CMS-PAS-HIG-19-001

第十四届TeV物理工作组学术研讨会

Measurement of Higgs properties in the H→ZZ*→4l channel with full Run-2 data at CMS

Mingshui Chen

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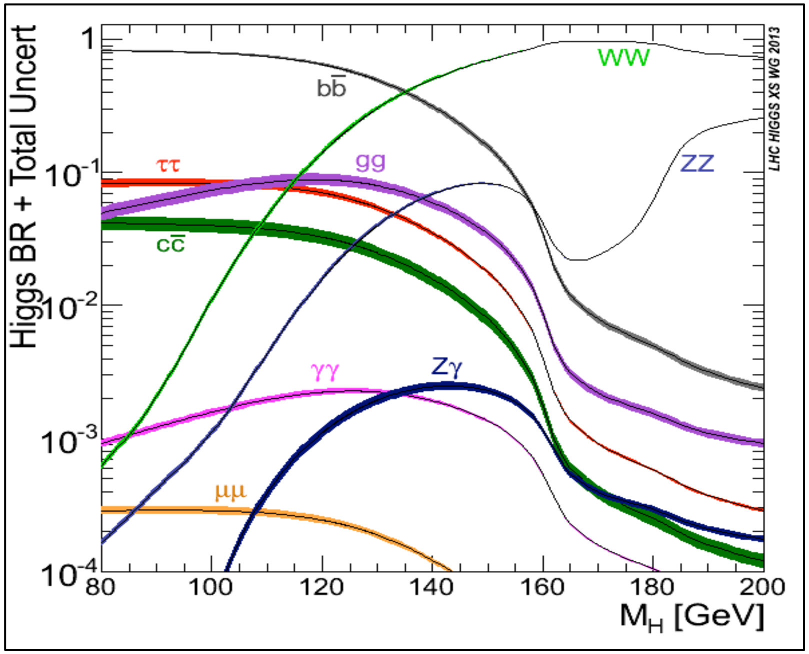
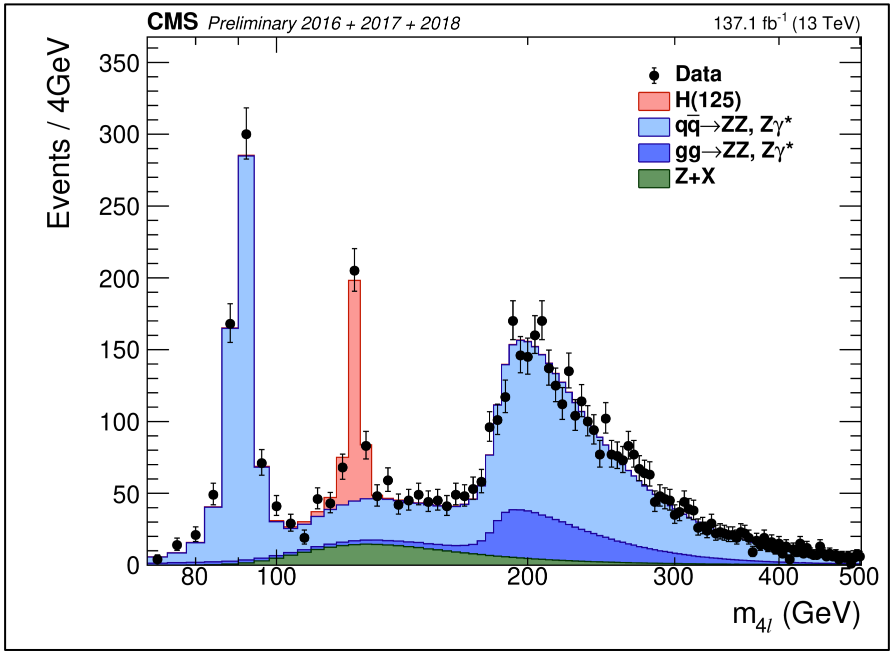
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Overview

- The **H→ZZ→4l** (l=e,μ) channel:
  - Large S/B ratio, excellent resolution, complete reconstruction of the final state
  - "Golden channel" for discovery and properties measurements





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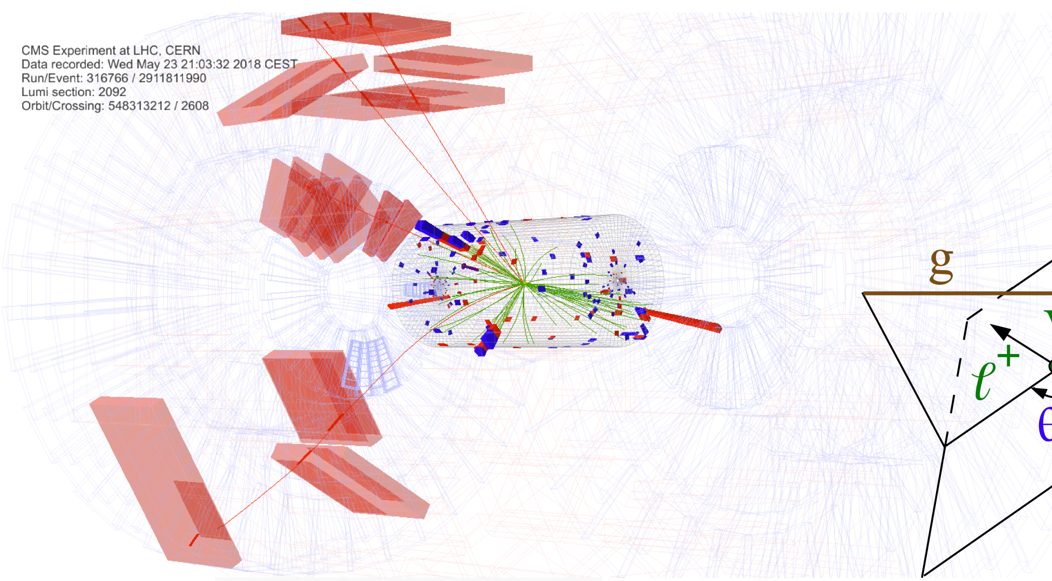
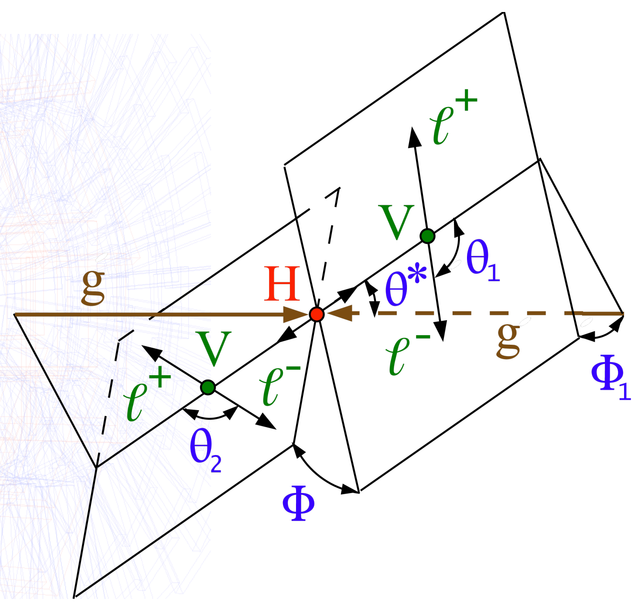


$t\bar{t}H$ event candidate



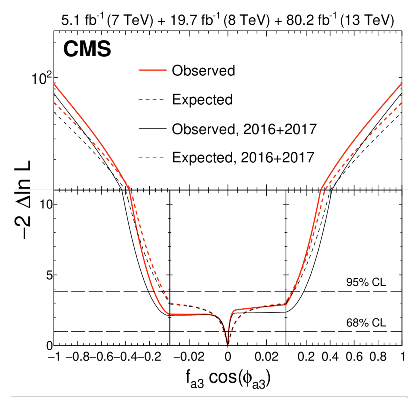
Results with *partial* datasets

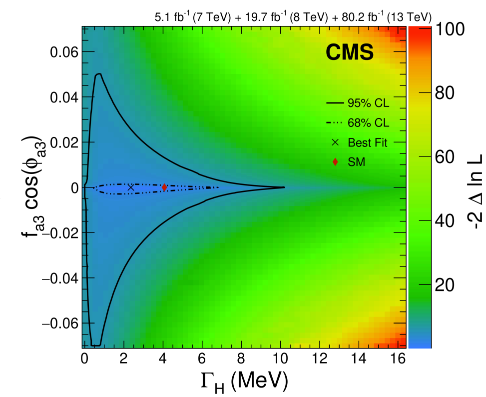
- Mass & width

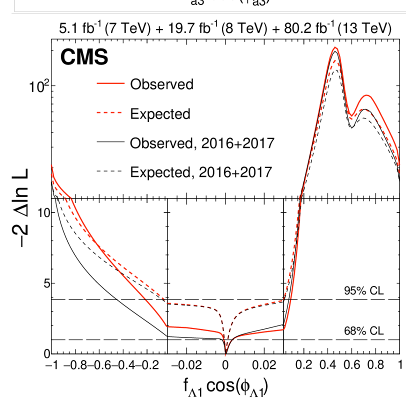
$$m_H = 125.26 \pm 0.20(stat) \pm 0.08(syst) GeV$$
$$\Gamma_H < 1.10 GeV \ at \ 95\% \ C.L.$$

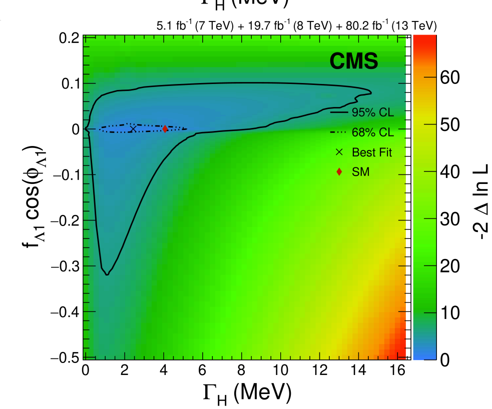
  - most precise determination of the mass so far

