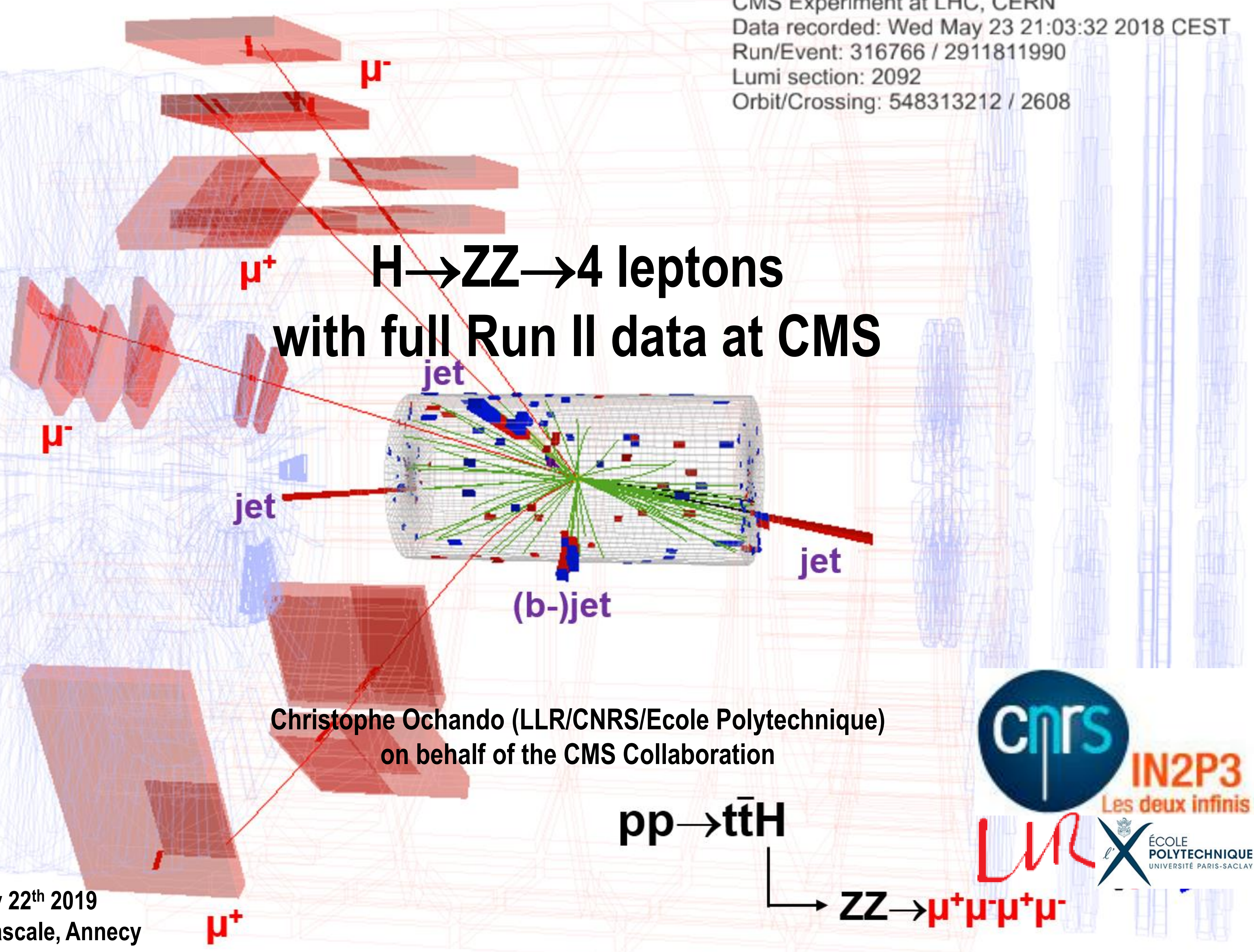
H→ZZ→4 leptons with full Run II data at CMS



Christophe Ochando (LLR/CNRS/Ecole Polytechnique)
on behalf of the CMS Collaboration

$pp \rightarrow t\bar{t}H$

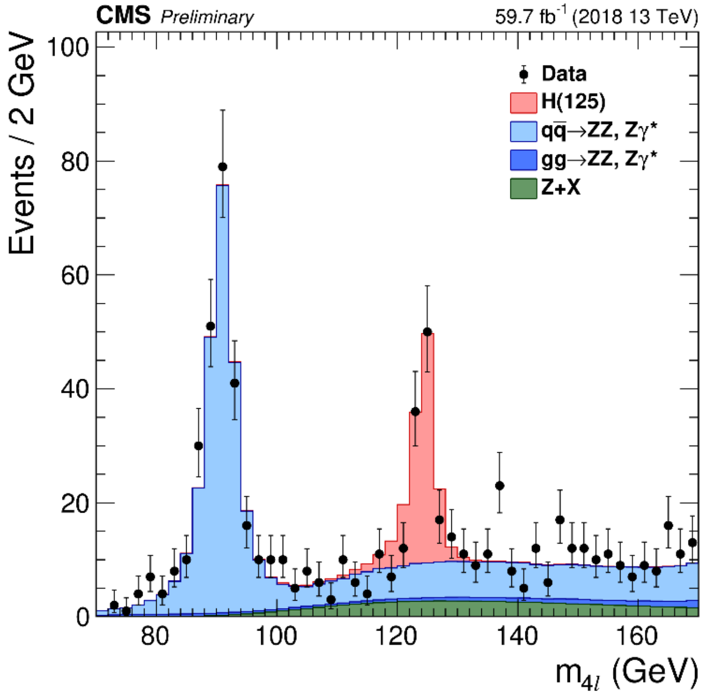
$\hookrightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$

May 22th 2019
IRN Terascale, Annecy

The H→ZZ→4 leptons channel

➢ H→ZZ(*)→4 leptons (e, μ):

- Clean experimental signature, large S/B, excellent resolution, full reconstruction of final states
- **Allows wide variety of precise measurements:** mass, width, couplings (SM-like, BSM, on-shell, off-shell), CP-violation studies, high mass searches, …

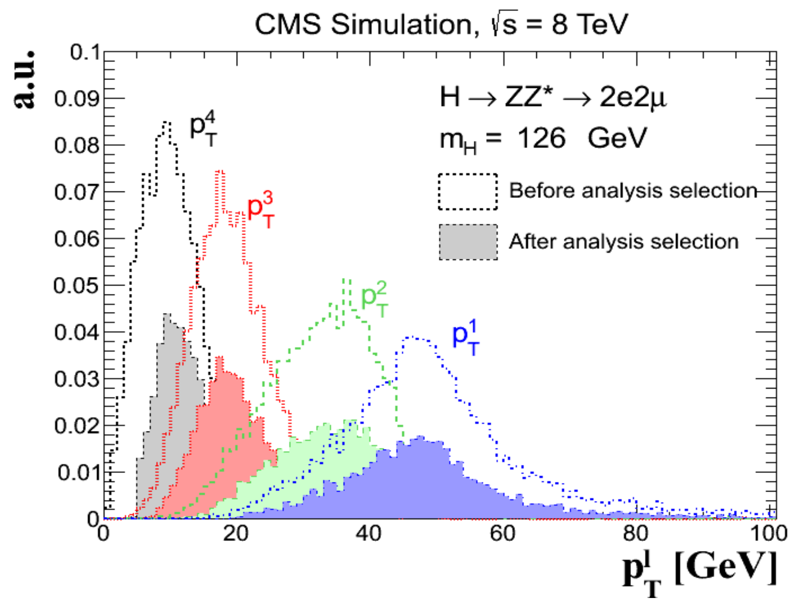


- 4 primary isolated leptons (e, μ)
- Narrow resonance (1-2% resolution) over ~flat background
- **BUT:** low signal yields (~7 events / fb)

➢ Extremely demanding channel for selection (ε^4):

