Search for LFV, rare, and invisible Higgs boson decays at CMS and ATLAS

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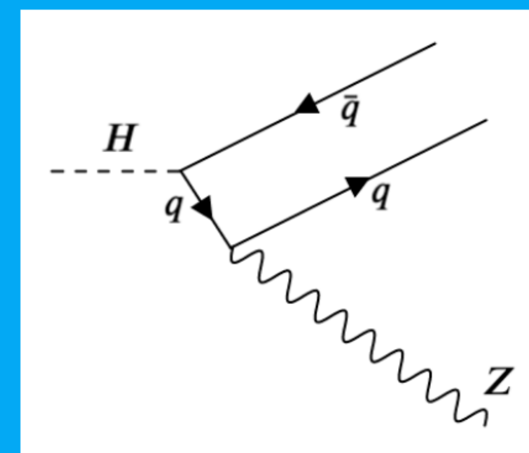
On behalf of the CMS and ATLAS collaboration

Higgs 2020 - Stony Brooks - 26 October, 2020

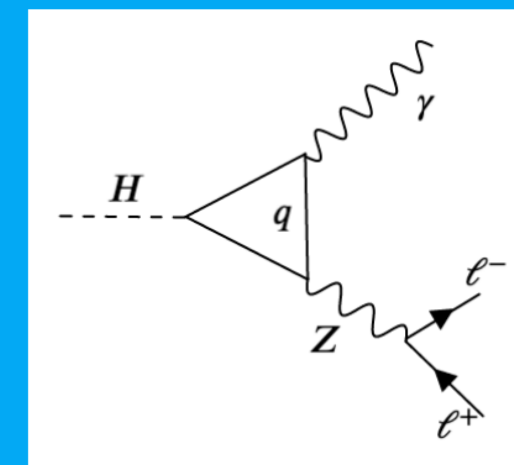
Overview

- Analyses Covered:
  - $H \to Z\rho/Z\phi$ at CMS
  - $H \to J/\psi\gamma$ at CMS
  - $H \to J/\psi\gamma, \psi(2S)\gamma, \Upsilon(nS)\gamma$ at ATLAS
  - $H \to Z\gamma$ at ATLAS
  - $H \to Z\gamma/\gamma^{*}\gamma$ at CMS
  - $H \to ee$ at ATLAS
  - LFV $H \to e\mu$ at ATLAS
  - LFV $H \to \mu\tau/e\tau$ at ATLAS
  - LFV $H \to \mu\tau/e\tau$ at CMS
  - $VBF\, H \to invisible$ at ATLAS
  - $t\bar{t}H \to invisible$ at ATLAS
  - $H \to invisible$ combination at ATLAS
  - $ZH \to invisible$ at CMS
  - $H \to invisible$ combination at CMS

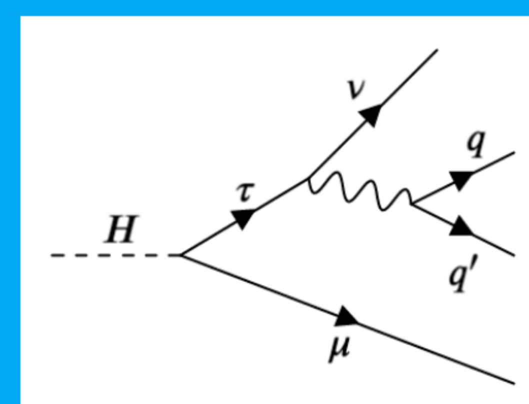
Higgs to Mesons



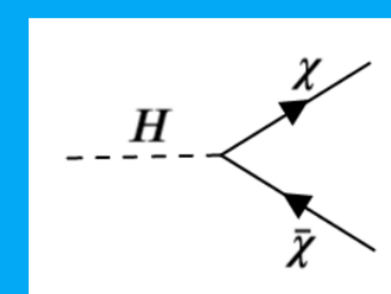
Higgs to Z Gamma



LFV Higgs Decays



Higgs Invisible Decays



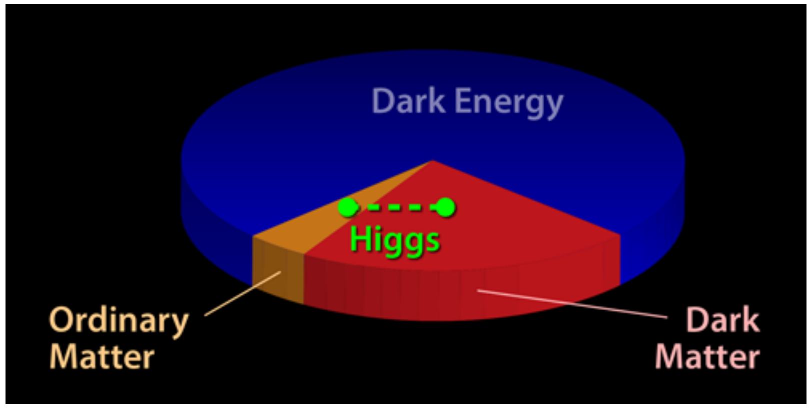
Introduction

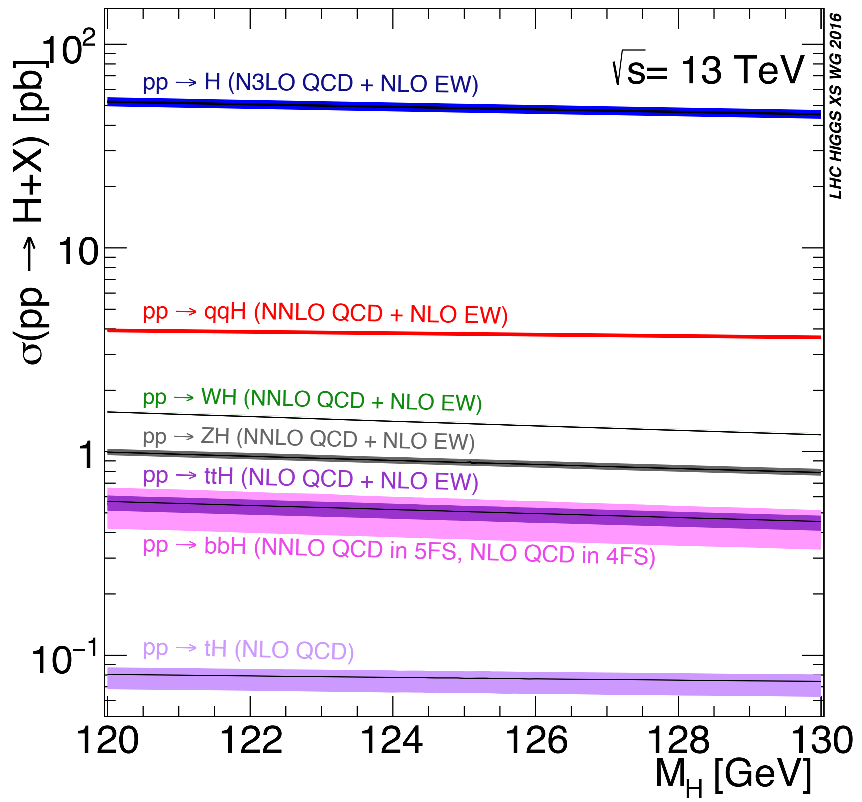
- Rare decays of the SM-like Higgs boson to mesonic final states provide a unique window onto light quark Yukawa couplings

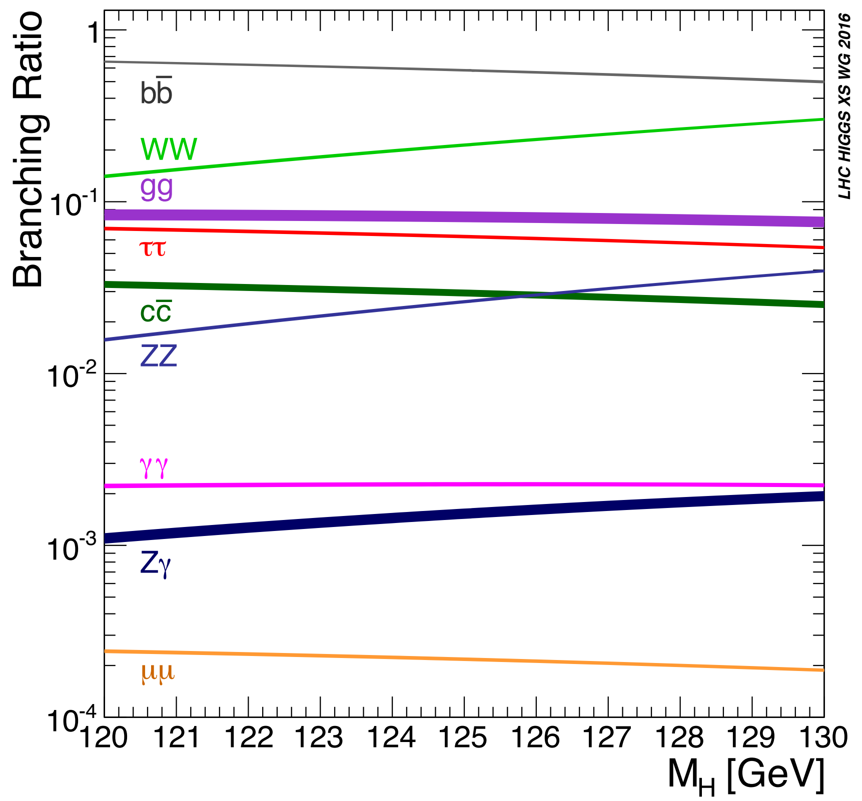
- SM predicts decay of Higgs boson into $Z\gamma$ through loop diagrams

- LFV decays of Higgs boson are a clear signature for BSM physics

- Higgs boson decays to DM particles can be indirectly inferred through missing transverse momentum as they escape detection

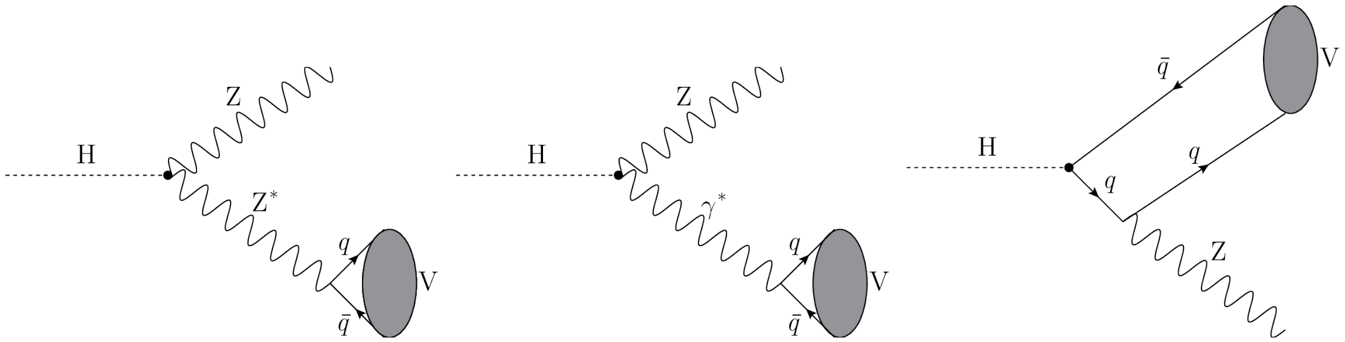






Search for $H \to Z\rho / Z\phi$

arXiv:2007.05122

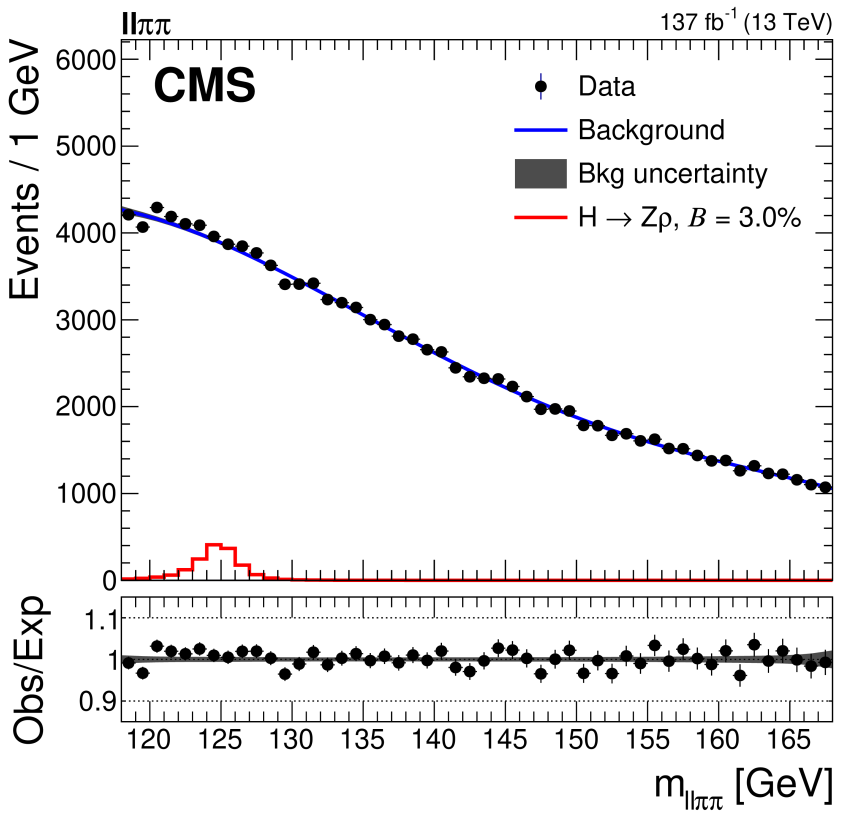


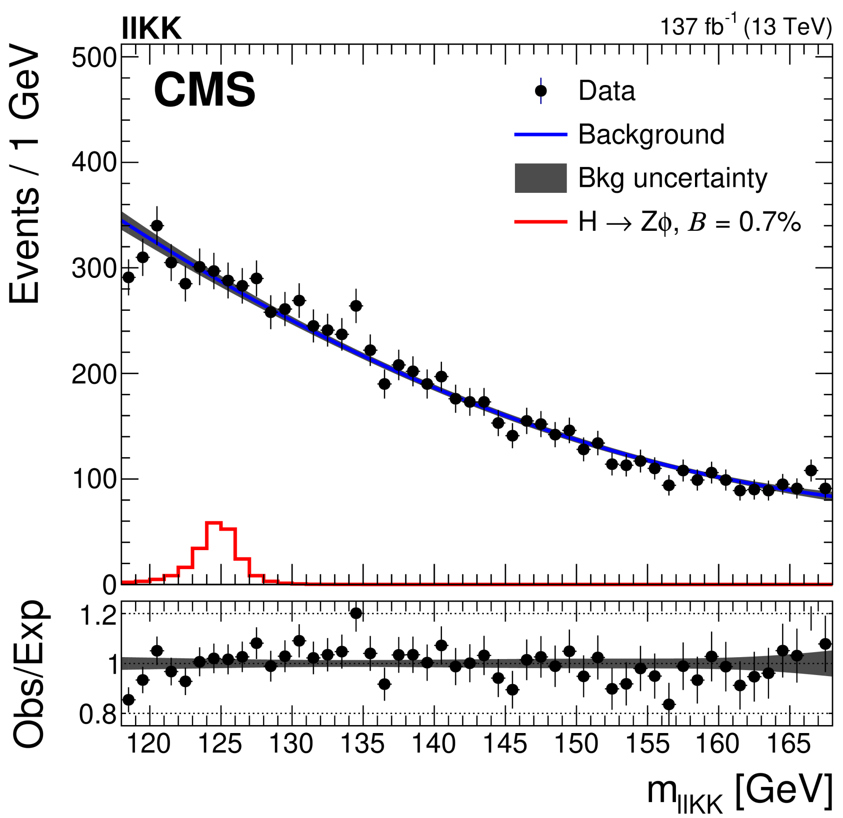
- **First limits** in this channel with full Run 2 data

- Selection:
  - Meson candidates: $p_T^{trk} > 1\,\text{GeV}$, $p_T^{leading\,trk} > 10\,\text{GeV}$, $\Delta R < 0.1$
  - Isolation: $I^{trk} < 0.5\,\text{GeV}$
  - ρ candidate: $0.6 < m_{\pi\pi} < 1.0\,\text{GeV}$
  - ϕ candidate: $1.005 < m_{KK} < 1.035\,\text{GeV}$

- Parametrization:
  - Background: Chebyshev polynomials (order 2 to 5)
  - Signal: Binned template with a bin width of 1GeV

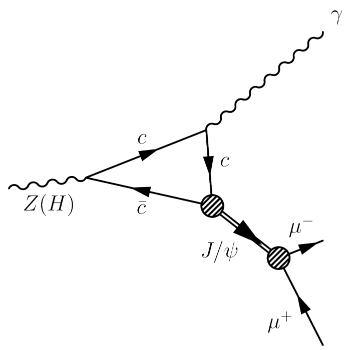
- **Results:**
  - **Observed 95% CL Upper Limits:** $B(H \to Z\rho) < 1.04 - 1.31\,\%$ **and** $B(H \to Z\phi) < 0.31 - 0.40\,\%$
  - **Variation in limits comes from polarization assumption: longitudinal - transversal (see backup)**

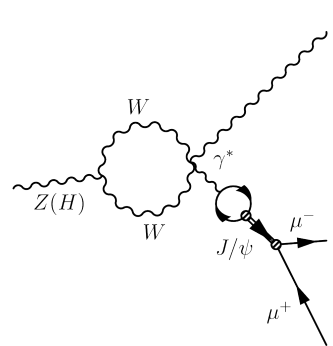




Search for $H \to J/\psi\gamma$

arXiv:1810.10056





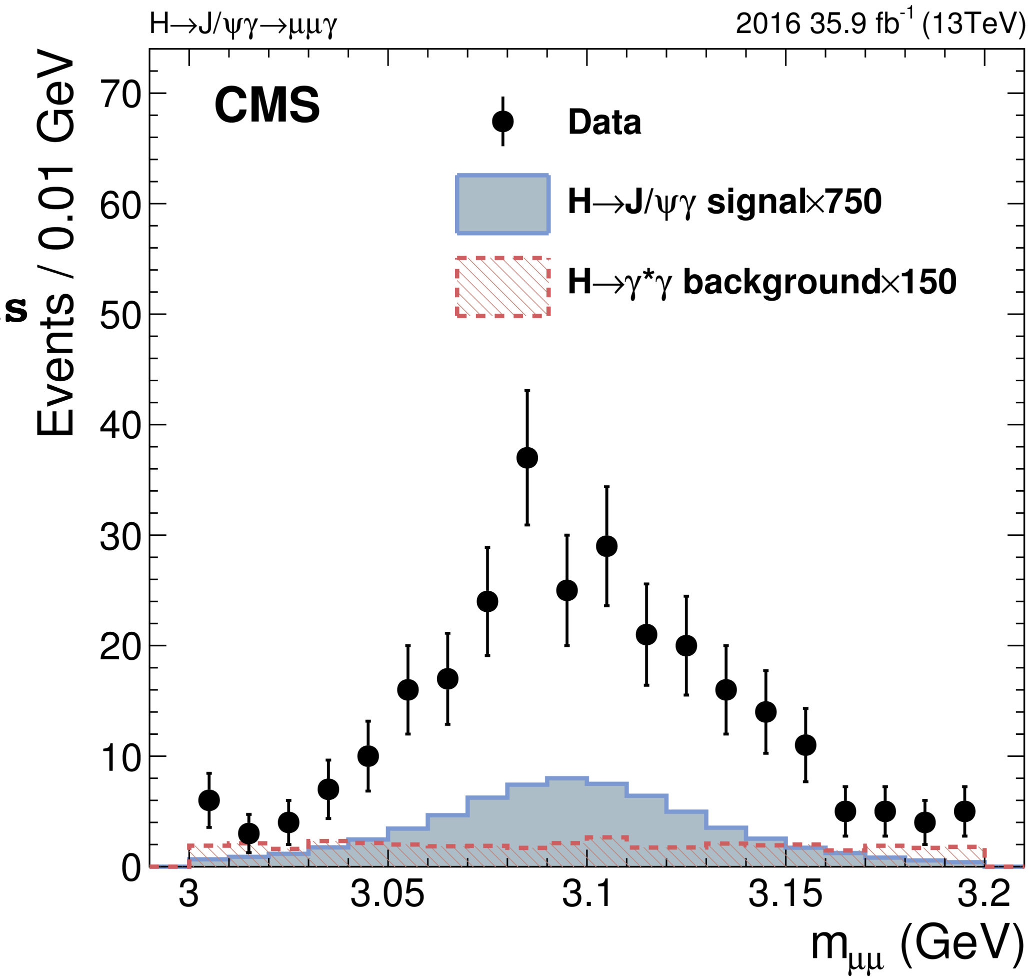
- **This search probes anomalous Higgs coupling to c-quarks**