- Spin & parity, tensor structure of the interaction



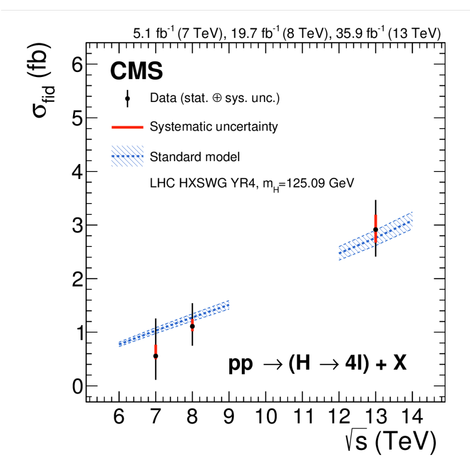


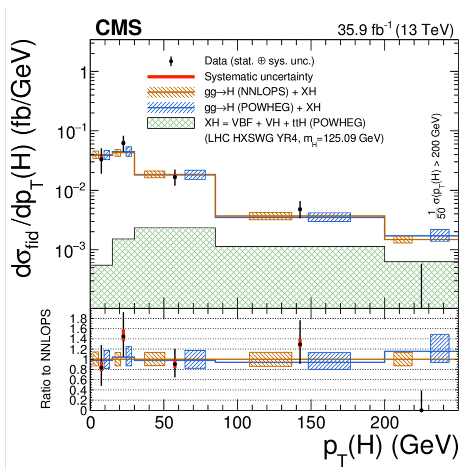




- Cross sections

$$\sigma_{fid} = 2.92^{+0.48}_{-0.44}(stat)^{+0.28}_{-0.24}(syst) fb$$



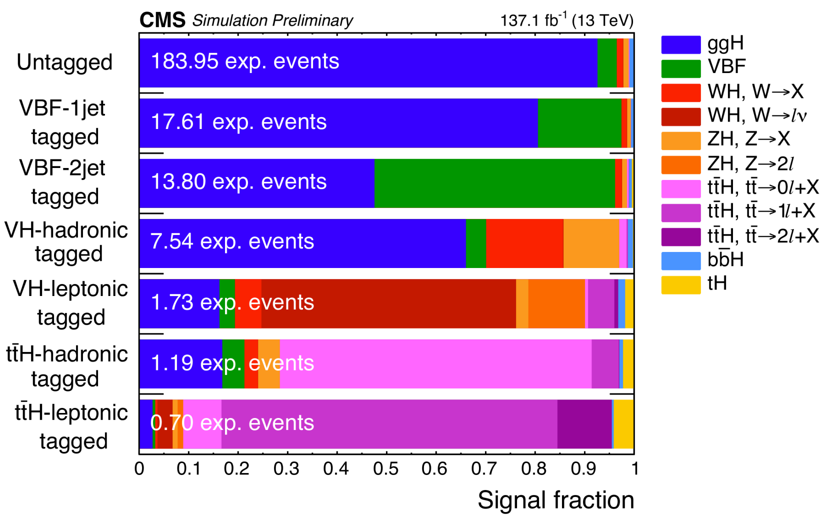


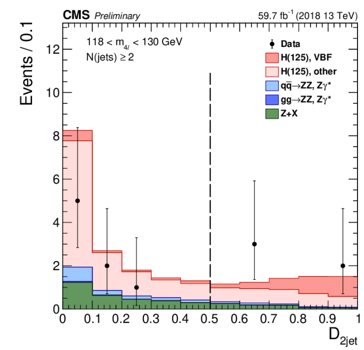
Analysis Strategy

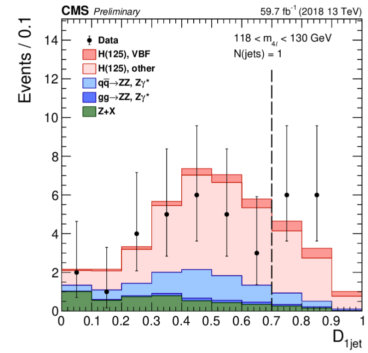
- Analysis strongly depends on ***(efficiency)***^{4} of selecting leptons:
  - Electrons (muons) reconstructed down to 7 (5) GeV
  - Electron identification BDT includes electron isolation variables and is retrained for the upgraded pixel detector leading to strongly reduced misidentification of electrons
- ZZ candidates built from selected leptons
- Background and signal modeling:
  - Irreducible: qq→ZZ and gg→ZZ from simulation with additional QCD and EW k-factors as a function of m_{4l}
  - Reducible: Z+X estimated from data in control regions using 2 independent methods
  - Signal: ggH, VBF, WH, ZH, ttH, tHq and bbH production modes considered from simulation

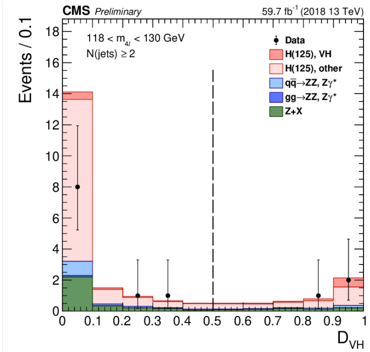
Event Categorization

- ZZ candidates classified into 7 categories designed to target main Higgs production modes
  - based on number of jets, b-tags, extra leptons and cuts on the 3 matrix-element based production discriminants (D_{2jet}, D_{1jet} and D_{VH})



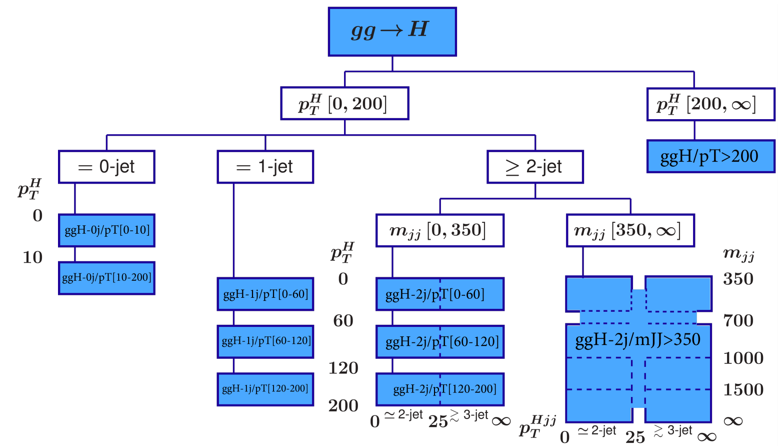


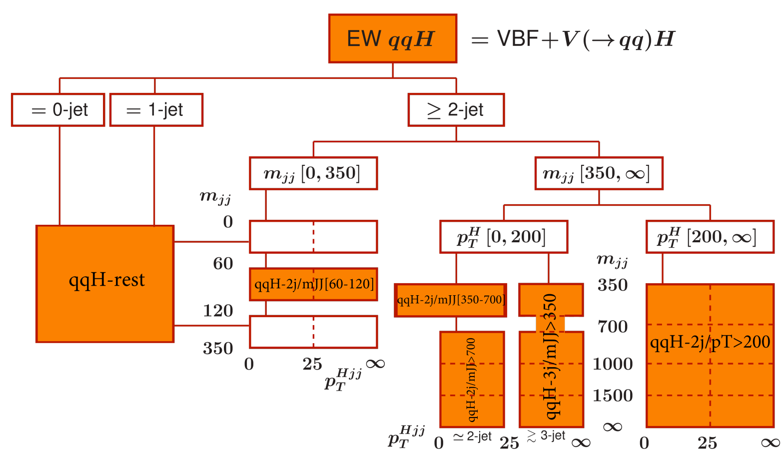


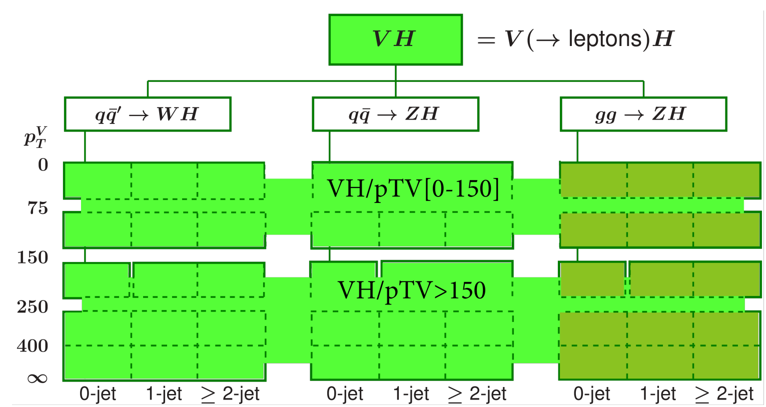


Event Categorization

- Events further classified in 22 stage 1.1 sub-categories to target different stage 1.1 production bins defined by LHCHXSWG
    - Define cross sections in exclusive fiducial regions
    - Maximize the sensitivity of measurements and reduce its theory dependence







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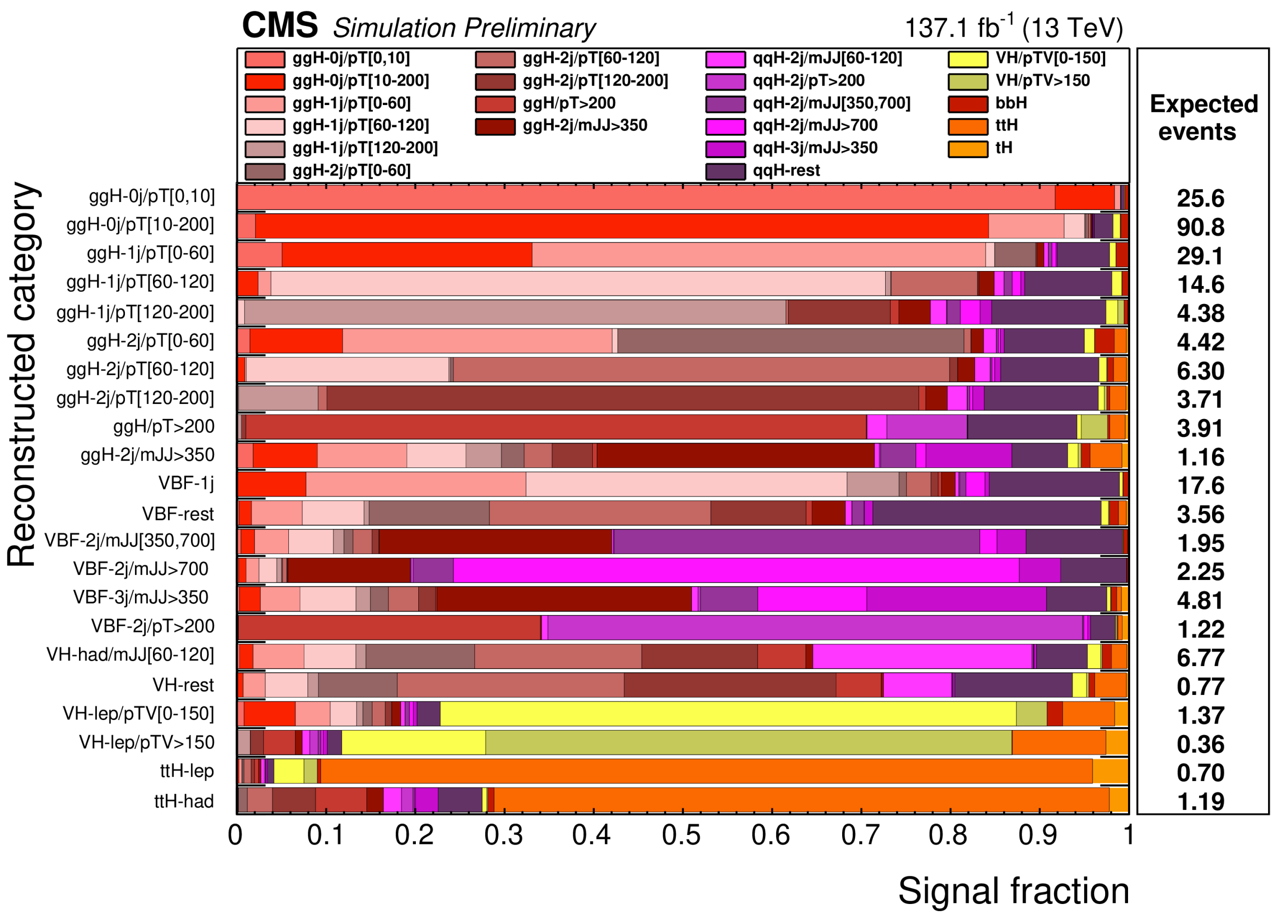
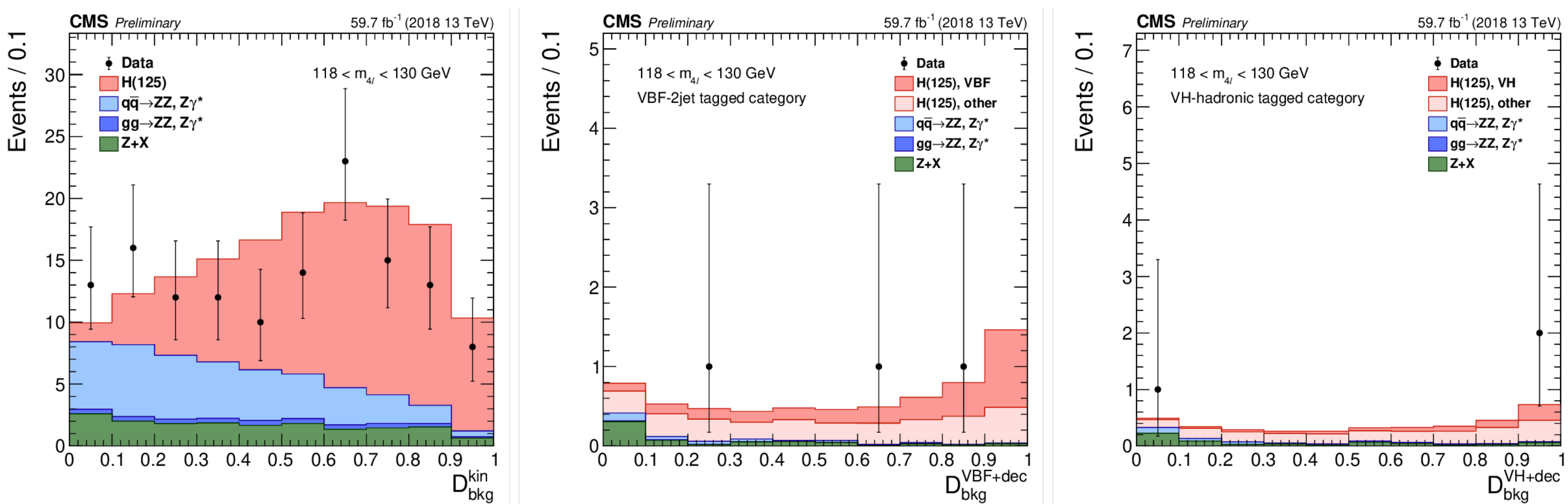