➢ **Low pT leptons**: major experimental challenge

- Reconstruction/Identification
- Background rejection & control

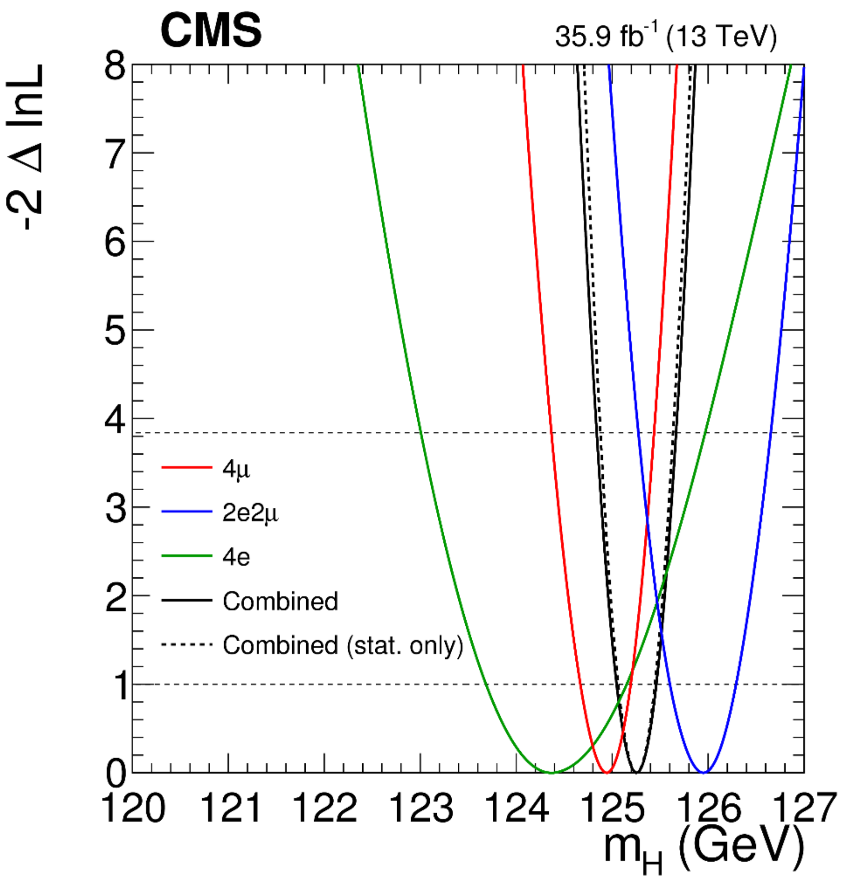


H→ZZ→4 leptons Run II: Recent highlights

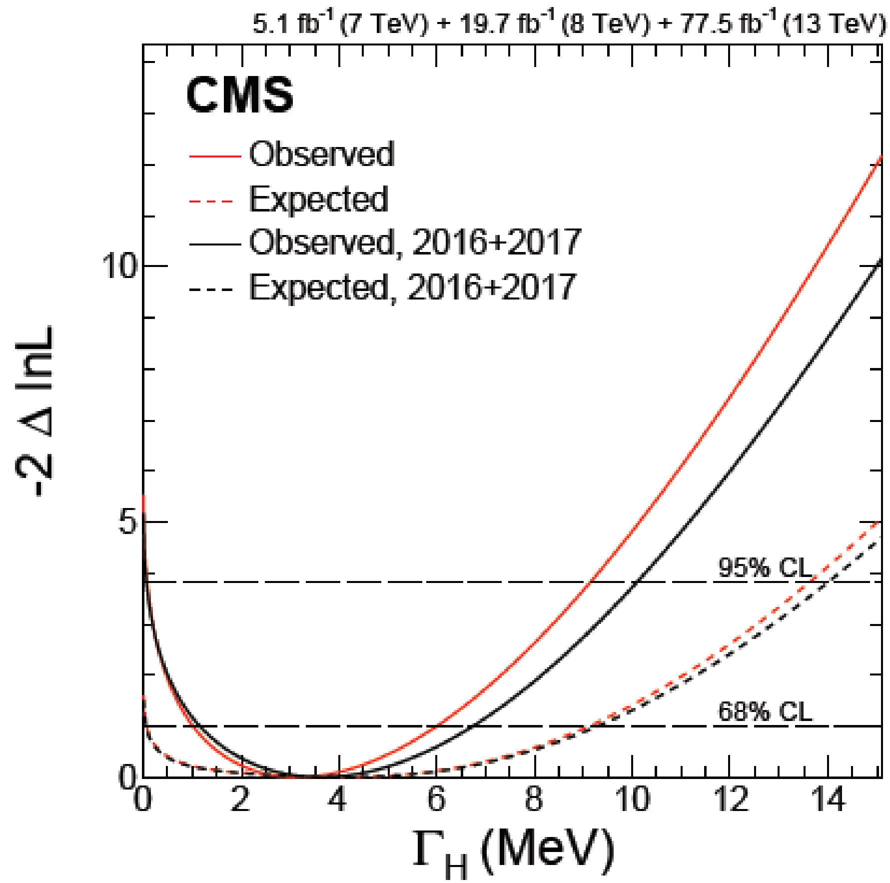
- **HIG-16-041, JHEP 1711 (2017) 047**
  - Inclusive and differential fiducial cross-sections
  - **2016 data (35.9 fb^{-1})**
  - **Most precise LHC measurement of m_H (1.7 per-mille!)**

- **HIG-18-002, Accepted by PRD:**
  - on-shell/off-shell properties.
  - **Combination of 2011 to 2017 data**
  - **Most precise LHC constraints on Γ_H.**

CMS-HIG-16-041
JHEP 1711 (2017) 047



$$m_H = 125.26 \pm 0.20\ (\text{stat.}) \pm 0.08\ (\text{sys.})\ \text{GeV}$$



Submitted to Phys. Rev. D
CMS-PAS-HIG-18-002

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

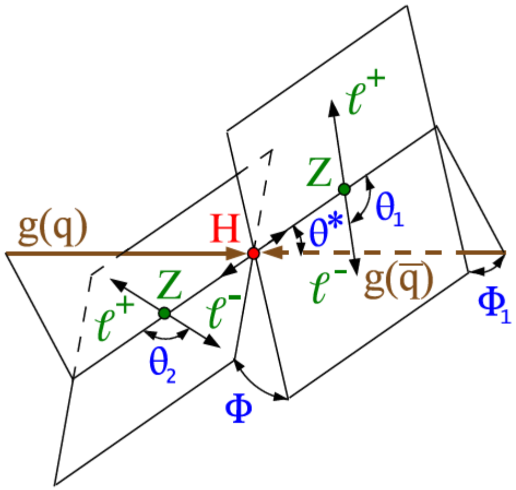
Full Run II Analysis Strategy

This talk: measurements will full Run II dataset (2016+2017+2018): **137.1 fb-1** (*)

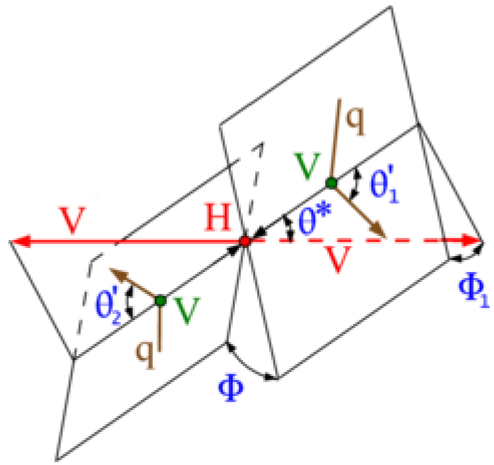
- **Select events with 4 primary isolated leptons (**)**
  - **Muons (electrons) down to 5 (7) GeV**
  - $40<m_{Z1}<120$ GeV, $12<m_{Z2}<120$ GeV
  - $m_{ZZ}>70$ GeV

- **Main Backgrounds:**
  - Irreducible (qq/gg→ZZ) from simulation
  - Reducible (Z+jets, ttbar, …) "Z+X": from data

- **Extensive usage of Matrix-Element Method (MEM)**
  - MEM-based kinematic discriminants
    - Separation of Higgs vs background
    - Separation of various Higgs production modes



- **Measurements:**
  - Couplings
  - Simplified Template Cross-Sections (STXS)
  - Differential cross-sections



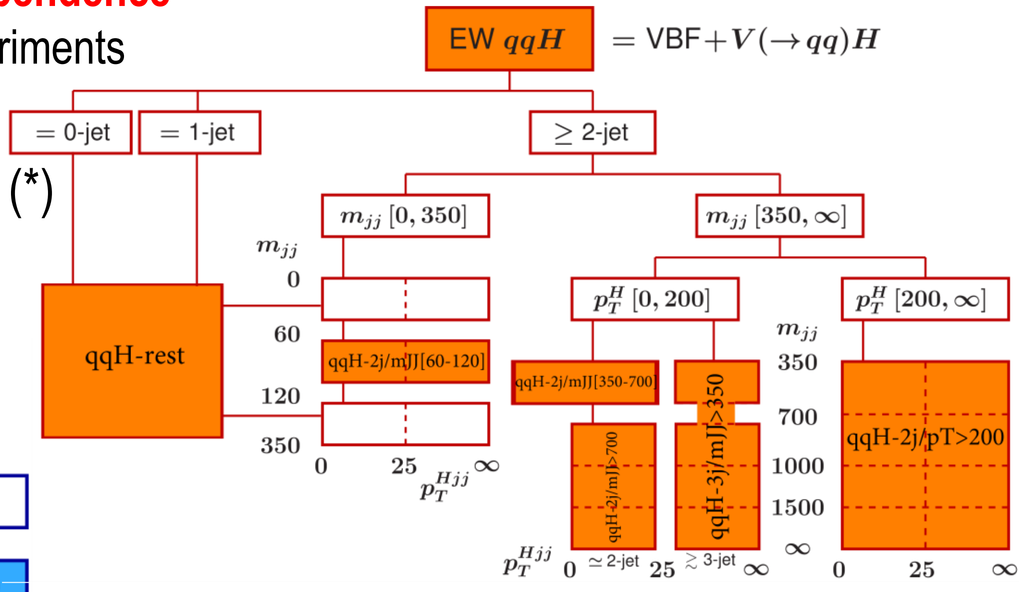
(*) **Full analysis of 2018 data** + re-categorization of 2017 (HIG-18-001) and 2016 (JHEP 1711 (2017) 047) public results

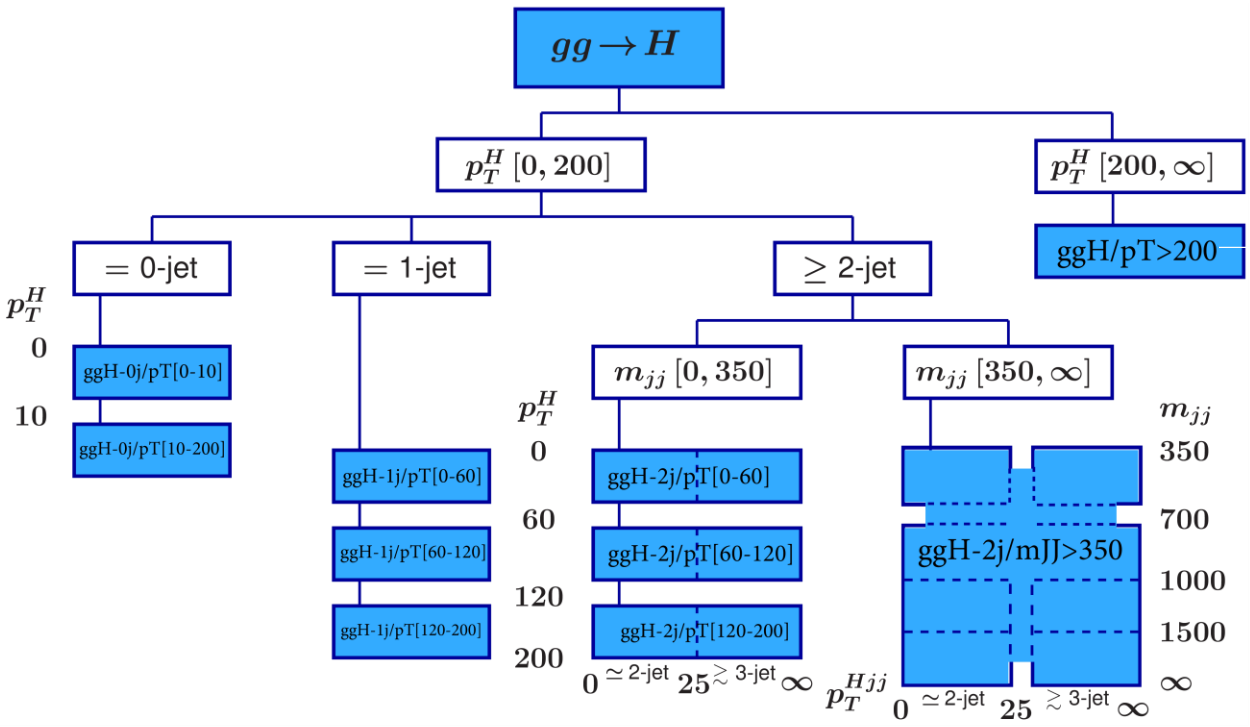
(**) Details on exact ZZ choice algorithm in back-up

