Search for rare and exotic decays of the Higgs boson in ATLAS

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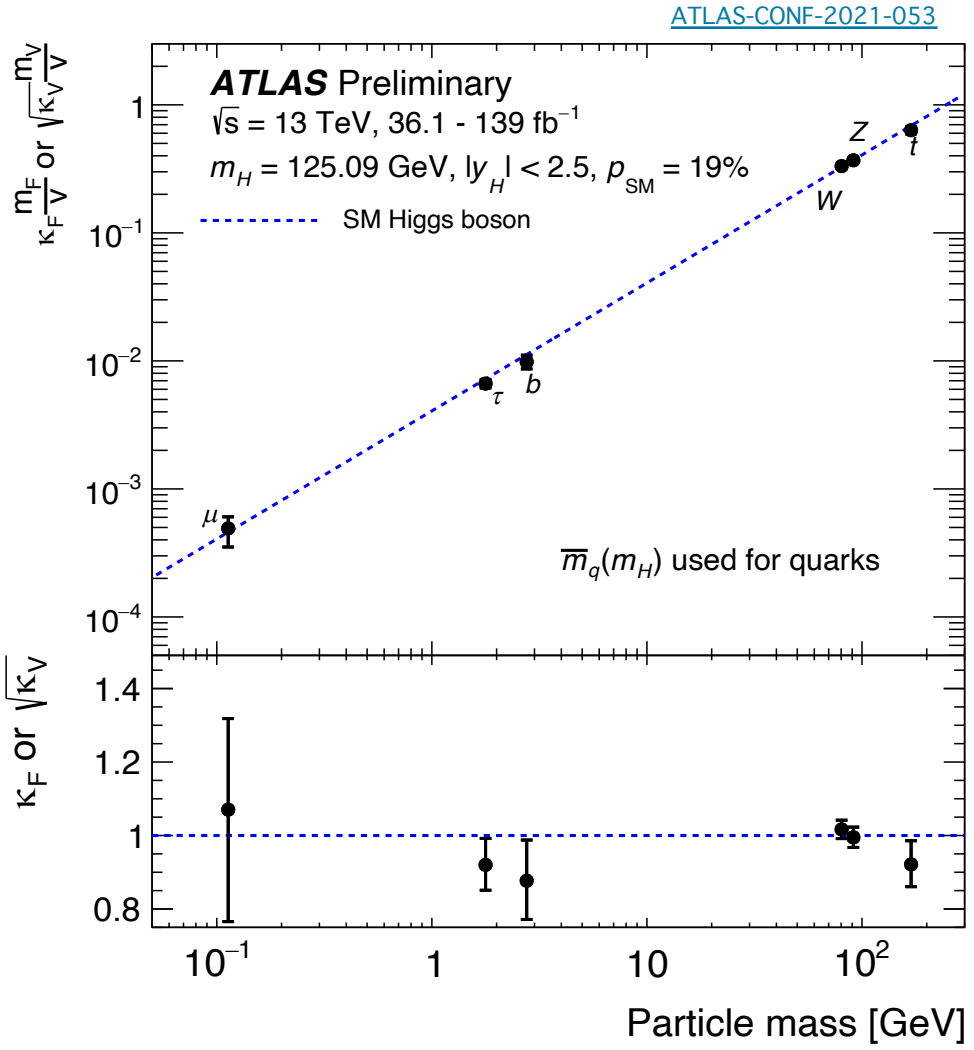
Introduction

- It has been 10 years since the discovery of the Higgs boson at the LHC!
- ATLAS and CMS have discovered all main production modes and decay channels
  - Couplings to bosons and 3rd generation fermions
  - Used in differential measurements (e.g. STXS)
- Couplings to 2nd generation fermions (H→μμ, H→cc, etc.) yet to be confirmed (at 5σ)
- Other rare/exotic decays could provide hints to new physics
  - Couplings to BSM can increase decay rate to final states otherwise suppressed in SM

In this talk

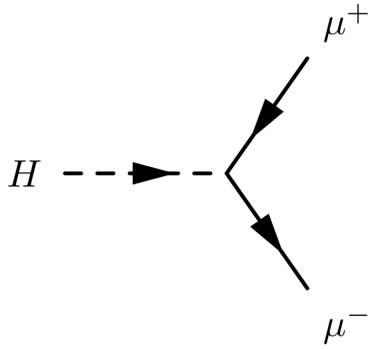
- Present recent searches of Higgs rare/exotic decays in ATLAS



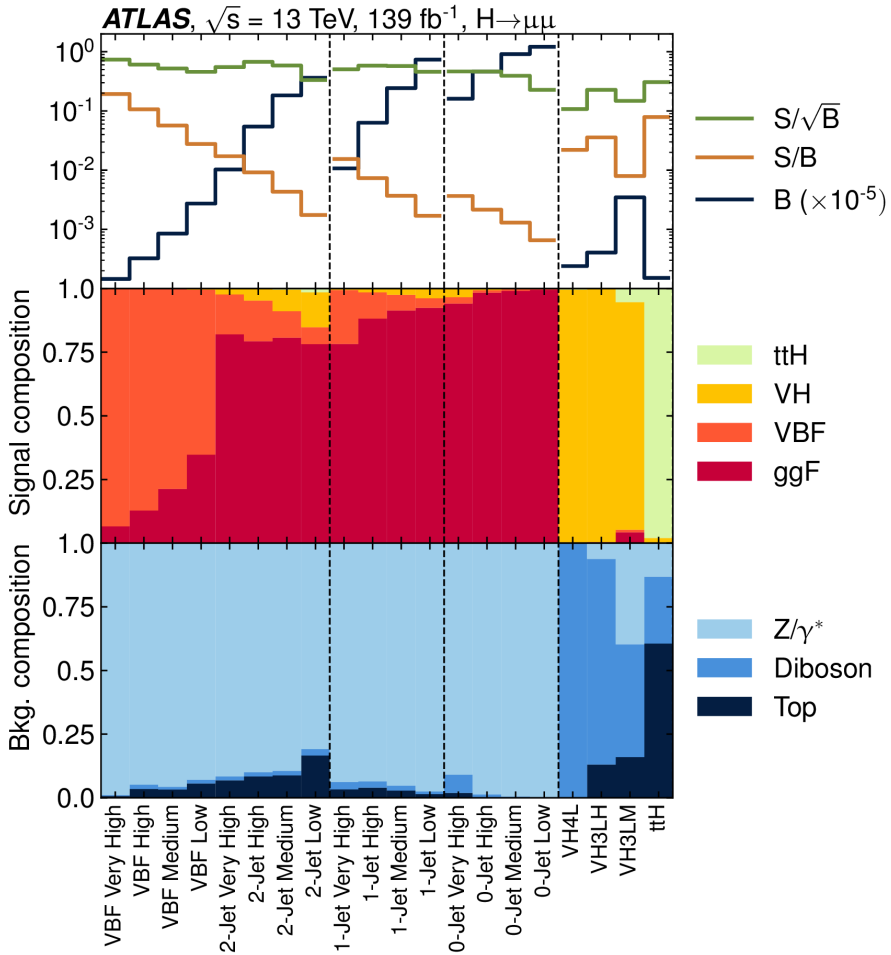
Searches for Higgs rare decays

H→μμ, 13TeV, 139fb^{-1}

- Offers best opportunity for probing the Higgs coupling to 2nd-generation fermions
- Challenging due to very small branching ratio (~2×10^{-4}) and large background (mainly Z→μμ)
  - Small S/B ratio ~0.1%



Phys. Lett. B 812 (2021) 135980



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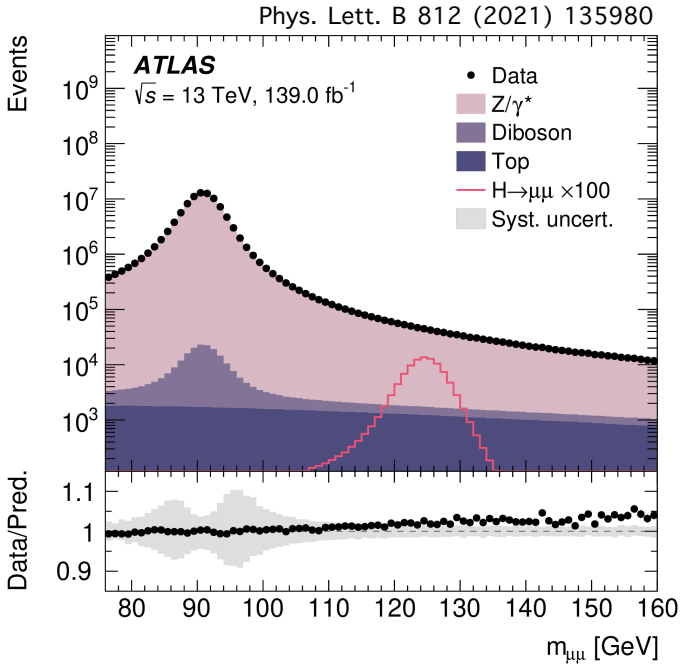
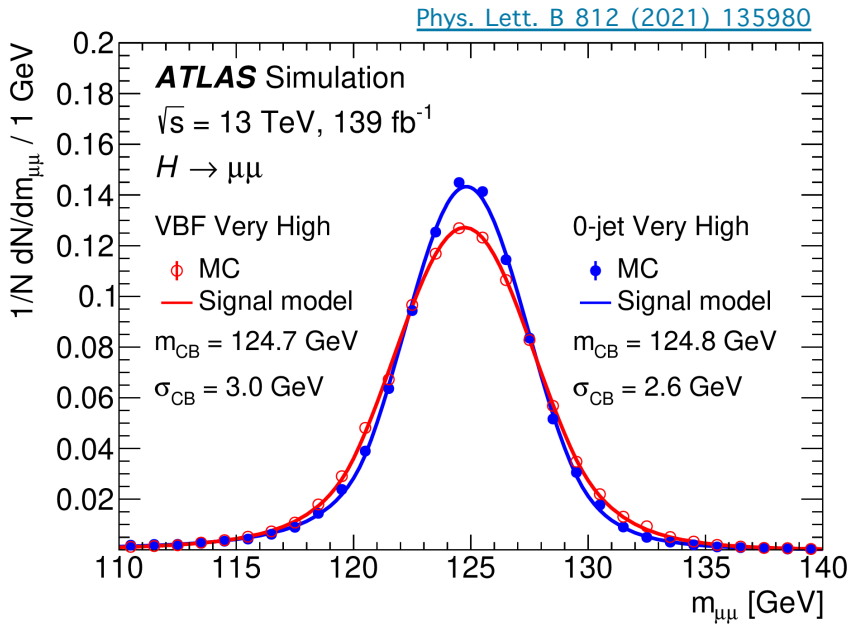


