Self-introduction

2011 University of Science and Technology of China, B.S.
Advisor Professor Zhengguo Zhao

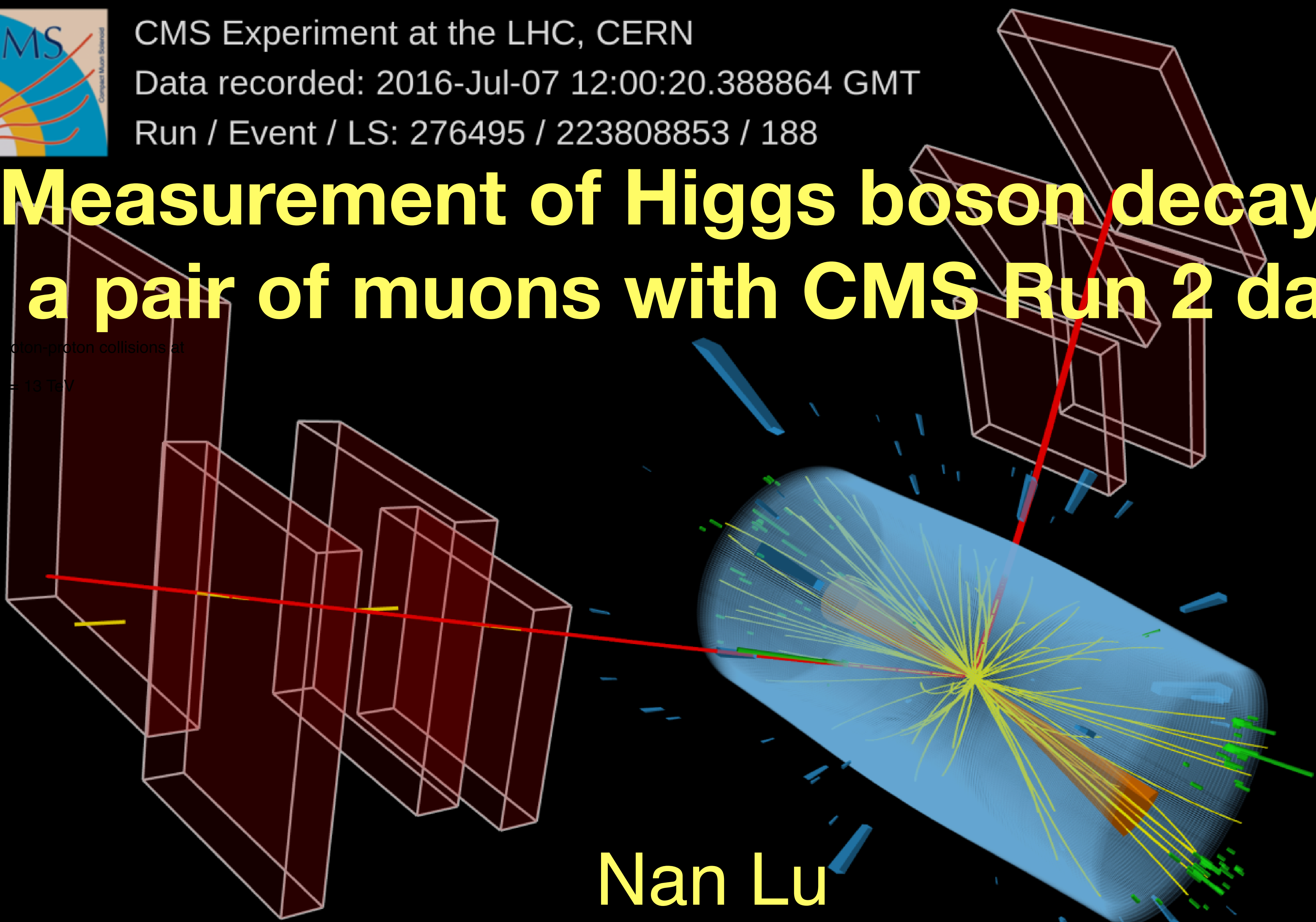
2017 University of Michigan - Ann Arbor, PhD,
Advisor Professor Bing Zhou

2017 - now, California Institute of Technology, postdoctoral researcher

- 2017 - 2020 David and Ellen Lee Distinguished Fellowship

Eight years of research experience at ATLAS and CMS. Current research focus:

- Higgs boson physics in CMS
- CMS MIP timing detector in the Phase II Upgrade



Measurement of Higgs boson decay to a pair of muons with CMS Run 2 data

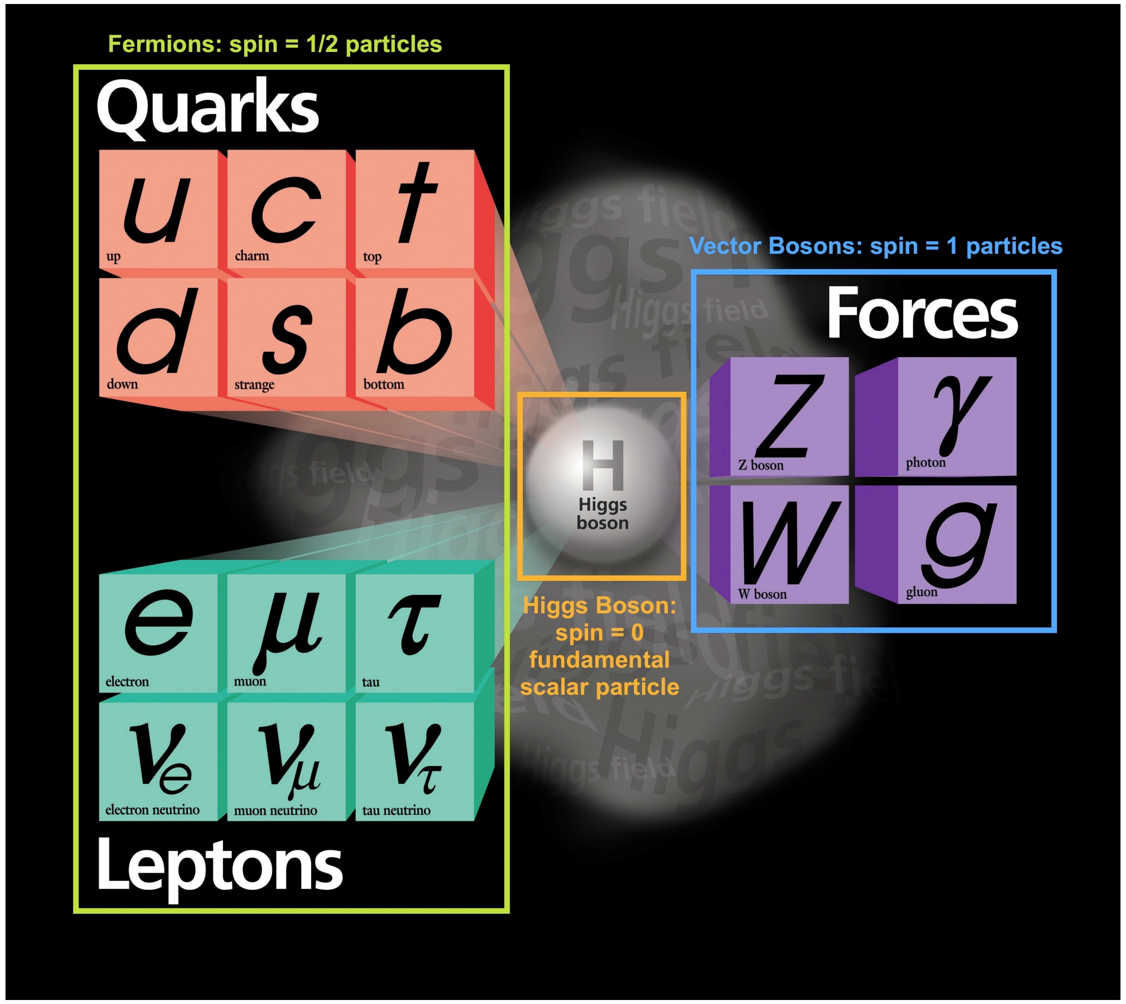
Nan Lu

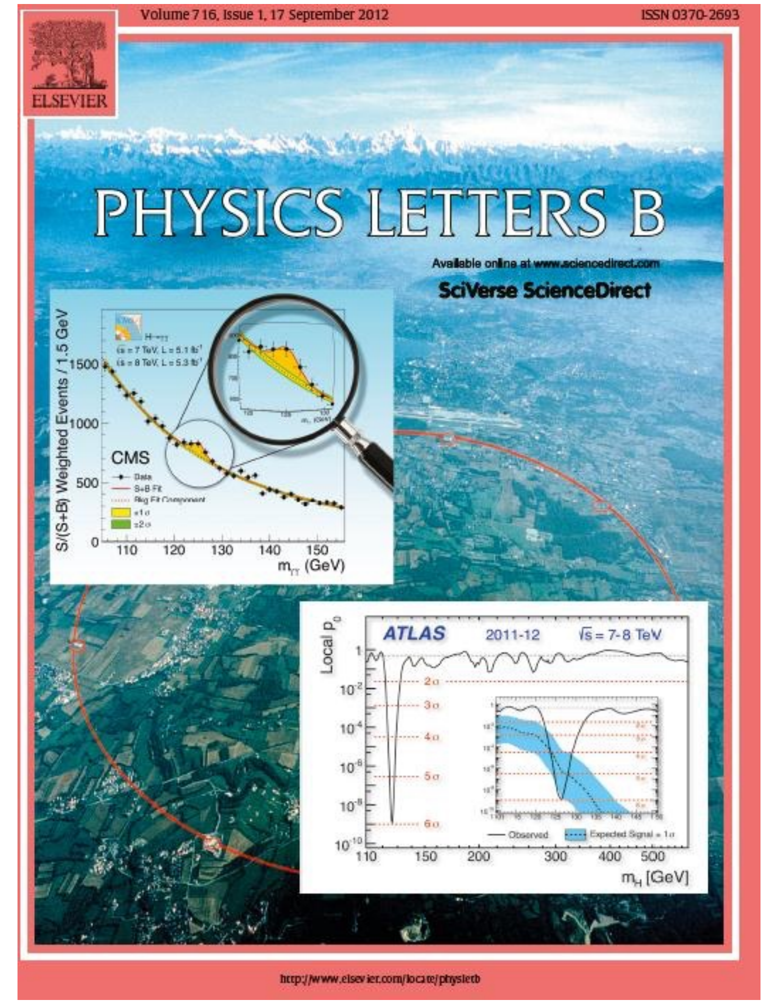
California Institute of Technology

Caltech

Peking University, August 13, 2020

The Standard Model Higgs Boson

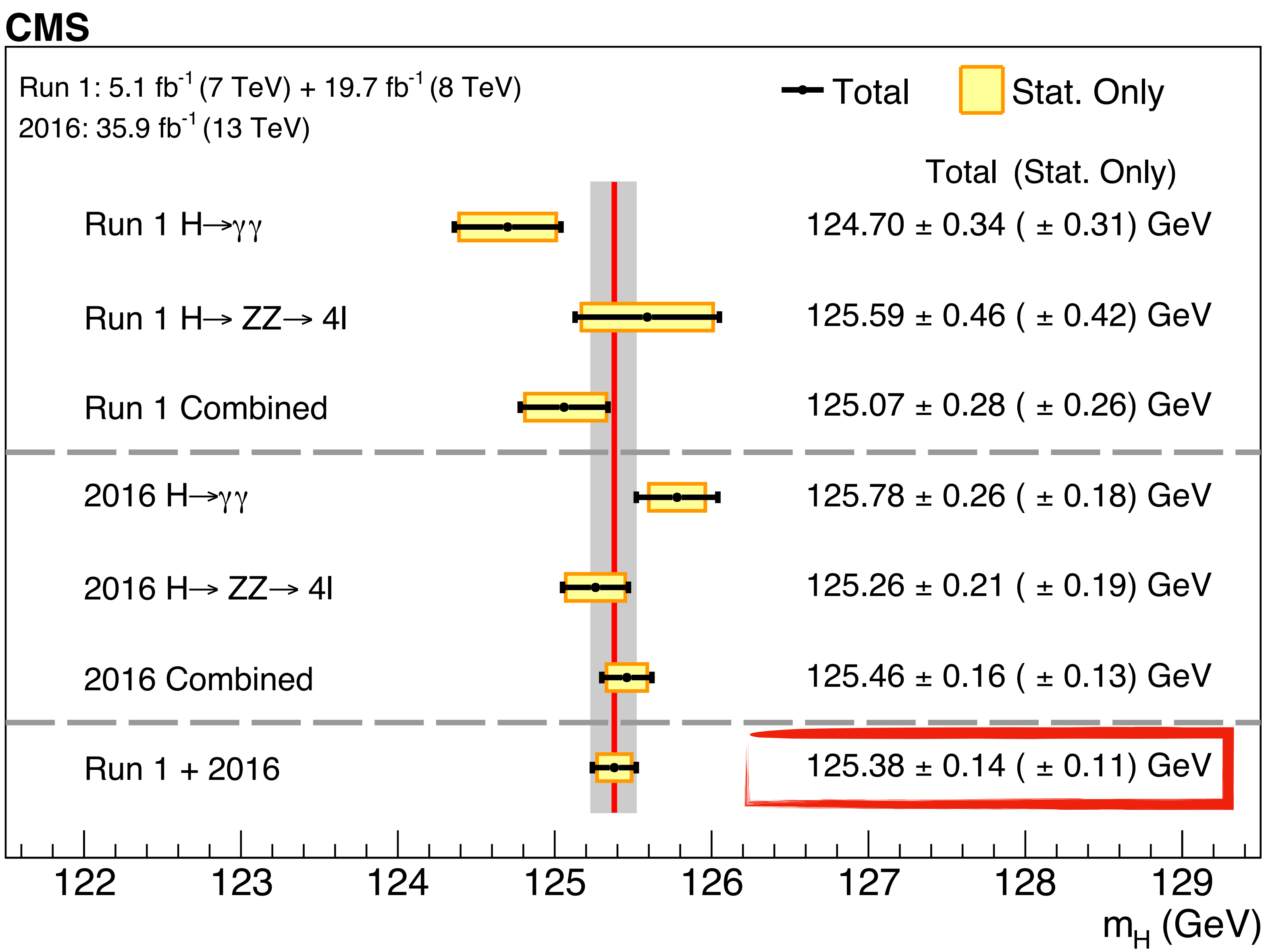


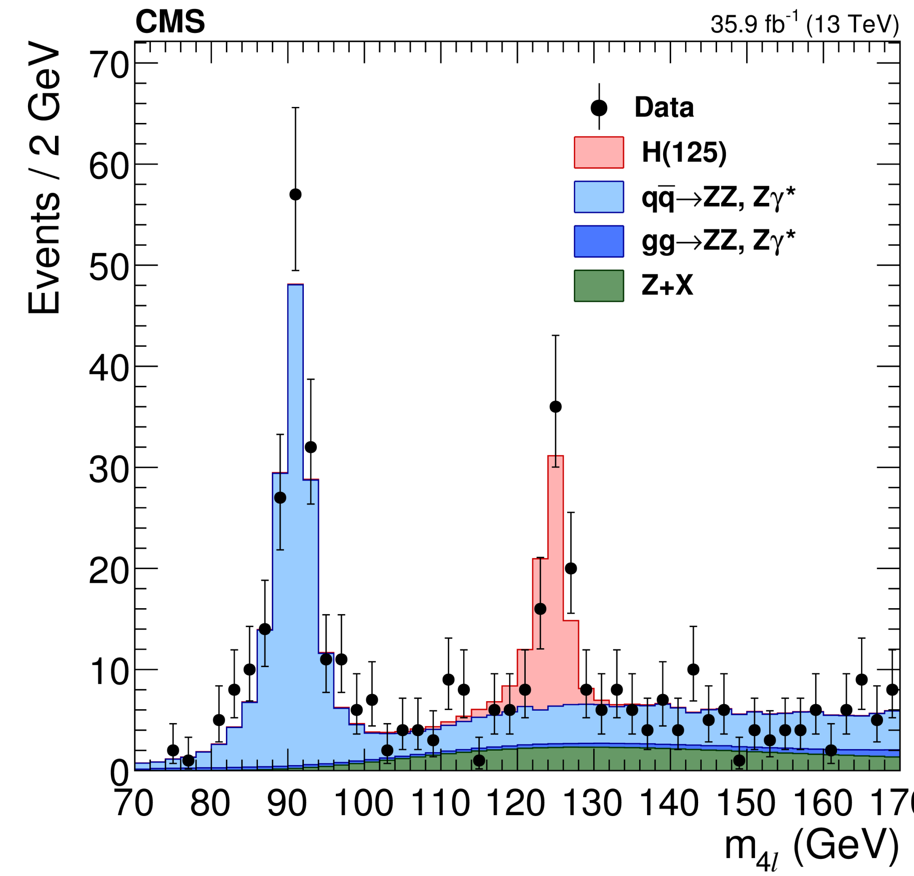


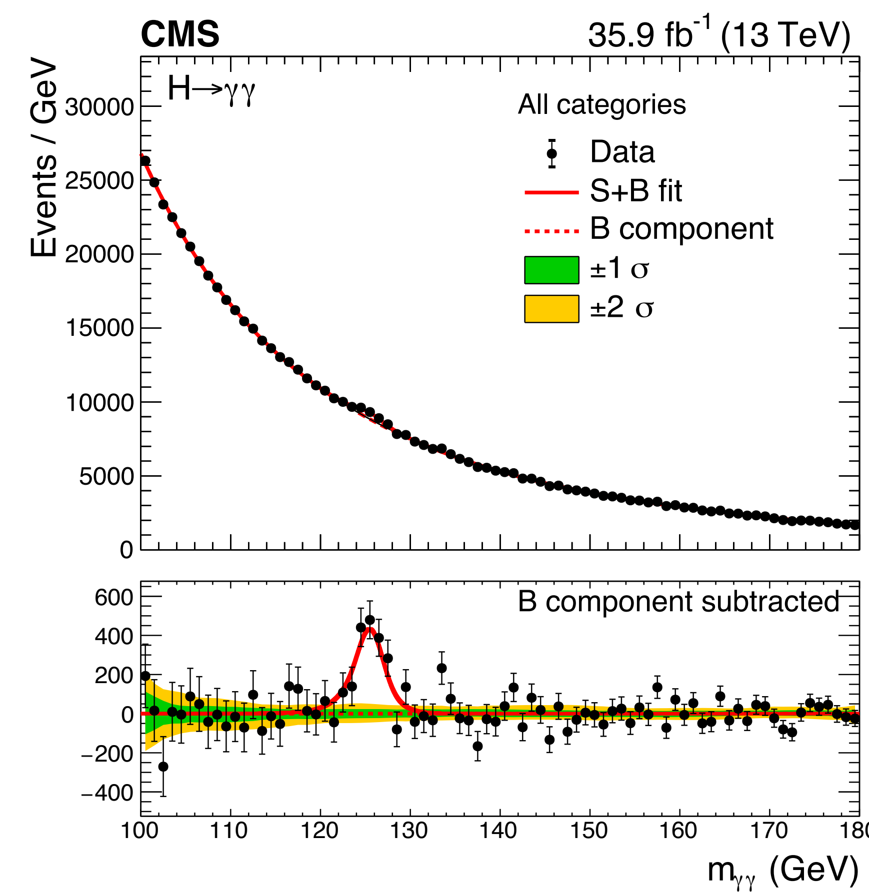
- Quarks, charged leptons, W/Z bosons acquire mass through the Brout-Englert-Higgs (BEH) mechanism in the Standard Model (SM)
- The discovery of the Higgs boson by ATLAS and CMS experiments at LHC in 2012 started the era of Higgs boson property measurement
  => test the SM, use Higgs as a tool to search for new physics

Higgs boson mass

- The Higgs boson mass m_H is a free parameter in the SM. Once m_H is known, all Higgs boson couplings to standard model particles are fixed.
- Most precise m_H measurement as of today: **~0.11%** precision by CMS experiment





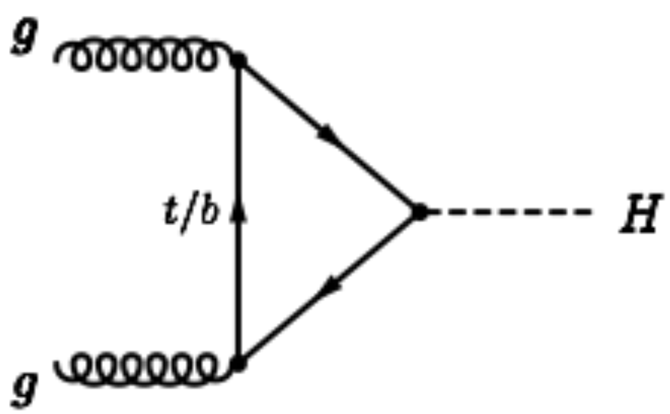


Phys. Lett. B 805 (2020) 135425

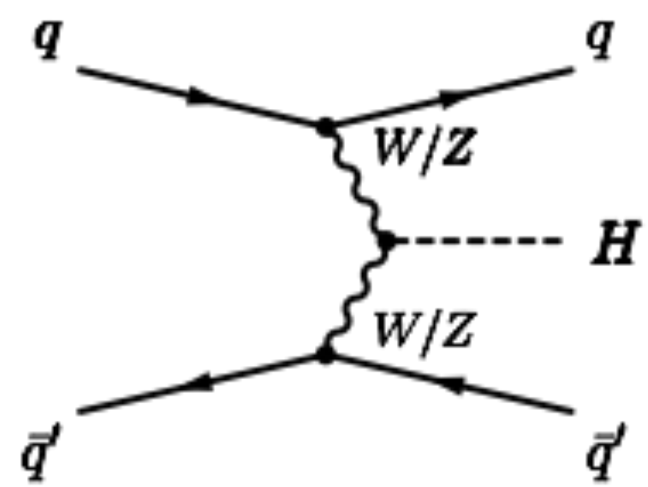
Higgs boson main production mechanism at the LHC

125.38 GeV Higgs boson production cross section @13 TeV

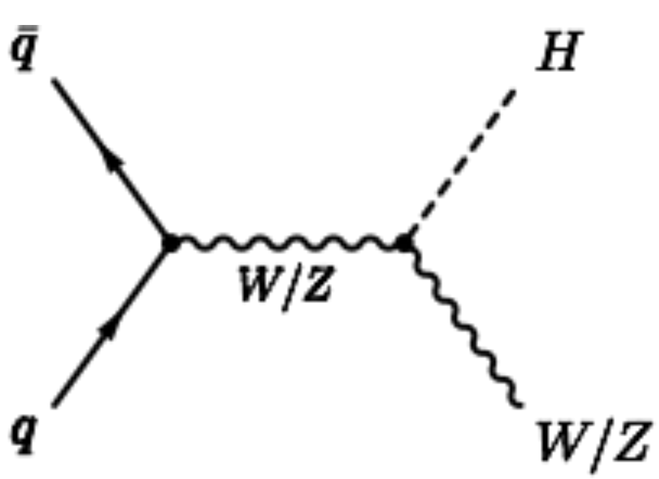
Gluon-fusion (ggH)
48.3 pb ~88%



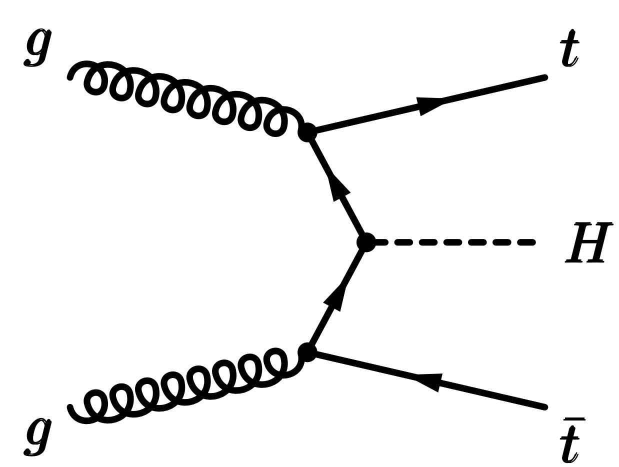
Vector boson fusion (VBF)
3.8 pb ~7%



Associated Higgs production with a W or Z boson (VH): 2.2 pb ~ 4%



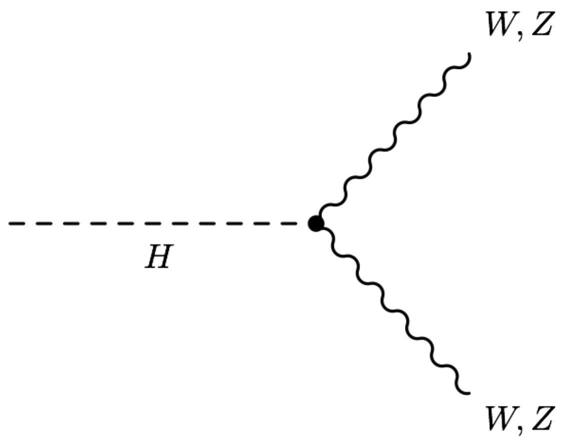
Associated Higgs production with a top quark pair (ttH): 0.5 pb ~1%



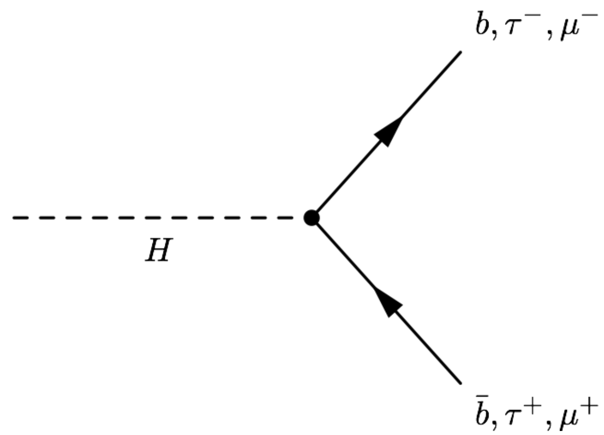
Higgs boson main decay channels

- $\gamma\gamma$, $ZZ^* \rightarrow 4l$, WW^* bosonic decays in precision measurement stage
- fermionic decays: bb, $\tau\tau$ observed
- channels not yet observed: cc, μμ, Zγ, …

