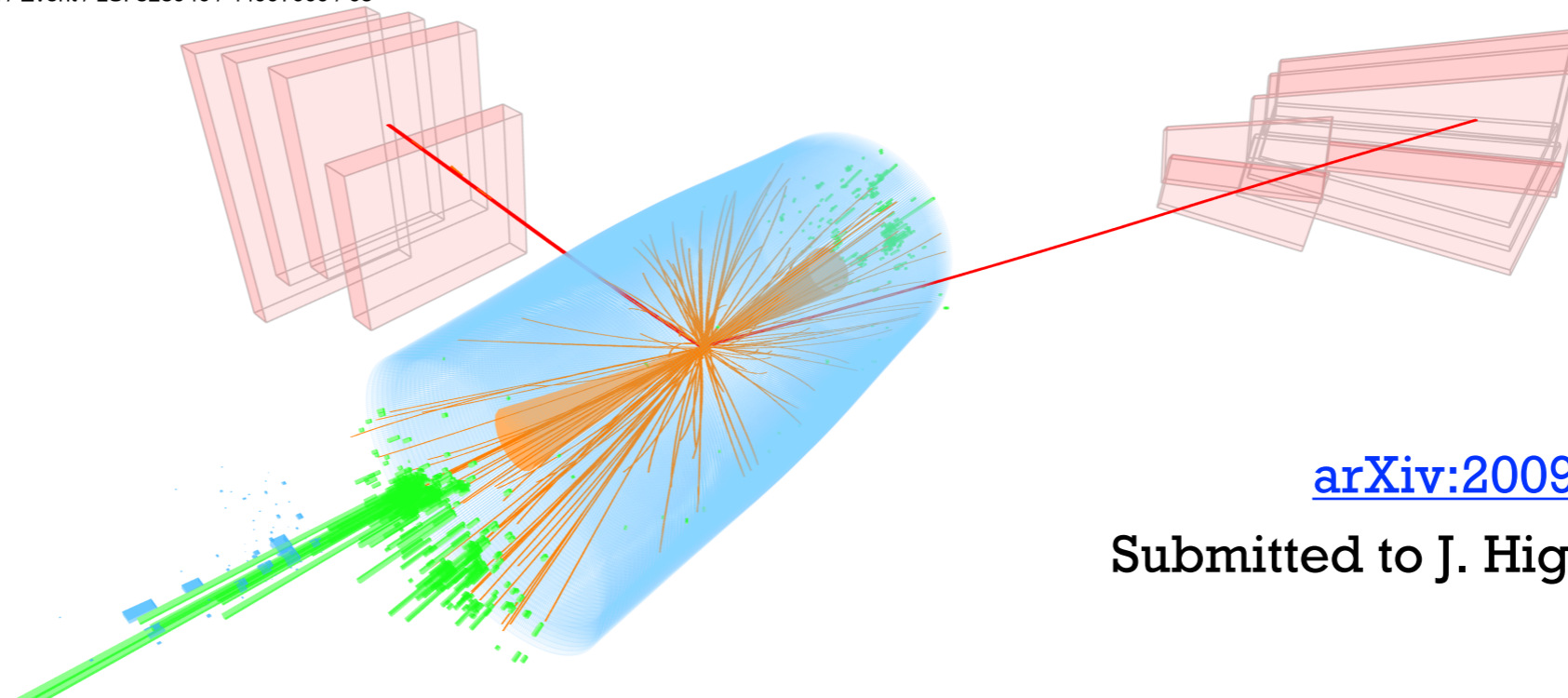


First evidence for Higgs boson decay to muons



CMS Experiment at the LHC, CERN
Data recorded: 2018-Oct-03 01:19:17.320393 GMT
Run / Event / LS: 323940 / 44997009 / 65



[arXiv:2009.04363](https://arxiv.org/abs/2009.04363)

Submitted to J. High Energy Phys.



Stephane Cooperstein (UC San Diego)

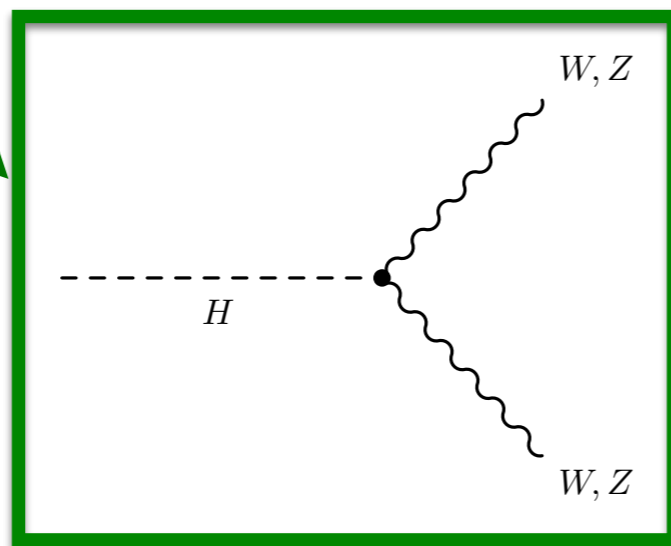
*FPD Seminar, SLAC
October 13, 2020*



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

- Mass generation for and Higgs interactions with gauge bosons is a direct consequence of electroweak symmetry breaking.

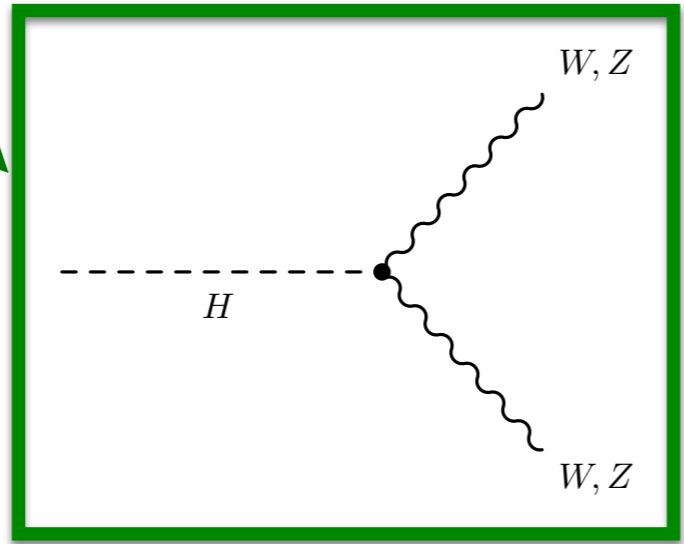
Bosonic Couplings



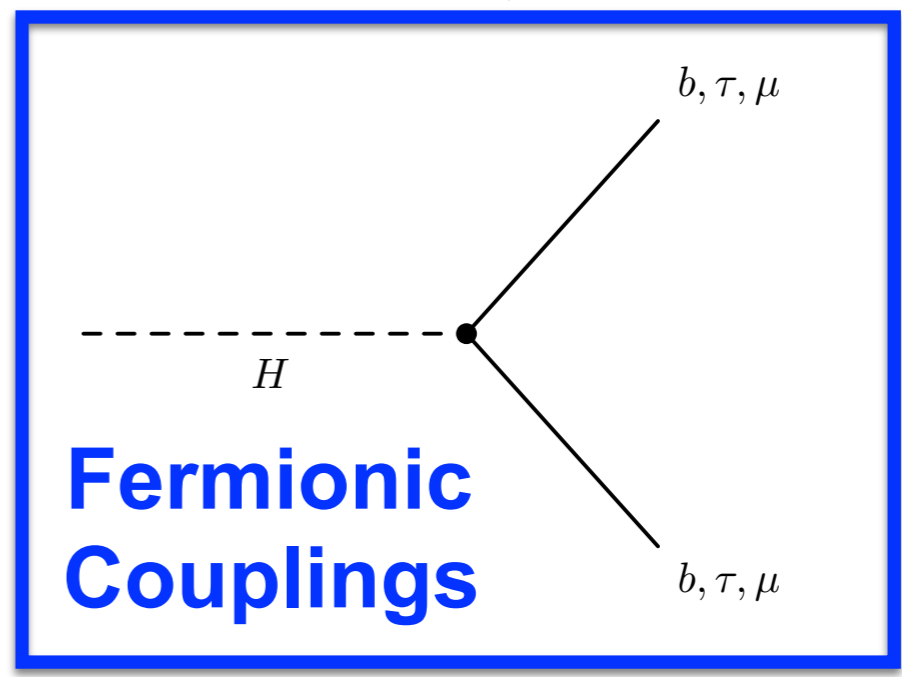
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

- Mass generation for and Higgs interactions with gauge bosons is a direct consequence of electroweak symmetry breaking.
- Yukawa interactions: fermion masses proportional to Higgs-fermion interaction strength.
- Each Yukawa coupling Y_f is a free parameter of the SM.

Bosonic Couplings

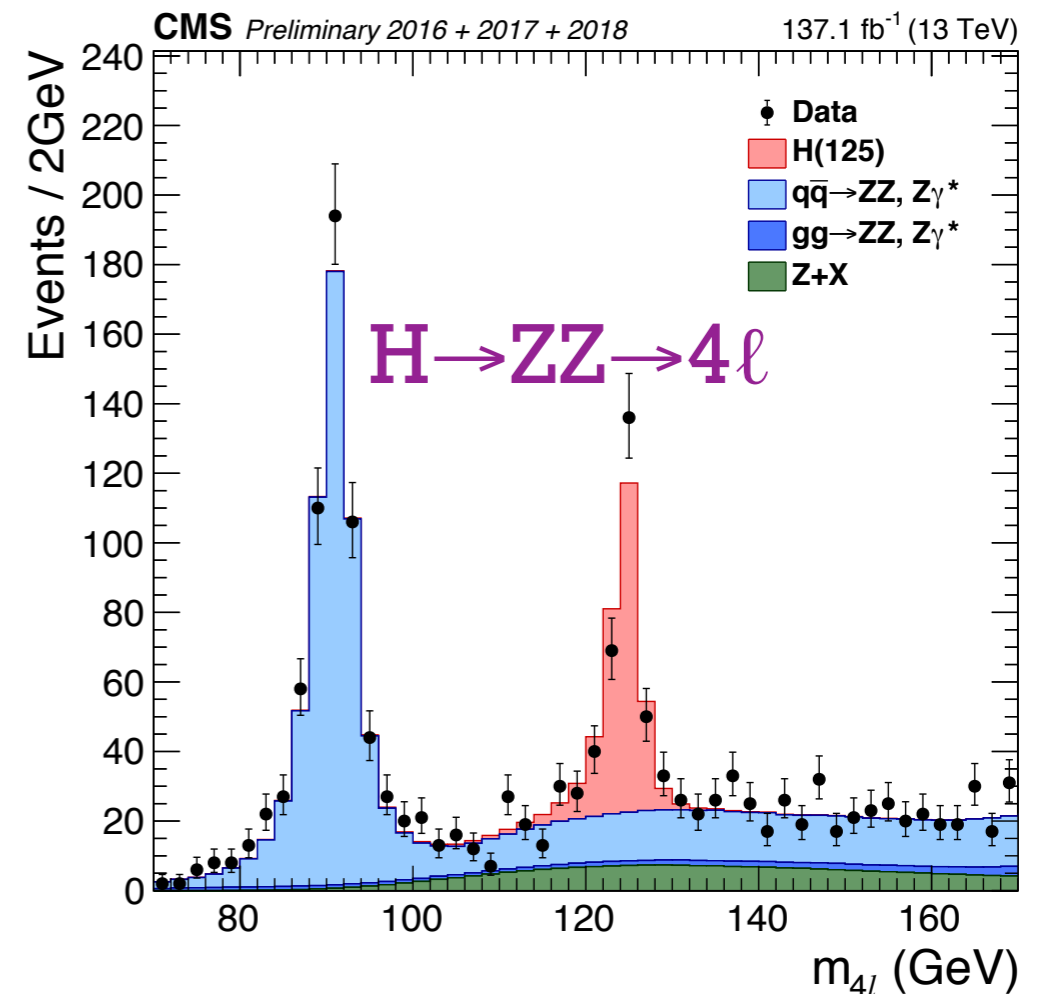
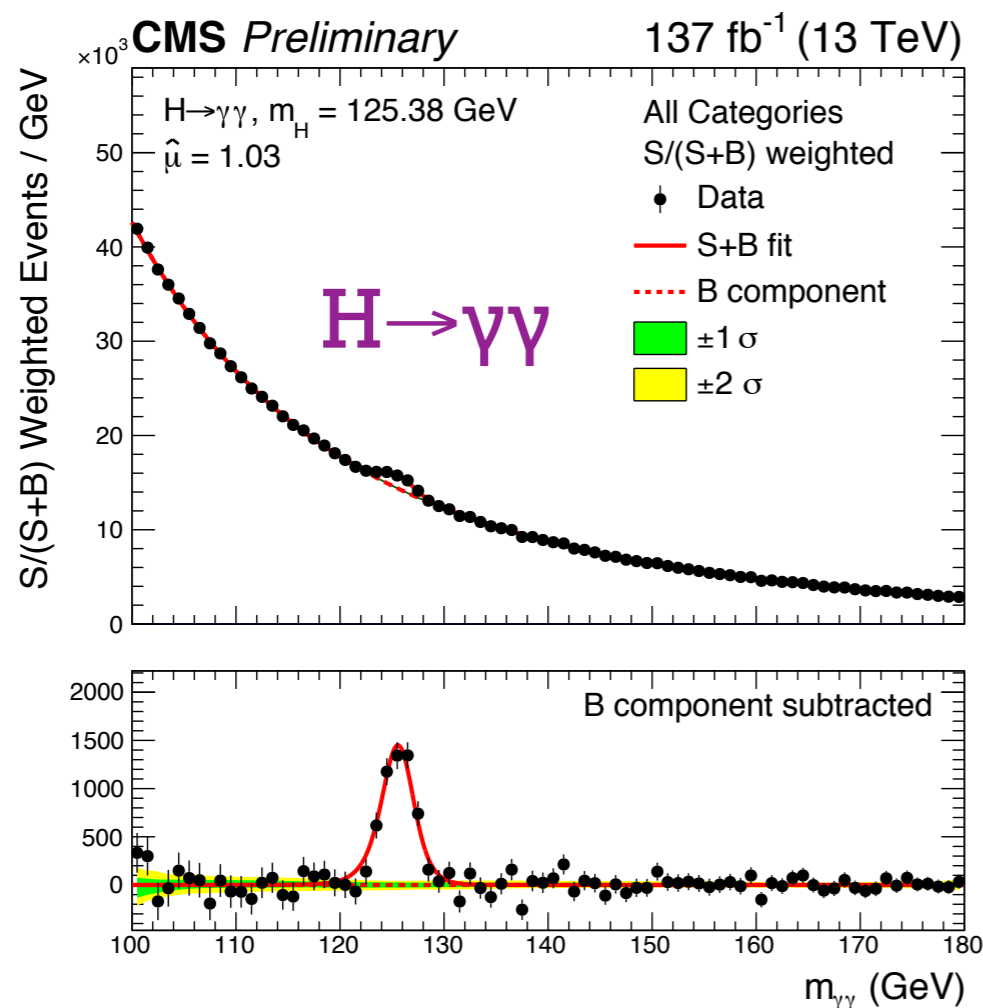


Fermionic Couplings



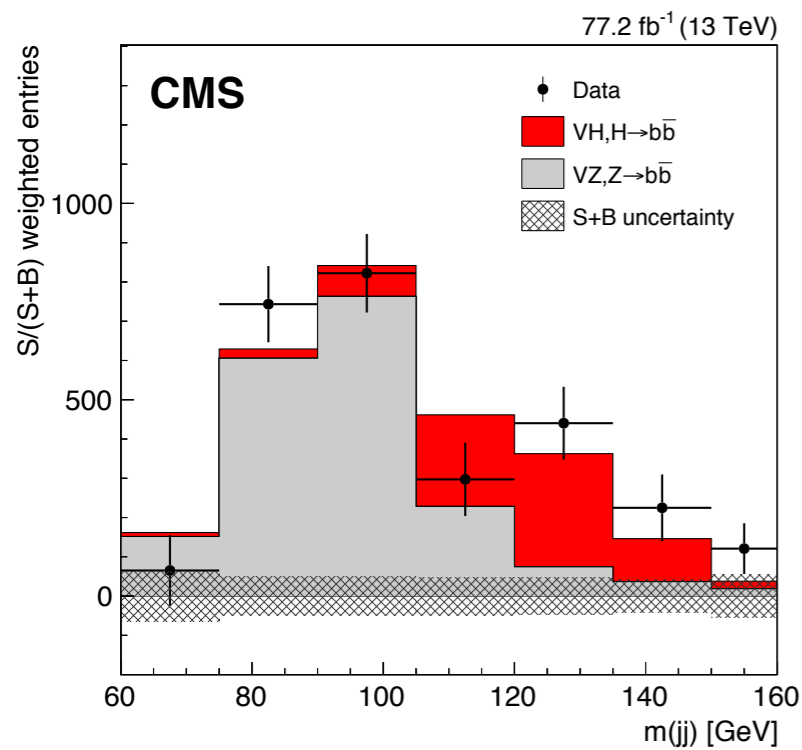
$$L_{\text{Yuk}} = (1 + \frac{H}{v}) m_f \bar{f}_L f_R$$

- *We have come a long way in studying the properties of the Higgs boson in the eight years since its discovery.*
- All measured properties (production rate, spin, CP, ...) consistent with SM.
- Mass measured at nearly per-mille level: $m_H = 125.38 \pm 0.14$ GeV ([Phys. Lett. B 805 \(2020\) 135425](#)).



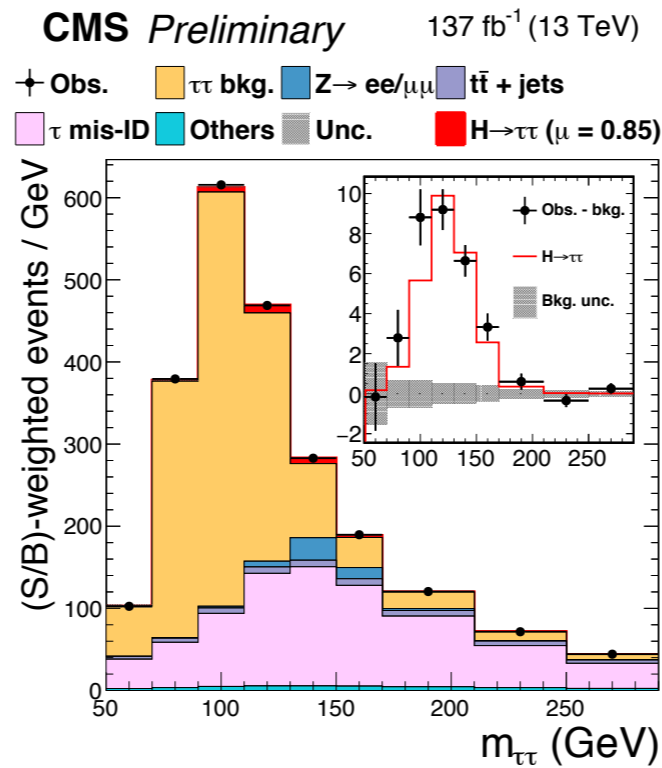
- In addition to gauge boson couplings, Higgs boson couplings to third generation fermions (t, τ , b) firmly established and consistent with SM.
- Yukawa interactions for third generation are clearly SM-like within the current experimental 10-20% precision.

$H \rightarrow b\bar{b}$



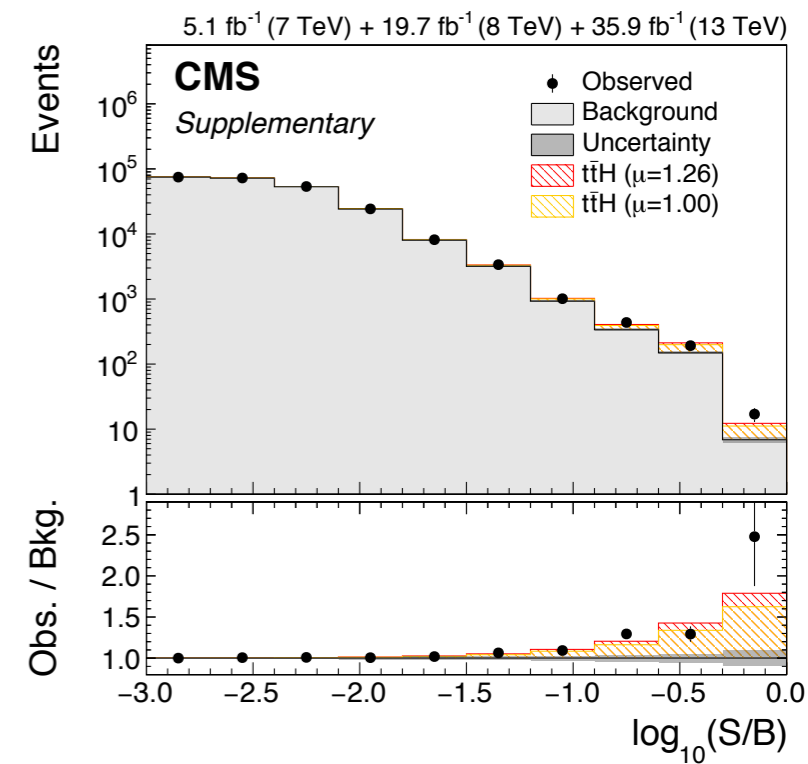
[Phys. Rev. Lett. 121 \(2018\) 121801](#)

$H \rightarrow \tau\tau$



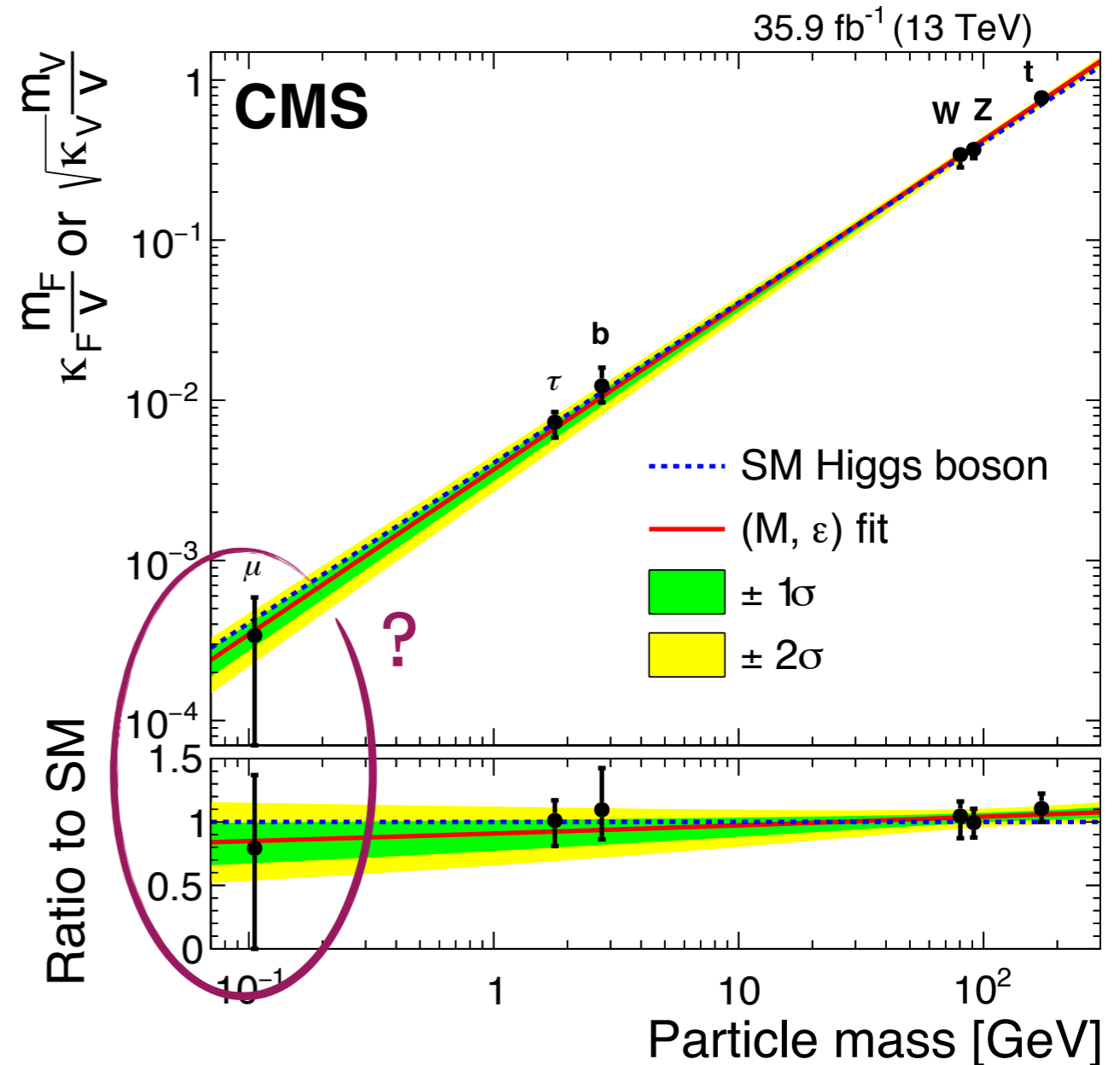
[CMS-PAS-HIG-19-010](#)

ttH



[Phys. Rev. Lett. 120 \(2018\) 231801](#)

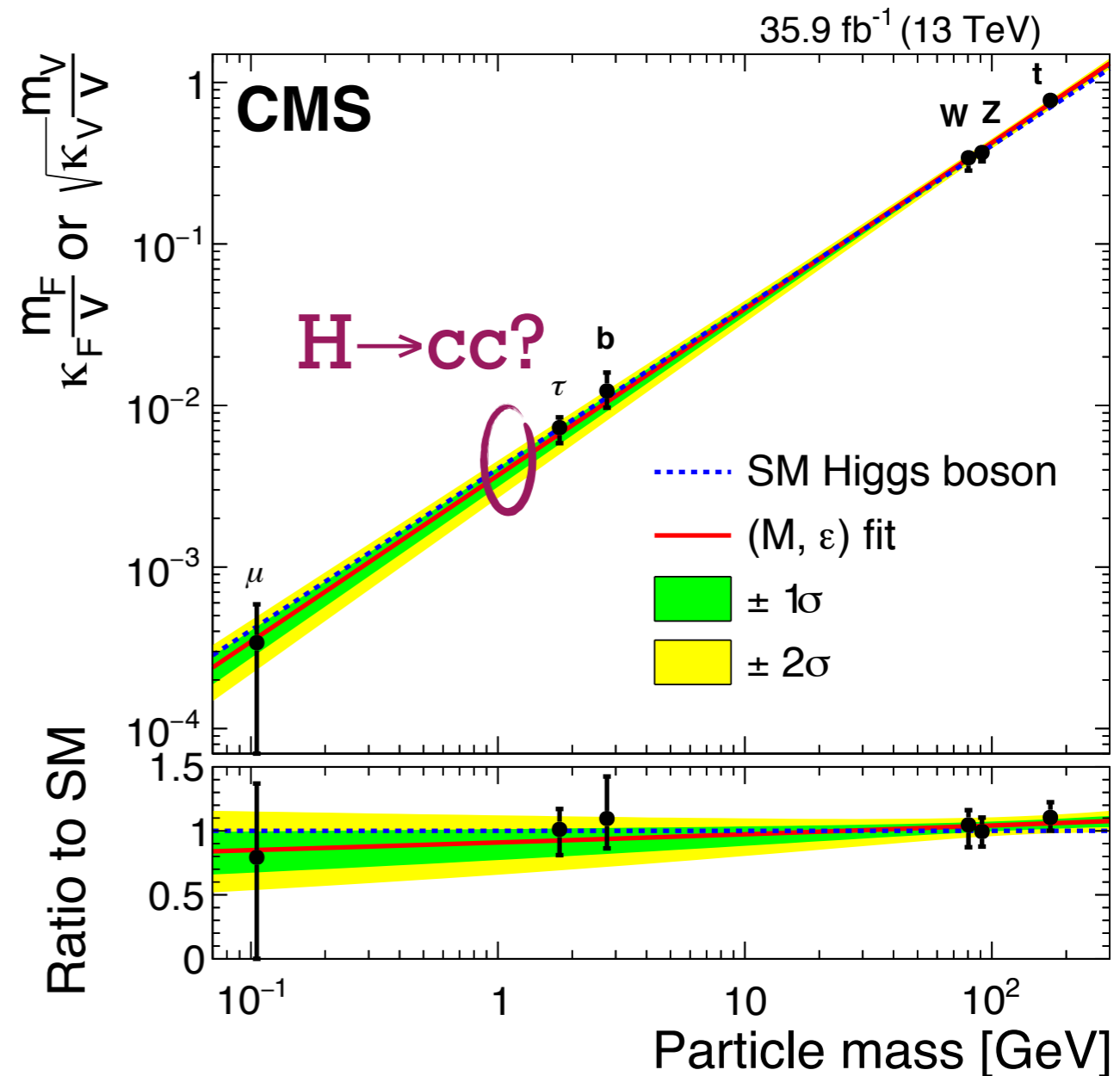
- *Next frontier: Higgs boson couplings to second generation fermions*
- **$H \rightarrow \mu\mu$ is likely the only accessible probe of first or second generation couplings at the LHC.**
- Extend probe of Higgs interactions by more than an order of magnitude in mass scale.



(from latest CMS Higgs couplings combination)

[Eur. Phys. J. C 79 \(2019\) 421](#)

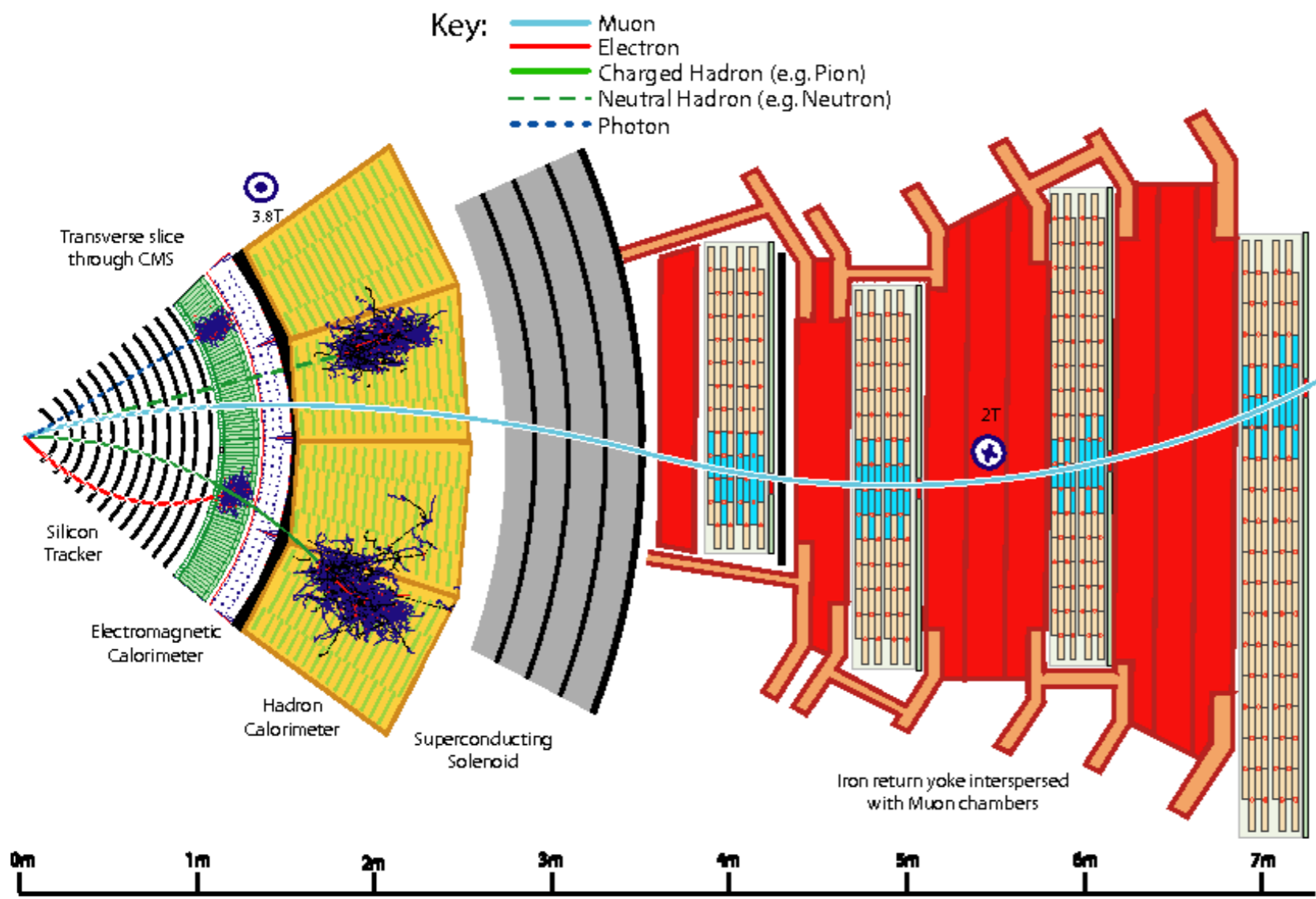
- *What about $H \rightarrow cc$?*
- $\text{BR}(H \rightarrow cc) = 2.9\%$!
- Significant branching fraction, but very large backgrounds and difficult to isolate jets originating from charm quarks.
- Current limits are factor ~ 40 higher than SM with partial Run-2 data set [1].
- ***Measuring $H \rightarrow cc$ will be very difficult, even with $3\text{-}4 \text{ ab}^{-1}$ from HL-LHC.***



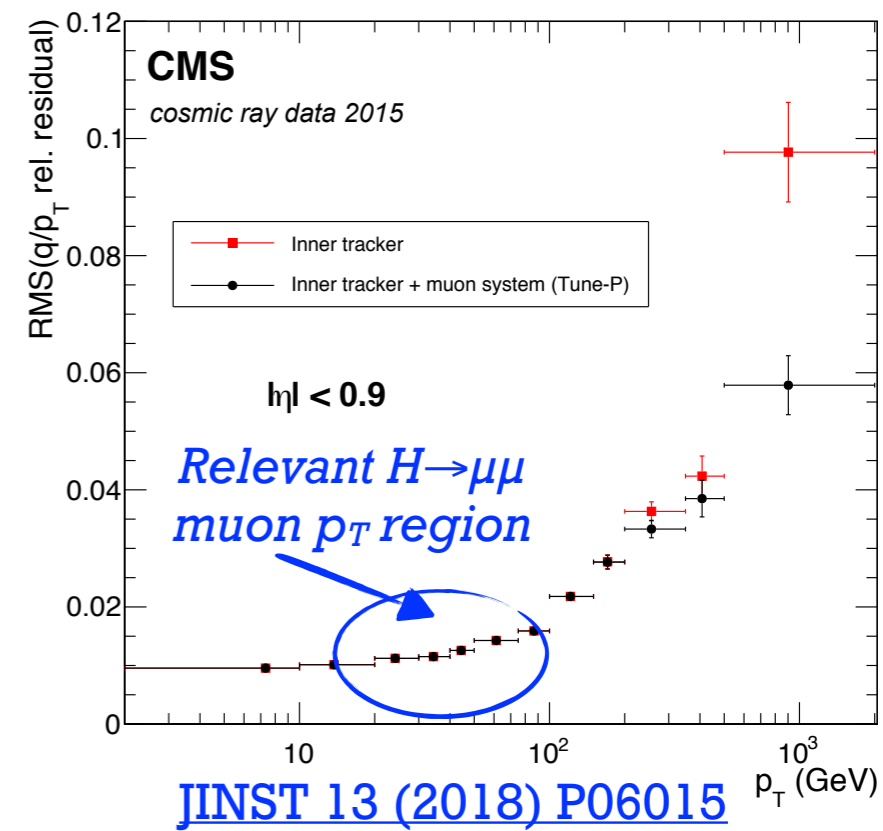
(from latest CMS Higgs couplings combination)

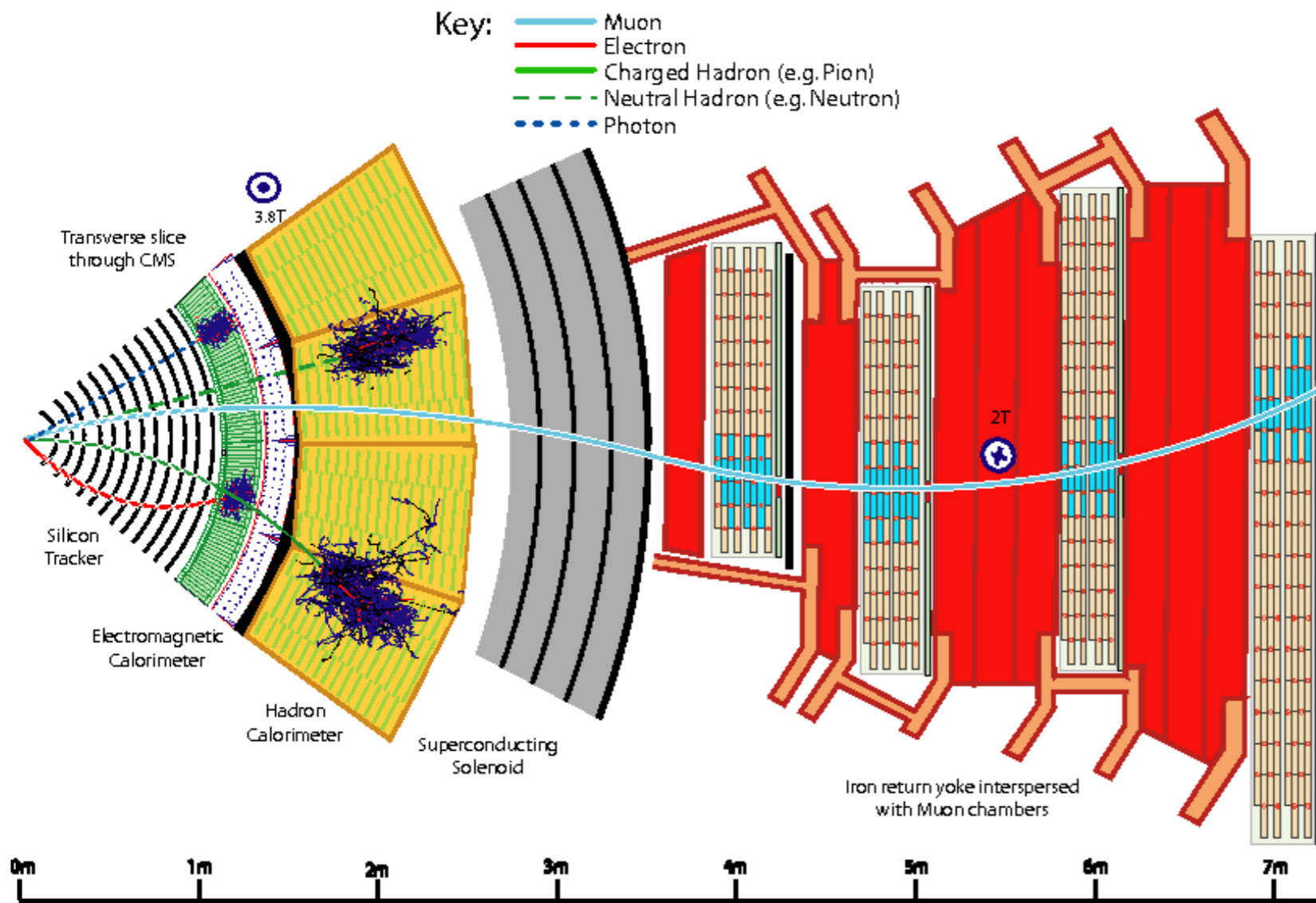
[Eur. Phys. J. C 79 \(2019\) 421](#)

[1] [JHEP 03 \(2020\) 131](#)

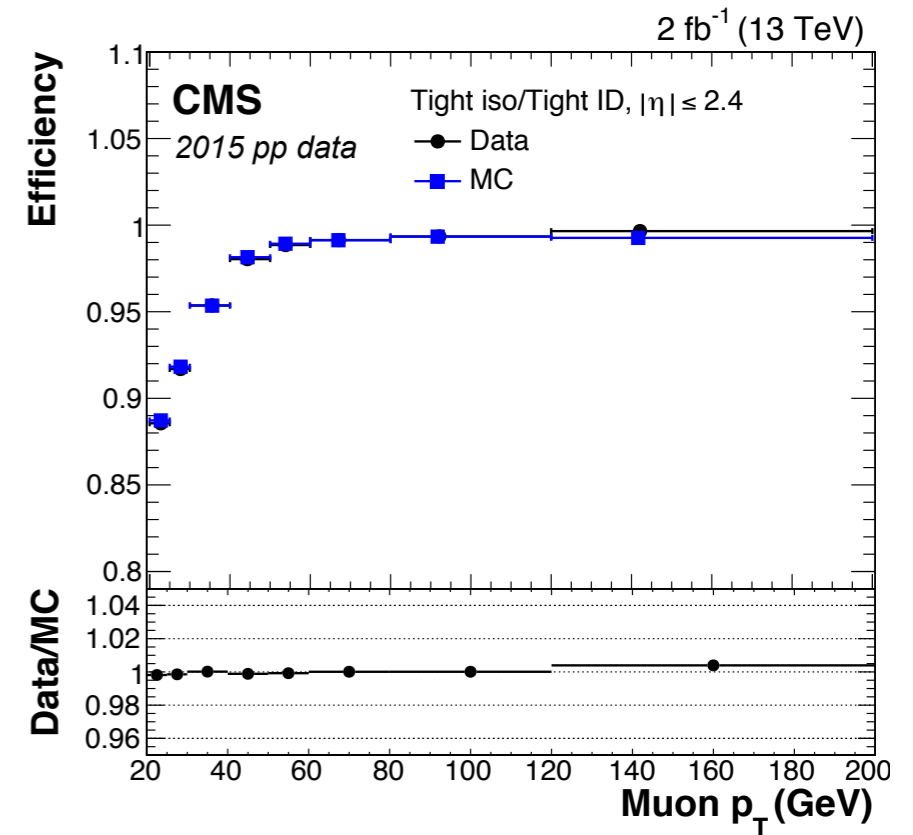


Muon momentum resolution vs $p_T(\mu)$



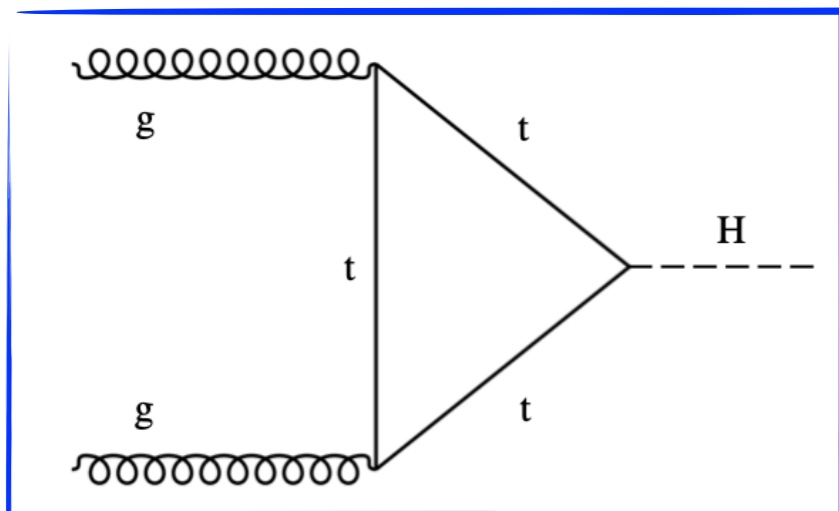


Muon reconstruction efficiency vs $p_T(\mu)$



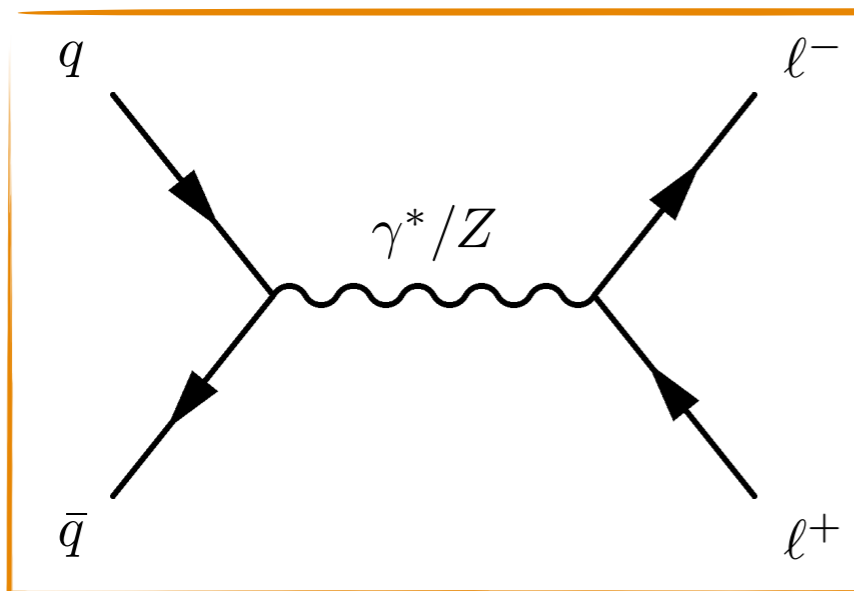
~95% selection efficiency for muons from $H \rightarrow \mu\mu$ decays.

Gluon-gluon fusion production (ggH)
dominant Higgs boson production
mode at the LHC



- Inclusive Higgs boson production cross section at 13 TeV: $\sigma_H \sim 50$ pb.
- Expected $H \rightarrow \mu\mu$ branching fraction for m_H near 125 GeV: **$\text{BR}(H \rightarrow \mu\mu) \sim 2.2 \cdot 10^{-4}$** .
- $\Rightarrow \sigma_{\text{eff}}(H \rightarrow \mu\mu) \sim 0.01$ pb
- **Roughly 1k total signal events in Run-2 (137 fb^{-1}) dataset.**

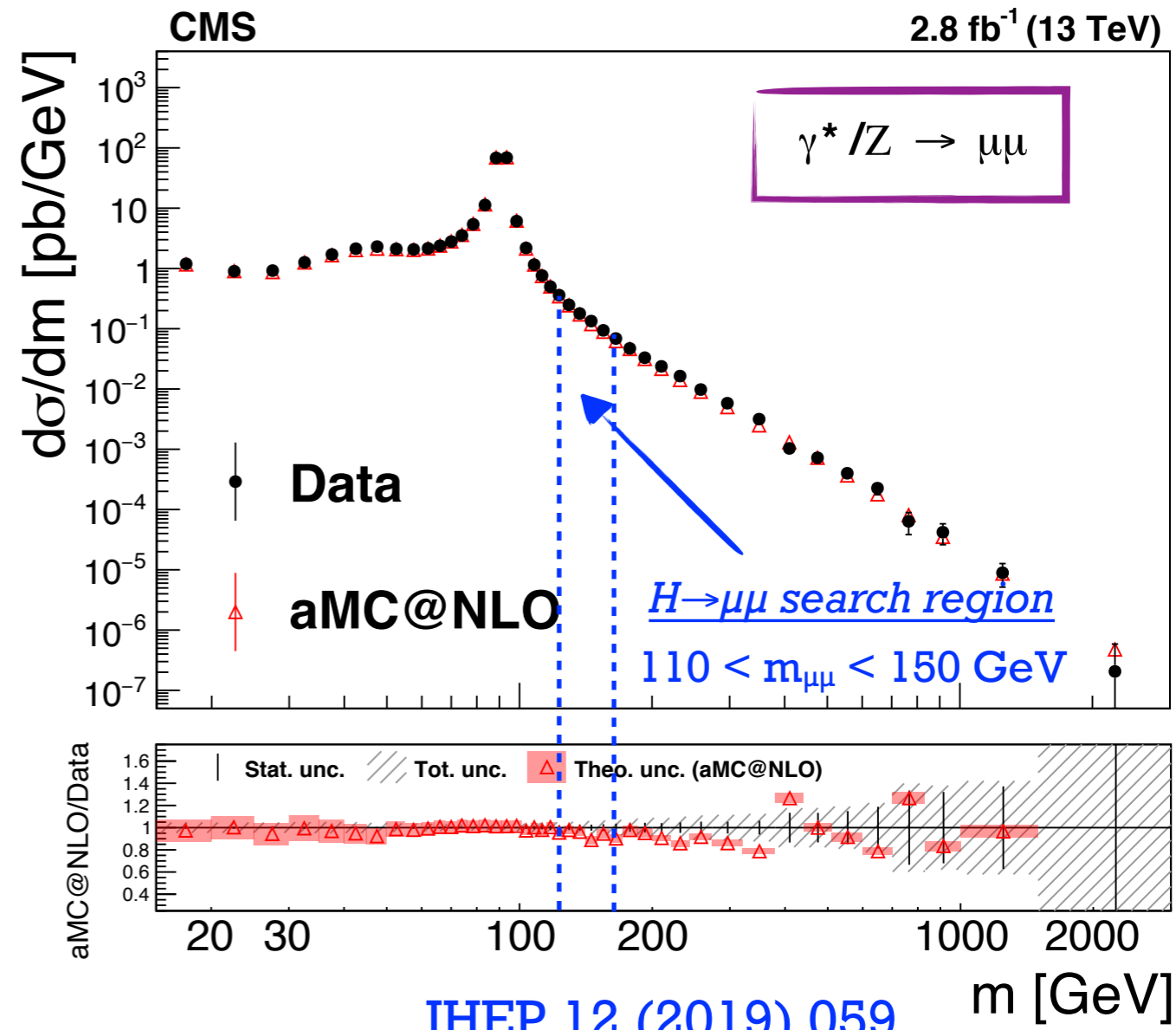
Drell-Yan (DY) production



Total effective cross section in $H \rightarrow \mu\mu$ search region with $110 < m_{\mu\mu} < 150$ GeV:

$$\sigma_{\text{eff}}(\text{DY}) \sim 15 \text{ pb}$$

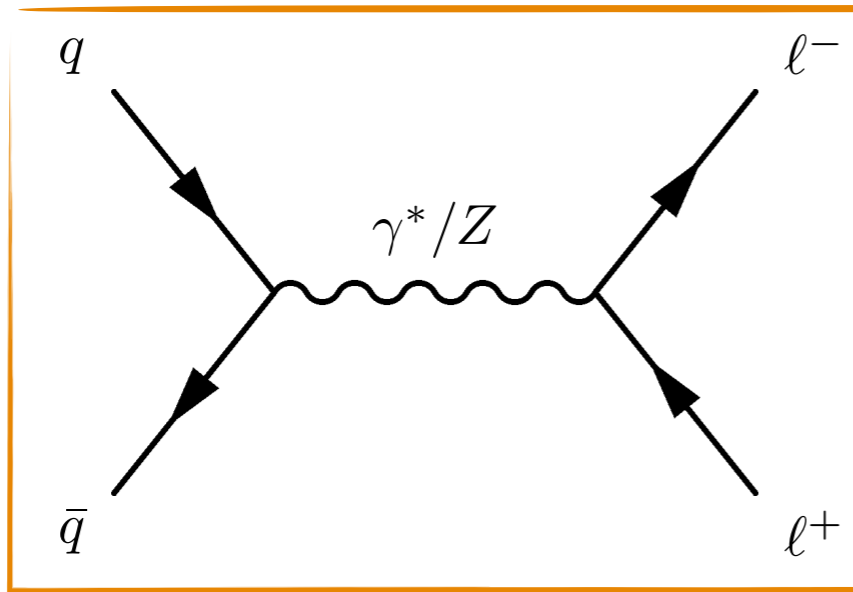
i.e. ~two million DY background events in $H \rightarrow \mu\mu$ preselected 13 TeV data sample with $m_{\mu\mu}$ near 125 GeV.



[JHEP 12 \(2019\) 059](#)

Drell-Yan (DY) production

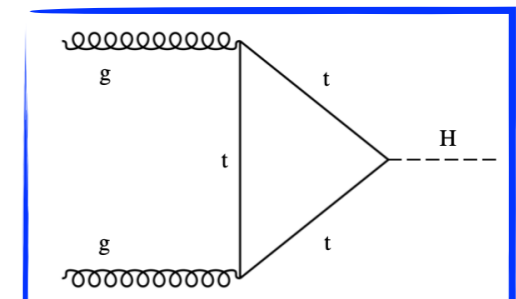
$$\sigma_{\text{eff}}(\text{DY}) \sim 15 \text{ pb}$$



- S/B \sim one per mille with $m_{\mu\mu}$ near 125 GeV
- Large additional background rejection necessary to measure $H \rightarrow \mu\mu$ signal.

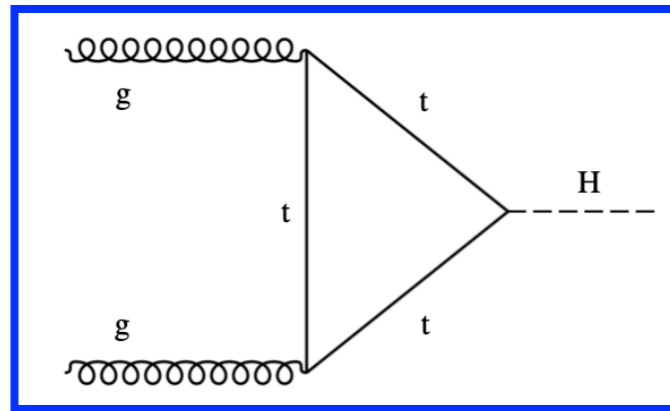
Three orders of magnitude more DY background than $H \rightarrow \mu\mu$ signal in preselected search region.

