# Analysis strategy for the SM Higgs boson search in the four-lepton final state in CMS

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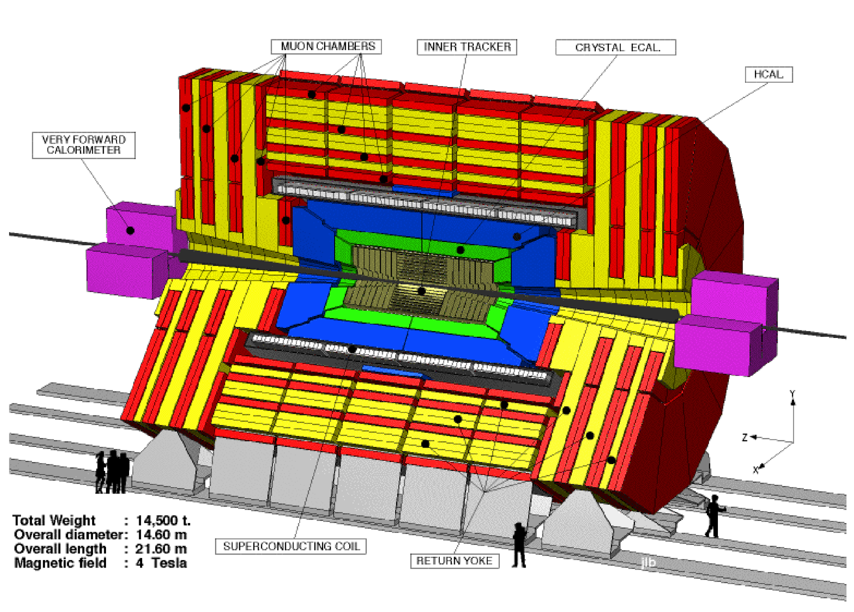
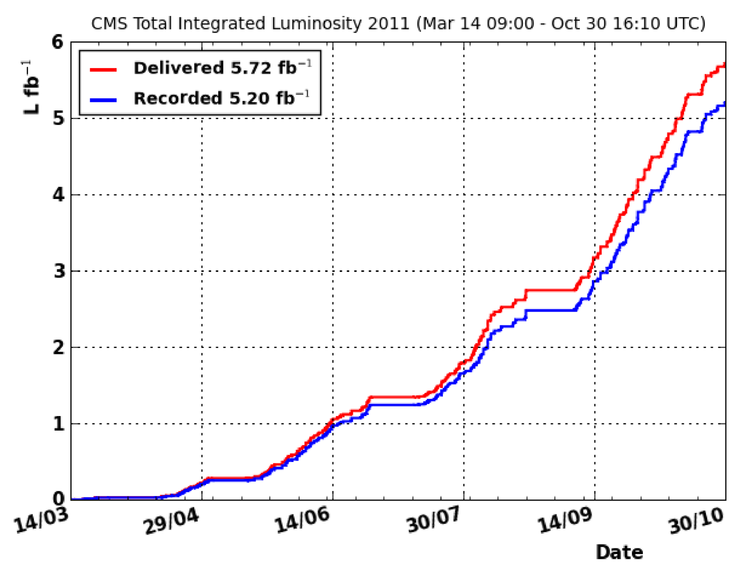
## The CMS experiment

