Evidence for Higgs boson decay to muons

*Result recently published in JHEP: **JHEP01(2021)148***

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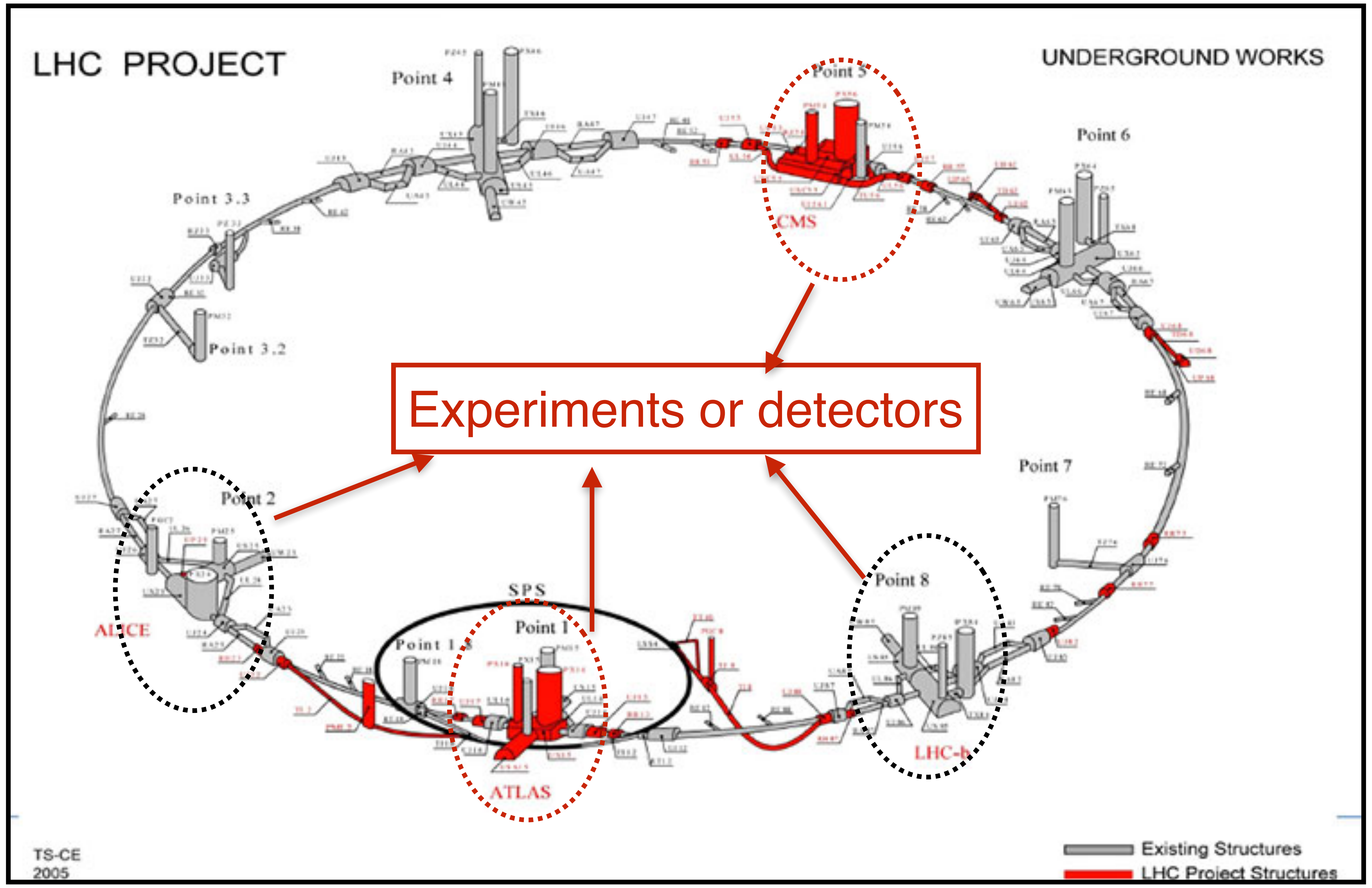
On behalf of the CMS Collaboration

HEP seminar at University of Liverpool, Department of Physics

The Large Hadron Collider (LHC)

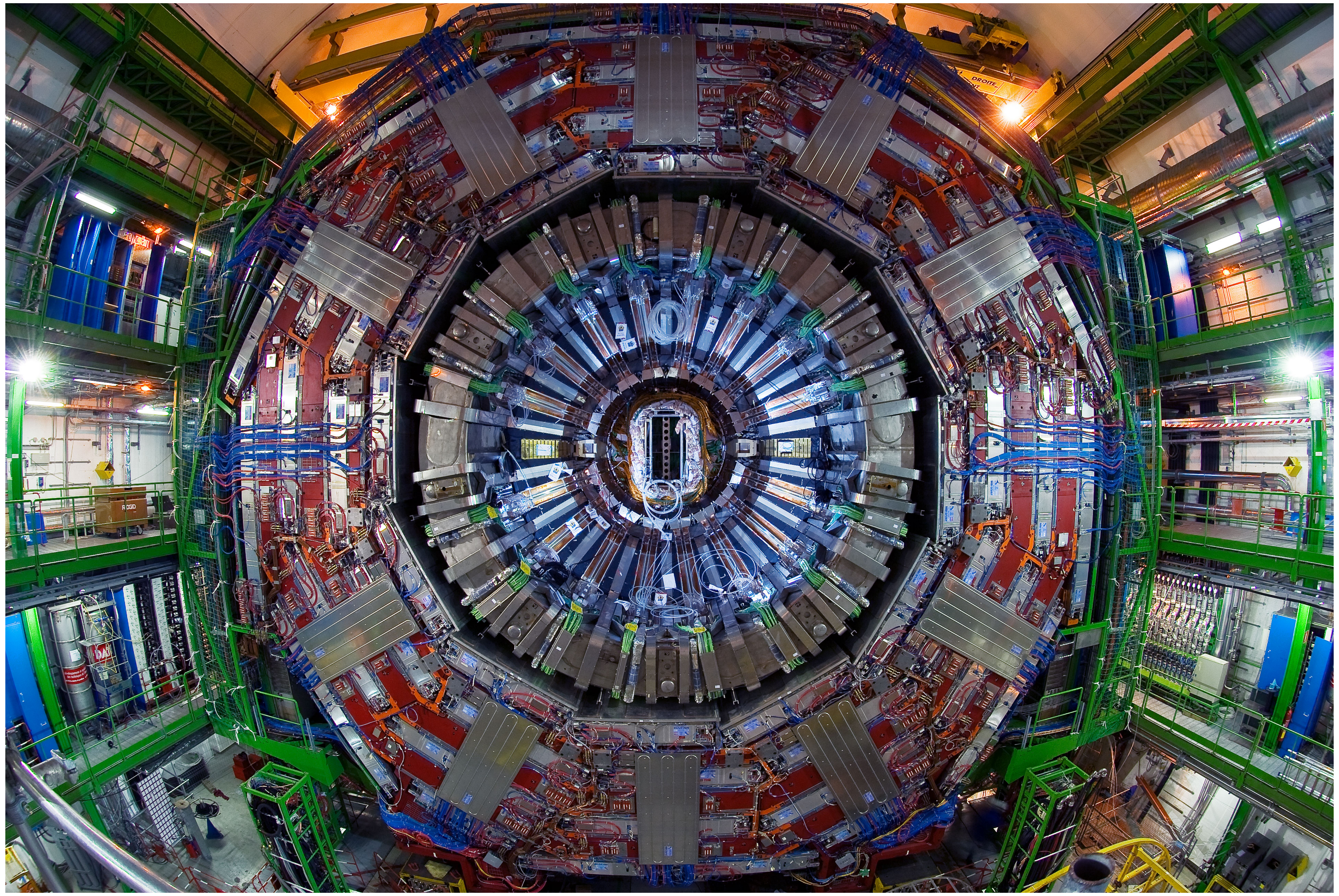
- ***Particle colliders*** $(e^+e^-, p\bar{p}, pp)$ are powerful instruments used to study the subatomic world
- The ***Large Hadron Collider (LHC)*** is a the highest energy particle accelerator ever built
  - It is a ***pp collider*** accelerating protons to an ***energy*** of 6.5 TeV → $\sqrt{s} = 13\ TeV$
  - ***Frequency*** of collisions 40 MHz → 25ns bunch spacing
  - ***Integrated luminosity*** in Run2 (2016-18) is ~140 fb^{-1} → measurement of amount of data recorded

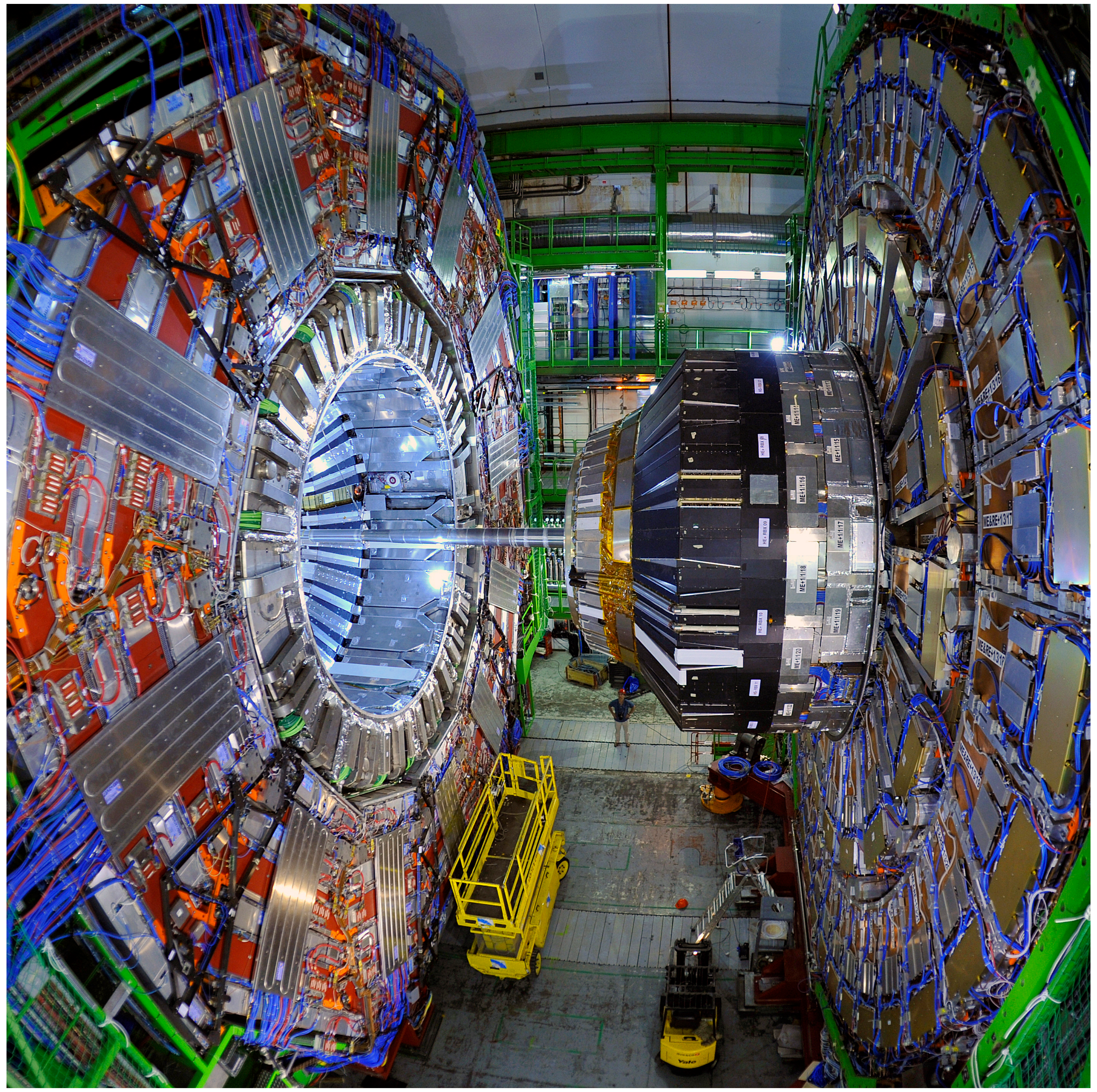


Experiments or detectors

The Compact Muon Solenoid (CMS) detector

- Results reported in this seminar are obtained from the “***high resolution photos***” of the pp collisions happening every 25ns at the LHC provided by the ***CMS detector***
- CMS scientific results are obtained thanks to the work of ***thousand of Collaborators*** that made this machine a fabulous instrument to ***chase the secrets of particle physics***

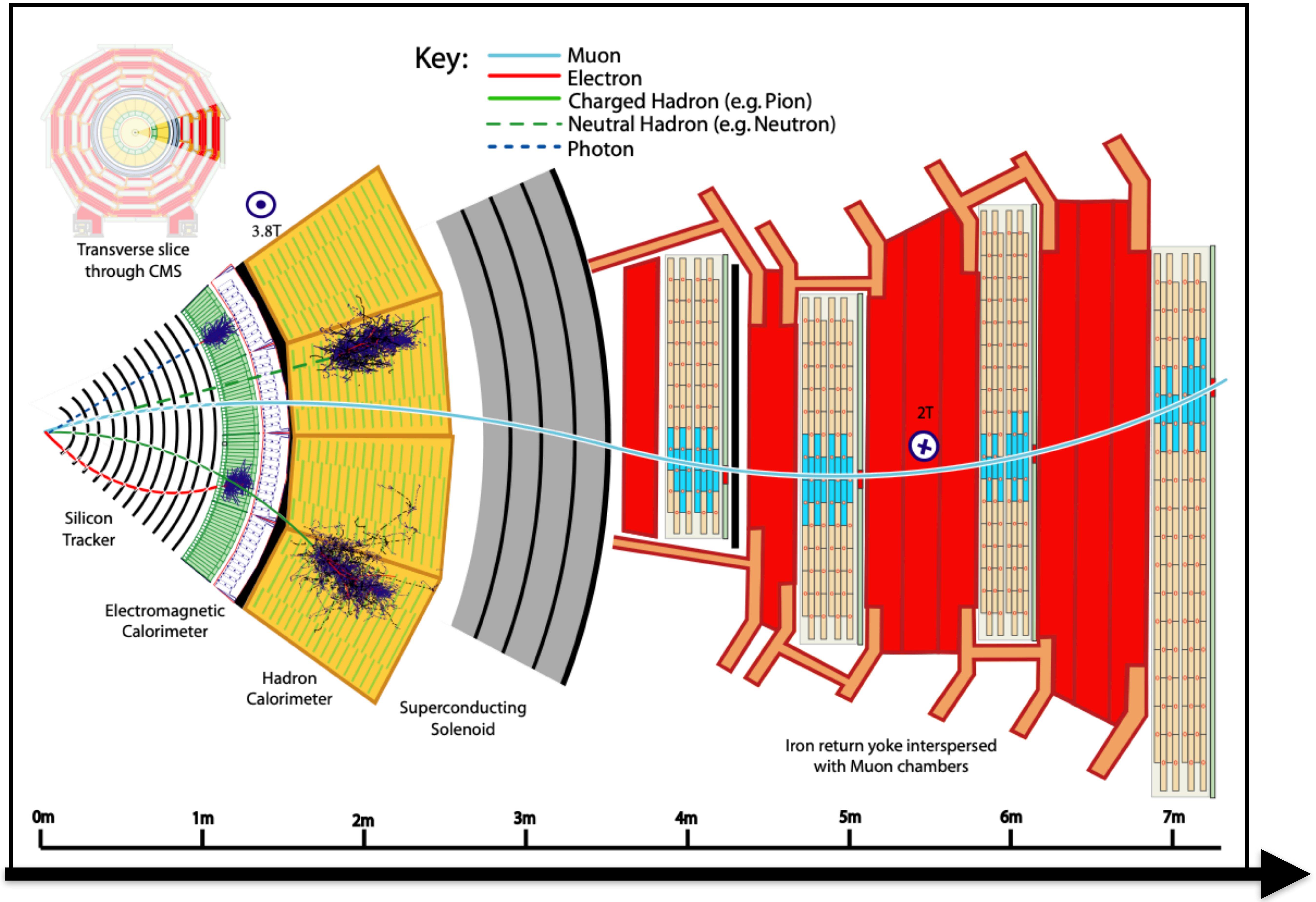




The CMS detector

- ***CMS is like an onion*** → made of layers dedicated to the measurement of a class of particles produced in collision

Transverse slice of the CMS detector



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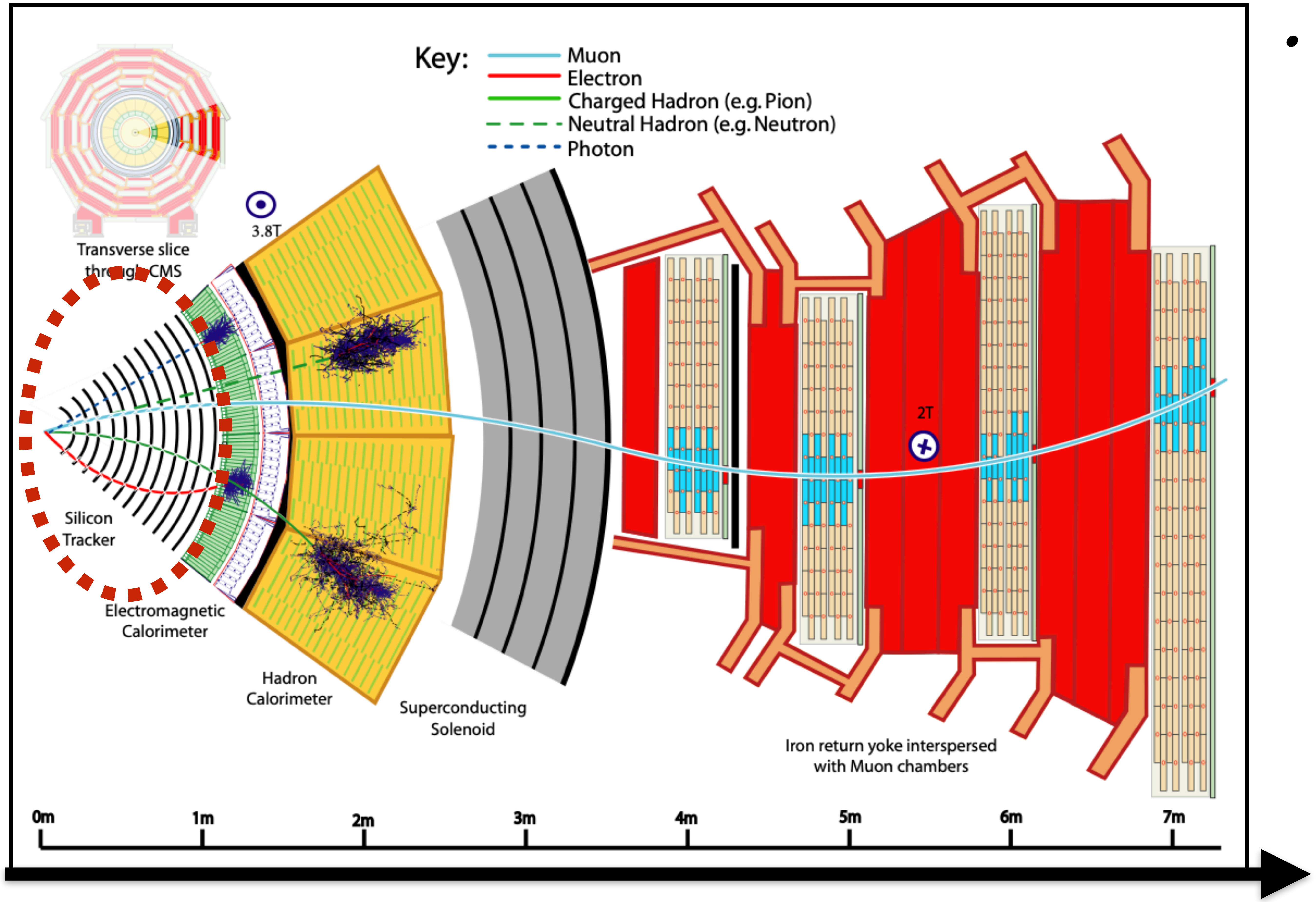

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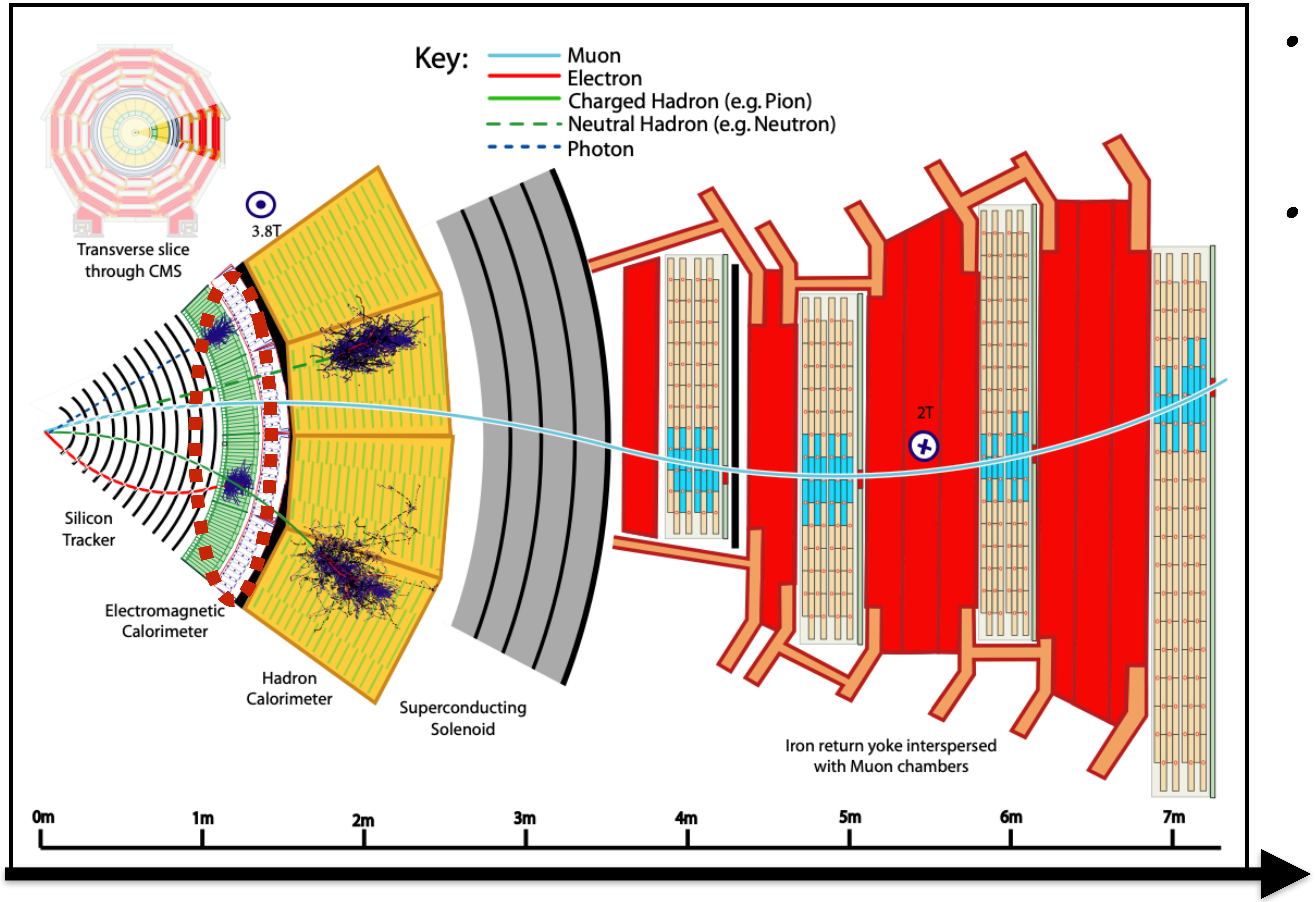

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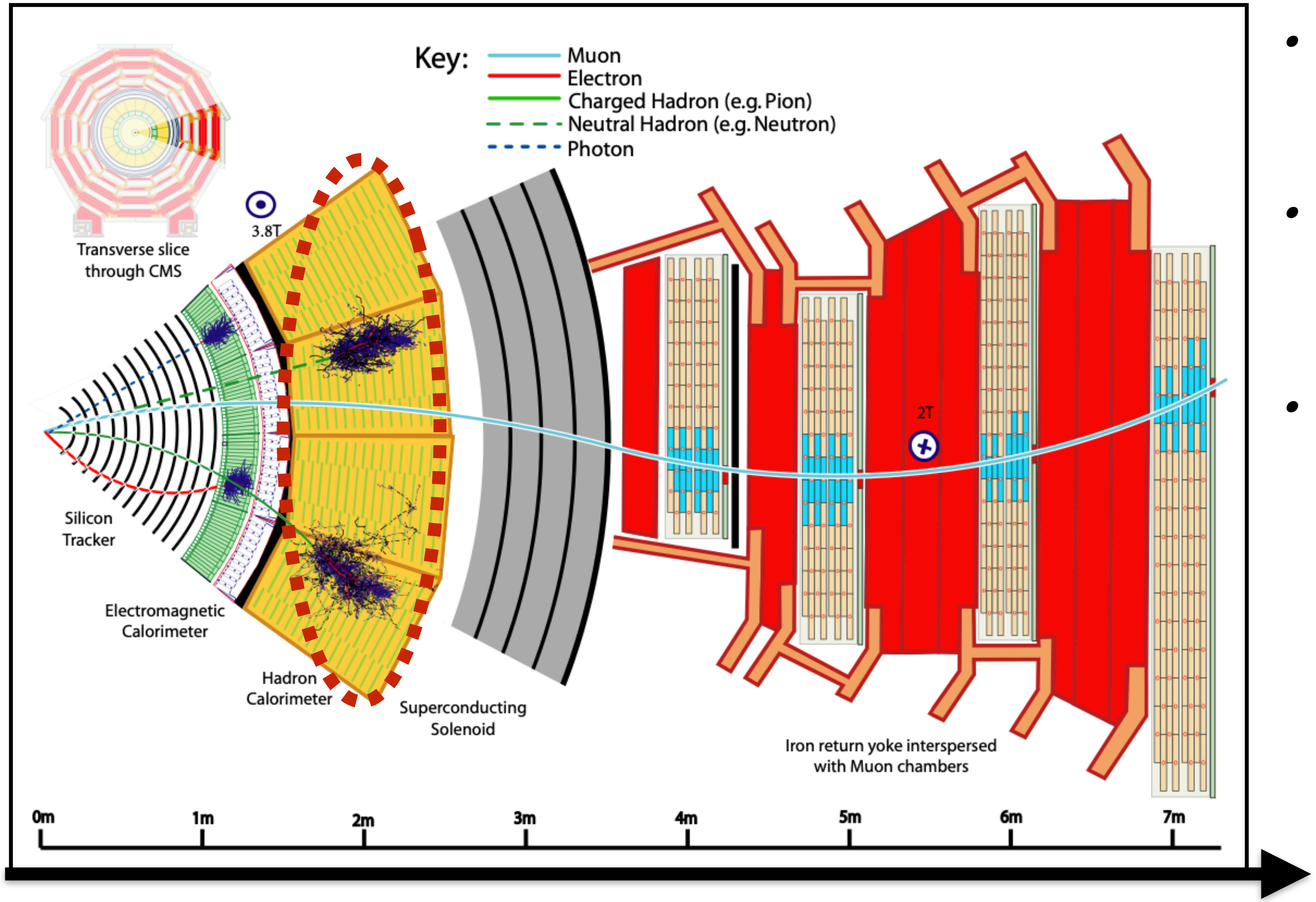

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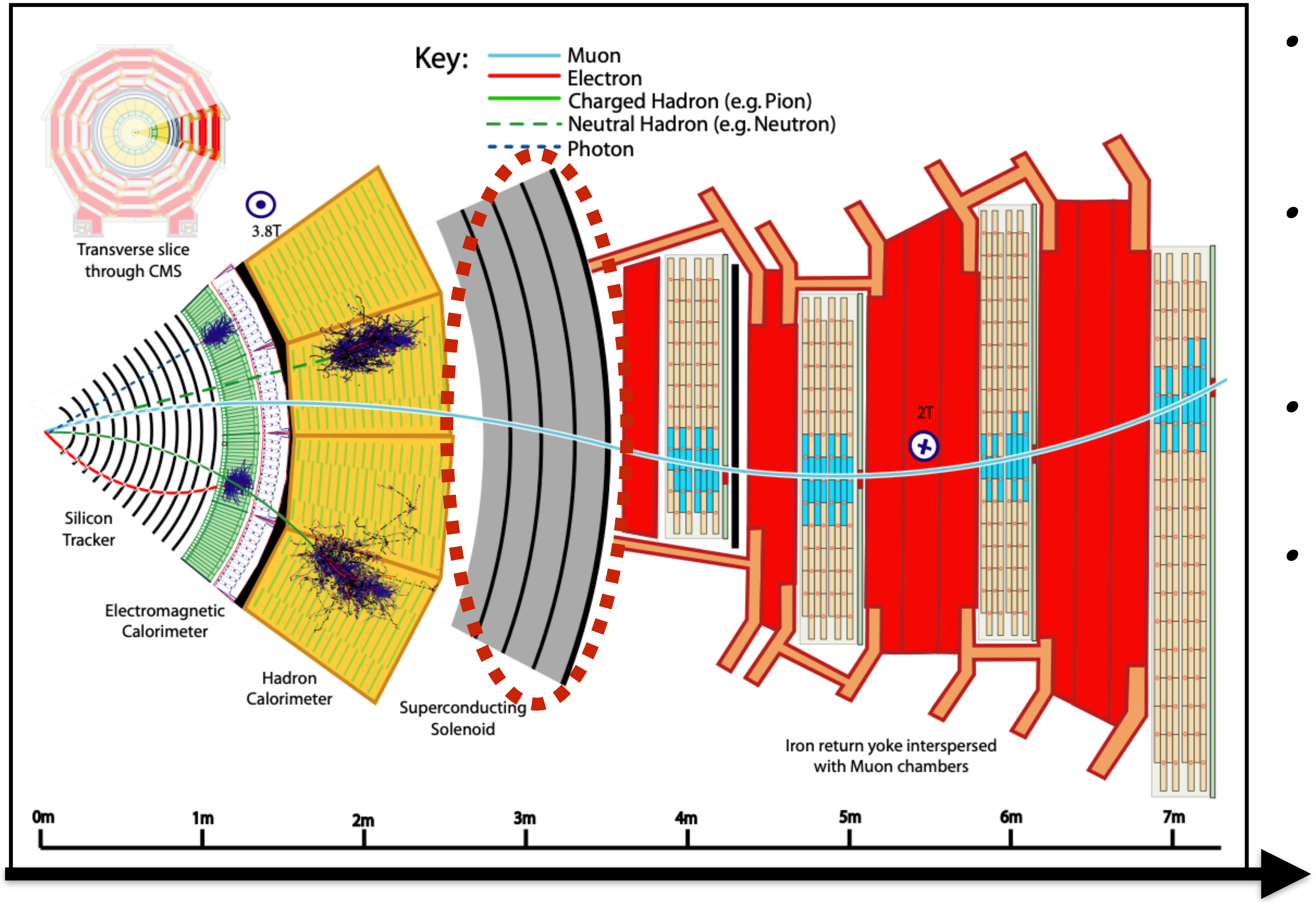

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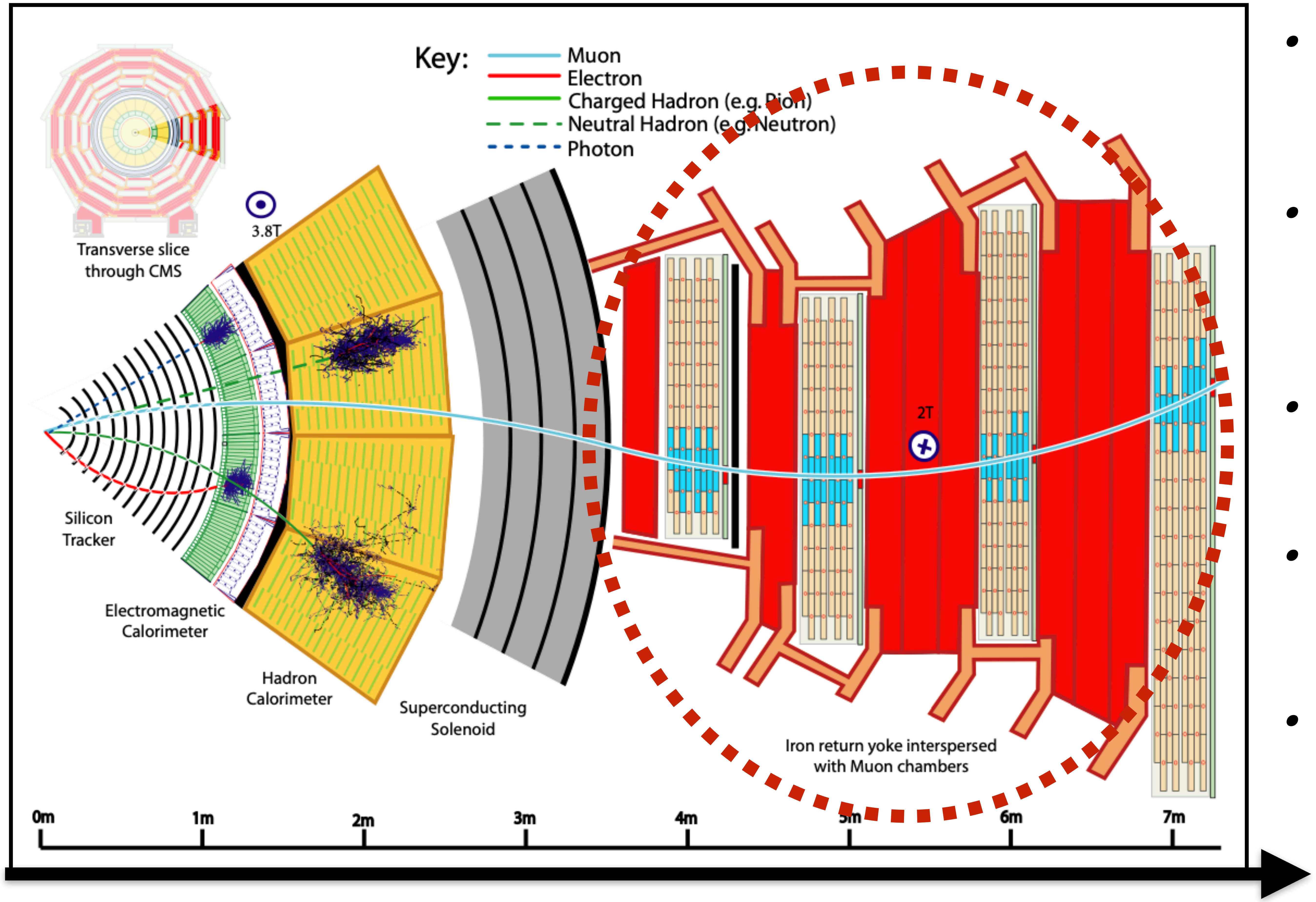

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- ***Muon system:*** along with tracking allows a high resolution p_T measurement and high performance trigger

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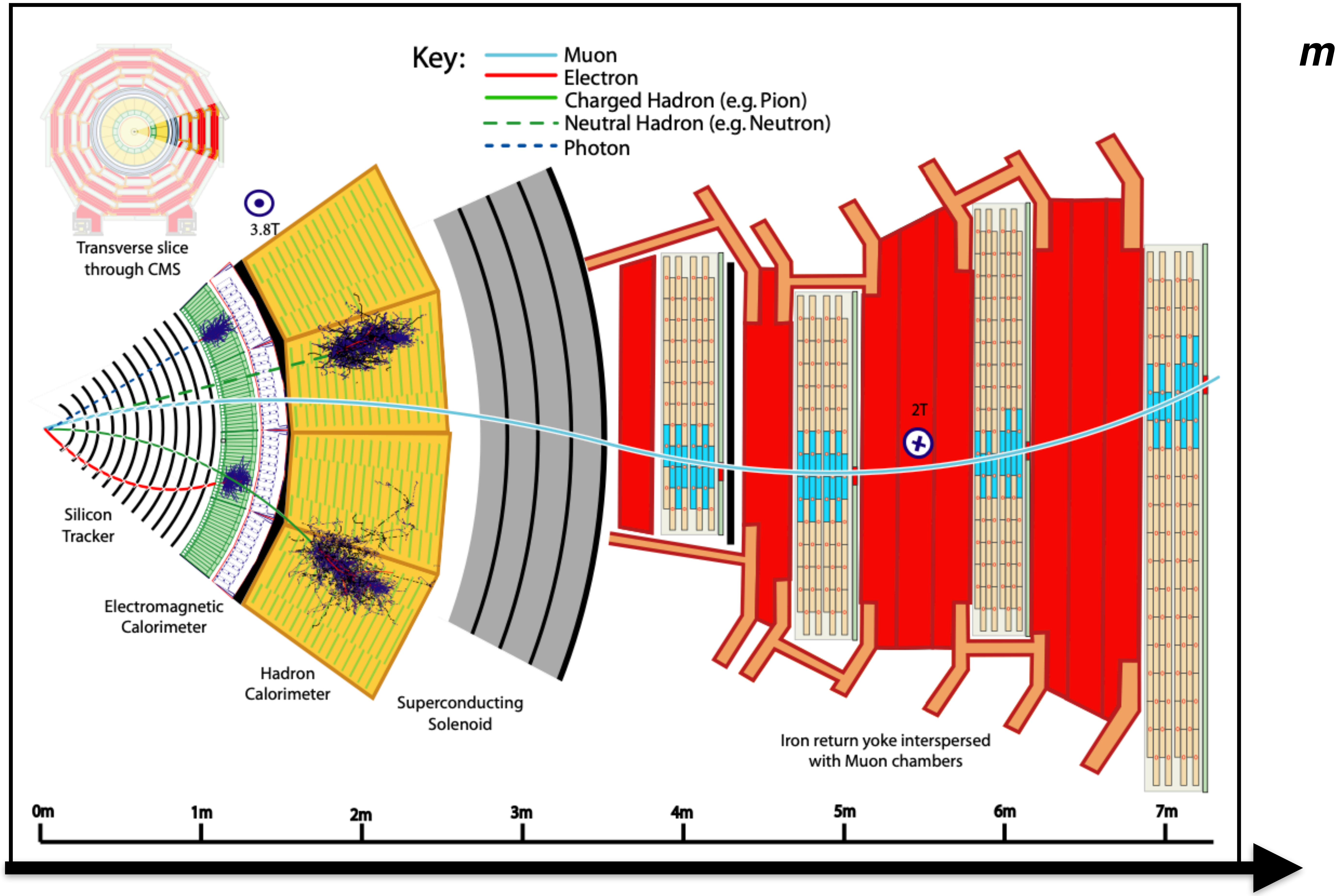
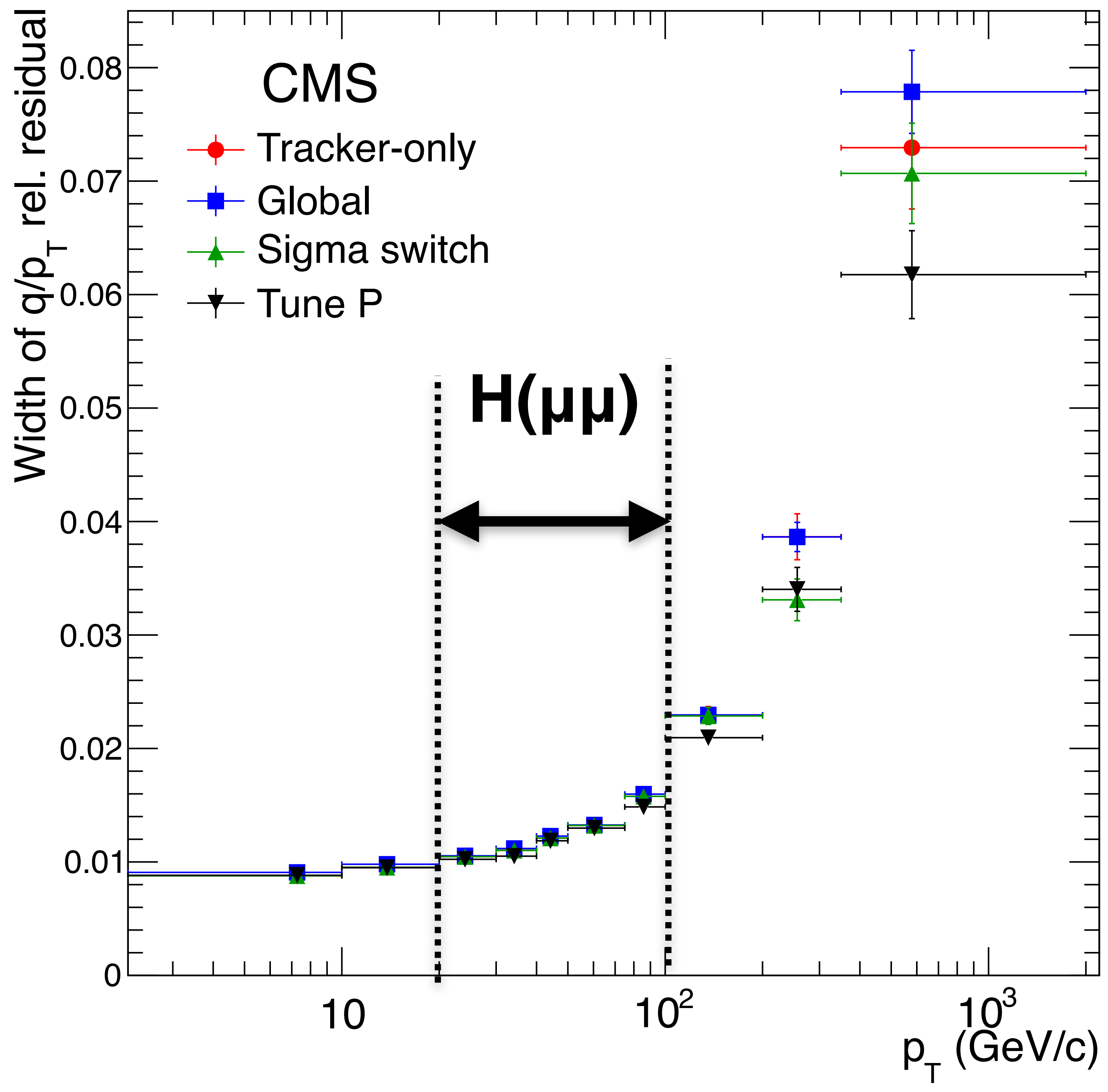


The muon p_T is precisely measured thanks to the high ***magnetic field (4T)***, and excellent tracking performances from ***inner tracker*** and ***muon chambers***



What are the main achievements of CMS ?

- Since 2008, the CMS Collaboration ***published more than 1000 papers*** on journal
- These contains several discoveries, observations of rare processes, stringent bounds on new physics models, etc ..

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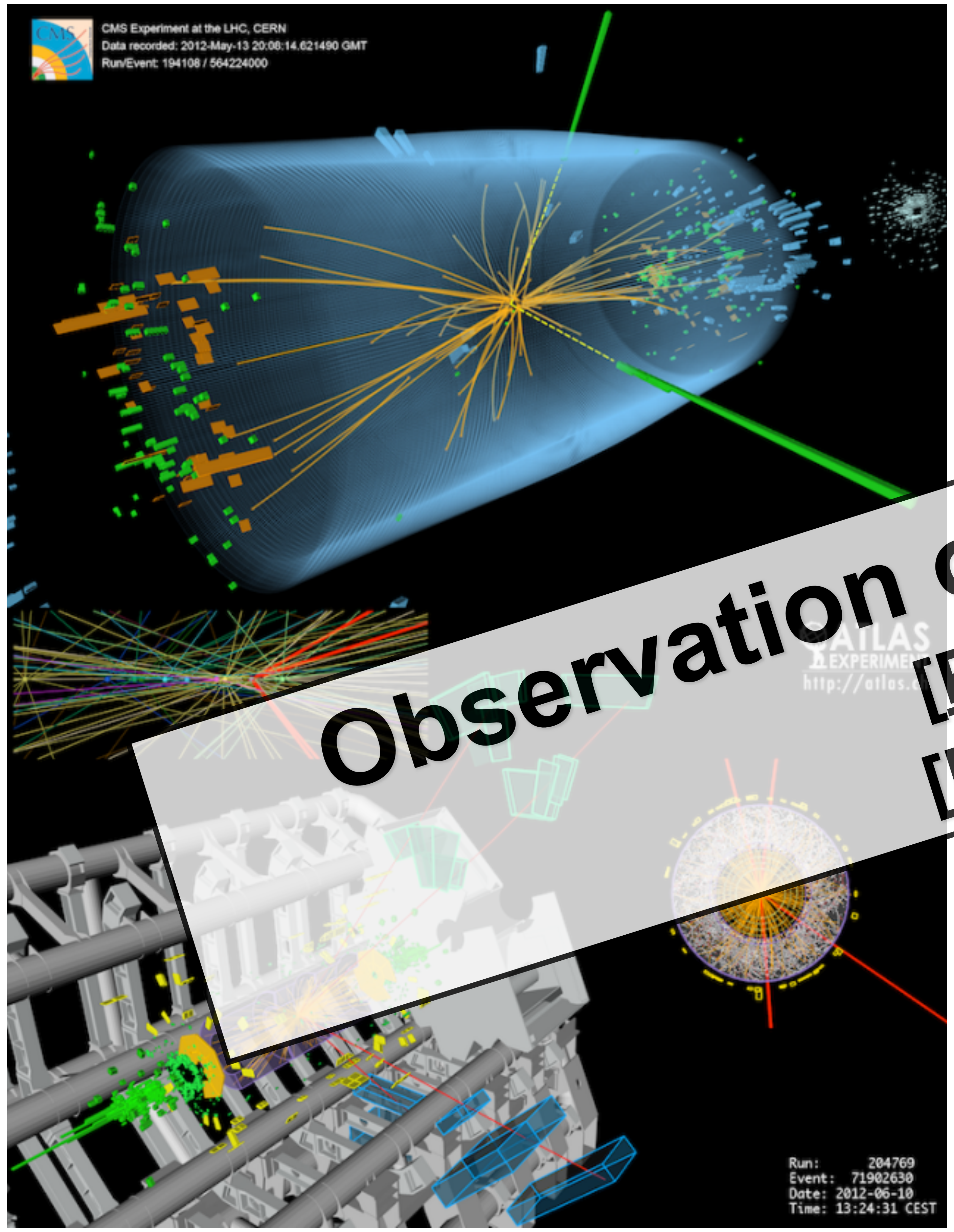
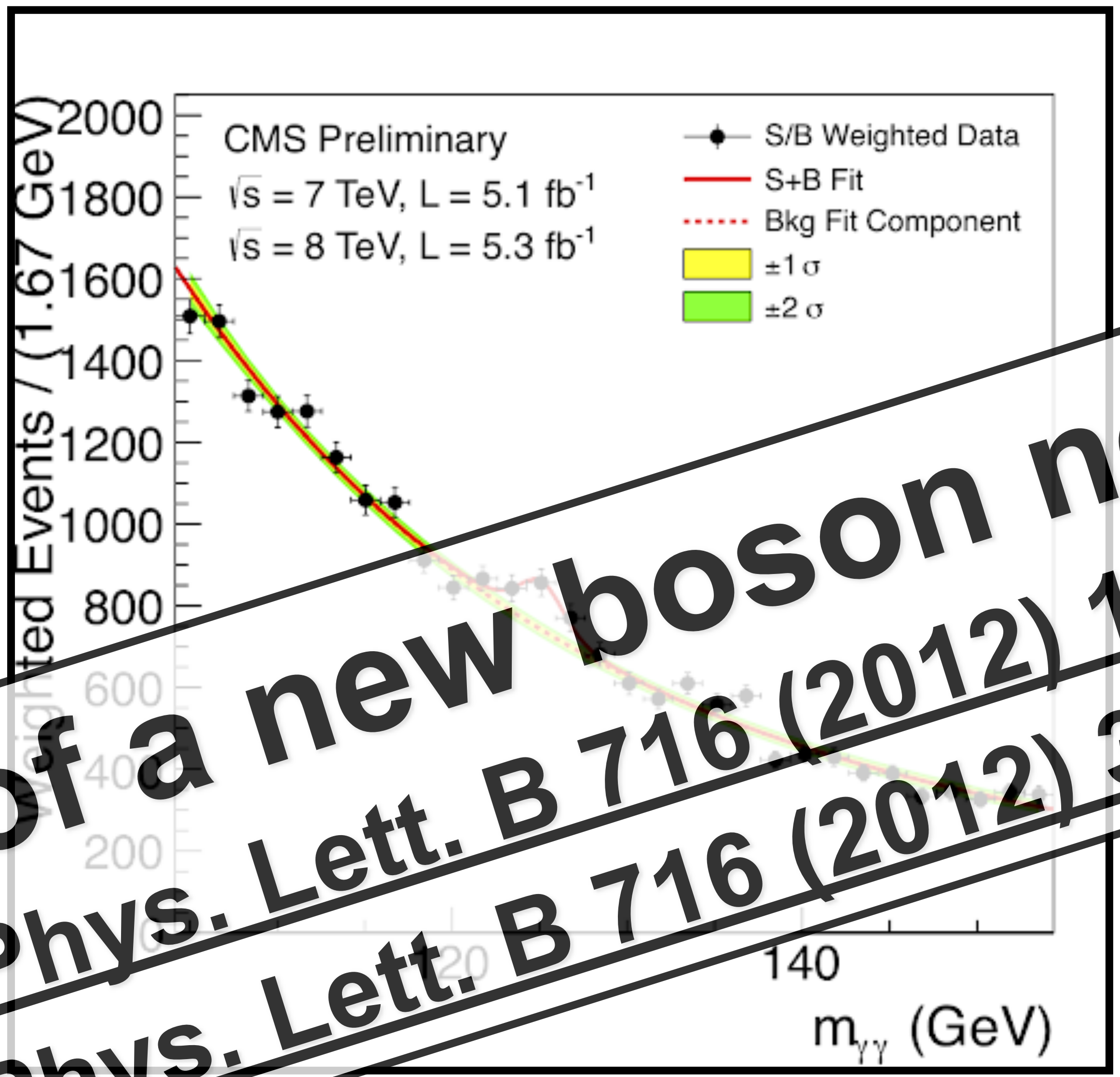
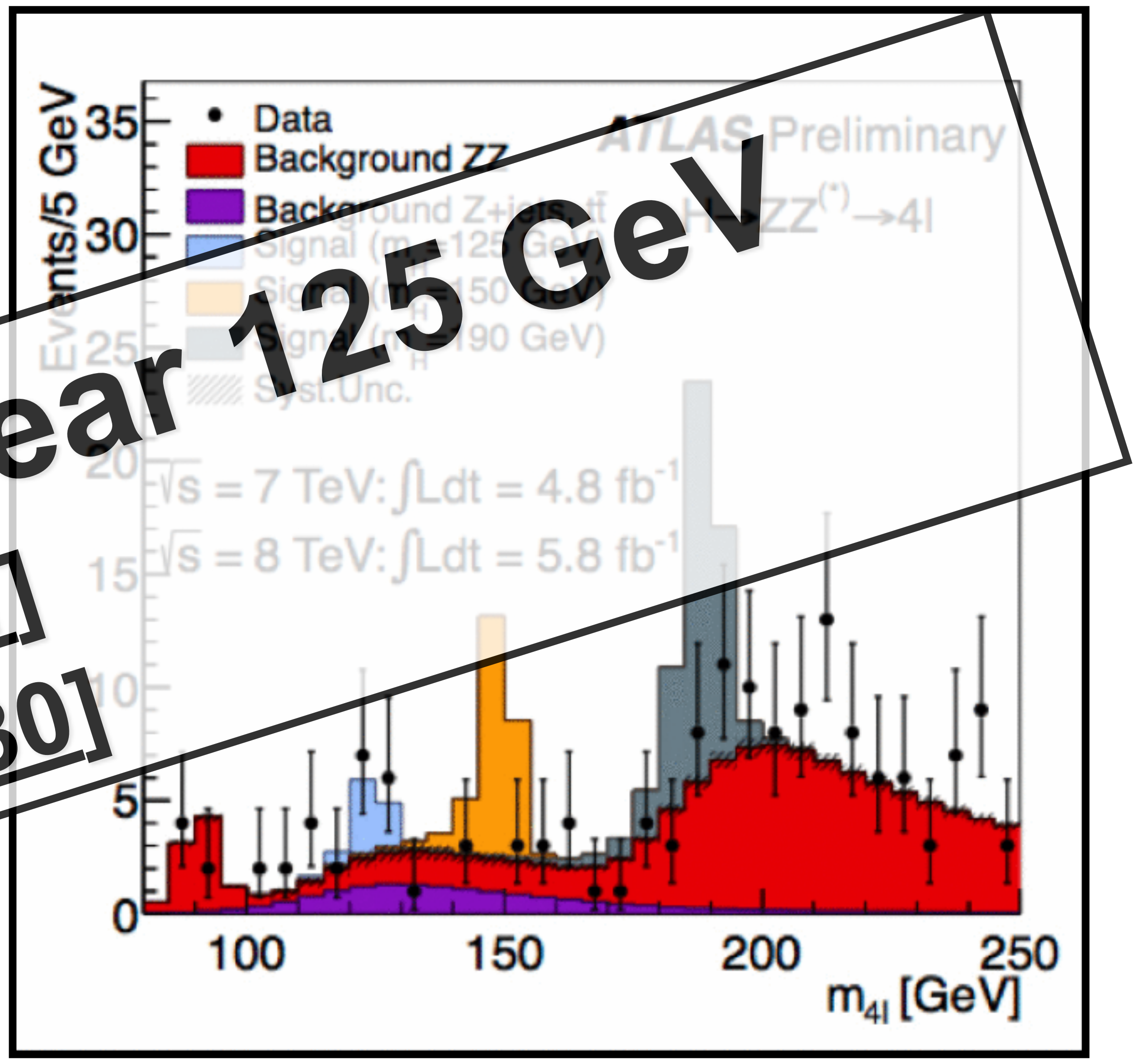






Observation of a new boson near 125 GeV

[Phys. Lett. B 716 (2012) 1]

[Phys. Lett. B 716 (2012) 30]

Higgs boson physics in 2021

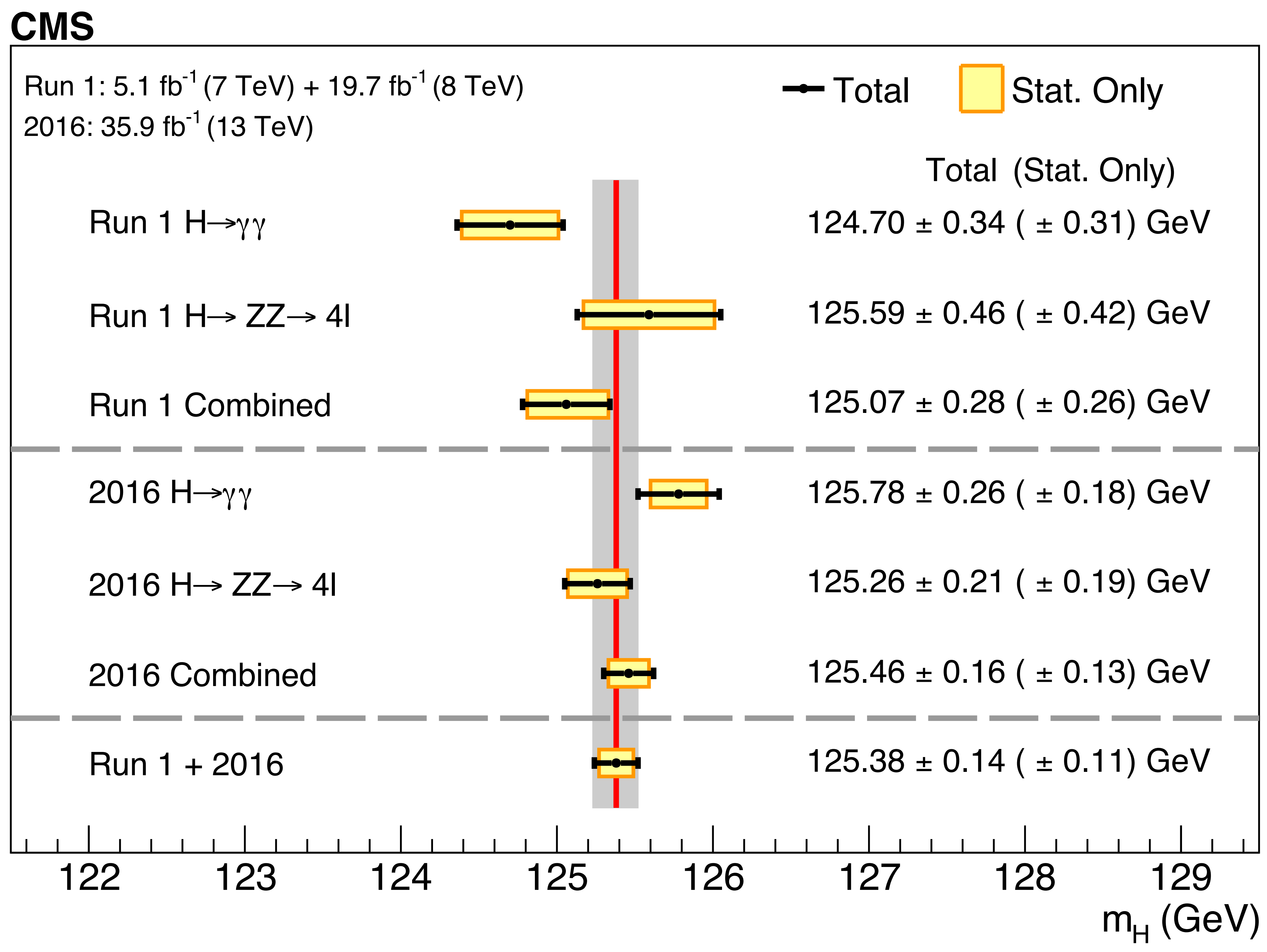
*Since its discovery, **CMS** performed **measurements** of Higgs boson **properties** and **interactions***

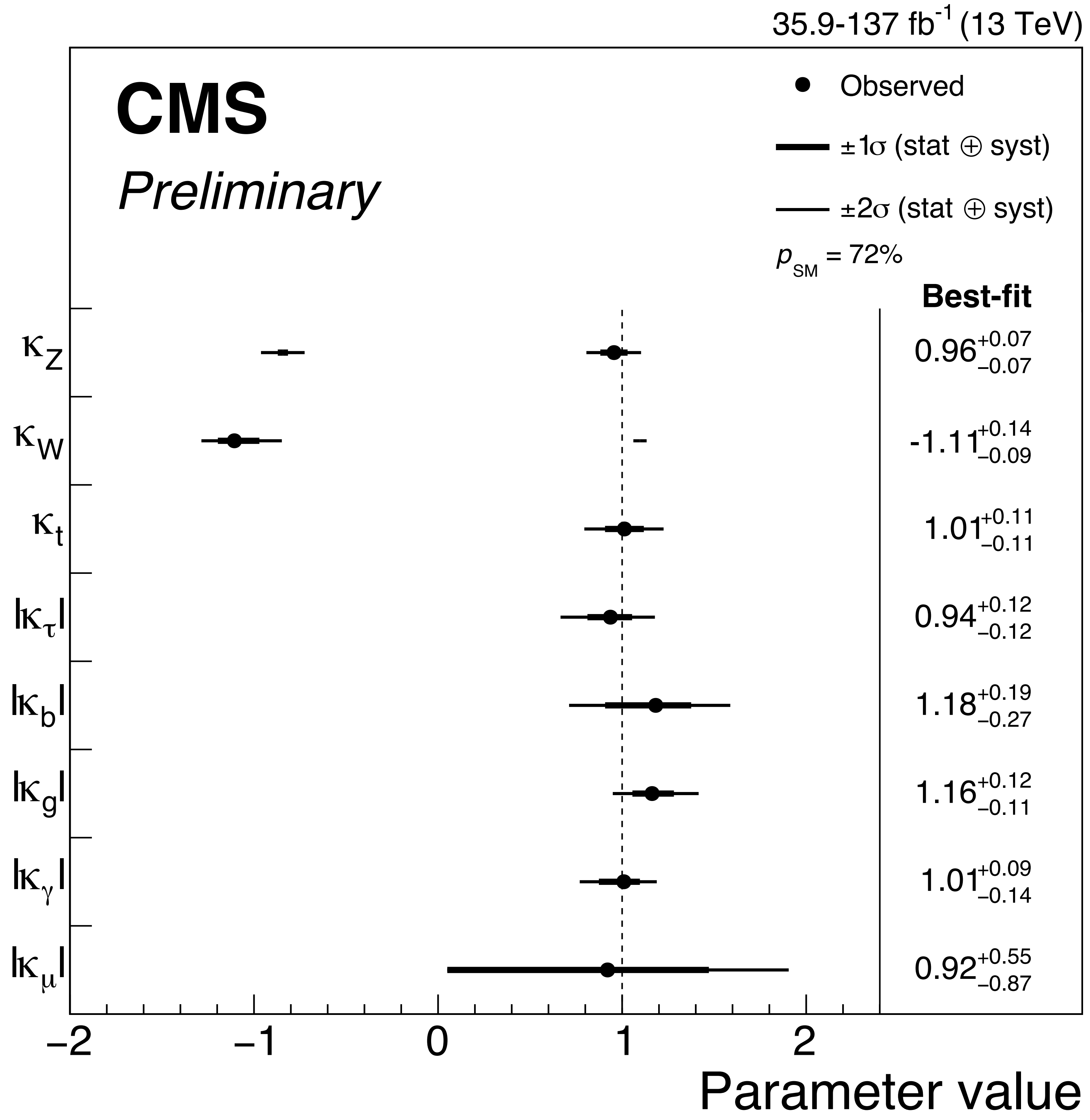
Higgs boson properties

- Mass (m_H), spin-parity J^{CP}, constraints on width (Γ_H)
- Most precise measurement of $m_H = 125.38 \pm 0.14$ GeV

- ***Higgs interactions*** with heaviest particles i.e. ***bosons*** (W, Z) and ***3rd generation of fermions*** (t, b, and τ)
- Found to be consistent with SM expectation

Phys. Lett. B 805 135425

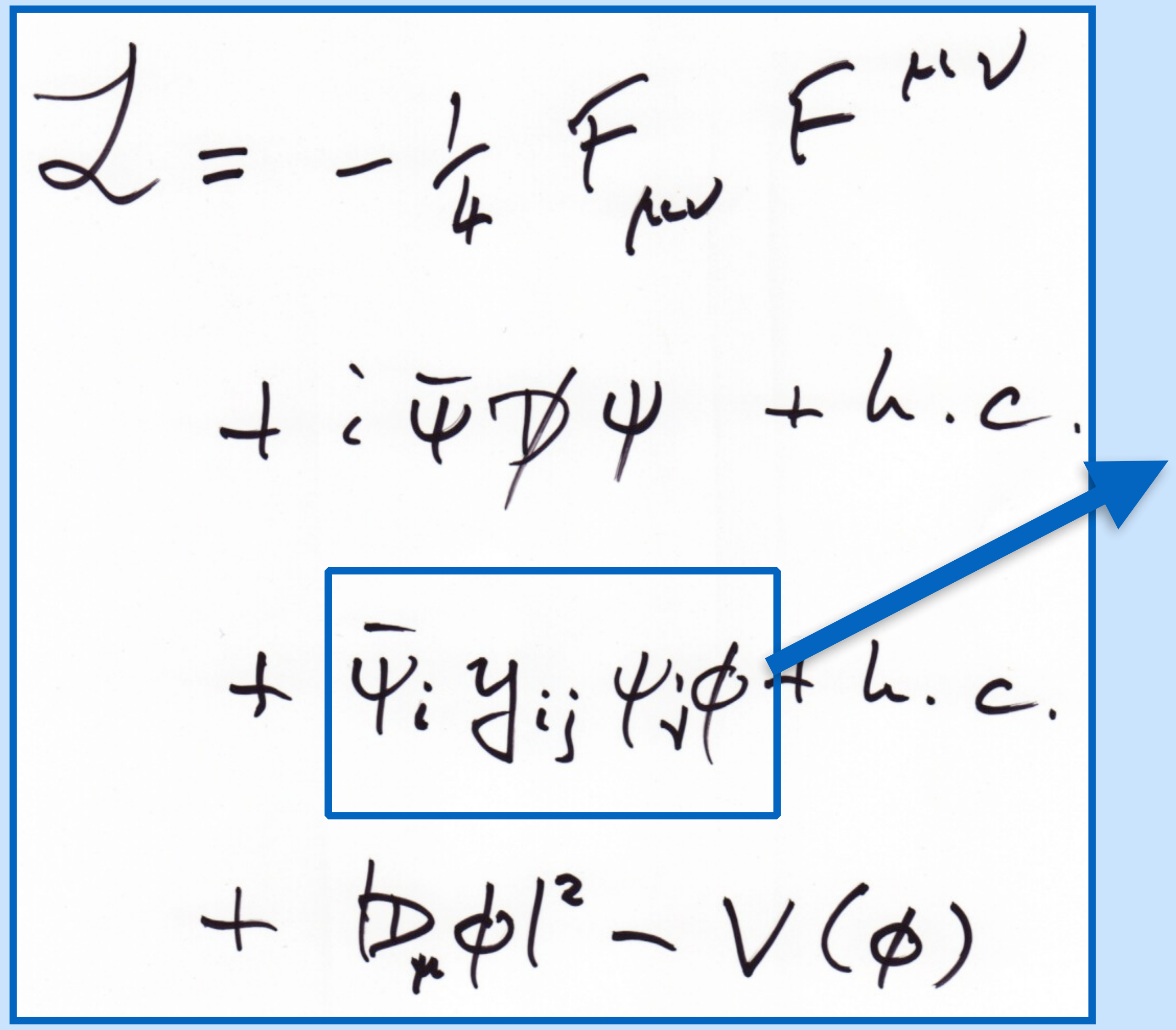




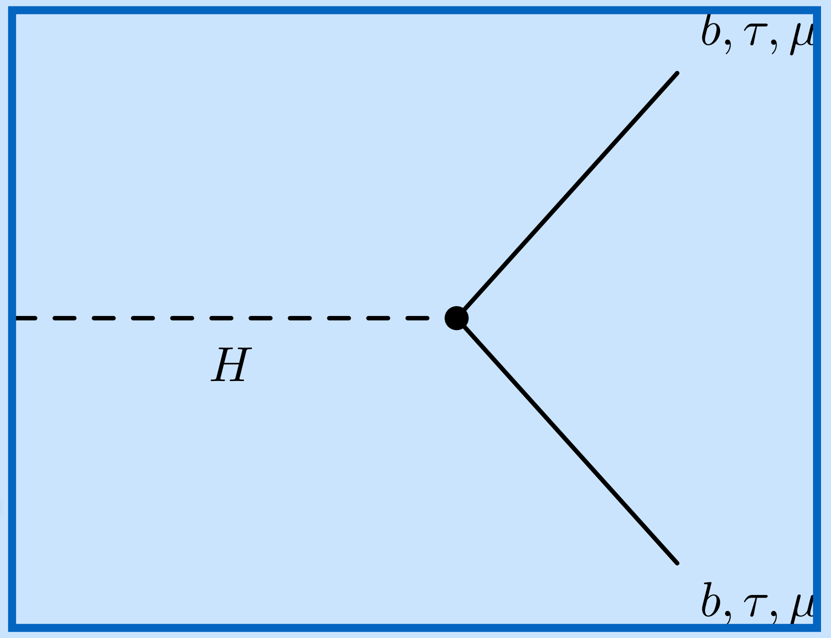
CMS-PAS-HIG-19-005

Next frontier: second fermion generation

- Probe the ***Yukawa interactions*** between the Higgs boson and ***2^{nd} generation fermions***



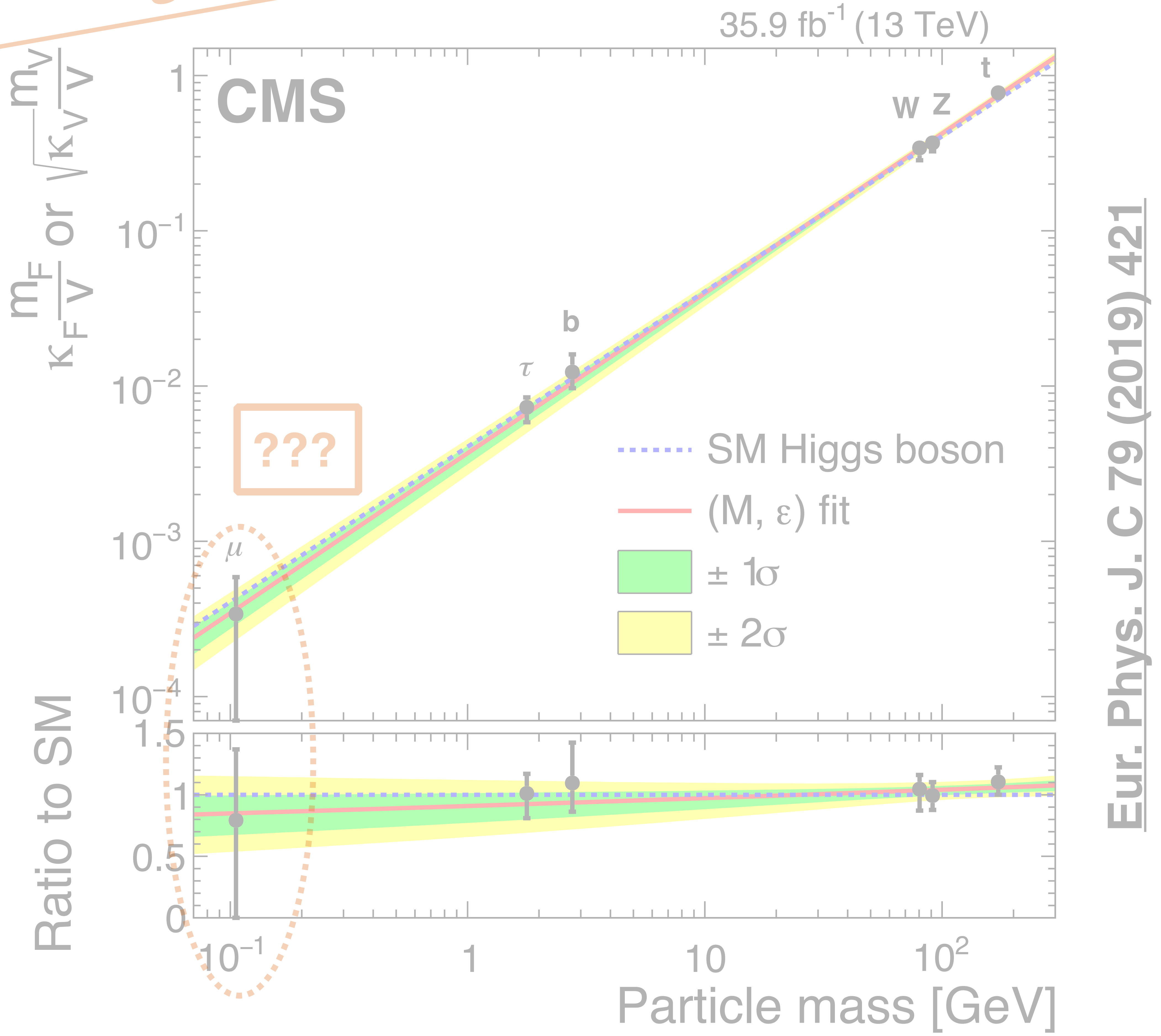
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \boxed{\bar{\psi}_i y_{ij}\psi_j\phi} + h.c. + |D_\mu\phi|^2 - V(\phi)$$



$$\Gamma \propto \frac{m_f^2}{v^2}$$

- These interactions are probed either via ***direct searches*** or via ***indirect constraints*** from other Higgs measurements
- ***Direct searches*** for ***H(cc)*** and ***H(μμ)*** developed in CMS
- ***H(cc)*** offers the largest rate but ***very challenging*** at LHC due to large ***background contamination***

H→μμ is probably the only accessible 2^{nd} generation interaction at the LHC



Eur. Phys. J. C 79 (2019) 421

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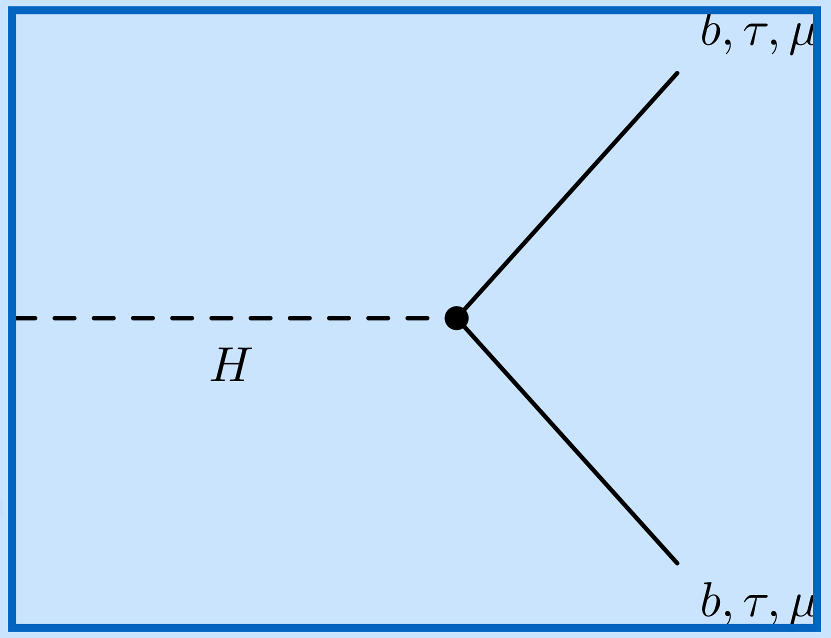

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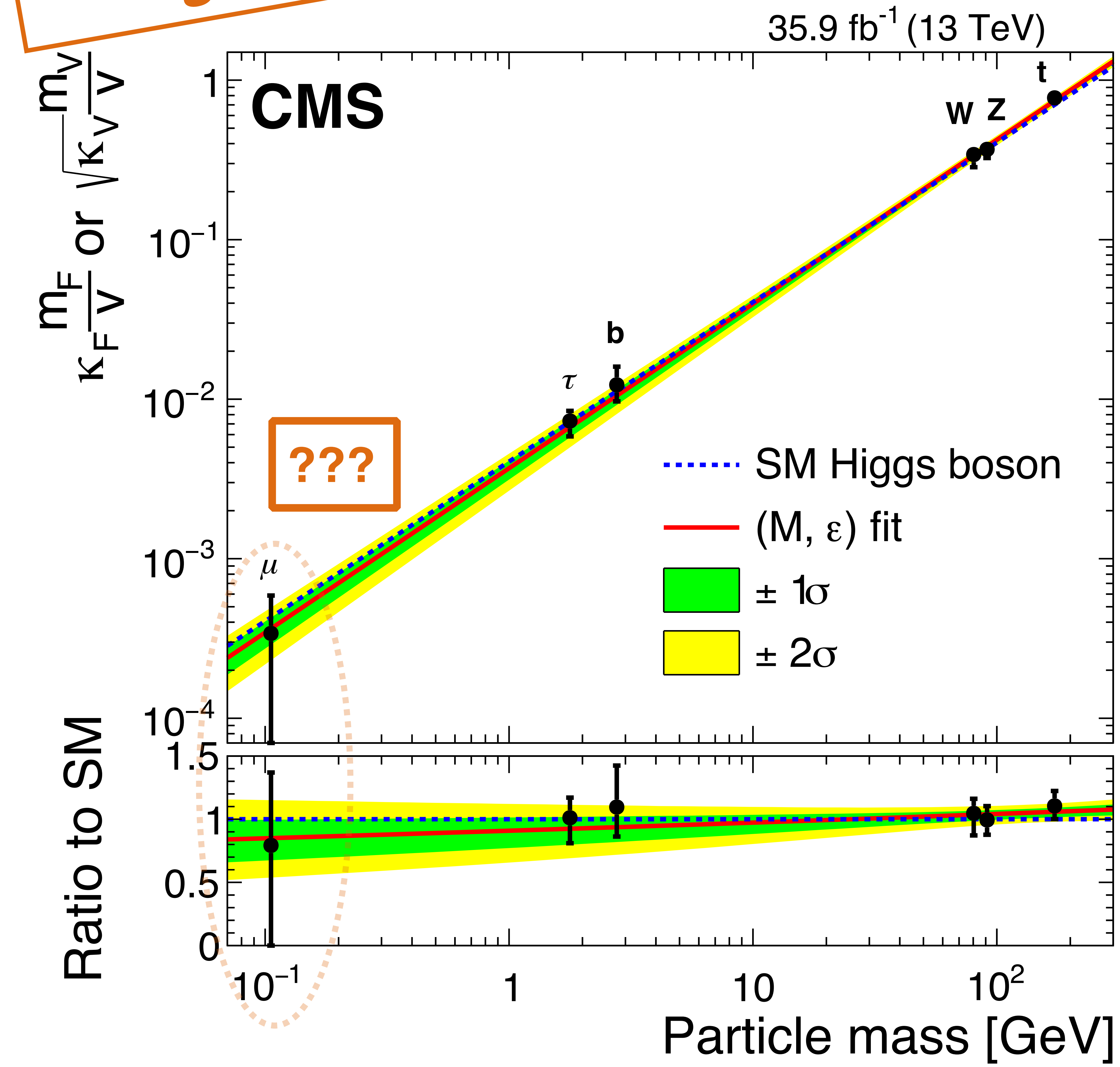

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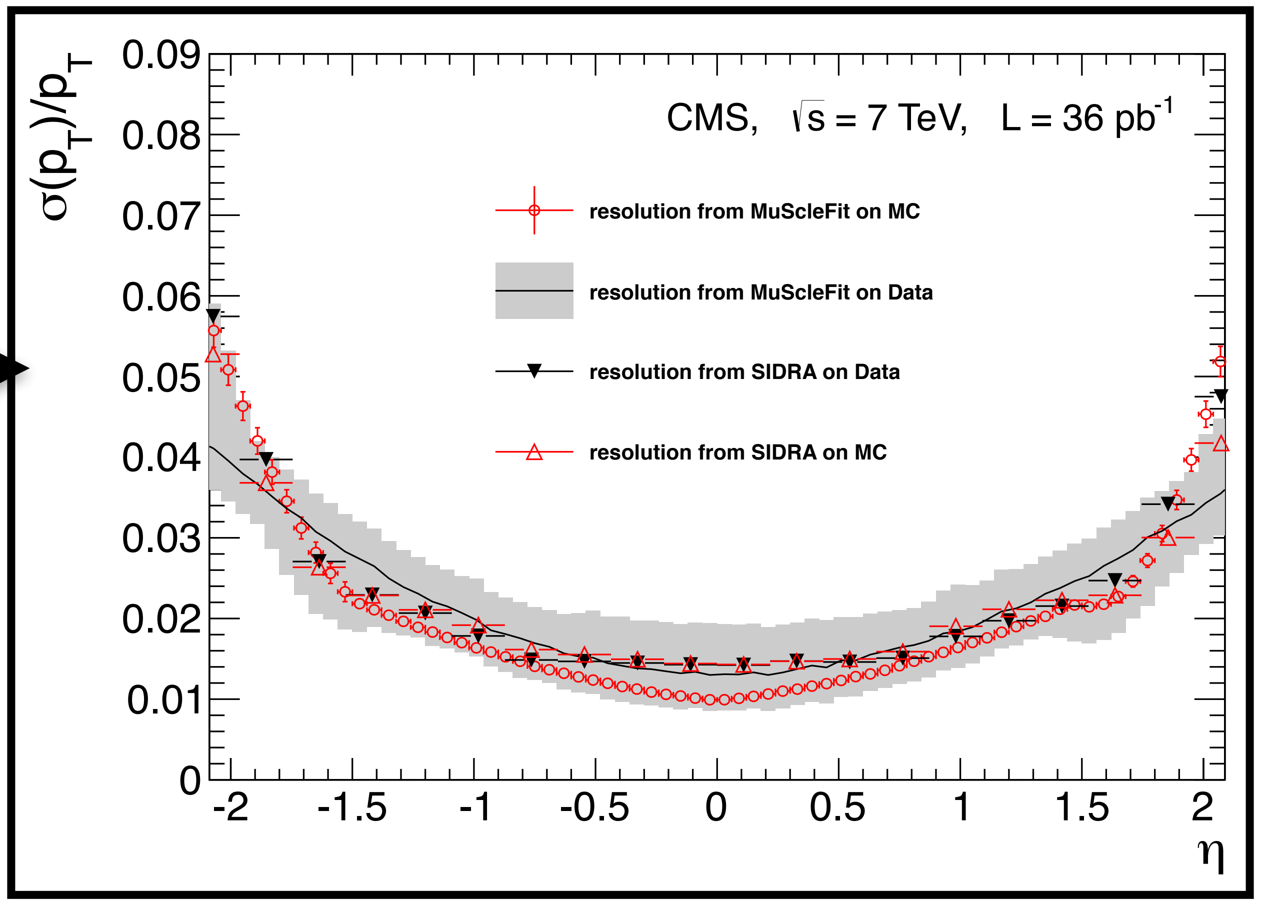
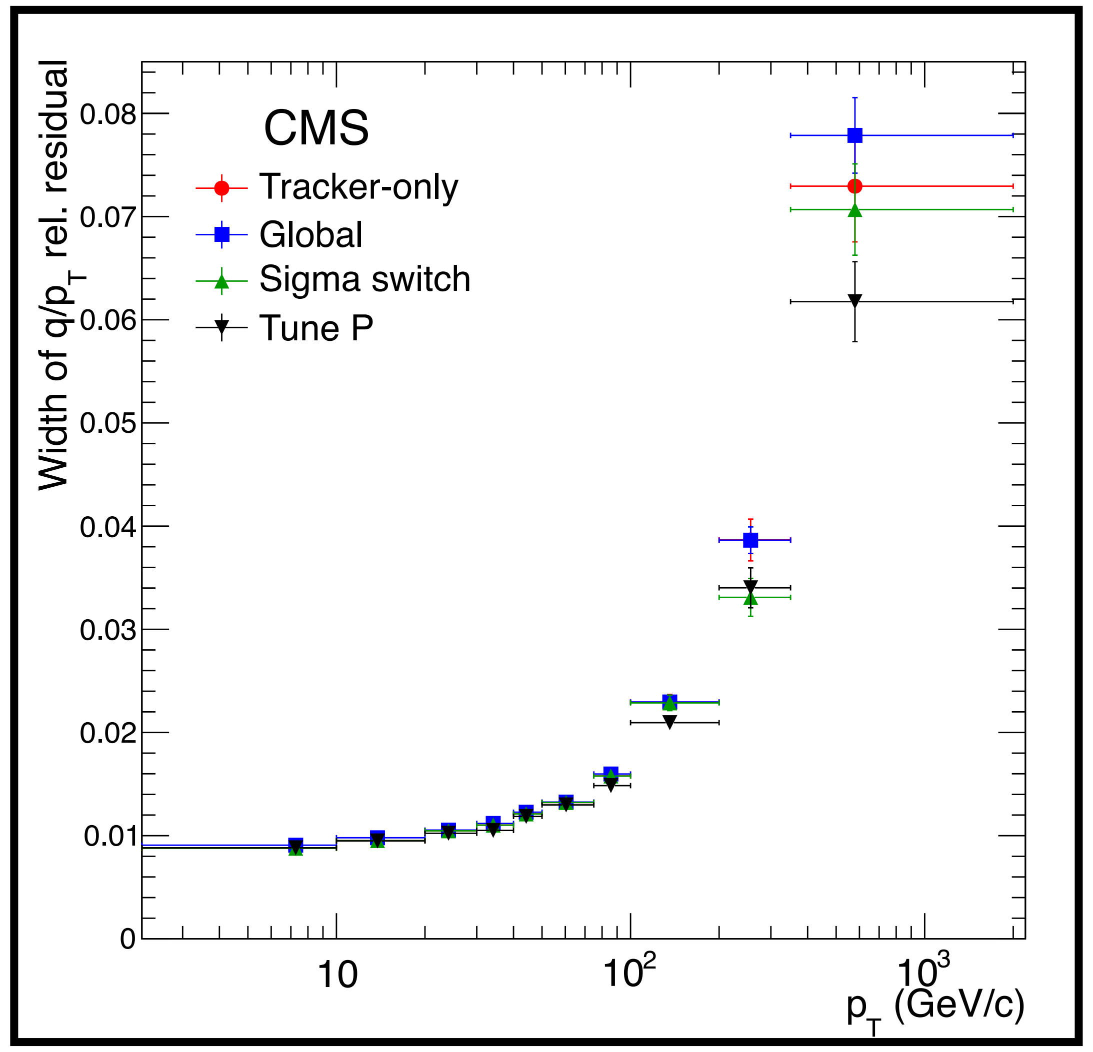
Hunting H → μμ decays

- The kinematics of the Higgs boson is fully accessible in H(μμ) decays
- Muon p_T can be measured with O(1%) resolution

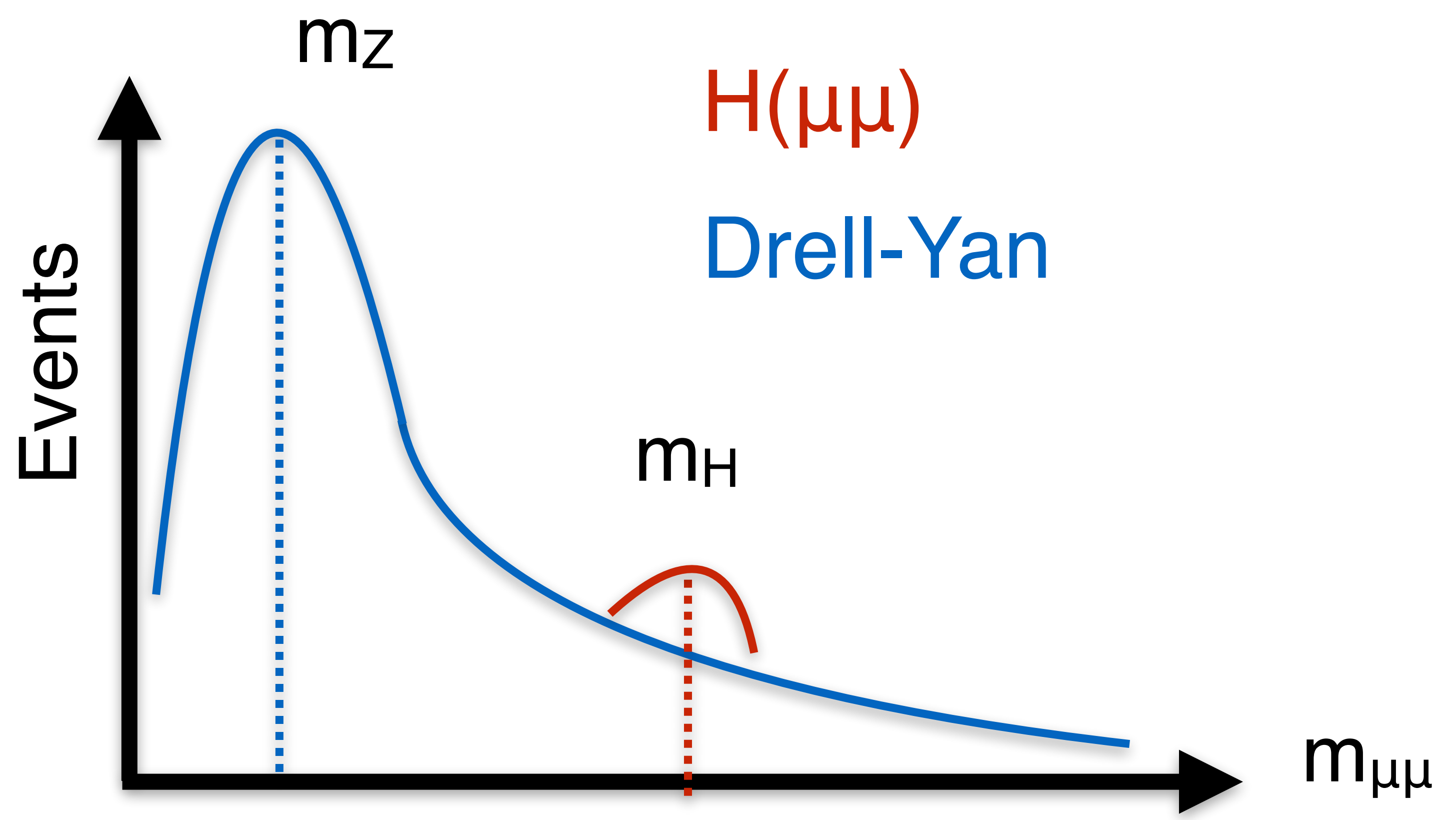
We can exploit the sharp $m_{\mu\mu}$ peak, resonant ~ 125 GeV, expected for H(μμ) decays





However, it is challenging to observe this peak @125 GeV

- σ(H) @ 13 TeV is 50 pb, BR H(μμ) is 2×10^{-4} → 1500 events expected
- Irreducible background from Z/γ→μμ with effective σ ~15 pb
- Inclusive S/B ratio in the $[10^{-3},10^{-2}]$ range



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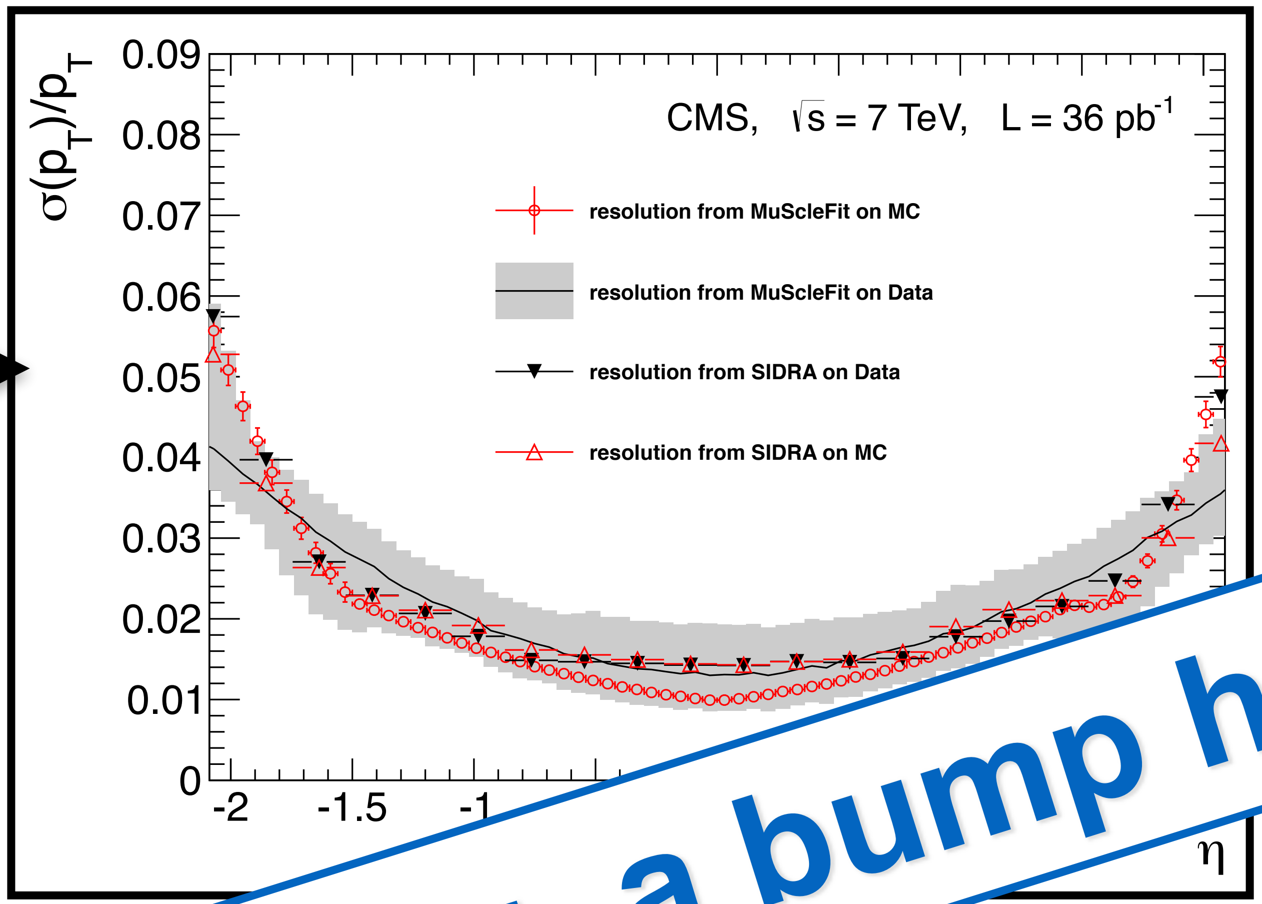

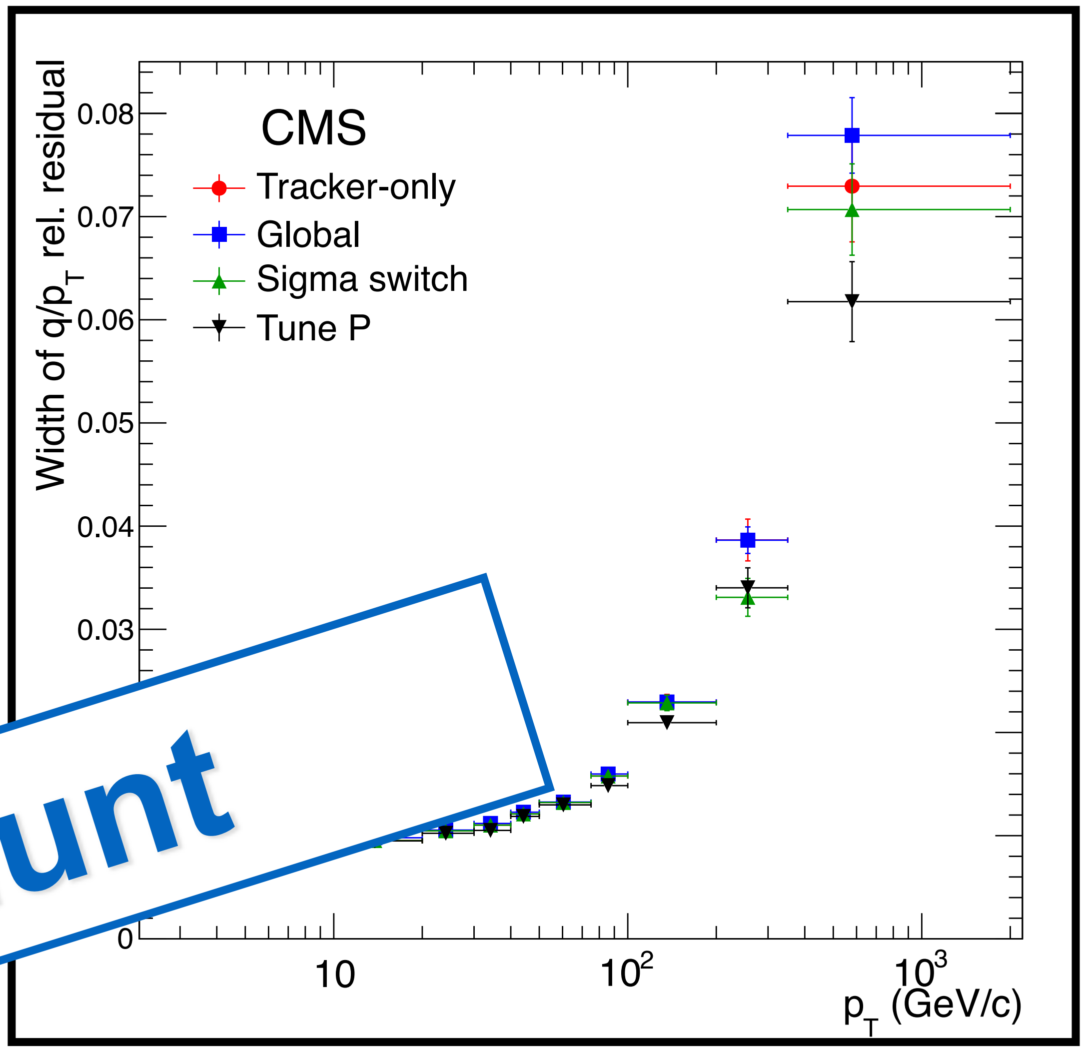

H→μμ is, broadly speaking, a bump hunt

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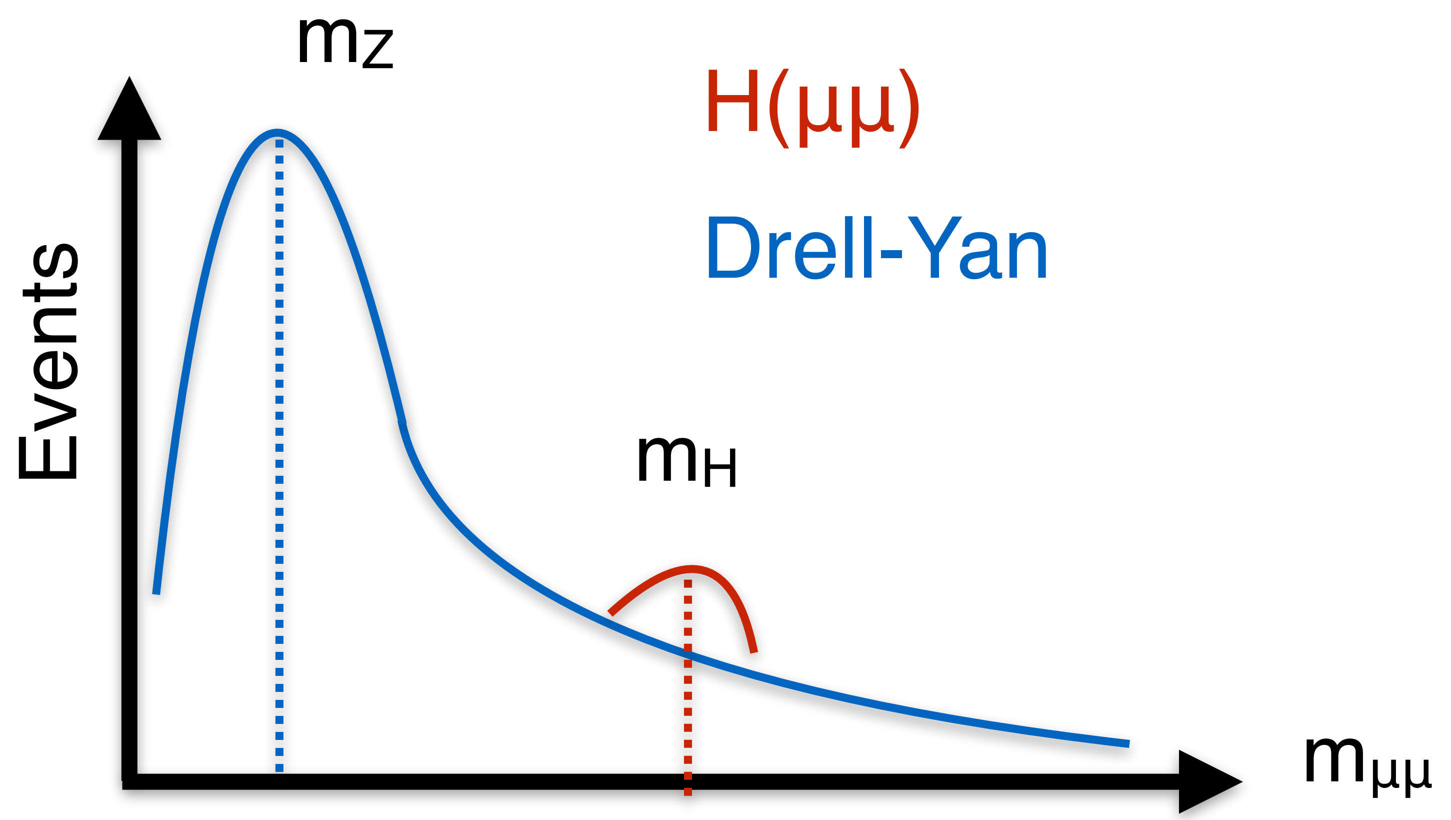