$H \rightarrow \mu\mu$ signal
 $\sigma_{\text{eff}}(H \rightarrow \mu\mu) \sim 0.01 \text{ pb}$



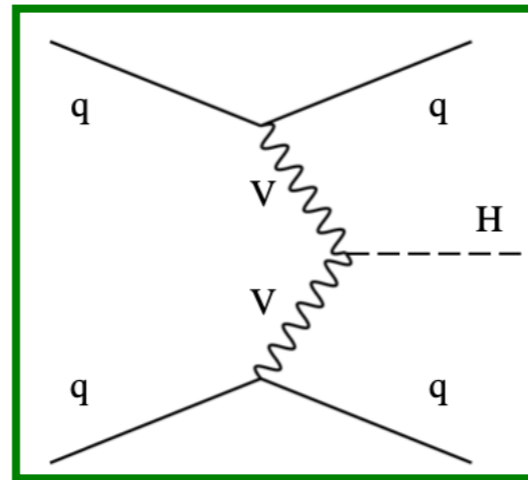
Effective cross section

Gluon-gluon fusion (ggH)

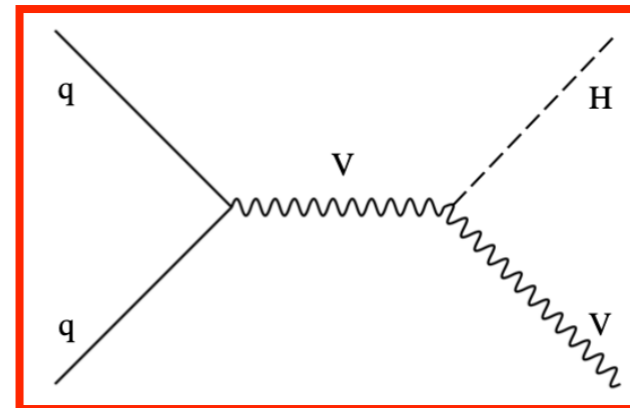


Improve signal-to-background separation by *splitting events into exclusive categories, each targeting a particular Higgs boson production mode.*

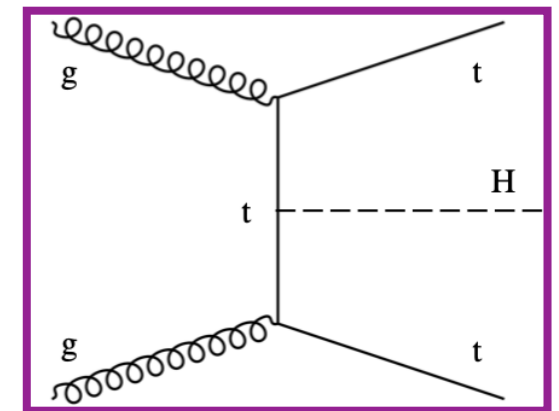
Vector boson fusion (VBF)



Associated production with W or Z (VH)



Associated production with top quarks (ttH)

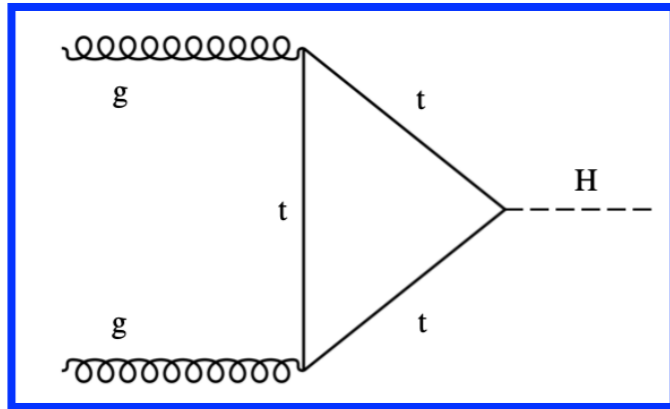


Effective cross section (rate)

Level of achievable signal purity

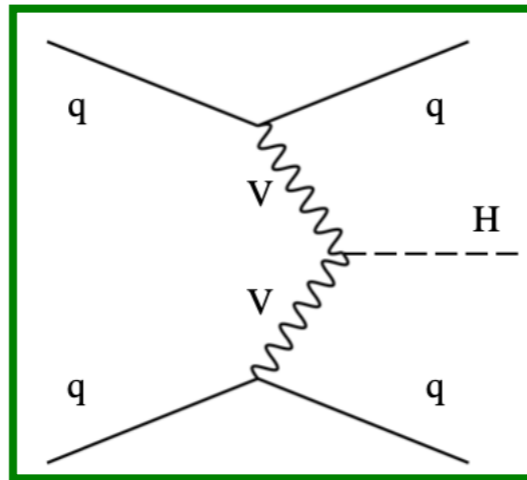
Effective cross section (rate)

Gluon-gluon fusion (ggH)



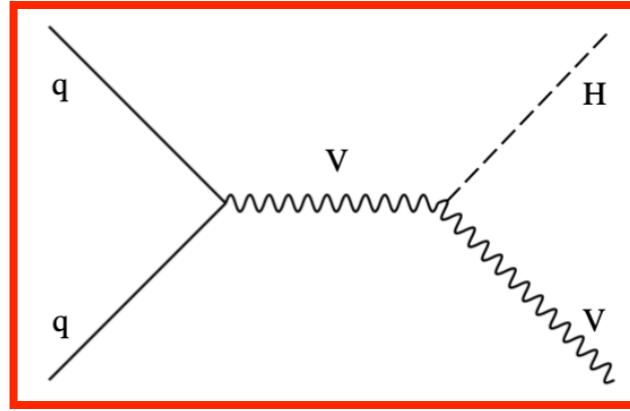
Significant improvements of existing strategy

Vector boson fusion (VBF)



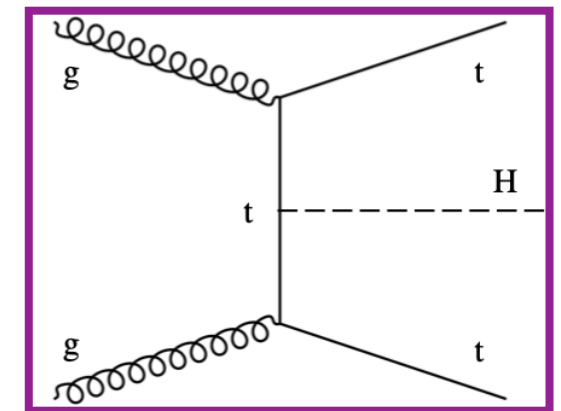
Completely redesigned strategy

Associated production with W or Z (VH)



New categories

Associated production with top quarks (ttH)



Level of achievable signal purity

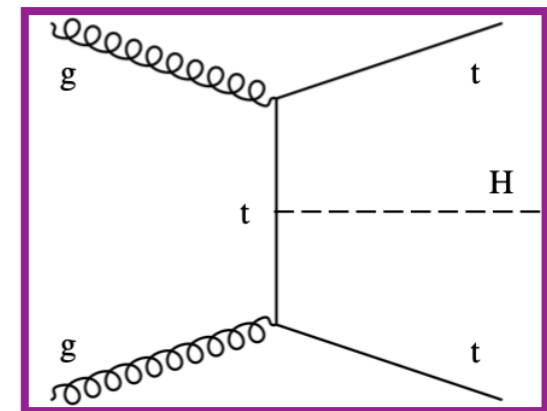
$\mu^+\mu^-$ pair with mass near 125 GeV

Presence of b-tagged jets?

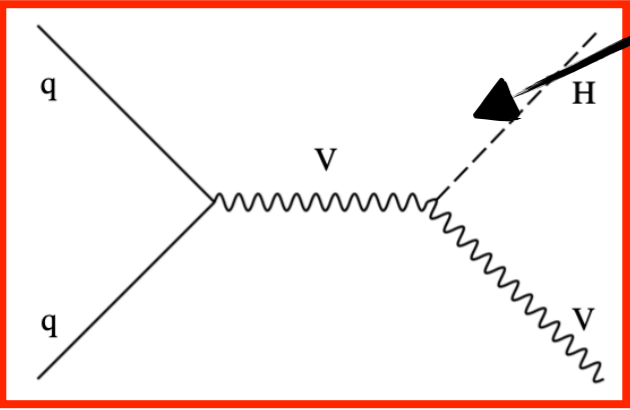
Additional electron(s) or muon(s)?

Two jets with large m_{jj} , $\Delta\eta(jj)$?

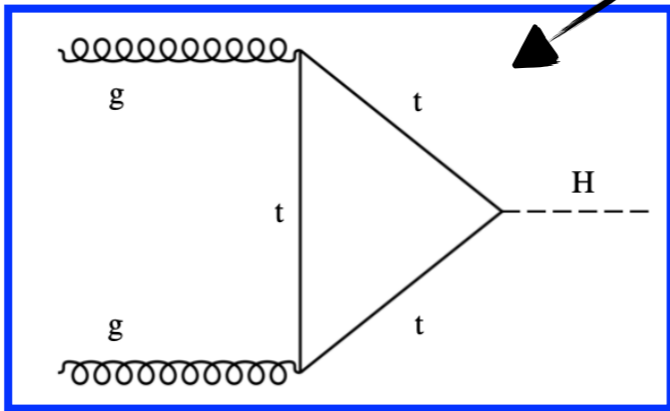
ttH category



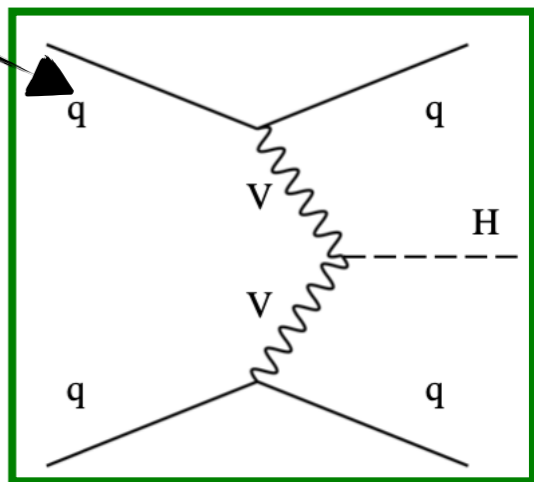
VH category



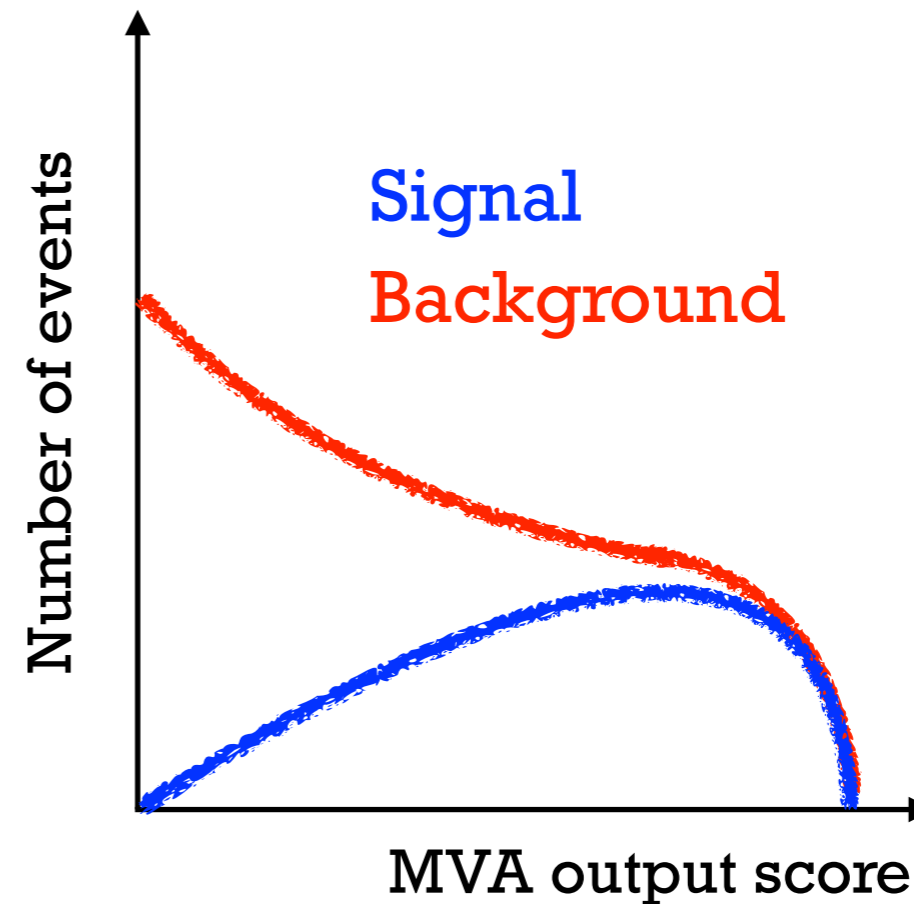
ggH category



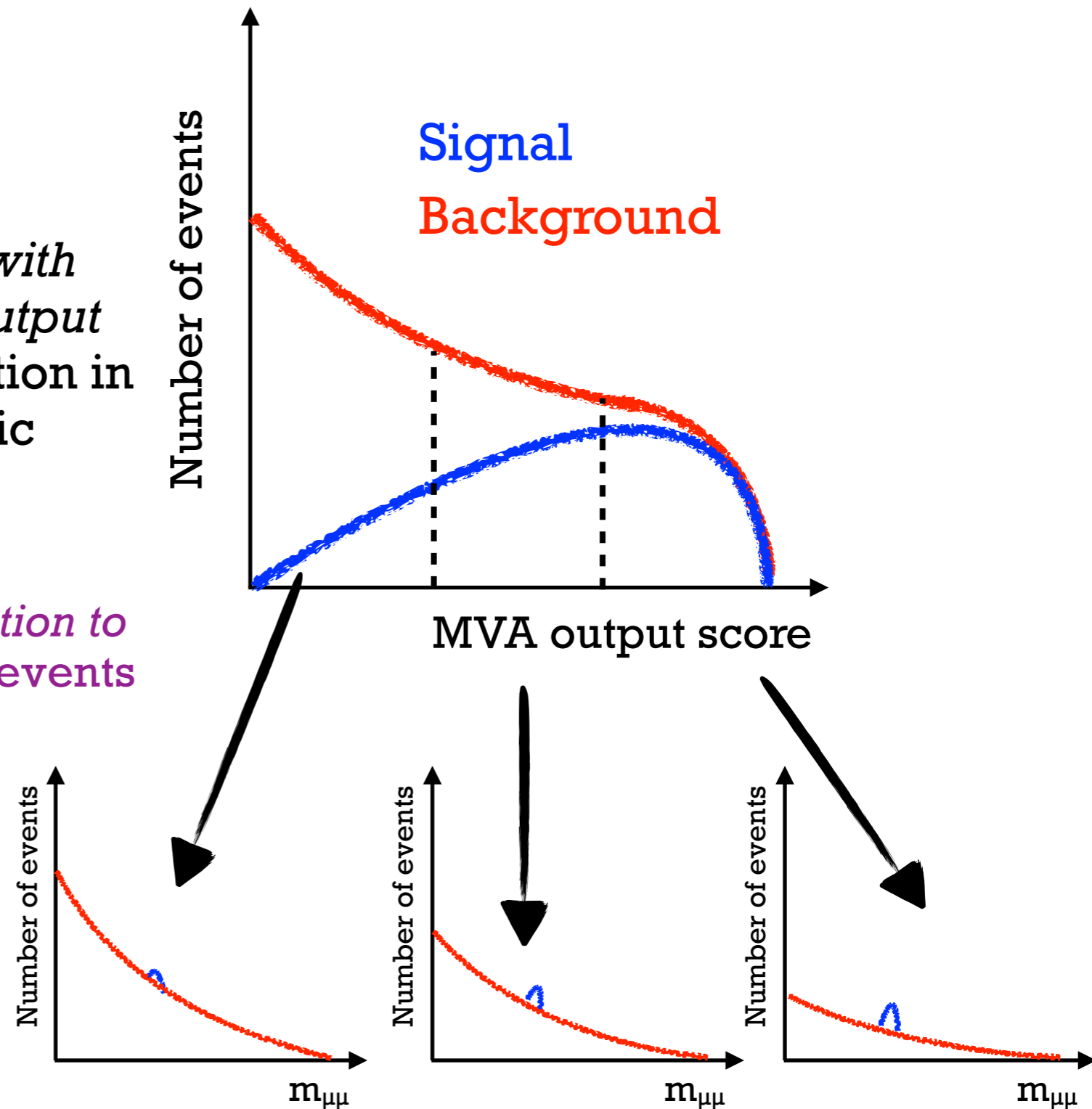
VBF category



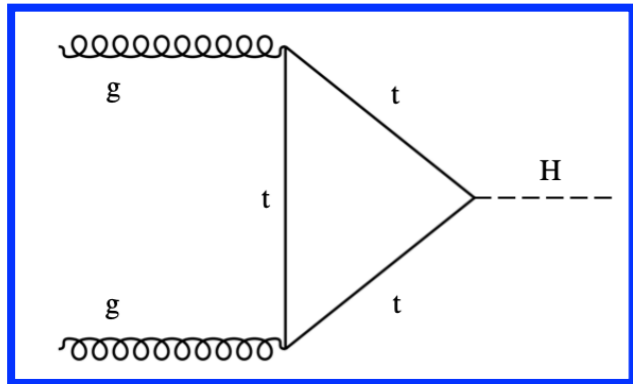
- *Train a multivariate (MVA) classifier to separate signal from background*
- Using kinematic input variables uncorrelated with H candidate mass.



- *Train a multivariate (MVA) classifier to separate signal from background*
- Using kinematic input variables uncorrelated with H candidate mass.
- **Divide** events into subcategories with varying signal purity using MVA output **and fit** the dimuon mass distribution in each subcategory with parametric functions.
- *Promote events with best mass resolution to high BDT score by weighting signal events by $1/\sigma_m$ in BDT training.*

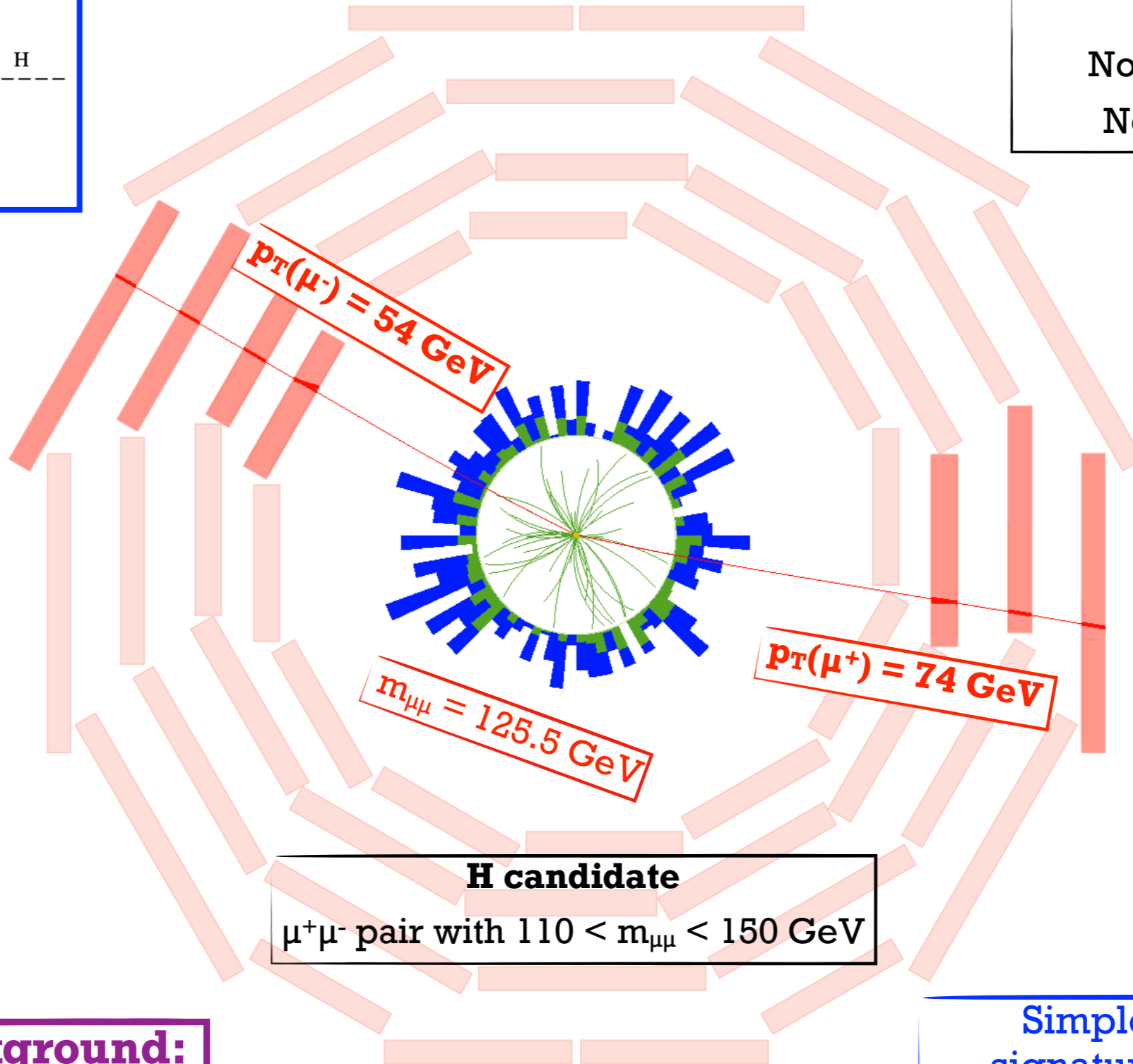


MVA subcategories with varying signal purity



Veto exclusive categories:

- No b jets
- No additional leptons
- No VBF-like jet pair



H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

Dominant background:
 Drell-Yan (DY)

Simple experimental signature, but difficult to distinguish from background.

- Train a Boosted Decision Tree (BDT) to discriminate signal from backgrounds.
- H candidate kinematic variables:
 - Dimuon p_T and rapidity, decay angles ϕ_{CS} , $\cos\theta_{CS}$
 - $\eta(\mu)$, $p_T(\mu)/m_{\mu\mu}$, ...
- Potential signature of initial state radiation:
 - Leading jet p_T and η .
 - Minimum angular separation between H candidate and jet.

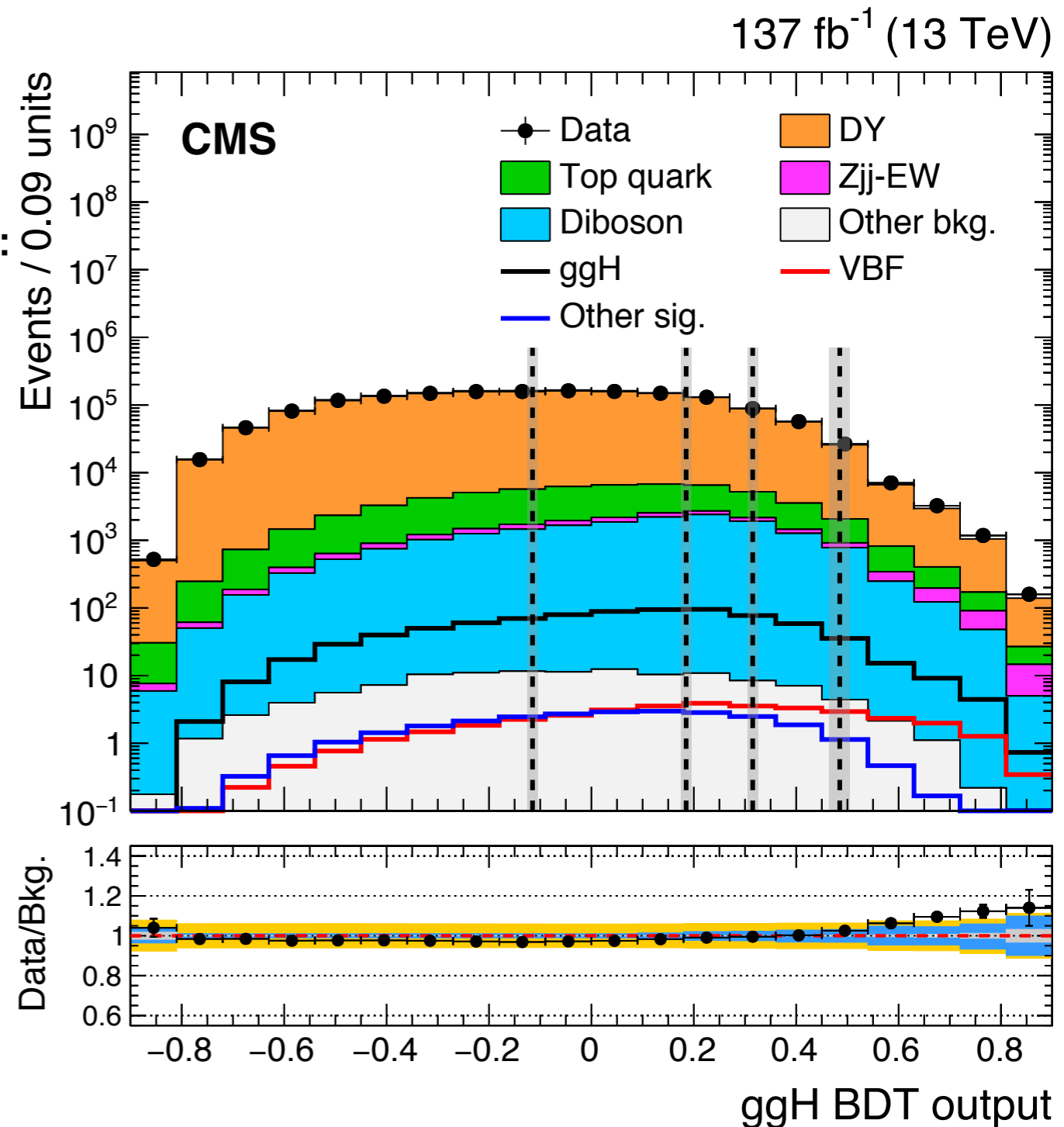
Mass resolution per ggH subcategory

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

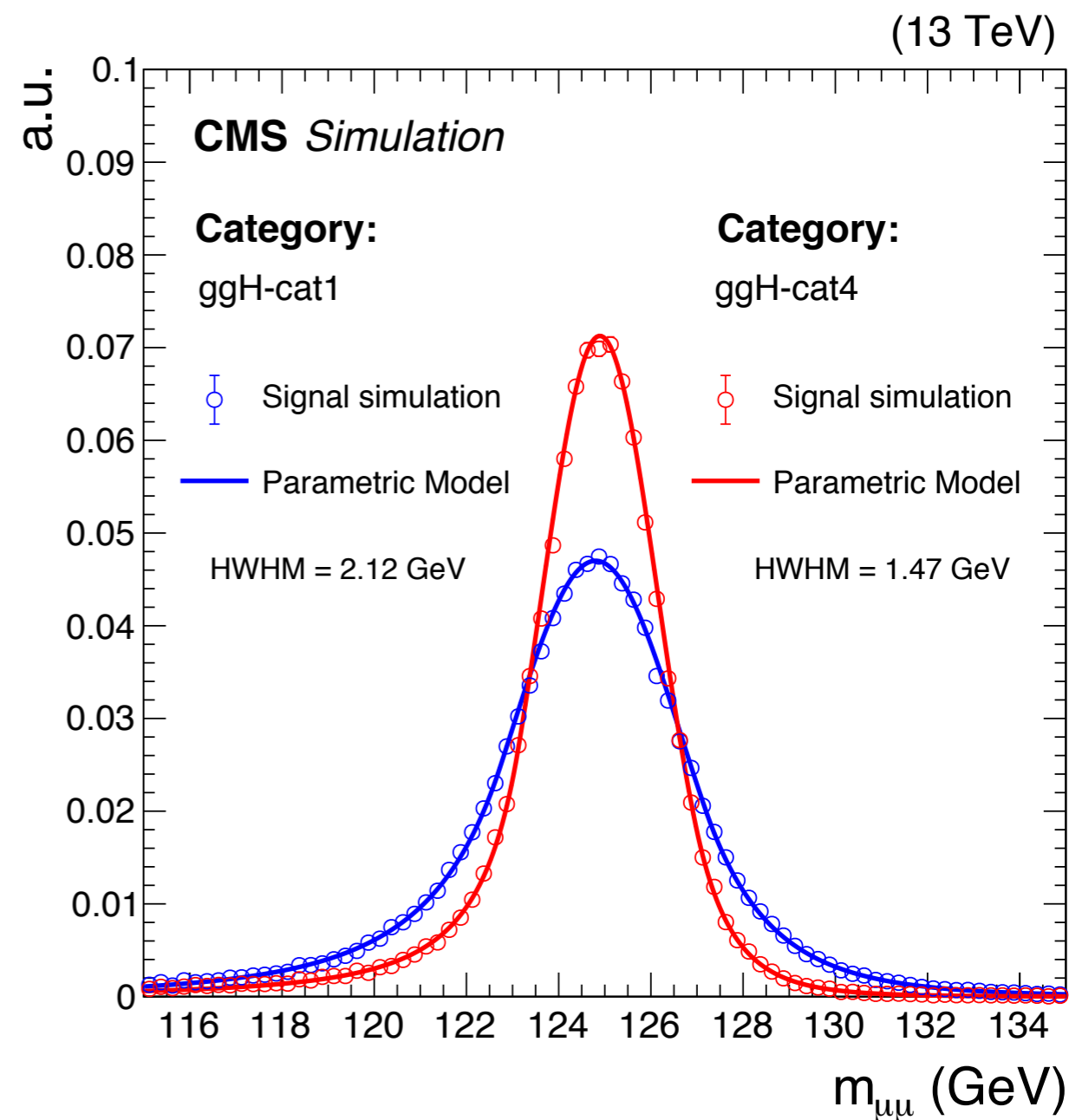
signal purity



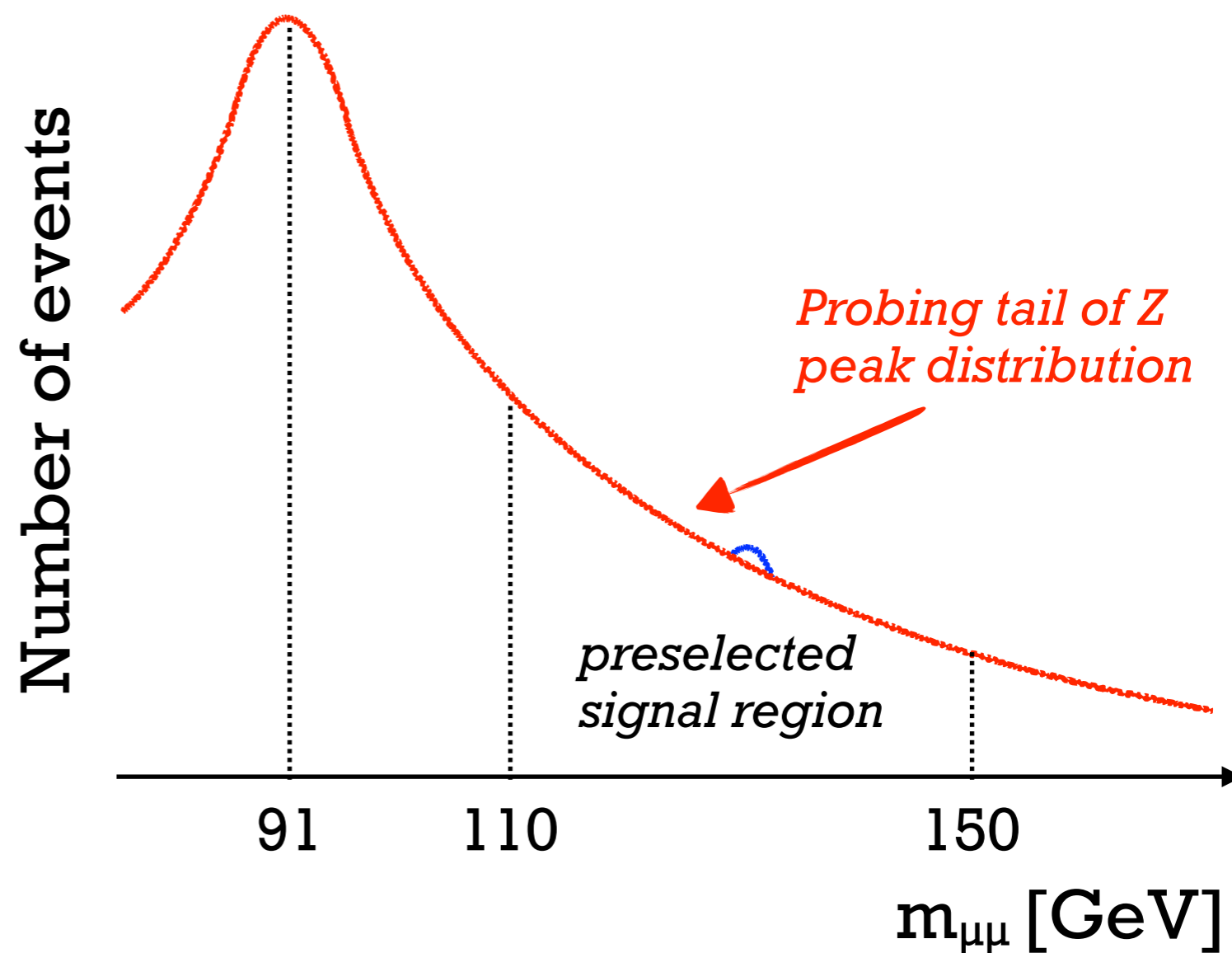
ggH category BDT score distribution



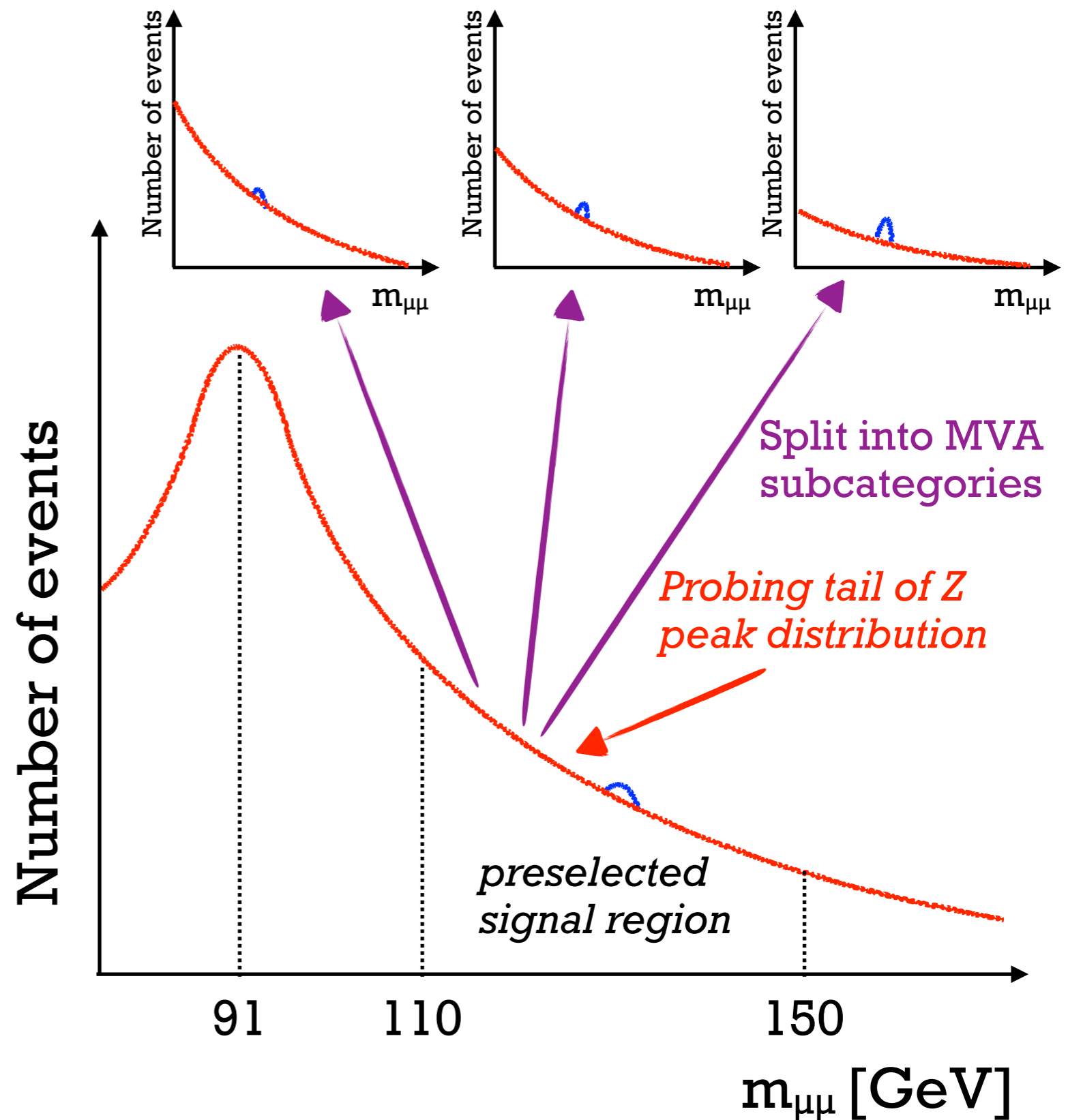
- Dimuon mass resolution ranges from 1 to 2% across subcategories, depending on muon p_T and η .
- Mass resolution further improved by:
 - recovery of photons from final state radiation ($\sim 3\%$)
 - constraining muon track to originate from interaction point ($\sim 4\%$)

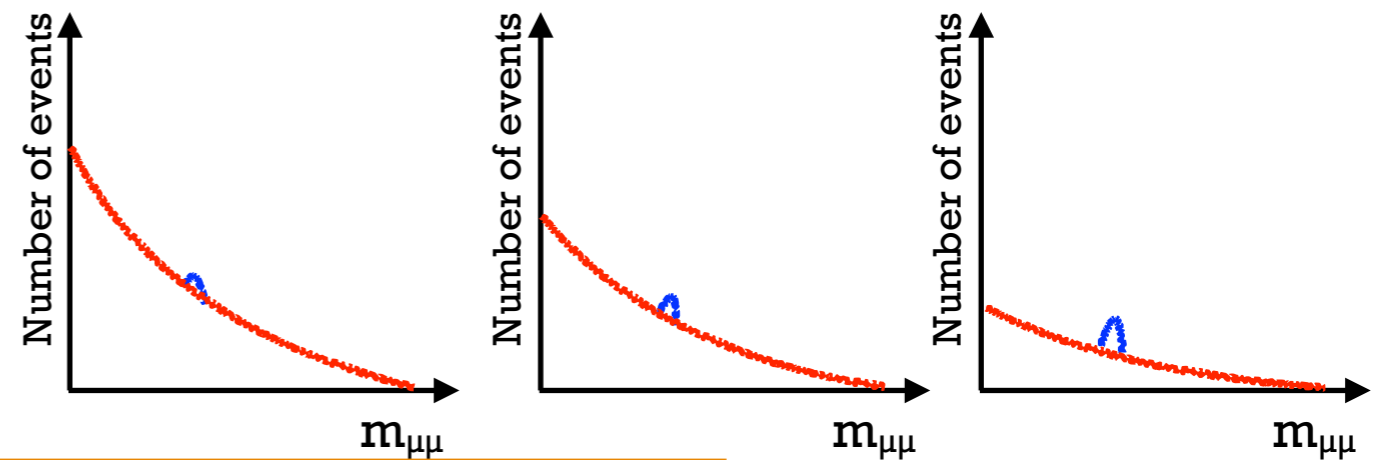


- Looking for small resonant peak over large smoothly falling DY background.



- Looking for small resonant peak over large smoothly falling DY background.
- Background shape expected to be similar across subcategories, with minor variations from differing muon kinematics.*



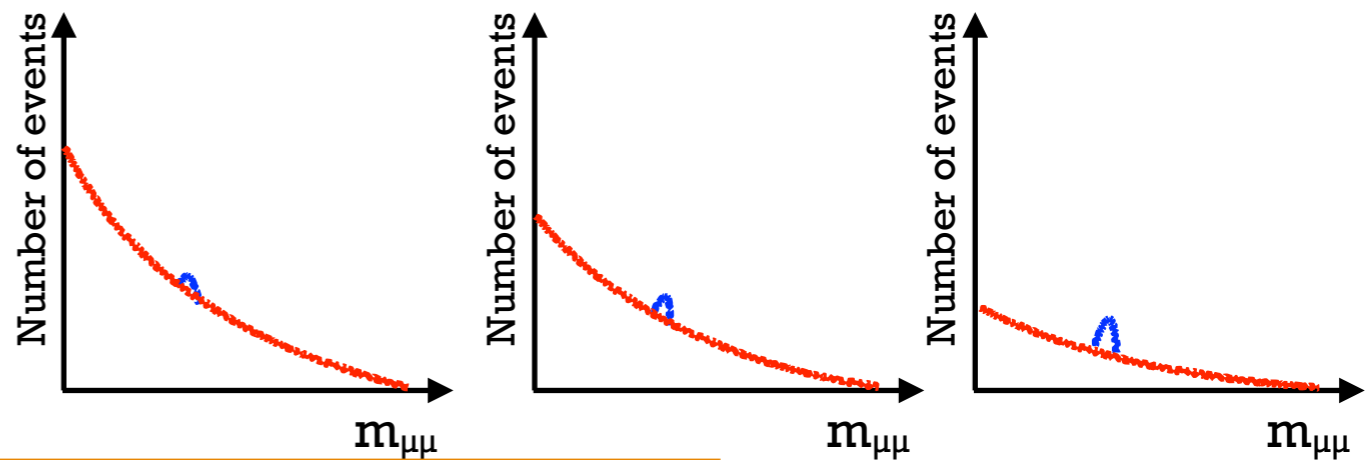


The "Core-PDF" method

$$B_{cat}(m_{\mu\mu}, \vec{\alpha}, \vec{\beta}) = N_B \times F_{core}(m_{\mu\mu}, \vec{\alpha}) \times T_{SMF}(m_{\mu\mu}, \vec{\beta})$$

Number of
bkg. events

"Core" function with **parameters correlated across subcategories.**



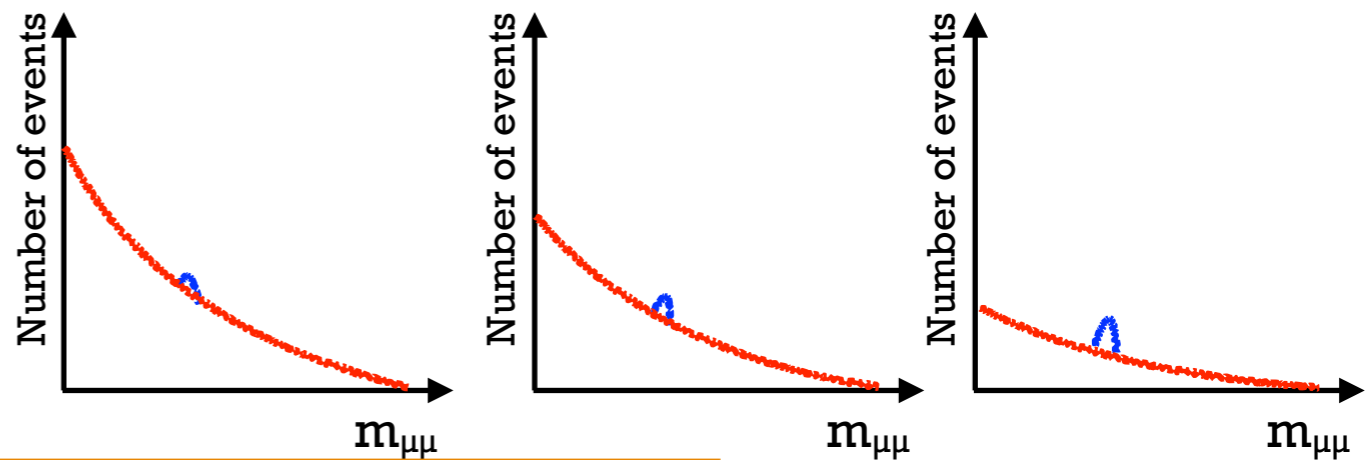
The "Core-PDF" method

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Number of
bkg. events

"Core" function with **parameters correlated across subcategories.**

Per-category polynomial shape modifier to adjust for kinematic differences.



The "Core-PDF" method

$$B_{cat}(m_{\mu\mu}, \vec{\alpha}, \vec{\beta}) = N_B \times F_{core}(m_{\mu\mu}, \vec{\alpha}) \times T_{SMF}(m_{\mu\mu}, \vec{\beta})$$

Number of
bkg. events

"Core" function with **parameters correlated across subcategories.**

Per-category polynomial shape modifier to adjust for kinematic differences.

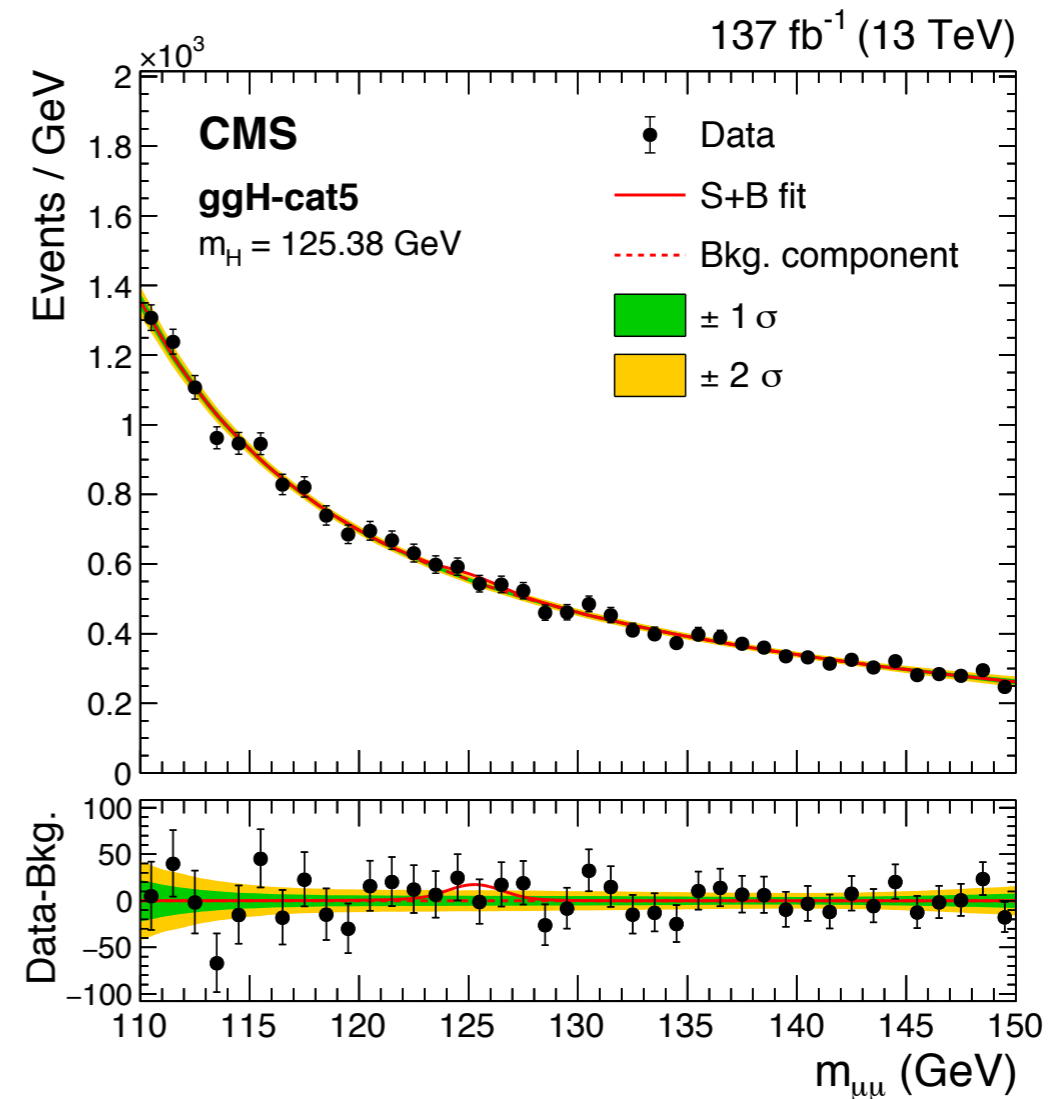
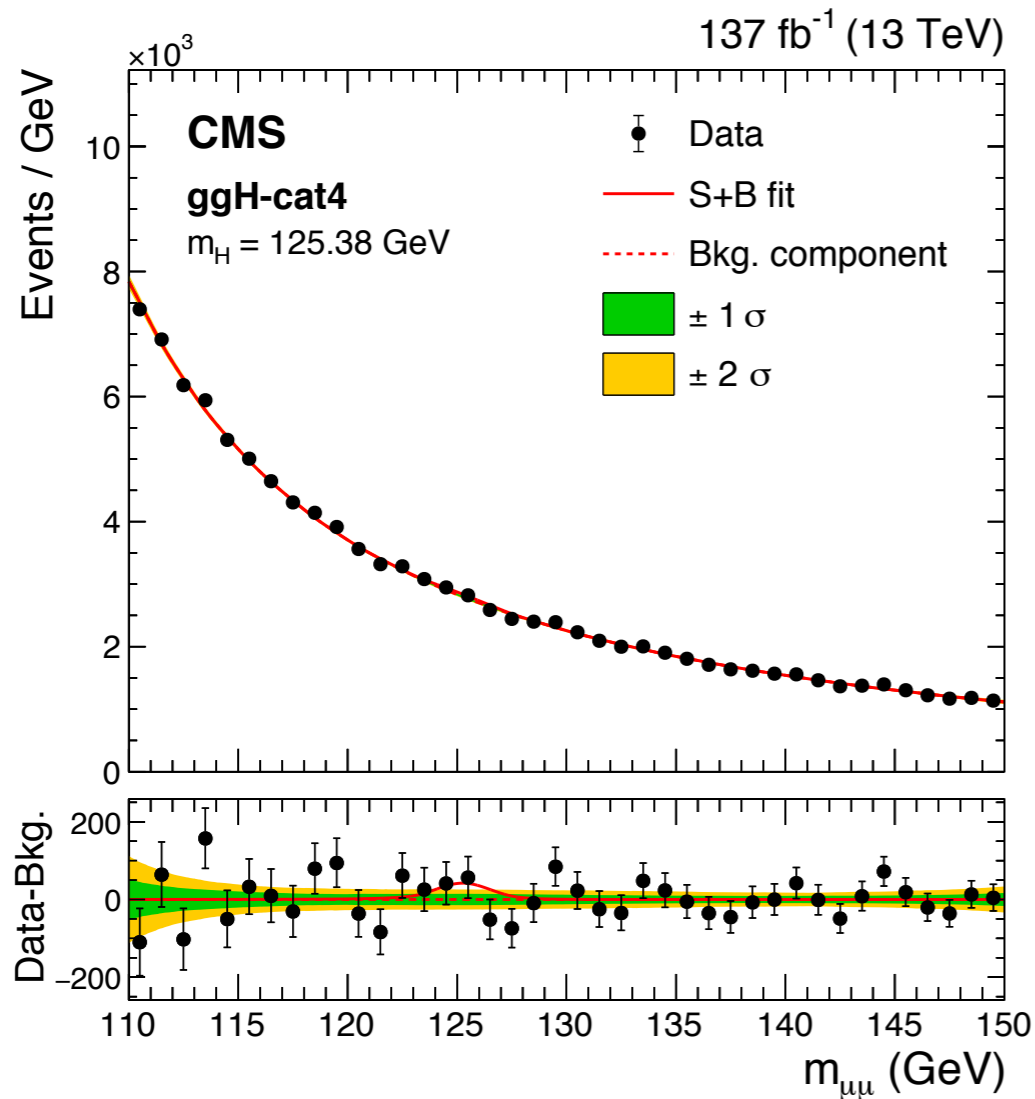
10% performance improvement and fewer total degrees of freedom with respect to previous strategy, while retaining negligible bias.

