Higgs fermionic decays

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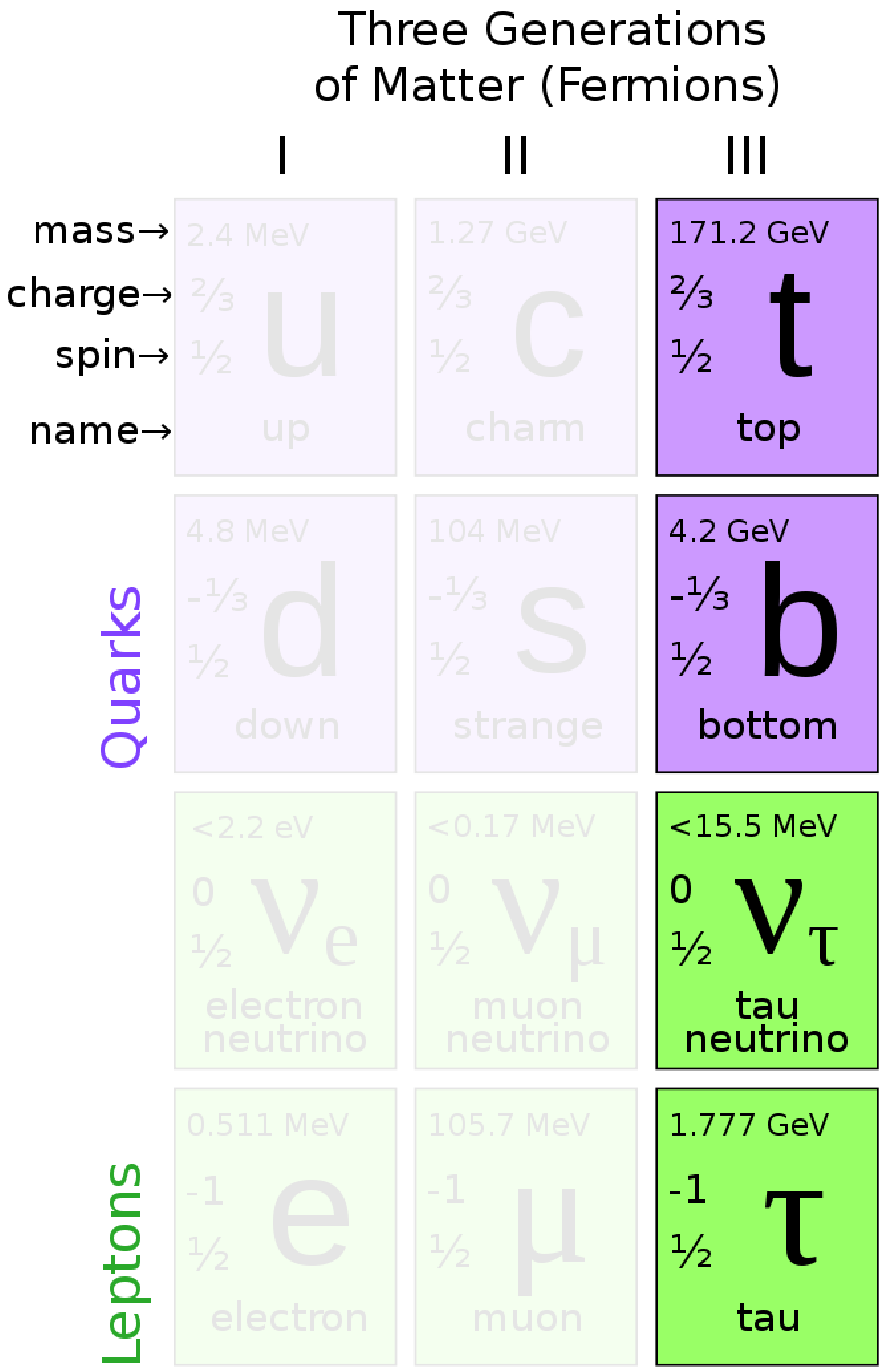
Introduction

- Fermions acquire masses from Yukawa couplings with the Higgs boson
  - This sector is essential to understand the nature of the Higgs boson, the flavor hierarchy etc.
- Measurements of H→ff decays provide a powerful way of probing these couplings
- Discuss the recent experimental measurements of Higgs boson decays to different generations of fermions in this talk

PDG

Decay channel	Branching ratio	
$H \to \gamma\gamma$	2.27×10^{-3}	
$H \to ZZ$	2.62×10^{-2}	
$H \to W^+W^-$	2.14×10^{-1}	
$H \to \tau^+\tau^-$	6.27×10^{-2}	Discovery
$H \to b\bar{b}$	5.82×10^{-1}	Discovery
$H \to c\bar{c}$	2.89×10^{-2}	
$H \to Z\gamma$	1.53×10^{-3}	
$H \to \mu^+\mu^-$	2.18×10^{-4}	Evidence



- The third generation with possible decay channels
  - $H \rightarrow bb$
  - $H \rightarrow \tau\tau$
  - …

Recent H→bb studies

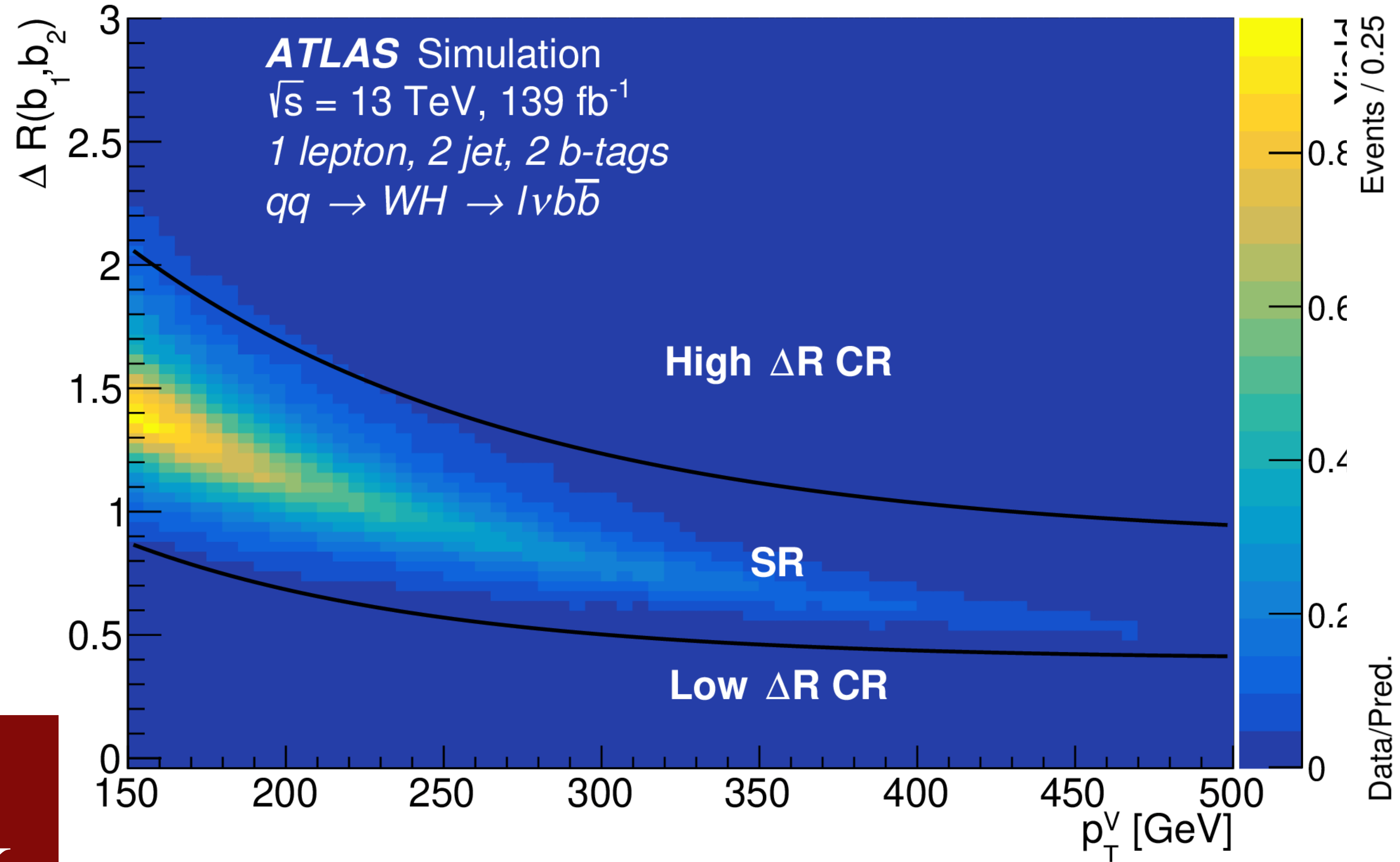
- ATLAS Full Run2 data
  - VH→bb XS, HIGG-2018-51, 2007.02873
  - VH→bb with merged jets, HIGG-2018-52, 2008.02508
  - VBF H→bb, HIGG-2019-04
  - VBF H→bb+γ, HIGG-2020-14, 2010.13651

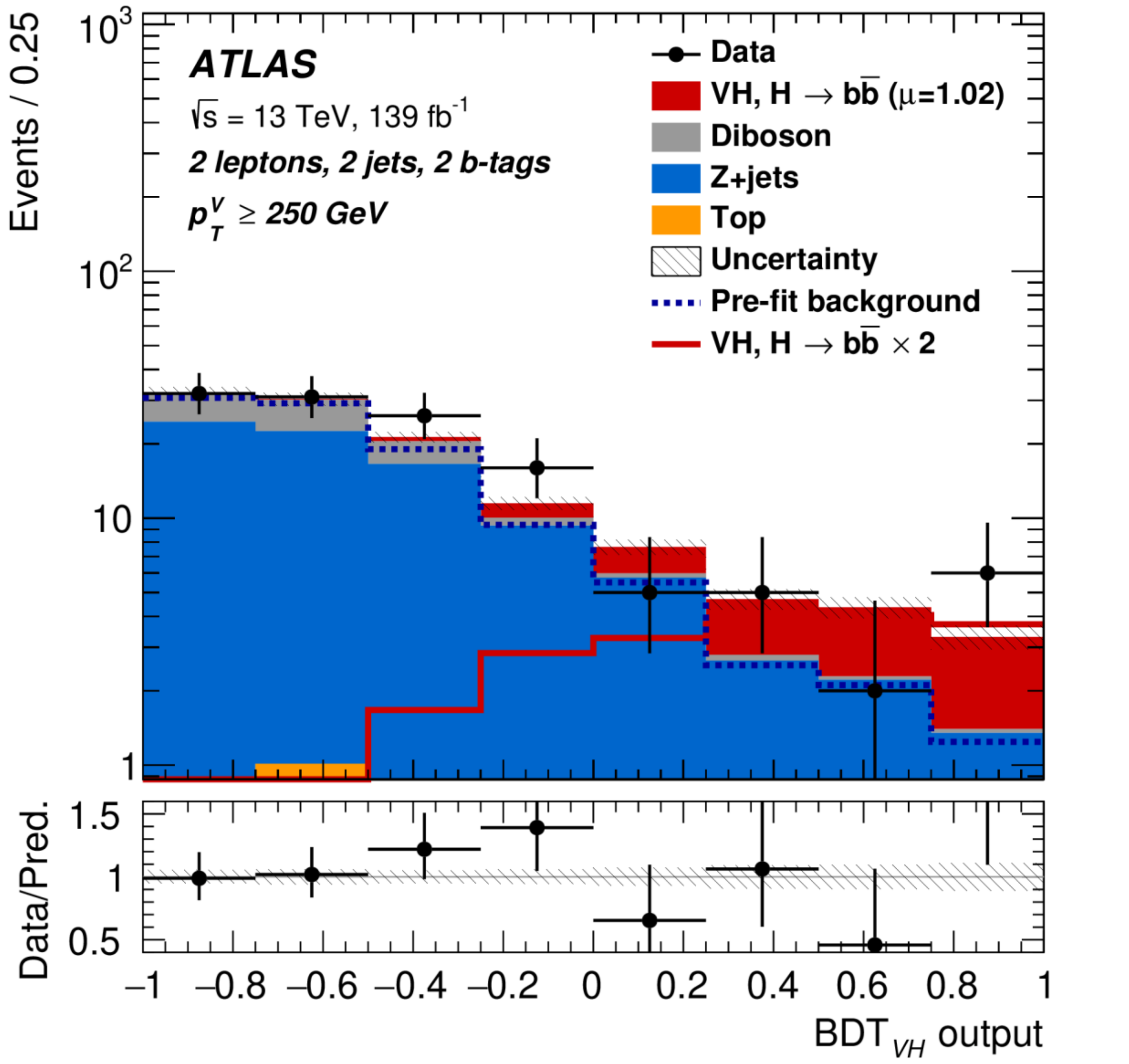
- CMS Full Run2 data
  - Inclusive H→bb with merged jets, HIG-19-003, 2006.13251

VH→bb XS

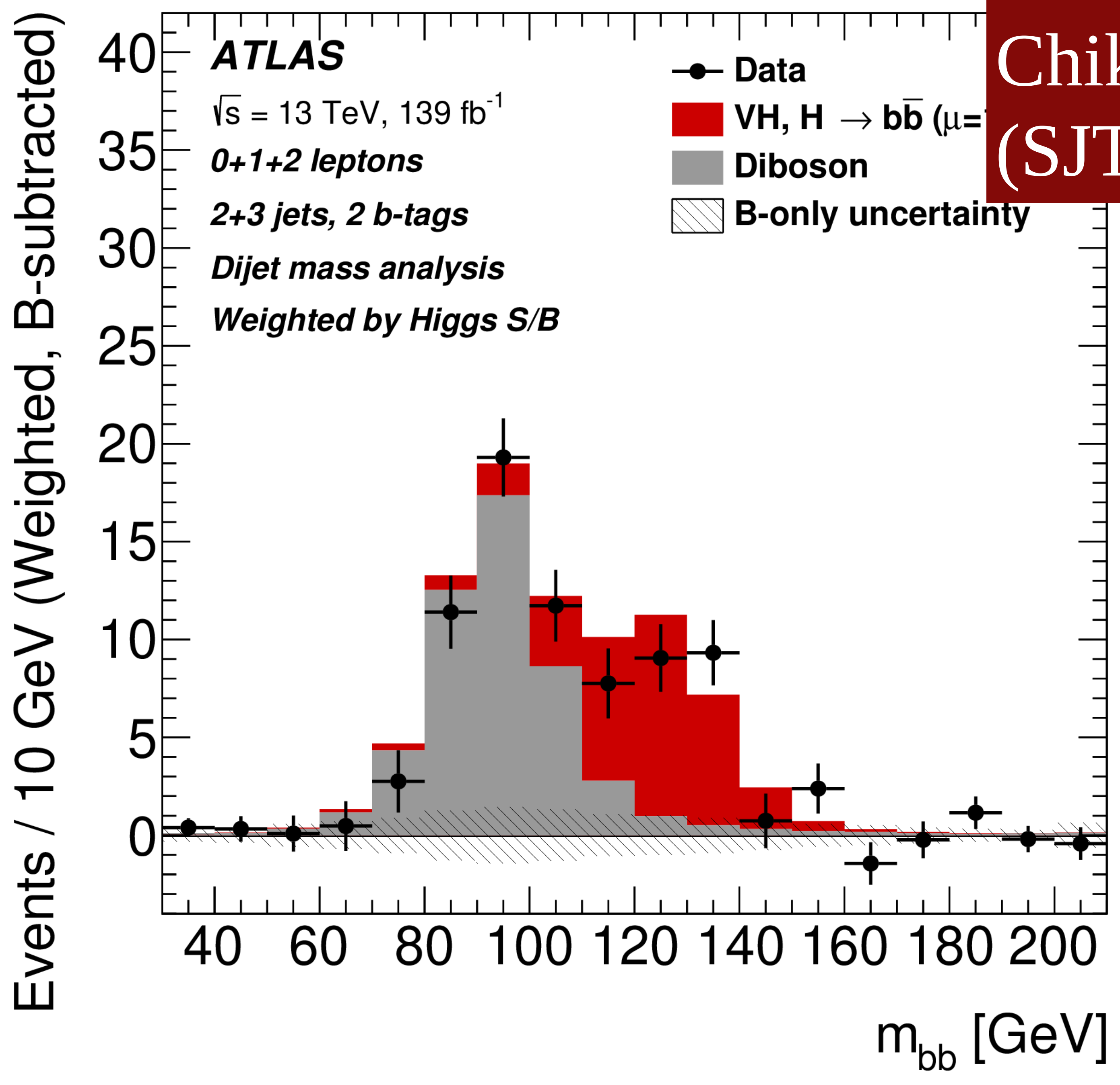
2007.02873

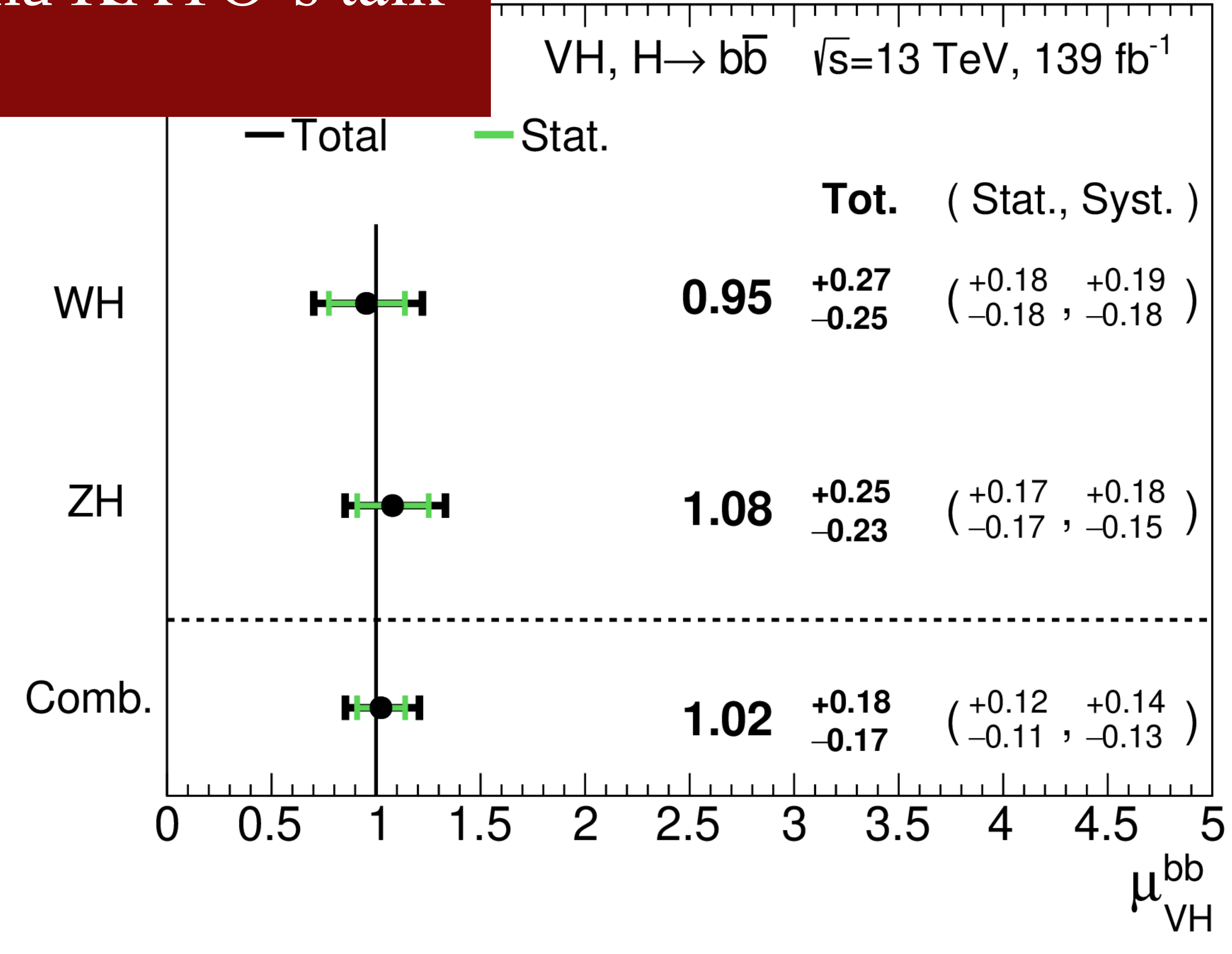
- Full Run2 results from ATLAS this summer
- Trigger with leptons or MET; separate $p_T(V)$ regions; define SR/CR with $\Delta R(b1,b2)$; fit on BDT scores
- Measure signal strength, STXS; set limits on SMEFT operators (D=6)
- Precisions are improved; measurements agree well with SM

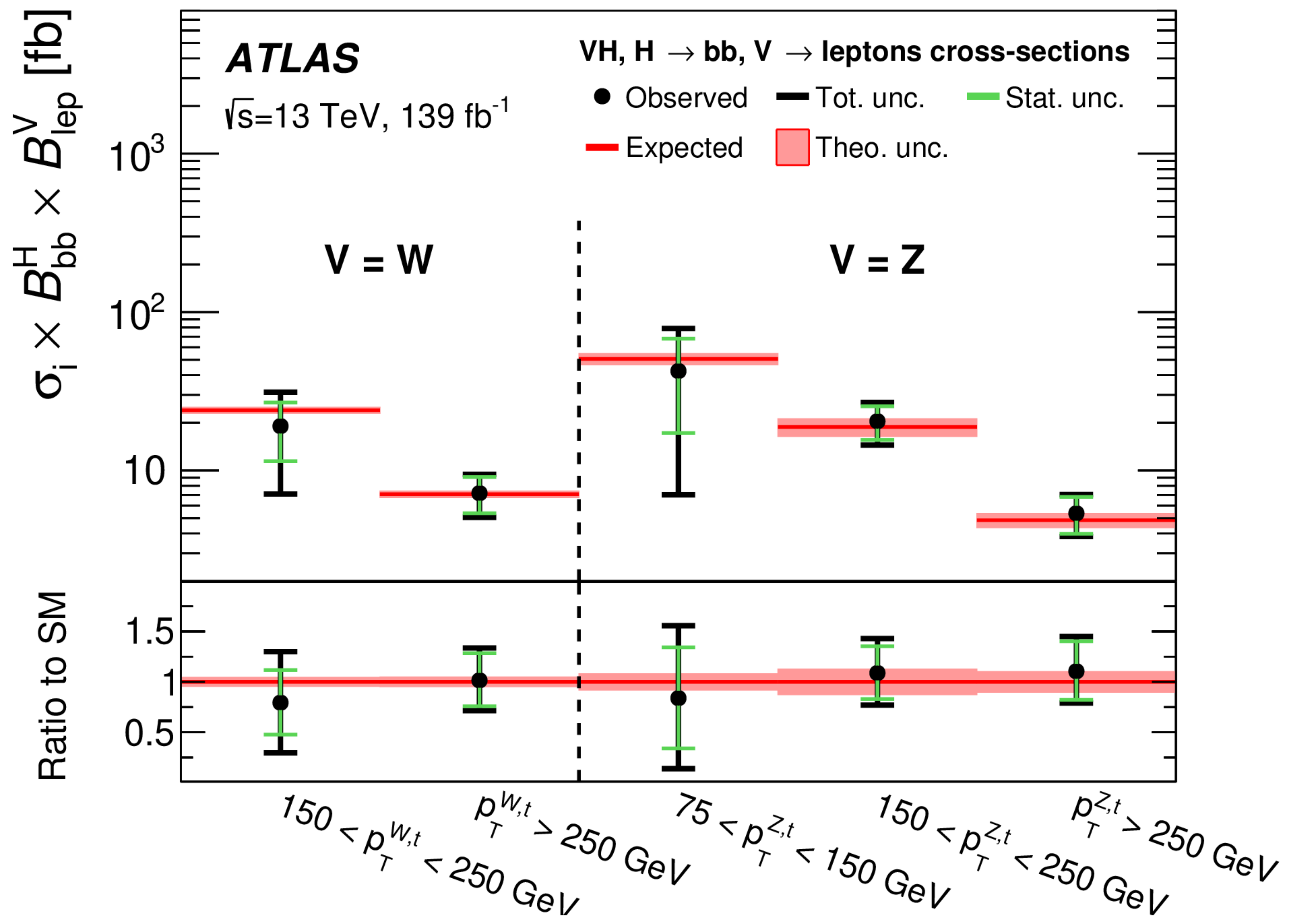




See more details from Chikuma KATO's talk (SJTU)



