Rare, Exotic, and Invisible Higgs Decays at CMS

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on behalf of the CMS Collaboration

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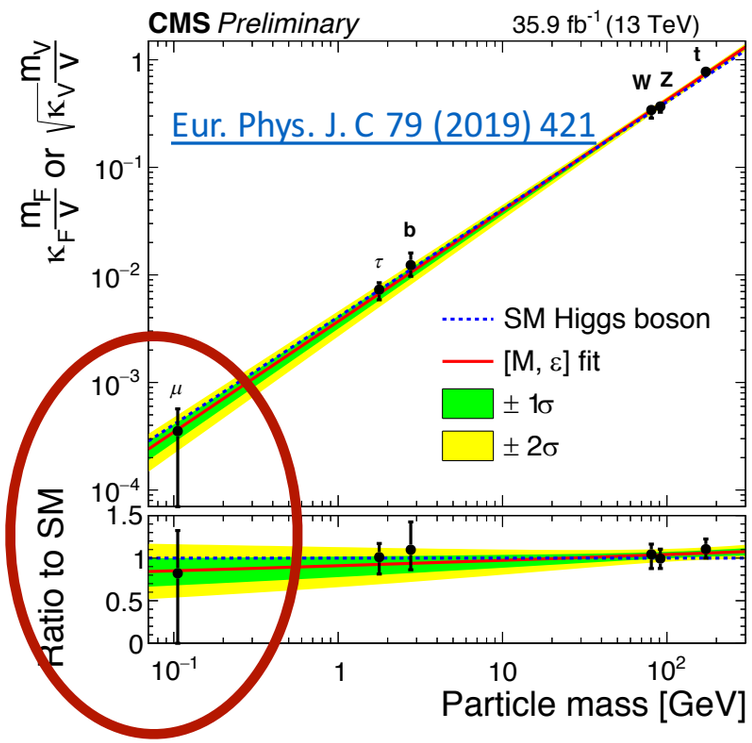
Introduction

- **This report summarises the following relevant (and recent) results from the CMS Collaboration:**
  - **Measurement of Higgs boson decay to a pair of muons in proton-proton collisions at 13 TeV**
    - JHEP 2101 (2021) 148
  - **Search for the Higgs boson decay to Zγ in proton-proton collisions at 13 TeV**
    - CMS-PAS-HIG-19-014
  - **Search for exotic decay of the Higgs boson into two light pseudoscalars with four photons in the final state at 13 TeV**
    - CMS-PAS-HIG-21-003
  - **Searches for the invisible decays of Higgs bosons at 13 TeV:**
    - VBF analysis: CMS-PAS-HIG-20-003
    - Mono-V/jet analysis: CMS-PAS-EXO-20-004 (Submitted to JHEP)
    - Z(ll)H analysis: EPJC 81 2021

Higgs boson decay to μμ: Strategy

- **Why the interest in the dimuon final state?**
  - A golden channel for probing the Higgs boson coupling with the 2nd generation fermions
  - Challenging due to: **B(H→μμ)** $\sim 2.19 \cdot 10^{-4}$

- **Approach: Events are collected using single muon trigger algorithms**
  - Common requirements for all channels:
    - Two identified and isolated muons with $110 < m_{\mu^+\mu^-} < 150$ **GeV**
  - Three **exclusive** channels that are new to the strategy: **ttH/VH/VBF**



- **ggH/ttH/VH categories:**
  - Formation of subcategories based on the final state
    - exp. **VH**: ZH and WH categories
  - Usage of boosted decision tree (BDT) multivariate discriminator
    - Dimuon mass decorrelated training
    - Trained separately for each data taking period to incorporate detector effects
  - **Significance is extracted by fitting $m_{\mu^+\mu^-}$ with analytical shapes inspired from simulation**

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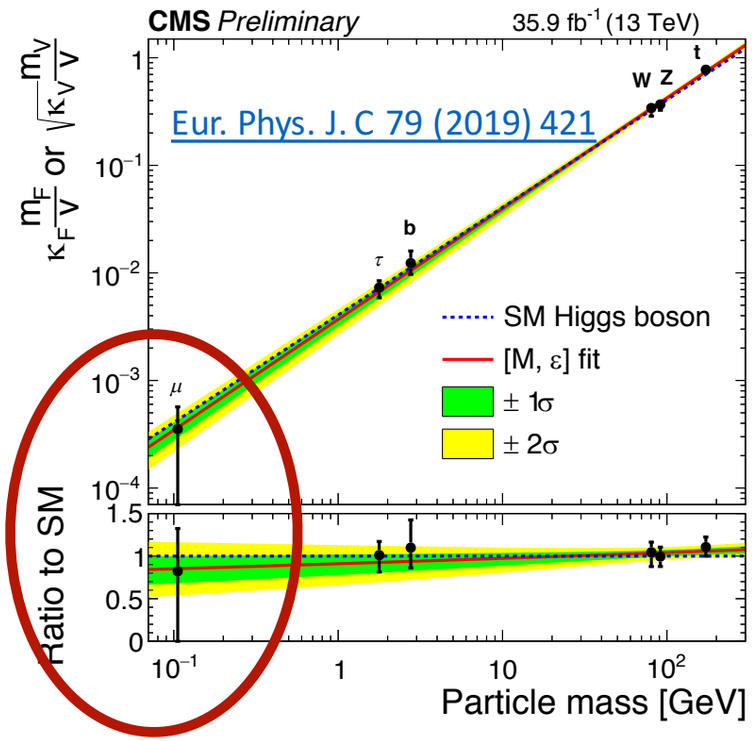

- **VBF category:**
  - **Specific jet topology allows for a tailored selection**
  - **Main backgrounds: QCD/EWK** production of **Z+jets**
  - Estimation through the usage of simulated events
    - Trading limited data statistics for simulation prediction with associated uncertainty
  - Signal extraction: Deep neural network (DNN) multivariate discriminant
  - Maximum likelihood fit to the DNN output score simultaneously in SR and SB

Higgs boson decay to μμ: Results

- **Simultaneous fit performed across all channels with** $\mu = \frac{[\sigma B(H \to \mu\mu)]_{observed}}{[\sigma B(H \to \mu\mu)]_{SM}}$**:**
  - $\mu = 1.19^{+0.41}_{-0.39}\ (stat)\ ^{+0.17}_{-0.16}\ (sys)$ for the m_H = 125.38 GeV
- An **excess** has been observed in data with **a significance of 3.0 σ!**
  - JHEP 01 (2021) 148
- A combination with Run 1 measurement has been performed:
  - **Run 1: Phys. Lett. B 744 (2015) 184**

Prod. Category	Obs. (exp.) significance	Obs. (exp.) 95% CL upper limit
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)	10.80 (5.13)
Comb. 13 TeV	2.95 (2.46)	1.94 (0.82)
Comb Run 1+2	2.98 (2.48)	1.93 (0.81)

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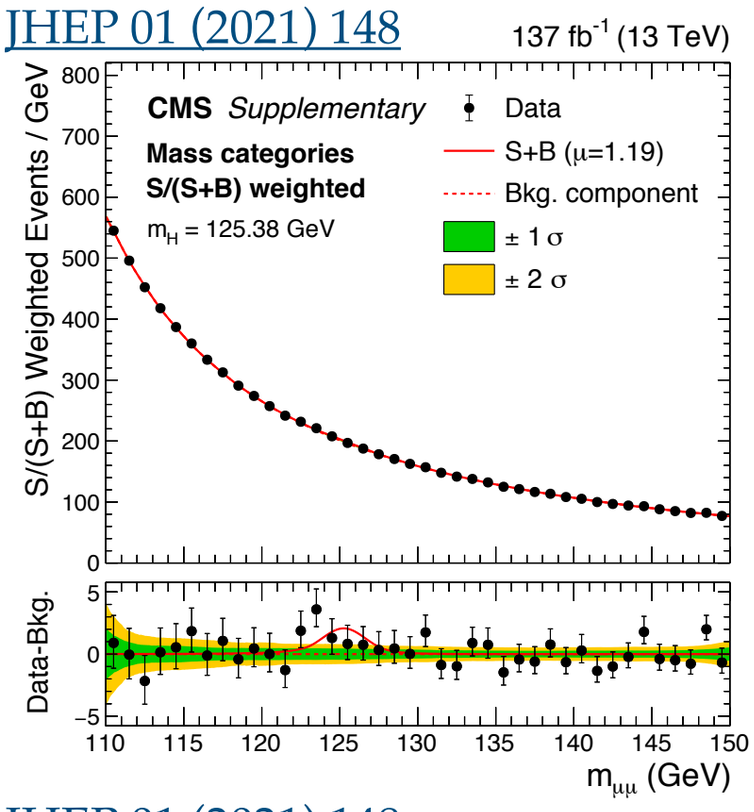

