Higgs Rare and Exotic Decays at the LHC

Miha Muškinja *obo the ATLAS and CMS Collaborations*

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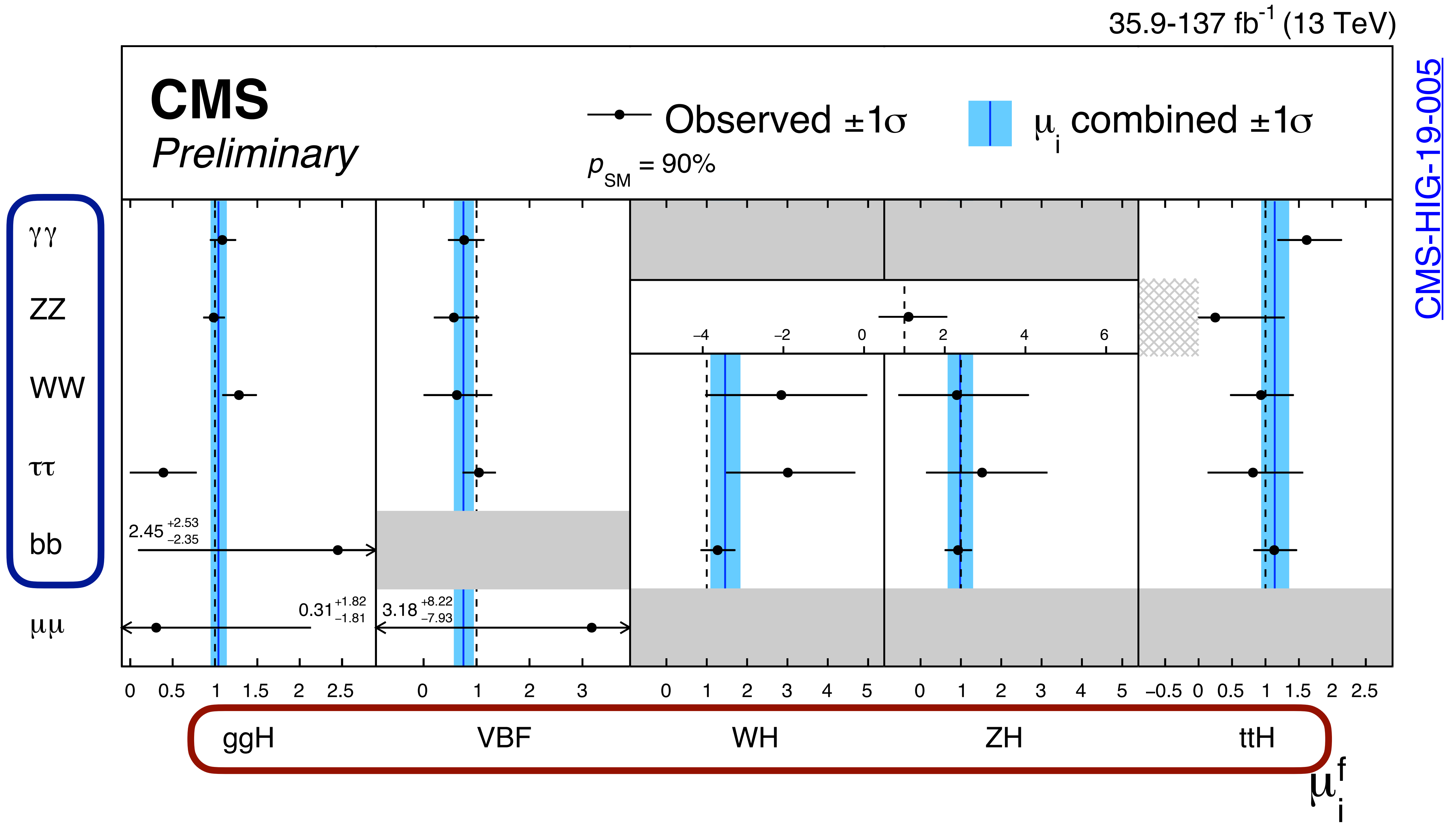
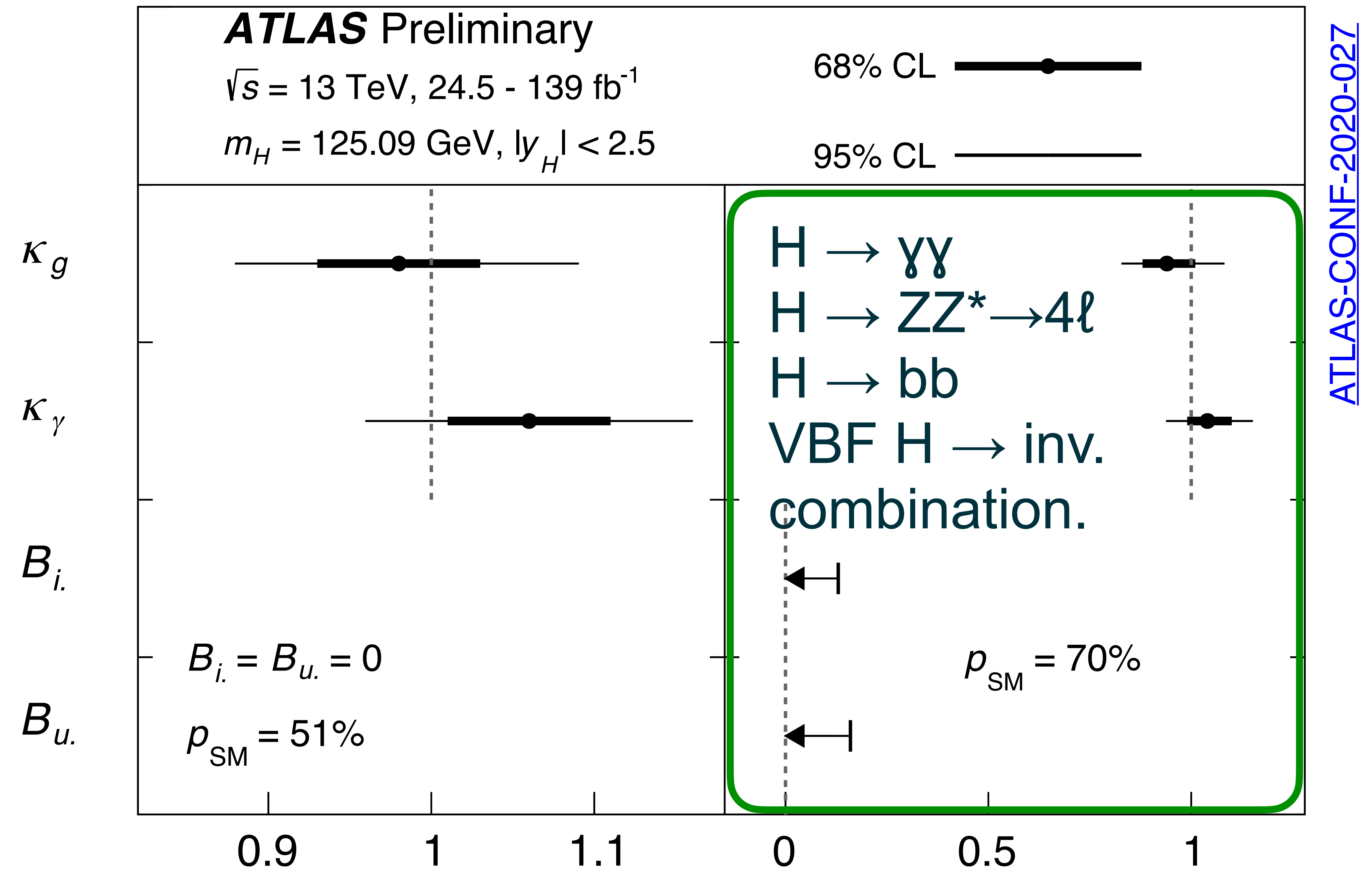
BERKELEY LAB

ATLAS EXPERIMENT

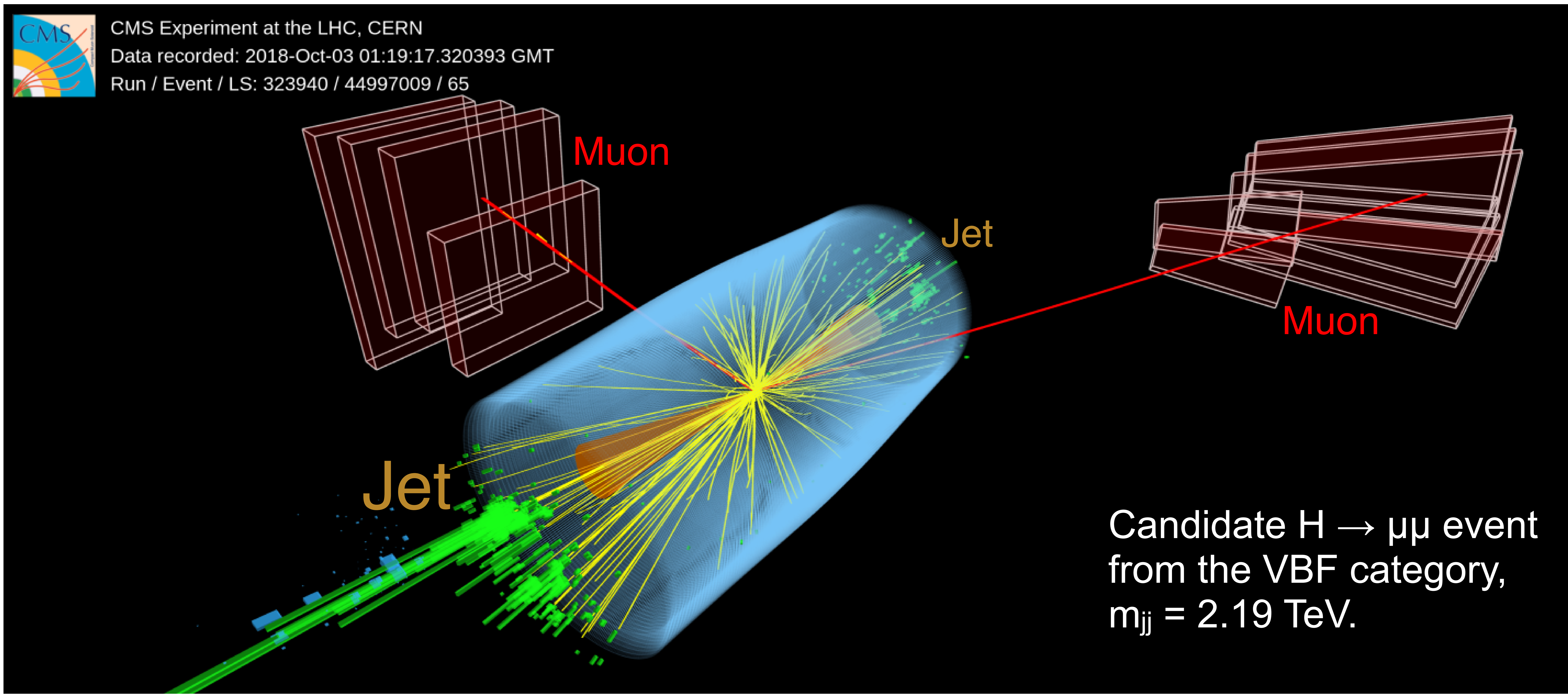
- It has been almost 10 years since the discovery of the Higgs boson at the LHC,
- ATLAS and CMS have discovered (>5σ) all main **production processes** and **decay channels**,
  - Coupling to bosons and 3rd gen. fermions,
  - Used in differential measurements (e.g. STXS).
- Searches for decays to 2nd generation fermions and other rare decays already show impressive results,
  - Today will cover H→μμ / ℓℓγ / cc in more detail.
- Both experiments also have extensive programs of searches for BSM Higgs decays,
  - Couplings to BSM can increase the decay rate to final states otherwise suppressed in SM,
  - Constraint on **Br(H→undetected) < 16%** (95% CL) from the Higgs combination measurement— lots of 'space' for new physics!





Searches for rare Higgs decays

A candidate H → μμ event in CMS



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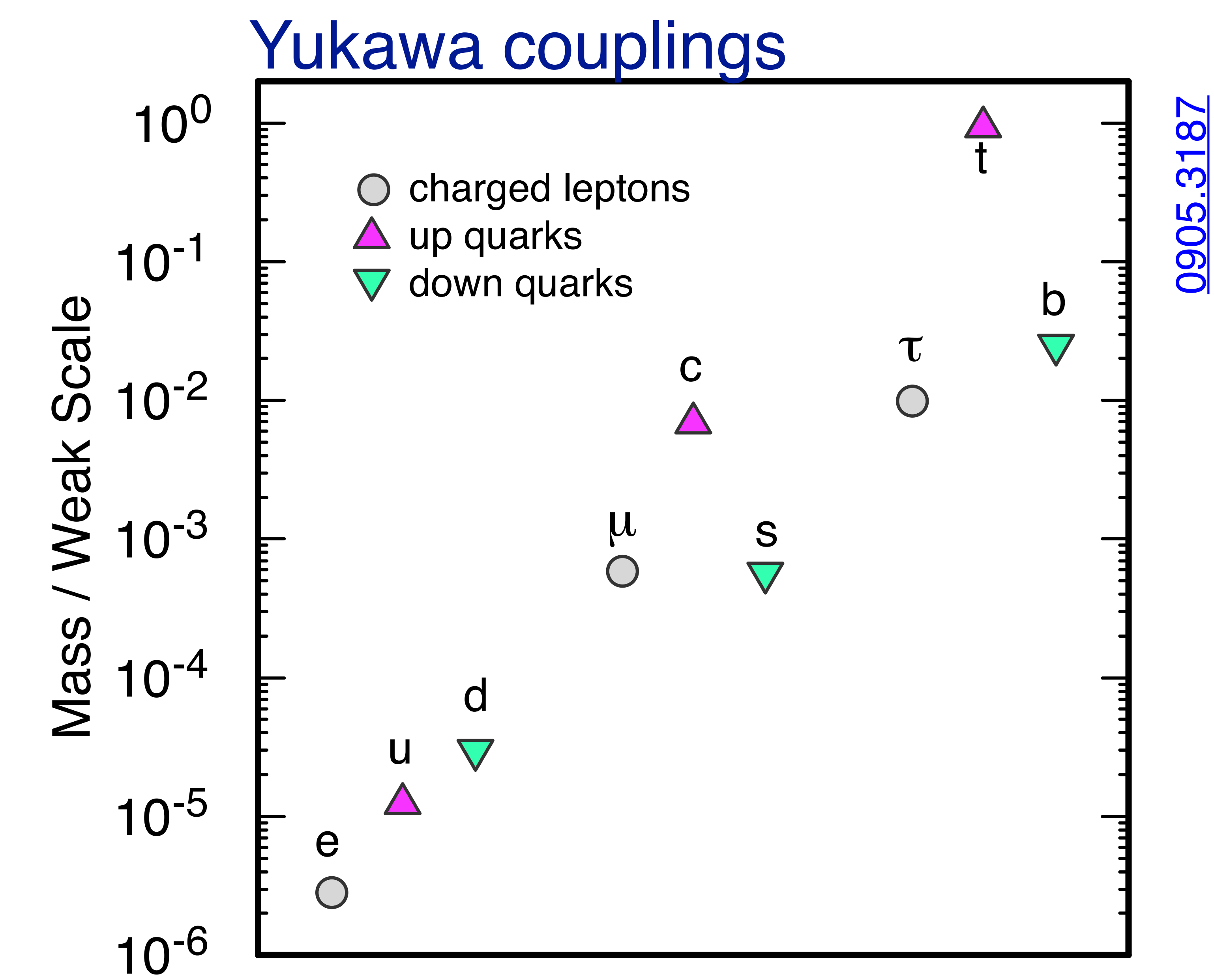
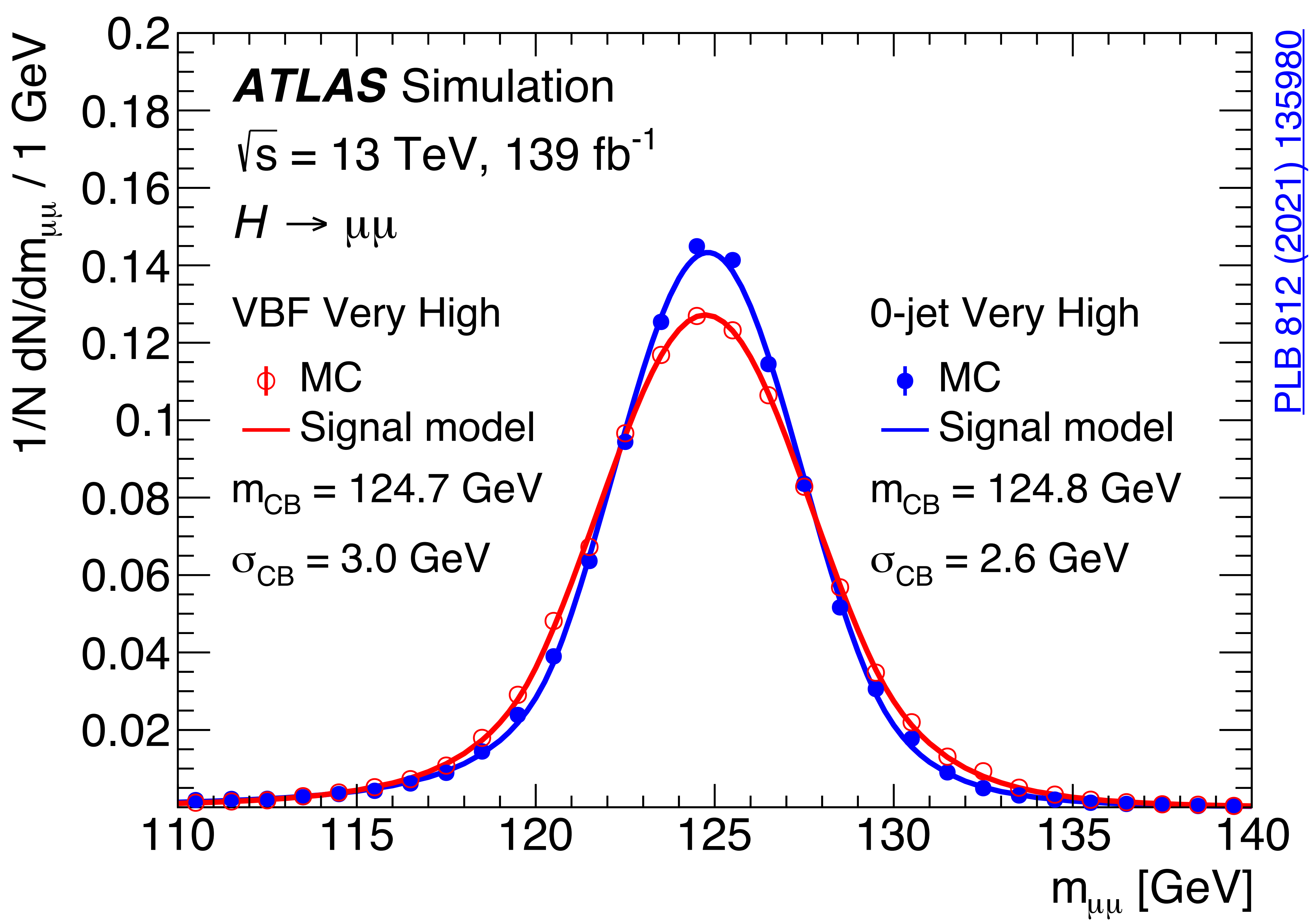
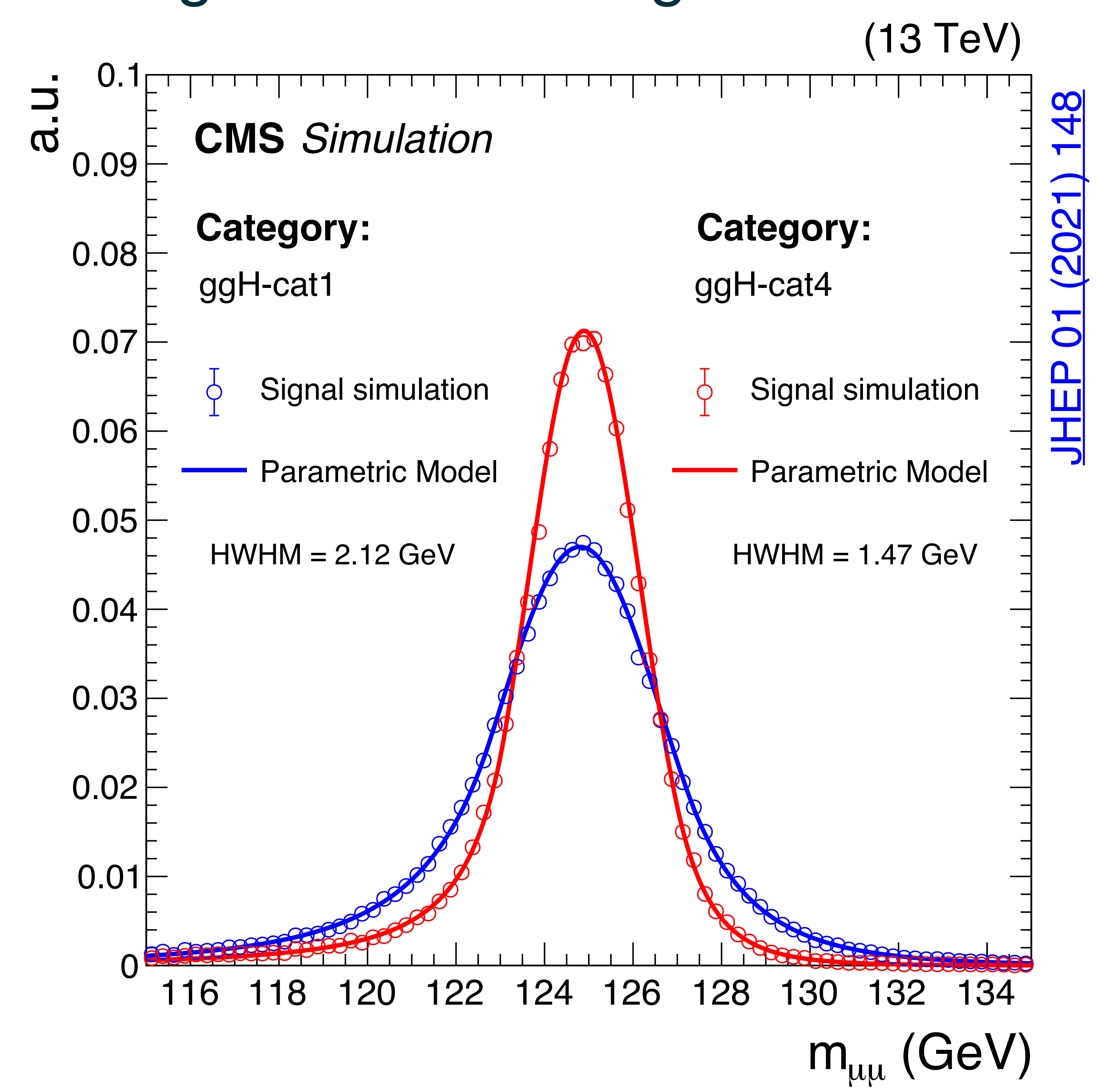
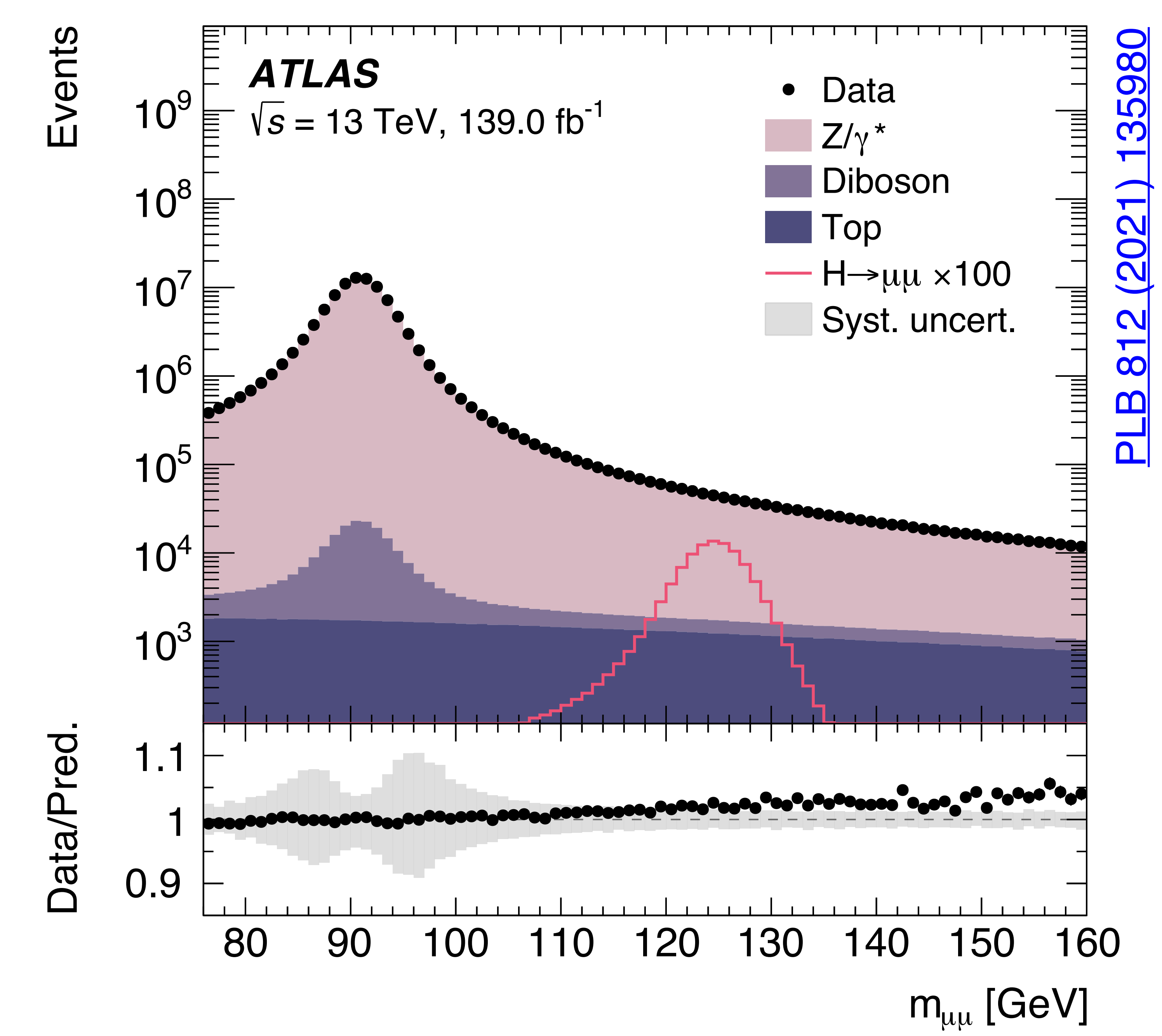
- H → μμ probes the Yukawa coupling for 2nd generation fermions,
  - Origin of the Yukawa couplings ranging over 6 orders of magnitude is unknown,
  - Any deviations from the SM would be a clear sign of new physics,
- H→μμ is a small peak on top of a smoothly falling background dominated by Z/γ*→μμ (S/B as low as 0.1%),
- The difference in the sensitivity between ATLAS and CMS driven mainly by the muon momentum resolution:



~2x better mass resolution in CMS due to the stronger solenoid magnetic field

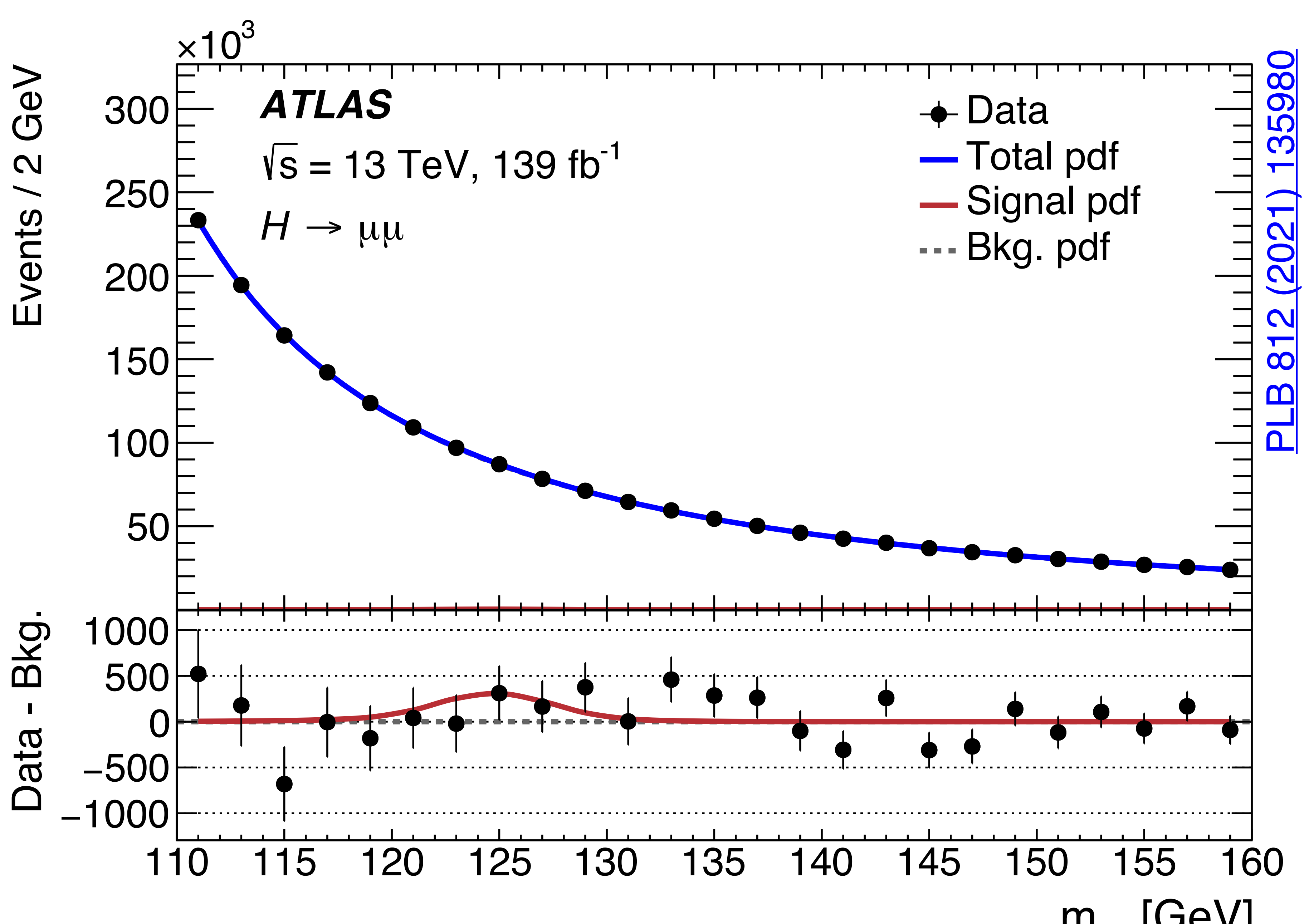


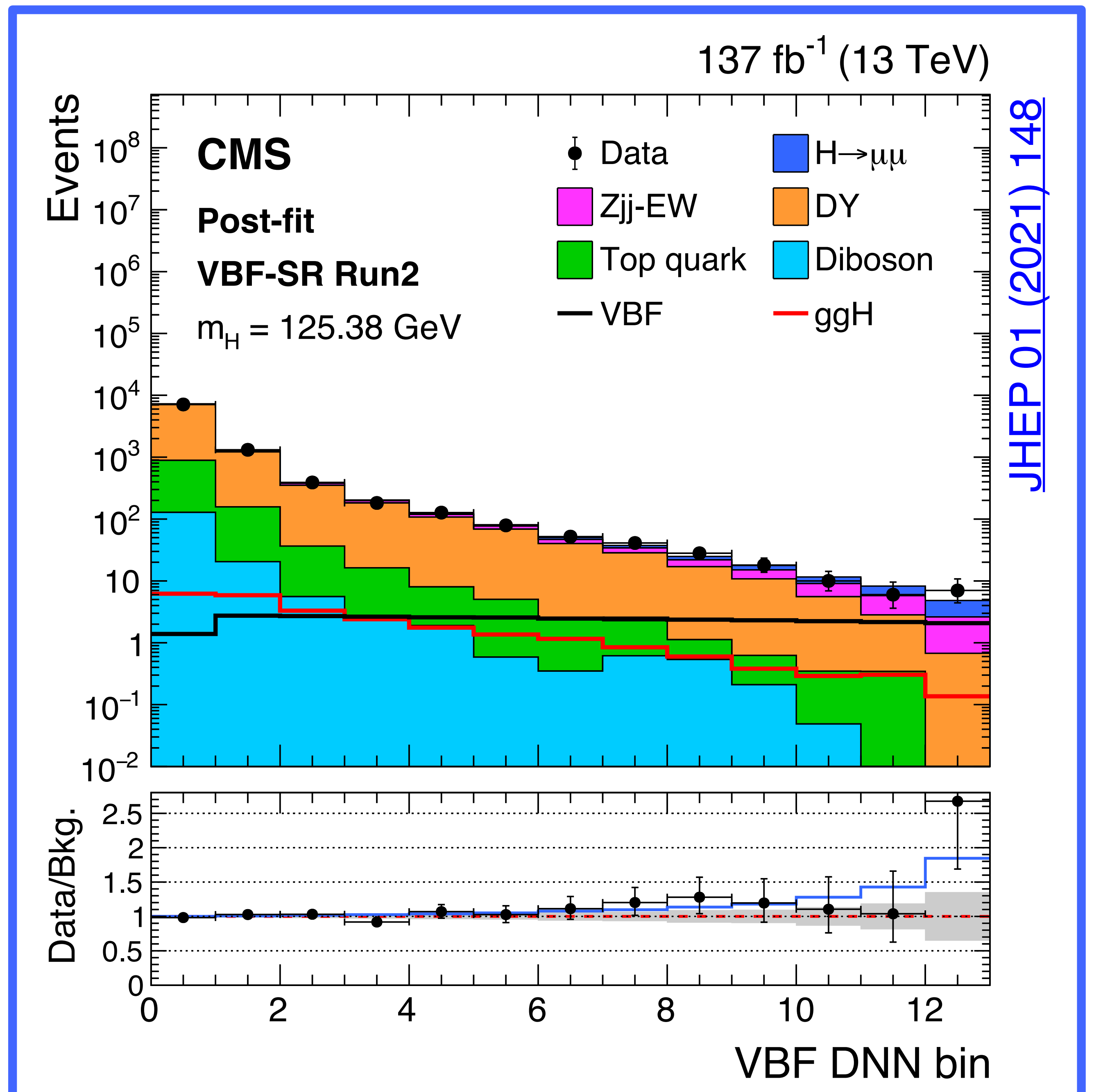


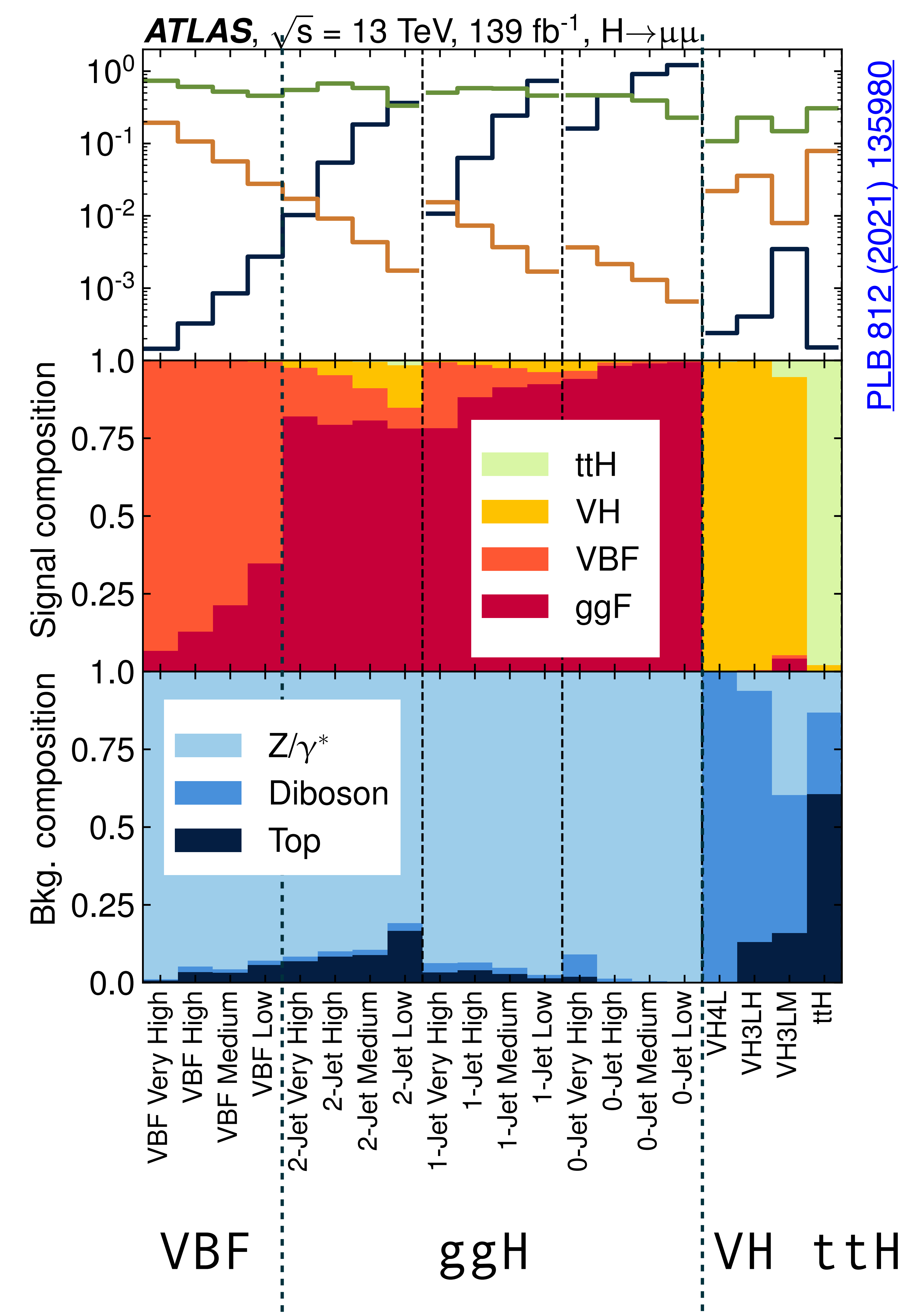


H → μμ Analysis Strategy

- A multivariate discriminant is trained to enhance the H → μμ signal against the main SM background in each category (DY in `ggH/VBF`, tt/ttZ in `ttH`, VV in `VH`):
  - `ggH`: 12 (5) BDT categories in ATLAS (CMS),
  - `VBF`: 4 BDT categories in ATLAS, **DNN** trained in CMS,
  - `VH` : 3 (5) BDT categories in ATLAS (CMS),
  - `ttH`: 1 (5) BDT categories in ATLAS (CMS),
- The $m_{\mu\mu}$ invariant mass is fitted with a **parametric model** in each region to extract the signal yield,
  - An exception is the VBF category in CMS where the **DNN** discriminant is fitted with a **MC-based model** to extract the VBF signal.

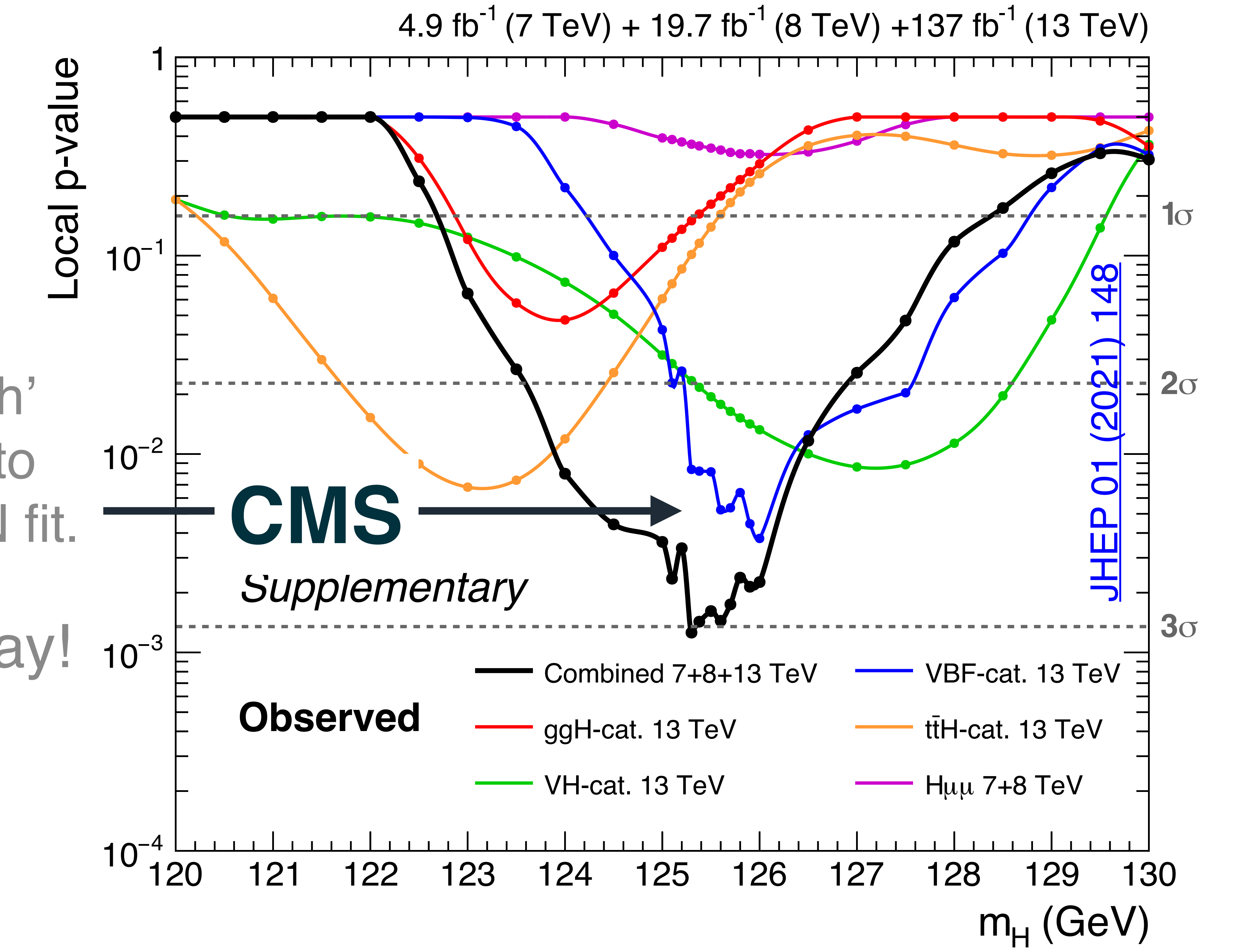




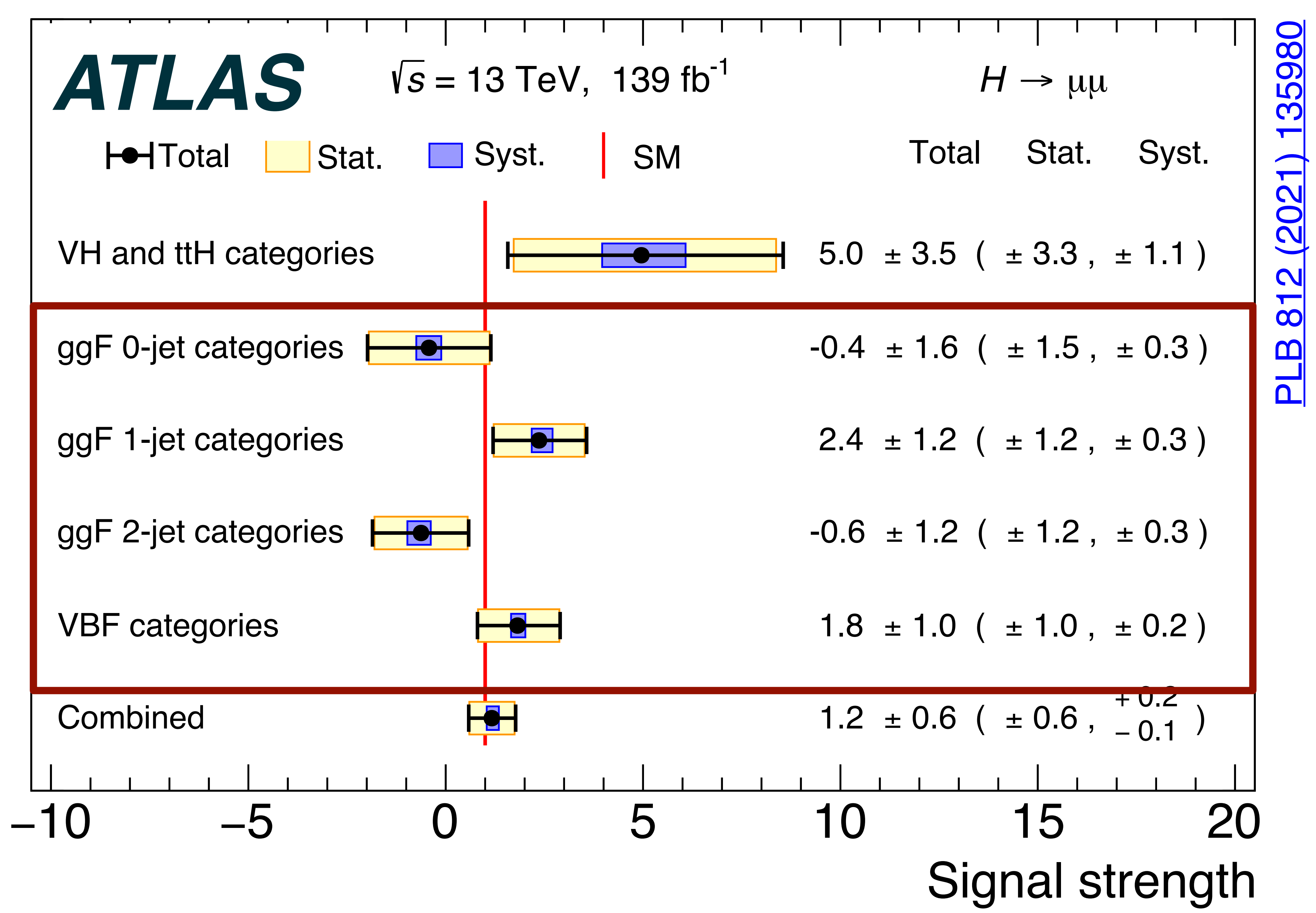


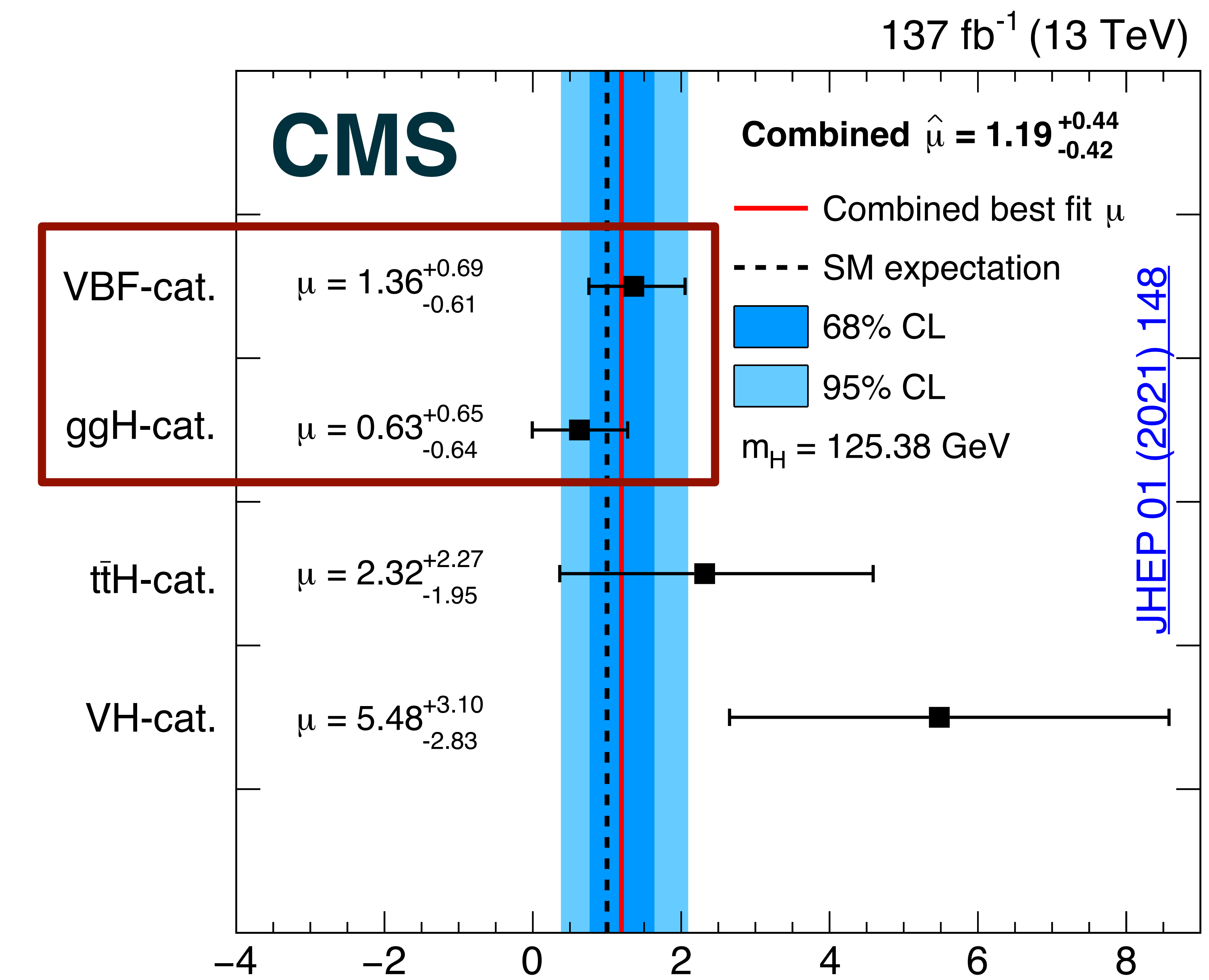
- The H → μμ search is statistically limited (relative stat. error in μ_{SIG} is 50% in ATLAS and 30% in CMS),
- VBF and ggH channels are the most sensitive,
- Observed compatibility with B-only hypothesis is:
  - 2.0σ (1.7σ expected) in ATLAS,
  - 3.0σ (2.5σ expected) in CMS, ← Evidence of the H → μμ decay!
- Potential for 5.0σ at the end or Run 3 with a combination?

VBF not 'smooth' like others due to the binned DNN fit.



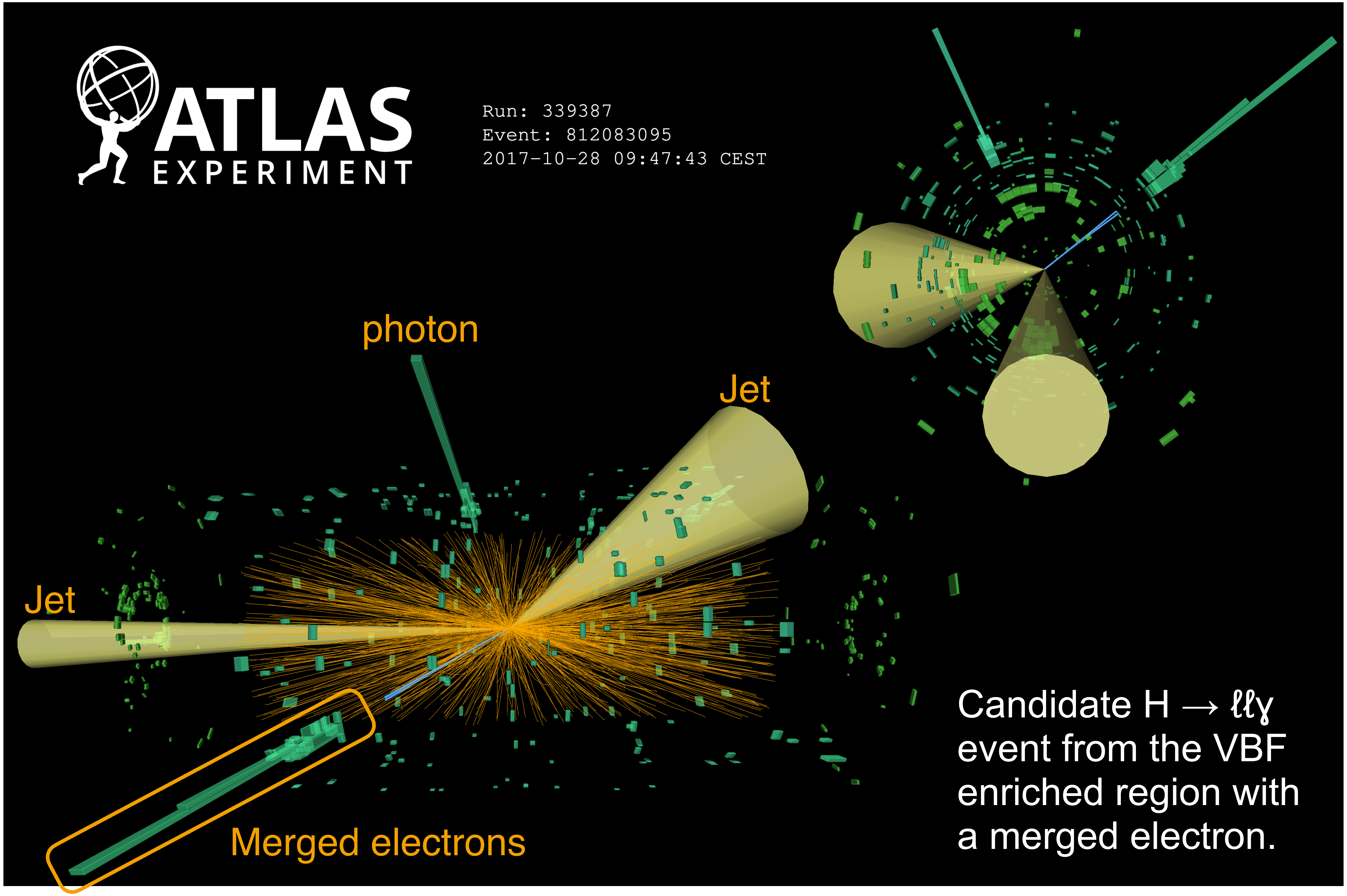
$$\mu = 1.17 \pm 0.58\,(\text{stat}) \pm 0.10\,(\text{spur.})^{+0.13}_{-0.08}\,(\text{theory})^{+0.07}_{-0.03}\,(\text{exp.})$$





$$\mu = 1.19 \pm 0.40\,(\text{stat}) \pm 0.15\,(\text{syst})$$ Best-fit μ

A candidate H → ℓℓγ event in ATLAS



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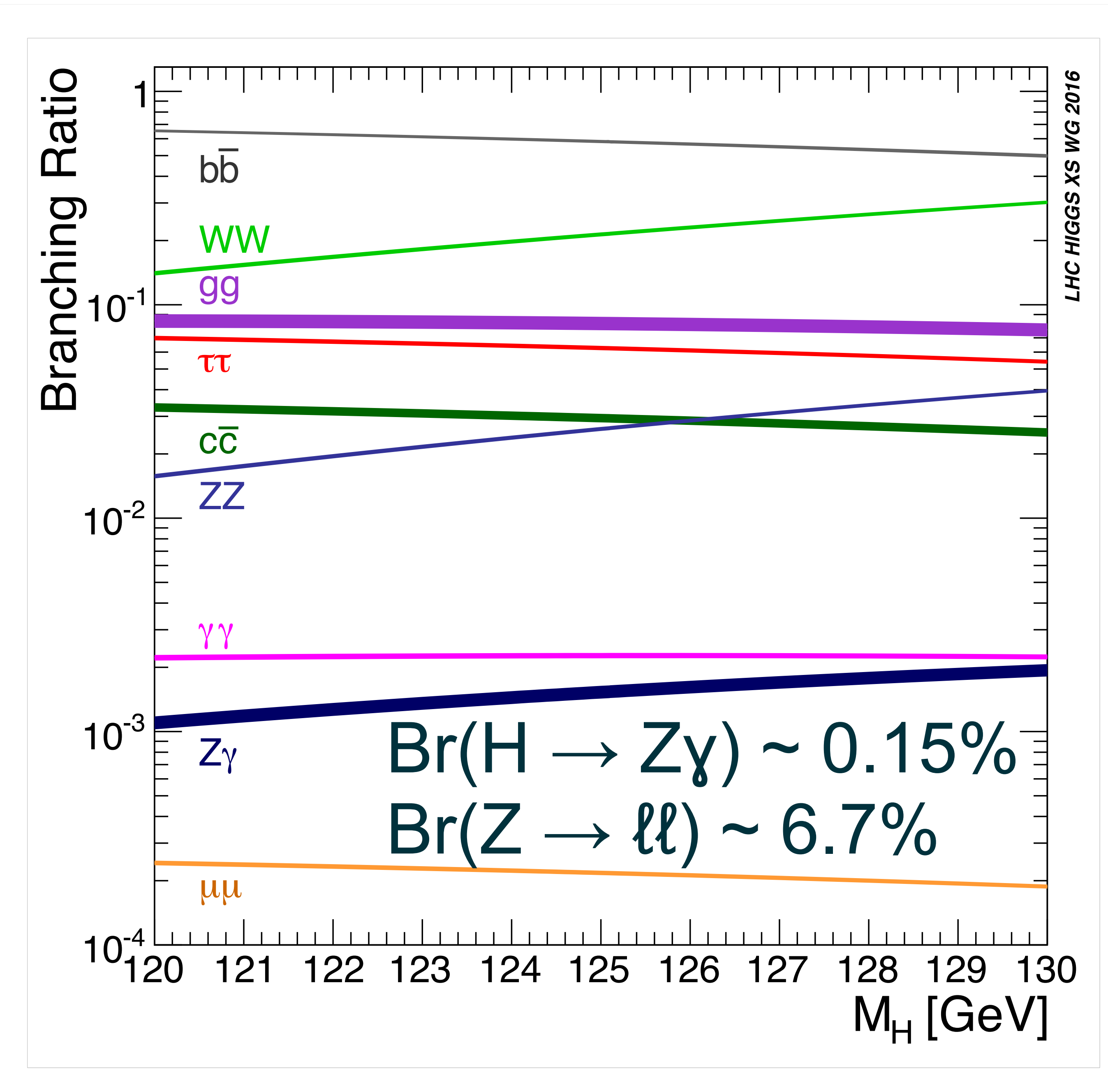
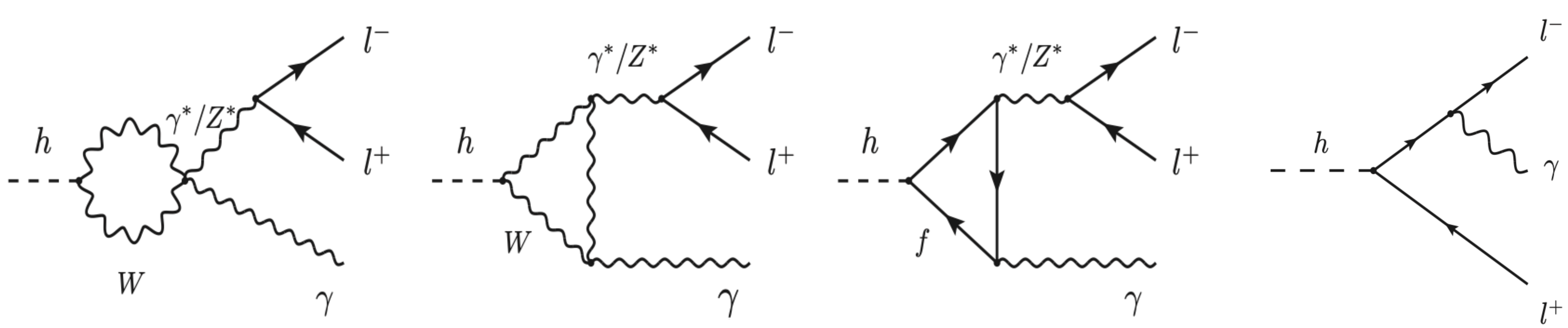
- Production of H → ℓℓɣ (ℓ = e,μ) either through loop processes or lepton pair + FSR production,
  - Loop processes sensitive to coupling modifications introduced by BSM extensions,
  - Relative contribution of ℓℓ+FSR depends lepton mass,
- Very low branching ratio— O(0.01%),
- In addition, H → ℓℓɣ can probe CP-violation in the Higgs sector because of the three-body decay (JHEP05 (2013) 061).
- Analyses generally split into low and high **di-lepton mass**:
  - $m_{\ell\ell}$ < 30 to 50 GeV dominated by H→ɣ*ɣ→ℓℓɣ,
  - $m_{\ell\ell}$ around 90 GeV dominated by H→Zɣ→ℓℓɣ.