Simplified Template Cross-Section (STXS), Stage 1.1

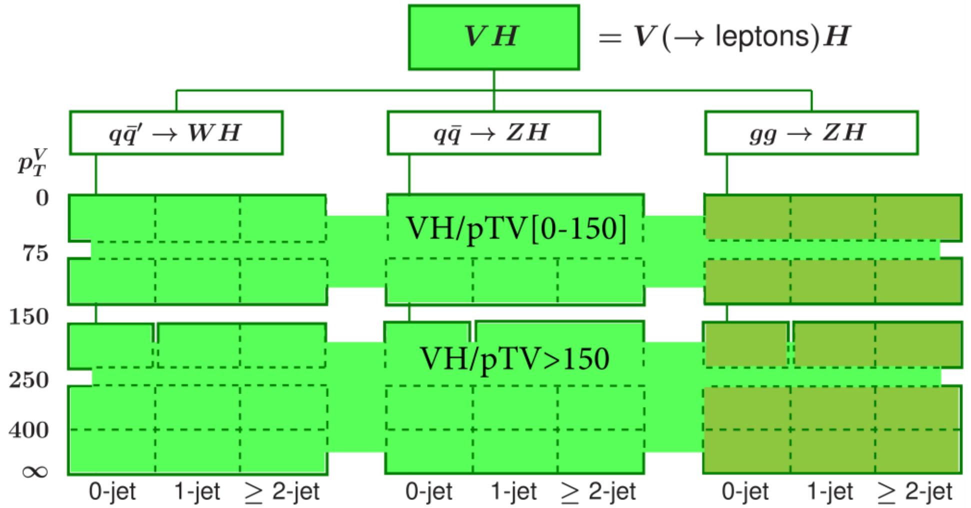
- **Simplified Template Cross-Section (from LHC XS group):**
  - Measure cross-sections in truth-level phase space regions
    - separated into production modes
  - **Target maximal sensitivity while minimizing theory dependence**
  - Designed to be “easily” combined across channels & experiments
  - **Results can be input to EFT interpretations**
- Measurement using **“Stage 1.1” latest recommendation** (*)
  - Split modes into dominant kinematic regions:

|yH|<2.5 at generator level





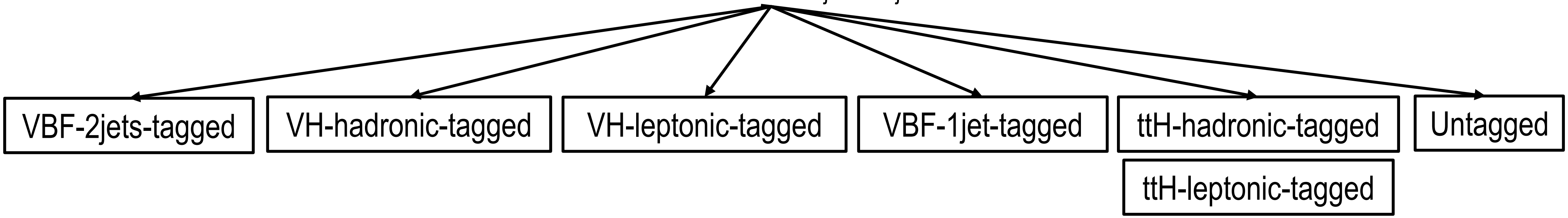
“bins” with no sensitivity are merged

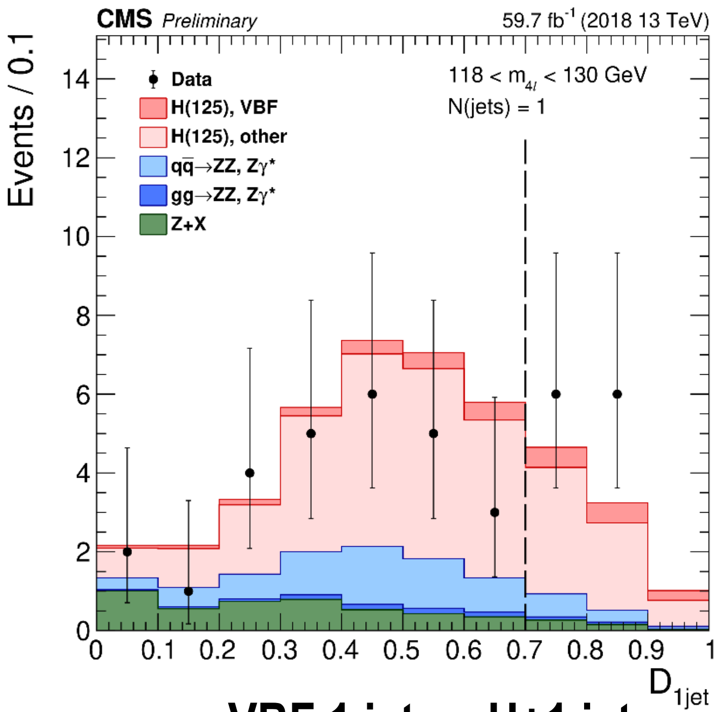


(*) https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGFiducialAndSTXS#Stage_1_1

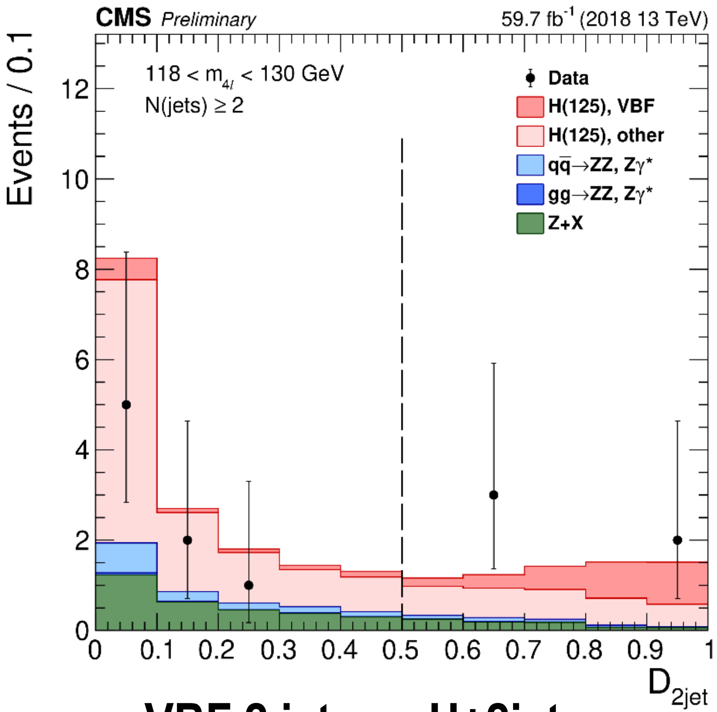
Experimental Categorization (1)

- **First, separate Higgs production modes (7 categories)**
  - Events split according to $N_{(b)\text{-jets}}$, N_{leptons}
  - + cuts on dedicated MEM-based discriminants (D_{1jet}, D_{2jet}, D_{VH})

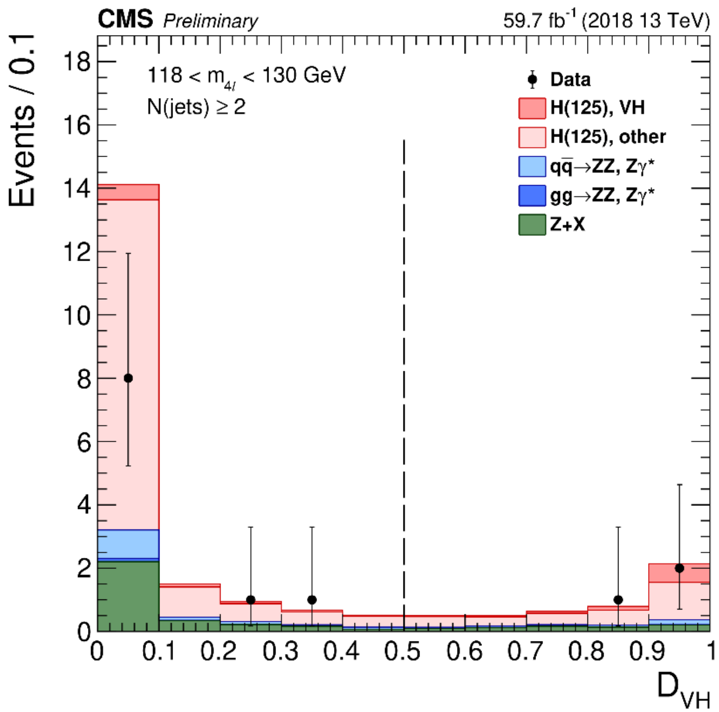




VBF 1 jet vs H+1 jet



VBF 2 jets vs H+2jets



WH/ZH vs H+2 jets

Experimental Categorization (2)

- **Second, further split for STXS measurement (22 categories in total)**
  - Events split according to mjj, pT(H), $N_{\text{-jets}}$, etc…

Categories: VBF-2jets-tagged, VH-hadronic-tagged, VH-leptonic-tagged, VBF-1jet-tagged, ttH-hadronic-tagged, ttH-leptonic-tagged, Untagged

VBF-2jets-tagged:

`VBF-2j/pT>200`: $p_T^H > 200$ GeV and $m_{jj} > 350$ GeV;

`VBF-2j/mJJ[350,700]`: $p_T^H < 200$ GeV, $p_T^{Hjj} < 25$ GeV, and $350 < m_{jj} < 700$ GeV;

`VBF-2j/mJJ>700`: $p_T^H < 200$ GeV, $p_T^{Hjj} < 25$ GeV, $m_{jj} > 700$ GeV;

`VBF-3j/mJJ>350`: $p_T^H < 200$ GeV, $p_T^{Hjj} > 25$ GeV, $m_{jj} > 350$ GeV;

`VBF-rest`: if not above.

VH-hadronic-tagged:

`VH-had/mJJ[60-120]`: $60 < m_{jj} < 120$ GeV;

`VH-rest`: not above.

VH-leptonic-tagged:

`VH-lep/pT[0-150]`: $p_T^H < 150$ GeV;

`VH-lep/pT>150`: $p_T^H > 150$ GeV.