Observables

- Two observables used in all PDFs: $\mathbf{m_{4l}}$ and **kinematic discriminant**
- Depending on event category **3 different** kinematic discriminants used:
  - D^{kin}_{bkg} (**decay only** information) provides separation between Higgs signal and SM backgrounds
  - **Production + decay discriminants** developed providing separation of VBF ($D^{VBF+dec}_{bkg}$) and VH (D^{VH+dec}_{bkg}) from gluon fusion signal and SM backgrounds using **additional jet information** (information about production) in combination with decay variables to build matrix elements

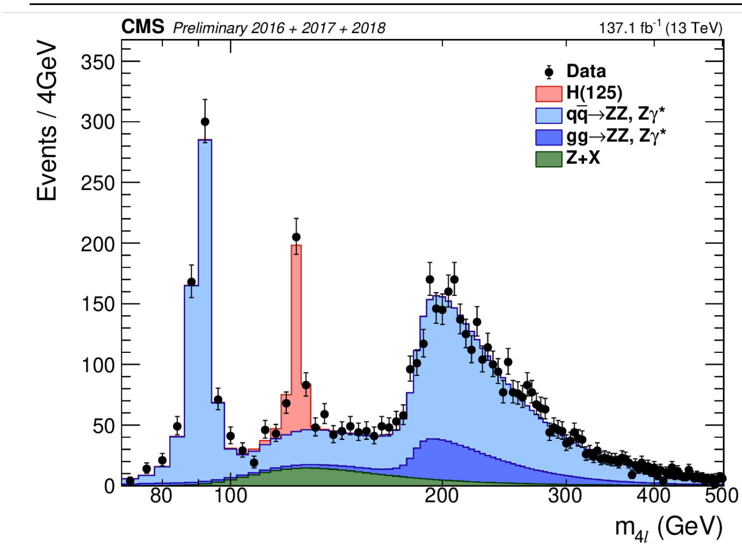


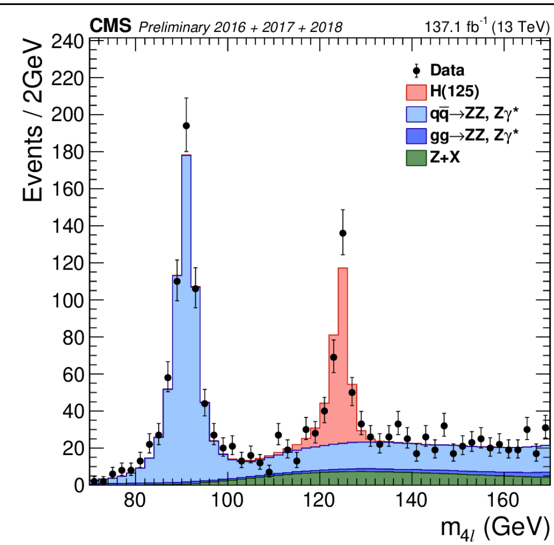
Results of Event Selection

- Good data/MC agreement over the whole m4l range in all 3 final states (4e, 4μ, 2e2μ)

Table for 2018 ~60/fb

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \to ZZ$	333^{+57}_{-53}	622^{+31}_{-44}	815 ± 73	1770^{+98}_{-101}
$gg \to ZZ$	$75.1^{+14.3}_{-13.5}$	$116.6^{+11.7}_{-12.8}$	176.9 ± 23.0	$368.5^{+29.5}_{-29.6}$
Z + X	19.3 ± 7.2	50.8 ± 15.2	64.6 ± 15.6	134.7 ± 22.9
Sum of backgrounds	$428^{+59.2}_{55.2}$	$790^{+36.4}_{-48.3}$	1057 ± 78.1	$2274^{+104.9}_{-107.7}$
Signal ($m_H = 125$ GeV)	$19.6^{+3.3}_{-3.1}$	$40.8^{+2.5}_{-2.9}$	50.7 ± 5.6	$111.1^{+6.9}_{-7.0}$
Total expected	$447^{+59.3}_{55.2}$	$830^{+36.5}_{-48.4}$	1108 ± 78.3	$2385^{+105.1}_{-107.9}$
Observed	462	850	1130	2442





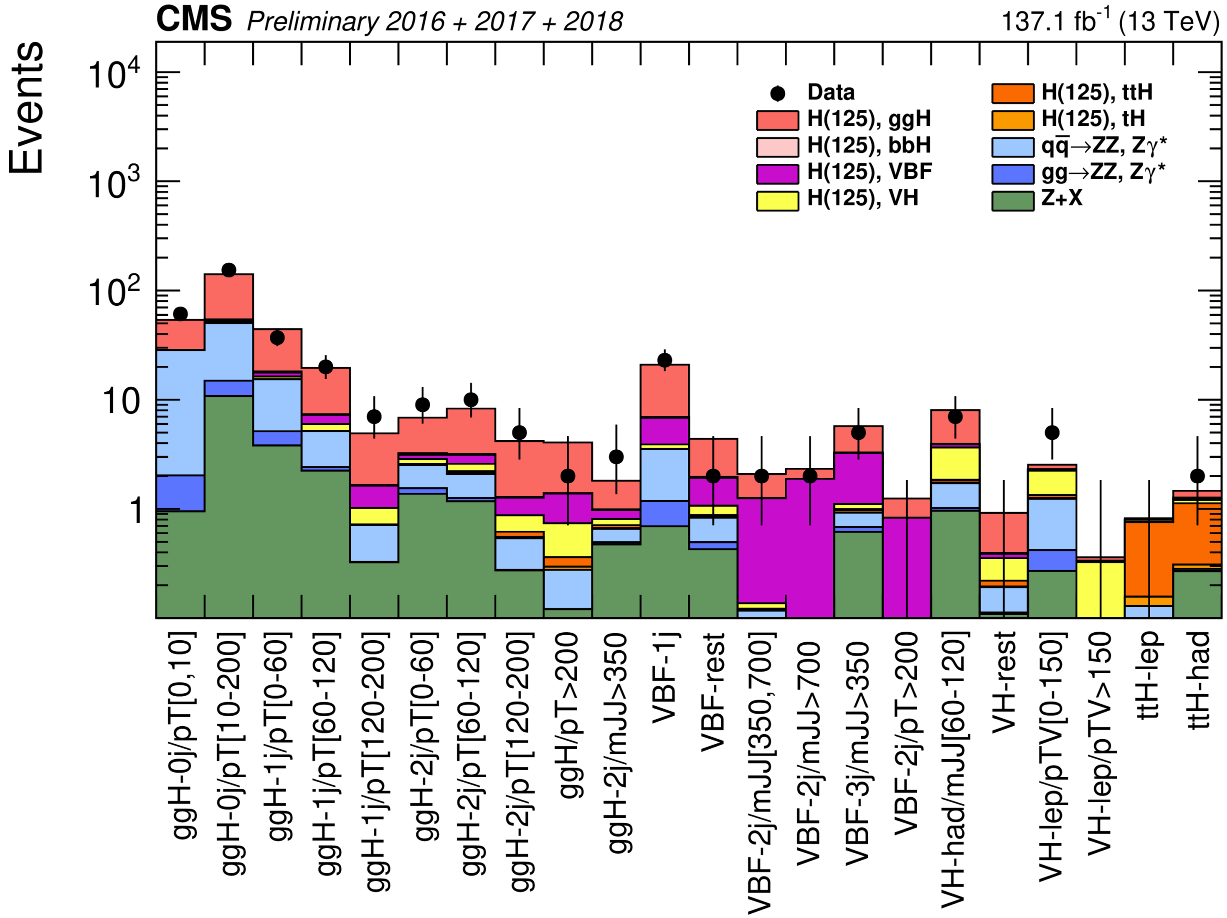
Results of Event Selection

- Good data/MC agreement over all event categories

Event category	Signal ggH	VBF	WH	ZH	ttH	bbH	tqH	Total signal	Background $q\bar{q} \to ZZ$	$gg \to ZZ$	$Z + X$	Total expected	Observed
ggH-0j/pT[0,10]	25.3	0.08	0.02	0.02	0.00	0.14	0.00	25.6	26.5	0.97	1.19	54.2	61
ggH-0j/pT[10-200]	86.8	1.69	0.54	0.86	0.00	0.90	0.00	90.8	35.4	3.79	15.5	145	153
ggH-1j/pT[0-60]	26.2	1.43	0.50	0.45	0.01	0.43	0.01	29.1	10.3	1.19	5.54	46.1	40
ggH-1j/pT[60-120]	12.4	1.24	0.45	0.47	0.01	0.10	0.01	14.6	2.76	0.16	3.21	20.8	17
ggH-1j/pT[120-200]	3.31	0.62	0.17	0.26	0.00	0.02	0.00	4.38	0.38	0.00	0.52	5.28	6
ggH-2j/pT[0-60]	3.68	0.29	0.14	0.14	0.06	0.09	0.02	4.42	0.97	0.15	2.07	7.60	9
ggH-2j/pT[60-120]	5.17	0.54	0.22	0.22	0.09	0.04	0.02	6.30	0.84	0.07	1.86	9.06	12
ggH-2j/pT[120-200]	2.90	0.40	0.15	0.17	0.07	0.01	0.02	3.71	0.26	0.00	0.40	4.37	5
ggH/pT>200	2.72	0.65	0.21	0.24	0.06	0.01	0.02	3.91	0.16	0.00	0.21	4.28	2
ggH-2j/mJJ>350	0.82	0.17	0.06	0.05	0.04	0.01	0.01	1.16	0.16	0.02	0.65	1.98	3
VBF-1j	14.2	2.94	0.20	0.18	0.00	0.12	0.01	17.6	2.37	0.43	1.05	21.5	20
VBF-2j/mJJ[350,700]	0.80	1.11	0.01	0.01	0.00	0.01	0.00	1.95	0.08	0.02	0.04	2.09	2
VBF-2j/mJJ>700	0.43	1.80	0.00	0.00	0.00	0.00	0.00	2.25	0.02	0.01	0.03	2.31	2
VBF-3j/mJJ>350	2.43	2.15	0.06	0.07	0.02	0.03	0.05	4.81	0.24	0.06	0.96	6.07	6
VBF-2j/pT>200	0.42	0.76	0.01	0.01	0.01	0.00	0.01	1.22	0.01	0.00	0.03	1.26	0
VBF-rest	2.40	0.87	0.11	0.10	0.03	0.04	0.01	3.56	0.34	0.06	0.74	4.70	2
VH-lep/pTV[0-150]	0.24	0.04	0.71	0.25	0.08	0.02	0.02	1.37	0.82	0.14	0.40	2.72	5
VH-lep/pTV>150	0.02	0.01	0.21	0.08	0.04	0.00	0.01	0.36	0.01	0.00	0.02	0.40	0
VH-had/mJJ[60-120]	4.11	0.25	1.01	1.20	0.11	0.07	0.02	6.77	0.70	0.05	1.36	8.89	8
VH-rest	0.56	0.04	0.08	0.07	0.03	0.00	0.00	0.77	0.08	0.00	0.15	1.01	1
ttH-had	0.19	0.05	0.03	0.06	0.82	0.01	0.03	1.19	0.01	0.00	0.45	1.66	2
ttH-lep	0.02	0.00	0.02	0.02	0.60	0.00	0.03	0.70	0.03	0.00	0.12	0.85	0