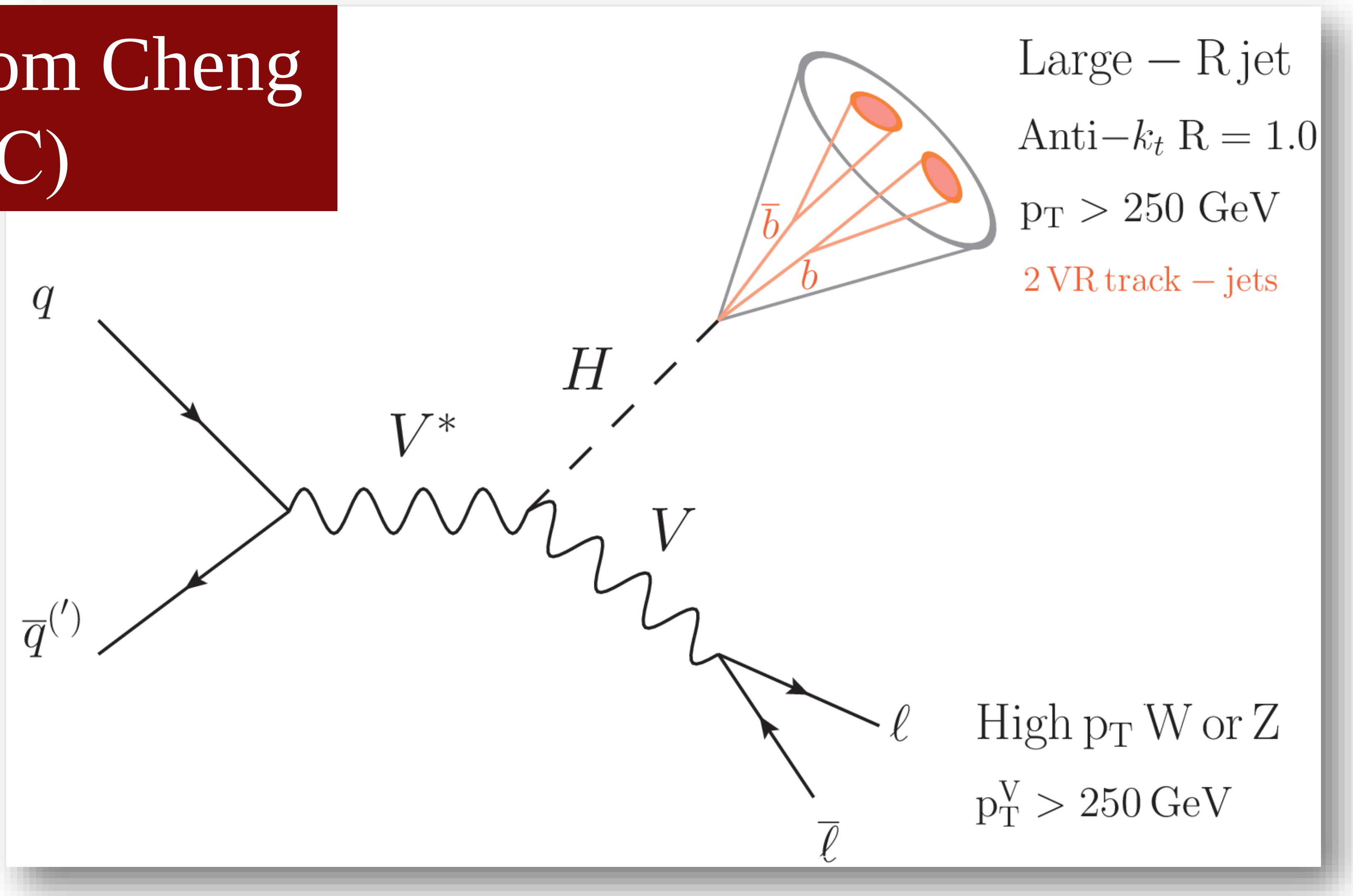




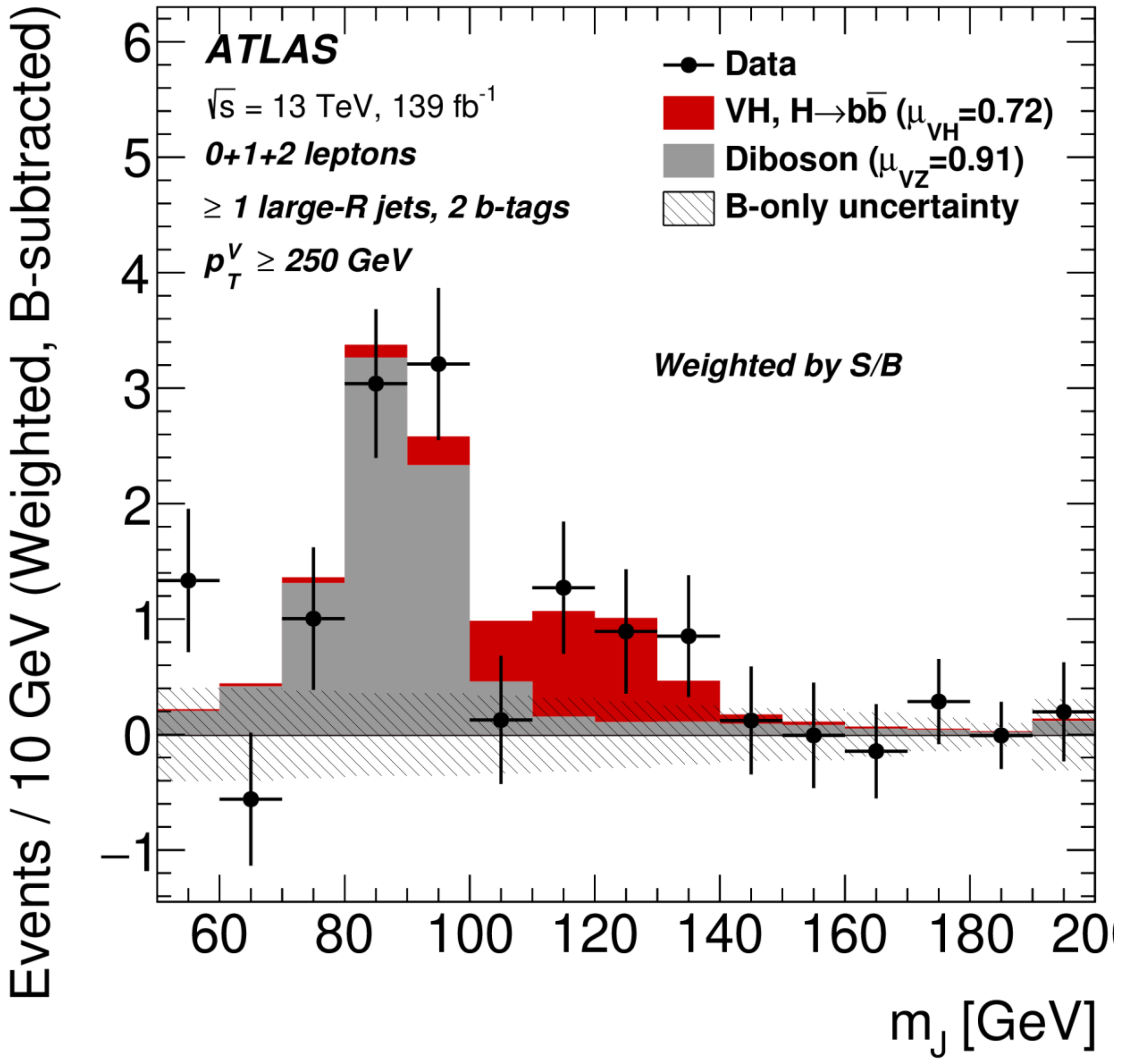
VH→bb with merged jets

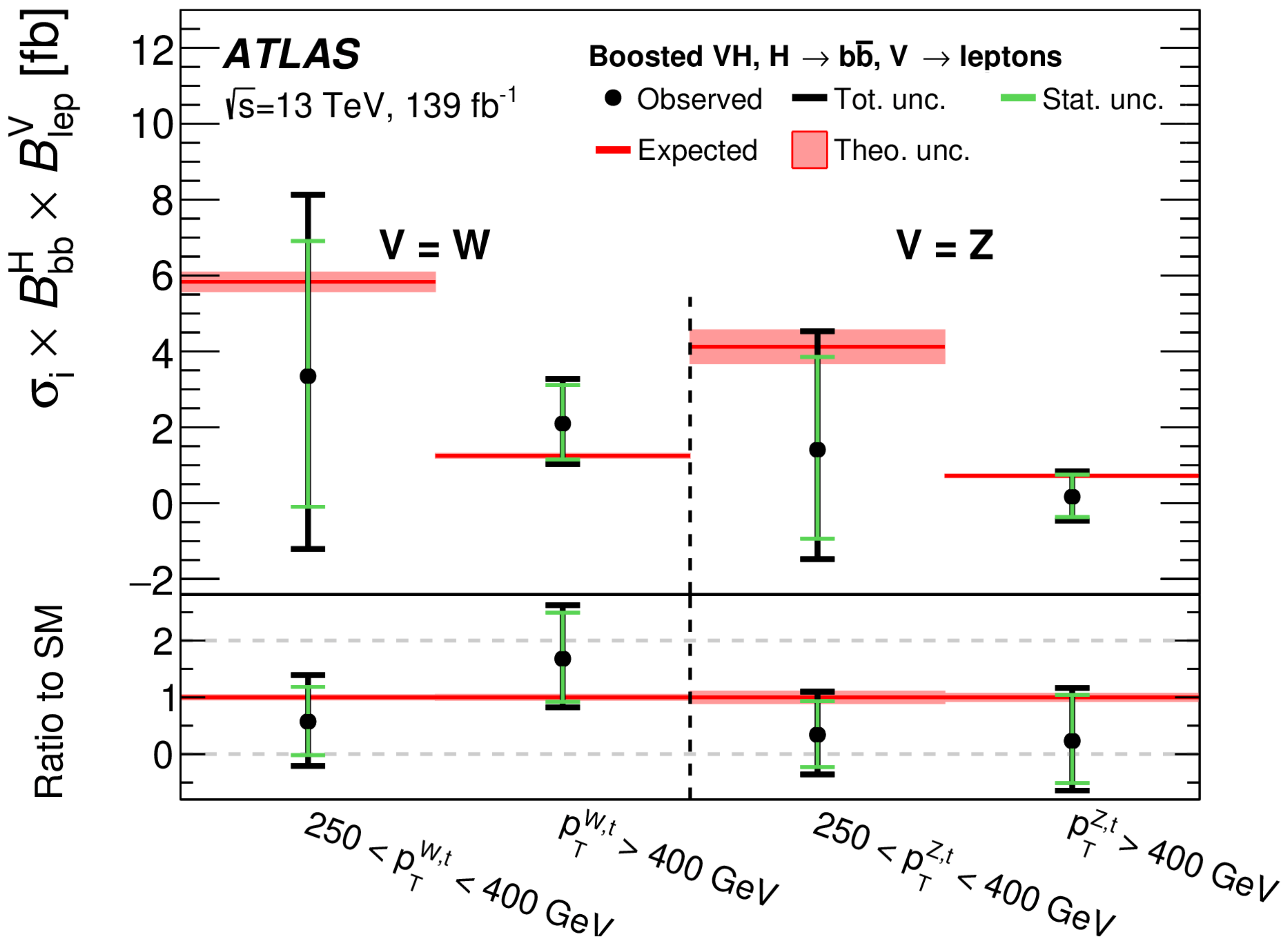
- Full Run2 results from ATLAS this summer
- Require one R=1.0 merged jet
- Interesting to high $p_T(V)$ where BSM effects could emerge
- Trigger with MET and leptons
  - Muon channel also uses MET trigger due to low efficiency of muon triggers in high pT

See more details from Cheng CHEN's talk (USTC)



- Apply sequential cuts; define categories by $p_T(V)$, (b)jets; fit on mJ
- Measure the signal strength, STXS, set limits on SMEFT couplings
- Obs (exp) significance is 2.1σ (2.7σ)

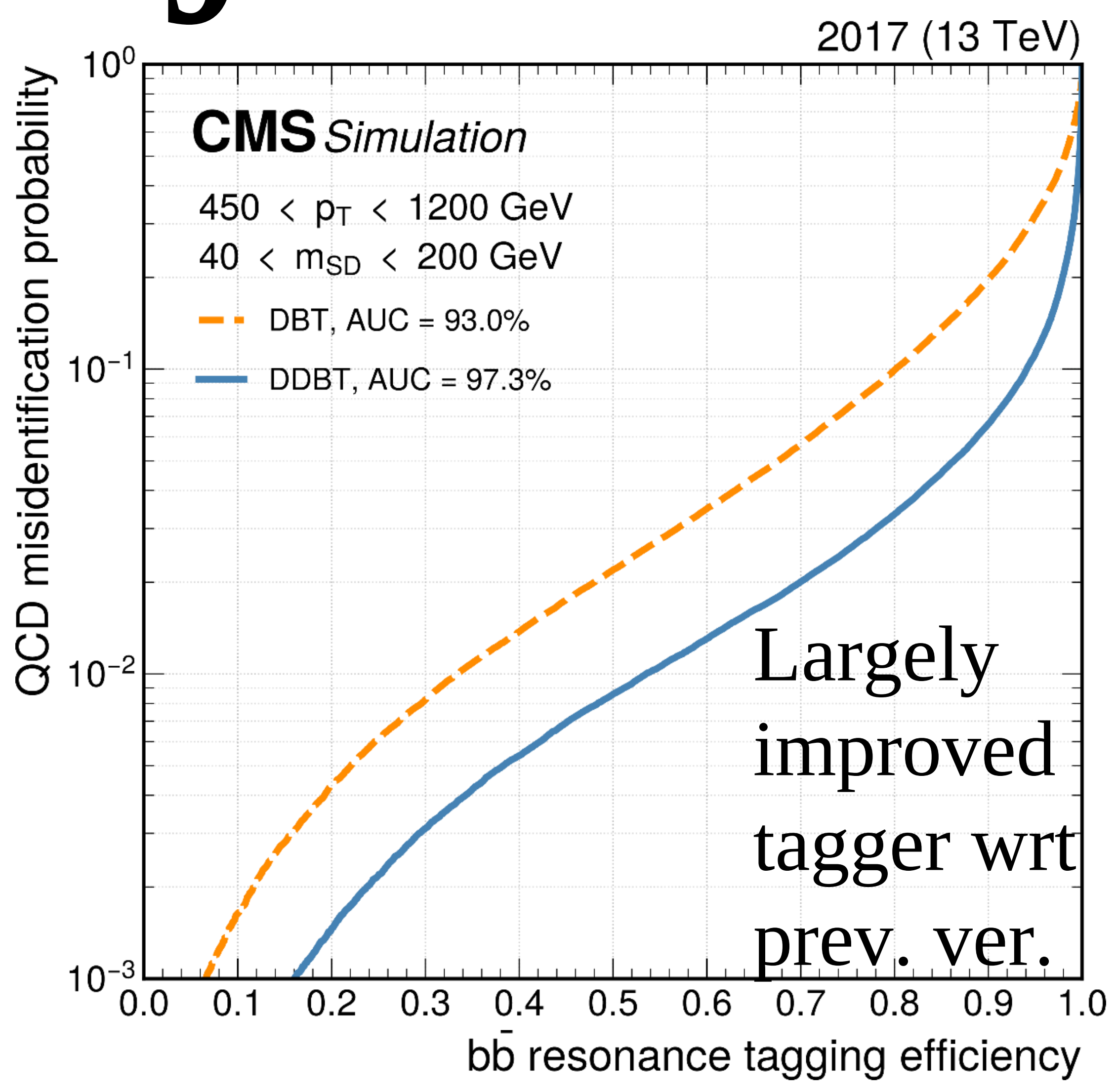




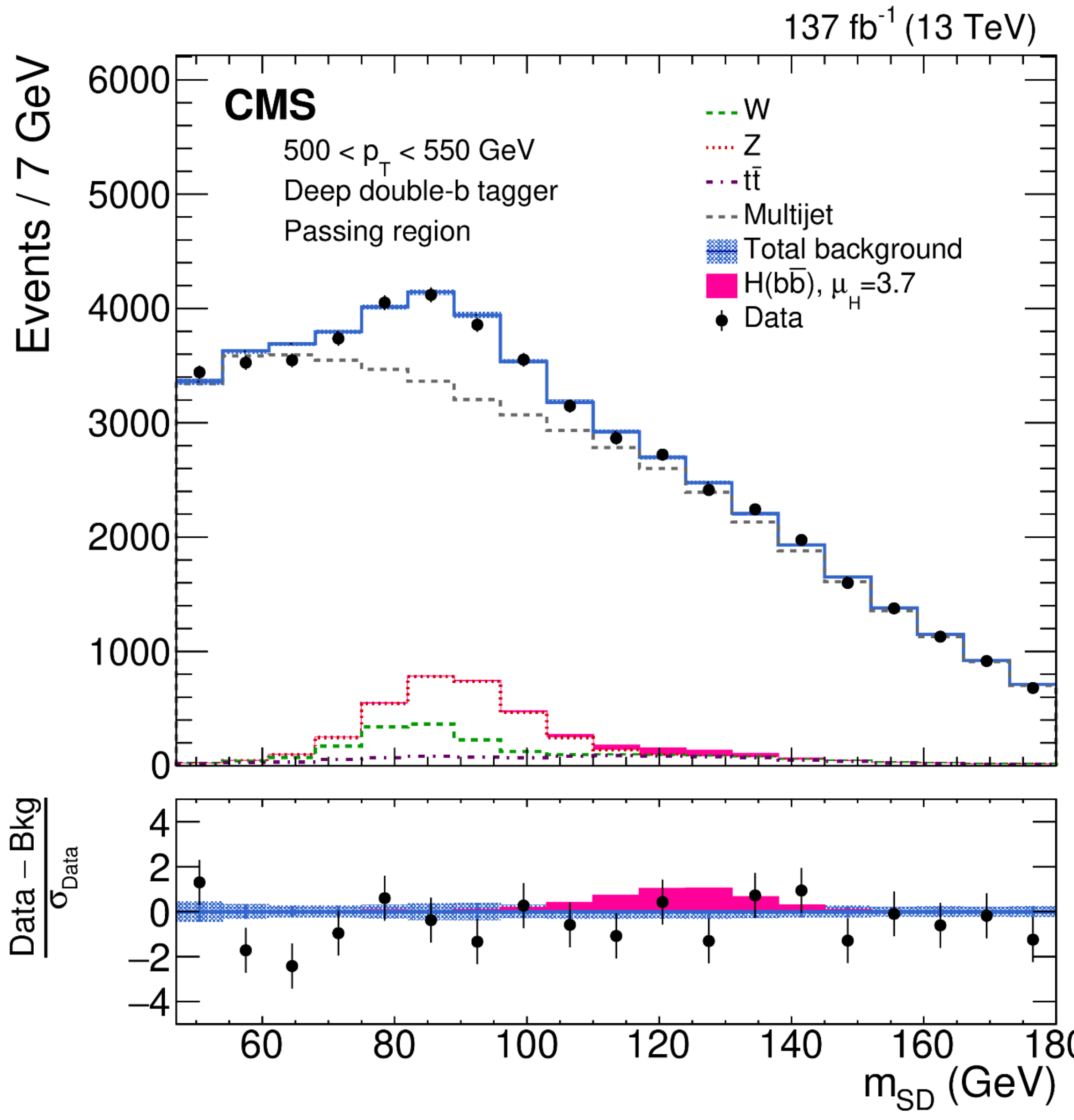
Incl. H→bb with merged jets

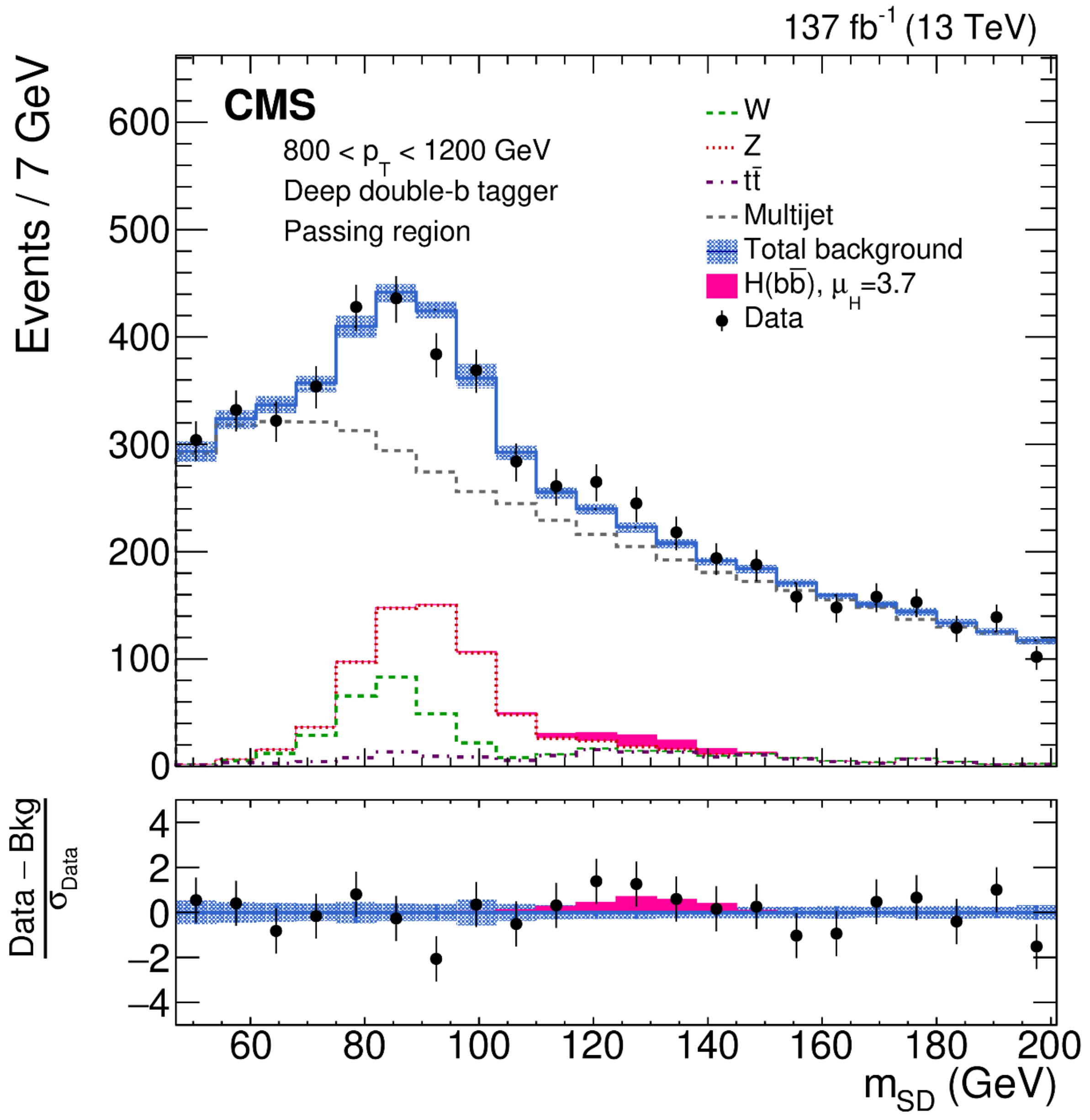
2006.13251

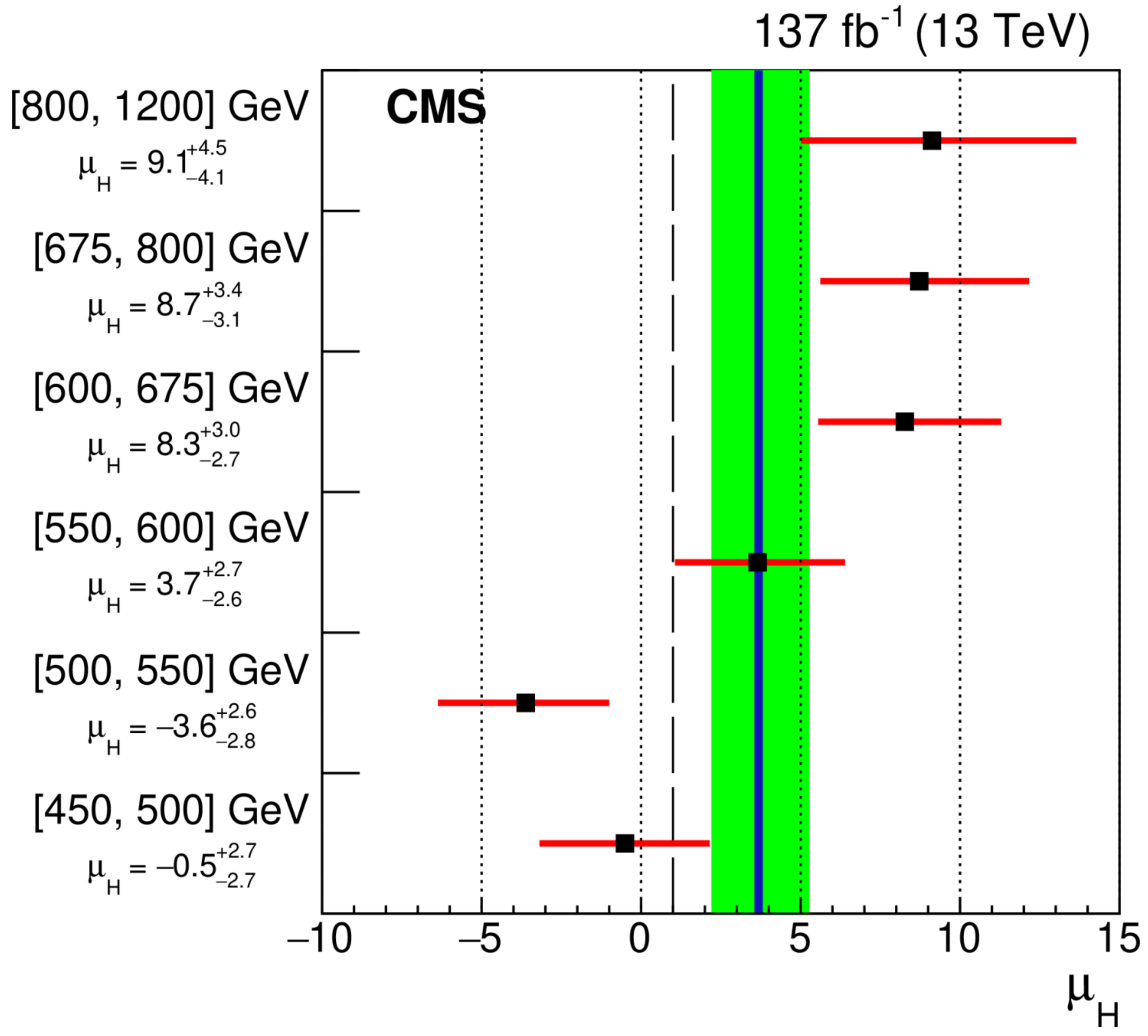
- Full Run2 results from ATLAS this summer
- Trigger with R=0.8 merged jets; train DDBT (deep NN) to tag large-R double-b jets
- Define categories with DDBT tagging and jet p_T; fit on mJ
- Measure signal strength of the incl. Higgs production and STXS for ggF
- The signal strength is 3.7 +1.6 -1.5 with a local significance of 2.5σ (0.7σ)



Largely improved tagger wrt prev. ver.





