STATE OF THE ART SEARCHES FOR HIGGS EXOTIC DECAYS IN ATLAS AND CMS

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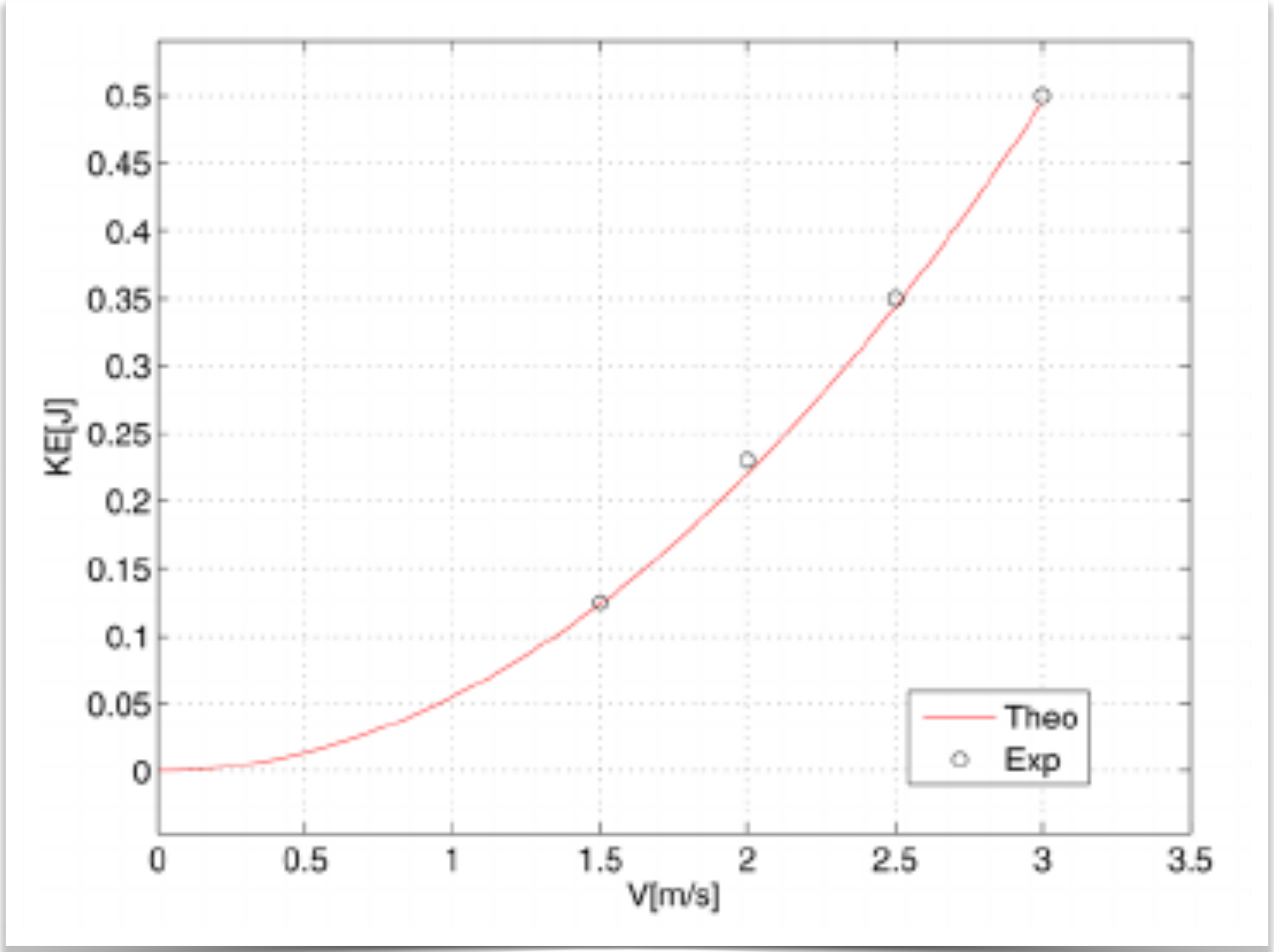
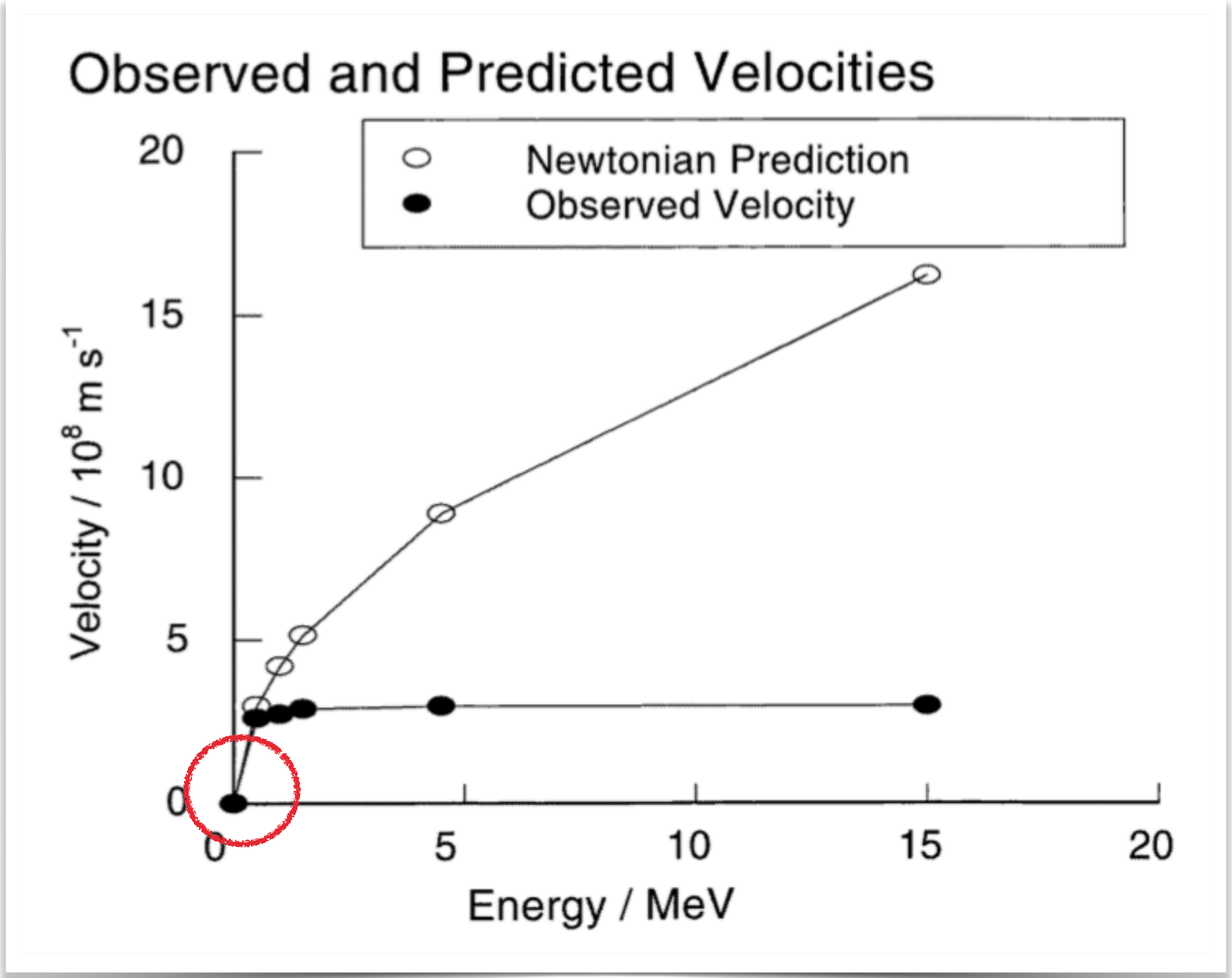
on behalf of ATLAS and CMS Collaborations

1st COMETA General Meeting, Izmir, Turkey 28.02.2024.

MOTIVATION

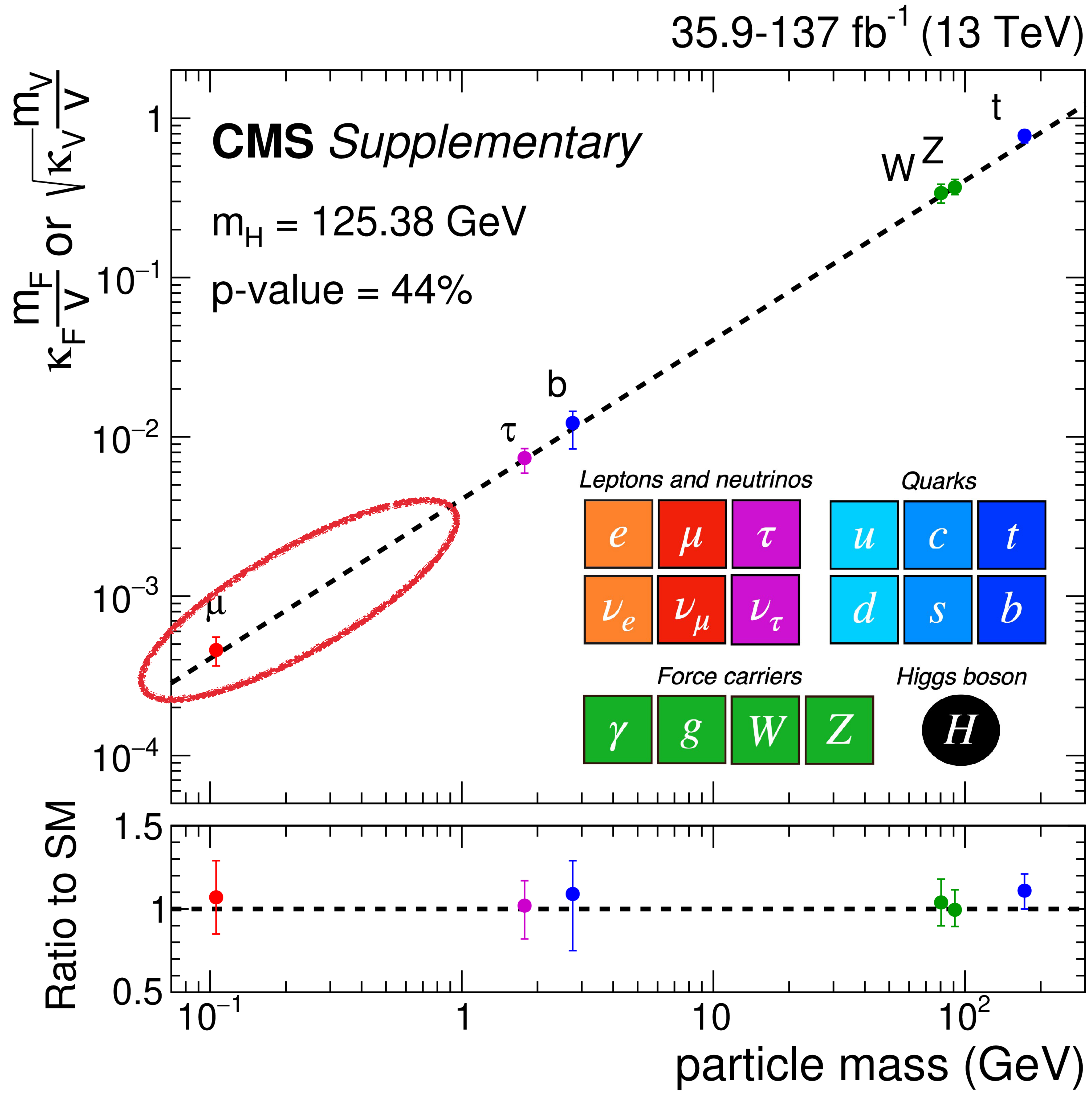
- History taught us that if we try hard enough, we will eventually find parameter-space where our current understanding of physics completely breaks down

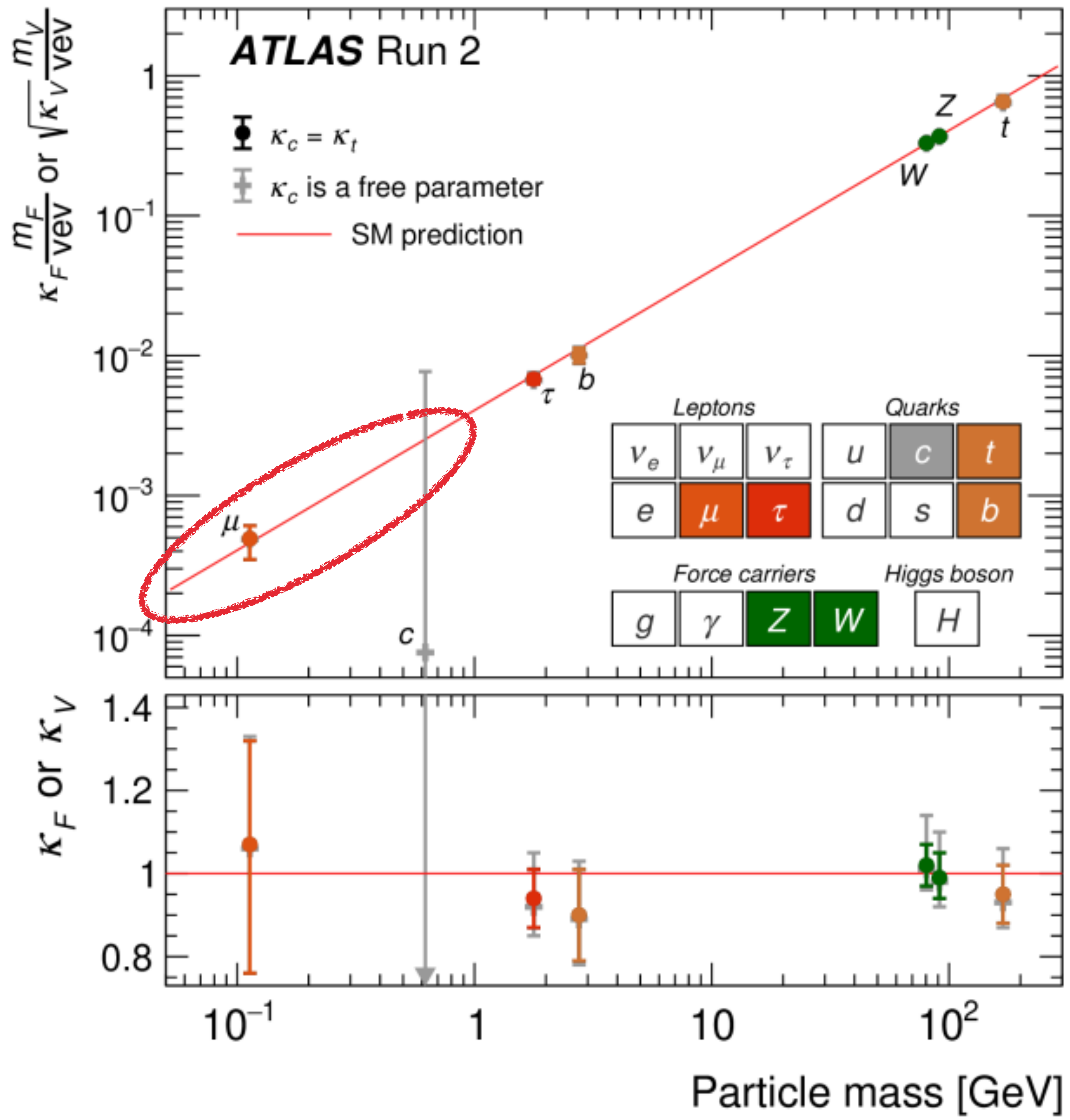




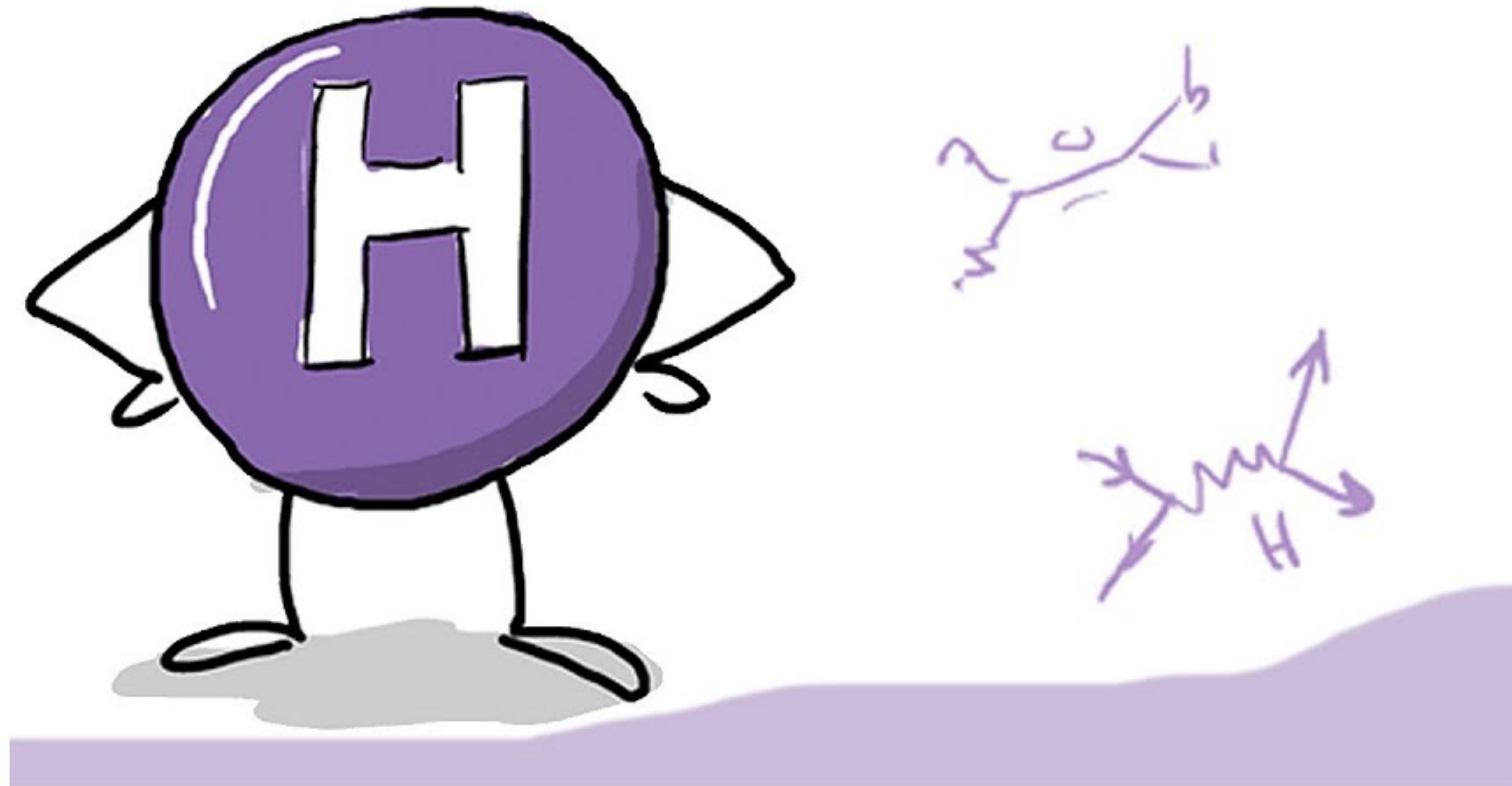
MOTIVATION

- We know that Standard Model has to break down, we just don't know where the parameter-space is!
- Higgs boson is the latest elementary particle we discovered and that makes it the least studied particle and the best candidate for BSM physics



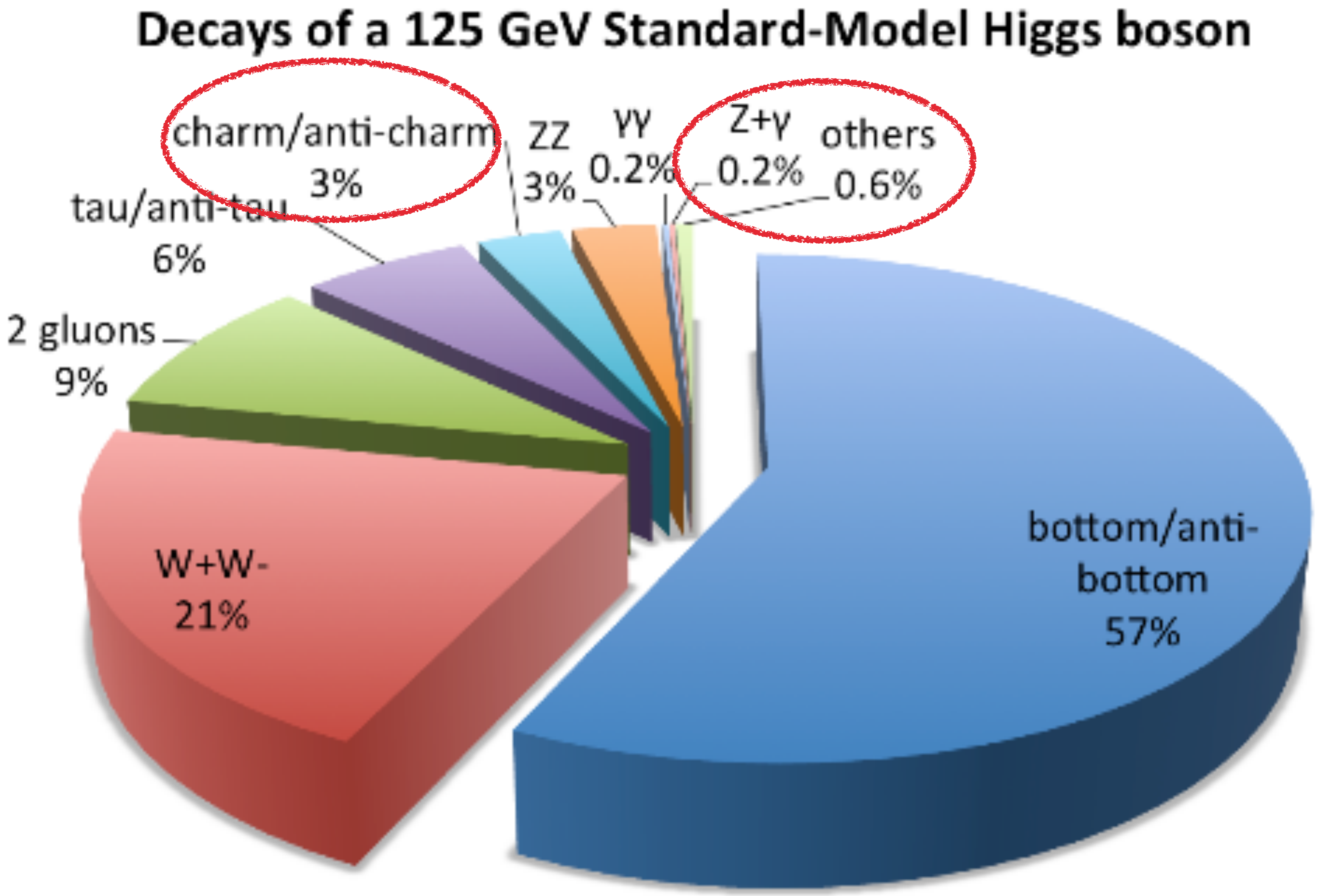


PART 1
RARE SM DECAYS



RARE HIGGS DECAYS

- Rare Higgs decays are a big challenge because of the interplay of extremely low branching ratios and overwhelming SM background
- Is the origin of mass of fermions really explained with the introduction of ad-hoc Yukawa terms?
- In the first part we focus on the ~4% if the Higgs boson decay pie, showing results utilising Run 2 data of ~140 fb^{-1} proton-proton collisions at 13 TeV