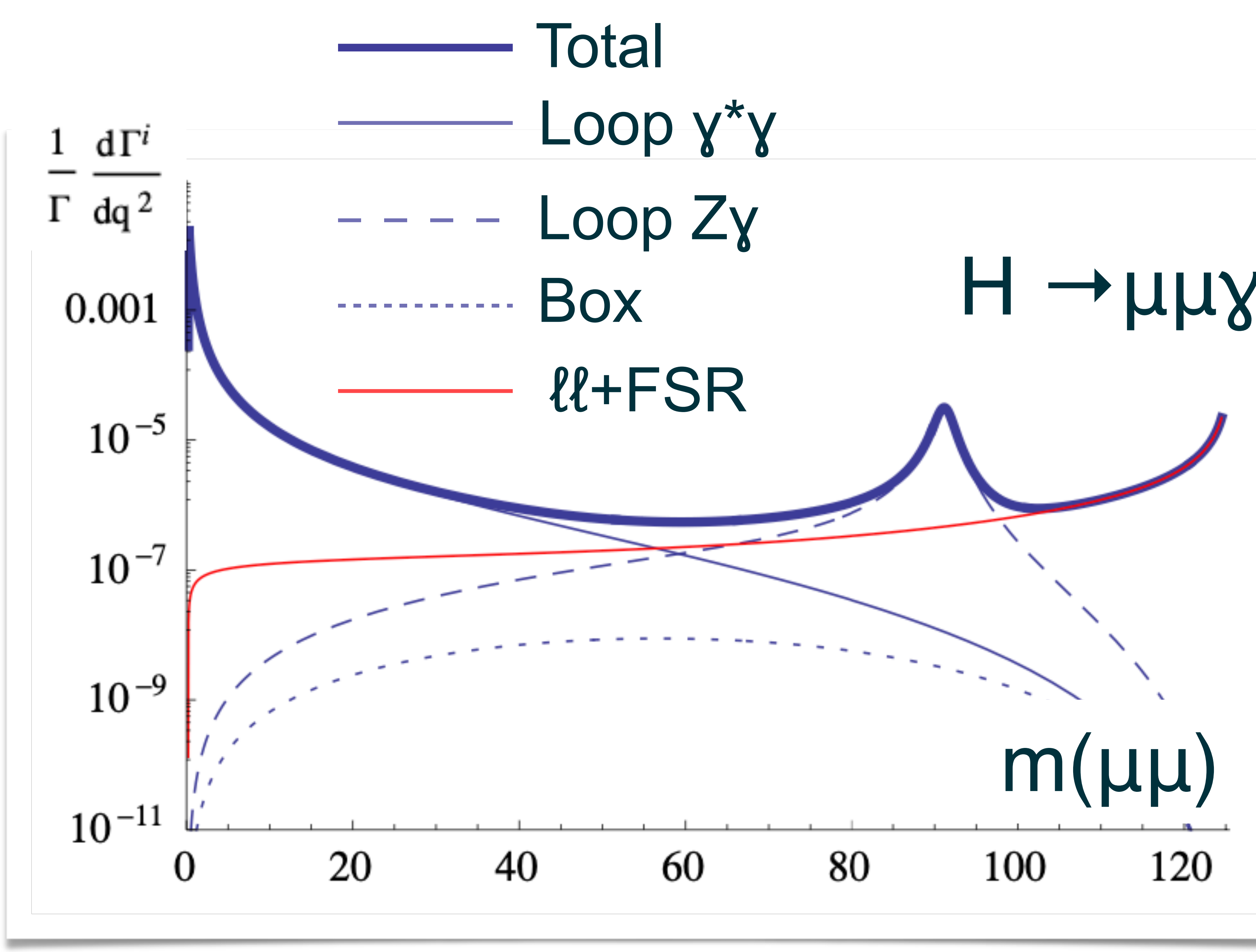


LHCHWG

Loop-induced processes

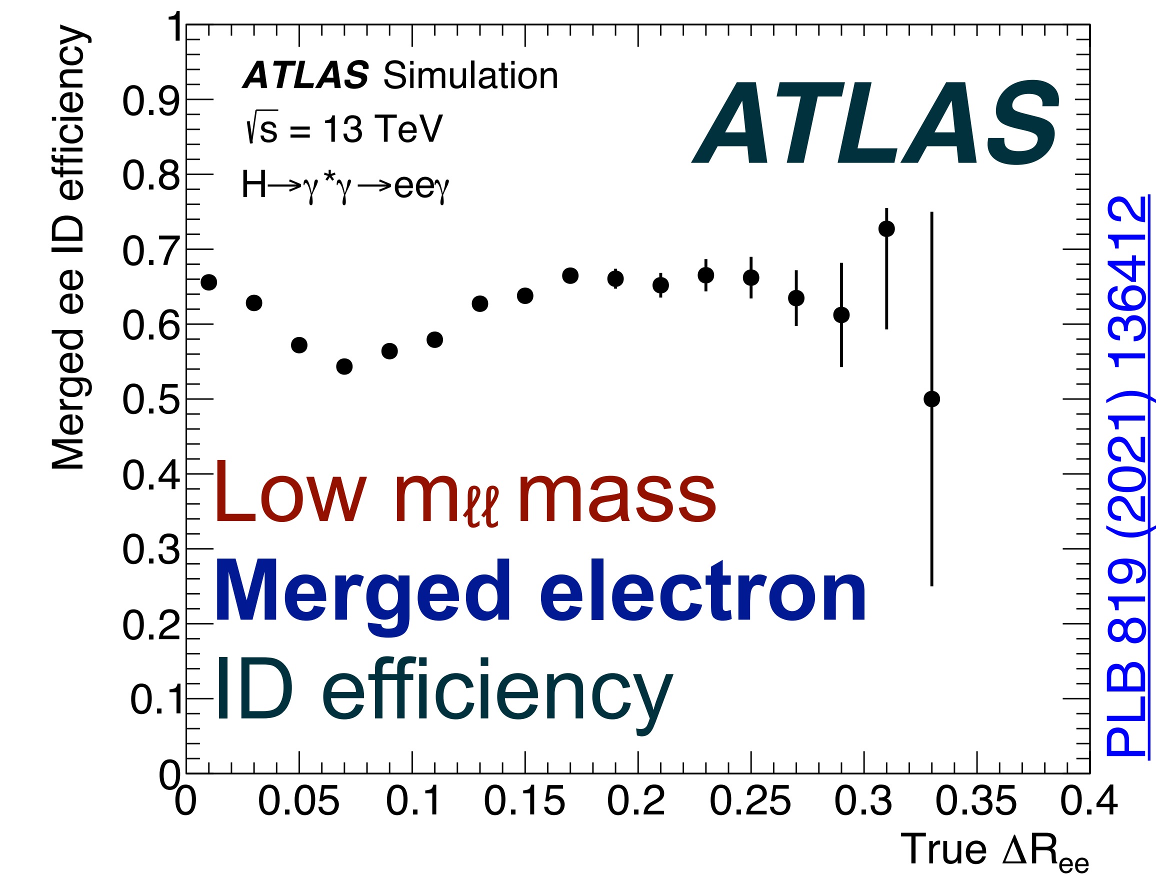
ℓℓ+FSR



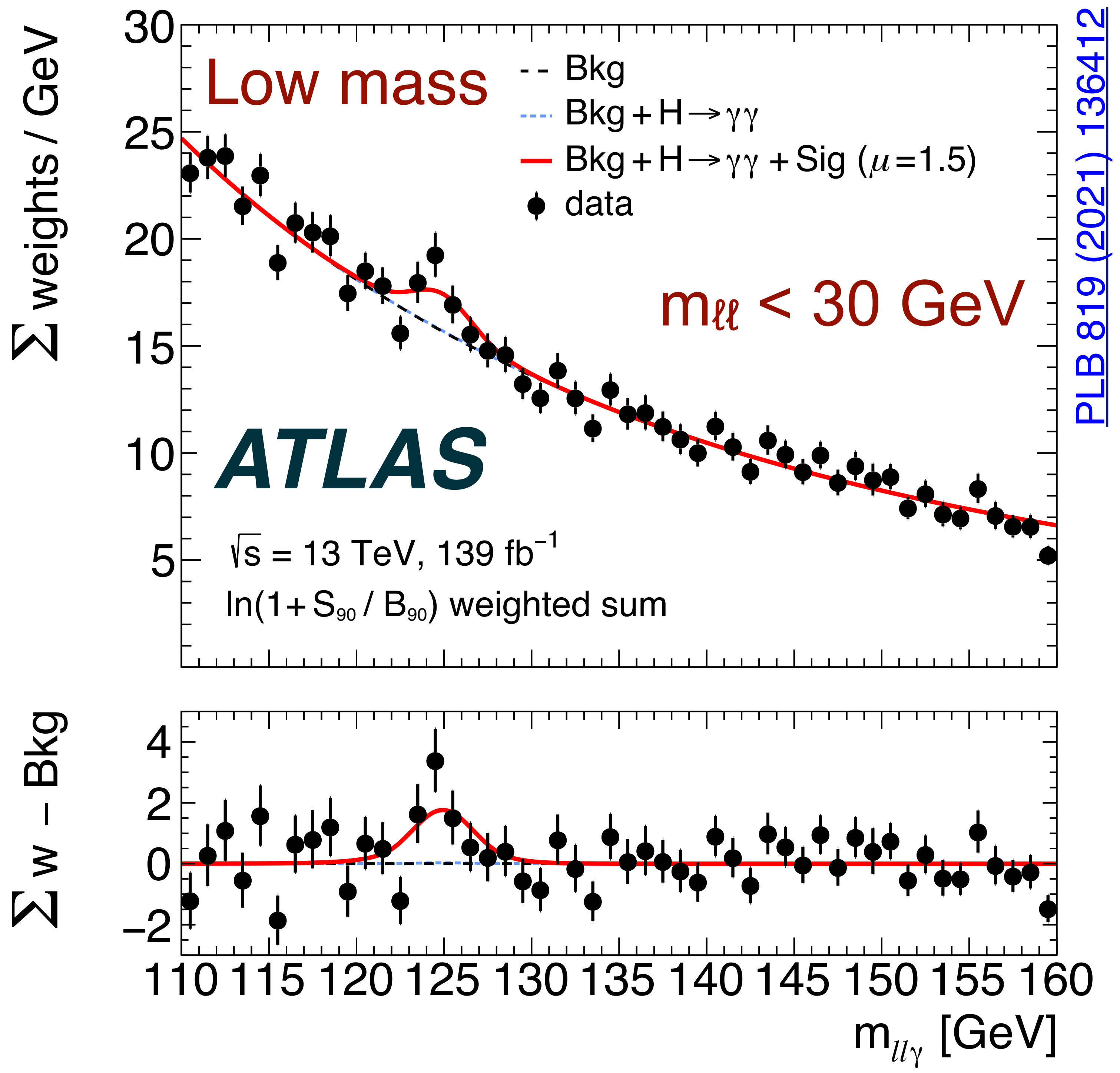


JHEP05 (2013) 061

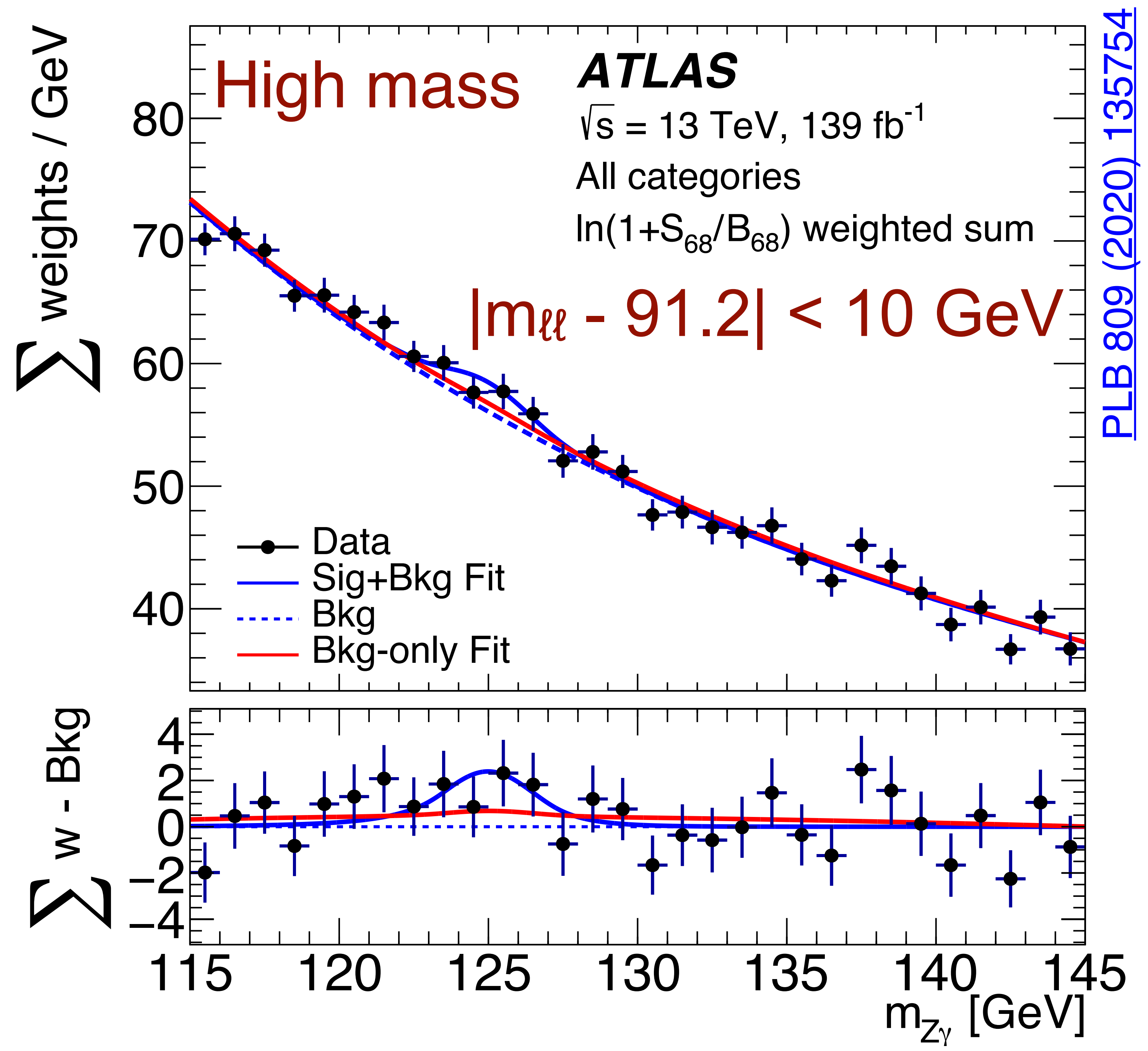
- The H → ℓℓγ searches are statistically limited,
- The low $m_{\ell\ell}$ mass search is more sensitive due to smaller SM backgrounds,
- Observed compatibility with B-only hypothesis with **full Run 2** ATLAS data:
  - Low mass: 3.2σ (2.1σ expected), ⟵ First evidence of the H→γ*γ→ℓℓγ decay!
  - High mass: 2.2σ (1.2σ expected),
- CMS set **upper limits** on the H → ℓℓγ production with **36 fb⁻¹**:
  - 3.9 × SM (2.0 × SM expected) for combined low + high mass.

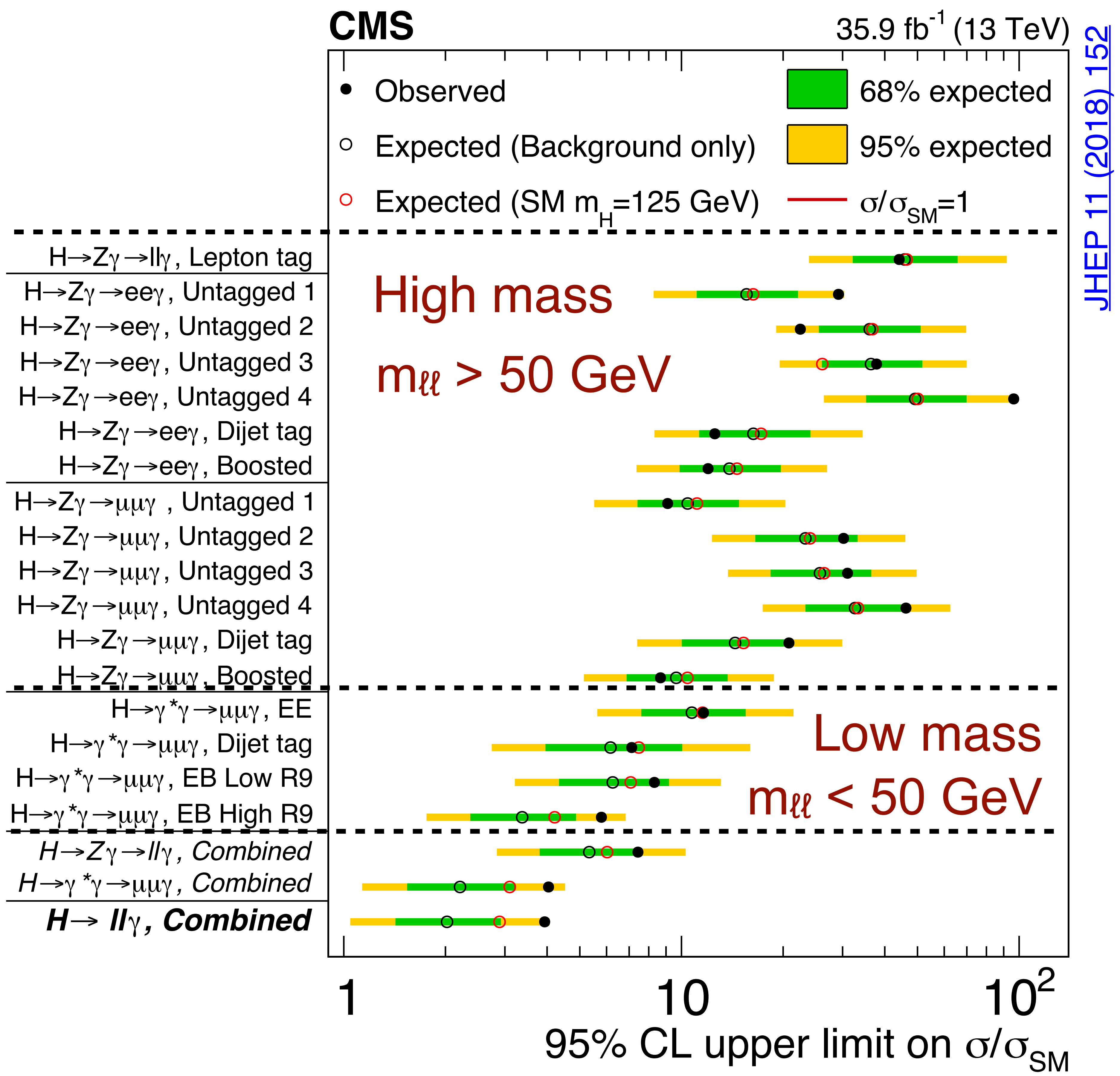


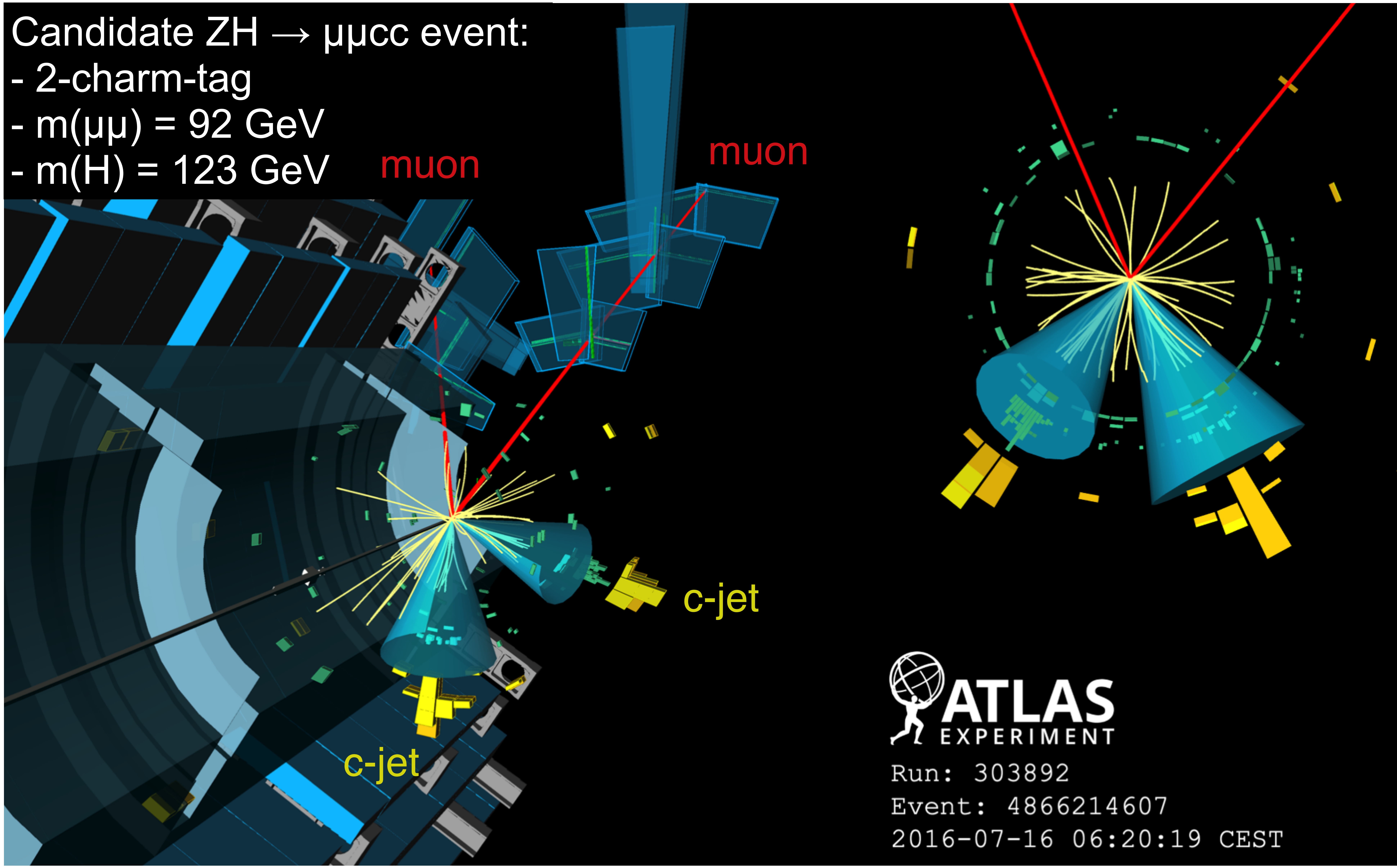
$\mu = 1.5 \pm 0.5\,(\text{stat}) \pm 0.2\,(\text{syst})$



$\mu = 2.0 \pm 0.9\,(\text{stat}) \pm 0.4\,(\text{syst})$



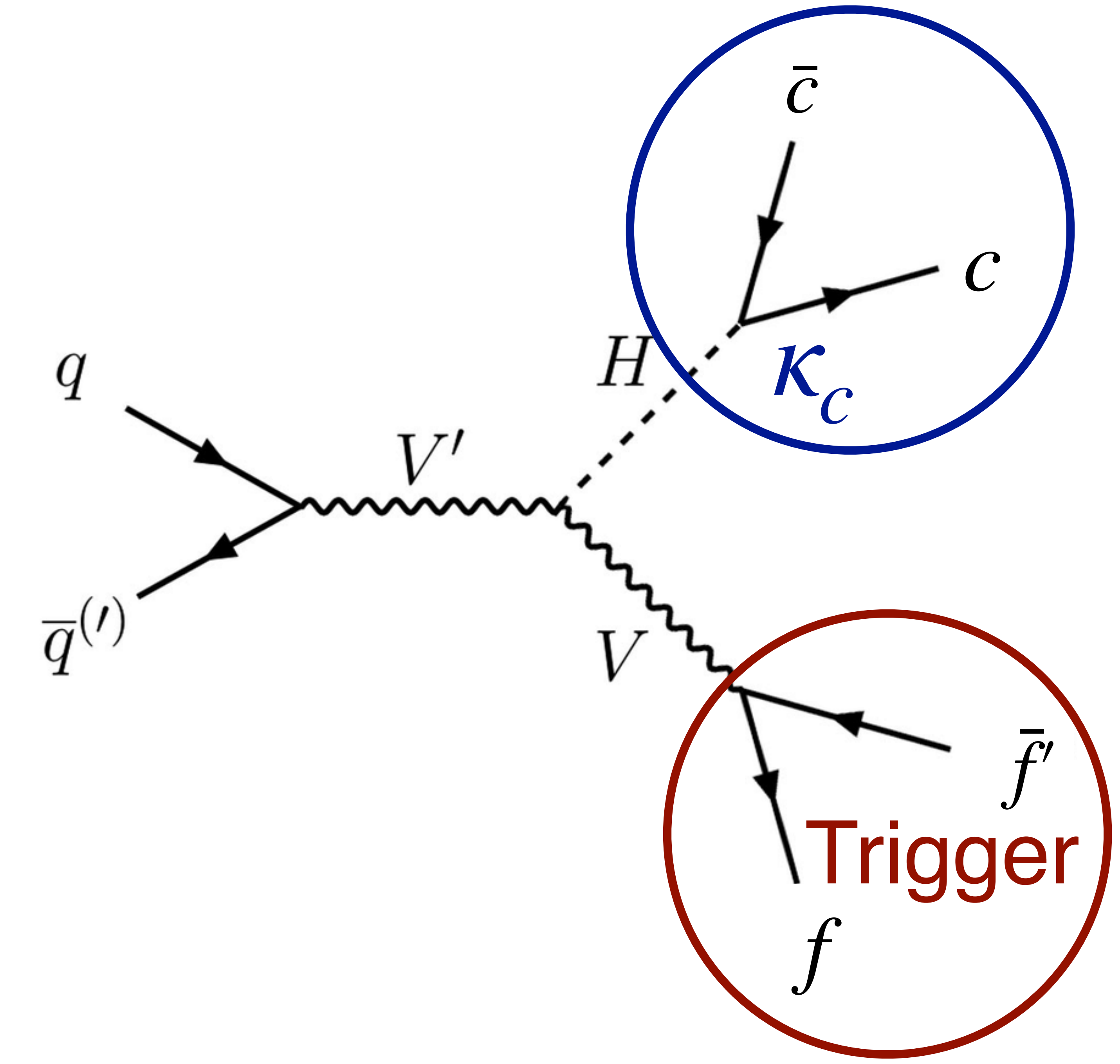




ATLAS-CONF-2021-021

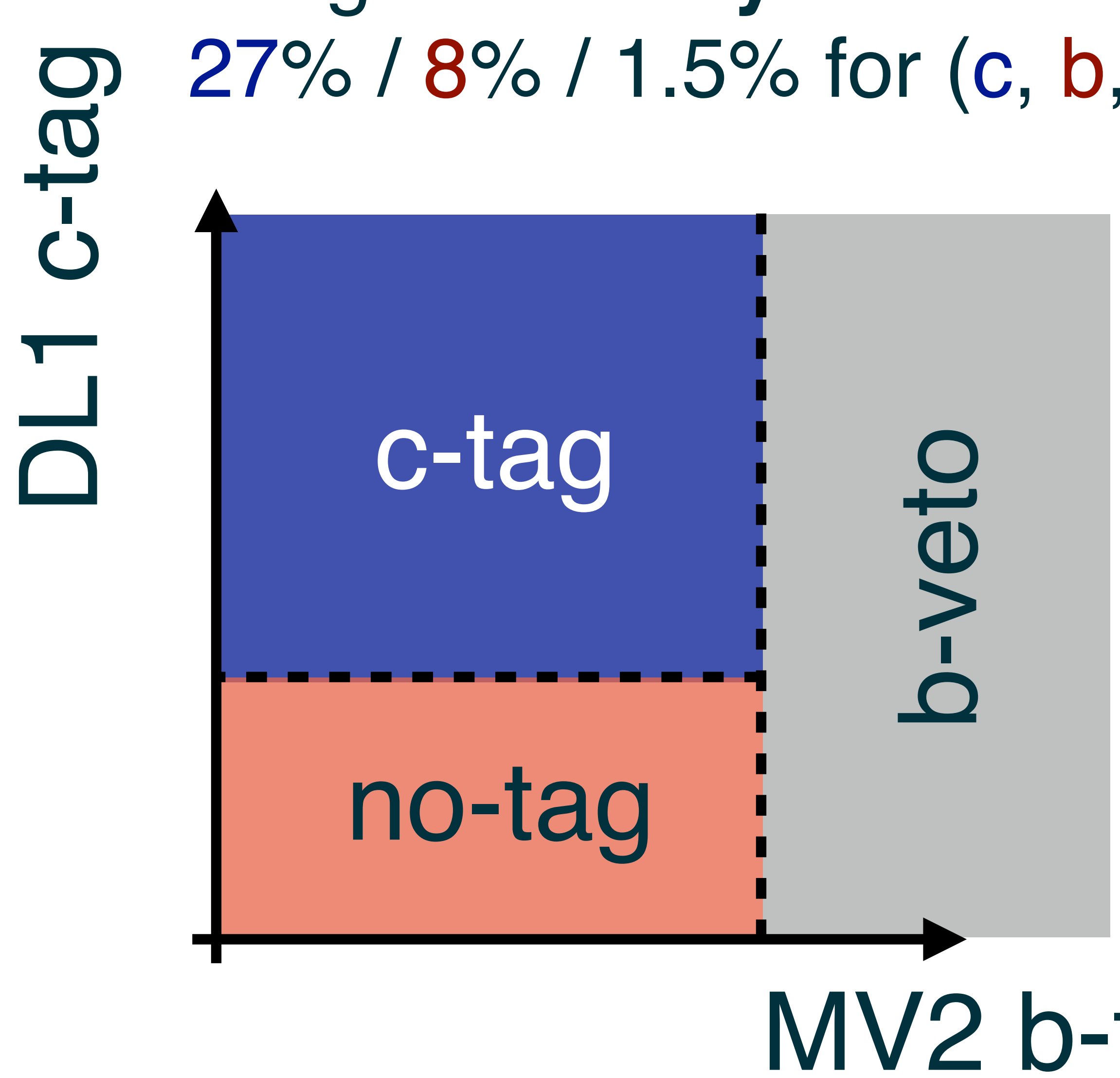
Search for the H → cc decay

- Br(H → cc) ≈ 130x Br(H → μμ), but lower sensitivity due to the worse efficiency, resolution, background separation, and triggering,
  - Both ATLAS (full Run 2) and CMS (36 fb^{-1}) have direct searches for H → cc with the VH production mode,
- Analysis split based on the lepton multiplicity:
  - `0-lepton`: Z(→ νν) H(→ cc), MET trigger,
  - `1-lepton`: W(→ ℓν) H(→ cc), lepton (and MET in ATLAS) trigger,
  - `2-lepton`: Z(→ ℓℓ) H(→ cc), lepton trigger,
- c-jet tagging and signal extraction is the central piece of the analysis.