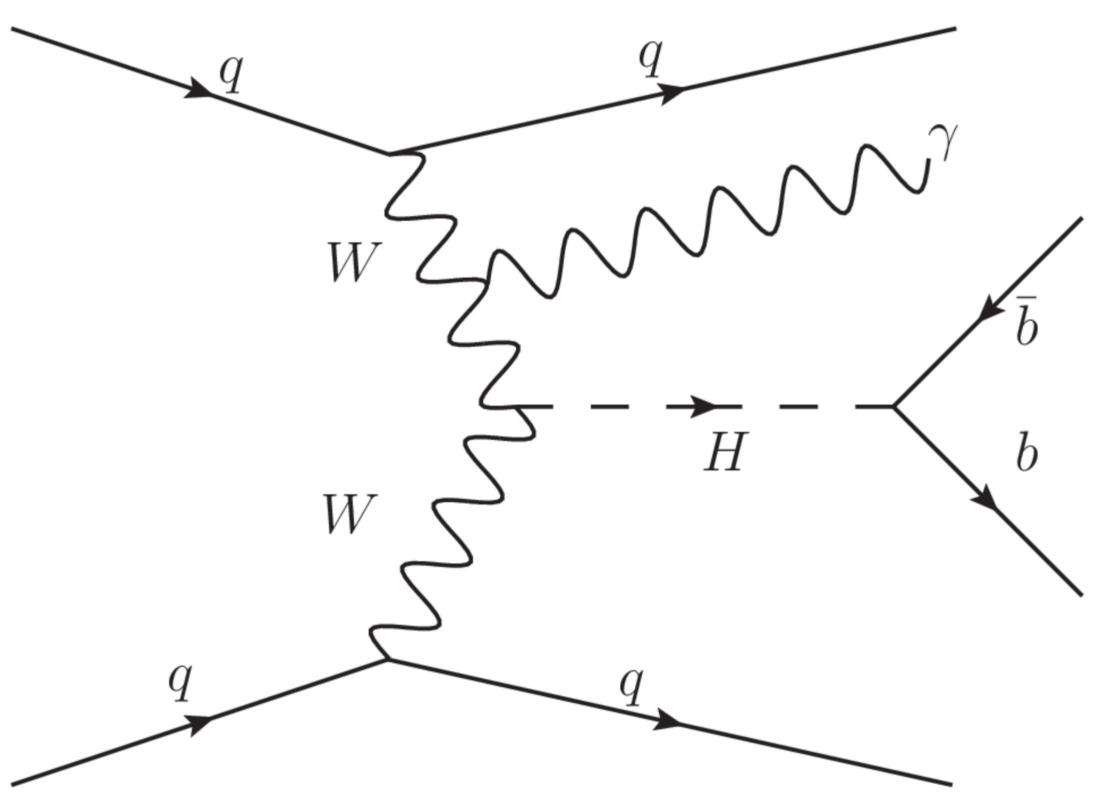


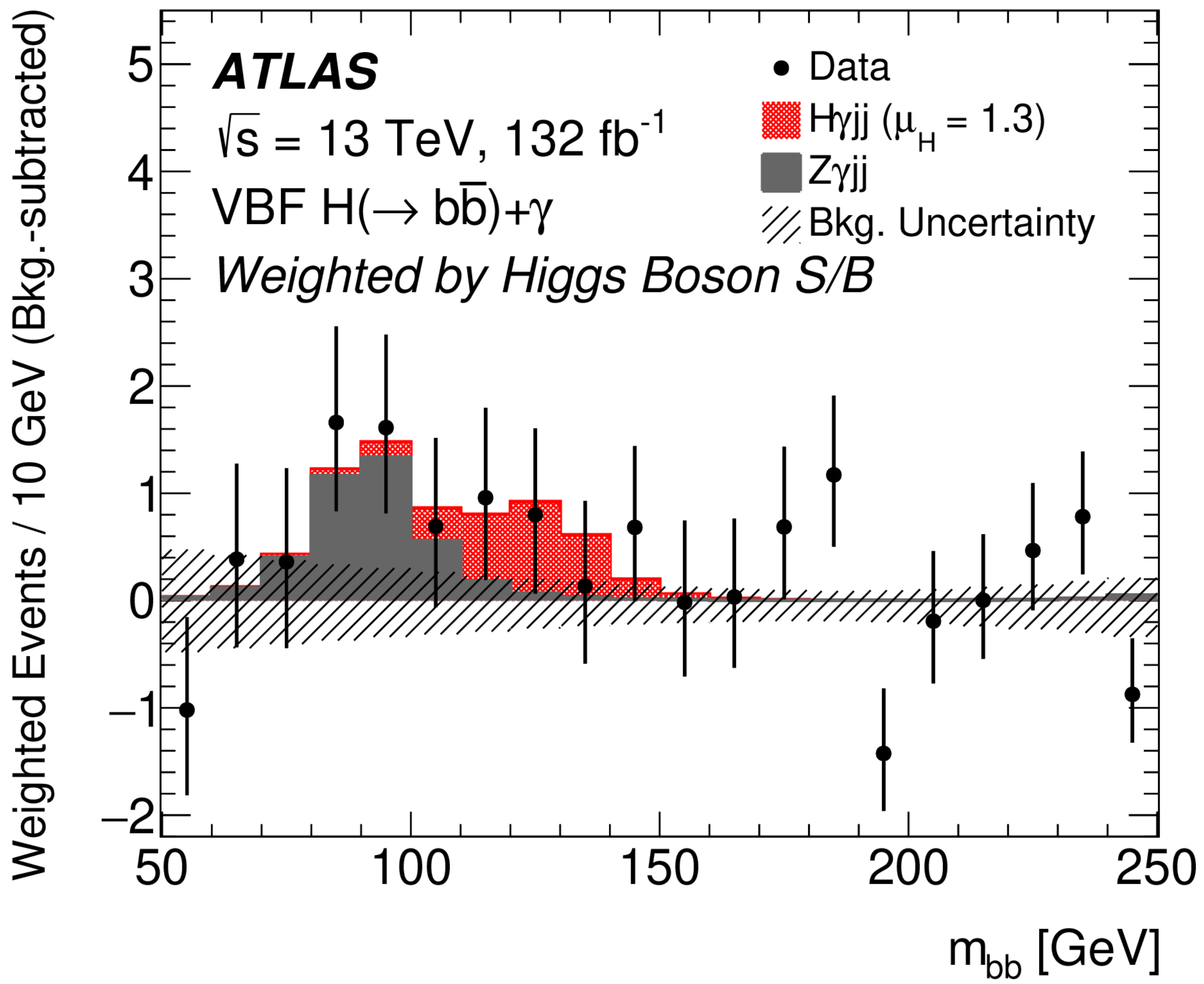
VBF H→bb

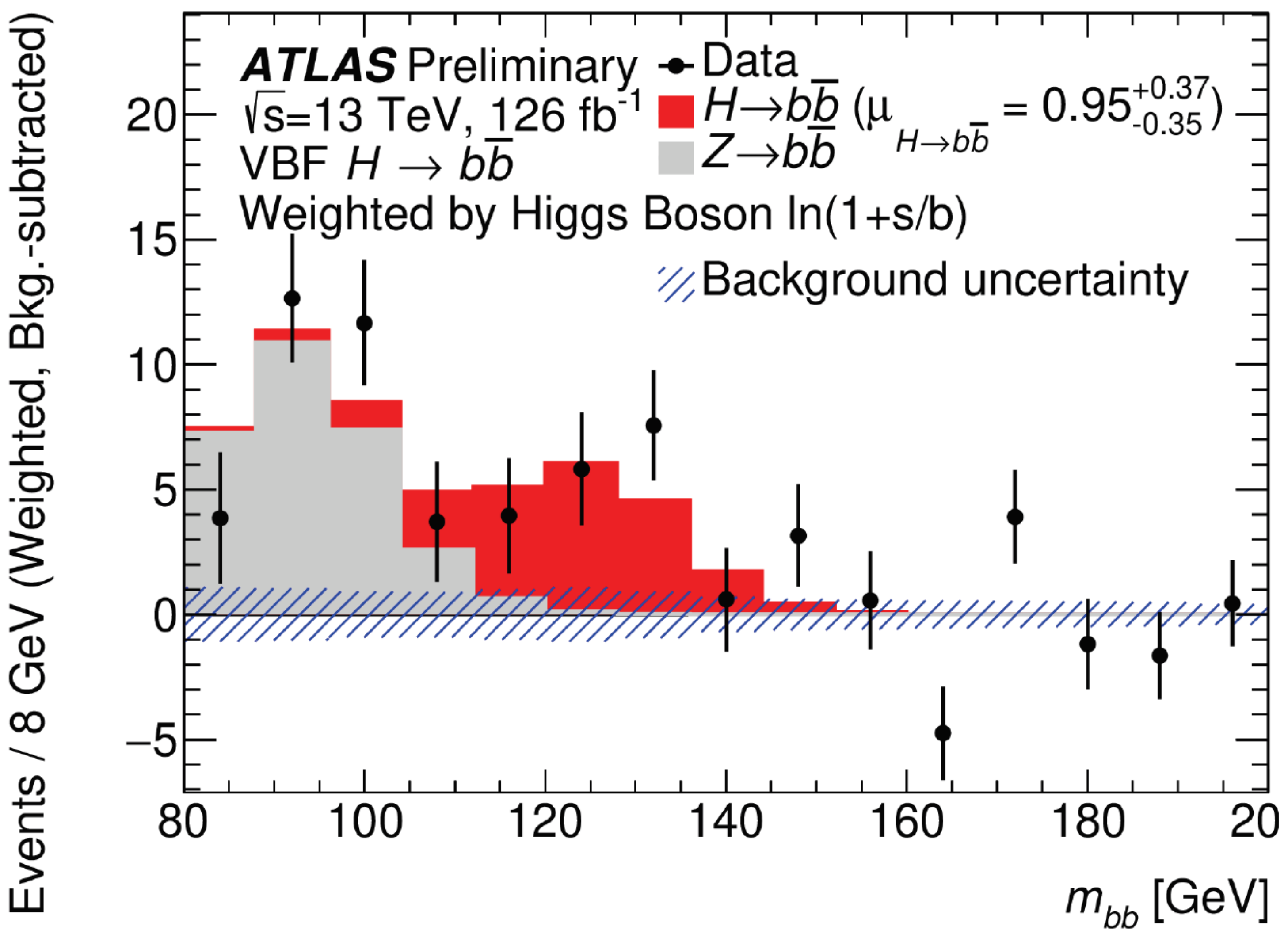
- Full Run2 results from ATLAS this summer
- VBF H→bb+γ:

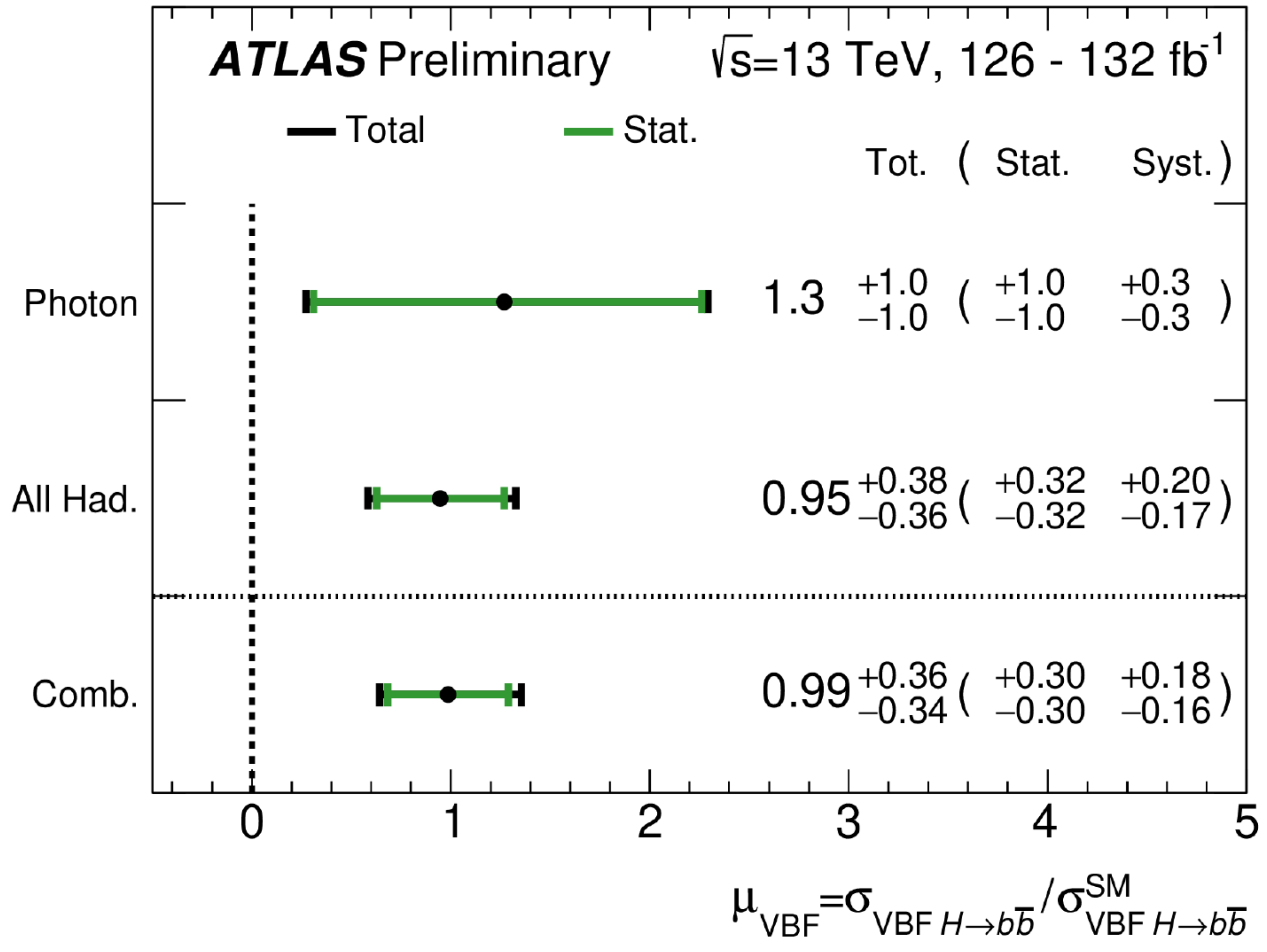
See more details from Bo LIU's talk (IHEP)

  - Unique probe of VBF with W-boson fusions
  - Trigger with photons; train BDT to define three regions with different S/B; fit on m(bb)
  - Measure the signal strength as 1.3 +/- 1.0, with a local significance of 1.3σ
- VBF H→bb:
  - Trigger with jets; train NN and define regions; fit on m(bb)
  - Measure the signal strength as 0.95 +0.37 –0.35
- A combination of VBF H→bb and VBF H→bb+γ reaches a local significance of 3.0σ









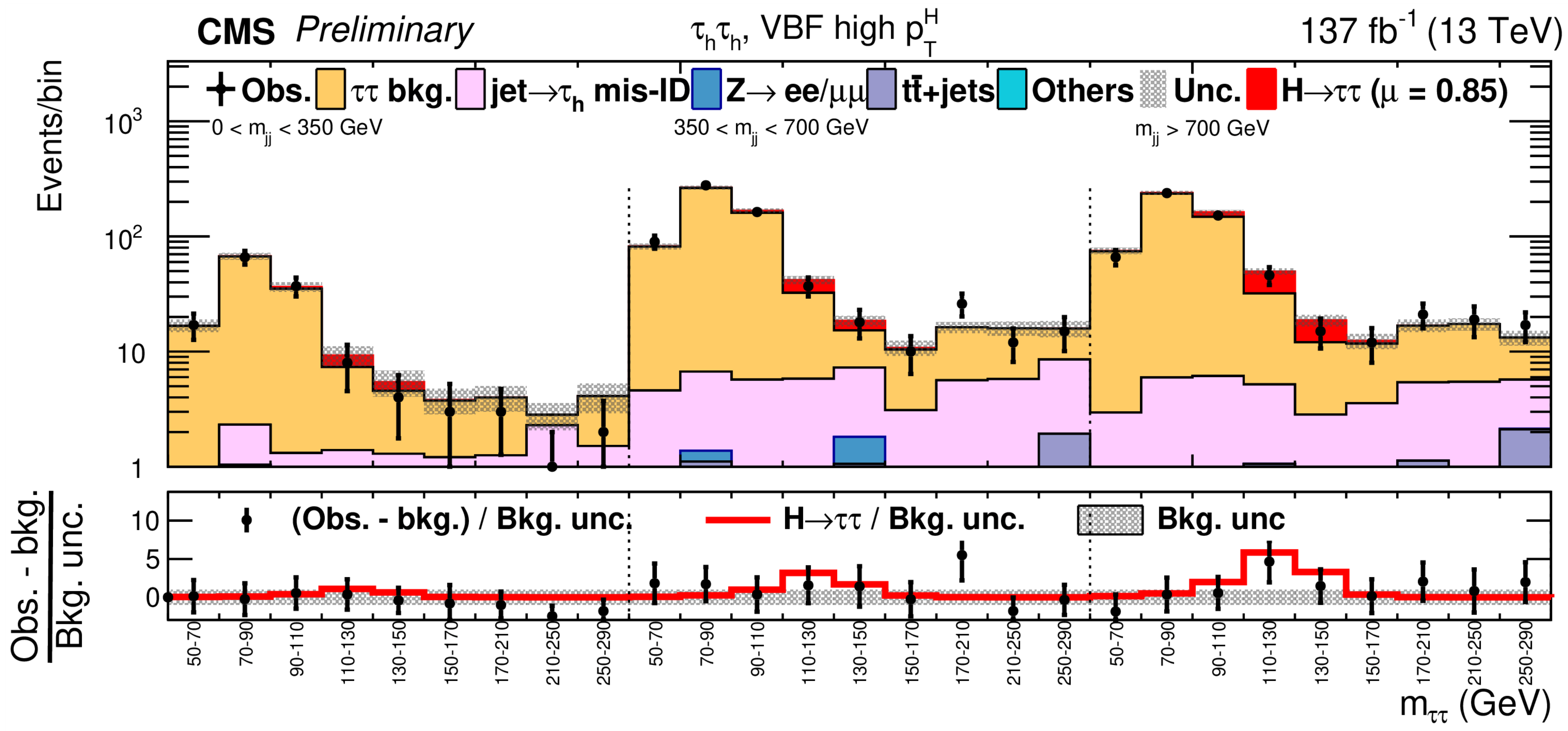
Recent H→ττ studies

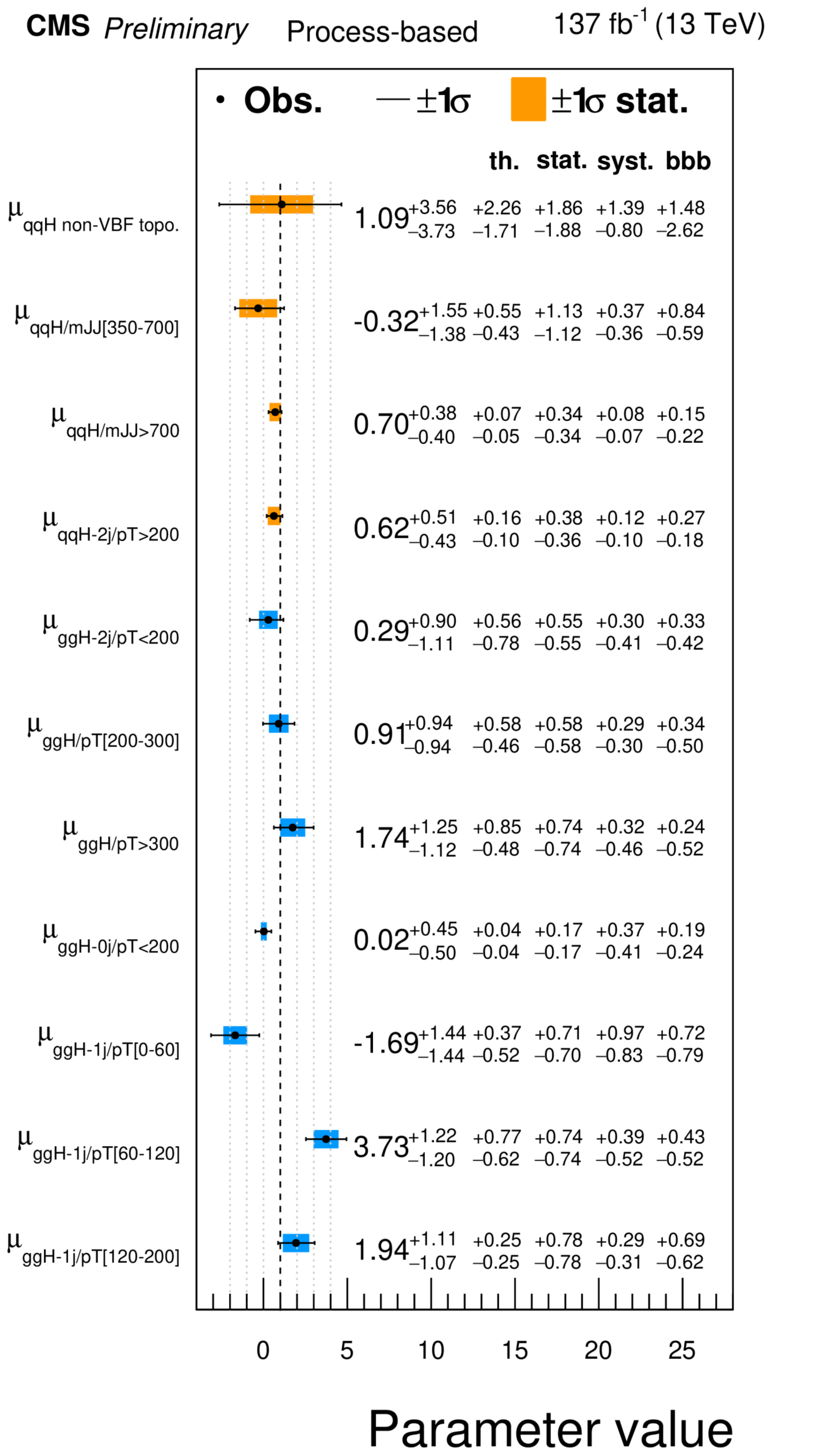
- ATLAS Early Run2 dataset
  - XS HIGG-2017-07, 1811.08856, Phys. Rev. D 99 (2019) 072001
  - CP HIGG-2018-14, 2002.05315, Phys. Lett. B 805 (2020) 135426
- CMS Full Run2 data
  - XS HIG-19-010, CMS-PAS-HIG-19-010
  - CP HIG-20-006, CMS-PAS-HIG-20-006
- Limited by the time, talk about full Run2 H→ττ studies here

H→ττ XS

CMS-PAS-HIG-19-010

- New in this summer. Focus on eμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Define 3 categories to target the different production modes: 0-jet (no jets present in event), VBF (at least 2 jets + m(jj) or |Δη(jj)| cuts), boosted
- Split into sub-categories to accommodate specific STXS bins
- Fits to m(ττ) in bins of m(jj) or $p_T(H)$ or $p_T(l\tau_h)$
- Measure signal strength, STXS. Agree well with SM