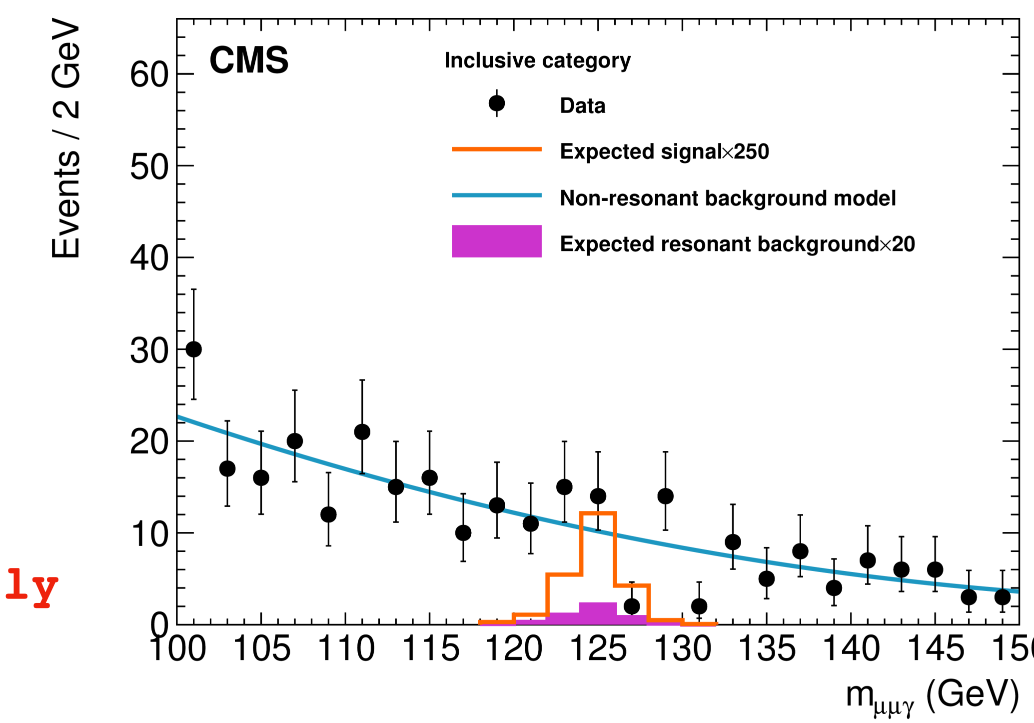
- Selection:
  - $\Delta R(\mu\mu, \gamma) > 2$ and $|\Delta\phi(\mu\mu, \gamma)| > 1.5$
  - $p_T / m_{\mu\mu\gamma} > 0.28$ rejects $\gamma^*/\gamma + jet$ backgrounds
  - $3.0 < m_{\mu\mu} < 3.2\,\mathrm{GeV}$ mass constraint for J/ψ

- Parametrization:
  - Background: order-two polynomial function
  - Signal: Crystal Ball + Gaussian

- **Results:**
  - **In SM,** $B(H \to J/\psi\gamma) = 3.0^{+0.2}_{-0.2} \times 10^{-6}$
  - **Observed 95% CL Upper Limits:**

    $B(H \to J/\psi\gamma) < 7.6\,(5.2^{+2.4}_{-1.6}) \times 10^{-4}$ **(J/ψ is assumed to be fully transversely polarized)**





Search for $H \to J/\psi\gamma, \psi(2S)\gamma, \Upsilon(nS)\gamma$

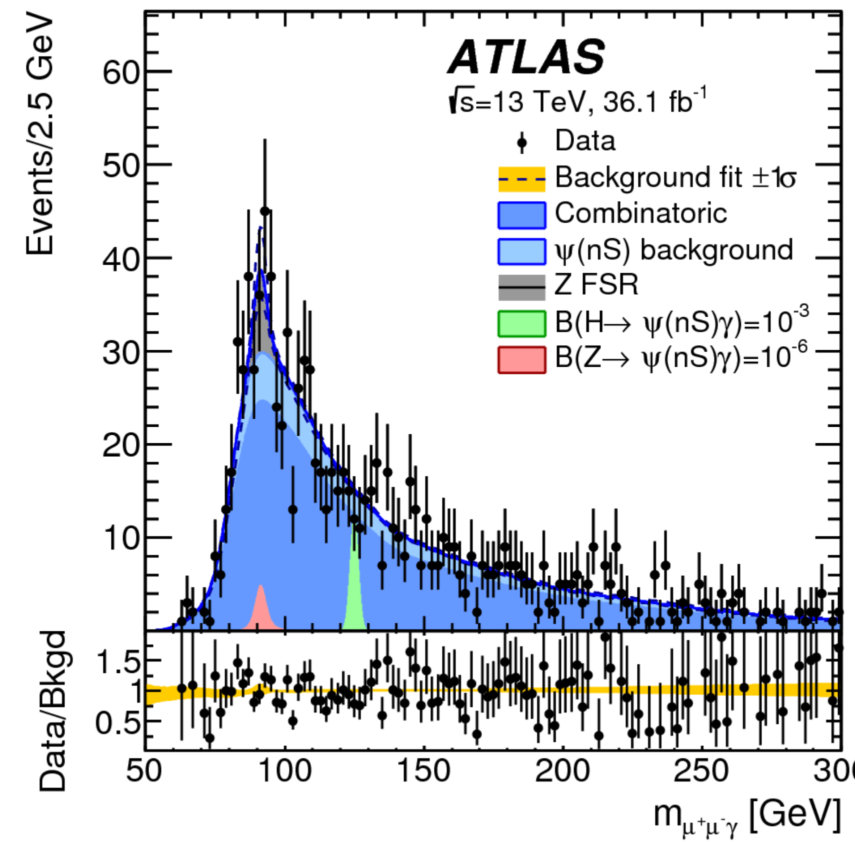
arXiv:1807.00802

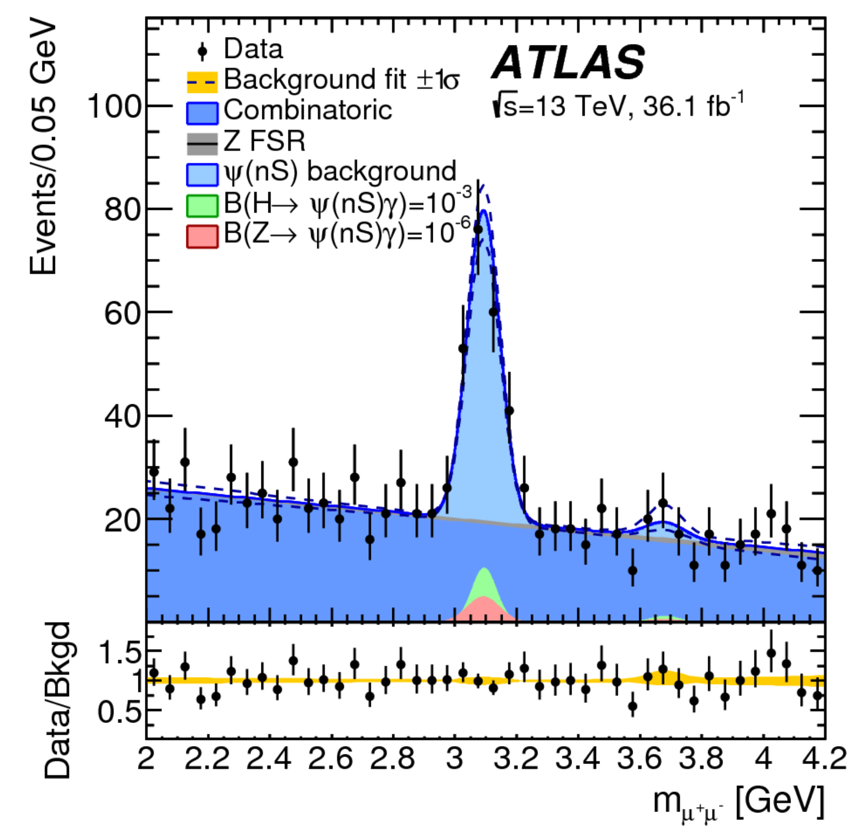
- **These searches probe anomalous Higgs coupling to c- and b-quarks**

- Selection:
  - $\psi(nS) \to \mu^+\mu^-$ candidates: $2.0 < m_{\mu^+\mu^-} < 4.2\,\text{GeV}$
  - $\Upsilon(nS) \to \mu^+\mu^-$ candidates: $8.0 < m_{\mu^+\mu^-} < 12.0\,\text{GeV}$
  - $\Delta\phi(Q,\gamma) > \pi/2$, $40\,(34) < p_T^Q < 54.4\,(52.7)\,\text{GeV}$ for $\psi(nS)\,(\Upsilon(nS))$

- Parametrization:
  - Signal: Bi-variate Gaussian distributions ($m_{\mu^+\mu^-\gamma}$ and $m_{\mu^+\mu^-}$)
  - Background: From “Generation Region - Loose Isolation, $p_T^Q > 30$” by sampling the pdfs

- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL:**
  - $B(H \to J/\psi\gamma) = 3.5\,(3.0) \times 10^{-4}$, $B(H \to \psi(2S)\gamma) = 19.8\,(15.6) \times 10^{-4}$
  - $B(H \to \Upsilon(nS)\gamma) = 4.9, 5.9, 5.7\,(5.0, 6.2, 5.0) \times 10^{-4}$





Search for $H \to Z\gamma$

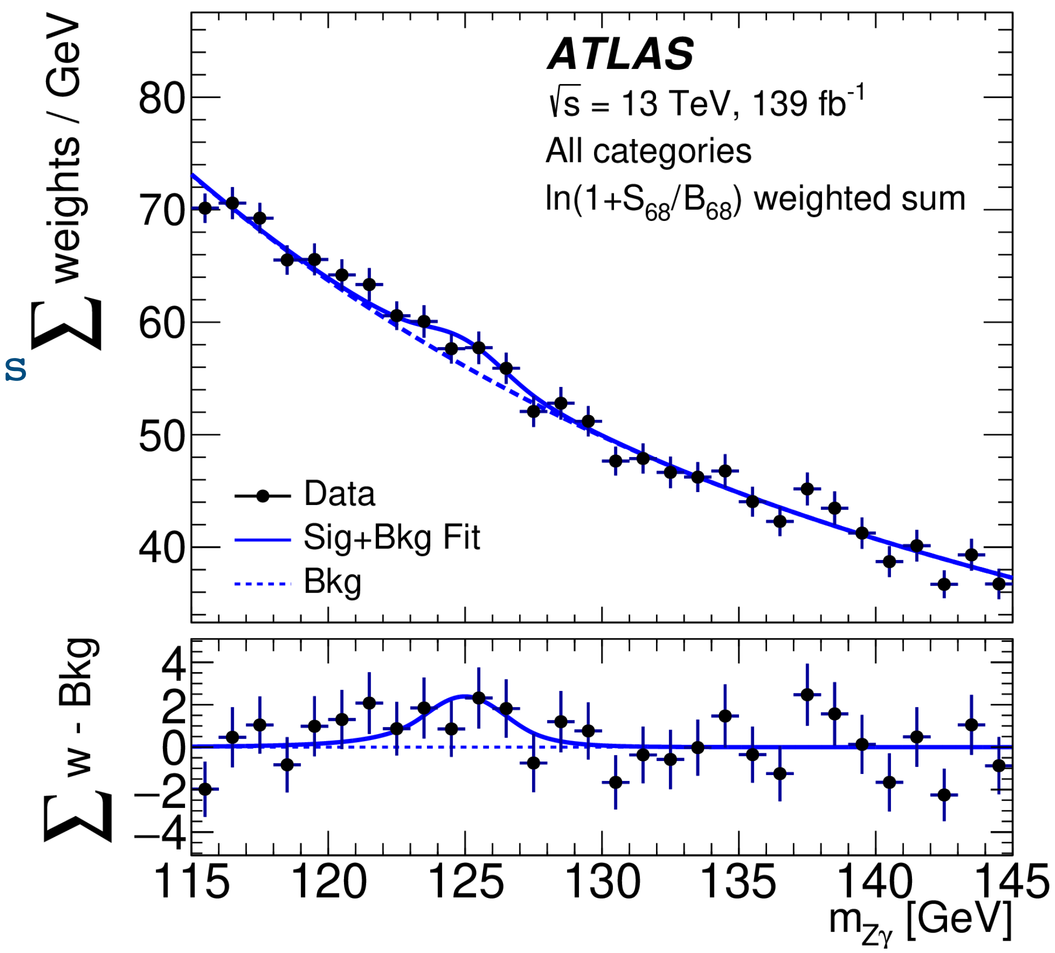
arXiv:2005.05382

- SM Higgs boson can decay into $Z\gamma$ through loop diagrams: $B(H \to Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$

- Selection:
  - FSR correction + constrained kinematic fit improves mass resolution by 14% for $H \to ee\gamma$ and 10% for $H \to \mu\mu\gamma$
  - To reduce background and simplify background modeling $p_T^{\gamma}/m_{Z\gamma} > 0.12$

- Parametrization:
  - Background: Bernstein Polynomial, Power, or exponential
  - Signal: Double-sided Crystal Ball

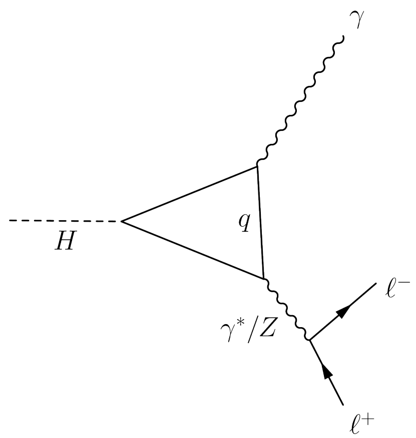
- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL on $\sigma \times BR$: 3.6 (2.6) times the SM prediction**

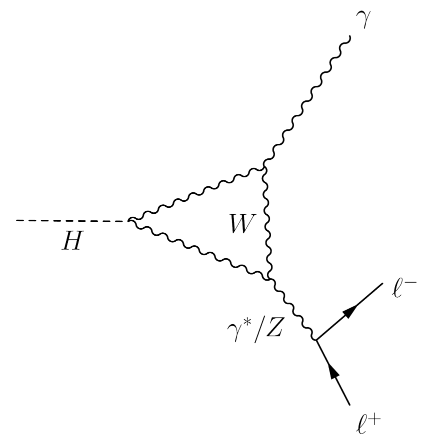


Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

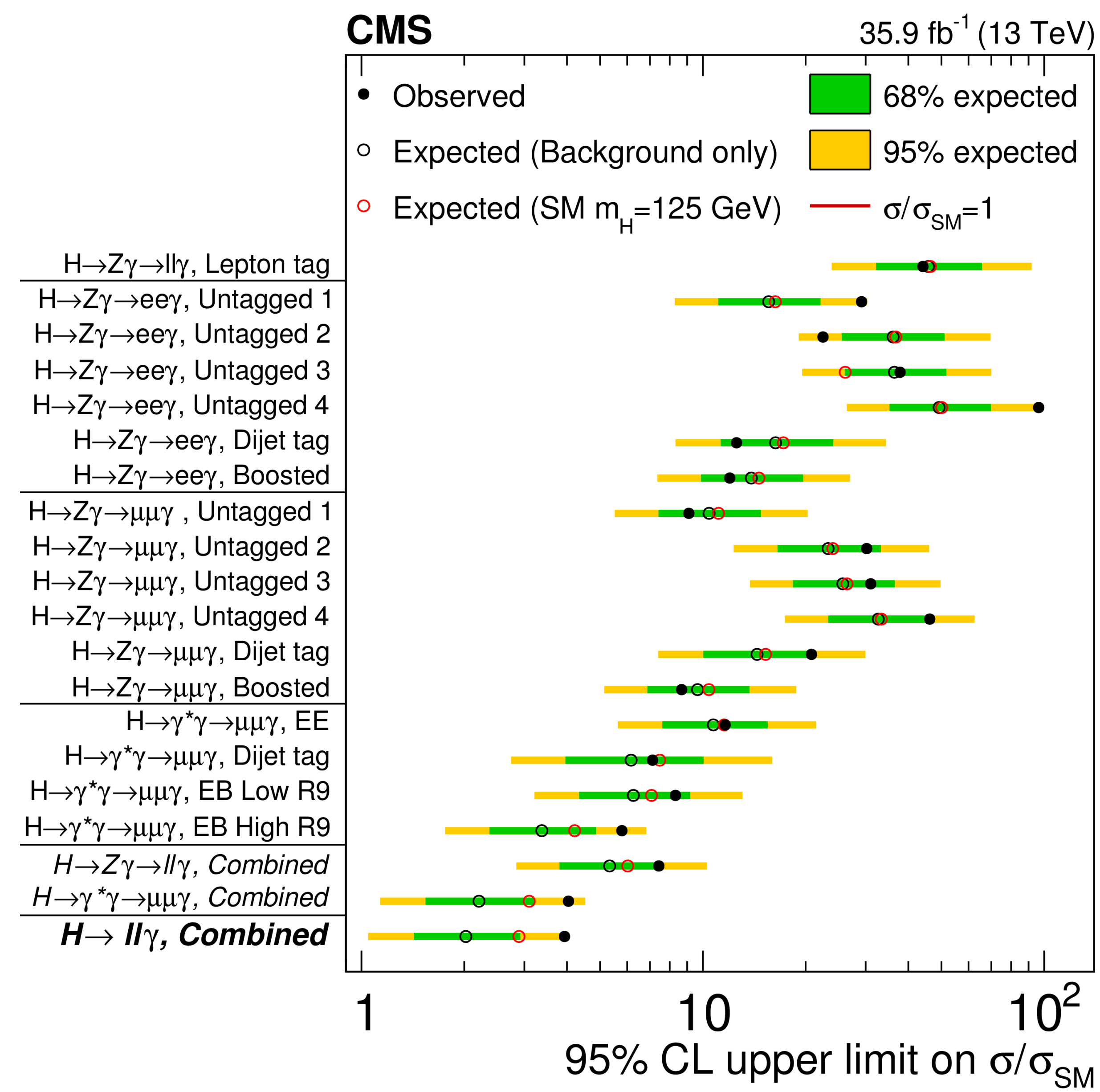
Search for $H \to Z\gamma/\gamma^*\gamma$

arXiv:1806.05996





- Parametrization:
  - Background: Bernstein Polynomial, Power, or exponential
  - Signal: Double-sided Crystal Ball for $H \to \gamma^*\gamma$, Crystal Ball + Gaussian for $H \to Z\gamma$



- Results:
  - Observed (Expected) Upper Limits on $\sigma \times BR$ vary between 1.4 and 4.0 (6.1 and 11.4) times the SM cross section for $H \to \gamma^*\gamma/Z\gamma$
  - 3.9 (2.0) for the combination