H(μμ) candidate selection

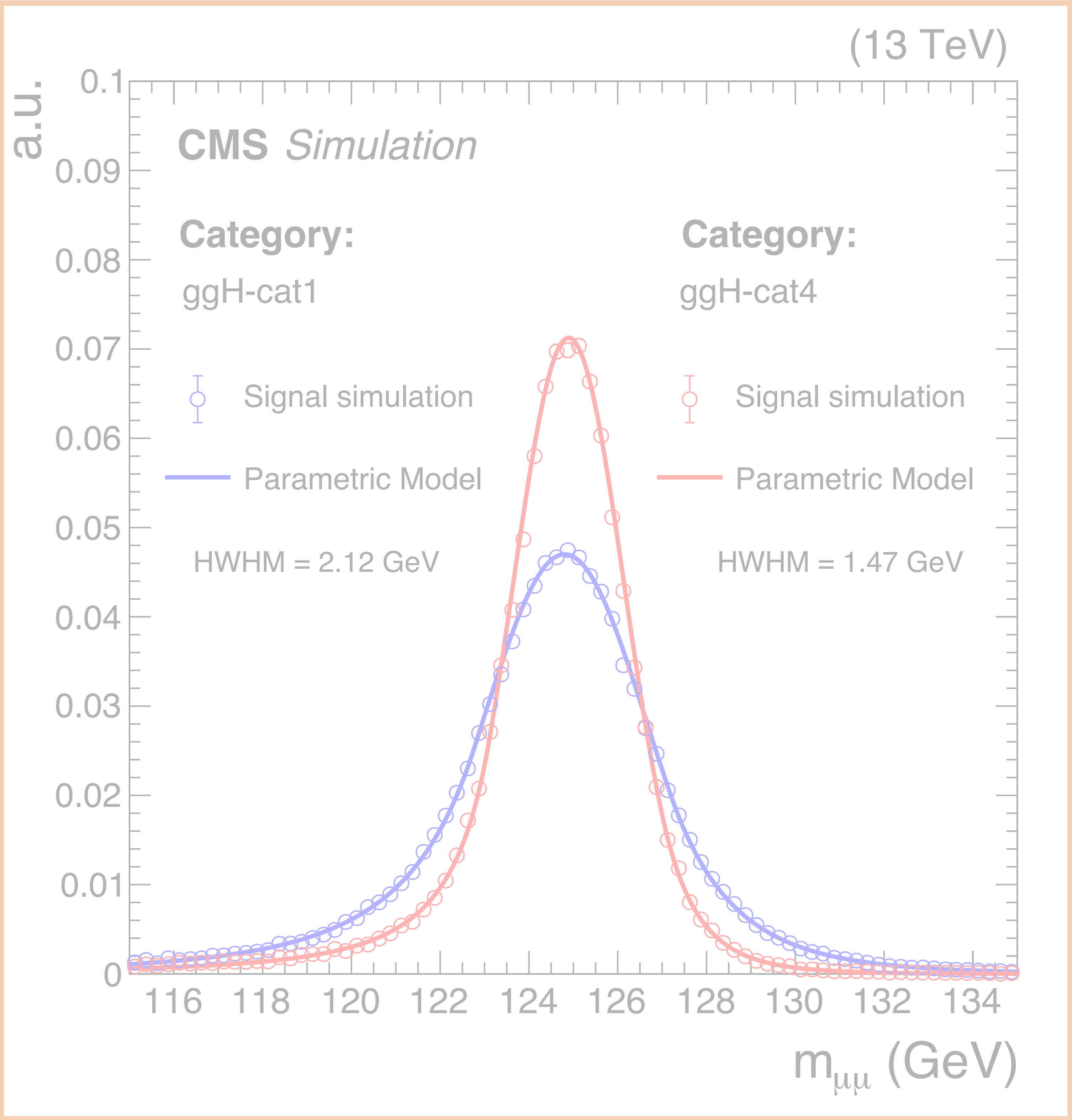
Baseline selection

- Events are collected online via ***single-muon triggers***
- Require ***at least two muons*** with $p_T > 20$ GeV, $|\eta| < 2.4$
  - Trigger efficiency is ~93% per muon
- Muons required to be ***identified*** and ***isolated*** → ~95% efficiency
- Muons must have ***opposite charge*** and ***$m_{\mu\mu}$ [110,150] GeV***

Signal events characterised by ***sharp peak*** at ***125 GeV***
$m_{\mu\mu}$ resolution plays a ***crucial role*** in the ***final sensitivity***

- **Recovery of final state photon radiation:** 3% gain in resolution
- ***Improvements in mass resolution ~5%*** by ***constraining*** the muon ***tracks*** to ***pass*** from the ***position of the interaction point***

Higgs signal peak in MC



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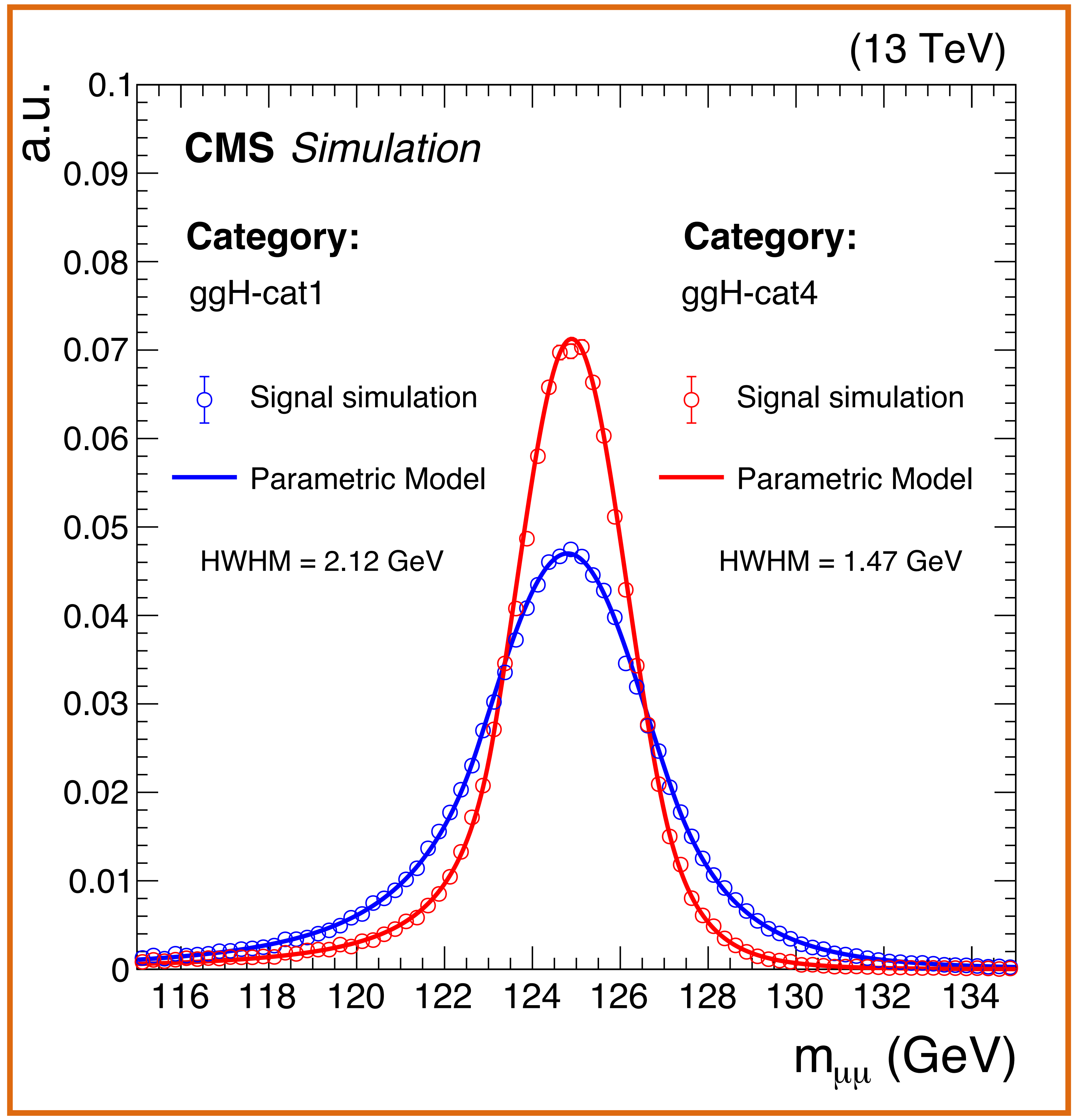

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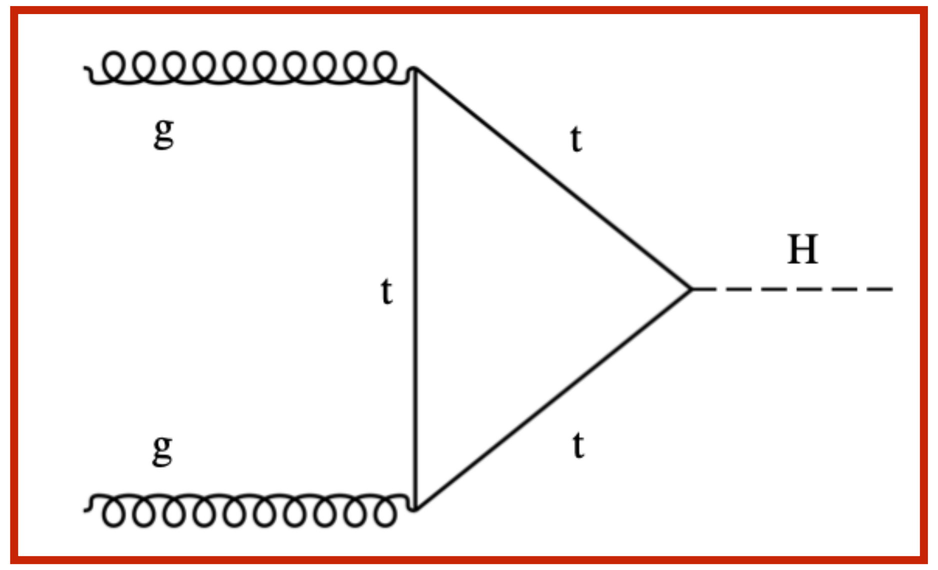
Higgs boson production modes

In order to ***maximise the sensitivity***, the ***H→μμ result combines exclusive analyses targeting*** the ***main Higgs boson production modes*** at the LHC

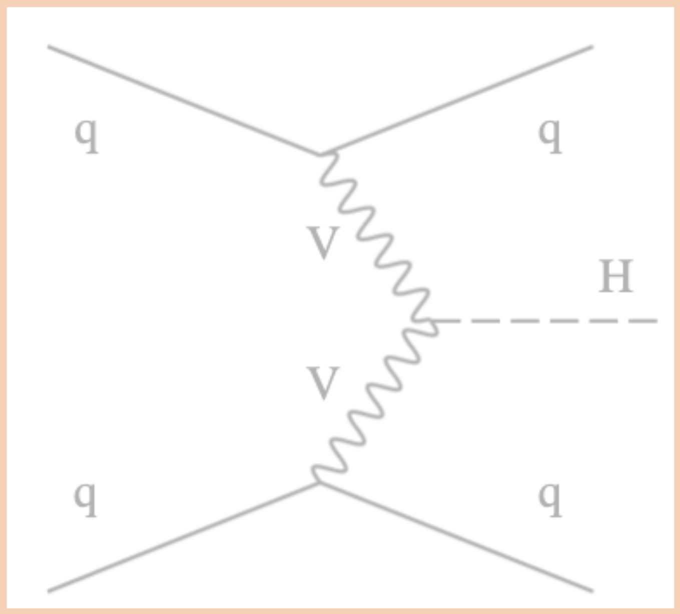
Cross Section (pb)

Gluon fusion (ggH)



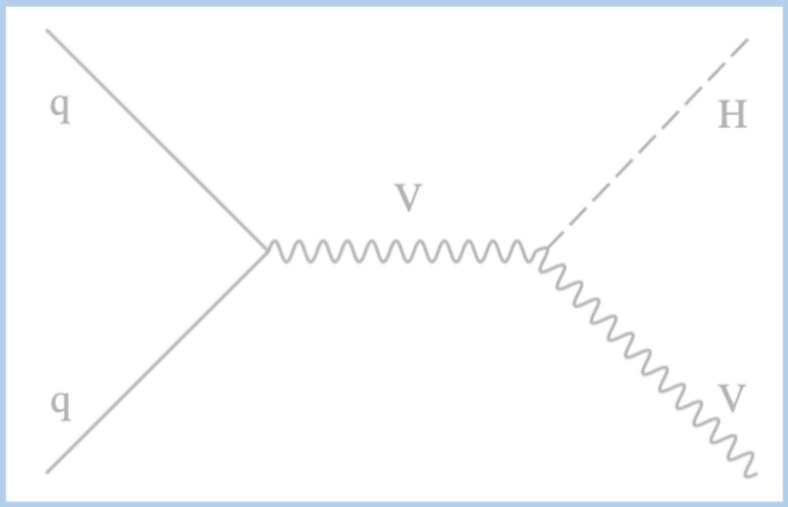
- ***87%*** of σ(H)
- Accessible for H(μμ)
- Hardly accessible for H(cc) for trigger limitations

Vector Boson Fusion (VBF)



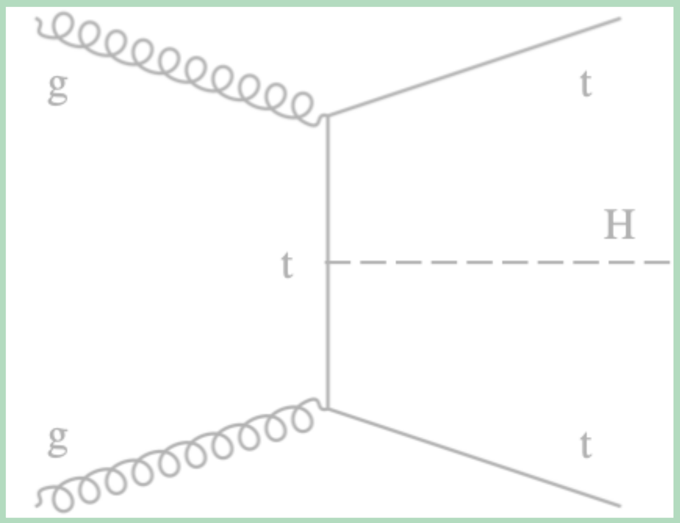
- ***7%*** of σ(H)
- VBF-jets properties: high m(jj) and Δη(jj)
- Hardly accessible in H(cc)

VH mode



- ***4%*** of σ(H)
- Hadronic W/Z decays lead to signatures similar to ggH+jets
- Leptonic modes accessed can be used for H(cc) and H(μμ)

ttH mode



- ***1%*** of σ(H)
- Additional jets, b-jets, and leptons from top decays offer topologies with high signal purity

Purity S/(S+B)

**** Rule of thumb: richer final state topology → better purity*

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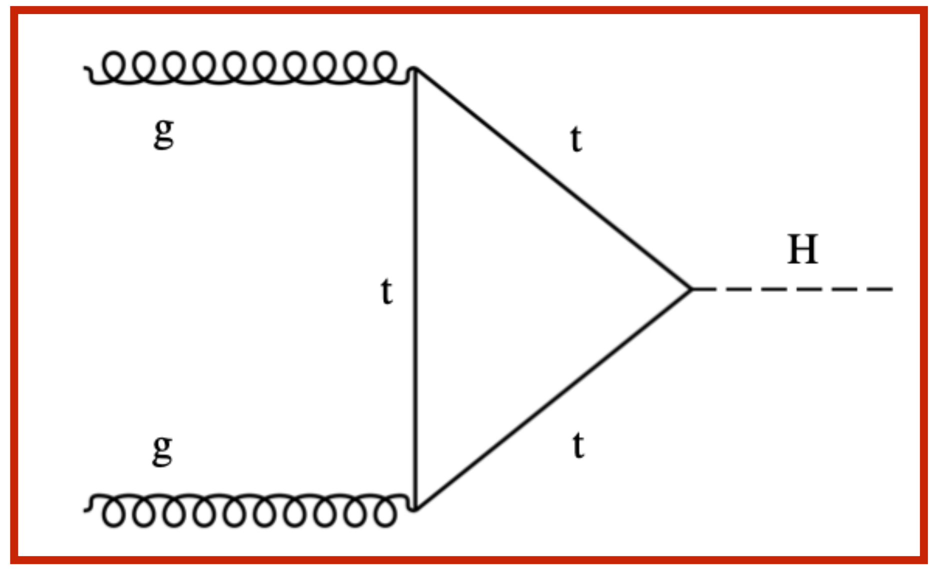

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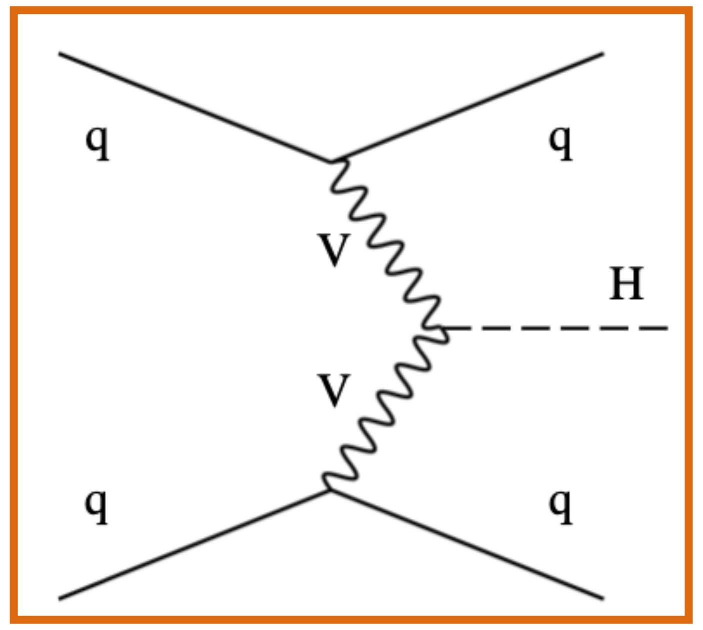

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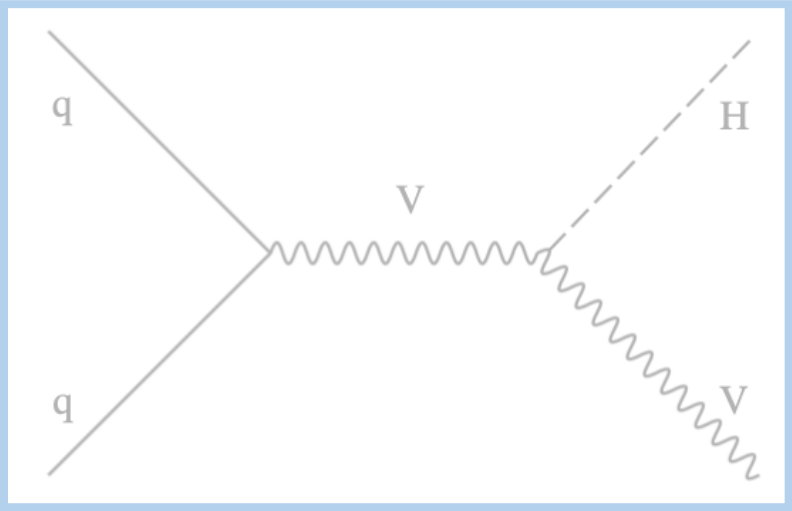

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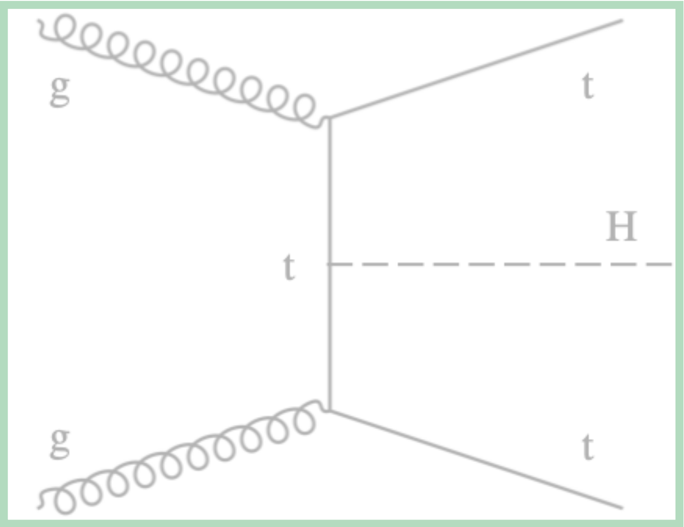

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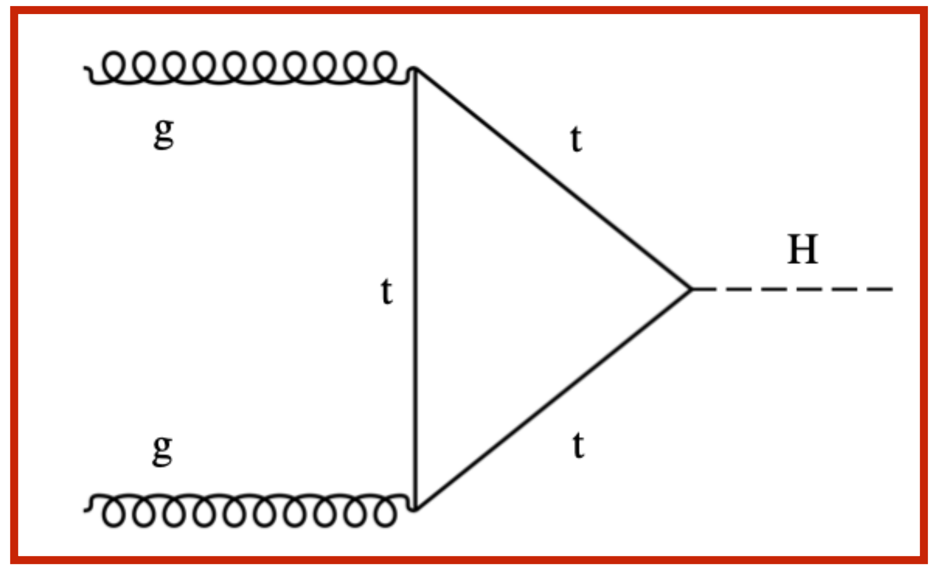

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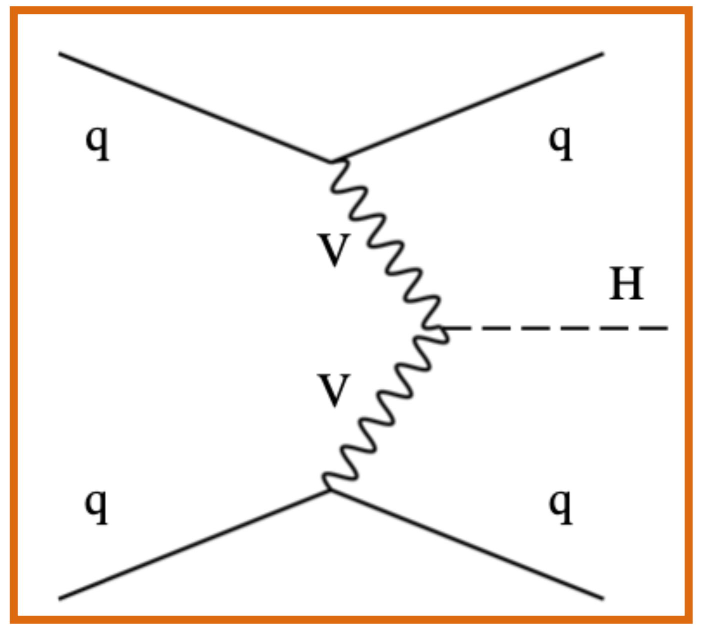

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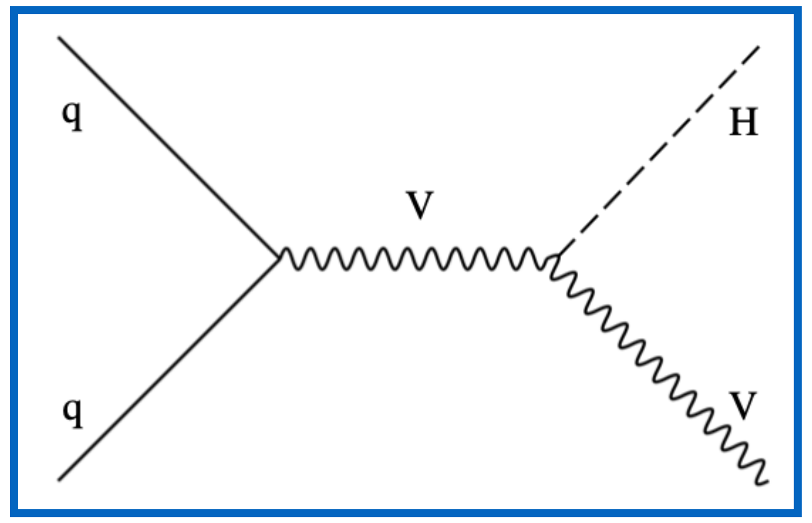

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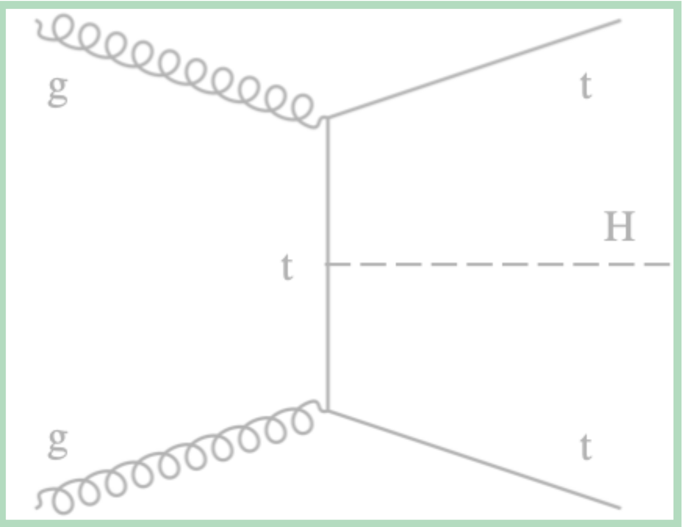

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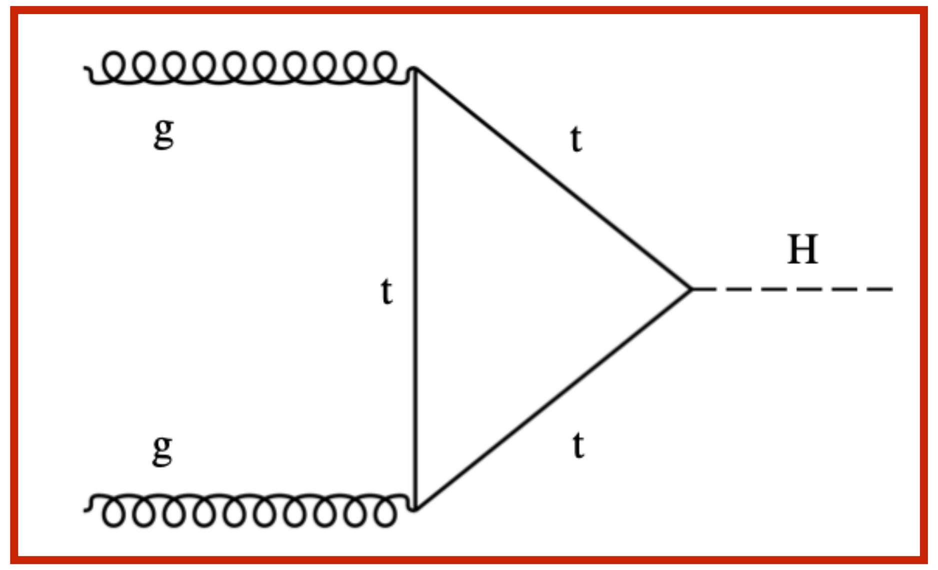

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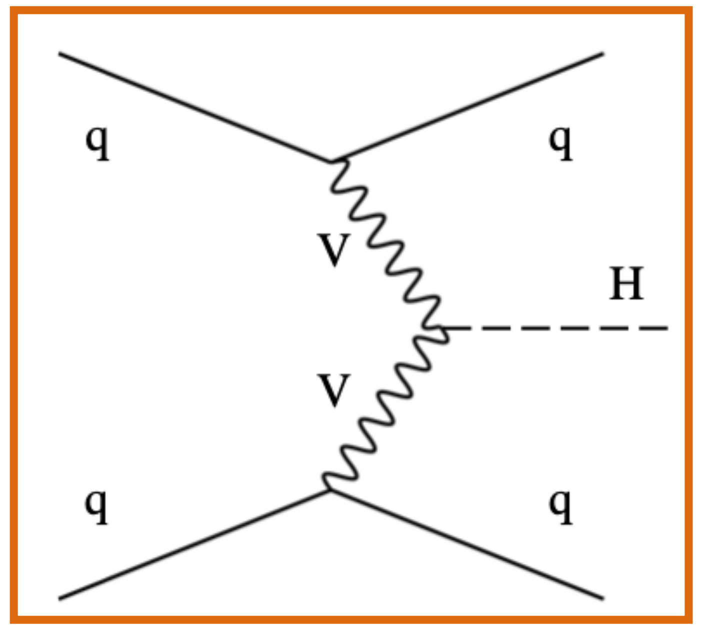

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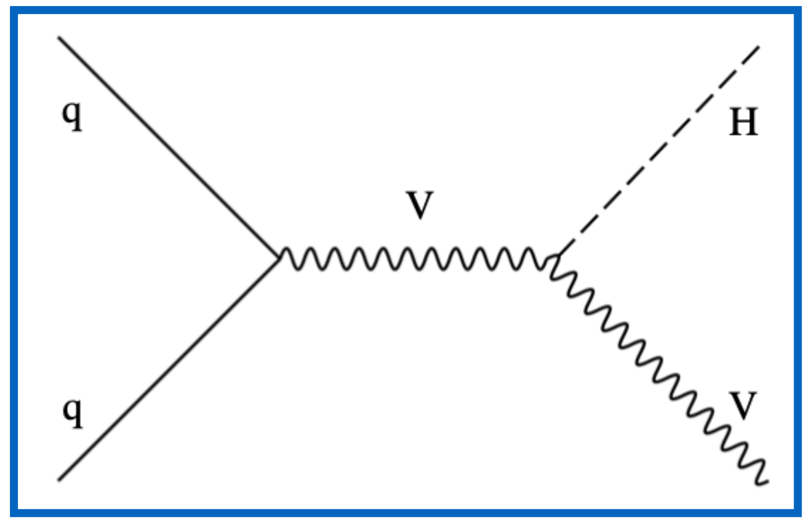
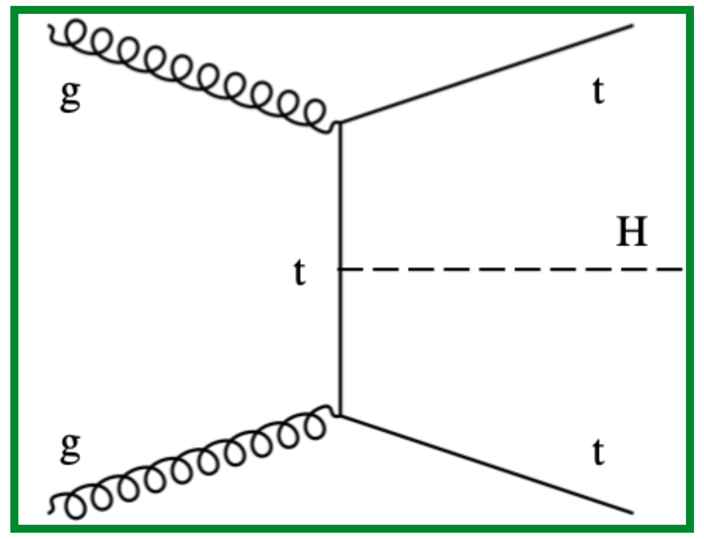


- **4%** of σ(H)
- Hadronic W/Z decays lead to signatures similar to ggH+jets
- Leptonic modes accessed can be used for H(cc) and H(μμ)

ttH mode

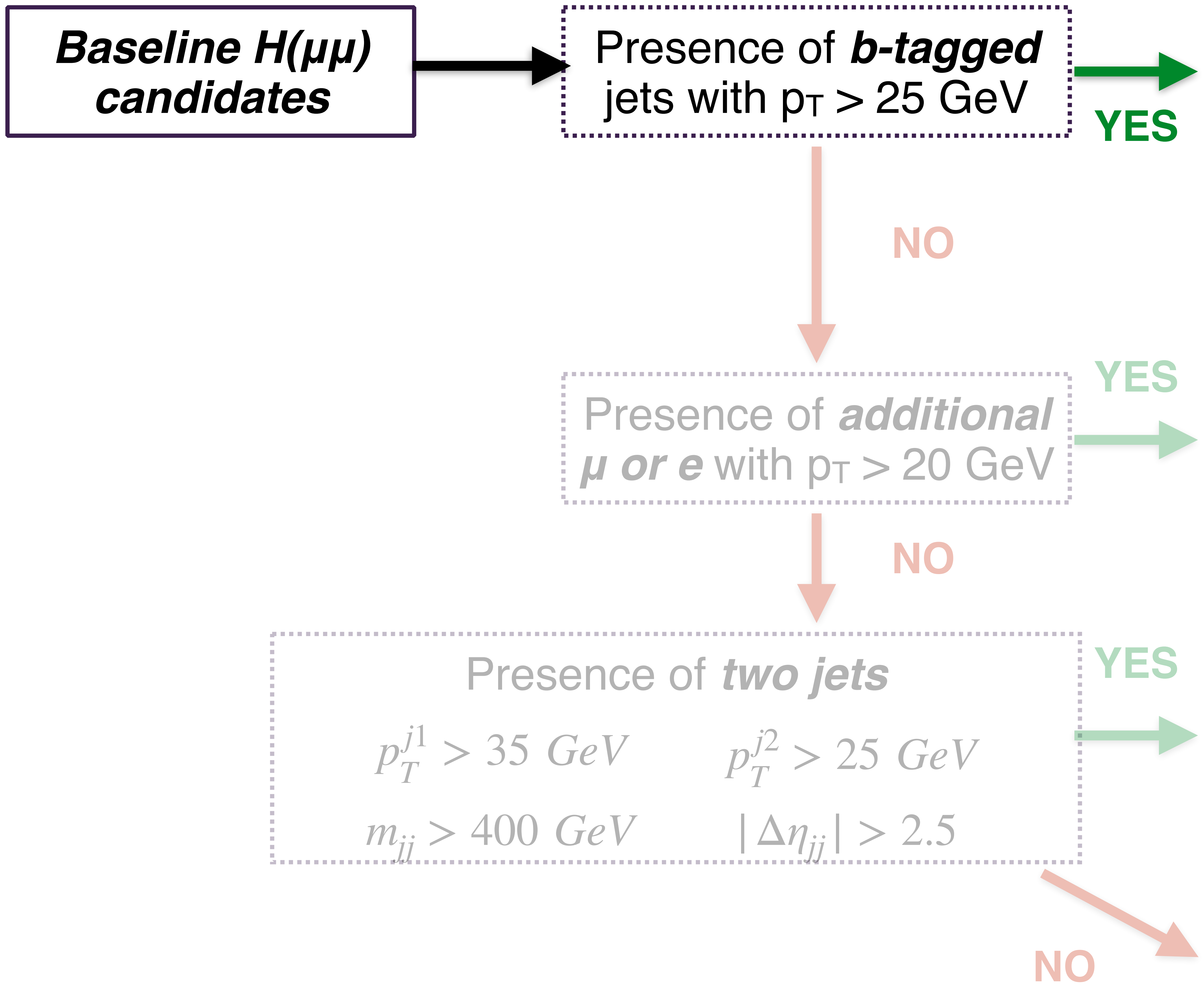


- **1%** of σ(H)
- Additional jets, b-jets, and leptons from top decays offer topologies with high signal purity

**** Rule of thumb: richer final state topology → better purity*

Purity S/(S+B)

H(μμ) production categories



Baseline H(μμ) candidates

Presence of ***b-tagged*** jets with $p_T > 25$ GeV

YES

NO

Presence of ***additional μ or e*** with $p_T > 20$ GeV

YES

NO

Presence of ***two jets***

$p_T^{j1} > 35\ GeV$ $\quad p_T^{j2} > 25\ GeV$

$m_{jj} > 400\ GeV$ $\quad |\Delta\eta_{jj}| > 2.5$

YES

NO

ttH event category

- **ttH leptonic:** additional μ or e with $p_T > 20$ GeV
- **ttH hadronic:** no additional leptons, at least one jet triplet compatible with t→W(qq)b decay

VH event category

- **WH leptonic:** additional μ or e with $p_T > 20$ GeV
- **ZH leptonic:** additional μμ or ee pair with mass ~m_Z

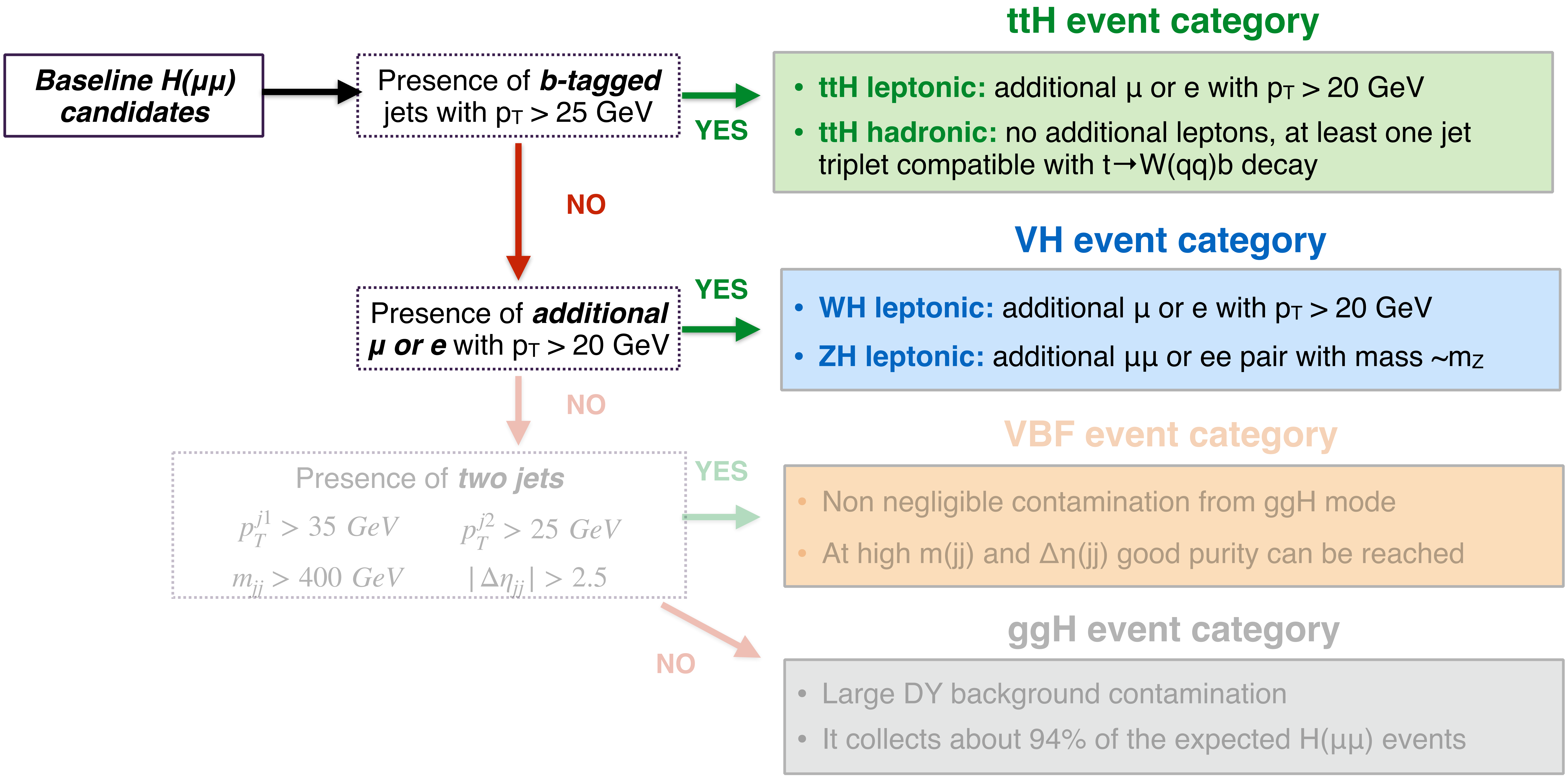
VBF event category

- Non negligible contamination from ggH mode
- At high m(jj) and Δη(jj) good purity can be reached

ggH event category

- Large DY background contamination
- It collects about 94% of the expected H(μμ) events

H(μμ) production categories



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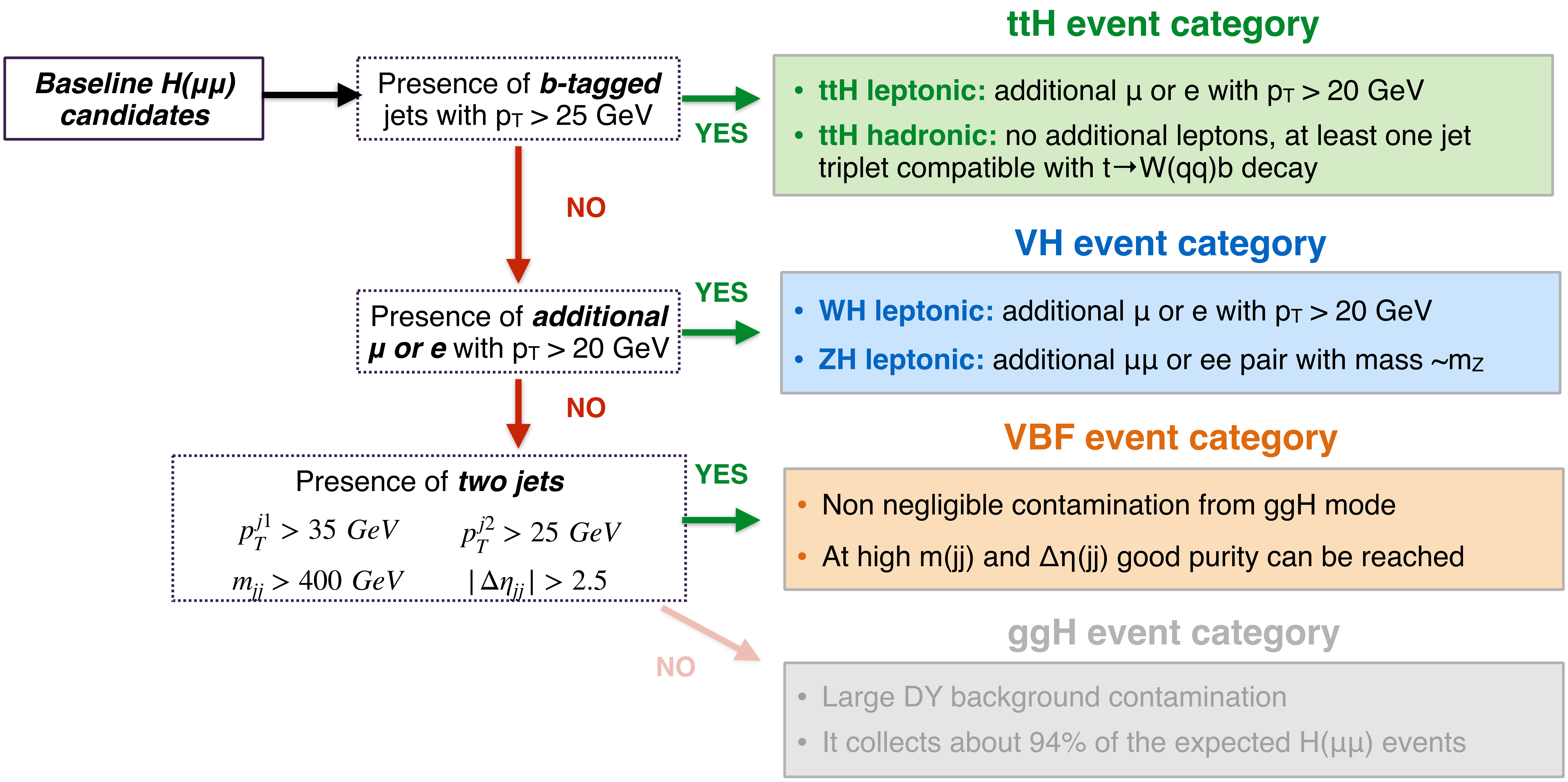

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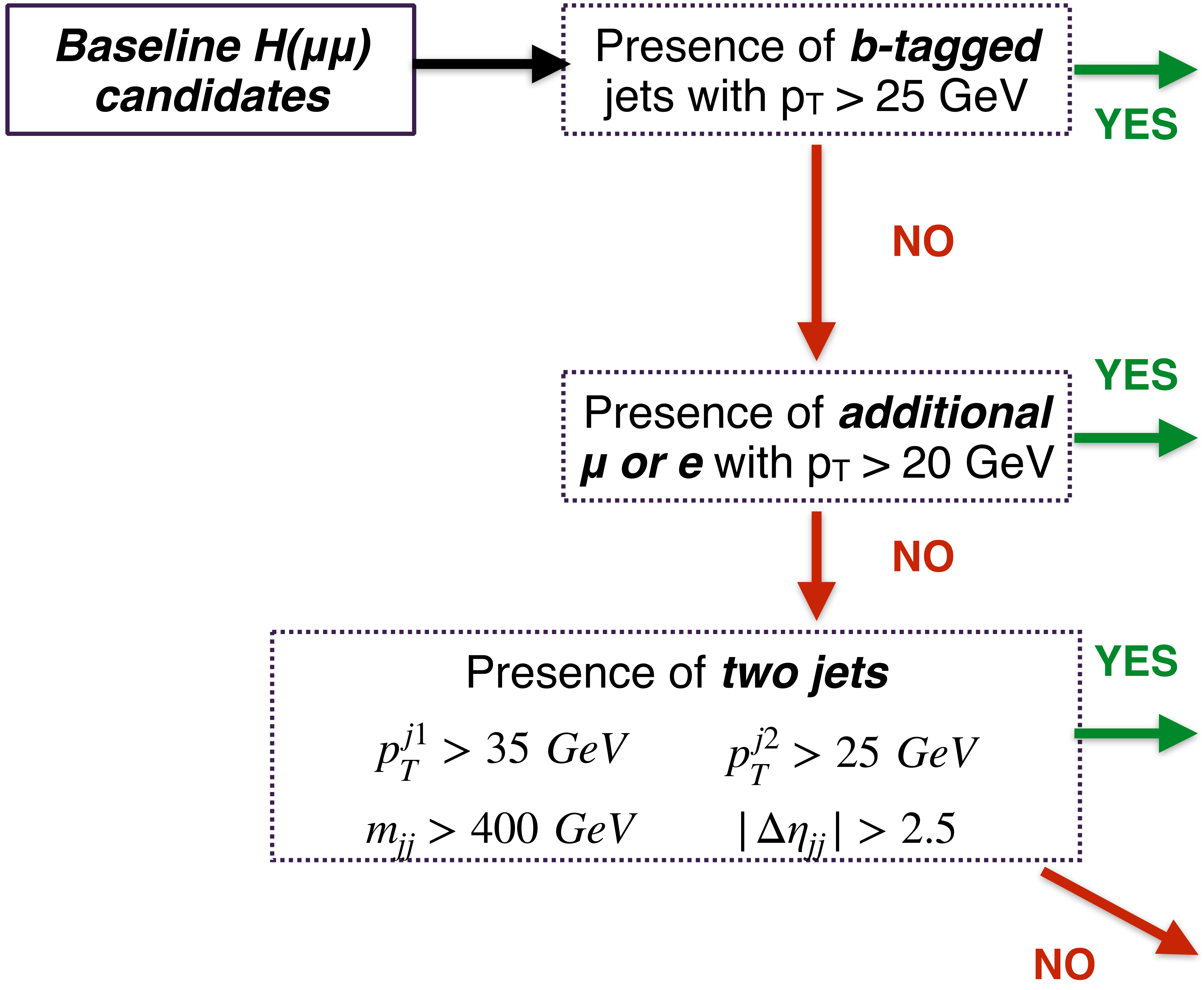

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YES

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H(μμ) production categories

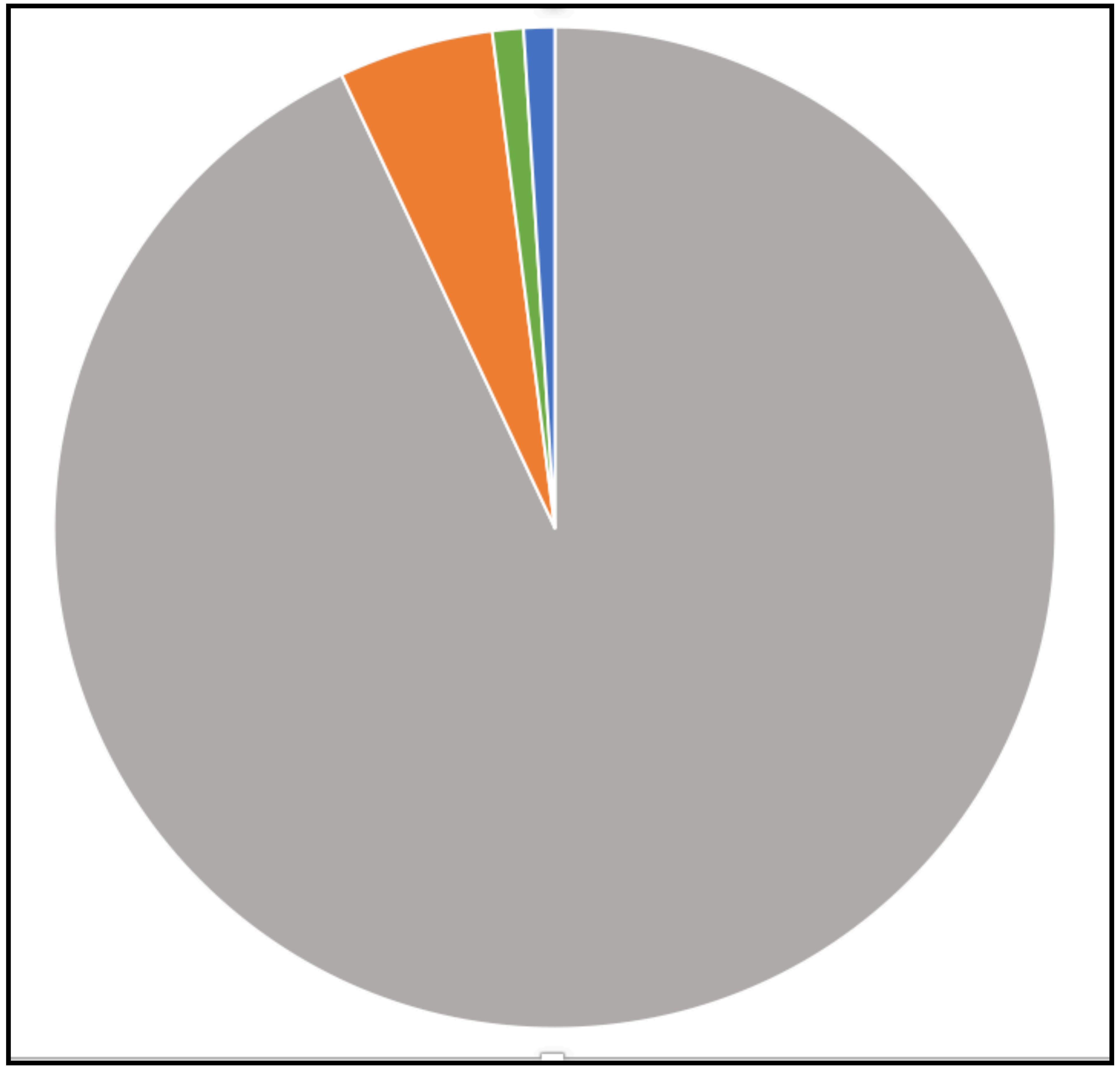
Fraction of H(μμ) expected signal events with $m_{\mu\mu}$ in the 110-150 GeV range

ggH category

VBF category

VH leptonic category

ttH category



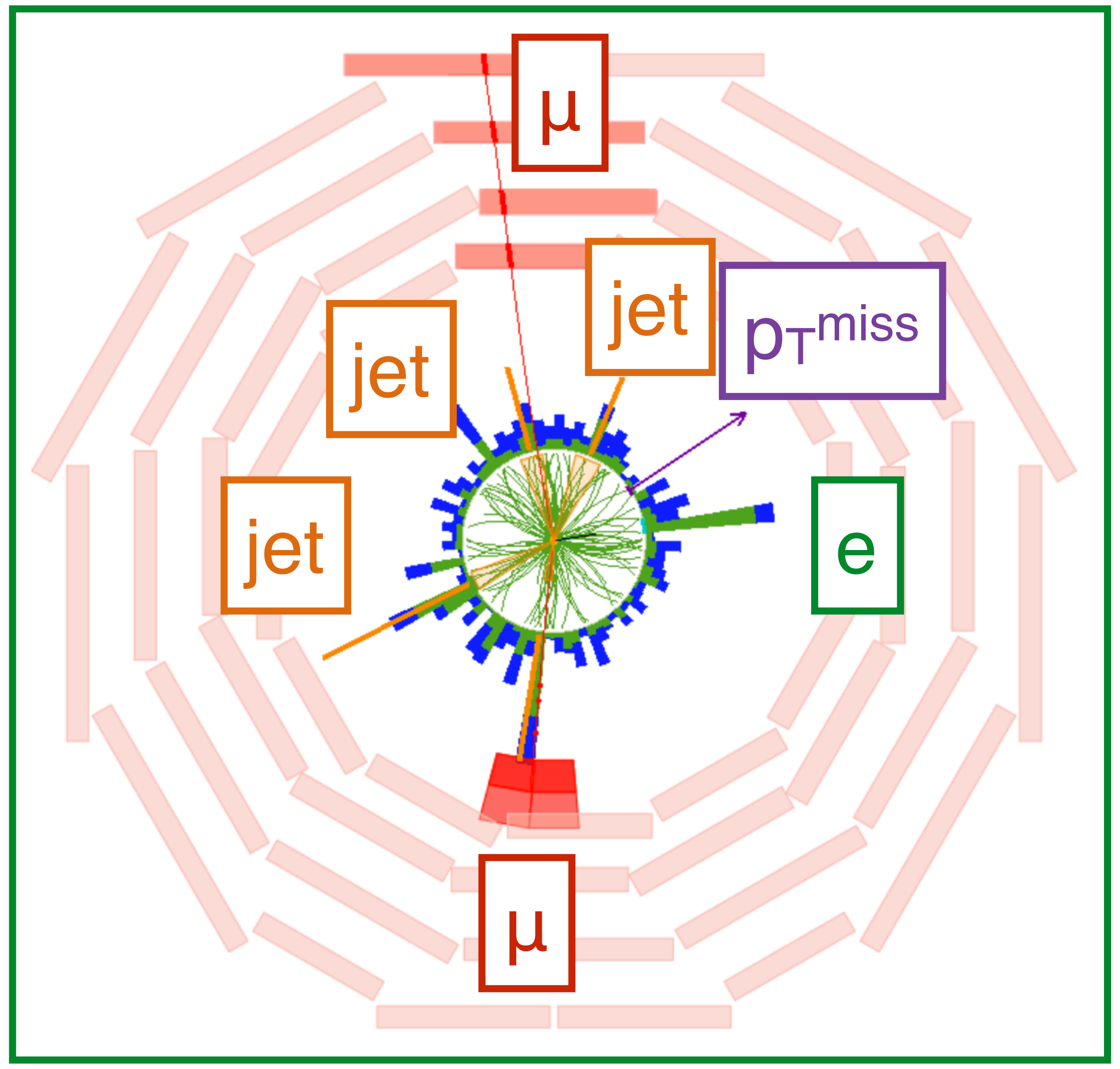
93.5% in ggH

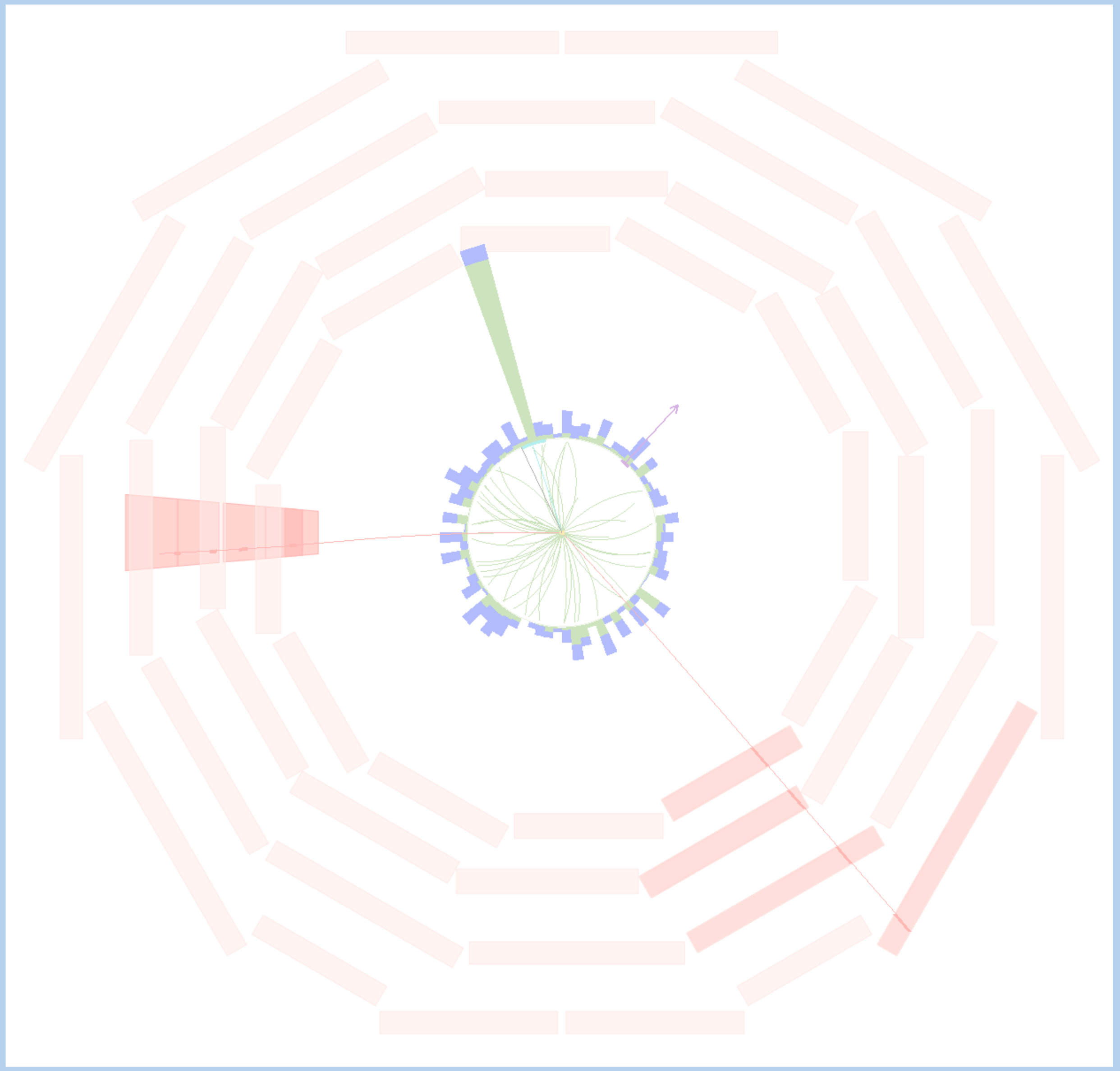
5% in VBF

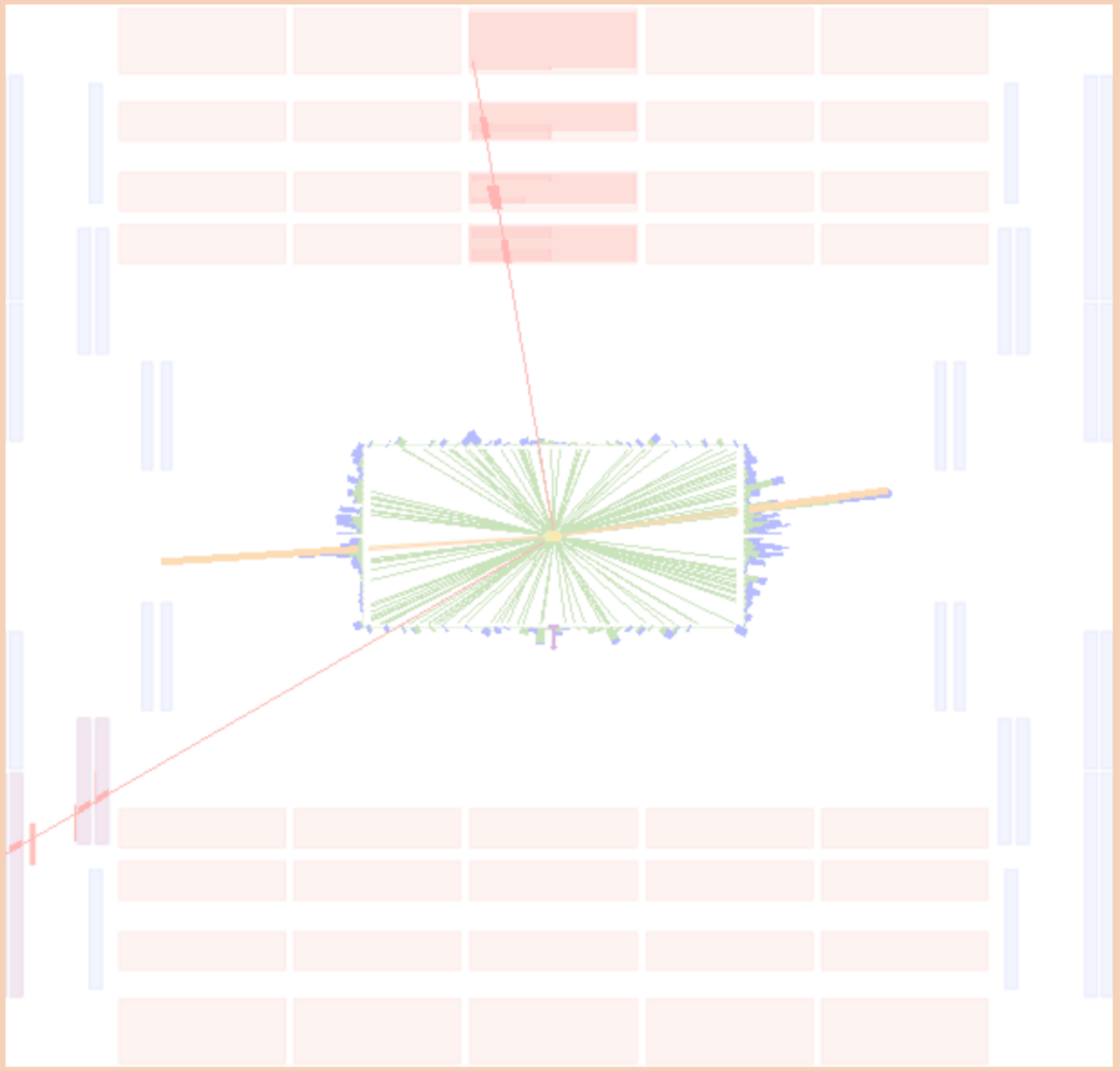
0.7% in VH

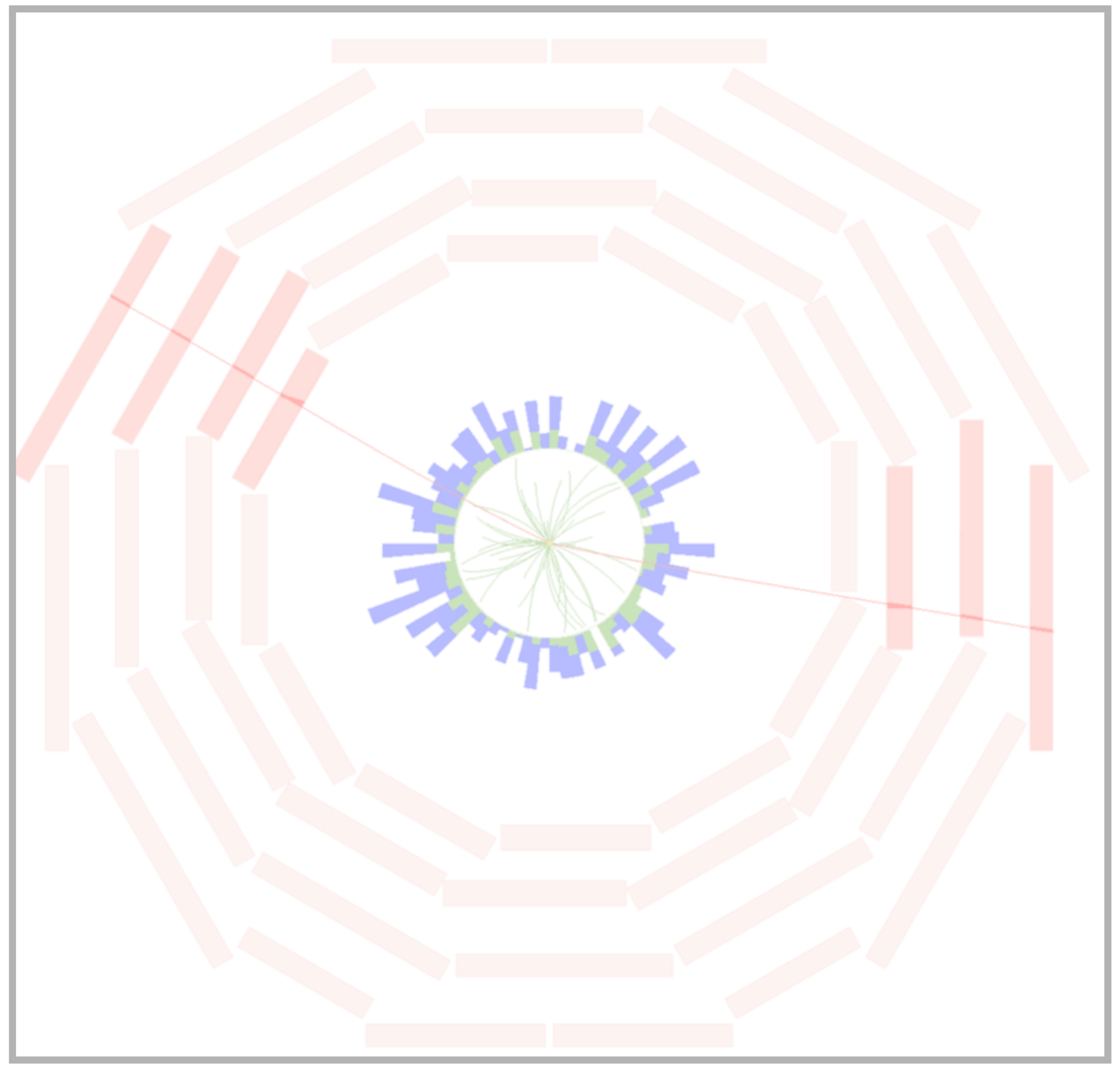
1.3% in ttH

H(μμ) event displays









- ***Crowded environment***
- One electron and p_T^{miss}
- Several jets $p_T > 25$ GeV

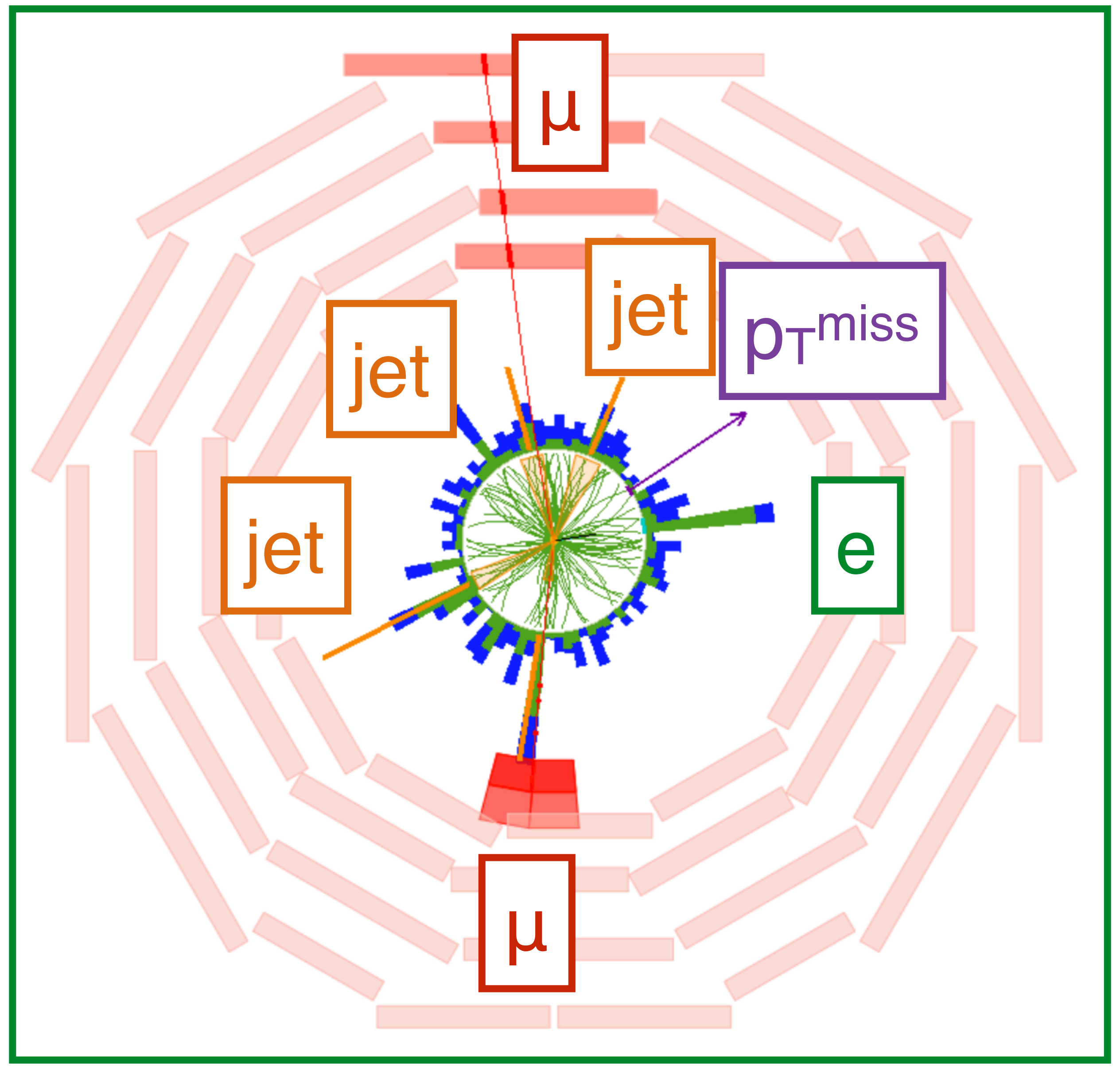
- ***One electrons and p_T^{miss}***
- Limited hadronic activity

- No other leptons in the event
- ***Two jets with VBF-like properties***

- ***Simple and clean topology***
- No significant hadronic activity

H(μμ) event displays

ttH(μμ) leptonic



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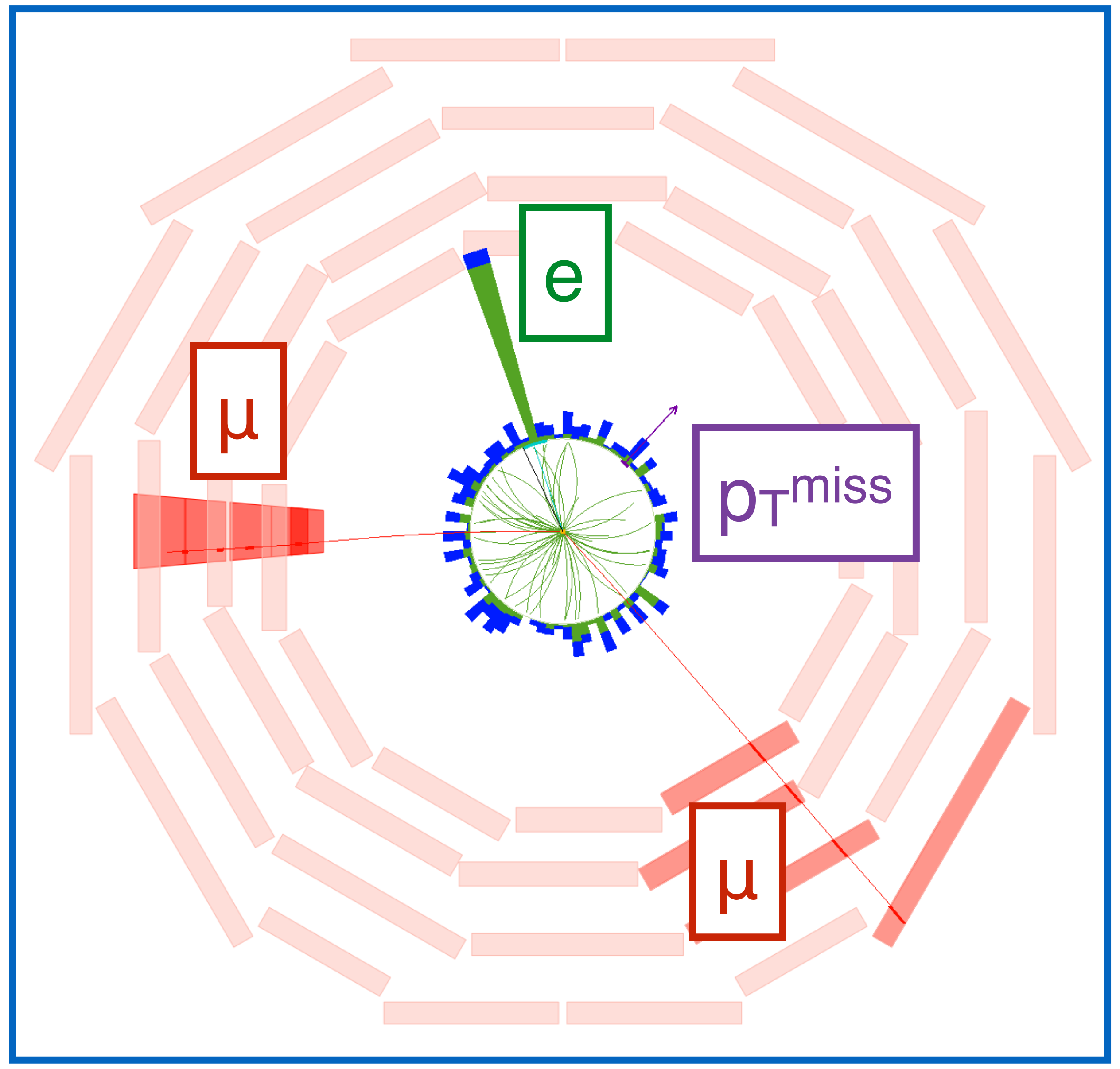
W(ev)H(μμ)



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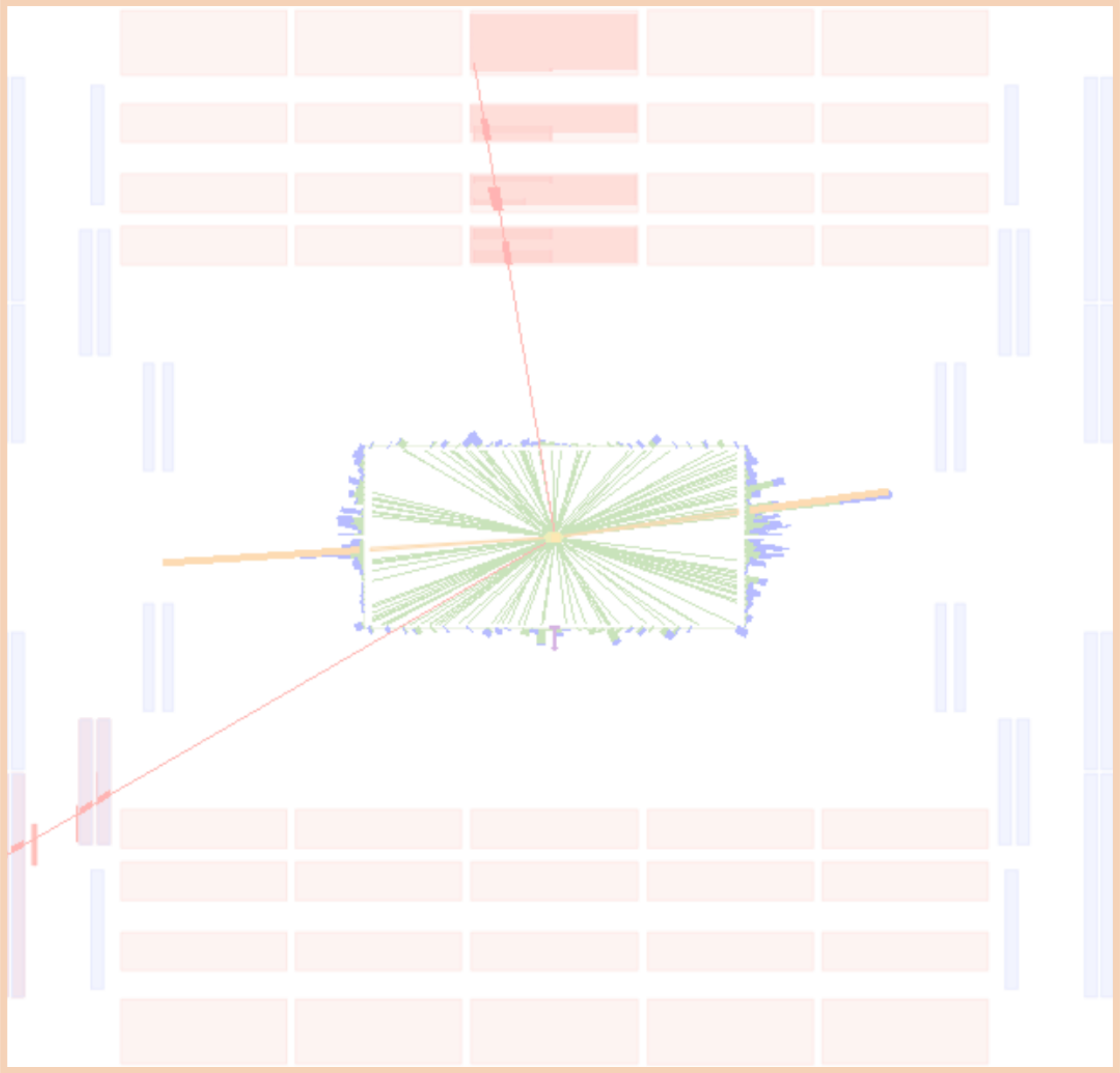
VBF H(μμ)



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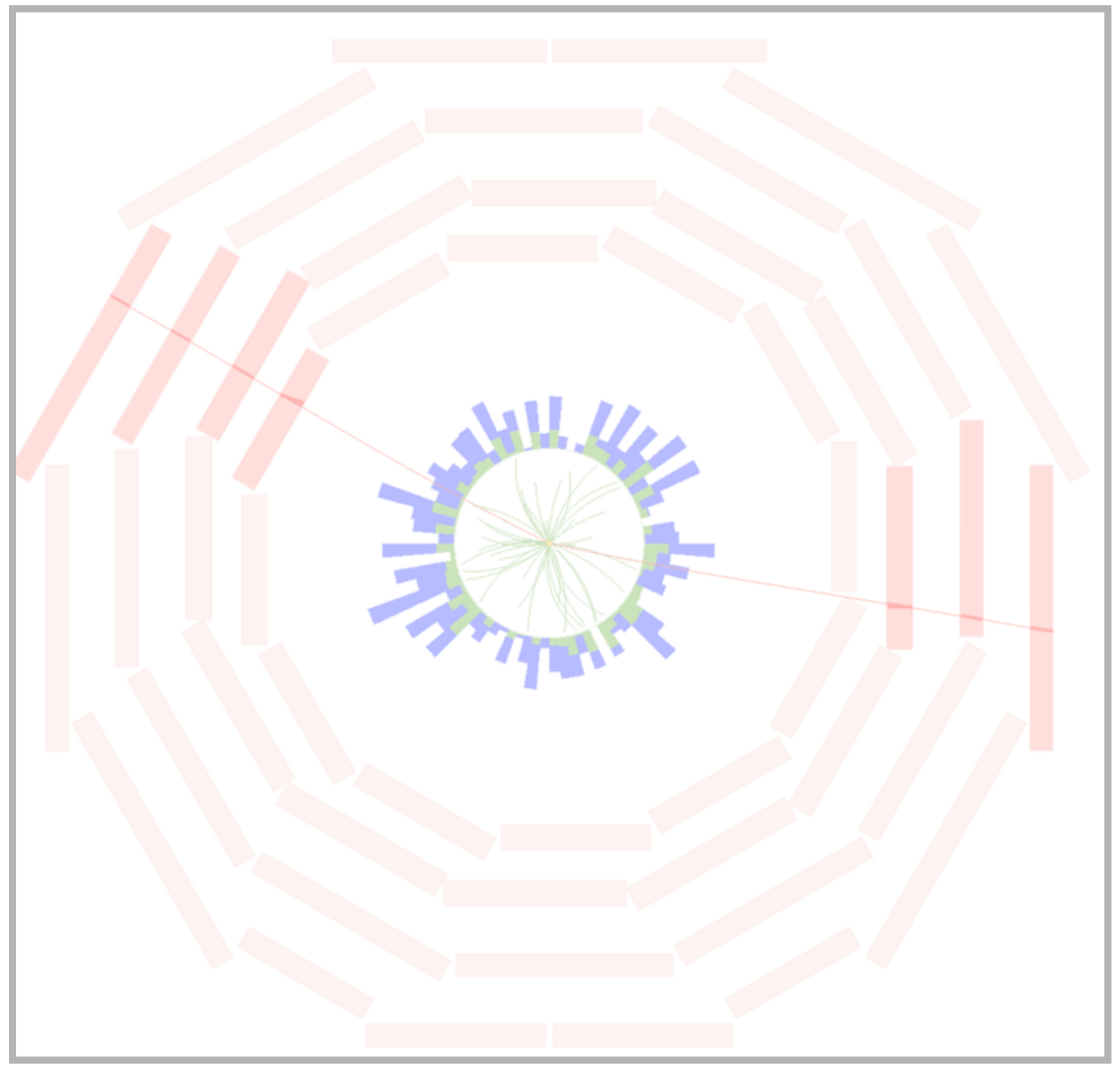
ggH(μμ)



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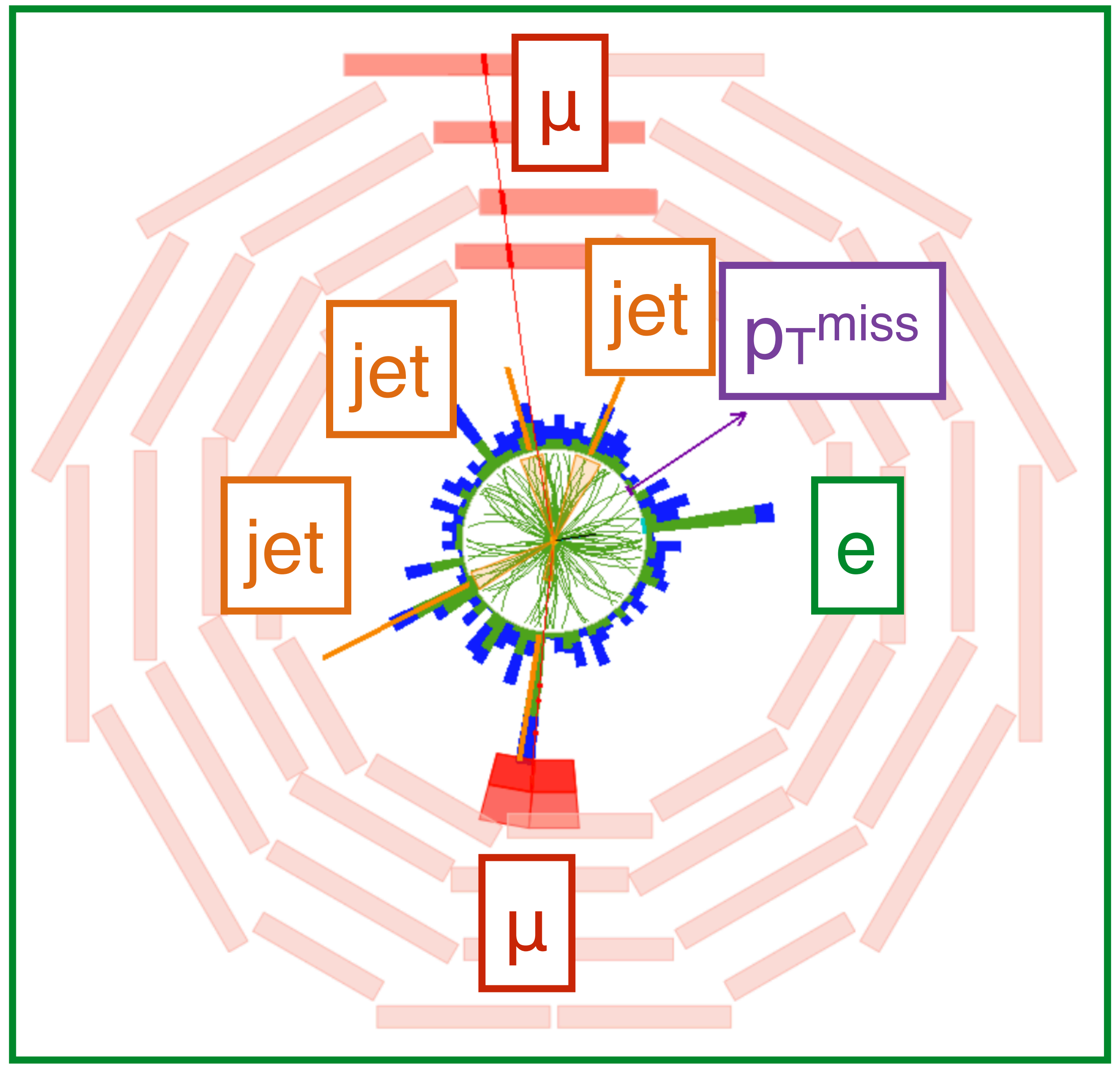

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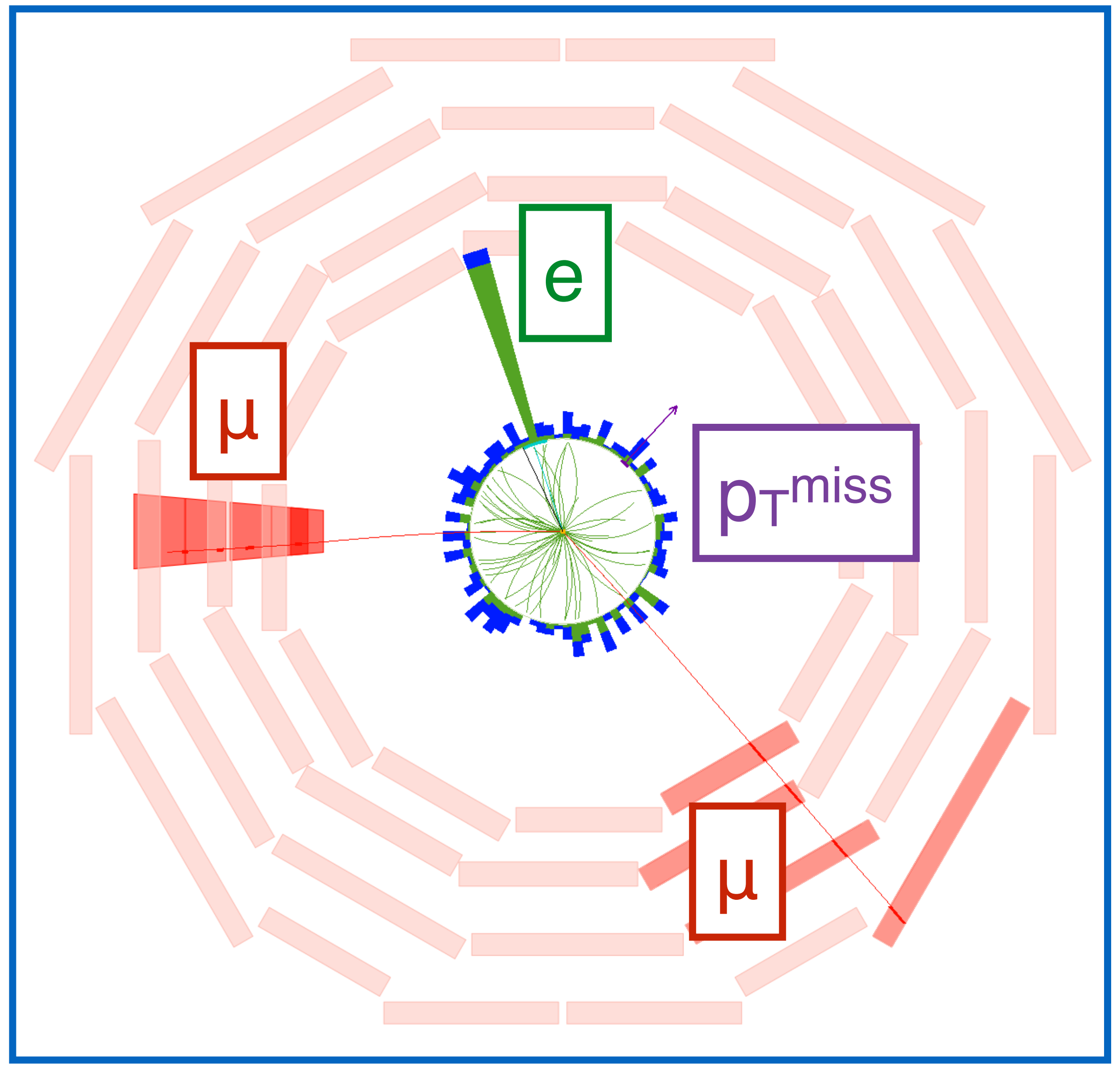

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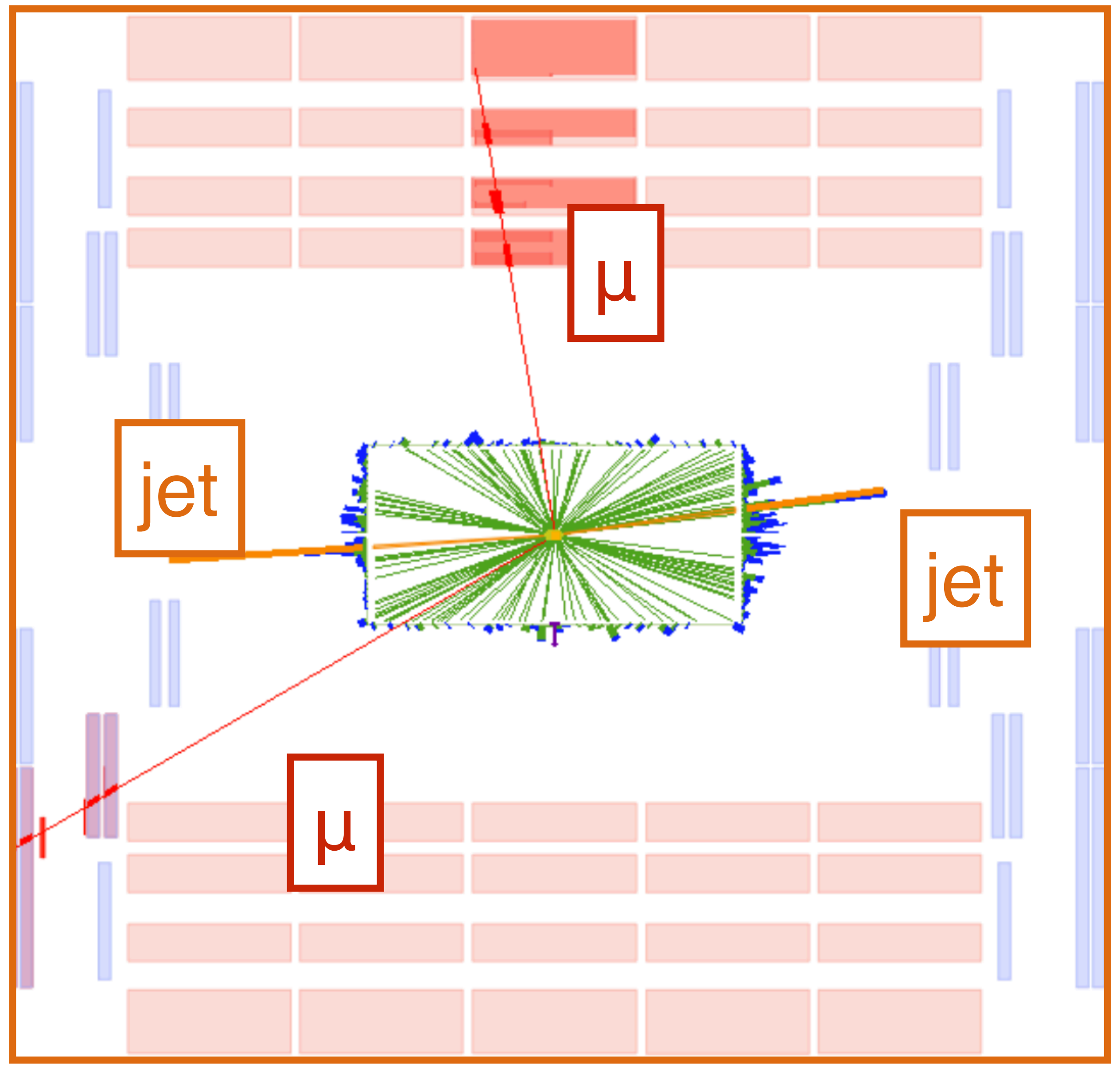

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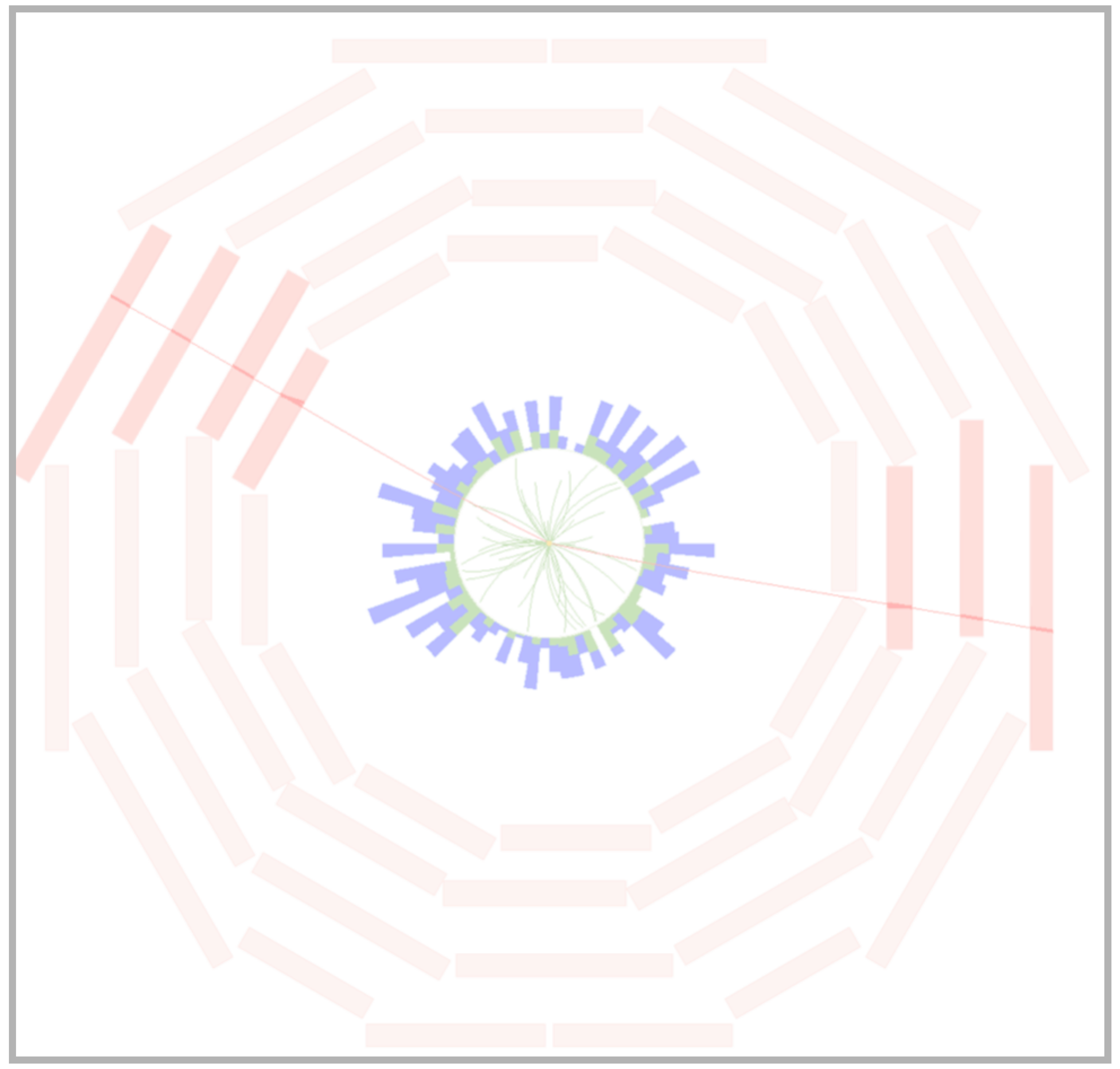

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H→μμ search in a nutshell

The so-called ***"divide-n-fit"*** *is the common* ***strategy*** *used in* ***bump hunts*** *to* ***increase*** *the* ***sensitivity***