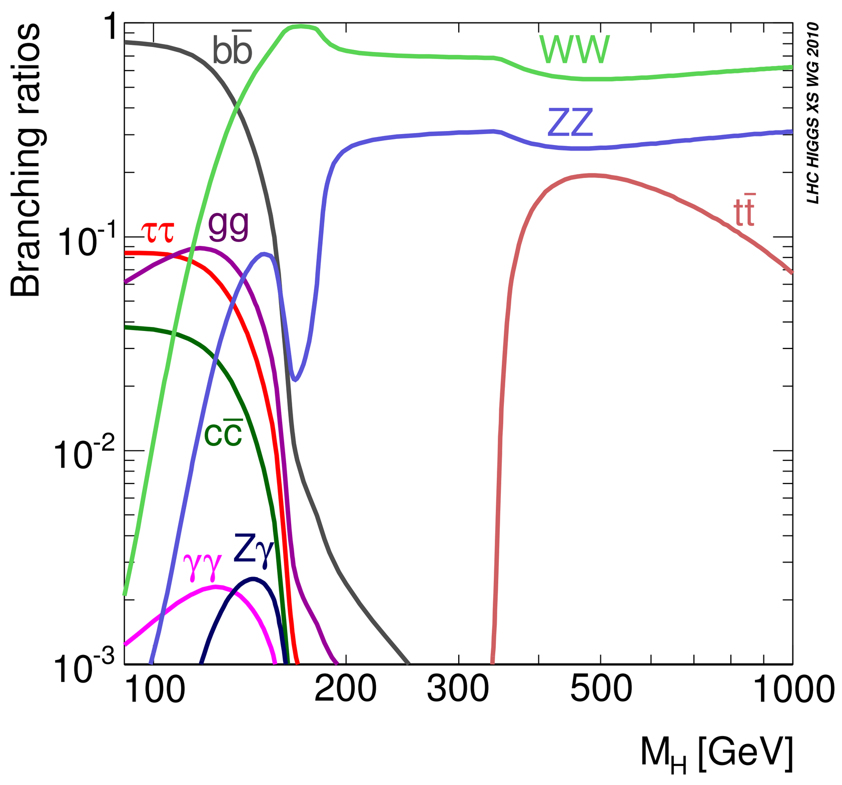
The CMS experiment at the LHC collider at CERN has recorded 5.20 $fb^{-1}$ of high-quality p-p collision data so far.



