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Measurement of boosted Higgs bosons produced via vector boson fusion or gluon fusion in the $H \to b\bar{b}$ decay mode using LHC proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

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Abstract

A measurement is performed of Higgs bosons produced with high transverse momentum (p_T) via vector boson or gluon fusion in proton-proton collisions. The result is based on a data set with a center-of-mass energy of 13 TeV collected in 2016–2018 with the CMS detector at the LHC and corresponds to an integrated luminosity of $138\,\text{fb}^{-1}$. The decay of a high-p_T Higgs boson to a boosted bottom quark-antiquark pair is selected using large-radius jets and employing jet substructure and heavy-flavor taggers based on machine learning techniques. Independent regions targeting the vector boson and gluon fusion mechanisms are defined based on the topology of two quark-initiated jets with large pseudorapidity separation. The signal strengths for both processes are extracted simultaneously by performing a maximum likelihood fit to data in the large-radius jet mass distribution. The observed signal strengths relative to the standard model expectation are $4.9^{+1.9}_{-1.6}$ and $1.6^{+1.7}_{-1.5}$ for the vector boson and gluon fusion mechanisms, respectively. A differential cross section measurement is also reported in the simplified template cross section framework.

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1 Introduction

The observation at the CERN LHC of a Higgs boson (H) consistent with the standard model (SM) expectation and the subsequent measurements of its properties [1–6] have advanced the understanding of electroweak (EW) symmetry breaking and the origin of the mass of fundamental particles [7–14]. Higgs boson production at high momentum transfer can be a sensitive probe of beyond the SM (BSM) physics at high energy scales, and measurements in this regime provide important input for effective field theory interpretations of H interactions [15–20]. Thus, studying Higgs bosons at high transverse momentum (p_T) has become an integral part of the physics program at the LHC.

The Higgs boson decay to a bottom quark-antiquark pair ($b\bar{b}$) has the highest branching fraction of any H decay mode in the SM [21]. When the Higgs boson is produced with high momentum, the $H \to b\bar{b}$ decay products are merged into a single large-radius jet. This distinctive boosted jet topology can be identified by its substructure and heavy flavor properties, and as a result the $H \to b\bar{b}$ decay provides an important channel for the exploration of Higgs boson production at high p_T.

Leading order (LO) Feynman diagrams of the three H production mechanisms with highest cross section in proton-proton (pp) collisions are shown in Fig. 1: gluon fusion (ggF), vector boson fusion (VBF), and vector boson associated production (VH). A small contribution to the H cross section also arises from associated production with a top quark-antiquark pair ($t\bar{t}H$). The dominant SM contribution comes from ggF, which contributes 87% of the H cross section at $\sqrt{s} = 13\,\text{TeV}$ when considering the full range of Higgs boson p_T. However, the relative contribution from ggF is expected to decrease with the p_T of the Higgs boson, contributing only 50 (30)% of the cumulative H cross section for $p_T > 450$ (1200) GeV [22]. While the relative contribution from VH increases as a function of Higgs boson p_T, that of VBF has minimal p_T dependence. Each of these production mechanisms provides a different probe of H interactions, and precise measurement of each one is necessary to investigate all possible manifestations of BSM physics in the Higgs sector.

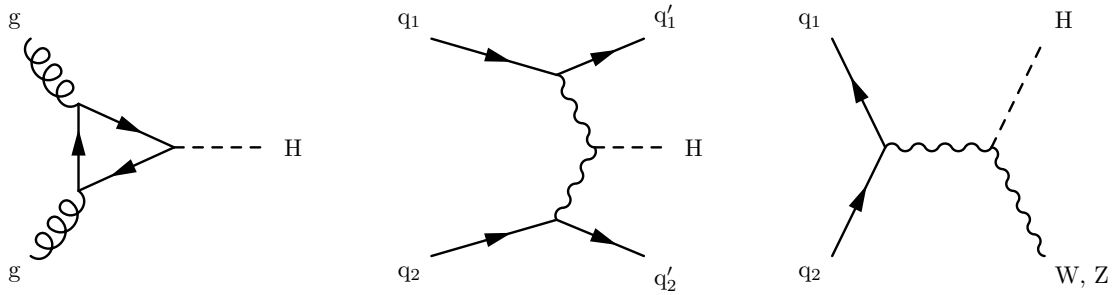

Figure 1: Lowest order Feynman diagrams of the Higgs boson production modes with highest cross section in 13 TeV proton-proton collisions, from left to right: gluon fusion, vector boson fusion, and vector boson associated production.

Existing searches in the boosted $H \to b\bar{b}$ channel from the ATLAS and CMS experiments have focused on inclusive Higgs boson production [23–25] or associated production with a vector boson [26–28]. This work extends, for the first time, high-p_T Higgs boson measurements in the $H \to b\bar{b}$ channel to VBF production. The analysis is performed using pp collision data collected with the CMS detector at the LHC in 2016–2018, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$ [29–31]. The VBF process, which is sensitive to H couplings to vector bosons, and the ggF process, which is primarily sensitive to H couplings to top quarks and gluons, are

measured simultaneously. In order to disentangle the two processes, the analysis is performed in two categories. The first category is enriched in VBF events and targets the characteristic topology of two quark-initiated jets with high pseudorapidity (η). The second category is enriched in ggF events.

In both categories, the $\mathrm{H} \to \mathrm{b\bar{b}}$ decay mode is isolated from quark- and gluon-initiated jets by a multivariate large-radius jet classifier known as the DeepDoubleB (DDB) tagger [32]. Updates with respect to the previous version of the DDB tagger [33, 34] yield a gain in expected signal significance of about a factor of 2 compared to the previous CMS $\mathrm{H} \to \mathrm{b\bar{b}}$ search [25]. As a result, the analysis reported here provides not only the first measurement of H production via VBF at high p_{T}, but also the most precise measurement of ggF Higgs boson production in this regime, superseding the measurement in Ref. [25].

2 The CMS detector

The CMS apparatus [35] is a multipurpose, nearly hermetic detector, designed to trigger on [36, 37] and identify electrons, muons, photons, and hadrons [38–40]. Information about particles traversing the detector is provided by the all-silicon inner tracker, and by the crystal electromagnetic and brass-scintillator hadron calorimeters, all of which operate inside a 3.8 T superconducting solenoid, and by the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [36]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [37].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [35].

The dataset used in this analysis is divided into four data-taking periods to account for the 2017 upgrade of the CMS tracking detector, differences in accelerator and detector conditions, and updates to reconstruction algorithms and calibrations. These data-taking periods correspond to early 2016, late 2016, 2017, and 2018. Data from 2016 is split into an early and a late data-taking period due to changes made mid-year.

3 Simulated samples

Simulated samples of signal and background events are produced using various Monte Carlo (MC) event generators, with the CMS detector response modeled by GEANT4 [41]. Independent samples are generated for each of the four data-taking periods using identical generator configurations, but accounting for changes in the accelerator and detector running conditions.

The background from jets produced via the strong interaction, referred to as quantum chromodynamics (QCD) multijet events, is modeled at LO accuracy using the MADGRAPH5_aMC@NLO 2.6.5 generator [42] with up to four partons from the matrix element calculation.

The W+jets and Z+jets processes are modeled at LO accuracy using the MADGRAPH5_aMC@NLO generator. These samples include decays of the bosons to all flavors of quarks and up to three (four) extra partons at the matrix element level for W+jets (Z+jets). Jets from the matrix ele-

ment calculations and parton shower description are matched using the MLM prescription [43]. Correction factors are applied to the W+jets and Z+jets samples to match the generator-level p_T distributions with those predicted by the highest available order in the perturbative expansion. The QCD next-to-LO (NLO) corrections are derived using MADGRAPH5_aMC@NLO, simulating W and Z boson production with up to two additional partons and FxFx matching to the parton shower [44]. The EW NLO corrections are taken from theoretical calculations in Refs. [45–48].

Electroweak production of W and Z bosons is modeled using MADGRAPH5_aMC@NLO at LO accuracy. Diboson processes are modeled at LO accuracy with PYTHIA 8.226 [49], and the total cross sections are corrected to next-to-NLO (NNLO) accuracy with the MCFM 7.0 program [50]. Top quark-antiquark ($t\bar{t}$) and single top quark production are modeled at NLO in QCD using POWHEG 2.0 [51–55].