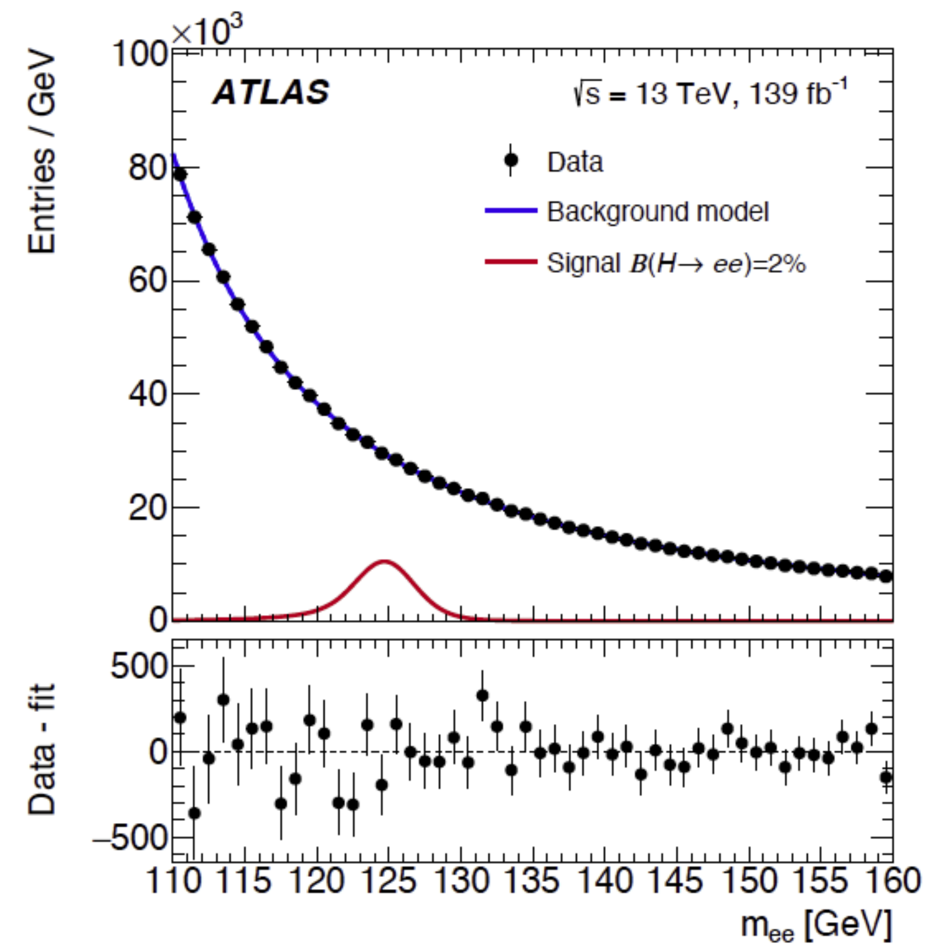
Search for $H \to ee$

arXiv:1909.10235

- In the SM, the $H \to ee$ BR: $G_F m_H m_e^2 / \left(4\sqrt{2}\pi\Gamma_H\right) \simeq 5 \times 10^{-9}$

- Selection:
  - $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 3.5\,\mathrm{GeV}^{1/2}$ for bkg. suppression

- Parametrization:
  - Background: Sum of a Breit-Wigner convoluted with a Gaussian, and an exponential divided by a cubic function
  - Signal: Sum of a Crystal-Ball and a Gaussian function



- Categories:
  - VBF: $|\Delta\eta_{jj}| > 3$, $m_{jj} > 500\,\mathrm{GeV}$
  - NonVBF: 'Central' if $|\eta^{\ell}| < 1.0$ else 'Non-central'
    - 'Low $p_T^{\ell\ell}$' ($p_T^{\ell\ell} \leq 15\,\mathrm{GeV}$)
    - 'Mid $p_T^{\ell\ell}$' ($15 < p_T^{\ell\ell} \leq 50\,\mathrm{GeV}$)
    - 'High $p_T^{\ell\ell}$' ($p_T^{\ell\ell} > 50\,\mathrm{GeV}$)

- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL:** $3.6 \times 10^{-4}\,(3.5 \times 10^{-4})$
  - **Factor of 5 improvement from previous result**
  - Statistically limited with largest systematic contribution from bkg. modeling uncertainty

Search for LFV $H \to e\mu$

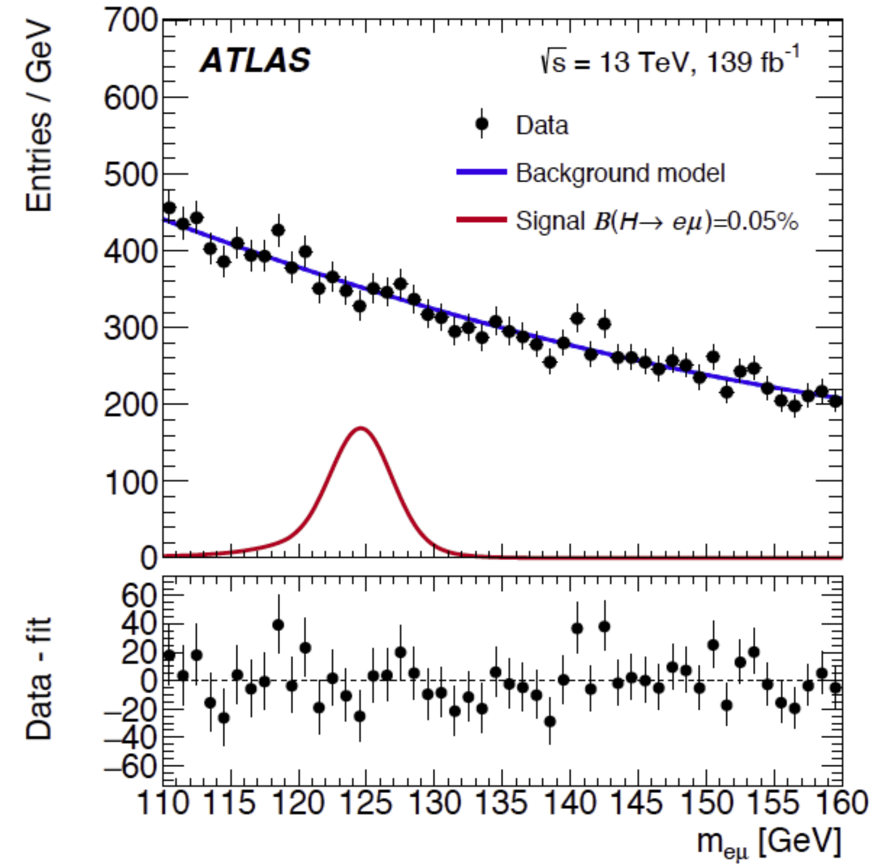
[arXiv:1909.10235](https://arxiv.org/abs/1909.10235)

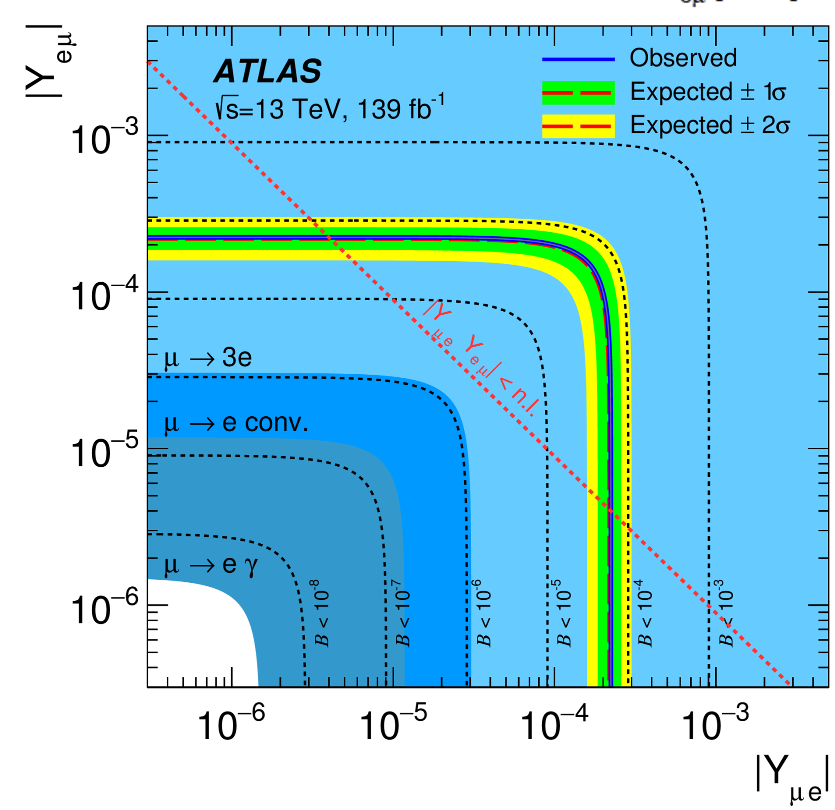
- Strong indirect constraints on $Y_{e\mu}$ from $\mu \to e\gamma$
  - $\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} < 3.6 \times 10^{-6}$

- Selection: $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 1.75\,\mathrm{GeV}^{1/2}$ for bkg. suppression
- Categories: $H \to ee$ categories + 'Low p_T^{ℓ}' ($p_T^{\ell,2} < 27\,\mathrm{GeV}$) due to non-prompt origin of lepton or is a misidentified photon or hadron

- Parametrization:
  - Background Model: Bernstein Polynomial
  - Signal Model: Crystal-Ball plus a Gaussian function

- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL:** $6.2 \times 10^{-5}\,(5.9 \times 10^{-5})$
  - **Factor of 6 improvement from previous result**
  - Statistically limited with largest systematic contribution from the Higgs boson production x-sec uncertainty





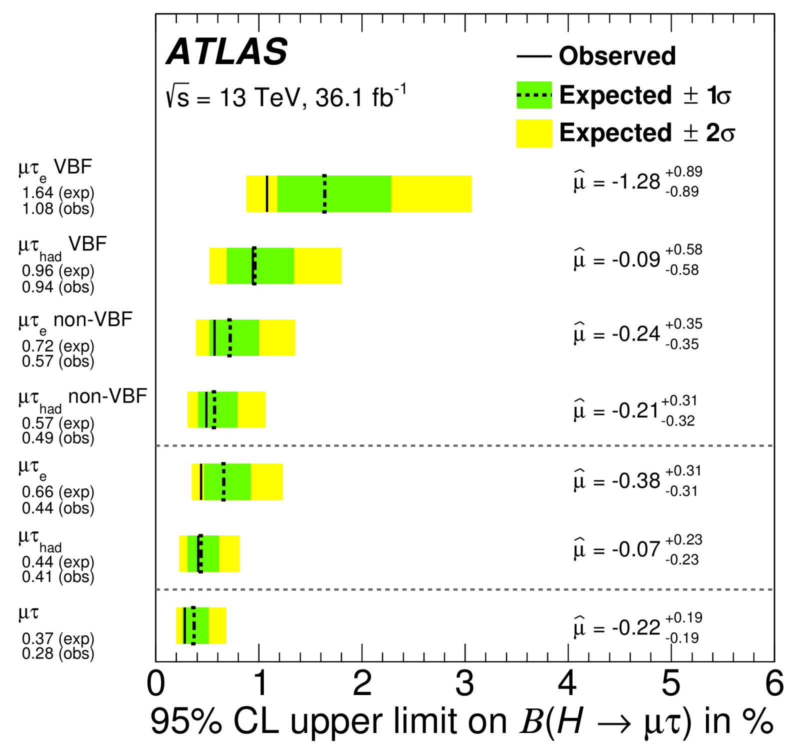
Search for LFV $H \to \mu\tau/e\tau$

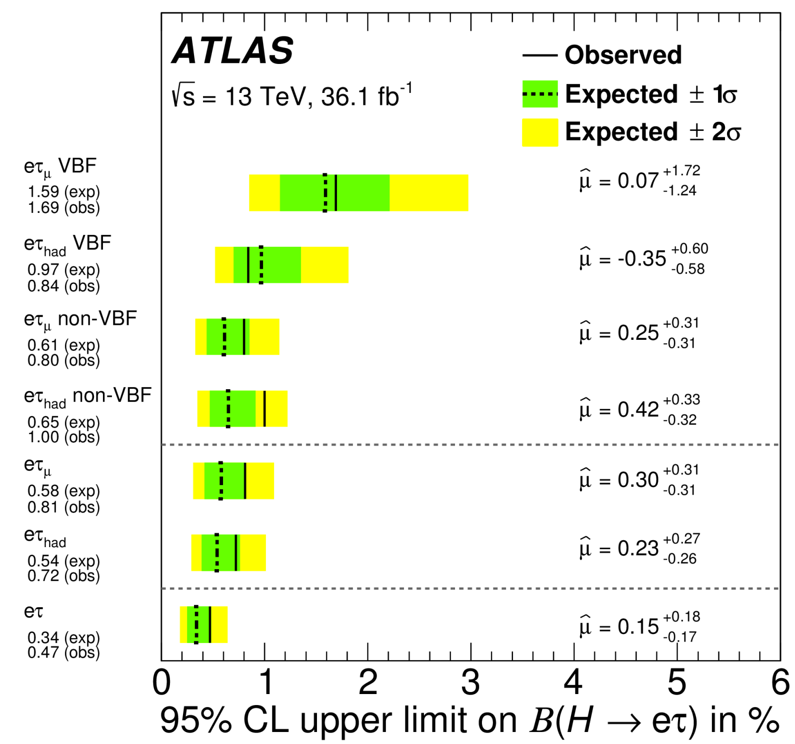
arXiv:1901.06131

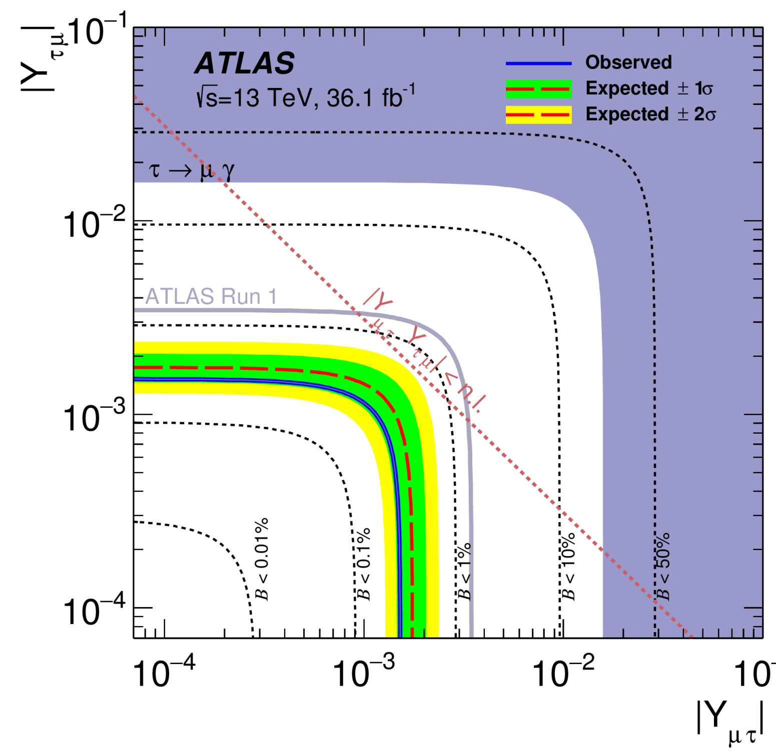
- Search involves both leptonic ($\tau \to \ell' \nu \bar{\nu}$) and hadronic ($\tau \to hadrons + \nu$) decays of τ leptons
- Dilepton final state $\ell\tau_{\ell'}$ only considers pairs of different-flavor leptons due to the large DY background
- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL:**

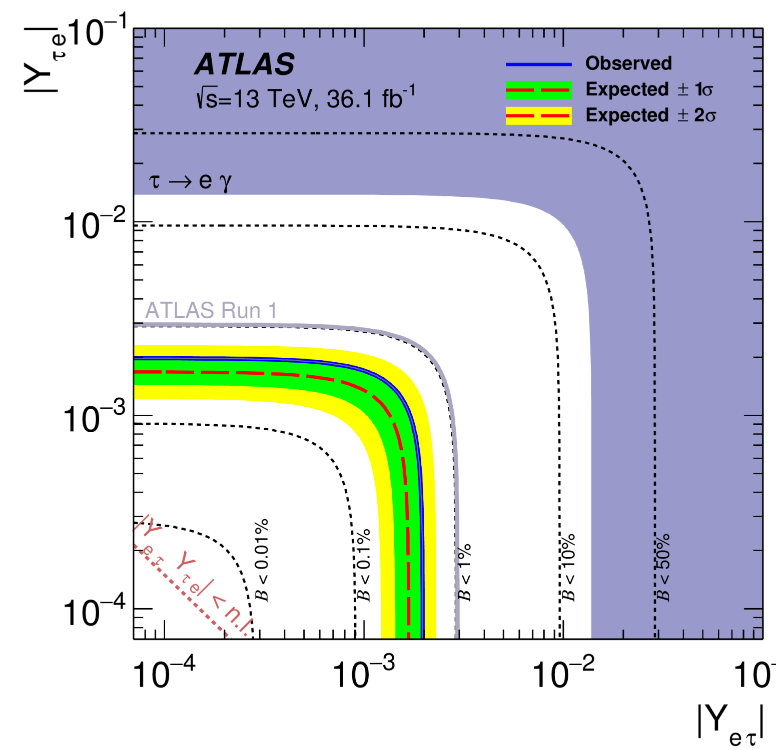
    $B(H \to e\tau) = 0.47(0.34^{+0.13}_{-0.10})\ \%$ **and**

    $B(H \to \mu\tau) = 0.28(0.37^{+0.14}_{-0.10})\ \%$
  - **Yukawa:** $\sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 0.0020$ **and** $\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 0.0015$





