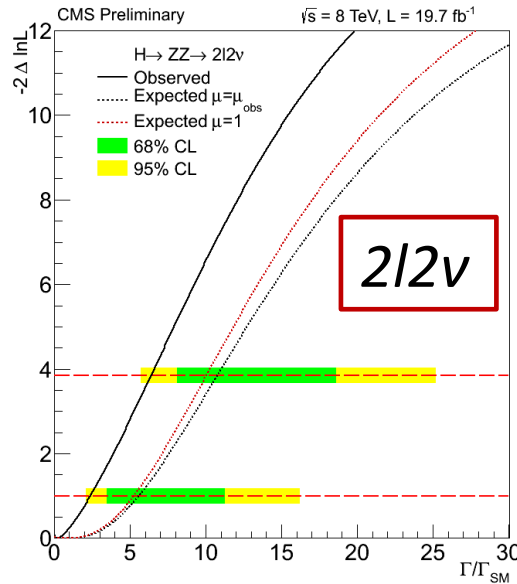
Width Measurement

To describe all the different contributions to the final state, a likelihood is defined, depending on:
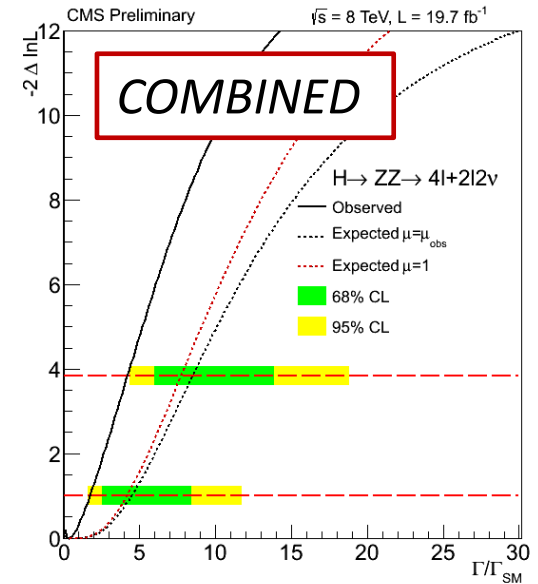
- **4l final state**: m_{4l} and a kinematic discriminant $\mathcal{D}_{gg}$, to separate $gg \rightarrow ZZ$ and $qq \rightarrow ZZ$ processes
- **2l2ν final state**: m_T and E_T^{miss}
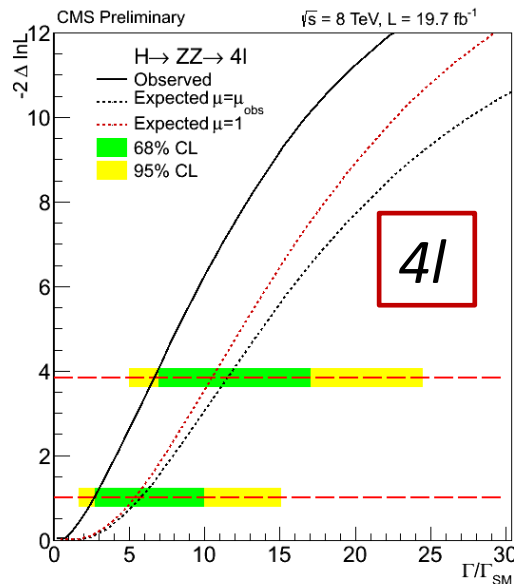
$\Gamma_H / \Gamma_H^{SM} < 6.6\ (11.5)$

$\Gamma_H / \Gamma_H^{SM} < 6.4\ (10.7)$

$\Gamma_H / \Gamma_H^{SM} < 4.2\ (8.5)$
$\Gamma_H < 17.4$ MeV

COUPLINGS

The Couplings

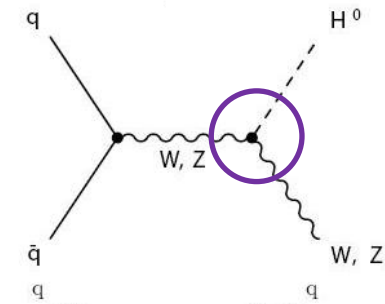$$\sigma \times BR(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

- σ_{ii} and Γ_{ff} are proportional to the square of effective Higgs boson couplings to the corresponding particle ($\sigma_{ii} \sim g_i^2$, $\Gamma_{ff} \sim g_f^2$)
- To test SM deviations, modified couplings are defined, denoted by scale factors k_i

Example: $gg \to H \to \gamma\gamma$

$$\sigma \cdot BR(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \, \kappa_\gamma^2}{\kappa_H^2}$$
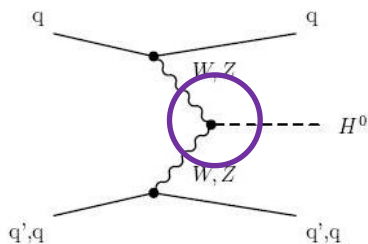
Significant deviations of any k from 1 would imply physics beyond the SM
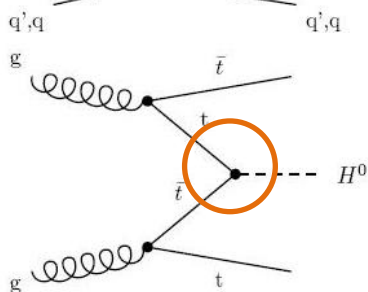
Production Mechanisms

VH
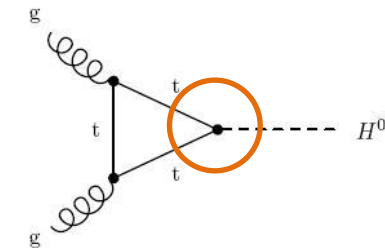Leptons, missing E_T or low-mass dijets from *W* or *Z* decays

