Search for Higgs boson decaying to muon pair at LHC

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Thanks to Stephane Cooperstein (UCSD) for very helpful discussions!

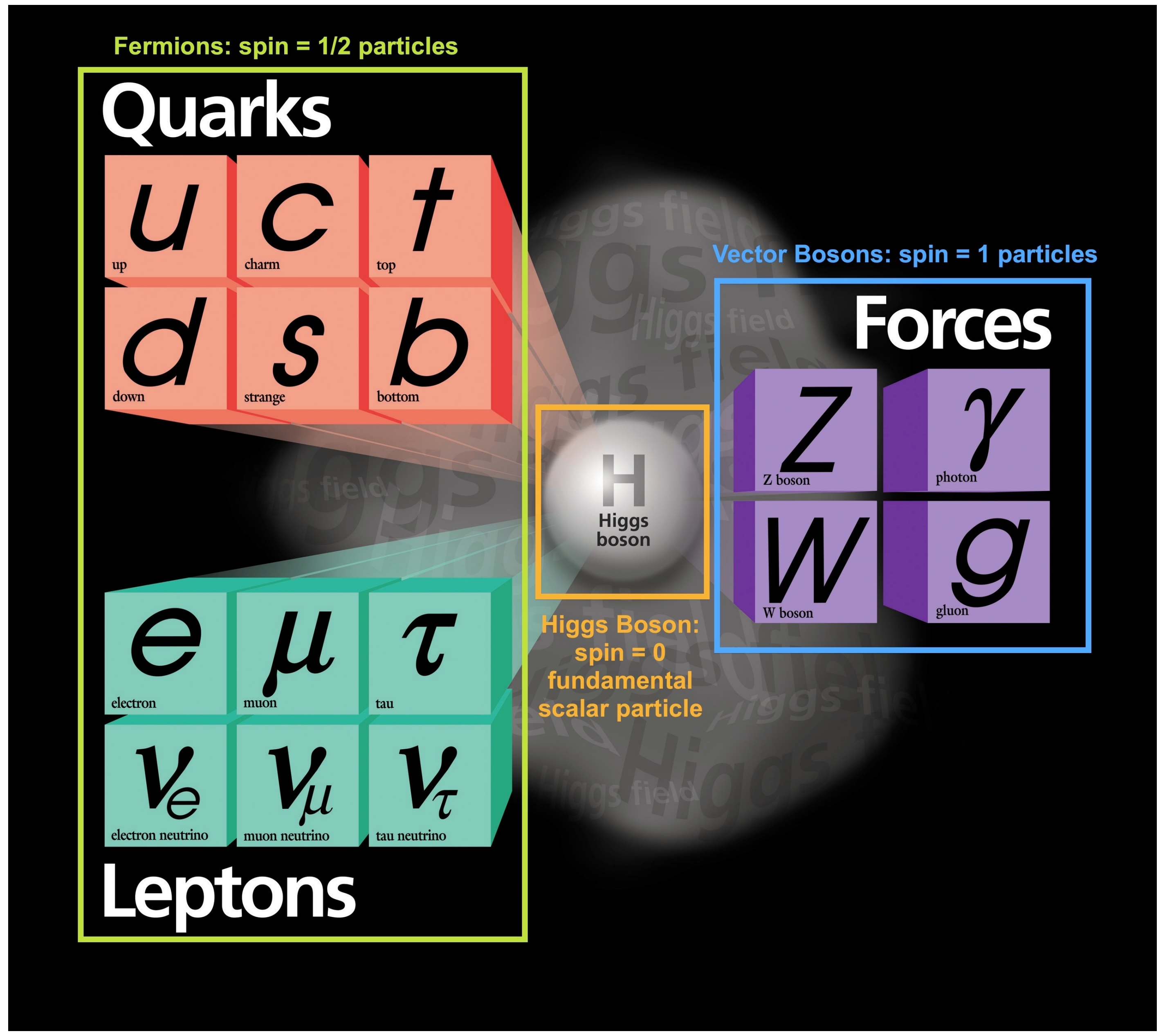
Workshop on Muon Physics at the Intensity and Precision Frontiers

Peking University, Beijing

April 21, 2024

Introduction

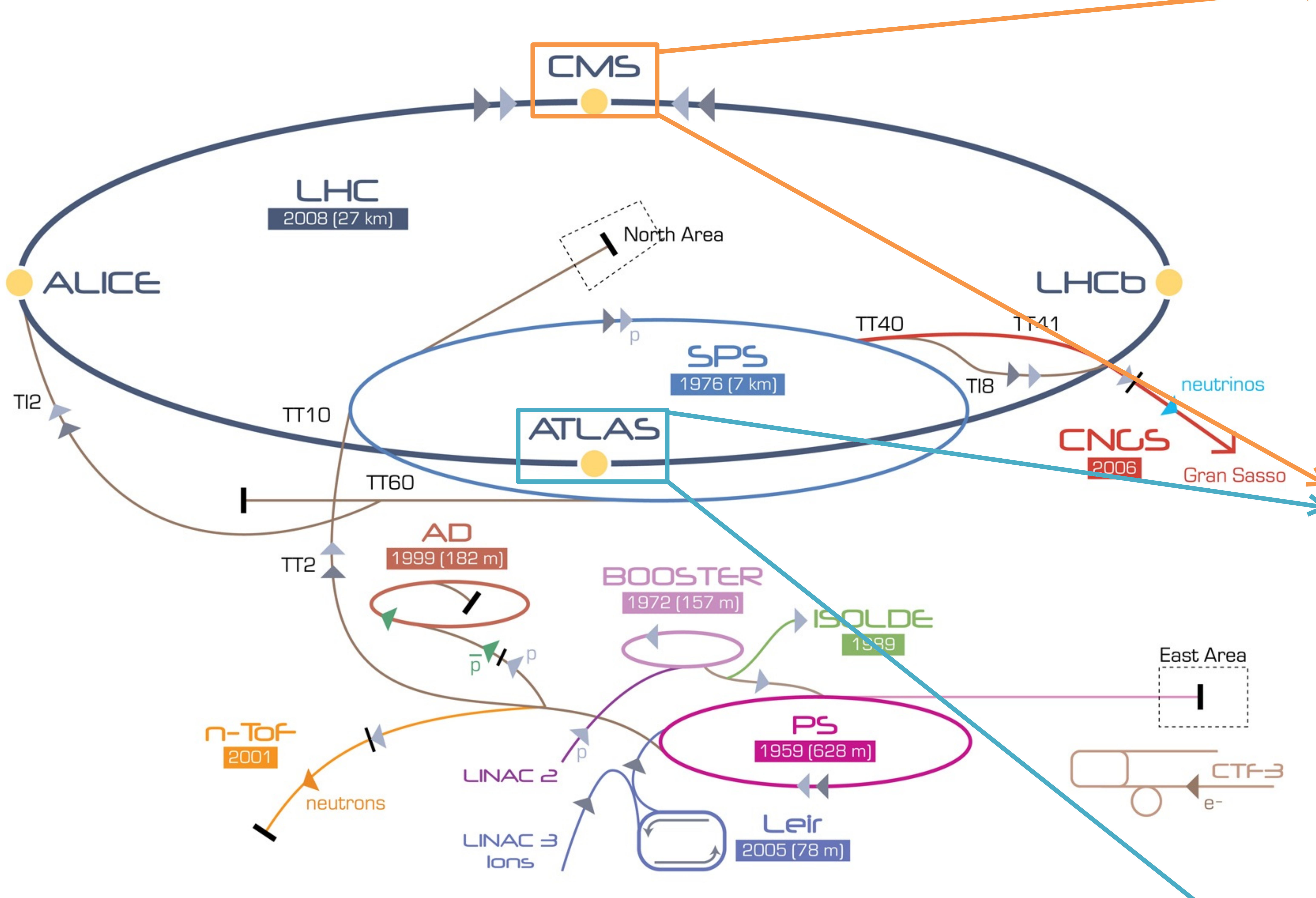
- Elementary particles acquire mass through interactions (couplings) with the Higgs field according to SM
  - **A new force of different nature than any other known ones!**
  - Higgs boson couplings to W/Z (Run 1) and 3rd generation fermions (Run 1 + 2) has been observed
  - Couplings to **2nd generation fermions** still to be established
- **H→μμ** provides an unique opportunity for exploring **mass genesis of 2nd generation fermions** at LHC
  - **Better sensitivity** than H→cc (H→ss hardly feasible)
  - **Muon mass precisely known**. H-μ coupling measurement therefore represents a key test of Higgs mechanism

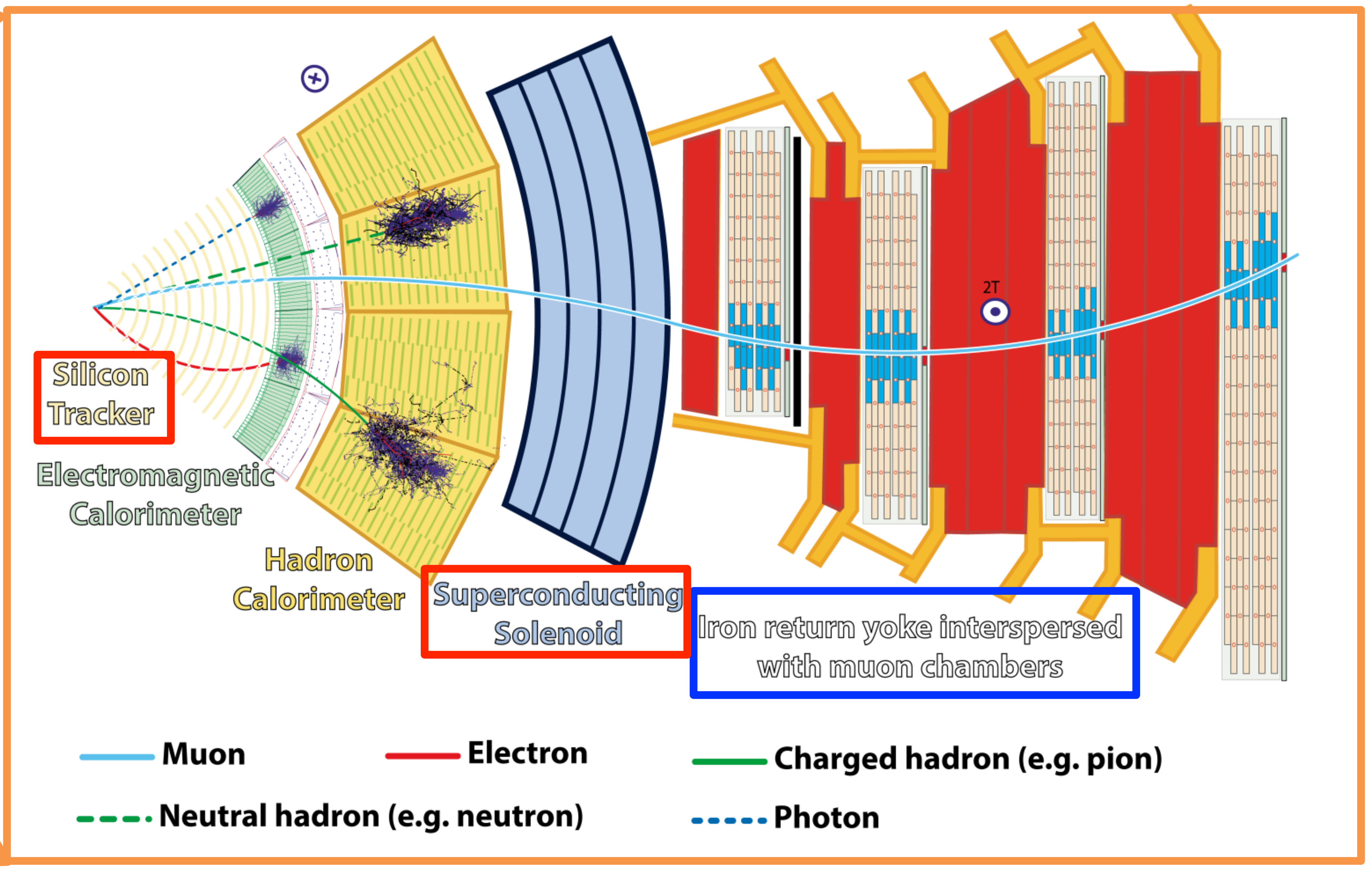


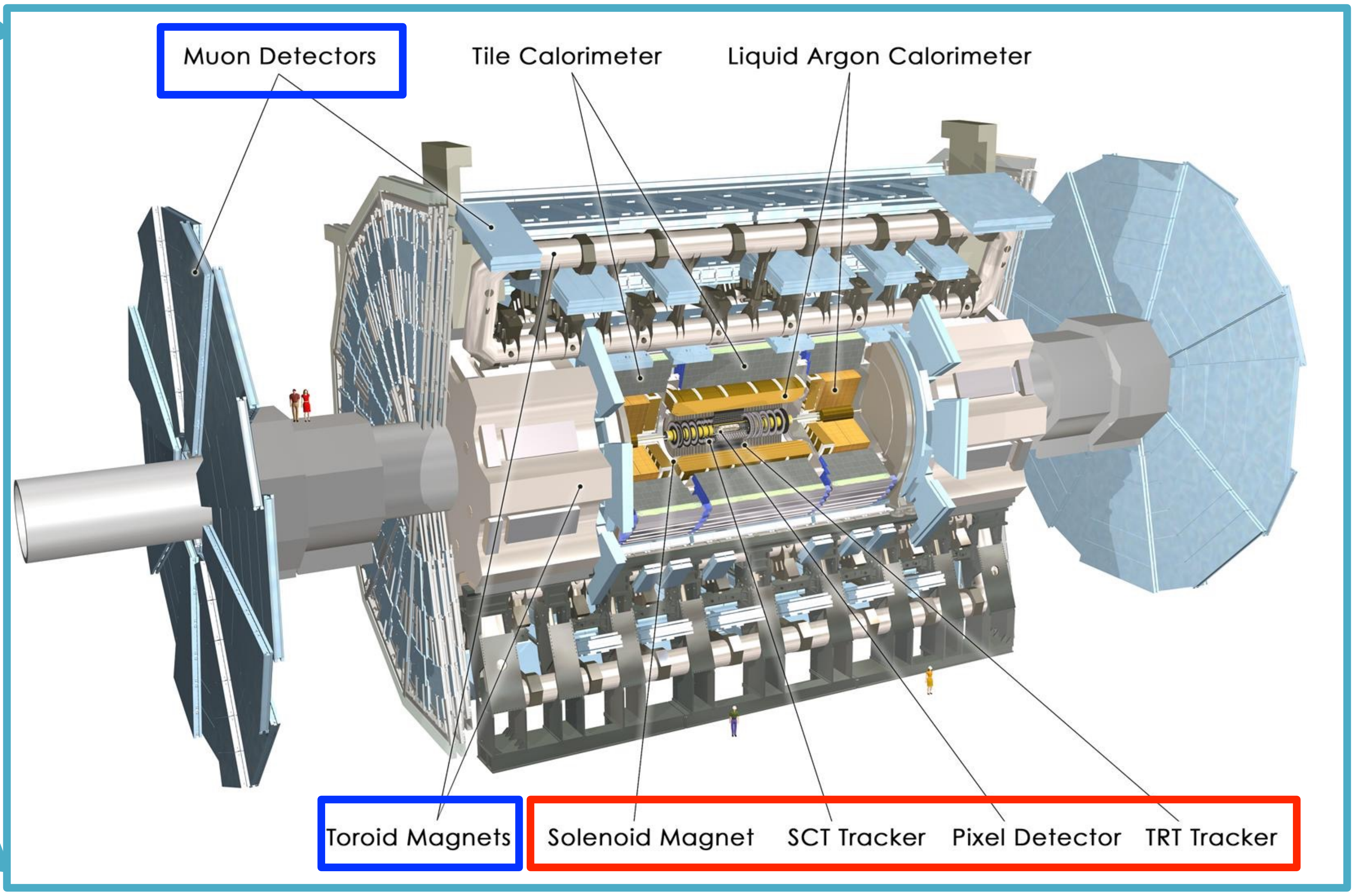
	Mass
μ	105.6583755±0.0000023 MeV
τ	1776.86±0.12 MeV
t	172.69±0.3 GeV
b	4.18±0.03 GeV
c	1.27±0.02 GeV

All values from PDG 2023

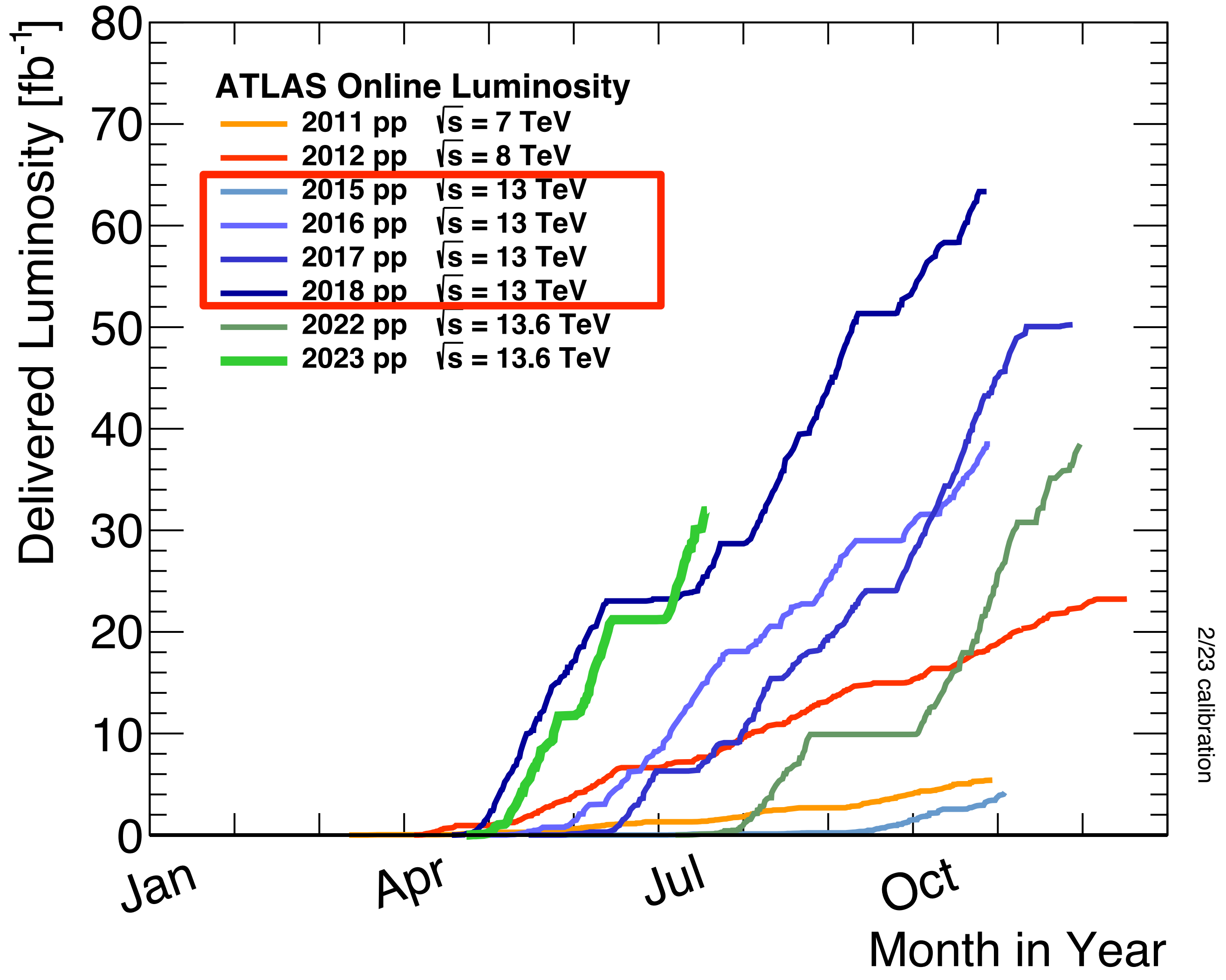
A Toroidal LHC ApparatuS (ATLAS) and Compact Muon Solenoid (CMS)