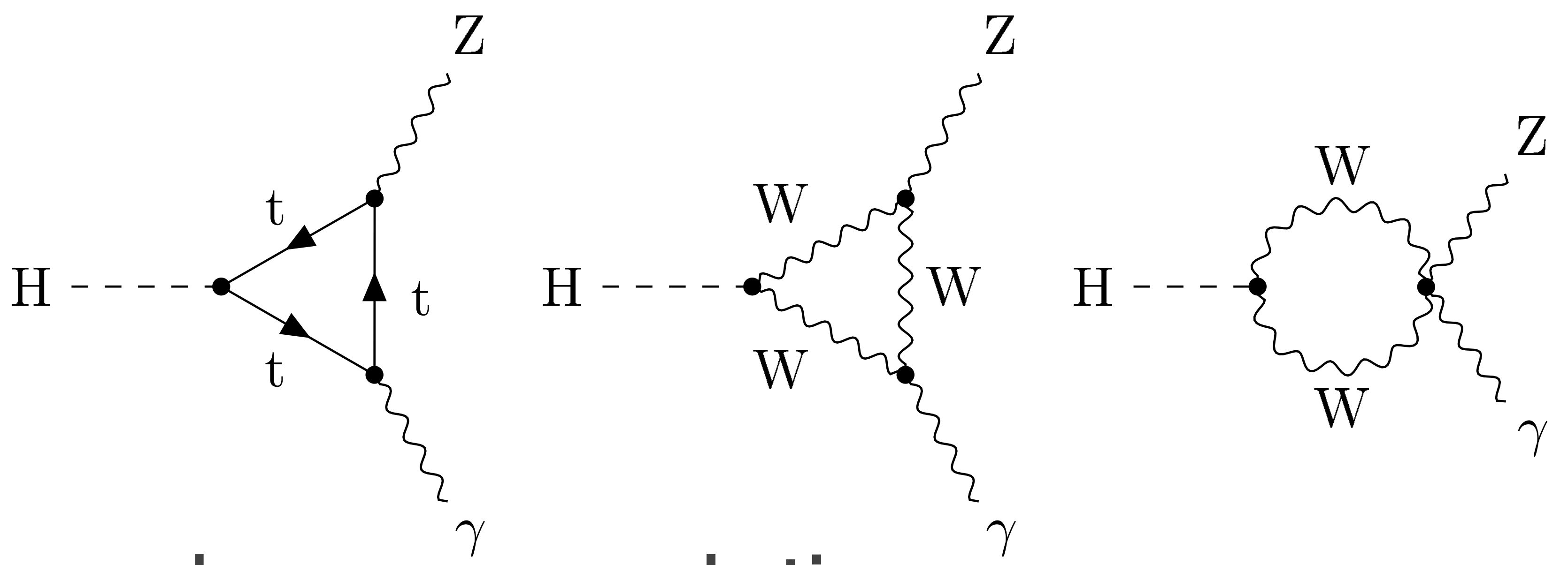


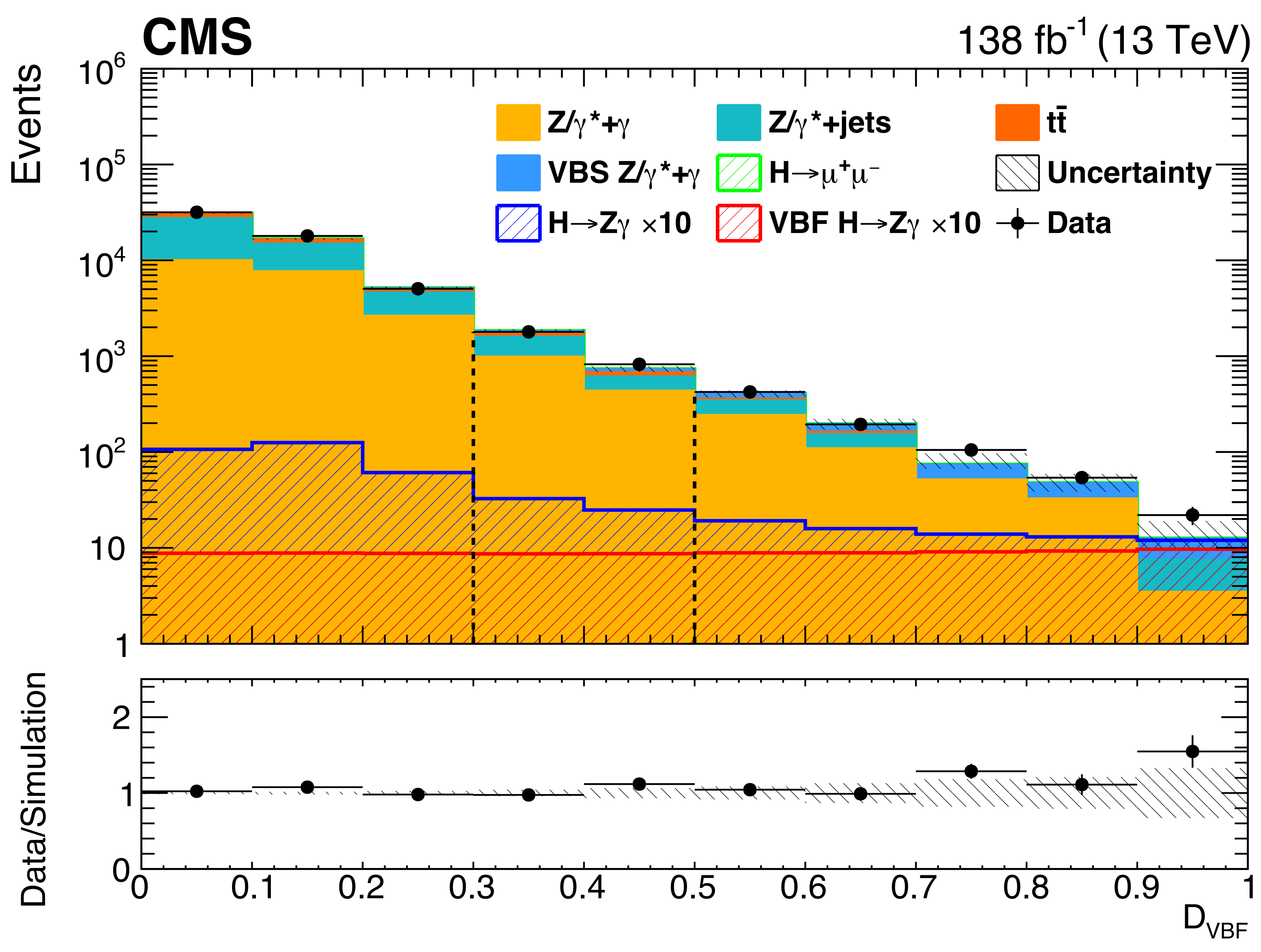
CHANNELS OVERVIEW

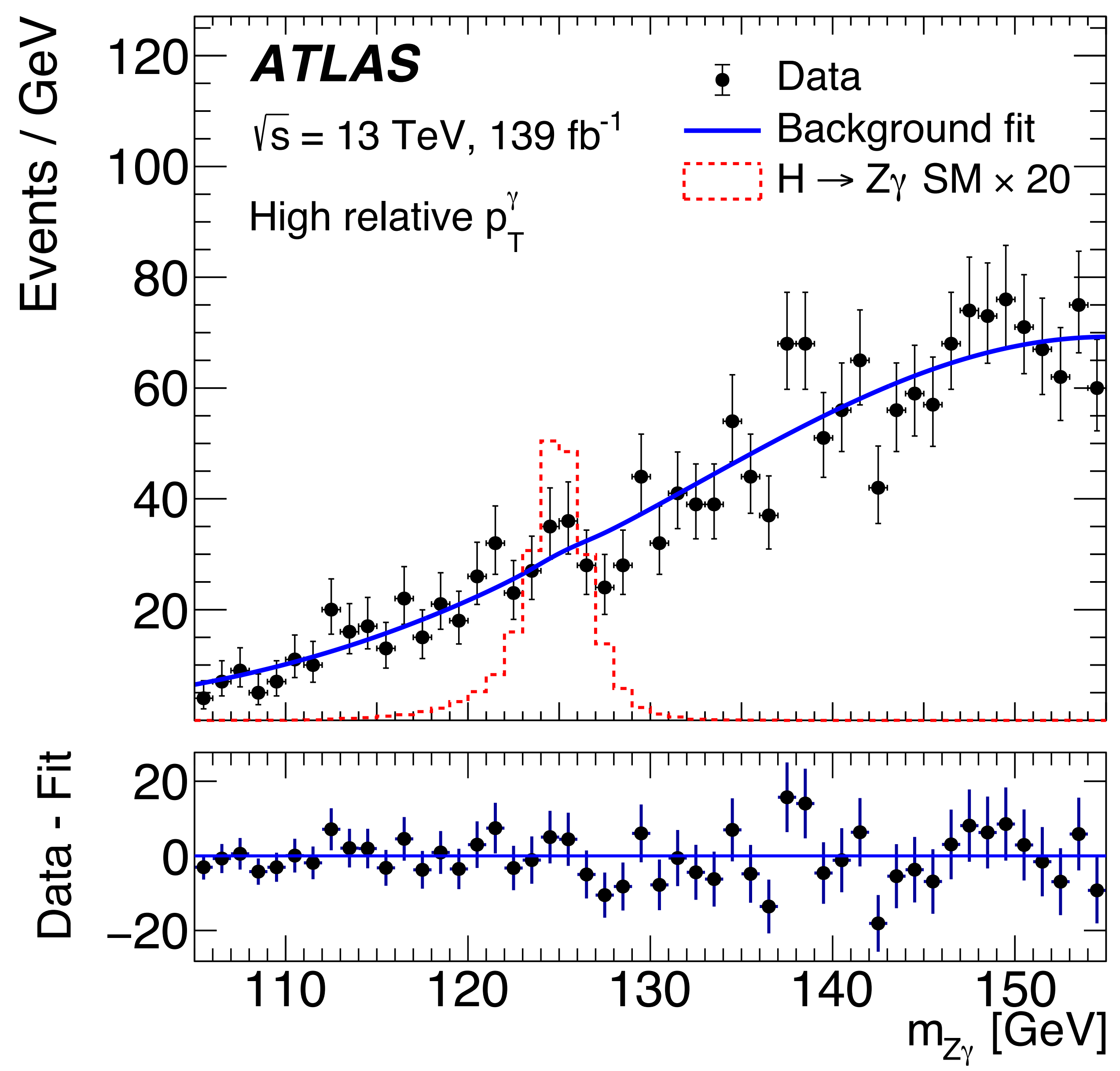
	Channel	Dataset	Publication
ATLAS	$H \to Z\gamma$	139 fb^{-1} (Run2)	Phys. Lett. B 809 (2020) 135754
CMS	$H \to Z\gamma$	138 fb^{-1} (Run2)	JHEP05(2023)233
ATLAS + CMS	$H \to Z\gamma$	139 fb^{-1}(Run2)	Phys. Rec. Lett. 132, 021803
ATLAS	$H \to \mu\mu$	139 fb^{-1}(Run2)	Phys. Lett. B 812 (2021) 135980
CMS	$H \to \mu\mu$	137 fb^{-1}(Run2)	JHEP01(2021)148
ATLAS	$H \to cc$	139 fb^{-1}(Run2)	EPJC82(2022)717
CMS	$H \to cc$	138 fb^{-1} (Run2)	Phys. Rev. Lett. 131 (2023) 061801
ATLAS	$H \to ee$	139 fb^{-1}(Run2)	Phys. Lett. B 801 (2020) 135148
CMS	$H \to ee$	138 fb^{-1}(Run2)	Phys. Lett. B 846 (2023) 137783

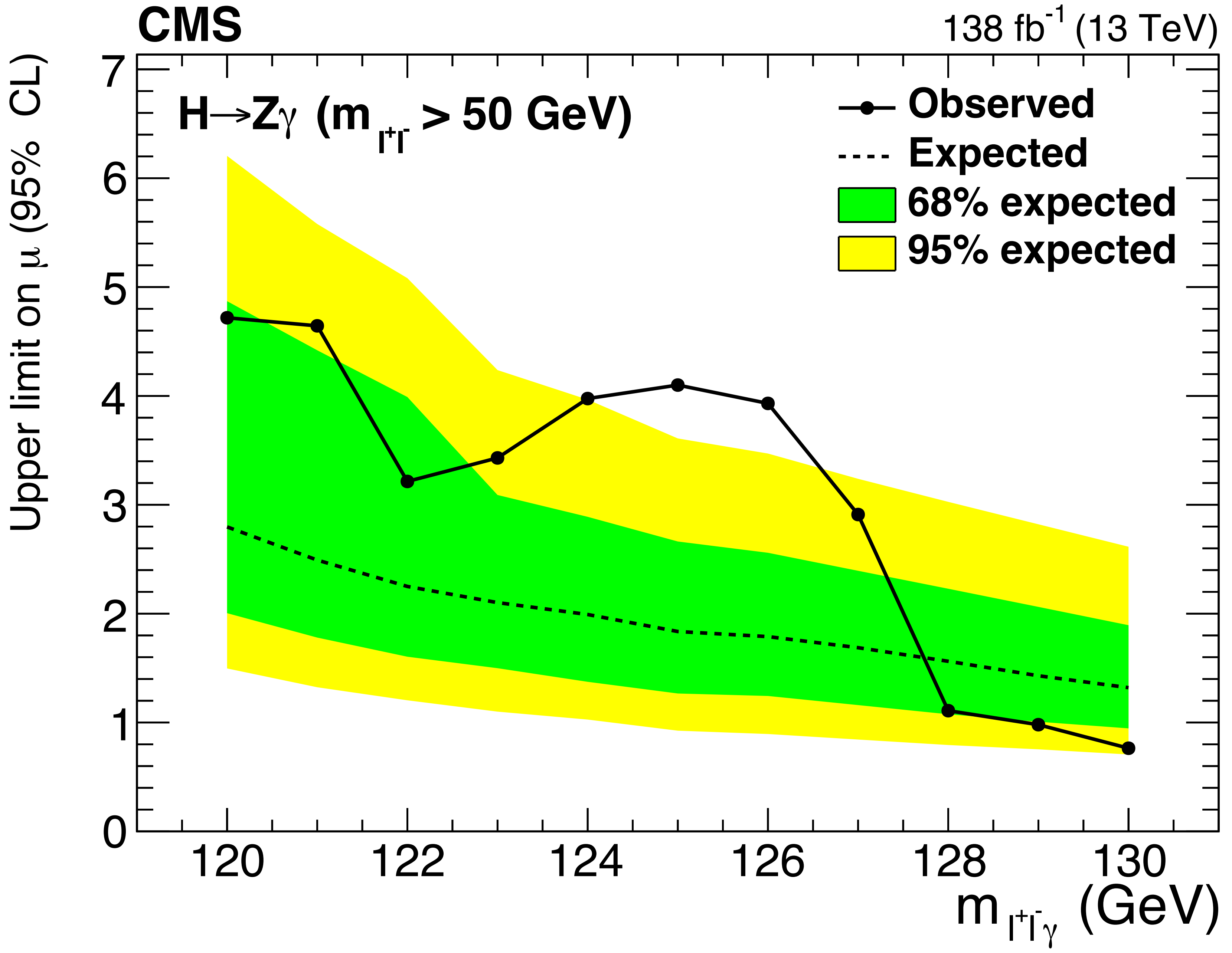
H→Zγ

- Branching ratio is 0.15%
- Analysis target ee/μμ + γ final states
  - OS SF leptons with tight mass window requirement
  - Improvements to mass resolution through FSR corrections and kinematic fits
- Several categories designed to target different production modes and mass resolution
  - machine learning classifiers used for better S/B separation
- Simultaneous S+B fit across all categories is performed on the Z γ invariant mass distribution to extract signal strengths



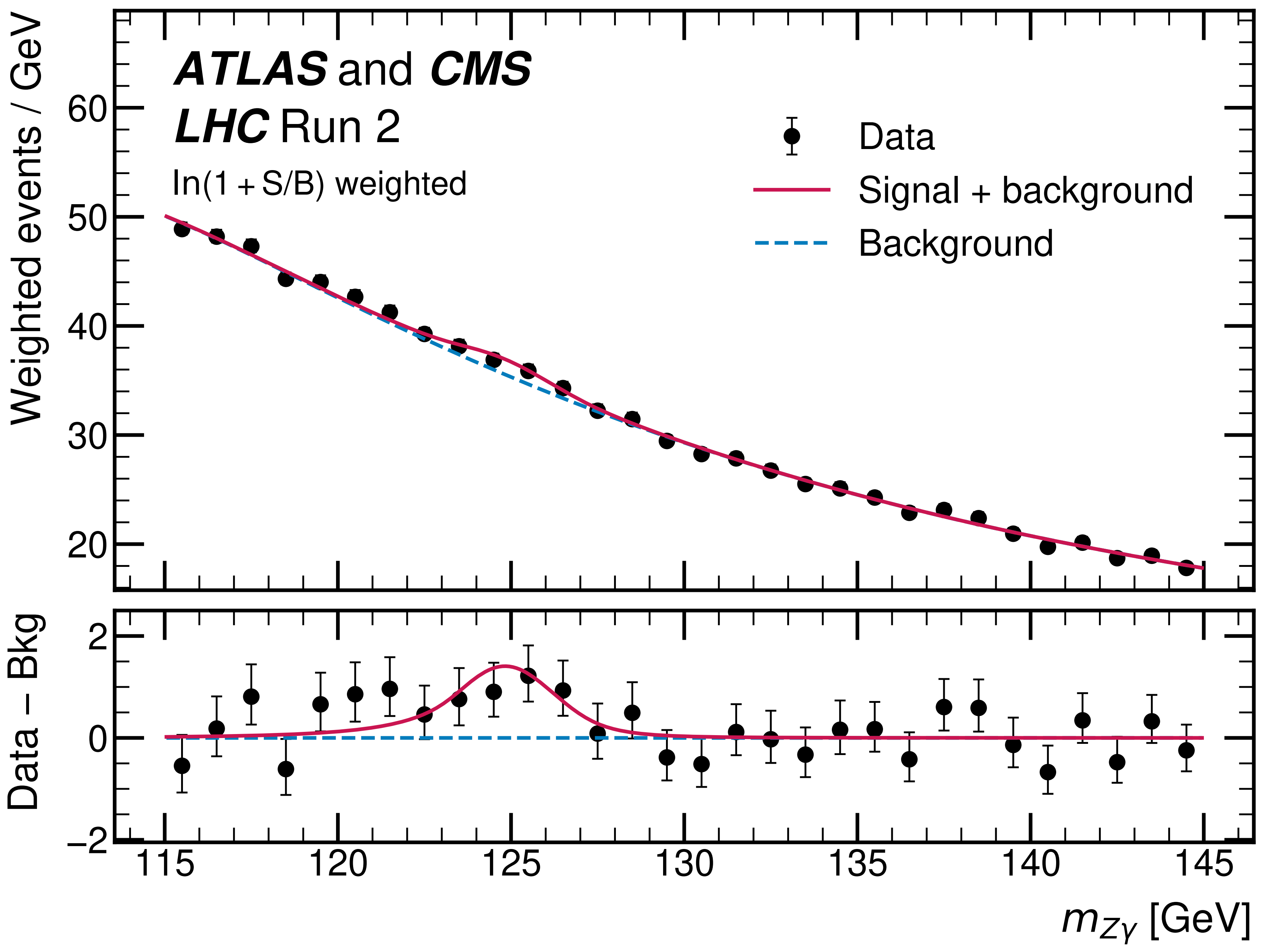


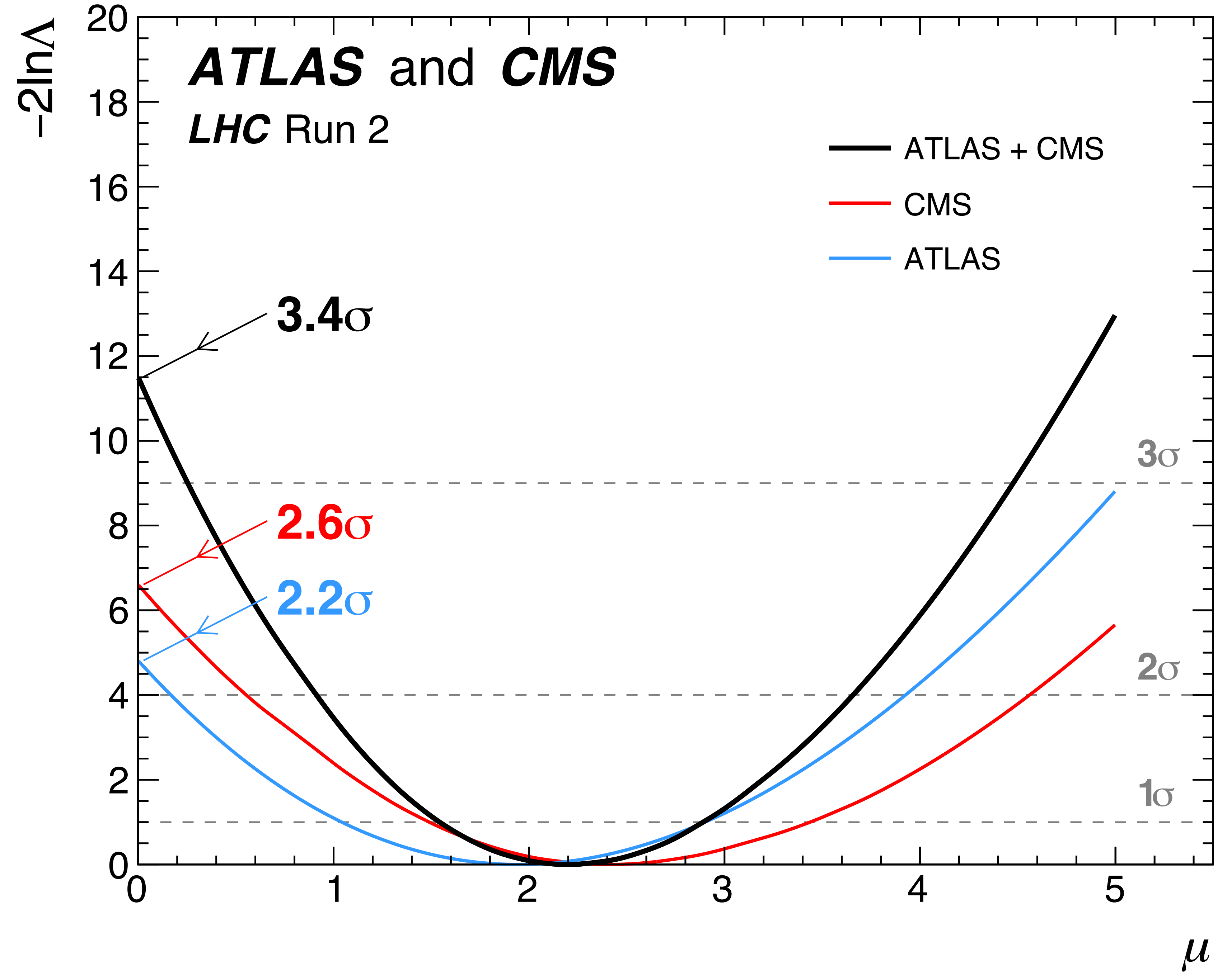




H→Zγ EVIDENCE

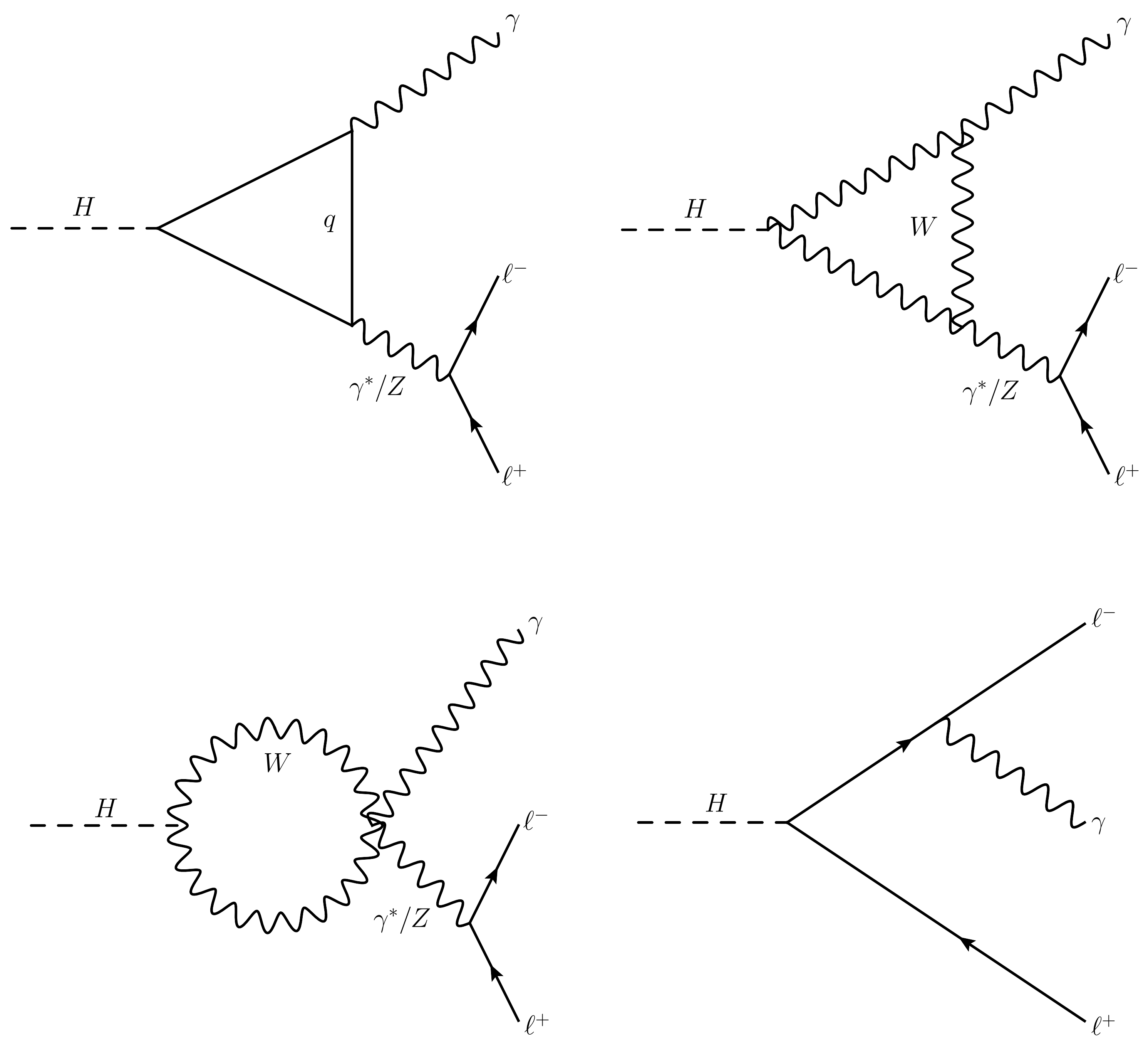
- ATLAS and CMS both observe excess compatible with SM prediction
  - ATLAS observed (expected) significance: 2.2σ (1.2 σ)
  - CMS observed (expected) significance: 2.7σ (1.2 σ)
- A combination of two measurements was performed for first evidence of H→Zγ decay:
  - ATLAS + CMS observed (expected) significance: 3.4σ (1.6 σ)
  - $\mu = 2.2 \pm 0.6\ (\text{stat.})^{+0.3}_{-0.2}\ (\text{syst.})$