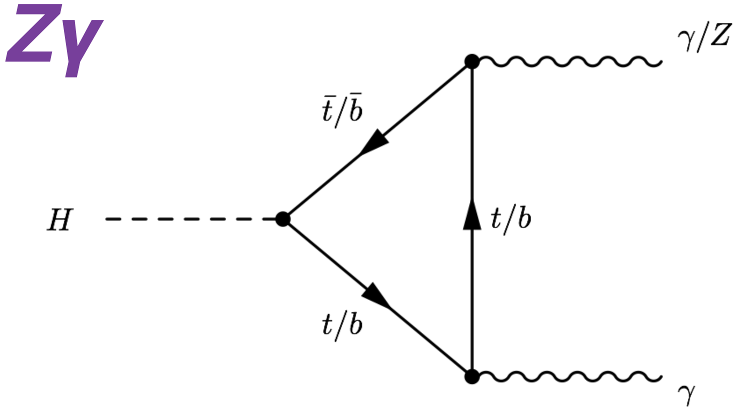
ZZ, WW

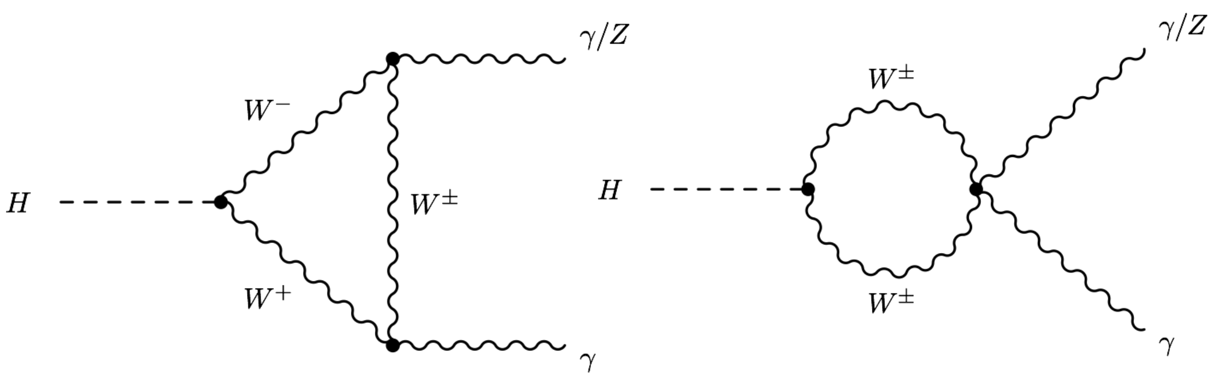


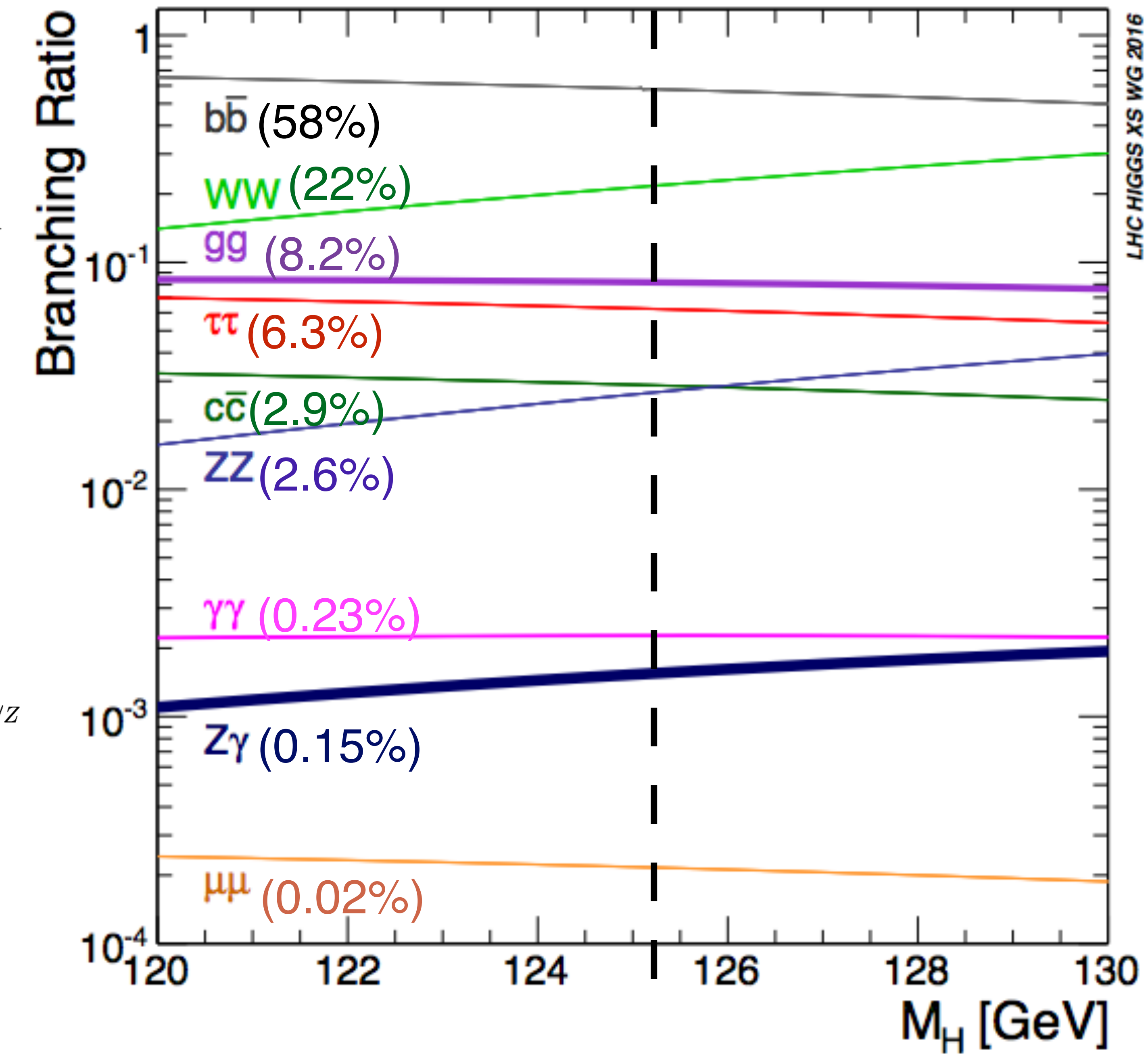
bb, ττ, μμ



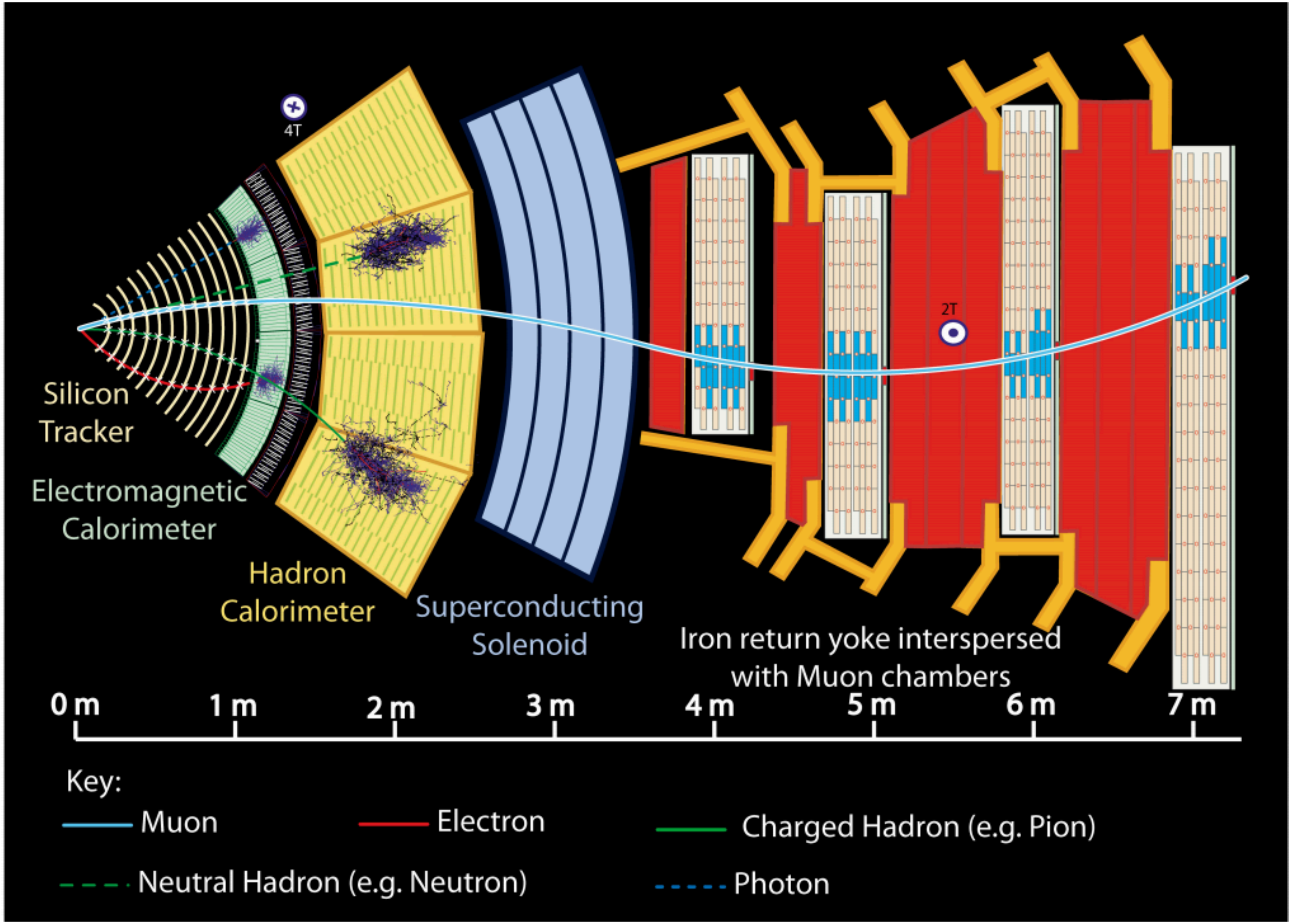
γγ, Zγ





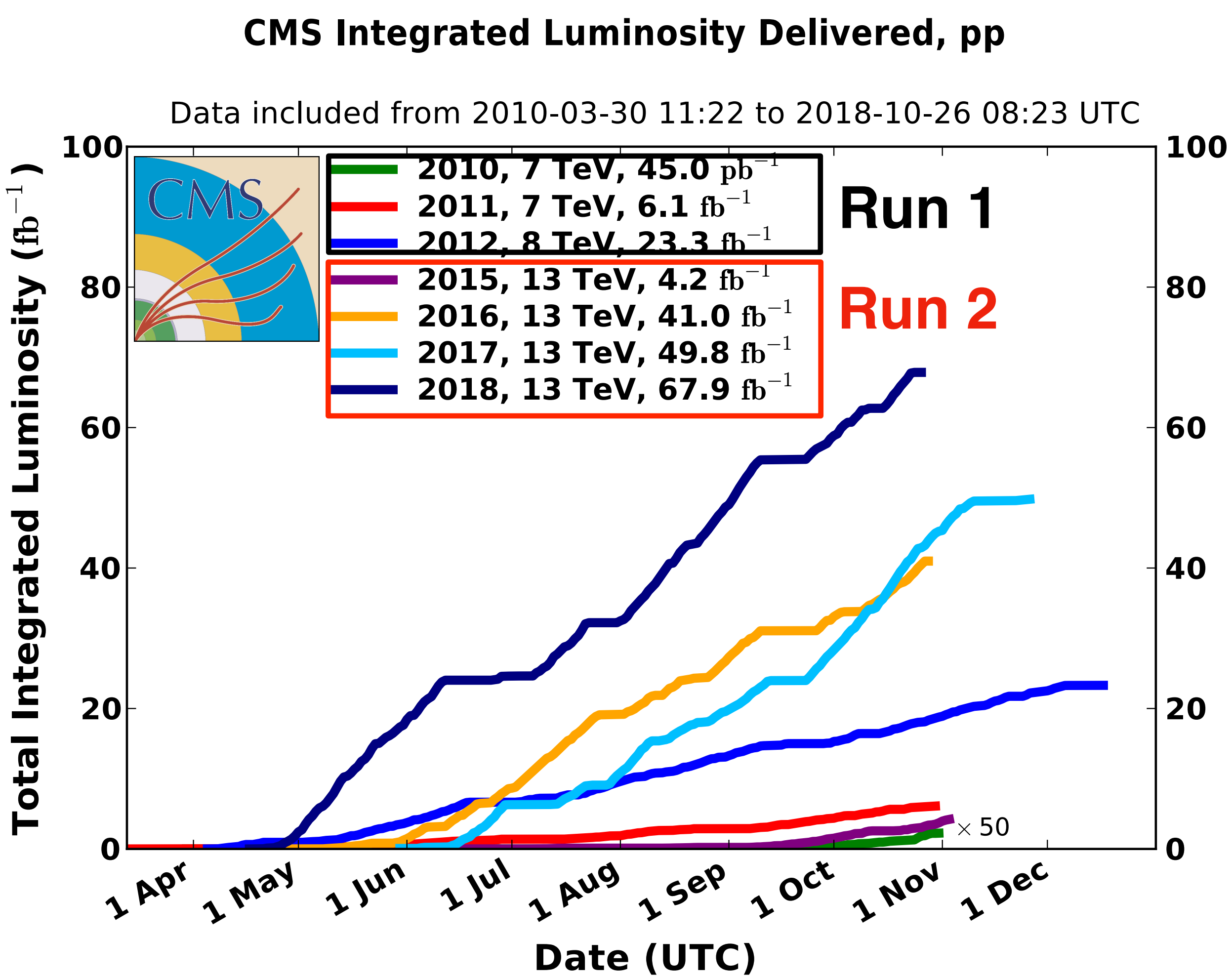


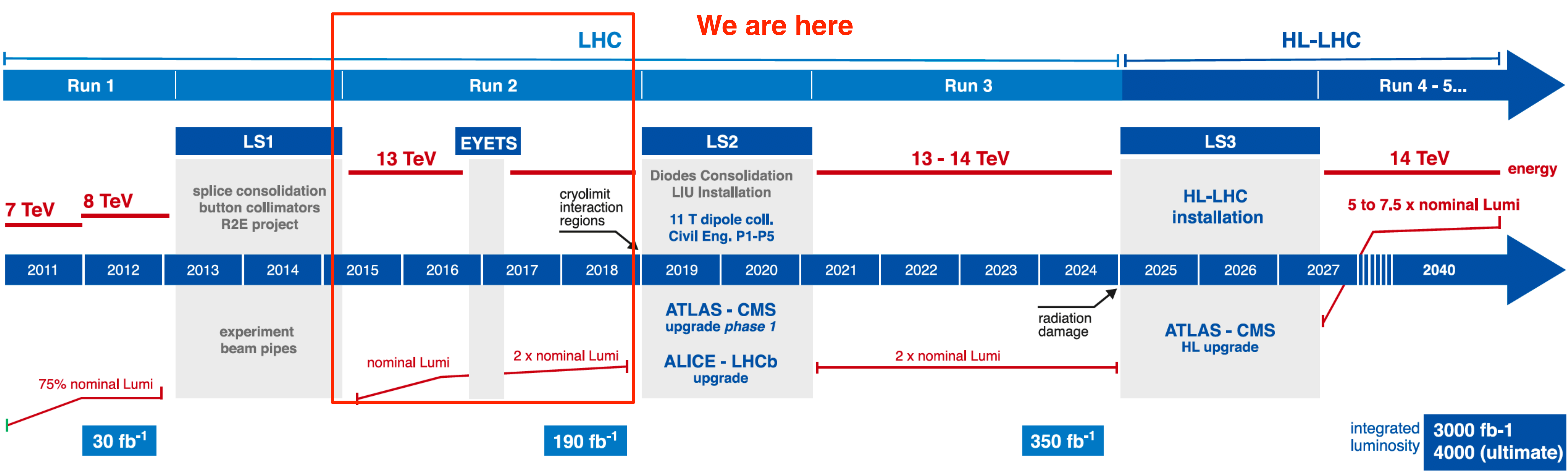
CMS Detector and Particle Flow



Run 2 data-taking

- **137 fb^{-1}** of **13 TeV** pp collision data collected for physics by the CMS detector in LHC Run 2
- Excellent performance of CMS detector and operation of the LHC

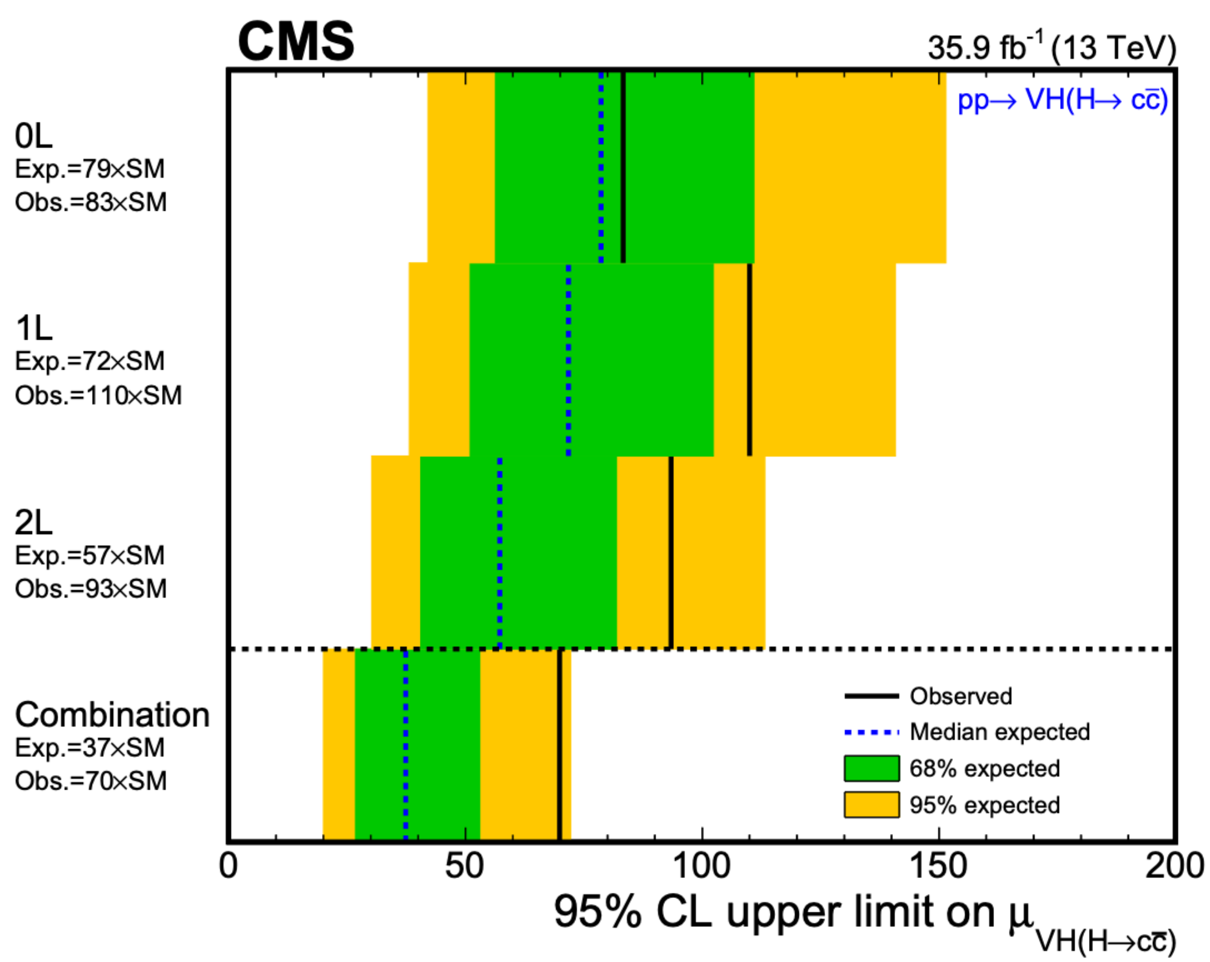




https://project-hl-lhc-industry.web.cern.ch/content/project-schedule

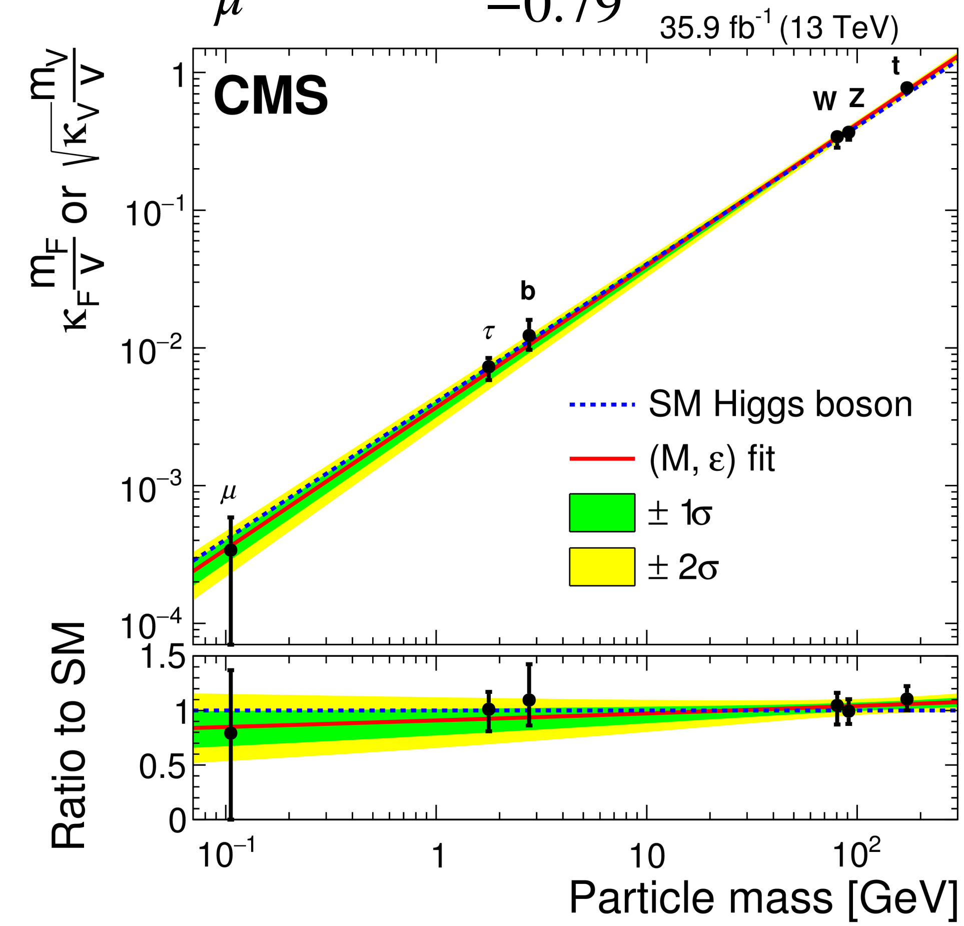
Why H→μμ ?