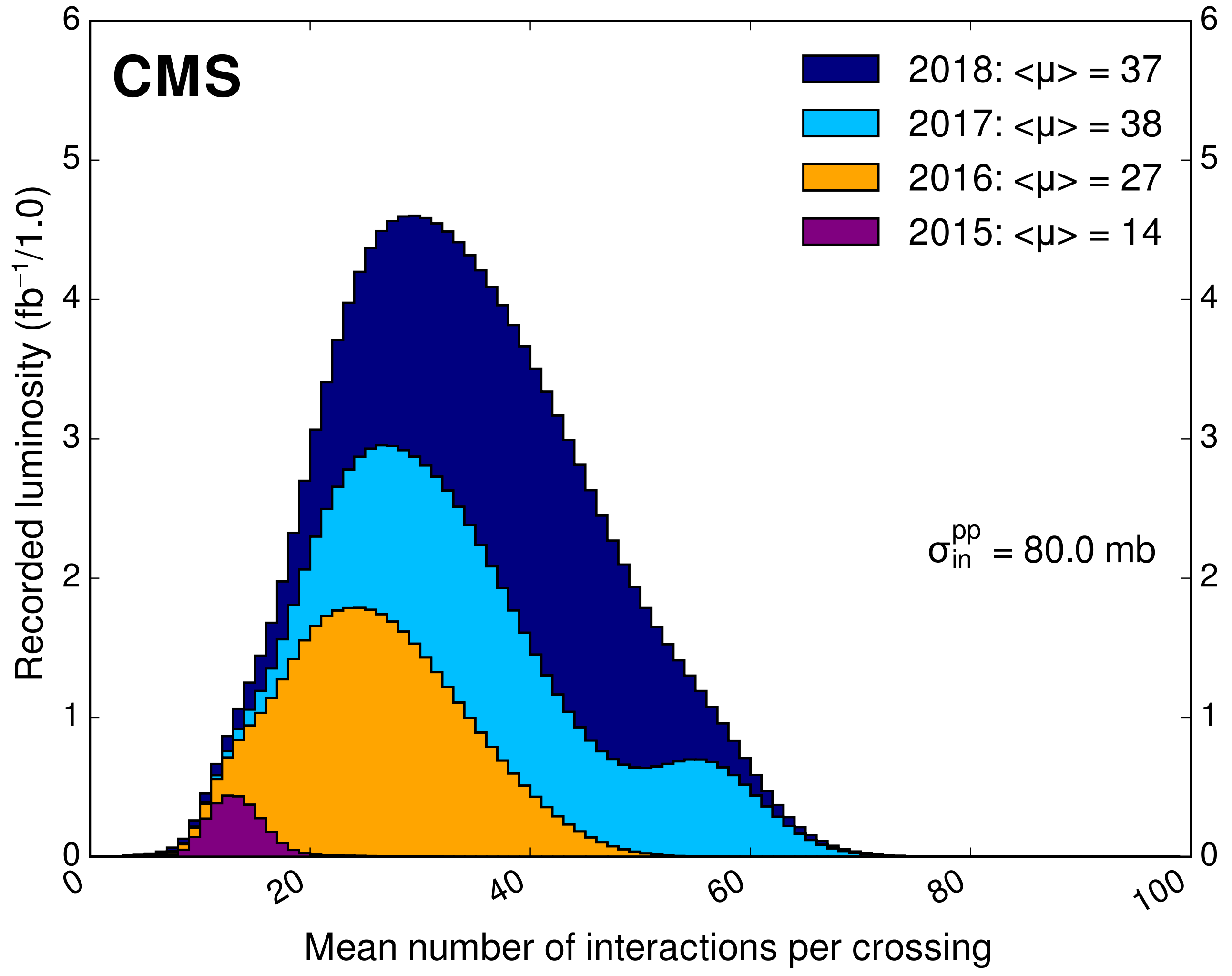




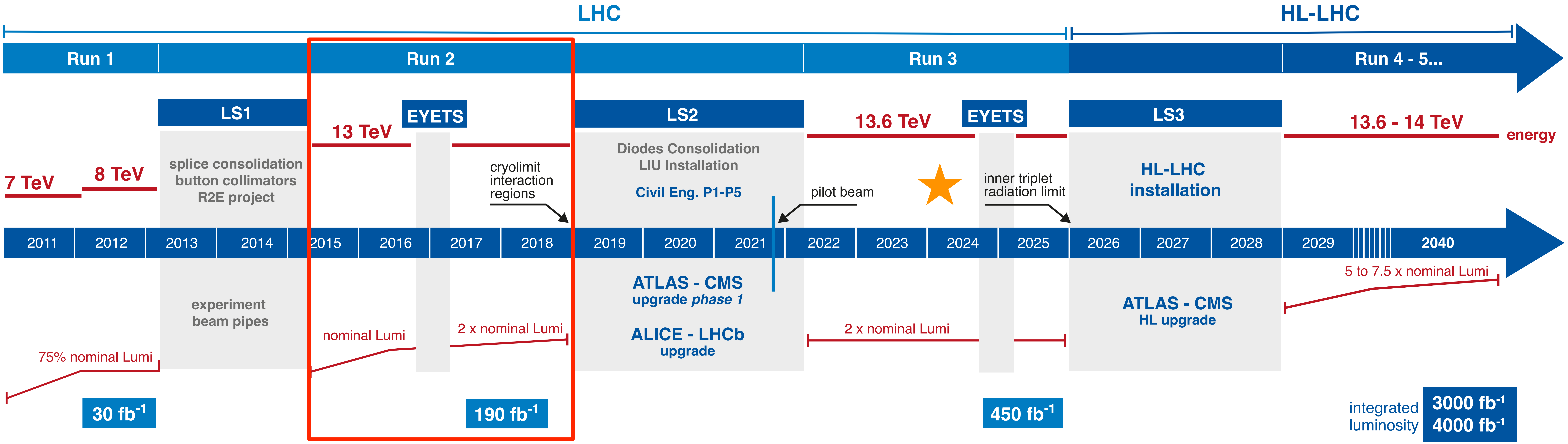


LHC Run 2



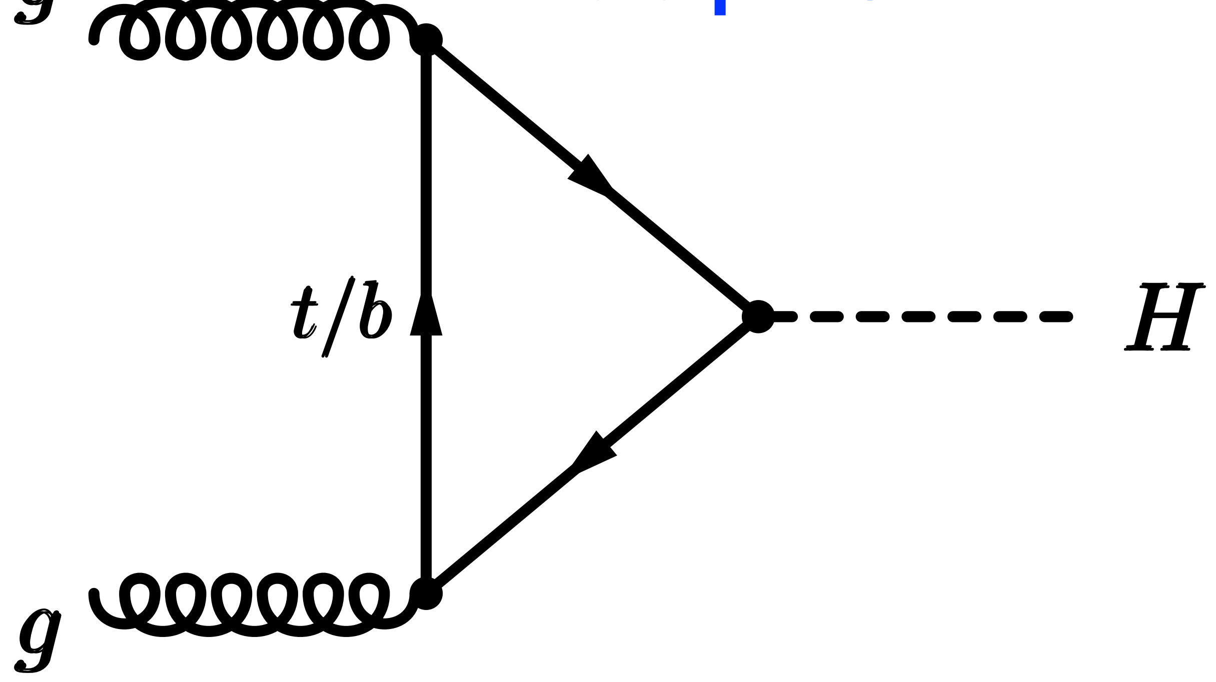


- Successful Run 2 pp collision data taking at $\sqrt{s}$ = **13 TeV** by both ATLAS and CMS
  - **~140 fb^{-1}** data collected by each experiment
  - Mean pileup ~30
- Run 3 data taking @13.6 TeV ongoing



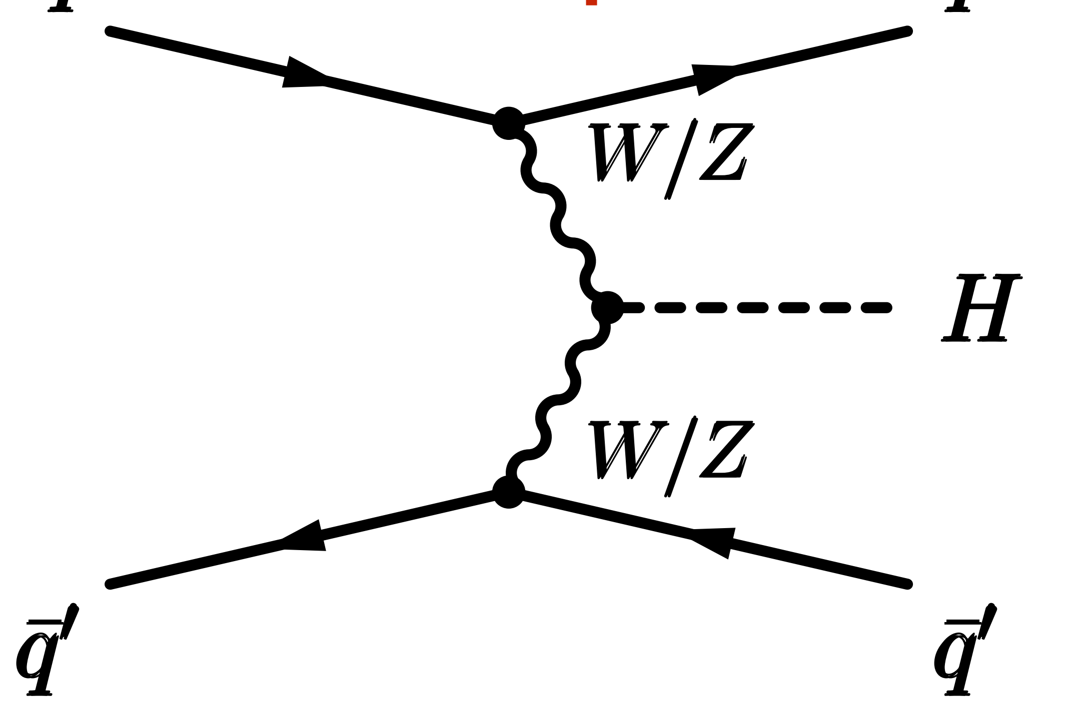
Higgs boson production and decay to dimuon

48.5 pb @13 TeV



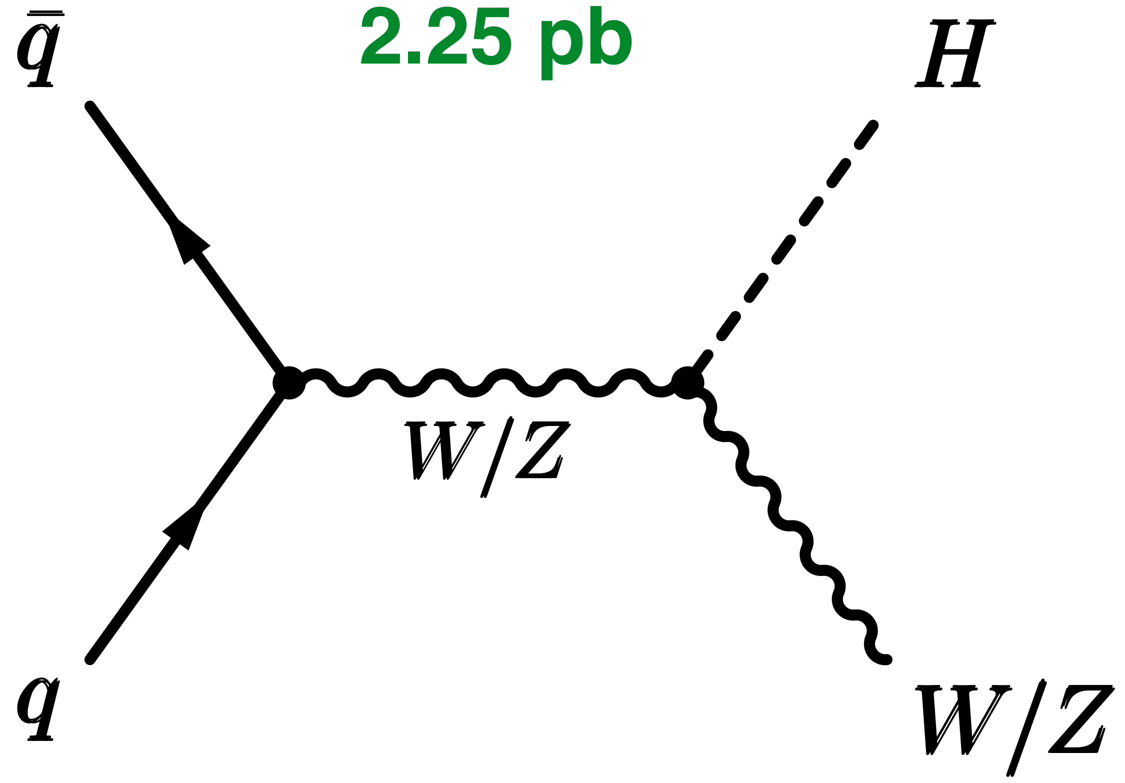
Gluon-fusion (ggF, ~87%)

3.78 pb



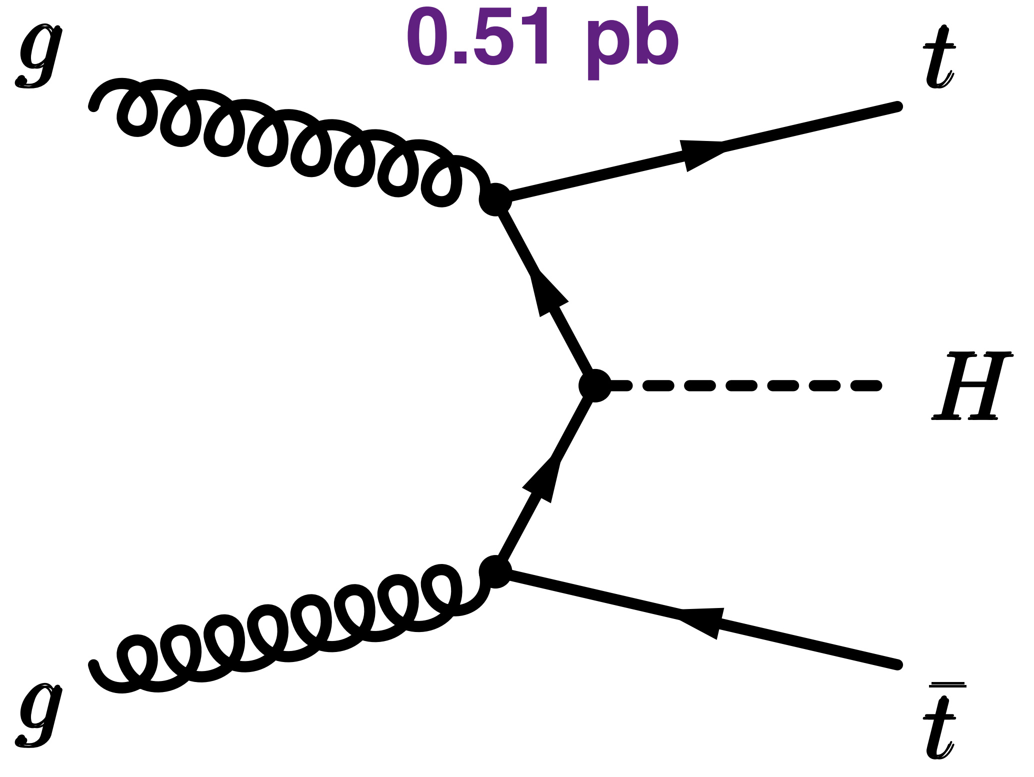
Vector boson fusion (VBF, ~7%)

2.25 pb



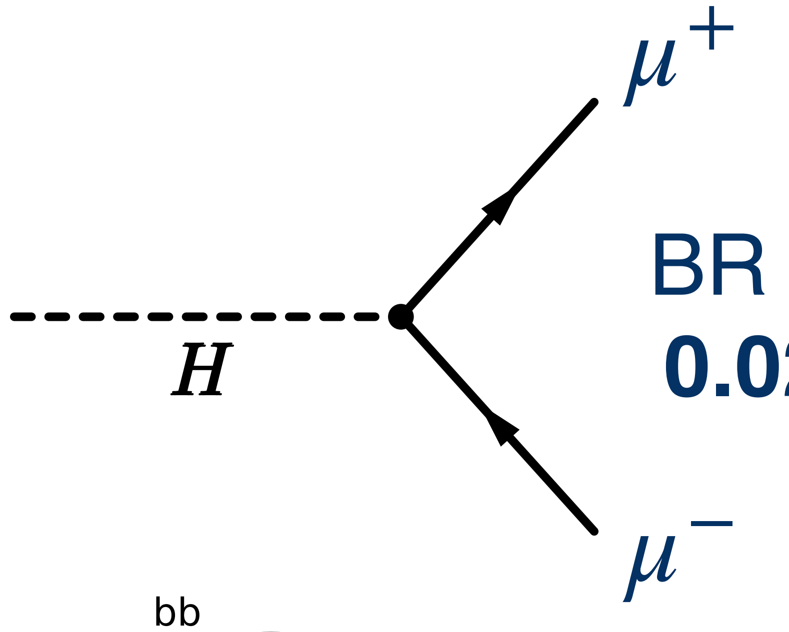
VH (~4%)

0.51 pb

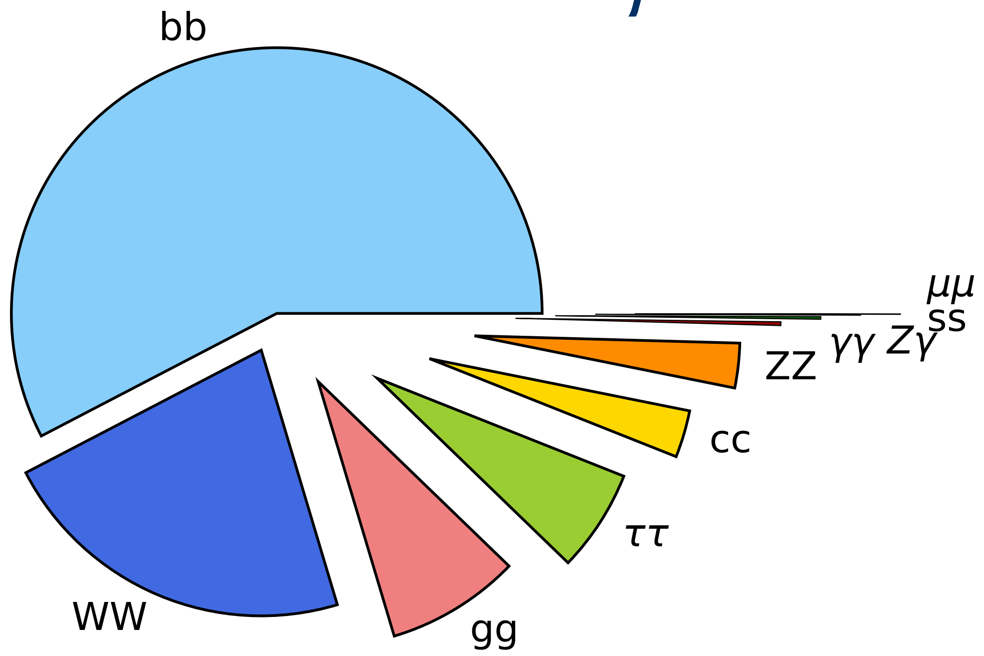


ttH (~1%)

- Physics analysis can explore different topologies of each production mode to maximize sensitivity
- Expect ~**1700** SM H→μμ candidates in Run 2 data collected by ATLAS and CMS each
  - Important to ensure high muon reconstruction efficiency and good momentum resolution

