Boosted Higgs production via vector boson fusion with the CMS experiment

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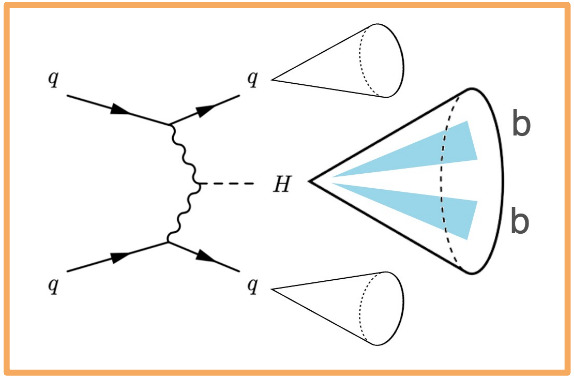
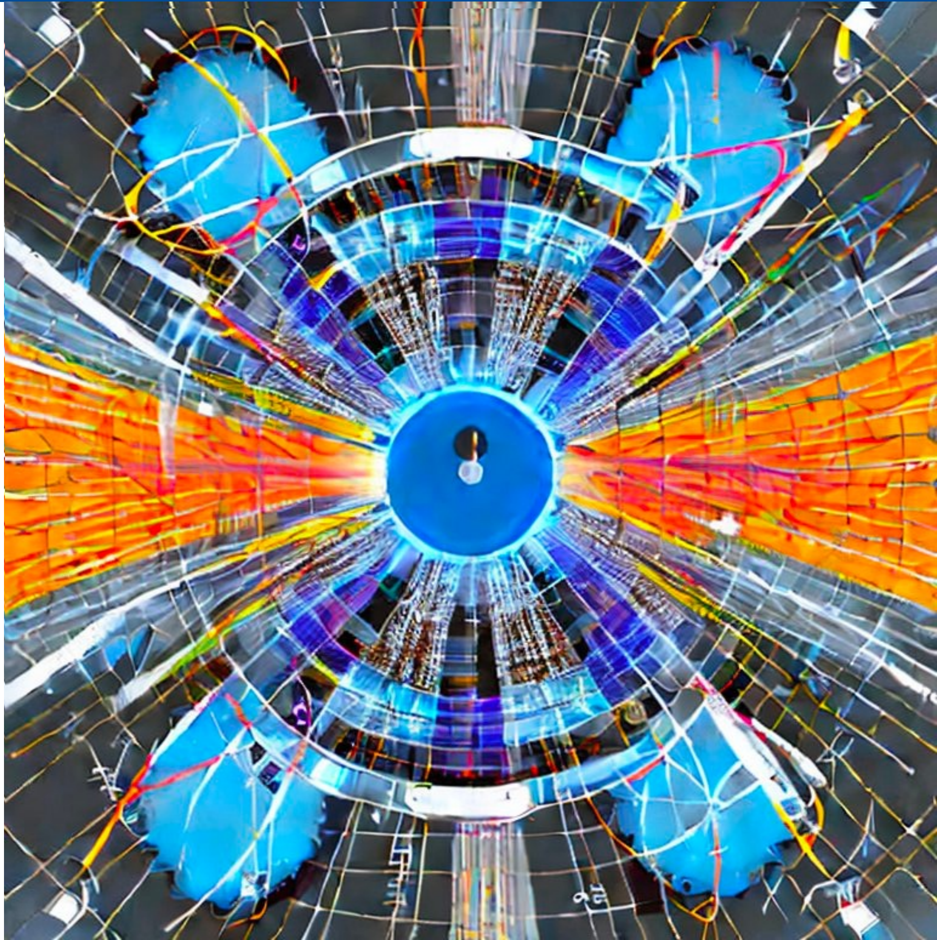
on behalf of the CMS Collaboration

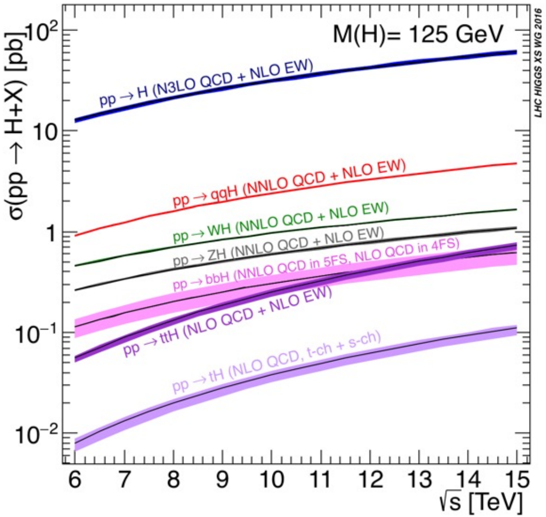
20th Workshop of the LHC Higgs Working Group





Higgs production in pp collisions

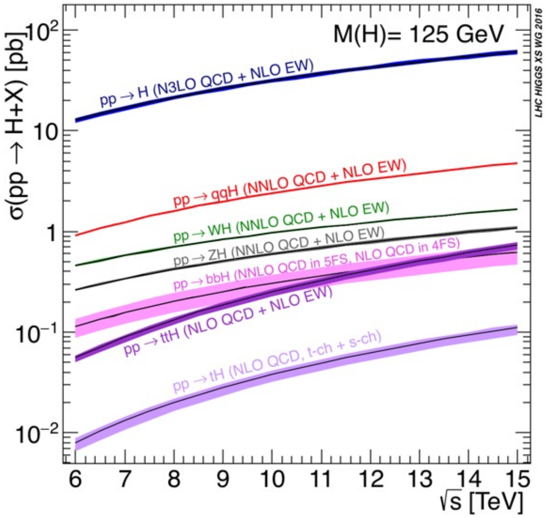
- Gluon fusion accounts for 90% of the Higgs boson cross section at 13 TeV