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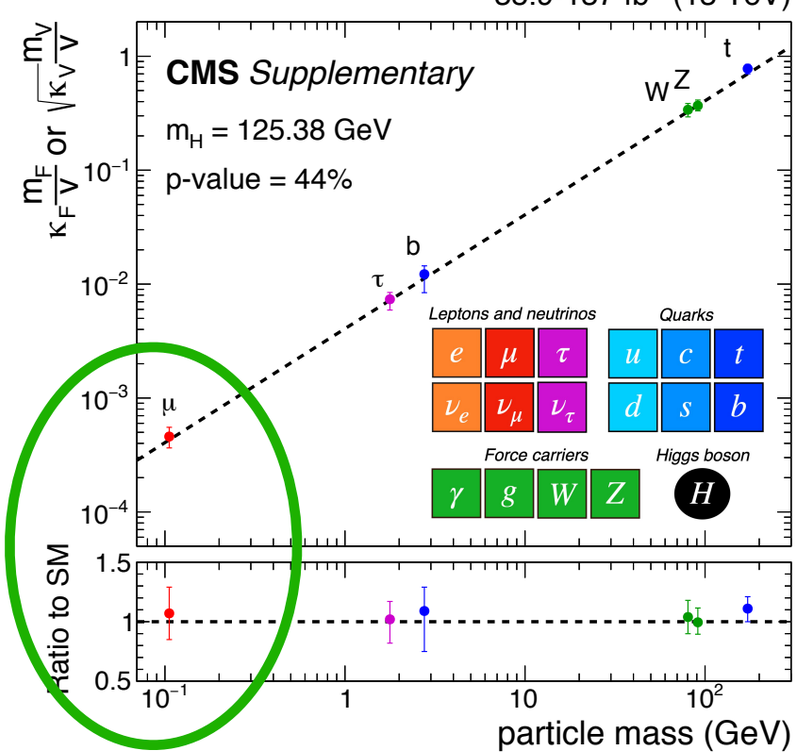


Higgs boson decay to Zγ: Strategy

- **Search for the H → Zγ decay where $Z \to l^+l^-$ (with $l = e, \mu$)**
  - Most experimentally accessible final state (for dilepton mass > 40 GeV)
  - Legacy Run 2 measurement using the full dataset (**137 fb^{-1}**) - **CMS-PAS-HIG-19-014**

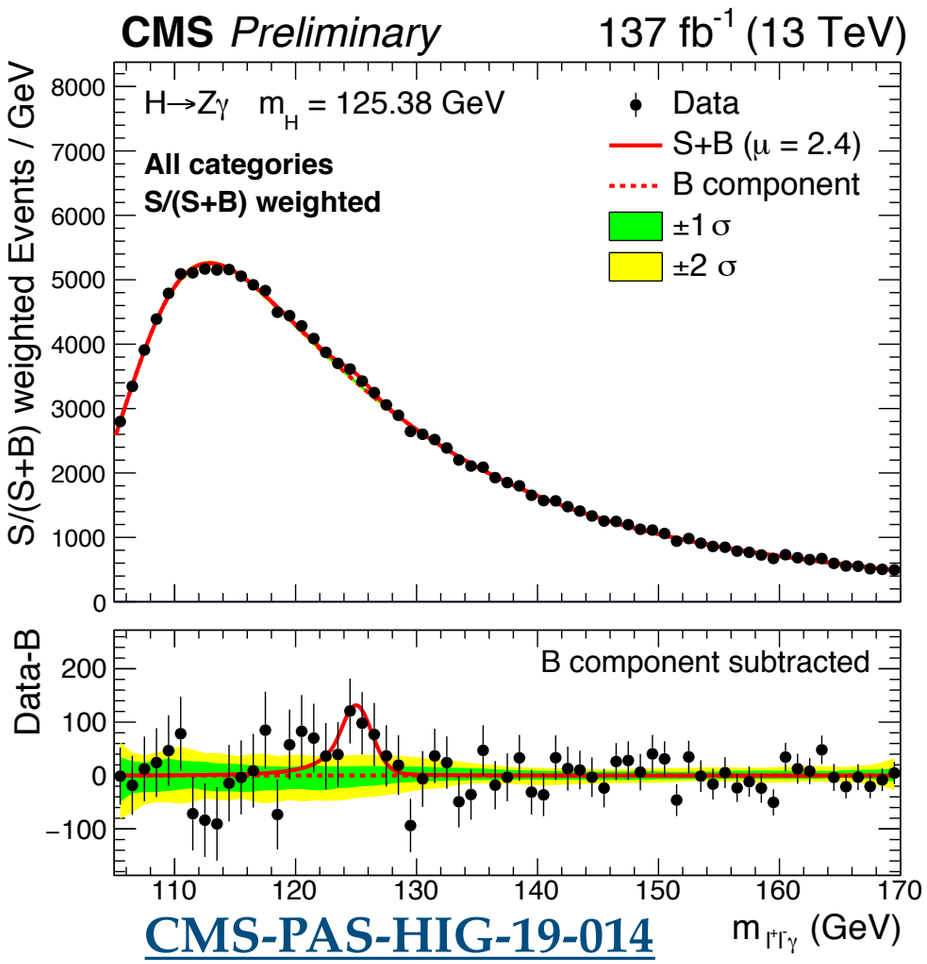
- **VH and ttH production modes targeted through the use of a lepton-tag category**
  - An additional lepton is present beyond the ones from the Zγ system

- **If the lepton-tag failing event has an additional dijet system it will fall under the VBF targeted category**
  - A VBF BDT classifier is used to further divide events into 3 “dijet" subcategories using the properties of the dijet system

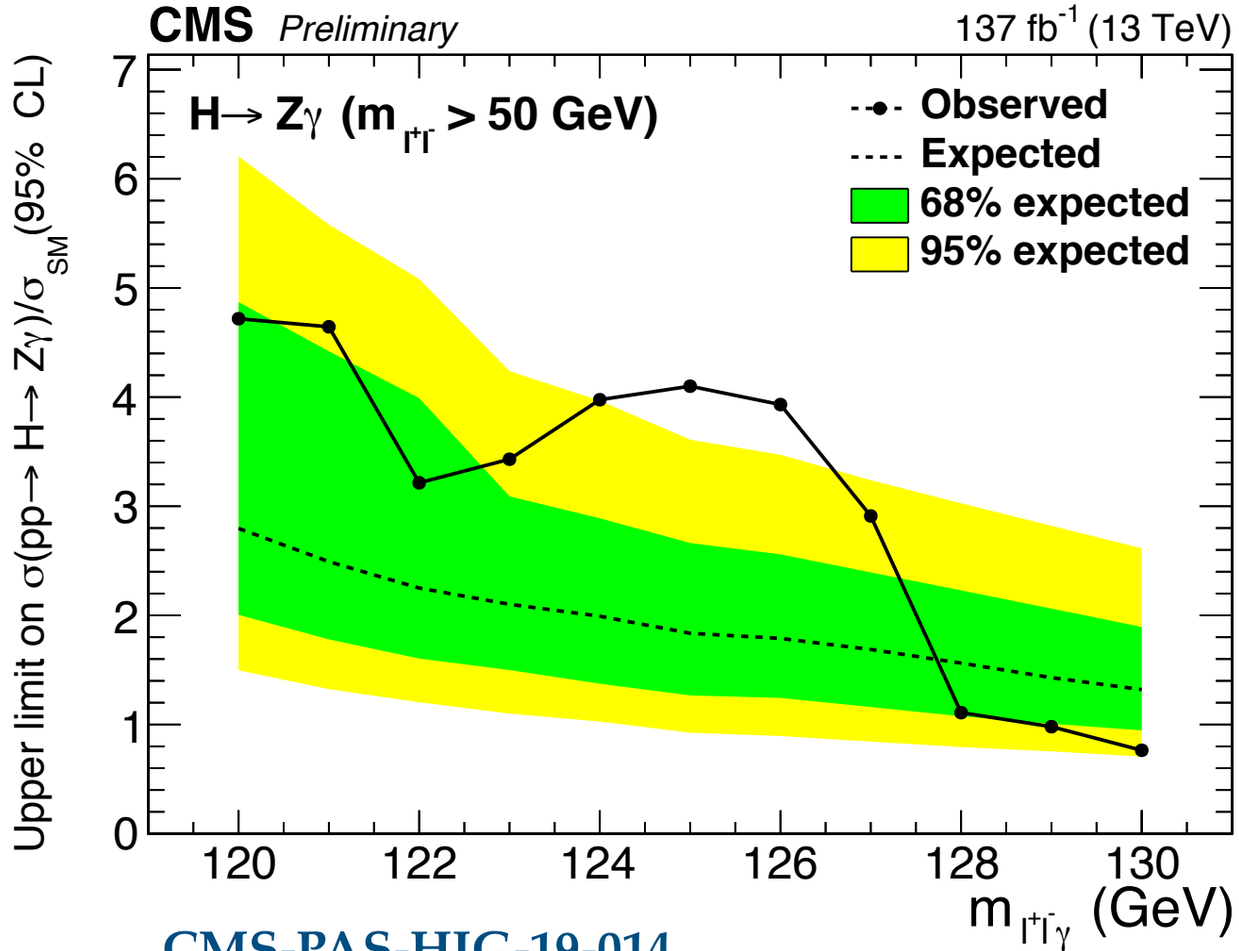
- **The ggH category collects the event which do not fall under any of previous categories**
  - A kinematic BDT classifier is used to further discriminate signal and background events
  - Resulting in 4 “Untagged" subcategories