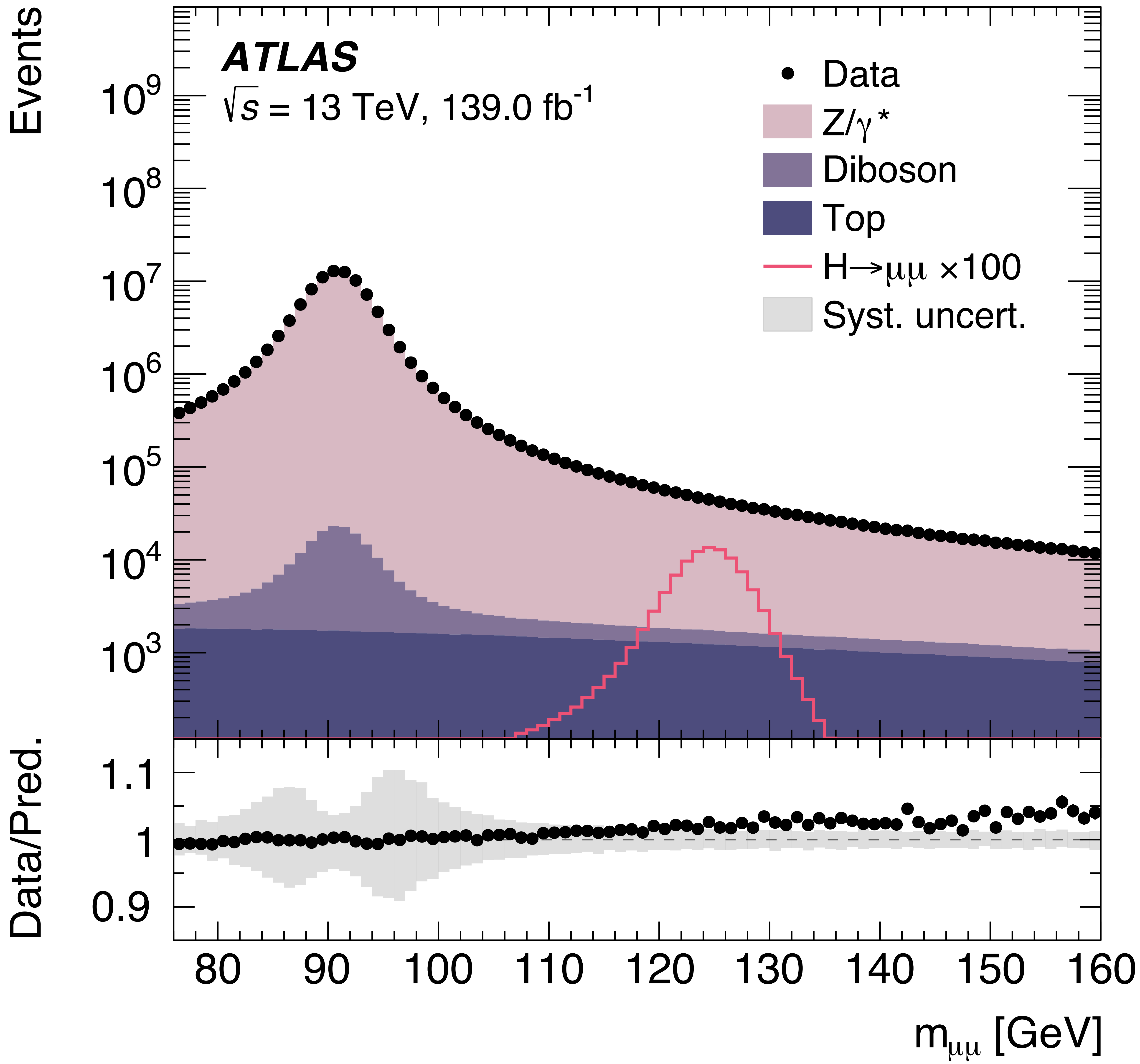


BR only **0.02%!**



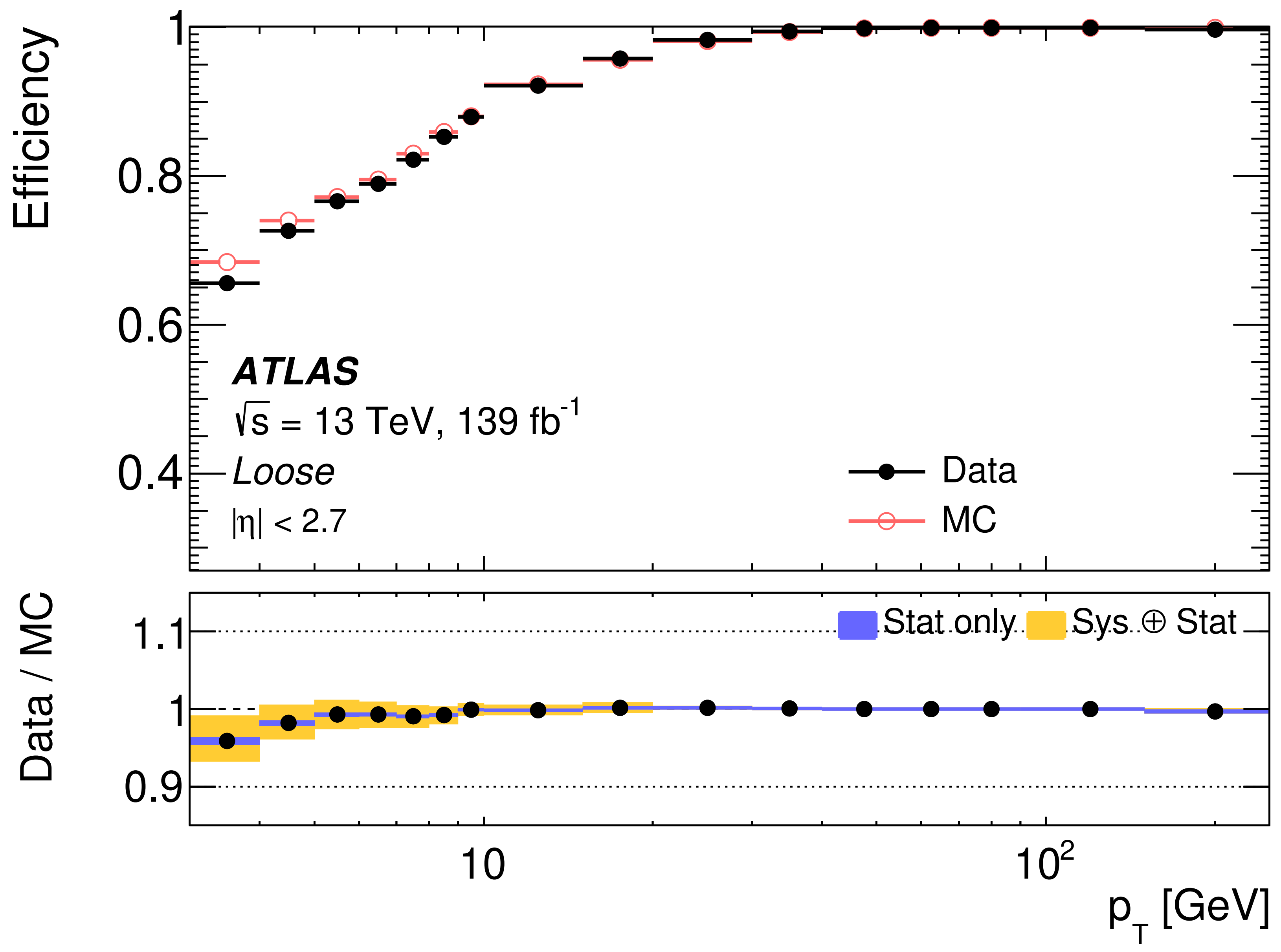
Background processes

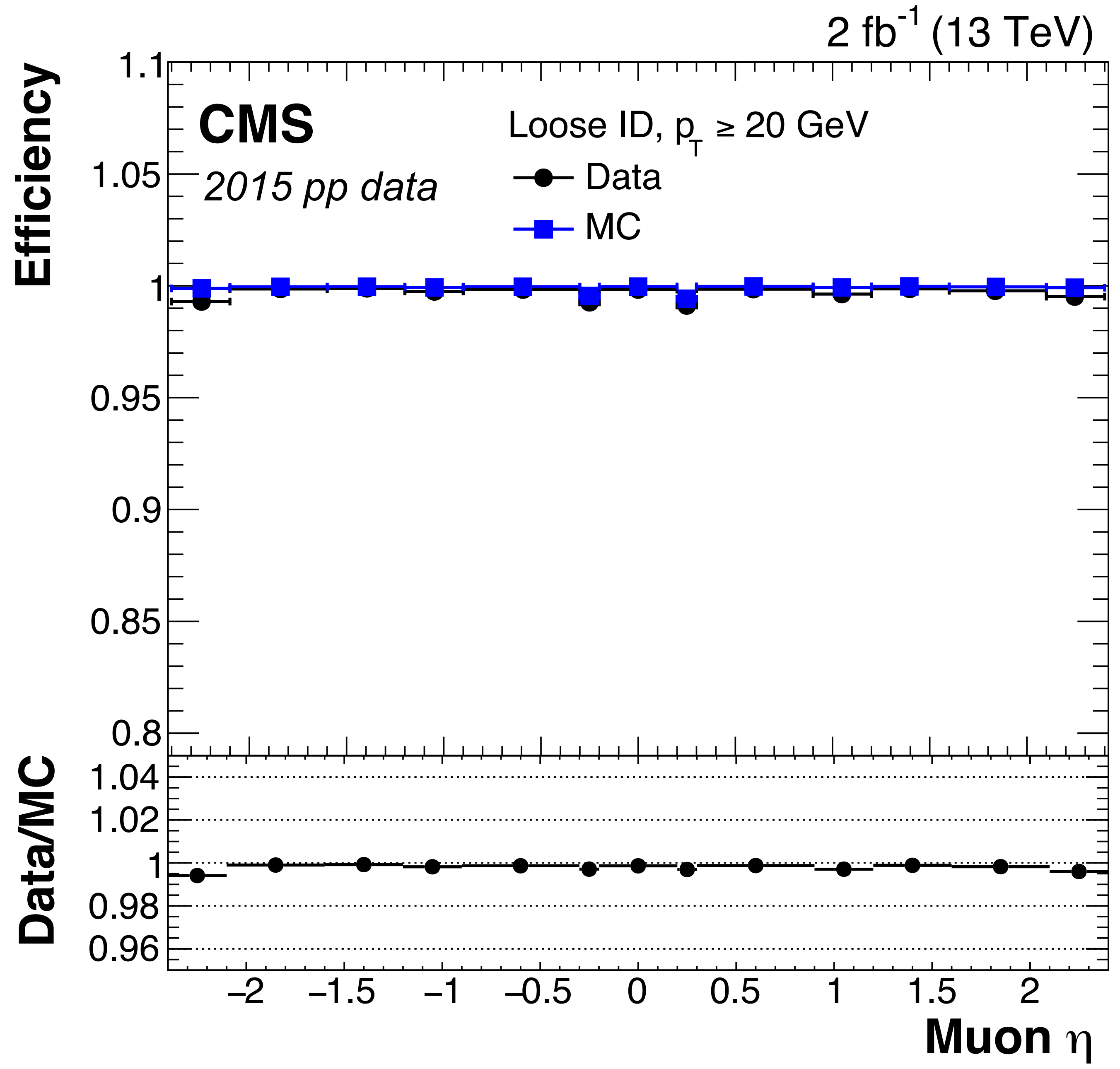
- **Drell-Yan** is the dominant background
- EW Zjj, diboson, top also important for studying VBF, VH, and ttH, respectively
- Typical S/B **O(0.1%)**
  - Accuracy of background modeling is the key to search for H→μμ signal!
  - Advanced analysis techniques i.e. machine learning needed to suppress background
- Background spectrum **smoothly falling** after Z-pole
  - Data-driven estimation feasible

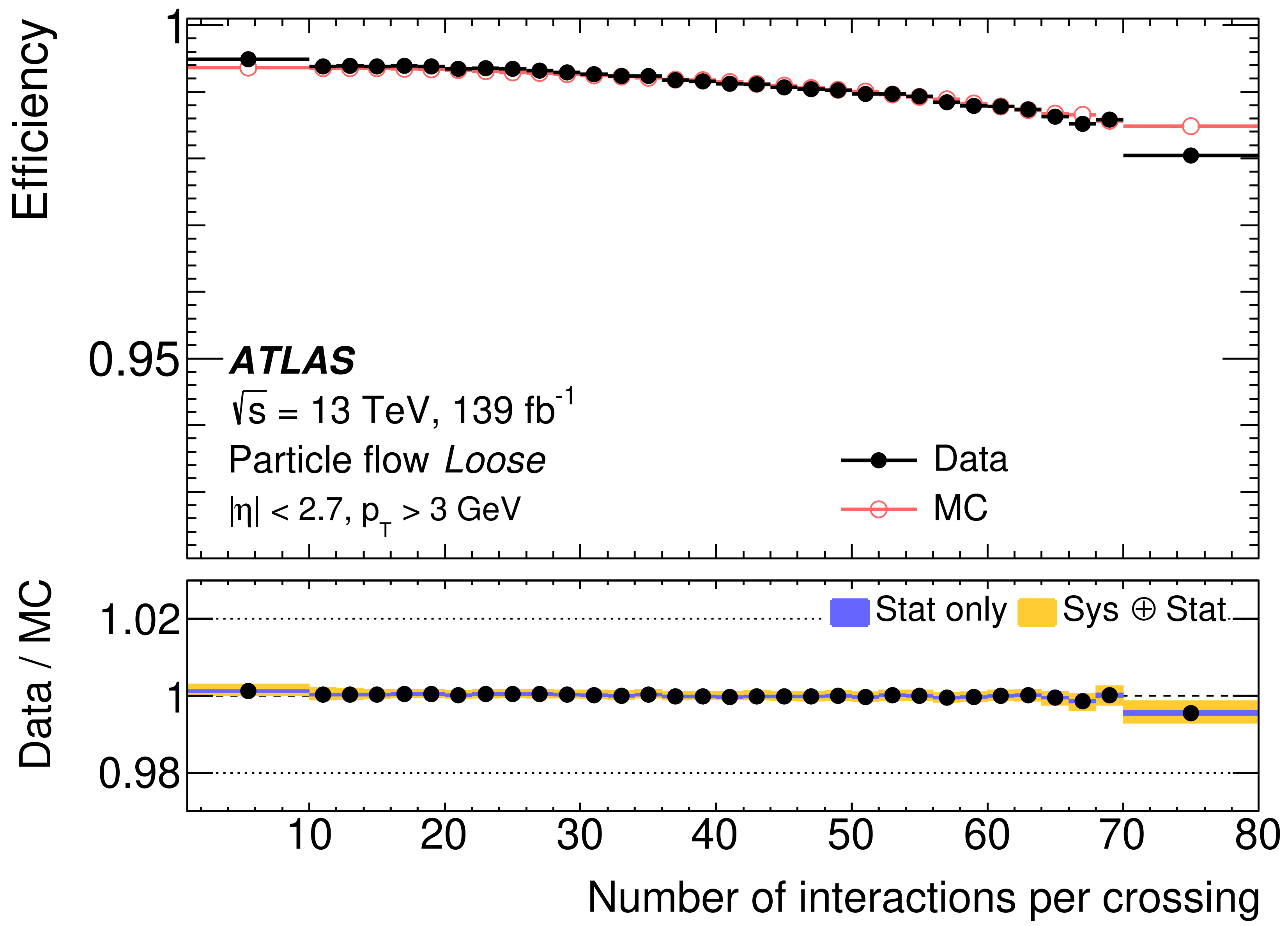


Muon reconstruction

- Most muons reconstructed from combining **inner tracker track + muon spectrometer track**
  - Also use lower quality tracks under certain conditions, e.g. MS-only track when out of inner tracker acceptance (2.5 < |η| < 2.7) in ATLAS
- **High efficiency** for muon reconstruction in both ATLAS and CMS
  - Small impact from high rate and pileup. Good MC modeling

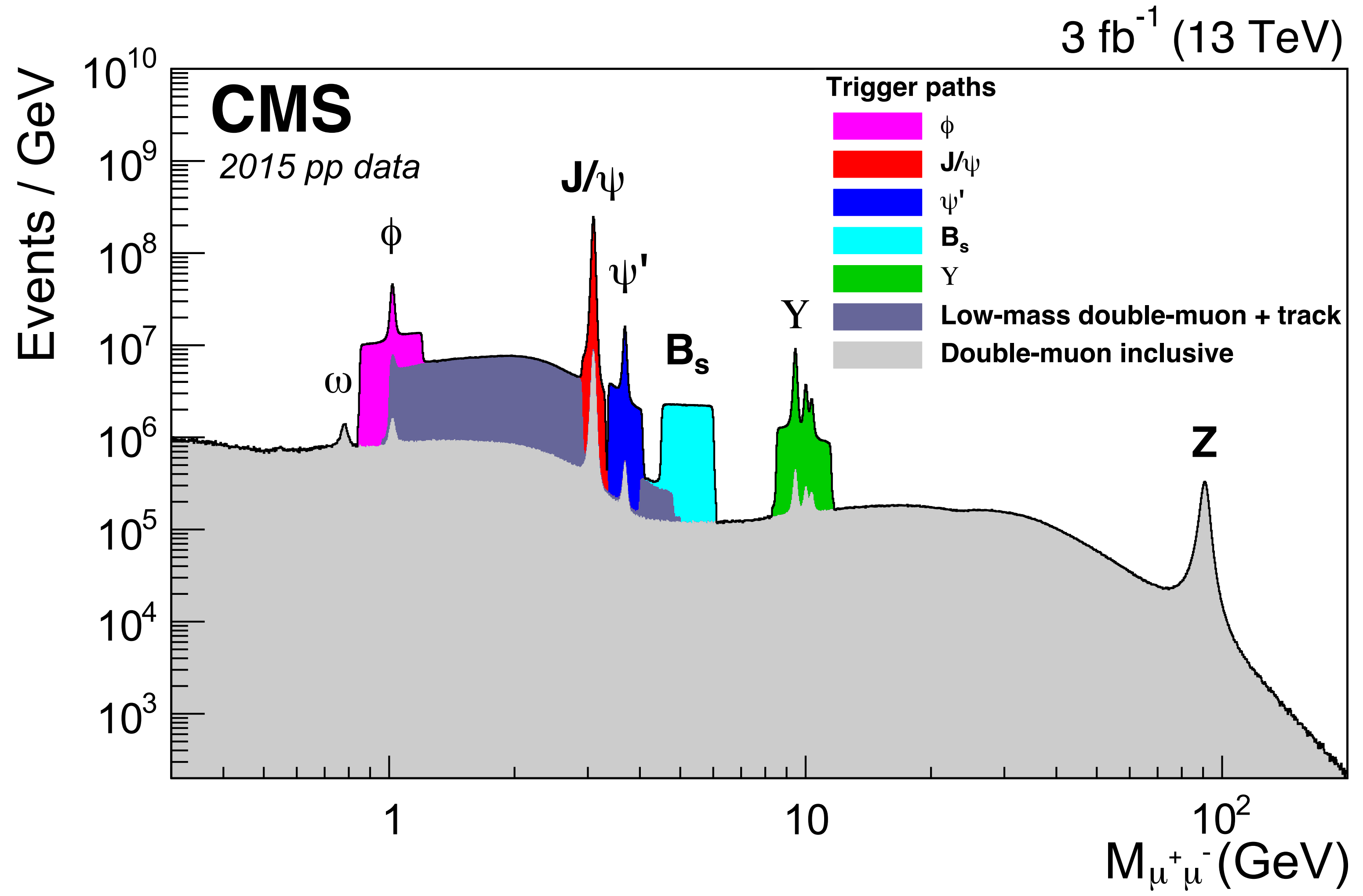


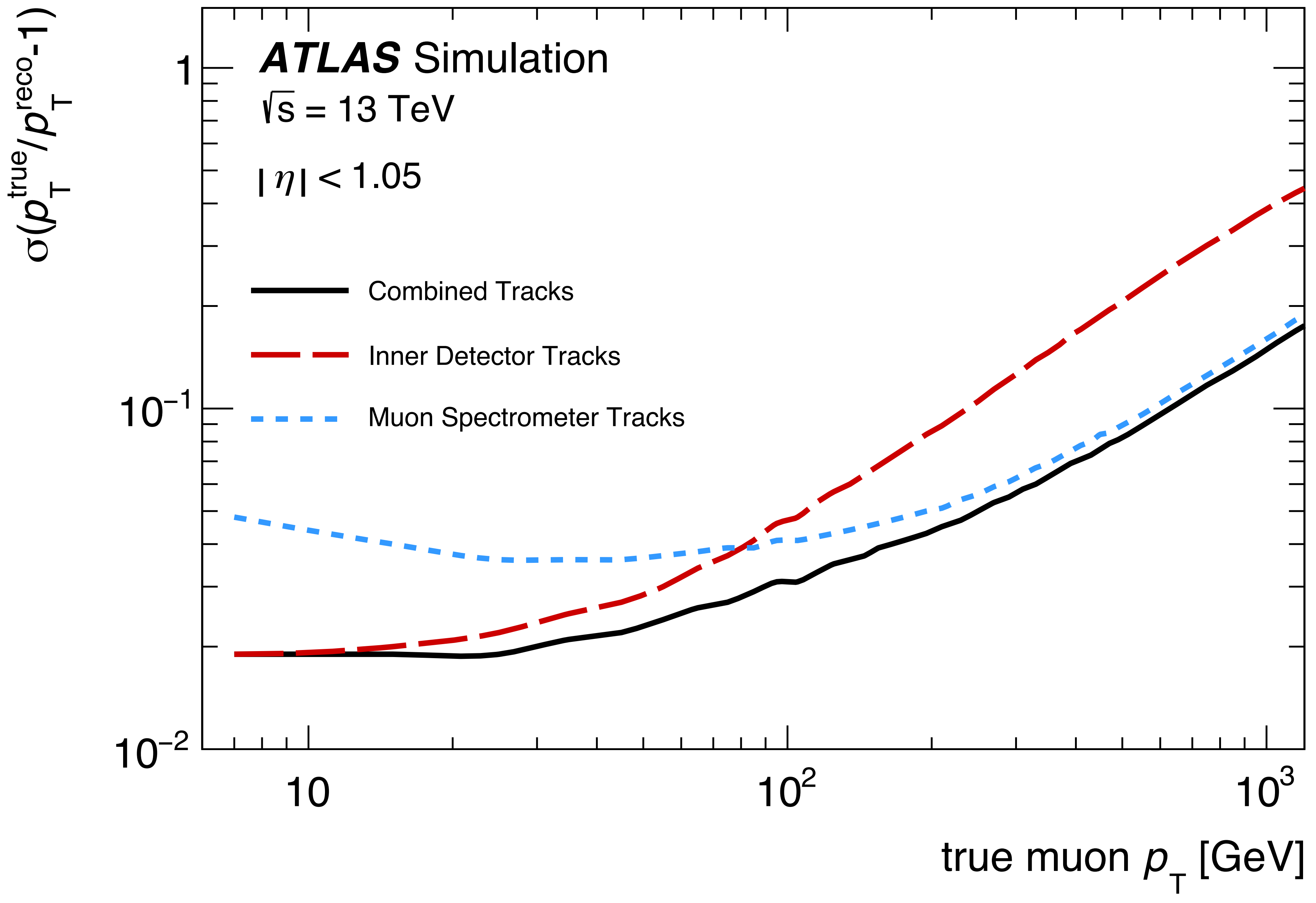


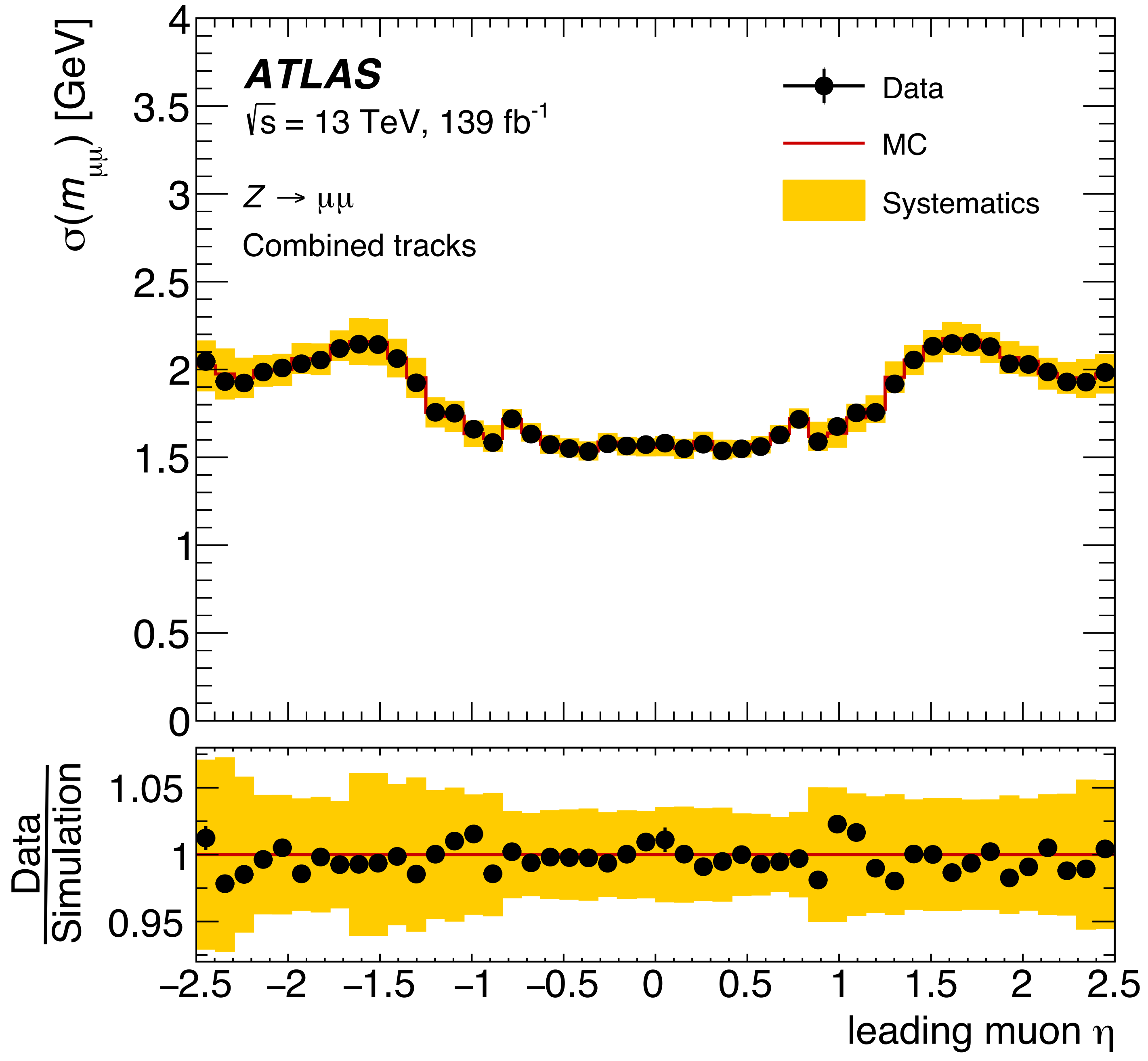


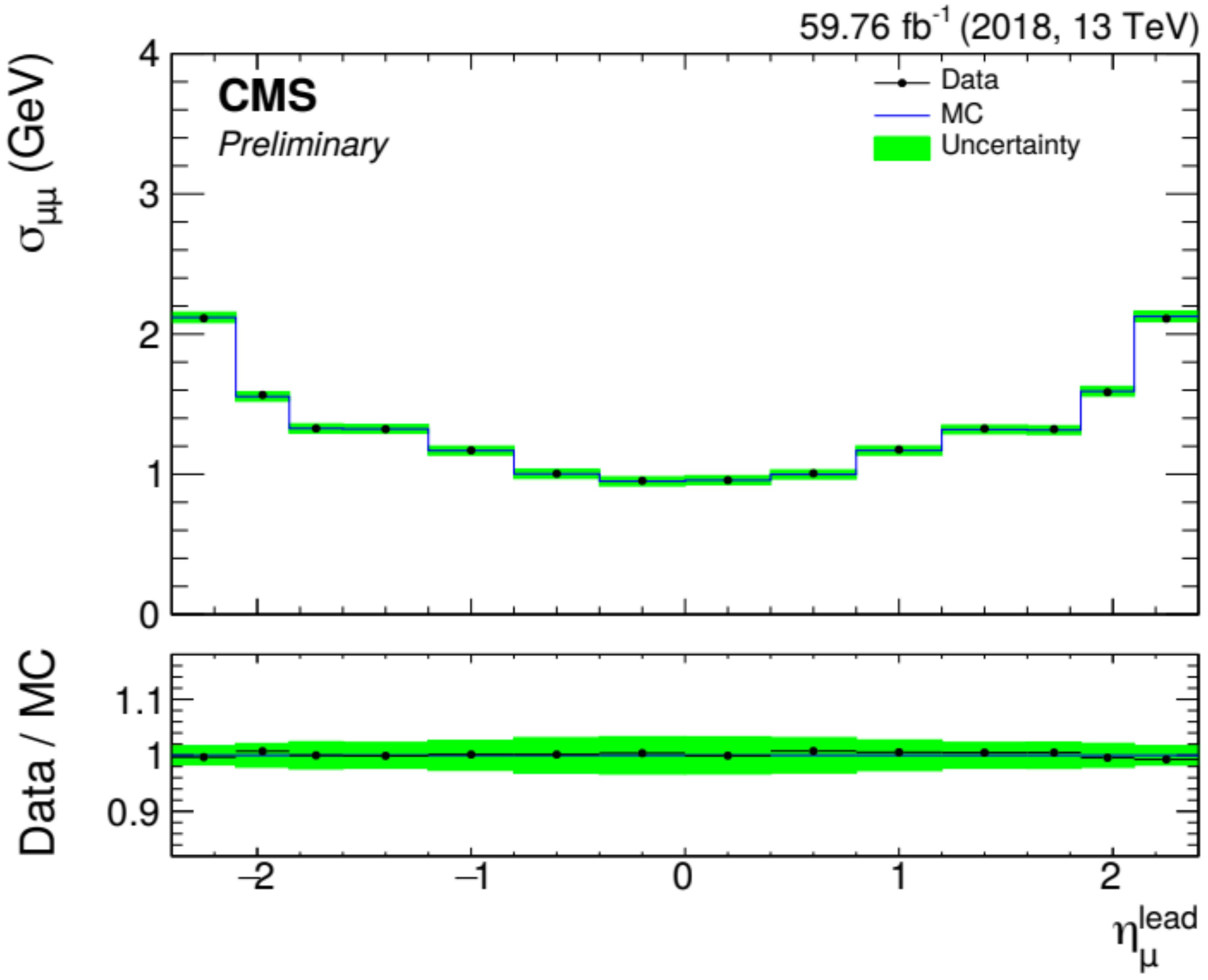
Muon momentum calibration

- Using Z pole as candle (+J/ψ, Y) for calibration
- Muon momentum resolution largely driven by **inner tracker** precision for O(10 GeV) p_T regime relevant to $H \to \mu\mu$ search