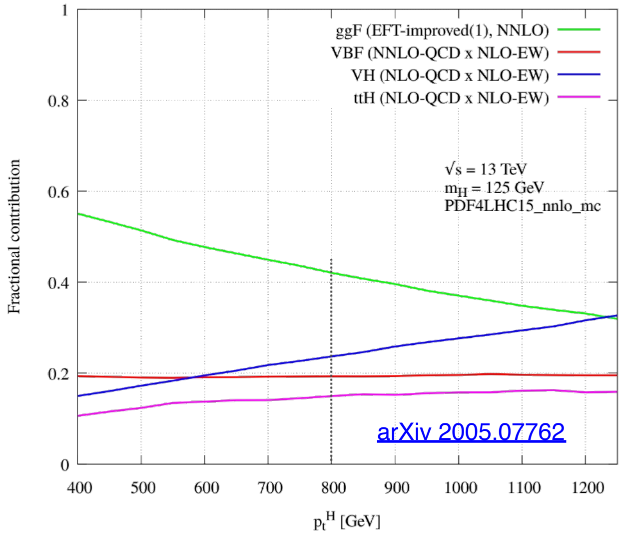


Higgs production in pp collisions

- Gluon fusion accounts for 90% of the Higgs boson cross section at 13 TeV …

if you measure inclusively in p_T





[arXiv 2005.07762](https://arxiv.org/abs/2005.07762)

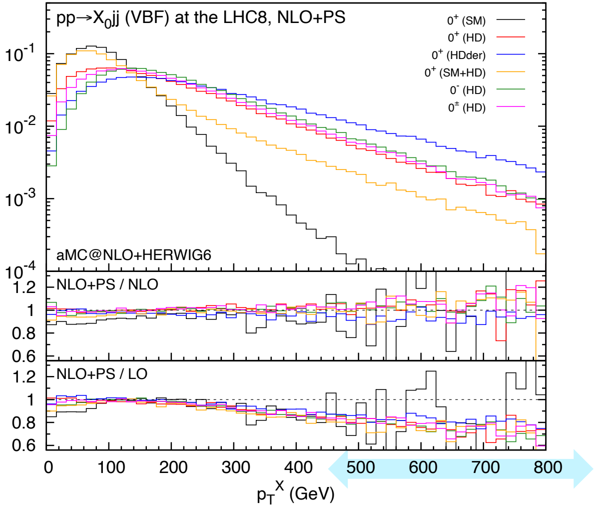
Why VBF at high p_T?

- ggF becomes less dominant at high p_T

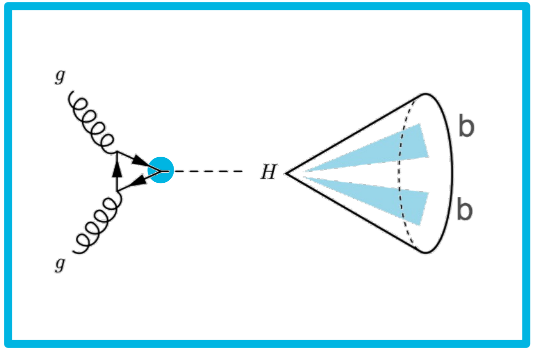
  And we have precise predictions for other production modes (link)

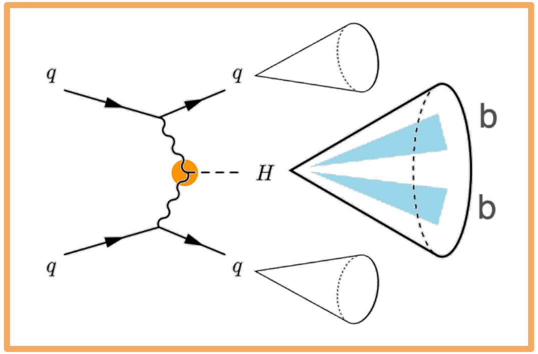
- High p_T tails are sensitive to new physics at high energy scales