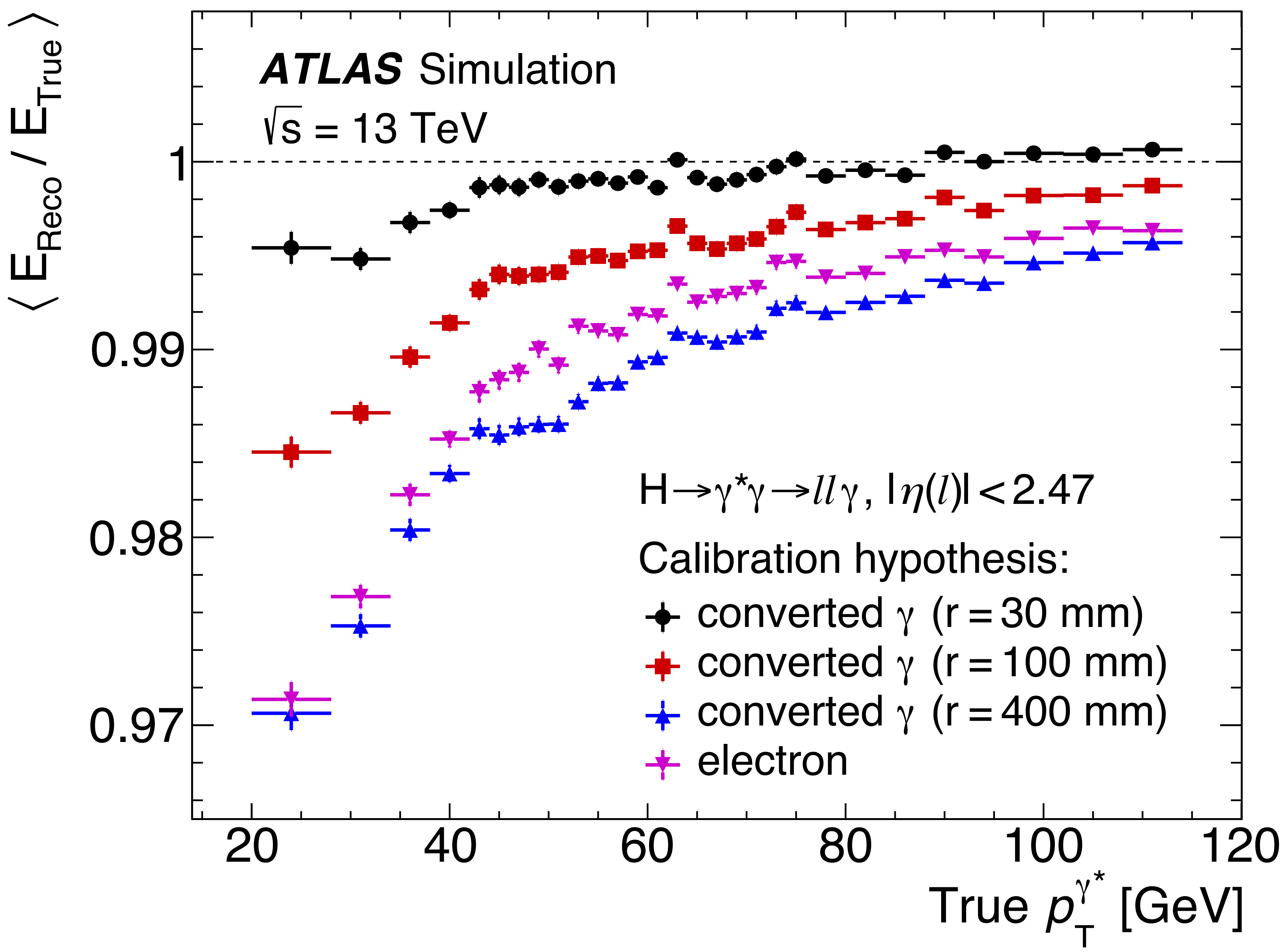


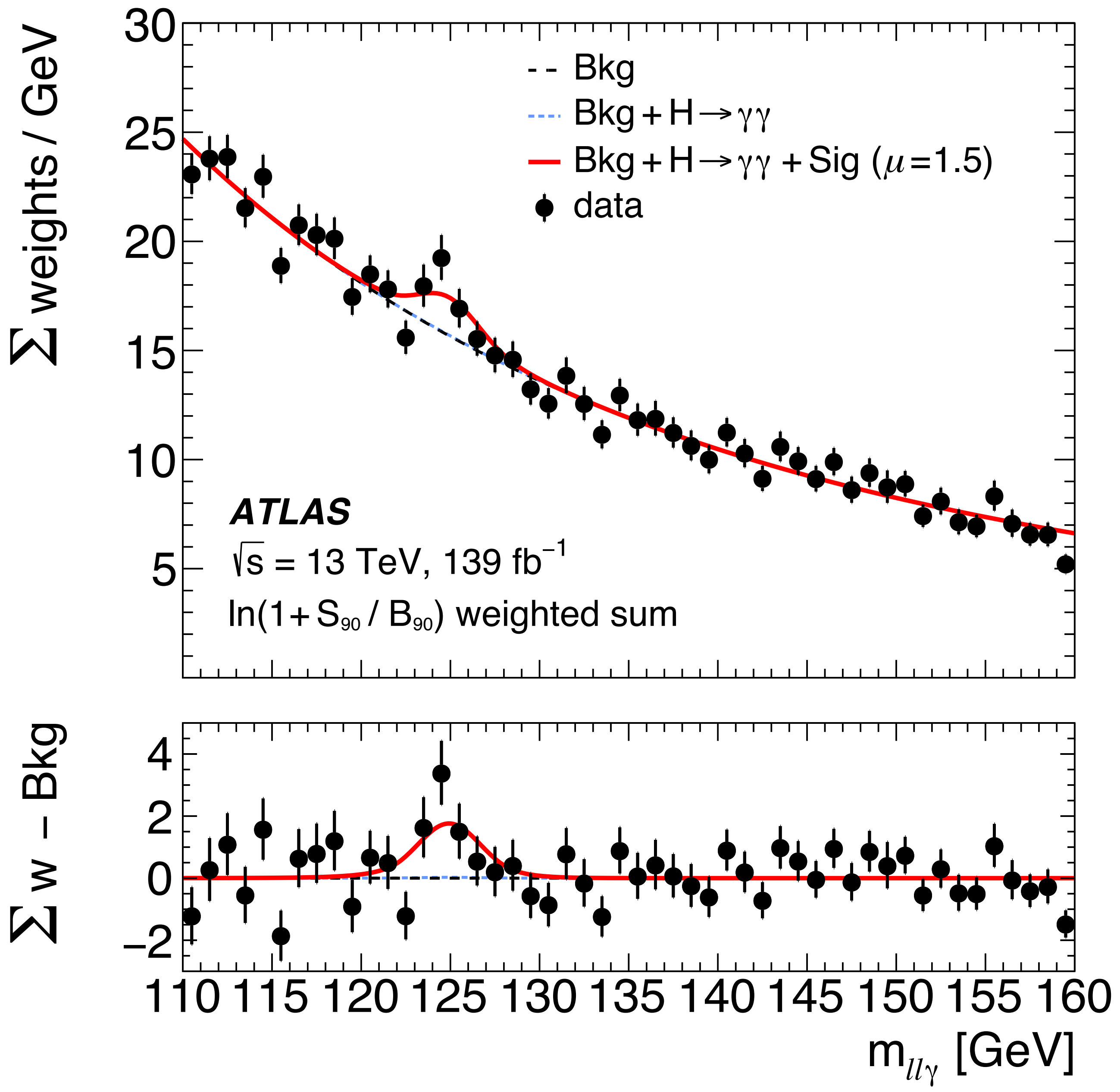


$H \to (Z/\gamma^*)\gamma$ EVIDENCE

- A dedicated analysis targeting Z/γ^* and decays of H boson to two leptons with a photon from FSR
  - $m_{ll} < 30$ GeV ensures orthogonality with previous analysis
- Because of event kinematics it is common for the energy deposit of two electrons to be reconstructed as a single cluster:
  - custom calibration and classification designed
- ATLAS observed (expected) significance: 3.2σ ($2.1\ \sigma$)
- $\mu = 1.5 \pm 0.5$



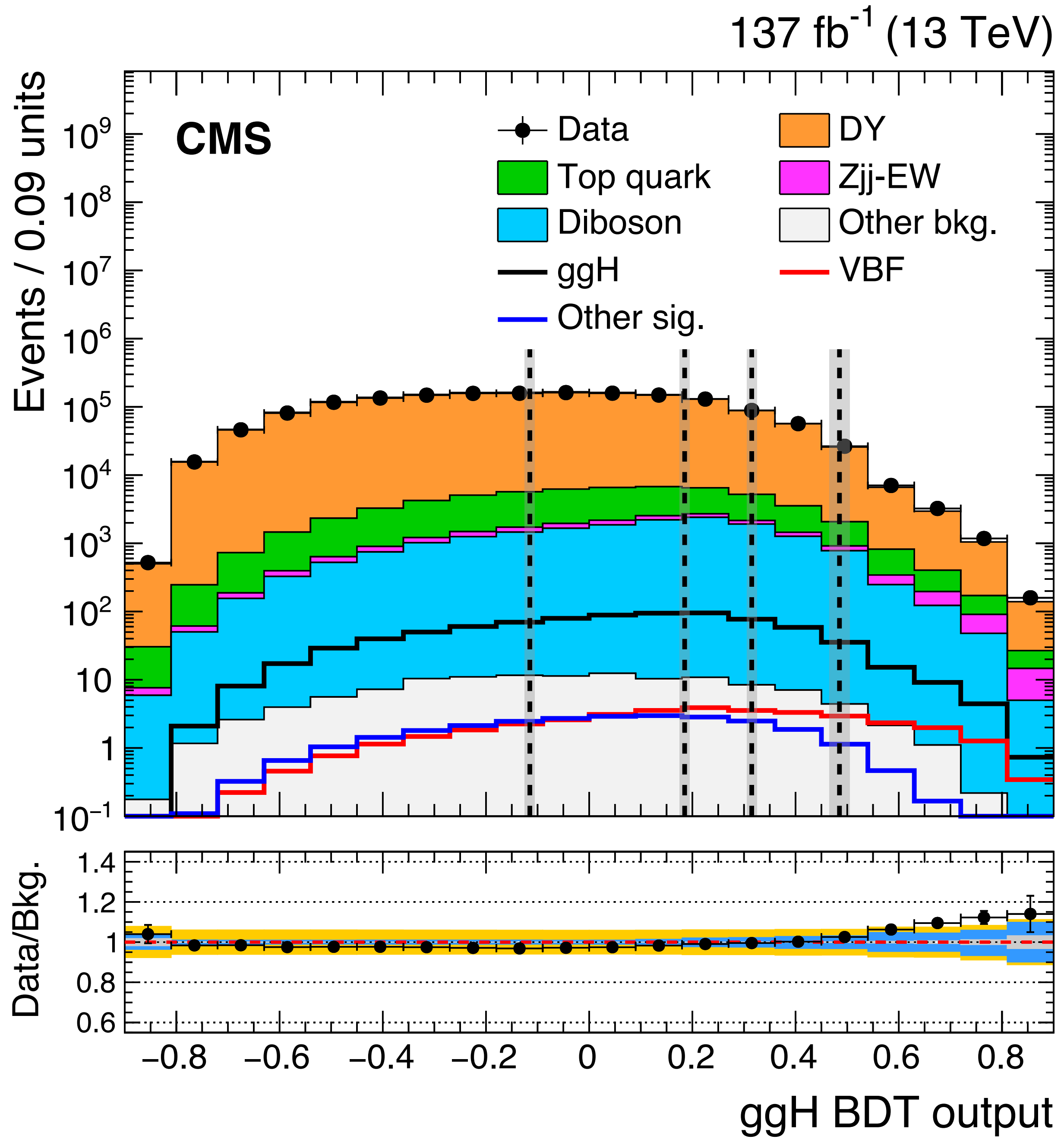


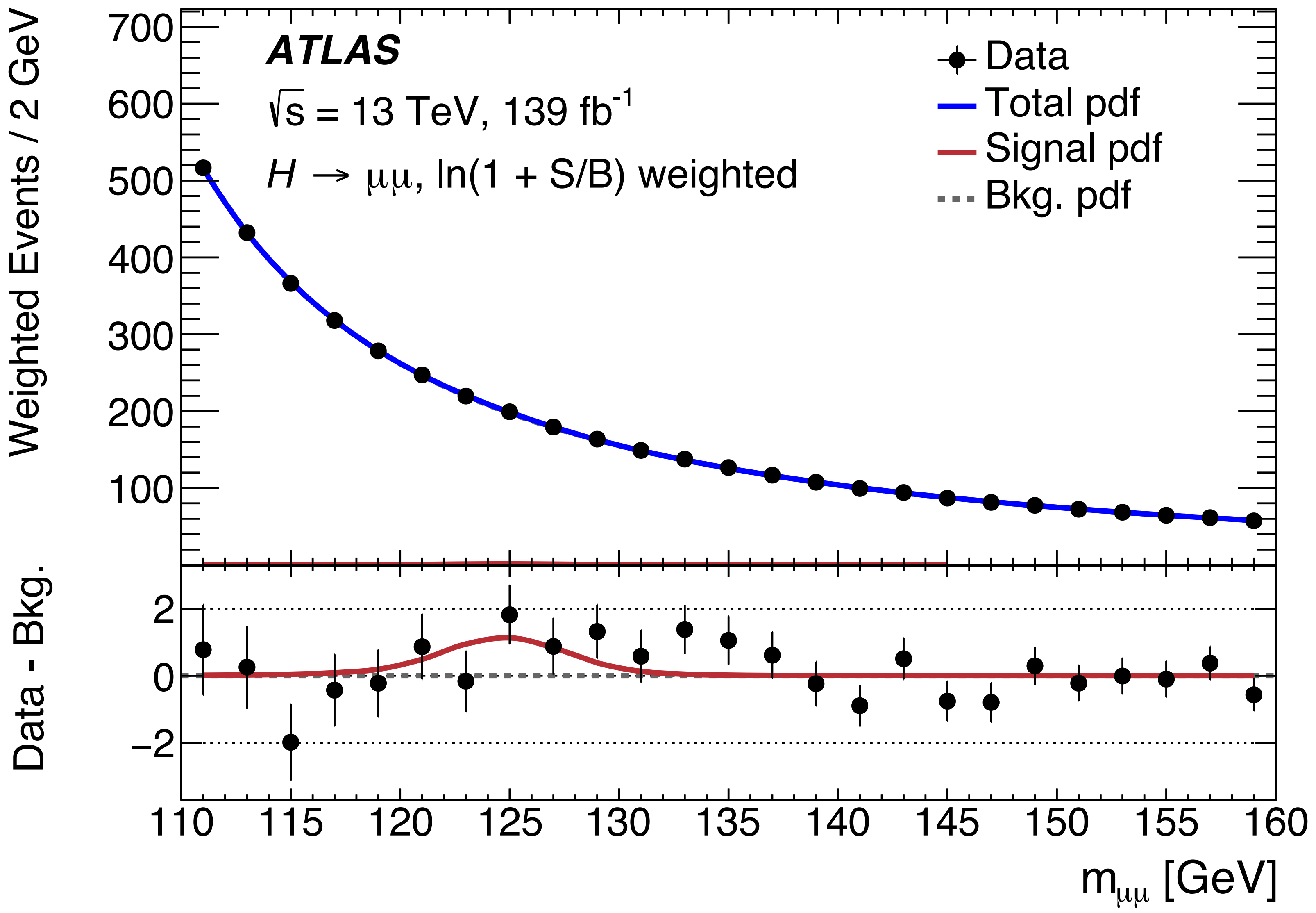


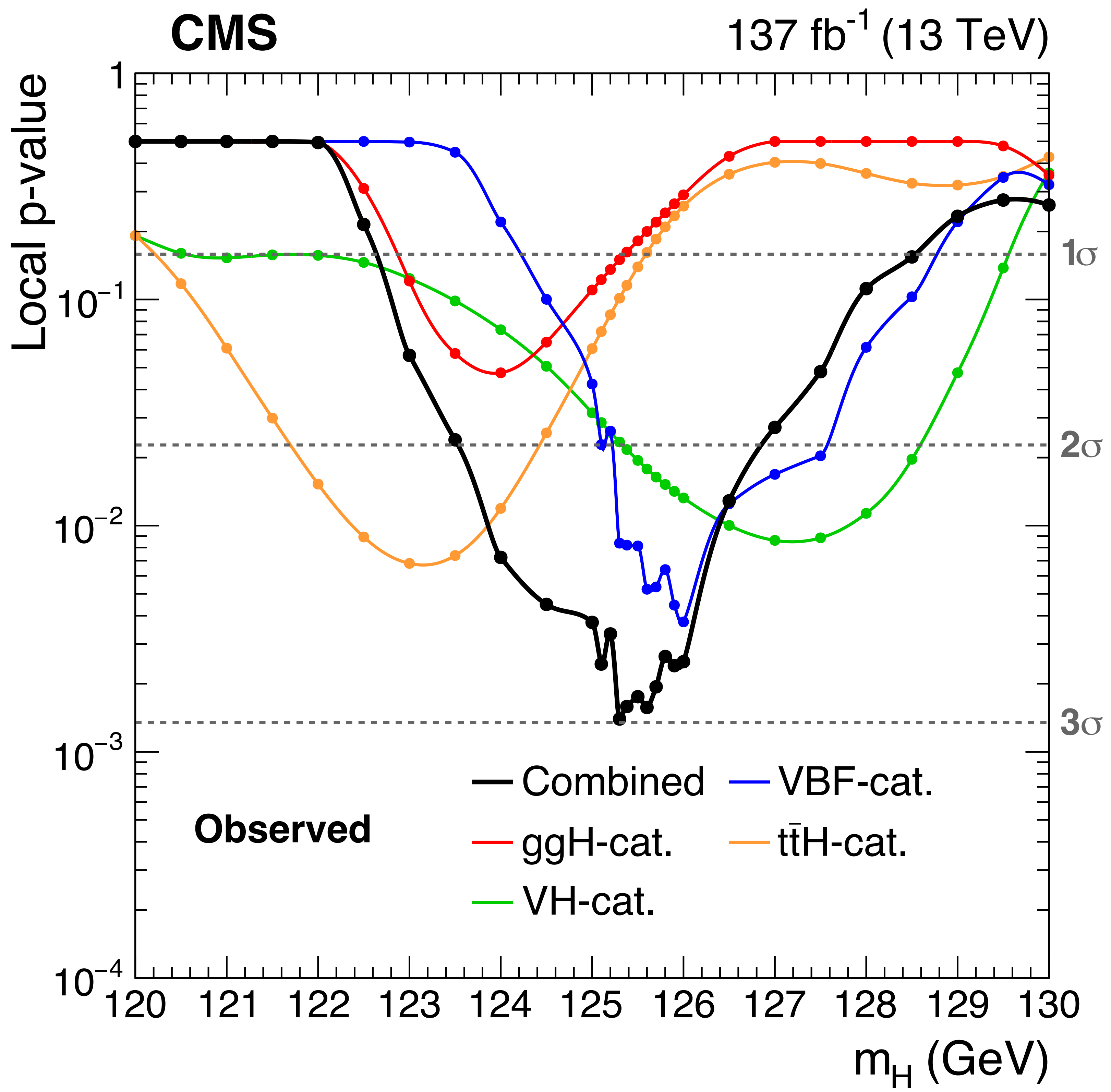
Phys. Lett. B 819 (2021) 136412

$H \rightarrow \mu\mu$

- Branching ratio is 0.02% + very high background rates
- Sensitivity highly correlated with $m_{\mu\mu}$ resolution
- Analysis categories designed to target main production modes
  - Sensitivity enhanced through FSR corrections + machine-learning
- ATLAS observed (expected) significance: 2.0σ (1.7 σ)
- CMS observed (expected) significance: 3.0σ (2.5 σ)

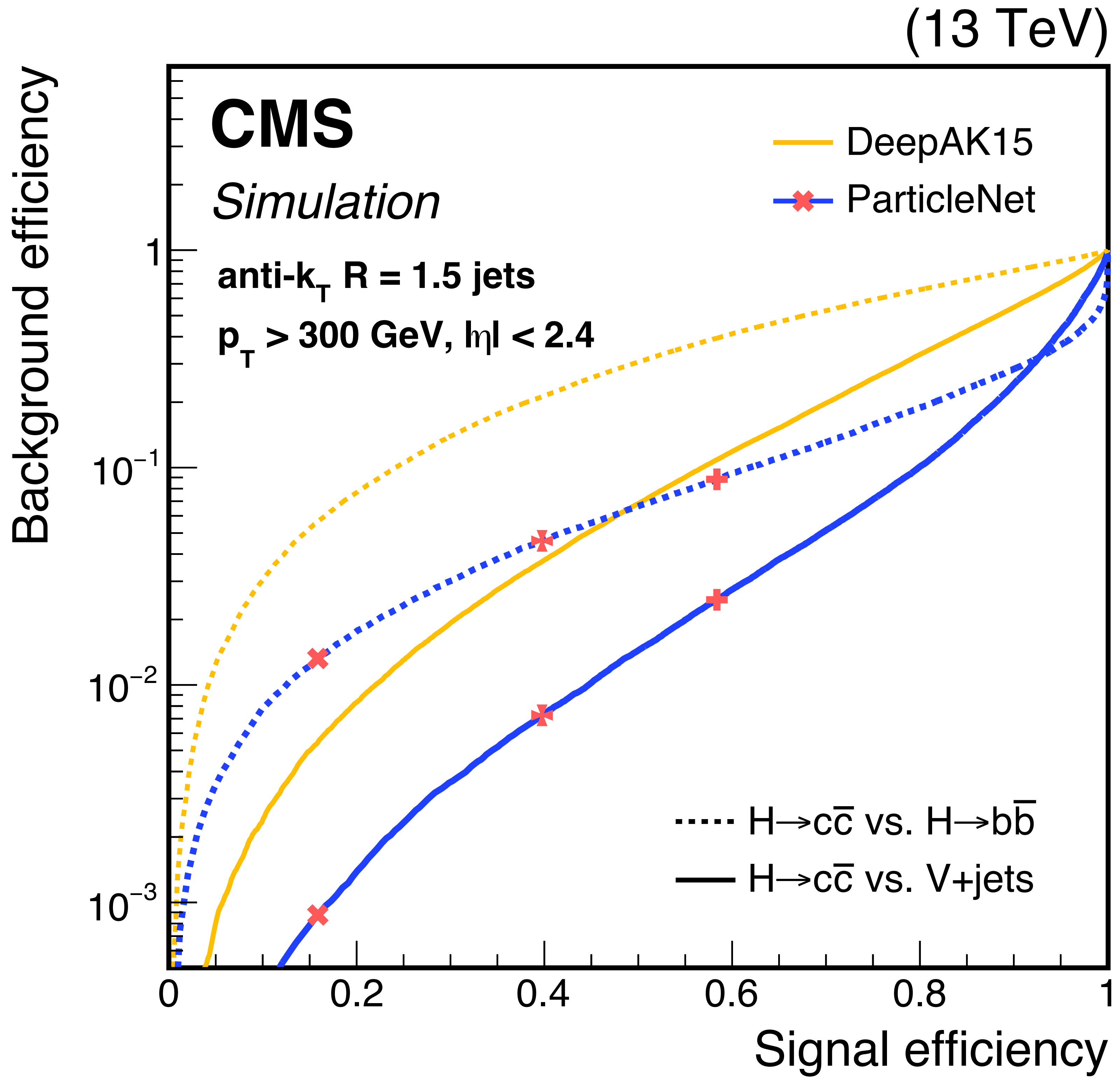






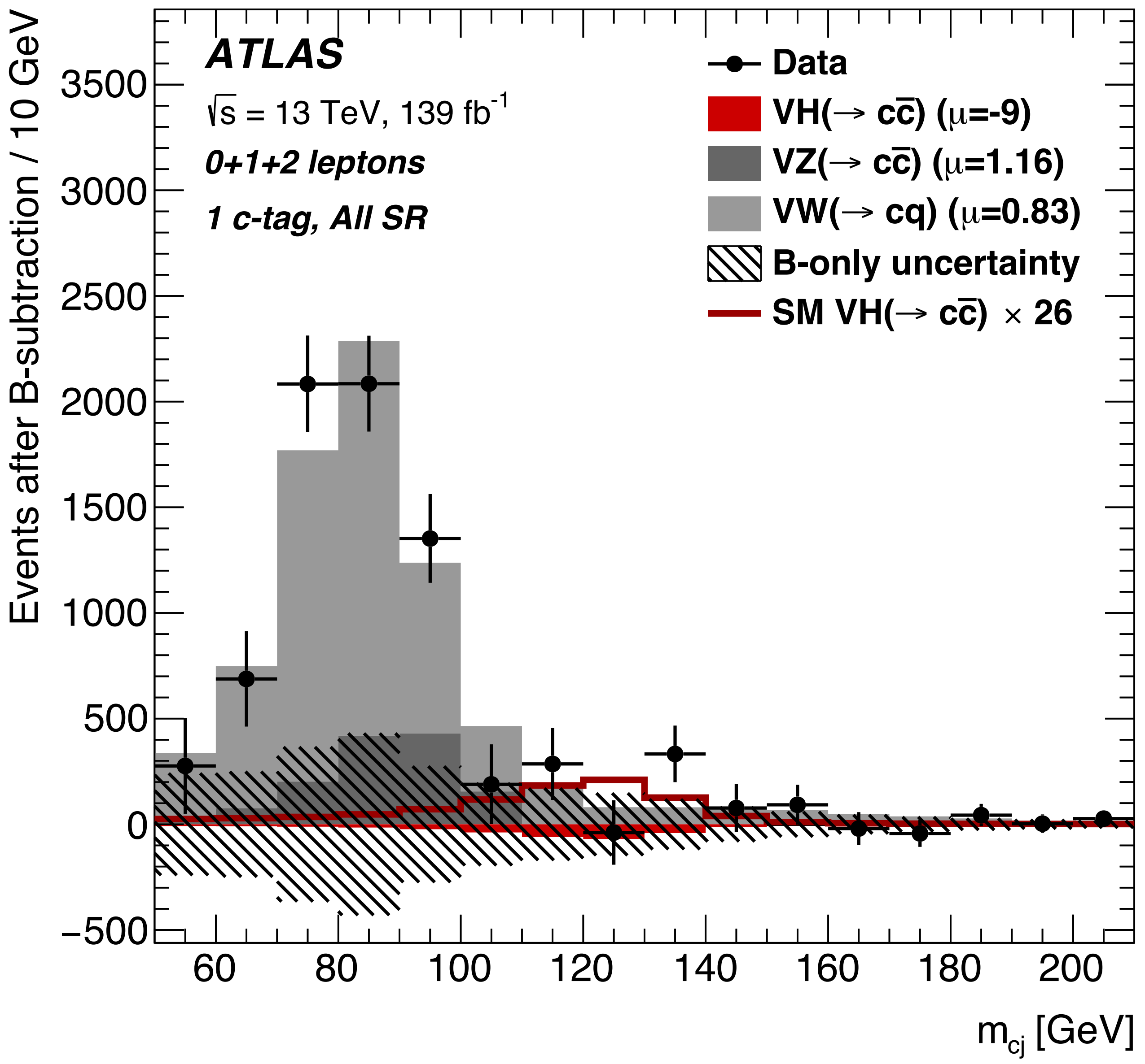
H→cc

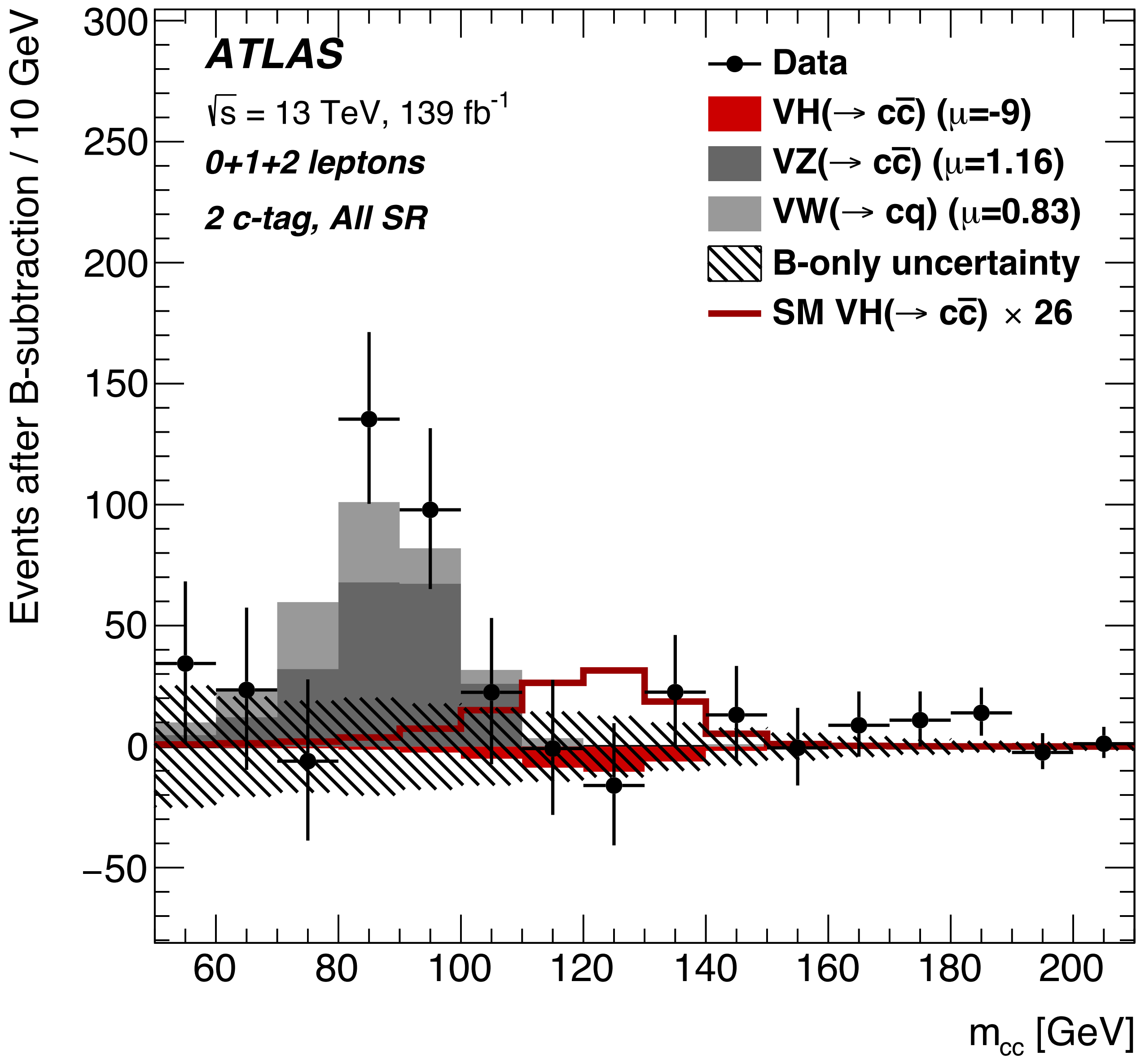
- Branching ratio is 3% + extremely high QCD background
- Associated production studied VH(cc)
- c-taggers critical for success
  - hadrons containing c-quarks have measurable lifetime (120 - 300 μm)
- Graphical neural networks used for c-tagging designed to separate signal vs:
  - light jets
  - H→bb
- c-tagging is still a challenge with ~20-50% efficiency with considerable background leakage of ~10%
  - still significant improvements wrt to precious state-of-the-art taggers
- Significant systematic uncertainties