ATLAS

c-tag **efficiency** @ttbar
27% / 8% / 1.5% for (c, b, light)



16 SR: split into 1-tag and 2-tag.

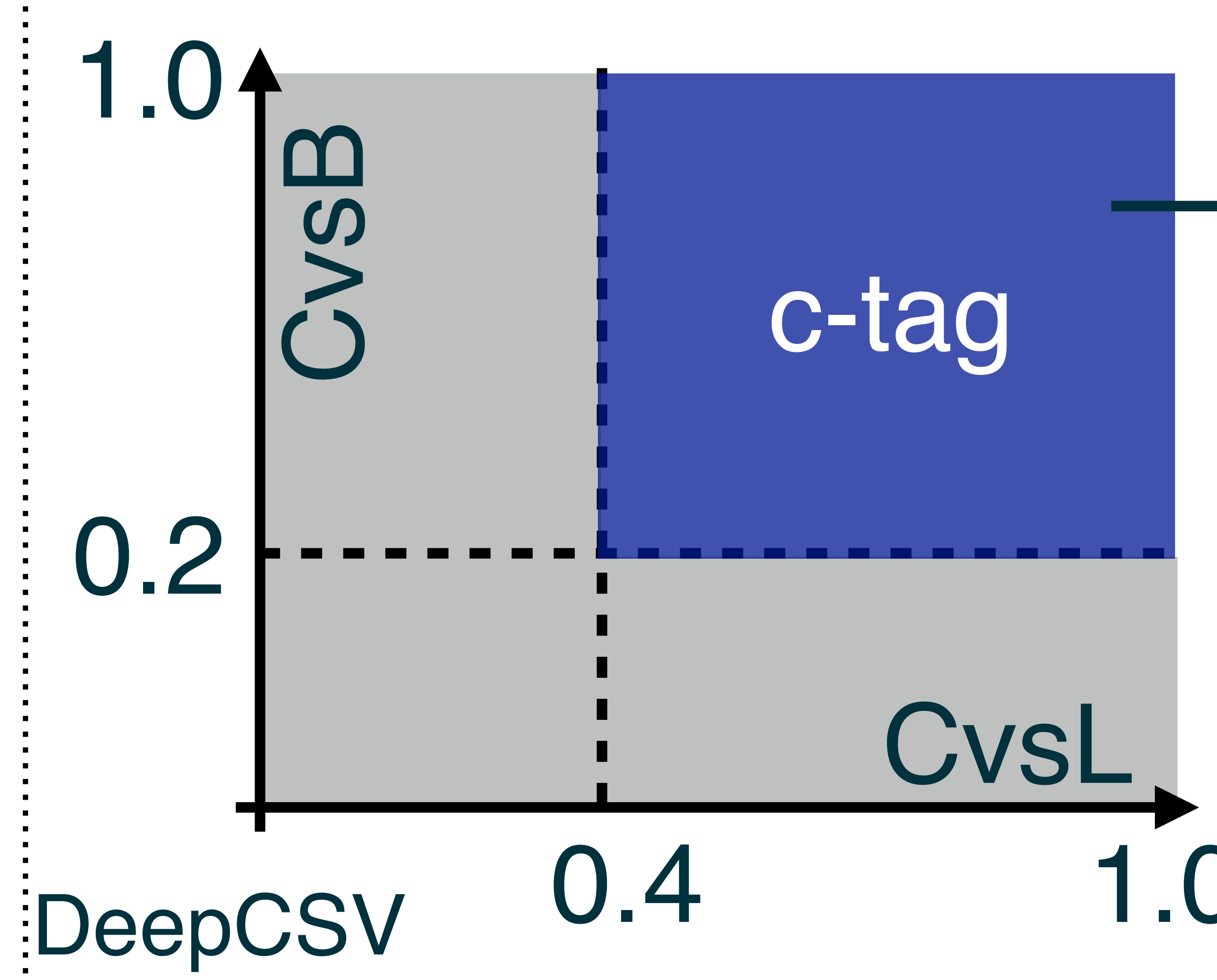
Fit m(cc) to extract the signal.

ATLAS-CONF-2021-021

CMS

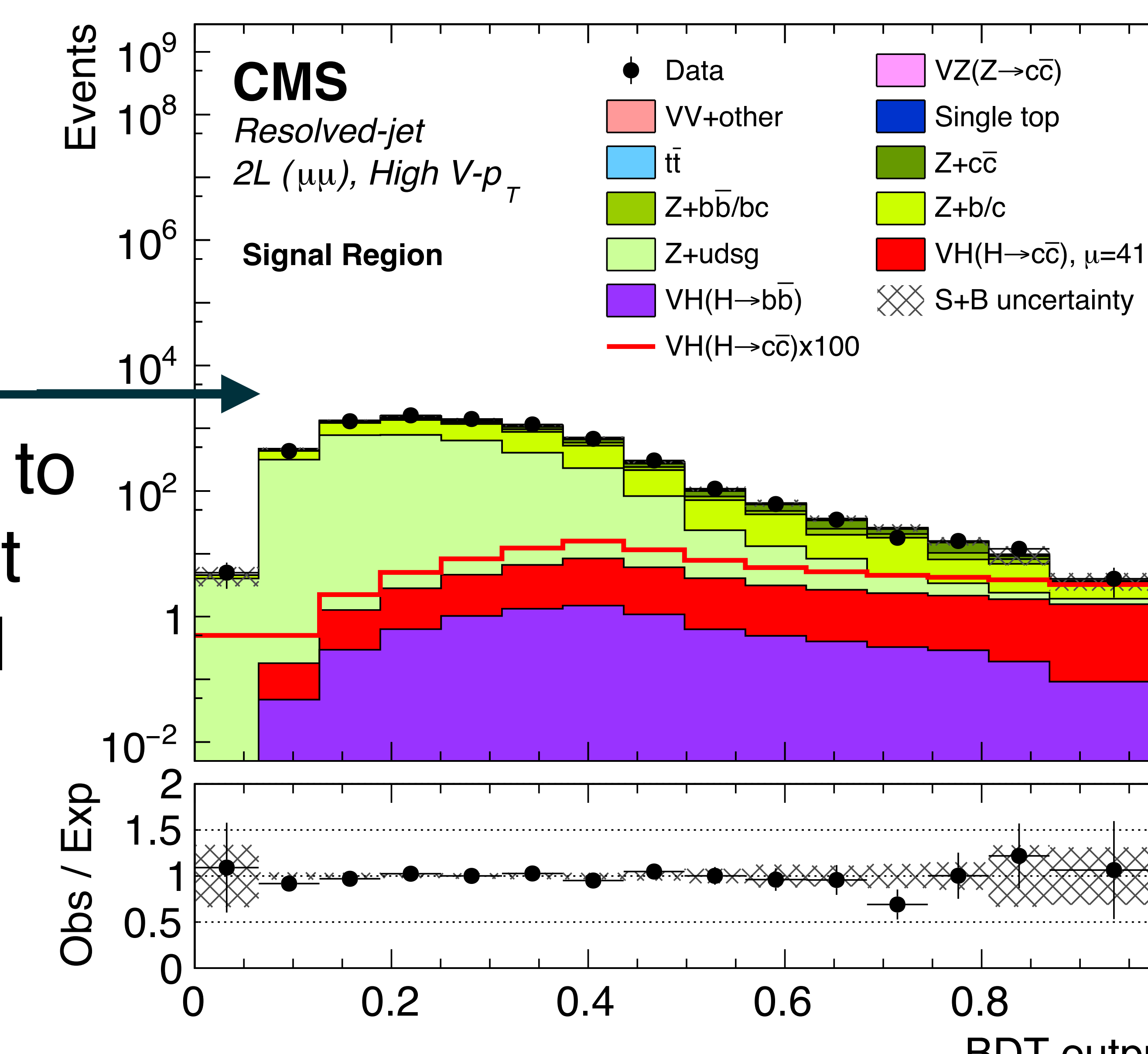
CvsL, CvsB, m(cc) used in BDT

c-tag **efficiency** @ttbar
28% / 14% / 4% for (c, b, light)



7 SRs

Fit BDT to extract signal



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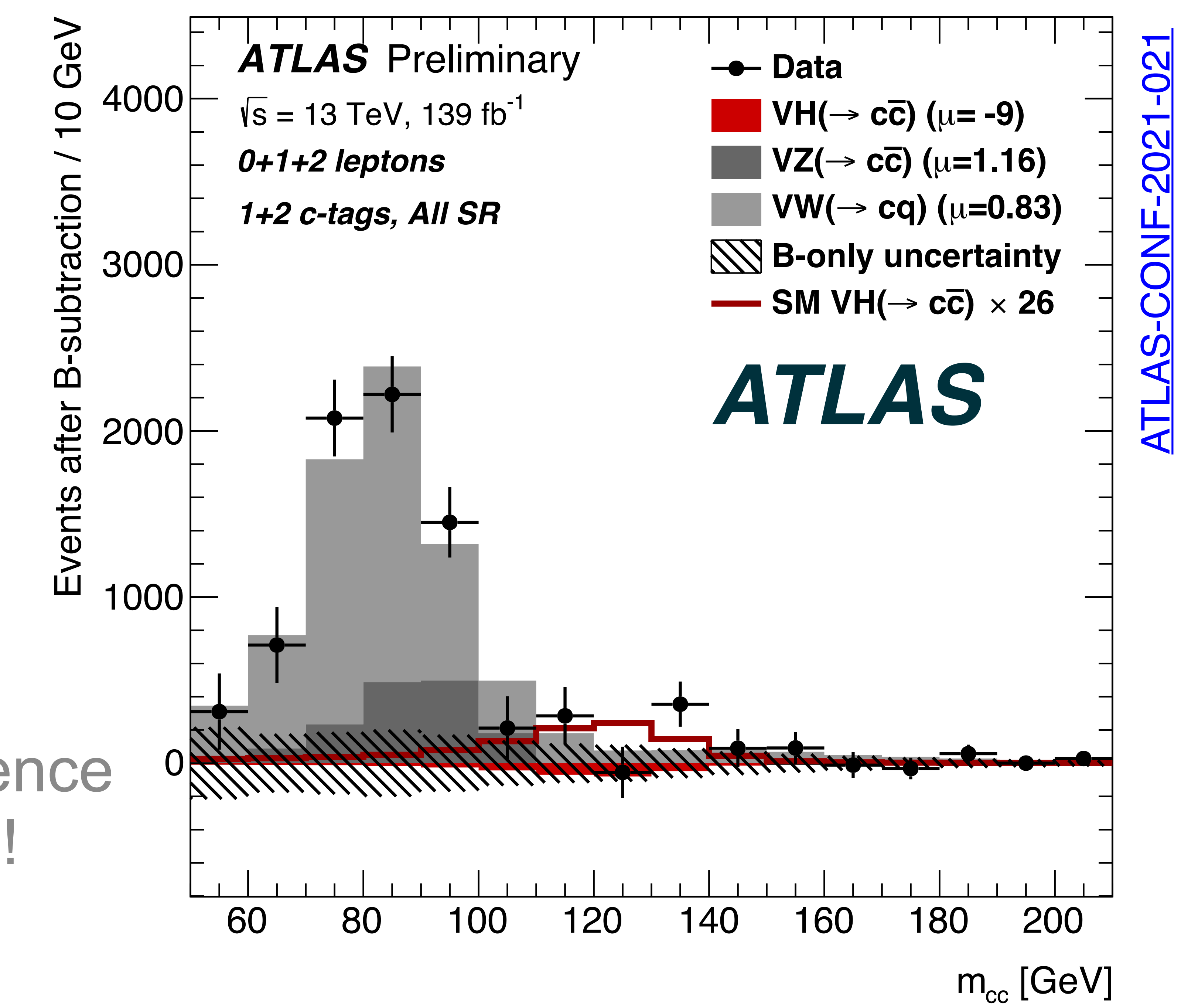
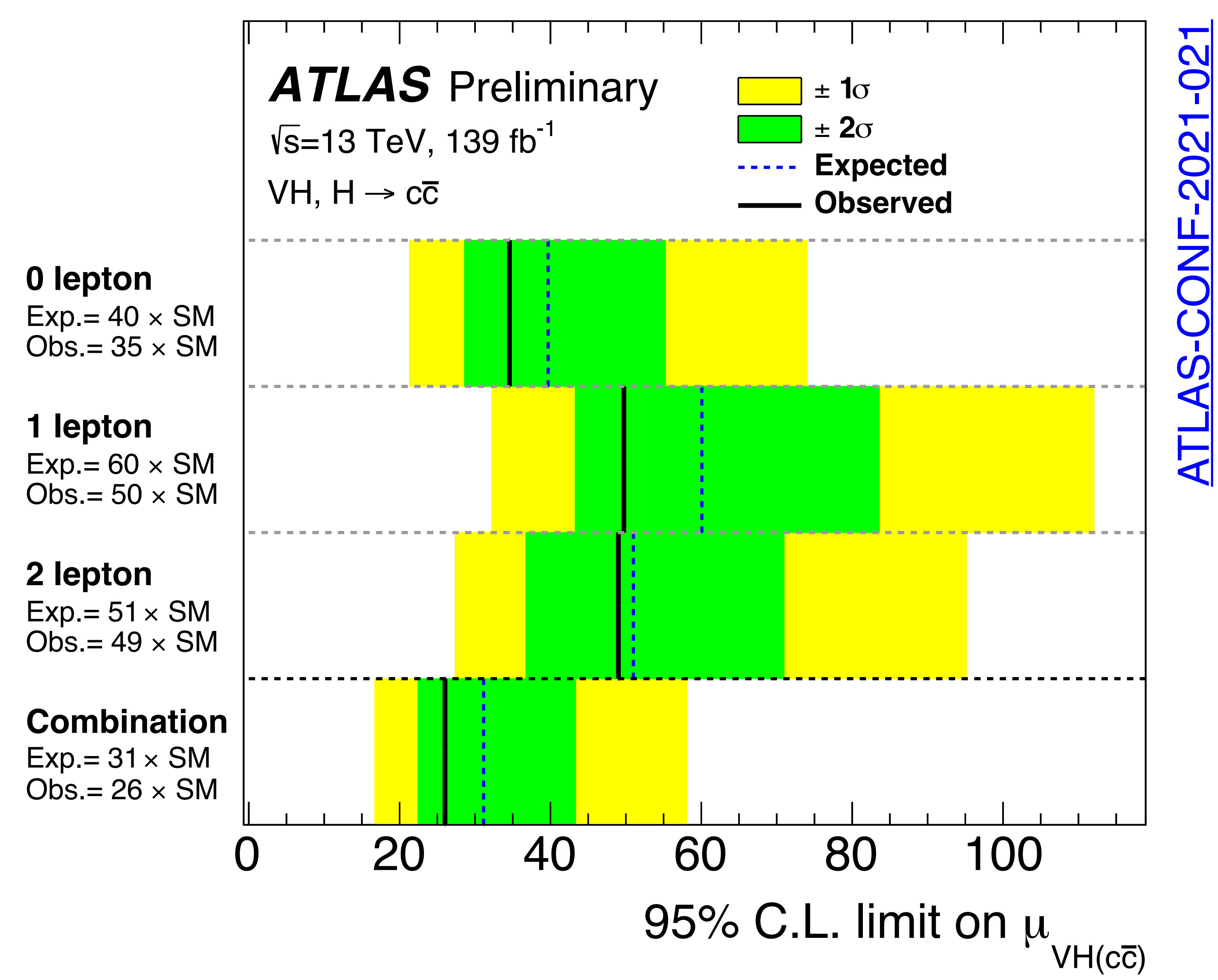
- Upper limit on signal strength at 95% CL:
  - ATLAS: 26 × SM (31 × SM expected),
  - CMS (36 fb^{-1}): 70 × SM (37 × SM expected),
- Signal strength:
  - ATLAS: -9 ± **10 (stat.)** ± **11 (syst.)**,
  - CMS (36 fb^{-1}): 37 ± **17 (stat.)** ± **10 (syst.)**,
- Similar size **systematic uncertainty** in μ_{SIG} between ATLAS and CMS— could decrease for CMS with full Run 2,
- Data **stat. uncertainty** match the lumi ratio of √(140 / 36),
- κ_c interpretation from ATLAS:
  - $|\kappa_c|$ < 8.5 at 95% CL,
  - More info in backup.

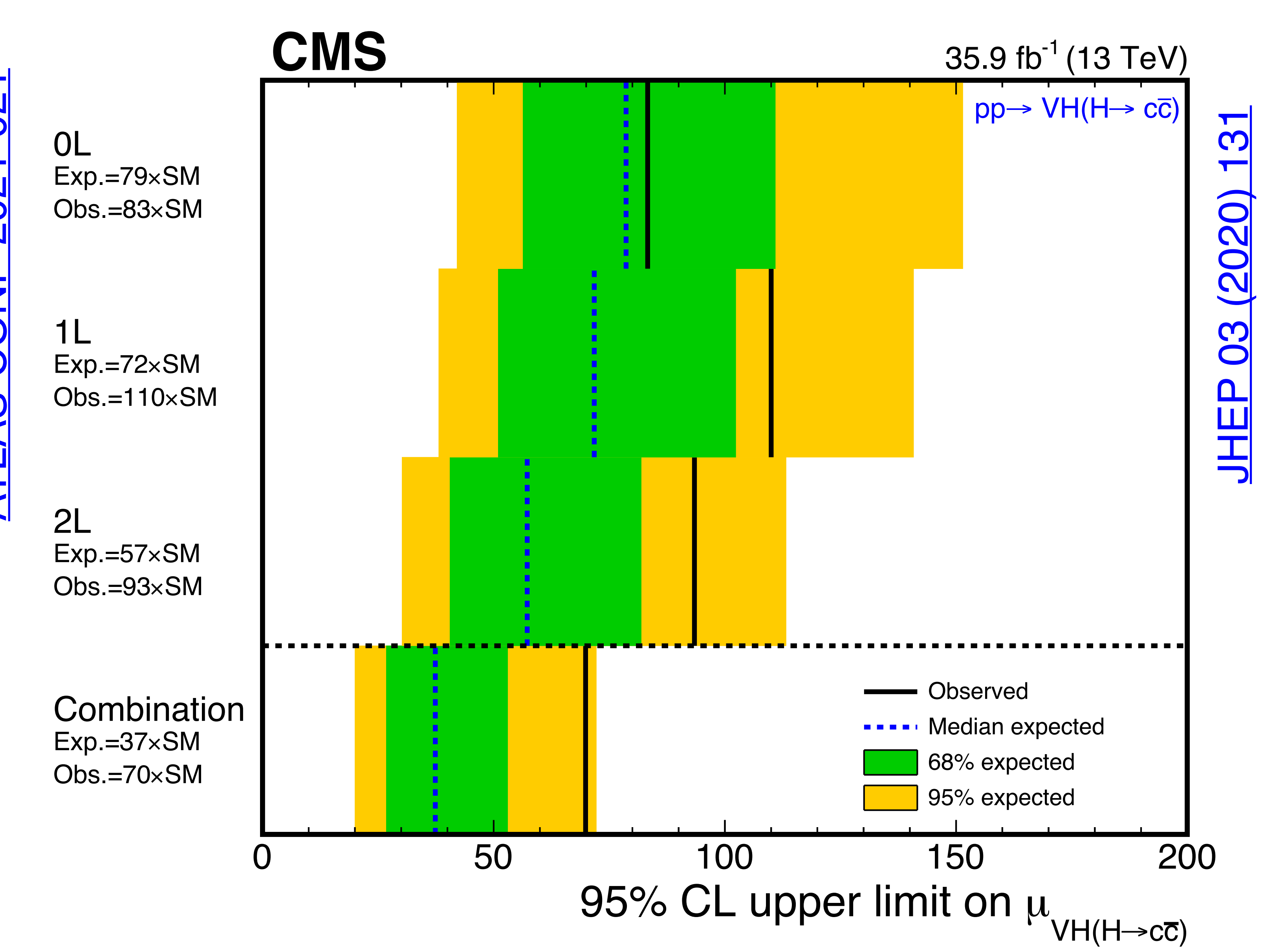
Diboson validation

	obs.	exp.
ATLAS		
VZ(cc):	2.6σ	(2.2σ)
VW(cq):	3.8σ	(4.6σ)
CMS		
VZ(cc):	1.5σ	(1.2σ)

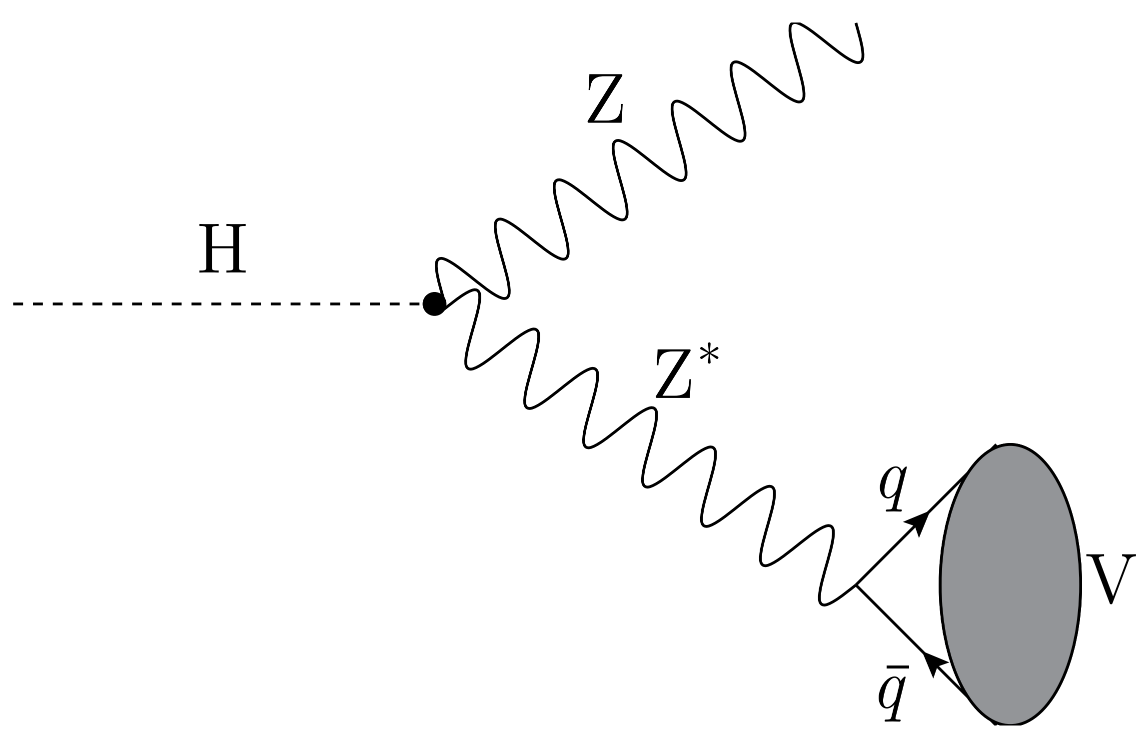
First evidence of VW(cq)!

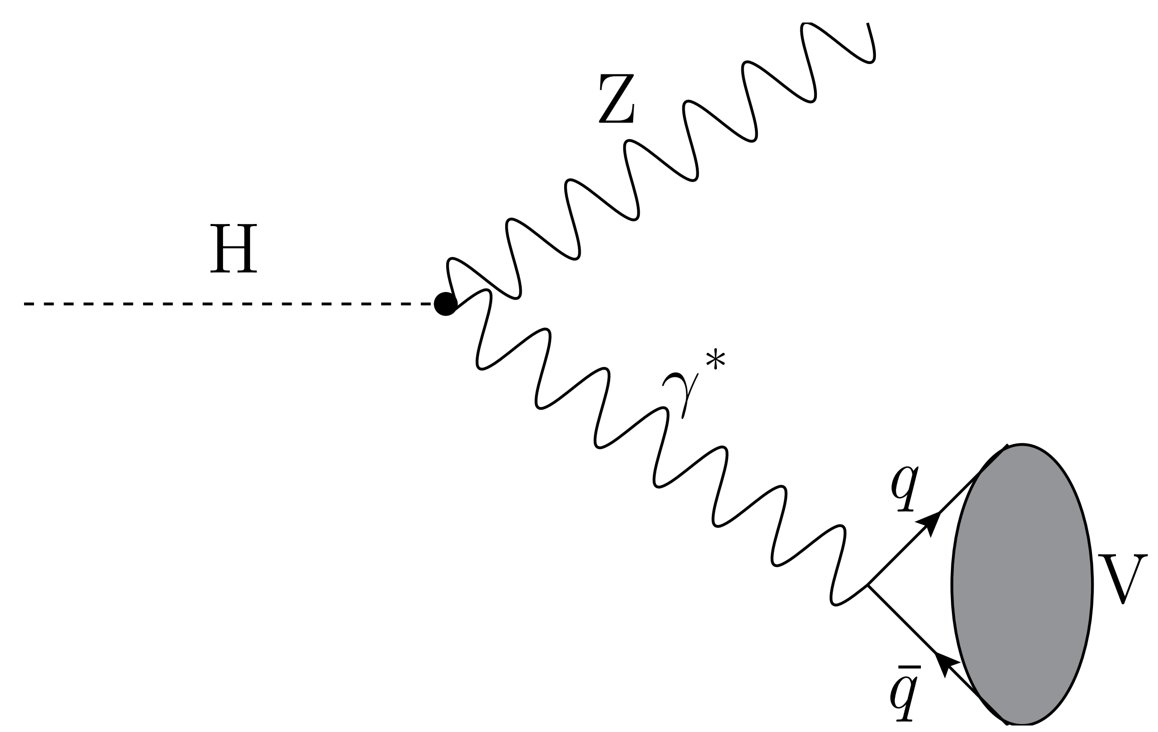


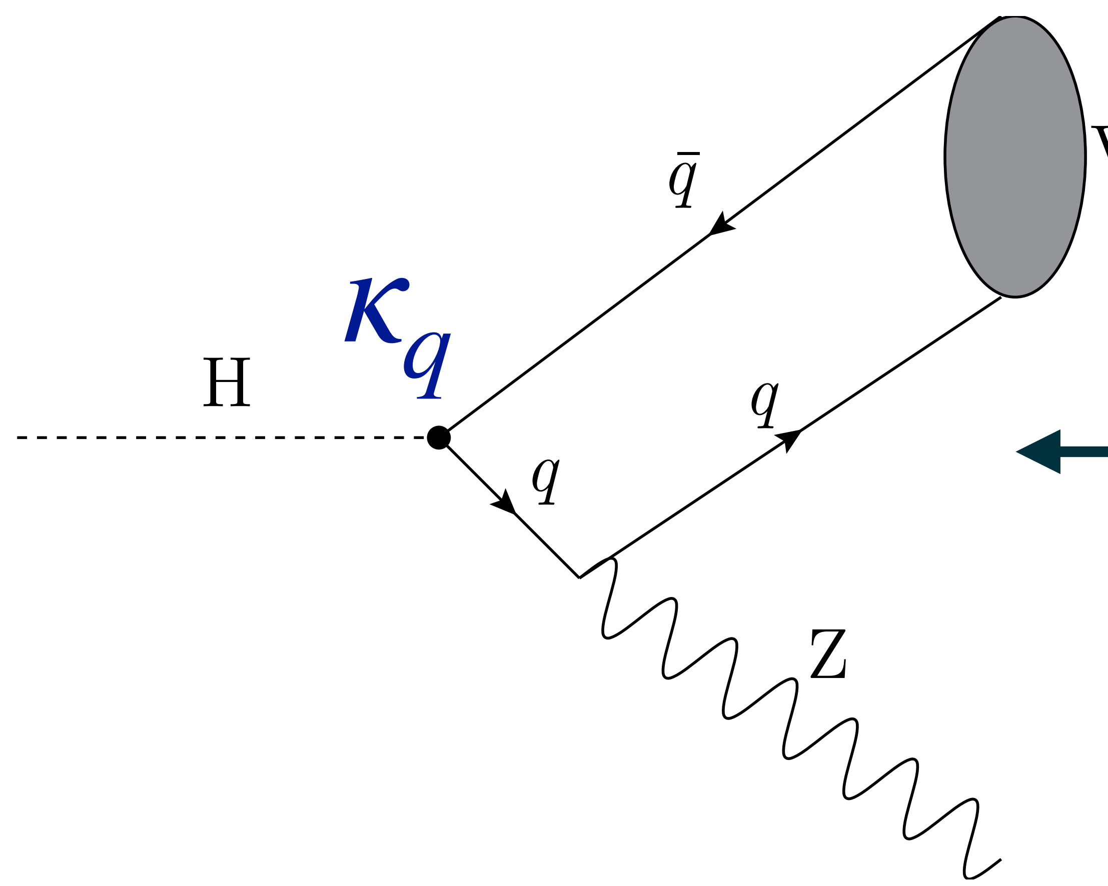




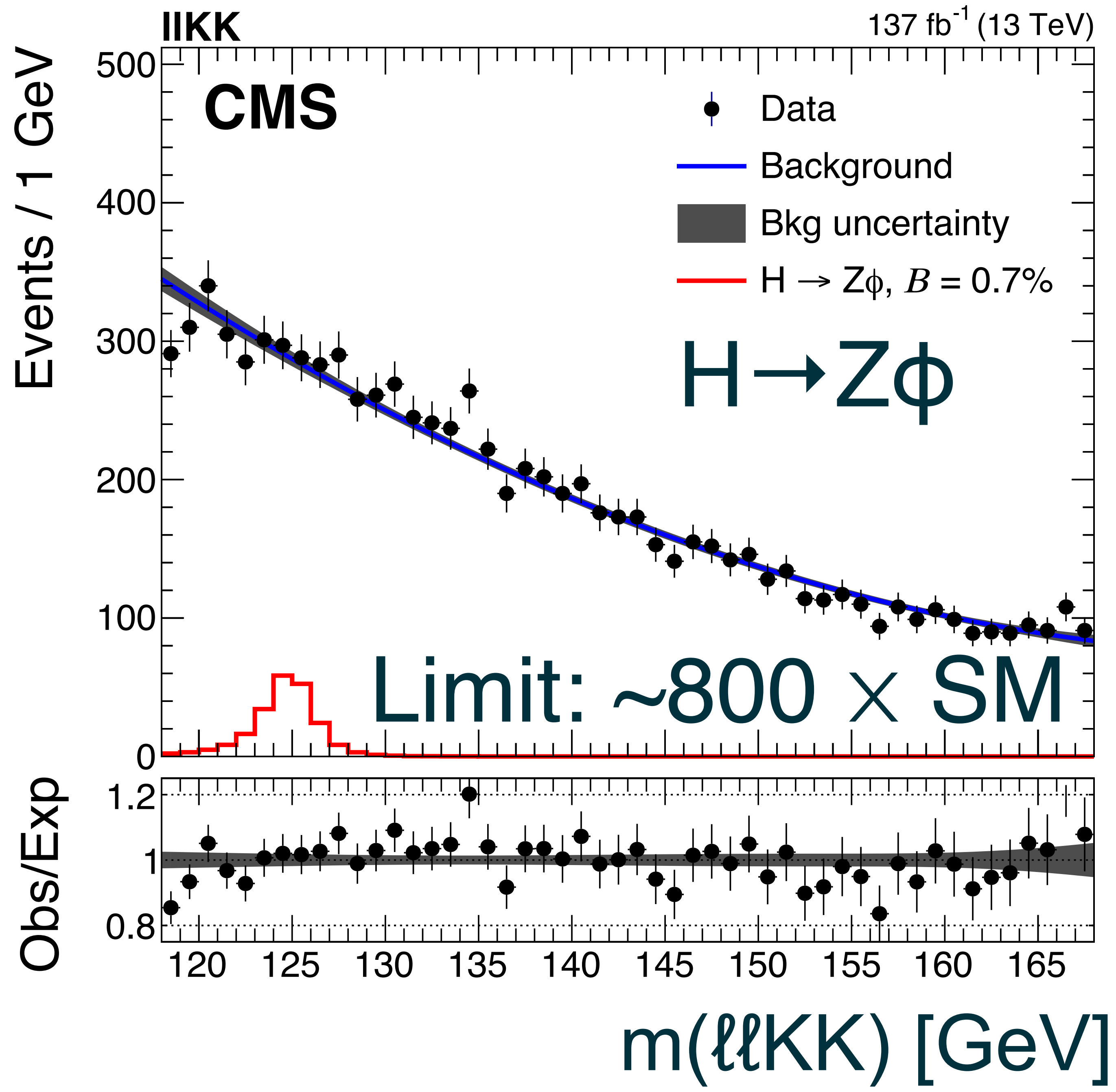
- Couplings to light quarks (s, u, d) accessible via Higgs decays to **vector meson resonances** in association with **ɣ or a massive Z boson**:
  - H ⟶ [**ϕ** or **ρ**] [**ɣ** or **Z**],
  - Limits on μ_{SIG} generally at 10^2 to $10^3 \times$ SM,
- BSM physics (e.g. 2HDM) may enhance the Yukawa coupling to light quarks and increase the signal strength to the level of the current limit.