Untagged:

`ggH/pT>200`: the Higgs boson has $p_T^H > 200$ GeV;

`ggH-0j/pT[0,10]`: 0 jet reconstructed and $0 < p_T^H < 10$ GeV;

`ggH-0j/pT[10-200]`: 0 jet reconstructed and $10 < p_T^H < 200$ GeV;

`ggH-1j/pT[0-60]`: 1 jet reconstructed and $0 < p_T^H < 60$ GeV;

`ggH-1j/pT[60-120]`: 1 jet reconstructed and $60 < p_T^H < 120$ GeV;

`ggH-1j/pT[120-200]`: 1 jet reconstructed and $120 < p_T^H < 200$ GeV;

`ggH-2j/mJJ>350`: 2 jets reconstructed and $m_{jj} > 350$ GeV;

`ggH-2j/pT[0-60]`: 2 jets reconstructed, $0 < p_T^H < 60$ GeV, and $m_{jj} < 350$ GeV;

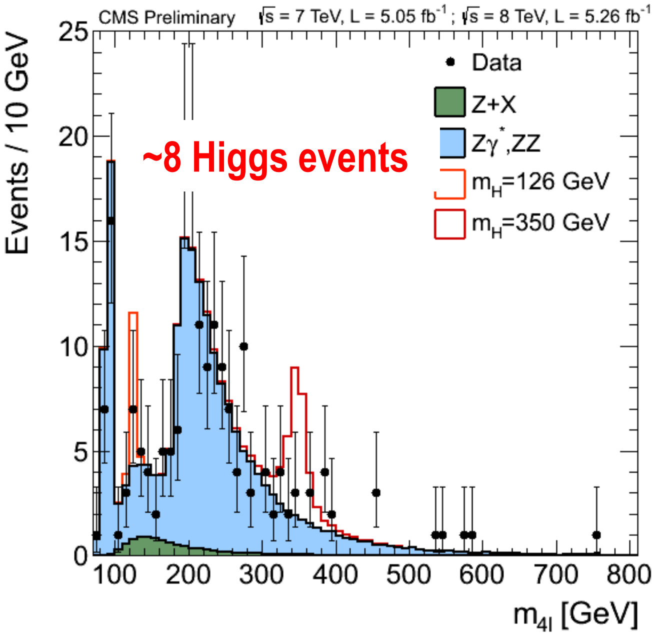
`ggH-2j/pT[60-120]`: 2 jets reconstructed, $60 < p_T^H < 120$ GeV, and $m_{jj} < 350$ GeV;

`ggH-2j/pT[120-200]`: 2 jets reconstructed, $120 < p_T^H < 200$ GeV, and $m_{jj} < 350$ GeV.

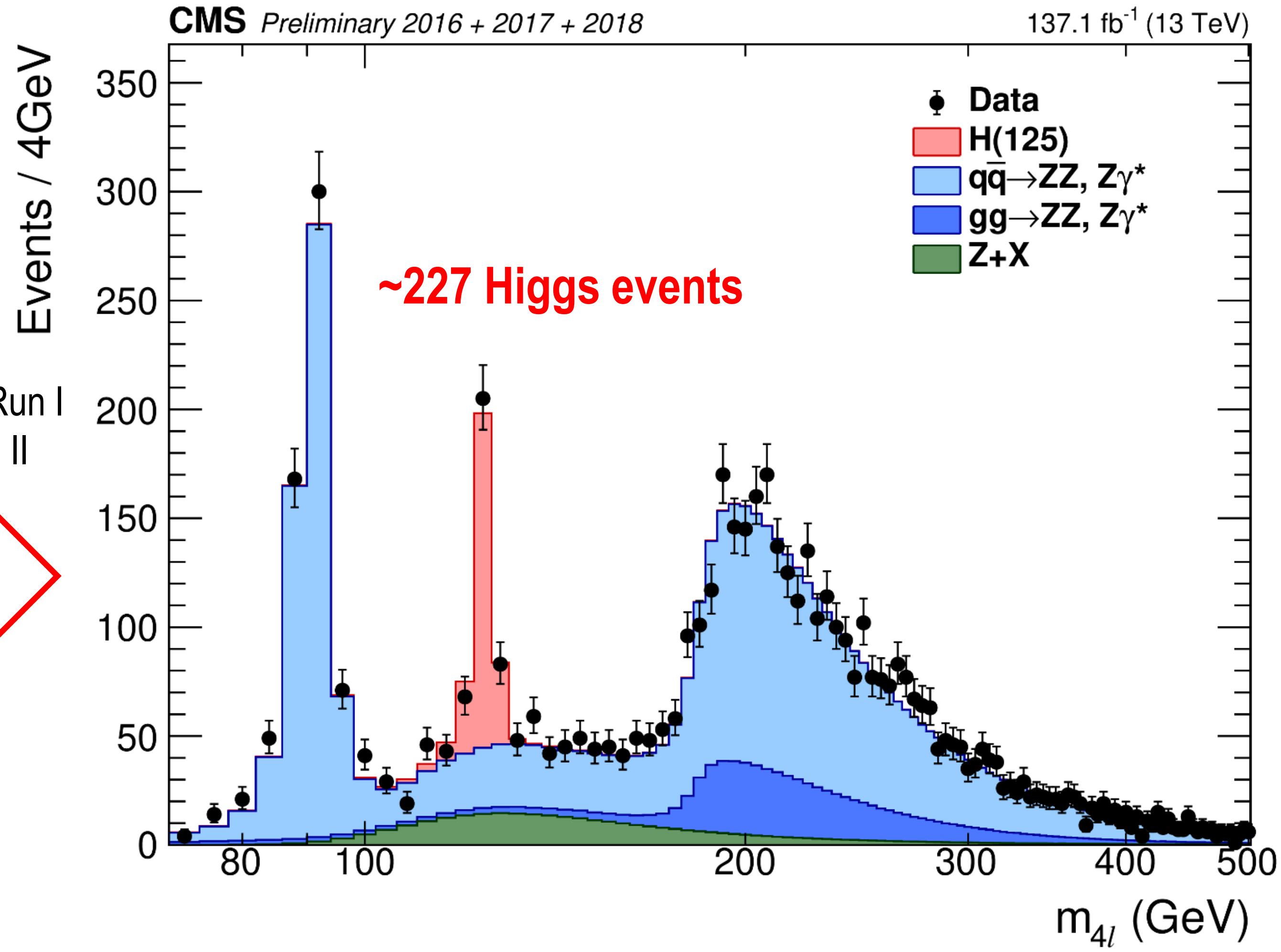
Results: m_{4l} distribution (inclusive)

We've come a long way since the discovery…

July 2012



From early Run I
to full Run II

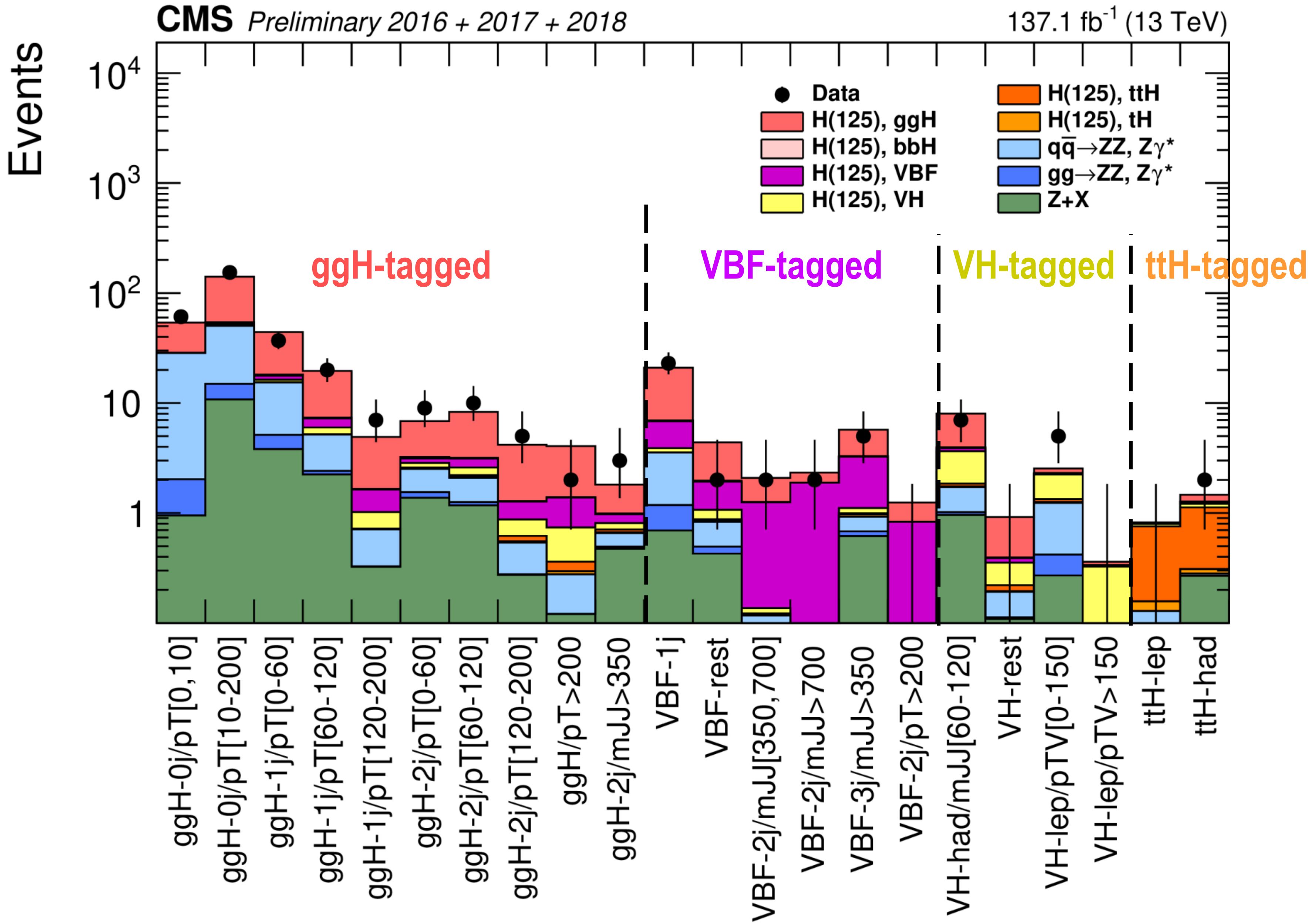


Expected and Observed events in 118 < m4l < 130 GeV

gg→H	VBF	WH	ZH	ttH	bbH	tqH	Total Signal	qq→ZZ	gg→ZZ	Z+X	Total expected	Observed
195,1	17,1	4,9	4,9	2,1	2,1	0,3	226,5	82,4	7,1	36,5	**352,6**	**356**

Results: m_{4l} distribution (22 categories)

Expected and Observed number of events in 118 < m4l < 130 GeV range, for each of the 22 categories for STXS measurement