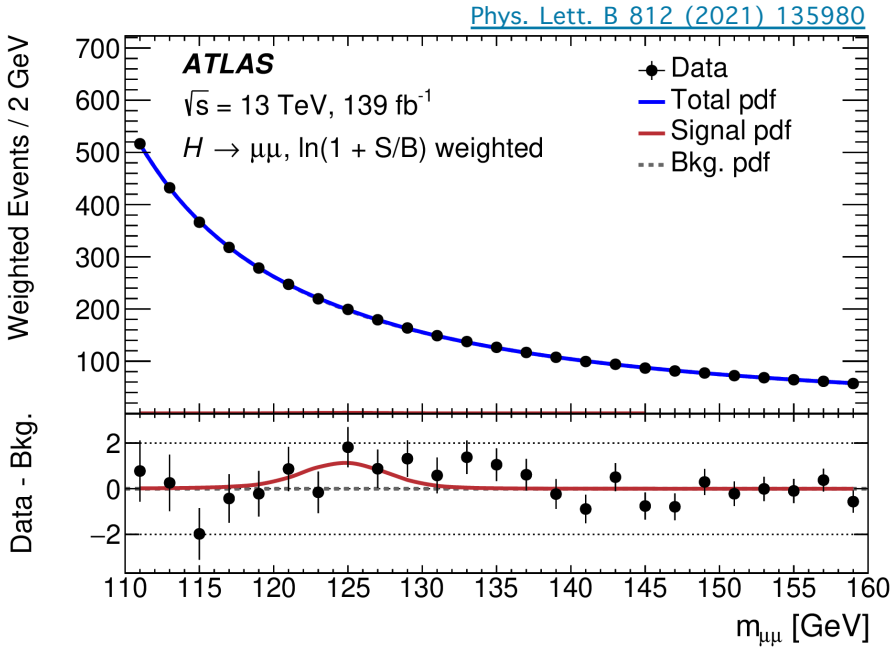
- Select events with 2 isolated opposite-sign muons using single muon trigger

- Focus on ggF, VBF, VH and ttH production modes
- Sensitivity enhanced by splitting events into 12 ggF, 4 VBF, 3 VH and 1 ttH categories with dedicated BDTs
  - Production modes well separated in most categories

H→μμ, 13TeV, 139fb^{-1}

- Perform fits in the $m_{\mu\mu}$ spectrum
- Signal and background shapes modeled by analytical functions
  - Signal modeled with double-sided crystal-ball function ($m_{\mu\mu}$ resolution ~3 GeV)
  - Background modeled with physics-motivated rigid shape multiplied by flexible functions

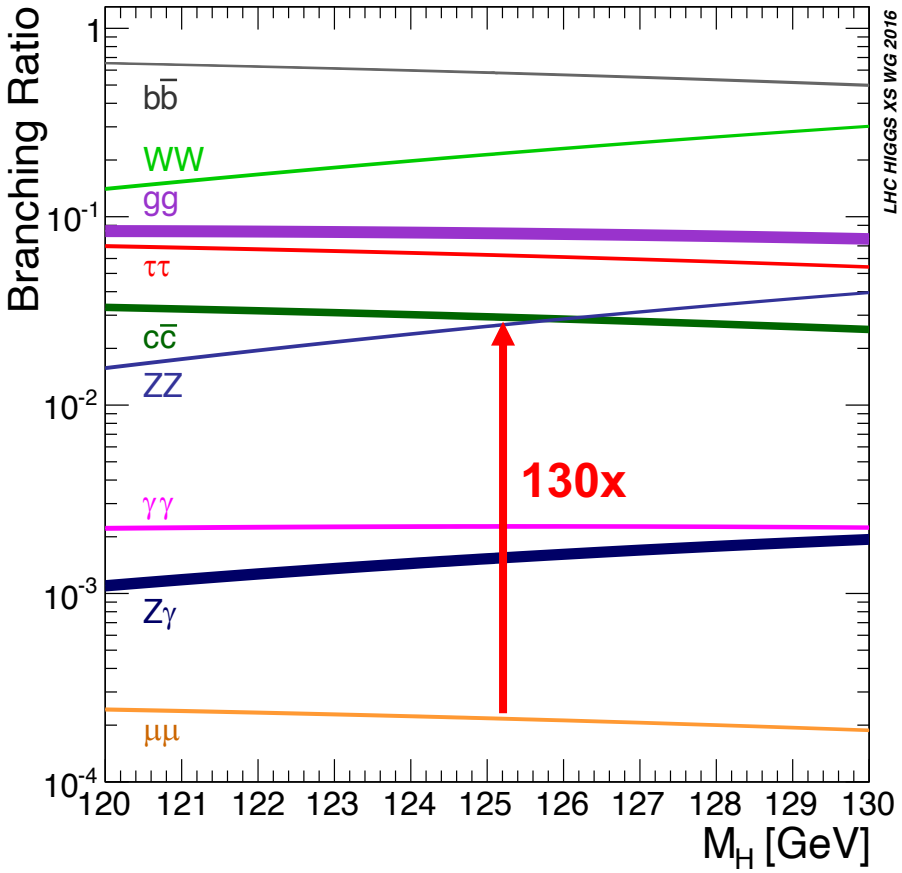


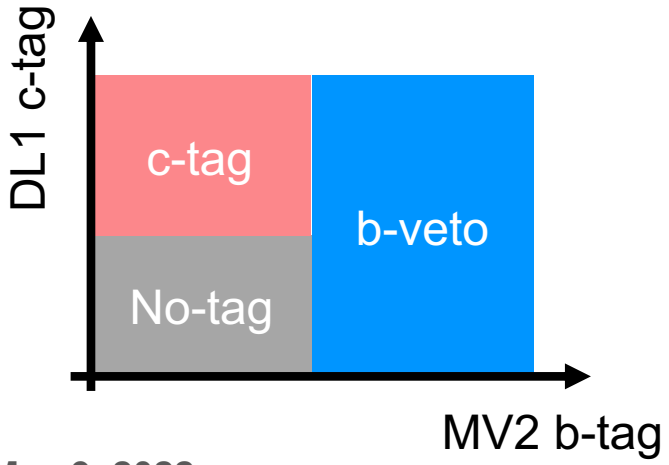


- Fitted signal strength:
  $1.2 \pm 0.6\ (\pm\ 0.6(\text{stat.})\ ^{+0.2}_{-0.1}(\text{syst.}))$
- Significance against no H→μμ signal hypothesis:
  2.0σ observed, 1.7σ expected
- Observed upper limit @ 95% CL:
  $\text{Br}(H\to\mu\mu) < 4.7\times10^{-4} = 2.2\times\text{SM}$
- ~2.5 improvement wrt 36fb^{-1} (25% from better analysis techniques)

H→cc, 13TeV, 139fb^{-1}

- SM predicts Br(H→cc) ~ 130×Br(H→μμ), but worse sensitivity due to worse signal reconstruction, resolution and larger background contamination
- Focus on VH production with V decays leptonically providing event triggers
- Separate to 3 channels based on lepton multiplicity
  - 0-lepton targets Z($\to\nu\nu$)H, MET trigger
  - 1-lepton targets W($\to\ell\nu$)H, MET+lepton trigger
  - 2-lepton targets Z($\to\ell\ell$)H, lepton trigger





- The c-jet tagging is crucial for this analysis
  - DL1 c-tagger to identify c-jet with MV2 b-tagger suppressing b-jet contamination (efficiency: **27%**/**8%**/1.5% for **c**/**b**/light-jets)
  - Select events containing either 1 or 2 c-tagged jets

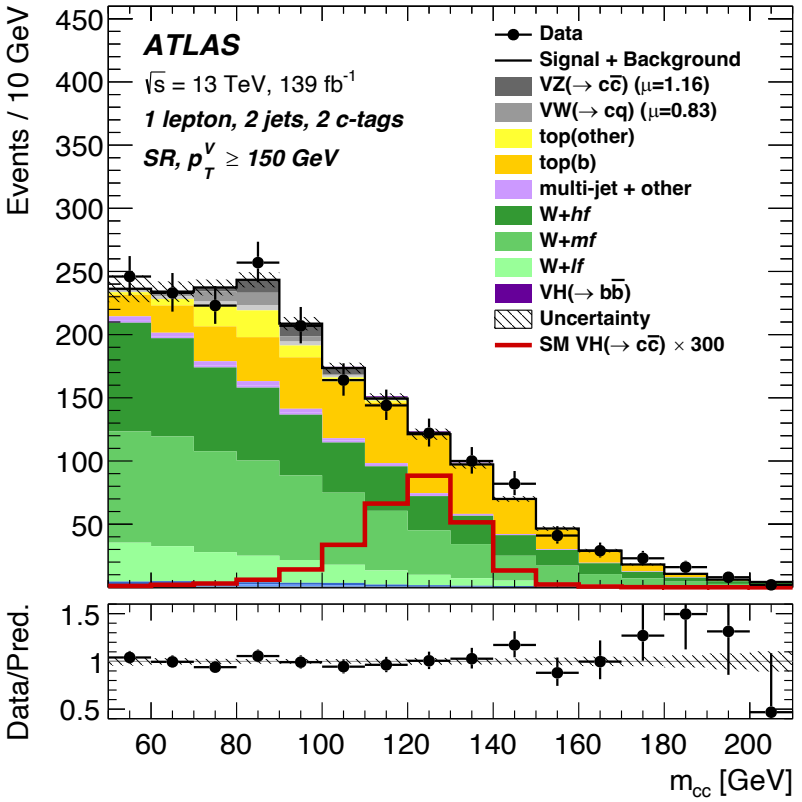
H→cc, 13TeV, 139fb^{-1}

- Signal and background modeled by MC simulation
- Perform fits in m_{cc} spectrum
- Signal strength:

  -9 ± 10(stat.) ± 12 (syst.)
- Observed (expected) limits @ 95% CL:

  Br(H→cc) < 26 (31) × SM
- Sensitivity improved by 5 times wrt 36fb^{-1} (link)
  - 43% improvement due to better flavour-tagging, event selections and categorization

arXiv:2201.11428



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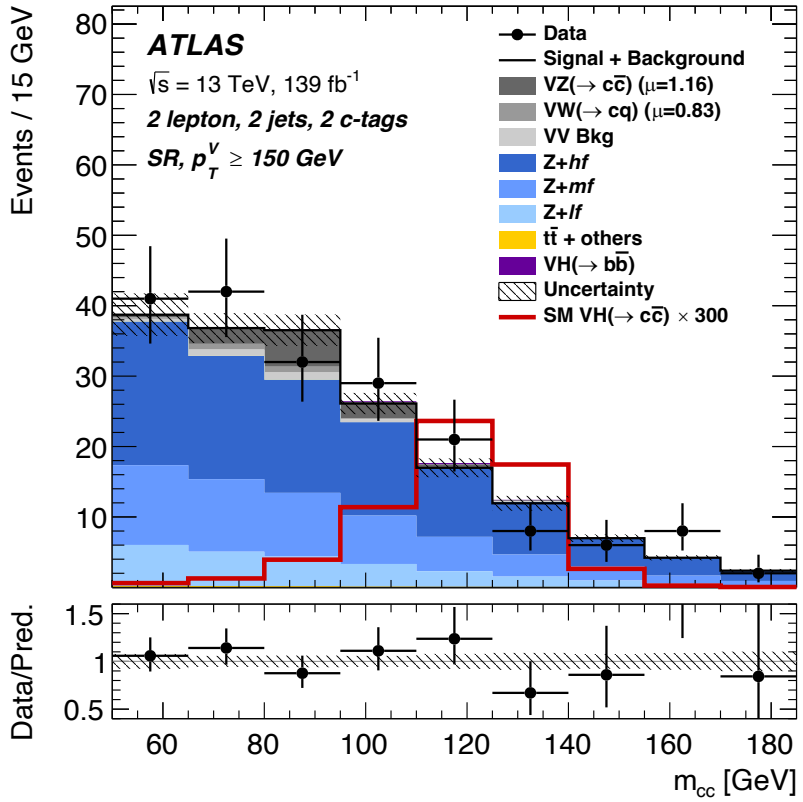
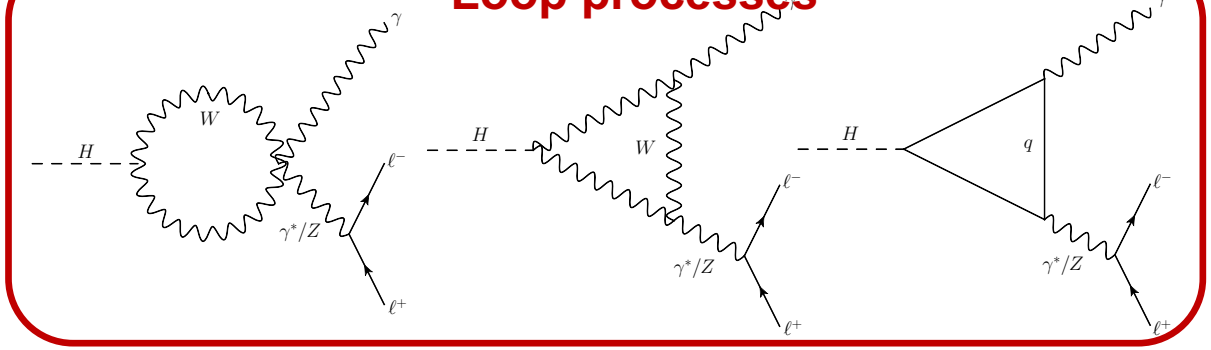


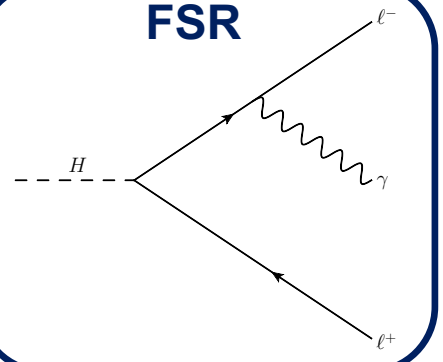
- Combine with ATLAS VH(bb) analysis to measure $|\kappa_c/\kappa_b|$:
  - Observed (expected) limit @ 95% CL: $|\kappa_c/\kappa_b| < 4.5$ (5.1)
  - Smaller than $m_b/m_c = 4.578 \pm 0.008$

H→$\ell\ell\gamma$, 13TeV, 139fb^{-1}

Loop processes



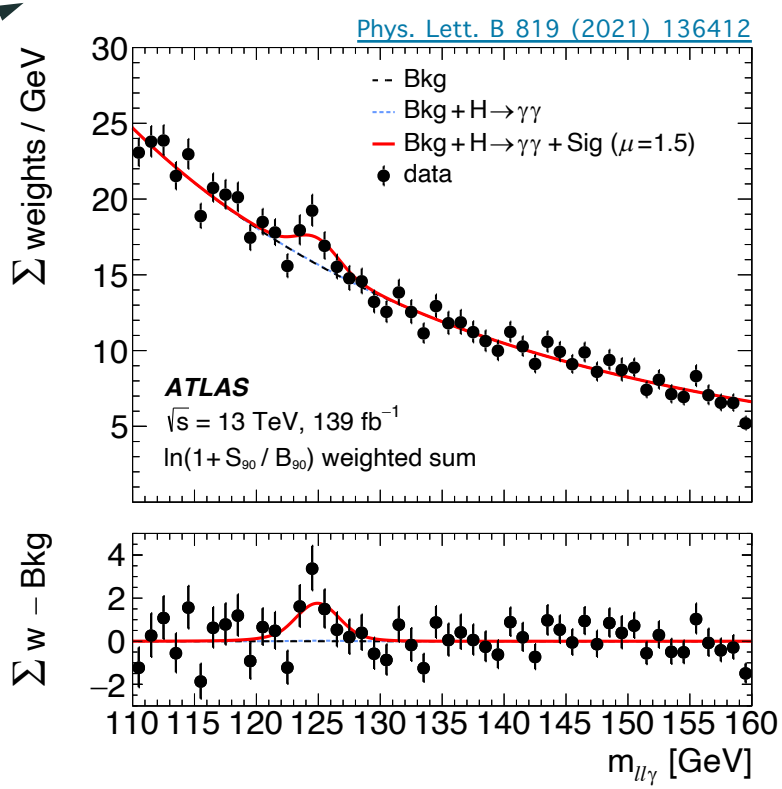
FSR



- Select events with γ + (e+e-/μ+μ-) with $m_{\ell\ell}$ < 30 GeV
- Observed (expected) significance = 3.2σ (2.1σ)
- First evidence of H→$\ell\ell\gamma$!
- $\mu = 1.5 \pm 0.5(\text{stat.}) \,^{+0.2}_{-0.1}(\text{syst.})$

- H→$\ell\ell\gamma$ is produced either through **loop processes** or **lepton pair + FSR**
  - Loop processes sensitive to coupling modifications induced by BSM extension
  - Can probe CP-violation in the Higgs sector due to the three-body decay (JHEP05 (2013) 061)
- Analyses split to high and low dilepton mass
  - $m_{\ell\ell}$ ~ 90 GeV dominated by H→Zγ→$\ell\ell\gamma$ (link)
  - $m_{\ell\ell}$ < 30 GeV dominated by H→$\gamma^*\gamma$→$\ell\ell\gamma$ (link)