H→ττ CP properties

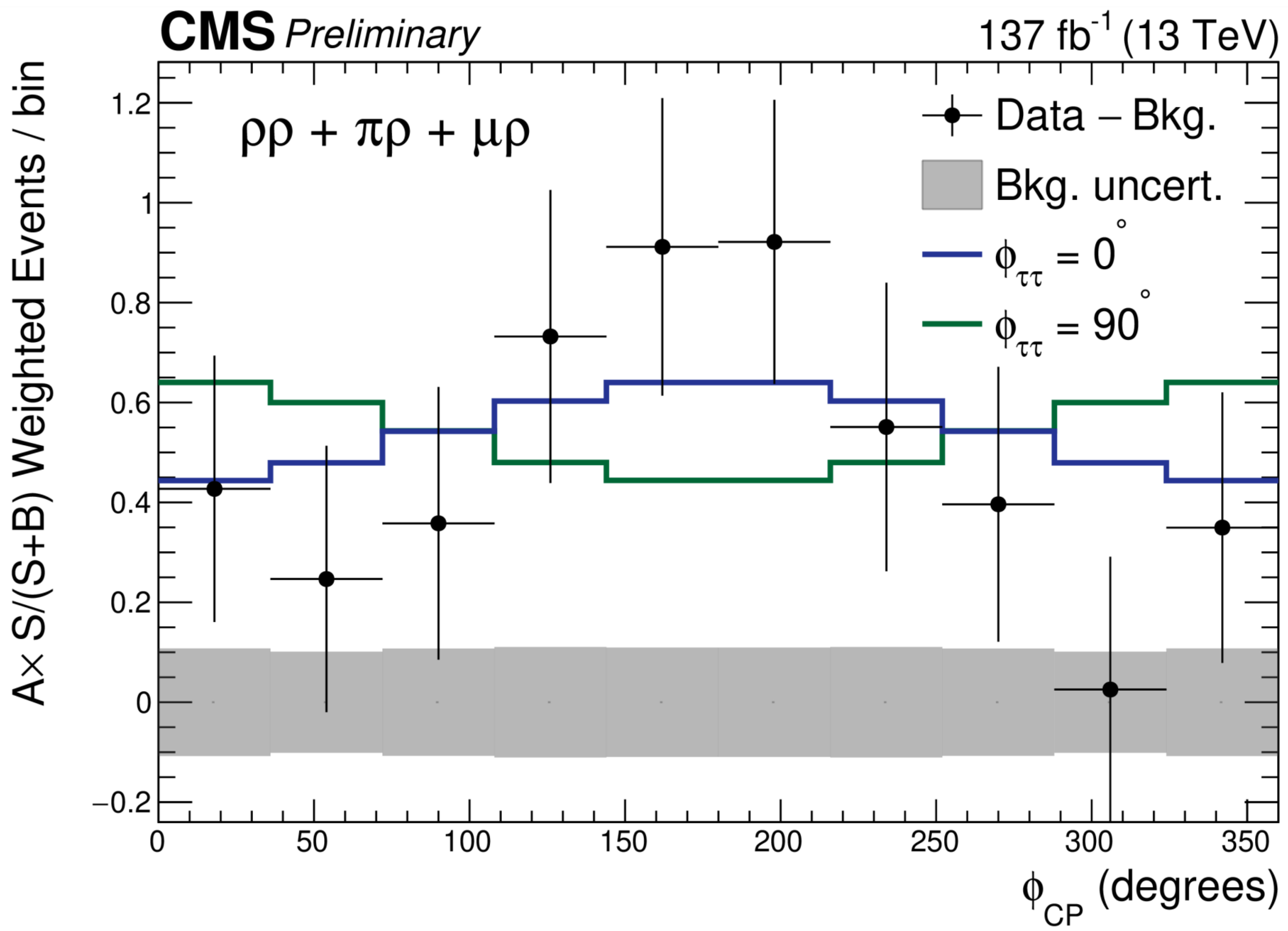
CMS-PAS-HIG-20-006

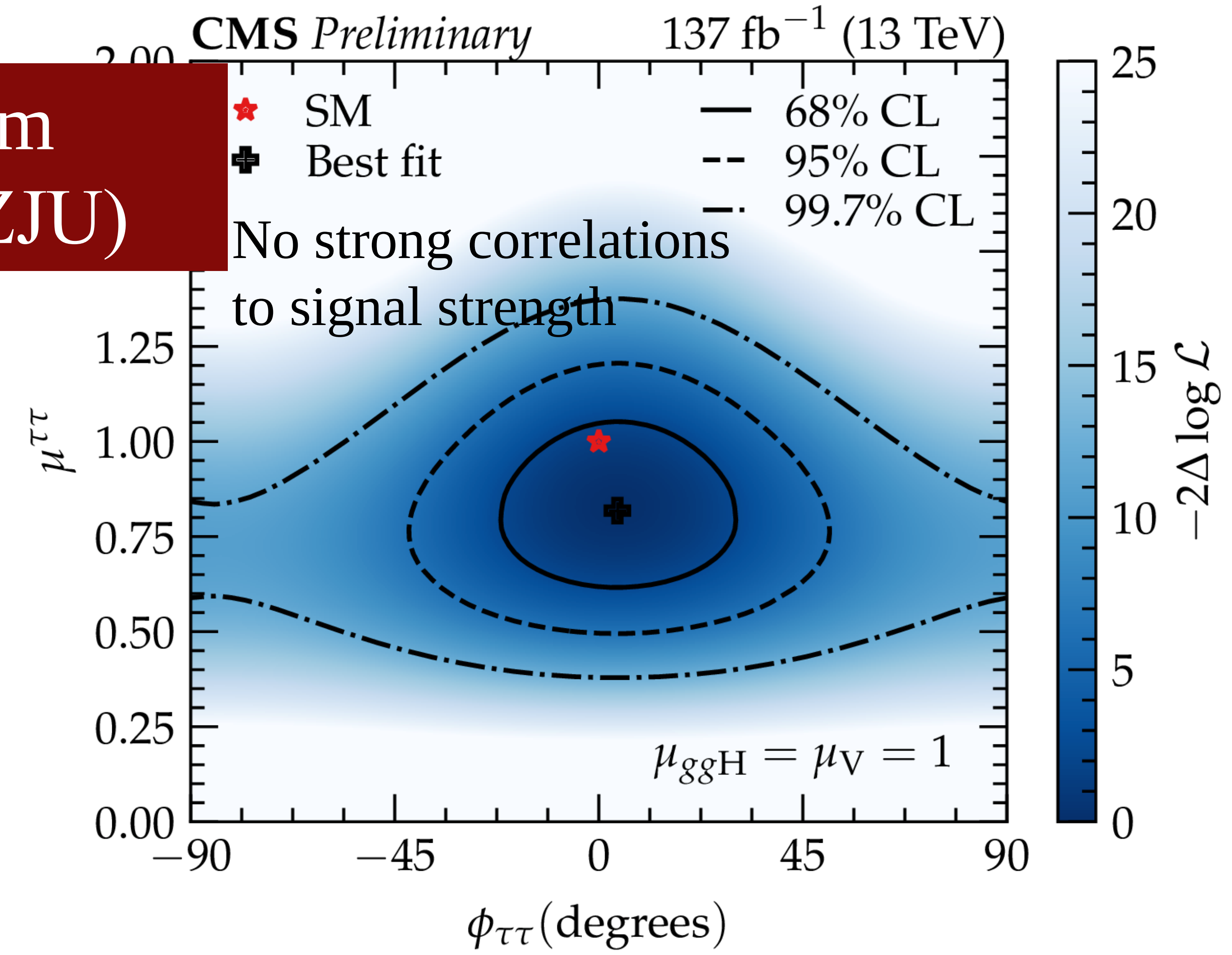
- New in this summer. Long history of CP studies using HVV, first studies using ttH done, and now complementary measurements using H→ττ
- CP-even: $|\Phi_{\tau\tau}|=0^o$, CP-odd: $|\Phi_{\tau\tau}|=90^o$, CP-mix: $0^o<|\Phi_{\tau\tau}|<90^o$
- Angle between τ decay planes in Higgs rest frame, Φ_{CP}, sensitive to $\Phi_{\tau\tau}$
- Measured value of $\Phi_{\tau\tau}$ is 4 ±17^o
- CP-odd exclusion at 3.2σ (2.3σ)
  - CMS ttHγγ gave 3.2σ
  - ATLAS ttHγγ gave 3.9σ

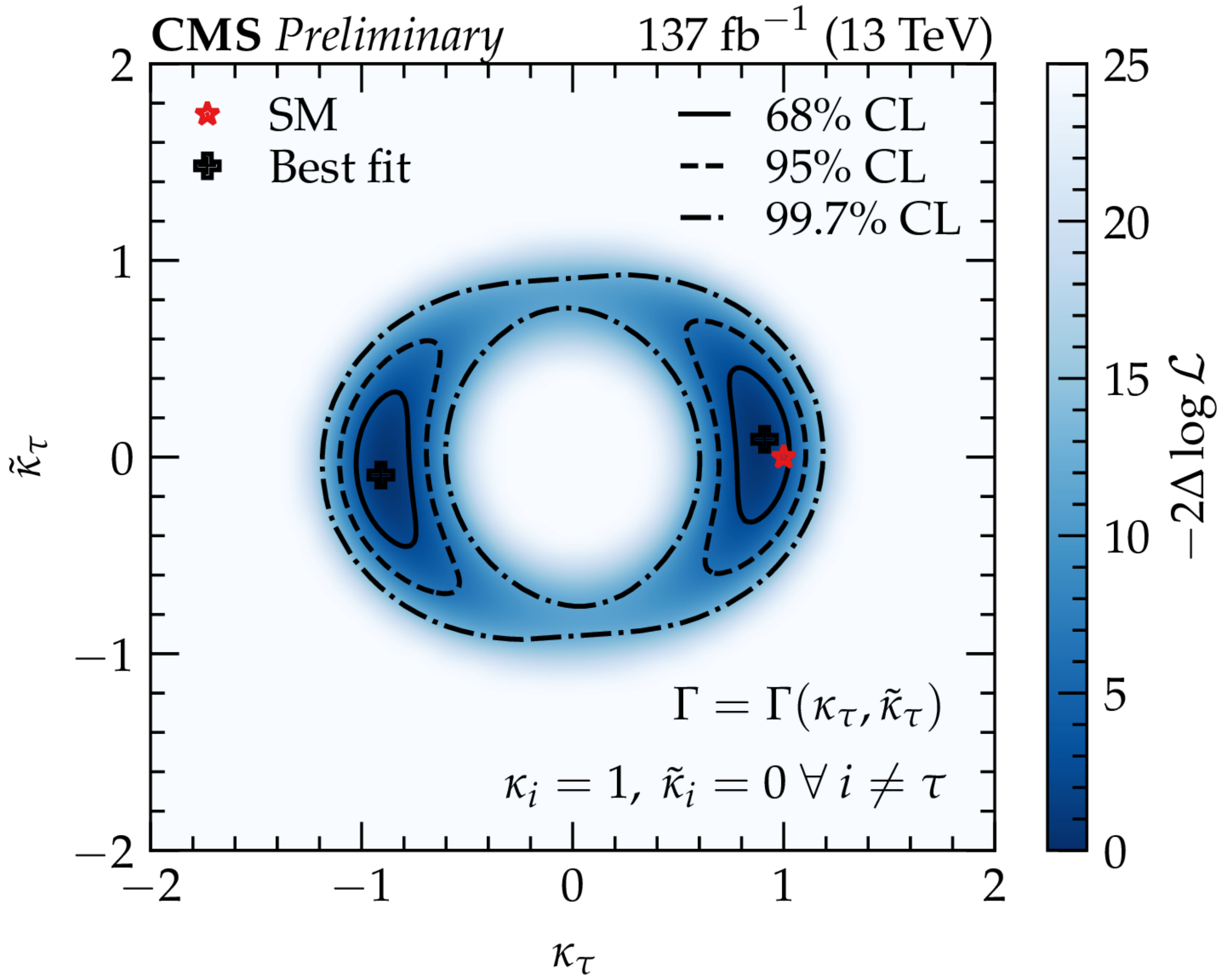
See more details from Renqi PAN's talk (ZJU)

$$\mathcal{L}_Y = -\frac{m_\tau}{v}\kappa_\tau\bar{\tau}\tau + \tilde{\kappa}_\tau\bar{\tau}i\gamma_5\tau$$

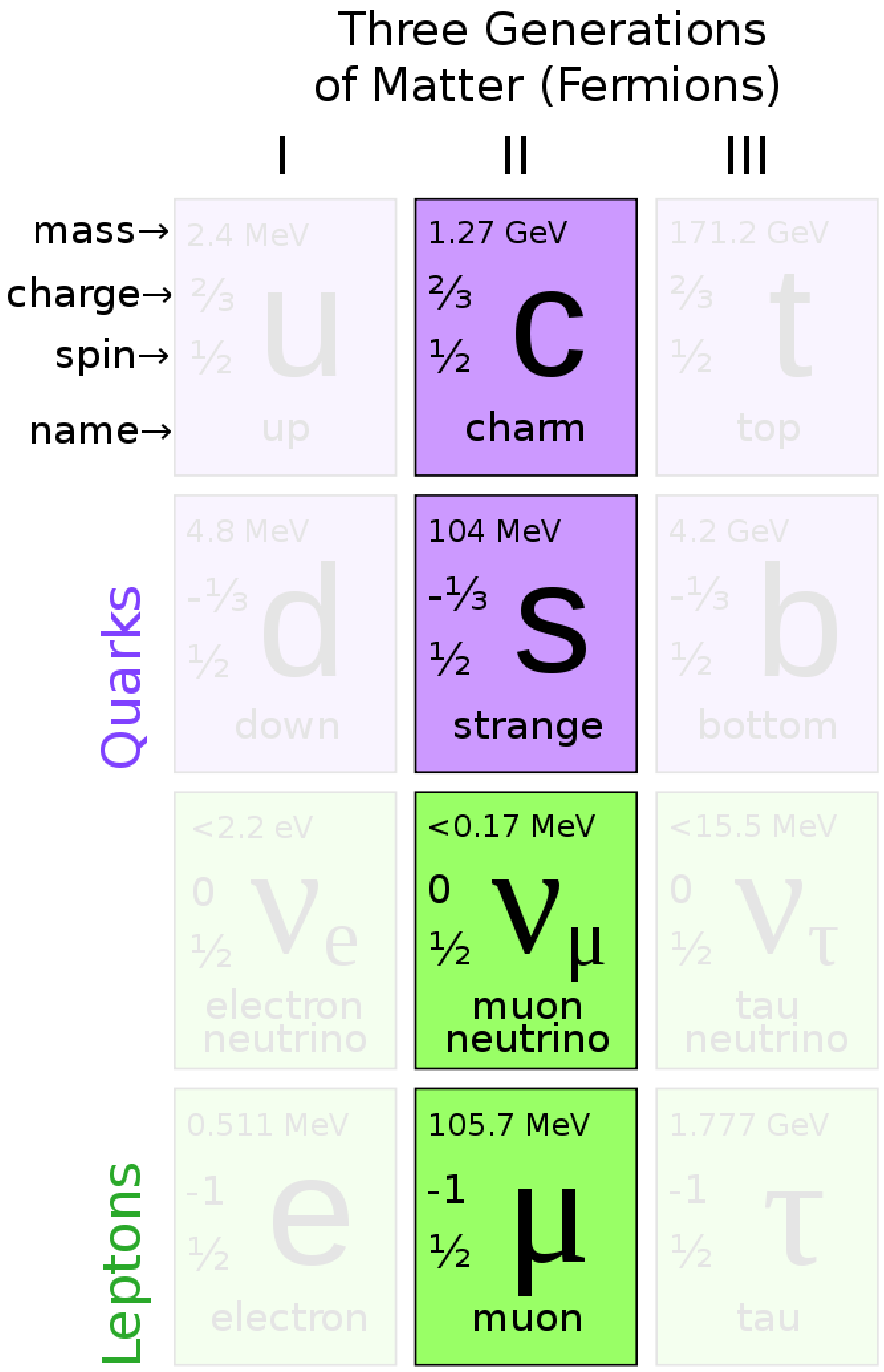
$$\tan\phi_{\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$







The fit is only sensitive to the rel. signs



- The second generation with possible decay channels
  - $H \to cc$
  - $H \to \mu\mu$
  - …

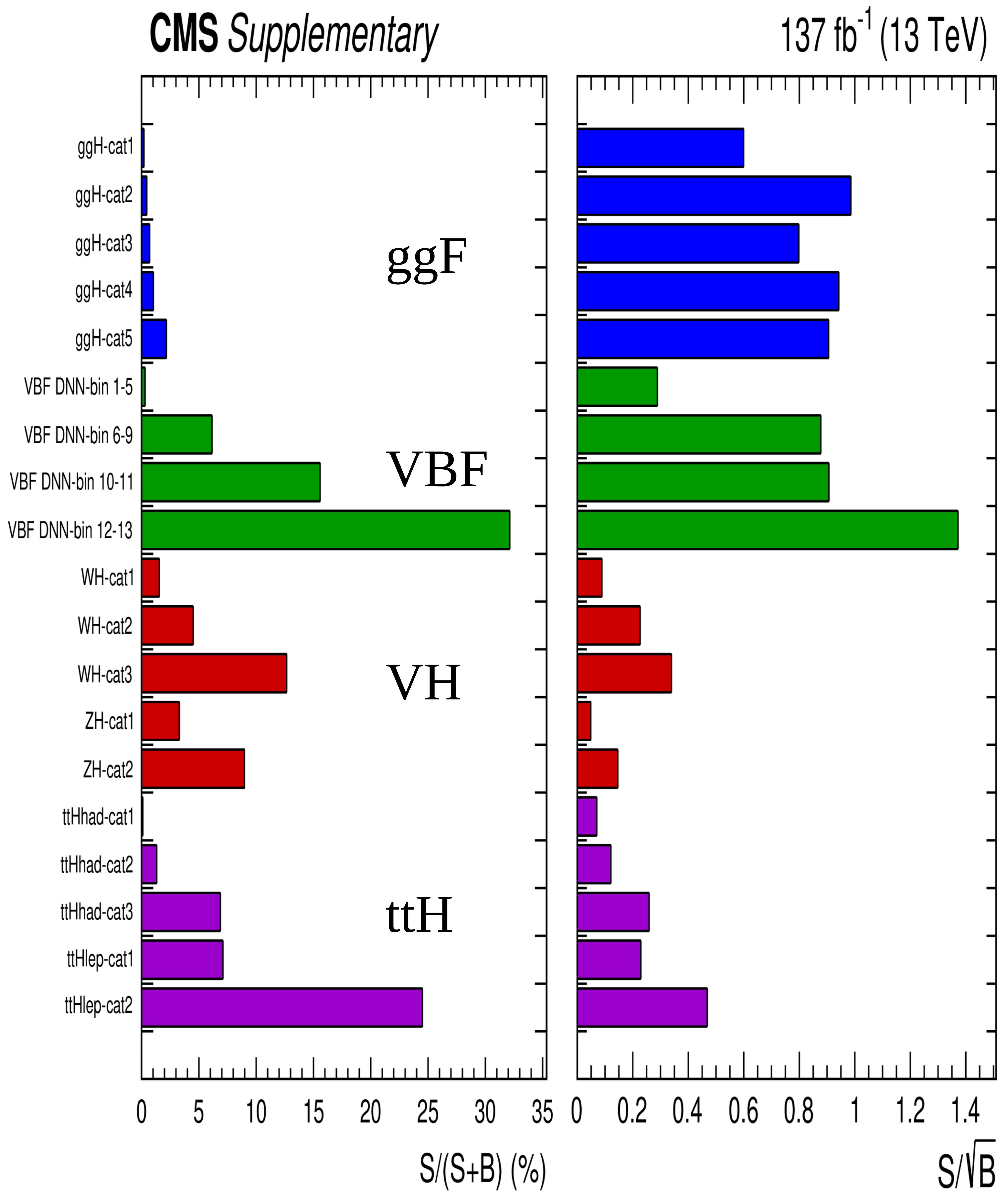
Recent H→μμ studies

- ATLAS Full Run2 data
  - HIGG-2019-14, 2007.07830

- CMS Full Run2 data
  - HIG-19-006, 2009.04363

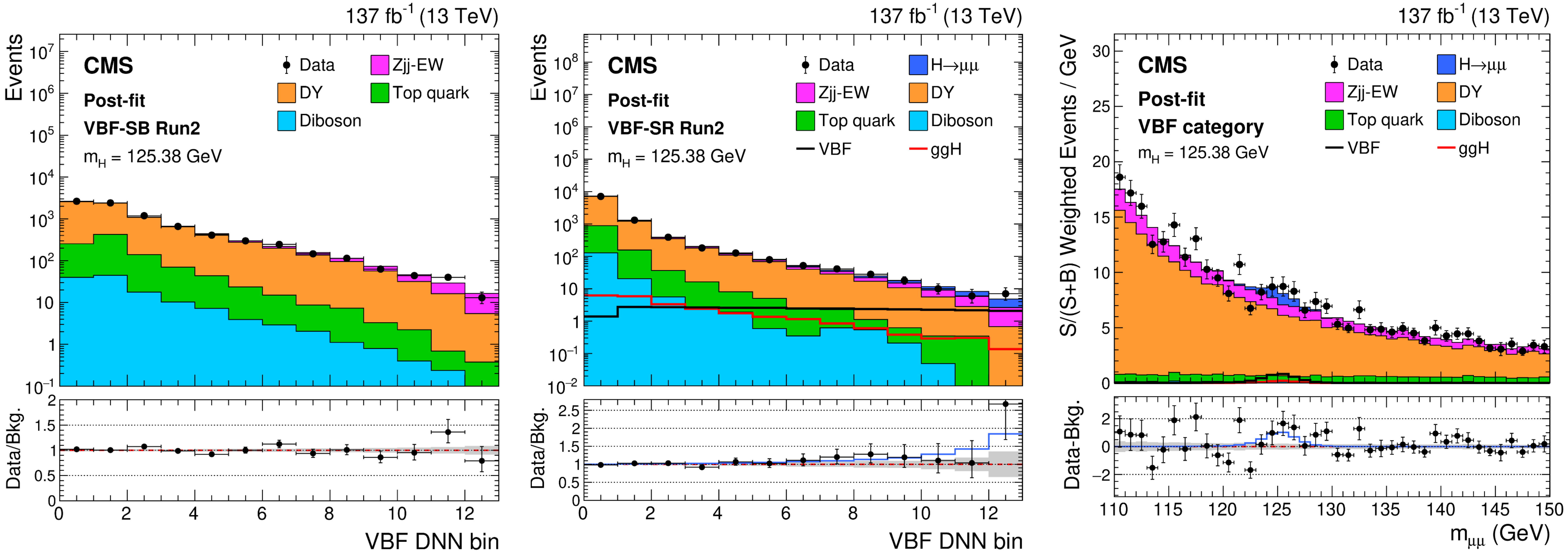
CMS H→μμ

- Single muon triggers
- Mass range: 110 < m(μμ) < 150 GeV
  - Signal region: 115 < m(μμ) < 135 GeV
  - Side band: the rest
- Selected events for smaller production modes first in such a sequence
  1. ttH categories: 1 medium or 2 loose bjets, additional e/μ for ttH(lep), otherwise for ttH (had)
  2. VH categories: no bjet, 1 additional e/μ for WH, while 2 for ZH
  3. VBF categories: no bjet, no additional lepton, m(jj) > 400 GeV, Δη(jj) > 2.5
  4. ggF categories: no bjet, no additional lepton, not VBF



CMS H→μμ: VBF

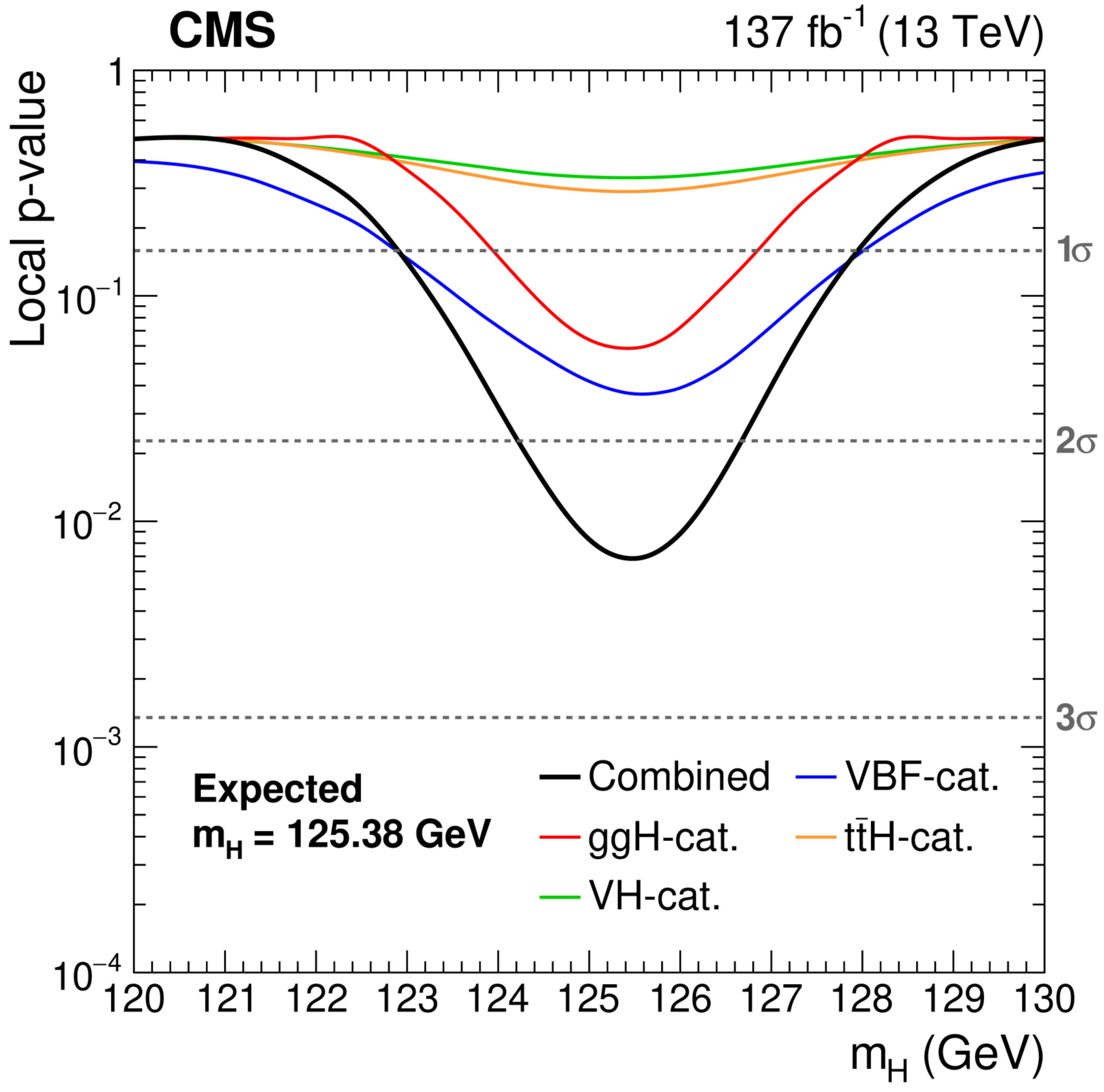
- No bjet, no additional lepton
- m(jj) > 400 GeV
- |Δη(jj)| > 2.5
- Fit on DNN score directly while all other production modes fits on m(μμ) in multiple categories