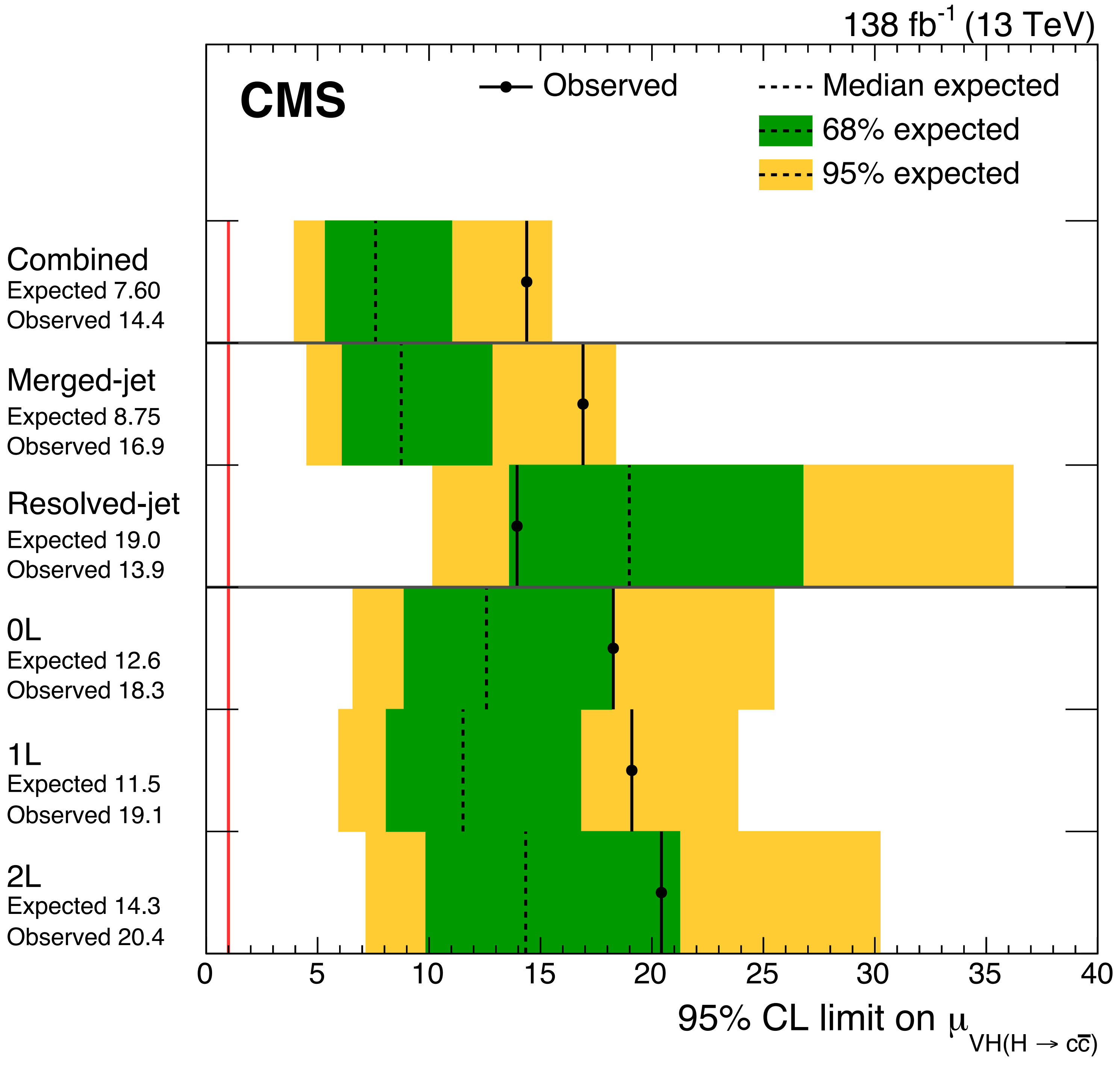


H→cc

- Targeting resolved (CMS + ATLAS) and boosted topologies (CMS)
  - Extensive use of machine-learning classifiers for better signal-background discrimination and category definition
- Signal extracted from c-tagging discriminant (CMS) or invariant mass m_{cc} (ATLAS)
- ATLAS observed (expected) upper limit @95% CL: $\mu < 26 * \mathrm{SM}\,(31\ \mathrm{exp.})$
- CMS observed (expected) upper limit @95% CL: $\mu < 14.4 * \mathrm{SM}\,(7.6\ \mathrm{exp.})$







$H \rightarrow cc$

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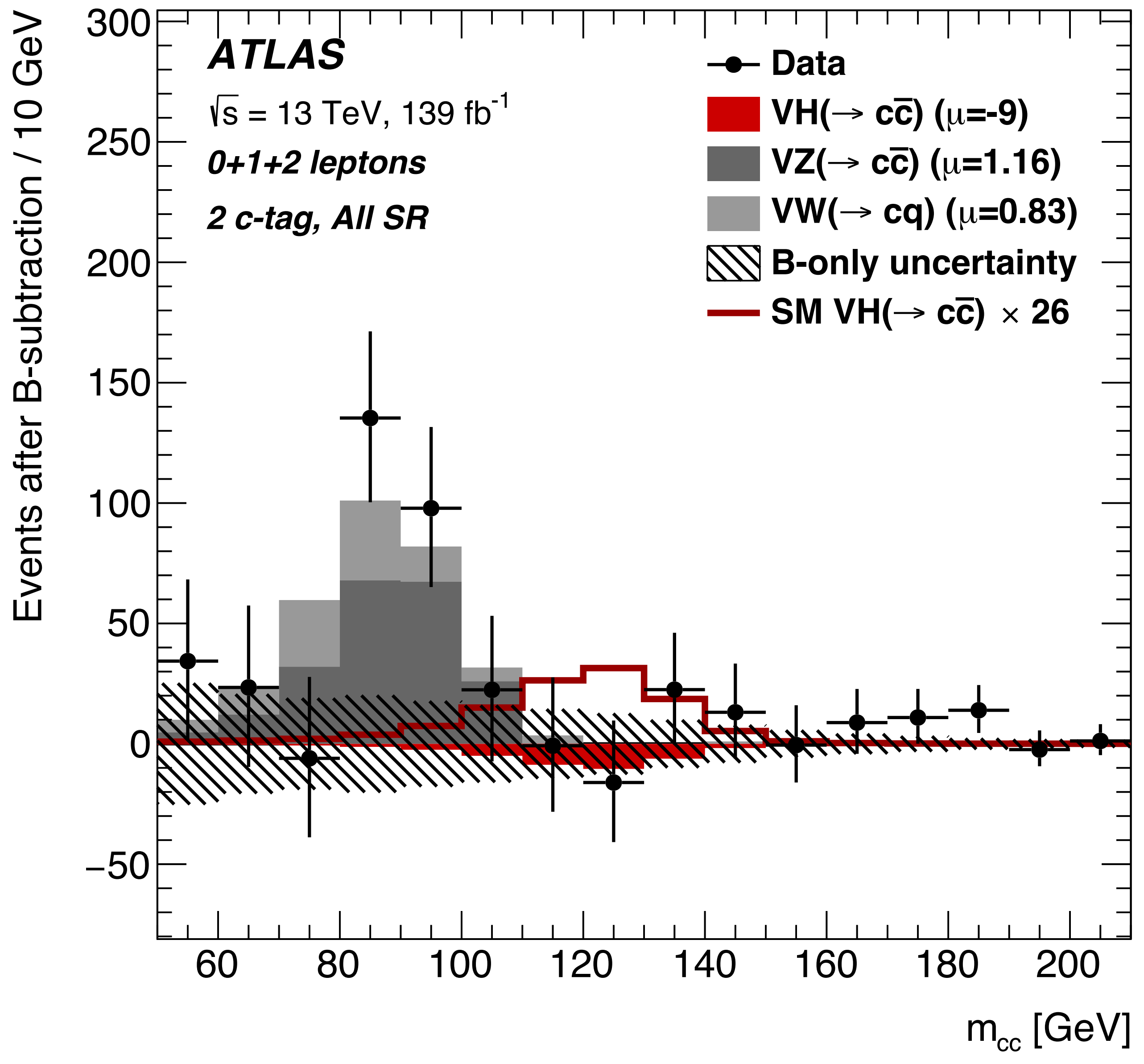
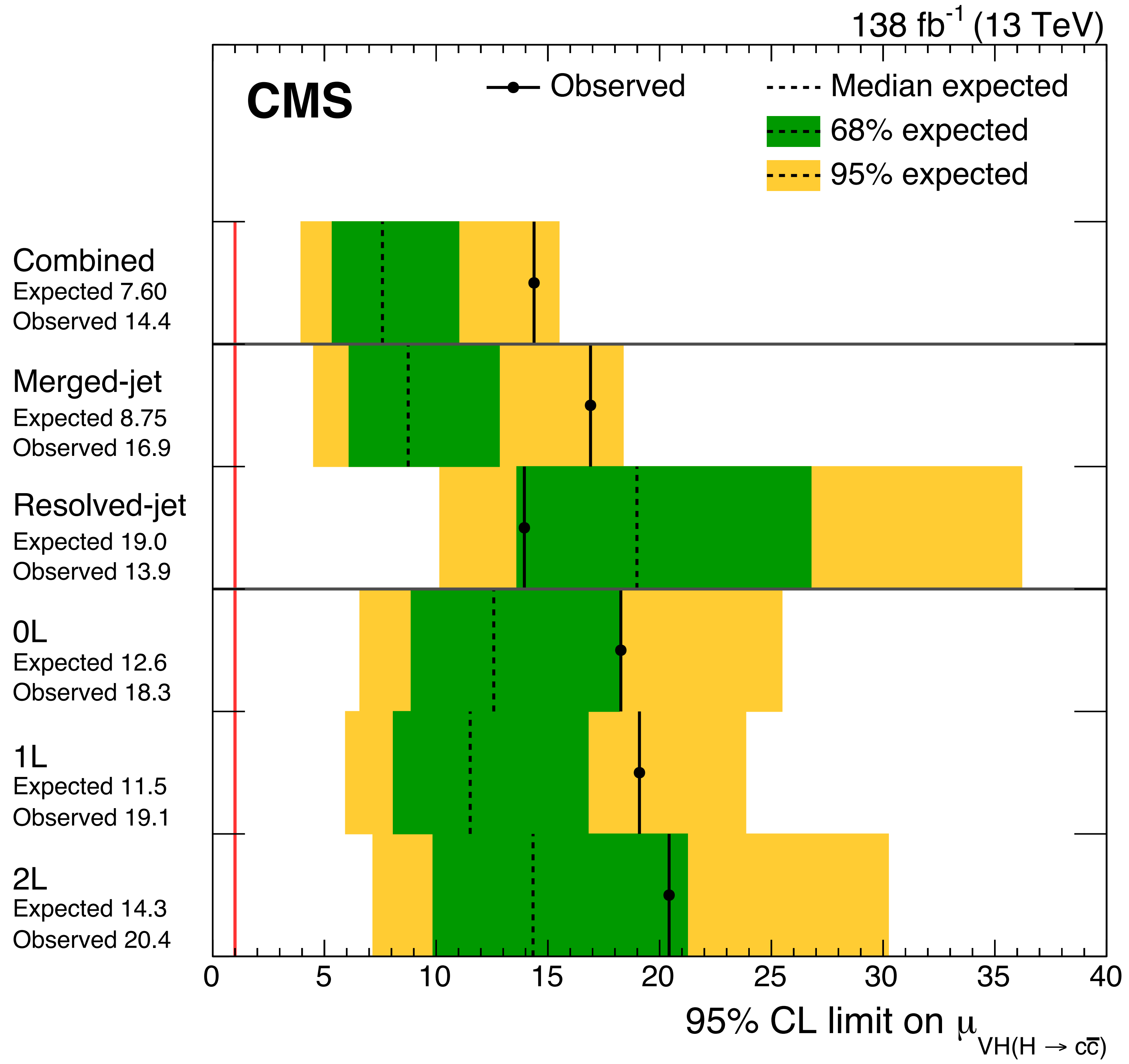
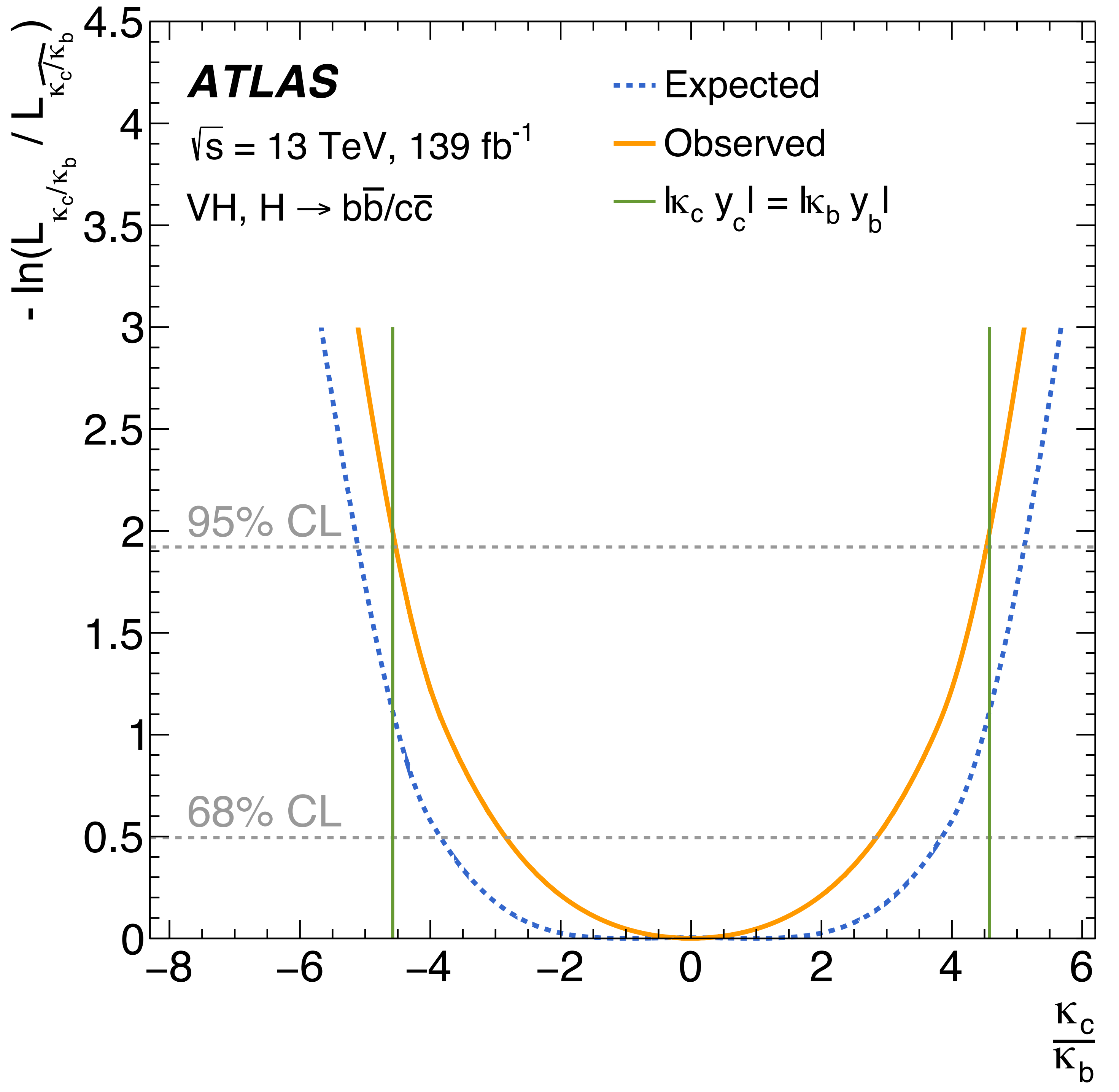
- Combination with VH(bb) used to set limits on κ_c/κ_b ratio < 4.5 (smaller than ratio of masses)

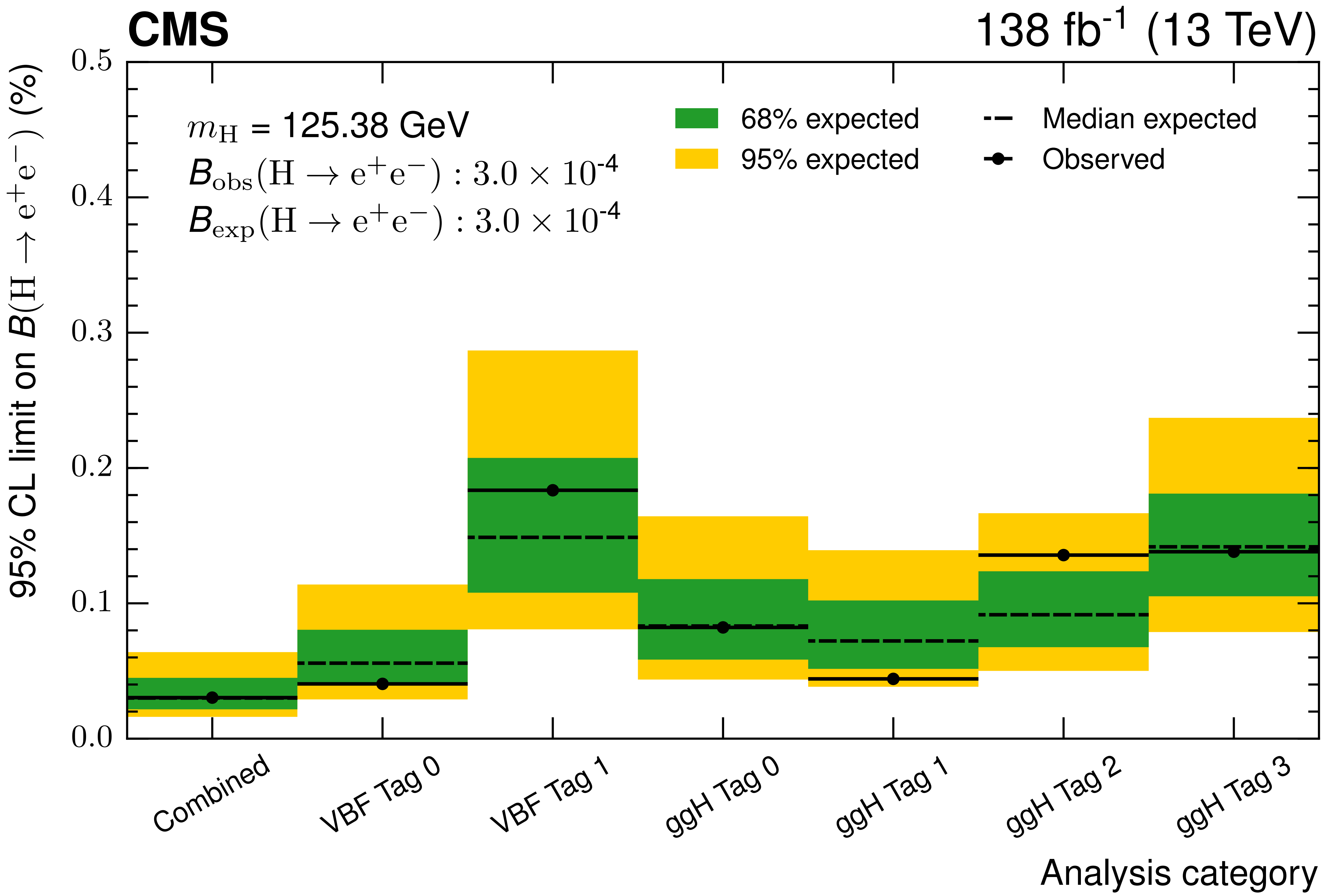


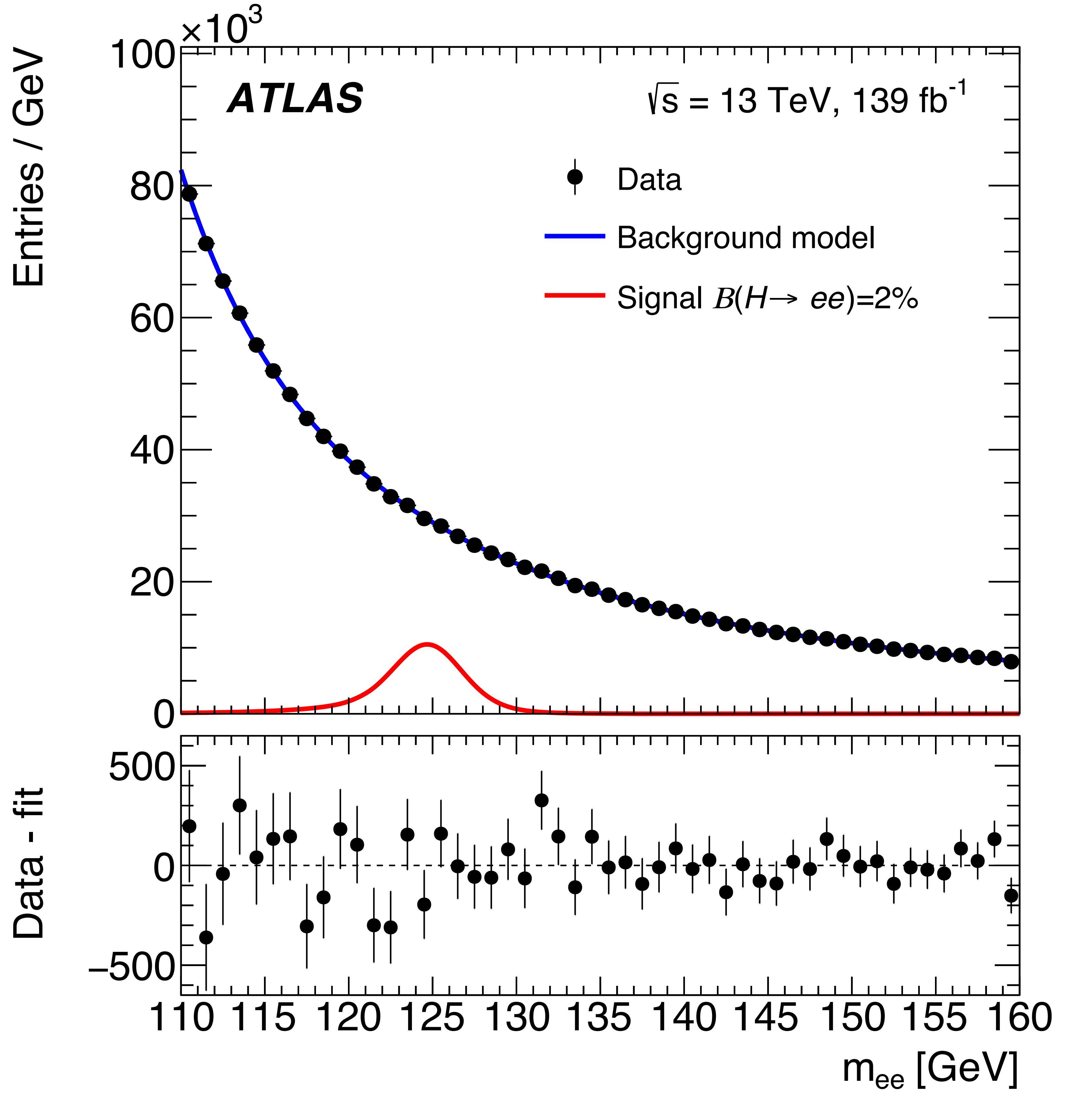




$H \to ee$

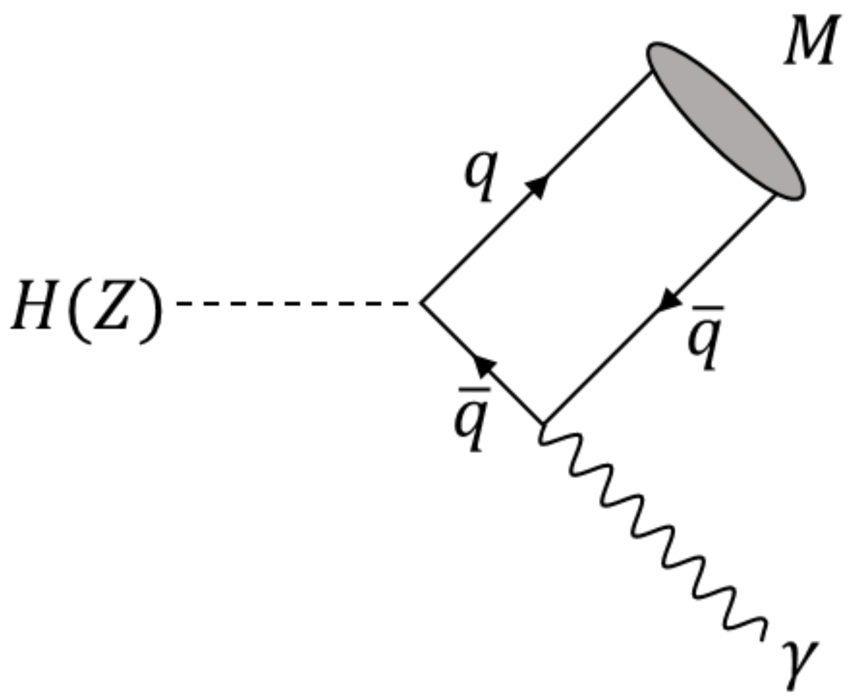
- Extremely small branching ratio of $5 \cdot 10^{-9}$
  - ATLAS upper limit @95% CL: $\mathrm{BR} < 3.6 \cdot 10^{-4}$
  - CMS upper limit @95% CL: $\mathrm{BR} < 3.0 \cdot 10^{-4}$

