# Search for a Higgs boson decaying into $\mu\mu\gamma$ with $m_{\mu\mu} < 20$ GeV in pp collisions at $\sqrt{s} = 8$ TeV

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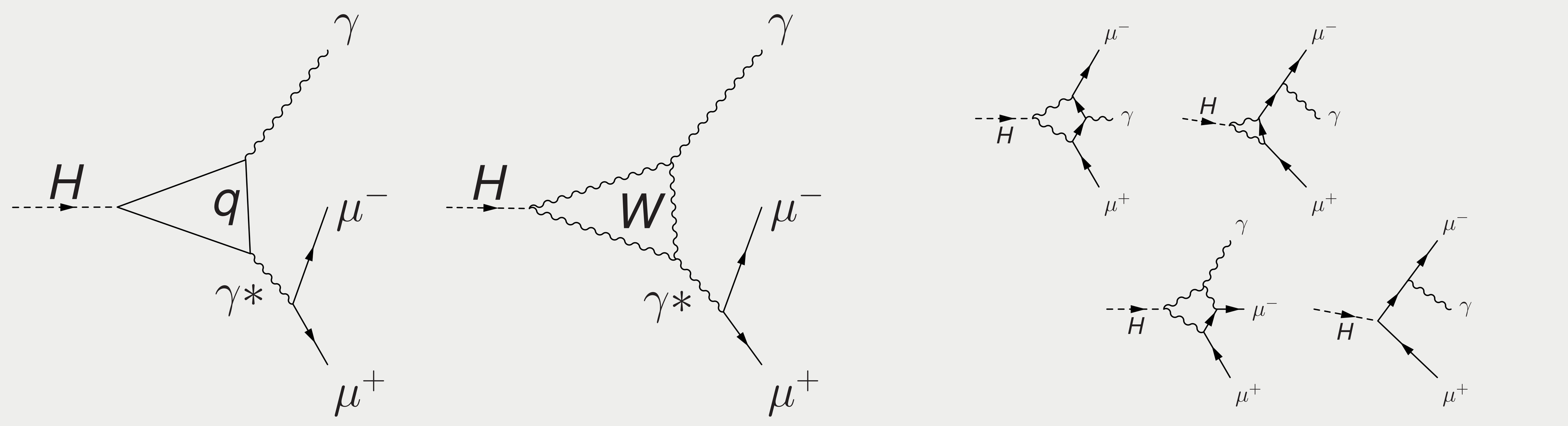
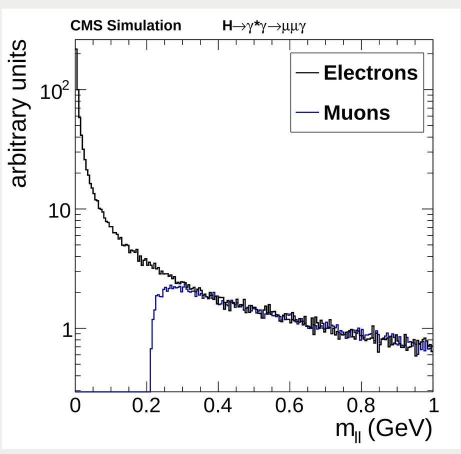
## Introduction: Higgs Dalitz decay

- Higgs boson decay into $\mu\mu\gamma$ final state, although rare, provides interesting information on the properties of the SM Higgs boson: (a) it gives an extra handle on the measurement of the Higgs' couplings; (b) consists of non-trivial angular correlations that could result in a forward-backward asymmetry; (c) it is sensitive to new-physics via loops;
- The dominant contribution to the $\mu\mu\gamma$ final state are from $h \to \gamma^*\gamma$ and $h \to Z^*\gamma$ processes, with an internal conversion of the $\gamma^*/Z^*$ into $\mu^+\mu^-$ pair (which occurs at 6% rate).
- In presented analysis we are interested only in $\gamma^* \to \mu\mu$ part, specifically the region of $m_{\mu\mu} < 20$ GeV, it is CMS-PAS-HIG-14-003 publication (while the complimentary $h \to Z^*\gamma$ analysis was performed at CMS earlier [1]).
- In analogy to $\pi_0 \to e^+e^-\gamma$ decays via an internal conversion of one of the photons, discovered by R.H.Dalitz, we call the $h \to \gamma^*\gamma$ process Higgs Dalitz decay [2].




