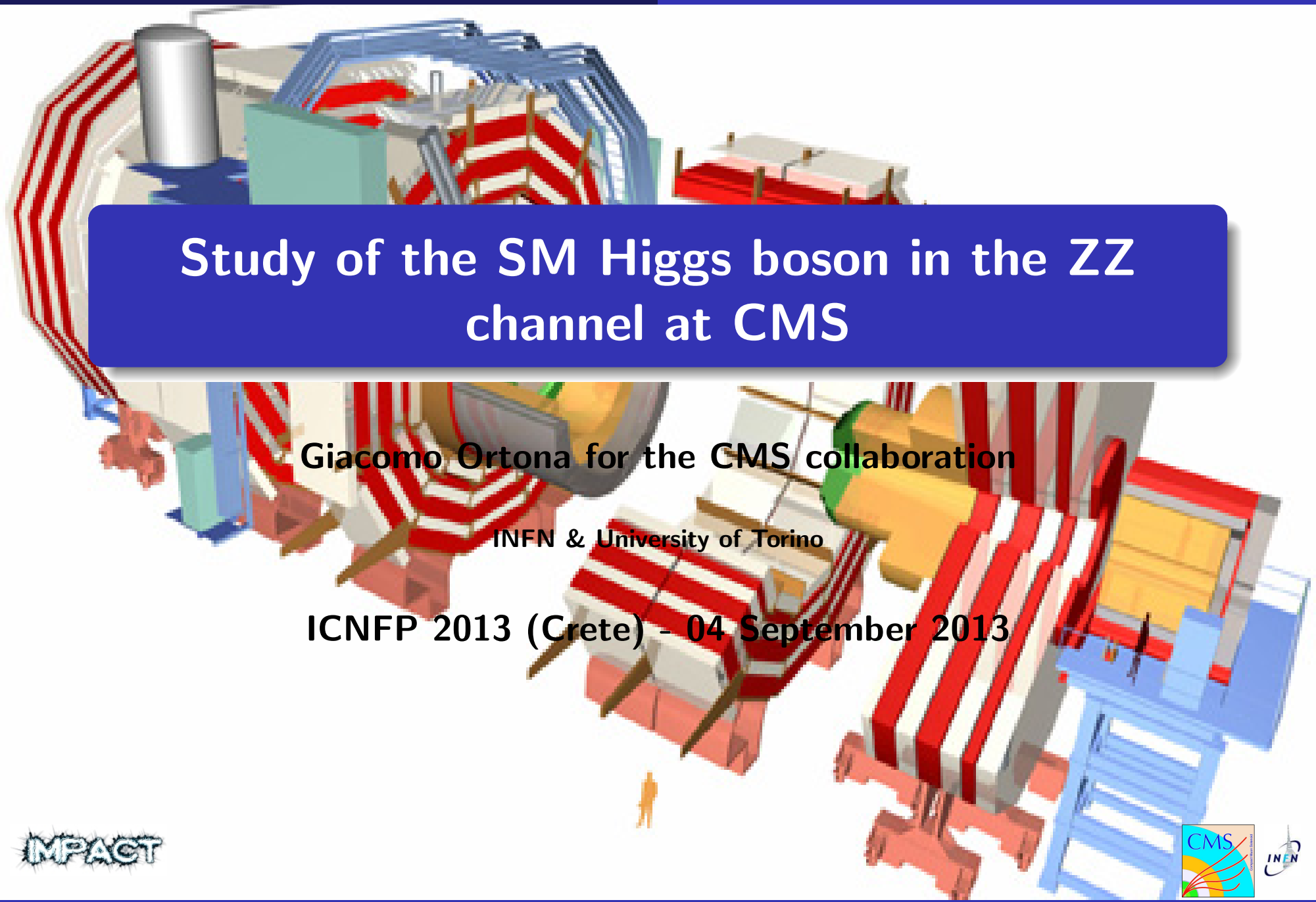


Study of the SM Higgs boson in the ZZ channel at CMS

Giacomo Ortona for the CMS collaboration

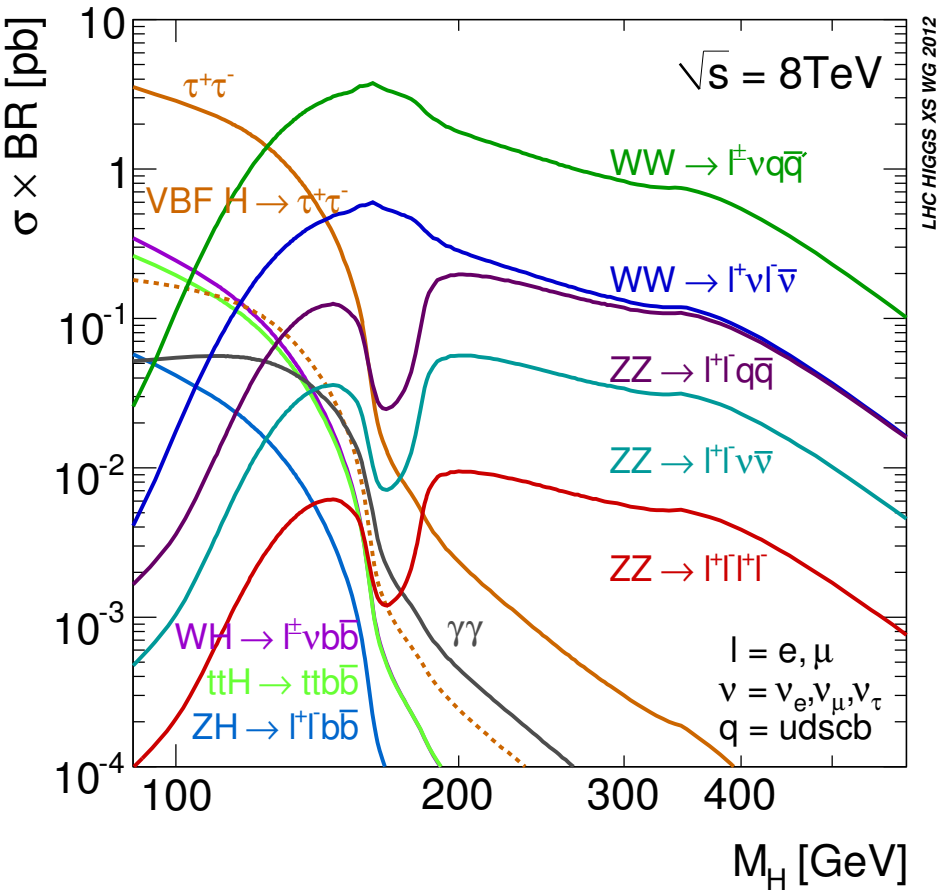
INFN & University of Torino

ICNFP 2013 (Crete) - 04 September 2013

Outline

Motivations

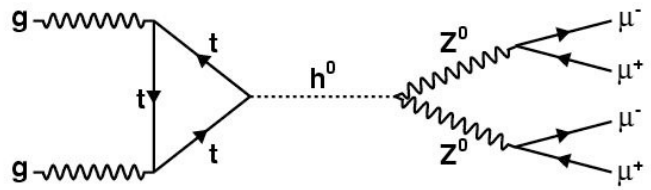
- SM Higgs is expected to have non negligible ZZ coupling.
- Several final states combinations are available:
  - H→ZZ→ 4*l*, includes 2*l*2τ at high mass
  - H→ZZ→ 2*l*2*q*
  - H→ZZ→ 2*l*2ν
- 2*l*2*q* and 2*l*2ν: large BR/low purity. Well suited for high mass Higgs searches.

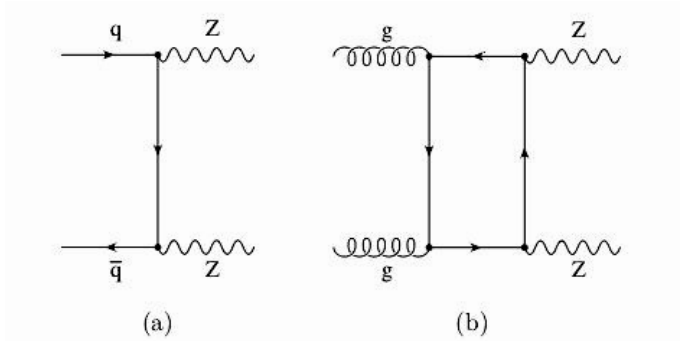


- 4*l* final state has low BR, but very clean signature and excellent resolution, **golden channel** for Higgs analysis. It allows high precision mass measurement and spin/parity study from the angular distribution of decay products.

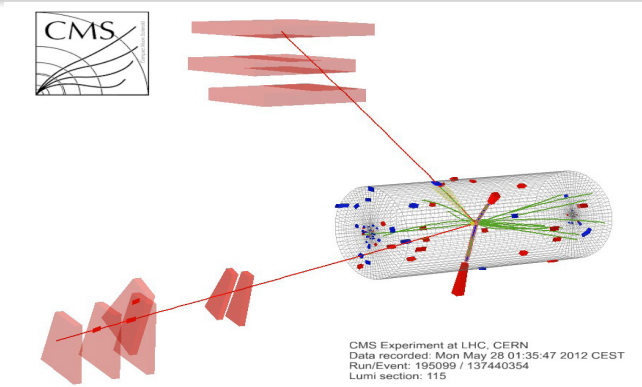
H→ZZ→ 4l: The golden channel

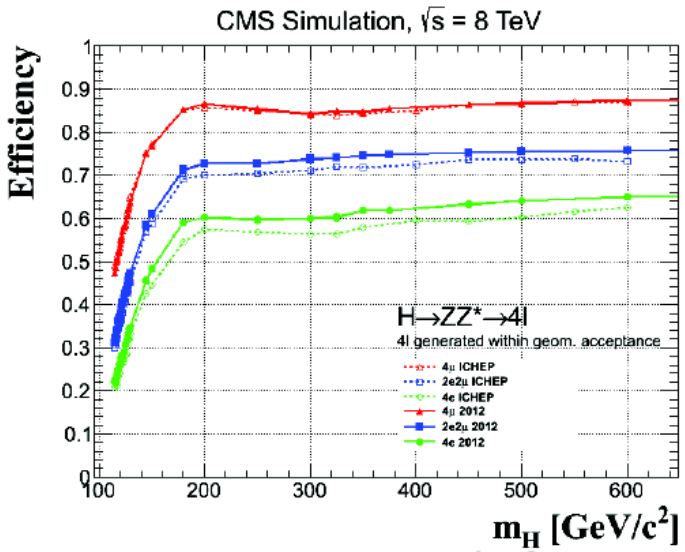
- Very clean signal: search for a narrow peak in the 4l invariant mass spectra
- Locally flat and small background
  - Reducible: Z+jets; Z+tt; WZ
  - Irreducible: ZZ*
- Sensitivity with current statistics $(5.1+19.8 fb^{-1})$:
  $110 < m_H < 1000$ GeV
- Small number of expected events, high efficiency required!
  - 2.8 ev/fb^{-1} expected at 125GeV
- high S/B (~ 2)
- Event properties from lepton angular distribution and masses
- Events are categorized based on jet multiplicity