VBF
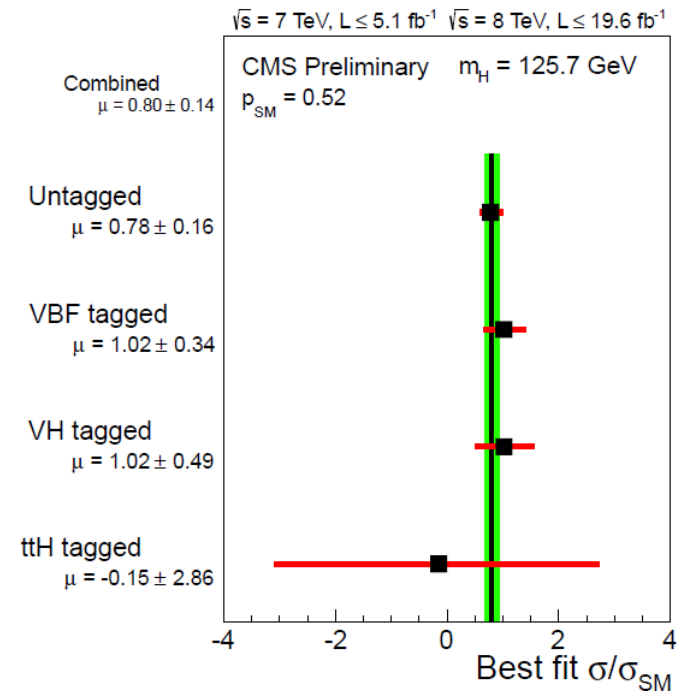Two high p_T jets with high-mass and large pseudorapidity separation

ttH
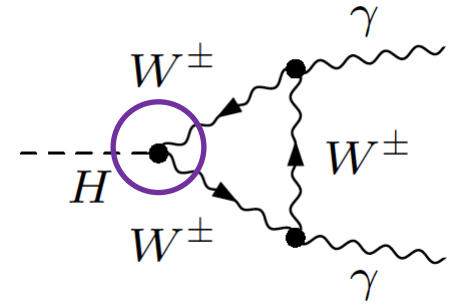Two top quarks: leptons, missing E_T, multijets or b-tagged jets

ggF
The rest

	Bosons
	Fermions

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

CMS Preliminary m_H = 125.7 GeV
p_{SM} = 0.52

Combined
$\mu = 0.80 \pm 0.14$

Untagged
$\mu = 0.78 \pm 0.16$

VBF tagged
$\mu = 1.02 \pm 0.34$

VH tagged
$\mu = 1.02 \pm 0.49$

ttH tagged
$\mu = -0.15 \pm 2.86$

Best fit σ/σ_{SM}
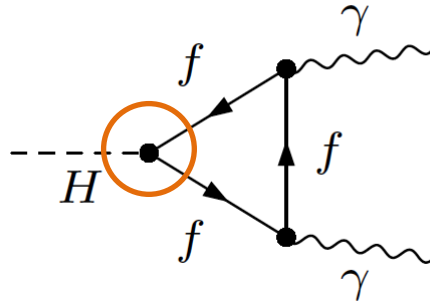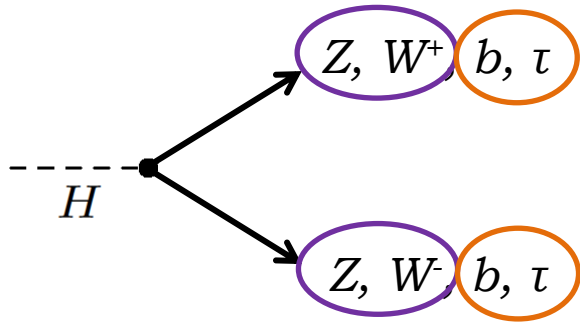
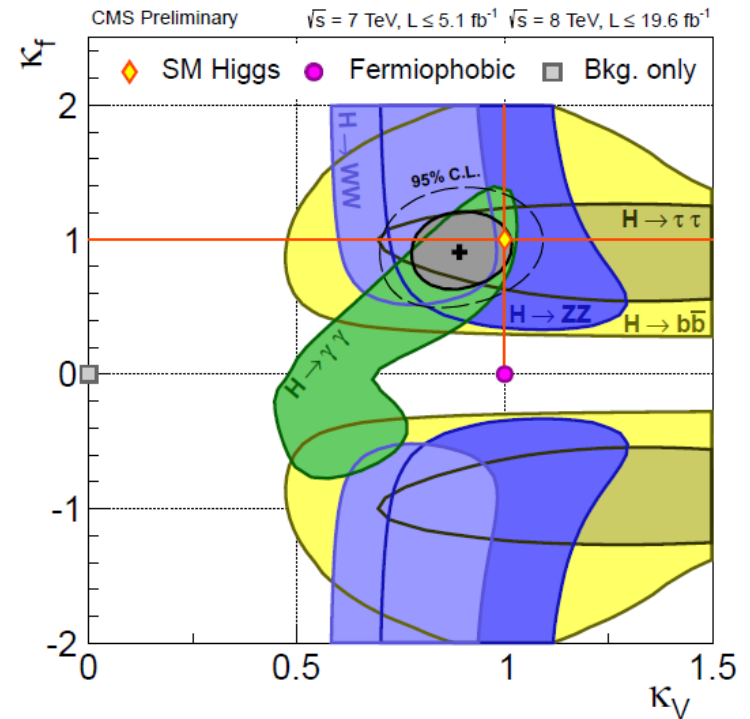# Vector Boson and Fermion Couplings

- At L.O. all partial widths scale either as k_V^2 or k_f^2, except for $\Gamma_{\gamma\gamma}$ that scales as $|\alpha k_V + \beta k_f|^2$