Higgs boson decay to Zγ: Results

- **The observed (expected) 95% CL upper limit on** $\mu = \dfrac{[\sigma B(H \to Z\gamma)]_{observed}}{[\sigma B(H \to Z\gamma)]_{SM}}$
  - Is placed at **4.1 (1.8), with** $\mu = 2.4 \pm 0.9$
  - Corresponding to : $\sigma B(H \to Z\gamma) = 0.21 \pm 0.08\ pb$
  - The statistical significance of the observed excess under the b-only hypothesis is **2.7** standard deviations (at $m_H = 125.38$ **GeV**)



CMS-PAS-HIG-19-014



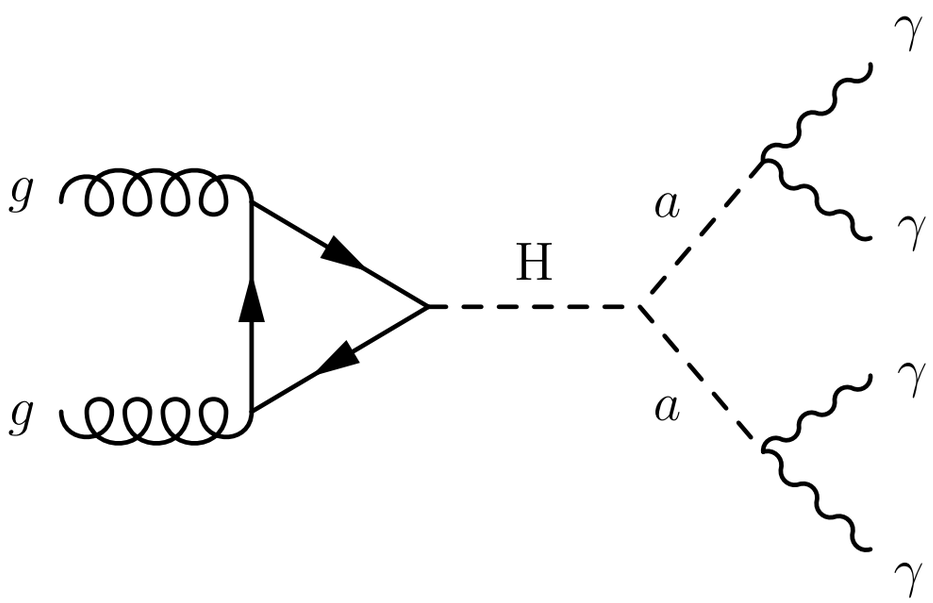
CMS-PAS-HIG-19-014

$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$: Strategy

- **The search for exotic decay of the Higgs boson into two light pseudoscalars (aa):**
  - Analysis focuses on events in which 4 photon objects (both pairs) are reconstructed as isolated objects
  - Explores the complete Run 2 dataset with 132 **fb $^{-1}$ of total integrated luminosity**

- **The search is performed for the m_a range 15-60 GeV:**
  - With 0.5 GeV increments until 40 GeV, followed by 1 GeV steps

- **The photon candidates are required to pass the 110 < $m_{4\gamma}$ < 180 GeV requirement**
  - An MVA is used to exploit the identification and kinematic information of photons and pseudscalar candidates
  - Trained to separate signal from background events in such way that $m_{4\gamma}$ cannot be inferred

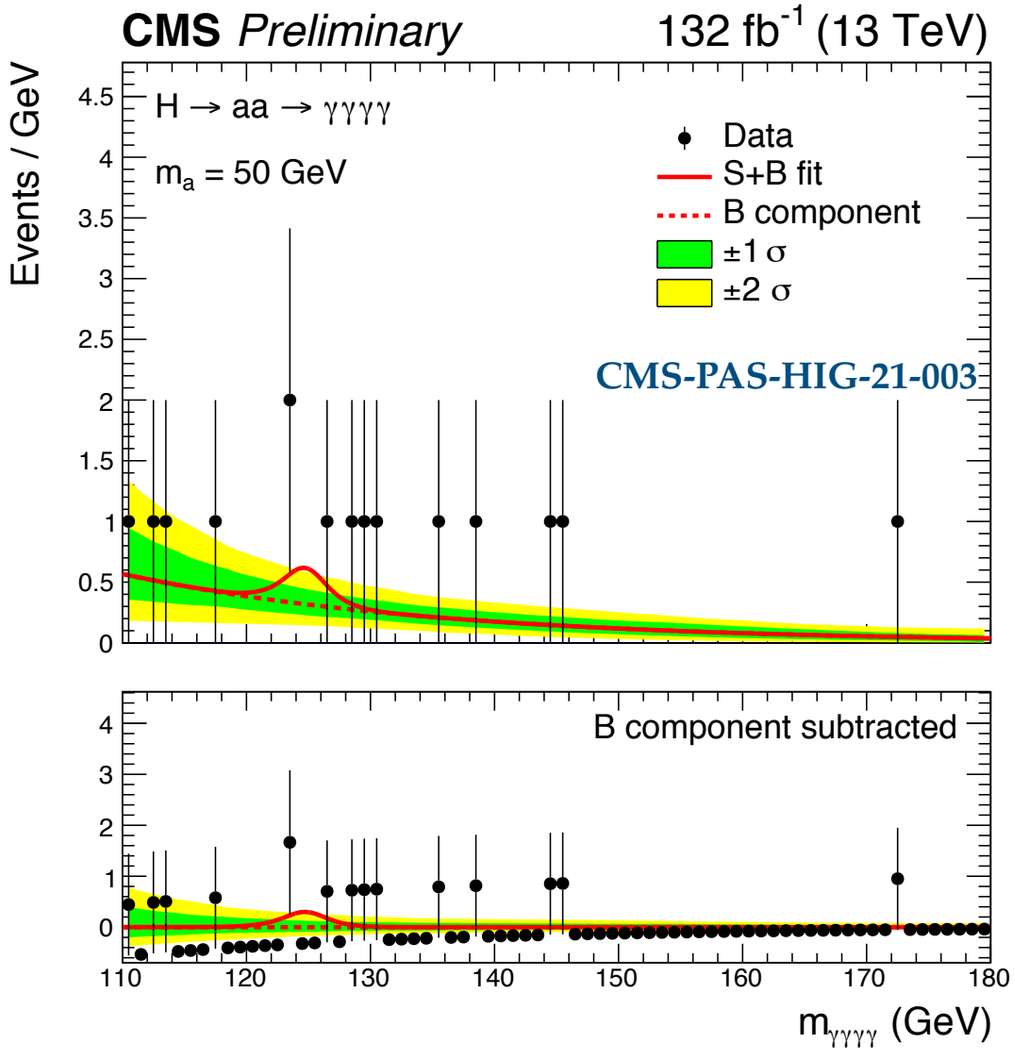


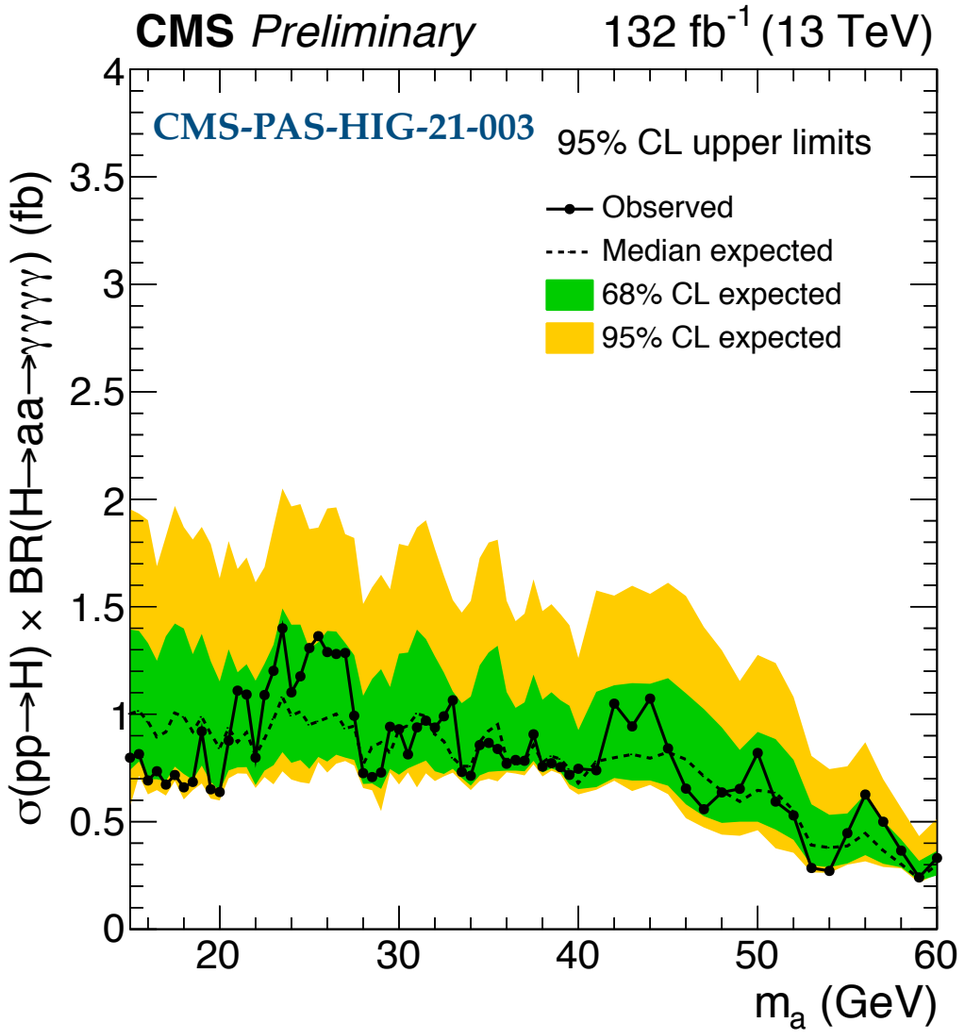
- **The search performs a simultaneous maximum likelihood fit of the signal and background models to the observed $m_{4\gamma}$**
  - Taking into account the MVA classifier output
  - Signal model is constructed from a parametric fit to the simulated signal
  - Background model is created using a data driven approach