  Different production modes probe different BSM operators



arXiv 1311.1829

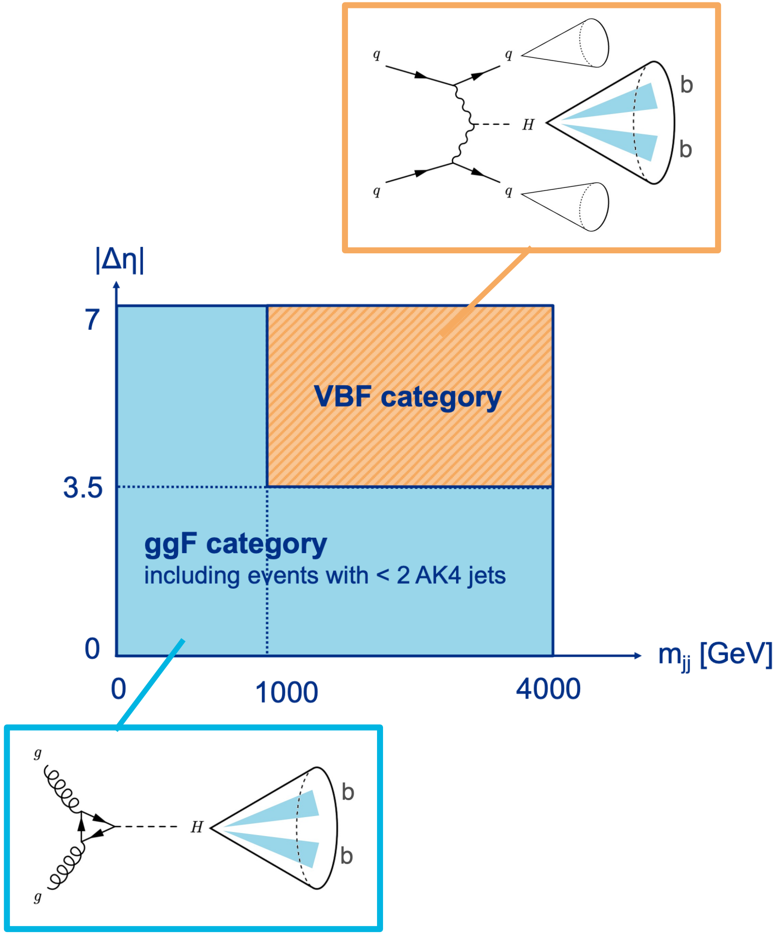




Fermilab

Analysis overview

- Apply selection targeting boosted Higgs candidates, rejecting backgrounds
- Add tailored cuts to target the VBF process
  - Define orthogonal ggF and VBF categories
- Divide into b-tag passing and failing regions using the **DeepDoubleB** (DDB) tagger
  - Use DDB fail for data-driven QCD background estimate
- Fit to the **soft drop** mass of the Higgs candidate jet in both b-tag regions
  - Simultaneously extract signal strength for ggF and VBF



Event selection

- Start with events passing ≥1 trigger selecting for H_T, jet p_T, jet mass, b-tagging

  Fully efficient for leading jet $p_T > 500$ GeV

- Require at least one **large radius jet**

  AK8 jet with $p_T > 450$ GeV, $|\eta| < 2.5$

  Must have **two-prong substructure:** N_2 variable decorrelated with mass $N_2^{DDT} < 0$

  If more than one jet qualifies, select the one with **highest DDB score**

- Lepton veto

- Top veto: MET < 140 GeV, no b-jet in the hemisphere opposite candidate jet

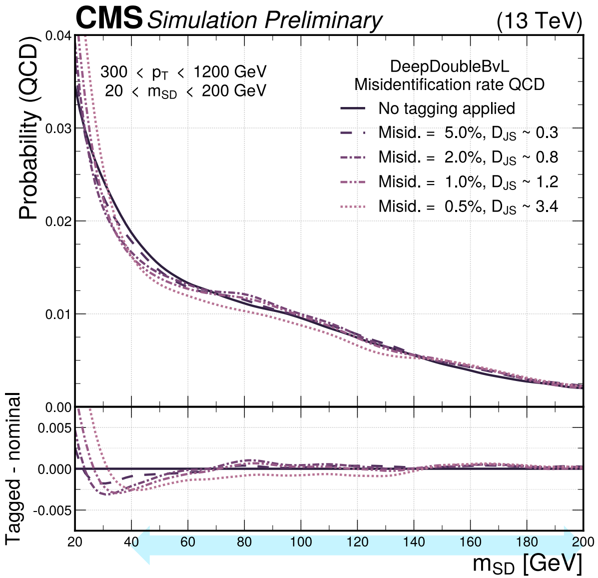
- If event has ≥ 2 more thin jets with **$\Delta\eta_{jj} > 3.5$ and $m_{jj} > 1$ TeV** ⟶ VBF category

  Otherwise ⟶ ggF category

DeepDoubleBvL-v2 tagger (DDB)

Congqiao's talk
CMS-DP-2022-041

- **CNN architecture** trained on simulation to separate QCD and scalar X ⟶ bb decays
  - Signal generated for m_X from 20-200 GeV
- Input features include:
  - Particle flow candidates (up to 40 charged, 60 neutral)
  - Secondary vertices
  - High-level jet variables
- DDB threshold chosen to optimize VBF sensitivity
  - Events below DDB threshold (DDB fail) are used to estimate QCD background
- **Tagger efficiency** is constrained in-situ by the Z ⟶ bb peak
  - One of the dominant experimental systematics