The ggF Higgs boson production process is simulated using the HJMINLO event generator [56, 57] with the Higgs boson mass set to 125 GeV. Finite top quark mass effects [58] are included following the recommendation in Ref. [22]. The POWHEG generator [59–61] is used to model Higgs boson production via VBF, VH, and $t\bar{t}H$ at NLO accuracy. The VBF sample is reweighted to account for NNLO corrections to the p_T spectrum and N^{3}LO corrections to the inclusive cross section [62, 63]. These corrections have a negligible effect on the yield for this process for events with Higgs boson $p_T > 450$ GeV. EW corrections are also applied to the VBF, VH, and $t\bar{t}H$ processes [22].

For parton showering and hadronization, all generated samples are interfaced with PYTHIA 8.230, with the parameters for the underlying event description set via the CP5 tune [64]. The diboson process exceptionally uses PYTHIA 8.226 for both the matrix element and parton shower evolution. The parton distribution function (PDF) set NNPDF3.1 [65] at NNLO accuracy is used for all processes.

4 Event reconstruction and selection

The particle-flow (PF) algorithm [66] aims to reconstruct and identify each individual particle in an event using an optimized combination of information from the various elements of the CMS detector. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Ref. [40].

Jets are reconstructed by clustering PF candidates using the anti-k_T algorithm [67] as implemented in the FASTJET software package [68]. Small-radius jets are clustered with a distance parameter of 0.4. Large-radius jets, which are used to capture the decay products of heavy boosted objects, use a distance parameter of 0.8 [69].

Jet momentum is taken to be the vectorial sum of all PF candidate momenta in the jet. Additional pp interactions within the same or nearby bunch crossings, known as pileup, can increase the apparent jet momentum by contributing additional tracks and calorimetric energy deposits. To mitigate this effect for small-radius jets, tracks originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [70]. For large-radius jets, the pileup per particle identification algorithm [71] is used to weight the PF candidates prior to jet clustering. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle level jets on average [72]. Additional selection criteria are applied to remove jets that are likely to be dominated by instrumental effects or reconstruction failures [69, 70].

To isolate the H signal, a large-radius jet with high p_T is required. Events are selected by a combination of triggers, with each trigger imposing a minimum threshold on either the p_T of a large-radius jet or the event H_T, the scalar p_T sum of all small-radius jets in the event with $|\eta| < 3$. For large-radius jets used in the trigger selection, a minimum trimmed jet mass [73] is also required. The trigger selection is about 90% efficient with respect to the offline selection for events containing large-radius jets with p_T from 450–500 GeV and $|\eta| < 2.5$, and is fully efficient for $p_T > 500$ GeV and $|\eta| < 2.5$. In order to ensure high trigger efficiency, each event is required to contain at least one large-radius jet with $p_T > 450$ GeV and $|\eta| < 2.5$. Large-radius jets are required to pass the tight jet identification requirement [69] and be separated from all isolated photons or charged leptons by a distance of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.8$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle, respectively.

For large-radius jets originating from the decay of a massive boson (W, Z, H), contamination from underlying event and pileup can lead to an overestimate of the jet invariant mass and degraded jet mass resolution. The soft drop algorithm [74], with parameters $\beta = 0$ and $z_{cut} = 0.1$, is applied to mitigate these effects by removing PF candidates consistent with soft and wide-angle radiation from the jet. For jets originating from the decay of a massive boson, the soft drop mass (m_{SD}) peaks at the boson mass, while for quark- and gluon-initiated jets, m_{SD} has a smoothly falling spectrum.

In order to avoid regions where non-perturbative effects lead to discrepancies in generator predictions [75], large-radius jets are required to have $\rho > -6.0$, where $\rho = 2\ln(m_{SD}/p_T)$. Large-radius jets with $\rho > -2.1$ are also vetoed, since above this threshold the jet constituents are no longer fully contained in a cone of $R = 0.8$. This ρ selection is fully efficient for H signal events.

The multivariate DDB tagger discriminant is used to determine whether a large-radius jet originates from a heavy particle decaying to a $b\bar{b}$ pair [32]. The DDB tagger is based on a deep neural network that is trained to distinguish large-radius jets containing scalar $X \to b\bar{b}$ decays from jets originating from light quarks or gluons. The DDB tagger is trained on jet features, such as the number of PF candidates and low-level quantities describing secondary vertices within the jet. The addition of low-level features leads to a large improvement in performance relative to the previous version of the tagger [33, 34]: for a QCD jet mistag rate of 1%, the signal efficiency of the updated DDB tagger is about 75%, representing an improvement of about 50% with respect to the previous version.

In order to ensure that the DDB tagger selection does not impact the shape of the background m_{SD} distribution, the DDB network is trained on a signal sample composed of simulated decays of bosons with masses ranging from 20 to 200 GeV. The success of this decorrelation method is demonstrated in Fig. 2, which shows the shape of the m_{SD} distribution for simulated QCD jets with $450 < p_T < 1200$ GeV after different DDB selection criteria have been applied. The shape of the m_{SD} distribution is shown to be mostly independent of the DDB threshold value.

The large-radius jet with the highest DDB score is identified as the Higgs boson candidate. This criterion selects a H candidate jet within $\Delta R < 0.8$ of the generated particle in more than 90% of simulated $H \to b\bar{b}$ events. Events in which the selected candidate jet does not correspond to the H decay are excluded from the signal yield, and their contribution is accounted for in the estimation of the QCD multijet background.

Events containing H candidate jets with high DDB tagger score enter the "DDB pass" region. The definition of the DDB pass region is chosen to maximize the expected sensitivity to VBF H production, and the DDB tagger threshold corresponds to a signal efficiency of about 40%

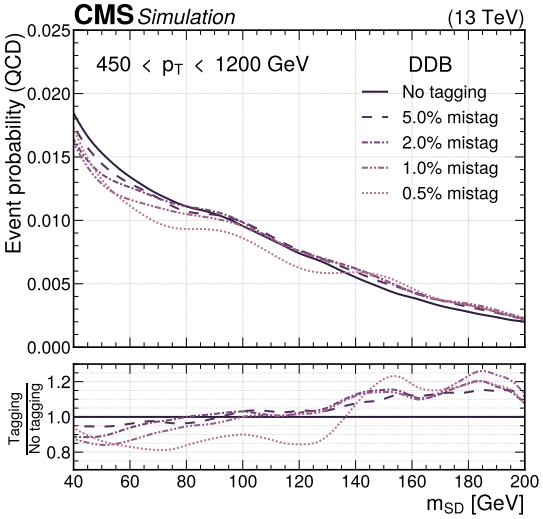

Figure 2: Soft drop mass distribution in simulated QCD events after applying the DDB selection at different working points. The distributions are obtained from simulated QCD events, smoothed using Gaussian kernel density estimation, and normalized to unit area. The lower panel shows the ratio to the inclusive distribution.

and a QCD multijet mistag rate of 0.5%. Events containing H candidate jets below this DDB threshold enter the "DDB fail" region, which is later used to constrain the normalization and shape of the QCD multijet background.

Higgs boson candidate jets are required to be consistent with the two-prong substructure of a $H \to b\bar{b}$ decay, reducing the contribution from $t\bar{t}$, single top, and QCD backgrounds. The substructure selection is based on the N_2^1 variable, a ratio of three-point to two-point energy correlation functions proposed in Ref. [76]. In order to minimize the dependence of the substructure selection on the p_T and m_{SD} of the H candidate, a variant of N_2^1 is defined using the designed decorrelated tagger (DDT) technique [77]. The value of N_2^1 that results in a background efficiency ϵ is determined as a function of jet p_T and ρ and denoted $N_\epsilon(p_T, \rho)$. A decorrelated substructure variable, which has a background efficiency that is independent of jet p_T and ρ, can be obtained by subtracting $N_\epsilon(p_T, \rho)$ from the nominal substructure variable. The following transformation defines the decorrelated substructure variable used in this analysis:

$$N_2^{1,\mathrm{DDT}} = N_2^1 - N_\epsilon(p_T, \rho). \tag{1}$$

A background efficiency of $\epsilon = 0.26$ is chosen to maximize the total H signal sensitivity, and $N_{0.26}(p_T, \rho)$ is derived from the simulated multijet distribution of N_2^1 separately in each data-taking period. Selected events are required to have $N_2^{1,\mathrm{DDT}} < 0$, which retains about 50% of H signal events and (by construction) rejects 74% of expected QCD events. The calibration of this substructure requirement and the associated uncertainties are described in Section 5.2.