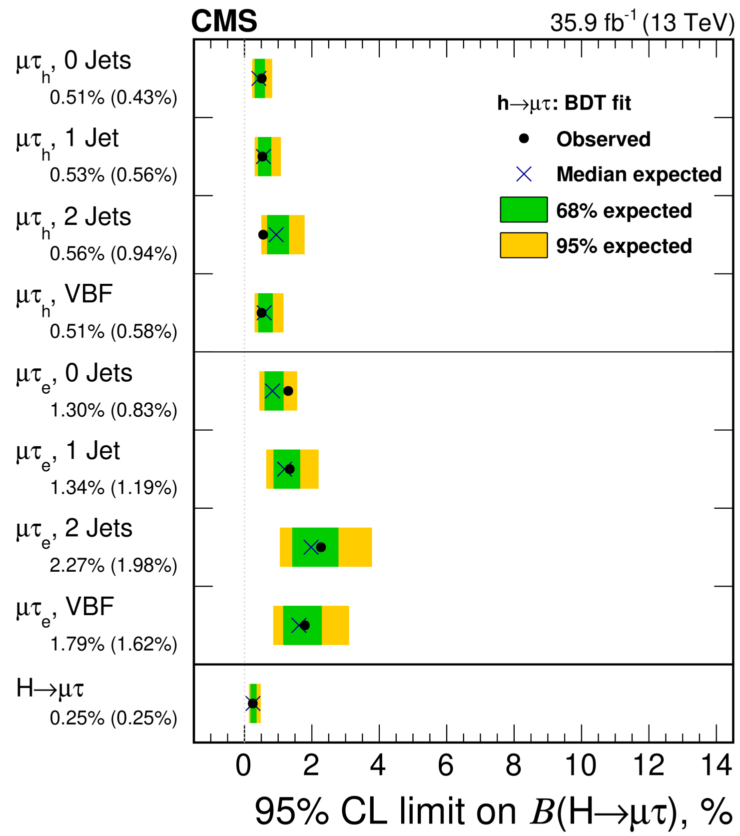


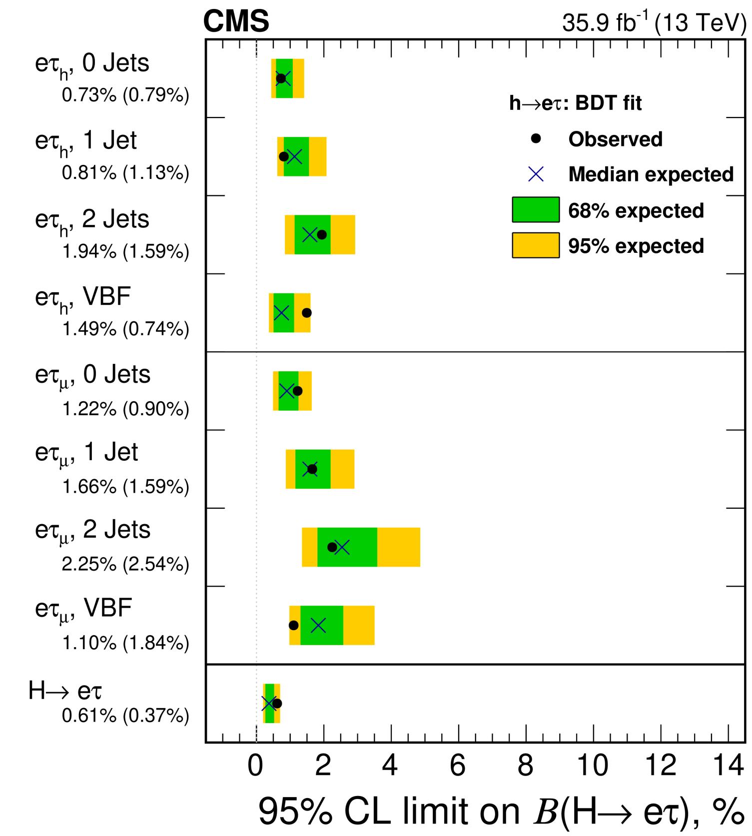


Search for LFV $H \to \mu\tau / e\tau$

arXiv:1712.07173

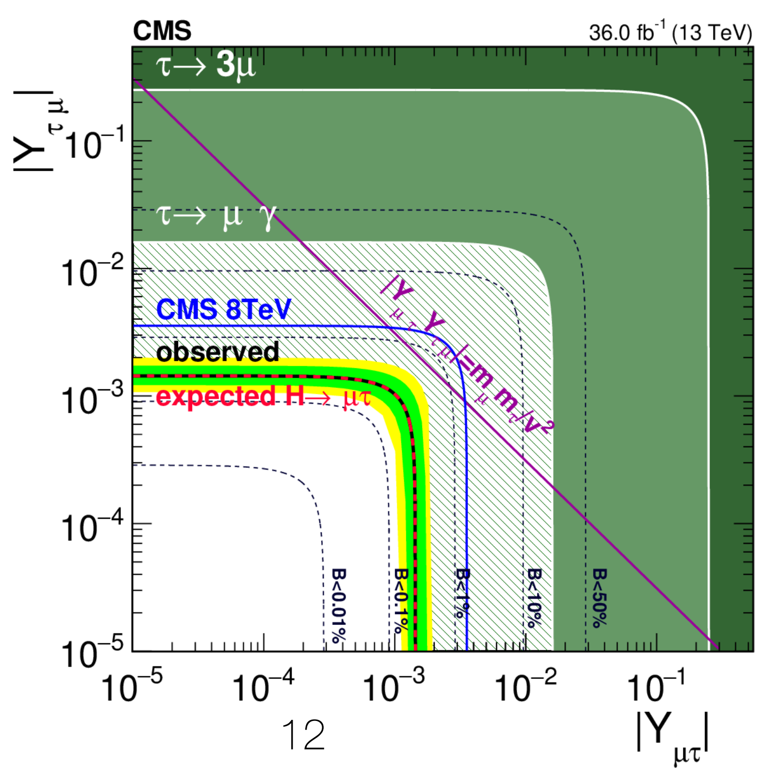
- In Run 1, a small excess of data w.r.t. the SM background-only hypothesis was observed in the $H \to \mu\tau$ channel (2.4σ), Best-fit: $B(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\ \%$
- **Results:**
  - **Excess observed in Run 1 was excluded with the 2016 results**

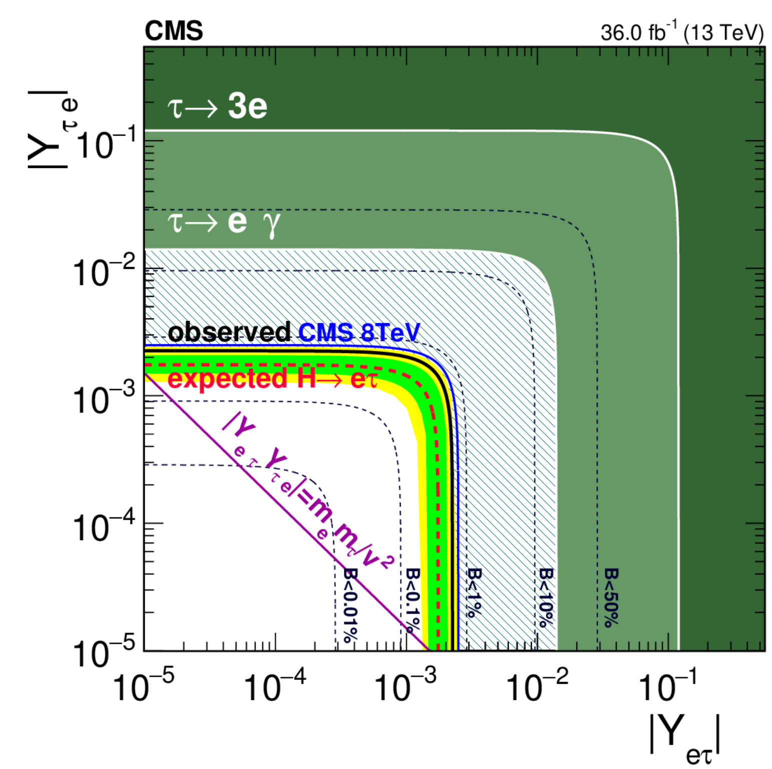




	Observed (expected) limits (%)	
	BDT fit	M_{col} fit
$H \to \mu\tau$	<0.25 (0.25)%	<0.51 (0.49) %
$H \to e\tau$	<0.61 (0.37) %	<0.72 (0.56) %

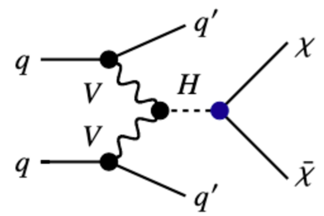
	BDT fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 1.43 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.26 \times 10^{-3}$



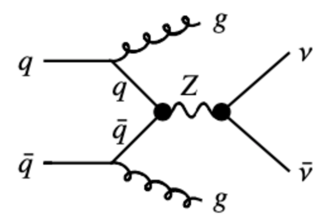


Search for VBF $H \rightarrow invisible$

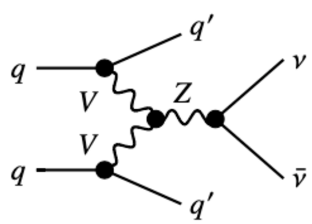
ATLAS-CONF-2020-008



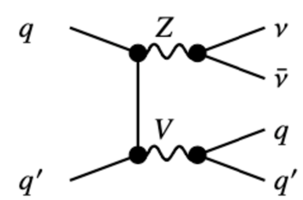
(a) Signal process



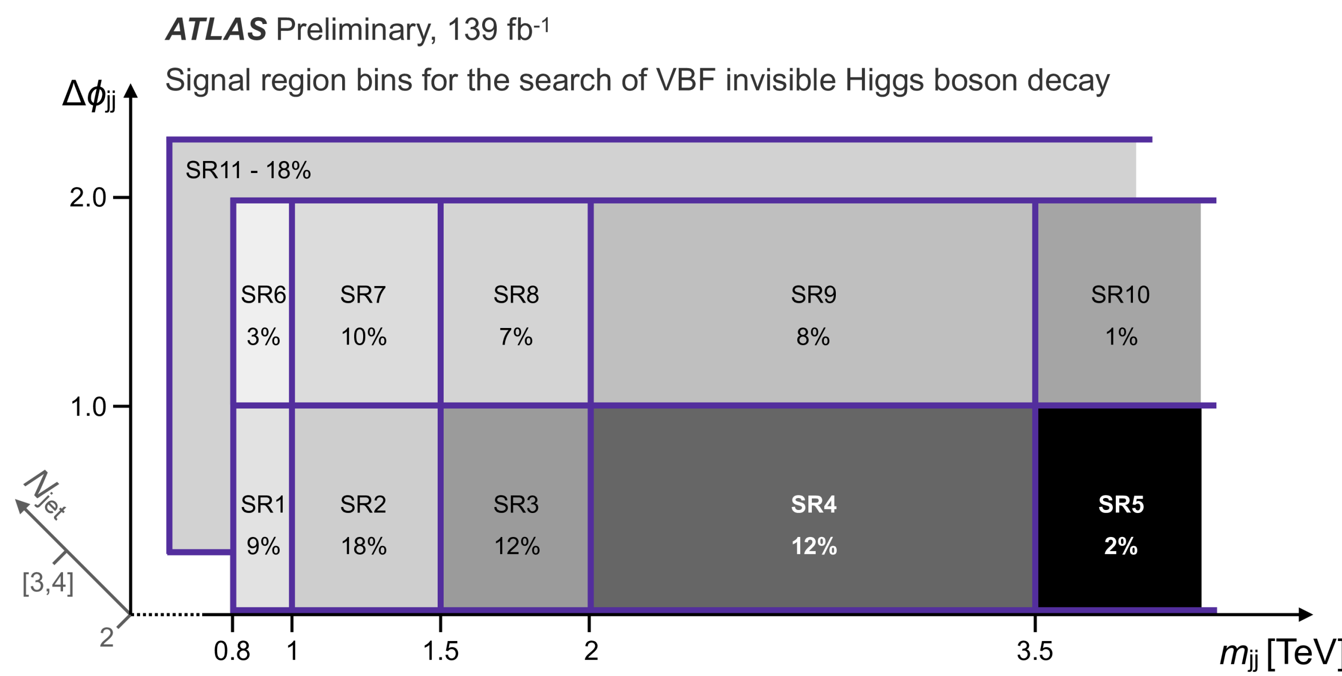
(b) Example diagram for the strong Z+jets background process



(c) Example diagram for the electroweak VBF Z+jets background process

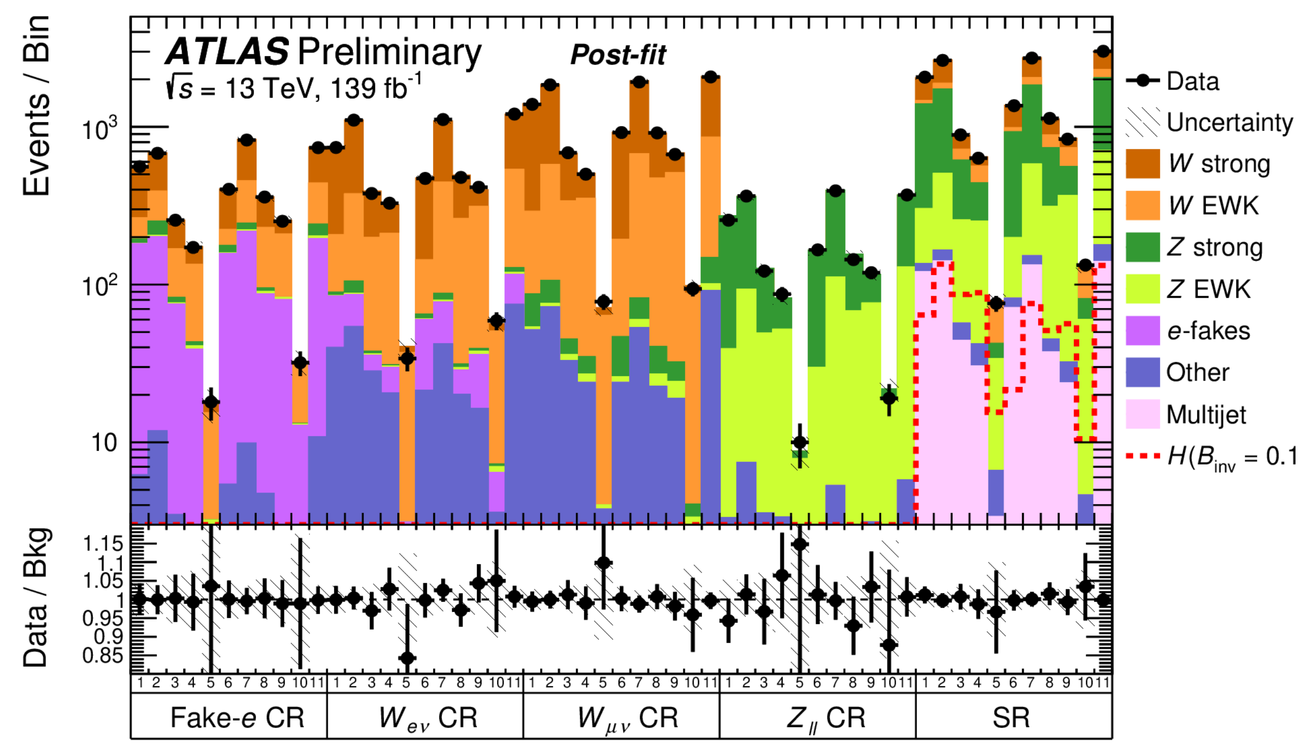


(d) Example diagram for the electroweak diboson process



- Selection: $p_T^{jet,1} > 80\,\text{GeV}, p_T^{jet,2} > 50\,\text{GeV}, p_T^{jet,3,4} > 25\,\text{GeV}$, $\eta^{j1}.\eta^{j2} < 0$ and $\Delta\eta_{jj} > 3.8$

- CRs enriched in $Z(ll) + jets$ and $W(l\nu) + jets$ are defined to constrain the MC normalization



- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL**

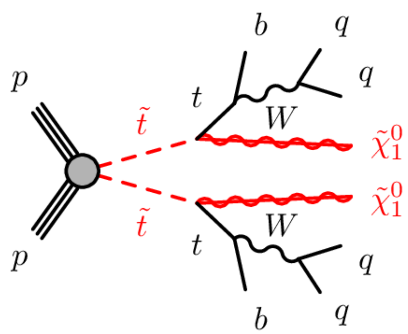
    $B(h \rightarrow invisible) : 0.13\,(0.13^{+0.05}_{-0.04})$

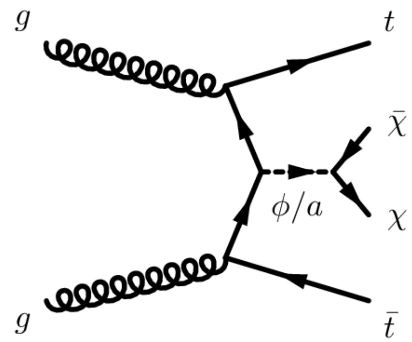
Search for $ttH \rightarrow invisible$

NEW

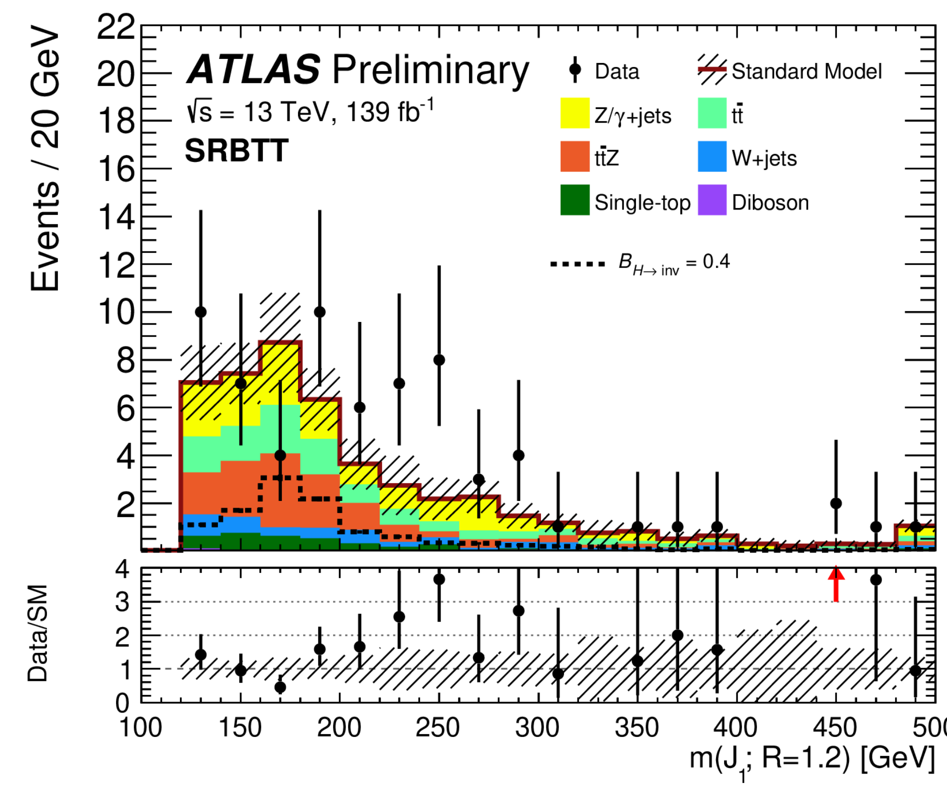
arXiv:2004.14060

ATLAS-CONF-2020-046

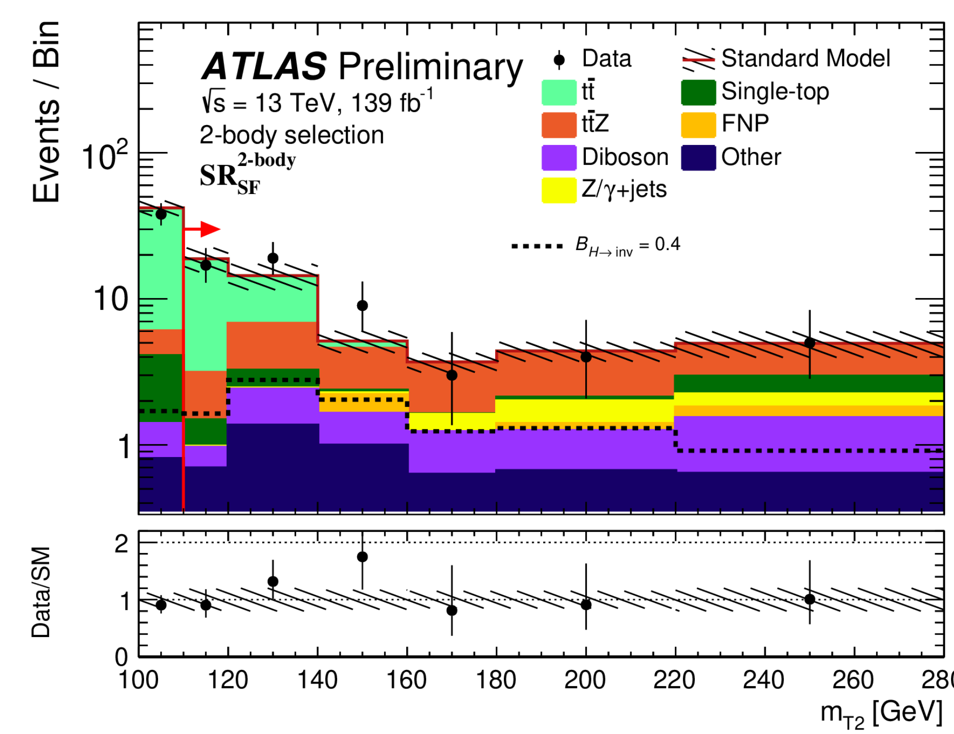




- **0-lepton final state:** # of b-tagged jets ≥ 2, $E_T^{miss} > 250\,\text{GeV}$, $m_2^{R=1.2} = [0, 60, 120, \infty]\,\text{GeV}$
- Backgrounds $Z+jets$, $W+jets$, $t\bar{t}Z$, $t\bar{t}$, and tW modeled with MC and constrained in CRs



- **2-lepton final state:** # of b-tagged jets ≥ 1, $E_T^{miss} - significance > 12$
- Backgrounds $t\bar{t}Z$, $t\bar{t}$ modeled with MC and constrained in CRs; fake lepton bkg. estimated in data-driven way



- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL**
    $B(h \rightarrow invisible) : 0.94\,(0.64^{+0.29}_{-0.19}),\ 0.37\,(0.42^{+0.19}_{-0.12})$ **for** $t\bar{t}H - 0l$, $t\bar{t}H - 2l$ **channels**

Search for $H \to invisible$ combination

NEW

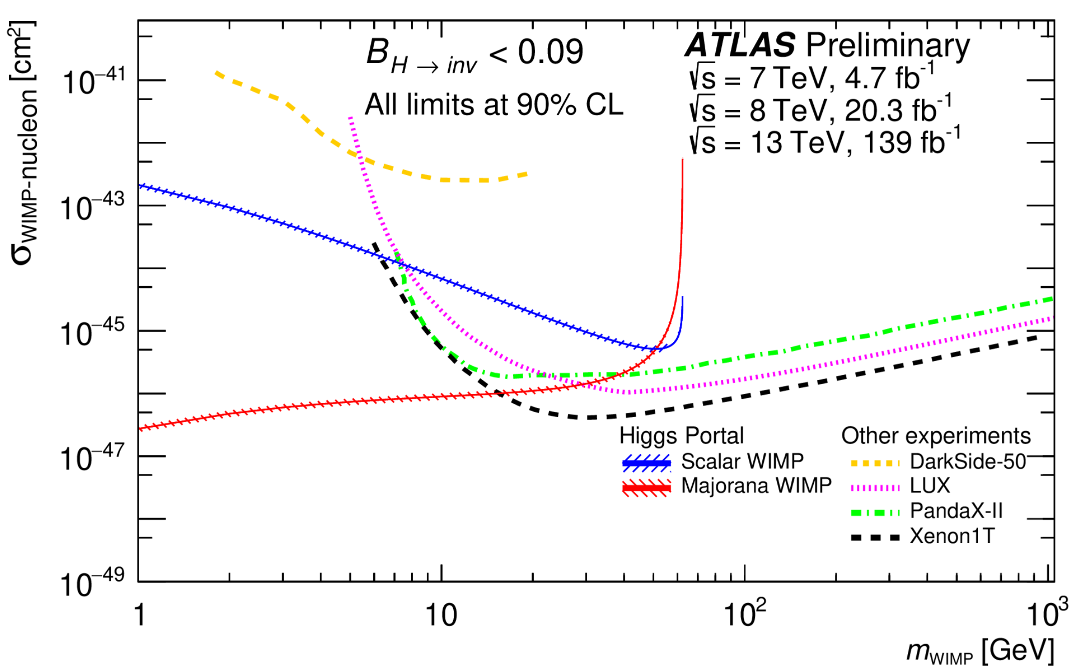
ATLAS-CONF-2020-052

- VBF $H \to inv$ and $ttH \to inv$ results from full Run 2 combined with Run 1 results to set the most stringent limit on $H \to inv$ to date
- No overlap between the events selected for the VBF and $t\bar{t}H$ topologies was found
- $t\bar{t}Z$-CR from the $t\bar{t}H-2\ell$ analysis is used to constrain the $t\bar{t}Z$ background in both channels

Analysis	$\sqrt{s}$ [TeV]	Int. luminosity [fb^{-1}]	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit	Reference
Run 2 VBF	13	139	$0.00^{+0.07}_{-0.07}$	0.13	$0.13^{+0.05}_{-0.04}$	[42]
Run 2 $t\bar{t}H$	13	139	$0.04^{+0.20}_{-0.20}$	0.40	$0.36^{+0.15}_{-0.10}$	This document
Run 2 Comb.	13	139	$0.00^{+0.06}_{-0.07}$	0.13	$0.12^{+0.05}_{-0.04}$	This document
Run 1 Comb.	7, 8	4.7, 20.3	$-0.02^{+0.14}_{-0.13}$	0.25	$0.27^{+0.10}_{-0.08}$	[36]
Run 1+2 Comb.	7, 8, 13	4.7, 20.3, 139	$0.00^{+0.06}_{-0.06}$	0.11	$0.11^{+0.04}_{-0.03}$	This document

- Previous Run 1+2 combination done by ATLAS has Observed (Expected) limits at 95% CL at $0.26\,(0.17^{+0.07}_{-0.05})$ - details in backup

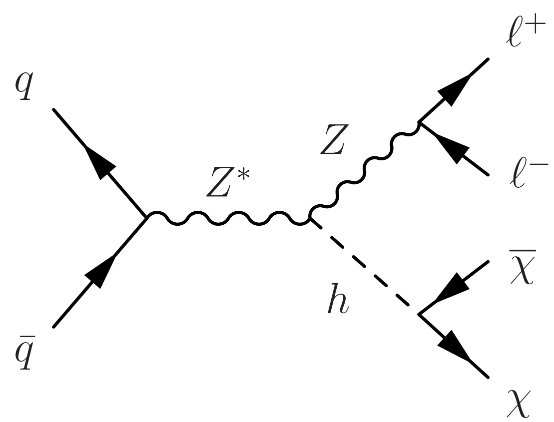
- Translation of the $H \to inv$ result into σ_{WIMP-N} relies on an effective field theory approach; Nuclear form factor $f_N = 0.308 \pm 0.018$ is used

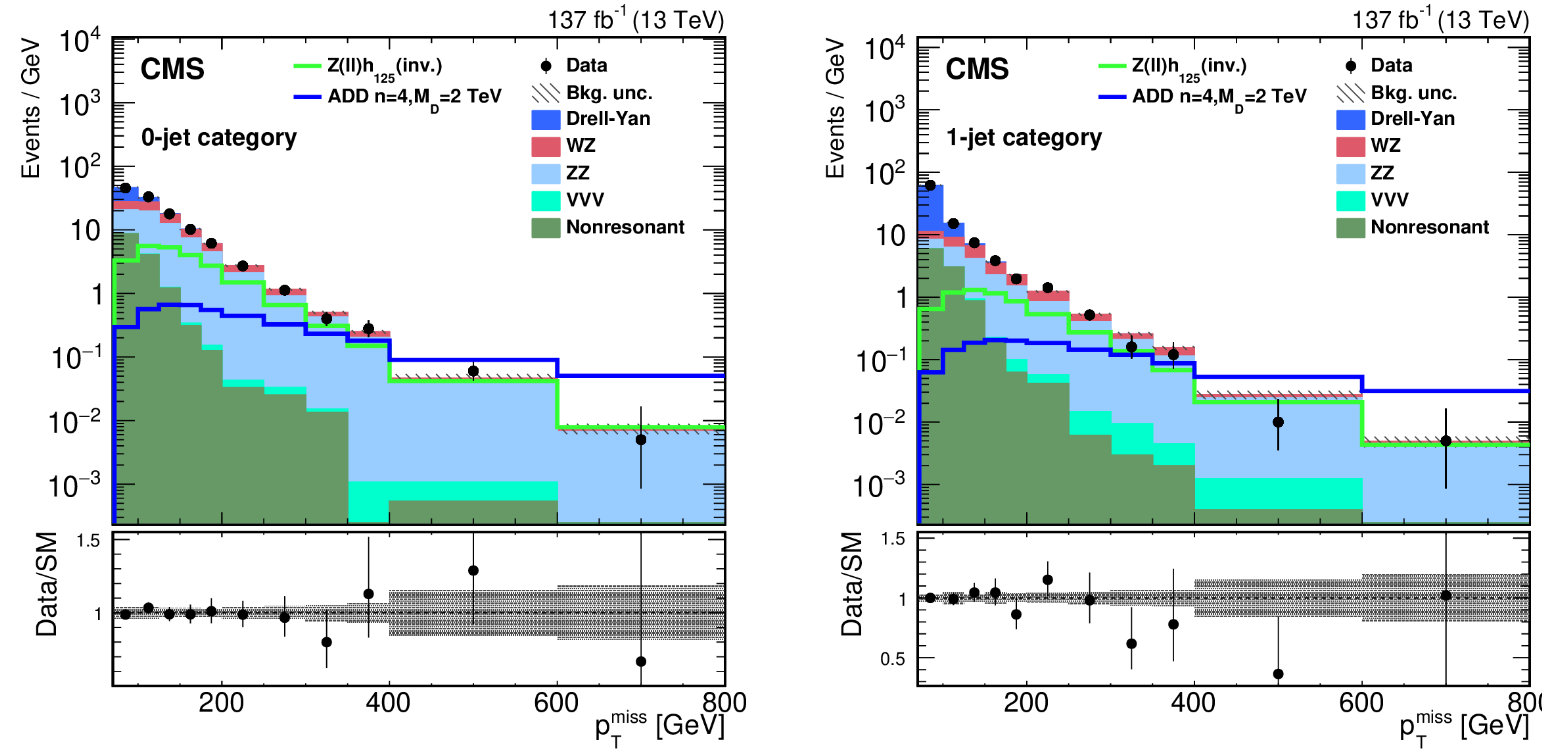


Search for $ZH \rightarrow invisible$

NEW

arXiv:2008.04735





- "Higgs portal" model: If $m_\chi < m_h/2$, the Higgs boson could decay invisibly into a pair of DM particles

- Selections: ⟶

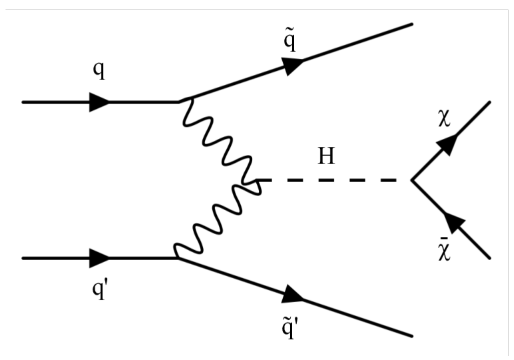
Quantity	Requirement	Target backgrounds
N_ℓ	=2 with additional lepton veto	WZ, VVV
p_T^ℓ	>25/20 GeV for leading/subleading	Multijet
Dilepton mass	$\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV	WW, top quark
Number of jets	≤ 1 jet with $p_T^j > 30$ GeV	DY, top quark, VVV
$p_T^{\ell\ell}$	>60 GeV	DY
b tagging veto	0 b-tagged jet with $p_T > 30$ GeV	Top quark, VVV
τ lepton veto	0 τ_h cand. with $p_T^\tau > 18$ GeV	WZ
$\Delta\phi(\vec{p}_T^{\,j}, \vec{p}_T^{\,miss})$	>0.5 radians	DY, WZ
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,miss})$	>2.6 radians	DY
$\lvert p_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell}$	<0.4	DY
$\Delta R_{\ell\ell}$	<1.8	WW, top quark
p_T^{miss} (all but 2HDM+a)	>100 GeV	DY, WW, top quark

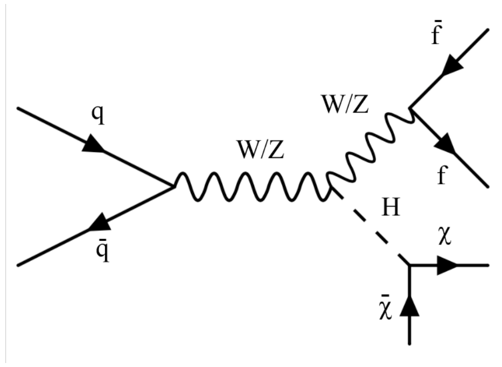
- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL**

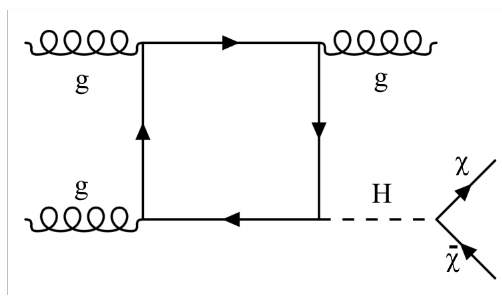
    $B(h \rightarrow invisible): 0.29\,(0.25^{+0.09}_{-0.07})$

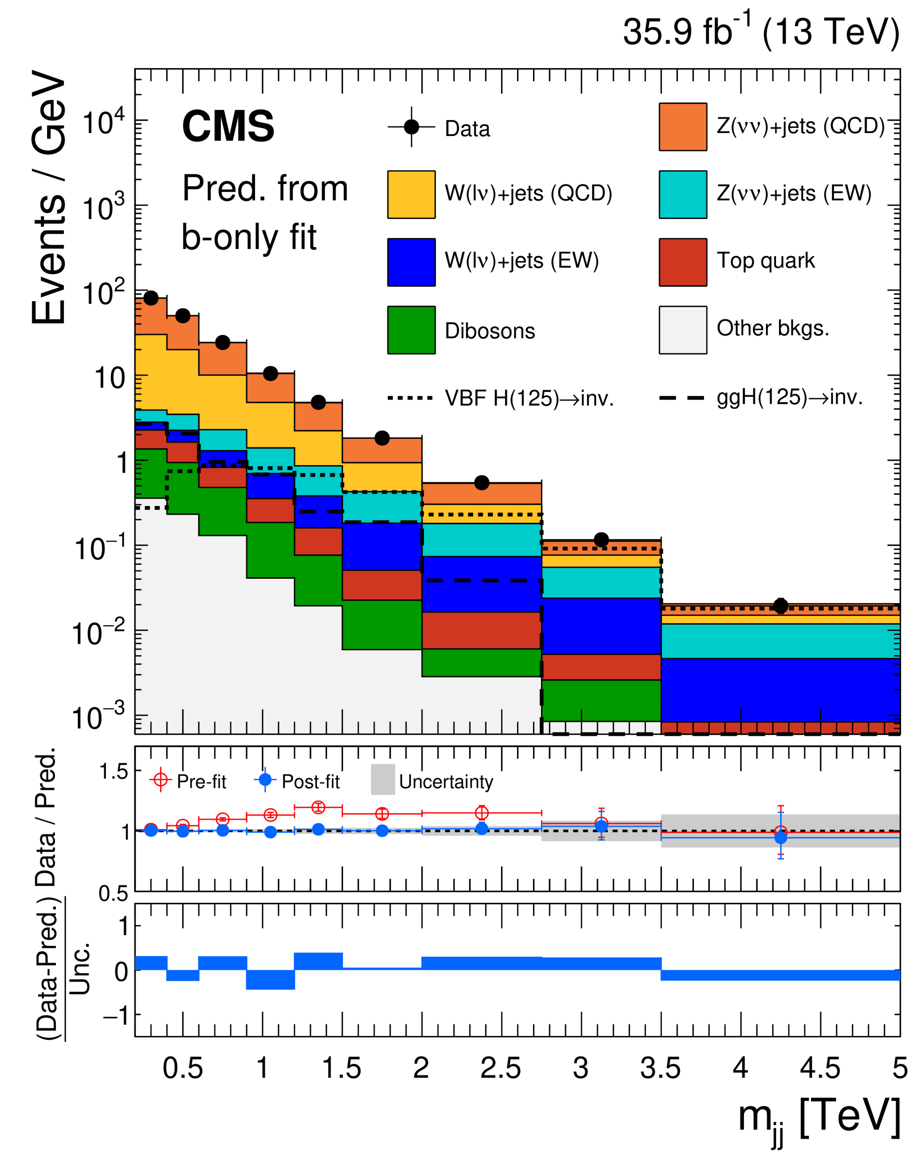
Search for $H \to invisible$ combination

arXiv:1712.07173

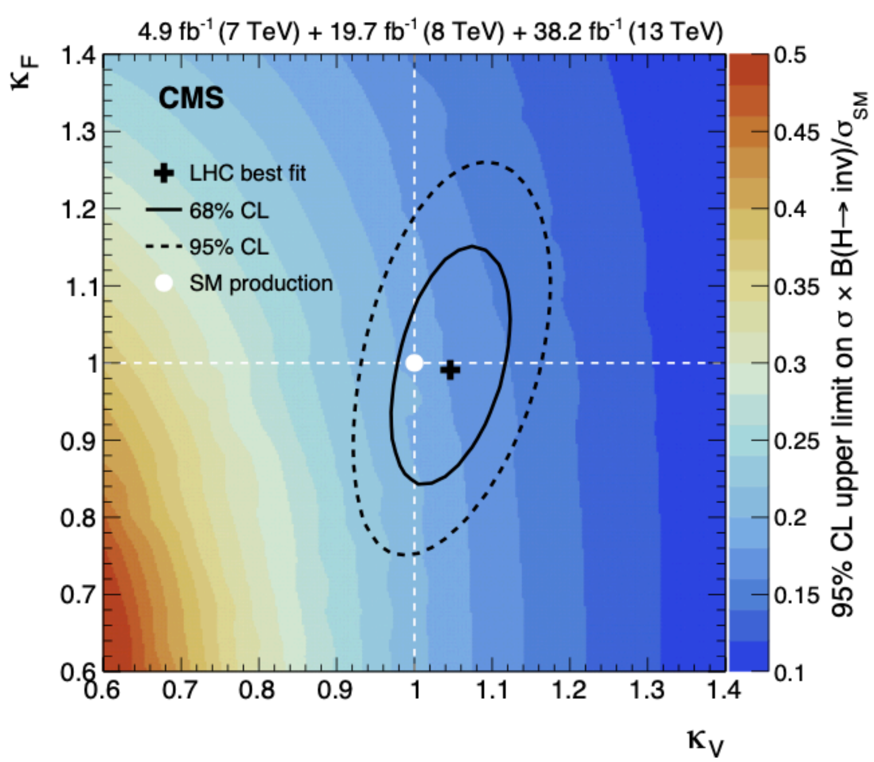


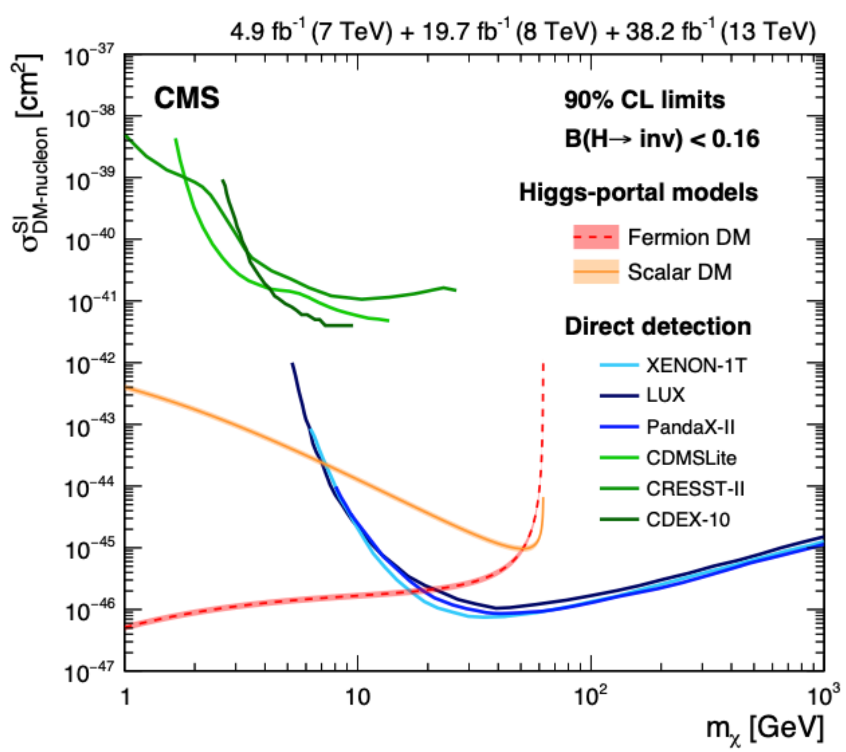






- Current analysis exploits the distinctive kinematic features of the VBF topology by fitting the shape of the m_{jj} distribution





- **Results:**
  - **Observed (Expected) Upper Limits at 95% CL**

    $B(h \to invisible) : 0.19\,(0.15^{+0.04}_{-0.04})$

Summary

- Search for $H \to Z\rho/Z\phi$ performed with full Run 2 data at CMS
- $H \to J/\psi\gamma$ and $H \to J/\psi\gamma, \psi(2S)\gamma, \Upsilon(nS)\gamma$ have been performed with 2016 data at CMS and ATLAS