- Best way to **measure** Higgs Yukawa coupling to 2nd-generation fermions at LHC
  - H→cc is more challenging, currently best 95% CL limit on **σ**(VH)xB(H→cc): < 70 (expected: 37) ×SM, based on 36.1 /fb CMS data at 13 TeV
  - 3nd-generation fermions coupling directly measured in H→bb and H→**ττ** decays and ttH production
  - 1nd-generation fermions coupling beyond LHC reach



JHEP 03 (2020) 131

$\kappa_\mu = 0.79^{+0.58}_{-0.79}$ at 68% CL

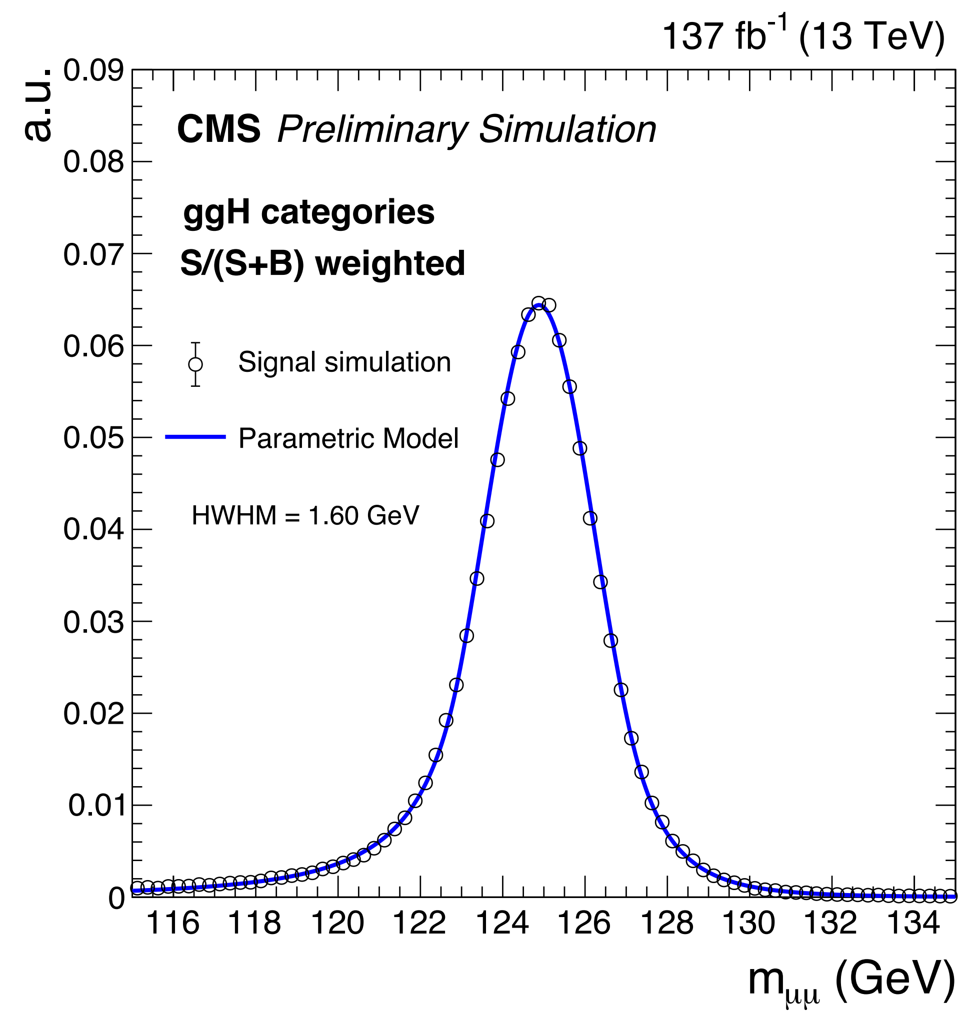


EPJC 79 (2019) 421

Introduction to H→μμ channel at CMS

H→μμ channel pro&cons:

- Narrow signal peak: **$\sigma(m_{\mu\mu})$~ 1.4 GeV**
  - Signal significance $\propto 1/\sqrt{\sigma(m_{\mu\mu})}$
  - Analysis level improvement to $\sigma(m_{\mu\mu})$:
    - FSR photon recovery: 2% improvement on $\sigma(m_{\mu\mu})$, 3% increase in signal yield.
    - Correction to muon pT by including interaction point position as an additional hit: 3-10% increase on $\sigma(m_{\mu\mu})$

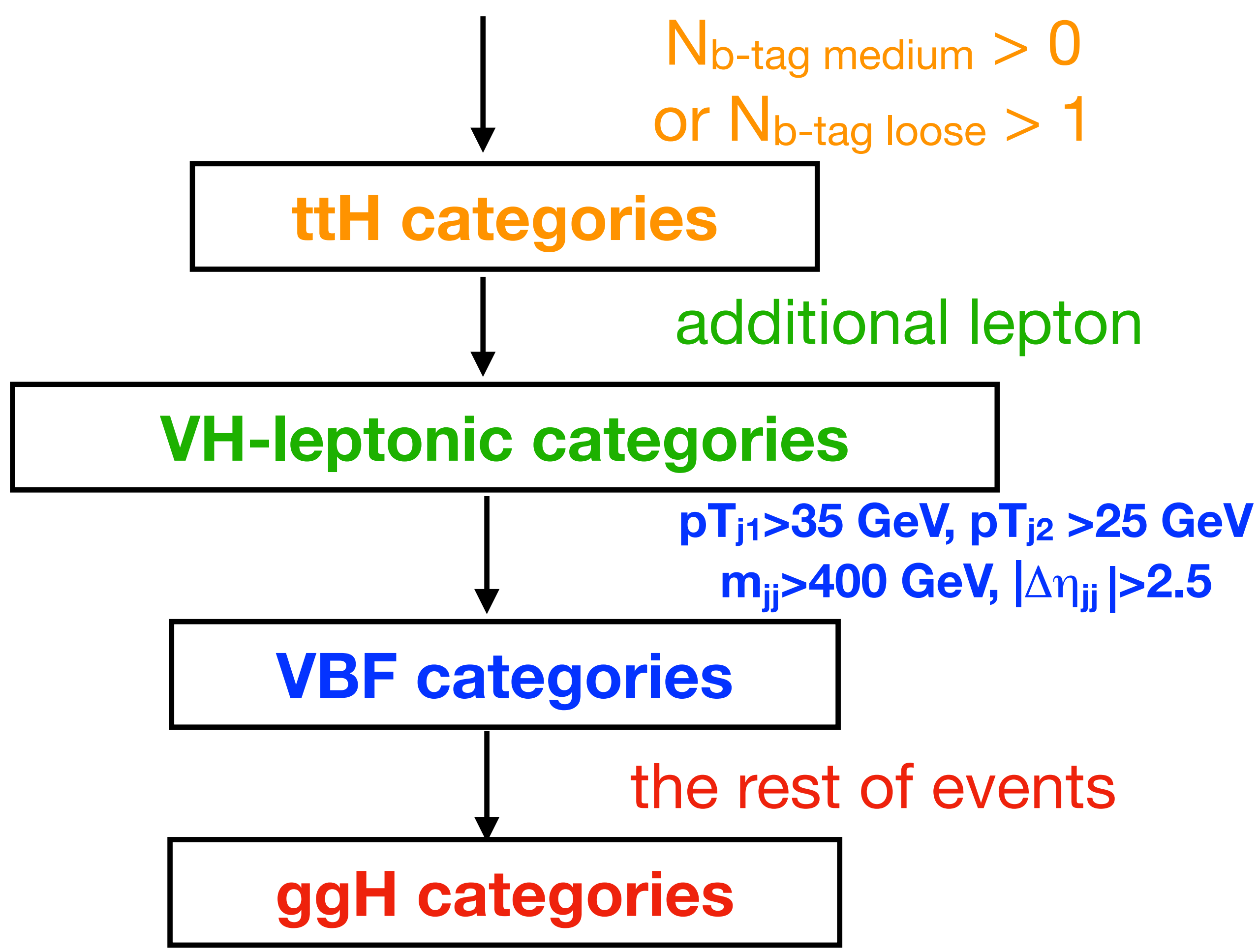


- Small branching ratio BR(H→μμ) ~2.2×10^{-4}
- Large background: **S/B~1/500, how to reduce background is a challenge**
  - dominated by Drell-Yan(DY) Z→μμ, electroweak production Z→μμ (EWZ)
  - other minor backgrounds: $t\bar{t}$, single top, diboson production

H→μμ analysis strategy overview

- Single muon high level trigger, muon pT>24 (2016, 2018)/27 (2017)
- Select event with two opposite charged and isolated muons of $|\eta|<2.4$, leading muon pT>26 (2016, 2018)/29 (2017), sub-leading muon pT>20 GeV
- Categorize events based on production modes => isolate events with high S/B

Exclusive categories



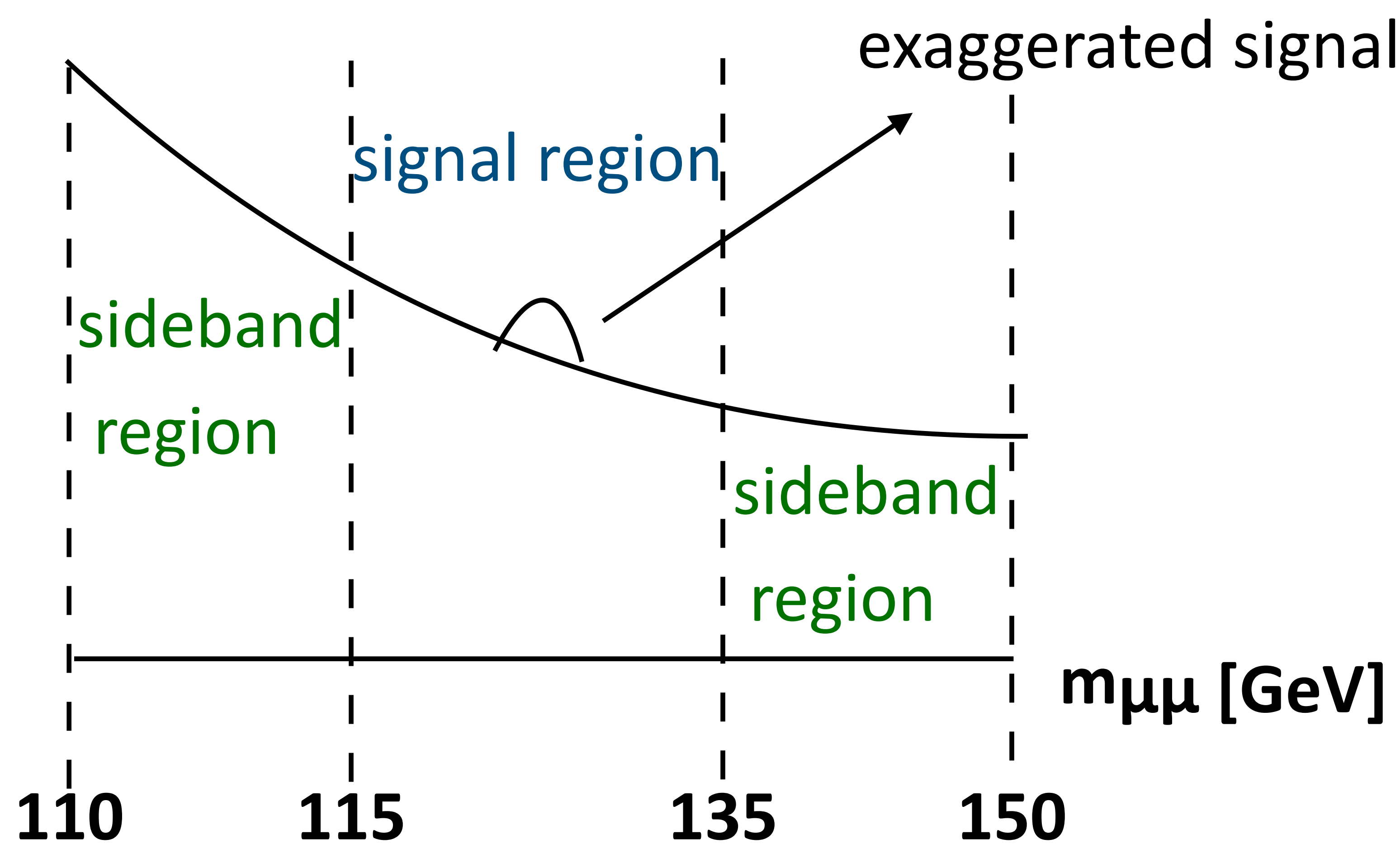
Analysis strategy:

- VBF: MC template fit
- ggH, ttH, VH: mass fit

VBF category overview

- Signal and sideband region (to constrain background prediction) defined based on $m_{\mu\mu}$
- A deep neural network (DNN) is used as final discriminant, the DNN is trained on kinematic information of the muons and two jets, $m_{\mu\mu}$ is included as a training variable

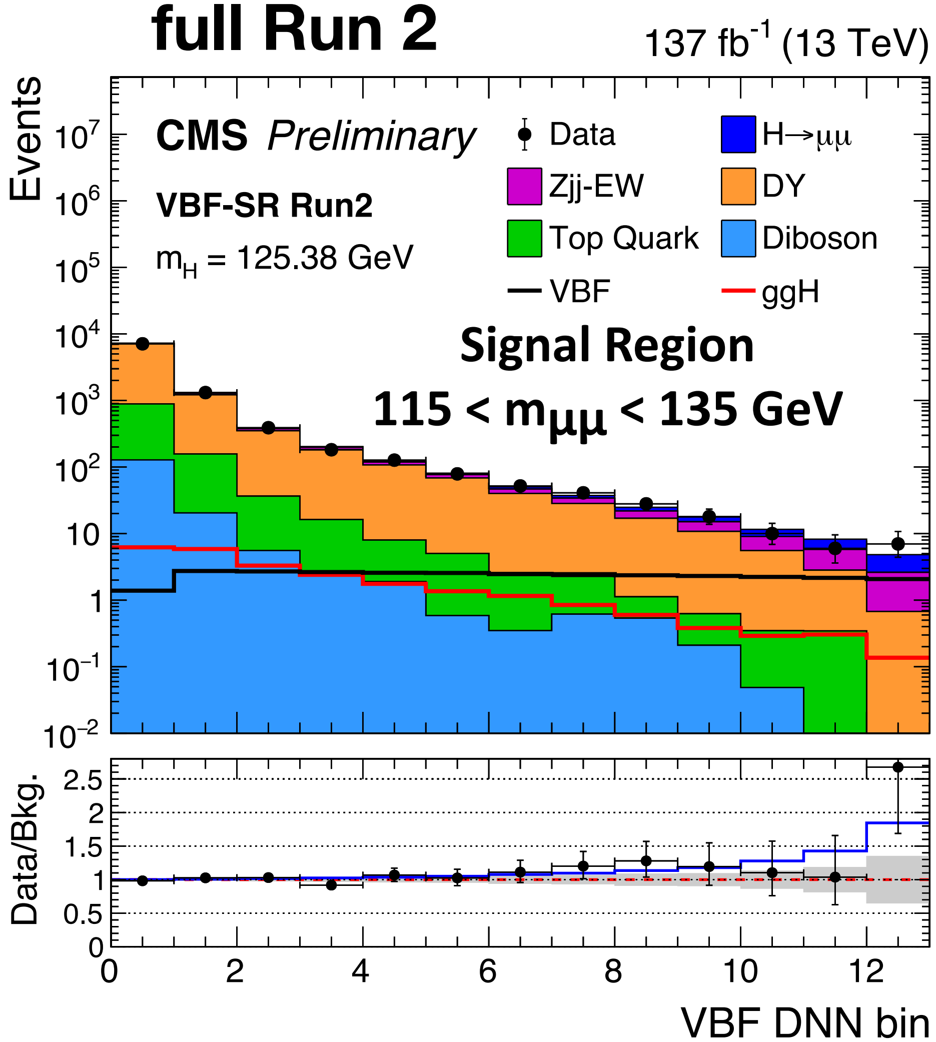
drawing of signal and control region definition



VBF category overview

- Achieve large S/B in the last few DNN bins.
  - last DNN bin S/B ~ 1 => cannot achieve same level of S/B with $m_{\mu\mu}$ fit method
  - with such large S/B, systematic uncertainties on the background MC templates smaller than uncertainty in background modeling if using $m_{\mu\mu}$ mass fit method
- 20% improvement in sensitivity compared to $m_{\mu\mu}$ mass fit method

full Run 2



- Sensitivity higher in last few bins:
  - main background processes are EWZ-jj, DY-jj

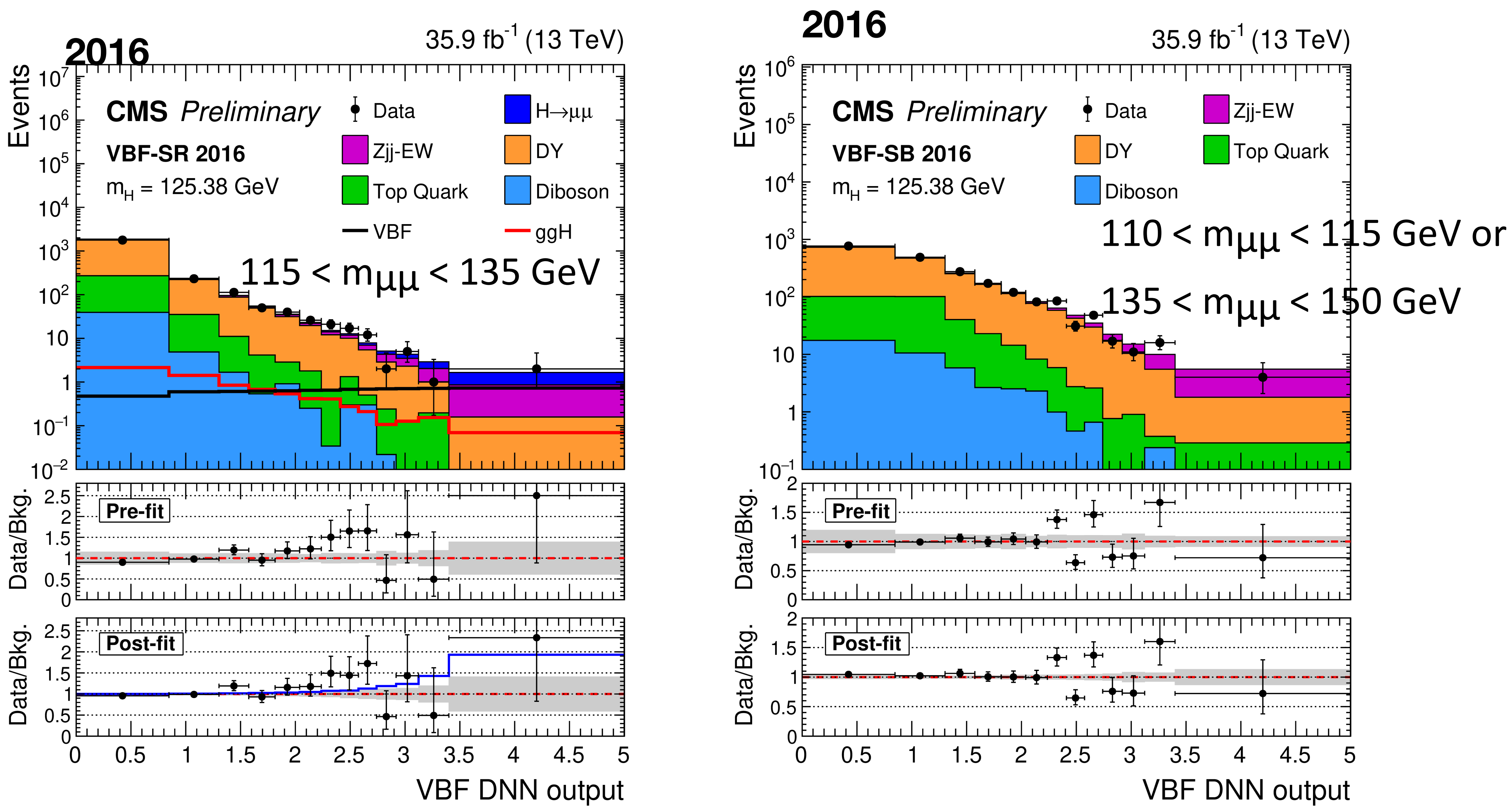
DNN bin	Signal	VBF (%)	ggH (%)	Bkg. ± ΔB	S/(S+B) (%)	$S/\sqrt{B}$	Data
1–3	19.5	30	70	8894 ± 67	0.22	0.21	8815
4–6	11.6	57	43	394 ± 8	2.90	0.59	388
7–9	8.43	73	27	103 ± 4	7.66	0.84	121
10	2.30	85	15	15.1 ± 1.4	13.2	0.60	18
11	2.15	88	12	9.1 ± 1.2	19.2	0.72	10
12	2.10	87	13	5.8 ± 1.1	26.7	0.88	6
13	1.87	94	6	2.6 ± 0.9	41.8	1.18	7

- observed (expected) significance is 2.40σ (1.77σ) , m_H = 125.38 GeV

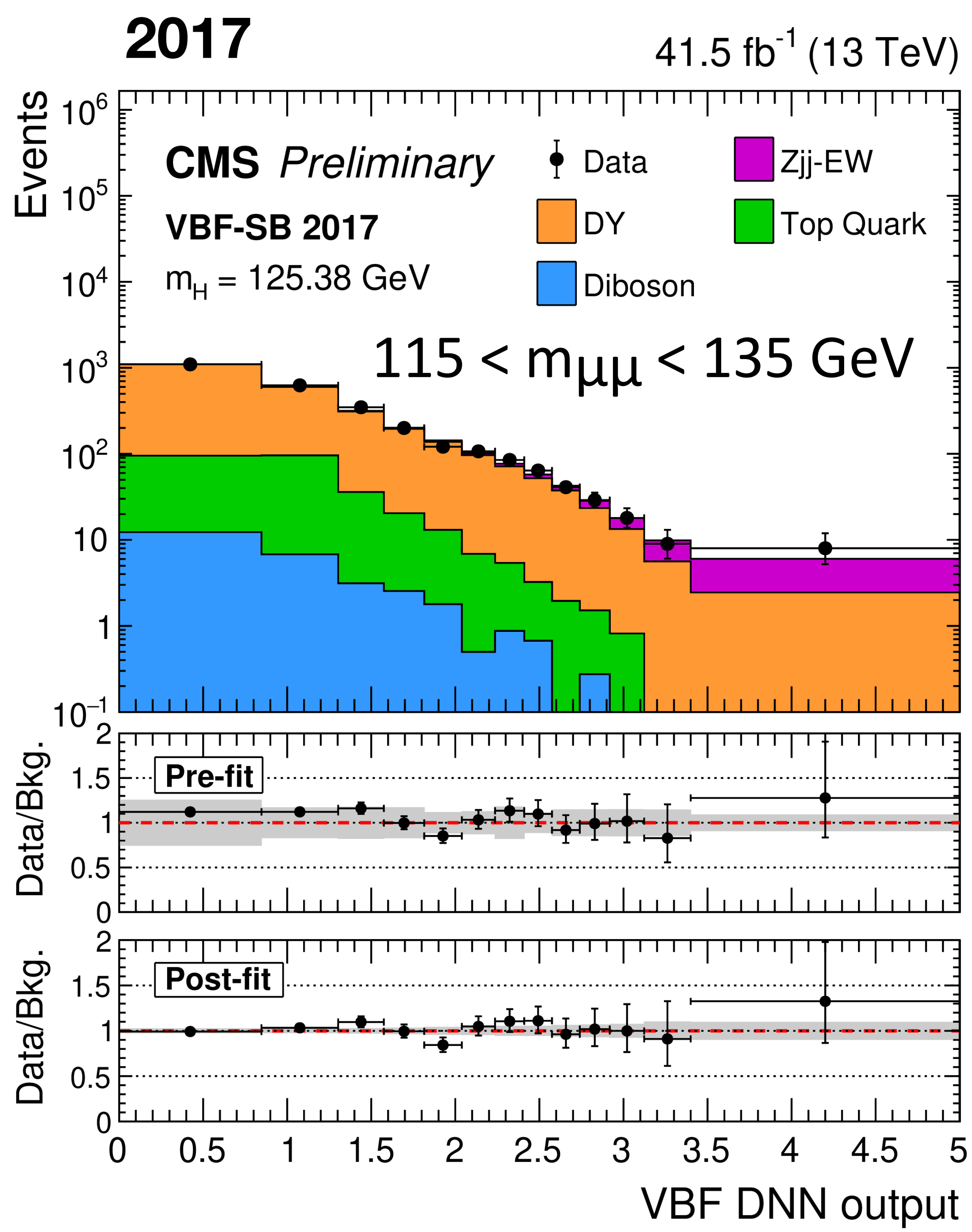
$m_{\mu\mu}$ - 0.38 GeV in DNN evaluation

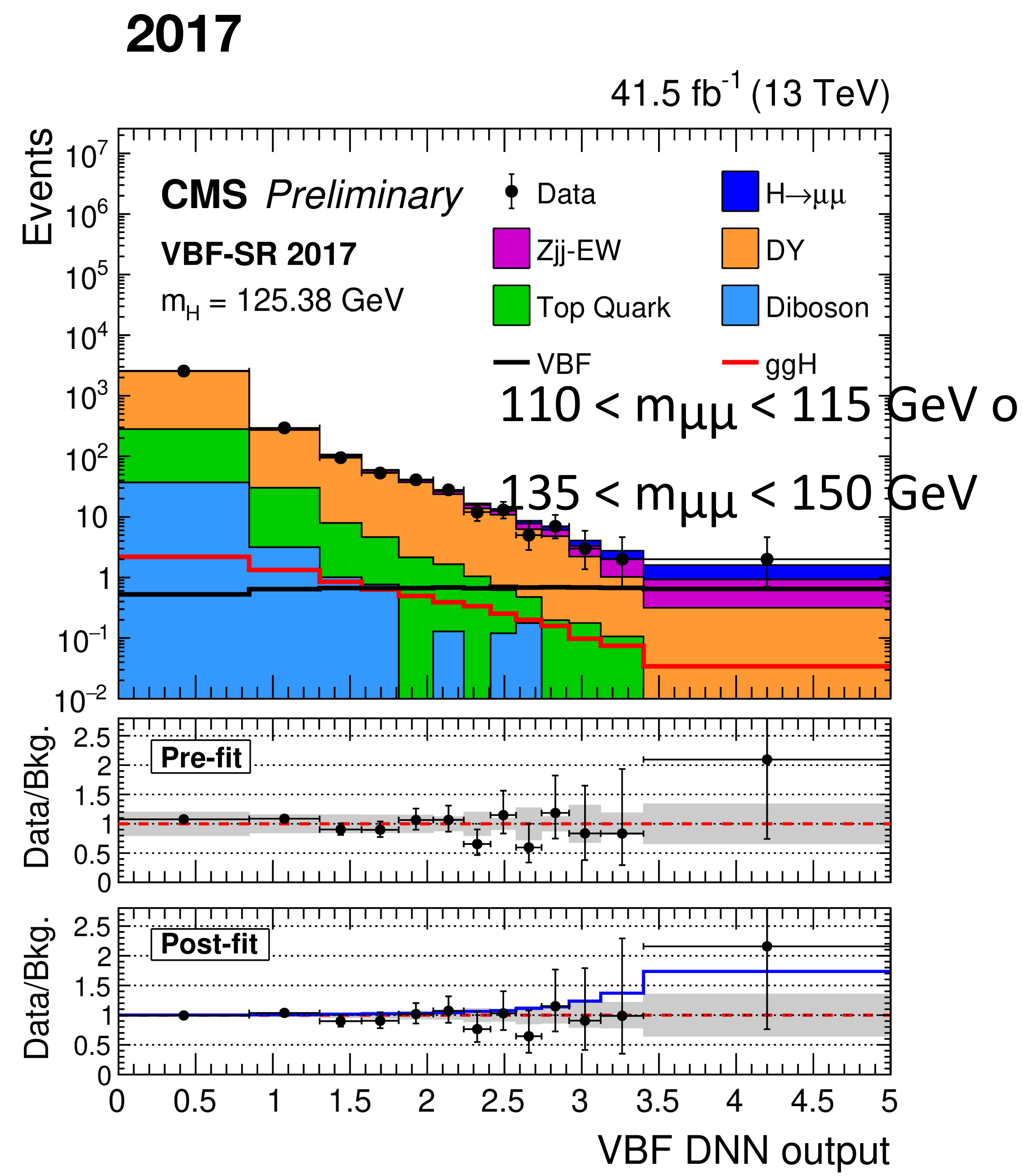
VBF category fitting strategy

- binned fit to data in DNN scores predicted by MC templates with systematic uncertainties, simultaneously in signal regions and sideband regions in three years => 6 VBF categories in total