Results of Event Selection

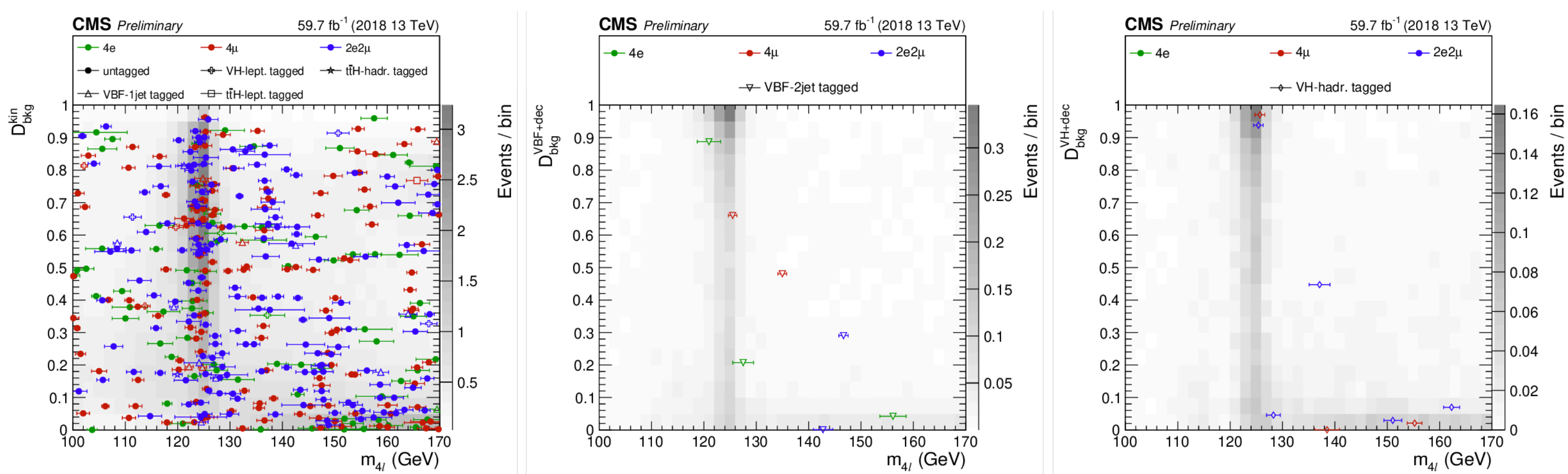
- Good data/MC agreement over all event categories



Measurement Strategy

- 2D maximum-likelihood fit in 3 final states x 22 categories
  - mass dimension un-binned, uses signal shape parameterized as a function of m_{4l}
  - 2D templates normalized to 1 for each bin of m_{4l}

$$\mathscr{L}_{2D}(m_{4\ell}, D_{\mathrm{bkg}}^{\mathrm{kin}}) = \mathscr{L}(m_{4\ell})\mathscr{L}(D_{\mathrm{bkg}}^{\mathrm{kin}} \,|\, m_{4\ell})$$

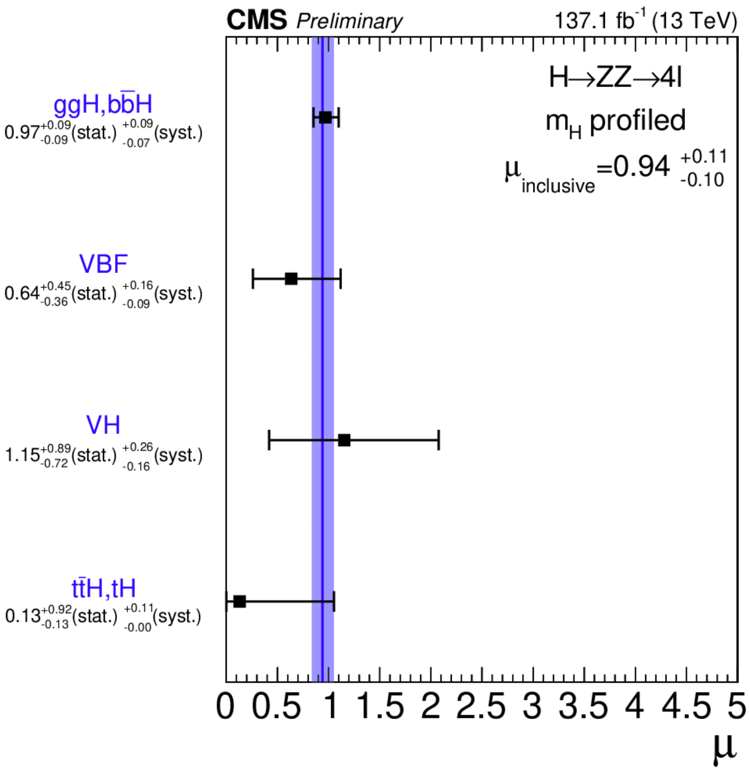


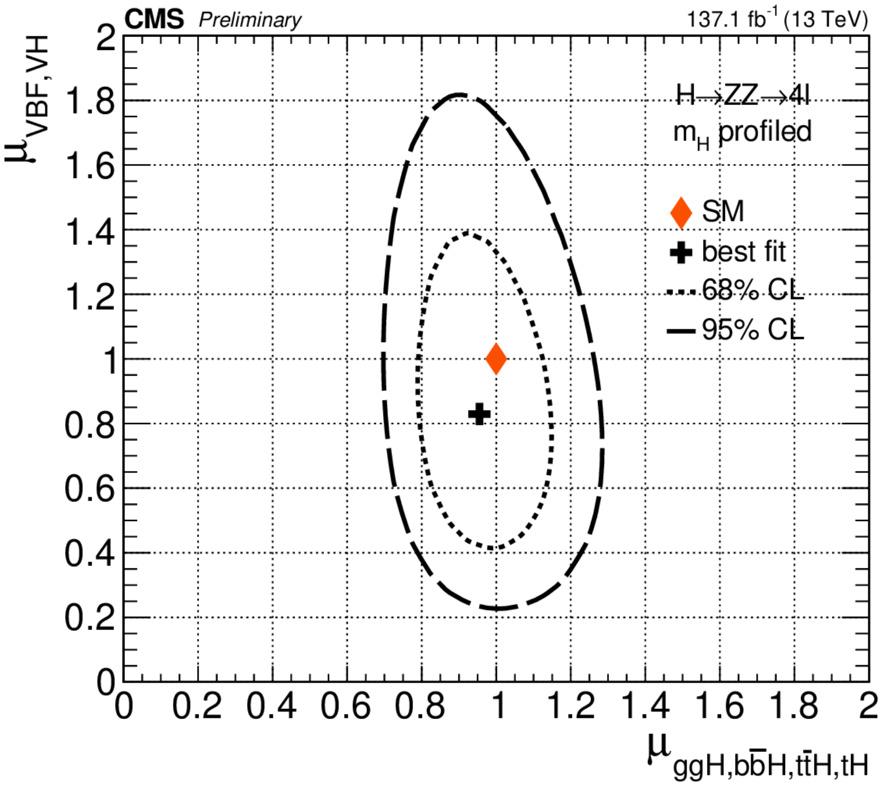
Probing Higgs Production Modes

- Combined signal strength at m_H=125.09 GeV

$$\mu = 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

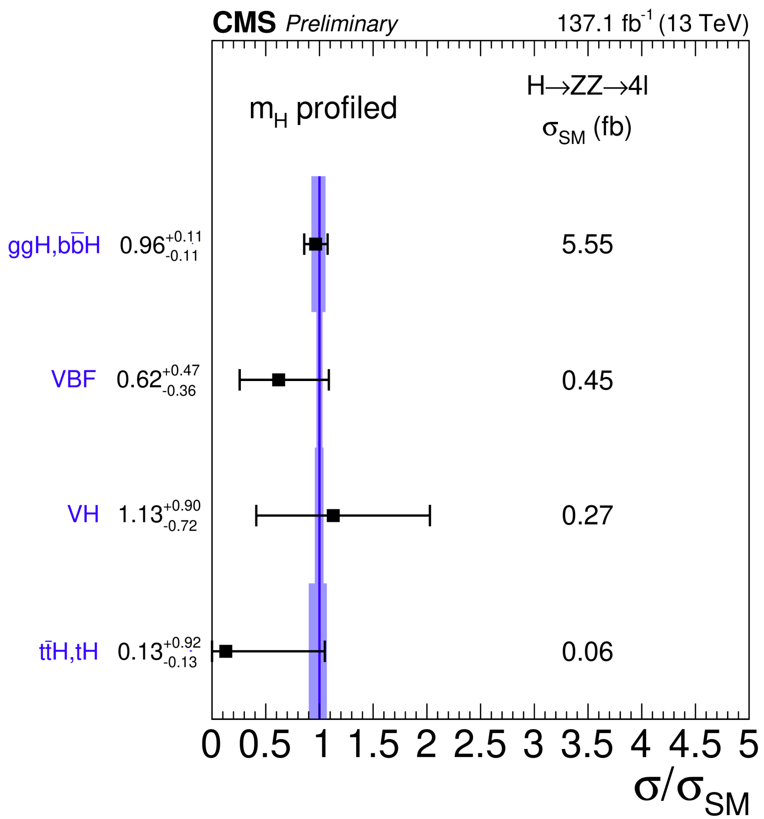
  - Extract signal strength in each major production mode
  - Extract signal strength of production processes in a 2-parameter model

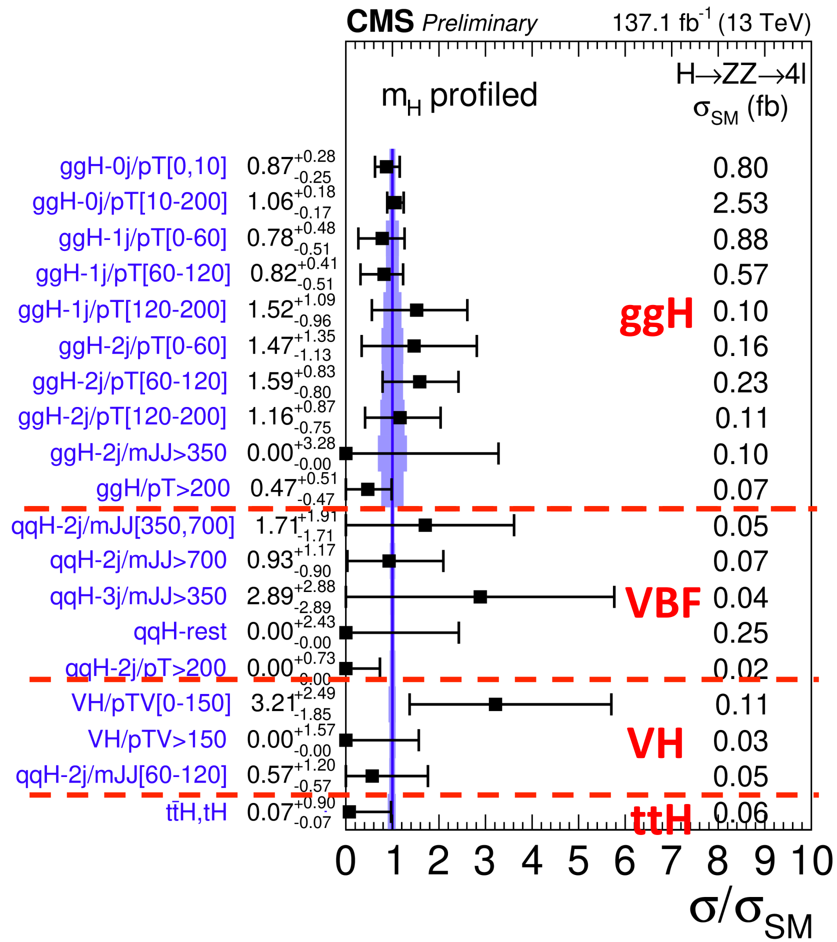




Probing Higgs Production Modes

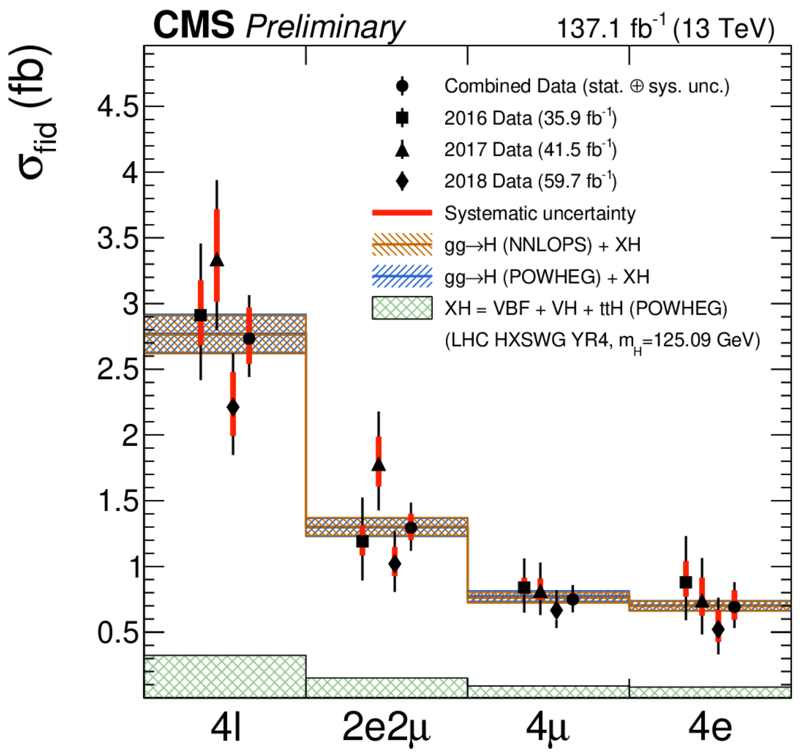
- Define simplified fiducial volume as $|y_H| < 2.5$ and remove theoretical uncertainties on the overall signal cross section