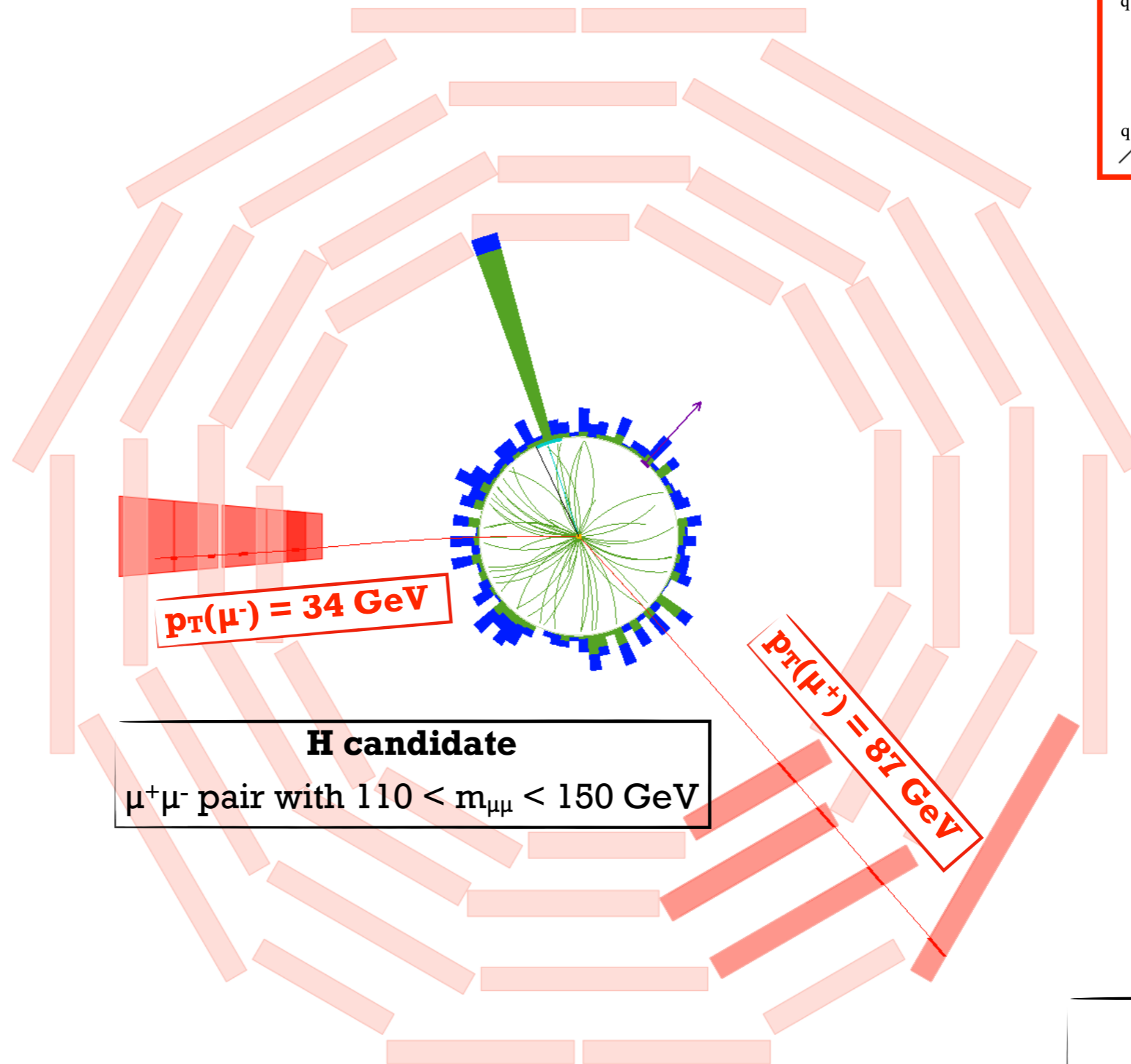
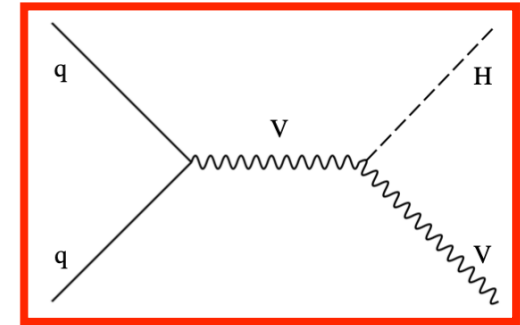
ggH category result

Observed (expected) significance: 1.0σ (1.6σ)

$$\mu = \frac{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)}{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)_{\text{SM}}} = 0.63^{+0.65}_{-0.65}$$

$m_{\mu\mu}$ distribution in the highest purity ggH subcategories

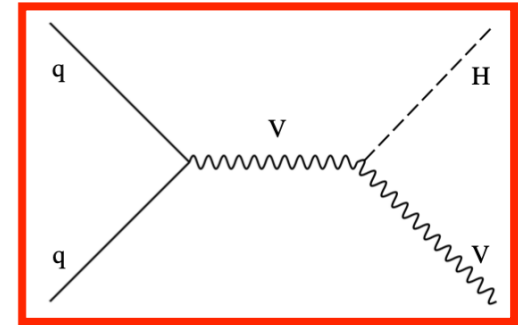




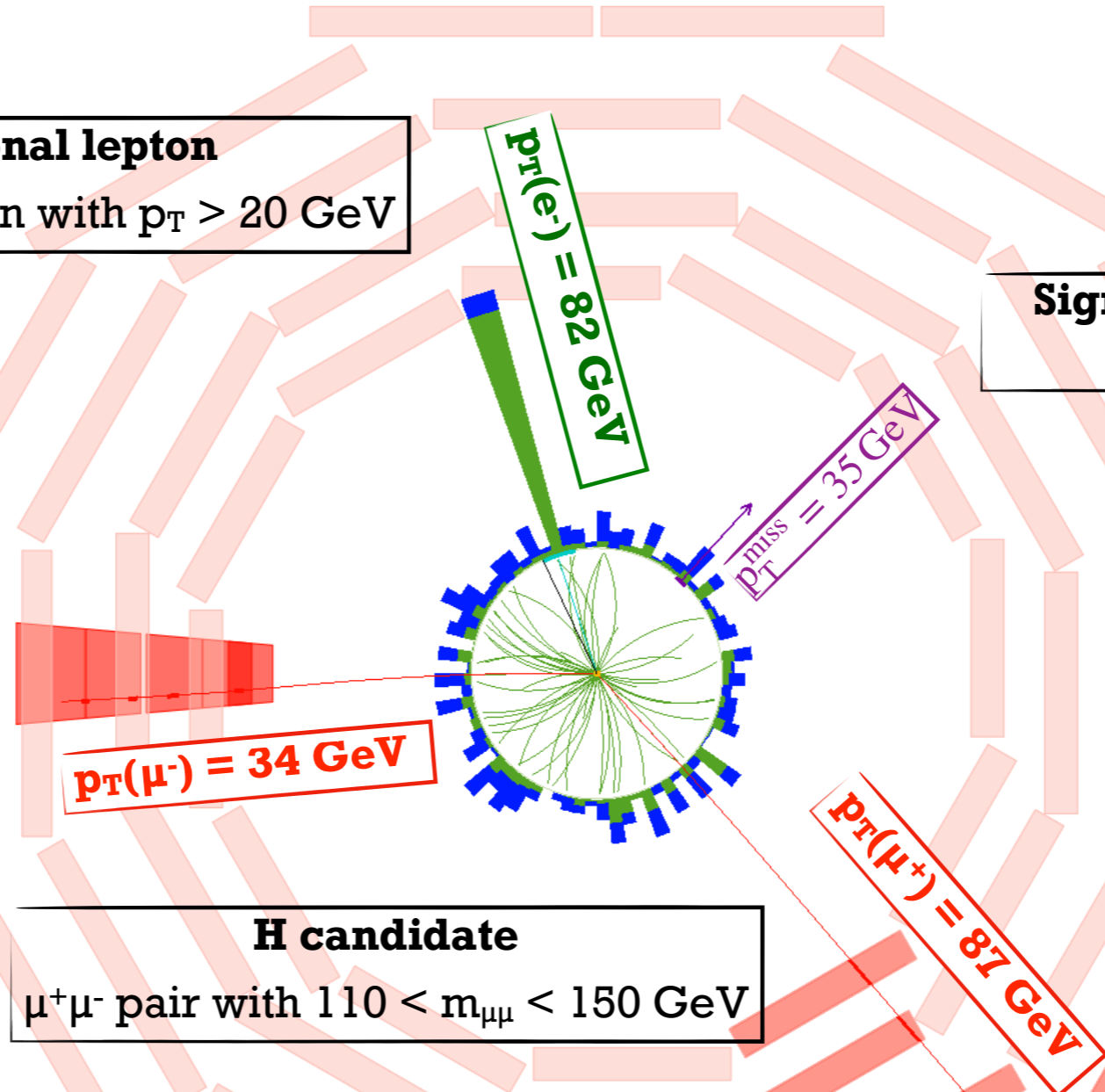
H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

b-jet veto
 No jets in event
 passing b-tagging

Additional lepton
Electron or muon with $p_T > 20$ GeV



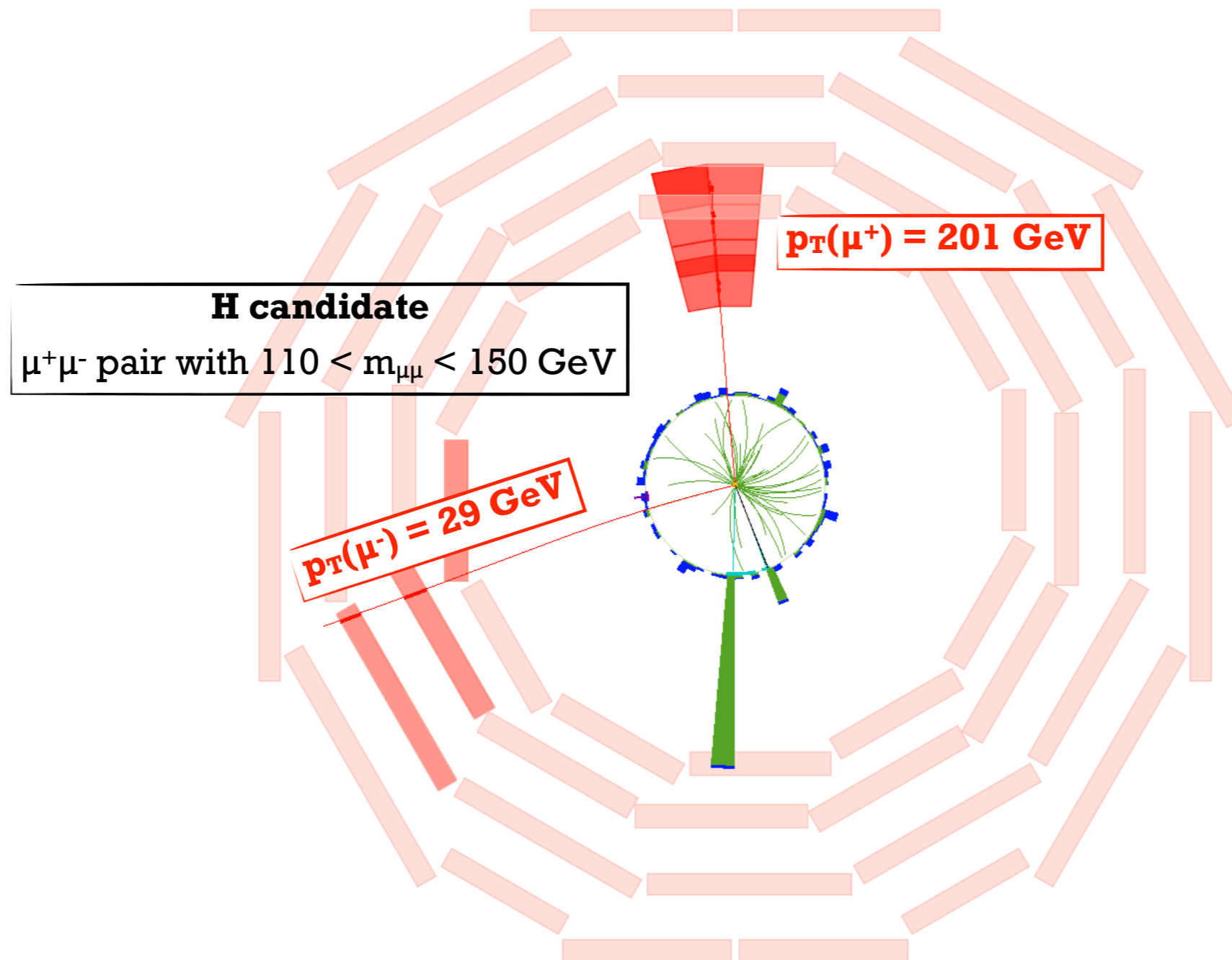
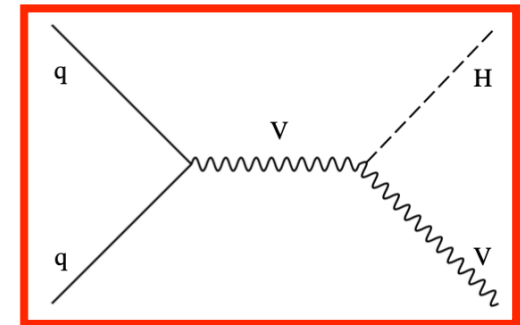
Significant momentum imbalance p_T^{miss}



H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

Dominant background:
 $WZ \rightarrow \ell \nu 2\mu$

b-jet veto
No jets in event passing b-tagging

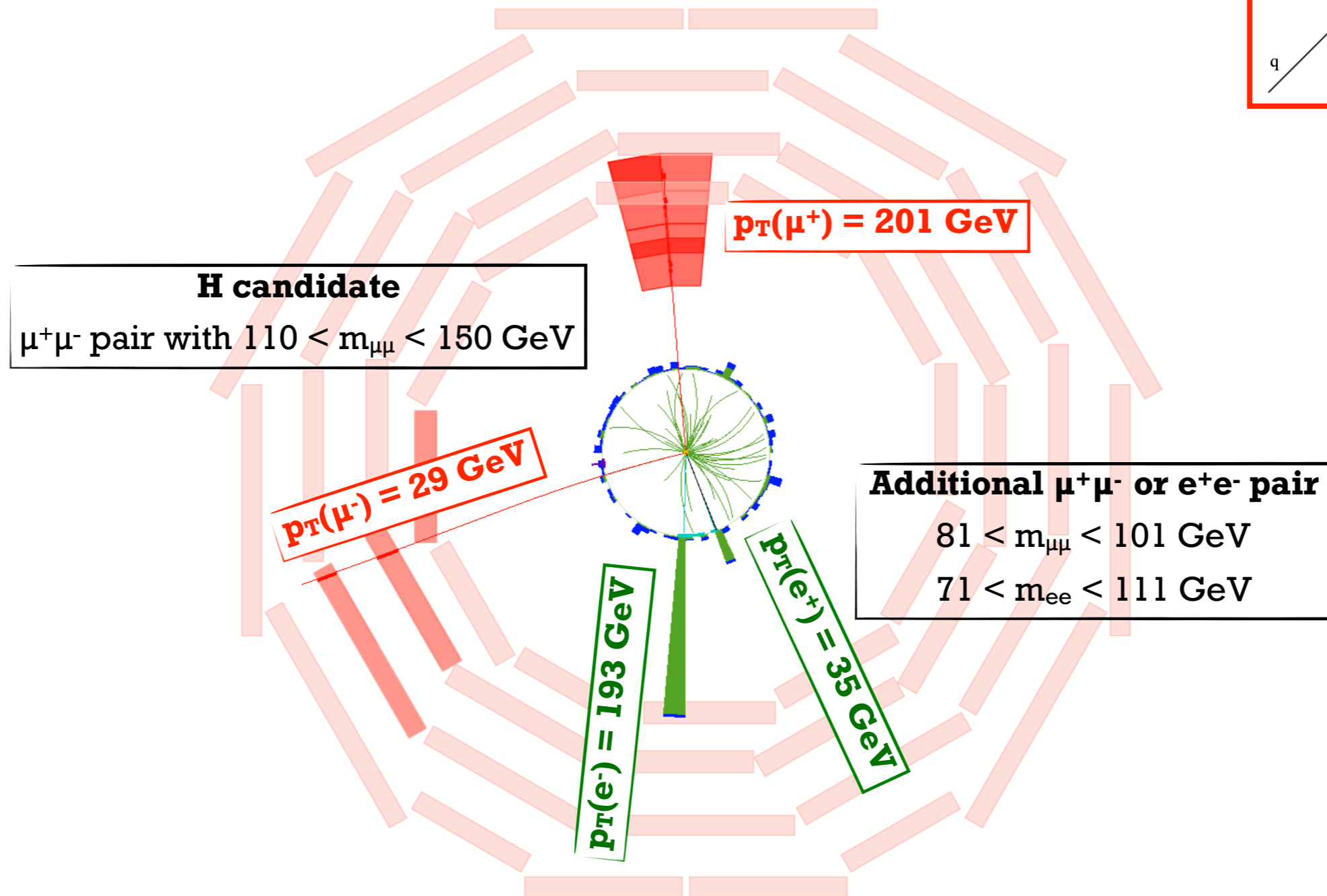
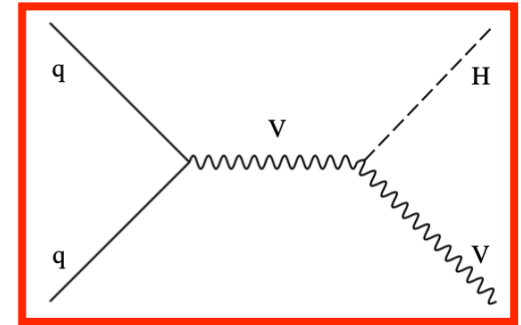


H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

$p_T(\mu^+) = 201$ GeV

$p_T(\mu^-) = 29$ GeV

b-jet veto
 No jets in event
 passing b-tagging



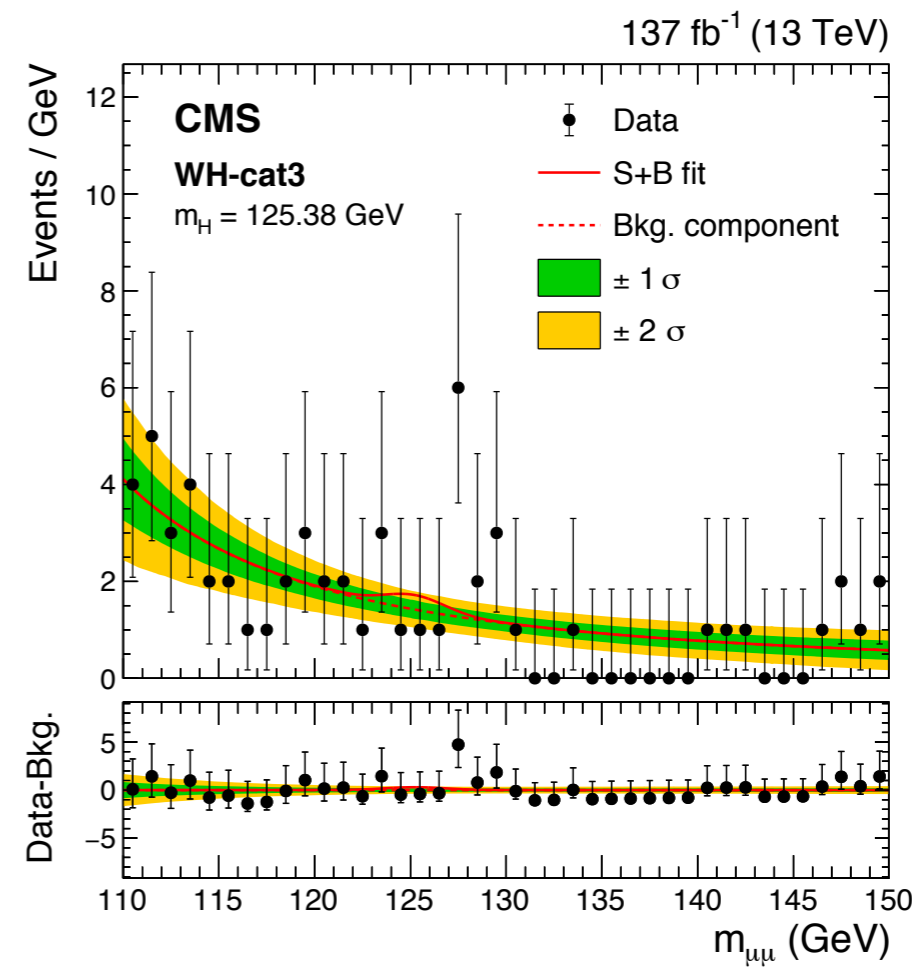
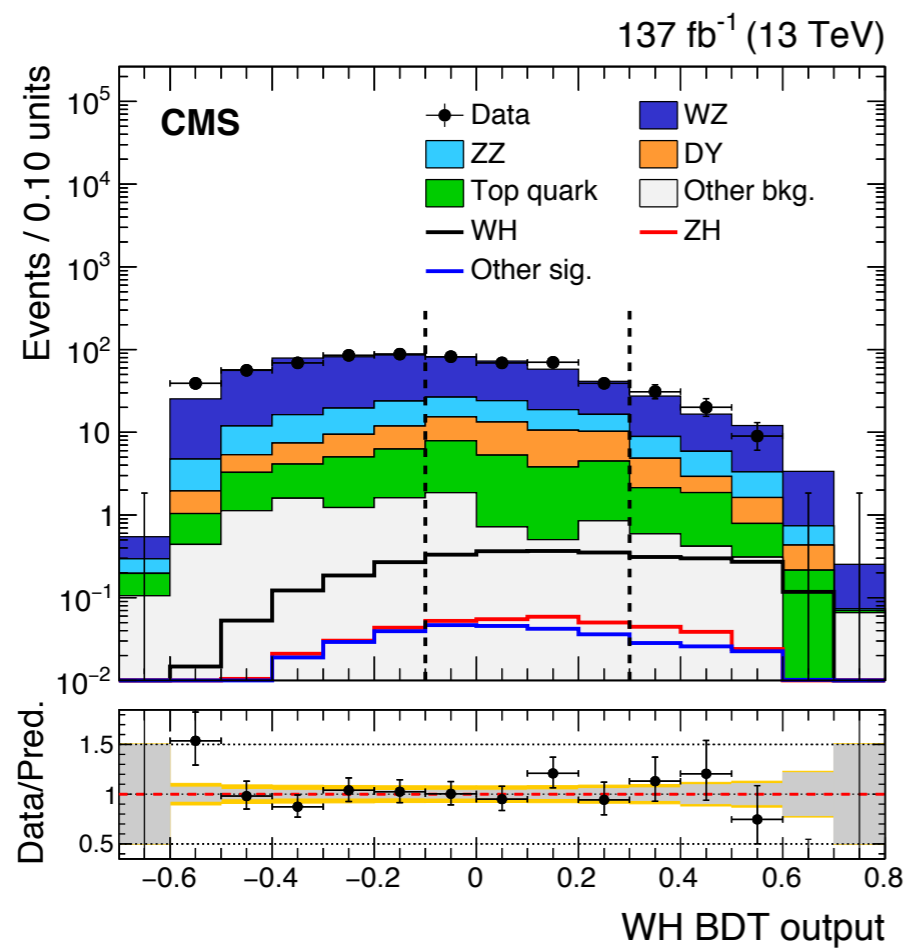
Dominant background:
 $ZZ \rightarrow 2\ell 2\mu$

b-jet veto
No jets in event
passing b-tagging

- Inputs to WH and ZH BDT classifiers:
 - H candidate kinematic variables: $p_T(\mu\mu)$, $\Delta\phi(\mu\mu)$, ...
 - WH system: $p_T(\ell_W)$, $\Delta\eta(\ell_W, H)$, $\Delta\phi(\ell_W, H)$, $m_T(\ell_W, p_T^{\text{miss}})$, ...
 - ZH system: $p_T(Z)$, $\eta(Z)$, m_Z , $\Delta\eta(Z, H)$, $\Delta\phi(Z, H)$, $\cos\theta^*(Z, H)$, ...

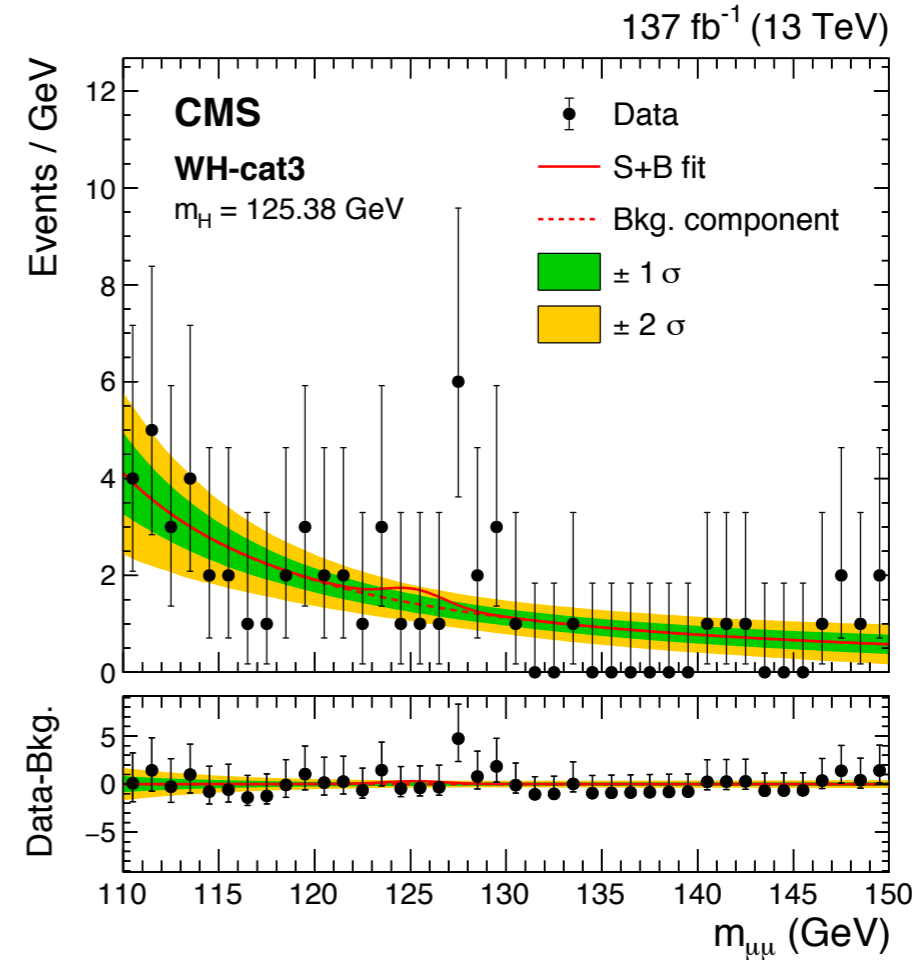
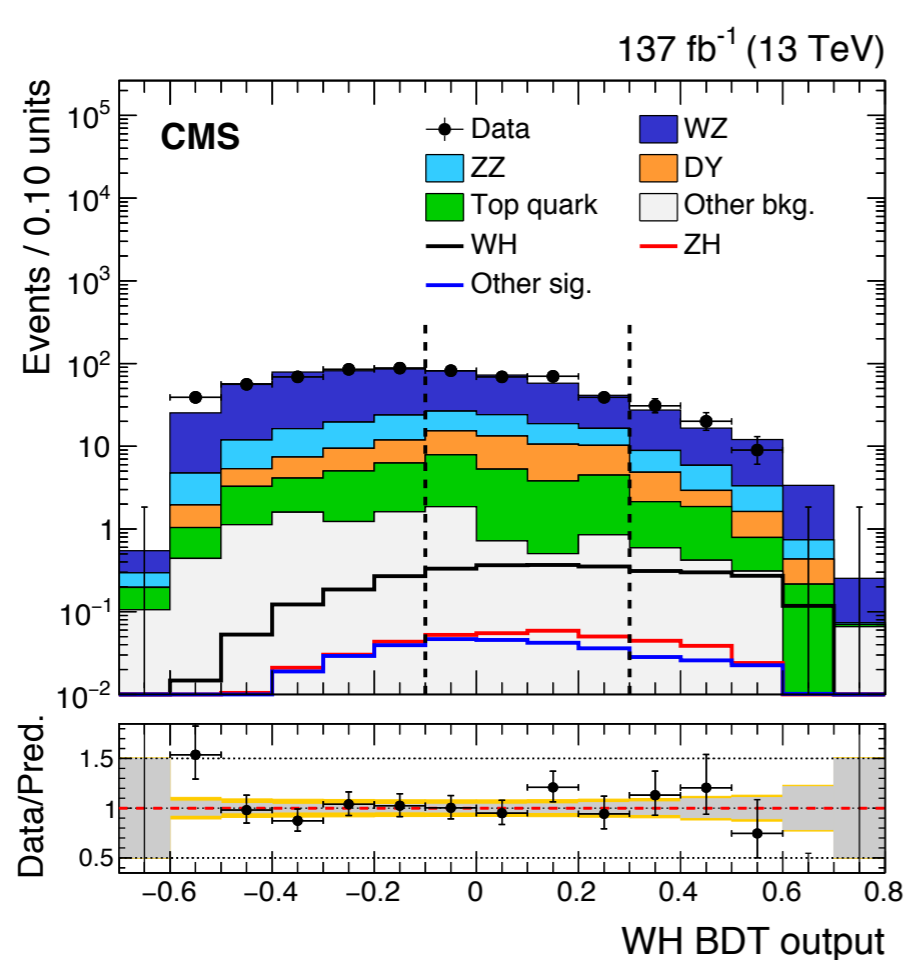
WH category BDT score

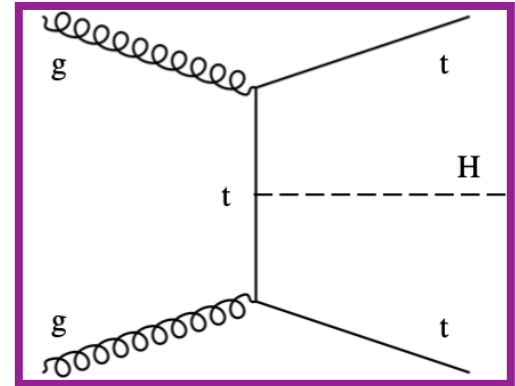
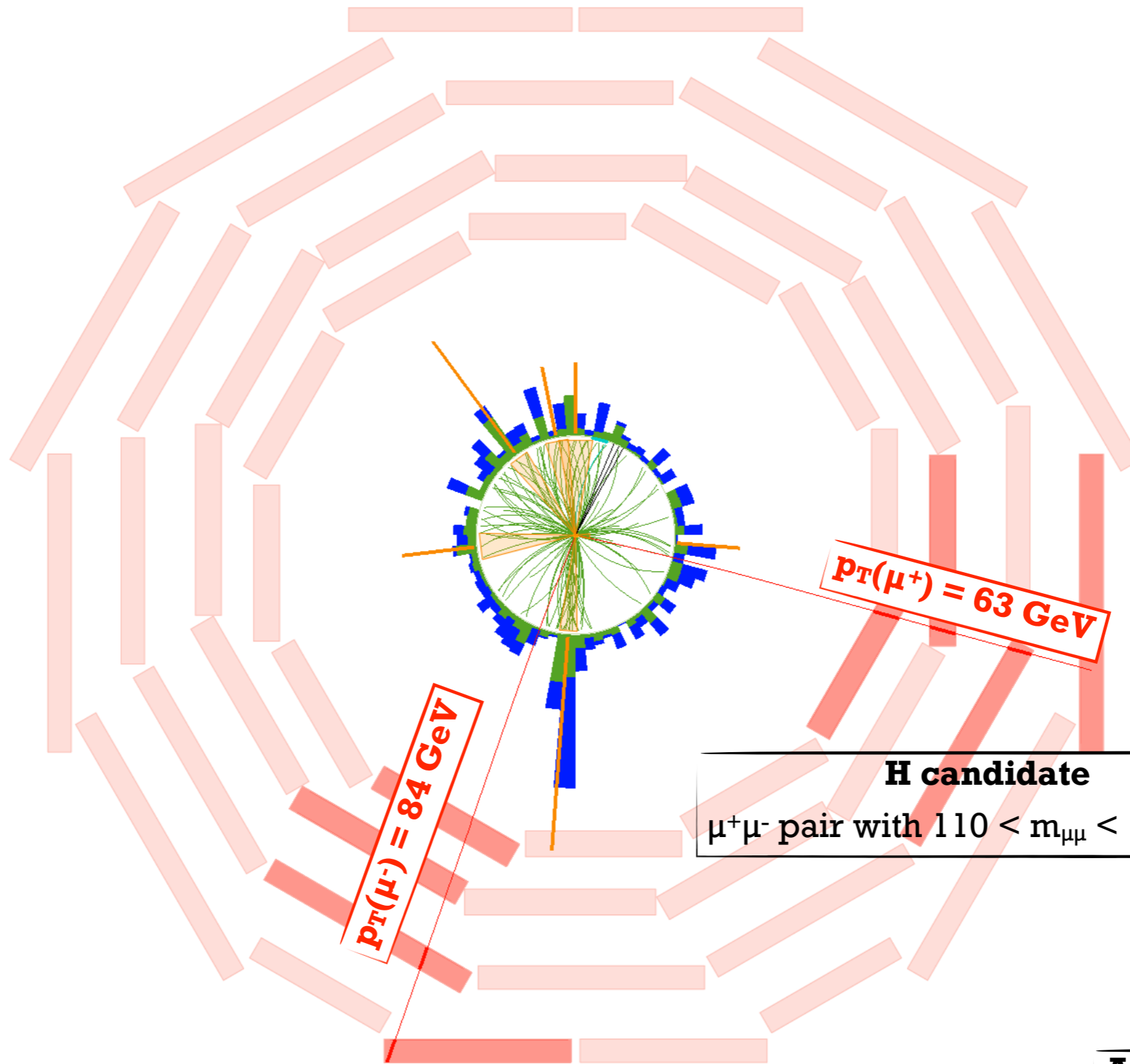
$m_{\mu\mu}$ distribution in the highest purity WH subcategory



- Inputs to WH and ZH BDT classifiers:
 - H candidate kinematic variables: $p_T(\mu\mu)$, $\Delta\phi(\mu\mu)$, ...
 - WH system: $p_T(\ell_W)$, $\Delta\eta(\ell_W, H)$, $\Delta\phi(\ell_W, H)$, $m_T(\ell_W, p_T^{\text{miss}})$, ...
 - ZH system: $p_T(Z)$, $\eta(Z)$, m_Z , $\Delta\eta(Z, H)$, $\Delta\phi(Z, H)$, $\cos\theta^*(Z, H)$, ...

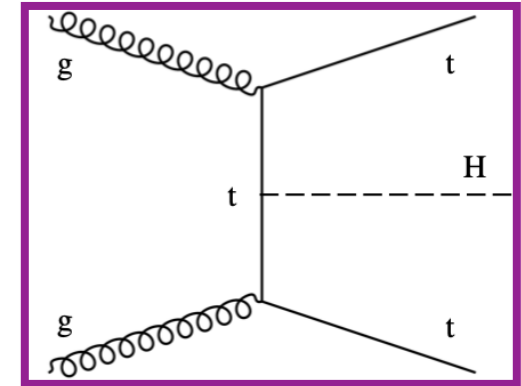
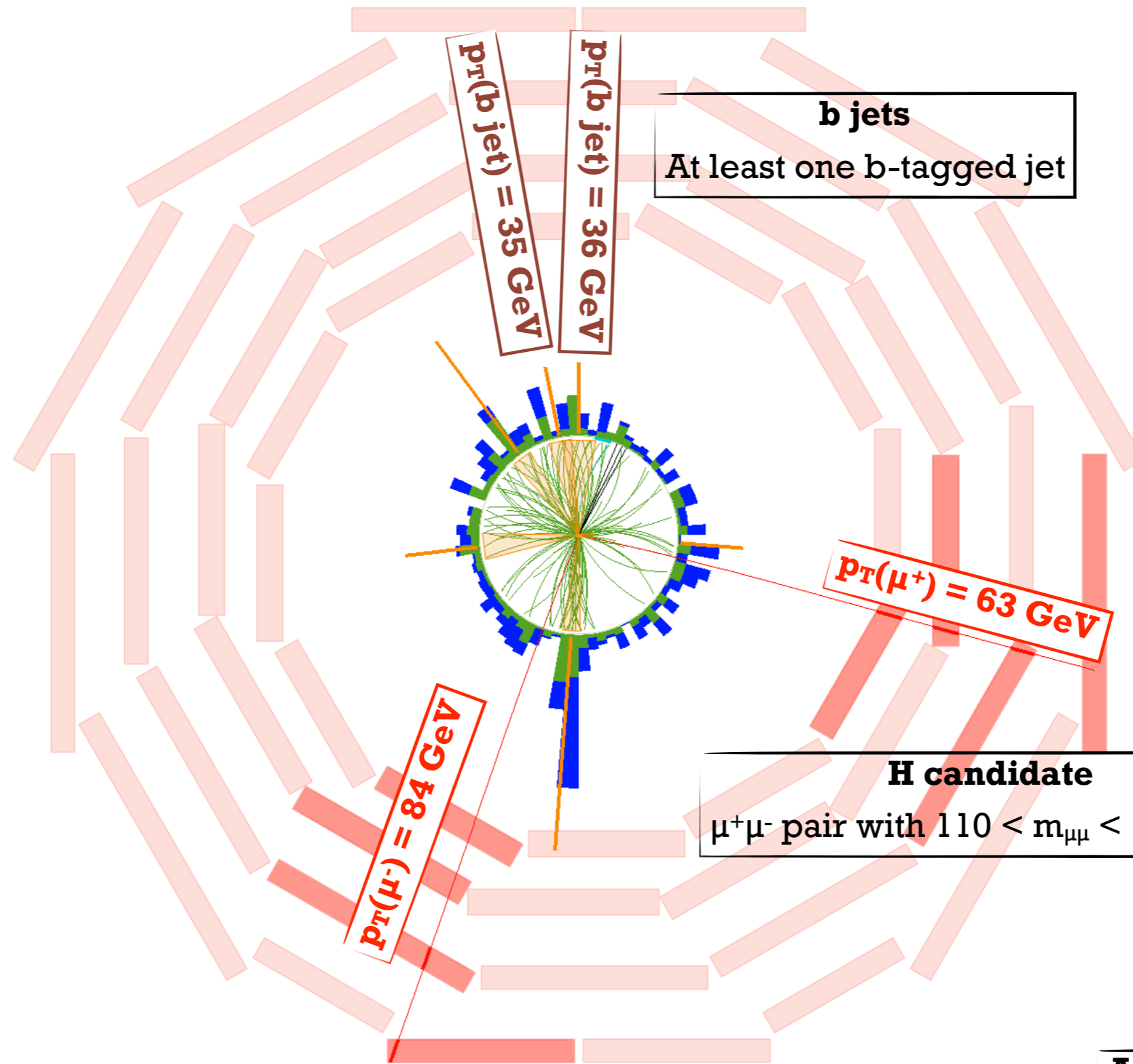
Combined WH and ZH category result
 Observed (expected) significance: 2.0σ (0.4σ)

$$\mu = \frac{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)}{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)_{\text{SM}}} = 5.48^{+3.10}_{-2.83}$$




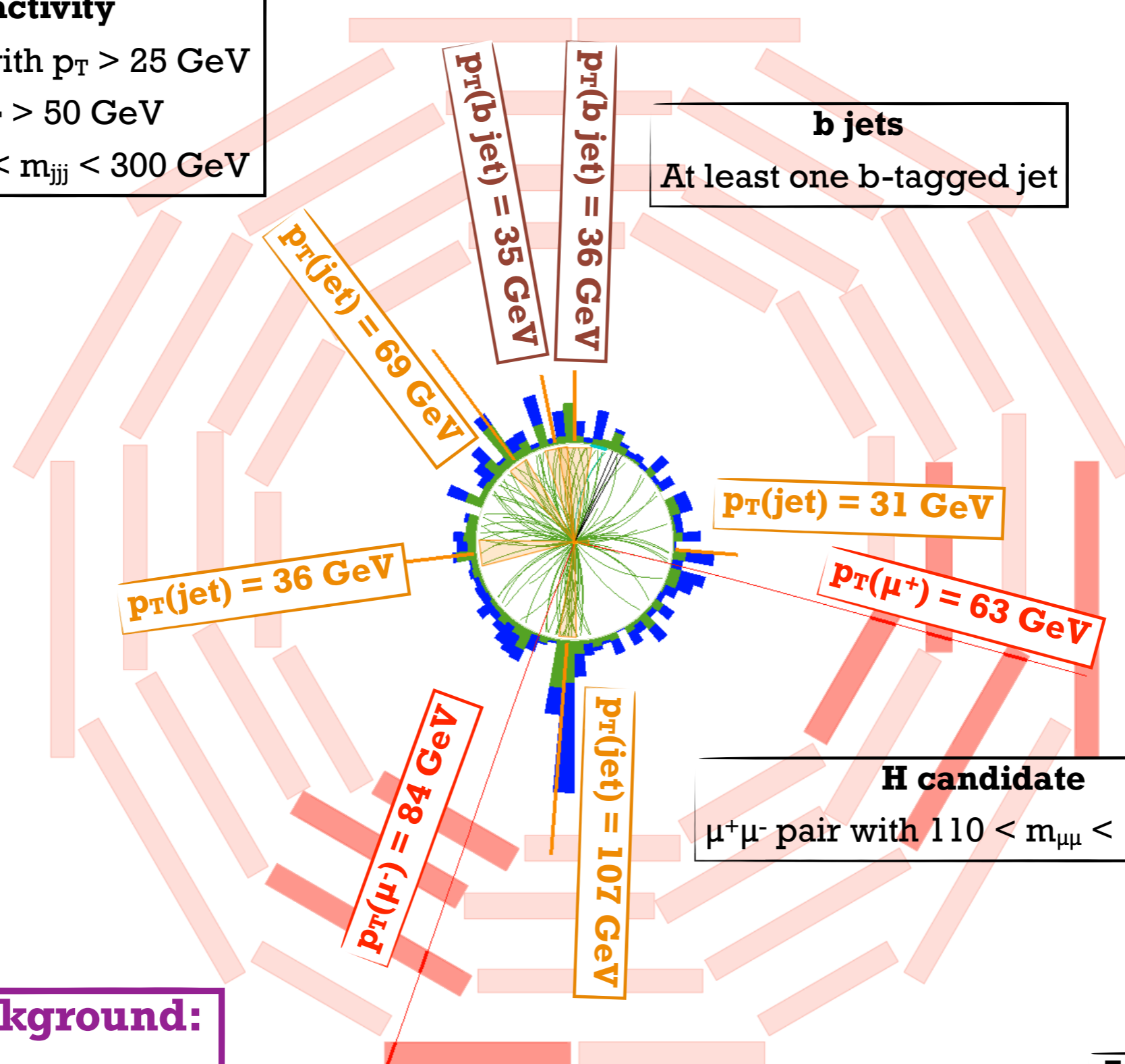
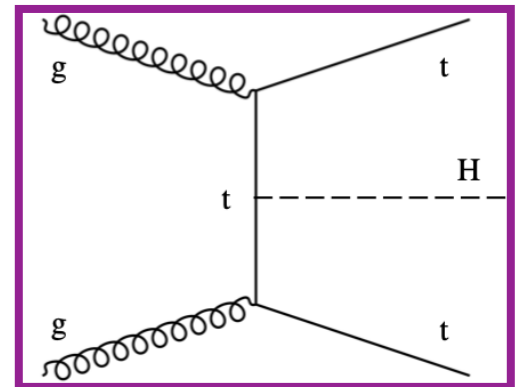
H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

Additional lepton veto



Hadronic activity
 At least three jets with $p_T > 25$ GeV
 Leading jet $p_T > 50$ GeV
 Jet triplet with $100 < m_{jjj} < 300$ GeV

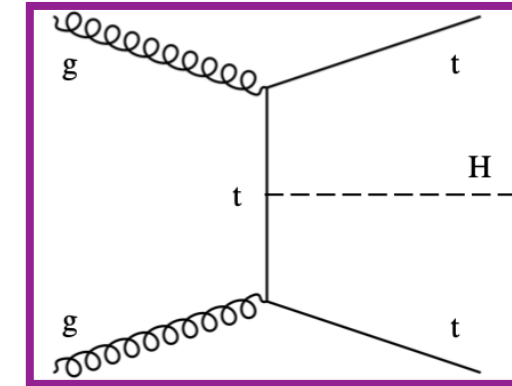
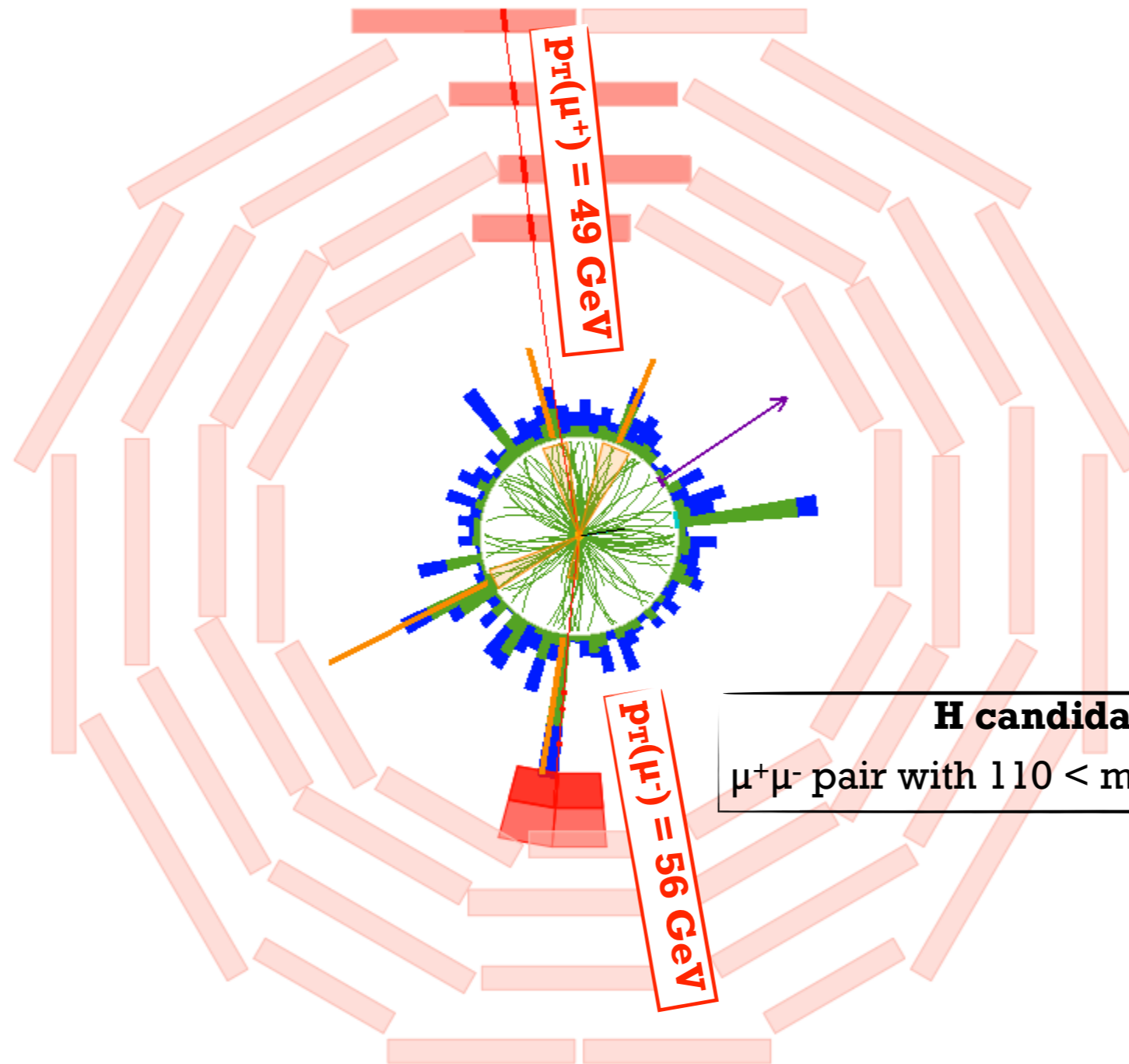
b jets
 At least one b-tagged jet



H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

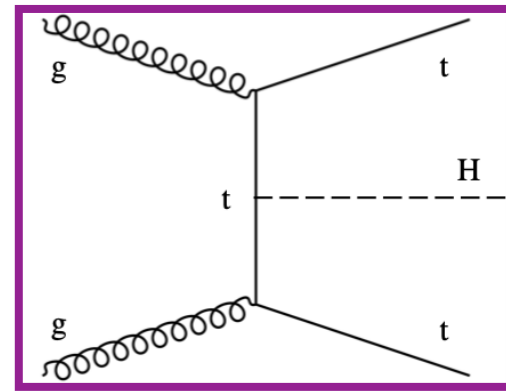
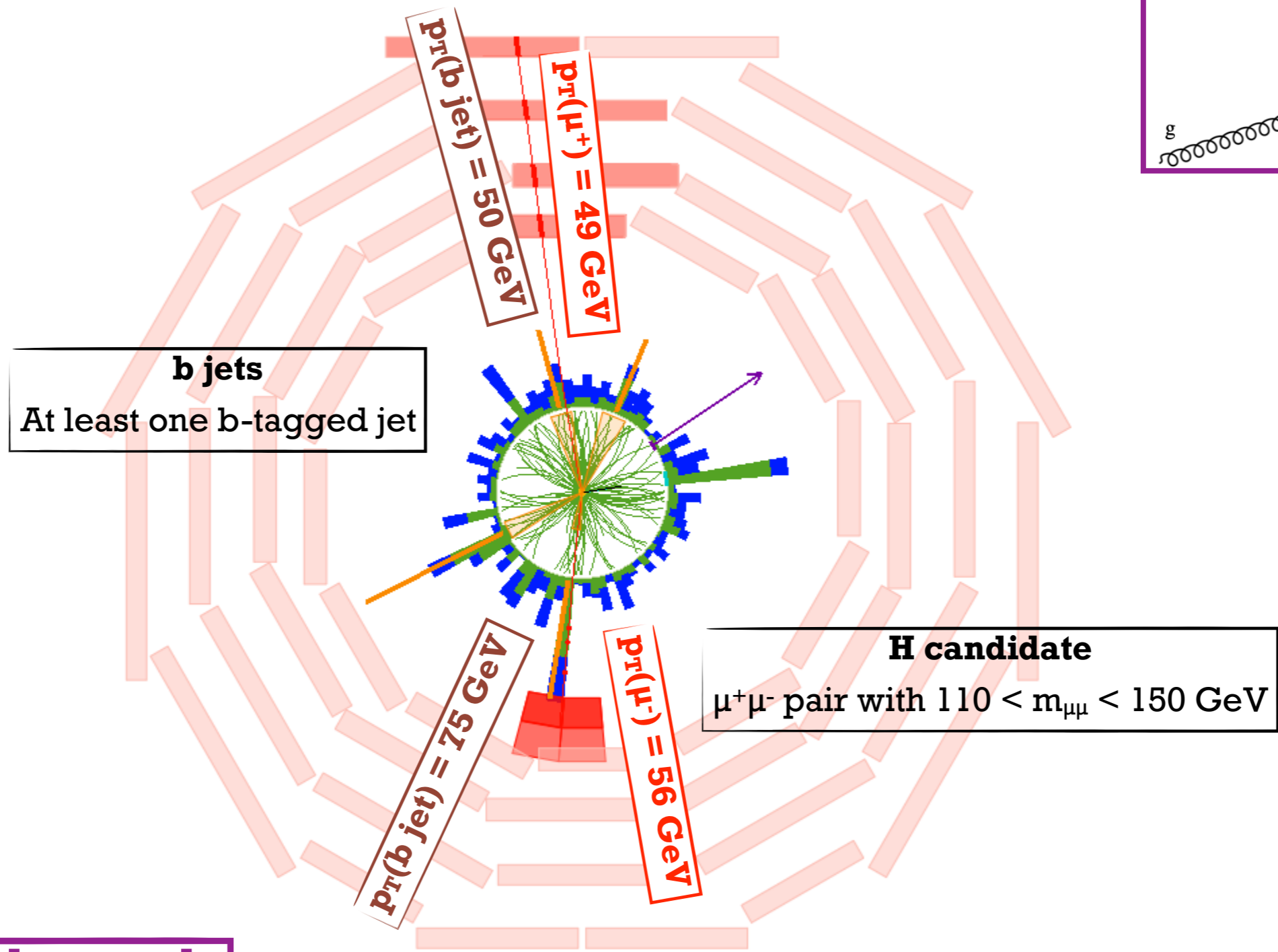
Dominant background:
 tt+jets