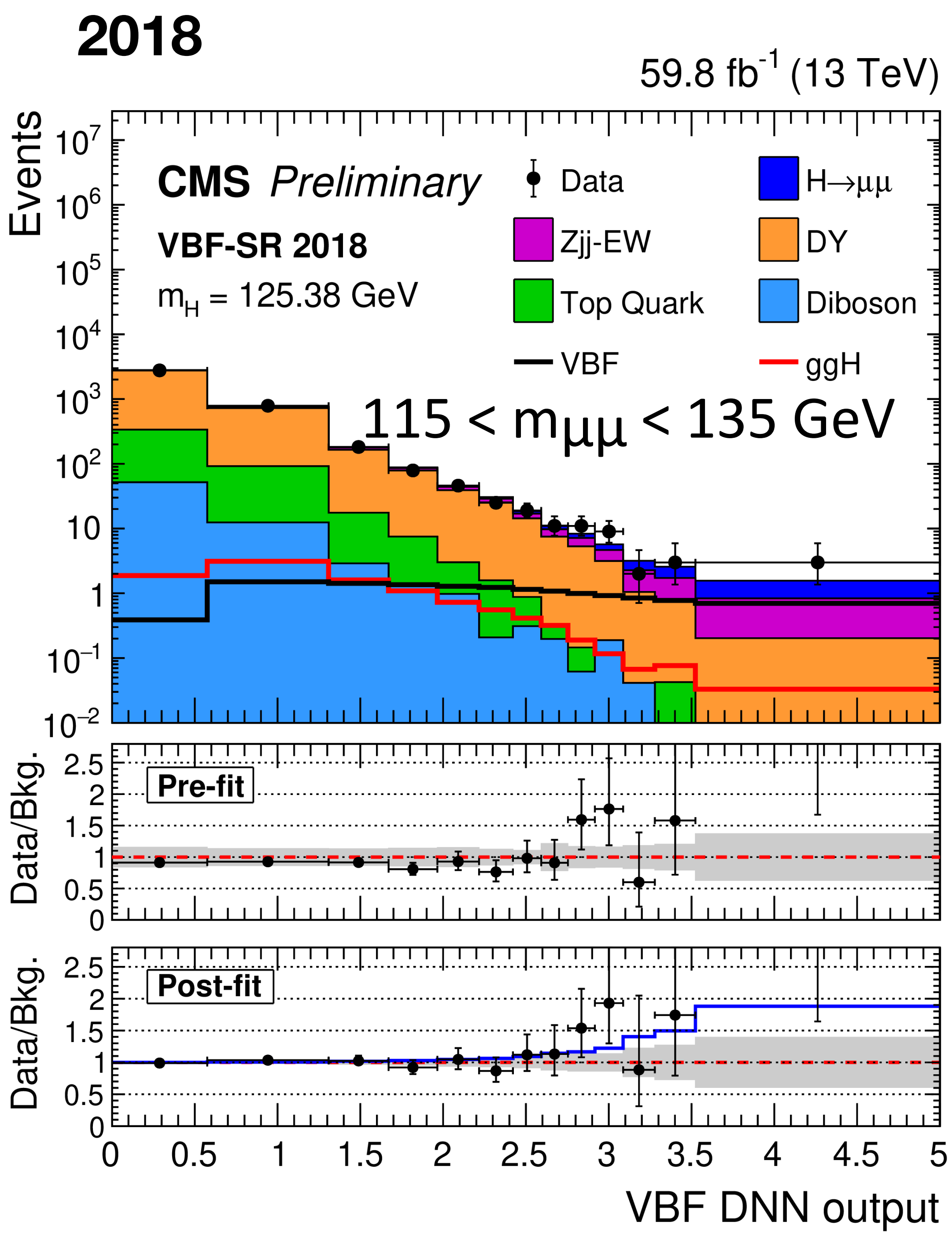


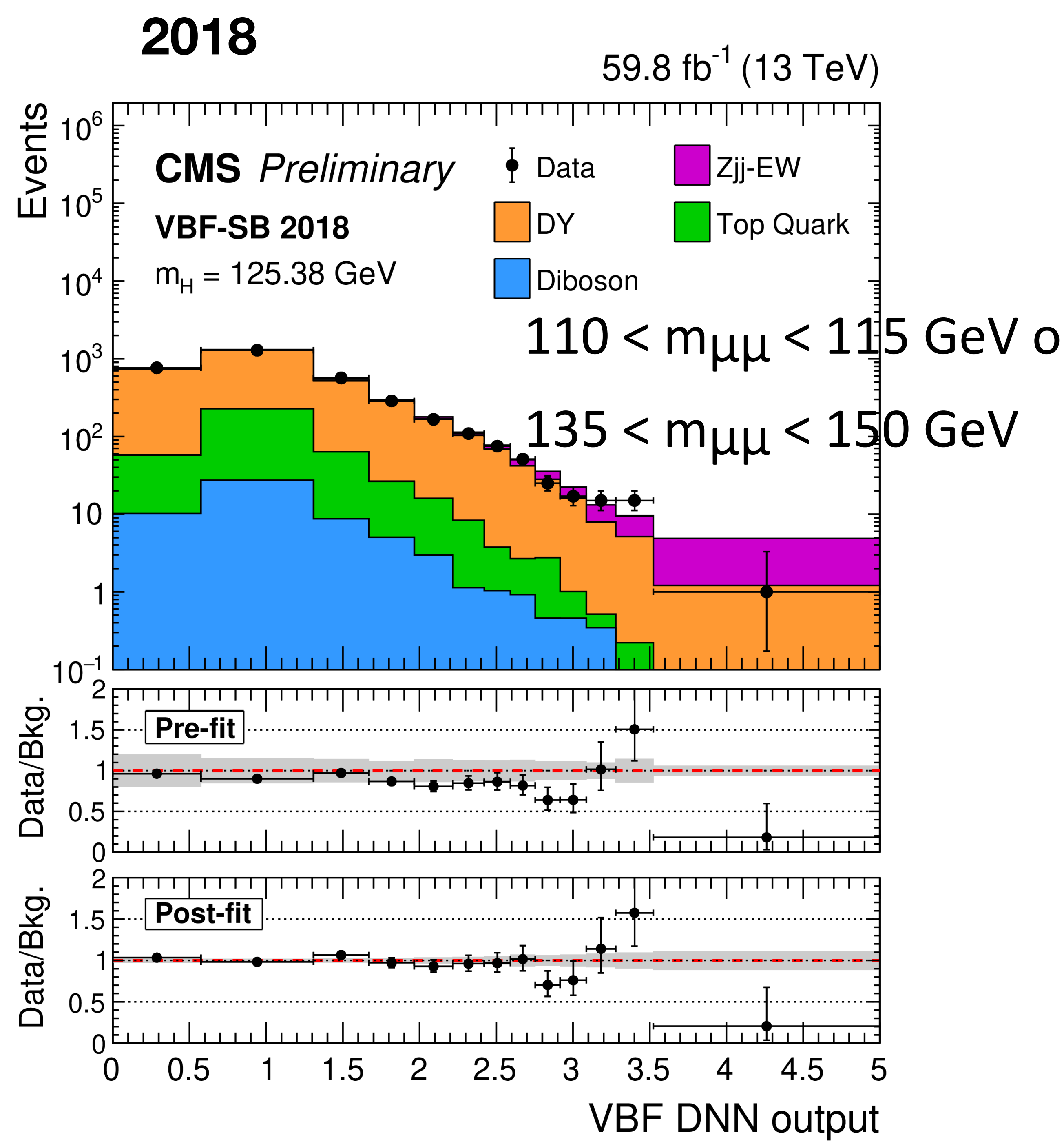
VBF category 2017 signal and sideband region



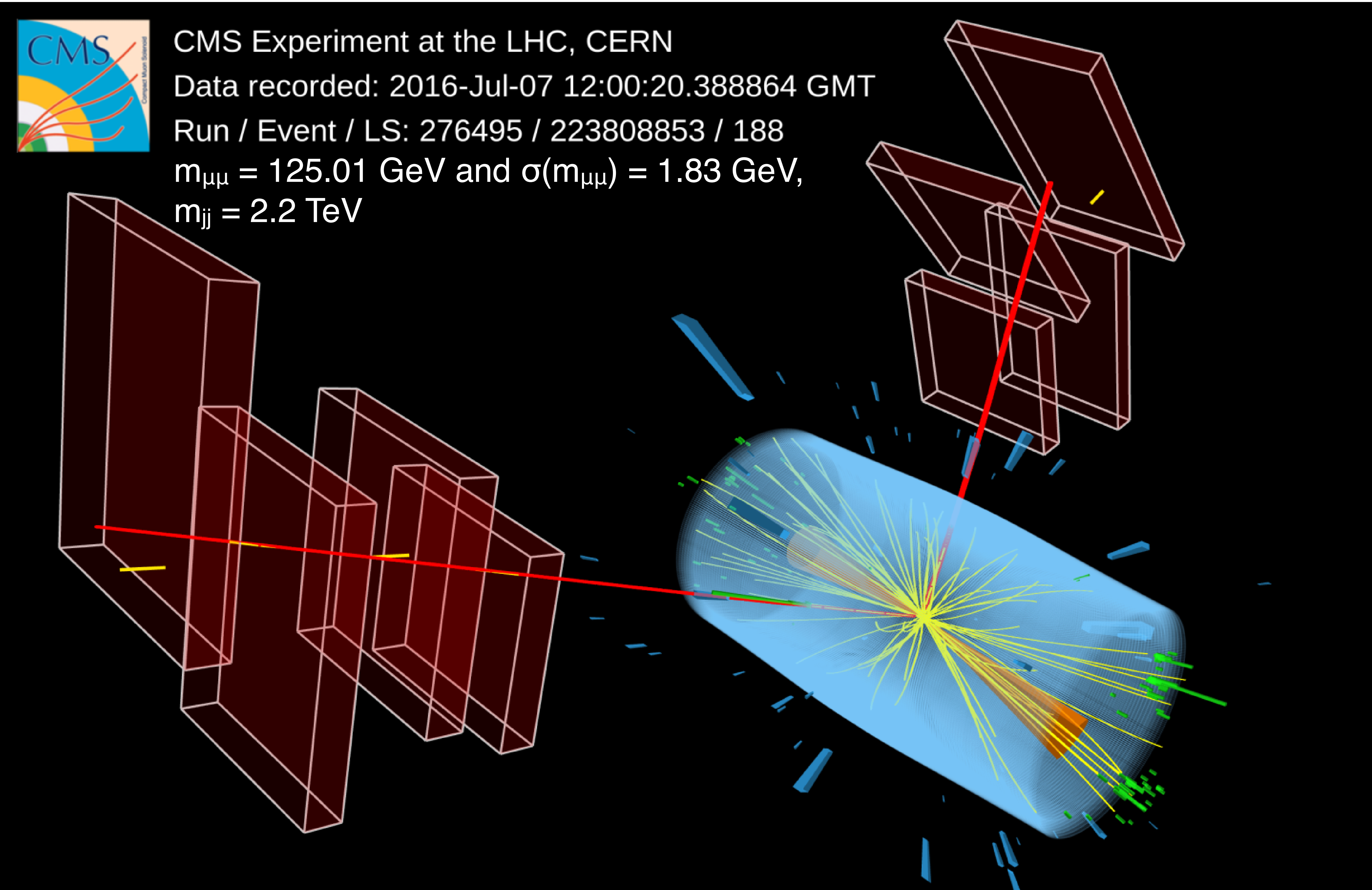


VBF category 2018 signal and sideband region



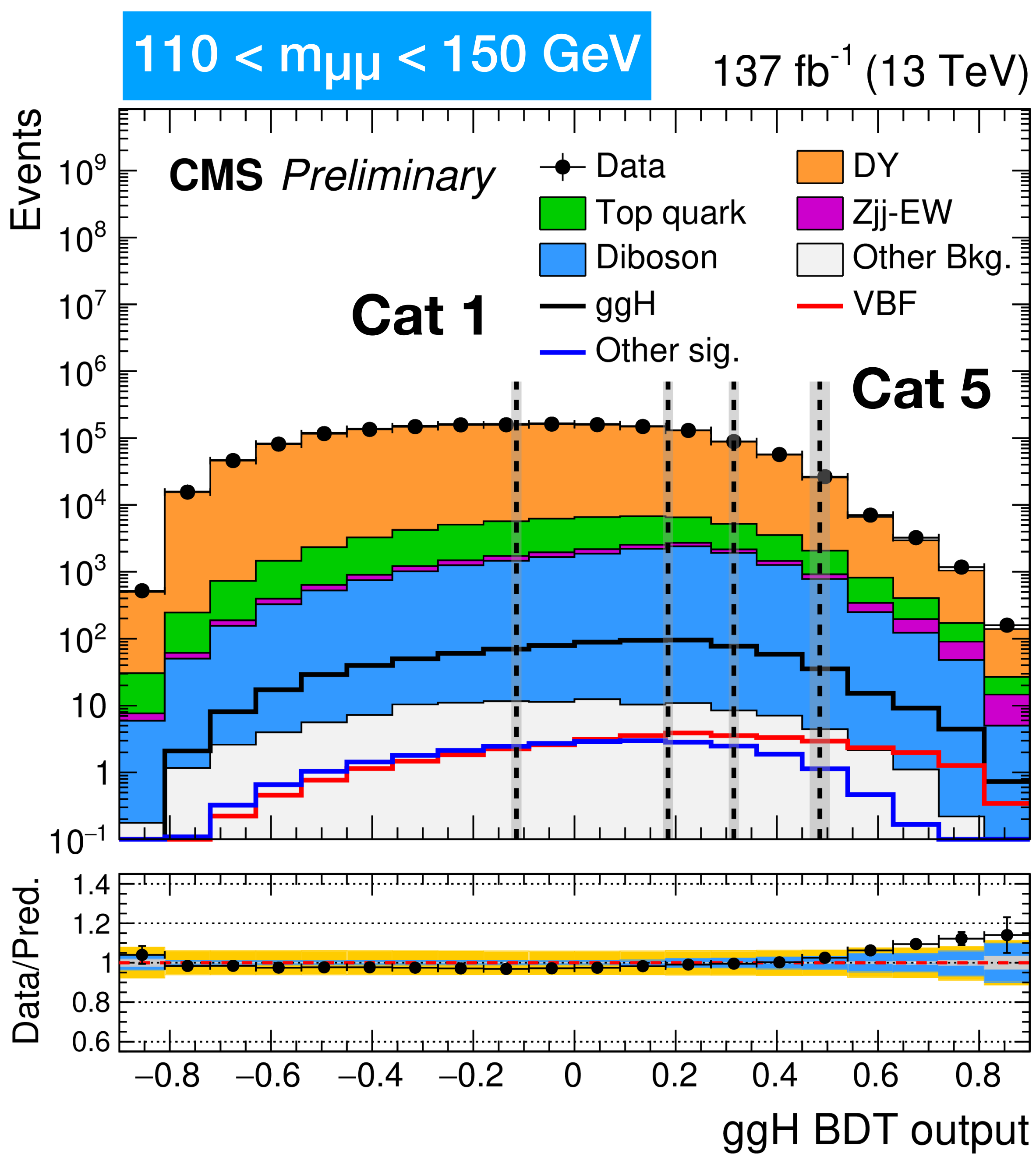


VBF candidate event



ggH category： BDT discriminant and categorization

- BDT trained using variables related to muon and jet kinematics information: does not learn $m_{\mu\mu}$
- Signal MC during BDT training assigned a weight ~ $1/\sigma_{\mu\mu}$ => increasing importance to the high-resolution signal events, thus improving $\sigma_{\mu\mu}/m_{\mu\mu}$ in the high BDT score region
- Cut on BDT score to define 5 ggH categories. S/B ~ 1% in most sensitive ggH category cat5

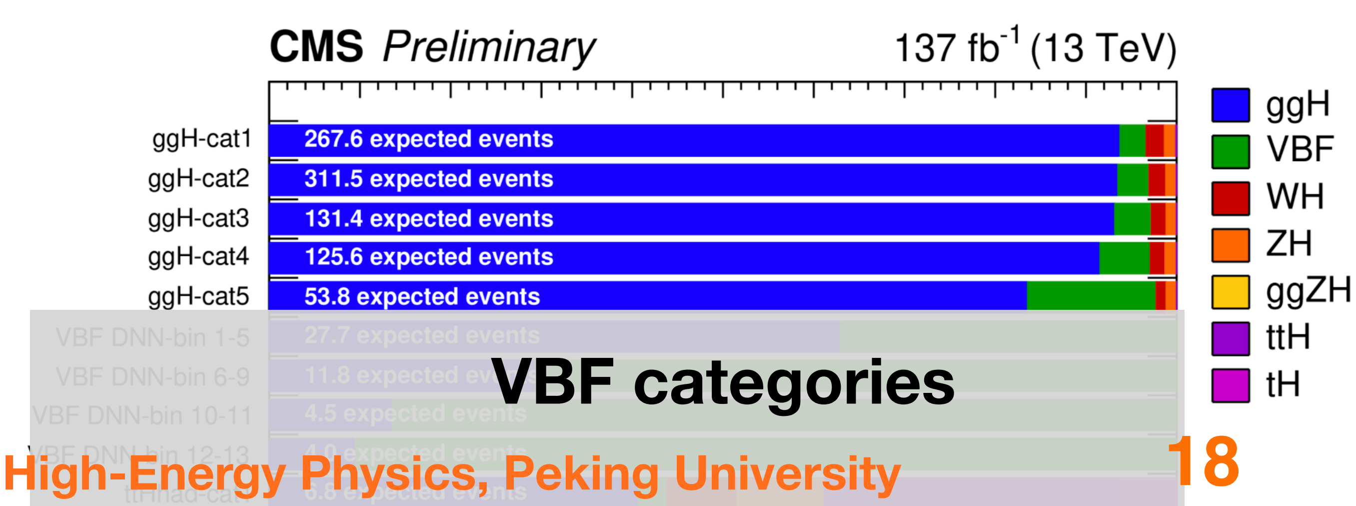


training variable

- $pT_{\mu\mu}$
- rapidity$_{\mu\mu}$
- $\cos(\theta_{CS})$
- ϕ_{CS}
- $pT_{\mu 1}/m_{\mu\mu}$
- $pT_{\mu 2}/m_{\mu\mu}$
- $\eta(\mu 1)$
- $\eta(\mu 2)$
- pT_{j1}
- η_{j1}
- pT_{j2}
- N_{jets}
- $\Delta\eta_{jj}$
- m_{jj}
- $\Delta\phi_{jj}$
- Zeppenfeld variable

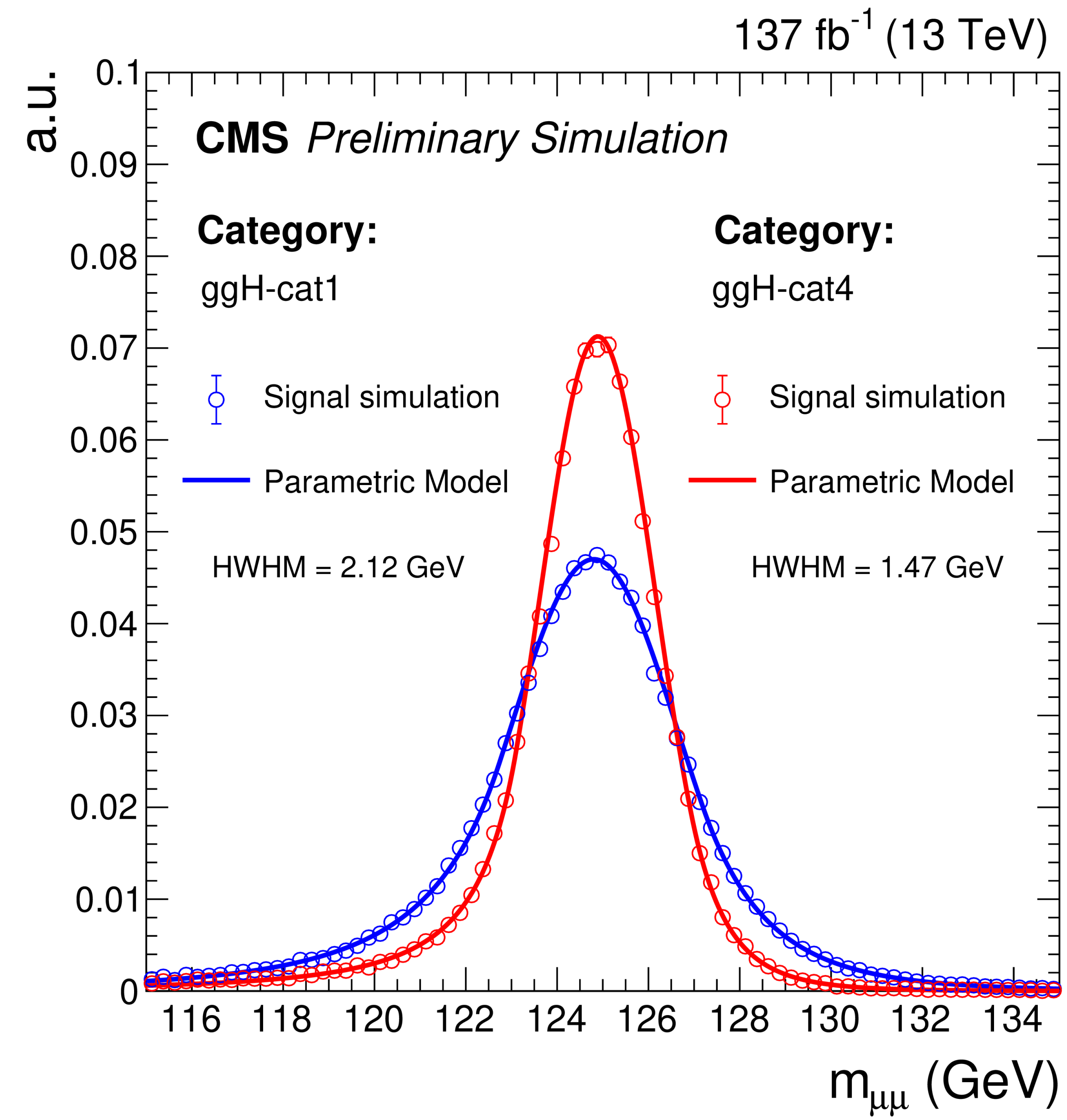
$$z^* = \frac{y_{\mu\mu} - (y_{j_1} + y_{j_2})/2}{|y_{j_1} - y_{j_2}|}$$

- min-$\Delta\phi(\mu\mu,(j1,j2))$
- min-$\Delta\eta(\mu\mu,(j1,j2))$



ggH category: signal modeling

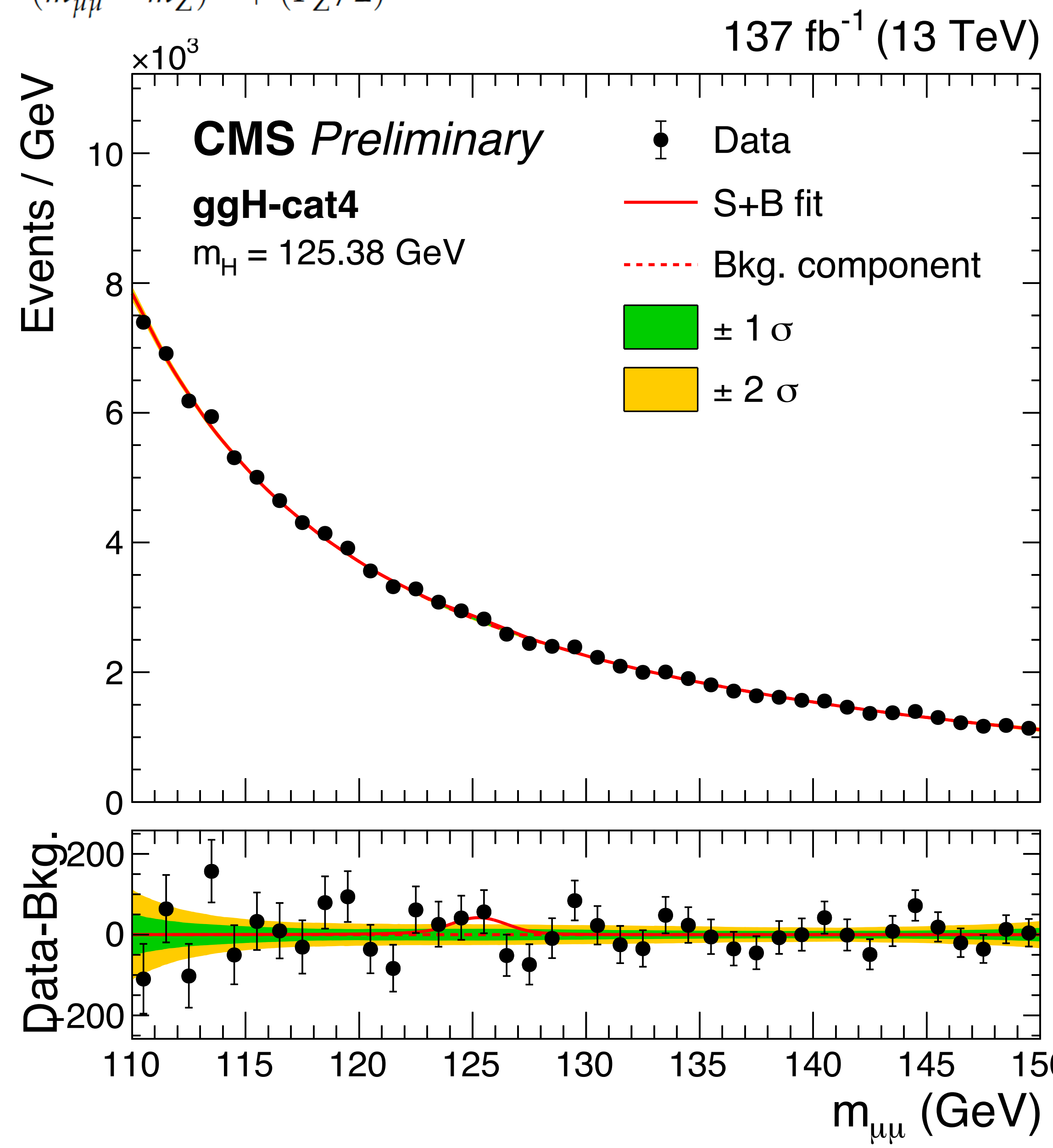
- Due to the weight $\propto 1/\sigma_{\mu\mu}$ applied to the signal MC in training the BDT, cat 4 has a smaller mass resolution than cat 1
- signal functional form: double-sided Crystal Ball function
  - Gaussian core with power-law tails on both sides
  - models well the signal in ttH and VH categories too, thus also used in ttH and VH categories.



$$\mathrm{DCB}(m_{\mu\mu}) = \begin{cases} e^{-(m_{\mu\mu}-\hat{m})^2/2\sigma^2} & -\alpha_\mathrm{L} < \frac{m_{\mu\mu}-\hat{m}}{\sigma} < \alpha_\mathrm{R} \\ \left(\frac{n_\mathrm{L}}{|\alpha_\mathrm{L}|}\right)^{n_\mathrm{L}} e^{-\alpha_\mathrm{L}^2/2}\left(\frac{n_\mathrm{L}}{|\alpha_\mathrm{L}|} - |\alpha_\mathrm{L}| - \frac{m_{\mu\mu}-\hat{m}}{\sigma}\right)^{-n_\mathrm{L}} & \frac{m_{\mu\mu}-\hat{m}}{\sigma} \leq -\alpha_\mathrm{L} \\ \left(\frac{n_\mathrm{R}}{|\alpha_\mathrm{R}|}\right)^{n_\mathrm{R}} e^{-\alpha_\mathrm{R}^2/2}\left(\frac{n_\mathrm{R}}{|\alpha_\mathrm{R}|} - |\alpha_\mathrm{R}| - \frac{m_{\mu\mu}-\hat{m}}{\sigma}\right)^{-n_\mathrm{R}} & \frac{m_{\mu\mu}-\hat{m}}{\sigma} \geq \alpha_\mathrm{R} \end{cases}$$

