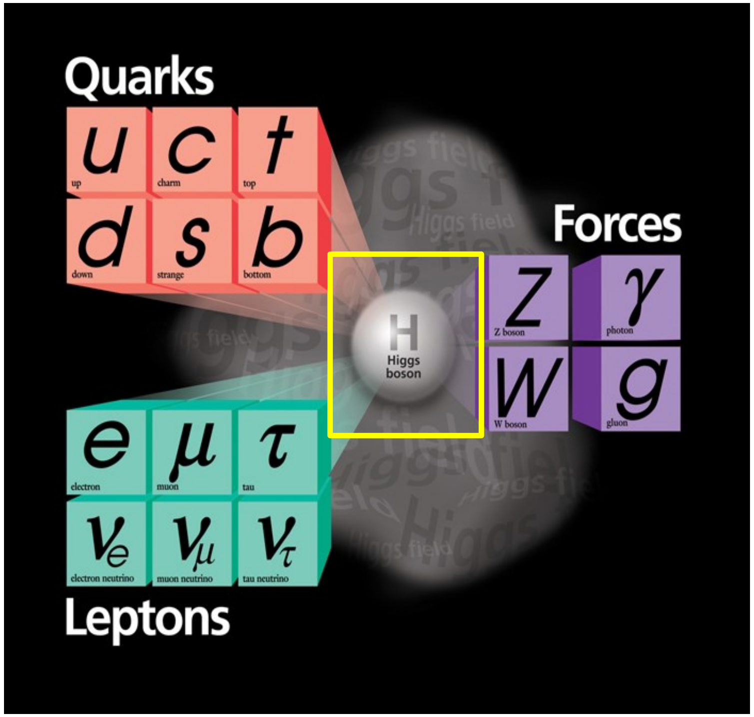
International Symposium on Higgs Boson and Beyond Standard Model Physics

Search for Higgs Rare Decays at ATLAS and CMS

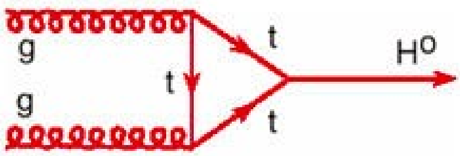
Liang Li
Shanghai Jiao Tong University
On Behalf of ATLAS and CMS Collaborations

Outline

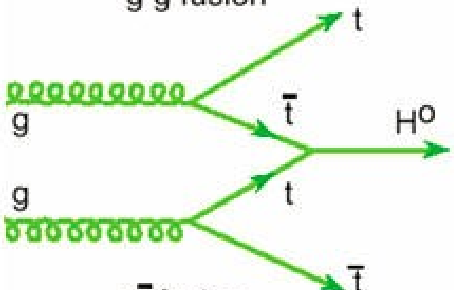
- **Motivation**
- **Higgs (Standard Model) Rare Decays**
- **Higgs (Beyond Standard Model) Exotic Decays**
- **Summary**



Higgs Production and Decay

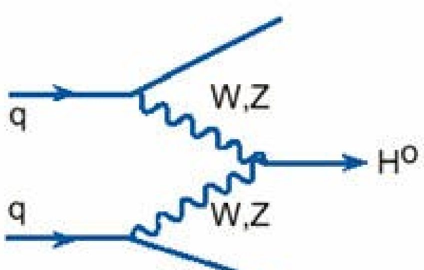


g g fusion



t t̄ fusion

W, Z bremsstrahlung

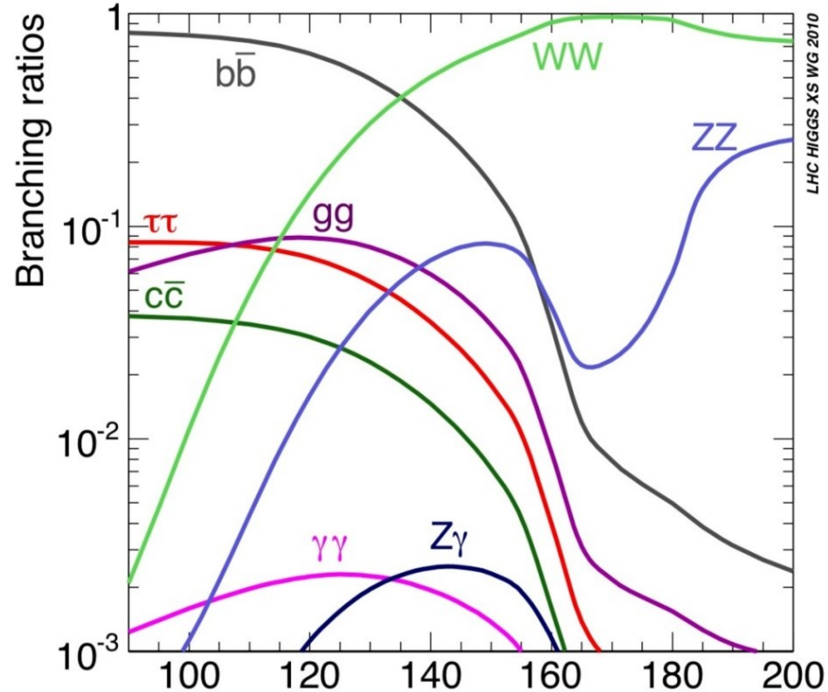


WW, ZZ fusion

Production

Decay

LHC 8 TeV
m_H=125 GeV
σ_H = 22.3 fb



Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Rare Decay:

H → μμ,ee

H → νννν

H → Z/γ* γ

H → J/ψγ,ϒγ

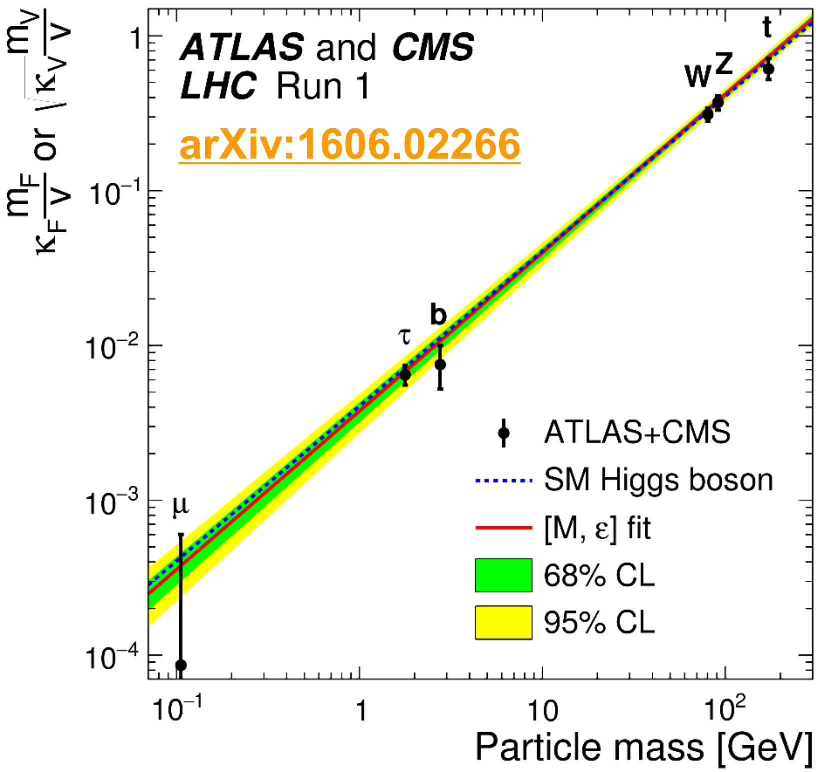
H → φγ

…

Why Higgs Rare Decay?

Fully explore Higgs particle

- **Higgs production**
  - **Cross section**
  - **Production modes: ggH, VBF, V/ttH, tHq/W**
- **Higgs decay**
  - **Mass**
  - **Couplings**
  - **Width**
  - **Spin, CP**
- **Higgs rare decay: New Physics?**
  - **Poorly constrained**
  - **Coupling < $O(10^{-3})$**
  - **Big impact on existing coupling**
  - **Current limit: $B(H \to BSM) < 0.34$**

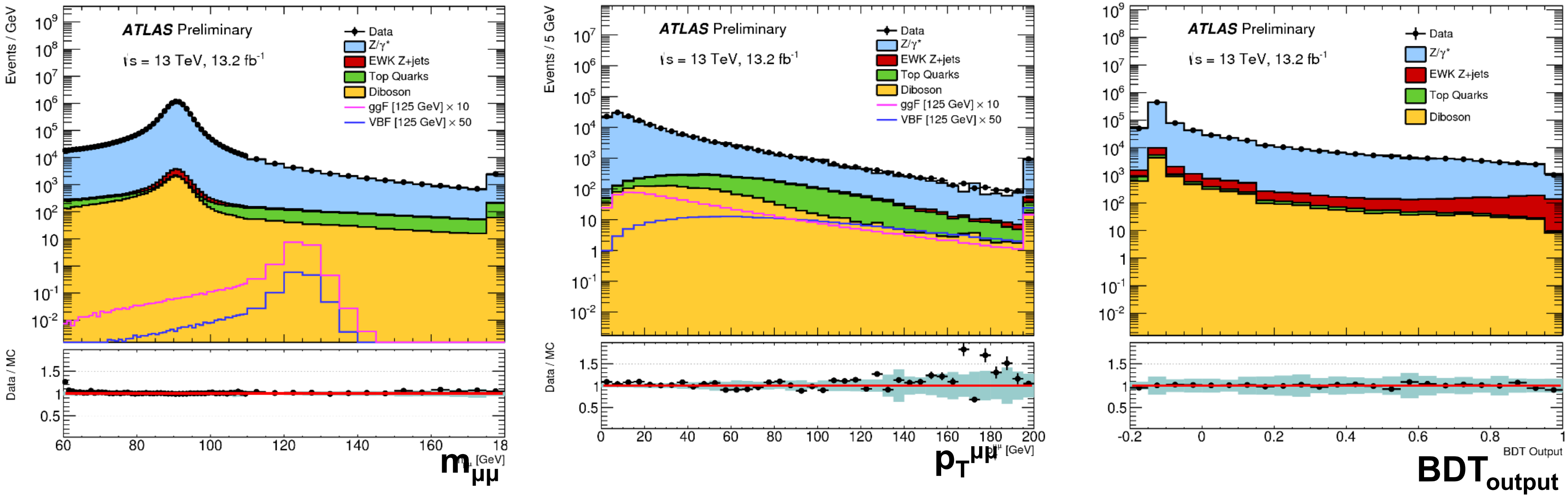


Consistent with SM, room for BSM

- **Rare decay not observed yet**
- **Sensitive to BSM**
- **Yukawa couplings**
- **Higgs portal model**