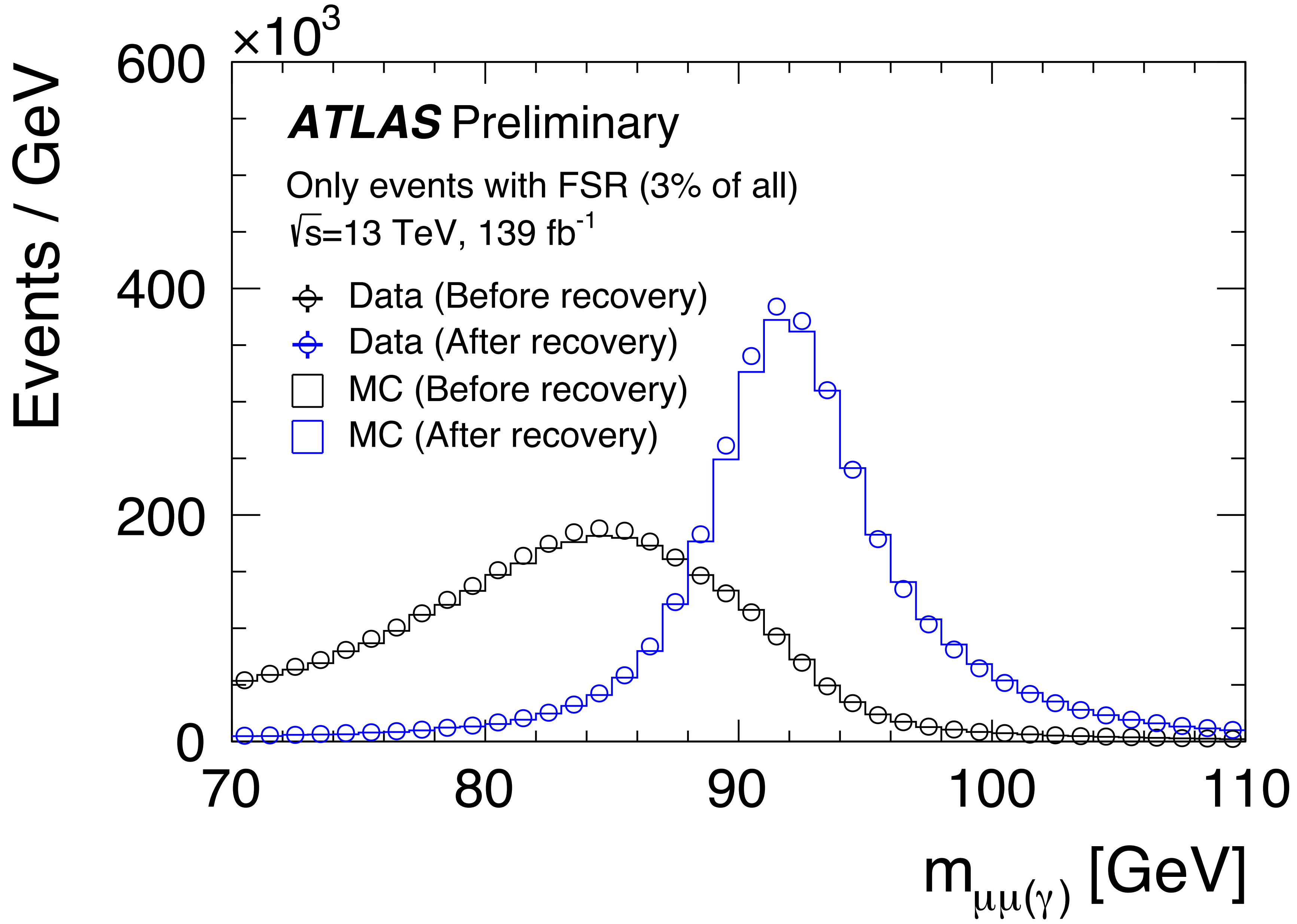




Event selection

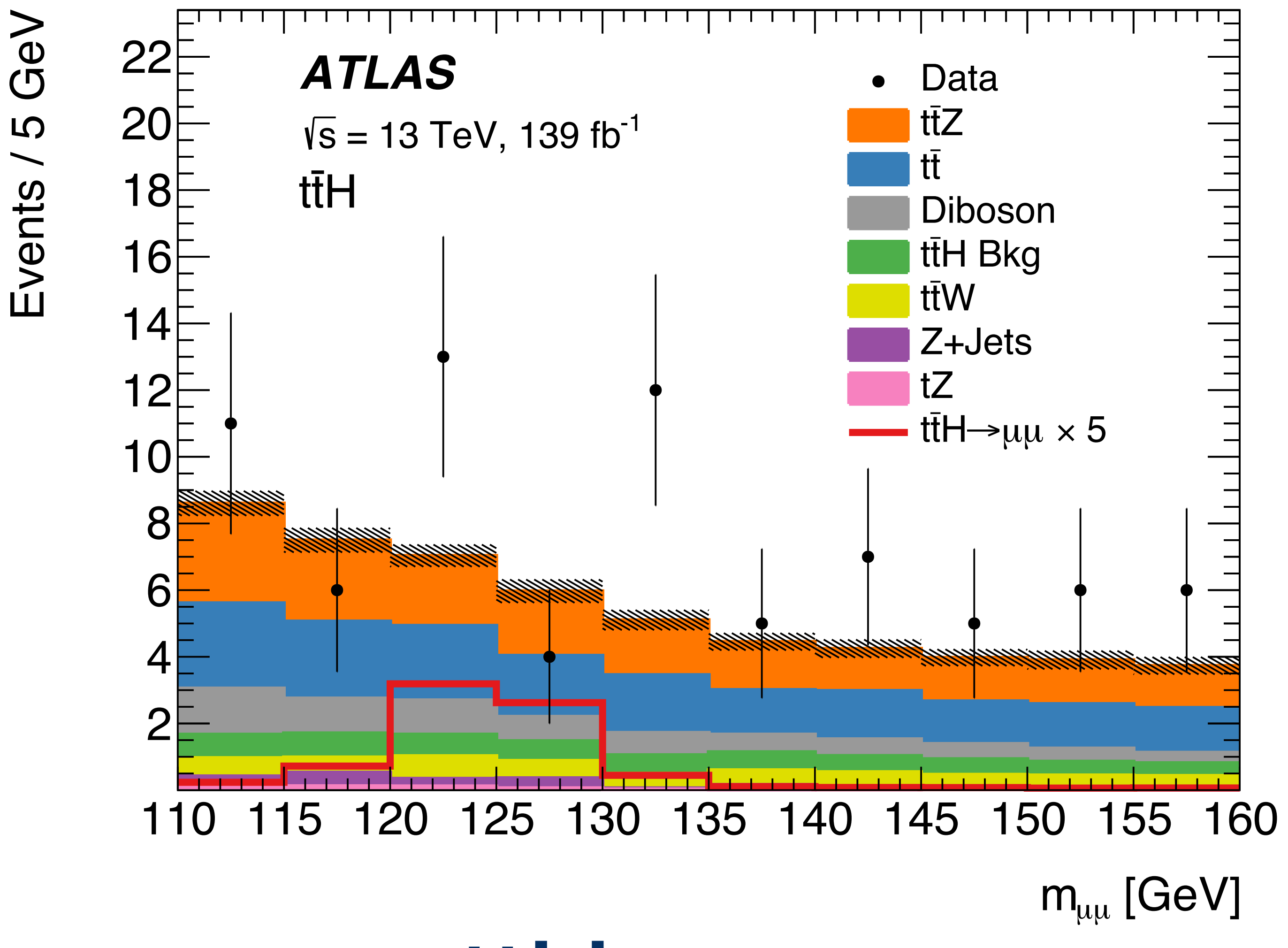
- Use single muon trigger
  - Trigger eff. ATLAS 91%, CMS 95%
- Select events with two opposite-charge high p_T muons within detector acceptance, with quality requirements
  - ATLAS select **52%** signal events selected in 120—130 GeV
- FSR recovery for better resolution

	ATLAS	CMS
Trigger	> 26 GeV + iso. or > 50 GeV	> 27 (24) GeV for 2017 (2016/2018)
p_T (leading, subleading)	>27 GeV >15 GeV	> 29 (26) GeV for 2017 (2016/2018) >20 GeV
$\lvert\eta\rvert$	< 2.7	< 2.4
Others	Identification, isolation, impact parameter cuts…	

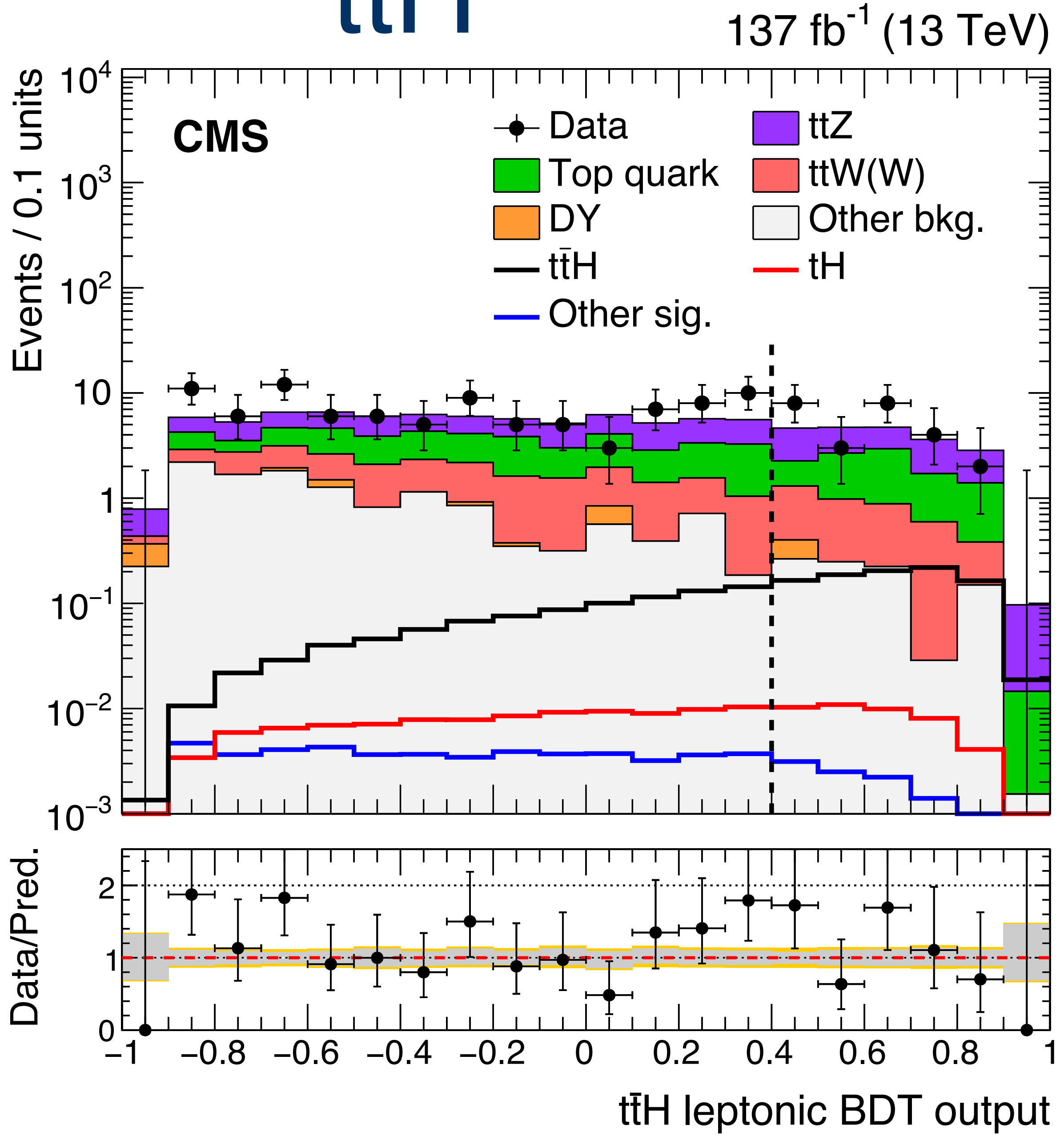


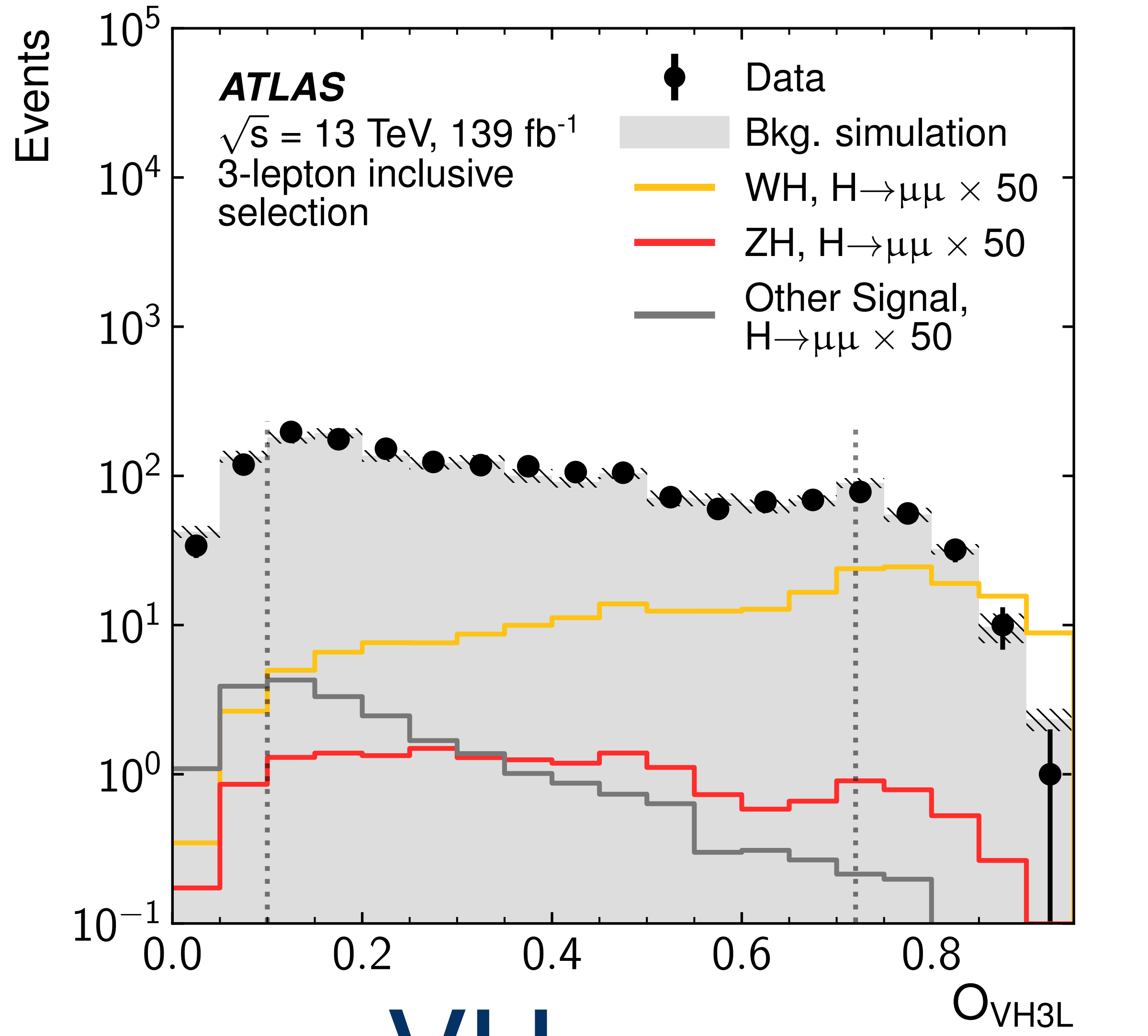
ttH and VH categories

- Use the decay products of W/Z/top to tag VH and ttH events
  - ttH: b-jet + jets or leptons
  - VH: additional leptons
- Use Boosted Decision Trees (BDT) to combine all inputs from event topologies
- Expect very low rate due to small cross-sections