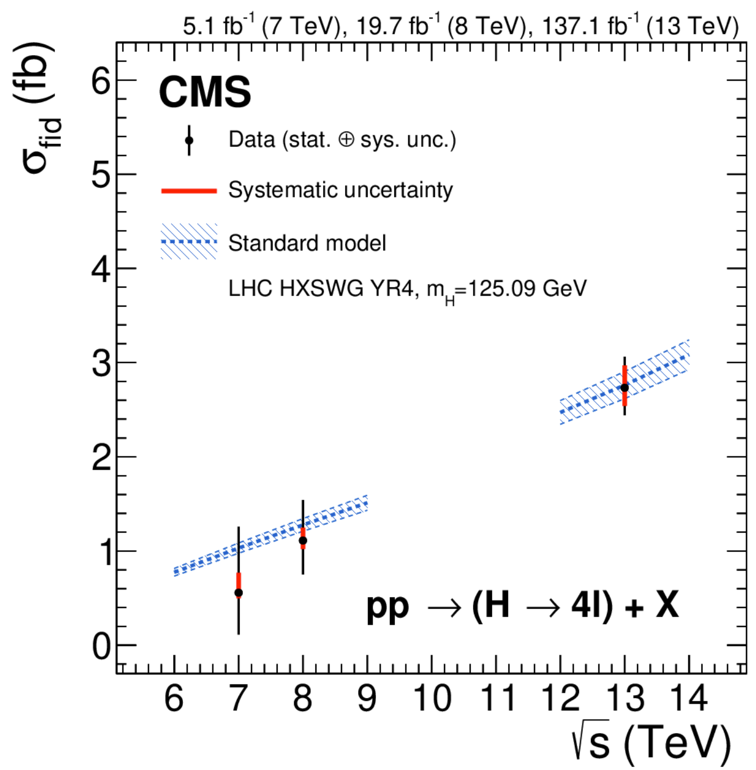




Fiducial Cross Sections

- Inclusive fidutial xsec: $\sigma_{\text{fid.}} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})$ fb

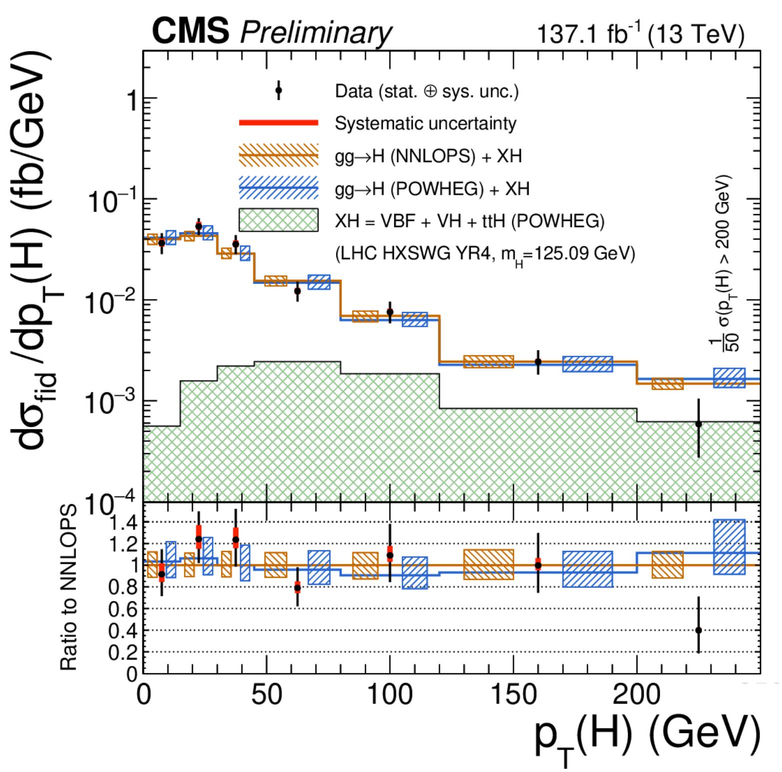


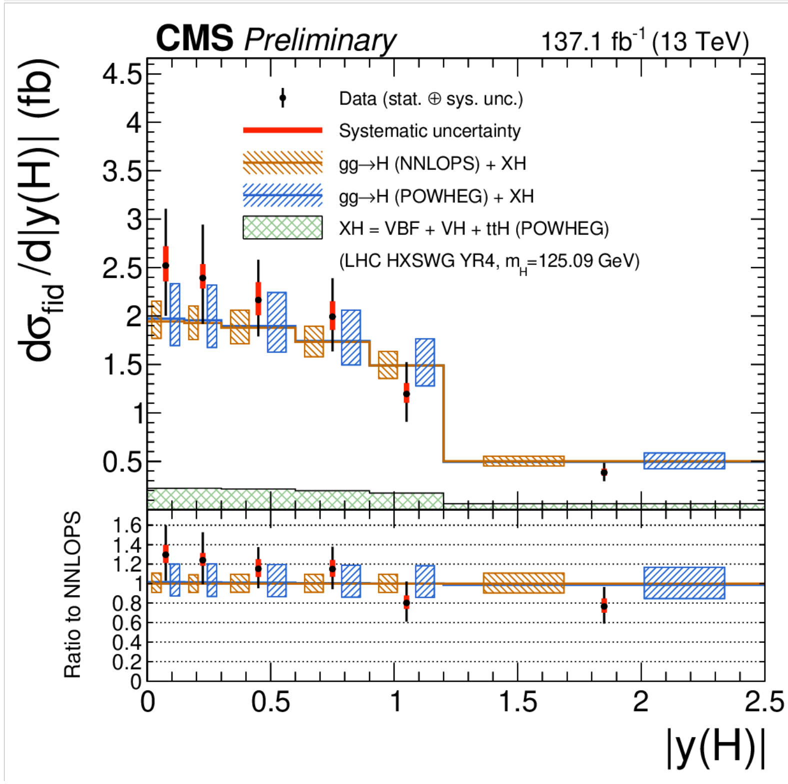


- Cross sections measured in tight fiducial volume closely matching reconstruction selection -> Maximum model independence
- Signal extracted using a 1D m_{4l} fit

Differential Cross Sections

- Unfolding performed by including response matrix in the likelihood
- Compared to predictions from POWHEG and NNLOPS





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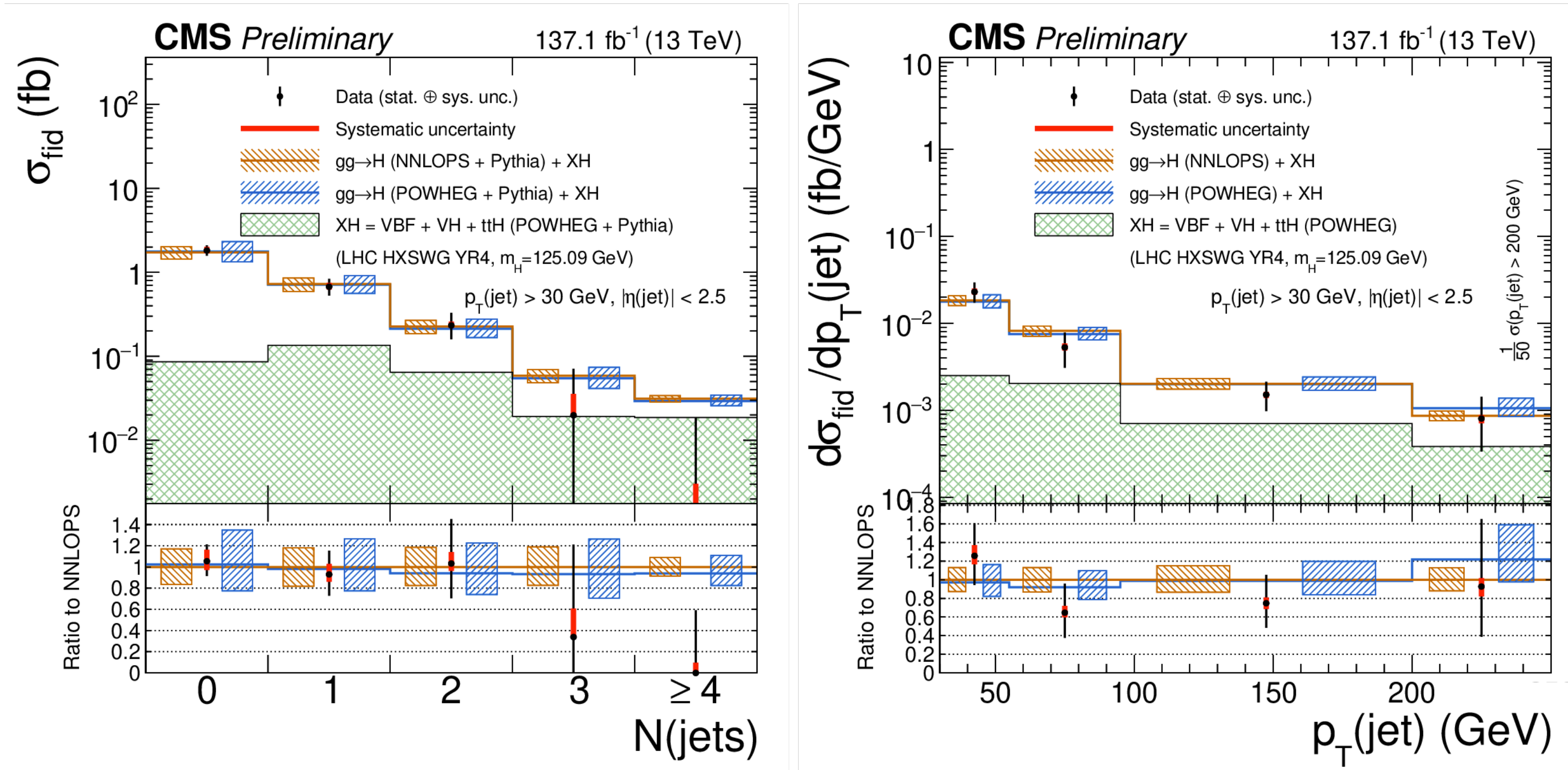