Small-radius jets are required to have $p_T > 30\,\mathrm{GeV}$ and $|\eta| < 5.0$. These jets must be separated from the H candidate jet by a distance of $\Delta R > 0.8$. The DEEPJET algorithm [78, 79] is used to identify small-radius jets within the volume of the silicon tracking detectors ($|\eta| < 2.5$) that originate from b quarks. In order to reduce contamination from $t\bar{t}$ background, events are vetoed if any of the four highest-p_T small-radius jets in the hemisphere opposite the H candidate is b tagged.

The missing transverse momentum vector $\vec{p}_T^{\,\mathrm{miss}}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, with modifications to account for

corrections to the energy scale of the reconstructed jets in the event [80]. The magnitude of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is denoted $p_{\mathrm{T}}^{\mathrm{miss}}$ and required to be less than 140 GeV.

Events containing charged leptons are vetoed. For purposes of this veto, electrons must have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.5$ and pass the loose identification criteria outlined in Ref. [38]. Muons must satisfy the loose identification criteria described in Ref. [39] and have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.4$. For electrons (muons), the isolation variable corresponds to the pileup-corrected sum p_{T} of charged hadrons and neutral particles in a cone of $R = 0.3$ (0.4) around the lepton divided by the lepton p_{T}. The isolation is required to be less than 0.15 and 0.25 for electrons and muons, respectively. Hadronically decaying tau leptons (τ_{h}) are reconstructed from jets using the hadrons-plus-strips algorithm [81]. To distinguish genuine τ_{h} decays from jets originating from the hadronization of quarks or gluons, as well as from electrons or muons, the DEEPTAU algorithm is used [82]. For the purposes of a lepton veto, τ_{h} must have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.3$.

In order to measure the VBF and ggF production mechanisms simultaneously, the selected events (both DDB pass and fail) are partitioned into two categories. The VBF category selection is optimized for sensitivity to VBF production by targeting the characteristic forward (high $|\eta|$) quark-initiated jets. Events entering this category are required to contain two small-radius jets in addition to the H candidate. The small-radius jets are required to have a pseudorapidity separation of $|\Delta\eta| > 3.5$ and invariant mass of $m_{\mathrm{jj}} > 1$ TeV, where the selection criteria are chosen to maximize the sensitivity to VBF production. If an event contains more than two small-radius jets, the highest and second highest in p_{T} are used to construct $\Delta\eta$ and m_{jj}. Events containing fewer than two small-radius jets, or where $|\Delta\eta| < 3.5$ or $m_{\mathrm{jj}} < 1$ TeV, fall into the ggF category. Figure 3 shows the predicted relative contribution of each production mechanism to the total Higgs boson signal in the VBF and ggF categories.

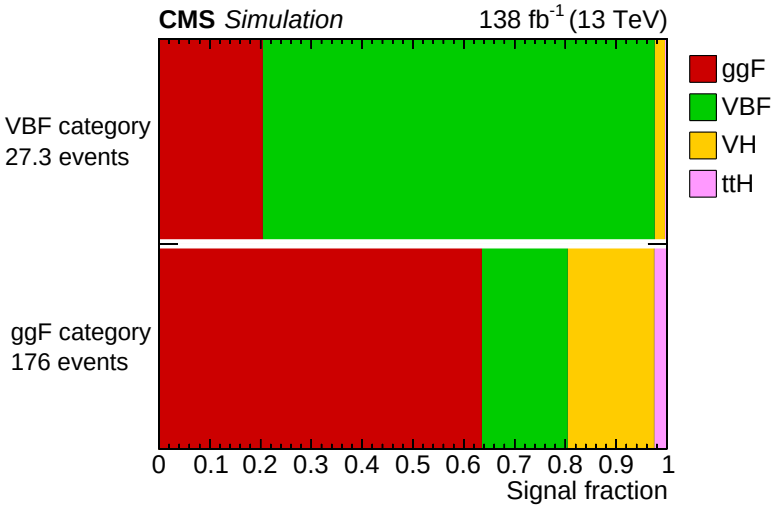

Figure 3: Simulated relative contributions of the four leading H production processes to the total H signal yield in the VBF and ggF categories, shown in the DDB pass region. Small contributions from the VH and $\mathrm{t\bar{t}H}$ processes are also included. The total number of predicted H events in the 138 fb^{-1} dataset are 27.3 and 176 in the VBF and ggF categories, respectively.

The VBF category is divided into two bins in m_{jj} with different signal purity: $1 < m_{\mathrm{jj}} < 2$ TeV and $m_{\mathrm{jj}} > 2$ TeV. When combined statistically, this yields about 20% improvement in the expected significance of a VBF signal compared to a single bin. Similarly, the ggF category is divided into six bins in the H candidate jet p_{T} with boundaries 450, 500, 550, 600, 675, 800,

and 1200 GeV. The upper p_T bound of 1200 GeV does not have a significant impact on the sensitivity and excludes a region where the QCD multijet background is difficult to model. The subdivision into p_T bins improves the expected ggF significance by about 20%.

5 Background estimation

Because of its large cross section, QCD multijet production is the dominant background in the combined DDB pass and fail regions. Significant resonant backgrounds arise from W+jets and Z+jets processes, where the two-prong decay of a high-p_T vector boson is mistagged as a H candidate. Electroweak W and Z boson production contribute in particular to the background in the VBF category because of the presence of two forward quark-initiated jets. For events in which a high-p_T top quark is produced, it is possible that a large-radius jet captures only two of the three prongs of the decay and passes the $N_2^{1,\mathrm{DDT}}$ selection. The presence of a bottom quark in these decays makes them more likely to pass the DDB requirement. In this way, top quark production contributes to the nonresonant component of the background. This section describes the estimate of the background contribution from each of these processes.

Additional small background contributions from diboson, VH, and $\mathrm{t\bar{t}H}$ processes (each expected to be $< 1\%$ of the total background) are estimated from simulation. Both VH and $\mathrm{t\bar{t}H}$ are assumed to occur at SM rates.

5.1 QCD background

The soft drop jet mass in QCD multijet events follows a steeply falling distribution. The predicted shape of the QCD background in the DDB pass region is derived using data in the background-enriched DDB fail region. The full prediction of the QCD background yield in the DDB pass region takes the form

$$N_{\mathrm{P}}^{i} = N_{\mathrm{F}}^{\mathrm{data},i}\, R_{\mathrm{P/F}}^{\mathrm{MC},i}\, T_{\mathrm{P/F}}(p_{\mathrm{T}}^{i}, \rho^{i})\, T_{\mathrm{res}}(p_{\mathrm{T}}^{i}, \rho^{i}), \tag{2}$$

where bin i corresponds to p_{T}^{i} and ρ^{i}. $N_{\mathrm{F}}^{\mathrm{data},i}$ is the number of data events minus the number of predicted non-QCD background events in bin i in the DDB fail region. The ratio $R_{\mathrm{P/F}}^{\mathrm{MC},i}$ is the number of simulated QCD events in the DDB pass region divided by that in the DDB fail region.

Two transfer factors, $T_{\mathrm{P/F}}$ and T_{res}, account for shape differences in the jet p_T and m_{SD} distributions between the DDB pass and fail regions. In the ggF category, the functional form of each transfer factor is taken to be a two-dimensional Bernstein polynomial in the H candidate jet p_T and ρ:

$$T_{\mathrm{P/F}}(p_{\mathrm{T}}, \rho) = \sum_{k=0}^{n_\rho} \sum_{l=0}^{n_{p_{\mathrm{T}}}} a_{k,l} \left[b_{k,n_\rho}(\rho)\, b_{l,n_{p_{\mathrm{T}}}}(p_{\mathrm{T}}) \right], \tag{3}$$

where n_ρ and $n_{p_{\mathrm{T}}}$ are the degrees of the polynomial in ρ and p_T, respectively, $a_{k,l}$ are fitted coefficients, and $b_{\nu,n}$ are one-dimensional Bernstein polynomials:

$$b_{\nu,n}(x) = \binom{n}{\nu} x^{\nu} (1-x)^{n-\nu}. \tag{4}$$

The variables p_T and ρ are affine transformed to lie within the domain of the Bernstein basis. Because the VBF category is not binned in p_T, the transfer factors in this category are parameterized only in ρ, and a sum of one-dimensional Bernstein polynomials is used.