## Signal Monte Carlo for $H \to \mu\mu\gamma$ Dalitz decay

- The first challenge of this analysis was to produce a proper signal MC samples. We accomplished that with MADGRAPH and generated the signal MC in three Higgs production channels (gluon fusion, vector boson fusion and V+H) at LO of QCD, with masses from 120 to 150 GeV. The samples were hadronized with PYTHIA and undergo the full CMS detector simulation.
- The $\sigma \times BR$ numbers for those processes were taken from MCFM (@NLO) and corrected based on $H \to Z\gamma$ predictions.




- There is a natural cut-off at $m_{\gamma*} > 2 \times m_\ell$, different for muons and electrons and important due to the kinematics at low $m_{\ell\ell}$
- The kinematic distributions of the MADGRAPH samples were also cross-checked with MCFM and found to be consistent.

## Features of the $h \to \ell^+\ell^-\gamma$ decay

- Due to the decay of massive particle (the Higgs) into two practically mass-less photons, the energies of the $\gamma$ and $\gamma^*$ are large and the two particles fly in the opposite directions. Therefore a hard cut on their $p_T$ as well as $\Delta R$ is possible and those reject a lot of backgrounds.
- The leptons from $\gamma^* \to \mu\mu$ decay are highly correlated in their $p_T$.
- The angular distance $\Delta R(\ell_1, \ell_2)$ is very close to zero for the bulk of the events. This makes it hard to perform the analysis in electron channel because the two electrons are merged in a single super-cluster at ECAL and are not resolved.
- Background composition in the signal region mainly consist of $\ell\ell\gamma$ ($\sim 1/4$) and $\ell\ell + jet$ ($\sim 3/4$) processes. We use a fit to the data events as the background model.

*Here is the full list of our final cuts on reconstructed analysis objects:*

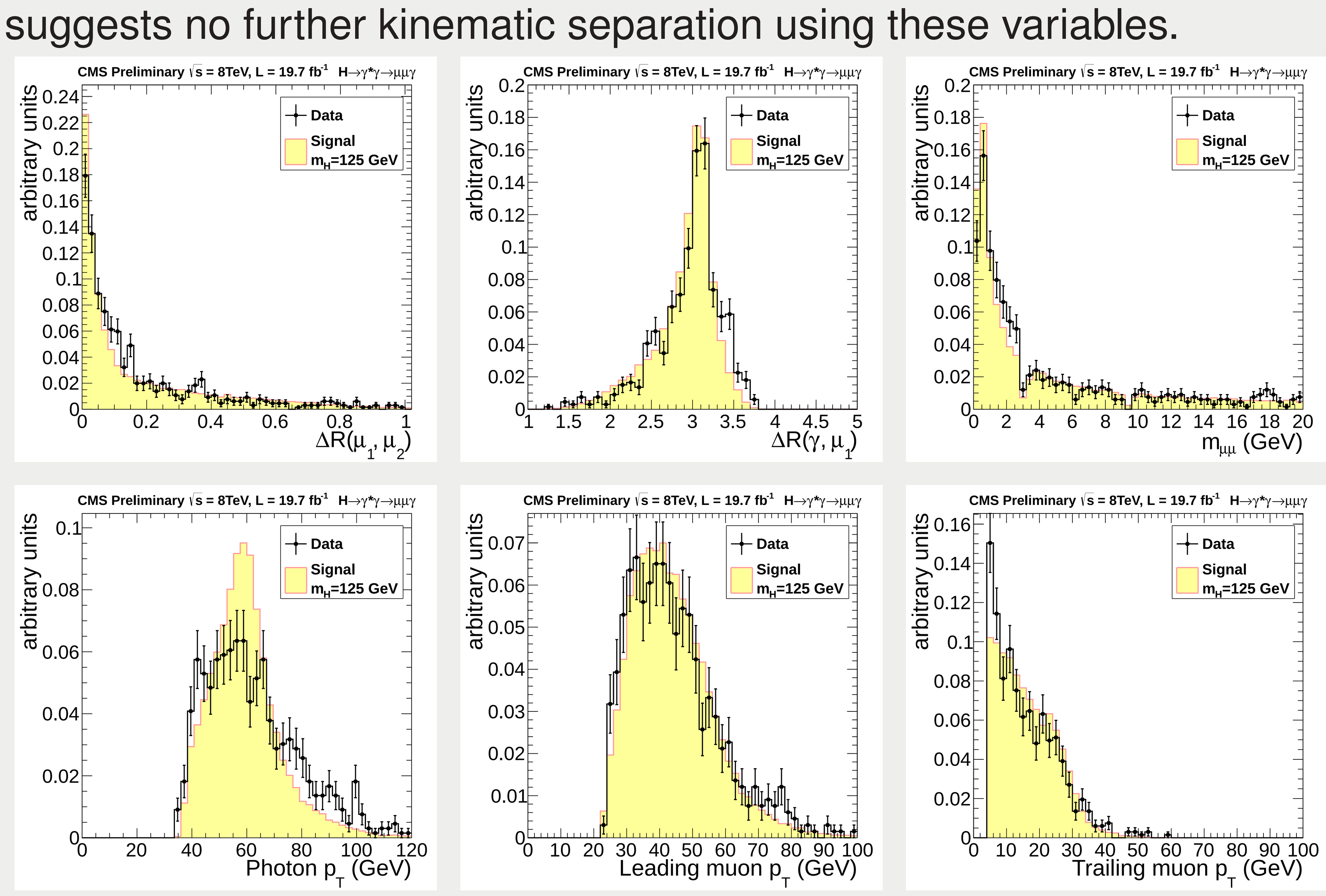
**Photon**
- $|\eta^\gamma| < 1.44$ and $p_T^\gamma > 25$ GeV, due to the trigger threshold