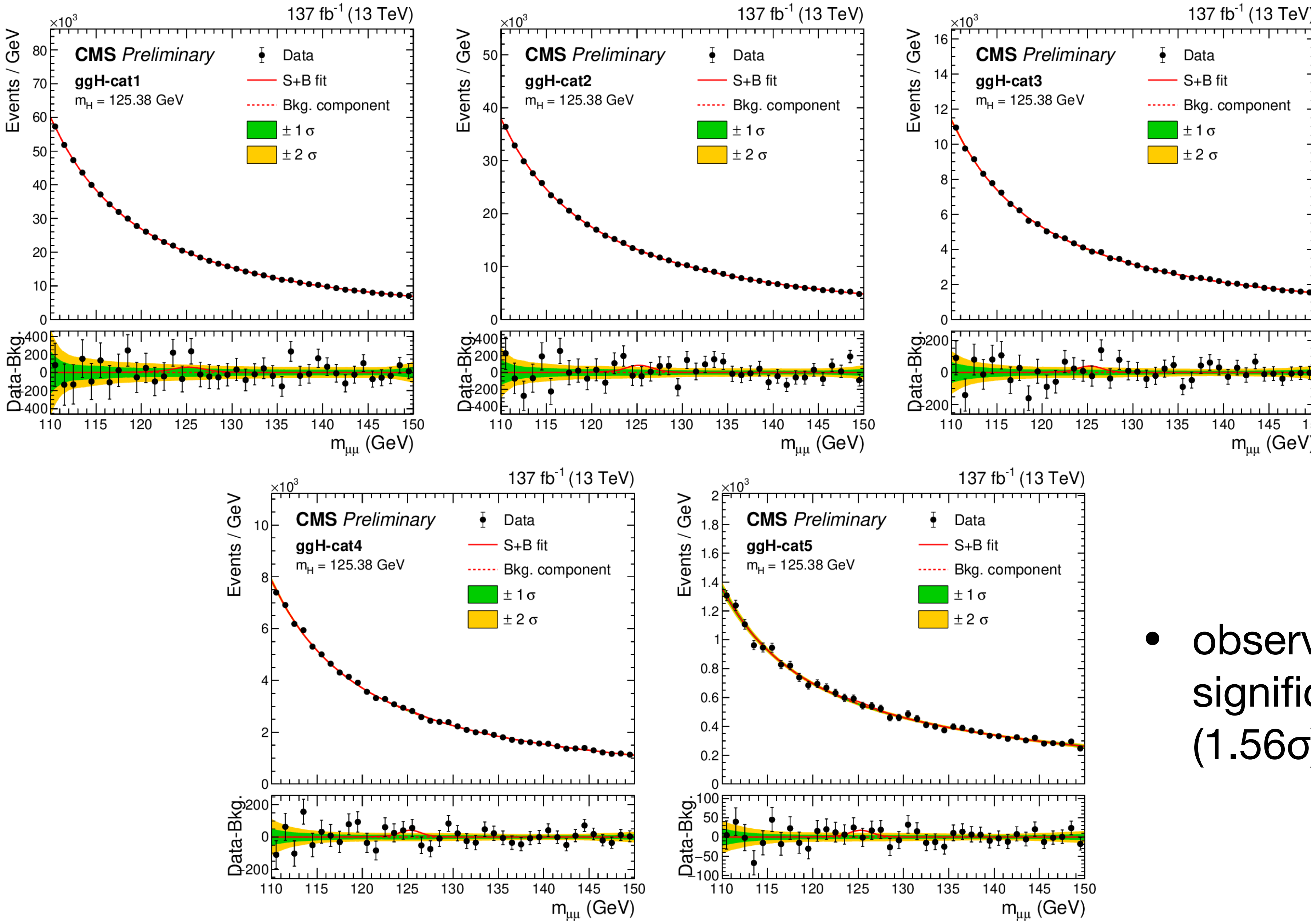
ggH category: background modeling

- background model with analytical functions: core-pdf method
  - core: discrete profiling of 3 kinds:
    - modified Breit–Wigner $\mathrm{mBW}(m_{\mu\mu}; m_Z, \Gamma_Z, a_1, a_2, a_3) = \frac{e^{a_2 m_{\mu\mu} + a_3 m_{\mu\mu}^2}}{(m_{\mu\mu} - m_Z)^{a_1} + (\Gamma_Z/2)^{a_1}}$
    - a sum of two exponential functions
    - shape derived from the FEWZ v3.1 generator × a third-order Bernstein polynomial
  - polynomial term specific to each event category modulates the core shape



- Robust against bias while preserving good performance
- Expected DY background dominating all categories (90-95%)

ggH category: mass fit



- observed(expected) significance is 0.99σ (1.56σ), m_H = 125.38 GeV

Category	Sig.	ggH (%)	VBF (%)	VH + $t\bar{t}$H (%)	HWHM (GeV)	Bkg. in HWHM	S/(S+B) (%) in HWHM	$S/\sqrt{B}$ in HWHM	Data in HWHM
ggH-cat1	267.6	93.7	2.9	3.4	2.12	86359	0.20	0.60	86632
ggH-cat2	311.5	93.5	3.4	3.1	1.75	46347	0.46	0.98	46393
ggH-cat3	131.4	93.2	4.0	2.8	1.60	12655	0.70	0.80	12738
ggH-cat4	125.6	91.5	5.5	3.0	1.47	8259	1.03	0.96	8377
ggH-cat5	53.8	83.5	14.3	2.2	1.50	1678	2.16	0.91	1711

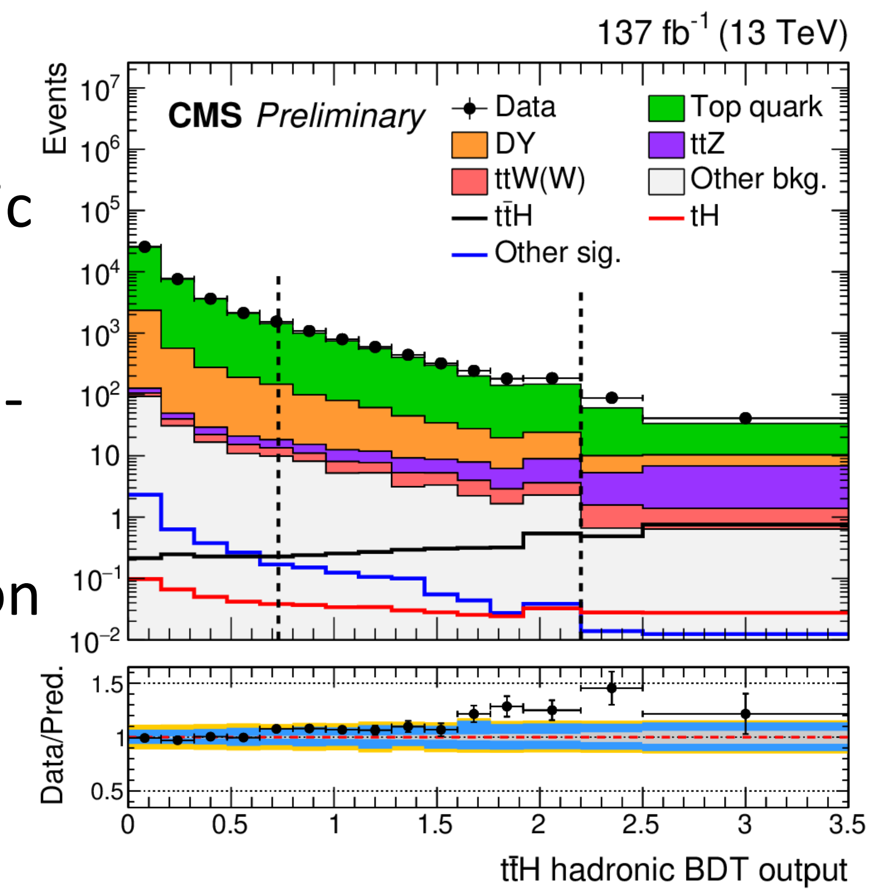
ttH category: overview

- Presence of a pair of top quarks in addition to the Higgs boson

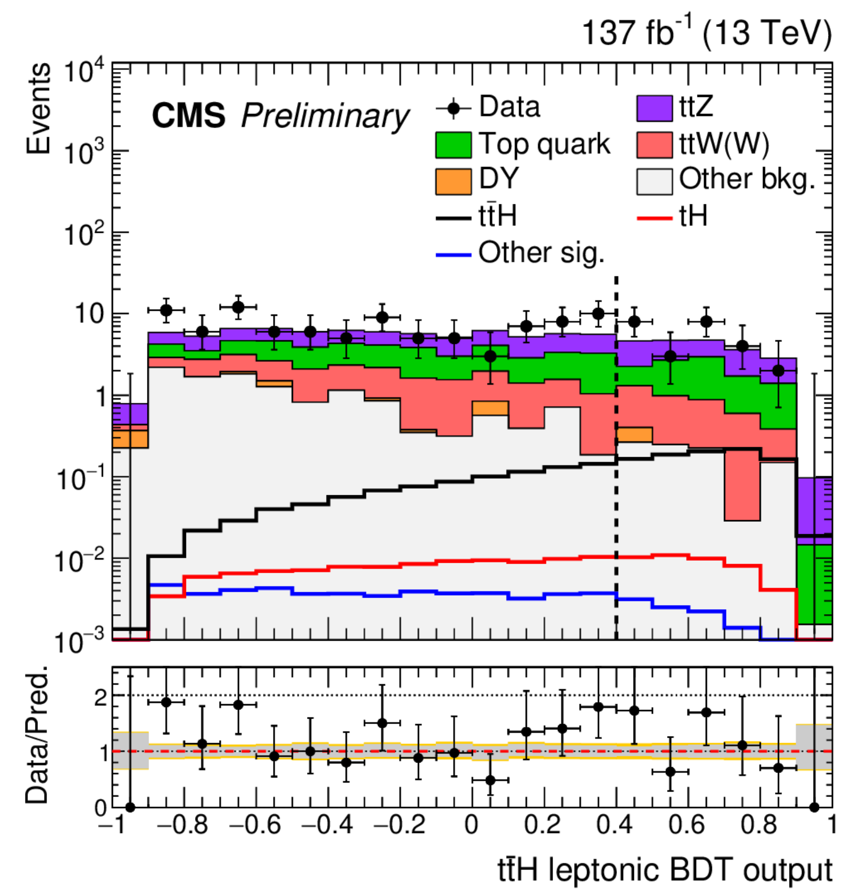
Selection	$t\bar{t}$H hadronic	$t\bar{t}$H leptonic
Number of b quark jets	> 0 medium or > 1 loose b-tagged jets	
Number of leptons	2	3 or 4
Lepton charge	$\sum q(\ell) = 0$	$\mathrm{N}(\ell) = 3\ (4) \rightarrow \sum q(\ell) = \pm 1\ (0)$
Jet multiplicity ($p_\mathrm{T} > 25\,\mathrm{GeV}$, $\lvert\eta\rvert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

- Fit $m_{\mu\mu}$ to data. background functional form using agnostic functions:
  - second-order Bernstein polynomial for ttH-hadronic
  - a sum of two exponentials (single exponential) for ttH-leptonic
- Two BDTs based on information on kinematic information of top quark and the muon pair, additional lepton, MET

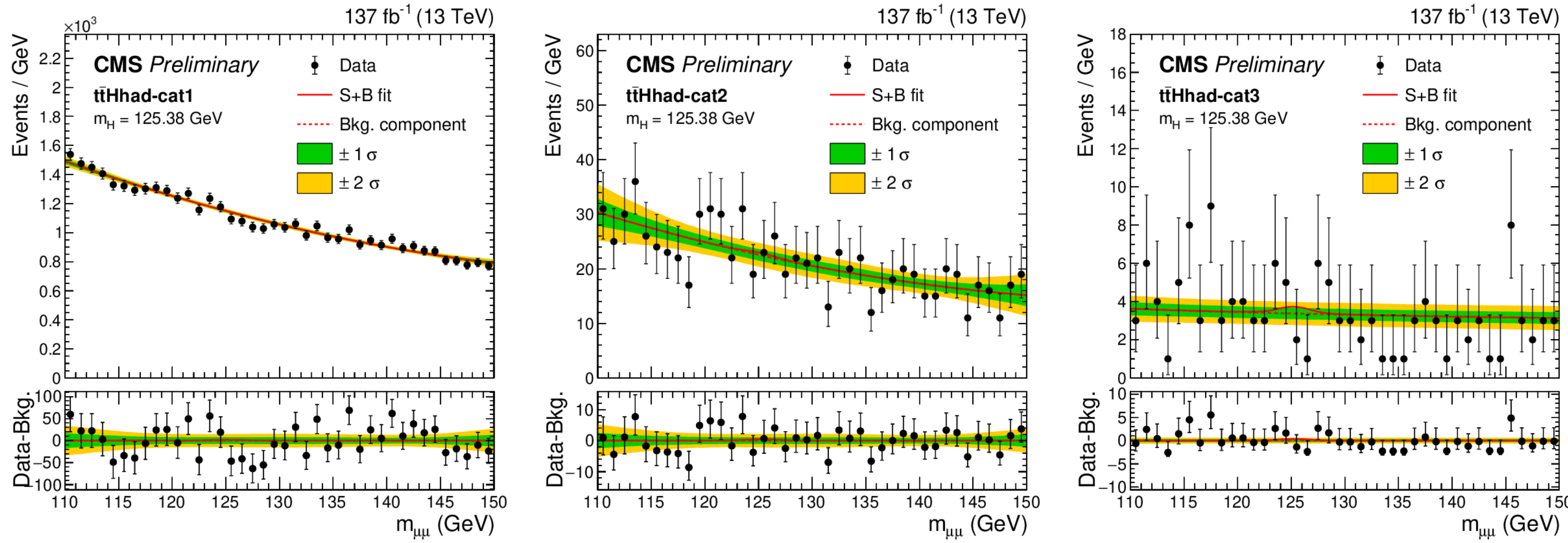
3 ttH hadronic categories main background: ttbar

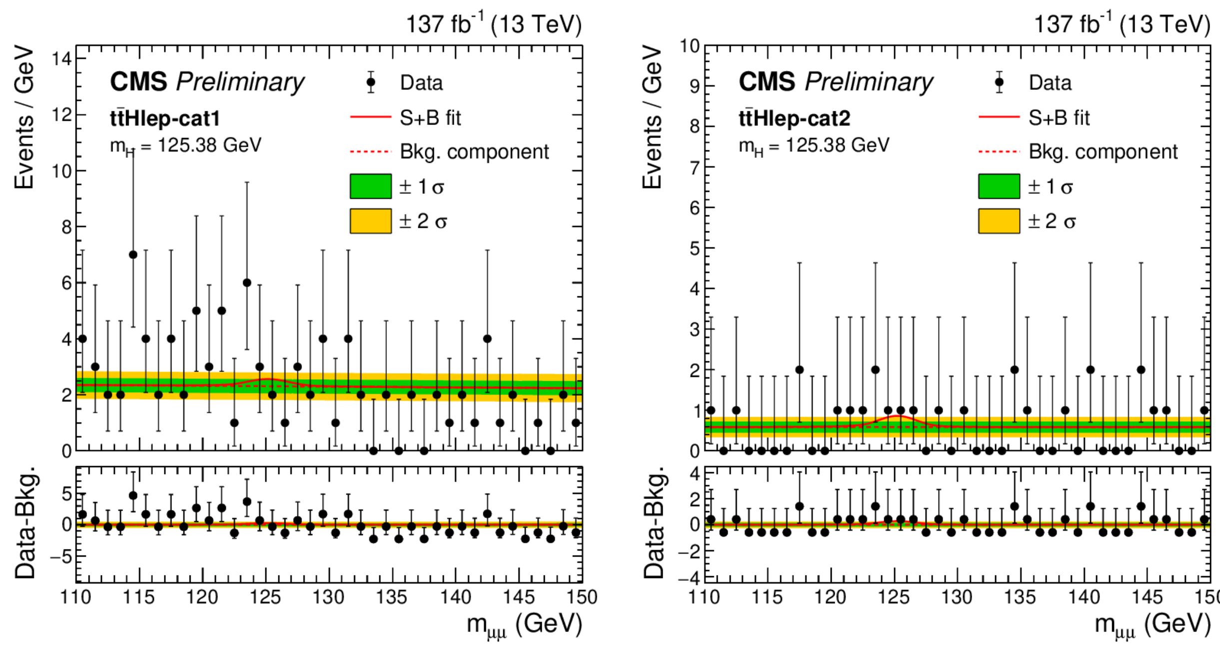


2 ttH leptonic categories main bkg: ttZ



ttH category: mass fit

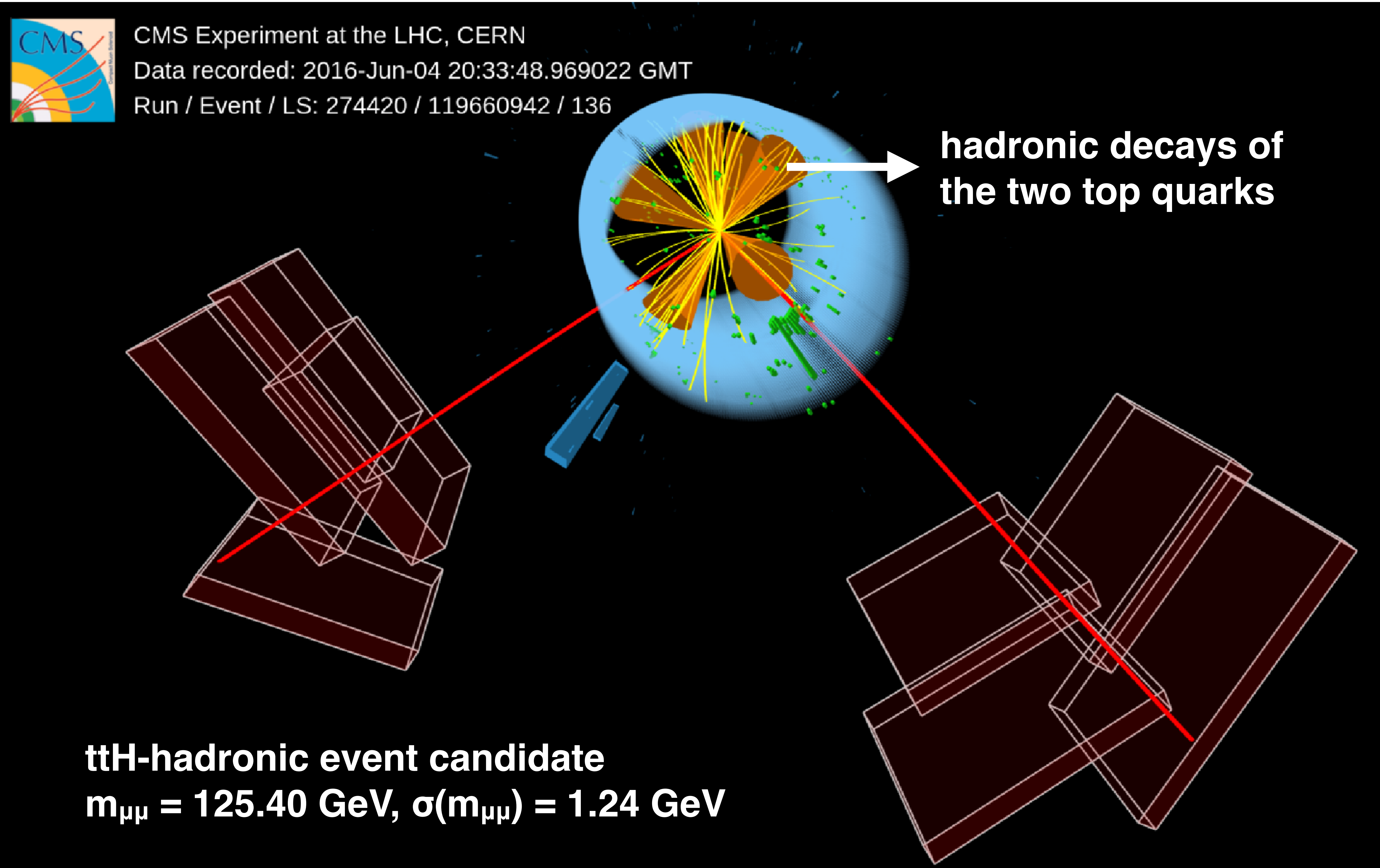




- observed(expected) significance is 1.20σ (0.54σ) , m_H = 125.38 GeV

Category	Sig.	tt̄H (%)	ggH (%)	VH (%)	tH (%)	VBF+bb̄H (%)	HWHM (GeV)	Bkg. in HWHM	S/(S+B) (%) in HWHM	$S/\sqrt{B}$ in HWHM	Data in HWHM
tt̄Hhad-cat1	6.87	32.3	40.3	17.2	6.2	4.0	1.85	4298	1.07	0.07	4251
tt̄Hhad-cat2	1.62	84.3	3.8	5.6	6.2	—	1.81	82.0	1.32	0.12	89
tt̄Hhad-cat3	1.33	94.0	0.3	1.3	4.2	0.2	1.80	12.3	6.87	0.26	12
tt̄Hlep-cat1	1.06	85.8	—	4.7	9.5	—	1.92	9.00	7.09	0.22	13
tt̄Hlep-cat2	0.99	94.7	—	1.0	4.3	—	1.75	2.08	24.5	0.47	4

ttH candidate events



VH category: overview

- Higgs decays to muon, and at least one additional lepton

Selection	WH leptonic		ZH leptonic	
	$\mu\mu\mu$	$\mu\mu e$	4μ	$2\mu 2e$
Number of loose (medium) b-tagged jets	≤ 1 (0)	≤ 1 (0)	≤ 1 (0)	≤ 1 (0)
N(μ) passing id.+iso.	3	2	4	2
N(e) passing id.+iso.	0	1	0	2
Lepton charge	$\sum q(\ell) = \pm 1$		$\sum q(\ell) = 0$	
Low mass resonance veto	$m_{\ell\ell} > 12\,\text{GeV}$			
N($\mu^+\mu^-$) pairs with $110 < m_{\mu\mu} < 150\,\text{GeV}$	≥ 1	1	≥ 1	1
N($\mu^+\mu^-$) pairs with $\|m_{\mu\mu} - m_Z\| < 10\,\text{GeV}\|$	0	0	1	0
N(e^+e^-) pairs with $\|m_{ee} - m_Z\| < 20\,\text{GeV}\|$	0	0	0	1

- Background functional form: modified Breit–Wigner

WH-cat1

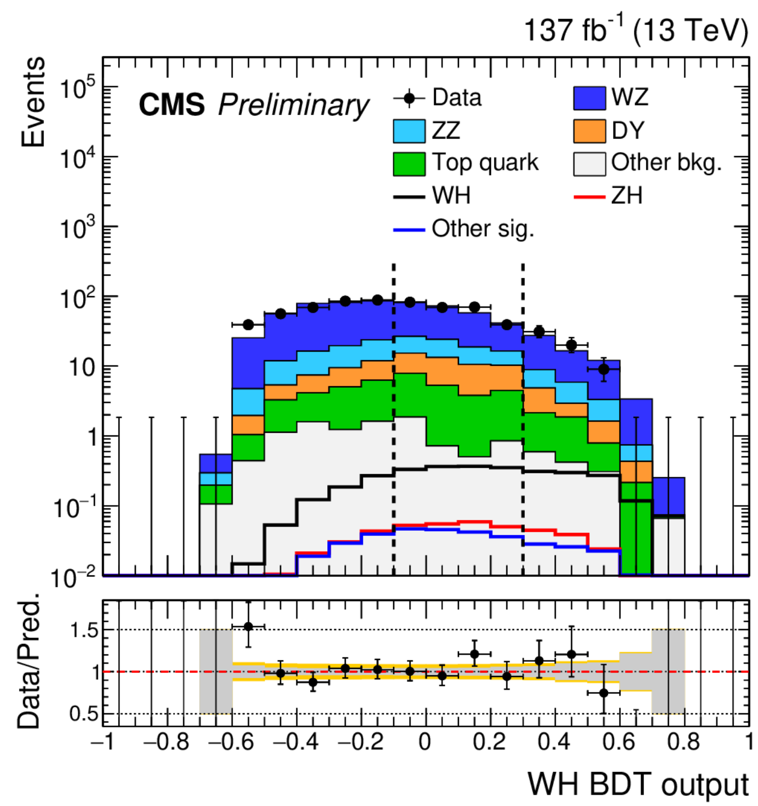
$$\text{BWZGamma}(m_{\mu\mu}; a, f, m_Z, \Gamma_Z) = f \times \text{BWZ}(m_{\mu\mu}; a, m_Z, \Gamma_Z) + (1-f) \times \frac{e^{a m_{\mu\mu}}}{m_{\mu\mu}^2}$$

other categories

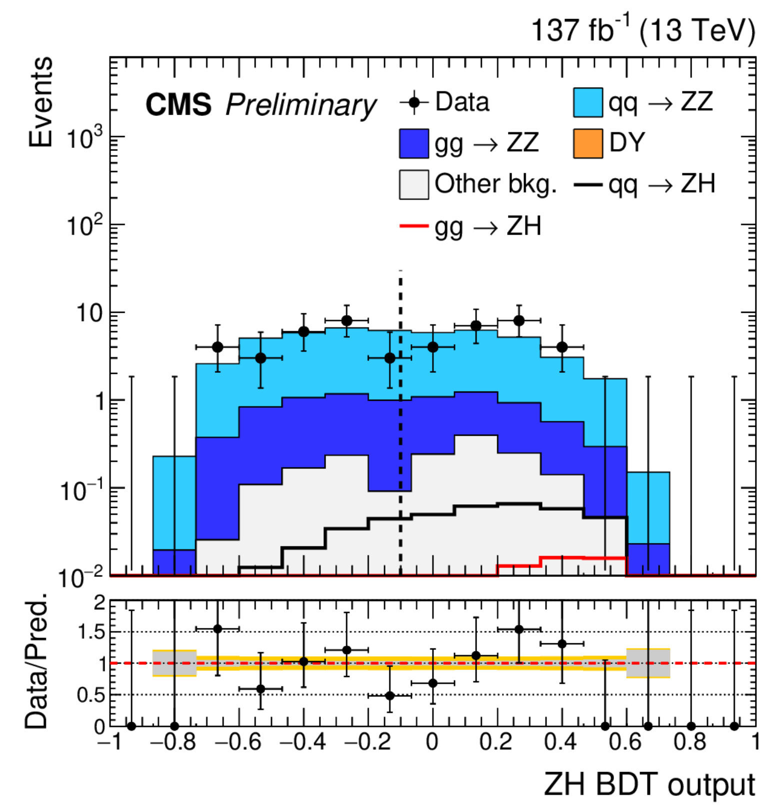
$$\text{BWZ}(m_{\mu\mu}; a, m_Z, \Gamma_Z) = \frac{\Gamma_Z e^{a m_{\mu\mu}}}{(m_{\mu\mu} - m_Z)^2 + (\Gamma_Z/2)^2}$$