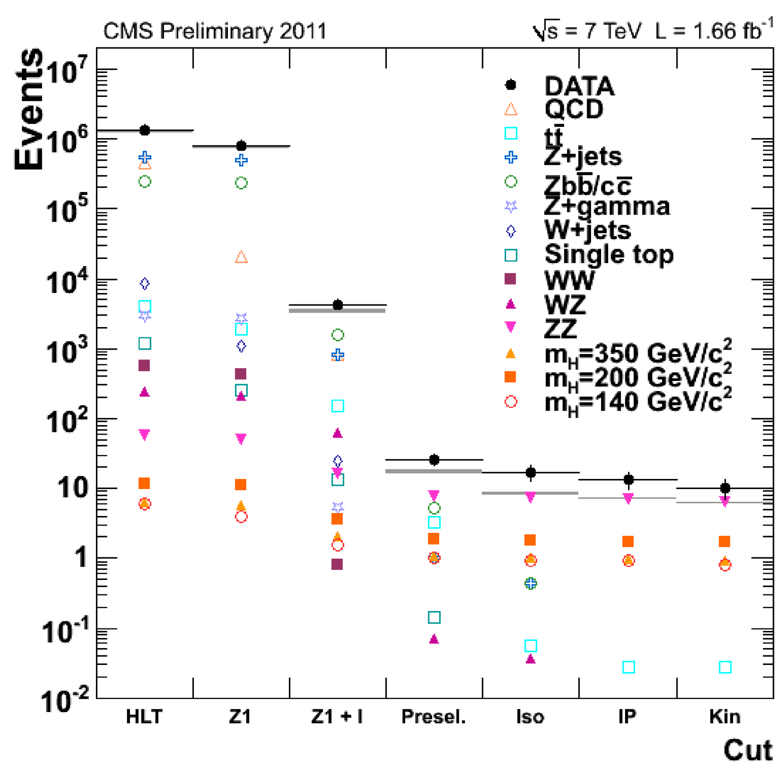

## Signal and backgrounds

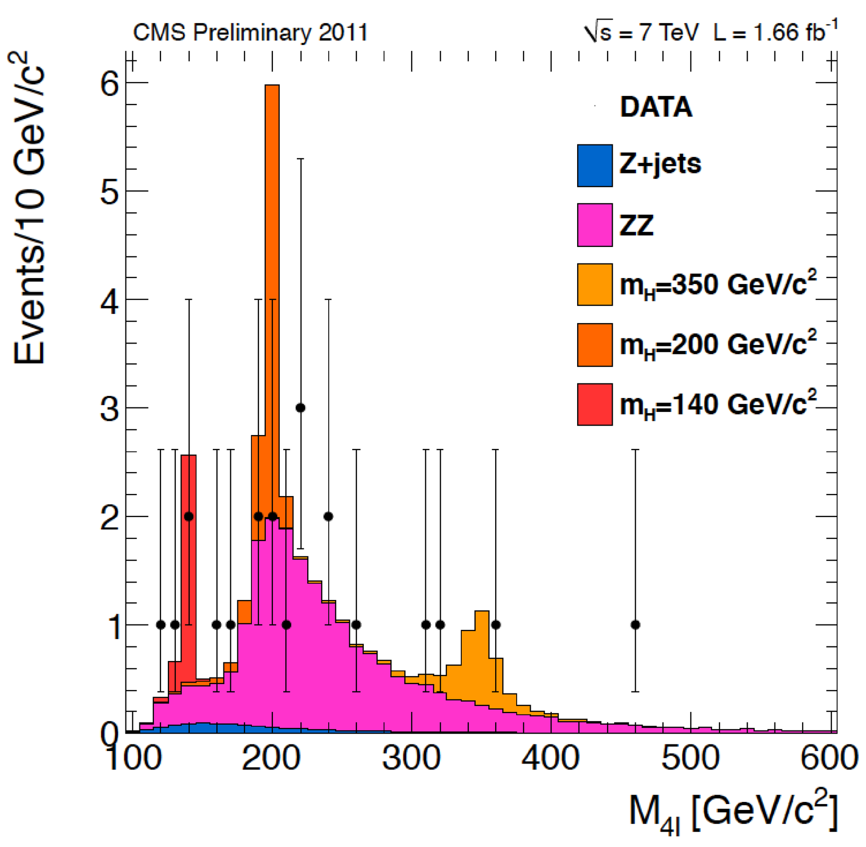
- The considered signal final states are $4\mu$, $4e$, $2e2\mu$
- The main backgrounds are $ZZ$, $t\bar{t}$, $Zb\bar{b}$, $Zc\bar{c}$, $W+jets$, $Z+jets$, $QCD$
- Very clean signature:
  - two pairs of same-flavour, opposite-sign, high-$p_T$ isolated leptons pointing to the same vertex
  - at least one Z is on-shell $\rightarrow$ at least one pair of leptons has $m_{inv}(\ell\ell) \simeq m_Z$
  - the SM Higgs is a scalar particle $\rightarrow$ angular correlations among the final-state leptons




## Event selection

- Requirements on *muons* and *electrons*
  - trigger matching
  - $p_T$ cuts
- $Z_1$ selection
- $Z_1 + 1$ lepton
- $Z_1 + 2$ same-flavour, opposite-charge leptons
- *'Best $4\ell$-candidate'* choice
- cut on relative isolation of leptons
- cut on significance of 3D impact parameter of leptons
- cuts on $Z_1$, $Z_2$ kinematics
  - 'baseline' selection: $20 < m_{Z_2} < 120$ $GeV$
  - 'high mass' selection: $60 < m_{Z_2} < 120$ $GeV$




| | baseline | | |
|---|---|---|---|
| | $4e$ | $4\mu$ | $2e2\mu$ |
| ZZ | $4.05 \pm 0.26$ | $6.02 \pm 0.40$ | $9.87 \pm 0.66$ |
| Z+jet | $0.48 \pm 0.08$ | $0.09 \pm 0.02$ | $0.61 \pm 0.11$ |
| $Zb\bar{b}/c\bar{c}, t\bar{t}$ | $0.01 \pm 0.01$ | $0.05 \pm 0.01$ | $0.06 \pm 0.01$ |
| WZ | $0.009 \pm 0.009$ | $0.009 \pm 0.009$ | $0.04 \pm 0.02$ |
| All background | $4.54 \pm 0.27$ | $6.12 \pm 0.40$ | $10.52 \pm 0.67$ |
| $m_H = 140\,GeV/c^2$ | 0.45 | 0.82 | 1.19 |
| $m_H = 200\,GeV/c^2$ | 1.20 | 1.71 | 2.80 |
| $m_H = 350\,GeV/c^2$ | 0.70 | 0.93 | 1.63 |
| Observed | 5 | 10 | 6 |

| | high-mass | | |
|---|---|---|---|
| | $4e$ | $4\mu$ | $2e2\mu$ |
| ZZ | $3.67 \pm 0.25$ | $5.22 \pm 0.34$ | $8.96 \pm 0.59$ |
| Z+jet | $0.20 \pm 0.07$ | $0.01 \pm 0.01$ | $0.22 \pm 0.07$ |
| $Zb\bar{b}/c\bar{c}, t\bar{t}$ | - | $0.01 \pm 0.01$ | $0.01 \pm 0.01$ |
| WZ | - | - | $0.009 \pm 0.009$ |
| All background | $3.87 \pm 0.26$ | $5.23 \pm 0.34$ | $9.18 \pm 0.59$ |
| $m_H = 140\,GeV/c^2$ | 0.007 | 0.01 | 0.02 |
| $m_H = 200\,GeV/c^2$ | 1.13 | 1.60 | 2.65 |
| $m_H = 350\,GeV/c^2$ | 0.67 | 0.89 | 1.55 |
| Observed | 2 | 6 | 6 |