H → μμ

ATLAS-CONF-2016-041



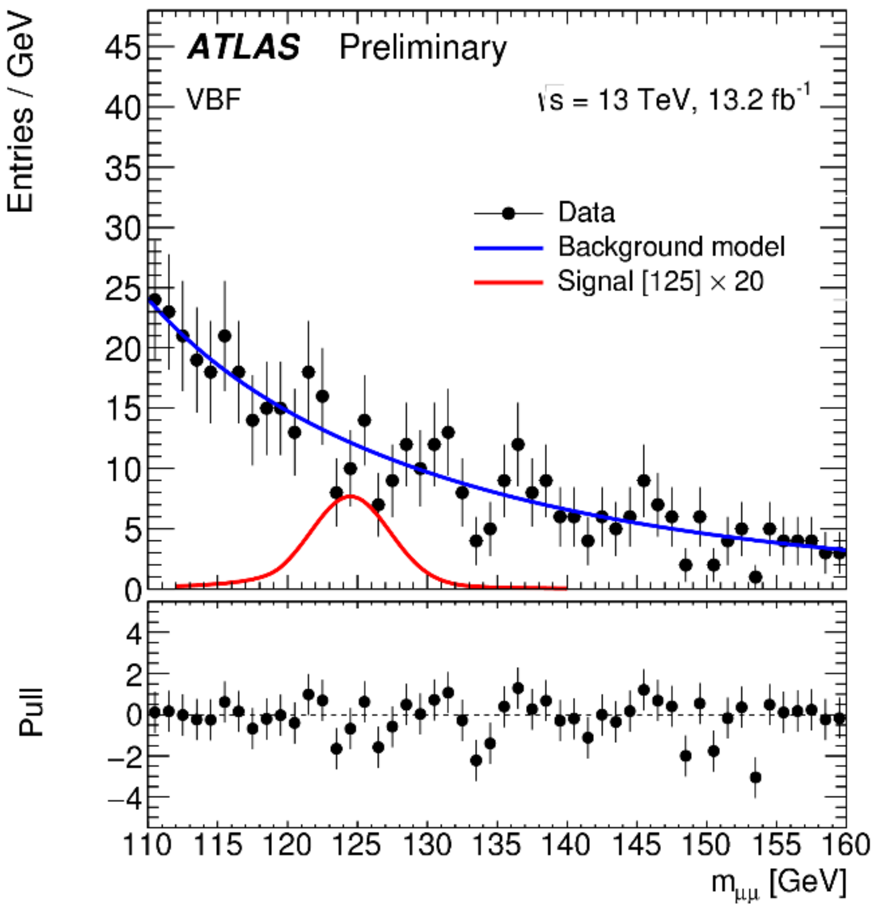
- **Small but clean signal**
- **Signal modeling**
  - **VBF categorized by MVA classifier**
  - **ggF categorized (6) by p_TH and $|\eta_\mu|$**
  - **Shape parametrized by**

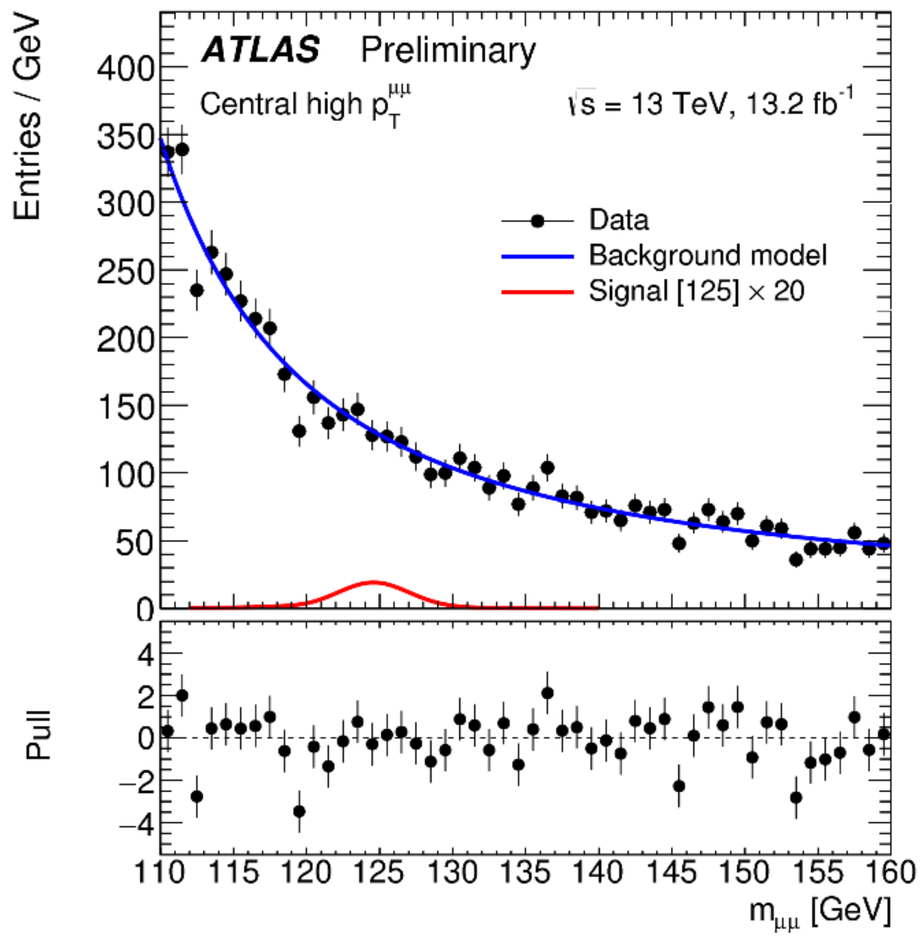
    Crystal-Ball + Gaussian

- **Dominated by Z→μμ (continuum) background**
- **Shape and normalization derived by fitting to the di-muon mass spectra:**

Breit-Wigner ⊗ Gaussian (Z-peak) + e^{Ax}/x^3 (continuum)

H → μμ





Binned maximum likelihood fit to $m_{\mu\mu}$ distributions

- **Simultaneous fitting in total seven signal regions (two are shown)**
- **Background shape parameters + normalization, signal strength**

H → μμ, H → ee

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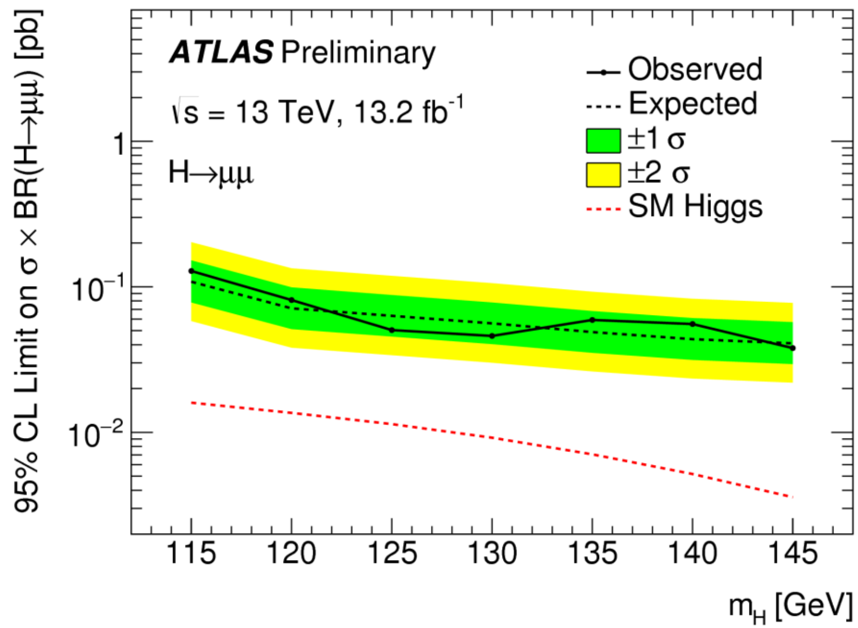
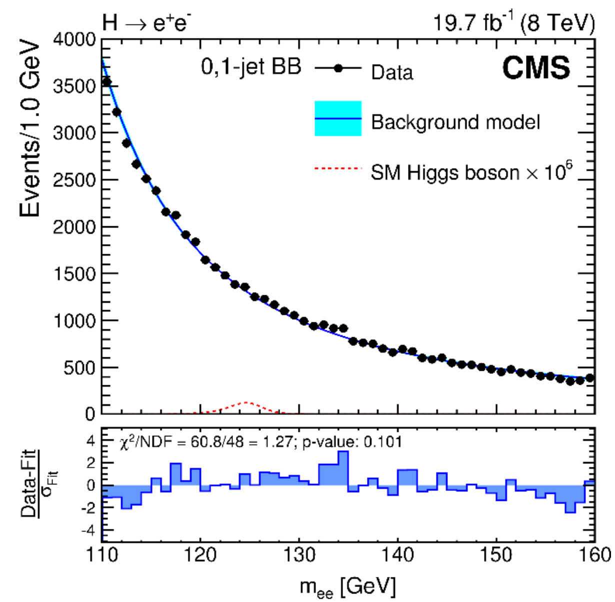
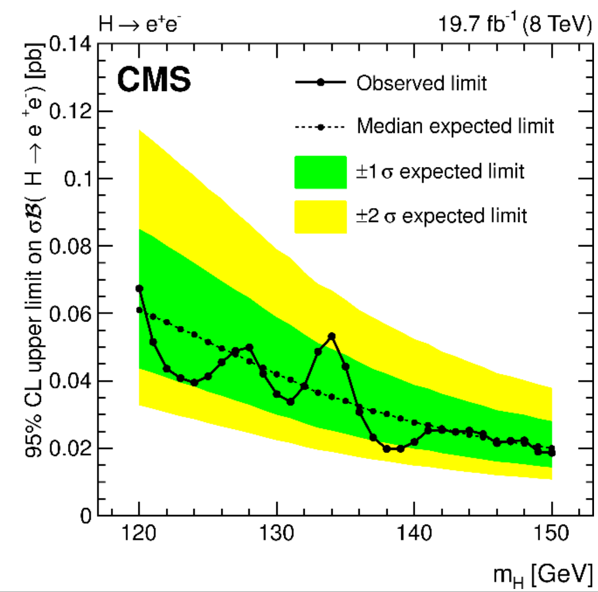
Phys. Lett. B 744 (2015) 184







H→μμ decay xs limit (i.t.o. signal strength)

- **ATLAS Run-2**

  $\mu < 4.4$ (obs.), 5.5 (exp.)