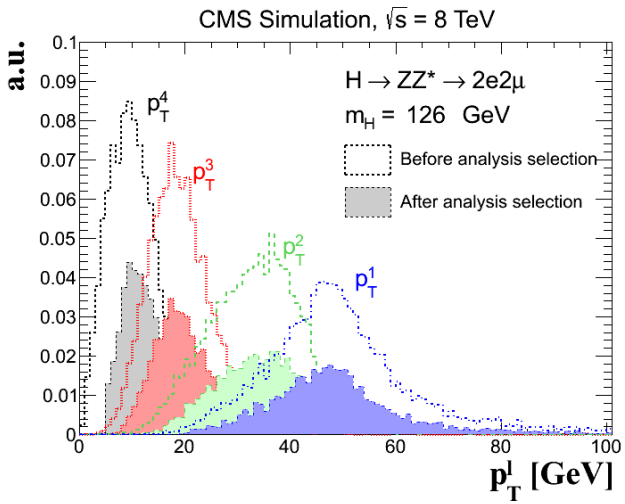




Kinematics





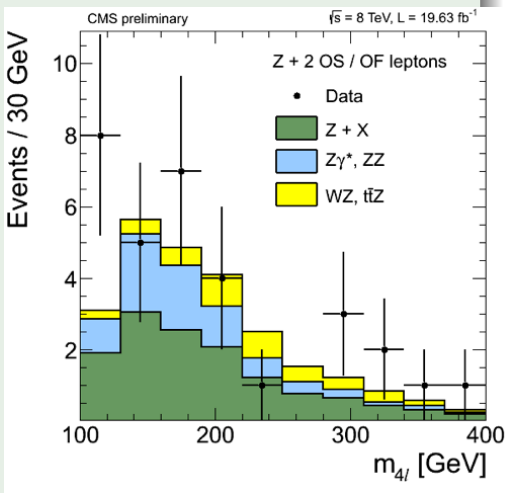


- Two pairs of OS/SF leptons. Z_1 closest to the Z mass, Z_2 the remaining with highest p_t
- $p_T^\mu > 5\text{GeV/c}$, $p_T^e > 7\text{GeV/c}$
- $40 < m_{Z_1} < 120\text{GeV}$
  $12 < m_{Z_2} < 120\text{GeV}$
- One lepton with $p_t > 20$ GeV/c, another with $p_t > 10$ GeV/c.
- $m_{4l} > 100$ GeV, any $m_{l^+l^-} > 4$ GeV
- Overall efficiency: 31%, 42%, 59% (4e,2e2μ,4μ)

Background and Systematic uncertainties

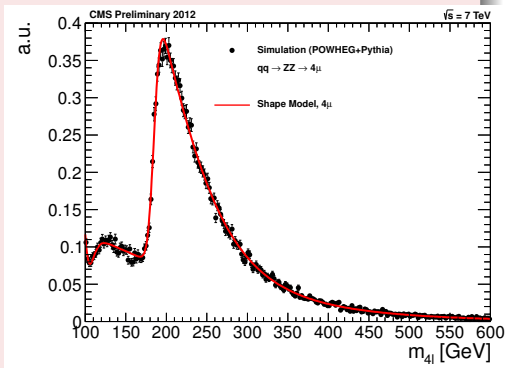
Reducible

- Zbb, Ztt, Z+jets, WZ+jets
- Estimated in Z_1+X and $Z_1 + l_{rec}$ control regions involving 1/2 fake leptons
- "fake rate"=tight/loose estimated using loose selection on leptons
- syst + stat uncertainties $\sim 50\%$

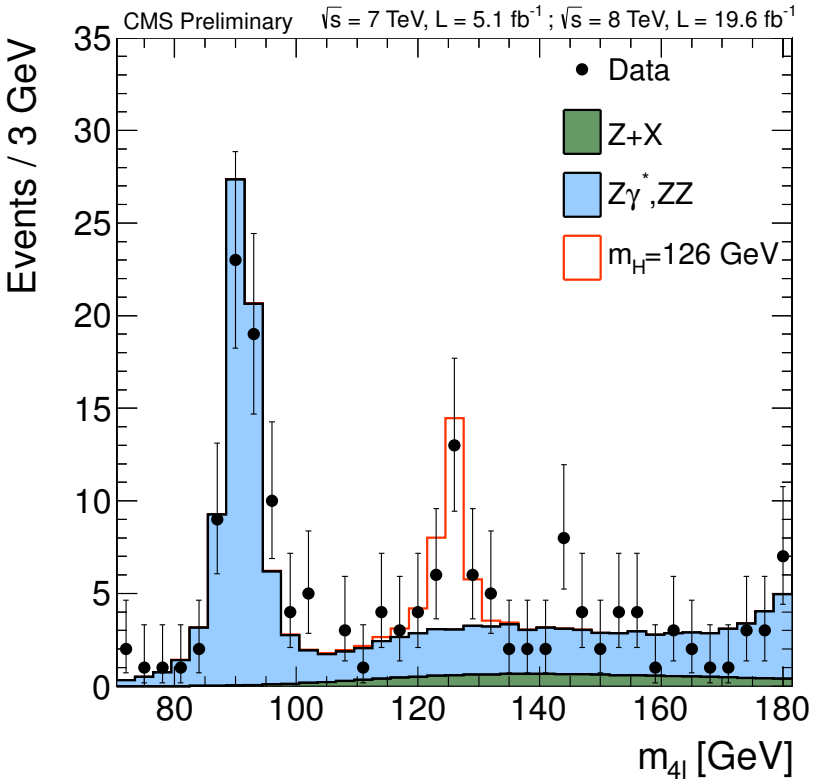


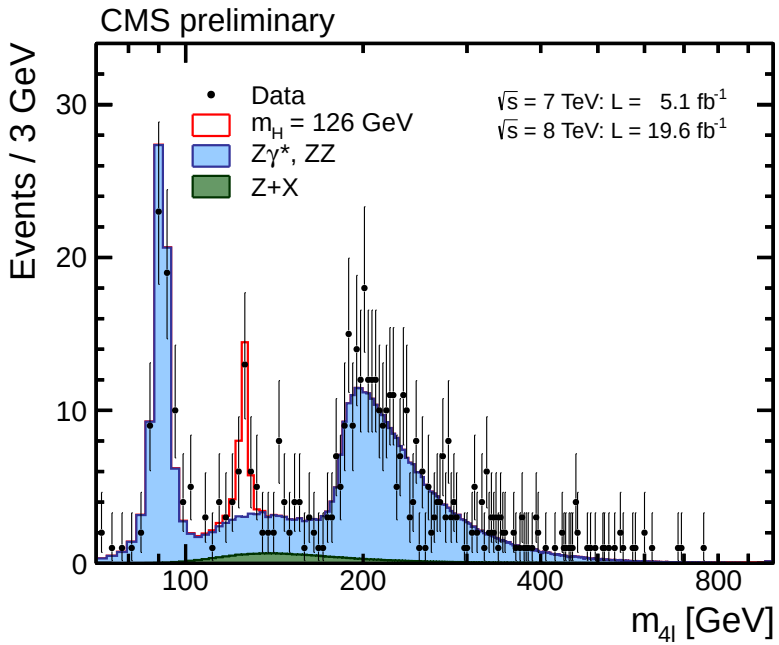
Irreducible

- Calculated from MC, including $q\bar{q}$ annihilation (POWHEG) and gluon fusion (GG2ZZ)
- Phenomenological model for the shape for qq→ZZ (gg→ZZ)



Mass distribution



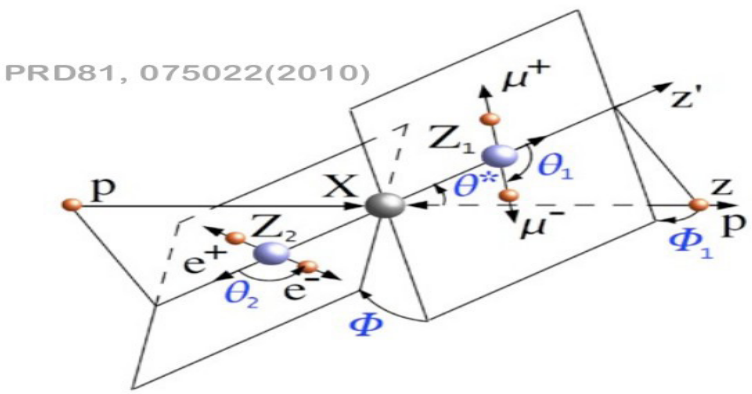


- Z peak at about $91 GeV/c$ nicely reproduced by the MC
- A clear excess is visible in the $4l$ invariant mass spectra at $\sim$ 126 GeV/c, indicating the presence of a new particle
  - $121.5 < m_{4l} < 130.5$: Expected (H126): 18.6 ev; Z+X bkg: 2.0 ev; ZZ bkg: 7.4; Observed 25