MVA training

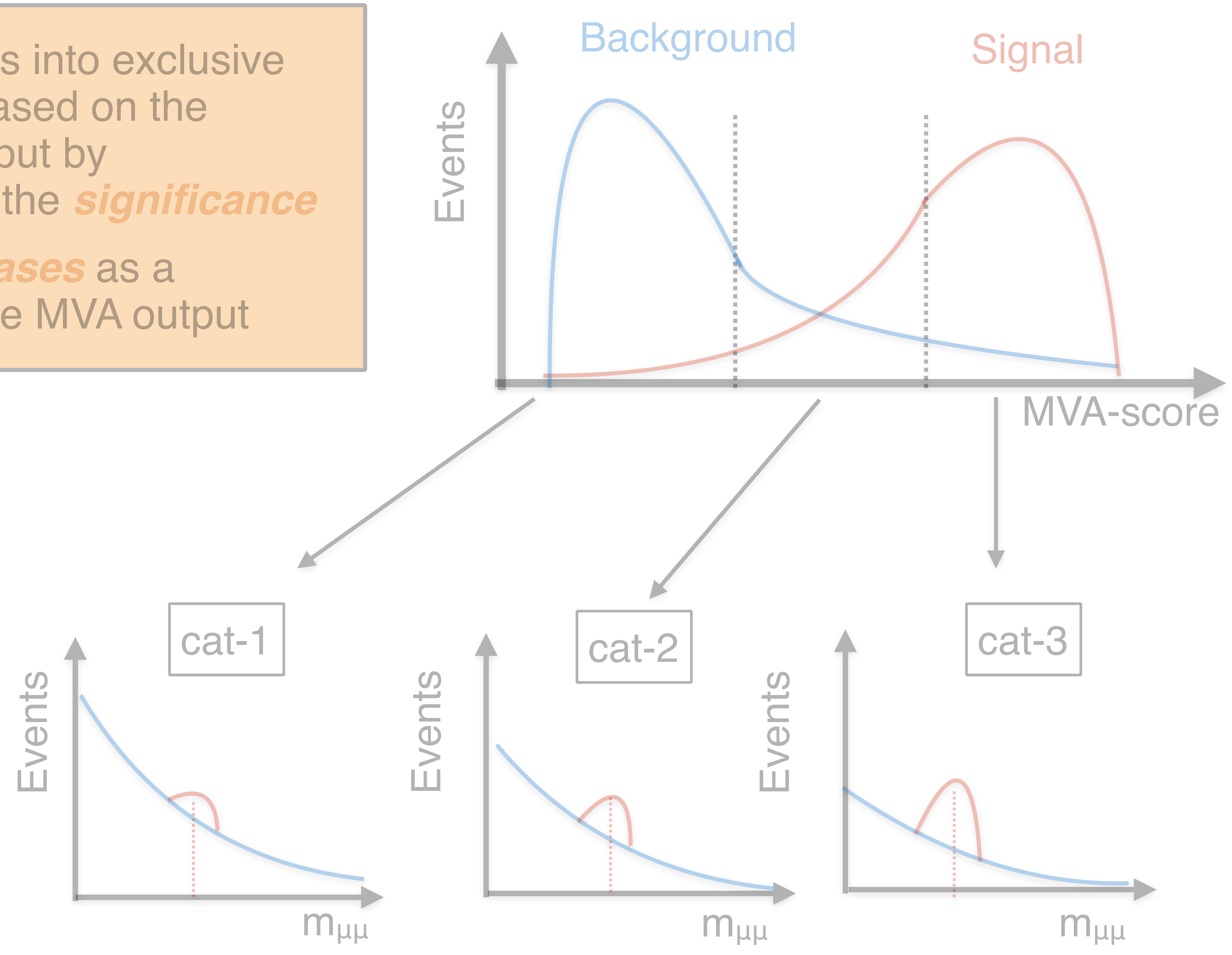
- ***Train*** a MVA classifier to separate signal from backgrounds
- Exploit full ***kinematics*** of the event apart from the **$m_{\mu\mu}$**
- Input features ***uncorrelated with $m_{\mu\mu}$***
- ***Signal*** events ***weighted by σ_m/m*** in the training to assign to ***high resolution*** events a ***higher score***

Event categories

- ***Divide*** events into exclusive categories based on the classifier output by ***maximising*** the ***significance***
- ***Purity increases*** as a function of the MVA output

Signal extraction

- ***Signal extracted*** by ***fitting $m_{\mu\mu}$*** distributions in each subcategories
- Signal and background modelled via ***parametric functions***
- ***Data-driven background prediction***



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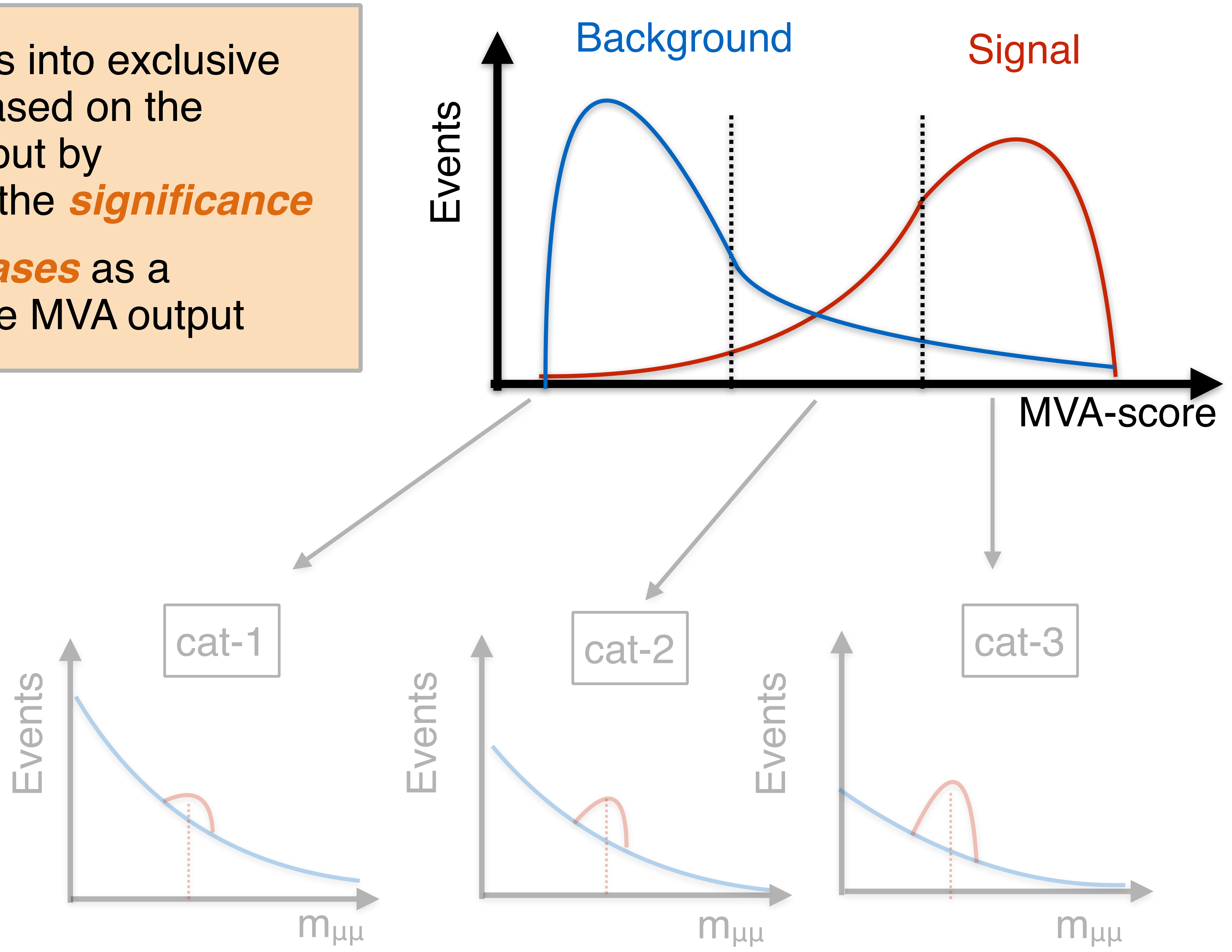

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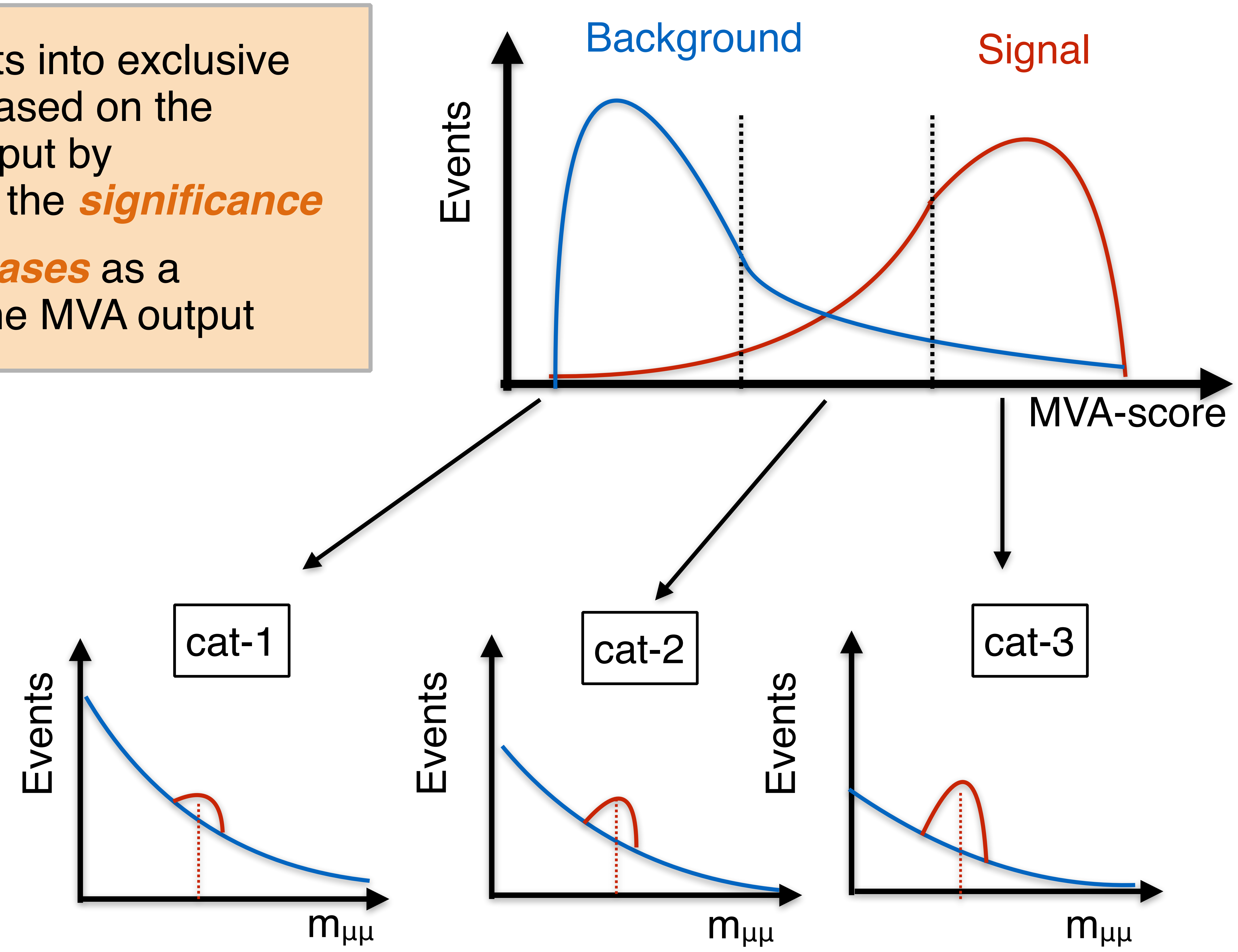


ttH(μμ) analysis

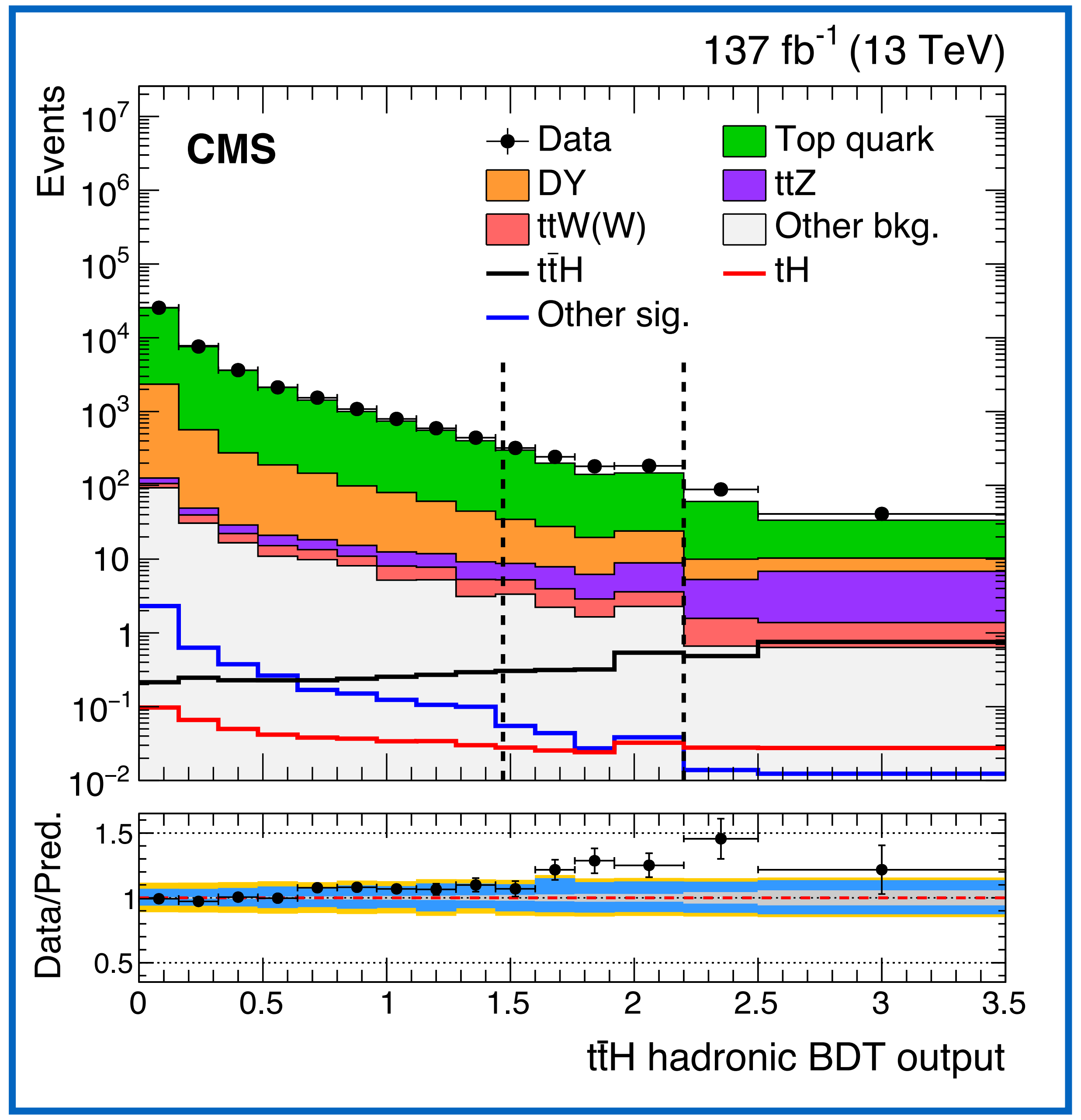
Divide-n-fit strategy is employed in the signal extraction

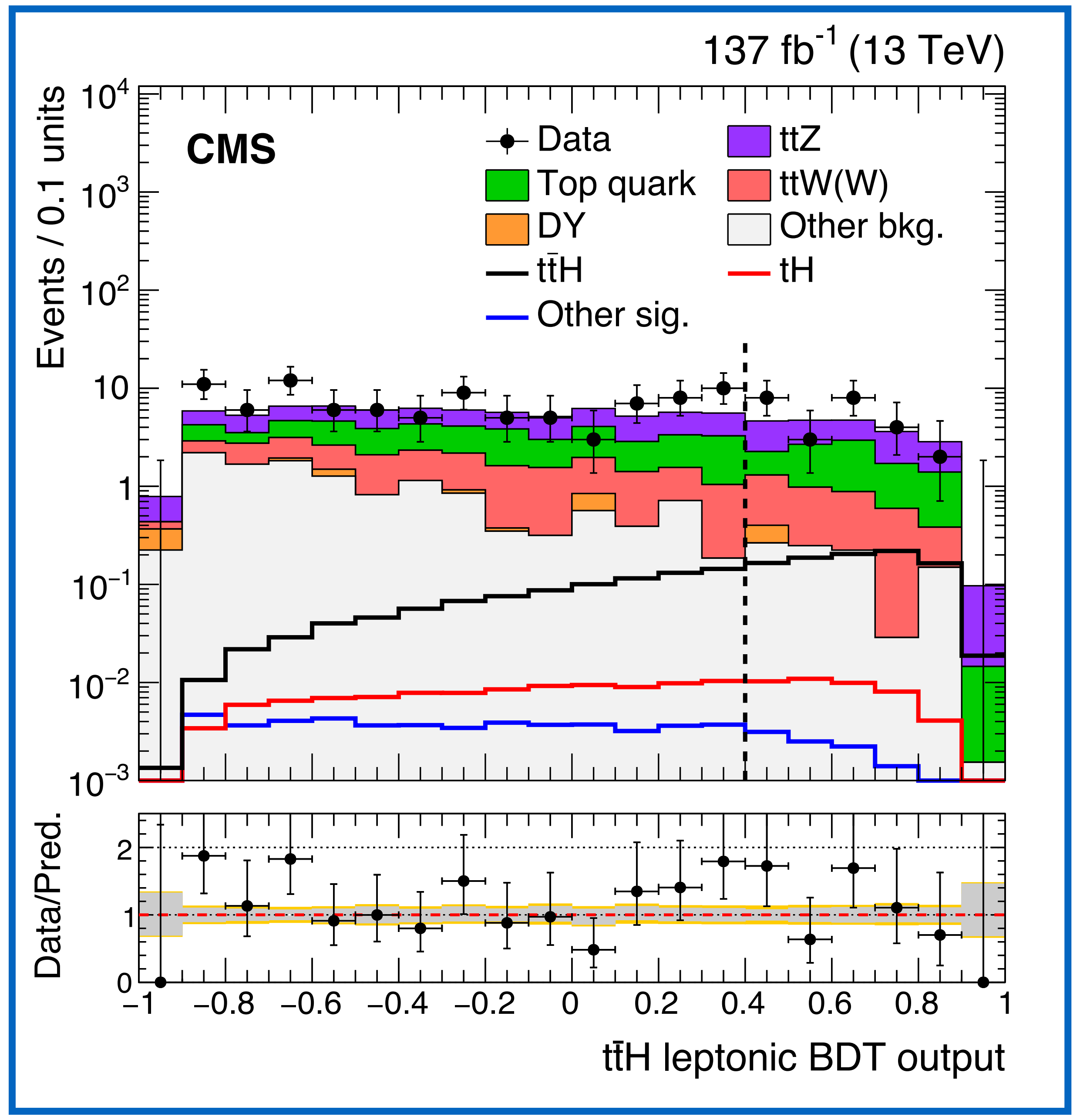
MVA training

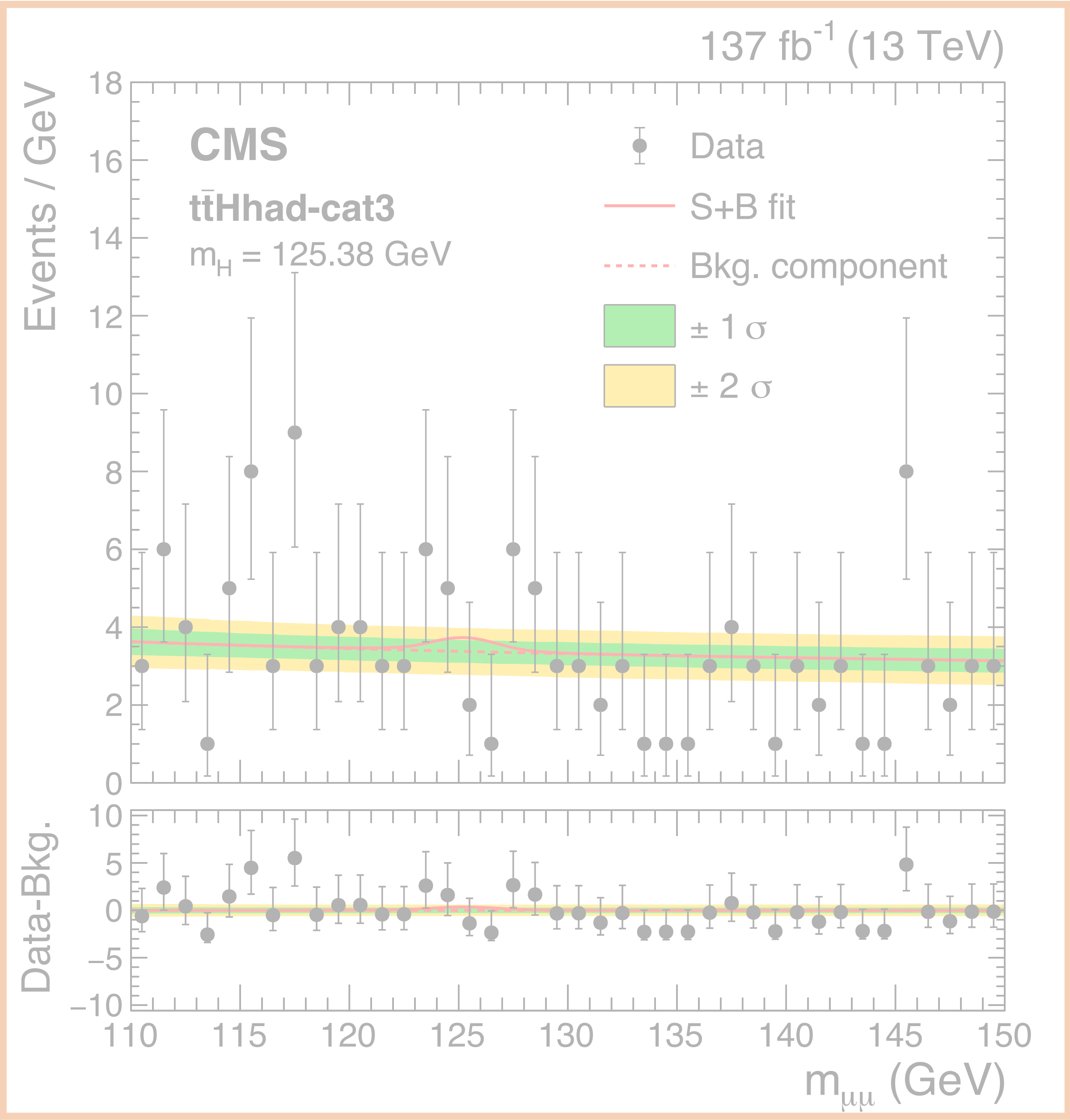
- Two BDTs are trained one for ttH-lep and one for ttH-had
- ***Input features:***
  - Kinematics of μμ-system apart from $m_{\mu\mu}$
  - Event variables
  - Jet & additional lepton kinematics

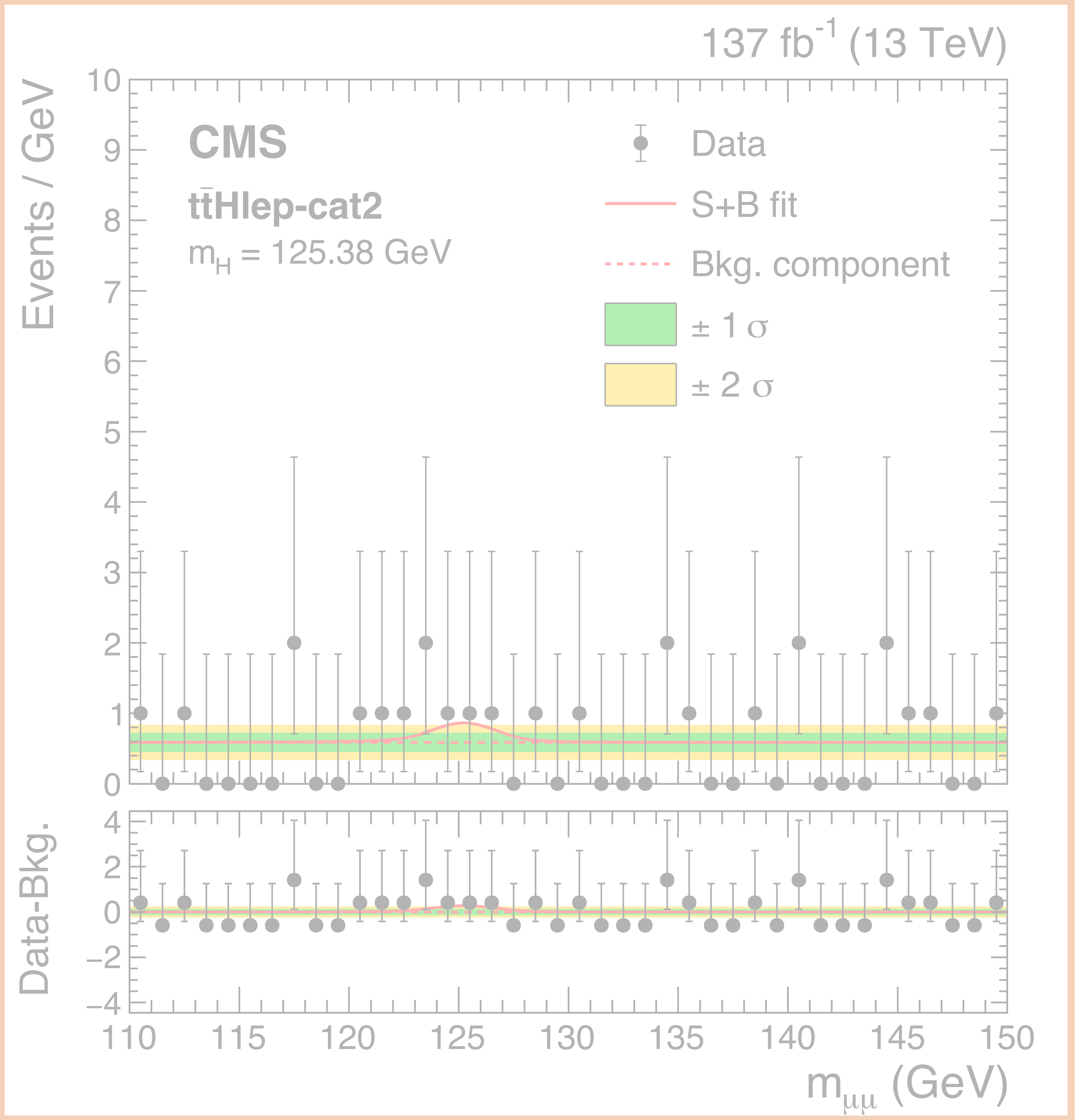
Signal extraction

- ***Categories:*** 3 in ttH-hadronic & 2 in ttH-leptonic
- ***Signal model $m_{\mu\mu}$*** → parametrised via Double Crystal-Ball
- ***Bkg. model $m_{\mu\mu}$*** → parametrised via empirical functions chosen to provide a ***negligible bias*** in the S+B fit









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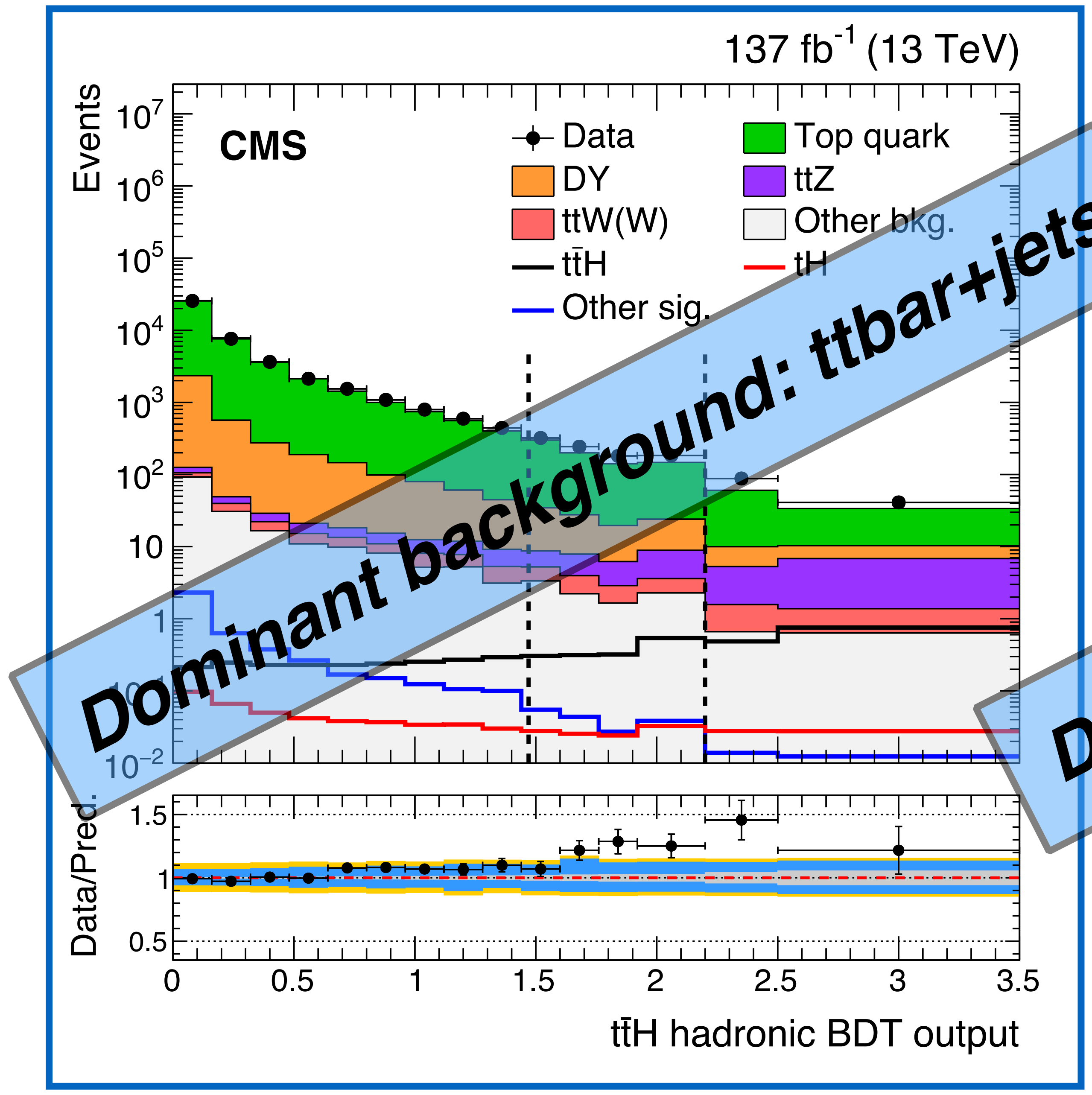
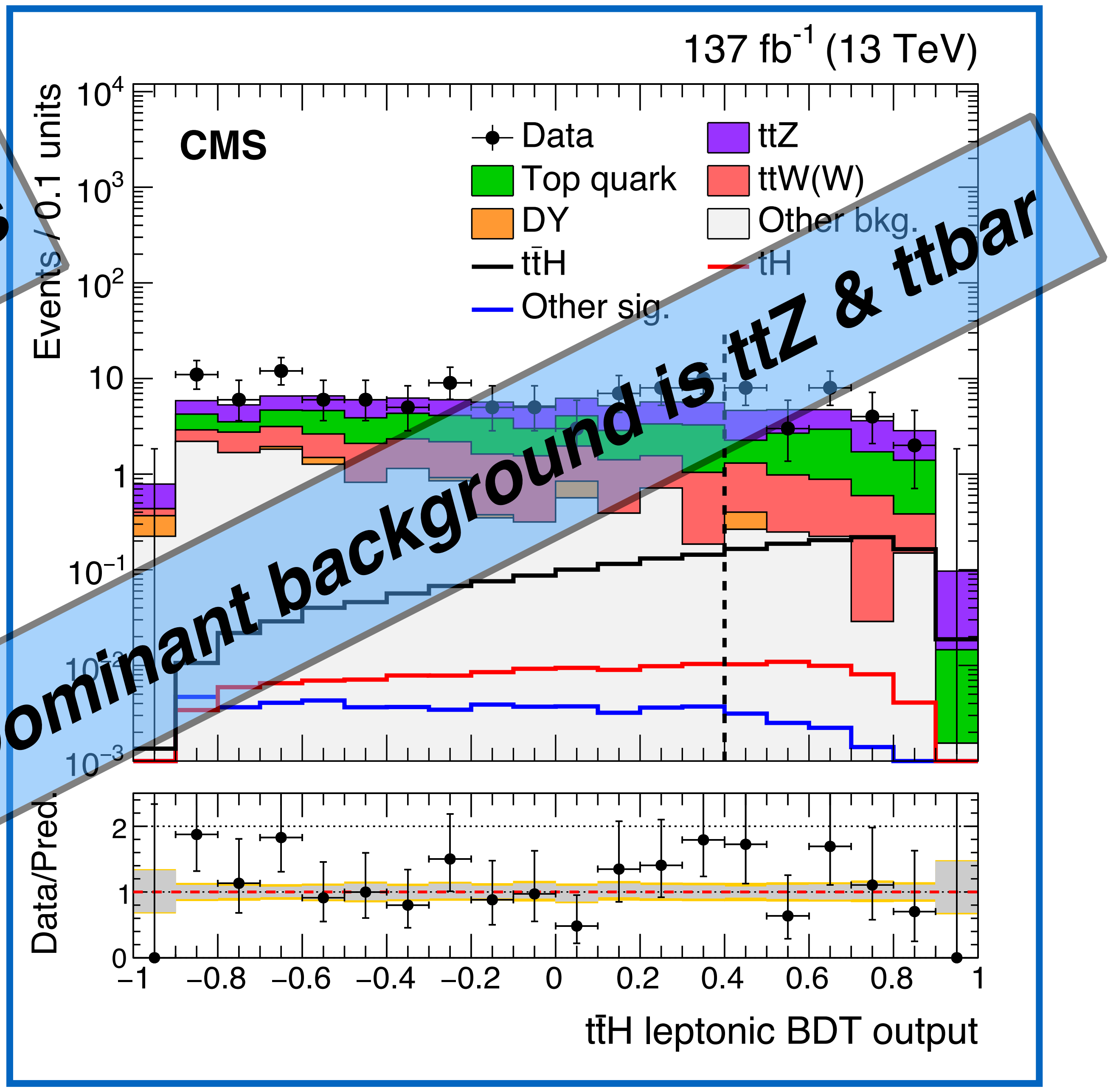
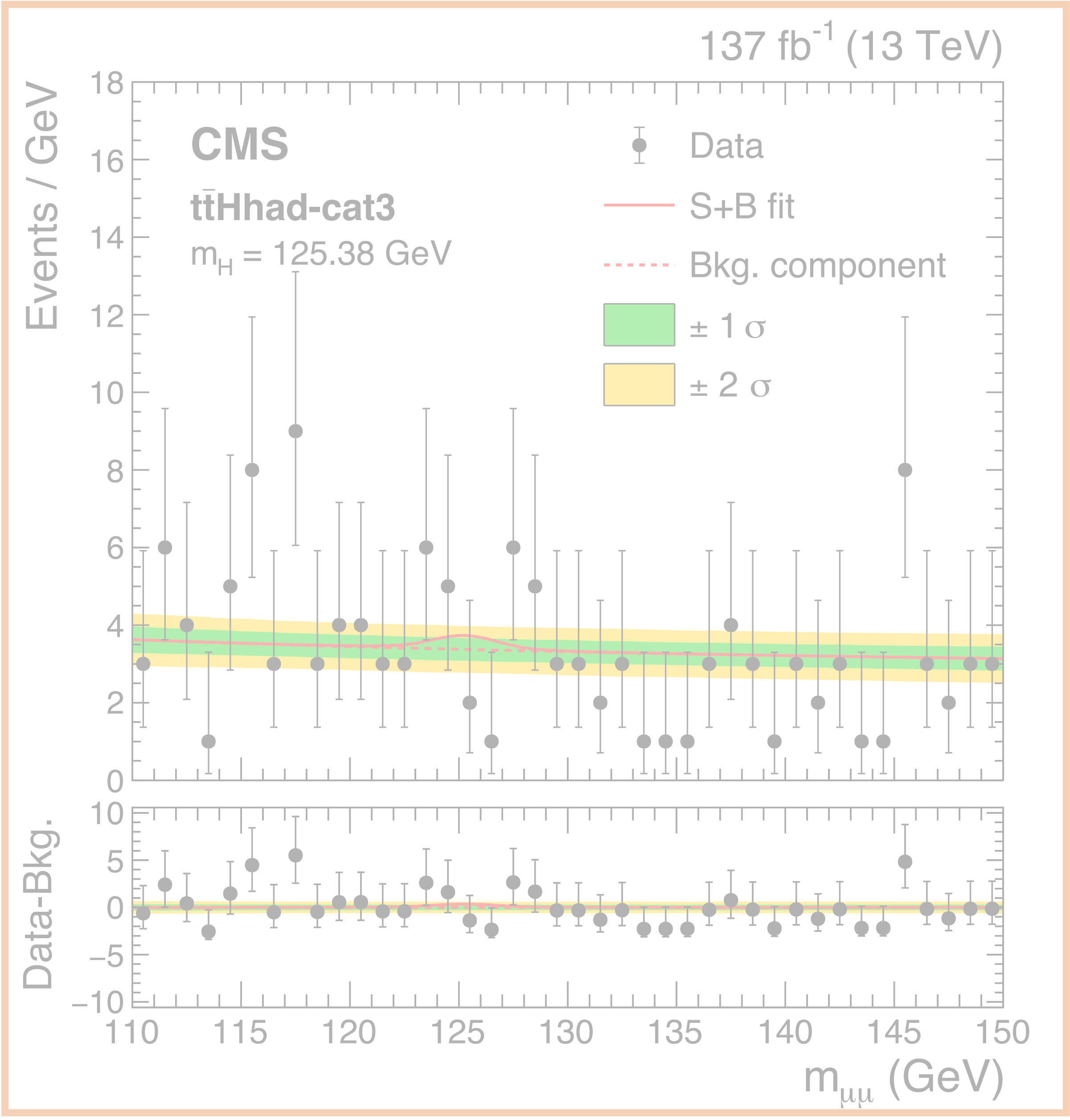
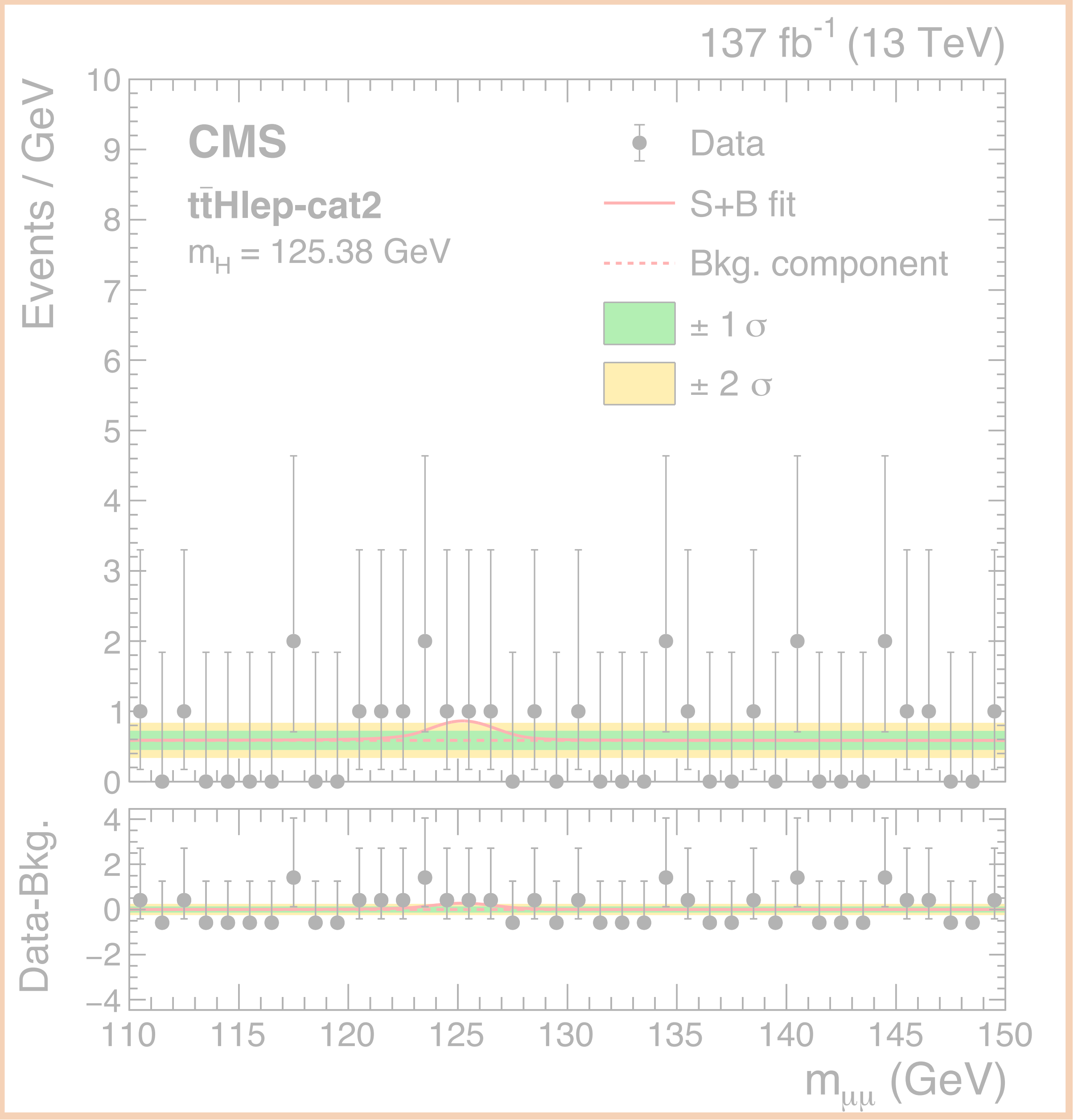


Dominant background: ttbar+jets



Dominant background is ttZ & ttbar





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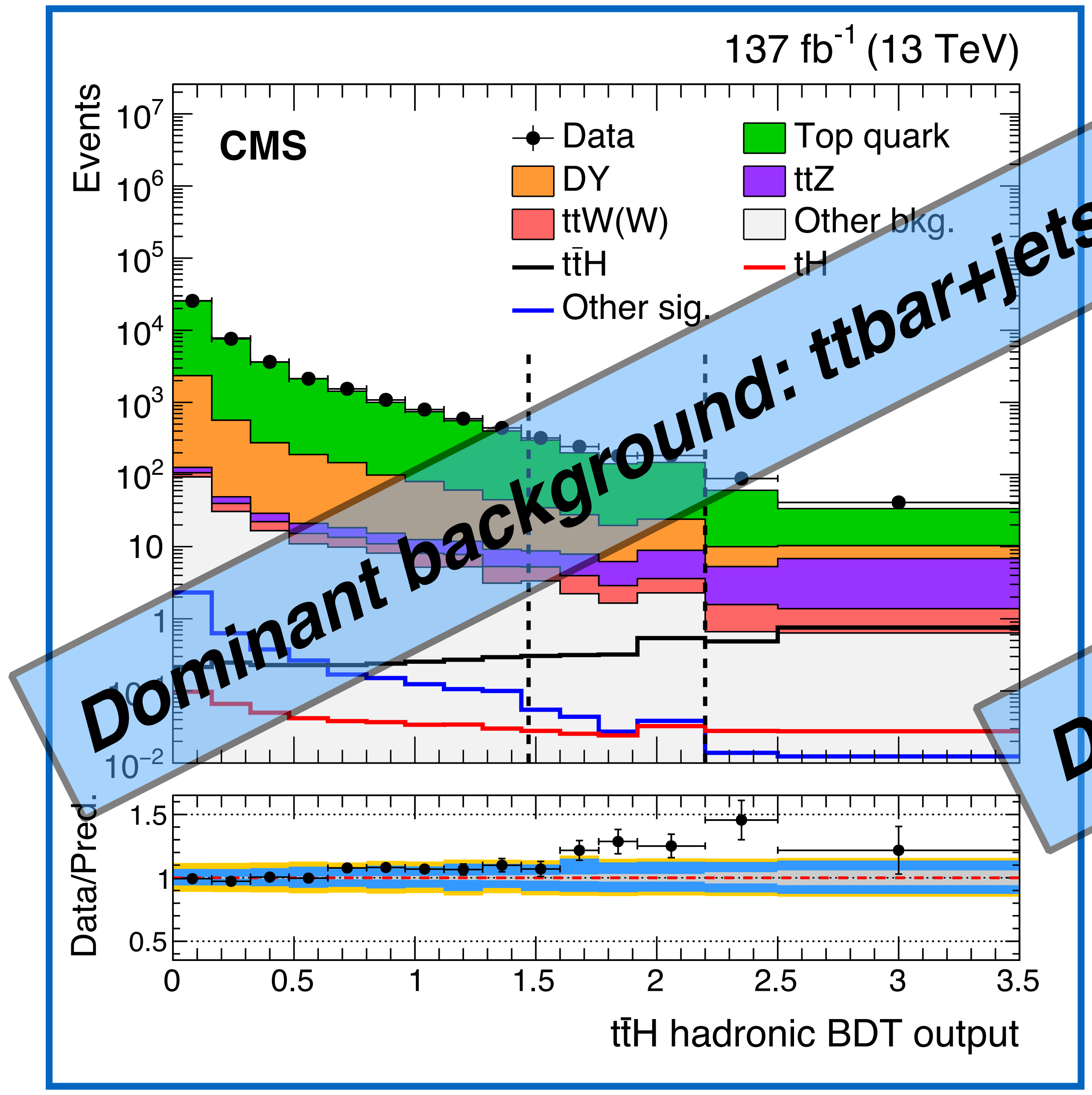

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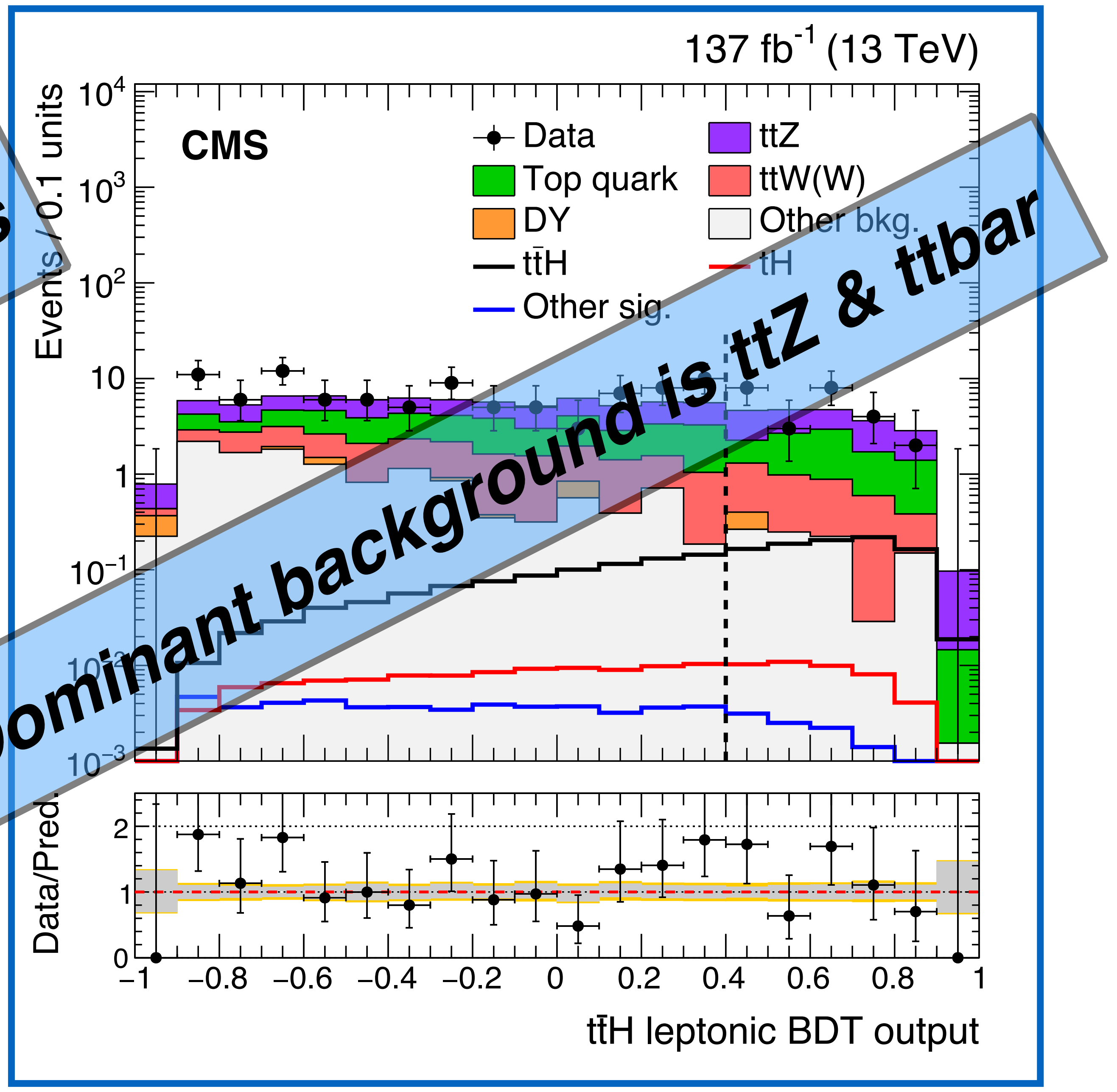

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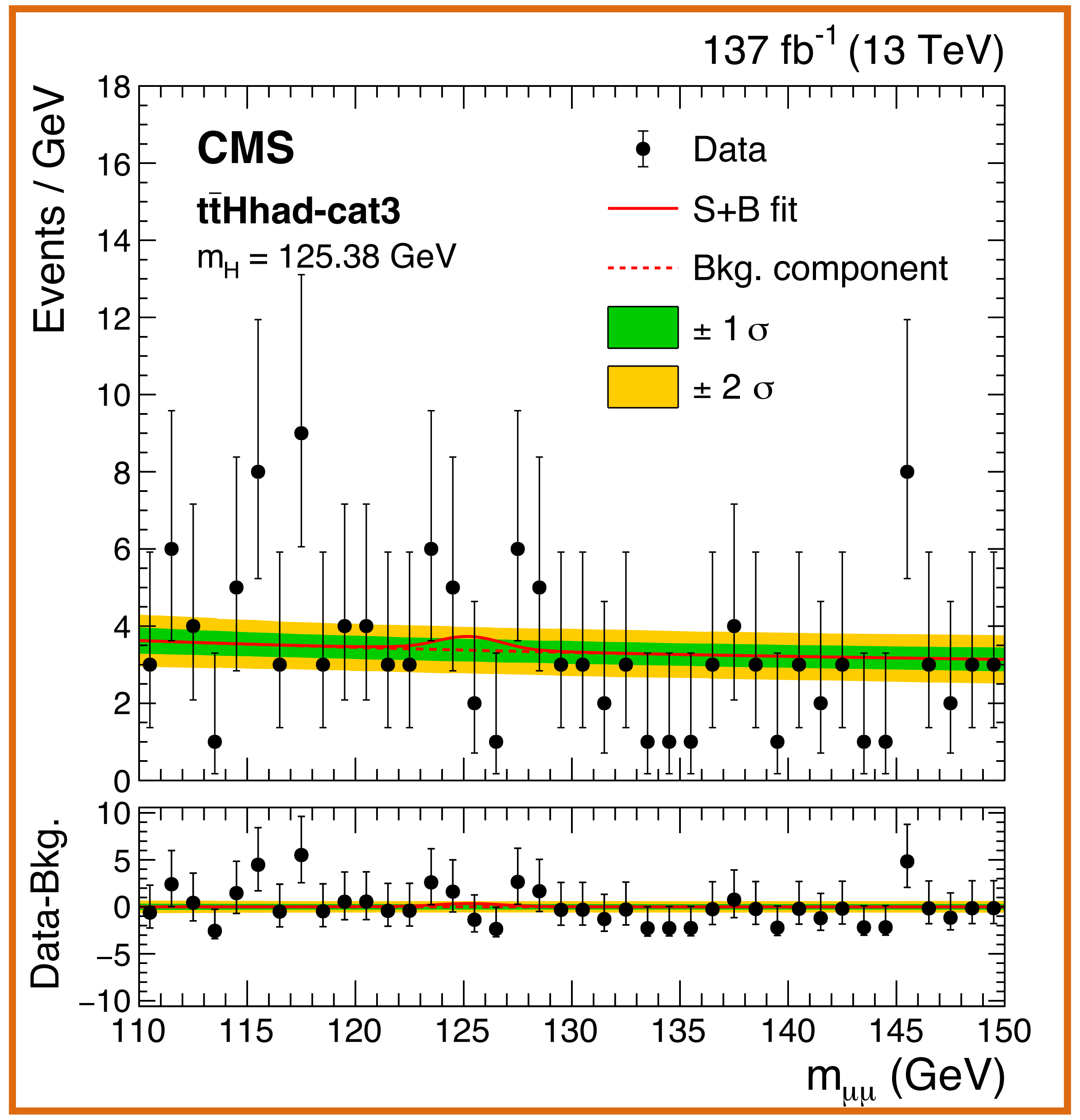

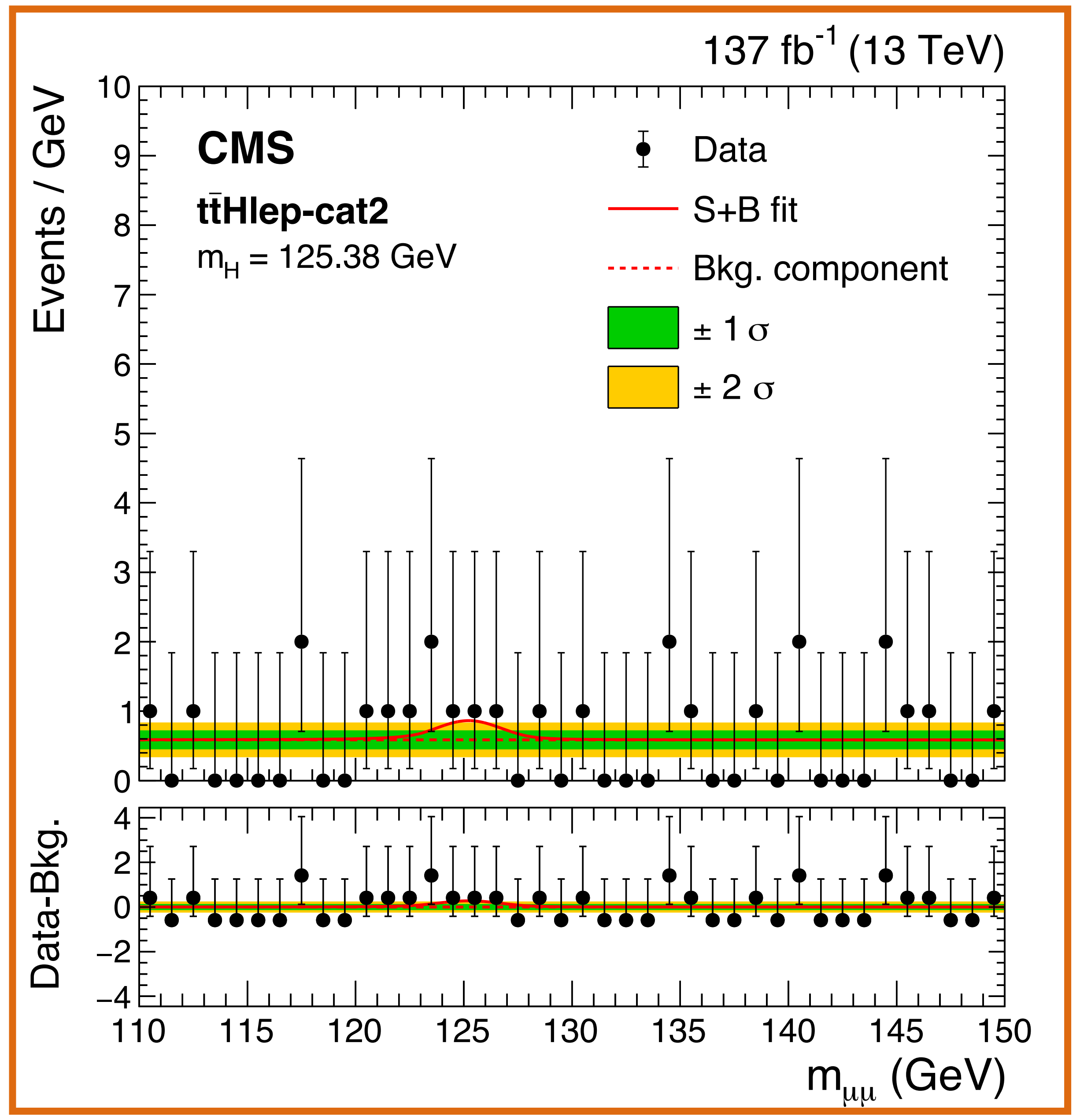

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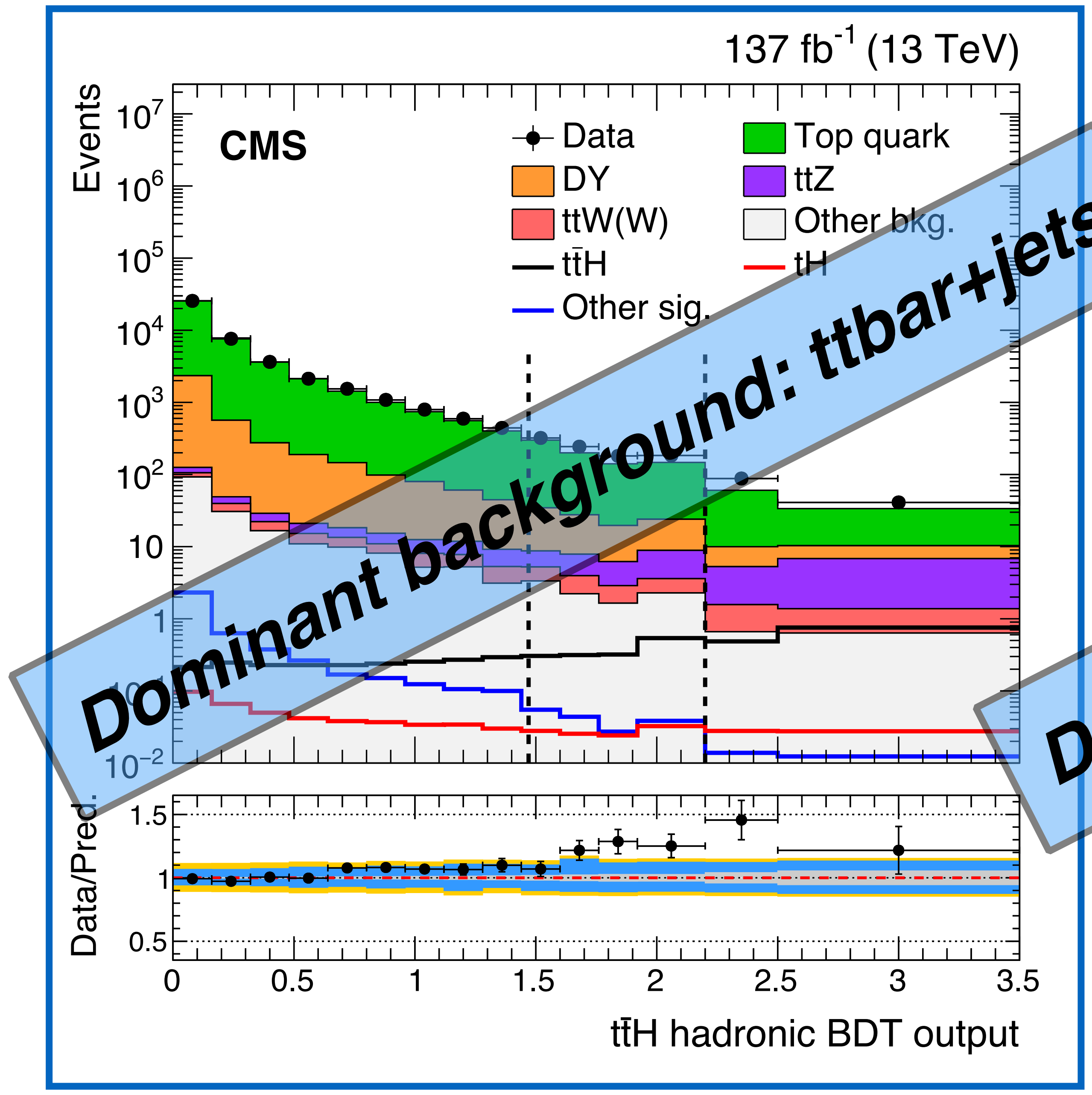

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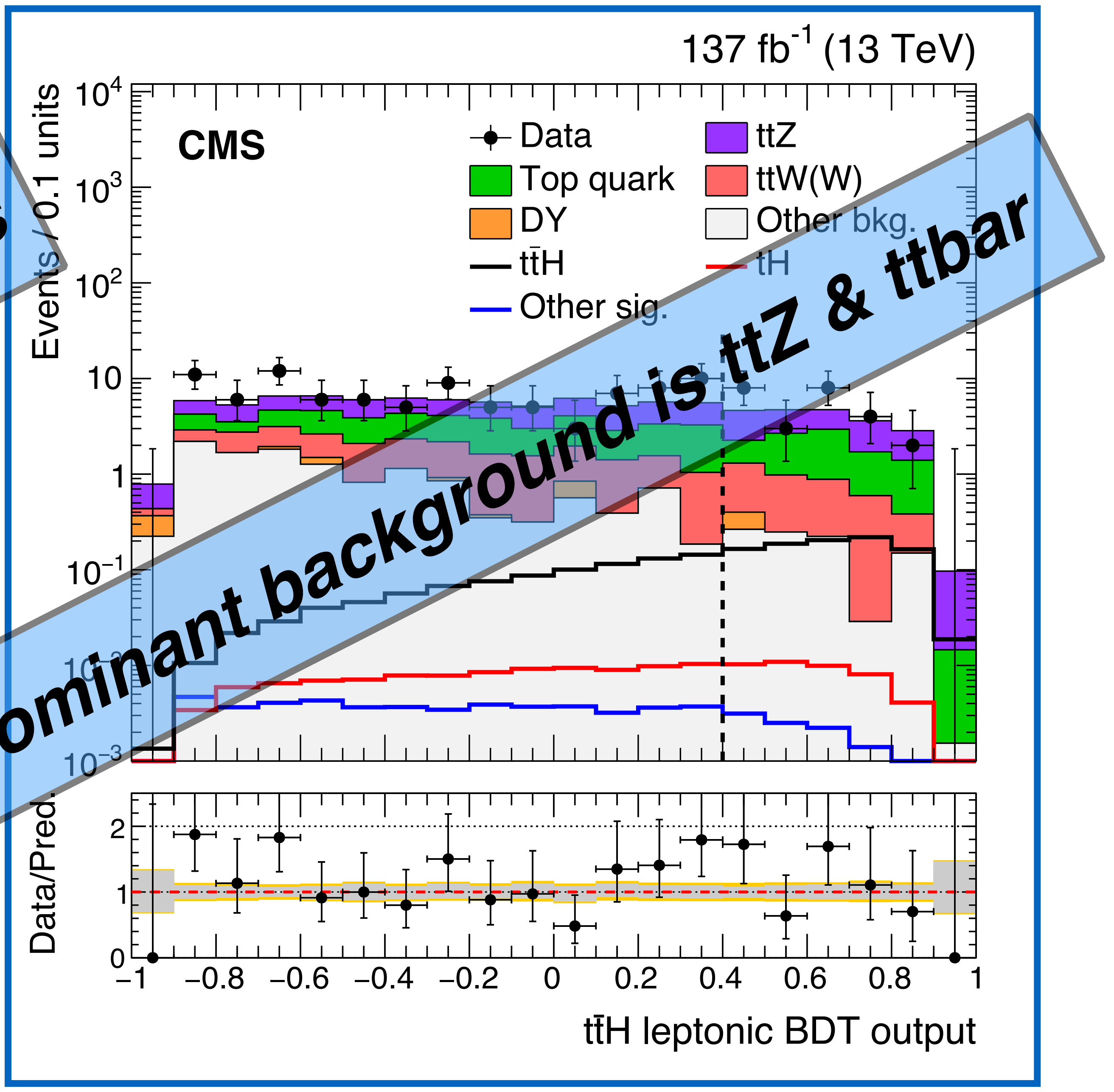
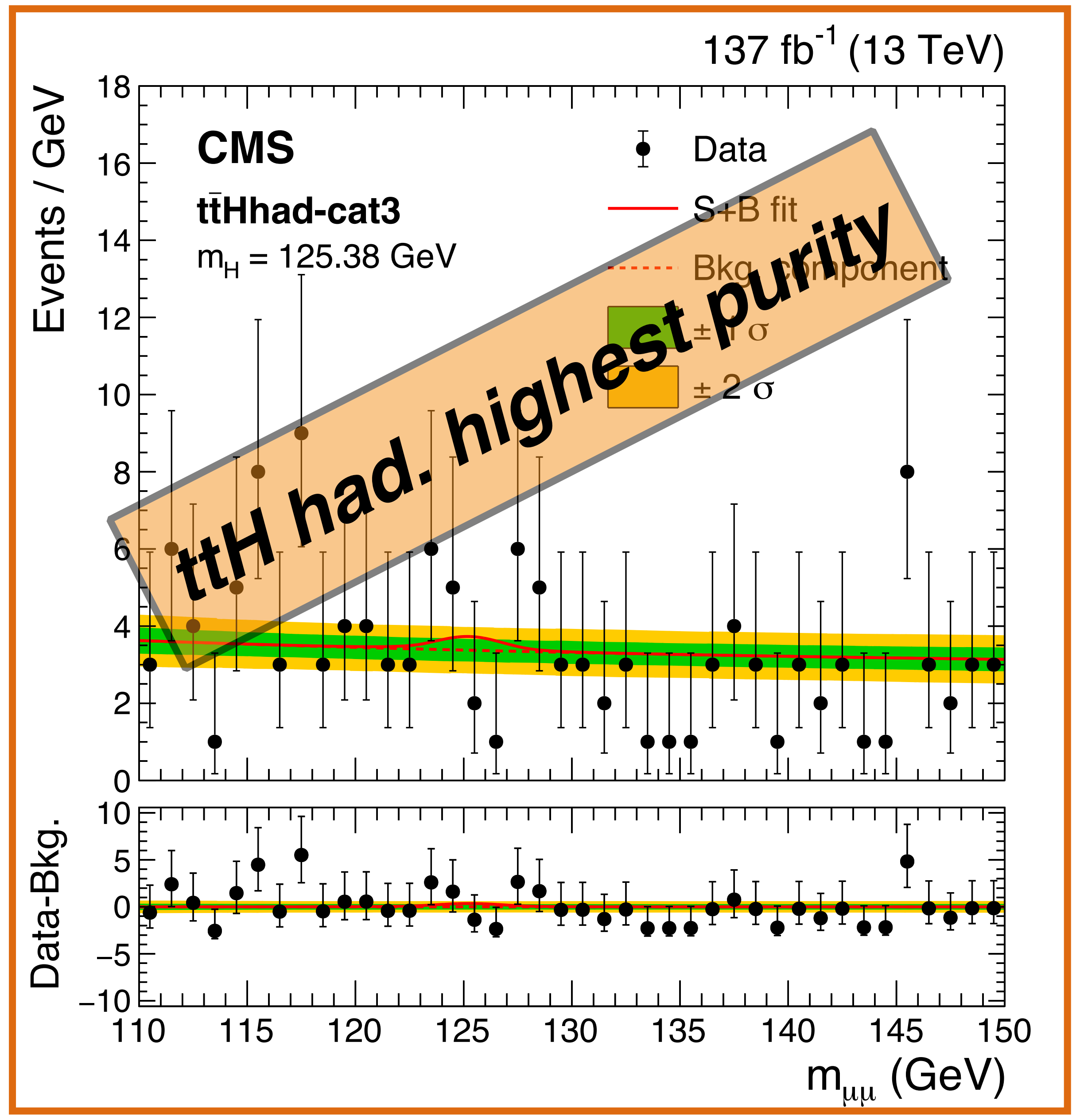
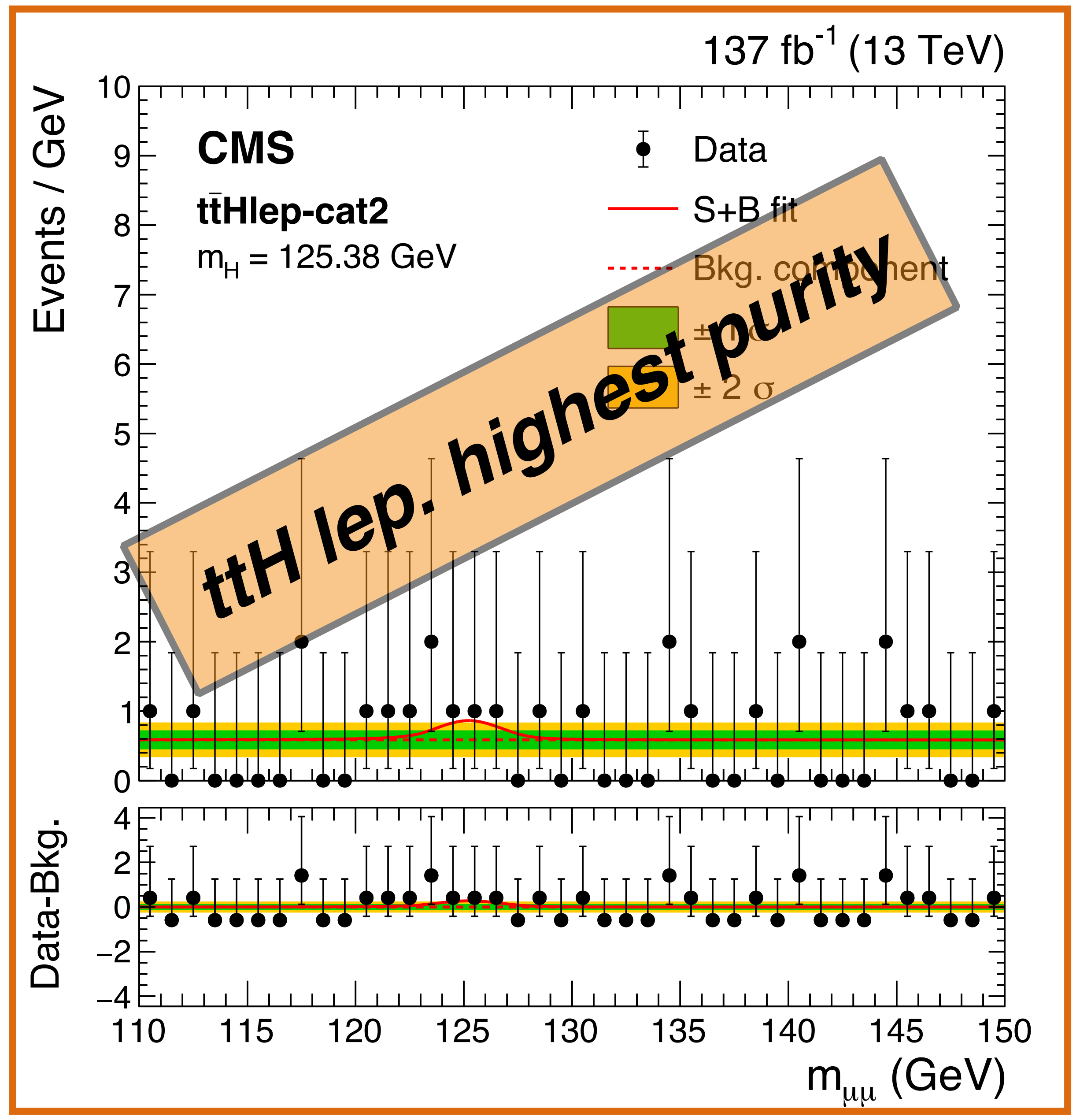


Dominant background is ttZ & ttbar



ttH had. highest purity



ttH lep. highest purity

ttH(μμ) analysis

Divide-n-fit strategy is employed in the signal extraction

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- ***Bkg. model $m_{\mu\mu}$*** → parametrised via empirical functions chosen to provide a ***negligible bias*** in the S+B fit

ttH analysis results

- Simultaneous fit to $m_{\mu\mu}$ of the five event categories
- Reference m_H of 125.38 GeV
- ***Expected*** significance of 0.5σ
- ***Observed*** significance of 1.2σ
- **Signal strength** $\mu = 2.32^{+2.27}_{-1.95}$

VH(μμ) analysis

Divide-n-fit strategy is employed in the signal extraction

MVA training

- Two BDTs are trained one for W(lν)H and one Z(ll)H
- ***Input features:***
  - Kinematics of μμ-system apart from $m_{\mu\mu}$
  - Event variables
  - Additional leptons, W/Z candidate kinematics ..

Signal extraction

- ***Categories:*** 3 in WH & 2 in ZH
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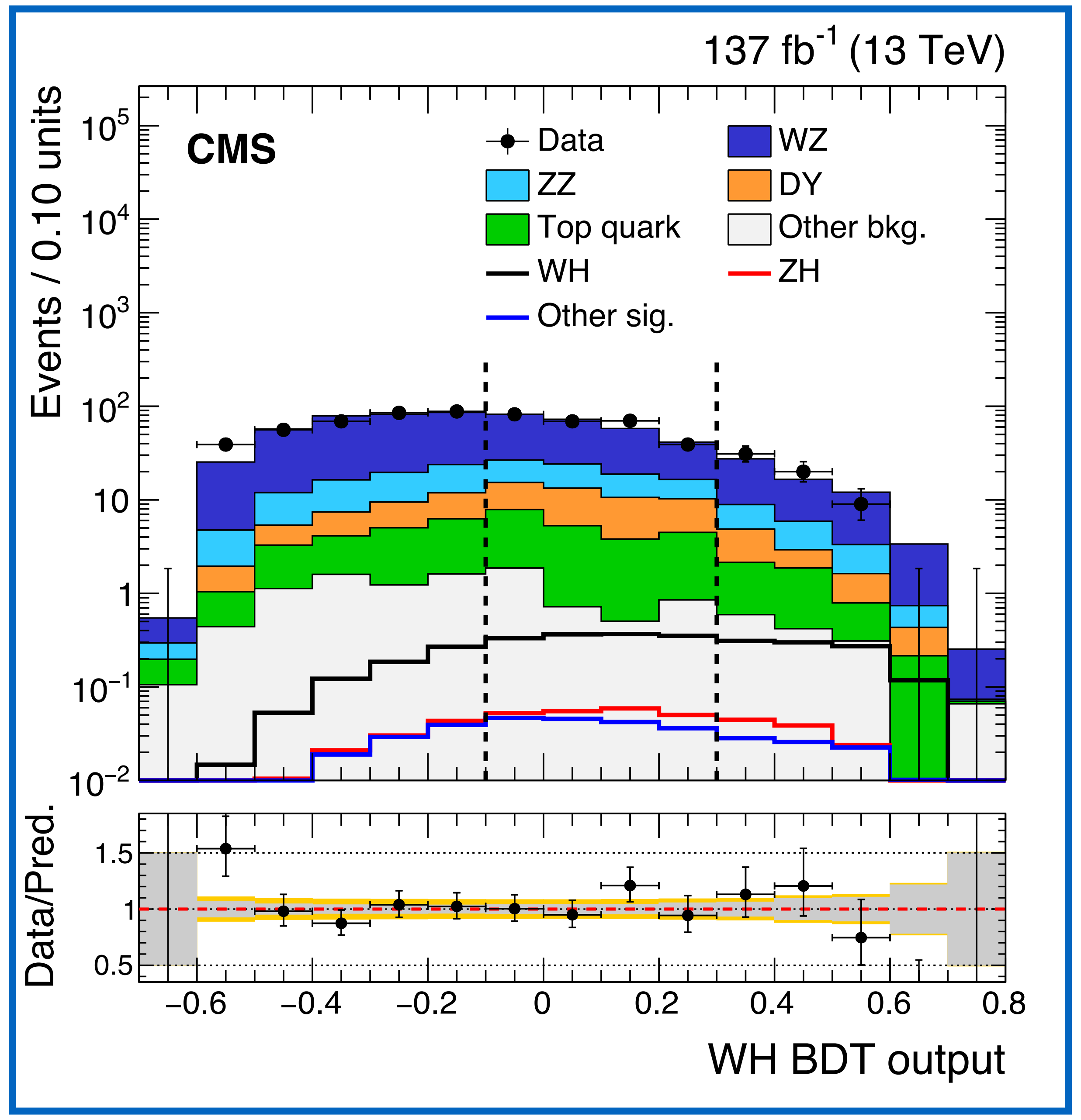
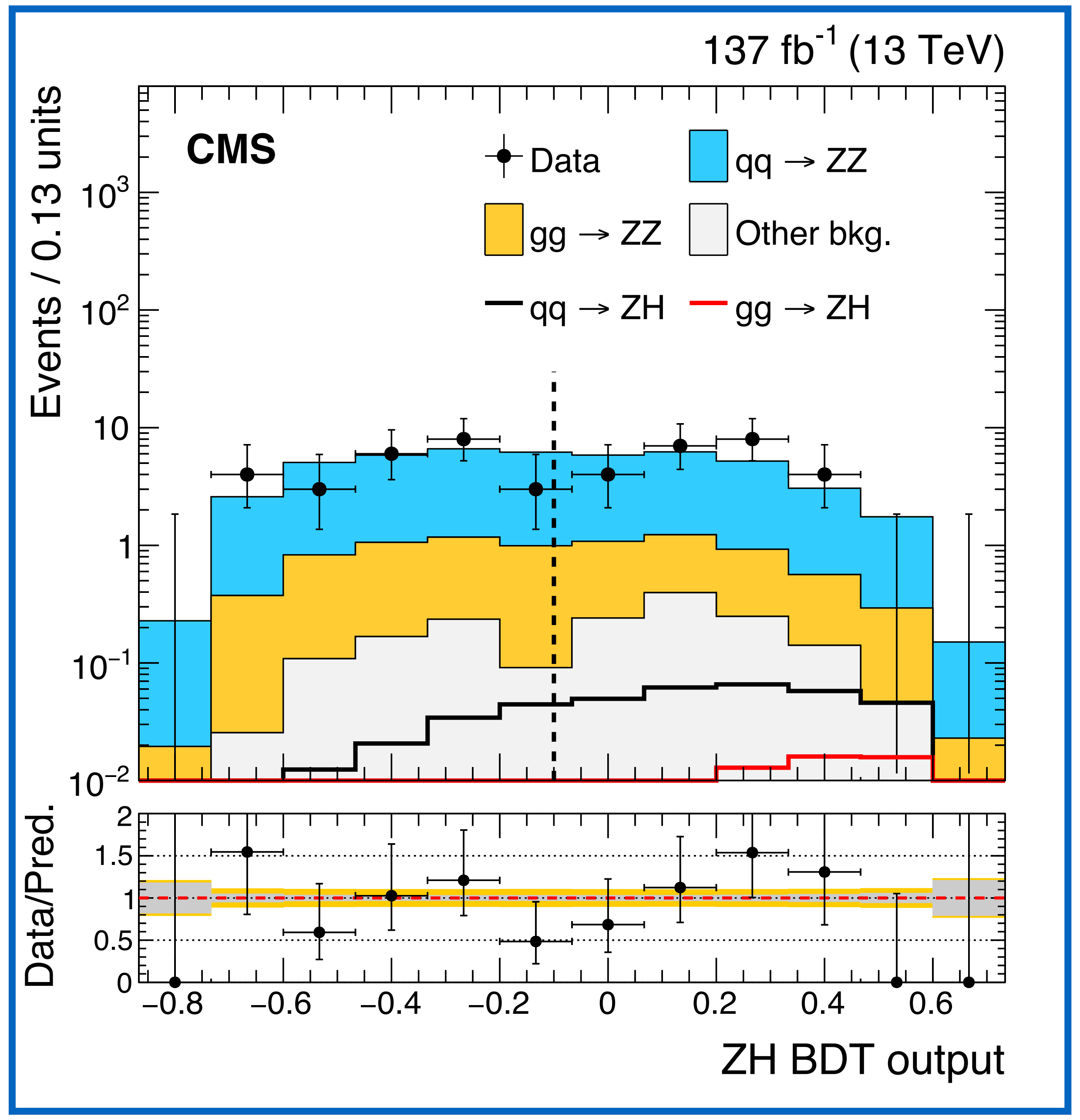
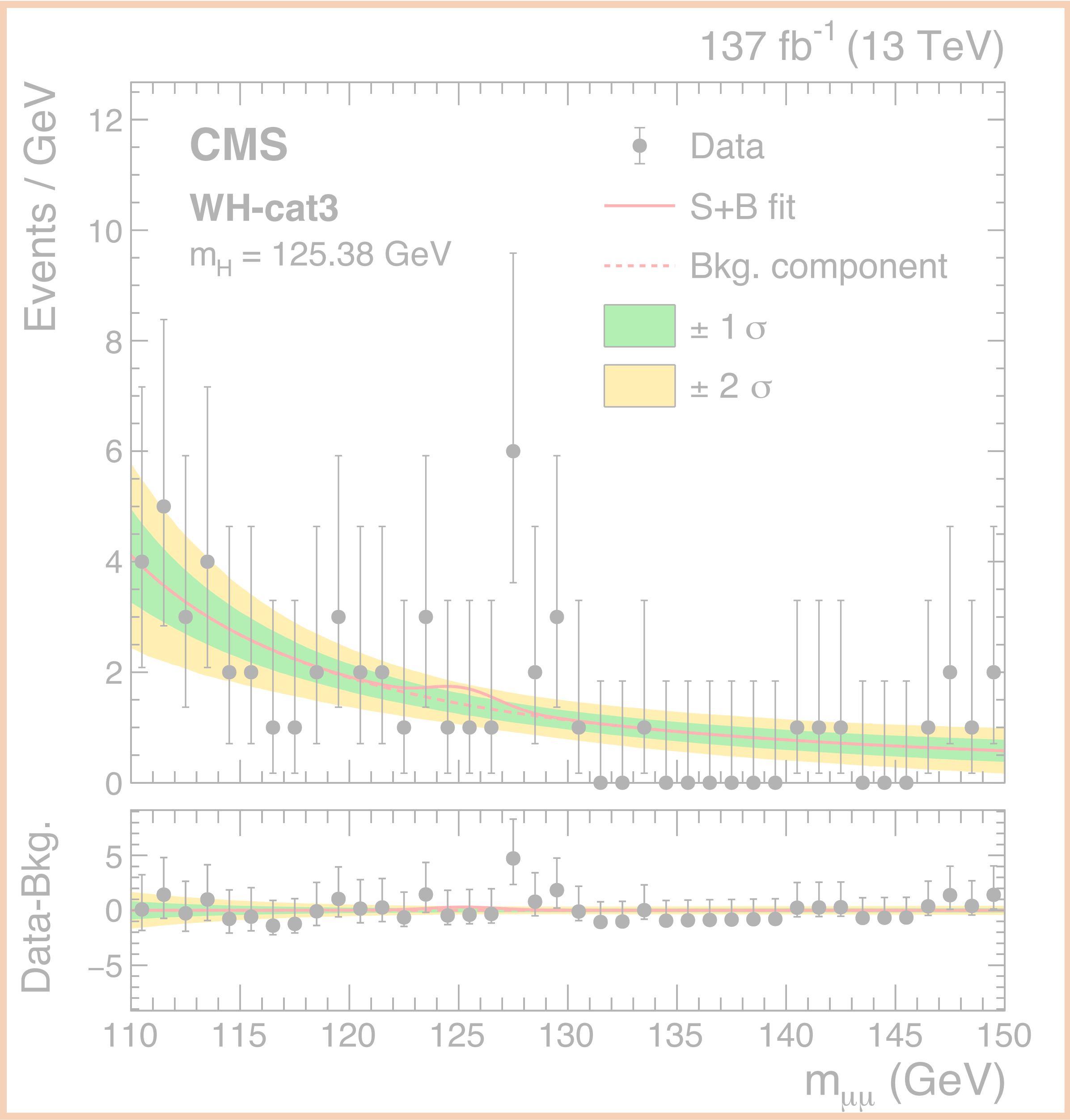
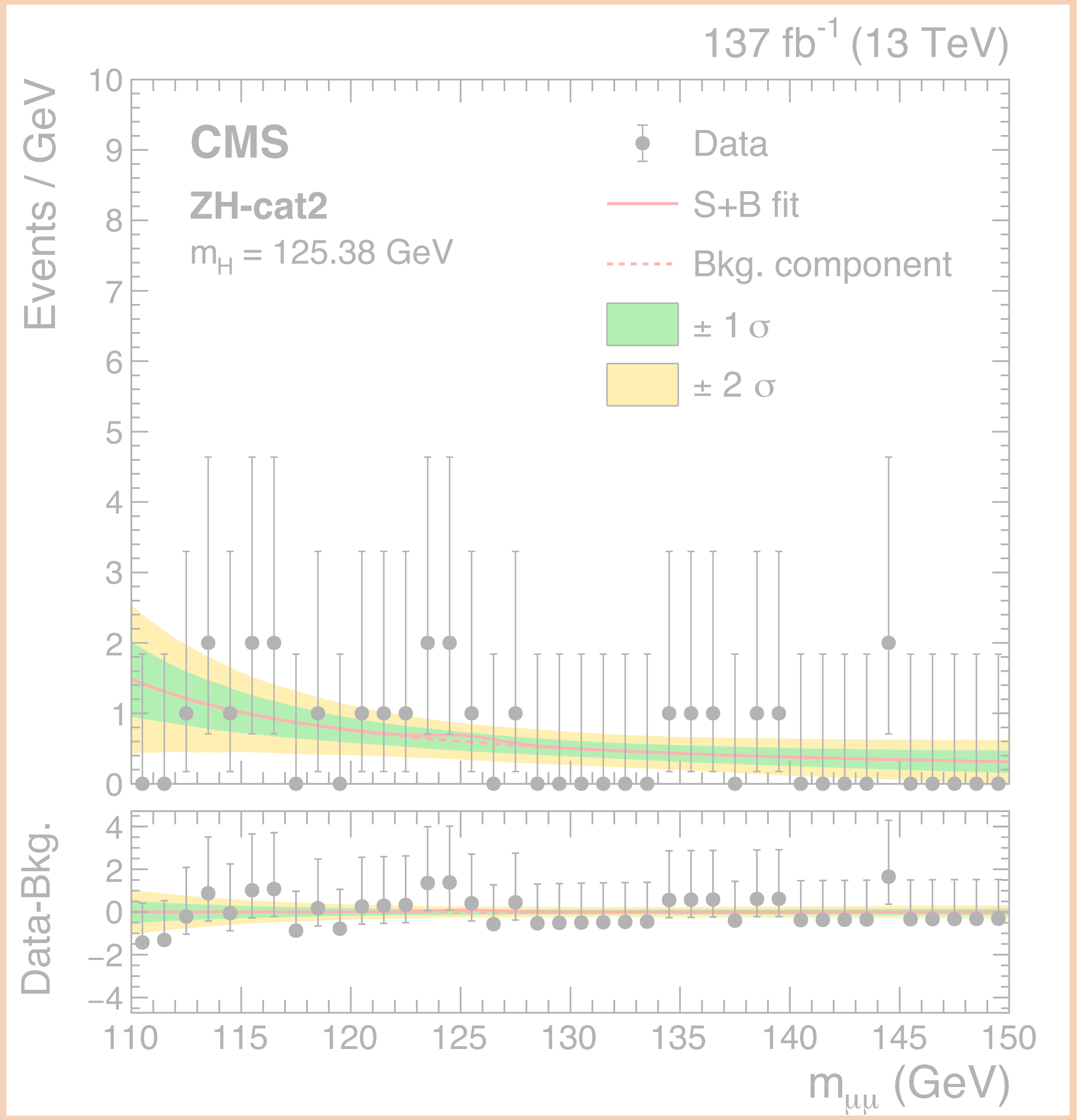
- ***Bkg. model $m_{\mu\mu}$*** → parametrised via empirical functions chosen to provide a negligible bias in the S+B fit









VH(μμ) analysis

Divide-n-fit strategy is employed in the signal extraction

MVA training

- Two BDTs are trained one for W(lν)H and one Z(ll)H
- ***Input features:***
  - Kinematics of μμ-system apart from $m_{\mu\mu}$
  - Event variables
  - Additional leptons, W/Z candidate kinematics ..