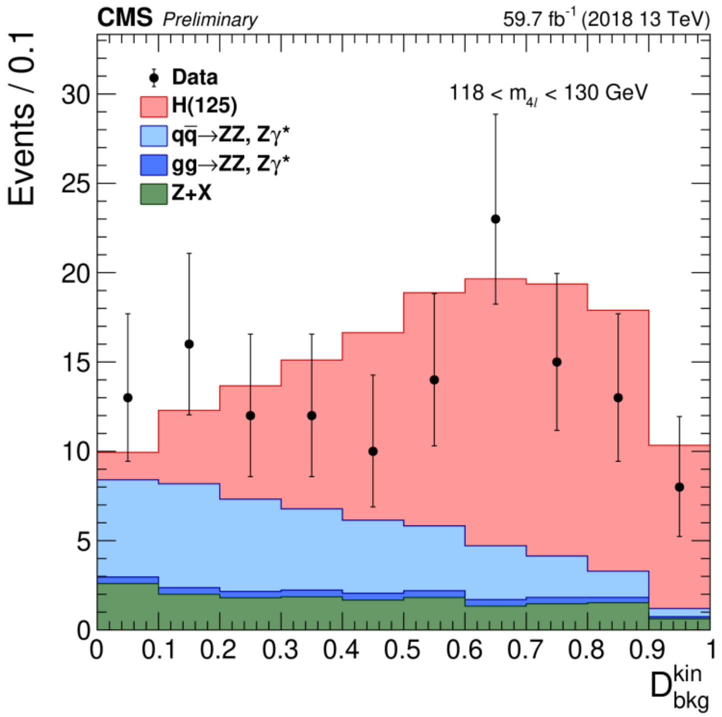


Signal Extraction

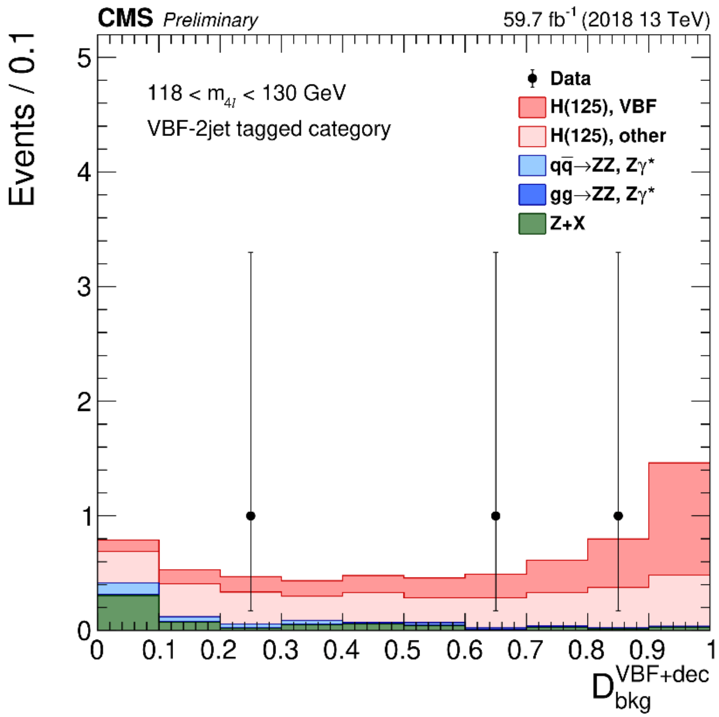
Signal extraction in each category: 22 x 3 (4e, 4mu, 2e2mu)
2D fit, m4l vs MEM-based Kinematic Discriminant

$$\mathcal{L}_{2D}(m_{4\ell}, \mathcal{D}^{\rm kin}_{\rm bkg}) = \mathcal{L}(m_{4\ell})\mathcal{L}(\mathcal{D}^{\rm kin}_{\rm bkg}|m_{4\ell}).$$

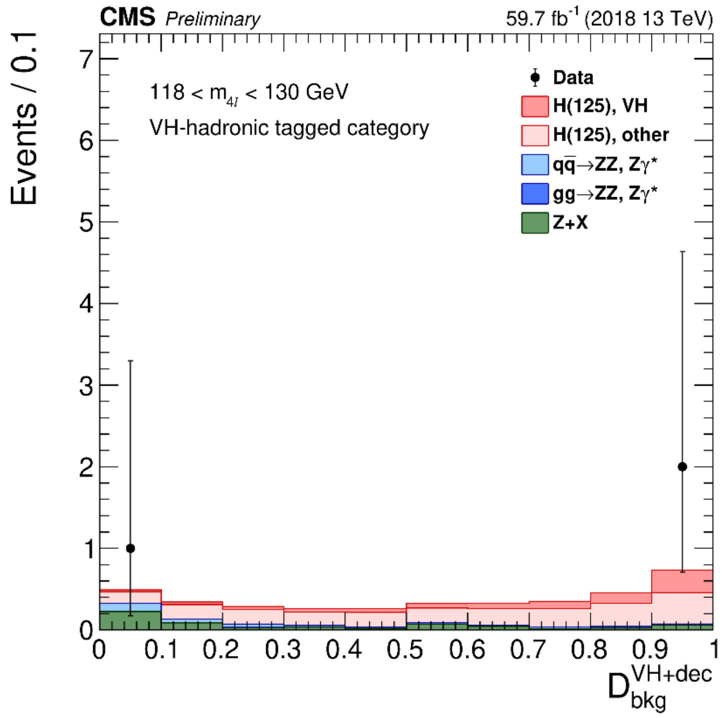
D_{bkg}^{kin}: **ggH vs qqZZ** (decay information only)
for *un-tagged, VBF-1 jet, VH-leptonic, ttH cat.*



$D_{bkg}^{VBF+dec}$: **VBF vs ggH, SM bkg**
(decay + production info)
for VBF2jets-tagged cat.

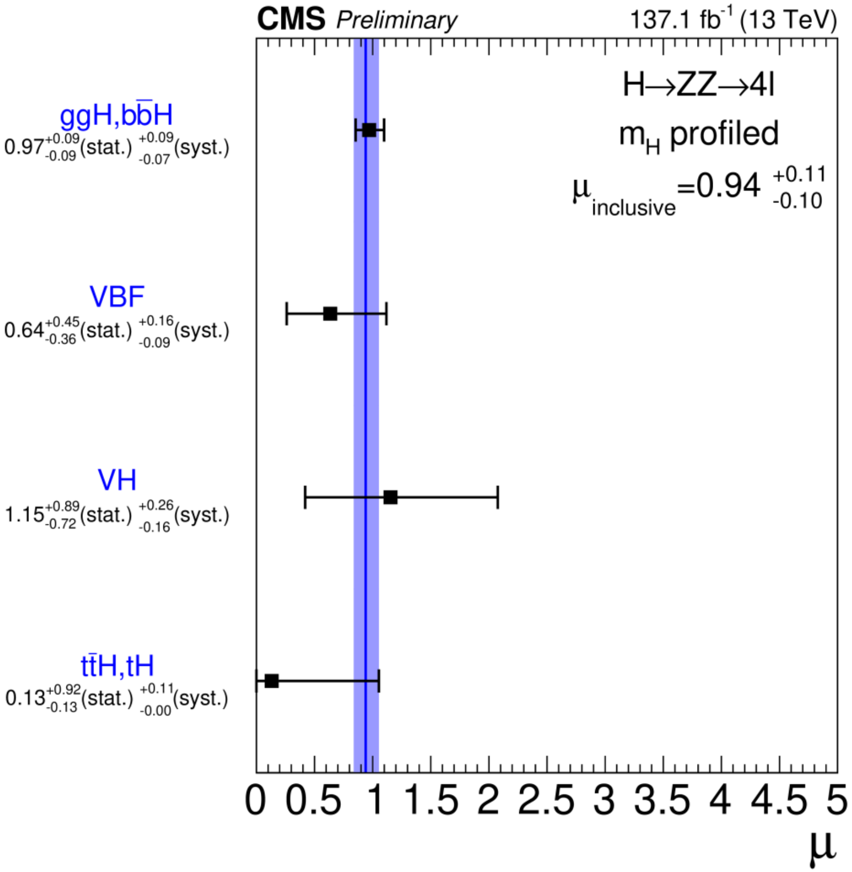


D_{bkg}^{VH+dec}: **VH vs ggH, SM bkg**
(decay + production info)
for VH-hadronic-tagged cat.



Measurement: Signal strength & STXS Stage 1.

Signal Strength

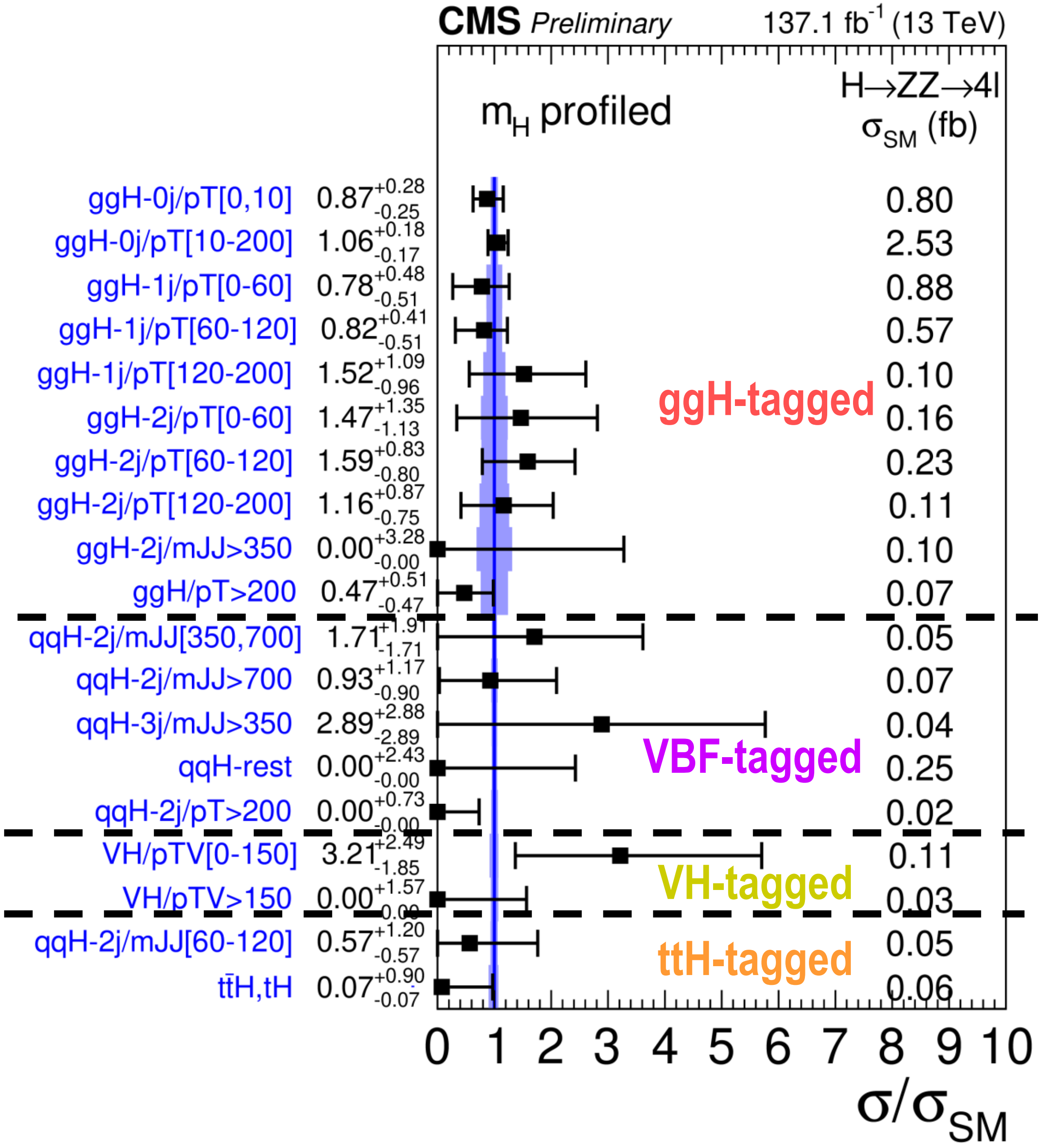


$$\mu = \sigma / \sigma_{SM} = 0.94^{+0.11}_{-0.10}$$
$$= 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

Overall uncertainty: ~10%

Systematic errors on par with statistics !