Summary

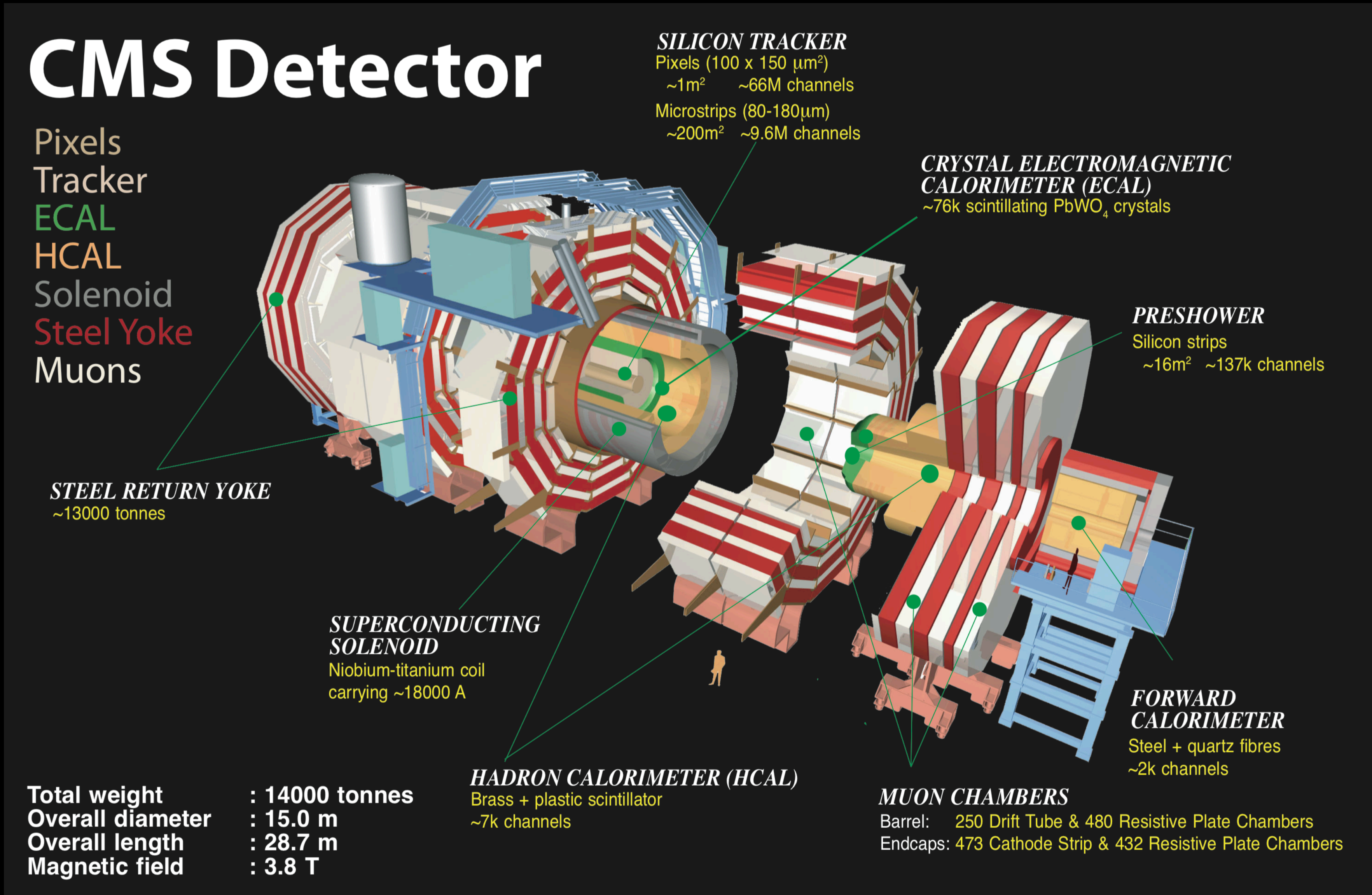
- Properties of Higgs boson in **$H \rightarrow ZZ \rightarrow 4l$** at $\sqrt{s}$=13 TeV using **full Run 2** data presented
  - All measurements compatible with SM predictions
- Improves on previously published CMS results Inclusive analysis no longer dominated by statistical uncertainties
- More Higgs properties measurements with full Run 2 data in pipeline

Back up

Thanks for your attention !

References

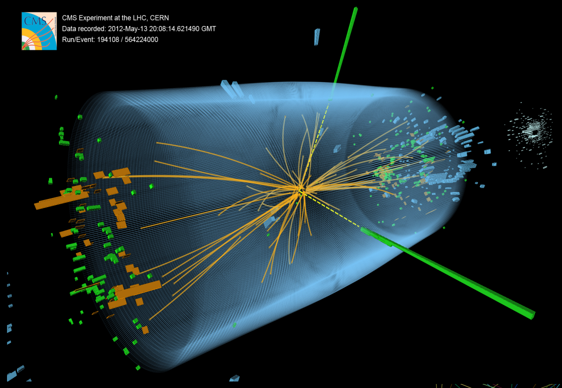
- CMS Higgs Physics Results
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG



CMS collaboration now has over 4000 members from ~200 institutes from more than 40 countries

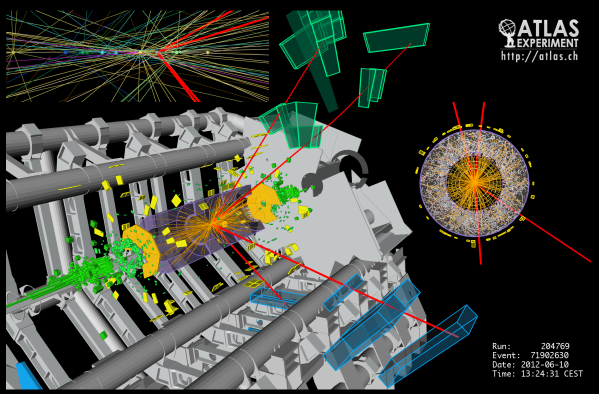
Higgs Discovery

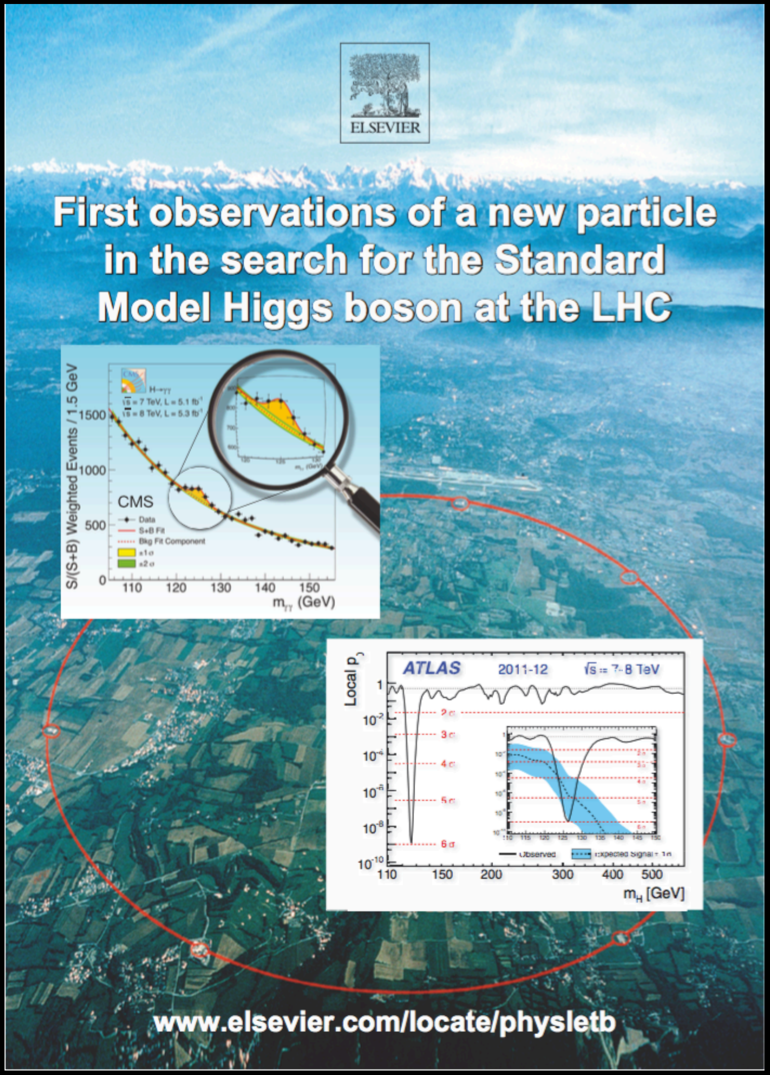
- On July 4th, 2012, Higgs discovered mainly in two high resolution channels



H⟶γγ candidate

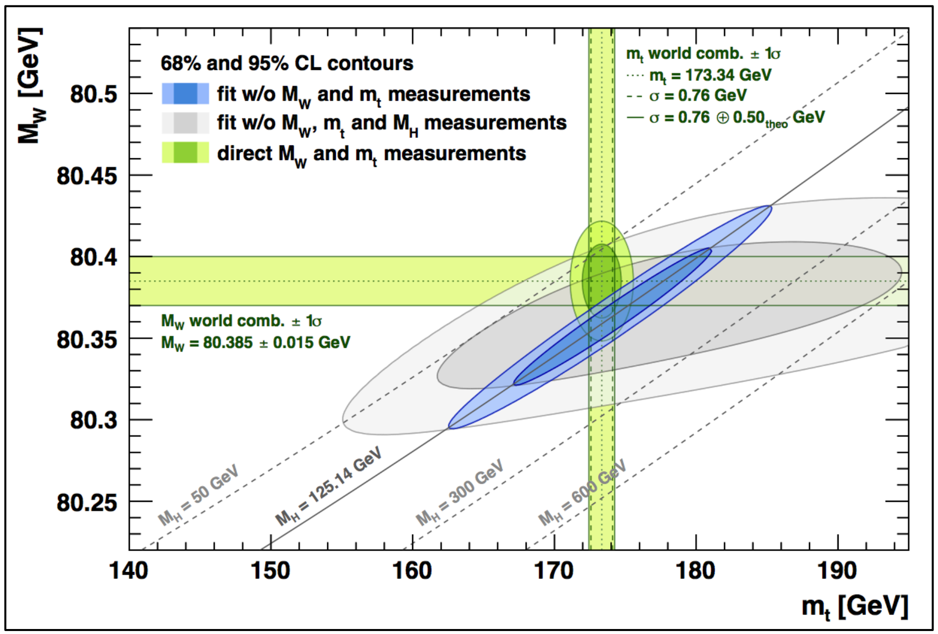
H⟶4μ candidate



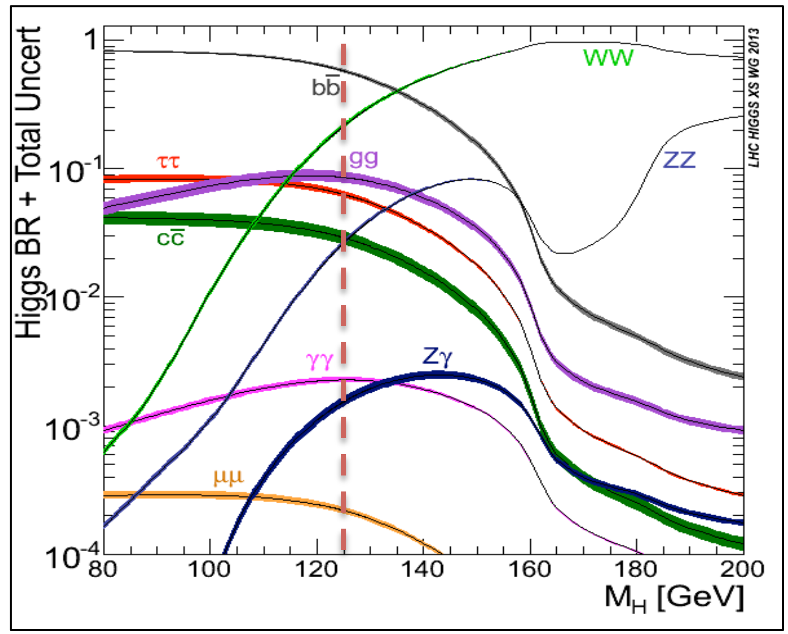


Higgs Mass

- A free parameter in the SM
- Fundamental position in the SM:
  - calculation of the Higgs boson production and decay rates
  - precise knowledge necessary to test the coupling structure