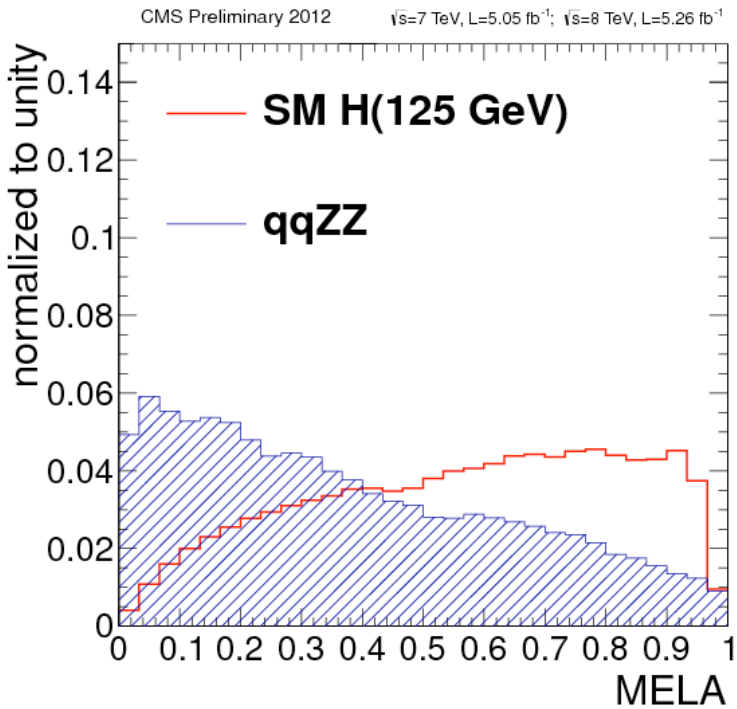
MELA

5 angles and 2 masses fully describe the H→ZZ→ 4*l* decay
Matrix Element Likelyhood Analysis: build a discriminant (KD) based on signal/bkg probabilities for SM and for the alternative hypotheses

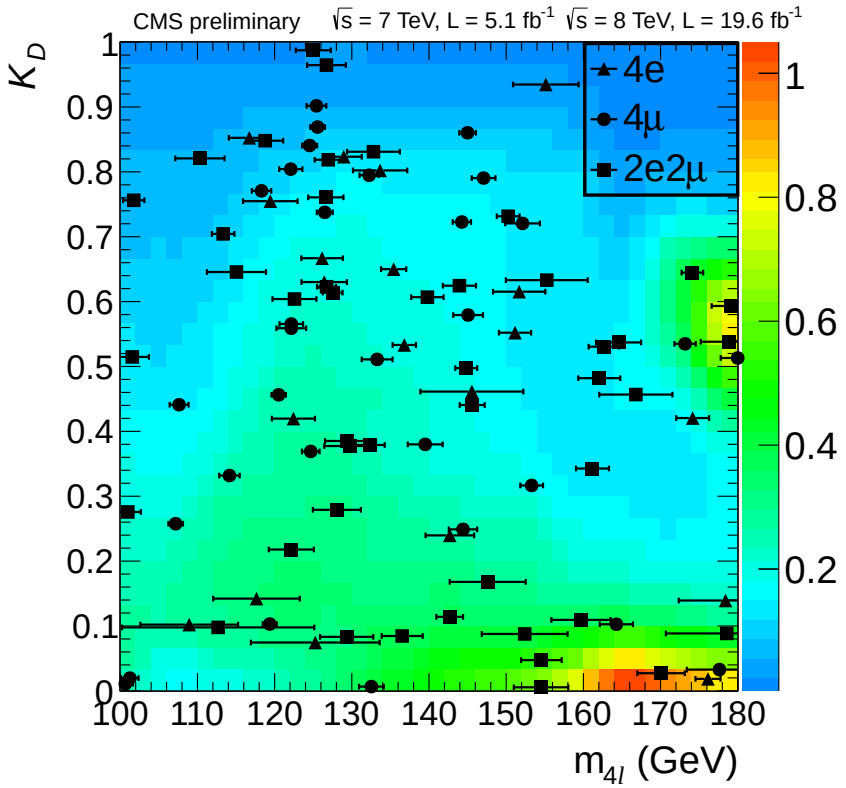
$$KD = \frac{P^{kin}_{0^+}}{P^{kin}_{0^+}+P^{kin}_{bkg}} = \left(1+\frac{P^{kin}_{bkg}(m_1,m_2,\Omega|m_{4l})}{P^{kin}_{0^+}(m_1,m_2,\Omega|m_{4l})}\right)^{-1}$$

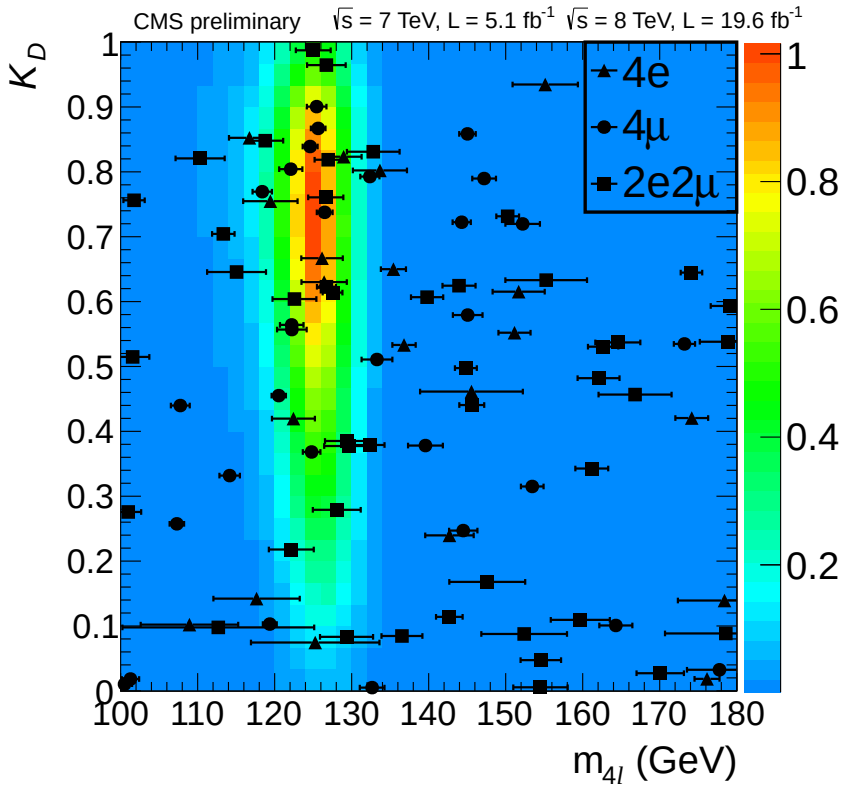


- Use angles and masses to discriminate
  - between signal/background hypothesis
  - between spin/parity hypothesis



KD vs mass





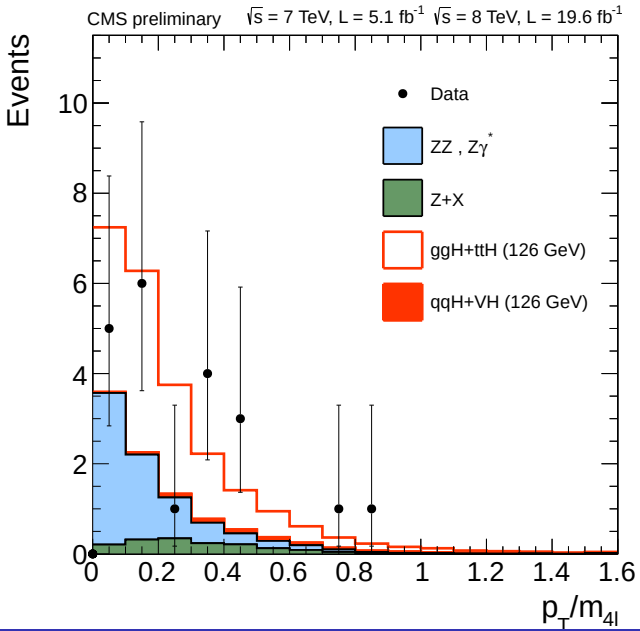
Distribution of the KD discriminant for background and signal as a function of the 4l mass, overlapped to the observed data (black points). A clustering of the events at high KD values is visible in the Higgs peak region

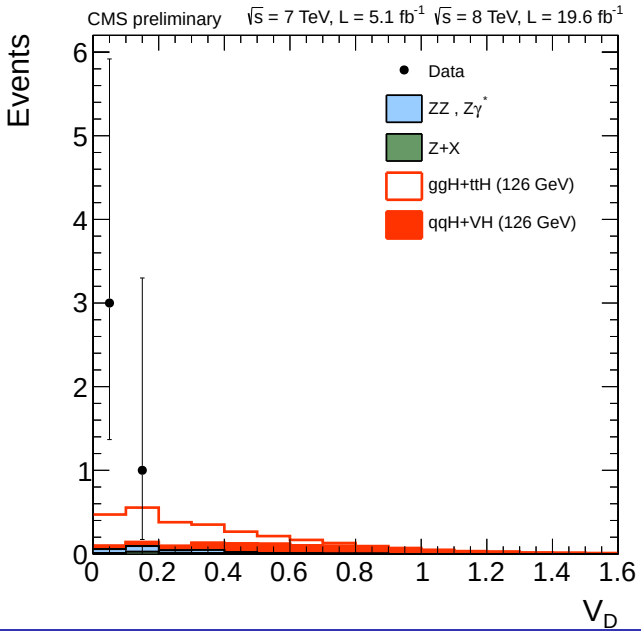
Event categorization

To increase sensitivity to VVH and ffH couplings ($\mu_V - \mu_F$) events are splitted in two exclusive categories:

- Untagged: less than 2 jets
- Dijet: At least 2 jets with $p_t > 30$ GeV/c

one extra dimension added to the analysis to separate the production mechanisms. p_t/m_{4l} in the 0/1 jet category, **Fisher discriminant** $D_{\text{jet}} = \alpha\Delta\eta_{jj} + \beta m_{jj}$ in the Dijet category