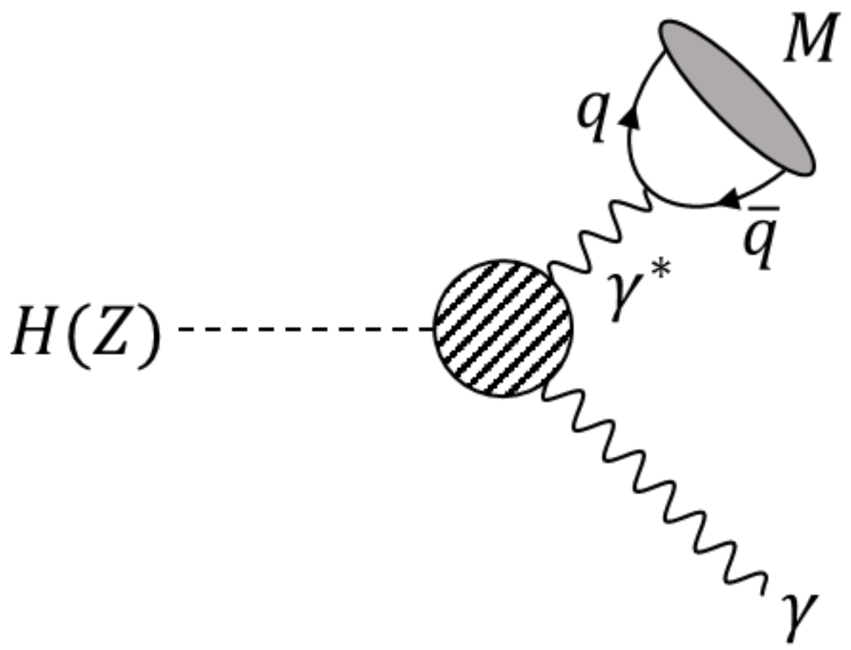


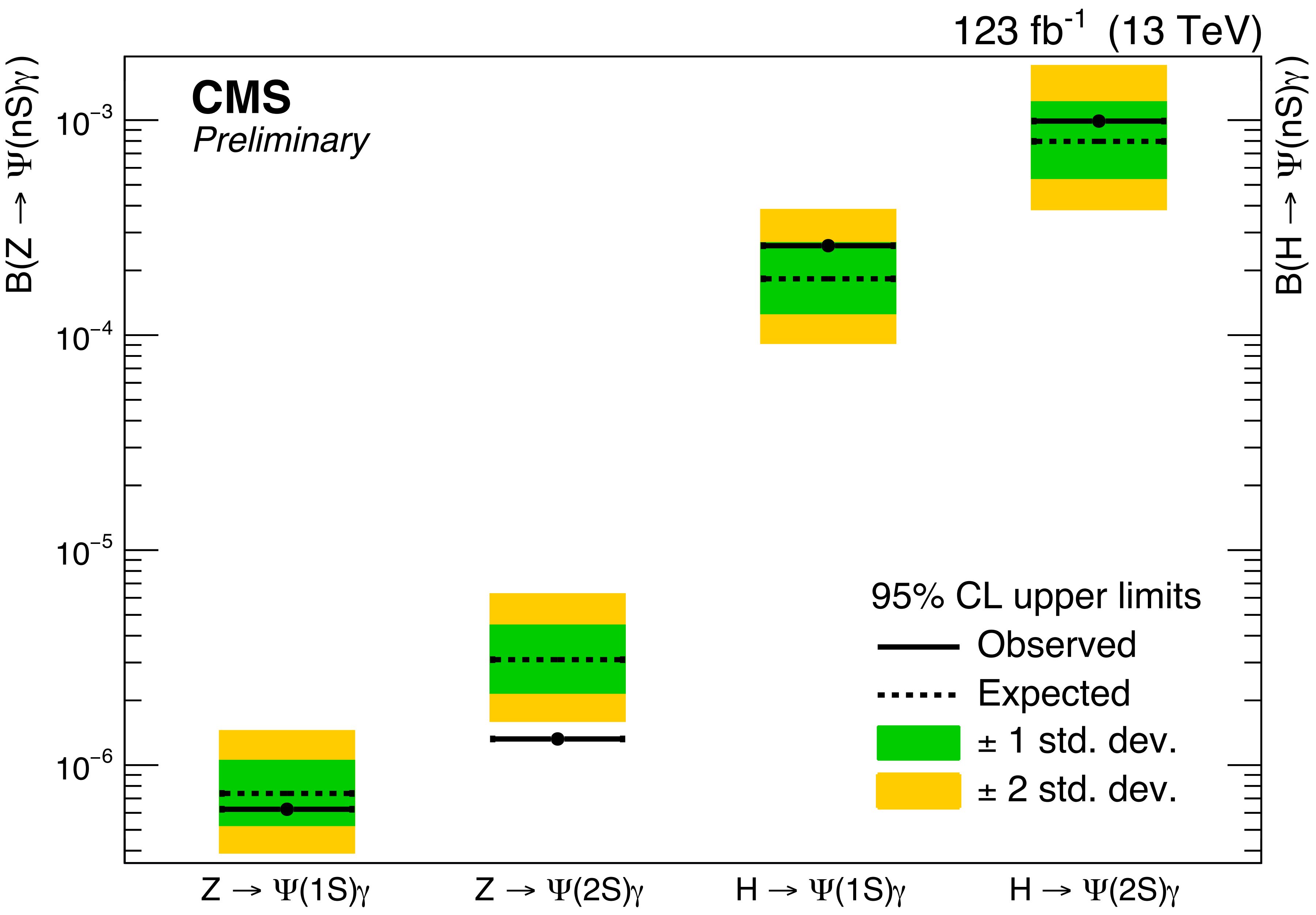


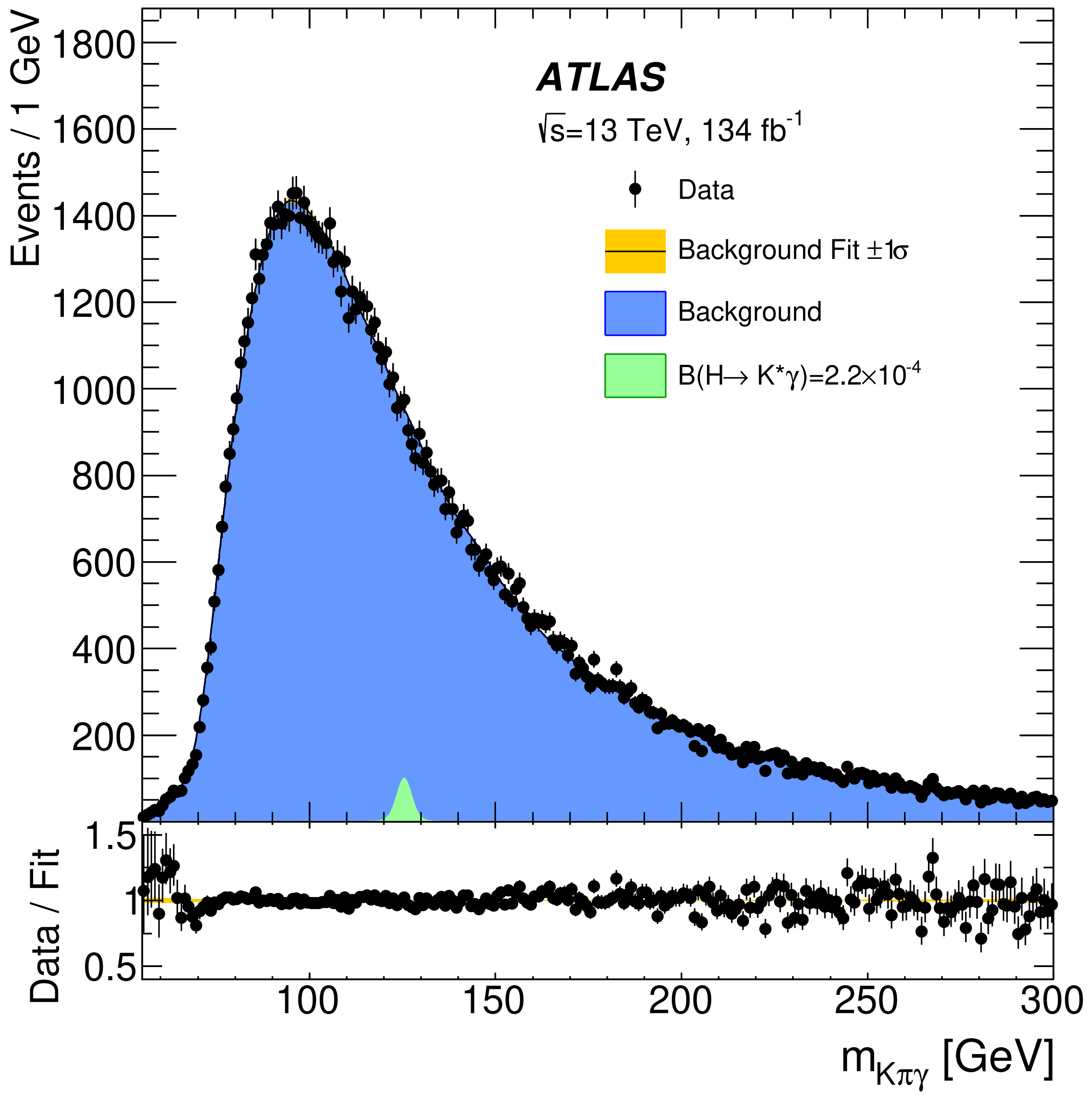
H→QUARKONIA

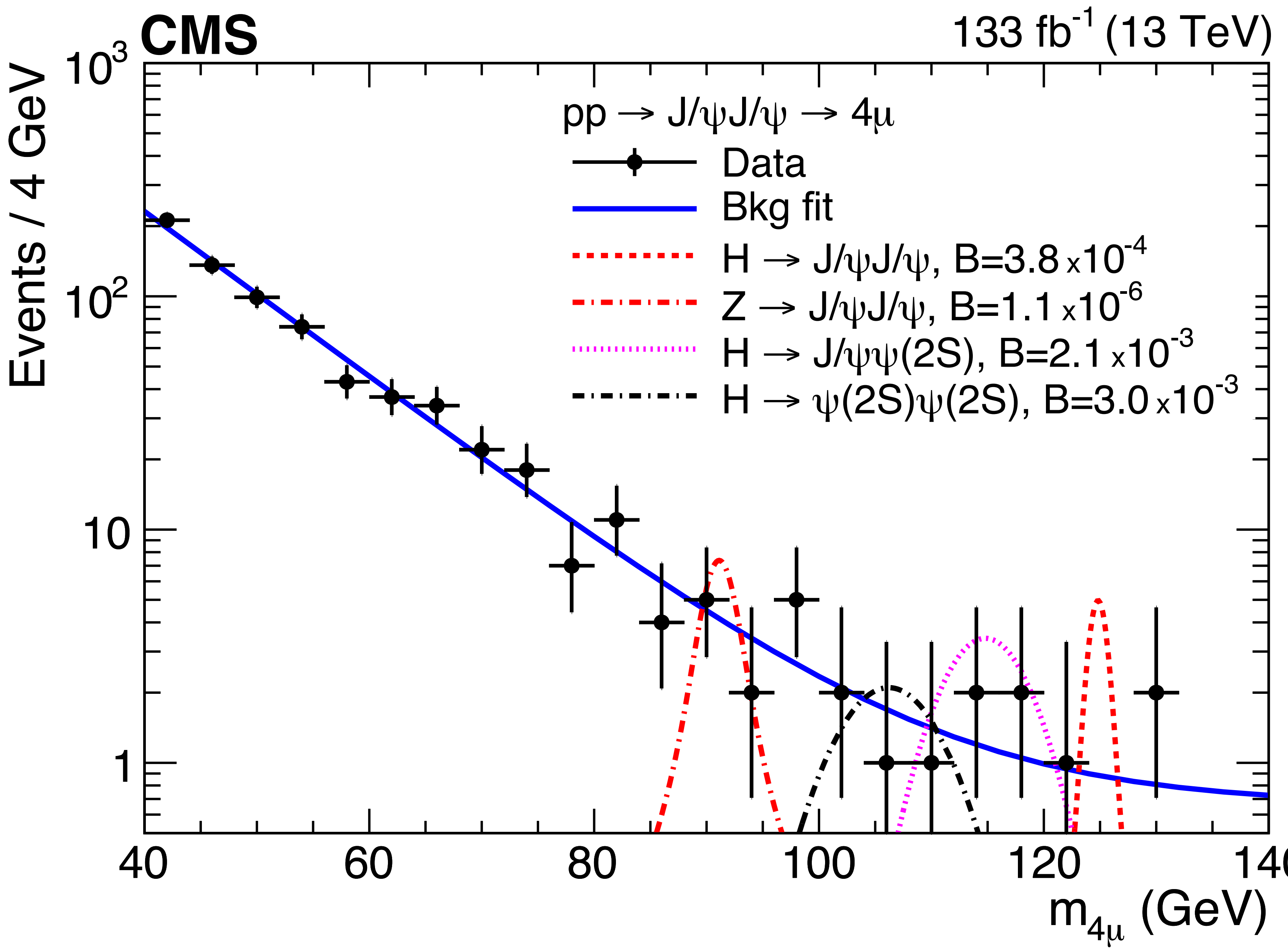
- Extremely small branching ratios in SM
- In theory sensitive to couplings to light quarks
  - strong interference between diagrams destroys scaling of BR with κ_q
- Many limits set, everything in agreement with SM prediction









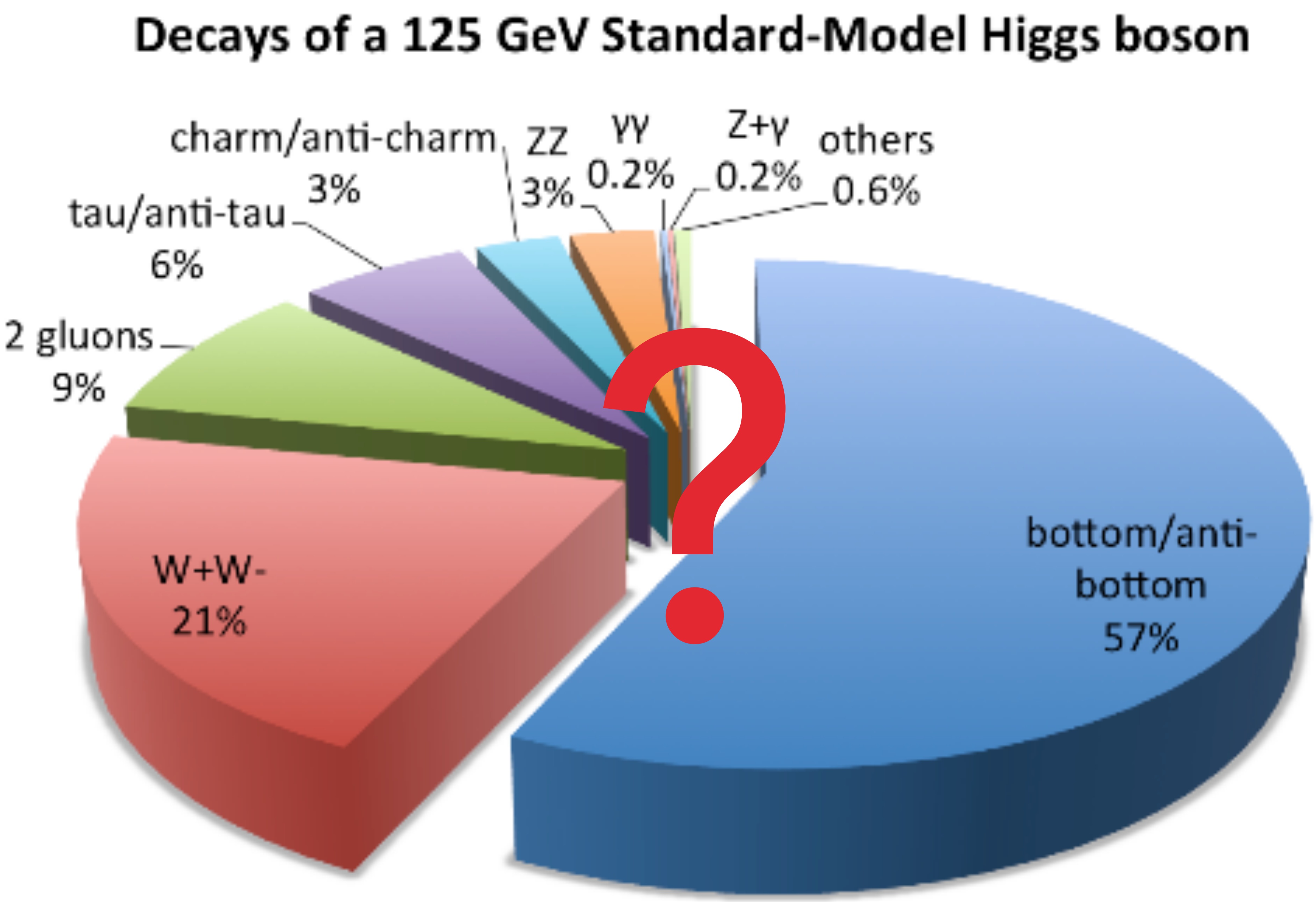


[CMS-PAS-SMP-22-012](#) [Phys. Lett. B 847 (2023) 138292](#) [Phys. Lett. B 842 (2022) 137534](#)

PART 2
EXOTIC BSM DECAYS

RARE HIGGS DECAYS

- BSM models predict exotic decays of the SM Higgs boson
- 4 MeV total width of the SM Higgs boson means a small BSM coupling can produce a large BSM branching fraction
- In the part 2 we focus on:
  - decays to (pseudo)scalars
  - invisible decays
  - Lepton Flavour Violation (LFV) decays
- Impossible to go through everything, only showing some selected analysis

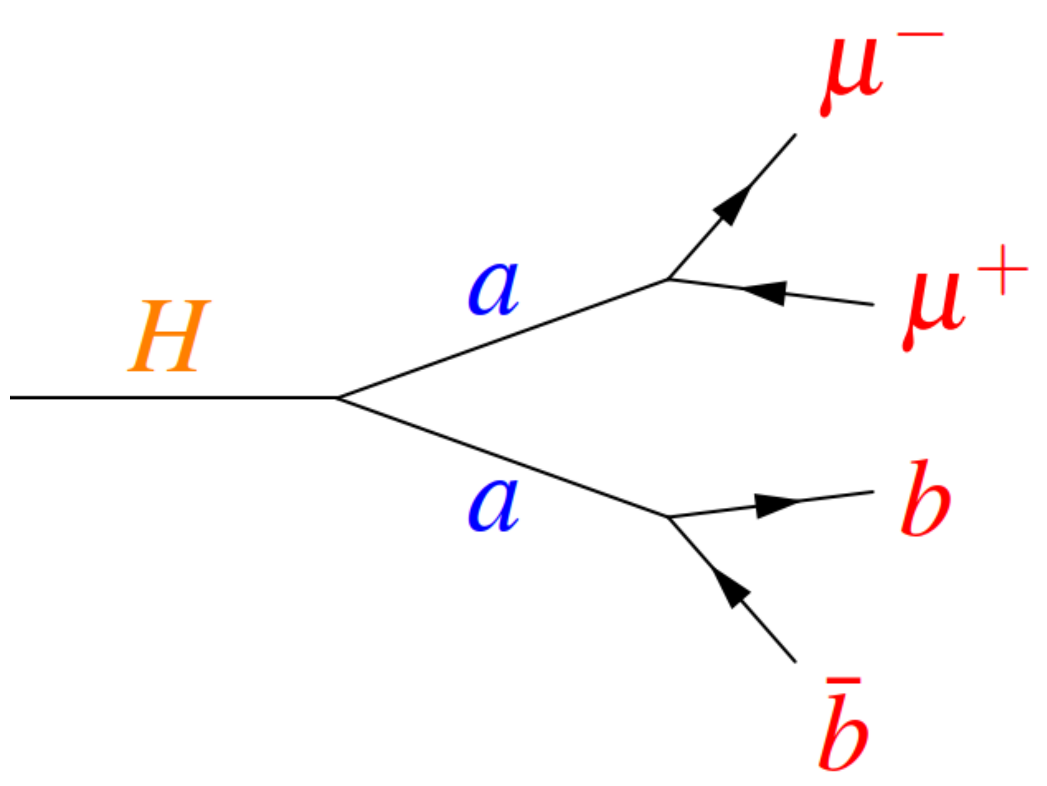


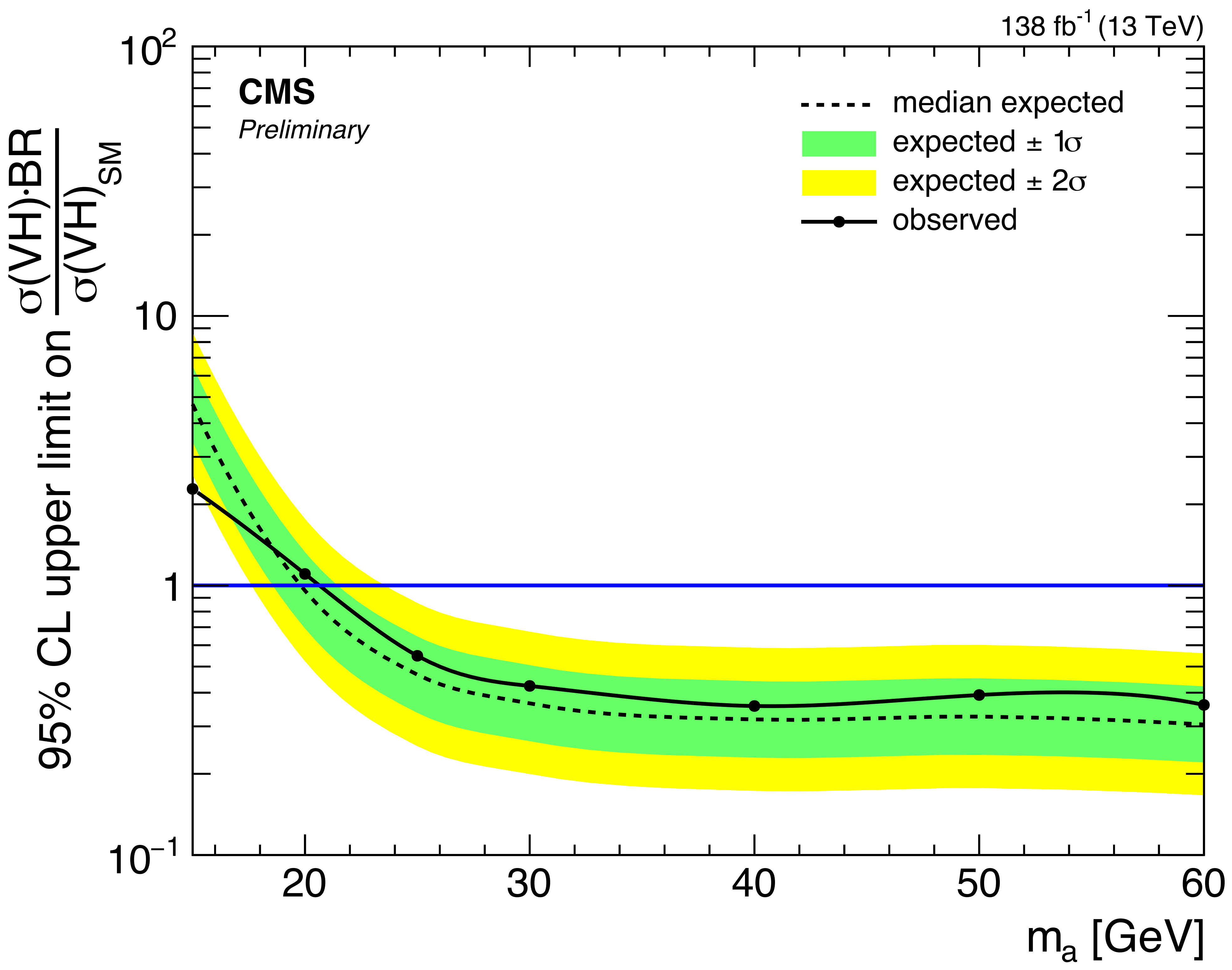
CHANNELS OVERVIEW

	Channel	Dataset	Publication
CMS	$H \to aa \to 4b$	138 fb^{-1} (Run2)	CMS-PAS-HIG-18-026
CMS	$H \to AA \to 4\gamma$	136 fb^{-1} (Run2)	Phys. Rev. Lett. 131 (2023) 101801 JHEP 07 (2023) 148
ATLAS	$H \to AA \to 4\gamma$	140 fb^{-1} (Run2)	ATLAS-CONF-2023-040
CMS	$H \to aa \to \mu\mu bb / \tau\tau bb$	138 fb^{-1} (Run2)	Submitted to EPJC
ATLAS	$H \to aa \to \mu\mu bb$	139 fb^{-1} (Run2)	Phys. Rev. D 105 (2022) 012006
CMS	$H \to Za \to ll\gamma\gamma$	138 fb^{-1} (Run2)	Submitted to Phys. Lett. B
ATLAS	$H \to Za \to ll\gamma\gamma$	139 fb^{-1} (Run2)	Submitted to Phys. Lett. B
ATLAS	$H \to Z_D Z_D \to 4l$	139 fb^{-1} (Run2)	JHEP 03 (2022) 041
CMS	$H \to Z_D Z_D \to 4l$	137 fb^{-1} (Run2)	Eur. Phys. J. C 82 (2022) 290
ATLAS	$H \to \gamma\gamma_D$	139 fb^{-1} (Run2)	JHEP 07 (2023) 133
CMS	$H \to e\tau / \mu\tau$	137 fb^{-1} (Run2)	Phys. Rev. D 104 (2021) 032013
ATLAS	$H \to e\tau / \mu\tau$	138 fb^{-1} (Run2)	JHEP 07 (2023) 166