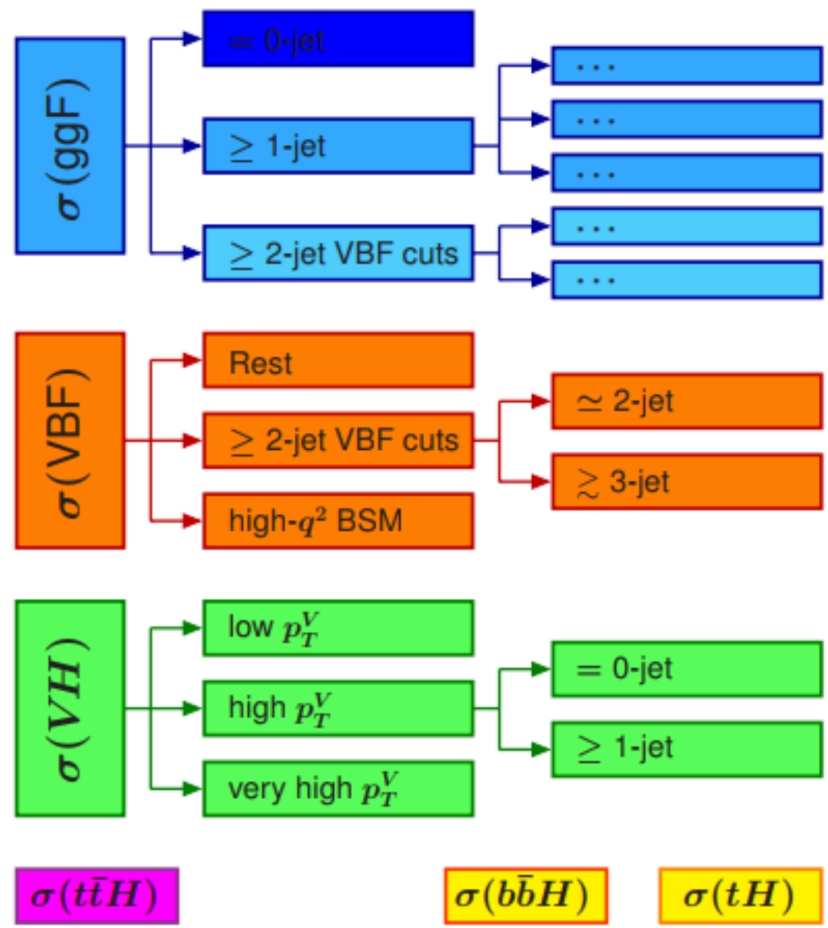
Consistency tests of SM parameters



For HWW/HZZ: $(\Delta BR/BR)/\Delta m_H \approx 8\%/\text{GeV}$

Simplified Template Cross Sections

- Aim to maximize the sensitivity of measurements and reduce its theory dependence
  - All decay channels are combined
- Cross-sections are measured directly instead of signal strengths
- Results obtained for a given production mode
- No need to normalize to a theory xsec which can change over time

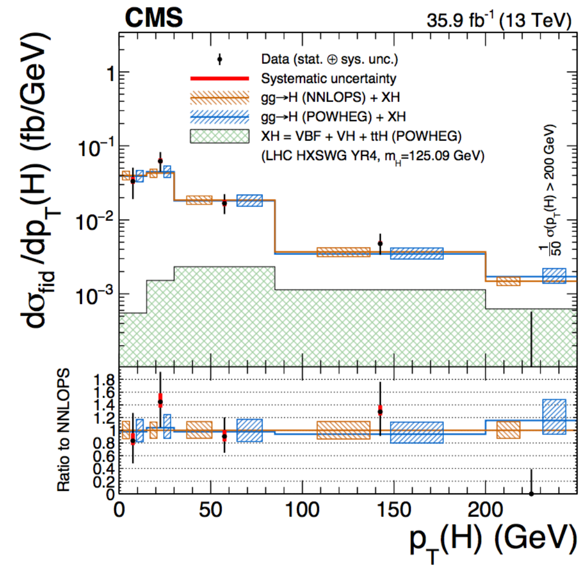


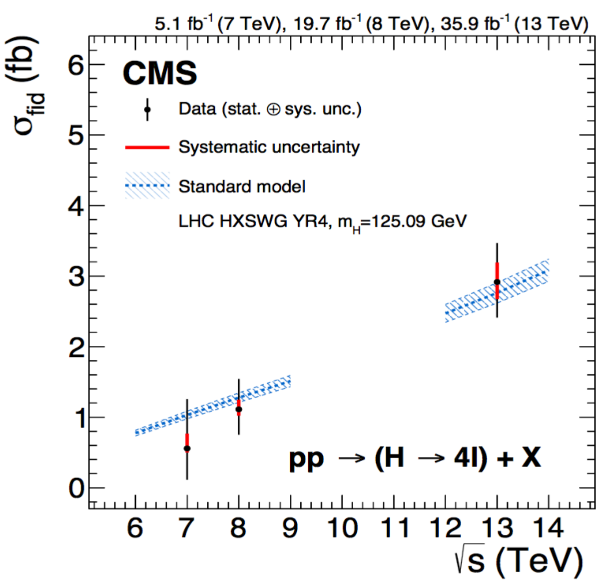
Stage-1 splitting

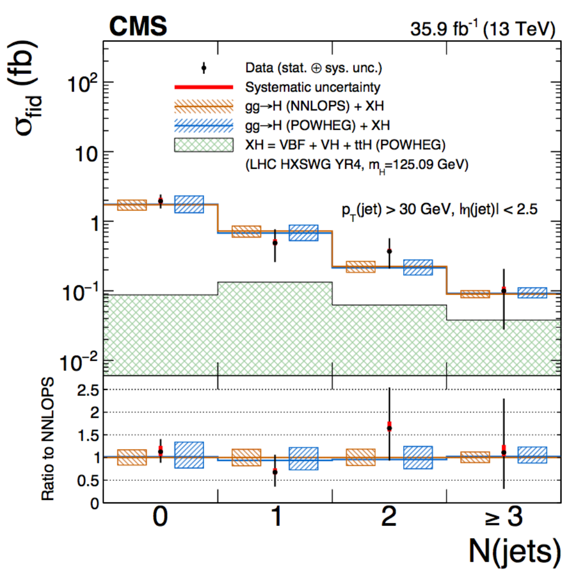
arXiv:1706.09936

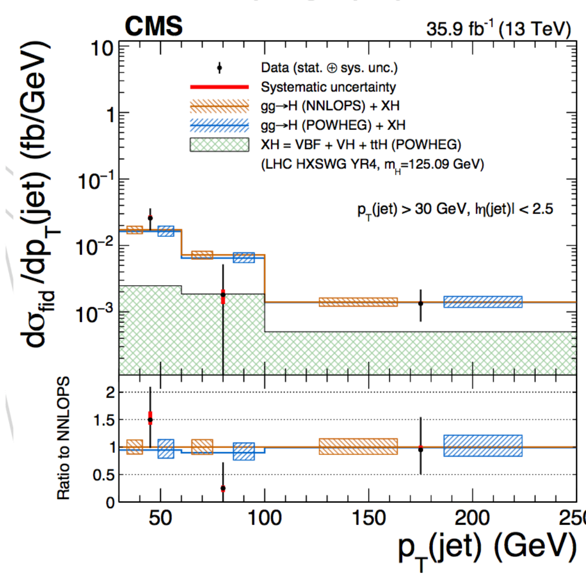
(Differential) Fiducial Cross Sections

- Measure within fiducial phase space to minimize model dependence
- Differential measurements of $p_T(H)$, N(jets), p_T(jet)









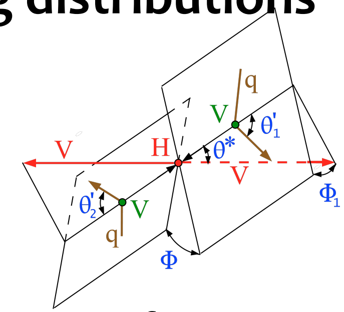
arXiv:1707.00541

Probing for Anomalous Couplings

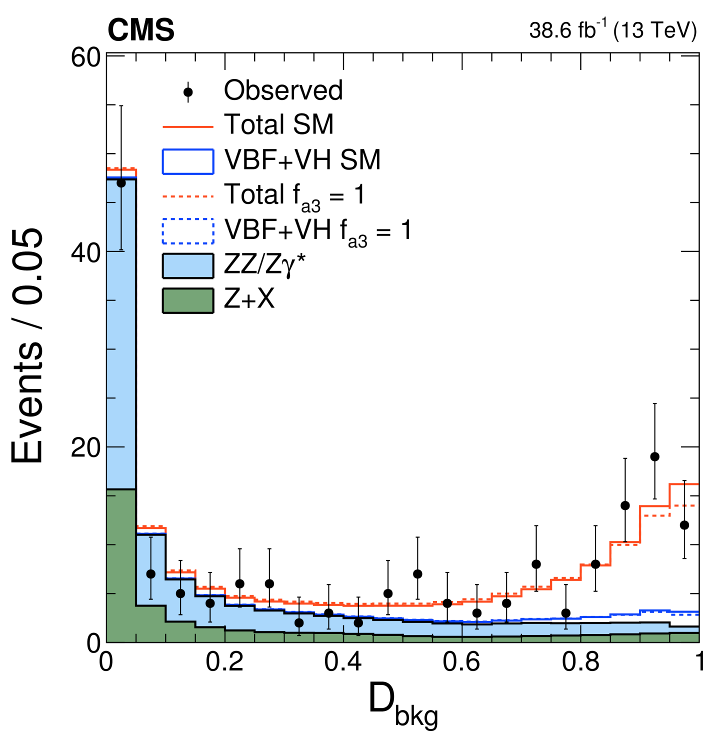
Test specific non-SM Lagrangian structure with discriminating distributions

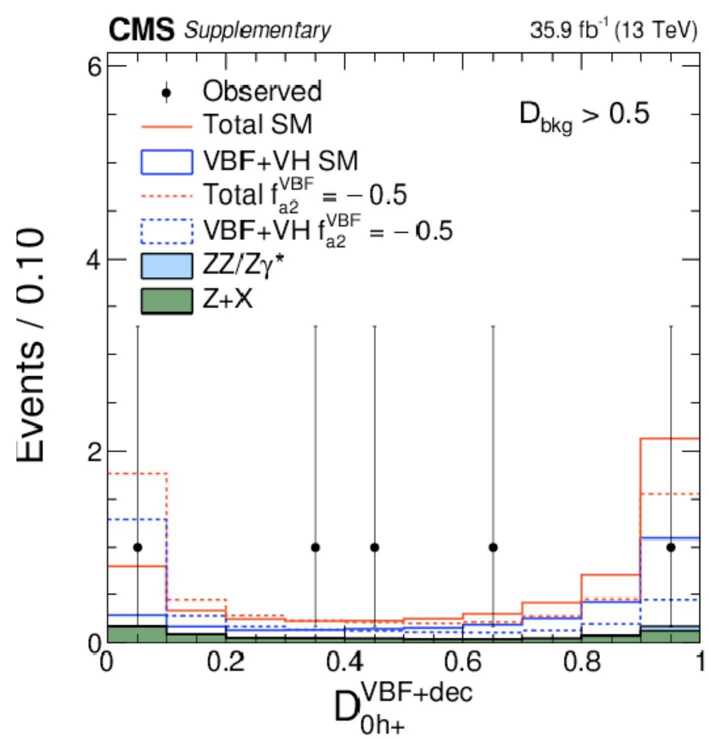
SM — BSM CP-even — BSM CP-odd

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$



Production (VBF and VH tagged events) used together with **decay** information





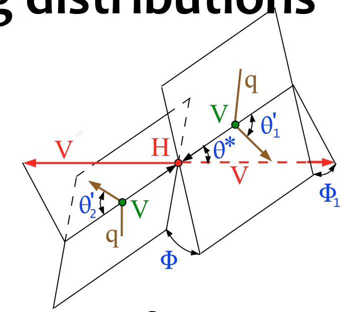
arXiv:1707.00541

Probing for Anomalous Couplings

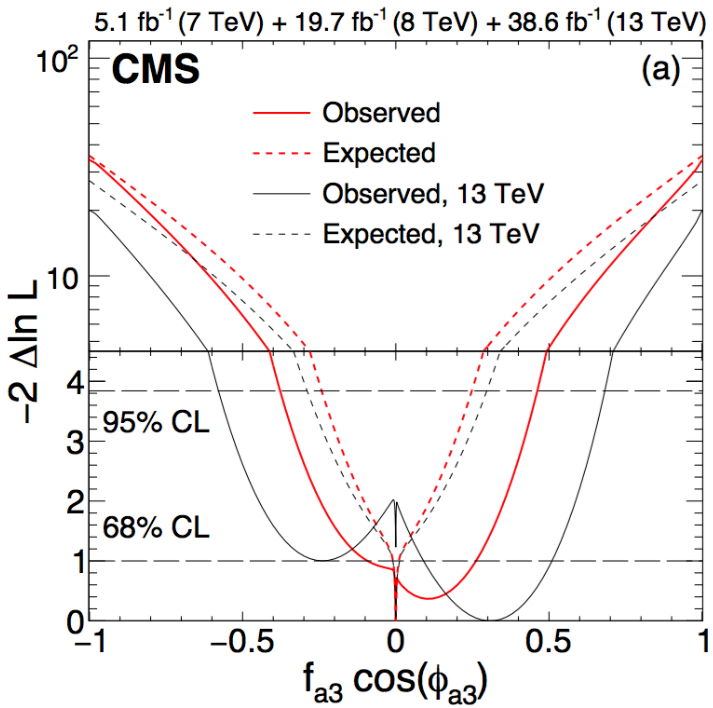
Test specific non-SM Lagrangian structure with discriminating distributions

