



Rare decays of the Higgs boson with CMS

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on behalf of the CMS Collaboration



53rd Rencontres de Moriond:
Electroweak interactions and unified theories

Why looking for rare decays ?



The measurements of the Higgs boson in the main decay channels show good agreement with the SM predictions

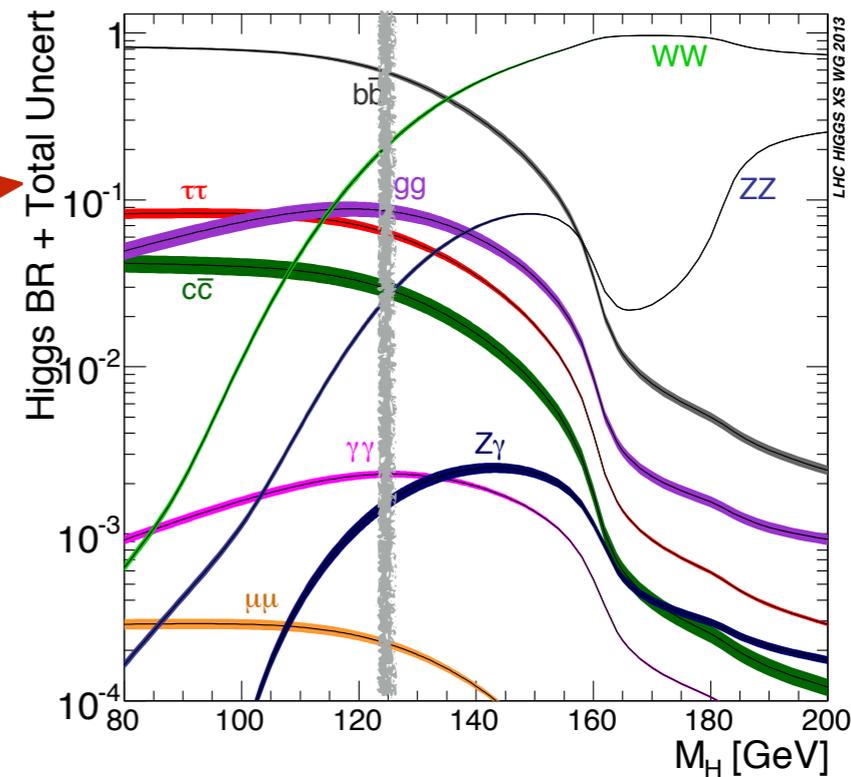
see updates
David Sperka

Testing rare decays can further gauge prediction for SM couplings to different particles or can be enhanced by BSM contributions

$BR(H \rightarrow BSM) < 34\%$
(Run I, arXiv:1606.02266)

Room for larger

- $H \rightarrow$ rare
- $H \rightarrow$ Invisible
- $H \rightarrow$ lepton flavor violation (LFV)



Channel	BR [%]
bb	58
WW	21
gg	8.2
$\tau\tau$	6.3
cc	2.9
ZZ	2.6
$\gamma\gamma$	0.23

Rare Decays

Channel	BR [%]
$\mu\mu$	0.022
$Z\gamma \rightarrow \gamma ll$	$5.2 \cdot 10^{-3}$
$\gamma^* \gamma \rightarrow \mu\mu\gamma$	$3.9 \cdot 10^{-3}$
$ZZ \rightarrow 4\nu$	0.1

Higgs to invisible searches



- SM H decays to invisible only through $H \rightarrow ZZ \rightarrow 4\nu$ (BR=0.1%)
- Higgs boson decays to invisible final states predicted by many BSM theories
- testing BSM invisible particles with $m < m_H/2$
- All Higgs production processes can be used
- Event signature: presence of a large missing transverse momentum
- Tag by the visible recoil of the system

Decay Mode	Dataset	ID
$H \rightarrow \text{inv} (qqH)$	36 fb ⁻¹ , 13 TeV	HIG-17-023
$H \rightarrow \text{inv} (ggH)$	36 fb ⁻¹ , 13 TeV	arXiv:1712.02345
$V(\rightarrow jj)H(\rightarrow \text{inv})$	36 fb ⁻¹ , 13 TeV	arXiv:1712.02345
$Z(\rightarrow \ell\ell)H(\rightarrow \text{inv})$	36 fb ⁻¹ , 13 TeV	arXiv:1711.00431

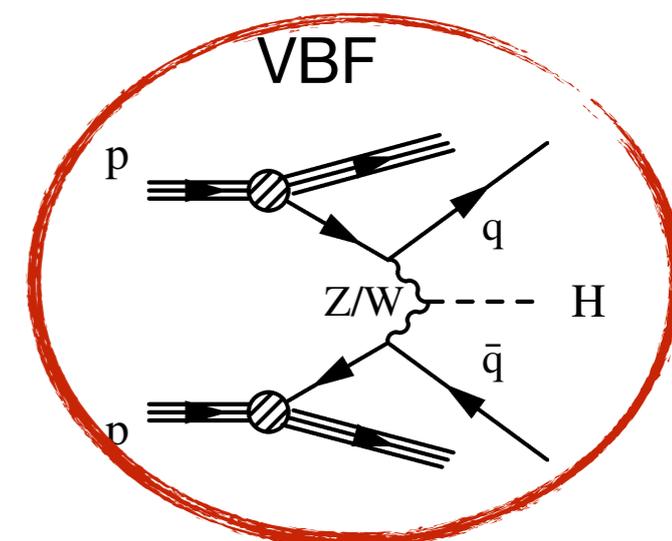
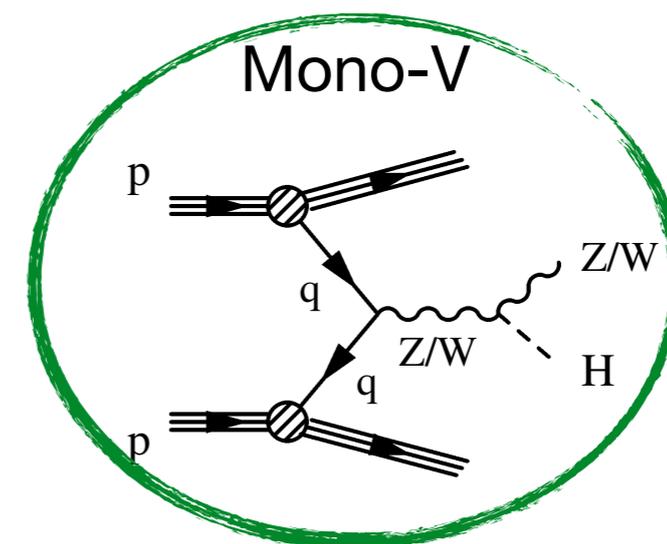
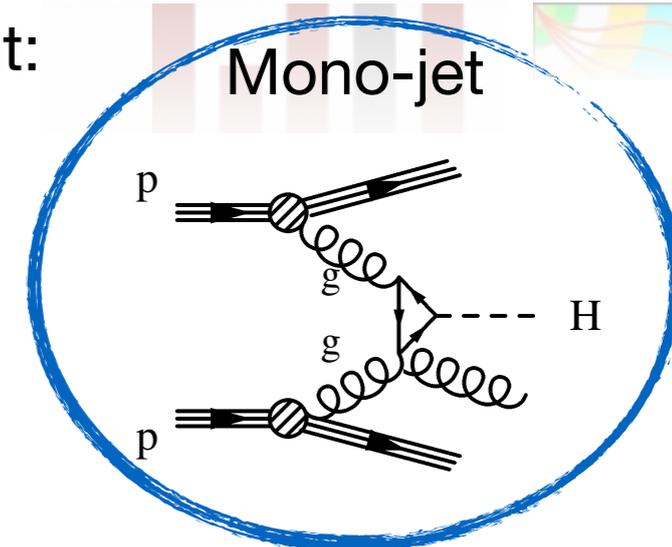


Higgs to invisible searches



Invisible Higgs search tags event due to the extra activity in the event:

- **mono-jet** tag, aiming to measure ggH process, where the Higgs system is boosted and recoils against a jet which is visible in the event
- **mono-V** tag, aiming at VH topology, the V (W or Z) can be tagged and recoil against missing momentum. Both hadronic and leptonic decays of the V are exploited
- **VBF tag** most sensitive channel, due to its unique topology, that makes it distinguishable from the main backgrounds
 - Two well separated forward backward jets
 - Large invariant mass (m_{jj}) and pseudo rapidity gap ($\Delta\eta$)
 - Jets are not color connected (low activity in the rapidity gap)



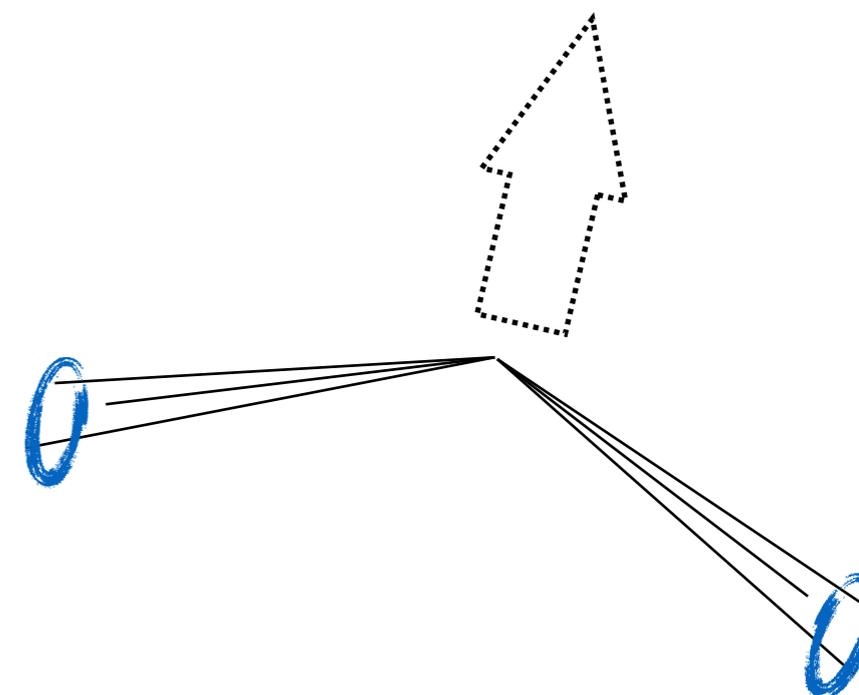
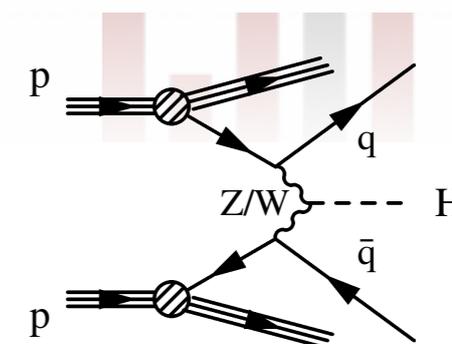
Selection of the $H \rightarrow \text{Inv}$ in the VBF tag