- Search for $H \to Z\gamma$ performed with full Run 2 data at ATLAS and with 2016 data at CMS
- Full Run 2 results from CMS are currently in the approval process

- $H \to ee$ search performed with full Run 2 data at ATLAS along with search for LFV $H \to e\mu$
- Both CMS and ATLAS have performed LFV $H \to \mu\tau/e\tau$ searches using the 2016 dataset
- Full Run 2 results from CMS are currently in the approval process

- Some full Run 2 $H \to invisible$ results are published with others soon to be published
- Both CMS and ATLAS have performed the $H \to invisible$ search using the 2016 dataset and their corresponding combination with Run 1 results have been presented

- **Available parameter space for new physics dramatically reduced after Run 2 of the LHC**

Backup

Search for $H \to Z\rho/Z\phi$

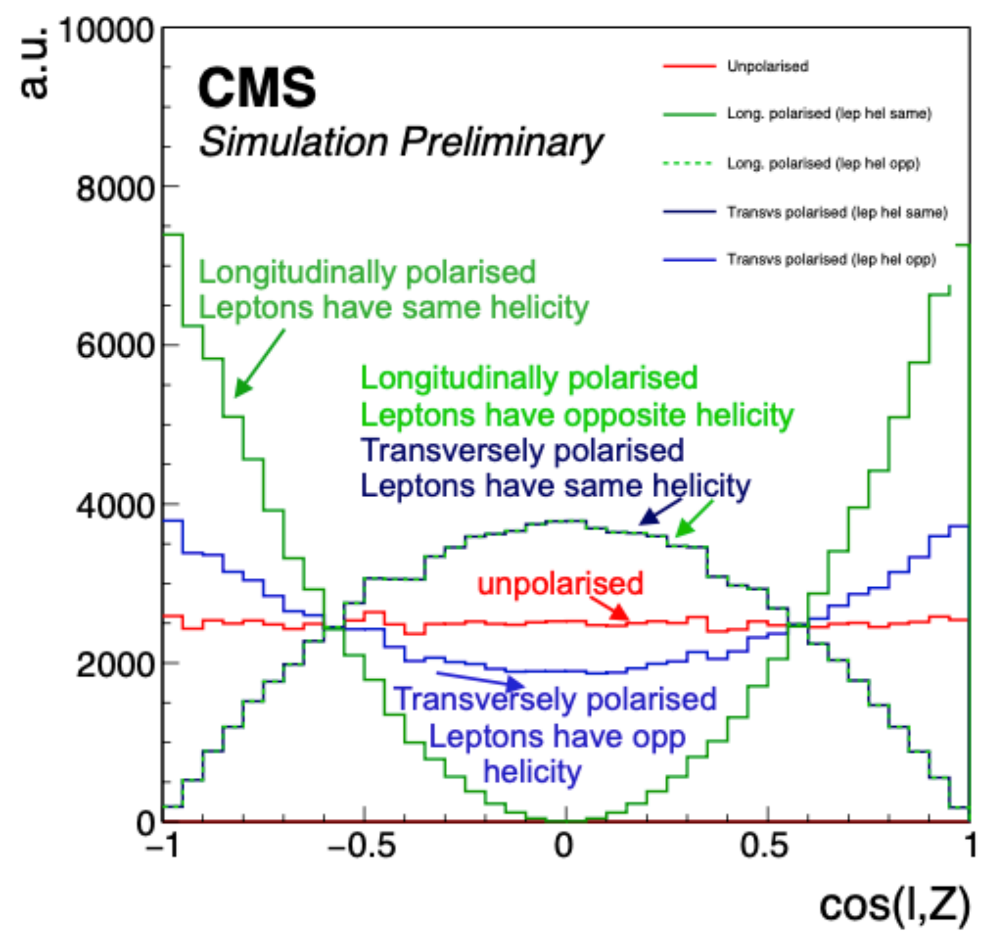
- In SM: $B(H \to Z\rho) = (1.4 \pm 0.08) \times 10^{-5}$ and $B(H \to Z\phi) = (4.2 \pm 0.25) \times 10^{-6}$

- **The direct process is negligible, but significantly enhanced light quark Yukawa couplings would increase the prevalence of it**

- Meson candidate reconstructed using high-purity tracks; Not overlapping with the leptons; Select the pair with highest p_T $\to$ maximizes correct selection of meson candidates

- Signal events generated with POWHEG, with $H \to Z\rho/Z\phi$ modeled with PYTHIA → isotropic modeling of decay even though polarization does play a role

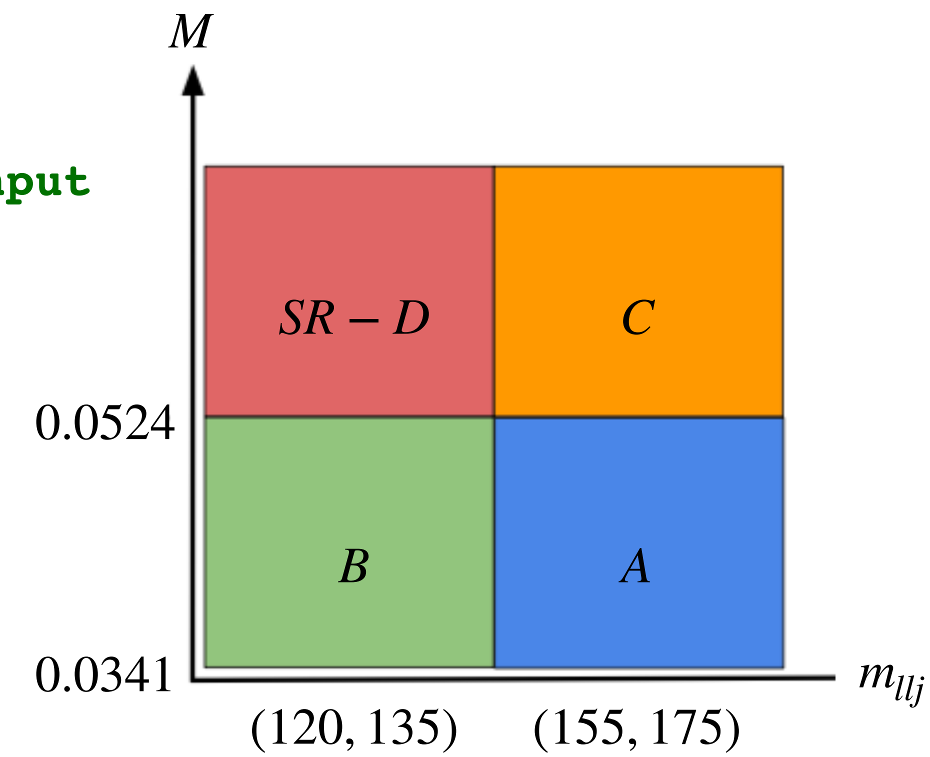
- Calculate angular distributions in limit of extreme polarization scenarios: **(longitudinally polarized, transversely polarized) x (leptons same helicity, opposite helicity)**



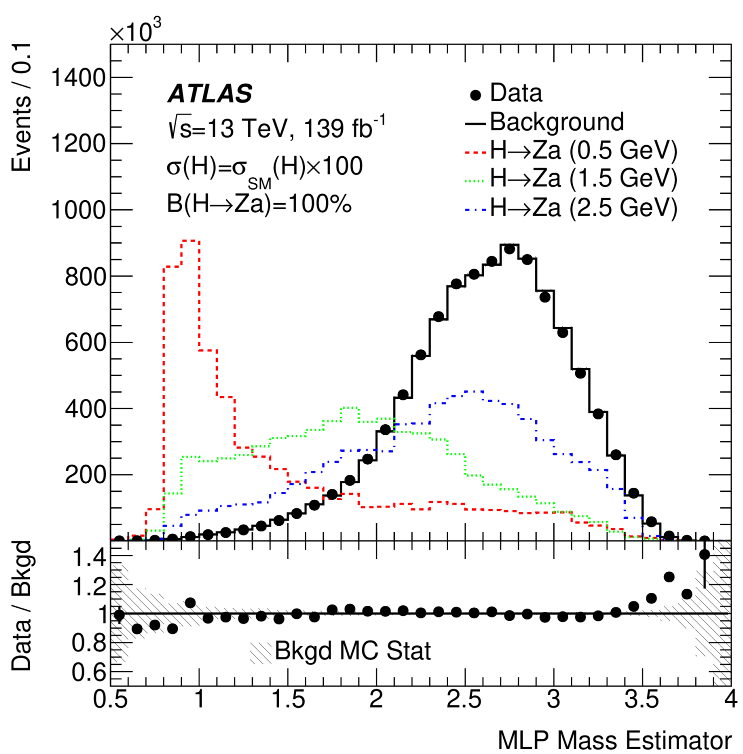
Search for $H \to Z\eta_c / ZJ/\psi / Za$

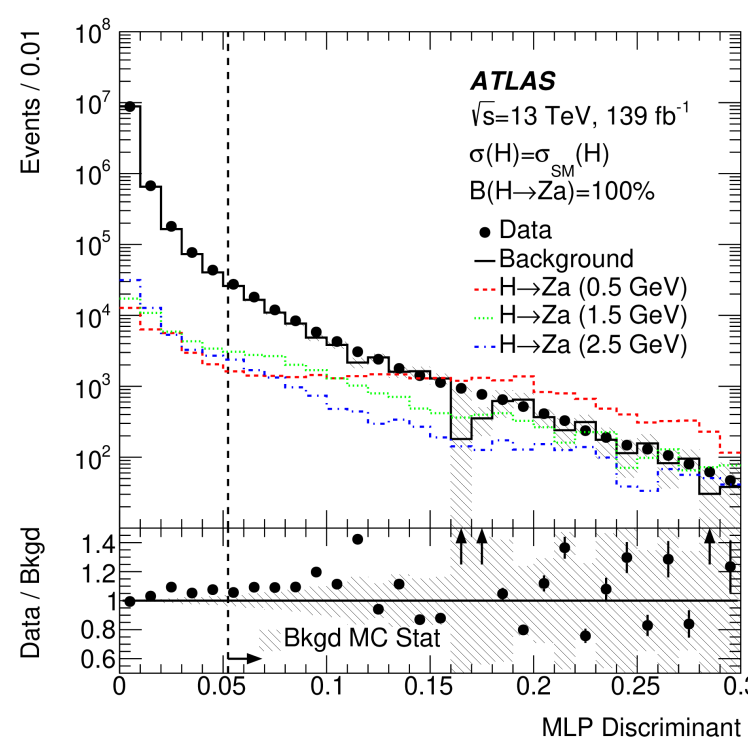
- In SM, $B(H \to Z\eta_c) = 1.4 \times 10^{-5}$ and $B(H \to ZJ/\psi) = 2.2 \times 10^{-6}$

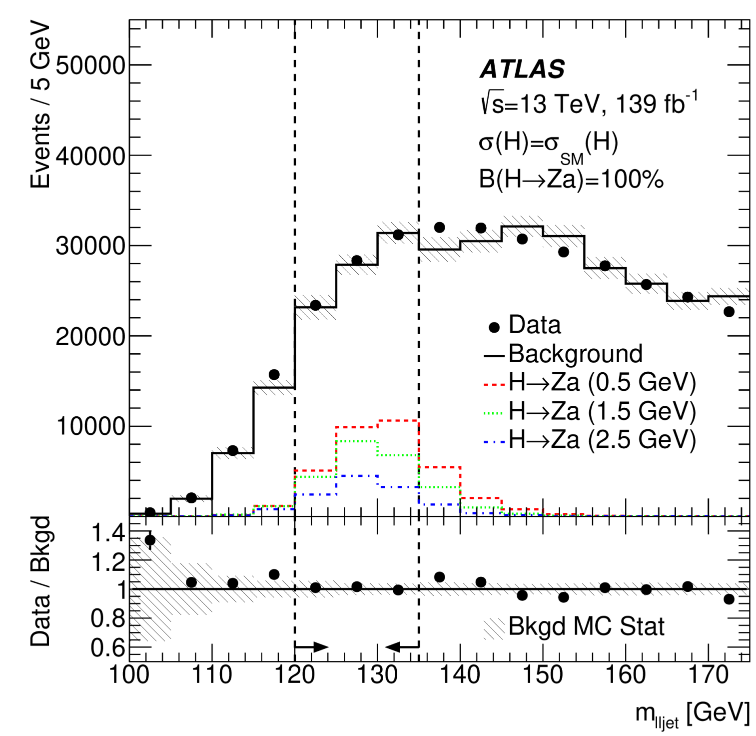
arXiv:2004.01678



- Selection:
  - **Regression MLP to estimate the mass of ‘a’; This is input to a classification MLP**
- **Results:**
  - **95% CL Upper Limits on** $\sigma(pp \to H)B(H \to Z(Q/a))$:
  - $110\,(100^{+40}_{-30})$ pb **and** $100\,(100^{+40}_{-30})$ pb **for** $H \to Z\eta_c$ **and** $H \to ZJ/\psi$
  - $17 - 340\,(16^{+6}_{-5} - 320^{+130}_{-90})$ pb **for the** $H \to Za$ **signal hypotheses**





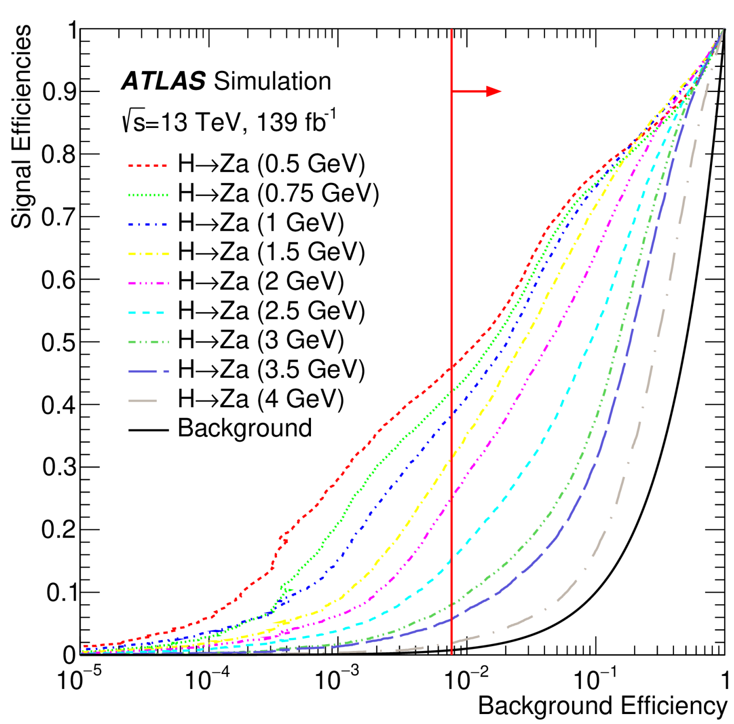


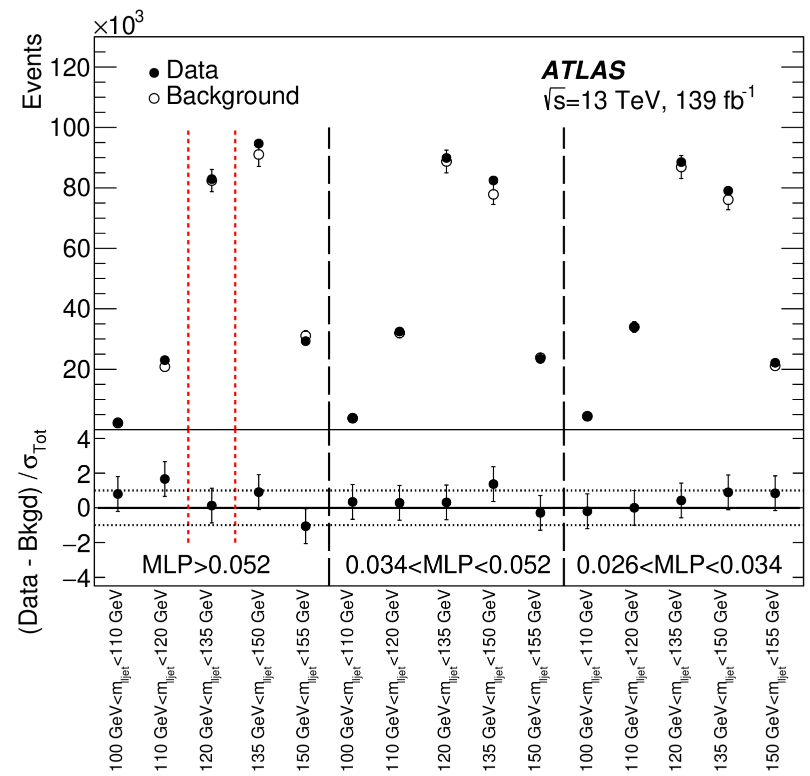
Search for $H \to Z\eta_c / ZJ/\psi / Za$

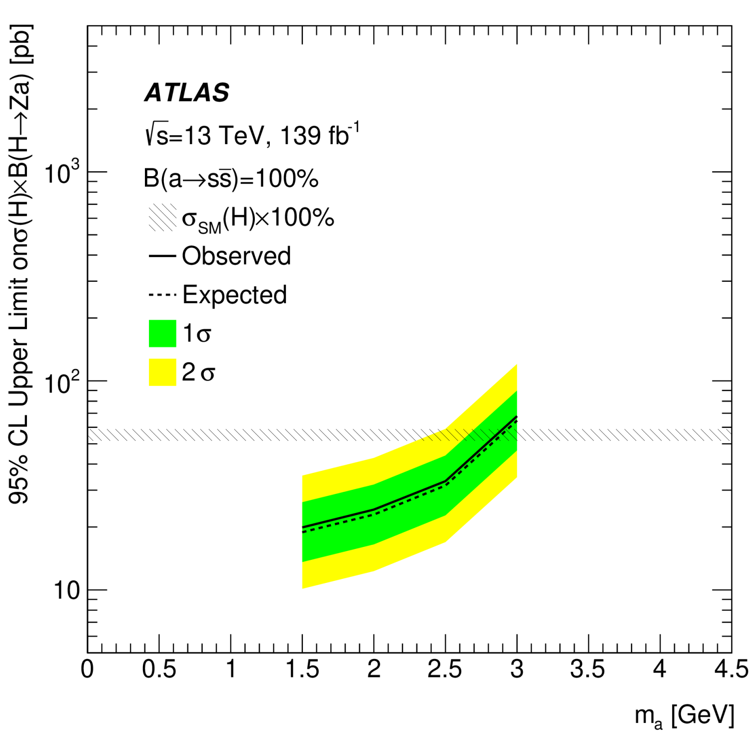
- MLP input variables are built using tracks matched by ghost-association to the calorimeter jet and their angles from the jet axis, in order to benefit from the high resolution of the tracking detector

- **These variables primarily capitalize on the presence of a narrow resonance, or two-pronged substructure in the track system**

- An initial data-driven background estimate in the SR is calculated as D = BC/A, then MC samples, reweighted to match data, are used to correct this estimate for the 13% correlation between the m_{llj} and M variables