The first transfer factor, $T_{\mathrm{P/F}}$, accounts for possible p_{T}- or m_{SD}-dependent effects due to the DDB selection by parameterizing the ratio of the QCD event yield in the DDB pass and fail regions. The coefficients $a_{k,l}$ of $T_{\mathrm{P/F}}$ are derived with a dedicated fit to the m_{SD} distribution in QCD MC simulation. Discrepancies in the tagger performance between data and simulation are accounted for with a second transfer factor, T_{res}. The coefficients of T_{res} are obtained in the final simultaneous fit to data described in Section 7. Independent transfer factors $T_{\mathrm{P/F}}$ and T_{res} are defined for each data-taking period, and in the ggF category and each of the two m_{jj} bins in the VBF category.

For each transfer factor, the optimal number of free parameters is determined by a Fisher F-test [83]. As a first step, a low-order polynomial of n_1 parameters is taken as the baseline function. An alternative function with $n_2 > n_1$ parameters is tested against the baseline. In the case where the baseline function has $n_\rho = n_{p_{\mathrm{T}}}$, the alternative function is determined by increasing the polynomial order in ρ. The alternative function is adopted as the new baseline if it provides a significantly better goodness-of-fit (F-statistic with p-value [84] less than 0.05). The polynomial order is optimized independently for $T_{\mathrm{P/F}}$ and T_{res}, separately in each data-taking period and in the ggF category and each of the two m_{jj} bins in the VBF category.

In the ggF category, the optimal polynomial order for $T_{\mathrm{P/F}}$ is determined to be $(n_{p_{\mathrm{T}}}, n_\rho) = (1,1)$ for early 2016 and $(n_{p_{\mathrm{T}}}, n_\rho) = (0,1)$ for late 2016, 2017, and 2018. The optimal polynomial order for T_{res} is found to be $(n_{p_{\mathrm{T}}}, n_\rho) = (0,2)$ for all data-taking periods. In the VBF category, the optimal polynomial order for both transfer factors is found to be $n_\rho = 0$ for all data-taking periods in both m_{jj} bins.

Tests with alternative functional forms for the transfer factors show that the final result has negligibly small dependence on the choice of the parameterization.

5.2 W+jets and Z+jets backgrounds

The W+jets and Z+jets backgrounds are modeled using simulation, with normalizations and kinematic distributions corrected for NLO QCD and EW effects, as described in Section 3. A scale factor (f_{sub}) is applied to the W+jets and Z+jets processes to correct for the efficiency of the two-prong substructure selection ($N_2^{1,\mathrm{DDT}} < 0$). A dedicated W tag control region (CR) is used to simultaneously derive f_{sub}, a correction factor on the jet mass resolution (f_σ), and a jet mass shift (δ_m). These corrections are applied to the predictions from simulation for W+jets and Z+jets, as well as all H signal processes.

Events entering the W tag CR must pass a trigger requiring a muon with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$. Events must contain a muon passing the tight identification requirements defined in Ref. [39] and have $p_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$. The p_{T} of the muon plus $p_{\mathrm{T}}^{\mathrm{miss}}$ system, which forms a W boson proxy, must be greater than 200 GeV. Finally, at least one b-tagged small-radius jet is required. This region contains a high fraction of $\mathrm{t\bar{t}}$ events, and the substructure variable requirements select primarily top quark decays to boosted W bosons.

Two template m_{SD} distributions are constructed from simulation in the W tag CR: events that contain a W boson, and events that do not. Variations in the jet mass scale and jet mass resolution are calculated for the template containing a W boson using linear morphing [85]. The desired corrections are then extracted from a template fit to data in the W tag CR. This fit is performed simultaneously in the regions passing and failing the two-prong substructure selection ($N_2^{1,\mathrm{DDT}} < 0$ and $N_2^{1,\mathrm{DDT}} > 0$, respectively).

The fitted values of f_{sub}, f_σ, and δ_m are shown in Table 1 with their uncertainties. These corrections are measured independently for each data-taking period in order to account for the

2017 upgrade of the CMS tracking detector, differences in pileup and detector conditions, and updates to reconstruction algorithms and calibrations. In the fit to the signal regions in data, the uncertainties on these corrections are treated as systematic uncertainties.

Table 1: Summary of corrections for the jet substructure selection (scale factor f_{sub}), jet mass resolution (scale factor f_σ), and jet mass scale (shift δ_m) for different data-taking periods.

	f_{sub}	f_σ	δ_m [MeV]
Early 2016	0.99 ± 0.16	1.13 ± 0.04	-240 ± 410
Late 2016	0.82 ± 0.15	1.21 ± 0.03	$+440 \pm 340$
2017	1.05 ± 0.10	1.09 ± 0.02	$+470 \pm 180$
2018	0.94 ± 0.08	1.07 ± 0.03	-990 ± 250

A nonresonant background arises from W+jets and Z+jets events in which the selected candidate jet does not correspond to the decay of the vector boson. Since such jets originate instead from QCD processes, they are accounted for in the QCD background estimation.

5.3 Top quark background

Top quark processes contribute a nonresonant component of a few percent to the total background. While the shape of the m_{SD} distributions in $\mathrm{t\bar{t}}$ and single top quark processes are estimated from simulation, both the overall normalization and the DDB tagger efficiency are constrained using data. This is accomplished by including a single-muon CR, which closely mimics the signal selection described above, but selects a semileptonic decay of the $\mathrm{t\bar{t}}$ pair rather than all-hadronic.

Events entering the single-muon CR must pass a trigger requiring a muon with $p_{\text{T}} > 50\,\text{GeV}$. Following trigger selection, events must contain a muon with $p_{\text{T}} > 55\,\text{GeV}$ and $|\eta| < 2.1$. The muon must satisfy the loose identification requirements defined in Ref. [39] and have isolation variable less than 0.25. Events containing electrons or τ_{h} are vetoed. At least one large-radius jet with $p_{\text{T}} > 400\,\text{GeV}$, $|\eta| < 2.5$, $m_{\text{SD}} > 40\,\text{GeV}$ and $N_2^{1,\text{DDT}} < 0$ is required, and this jet must be separated from the muon by an angular distance of $\Delta\phi > 2\pi/3$. At least one small-radius b-tagged jet with $p_{\text{T}} > 50\,\text{GeV}$ and $|\eta| < 2.5$ is also required. The resulting CR is more than 80% pure in top quark processes. Small contributions from QCD, W+jets, and Z+jets processes are estimated from simulation.

In order to account for kinematic differences between the single-muon CR and the VBF-specific phase space, an additional systematic uncertainty is applied to the $\mathrm{t\bar{t}}$ yield in the VBF category. The magnitude of this uncertainty is derived from a comparison of the data-to-simulation scale factor obtained in the inclusive single-muon CR and in the same CR with additional requirements on the number of small-radius jets, $\Delta\eta$, and m_{jj}.

The DDB pass and fail regions of the single-muon CR are treated as single-bin counting experiments in the final fit framework.

6 Systematic uncertainties

Several sources of experimental uncertainty arise from the reconstruction and calibration of physics objects from low-level detector responses.

A data-to-simulation scale factor is applied to the $\mathrm{H} \to \mathrm{b\bar{b}}$ and $\mathrm{Z} \to \mathrm{b\bar{b}}$ predictions to account for the difference in efficiency of the DDB tagger selection. This scale factor is included in

the signal extraction fit as a constrained nuisance parameter with a nominal value of unity and a conservative uncertainty of 30%. The magnitude of this uncertainty is based on the results of dedicated measurements in QCD multijet events with gluon to $\mathrm{b\bar{b}}$ splitting topologies similar to the $\mathrm{H} \to \mathrm{b\bar{b}}$ signal [86], but a precise scale factor cannot be derived due to the limited number of gluon splitting events in the p_{T} regime relevant for this analysis. The DDB scale factor is instead constrained in situ via the observed $\mathrm{Z} \to \mathrm{b\bar{b}}$ yield in the DDB pass and fail regions and constitutes the dominant experimental uncertainty. The extracted DDB scale factors and uncertainties are shown in Table 2.

Table 2: Post-fit DDB tagger selection efficiency scale factor and uncertainty for different data-taking periods.