Additional lepton veto



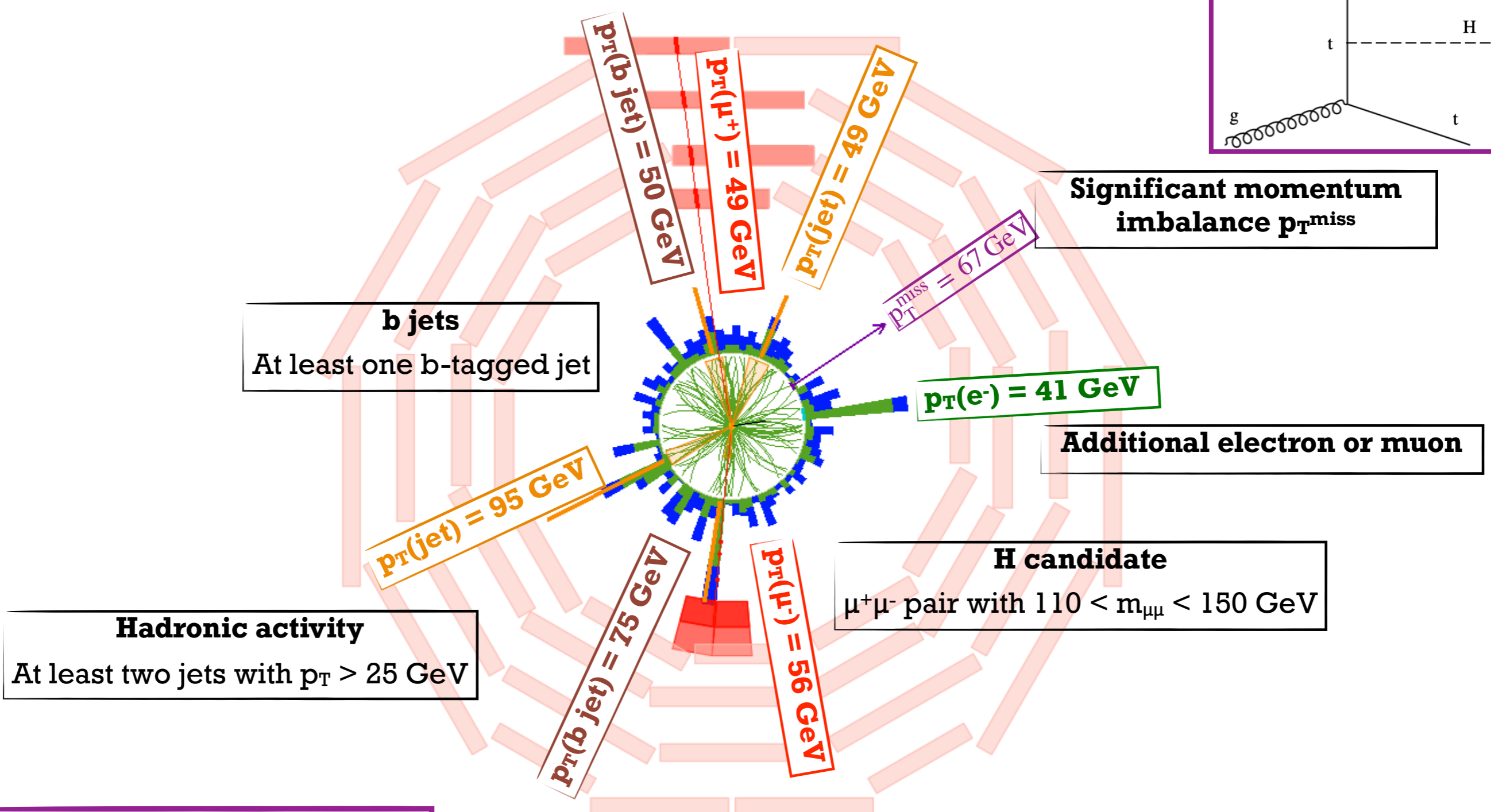
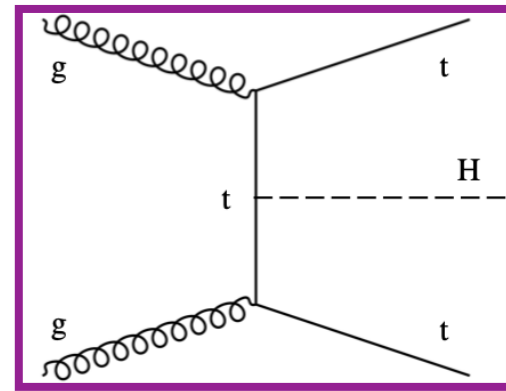
H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

**Dileptonic ttH events also considered*



Dominant background:
tt, ttZ

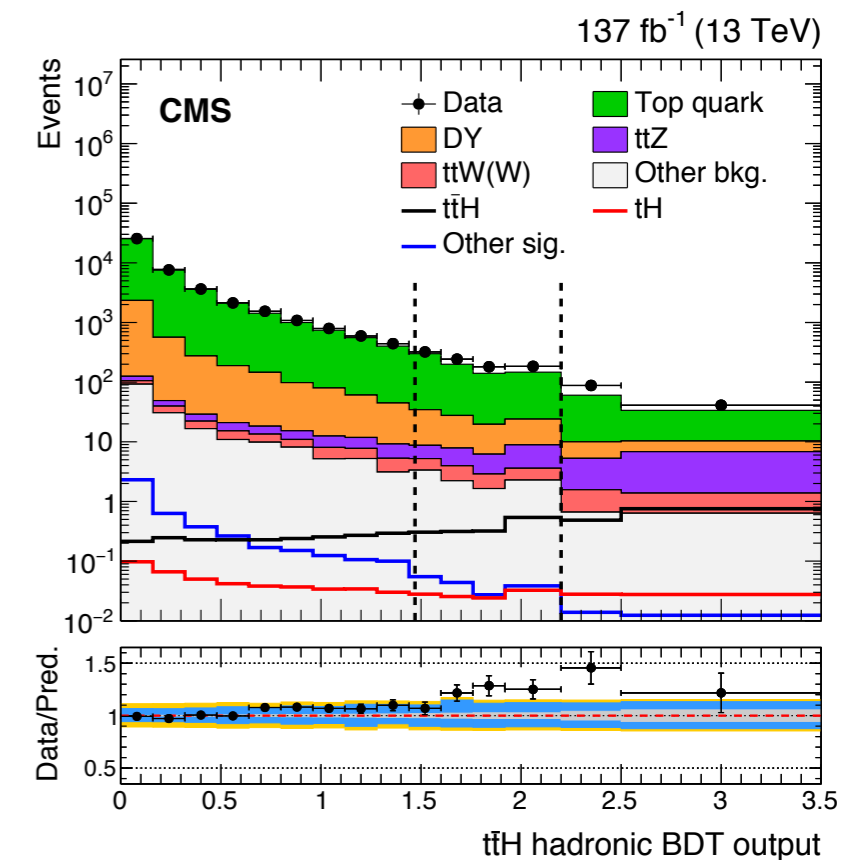
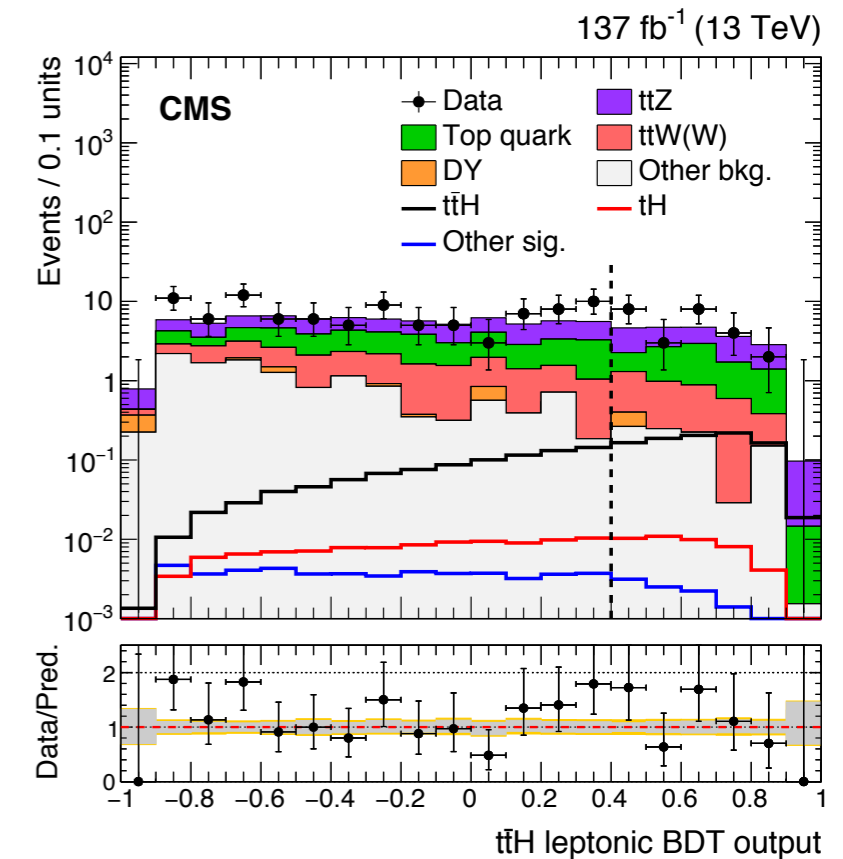
**Dileptonic ttH events also considered*



Dominant background:
tt, ttZ

**Dileptonic ttH events also considered*

- **Common ttH BDT inputs:**
 - Dimuon p_T and rapidity, decay angles ϕ_{CS} , $\cos\theta_{CS}$, ...
 - p_T^{miss} , H_T , jet multiplicity, ...
- **Specific inputs for hadronic category:**
 - p_T , η of the three leading jets
 - top quark candidate: jet triplet with maximum Resolved Hadronic Top Tagger (RHTT) score
 - $p_T(\text{jjj})$, RHTT score, $p_T\text{-balance}(H, \text{jjj})$
- **Specific inputs for leptonic category:**
 - ℓ^T : highest- p_T additional lepton
 - $\Delta\phi(\ell^T, H)$, $\text{mass}(\text{b jet}, \ell^T)$, $m_T(p_T^{\text{miss}}, \ell^T)$

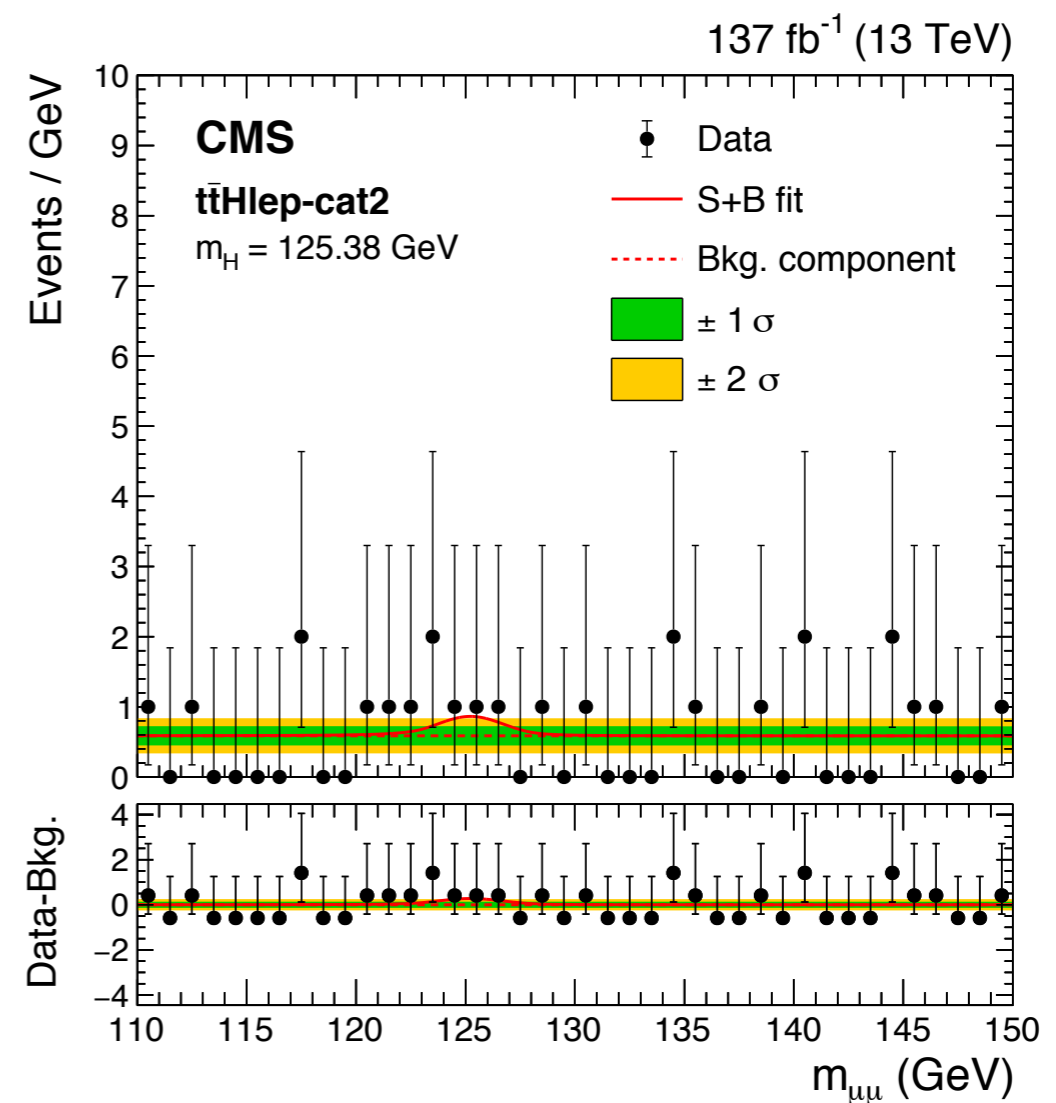
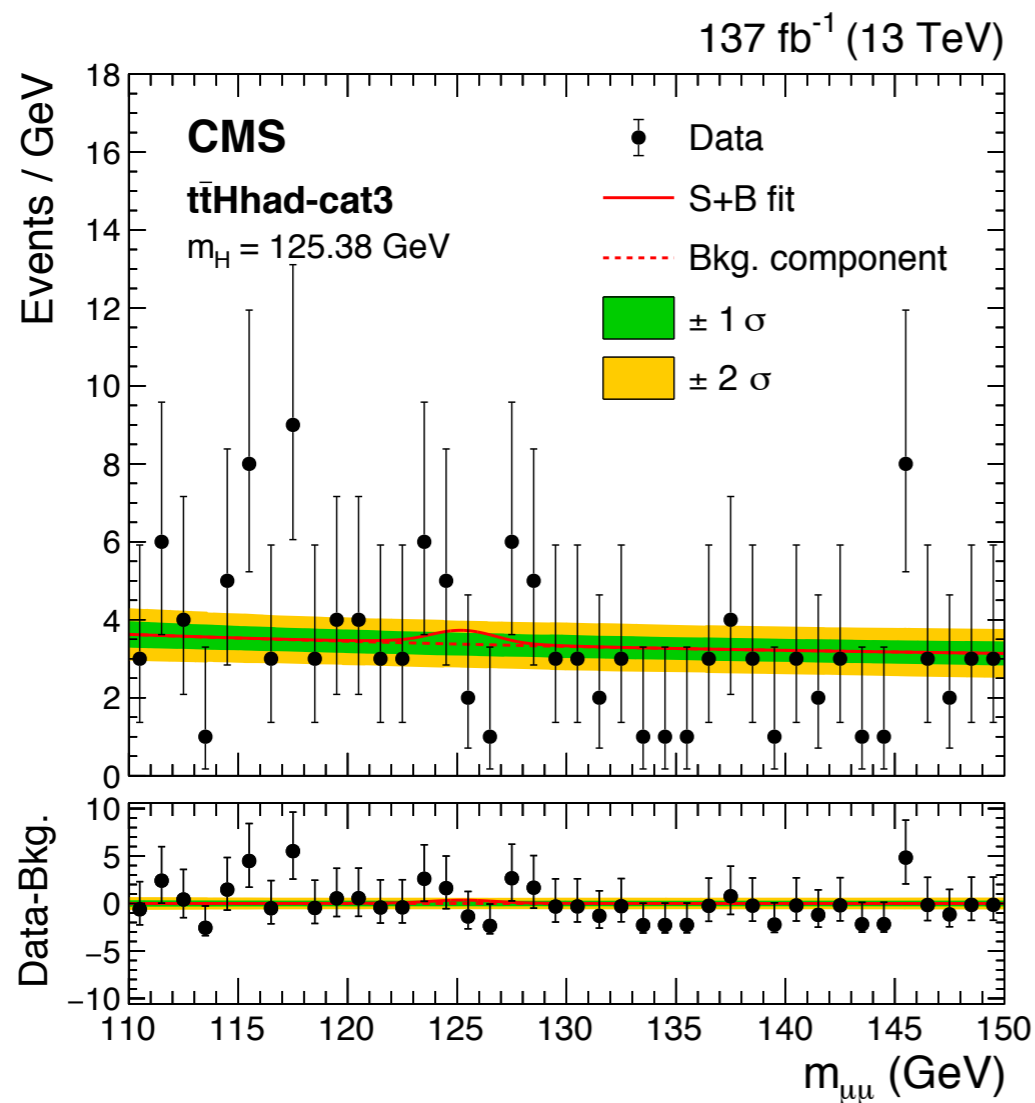


Combined ttH (hadronic + leptonic) category result

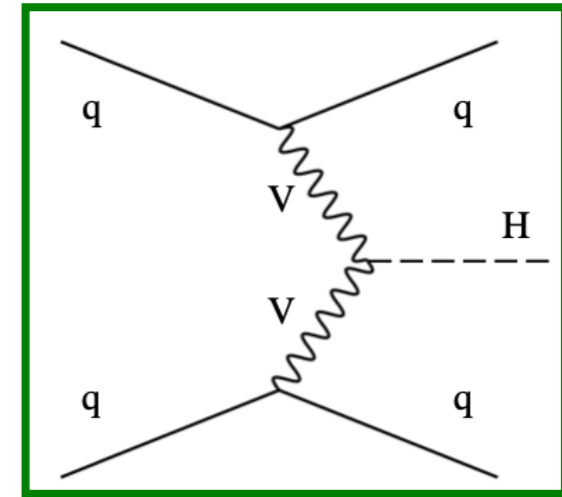
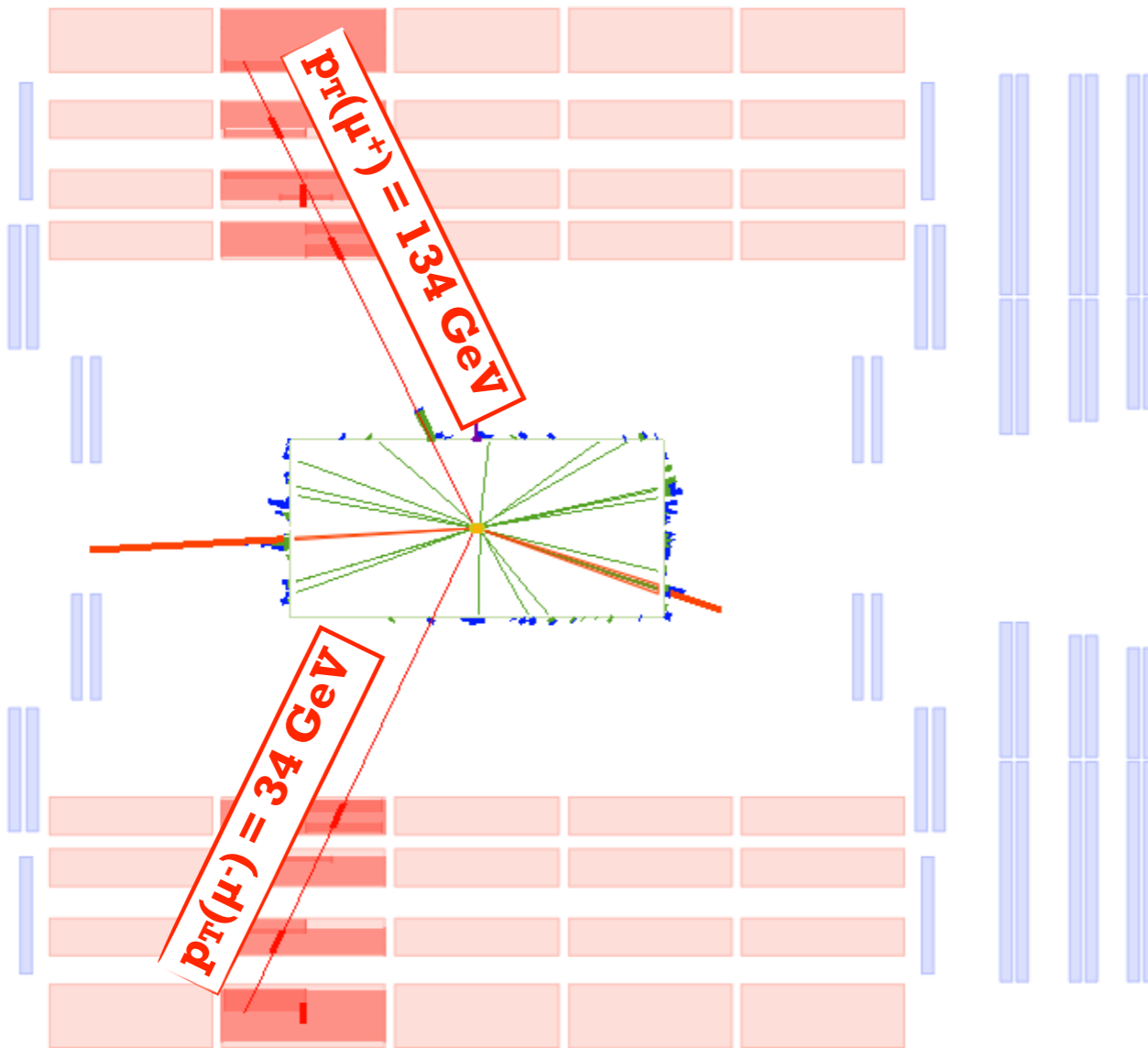
Observed (expected) significance: 1.2σ (0.5σ)

$$\mu = \frac{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)}{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)_{\text{SM}}} = 2.32^{+2.27}_{-1.95}$$

$m_{\mu\mu}$ distribution in the highest purity ttH subcategories

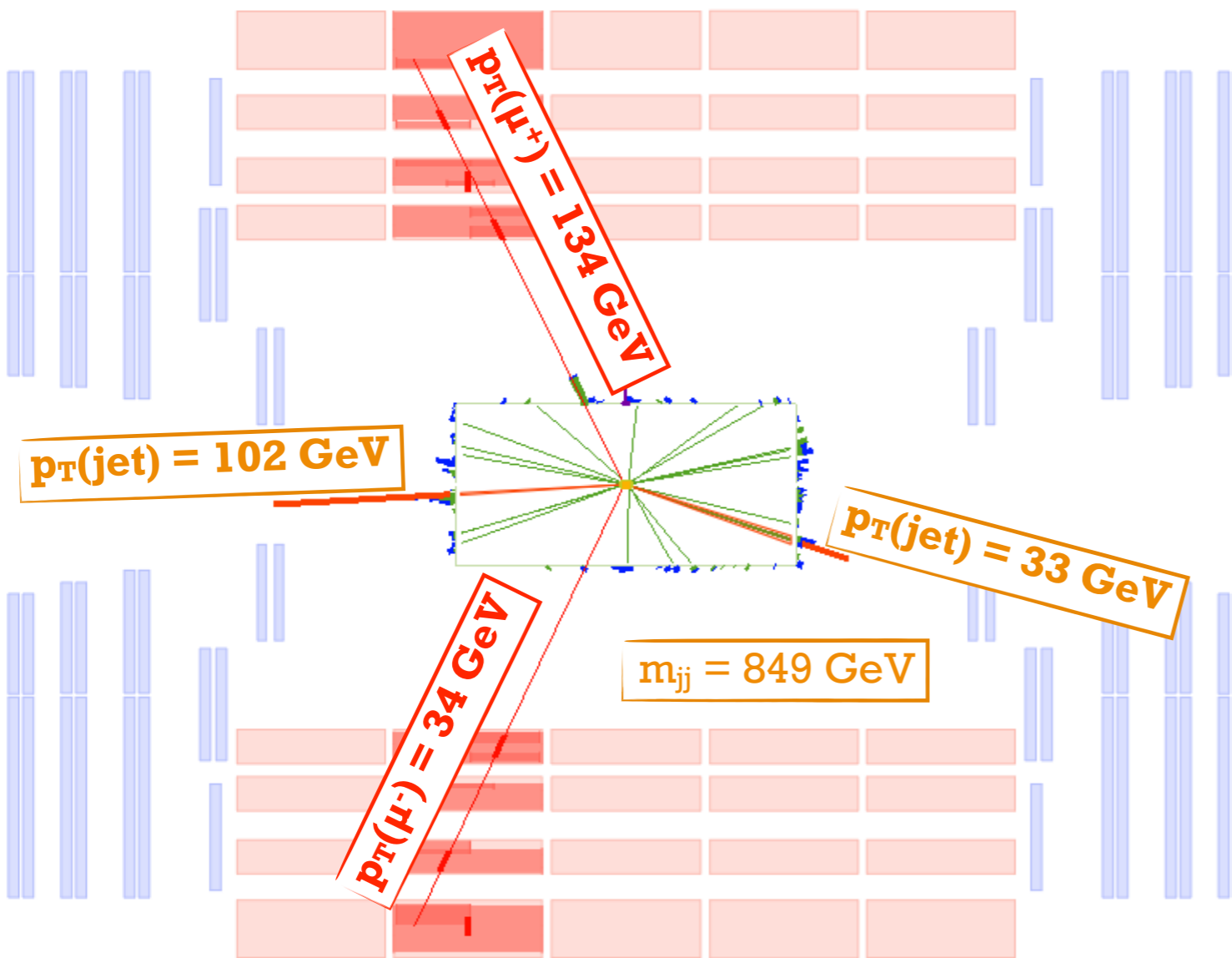
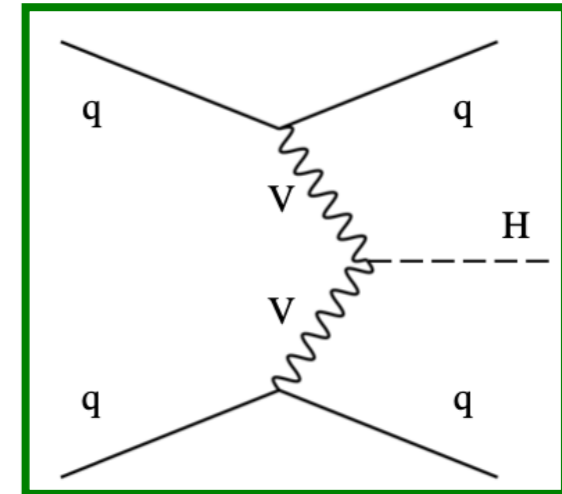


H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV



No additional leptons, no b jets.

H candidate
 $\mu^+\mu^-$ pair with $110 < m_{\mu\mu} < 150$ GeV

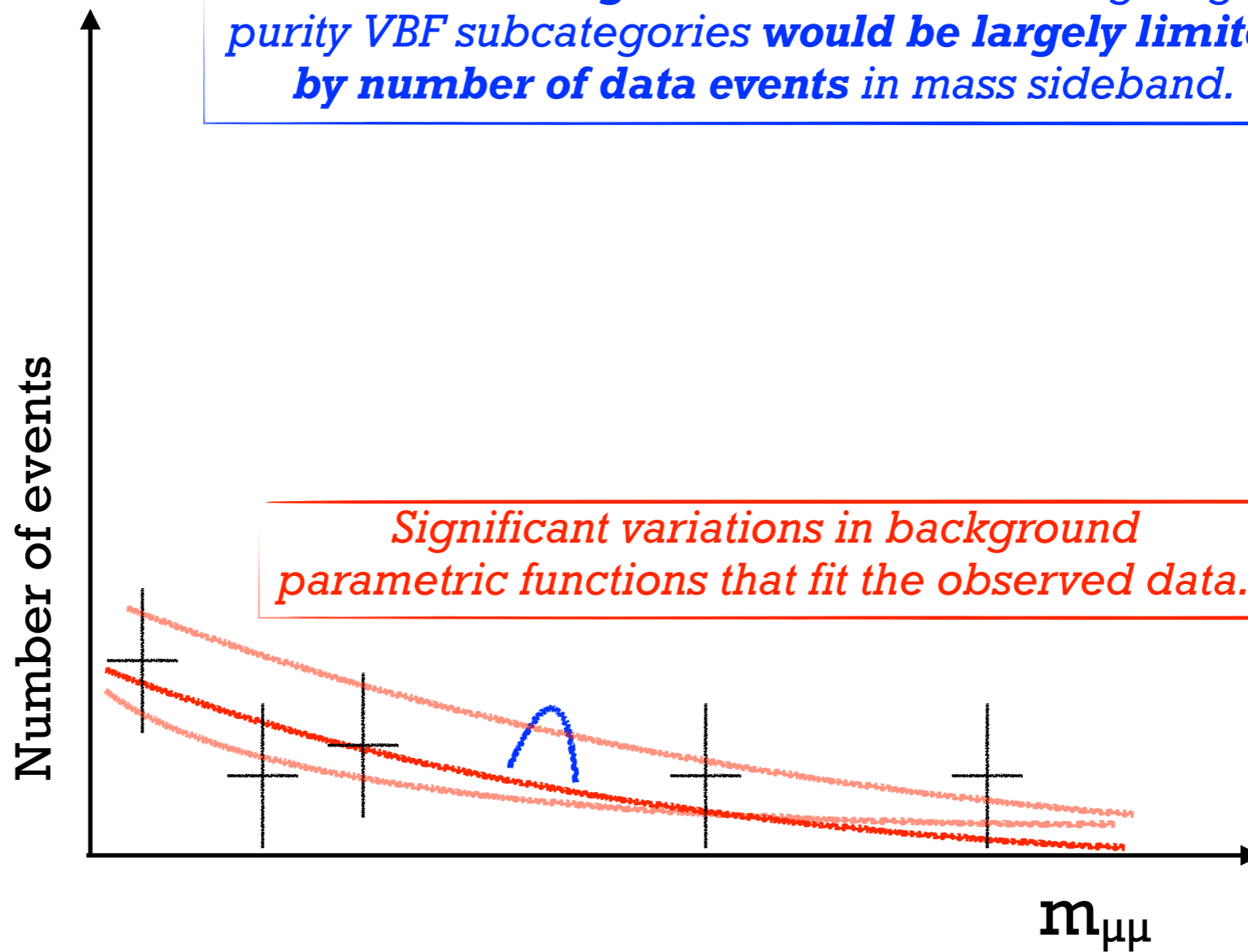


VBF selections:
 At least two jets with $p_T > 25$ GeV and $|\eta| < 4.7$,
 leading jet $p_T > 35$ GeV,
 $m_{jj} > 400$ GeV and $|\Delta\eta(jj)| > 2.5$

Dominant backgrounds:
 Drell-Yan (DY), EW Zjj

No additional leptons, no b jets.

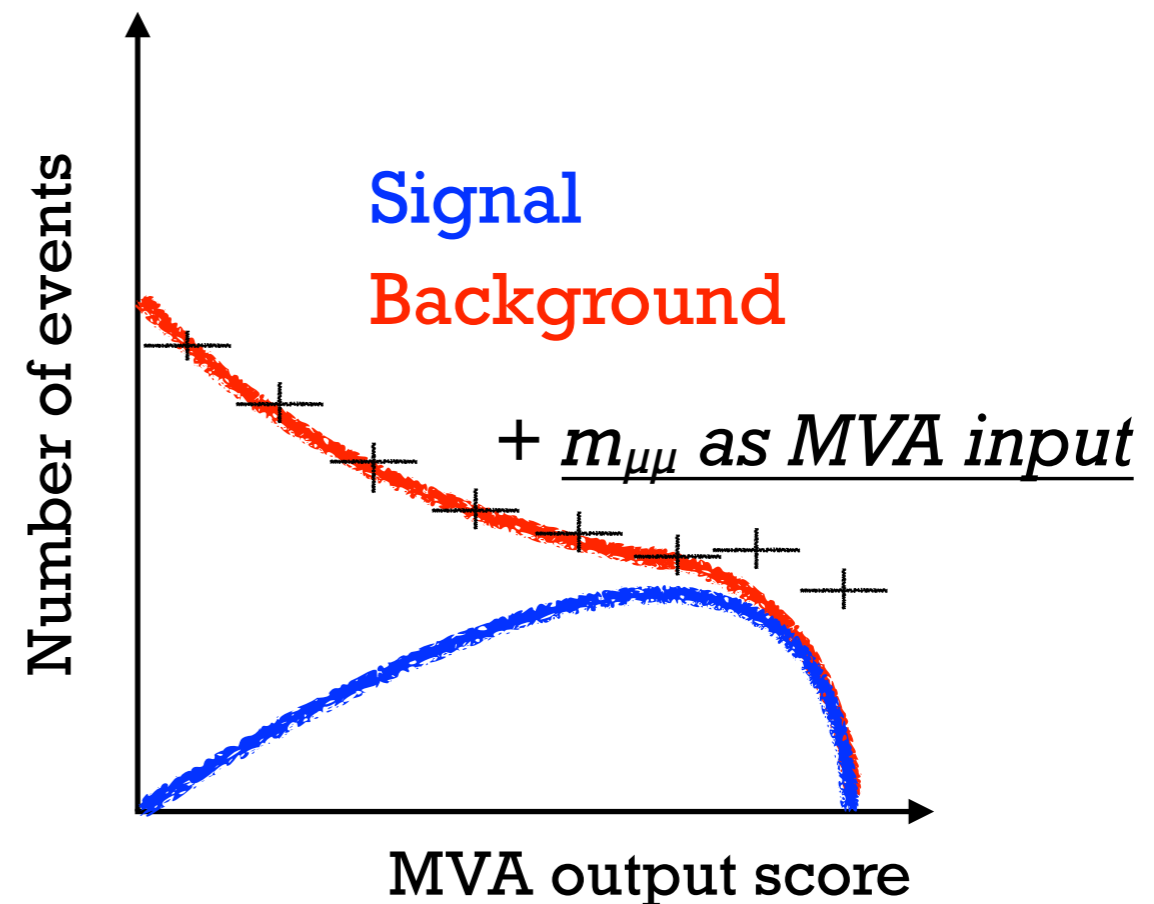
Data-driven background estimation in high signal purity VBF subcategories would be largely limited by number of data events in mass sideband.



Significant variations in background parametric functions that fit the observed data.

(representation of high purity VBF subcategory)

- *New approach for the VBF category:*
 - Include $m_{\mu\mu}$ as **MVA input** variable.
 - **Fit MVA output directly** to extract $H \rightarrow \mu\mu$ signal.
 - Take **background prediction from simulated samples**.
- Trading limited number of data events in mass sideband for systematic uncertainties in simulation.
- Following strategy similar to CMS EW Z_{jj} measurement [1] and $H \rightarrow bb$ observation [2].



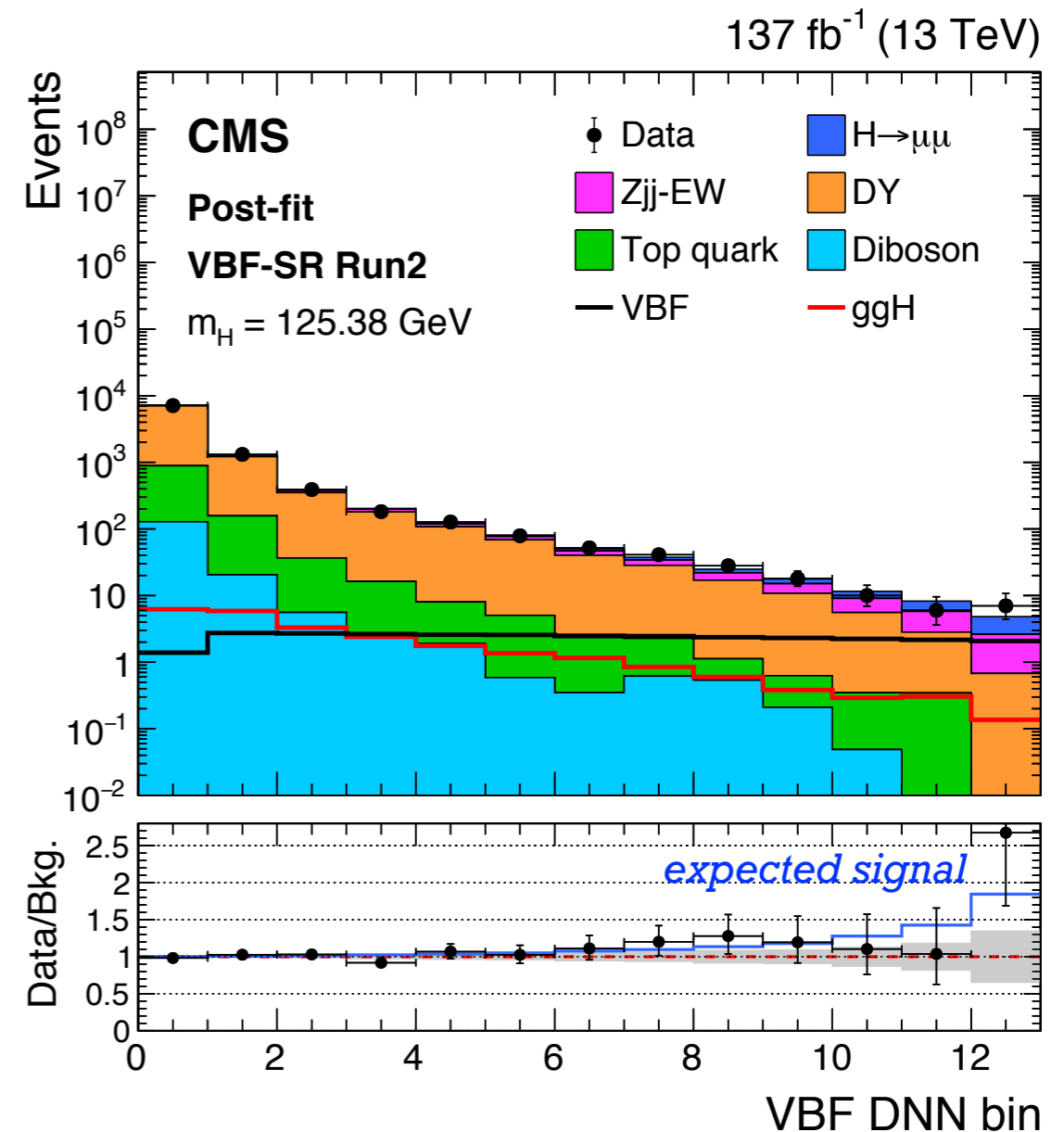
\Rightarrow 20% improvement in performance in VBF category

[1] [Eur. Phys. J. C 78 \(2018\) 589](#)

[2] [Phys. Rev. Lett. 121 \(2018\) 121801](#)

- Train a deep neural network (DNN) including the H candidate mass $m_{\mu\mu}$ as an input.
- DNN inputs targeting VBF H signal:
 - m_{jj} , $\Delta\eta(jj)$, $\Delta\phi(jj)$, $\min\text{-}\Delta\eta(H,j)$, $\min\text{-}\Delta\phi(H,j)$, $p_T\text{-balance}(H,jj)$, H centrality, ...
 - Suppressed hadronic activity in jet rapidity gap expected for VBF signal \Rightarrow track-jet multiplicity and H_T in jet rapidity gap.

VBF category DNN score in signal region

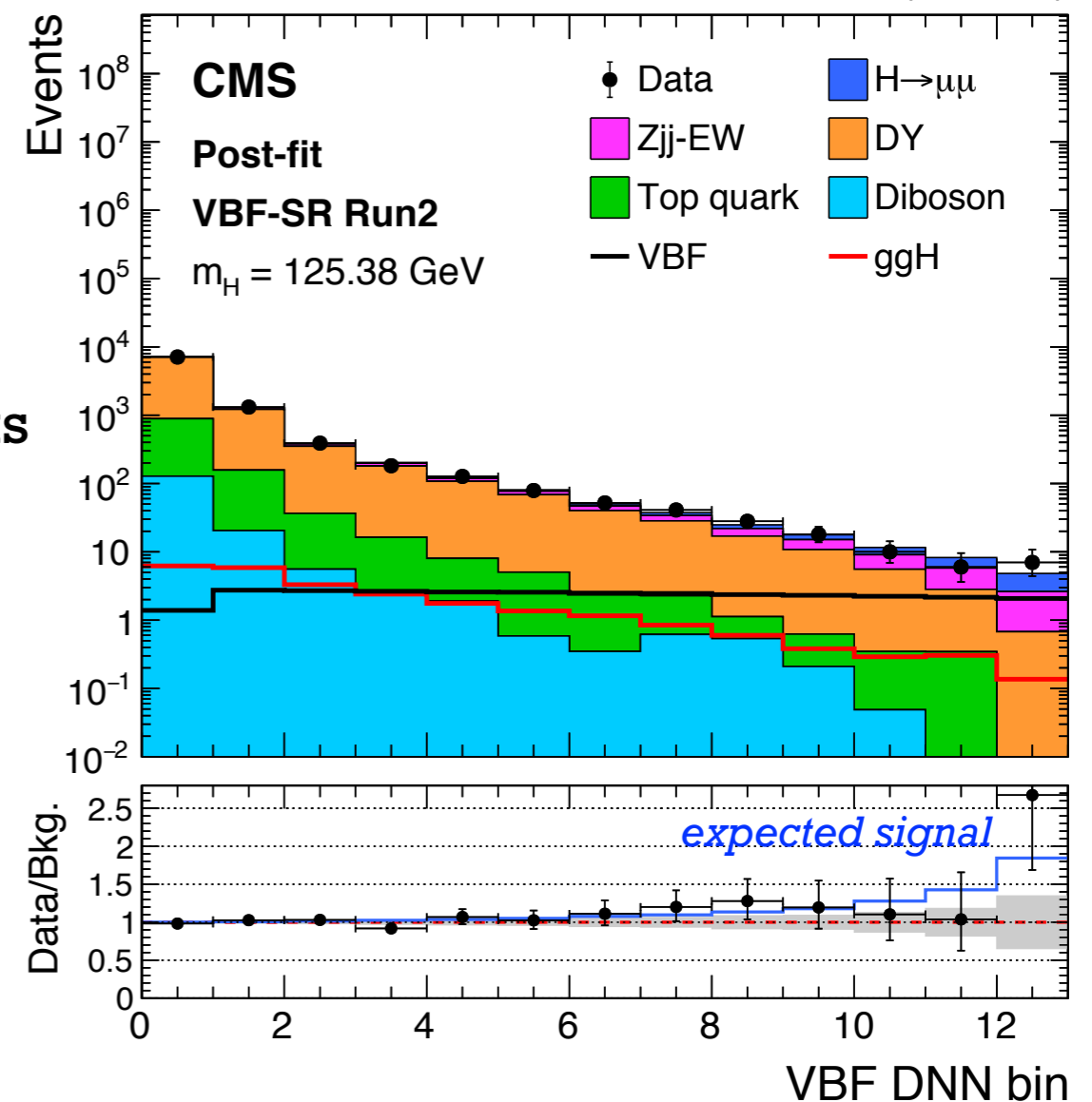


Total systematic uncertainty impact <5%

VBF category DNN score in signal region

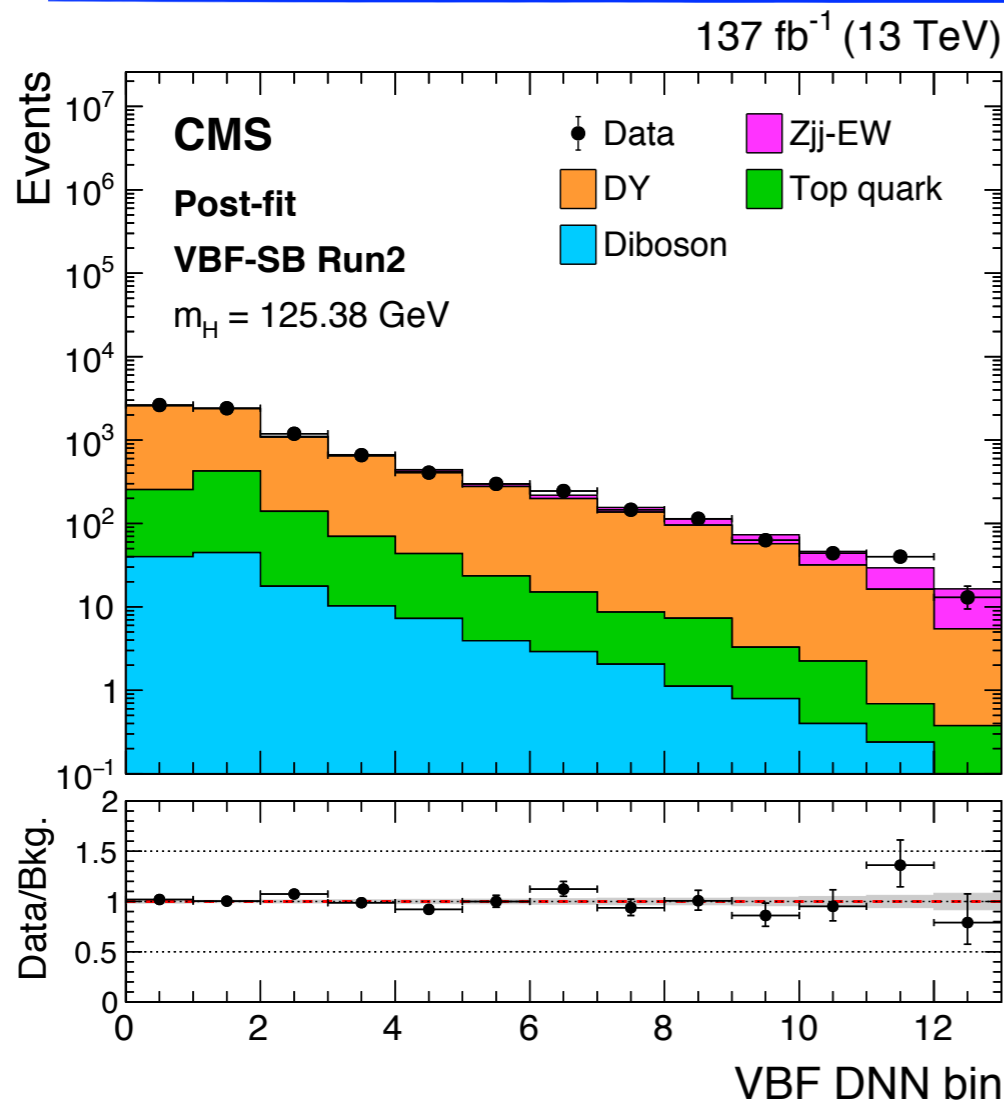
137 fb⁻¹ (13 TeV)

- **Largest systematic uncertainties:**
 - VBF (H signal and Z background) parton shower modeling
 - Jet energy scale and resolution
 - DY contribution with one or more pileup jets
 - Statistical precision of simulated events
 - Theory uncertainties: missing higher order corrections, etc.

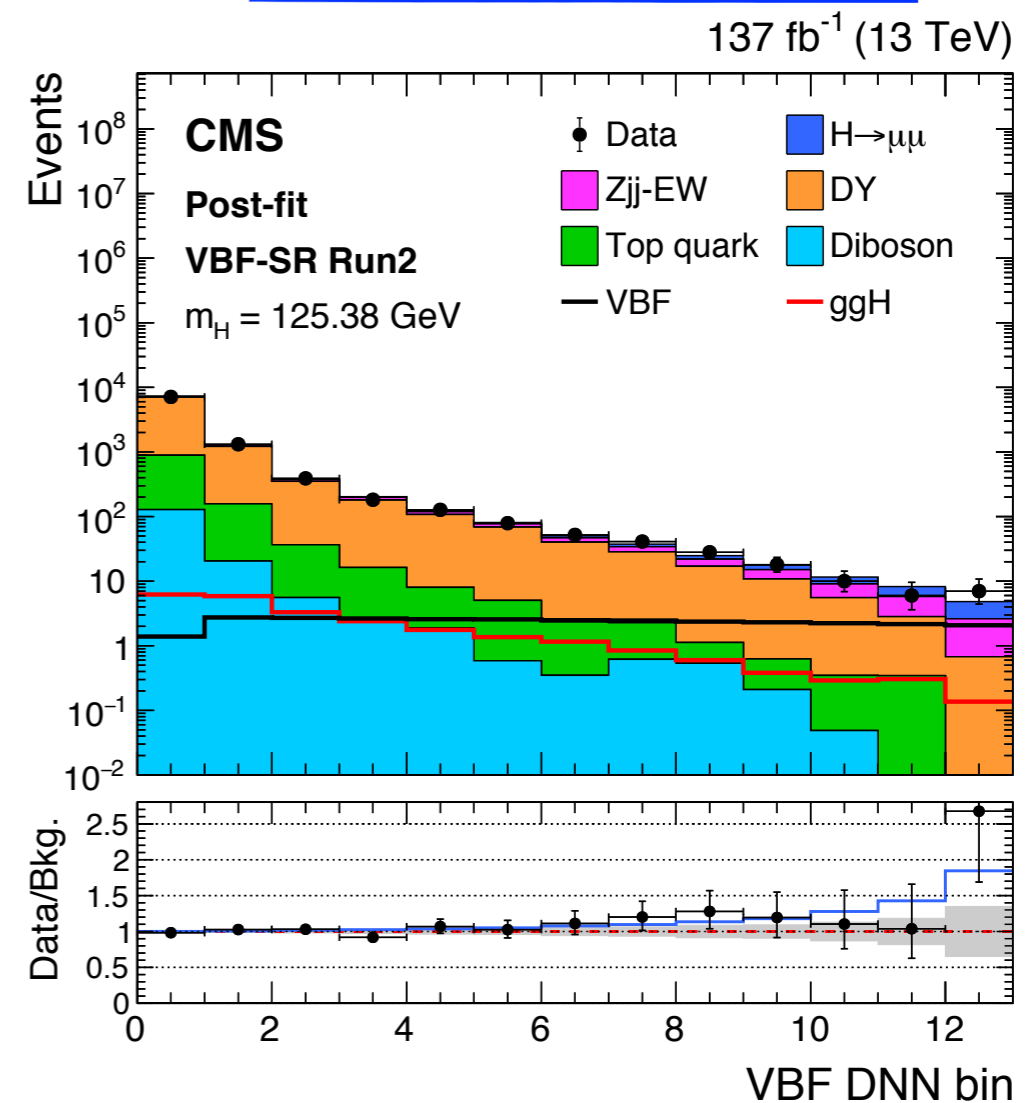


- Binned maximum-likelihood fit to DNN score simultaneously in the *signal region* and the *mass sideband region* to better constrain uncertainties.