Tiny in SM, but may be greatly enhanced by BSM.



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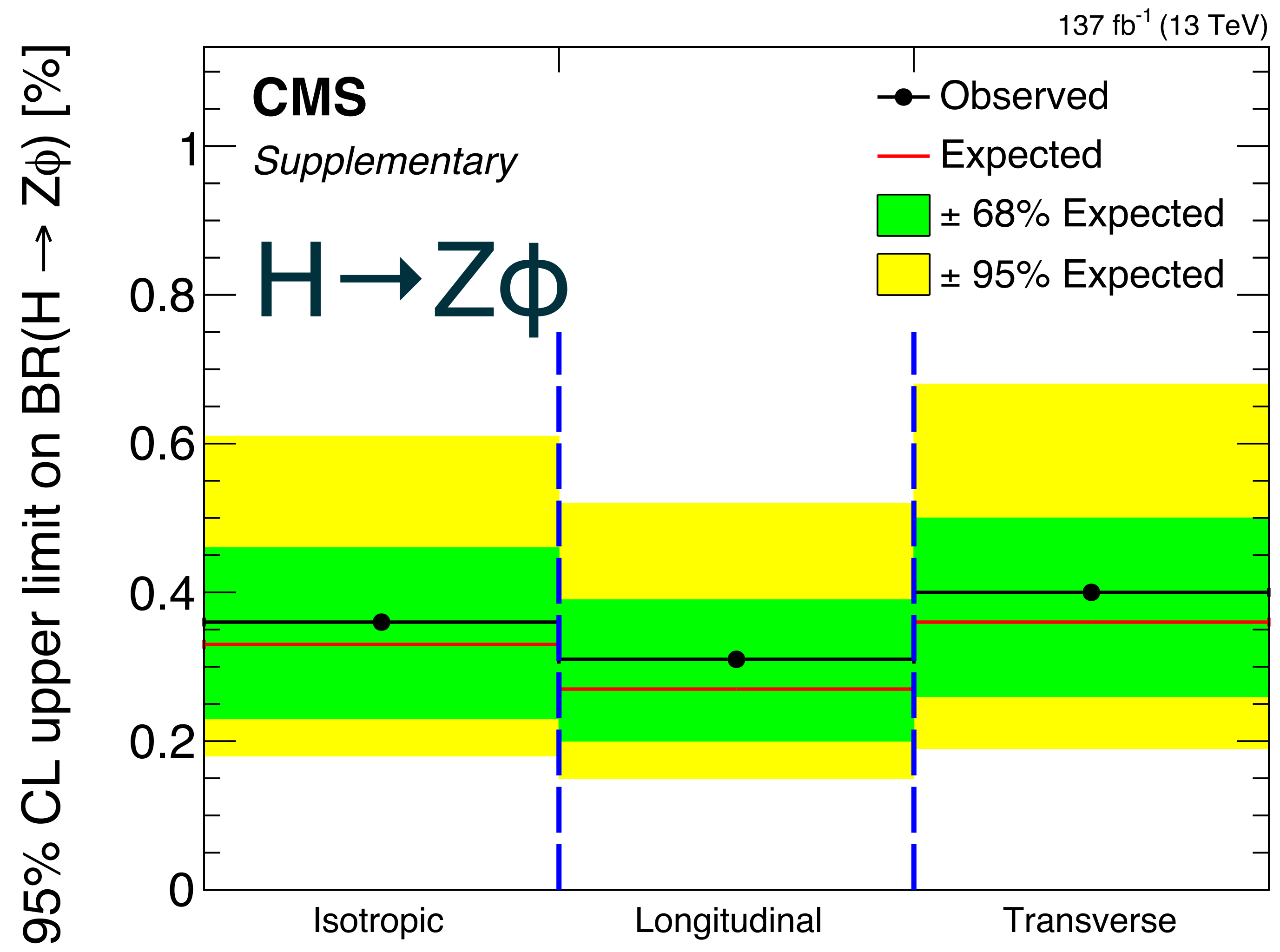

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Searches for BSM Higgs decays

Landscape of searches for BSM Higgs decays

- The general strategy is to look for decays of the Higgs boson to BSM particles or final states that are otherwise forbidden in the SM,
- Searches with BSM decay products usually interpreted with the ‘2HDM+S Type-N’ benchmark model,
  - Two Higgs doublets + an EWK singlet, enabling the $H \rightarrow aa \rightarrow XXYY$ decay topology,
- Constraint on **Br(H→undetected) < 16%** (95% CL) from the Higgs combination (see 1st page).

Leptons — Bosons — Quarks — Mesons — 2Lep — 2q/g — 2γ — 2b

Y \ X	$e^\pm$	$\mu^\pm$	$\tau^\pm$	Z	W	γ	q/g	c	b	Inv.	ϕ,ρ	$J/\psi,\Upsilon$	$\ell^\pm\ell^\mp$	$\tau^\pm\tau^\mp$	$q\bar{q}/gg$	$\gamma\gamma$	$b\bar{b}$	Other
$e^\mp$	[12]	[12]	[13]															
$\mu^\mp$		[14]	[13]															
$\tau^\mp$			SM															
Z/Z^*				SM		[15]				–	–	[3]	[7]	–	[3]	–	–	–
W/W^*					SM													–
γ						SM				[16]	[17]	[18]	[19]	–	–	–	–	–
q/g							–	–	–									
c								[20]										
b									SM									
Inv.										[21]			–	–	–	–	–	–
ϕ,ρ											–	–						
$J/\psi,\Upsilon$												–						
$\ell^\pm\ell^\mp$													[7]	[10]	–	–	[2]	–
$\tau^\pm\tau^\mp$														–	–	–	–	–
$q\bar{q}/gg$															–	[6]	–	–
$\gamma\gamma$																[9]	–	–
$b\bar{b}$																	[4, 5]	–
Other																		Many LLP

LFV

SM decay products

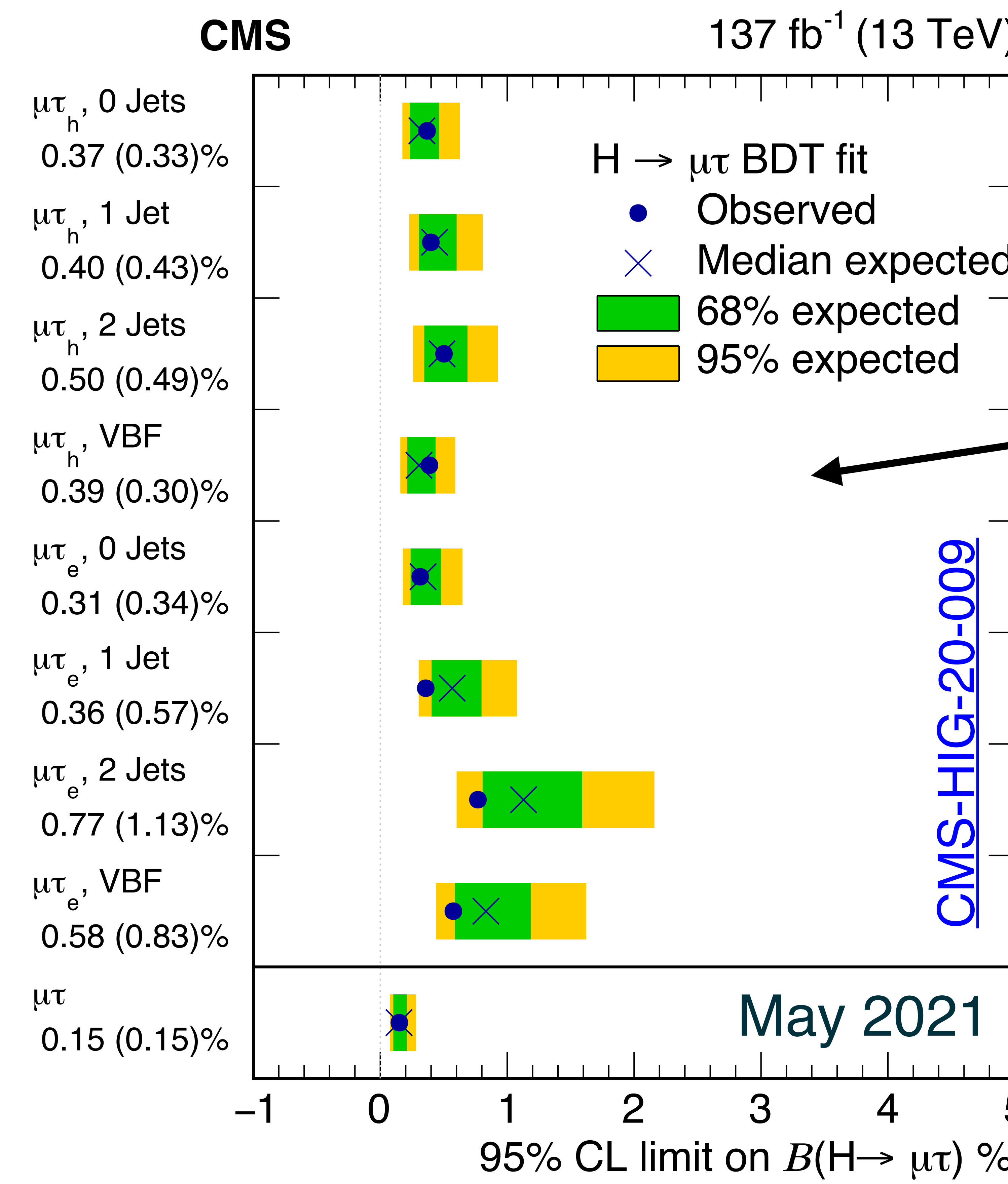
Invisible

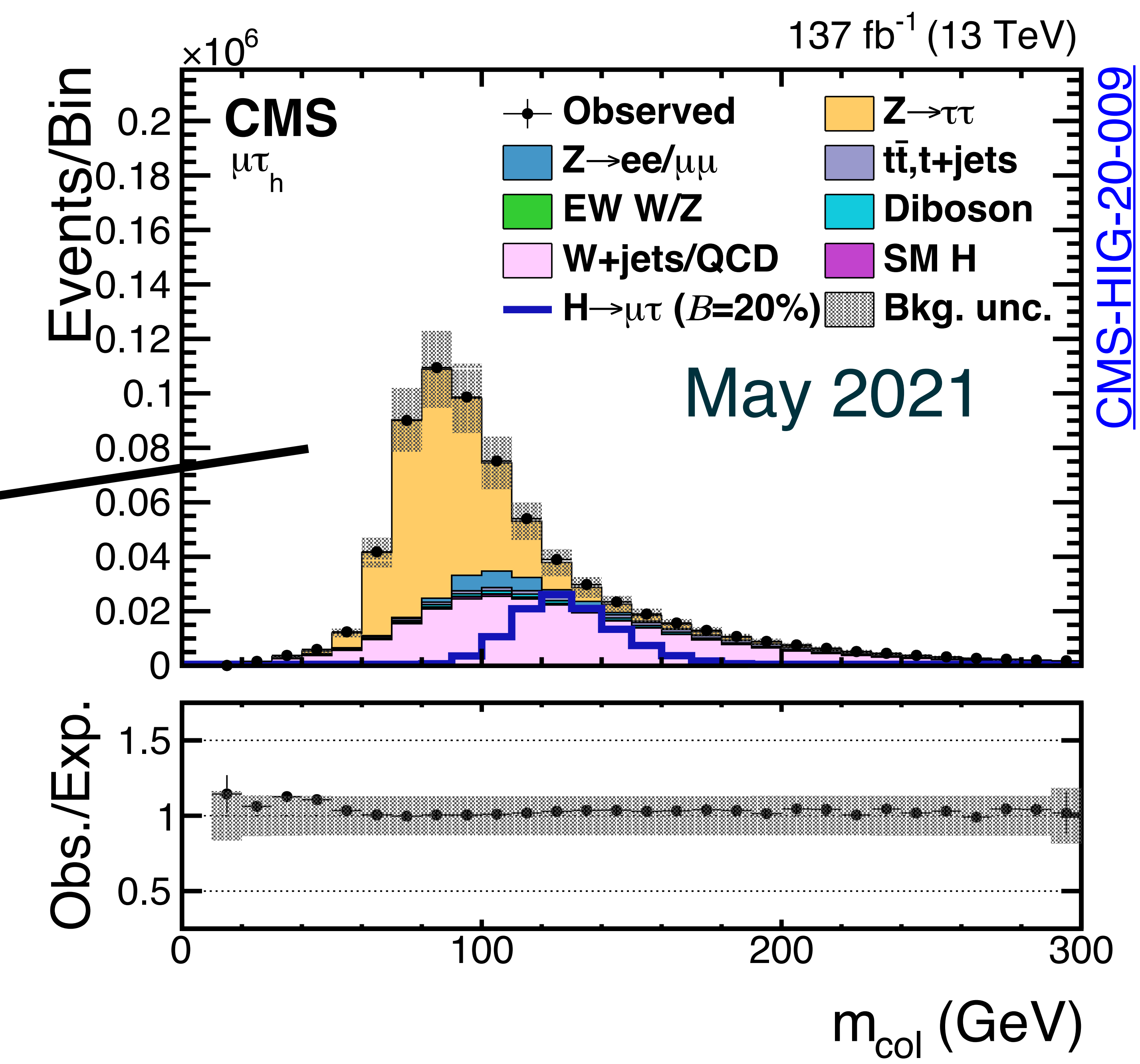
BSM decay products

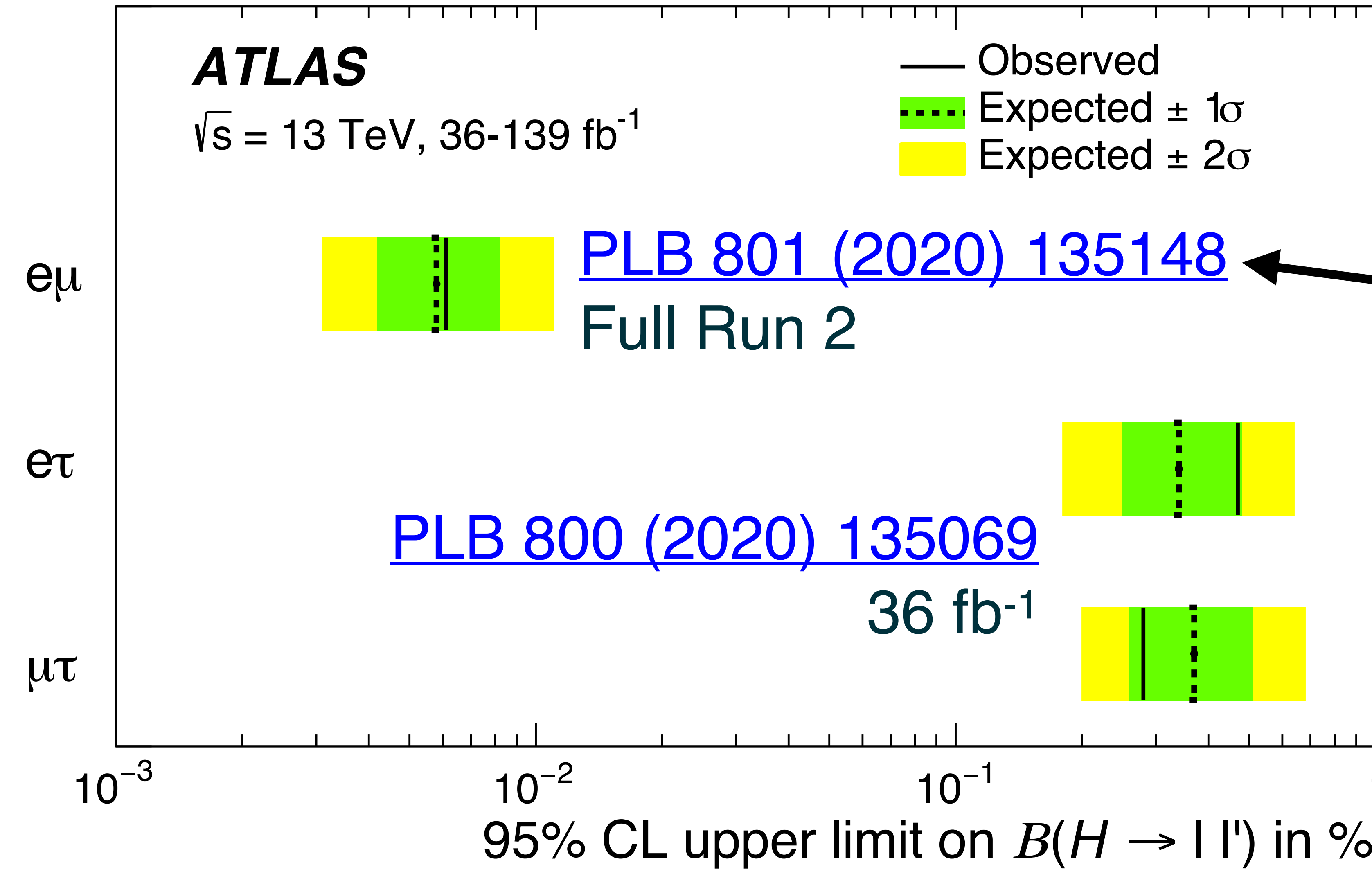
ATL-PHYS-PUB-2021-008

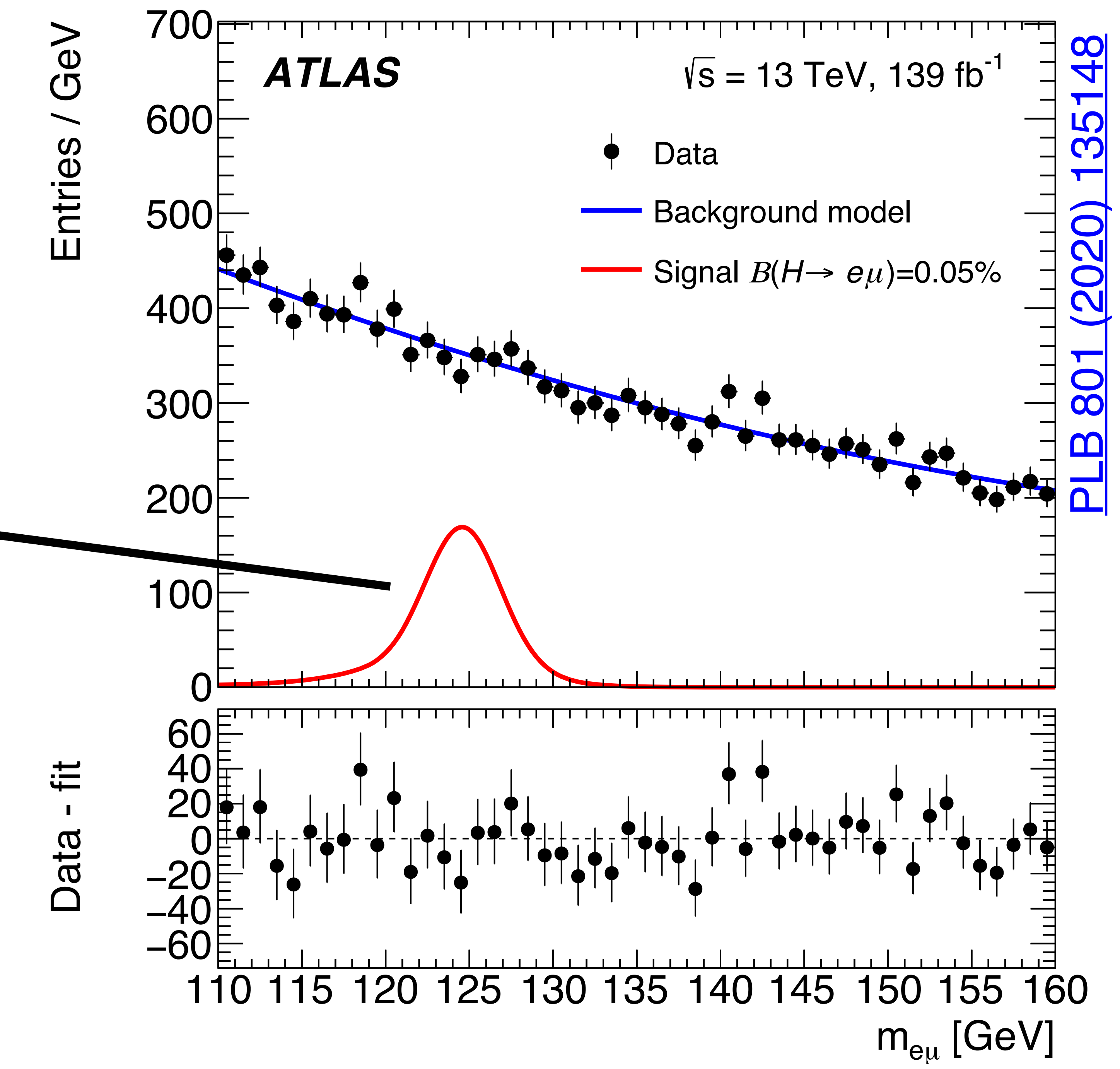
Lepton Flavor Violating Higgs Decays

- Both ATLAS and CMS looked for LFV Higgs decays and had set upper limit on the branching ratios (95% CL),
- ATLAS Full Run 2:
  - Br(H→eμ): **6.1×10⁻³** %,
  - Br(H→ee): **3.6×10⁻²** %,
- CMS Full Run 2:
  - Br(H→μτ): **0.15%**,
  - Br(H→eτ): **0.22%**,
- ATLAS 36 fb⁻¹:
  - Br(H→μτ): **0.28%**,
  - Br(H→eτ): **0.47%**.

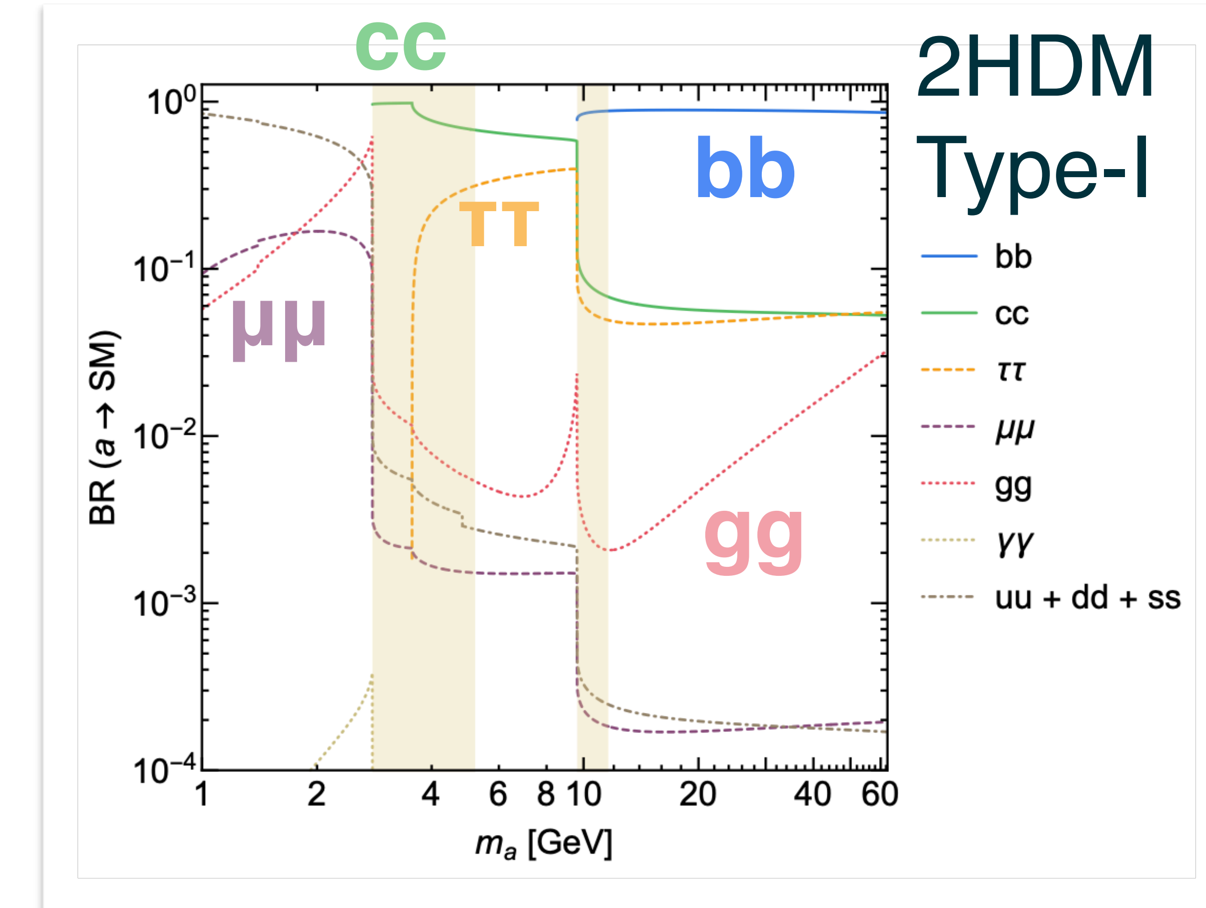








- The phase-space covered from m_a = 1 GeV to m_a = 60 GeV,
- Limit on [Br(H → undetected) < 16%] from the Higgs combination,
- Interpreted with 2HDM+S, limits depend on the model parameters,
  - Different final states dominate different mass ranges due to the **Br** dependence,
- The strongest limits generally placed with leptonic final states,
- A few highlights given in the following slides.



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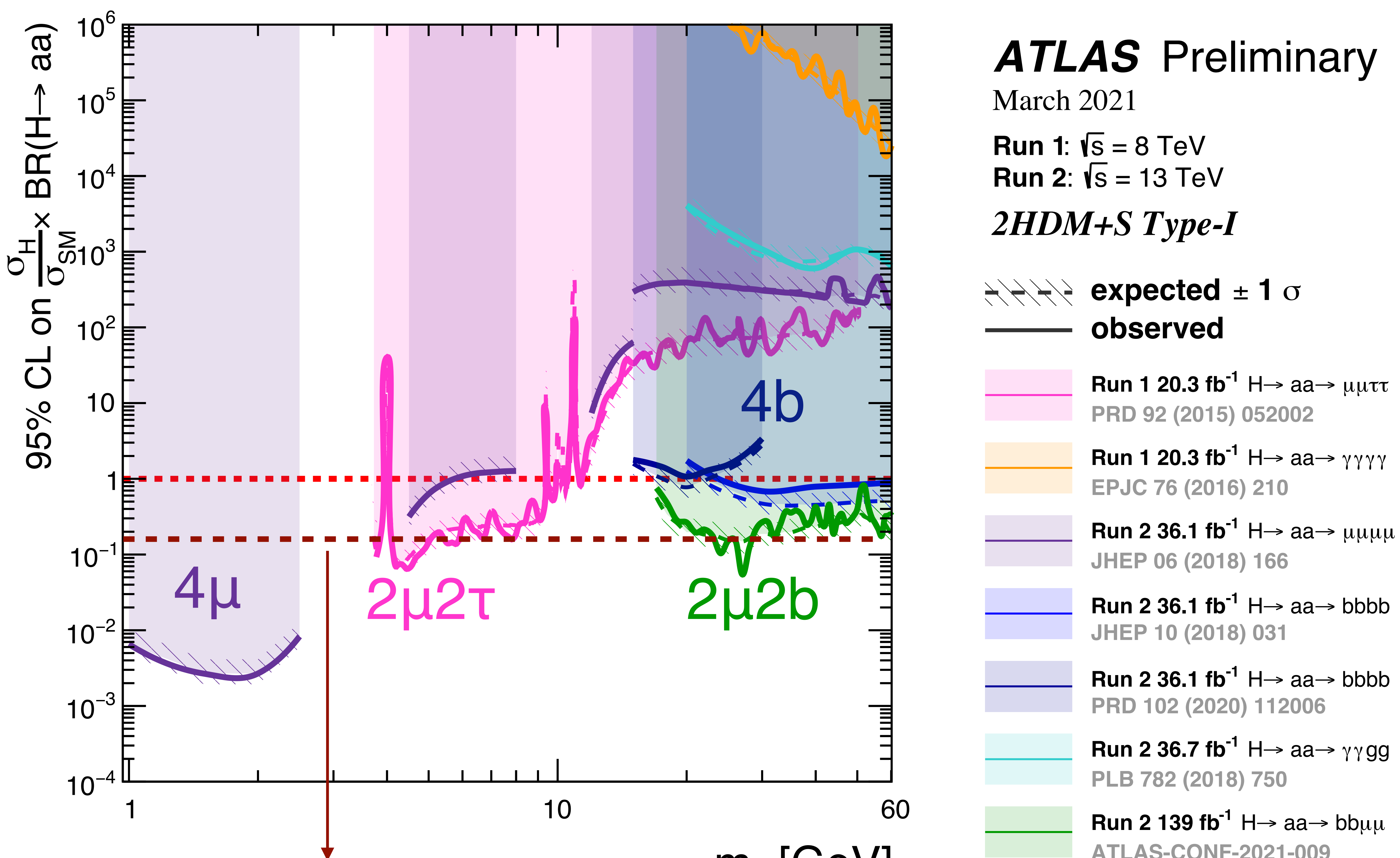
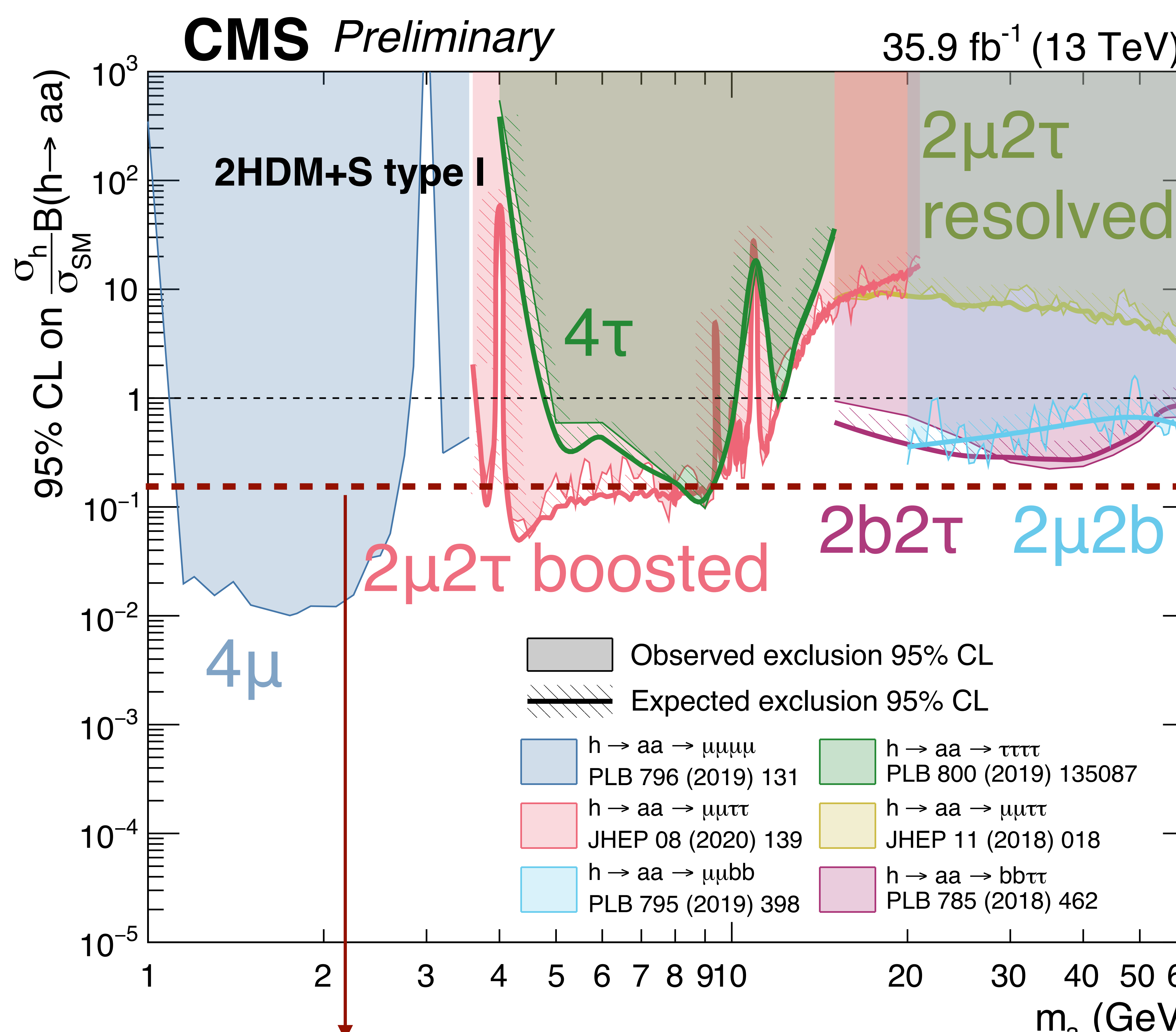