**Muons**
- $|\eta_\mu| < 2.4$; $p_T^{\mu_1} > 23$ GeV, driven by the trigger threshold) and $p_T^{\mu_2} > 4$ GeV (as low as we can go in $p_T$)
- $m_{\mu\mu} < 20$ GeV - due to Dalitz signal topology. NB: this corresponds to $\Delta R(\mu\mu) <\sim 1.0$
- Veto events with $m_{\mu\mu}$ consistent with $J/\psi$ or $\Upsilon$.

**Photon + Lepton**
- Muon+Photon trigger with $p_T > 22$ GeV cut on both muon and a photon objects. The efficiency of that trigger is found to be 85% based on our signal MC.
- $\Delta R(\gamma, \mu) > 1$- rejects FSR photons, not affecting the signal;
- $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$ and $p_T^\gamma/m_{\mu\mu\gamma} > 0.3$ – increases the sensitivity at high masses, preserving the shape of $m_{\ell\ell\gamma}$ distribution.
- 110 GeV $< m_{\mu\mu\gamma} <$ 170 GeV – this is our fit region.

## Relevant distributions and event yield

- After the full selection one can look at the distributions of interest: $m_{\mu\mu}$, $p_T^{\mu_1}$, $p_T^{\mu_2}$, $p_T^\gamma$, $\Delta R(\mu_1, \mu_2)$ and $\Delta R(\mu, \gamma)$ for data and signal MC. The fact that the shapes of all of those distributions are quite similar suggests no further kinematic separation using these variables.