➡ $\gamma\gamma$ channel is sensitive to the relative sign of k_V and k_f
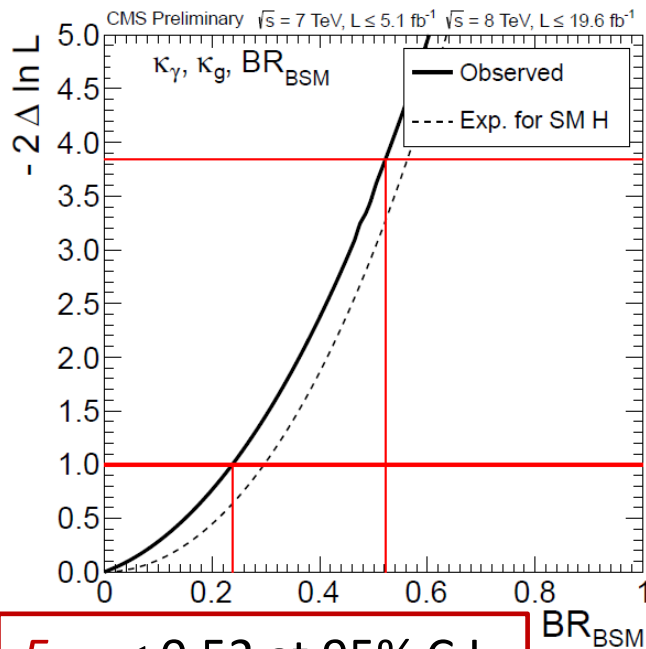
Anomalous $k_f < 0$ disfavored at ~ 2.7σ

Data are consistent with the expectation

Search for New Physics
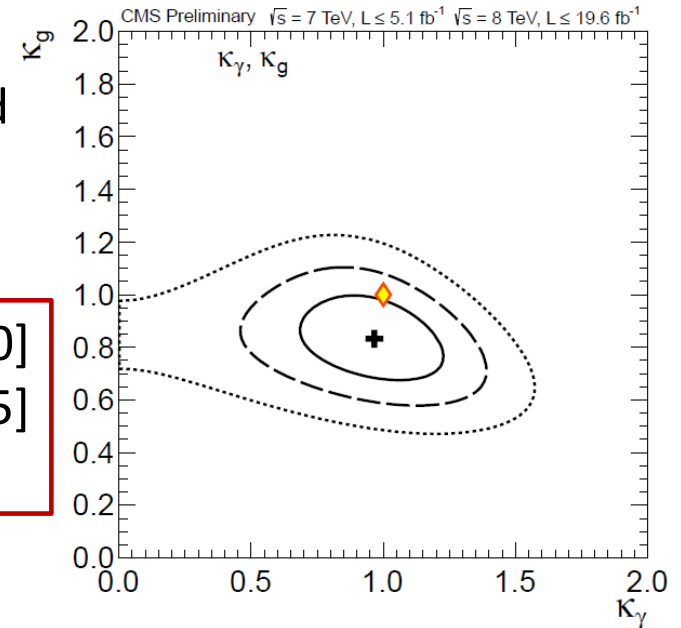
- Processes induced by loop diagrams ($H \to \gamma\gamma$ and $gg \to H$) are particularly sensitive to new physics

➡ Data fitted for k_γ and k_g

$k_\gamma \in [0.59, 1.30]$
$k_g \in [0.63, 1.05]$
at 95% C.L.

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

κ_γ, κ_g

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

$\kappa_\gamma, \kappa_g, BR_{BSM}$

— Observed
--- Exp. for SM H

- Higgs could decay into invisible particles or not detectable at LHC

➡ Modified total Higgs width, left free to float in the fit

$\Gamma_{BSM} < 0.52$ at 95% C.L.

Results are compatible with the expectation

Conclusions

- The mass of the analyzed resonance is measured with high precision

- The particle is compatible within uncertainties with a SM Higgs boson and alternative spin-parity hypotheses are disfavored by the data

- The experimental constraint on Higgs total width is determined using off-shell production and decay, improving by more than two orders of magnitude the previous experimental result

- A comprehensive set of Higgs coupling fits is reported and no significant deviation from SM predictions is observed within the uncertainties

Backup

Bosonic Decay Modes
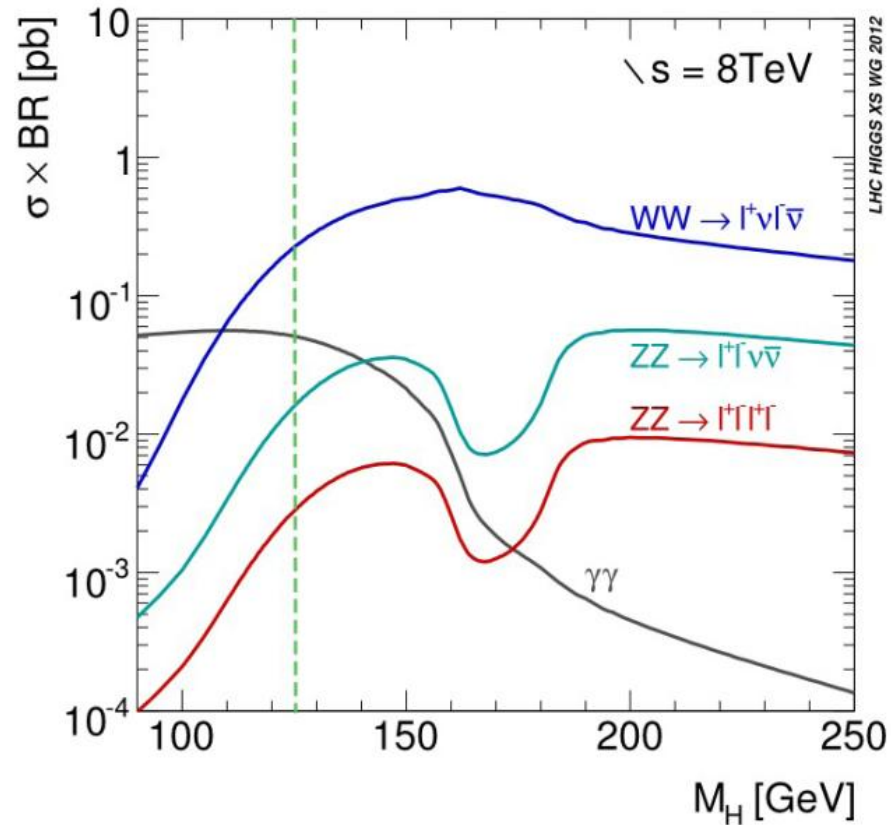
Kinematic Discriminant