## $ZZ \rightarrow 4\ell$ cross section measurement

The $ZZ \rightarrow 4\ell$ inclusive cross section has been measured after the cuts $60 < M_{Z_1} < 120$ $GeV$ & $60 < M_{Z_2} < 120$ $GeV$ (*'high mass' selection*) as

$$\sigma(pp \rightarrow ZZ + X) \times BR(ZZ \rightarrow 4\ell) = \frac{\sum(N^{ich}_{obs} - N^{ich}_{bkg})}{\mathcal{A}_{4\ell} \times \varepsilon_{ZZ\rightarrow 4\ell} \times \mathcal{L}} =$$

$$= 20.84^{+6.8}_{-4.0}\,(\text{stat.}) \pm 0.54(\text{syst.}) \pm 0.94(\text{lumi.})\ fb$$

This result should be compared with the theoretical value

$$\sigma_{TH}(pp \rightarrow ZZ + X) \times BR(ZZ \rightarrow 4\ell) = 28.32 \pm 2.57\ fb$$

## ZZ background control

**Normalization to single Z:**

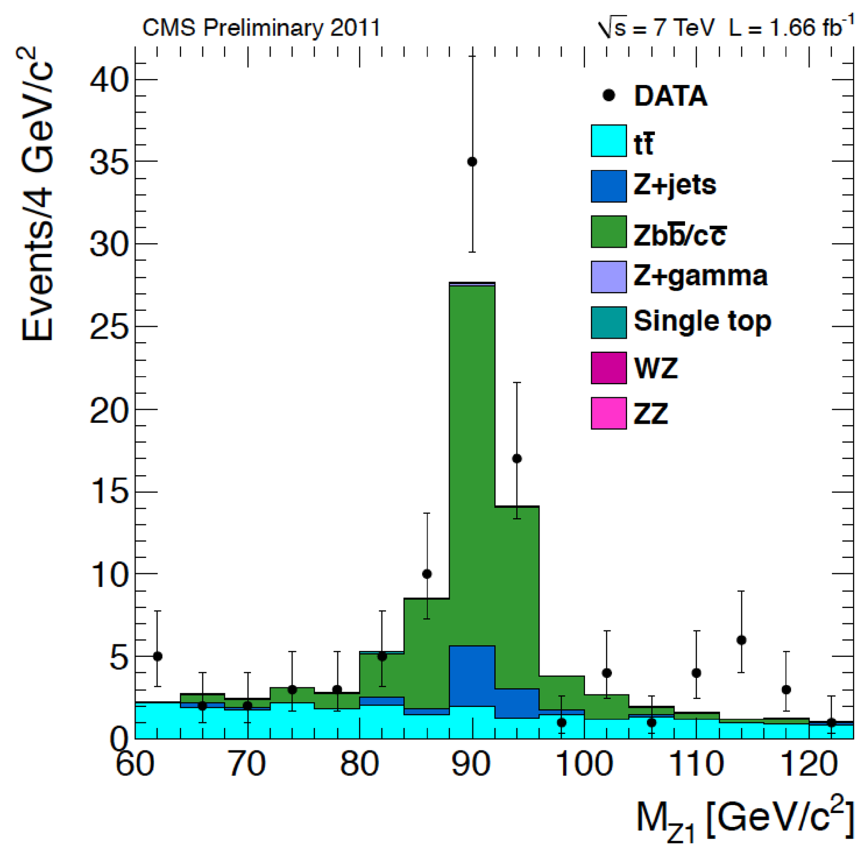
$$N_{ZZ\rightarrow 4\ell} = \frac{\sigma^{NLO}_{q\bar{q}\rightarrow ZZ\rightarrow 4\ell} + \sigma^{LO}_{gg\rightarrow ZZ\rightarrow 4\ell}}{\sigma^{NNLO}_{pp\rightarrow Z\rightarrow 2\ell}} \cdot \frac{\varepsilon^{MC}_{ZZ\rightarrow 4\ell}}{\varepsilon^{MC}_{Z\rightarrow 2\ell}} \cdot N^{observed}_{Z\rightarrow 2\ell}$$