- Two dedicated BDT training
  - WH BDT: kinematic features of the three leptons, $p_{T,miss}$
  - ZH BDT: observables constructed from the two lepton pairs forming the Higgs and Z boson candidate

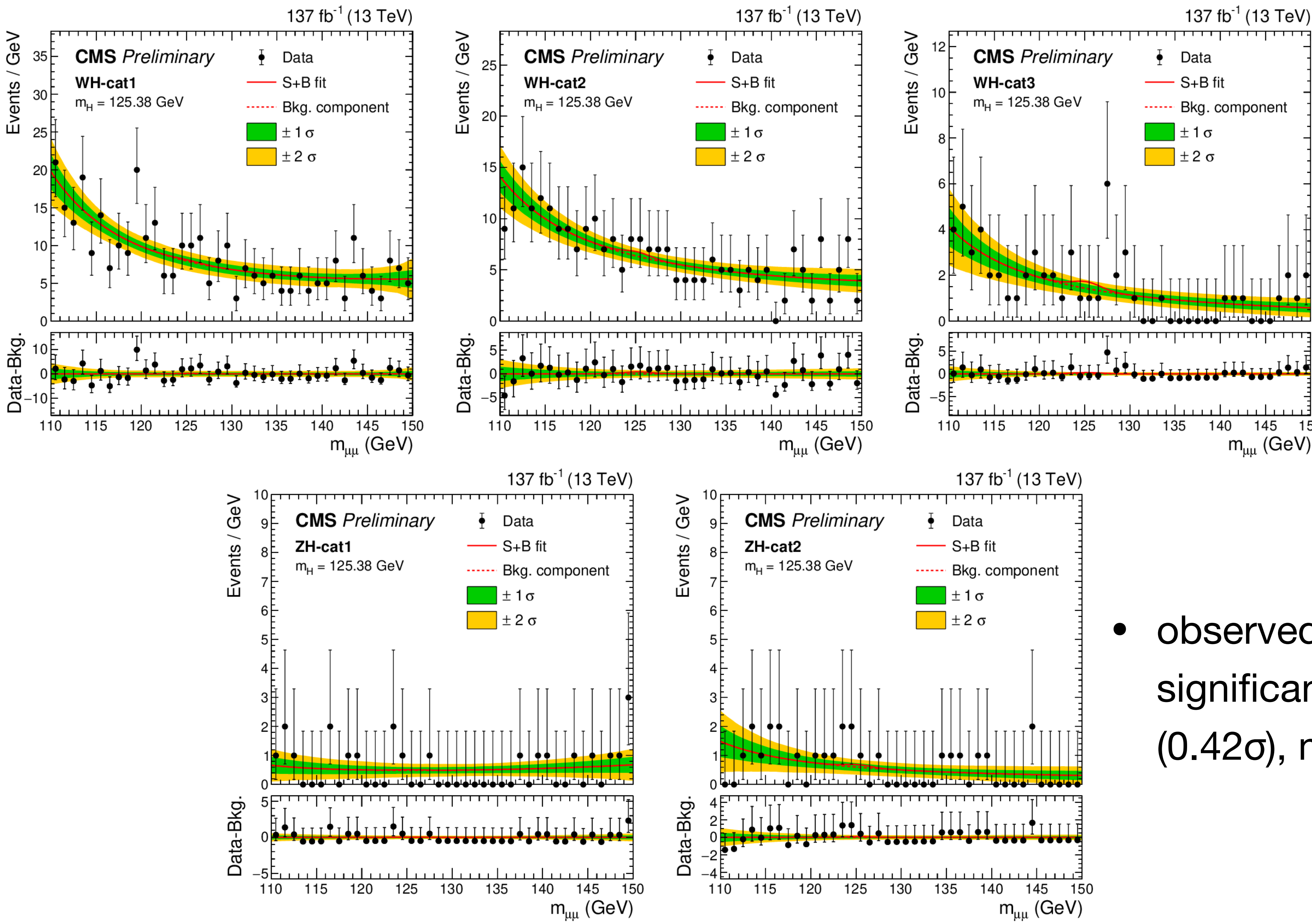
3 WH categories



2 ZH categories



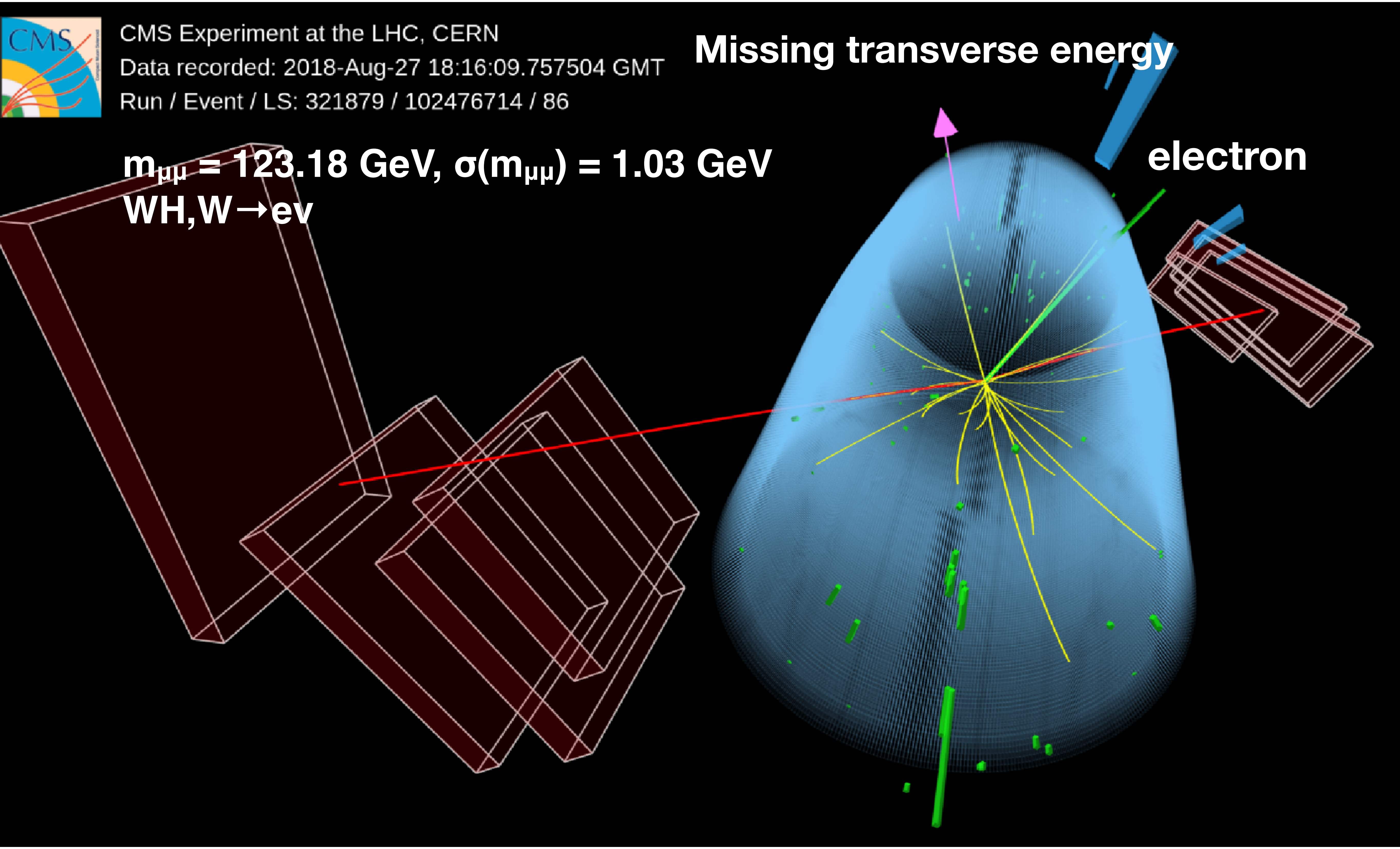
VH category: mass fit



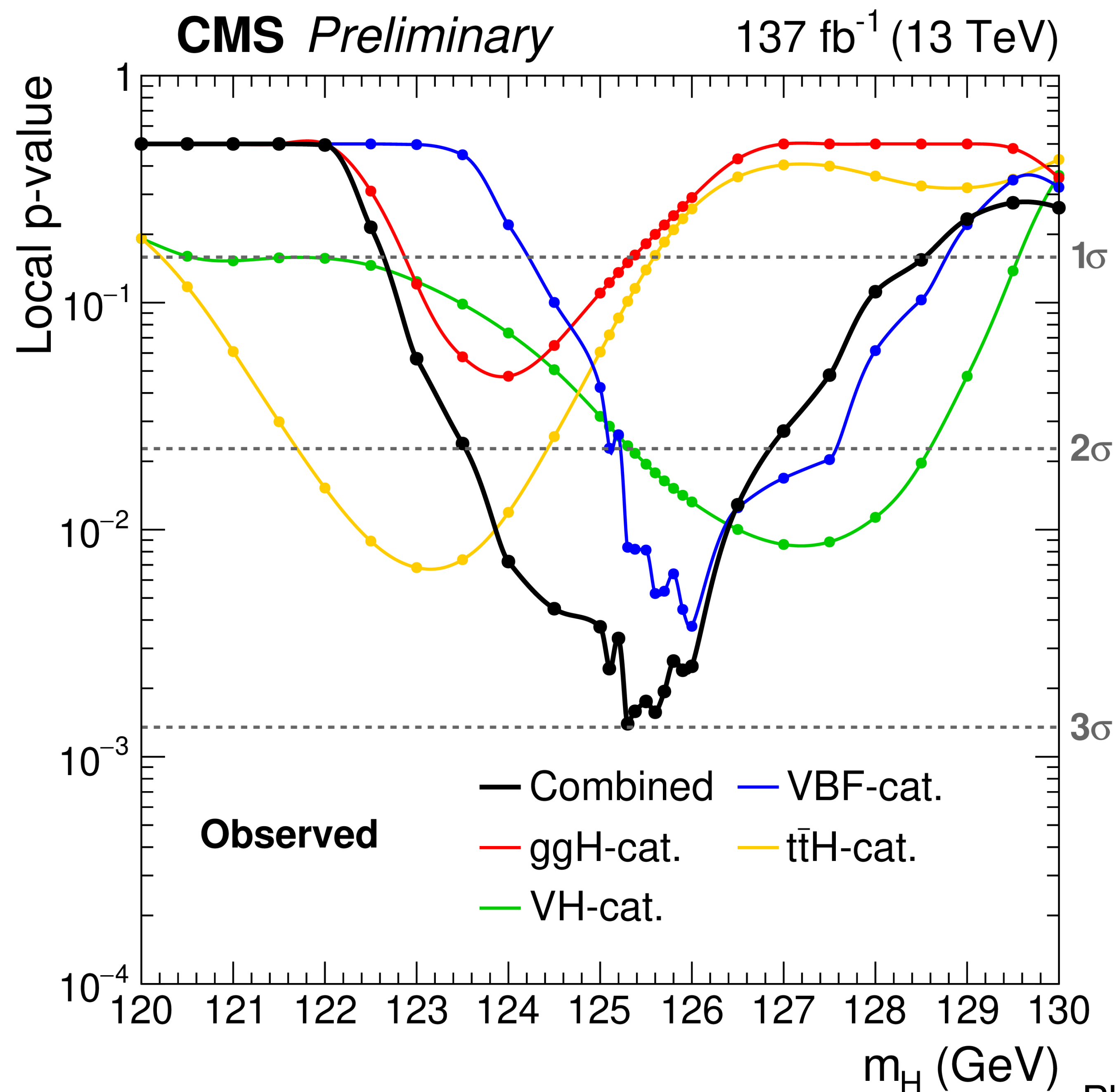
- observed(expected) significance is 2.02σ (0.42σ), m_H = 125.38 GeV

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

WH candidate event



First evidence of H→μμ

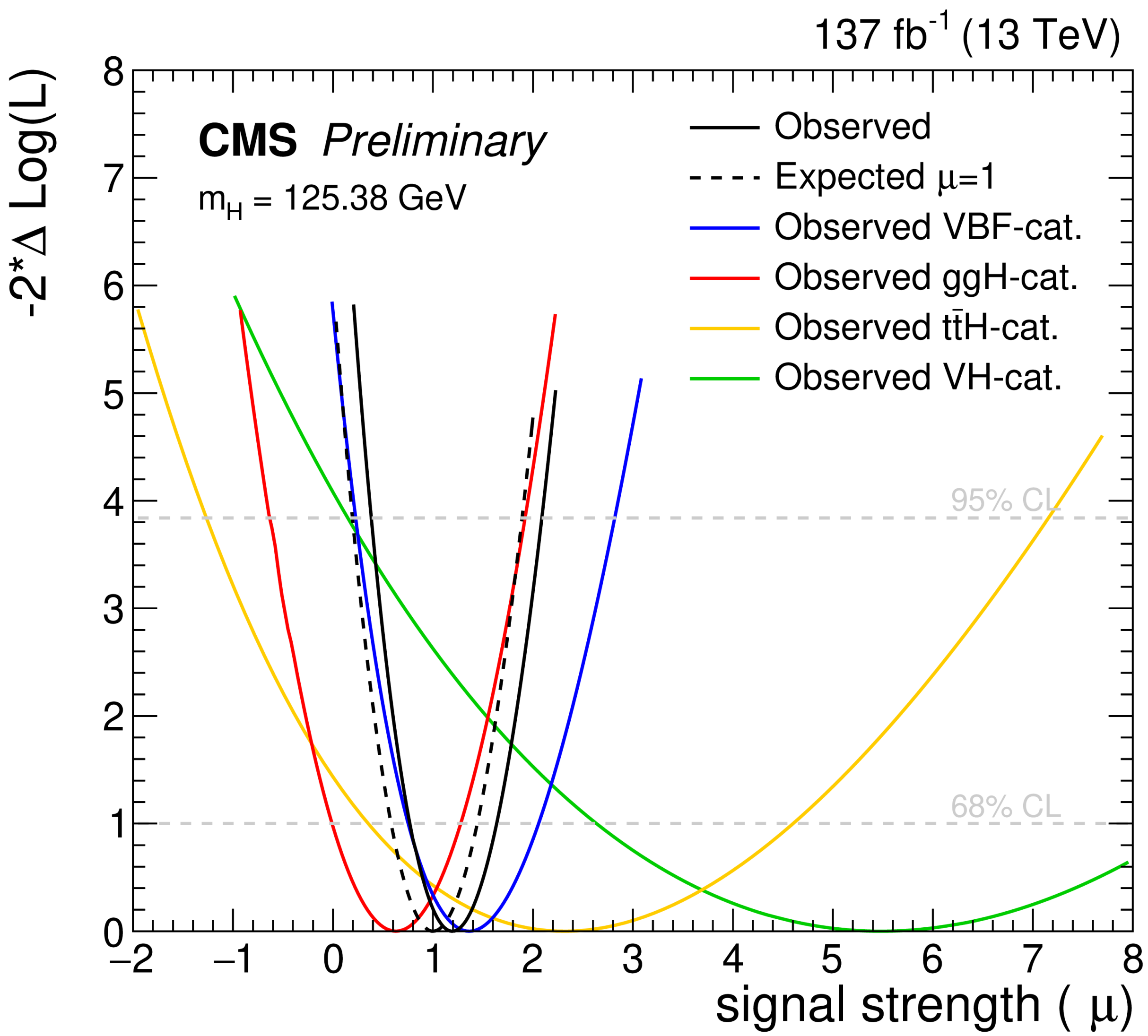


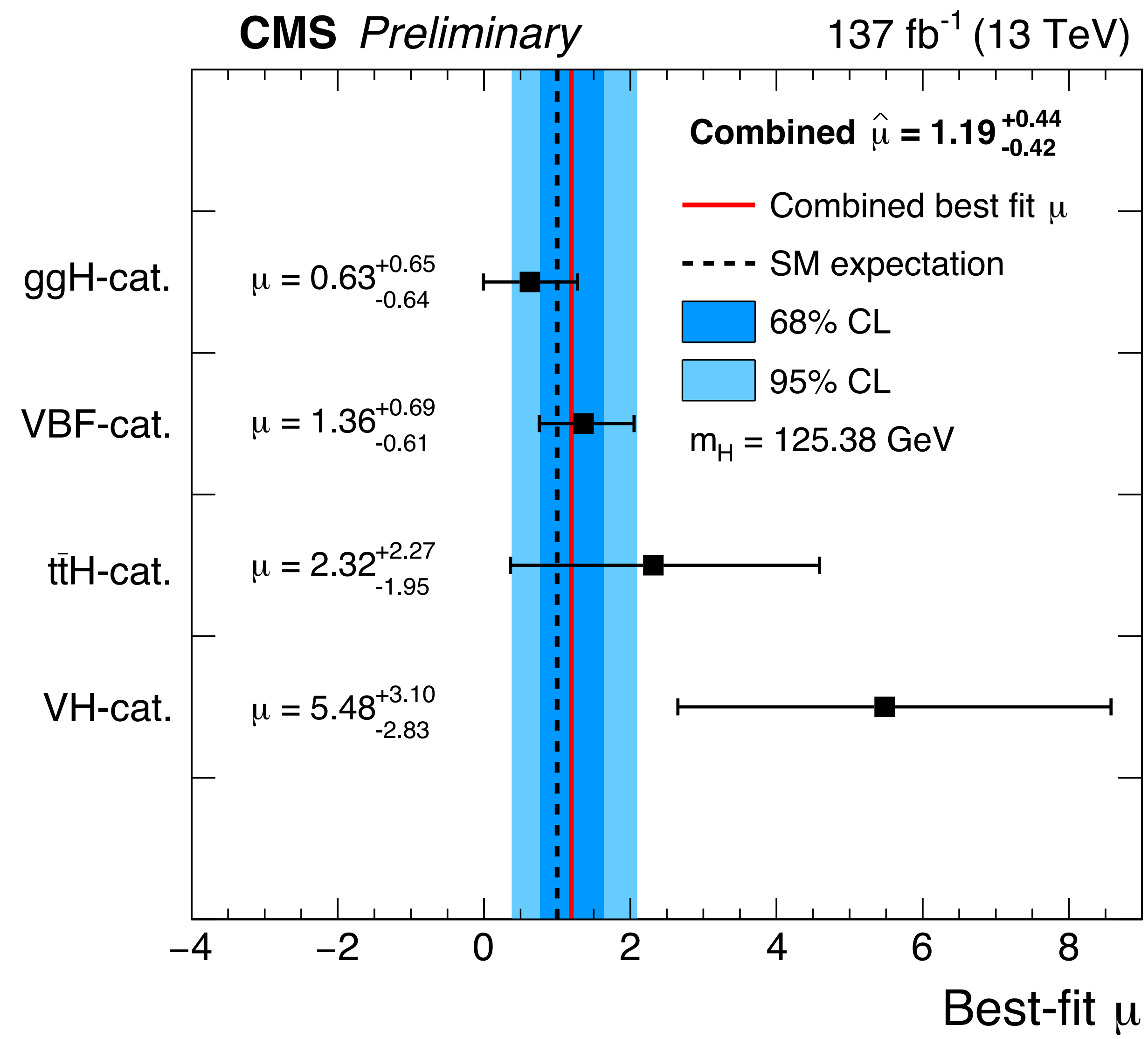
Phys. Lett. B 805 (2020) 135425

m_H = 125.38 GeV most precisely measured Higgs boson mass

- Run 2: observed (expected) significance is 2.95σ (2.46σ)
- Run 2 + Run 1: observed (expected) significance is 2.98σ (2.48σ), 1% improvement by adding Run 1 result

Signal strength measurement of H→μμ





Combined signal strength : $\mu = \sigma B(H \rightarrow \mu\mu)_{obs} / \sigma B(H \rightarrow \mu\mu)_{SM}$

$$\mu = 1.19^{+0.41}_{-0.39}(stats.)^{+0.10}_{-0.11}(theo.)^{+0.12}_{-0.10}(exp.)^{+0.07}_{-0.06}(MCstats.)$$

measurement dominated by statistical uncertainty in data (34%).

systematic uncertainty much smaller (14%)

Boson and fermion-mediated production processes

Higgs production modes:

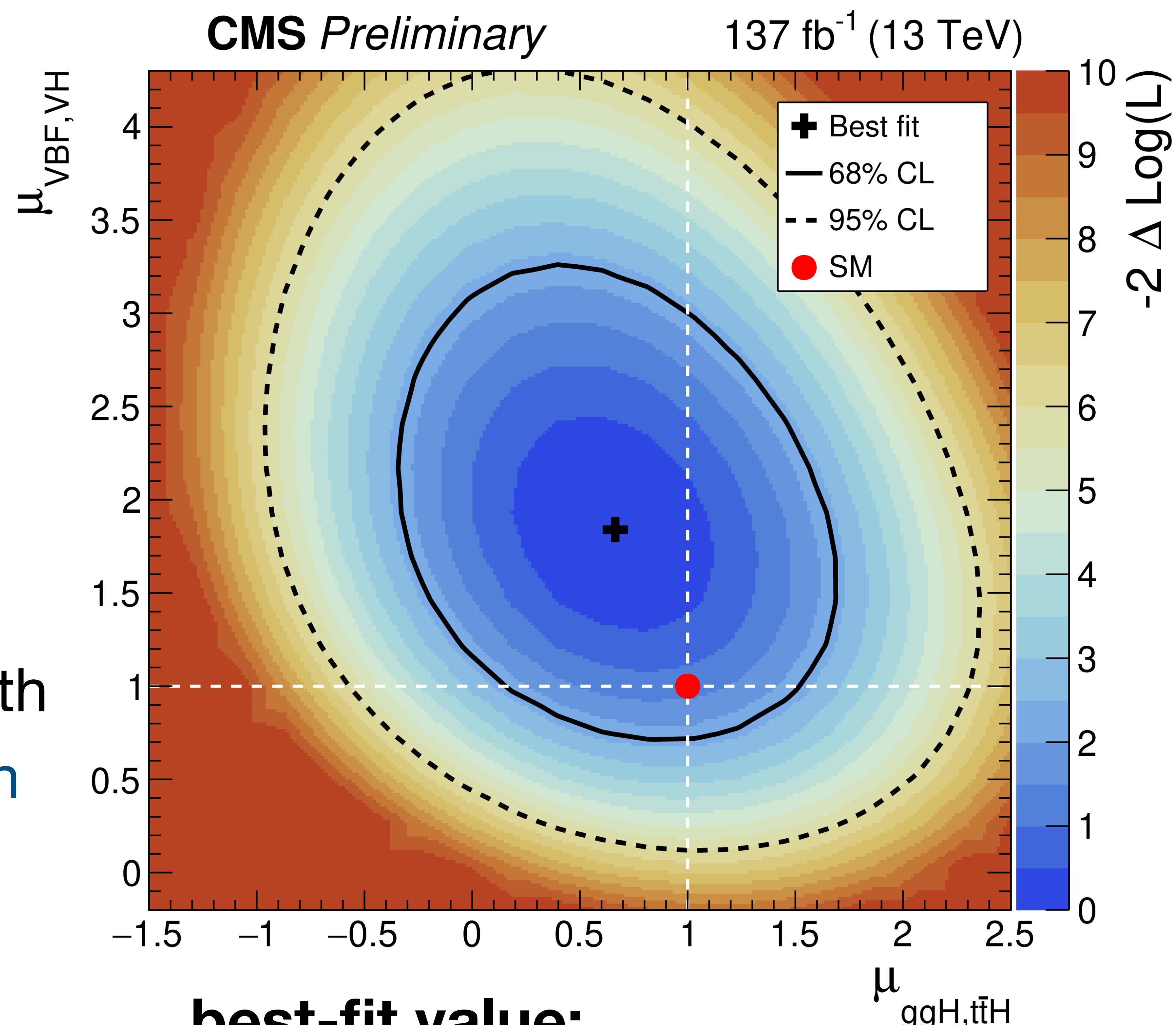
Fermion mediated

$$\mu^{\mu\mu}_{gg,ttH} = \mu^{\mu\mu}_{ggH} = \mu^{\mu\mu}_{ttH}$$

Boson mediated

$$\mu^{\mu\mu}_{VBF,VH} = \mu^{\mu\mu}_{VBF} = \mu^{\mu\mu}_{VH}$$

2D measurement signal strength in the vector boson vs fermion mediated production modes consistent with SM within 1σ