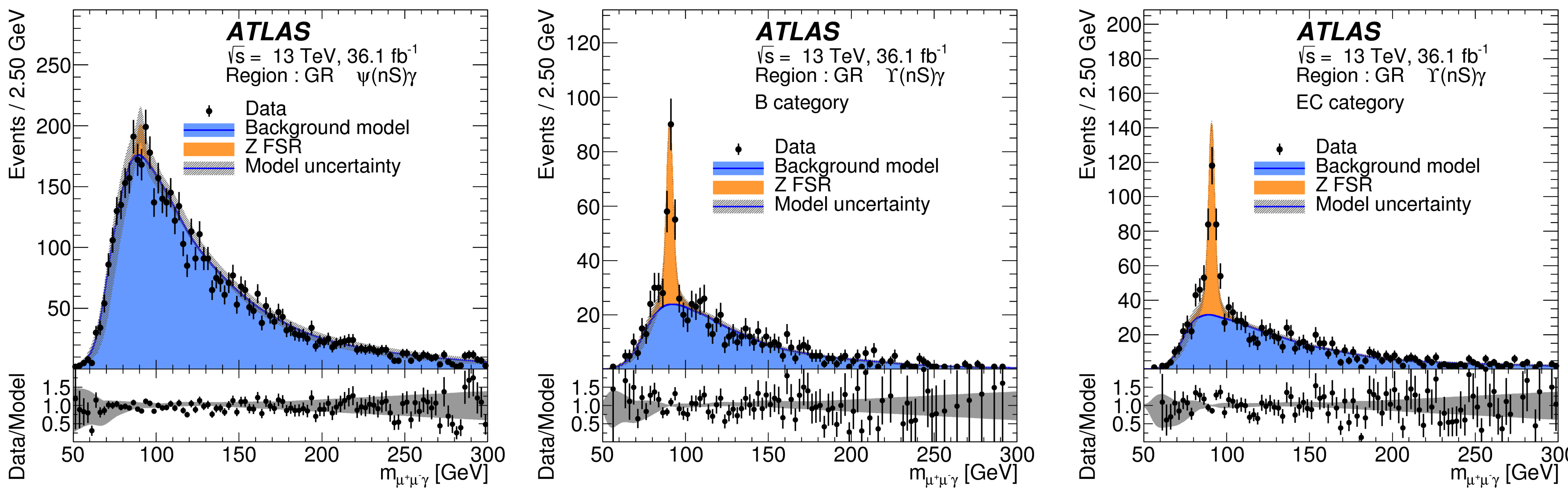




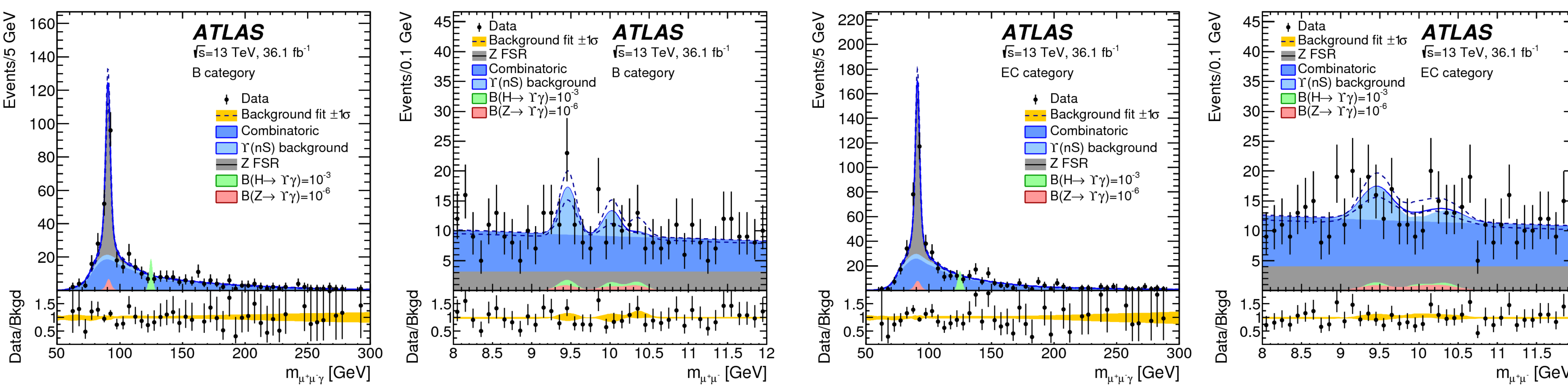
Search for $H \to J/\psi\gamma, \psi(2S)\gamma, \Upsilon(nS)\gamma$

- In SM, $B(H \to J/\psi\gamma) = 2.99 \times 10^{-6}$, $B(H \to \psi(2S)\gamma) = 1.03 \times 10^{-6}$, $B(H \to \Upsilon(nS)\gamma) = (5.22, 1.42, 0.91) \times 10^{-9}$ for (n = 1, 2, 3)

Generation Region



Signal Region

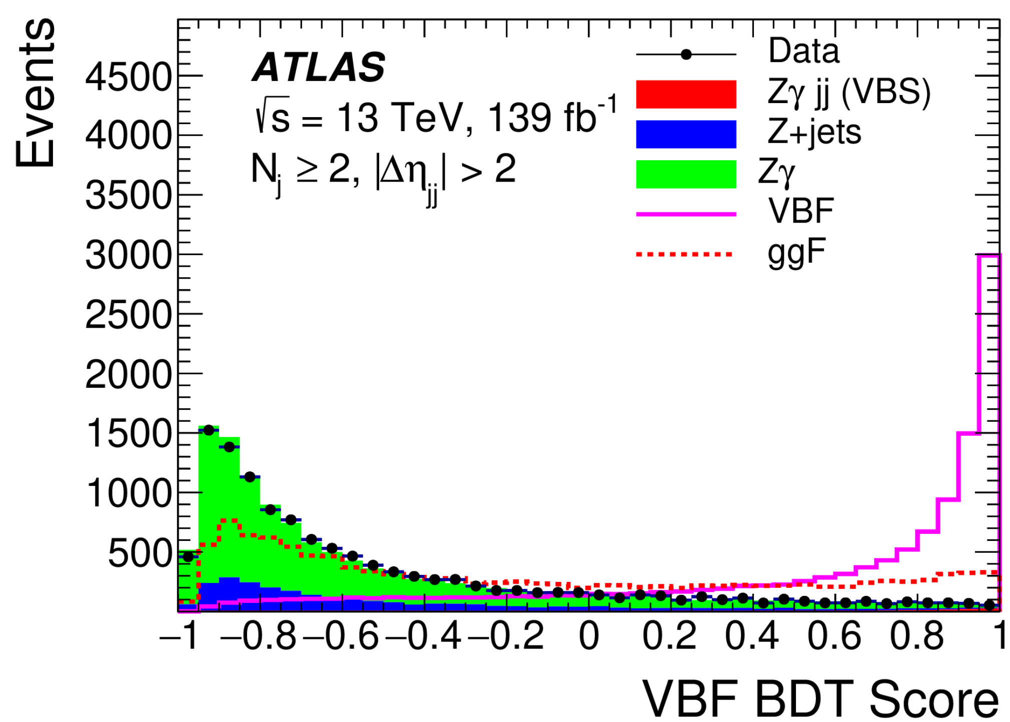


Categorize: "Barrel" if $|\eta^{\mu}_{1,2}| < 1.05$ else "Endcap"

Search for $H \to Z\gamma$

- Background: Non-resonant production of a Z boson and a photon + production of Z bosons in association with jets, with one jet misidentified as a photon

- Selection:
  - Photon candidates within $\Delta R = 0.3$ cone around the leptons are rejected to suppress FSR
  - Resolution of invariant mass of $Z \to \mu\mu$ candidates is improved by 3% by correcting muon momenta for collinear **FSR** $\Delta R < 0.15$, using all photons identified in EM calorimeter
  - **Constrained kinematic fit:** Applied to dilepton invariant mass for all Z boson candidates uses a line shape modeled by a Breit-Wigner distribution and a single Gaussian to model lepton momentum response



- Categorization:
  - VBF-enriched category: BDT score > 0.87
  - High relative p_T: $p_T^{\gamma}/m_{Z\gamma} > 0.4$
  - $P_{Tt} = 40\,\mathrm{GeV}$ threshold used for other categories,

$$p_{Tt} = |\vec{p}_T^{\,Z\gamma} \times \hat{t}\,|,\ \hat{t} = \left(\vec{p}_{\mathrm{T}}^{\,Z} - \vec{p}_{\mathrm{T}}^{\,\gamma}\right) / \left|\vec{p}_{\mathrm{T}}^{\,Z} - \vec{p}_{\mathrm{T}}^{\,\gamma}\right|$$

Search for $H \to Z\gamma/\gamma^*\gamma$

CMS

- In SM: $\mathscr{B}(\mathrm{H} \to \gamma^*\gamma) = (1.69 \pm 0.10)\,\%$ and $\mathscr{B}(\mathrm{H} \to \mathrm{Z}\gamma) = (2.27 \pm 0.14)\,\%$ w.r.t. $\mathscr{B}(\mathrm{H} \to \gamma\gamma)$

- Selection $H \to Z\gamma$:
  - $M_{ll} > 50\,\mathrm{GeV}$ with $M_{ll\gamma} + M_{ll} > 185\,\mathrm{GeV}$ to **reject events with FSR from DY processes**
  - $E_T > 0.14 m_{ll\gamma}$ **rejects the Z+jets background**
  - Di-jet event selection: $|\eta_{j1} - \eta_{j2}| > 3.5$, $\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2 < 2.5$, $M_{j1j2} > 500\,\mathrm{GeV}$, $\Delta\phi_{j1j2-Z\gamma} > 2.4$

- Selection $H \to \gamma^*\gamma$:
  - $M_{\mu\mu} < 50\,\mathrm{GeV}$, Reject J/ψ: $2.9 < M_{\mu\mu} < 3.3\,\mathrm{GeV}$ and Υ: $9.3 < M_{\mu\mu} < 9.7\,\mathrm{GeV}$
  - $p_T^{\gamma}/M_{\mu\mu\gamma} > 0.3$, $p_T^{\mu\mu}/M_{\mu\mu\gamma} > 0.3$ rejects the $\gamma*$+*jet* and $\gamma+$*jet* backgrounds
  - $\Delta R > 1$ to suppress DY background events with FSR

Category	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
Lepton tag	Additional electron ($p_T > 7\,\mathrm{GeV}$) or muon ($p_T > 5\,\mathrm{GeV}$)	
Dijet tag	At least 2 jets required dijet selection	At least 2 jets required dijet selection
Boosted	$p_T(ee\gamma) > 60\,\mathrm{GeV}$	$p_T(\mu\mu\gamma) > 60\,\mathrm{GeV}$
Untagged 1	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 > 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 > 0.94$
Untagged 2	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 < 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 < 0.94$
Untagged 3	Photon $0 < \|\eta\| < 1.4442$ At least one lepton $1.4442 < \|\eta\| < 2.5$ No requirement on R_9	Photon $0 < \|\eta\| < 1.4442$ Both leptons in $\|\eta\| > 0.9$ or one lepton in $2.1 < \|\eta\| < 2.4$ No requirement on R_9
Untagged 4	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.5$ No requirement on R_9	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.4$ No requirement on R_9

Search for LFV $H \to \mu\tau/e\tau$

ATLAS

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly $1e$ and 1μ, OS	exactly 1ℓ and $1\tau_{\text{had-vis}}$, OS
	$p_{\text{T}}^{\ell_1} > 45$ GeV	$p_{\text{T}}^{\ell} > 27.3$ GeV
	$p_{\text{T}}^{\ell_2} > 15$ GeV	$p_{\text{T}}^{\tau_{\text{had-vis}}} > 25$ GeV, $\lvert\eta^{\tau_{\text{had-vis}}}\rvert < 2.4$
	$30\ \text{GeV} < m_{\text{vis}} < 150$ GeV	$\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_{\text{T}}^{\text{miss}}) > -0.35$
	$p_{\text{T}}^{e}(\text{track})/p_{\text{T}}^{e}(\text{cluster}) < 1.2$ ($\mu\tau_e$ only)	$\lvert\Delta\eta(\ell, \tau_{\text{had-vis}})\rvert < 2$
	b-veto (for jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.4$)	
VBF	Baseline	
	≥ 2 jets, $p_{\text{T}}^{j_1} > 40$ GeV, $p_{\text{T}}^{j_2} > 30$ GeV	
	$\lvert\Delta\eta(j_1, j_2)\rvert > 3$, $m(j_1, j_2) > 400$ GeV	
	–	$p_{\text{T}}^{\tau_{\text{had-vis}}} > 45$ GeV
Non-VBF	Baseline plus fail VBF categorization	
	$m_{\text{T}}(\ell_1, E_{\text{T}}^{\text{miss}}) > 50$ GeV	–
	$m_{\text{T}}(\ell_2, E_{\text{T}}^{\text{miss}}) < 40$ GeV	–
	$\lvert\Delta\phi(\ell_2, E_{\text{T}}^{\text{miss}})\rvert < 1.0$	–
	$p_{\text{T}}^{\tau}/p_{\text{T}}^{\ell_1} > 0.5$	–
Top-quark CR	inverted b-veto:	
VBF and non-VBF	≥ 1 b-tagged jet ($p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.4$)	
$Z \to \tau\tau$ CR	inverted $p_{\text{T}}^{\ell_1}$ requirement:	
VBF and non-VBF	$35\ \text{GeV} < p_{\text{T}}^{\ell_1} < 45$ GeV	

Search for LFV $H \to \mu\tau/e\tau$

CMS

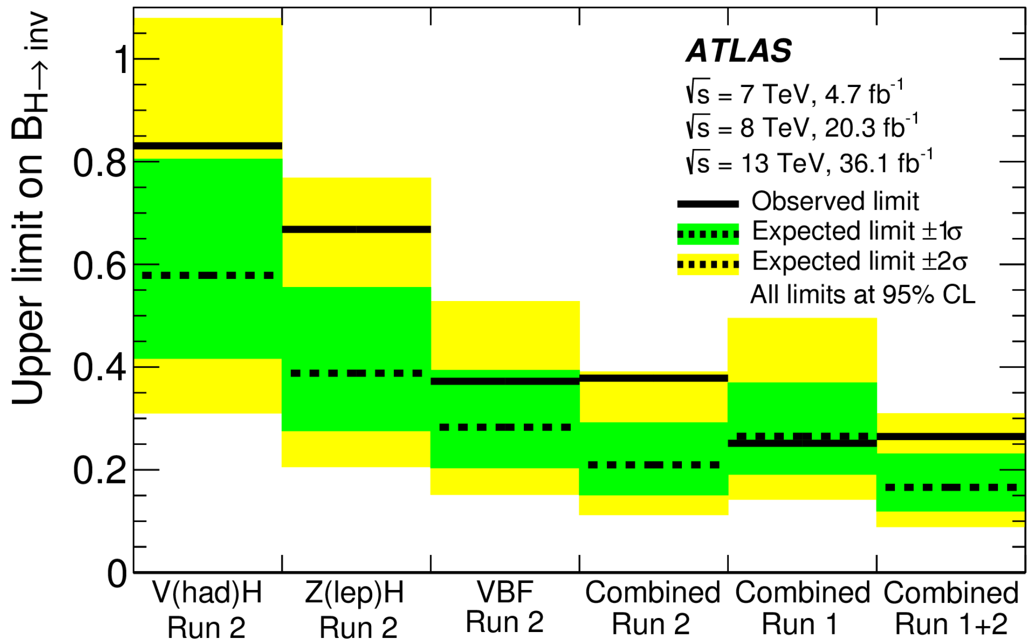
Variable		$H \to \mu\tau_h$				$H \to \mu\tau_e$			
		0 jet	1 jet	2 jet		0 jet	1 jet	2 jet	
				ggH	VBF			ggH	VBF
M_{jj}	[GeV]	—	—	<550	≥550	—	—	<550	≥550
p_T^e	[GeV]	—				>10			
p_T^μ	[GeV]	>26				>26			
$p_T^{\tau_h}$	[GeV]	>30				—			
$\lvert\eta^e\rvert$		—				<2.4			
$\lvert\eta^\mu\rvert$		<2.4				<2.4			
$\lvert\eta^{\tau_h}\rvert$		<2.3				—			
I_{rel}^e		—				<0.1			
I_{rel}^μ		<0.15				<0.15			
M_{col} fit selection									
p_T^μ	[GeV]	—				>30	—	—-	—
$M_T(\mu)$	[GeV]	—				>60	>40	>15	>15
$M_T(\tau_h)$	[GeV]	<105	<105	<105	<85	—			
$\Delta\phi(e, \vec{p}_T^{miss})$	[radians]	—				<0.7	<0.7	<0.5	<0.3
$\Delta\phi(e, \mu)$	[radians]	—				>2.5	>1.0	—	—

Variable		$H \to e\tau_h$				$H \to e\tau_\mu$			
		0 jet	1 jet	2 jet		0 jet	1 jet	2 jet	
				ggH	VBF			ggH	VBF
M_{jj}	[GeV]	—	—	<500	>500	—	—	<500	>500
p_T^e	[GeV]	>26				>24			
p_T^μ	[GeV]	—				>10			
$p_T^{\tau_h}$	[GeV]	>30				—			
$\lvert\eta^e\rvert$		<2.1				<2.1			
$\lvert\eta^\mu\rvert$		—				<2.4			
$\lvert\eta^{\tau_h}\rvert$		<2.3				—			
I_{rel}^e		<0.15				<0.1			
I_{rel}^μ		—				<0.1			
M_{col} fit selection									
$M_T(\tau_h)$	[GeV]	<60				—			
$M_T(e)$	[GeV]	—				>60			
$\Delta\phi(e, \vec{p}_T^{miss})$	[radians]	—				<1.0			
$p_\zeta - 0.85\, p_\zeta^{vis}$	[GeV]	—				> − 60			

Search for $H \rightarrow invisible$ combination

arXiv:1904.05105

- Overview of Run 2 searches:
  - **VBF topology:** $E_T^{miss} > 180\,\mathrm{GeV}$, $|\Delta\eta_{jj}| > 4.8$, Final discriminant is # of events in 3 m_{jj} regions (1, 1.5, 2, ∞) TeV
  - **Z(lep)H topology:** $E_T^{miss} > 90\,\mathrm{GeV}$, $E_T^{miss}/H_T > 0.6$, Dilepton back-to-back to E_T^{miss}; Final discriminant is E_T^{miss}
  - **V(had)H topology:** $E_T^{miss} > 250\,\mathrm{GeV}$ and $\geq 1\,\mathrm{jet}$ (R=1.0) or $E_T^{miss} > 150\,\mathrm{GeV}$ and ≥ 2 jets (R=0.4); Categorize: $70 \leq m_J, m_{jj}/\mathrm{GeV} \leq 100$ for VH and $100 \leq m_J, m_{jj}/\mathrm{GeV} \leq 250$ for ggH and VBF

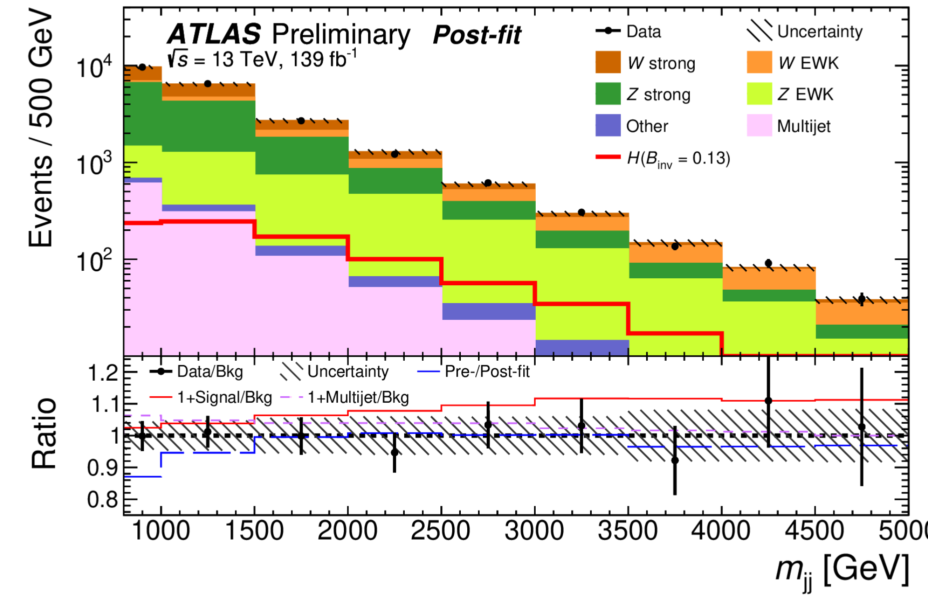


Analysis	$\sqrt{s}$	Int. luminosity	Observed	Expected	p_{SM}-value	Reference
Run 2 VBF	13 TeV	36.1 fb^{-1}	0.37	$0.28^{+0.11}_{-0.08}$	0.19	[36]
Run 2 Z(lep)H	13 TeV	36.1 fb^{-1}	0.67	$0.39^{+0.17}_{-0.11}$	0.06	[37]
Run 2 V(had)H	13 TeV	36.1 fb^{-1}	0.83	$0.58^{+0.23}_{-0.16}$	0.12	[38]
Run 2 Comb.	13 TeV	36.1 fb^{-1}	0.38	$0.21^{+0.08}_{-0.06}$	0.03	this Letter
Run 1 Comb.	7, 8 TeV	4.7, 20.3 fb^{-1}	0.25	$0.27^{+0.10}_{-0.08}$	—	[35]
Run 1+2 Comb.	7, 8, 13 TeV	4.7, 20.3, 36.1 fb^{-1}	0.26	$0.17^{+0.07}_{-0.05}$	0.10	this Letter