- most systematic uncertainties cancel out (e.g. those related to luminosity)
- most diagrams are shared by the two processes

| | channel | Normalization to Z rate | MC model simulation |
|---|---|---|---|
| baseline | $N^{ZZ\rightarrow 4e}$ | $4.05 \pm 0.26$ | $4.07 \pm 0.38$ |
| | $N^{ZZ\rightarrow 4\mu}$ | $6.02 \pm 0.40$ | $6.23 \pm 0.57$ |
| | $N^{ZZ\rightarrow 2e2\mu}$ | $9.87 \pm 0.66$ | $10.06 \pm 0.93$ |
| high-mass | $N^{ZZ\rightarrow 4e}$ | $3.67 \pm 0.25$ | $3.70 \pm 0.34$ |
| | $N^{ZZ\rightarrow 4\mu}$ | $5.22 \pm 0.34$ | $5.38 \pm 0.48$ |
| | $N^{ZZ\rightarrow 2e2\mu}$ | $8.96 \pm 0.59$ | $9.14 \pm 0.85$ |

## $Zb\bar{b}$, $Zc\bar{c}$, $t\bar{t}$ background control

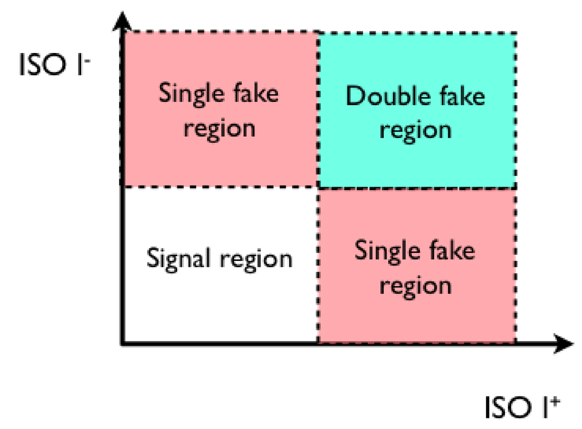
- same $Z_1$ selection as for signal events
- flavour, charge and isolation requirements are relaxed for the two other leptons
- the cut on the 3D impact parameter significance is reversed for these two leptons: $|SIP_{3D}| > 5$
- to propagate from the control region to the signal region:
  - $m_{2\ell} > 12$ $GeV$, $m_{4\ell} > 100$ $GeV$
  - combinatorial factor to account for lepton flavour and charge combinations
  - acceptance factors from MC:
    $R_{SIP_{3D}} = A_{|SIP_{3D}|<4}/A_{|SIP_{3D}|>5}$
    $R_{ISO} = A_{CombRelIso<0.35}/A$




## $Z + jets$ background control

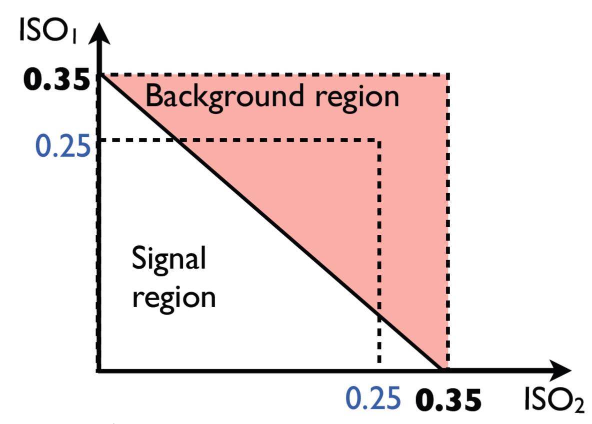
**Single-lepton fake rate measurement:**

- same $Z_1$ selection as for signal events
- exactly one additional *'fakeable object'* (e, $\mu$)
- $MET < 25$ $GeV$ to suppress the WZ contribution
- Fake rate $= \varepsilon(p^{\ell}_T, \eta^{\ell}) = \frac{\text{N(passing ID and isolation cuts)}}{\text{N(fakeable objects)}}$