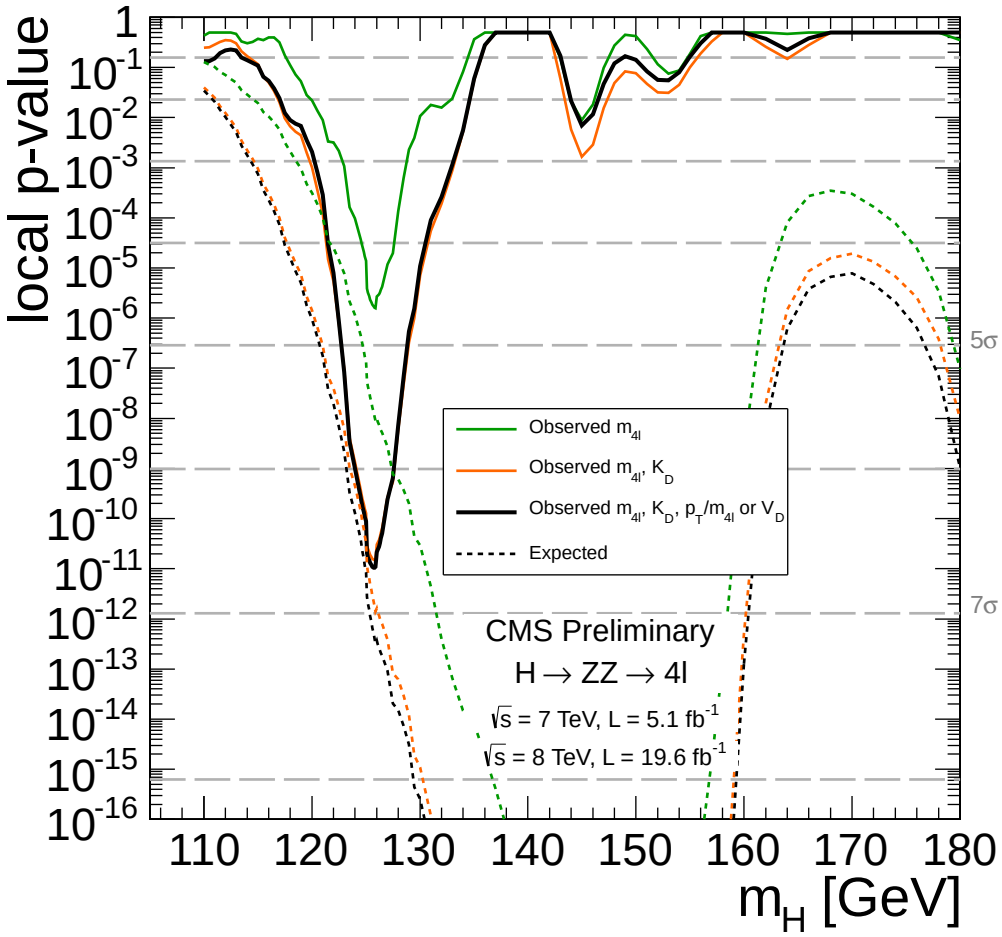




Local p-value

0/1 Jets: $P(m_{4l}, KD, p_T) = P(p_T/m_{4l}|m_{4l}) \times P(K_D|m_{4l}) \times Pm_{4l}$
Dijet: $P(m_{4l}, KD, p_T) = P(V_D|m_{4l}) \times P(K_D|m_{4l}) \times Pm_{4l}$

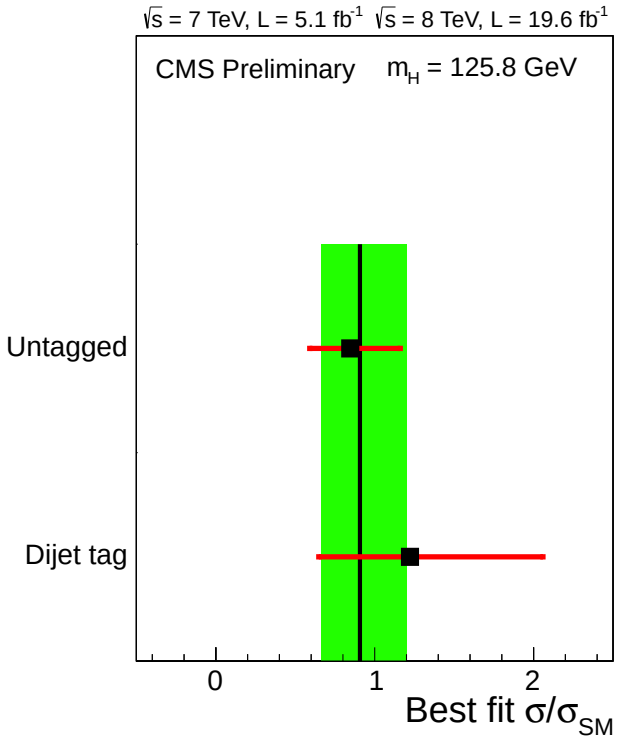
- Local minimum at 125.7 GeV
- Observed: 6.7σ
  - 1D: 4.7
  - 2D: 6.6
- Expected: 7.2σ
  - 1D: 5.6
  - 2D: 6.9

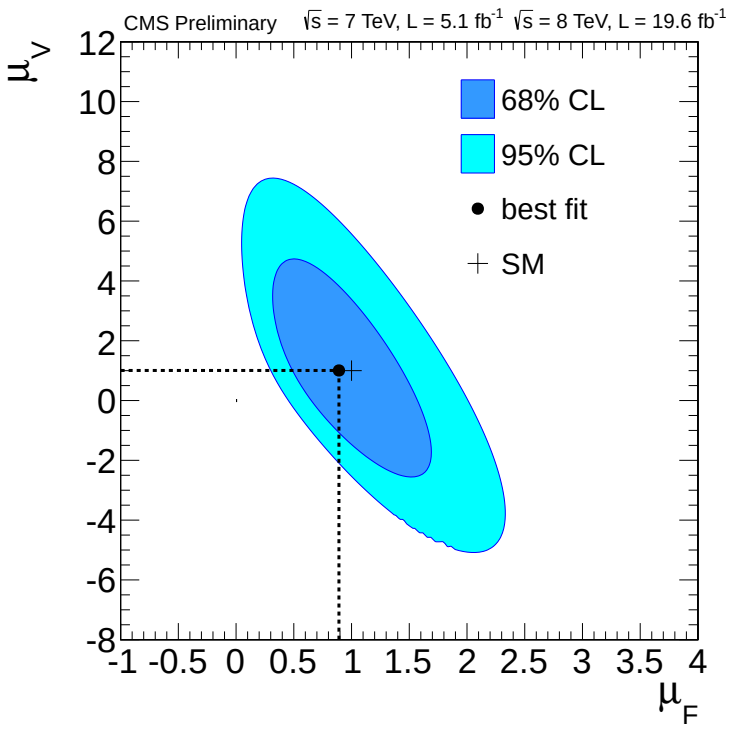


Discovery in this channel alone.

σ/σ_{SM}

- $\mu = 0.91^{+0.30}_{-0.24}$
- $\mu_V = 1.0^{+2.4}_{-2.3}$
- $\mu_f = 0.9^{+0.5}_{-0.4}$
- $\mu_{\text{dijet}} = 1.22^{+0.84}_{-0.57}$
- $\mu_{\text{untag}} = 0.85^{+0.32}_{-0.26}$

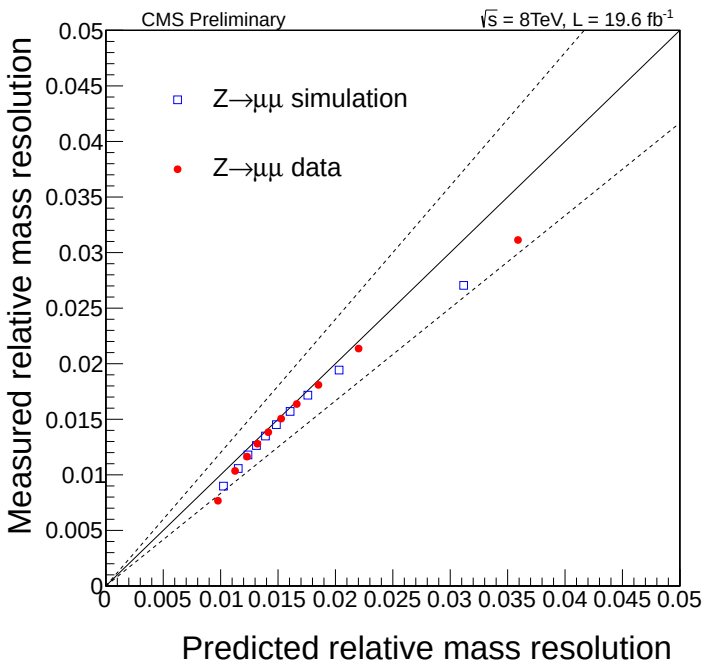


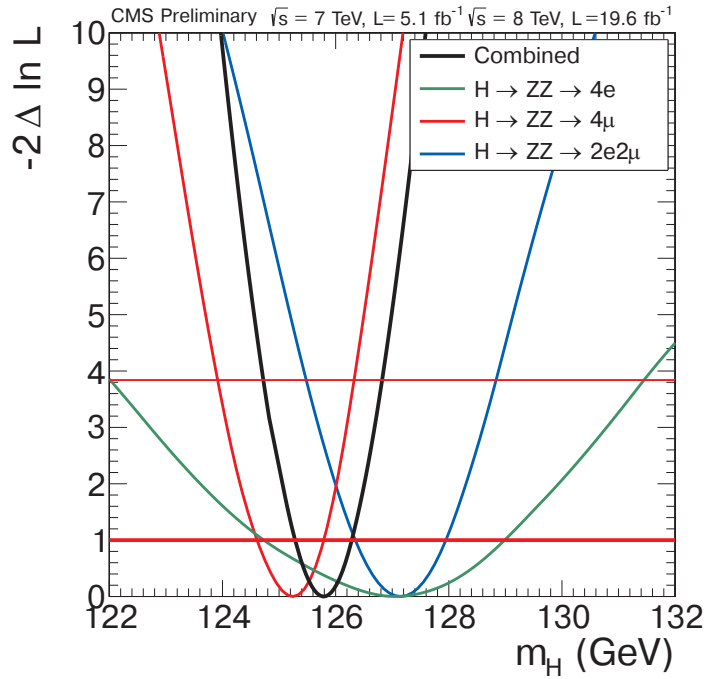


Results are nicely compatible with SM expectations

Mass measurement

- Mass measurement is performed with a 3D fit using
  - m_{4l}, per-event mass error, KD
- Scale and resolution calibrated and validated using $Z/J/\Psi \rightarrow ll$ and $Z \rightarrow 4l$ event
  - 0.1-0.3% uncertainty on the 4l mass scale
  - 20% uncertainty on the 4l mass resolution