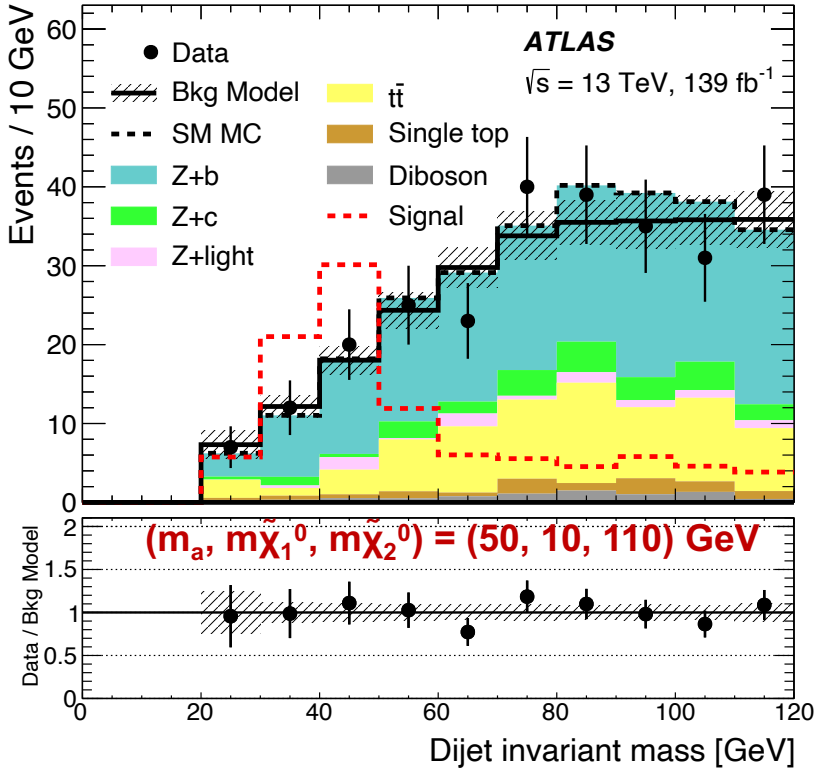
Phys. Lett. B 819 (2021) 136412

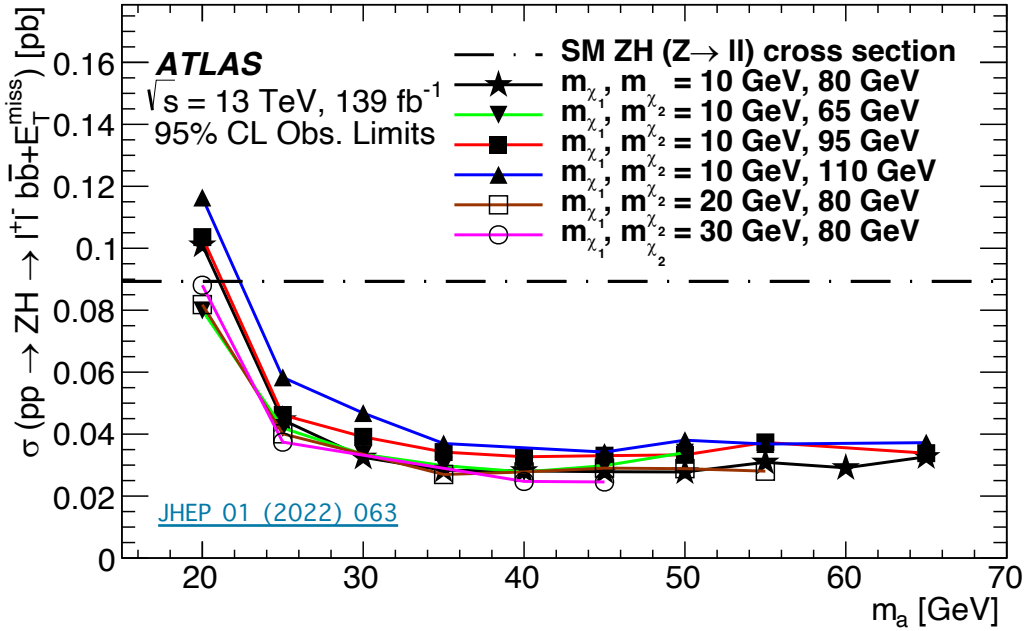


Searches for exotic Higgs decays

H→bb+MET, 13TeV, 139fb^{-1}

- Sensitive to NMSSM with $H\to\tilde{\chi}_2^0\tilde{\chi}_1^0\to a(\to bb)\tilde{\chi}_1^0\tilde{\chi}_1^0$
  - a = light pseudoscalar Higgs boson
  - $\tilde{\chi}_{1,2}^0$ = 2 lightest neutralinos
- Targets ZH production with $Z\to\ell\ell$ providing trigger
- Require 2 leptons with same flavor and opposite charge, >2 jets with >1 b-tagged, MET>100 GeV
- Lepton pair must be consistent with a Z boson



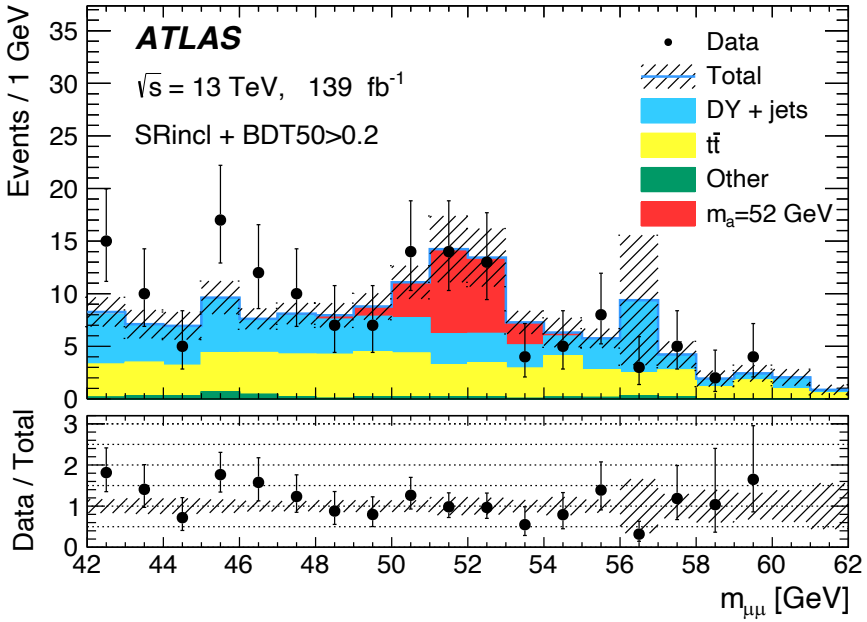


- Main backgrounds Z+HF and $t\bar{t}$ modeled with dedicated control regions
- Fit to m_{jj} spectrum (SR+CRs)
- Analysis statistically dominated; dominant systematics includes background modeling
- $Br(H\to\tilde{\chi}_2^0\tilde{\chi}_1^0\to a(\to bb)\tilde{\chi}_1^0\tilde{\chi}_1^0)$ < 31% in region of highest sensitivity

$H \to aa \to bb\mu\mu$, 13TeV, 139fb^{-1}

- Targets Higgs decays to 2 pseudoscalars ($H \to aa$)
  - $a \to bb$ provides large decay rate
  - $a \to \mu\mu$ provides event trigger
- Select events with 2 opposite-sign muons + exactly 2 b-jets using single-muon or dimuon triggers
  - m_{bb} and $m_{\mu\mu}$ required to be consistent
  - $m_{bb\mu\mu}$ consistent with Higgs mass (110-140 GeV)
- BDT trained for each m_a to separate signal and background
- Main backgrounds (DY, $t\bar{t}$) modeled with control regions
- $m_{\mu\mu}$ used as the fit discriminant (instead of m_{bb} due to better resolution of $m_{\mu\mu}$)
- Largest discrepancy found at $m_{\mu\mu}$ = 52 GeV
  - Local (global) significance = 3.3σ (1.7σ)
- Upper limits set on Br($H \to aa \to bb\mu\mu$) for different m_a
  - Factor of 2~5 improvement wrt 36 fb^{-1} result (~2 due to the BDT selection)

Phys. Rev. D 105 (2022) 012006



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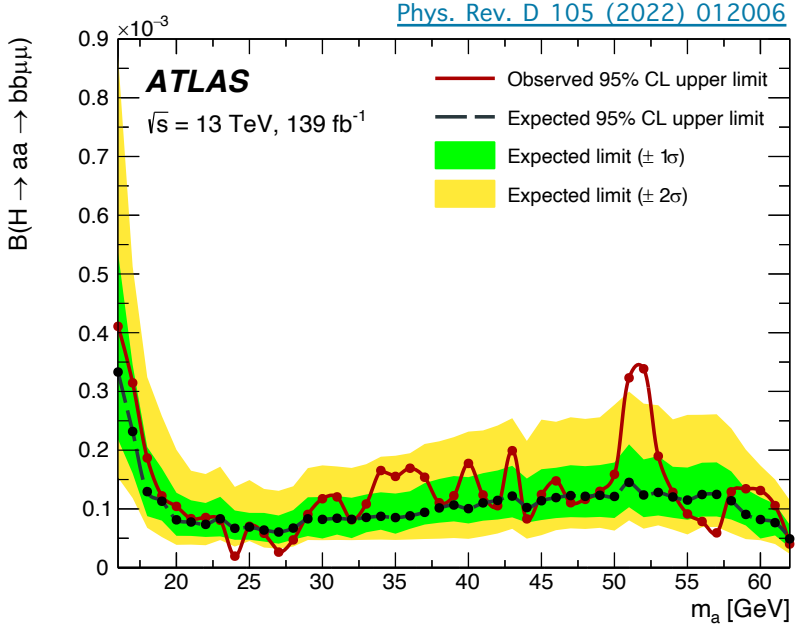
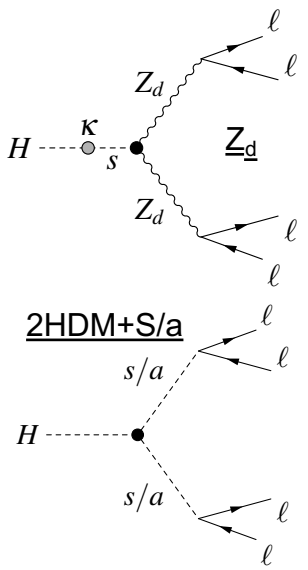
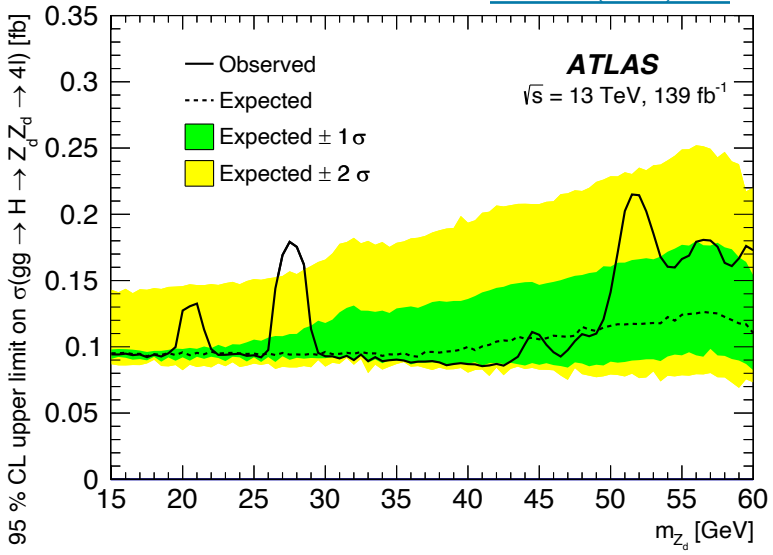


H→XX/ZX→4ℓ, 13TeV, 139fb^{-1}

- Targets H→XX/ZX→4ℓ where X is a spin-0/1 boson
- Split to 3 channels:
  - High-mass (HM): H→XX→4ℓ ($15 < m_x < 60$ GeV)
  - Low-mass (LM): H→XX→4ℓ ($1 < m_x < 15$ GeV)
  - Single Z-boson (ZX): H→ZX→4ℓ ($15 < m_x < 55$ GeV)
- 4ℓ = ($e^+e^-+e^+e^-$), ($e^+e^-+\mu^+\mu^-$) or ($\mu^+\mu^-+\mu^+\mu^-$)