- two high energetic jets:
 - large rapidity gap, $\Delta\eta(j_1, j_2)$,
 - large invariant mass, $m_{jj} > 200 \text{ GeV}$
- large missing energy: trigger $p_T^{\text{miss}} > 250 \text{ GeV}$
- Two strategies :

shape analysis based on m_{jj}

new approach, use the full discrimination power of the invariant mass distribution

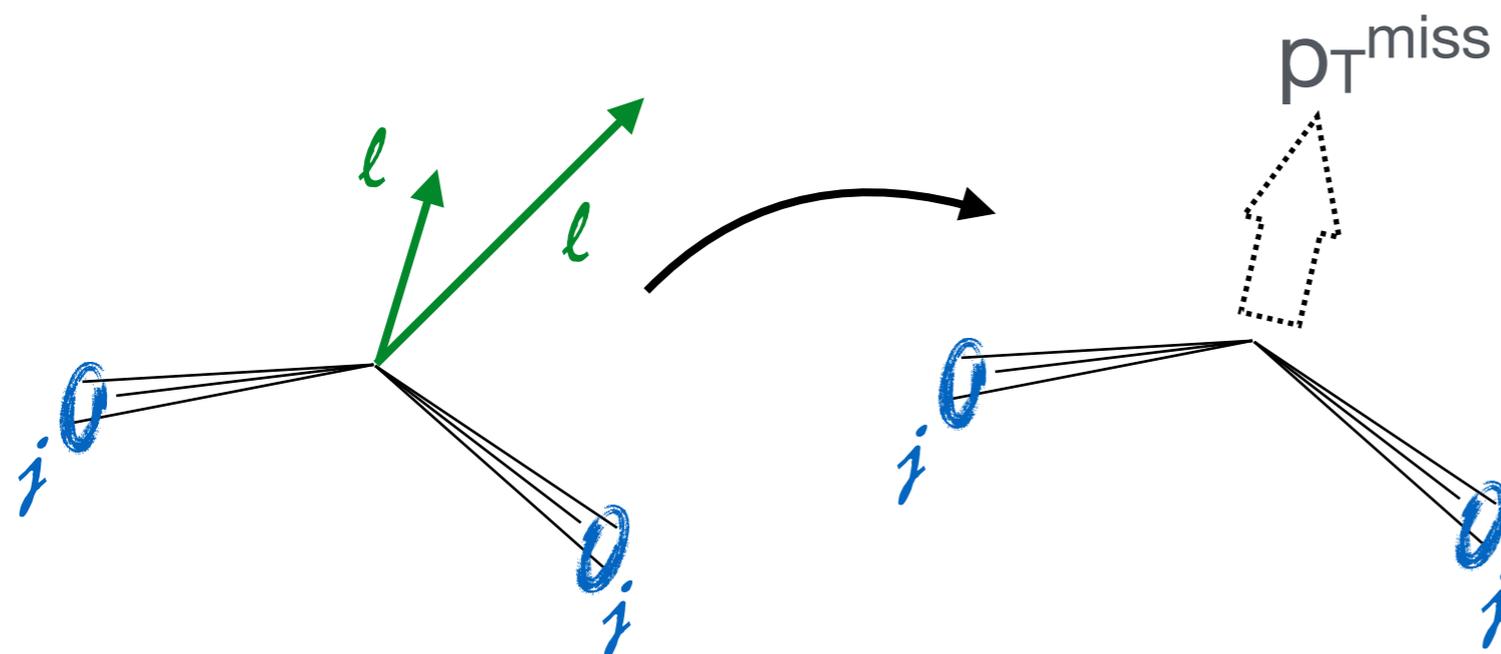
cut & count, cross-validate shape analysis,
minimize model dependence
more extreme selection to optimize sensitivity
as in Run I



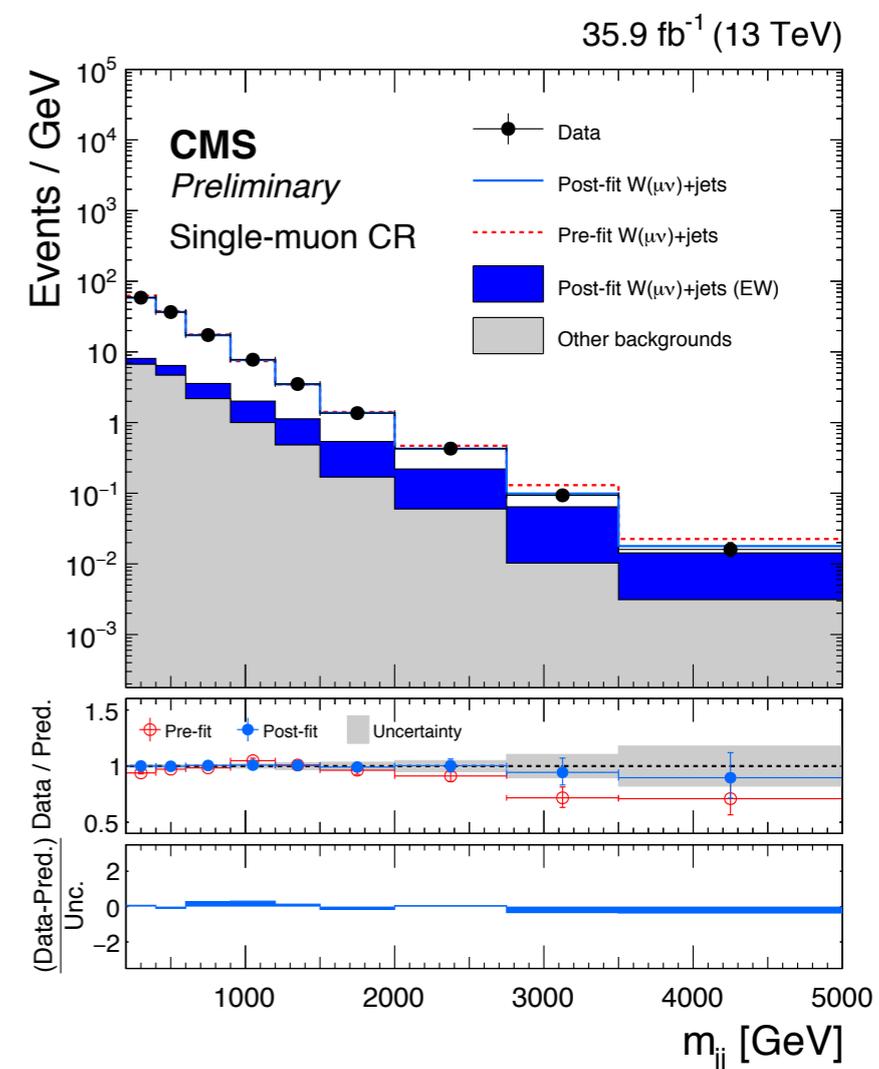
Background Estimation



- Main background is $Z \rightarrow \nu\nu$ and $W+\text{jets}$ production
- Constrained using dilepton (Z_{ee} , $Z_{\mu\mu}$) and single lepton ($W_{e\nu}$, $W_{\mu\nu}$) control regions constrains $Z \rightarrow \nu\nu$ and $W+\text{jets}$ respectively
- Leptons added to the p_T^{miss} to mimic the search region



- QCD multi-jet enriched CR with inverted p_T^{miss} and $\Delta\phi(p_T^{\text{miss}}, \vec{j})$ requirements



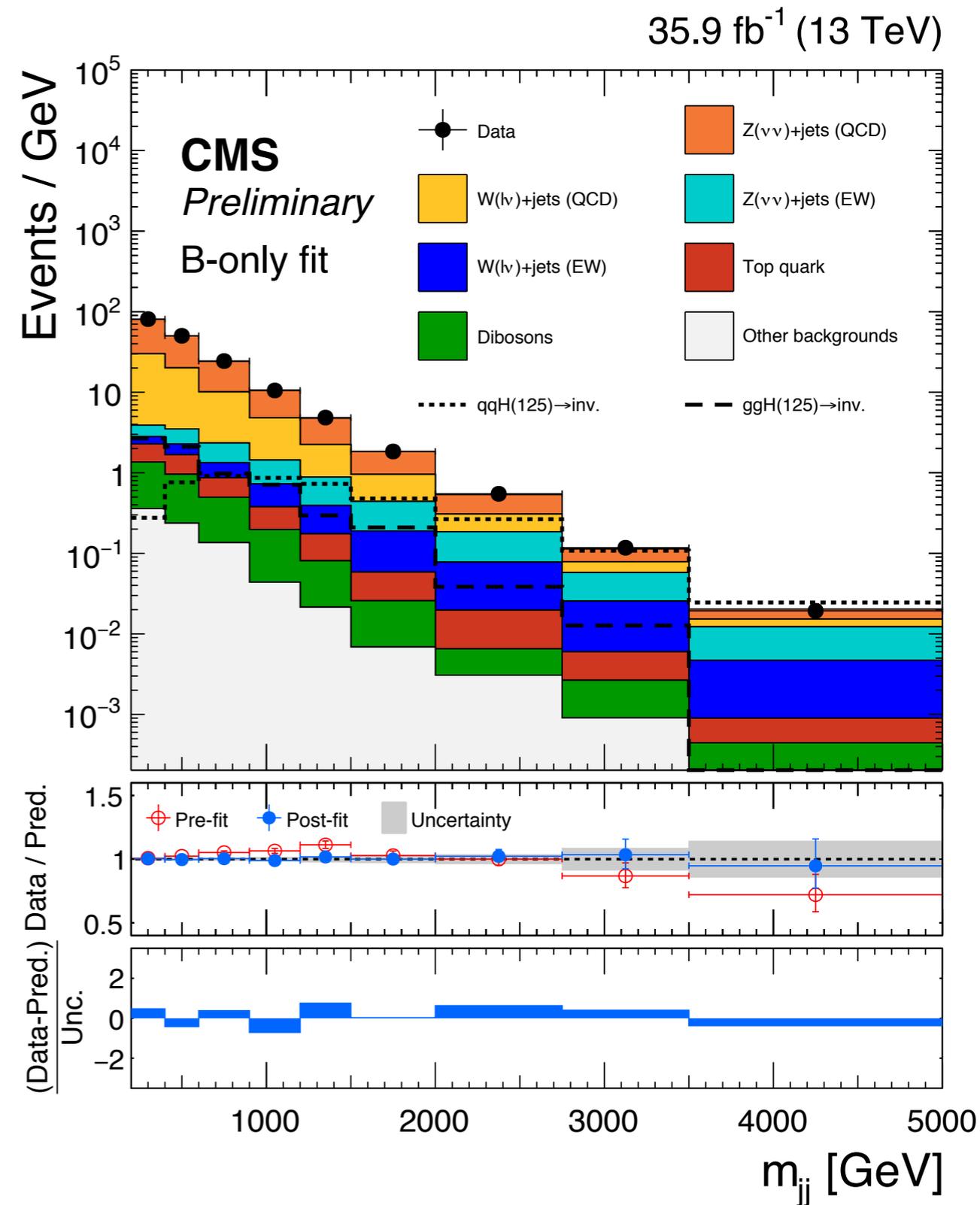
Limits on H to invisible production



- **Run I:** cut&count: 0.44 (0.31)
JHEP 02 (2017) 135

Observed (expected) 95% CL upper limits on the $BR(H \rightarrow \text{inv})$ are:

- **Cut-and-count analysis: 0.52 (0.27)**
- **Shape analysis: 0.28 (0.21)**

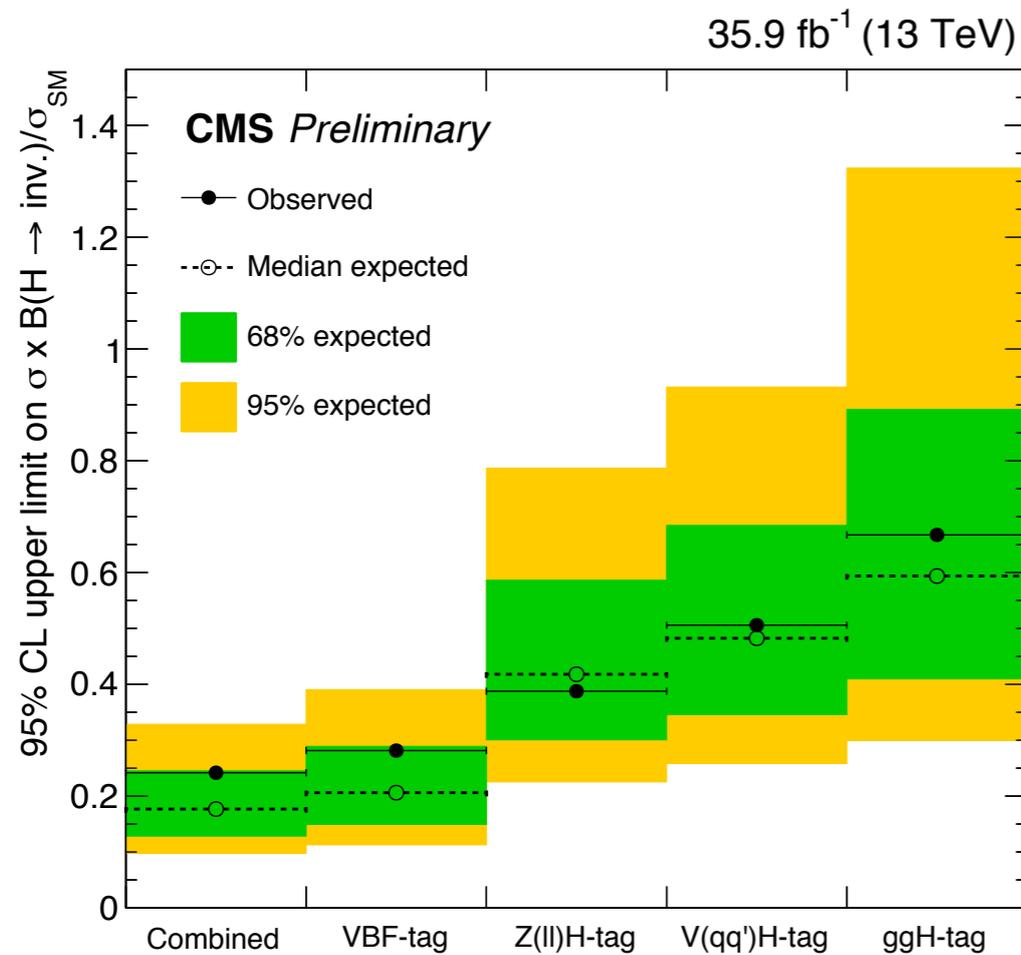


Combination of Invisible searches



- The observed (expected) 95% CL limit on $B(H \rightarrow \text{inv})$ (assuming SM) is **0.24 (0.18)**

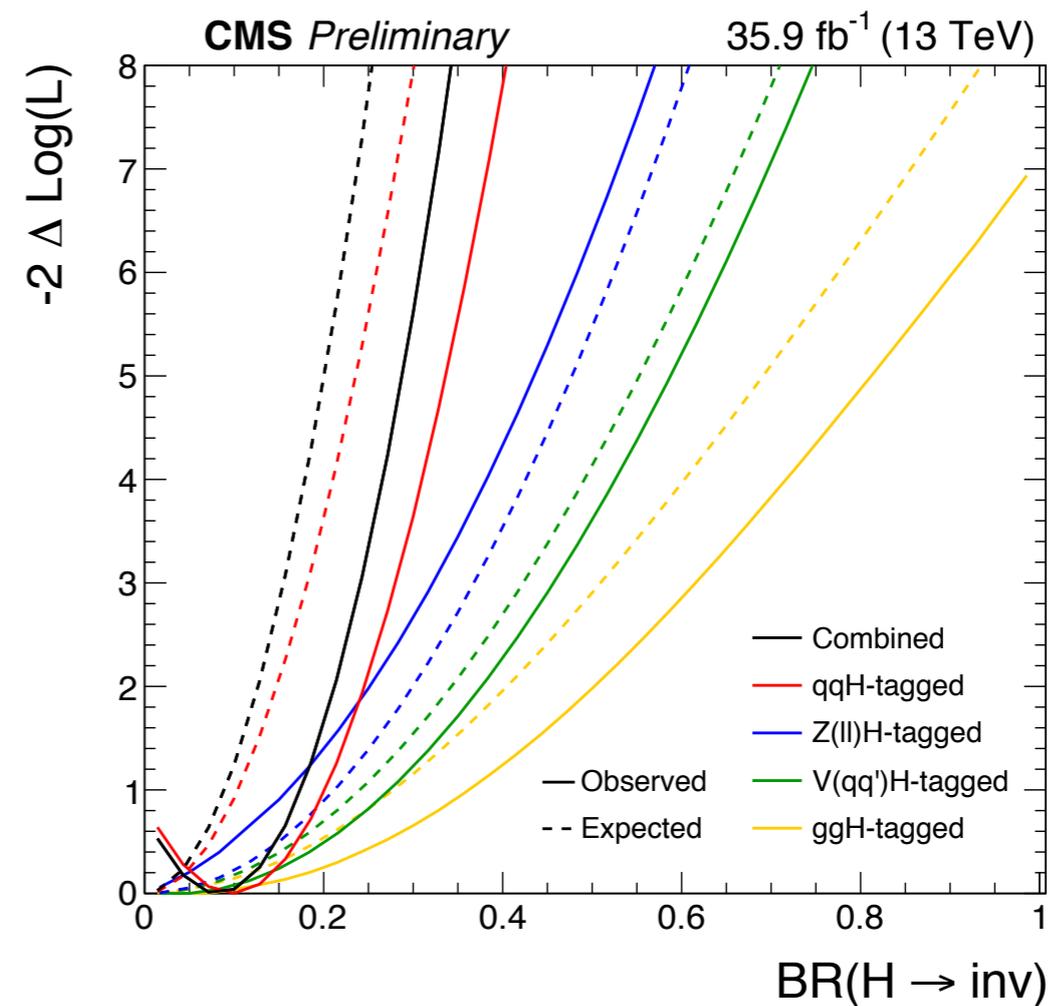
Analysis	Final state	Signal composition	Observed limit	Expected limit
qqH-tagged	VBF-jets + p_T^{miss}	52% qqH, 48% ggH	0.28	0.21
VH-tagged	$Z(\ell\ell) + p_T^{\text{miss}}$ [11]	79% qqZH, 21% ggZH	0.40	0.42
	$V(qq') + p_T^{\text{miss}}$ [12]	39% ggH, 7% qqH, 33% WH, 21% ZH	0.50	0.48
ggH-tagged	jets + p_T^{miss} [12]	76% ggH, 10% qqH, 4% WH, 3% ZH	0.64	0.58



HIG-17-023

arXiv:1712.02345

arXiv:1711.00431



Search for Higgs into muons



Probing 2nd generation of leptons

Search for a tiny peak over a big background (DY)

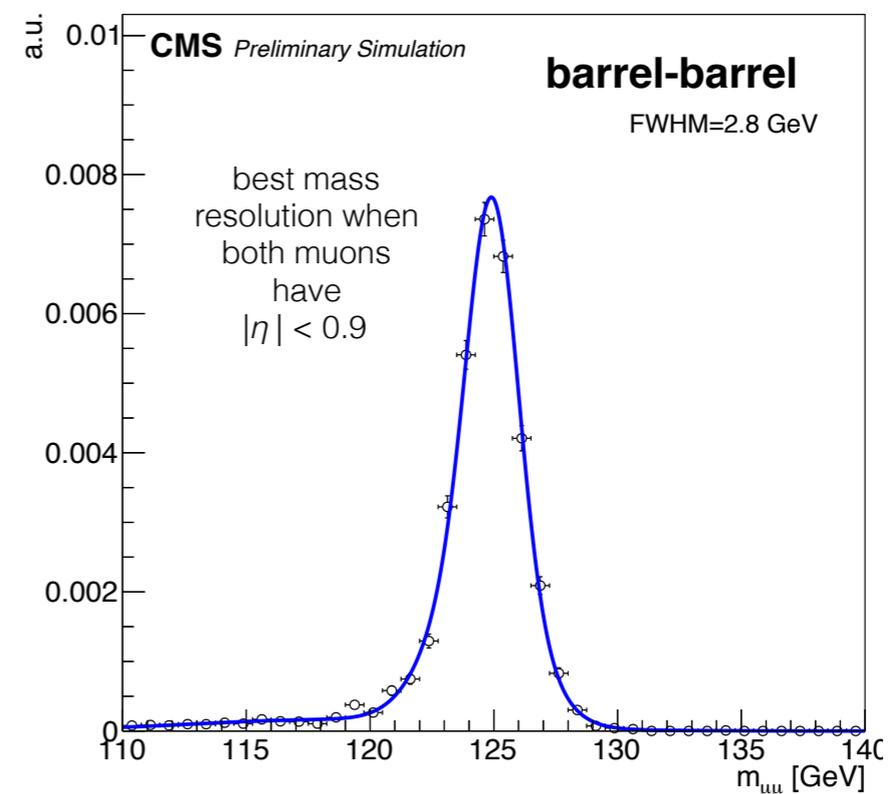
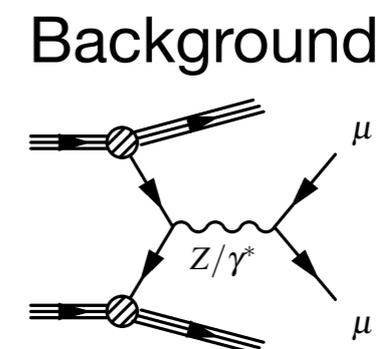
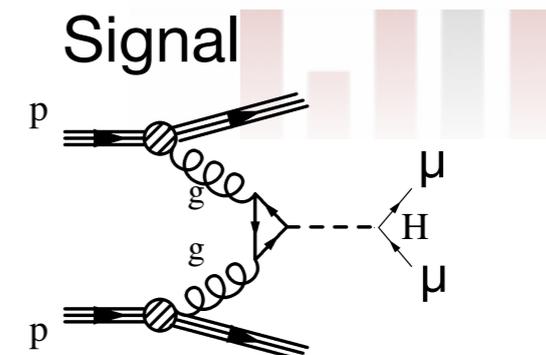
- 2 oppositely charged muons