	Scale factor	Uncertainty	
Early 2016	0.88	$+0.19$	-0.15
Late 2016	0.92	$+0.18$	-0.13
2017	0.79	$+0.12$	-0.10
2018	0.85	$+0.11$	-0.10

The uncertainties on the corrections for substructure selection, jet mass scale, and jet mass resolution detailed in Section 5.2 are treated as constrained nuisance parameters. These uncertainties are correlated among the W, Z, and Higgs boson production processes, and are further constrained by the presence of W and Z boson resonances in the m_{SD} distribution. Additional systematic uncertainties are applied to the event yields of W+jets, Z+jets, $\mathrm{t\bar{t}}$, and Higgs boson production to account for the uncertainties due to the jet energy scale and resolution [72, 87] and the limited event count of simulated samples. A bin-by-bin uncertainty is applied to account for the limited number of simulated QCD events in the dedicated fit to determine the transfer factor $T_{\mathrm{P/F}}$.

Other experimental uncertainties, including those related to the determination of the integrated luminosity [29–31], variations in the amount of pileup obtained by adjusting the total inelastic cross section, modeling of the trigger efficiency, and the isolation and identification of the veto leptons are also considered, and contribute only a few percent to the total uncertainty.

In addition to experimental uncertainties, theoretical uncertainties are included in the final fit to account for inaccuracy in the modeling of SM processes.

The dominant theoretical uncertainty is due to the renormalization and factorization scales chosen for the simulated H samples. These uncertainties are applied to all H production processes and are propagated to the total expected yield of the H signal according to the prescription recommended in Ref. [22]. They amount to approximately 20% and 5% in the ggF and VBF signal yields, respectively. Uncertainties in the event yields due to initial- and final-state radiation are also calculated for all H production processes by varying the renormalization scale and non-singular term using the PYTHIA 8 showering algorithm [88]. The Hessian PDF uncertainty is also applied to H signal yield, according to the prescription of Ref. [89].

Theoretical uncertainties on the W+jets and Z+jets processes account for missing higher-order QCD and mixed QCD-EW effects beyond the corrections described in Section 3, following the prescription of Ref. [48].

All theoretical uncertainties are considered to be correlated across all data-taking periods, and experimental systematic uncertainties are considered to be uncorrelated, with the exception of a correlated component of the uncertainty on the integrated luminosity ($\mathcal{L}$). All systematic uncertainties are incorporated into the analysis via nuisance parameters and treated according

to the frequentist paradigm [90].

Among the largest sources of systematic uncertainty are the theoretical uncertainties in the Higgs boson production cross section, the size of simulated signal samples, and the uncertainty in the data-to-simulation scale factor on the DDB tagger selection. Overall, the measurement is limited by the statistical uncertainty in data, including the limited sample size available to determine the QCD background yield under the Higgs boson peak via the transfer factor T_{res}, as discussed in Section 5.1.

7 Results

A binned maximum likelihood fit to the observed m_{SD} distributions is performed using the sum of the signal and background contributions. The test statistic chosen to determine the signal yield is based on the profile likelihood ratio [90]. The fit is performed simultaneously in many bins: in both m_{jj} bins of the VBF category and all p_T bins of ggF category, in the single-muon control region, in both the DDB pass and fail regions, and in all four data-taking periods. The observed data and post-fit m_{SD} distributions in the VBF category are shown in Fig. 4. For display purposes, the data and fitted distributions are summed over both m_{jj} bins and all four data-taking periods. For the ggF category, the observed data and post-fit m_{SD} distributions are shown in Fig. 5, again summed over all six p_T bins and all data-taking periods for display purposes.

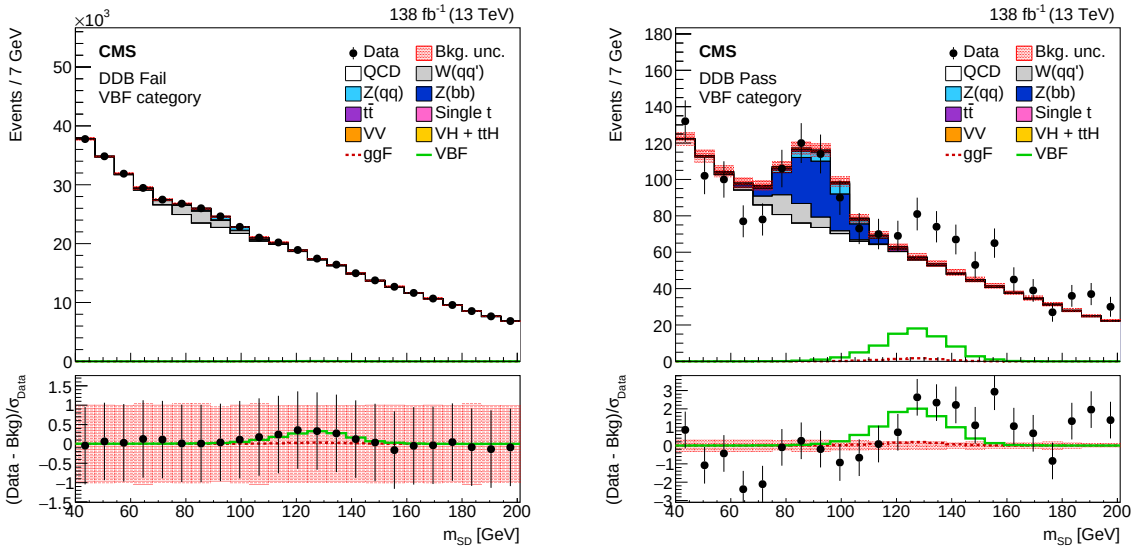

Figure 4: Post-fit soft drop mass distribution in the VBF category, summed over all m_{jj} bins and data-taking periods for display purposes. The DDB fail (left) and pass (right) regions are shown. The total background is broken down into contributions from different processes, and the total uncertainty is shown as a red band. The lower panels show the difference between the data and background prediction divided by the statistical uncertainty in data. The near-perfect model agreement with data in the DDB fail region is by construction. The ggF and VBF distributions are overlaid in red and green, respectively. Each signal is scaled to its fitted event yield.

The best fit value of the signal strength, defined as the ratio of the measured to the SM expected cross section times $H \to b\bar{b}$ branching fraction, and an approximate 68% confidence level (CL) interval are extracted following Ref. [91]. The fitted signal strengths for VBF and ggF

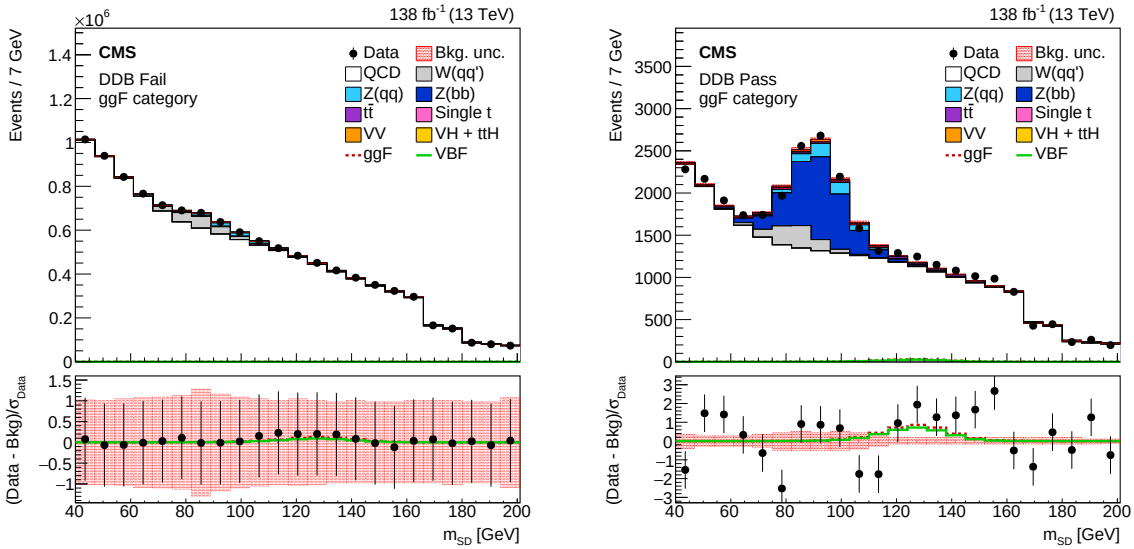

Figure 5: Post-fit soft drop mass distribution in the ggF category, summed over all p_{T} bins and data-taking periods for display purposes. The DDB fail (left) and pass (right) regions are shown. The total background is broken down into contributions from different processes, and the total uncertainty is shown as a red band. The lower panels show the difference between the data and background prediction divided by the statistical uncertainty in data. The near-perfect model agreement with data in the DDB fail region is by construction. The ggF and VBF distributions are overlaid in red and green, respectively. Each signal is scaled to its fitted event yield. The apparent discontinuity at high mass is due to the exclusion of bins with extreme values of ρ.