Mass sideband region:
 $m_{\mu\mu}$ in $[105, 115] + [135, 150]$ GeV



Signal region:
 $115 < m_{\mu\mu} < 135$ GeV



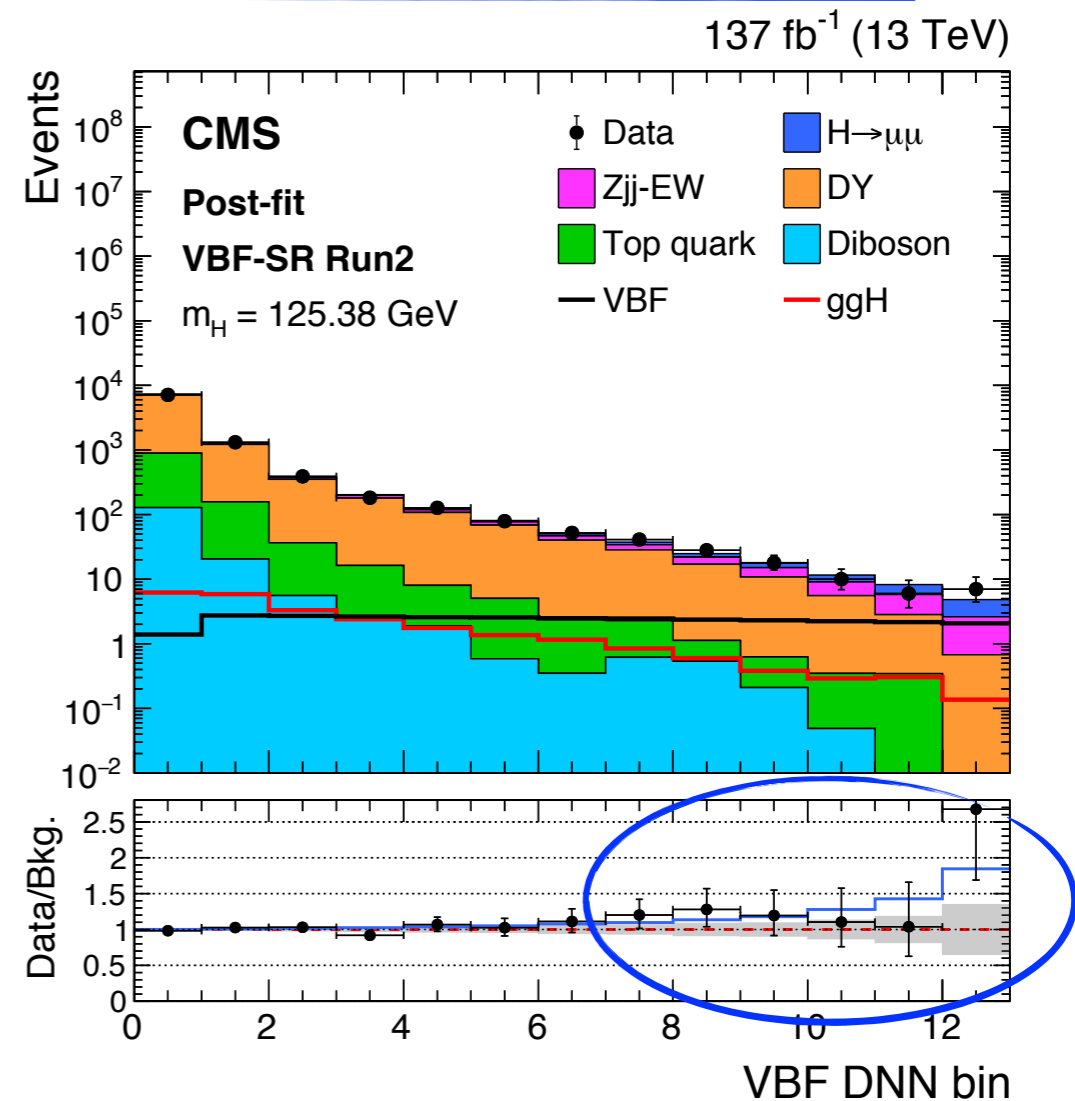
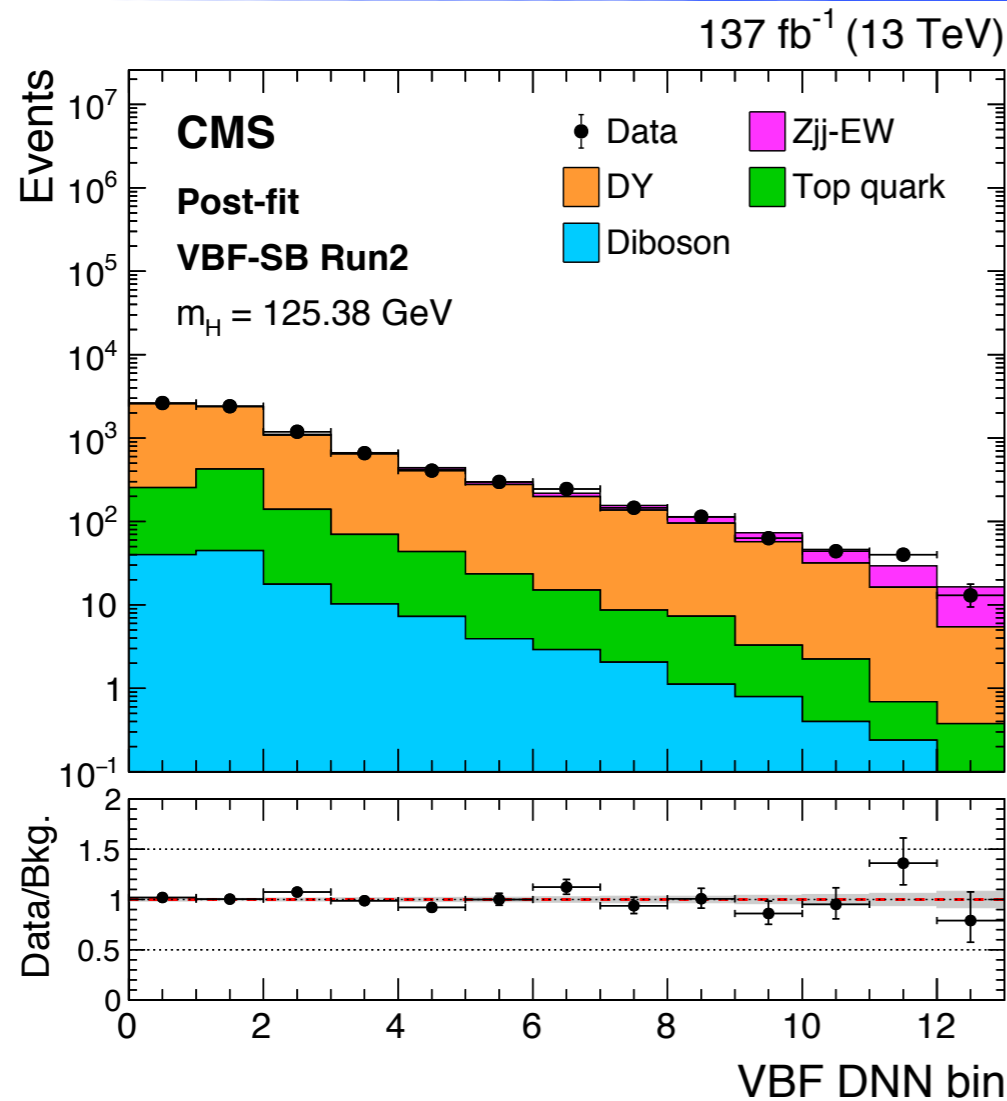
VBF category result

Observed (expected) significance: 2.4σ (1.8σ)

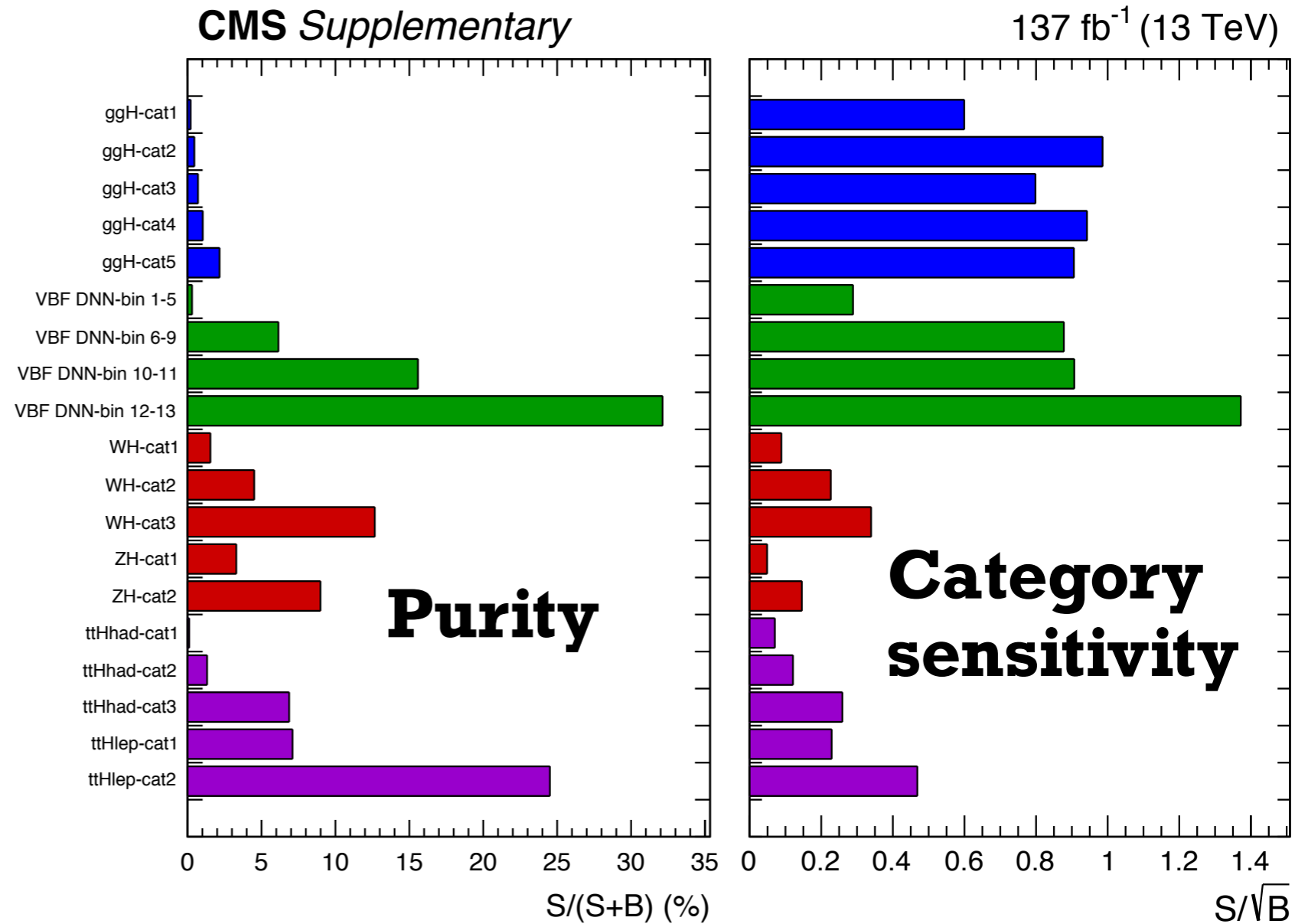
$$\mu = \frac{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)}{\sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)_{\text{SM}}} = 1.36^{+0.69}_{-0.61}$$

Mass sideband region:
 $m_{\mu\mu}$ in $[105, 115] + [135, 150]$ GeV

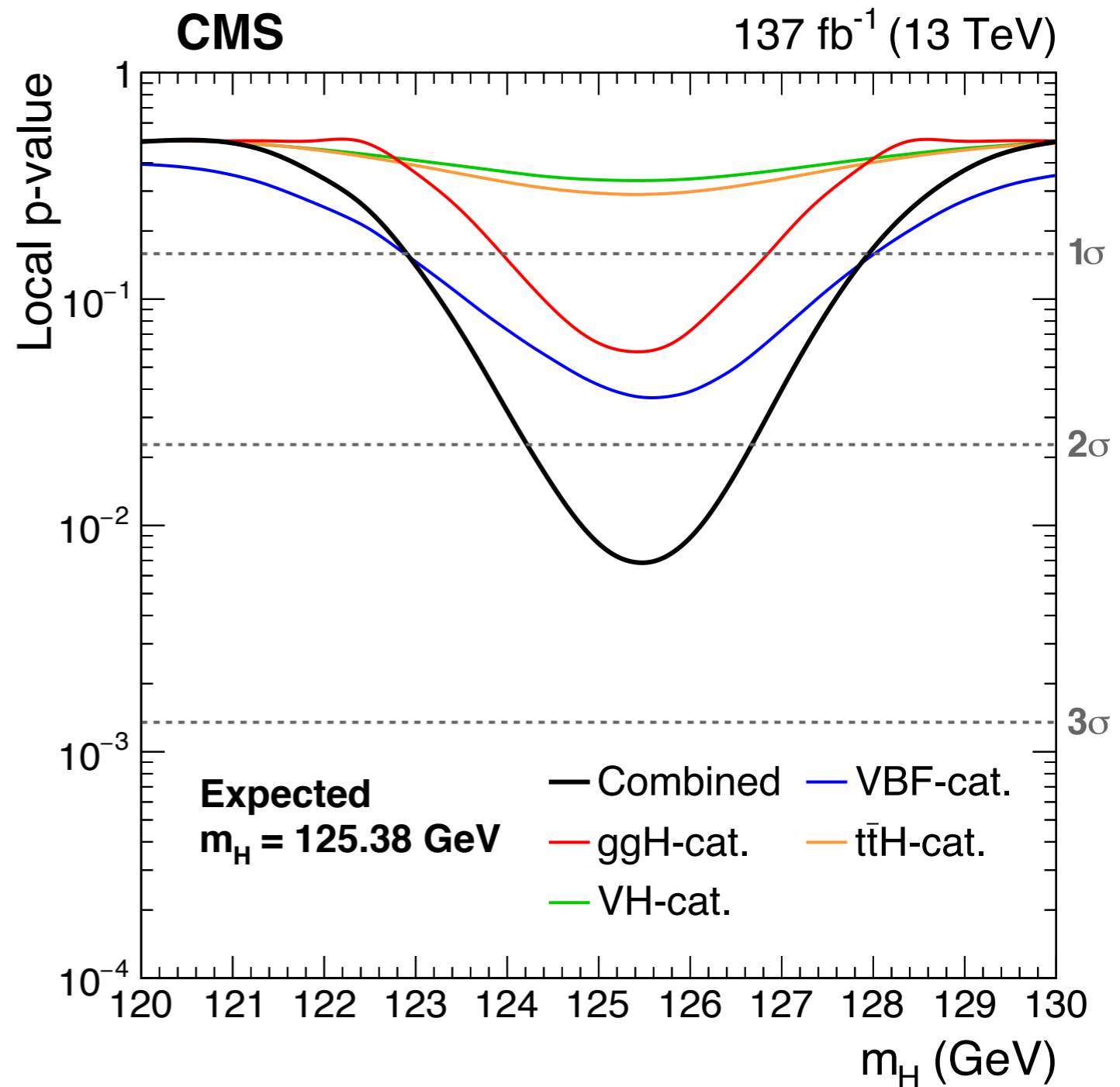
Signal region:
 $115 < m_{\mu\mu} < 135$ GeV



- Sensitivity of each category is a balance between purity and signal yield.
- ggH and VBF category sensitivities are comparable, with VBF slightly better.
- ttH and VH categories are strongly limited by small signal yield.

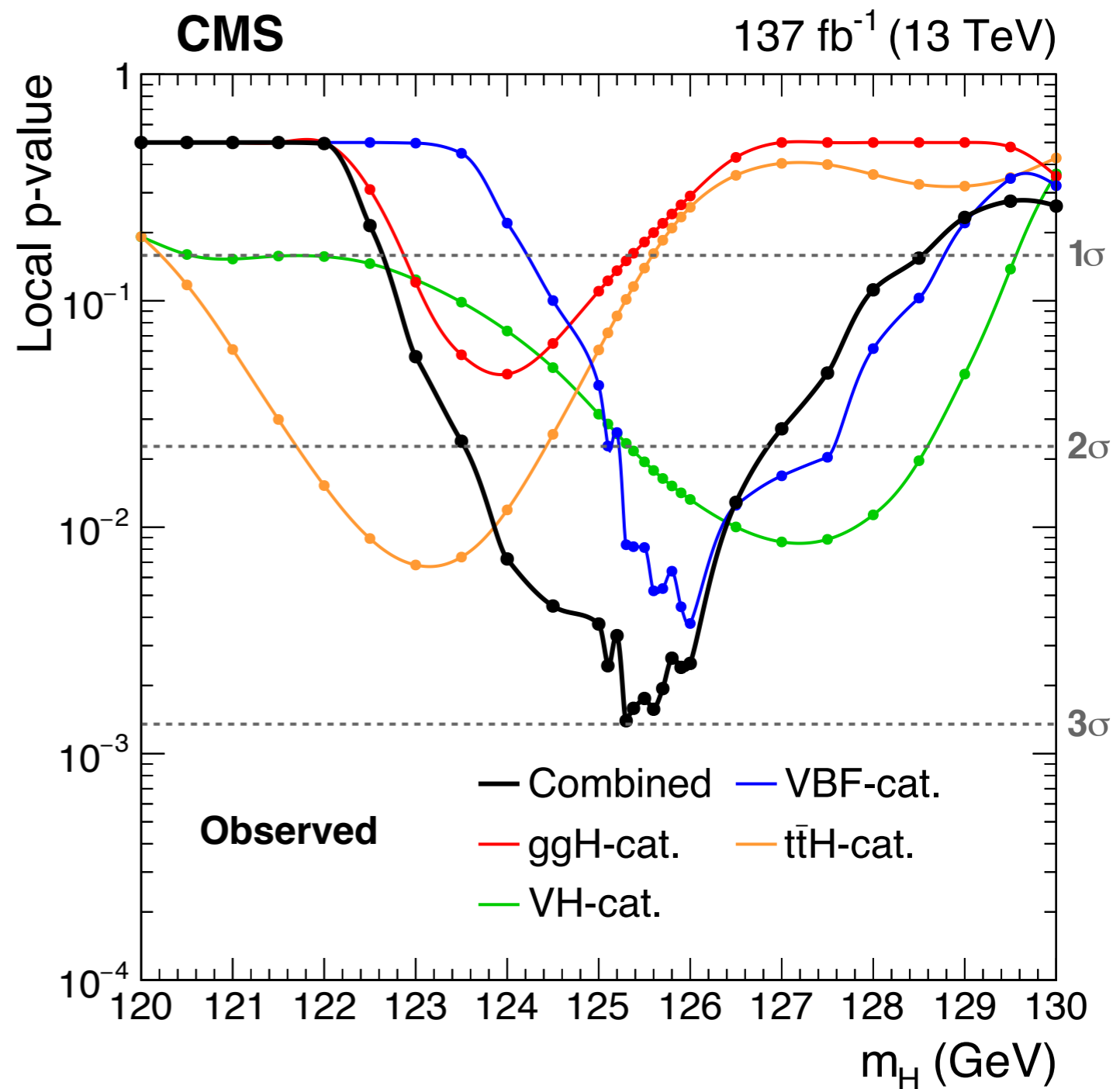


- Simultaneous fit of all categories to extract combined $H \rightarrow \mu\mu$ signal.
- *VBF category* has the best expected sensitivity, followed by the *ggH category*.



Expected ($m_H = 125.38$ GeV)
combined significance: 2.5σ

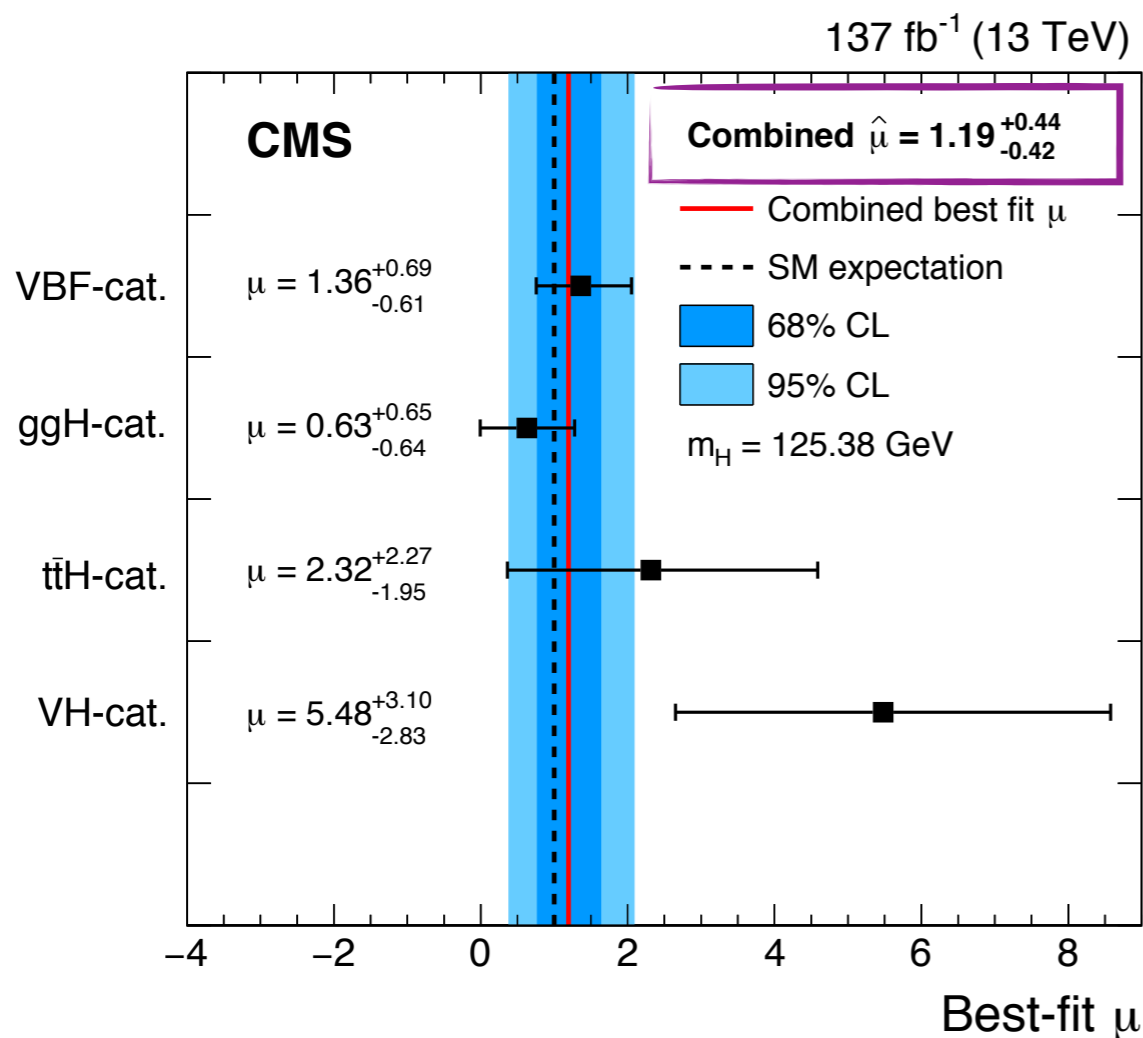
- Excess over background-only prediction observed at $m_H = 125.38$ GeV with a statistical significance of 3.0σ .
- *This constitutes the first evidence for the $H \rightarrow \mu\mu$ decay.*
- Fluctuations in the observed p-value arising from discrete nature of the mass profiling in the VBF category.



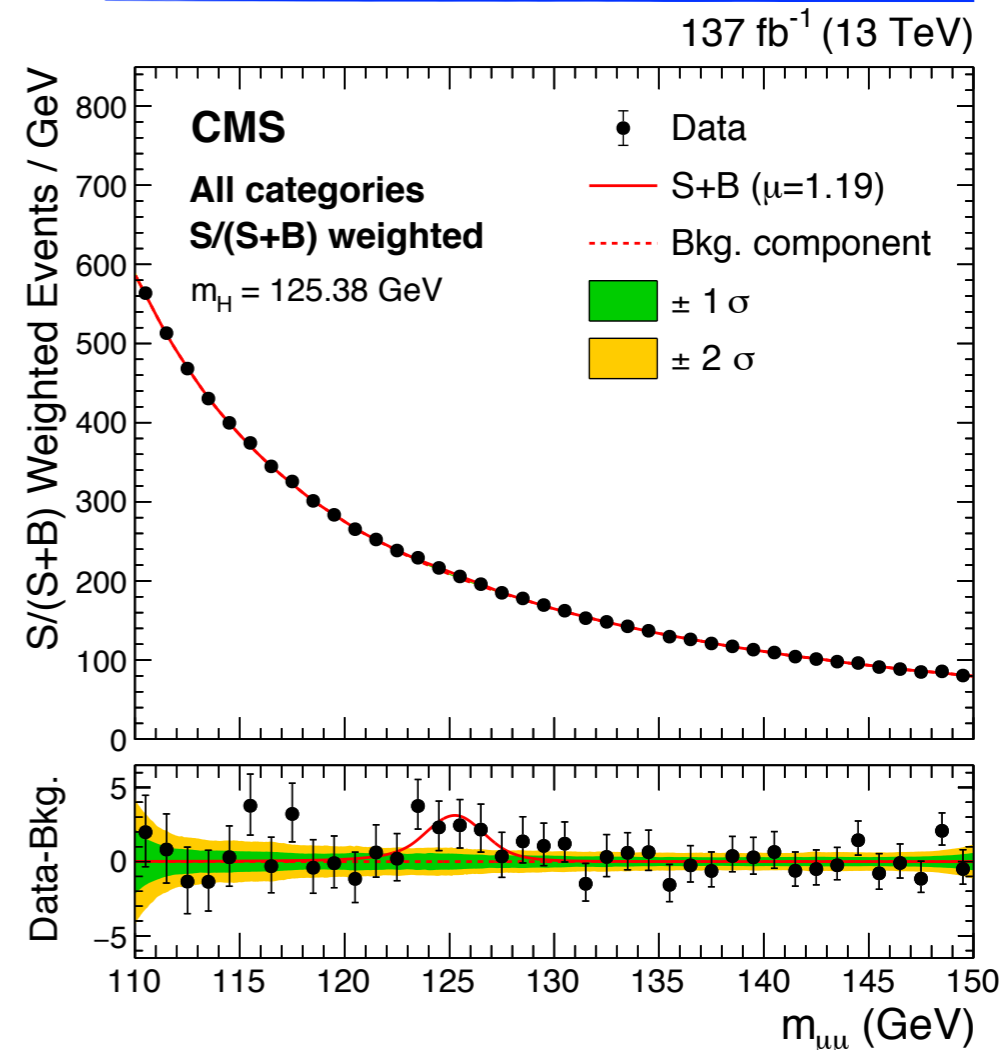
**Observed ($m_H = 125.38$ GeV)
combined significance: 3.0σ**

- *The observed signal is well compatible, within uncertainties, with the SM expectation for the Higgs boson interaction with the muon.*
- Dominant uncertainties are statistical \Rightarrow with more data, we will more precisely test this interaction.

Signal strength per category



Visualization of the observed excess vs. $m_{\mu\mu}$



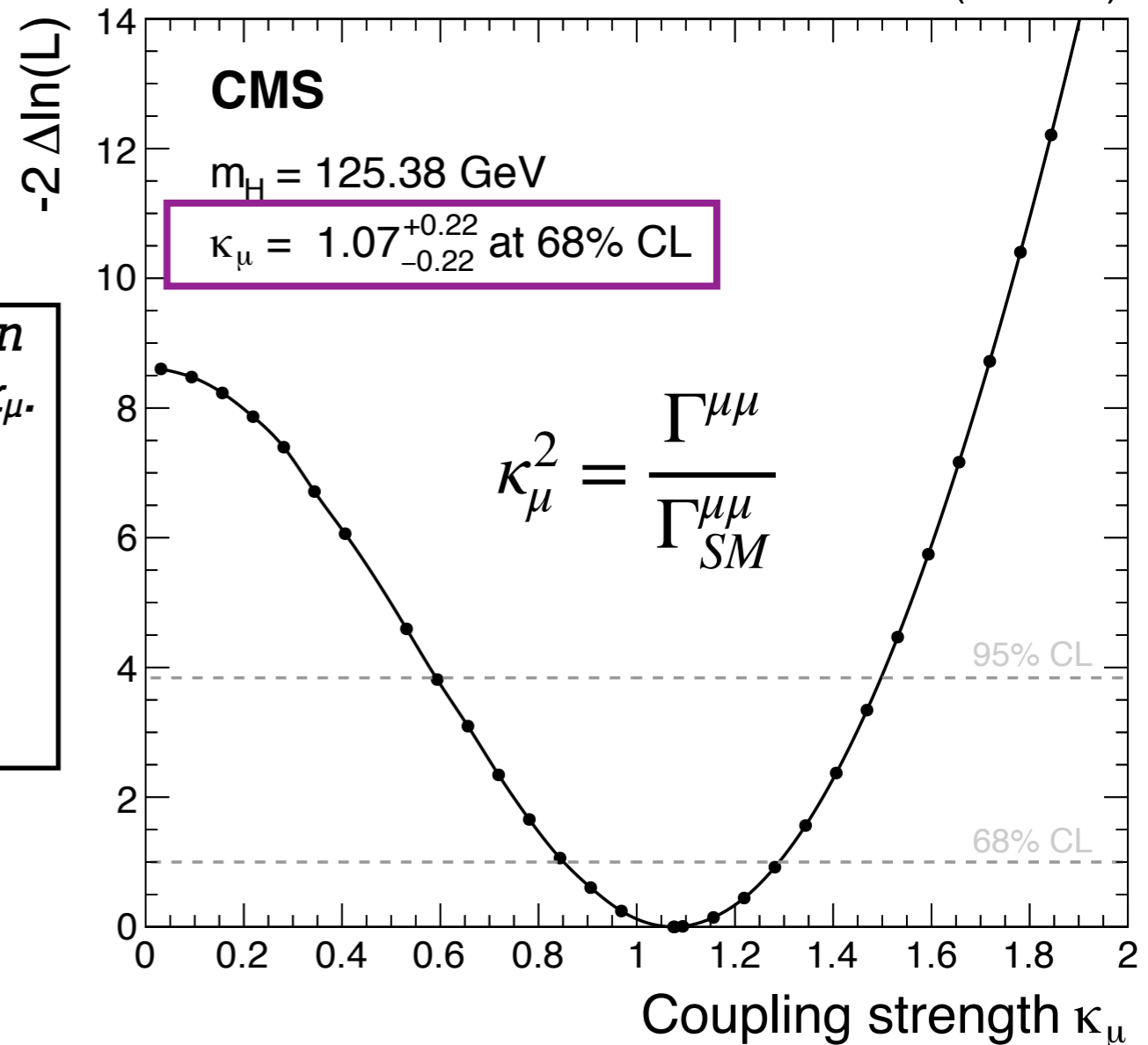
Direct access to H- μ interaction

$$\mu = \sigma_H \cdot \text{BR}(H \rightarrow \mu\mu)$$

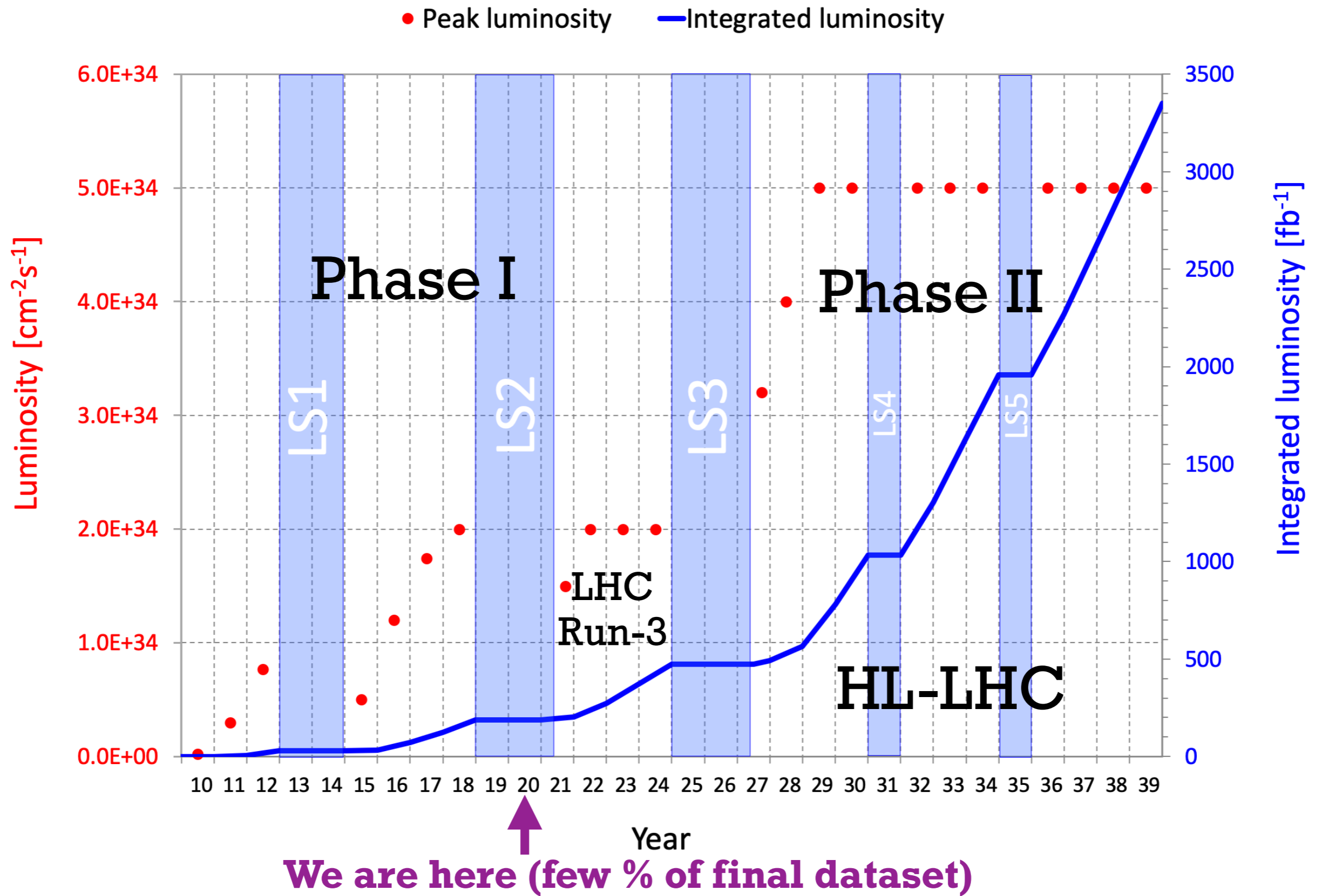
Depends on Higgs boson interaction strength with t, W, Z, ...

H- μ coupling strength from combination with measurements of other Higgs channels (EPJC 79 (2019) 421)

35.9-137 fb⁻¹ (13 TeV)



- *Combine with other Higgs channels to obtain direct constraints on H- μ coupling strength κ_μ .*
- *Coupling strength of Higgs boson to muon measured with nearly 20% precision at 68% confidence level.*



[CMS-PAS-FTR-18-011](#)

(based on previous $H \rightarrow \mu\mu$ published analysis)

300 fb⁻¹ (13 TeV)

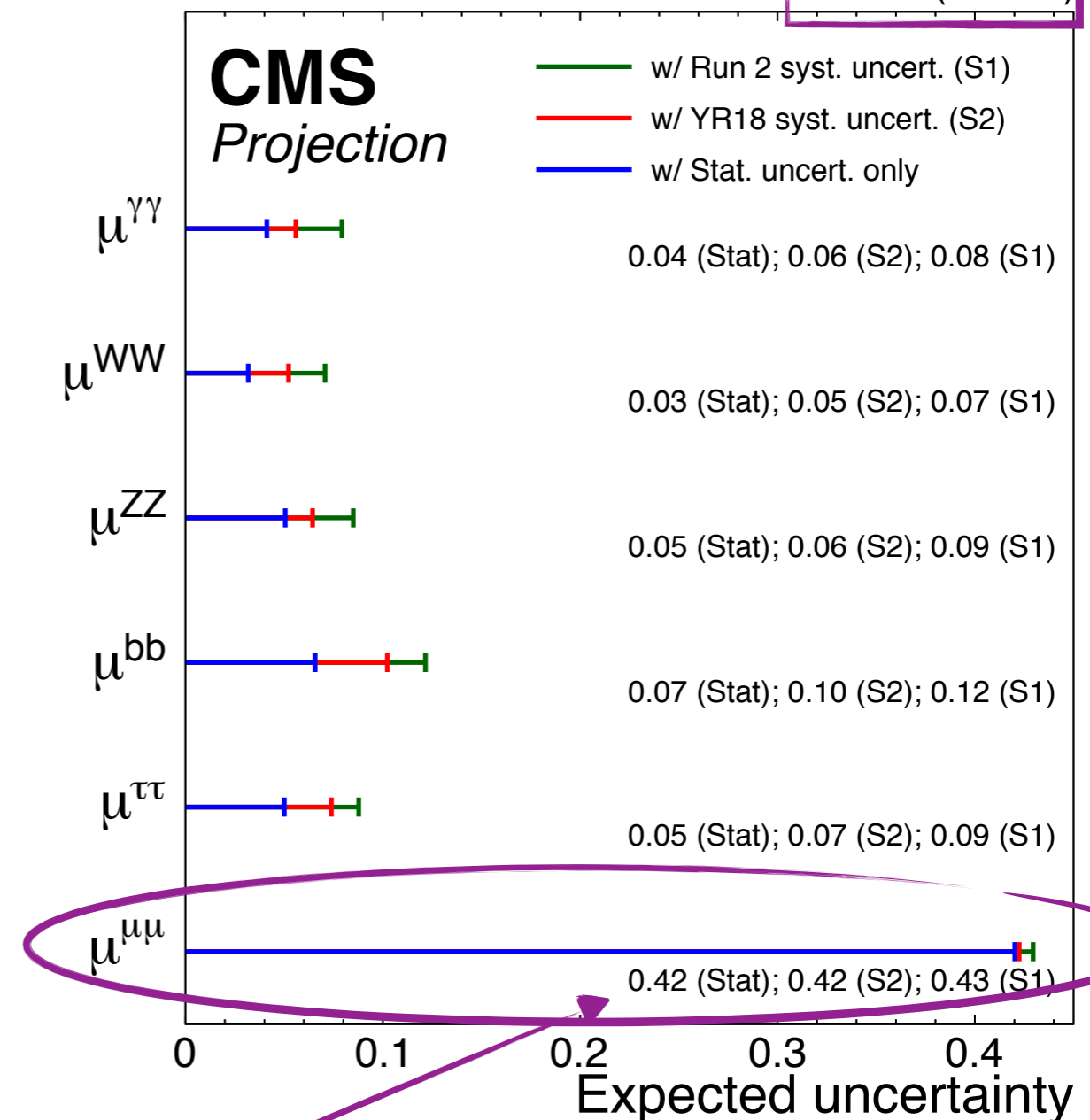
- CMS has released projections of expected precision of Higgs measurements up to end of HL-LHC.

- Including $H \rightarrow \mu\mu$, based on projections from previous CMS $H \rightarrow \mu\mu$ publication [1].

- *The future is hard to predict!*

- Cannot extrapolate ingenuity, new ideas, new methods, precise performance and usage of new technologies, etc.

- So please keep this in mind...



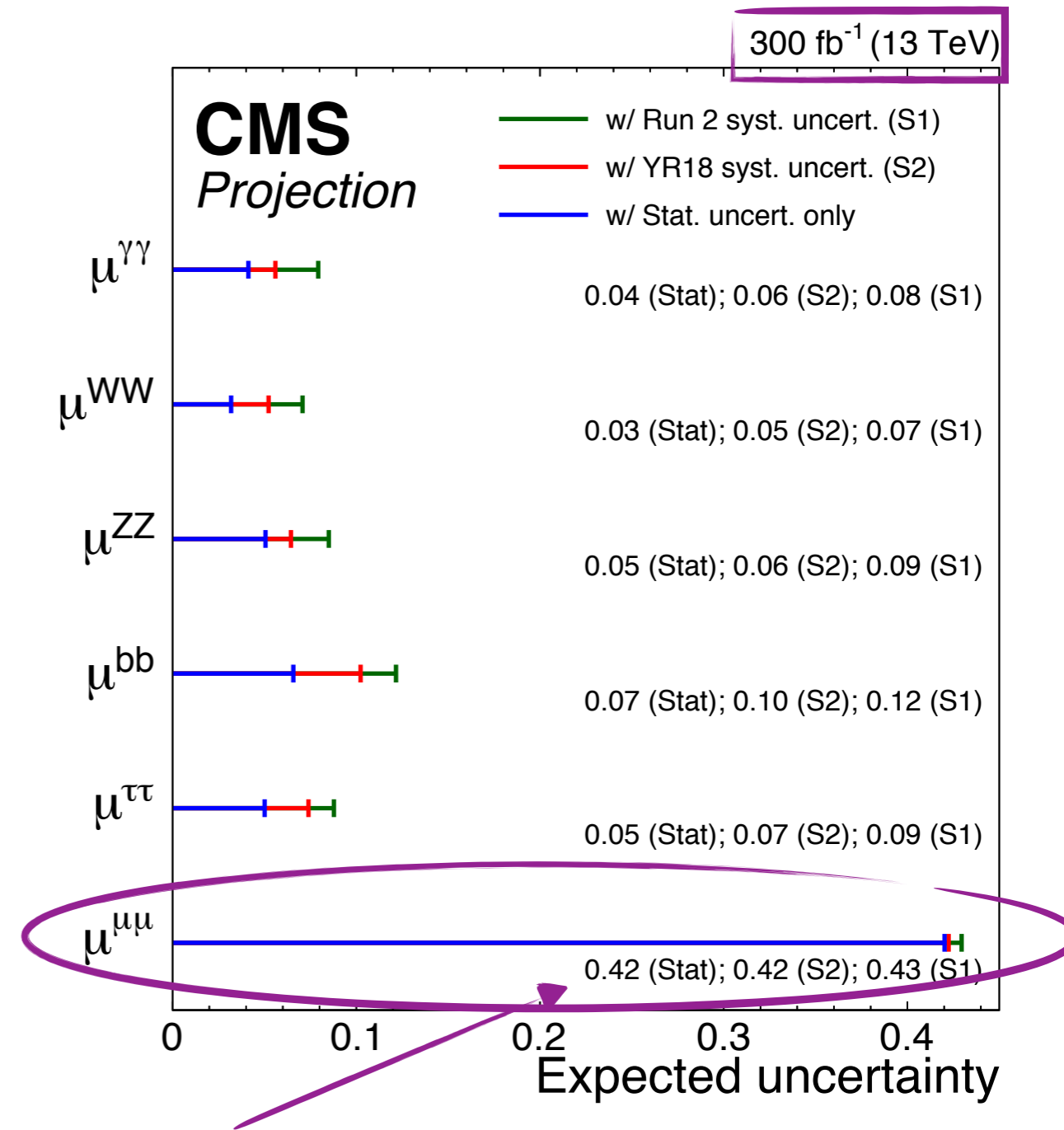
We are already here with 137 fb⁻¹ !

[1] [Phys. Rev. Lett. 122 \(2019\) 021801](#)

- LHC Run-3 (2022-2024) expected to deliver about 200 fb⁻¹ of 13 or 14 TeV data.
- Data conditions similar to those at end of Run-2.
- Some small upgrades to CMS detector, but similar performance expected overall.
- Assuming no significant improvements to the analysis, expect *roughly 4σ* sensitivity to H → μμ including Run-3 data.

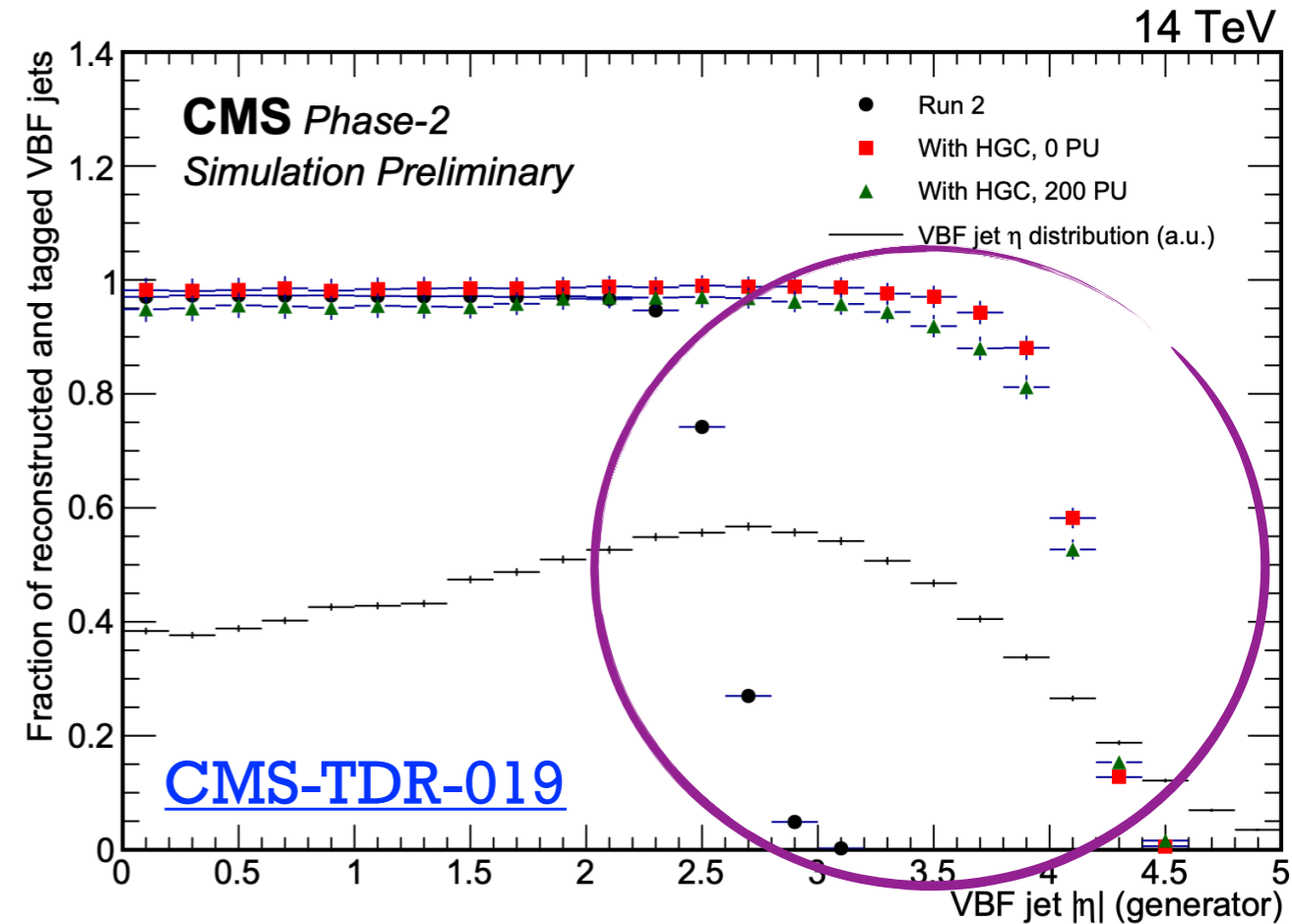
[CMS-PAS-FTR-18-011](#)

(based on previous H → μμ published analysis)



We are already here with 137 fb⁻¹ !

- CMS detector will largely be fully redesigned, improved.
- Tracking coverage extended in η from 2.4 to 4.0.
- High-granularity forward calorimetry with improved resolution.
- Improved muon resolution and efficiency, $\eta(\mu)$ extended from 2.4 to 2.8.



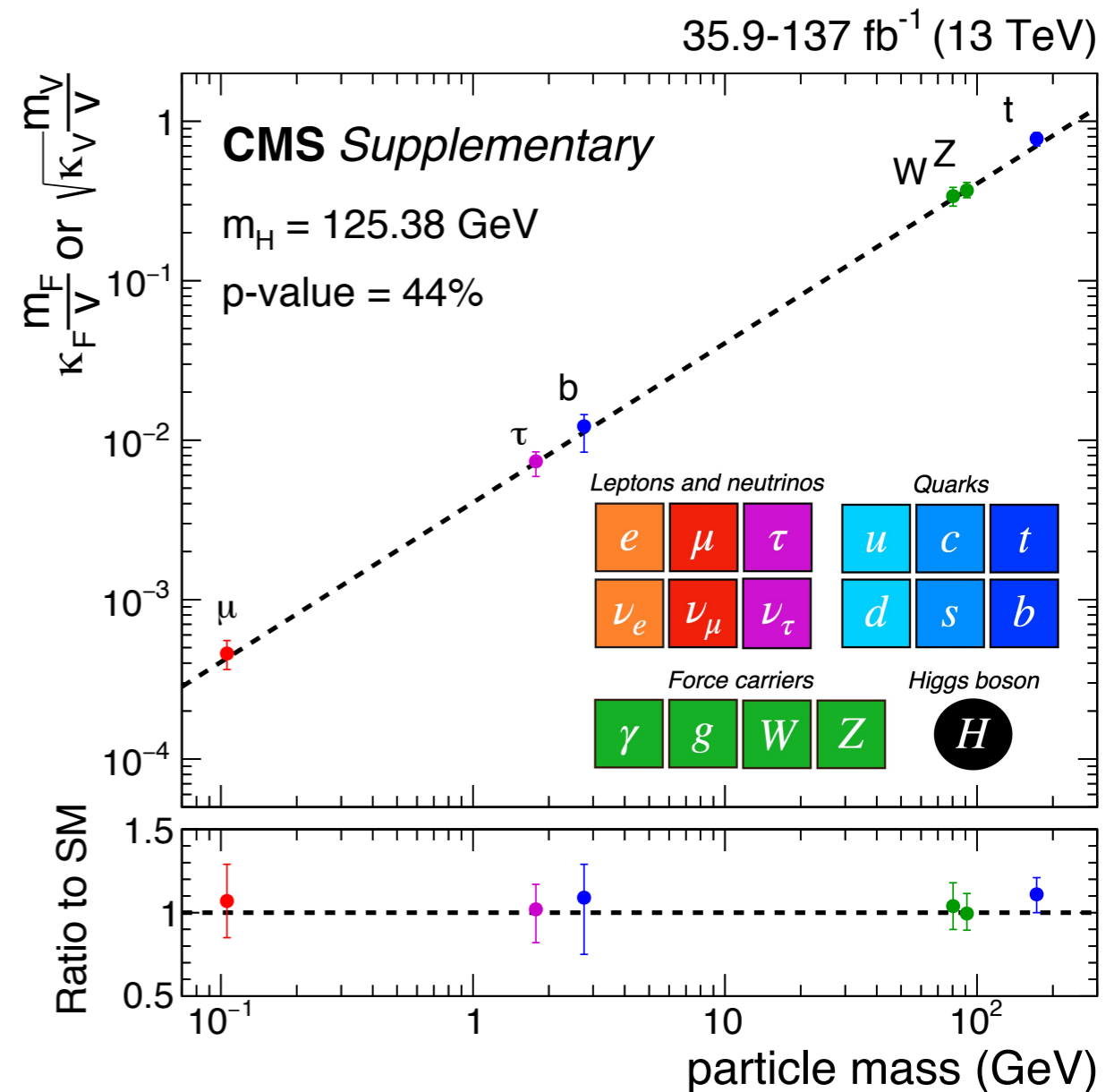
- Currently projecting $\sim 10\%$ uncertainty on $H \rightarrow \mu\mu$, i.e. $\sim 5\%$ precision on κ_μ .
- Note that projection only considers increased dataset and improved mass resolution.