Other objects used for categorization

- hadronic activity in the event
- b tag jets,

- Muon momentum resolution, corrections to align MC to data derived from J/ψ and Z boson

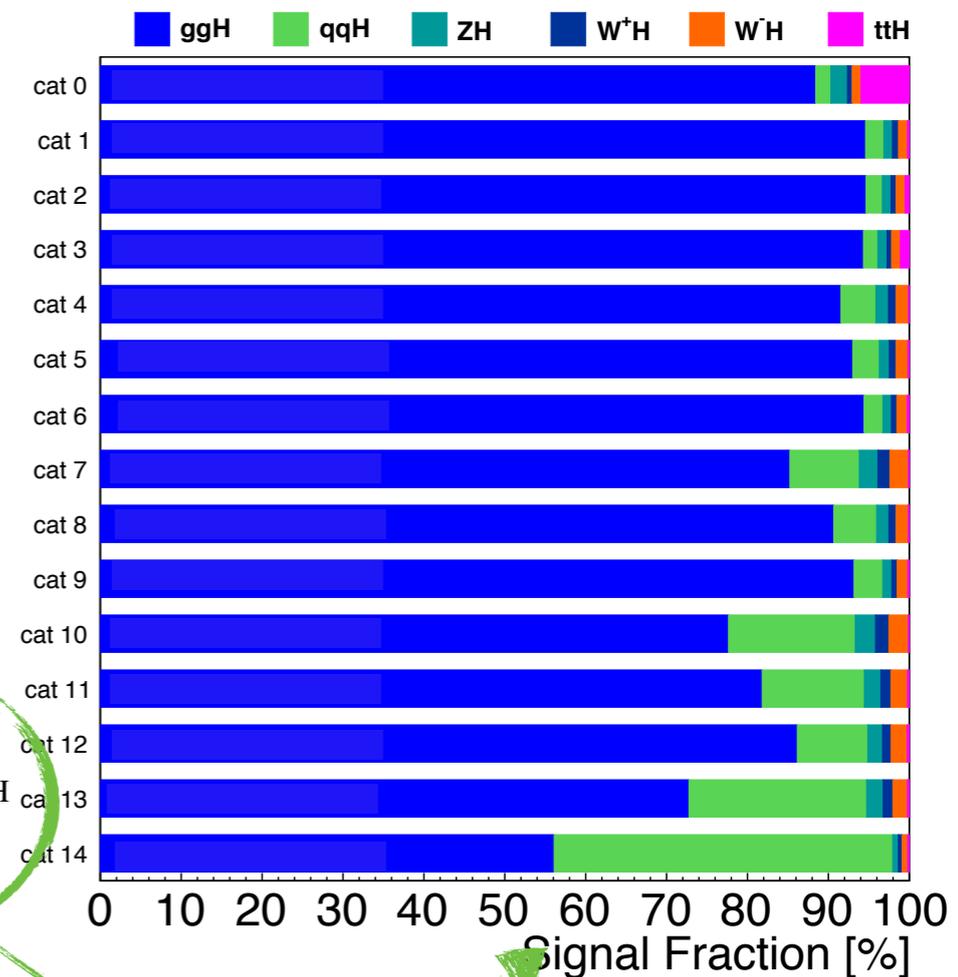
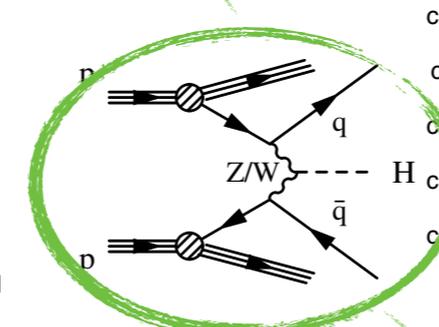
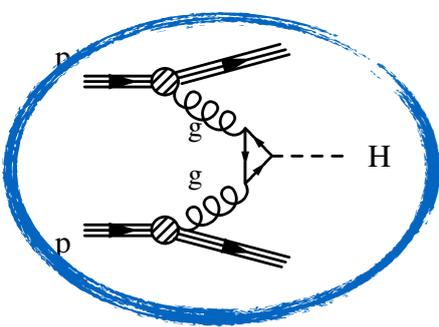
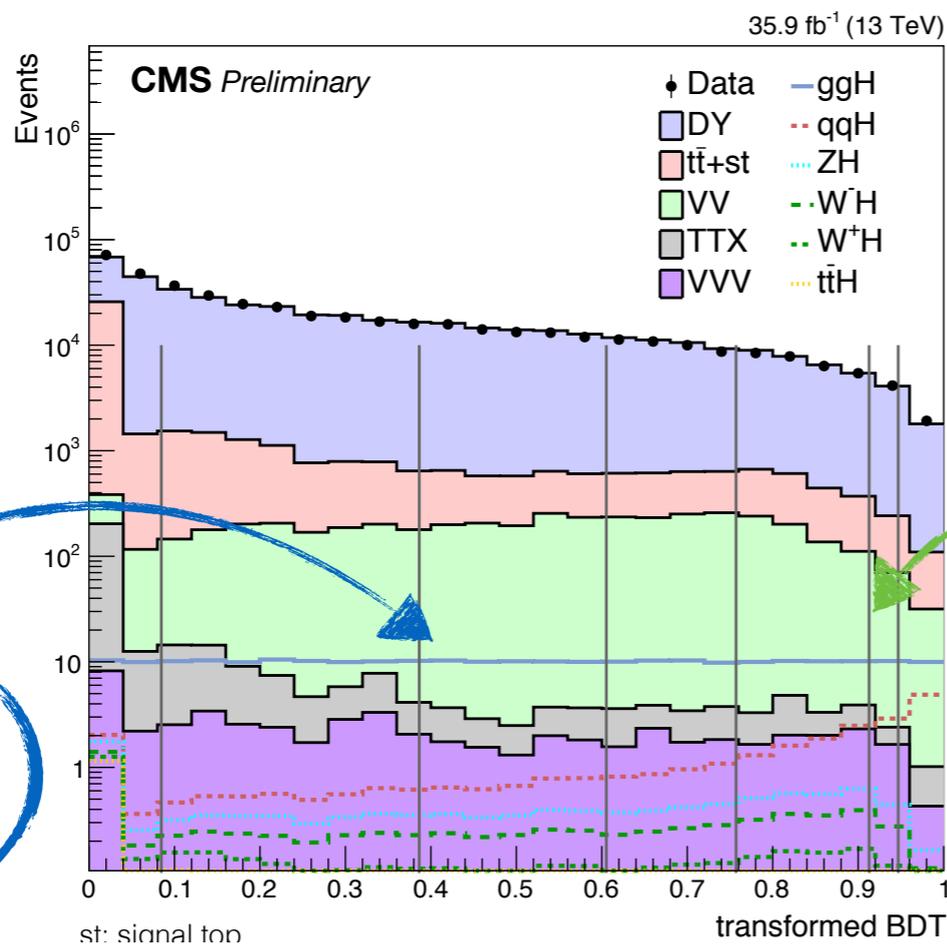
- About 58% of signal efficiency



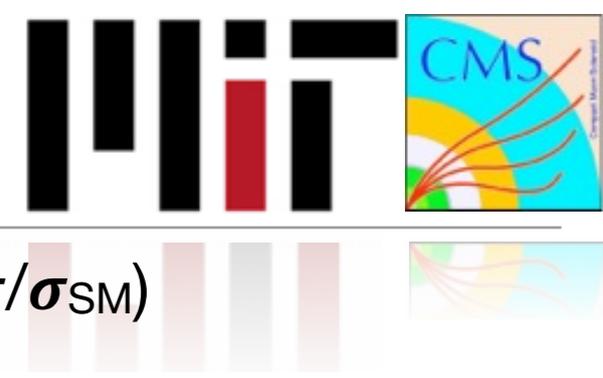
Categorization and Signal extraction



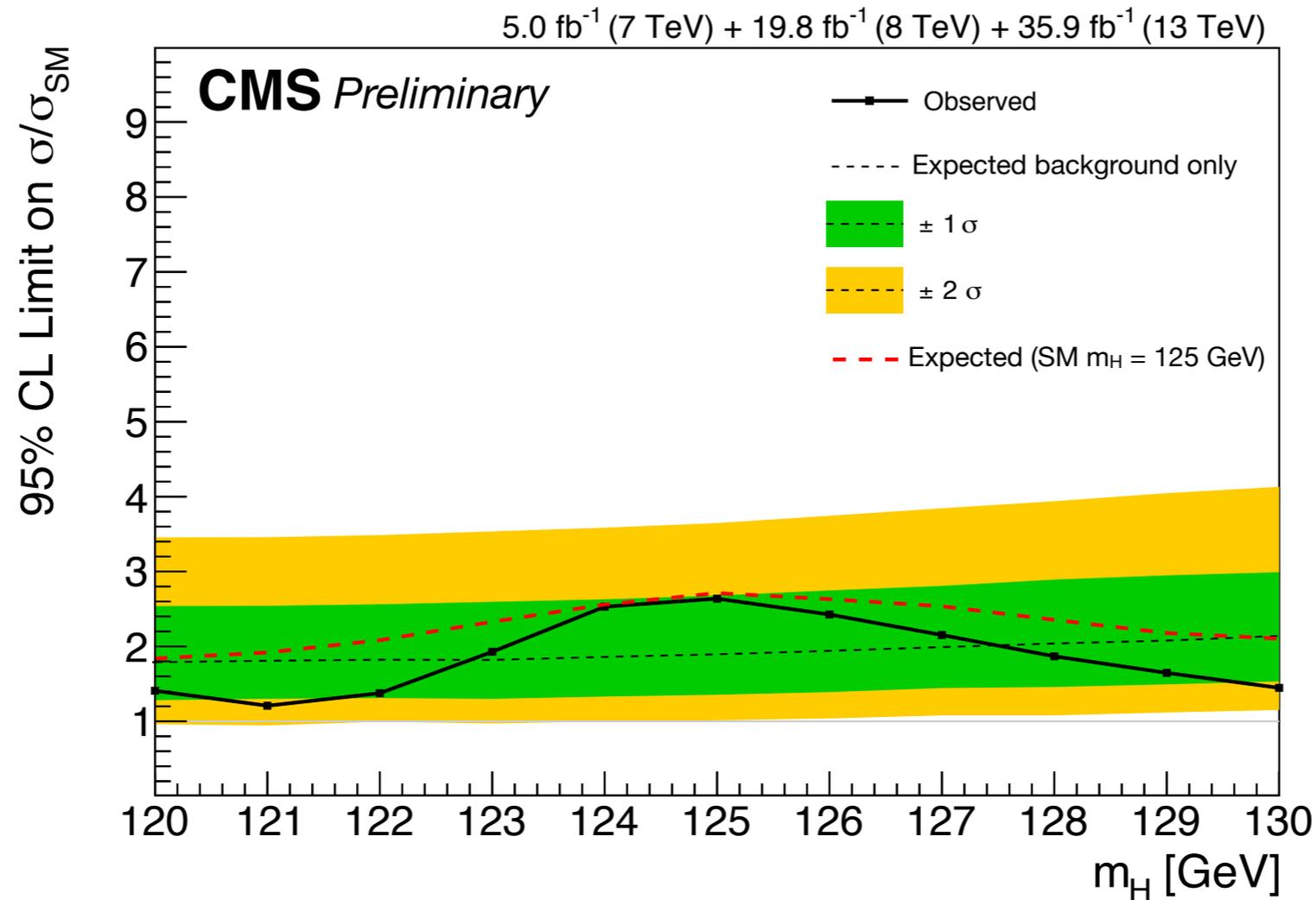
- BDT to enhance S/B discrimination
- loosely correlated with VBF production
- Extra categorization on $|\eta_{\mu}|$ to gauge peak resolution