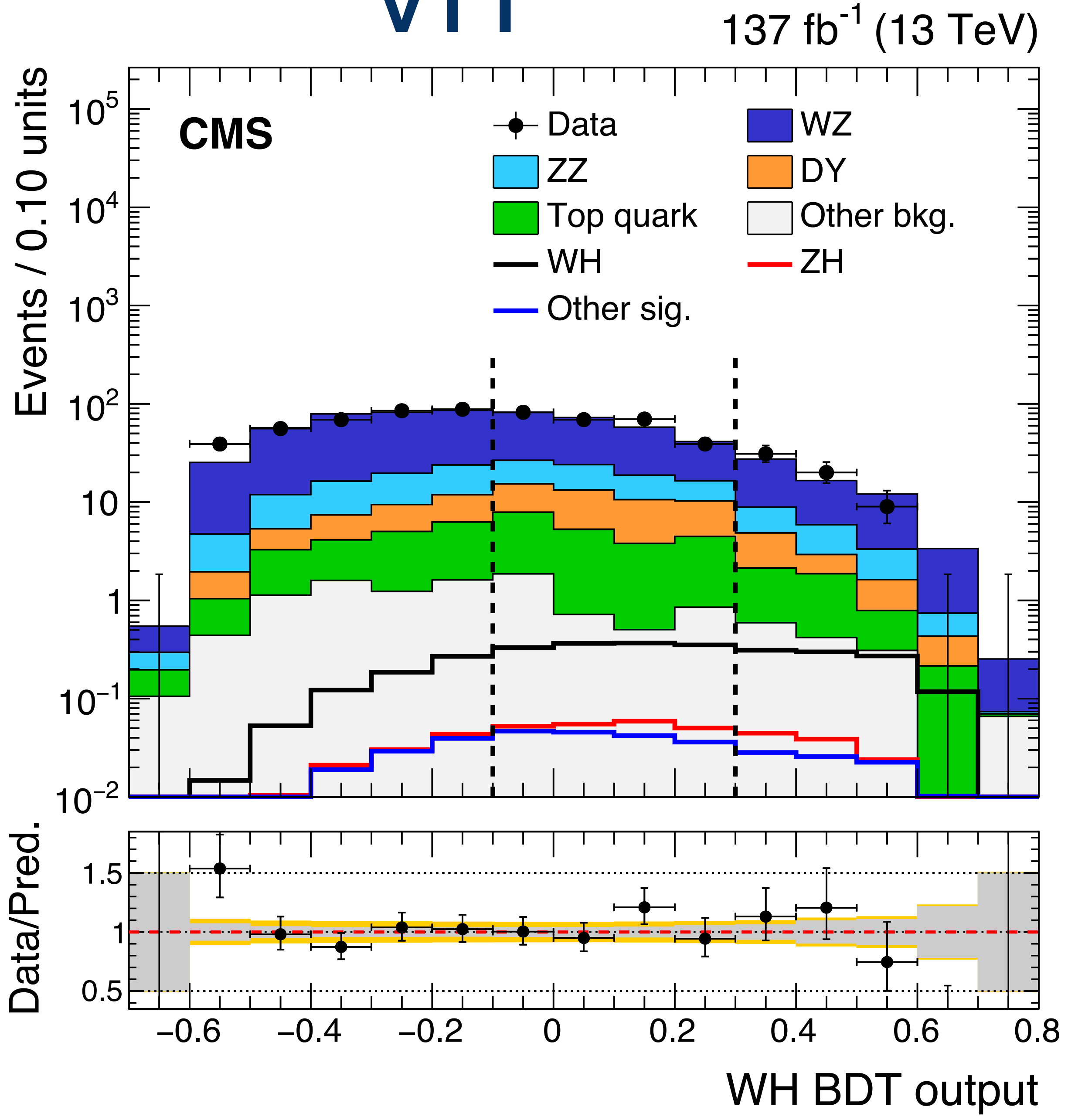


ttH



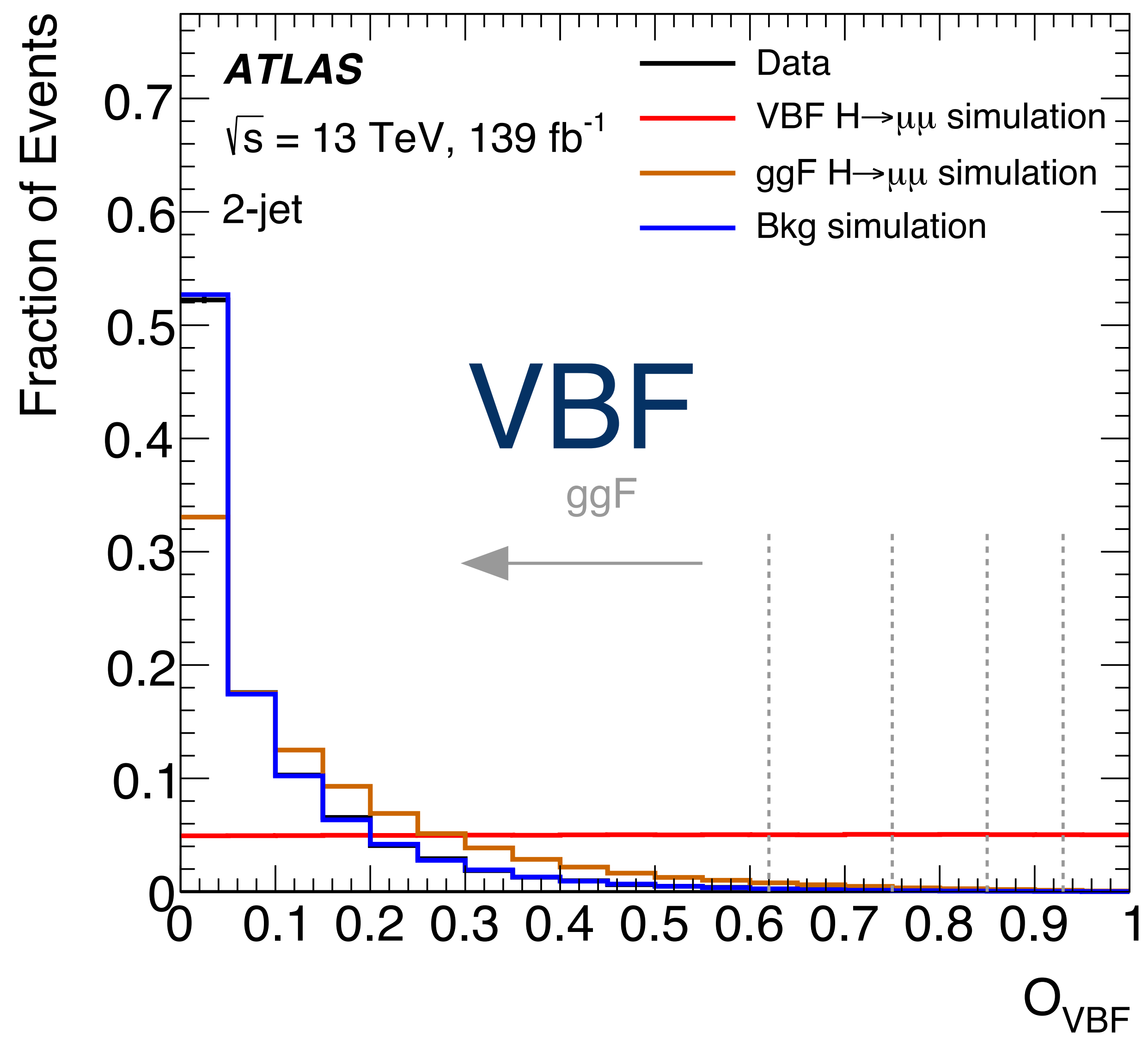


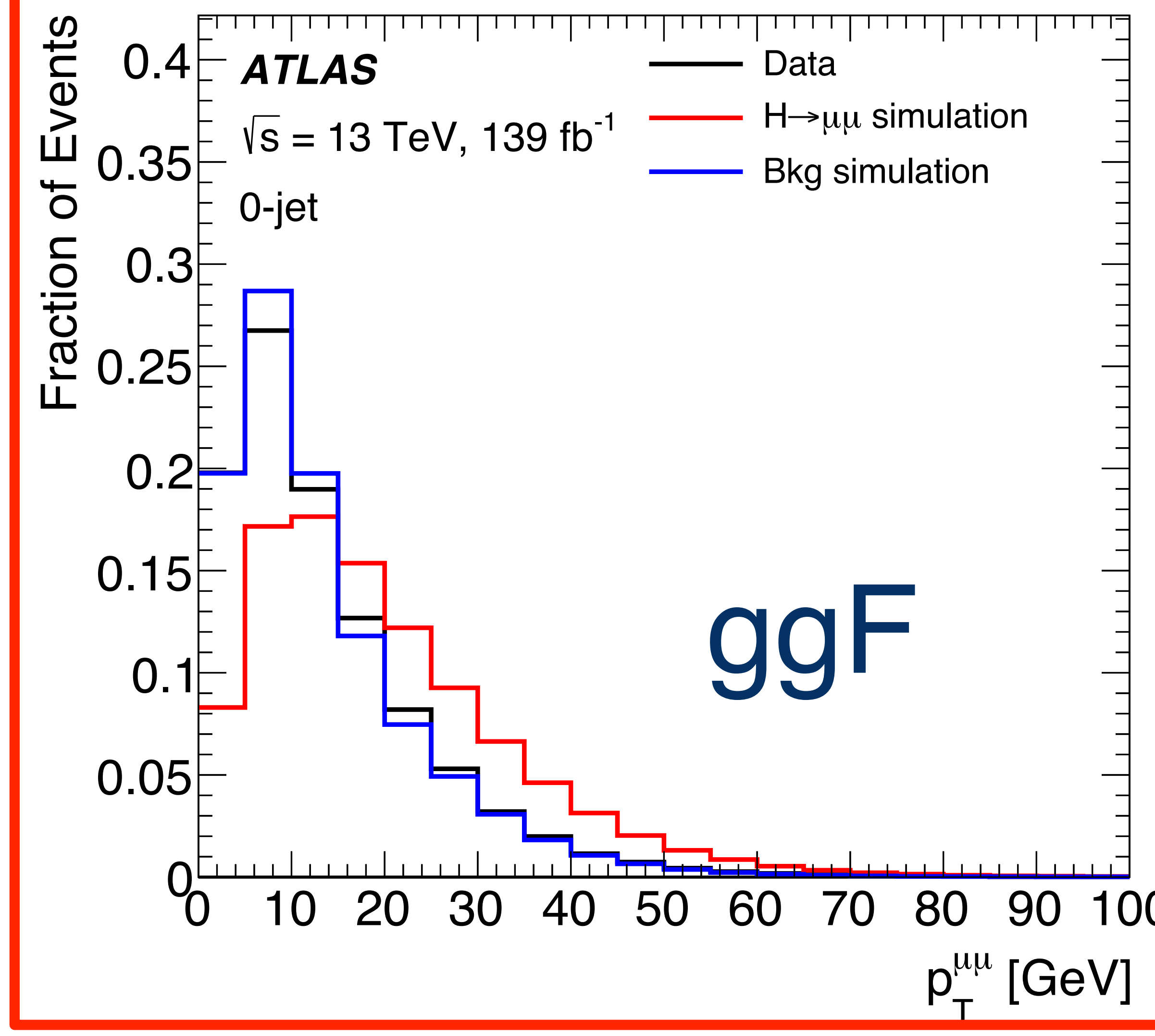
VH

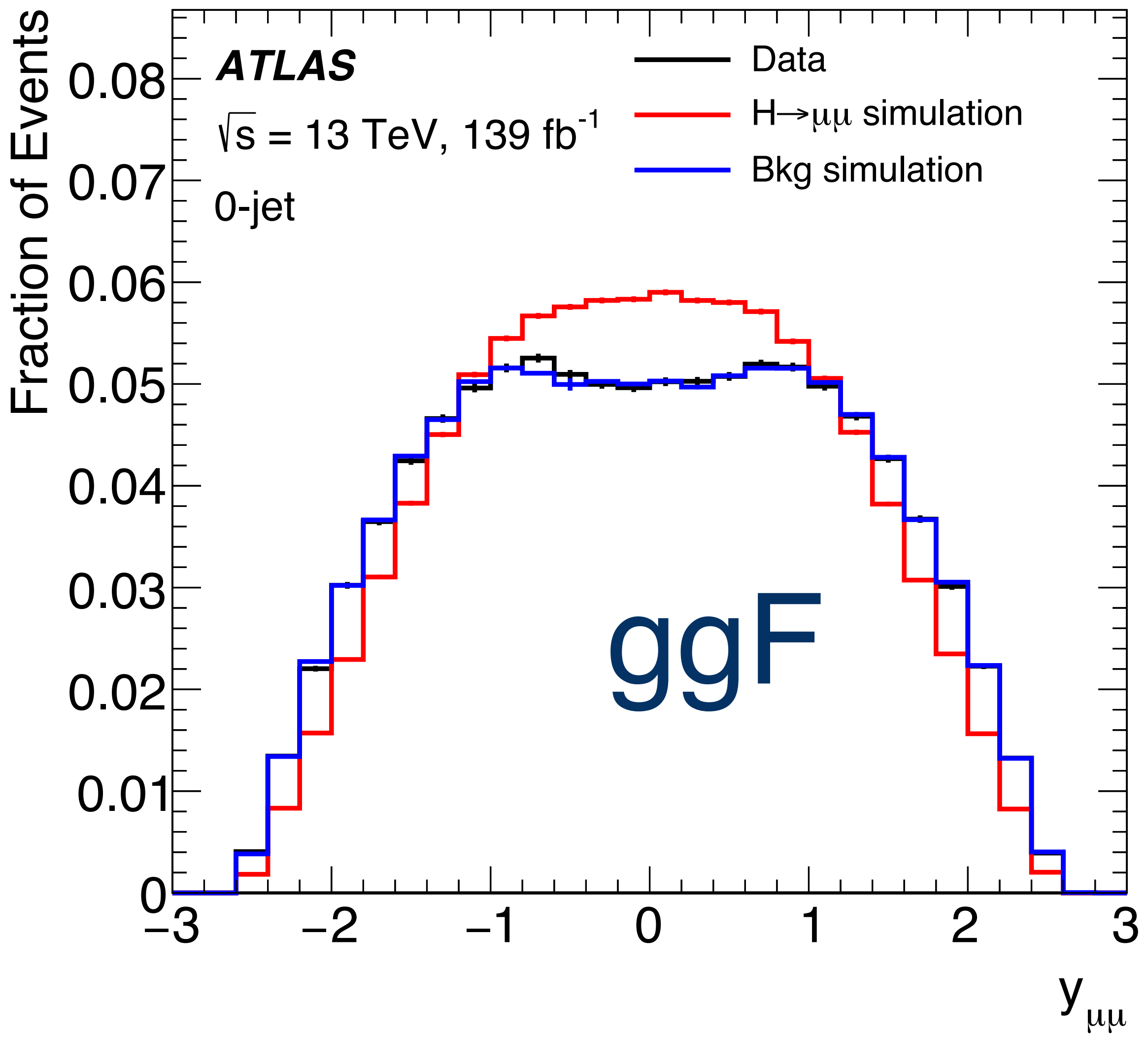


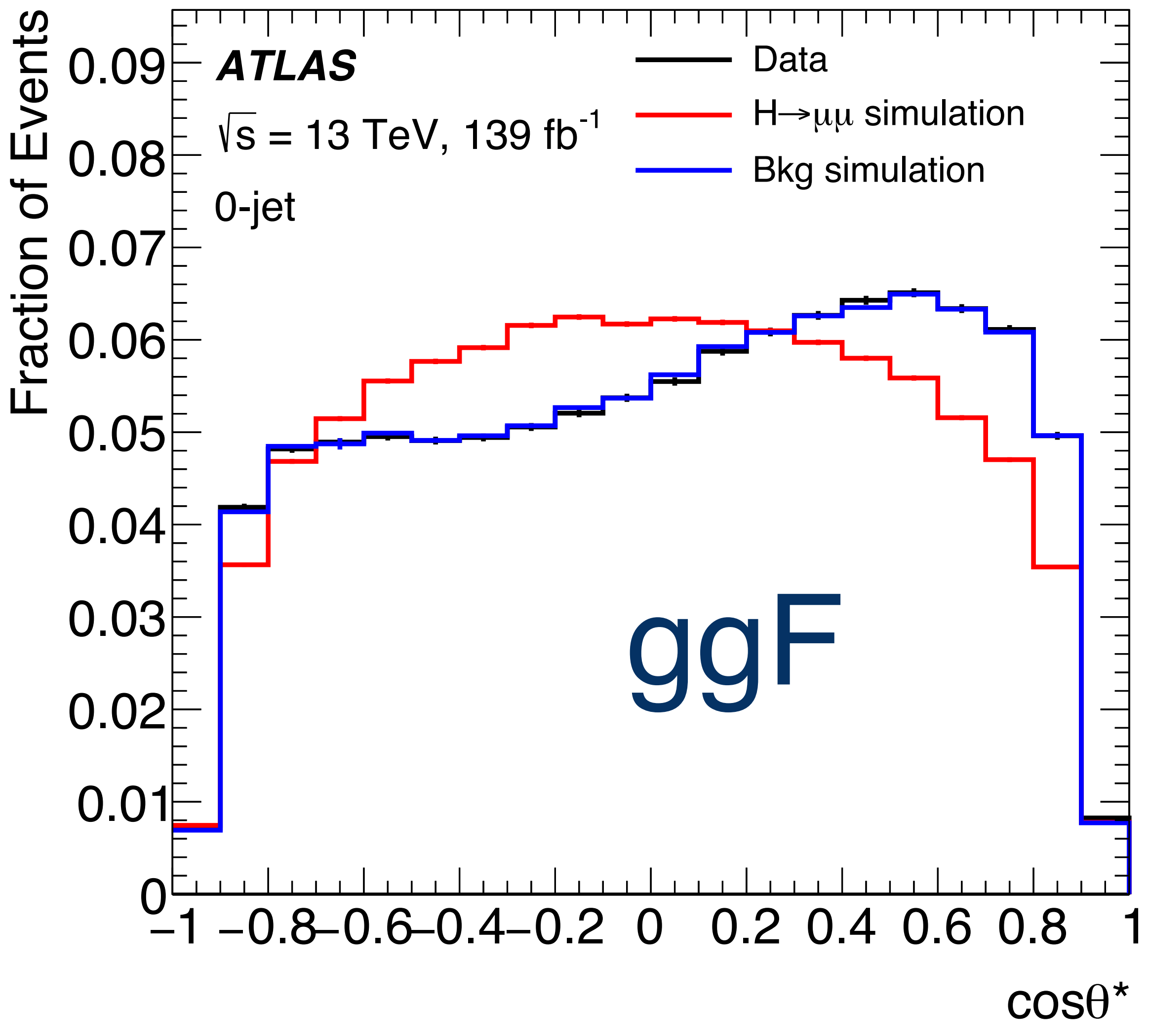
VBF and ggF categories

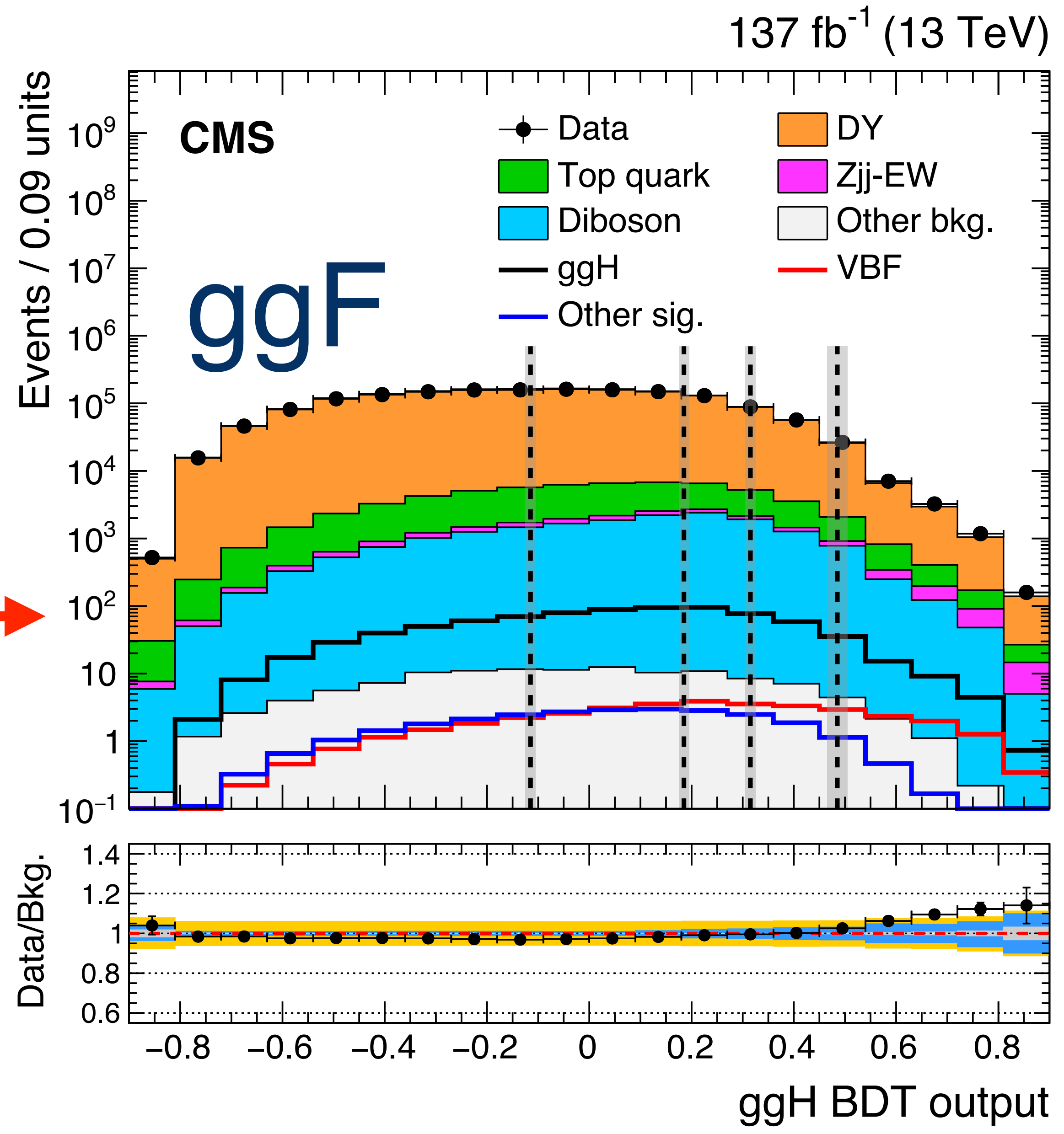
- VBF: isolate out VBF signal featuring 2 jets with **large m_{jj}, large $\Delta\eta_{jj}$** etc. Use Deep Neural Network (DNN) or BDT to enhance sensitivity
- ggF: exploit boost of dimuon pT, angular dist. etc. to suppress background with BDT
- Veto events with b-tagged jet to suppress top background