Projections: 3 ab⁻¹ of HL-LHC data

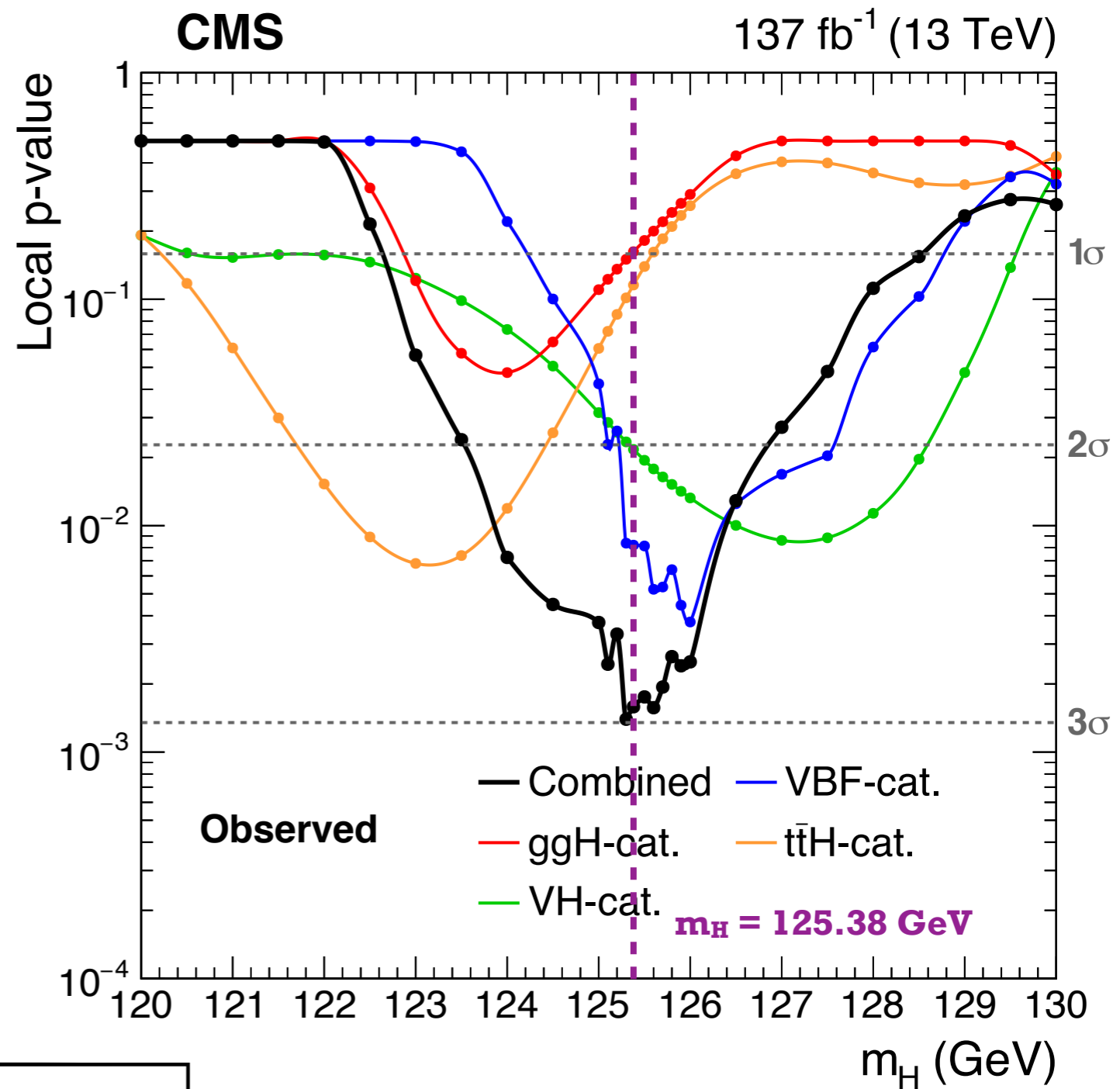
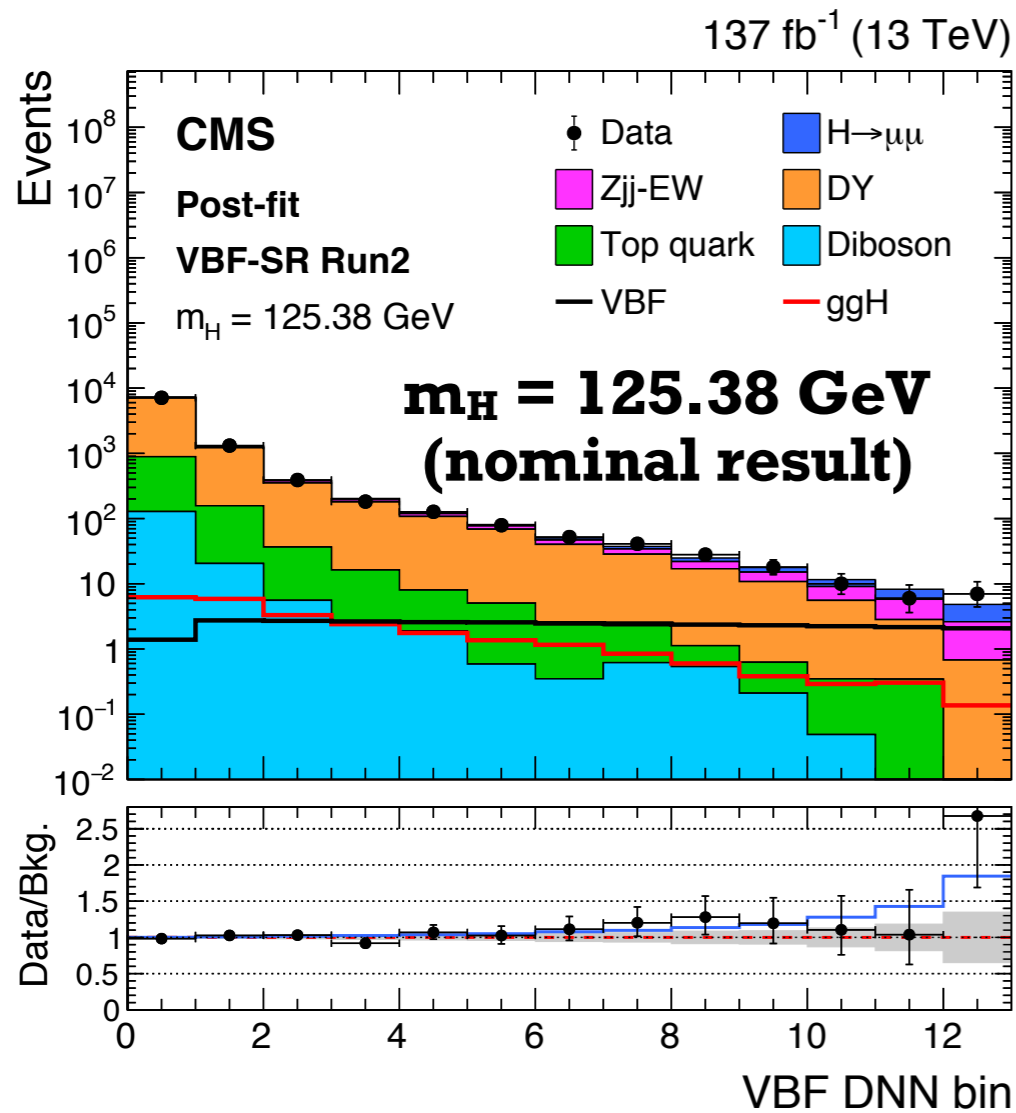
Experiment	CMS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	13%	10%
Statistical uncert.	9%	9%
Experimental uncert.	8%	2%
Theory uncer.	5%	3%

[arXiv:1902.00134](https://arxiv.org/abs/1902.00134)

- Measurement of $H \rightarrow \mu\mu$ performed by CMS with 137 fb^{-1} of 13 TeV Run-2 data.
- Observed (expected) significance: 3.0 (2.5) σ .
- First evidence for $H \rightarrow \mu\mu$ decay.
- First evidence of Higgs boson interaction with second generation fermions.
- *Remarkable success of the standard model (unfortunately) continues!*

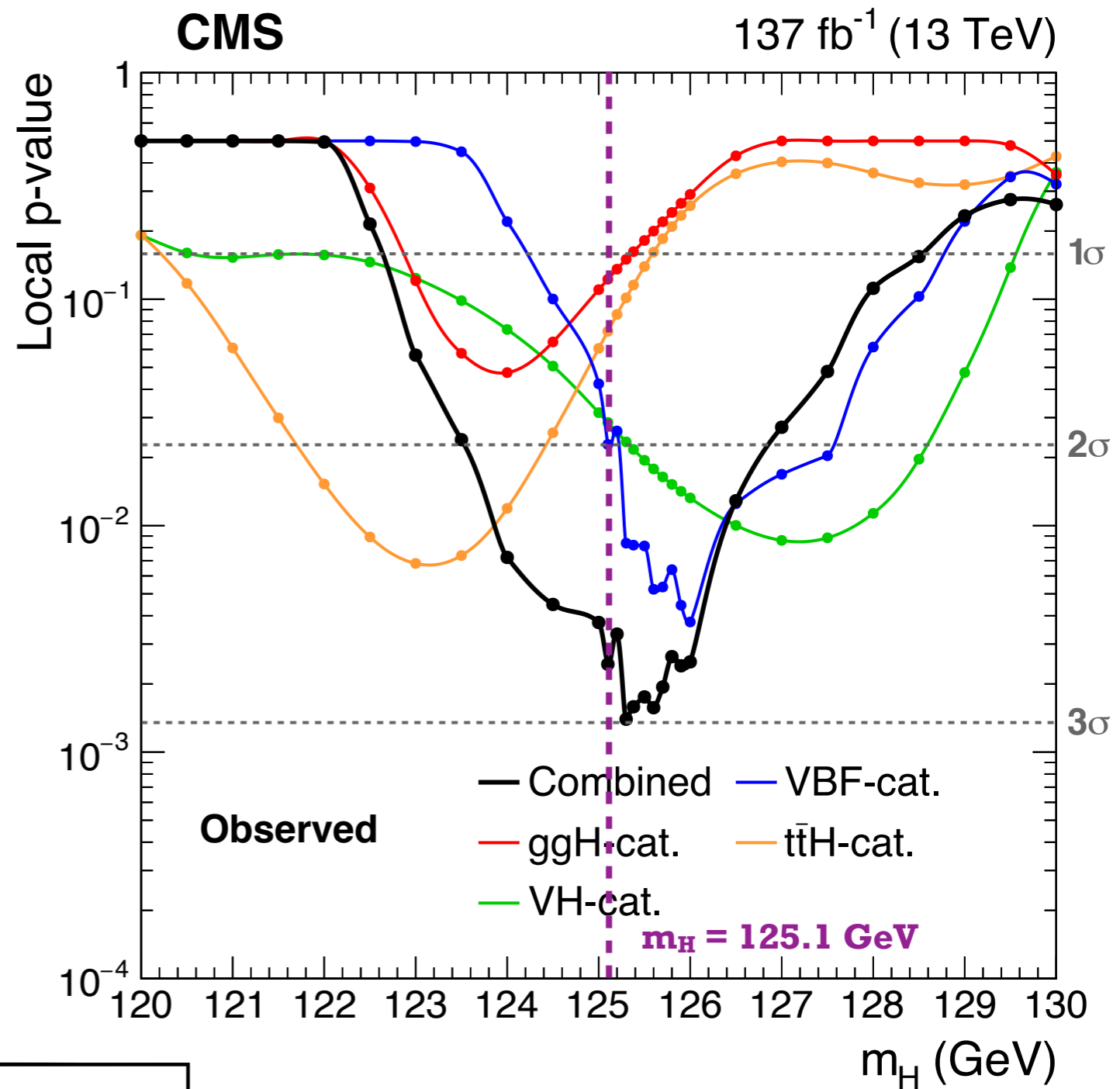
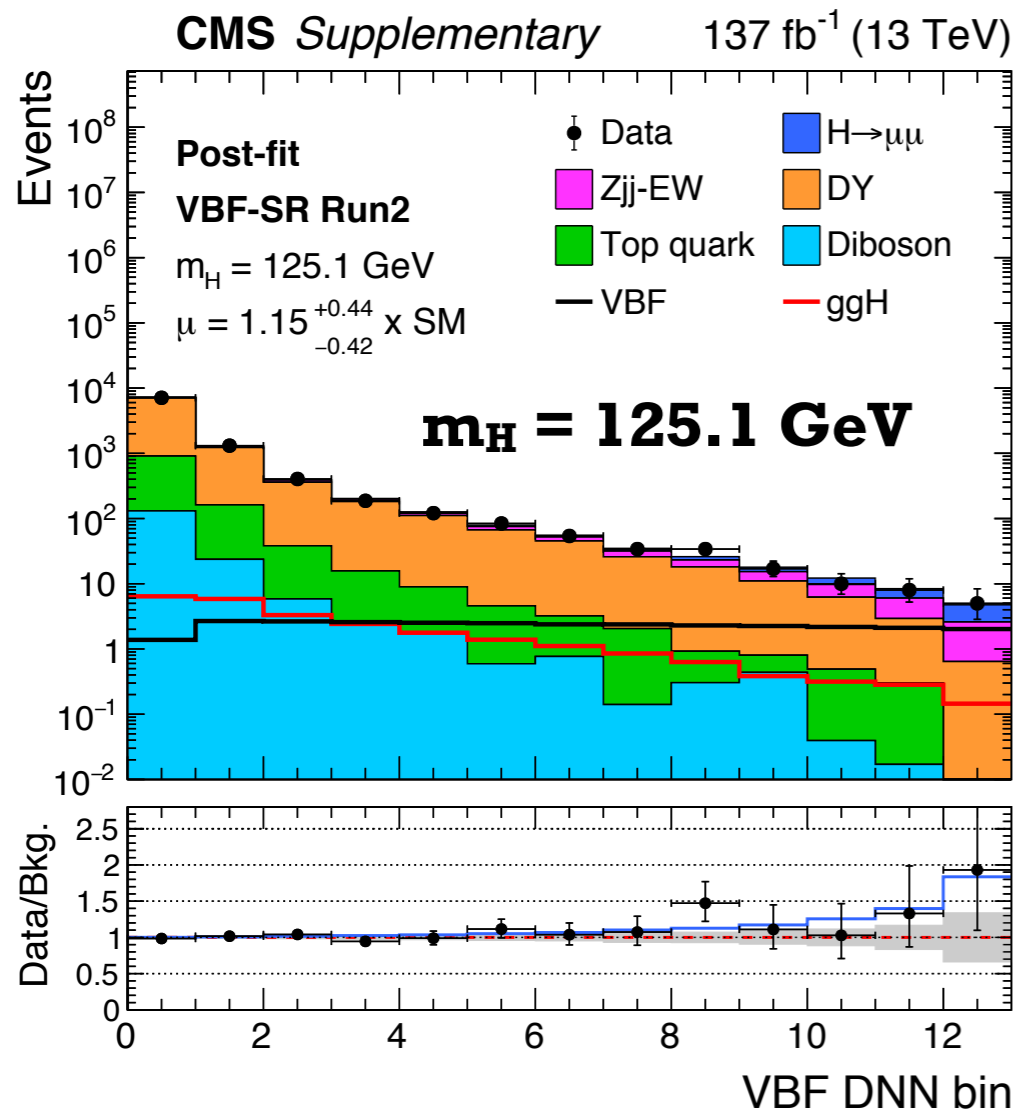


Additional Material



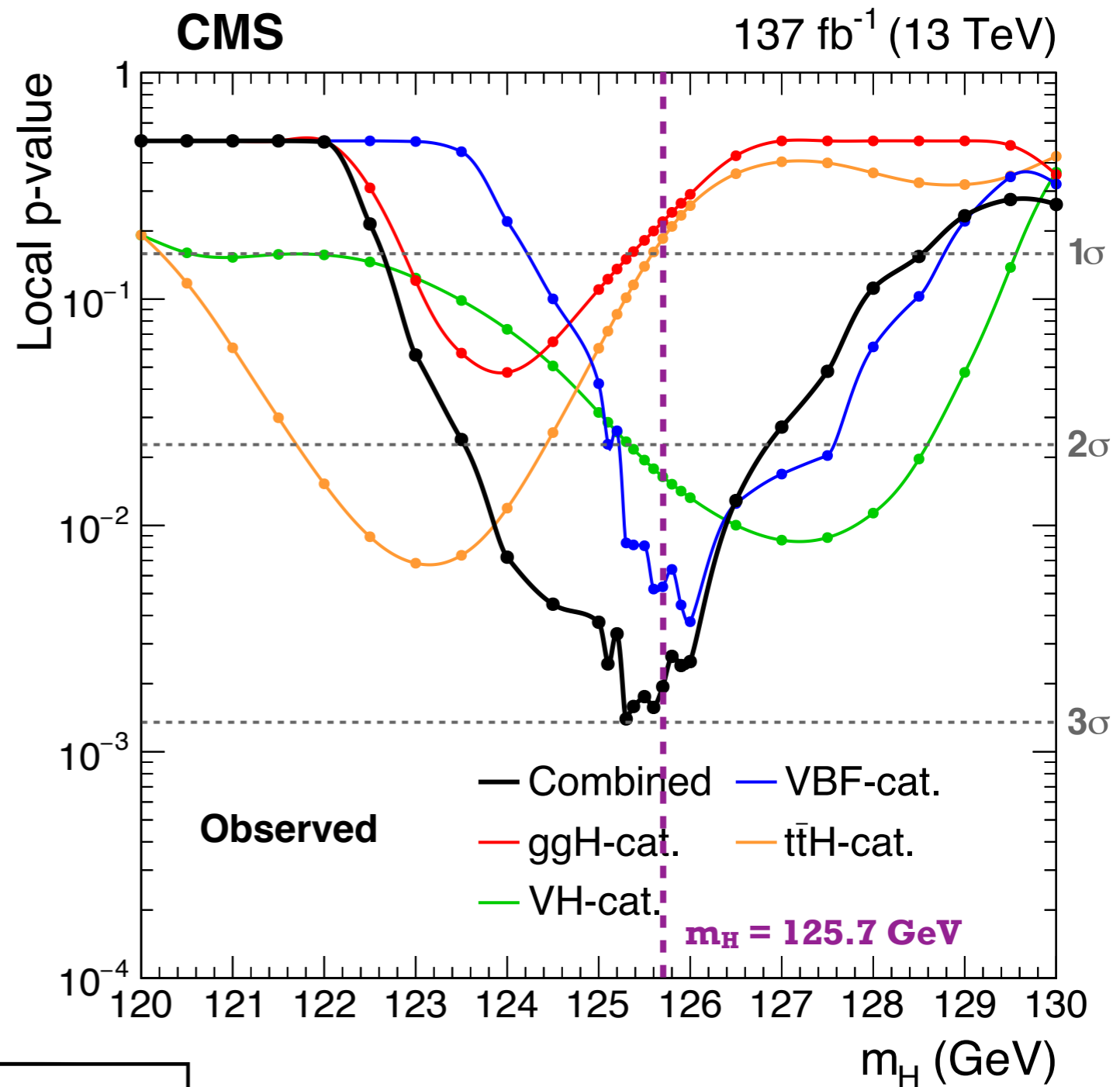
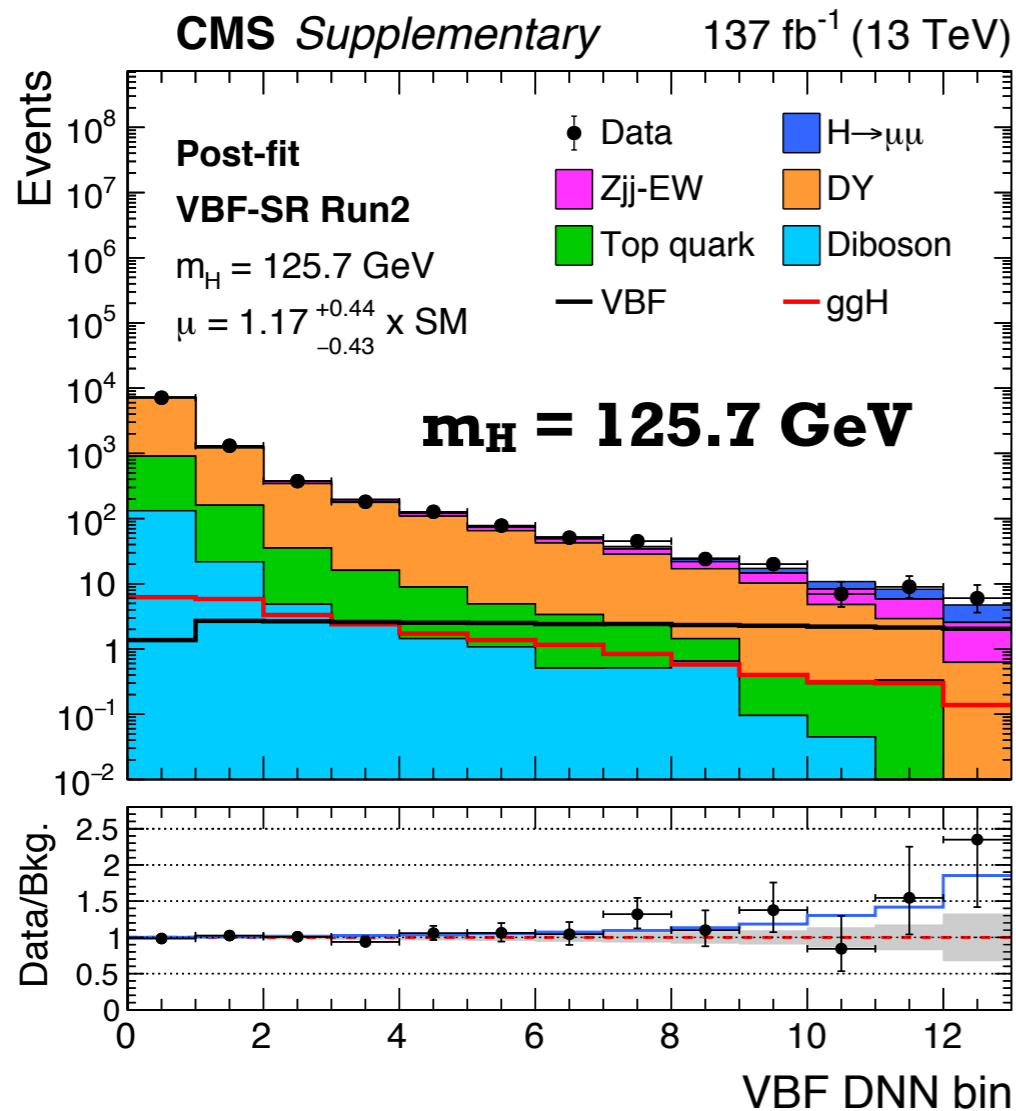
Small change in m_H hypothesis leads to:

- ⇒ **shuffling of a few data events at high DNN score.**
- ⇒ **discrete jumps in observed p-value at few percent level.**



Small change in m_H hypothesis leads to:

- ⇒ **shuffling of a few data events at high DNN score.**
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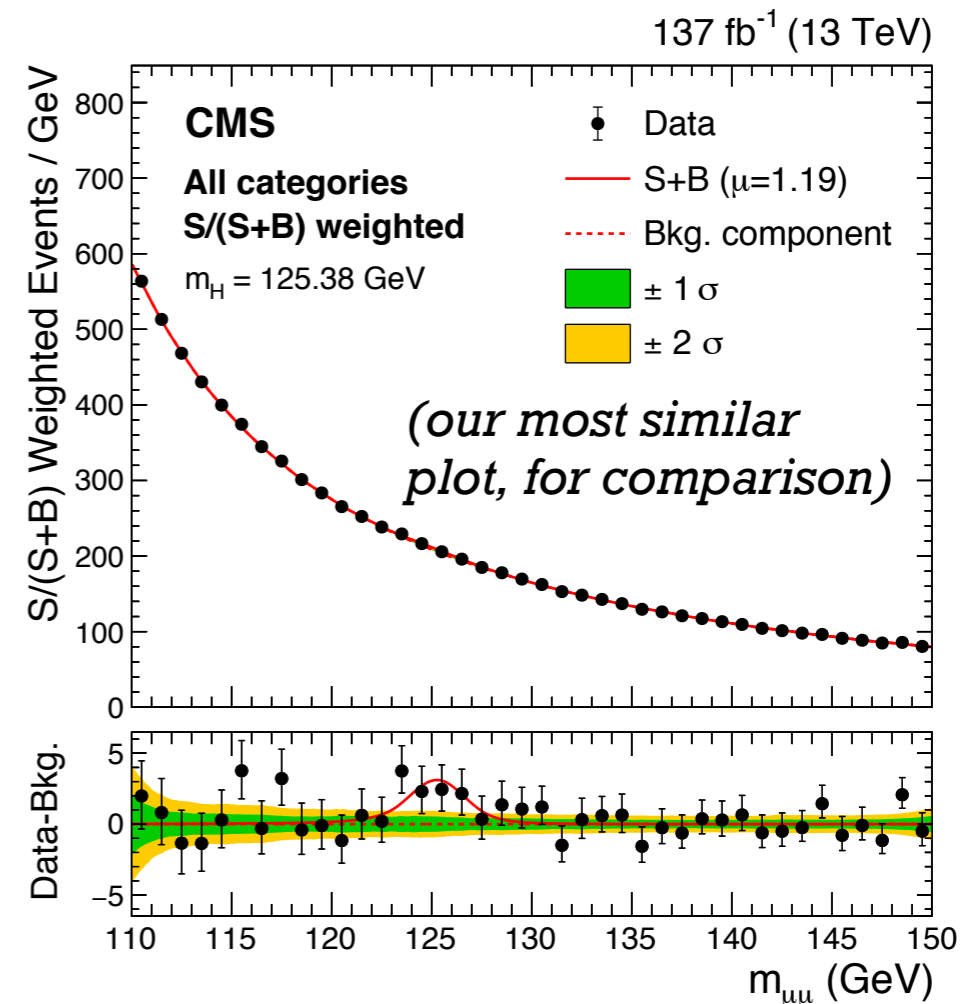
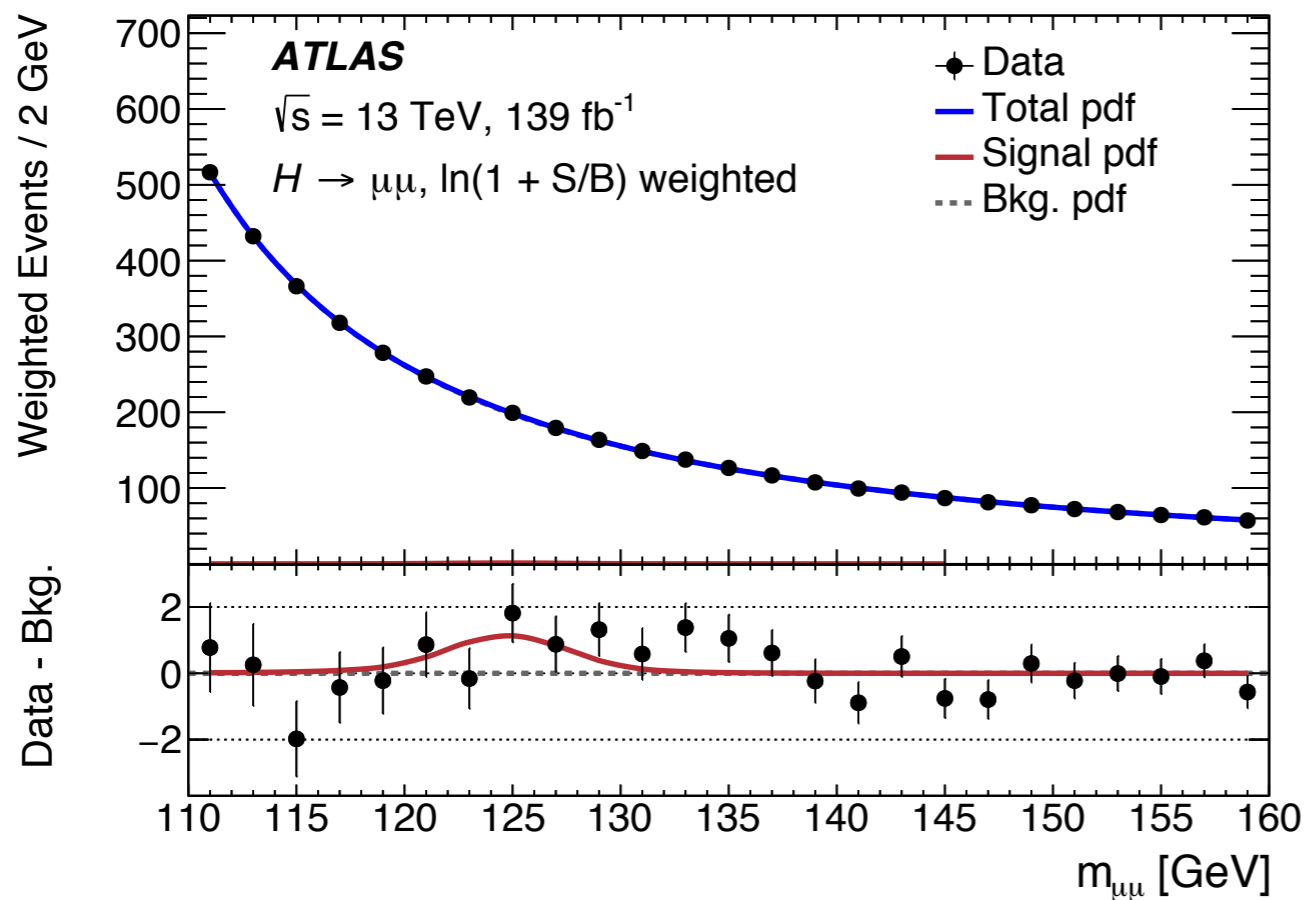
Small change in m_H hypothesis leads to:

- ⇒ **shuffling of a few data events at high DNN score.**
- ⇒ **discrete jumps in observed p-value at few percent level.**

- Both CMS and ATLAS results include exclusive ttH and VH categories, as well as VBF-targeted region.
- However, many details are sufficiently different to make a direct comparison of these two new results quite complicated.

Obs. (exp.) significance: 2.0 (1.7) s.d.
Signal strength $\mu = 1.2 \pm 0.6$

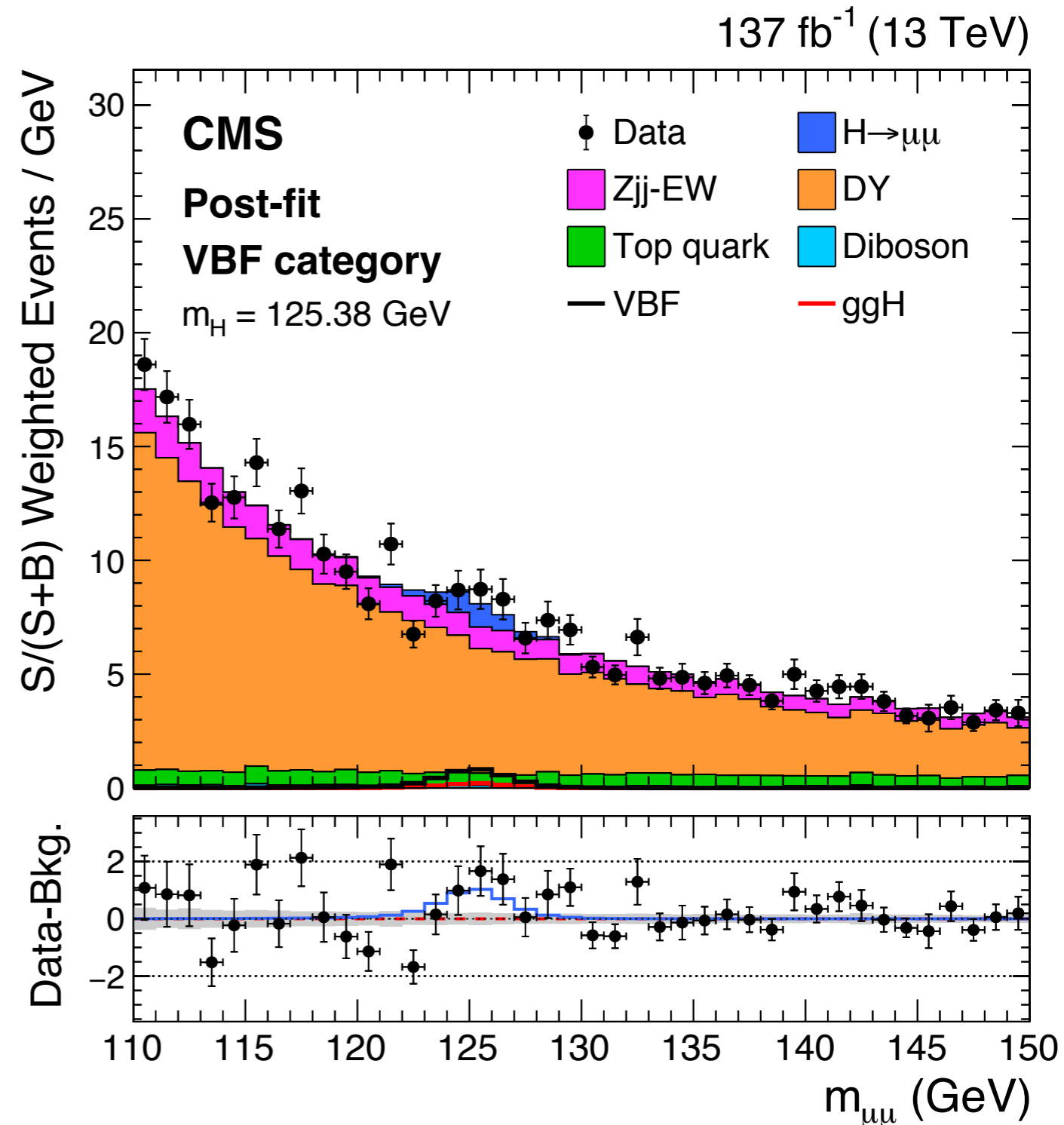
Obs. (exp.) significance: 3.0 (2.5) s.d.
Signal strength $\mu = 1.2 \pm 0.4$



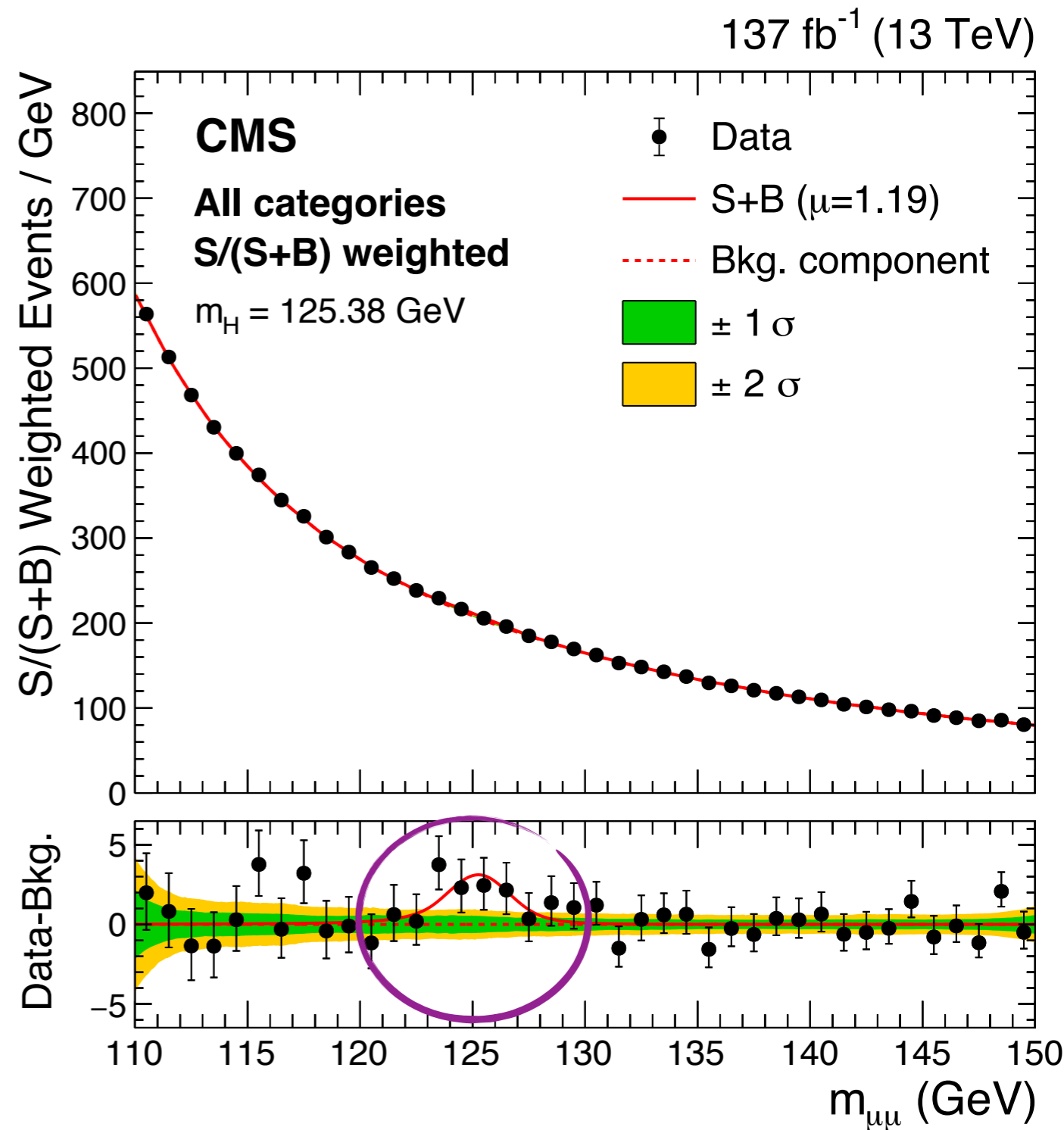
[1] [arXiv:2007.07830](https://arxiv.org/abs/2007.07830), submitted to PLB

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	$18 320 \pm 90$	0.66	0.5	2.9
2-jet Low	36 409	63 ± 17	70 ± 40	$36 340 \pm 140$	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	$24 290 \pm 100$	0.67	0.4	2.7
1-jet Low	73 459	125 ± 17	150 ± 70	$73 480 \pm 190$	0.53	0.2	2.8
0-jet Very High	15 986	59 ± 11	70 ± 40	$16 090 \pm 90$	0.55	0.4	2.6
0-jet High	46 523	99 ± 13	120 ± 60	$46 190 \pm 150$	0.54	0.3	2.6
0-jet Medium	91 392	119 ± 14	140 ± 70	$91 310 \pm 210$	0.46	0.2	2.7
0-jet Low	121 354	79 ± 10	90 ± 50	$121 310 \pm 280$	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

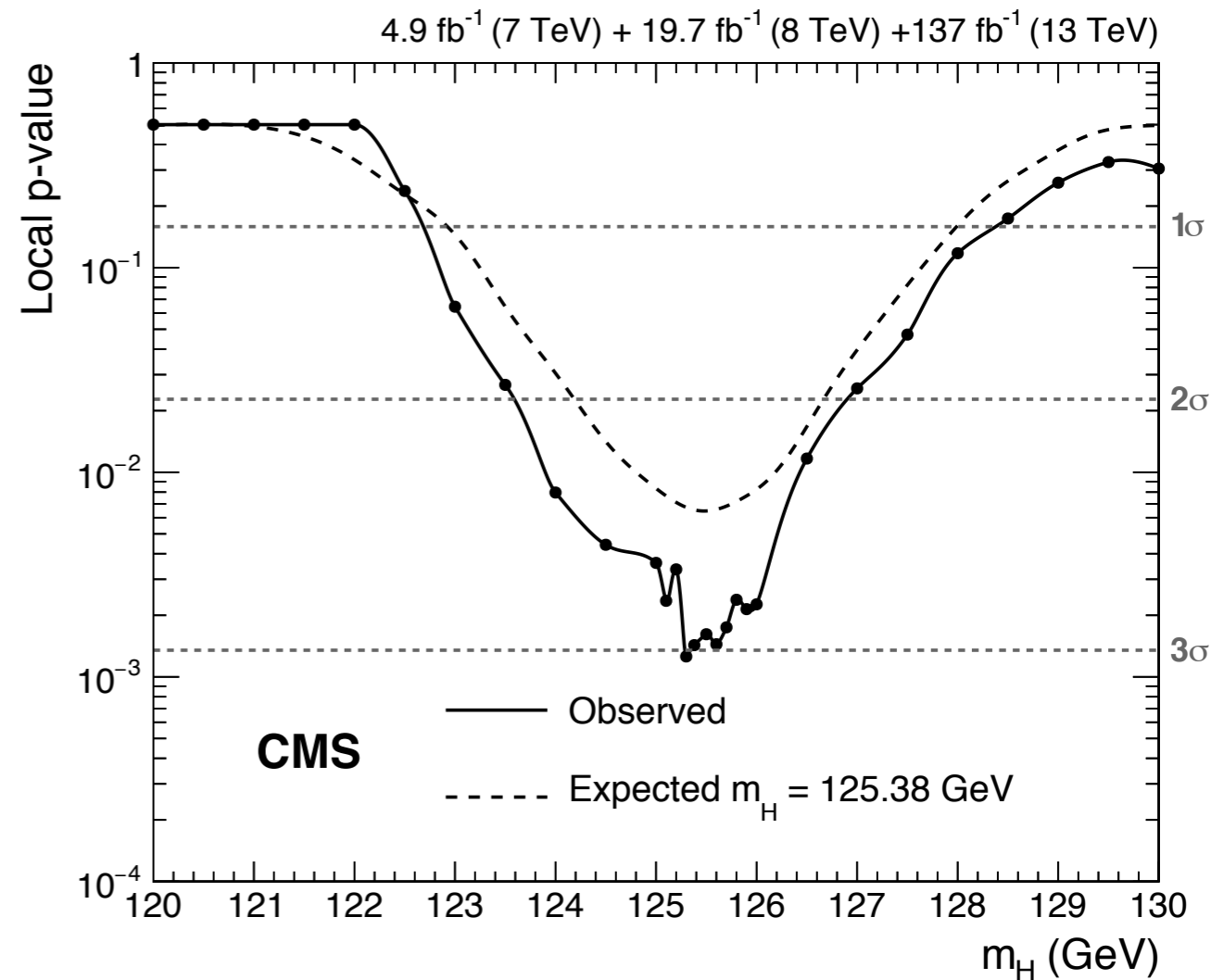
- For VBF channel, assign per-event S/S+B calculated as a function of mass-decorrelated (m_H fixed to 125 GeV) DNN score
- This binned $m_{\mu\mu}$ histogram is interpolated with a spline and merged with the other channels for the combined mass plot.
- *Note that this is just a way to visualize the observed excess, not the fit result itself.*



- Weight $m_{\mu\mu}$ distribution in each ggH, VH, and ttH category by $S/S+B$ within signal HWHM.
- Interpolate binned VBF category $m_{\mu\mu}$ histogram (see previous slide) with spline and merge with other categories.
- *Note that this is just a way to visualize the observed excess, not the fit result itself.*



- Combination performed with CMS Run-1 $H \rightarrow \mu\mu$ search.
- Full p-value scan vs. m_H .
- Run-1 adjusted to $m_H = 125.38$ GeV signal hypothesis.
- **Observed (expected) significance 2.98σ (2.48σ).**
- *Local minimum at $m_H = 125.3$ GeV is 3.02σ .*

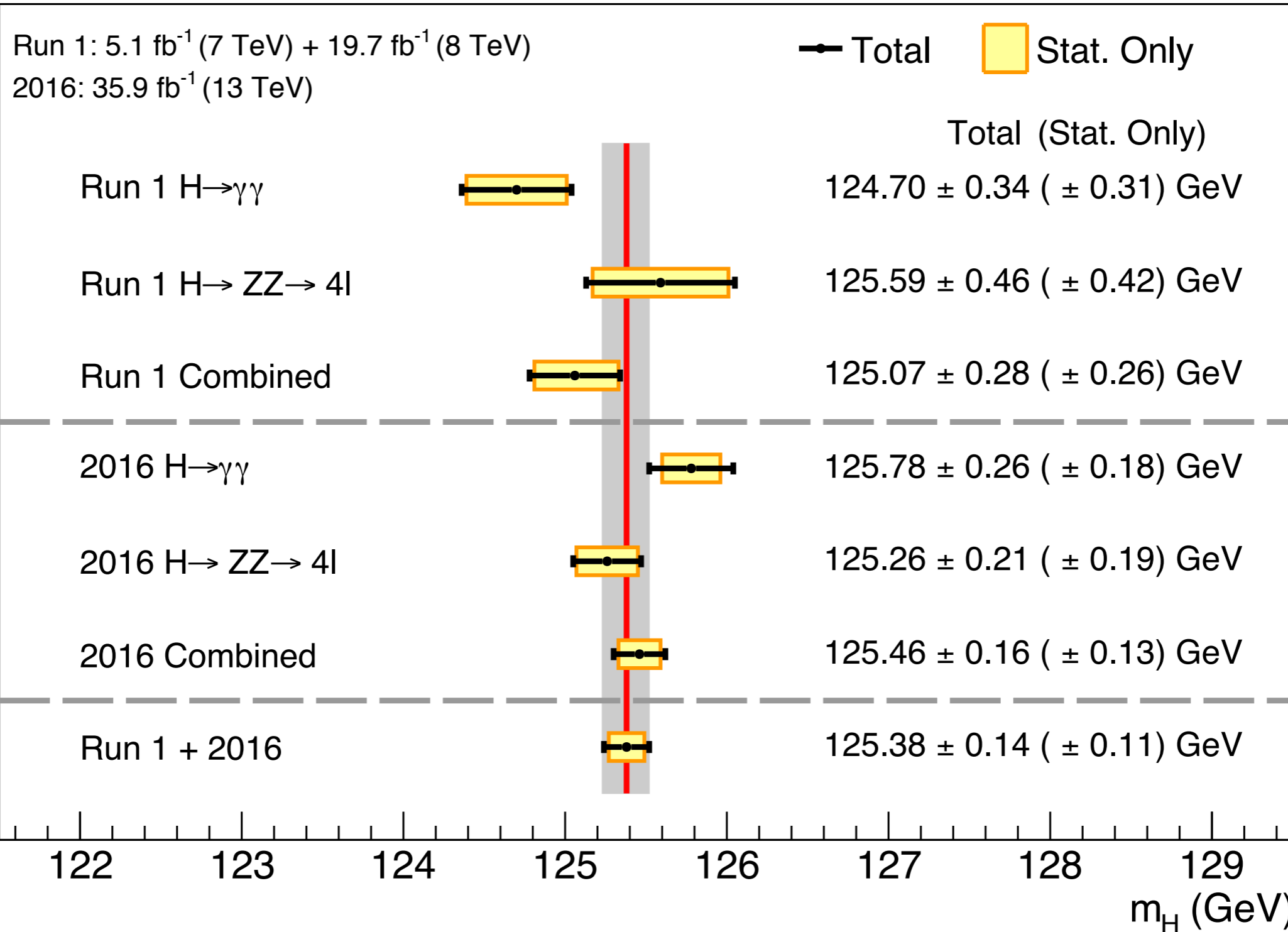


Production category	Observed (expected) signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
ttH	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13$ TeV	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7, 8, 13$ TeV	2.98 (2.48)	1.93 (0.81)

- Precision in all channels dominated by limited amount of data.
 - Largest impact from systematics in VBF category (<5%).
- Largest systematic uncertainty impacts from limited MC statistics in VBF category and VBF (signal and EW Zjj) parton shower modeling.

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

CMS



[Phys. Lett. B 805 \(2020\) 135425](#)

- Background composition is quite stable across categories and dominated by DY (>90%).
- Core background function built as discrete profile of two physics-inspired (Breit-Wigner, FEWZ) and an agnostic (sum of exponentials) function.
- Bias studied against multiple physics-inspired and agnostic background functions and always < 20% (negligible impact on result).
- No prior assumption on background shape or normalization

$$B_{cat}(m_{\mu\mu}, \vec{\alpha}, \vec{\beta}) = N_B \times F_{core}(m_{\mu\mu}, \vec{\alpha}) \times T_{SMF}(m_{\mu\mu}, \vec{\beta})$$

Number of
bkg. events

Core-PDF, defined as a **discrete profile** of three functions.
Associated **parameters** are **correlated across categories**

Per-category **polynomial shape modifier** use to “morph” the core component

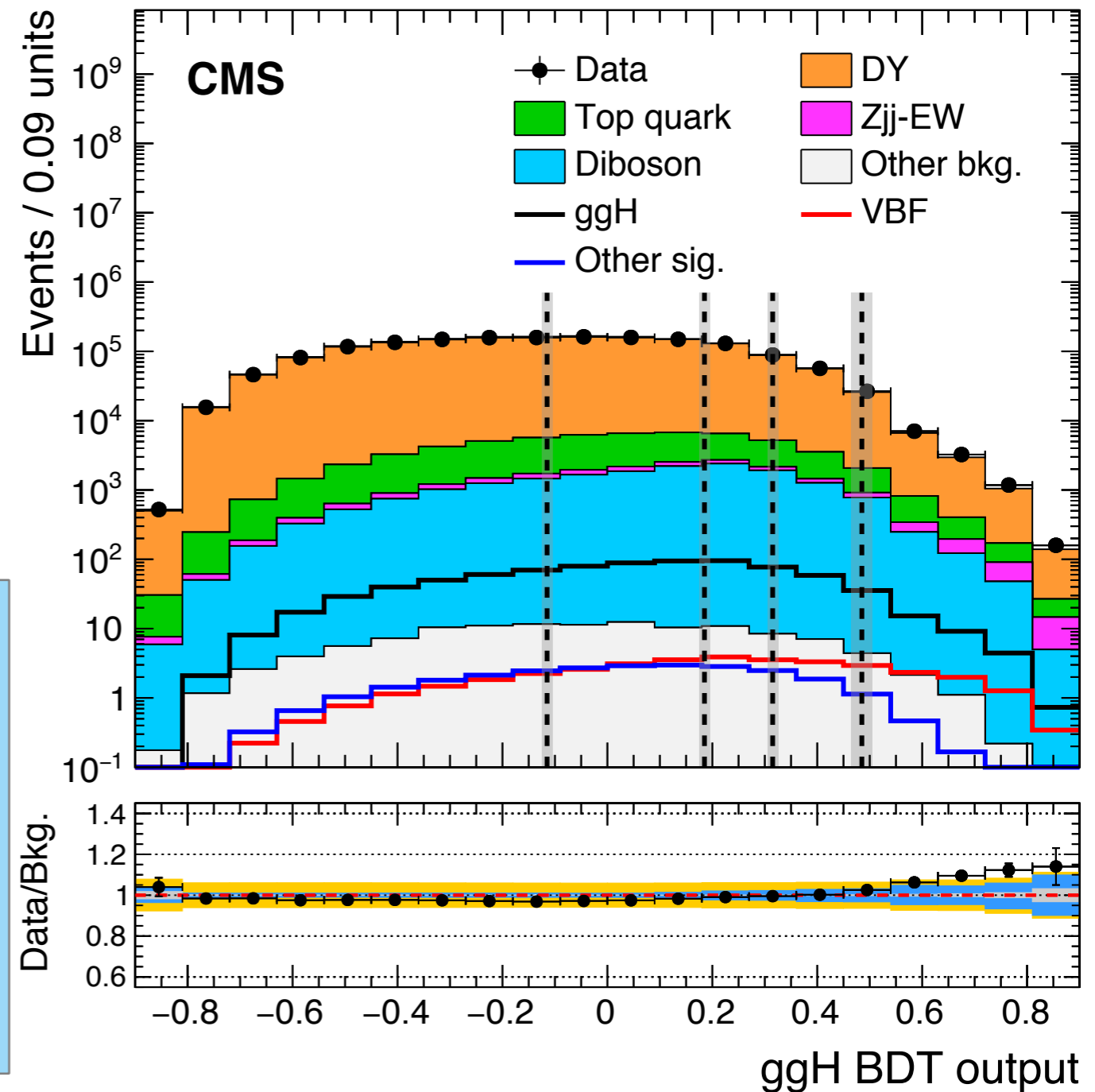
*method in ggH channel only

- Consider all events not selected by exclusive categories.
- About 96% of total inclusive events selected in ggH category.
- Largest signal yield, but smallest S/B $\sim 0.1\%$.
- Train mass-decorrelated BDT based on muon kinematics + possible jet kinematics (to pick up also ggH+X, residual VBF, hadronic VH)

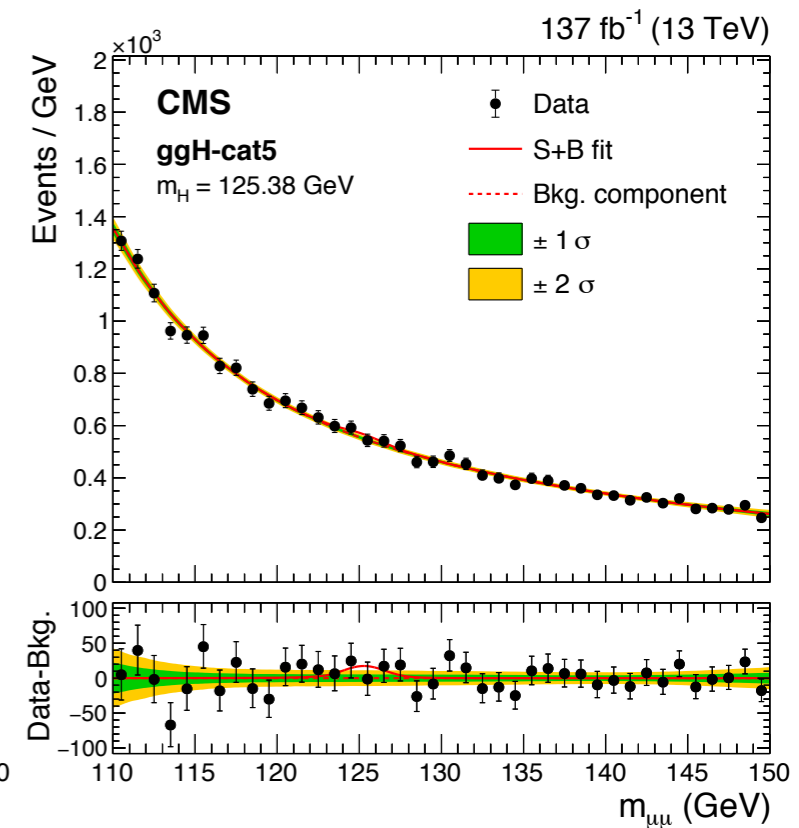
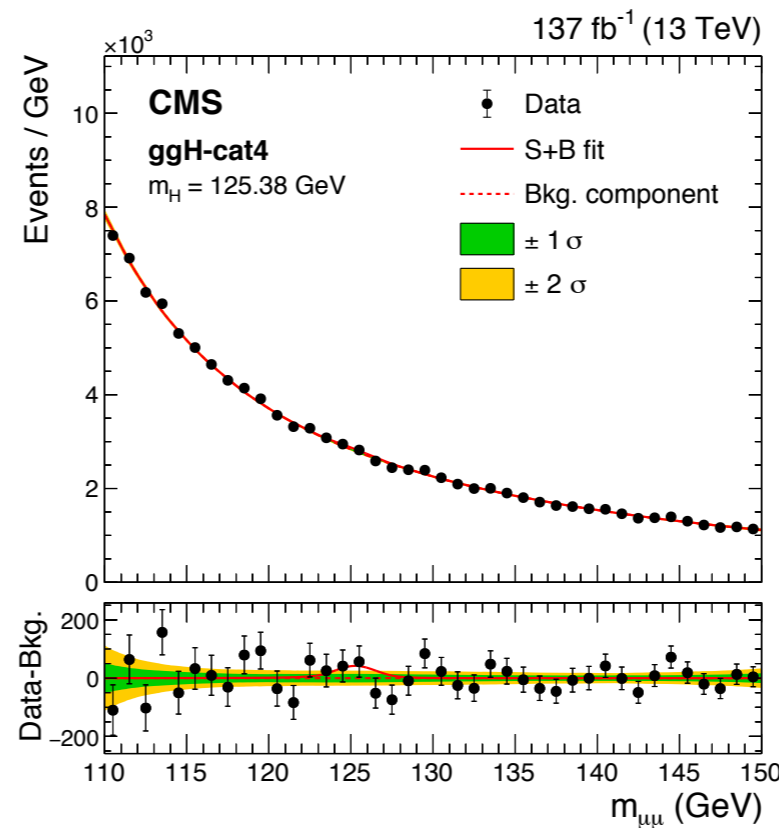
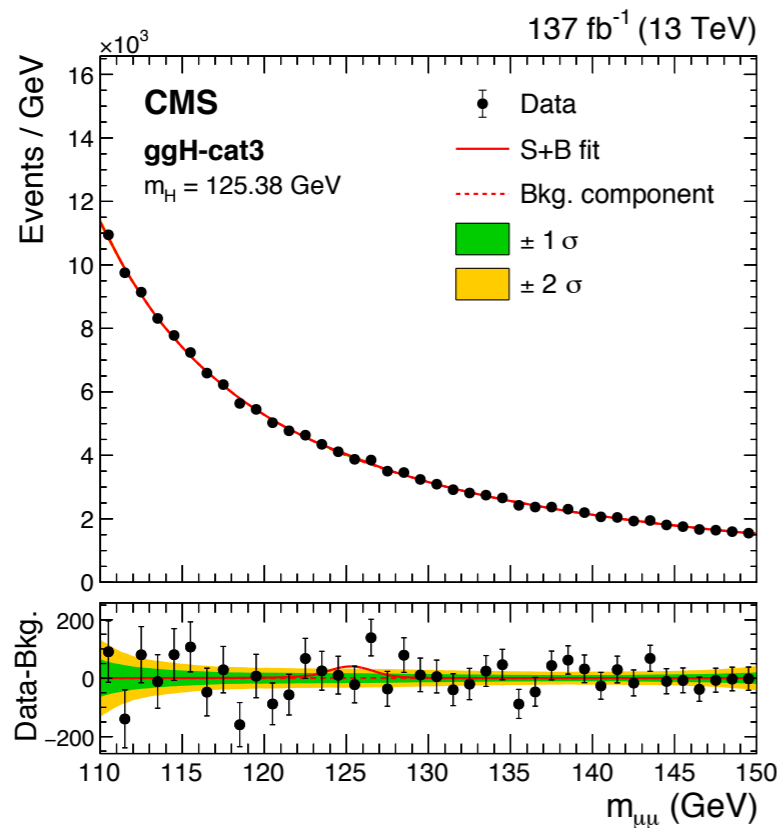
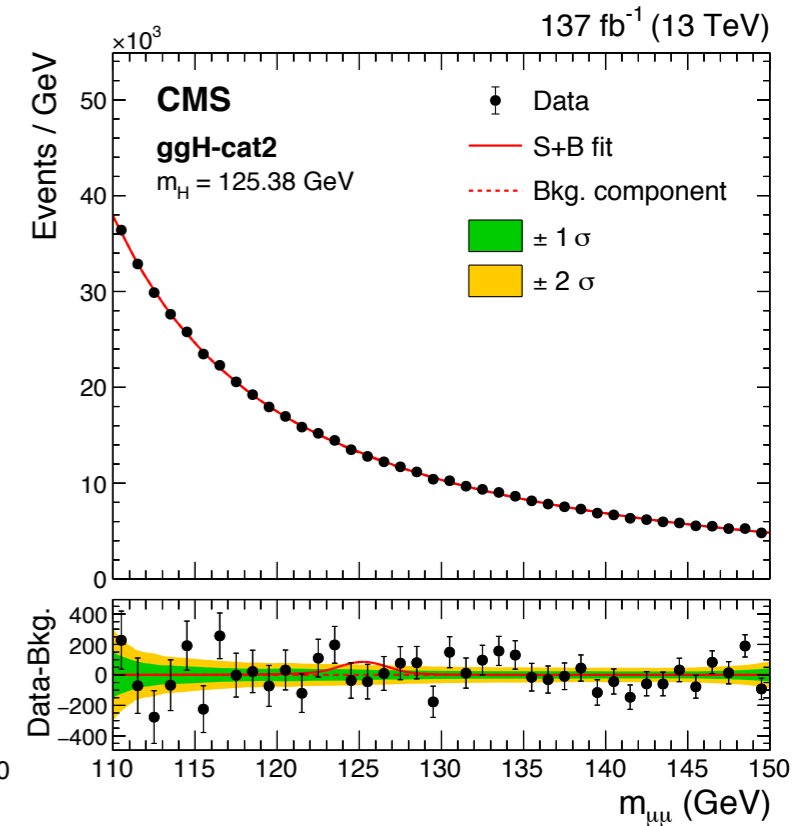
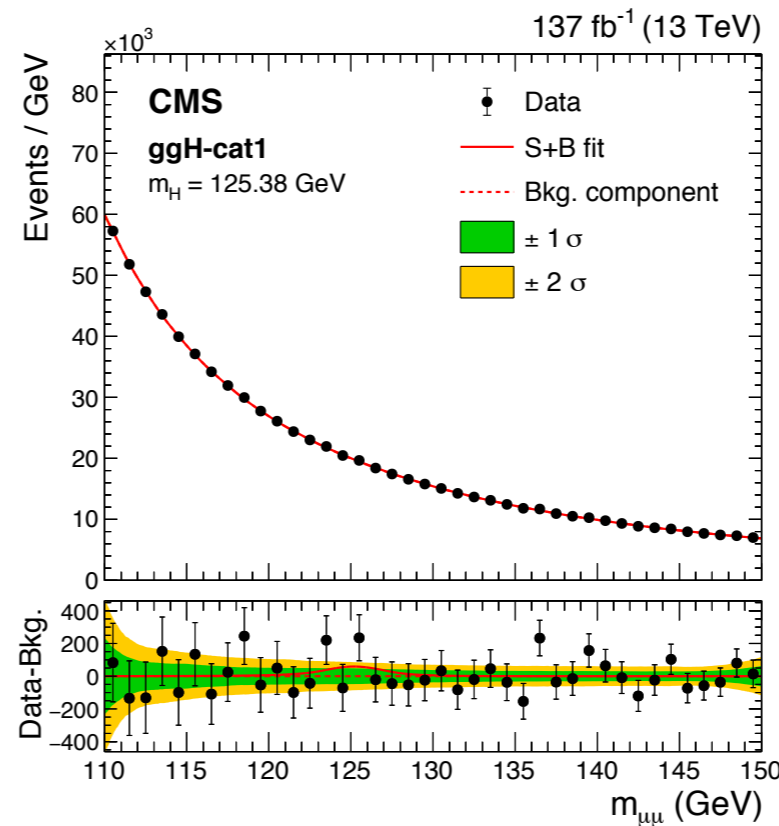
BDT subcategory boundaries optimized iteratively based on significance from full fit to MC.