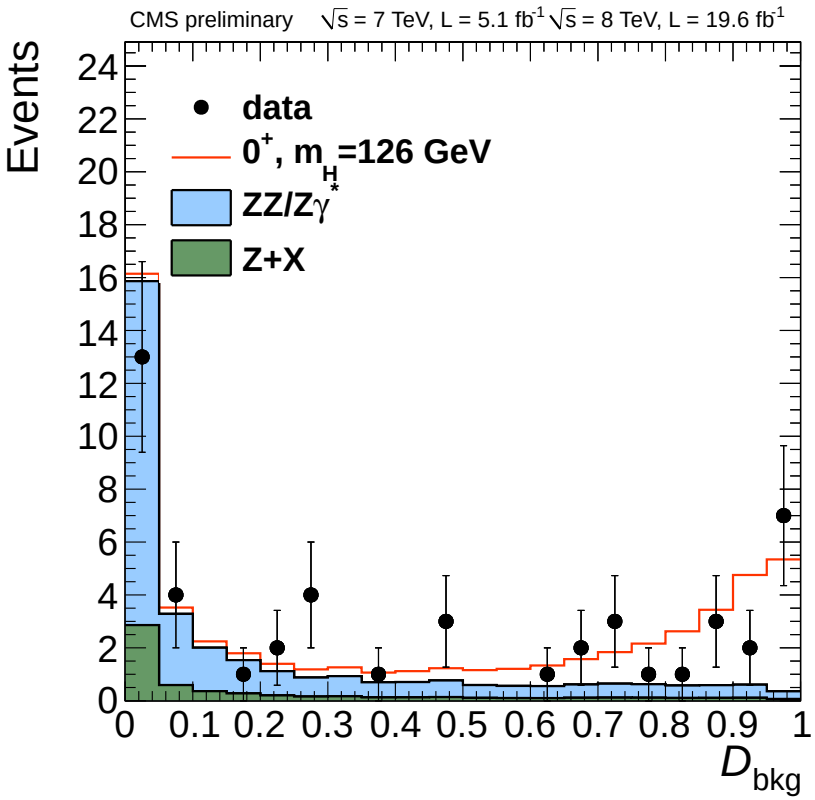


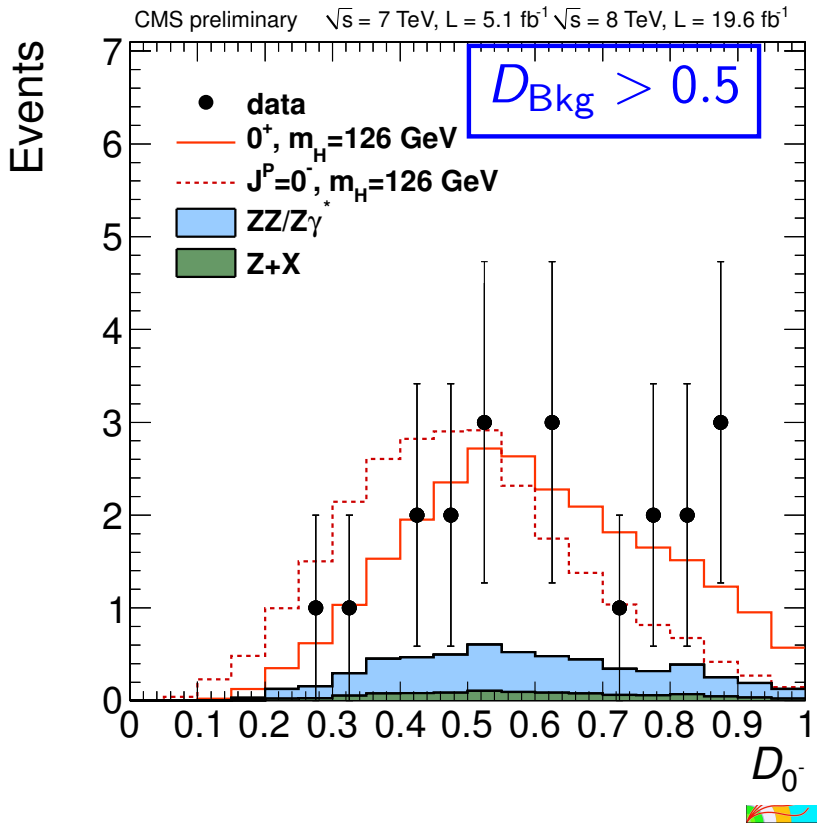


$$m_H = 125.8 \pm 0.5(stat.) \pm 0.2(syst.)\ \text{GeV}$$

Spin-parity: models

- KDs used to discriminate between different spin-parity hyp.
- Based on 2D PDF from for pairs of kinematic discriminants (D_{bkg}, D_{JP})
- 6 models tested so far: D_{0^-}, $D_{0_h^+}$, D_{1^-}, D_{1^+}, $D_{2_m^+}^{ggh}$, $D_{2_m^+}^{qq}$

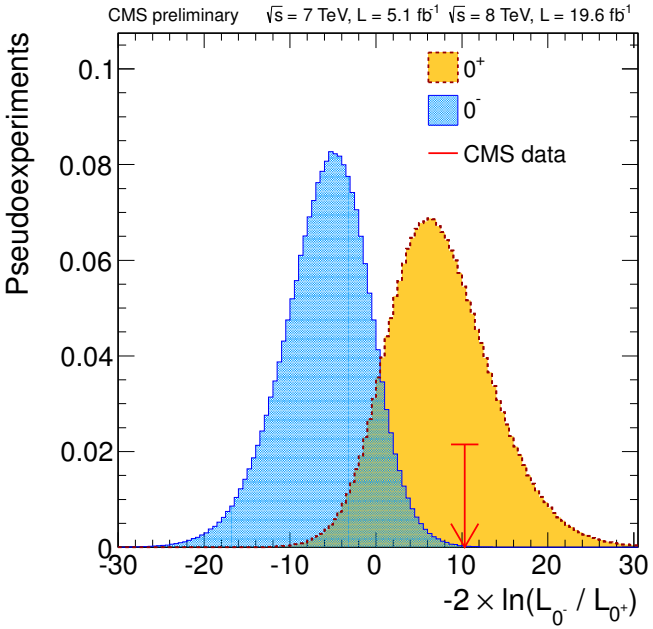


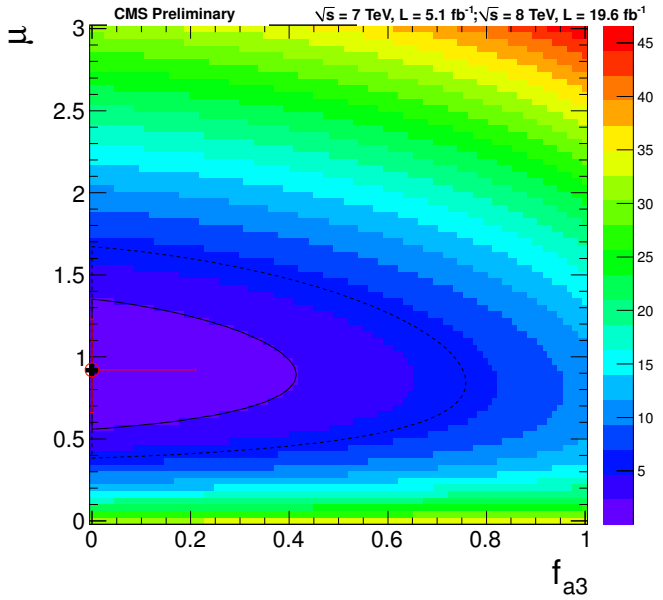


Spin-parity: characterization

J^P model	J^P production	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_m	$gg \to X$	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
2^+_m	$q\bar{q} \to X$	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	2.8σ (3.1σ)	1.4σ	$> 4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	2.3σ (2.6σ)	1.7σ	$> 4.0\sigma$	<0.1%

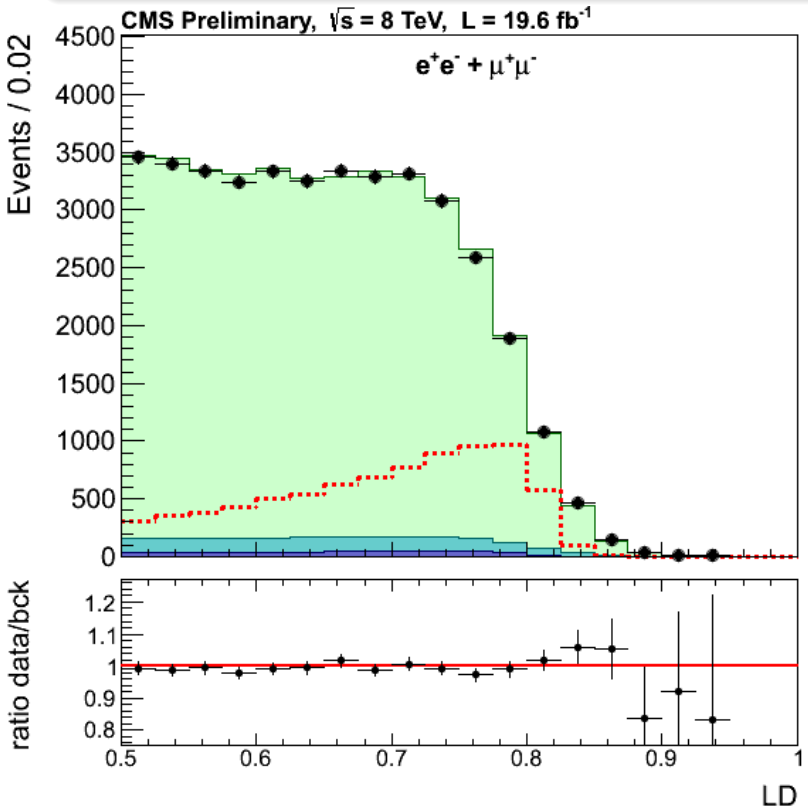
- 0^+ hypothesis highly favoured against all other alternative spin-parity hyp.
- Fraction of *CP*-odd contributions: $f_{a3} = 0.00^{+0.23}_{-0.00}$