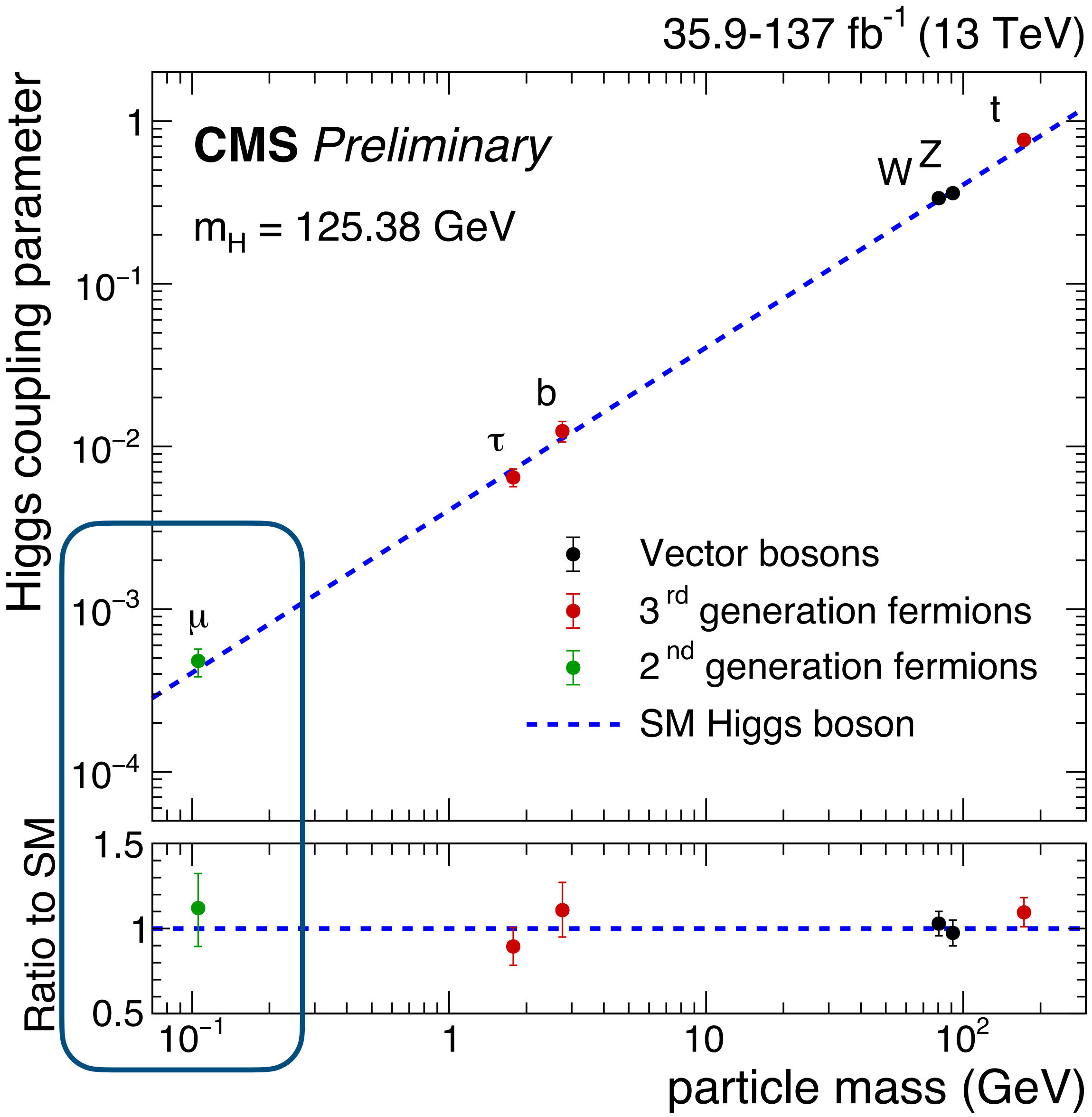


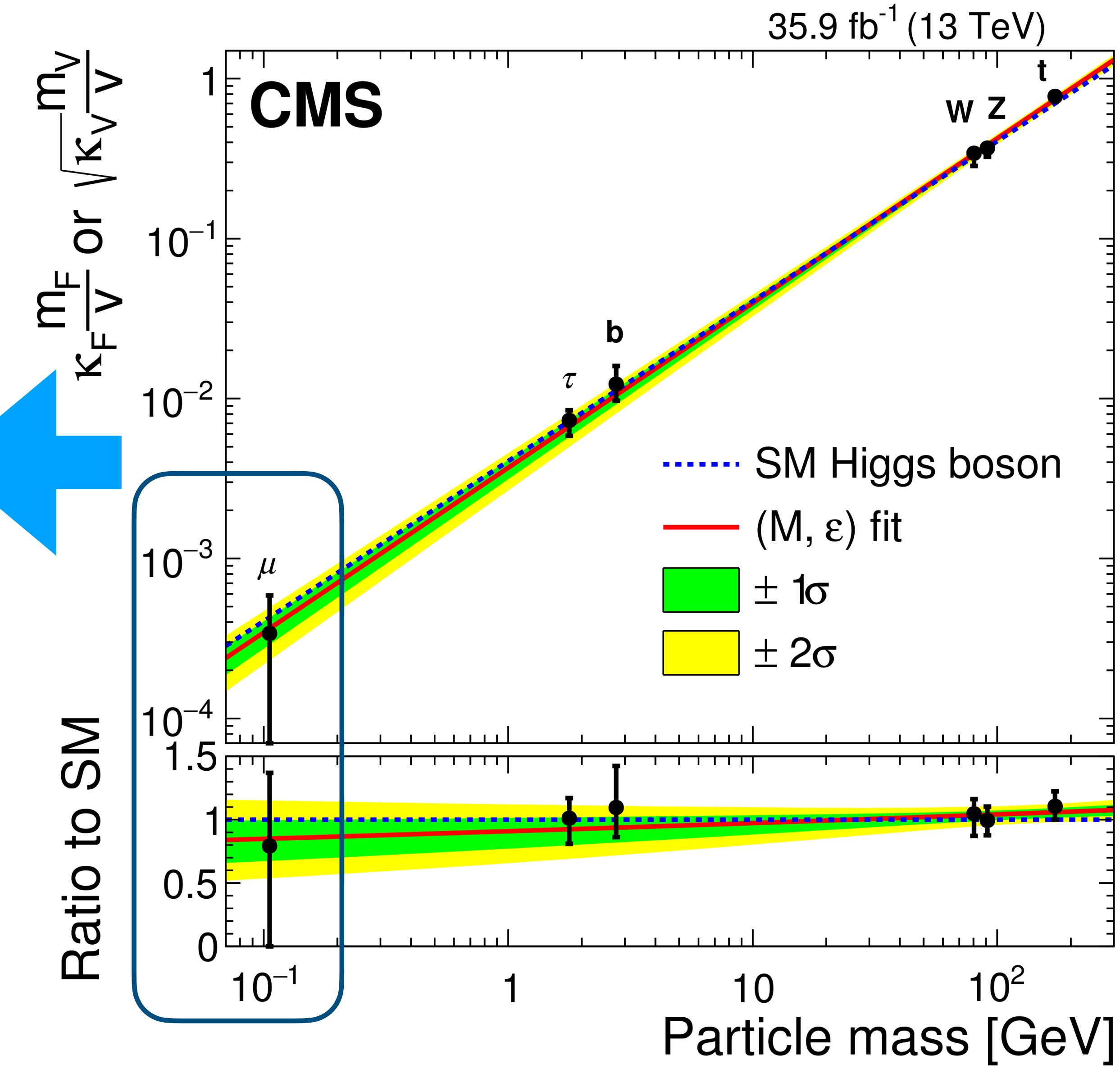
best-fit value:

$$(\hat{\mu^{\mu\mu}_{VBF,VH}},\ \hat{\mu^{\mu\mu}_{ggH,ttH}}) = (0.66,\ 1.84)$$

Higgs boson coupling to muons

Higgs boson coupling to muons precision improved from 89% to 19% in two years!





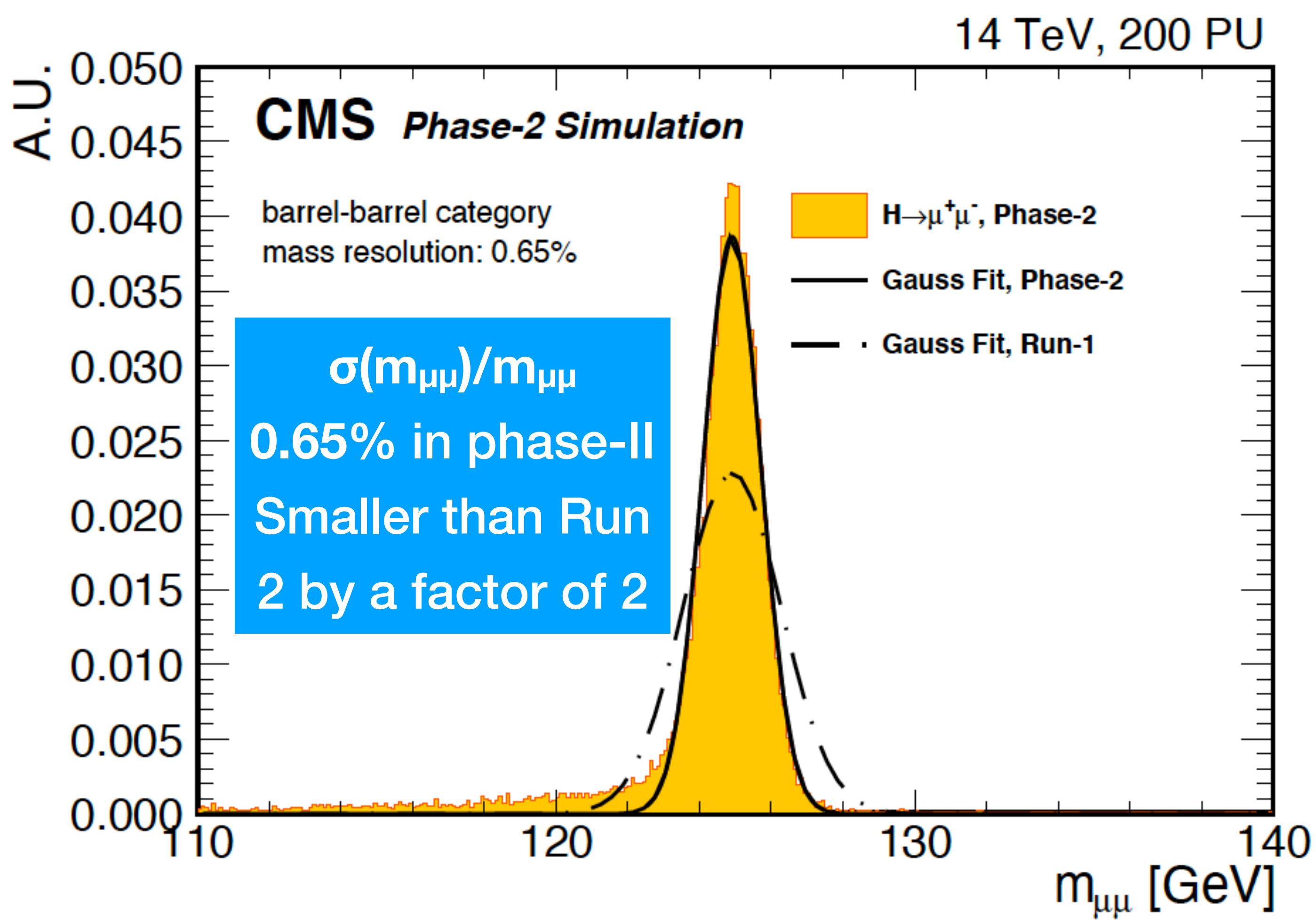
EPJC 79 (2019) 421

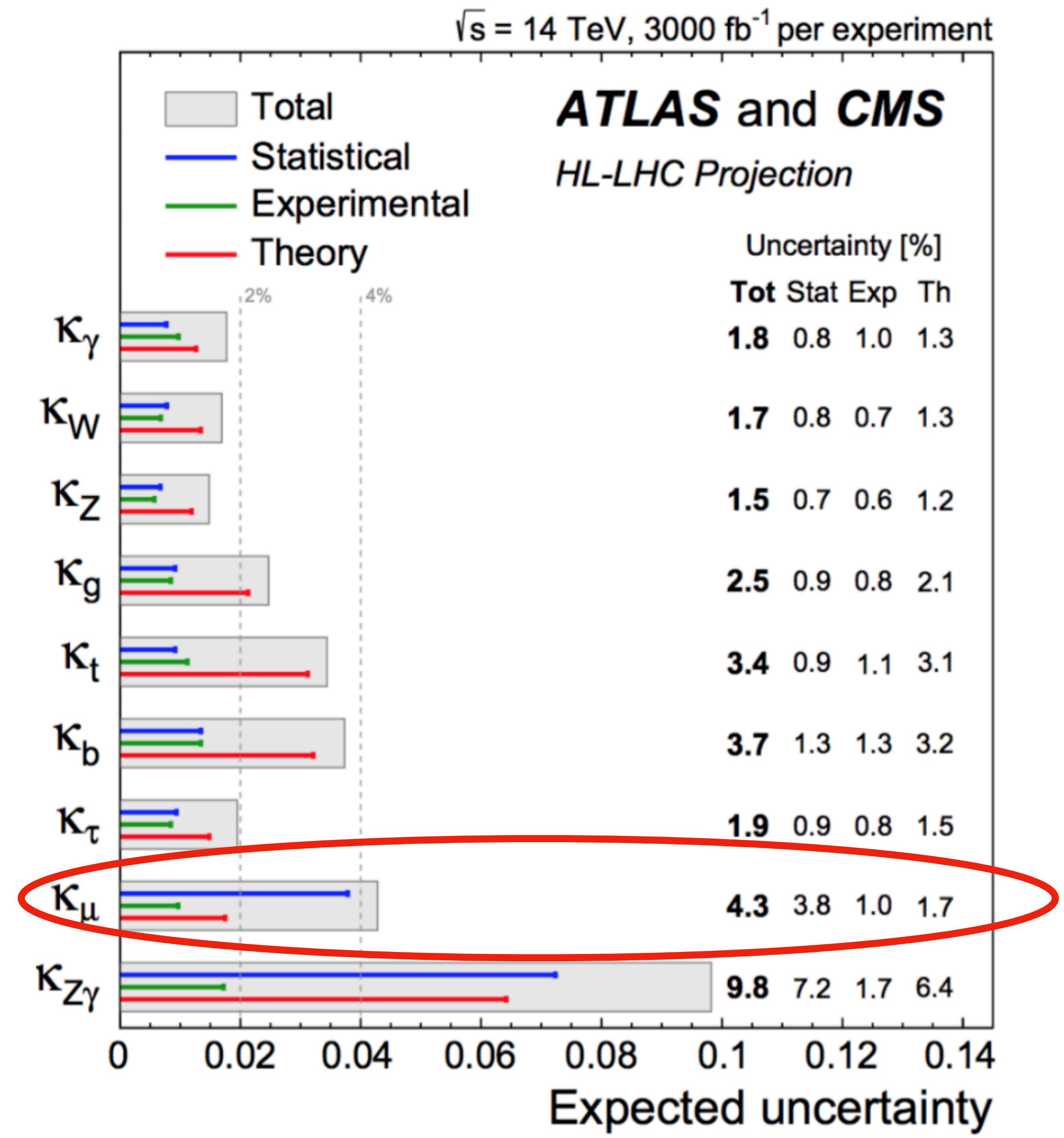
$\kappa_\mu = 1.13^{+0.21}_{-0.22}$ at 68% CL

$\kappa_\mu = 0.79^{+0.58}_{-0.79}$ at 68% CL

Prospect of precision measurement of Higgs coupling to muons

- These results will be further refined with the data in Run 3 and HL-LHC
- An intensive detector upgrade program is on-going to meet the challenge of the HL-LHC and ensure excellent performance of the CMS detector





- New muon chambers extends η coverage for combined muons from 2.4 to 2.8 in HL-LHC

CMS-TDR-014, *CMS-TDR-016*

arxiv:1902.00134

Summary

- CMS achieved first 3σ experimental evidence for H→μμ with Run 2 data (CMS Physics Briefing, CERN Press Release)

- Higgs boson coupling is measured with 19% precision and is **in agreement** with Standard Model prediction

$$\kappa_\mu = 1.13^{+0.21}_{-0.22} \text{ at 68\% CL}$$

- This is not the end: more data which we expect to collect in **Run 3 and HL-LHC** will enable the **observation and a precise measurement** of this Higgs boson coupling to muons through H→μμ decay channel

Contribution to H→μμ

I lead the Caltech Team in the H→μμ analysis with an end-to-end full chain analysis and made important contributions to the most sensitive category: VBF category. In particular, we have contributed to the following areas in the VBF category:

- proposal of the p-value vs mass scan method
- studies for the analysis review process
- systematic uncertainty, statistical analysis and the final result
- machine learning deep neural network application
- event displays

Caltech

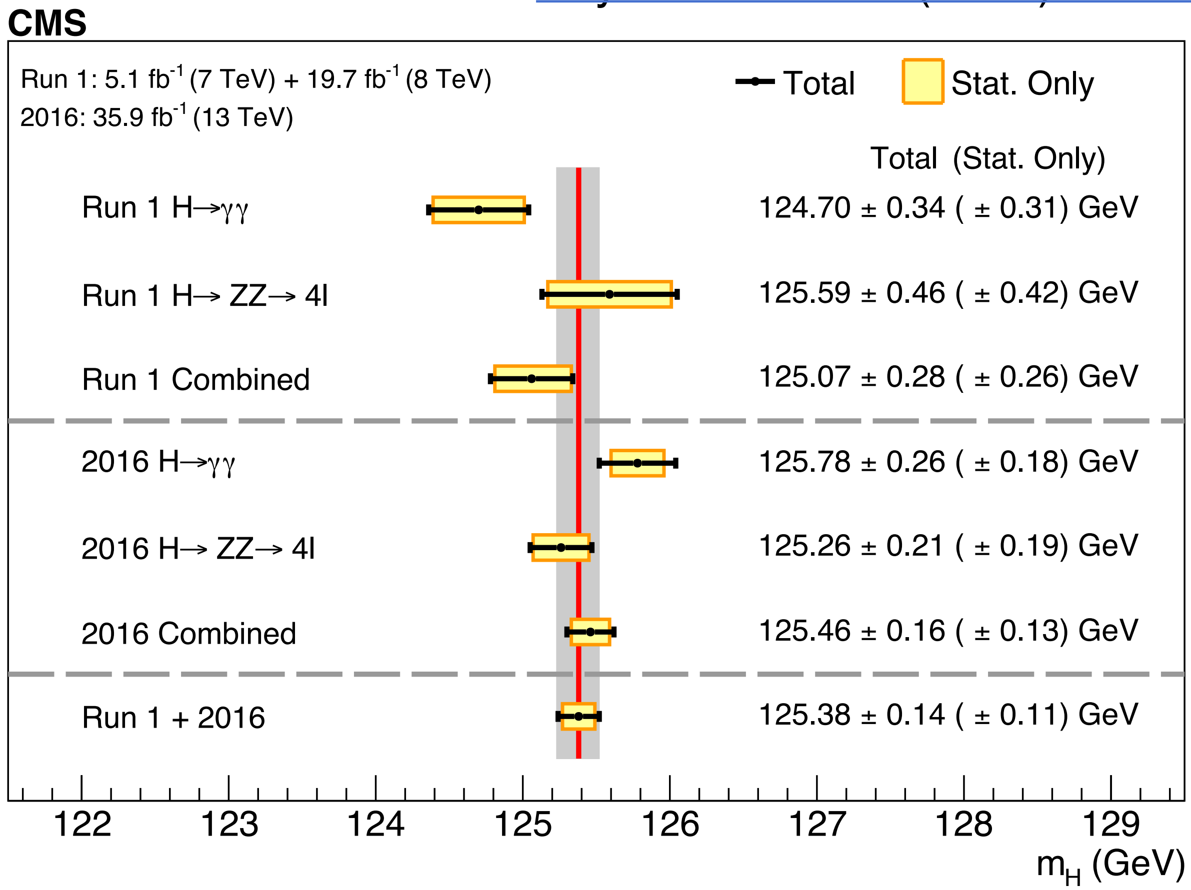
Thank you!

backup slides

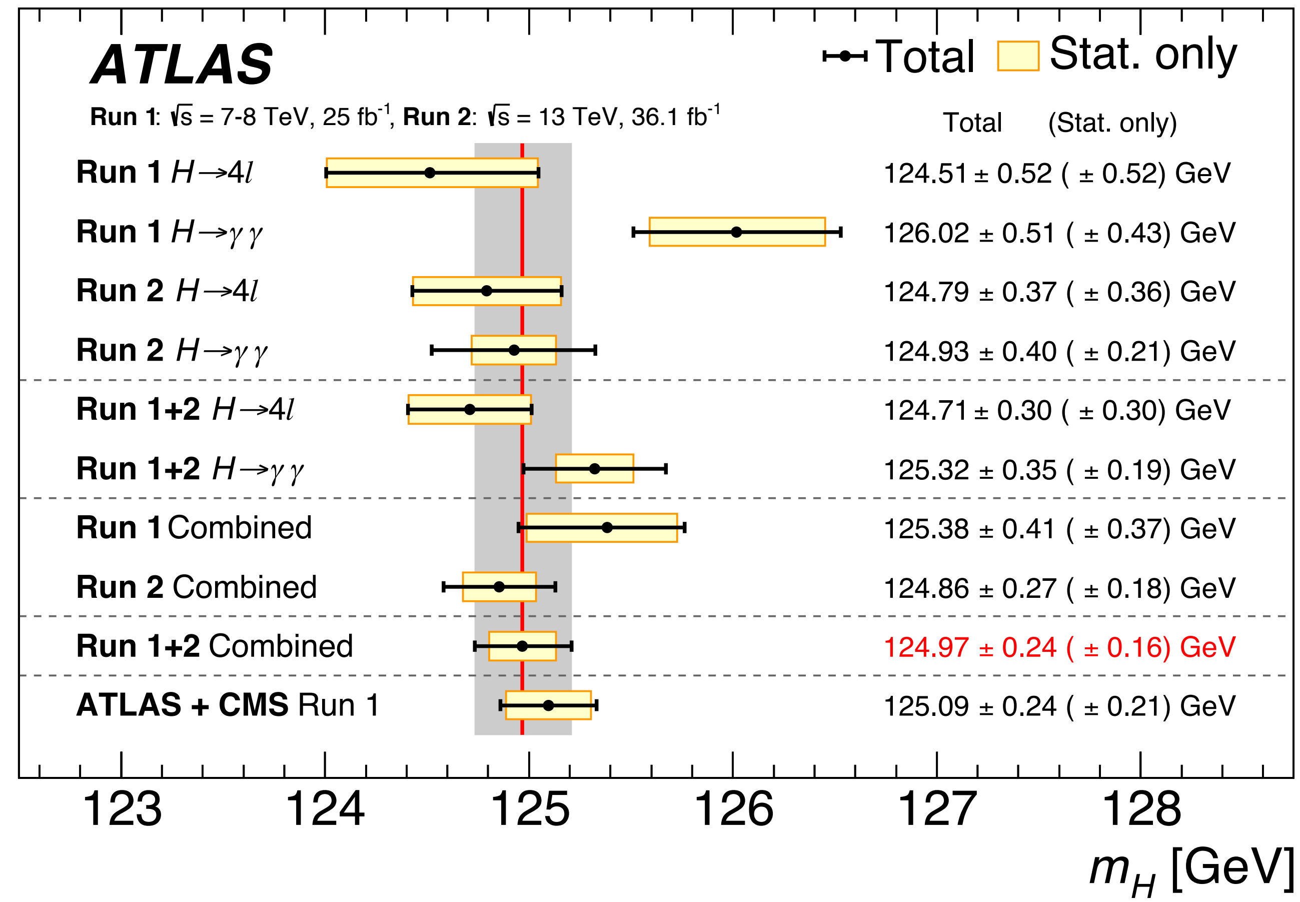
Recent Higgs results: Higgs boson mass measurement

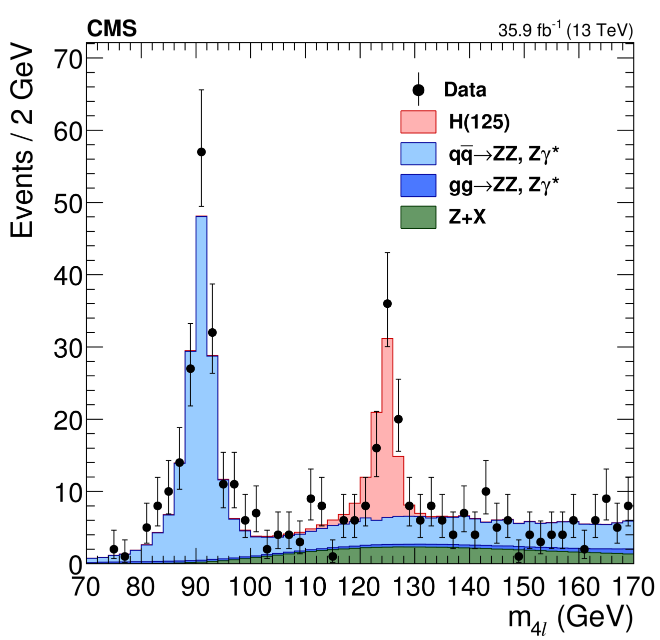
- *m_H precision exceeding Run 1 result: ~0.11% precision by CMS, 0.19% by ATLAS*

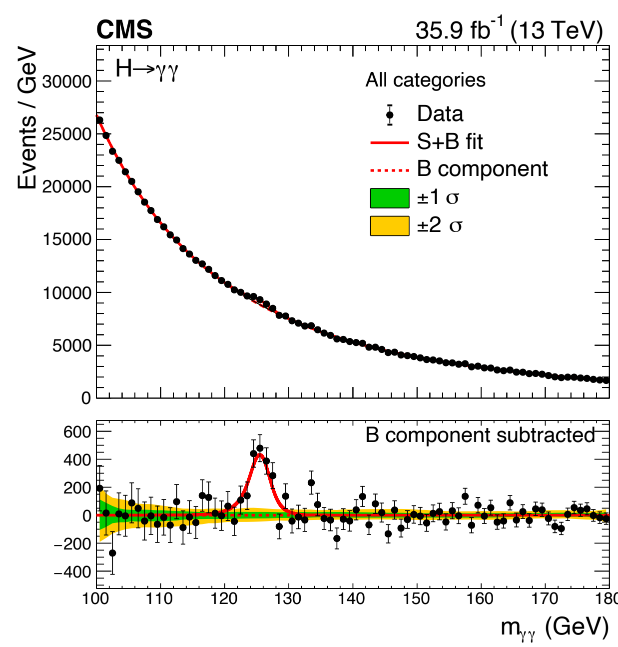
Phys. Lett. B 805 (2020) 135425

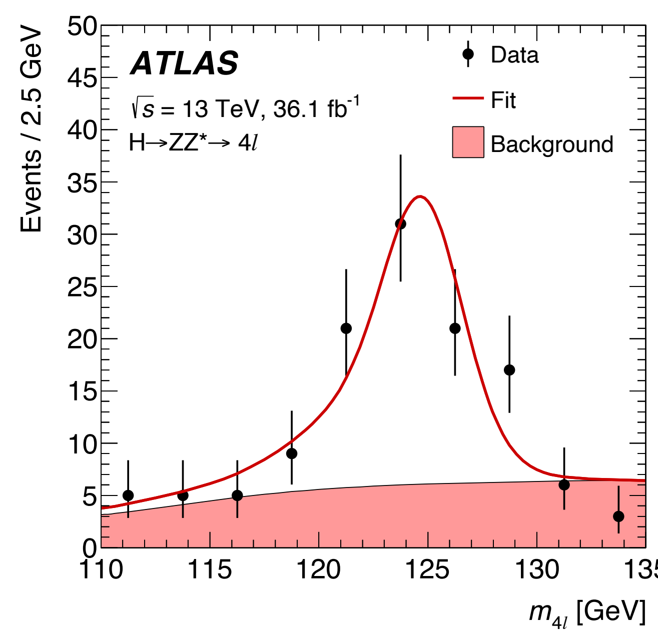


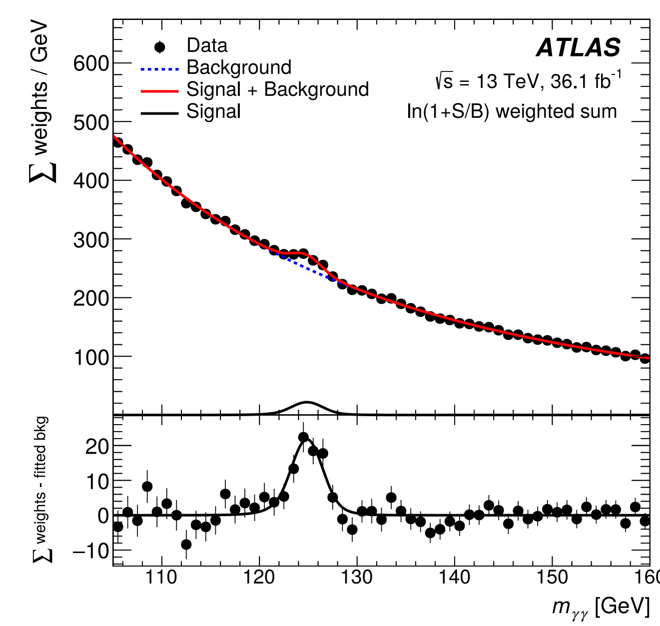
Phys. Lett. B 784 (2018) 345











$H \to \mu\mu$: VBF category DNN

DNN trained using **125 GeV** VBF signal and background MC samples

DNN are trained for 3 years separately, because of different data-taking conditions.