$H \to aa \to \gamma\gamma\gamma\gamma$: Results

- **An unbinned maximum likelihood fit is performed to the $m_{4\gamma}$ in the 110-180 GeV range**
  - Done for each m_a hypothesis
  - Combined Run 2 dataset is used in the fit - published as **CMS-PAS-HIG-21-003**

- **No significant deviation form the b-only hypothesis is observed and the result is expressed as the 95% CL upper limit on $\sigma B(H \to aa \to \gamma\gamma\gamma\gamma)$**





Why the interest for the invisibly decaying Higgs?

- **The "crown jewel" of the experimental particle physics:**
  - Higgs boson was discovered by **ATLAS** and **CMS experiments** at CERN in 2012
  - All of the following measurements of its properties have been **consistent** with the **Standard Model (SM)**
  - Large uncertainties of these measurements can allow for physics beyond the SM

Why the interest in the invisible final state?

- **According to the SM, the probability of Br(H → 4ν) ~ 0.1 %**
  - **Can represent a good way of testing for BSM physics!**
  - **Higgs boson** could be a **mediator between SM and DM** sector
  - Detection would require it to recoil against a visible system

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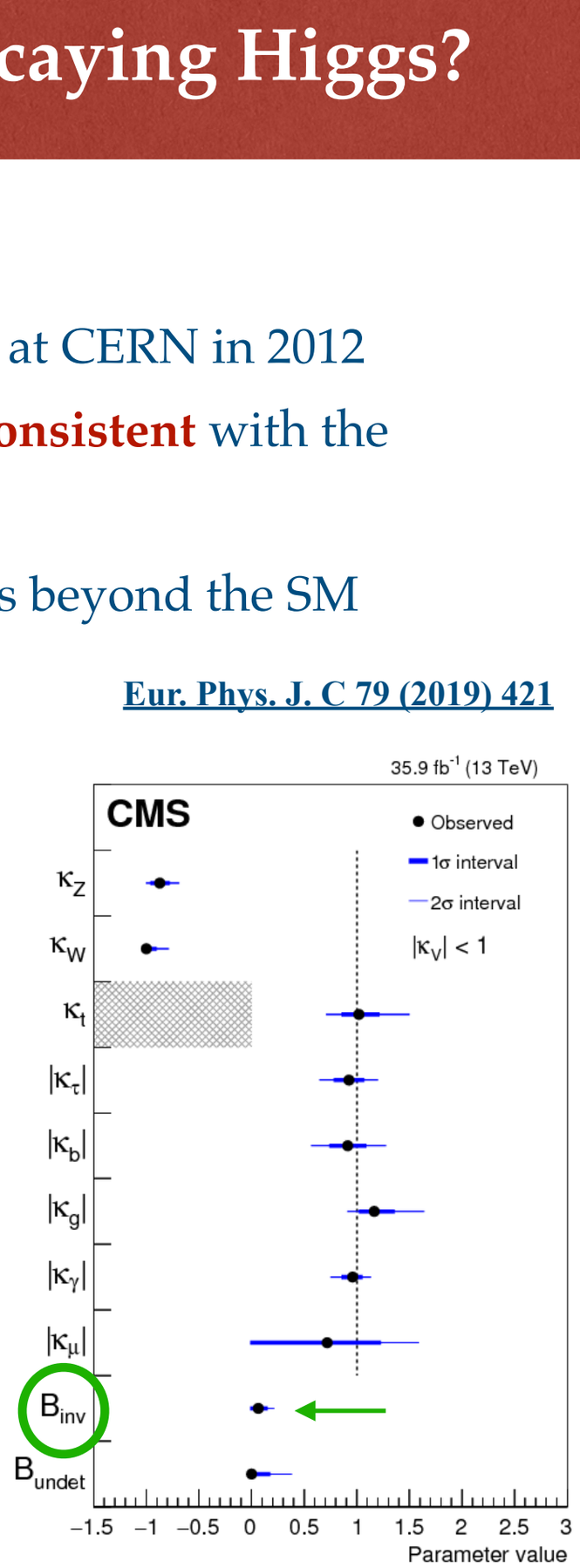
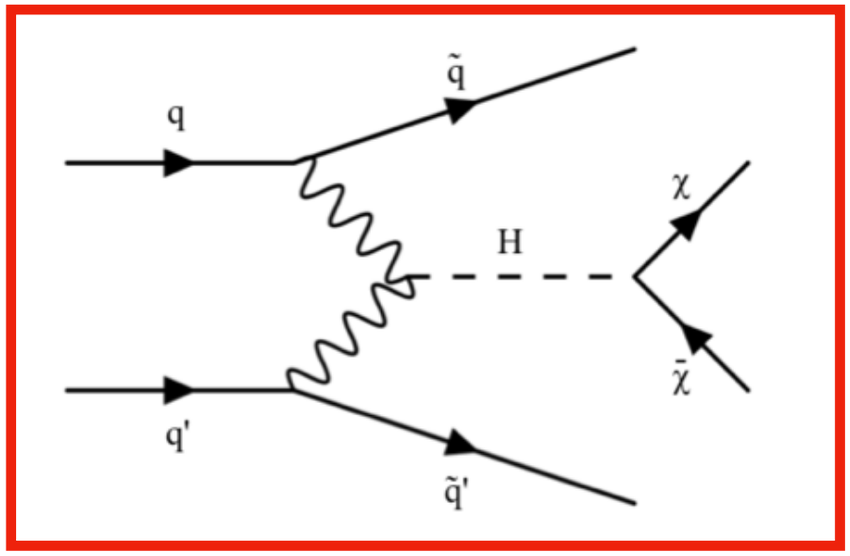
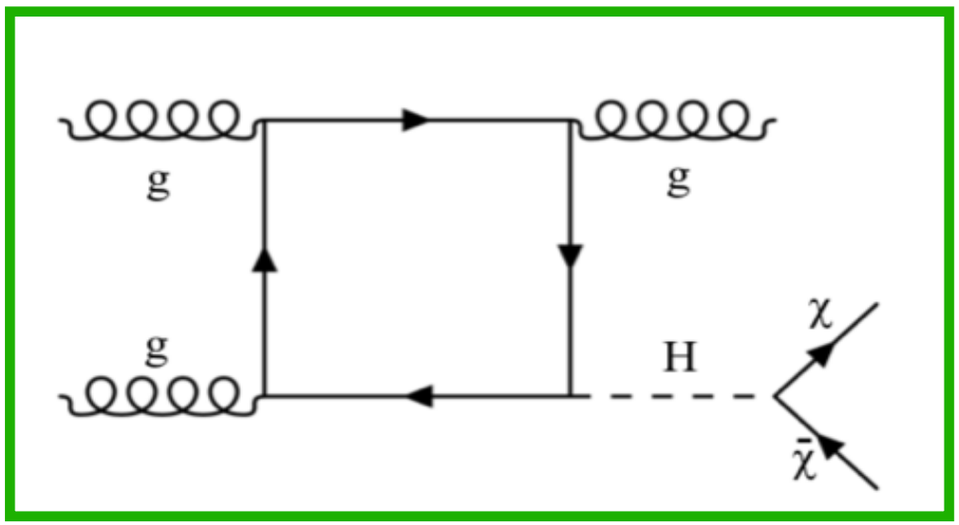


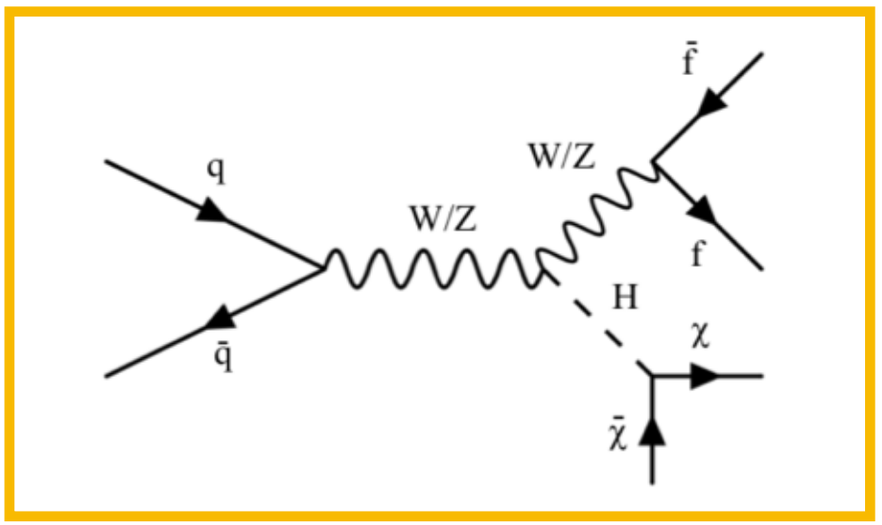
Why the interest for the invisibly decaying Higgs?