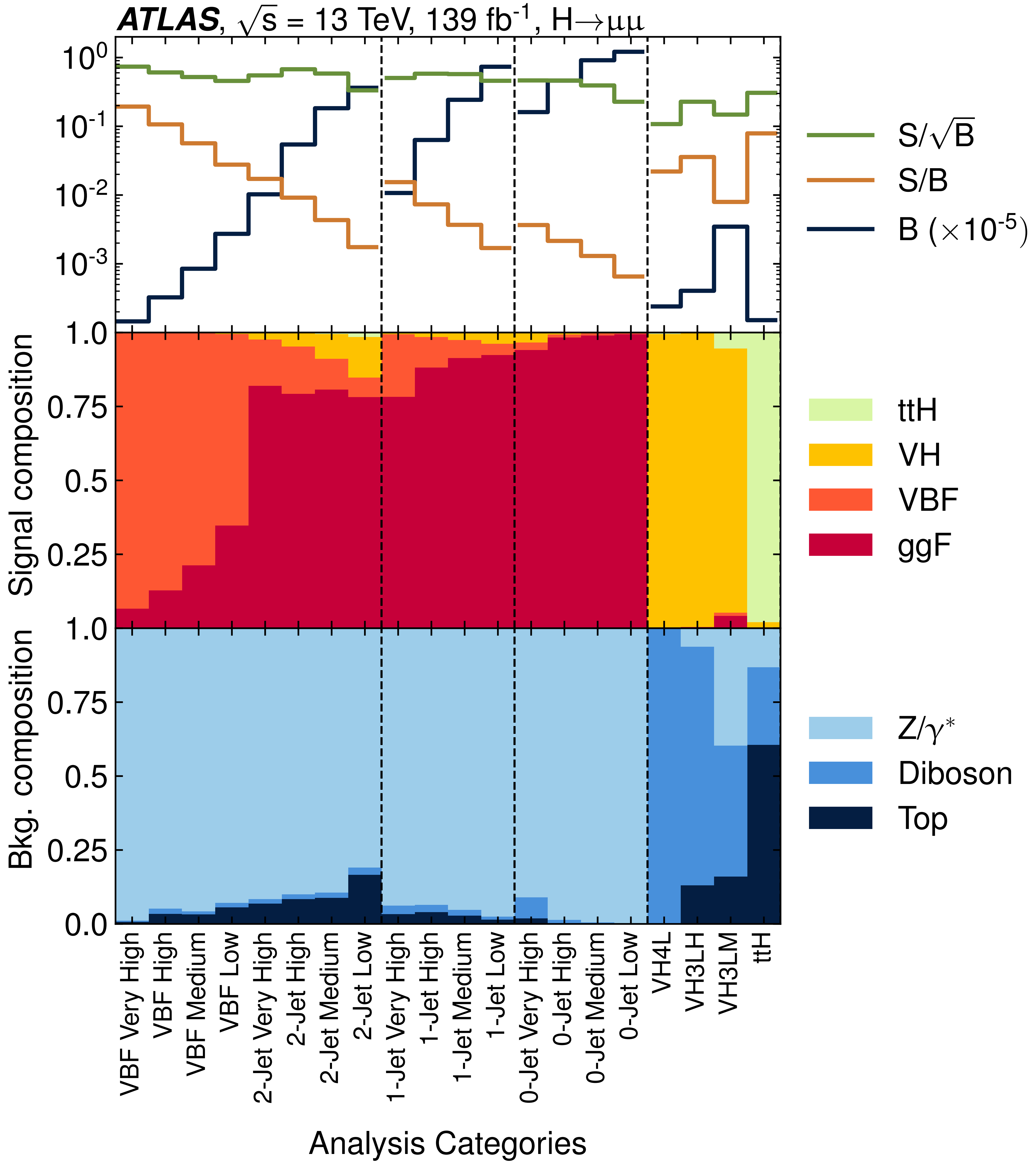


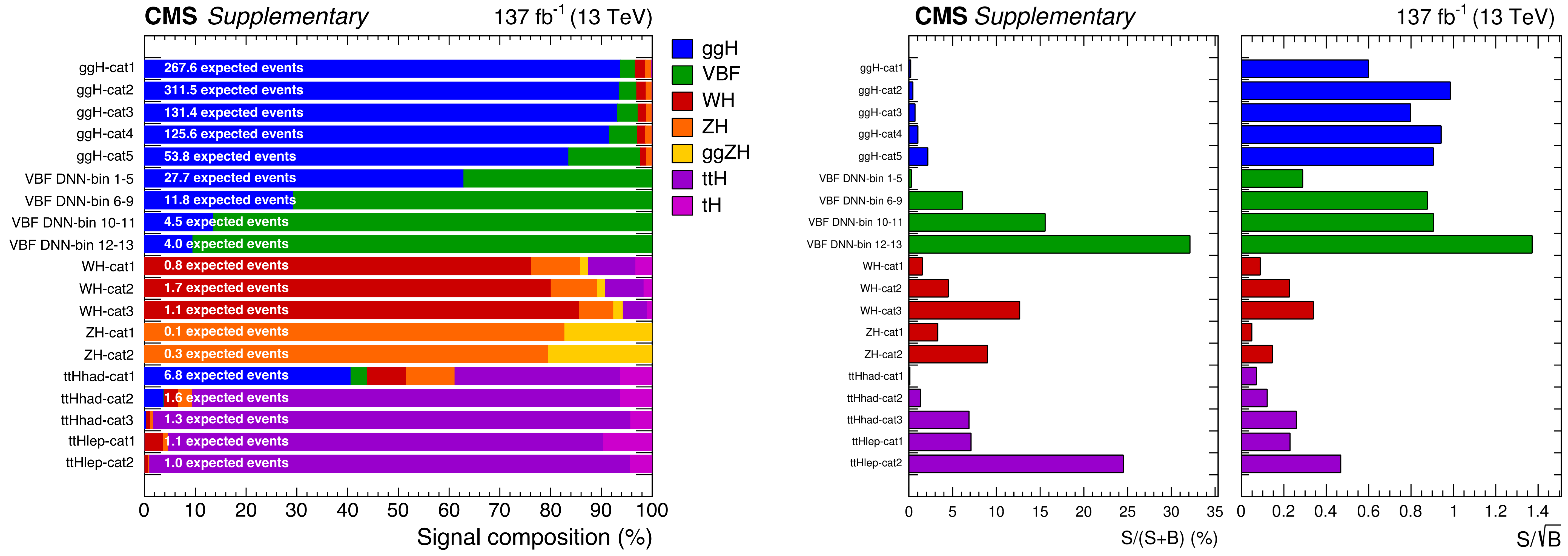






Summary of categorization

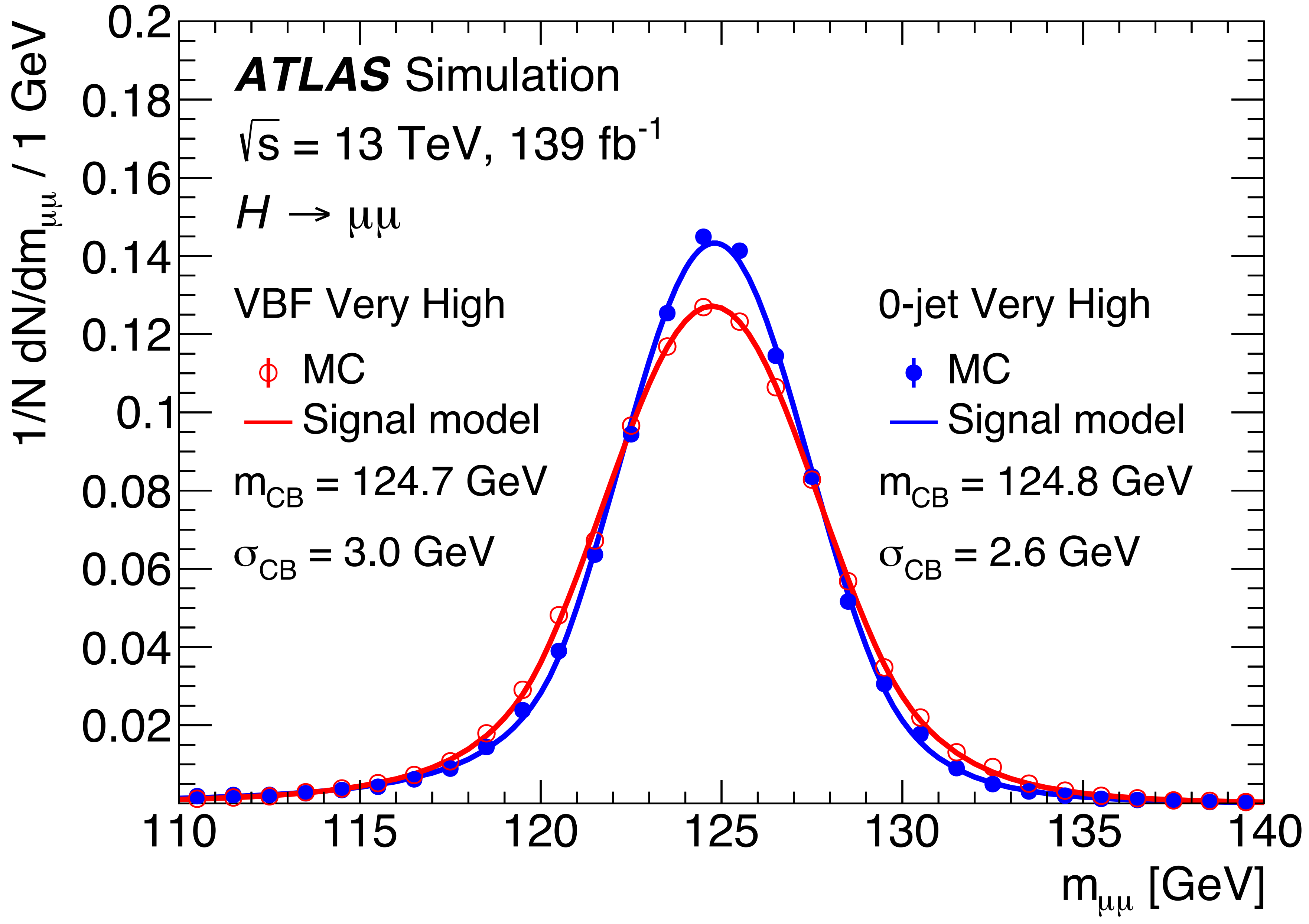


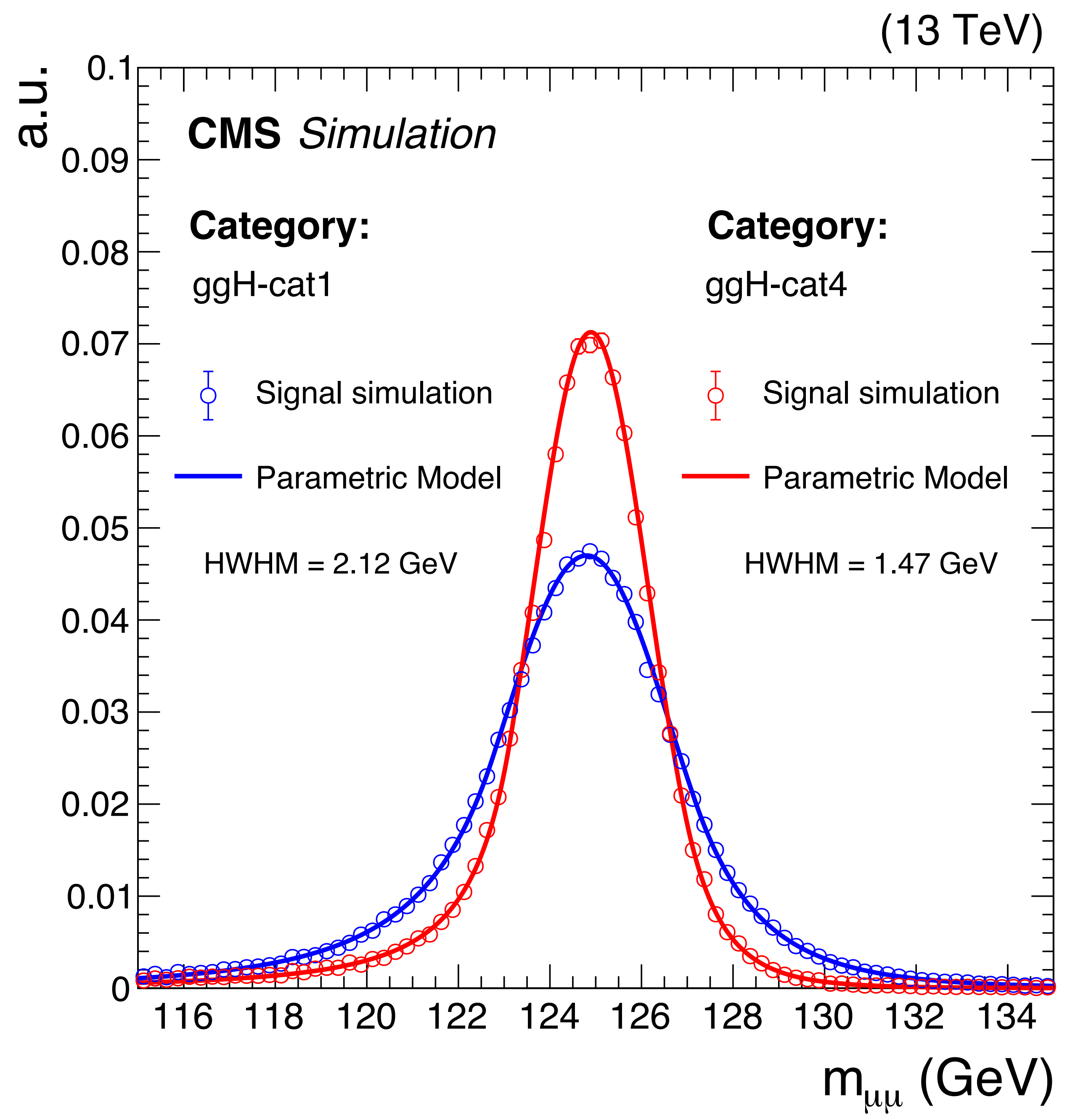


- Good purity of target signals
- Sensitivity driven by **VBF** and **ggF** categories for a SM signal
  - S/B can reach to 20~30% in best VBF category (region)

Signal modeling

- SM Higgs boson width only 4 MeV: signal line-shape fully driven by **detector resolution** (~2 GeV)
- CMS signal resolution **up to ~2 better** than ATLAS mainly due to **stronger magnetic field in the inner tracker** (ATLAS 2 T vs. CMS 3.8 T)

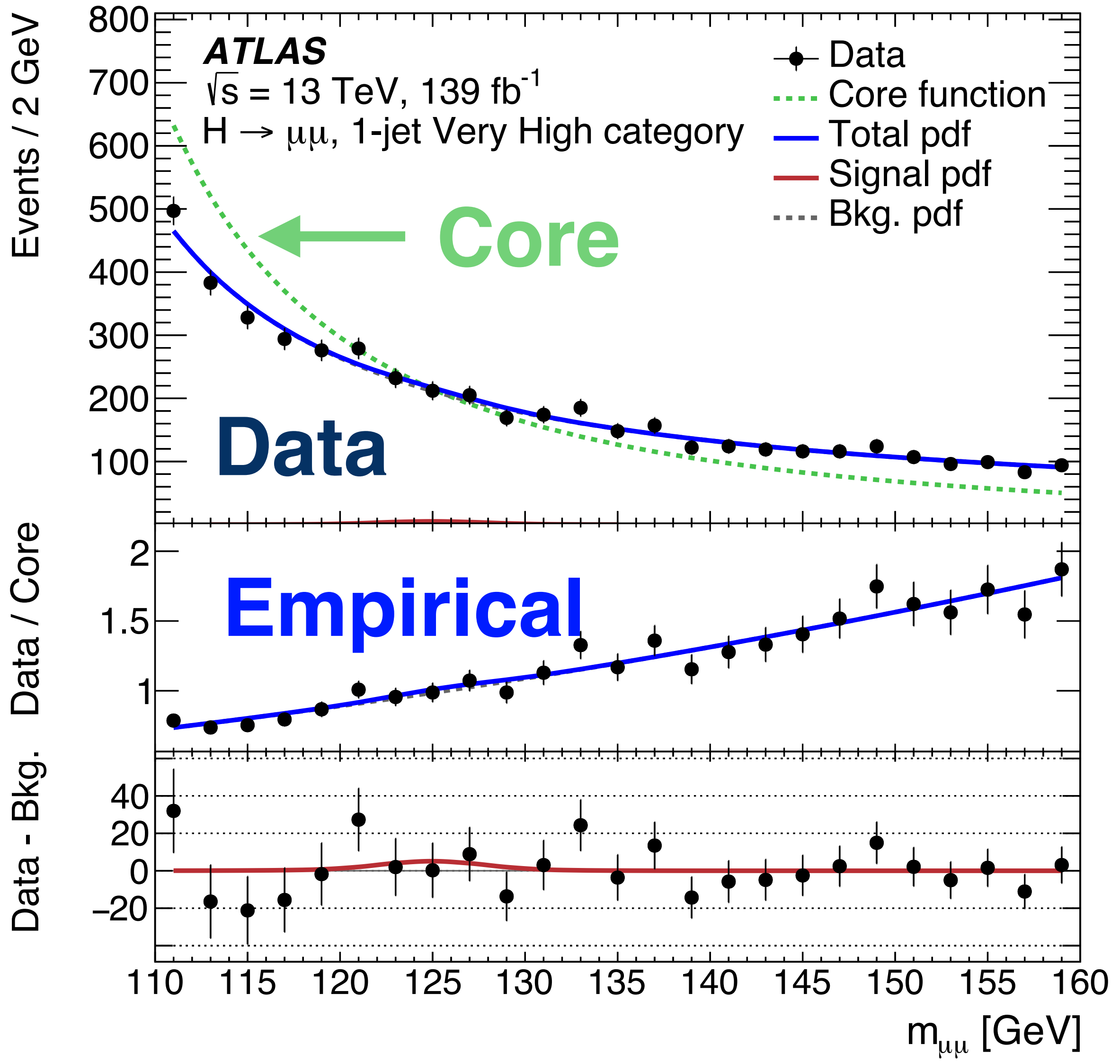


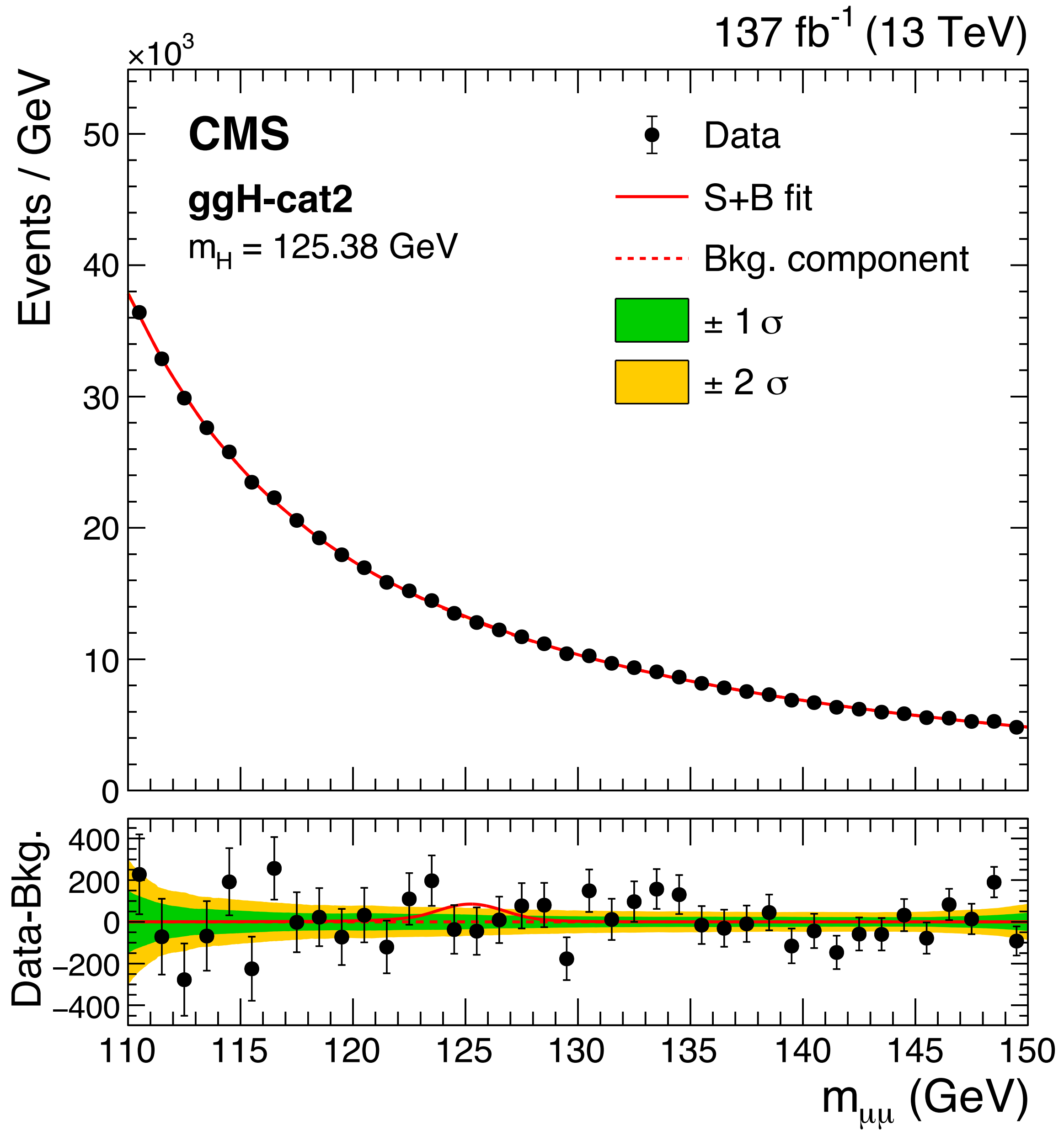


- Muon momentum scale uncertainty: O(0.1%)
- Muon momentum resolution uncertainty: O(1%)
- **Systematics on signal are in general negligible compared to data statistics**

Background modeling: data-driven sideband fit

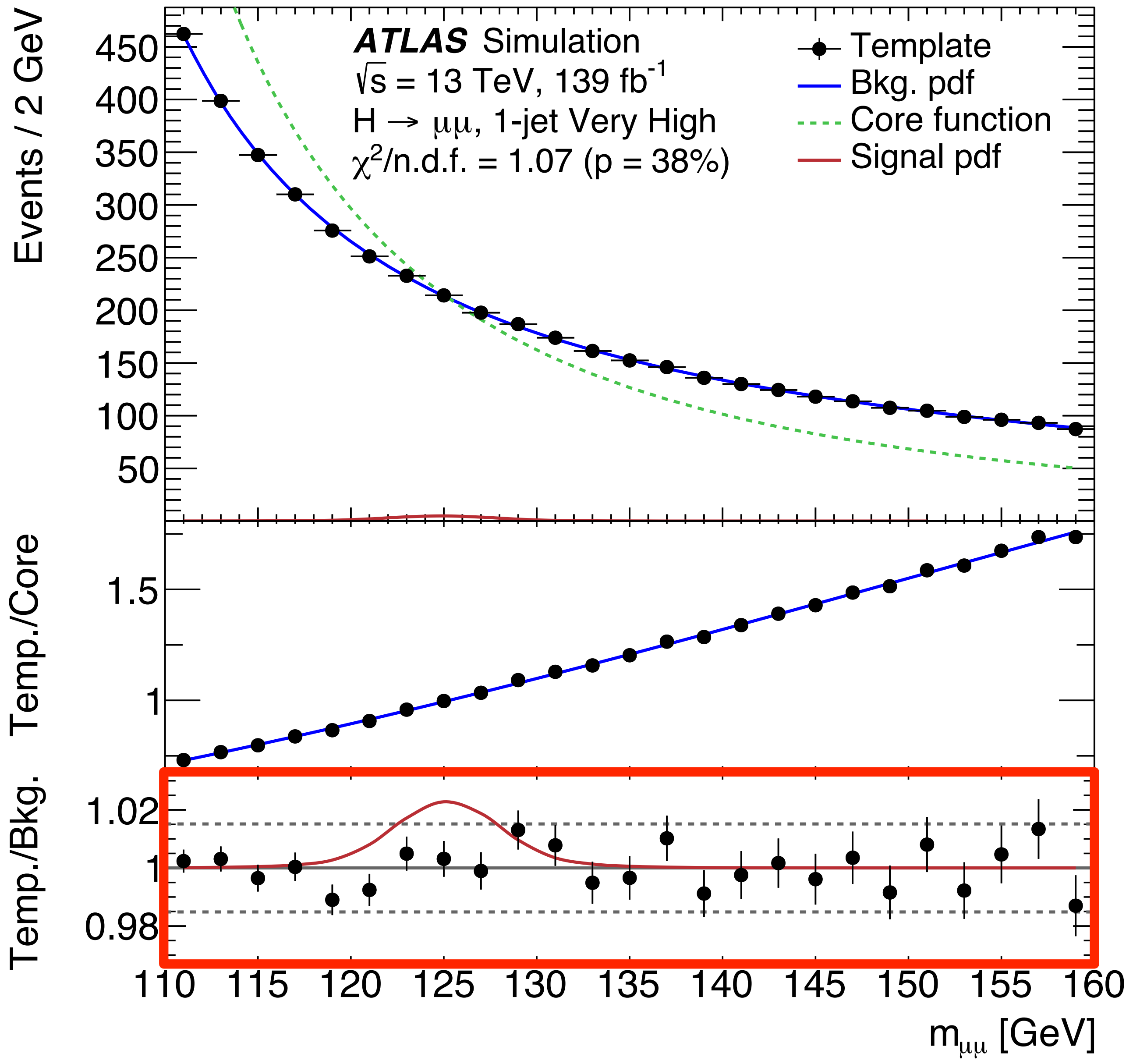
- Used by ATLAS and most CMS categories
- ATLAS and CMS independently converged on "**core×empirical**" strategy
  - **Core function**: capture the bulk of the spectrum shape
    - ATLAS: LO Drell-Yan line-shape convoluted with detector resolution, fully rigid
    - CMS: discrete profile of a set of physics-driven or customized functions, contains free parameters correlated among ggF categories
  - **Empirical function**: absorb remaining difference