Table 3: Fitted signal strength for $H \to b\bar{b}$ in the VBF and ggF channels for each data-taking period and for the full data set. The total uncertainty is shown, followed by the statistical component in parentheses.

	$\mathcal{L}$ [fb^{-1}]	VBF signal strength	ggF signal strength
Early 2016	19.5	$5.2^{+4.6}_{-3.8}$ ($^{+3.9}_{-3.6}$ stat)	$2.5^{+4.7}_{-4.3}$ ($^{+3.8}_{-3.7}$ stat)
Late 2016	16.8	$5.6^{+5.8}_{-4.2}$ ($^{+4.5}_{-4.0}$ stat)	$0.6^{+4.4}_{-4.8}$ ($\pm$3.8 stat)
2017	41.5	$0.8^{+2.8}_{-2.5}$ ($^{+2.7}_{-2.5}$ stat)	$3.3^{+3.1}_{-2.7}$ ($\pm$2.5 stat)
2018	59.8	$8.3^{+3.9}_{-3.0}$ ($^{+2.8}_{-2.7}$ stat)	$0.4^{+2.6}_{-2.7}$ ($\pm$2.3 stat)
Combined	138	$4.9^{+1.9}_{-1.6}$ ($\pm$1.5 stat)	$1.6^{+1.7}_{-1.5}$ ($\pm$1.4 stat)

H production, denoted μ_{VBF} and μ_{ggF}, respectively, are extracted separately for the four data-taking periods, and a combined fit over the full data set is performed for the final result. The VH and $t\bar{t}H$ processes are assumed to occur at SM rates. The results are summarized in Table 3. The combined signal strength for the VBF process is measured to be $4.9^{+1.9}_{-1.6}$, and the combined signal strength for the ggF process is measured to be $1.6^{+1.7}_{-1.5}$. The expected signal strengths for VBF and ggF are $1.0^{+1.4}_{-1.3}$ and $1.0^{+1.4}_{-1.3}$, respectively. The observed (expected) correlation between these two signal strengths is -0.41 (-0.41). Tabulated results are provided in the HEPData record for this analysis [92].

Figure 6 shows the combined two-dimensional likelihood scan performed over the VBF and ggF signal strengths. The best fit point differs from the SM expectation by $2.7\,\sigma$, and from the null hypothesis (no H production) by $4.0\,\sigma$.

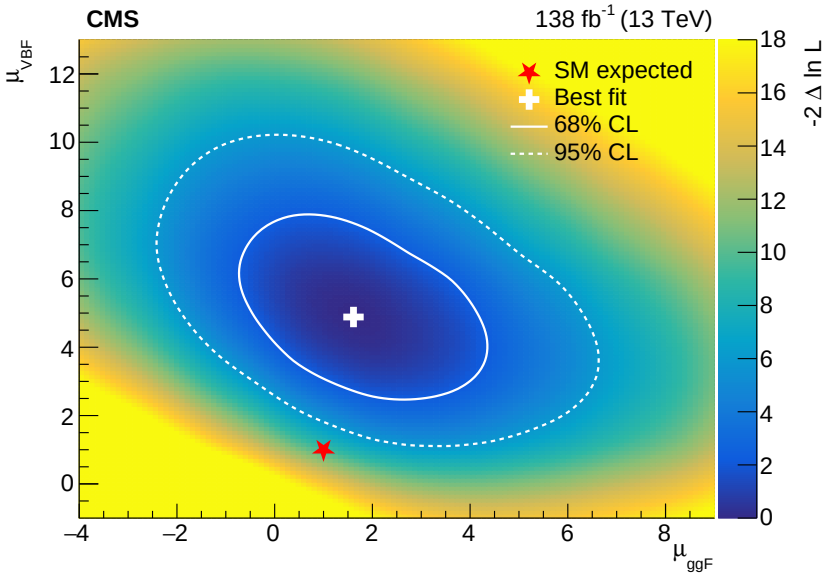

Figure 6: Two-dimensional likelihood contour of the VBF and ggF signal strengths. The color scale represents twice the negative log likelihood difference with respect to the best fit point. The observed 95% (dashed) and 68% (solid) contours are shown in white, and the best fit point as a white cross. The SM expectation is marked by a red star.

7.1 Differential measurement

The observed m_{SD} distributions in the DDB pass region are shown separately in each bin in Figs. 7 and 8, for VBF and ggF, respectively. The signal strength is also fitted independently per reconstruction-level bin. Because the VBF (ggF) category can only weakly constrain the ggF (VBF) process, the ratio of ggF to VBF is fixed to the value obtained in the signal strength fit described above. The results are shown in Fig. 9.

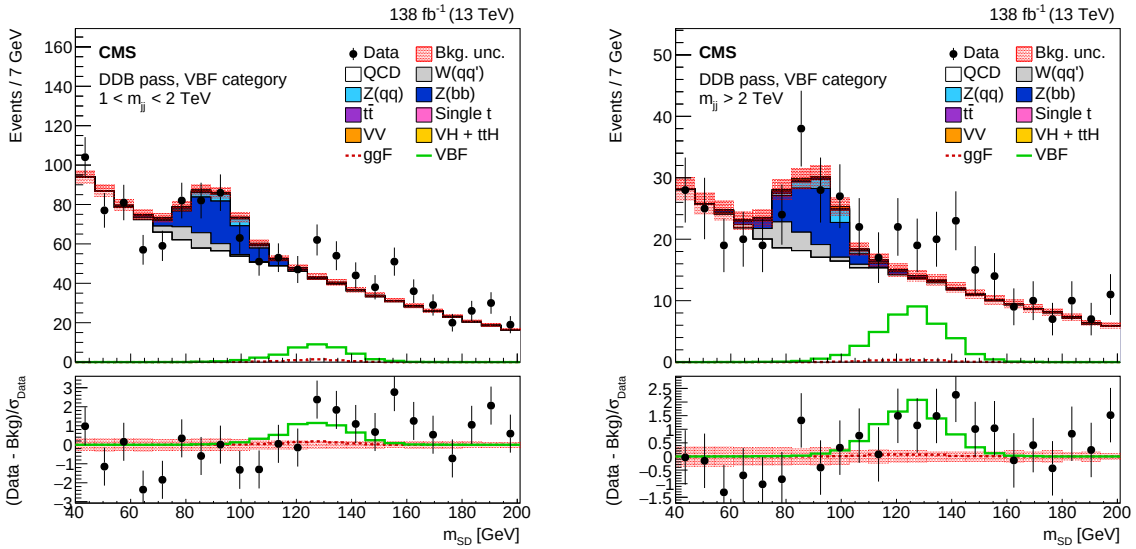

Figure 7: Post-fit soft drop mass distribution in each of the two m_{jj} bins in the VBF category, summed over all data-taking periods for display purposes. The DDB pass region is shown. The lower panels show the difference between the data and background prediction divided by the statistical uncertainty in data. The ggF and VBF distributions are overlaid in red and green, respectively. Each signal is scaled to its fitted event yield.

A maximum likelihood unfolding technique [93] is used to remove the effects of limited detector acceptance and response on the measured production cross section. The fiducial cross section is extracted simultaneously in five bins, each of which is considered as a separate process and modified by a freely floating signal strength parameter in the likelihood model. The three bins in the ggF channel correspond to fiducial regions with generated Higgs boson rapidity $|y^{H,gen}| < 2.5$ and p_T ($p_T^{H,gen}$) in the ranges 300–450, 450–650, and > 650 GeV. The two bins in the VBF channel correspond to rapidity $|y^{H,gen}| < 2.5$, $p_T^{H,gen} > 200$ GeV, and m_{jj}^{gen} in the ranges 1000–1500 GeV and > 1500 GeV, where m_{jj}^{gen} is the generator-level invariant mass of the forward quark-initiated jets. This choice of bins is consistent with the simplified template cross section (STXS) stage 1.2 scheme [21, 94]. Additional STXS bins corresponding to ggF with $p_T^{H,gen} < 300$ GeV and VBF with $p_T^{H,gen} < 200$ GeV or $m_{jj}^{gen} < 1000$ GeV are found to have negligible contribution to the signal region. The H signal yields in these bins are assumed to occur at SM rates.