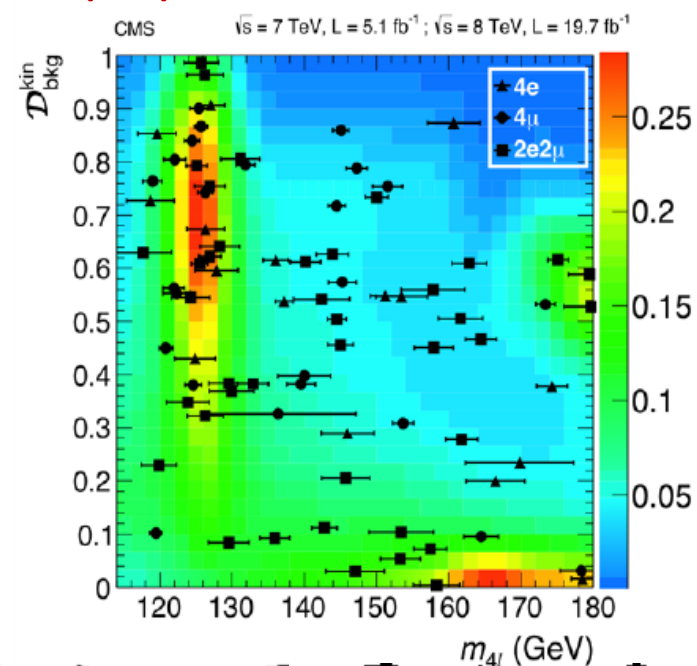Signal/background kinematic discriminant defined using matrix element techniques

$$\mathcal{D}_{bkg}^{kin} = \frac{\mathcal{P}_{sig}^{kin}}{\mathcal{P}_{sig}^{kin} + \mathcal{P}_{bkg}^{kin}}$$
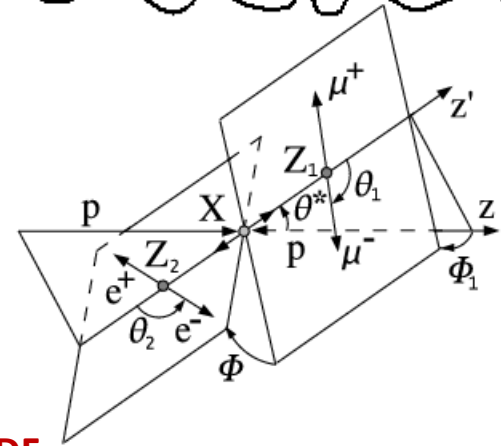
121.5 < m$_{4l}$ < 130.5 GeV
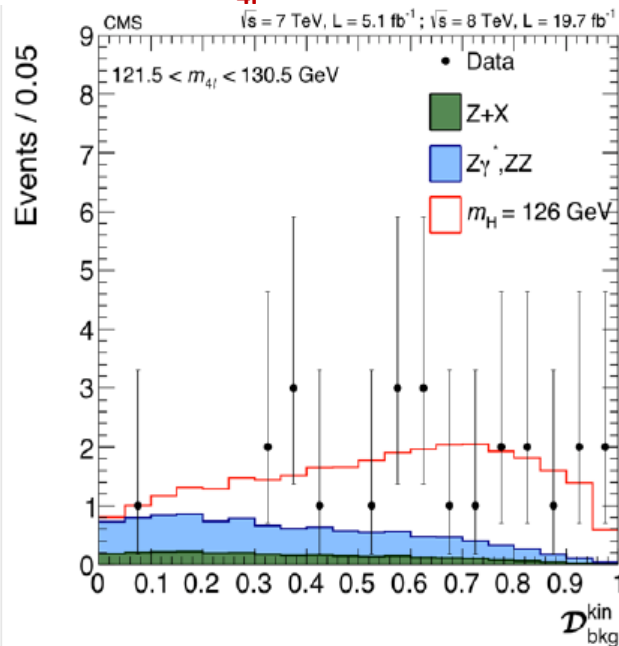
H(126) 2D PDF

# Mass Systematic Uncertainties

$H \rightarrow ZZ \rightarrow 4l$

source	systematic uncertainties
Muon momentum scale uncertainty	± 0.1% (4μ)
Electron energy uncertainty	± 0.3% (4e)

$H \rightarrow \gamma\gamma$

source	systematic uncertainties
non linearity when extrapolating from Z	± 0.4%
upstream material simulation	± 0.25%