JHEP 03 (2022) 041



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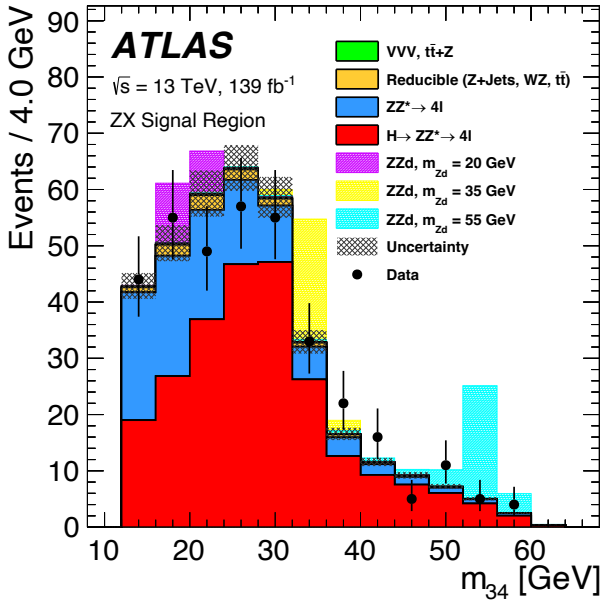

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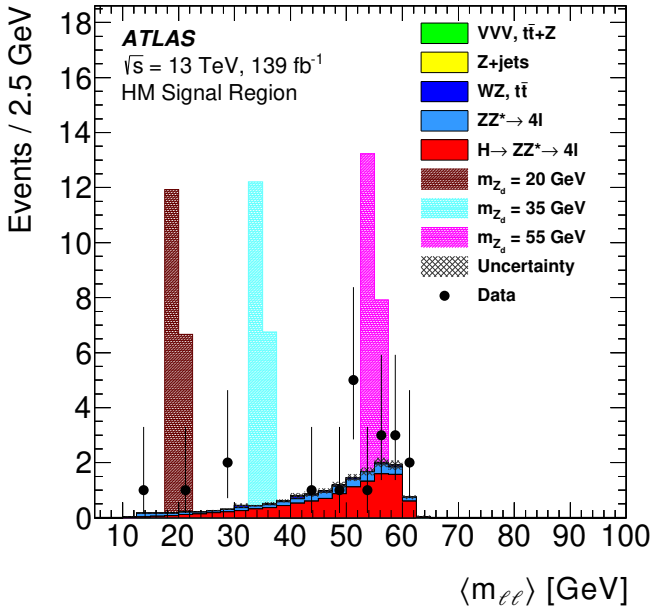
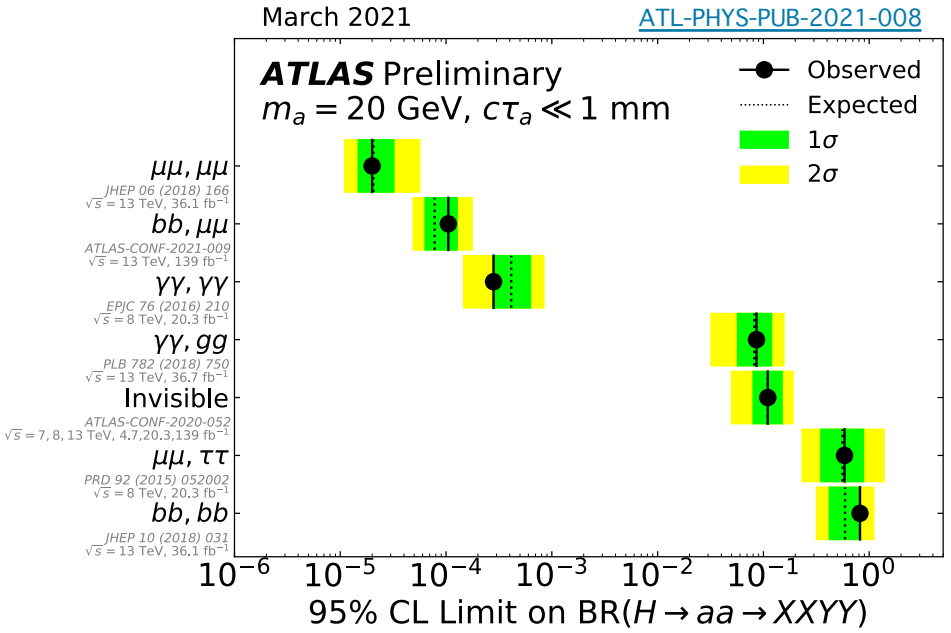
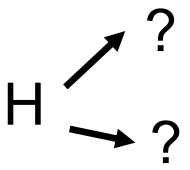


- m_{4l} consistent with Higgs (115-130 GeV)
- LM and HM require m_{12} and m_{34} consistent
- ZX requires m_{12} closer to Z-mass than m_{34}
- Main background (H→ZZ, ZZ) estimated with MC simulation
- Fits to $\langle m_{\ell\ell} \rangle$ (for HM/LM) and m_{34} for ZX
- No excess found in all channels (0 event in LM)
- Limits set on dark boson (Z_d) and 2HDM+S/a

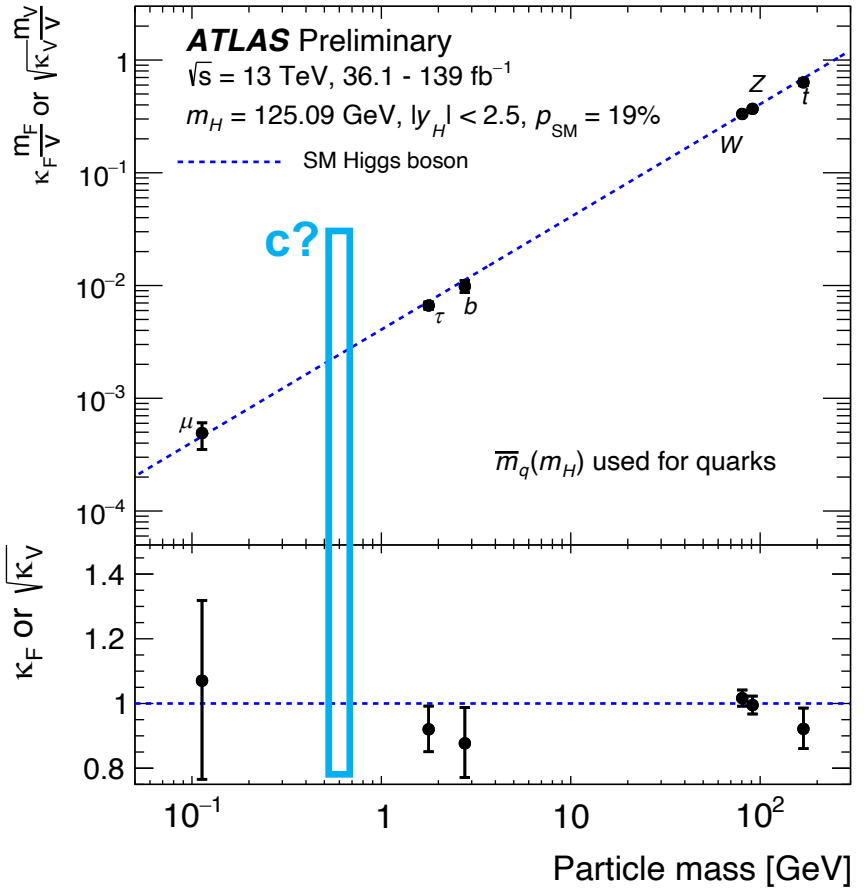
Summary

- Extensive searches for rare and exotic Higgs decays performed in ATLAS
- Observed 2σ for H→μμ
  - One step closer to discovering Higgs coupling to 2nd-generation fermions
- First evidence (3.2σ) of H→$\ell\ell\gamma$ ($m_{\ell\ell}$ < 30 GeV)
- Limit set on Br(H→cc) < 26×SM





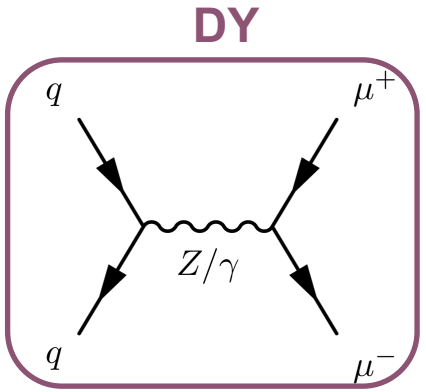
ATLAS-CONF-2021-053



- No significant excess found for all exotic Higgs decay searches
  - Upper limits set for benchmark BSM scenarios (e.g. NMSSM, Zd, 2HDM+a/S, etc.)