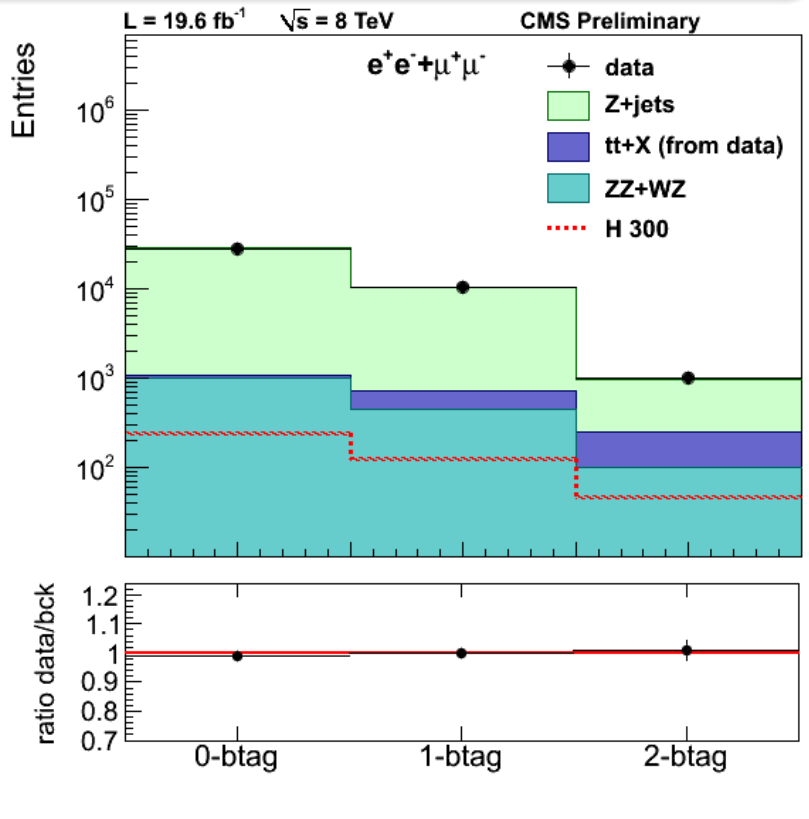




$2l2q$

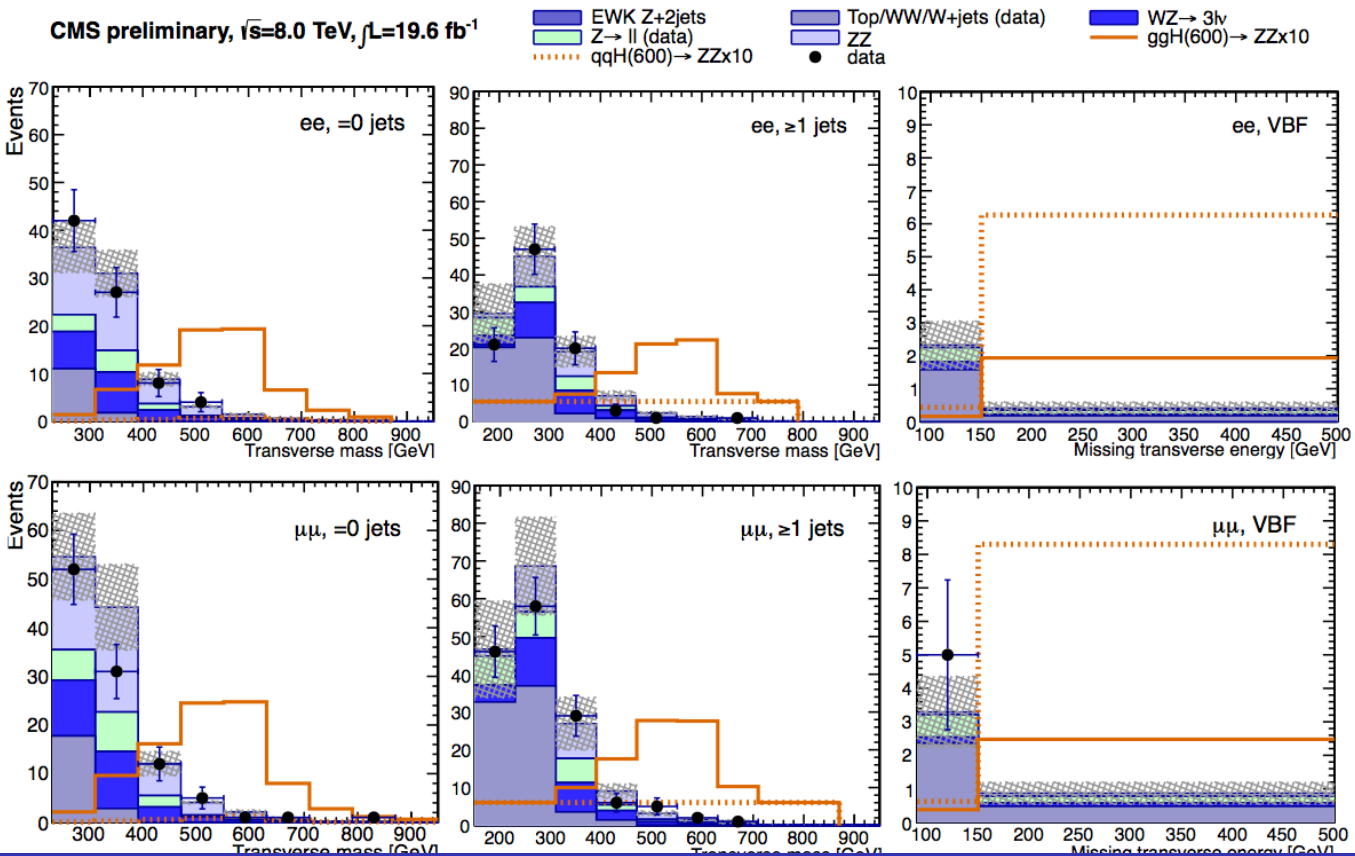
- 2 leptons + 2 jets
- Powerful channel for the search of heavy Higgs
- Events classified from the probability of the jets to come from q
- Angles to discriminate signal from bkg



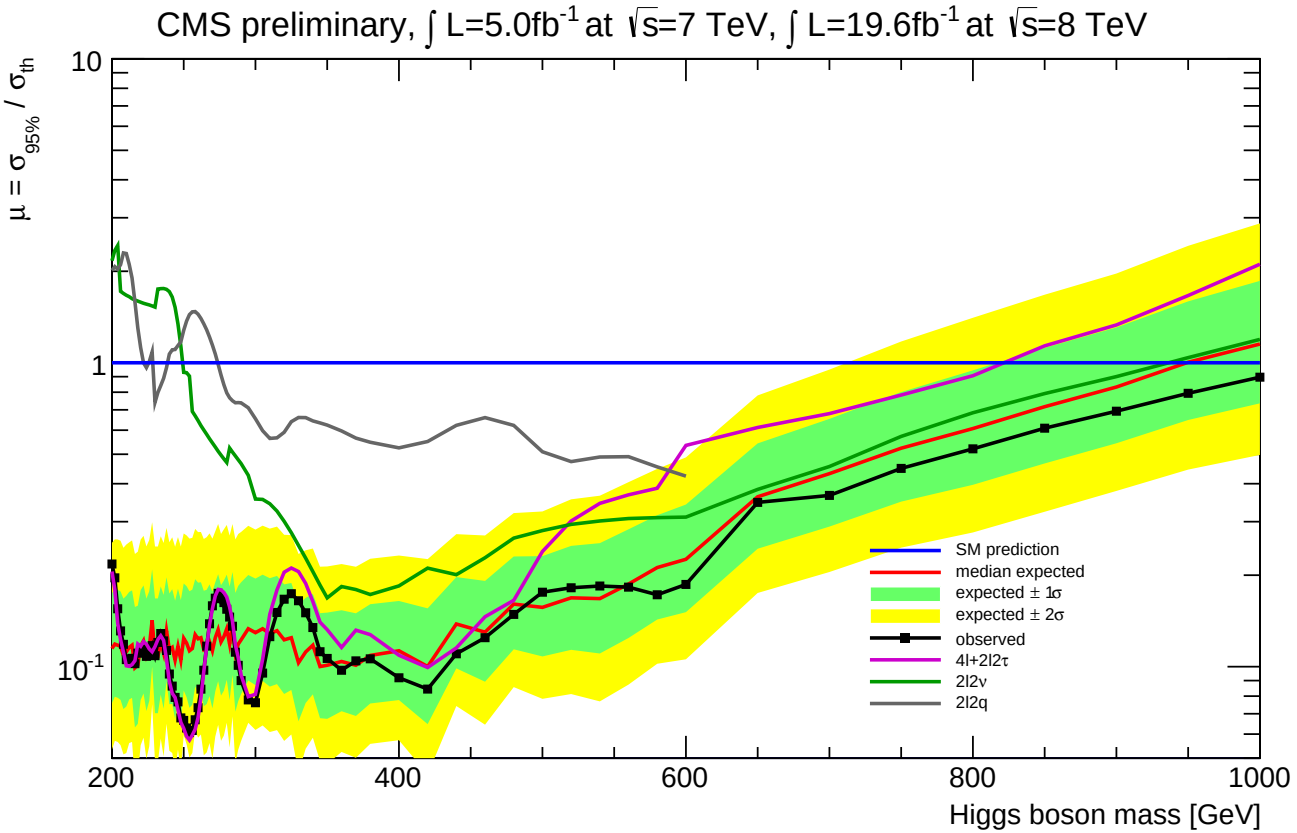


2l2ν

- 2 leptons + missing energy
- Sensitive to Higgs $m_H > 200$ GeV (6× larger BR than 4l)
- Optimised separately for VBF/gluon-fusion production
- BSM reinterpretation of the results (→backup)



Limits on SM Higgs boson



- Obs (exp) exclusion ranges:
- $ZZ -\rightarrow 4l + ZZ \rightarrow 2l2\tau$: $130 - 827(113.5 - 778)$
- $ZZ \rightarrow 2l2\nu$: $248 - 930(254 - 898)$
- $ZZ \rightarrow 2l2q$: $290 - 600(266 - 600)$
- combined: $200 - 1000(200 - 950)$

The combination of all ZZ channels completed the search for SM-like Higgs in the 200-1000 GeV region

Conclusions

- The $H \to ZZ \to 4l$ analysis at CMS has been presented
- The new resonance discovered at 126 GeV is clearly visible and the $H \to ZZ \to 4l$ decay channel allows to study the properties of the resonance (mass, spin, parity) with high precision.
- The discovered Higgs boson is compatible within uncertainties with a SM Higgs with mass $\sim$ 126GeV
  - $m_H = 125.8 \pm 0.5(stat.) \pm 0.2(syst.)$ GeV
  - $\mu = \sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$
- Alternative spin-parity hypotheses are disfavoured by the data
- High mass searches, performed jointly with other final states channels show no evidence of other SM-like resonances up to 1 TeV