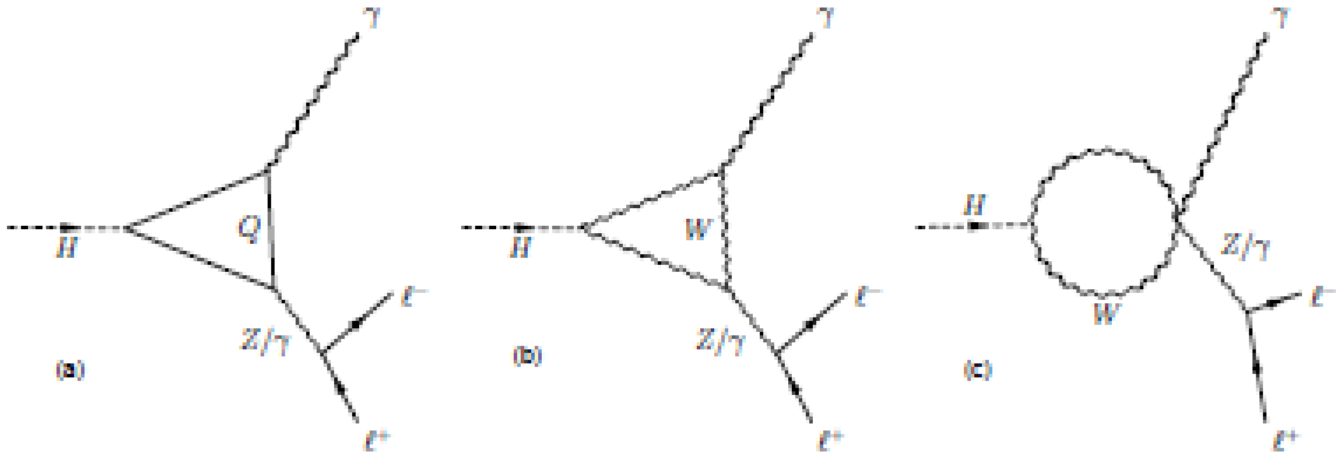
- **ATLAS Run-1+Run-2**

  $\mu < 3.5$ (obs.), 4.3 (exp.)

H→ee decay branching ratio

- **CMS Run-1: B < 0.0019 (~3.7X10^5 SM)**

$H \rightarrow Z/\gamma^* \gamma$

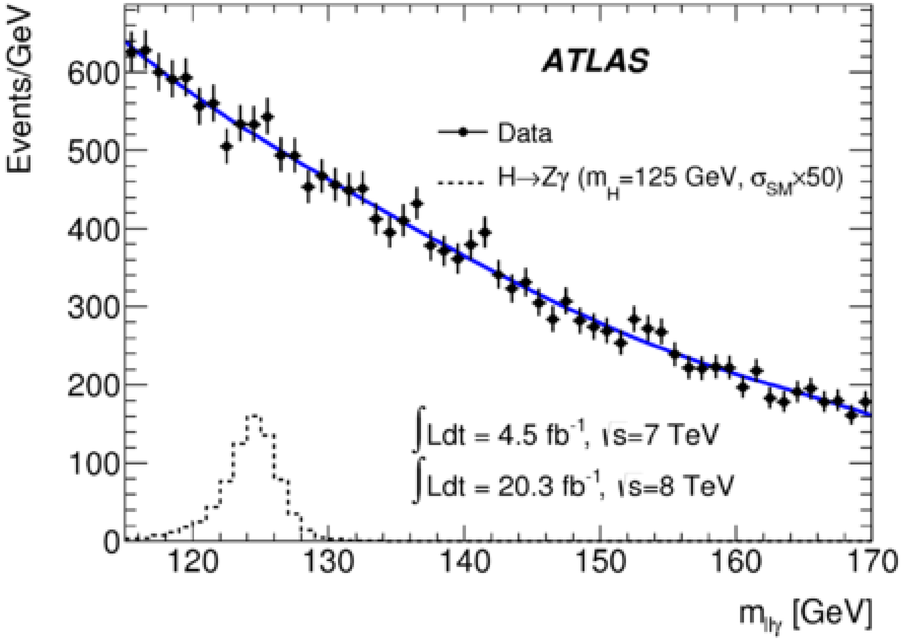


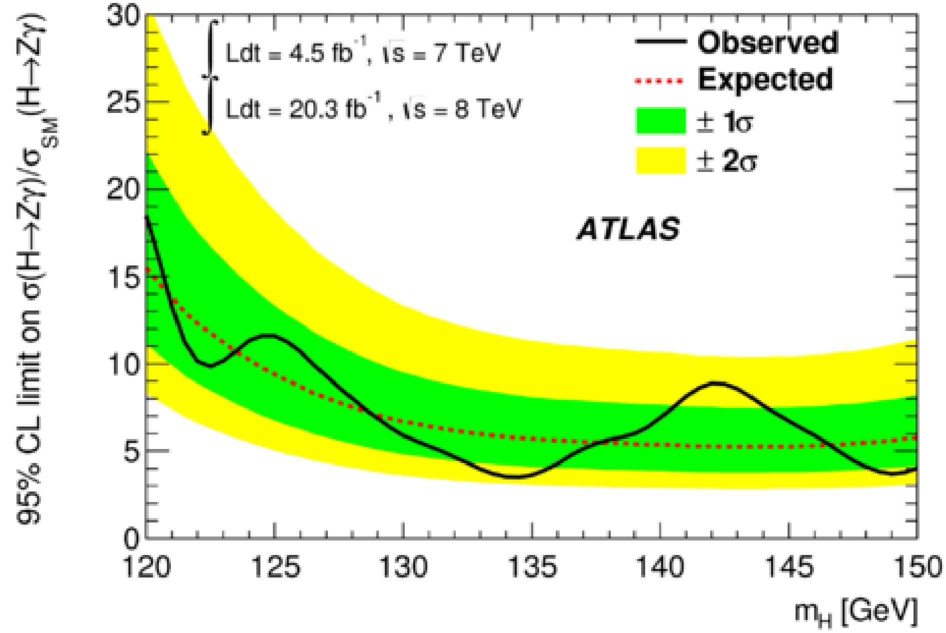
Search for narrow resonance using three-body ($\ell\ell\gamma$) invariant mass distribution over large continuum ($Z\gamma$) backgrounds

- **High (low) mass di-lepton final states**
  - **ATLAS ($Z\gamma$): $m_{\ell\ell} > m_Z - 10$ GeV and $115 < m_{\ell\ell\gamma} < 170$ GeV**
  - **CMS ($\gamma^*\gamma$): $m_{\ell\ell} < 20$ GeV and $110 < m_{\ell\ell\gamma} < 170$ GeV**
- **Background modeling: likelihood fit to data to determine background shape and normalization**
- **Signal modeling: Crystal-Ball + Gaussian function fit to $m_{\ell\ell\gamma}$**

H → Zγ

Phys. Lett. B 732C (2014), 8-27

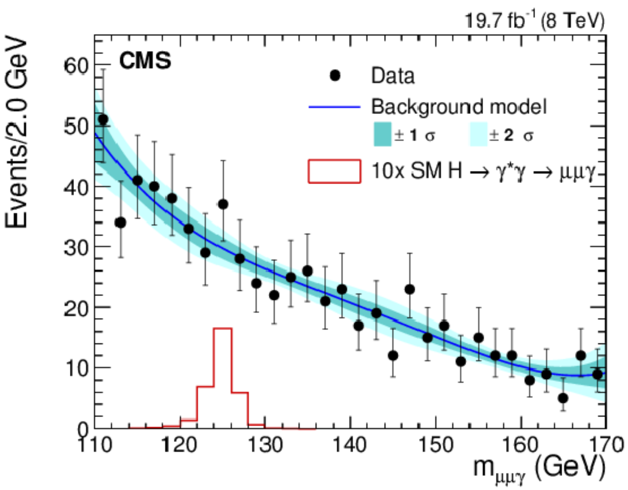


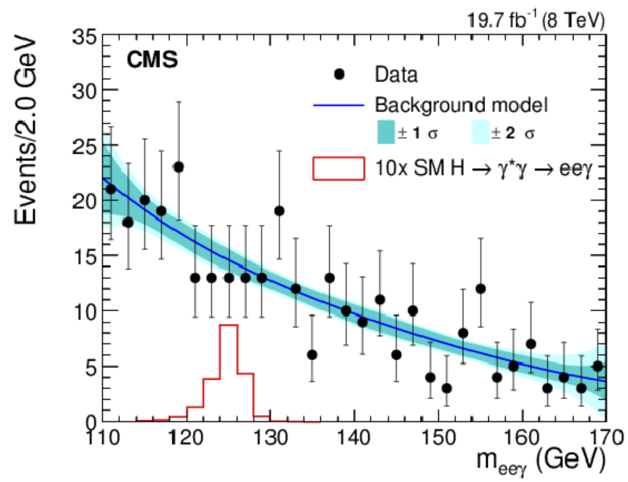


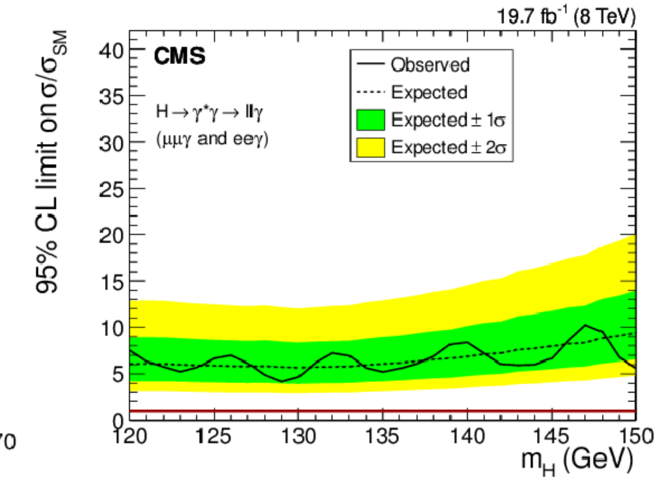
- Three-body mass resolution improved after Z-mass kinematic constraint
- One photon (p_T > 15 GeV) and two opposite sign same flavor leptons (p_T > 10 GeV for electrons and p_T > 15 GeV for muons)
- 10 event categories depending on lepton flavor, $\Delta\eta_{Z\gamma}$ and Higgs p_{Tt}
- Likelihood fit with signal strength μ and nuisance parameters
  - $\mu < 11$ (obs.), 9 (exp.) @ 95% C.L for m_H = 125.5 GeV
  - Dominated by statistics uncertainties