H→(PSEUDO)SCALARS

- Several BSM models predict Higgs decays to a pair of on-shell (pseudo) scalar bosons (a/A)
- (Pseudo)scalar a/A generally decays to fermions
  - can also decay to bosons in some models
- Variety of decay modes studied:
  - H→aa→4b: interpretation in 2HDM+S models





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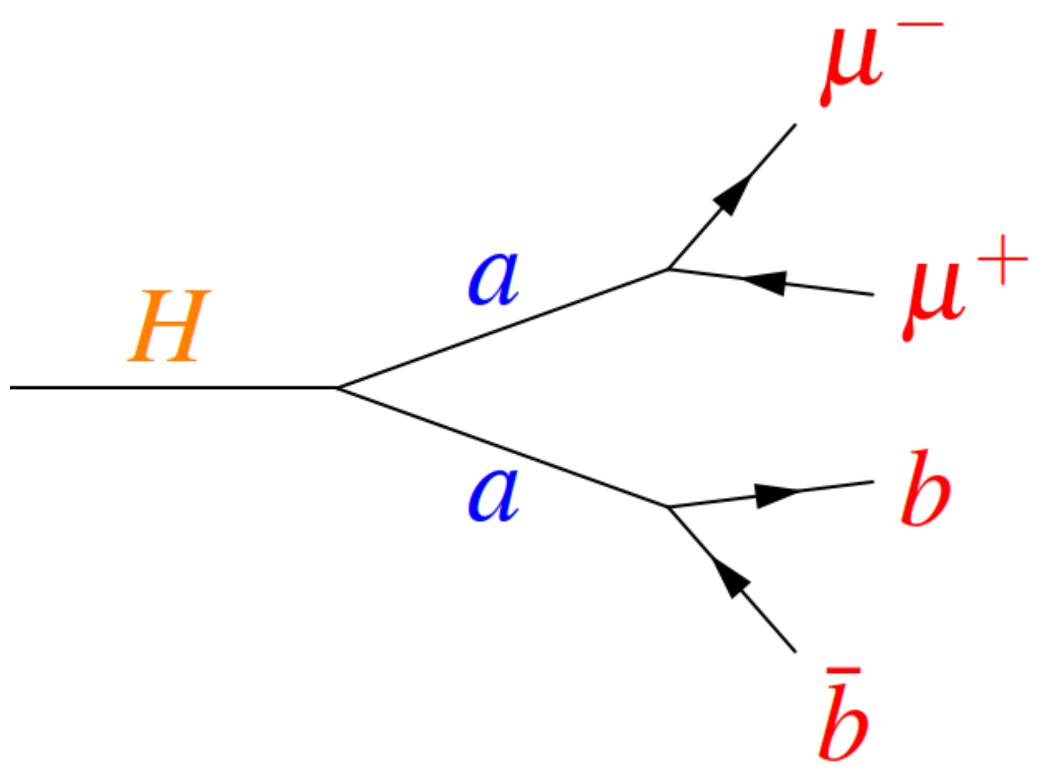

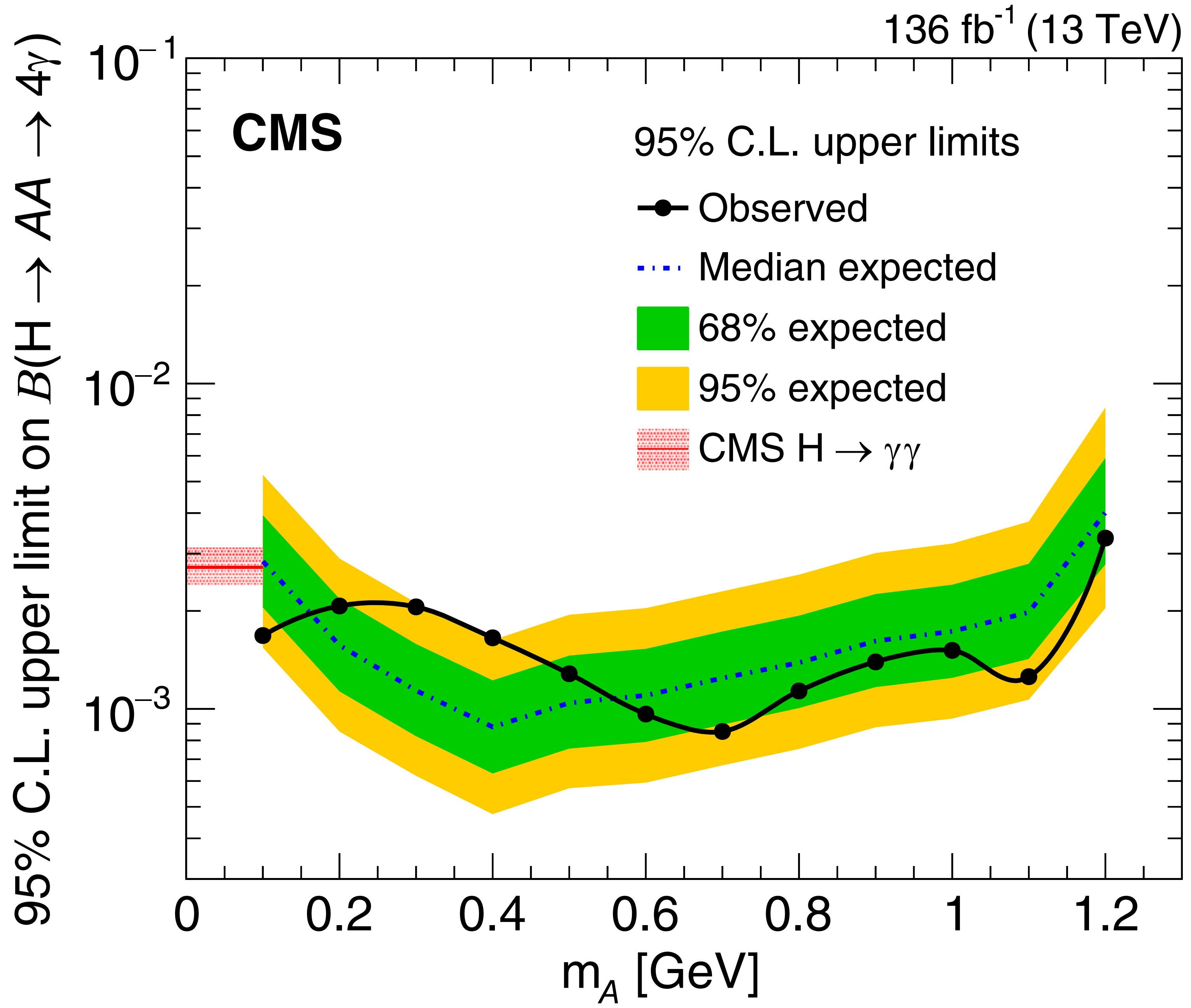

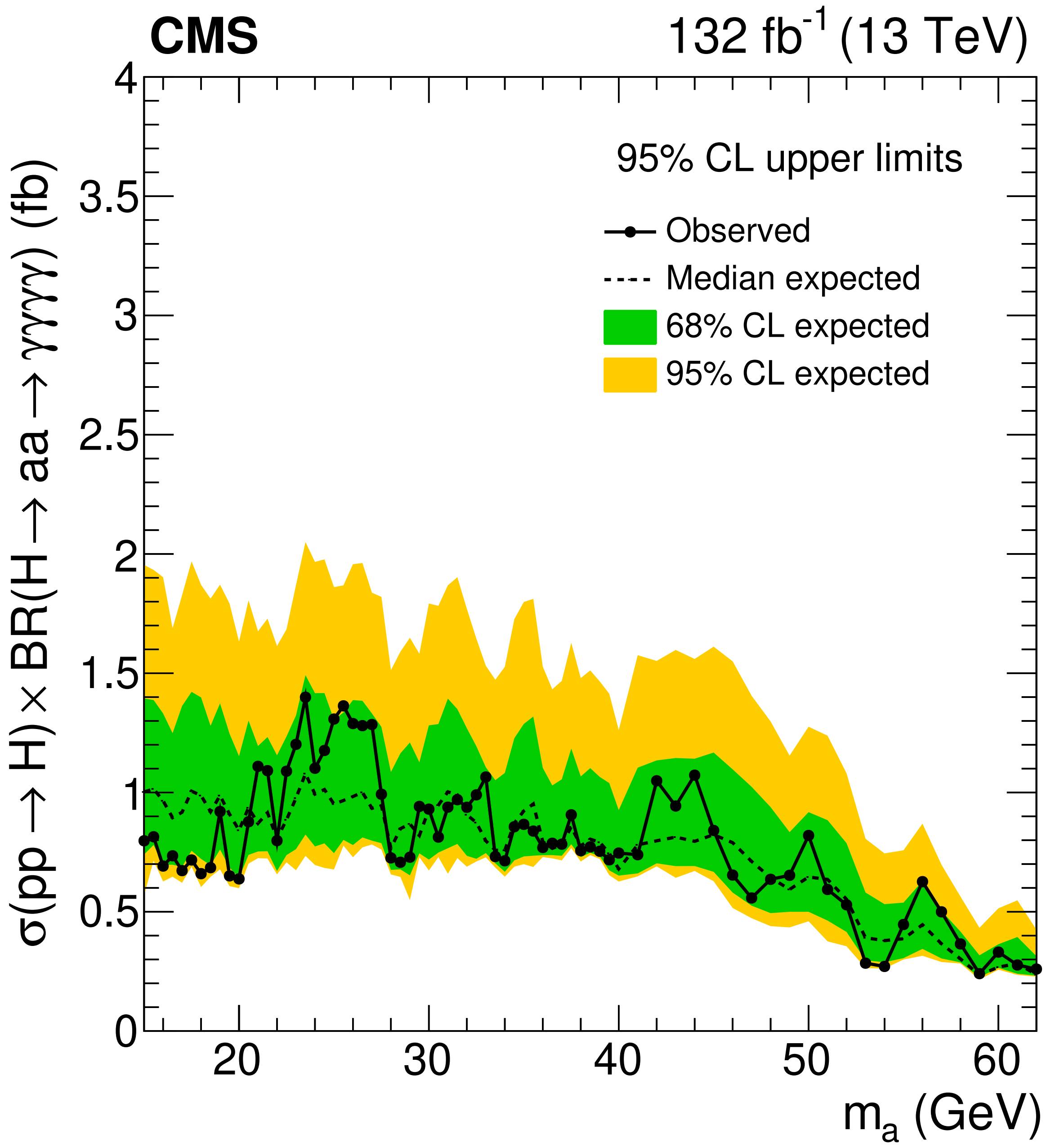

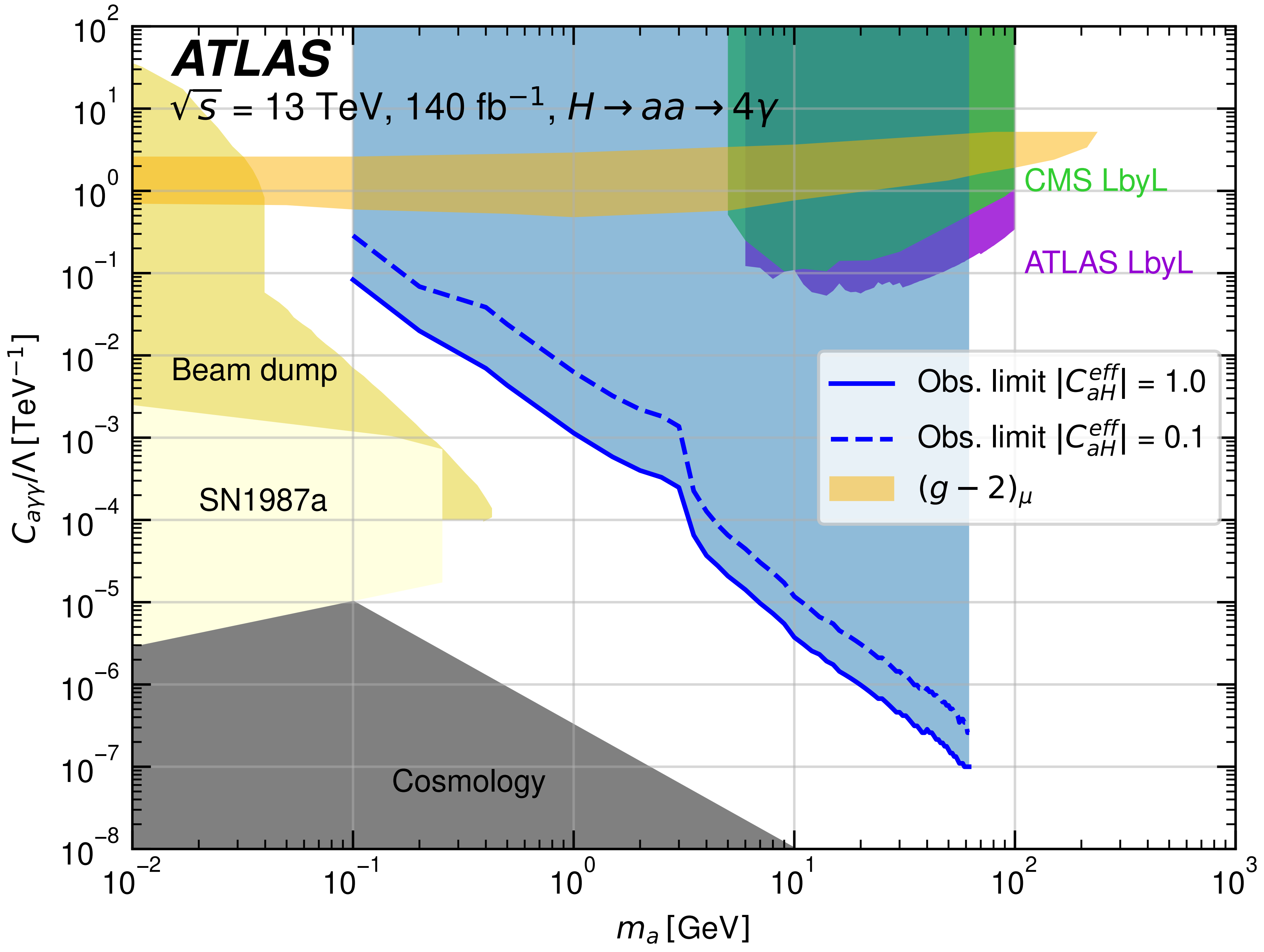

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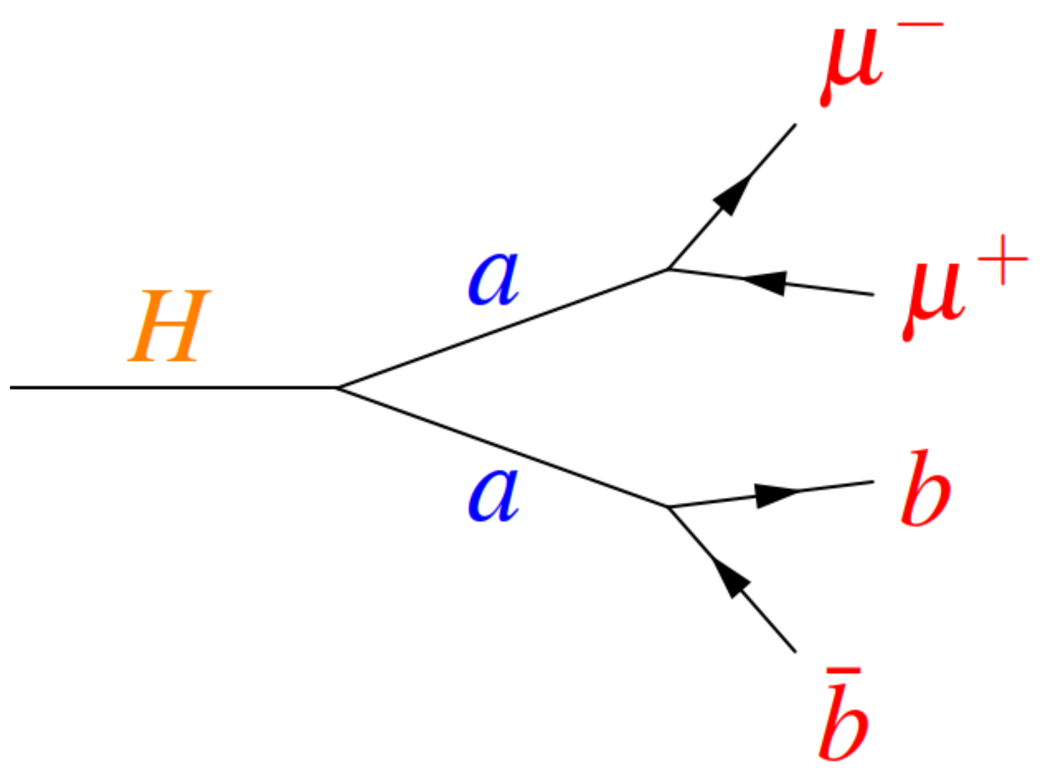
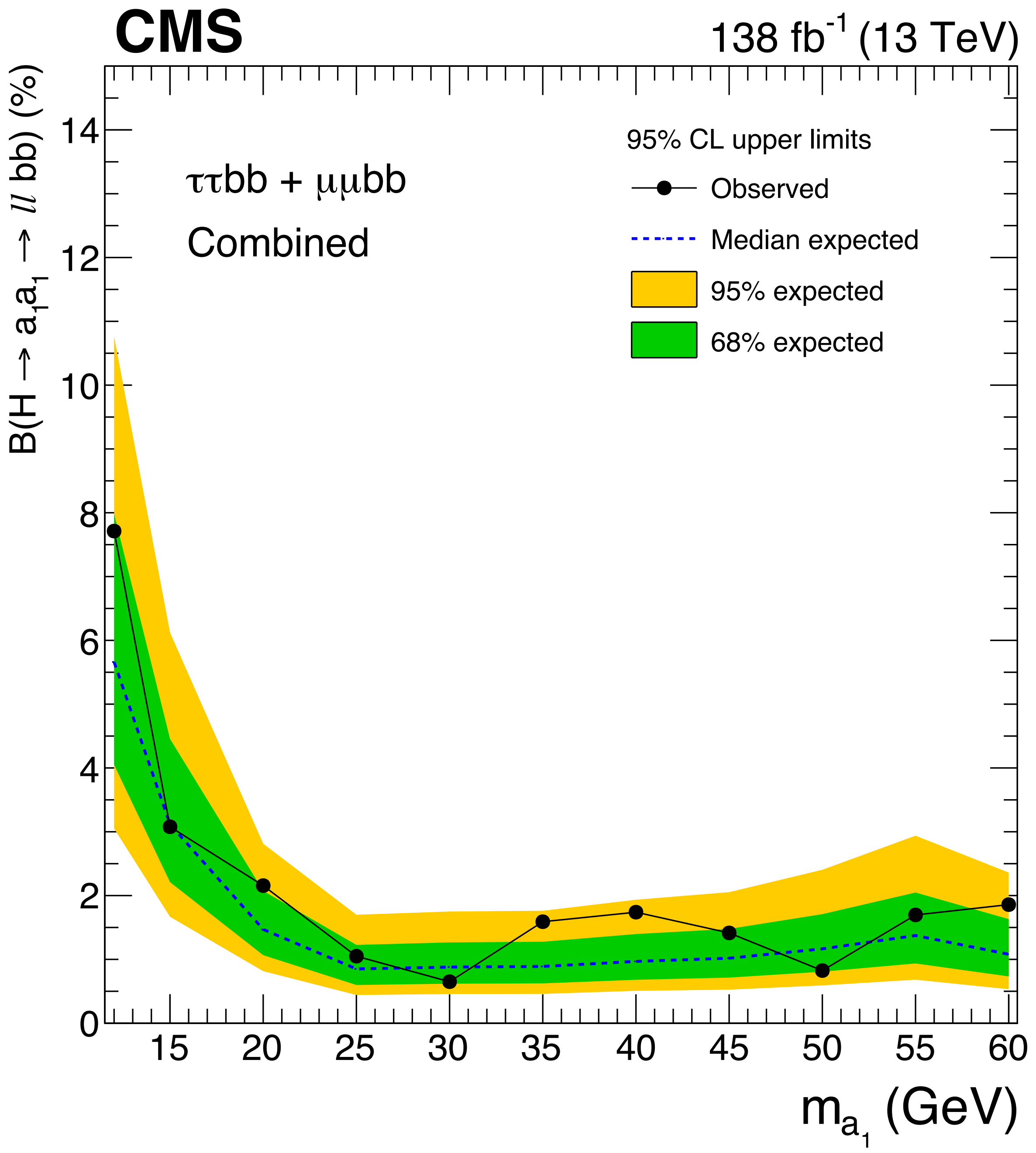
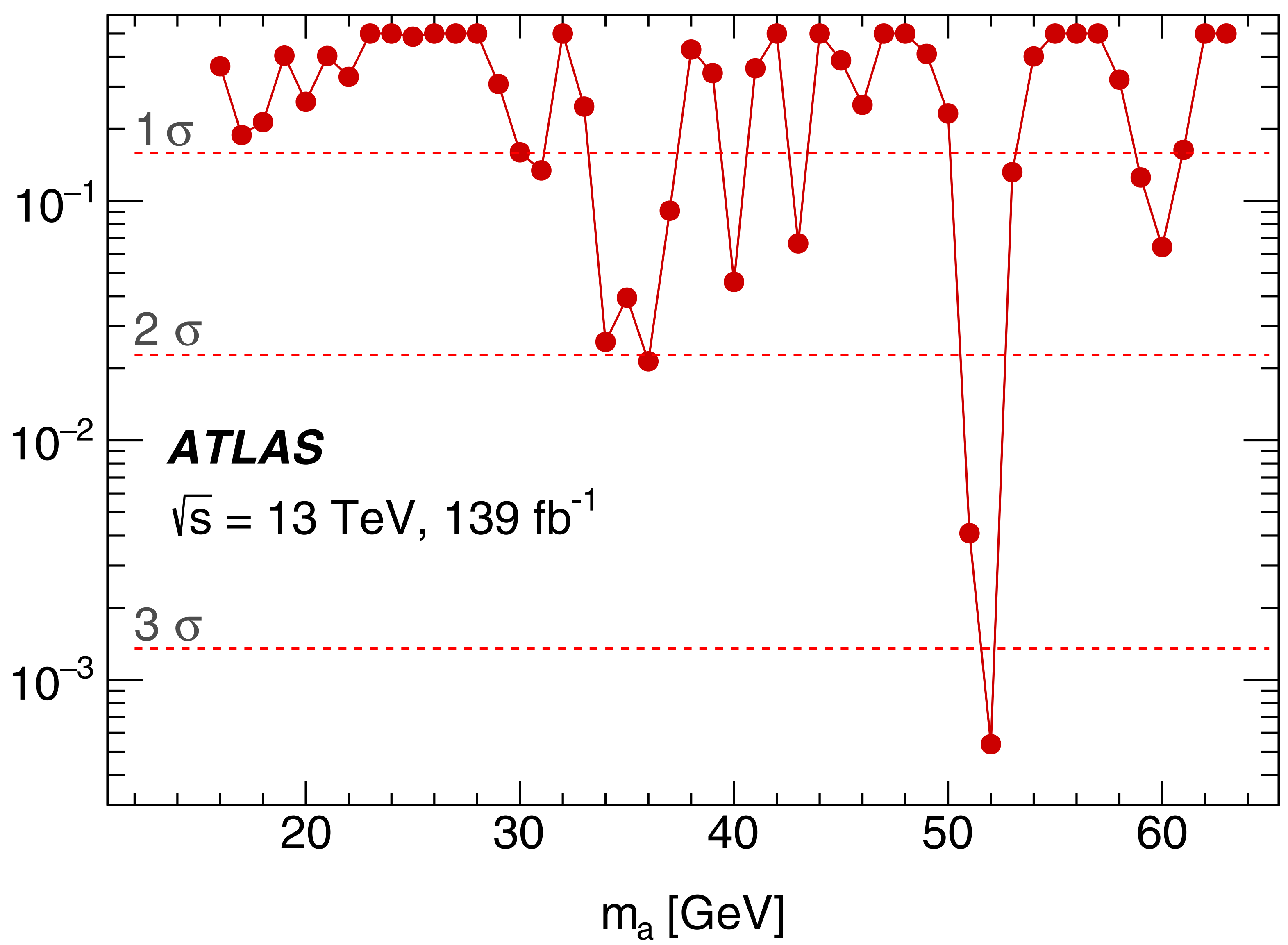
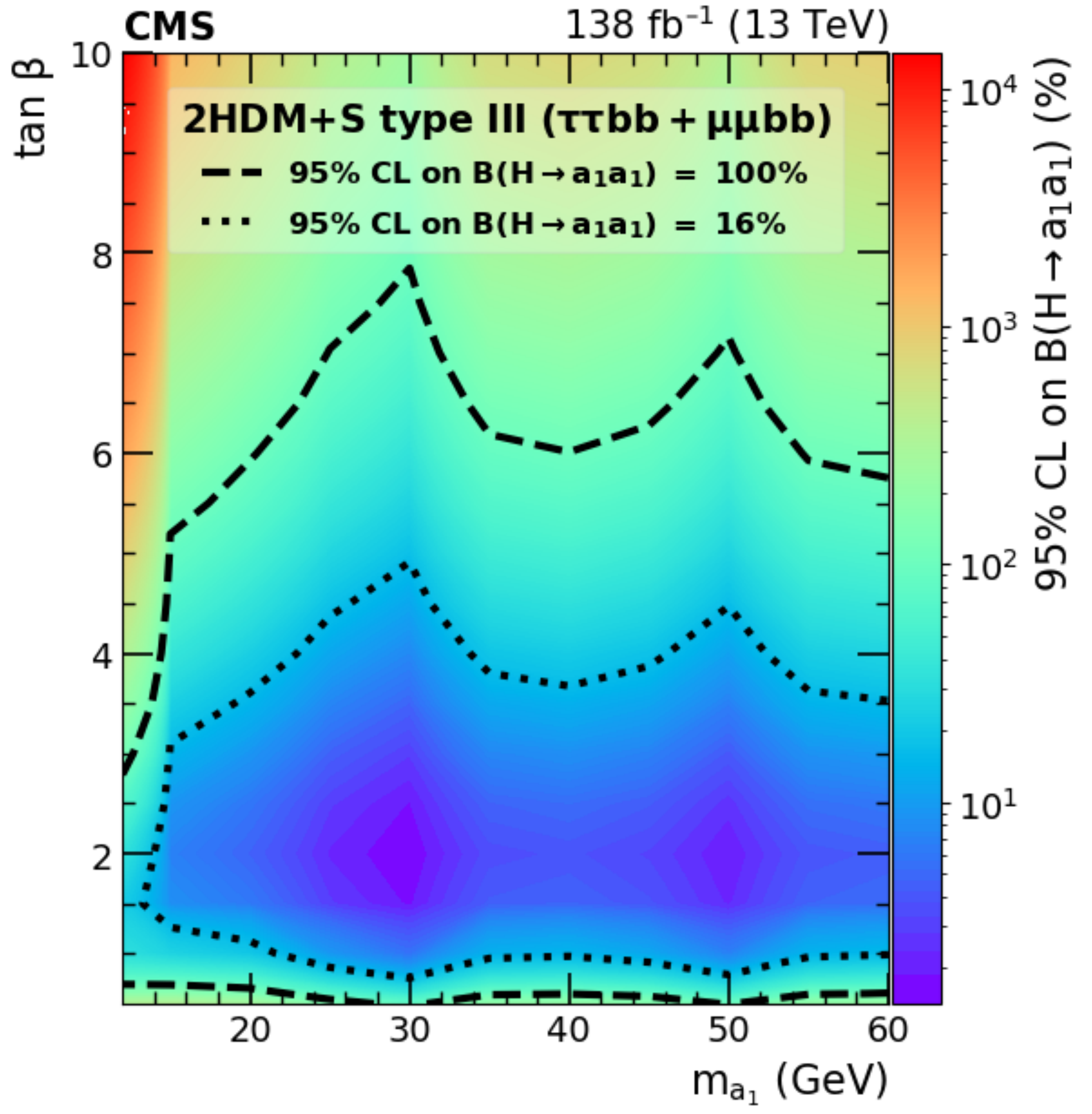