Br(H → undet.) < 16%

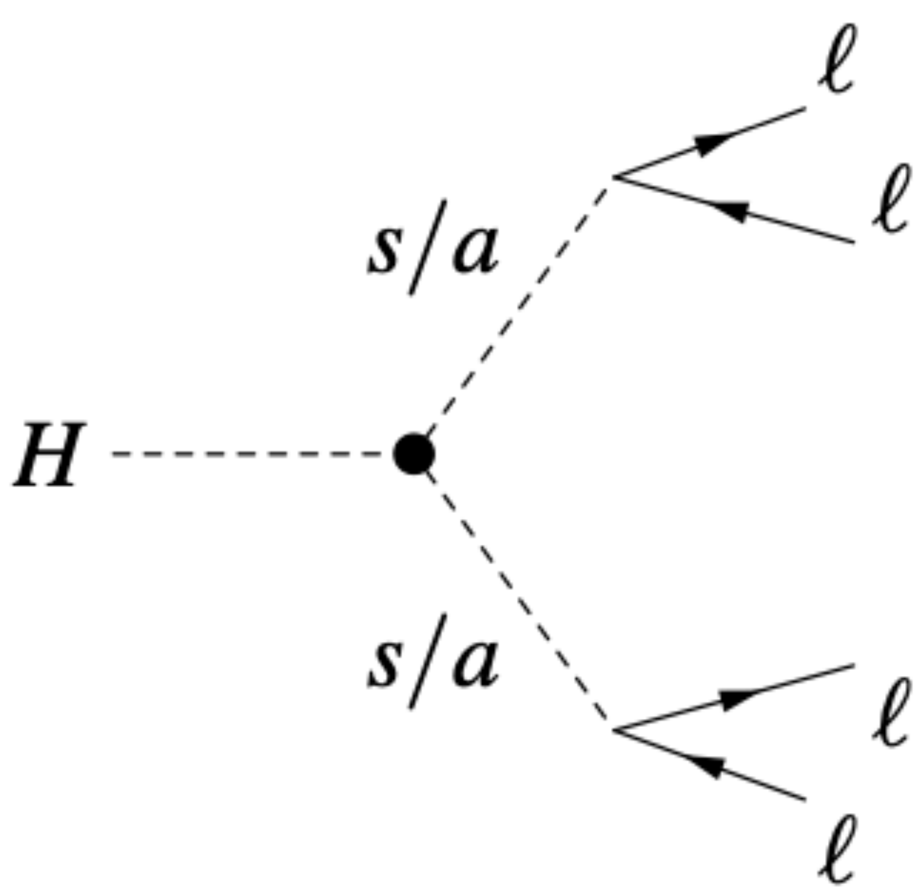


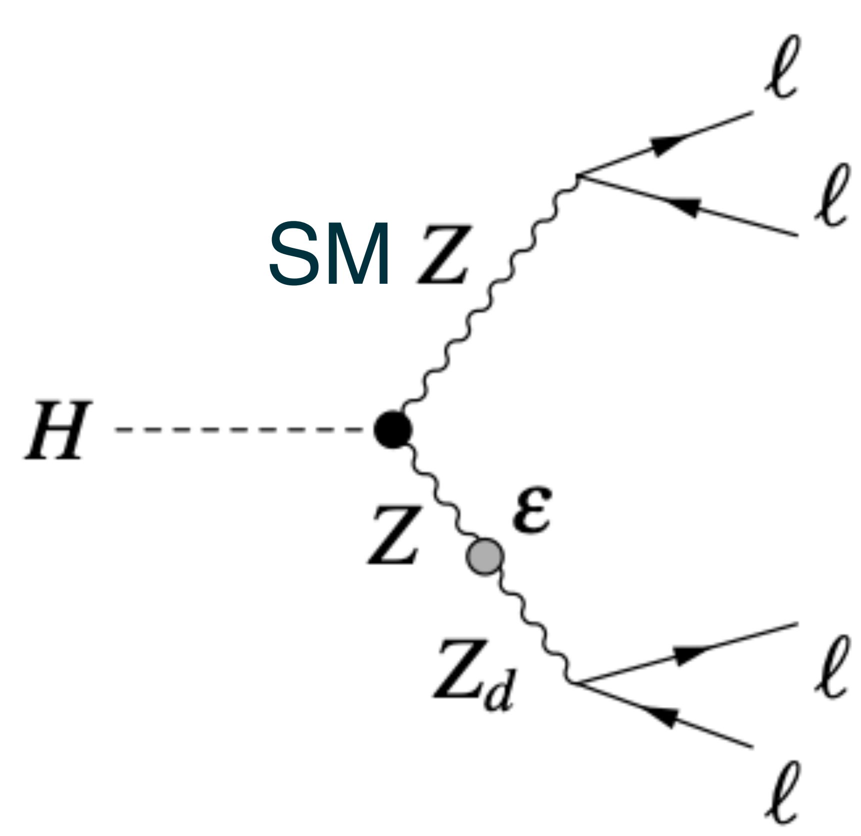
Br(H → undet.) < 16%

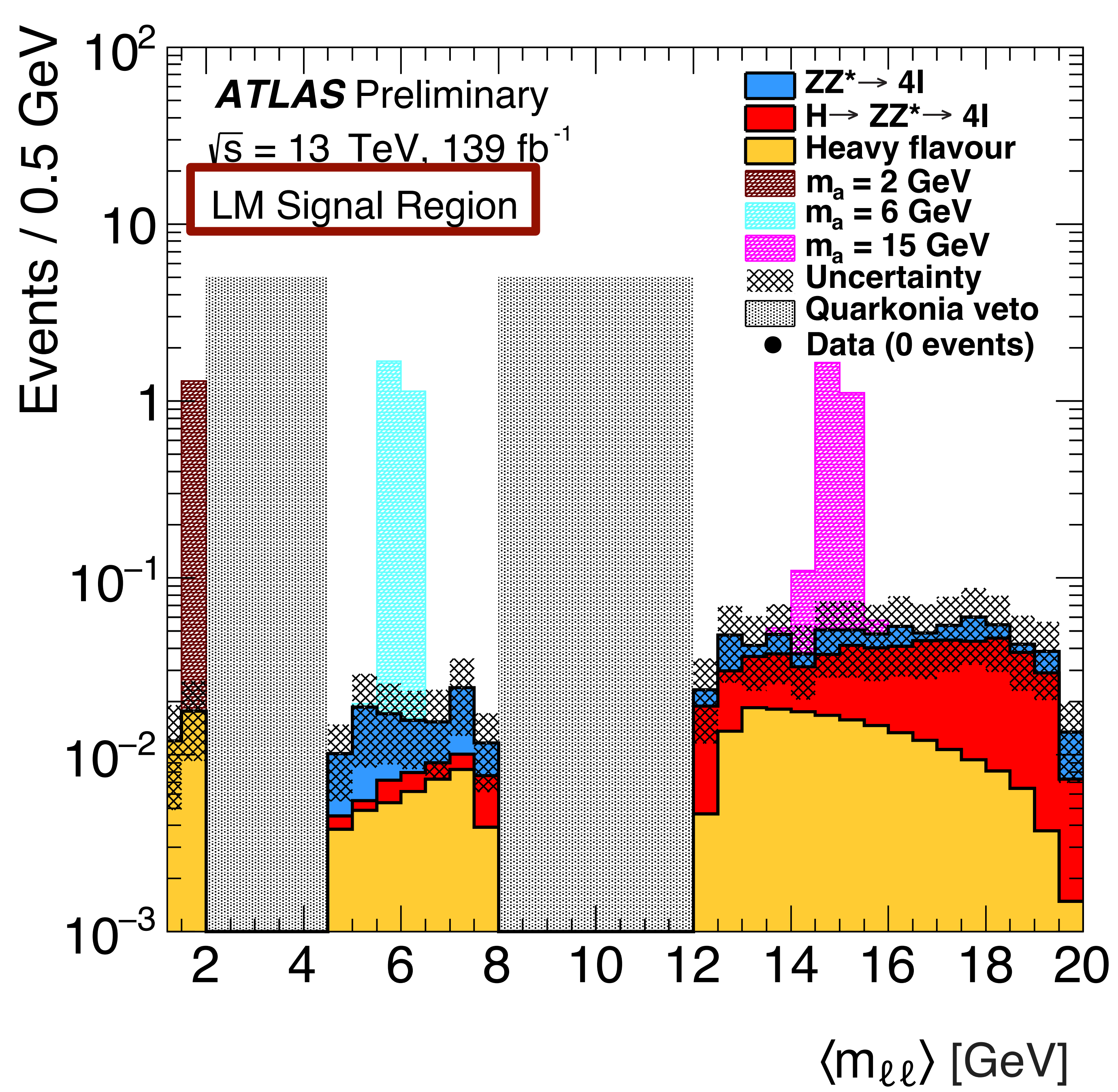
Search for H → 4ℓ in ATLAS (July 2021)

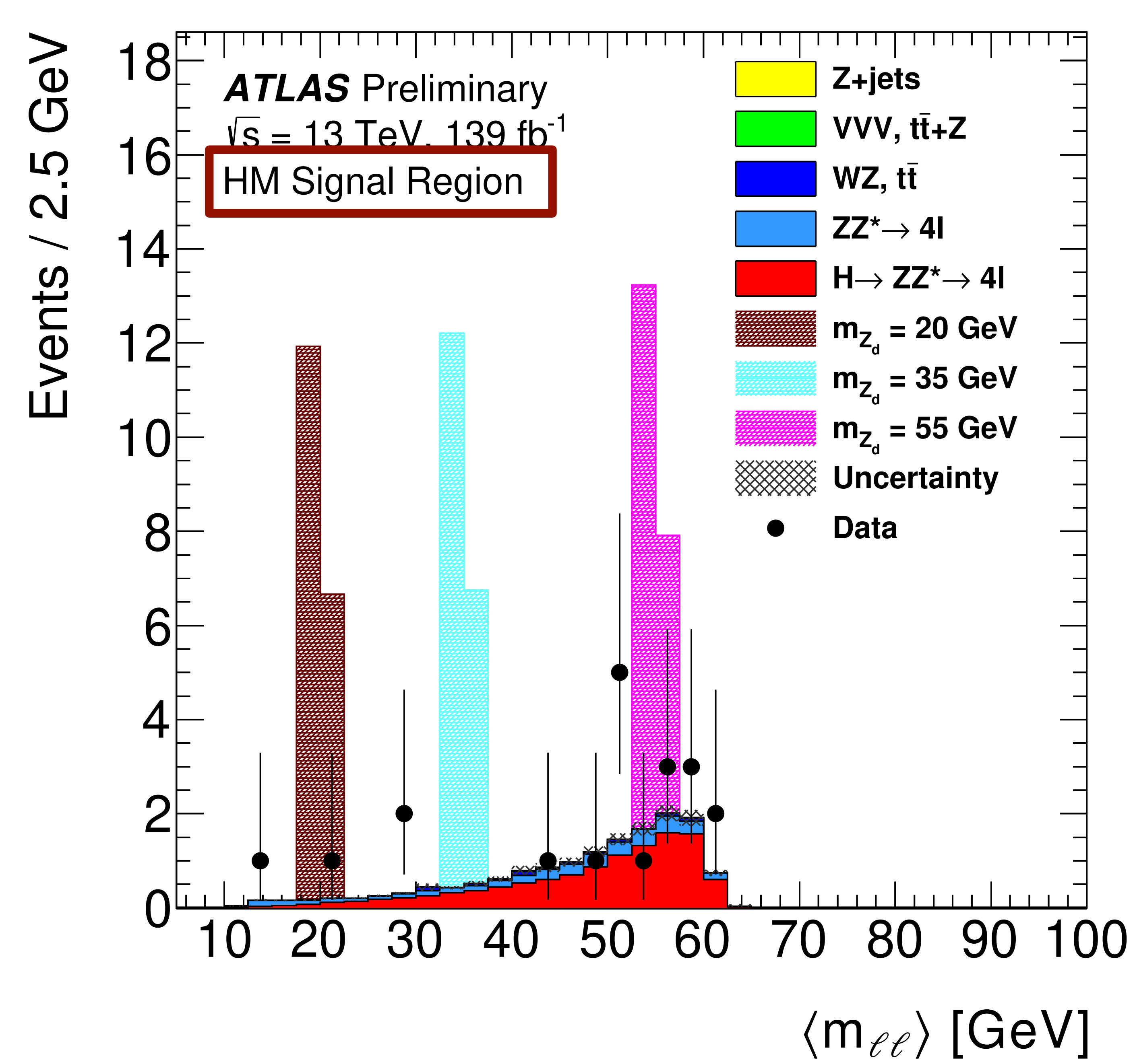
ATLAS-CONF-2021-034

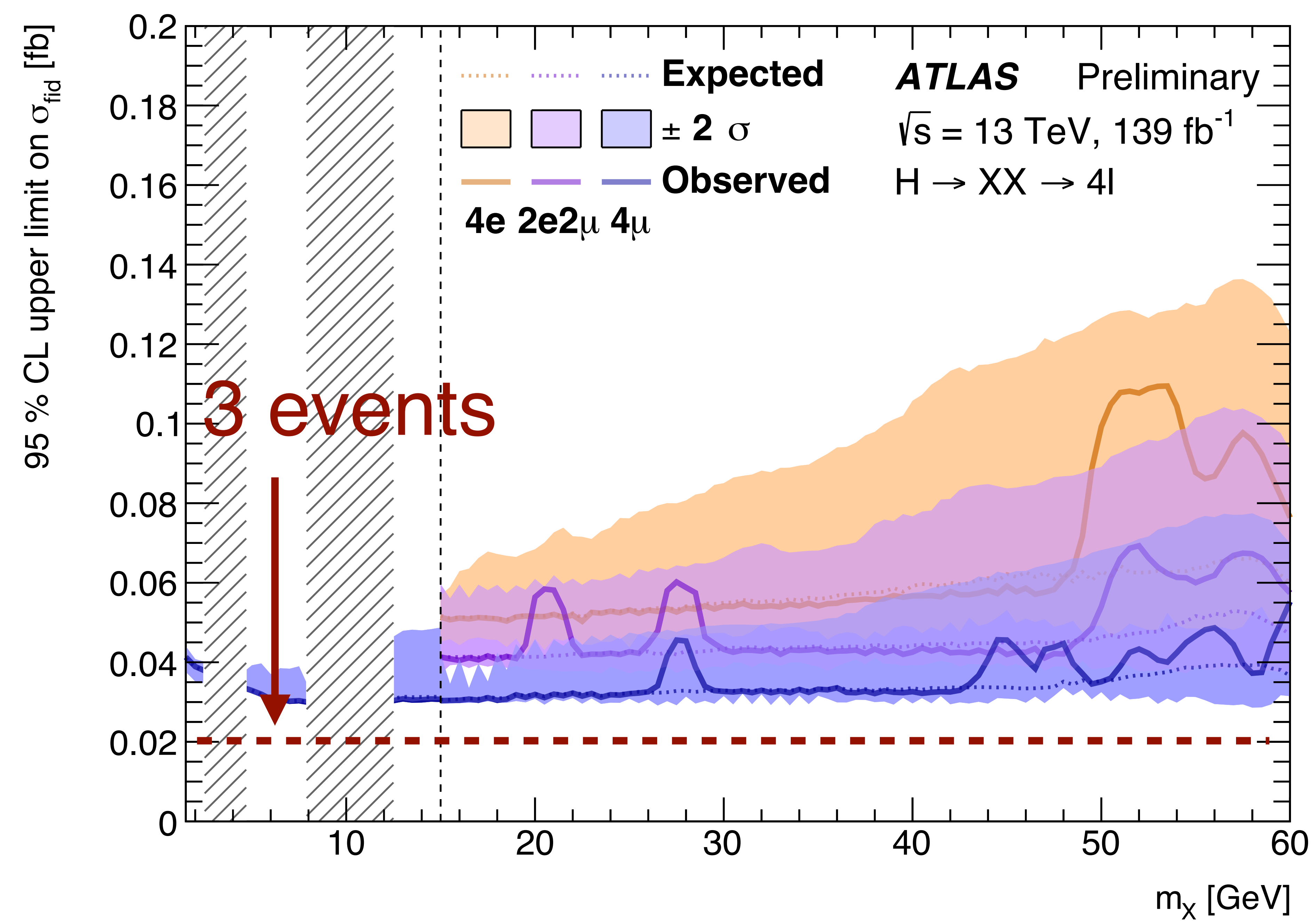
- Search for final states with 4ℓ via spin-0 or spin-1 resonances (dark boson Z_d, or s/a from 2HDM),
  - Low Mass (LM): $H \to XX \to 4\ell$ ($1 < m_X < 15$ GeV) **zero observed events,**
  - High Mass (HM): $H \to XX \to 4\ell$ ($15 < m_X < 60$ GeV) **20 observed events,**
  - ZX Analysis: $H \to ZX \to 4\ell$ ($15 < m_X < 55$ GeV) **O(1000) observed events,**
- Model independent limits set on fiducial cross section in each channel,
- Model dependent limits set using the Zd and 2HDM benchmark models.



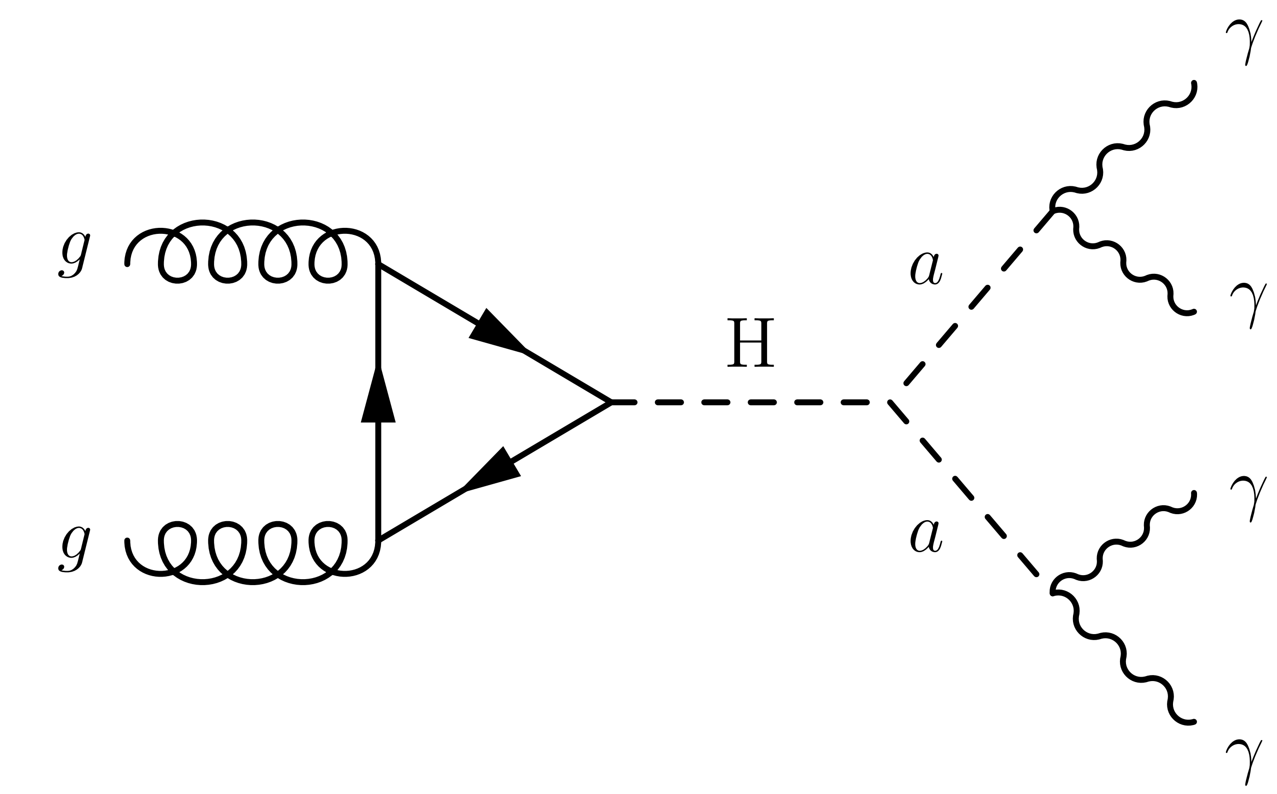


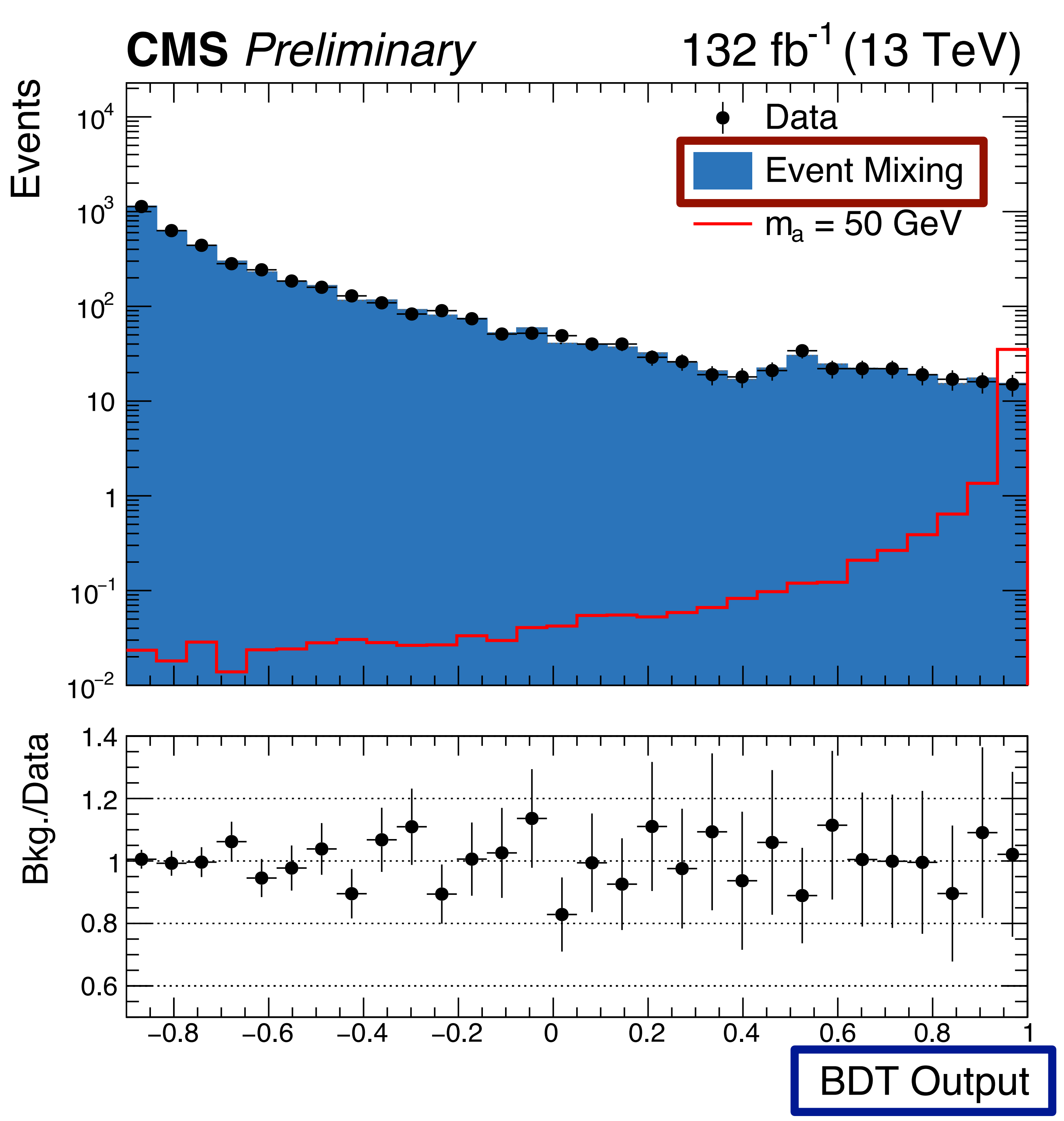


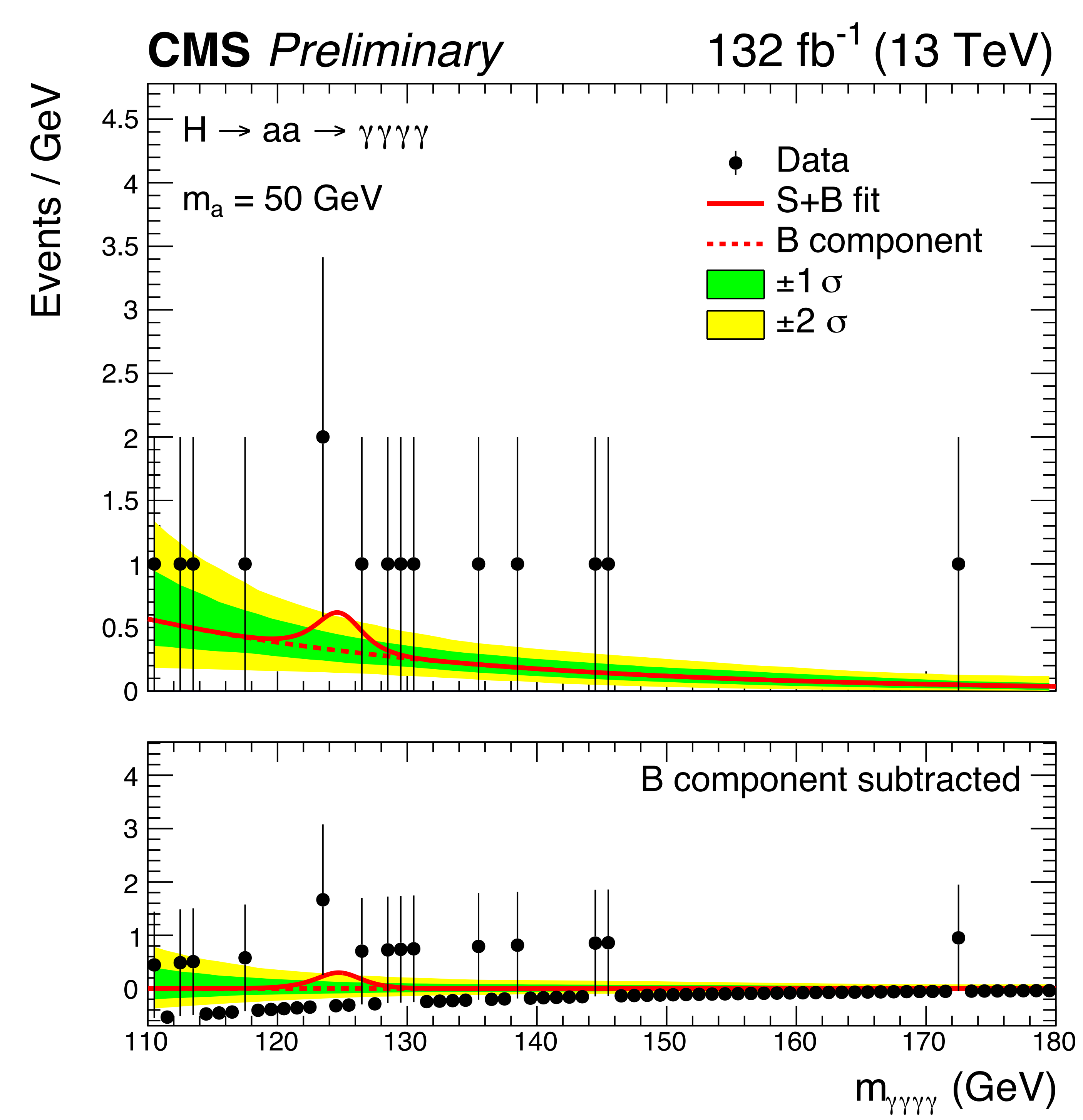


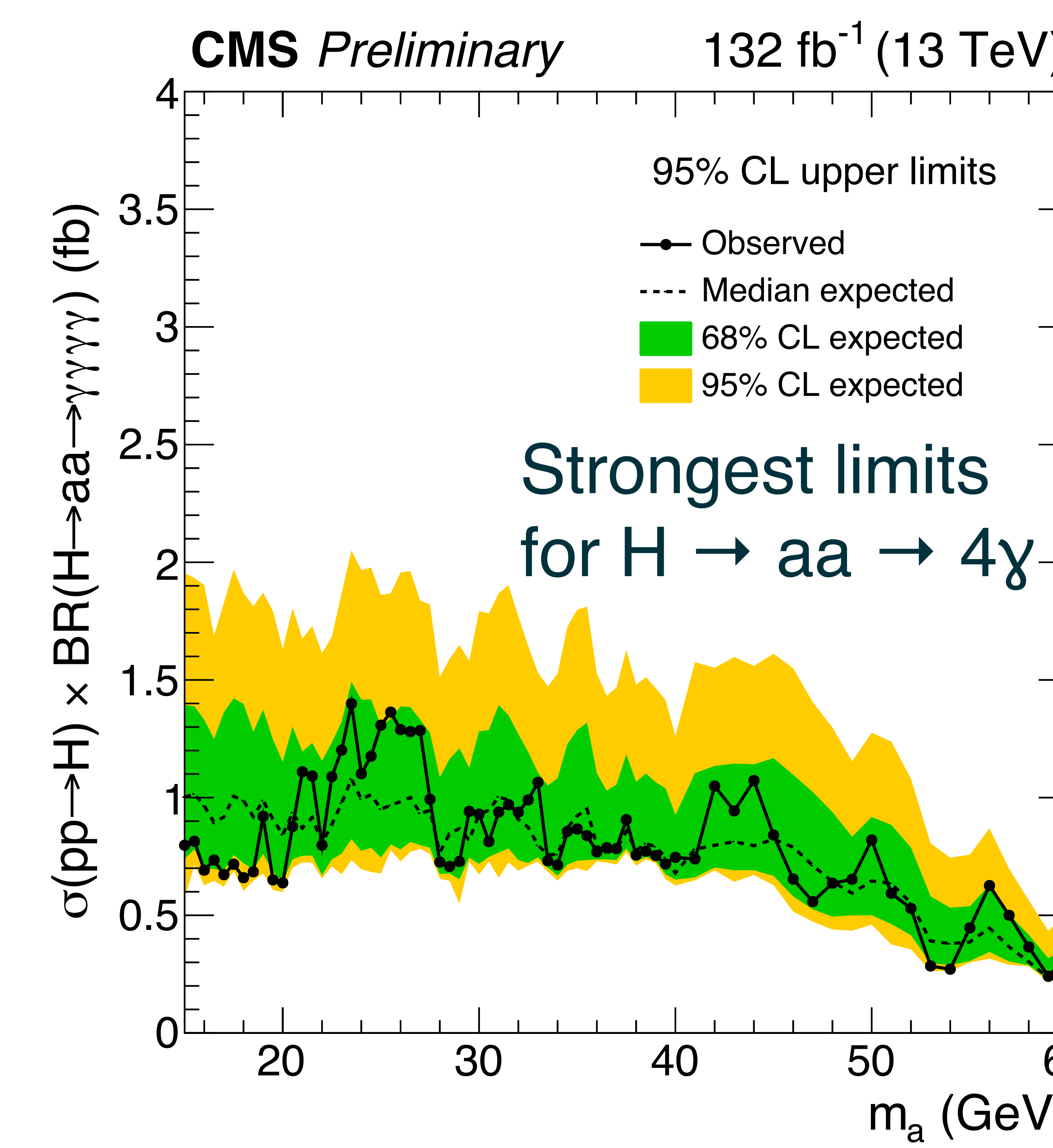


- Search for final states with 4γ via spin-0 resonances,
- SM background from γγ + jets, γ + jets, and multi-jet with fake photons,
  - Estimated in a data-driven way with '**Event Mixing**'— take the measured dataset, but replace 3/4 photons from consecutive events,
- Train a **BDT** to separate between signal and background,
  - Trained separately for each m_a,
- Signal extracted with a fully parametric fit to the $m_{4\gamma}$ spectrum.