Supported by Università Degli Studi di Torino/Compagnia di San Paolo, grant ORTO11TPXK

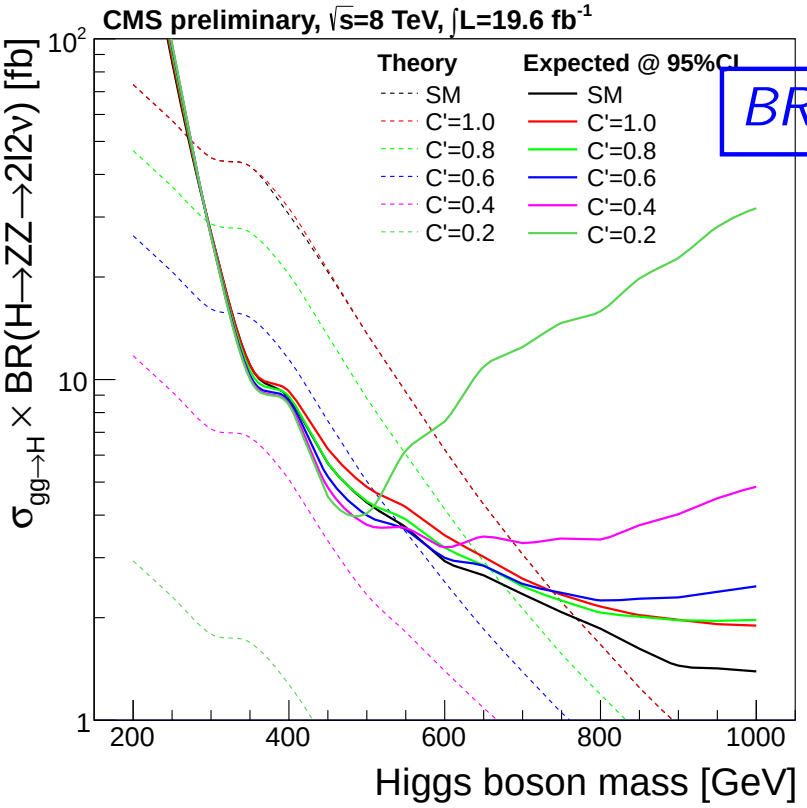
BACKUP

$2l2\nu$: BSM

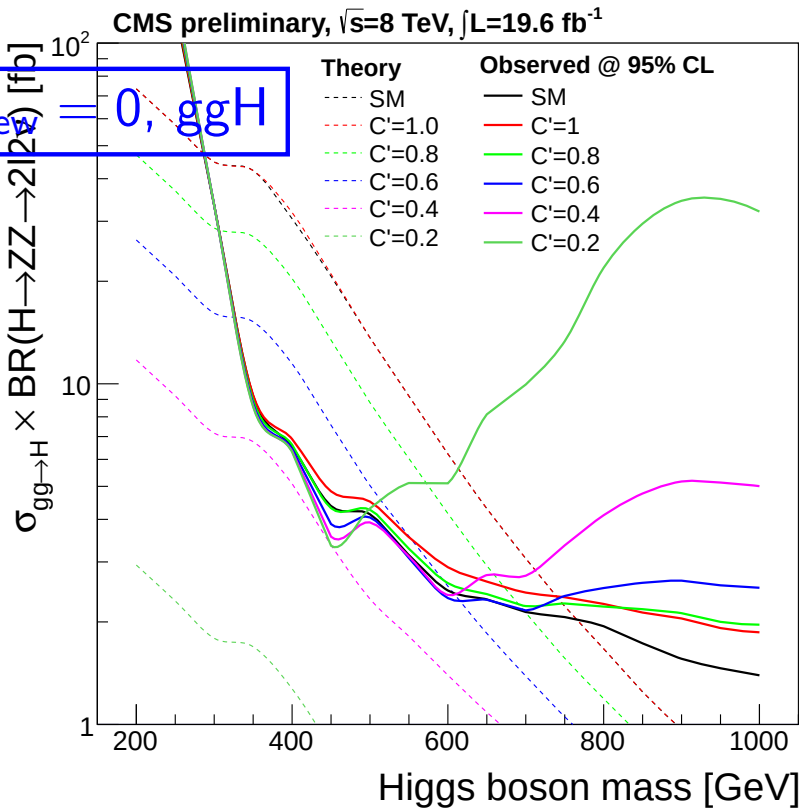
Search for mixing between SM-Higgs and EW singlet scalar

- $\mu' = C'^2(1 - BR_{\text{new}})$ (with $C'^2 \leq (1 - BR_{\text{new}})$)
- $\Gamma' = \Gamma_{\text{SM}} \frac{C'^2}{(1-BR_{\text{new}})}$

CMS-PAS-HIG-13-014

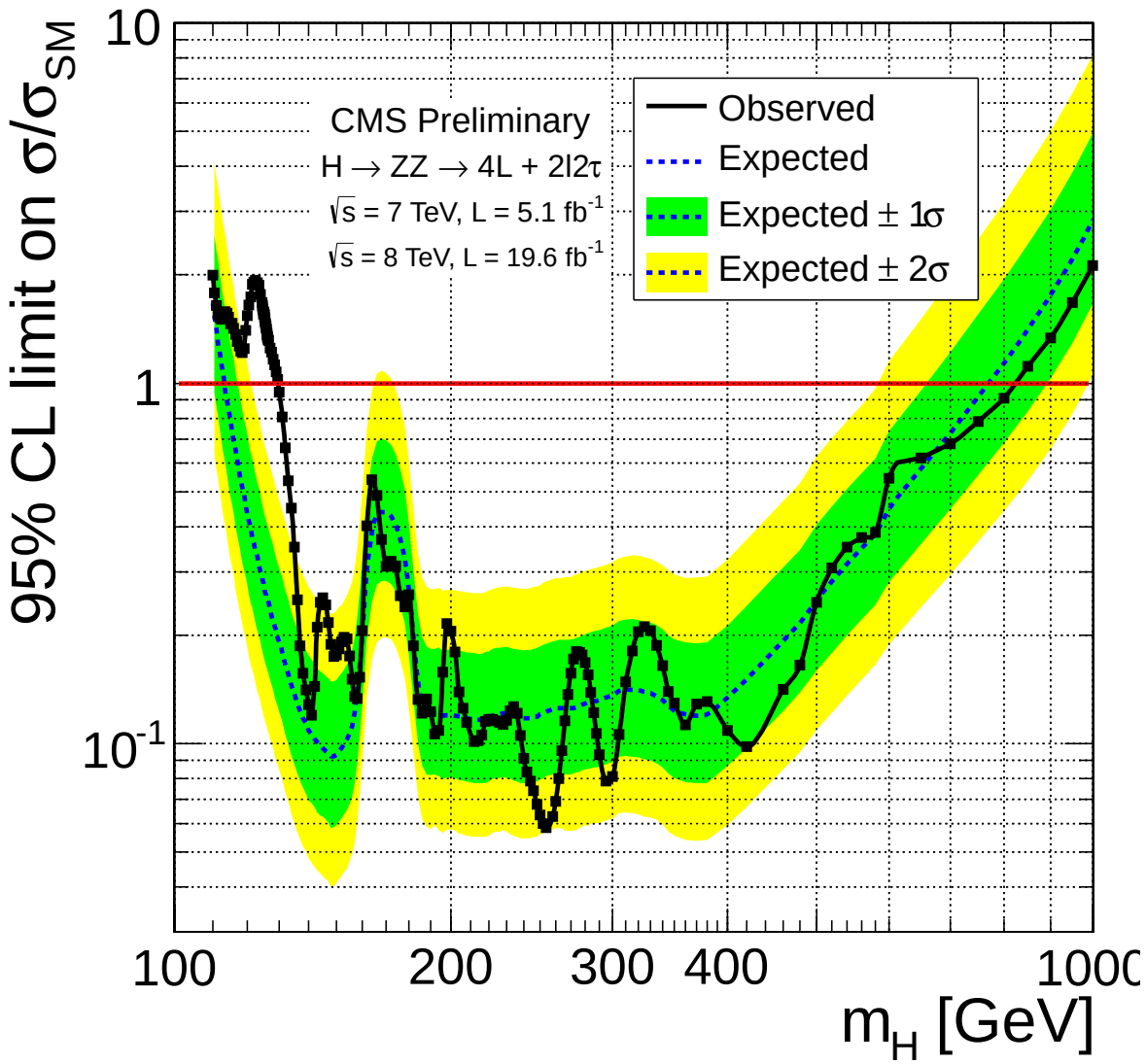


$BR_{\text{new}} = 0$, ggH



Reinterpretation from $2l2q$ and $4l$ data is work in progress

Limits on SM Higgs boson (4l)



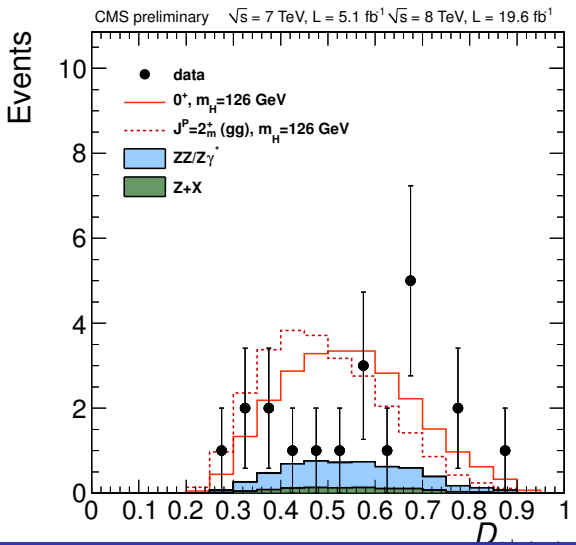
- 2D limit on SM Higgs
- Observed exclusion: 130-827
- Expected exclusion: 113.5-778