Signal extraction

- ***Categories:*** 3 in WH & 2 in ZH
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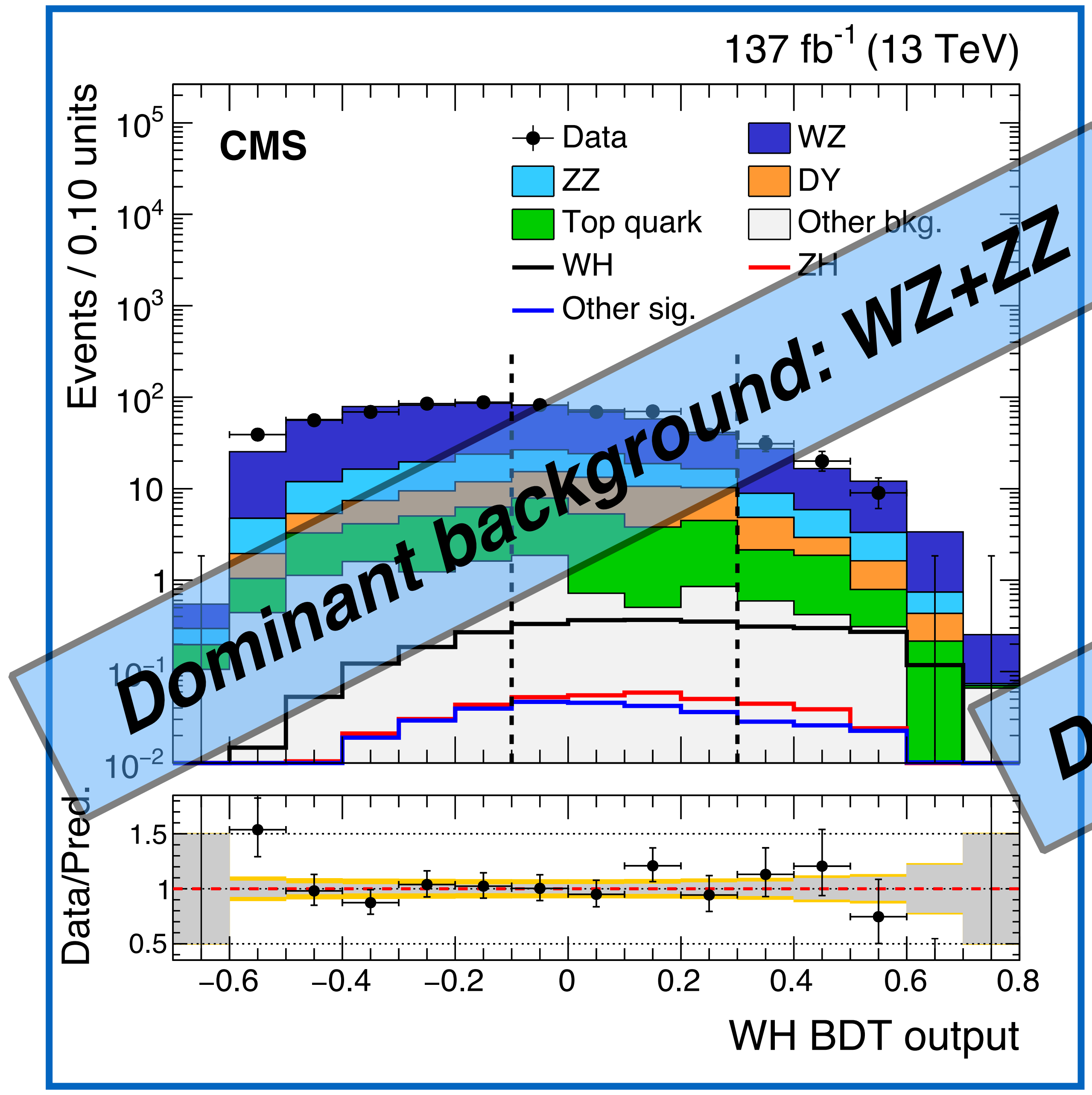
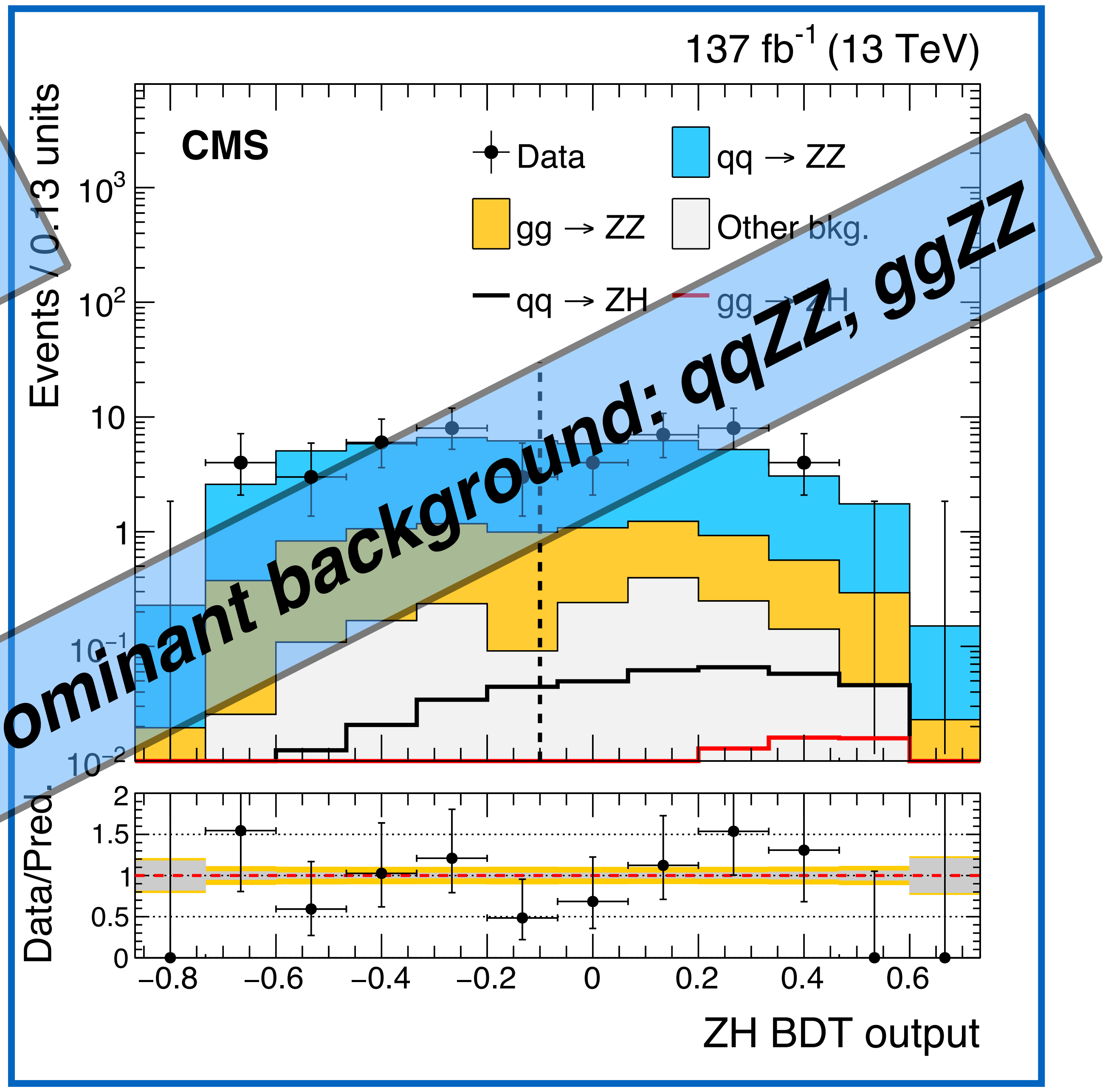
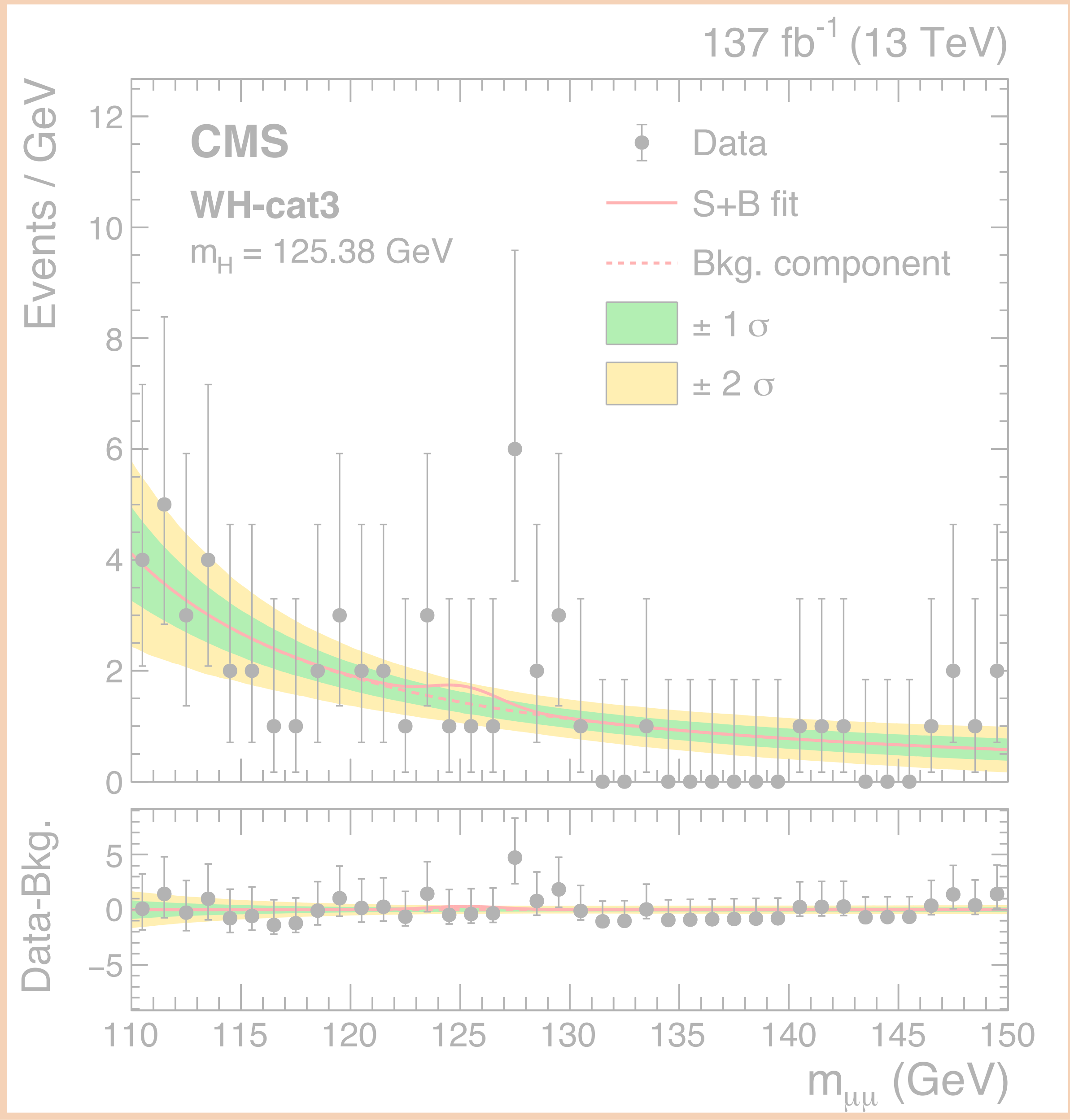
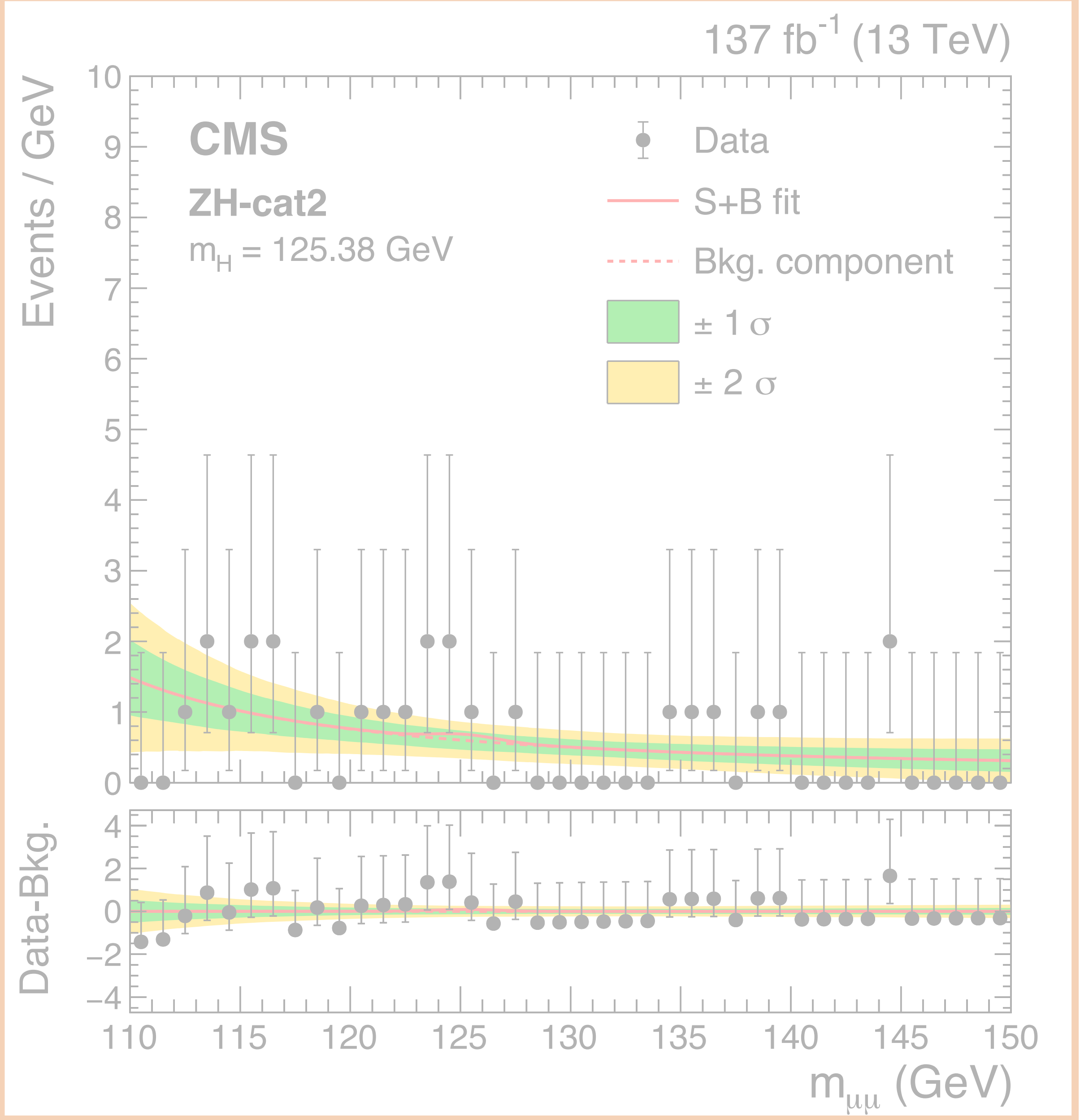


Dominant background: WZ+ZZ



Dominant background: qqZZ, ggZZ





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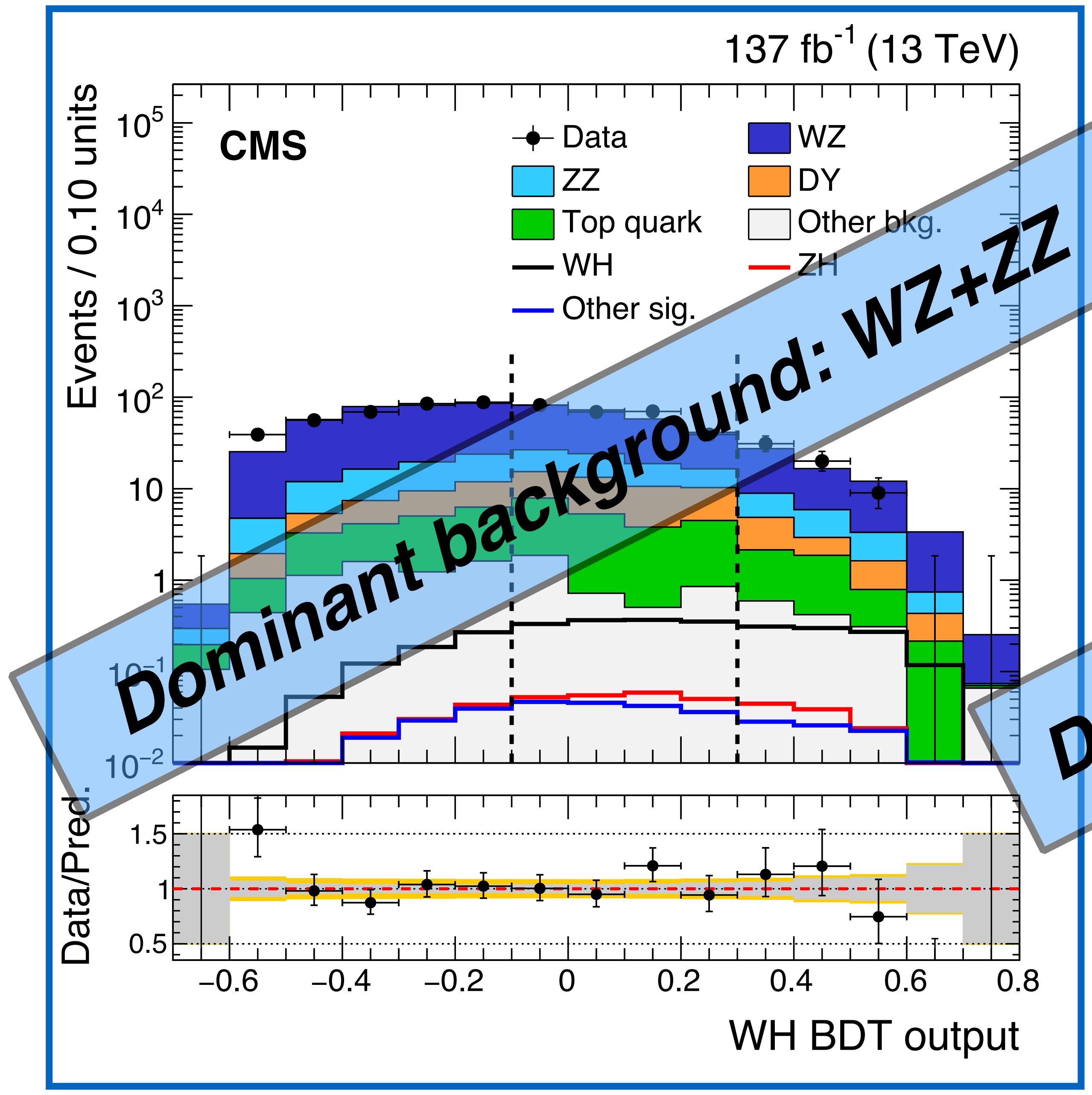

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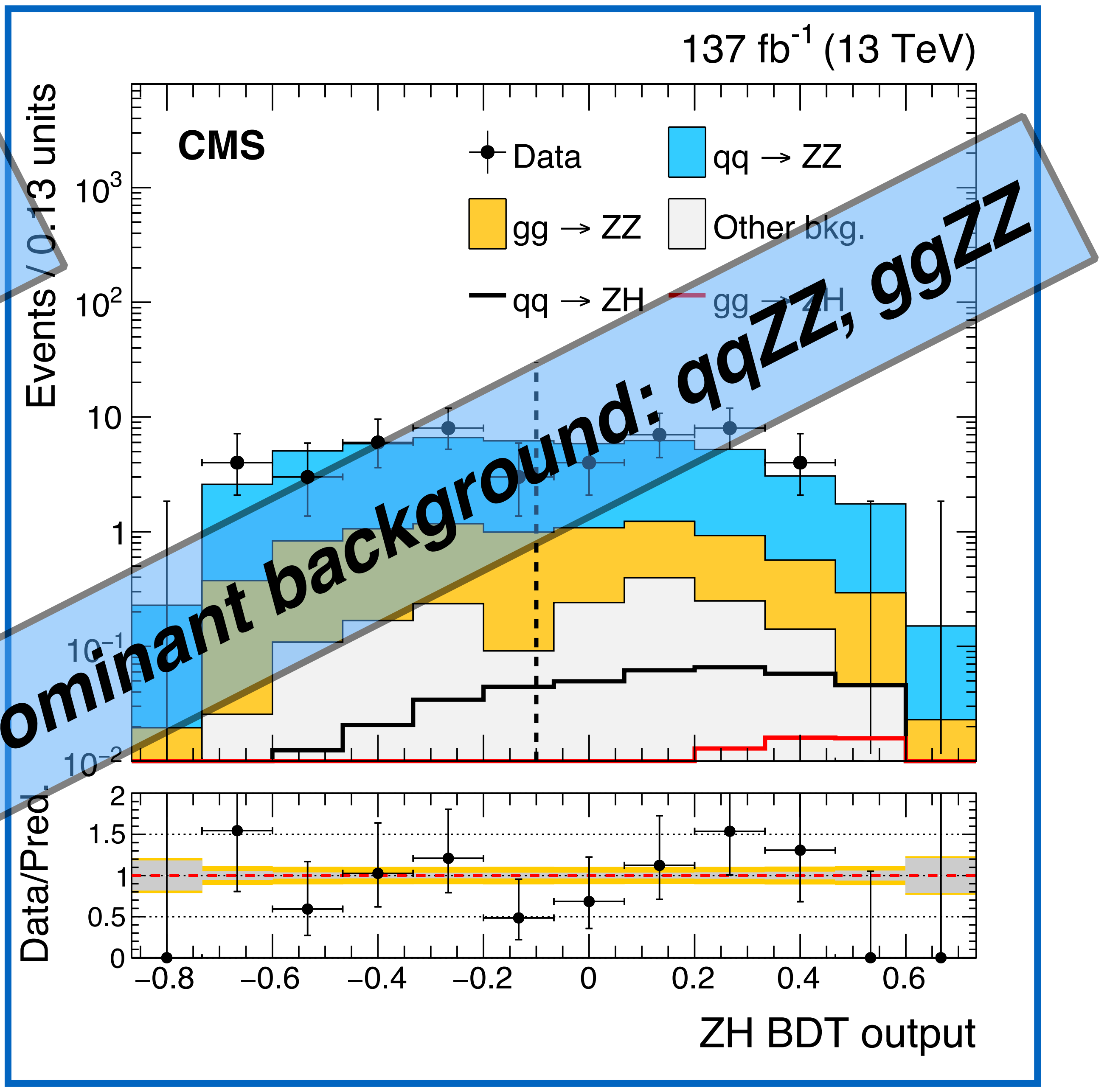

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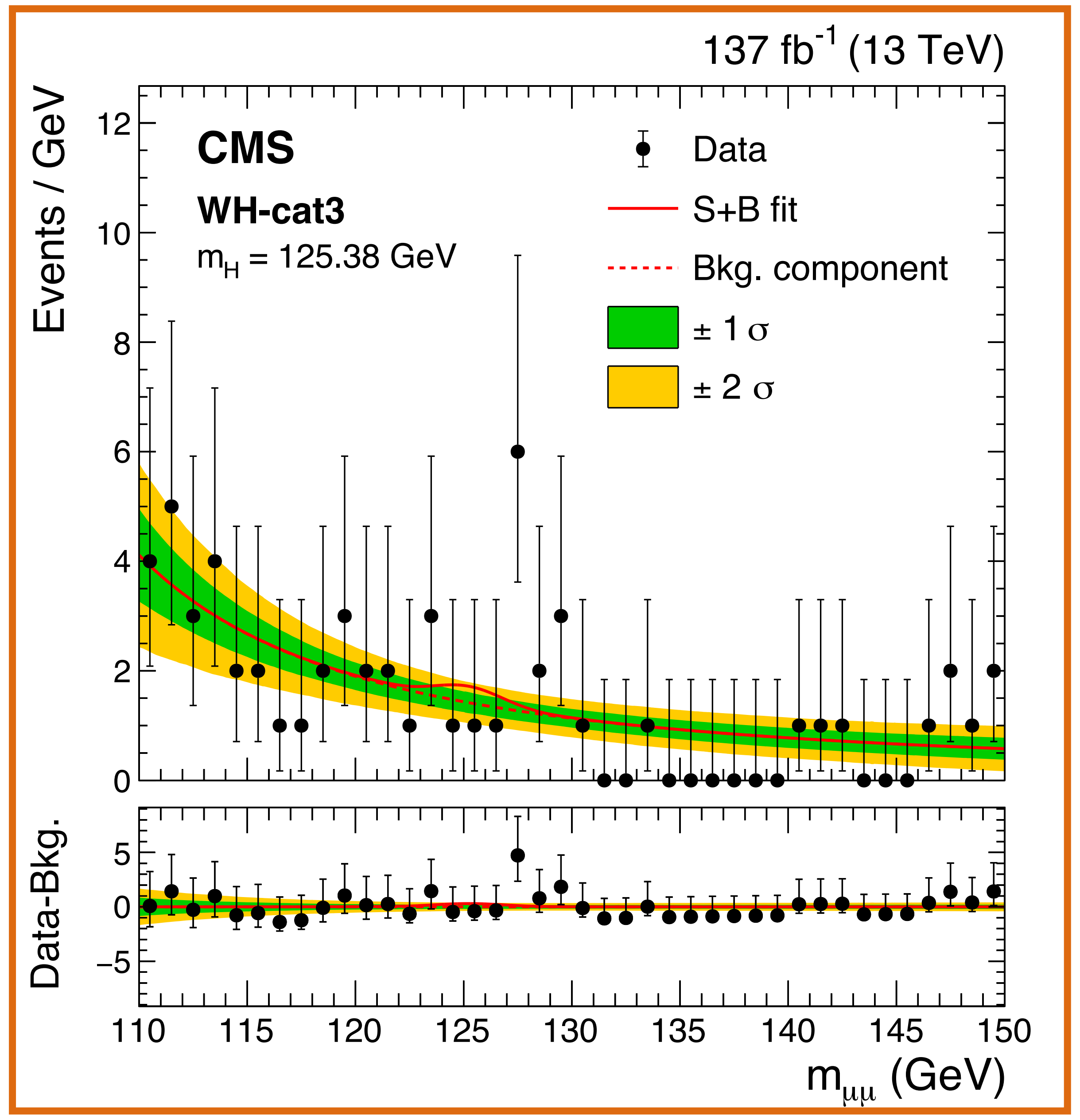

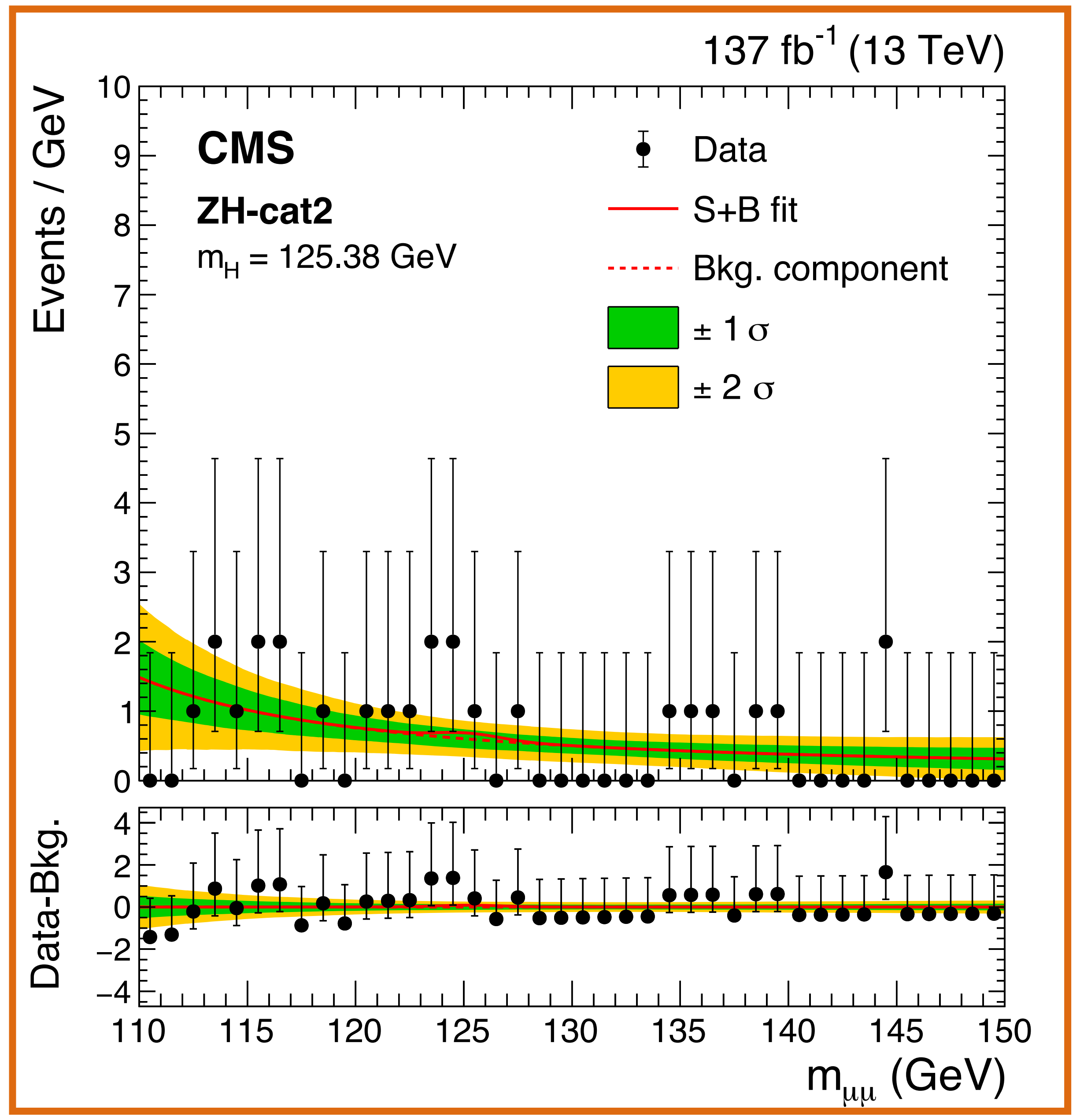

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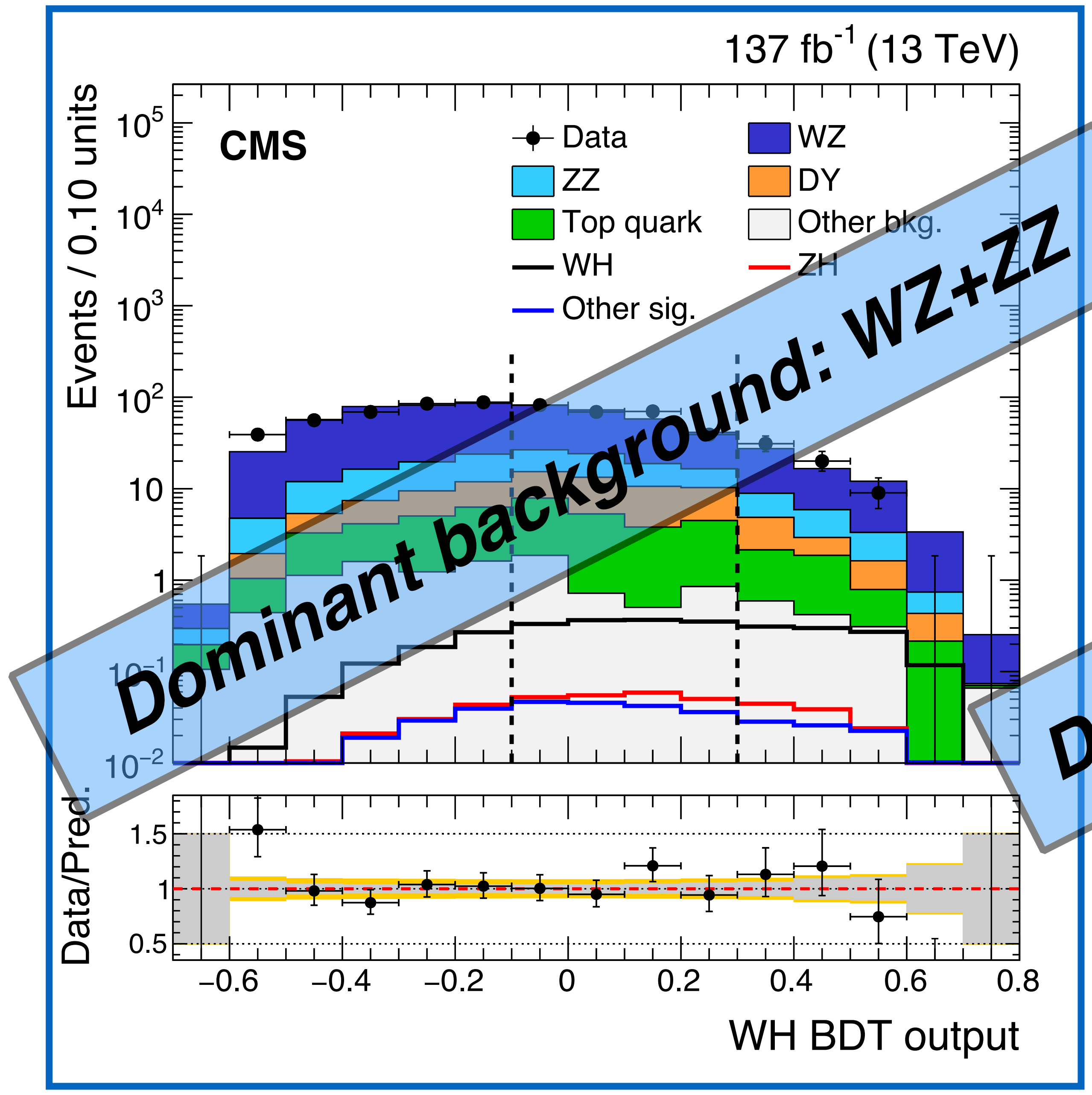

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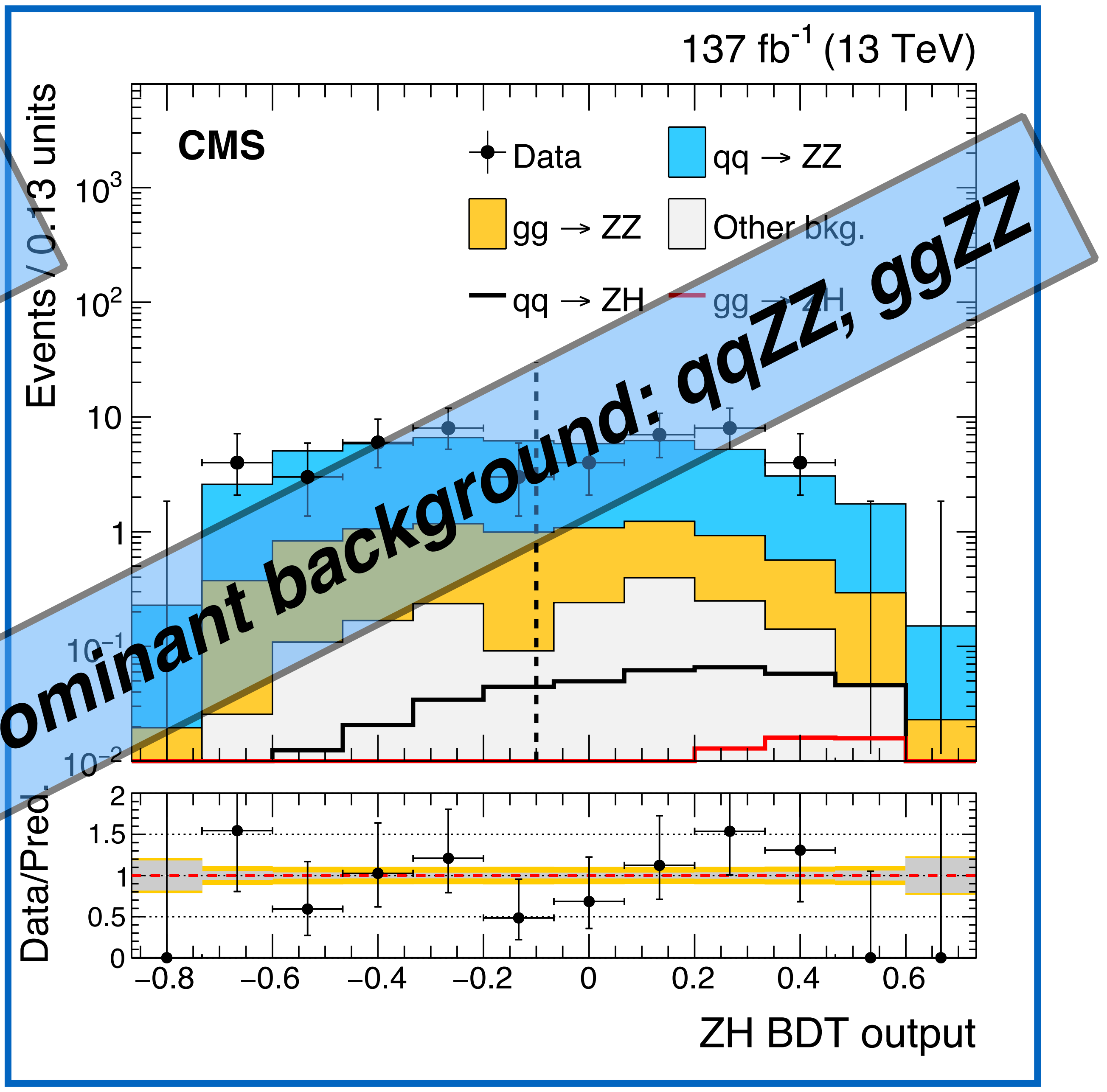

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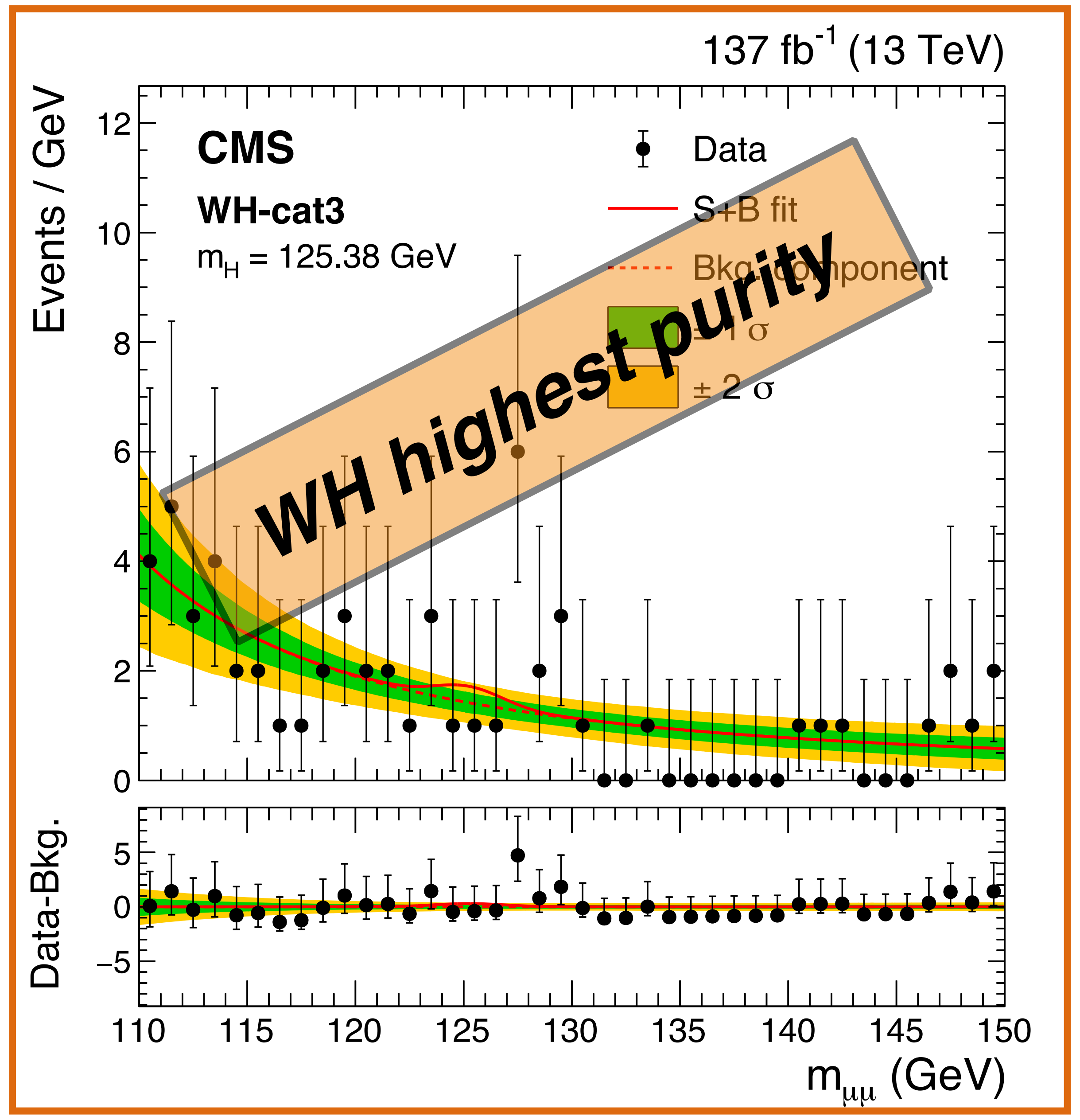
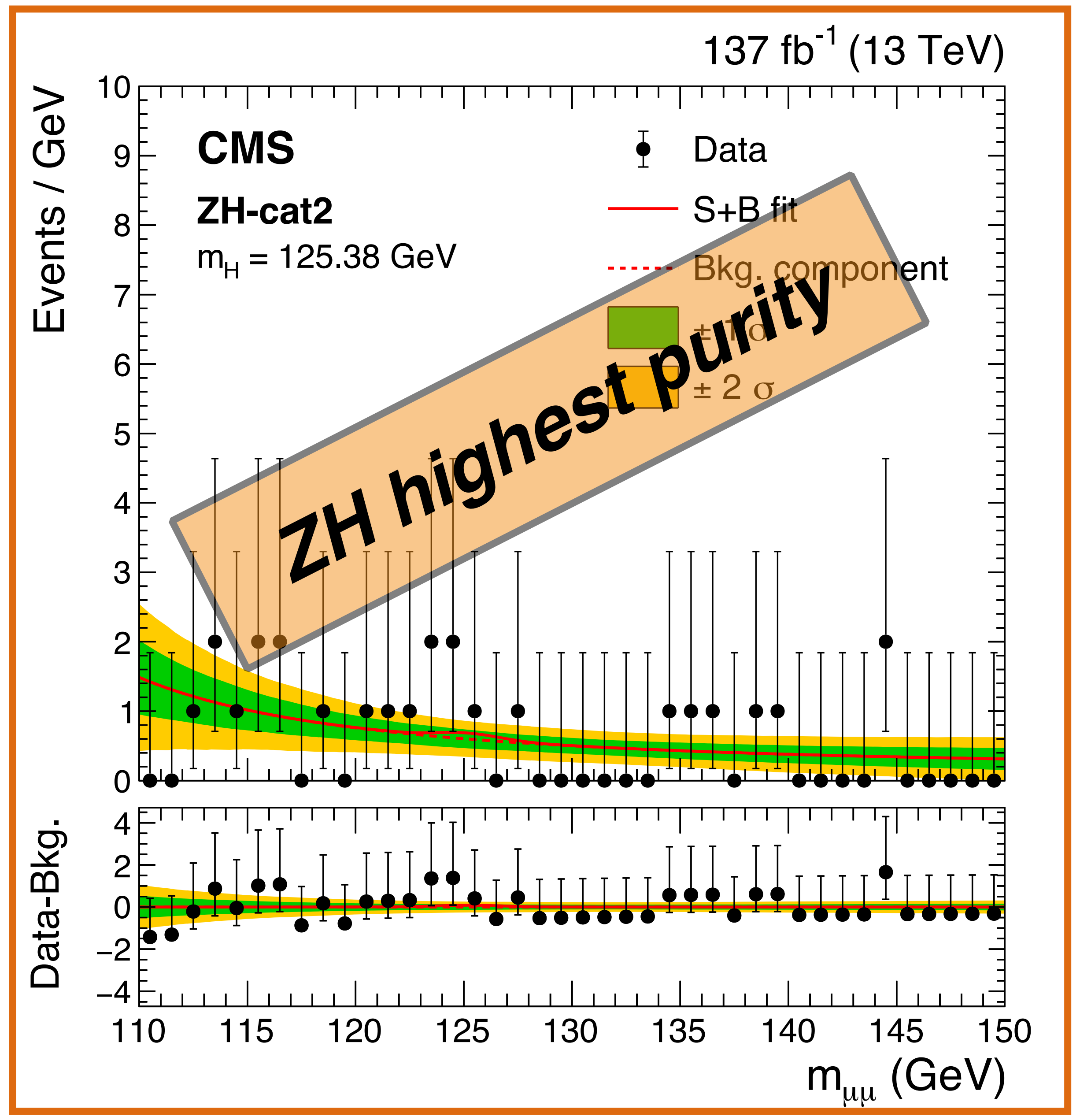


WH highest purity



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VH analysis results

- Simultaneous fit to $m_{\mu\mu}$ of the five event categories
- Reference m_H of 125.38 GeV
- ***Expected*** significance of 0.4σ
- ***Observed*** significance of 2.0σ
- **Signal strength** $\mu = 5.48^{+3.10}_{-2.83}$

ggH(μμ) analysis

Divide-n-fit strategy is employed in the signal extraction

BDT training: input features

- **Higgs candidate:** p_T, rapidity, decay angles (ϕ_{CS}, $\cos(\theta)_{CS}$)
- η and $p_T/m_{\mu\mu}$ of the muons from Higgs candidate
- N_{jets}, p_T and η of the leading jet
- ***Events $N_{jets} = 1$***: $\Delta\eta(\mu\mu,j)$ and $\Delta\phi(\mu\mu,j)$
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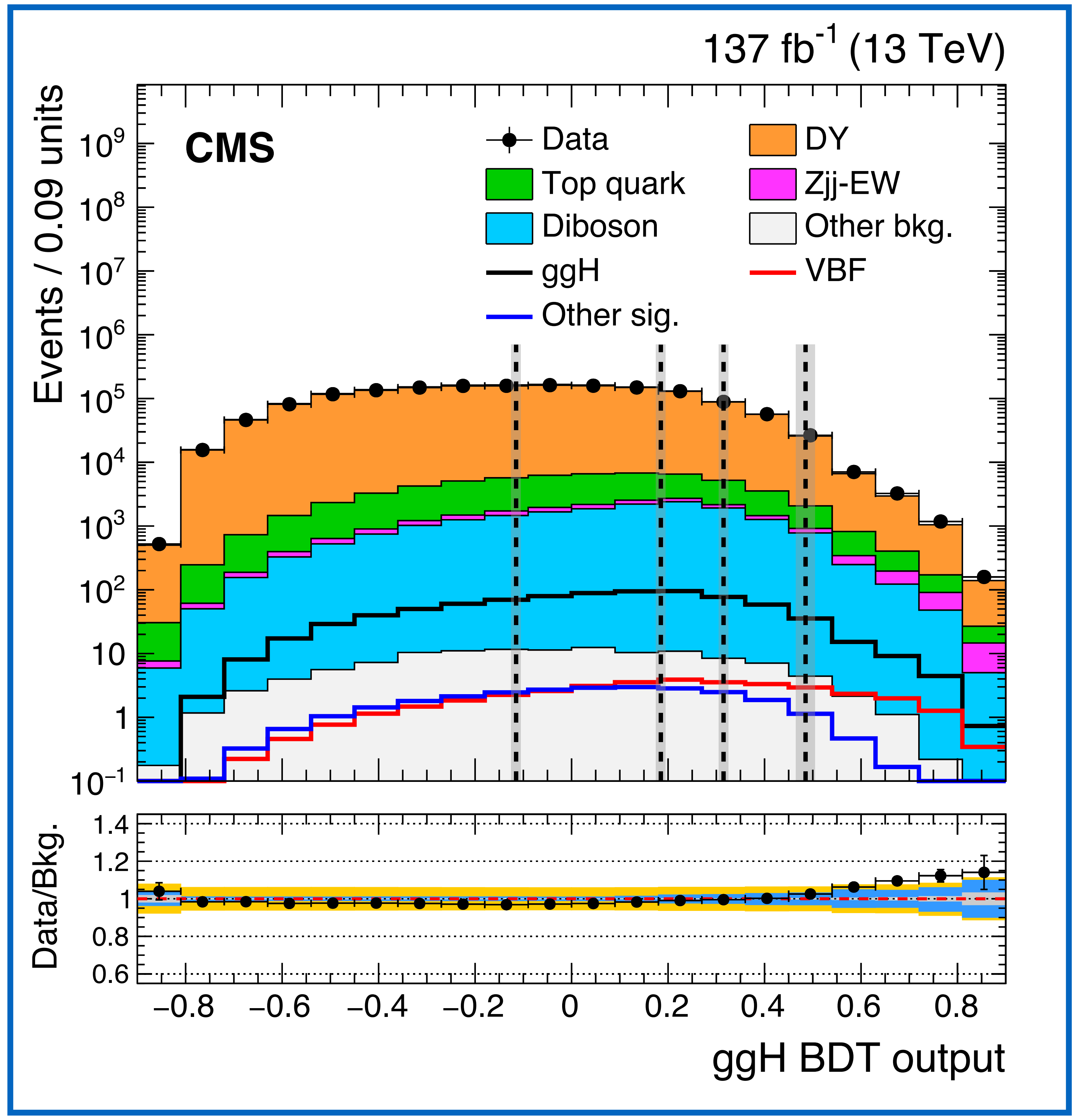

$m_{\mu\mu}$ resolution

- Signal events ***weighted*** according to σ_m/m during training
- Events with ***high $m_{\mu\mu}$ resolution*** promoted to ***high score***
- Muon p_T resolution evolves non-trivially with (p_T,η, etc.)

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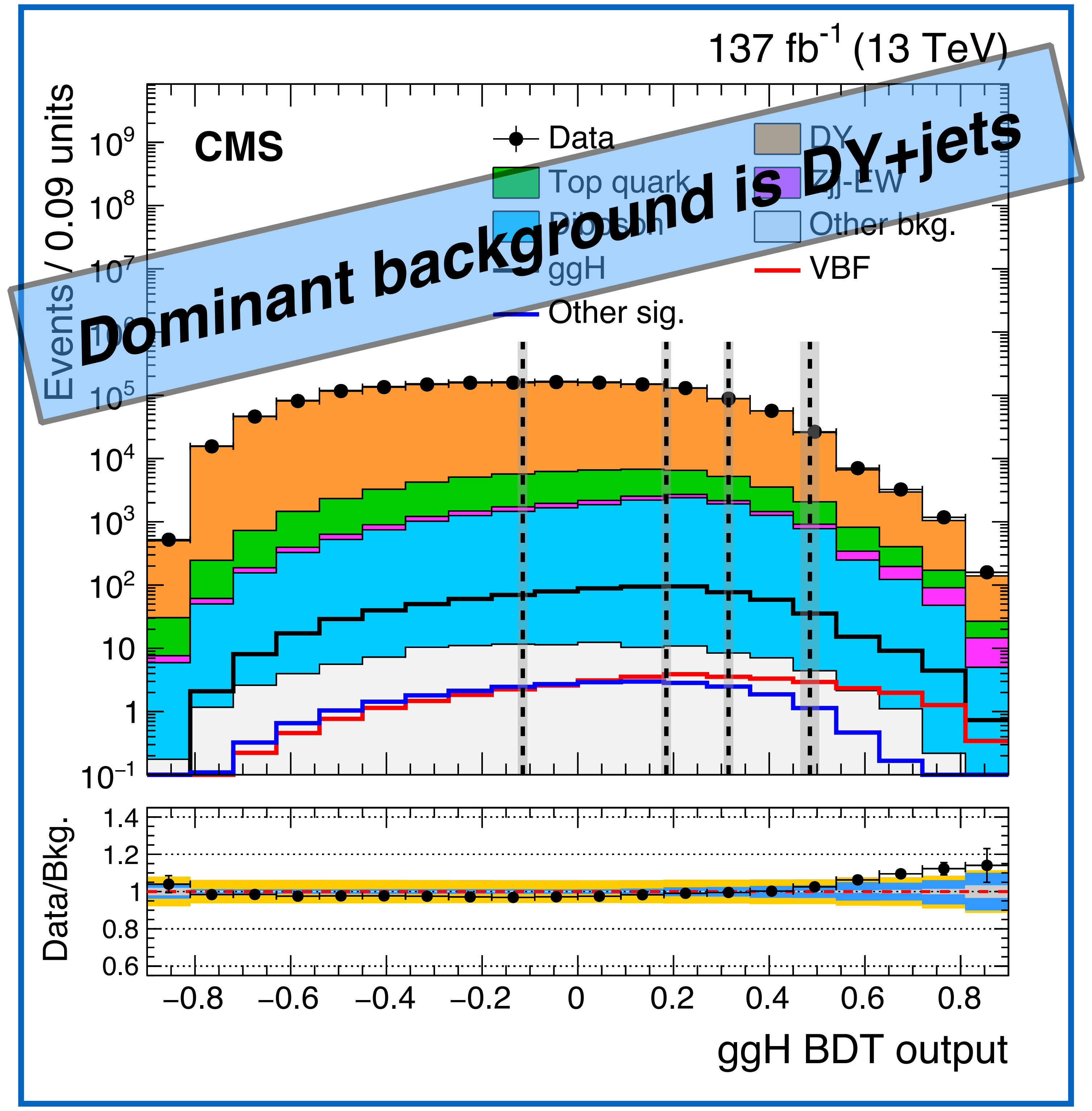

Dominant background is DY+jets

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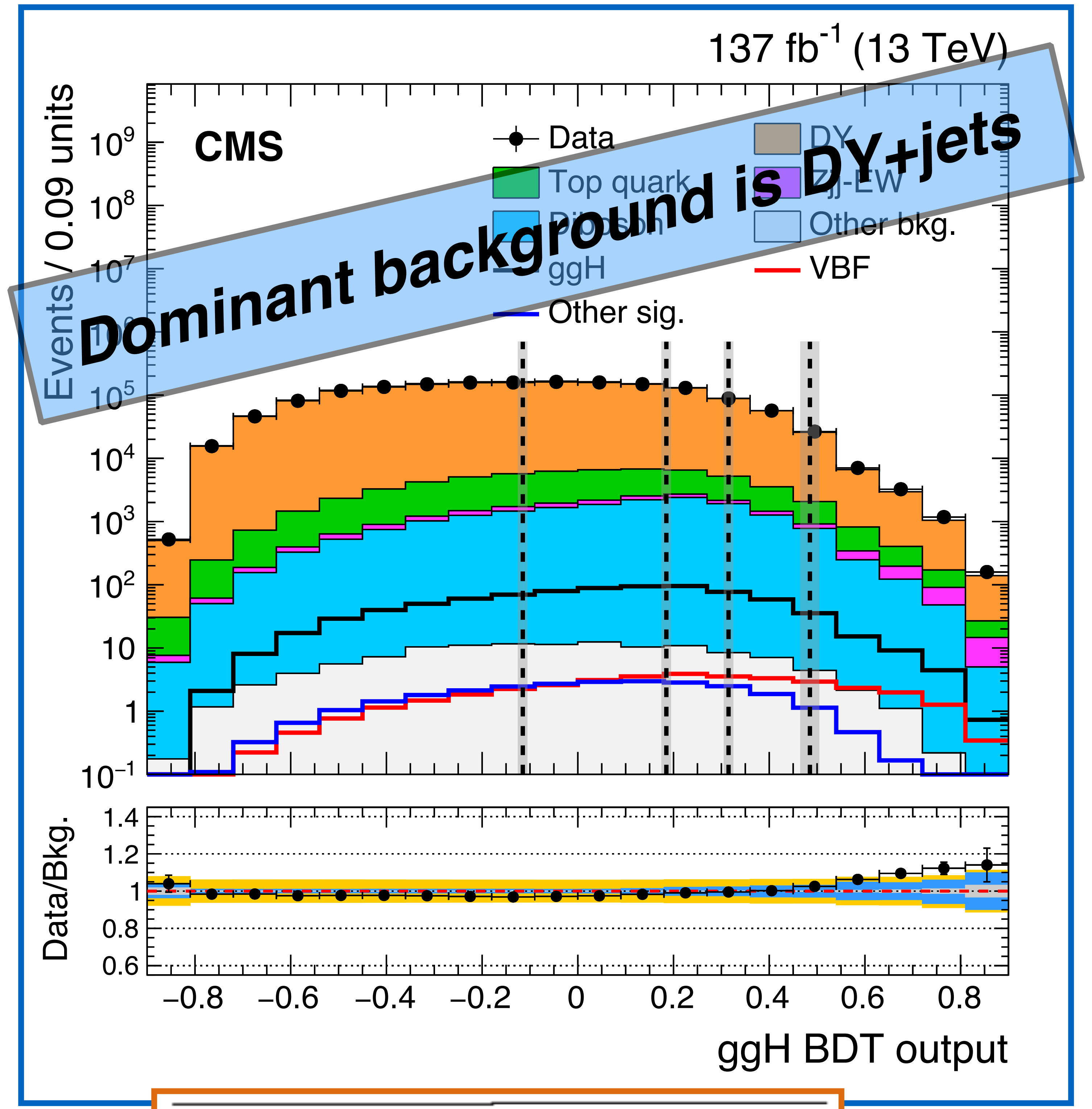

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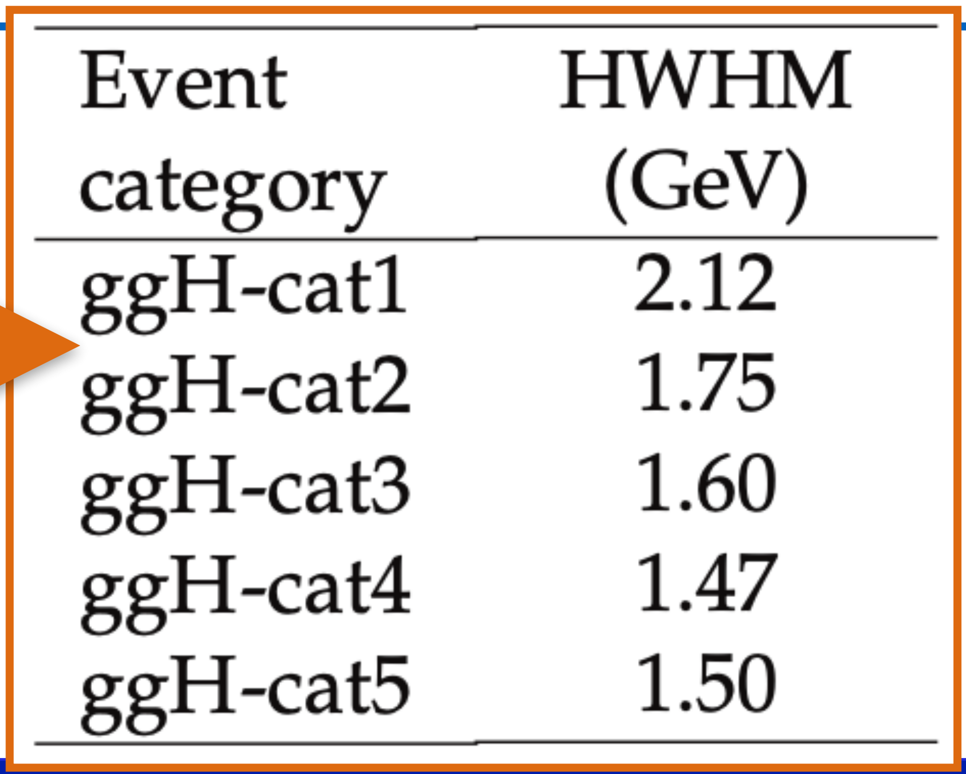
Five optimized subcategories



Event category	HWHM (GeV)
ggH-cat1	2.12
ggH-cat2	1.75
ggH-cat3	1.60
ggH-cat4	1.47
ggH-cat5	1.50

ggH(μμ) analysis: background extraction

- The ***“classical approach”*** is to fit the $m_{\mu\mu}$ distribution in each subcategory independently

ggH(μμ) background composition

- Background composition well known from simulation
- ***Background shape*** *similar* across subcategories driven by DY+jets events
- ***Minor variations*** across subcategories due to difference in muon kinematics and mass resolution

Background model in a subcategory = ***Core function*** X ***Per-category shape modifier*** X ***Background yield***

Core function

- ***Common shape*** across categories
- ***Parameters*** are ***constrained*** by data in ***all categories***

Per-category shape modifier

- ***Parameters*** are ***uncorrelated*** across categories
- ***Account*** for ***shape variations***

Background yield

- ***Per-category*** total ***background rate***

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- ategories
- d mass r

This background model allows to use fewer parameters to the describe the background w.r.t classical approach

It allows for a 10% improvement in the sensitivity while keeping a negligible bias in the signal extraction

Background in a subca

e function

X

Per-category shape modifier

X

Background yield

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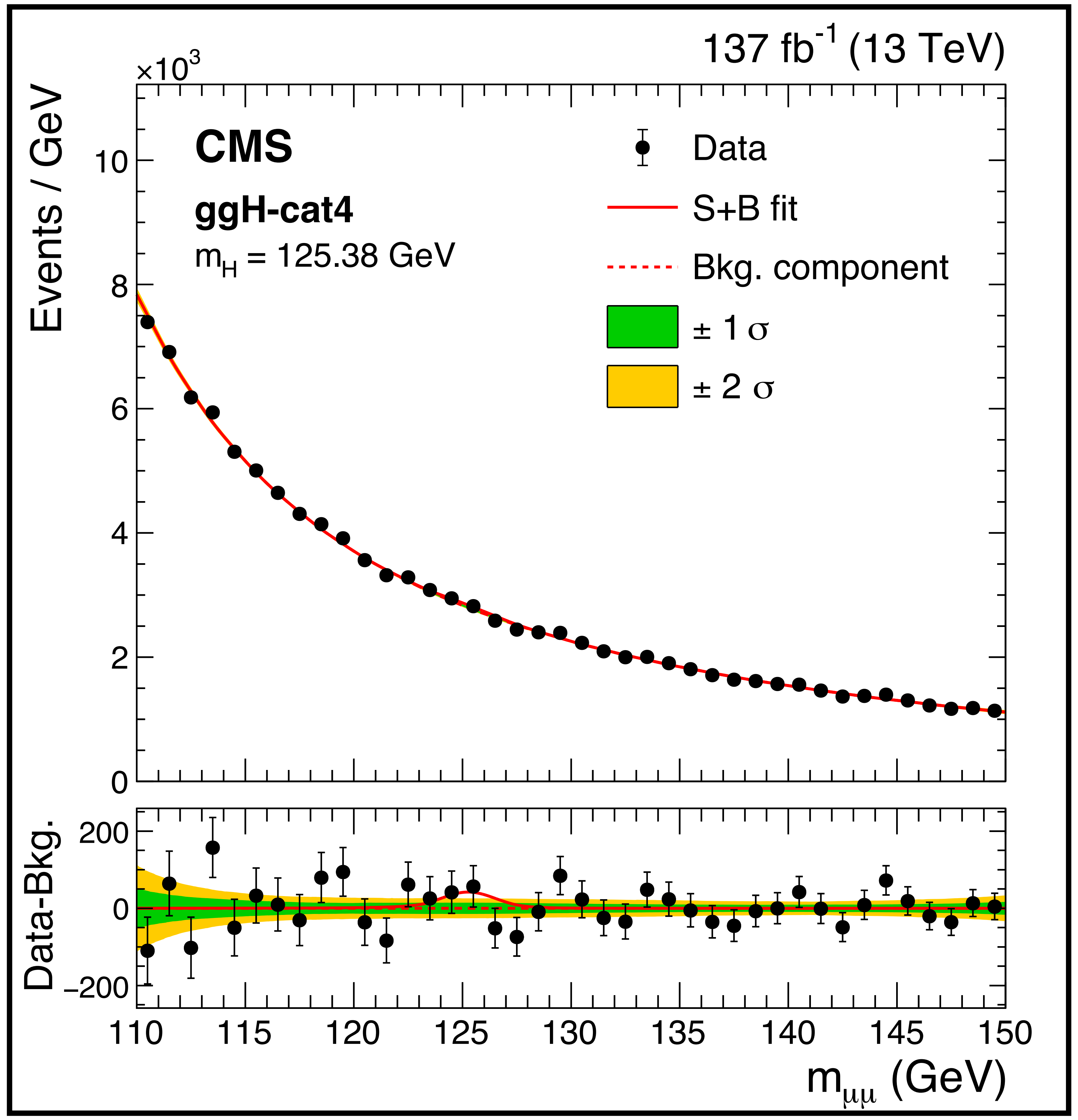
- ***Account*** for ***shape variations***

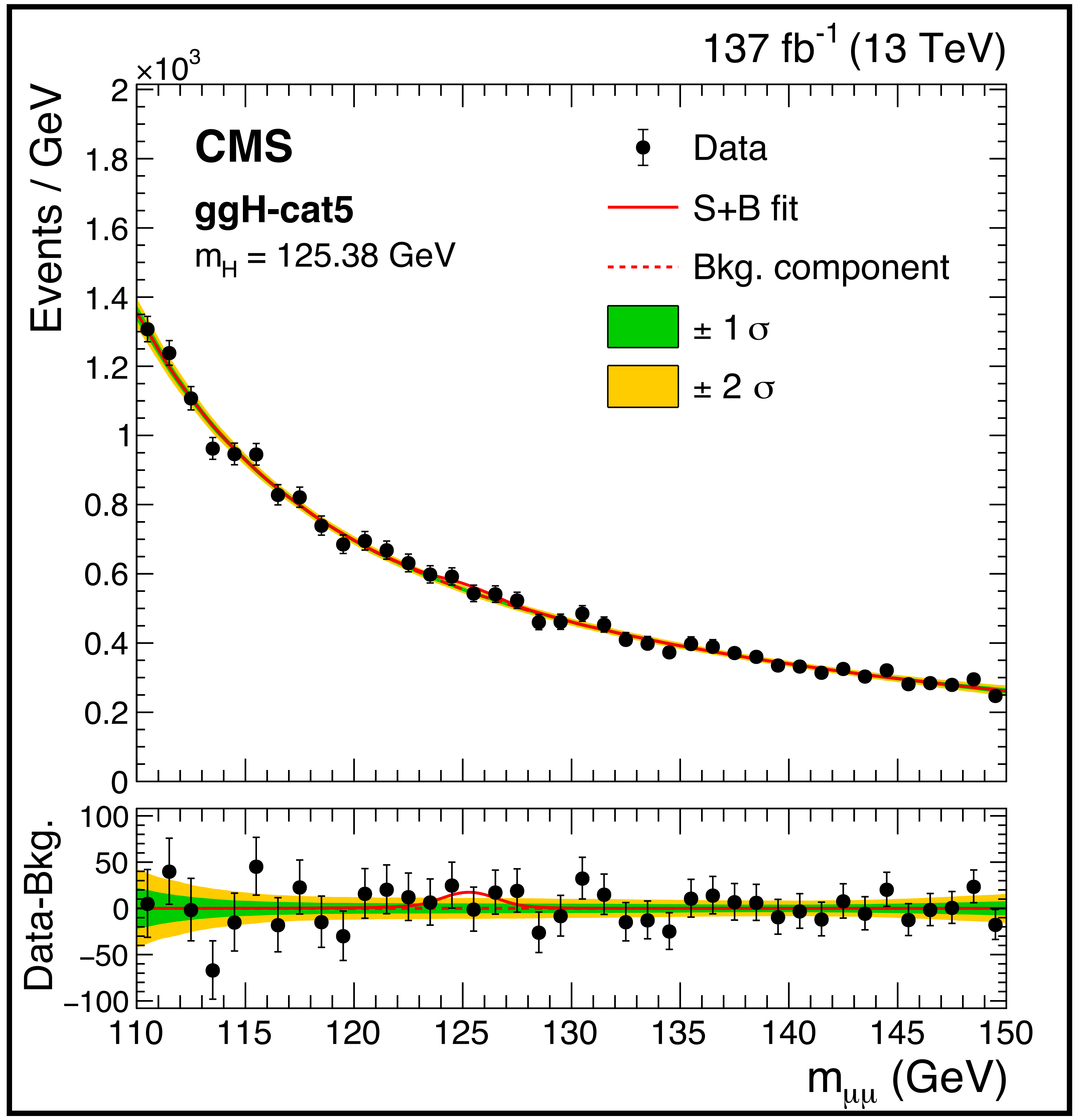
- ***Per-category*** total ***background rate***

ggH(μμ) analysis results

- ***Divide-n-fit*** strategy → **five** event subcategories
- ***Signal*** $m_{\mu\mu}$ distributions parametrised via Double Crystal-Ball function
- ***Background*** $m_{\mu\mu}$ mass distributions modelled via the method described before

Highest purity ggH categories





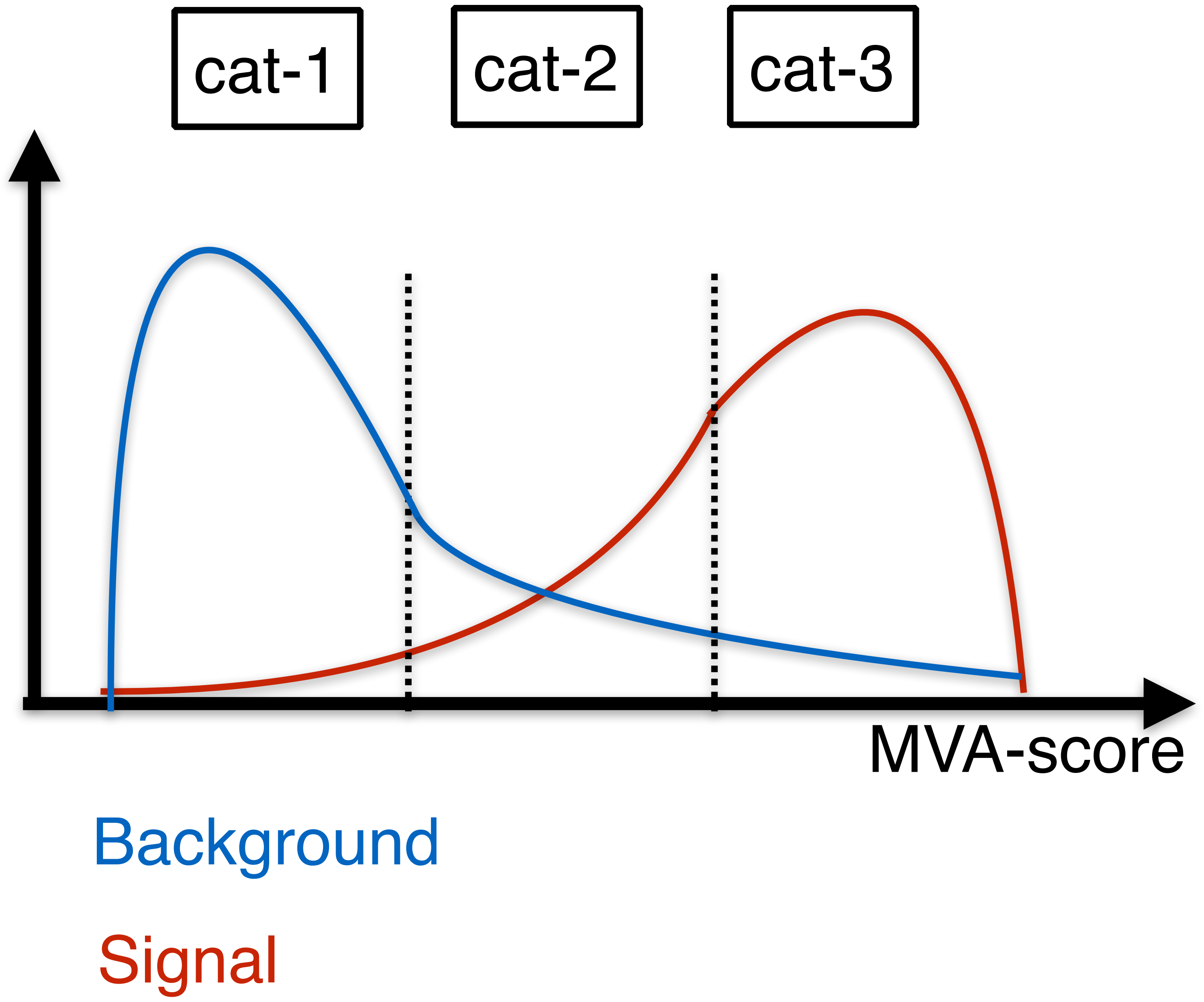
ggH analysis results

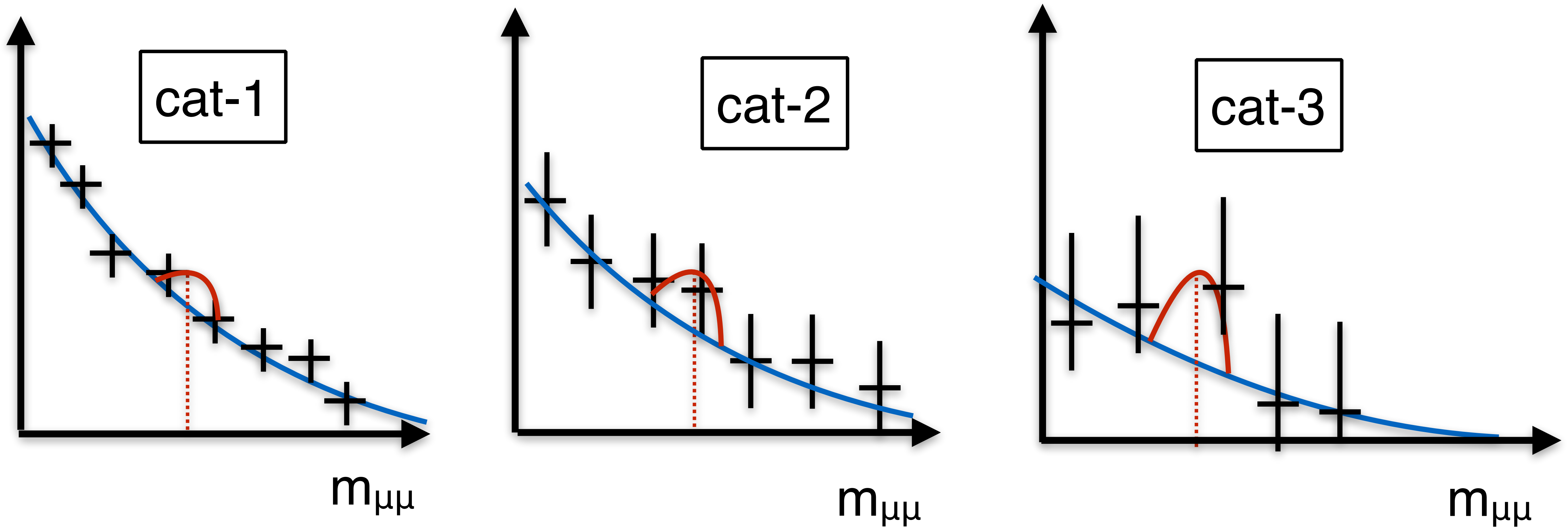
- Reference m_H of 125.38 GeV
- ***Expected*** significance of 1.6σ
- ***Observed*** significance of 1.0σ
- **Signal strength** $\mu = 0.63^{+0.65}_{-0.64}$

VBF H(μμ) analysis strategy

- ***Pros of divide-n-fit strategy:*** fully data-driven background estimate
  - Useful when the background ***cannot*** be reliably ***modelled via simulation***
  - Useful when an alternative analysis based on MC predictions is ***systematically limited***

- ***Cons of divide-n-fit strategy:*** add categories at high signal purity does not improve the performance
  - At high signal purity, the small number of observed events in sideband may ***limit the sensitivity***





Moving from low to high MVA score, progressively smaller constraint power from the observed data in the mass sidebands

VBF analysis strategy

- In the VBF analysis it is possible to reach ***15-30% purity*** at ***high m_{jj} - $\Delta\eta_{jj}$***
  - In this regime: ***few events*** in the ***mass sidebands*** (SB) to ***constrain*** the ***bkg***. with a ***parametric fit***
  - ***30-50% uncertainty*** on the ***predicted background*** under the Higgs peak

Different approach simulation based

- ***Include $m_{\mu\mu}$*** in the MVA classifier
- Extract the signal via a ***fit to the MVA output***
- ***Background*** estimation ***from simulation***

** Analysis strategy inspired from the one used in the H(bb) observation reported in PRL 121 (2018) 121801

Motivations

- ***DY*** and ***Zjj-EW*** simulations well reproduce the observation in data as in EPJC 78 (2018) 589
- ***Simulation*** provides a ***background prediction*** with ***better precision***, including systematics, than a parametric fit
- ***About 20% improvement*** in expected significance

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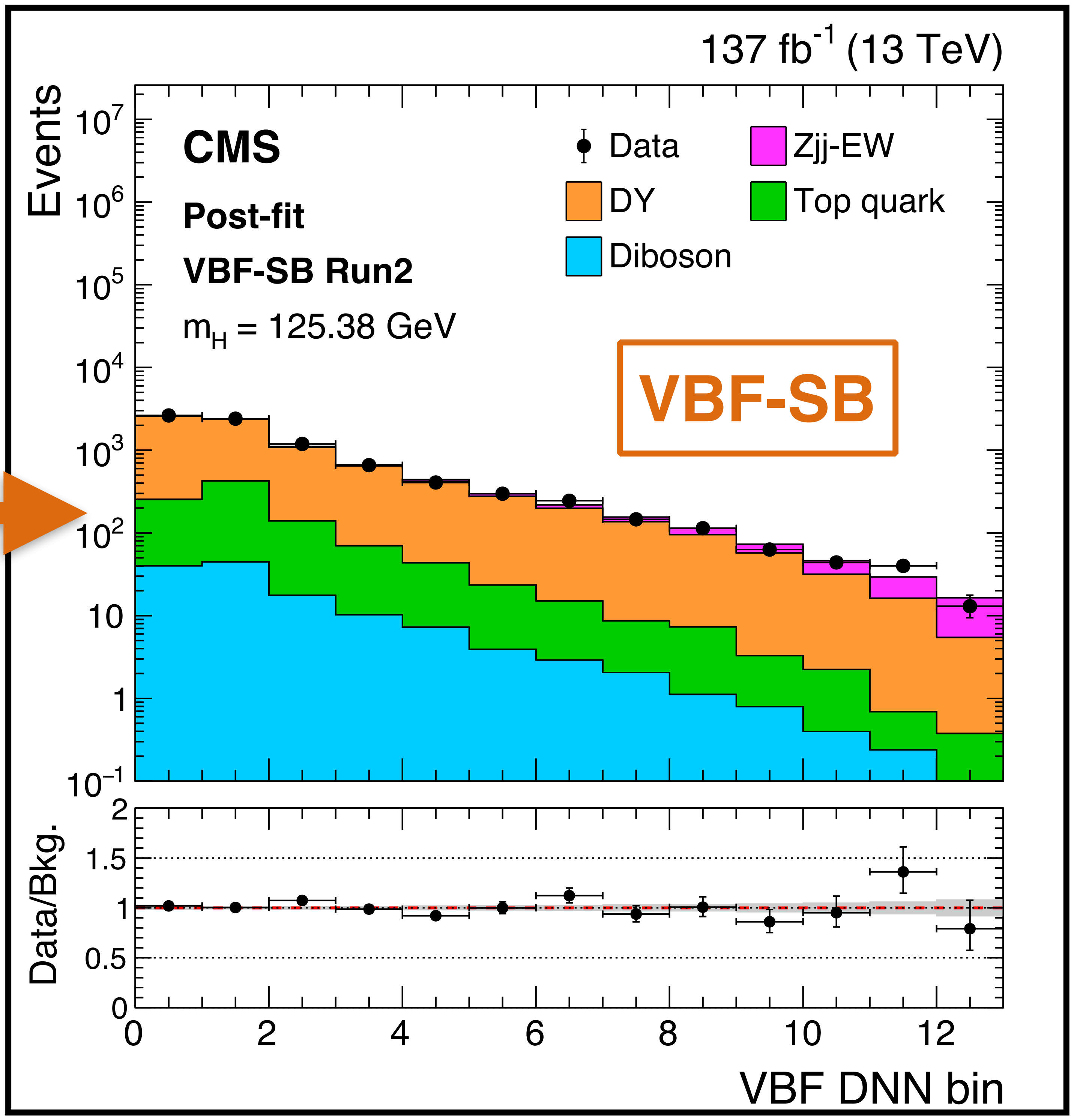
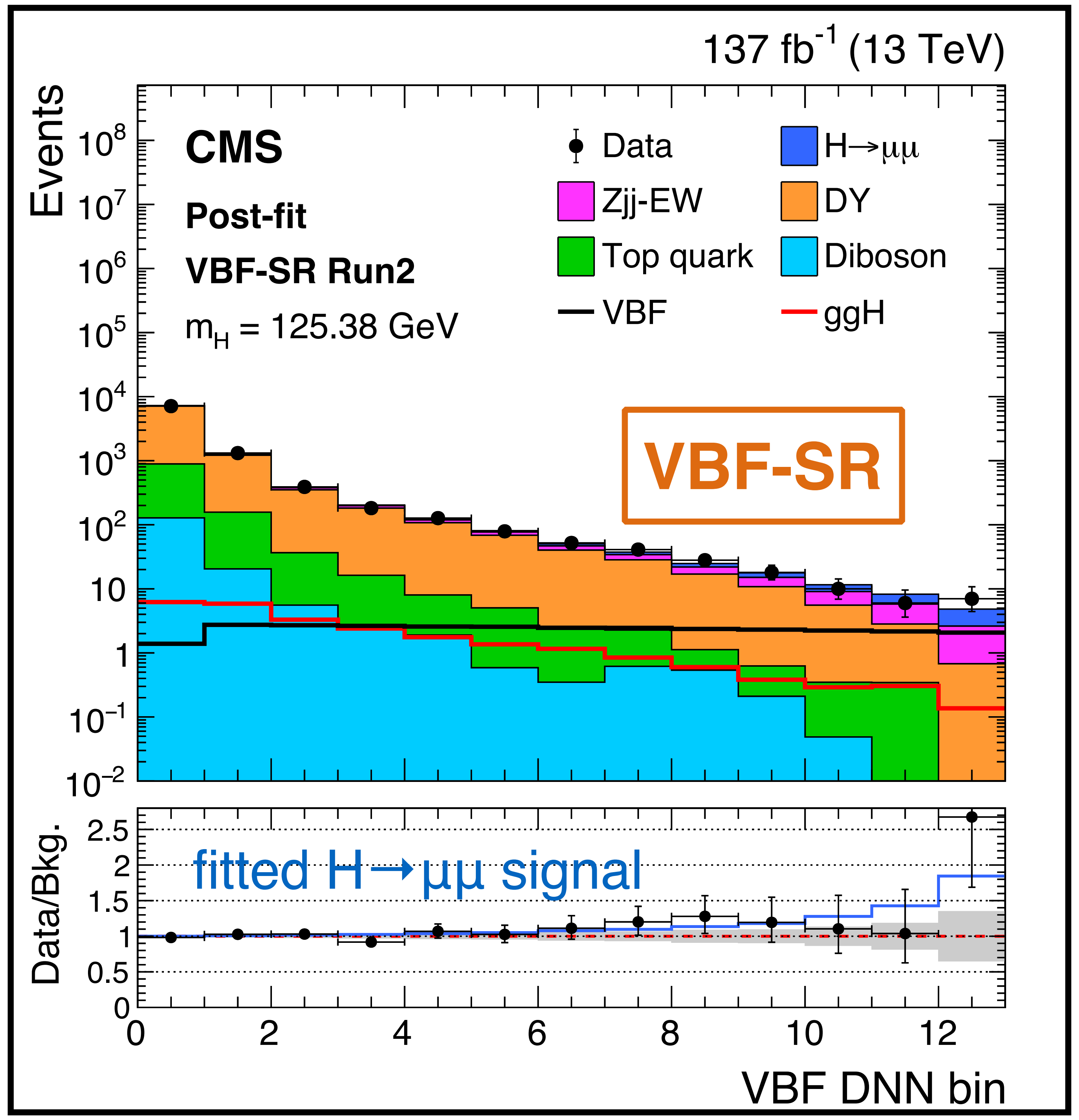
VBF DNN classifier

- ***DNN classifier*** trained to maximise the separation between VBF Higgs and backgrounds
  - **Higgs candidate: $m_{\mu\mu}$,** p_T, rapidity, and decay angles (ϕ_{CS} , $\cos\theta_{CS}$)
  - **VBF jets:** jet kinematics, $\Delta\eta_{jj}$, m_{jj}, $\Delta\phi_{jj}$, Zeppenfeld, p_T balance ($\mu\mu$,jj)
  - **Additional activity:** soft track-jets reconstructed from tracks associated to PV with $p_T > 5$ GeV

Binned template fit

- Fit performed ***simultaneously*** in ***SR*** and ***SB regions***
- **VBF-SR:** $115 < m_{\mu\mu} < 135$ GeV
- **VBF-SB:** $110 < m_{\mu\mu} < 115$ GeV or $135 < m_{\mu\mu} < 150$ GeV
- ***Mass-decorrelated DNN*** used in the VBF-SB





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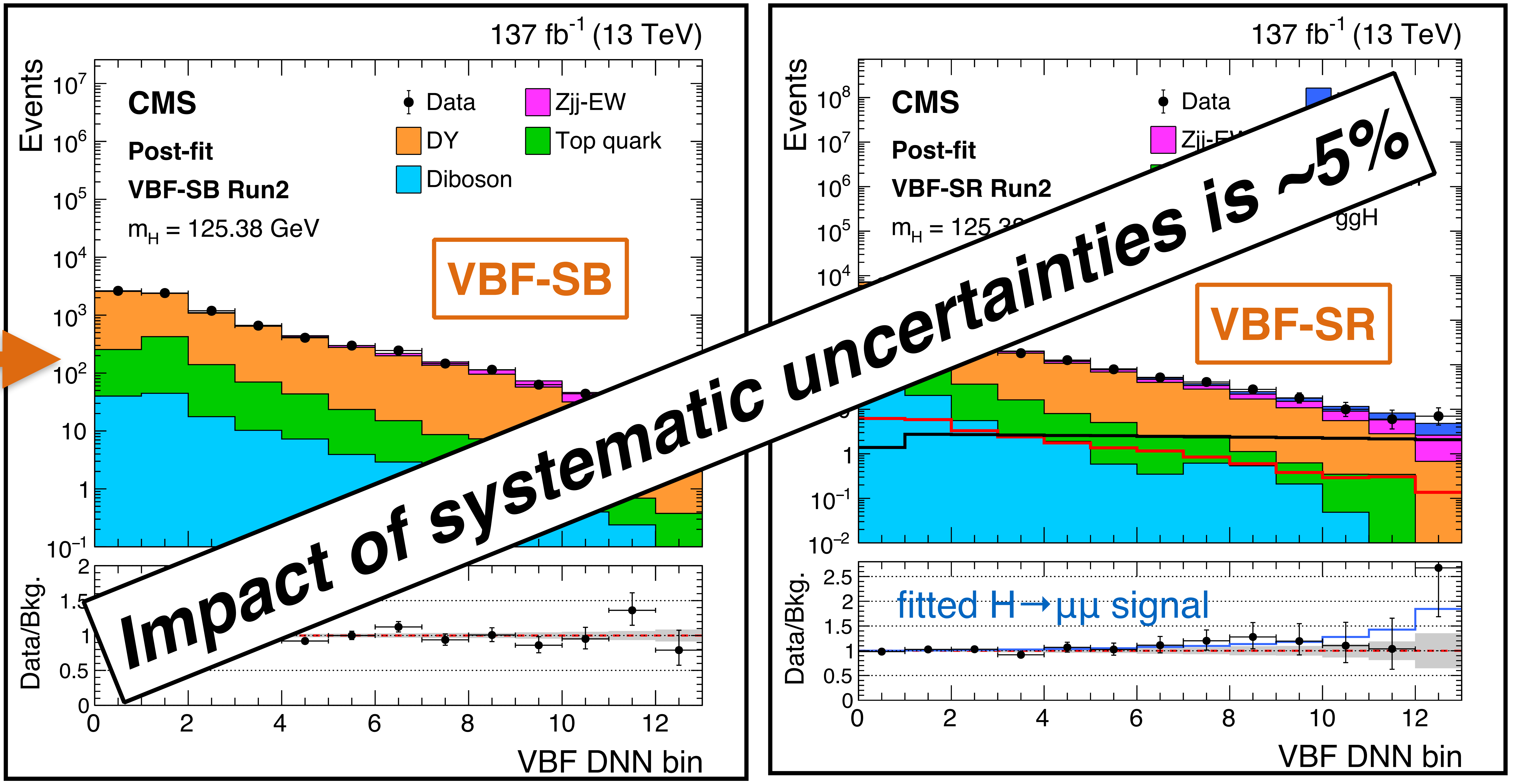
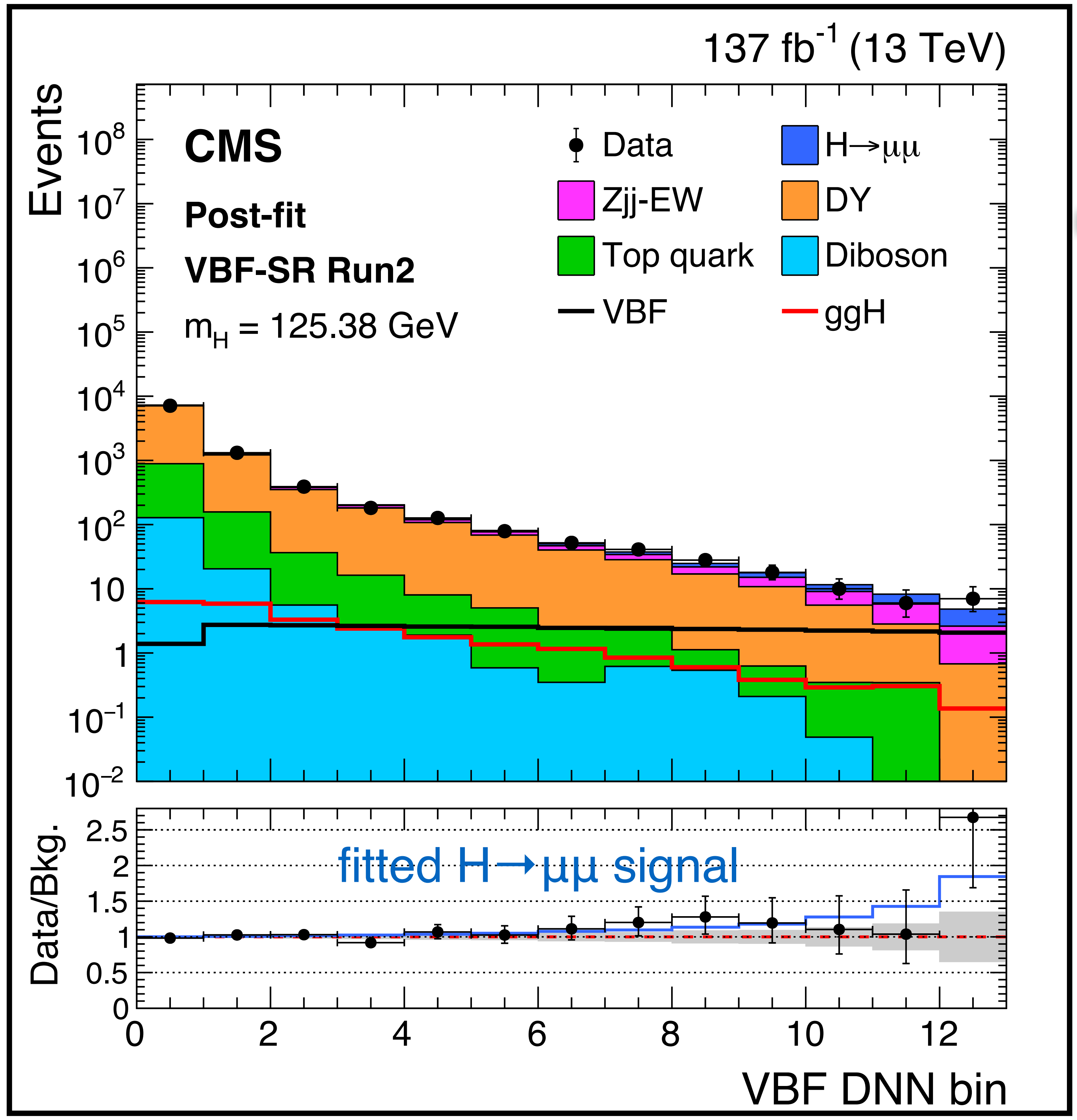


Impact of systematic uncertainties is ~5%

VBF-H(μμ): analysis results

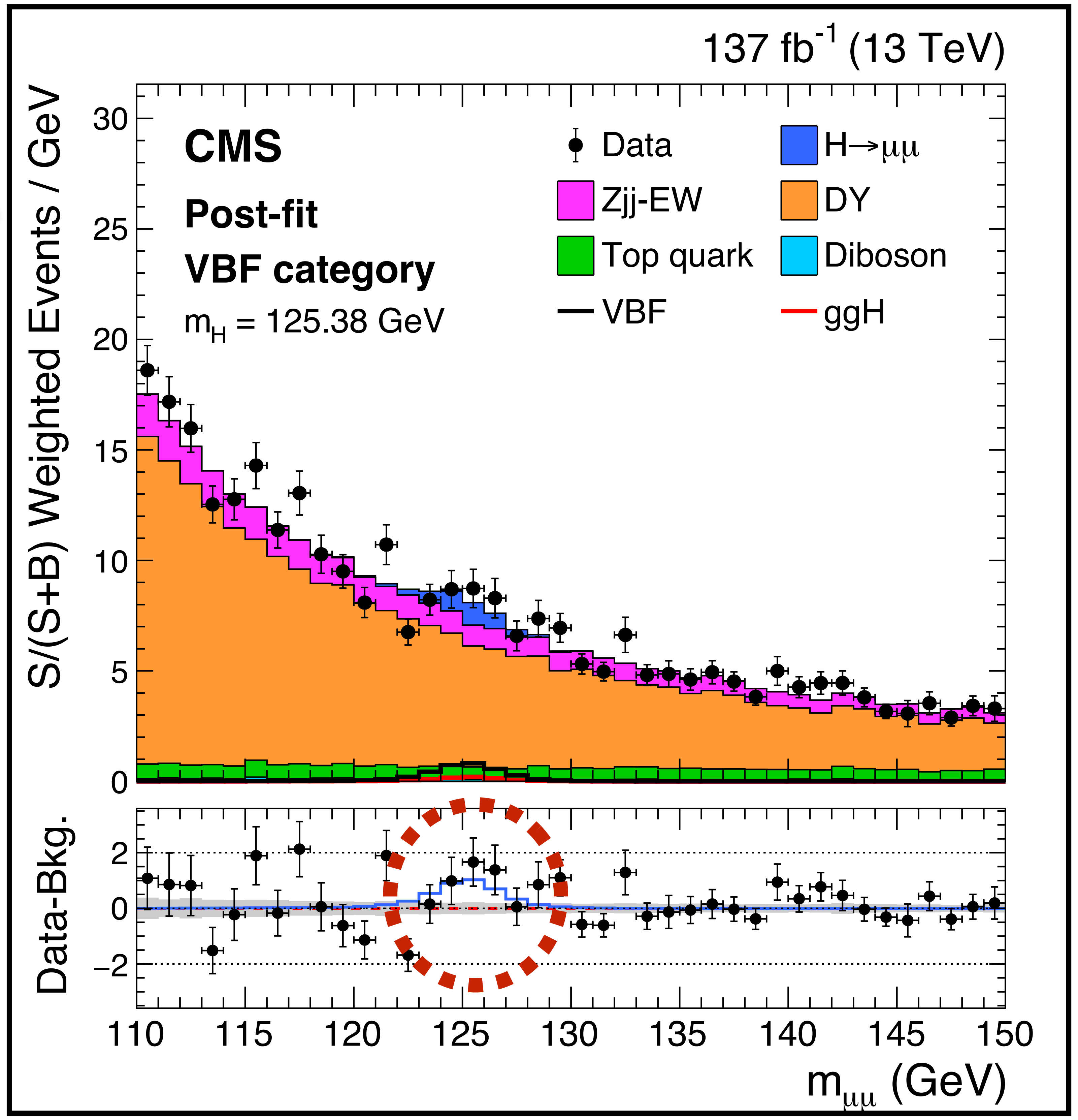
Signal extraction: simultaneous binned fit performed across data-taking periods, VBF-SB and VBF-SR regions

Result in VBF-SR



m(μμ)** distribution obtained via a mass de-correlation procedure. Events are **S/(S+B) weighted

for illustration only



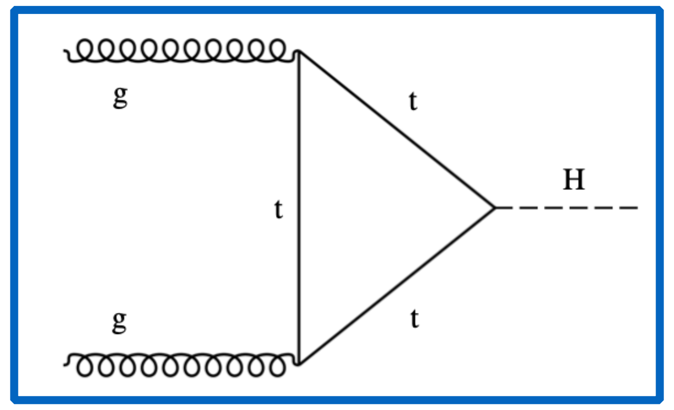
VBF category results

- Reference m_H of 125.38 GeV
- ***Expected*** significance of 1.8σ
- ***Observed*** significance of 2.4σ
- ***Signal strength*** $\mu = 1.36^{+0.69}_{-0.61}$

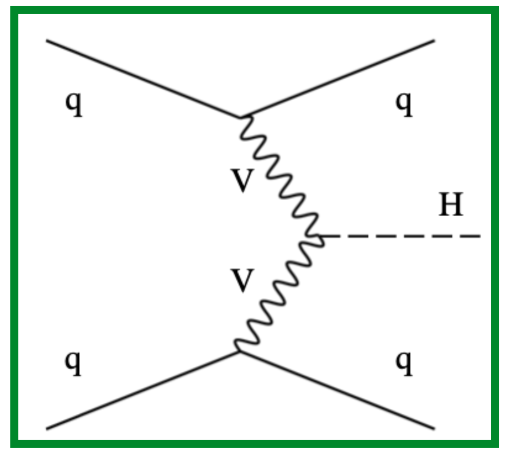
H(μμ) categories towards a combination …

- ***H→μμ analysis*** divided in ***exclusive production categories*** targeting ***ggH***, ***VBF***, ***VH***, and ***ttH*** modes
- Each of them is further ***divided into subcategories*** optimising the significance for H→μμ decays

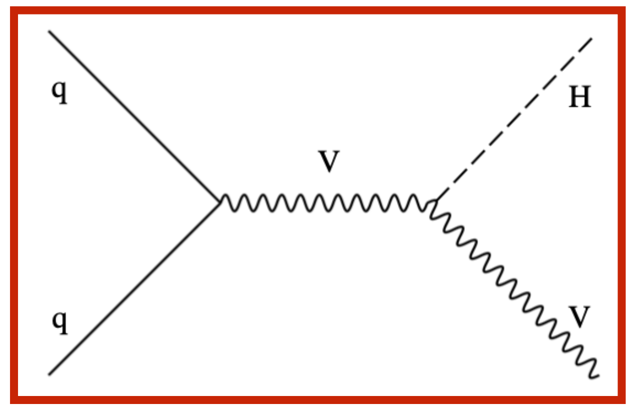
ggH



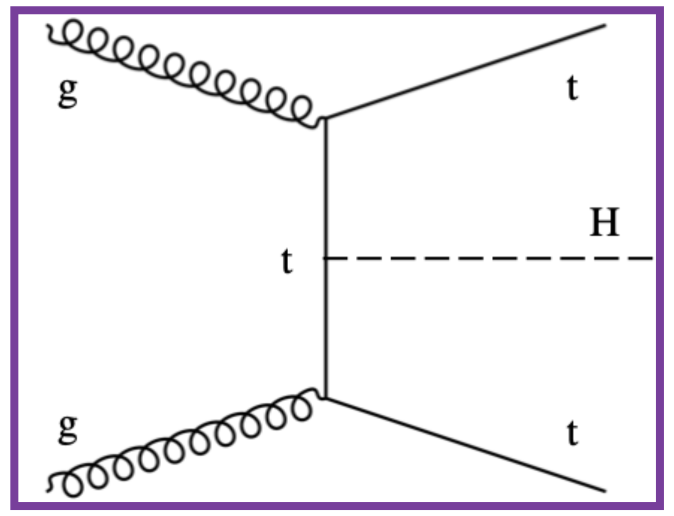
VBF

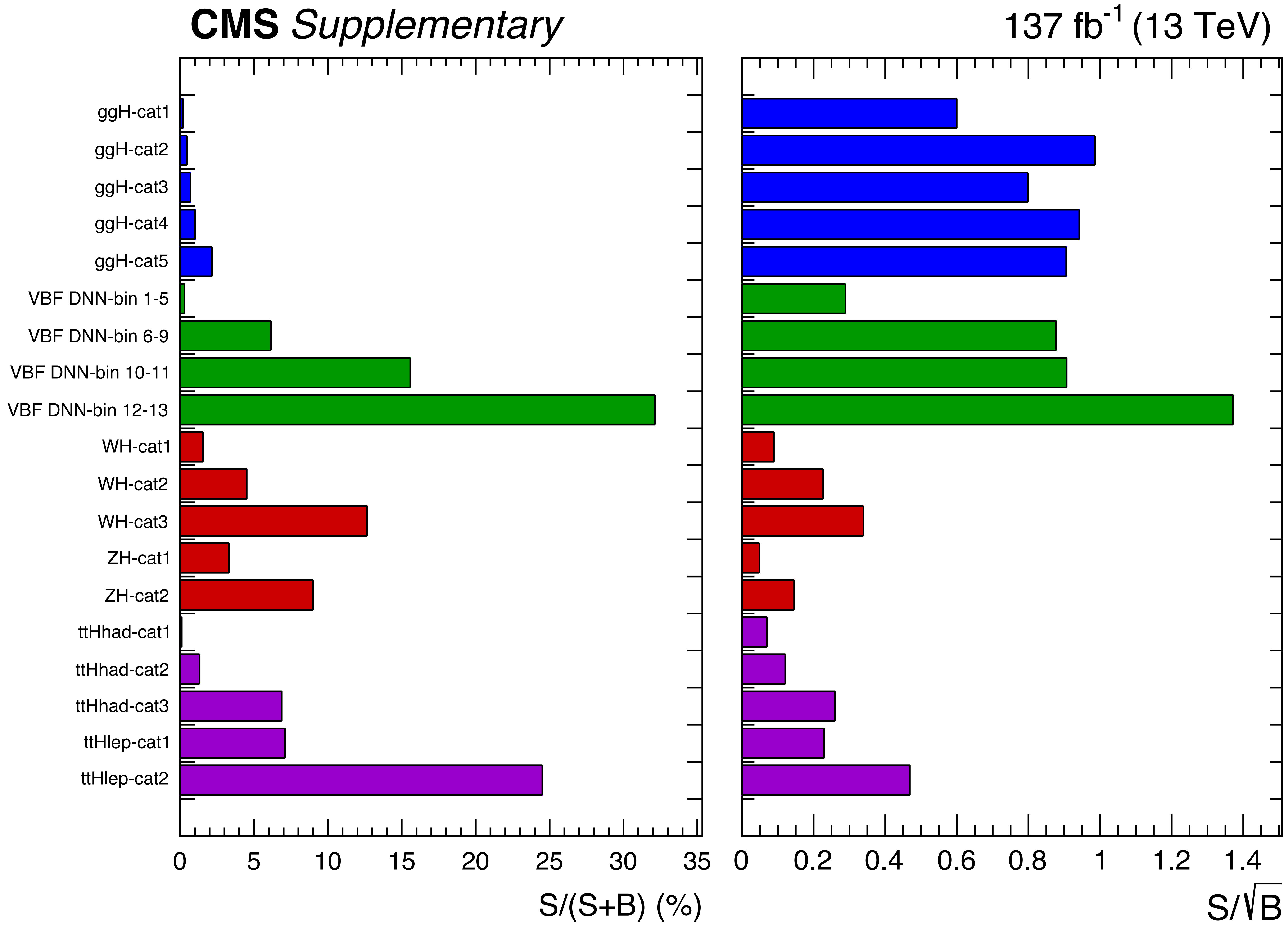


VH



ttH





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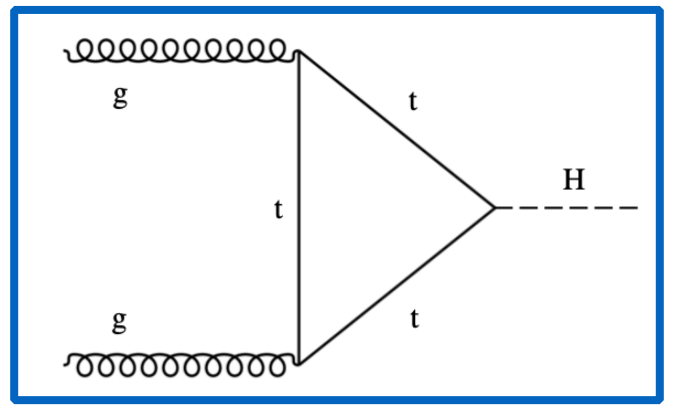
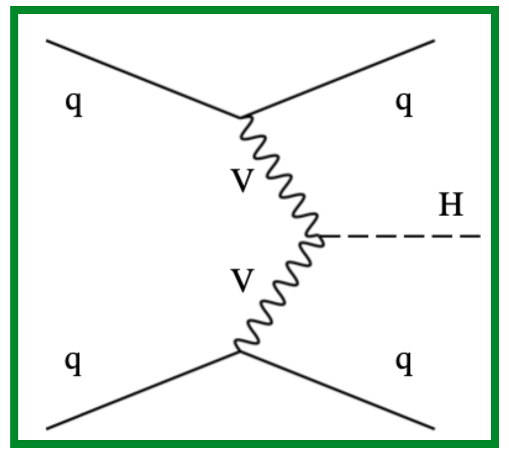
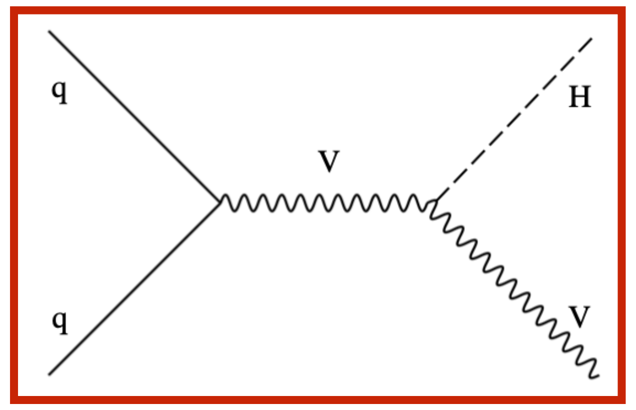


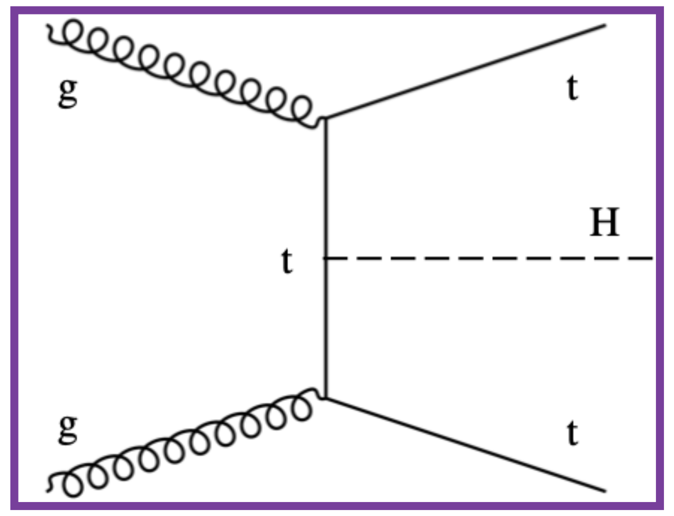
VBF

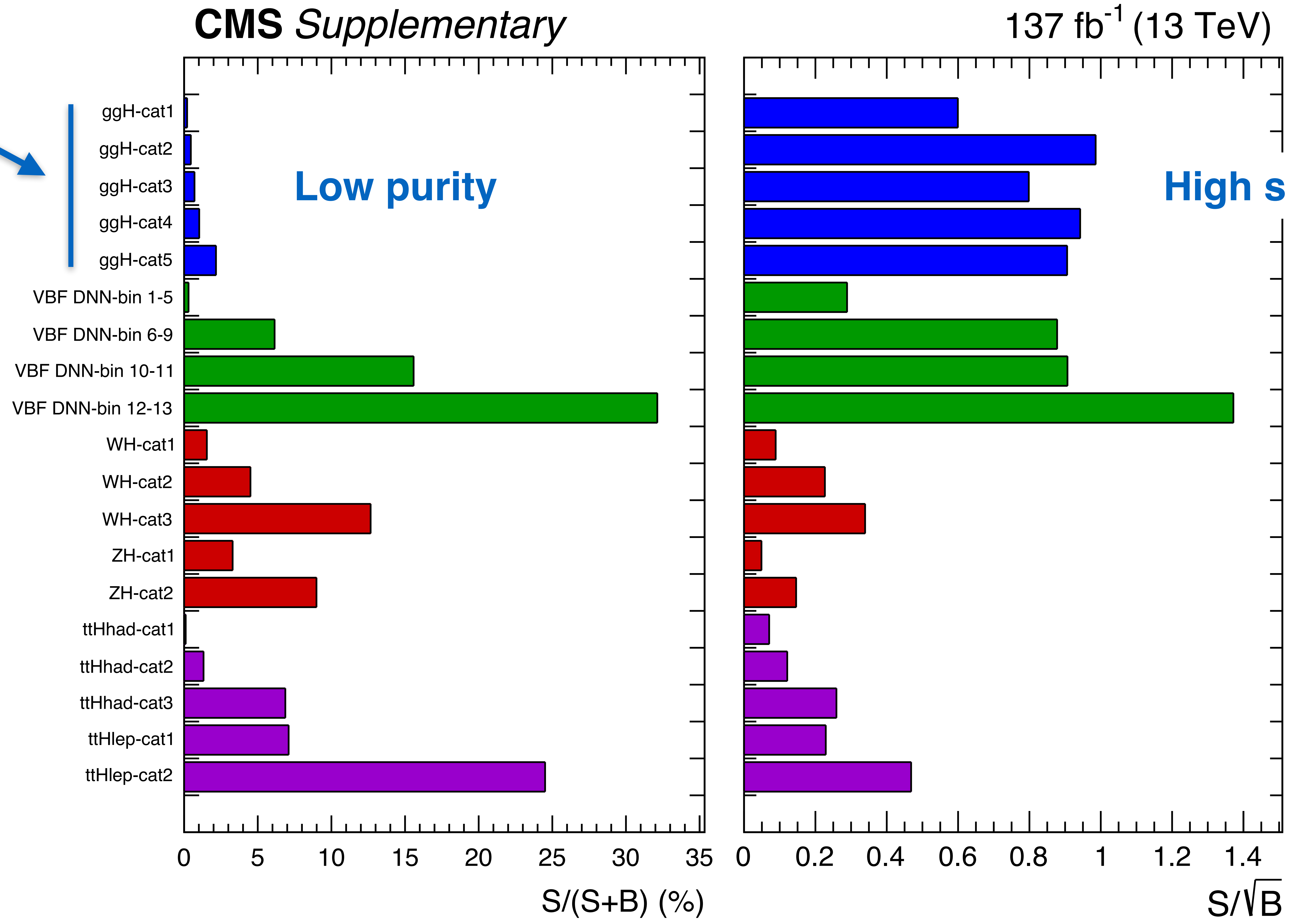


VH



ttH





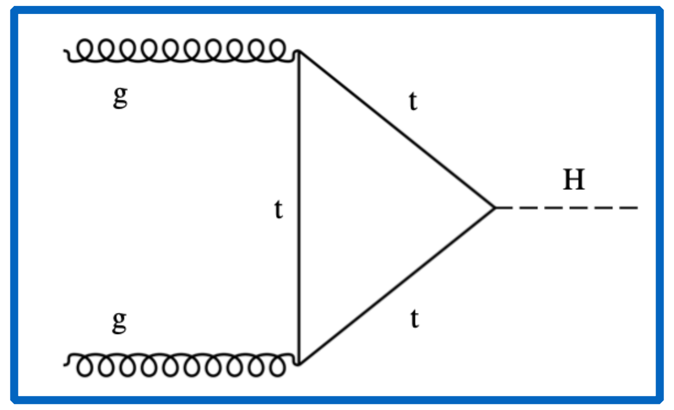
Low purity

High significance

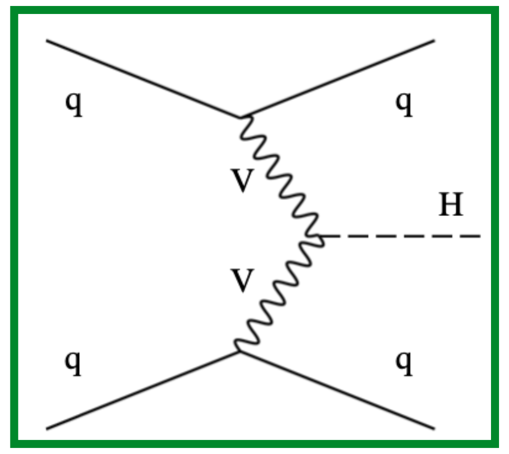
H(μμ) categories towards a combination …