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Signal Monte Carlo

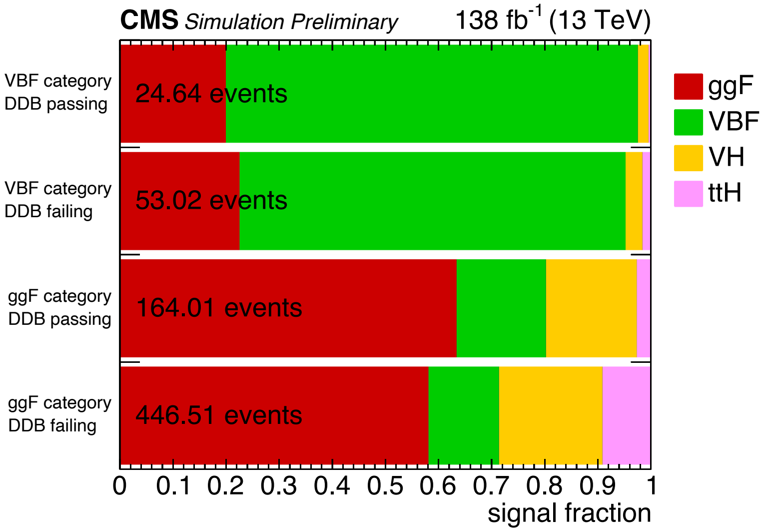
- **ggF**: POWHEG HJMINLO

  Good agreement with LHC XS WG recommendations

- **VBF**: POWHEG re-weighted for EW and N^3LO corrections

  Good agreement with LHC XS WG recommendations

- **Other Higgs** (WH, ZH, ttH, ggZH): POWHEG reweighted for EW corrections



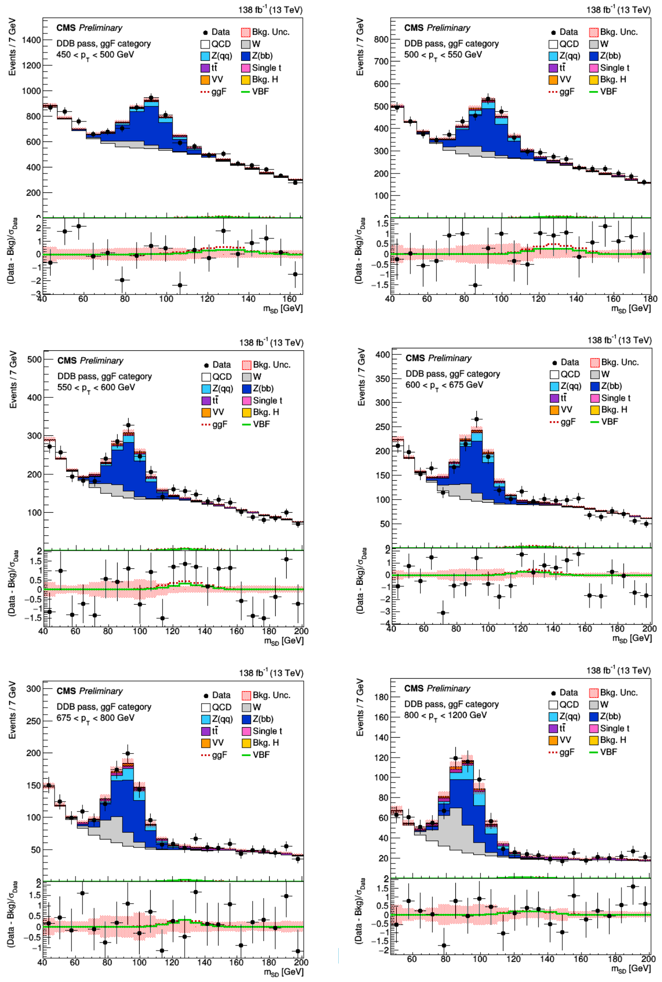
- Renormalization/factorization scale, PDF and parton shower uncertainties included on all Higgs samples

  Scale uncertainty on ggF (~20%) and VBF (~5%) is the dominant theory systematic

Differential bins

- Combining multiple bins with different signal purity gives better sensitivity
- **ggF category**: 6 bins in Higgs candidate p_T

  [450, 500, 550, 600, 675, 800, 1200] GeV



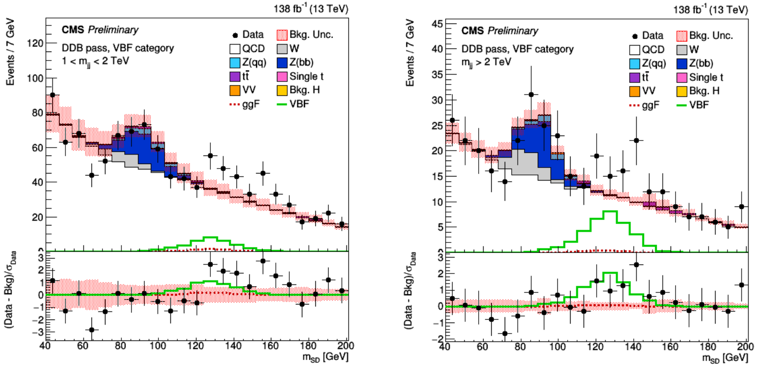
Differential bins

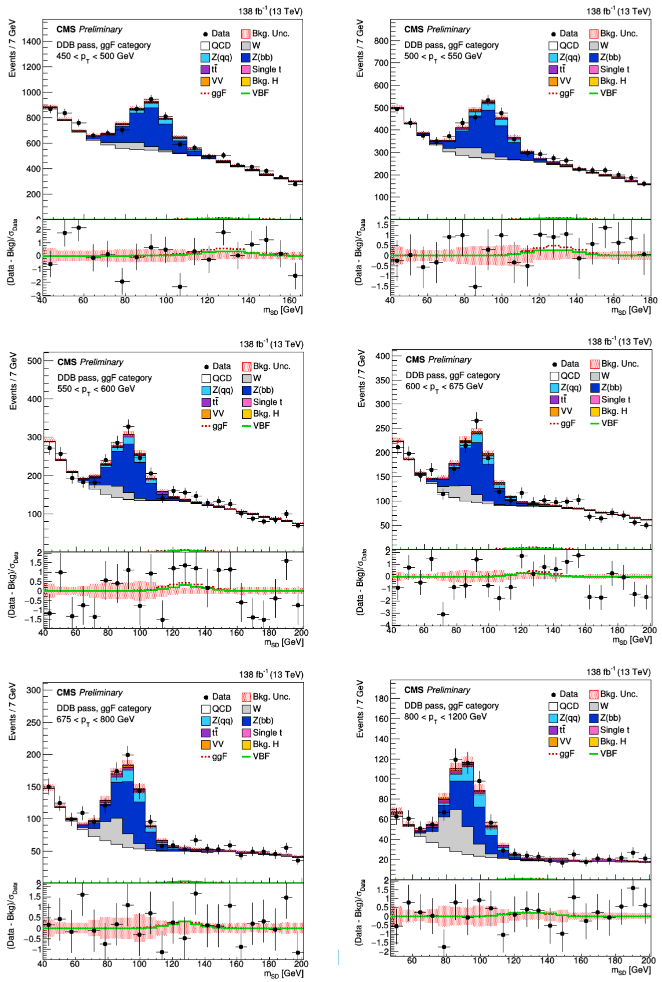
- Combining multiple bins with different signal purity gives better sensitivity
- **ggF category**: 6 bins in Higgs candidate p_T