Backup slides

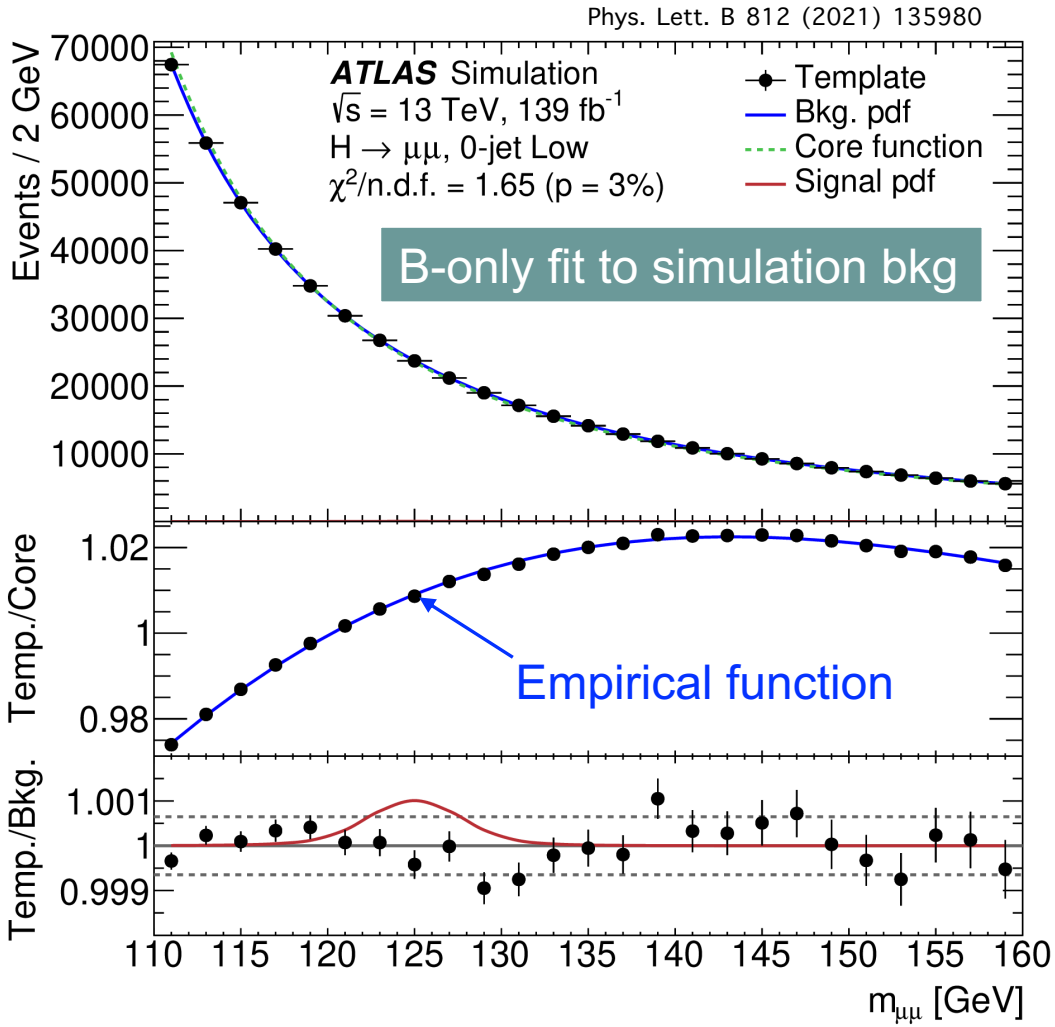
H→μμ – background modeling



- Major challenge due to the very low S/B ratio
- Mainly focus on the non-trivial shape of the DY $m_{\mu\mu}$ spectrum: model with (Core) × (Empirical)
  - Core function: LO DY line-shape convolved with the Gaussian muon resolution function
    - All parameters are fixed
  - Empirical function: Power-law or Epoly functions (different in each category)
    - With free parameters to absorb the mismodeling from the core function
- Function choices are selected based on spurious signal test procedure with high statistics simulation

H→μμ – spurious signal test

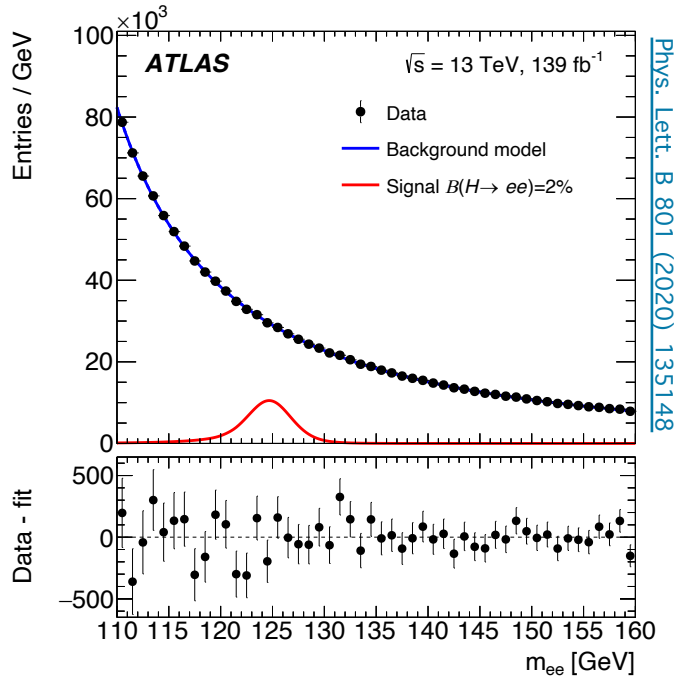
- Evaluate the background modeling bias by performing a S+B fit to the simulation background
  - Resulting S is the "spurious signal" (SS)
- Selected functions must pass the fit quality criteria:
  - SS < 20% of expected statistical uncertainty in data
  - χ^2 p-value > 1% for B-only fits to simulation background and data sideband

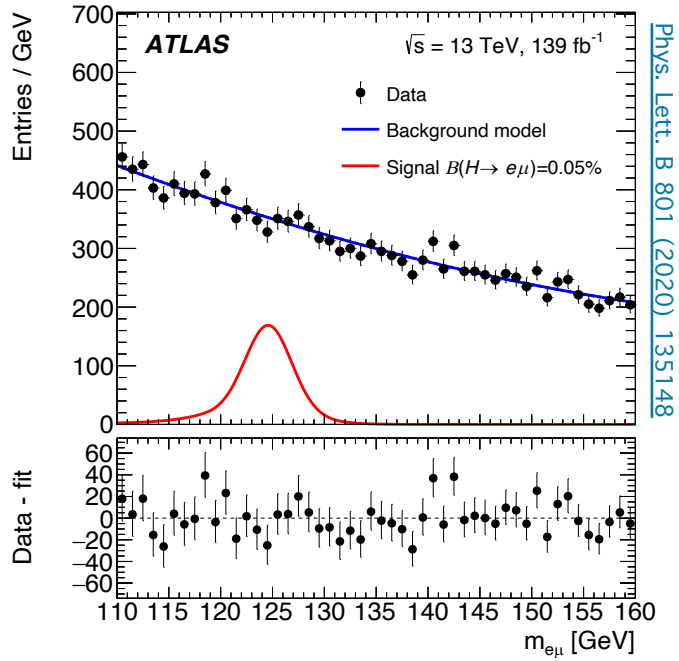


- Eventually SS in each category is taken as a background modeling uncertainty

H→ee/eμ, 13TeV, 139fb^{-1}

- SM prediction of H→ee far below LHC sensitivity
  - Sensitive to enhancements by BSM
- H→eμ directly probes the off-diagonal $Y_{e\mu}$ coupling
- Select events with exactly 2 electrons or 1 electron + 1 muon (using single-lepton triggers)
  - Veto events containing b-jets to suppress t-quark background
  - Split to 7(8) categories for ee(eμ) channel based on jet and lepton kinematics
- Simultaneous fit to $m_{\ell\ell}$ spectrum with signal/bkg shape modelled with analytic functions
- Observed (expected) limit @ 95% CL:
  - Br(H→ee) < 3.6×10^{-4} (3.5×10^{-4})
  - Br(H→eμ) < 6.2×10^{-4} (5.9×10^{-4})





H→ee/eμ – signal and background modeling

- Signal (crystal-ball (f_{CB}) + gaussian (f_{GS})):

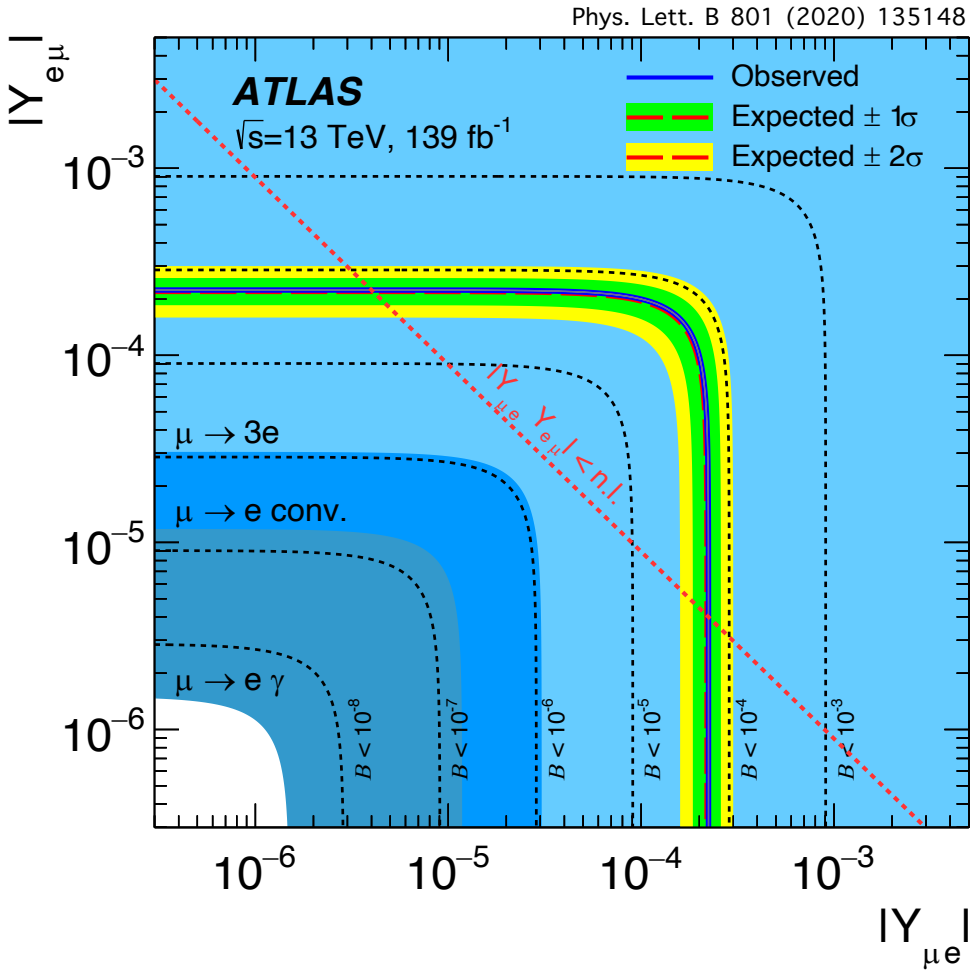
$$P_{\mathrm{S}}(m_{\ell\ell}) = f_{\mathrm{CB}} \times F_{\mathrm{CB}}(m_{\ell\ell}|m_{\mathrm{CB}}, \sigma_{\mathrm{CB}}, \alpha, n) + (1 - f_{\mathrm{CB}}) \times F_{\mathrm{GS}}\left(m_{\ell\ell}|m_{\mathrm{GS}}, \sigma_{\mathrm{GS}}^{\mathrm{S}}\right)$$