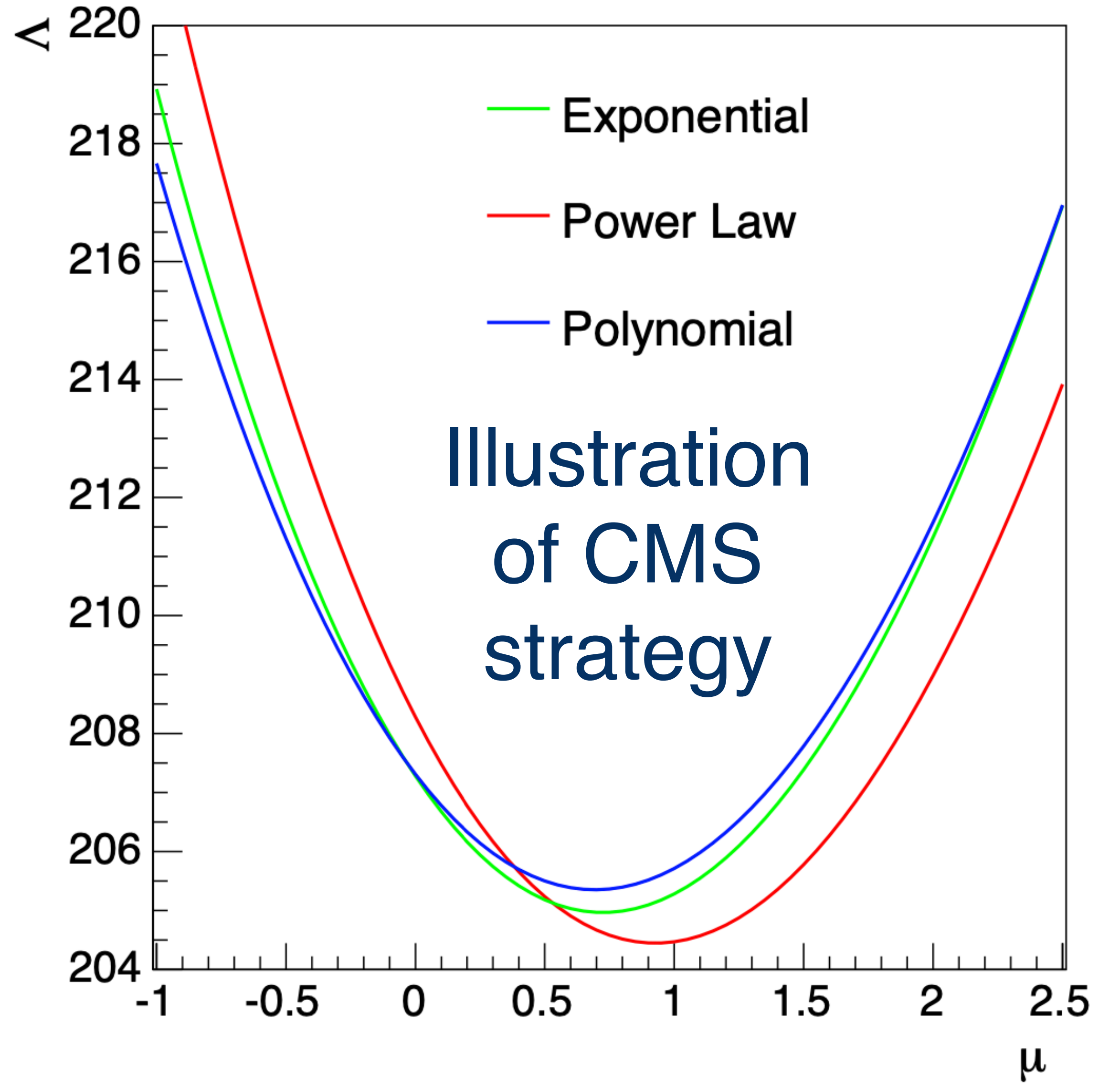




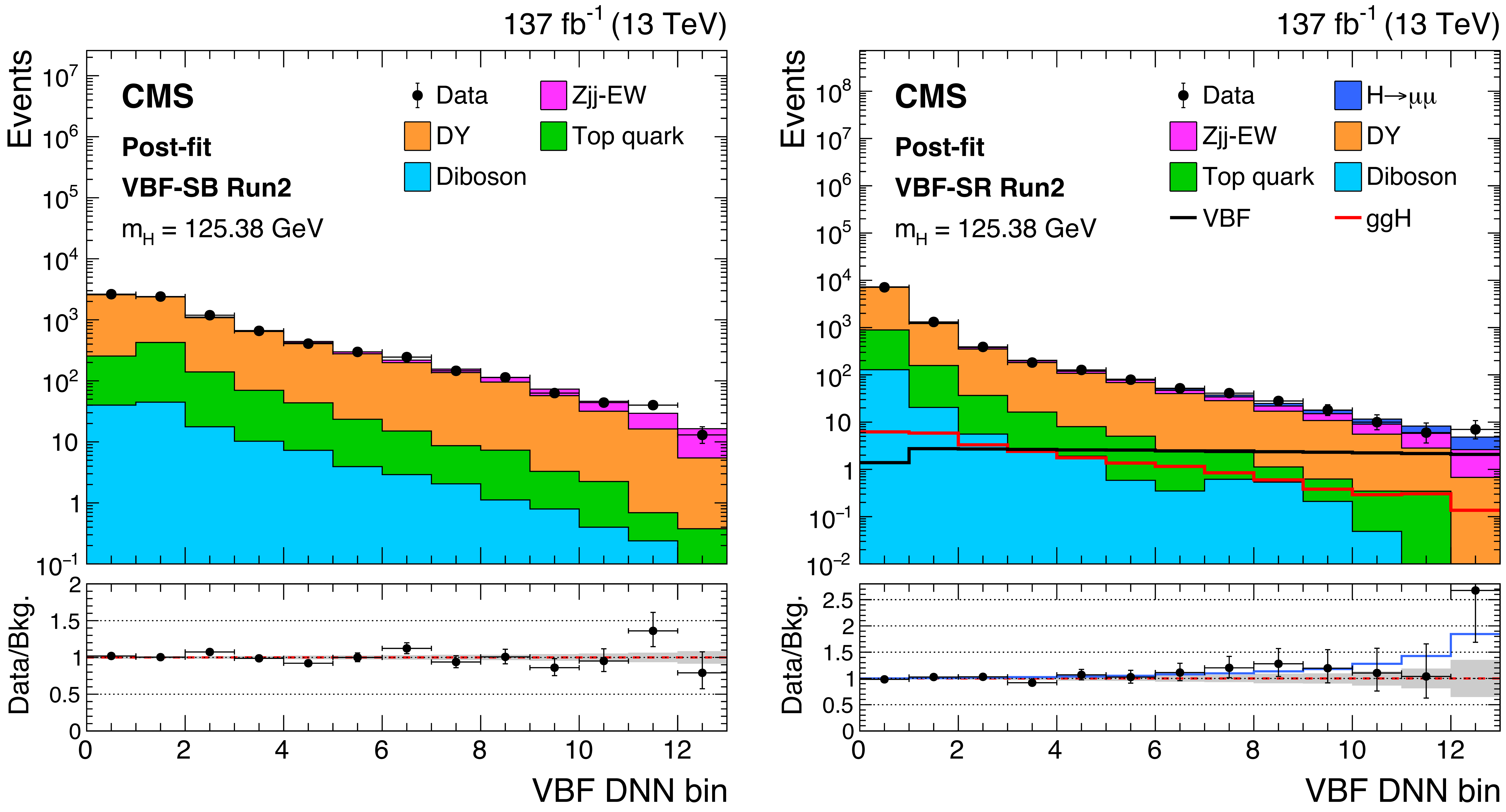
How to decide data-driven parameterization

- ATLAS: **single model** selected by **spurious signal** test based on high statistics MC background template
  - Fit S+B model to a bkg.-only MC template. Fitted signal yield called “spurious signal” (SS). It is used to
  1. Select bkg. model (SS < 20% of data stat. uncert.)
  2. Assigned as background model systematic
- CMS: **multi-model discrete profile**
  - Select models with bias < 20% of data stat. uncert.
  - Let data decide the best model in the fit (discrete-profile)





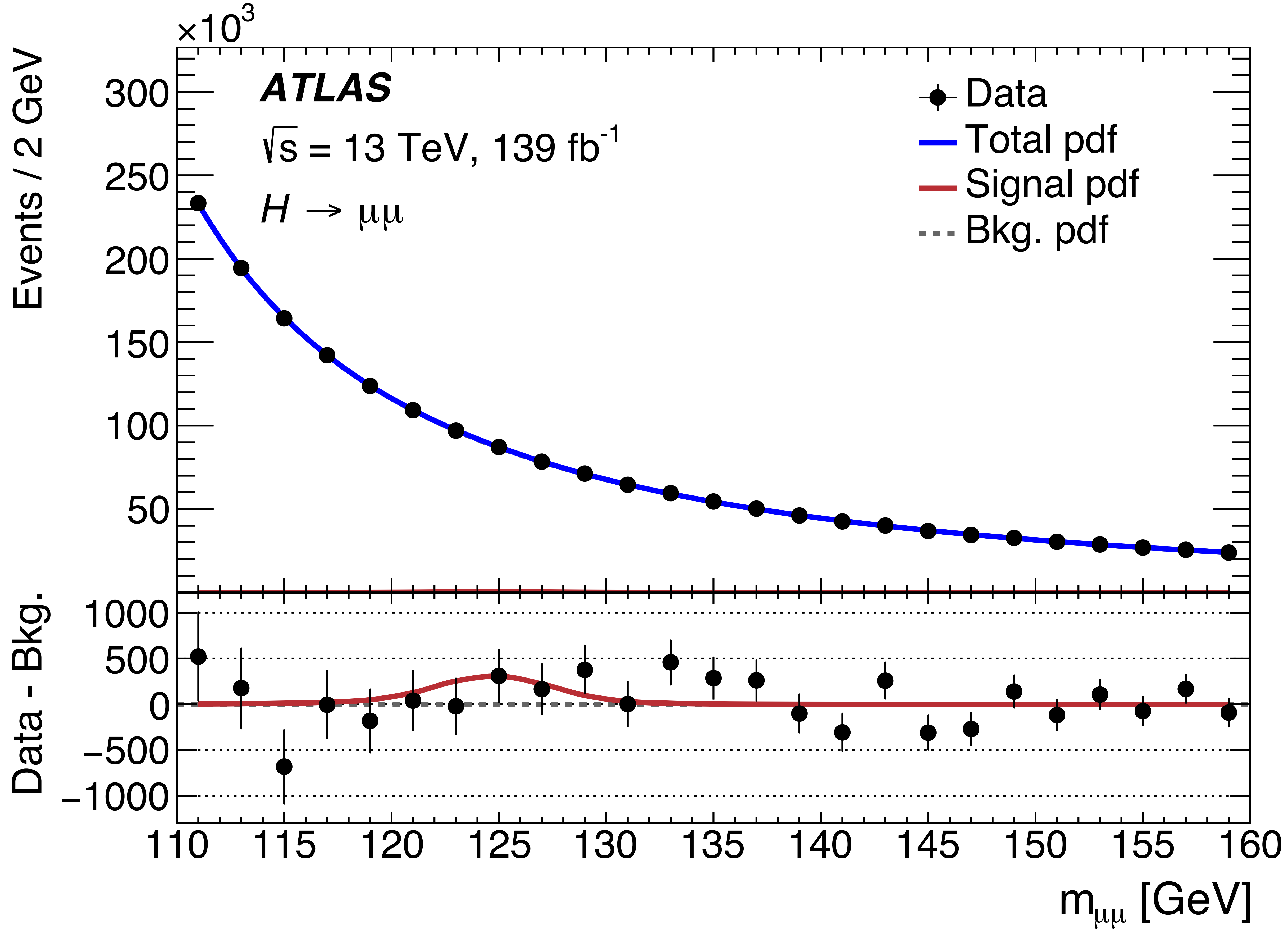
MC template fit for CMS VBF category

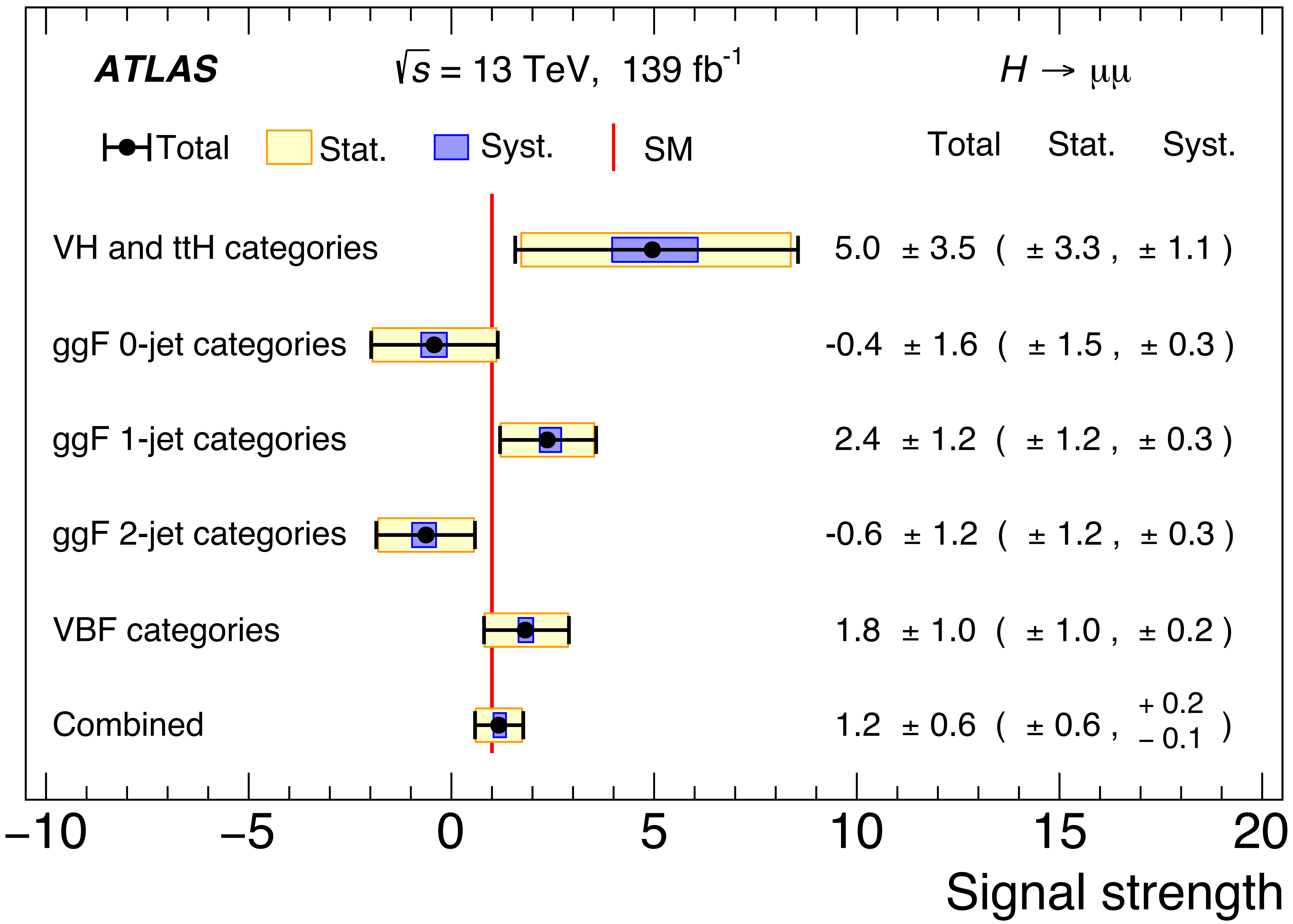


- Directly fit MC templates to data
  - **20% improvement** compared with data-driven approach in VBF category
  - Data sideband stat. uncert. + bkg. modeling uncert. → experiment and theory syst. in MC

- Simultaneous fit signal region and sideband. DY (@NLO) and EW Zjj (@LO) production both simulated with MG5_aMC. Bkg. normalized to state-of-art cross-section calculations

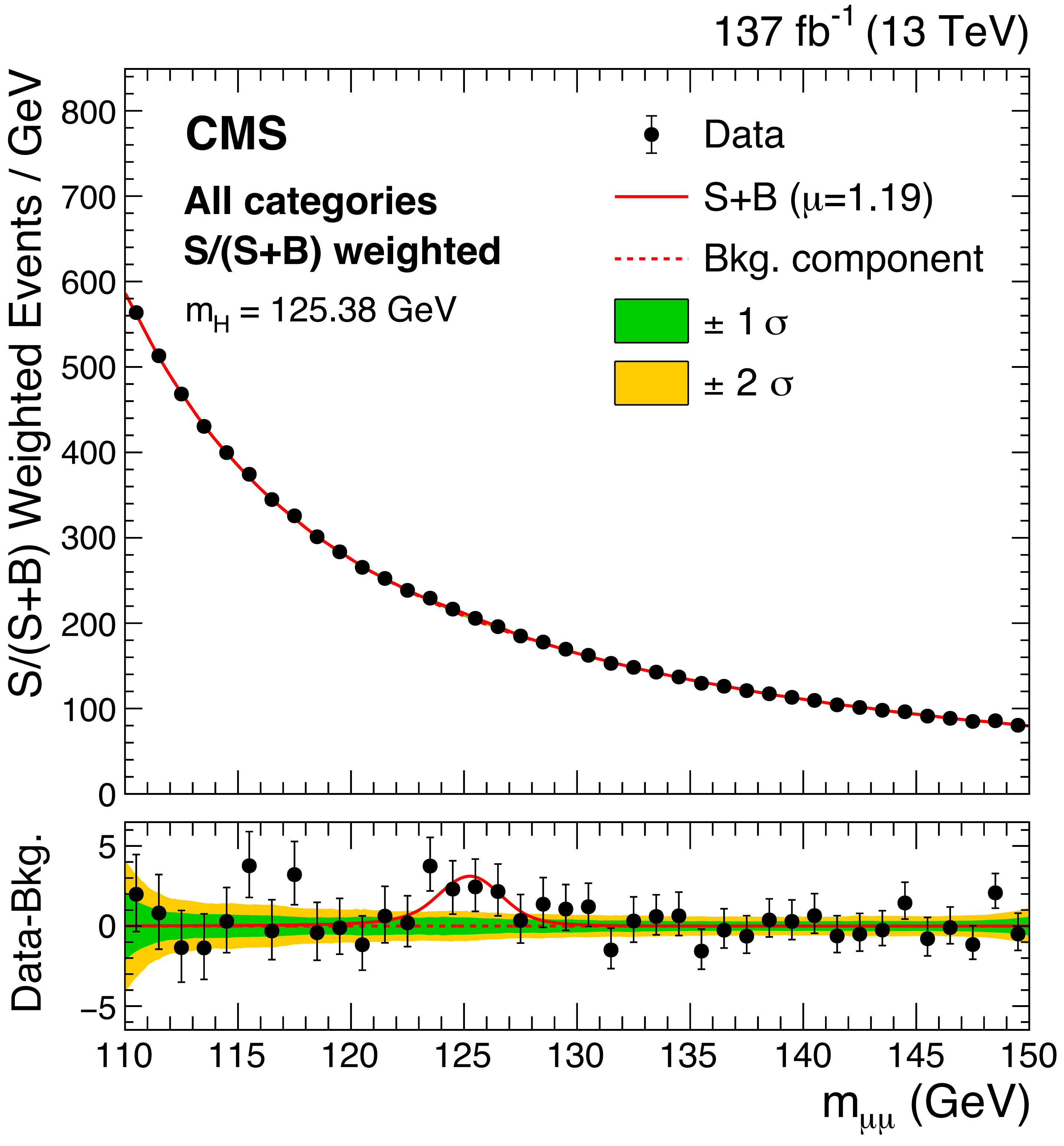
ATLAS results

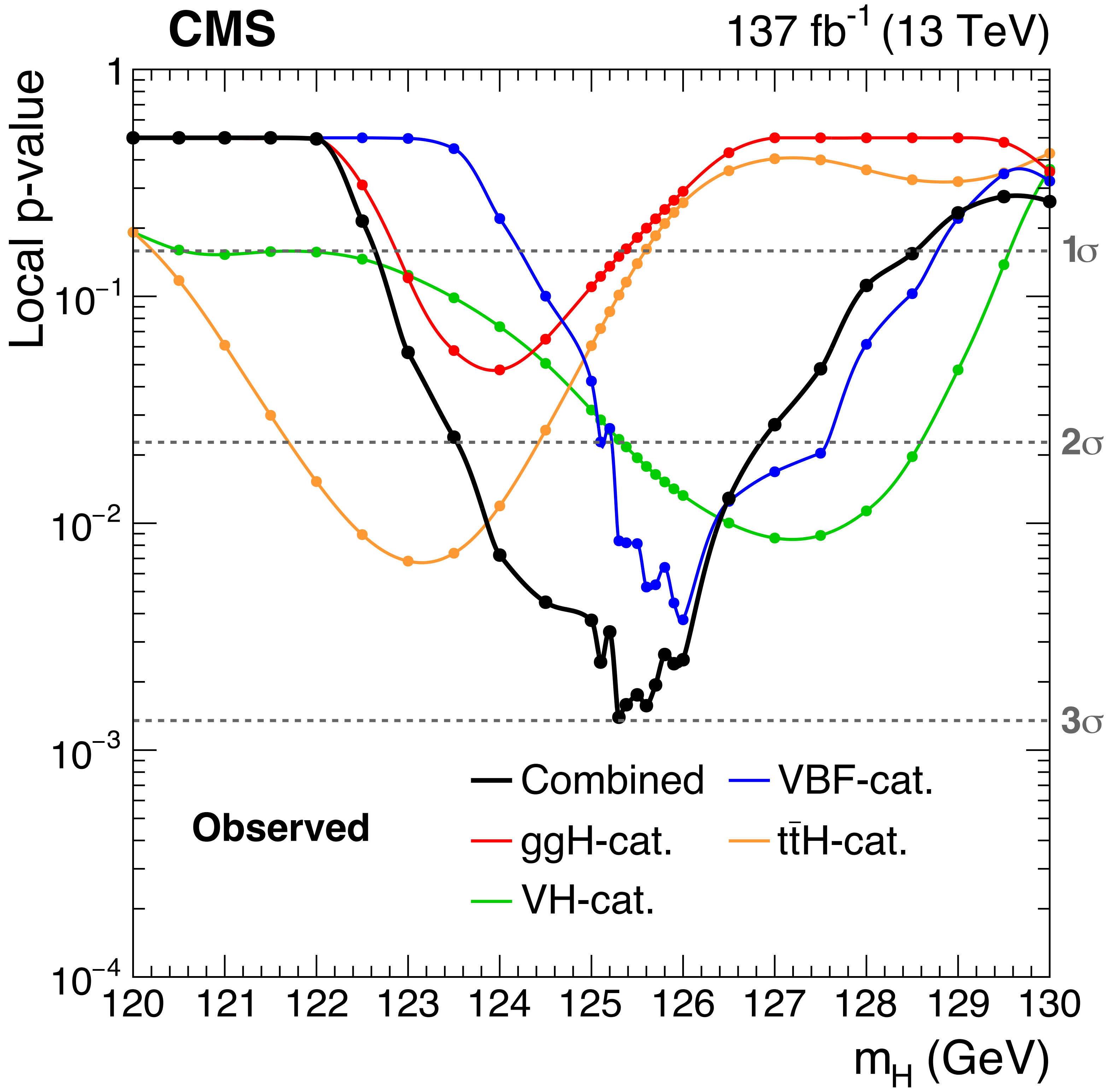


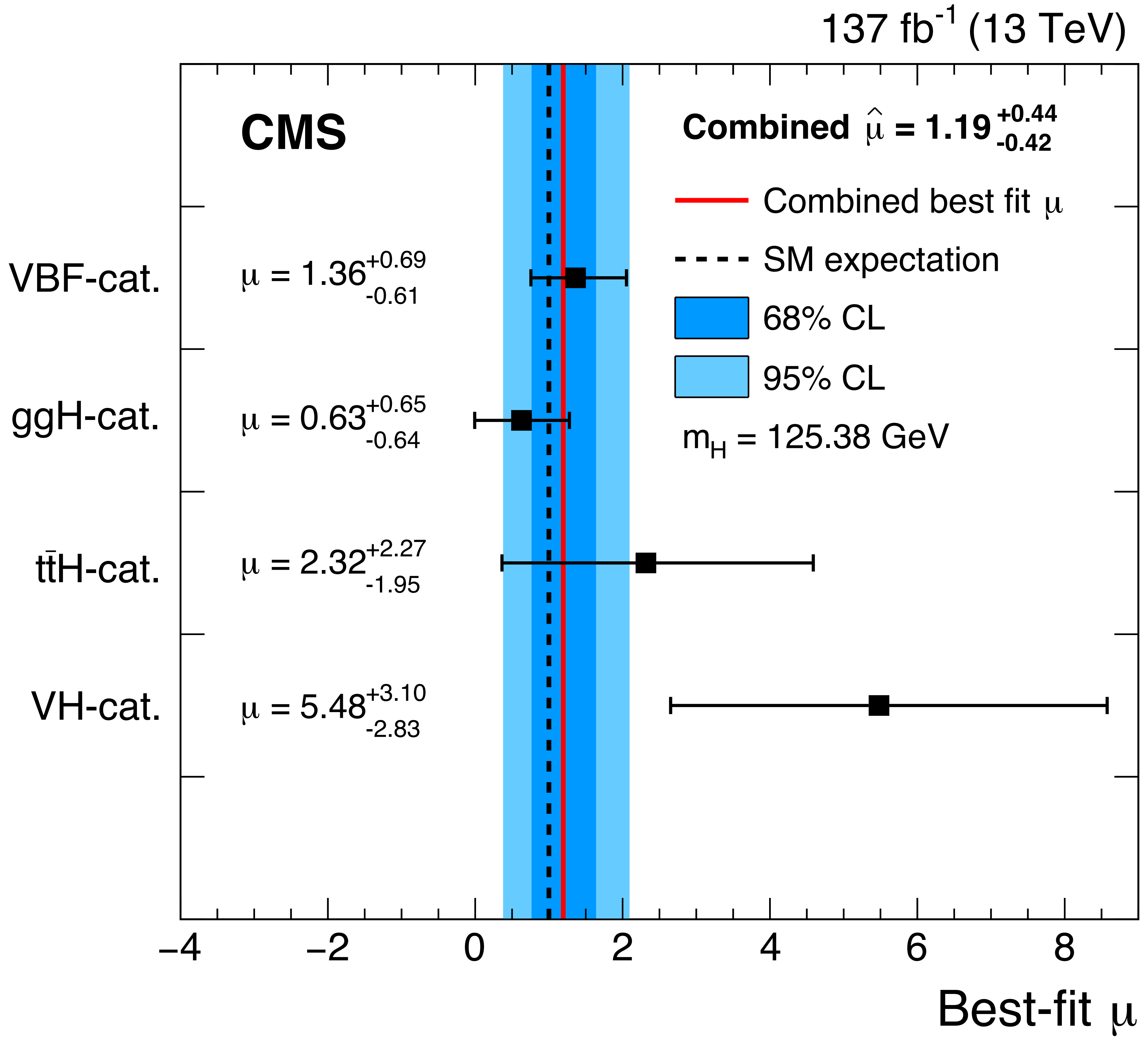


- Expected significance 1.7σ, **observed 2.0σ** (m_H = 125.09 GeV)
- Signal strength $\mu = 1.2 \pm 0.58\,(\text{stat})\,^{+0.13}_{-0.08}\,(\text{theory})\,^{+0.07}_{-0.03}\,(\text{exp})\ \pm 0.10\,(\text{spurious})$