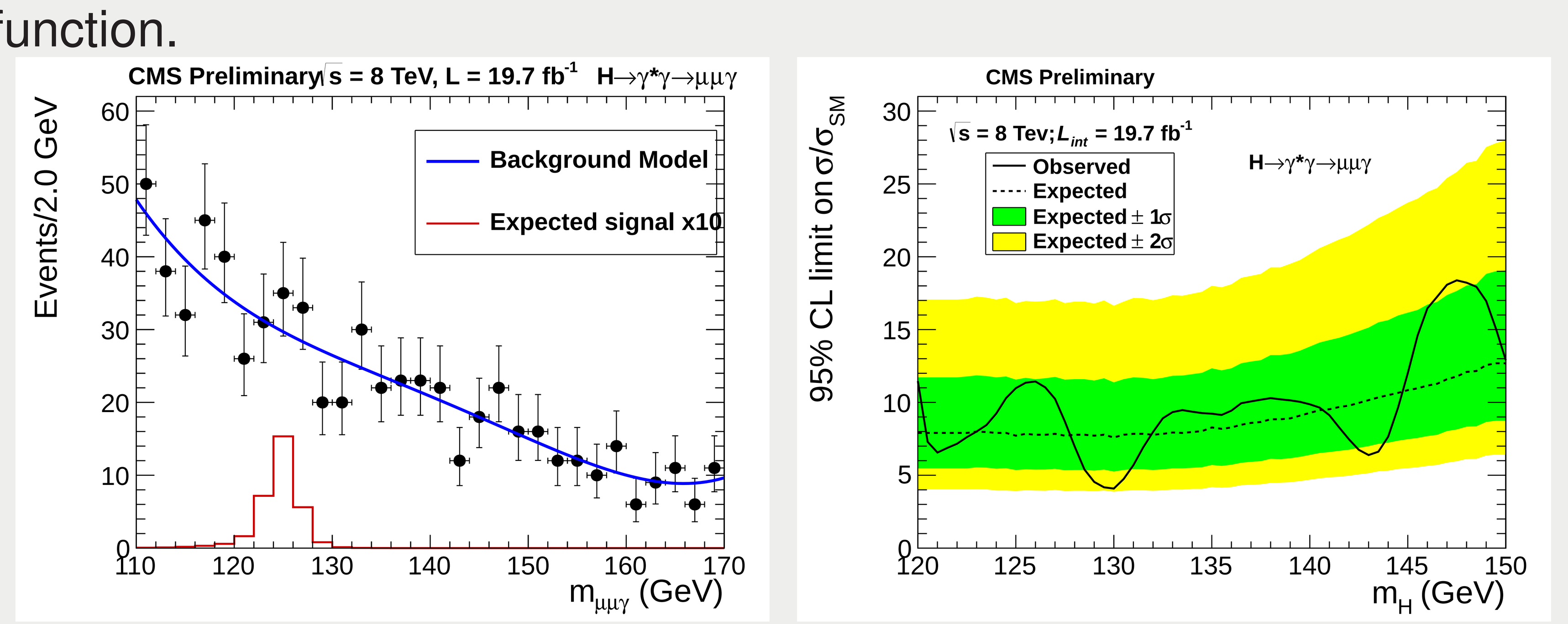



- At last, the event yield after each cut can be looked at:

| Requirement | Observed event yield in data | Expected signal for $m_H = 125$ |
|---|---|---|
| Trigger and $p_T^\gamma > 25$ GeV, $\lvert\eta\rvert < 1.44$ | 0.6M | 6.2 |
| $p_T^{\mu_1} > 23$ GeV and $p_T^{\mu_2} > 4$ GeV | 55836 | 4.7 |
| $110 < m_{\mu\mu\gamma} < 170$ GeV | 7800 | 4.7 |
| $m_{\mu\mu} < 20$ GeV | 1142 | 3.9 |
| $\Delta R(\mu, \gamma) > 1$ | 1138 | 3.9 |
| Removal of resonances | 1020 | 3.7 |
| $p_T^\gamma/m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$ | 665 | 3.3 |
| $122$ GeV $< m_{\mu\mu\gamma} < 128$ GeV | 99 | 2.9 |

## Results: three body mass spectrum and the limits

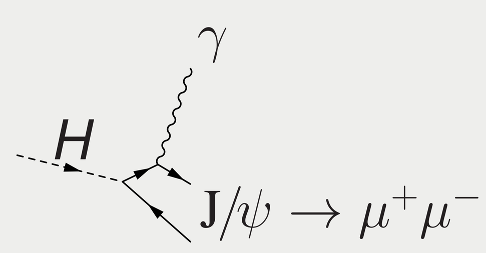
- Finally, we fit the data distribution of $m_{\mu\mu\gamma}$ to a $4^{th}$-order polynomial function and search for the peaks of signal on top of it. The signal model comes from MC and has a form of a Gaussian plus a Crystal-Ball function.




- No signal was observed in the range from 110 to 170 GeV, consequentially the limits on $\mu = \sigma \times BR/(\sigma \times BR)_{SM}$ are obtained. @$m_H = 125$ GeV expected limit is 7.5 while the observed is $11.5 \times SM$
- The largest systematic uncertainties are theoretical ones, on the higgs production cross section and BR, $\sim 15\%$. Second largest is the uncertainty on di-muon efficiency which amounts to $\sim 11\%$

## The future and an interesting twist

- At the end of LHC Run-2 (L=300 fb$^{-1}$) we expect to observe the signal in this channel.
- Higgs Dalitz decay is an important step towards $H \to J/\psi\gamma$ [3] as well as $H \to \Upsilon\gamma$ measurements, which are sensitive to Hcc and Hbb couplings.
  - Those analyses at LHC could be possible at 3000 fb$^{-1}$ of data at LHC Run-3.




[1] *Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s}$ = 7 and 8 TeV*, CMS Collaboration, Phys.Lett., B726, arxiv:1307.5515
[2] *Higgs Boson Production and Decay: Dalitz Sector*, Passarino, Giampiero, Phys.Lett., B727, arxiv:1308.0422
[3] *Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling*, Bodwin *et al.*, Phys.Rev., D88, arxiv:1306.5770