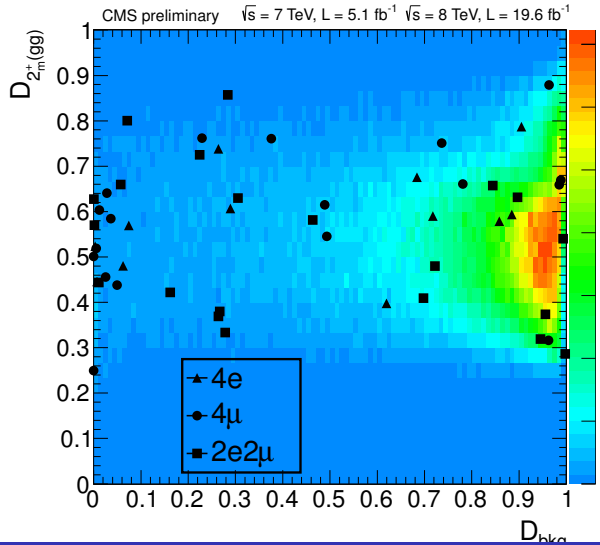
Signal model

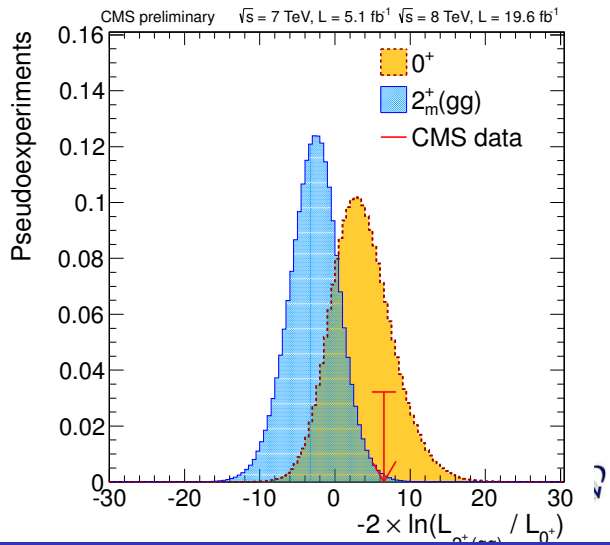
- Low mass region ($m_H < 400$GeV):
  - double Crystall Ball$\otimes$Breit-Wigner
  - 6 parameters of DCB obtained from MC fit for each available m_H
  - Interpolation of the parameters for intermediate m_H values
  - Systematics: 0.4%; 20%; 5% (mean, σ, tail)
- High mass region:
  - Modified Breit-Wigner with free Γ $\otimes$DCB
  - Narrow width approx. breaks down $\rightarrow$ Complex Pole Scheme
  - Higgs samples reweighted to match CPS lineshape predictions (computed by Higgs CS working group)
  - Corrections introduced to account for $H \rightarrow ZZ$ and $gg \rightarrow ZZ$ interference effects
    - Interference constructive below the peak, destructive above
    - Small effect on total CS
    - Bias on invariant mass distribution
  - Interference at LO, signal at NNLO. Alternative lineshapes to set uncertainties due to missing orders
  - 5% systematic uncertainty from high mass corrections

Spin-parity statistical analysis

- $D_{J^P} = \frac{P_{SM}}{c' \times P_{SM} + P_{J^P}} = \left[1 + \frac{c' \times P^{ang}_{J^P}}{P^{ang}_{SM}}\right]^{-1}$
- $D_{bkg} = \frac{P_{SM}}{c \times P_{SM} + P_{bkg}} = \left[1 + \frac{c \times P^{ang}_{bkg} \times P^{mass}_{bkg}}{P^{ang}_{SM} \times P^{mass}_{sig}}\right]^{-1}$
- c, c' tuned to adjust relative normalization of probabilities
- Event yields corrected in each channel for lepton interference and scaled to account detector effects $N^{J^P}_{norm}(k) = N^{J^P}_{exp}(k) \frac{\sum N^{SM}_{exp}(i)}{\sum N^{J^P}_{exp}(i)}$
- Build 2D templates (D_{J^P}, D_{bkg}) and likelihood L for 0^+ and J^P
- Toys to generate the distribution of $q = -2 \ln \frac{L_{J^P}}{L_{0^+}}$ for 0^+ and J^P

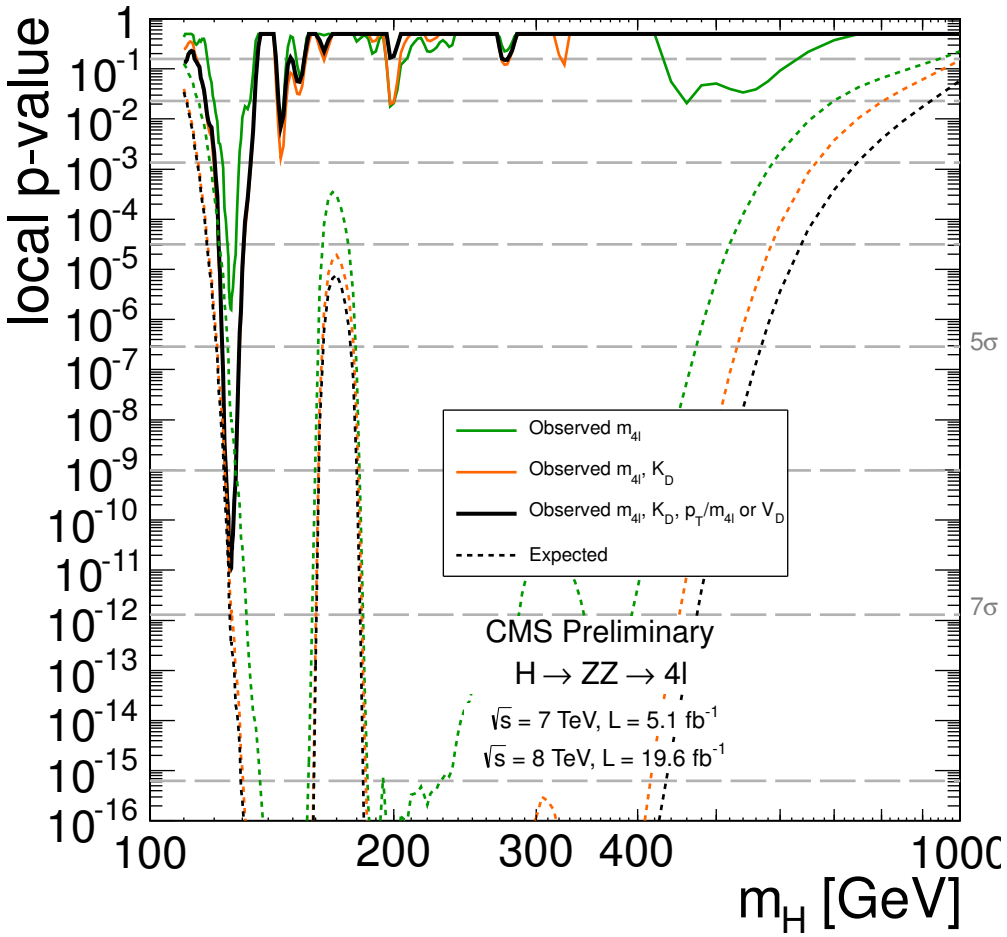






Significance

- Local minimum at 125.7 GeV
- Observed: 6.7σ
  - 1D: 4.7
  - 2D: 6.6
- Expected: 7.2σ
  - 1D: 5.6
  - 2D: 6.9



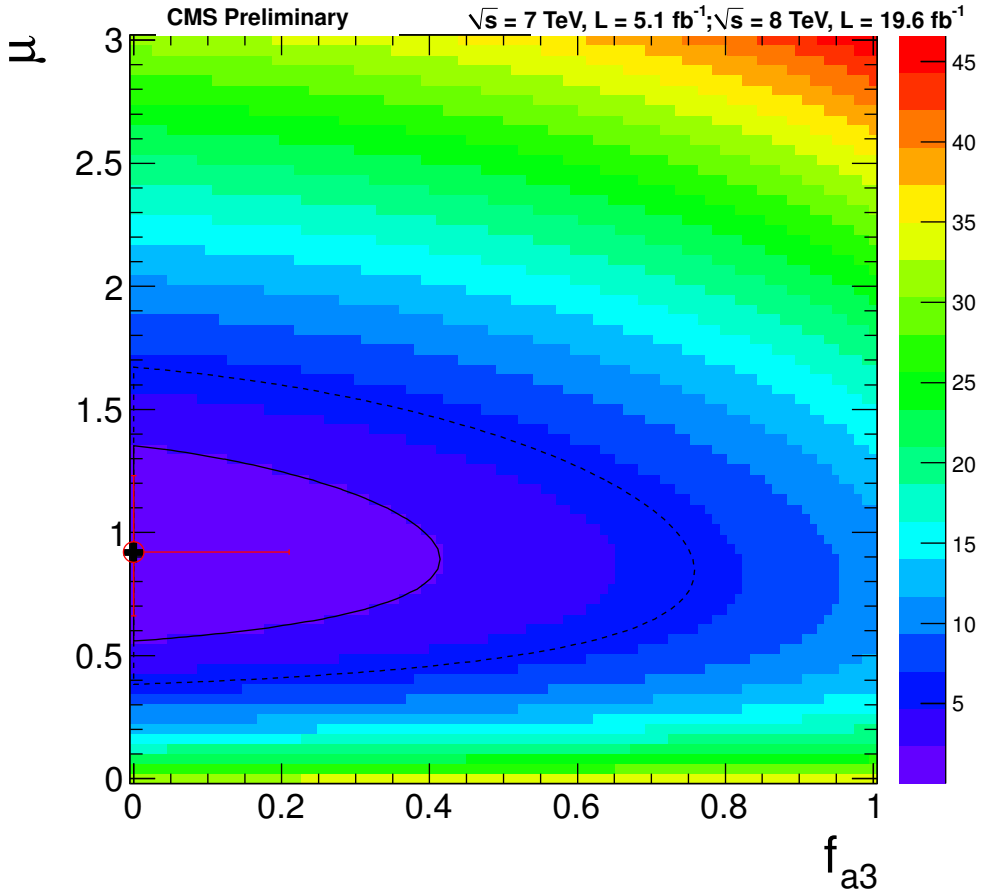
f_{a3} parameter

Higgs decay amplitude:

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

0^+ dominated by A_1, 0^- by A_3

- Fraction of *CP*-odd contributions: $f_{a3} = |A_3|^2/(|A_1|^2 + |A_3|^2)$
- Interference is negligible
- The shape of D_{0-} discriminant depends on the value of f_{a3}. We can use it to measure f_{a3}
- We could set a limit on *CP* violating contributions to *HZZ* coupling



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