3.3σ local (1.7σ global) excess





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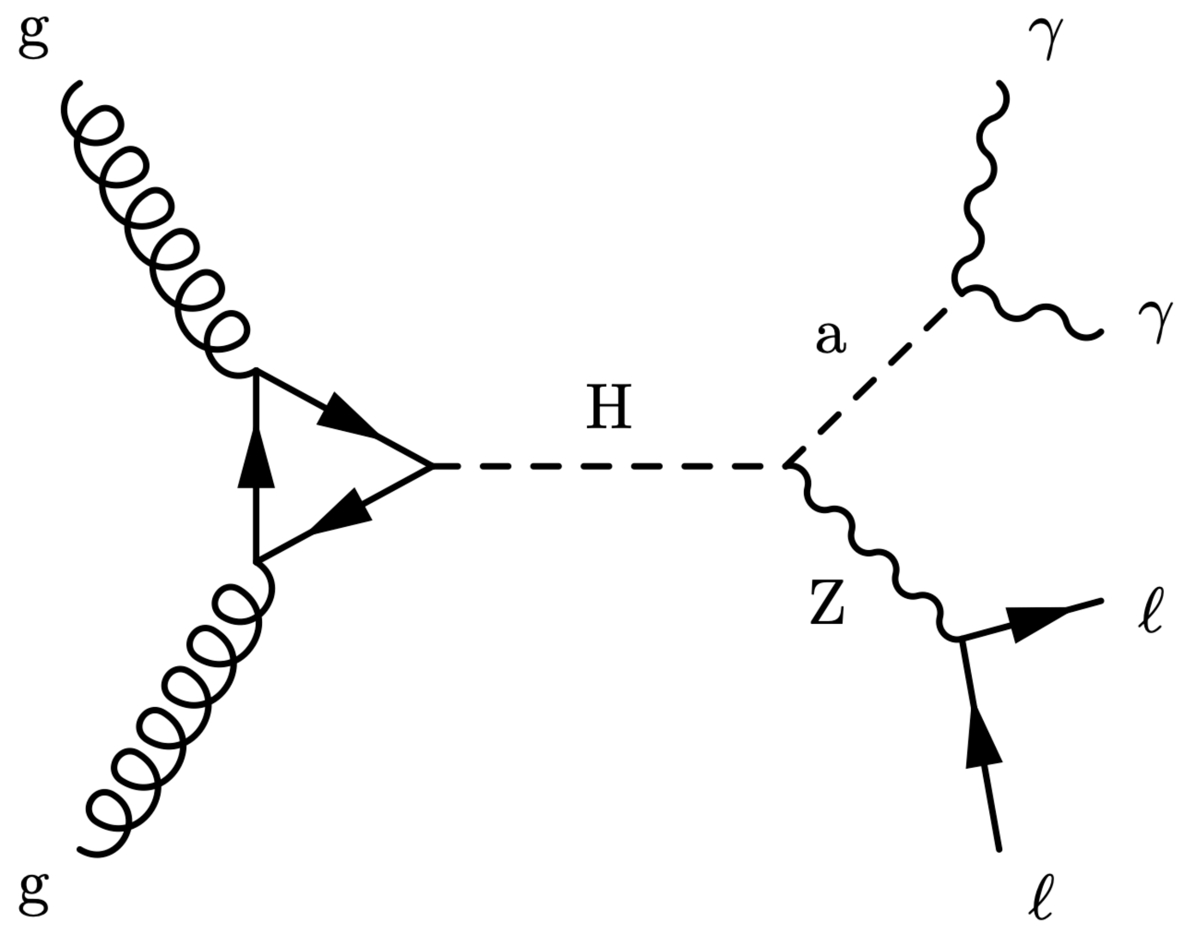
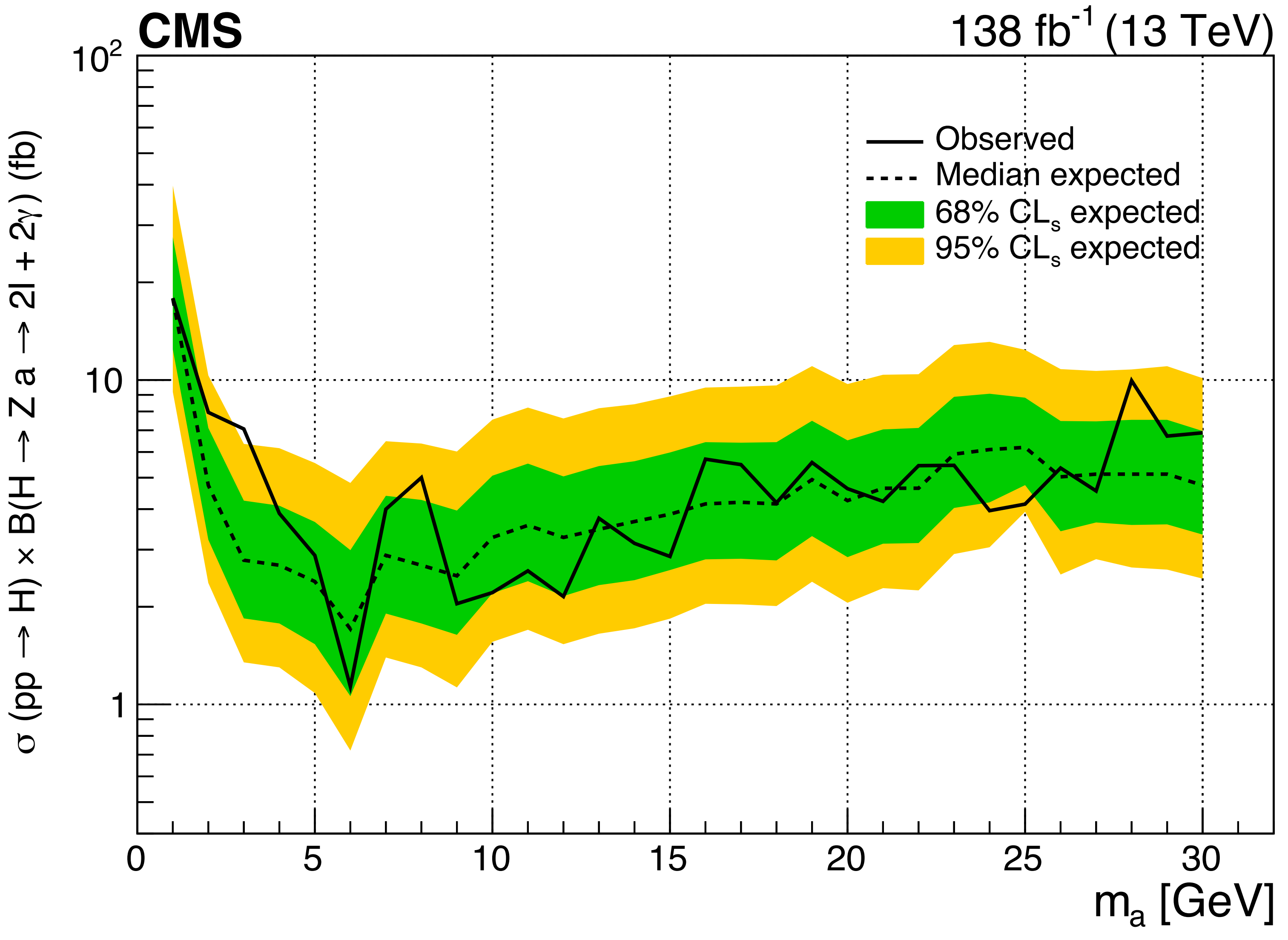
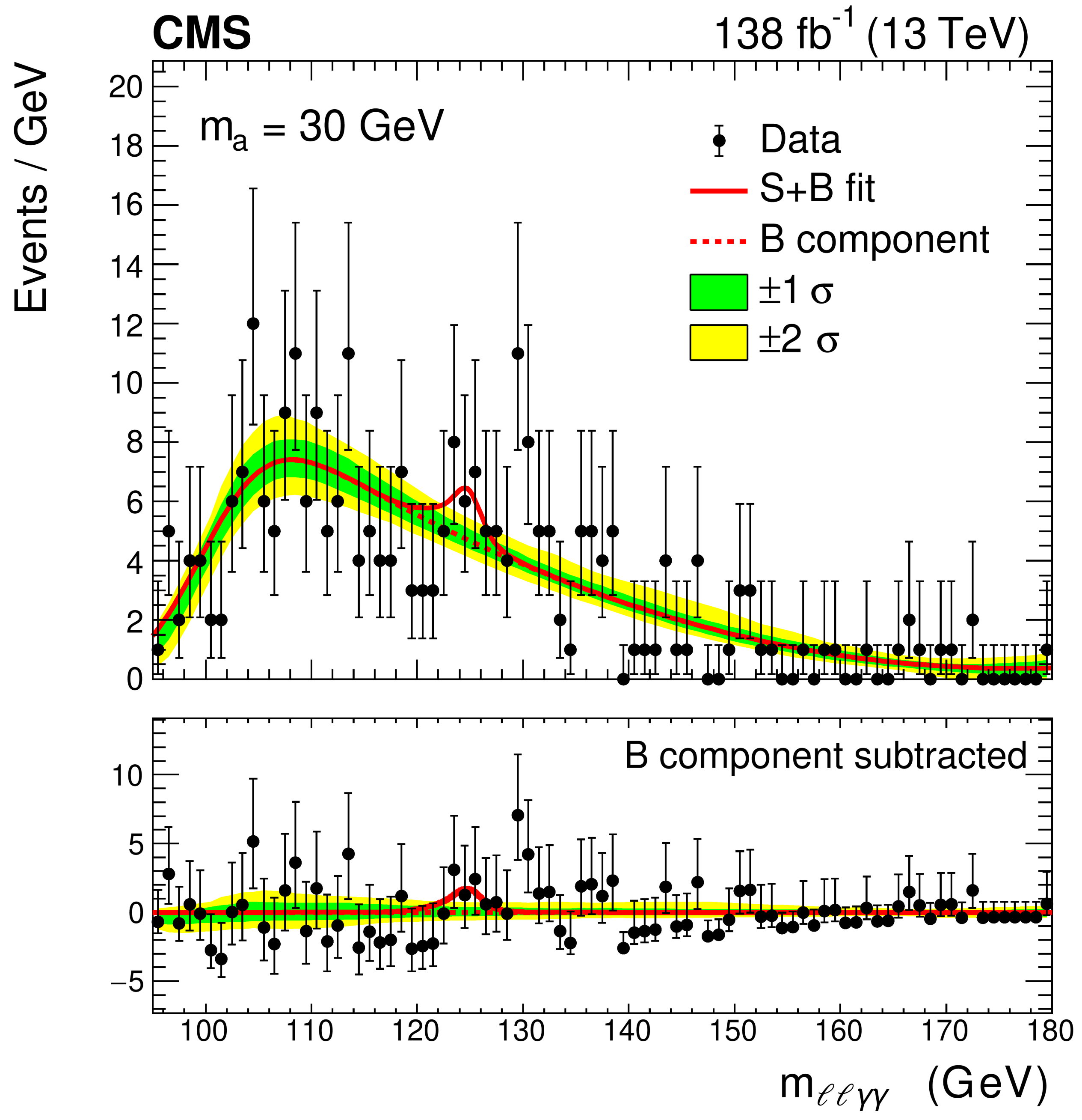
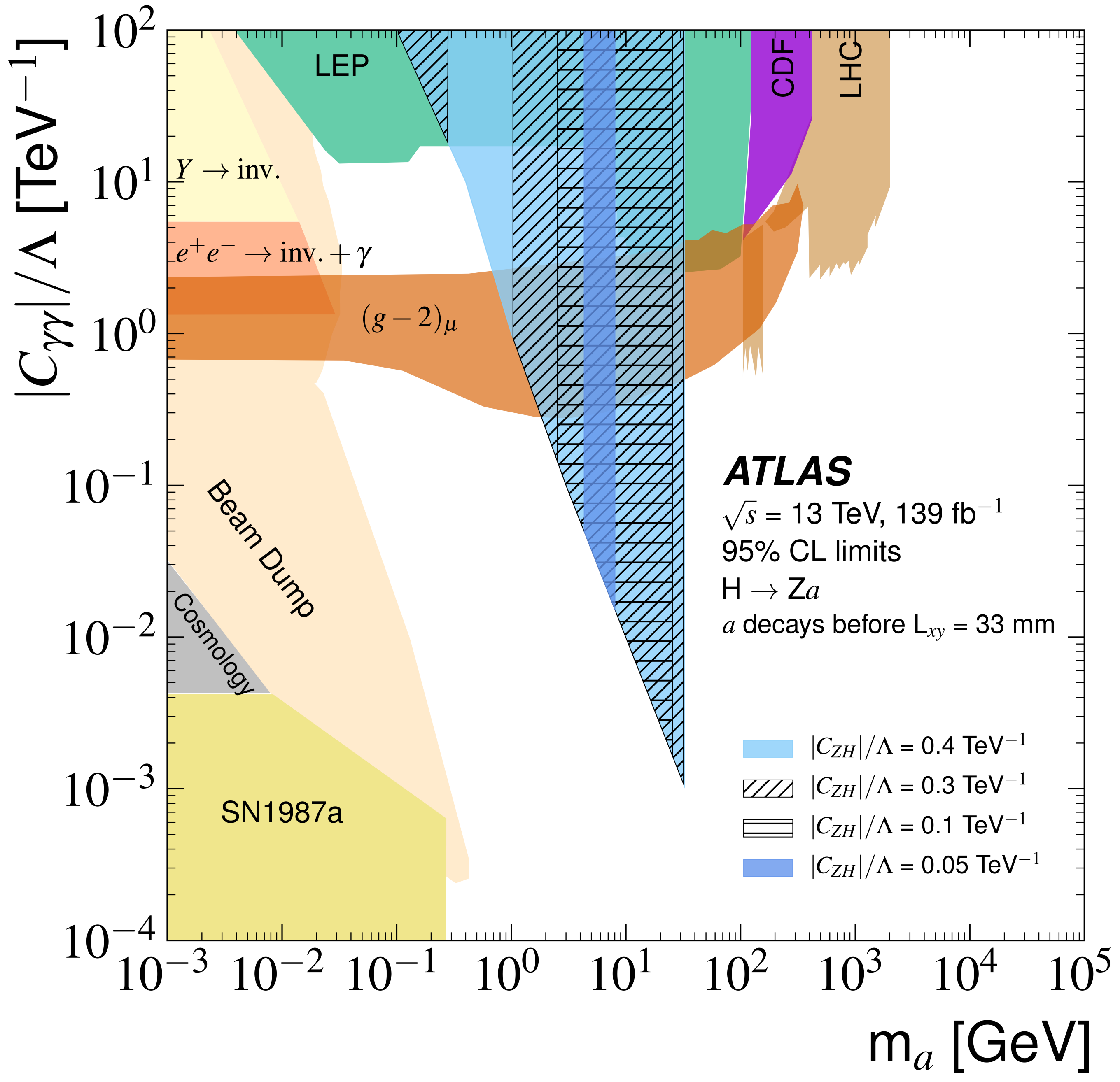
  - H→aa→$\mu\mu$bb/$\tau\tau$bb: interpretation in 2HDM+S models
  - H→Za→ll$\gamma\gamma$: first search using this signature