$H \rightarrow \gamma\gamma$ Decay Channel

- 2^+_m hypothesis tested (direct decay of a spin-1 particle into $\gamma\gamma$ forbidden by the Landau-Yang theorem)
- Discriminating variable: *cos(θ*)*
  - ➡ photons from a spin-0 particle are isotropic
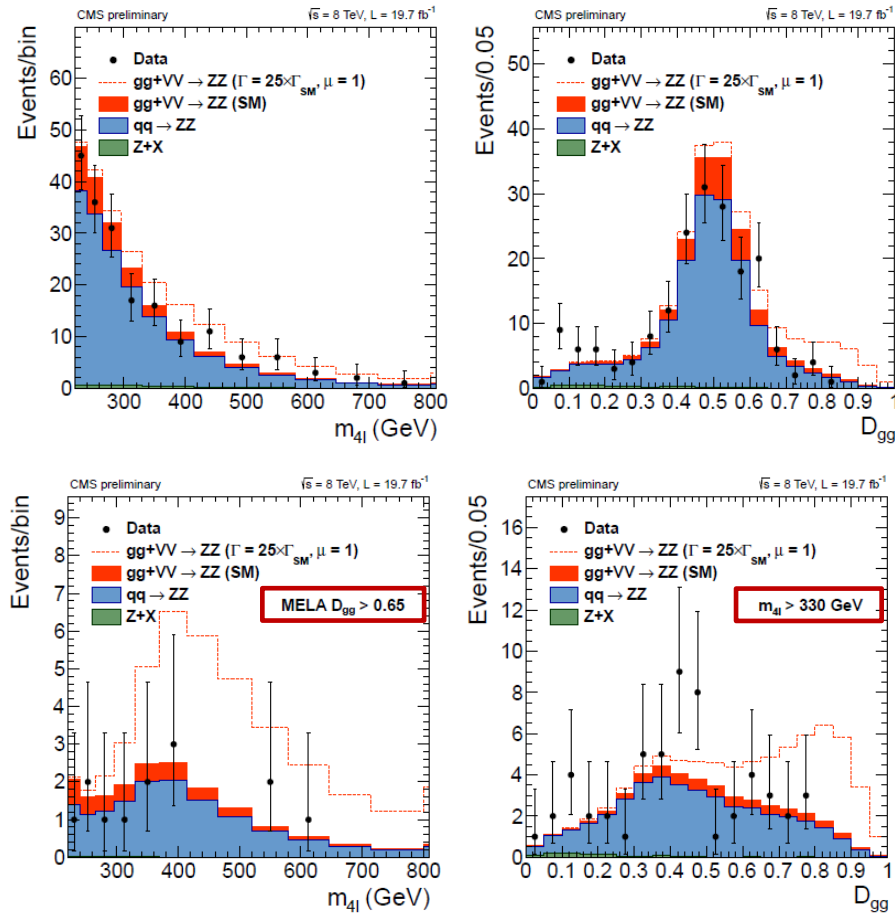- Event categorization according to photon resolution and *cos(θ*)*
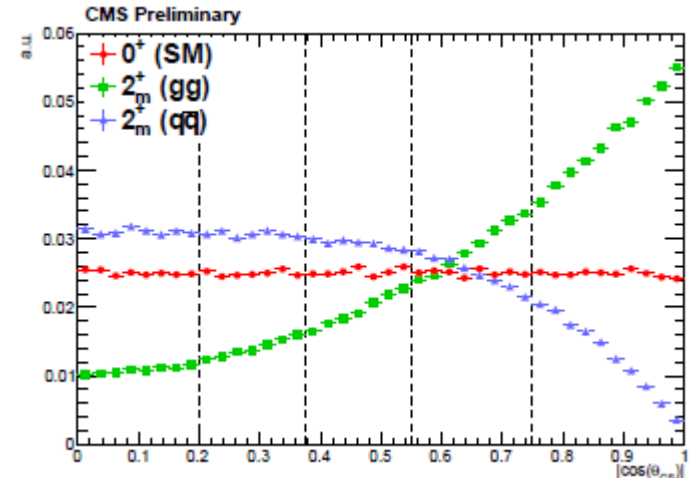
In this case, 2^+_m spin hypothesis can not be excluded

$CL_S = 60.1\%$

$CL_S = 17.4\%$
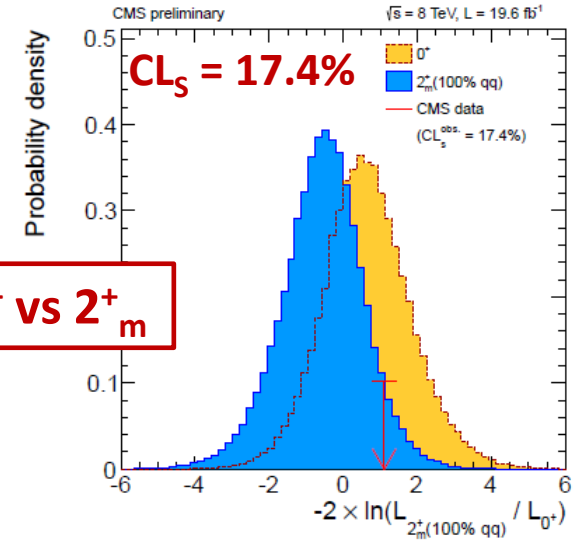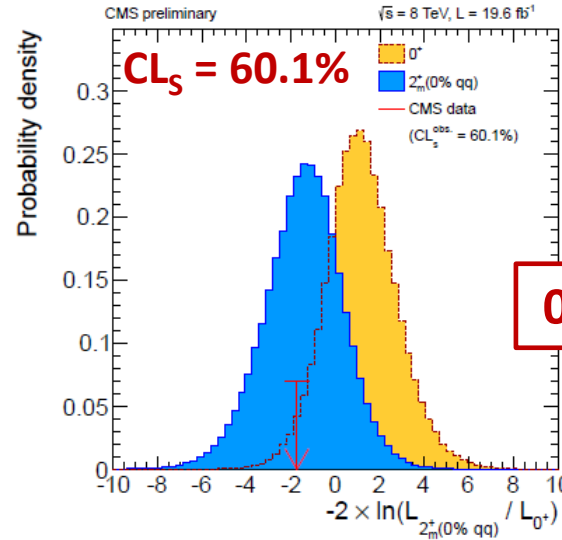
0^+ vs 2^+_m