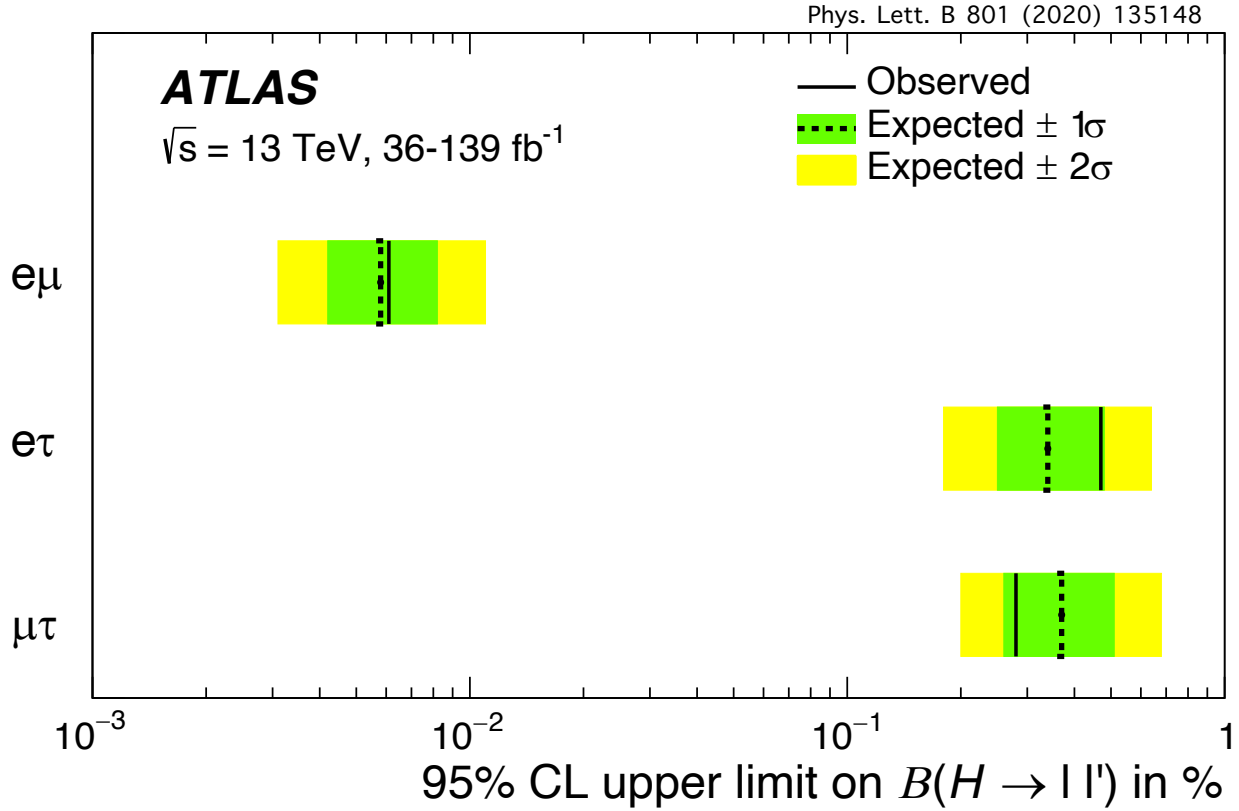
- Background (Breit-Wigner (F_{BW}) + exponential/cubic) for ee channel:

$$P_{\mathrm{B}}(m_{ee}) = f \times [F_{\mathrm{BW}}(m_{ee}|m_{\mathrm{BW}}, \Gamma_{\mathrm{BW}}) \otimes F_{\mathrm{GS}}(m_{ee}|\sigma_{\mathrm{GS}}^{\mathrm{B}})] + (1 - f) \times C\mathrm{e}^{A \cdot m_{ee}}/m_{ee}^{3},$$

- Background for eμ channel: Bernstein polynomial of degree two

H→ee/eμ – results





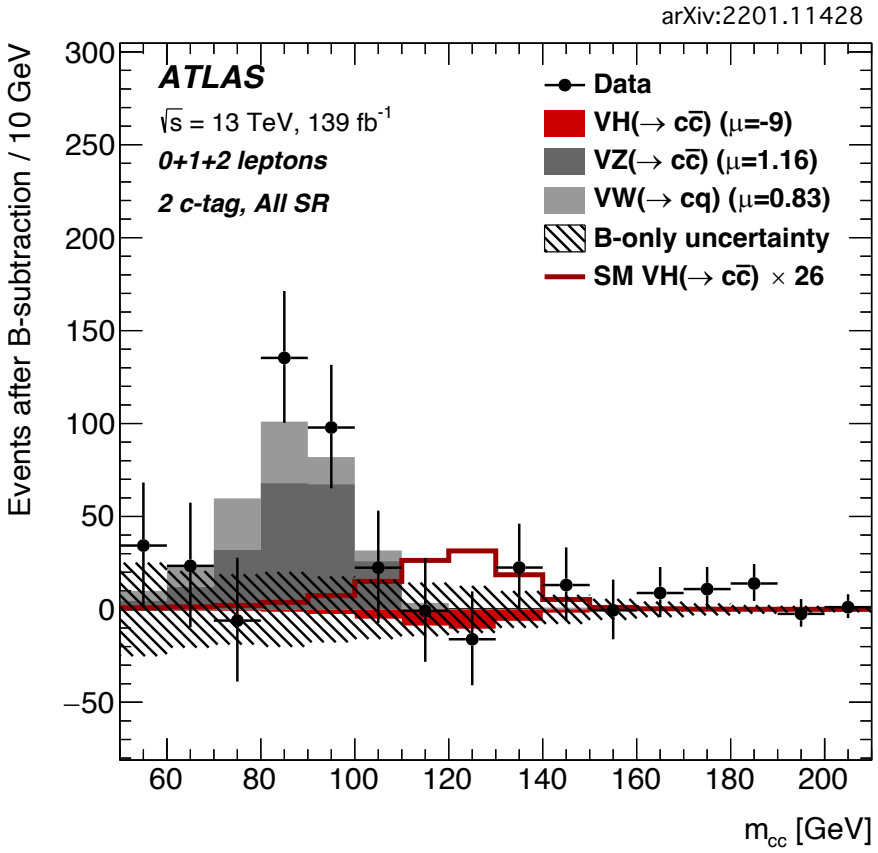
H→cc – event selections

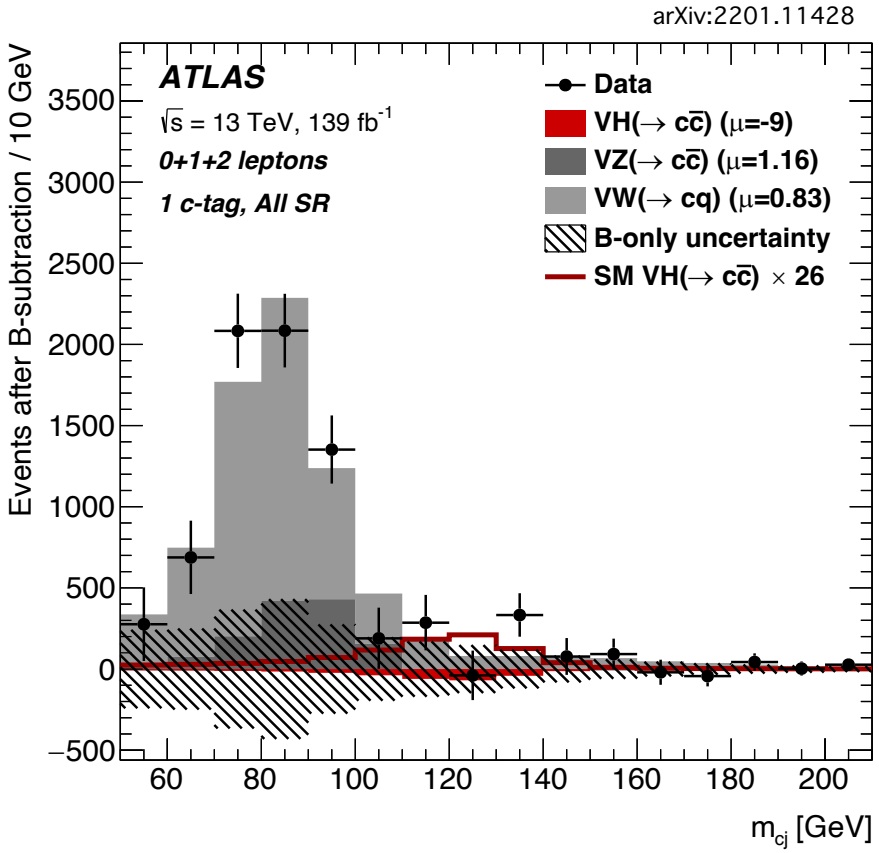
arXiv:2201.11428

Common Selections	
Central jets	≥ 2
Signal jet p_{T}	≥ 1 signal jet with $p_{\mathrm{T}} > 45$ GeV
c-jets	One or two c-tagged signal jets
b-jets	No b-tagged non-signal jets
Jets	2, 3 (0- and 1-lepton); 2, ≥ 3 (2-lepton)
p_{T}^{V} regions	75–150 GeV (2-lepton) > 150 GeV
$\Delta R(\mathbf{jet1}, \mathbf{jet2})$	$75 < p_{\mathrm{T}}^{V} < 150$ GeV: $\Delta R \leq 2.3$ $150 < p_{\mathrm{T}}^{V} < 250$ GeV: $\Delta R \leq 1.6$ $p_{\mathrm{T}}^{V} > 250$ GeV: $\Delta R \leq 1.2$
0 Lepton	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	No *loose* leptons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 30 GeV
H_{T}	> 120 GeV (2 jets), > 150 GeV (3 jets)
$\min \lvert\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{jet})\rvert$	$> 20°$ (2 jets), $> 30°$ (3 jets)
$\lvert\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{H})\rvert$	$> 120°$
$\lvert\Delta\phi(\mathbf{jet1}, \mathbf{jet2})\rvert$	$< 140°$
$\lvert\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$	$< 90°$
1 Lepton	
Trigger	e sub-channel: single electron μ sub-channel: $E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	One *tight* lepton and no additional *loose* leptons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 30 GeV (e sub-channel)
m_{T}^{W}	< 120 GeV
2 Lepton	
Trigger	Single lepton
Leptons	Exactly two *loose* leptons Same flavour, opposite charge for $\mu\mu$
$m_{\ell\ell}$	$81 < m_{\ell\ell} < 101$ GeV