- **Higgs boson can take a role of a mediator between SM and DM particles:**
  - Detection requires for the **Higgs to recoil against a visible system**
  - **Large** missing transverse energy **(MET)**

- **qqH** : Higgs boson is produced in a vector boson fusion topology (VBF)
- **VH**: Higgs boson production with a vector boson
- ggH: Higgs boson produced via gluon fusion.



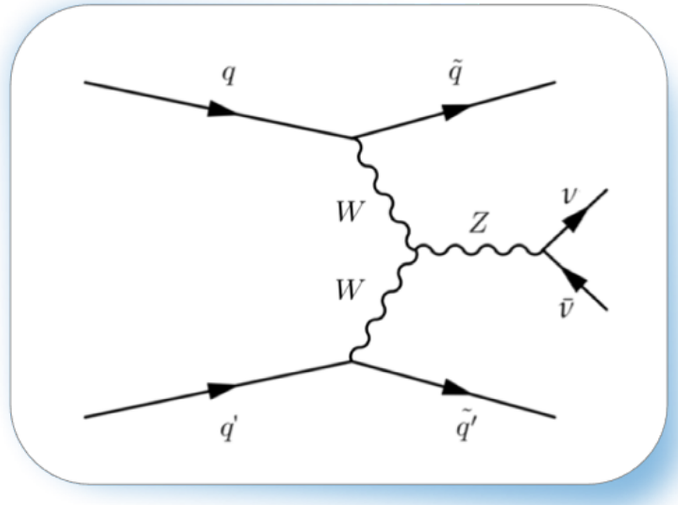


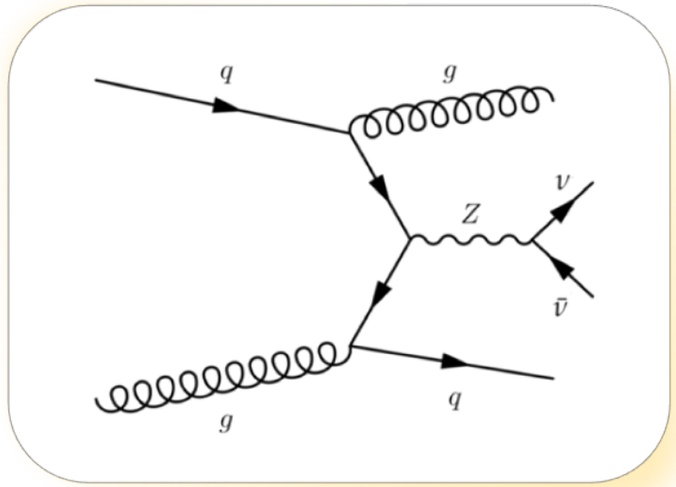


The shared approach: Example - VBF analysis

- **VBF production mode of the Higgs boson has a characteristic signature:**
  - **Two jets** with a **large geometrical separation**
  - **High dijet invariant mass** (a good way to control S/B)
  - Represents a channel with the largest sensitivity

- **Main backgrounds:**
  - **QCD and EWK produced V+jets (where V= W/Z)**
    - Irreducible when Z->νν and W->lν
      - With the charged lepton being missed in the detection





- **Estimated through dedicated control regions in data (CR):**
  - Z or W boson associated with the same dijet topology
  - Resulting in four CRs separated by lepton flavour (e/μ)

- **QCD multi jet processes - data driven estimation**

Where are we now? Early Run 2 combination

- **The first combination measurement using Run 2 data was published using the 2016 dataset**
- **No significant deviation from the SM was reported:**
  - The result of the measurement is expressed as the **95% CL upper limit on the B(H → inv.)**
  - **This publication also included a first combination of Run 1 and 2015+2016 data**
    - Setting the B(H → inv) limit to be at **0.19 (0.15)** for the observed (expected) value