  [450, 500, 550, 600, 675, 800, 1200] GeV

- **VBF category**: 2 bins in the invariant mass of the forward jets, m_{jj}

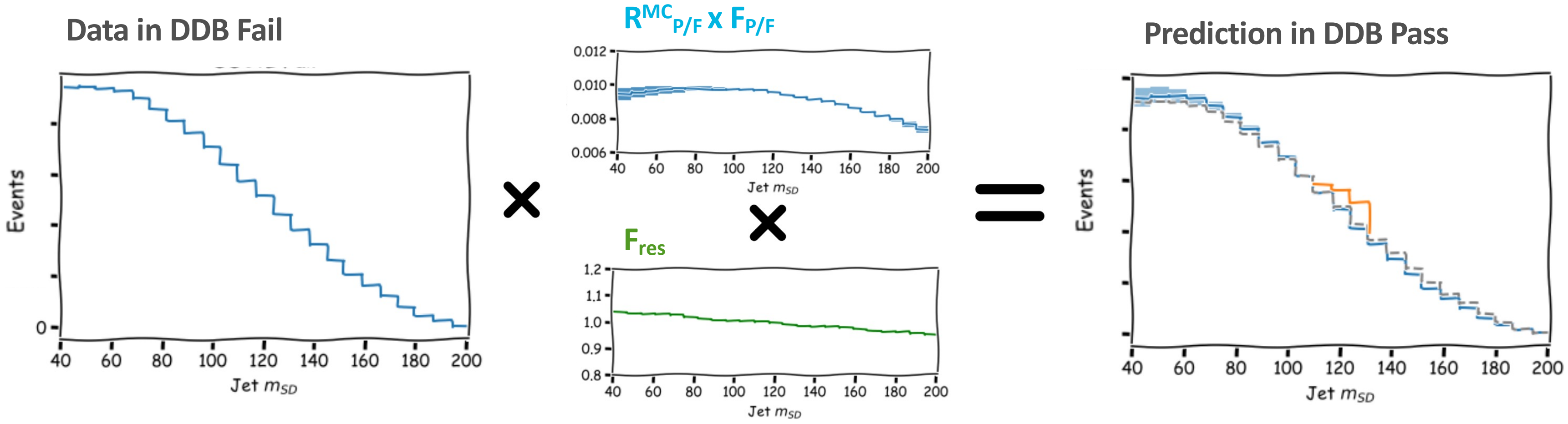
  [1000, 2000, ∞] GeV





QCD background estimation

- Goal: predict the QCD distribution in the DDB pass region
- Use data in the DDB fail region as a starting point and apply two polynomial **transfer factors**



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First transfer factor: $F_{P/F}$

- Accounts for differences in the m_{SD} shape in the DDB pass / fail regions due to tagger selection
- Coefficients extracted from a standalone fit to the DDB pass / fail ratio in QCD MC only

Overall normalization is treated as a separate factor, $R_{P/F}^{MC}$

Uncertainties are propagated to the final fit

$$\frac{N_P^{\mathrm{MC},i}}{N_F^{\mathrm{MC},i}} = R_{\mathrm{P/F}}^{\mathrm{MC}}\, F_{\mathrm{P/F}}^{i}$$

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Uncertainties are propagated to the final fit

$$\frac{N_P^{\mathrm{MC},i}}{N_F^{\mathrm{MC},i}} = R^{\mathrm{MC}}_{\mathrm{P/F}}\, F^i_{\mathrm{P/F}}$$

Second transfer factor: F_{res}

- Accounts for any additional differences the m_{SD} shape in the DDB pass / fail regions
- Coefficients extracted from simultaneous fit to DDB pass and fail regions

Uncertainty on fitted polynomial coefficients is a dominant systematic

$$N_P^i = R^{\mathrm{MC}}_{\mathrm{P/F}}\, F^i_{\mathrm{P/F}}\, F^i_{\mathrm{res}}\, N_F^{\mathrm{data},i}$$

Transfer factor polynomials

- **ggF category**

  1 x 2D Bernstein polynomial in jet p_T and $\rho = \ln(m_{SD}^2/p_T^2)$

- **VBF category**

  2 x 1D Bernstein polynomial in jet ρ only (one per m_{jj} bin)

$$F_{P/F}(p_T, \rho) = \sum_{k=0}^{n_\rho} \sum_{l=0}^{n_{p_T}} a_{k,l} \left[b_{k,n_\rho}(\rho) b_{l,n_{p_T}}(p_T) \right]$$

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

- Determining polynomial order

  Start with a low order polynomial, which is nested within higher order polynomials

  Systematically increase polynomial order until the goodness of fit no longer increases significantly

- Independent fits performed per category, per data-taking period

Control regions

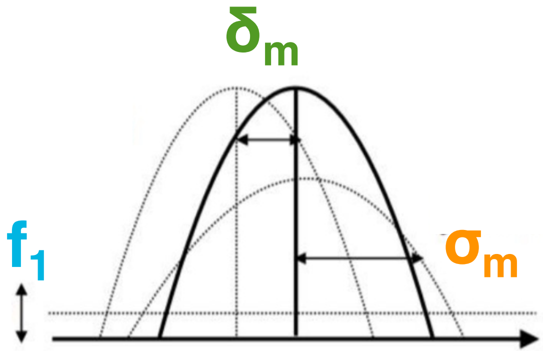
- **Top control region**: derive normalization and DDB efficiency on top background processes from data

  Nominal selection, but 0 $\mu \longrightarrow$ 1 loose μ and require an additional b-jet

  Treated as a single bin counting experiment per data taking period in the final fit