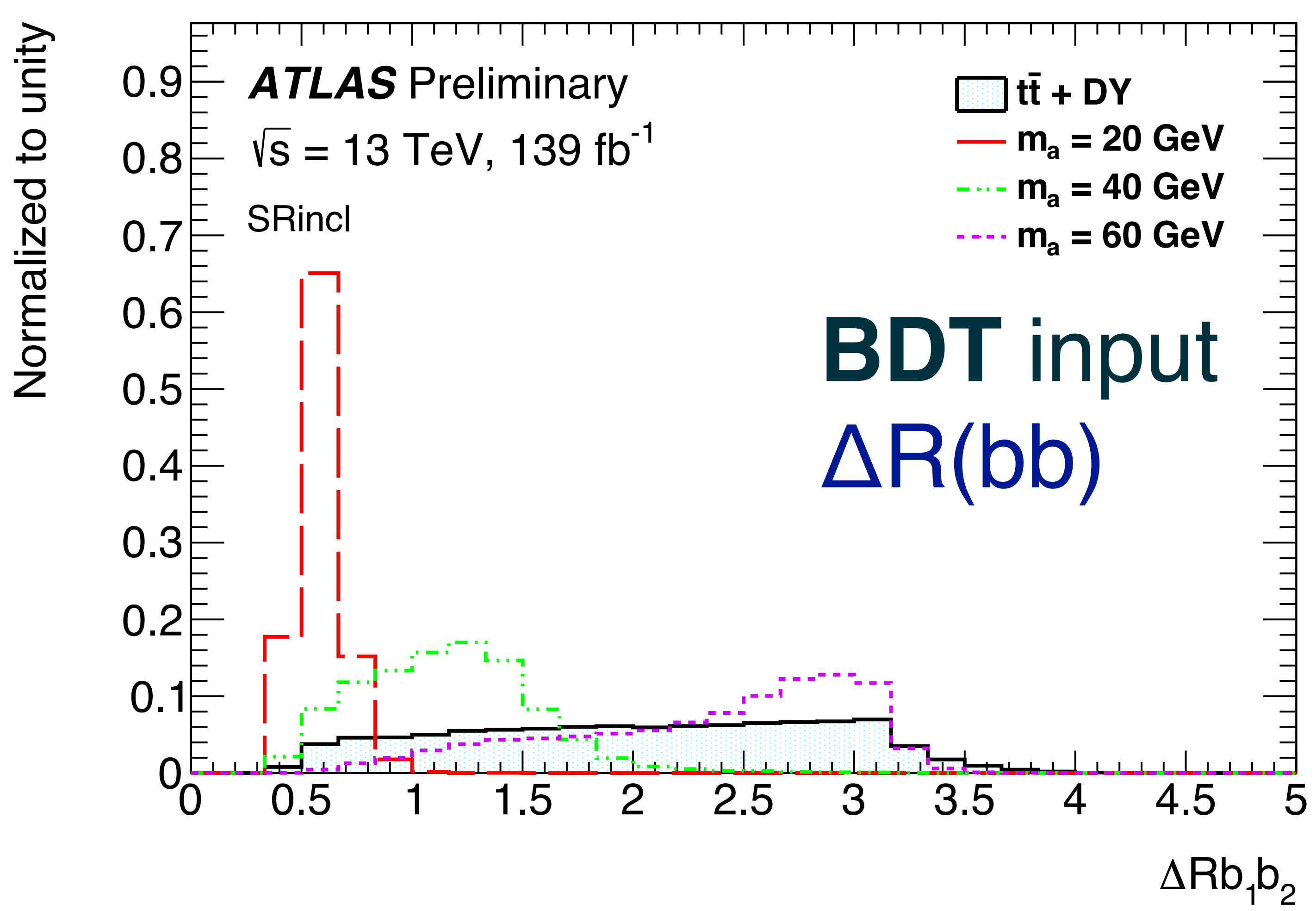


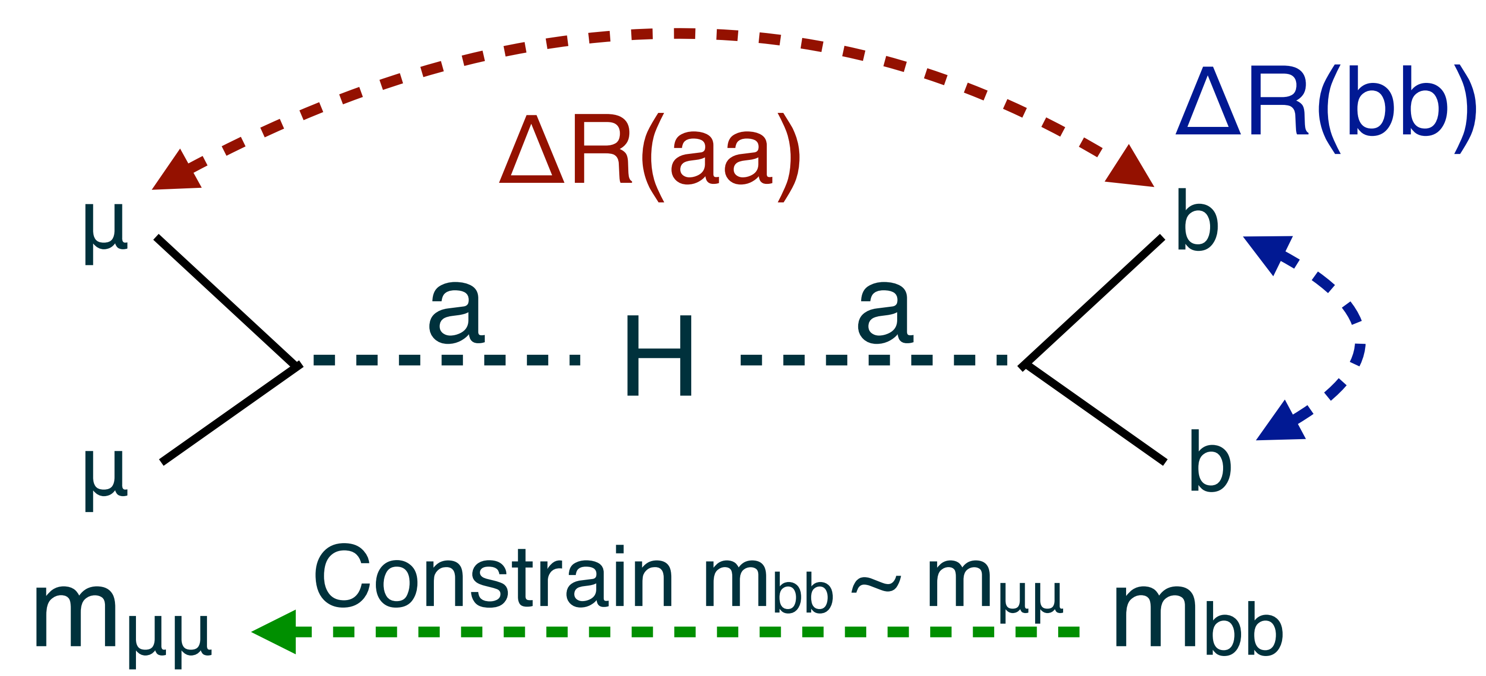




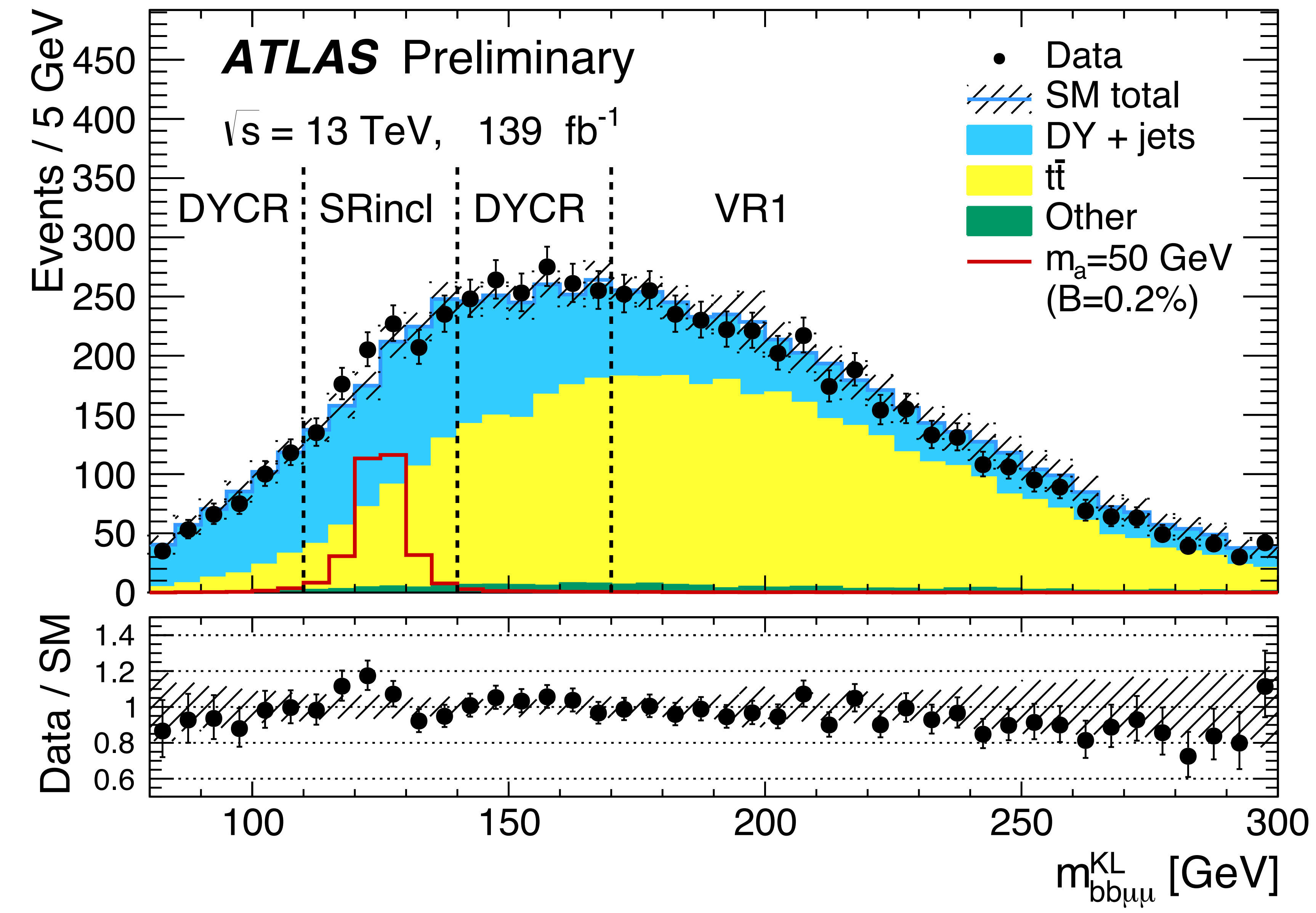


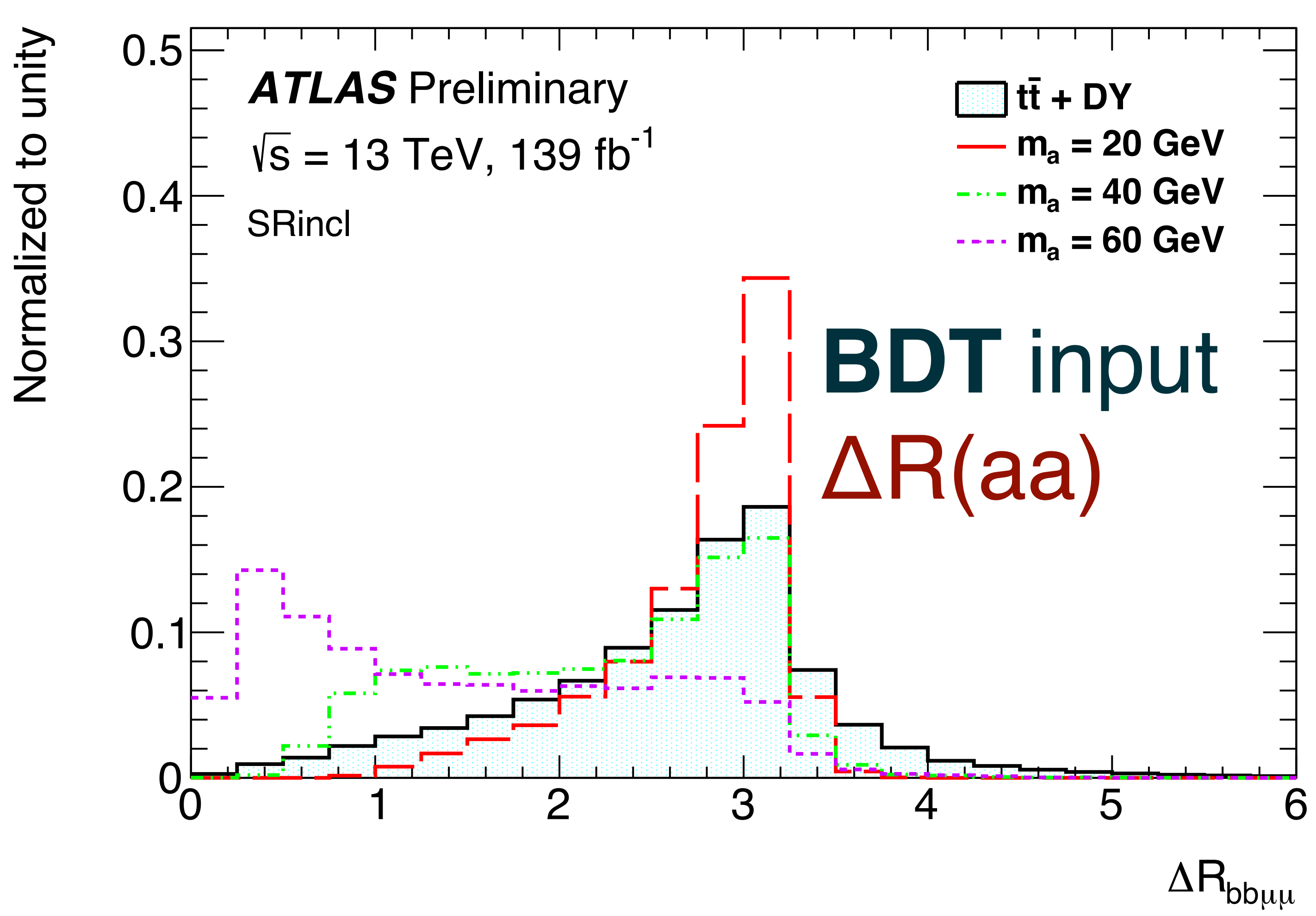
- SM background from DY + jets and ttbar reduced with **BDTs**,
  - Separately for each m_a because the topology changes with mass,
- Kinematic likelihood fit constrains m_{2b} to $m_{2\mu}$ to improve $\sigma(m_{2b2\mu})$,
- Fit the $m_{2b2\mu}$ with a MC-based statistical model to extract the signal.

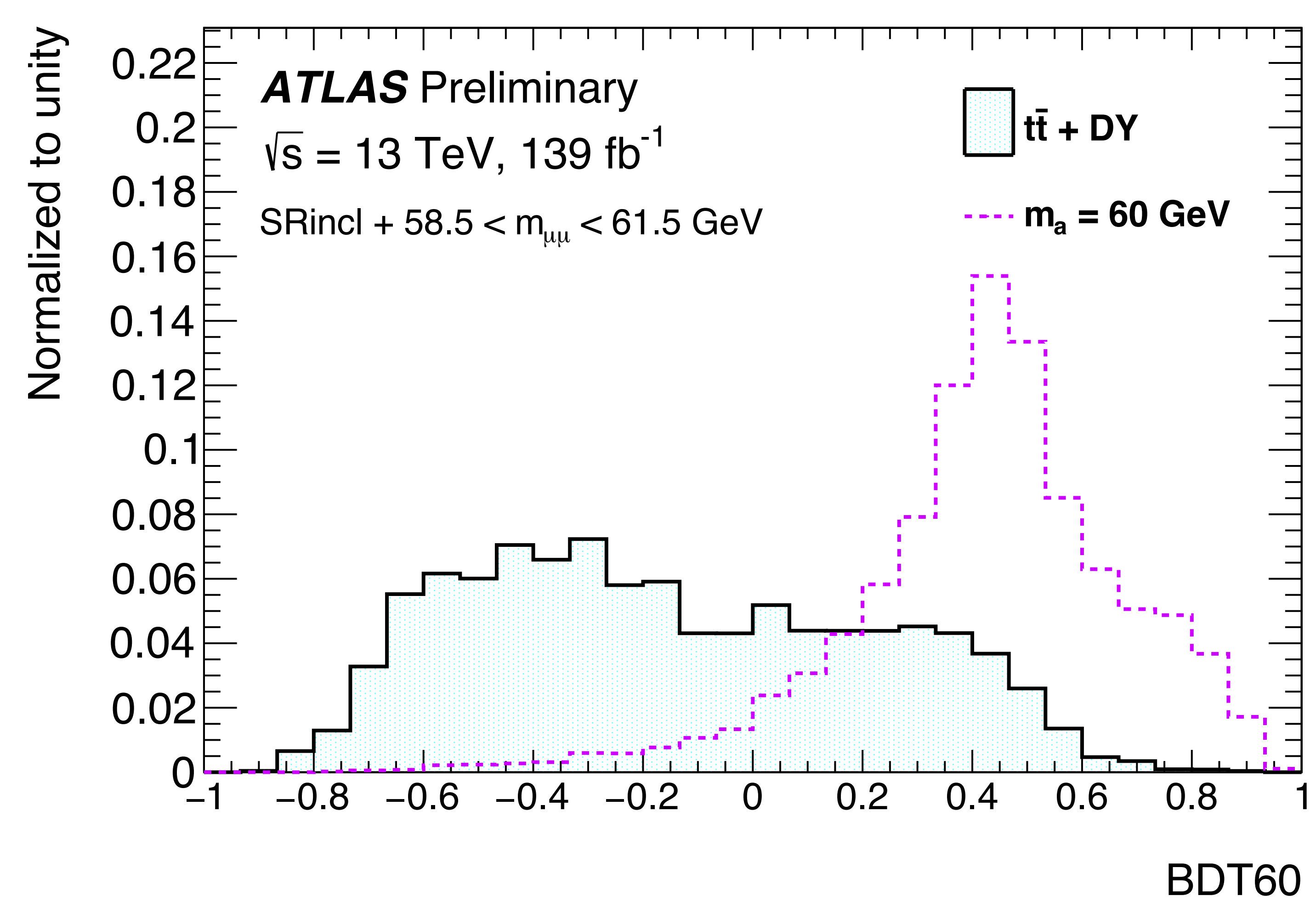


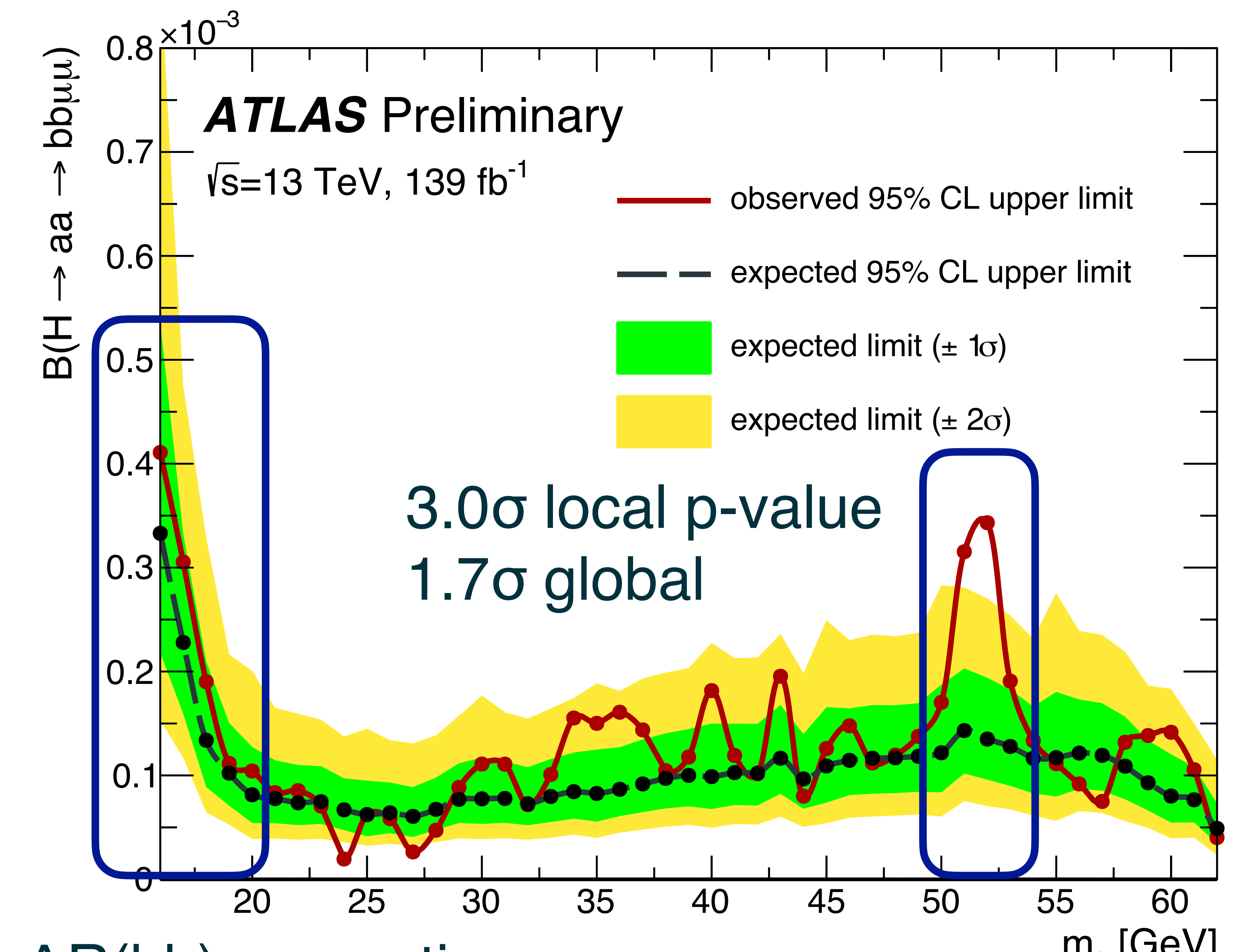


$m_{\mu\mu}$ resolution ~10x better than m_{bb}.





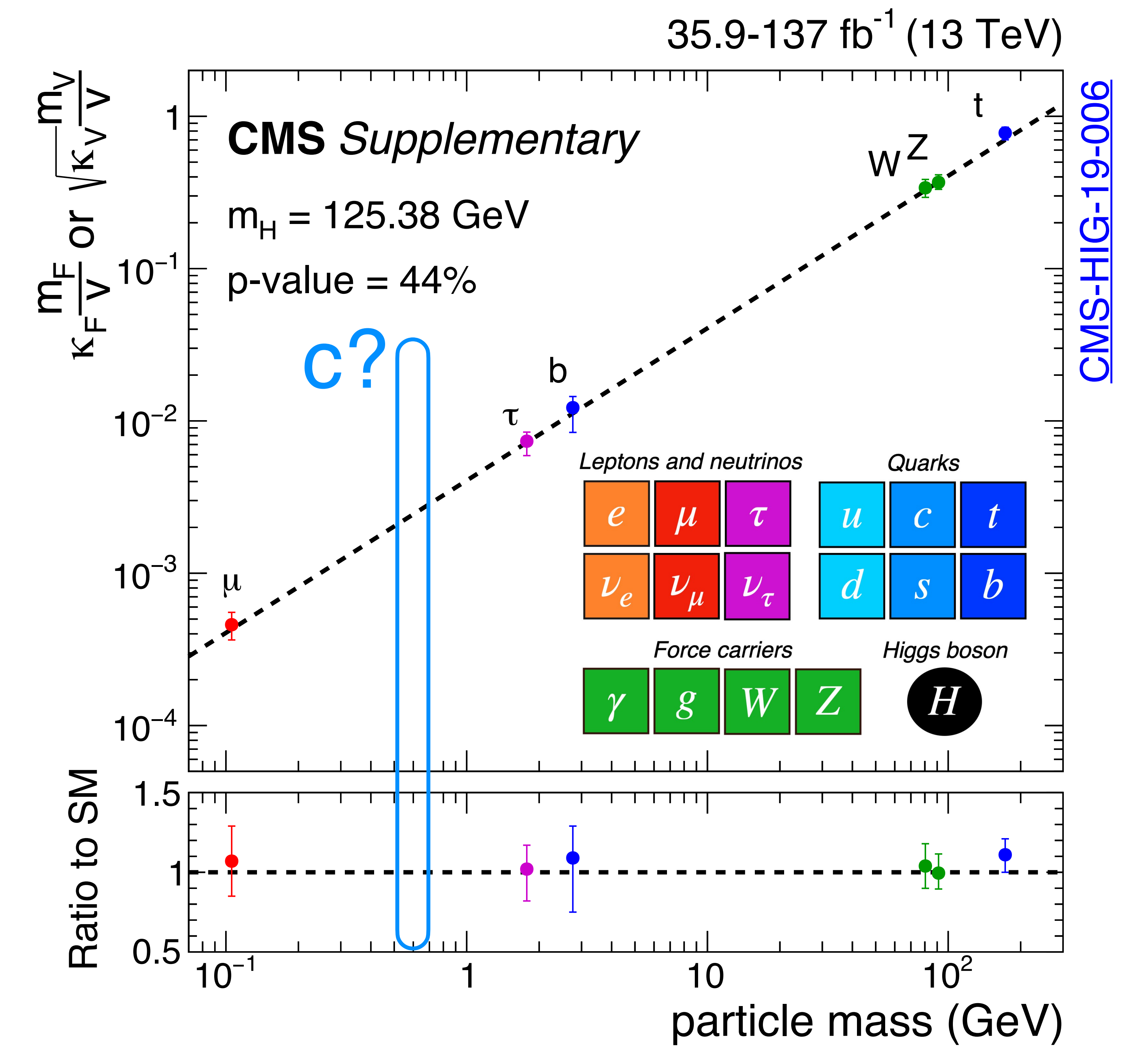


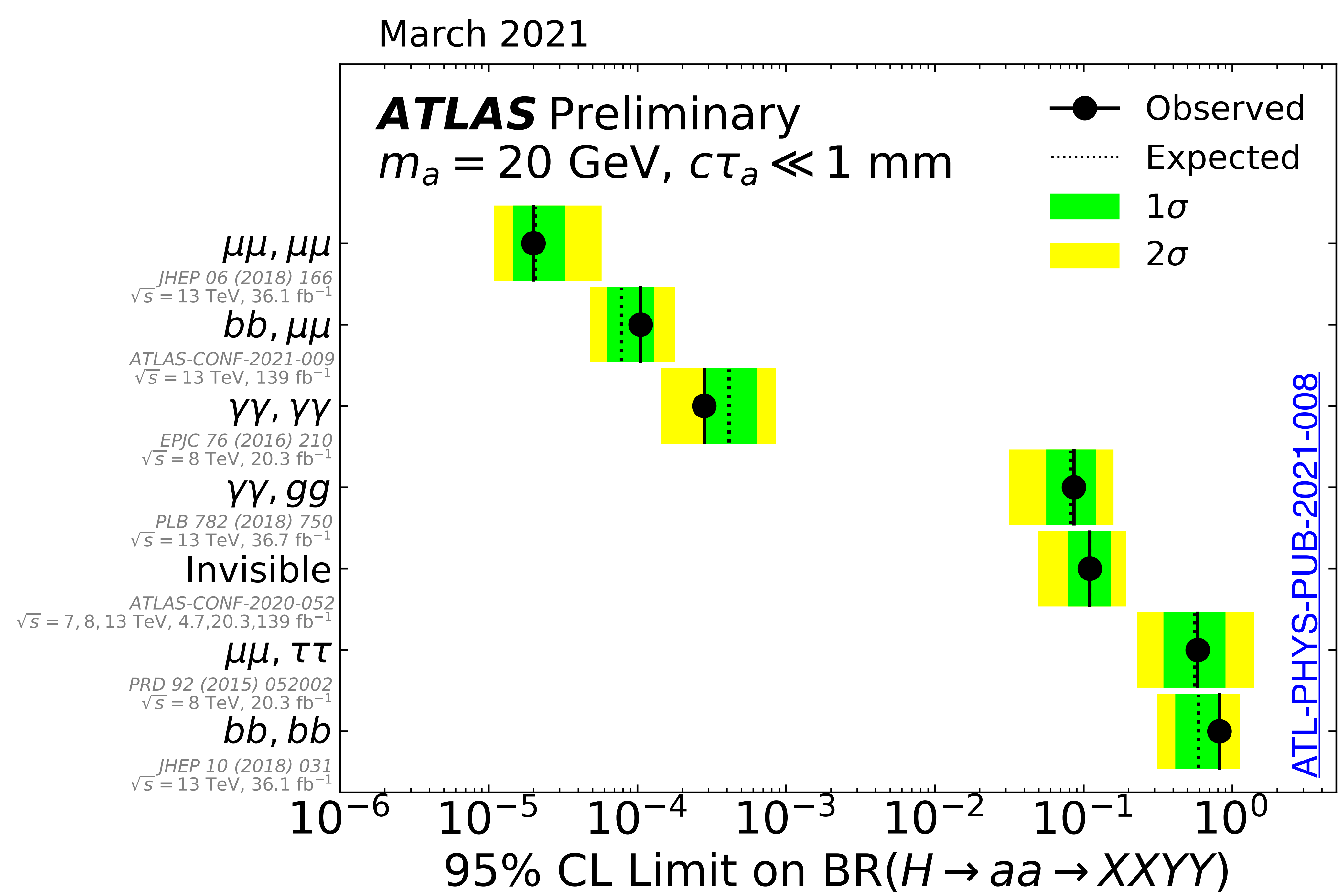


Poor ΔR(bb) separation

Higgs Rare and Exotic Decays: Summary

- Decays to heavy bosons and 3rd gen. fermions firmly established,
- With the evidence of H → μμ experiments became sensitive to the BEH mechanism for 2nd gen. fermions,
- First evidence of H → ℓℓɣ for $m_{\ell\ell}$ < 30 GeV,
  - High $m_{\ell\ell}$ mass H → Zɣ at 2σ sensitivity,
- Limit of $\mu(VH_{cc})$ < 26 × SM placed with the direct H → cc search,
- Searches for other rare couplings such as electrons, s-quarks, and light-quarks also performed and no significant deviations from SM found.