137 fb⁻¹ (13 TeV)

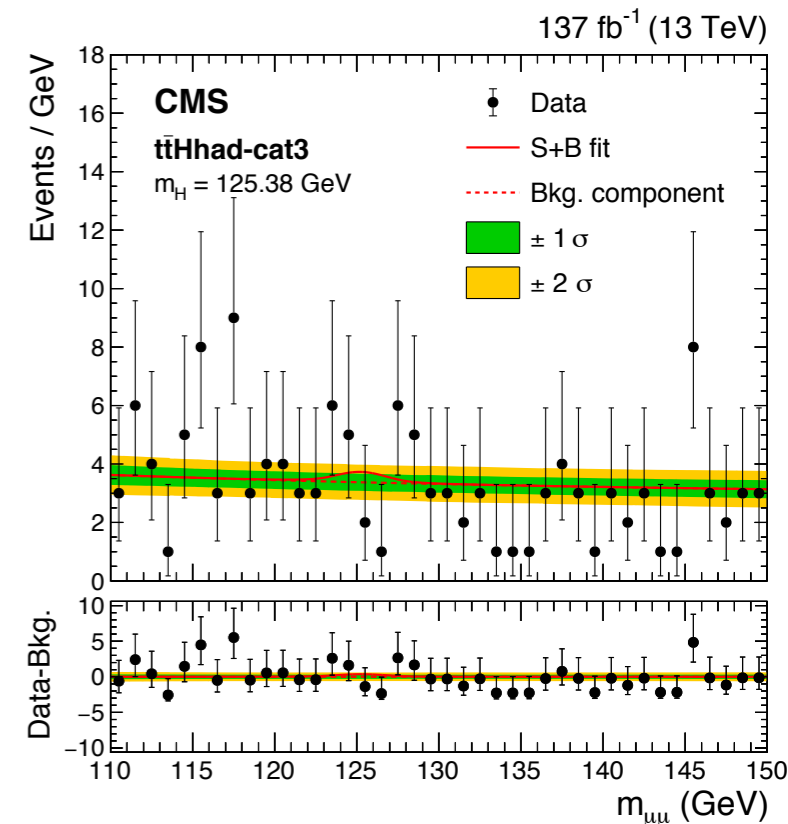
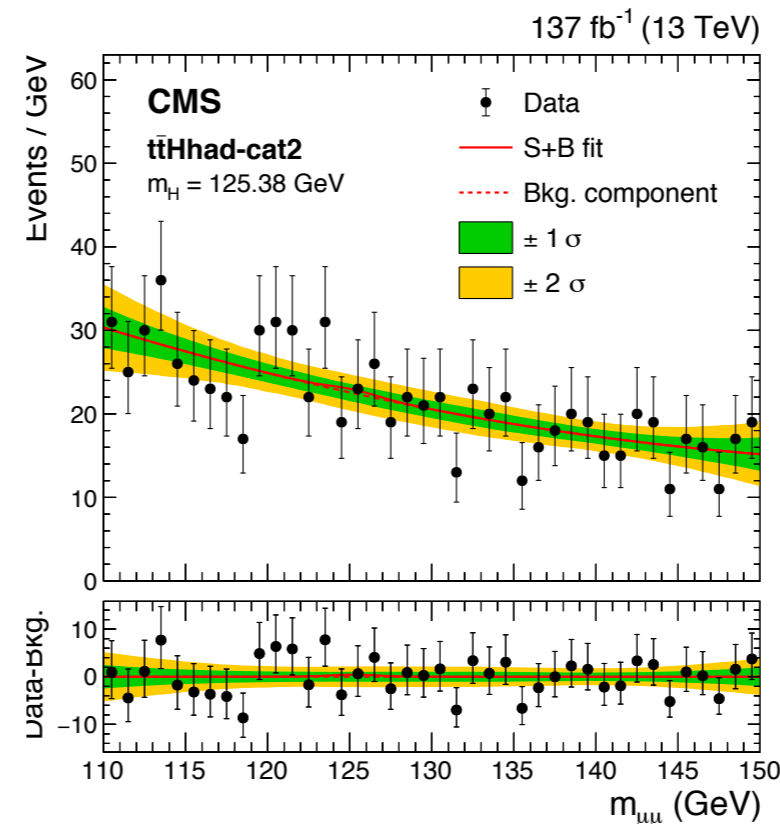
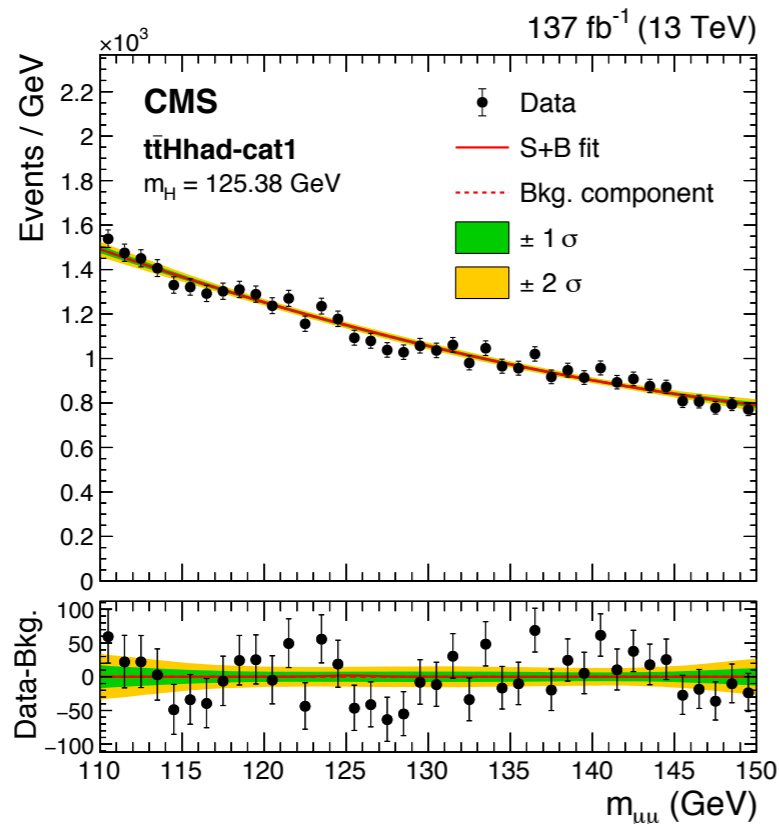
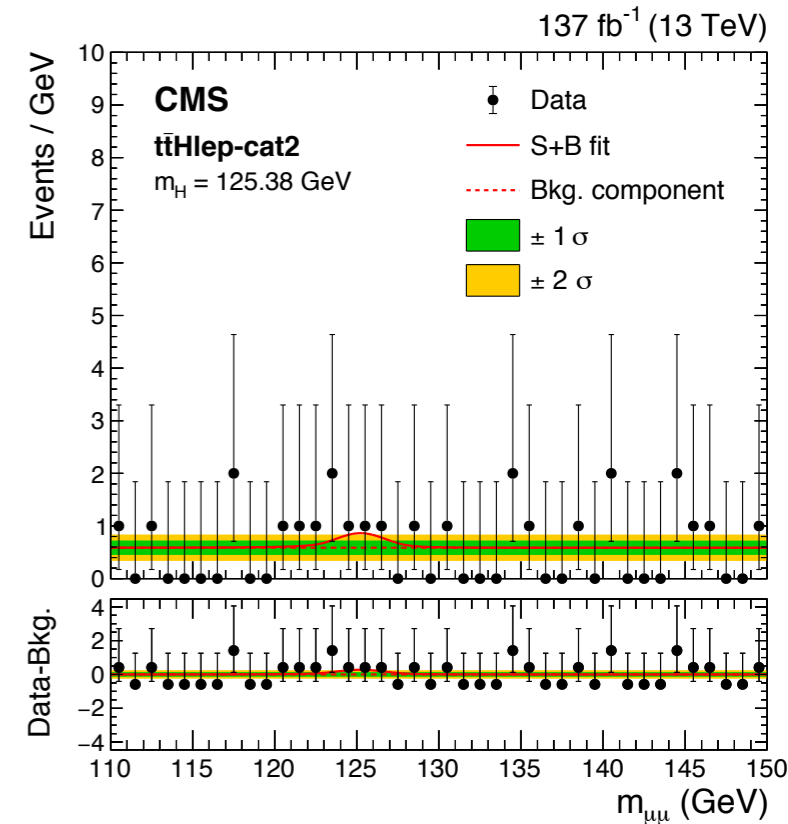
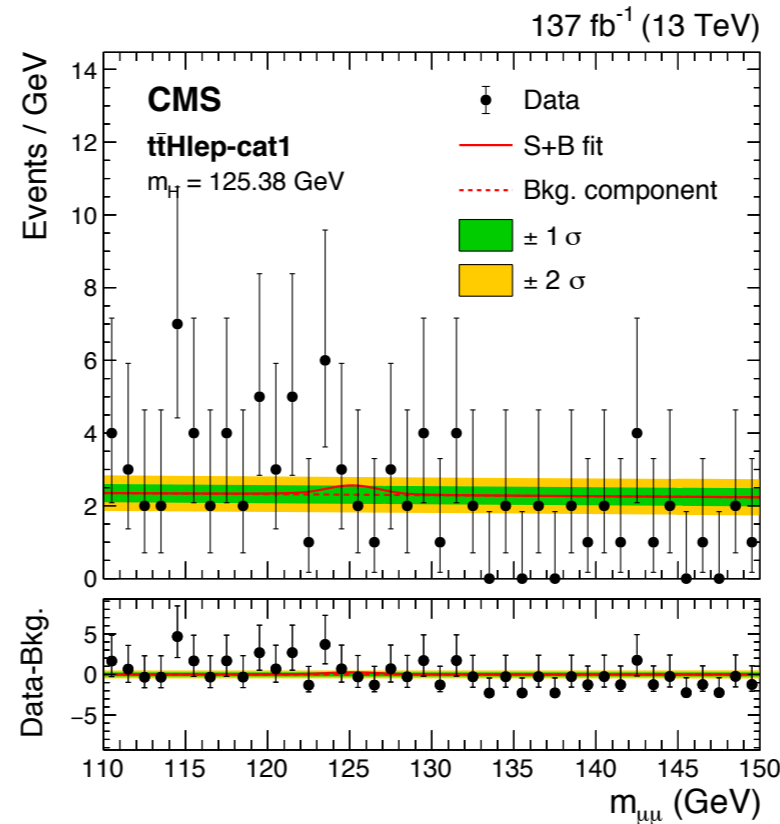
Dimuon system <ul style="list-style-type: none"> • $p_T(\mu\mu)$ • $y(\mu\mu)$ • Colin-Soper angles 	Leading jet <ul style="list-style-type: none"> • $p_T(j_1)$ • $\eta(j_1)$ • $\Delta\eta(\mu\mu, j_1)$ • $\Delta\phi(\mu\mu, j_2)$ 	Dijet system <ul style="list-style-type: none"> • $m(jj)$ • $\Delta\eta(jj)$ • $\Delta\phi(jj)$ • Zeppenfeld • $p_T(j_2)$ • $\min\text{-}\Delta\eta(\mu\mu, j)$ • $\min\text{-}\Delta\phi(\mu\mu, j)$
Single muon <ul style="list-style-type: none"> • $p_T(\mu)/m(\mu\mu)$ • $\eta(\mu)$ 	Event variables <ul style="list-style-type: none"> • N_{jets} 	



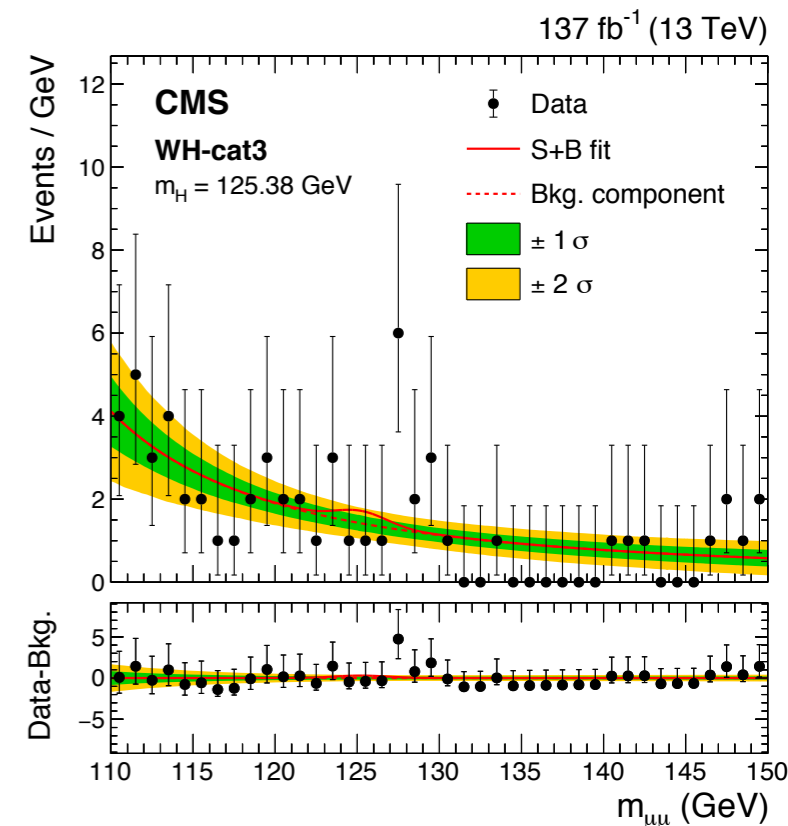
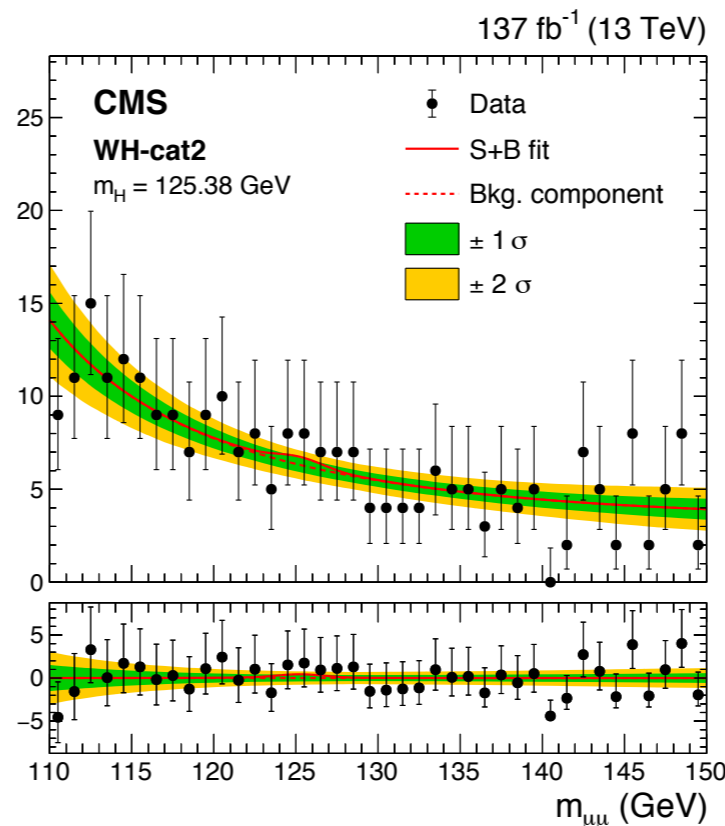
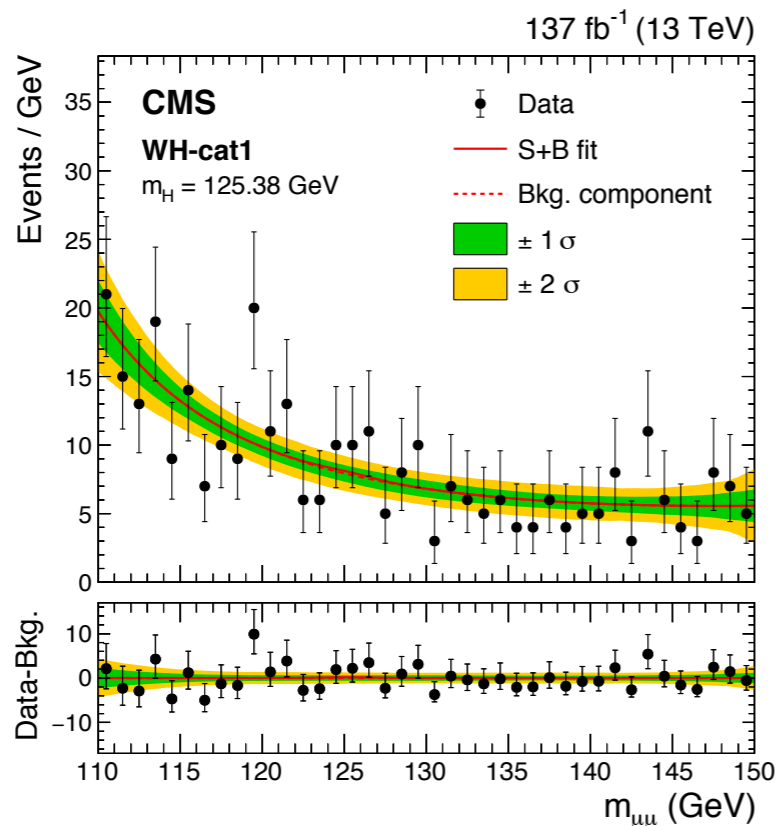
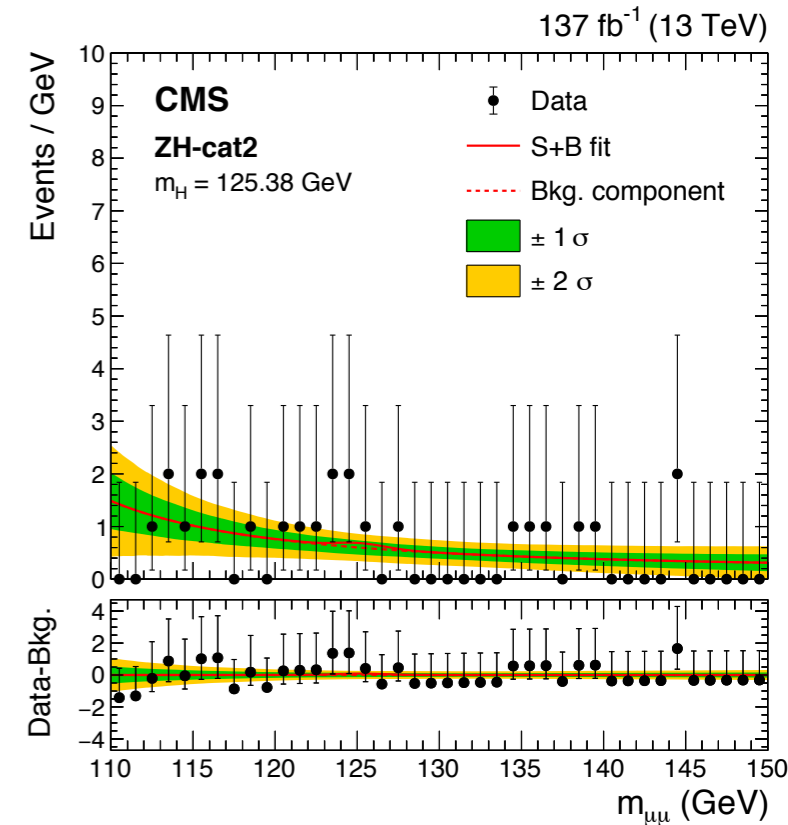
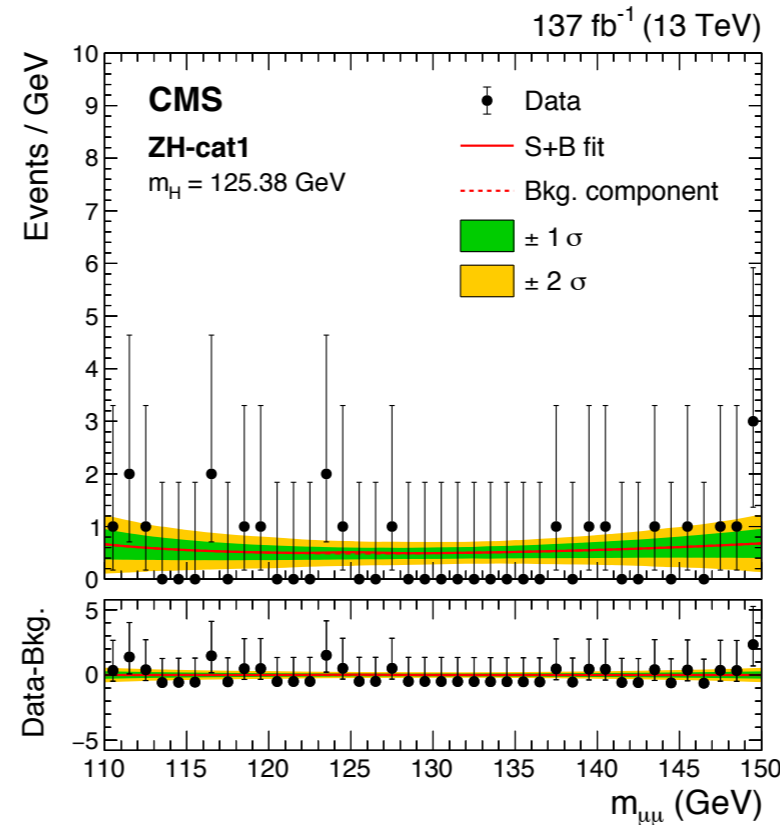
- S+B background fit describes the data well throughout the $m_{\mu\mu}$ spectrum in all categories.

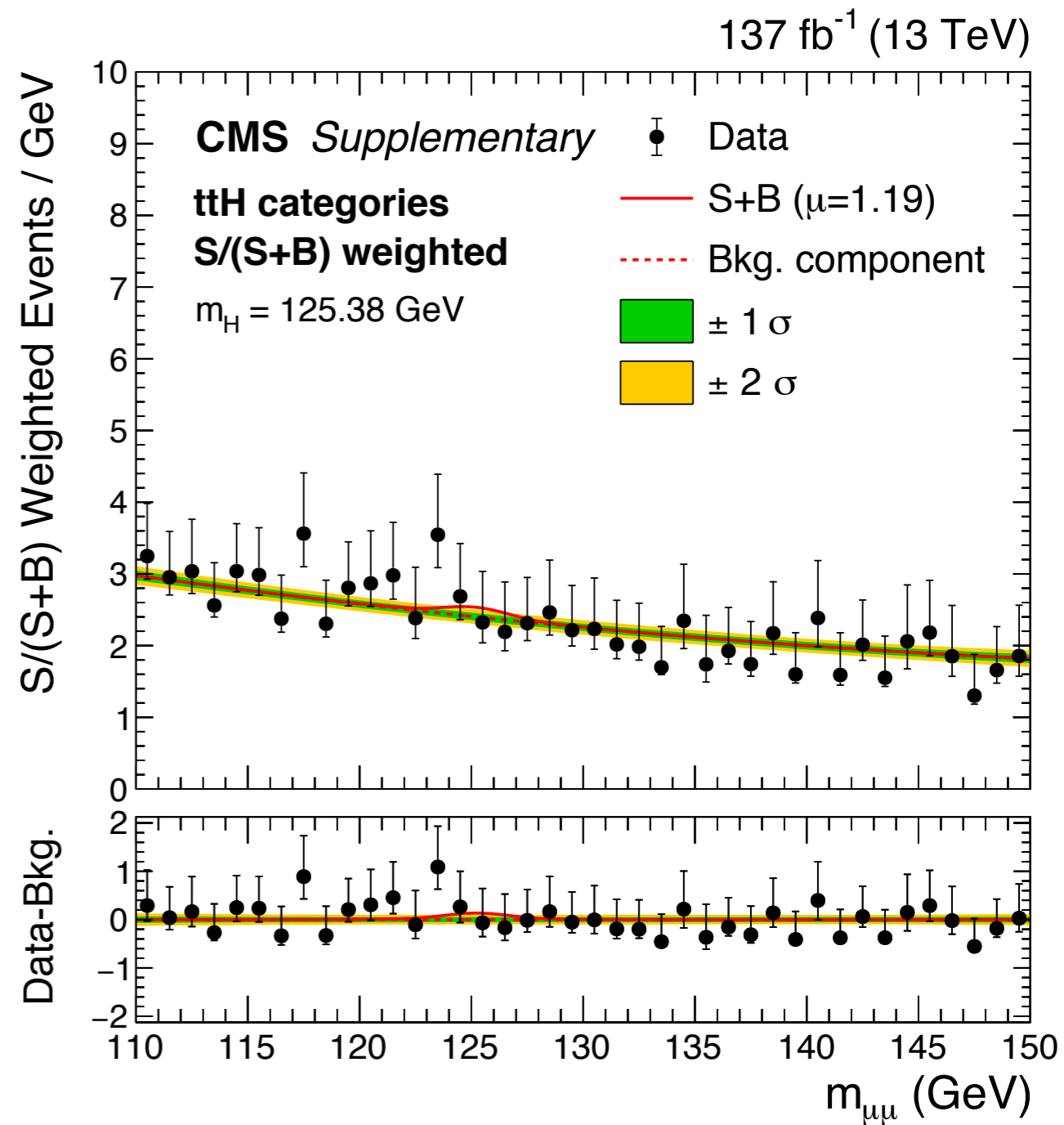
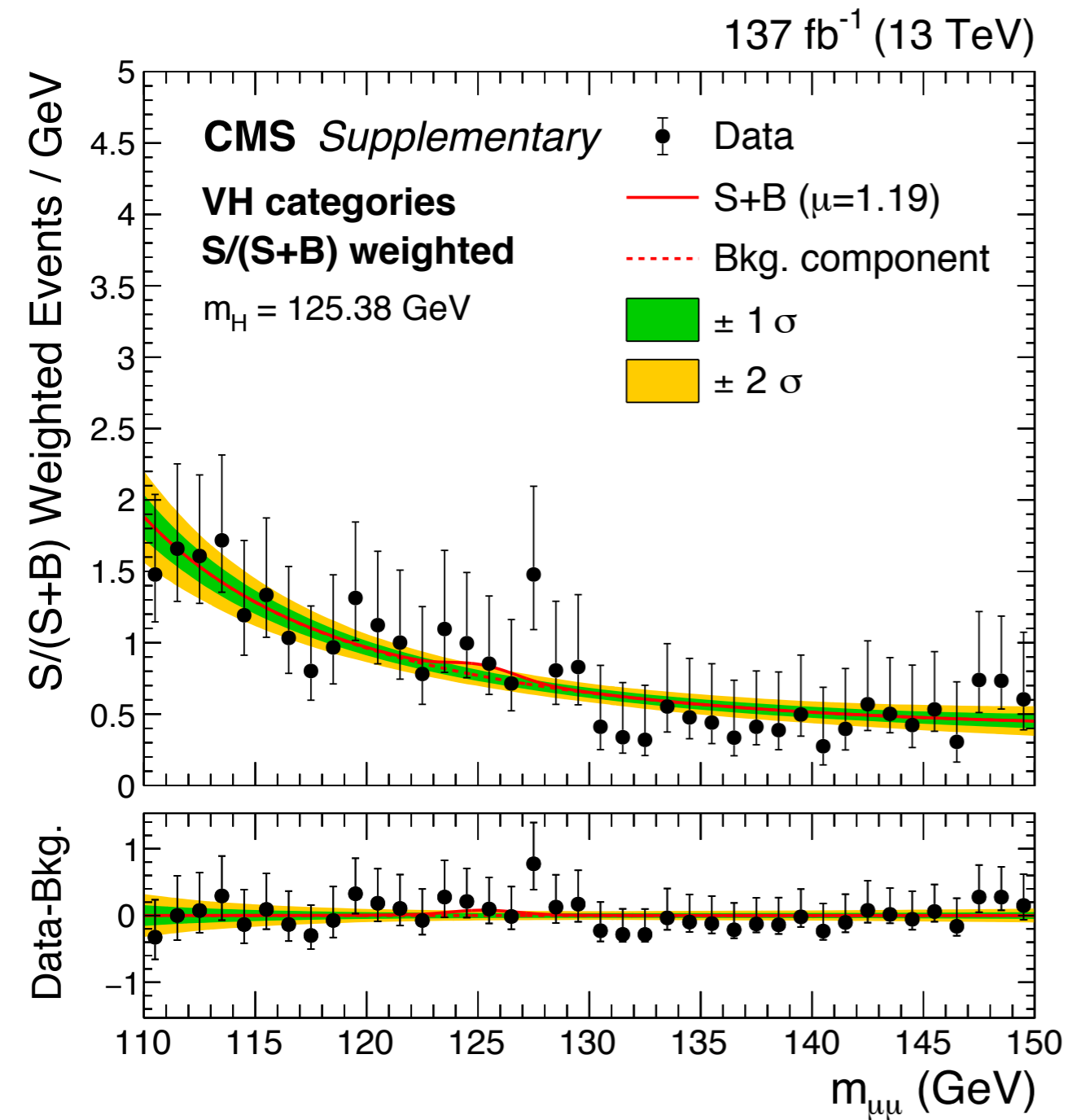


- Background fit with simple exponential (ttH-lep) or polynomial (ttH-had).
- Bias checked following similar procedure as in ggH channel.
- Categories optimized following same strategy as ggH channel.

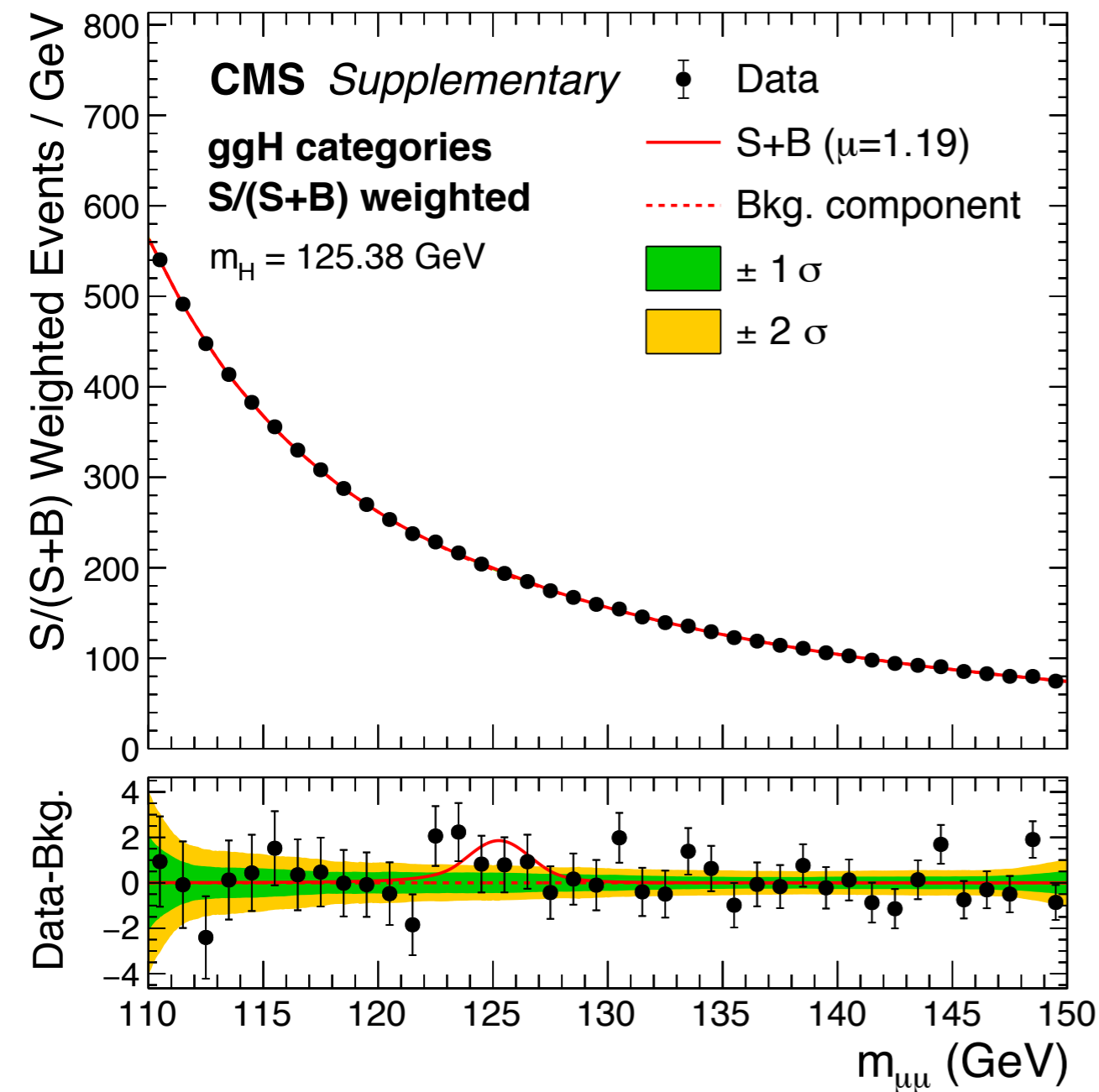


- Background fit with BWZ function.
- Choice of functions and bias studies similar to other channels.
- Small excesses in data near 125 GeV, but consistent with expectation within (large) statistical uncertainties.

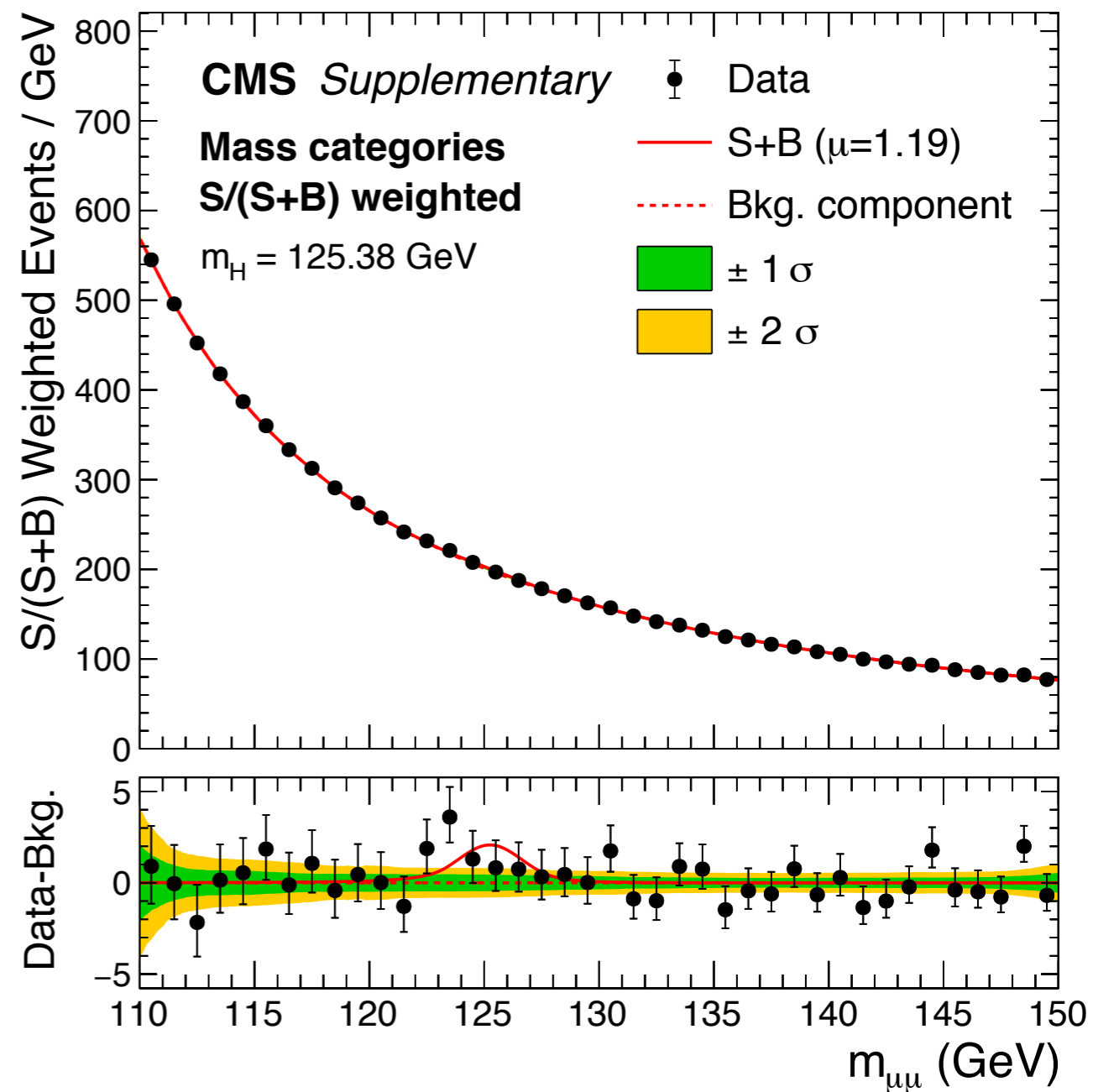




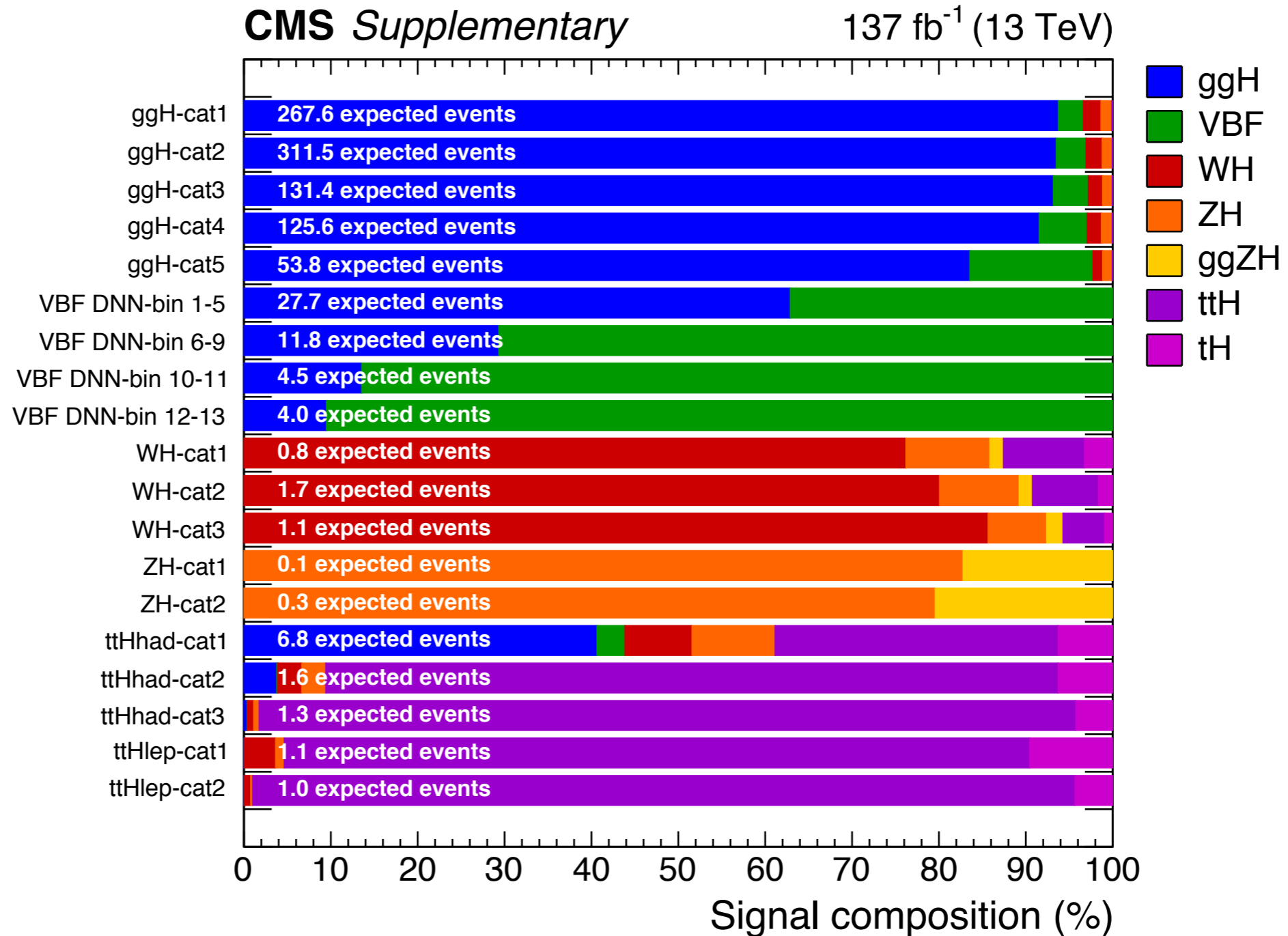
137 fb⁻¹ (13 TeV)



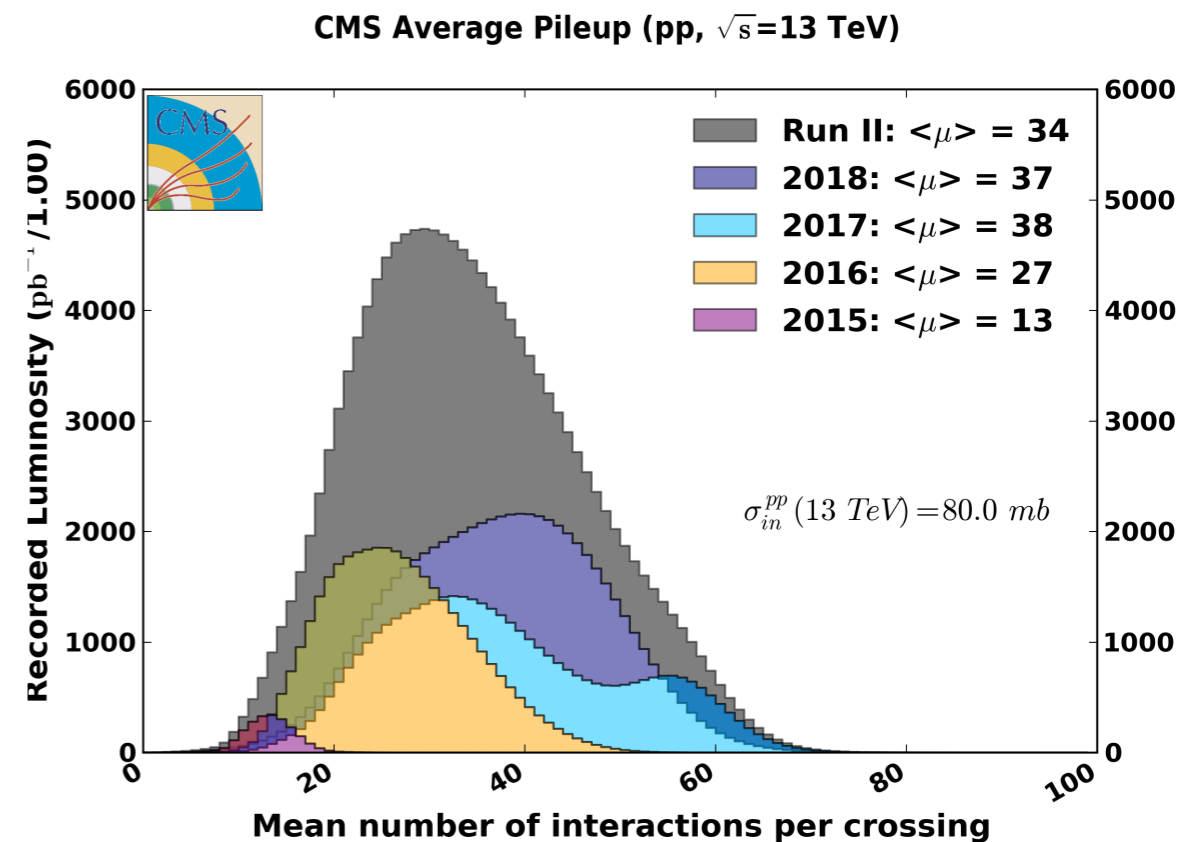
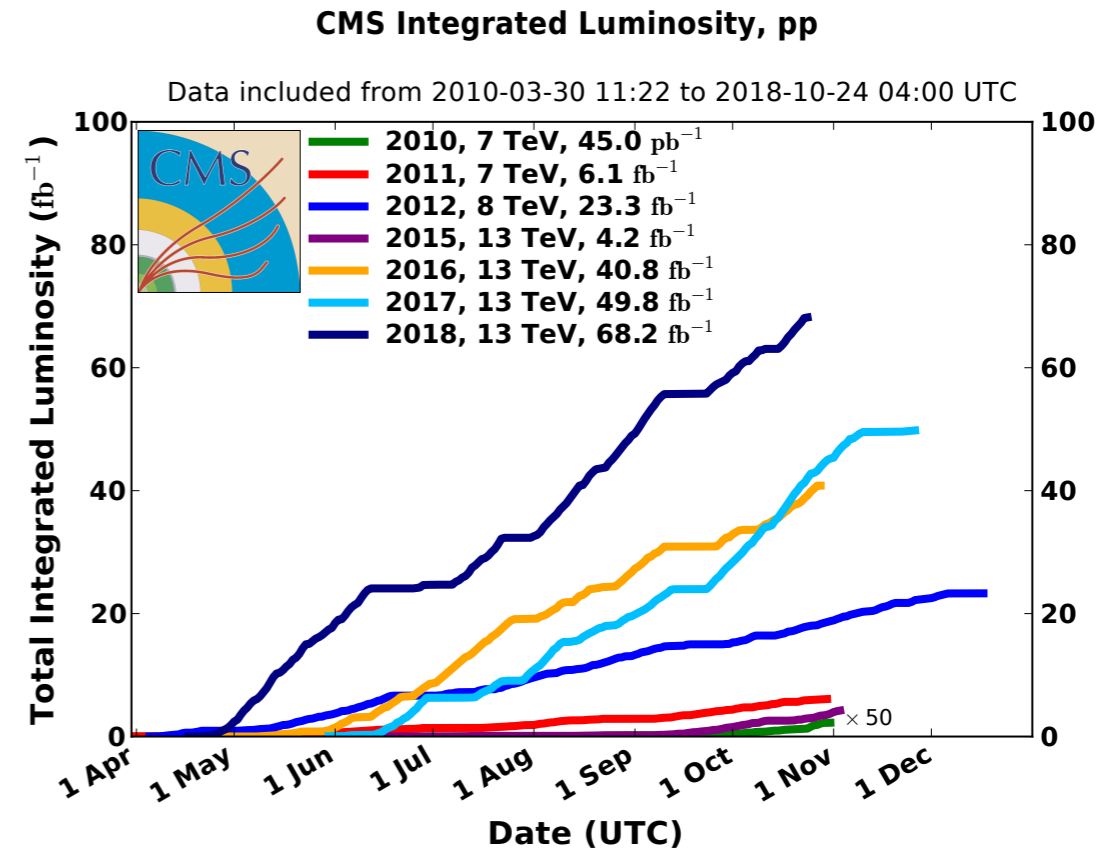
137 fb⁻¹ (13 TeV)



- Relatively high purity in targeted Higgs boson production mode achieved in each category.



- *This result focuses on 137 fb⁻¹ of 13 TeV data collected by CMS from 2016 to 2018.*
- Including new analysis of recalibrated 2016 data, which had been used for previous CMS H→μμ search.
- With excellent LHC performance comes the challenge of high rates and many simultaneous collisions (pileup).