Control regions

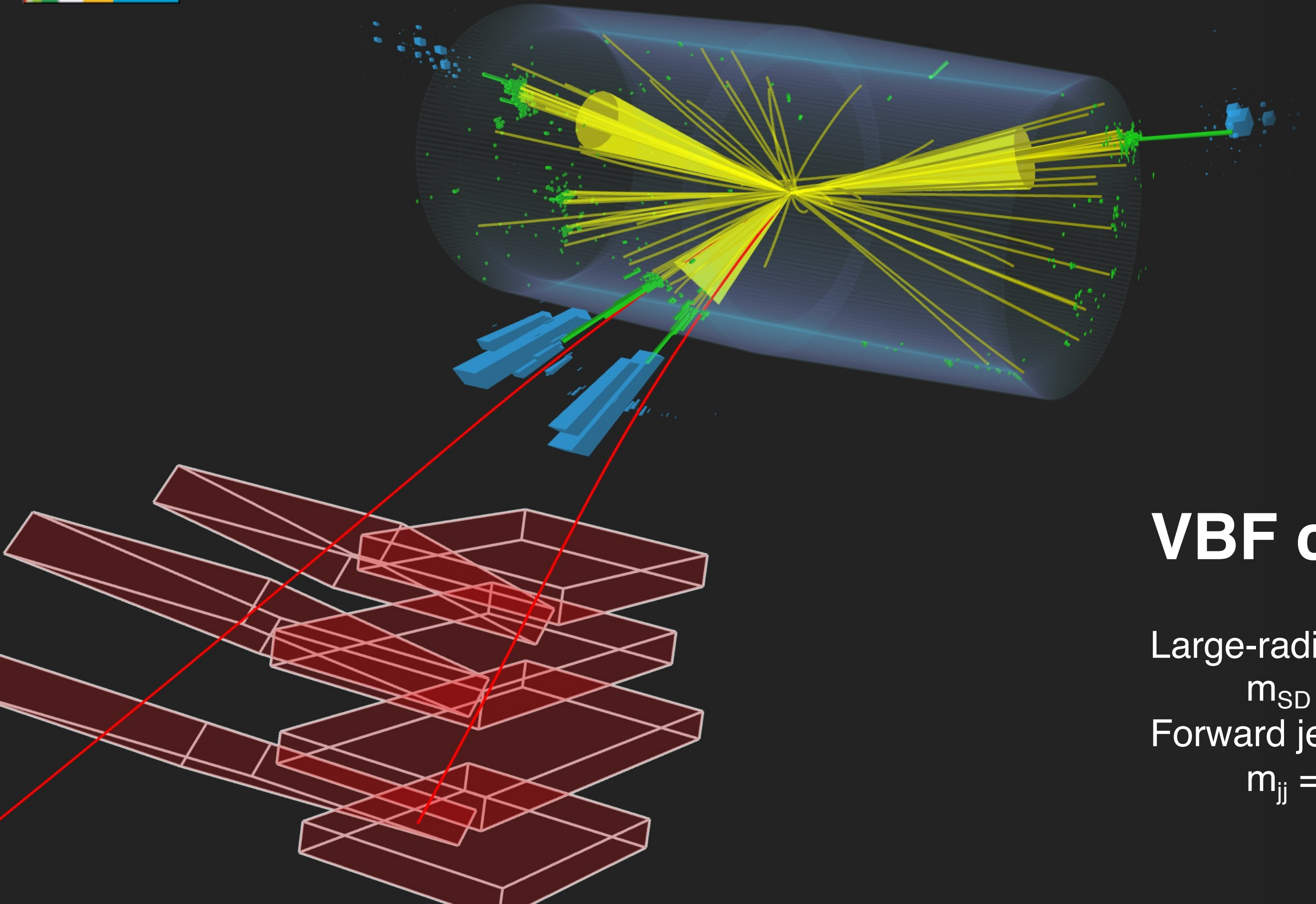
- **Top control region**: derive normalization and DDB efficiency on top background processes from data
  - Nominal selection, but 0 μ ⟶ 1 loose μ and require an additional b-jet
  - Treated as a single bin counting experiment per data taking period in the final fit
- **W-tag control region**: derive scale factors for substructure selection, jet mass scale & resolution
  - Require μ and MET ⟶ reco W = (μ+MET) with $p_T > 200$ GeV
  - Split each MC sample into truth W-matched and unmatched
  - Fit regions $N_2^{DDT} > 0$ and < 0 simultaneously for **substructure scale factor**, **jet mass resolution** and **jet mass scale**



CMS Experiment at the LHC, CERN

Data recorded: 2018-Sep-29 22:54:37.754176 GMT

Run / Event / LS: 323727 / 488169591 / 262



VBF candidate event

Large-radius jet:

m_{SD} = 125.2 GeV, p_T = 613.5 GeV

Forward jets:

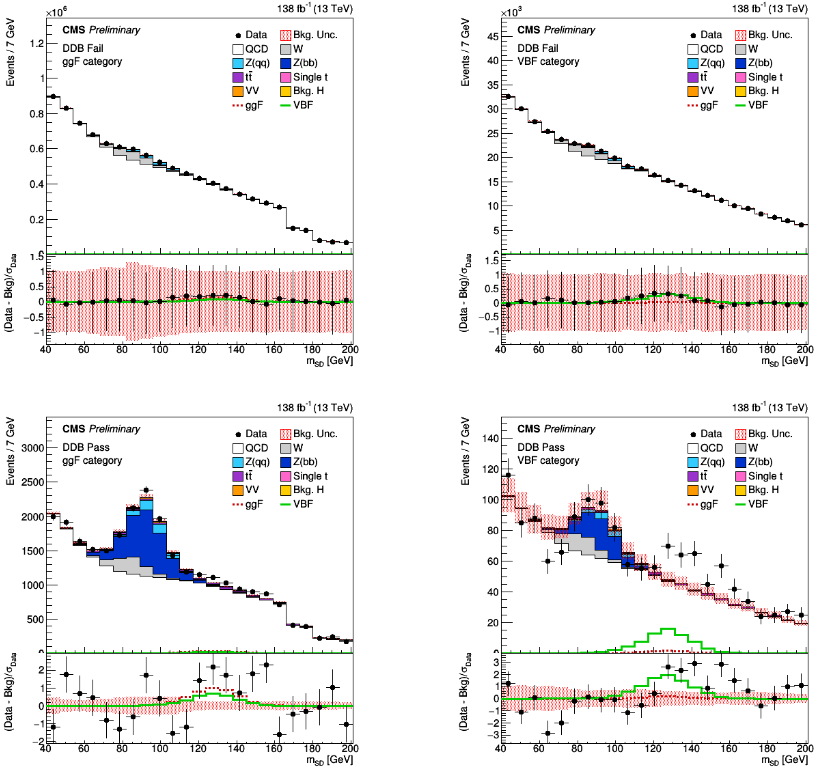
m_{jj} = 2220.7 GeV, $\Delta\eta_{jj}$ = 4.2