STXS Stage 1.1



Measurement: Fiducial Cross-Sections

- Unfold cross-section to truth-level fiducial volume, closely matches reconstruction level (**see back-up**)
- Experimentally: maximum likelihood fit of the signal and background parameterizations to the observed 4l mass distribution in every bin to measure.
  - No categories used,
  - m_H=125.09 GeV assumed

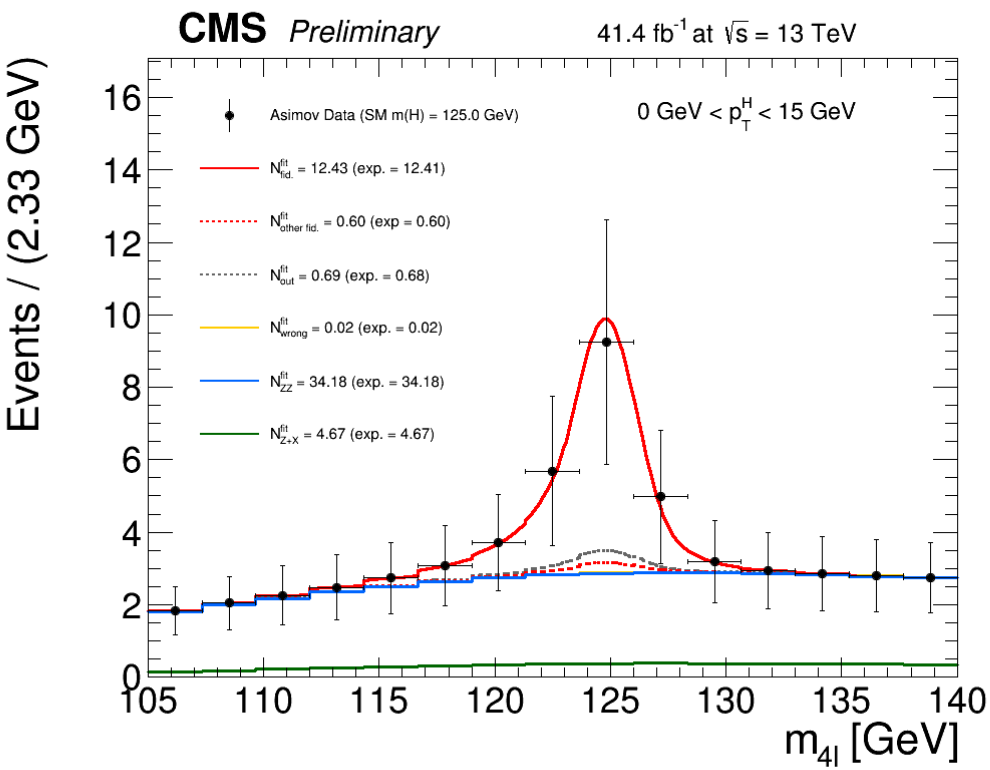
Fiducial signal — Non-resonant signal — Non fiducial signal — Background contribution

$$N_{\rm obs}^{{\rm f},i}(m_{4\ell}) = N_{\rm fid}^{{\rm f},i}(m_{4\ell}) + N_{\rm nonres}^{{\rm f},i}(m_{4\ell}) + N_{\rm nonfid}^{{\rm f},i}(m_{4\ell}) + N_{\rm bkg}^{{\rm f},i}(m_{4\ell})$$
$$= \left(1 + f_{\rm nonfid}^{{\rm f},i}\right) \cdot \sigma_{\rm fid}^{{\rm f},j} \cdot \epsilon_{i,j}^{\rm f} \cdot \mathcal{L} \cdot \mathcal{P}_{\rm res}(m_{4\ell})$$
$$+ N_{\rm nonres}^{{\rm f},i} \cdot \mathcal{P}_{\rm nonres}(m_{4\ell}) + N_{\rm bkg}^{{\rm f},i} \cdot \mathcal{P}_{\rm bkg}(m_{4\ell}),$$

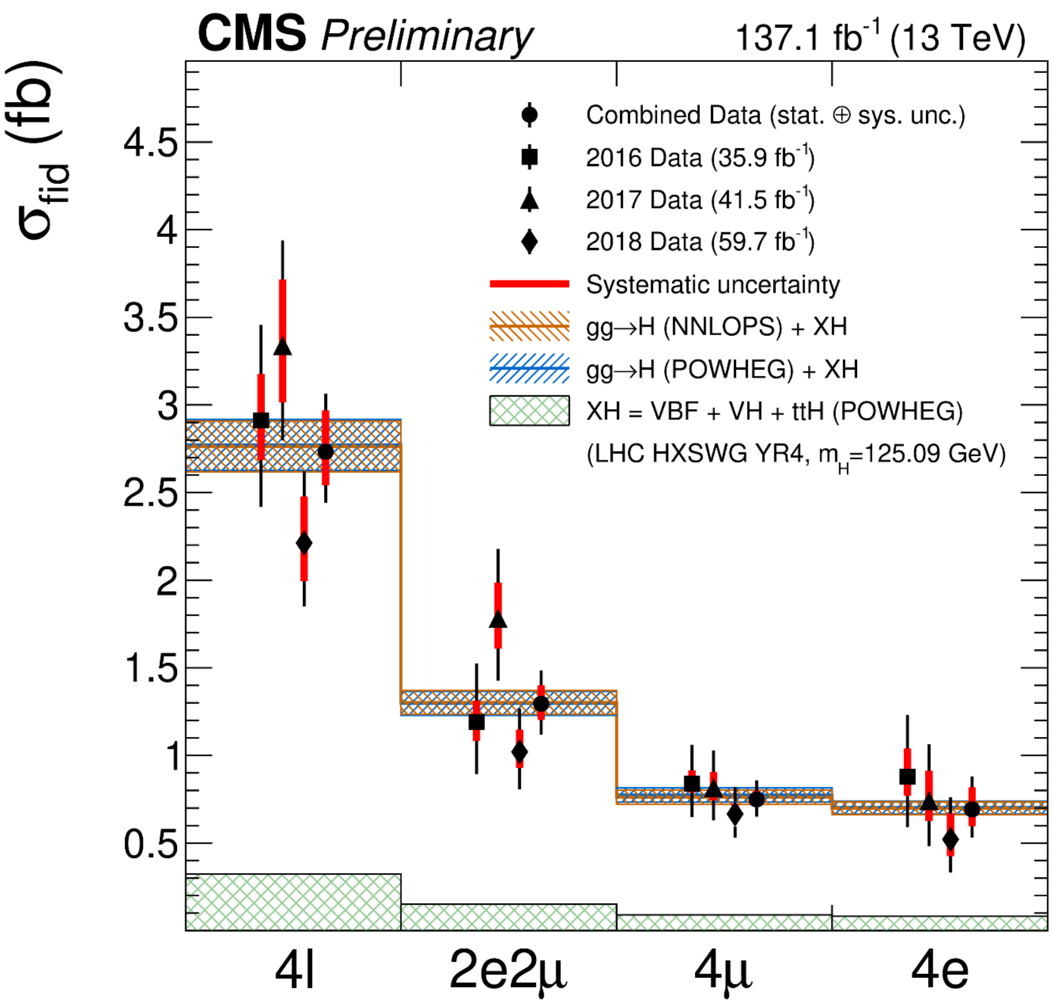
Parameter of interest

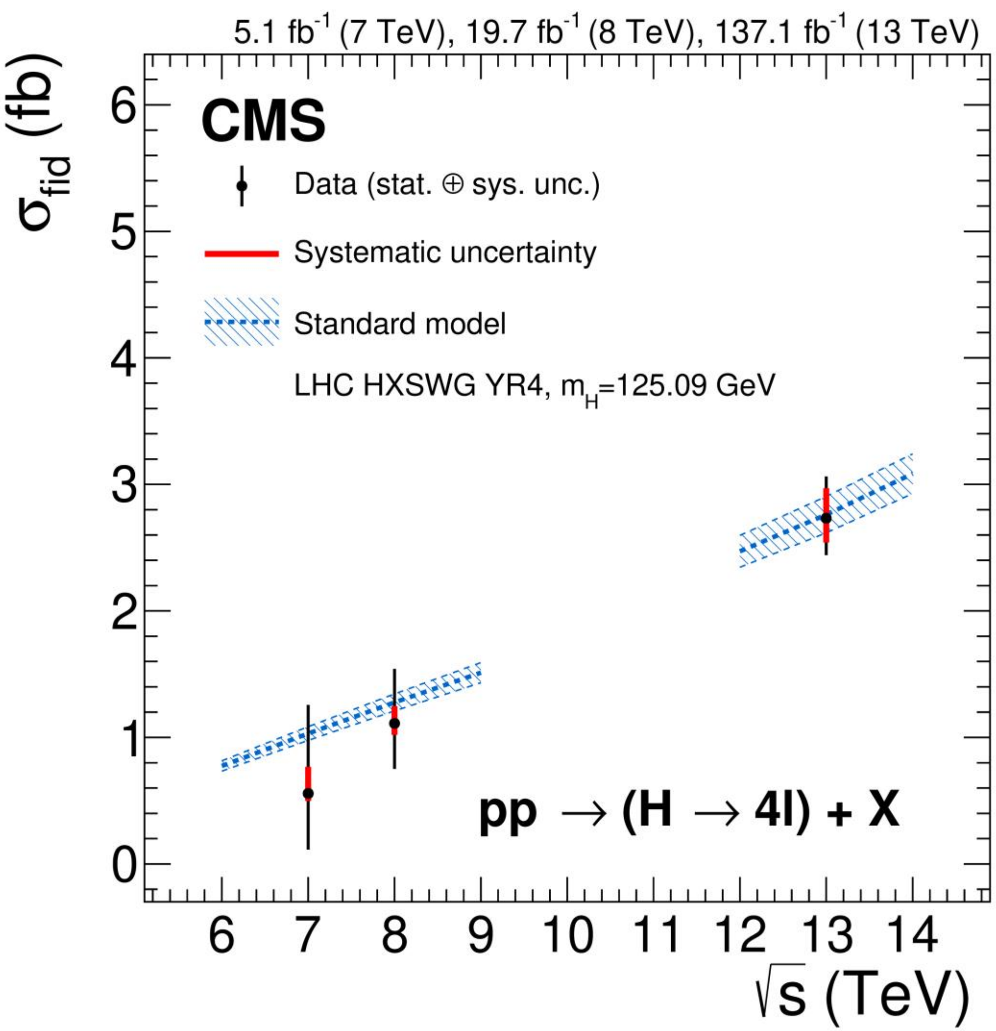
Probability density function for resonant, non-resonant and background