Results



- Setting 95% CL upper limit on the SM production strength modifiers ($\sigma/\sigma_{\text{SM}}$) in combination with Run I: 2.64 (1.89)
- No significant excess observed



- Paper draft being finalized

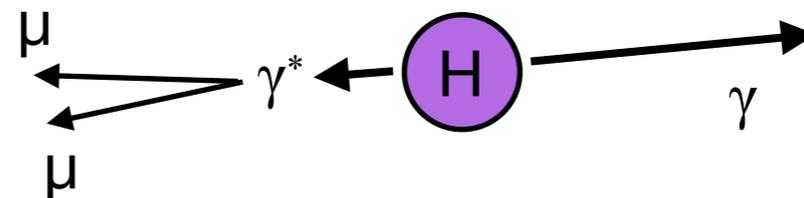
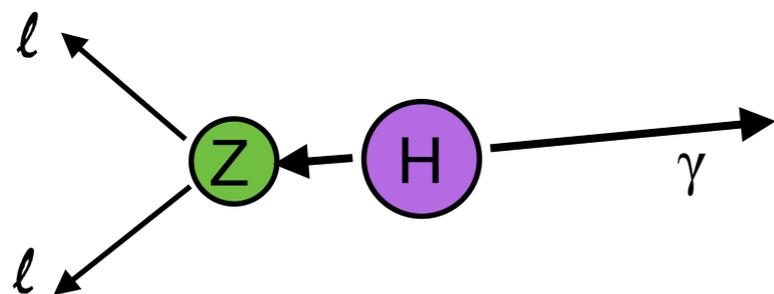
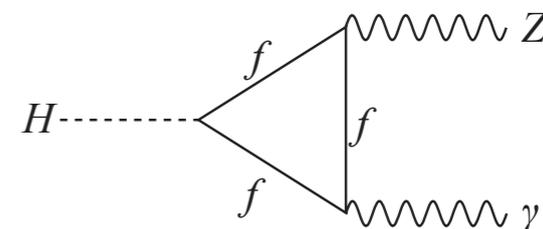
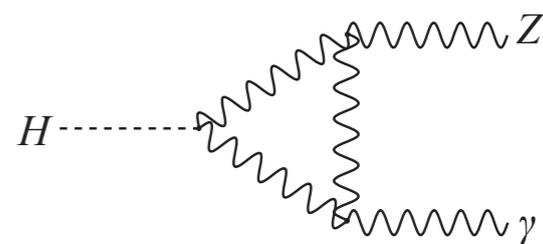
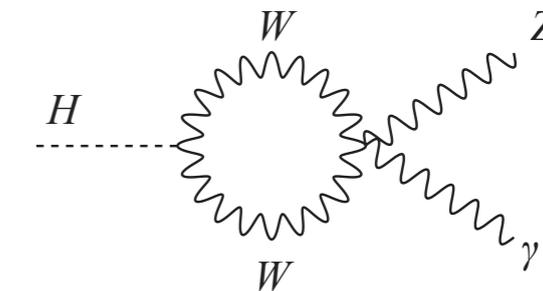
Searches for $H \rightarrow Z\gamma$ and $H \rightarrow \gamma^*\gamma$



Searches of SM Higgs decaying into $Z\gamma$ and $\gamma^*\gamma$ in the leptonic channels:

- $H \rightarrow Z\gamma \rightarrow \gamma\ell\ell$ ($\ell=e, \mu$)
 - $H \rightarrow \gamma^*\gamma \rightarrow \gamma\ell\ell$ ($\ell=\mu$)
- ↻ difference in the $m_{\ell\ell}$ requirement transition at 50 GeV

- Probe couplings to many particles in the loop,
- Enhance understanding of SM H
- $Z/\gamma^* \rightarrow \ell\ell$ decays have little background contamination
 - In the $H \rightarrow \gamma^*\gamma$ search only the muon channel is used because the boost of the γ^* makes the decay products collimated (challenging to trigger and to identify)



Selection Criteria & Categorization



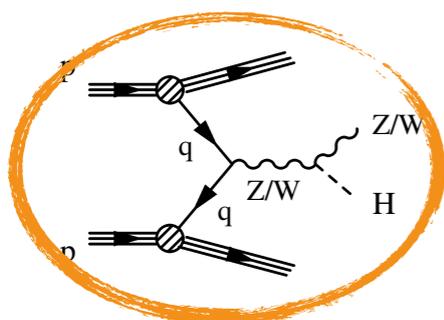
$$H \rightarrow Z\gamma \rightarrow \gamma ll \quad (l=e, \mu) \star$$

and

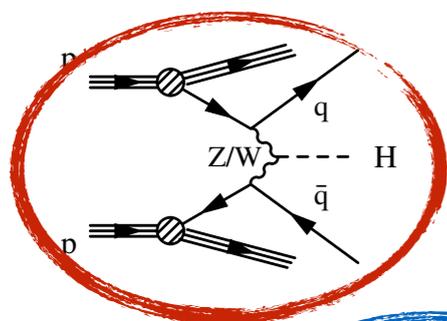
$$H \rightarrow \gamma^*\gamma \rightarrow \gamma ll \quad (l=\mu) \star$$

- separation at $m_{ll} = 50$ GeV
- 2 leptons and 1 photon

- Additional categorization in order to increase S/B, different production mode and to enhance the peak resolution



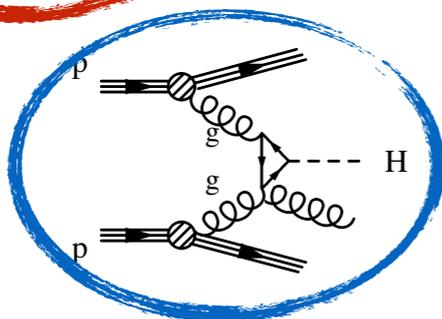
Lepton tag



Dijet tag



$N_{\text{jets}} \geq 2,$
 $\Delta\eta_{jj} > 3.5, m_{jj} > 500$ GeV



Boosted tag:

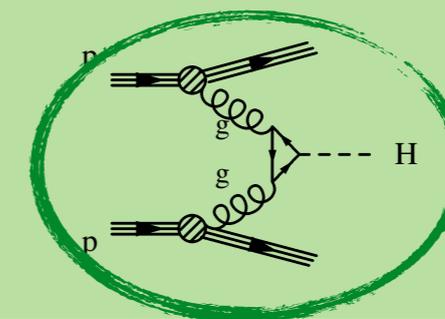


$p_T^{\gamma ll} > 60$ GeV

Untag categories:



enhance momentum resolution of muon, electron and photons



- Signal efficiency 22–29%, sensitivity enhancement by categorization 11–18%

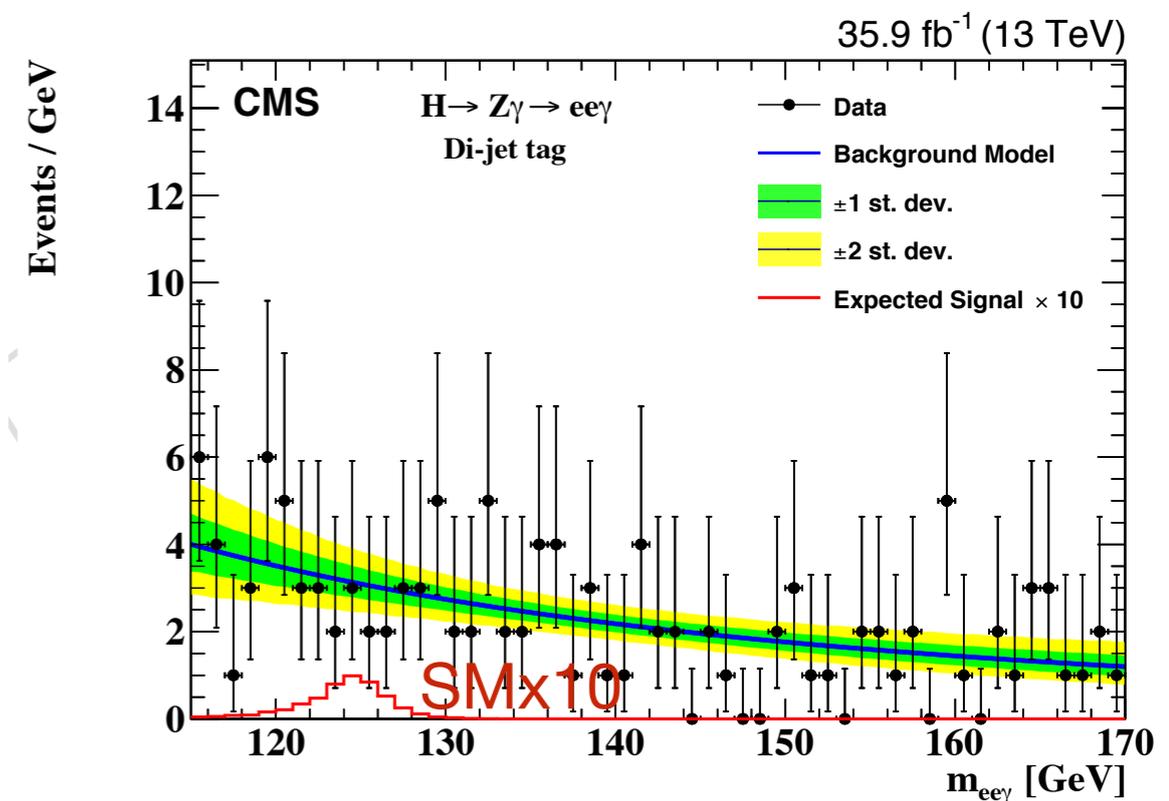
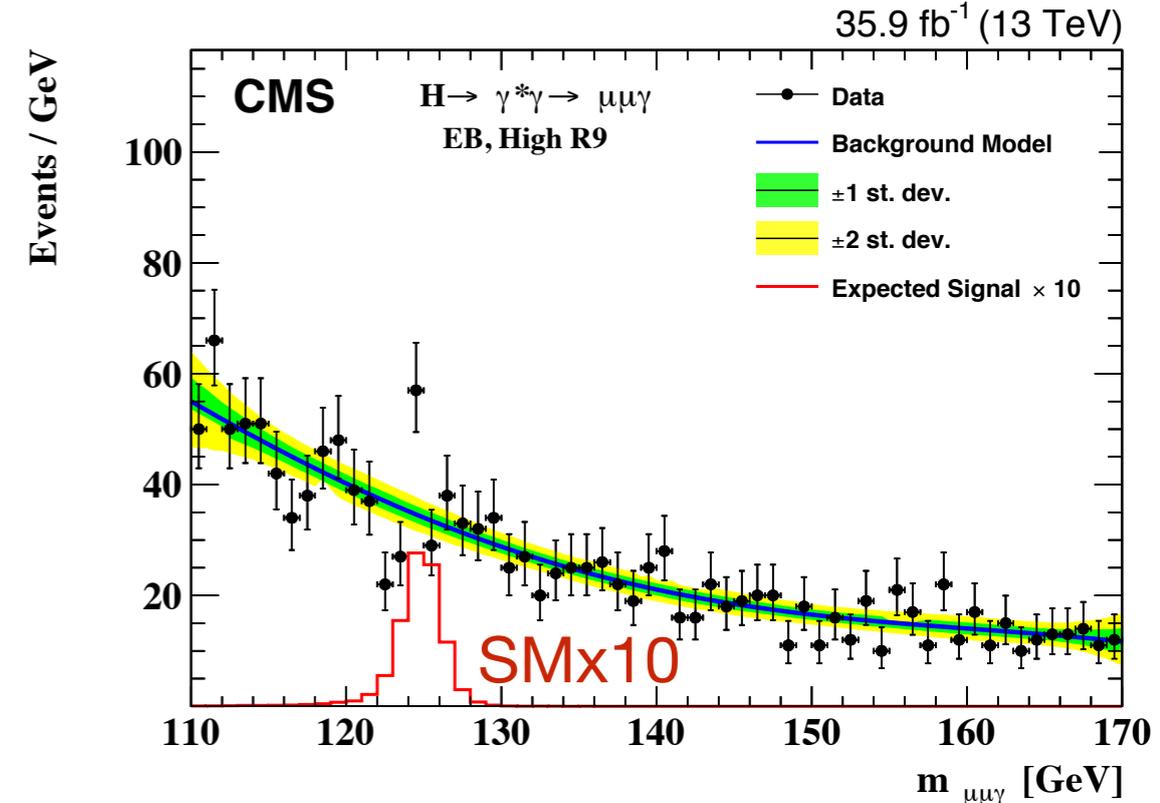
Signal Extraction