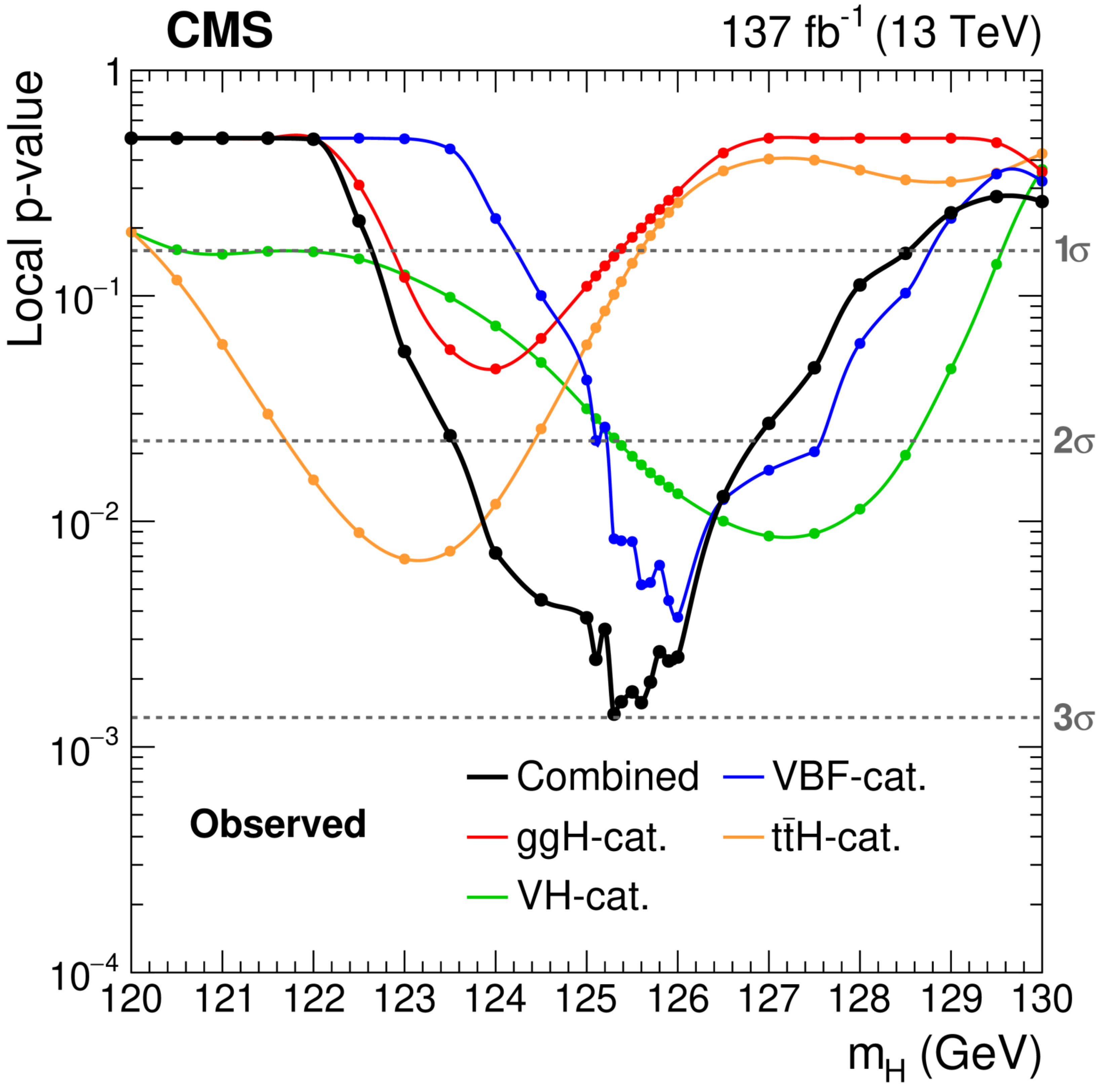


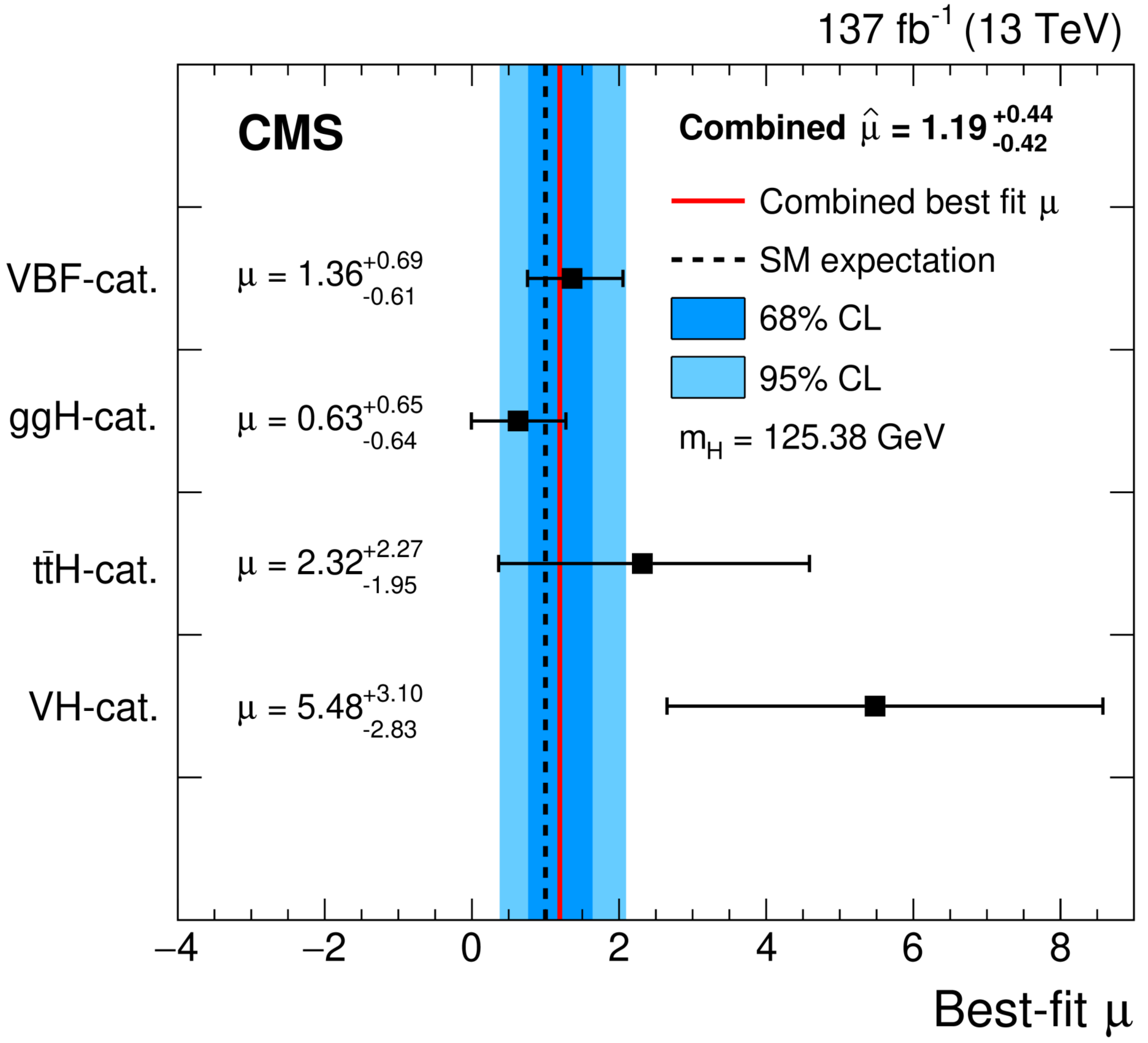
- Inputs from H
  m(μμ), di-muon p_T & rapidity, decay angles ϕ_{CS}, $\cos\theta_{CS}$ etc.
- Inputs from VBF jets
  m(jj), Δη(jj), Δϕ(jj), min-Δη(H, j) , min-Δϕ(H, j), Zeppenfeld variable, pT-balance(H, jj)
- Inputs due to low hadronic activity in η-gap
  number & H_T of soft jets used as DNN inputs etc.

Combined VBF:
Signal strength $\mu = 1.36^{+0.69}_{-0.61}$
Obs (exp) significance 2.4σ (1.8σ)

CMS H→μμ: results







Production category	Observed (expected) signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
$t\bar{t}$H	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13$ TeV	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7, 8, 13$ TeV	2.98 (2.48)	1.93 (0.81)

Obs (exp) significance 3.0σ (2.9σ)

Signal strength $1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})$

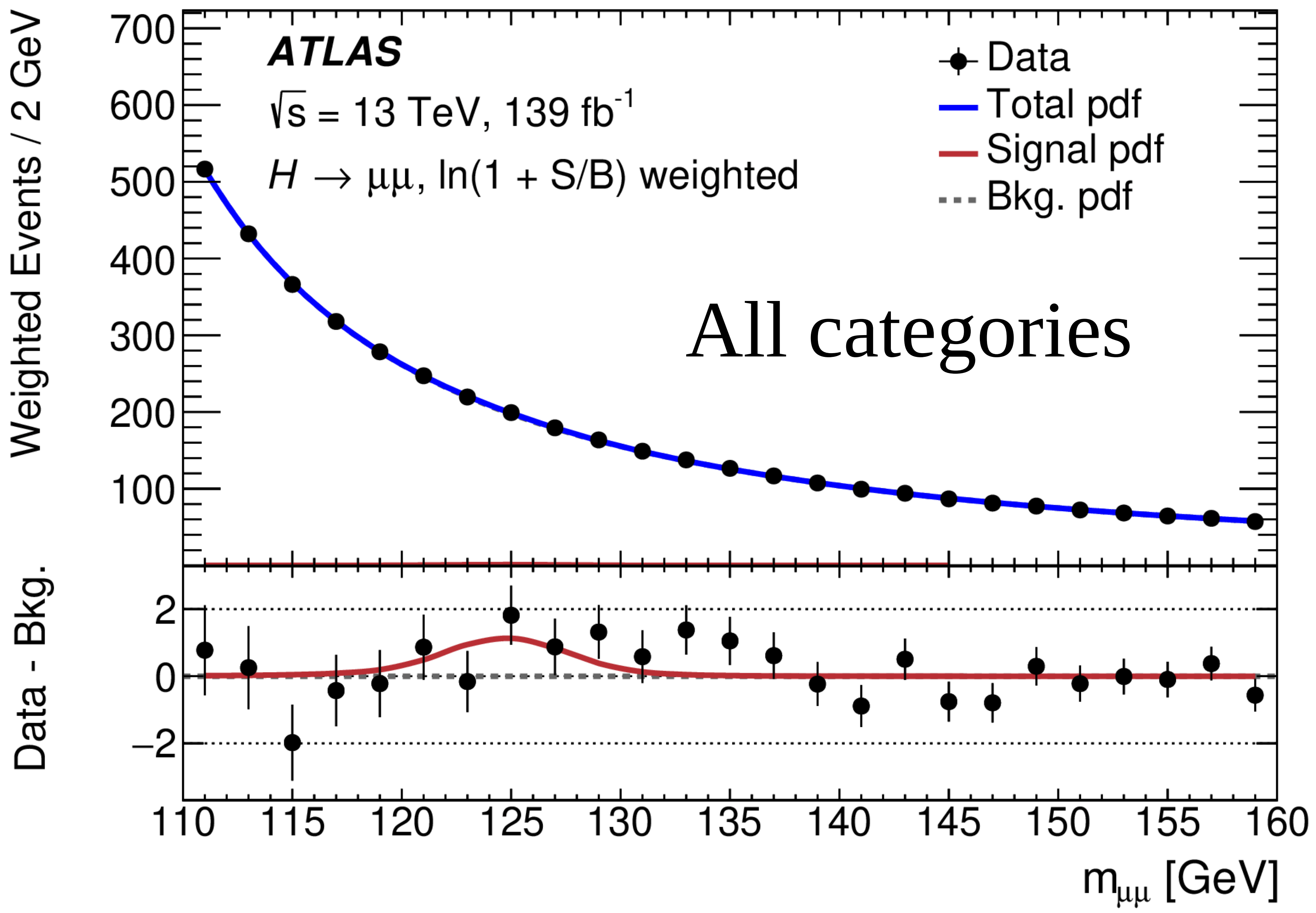
The evidence of Higgs decaying to a pair of muons is observed

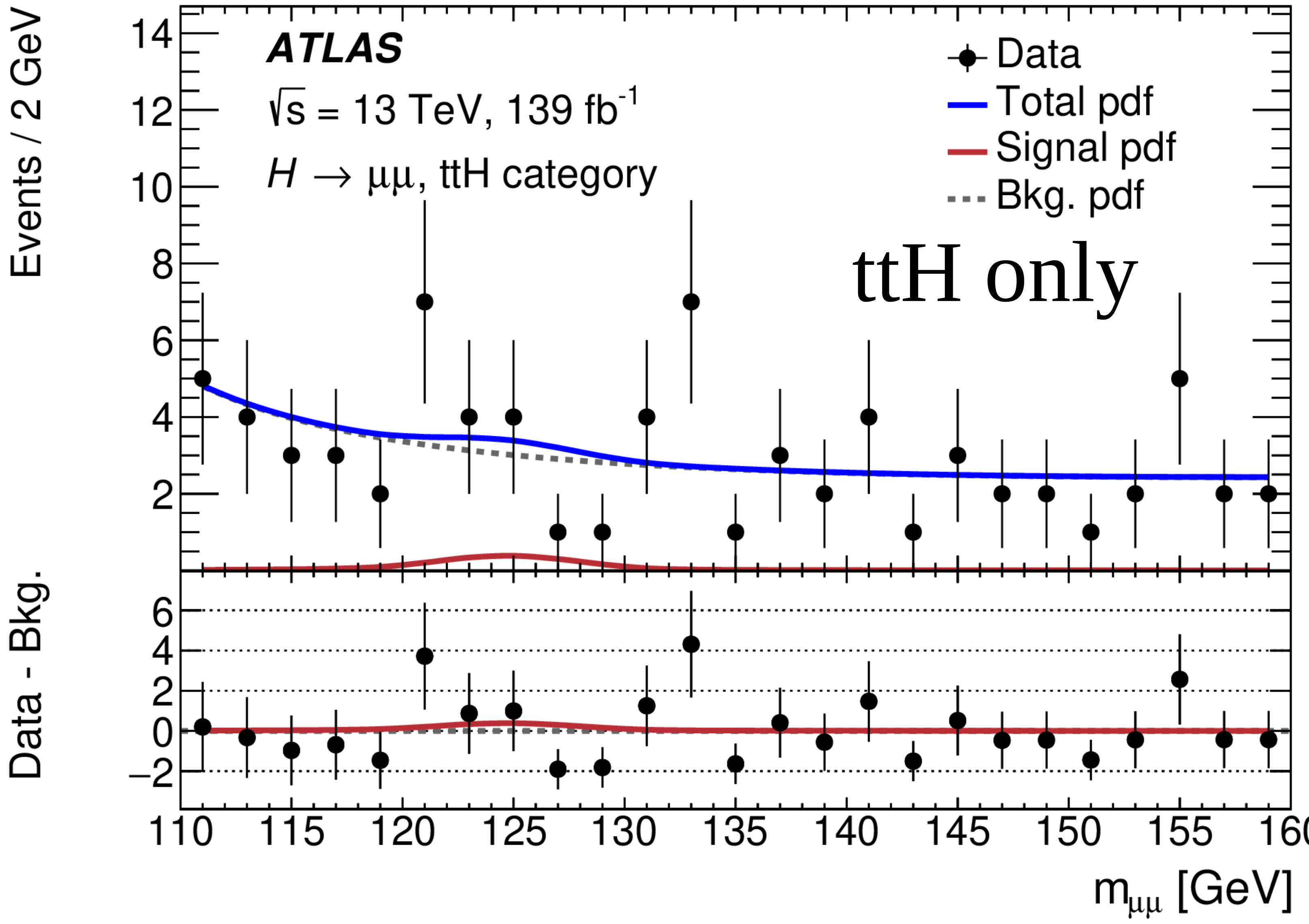
ATLAS H→μμ

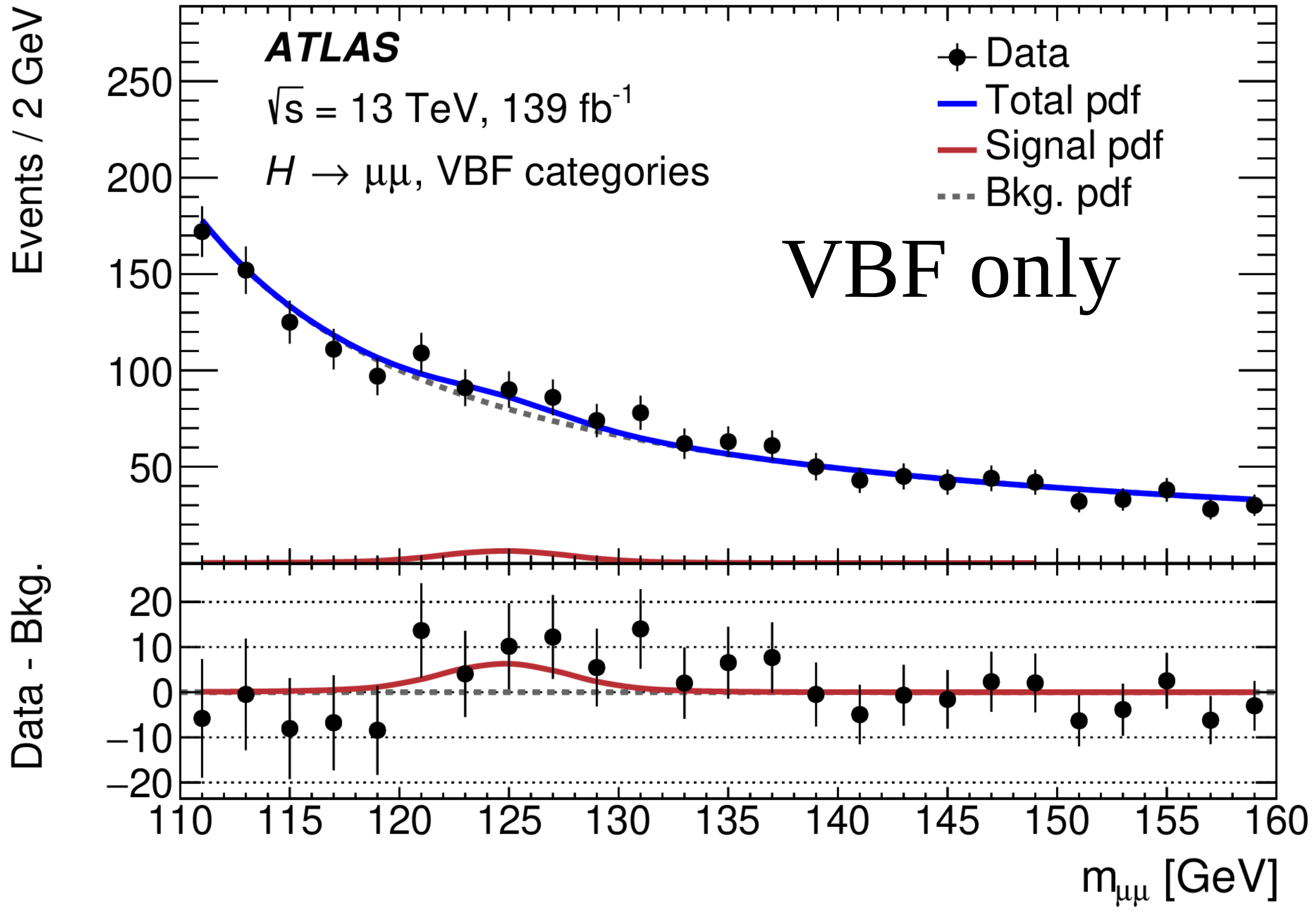
2007.07830

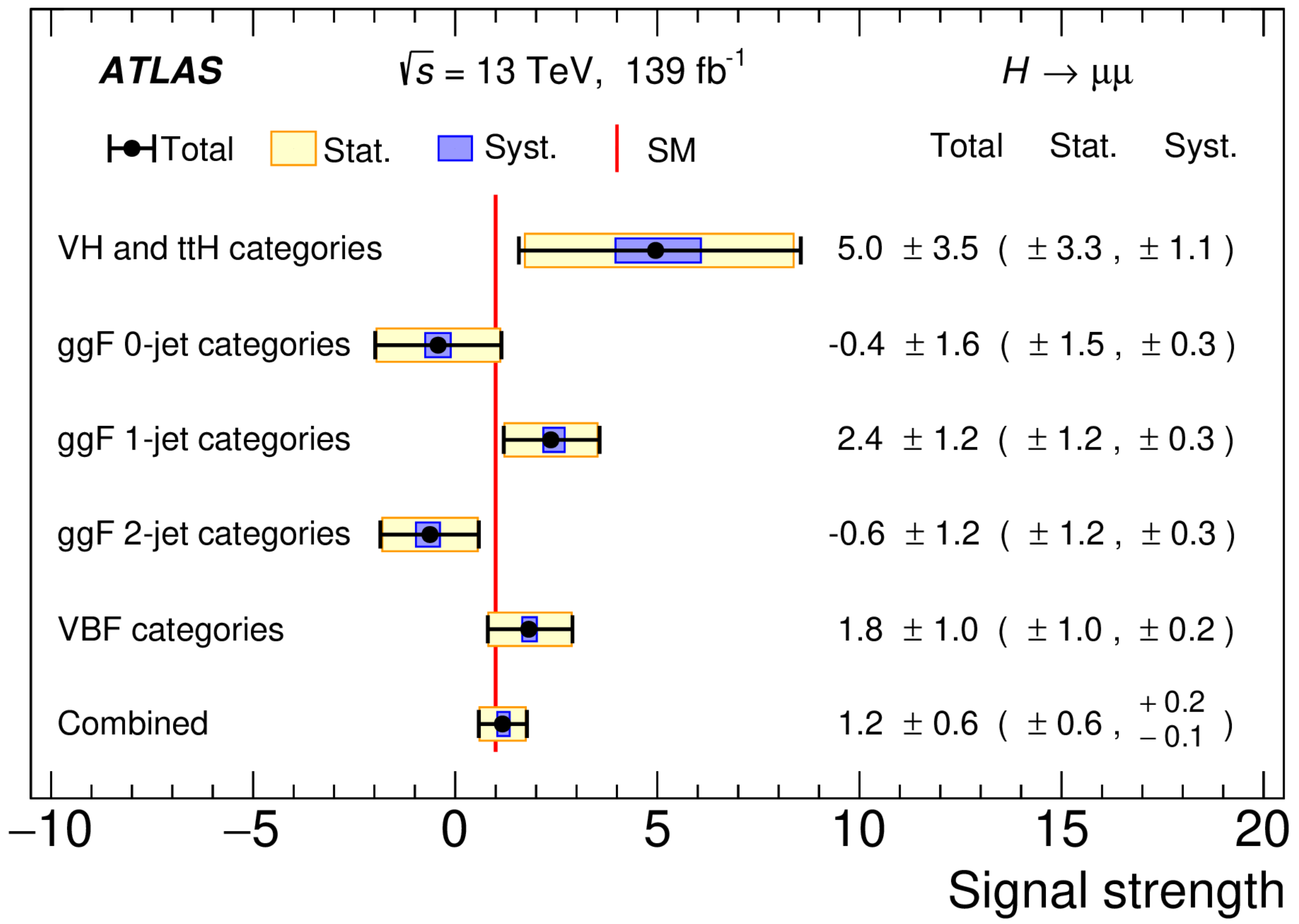
- Similar strategy as CMS
- Categorize events with MVA scores
- Fit on m(μμ) in all categories
- Obs (exp) significance is 2.0σ (1.7σ)
- Signal strength is 1.2 +/- 0.6

For more details, please follow Jie ZHANG's talk (SDU)









Recent H→cc studies

- ATLAS Early Run2 dataset
  - VH→cc, HIGG-2017-01, 1802.04329

- CMS Early Run2 dataset
  - VH→cc, HIG-18-031, 1912.01662

H→cc

PhysRevLett.120.211802
JHEP03(2020)131

- Very challenge: small BR, high background level, broad energy resolution (c-jet), difficult charm tagging …
- A general strategy is to use VH with lepton triggers and heavily apply ML techniques