Discriminating Variable Distributions

4*l* final state

$$\mathcal{L}_i = N_{\text{gg}\to\text{ZZ}} \left[\mu r \times \mathcal{P}_{\text{sig}}^{gg} + \sqrt{\mu r} \times \mathcal{P}_{\text{int}}^{gg} + \mathcal{P}_{\text{bkg}}^{gg} \right] + \dots$$
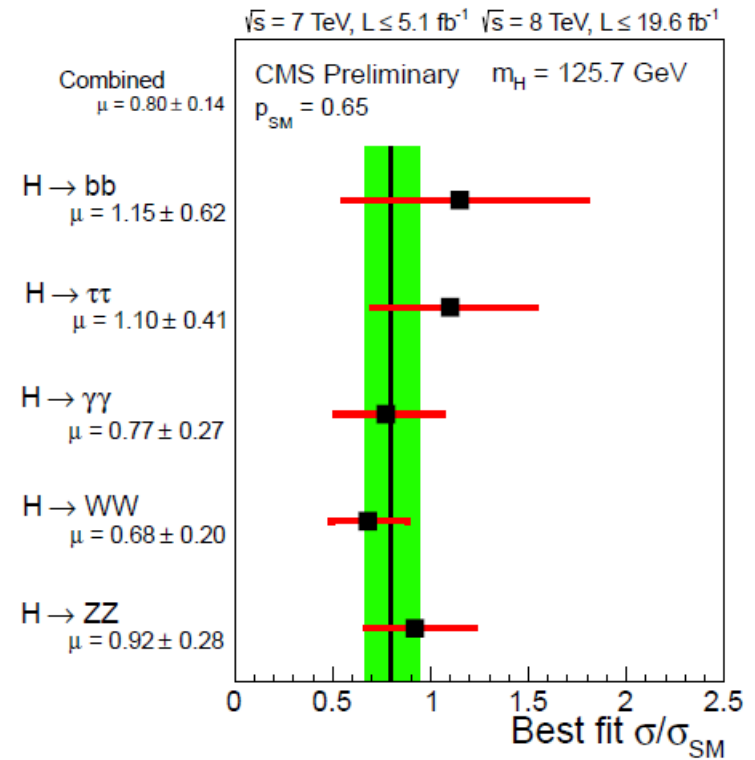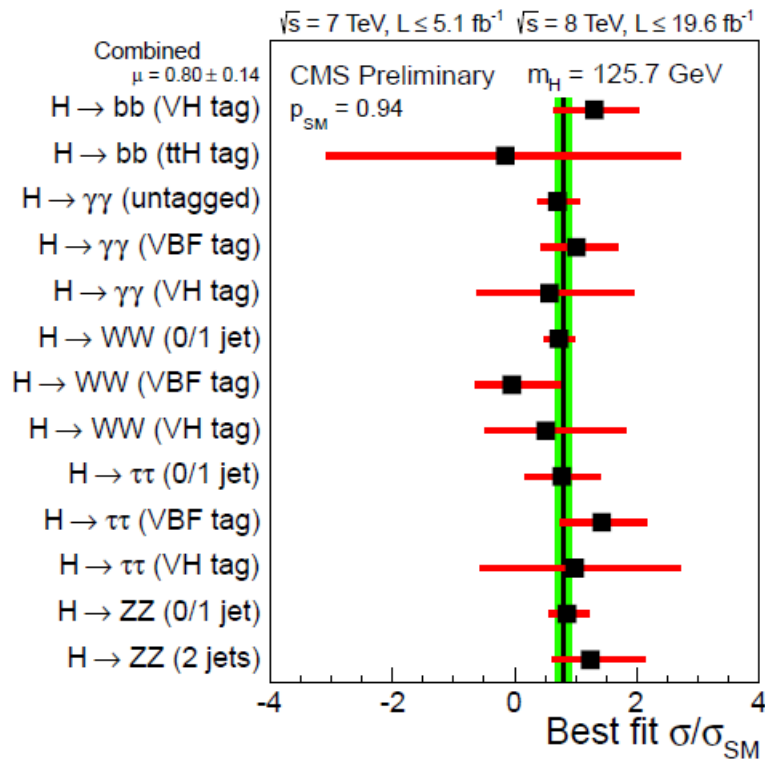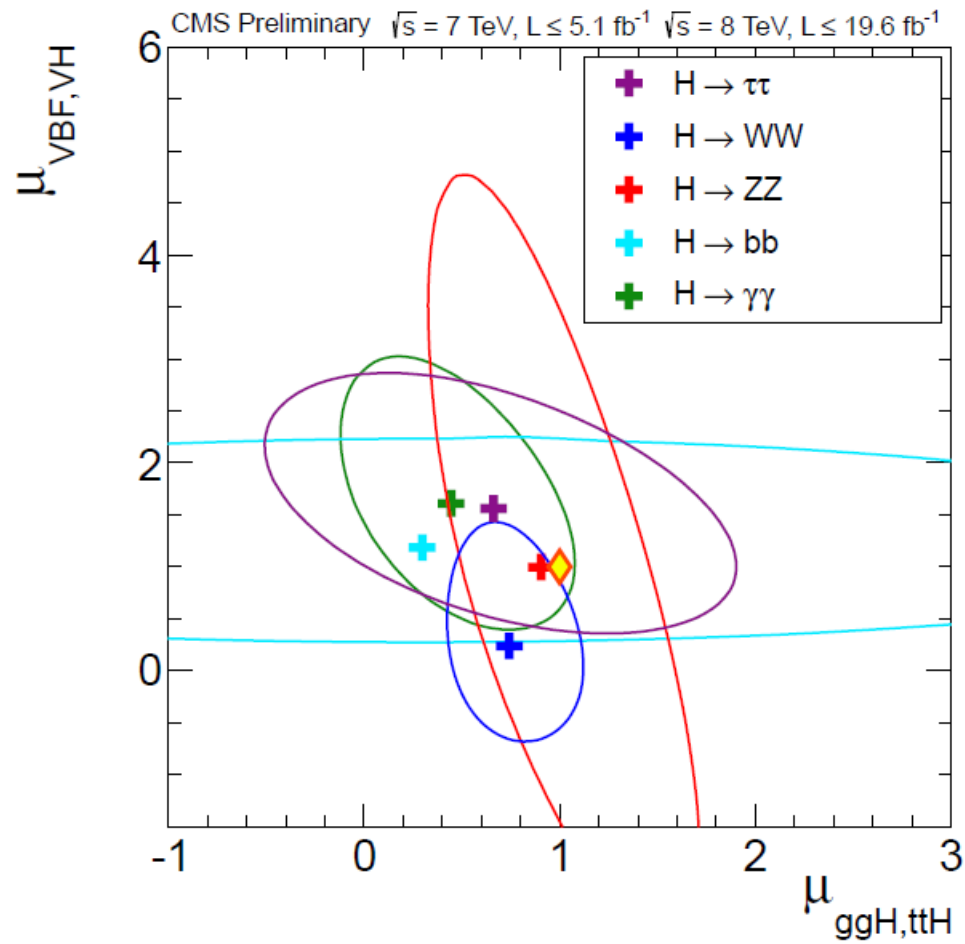
Discriminating Variable Distributions