Example of m4l fit in a given bin in pT



Fiducial Cross-sections (inclusive)



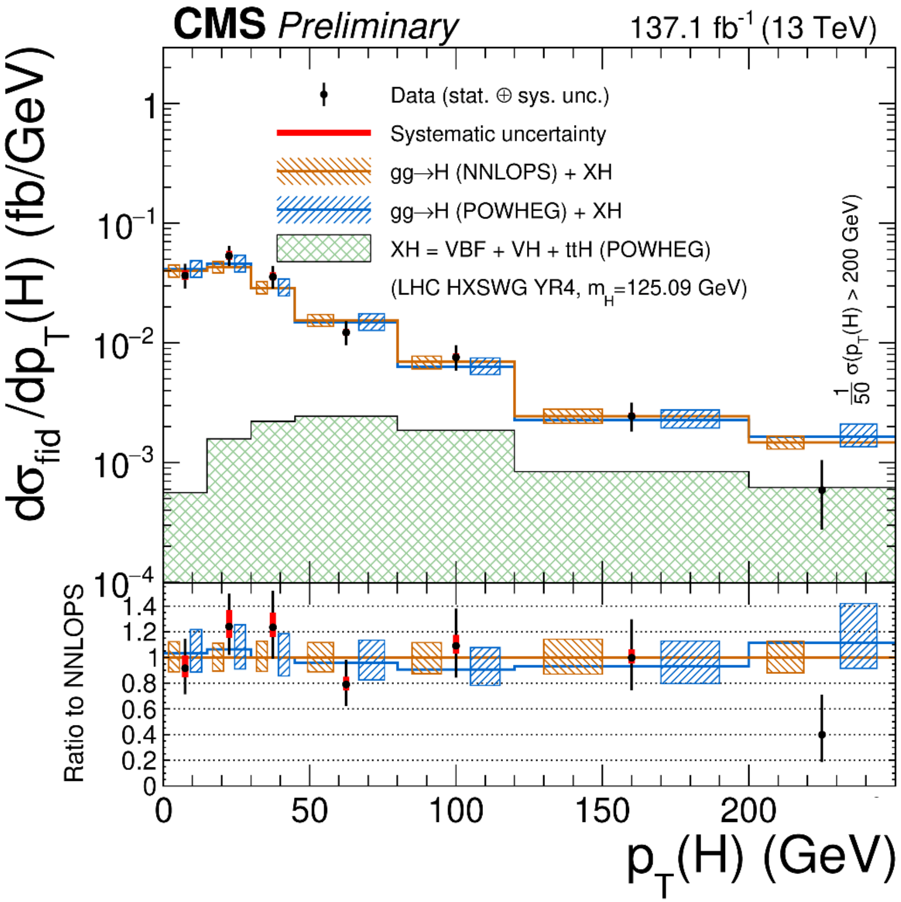


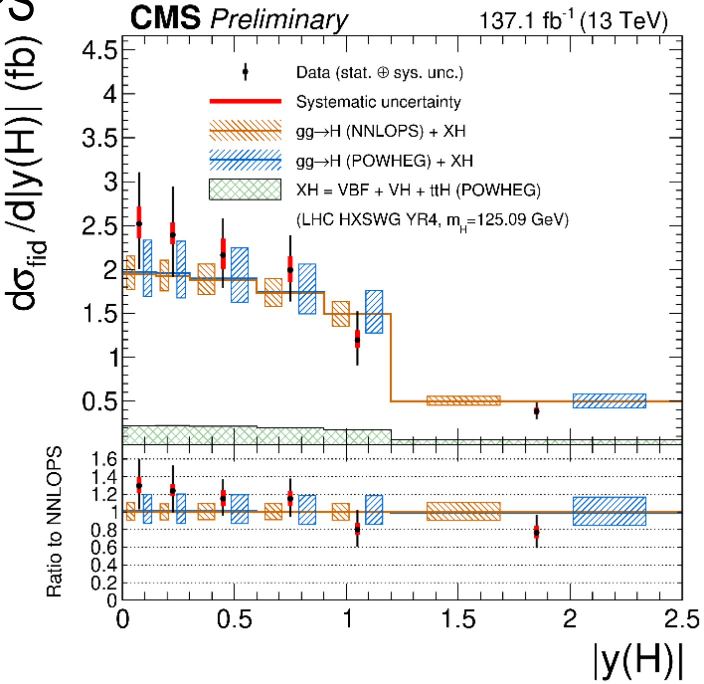
$$\sigma_{\text{fid.}} = 2.73^{+0.30}_{-0.29} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})\ \text{fb}$$

$$\sigma^{\text{SM}}_{\text{fid.}} = 2.76 \pm 0.14\ \text{fb}.$$

Fiducial Cross-sections (differential)

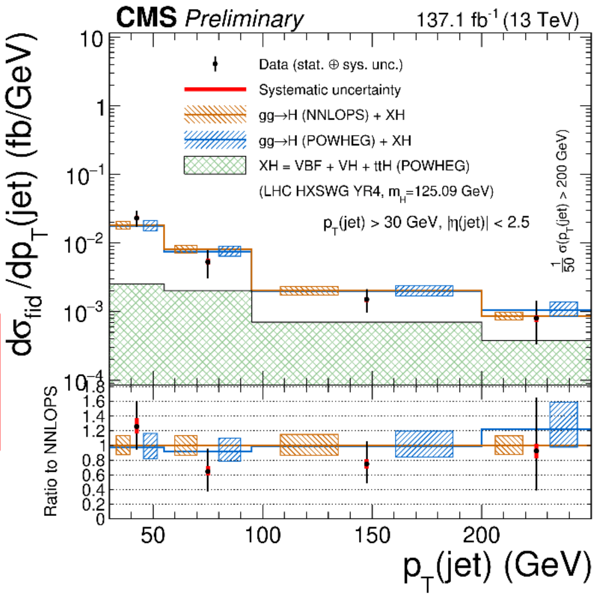
- Unfolding performed by including response matrix in the likelihood
- Comparisons to predictions from POWHEG and NNLOPS

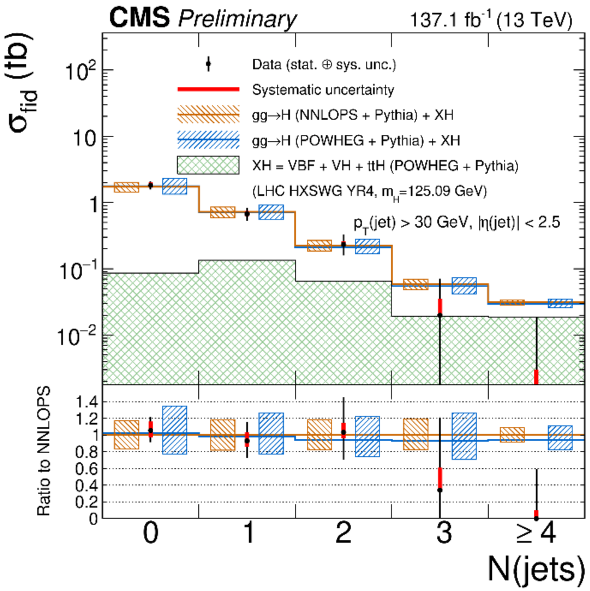




Probes of PDFs, production mode,…

pT(H): Sensitive to perturbative QCD modelling, production mode, Yukawa couplings,…





Test of modelling QCD radiation, production mechanism

Ony jets with |η|<2.5 considered

Summary & Prospects

First CMS Higgs results with Full Run II statistics.

- **Several measurements reported:**
  - **Overall signal strength:** $\mu = \sigma / \sigma_{SM} = 0.94^{+0.11}_{-0.10}$
    $= 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$

    Total Uncertainty ~10%
    (systematics and statistics at the same level)
  - **Vector boson and Fermions couplings modifiers:**

$$\mu_{\mathrm{ggH,\,t\bar{t}H,b\bar{b}H,tH}} = 0.96^{+0.11}_{-0.12} \text{ and } \mu_{\mathrm{VBF,VH}} = 0.83^{+0.29}_{-0.35}.$$

  - **First measurement of STXS Stage 1.1**
  - **Fiducial (total) cross-section:**
    - In perfect agreement with SM predictions:

$$\sigma_{\text{fid.}} = 2.73^{+0.30}_{-0.29} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})\text{ fb}$$

$$\sigma^{\text{SM}}_{\text{fid.}} = 2.76 \pm 0.14\text{ fb.}$$

  - And **differential cross-section**: pT(H), Y(H), N(jets), pT (leading jet)

- **Harvest of Run II is just starting:**
  - Paper in the pipeline with improved reconstruction and calibrations and reduced systematics
  - + other measurements to come: mass, width, tensor structure

BACK UP SLIDES

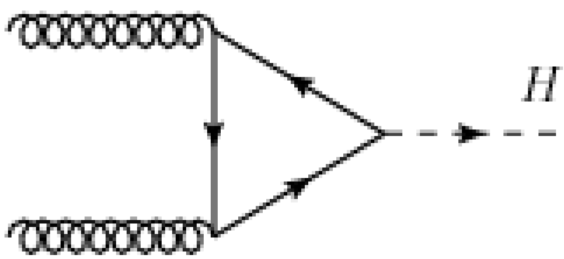
Reminder: Higgs production & decay at colliders

Main production Modes

(for mH=125 GeV, LHCXSWG 4)

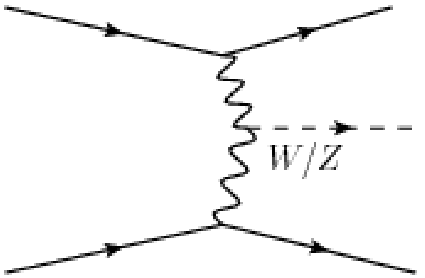
Glusion fusion (ggH)

48.58 pb



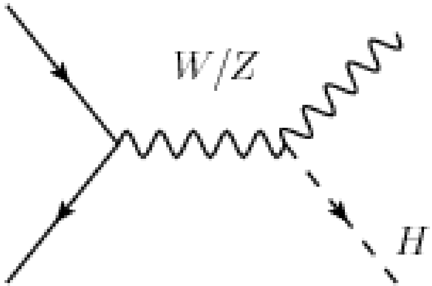
Vector Boson Fusion (VBF)

3.78 pb



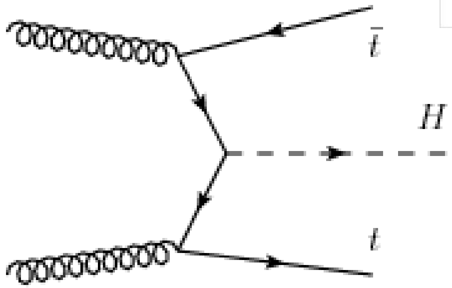
Associated production with Vector Boson (VH)

1.373 pb (WH)
0.8839 pb (ZH)