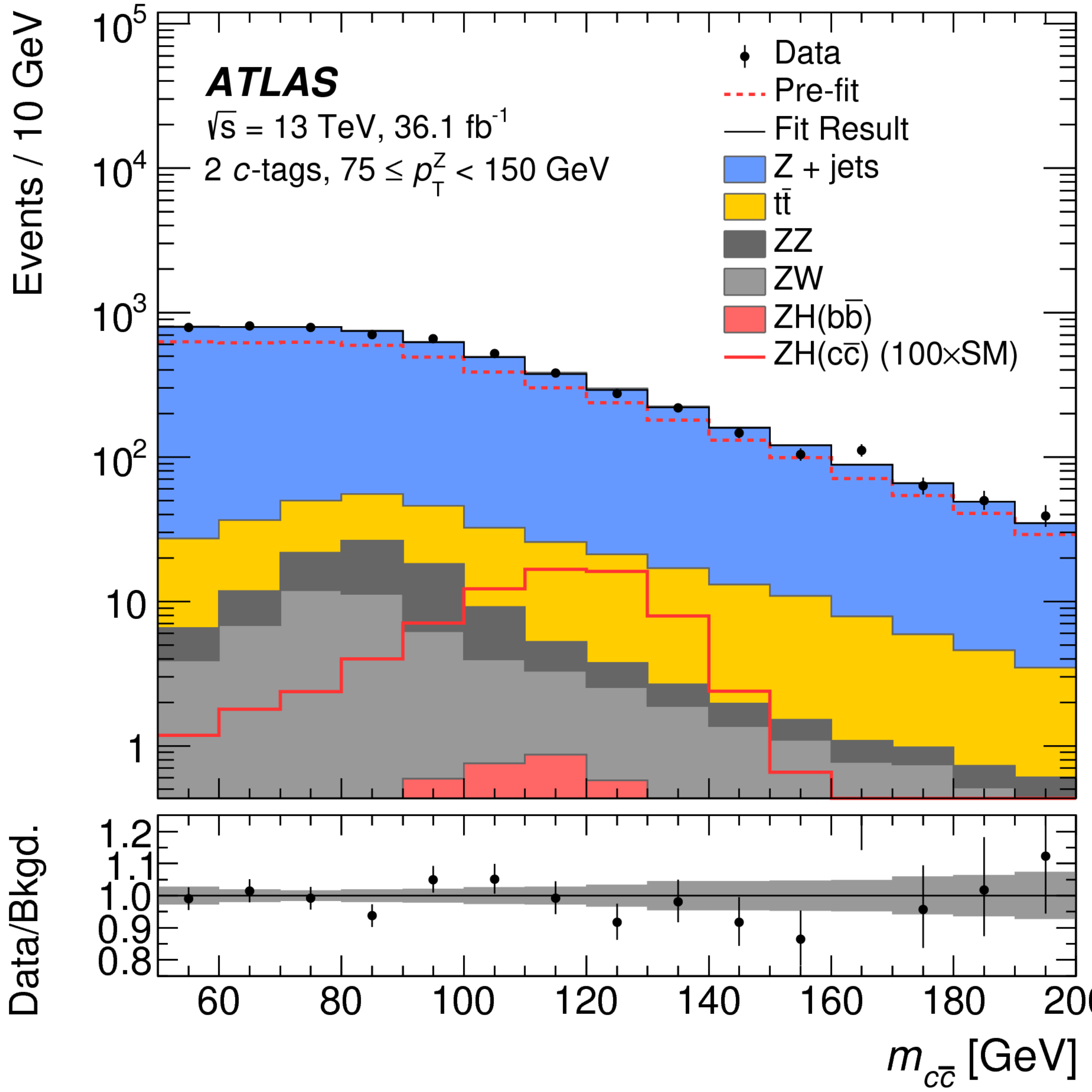
ATLAS: ZH→llcc
Two same-flavor leptons
Two R=0.4 resolved c-jets
Categories: 1,2 c-tag and pTZ split at 150 GeV

Simultaneous fit to m(cc) in 4 categories

Two BDT
41% c-tagging eff
5% l-jet mistag rate
25% b-jet mistag rate

CMS: VH→llcc, vvcc, lvcc
ee, μμ, eν, μν, νν
Two R=0.4 resolved c-jets
Multiple categories for signals and backgrounds separated by c-tagging scores
Simultaneous fit to BDT scores in all categories

DeepCSV (DNN)
28% c-tagging eff
4% l-jet mistag rate
15% b-jet mistag rate

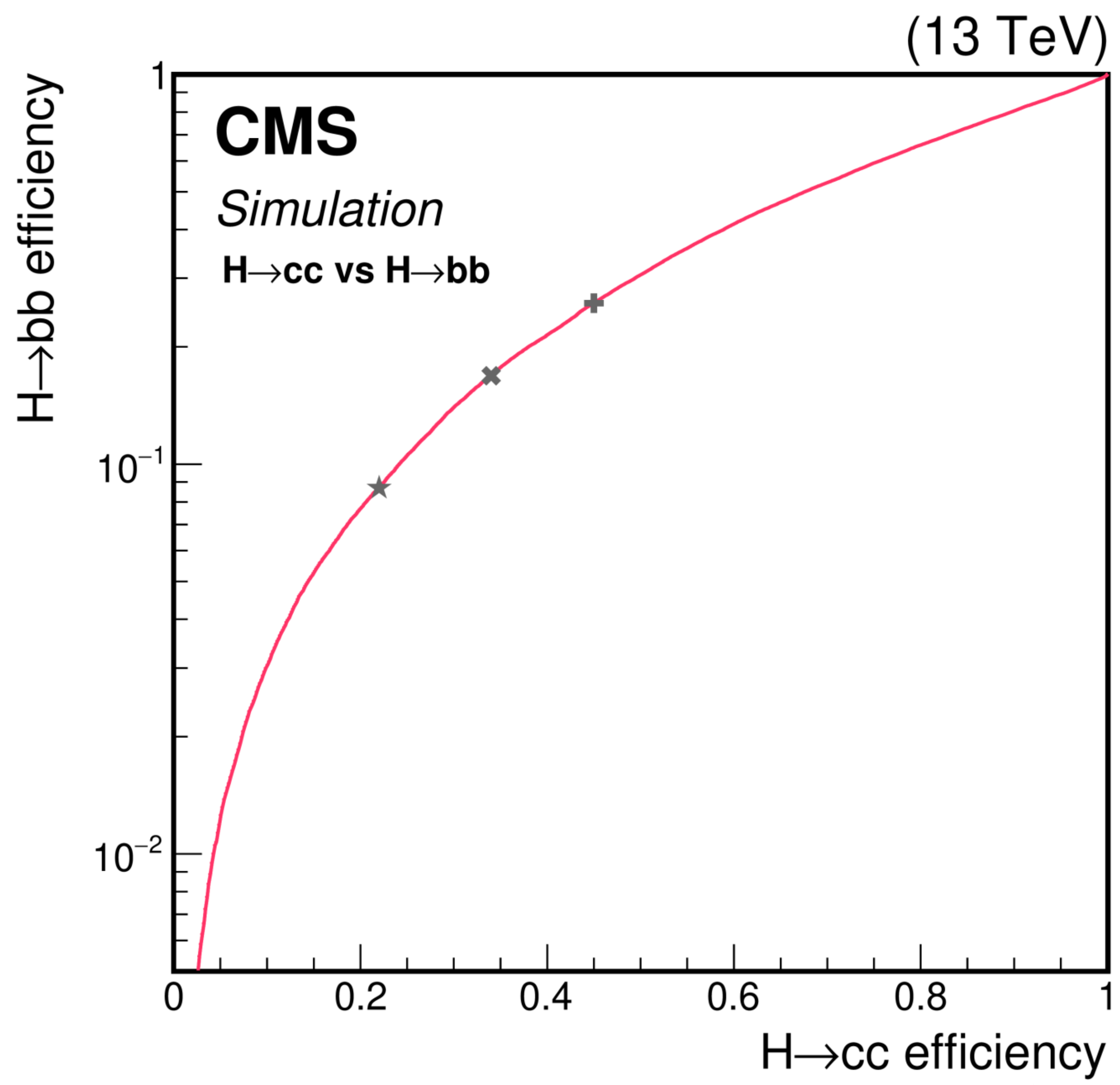


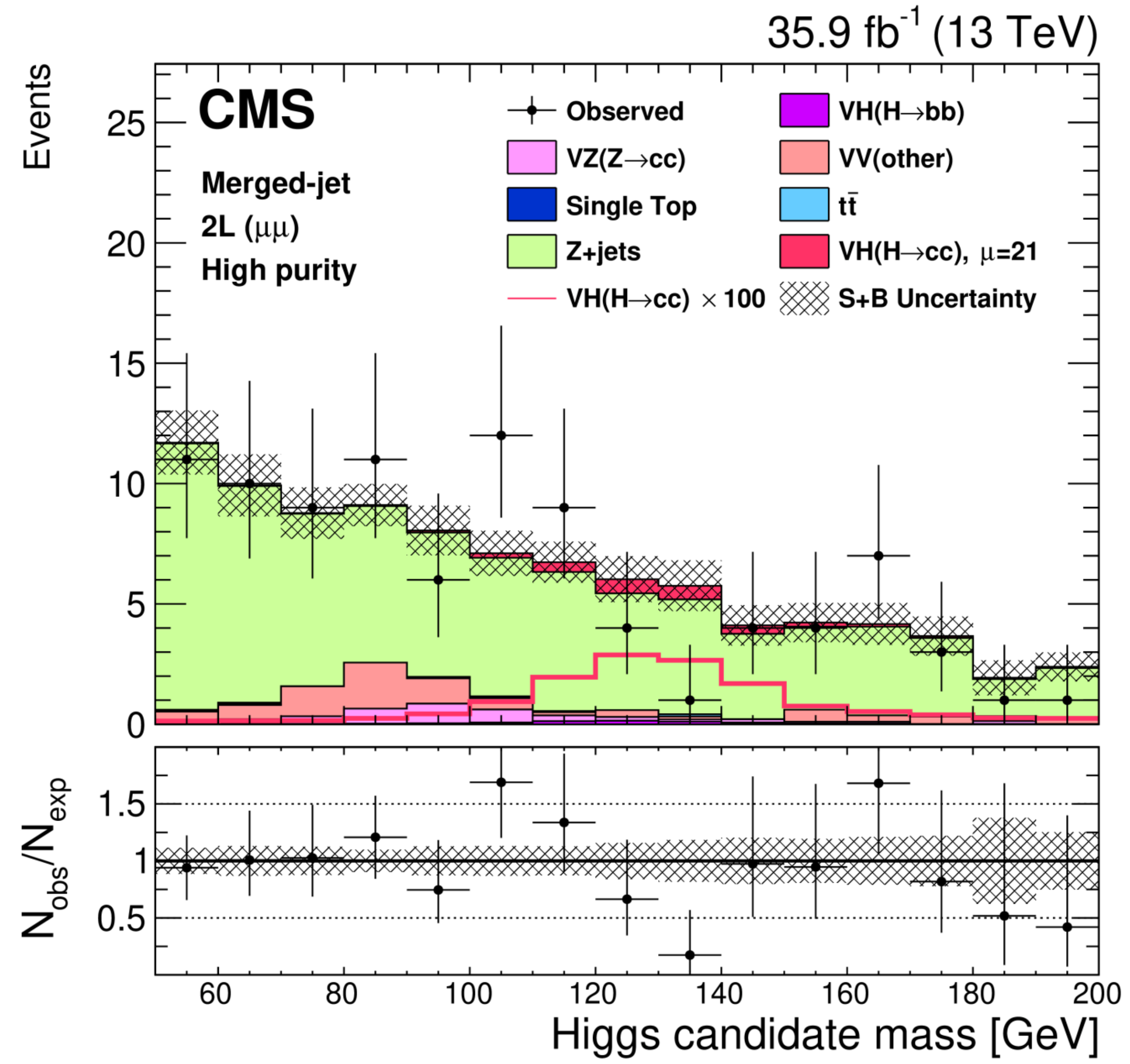
C-tagging performance is crucial, especially in the b-jet rejection

H→cc

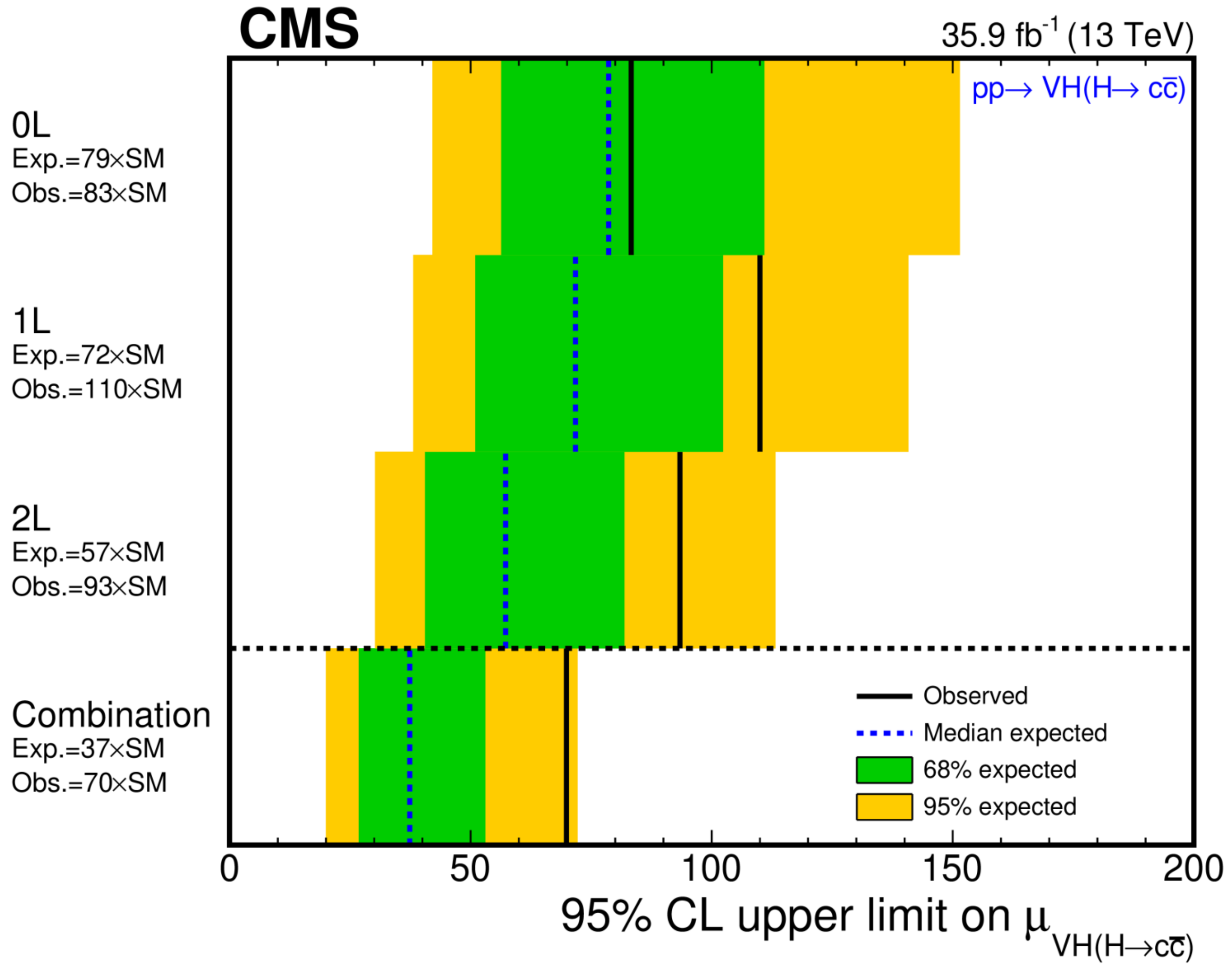
PhysRevLett.120.211802
JHEP03(2020)131

- Special from CMS: merged categories, one R=1.5 merged c-jet, $p_T(V)$ > 200 GeV
- Train DNN to separate H→cc, H→bb, light fat jets, and define three purity categories: cc efficiency 23/35/46%, bb mistag rate 9/17/27%, Vjets mistag rate 1/2.5/5%
- Simultaneous fits to m(H) in all categories

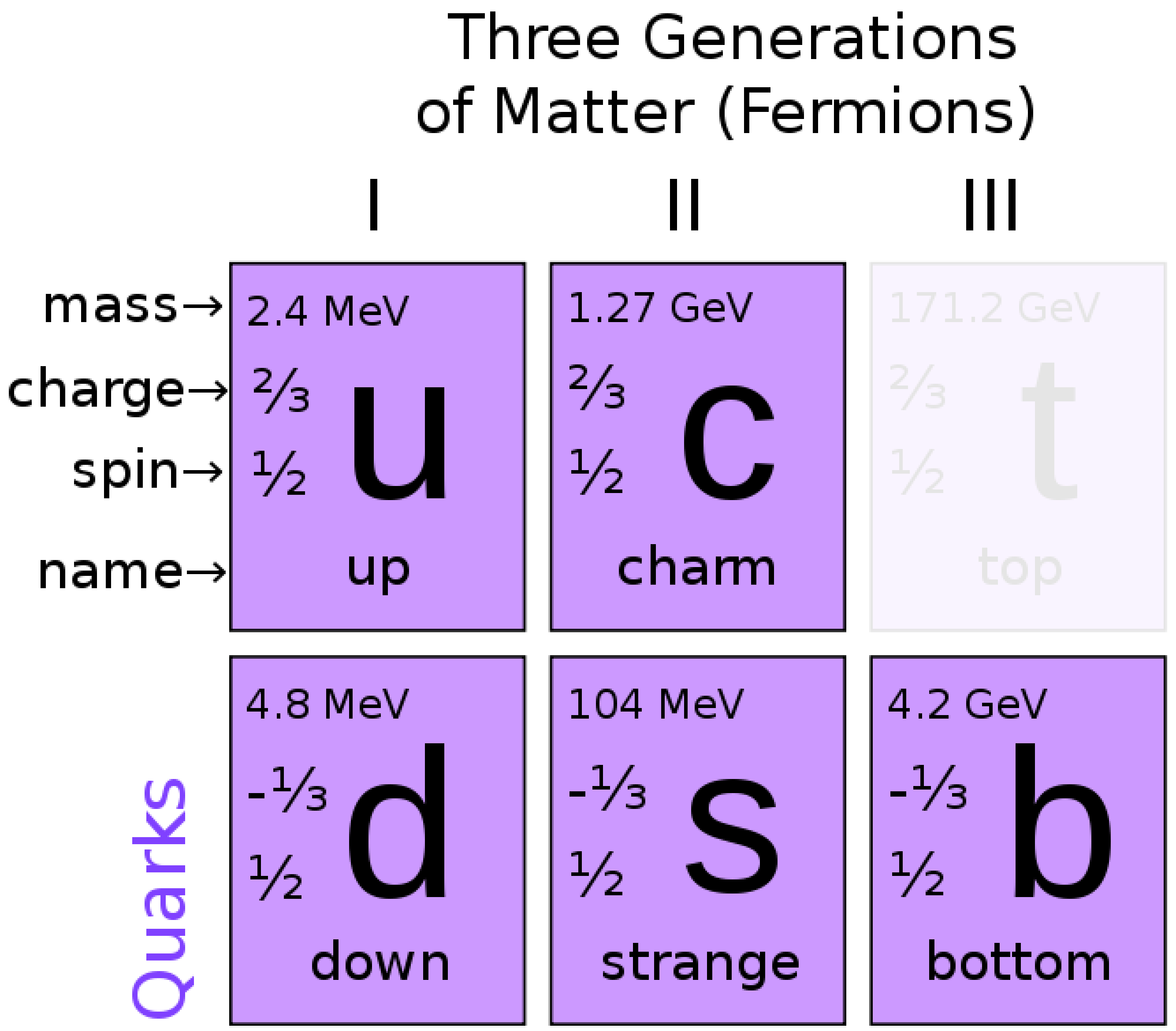


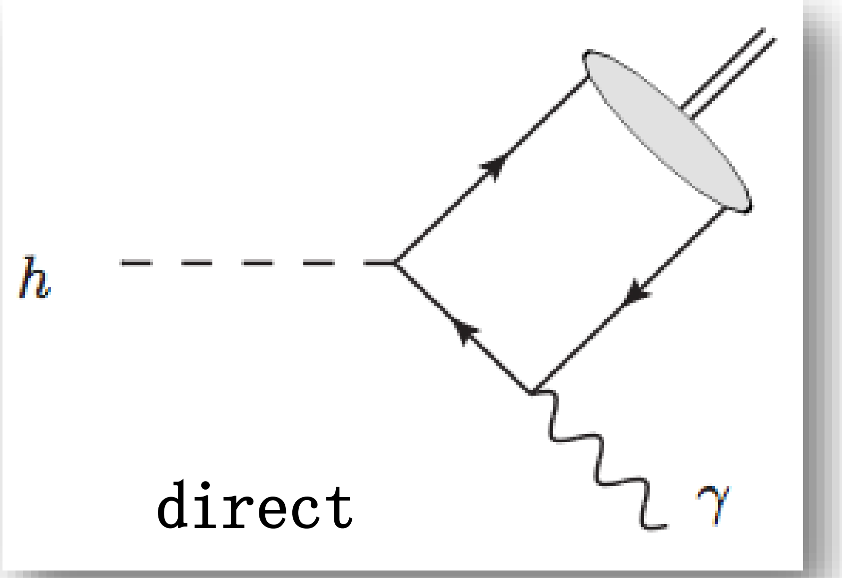


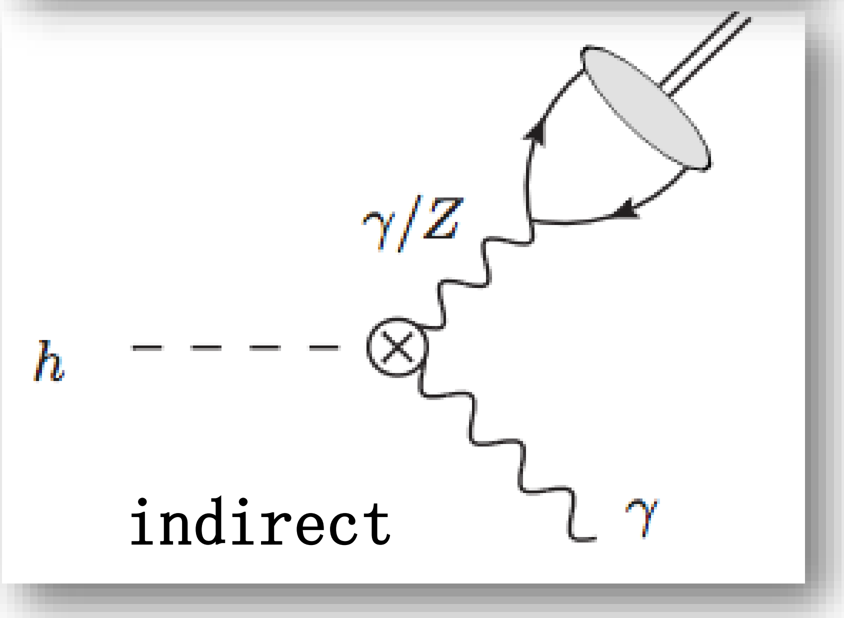
- No significant signal is found, thus set limits on signal strength
- ATLAS: 110 (150) xSM
- CMS: 70 (37) xSM (2L leads the sensitivity)