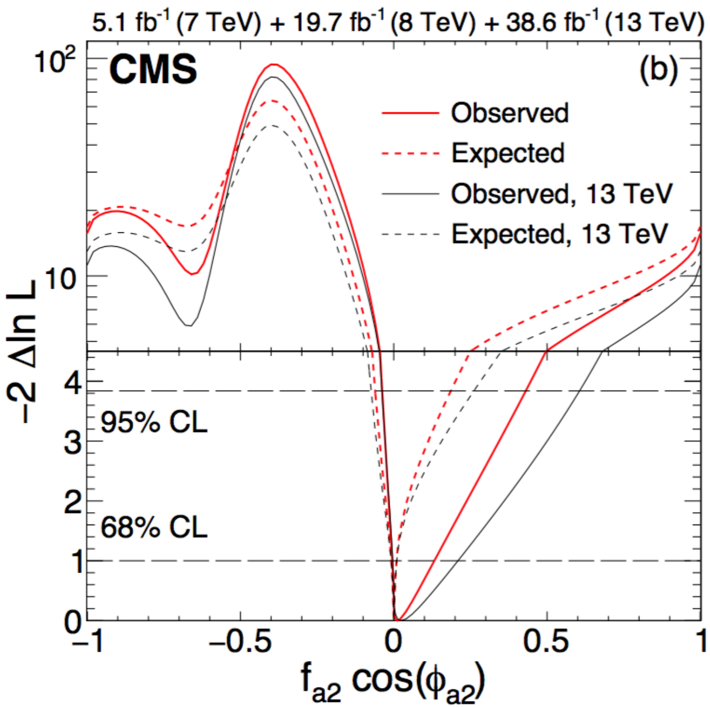
SM / BSM CP-even / BSM CP-odd

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$



Production (VBF and VH tagged events) used together with **decay** information





Matrix Element Discriminators

Used in categorisation of events to provide discrimination between different production mode

$$\mathcal{D}_{\rm bkg}^{\rm kin} = \left[1 + \frac{\mathcal{P}_{\rm bkg}^{q\bar{q}}(\vec{\Omega}^{\rm H\to4\ell}|m_{4\ell})}{\mathcal{P}_{\rm sig}^{gg}(\vec{\Omega}^{\rm H\to4\ell}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm bkg}^{\rm VBF+dec} = \frac{\mathcal{P}_{\rm sig}^{\rm VBF+VH+dec}(\vec{\Omega})}{\mathcal{P}_{\rm sig}^{\rm VBF+VH+dec}(\vec{\Omega}) + c^{\rm VBF2jet}(m_{4\ell}) \times (\mathcal{P}_{\rm bkg}^{\rm VBS+VVV}(\vec{\Omega}) + \mathcal{P}_{\rm bkg}^{\rm QCD+dec}(\vec{\Omega}))}$$

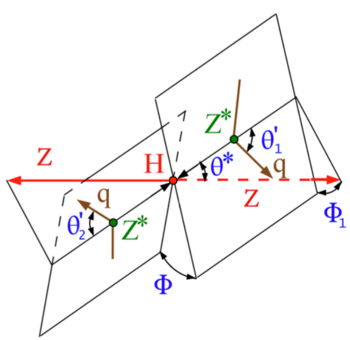
$$\mathcal{D}_{\rm bkg}^{\rm VH+dec} = \frac{\mathcal{P}_{\rm sig}^{\rm VBF+VH+dec}(\vec{\Omega})}{\mathcal{P}_{\rm sig}^{\rm VBF+VH+dec}(\vec{\Omega}) + c^{\rm had.VH}(m_{4\ell}) \times (\mathcal{P}_{\rm bkg}^{\rm VBS+VVV}(\vec{\Omega}) + \mathcal{P}_{\rm bkg}^{\rm QCD+dec}(\vec{\Omega}))},$$

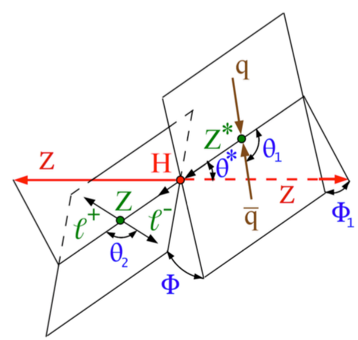
$$\mathcal{D}_{\rm 2jet} = \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm VBF}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm 1jet} = \left[1 + \frac{\mathcal{P}_{\rm HJ}(\vec{\Omega}^{\rm H+J}|m_{4\ell})}{\int d\eta_{\rm J}\mathcal{P}_{\rm VBF}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm WH} = \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm ZH}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm ZH} = \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm WH}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$





Coupling Deviations in BSM

- How well do we need to measure Higgs couplings ?
- Typical effect on coupling from heavy particle M or new physics at scale M:

$$\Delta \sim \left(\frac{v}{M}\right)^2 \sim 5\% \text{ @ M} \sim 1 \text{ TeV}$$

*Han et al., hep-ph/*0302188
*Gupta et al., arXiv:*1206.3560
……

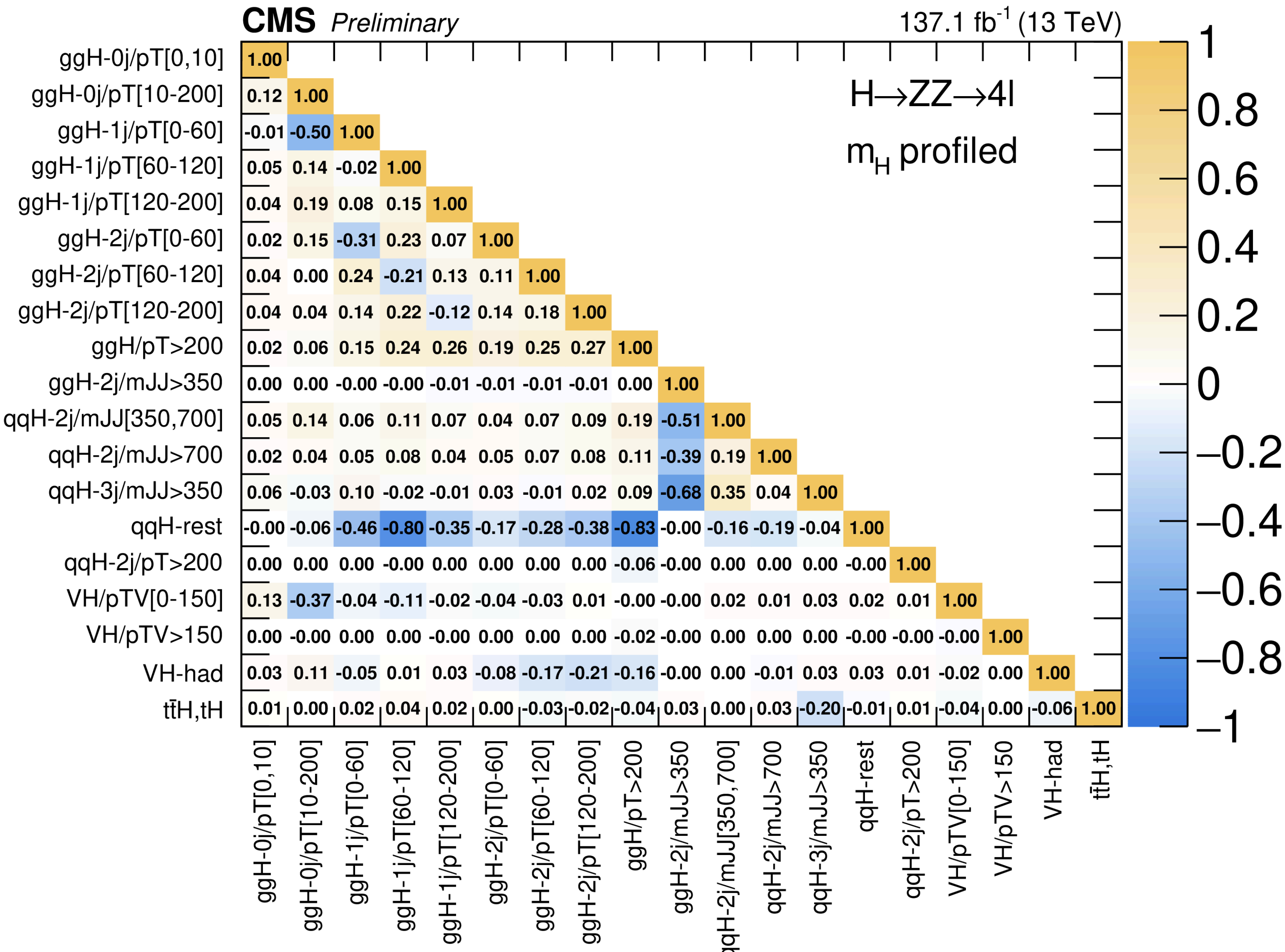
Typical sizes of coupling modifications: arXiv:1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Fiducial Volume

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\text{GeV}$
Subleading lepton p_T	$p_T > 10\,\text{GeV}$
Additional electrons (muons) p_T	$p_T > 7\,(5)\,\text{GeV}$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5\,(2.4)$
Sum p_T of all stable particles within $\Delta R < 0.3$ from lepton	$<0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Invariant mass of the Z_1 candidate	$40 < m_{Z_1} < 120\,\text{GeV}$
Invariant mass of the Z_2 candidate	$12 < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Invariant mass of any opposite-sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Invariant mass of the selected four leptons	$105 < m_{4\ell} < 140\,\text{GeV}$

Correlation matrix of the fitted signal strengths for Stage 1.1 Bins

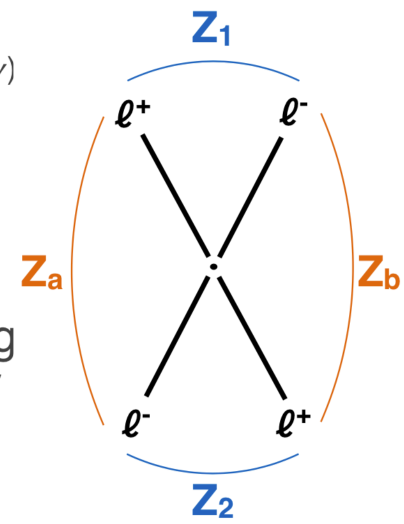


ZZ Candidate Selection

Z candidate = any OS-SF pair that satisfy $12 < m_{ll(\gamma)} < 120$ GeV

Build all possible ZZ candidates, define Z_1 candidate with $m_{ll(\gamma)}$ closest to the PDG m(Z) mass

- $m_{Z1} > 40$ GeV, $p_T(l1) > 20$ GeV, $p_T(l2) > 10$ GeV
- $\Delta R > 0.02$ between each of the four leptons
- $m_{ll} > 4$ GeV for OS pairs (regardless of flavour)
- reject 4μ and 4e candidates where the alternate pairing Z_aZ_b satisfies $|m(Z_a)-m(Z)|<|m(Z_1)-m(Z)|$ and $m(Z_b)<12$ GeV
- $m_{4l} > 70$ GeV



If more than one ZZ candidate is left, choose the one of highest $\mathcal{D}^{\text{kin}}_{\text{bkg}}$
If $\mathcal{D}^{\text{kin}}_{\text{bkg}}$ is the same, take the one with Z_1 mass closest to m(Z)*

*For fiducial measurements take the one with Z_1 mass closest to m(Z)