Results

- Observed significance is calculated with other process freely floating
- VBF: 3.0σ (0.9σ expected)
- ggF: 1.2σ (0.9σ expected)

	Lumi [fb^{-1}]	μ_{VBF}	μ_{ggF}
Early 2016	19.5	$2.9^{+5.8}_{-4.5}$	$4.3^{+5.5}_{-5.4}$
Late 2016	16.8	$5.8^{+6.3}_{-4.7}$	$-0.9^{+4.7}_{-5.1}$
2017	41.5	$-0.7^{+2.8}_{-2.6}$	$6.7^{+4.0}_{-3.1}$
2018	59.8	$10.0^{+4.4}_{-3.4}$	$-0.6^{+2.8}_{-3.1}$
Combined	137.6	$5.0^{+2.1}_{-1.8}$	$2.1^{+1.9}_{-1.7}$

ggF category　　　VBF category



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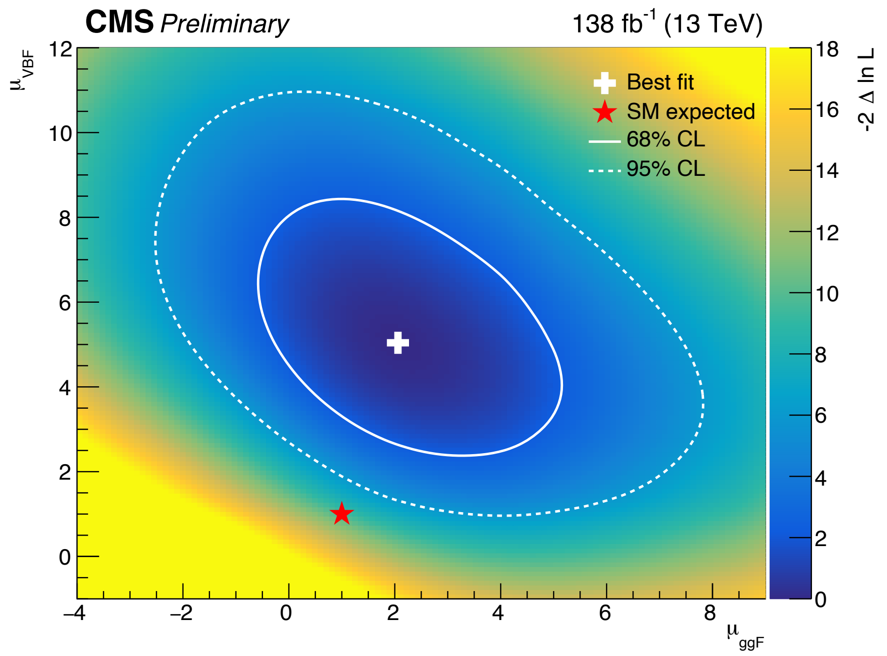
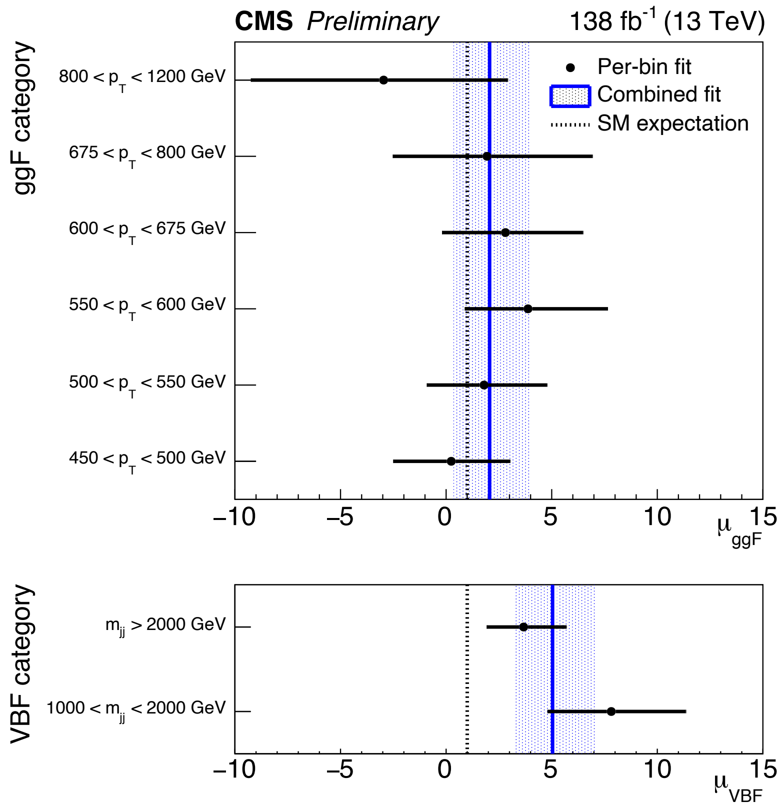
Results