H → γ*γ

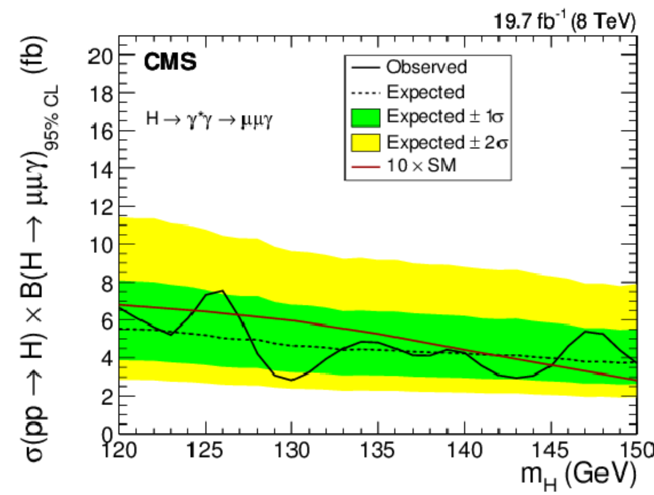
Phys. Lett. B 753 (2016) 341







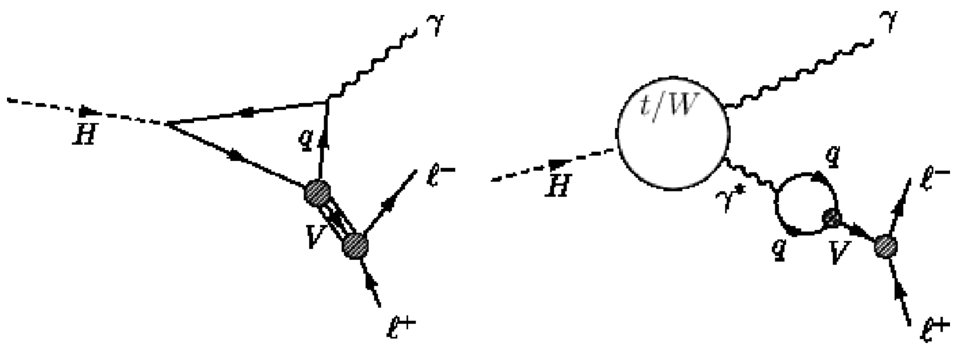
- **Clean $\mu\mu\gamma$ topology with 1.6 % mass resolution**
- **eeγ merged shower in ECAL, 1.8% resolution**
- **photon and di-lepton $p_T > 0.3\ m_{\ell\ell\gamma}$**
- **Muon $p_T > 23$ GeV, electron track $p_T > 30$ GeV, $\Delta R_{\ell\gamma} > 1$, $m_{ee} < 1.5$ GeV, $m_{\ell\ell} < 20$ GeV**
- **Unbinned maximum likelihood fit**
- **$\mu < 6.7$ (obs.), 5.9 (exp.) for $m_H = 125$ GeV**

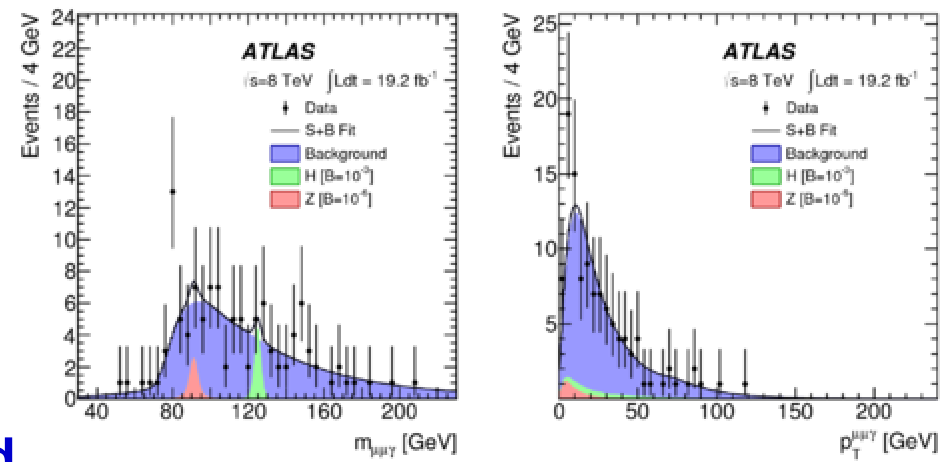


- **$\sigma(pp\to H)B(H\to\mu\mu\gamma)$: $\mu < 7.3$ fb (obs.), 5.2 fb (exp.) for $m_H = 125$ GeV**

$H \rightarrow J/\Psi\ \gamma$

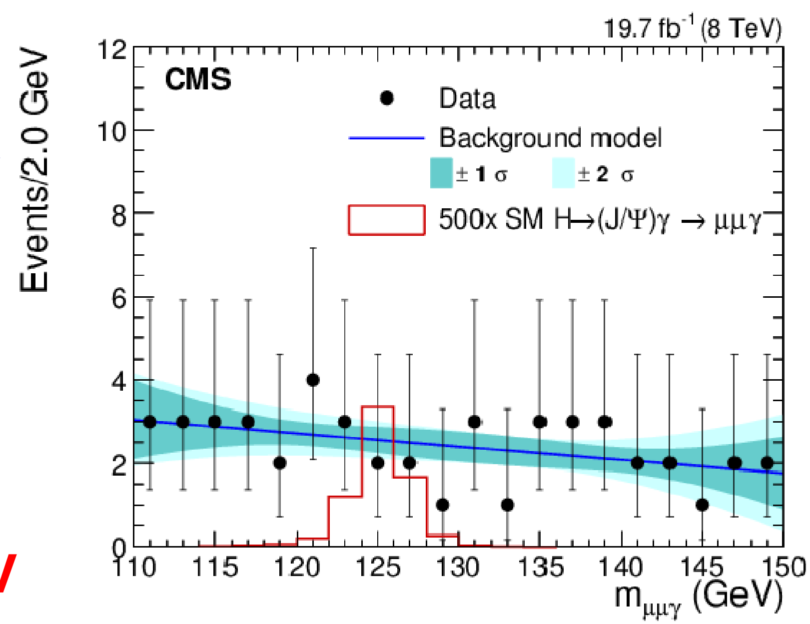
Phys. Rev. Lett. 114 (2015) 121801





Explore H→cc coupling

- **ATLAS: inclusive QCD background modelled by data-driven template fitting**
- **Muon p_T > 20 GeV, $p_T^{\mu\mu}$ > 36 GeV**
- **$|m_{\mu\mu} - m_{J/\psi}|$<0.2 GeV, photon p_T > 36 GeV**
- **$\Delta\Phi(\mu\mu,\gamma)$ > 0.5, 4 event categories**
- **Simultaneous unbinned maximum likelihood fit on $m_{\mu\mu\gamma}$ and $p_T^{\mu\mu\gamma}$**
- **$B(H \rightarrow J/\Psi\ \gamma) < 1.5 \times 10^{-3}$ (~540 x SM)**