CMS results

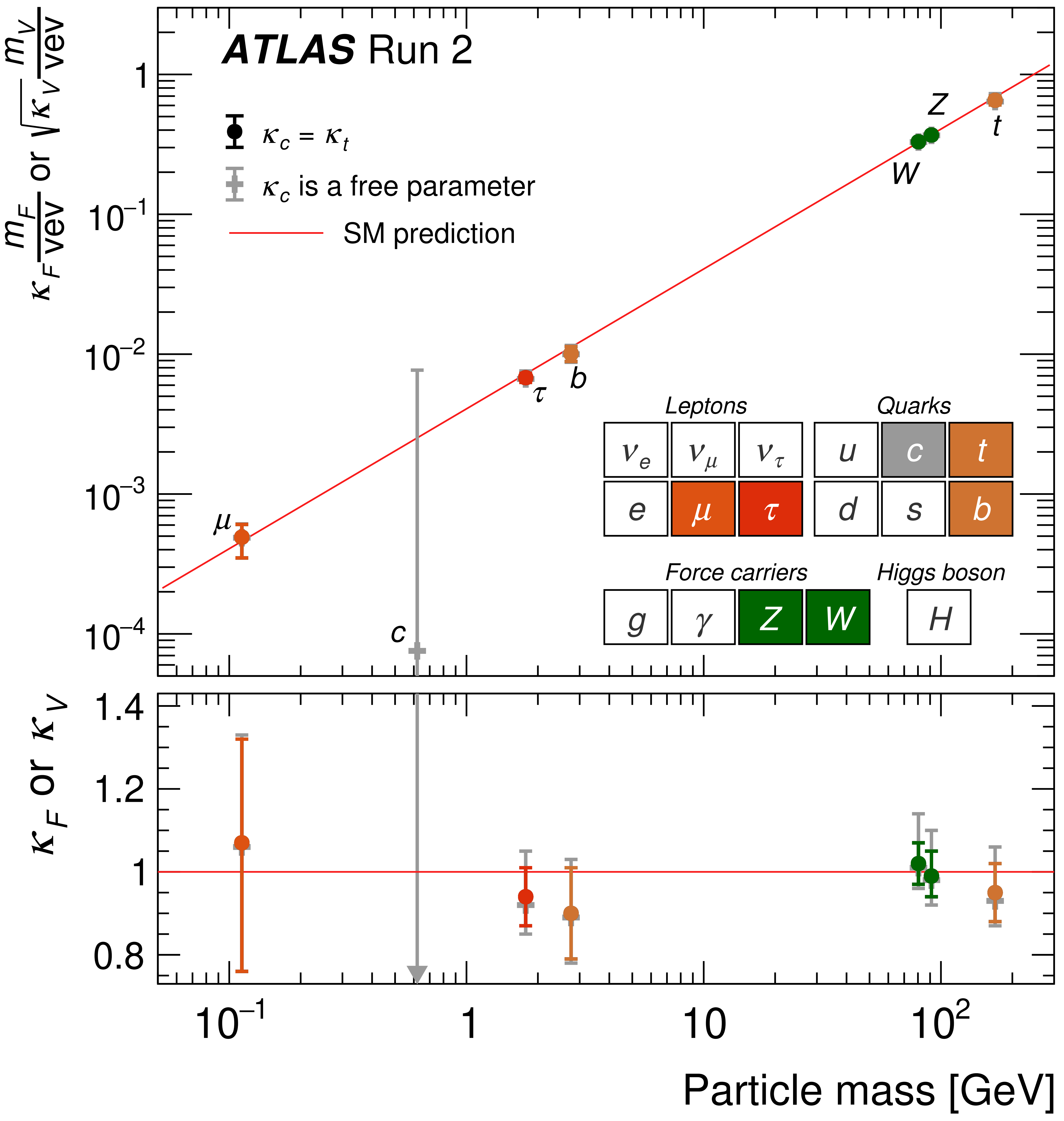


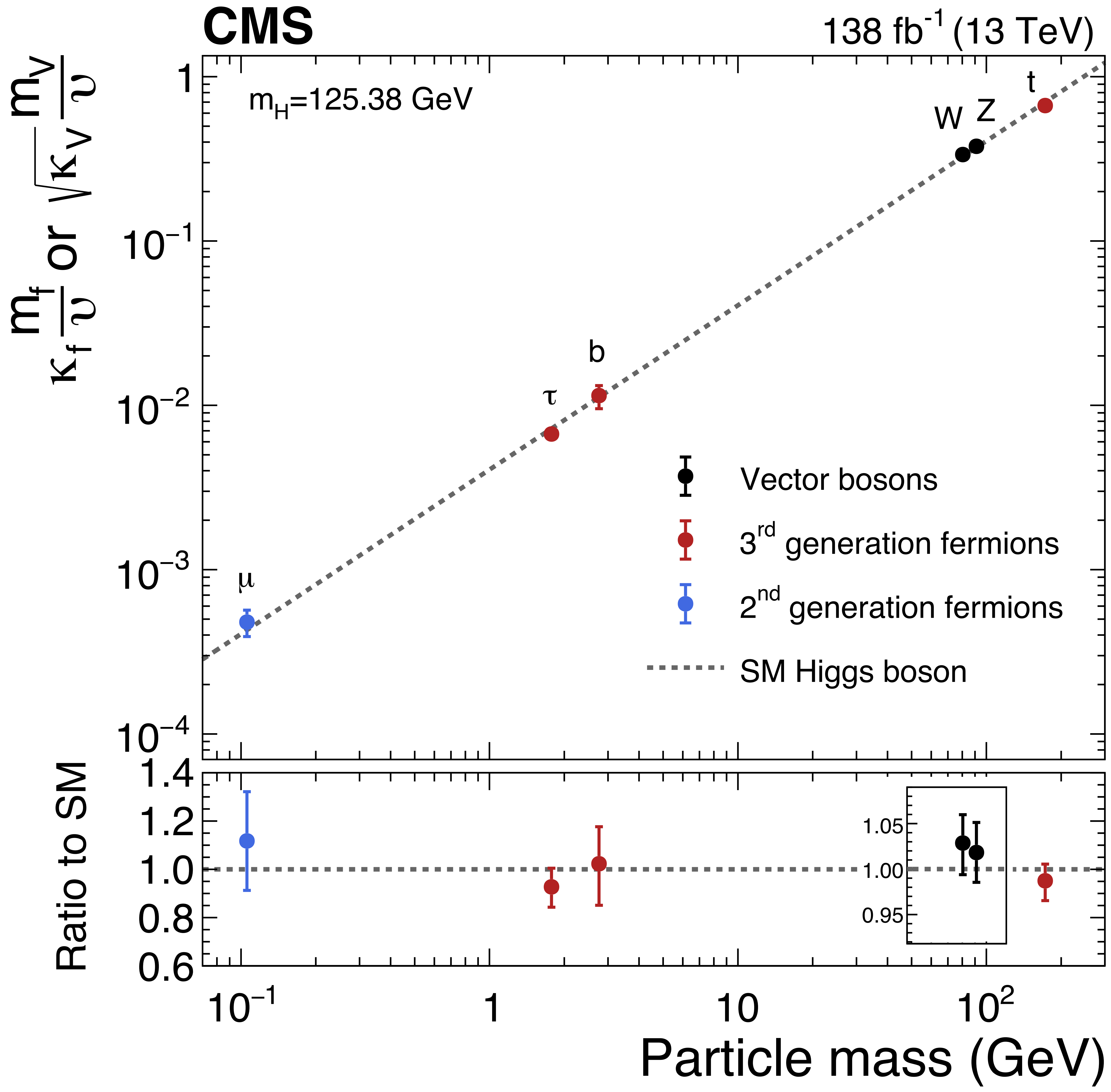




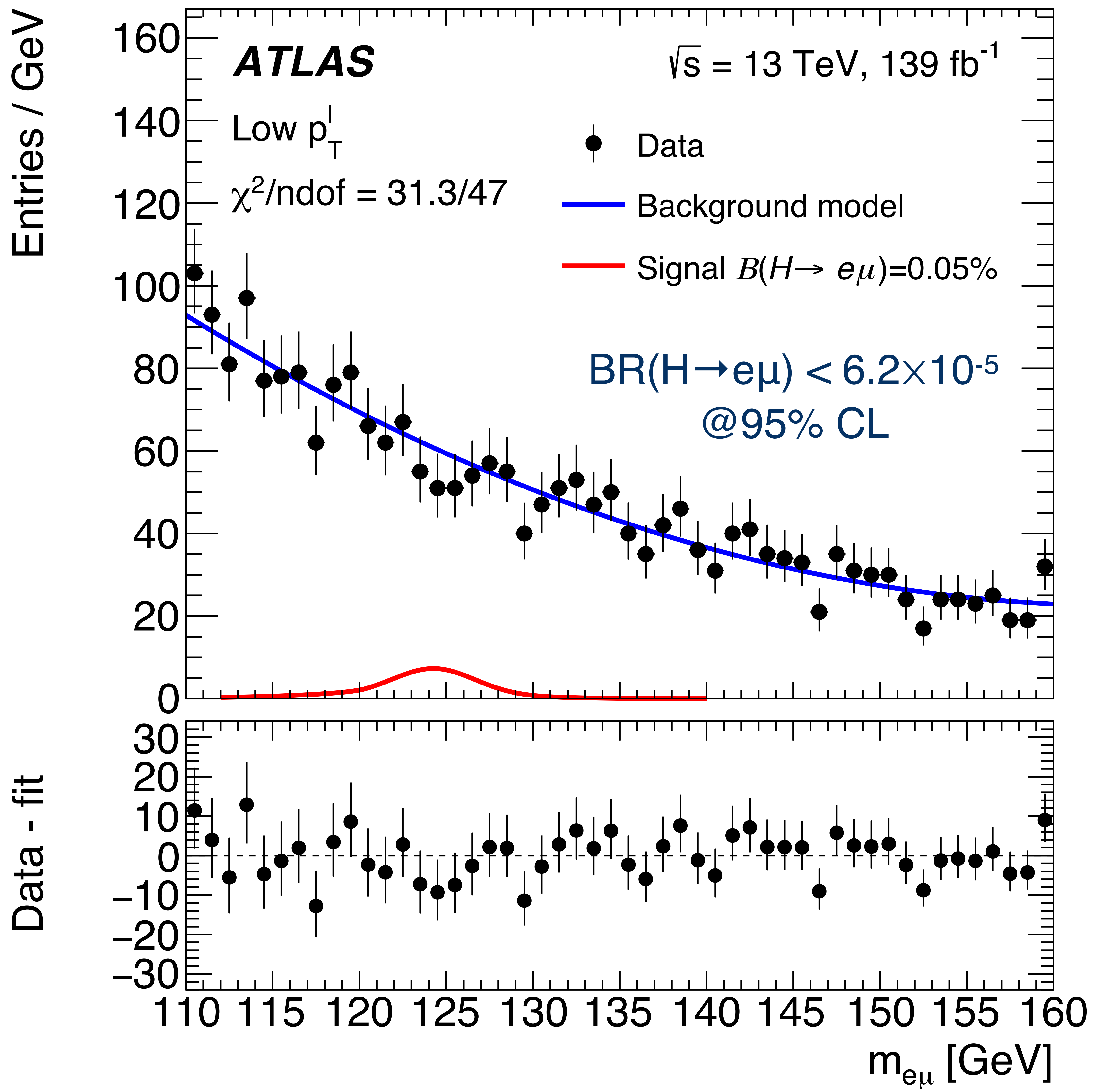
- Expected significance 2.5σ, **observed 3.0σ** (m_H = 125.38 GeV)
- Signal strength $\mu = 1.19^{+0.41}_{-0.40}(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})$

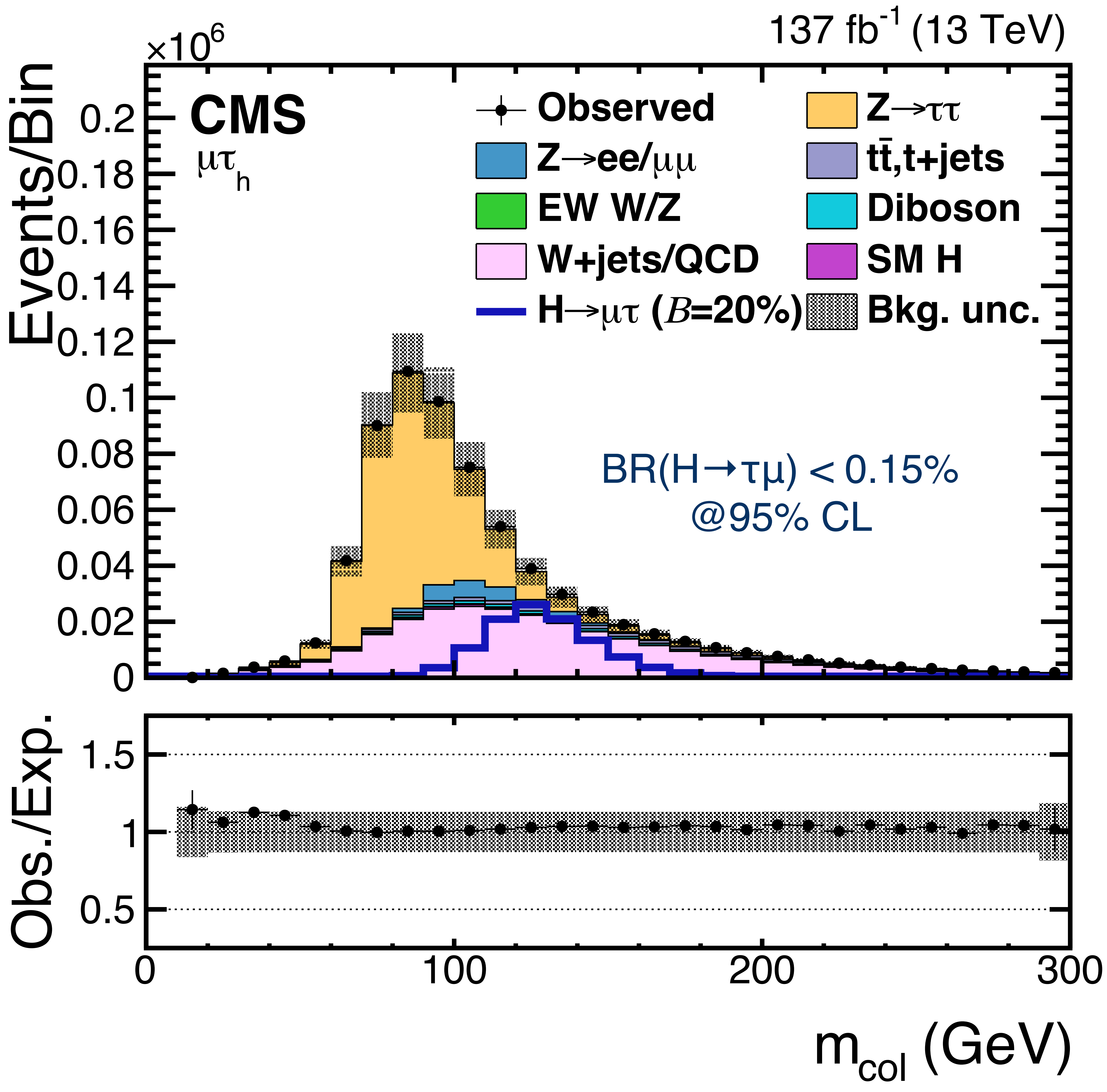
Muon Yukawa coupling strength test





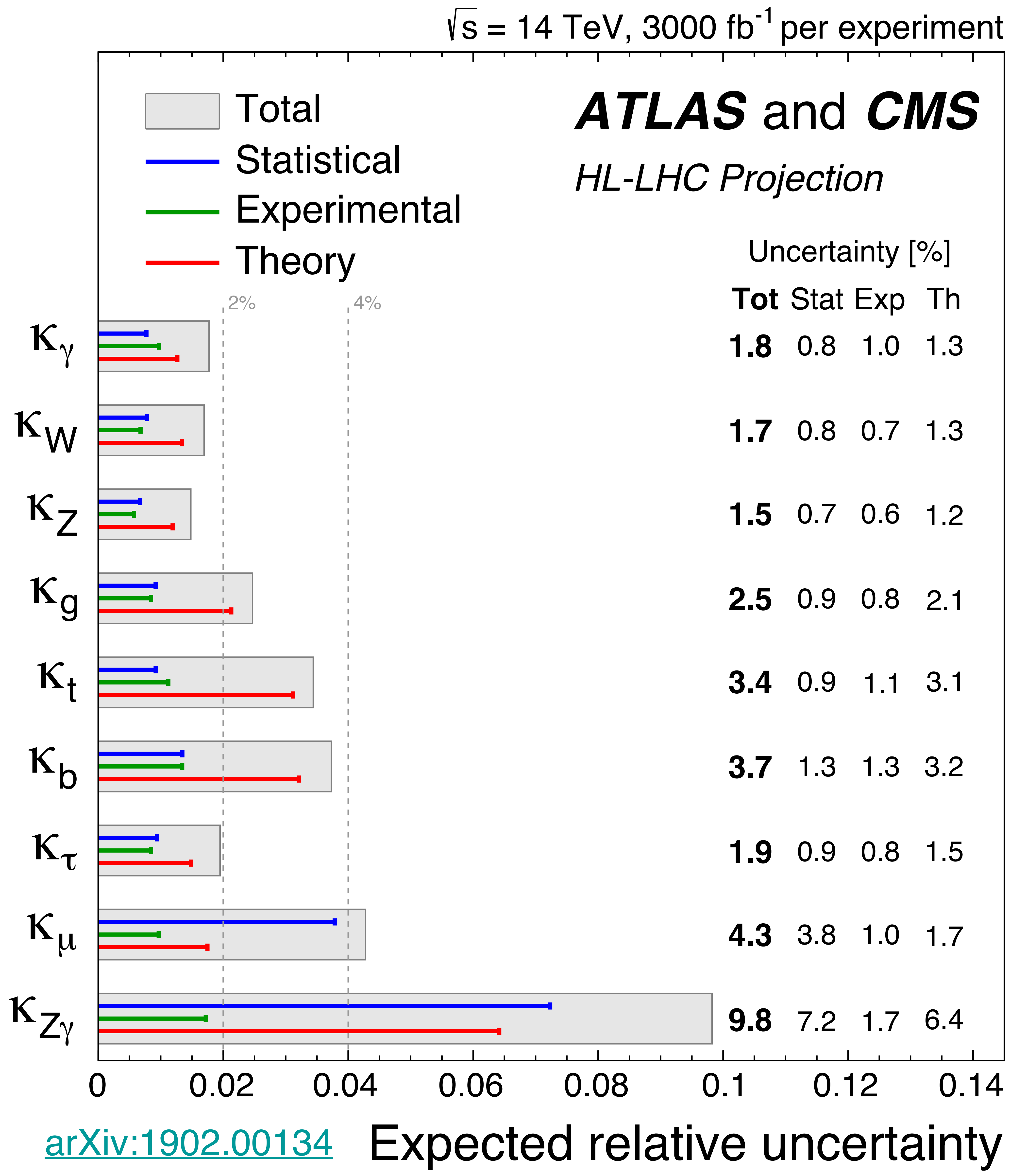
LFV Higgs boson decay searches





Conclusions

- **First evidence of H→μμ** declared with LHC Run 2 data (CERN press release)
- Run 3 data analysis ongoing. Expect ~250 fb^{-1} @13.6 TeV
  - Observation might be possible combining ATLAS+CMS?
- Single experiment observation expected in the middle of HL-LHC
- H→μμ will hopefully provide very interesting test of SM by the end of LHC lifetime!



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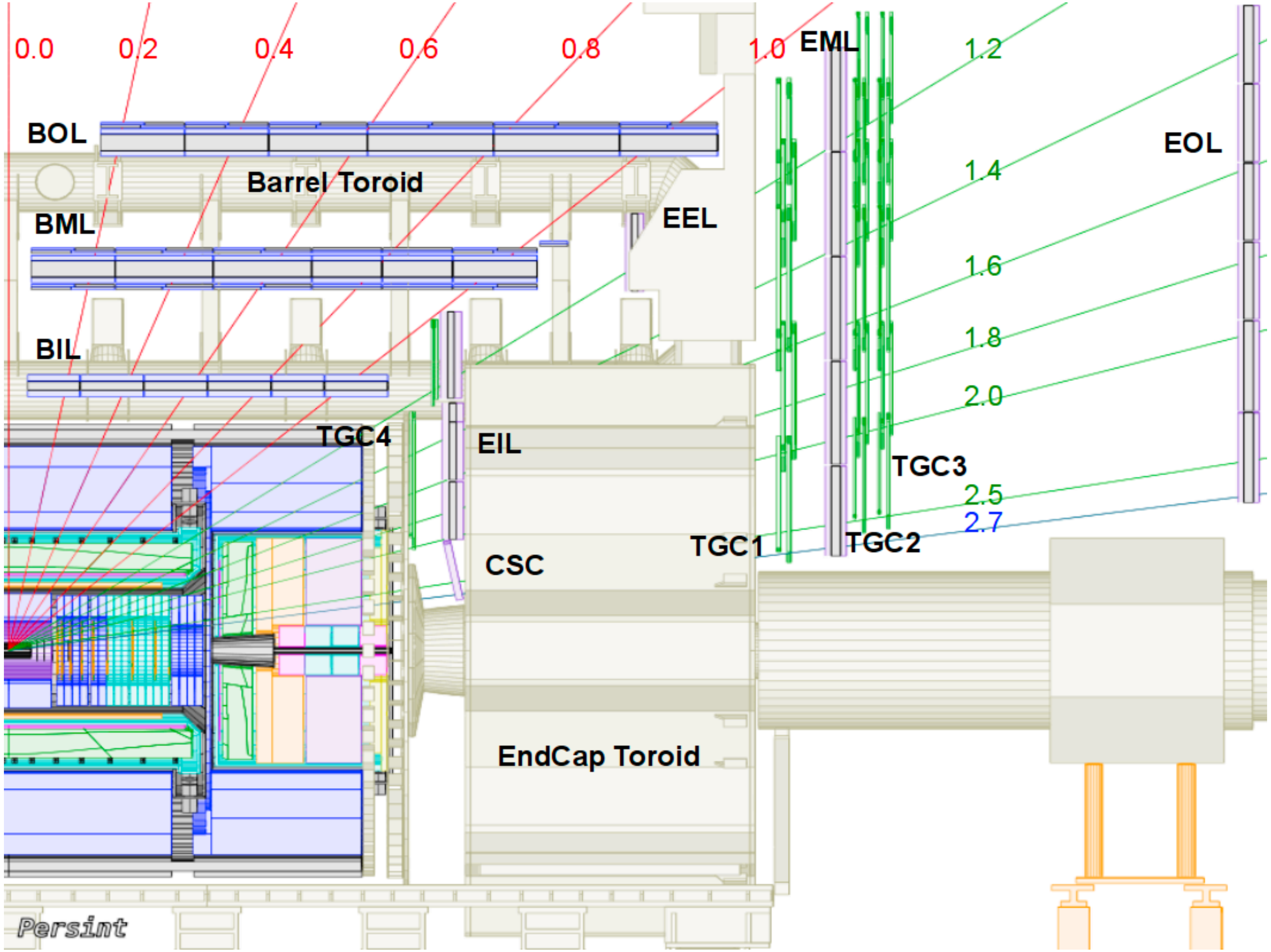
Backup

ATLAS muon spectrometer



CMS muon spectrometer