- ***H→μμ analysis*** divided in ***exclusive production categories*** targeting ***ggH***, ***VBF***, ***VH***, and ***ttH*** modes
- Each of them is further ***divided into subcategories*** optimising the significance for H→μμ decays

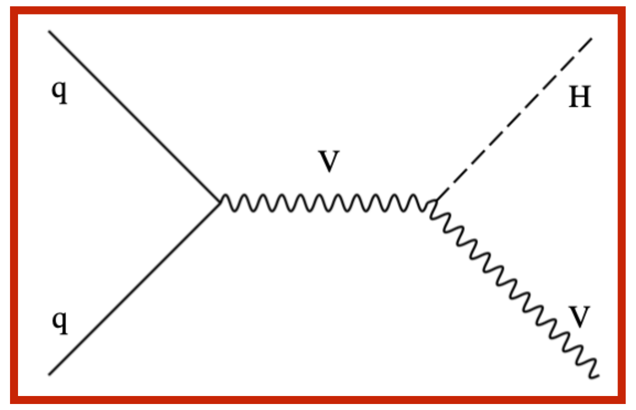
ggH



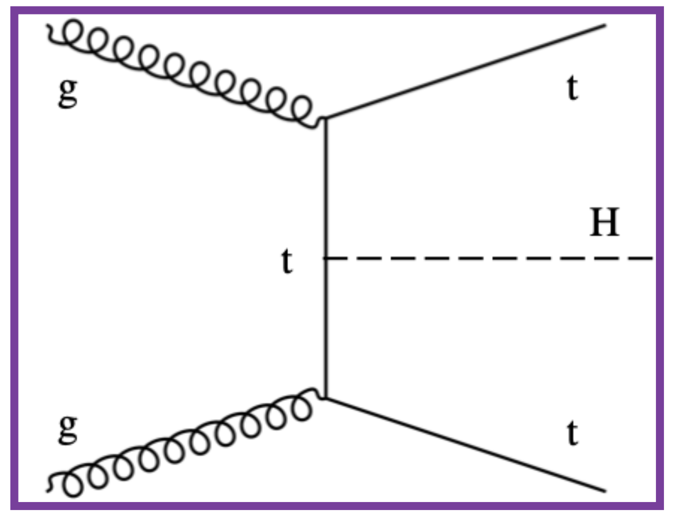
VBF

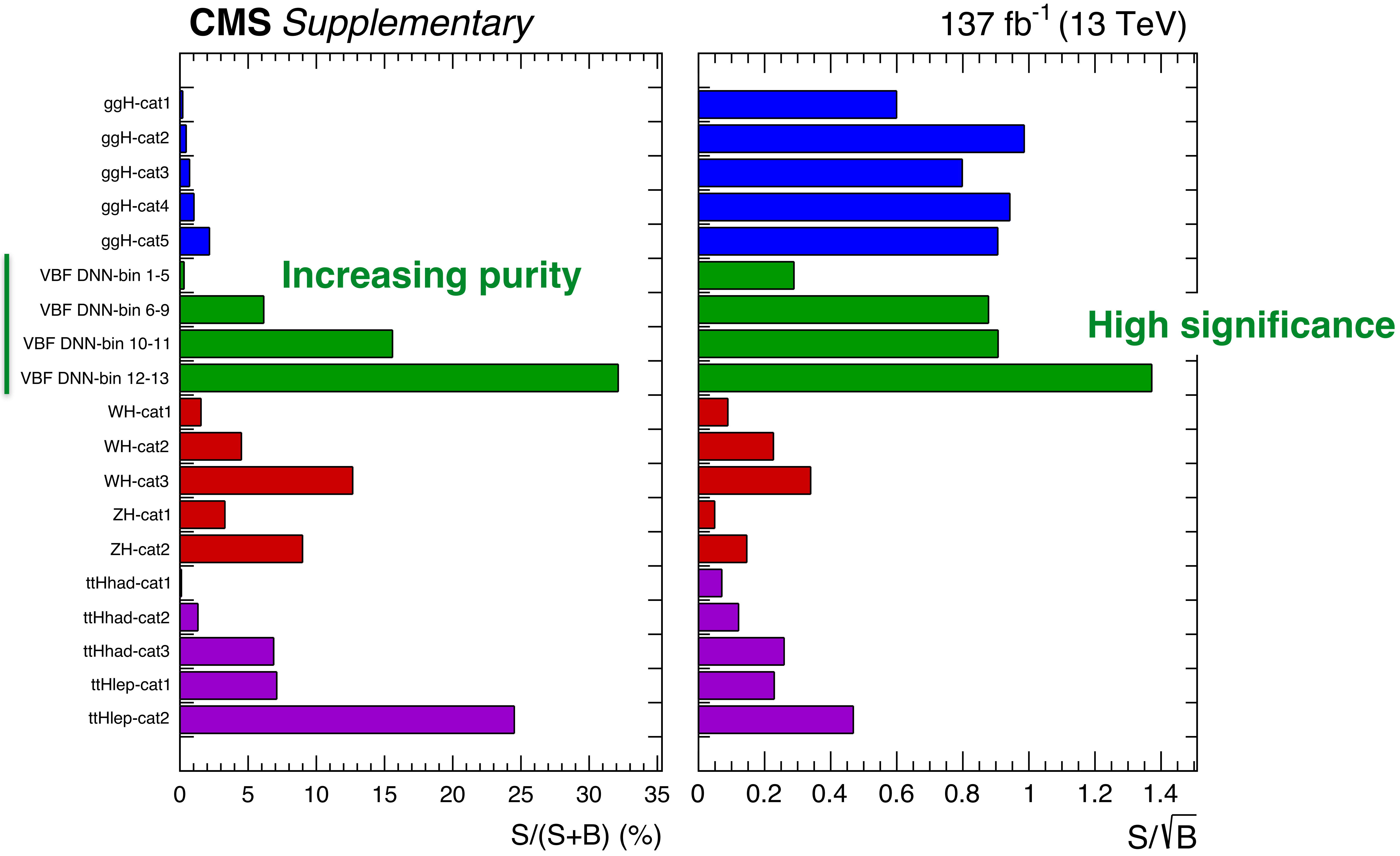


VH



ttH





Increasing purity

High significance

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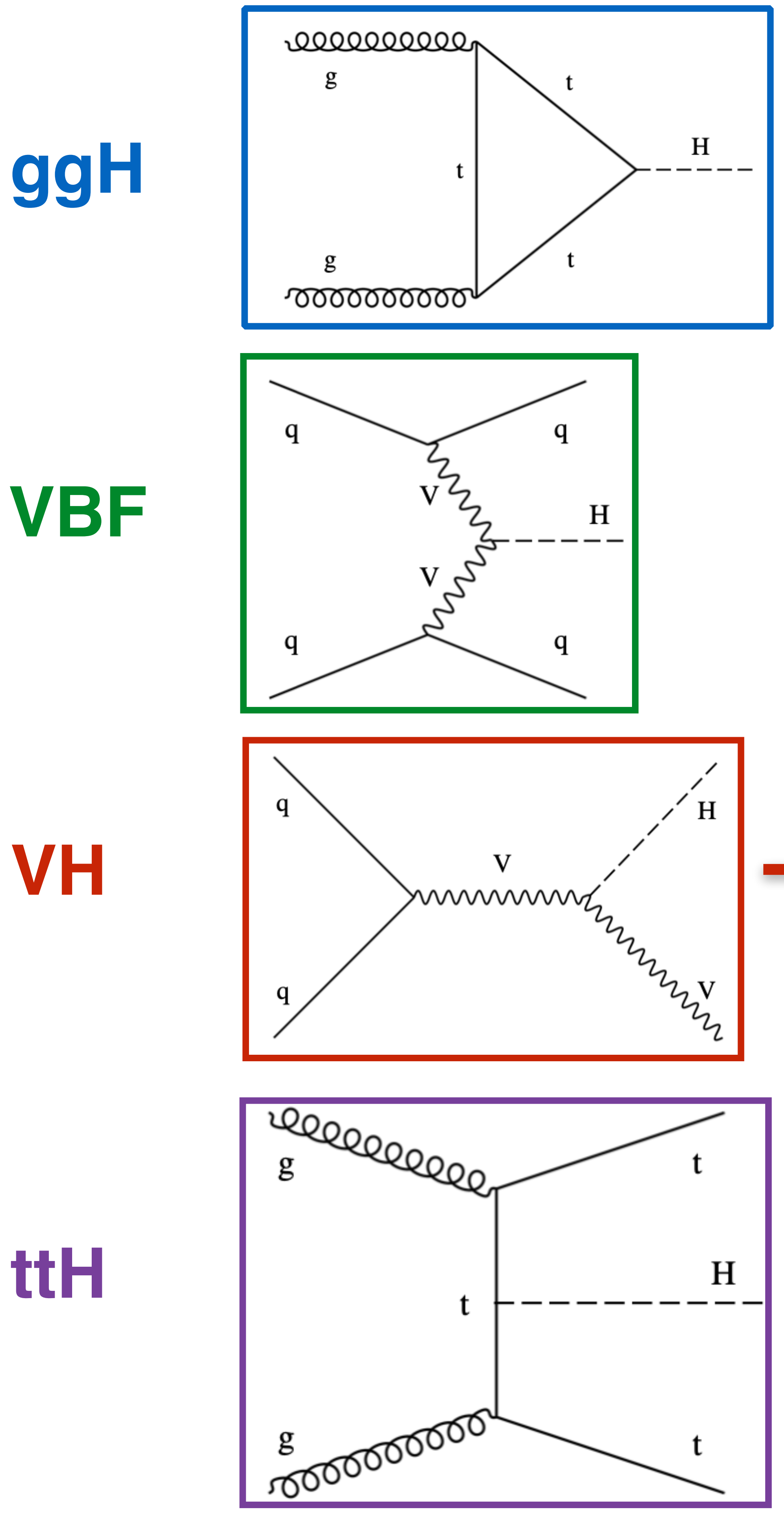

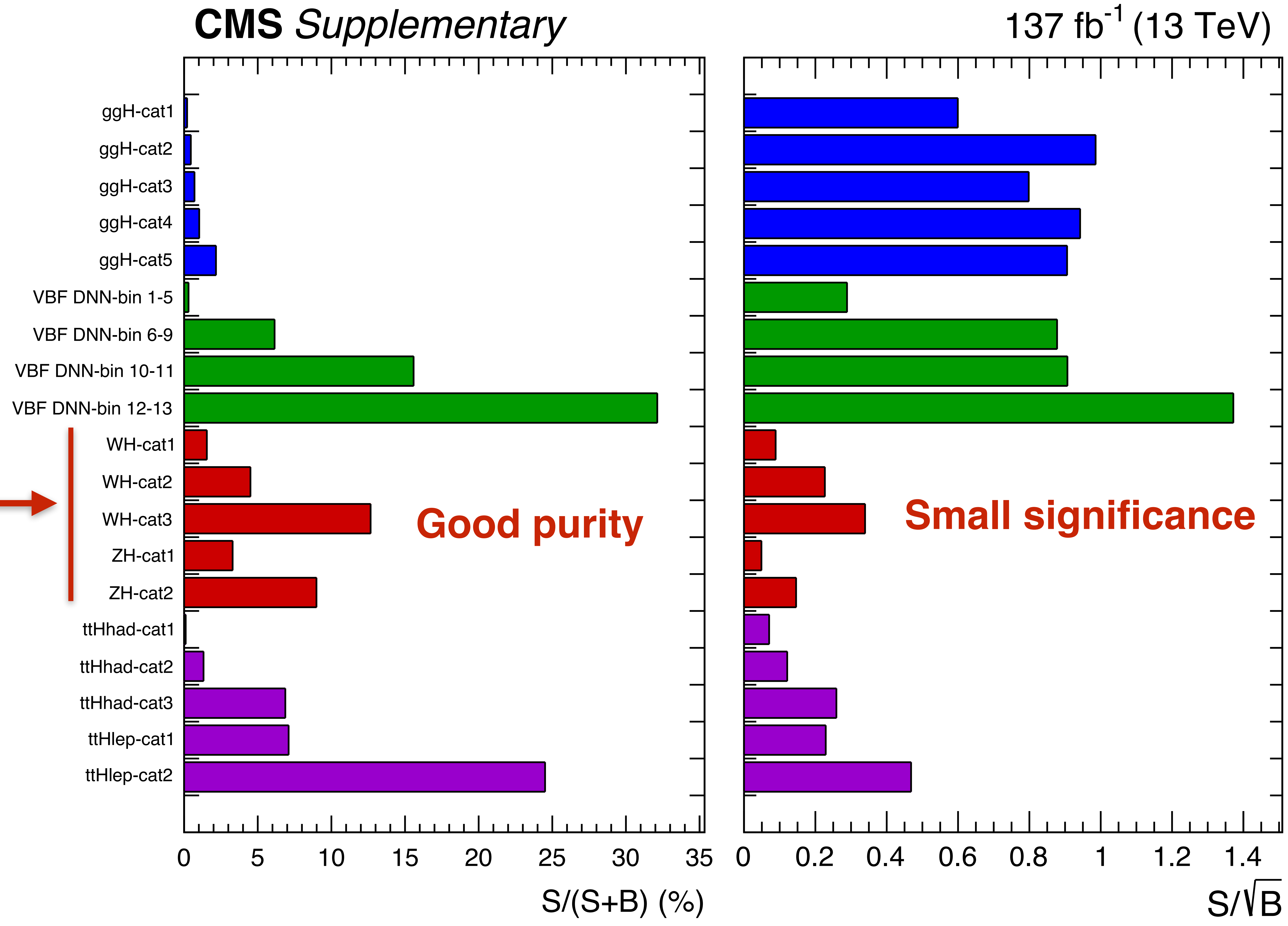

Good purity

Small significance

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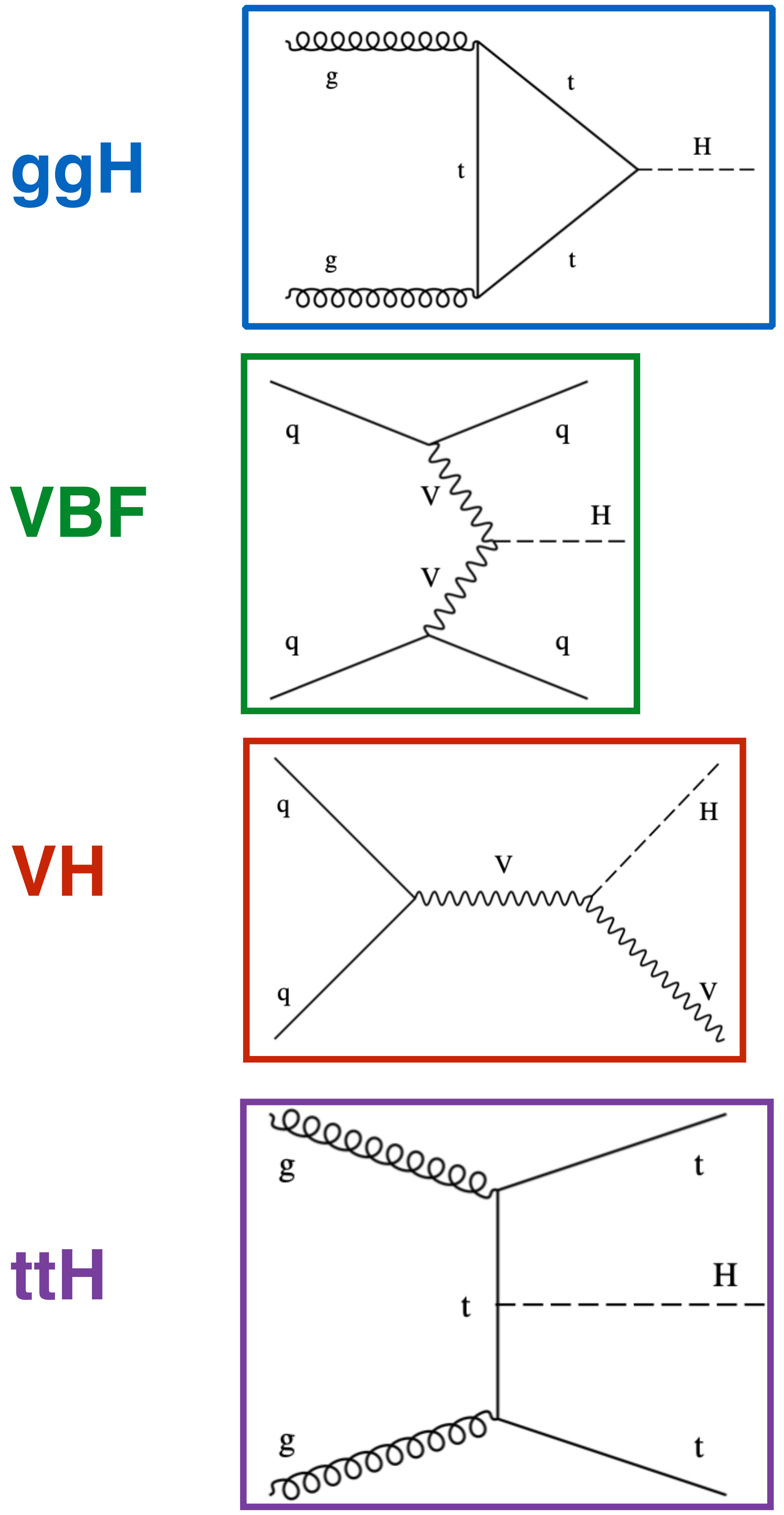
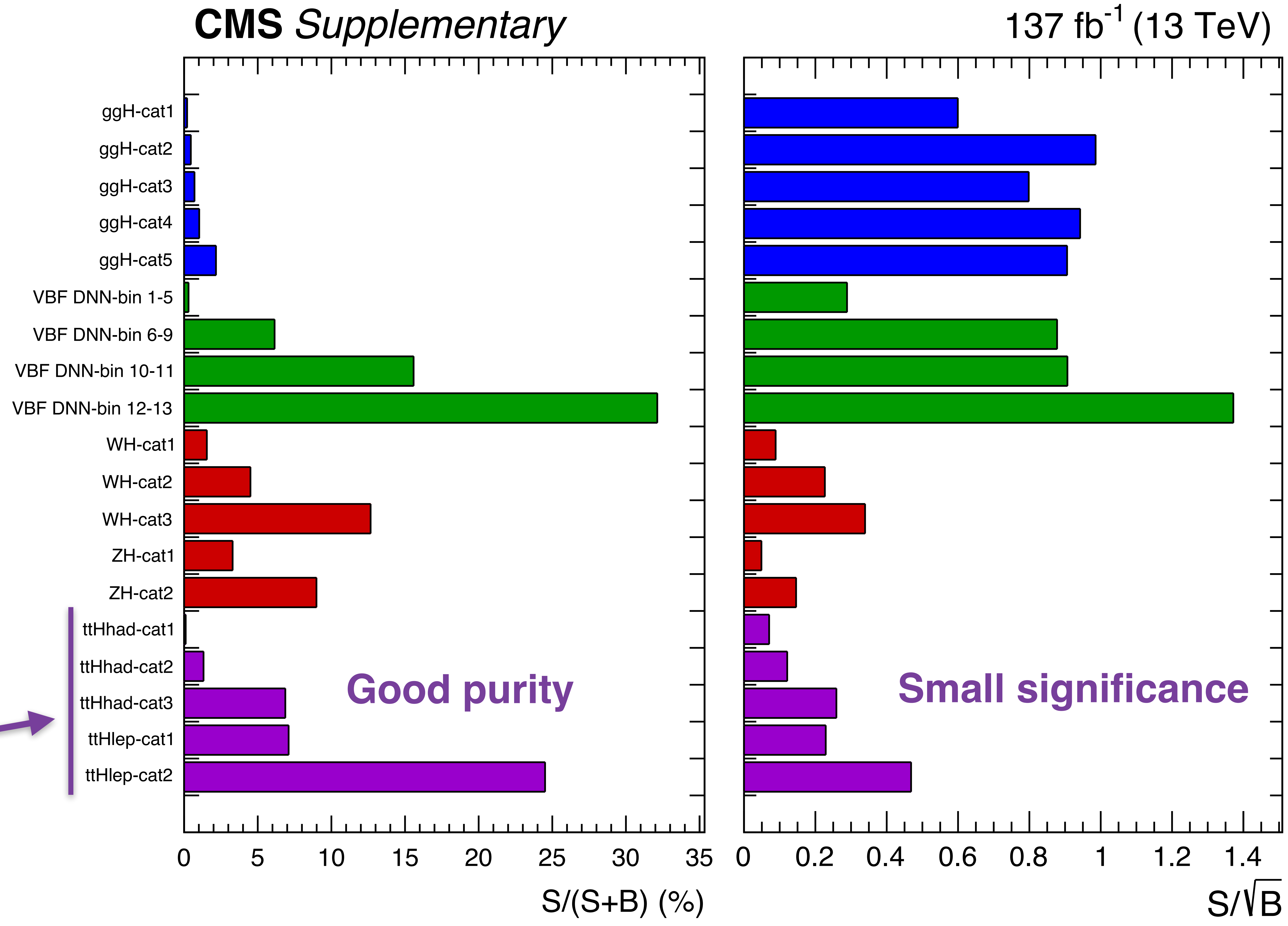




Good purity

Small significance

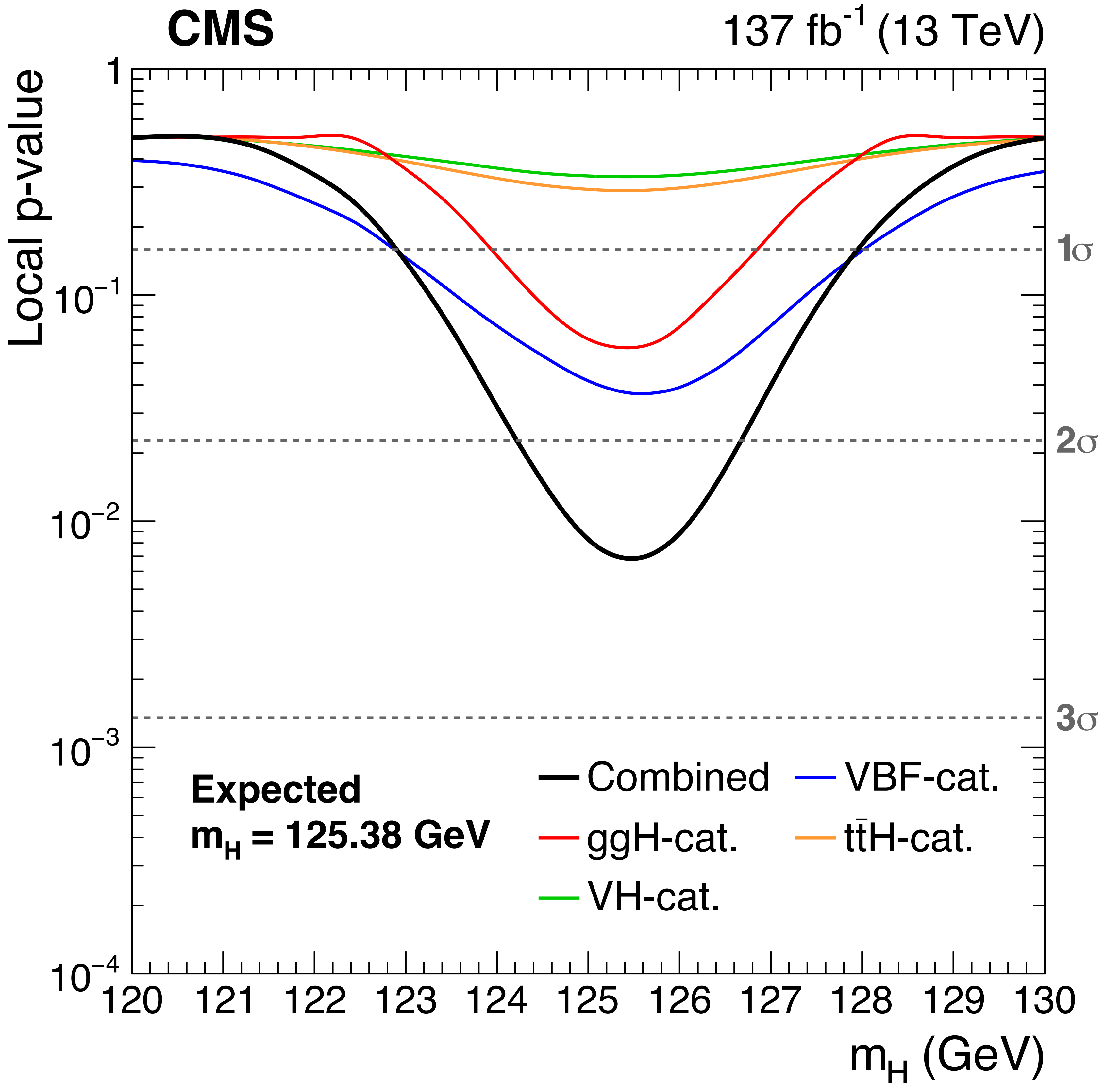
H(μμ) final result

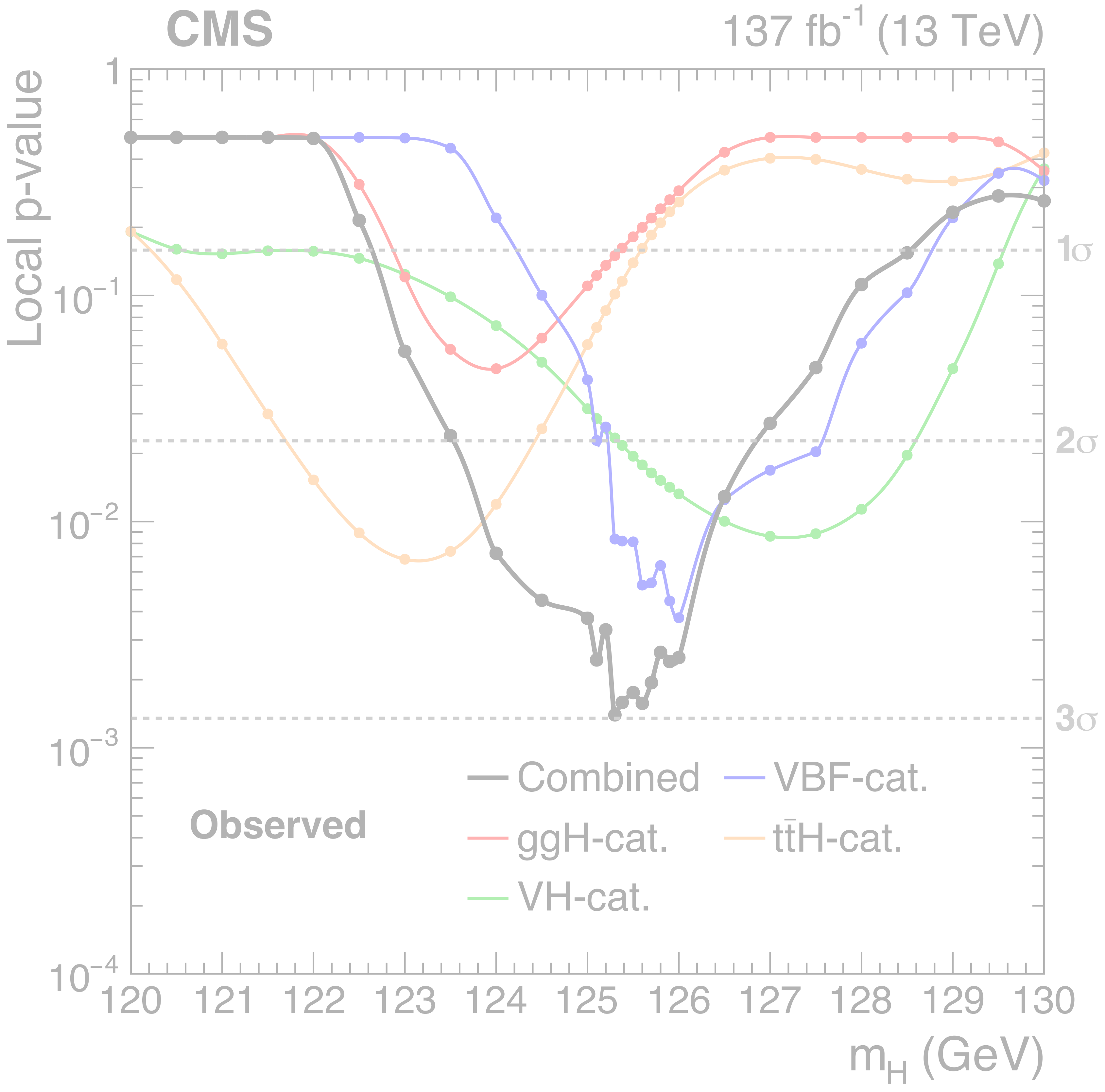
Reference m_H of 125.38 GeV

Corresponds to the best m_H measurement up to date

Phys. Lett. B 805 135425

- ***Combined fit*** performed ***across all event categories*** (ggH, VBF, VH, and ttH)
- Systematic uncertainties are typically correlated across data-taking periods and categories





Expected significance for m_H = 125.38 GeV is **2.5σ**

Observed significance for m_H = 125.38 GeV is **3.0σ**

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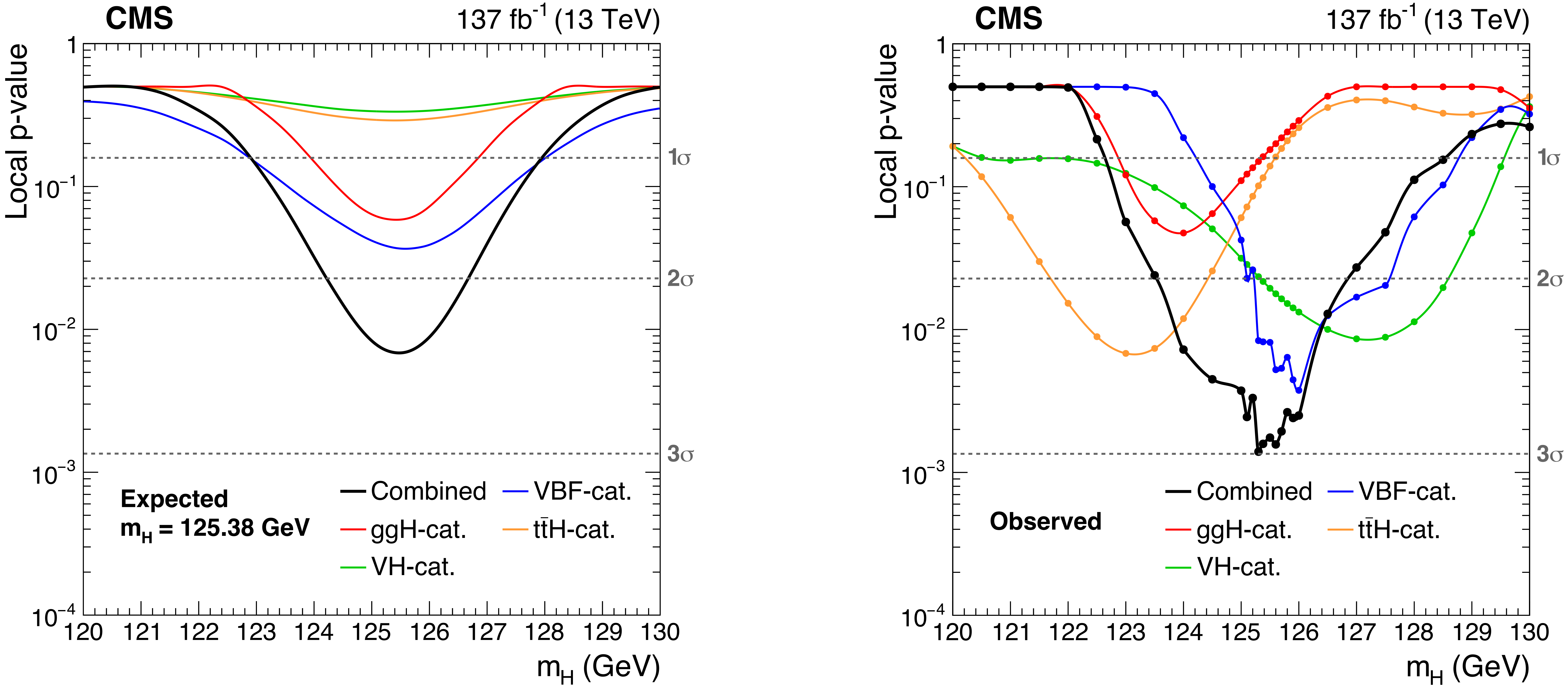

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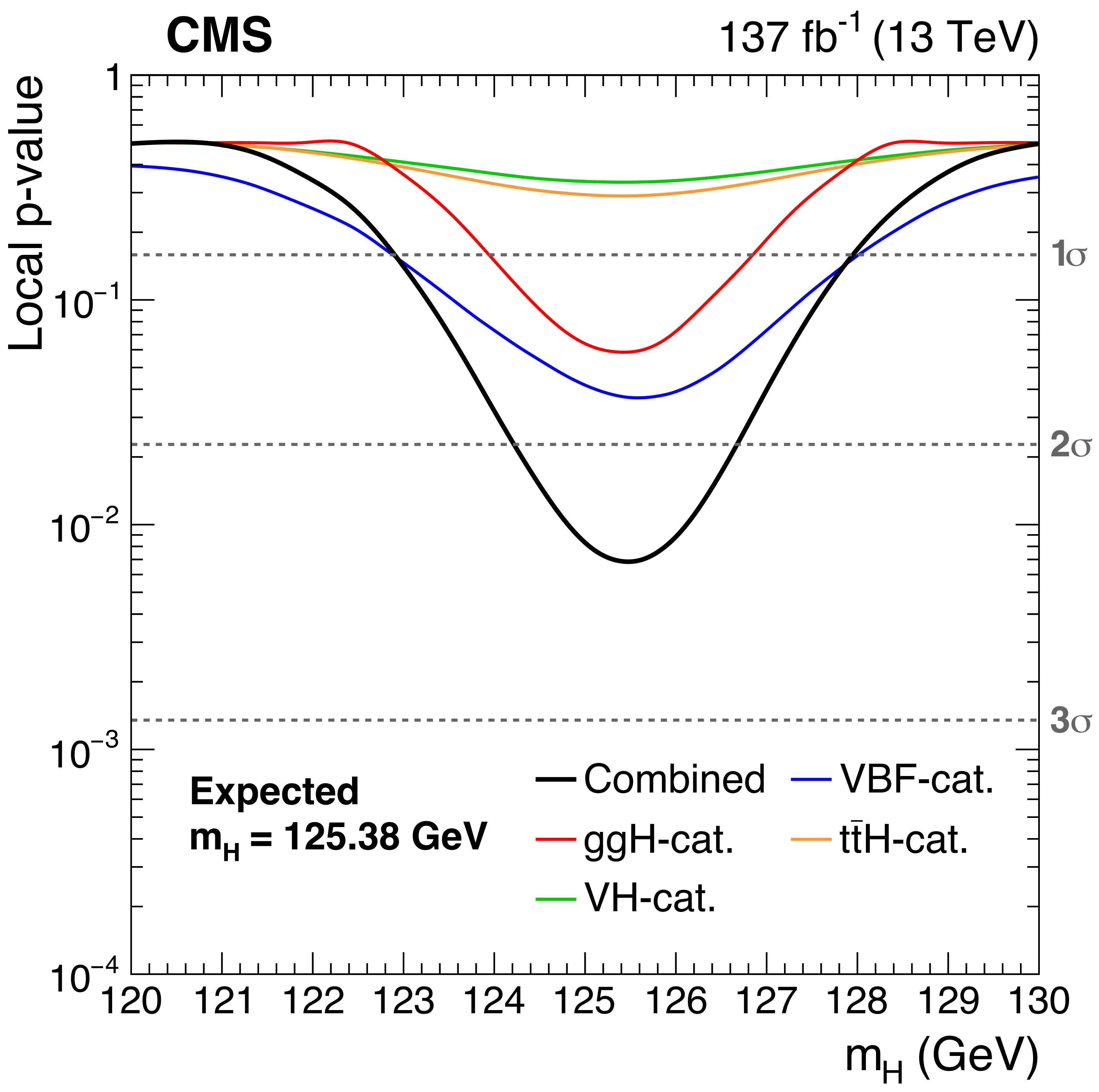

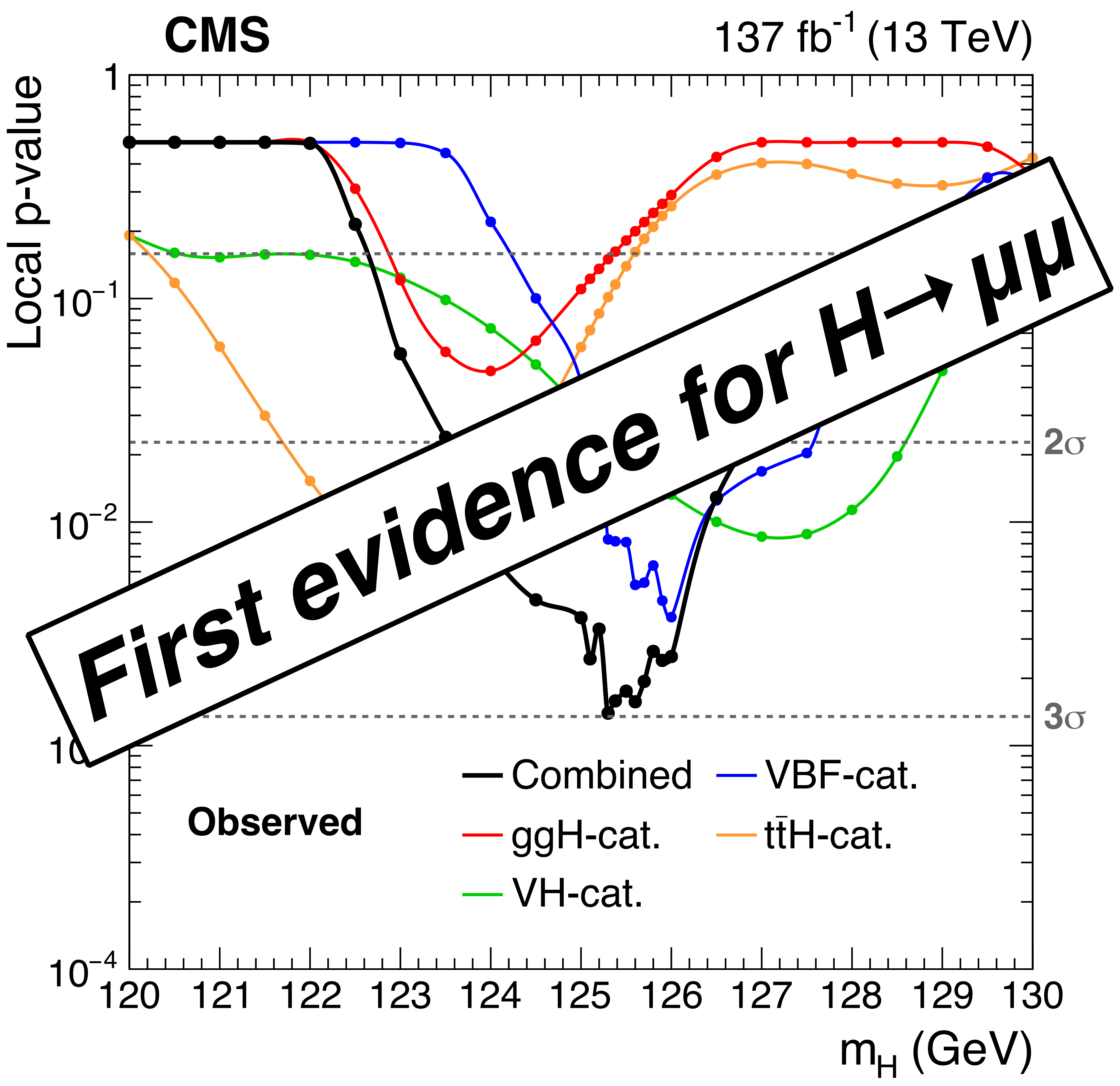

First evidence for H→ μμ

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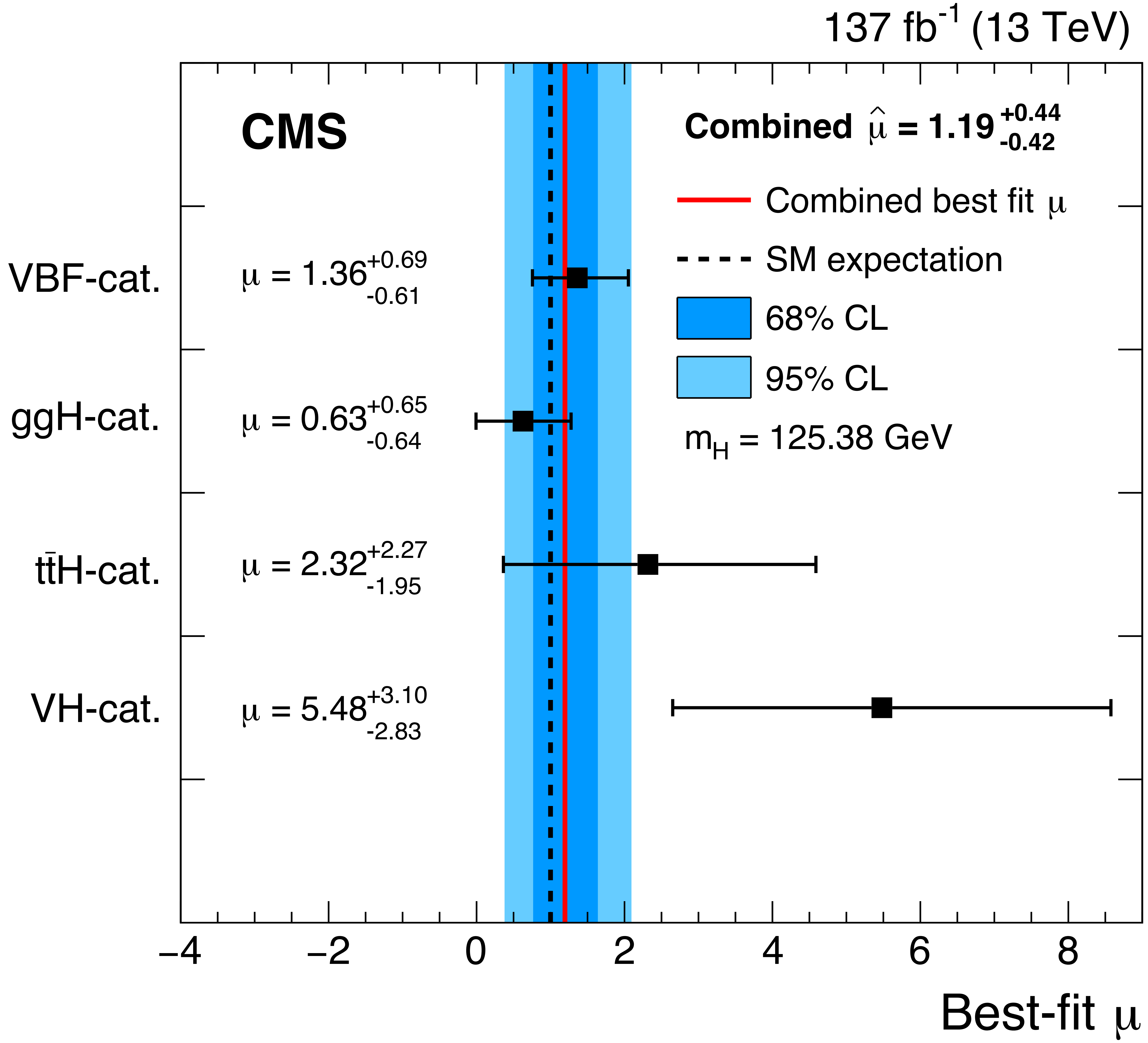
Observed significance for m_H = 125.38 GeV is **3.0σ**

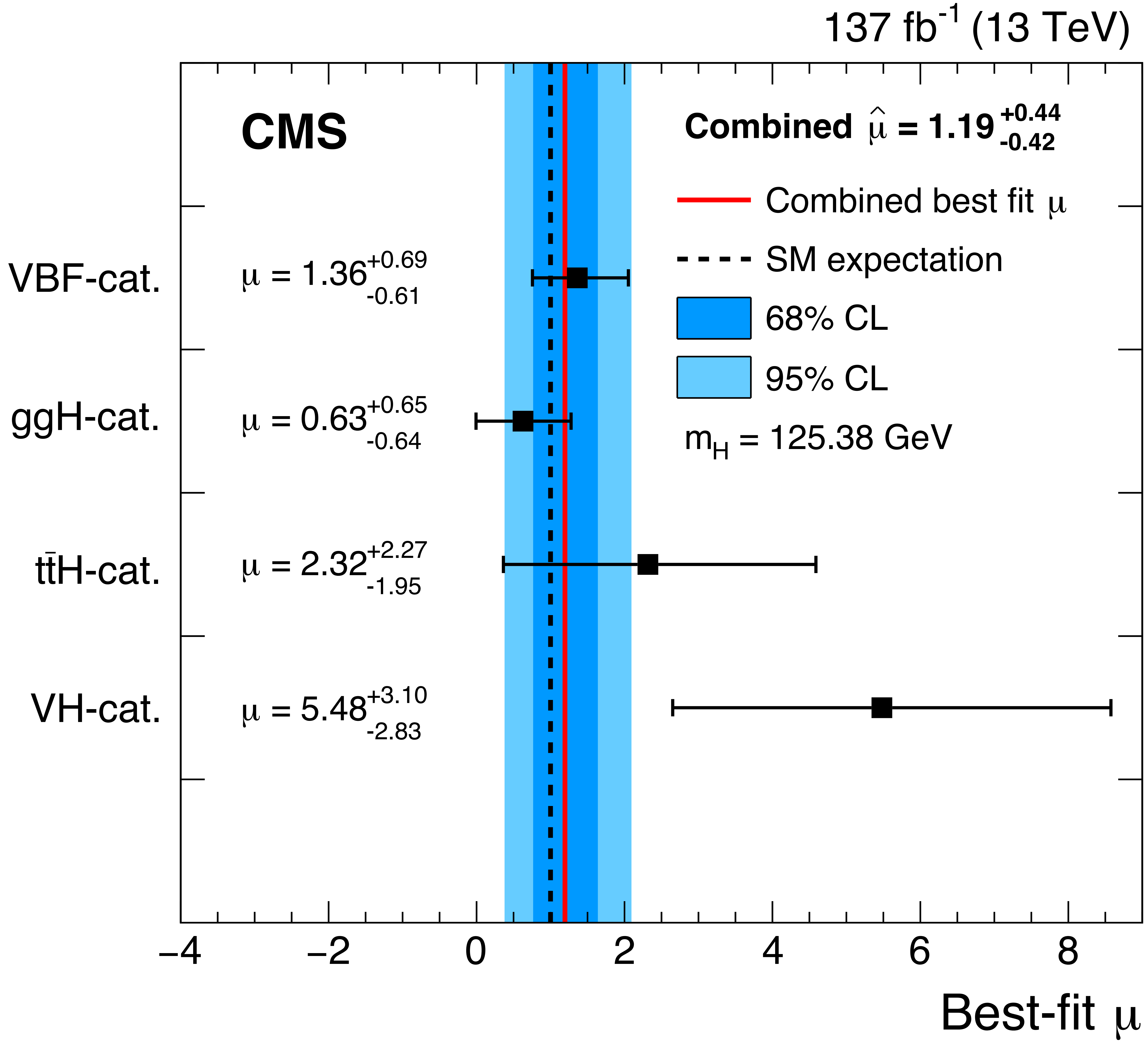
H(μμ): analysis of the excess



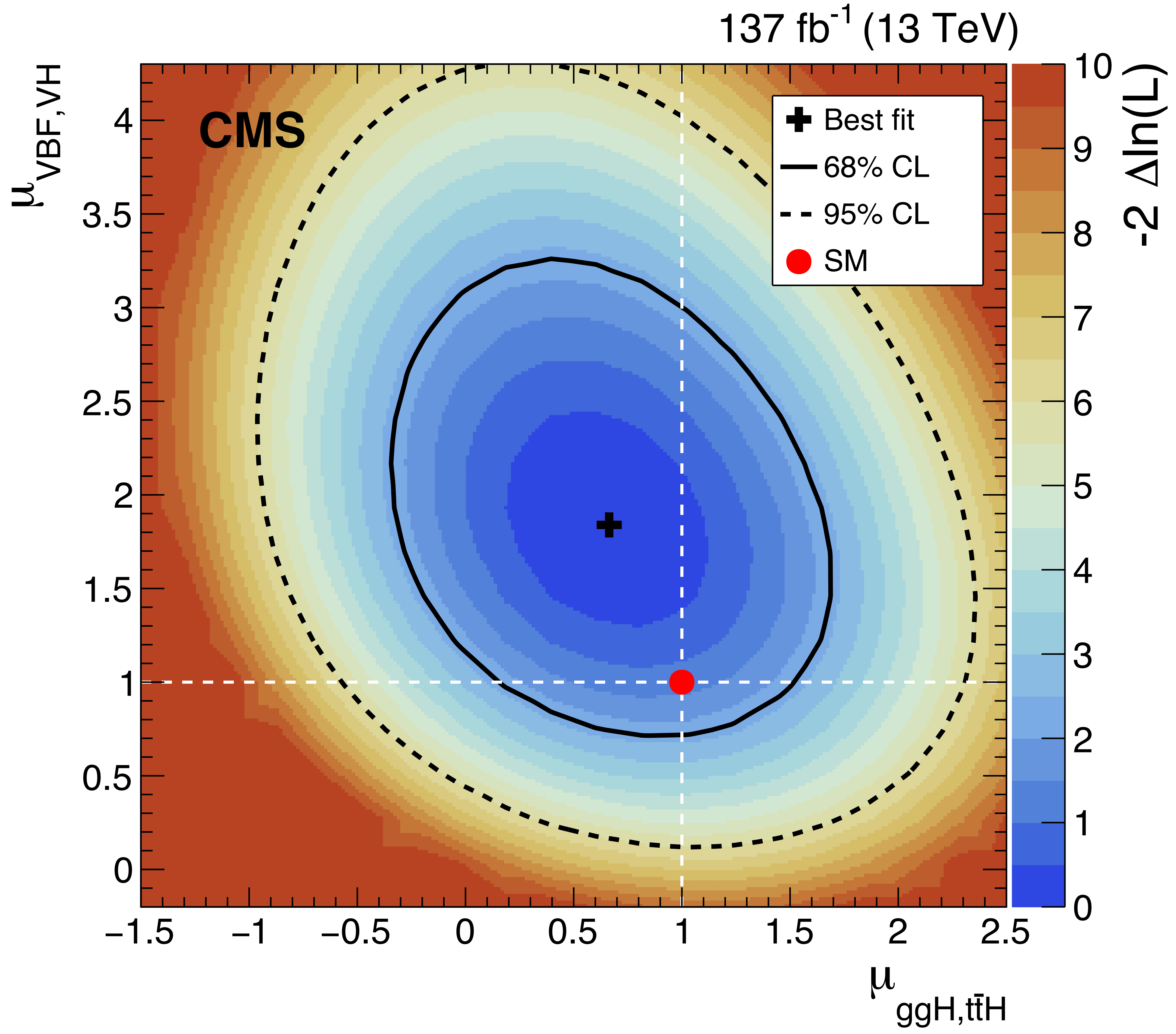
- **Best fit** $\mu = 1.19^{+0.44}_{-0.42}$
- Result is compatible with SM expectations
- Production mode measurements are also compatible with SM expectations
- ***Uncertainty dominated by statistics***

Uncertainty source	$\Delta\mu$	
Post-fit uncertainty	$+0.44$	-0.42
Statistical uncertainty	$+0.41$	-0.40
Systematic uncertainty	$+0.17$	-0.16
Experimental uncertainty	$+0.12$	-0.11
Theoretical uncertainty	$+0.10$	-0.11
Size of simulated samples	$+0.07$	-0.06

H(μμ): analysis of the excess

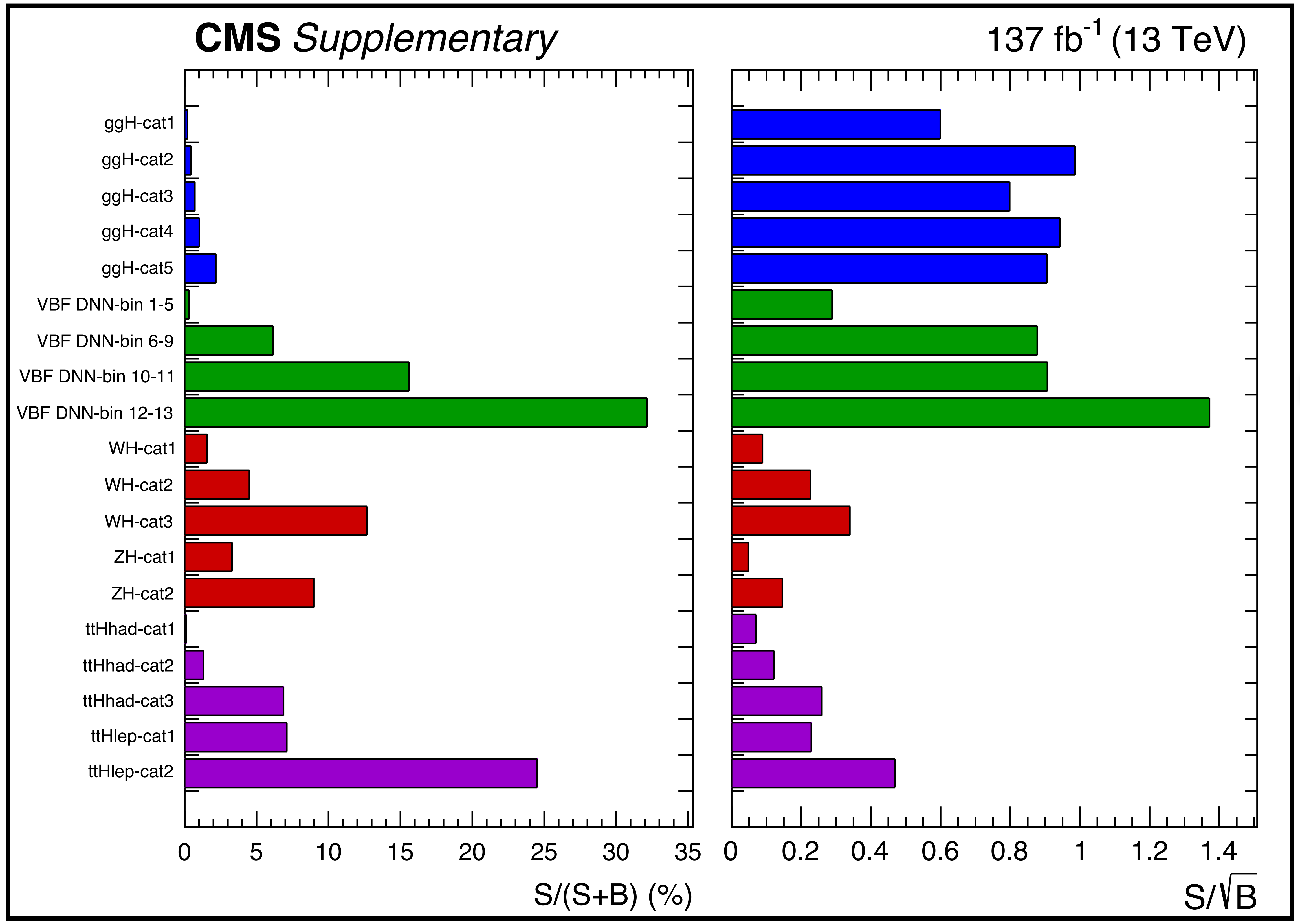


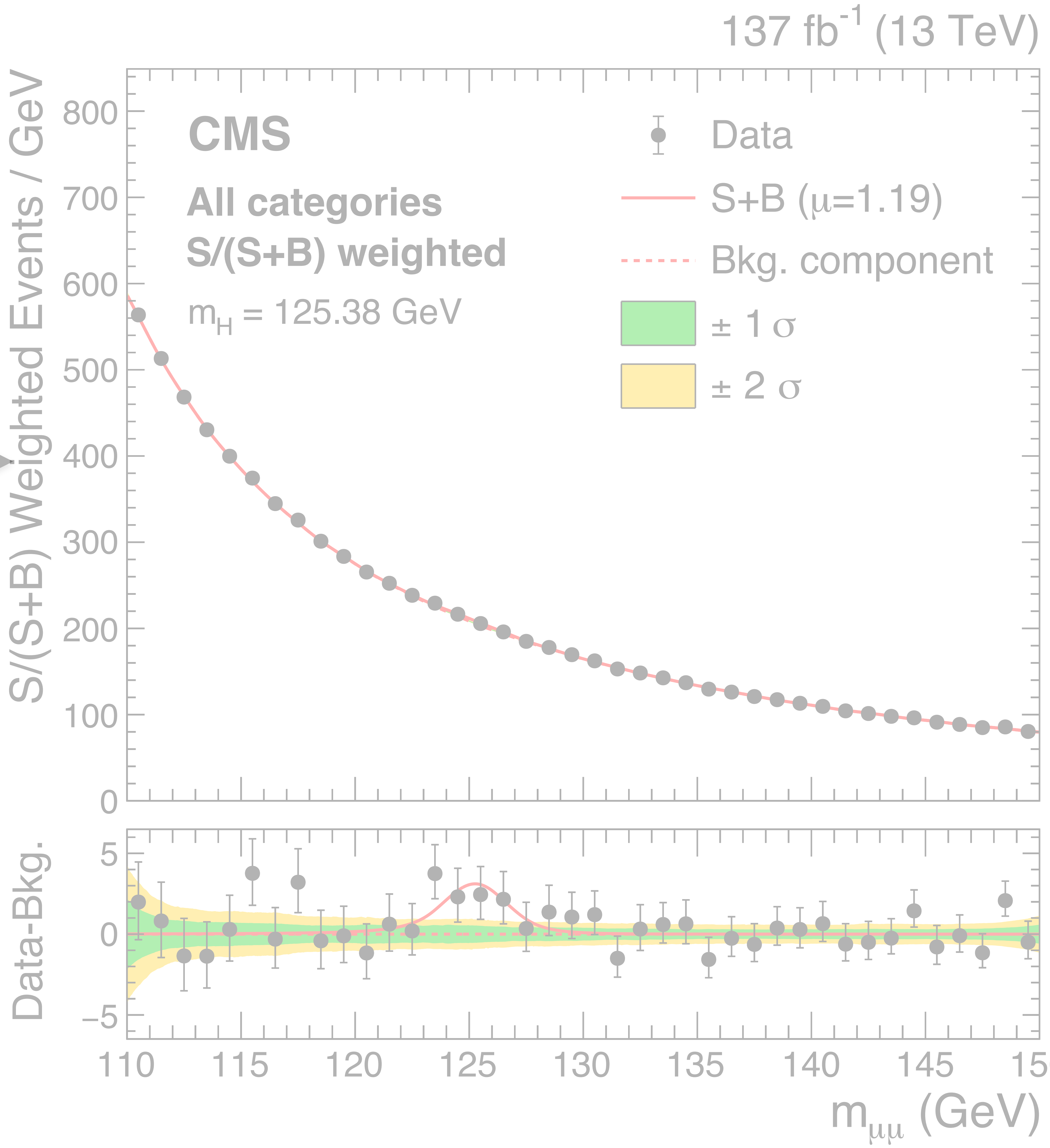
- Perform the same fit estimating two signal strength:
  - One for ggH/ttH → ***fermion coupling in production***
  - One for VBF/VH → ***boson coupling in production***



Is this signal real?

Categories in the simultaneous combined fit





The ***S*** and ***B*** yields are estimated within the ***full-width-half maximum*** of the signal peak

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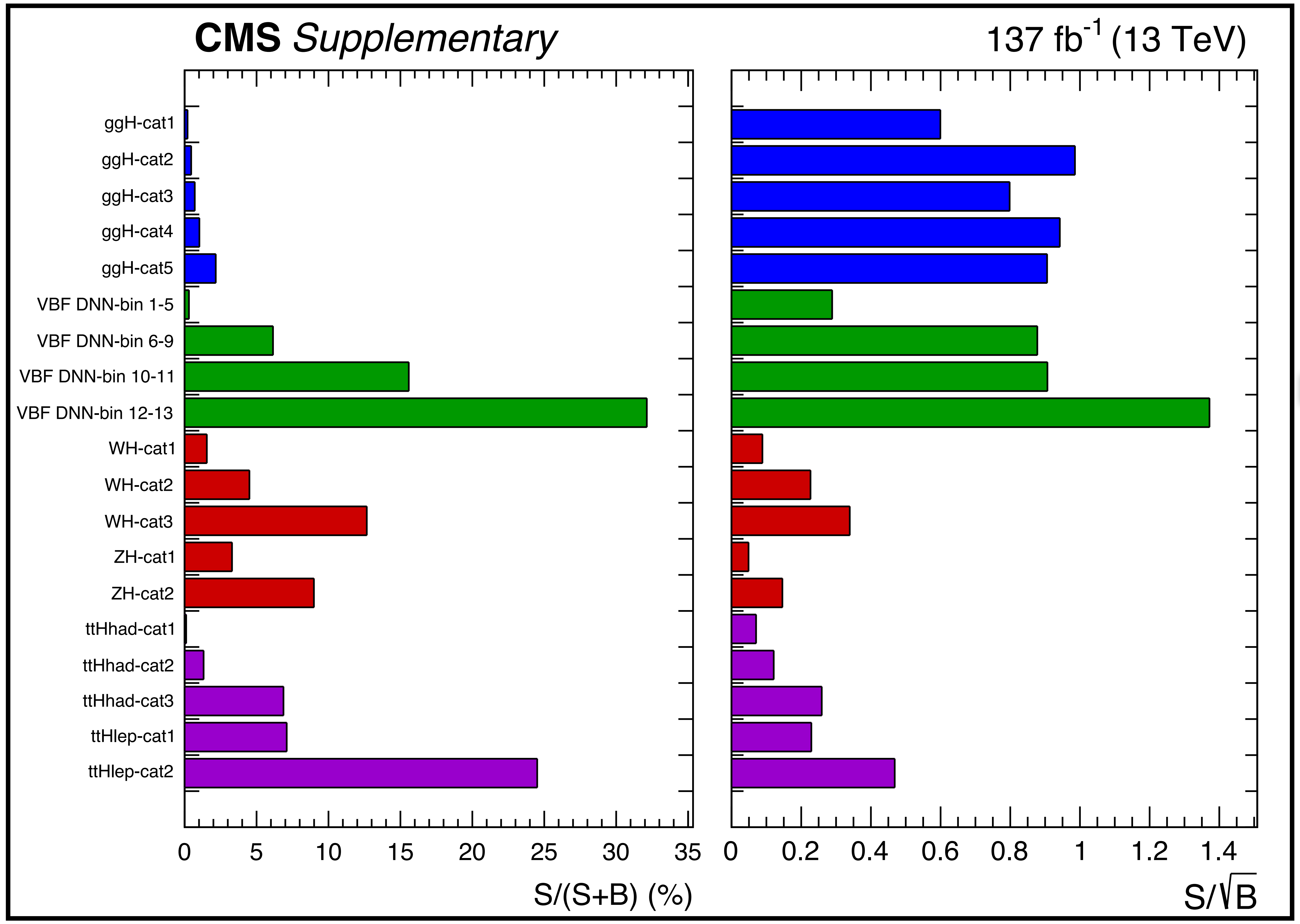
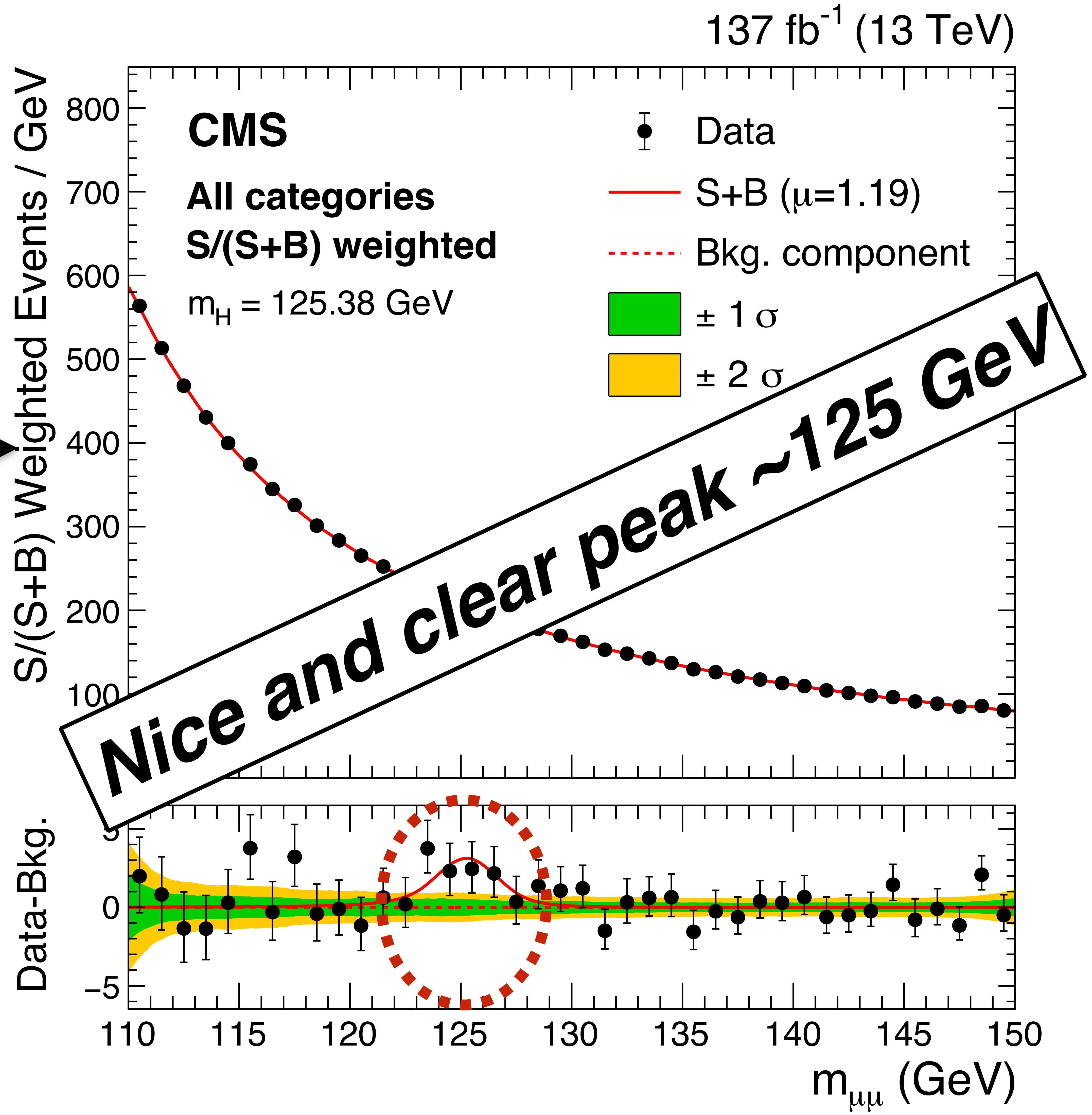
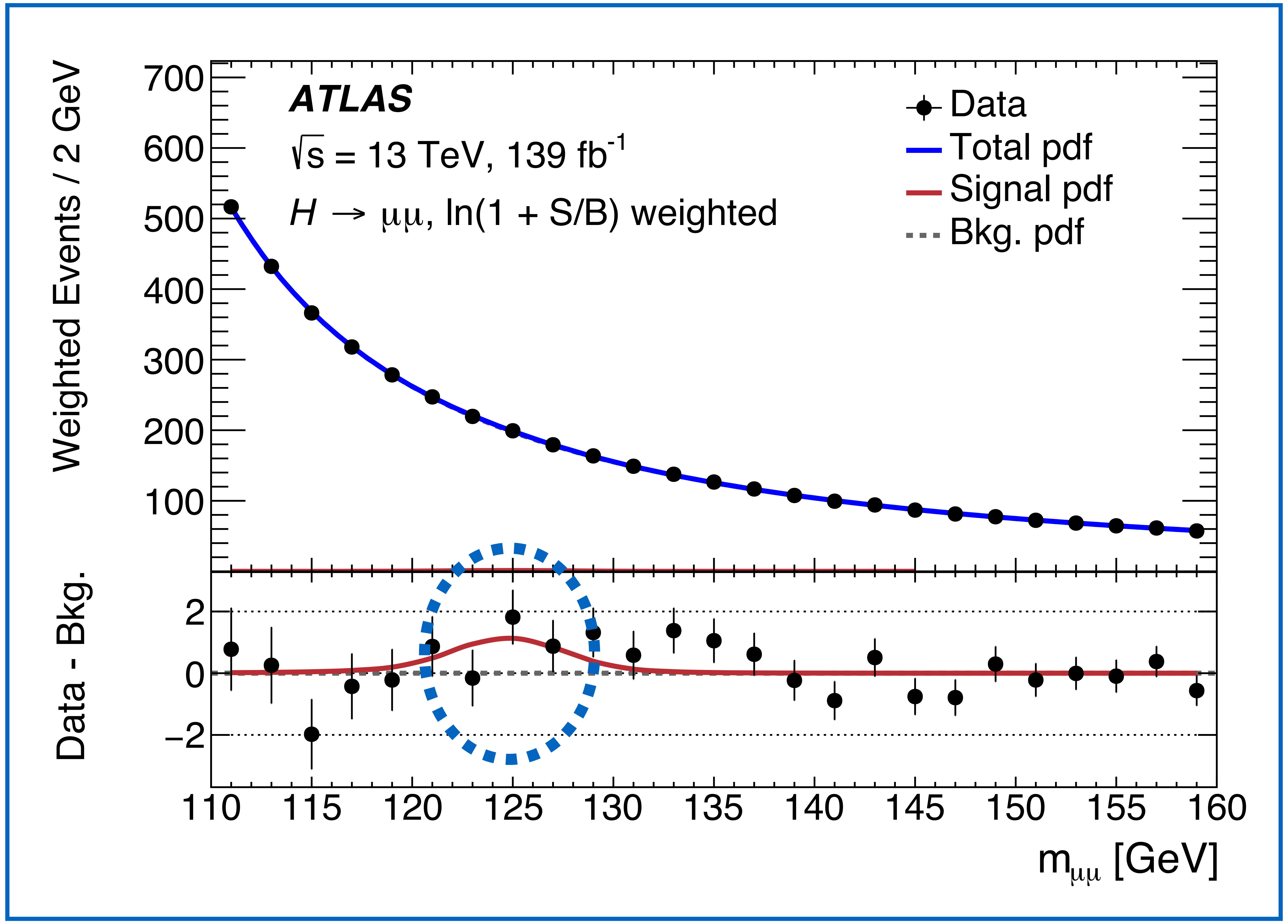


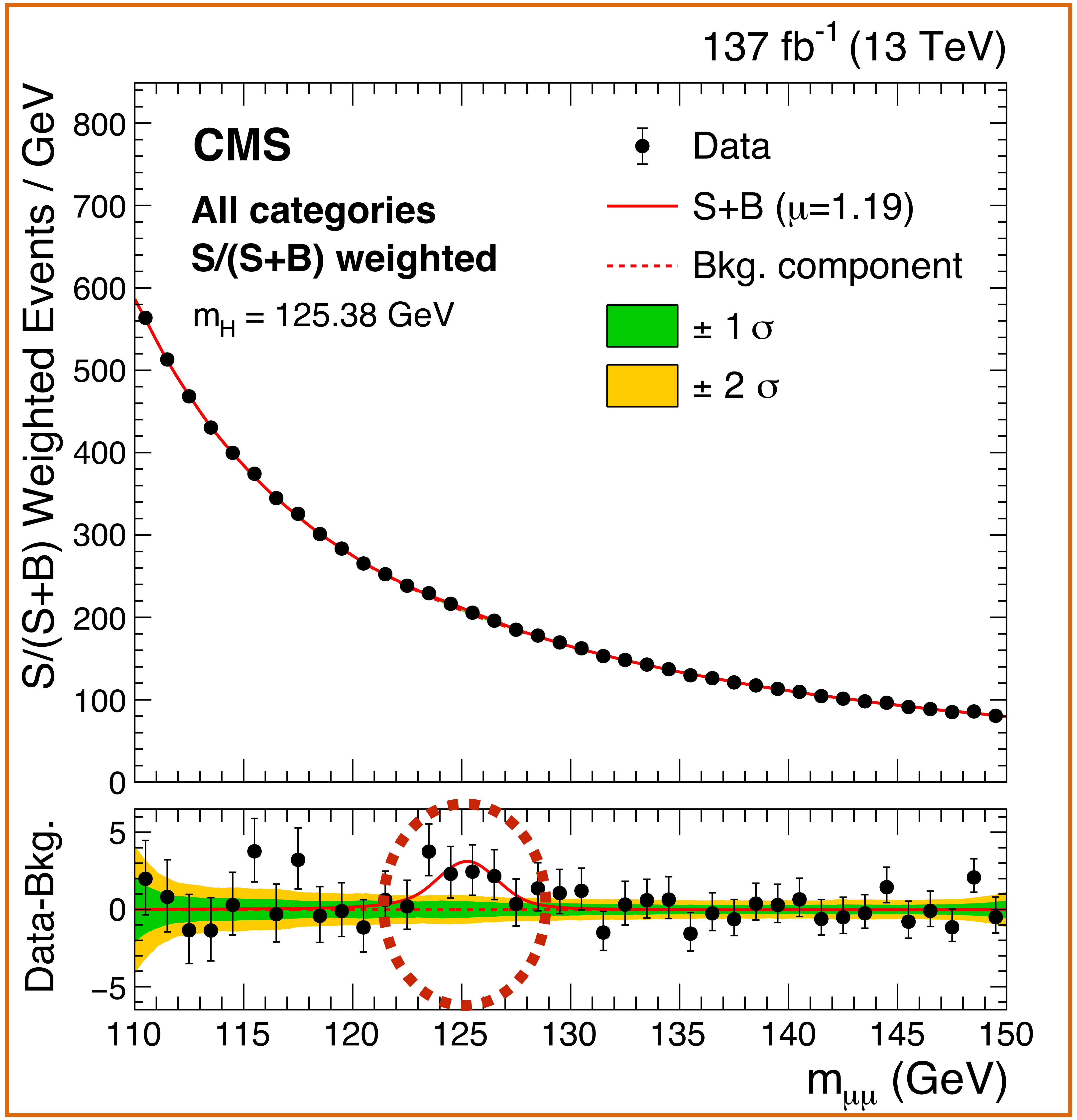


Nice and clear peak ~125 GeV

The ***S*** and ***B*** yields are estimated within the ***full-width-half maximum*** of the signal peak

Is this signal real?





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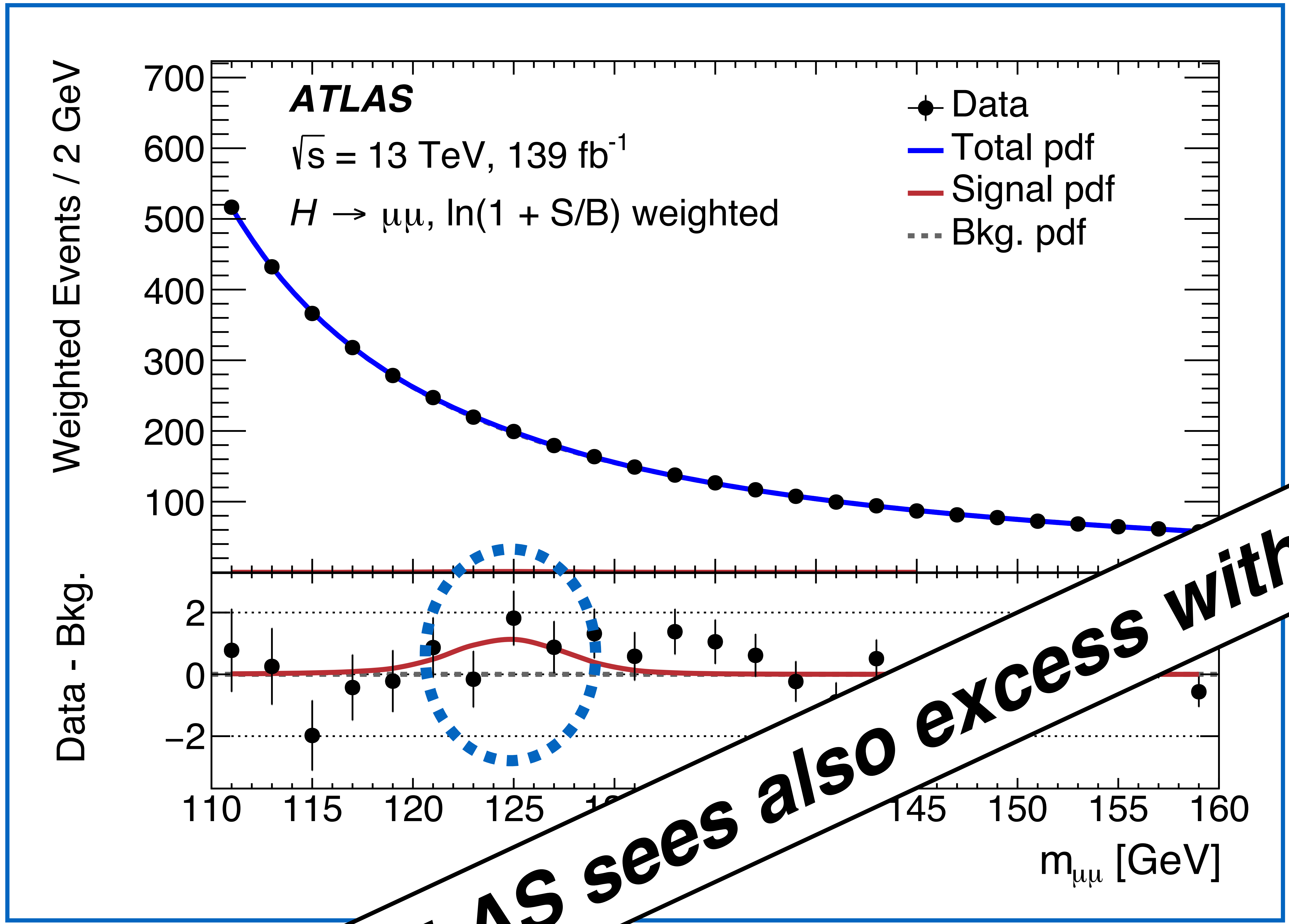
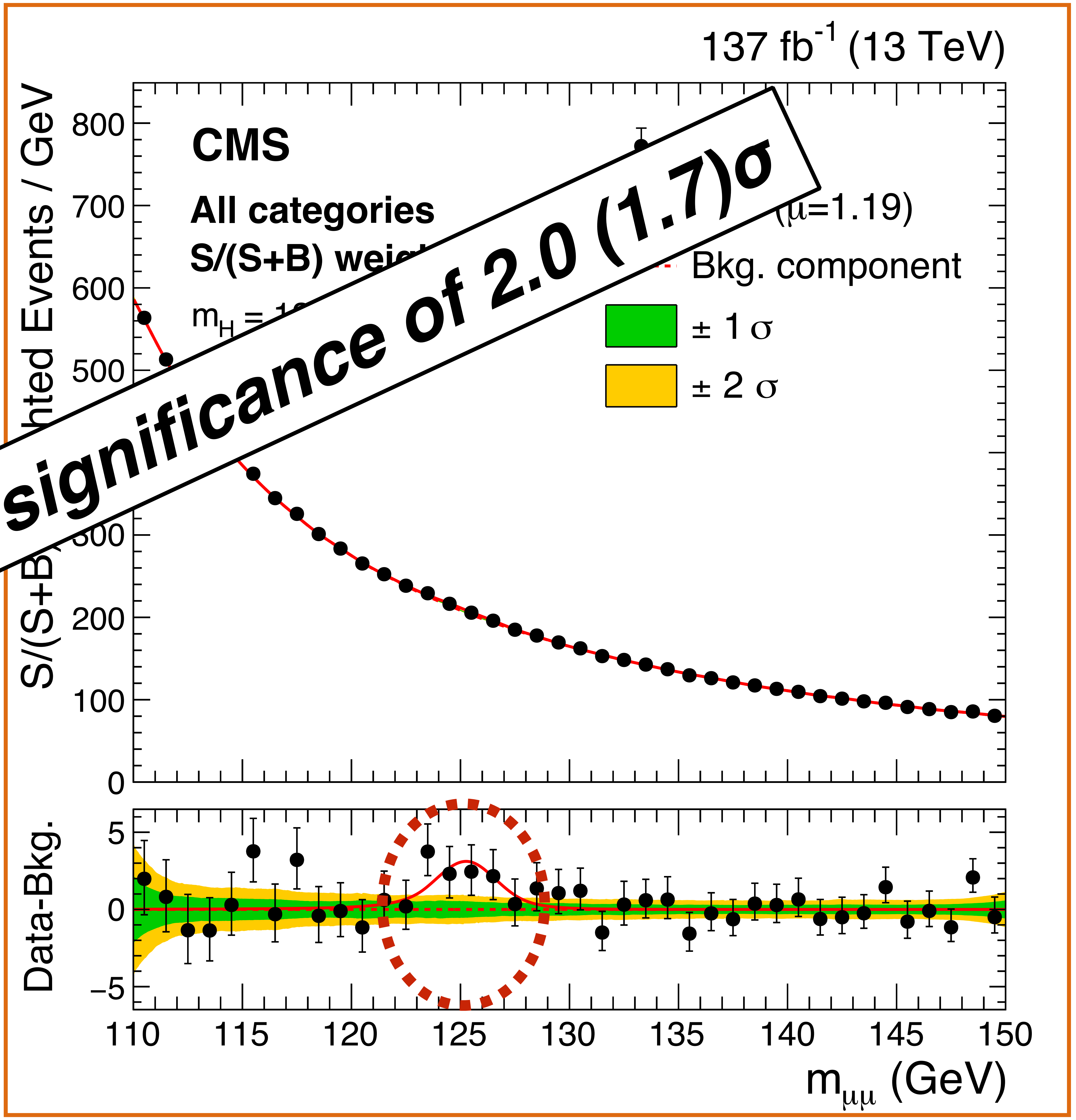
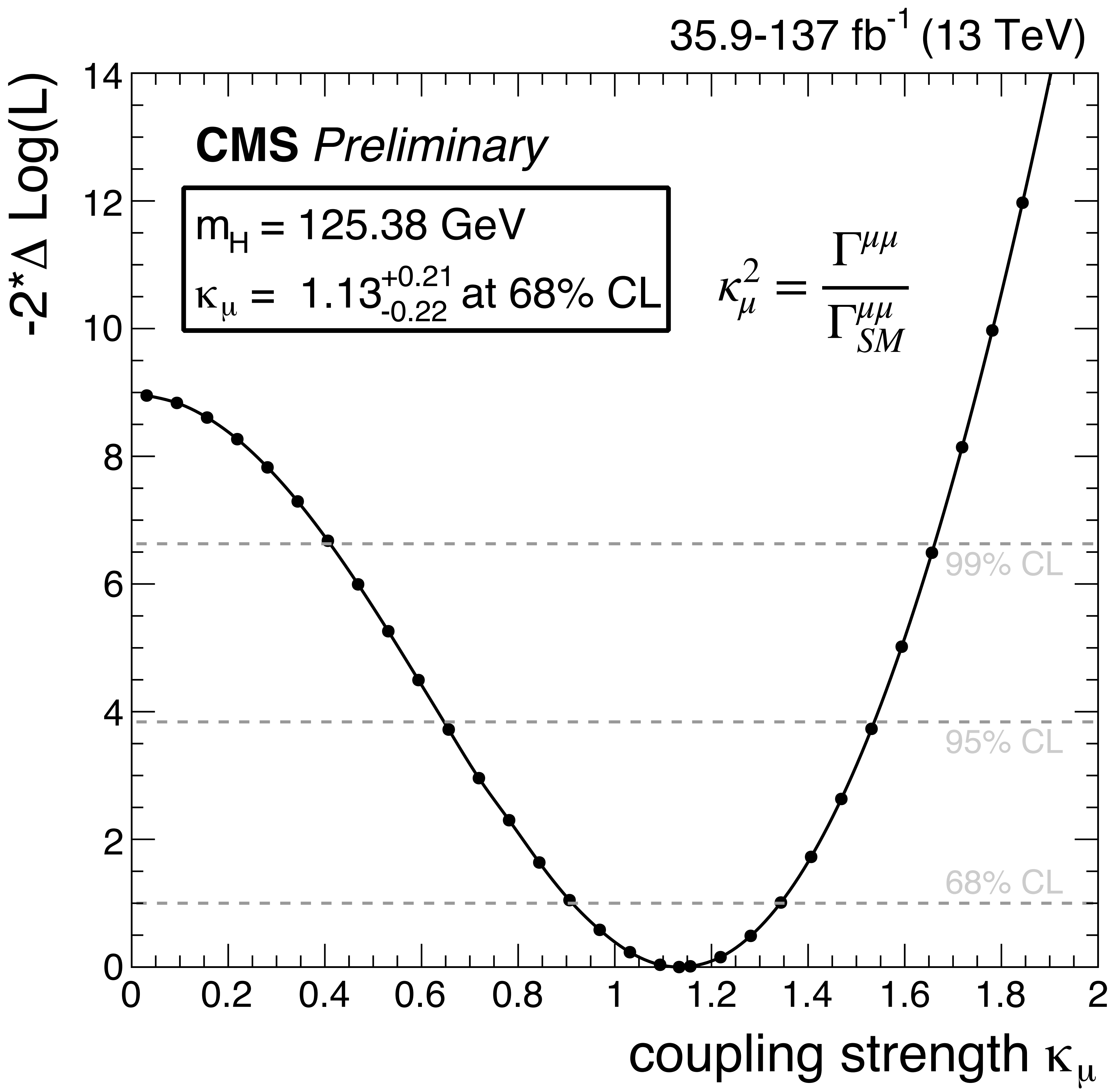


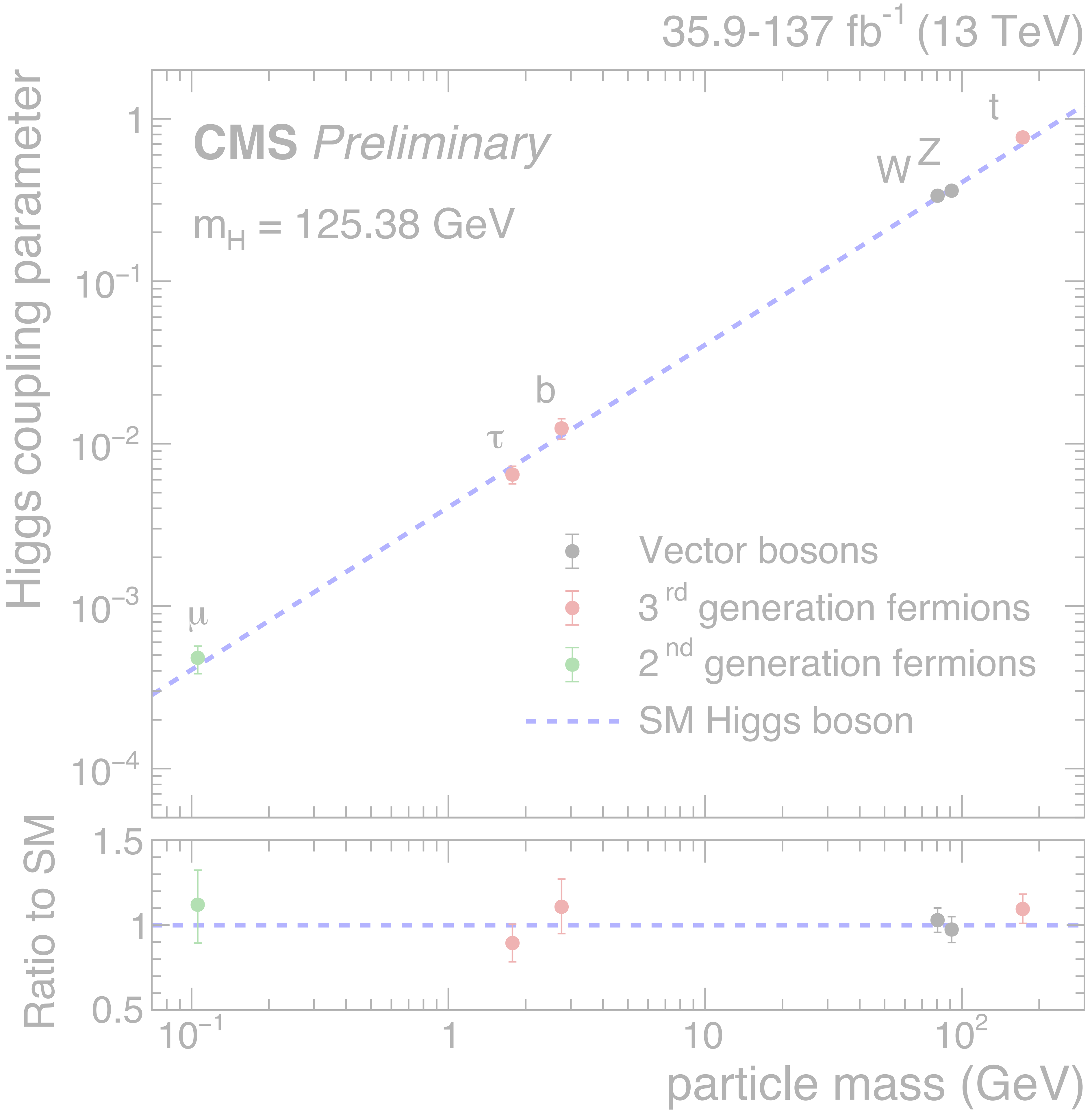


ATLAS sees also excess with significance of 2.0 (1.7)σ

Higgs boson couplings to muons

- The ***H(μμ) coupling strength*** is obtained from a combination with measurements from ***other Higgs channels***
- This ***H(μμ) result*** is ***combined*** with the ***analyses reported*** in ***CMS-PAS-HIG-19-005***





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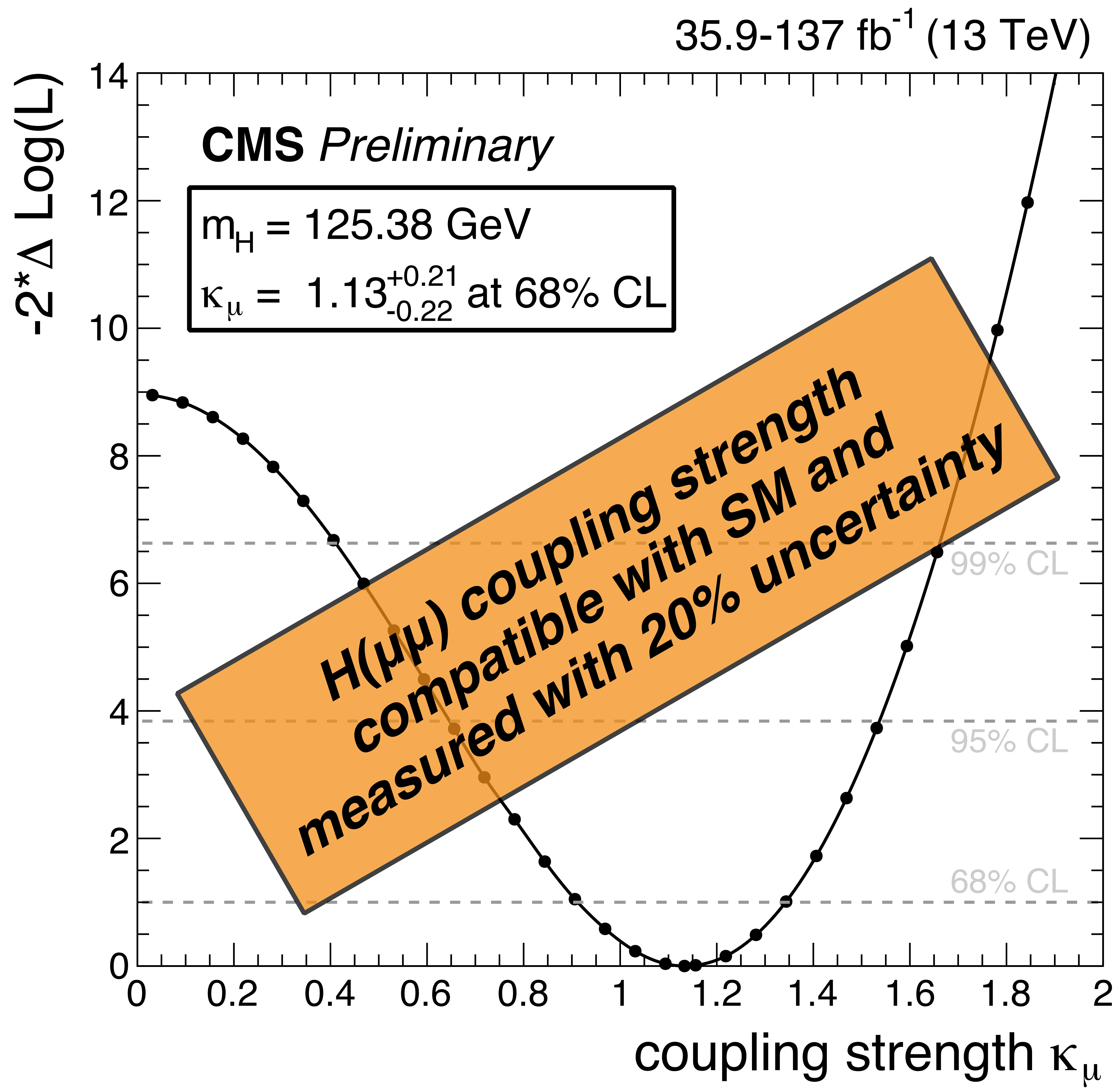
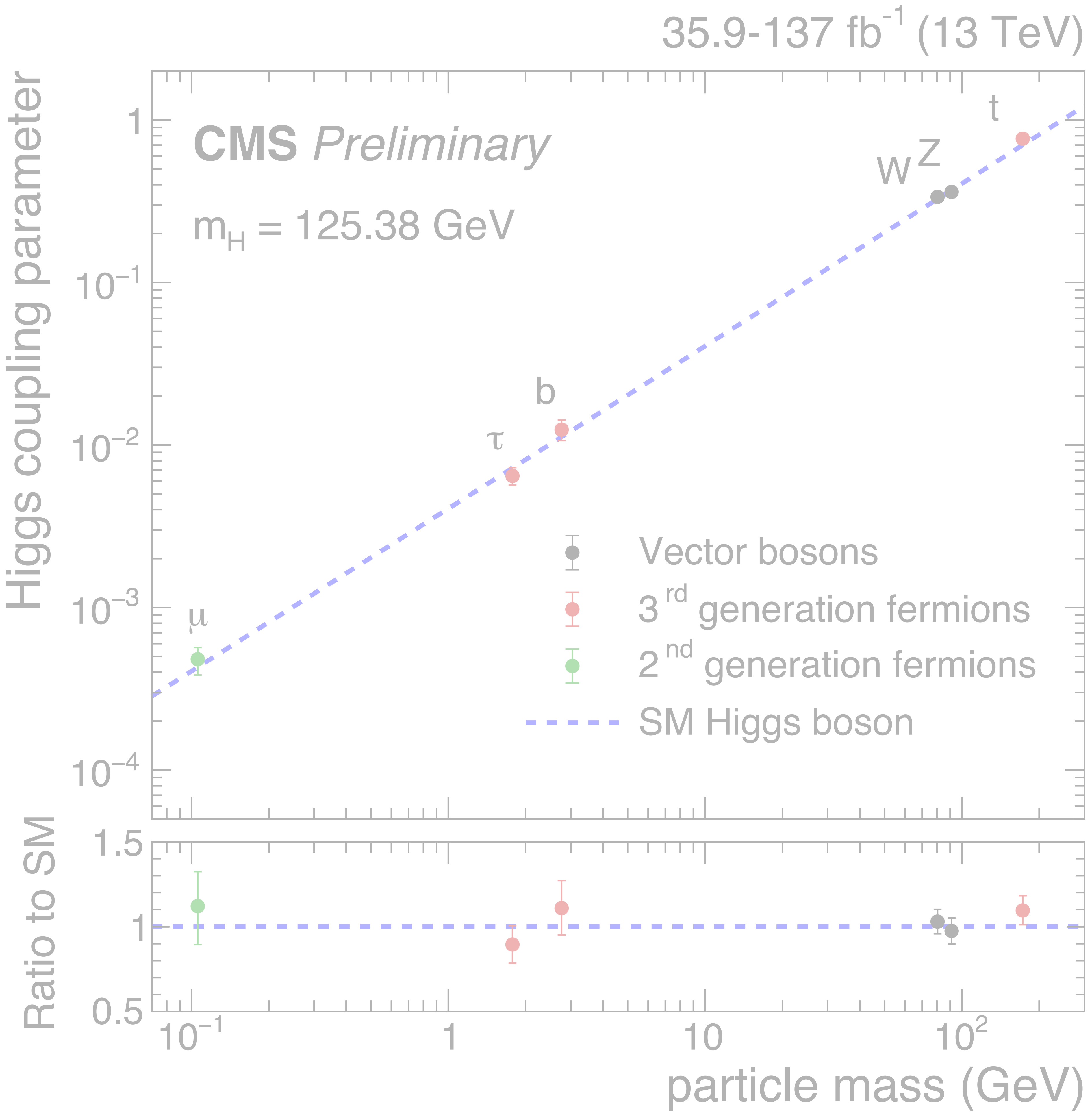


m_H = 125.38 GeV

κ_μ = $1.13^{+0.21}_{-0.22}$ at 68% CL

H(μμ) coupling strength compatible with SM and measured with 20% uncertainty



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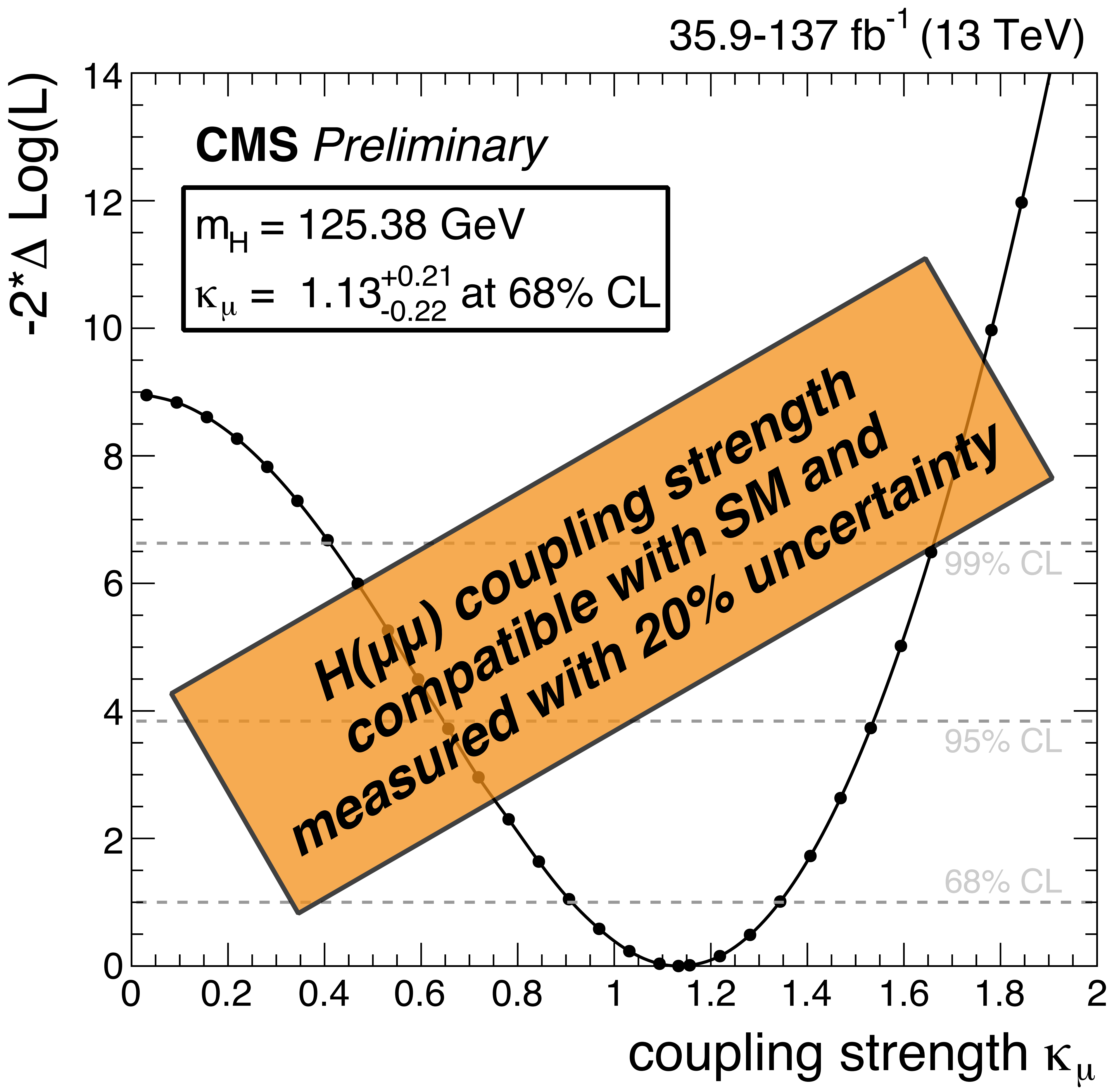