Recent Higgs meson-boson decays

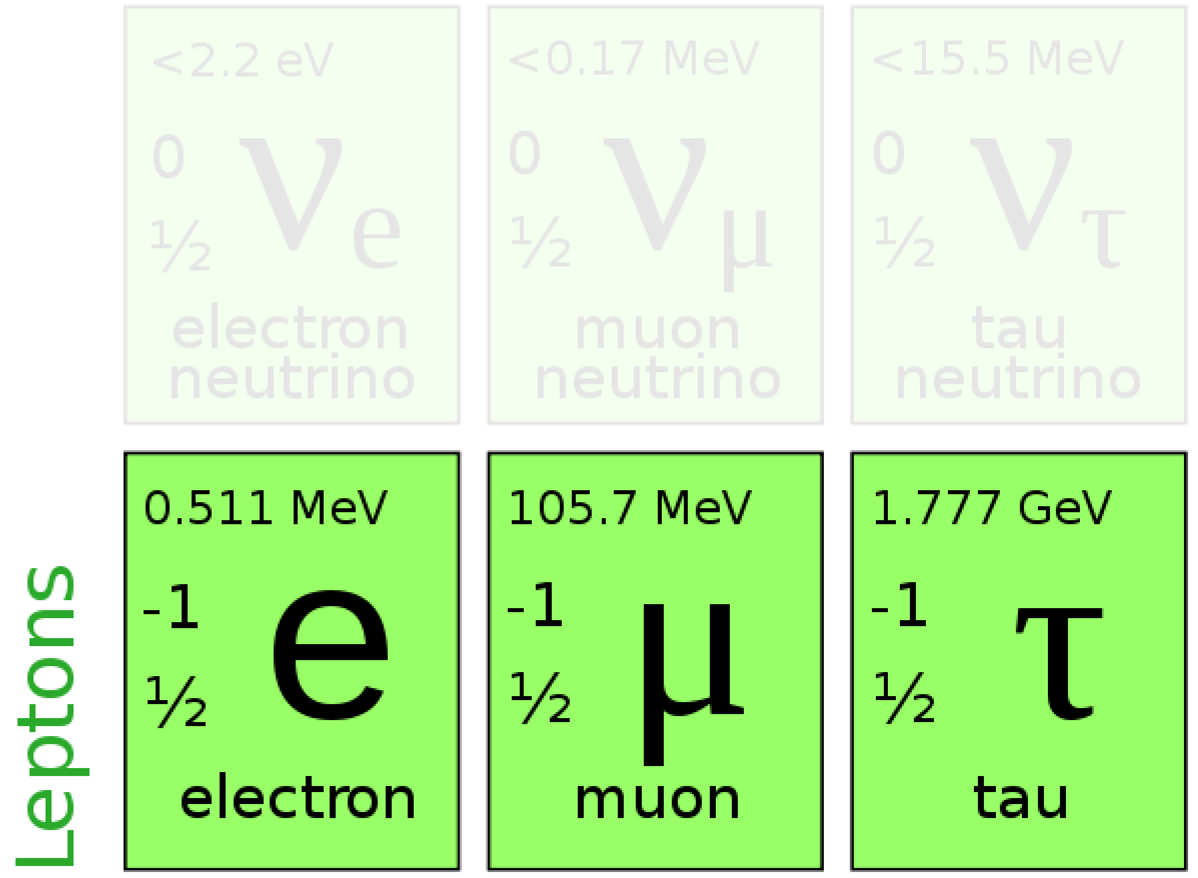


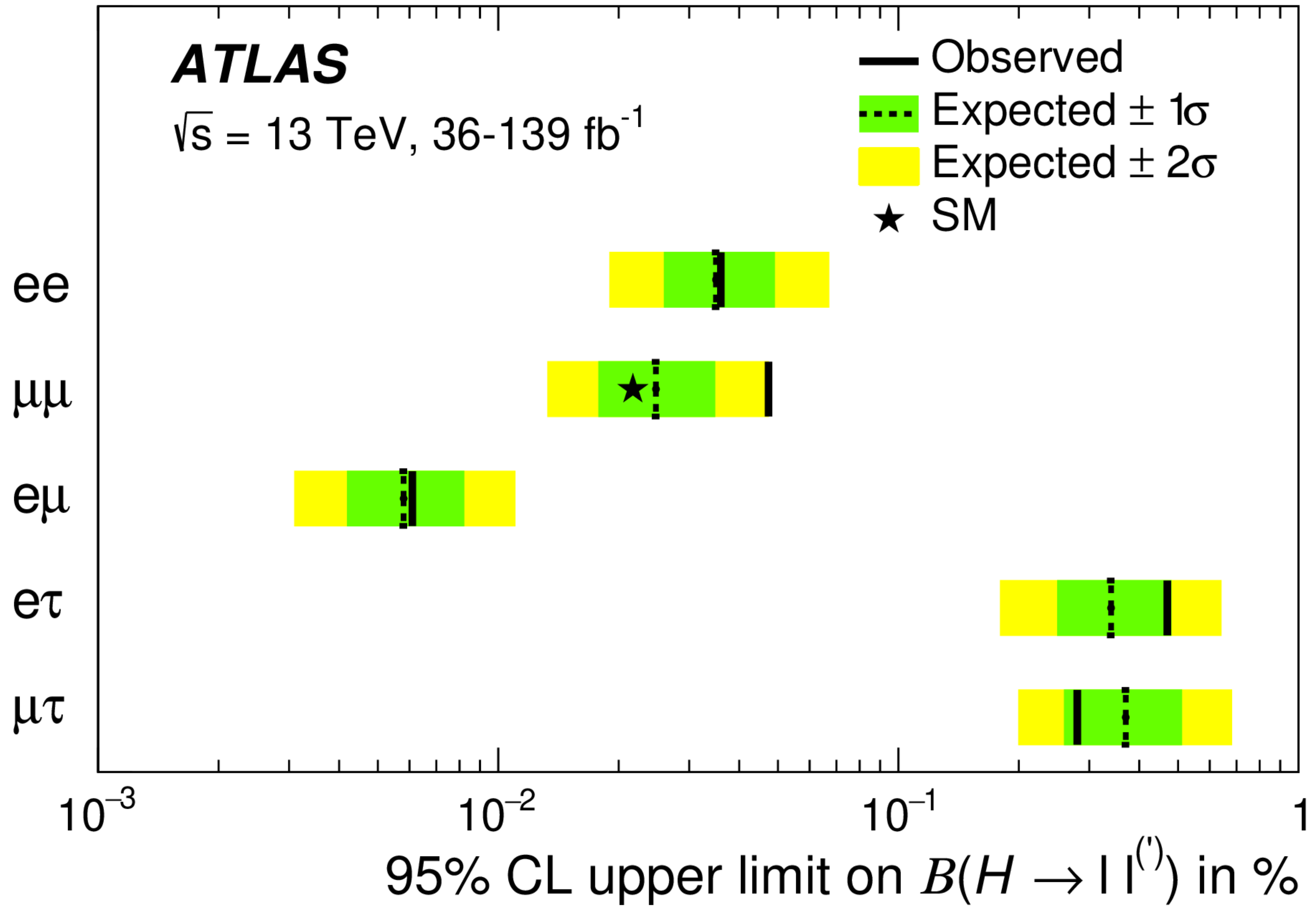




- Higgs to meson + boson decays provide complementary probes to Higgs couplings to quarks, with much smaller BR than Higgs fermion decays
  - Thus are usually used for BSM searches
- H→cc and bb:
  - ATLAS full Run2, H→J/ψγ, η_c, HDBS-2018-37, 2004.01678
  - ATLAS early Run2, H→J/ψγ, ψ(2S)γ, and Υ(nS)γ, HIGG-2016-23, 1807.00802
  - CMS full Run2, H→J/ψJ/ψ and ΥΥ(nS), HIG-18-025, 1905.10408
  - CMS early Run2 H→J/ψγ, SMP-17-012, 1810.10056
- H→uu/dd and ss:
  - ATLAS early Run2, H→ρ(770)γ and ϕ(1020)γ, HIGG-2016-13, 1712.02758
  - CMS full Run2, H→ρ(770)Z and ϕ(1020)Z HIG-19-012, 2007.05122
- These analyses set BR limits at several orders of magnitude above the SM prediction

Recent Higgs ee and LFV decays





HIGG-2019-14

- H to leptons can a good playground for BSM, such as lepton flavor violation
  - H→ee and H→eμ, ATLAS full Run2, HIGG-2018-58, 1909.10235
    - H→ee < 3.6 x 10^{-4} (3.5 x 10^{-4}), H→eμ < 6.1 x 10^{-5} (5.8 x 10^{-5})
  - H→ eτ and H→ μτ, ATLAS early Run2, HIGG-2017-08, 1907.06131
    - H→eτ < 0.47% (0.34%) H→μτ < 0.28% (0.37%)
  - H→ eτ and H→ μτ, CMS early Run2, HIG-17-001, 1712.07173
    - H→eτ < 0.61% (0.37%) H→μτ < 0.25% (0.25%)

Summary

- A big variety of Higgs→ff studies have been performed with partial and full Run2 data at ATLAS and CMS
- A wide range of knowledge on the interaction of Higgs and fermions have been learned

- Third generation:
  - Keep improving the precisions in H→bb and H→ττ (ttH as well, see Hideki's talk)
  - Reaching out to Higgs properties with CP measurements in H→ττ (ttH as well)
- Second generation:
  - Approaching the edge of discovering H→μμ
  - Full speed heading to H→cc
- First generation:
  - Almost a mission impossible at the LHC, but a good place for BSM searches such as lepton flavor violation etc. Performed several attempts and already set first sets of limits

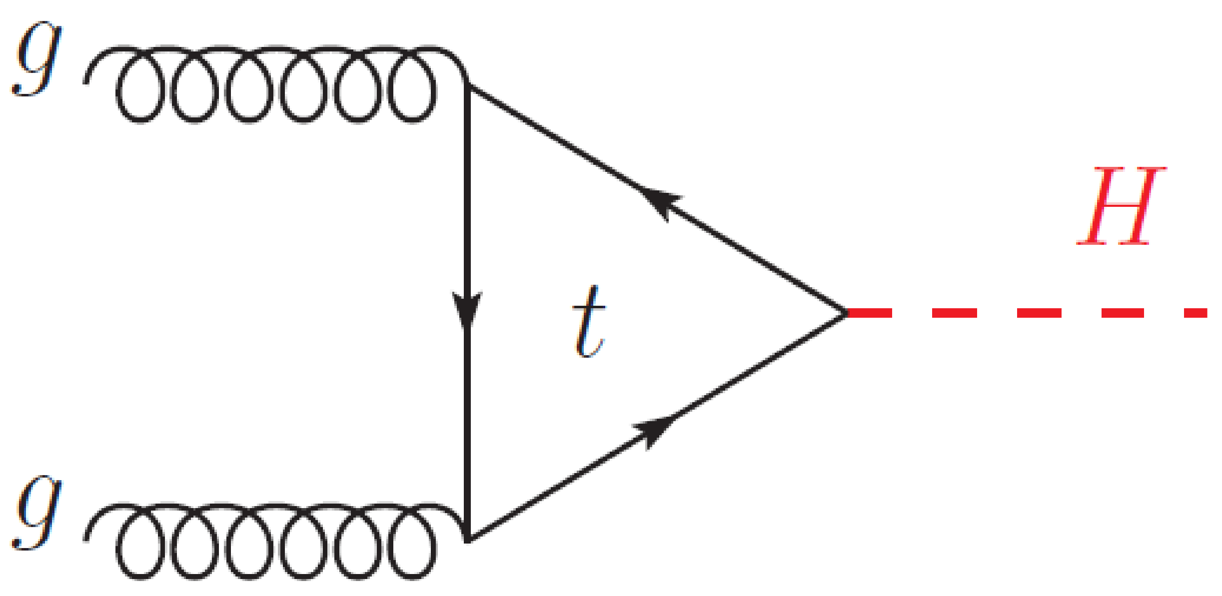
Backup slides

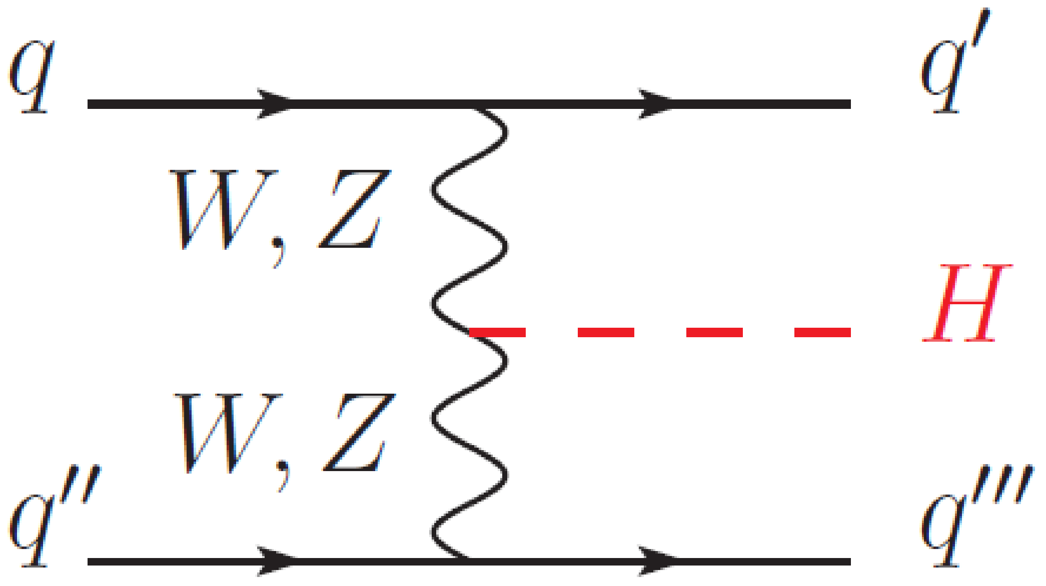
Htautau CMS

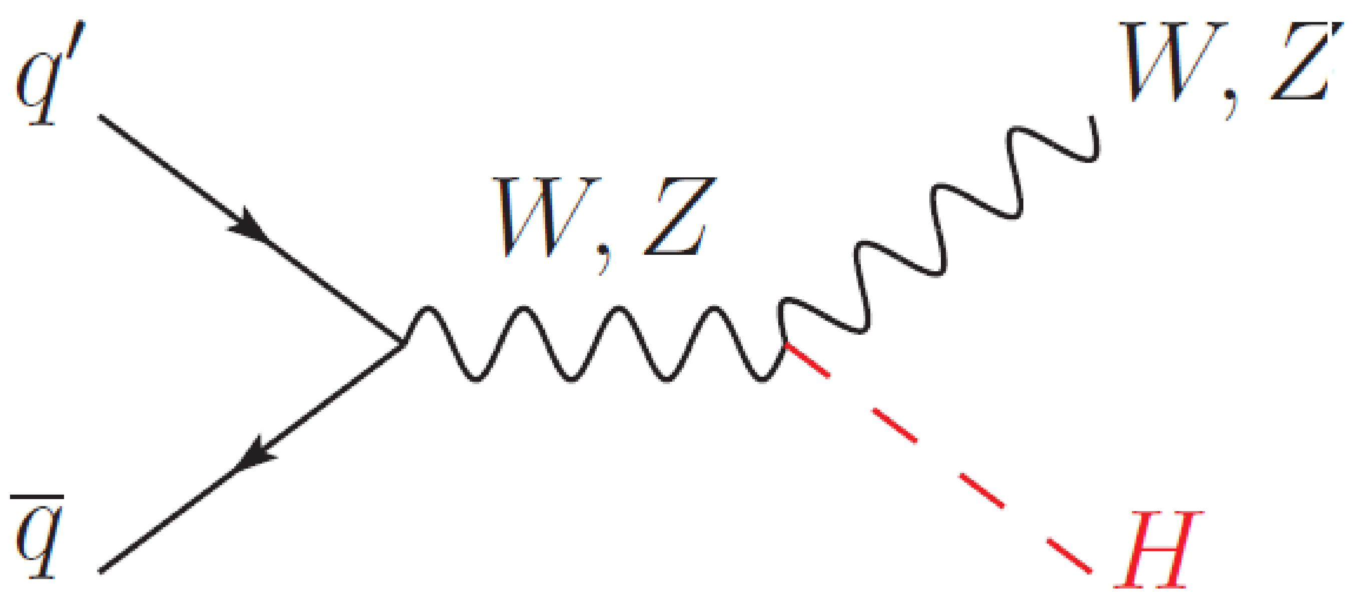
Final state	Category	Selection	Observables
$\ell\tau_h$, $e\mu$	0-jet	0 jet	$m_{\tau\tau}$, τ_h p_T ($\ell\tau_h$) $m_{\tau\tau}$ ($e\mu$)
	VBF low p_T^H	≥ 2 jets, $m_{jj} > 350$ GeV, $p_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	≥ 2 jets, $m_{jj} > 350$ GeV, $p_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, p_T^H
	Boosted ≥ 2 jets	Not in VBF, ≥ 2 jets	$m_{\tau\tau}$, p_T^H
$\tau_h\tau_h$	0-jet	0 jet	$m_{\tau\tau}$
	VBF low p_T^H	≥ 2 jets, $\Delta\eta_{jj} > 2.5$(2.0 for 2016), $100 < p_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	≥ 2 jets, $\Delta\eta_{jj} > 2.5$(2.0 for 2016), $p_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, p_T^H
	Boosted ≥ 2 jets	Not in VBF, ≥ 2 jets	$m_{\tau\tau}$, p_T^H

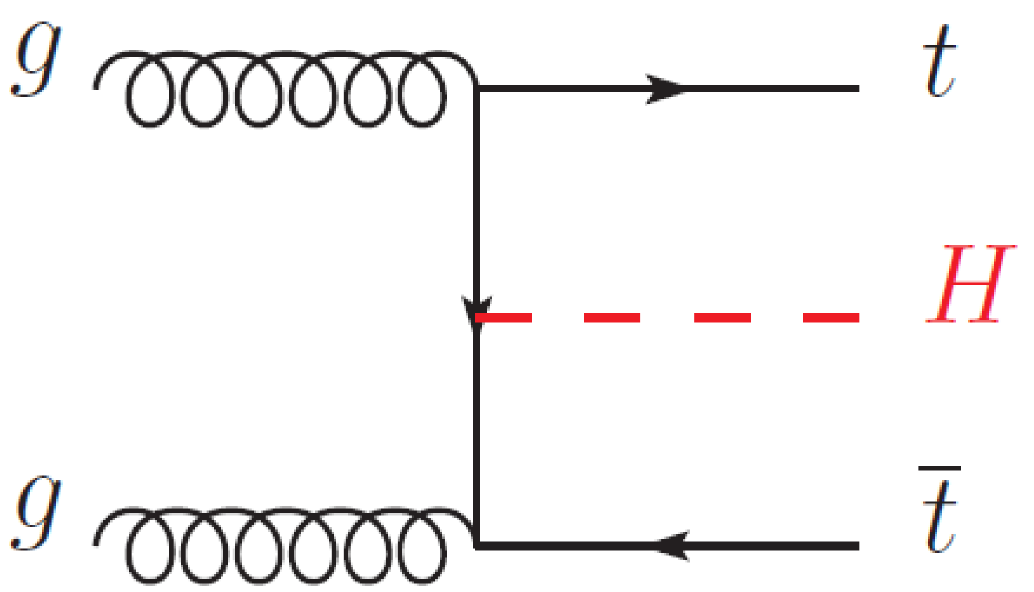
CMS Hmumu: strategy

- $\mathscr{B}H\rightarrow\mu\mu=2.18\times10-4$, roughly a tenth of H→gamgam, very challenging
- The general strategy is to simultaneously fit in multiple categories optimized for the four leading Higgs production modes









Largest production
But also large background (DY)

Characteristic forwards jets, large mjj, large eta gap
Main background: DY and EWK Zjj

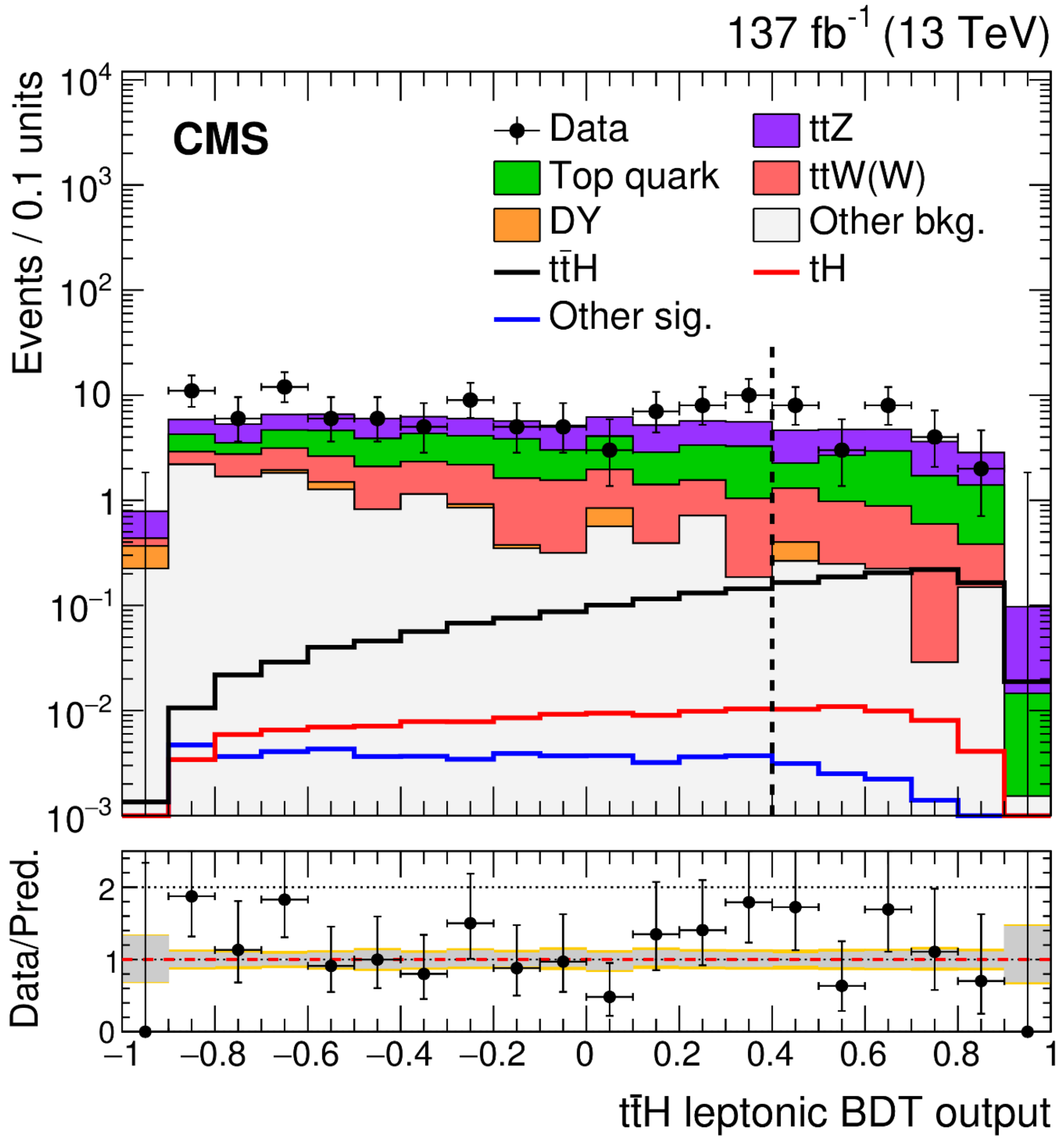
Additional leptons
Main background: ZZ, WZ

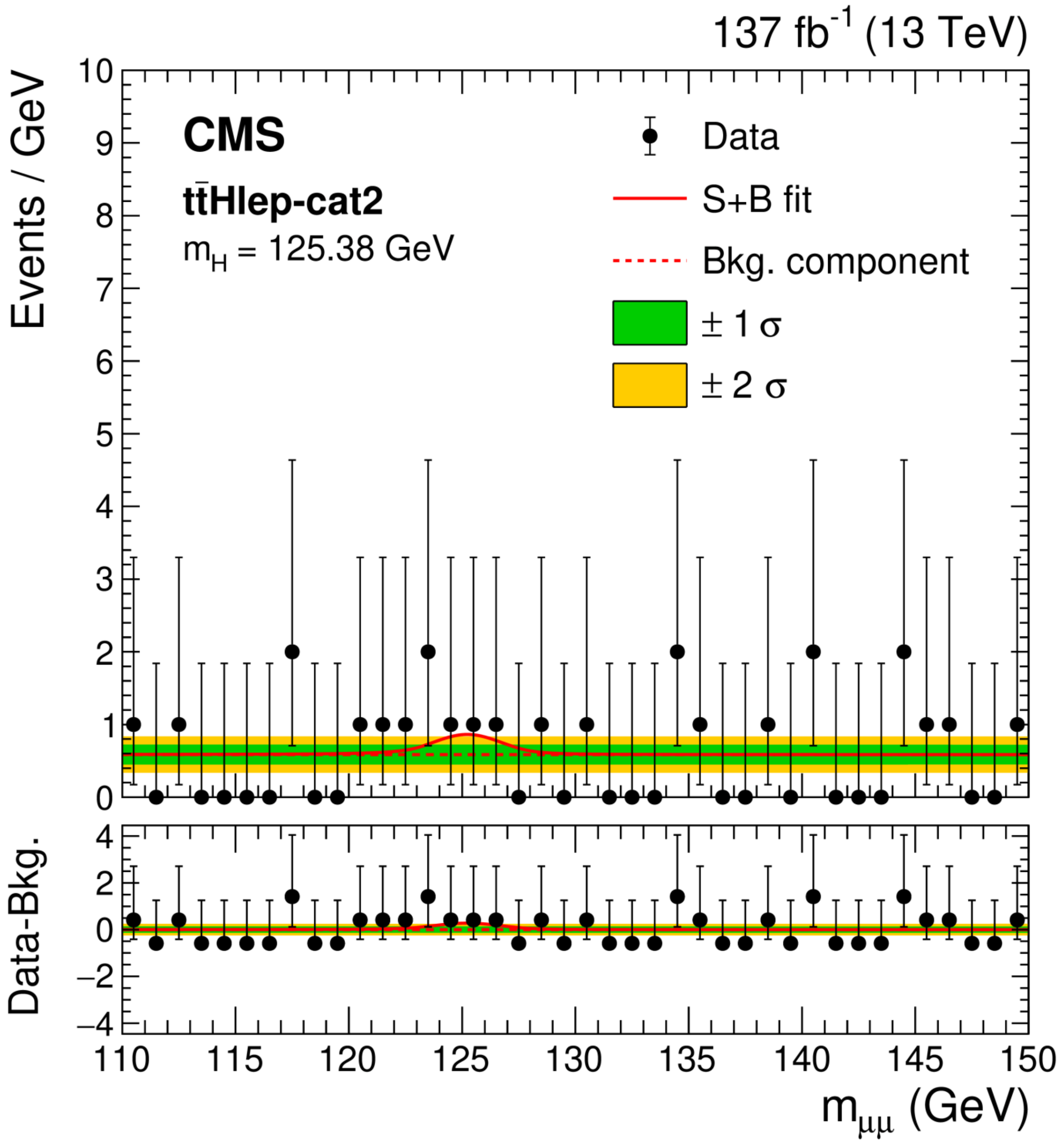
Small production, rich final states (bjets, additional leptons)
Main background: tt, ttZ

CMS Hmumu: ttH

- ttH common: 1 medium or 2 loose bjets
- ttH (hadronic)
  - >= 3 jets with pT > 25 GeV
  - Leading jet pT > 50 GeV
  - >= 1 jet triplet with 100 < mjjj < 300 GeV
- ttH (leptonic)
  - 1 or 2 additional e mu
  - >= 2 jets with pT > 25 GeV
  - Significant MET

Input variables for ttH (lep): $\Delta\phi(H, \ell 1)$, mass(b, ℓ1), transverse mass (MET, ℓ1) etc. where ℓ1 is the leading-pT lepton