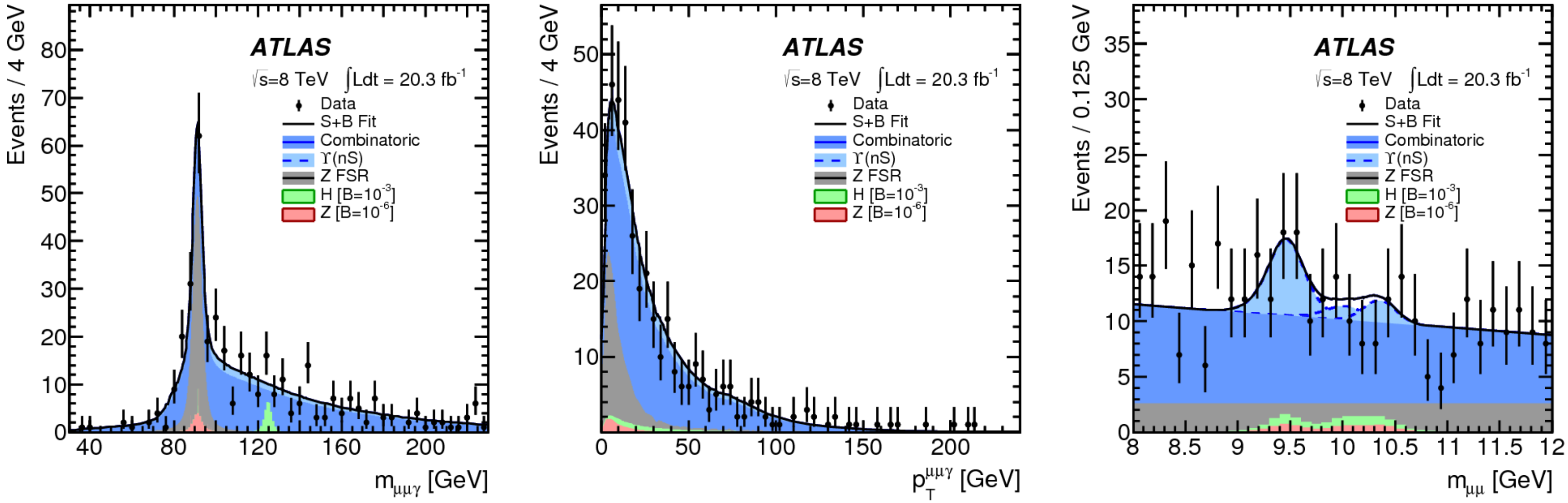


Similar to $H \rightarrow \gamma^*\gamma$ except 2.9 < $m_{\mu\mu}$ < 3.3 GeV

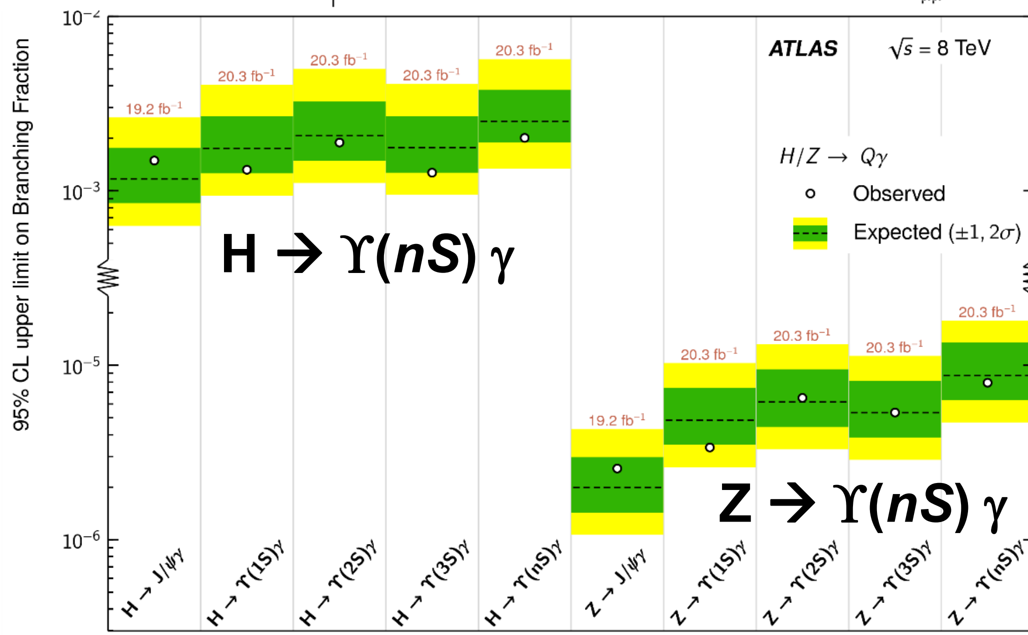
- **CMS: $B(H \rightarrow J/\Psi\ \gamma) < 1.5 \times 10^{-3}$**

H → ϒ(*nS*) γ

[Phys. Rev. Lett. 114 (2015) 121801]

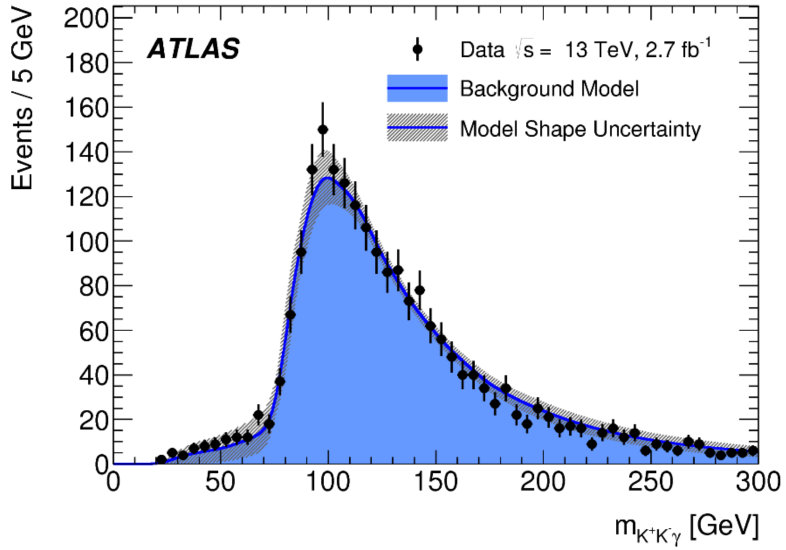


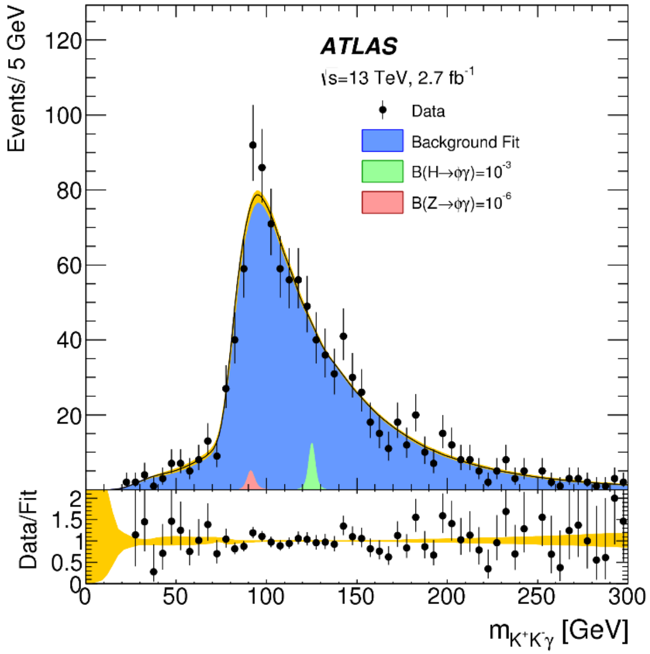
- **Simultaneous unbinned maximum likelihood fit on $m_{\mu\mu\gamma}$, $p_T^{\mu\mu\gamma}$ and $m_{\mu\mu}$**
- **8 GeV < $m_{\mu\mu}$ < 12 GeV**
- **B(H → ϒ(*1S*)γ) < 1.3 x 10^{-3}**
  B(H → ϒ (*2S*)γ) < 1.9 x 10^{-3}
  B(H → ϒ(*3S*)γ) < 1.3 x 10^{-3}
  B(H → ϒ(*nS*)γ) < 2.0 x 10^{-3}
- **Limit ~ 10^7 x SM**



H → Φγ

arXiv:1607.03400



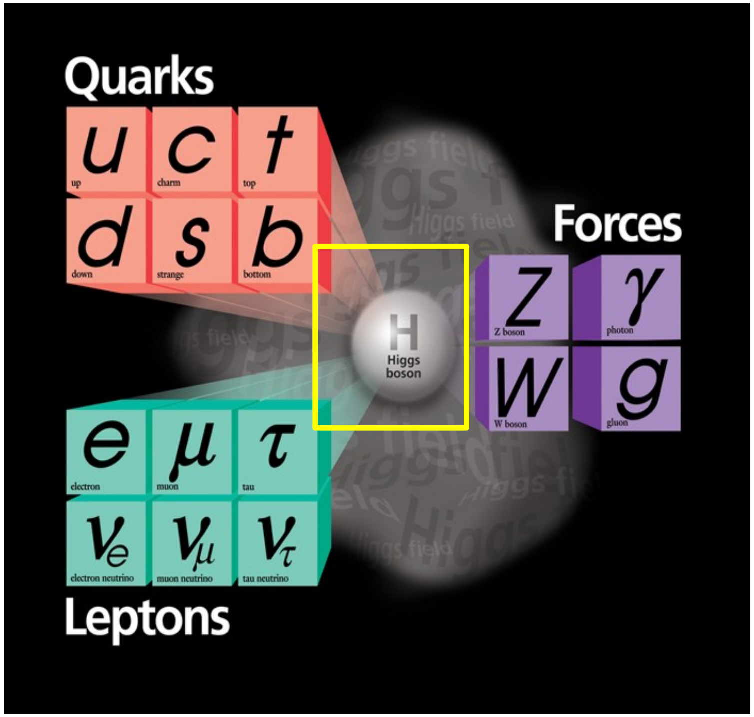


Explore H→ss coupling, reconstruct $\Phi \to K^+K^-$

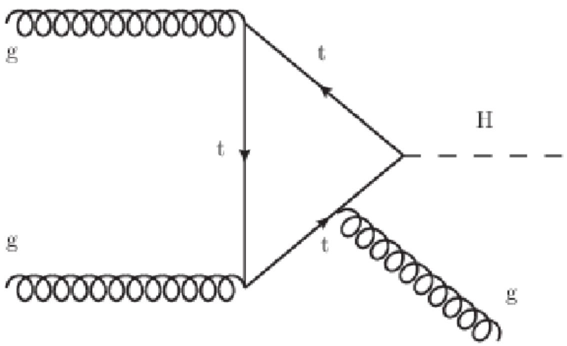
- Kaon p_T > 15 GeV & $|\eta|$ < 2.5, isolated track leading p_T > 20 GeV
- $|m_{K+K-} - m_{\Phi}|$ < 20 MeV, photon p_T > 35 GeV
- $\Delta\Phi(K^+K^-,\gamma)$ > 0.5, p_T^{KK} > 40-45 GeV
- Inclusive QCD and γ+jet backgrounds shape modelled by data-driven templates, normalization extracted by fitting to data
- Unbinned maximum likelihood fit on $m_{K+K-\gamma}$
- B(H → Φγ) < 1.4 x 10^{-3} (~600 x SM) (obs.) , 1.5 x 10^{-3} (exp.)