For the theoretical uncertainties, only those that affect the acceptance of signal events in the analysis selection are taken into account. Each fitted signal strength parameter and its uncertainty are scaled by the corresponding simulated cross section to obtain the best fit estimator for the cross section and its uncertainty.

The unfolded fiducial cross sections are shown in Fig. 10, with the predictions from the signal event generators overlaid. The measured cross sections and uncertainties are also reported in

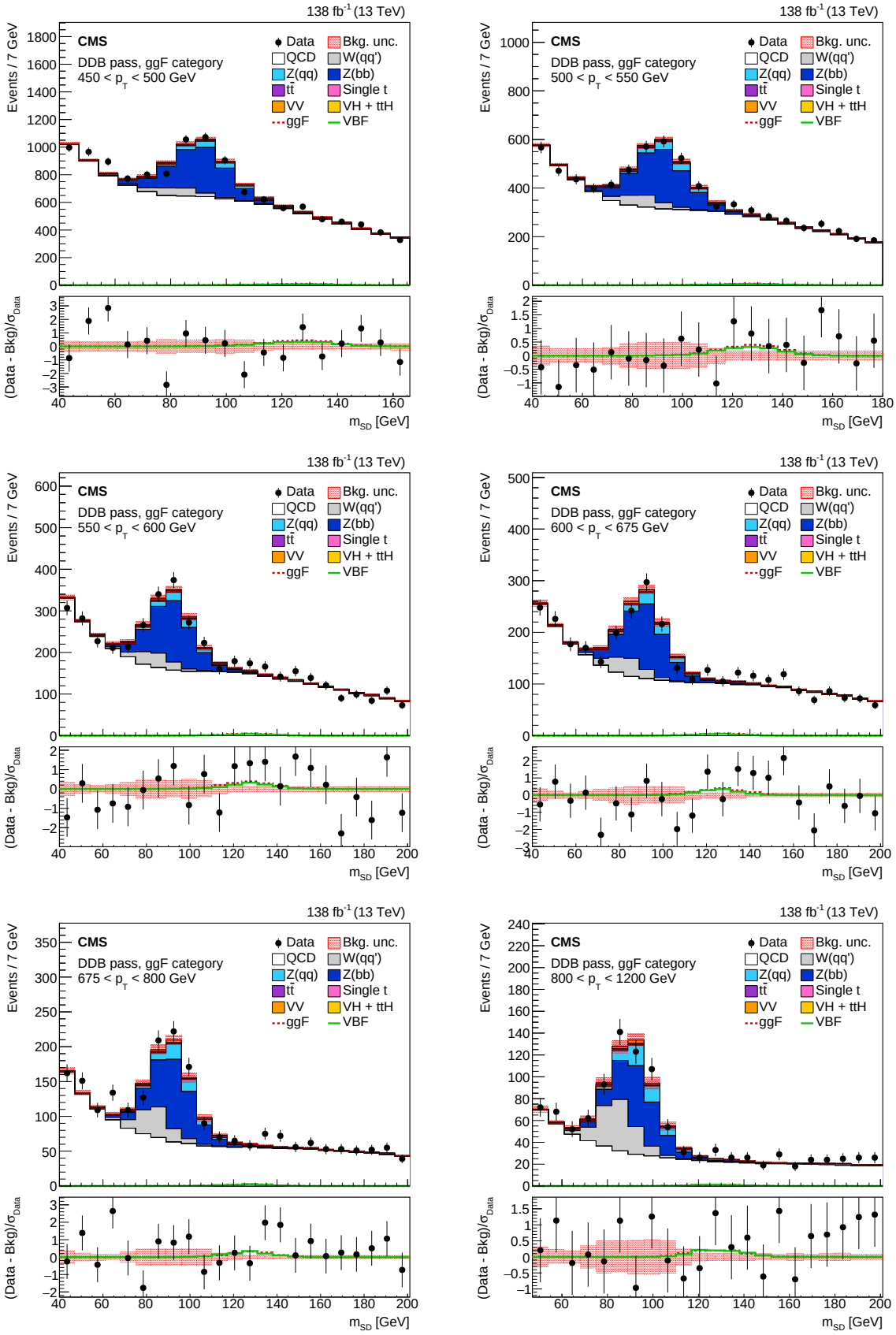

Figure 8: Post-fit soft drop mass distribution in each of the p_T bins in the ggF category, summed over all data-taking periods for display purposes. The DDB pass region is shown. The lower panels show the difference between the data and background prediction divided by the statistical uncertainty in data. The ggF and VBF distributions are overlaid in red and green, respectively. Each signal is scaled to its fitted event yield.

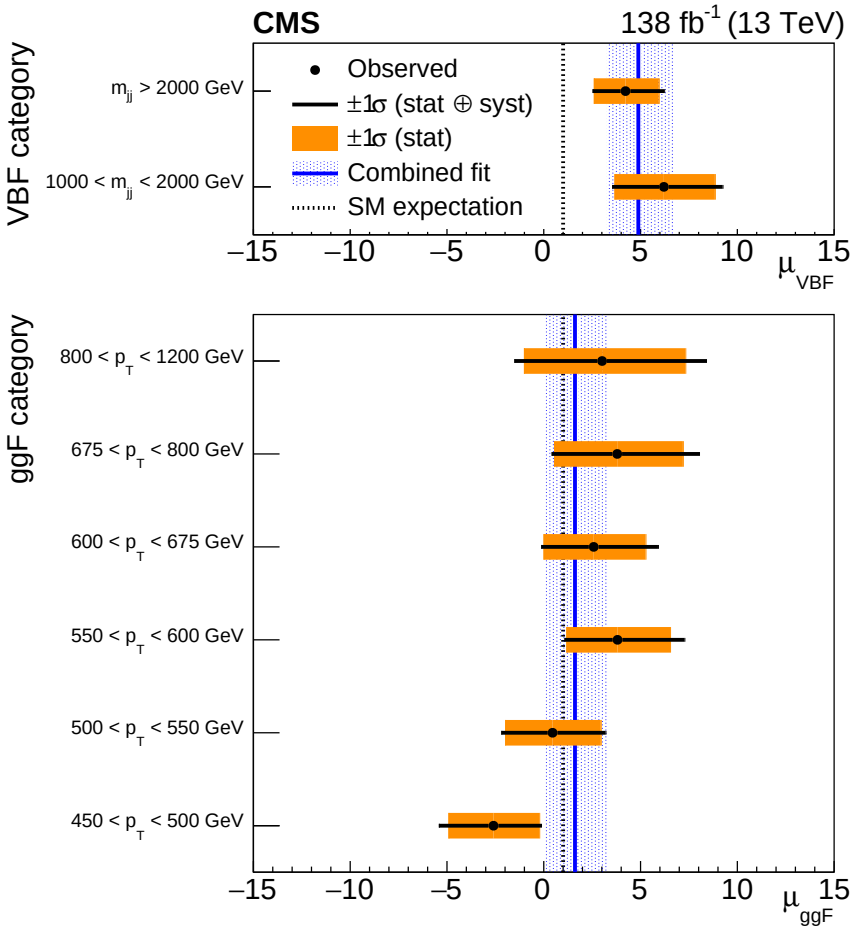

Figure 9: Upper: the VBF signal strength is shown in black, fitted per m_{jj} bin, with the ratio of the ggF and VBF cross sections fixed to the value obtained in the signal strength fit. The horizontal black line represents the total uncertainty, and the orange bar represents the statistical-only component. The combined VBF signal strength and its uncertainty are shown in blue. The SM expectation is shown as a dashed line. Lower: the ggF signal strength is shown in black, fitted per p_T bin, with the ratio of the ggF and VBF cross sections fixed to the value obtained in the signal strength fit. The horizontal black line represents the total uncertainty, and the orange bar represents the statistical-only component. The combined ggF signal strength and its uncertainty are shown in blue. The SM expectation is shown as a dashed line.

Table 4. The best fit for the ggF bin with $300 < p_{\mathrm{T}}^{\mathrm{H,gen}} < 450\,\mathrm{GeV}$ lies below zero cross section, as can happen when the signal is estimated with a fit over a large background. However, the uncertainty in this bin is found to be comparatively large due to the limited number of these events passing the analysis selection, and the SM cross section value is well within the uncertainty.