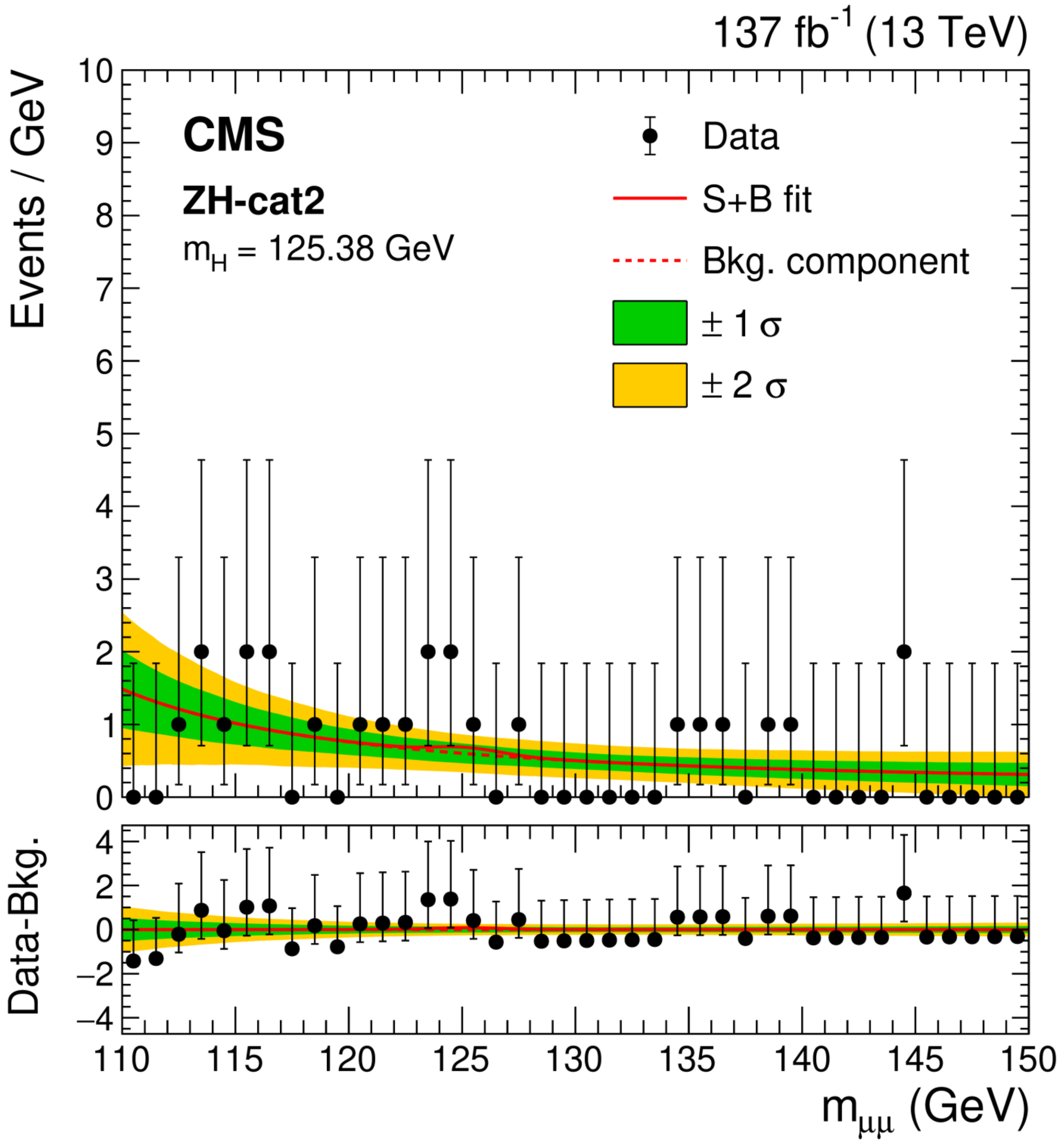


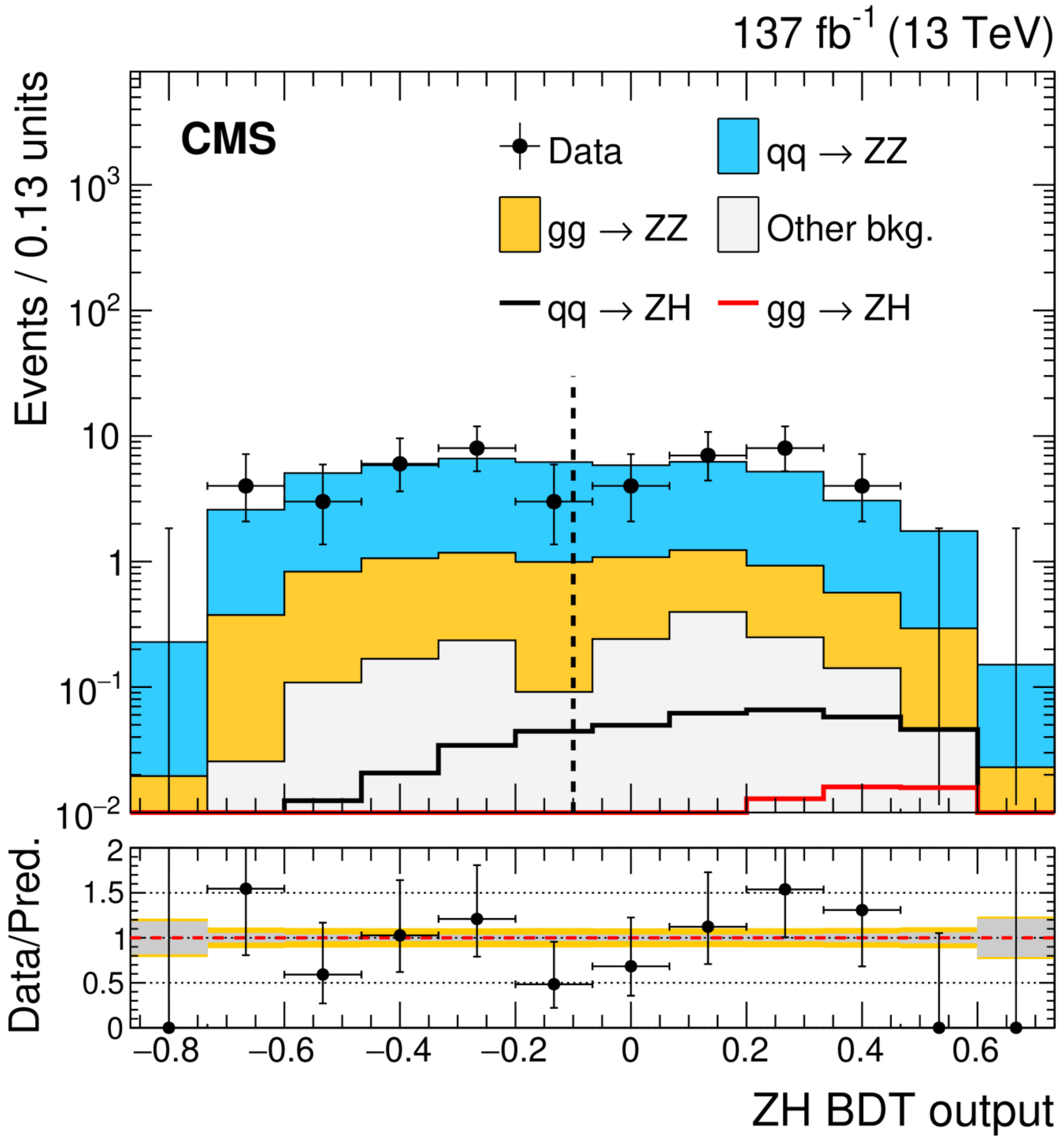
Fit on m(mumu) spectrum
Combined ttH:
Signal strength $\mu = 2.32^{+2.27}_{-1.95}$
Obs (exp) significance 1.2 (0.5) σ

CMS Hmumu: VH

- VH common: no bjet
- WH
  - Additional e or mu with pT > 20 GeV
  - Significant MET or MHT
- ZH
  - Additional ee or mumu with
  - 81 < m(ee) < 101 GeV
  - 71 < m(mumu) < 111 GeV

Input variables for ZH:
Z: pT, η, mZ, Δη(Z,H), Δϕ(Z,H), cosθ*(Z,H) etc.
Higgs: dimuon pT, η, Δϕ(μμ), etc.

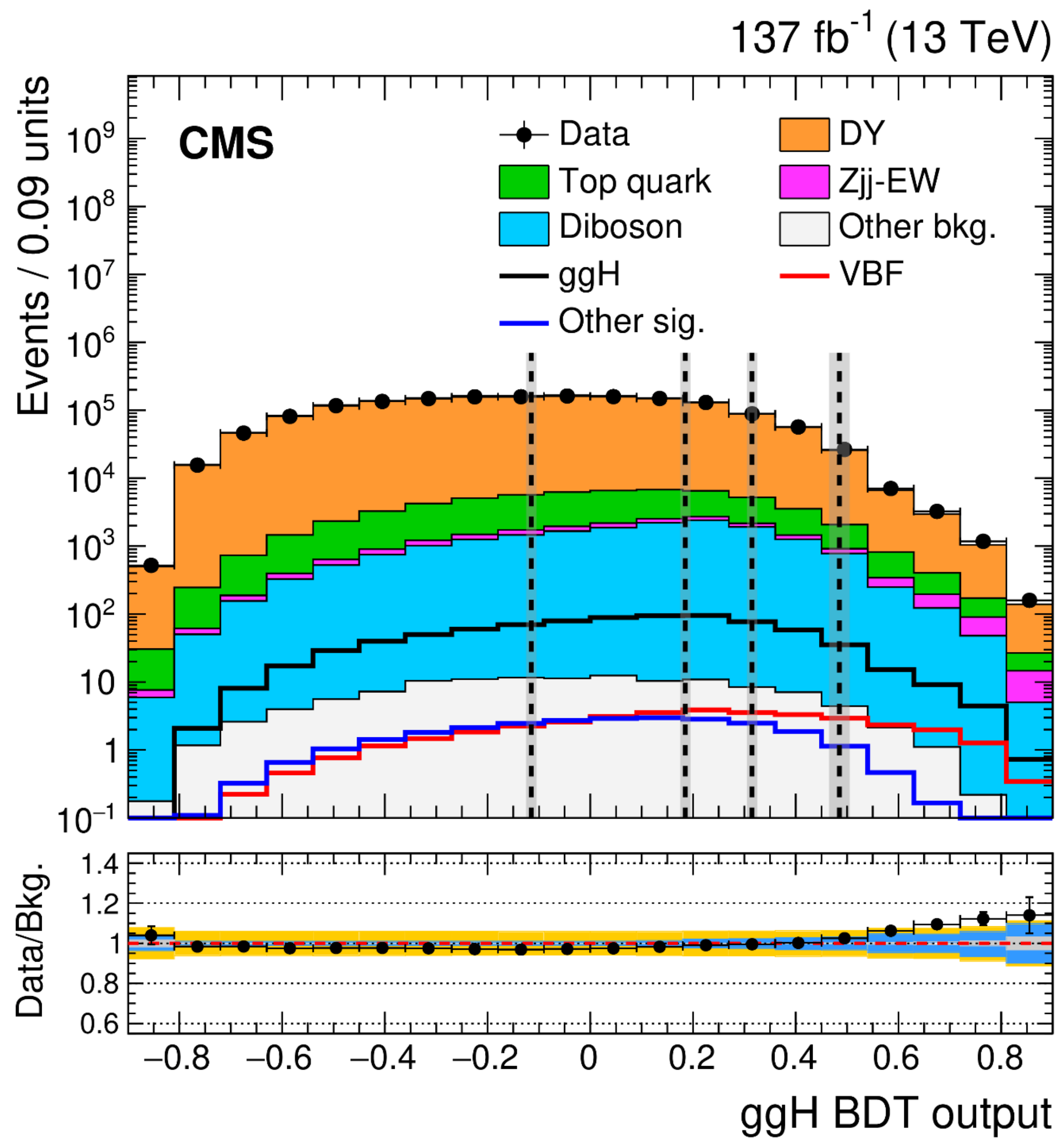




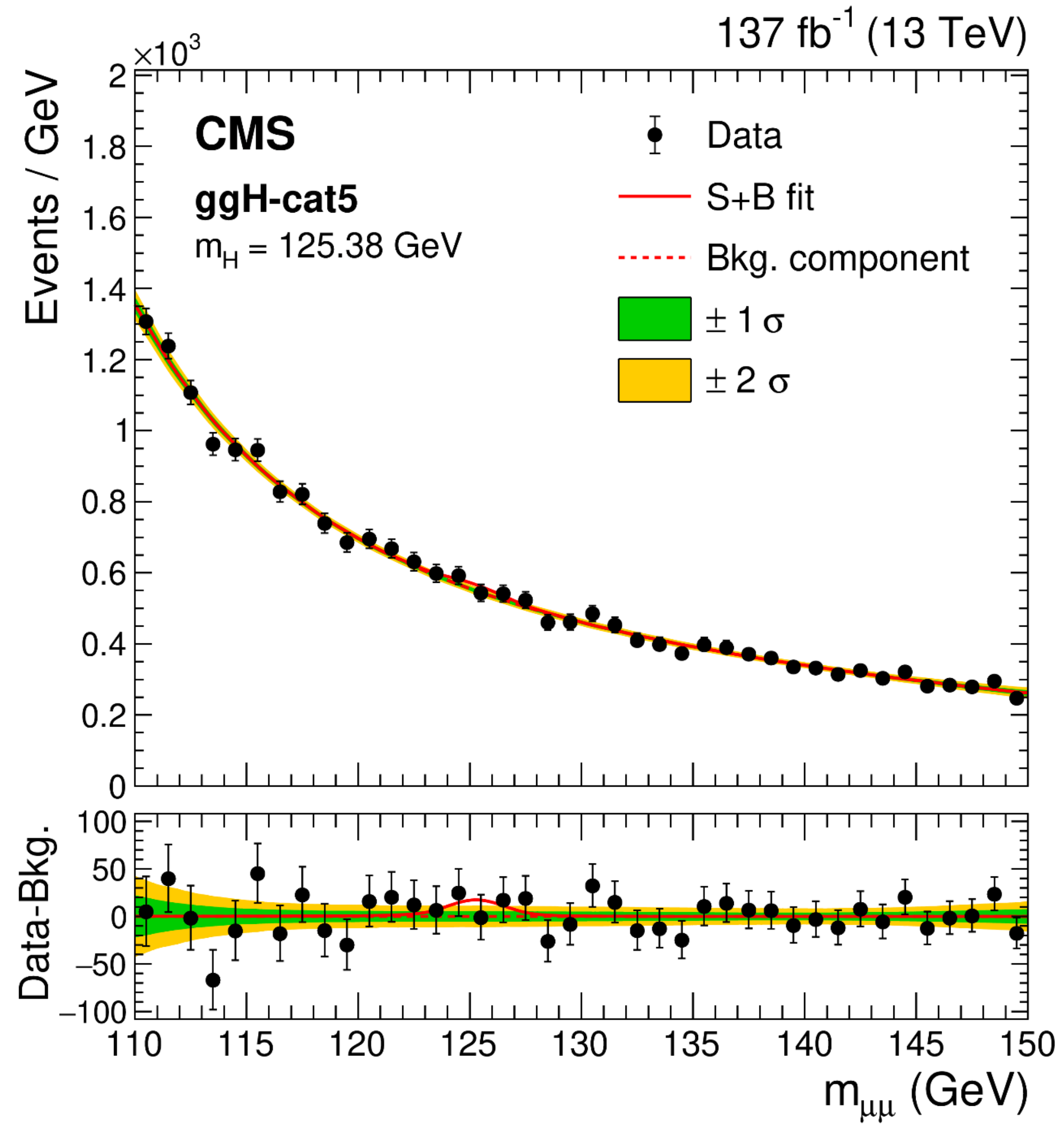
Fit on m(mumu) spectrum
Combined ZH:
Signal strength $\mu = 5.48^{+3.10}_{-2.83}$
Obs (exp) significance 2.0 (0.4) σ

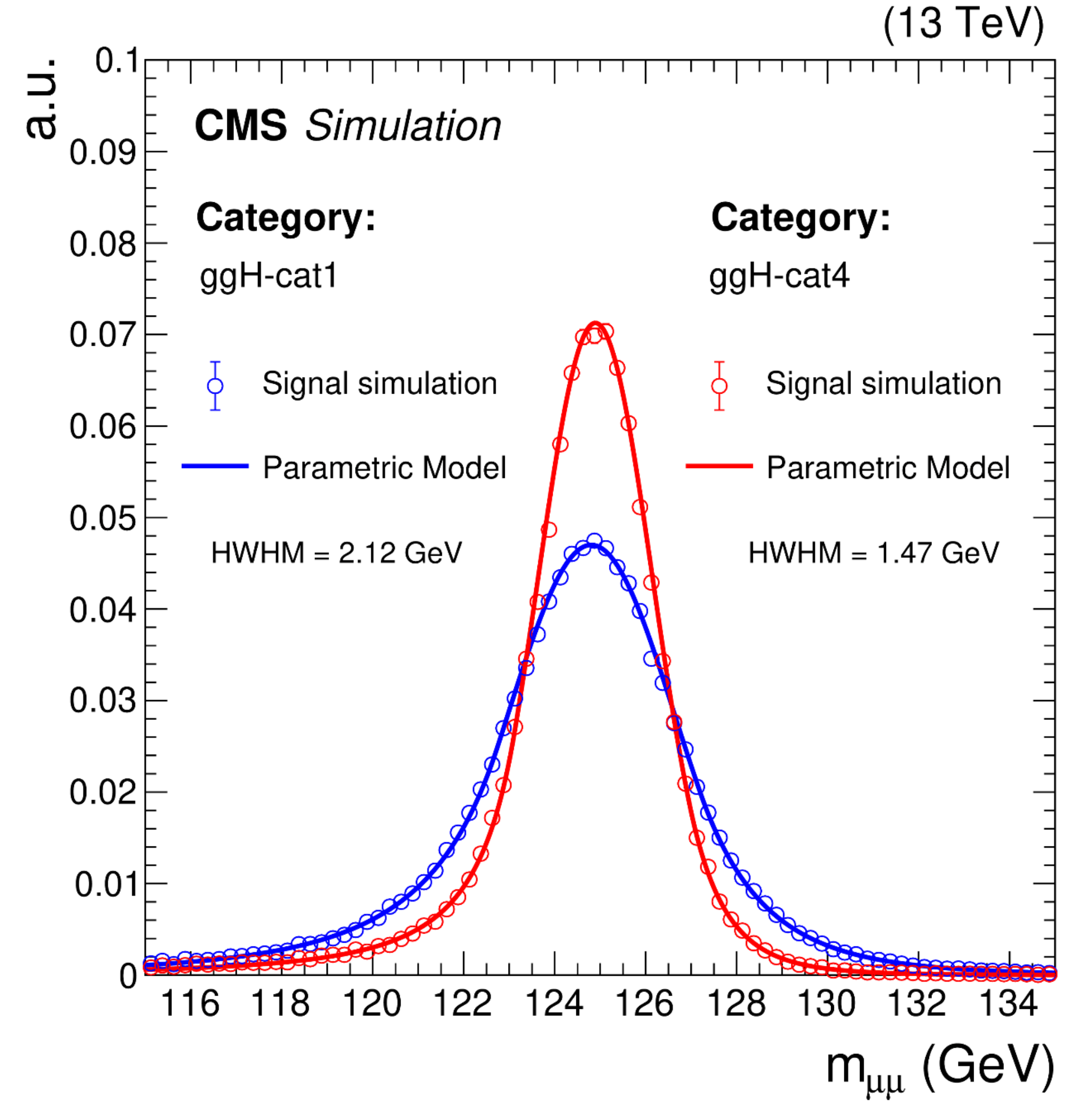
CMS Hmumu: ggF

- The rest of signal events fall into ggF category
- Input variables from Higgs
  - Dimuon pT & rapidity, decay angles ϕCS, cosθCS, η(μ), pT(μ)/mμμ etc.
- Input variables from ISR jets
  - pT, η of the leading jet
  - DeltaEta(H,j), DeltaPhi(H,j) if jets exist … NEED COMPLETE

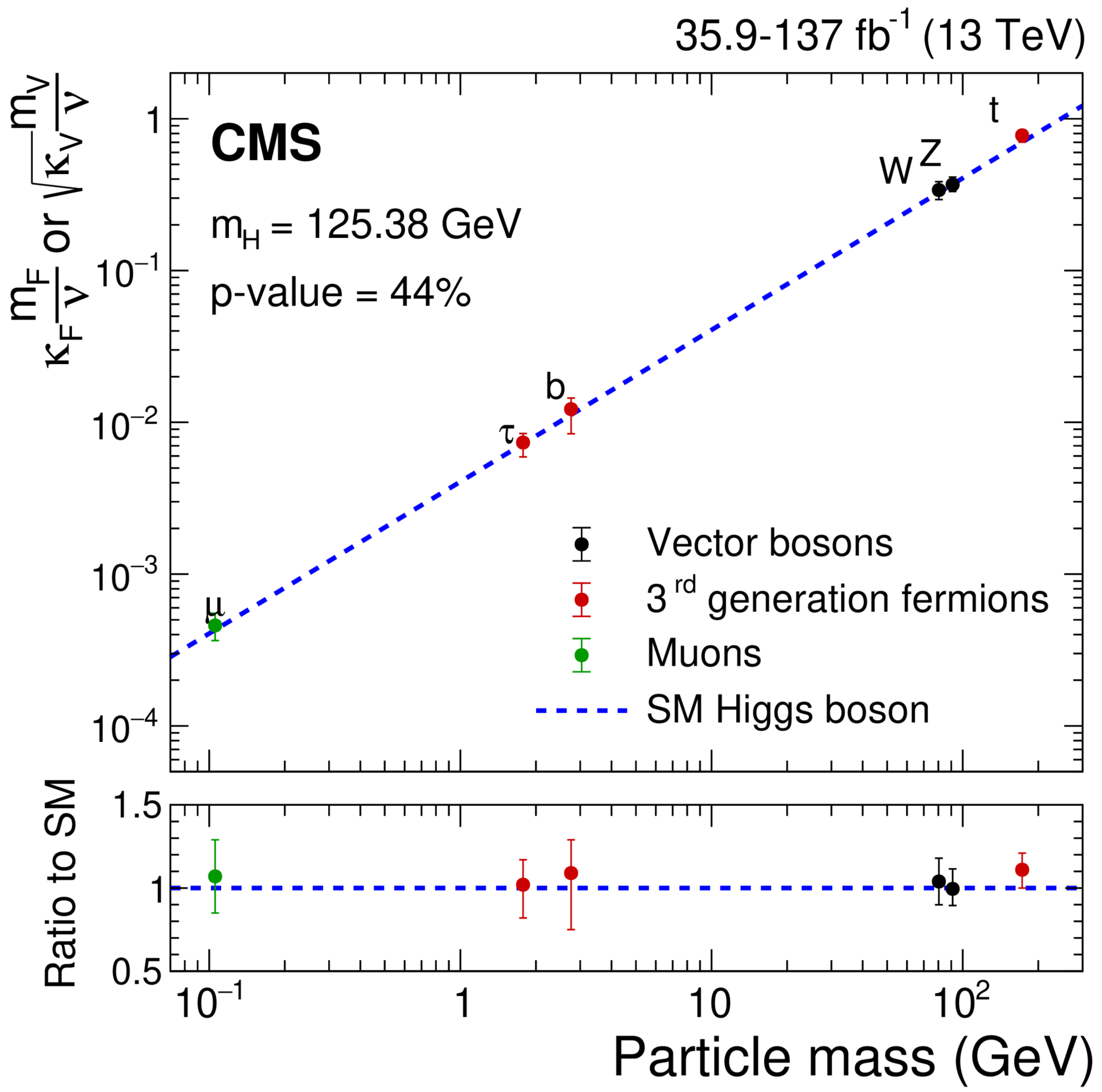


Fit on m(mumu) spectrum
Combined ggF:
Signal strength $\mu = 0.63^{+0.65}_{-0.64}$
Obs (exp) significance 1.0 (1.6) σ





CMS Hmumu: results



$1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})$

H→cc

ATLAS

Sample	Yield, 50 $GeV < m_{c\bar{c}} <$ 200 GeV			
	1 c-tag		2 c-tags	
	$75 \leq p_T^Z < 150\,GeV$	$p_T^Z \geq 150\,GeV$	$75 \leq p_T^Z < 150\,GeV$	$p_T^Z \geq 150\,GeV$
$Z+$jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	-143 ± 170 (2.4)	-84 ± 100 (1.4)	-30 ± 40 (0.7)	-20 ± 29 (0.5)
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

CMS

	Resolved-jet (inclusive)				Merged-jet (inclusive)			
	0L	1L	2L	All channels	0L	1L	2L	All channels
Expected UL	84^{+35}_{-24}	79^{+34}_{-23}	59^{+25}_{-17}	38^{+16}_{-11}	81^{+39}_{-24}	88^{+43}_{-27}	90^{+48}_{-29}	49^{+24}_{-15}
Observed UL	66	120	116	75	74	120	76	71

CMS

	95% CL exclusion limit on $\mu_{VH(H\to c\bar{c})}$					
	Resolved-jet	Merged-jet	Combination			
	($p_T(V) <$ 300 GeV)	($p_T(V) \geq$ 300 GeV)	0L	1L	2L	All channels
Expected	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	37^{+16}_{-11}
Observed	86	75	83	110	93	70

The resolved (full PTV) and merge (PTV>200GeV) analyses have substantial overlap