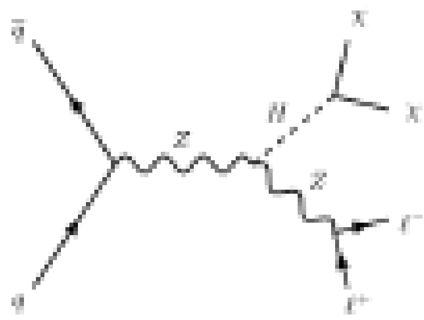
Higgs Rare Decay

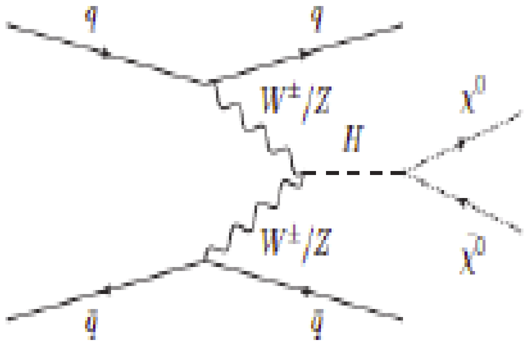
- Higgs (Beyond Standard Model) Exotic Decays
  - H → invisible
  - H → scalar boson (see Kono & Yuan's talks)
  - Higgs decay with Lepton Flavor Violation (see Kono & Yuan's talks)



H → invisible



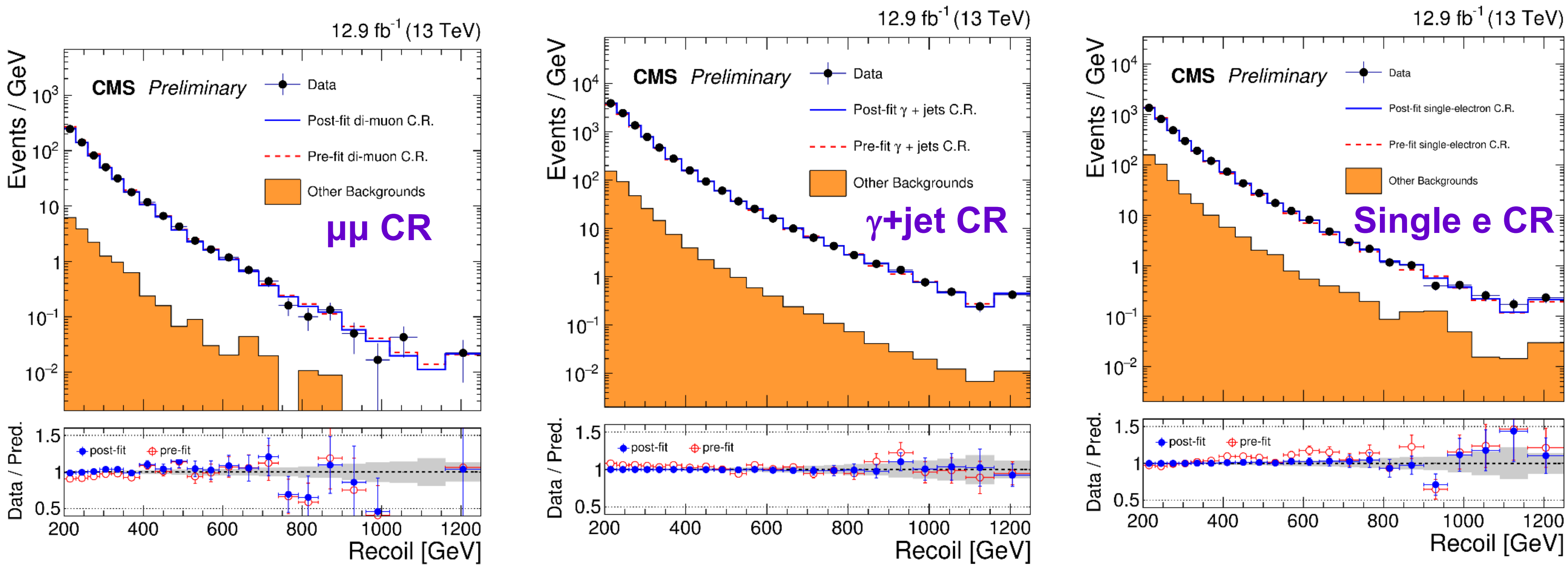




Explore BSM scenario using Higgs invisible decays

- Higgs portal: mediator between SM and dark sector
- SM scenario: H→ZZ*→4v ~ $O(10^{-3})$
- Large missing transverse momentum:
  - gluon-gluon fusion: mono-jet final state
  - association with vector boson: mono-V → two leptons or two-jets final state
  - vector boson fusion: two well-separated jets final state

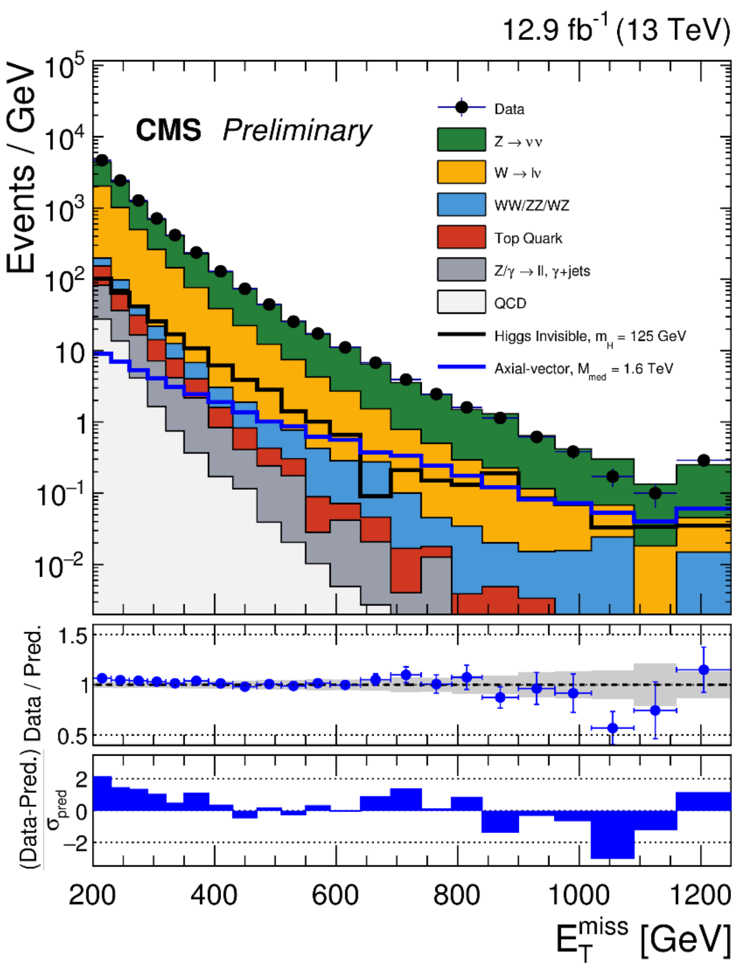
ggH → invisible + jet

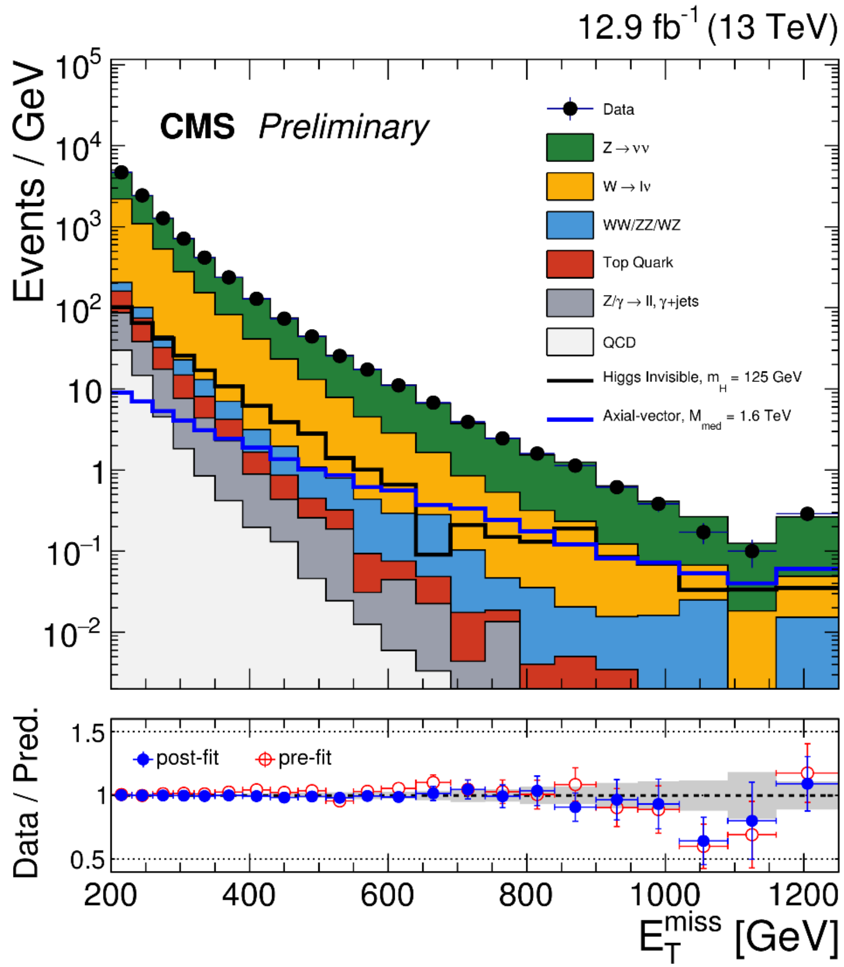


CMS-PAS-EXO-16-037

- **High pT, central jet with large missing energy:**
  - **p_T^J > 100 GeV, |η| < 2.5, E_T^{miss} > 200 GeV**
- **Dominant V+jets backgrounds estimated by fitting redefined E_T^{miss} to data in ten independent control regions**
  - **Hadronic recoil energy (w/o lepton & photon) mimics E_T^{miss} shape**
- **Using transfer factors to estimate backgrounds in the signal region**