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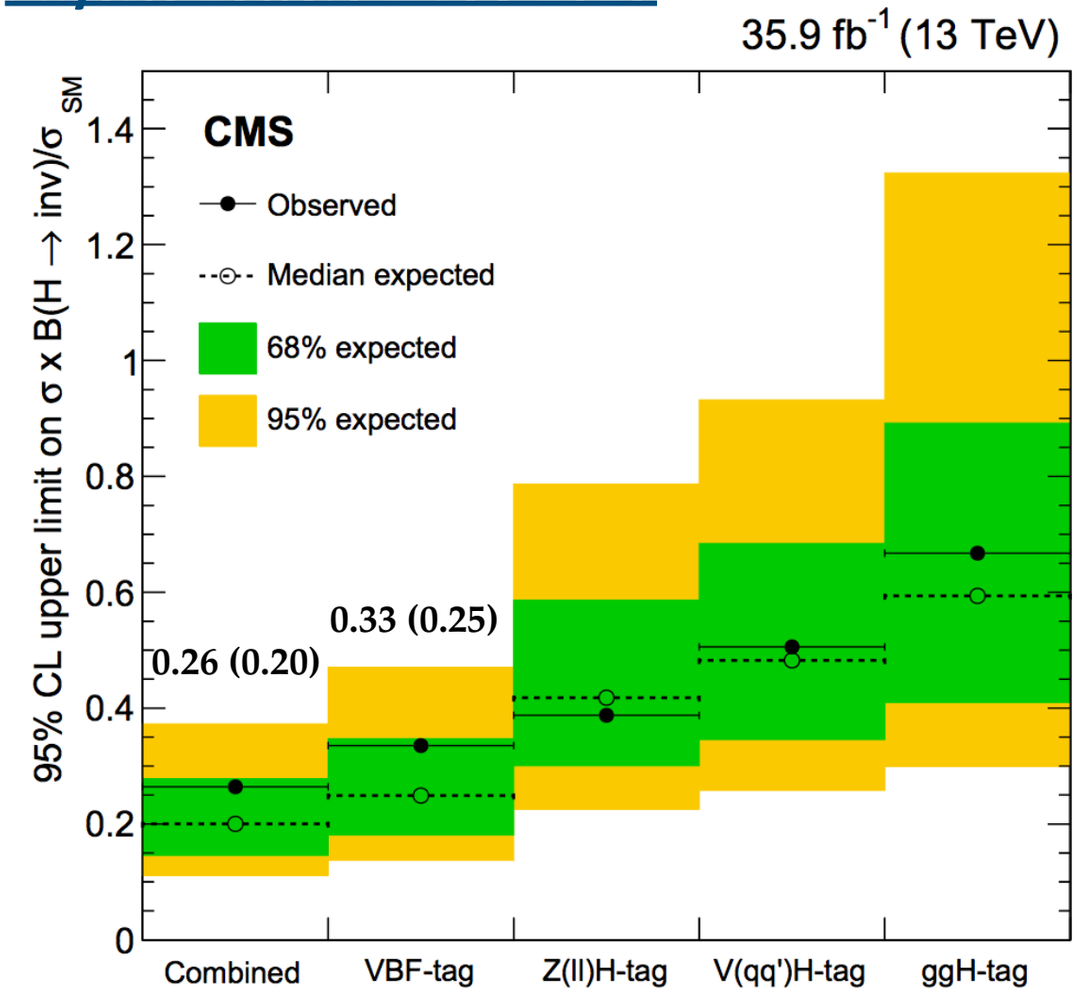
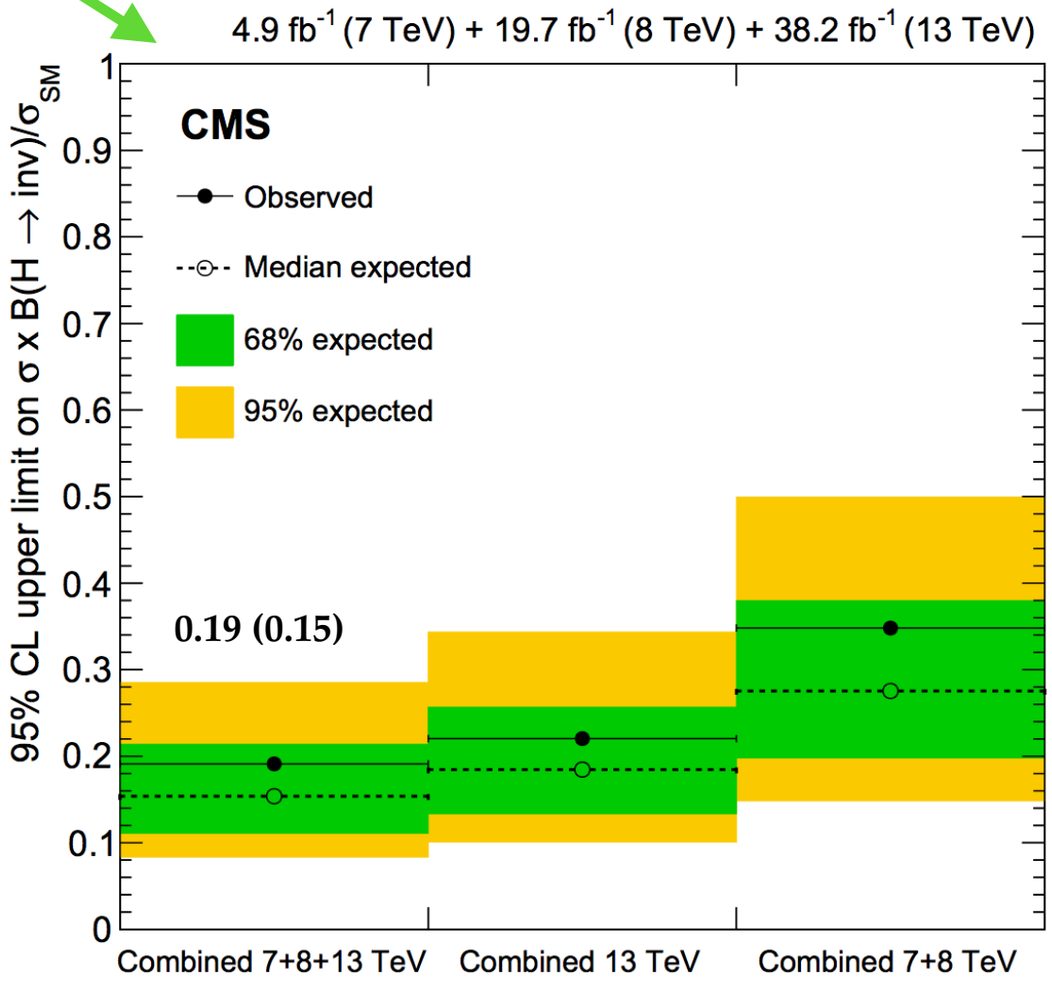
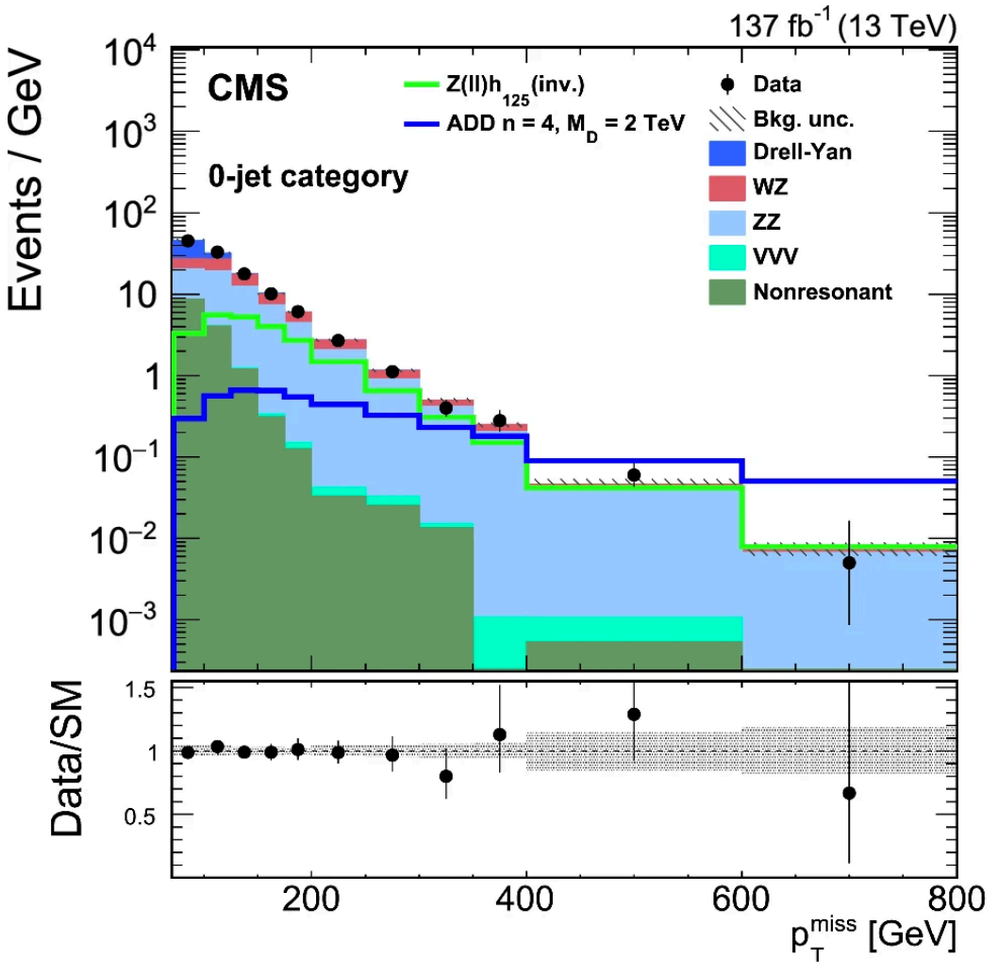
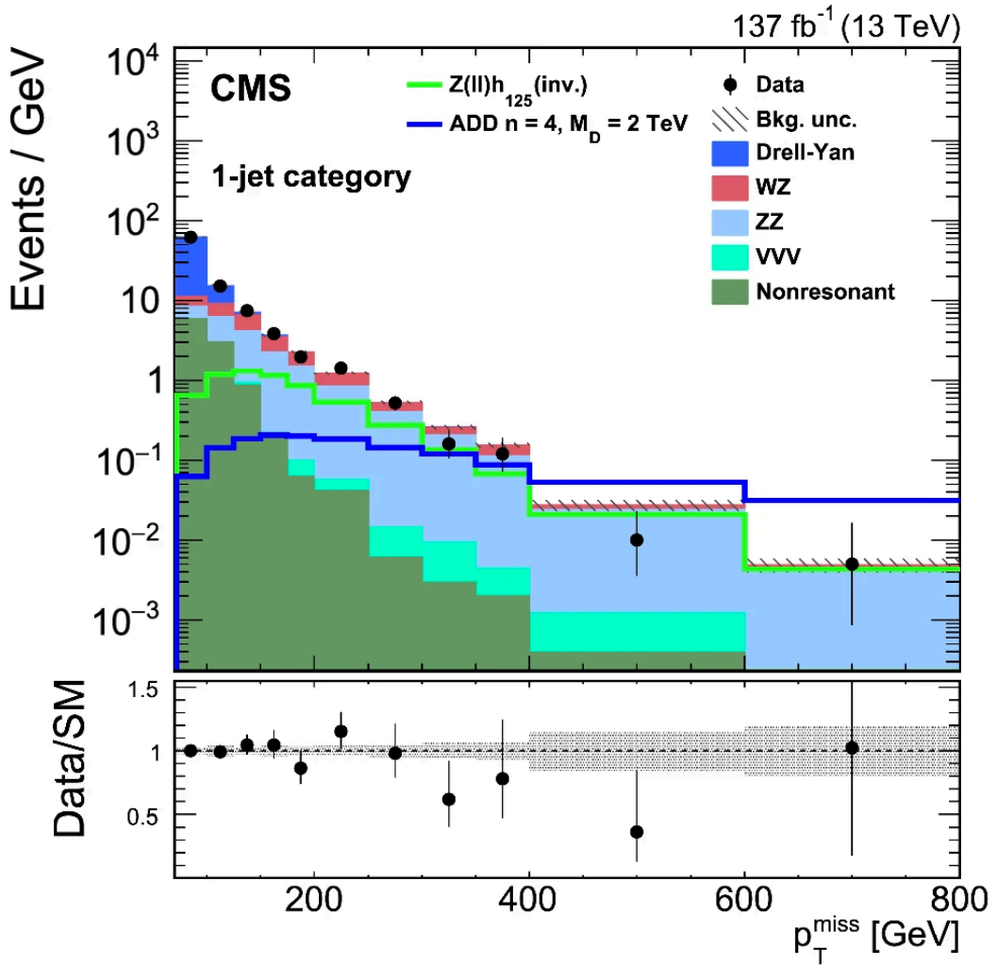