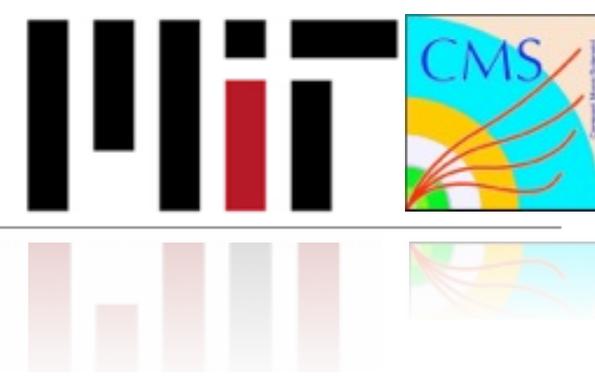
- Background is fitted with smoothly falling functional forms
- Pseudo-data are thrown in order to minimize the bias of the chosen functional form

$$b = \frac{(\hat{\mu} - \mu_T)}{\hat{\sigma}_\mu}$$

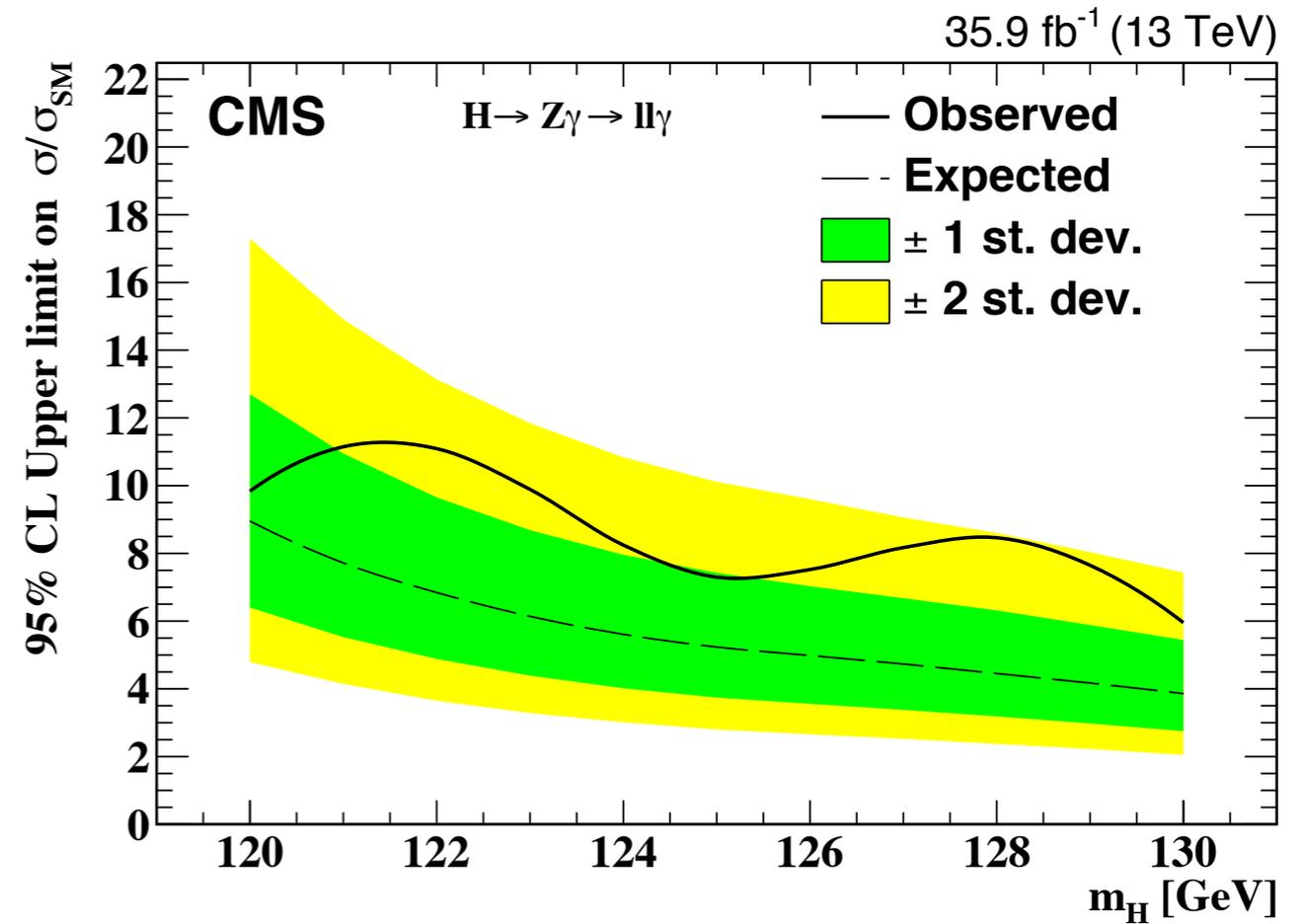
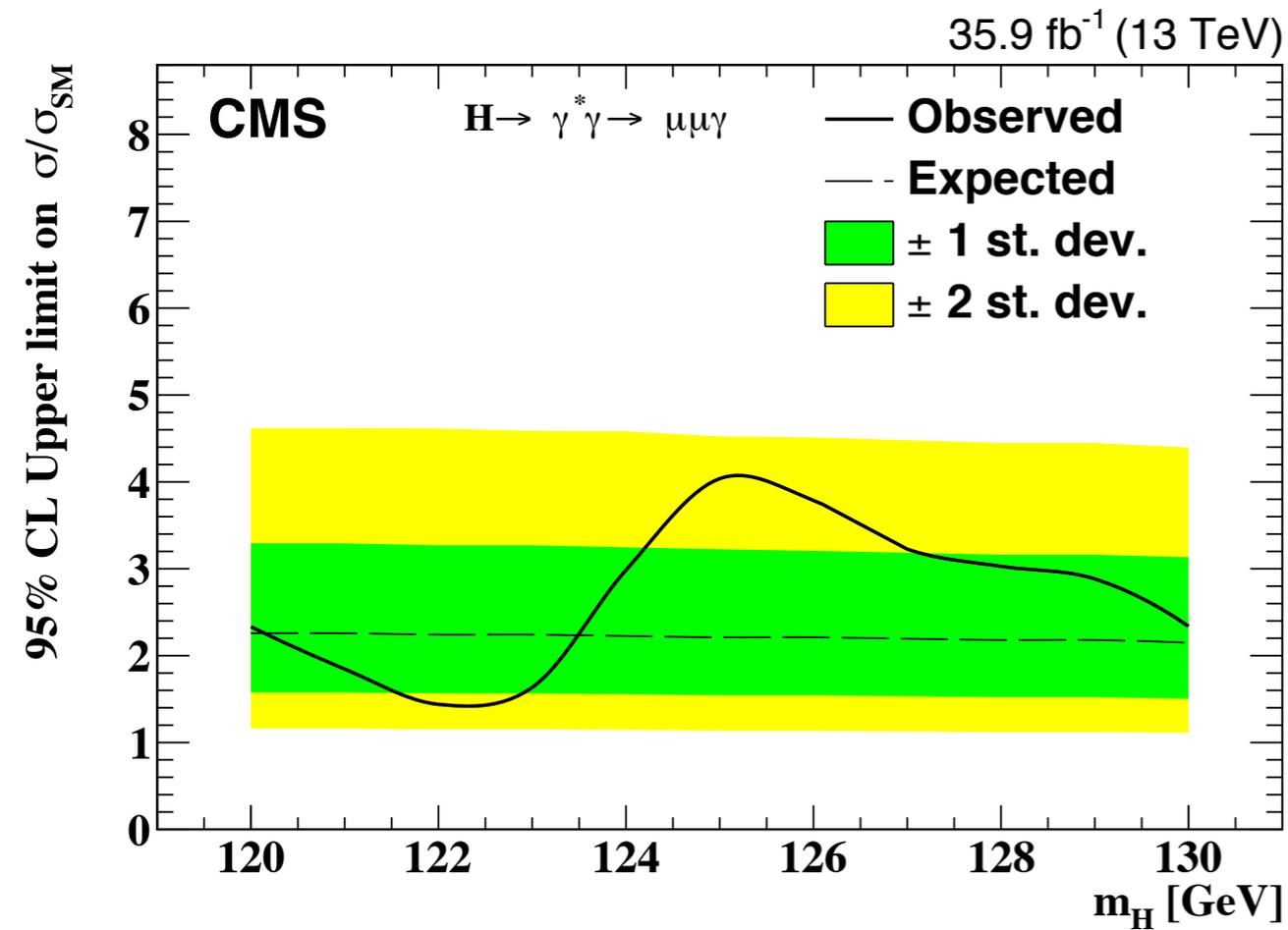
- Signal is modeled with a
 - Double sided “Crystal Ball” function
 - and a Crystal Ball + a Normal distribution
 - for the $\gamma^*\gamma$ and $Z\gamma$ channels