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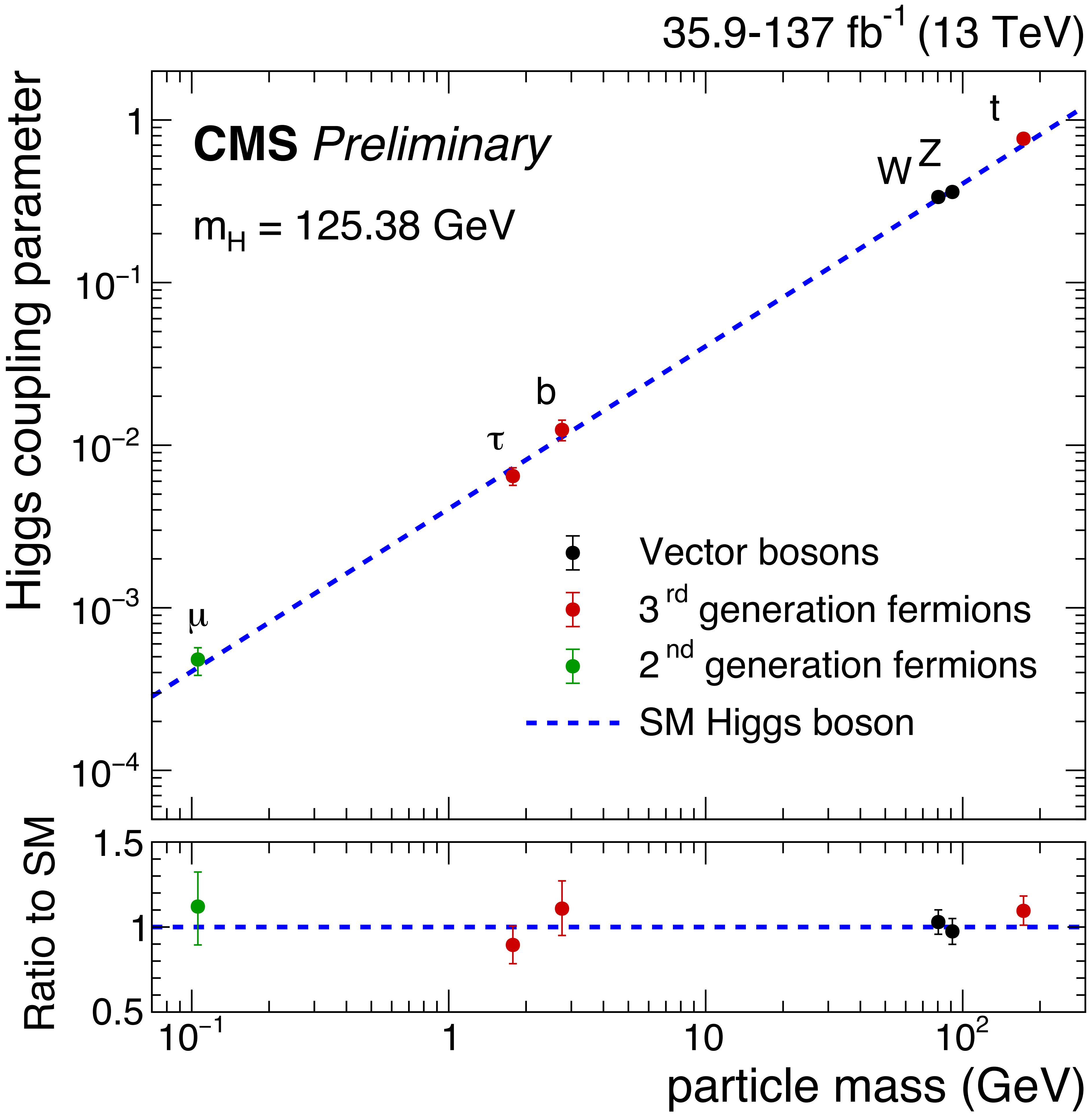

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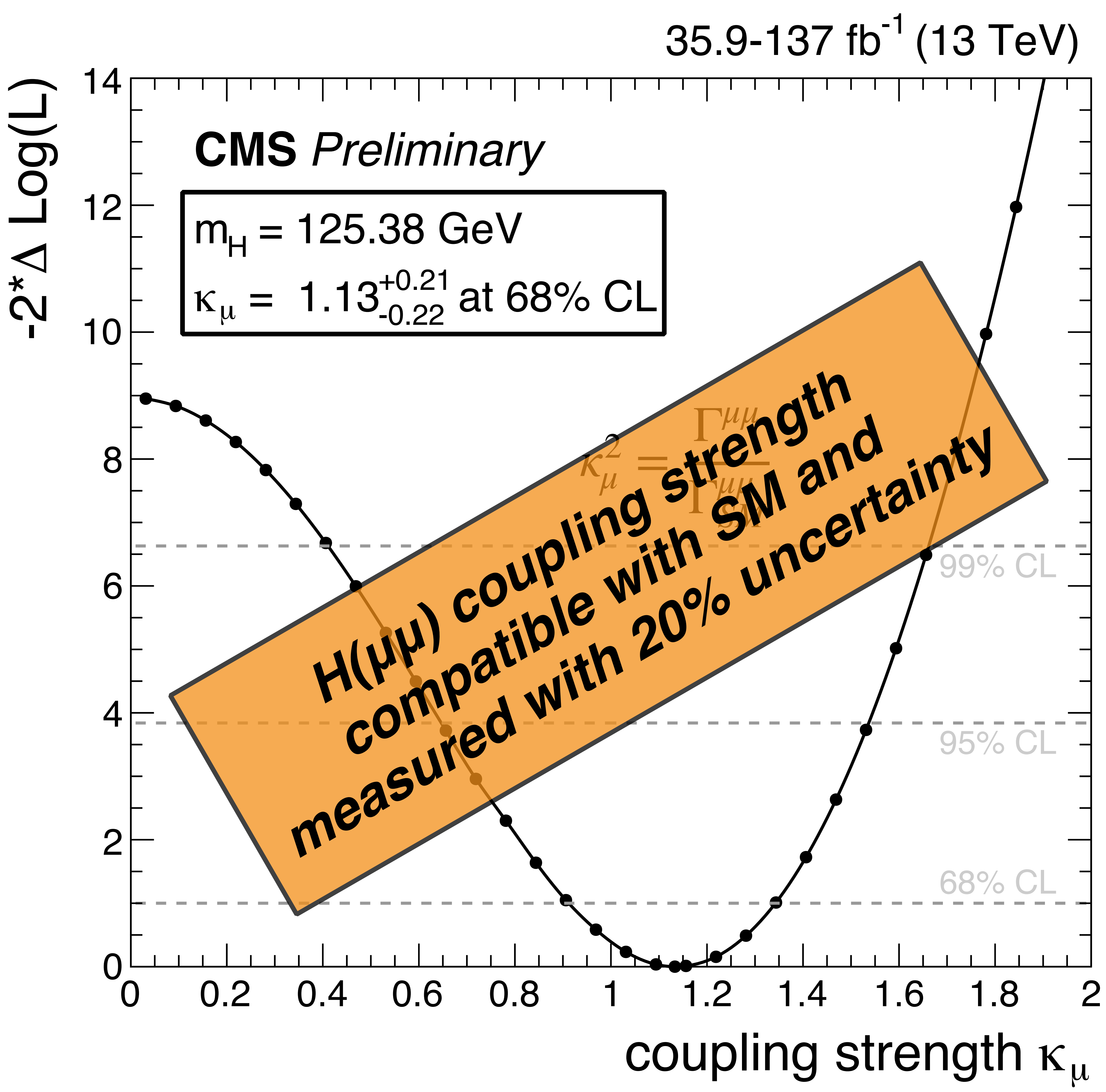

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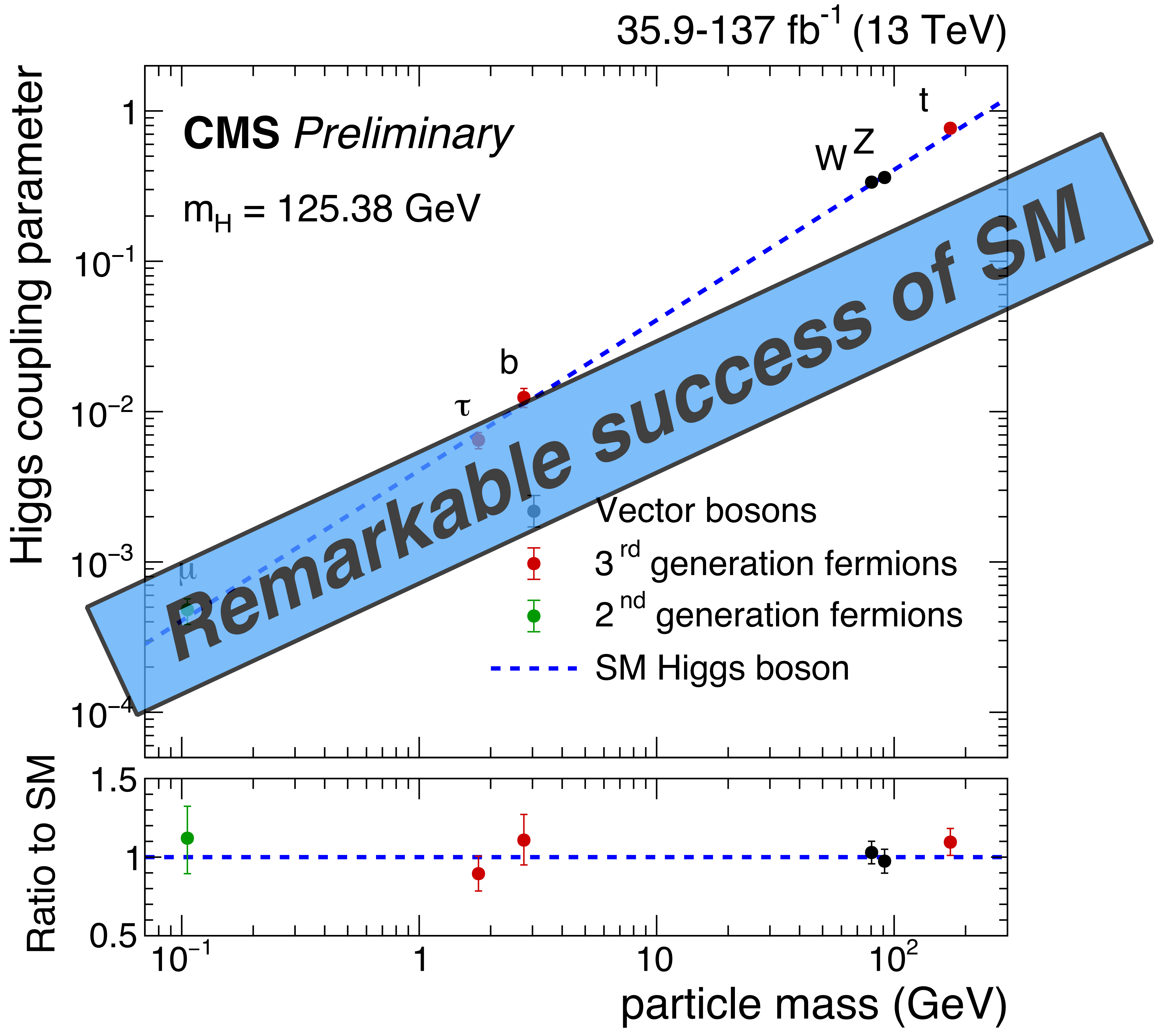


Remarkable success of SM

H→μμ analysis: future prospects @ HL-LHC

Material from ***arXiv:1902.00134v2***

Introduction to HL-LHC

- **HL-LHC:** high luminosity LHC Run from 2027 onwards → 3-4 ab^{-1} of pp collision data @ $L = 5 \times 10^{34}$ /cm^2 /s
  - In this regime → $\langle\mu\rangle = 200$ concurrent soft pp interaction per bunch-crossing (25ns) ***(pileup)***
  - Detector sensors exposed to ***very high radiation dose***
- **Physics goals:**
  - Precision measurements in ***Higgs sector*** → ***HL-LHC will be an "Higgs factory"***
  - Chaise the ***Higgs self-coupling measurement*** via HH production
  - **EW physics:** high precision differential measurements, VBS measurements, more precise m_W and m_t, etc …
  - **Dark Matter:** for m_{DM} bounds from colliders from simplified-models DM stronger than DD or ID experiments
  - **Cons:** precision physics in challenging environment, some measurements ***limited*** by theo. and exp. ***systematics***
- **Experiment performance goals:**
  - Retain at least the same detector performance shown with Run2 data in the HL-LHC environment

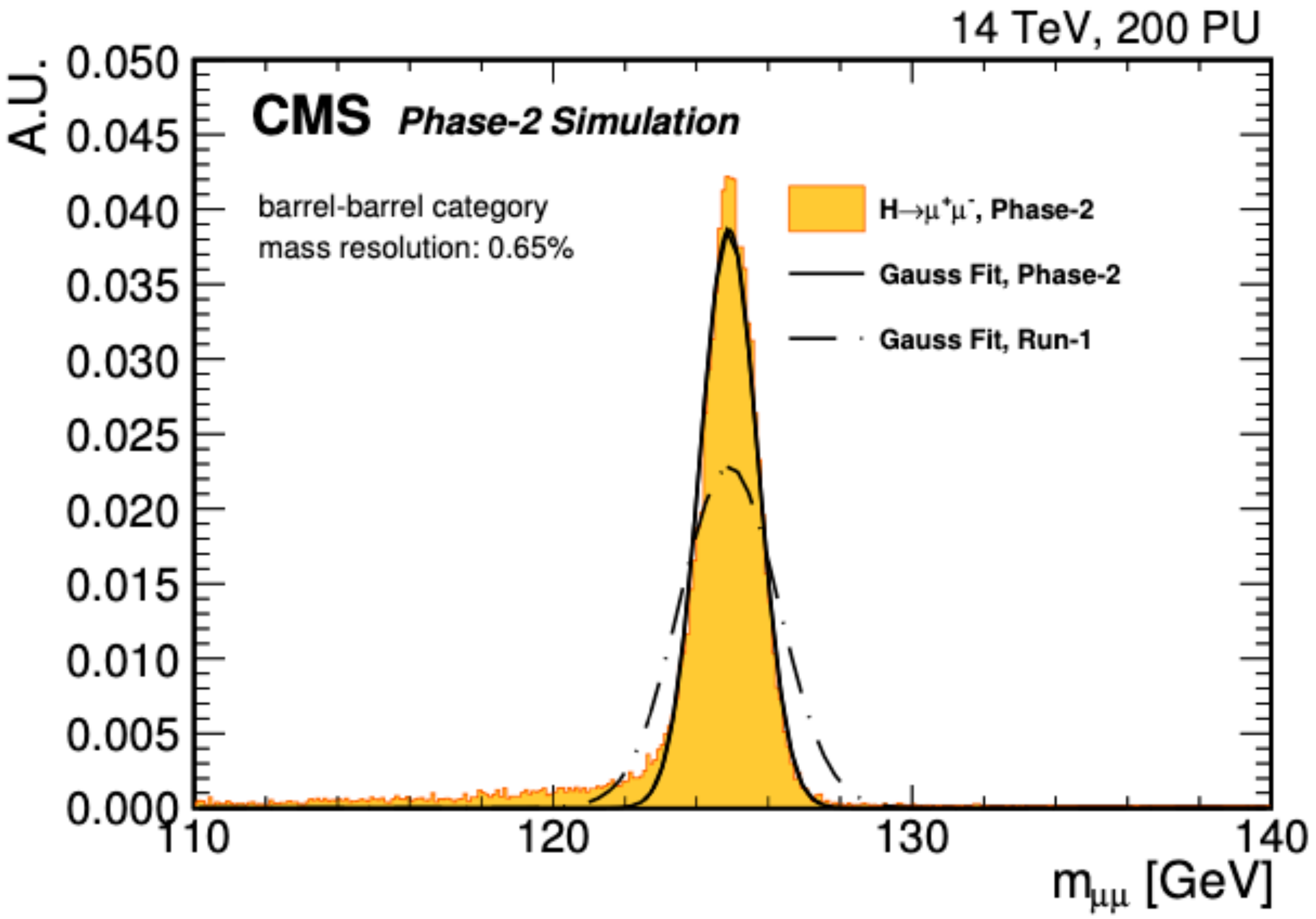
Requires new tracking, forward calorimeters & muon system, readout electronics …
improve in detector granularity and radiation resistance

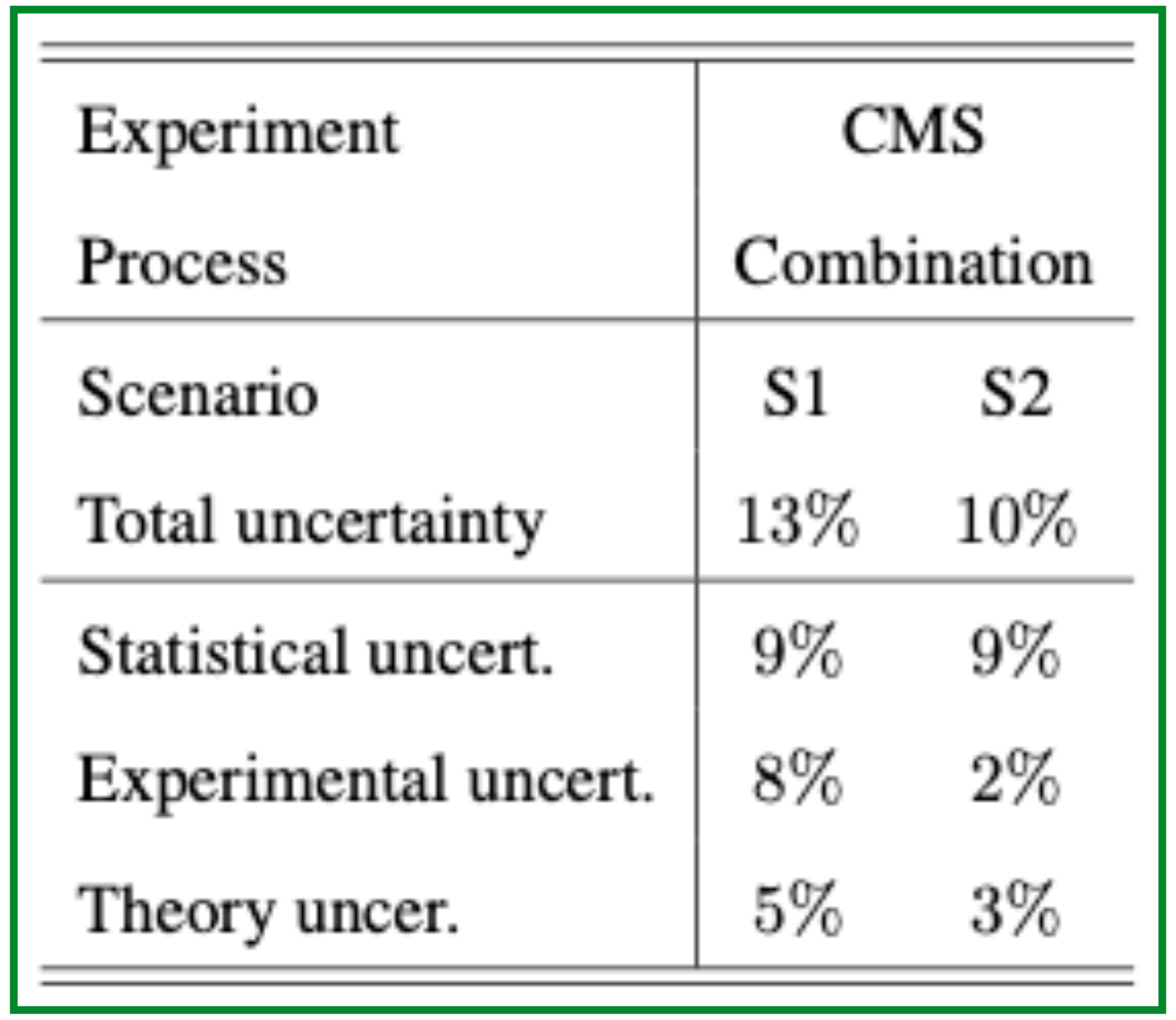
H(μμ) measurements @ HL-LHC

- CMS expects ***substantial improvements*** in ***muon p_T resolution*** from the upgraded detectors
- Improvement of ***30-40%*** thanks to new tracker (IT and OT) and upgraded muon system

- Crucial aspect represented by ***VBF-jet tagging*** since VBF is the most sensitive channel
- Good improvements expected thanks to tracking coverage up to |η| ~ 4.0 and the ***high-granularity endcap calorimeter*** (HGCAL)

- ***H→μμ*** analysis will still be mostly limited by statistical uncertainty
  - Bias uncertainty in bkg modelling has the largest impact
  - ***S1*** (Run2 uncertainties) and ***S2*** (reduced uncertainties) differs for theoretical and experimental sys on the ***signal model***





Experiment	CMS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	13%	10%
Statistical uncert.	9%	9%
Experimental uncert.	8%	2%
Theory uncer.	5%	3%

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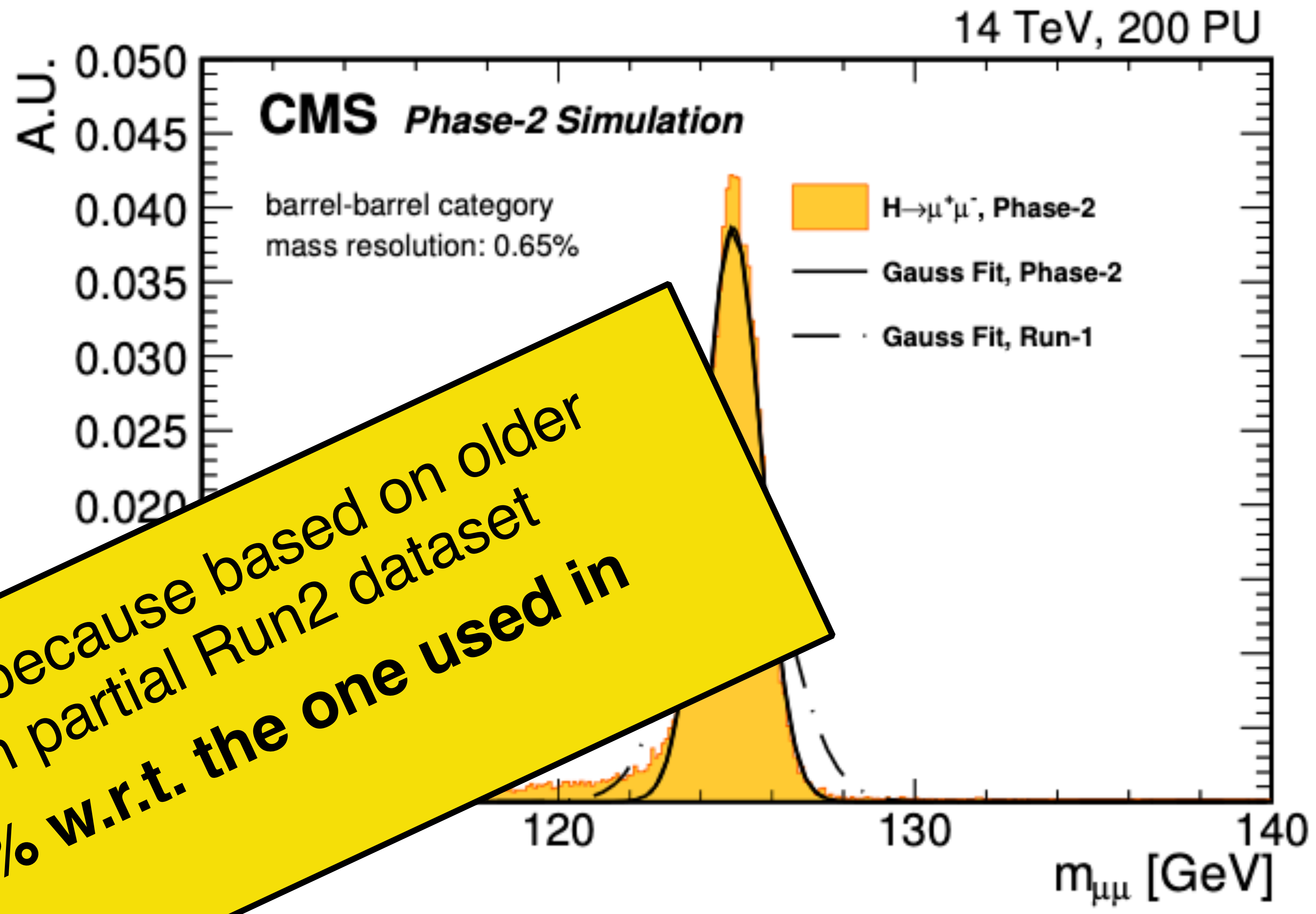

- Crucial aspect represented by ***VBF-jet tagging*** since VBF is the most sensitive channel
- Good improvements expected thanks to tracking coverage up to |η| ~ 4.0 and the ***high-granularity endcap calorimeter*** (HGCAL)

NB: these projections are already superseded because based on older version of the CMS Hμμ analyses based on partial Run2 dataset

The CMS analysis improved by about 40% w.r.t. the one used in these projections

- ***H→μμ*** analysis will still uncertainty
  - Bias uncertainty in bkg m gest impact
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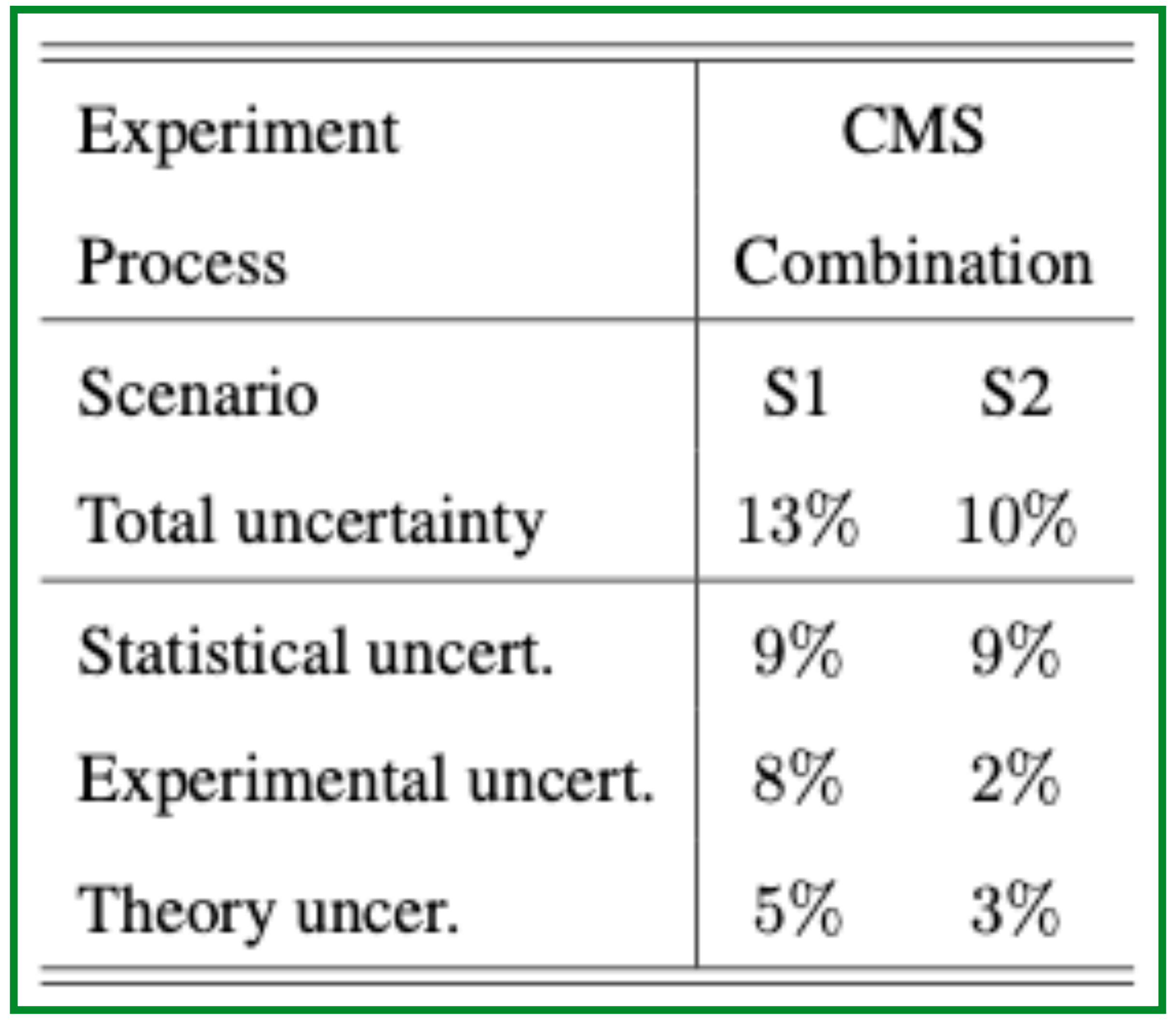

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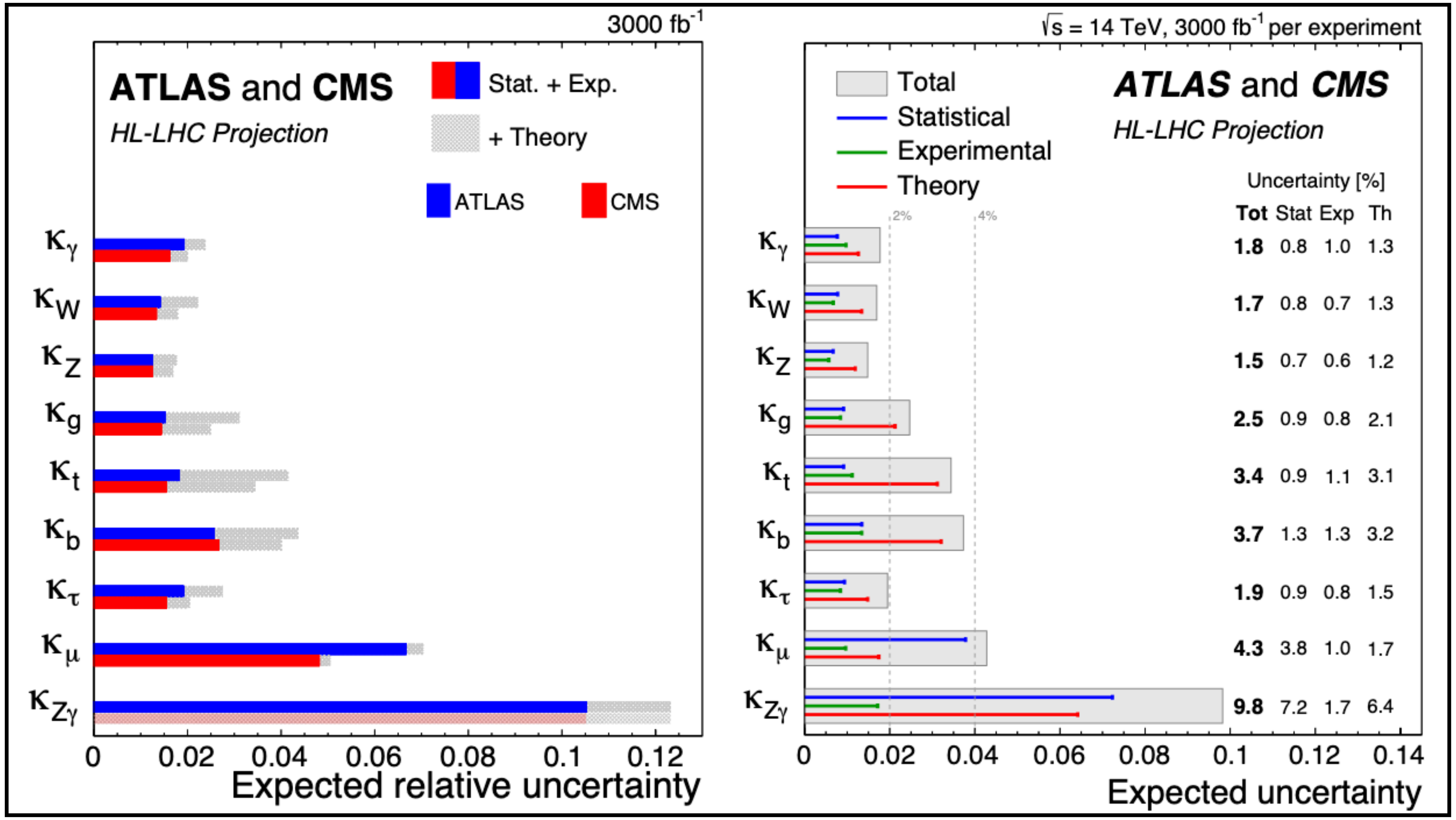
Higgs couplings @ HL-LHC

- Combination for: H(γγ), H(ZZ), HWW, H(ττ) (ggH & VBF), H(bb) (ggH & VH & ttH), H(μμ) (ggH & VBF), H(Zγ) (ggH & VBF)
- Combination of ATLAS and CMS performed via the BLUE method considering correlation between fit parameters

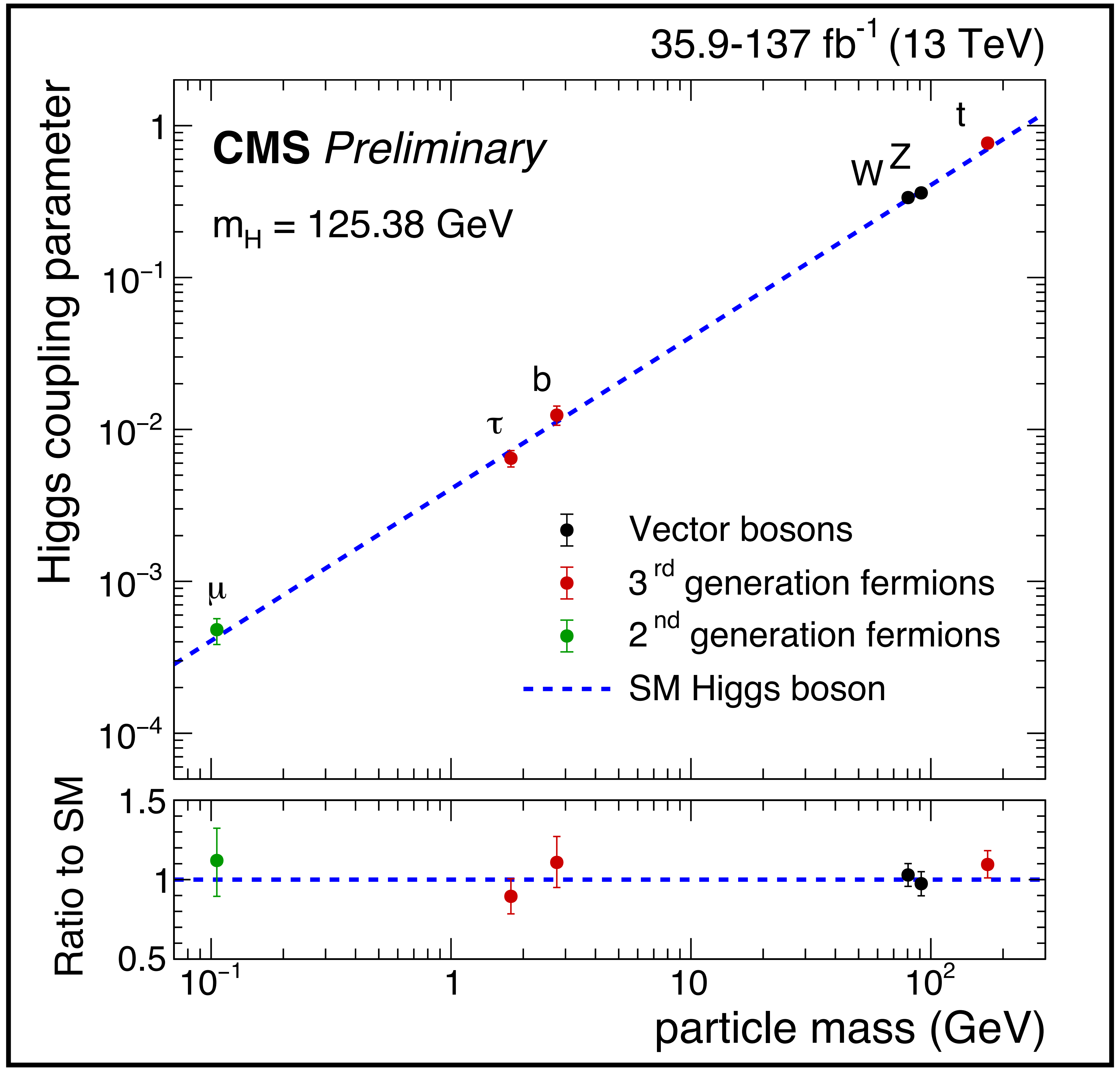


- Predictions obtained assuming ***50% smaller*** experimental and theoretical ***systematic uncertainties***
- ***Higgs couplings*** obtained in the un-resolved k-framework assuming ***no-BSM*** and ***undetermined width*** of the Higgs
- All couplings are measured with a ***4% precision*** including H(μμ)
- k_c not included in these studies

H(μμ) results are old and so ***pessimistic*** by a non-negligible amount … ***we may reach the same level of k_b and k_t***

Conclusions

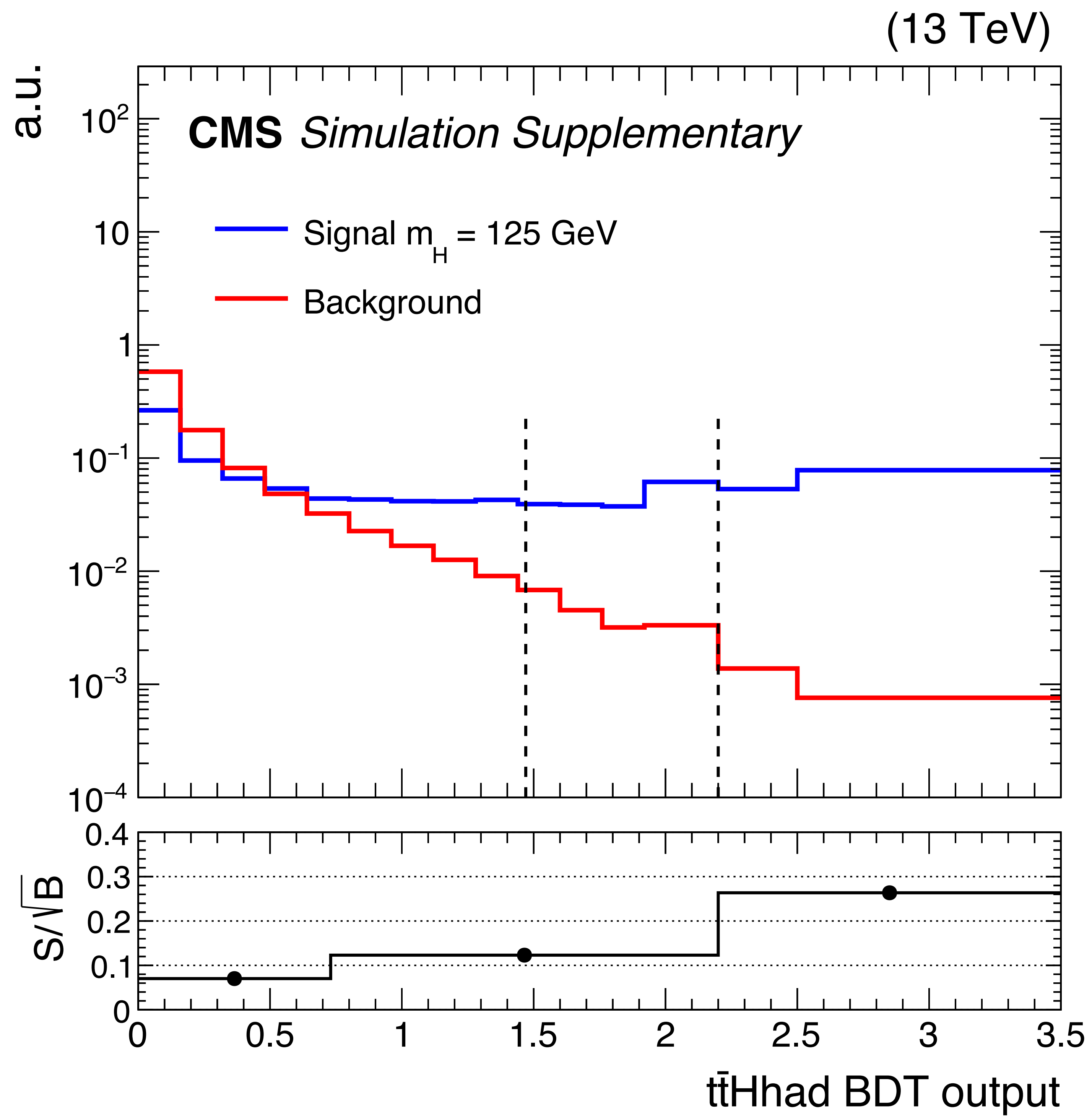
- H→μμ analysis performed using 137 fb^{-1} of 13 TeV data
- ***Observed*** *(exp)* **significance** of ***3.0σ*** *(2.5σ)* at m_H = *125.38 GeV*
- ***First evidence for H→μμ decays***
- ***First evidence for Higgs interactions with 2nd generation of fermions***
- Measured signal strength of $\mu = 1.19^{+0.44}_{-0.42}$
- ***The success of the SM continues!***
- Result published in JHEP: ***JHEP01(2021)148***

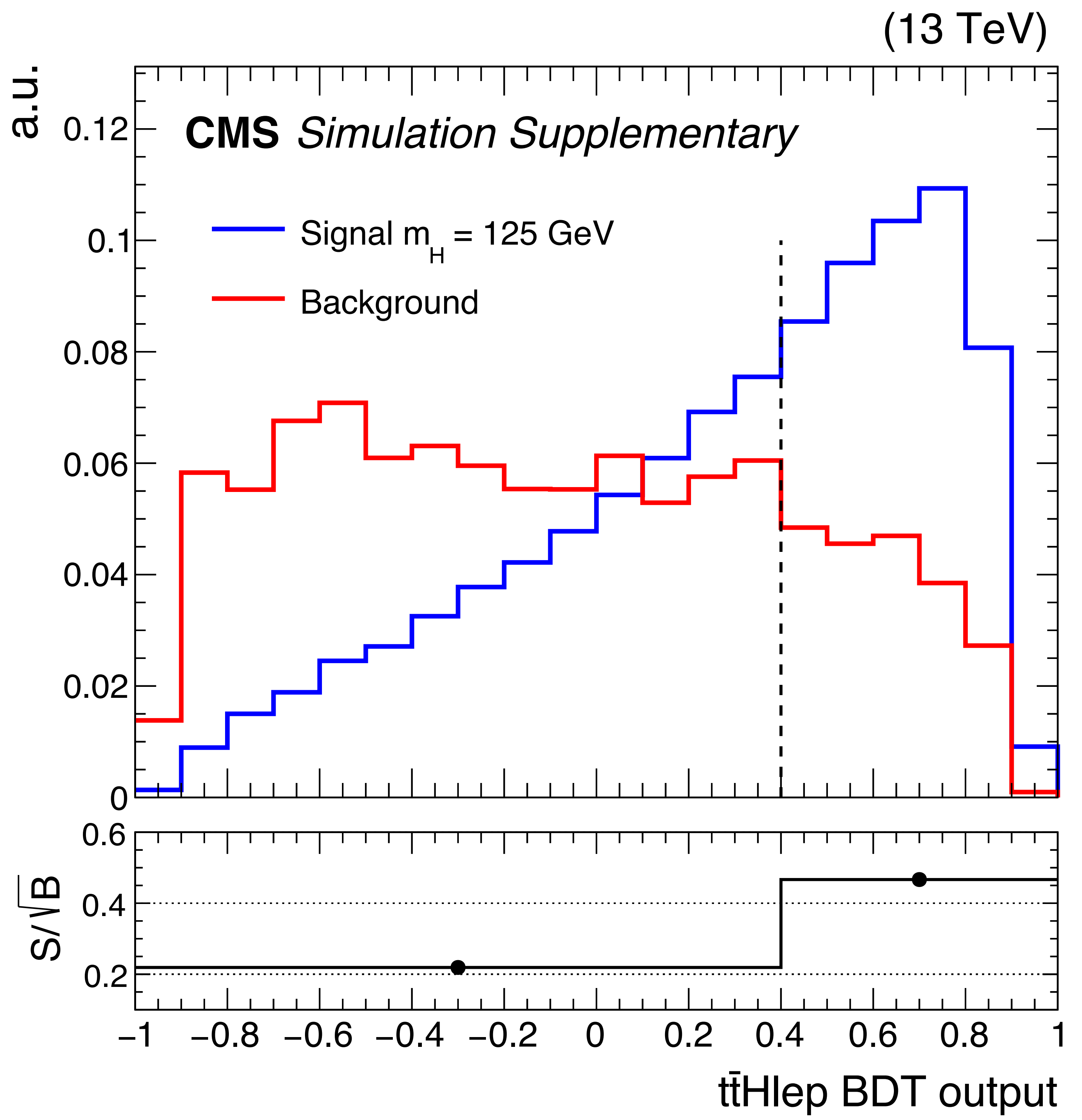


We don't expect to observe H(μμ) decays with Run2+Run3 LHC data, where expected significance would be ~4σ. The discovery and the high precision measurement of the Higgs boson couplings to muons will be left to the HL-LHC

Backup slides

ttH analysis

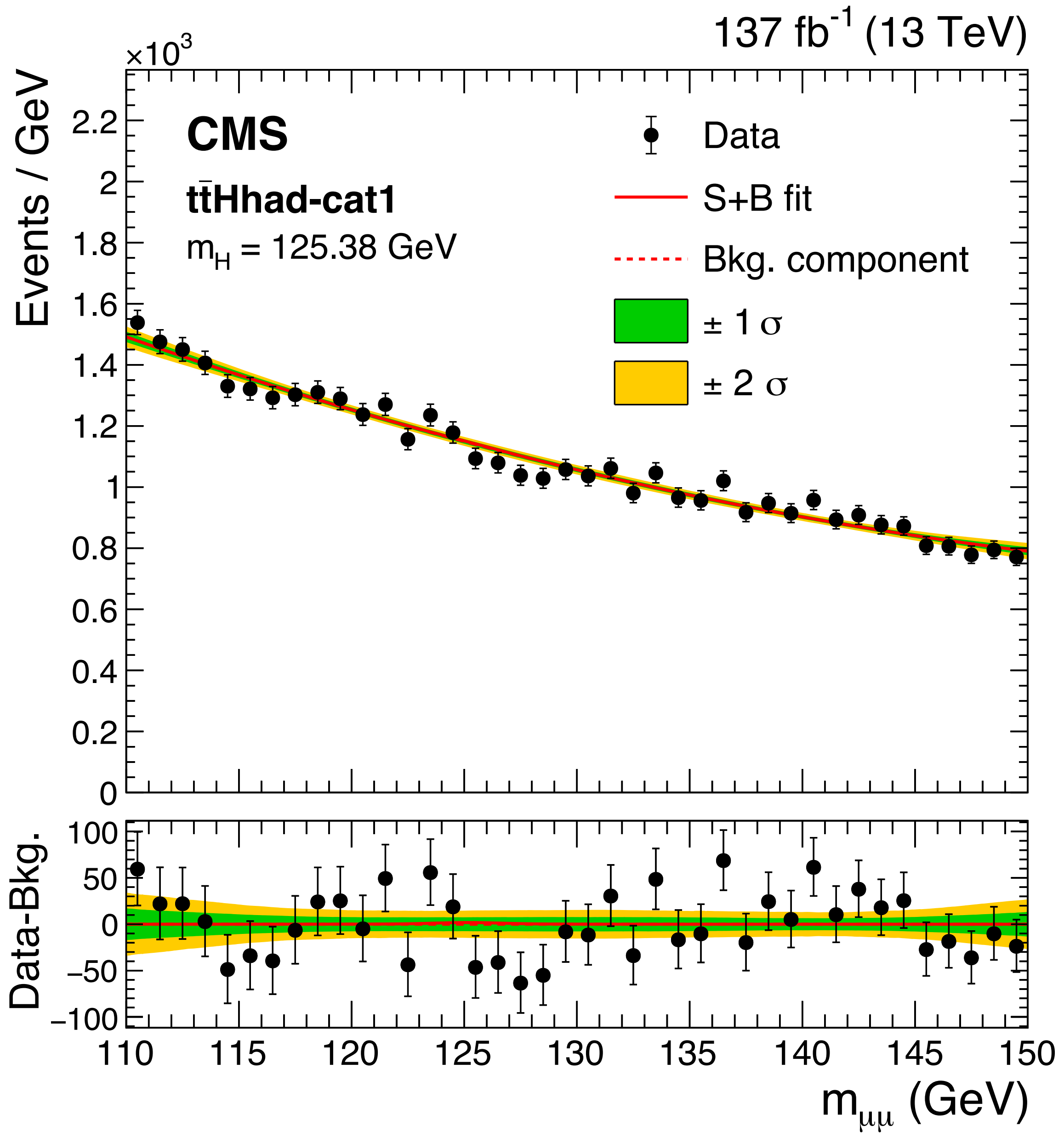


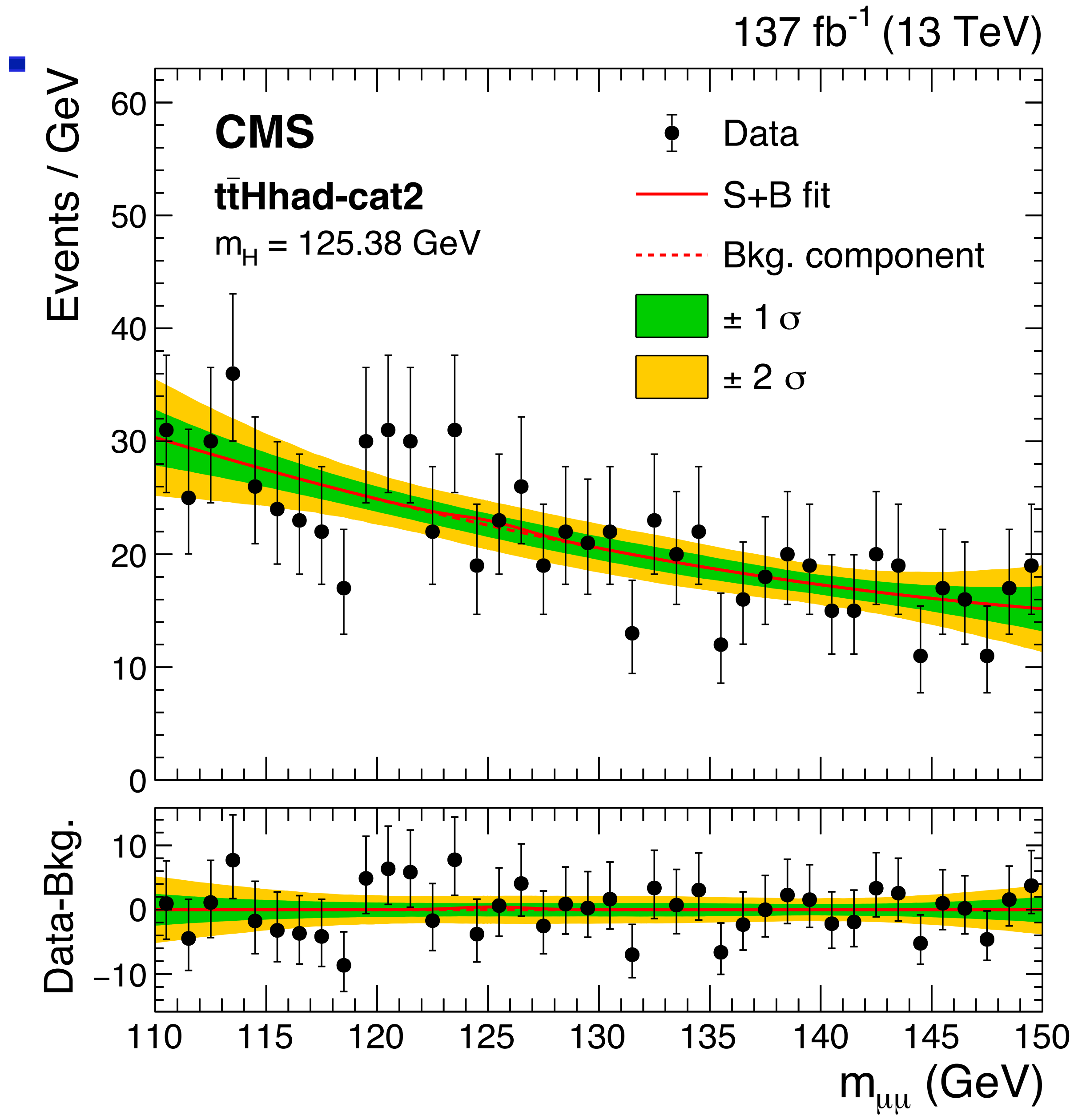


Event category	Total signal	$t\bar{t}$H (%)	ggH (%)	VH (%)	Other (%)	HWHM (GeV)	Bkg. fit function	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	$S/\sqrt{B}$ @HWHM
$t\bar{t}$Hhad-cat1	6.87	32.3	40.3	17.2	10.2	1.85	Bern(2)	4298	4251	1.07	0.07
$t\bar{t}$Hhad-cat2	1.62	84.3	3.8	5.6	6.2	1.81	Bern(2)	82.0	89	1.32	0.12
$t\bar{t}$Hhad-cat3	1.33	94.0	0.3	1.3	4.4	1.80	S-Exp	12.3	12	6.87	0.26
$t\bar{t}$Hlep-cat1	1.06	85.8	—	4.7	9.5	1.92	Exp	9.00	13	7.09	0.22
$t\bar{t}$Hlep-cat2	0.99	94.7	—	1.0	4.3	1.75	Exp	2.08	4	24.5	0.47

ttH mass distributions

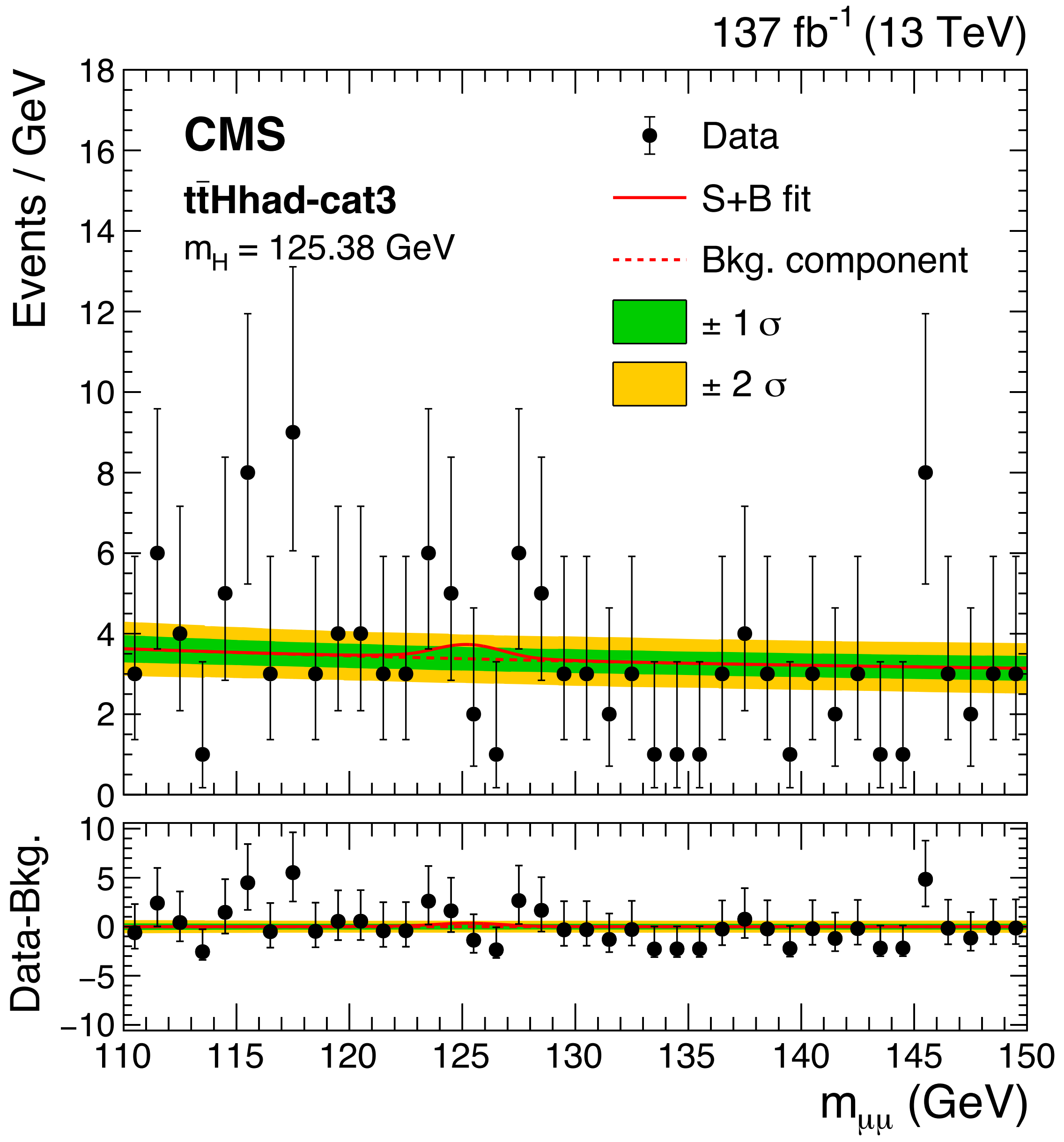
Observable	$t\bar{t}$H hadronic	$t\bar{t}$H leptonic
Number of b quark jets	>0 medium or >1 loose b-tagged jets	
Number of leptons ($N(\ell = \mu, e)$)	$=2$	$=3$ or 4
Lepton charge ($q(\ell)$)	$\sum q(\ell) = 0$	$N(\ell) = 3\ (4) \rightarrow \sum q(\ell) = \pm 1\ (0)$
Jet multiplicity ($p_T > 25\,\text{GeV}$, $\lvert\eta\rvert < 4.7$)	≥ 3	≥ 2
Leading jet p_T	$>50\,\text{GeV}$	$>35\,\text{GeV}$
Z boson veto	—	$\lvert m_{\ell\ell} - m_Z\rvert > 10\,\text{GeV}$
Low-mass resonance veto	—	$m_{\ell\ell} > 12\,\text{GeV}$
Jet triplet mass	$100 < m_{jjj} < 300\,\text{GeV}$	—

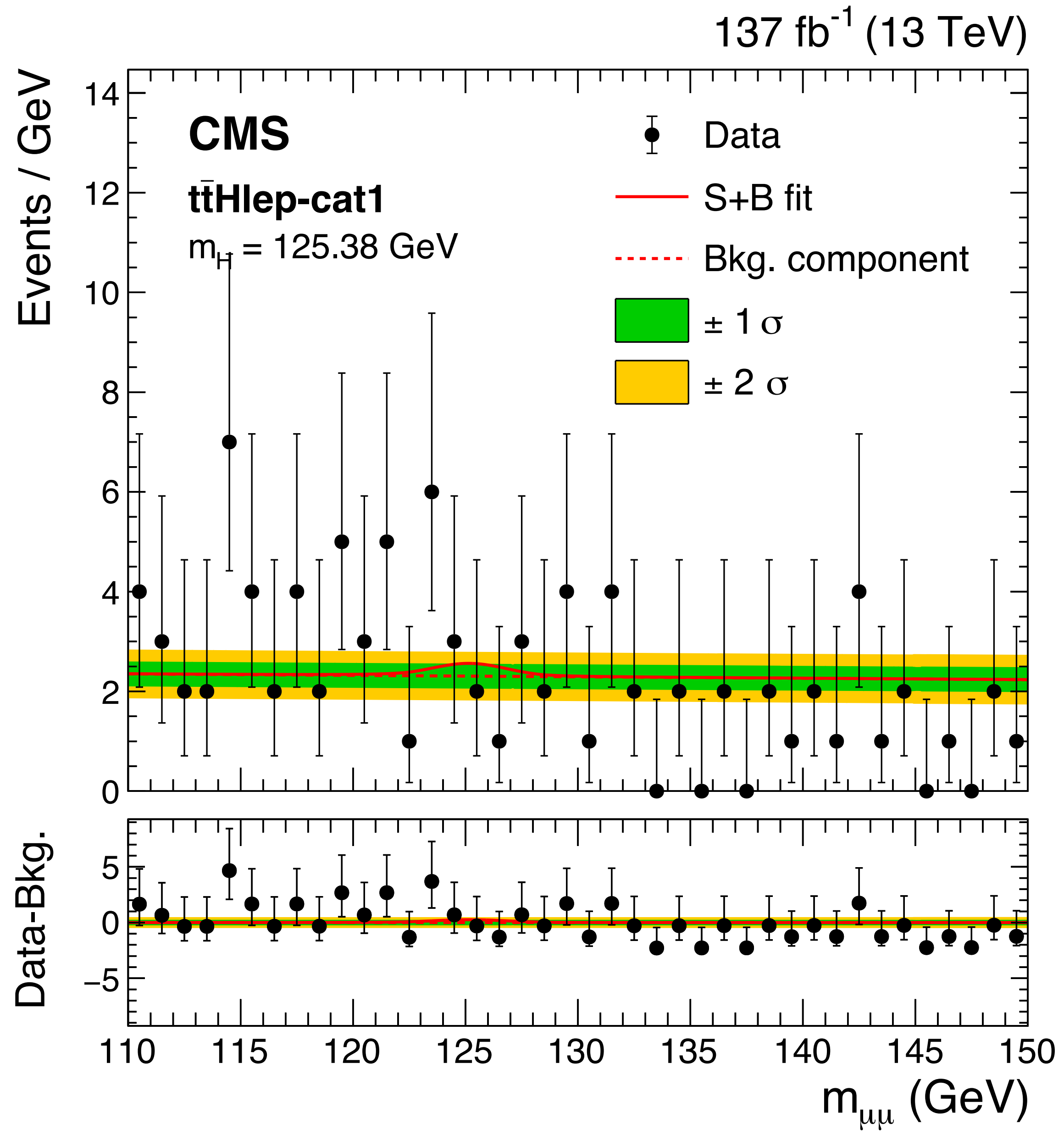


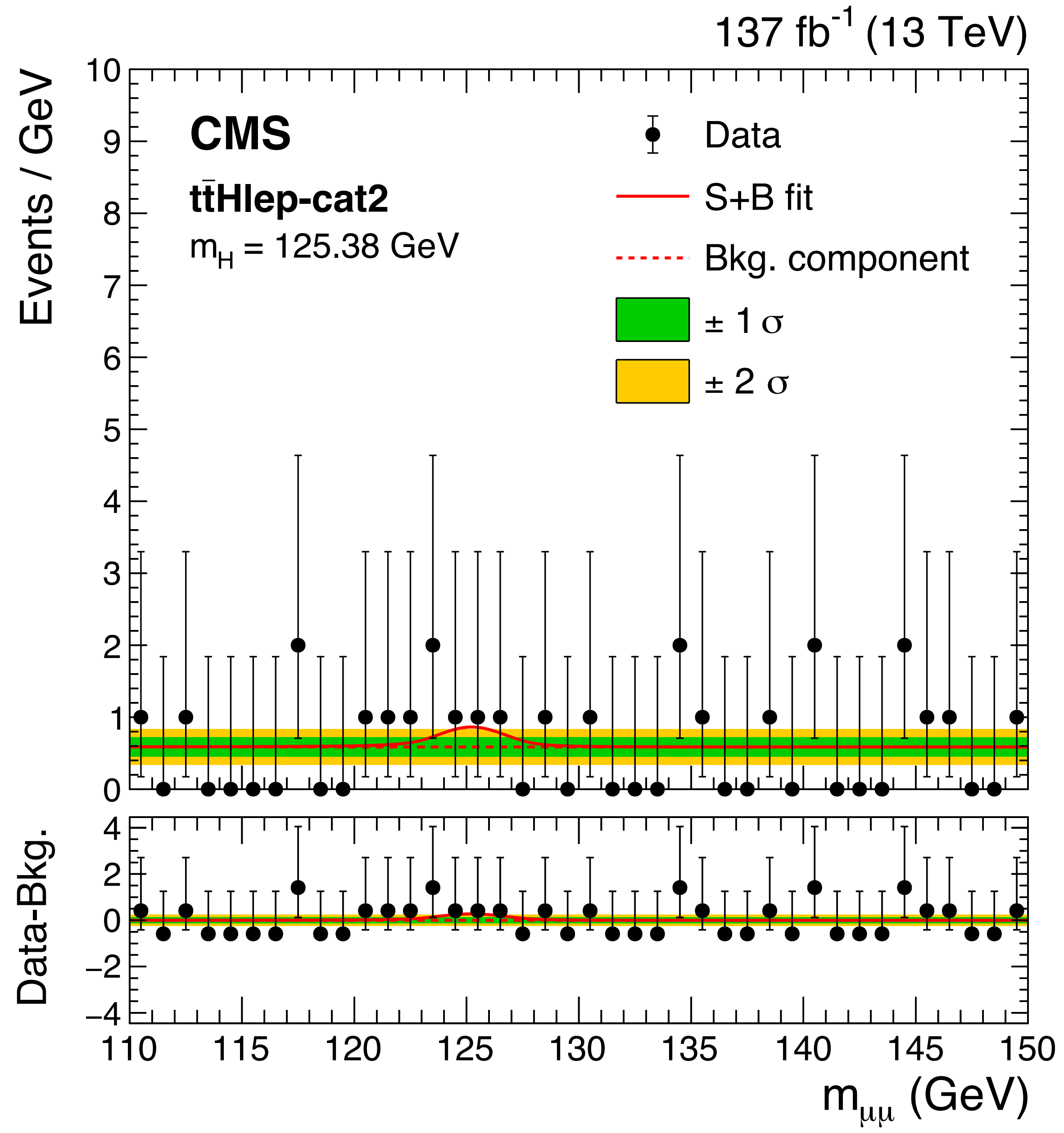


Background model

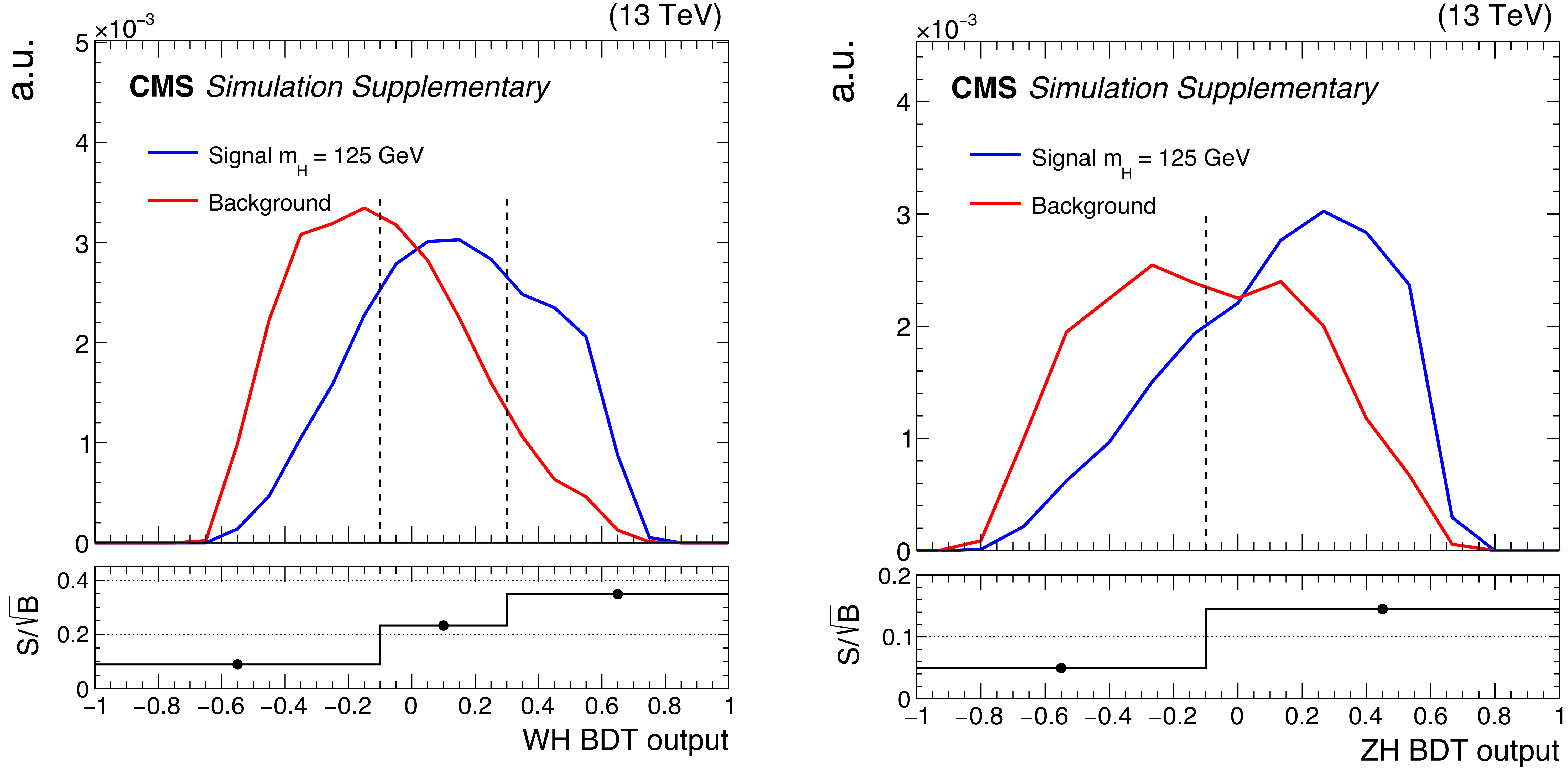
- ttH-had cat1 and cat2: 2nd order Bernstein polynomial
- ttH-had cat3 sum of two expo
- ttH-leptonic with simple exponential







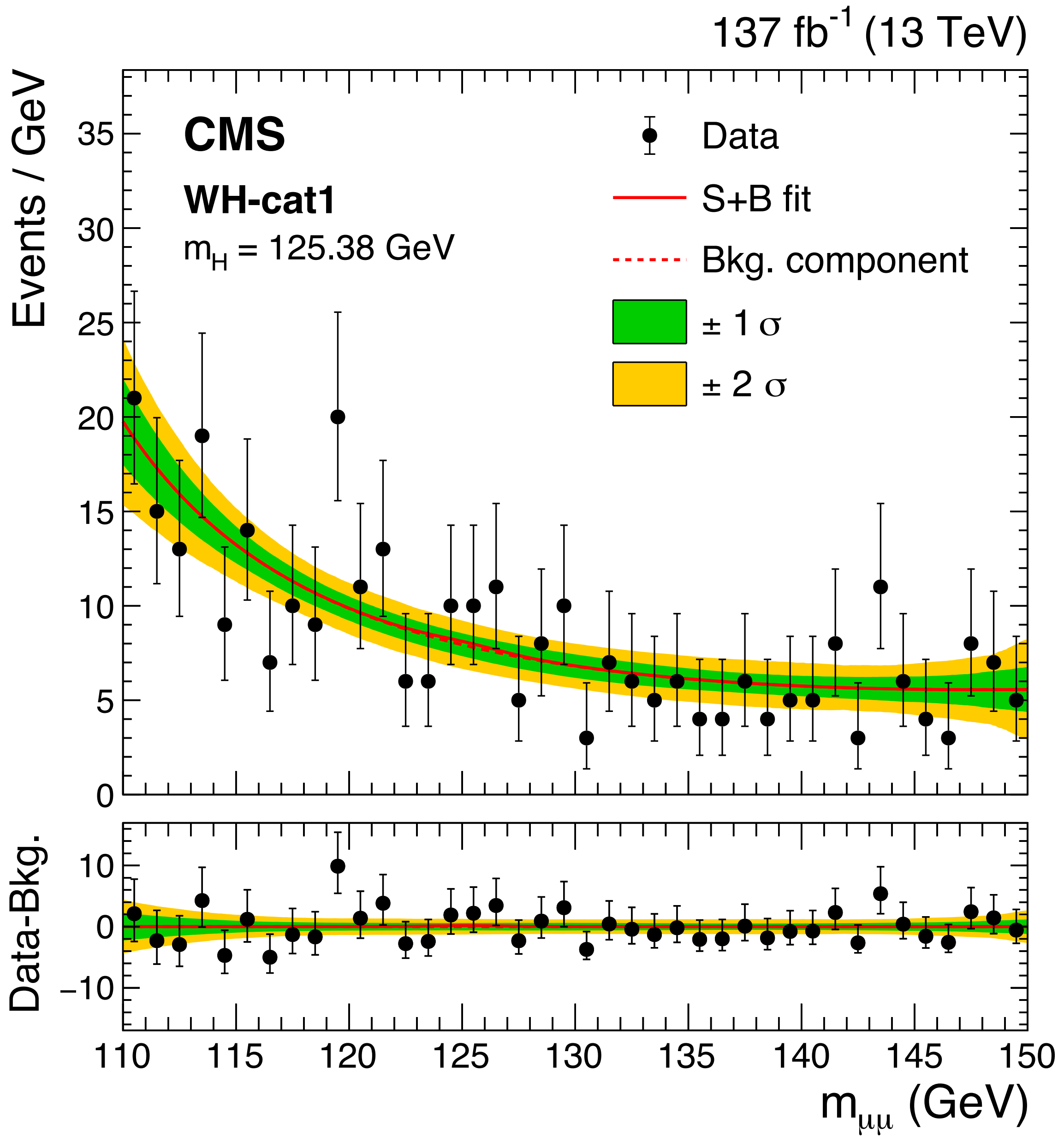
VH analysis

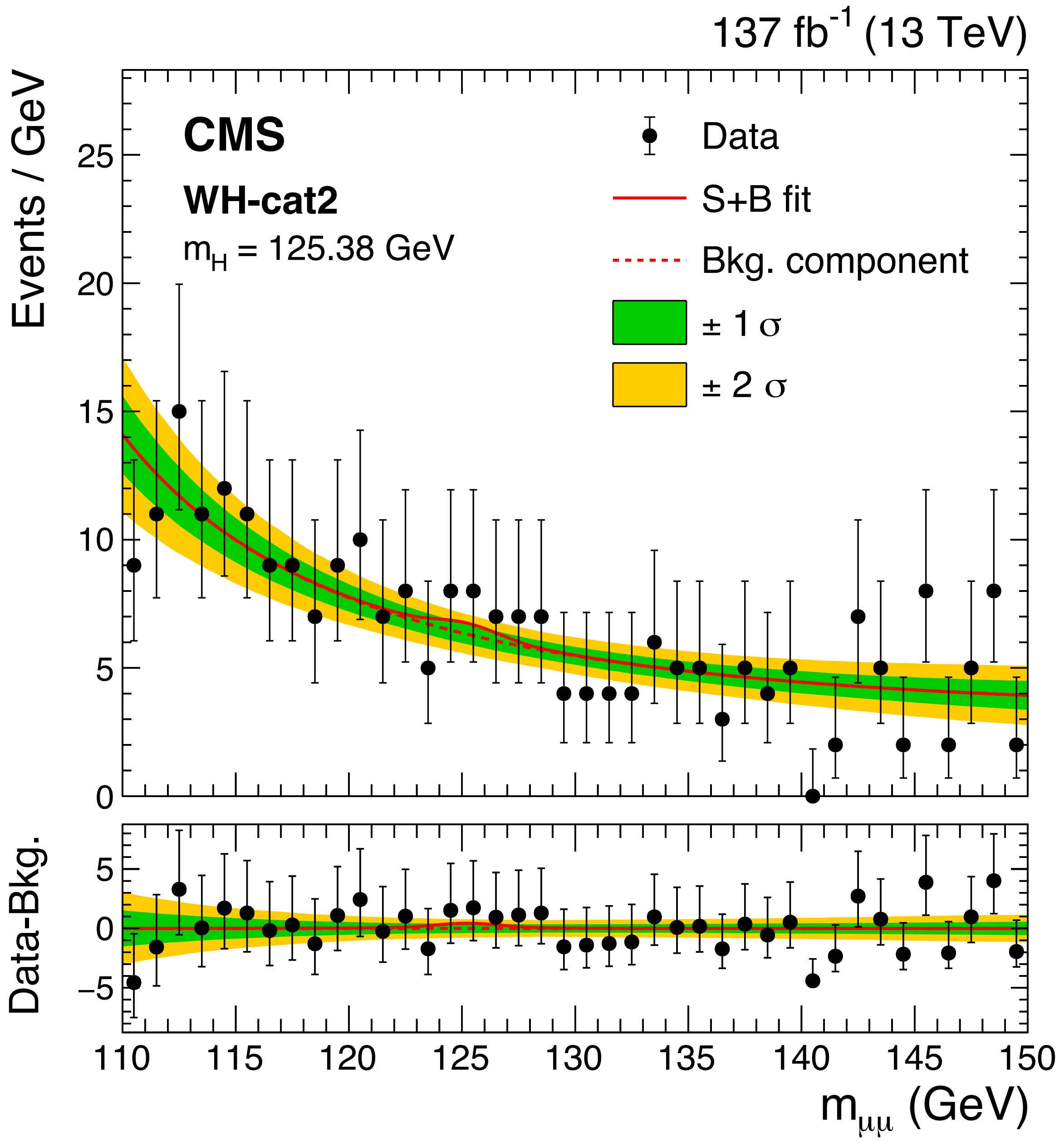


Event category	Total signal	WH (%)	qqZH (%)	ggZH (%)	$t\bar{t}$H+tH (%)	HWHM (GeV)	Bkg. fit function	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	$S/\sqrt{B}$ @HWHM
WH-cat1	0.82	76.2	9.6	1.6	12.6	2.00	BWZγ	32.0	34	1.54	0.09
WH-cat2	1.72	80.1	9.1	1.5	9.3	1.80	BWZ	23.1	27	4.50	0.23
WH-cat3	1.14	85.7	6.7	1.8	4.8	1.90	BWZ	5.48	4	12.6	0.35
ZH-cat1	0.11	—	82.8	17.2	—	2.07	BWZ	2.05	4	3.29	0.05
ZH-cat2	0.31	—	79.6	20.4	—	1.80	BWZ	2.19	4	8.98	0.14

VH mass distributions

Observable	WH leptonic		ZH leptonic	
	$\mu\mu\mu$	$\mu\mu$e	4μ	$2\mu2$e
Number of loose (medium) b-tagged jets	≤1 (0)	≤1 (0)	≤1 (0)	≤1 (0)
Number of selected muons	$=3$	$=2$	$=4$	$=2$
Number of selected electrons	$=0$	$=1$	$=0$	$=2$
Lepton charge ($q(\ell)$)	$\sum q(\ell) = \pm1$		$\sum q(\ell) = 0$	
Low-mass resonance veto	$m_{\ell\ell} > 12\,\mathrm{GeV}$			
N($\mu^+\mu^-$) pairs with $110 < m_{\mu\mu} < 150\,\mathrm{GeV}$	≥1	$=1$	≥1	$=1$
N($\mu^+\mu^-$) pairs with $\lvert m_{\mu\mu} - m_Z\rvert < 10\,\mathrm{GeV}$	$=0$	$=0$	$=1$	$=0$
N(e^+e^-) pairs with $\lvert m_{ee} - m_Z\rvert < 20\,\mathrm{GeV}$	$=0$	$=0$	$=1$	$=1$





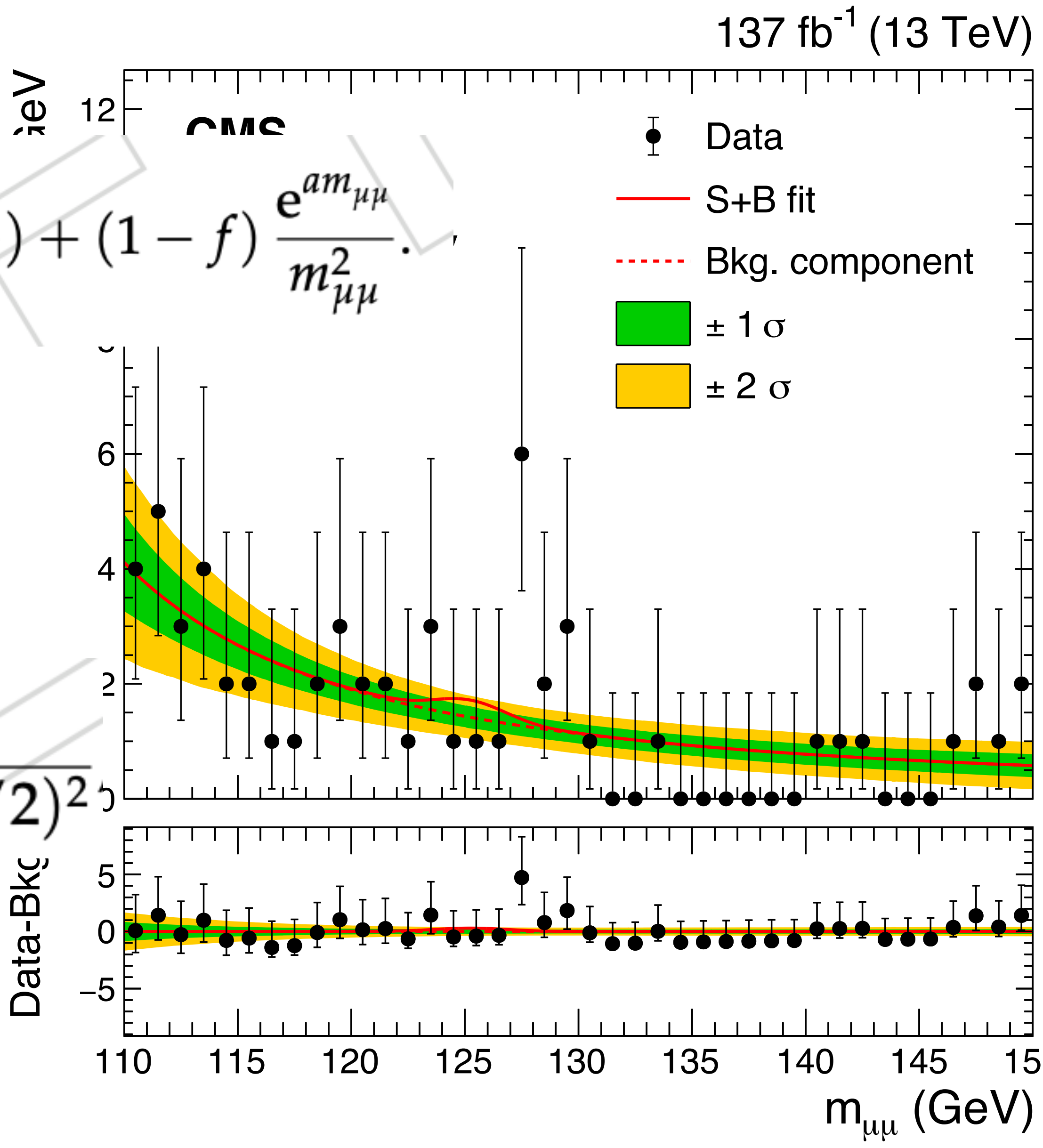
Background model

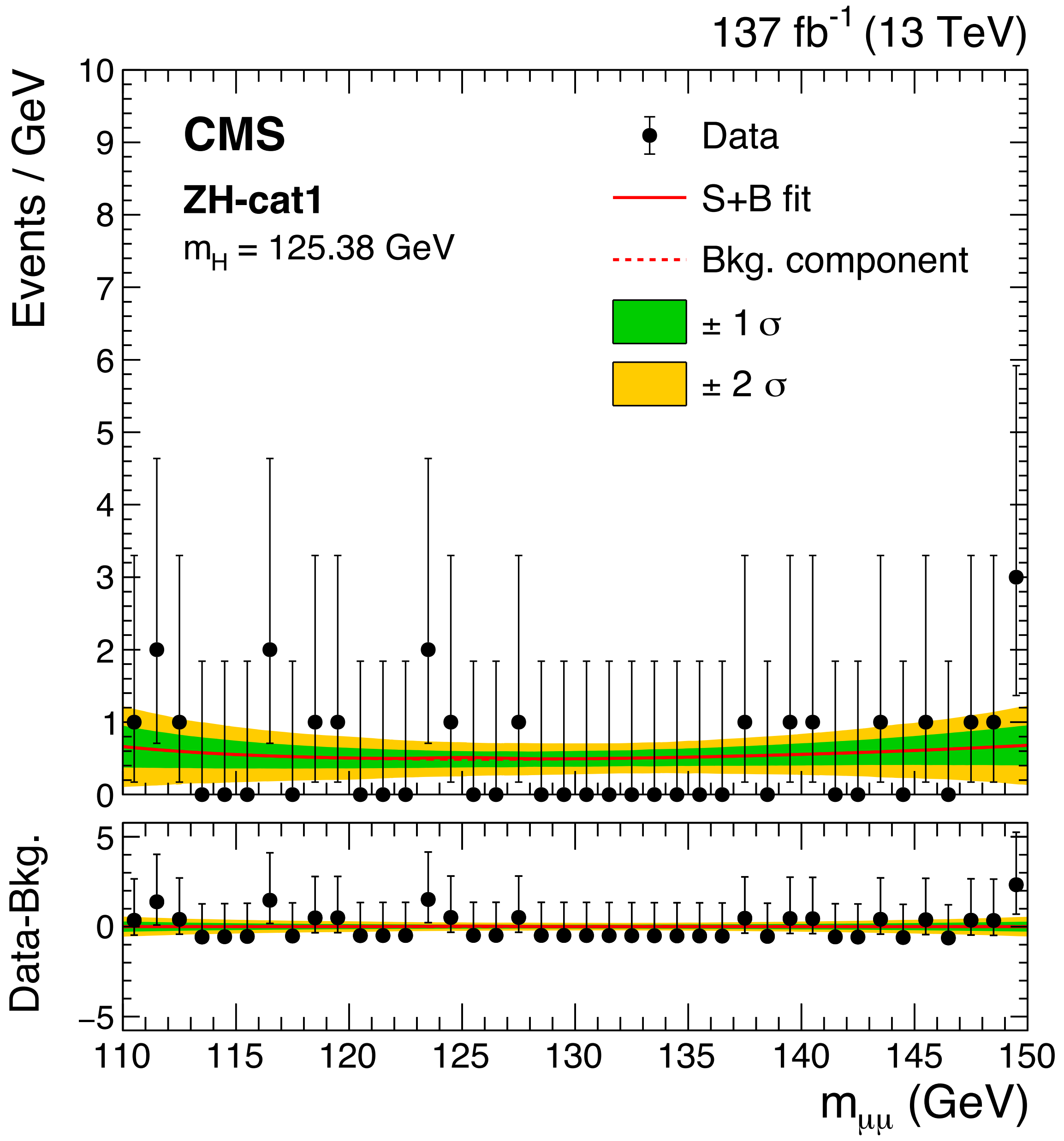
- BWZγ in WH-cat1

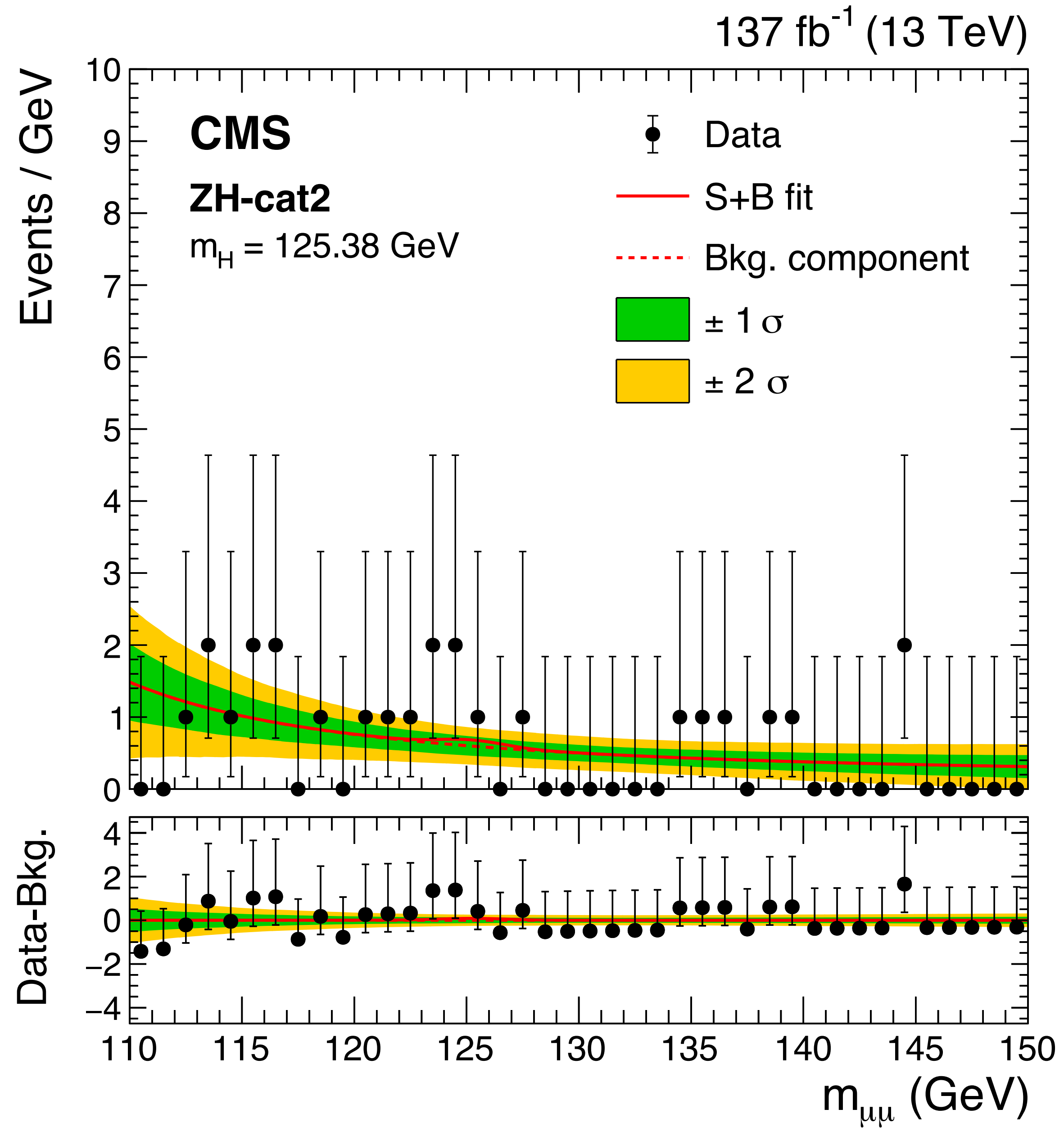
$$\mathrm{BWZ}\gamma(m_{\mu\mu}; a, f, m_Z, \Gamma_Z) = f\,\mathrm{BWZ}(m_{\mu\mu}; a, m_Z, \Gamma_Z) + (1-f)\,\frac{e^{a m_{\mu\mu}}}{m_{\mu\mu}^2}.$$

- BWZ in WH-cat2, WH-cat3 and ZH categories

$$\mathrm{BWZ}(m_{\mu\mu}; a, m_Z, \Gamma_Z) = \frac{\Gamma_Z e^{a m_{\mu\mu}}}{(m_{\mu\mu} - m_Z)^2 + (\Gamma_Z/2)^2}$$



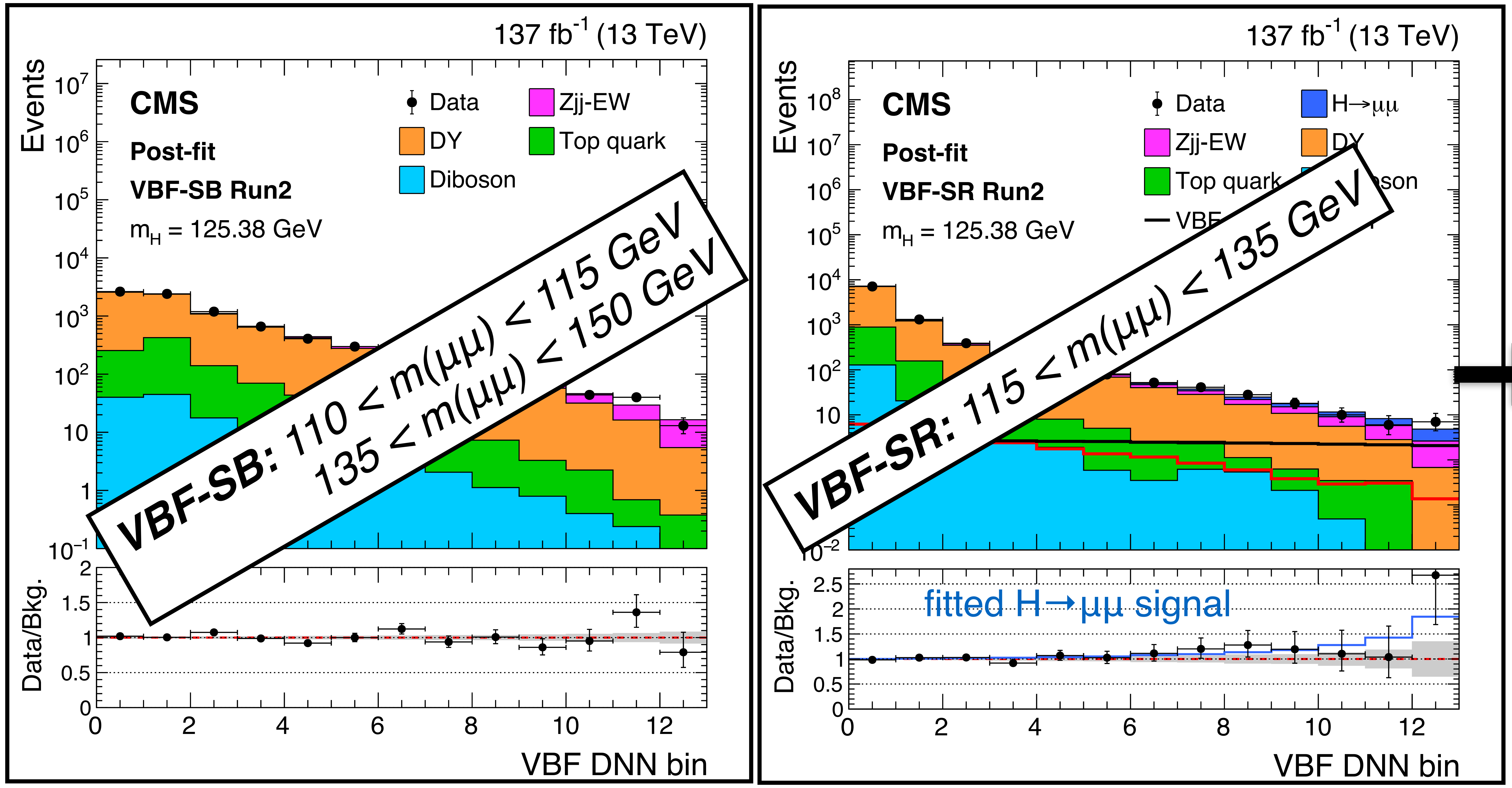




VBF-H(μμ): systematic uncertainties

- In the ***DNN high-score region*** → ***statistical uncertainty*** in the most sensitive bins ranges in ***40-70%***
- ***Systematic uncertainties*** on the ***background prediction*** are, in these regions, ***<< statistical uncertainty***

Impact of systematic uncertainties is ~5%



VBF-SB: $110 < m(\mu\mu) < 115$ GeV $135 < m(\mu\mu) < 150$ GeV

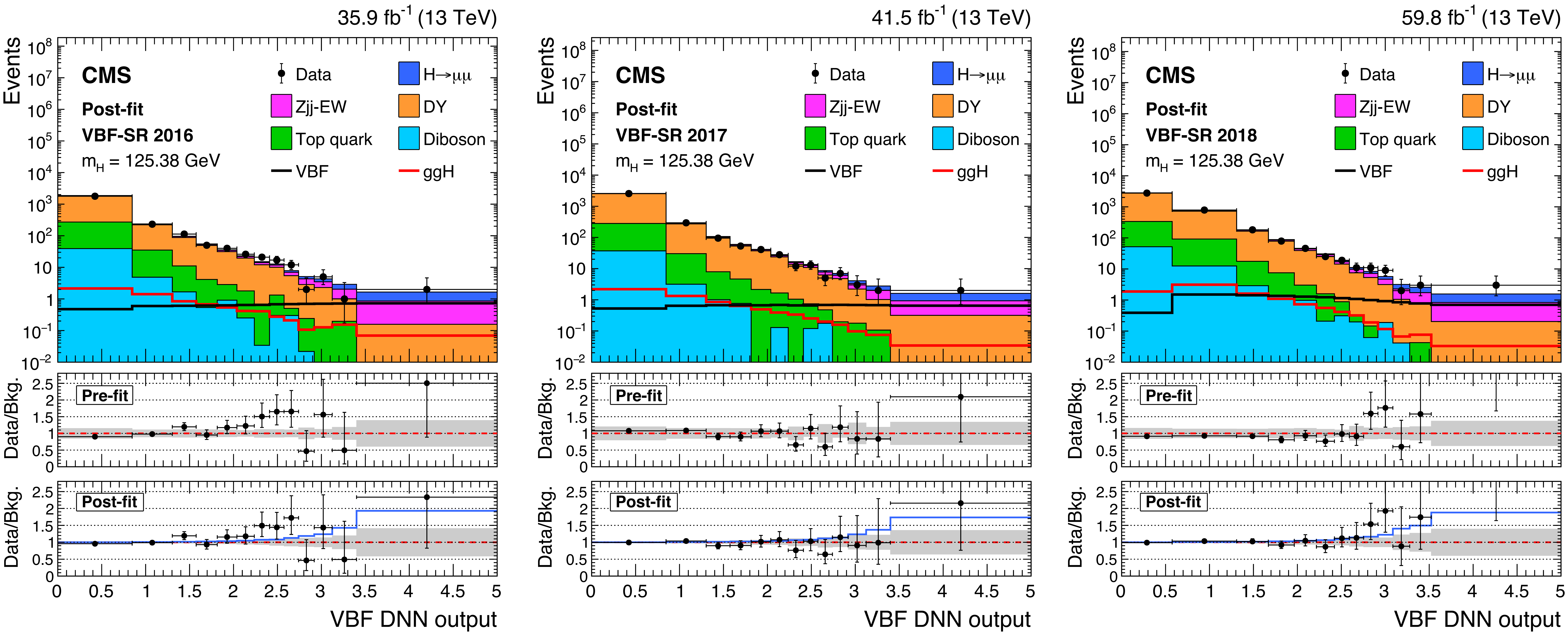
VBF-SR: $115 < m(\mu\mu) < 135$ GeV

fitted H→μμ signal

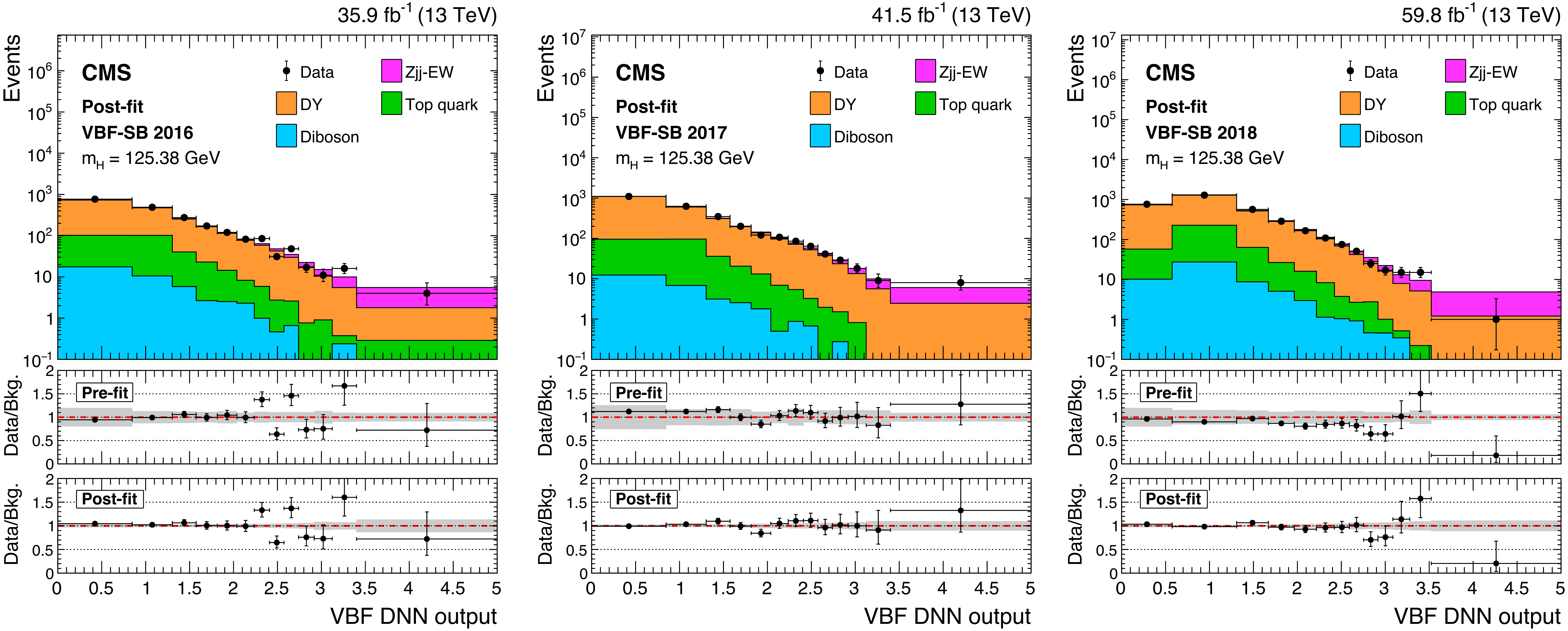
Leading systematic uncertainties

- ***Parton shower*** modelling of VBF-H and Zjj-EW (Pythia vs Herwig)
- ***Jet energy scale*** and ***resolution***
- ***DY*** events from ***one*** or ***more pileup jets***
- ***Statistical*** precision of ***simulation***
- ***Theory uncertainties***: missing higher order corrections, etc ..