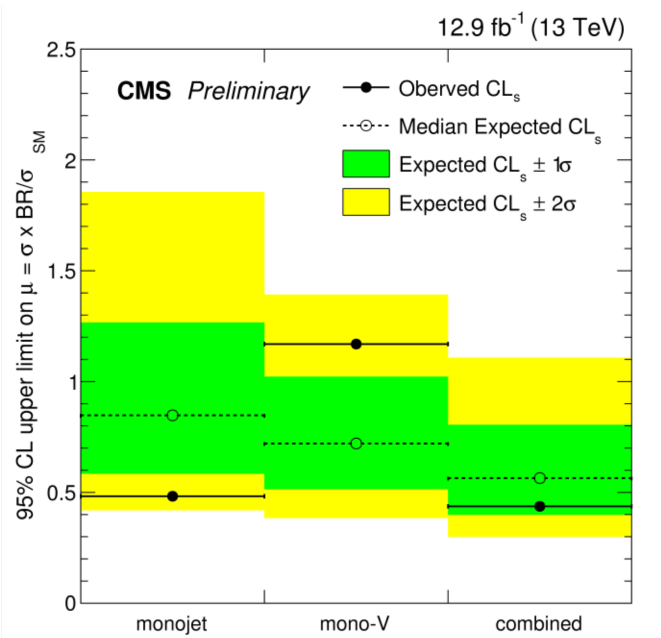
ggH → invisible + jet

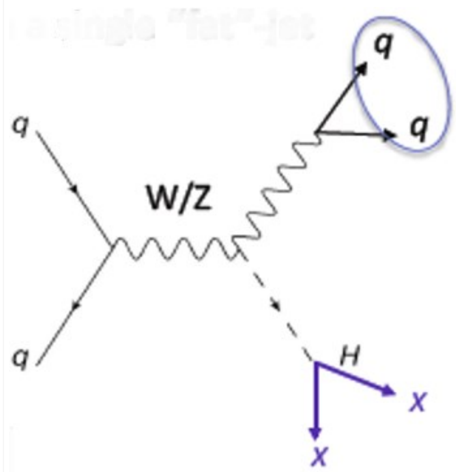


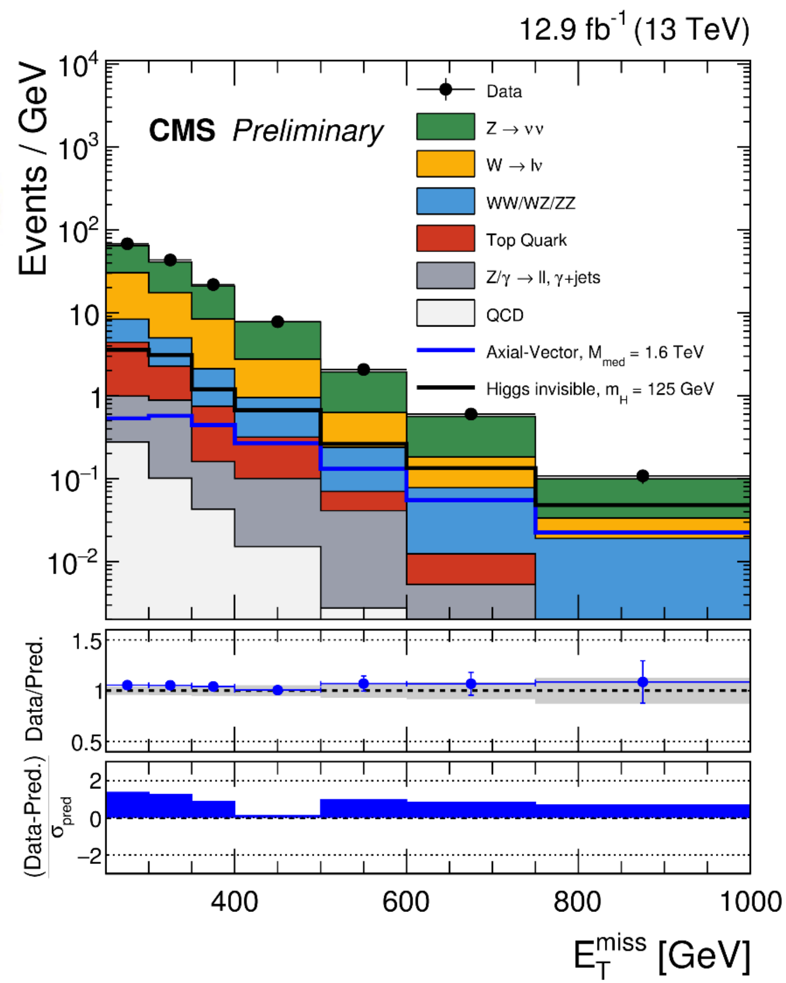


- **Signal extracted by fitting to E_T^{miss} taking into account uncertainties**
- **Data agrees with the SM prediction**

VH → invisible + jet(s)





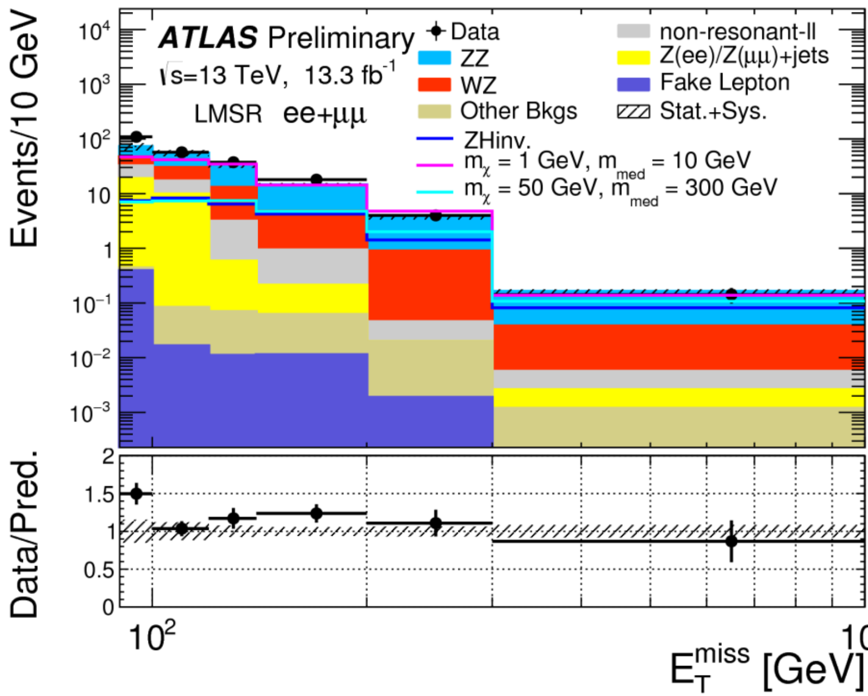


- **Hadronic decay V-boson forms a single "fat" jet**
  - **$65 < m_J < 100$ GeV**
  - **$p_T^J > 250$ GeV, $E_T^{miss} > 250$ GeV**
  - **$\Delta\Phi(J, E_T^{miss}) > 0.5$**
  - **Jet substructure $\tau_2/\tau_1 < 0.6$**

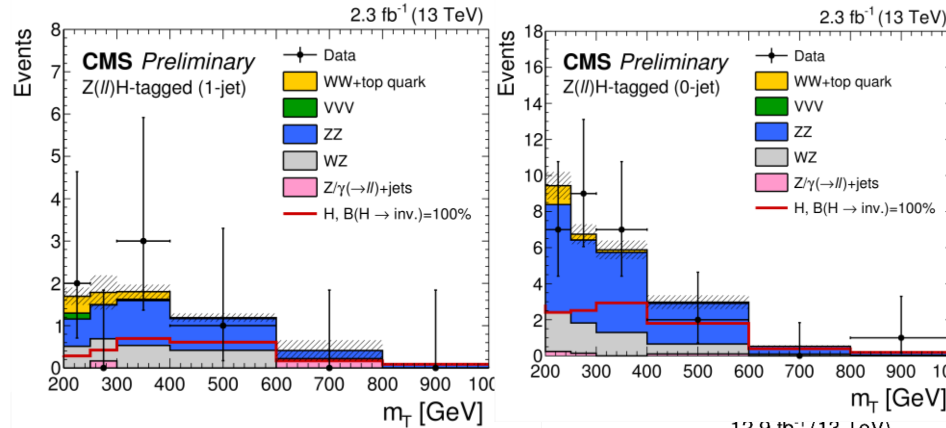
B(H→invisible(mono-jet)) < 0.48
B(H→invisible(mono-V)) < 1.17
B(mono-jet+mono-V) < 0.44

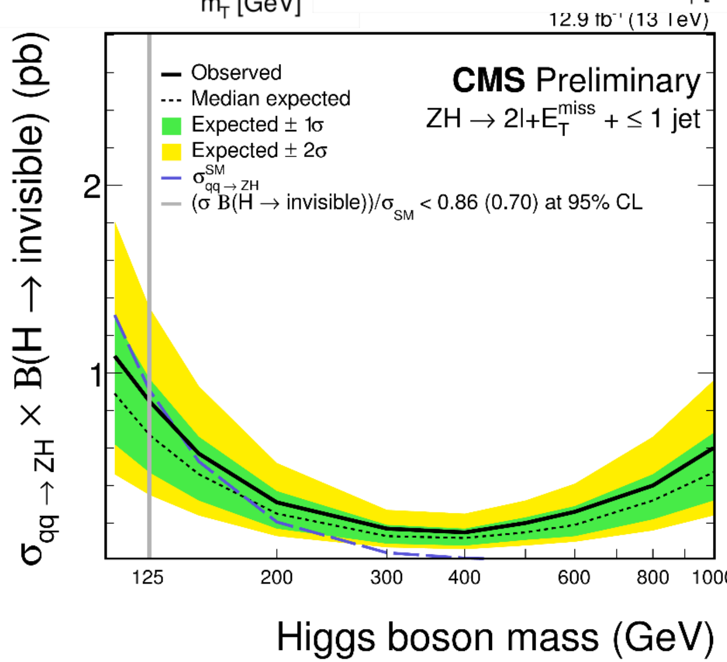
ZH → invisible + leptons

ATLAS-CONF-2016-056



CMS-PAS-HIG-16-008





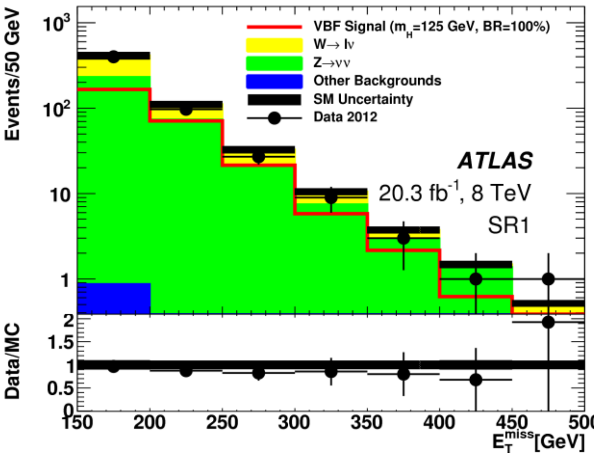
- **Leptonic Z decay provides clean final state: one opposite sign ee/μμ pair within M_Z window, no b-tagged jet**
- **Dominant ZZ bkgs from NLO, other normalization from data, shape from MC**
- **Maximum likelihood fit of E_T^{miss}**