Results



- 95% CL upper limit on the SM strength modifier placed



Combination at $m_H = 125$ GeV



- Combination at $m_H=125$ GeV

CMS

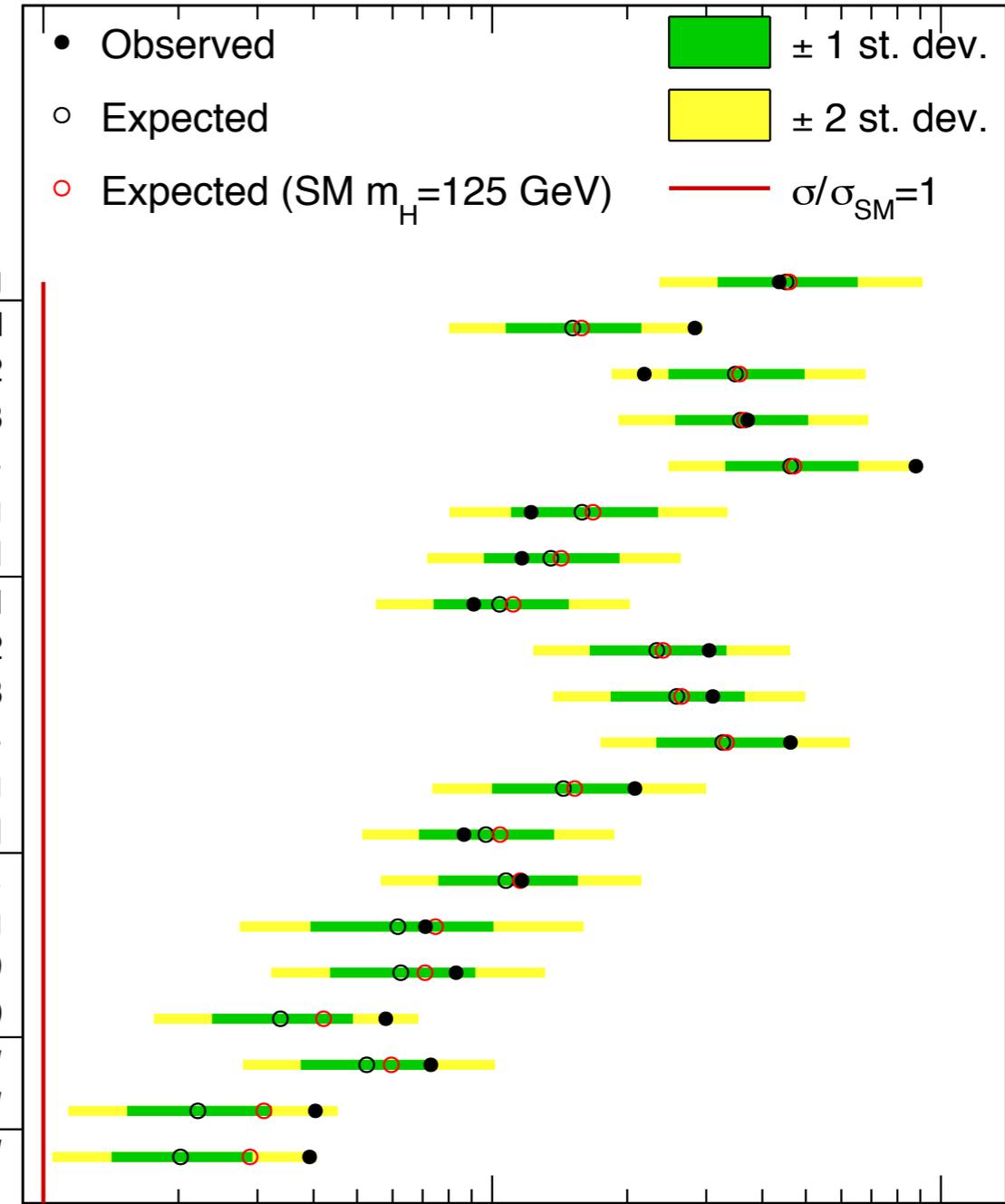
35.9 fb⁻¹ (13 TeV)

- Observed █ ± 1 st. dev.
- Expected █ ± 2 st. dev.
- Expected (SM $m_H=125$ GeV) ○ $\sigma/\sigma_{SM}=1$

$H \rightarrow Z\gamma \rightarrow ll\gamma$, Lepton tag
$H \rightarrow Z\gamma \rightarrow ee\gamma$, Untagged 1
$H \rightarrow Z\gamma \rightarrow ee\gamma$, Untagged 2
$H \rightarrow Z\gamma \rightarrow ee\gamma$, Untagged 3
$H \rightarrow Z\gamma \rightarrow ee\gamma$, Untagged 4
$H \rightarrow Z\gamma \rightarrow ee\gamma$, Dijet tag
$H \rightarrow Z\gamma \rightarrow ee\gamma$, Boosted
$H \rightarrow Z\gamma \rightarrow \mu\mu\gamma$, Untagged 1
$H \rightarrow Z\gamma \rightarrow \mu\mu\gamma$, Untagged 2
$H \rightarrow Z\gamma \rightarrow \mu\mu\gamma$, Untagged 3
$H \rightarrow Z\gamma \rightarrow \mu\mu\gamma$, Untagged 4
$H \rightarrow Z\gamma \rightarrow \mu\mu\gamma$, Dijet tag
$H \rightarrow Z\gamma \rightarrow \mu\mu\gamma$, Boosted
$H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$, EE
$H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$, Dijet tag
$H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$, EB Low R9
$H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$, EB High R9
$H \rightarrow Z\gamma \rightarrow ll\gamma$, Combined
$H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$, Combined
$H \rightarrow ll\gamma$, Combined

- Observed (expected) upper limit for $\sigma/\sigma_{SM}(H \rightarrow \gamma ll)$ is **3.9 (2.0)**
- corresponding to a p-value of $\sim 2\sigma$

95% CL upper limit on σ/σ_{SM}

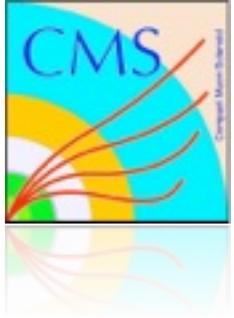


CMS has a broad program of rare and invisible Higgs searches:

- Probing SM Higgs through rare decays, and next generation of particles
 - Presented $H \rightarrow \mu\mu$ and newly $H \rightarrow Z\gamma$ and $H \rightarrow \gamma^*\gamma$ searches 
- Invisible searches may open BSM scenarios:
 - looking for direct production of invisible Higgs
 - presented the most sensitive channel for SM $H \rightarrow \text{inv}$ in the VBF tag 

Observations are in agreement with SM theory





Backup

Selection in the VBF tag



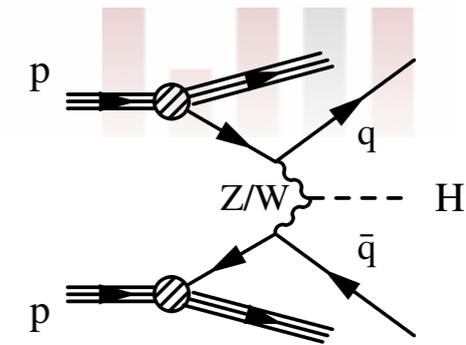
Selection of the $H \rightarrow \text{Inv}$ in the VBF tag

- $p_{T}^{j^1} > 80$ and GeV, $p_{T}^{j^2} > 40$ GeV, $|\eta^{j^1}| < 3$ or $|\eta^{j^2}| < 3$
- $p_{T}^{\text{miss}} > 250$ GeV
- $\Delta\phi(p_{T}^{\text{miss}}, \text{jet}^{1..4}) > 0.5$
- $\Delta\eta(j_1, j_2) > 1.0$, $m_{jj} > 200$ GeV, $\Delta\phi(j_1, j_2) < 1.5$

shape analysis based on m_{jj}

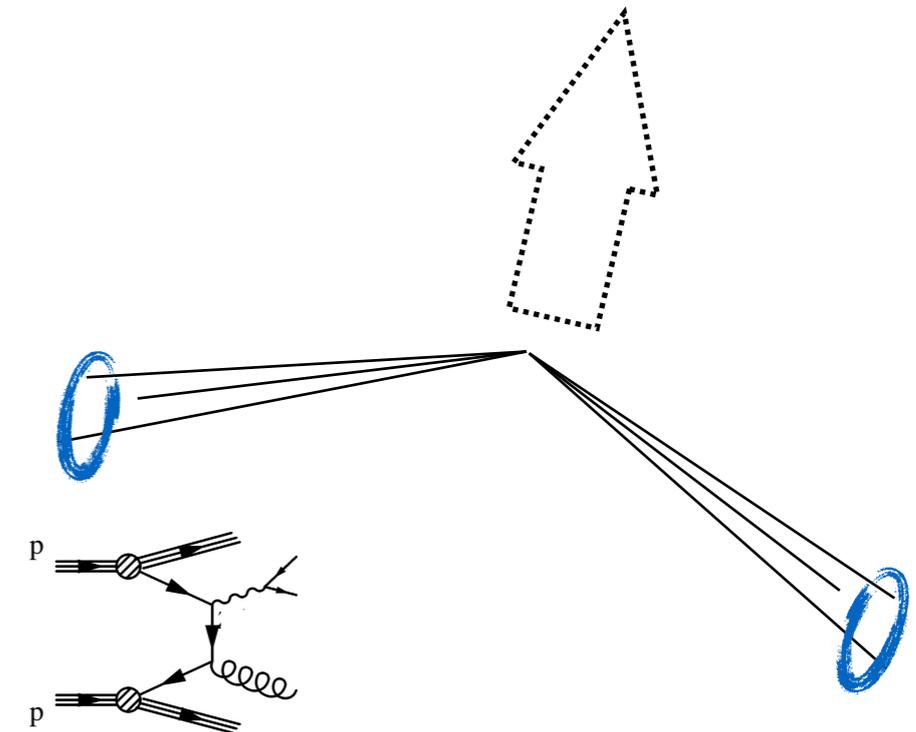
- cut & count,
 $\Delta\eta(j_1, j_2) > 4.0$, $m_{jj} > 1.3$ TeV, $\Delta\phi(j_1, j_2) < 1.5$

Trigger
QCD



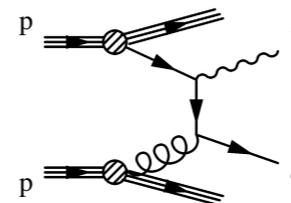
Lepton veto (reduce W+jets):

- $p_{T}^{e,\mu} > 10$ GeV $|\eta^{\mu(e)}| < 2.4$ (2.5), $p_{T}^{\tau_h} > 18$ GeV $|\eta| < 2.3$