Z(ll)H(invisible): Full Run 2 measurement

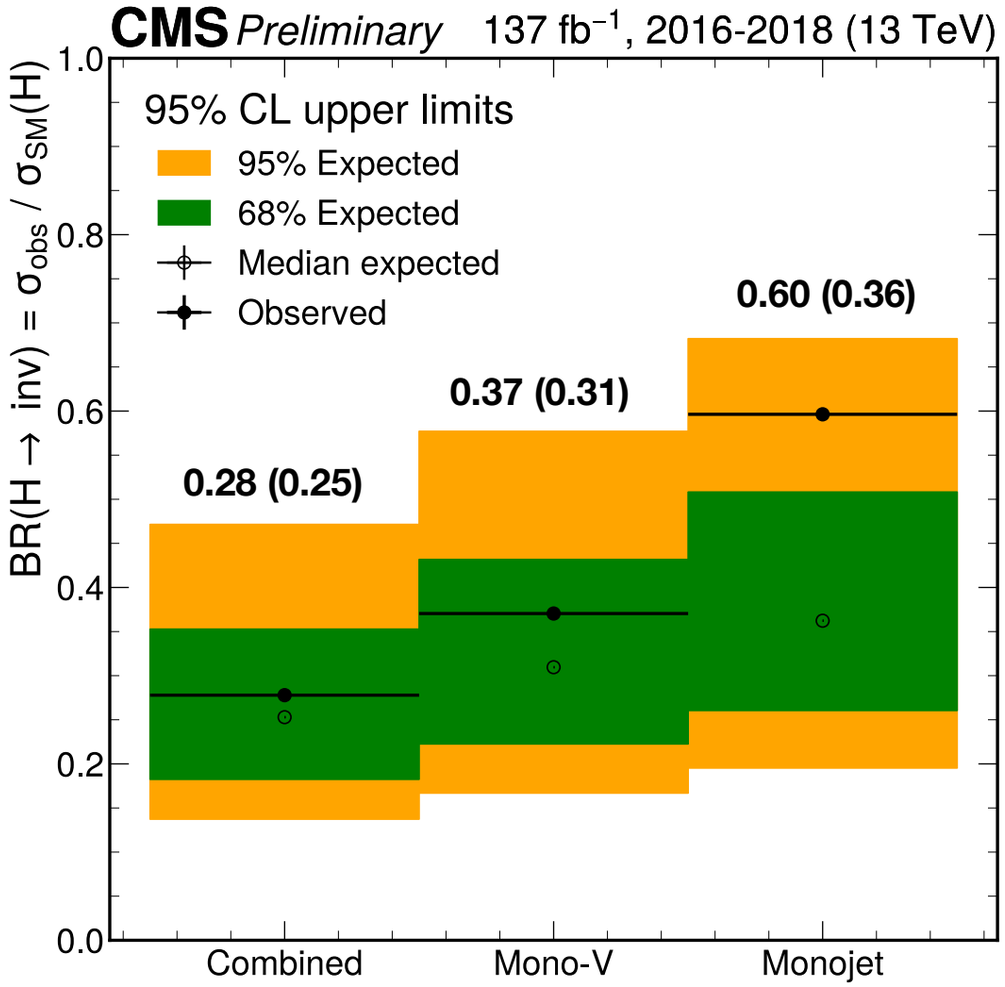
- **The Z(ll)H(invisible) measurement using full Run 2 data**
  - Interpretation of a wider search for **Dark Matter in association with a Z boson (EPJC 81 2021)**
  - No significant deviation from the Standard Model was reported
  - **The observed (expected) 95% CL upper limit computed using m_H= 125 GeV:**
    - **B(H → inv) = 0.29 (0.25)**



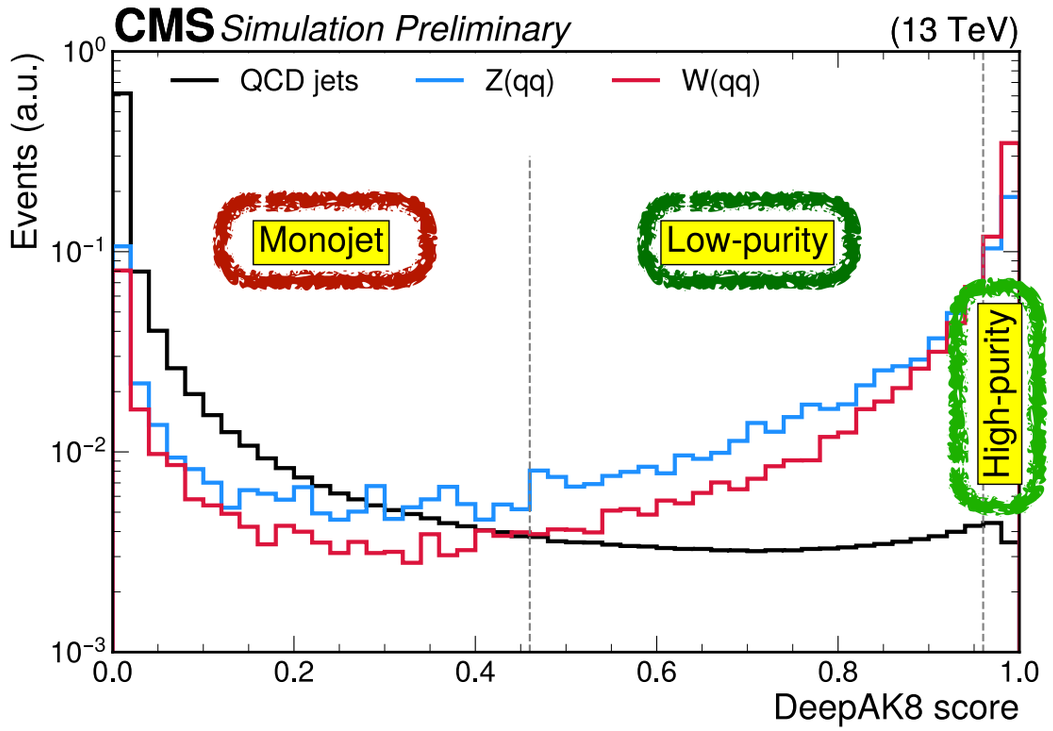


Mono jet/mono V: Full Run 2 measurement - Results

- **The mono jet/mono V measurement using full Run 2 data**
  - Interpretation of a wider search for **new particles in association with jets and $E_{T,miss}$**
    - **Published in: CMS-PAS-EXO-20-004** (Submitted to JHEP)
    - No significant deviation from the Standard Model was reported
  - **The observed (expected) 95% CL upper limit computed using m_H= 125 GeV:**
    - **B(H → inv) = 0.28 (0.25)**



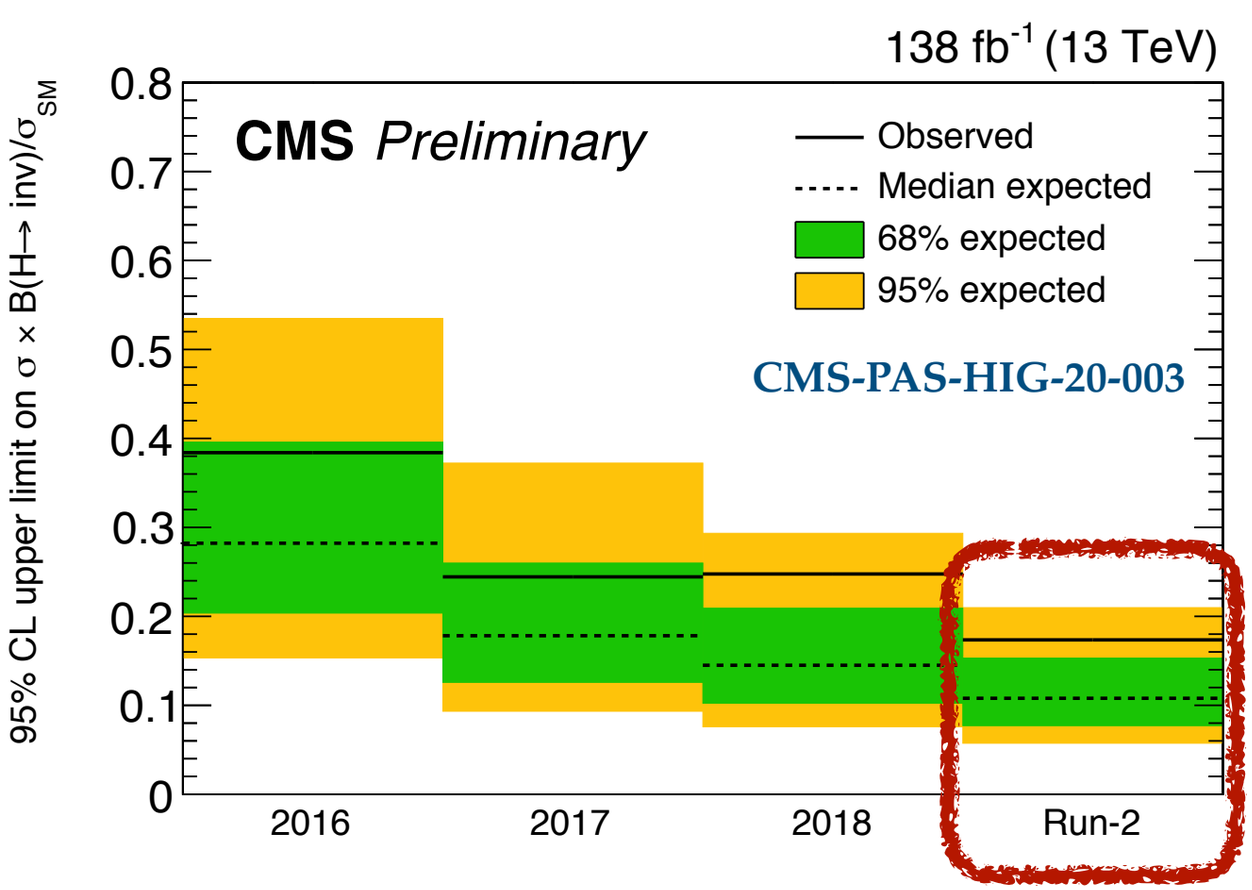
- **ML techniques employed in search for the V(qq) events (separating from QCD multijet)**
- Neural network tagger - categories based on the DeepAK8 tagger score
  - (JINST 15 P06005)
- **High purity VH (90% VH), Low purity VH (40% VH)** and **mono Jet (75% ggH, 20% VBF)**