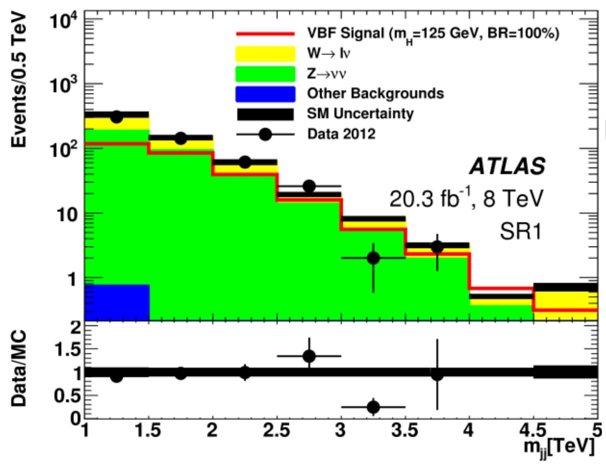
B(ZH→invisible+ll) < 0.98 (obs.) 0.65 (exp.)

B(ZH→invisible+ll) < 0.86 (obs.) 0.70 (exp.)

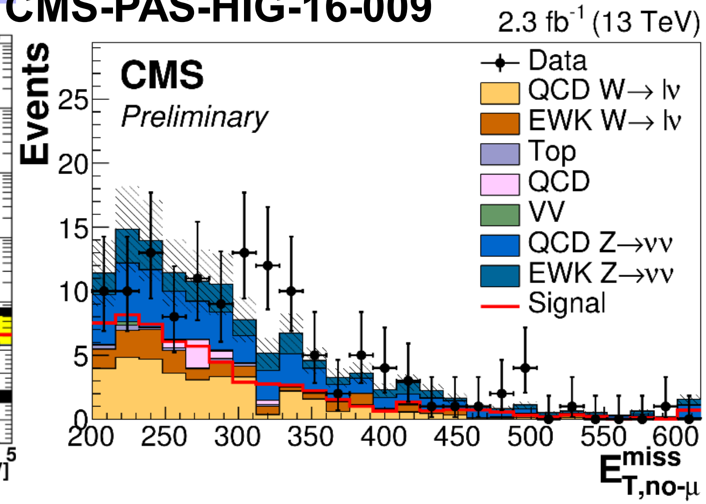
VBF(H) → invisible + jets

JHEP 01 (2016) 172





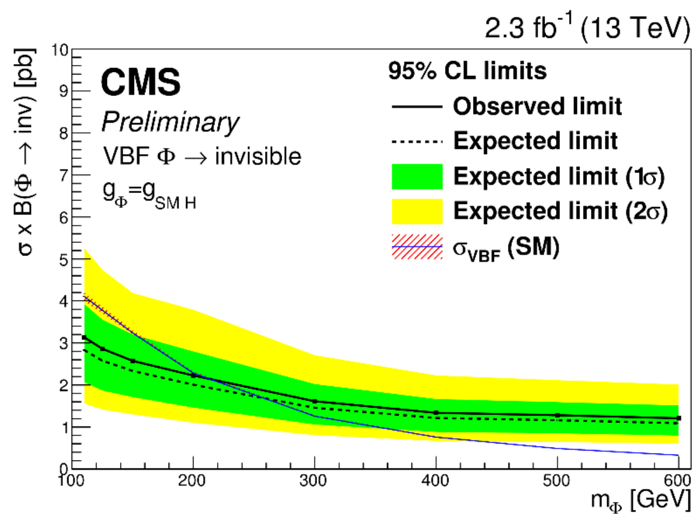
CMS-PAS-HIG-16-009



- Two high pT jets with large rapidity gap and large dijet mass, high E_T^{miss}
- Dominant V+jets bkgs from W/Z control samples in data, QCD data-driven method
- ATLAS Run-1: Maximum likelihood fit to yields in all signal and control regions

  B(H→invisible+jets) < 0.28 (0.31) obs. (exp.

- CMS Run-2: counting experiment with in-situ backgrounds estimation via simultaneous fitting in all signal and control regions

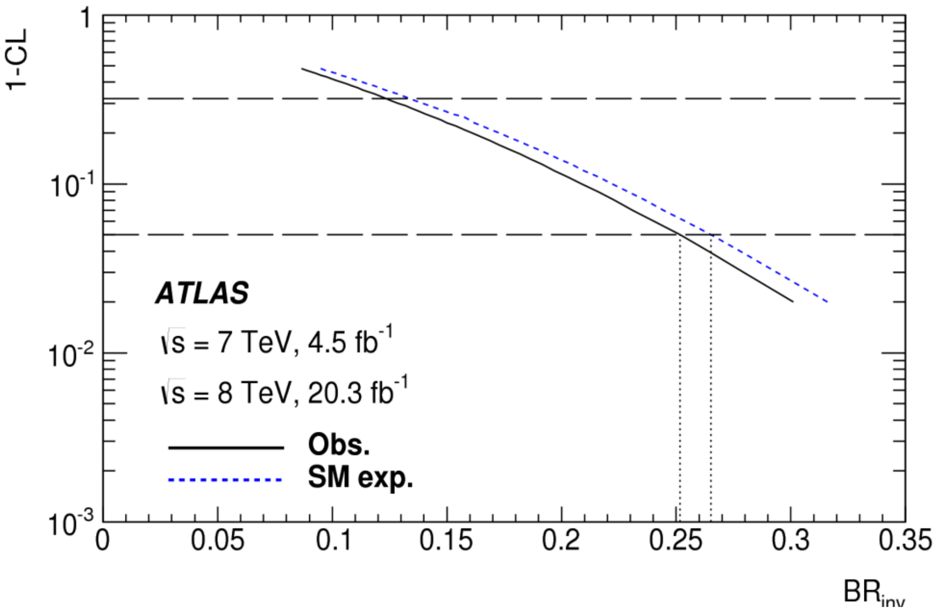


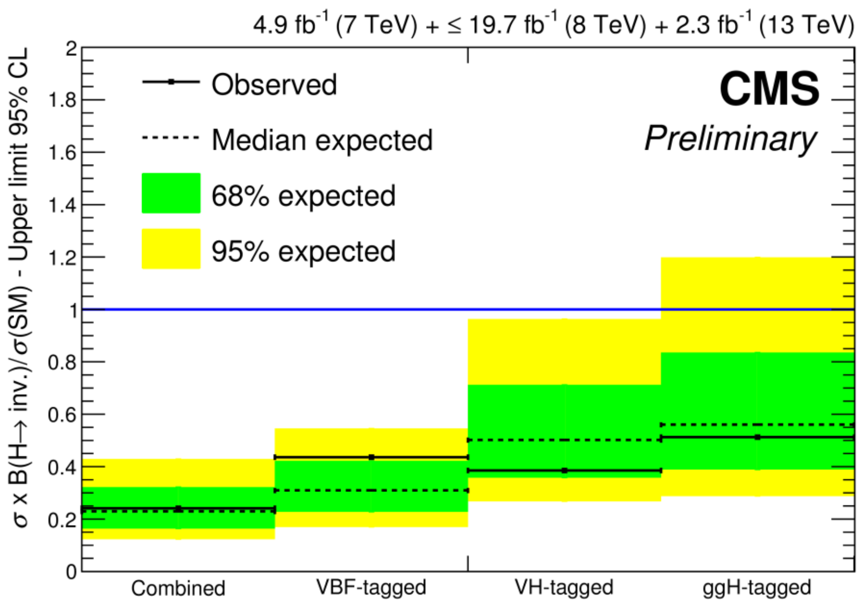
B(H→invisible+jets) < 0.69 (0.62) obs. (exp.)

Combination

JHEP11(2015)206

CMS-PAS-HIG-16-016





Decay channels	Coupling parameterisation	κ_i assumption	Upper limit on BR_{inv} Obs.	Exp.
Invisible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	**None**	**0.23**	**0.24**
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z} \leq 1$	0.23	0.23

ATLAS Run-1 data:
B(H→invisible) < 0.23 (obs.)
0.24 (exp.)

CMS Run-1+2015 data:
B(H→invisible) < 0.24 (obs.)
0.23 (exp.)

Summary

Many searches for Higgs rare decays have been done at LHC

- Standard Model rare decays not yet observed
  - $H \rightarrow \mu\mu, ee$
  - $H \rightarrow Z/\gamma^* \gamma$
  - $H \rightarrow J/\psi\gamma, \Upsilon\gamma$
  - $H \rightarrow \varphi\gamma$
- Higgs (Beyond Standard Model) Exotic Decays
  - $H \rightarrow$ invisible
    - No evidence found
  - $H \rightarrow$ scalar boson
  - Higgs decay with Lepton Flavor Violation
- Largely limited by statistics but systematics are becoming important, expect to make observation at ~10^3 fb^{-1} (e.g. $H \rightarrow \mu\mu$)