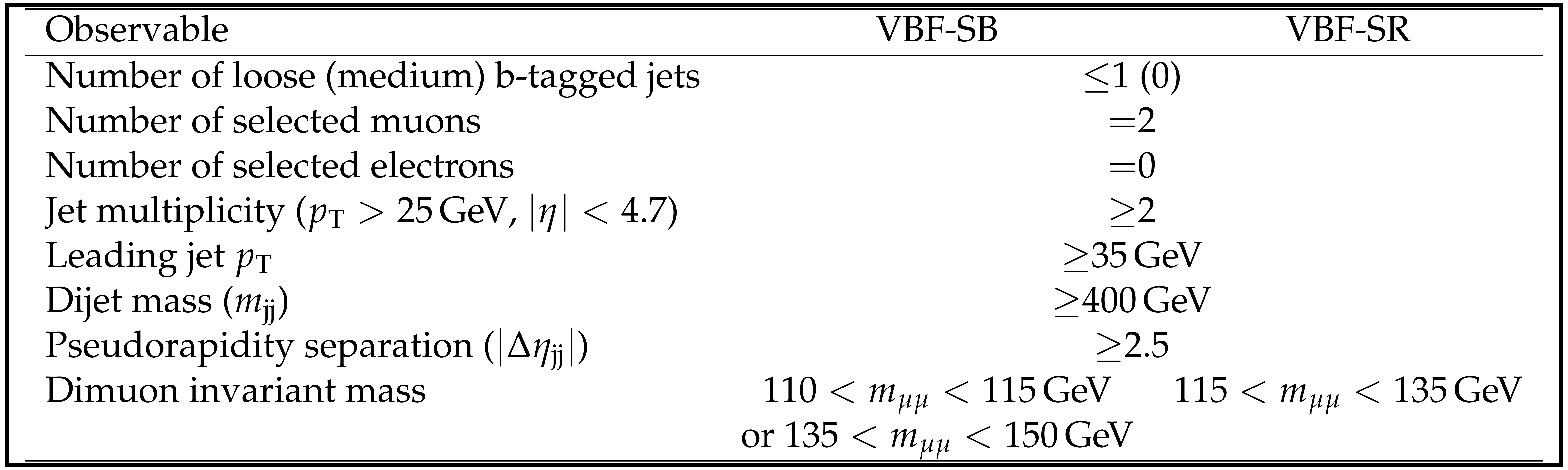
VBF fit breakdown in data-taking periods



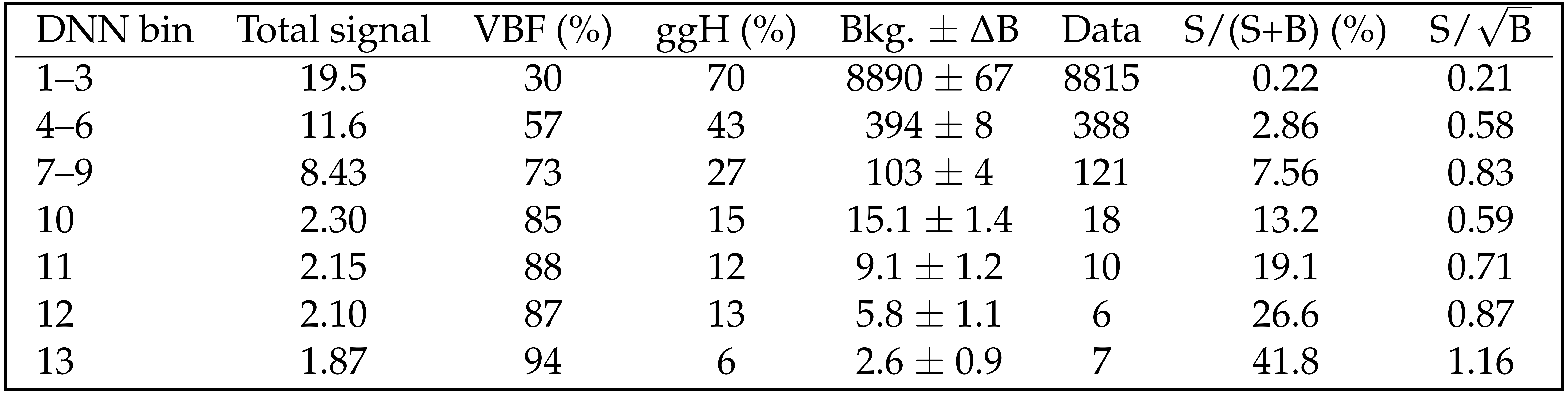
VBF fit breakdown in data-taking periods



VBF summary tables



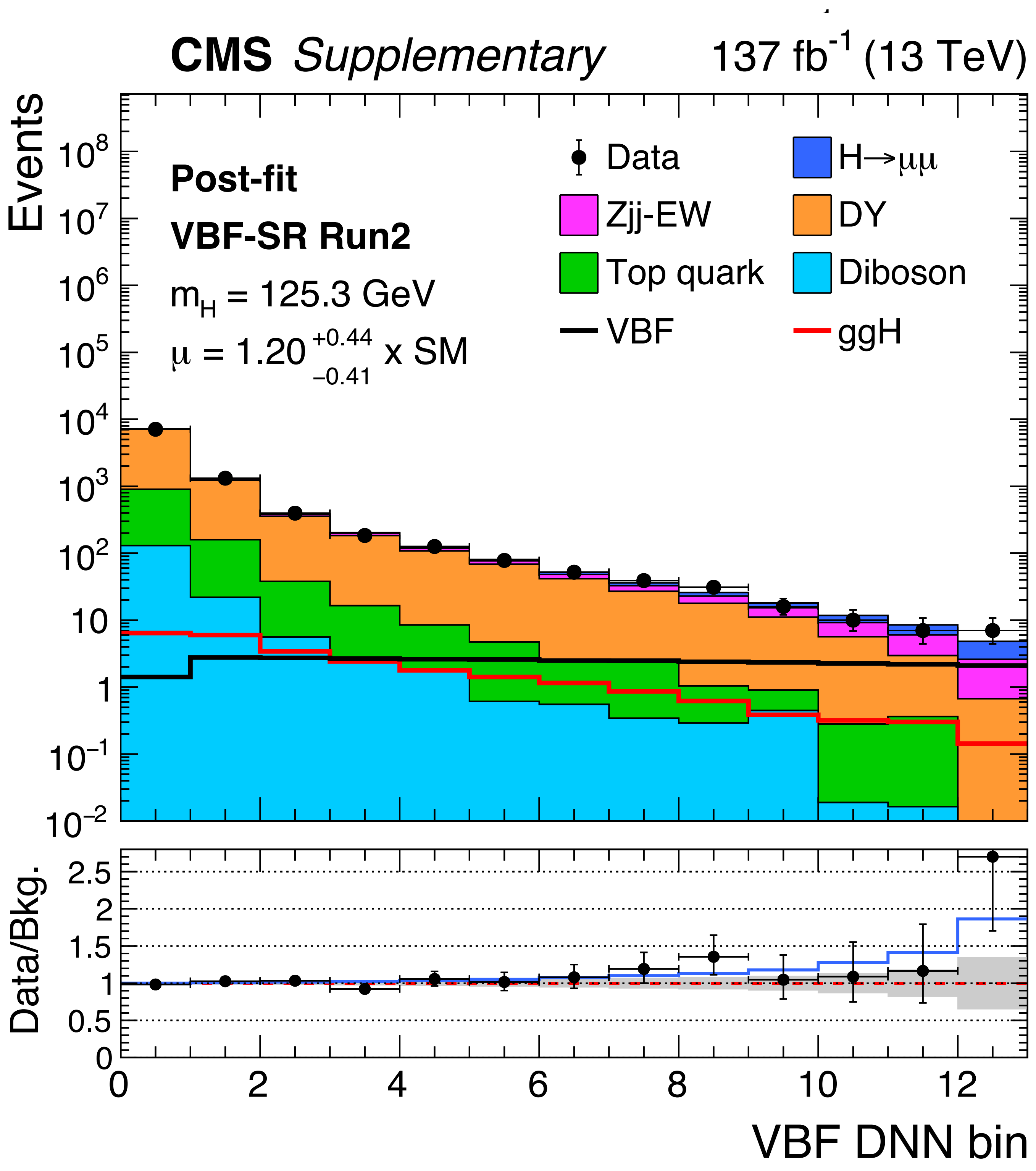
Observable	VBF-SB	VBF-SR
Number of loose (medium) b-tagged jets	$\leq$1 (0)	
Number of selected muons	$=$2	
Number of selected electrons	$=$0	
Jet multiplicity ($p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.7$)	$\geq$2	
Leading jet p_{T}	$\geq$35 GeV	
Dijet mass (m_{jj})	$\geq$400 GeV	
Pseudorapidity separation ($\lvert\Delta\eta_{\mathrm{jj}}\rvert$)	$\geq$2.5	
Dimuon invariant mass	$110 < m_{\mu\mu} < 115\,\mathrm{GeV}$ or $135 < m_{\mu\mu} < 150\,\mathrm{GeV}$	$115 < m_{\mu\mu} < 135\,\mathrm{GeV}$



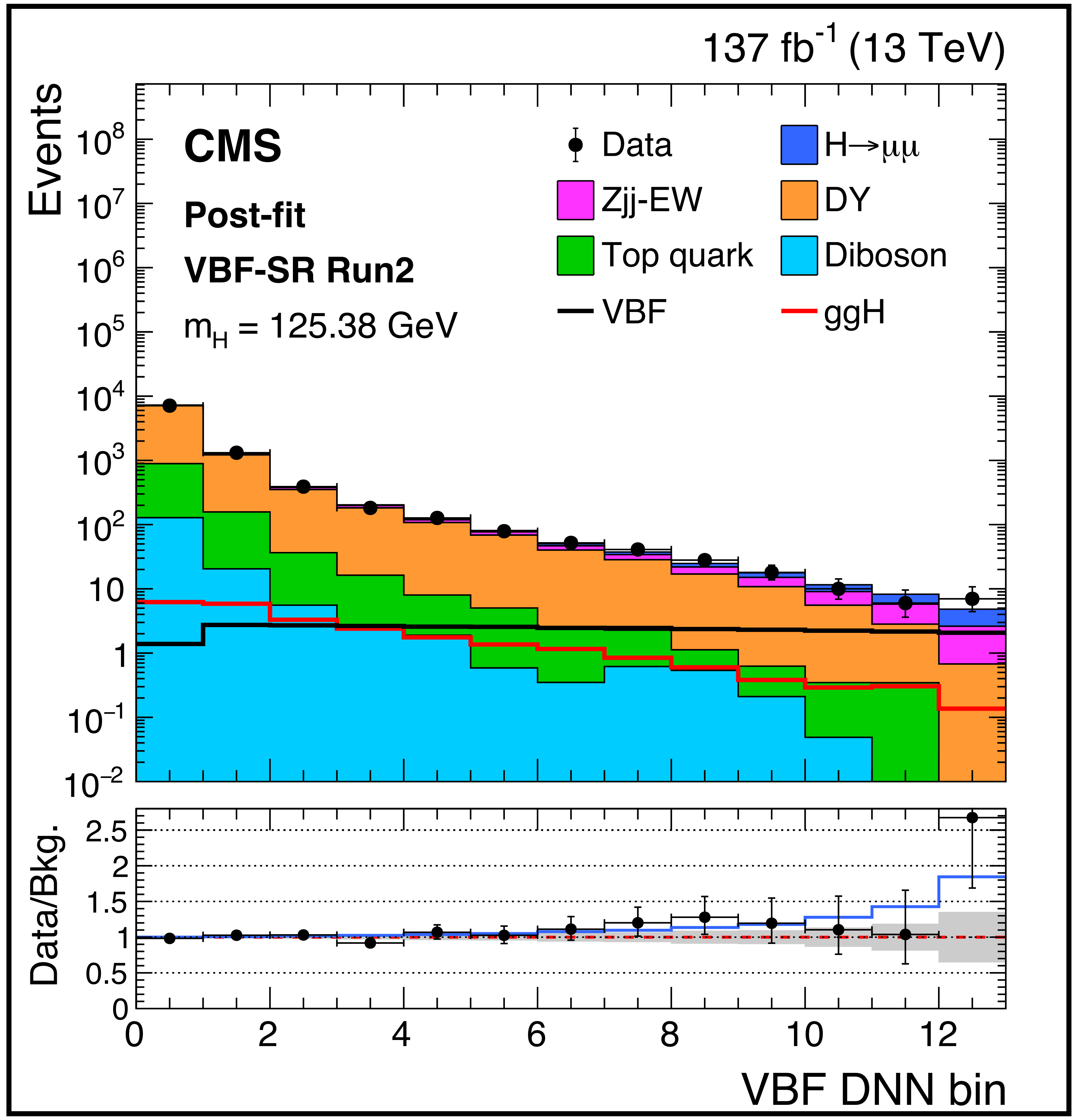
DNN bin	Total signal	VBF (%)	ggH (%)	Bkg. $\pm$ ΔB	Data	S/(S+B) (%)	S/$\sqrt{\mathrm{B}}$
1–3	19.5	30	70	8890 $\pm$ 67	8815	0.22	0.21
4–6	11.6	57	43	394 $\pm$ 8	388	2.86	0.58
7–9	8.43	73	27	103 $\pm$ 4	121	7.56	0.83
10	2.30	85	15	15.1 $\pm$ 1.4	18	13.2	0.59
11	2.15	88	12	9.1 $\pm$ 1.2	10	19.1	0.71
12	2.10	87	13	5.8 $\pm$ 1.1	6	26.6	0.87
13	1.87	94	6	2.6 $\pm$ 0.9	7	41.8	1.16

VBF DNN in SR vs m_H hypotheses

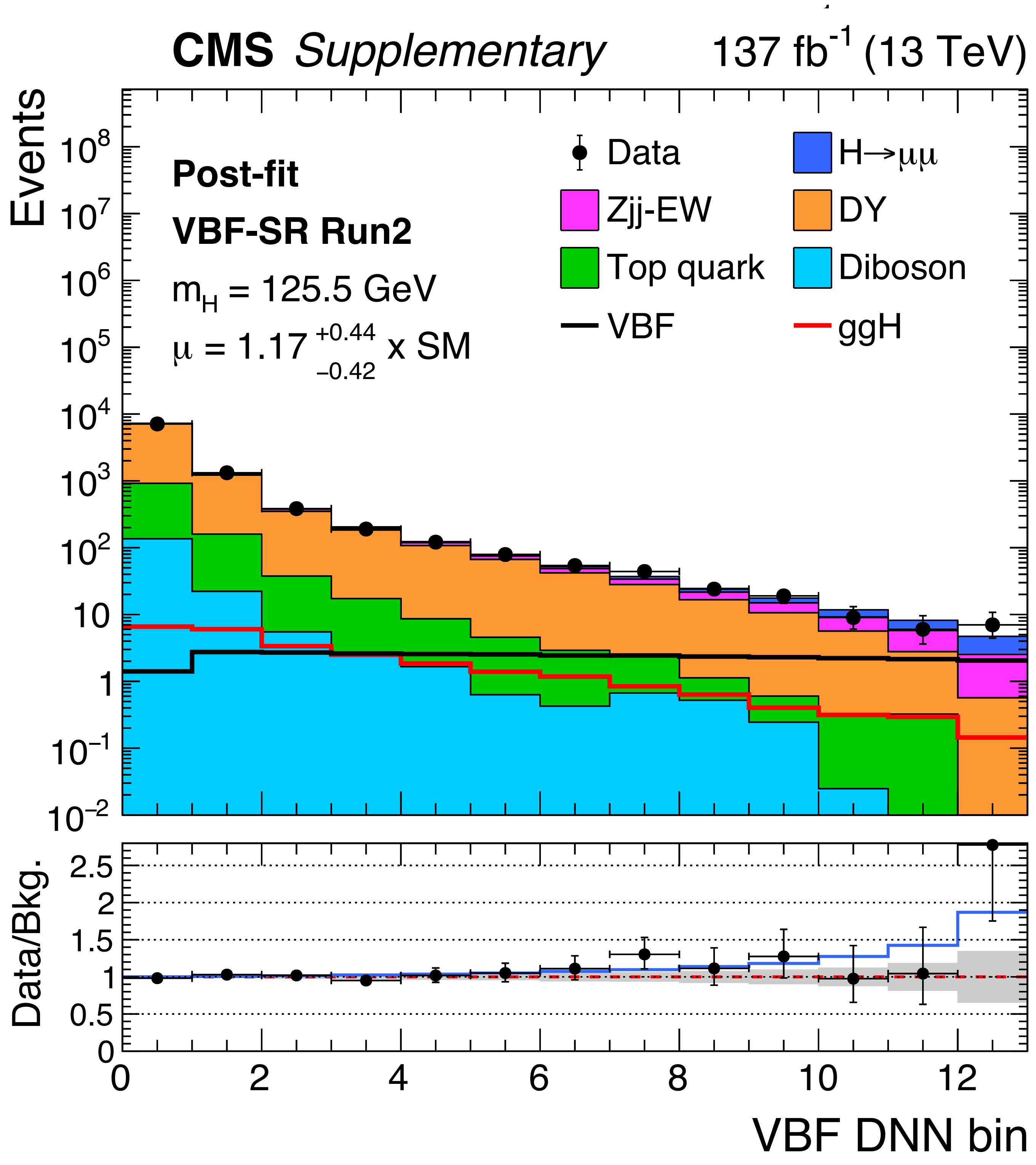
m_H = 125.3 GeV



m_H = 125.38 GeV

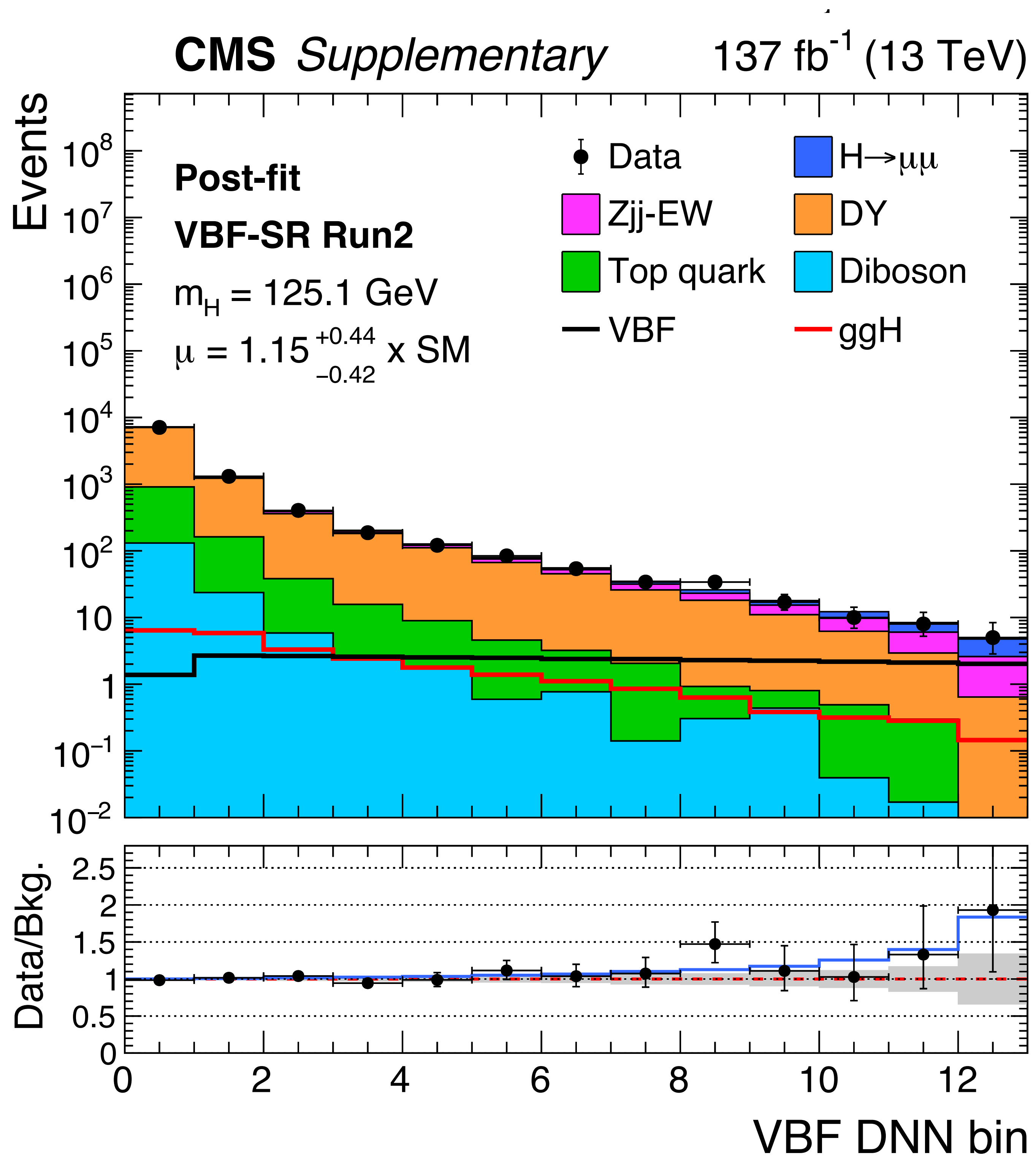


m_H = 125.5 GeV

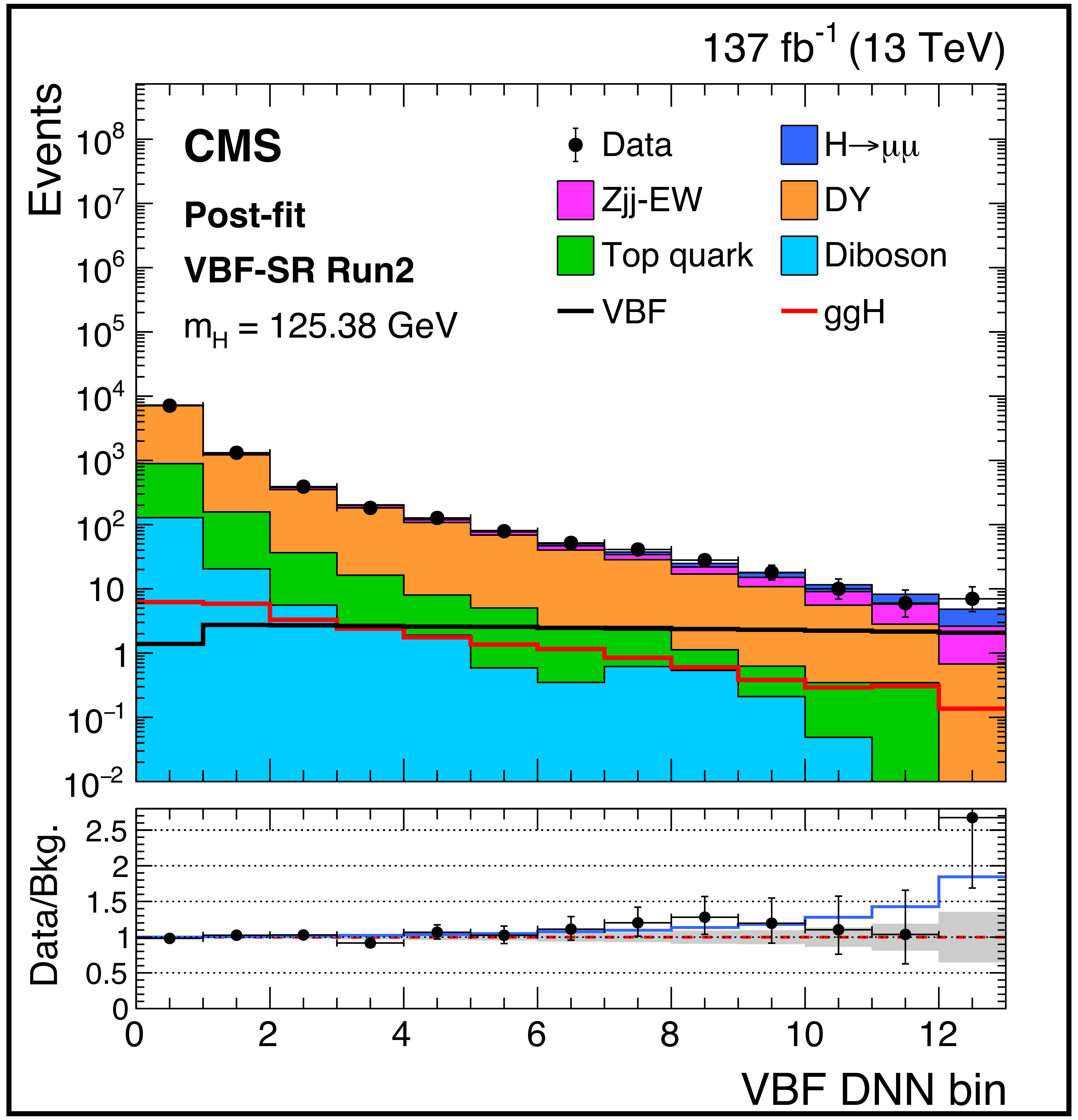


VBF DNN in SR vs m_H hypotheses

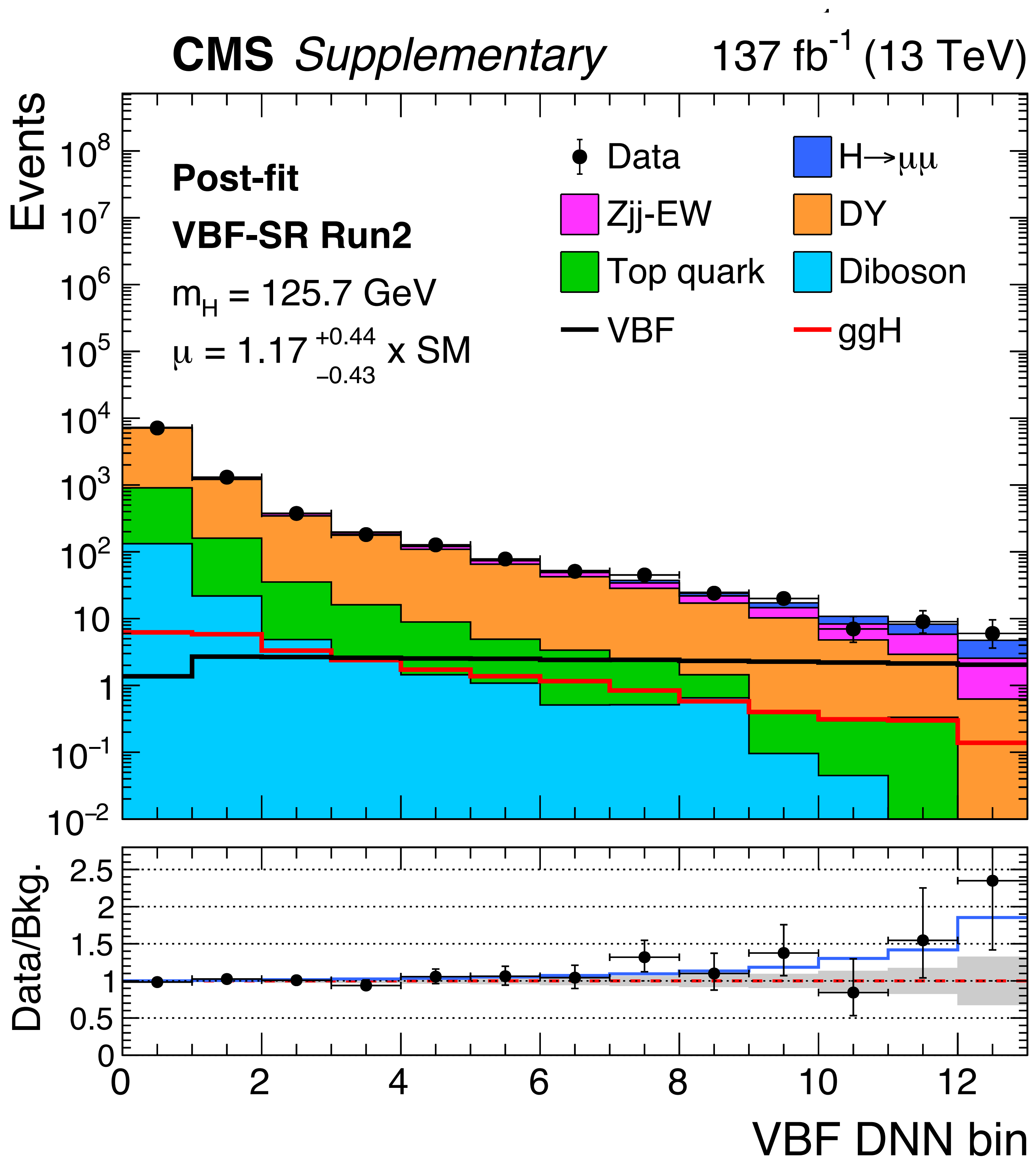
m_H = 125.1 GeV



m_H = 125.38 GeV



m_H = 125.7 GeV



ggH mass distributions

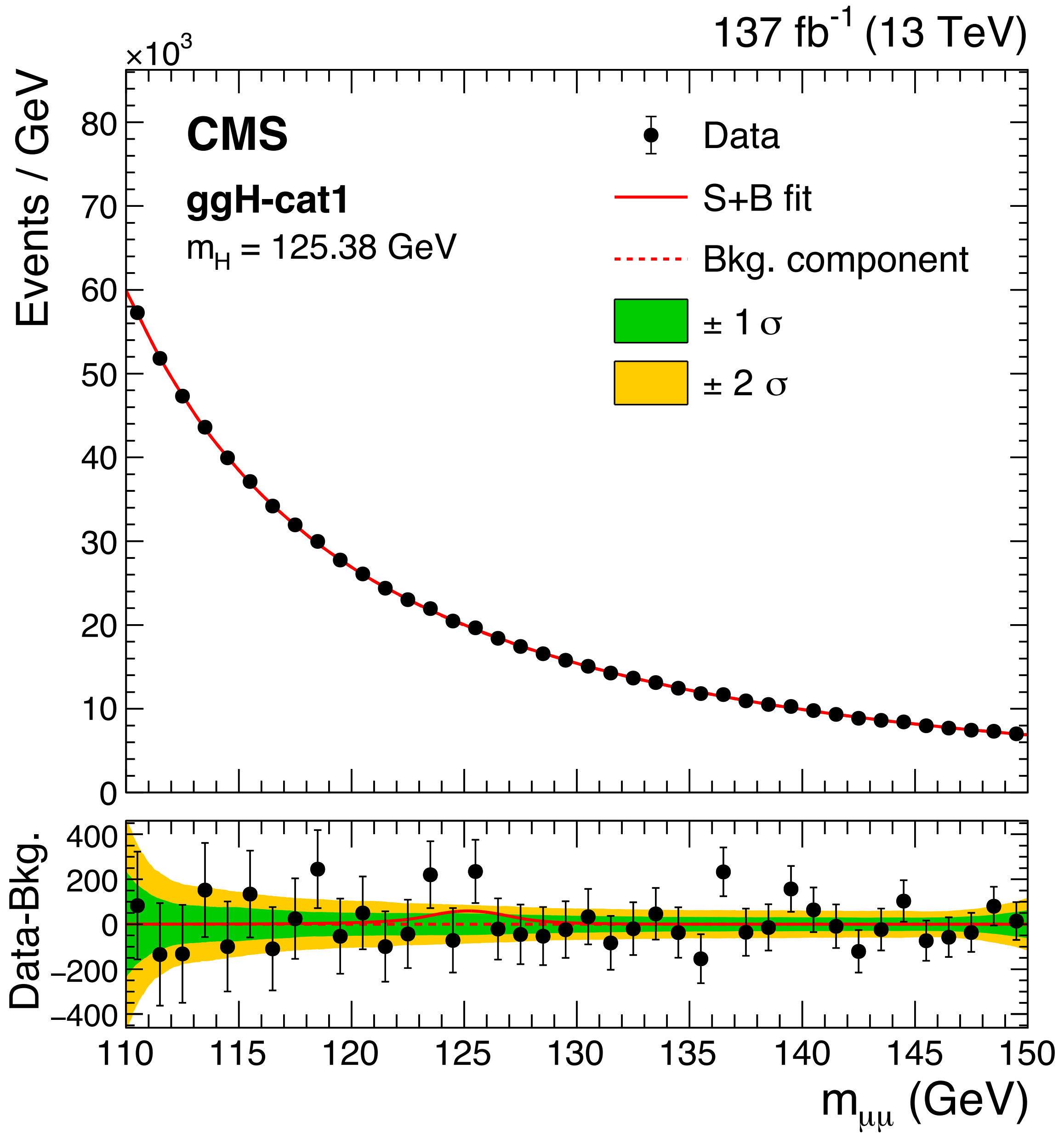
Observable	Selection
Number of loose (medium) b-tagged jets	≤ 1 (0)
Number of selected muons	=2
Number of selected electrons	=0
VBF selection veto	if $\mathrm{N_{jets}} \geq 2$ $m_{\mathrm{jj}} < 400\,\mathrm{GeV}$ or $\lvert\Delta\eta_{\mathrm{jj}}\rvert < 2.5$ or $p_{\mathrm{T}}(\mathrm{j}_1) < 35\,\mathrm{GeV}$

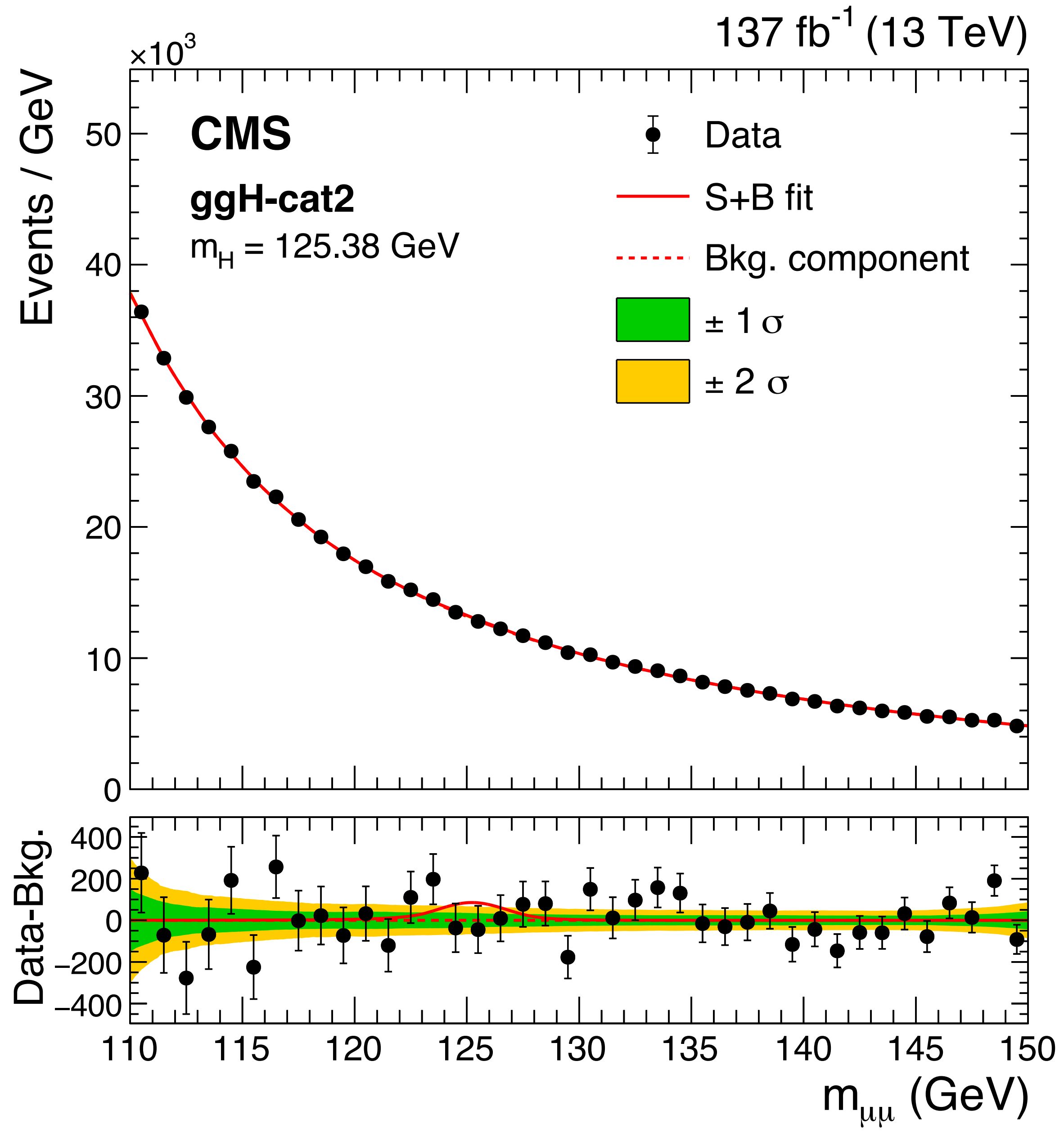
Background model

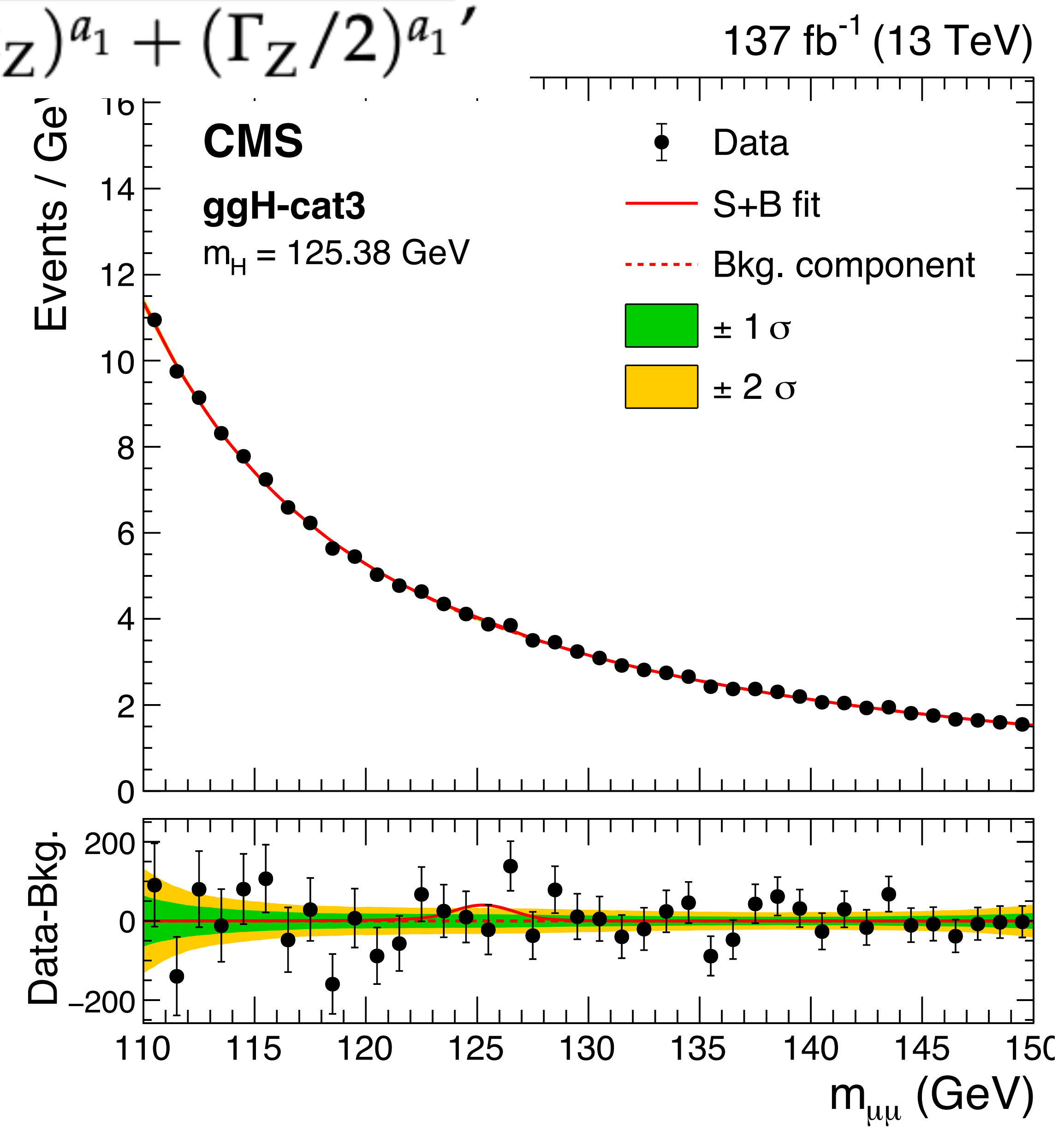
- ***Core function*** → discrete envelope of
  - Modified Breit-Wigner function

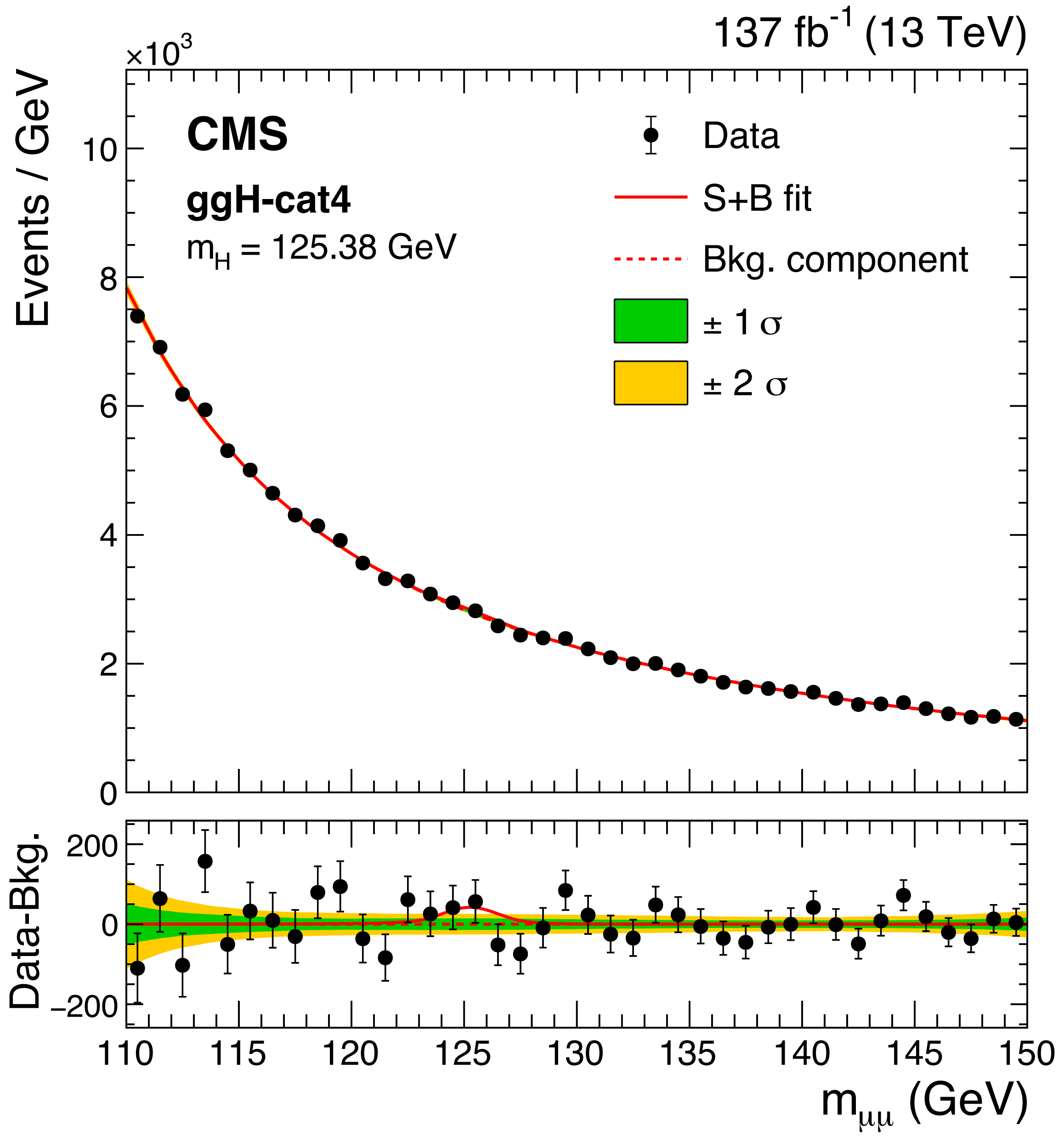
$$\mathrm{mBW}(m_{\mu\mu}; m_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}, a_1, a_2, a_3) = \frac{\mathrm{e}^{a_2 m_{\mu\mu} + a_3 m_{\mu\mu}^2}}{(m_{\mu\mu} - m_{\mathrm{Z}})^{a_1} + (\Gamma_{\mathrm{Z}}/2)^{a_1}},$$

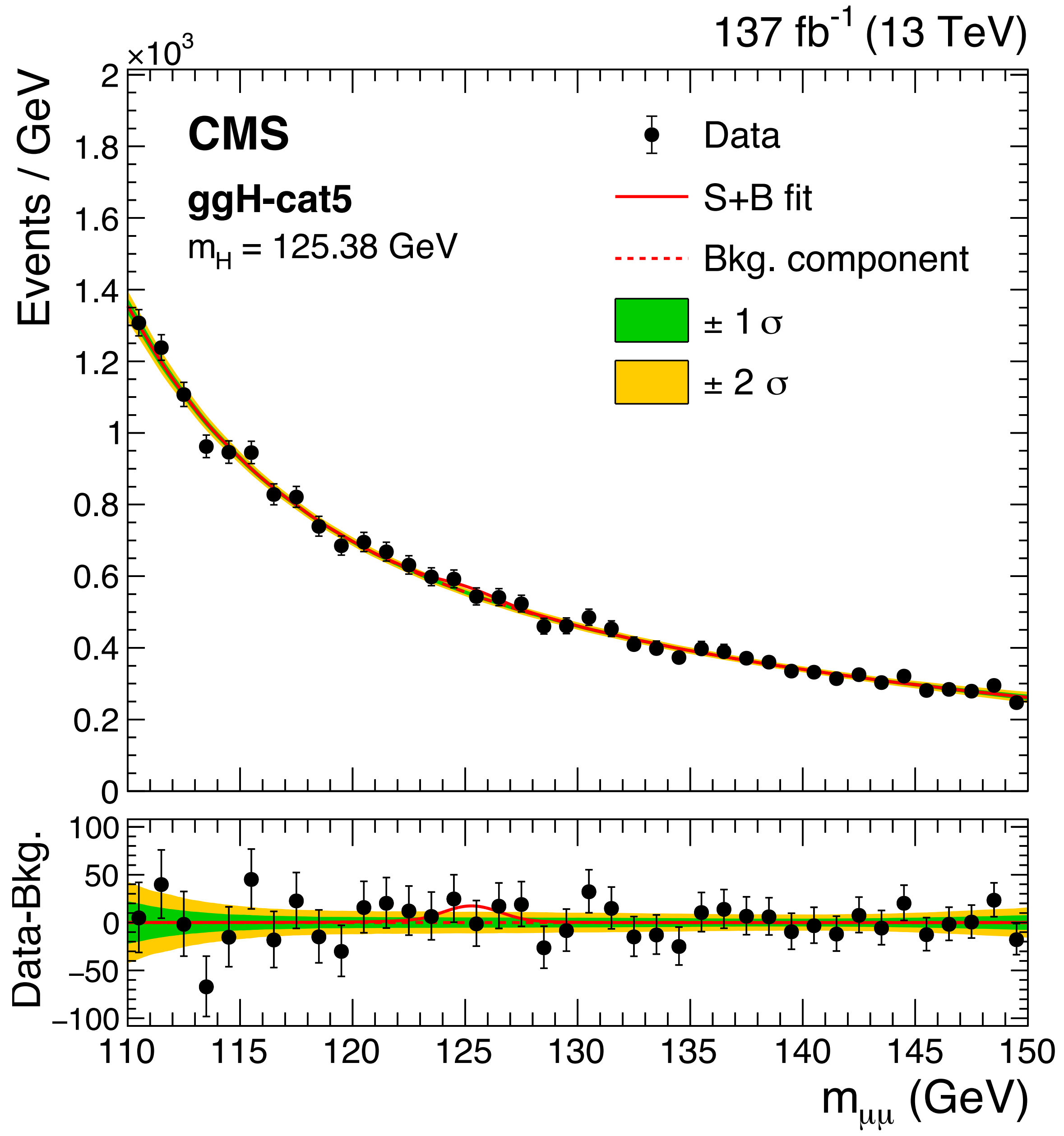
  - Sum of two exponentials
  - Non parametric shape from spline interpolation of FEWZ prediction times a 3rd Bernstein polynomial
- ***Shape modifier:***
  - 3rd or 2nd order Chebyshev polynomial





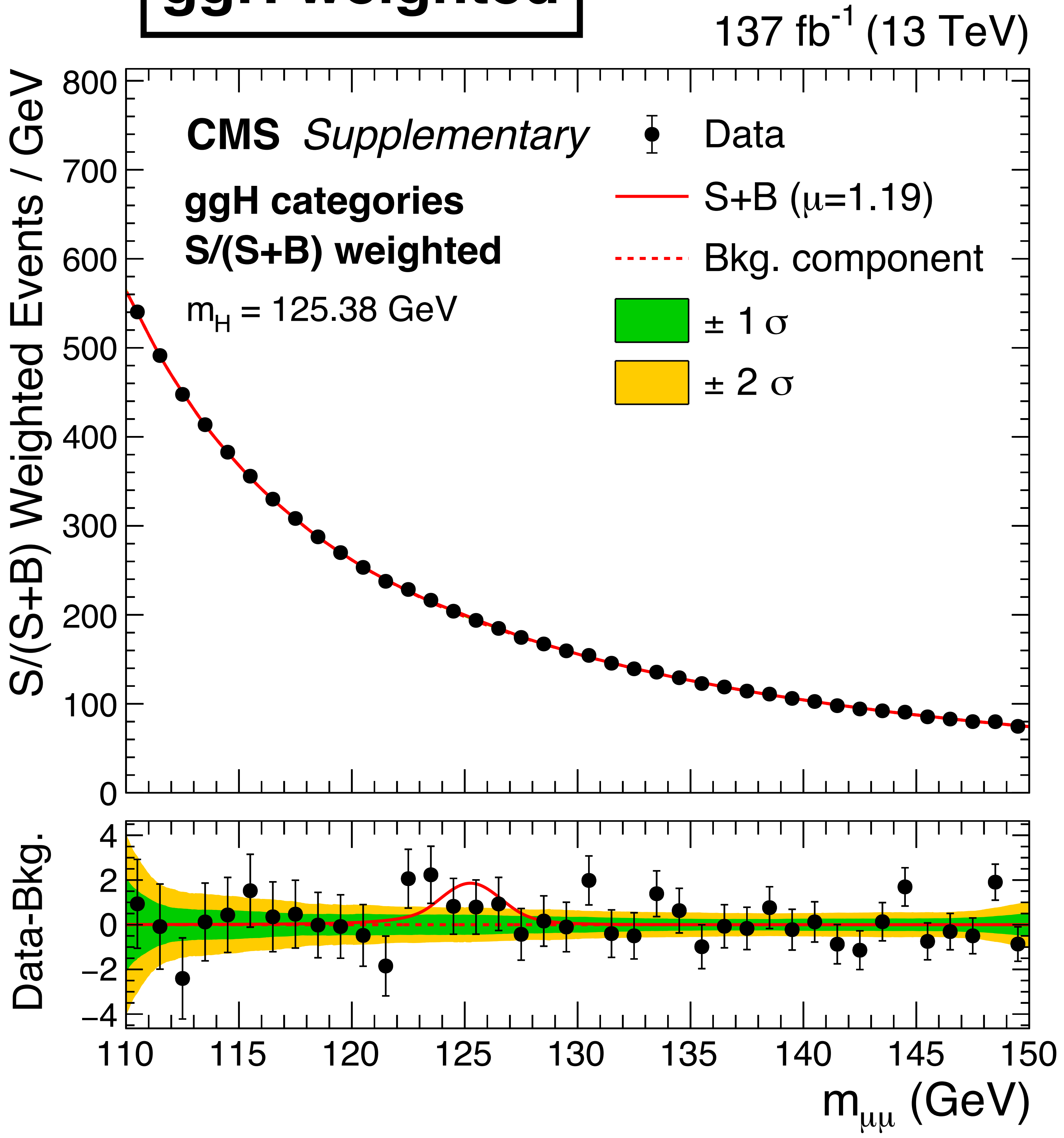




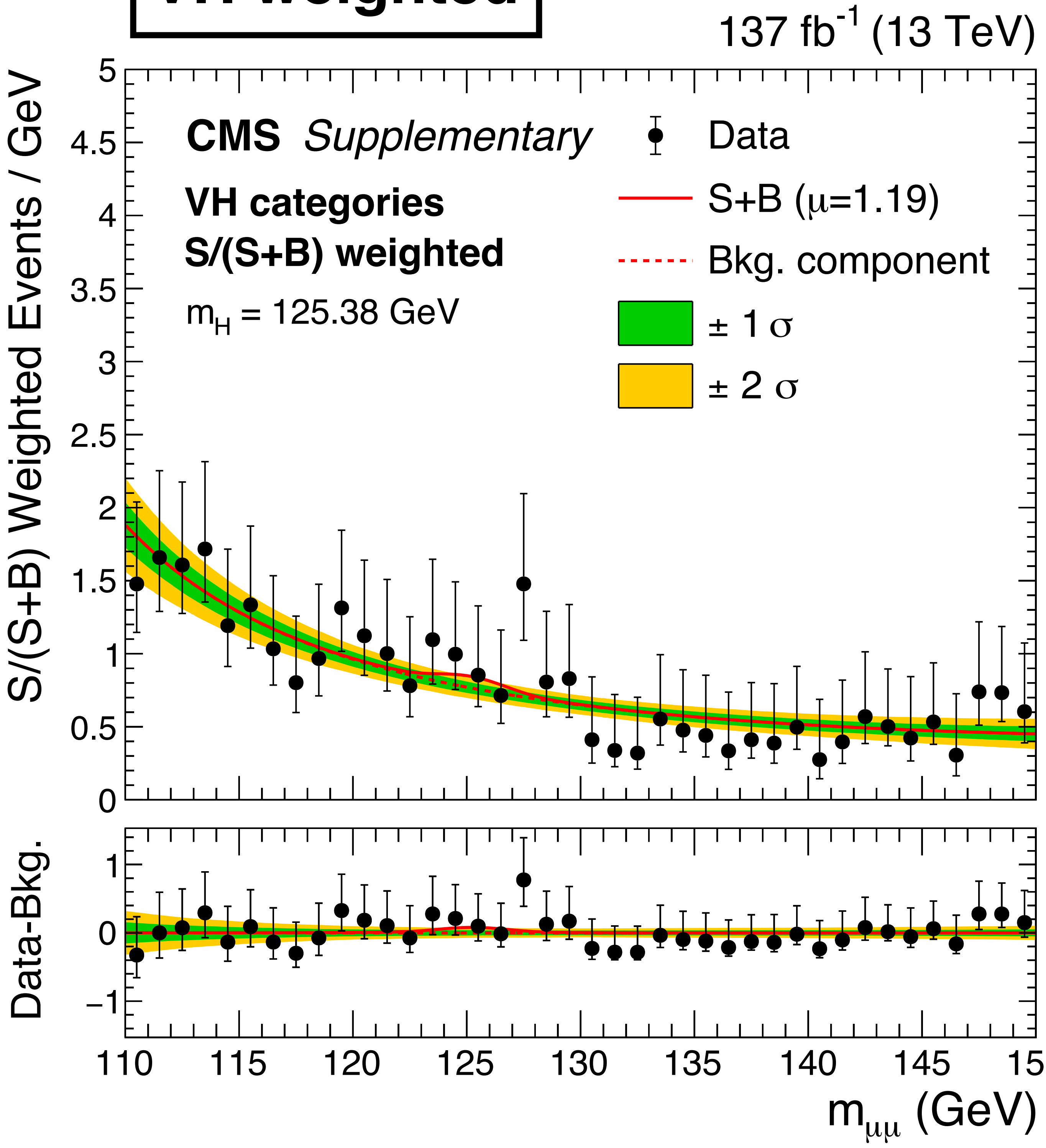


S/(S+B) weighted distributions

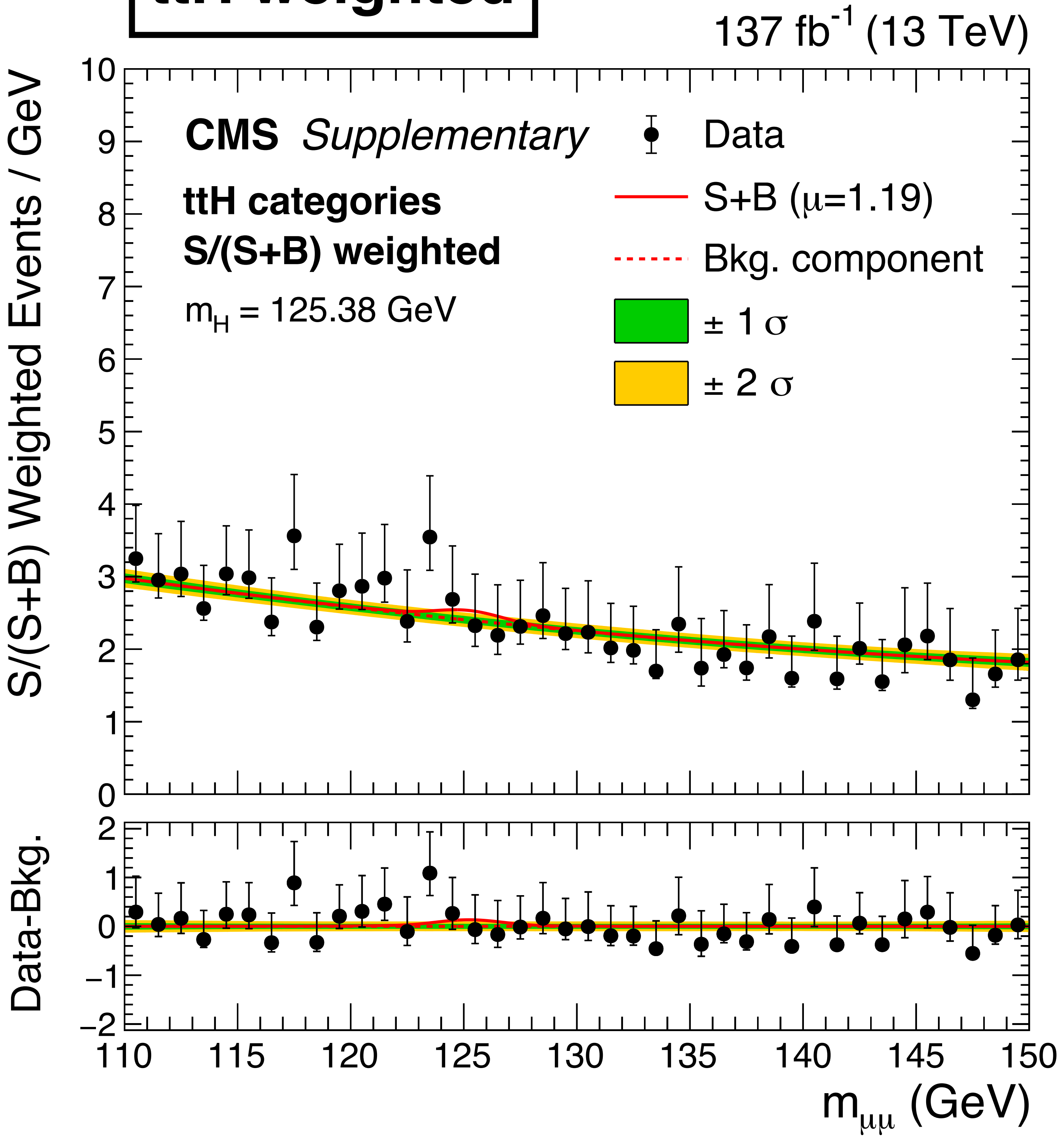
ggH weighted



VH weighted

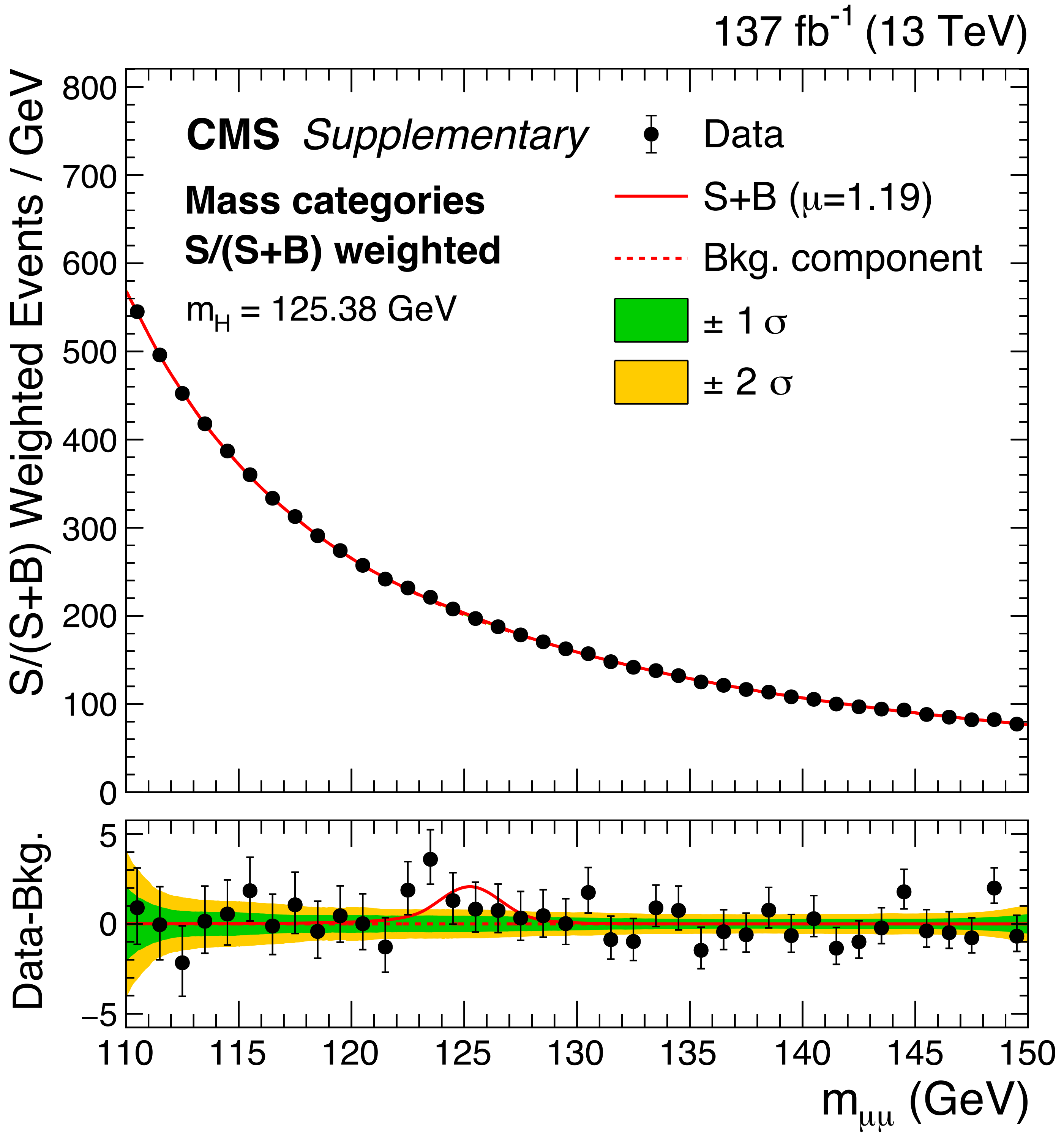


ttH weighted

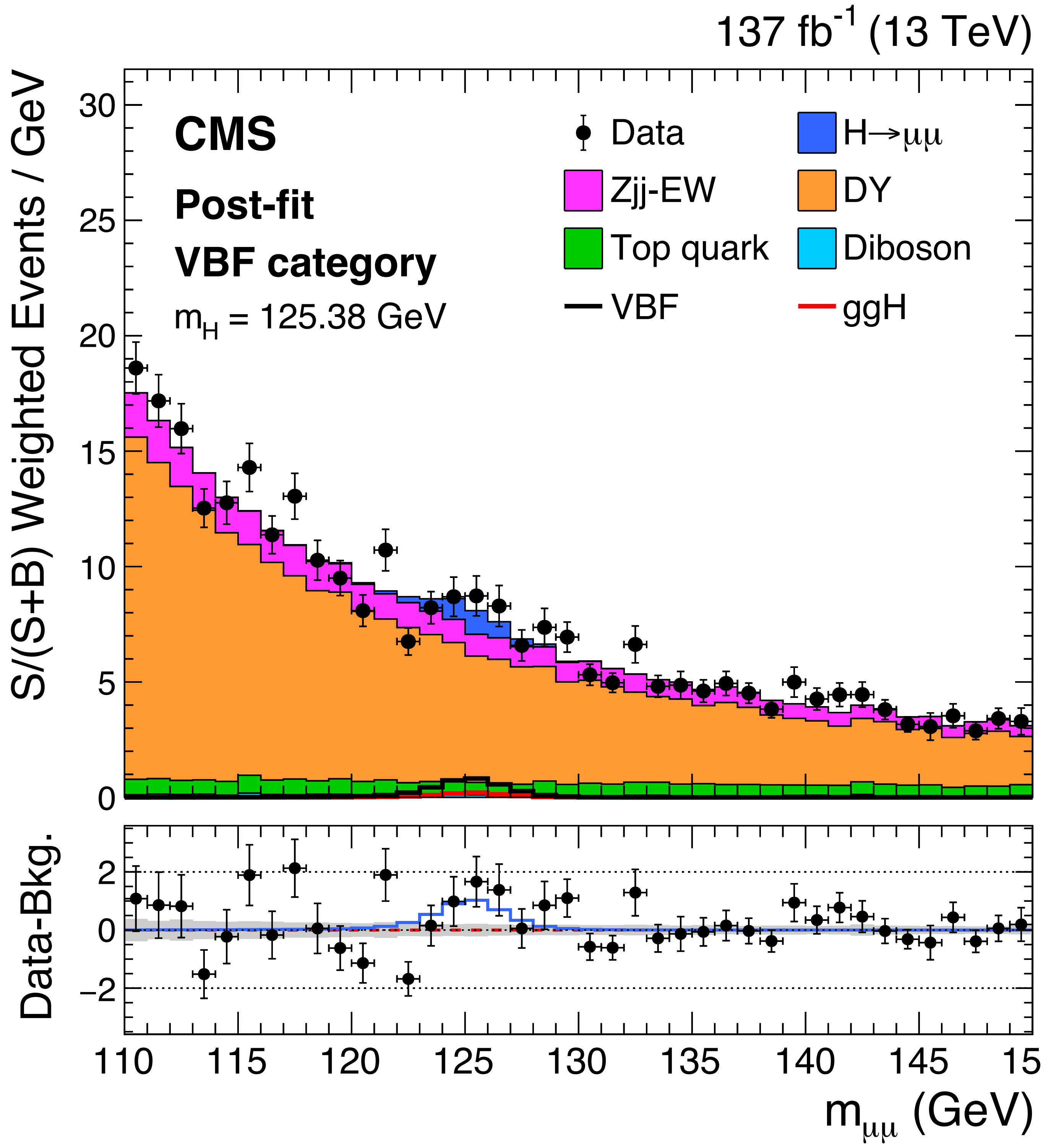


S/(S+B) weighted distributions

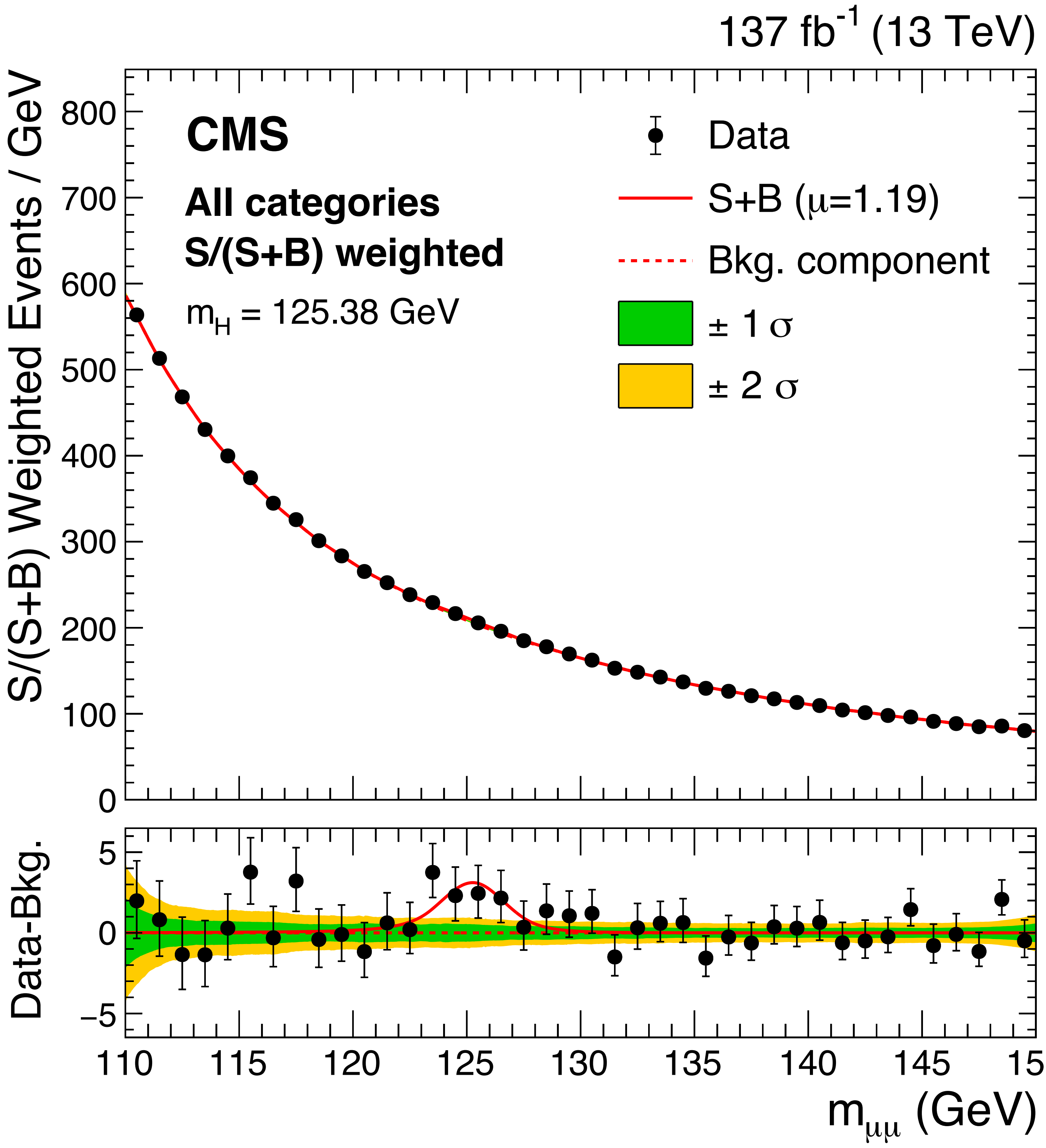
ggH+VH+ttH weighted



VBF weighted



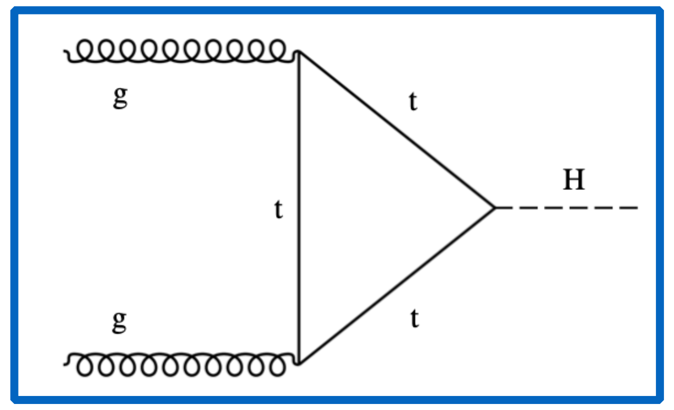
All categories



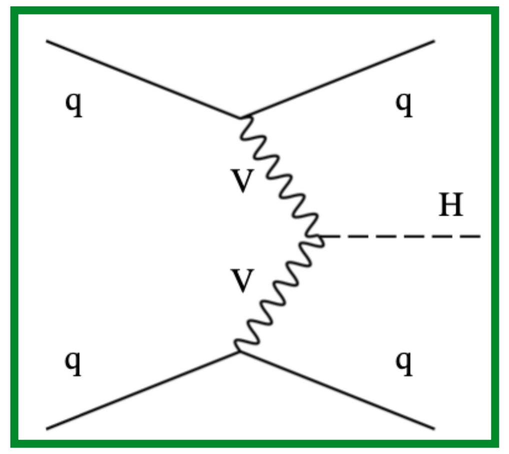
Summary of event categories

- ***H→μμ analysis*** divided in ***exclusive production categories*** targeting ggH, VBF, VH, and ttH modes
- Each of them is further ***divided into subcategories*** optimising the expected significance for H→μμ decays

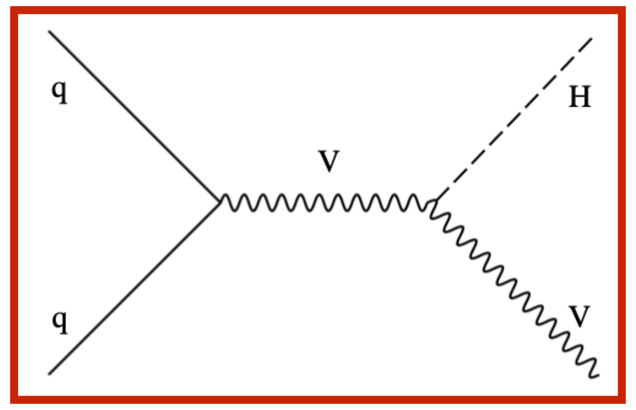
ggH



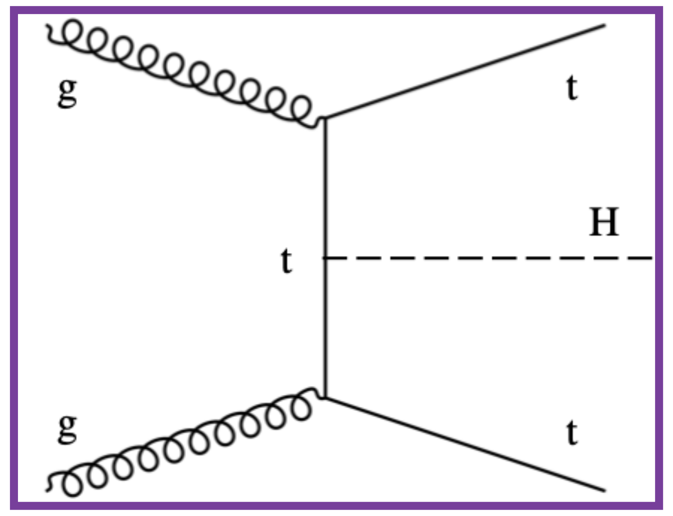
VBF

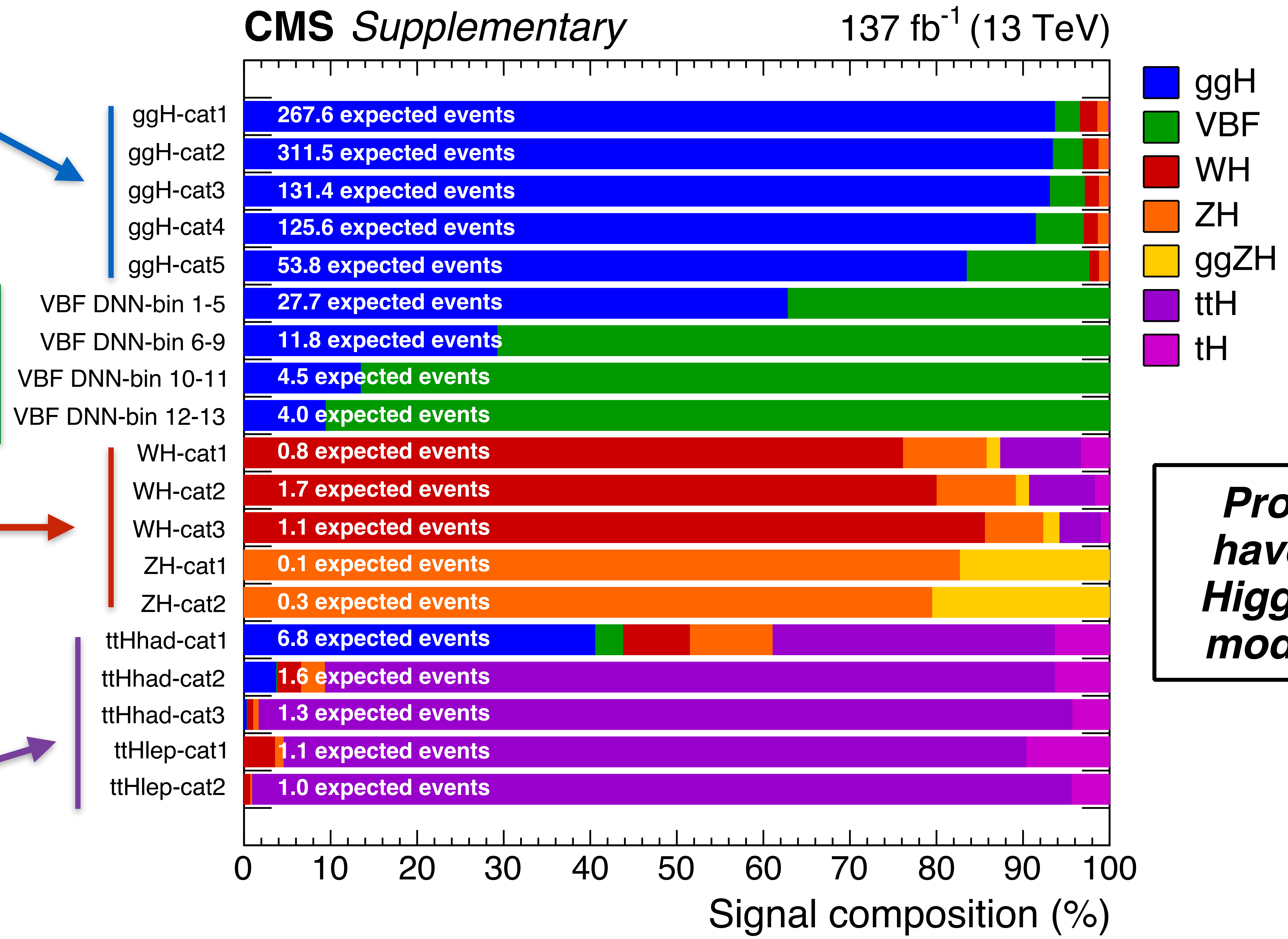


VH



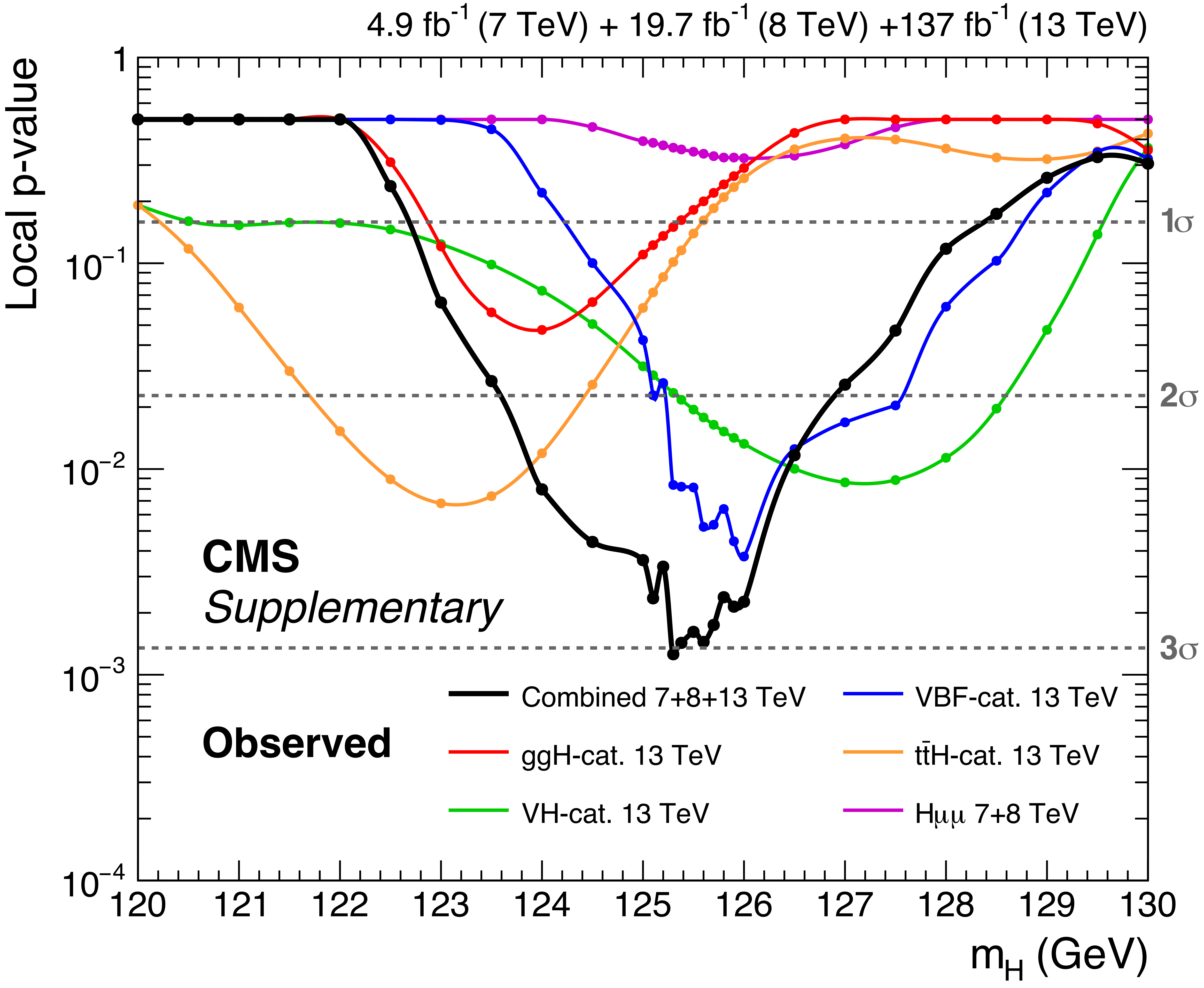
ttH

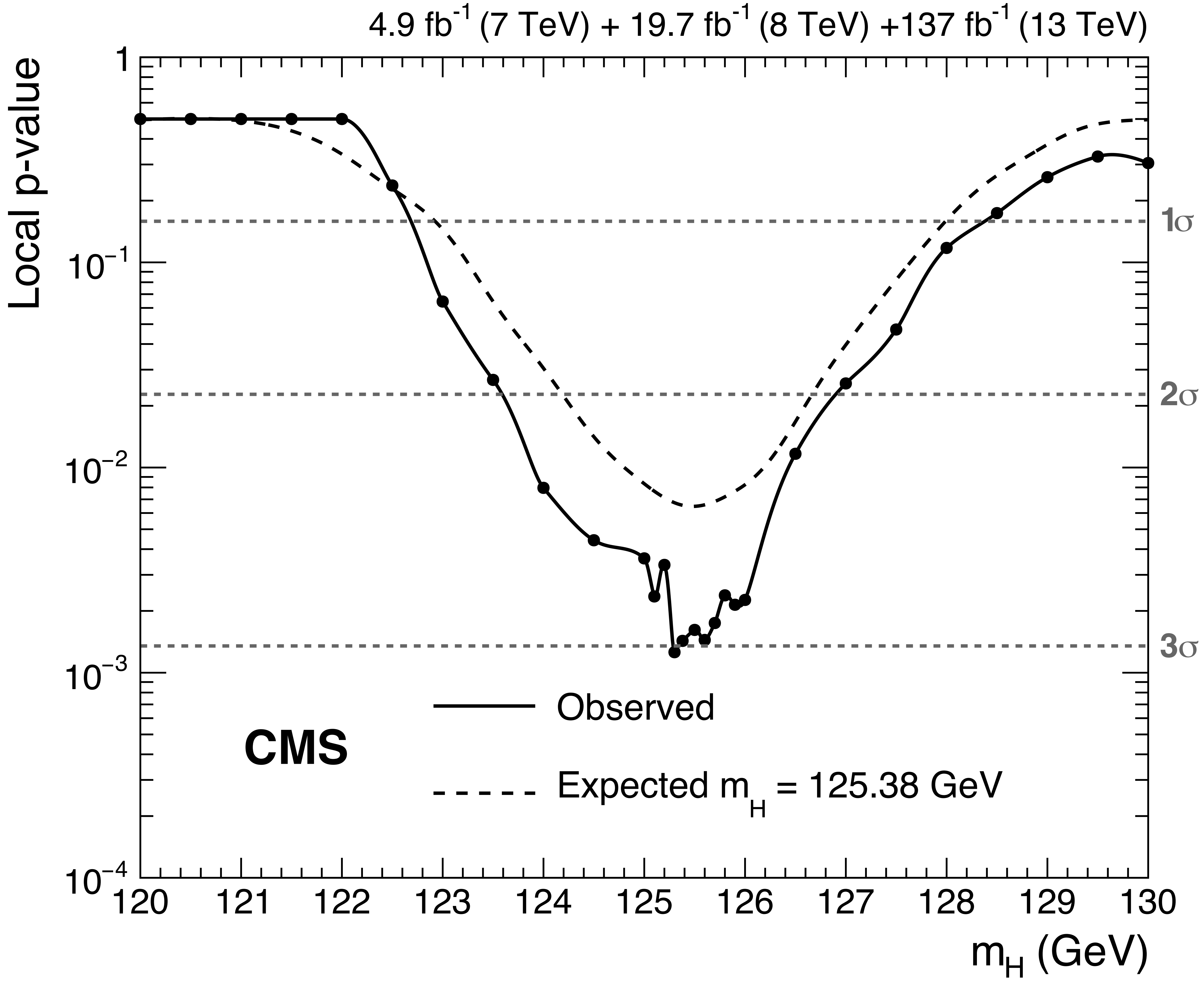




Production categories have good purity in the Higgs boson production mode they are targeting

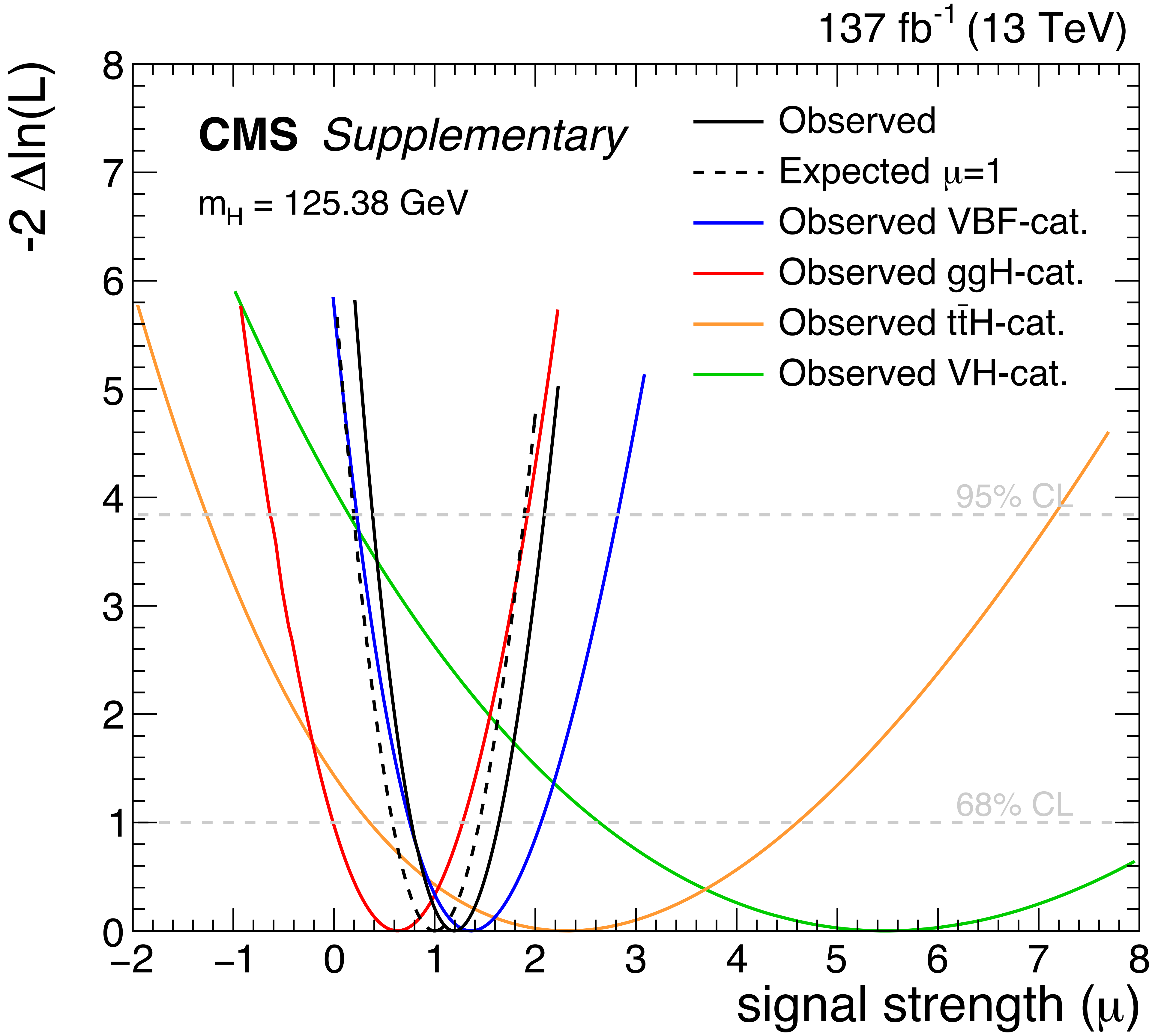
Run1+Run2 combination





H→μμ signal

Likelihood scans vs μ for m_H = 125.38 GeV

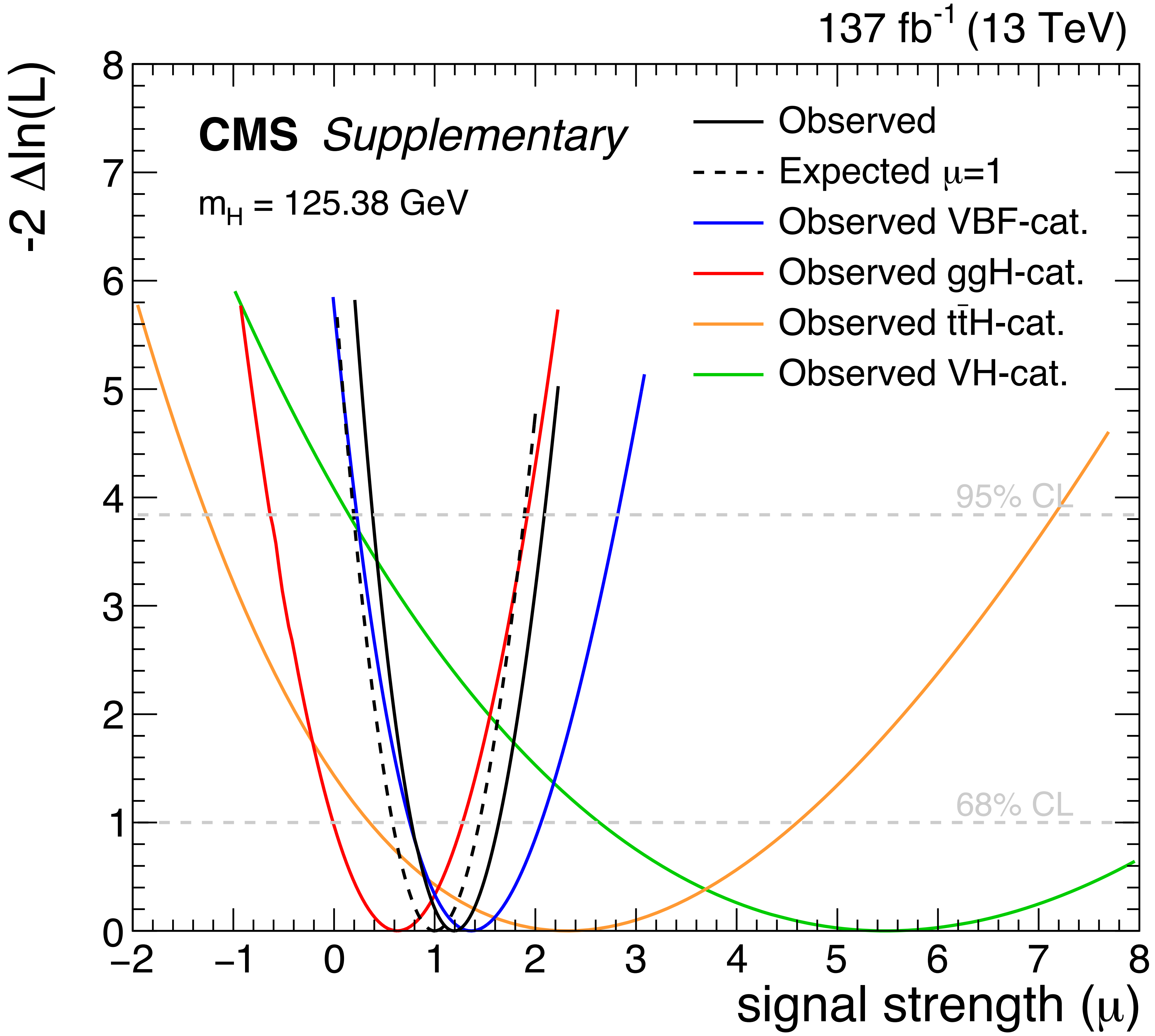


Best fit $\mu = 1.19^{+0.44}_{-0.42}$ → via partial likelihood scans the post-fit uncertainty is breakdown into statistical and systematics

Uncertainty source	$\Delta\mu$	
Post-fit uncertainty	$+0.44$	-0.42
Statistical uncertainty	$+0.41$	-0.40
Systematic uncertainty	$+0.17$	-0.16
Experimental uncertainty	$+0.12$	-0.11
Theoretical uncertainty	$+0.10$	-0.11
Size of simulated samples	$+0.07$	-0.06