- Best fit differs from SM by 2.6σ

  and from (0,0) by 3.9σ





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Summary

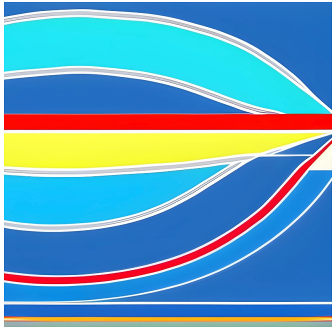
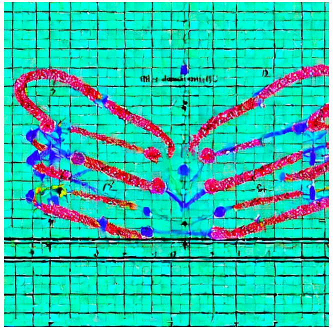
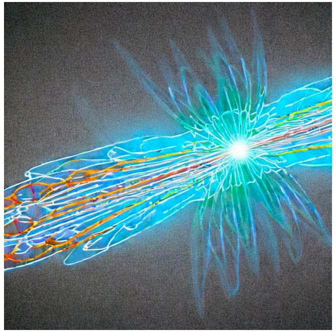
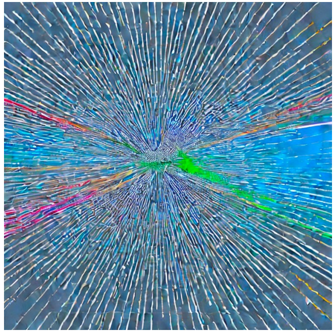
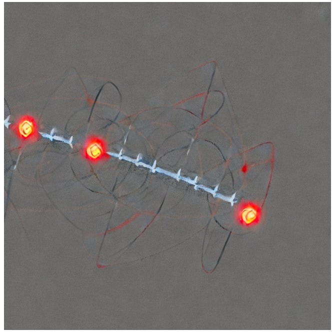
- We have presented the first search for **VBF in the boosted H(bb) channel**
- Simultaneous measurement of ggF and VBF signals is performed

$\mu_{VBF} = 5.0^{+2.1}_{-1.8}$

$\mu_{ggF} = 2.1^{+1.9}_{-1.7}$

- Observed results differ from SM expectation by **2.6σ**
- Further details in HIG-21-020

Additional material

Background simulation

- **V+jets**:

  Madgraph LO corrected to NLO gen-level p_T spectrum

  NNLO QCD, EW corrections applied following "mono-jet" prescription
- **Electroweak V**: Madgraph LO
- **Diboson**: Pythia LO corrected to NNLO with MCFC
- **ttbar, single top**: POWHEG NLO
- **QCD**: p_T sliced Pythia8

  Estimation mostly from data

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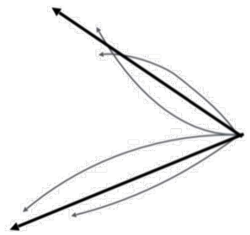
Substructure selection

- Variable N_2 (N_2^1) identifies two-prong jets using IRC safe energy correlation functions

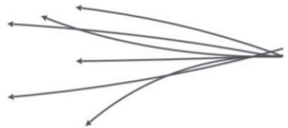
$$e_2^\beta = \sum_{1\le i<j\le n_J} z_i z_j \Delta R_{ij}^\beta$$

$$e_3^\beta = \sum_{1\le i<j<k\le n_J} z_i z_j z_k \Delta R_{ij}^\beta \Delta R_{ik}^\beta \Delta R_{jk}^\beta$$

$$\longrightarrow \quad N_2^\beta = \frac{{}_2e_3^\beta}{({}_1e_2^\beta)^2}$$



- Find the cut value on N_2 that has 26% efficiency on QCD MC, as a function of p_T and ρ: $c_{0.26}(p_T, \rho)$
- Resulting variable is decorrelated from jet p_T and mass



$$N_2^{1,\mathrm{DDT}} = N_2^1 - c_{0.26}(p_\mathrm{T}, \rho)\ .$$

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W-tag control region

- Derive scale factors for substructure selection, jet mass scale & resolution

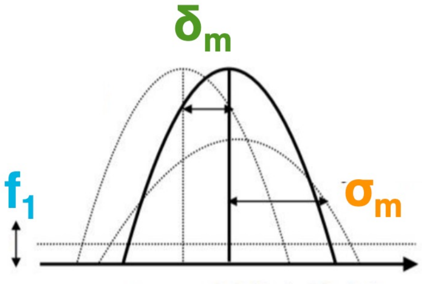
  Require μ and MET ⟶ reco W = (μ+MET) with $p_T > 200$ GeV

  Split each MC sample into truth W-matched and unmatched

  Fit regions $N_2^{DDT} > 0$ and < 0 simultaneously for **substructure scale factor**, **jet mass resolution** and **jet mass scale**

-

$$f_1 n^{\text{P-sub}}_{\text{match}}(\delta_m,\sigma_m) + \left[(1-f_1)\frac{\sum N^{\text{P-sub}}_{\text{match}}}{\sum N^{\text{F-sub}}_{\text{match}}} + 1\right] N^{\text{F-sub}}_{\text{match}}(\delta_m,\sigma_m) +$$
$$f_2 N^{\text{P-sub}}_{\text{unmatch}} + \left[(1-f_2)\frac{\sum N^{\text{P-sub}}_{\text{unmatch}}}{\sum N^{\text{F-sub}}_{\text{unmatch}}} + 1\right] N^{\text{F-sub}}_{\text{unmatch}}$$



	Substructure (f_1)	Mass scale (δ_m) [GeV]	Mass resolution (σ_m)
Early 2016	0.85 ± 0.14	-1.50 ± 0.45	0.98 ± 0.04
Late 2016	0.68 ± 0.18	$+1.13 \pm 0.41$	1.26 ± 0.04
2017	1.18 ± 0.14	$+0.49 \pm 1.16$	1.18 ± 0.08
2018	0.90 ± 0.10	-0.84 ± 0.24	1.14 ± 0.04