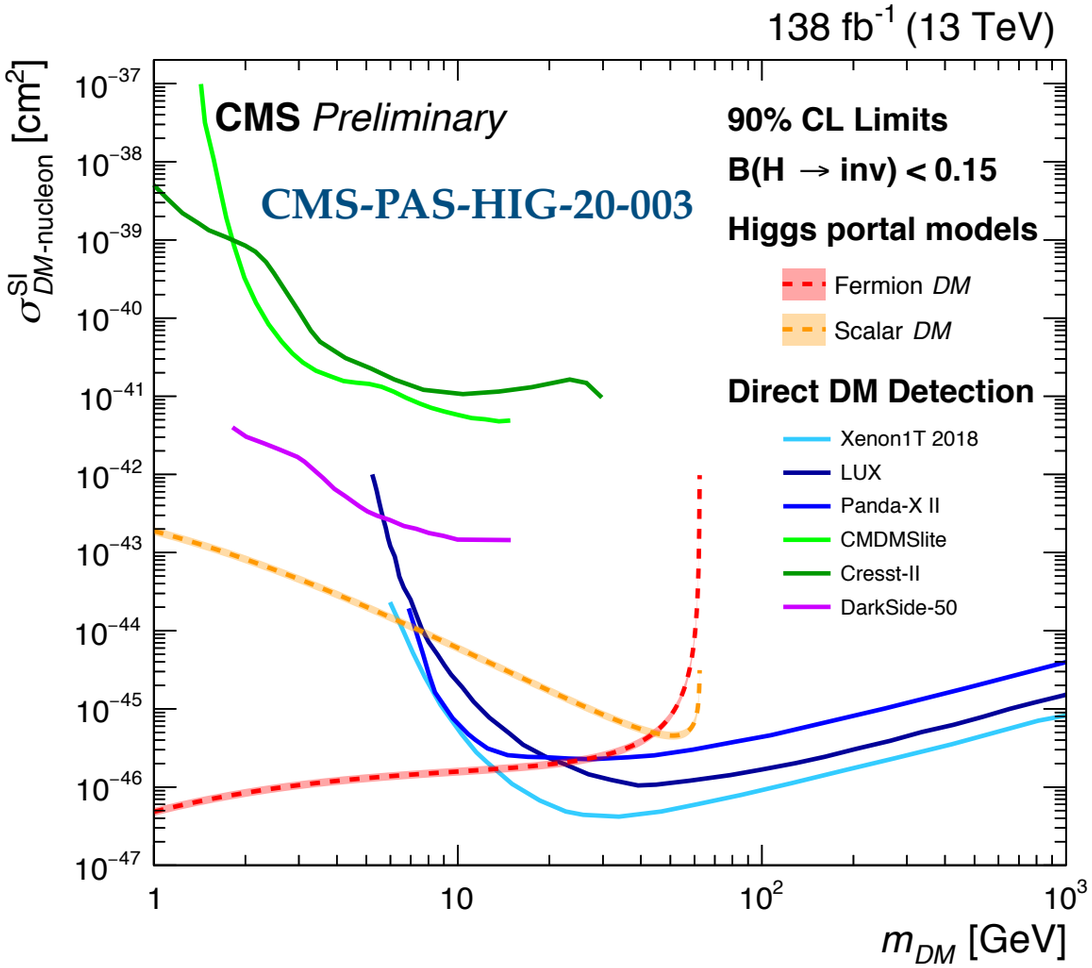


VBF analysis: Full Run 2 measurement - Results

- **The VBF H(invisible) measurement using full Run 2 data - new result (CMS-PAS-HIG-20-003)**
  - Improvements to he analysis strategy:
    - **Addition of new VBF H(invisible) topology targeting triggers**
      - **Creating of a new, low E_T^{miss}, analysis category**
    - Addition of another (γ) control region
      - Helping with statistical precision of Z(ll) CRs
    - Brought ~20% gain in terms of signal sensitivity (when compared to 2016 strategy)

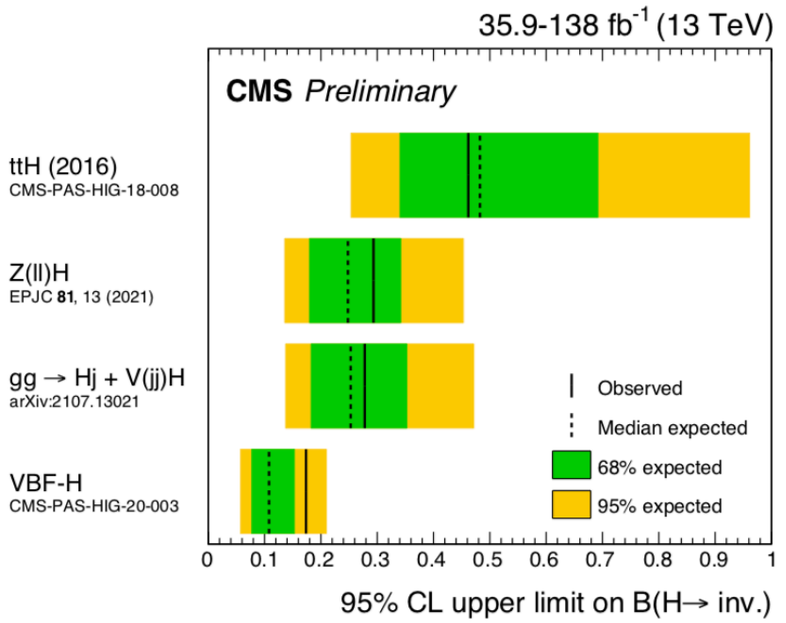
- **No significant deviation from the SM was reported and the observed (expected) 95% CL upper limit was placed at:**
  - **B(H → inv) = 0.17 (0.11)**





Summary

- **These slides have summarised the recent studies on rare, invisible and exotic decays of the Higgs boson from the CMS Collaboration:**
  - The **full Run 2** measurement targeting the $H \to \mu\mu$ **final state**
    - **Combination of 4 exclusive channels: VBF, ggH, VH and ttH**
    - **Observed (expected) significance: 3.0 (2.5)** σ
  - Search for the **H** $\to$ **Z**γ **decay** where $Z \to l^+l^-$ (with $l = e, \mu$)
    - $\sigma B(H \to Z\gamma) = 0.21 \pm 0.08\ pb$
    - The statistical significance of the observed excess under the b-only hypothesis is 2.7 standard deviations
  - Search for H $\to$ aa $\to \gamma\gamma\gamma\gamma$ using the full Run 2 dataset:
    - Result is expressed as the 95% CL upper limit on $\sigma B(H \to aa \to \gamma\gamma\gamma\gamma)$
      - Ranging from 0,80 (1.00) fb for m_a = 15 GeV to 0.33 (0.30) fb for m_a = 60 GeV
  - **H(Invisible):** The **latest combination of H(invisible) studies**
    - Focused on the **Run 1 + early Run 2 measurements**
    - Sets a limit on B(H $\to$ inv) at 0.19 (0.15) for the observed (expected) value
  - **Measurements using the full Run 2 dataset:**
    - **Z(ll)H(invisible):** B(H $\to$ inv) = 0.29 (0.25)
    - **Mono V/mono Jet:** B(H $\to$ inv) = 0.28 (0.25)
    - **VBF H(invisible):** B(H $\to$ inv) = 0.17 (0.11)



Thank you for your time!

BACKUP