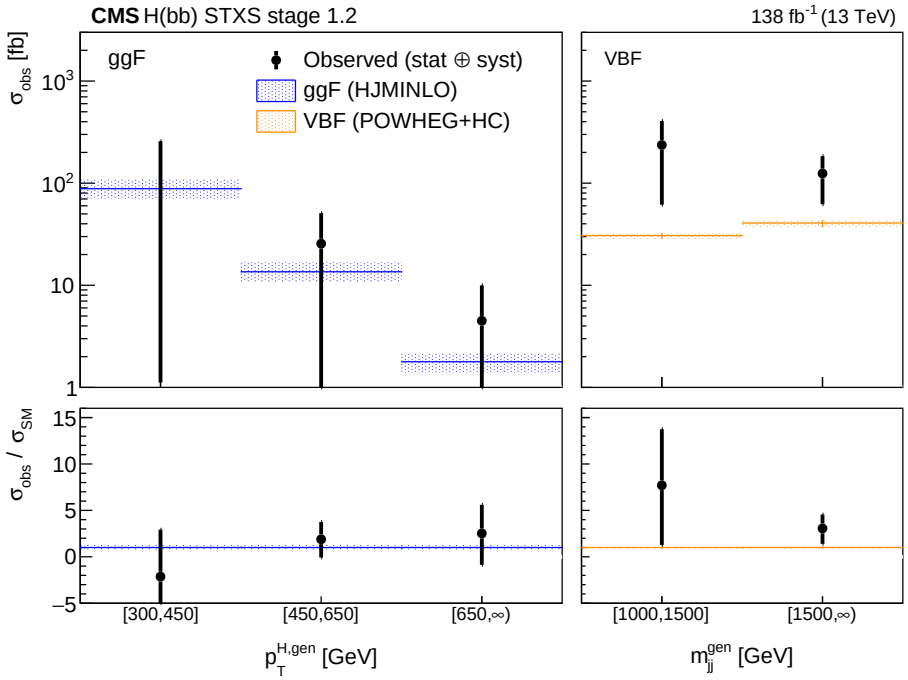

Figure 10: Unfolded cross section in five of the STXS stage 1.2 bins: three bins of Higgs boson p_{T} in ggF, and two bins of generator-level m_{jj} in VBF. The SM prediction from HJMINLO and POWHEG (plus higher order EW and NNLO QCD corrections) is overlaid for the ggF and VBF production mechanisms, respectively. The lower panel shows the ratio of the measured cross section to the SM prediction.

Table 4: Summary of the best fit estimators for the cross sections. In addition to the listed selection, each fiducial region has a rapdity requirement of $|y^{\mathrm{H,gen}}| < 2.5$. The third column shows the SM predicted cross section and uncertainty. The fourth column shows the fitted cross section, and the final column shows the total uncertainty followed by the statistical component in parentheses.

Process	Fiducial region	σ_{SM} [fb]	σ_{obs} [fb]	Uncertainty [fb]
ggF	$300 < p_{\mathrm{T}}^{\mathrm{H,gen}} < 450$ GeV	90 ± 20	-190	$^{+430}_{-450}$ (± 410 stat)
ggF	$450 < p_{\mathrm{T}}^{\mathrm{H,gen}} < 650$ GeV	14 ± 3	26	$^{+25}_{-27}$ ($^{+24}_{-23}$ stat)
ggF	$p_{\mathrm{T}}^{\mathrm{H,gen}} > 650$ GeV	2 ± 0.4	4	$^{+6}_{-5}$ (± 5 stat)
VBF	$p_{\mathrm{T}}^{\mathrm{H,gen}} > 200$ GeV, $1.0 < m_{\mathrm{jj}}^{\mathrm{gen}} < 1.5$ TeV	31^{+1}_{-2}	240	$^{+200}_{-190}$ (± 170 stat)
VBF	$p_{\mathrm{T}}^{\mathrm{H,gen}} > 200$ GeV, $m_{\mathrm{jj}}^{\mathrm{gen}} > 1.5$ TeV	41^{+2}_{-3}	120	$^{+68}_{-61}$ ($^{+62}_{-59}$ stat)

8 Summary

A measurement has been performed of boosted Higgs bosons (H) produced via vector boson fusion (VBF) or gluon fusion (ggF) and decaying to bottom quark-antiquark pairs. The analysis goes beyond the inclusive $H \to b\bar{b}$ measurements performed thus far to provide the first exploration of Higgs bosons produced with high transverse momentum ($p_T > 450\,GeV$) in the VBF channel. The signal strengths for both processes are extracted simultaneously by performing a maximum likelihood fit to data in the large-radius jet mass distribution. The observed signal strengths for the VBF and ggF processes are $4.9^{+1.9}_{-1.6}$ and $1.6^{+1.7}_{-1.5}$, corresponding to a $2.7\,\sigma$ difference between data and the standard model expectation. The unfolded simplified template cross sections, which will provide an important input to future combined interpretations of H interactions, are also reported.

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[21]Also at Purdue University, West Lafayette, Indiana, USA
[22]Also at Université de Haute Alsace, Mulhouse, France
[23]Also at Istinye University, Istanbul, Turkey
[24]Also at The University of the State of Amazonas, Manaus, Brazil
[25]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[26]Also at University of Hamburg, Hamburg, Germany
[27]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[28]Also at Isfahan University of Technology, Isfahan, Iran
[29]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[30]Also at Brandenburg University of Technology, Cottbus, Germany
[31]Also at Forschungszentrum Jülich, Juelich, Germany
[32]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[33]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
[34]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[35]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[36]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[37]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[38]Also at Punjab Agricultural University, Ludhiana, India
[39]Also at University of Visva-Bharati, Santiniketan, India
[40]Also at Indian Institute of Science (IISc), Bangalore, India
[41]Also at Birla Institute of Technology, Mesra, Mesra, India
[42]Also at IIT Bhubaneswar, Bhubaneswar, India
[43]Also at Institute of Physics, Bhubaneswar, India
[44]Also at University of Hyderabad, Hyderabad, India
[45]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[46]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[47]Also at Sharif University of Technology, Tehran, Iran
[48]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[49]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic

Development, Bologna, Italy
[50]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[51]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[52]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[53]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[54]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[55]Also at Riga Technical University, Riga, Latvia
[56]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[57]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[58]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[59]Also at Saegis Campus, Nugegoda, Sri Lanka
[60]Also at National and Kapodistrian University of Athens, Athens, Greece
[61]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[62]Also at Universität Zürich, Zurich, Switzerland
[63]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[64]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[65]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[66]Also at Konya Technical University, Konya, Turkey
[67]Also at Izmir Bakircay University, Izmir, Turkey
[68]Also at Adiyaman University, Adiyaman, Turkey
[69]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[70]Also at Marmara University, Istanbul, Turkey
[71]Also at Milli Savunma University, Istanbul, Turkey
[72]Also at Kafkas University, Kars, Turkey
[73]Now at Istanbul Okan University, Istanbul, Turkey
[74]Also at Hacettepe University, Ankara, Turkey
[75]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[76]Also at Yildiz Technical University, Istanbul, Turkey
[77]Also at Vrije Universiteit Brussel, Brussel, Belgium
[78]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[79]Also at University of Bristol, Bristol, United Kingdom
[80]Also at IPPP Durham University, Durham, United Kingdom
[81]Also at Monash University, Faculty of Science, Clayton, Australia
[82]Also at Università di Torino, Torino, Italy
[83]Also at Bethel University, St. Paul, Minnesota, USA
[84]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[85]Also at California Institute of Technology, Pasadena, California, USA
[86]Also at United States Naval Academy, Annapolis, Maryland, USA
[87]Also at Bingol University, Bingol, Turkey
[88]Also at Georgian Technical University, Tbilisi, Georgia
[89]Also at Sinop University, Sinop, Turkey
[90]Also at Erciyes University, Kayseri, Turkey
[91]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[92]Now at another institute or international laboratory covered by a cooperation agreement

with CERN
[93]Also at Texas A&M University at Qatar, Doha, Qatar
[94]Also at Kyungpook National University, Daegu, Korea
[95]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[96]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
[97]Also at Northeastern University, Boston, Massachusetts, USA
[98]Also at Imperial College, London, United Kingdom
[99]Now at Yerevan Physics Institute, Yerevan, Armenia
[100]Also at Universiteit Antwerpen, Antwerpen, Belgium