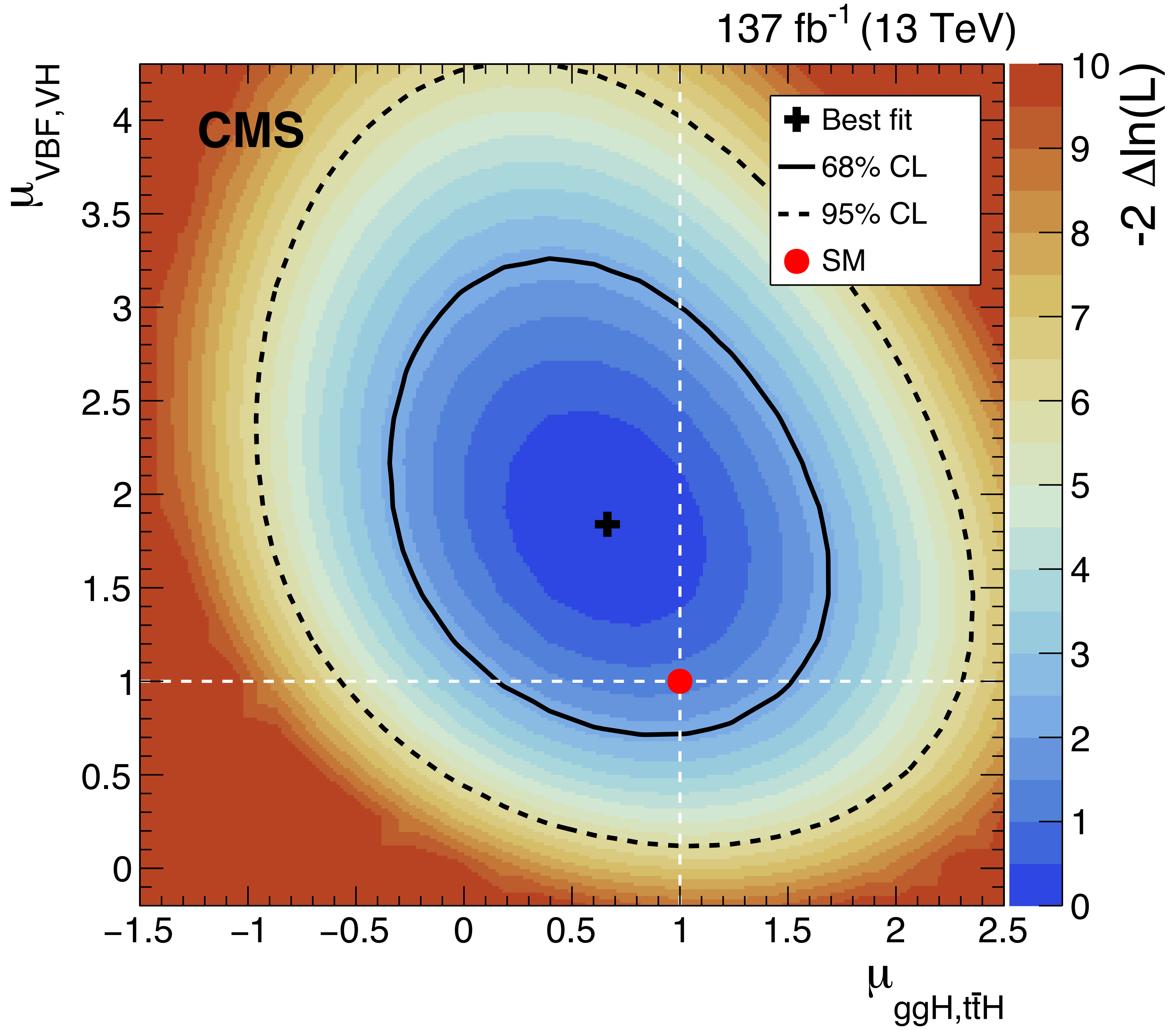
H→μμ signal

Likelihood scans vs μ for m_H = 125.38 GeV



Likelihood scans vs μ_F and μ_V for m_H = 125.38 GeV

- μ_F targets production modes involving Higgs-to-fermions couplings (ggH and ttH)
- μ_V targets production modes involving Higgs-to-vector boson couplings (VBF and VH)



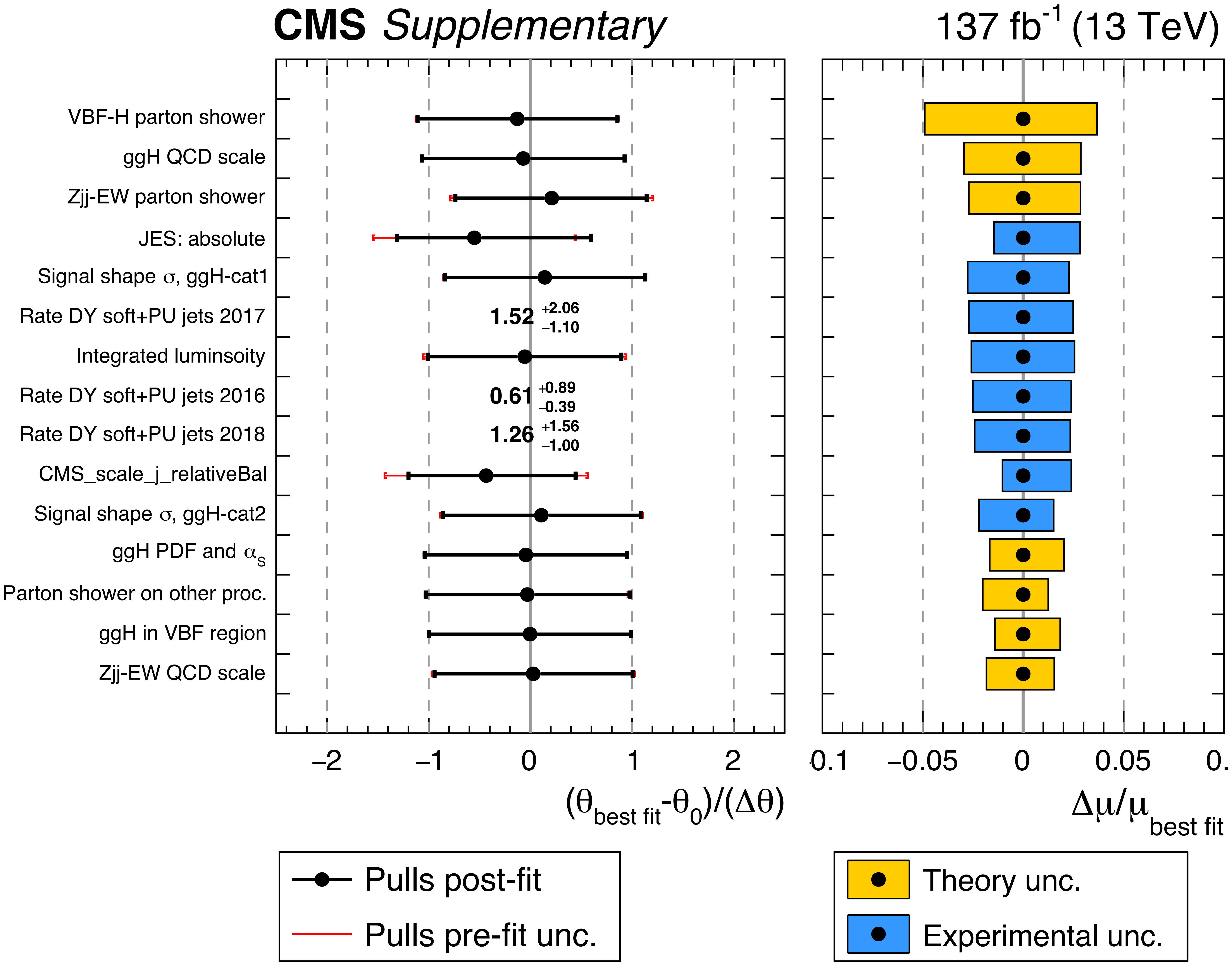
Simulated samples and cross sections

Process	Generator (Perturbative order)	Parton shower	Cross section	Additional corrections
ggH	MadGraph5_amc@nlo (NLO QCD)	pythia	N3LO QCD, NLO EW	p_{T}(H) from nnlops
VBF	powheg (NLO QCD)	pythia dipole shower	NNLO QCD, NLO EW	—
qq → VH	powheg (NLO QCD)	pythia	NNLO QCD, NLO EW	—
gg → ZH	powheg (LO)	pythia	NNLO QCD, NLO EW	—
$t\bar{t}$H	powheg (NLO QCD)	pythia	NLO QCD, NLO EW	—
$b\bar{b}$H	powheg (NLO QCD)	pythia	NLO QCD	—
tHq	MadGraph5_amc@nlo (LO)	pythia	NLO QCD	—
tHW	MadGraph5_amc@nlo (LO)	pythia	NLO QCD	—
Drell–Yan	MadGraph5_amc@nlo (NLO QCD)	pythia	NNLO QCD, NLO EW	—
Zjj-EW	MadGraph5_amc@nlo (LO)	herwig++/herwig 7	LO	—
$t\bar{t}$	powheg (NLO QCD)	pythia	NNLO QCD	—
Single top quark	powheg/MadGraph5_amc@nlo (NLO QCD)	pythia	NLO QCD	—
Diboson (VV)	powheg/MadGraph5_amc@nlo (NLO QCD)	pythia	NLO QCD	NNLO/NLO K factors
gg → ZZ	mcfm (LO)	pythia	LO	NNLO/LO K factors
$t\bar{t}$V, $t\bar{t}$VV	MadGraph5_amc@nlo (NLO QCD)	pythia	NLO QCD	—
Triboson (VVV)	MadGraph5_amc@nlo (NLO QCD)	pythia	NLO QCD	—

Systematic uncertainties: correlation

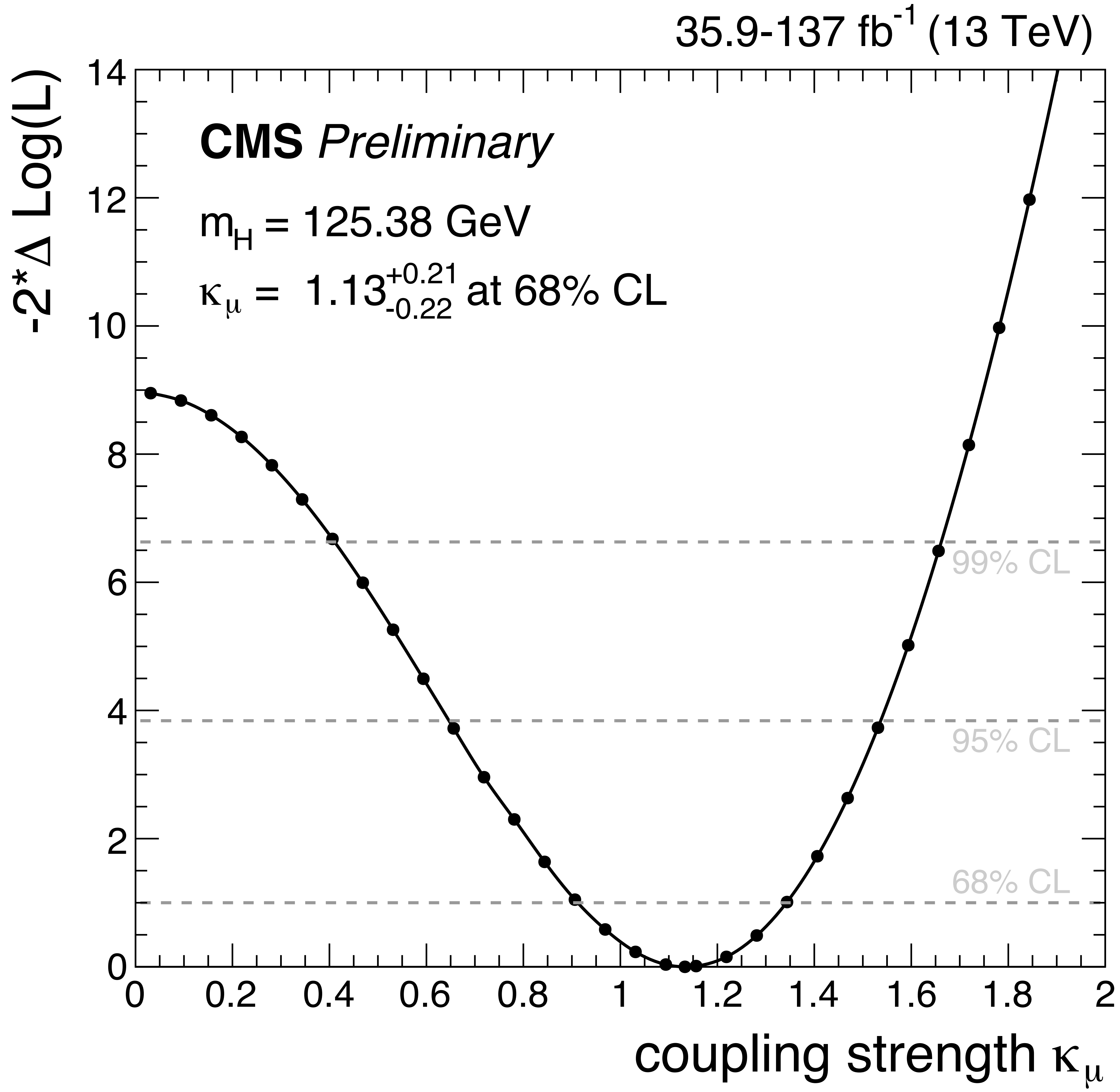
Source of uncertainty	Categories and processes	Type	Correlation vs cat.	Correlation vs year
		Experimental uncertainties		
Integrated luminosity	Sig. in all cat., bkg. in VBF	Rate	Correlated	Partial
Muon efficiency	Sig. in all cat., bkg. in VBF	Rate	Correlated	Correlated
Electron efficiency	Sig. in $\mathrm{t\bar{t}H}$ and VH	Rate	Correlated	Correlated
Muon trigger	Sig. in all cat., bkg. in VBF	Rate	Correlated	Correlated
Muon p_{T} scale	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Correlated
Nonprompt leptons	Sig. in $\mathrm{t\bar{t}H}$ and VH	Rate	Correlated	Correlated
Pileup model	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Uncorrelated
L1 inefficiency	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Uncorrelated
B-tagging efficiency	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Correlated
Jet energy scale	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Partial
Jet energy resolution	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Uncorrelated
		Theoretical uncertainties		
μ_{R} and μ_{F} for ggH	ggH in all cat.	Rate	Correlated	Correlated
μ_{R} and μ_{F} for VBF	VBF in all cat.	Rate	Correlated	Correlated
μ_{R} and μ_{F} for $\mathrm{t\bar{t}H}$	$\mathrm{t\bar{t}H}$ in all cat.	Rate	Correlated	Correlated
μ_{R} and μ_{F} for VH	VH in all cat.	Rate	Correlated	Correlated
PDF for ggH	ggH in all cat.	Rate	Correlated	Correlated
PDF for VBF	VBF in all cat.	Rate	Correlated	Correlated
PDF for $\mathrm{t\bar{t}H}$	$\mathrm{t\bar{t}H}$ in all cat.	Rate	Correlated	Correlated
PDF for VH	VH in all cat.	Rate	Correlated	Correlated
ggH accept. vs (p_{T}(H),N$_{\mathrm{j}}$,m_{jj})	ggH in all cat.	Shape in VBF, rate in others	Correlated	Correlated
VBF accept. vs (p_{T}(H),N$_{\mathrm{j}}$,m_{jj})	VBF in all cat.	Shape in VBF, rate in others	Correlated	Correlated
$\mathrm{t\bar{t}H}$ accept. from μ_{R} and μ_{F}	$\mathrm{t\bar{t}H}$ in all cat.	Rate	Correlated	Correlated
VH accept. from μ_{R} and μ_{F}	VH in all cat.	Rate	Correlated	Correlated
$\mathrm{t\bar{t}H}$ accept. from PDF	$\mathrm{t\bar{t}H}$ in all cat.	Rate	Correlated	Correlated
VH accept. from PDF	VH in all cat.	Rate	Correlated	Correlated
PYTHIA ISR and FSR	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Correlated
PYTHIA vs HERWIG)	VBF and Zjj-EW in VBF cat.	Shape	Correlated	Correlated
μ_{R} and μ_{F} for Drell–Yan	VBF cat.	Shape	Correlated	Correlated
μ_{R} and μ_{F} for Zjj-EW	VBF cat.	Shape	Correlated	Correlated
μ_{R} and μ_{F} for top bkgs.	VBF cat.	Shape	Correlated	Correlated
μ_{R} and μ_{F} for diboson	VBF cat.	Shape	Correlated	Correlated
PDF for Drell–Yan	VBF cat.	Shape	Correlated	Correlated
PDF for Zjj-EW	VBF cat.	Shape	Correlated	Correlated
PDF for top bkgs.	VBF cat.	Shape	Correlated	Correlated
PDF for dibosons	VBF cat.	Shape	Correlated	Correlated
Size of simulated samples	VBF cat.	Bin-by-bin	—	Uncorrelated

Systematic uncertainties: pulls and impacts

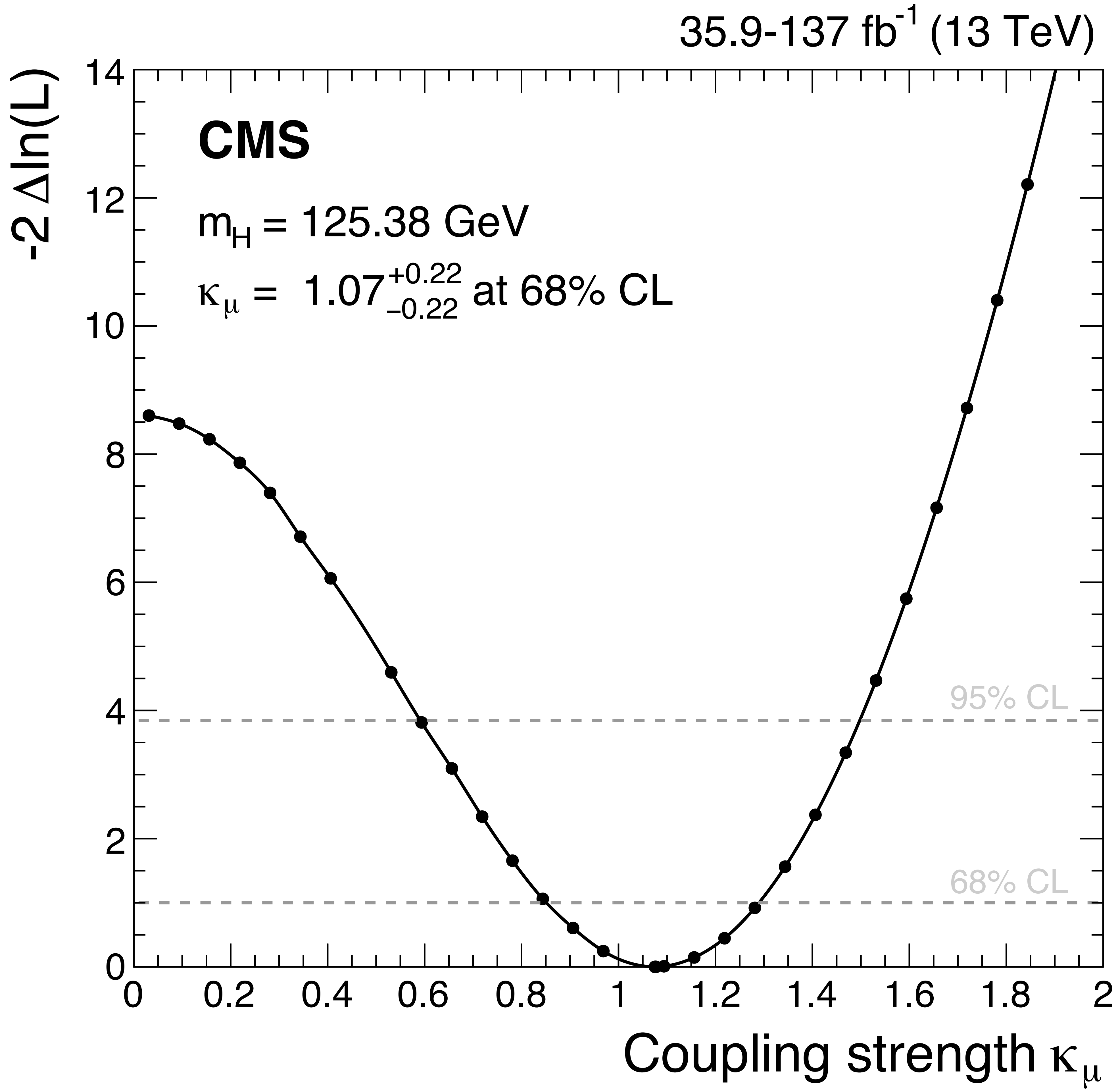


Coupling fit

Combination with ***CMS-PAS-HIG-19-005***



Combination with ***Eur. Phys. J. C 79 (2019) 421***



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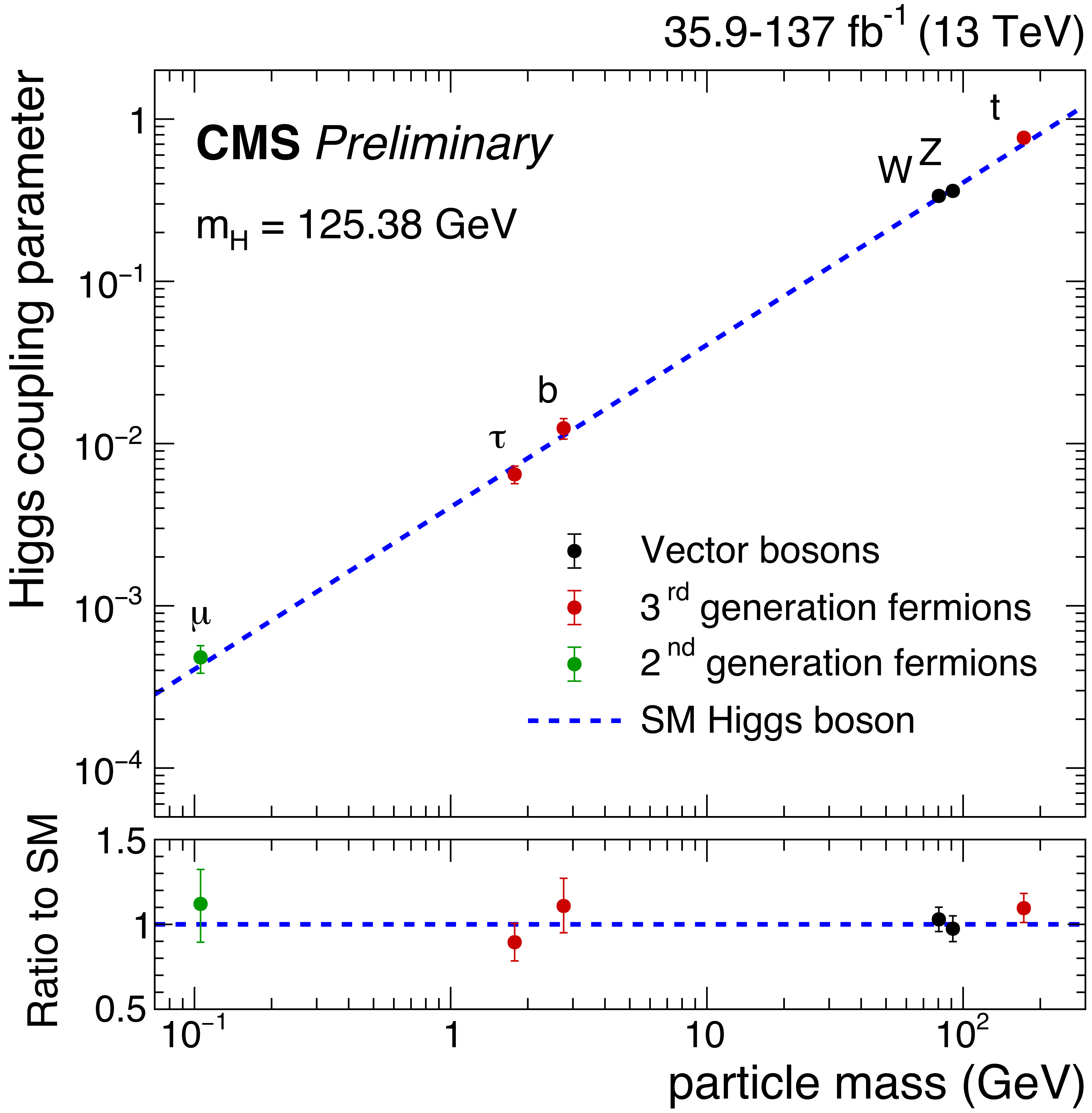

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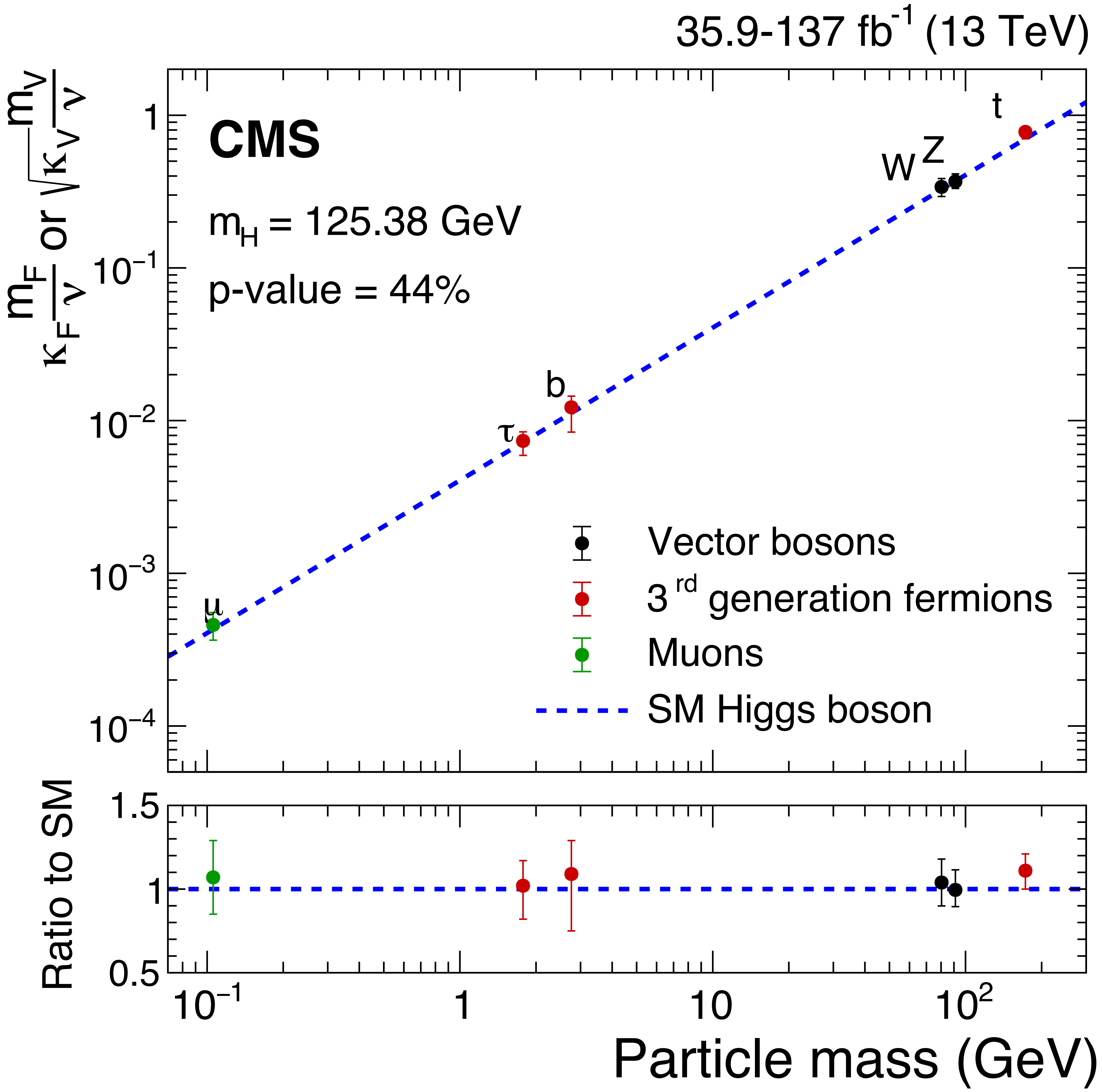


H→μμ analysis: ATLAS vs CMS

*** **Disclaimer:** an apple-to-apple comparison between ***ATLAS*** and ***CMS*** results is not straightforward, ***can be only based*** on information provided in the corresponding ***papers*** submitted to PLB and JHEP, respectively

*** **Disclaimer:** ATLAS results interpreted for m_H = 125.09 GeV, CMS ones for m_H = 125.38 GeV

ATLAS vs CMS: results

Similarities

- Both experiments rely on ***single-muon triggers*** with similar overall efficiency
- ***Comparable acceptance*** of the baseline dimuon selection
- Both experiments developed ***dedicated analyses*** for ttH, VH, VBF, and ggH production modes
- ***ttH,VH, VBF,*** and ***ggH*** MVAs exploit similar input features to maximise the S to B separation
- Similar choice for ***signal event generation***: NNLOPS prediction used as target for ggH, POWHEG NLO for other processes (VBF, VH, ttH)

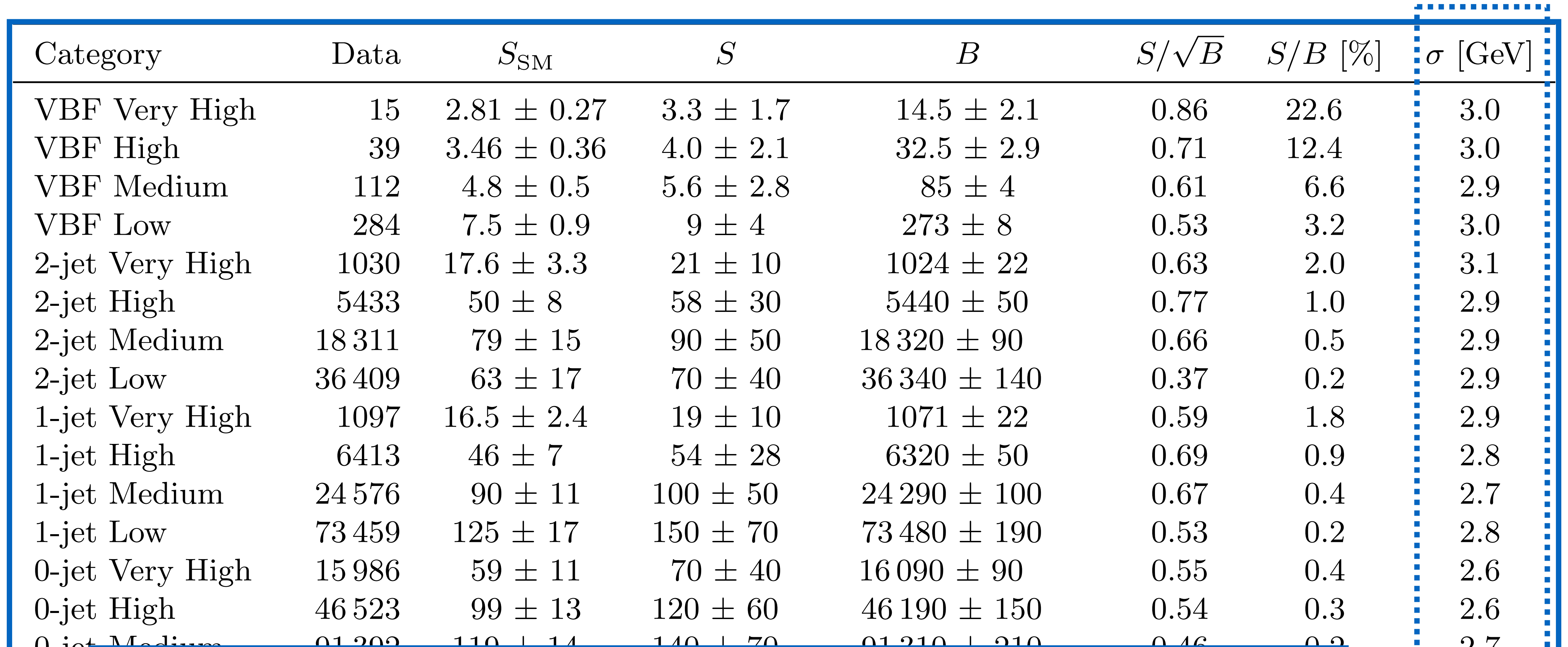
Differences

- **mass resolution:** CMS has a substantially better resolution on muon p_T
- In CMS all ***MVAs*** are ***sensitive*** to both ***event kinematic*** and ***$m_{\mu\mu}$ resolution***, while ATLAS does not embed the resolution information
- The p_T threshold for ***additional leptons*** in ttH and VH are lower in ATLAS than in CMS
- ***VBF analysis:*** ATLAS uses a divide-n-fit strategy, while CMS adopted a MC-based analysis
- ***ggH analysis:*** ATLAS trained independent BDTs in each jet-bin, while CMS has a single MVA classifier
- ***ggH analysis:*** ATLAS has 4 categories per MVA, while CMS has just five ggH categories in total

The difference in $m_{\mu\mu}$ resolution is the main reason behind the stronger CMS result

ATLAS vs CMS: mass resolution

ATLAS categories



Category	Data	S_{SM}	S	B	$S/\sqrt{B}$	S/B [%]	σ [GeV]
VBF Very High	15	2.81 ± 0.27	3.3 ± 1.7	14.5 ± 2.1	0.86	22.6	3.0
VBF High	39	3.46 ± 0.36	4.0 ± 2.1	32.5 ± 2.9	0.71	12.4	3.0
VBF Medium	112	4.8 ± 0.5	5.6 ± 2.8	85 ± 4	0.61	6.6	2.9
VBF Low	284	7.5 ± 0.9	9 ± 4	273 ± 8	0.53	3.2	3.0
2-jet Very High	1030	17.6 ± 3.3	21 ± 10	1024 ± 22	0.63	2.0	3.1
2-jet High	5433	50 ± 8	58 ± 30	5440 ± 50	0.77	1.0	2.9
2-jet Medium	18 311	79 ± 15	90 ± 50	18 320 ± 90	0.66	0.5	2.9
2-jet Low	36 409	63 ± 17	70 ± 40	36 340 ± 140	0.37	0.2	2.9
1-jet Very High	1097	16.5 ± 2.4	19 ± 10	1071 ± 22	0.59	1.8	2.9
1-jet High	6413	46 ± 7	54 ± 28	6320 ± 50	0.69	0.9	2.8
1-jet Medium	24 576	90 ± 11	100 ± 50	24 290 ± 100	0.67	0.4	2.7
1-jet Low	73 459	125 ± 17	150 ± 70	73 480 ± 190	0.53	0.2	2.8
0-jet Very High	15 986	59 ± 11	70 ± 40	16 090 ± 90	0.55	0.4	2.6
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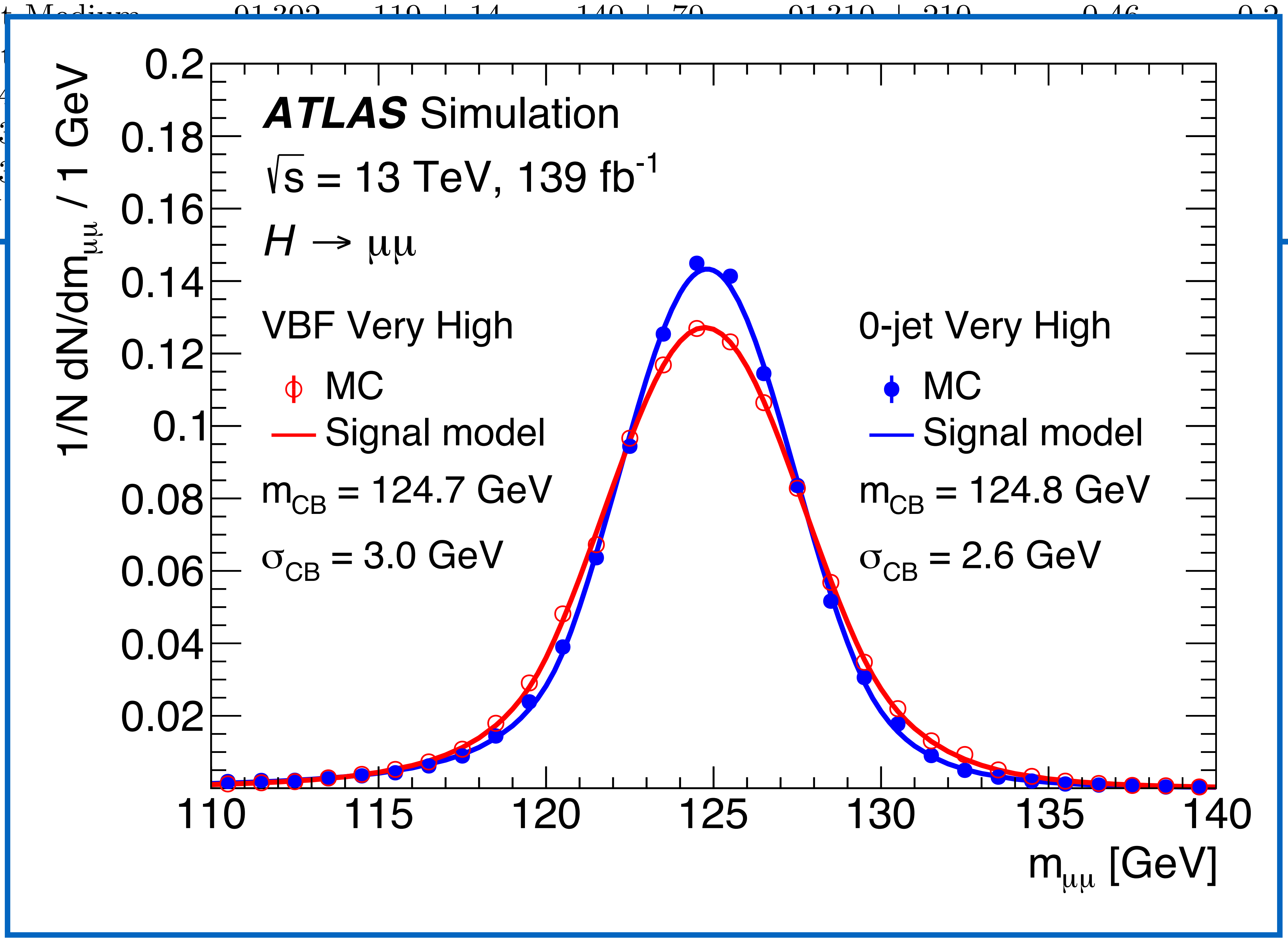
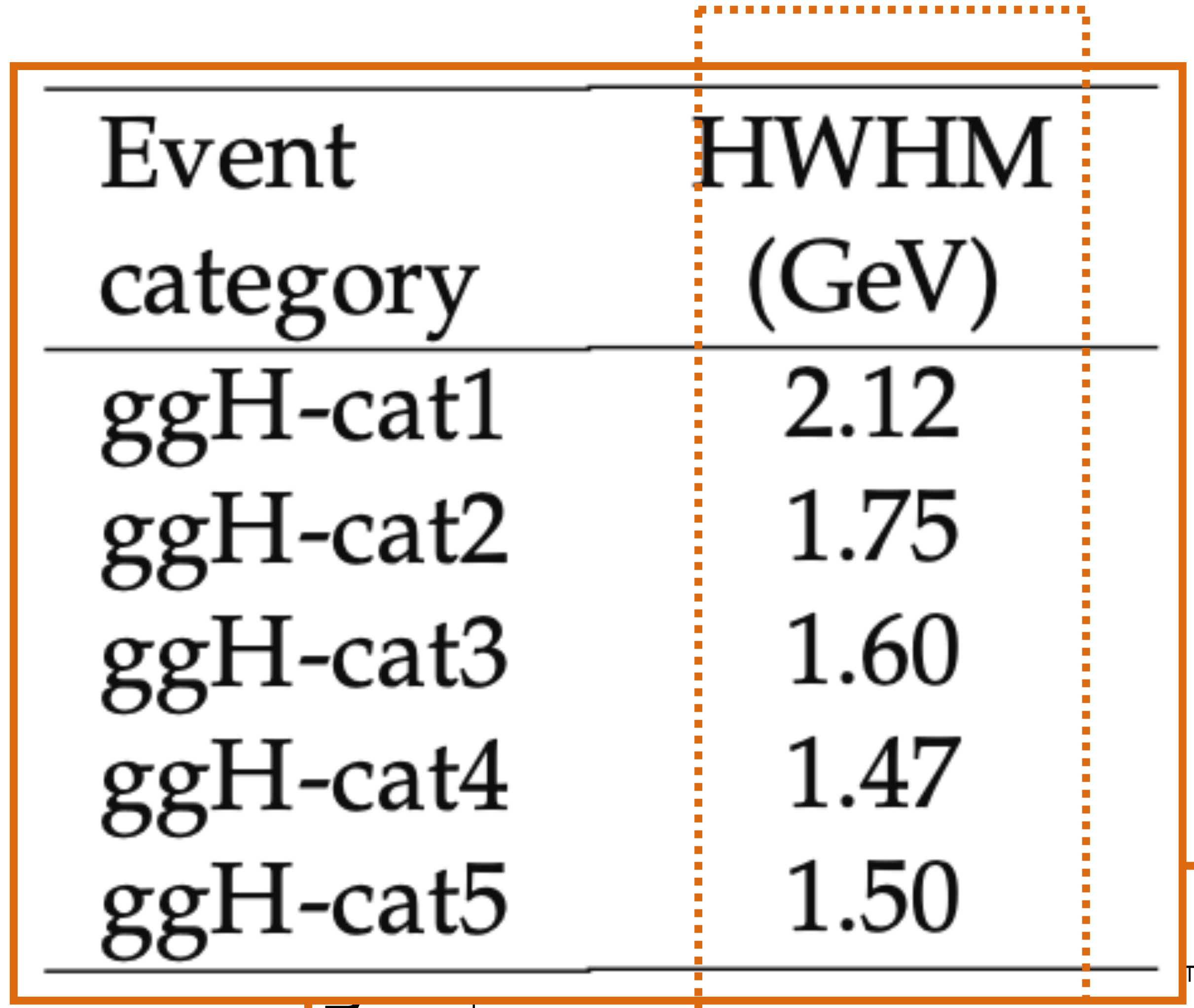
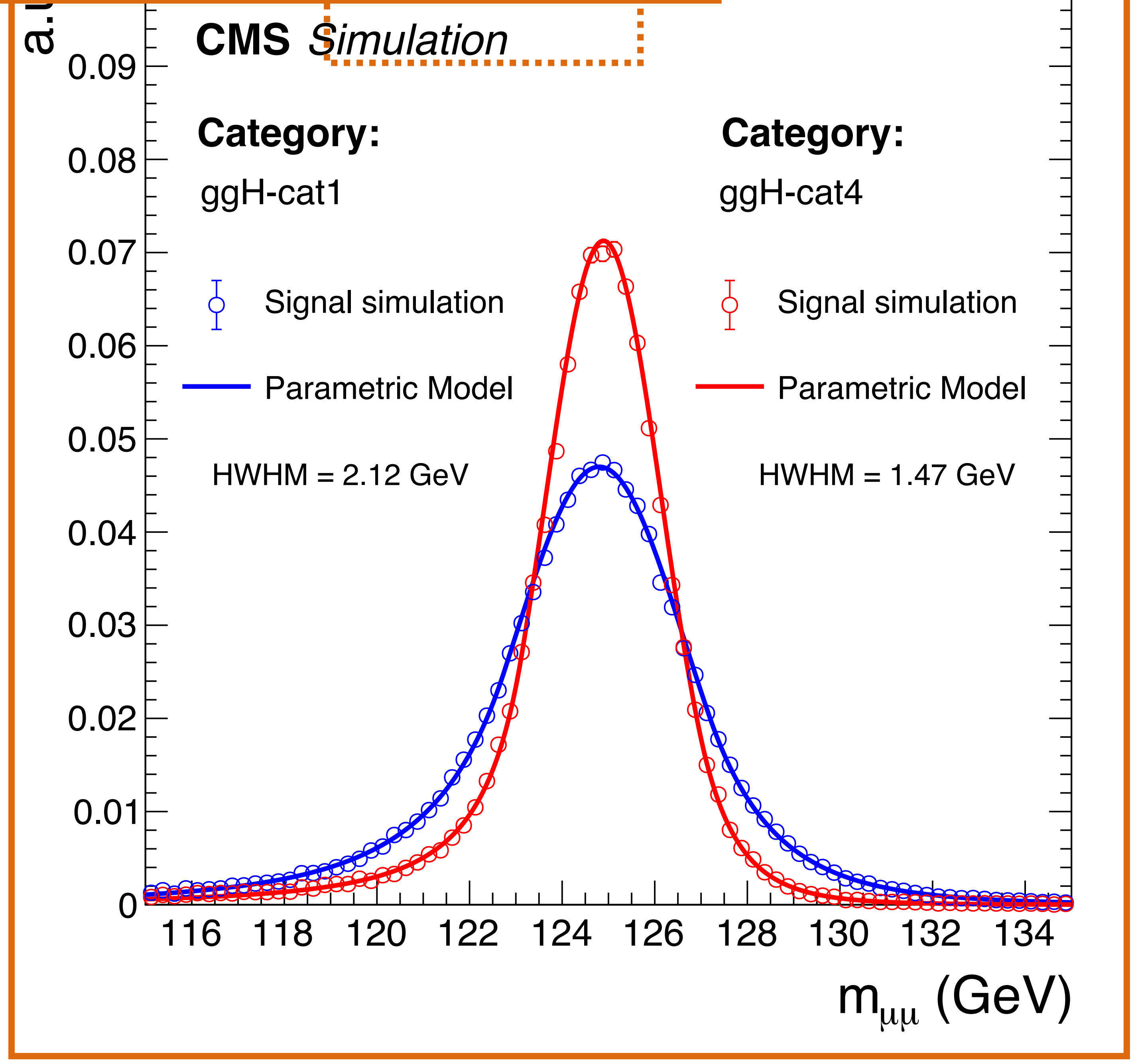
0-jet							2.7
0-jet							2.7
VH4							2.9
VH3							3.1
VH3							3.0
$t\bar{t}H$							3.2



CMS resolution in ggH



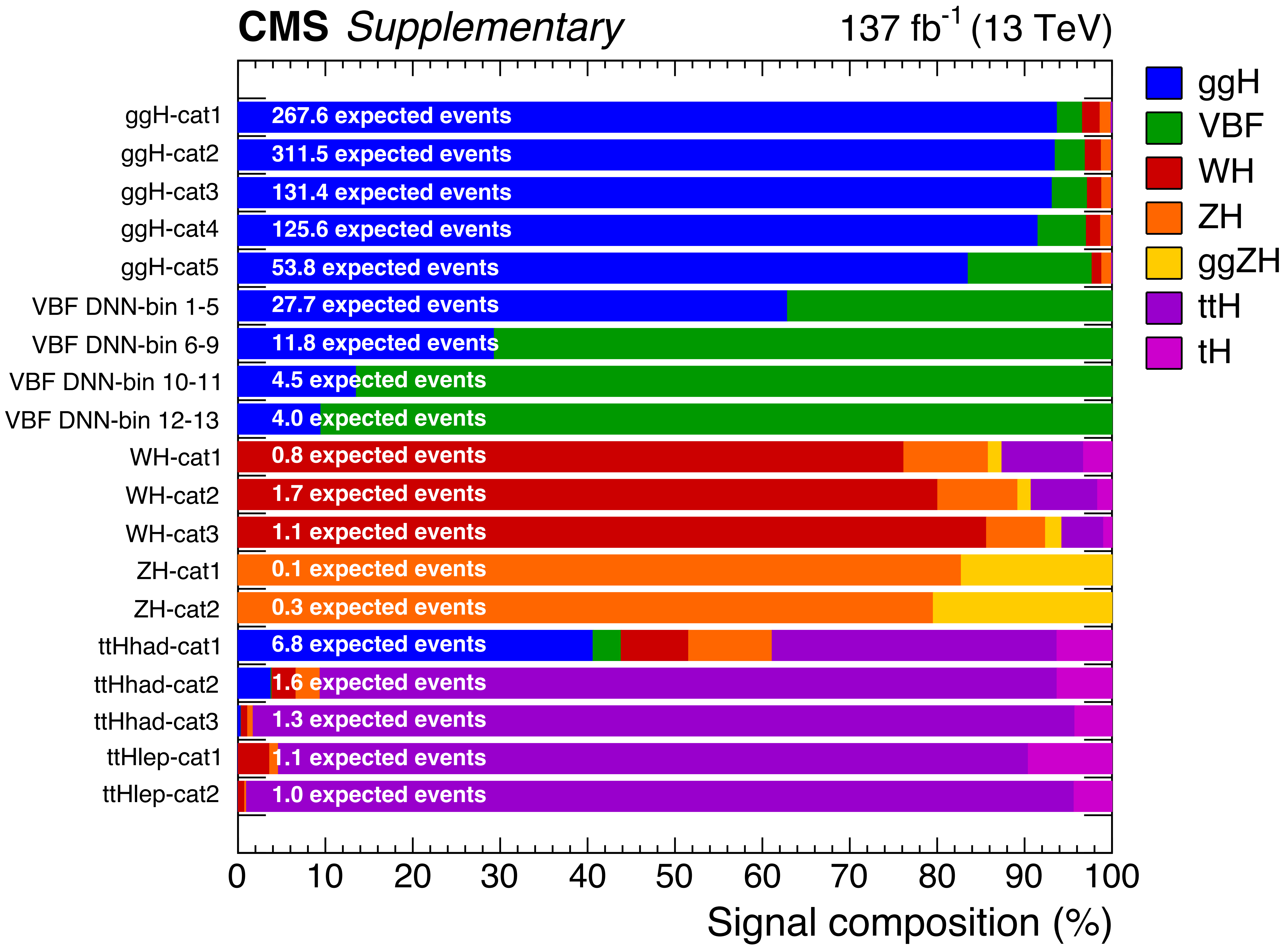
Event category	HWHM (GeV)
ggH-cat1	2.12
ggH-cat2	1.75
ggH-cat3	1.60
ggH-cat4	1.47
ggH-cat5	1.50



ATLAS and CMS H→μμ result

ATLAS categories

Category	*ggF*	VBF	*WH*	*ZH*	$t\bar{t}H$
VBF Very High	6.6%	93.3%	0.0%	0.0%	0.0%
VBF High	12.8%	87.1%	0.0%	0.0%	0.0%
VBF Medium	21.3%	78.5%	0.1%	0.1%	0.0%
VBF Low	34.8%	64.8%	0.2%	0.2%	0.0%
2-jet Very High	82.0%	15.7%	1.2%	1.0%	0.2%
2-jet High	79.3%	16.0%	2.7%	1.8%	0.3%
2-jet Medium	80.7%	10.4%	5.4%	3.0%	0.5%
2-jet Low	78.2%	6.6%	8.8%	4.9%	1.5%
1-jet Very High	78.2%	21.2%	0.3%	0.3%	0.0%
1-jet High	88.2%	10.4%	0.9%	0.6%	0.0%
1-jet Medium	91.4%	6.1%	1.6%	0.9%	0.0%
1-jet Low	92.4%	3.8%	2.6%	1.2%	0.0%
0-jet Very High	94.1%	2.5%	1.4%	2.0%	0.0%
0-jet High	98.3%	1.0%	0.4%	0.3%	0.0%
0-jet Medium	99.1%	0.6%	0.2%	0.1%	0.0%
0-jet Low	99.5%	0.3%	0.1%	0.1%	0.0%
VH4L	0.0%	0.0%	0.1%	99.5%	0.4%
VH3LH	0.3%	0.1%	96.9%	2.6%	0.1%
VH3LM	4.2%	1.0%	80.8%	8.6%	5.3%
$t\bar{t}H$	0.1%	0.0%	1.5%	0.4%	98.0%



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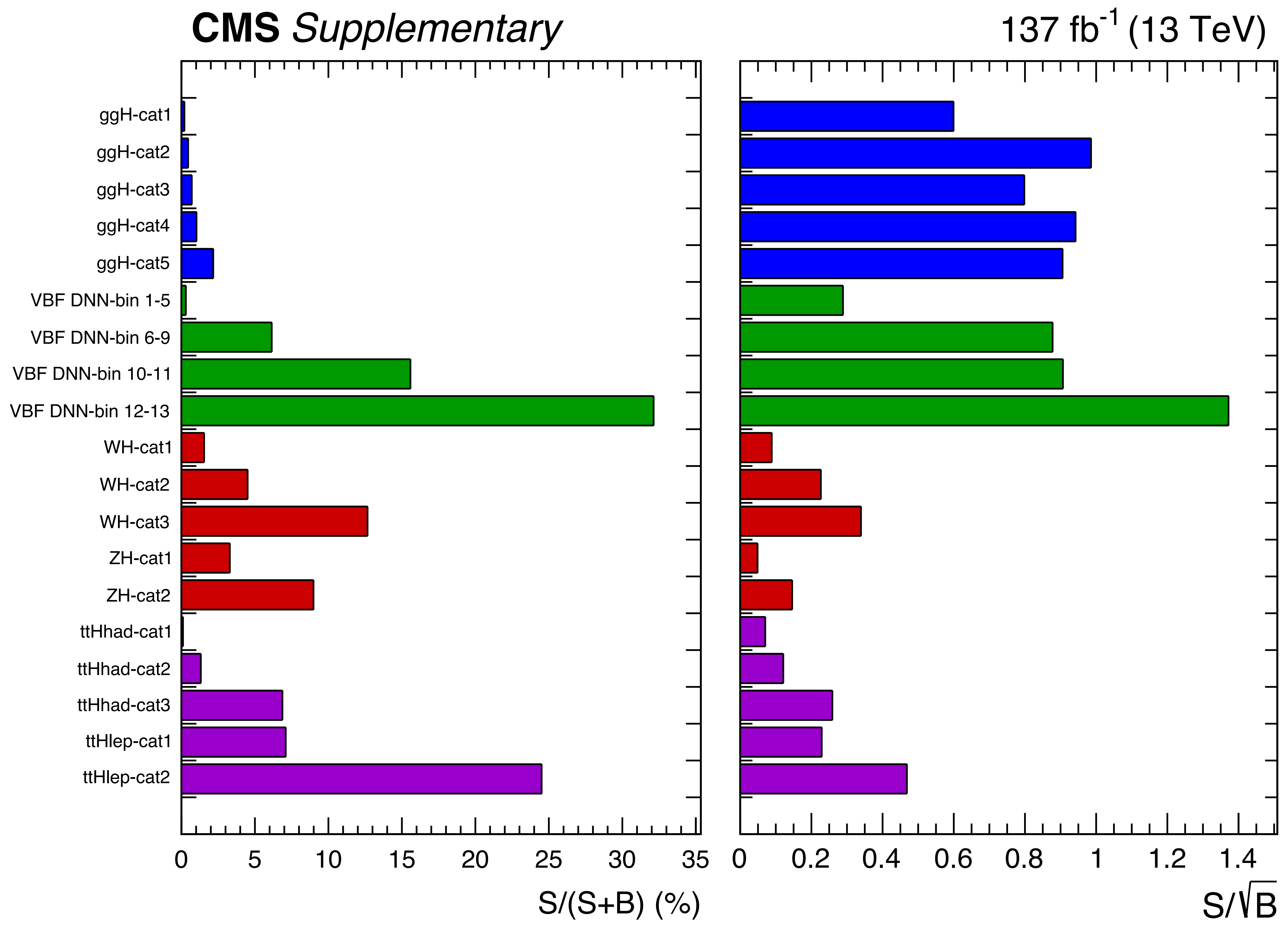
0-jet Medium	91 392	119 ± 14	140 ± 70	91 310 ± 210	0.46	0.2	2.7
0-jet Low	121 354	79 ± 10	90 ± 50	121 310 ± 280	0.26	0.1	2.7
VH4L	34	0.53 ± 0.05	0.6 ± 0.3	24 ± 4	0.13	2.6	2.9
VH3LH	41	1.45 ± 0.14	1.7 ± 0.9	41 ± 5	0.27	4.2	3.1
VH3LM	358	2.76 ± 0.24	3.2 ± 1.6	347 ± 15	0.17	0.9	3.0
$t\bar{t}H$	17	1.19 ± 0.13	1.4 ± 0.7	15.1 ± 2.2	0.36	9.2	3.2



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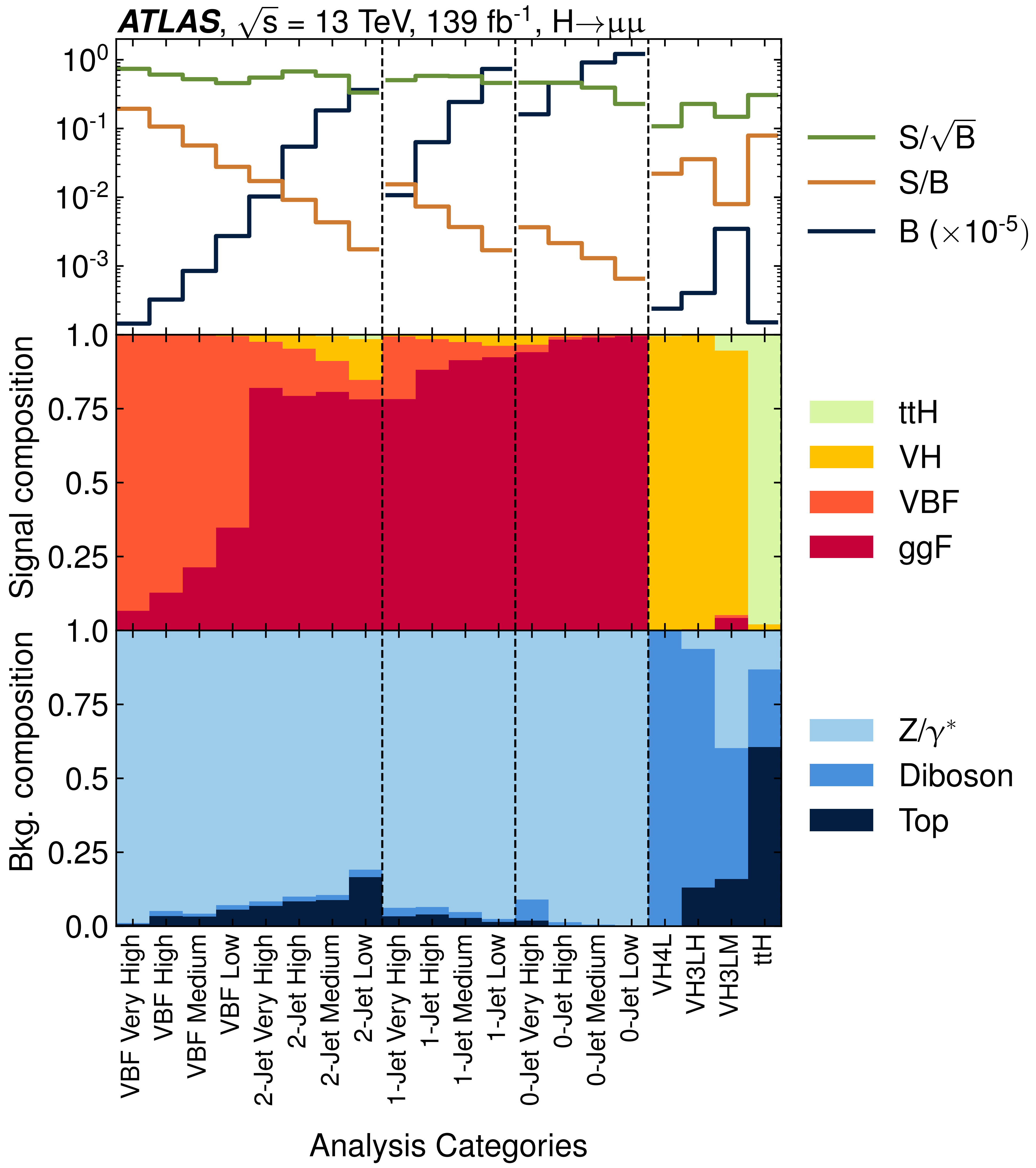

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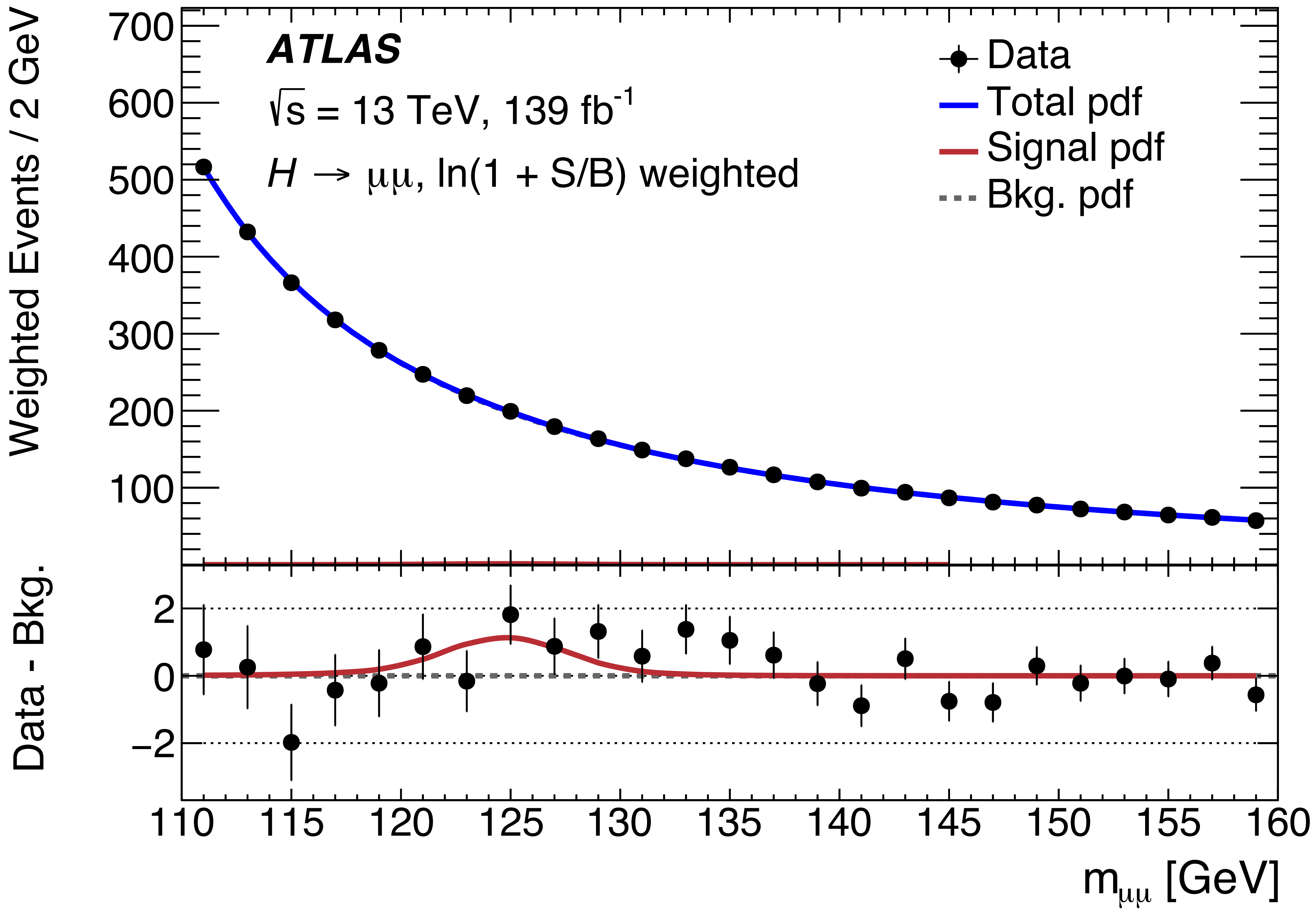
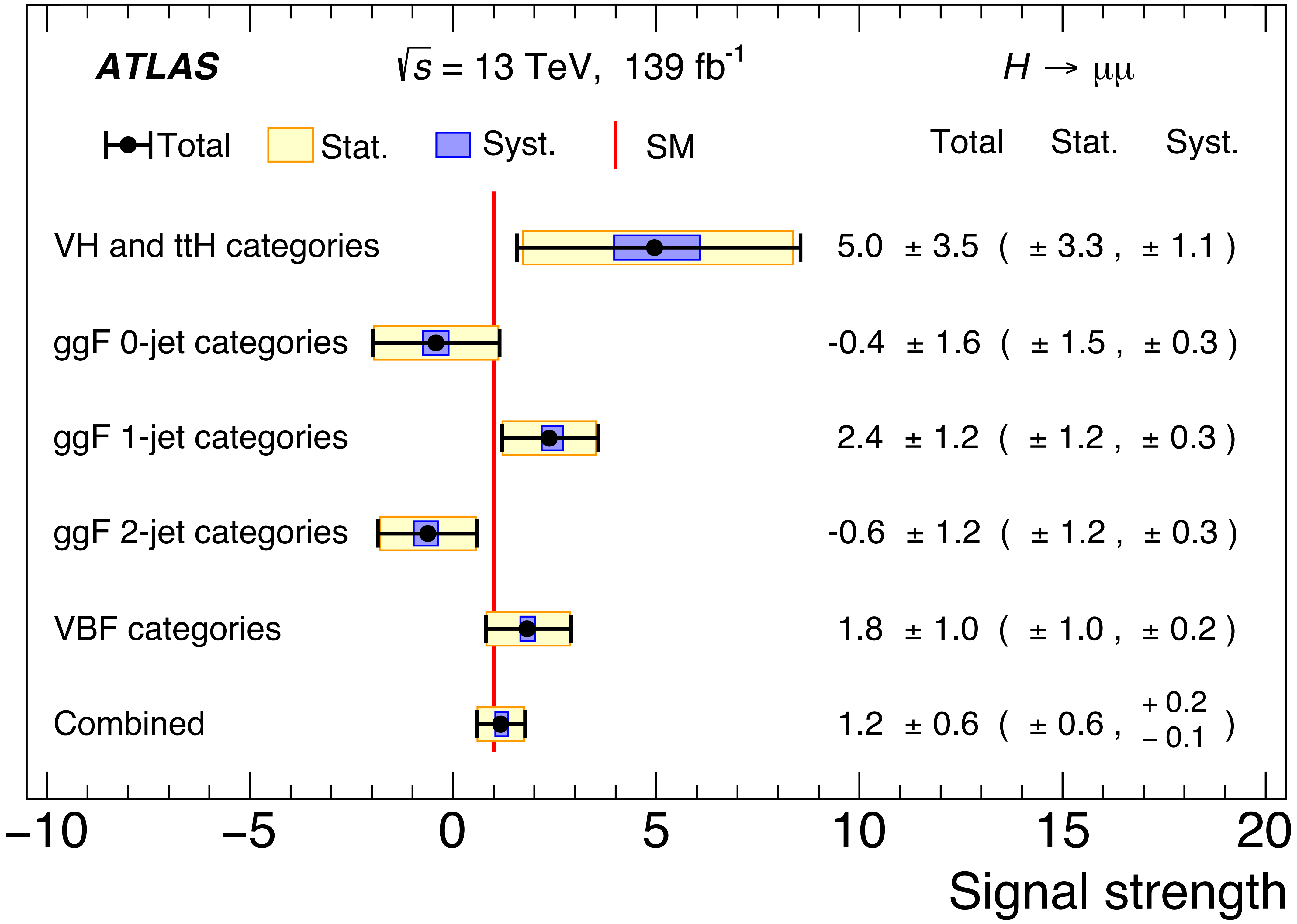
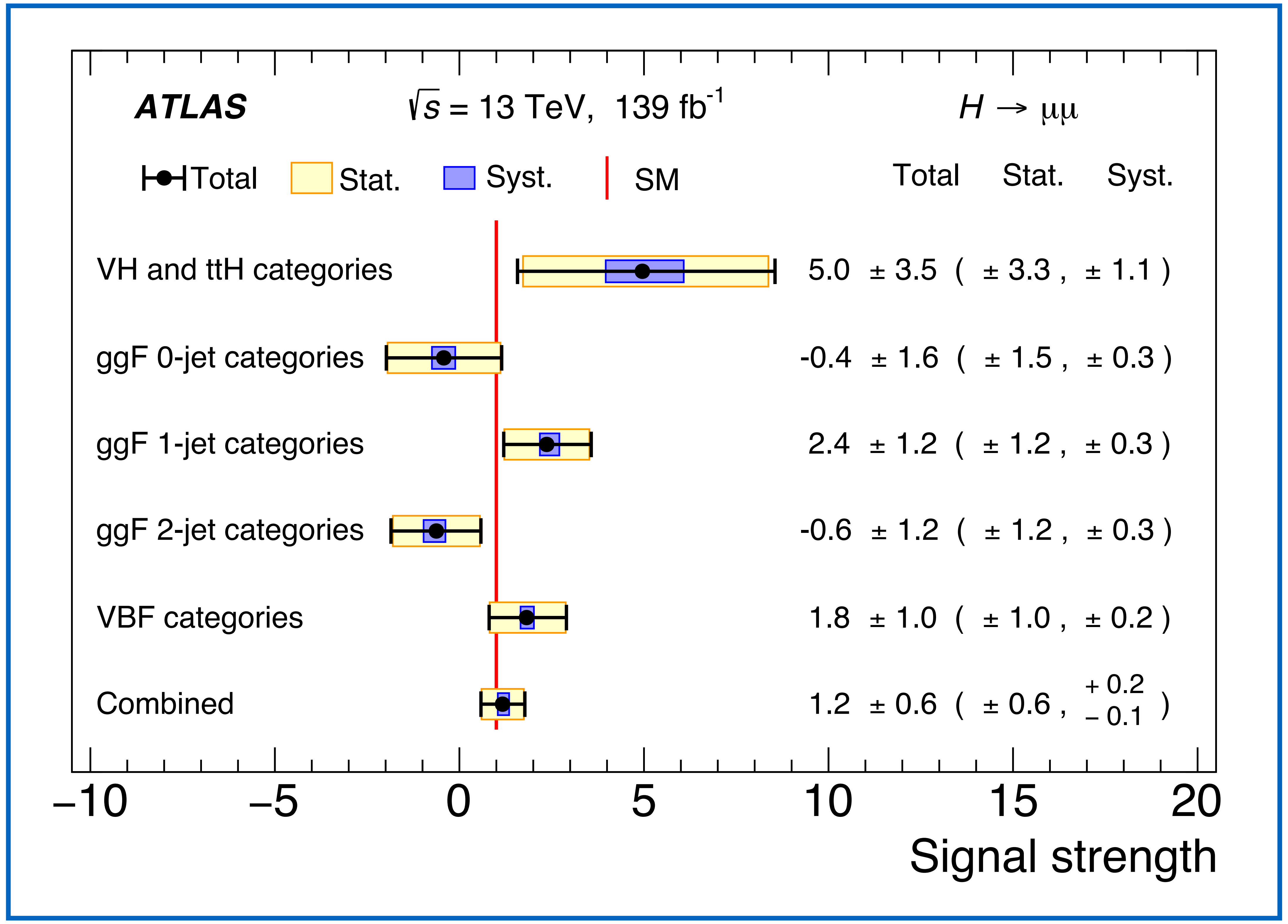
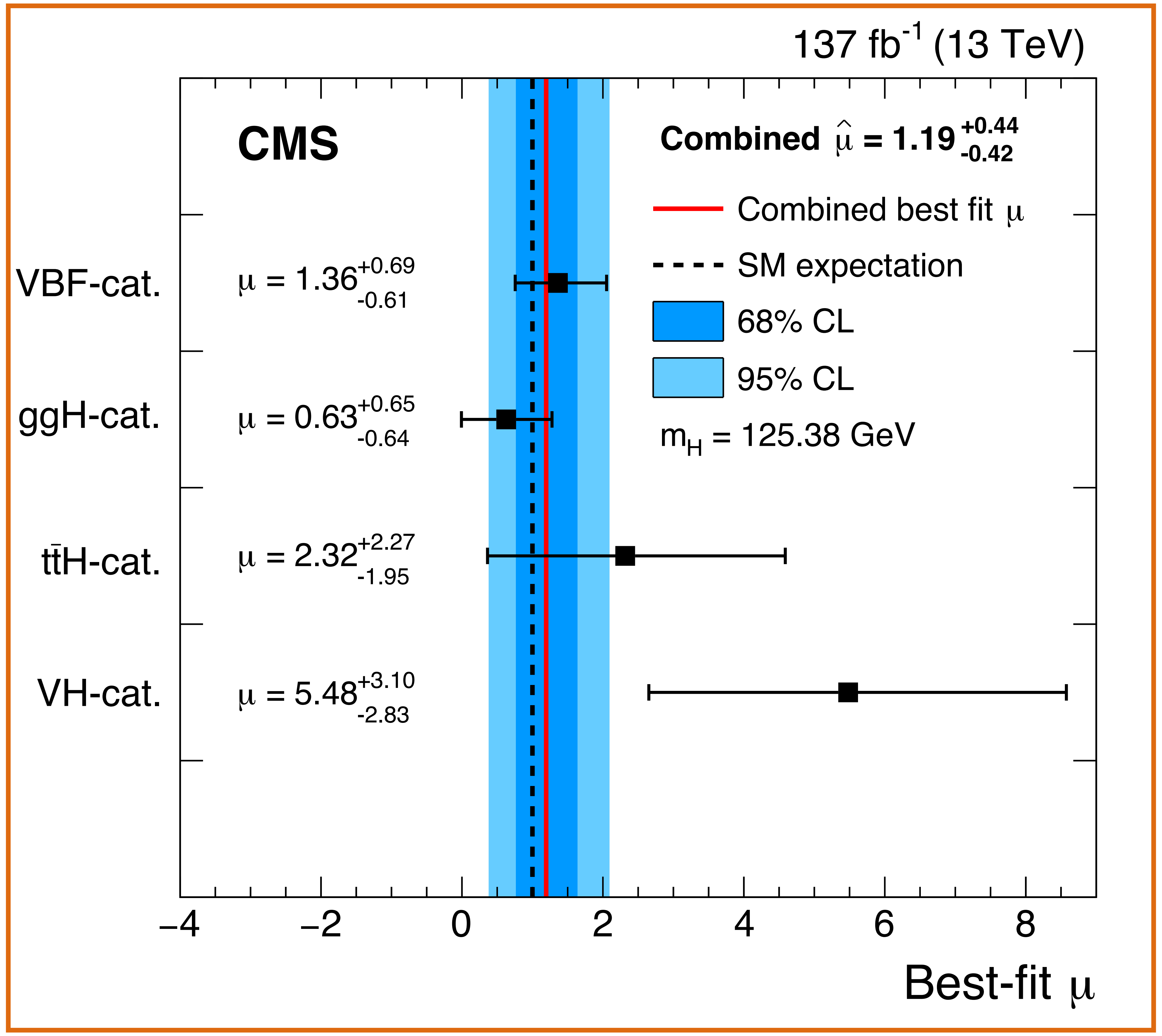




ATLAS vs CMS: results

- Comparison of the final weighted mass distributions as well as fitted signal strength

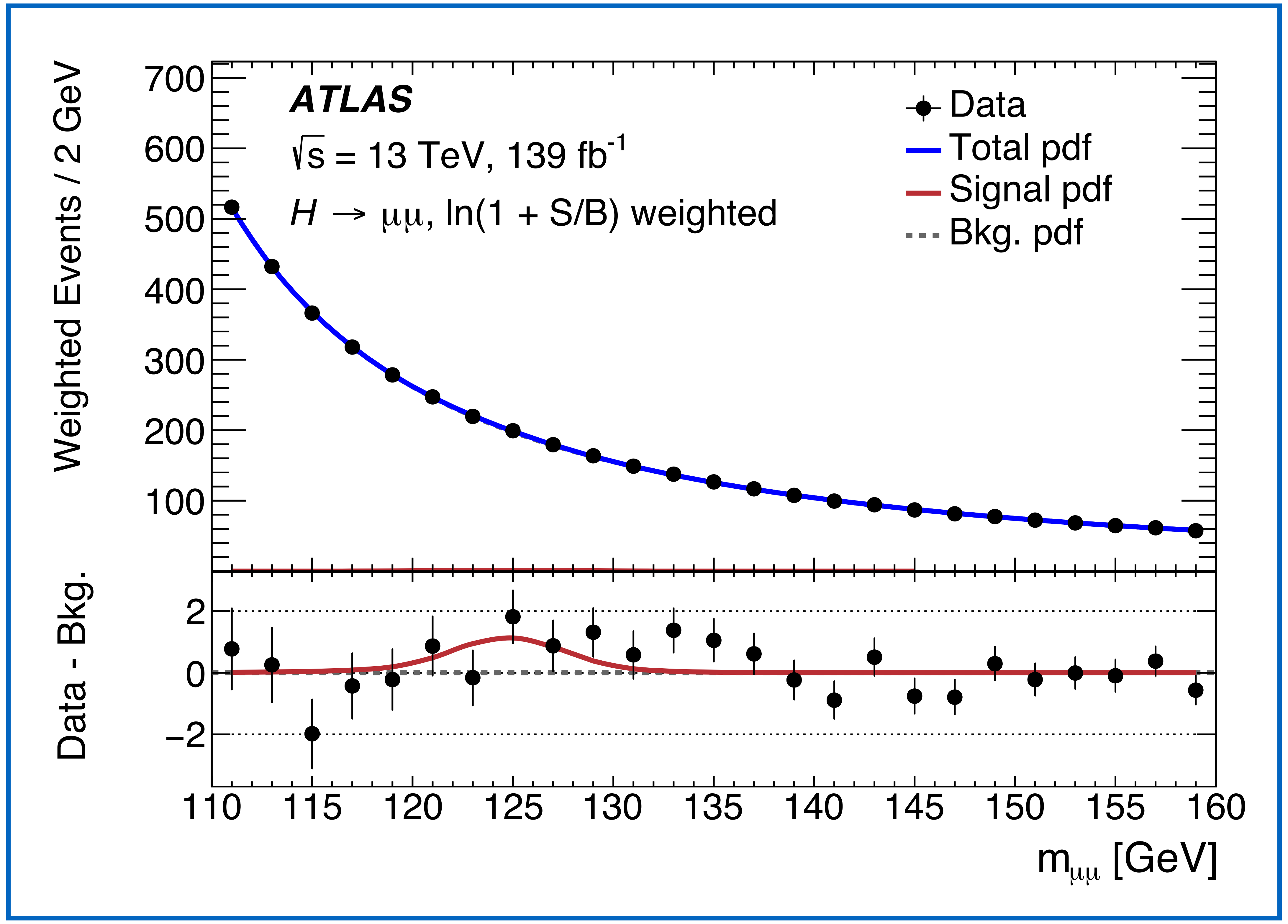


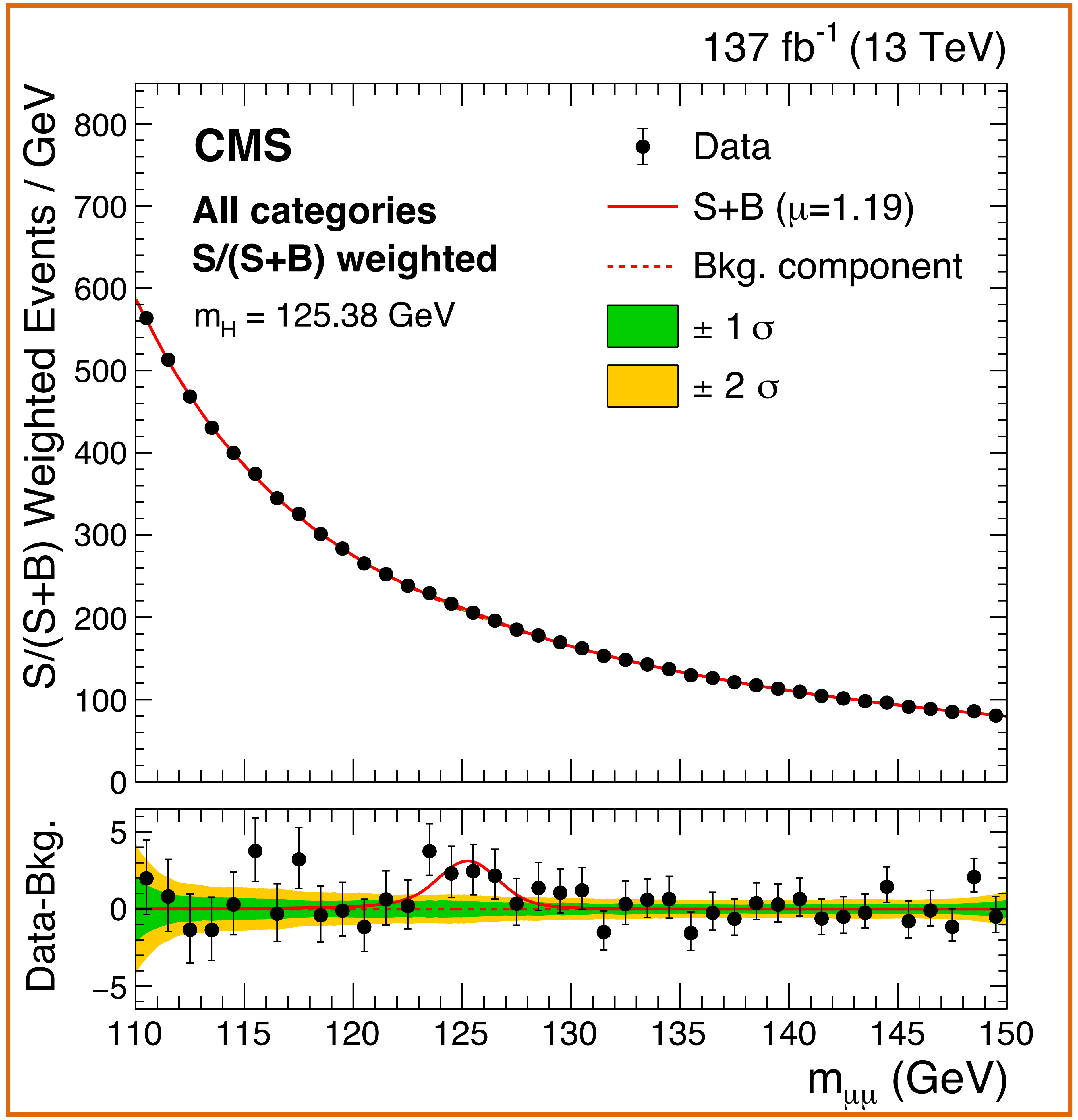


- **ATLAS:** best fit signal strength of 1.2 ± 0.6
- **CMS:** best fit signal strength of 1.19 ± 0.43

ATLAS vs CMS: results

- Comparison of the final weighted mass distributions from the two experiments





- **ATLAS:** observed (exp) significance 2.0 (1.7) σ
- **CMS:** observed (exp) significance 3.0 (2.5) σ

$H \rightarrow \mu\mu$ analysis: future prospects

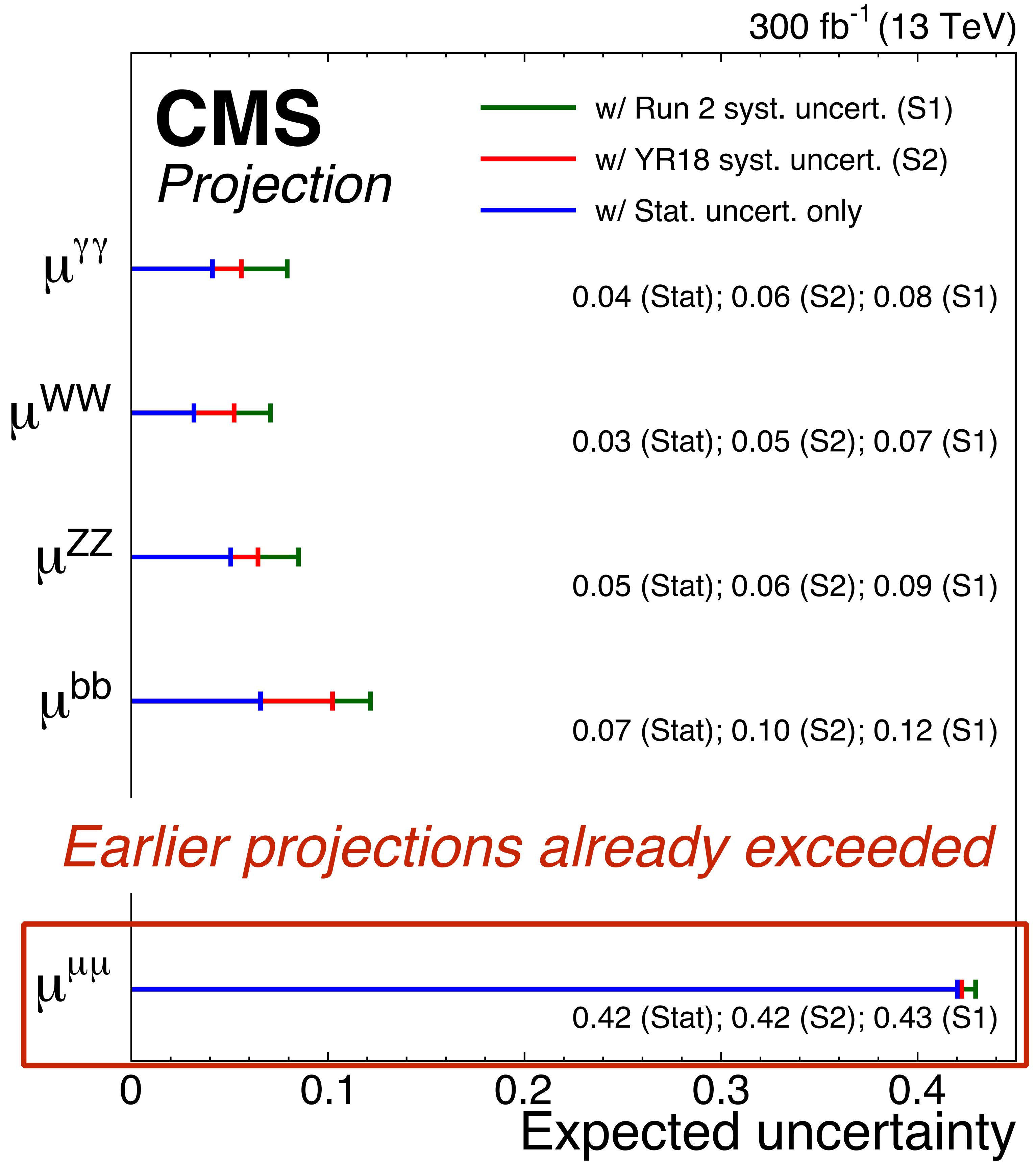
H→μμ analysis in Run3

- The ***LHC Run3*** will begin in February 2022
  - Total integrated luminosity of about **200 fb^{-1}**
  - ***Pileup*** similar to the one of ***2018 data-taking***
  - Center-of-mass energy possibly raised to ***14 TeV***

Small upgrades in the CMS detector performed during LS2

- ***Conservative*** projections for H→μμ reported in ***FTR-18-011***
- Projections from an extrapolation of earlier H→μμ
- ***The result presented before already provides a 40% uncertainty in the BR(H→μμ) estimate***
- ***Our Run2 result went well beyond our previous expectations***

- ***Performance of H→μμ in Run3 expected to be same of Run2***
- Very similar detector, pileup level, trigger setup etc ..
- The analysis is ***statistically limited*** so it will ***improve as sqrt(L)***



Earlier projections already exceeded

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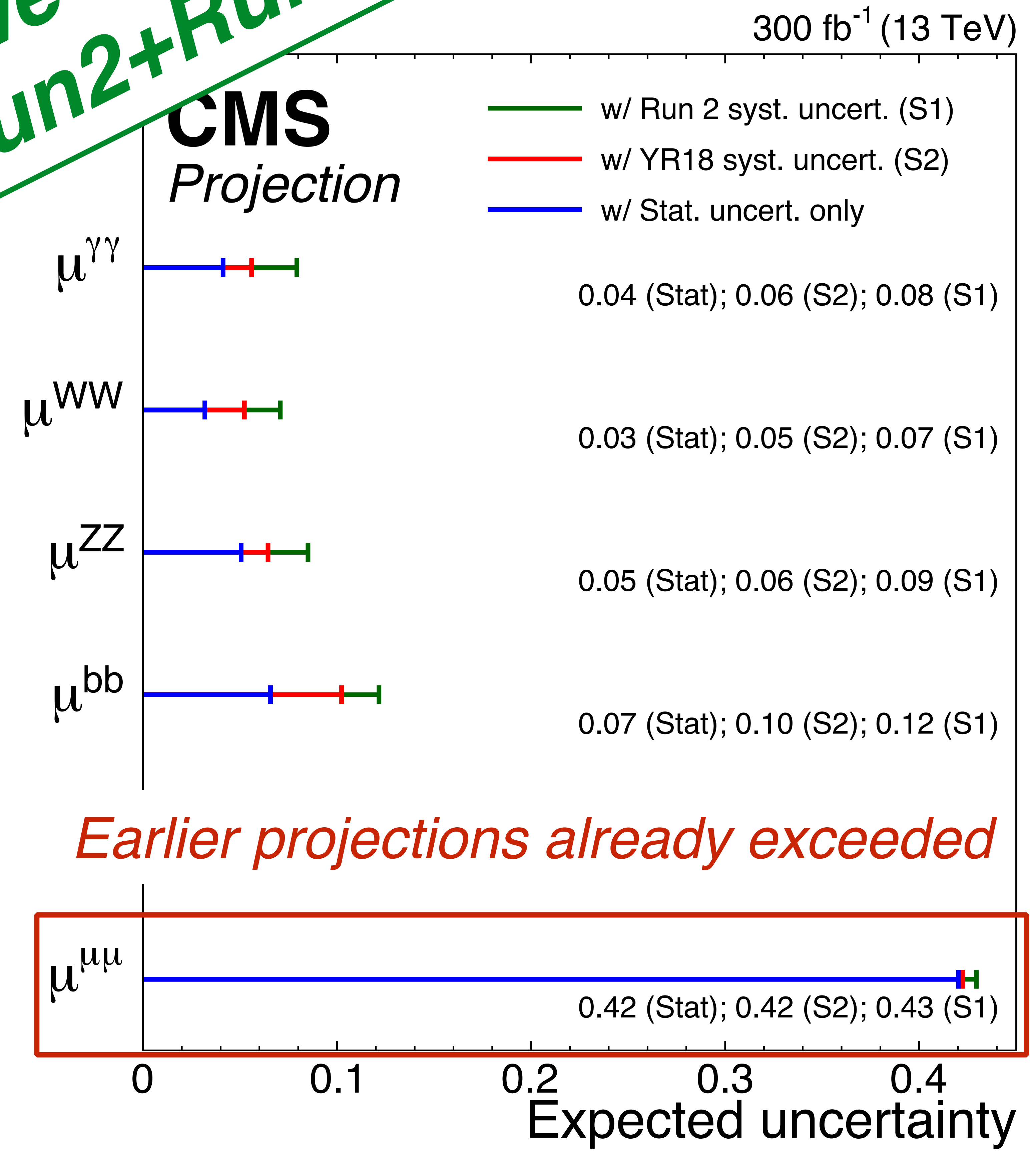
Sma ... MS detector ...uring LS2



Earlier projections already exceeded

- ***Conservative*** projections for H→μμ reported in ***FTR-1***
- Projections from an extrapolation of earlier H→
- ***The result presented before already***
  uncertainty in the BR(H→μμ) e
- ***Our Run2 result went w*** ... ***ious expectations***

- ***Perfo*** ... ***→μμ in Run3 expected to be same of Run2***
- Very si ... detector, pileup level, trigger setup etc ..
- The analysis is ***statistically limited*** so it will ***improve as sqrt(L)***

Assuming no improvements or losses, we expect to reach an expected significance of 4σ with Run2+Run3 dataset

H→μμ analysis in HL-LHC

- The HL-LHC will start in 2026 delivering about ***3-4 ab^{-1}*** of pp collision data at ***14 TeV***
  - ***Extreme pileup conditions*** → 200 concurrent interactions every bunch crossing
  - To operate in this environment, ***the detector will upgrade or replace severals subsystems***

Upgraded detector

- ***New tracker*** with coverage up to |η|=4 and L1 track trigger
- ***Upgraded muon system*** with coverage up to |η|=2.8
- ***New high granularity*** endcap ***calorimeter (HGCal)***

Improvements expected in the H→μμ analysis

- Increased acceptance due to muon coverage up to |η|=2.8
- Possibly reconstruct muons with tracker-only up to |η|=4.0
- Substantial improvement in ***muon p_T resolution***
- **VBF category:** improved ***jet-energy-resolution*** for endcap and forward jets
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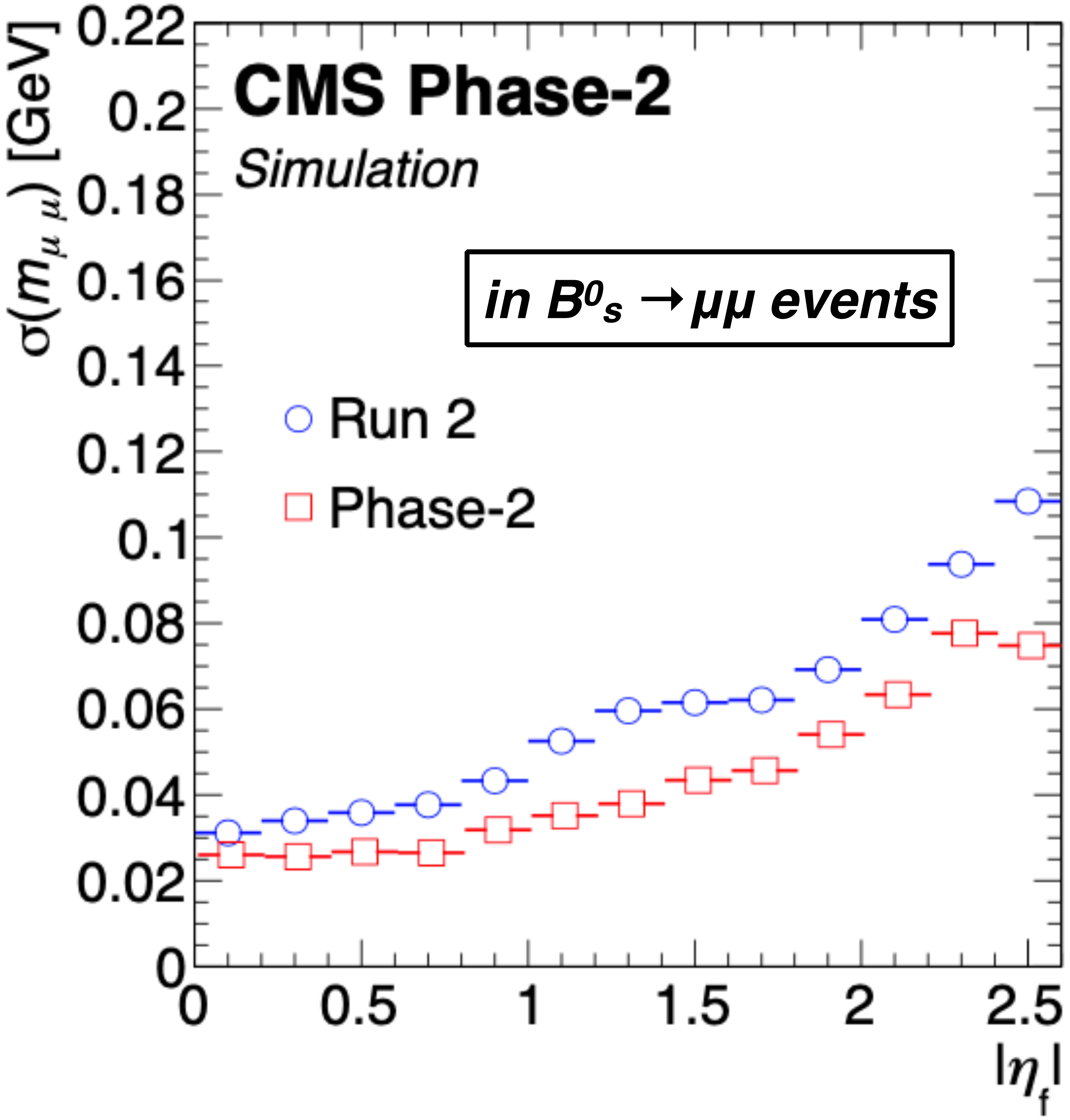

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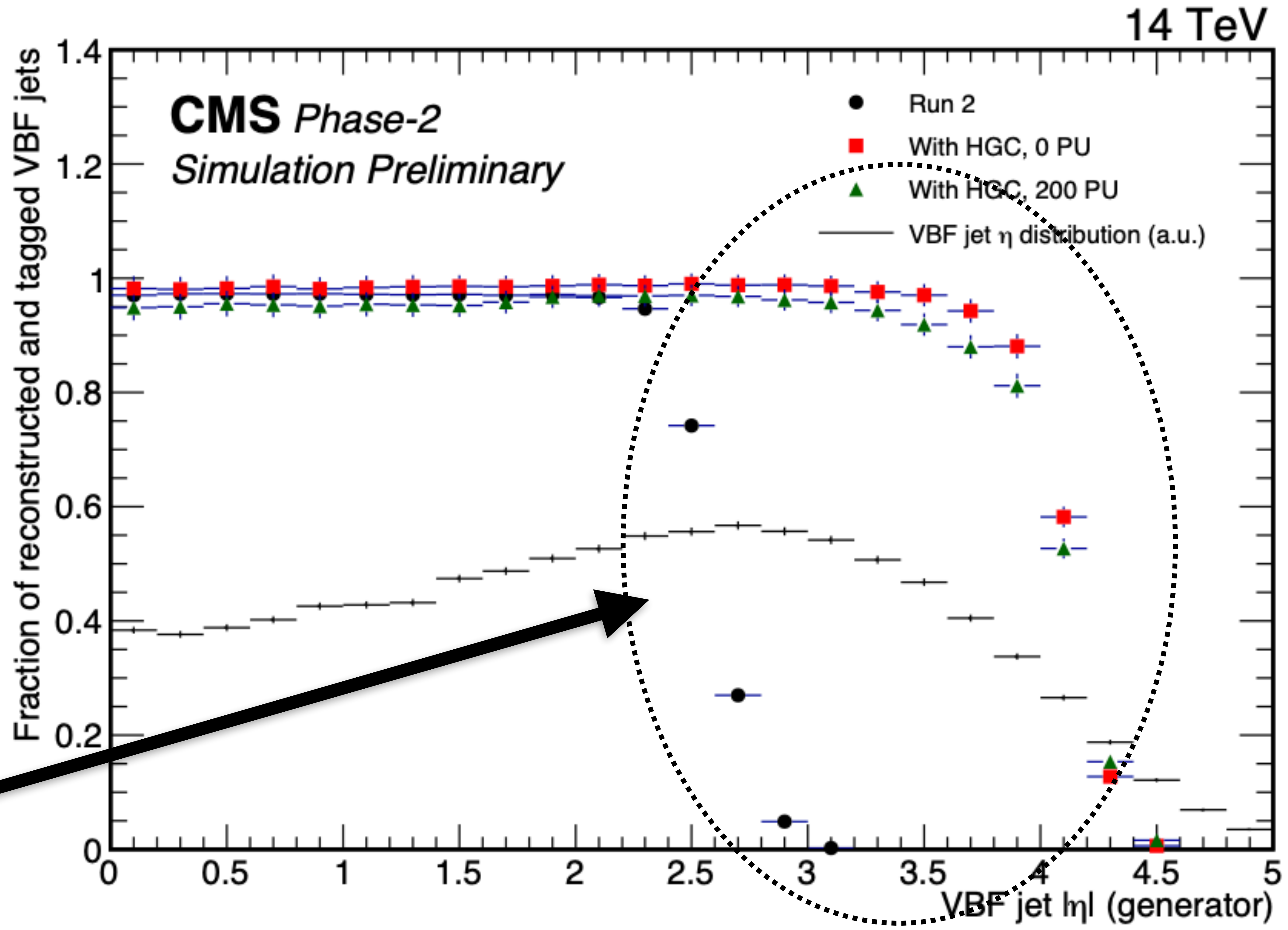

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At the HL-LHC, ATLAS+CMS may measure Higgs-to-muon couplings with 4% precision (arXiv 1902.00134)