- Extensive searches for BSM decays performed,
- Strong limits on LFV Higgs decays (H → eμ/eτ/μτ),
- Good coverage of H → (aa / Za) → *XXYY* models,
  - Presented new results: ATLAS **4ℓ**, **2b2μ** and CMS **4ɣ**,
  - Some final states remain uncovered, e.g. *XX ≠ YY* or light jets final states (u, d, s, g),
- Many possible Long Live Particle scenarios left to explore.

Backup

Innovative Background Modeling in $H \to \mu\mu$

- Background modeling is difficult because it needs to be reliable at the level of S/B (as low as 0.1% in some ggH categories), while the number of background events is $O(10^5)$,
- Both ATLAS and CMS pursued this crucial idea:

$$B(m_{\mu\mu}) = N_{bkg} \times \textbf{Core}(m_{\mu\mu}) \times \textbf{Polynomial}(m_{\mu\mu})$$

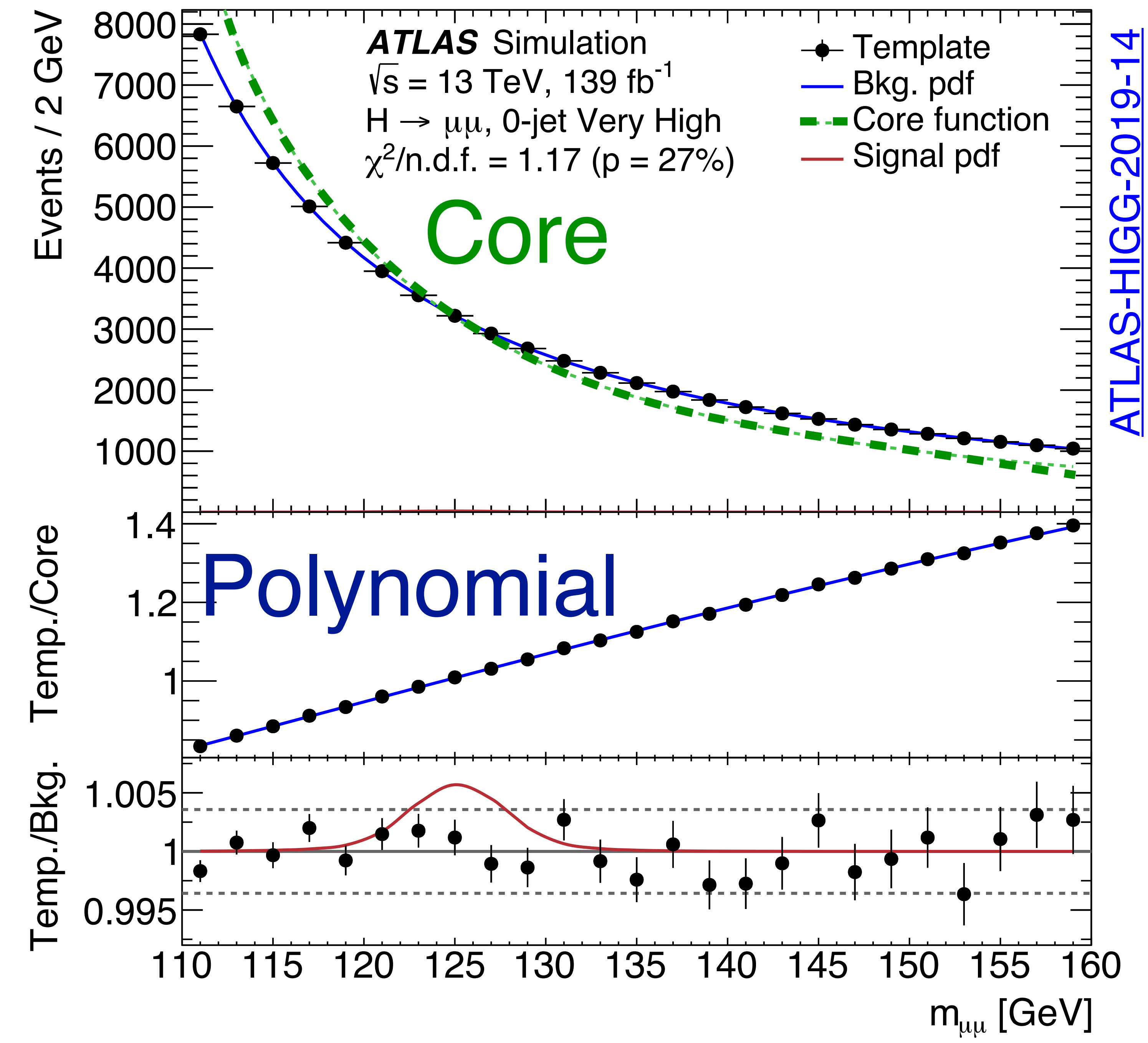
Non-analytical (binned) Drell—Yan mass shape derived with MC simulation. Correlated across multiple categories.

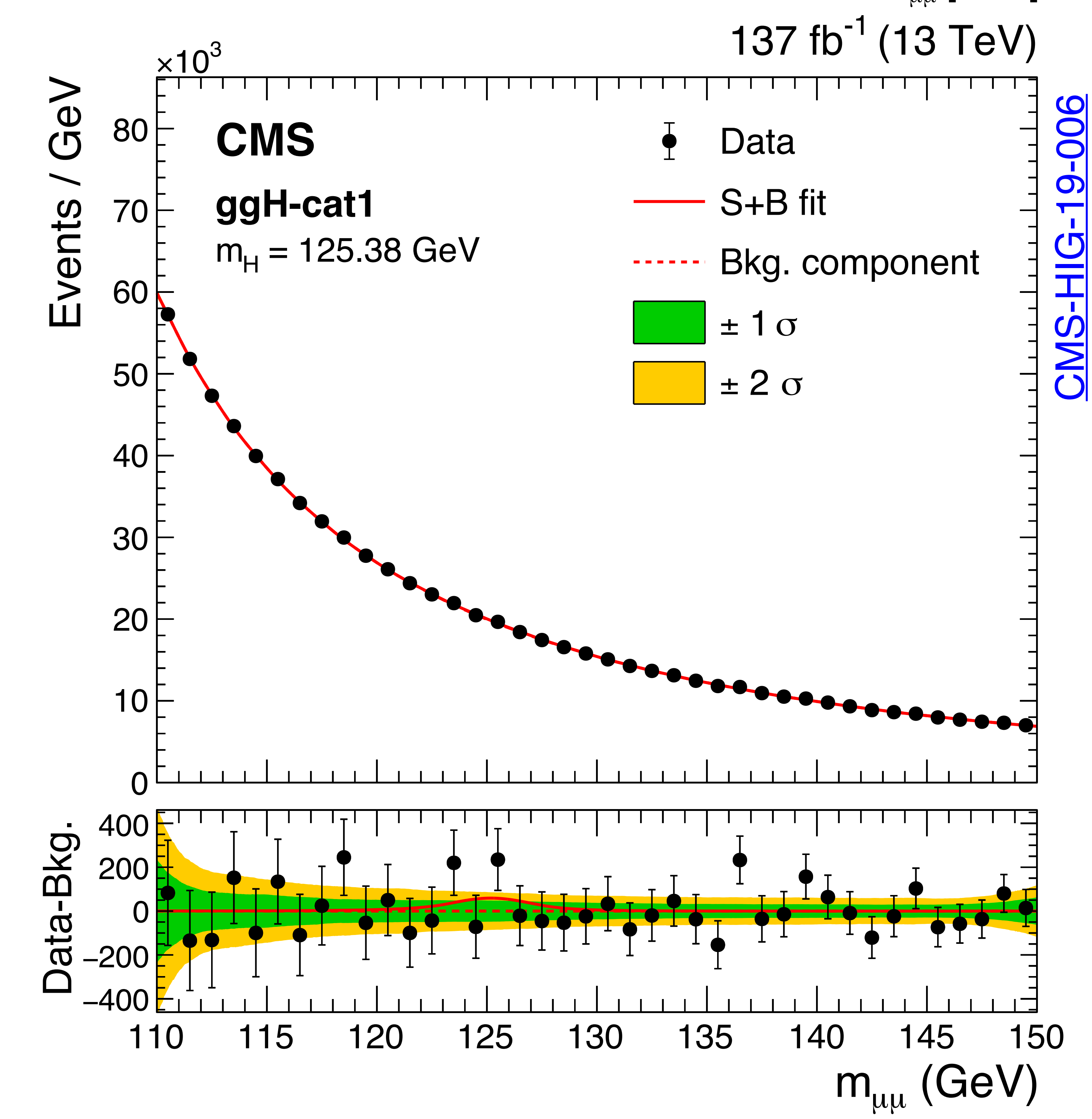
ATLAS: Further convoluted with the detector resolution, **0 DoF** in total.

CMS: Further combined with analytical functions, 9 DoF in total.

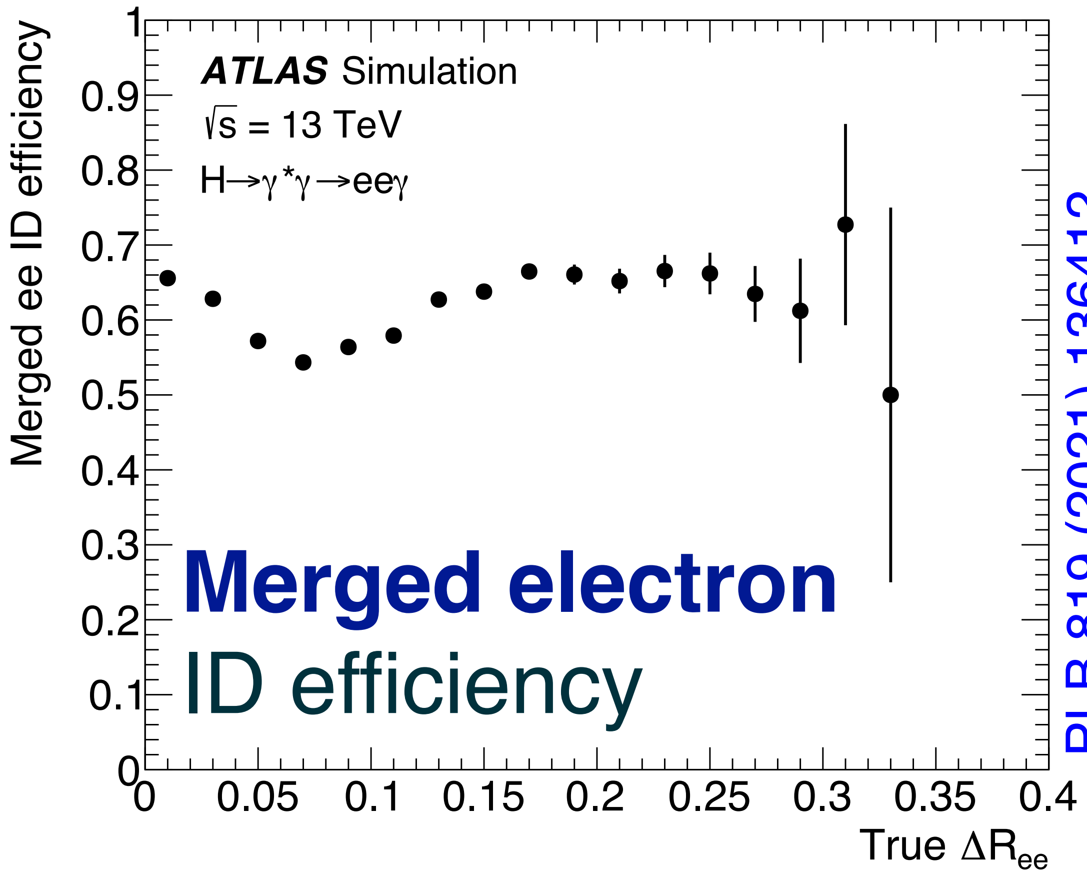
Parameters uncorrelated across categories. Additionally 1 to 4 DoF per category.

This construction minimizes the needed DoF, hence maximizing the sensitivity!





- Mostly a cut-based selection depending on lepton and photon kinematics,
  - VBF events selected with additional jets,
  - VH and ttH events selected with additional lepton requirements in the **CMS analysis only**,
- ATLAS developed a **BDT to select VBF**-enriched events at high $m_{\ell\ell}$ mass,
- A challenge at low $m_{\ell\ell}$ mass is poor separation between the two leptons,
- **ATLAS developed** a special ID for ‘**merged electrons**’ with EM showers overlapped in the calorimeter,
- A parametric fit of the $m_{\ell\ell\gamma}$ distribution performed in each category to extract the signal,
- Number of categories:
  - Low mass: 9 (4) in ATLAS (CMS),
  - High mass: 6 (13) in ATLAS (CMS).



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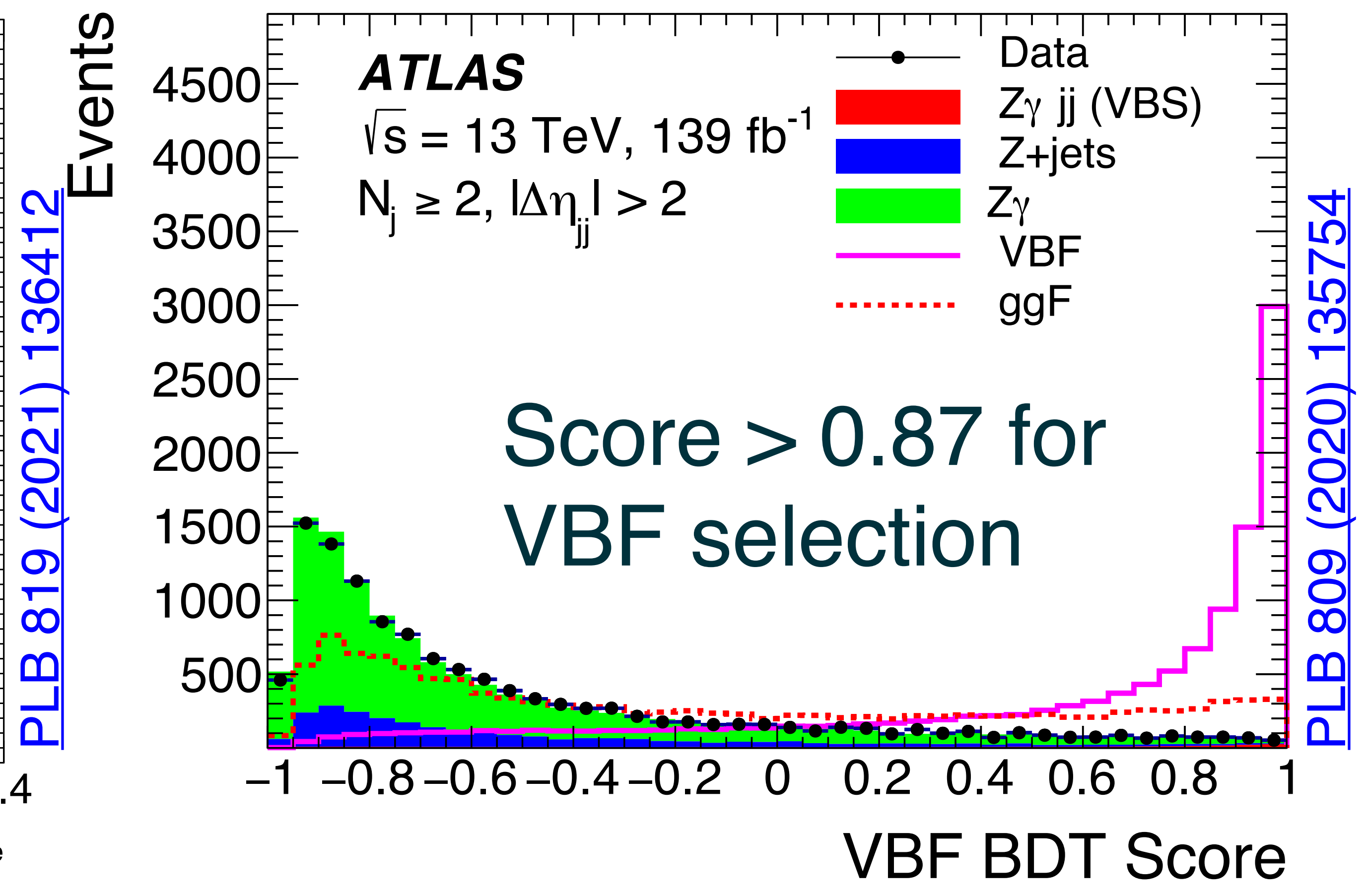

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Analysis	Channel	Category	Number of signal events for $m_H = 125\,\text{GeV}$ ggH	VBF	VH + $t\bar{t}$H
	$\mu\mu$	EB, high R_9	9.18	0.47	0.33
	$\mu\mu$	EB, low R_9	5.17	0.27	0.18
$H \to \gamma^*\gamma \to \mu\mu\gamma$ Low mass	$\mu\mu$	EE	3.80	0.20	0.25
	$\mu\mu$	Dijet tag	0.45	0.39	0.01
	ee + $\mu\mu$	Lepton tag	0.08	0.014	0.33
	ee	Dijet tag	0.34	0.47	0.02
	ee	Boosted	3.38	0.56	0.33
	ee	Untagged 1	5.2	0.15	0.06
	ee	Untagged 2	3.2	0.09	0.04
	ee	Untagged 3	3.9	0.12	0.06
$H \to Z\gamma \to \ell\ell\gamma$	ee	Untagged 4	2.8	0.08	0.04
	$\mu\mu$	Dijet tag	0.44	0.62	0.02
High mass	$\mu\mu$	Boosted	4.51	0.74	0.44
	$\mu\mu$	Untagged 1	7.6	0.22	0.097
	$\mu\mu$	Untagged 2	4.8	0.14	0.06
	$\mu\mu$	Untagged 3	4.1	0.12	0.06
CMS, 36 fb^{-1}	$\mu\mu$	Untagged 4	3.5	0.11	0.06

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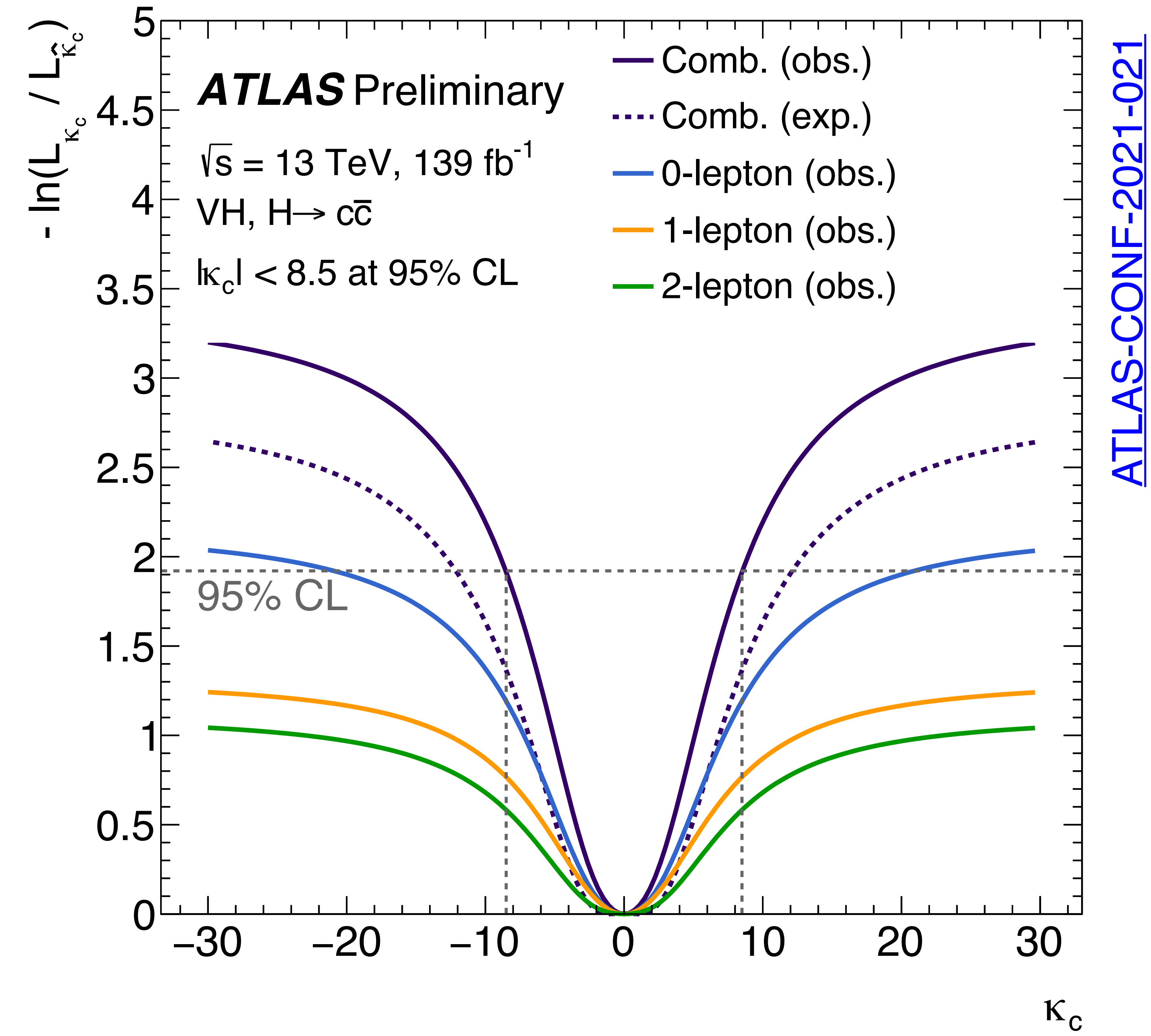
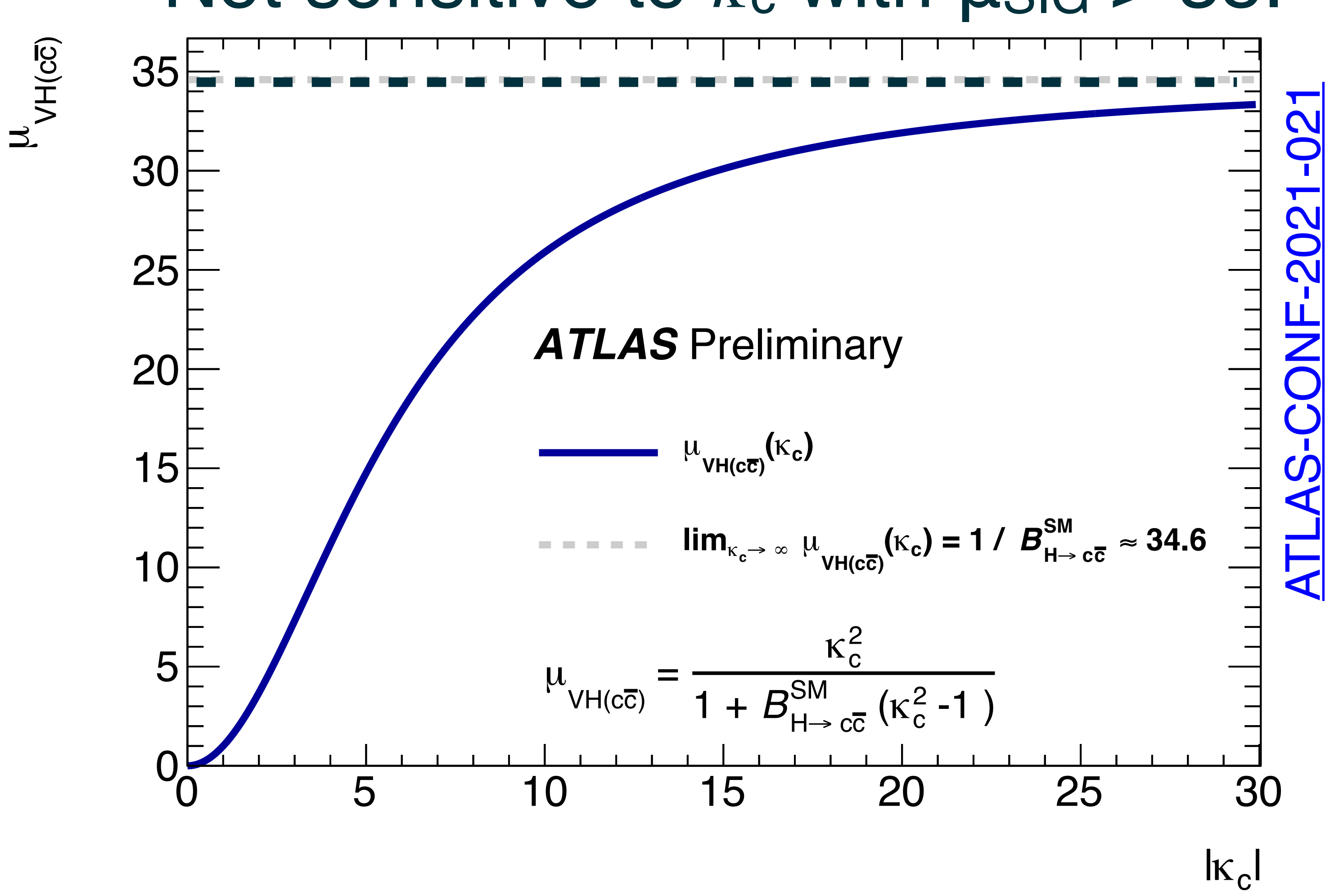
VH(→ cc) Kappa Framework Interpretation

- Assume κ_X = 1.0 for other fermions and bosons and no BSM,
- Direct limit: $|\kappa_c|$ < 8.5 at 95% CL.
- Differential $p_T(H)$ measurements also give indirect constraints on κ_c,
  - Modifies the rates through the production and decay loops,
  - Most sensitive are H → ZZ* and H → γγ decay modes,
  - Indirect limits **depends heavily on model assumptions**,
  - Generally comparable to the direct constraints from VH(→ cc).

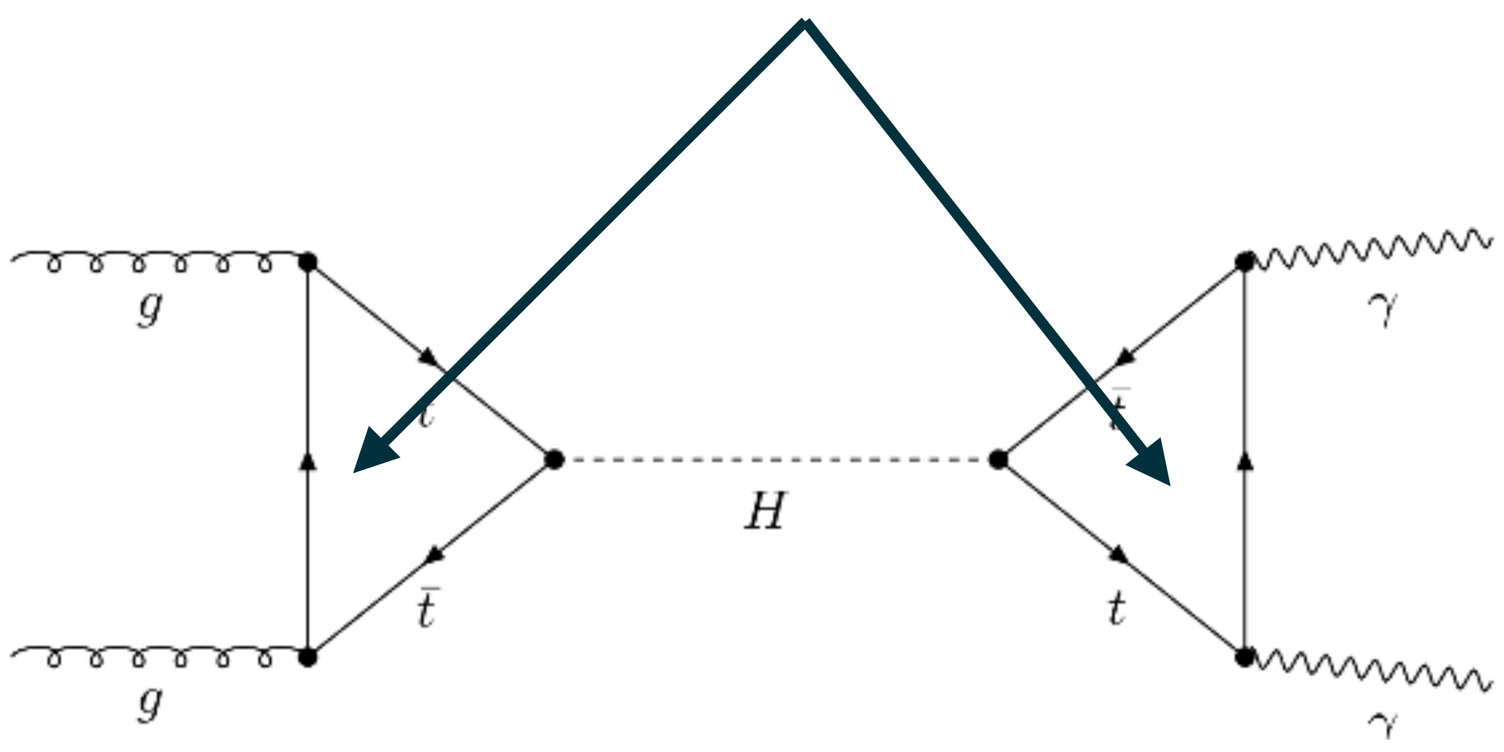
Direct κ_c constraint from VH(→ cc)



Not sensitive to κ_c with μ_{SIG} > 35.



Indirect κ_c constrain through loop effects



Assume Br = Br(κ_c, κ_b)