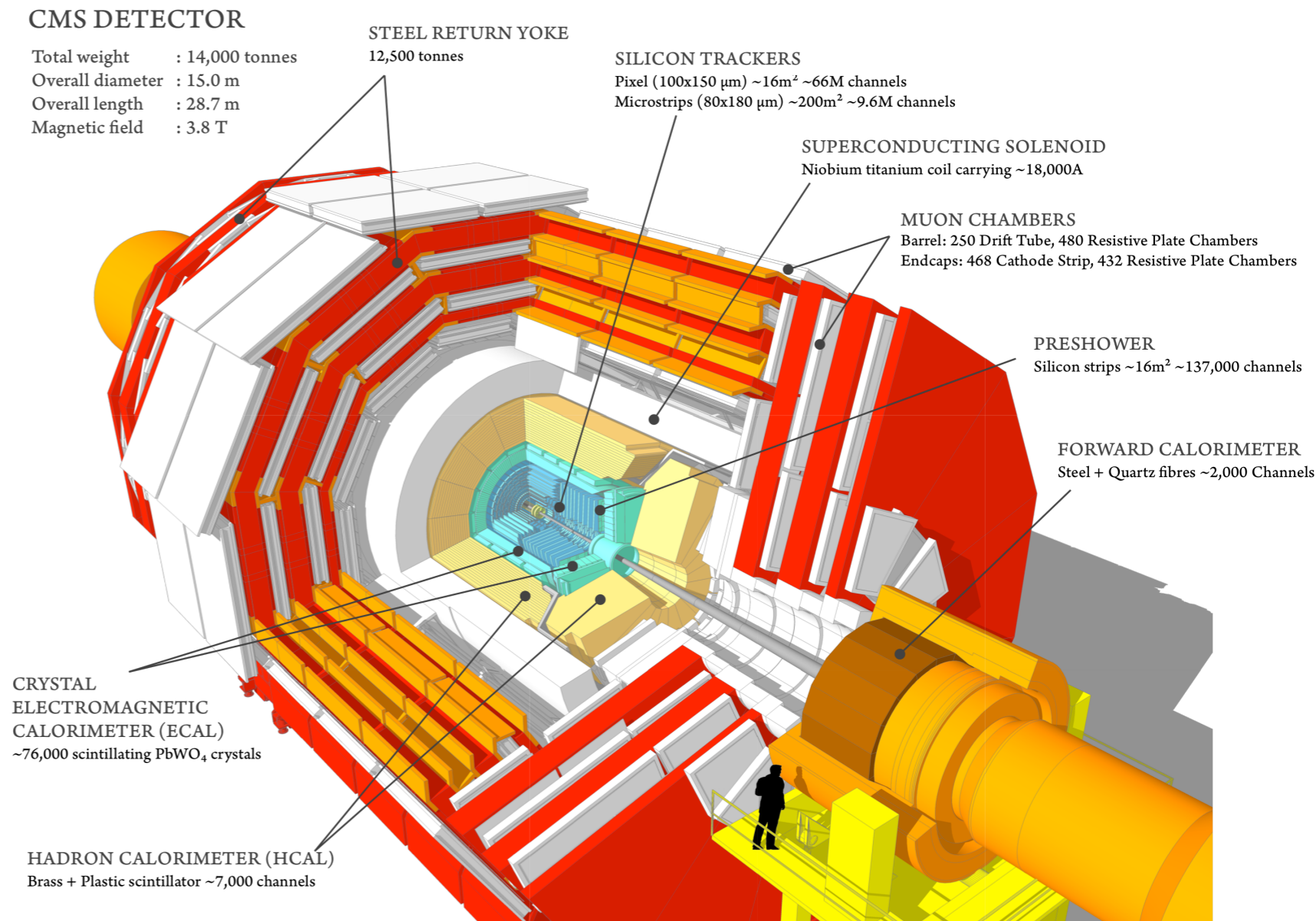
- 3.8T superconducting solenoidal magnet with 6m diameter.

- **Tracker System:** silicon strip+ pixel system which reconstructs the trajectories of charged particles.

- **Electromagnetic calorimeter (ECAL):** scintillator made from lead tungstate crystals sensitive to energy deposits from electrons and photons.

- **Hadronic calorimeter (HCAL):** brass scintillator sensitive to energy deposits from hadrons, mainly pions and kaons.

- Gas ionization chambers for **muon detection**.



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

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

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 $N_{\text{jets}} \geq 2$ $m_{jj} < 400 \text{ GeV}$ or $ \Delta\eta_{jj} < 2.5$ or $p_T(j_1) < 35 \text{ GeV}$

Event category	Total signal	ggH (%)	VBF (%)	Other (%)	HWHM (GeV)	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	S/ \sqrt{B} @HWHM
ggH-cat1	268	93.7	2.9	3.4	2.12	86 360	86 632	0.20	0.60
ggH-cat2	312	93.5	3.4	3.1	1.75	46 350	46 393	0.46	0.98
ggH-cat3	131	93.2	4.0	2.8	1.60	12 660	12 738	0.70	0.80
ggH-cat4	126	91.5	5.5	3.0	1.47	8260	8377	1.03	0.96
ggH-cat5	53.8	83.5	14.3	2.2	1.50	1680	1711	2.16	0.91

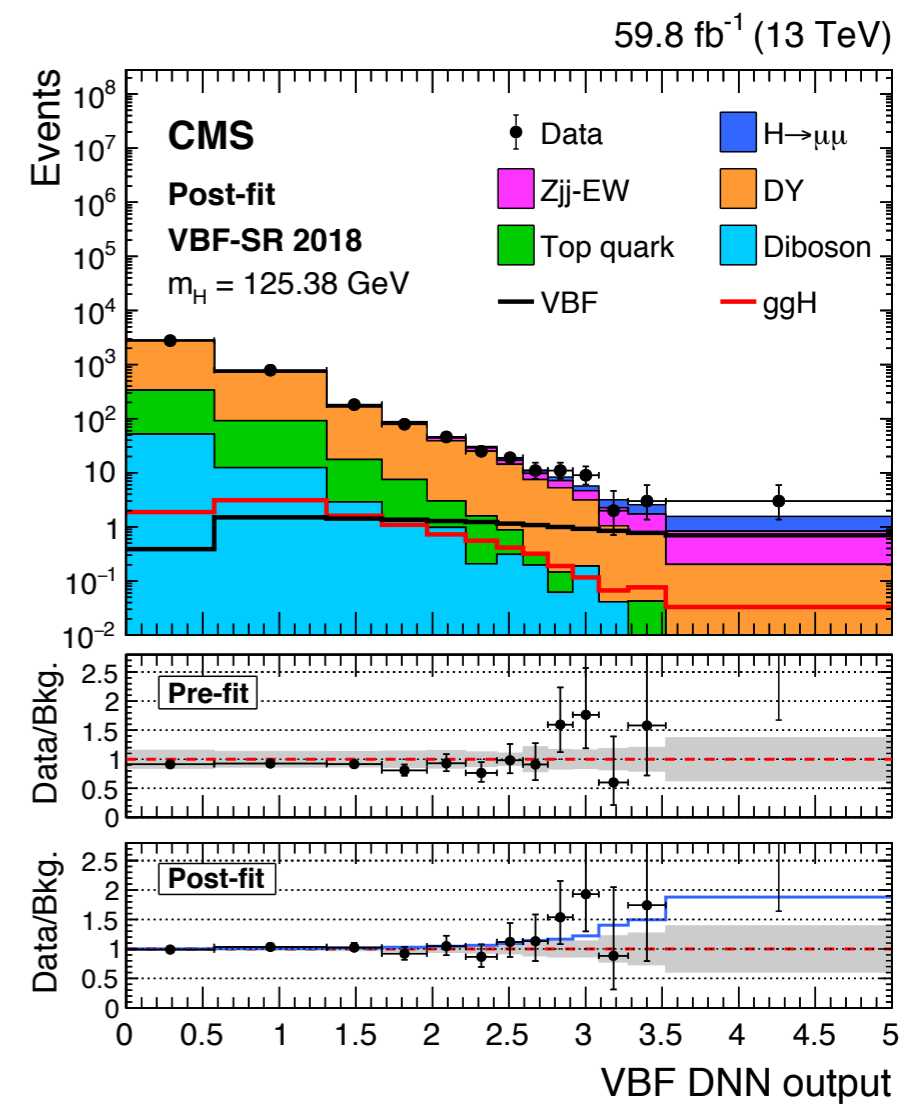
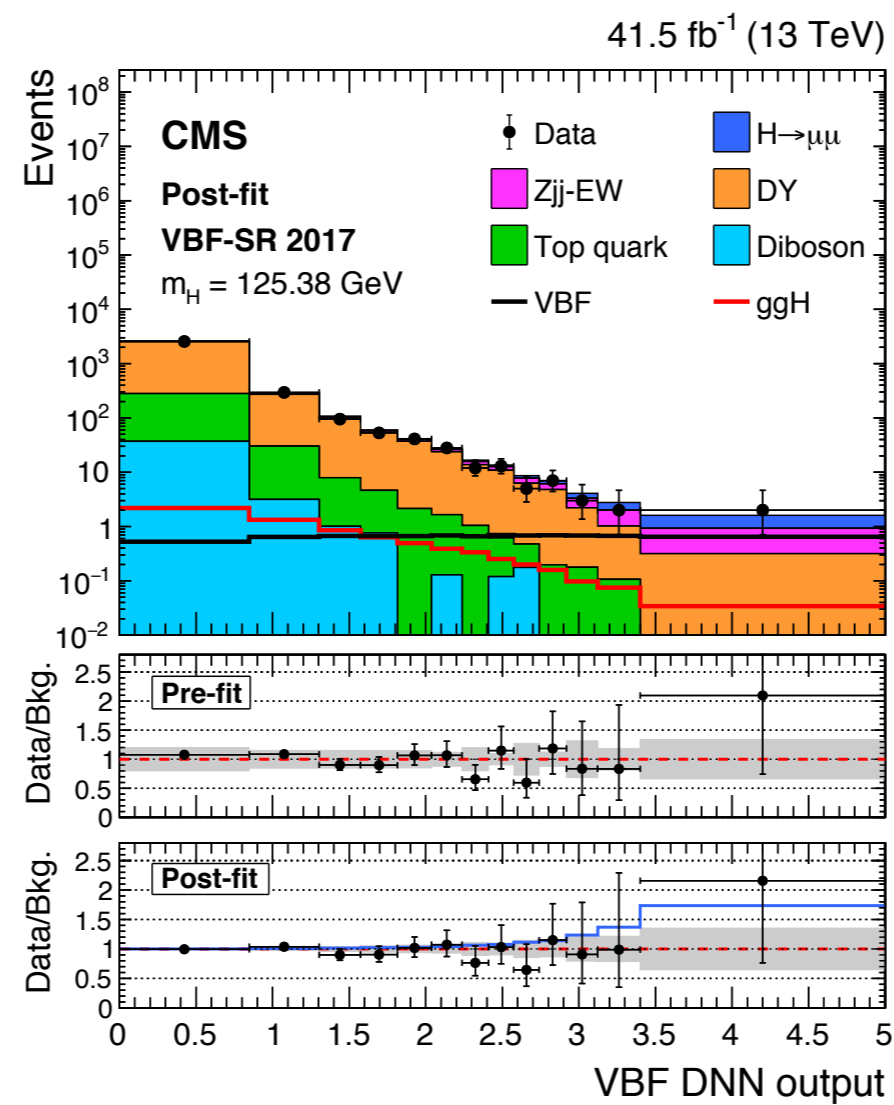
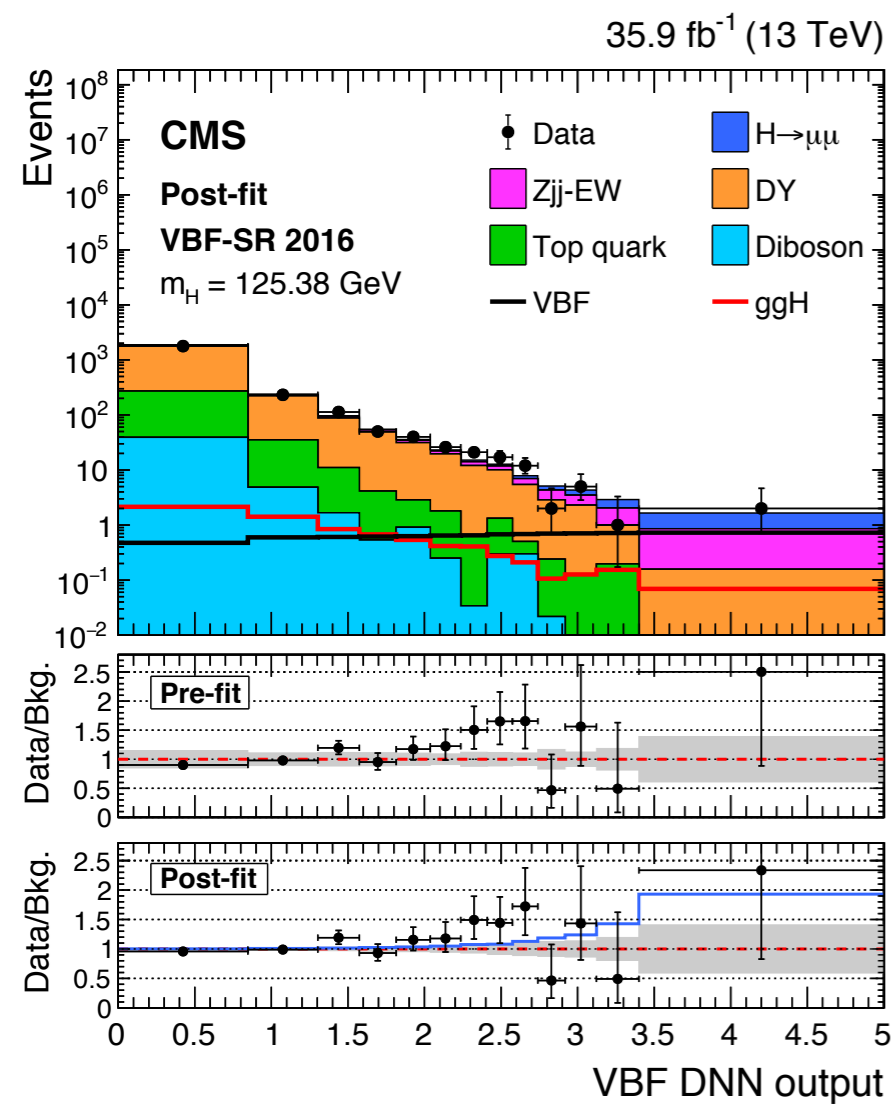
Observable	ttH hadronic	ttH leptonic
Number of b quark jets	>0 medium or >1 loose b-tagged jets	>1 loose b-tagged jets
Number of leptons ($N(\ell = \mu, e)$)	=2	=3 or 4
Lepton charge ($q(\ell)$)	$\sum q(\ell) = 0$	$N(\ell) = 3 (4) \rightarrow \sum q(\ell) = \pm 1 (0)$
Jet multiplicity ($p_T > 25 \text{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

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

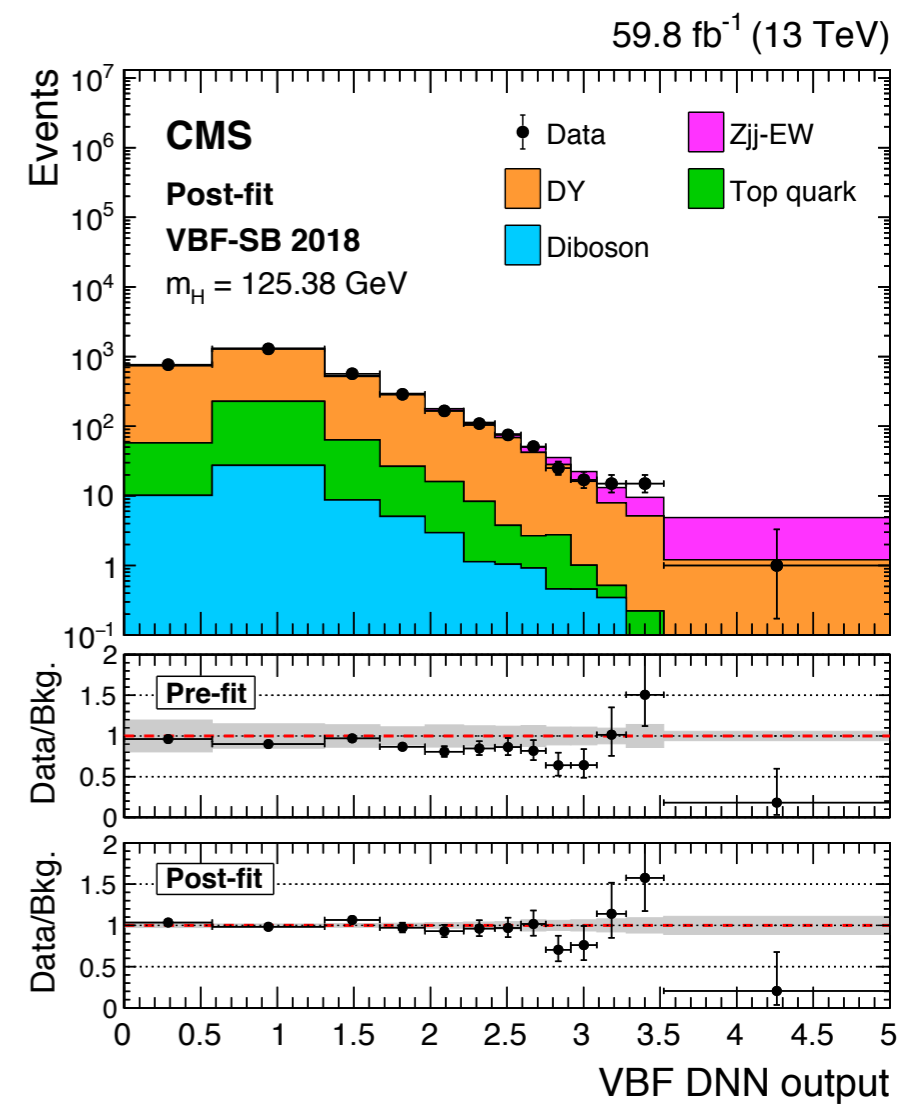
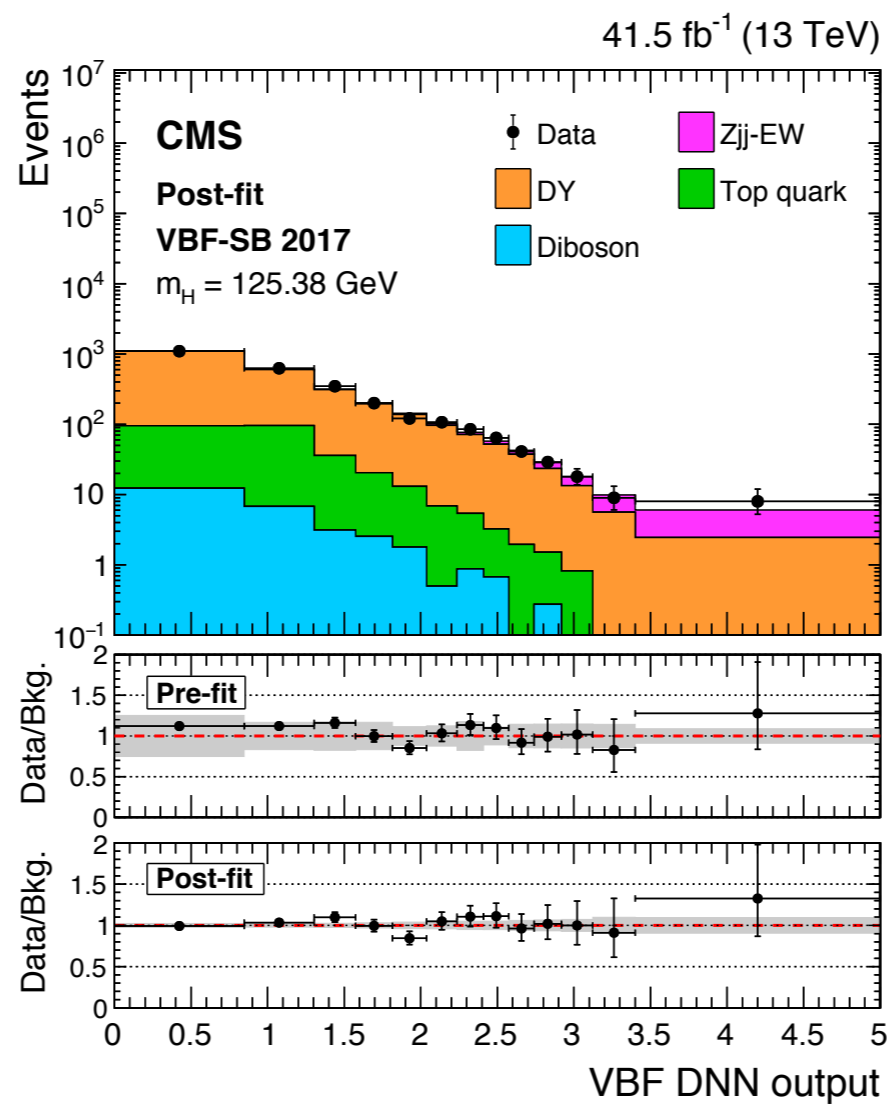
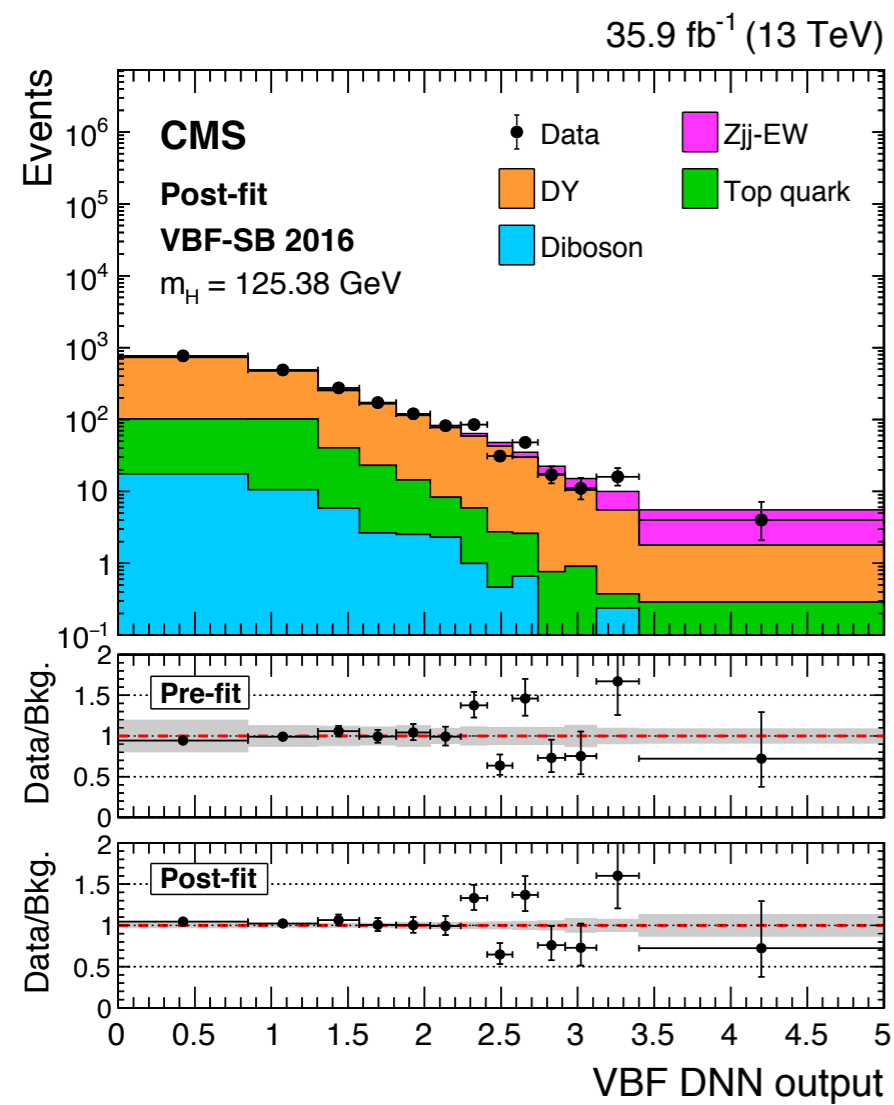
Observable	WH leptonic		ZH leptonic	
	$\mu\mu\mu$	$\mu\mu e$	4μ	$2\mu 2e$
Number of loose (medium) b-tagged jets	≤ 1 (0)	≤ 1 (0)	≤ 1 (0)	≤ 1 (0)
Number of selected muons	$= 3$	$= 2$	$= 4$	$= 2$
Number of selected electrons	$= 0$	$= 1$	$= 0$	$= 2$
Lepton charge ($q(\ell)$)	$\sum q(\ell) = \pm 1$		$\sum q(\ell) = 0$	
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}$	$= 0$	$= 0$	$= 1$	$= 1$

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	BWZ γ	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

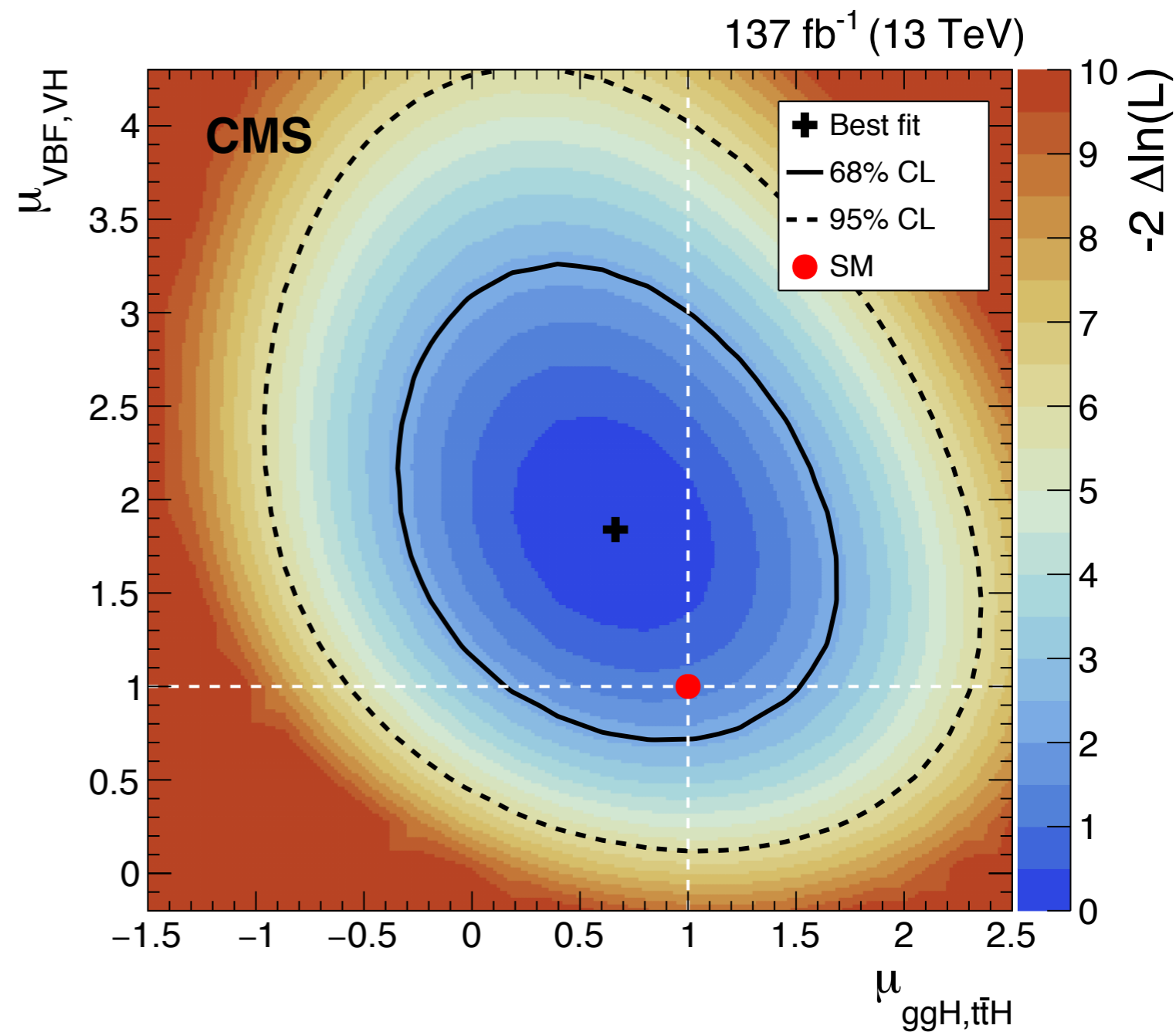
VBF signal region,
 $115 < m(\mu\mu) < 135 \text{ GeV}$



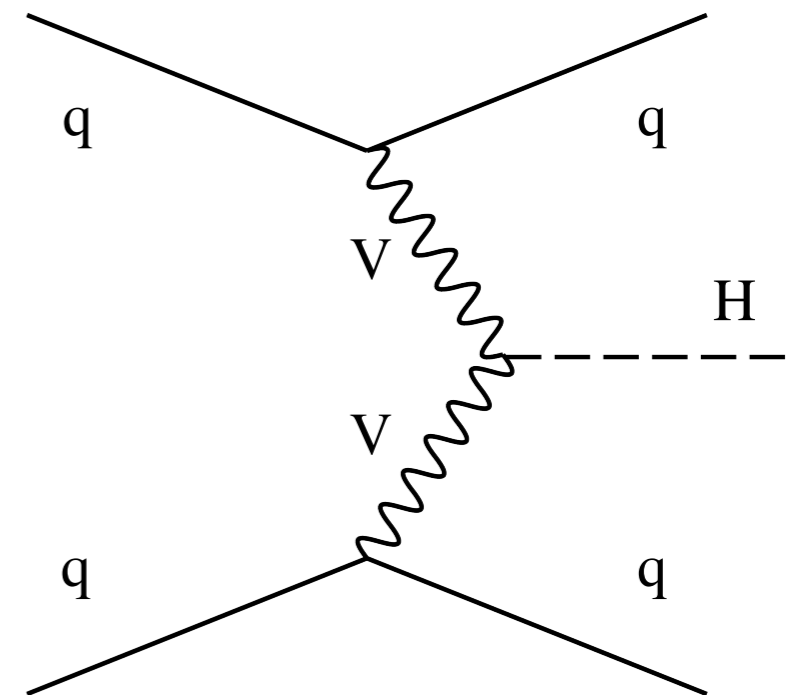
VBF mass sideband,
 $110 < m(\mu\mu) < 115 \text{ GeV}$,
 $135 < m(\mu\mu) < 150 \text{ GeV}$



- Independent fit for Higgs boson production channels sensitive to vector boson couplings (VBF, VH) and top quark coupling (ggH, ttH).
- Result well consistent with SM within uncertainties.

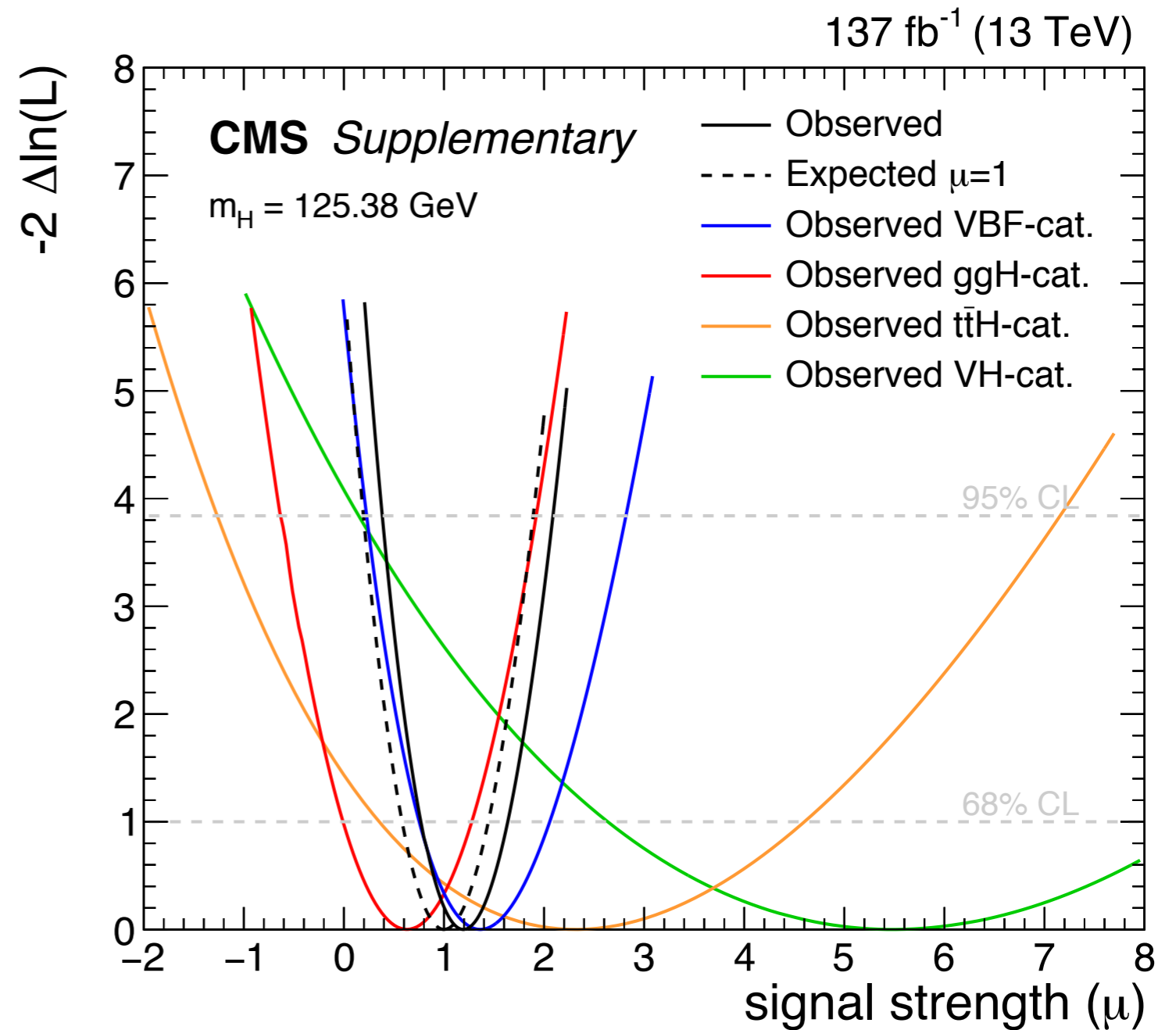


- VBF process incoming and outgoing quark lines are color-connected (pure EW exchange).
- Until recently, PYTHIA did not account for this effect (default “global recoil” scheme).
 - “Dipole recoil” scheme recently implemented into PYTHIA that takes this effect into account.
 - Herwig7 default angular-ordered shower considers effect similar to PYTHIA with dipole recoil.
- Private VBF $H \rightarrow \mu\mu$ signal samples generated with PYTHIA dipole recoil (nominal prediction) and HERWIG7 (to assess systematic uncertainty).

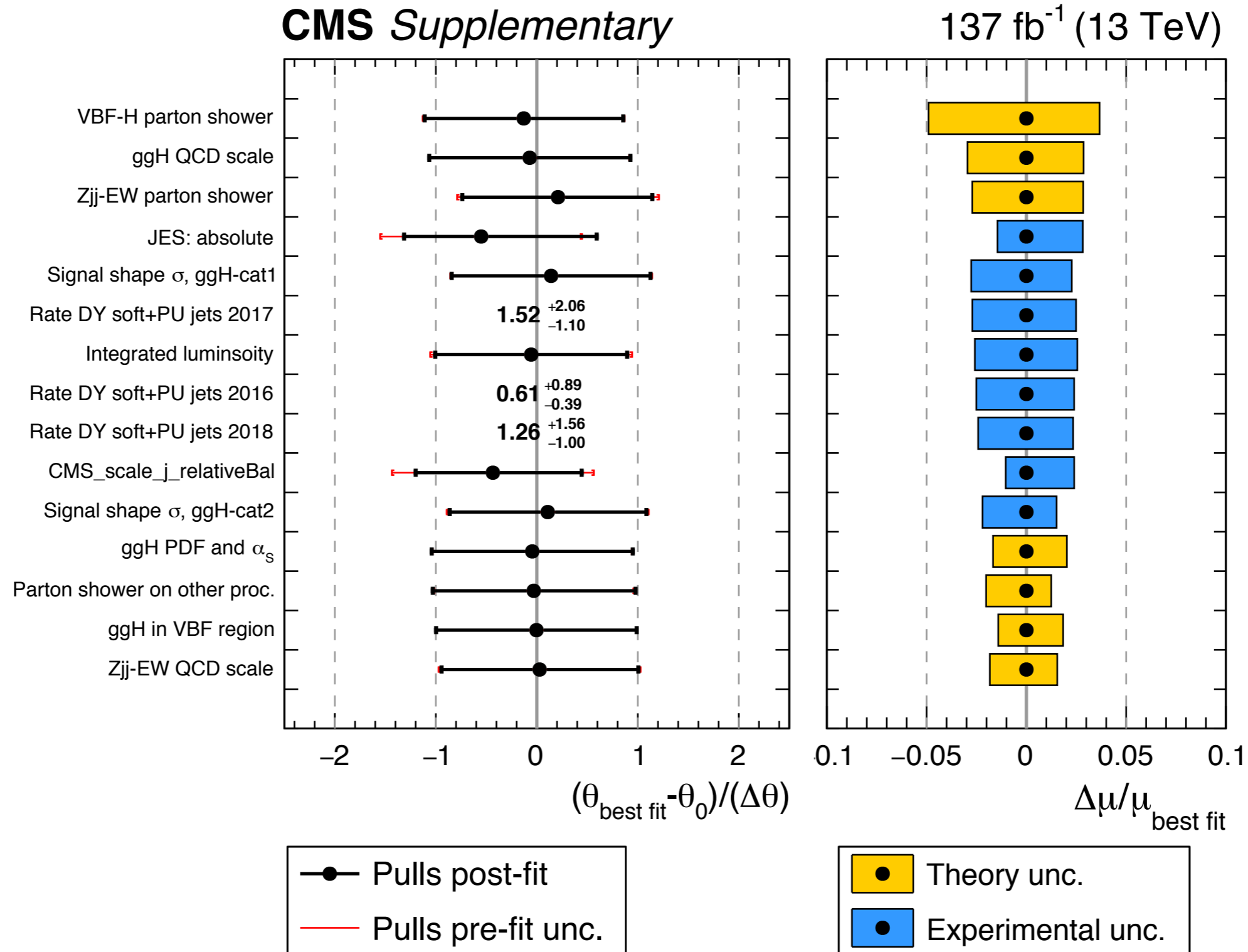


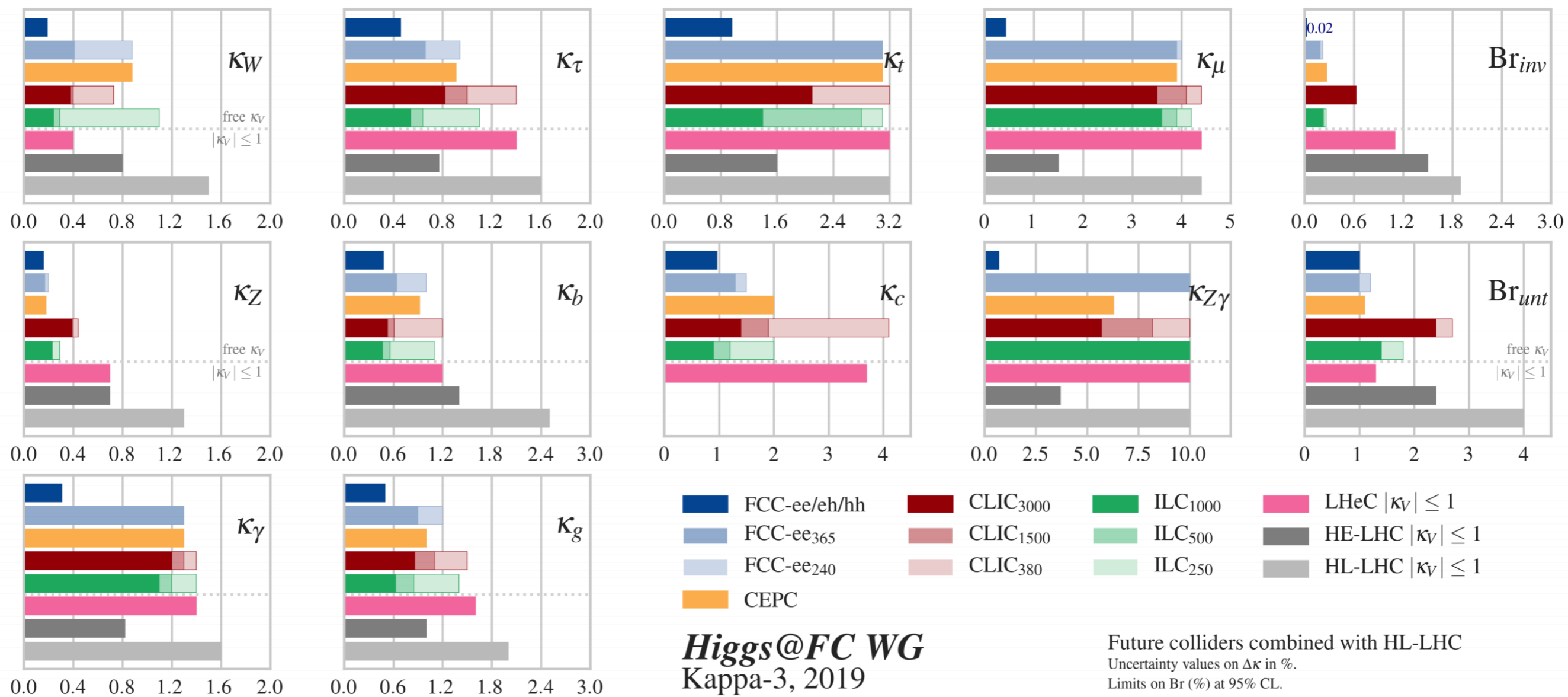
*discussed within VBF HXSWG and recent dedicated theory paper [arXiv:2003.12435](https://arxiv.org/abs/2003.12435)

- Observed log-likelihood ratios as a function of signal strength for the combined result as well as the individual channels.
- For the combination, also the expected likelihood shape with $\mu = 1$ signal injected.



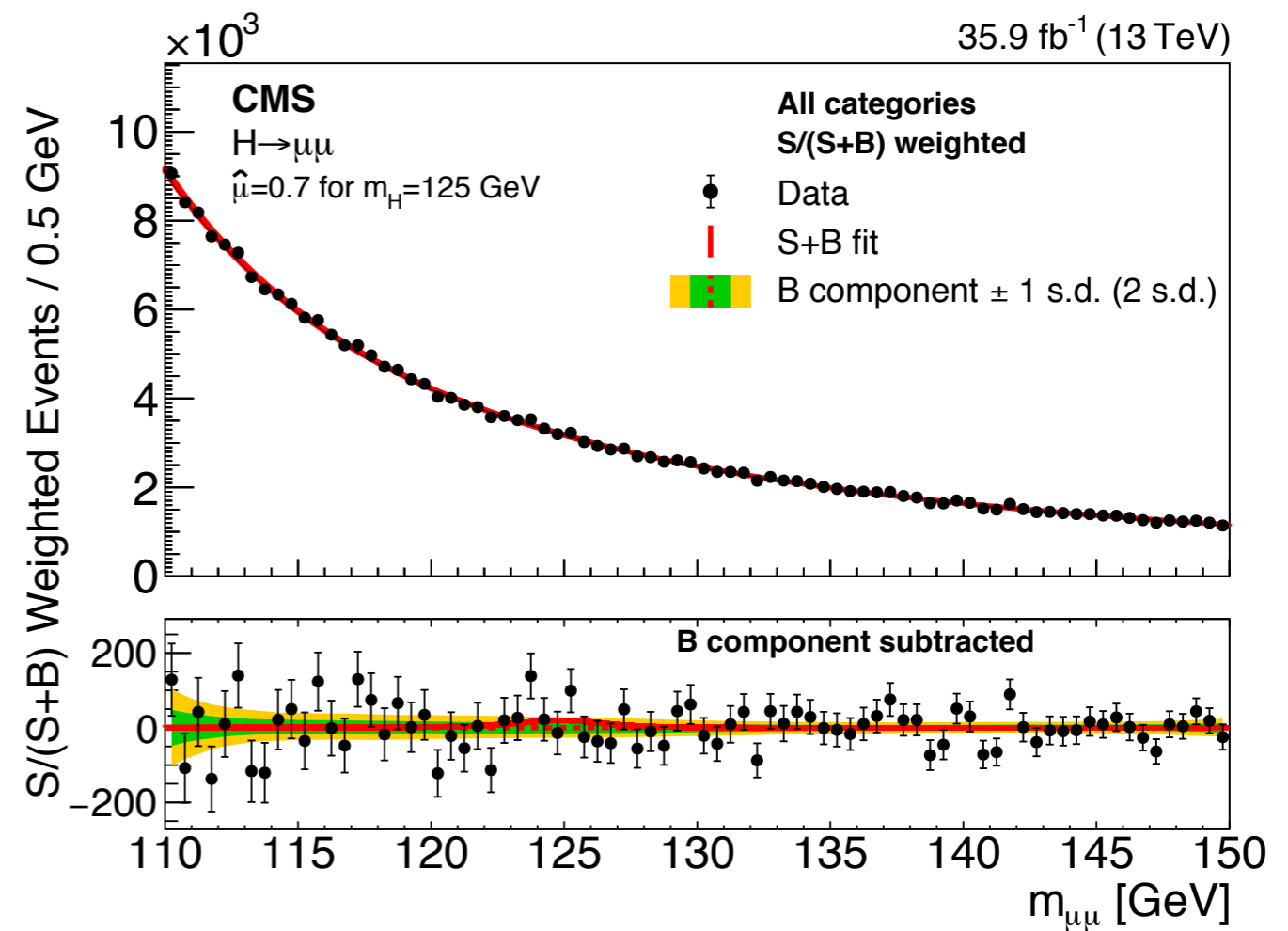
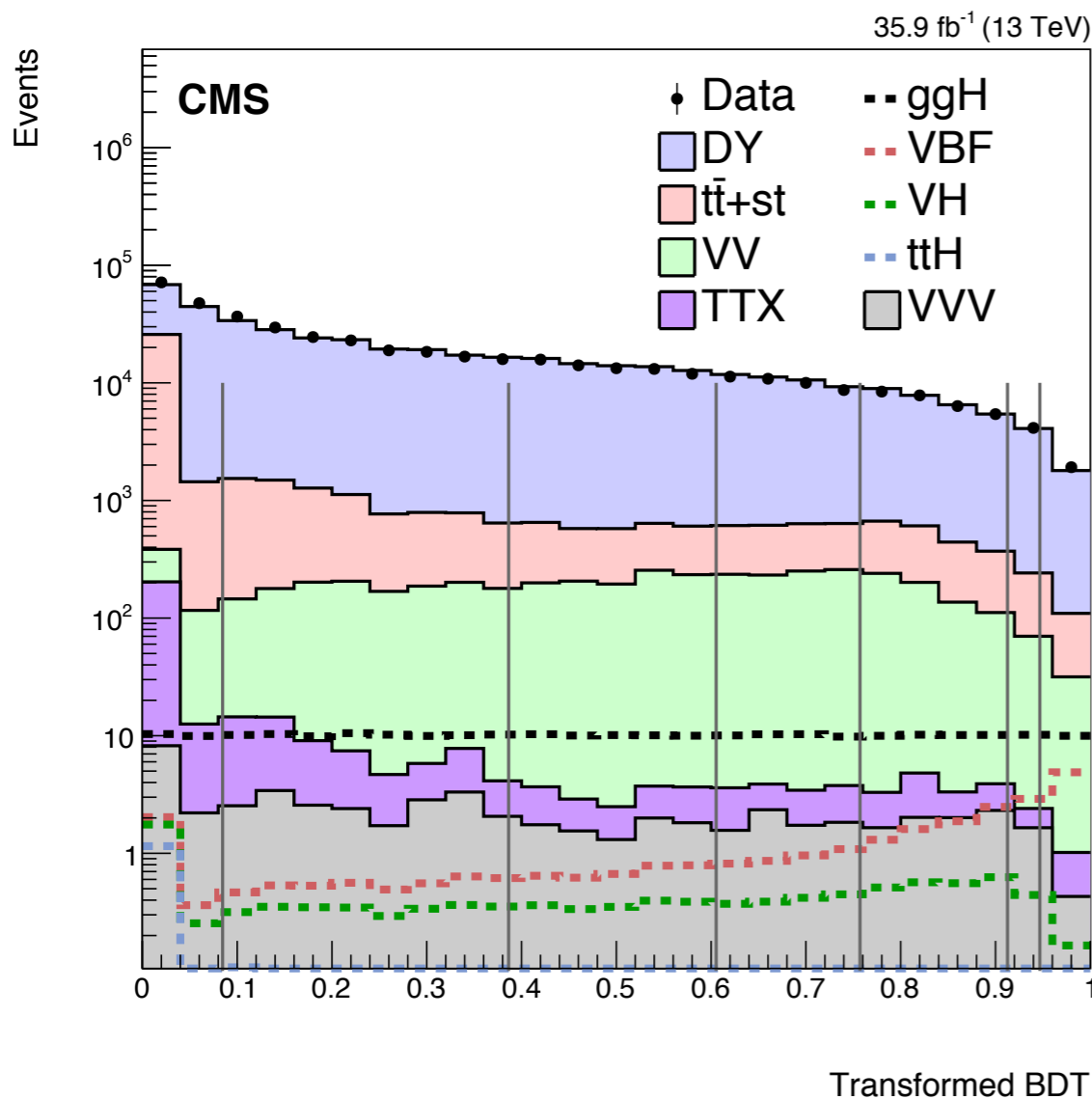
Overall impact of systematics uncertainties on measurement is a few percent.





[From Physics Briefing Book](#)

- With 35.9 fb⁻¹ 13 TeV data:
- Observed (expected) significance 0.6 (0.9) σ , signal strength $\mu = 0.7 \pm 1.0$
- Combined with 7 and 8 TeV data:
- Observed (expected) significance 0.9 (1.0) σ , signal strength $\mu = 1.0 \pm 1.0$



- SingleMuon primary data sets used by all channels.
- Background simulation (specifically requested for $H \rightarrow \mu\mu$):
 - DY Madgraph samples at NLO with $m(\mu\mu)$ [105,160] GeV filter, including set of VBF-enriched ($m_{jj,GEN} > 350$ GeV) samples.
 - VBF Z Madgraph samples at LO with Herwig PS* and $m(\mu\mu)$ [105,160] GeV filter.
 - Detailed studies of stability of prediction vs. Madgraph version and $p_T(j)$ minimum threshold.
- Signal simulation:
 - ggH signal: MG_aMC at NLO with up to two partons in final state at ME level
 - VBF signal: POWHEG interfaced with PYTHIA parton shower with dipole recoil shower (more details in backup)
 - VH, ttH signal: POWHEG + PYTHIA PS

*as studied extensively in CMS VBF Z measurement:

[Eur. Phys. J. C 78 \(2018\) 589](#)

*highlighting just the most relevant MC samples used

Muons

- Muons passing medium ID and loose PF isolation.
- $p_T > 26-29$ (20) GeV, $|\eta| < 2.4$
- Momentum scale and resolution calibration with Rochester corrections.
- FSR recovery: strategy inspired by H(4l) and optimized for $H \rightarrow \mu\mu$.
 - Negligible $H \rightarrow Z\gamma$
- GeoFit correction: using beam spot as additional track constraint to improve resolution.
 - 3-10% improvement in $\sigma(m_{\mu\mu})$.

Jets

- AK4 CHS jets with $p_T > 25$ GeV and $|\eta| < 4.7$
- Loose (tight) jet ID in 2016 (2017/2018).
- Loose pileup jet ID for jets with $p_T < 50$ GeV.
- Dedicated 2017 pileup jet ID training \Rightarrow 15% improvement in 2017 signal efficiency.
- Latest JEC applied, JER not applied but used for systematic uncertainty.

Electrons

- $p_T > 20$ GeV and $|\eta| < 2.5$
- Passing MVA ID WP90

B-tagging

- $p_T > 25$ GeV and $|\eta| < 2.5$
- Passing DeepCSV loose or medium WPs.

Pileup re-weight

- Applied taking the certified pileup profile in data
- **Uncertainty** estimated by varying the minimum bias cross section

L1 prefiring

- In 2016/17, **mis-timed ECAL TPs** lead to inefficiency in the L1 trigger
- **Corrections** measured from a set of **unpreferable events** by JetMET
- **Corrections applied** in the analysis and **only relevant for VBF channel**

DY $p_T(Z)$ spectrum

- DY MC poorly describe the data for $p_T(\mu\mu) < 40$ GeV
- This is due to **missing resummation** effects [[10.1007/JHEP12\(2019\)061](https://arxiv.org/abs/10.1007/JHEP12(2019)061)]
- **Reweighting** performed using **data** with **70 < m($\mu\mu$) < 110 GeV**, as a function of $p_T(\mu\mu)$ and N_{jets}

ggH $p_T(H)$ spectrum

- **Reweighed to NNLOPS** in bins of N_{jets} at the generator level