2l2v final state

CMS preliminary, $\sqrt{s}$=8.0 TeV, $\int L$=19.7 fb^{-1}

Legend:
- ● Data
- $qq \to ZZ \to 2l2\nu$
- $WZ \to 3l\nu$
- Top/W/WW
- Z+jets
- SBI$_{gg}$(r=10)
- SBI$_{qq}$(r=10)
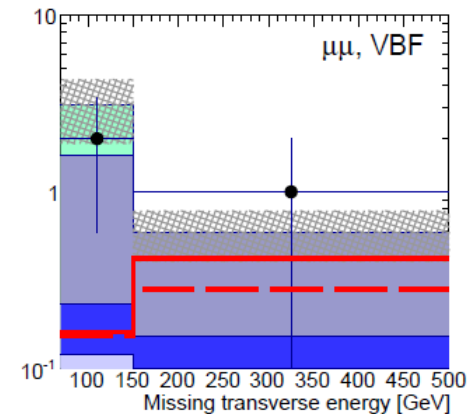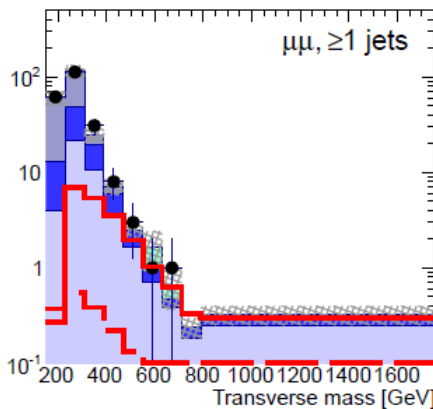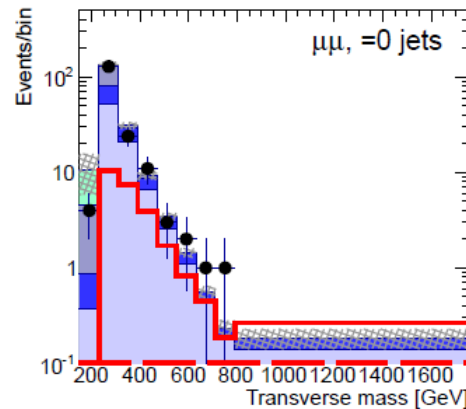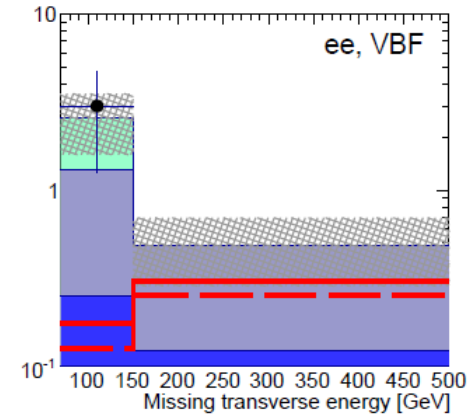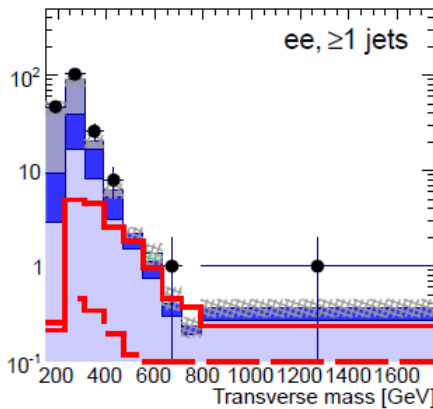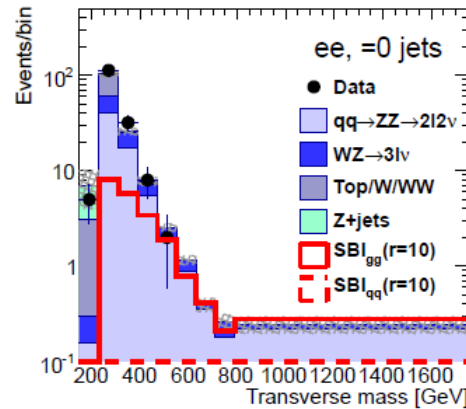
Signal Strength