- 16 signal regions
  - (0/1/2lep) x (2/3jet) x (1/2c)
  - 2lep split to high PTV and low PTV
- 16 ΔR control regions (for V-jets)
- 2 0/1-lep top control regions:
  - Require 1 c-tag + 1 b-tag
- 4 2-lep top control regions (for ttbar):
  - Require 1e+1μ and 1 c-tag
  - For each nj and PTV
- 4 0-tag control regions (for V + light flavour)
  - Require 0 c-tag and 0 b-tag
  - For each nj and PTV

H→cc – results





$$\mu_{VH(c\bar{c})} = -9 \pm 10\,(\text{stat.}) \pm 12\,(\text{syst.})$$
$$\mu_{VW(cq)} = 0.83 \pm 0.11\,(\text{stat.}) \pm 0.21\,(\text{syst.})$$
$$\mu_{VZ(c\bar{c})} = 1.16 \pm 0.32\,(\text{stat.}) \pm 0.36\,(\text{syst.}).$$

- Observed (expected) significance:
  - VW(cq): 3.8σ (4.6σ)
  - VZ(cc): 2.6σ (2.2σ)

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H→$\ell\ell\gamma$ – event selections

Category	Events	S_{90}	B_{90}^{N}	$B_{H\to\gamma\gamma}$	f_{90} [%]	Z_{90}
ee resolved VBF-enriched	10	0.4	1.6	0.009	20	0.3
ee merged VBF-enriched	15	0.8	2.0	0.07	27	0.5
$\mu\mu$ VBF-enriched	33	1.3	5.9	-	18	0.5
ee resolved high-$p_{\mathrm{T}t}$	86	1.1	12	0.02	9	0.3
ee merged high-$p_{\mathrm{T}t}$	162	2.5	18	0.2	12	0.6
$\mu\mu$ high-$p_{\mathrm{T}t}$	210	4.0	34	-	11	0.7
ee resolved low-$p_{\mathrm{T}t}$	3713	22	729	0.5	2.9	0.8
ee merged low-$p_{\mathrm{T}t}$	5103	29	942	2	3.0	1.0
$\mu\mu$ low-$p_{\mathrm{T}t}$	9813	61	1750	-	3.4	1.4

- ee can be either resolved or merged merged = 2 ID tracks match to the same EM calorimeter cluster
- Select events with γ + (e+e-/μ+μ-) with $m_{\ell\ell}$ < 30 GeV
- Muons and resolved electrons must have pT > 11 (13) GeV
- Merged-ee pT > 20 GeV
- Priority: μμ -> resolved or merged ee with highest vector pT sum of the ID tracks
- 2.9 (2.5) < $m_{\mu\mu(ee)}$ < 3.3 (3.5) GeV to suppress J/ψ
- 9.1 (8) < $m_{\mu\mu(ee)}$ < 10.6 (11) GeV to suppress Υ(nS)
- pT_{γ} and $pT_{\ell\ell}$ > 0.3 $m_{\ell\ell\gamma}$

$H \to \ell\ell\gamma$ – signal and background modeling

- Signal: DSCB (mass resolution 1.6~2.2 GeV)
- Resonant background ($H \to \gamma\gamma$): DSCB (same as signal) normalized to SM
- Non-resonant background: non-resonant $\ell\ell\gamma$ process (dominant) + misidentified photon/leptons
  - Analytic functions selected from exponential, Epoly or power-law
  - Based on spurious signal test
- Main systematics -> background modeling

H→bb+MET – event selections

- Single-lepton trigger

	SR	CRZ	CRTop	VRMET
Number of leptons			2	
Number of jets			≥ 2	
Number of b-tagged jets			≥ 1	
Dilepton p_{T} [GeV]			> 40	
p_{T} fraction			[0.8, 1.2]	
Dilepton mass [GeV]	[81, 101]	[81, 101]	[50, 81] or > 101	[81, 101]
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 100	[60, 100]	> 100	> 50
Dijet mass [GeV]	[20, 120]	[20, 120]	[20, 120]	> 150

H→aa→bbμμ

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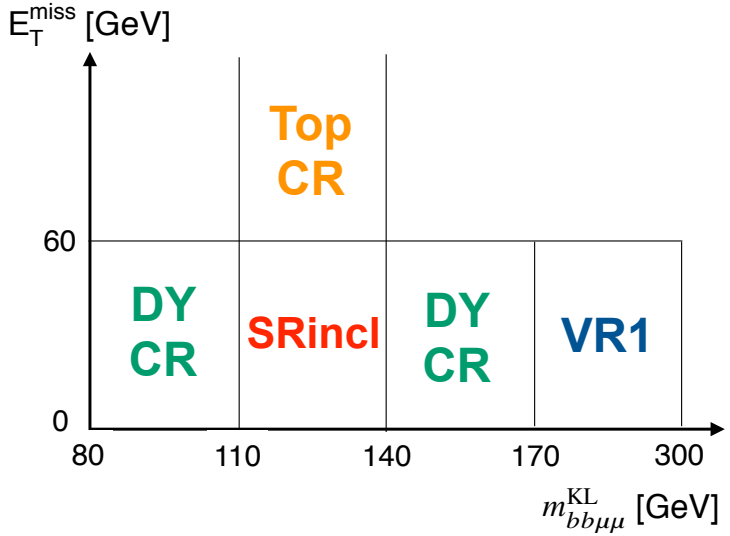
	TCR	DYCR	SRincl	VR1	VR2
$m_{\mu\mu}$ [GeV]	[15, 65]				
$m^{\mathrm{KL}}_{bb\mu\mu}$ [GeV]	[110, 140]	[80, 110] or [140, 170]	[110, 140]	[170, 300]	[110, 140]
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60	< 60			
$\ln(L^{\max})$	> -8				$[-11, -8]$
SR bins	SRincl & BDT$m_a > 0.2$ 2-GeV-wide (3-GeV-wide) $m_{\mu\mu}$ bins for $m_a \leq 45$ GeV ($m_a > 45$ GeV)				



- DY shape modeled from data in DYCR with 0 b-tag (instead of 2 b-tag)
- Main systematics: jet energy resolution and calibration, b-tagging efficiency

$H \to XX/ZX \to 4\ell$ – event selections

arXiv:2119.13673

- Single-lepton or dilepton trigger

		Single Z (ZX) analysis $H \to ZX \to 4\ell$ ($\ell = e, \mu$)	High-mass (HM) analysis $H \to XX \to 4\ell$ ($\ell = e, \mu$)	Low-mass (LM) analysis $H \to XX \to 4\mu$
Mass range		$15\,\text{GeV} < m_X < 55\,\text{GeV}$	$15\,\text{GeV} < m_X < 60\,\text{GeV}$	$1\,\text{GeV} < m_X < 15\,\text{GeV}$
Baseline electrons		$p_\text{T} > 7\,\text{GeV}$ and $\lvert\eta\rvert < 2.47$; Loose identification with an IBL hit $\lvert z_0 \sin\theta\rvert < 0.5\,\text{mm}$		—
Baseline muons		$p_\text{T} > 5\,\text{GeV}$ (15 GeV if calo-tagged) and $\lvert\eta\rvert < 2.7$; Loose identification $\lvert z_0 \sin\theta\rvert < 0.5\,\text{mm}$ and $d_0 < 1\,\text{mm}$ (except for stand-alone muons)		
Quadruplet selection		Trigger-matched $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, or $\mu^+\mu^-\mu^+\mu^-$; ≤ 1 SA+CT μ Three leading-p_T leptons satisfying $p_\text{T} > 20\,\text{GeV}$, 15 GeV, 10 GeV Define pairs m_{12} and m_{34} such that $\lvert m_{12} - m_Z\rvert < \lvert m_{34} - m_Z\rvert$		
		$50\,\text{GeV} < m_{12} < 106\,\text{GeV}$ $12\,\text{GeV} < m_{34} < 115\,\text{GeV}$ $m_{14,32} > 5\,\text{GeV}$ ($4e/4\mu$)	—	
		$\Delta R(\ell, \ell') > 0.10$ (0.20) for same-flavour (different-flavour) ℓ, ℓ'		—
Quadruplet ranking		In order 4μ, $2e2\mu$, $2\mu2e$, $4e$ Smallest $\lvert m_Z - m_{12}\rvert$ Smallest $\lvert m_Z - m_{34}\rvert$	Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34}\rvert$	
Event selection	Isolation & impact parameter	Track and calorimeter isolation, excluding tracks/clusters from other leptons in the quadruplet $d_0/\sigma_{d_0} < 5$ for electrons and $d_0/\sigma_{d_0} < 3$ for muons		
	$m_{4\ell}$	$115\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$		$120\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$
	Z-veto	—	$10\,\text{GeV} < m_{12,34} < 64\,\text{GeV}$ For $4e$ and 4μ channels: $5\,\text{GeV} < m_{14,23} < 75\,\text{GeV}$	—
	Heavy-flavour veto	—	Reject event if $m_{12,34,14,23}$ in: $(m_{J/\Psi} - 0.25\,\text{GeV})$ to $(m_{\Psi(2S)} + 0.30\,\text{GeV})$, or $(m_{\Upsilon(1S)} - 0.70\,\text{GeV})$ to $(m_{\Upsilon(3S)} + 0.75\,\text{GeV})$	
	Signal region	—	$m_{34}/m_{12} > 0.85 - 0.1125\,f(m_{12})$	$1.2\,\text{GeV} < m_{12,34} < 20\,\text{GeV}$ $m_{34}/m_{12} > 0.85$ Reject event if $m_{12,34}$ in: 2 GeV to 4.4 GeV, or 8 GeV to 12 GeV

HDBS Summary