**Control region:**

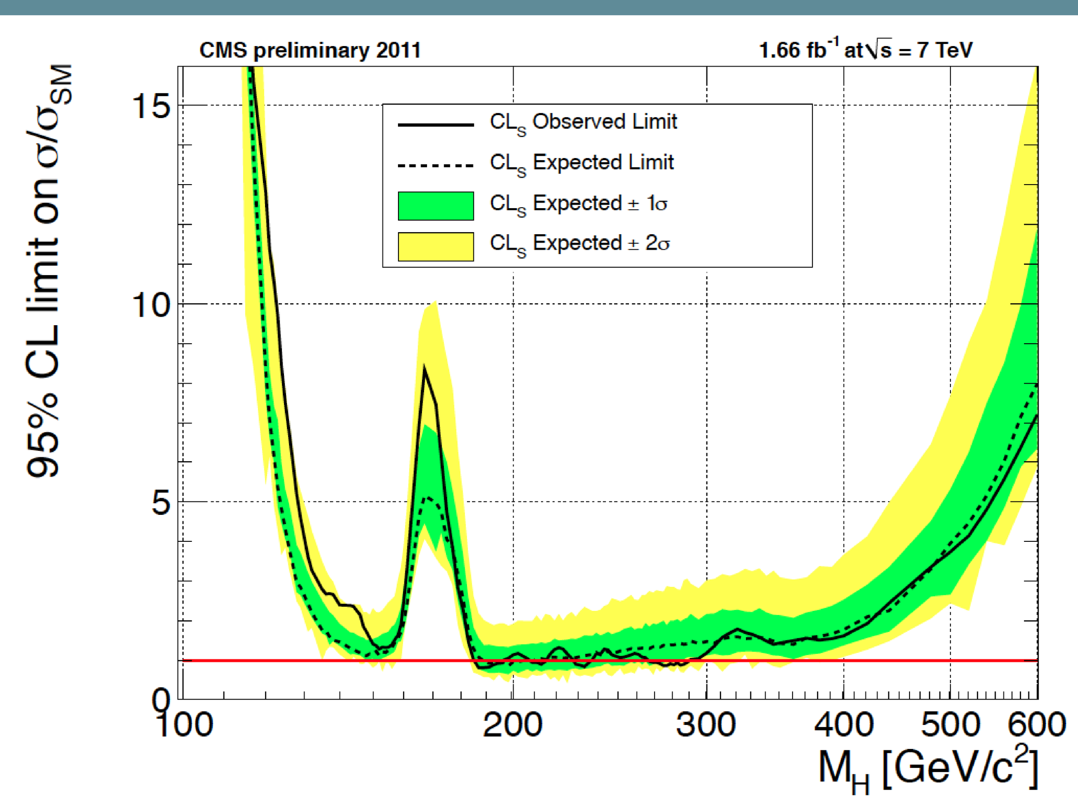
- same $Z_1$ selection as for signal events
- two other leptons of same flavour and same charge (to avoid signal contamination) $\ell_3^{\pm}$, $\ell_4^{\pm}$ are looked for
- no ID, isolation requirements on them
- a cut is applied on $m(\ell_3\ell_4)$ and on $m(4\ell)$




**Extrapolation to the signal region:**

$$N^{Z+jets}_{SR} = N^{Z+jets}_{CR} \times \frac{1}{2} \times \frac{\varepsilon(p^{\ell_3}_T, \eta^{\ell_3}) \times \varepsilon(p^{\ell_4}_T, \eta^{\ell_4})}{[1 - \varepsilon(p^{\ell_3}_T, \eta^{\ell_3})] \times [1 - \varepsilon(p^{\ell_4}_T, \eta^{\ell_4})]}$$

## Exclusion limits for $\sqrt{s} = 7$ $TeV$, $L = 1.66$ $fb^{-1}$




Upper limits at 95% C.L. on $\sigma \cdot BR$ for a SM-like Higgs boson exclude cross sections from about one to two times the expected SM ones in the mass range $150 < m_H < 420$ $GeV$

## References

- CMS PAS 2011/015: The CMS Collaboration, "Search for a Standard Model Higgs boson in the decay channel $H \rightarrow ZZ \rightarrow 4\ell$
- CMS PAS 2011/004: The CMS Collaboration, "Search for a Standard Model Higgs boson in the decay channel $H \rightarrow ZZ \rightarrow 4\ell$
- CMS AN 2011/123: N. Amapane et al., "Search for a Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$"



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