Training variables includes:

- $m_{\mu\mu}$, $\sigma(M_{\mu\mu})$, $Pt_{\mu\mu}$, $y_{\mu\mu}$, $\cos\theta^*$, ϕ^*
- pT, η, ϕ of the two leading jets, M_{jj}, $\Delta\eta_{jj}$
- Angular variables between jj and μμ system
- Zeppenfeld variable $z^* = \frac{y_{\mu\mu} - (y_{j_1} + y_{j_2})/2}{|y_{j_1} - y_{j_2}|}$
- Pt(μμ,jj) balance $R(p_T) = \frac{|\vec{p_T}^{\mu\mu} + \vec{p_T}^{jj}|}{p_T(\mu\mu) + p_T(j_1) + p_T(j_2)}$
- $N_{\text{soft jet}}$, $HT_{\text{soft jet}}$ jets from PV with pT>5GeV
- Quark/gluon likelihood of 2 leading jets

$m_{\mu\mu}$ most sensitive variable => $m_{\mu\mu}$ in DNN training, using similar approach as in $H \to bb$ analysis

$H \to \mu\mu$: systematic uncertainties of the VBF channel

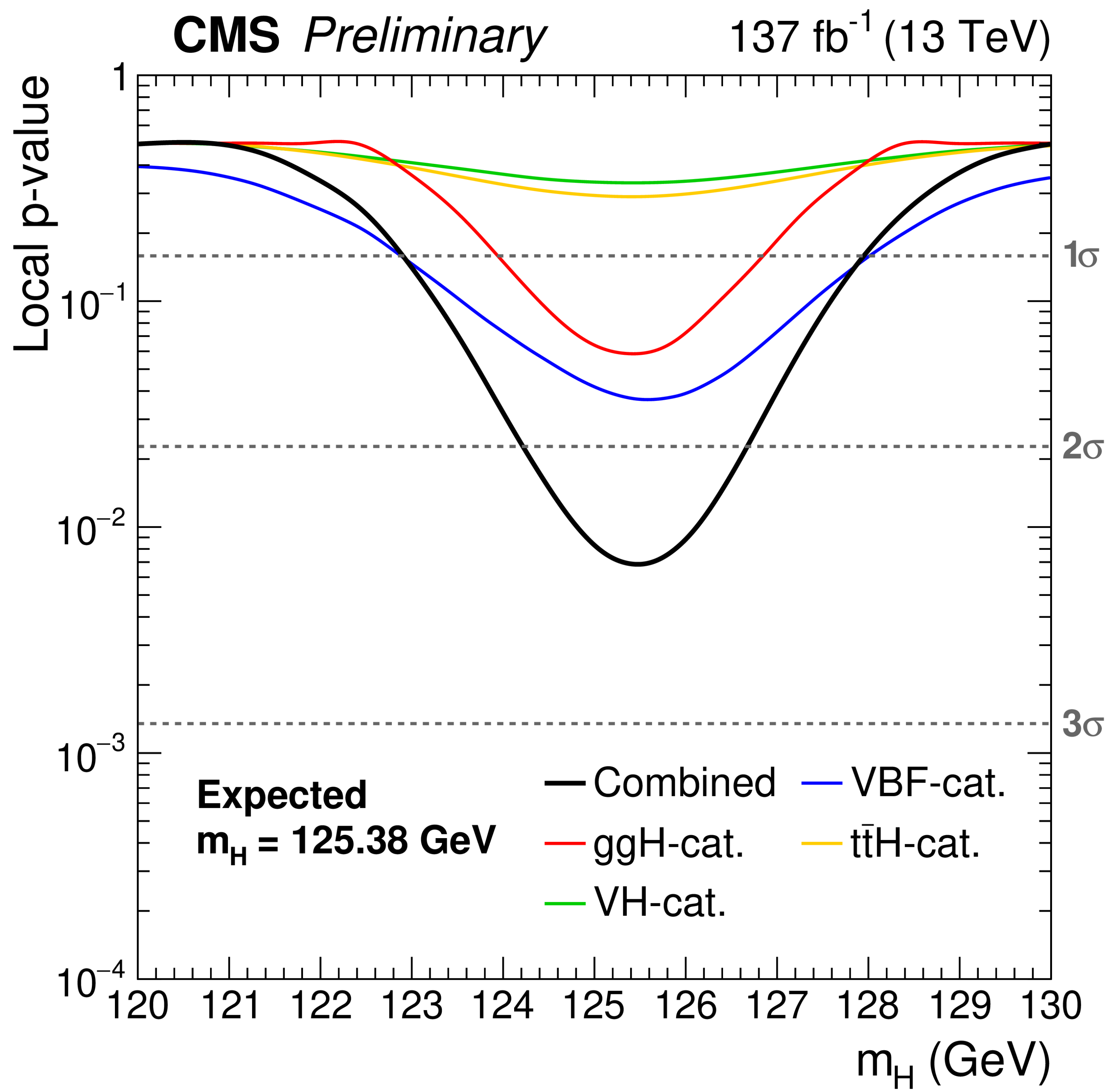
Experimental uncertainties

- Jet energy scale and resolution uncertainties
- the rate of DY process with a jet not matched to a generator level jet, contained by the low DNN score events.
- MC stats uncertainty
- 2016 and 2017 a 20% uncertainty of the correction for the modeling of the inefficiency in the L1 trigger in region 2.4<eta<3
- Luminosity uncertainty
- modeling of the pileup conditions during data taking
- measurement of muon selection and trigger efficiencies
- muon energy scale and resolution

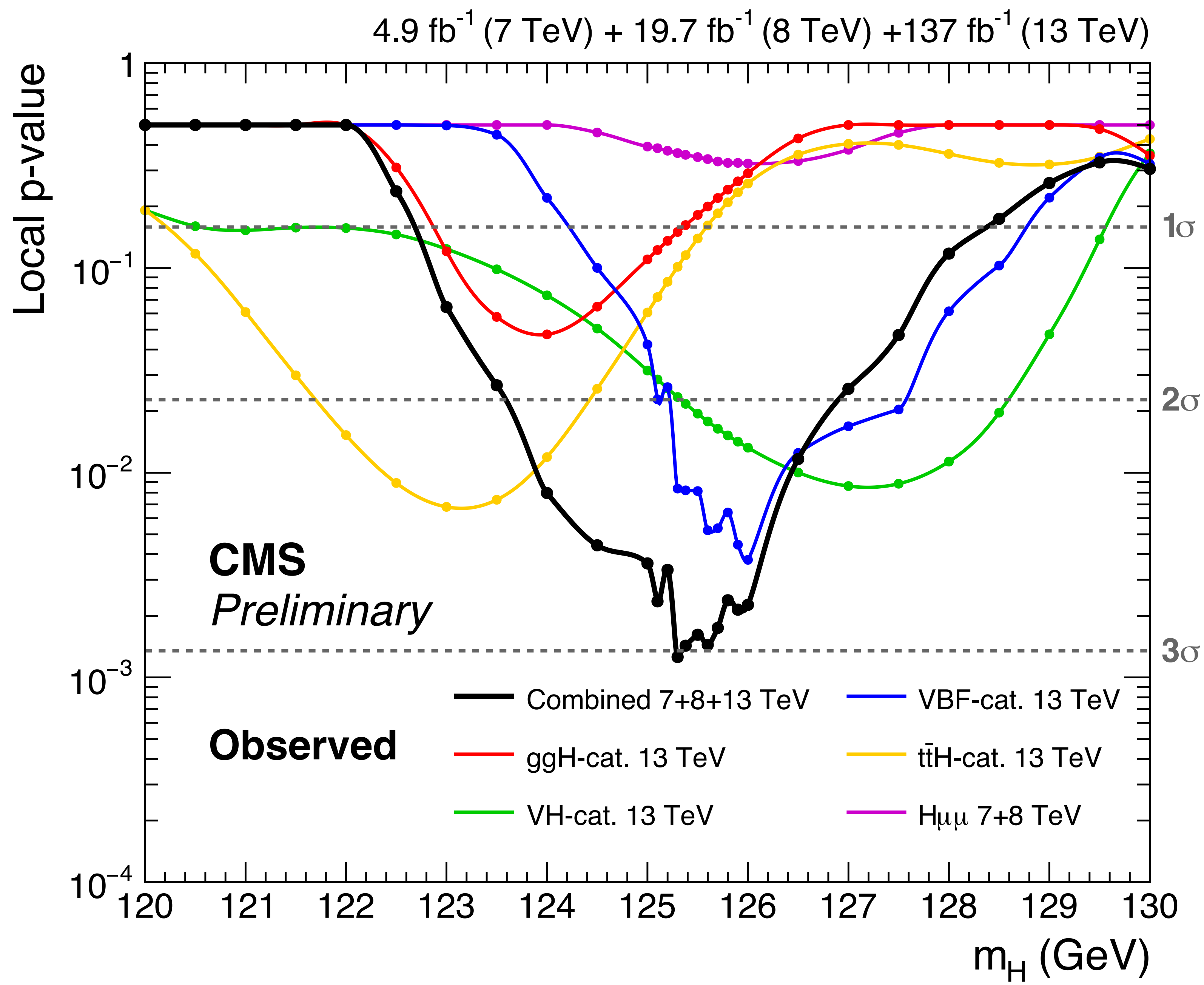
Theory uncertainties

- QCD scale, pdf, parton shower (PS) uncertainty for signal and background is included. In particular VBF and electroweak Zjj-EW PS uncertainty: difference between HERWIG (angular-ordered) and PYTHIA (dipole shower)

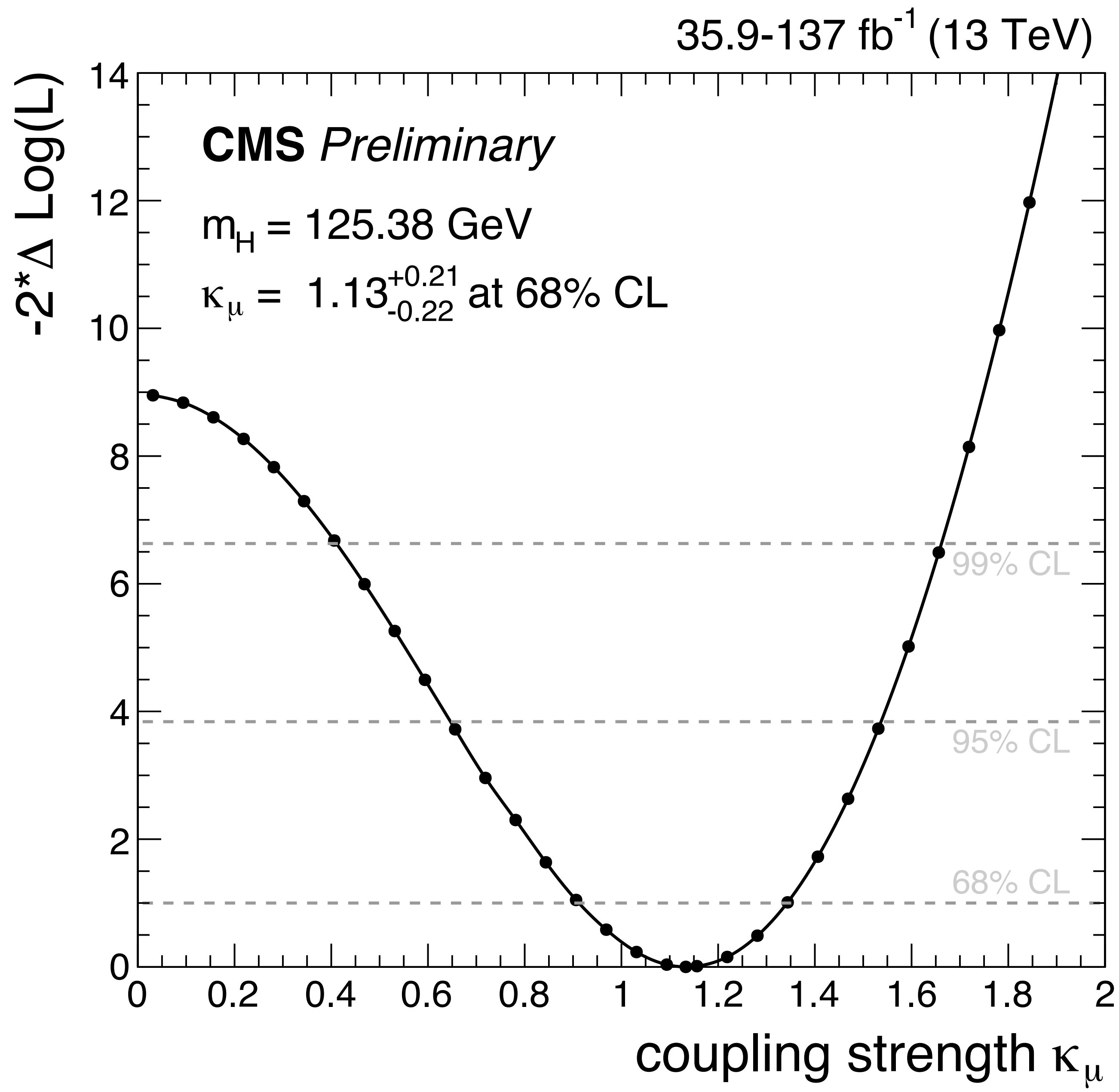
H→μμ: Run 2 expected sensitivity



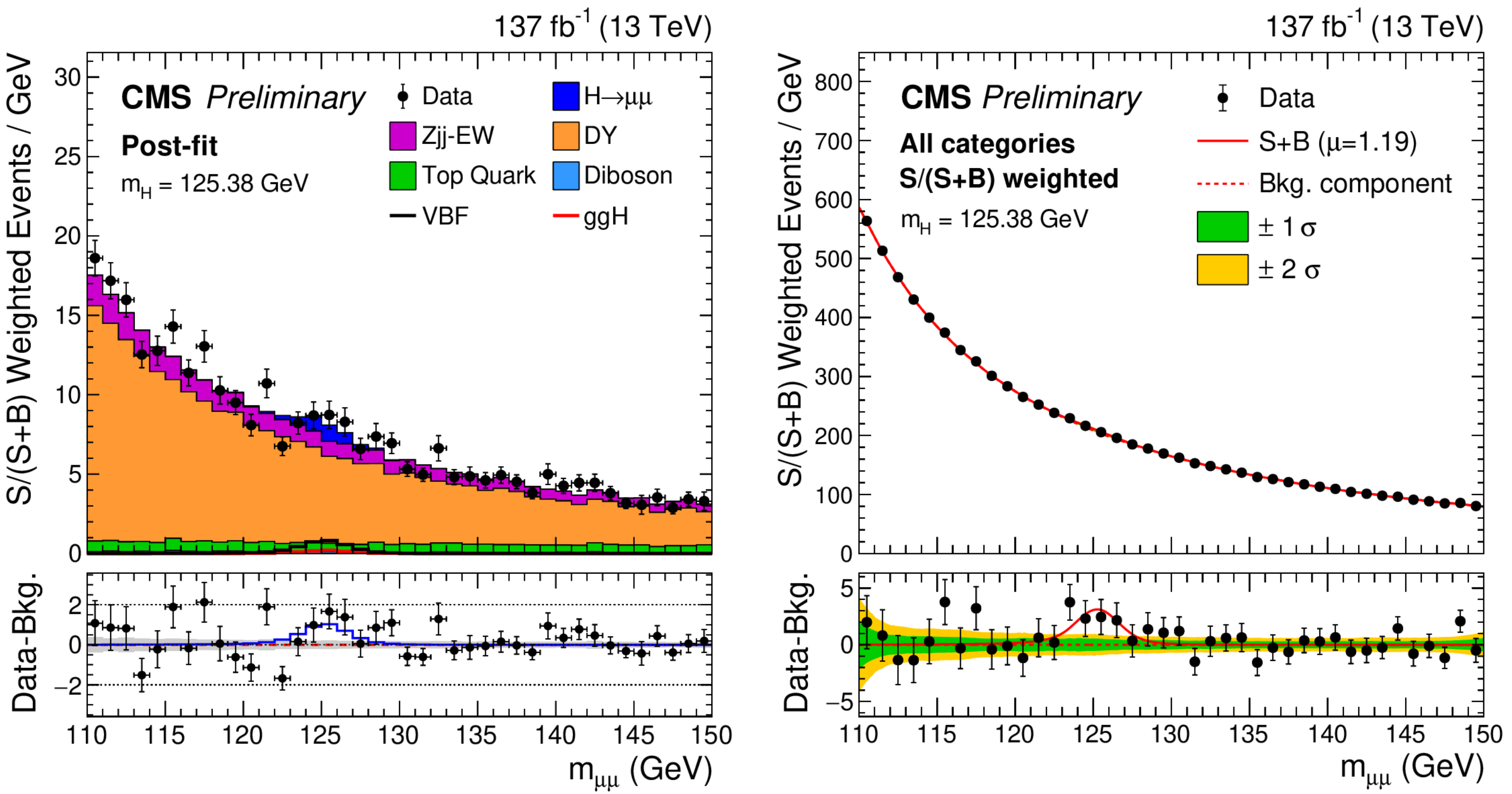
H→μμ: Run 1 and Run 2 combination



H→μμ: Higgs boson coupling to muons



H→μμ: S/(S+B) reweighed mass spectra



Framework for coupling-strength measurements

Leading order tree-level motivated framework with assumptions:

- Signal observed in different channels originate from a single resonance $m_H \sim 125.36$ GeV
- Narrow width approximation.
- Lagrangian tensor structure: SM hypothesis $J^{CP} = 0^{++}$

Yield for the production and decay *i*→*H*→*f* parametrized in terms of coupling scale factors scaling the SM cross sections and widths

Coupling scale factors:

$$\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}\right)$$

Coupling scale factors:

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}} \qquad \kappa_H^2 = \frac{\sum \Gamma_f}{\sum \Gamma_f^{SM}}$$

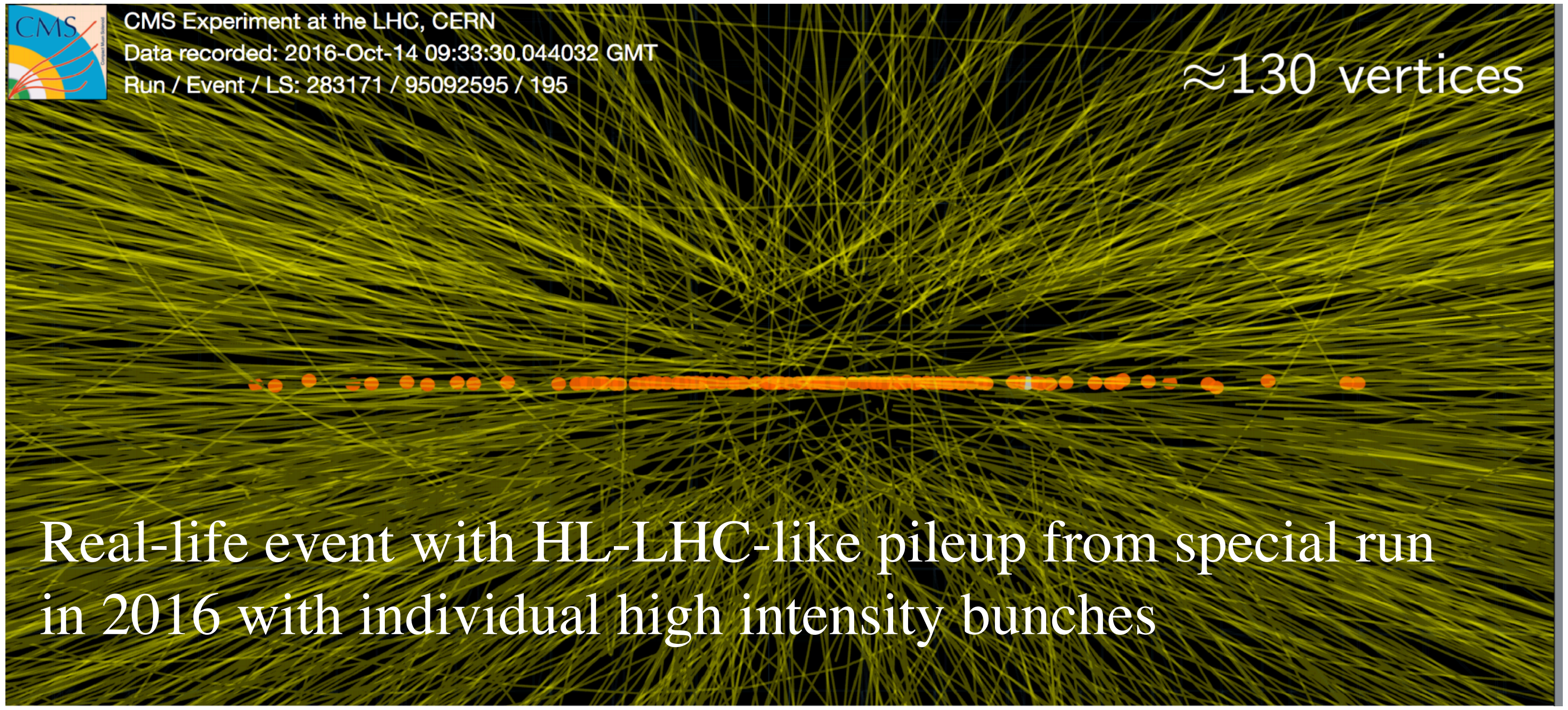
Production **Decay** **Total width**

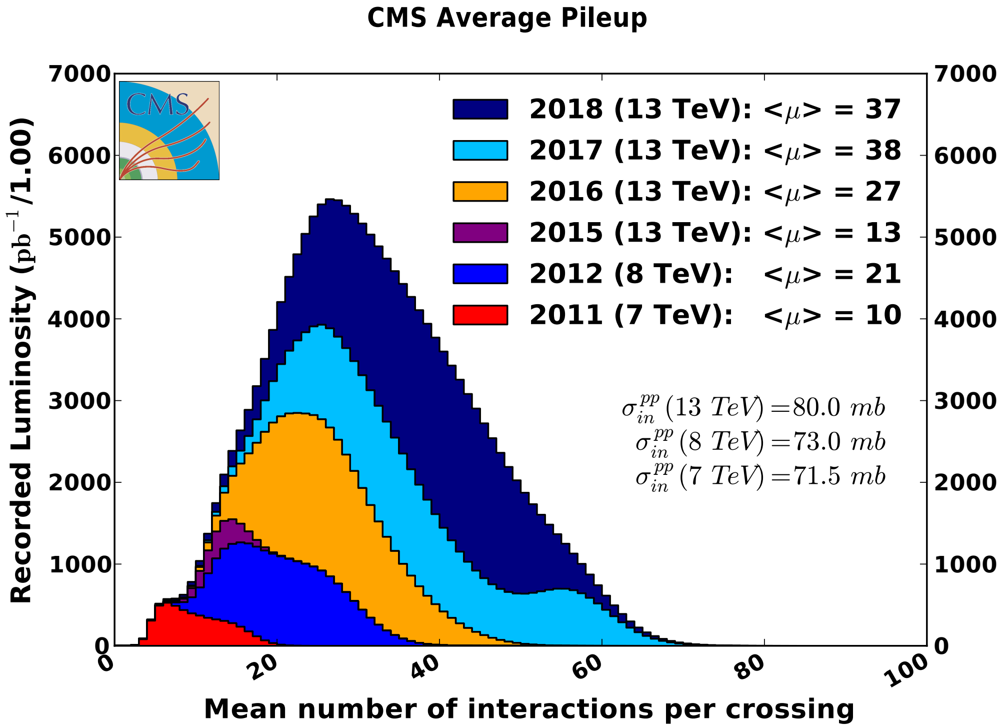
Higgs boson width Γ_H not experimentally constrained to a meaningful precision at the LHC:

- No assumptions on Γ_H: Ratios of coupling strength can be measured
- Make assumption on Γ_H: absolute coupling strengths can be measured.

The HL-LHC challenge and detecter upgrade

- *Phase-2 detector upgrade is crucial to meet the challenge of the HL-LHC*
  - *high pileup: 140-200 interactions per bunch crossing*
  - *severe radiation environment*





HL-LHC Higgs self-coupling projection