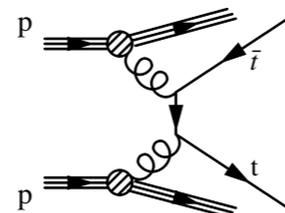
Photon veto (reduce γ +jets and $V\gamma$):

- $p_{T}^{\gamma} > 15$ GeV, $|\eta^{\gamma}| < 2.5$



B-jet veto (reduce ttbar):

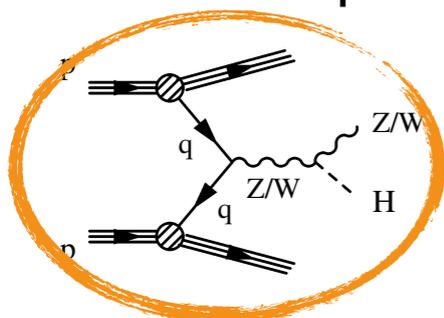
- $p_{T}^b > 20$ GeV, $|\eta^b| < 2.4$



Selection Criteria & Categorization

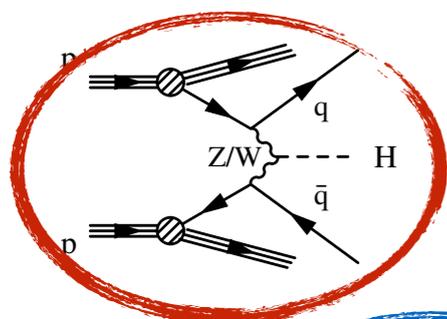


- $H \rightarrow Z\gamma \rightarrow \gamma ll$ ($l=e, \mu$)
- $p_{T^{\mu^{1(e1)}}} > 20$ (25) GeV, $p_{T^{\mu^{2(e2)}}} > 5$ (10) GeV, $|\eta^{\mu(e)}| < 2.4$ (2.5)
- $p_{T^\gamma} > 30$ GeV, $|\eta^\gamma| < 2.5$
- $m_{ll} > 50$ GeV, $m_{ll+m_{ll\gamma}} > 185$ GeV, $p_{T^\gamma}/m_{ll\gamma} > 15/110$
- Additional categorization in order to increase S/B, different production mode and to enhance the peak resolution



Lepton tag:

$$p_{T^\mu} > 7 \text{ GeV or } p_{T^e} > 7 \text{ GeV}$$

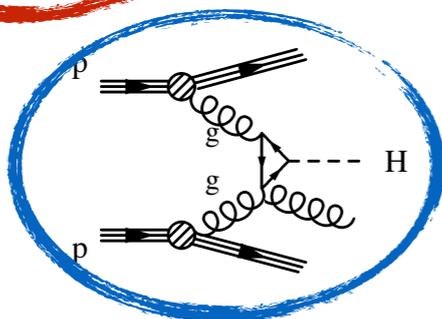


Dijet tag:

$$N_{\text{jets}} \geq 2, p_{T^i} > 30 \text{ GeV}, |\eta_j| < 4.7$$

$$\Delta\eta_{jj} > 3.5, |\eta_{\gamma ll} - (\eta_{j1} + \eta_{j2})/2| < 2.5$$

$$m_{jj} > 500 \text{ GeV}, \Delta\phi(\gamma ll, jj) > 2.4$$

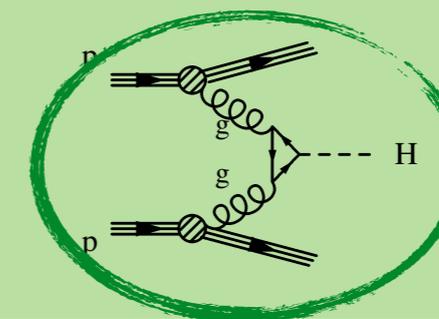


Boosted tag:

$$p_{T^{\gamma ll}} > 60 \text{ GeV}$$

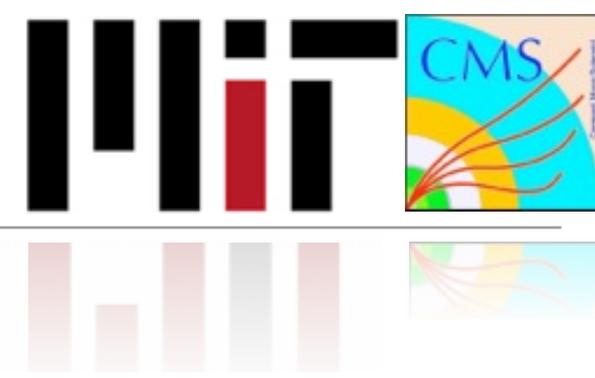
4 untag categories:

enhance momentum resolution of muon, electron and photons

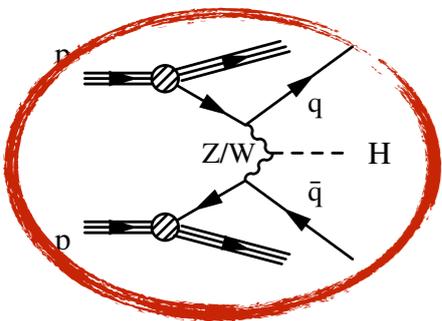


- Signal efficiency $\sim 29\%$ ($\sim 22\%$) for μ (e), sensitivity enhancement by categorization $\sim 18\%$

Selection and Categorization



- $H \rightarrow \gamma^* \gamma \rightarrow \gamma \ell \ell$ ($\ell = \mu$)
- $p_{T^\mu} > 20$ (4) GeV
- $m_{\ell\ell} < 50$ GeV
 - J/ ψ and Y resonances are excluded ($2.9 < m_{\mu\mu} < 3.3$ GeV, $9.3 < m_{\mu\mu} < 9.7$ GeV)

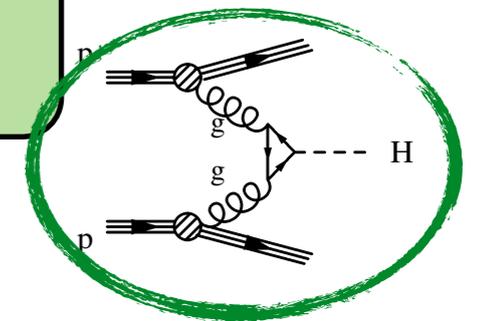


Dijet tag:

$$N_{\text{jets}} \geq 2, p_{T^j} > 30 \text{ GeV}, |\eta^j| < 4.7$$
$$\Delta\eta_{jj} > 3.5, |\eta_{\gamma\ell\ell} - (\eta_{j1} + \eta_{j2})/2| < 2.5$$
$$m_{jj} > 500 \text{ GeV}, \Delta\phi(\gamma\ell\ell, jj) > 2.4$$

3 untag categories:

enhance momentum resolution of the muons, and the photon



- Signal efficiency $\sim 26\%$, sensitivity enhancement by categorization $\sim 11\%$

Systematic Uncertainties



- Prefit uncertainties for $H \rightarrow Z\gamma$ and $H \rightarrow \gamma^*\gamma$

Sources	$H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$	$H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$
Theory		
- Gluon-gluon fusion cross section (scale)	3.9%	3.9%
- Gluon-gluon fusion cross section (PDF)	3.2%	3.2%
- Vector boson fusion cross section (scale)	+0.4% -0.3%	+0.4% -0.3%
- Vector boson fusion cross section (PDF)	2.1%	2.1%
- W associate production (scale)	+0.5% -0.7%	+0.5% -0.7%
- W associate production (PDF)	1.9%	1.9%
- Z associate production (scale)	+3.8% -3.1%	+3.8% -3.1%
- Z associate production (PDF)	1.6%	1.6%
- Top pair associate production (scale)	+5.8% -9.2%	n.a.
- Top pair associate production (PDF)	3.6%	n.a.
Underlying Event/Parton Shower		
- Muon	3%	4.7%
- Electron	3%	n.a.
Branching fraction	5.7%	6%
Luminosity	2.5%	2.5%
Lepton identification (ID) and isolation		
- Muon channel	0.6%	2%
- Electron channel	1.2%	n.a.
Photon identification (ID) and isolation		
- Muon channel	2.3%	1.6%
- Electron channel	2.2%	n.a.
Pileup reweighting		
- Muon channel	0.6%	0.3%
- Electron channel	0.9%	n.a.
R_9 reweighting		
- Muon channel	6.5%	9%
- Electron channel	6.8%	n.a.
Trigger		
- Muon	1.3%	4%
- Electron	1%	n.a.
Energy/Momentum – muon channel		
- signal mean	0.04%	0.08%
- signal resolution	4%	5%
Energy – electron channel		
- signal mean	0.15%	n.a.
- signal resolution	4%	n.a.
Jet energy scale		
- Muon	2.5%	3.8%
- Electron	2.7%	n.a.
Jet energy resolution		
- Muon	0.3%	0.7%
- Electron	0.3%	n.a.

Systematic Uncertainties



- Dominant uncertainties for H inv VBF

Source of uncertainty	Ratios	Uncertainty vs m_{jj}	Impact on $\sigma\mathcal{B}(H \rightarrow \text{inv})/\sigma_{\text{SM}}$
Theoretical uncertainties			
Renorm. scale V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	9–12%	48%
Renorm. scale V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	9–12%	23%
Fact. scale V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	2–7%	4%
Fact. scale V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	2–7%	2%
NLO EW corr.	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	1–2%	< 1%
PDF V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	0.5–1%	< 1%
PDF V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	0.5–1%	< 1%
Experimental uncertainties			
$p_{\text{T}}^{\text{miss}}$ trigger	All ratios	$\approx 2\%$	18%
Muon id. eff.	$W(\mu\nu)/W(\ell\nu), Z(\mu\mu)/Z(\nu\nu)$	$\approx 1\%$ (per leg)	8%
Muon reco. eff.	$W(\mu\nu)/W(\ell\nu), Z(\mu\mu)/Z(\nu\nu)$	$\approx 1\%$ (per leg)	8%
Ele. id. eff.	$W(e\nu)/W(\ell\nu), Z(ee)/Z(\nu\nu)$	$\approx 1.5\%$ (per leg)	4%
Ele. reco. eff.	$W(e\nu)/W(\ell\nu), Z(ee)/Z(\nu\nu)$	$\approx 1\%$ (per leg)	3%
τ veto	$W(\text{CRs})/W(\ell\nu), Z(\nu\nu)/W(\ell\nu)$	≈ 3.5 (3)% for EW (QCD)	13%
Muon veto	$W(\text{CRs})/W(\ell\nu), Z(\nu\nu)/W(\ell\nu)$	≈ 2.5 (2)% for EW (QCD)	7%
Ele. veto	$W(\text{CRs})/W(\ell\nu), Z(\nu\nu)/W(\ell\nu)$	≈ 1.5 (1)% for EW (QCD)	5%
Jet energy scale	$Z(\text{CRs})/Z(\nu\nu), W(\text{CRs})/W(\ell\nu)$	≈ 1 (2)% for Z/Z (W/W)	2%
Ele. trigger	$W(e\nu)/W(\ell\nu), Z(ee)/Z(\nu\nu)$	$\approx 1\%$	< 1%