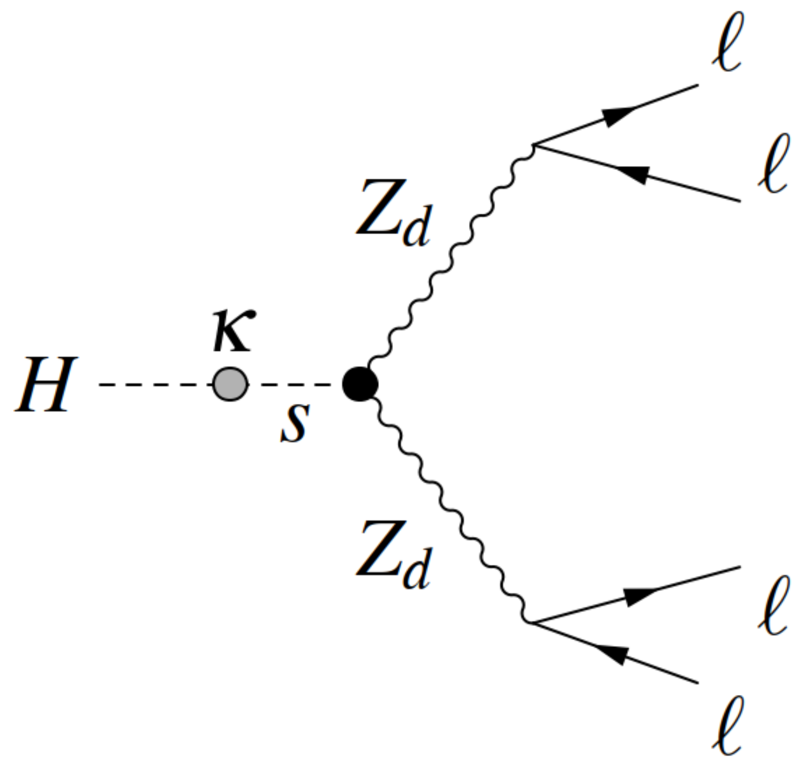


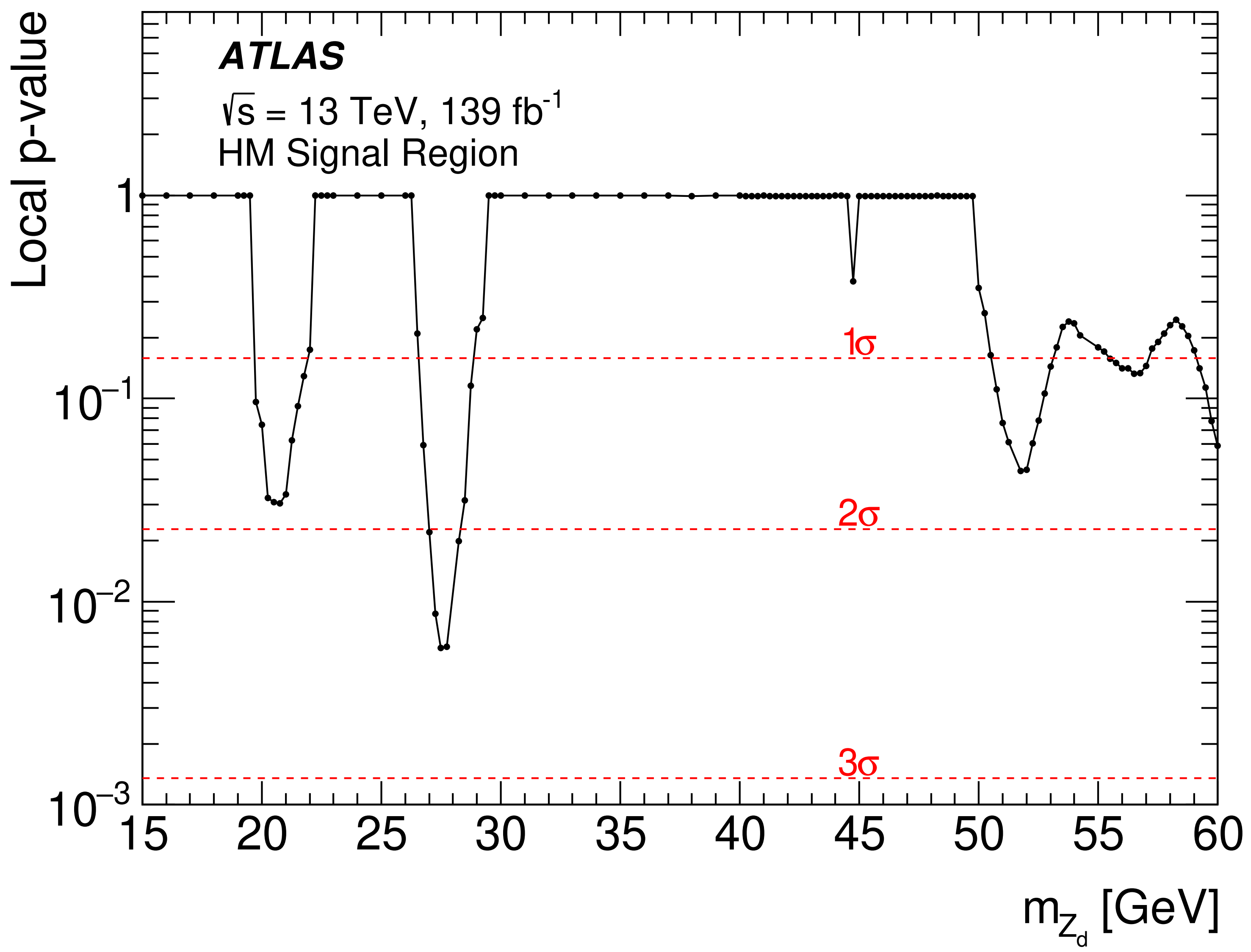


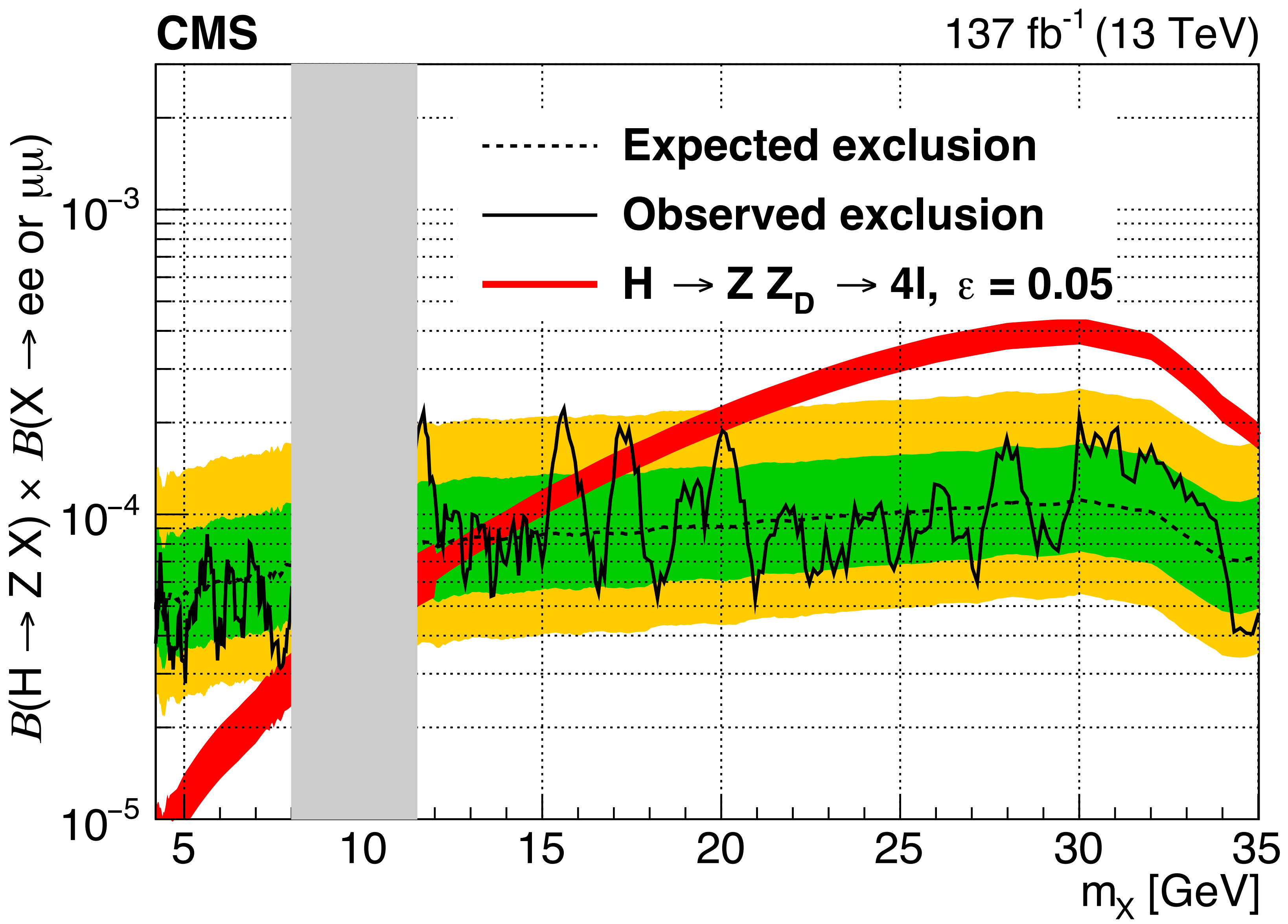


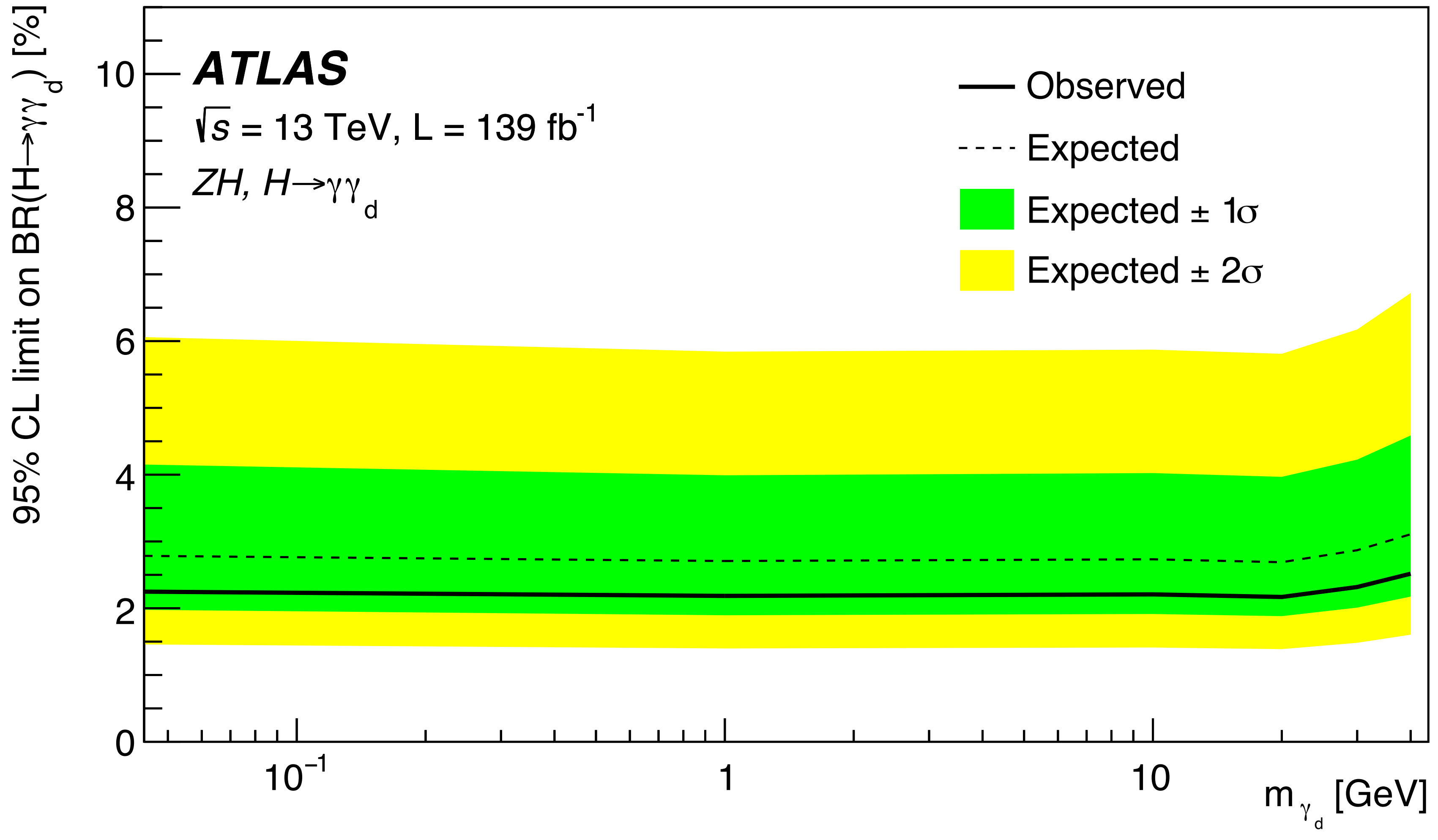
$H \to Z_D Z_D / Z Z_D$

- Many BSM models include a U(1) dark gauge symmetry with gauge boson Z_D and mixing with SM H and Z
- Z_D decays to two leptons ~20-30%
- Several analysis:
  - 4 leptons: search for intermediate scalars or vector bosons
  - $H \to \gamma\gamma_D$: ZH production + missing energy signature



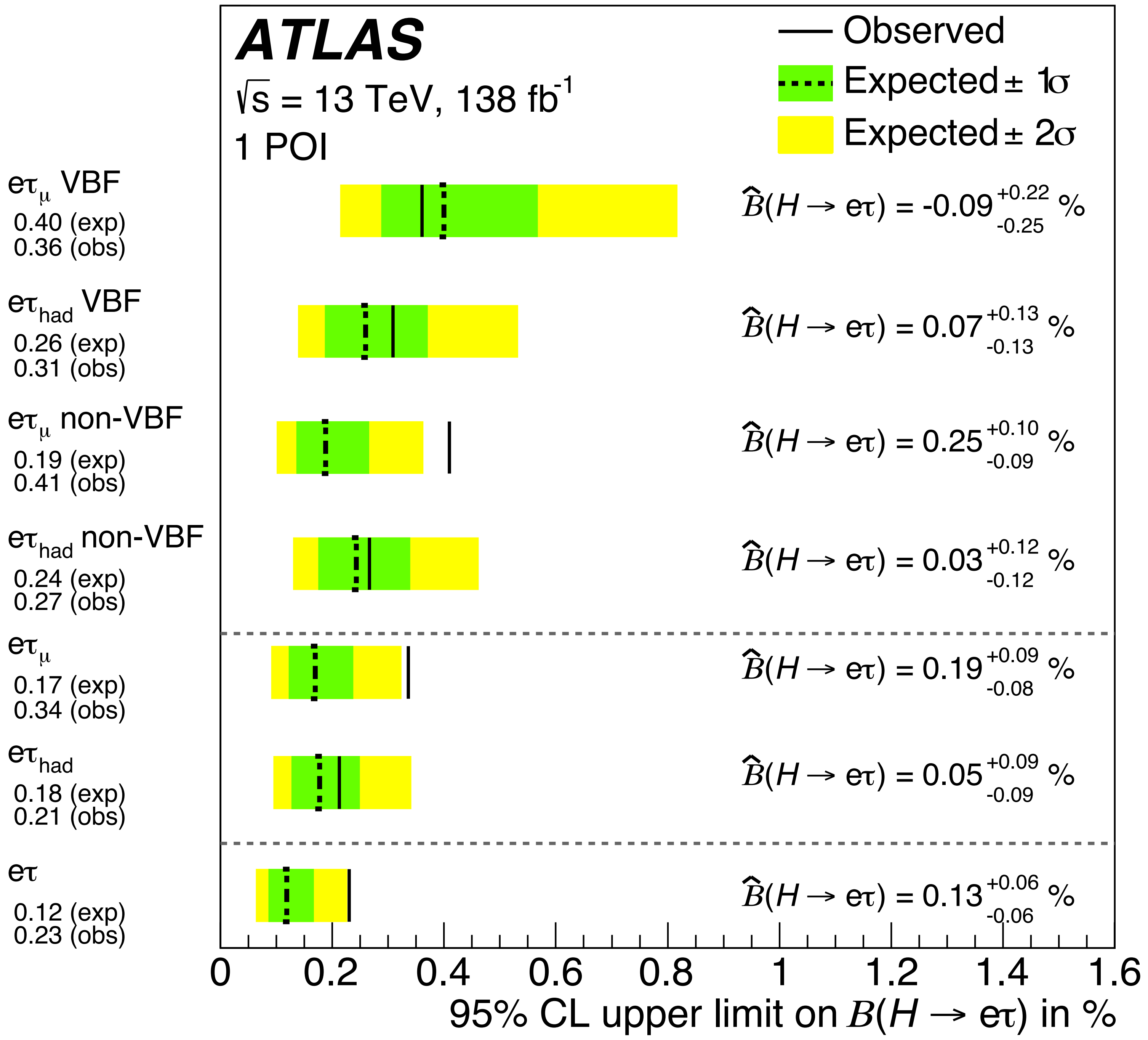


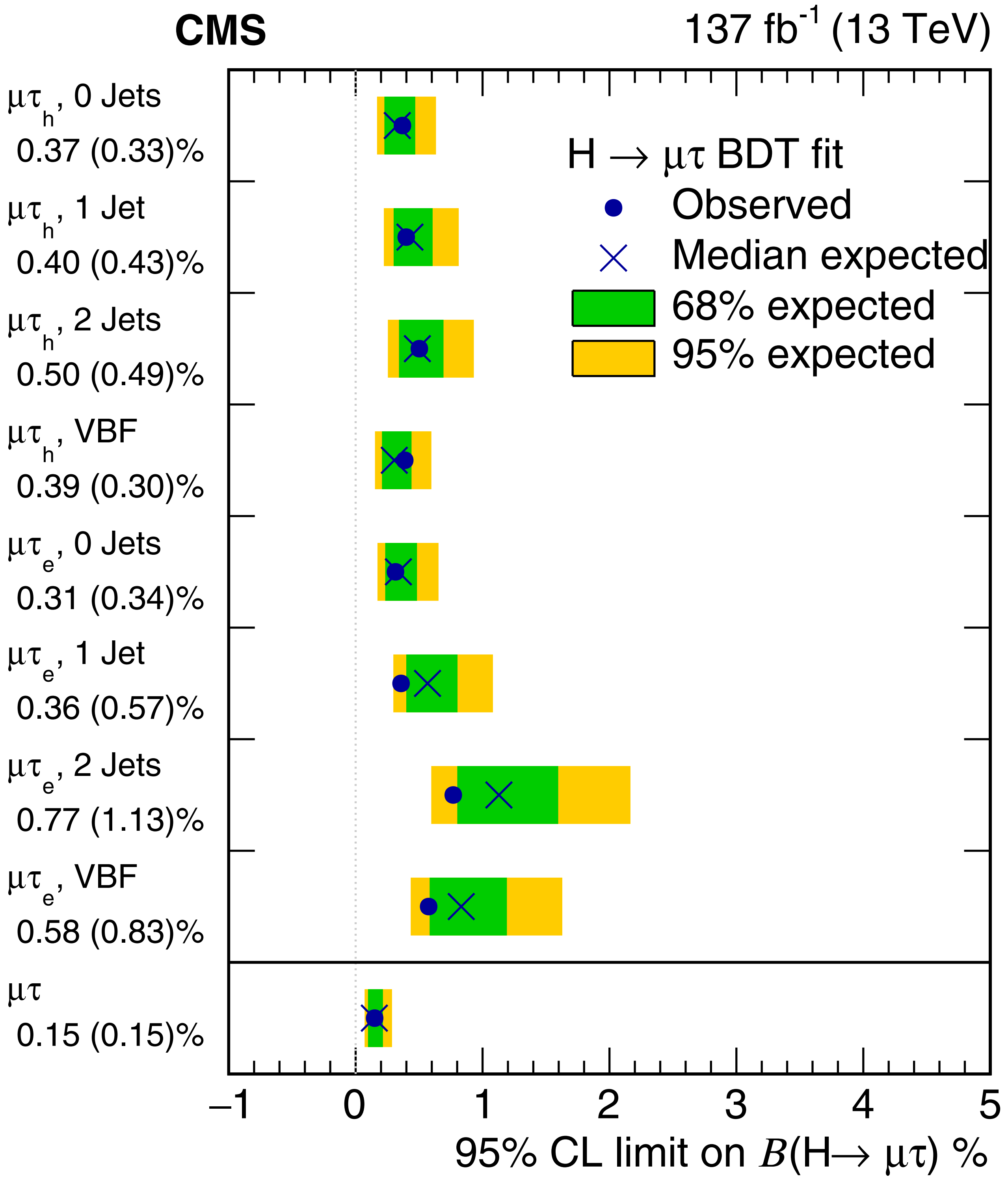


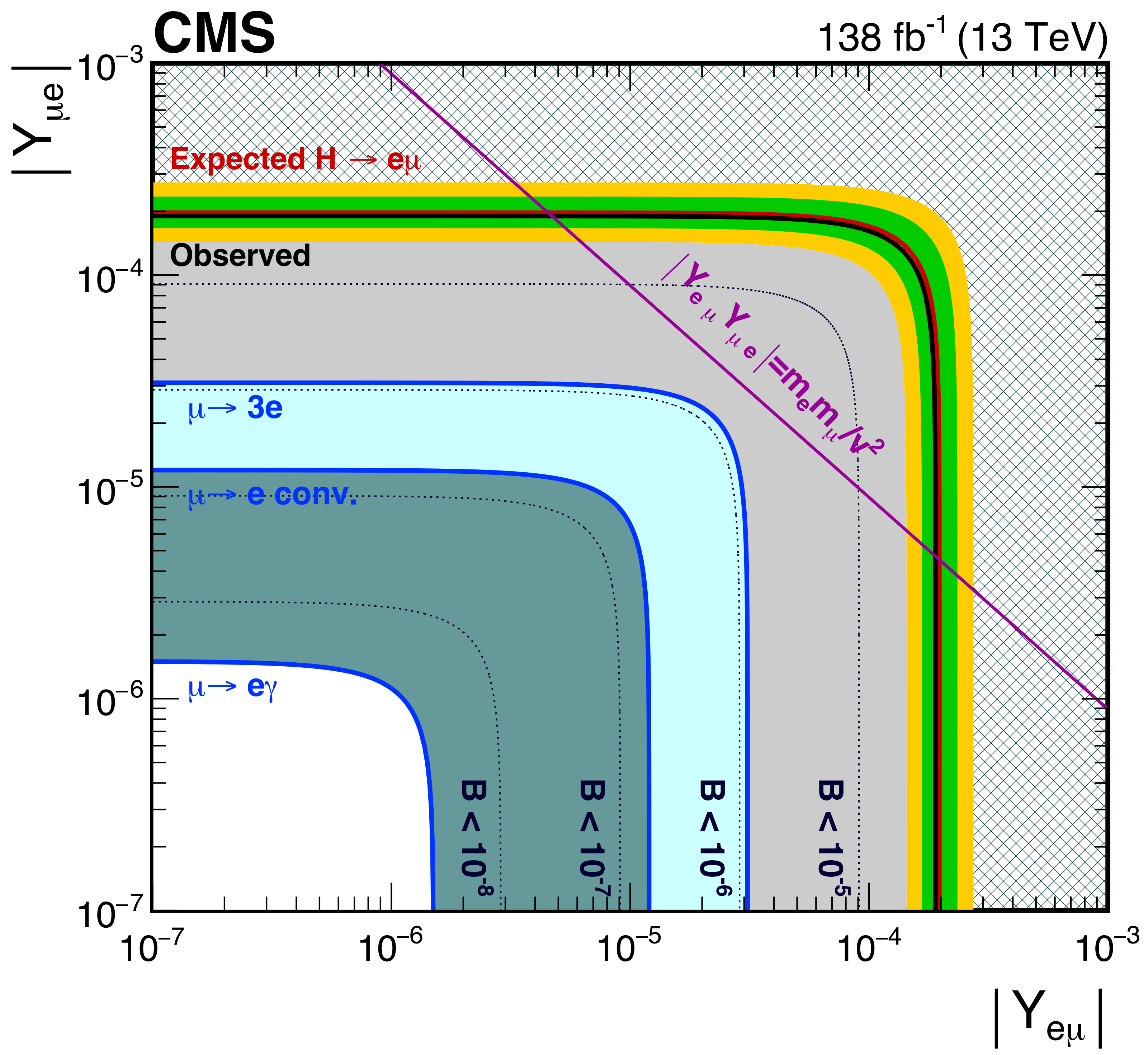


LFV DECAYS

- Some BSM theories allow LFV processes
- H→$e\mu$, H→$e\tau$, H→$\mu\tau$ become possible
- Constrains on LFV Yukawa couplings

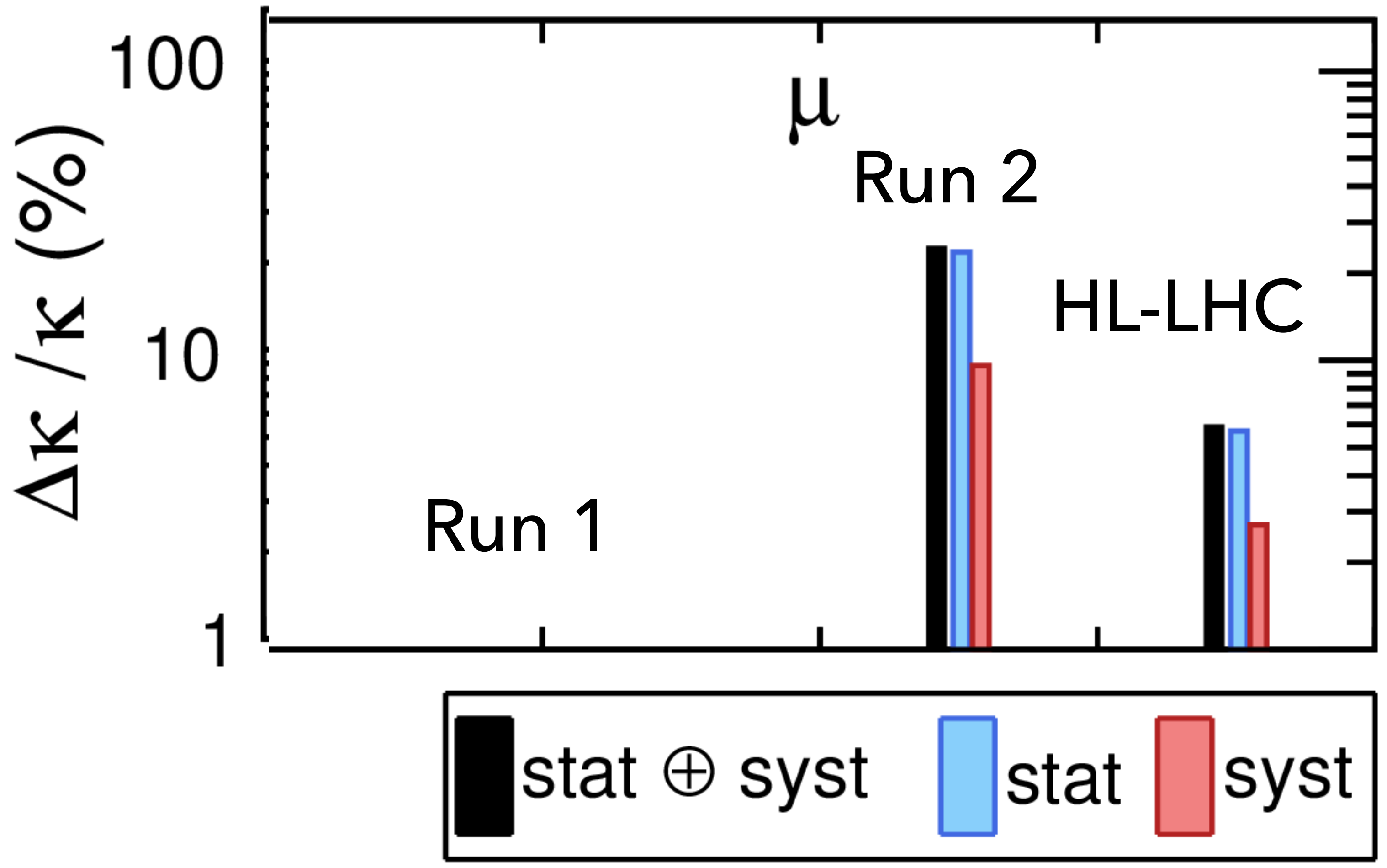


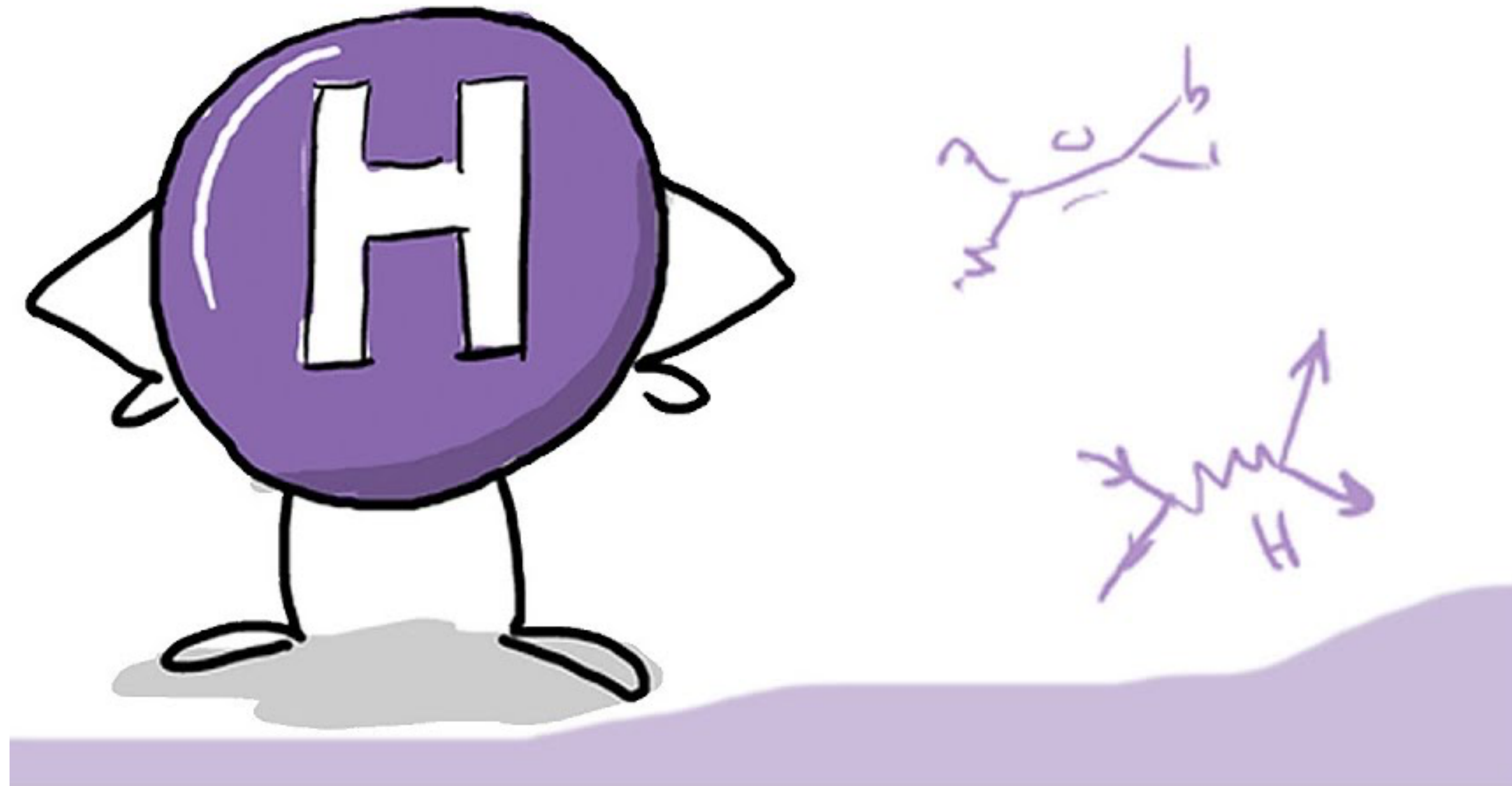




OUTLOOK

- Rare decays highly limited by statistical uncertainties
- Significant improvements with more data (HL-LHC)
- $H \to cc$ will remain challenging because of c-tagging
- Many exotic Higgs decays studied, no new particles discovered (yet)
- This presentation shows that rare and exotic Higgs decays are an active field of study with many new channels probed in Run 2
- We are continuously improving experimental limits and collecting more data, so expect much more in HL-LHC!





BACKUP