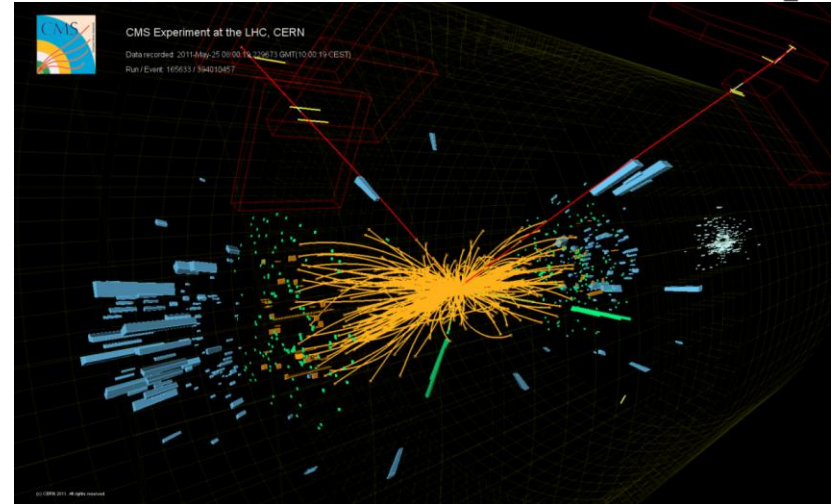# Signal Strength

H→ZZ→4l Decay Channel

Channel features

- Very small branching fraction
- Very clean signature
  - 2 pairs of high p_T and isolated μ or e
  - full reconstructed event topology
- Small background contribution
- Excellent mass resolution

Analysis strategy

- Event categorization according to lepton flavor
- Mass measurement performed using 3D fit with (m_{4l}, δm_{4l}, $\mathcal{D}_{kin}$)
- 8% improvement using per-event mass errors
- Main systematic uncertainties due to lepton scale and resolution
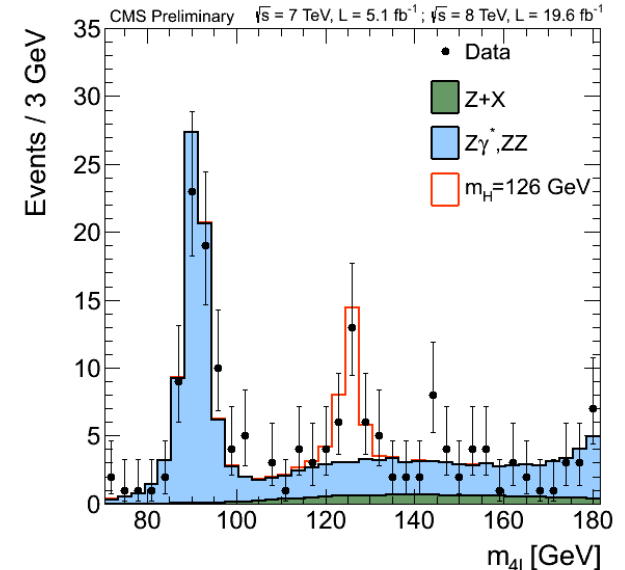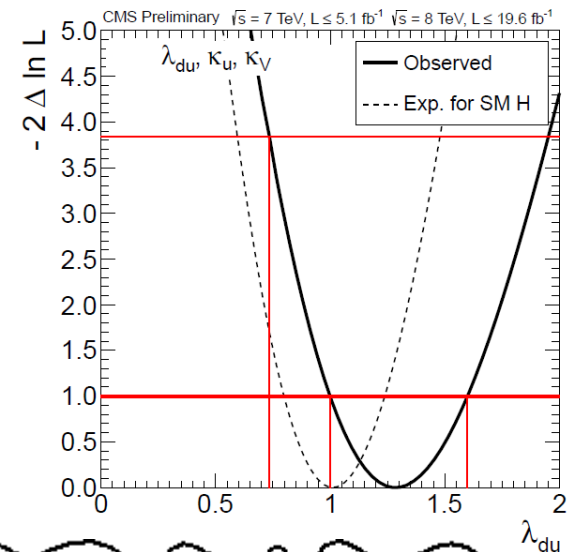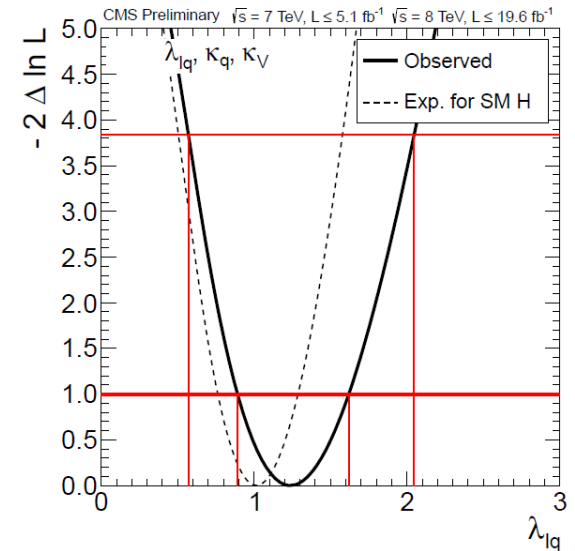
Asymmetries in Fermion Couplings

• Modifications to the fermion couplings may arise from theories beyond the SM

➡ Study of $\lambda_{lq} = k_l/k_q$ and $\lambda_{du} = k_d/k_u$ ratios (constrained to be positive)

$\lambda_{lq} \in [0.57, 2.05]$
$\lambda_{du} \in [0.74, 1.95]$
at 95% C.L.

Data are consistent with the expectation

Fit six Couplings at once

Assumptions

• Custodial symmetry ($k_W = k_Z = k_V$)

• Scale factors for couplings to 1st and 2nd generation fermions are equal to the 3rd ones

• No beyond SM decays ($\Gamma_{BSM} = 0$)

Data are consistent with the SM