Search for VBF $H \rightarrow invisible$

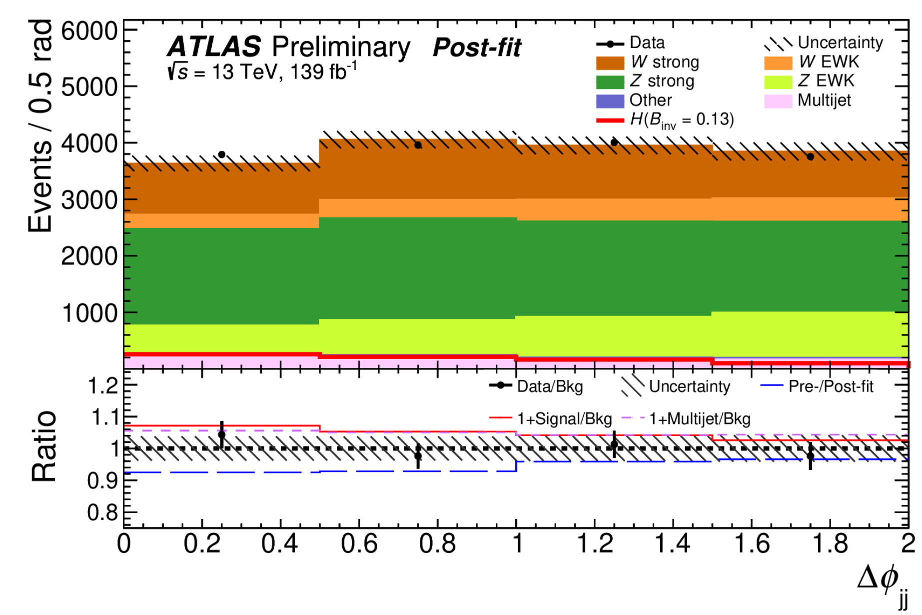
ATLAS-CONF-2020-008

- **There is complementarity between the direct searches for invisible Higgs decays and the indirect constraints from the visible decays**



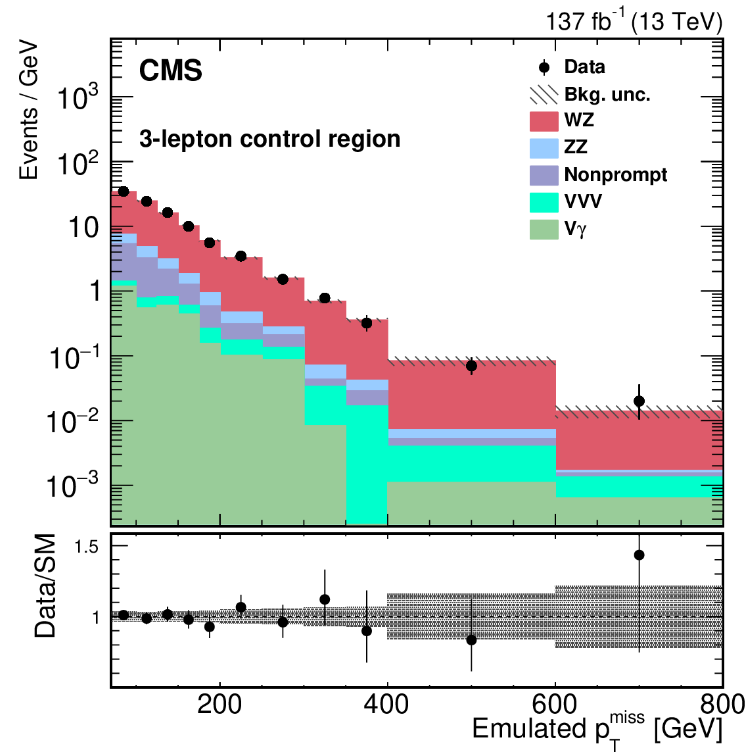
- Selection:
  - To enrich the contribution from multi-jet events with a $fake_e$ in the one electron CR $S_{\mathrm{MET}} = \dfrac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sqrt{p_{\mathrm{T}}^{\mathrm{j1}} + p_{\mathrm{T}}^{\mathrm{j2}} + p_{\mathrm{T}}^{e}}}$
  - No lepton candidate, nor a photon
  - $E_T^{miss} > 200\,\mathrm{GeV}$ and $H_T^{miss} > 180\,\mathrm{GeV}$
  - Soft track term of the $E_T^{miss} < 20\,\mathrm{GeV}$
  - $C_i < 0.6$ and $m_i^{rel} < 0.05$ for the additional jets, where Centrality C_i of extra jet is

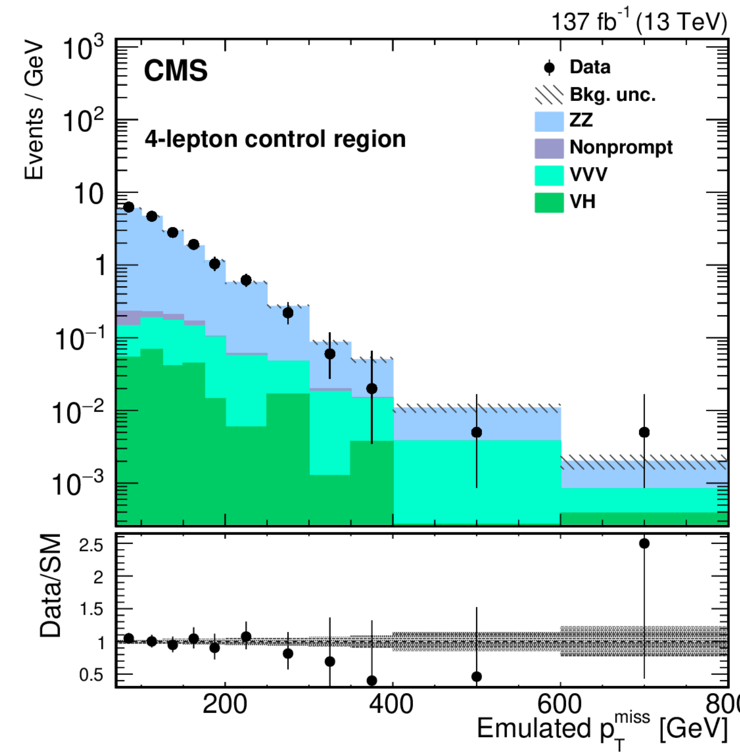
$$C_i = \exp\left(-\frac{4}{(\eta^{\mathrm{j1}} - \eta^{\mathrm{j2}})^2}\left(\eta^i - \frac{\eta^{\mathrm{j1}} + \eta^{\mathrm{j2}}}{2}\right)^2\right)$$ and invariant mass of the extra jet $m_i^{\mathrm{rel}} = \dfrac{\min\left\{m_{\mathrm{j1},i}, m_{\mathrm{j2},i}\right\}}{m_{\mathrm{jj}}}$

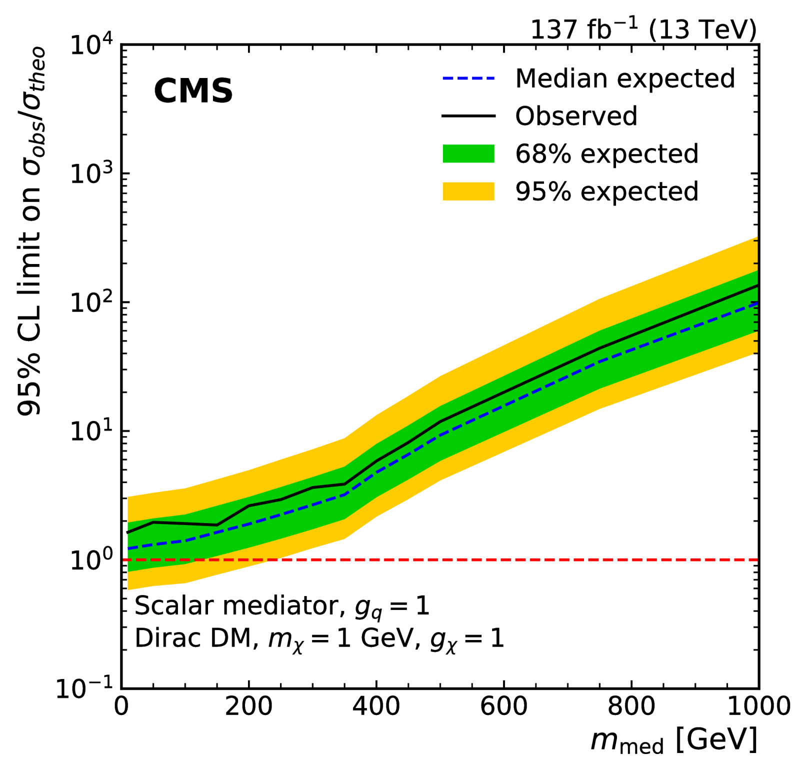


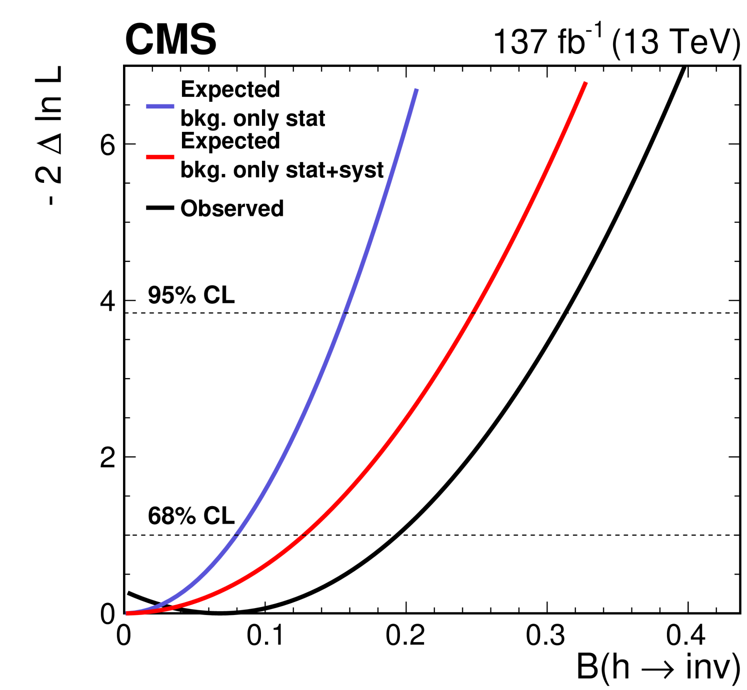
Search for $ZH \rightarrow invisible$

- To simulate the consequences of not detecting the third lepton, the "emulated p_T^{miss}" is estimated from the vectorial sum of p_T^{miss} and the transverse momentum of the additional lepton/s (in three-lepton and four-lepton control regions)



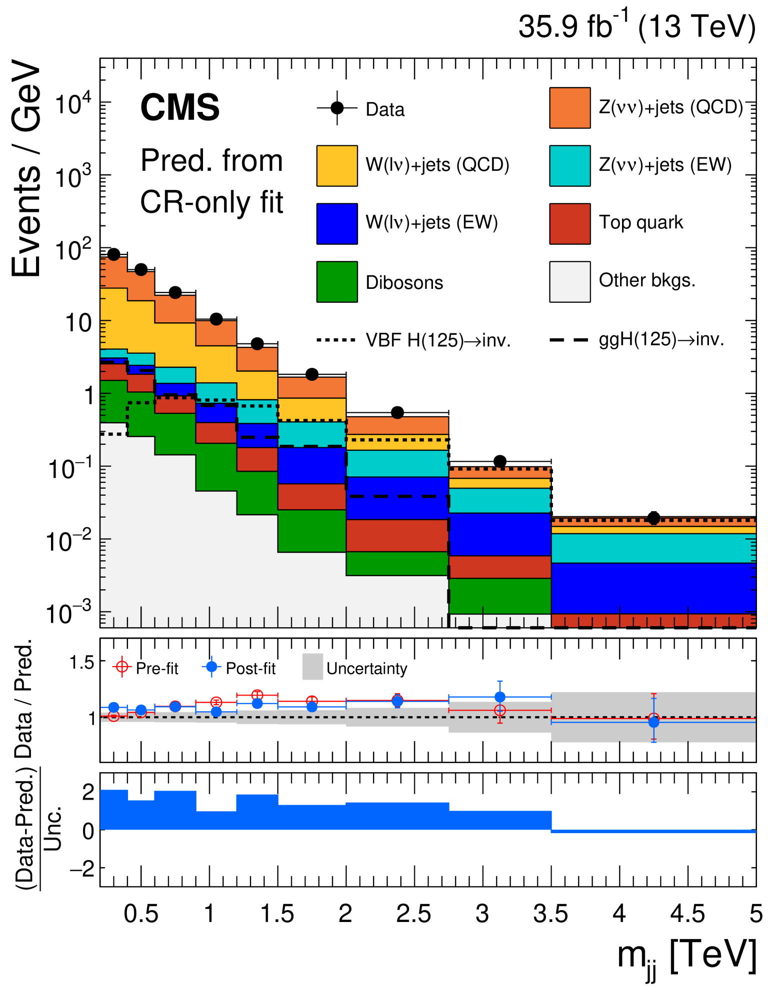


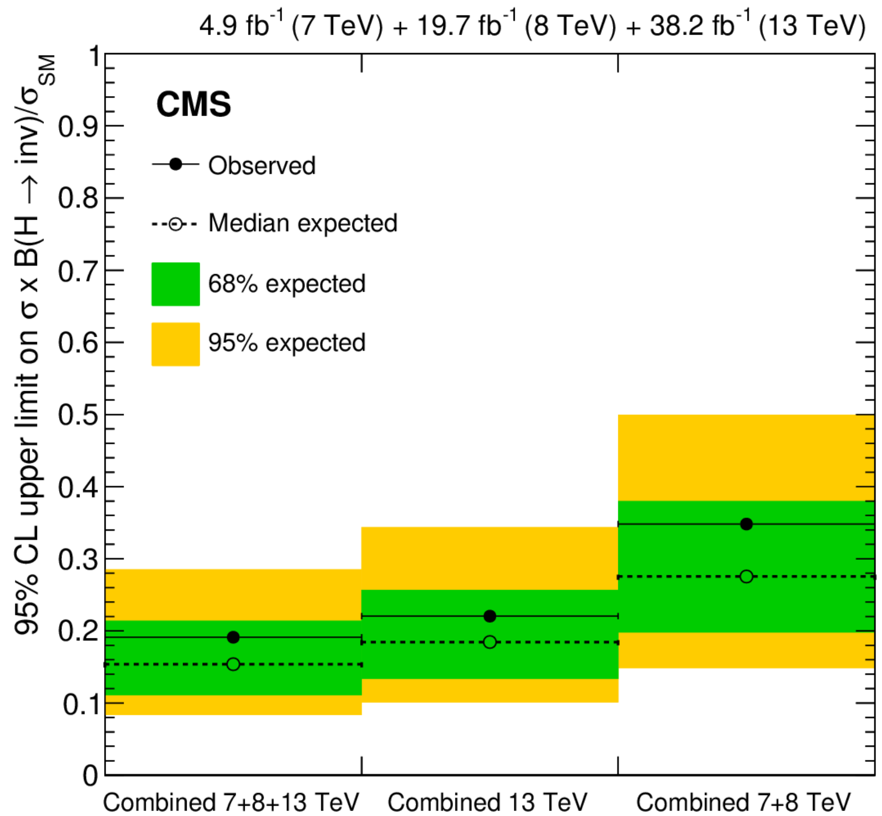


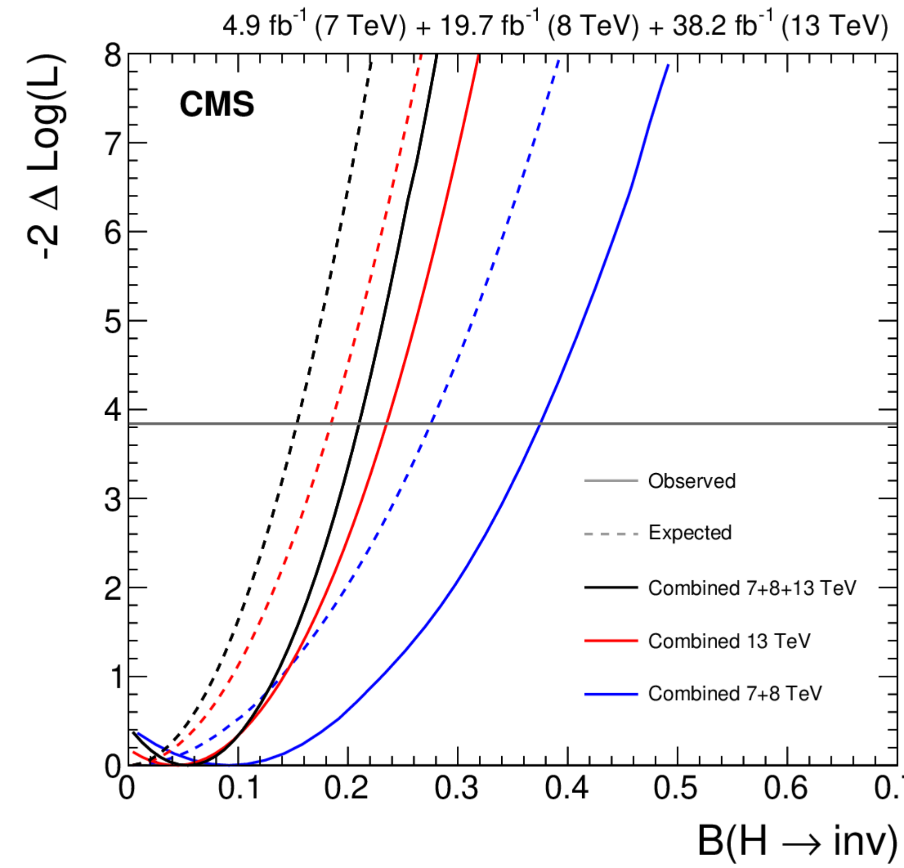


Search for $H \rightarrow invisible$ combination

arXiv:1712.07173







Observable	Shape analysis	Cut-and-count analysis	Target background
Leading (subleading) jet	$p_T > 80\,(40)$ GeV, $\|\eta\| < 4.7$		All
p_T^{miss}	>250 GeV		QCD multijet, $t\bar{t}$, γ+jets, V+jets
$\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet})$	>0.5 rad		QCD multijet, γ+jets
Muons (electrons)	$N_{\mu,e} = 0$ with $p_T > 10$ GeV, $\|\eta\| < 2.4\,(2.5)$		$W(\ell\nu)$+jets
τ_h candidates	$N_{\tau_h} = 0$ with $p_T > 18$ GeV, $\|\eta\| < 2.3$		$W(\ell\nu)$+jets
Photons	$N_\gamma = 0$ with $p_T > 15$ GeV, $\|\eta\| < 2.5$		γ+jets, $V\gamma$
b quark jet	$N_{jet} = 0$ with $p_T > 20$ GeV, CSVv2 > 0.848		$t\bar{t}$, single top quark
$\eta_{j1}\,\eta_{j2}$	<0		$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets
$\|\Delta\phi_{jj}\|$	<1.5 rad		$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets
$\|\Delta\eta_{jj}\|$	>1	>4	$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets
m_{jj}	>200 GeV	>1.3 TeV	$Z(\nu\bar{\nu})$+jets, $W(\ell\nu)$+jets