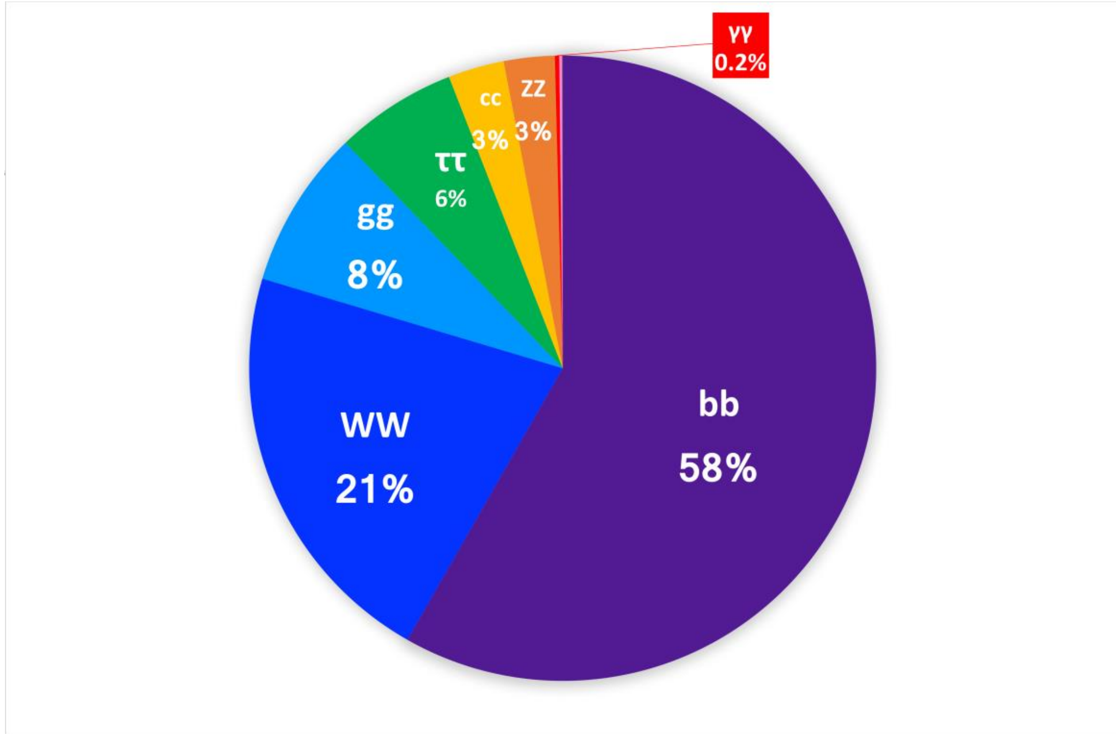


Associated production with quarks (ttH, bbH)

0.5071 pb (ttH)
0.488 pb (bbH)



Main decay Modes



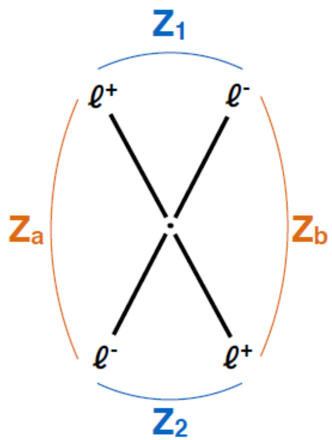
HZZ4l: Selection

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)

FSR RECOVERY

FSR recovery steps

- Per-lepton FSR recovery
- γ preselection: $p_T > 2$ GeV, $|\eta| < 2.4$
- photon relPFIso < 1.8
- Electron SC veto by PF reference
- Associate γ to the closest loose lepton
- $\Delta R(\gamma,l) < 0.5$ and $\Delta R(\gamma,l)/E_{T,\gamma}^2 < 0.012$, choose photon with lowest $\Delta R(\gamma,l)/E_{T,\gamma}^2$
- Remove selected FSRs from lepton isolation cone for all loose leptons

HZZ4l: First Categorization

- **The VBF-2jet-tagged category** requires exactly four leptons. In addition, there must be either two or three jets of which at most one is b tagged, or four or more jets none of which are b-tagged. Finally, $\mathcal{D}_{2jet} > 0.5$ is required.
- **The VH-hadronic-tagged category** requires exactly four leptons. In addition, there must be two or three jets, or four or more jets none of which are b-tagged. $\mathcal{D}_{VH} \equiv \max(\mathcal{D}_{ZH}, \mathcal{D}_{WH}) > 0.5$ is required.
- **The VH-leptonic-tagged category** requires no more than three jets and no b-tagged jets in the event, and exactly one additional lepton or one additional pair of OS, same-flavor leptons. This category also includes events with no jets and at least one additional lepton.
- **The $t\bar{t}$H-hadronic-tagged category** requires at least four jets of which at least one is b tagged and zero additional leptons.
- **The $t\bar{t}$H-leptonic-tagged category** requires at least one additional lepton.
- **The VBF-1jet-tagged category** requires exactly four leptons, exactly one jet and $\mathcal{D}_{1jet} > 0.5$.
- **Untagged category** consists of the remaining selected events.

Expected and Observed number of events (118<m4l<130 GeV)

Event category	ggH	VBF	WH	ZH	ttH	bbH	tqH	Total signal	$q\bar{q} \to ZZ$	$gg \to ZZ$	Z + X	Total expected	Observed
	Signal								Background				
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

Signal Purity

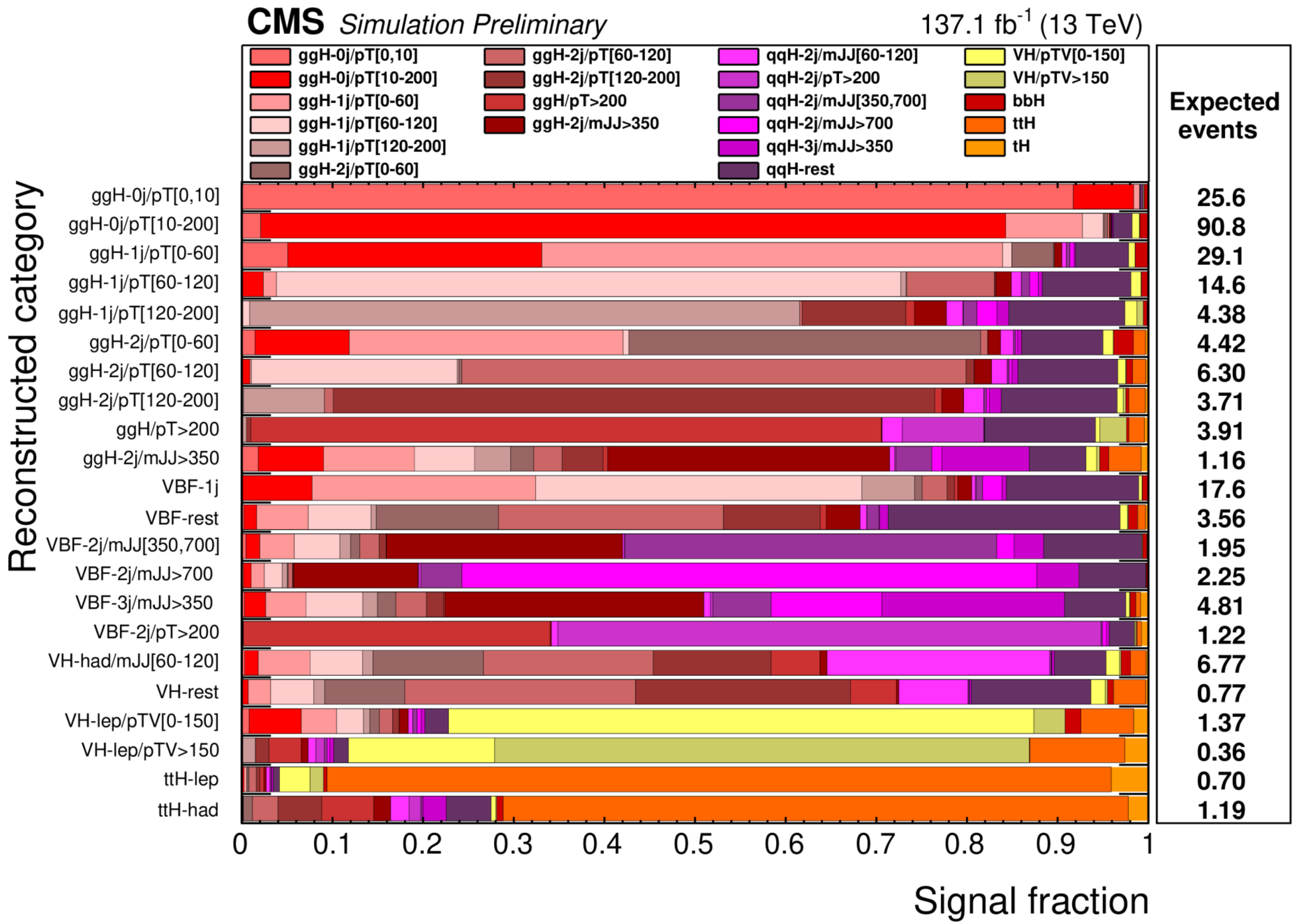


Figure 5: Signal relative purity of the 22 event sub-categories in terms of the STXS Stage 1.1 Bins in a $118 < m_{4\ell} < 130\,\mathrm{GeV}$ mass window.

Fiducial phase space & Acceptance

Requirements for the $\mathrm{H} \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_\mathrm{T} > 20$ GeV
Next-to-leading lepton p_T	$p_\mathrm{T} > 10$ GeV
Additional electrons (muons) p_T	$p_\mathrm{T} > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_\mathrm{T}$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\mathrm{GeV} < m_{\mathrm{Z}_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12\,\mathrm{GeV} < m_{\mathrm{Z}_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105\,\mathrm{GeV} < m_{4\ell} < 140\,\mathrm{GeV}$

Signal process	$\mathcal{A}_\mathrm{fid}$	ϵ	f_nonfid	$(1 + f_\mathrm{nonfid})\epsilon$
Individual Higgs boson production modes				
gg→H (POWHEG)	0.402 ± 0.001	0.592 ± 0.002	0.053 ± 0.001	0.624 ± 0.002
VBF (POWHEG)	0.444 ± 0.002	0.605 ± 0.003	0.043 ± 0.001	0.631 ± 0.003
WH (POWHEG+MINLO)	0.325 ± 0.002	0.588 ± 0.003	0.075 ± 0.002	0.632 ± 0.004
ZH (POWHEG+MINLO)	0.340 ± 0.003	0.594 ± 0.005	0.081 ± 0.004	0.643 ± 0.006
ttH (POWHEG)	0.314 ± 0.003	0.585 ± 0.006	0.169 ± 0.006	0.684 ± 0.007

9 Systematic uncertainties

The experimental uncertainties common to all final states include the uncertainty in the integrated luminosity (from 2.3% to 2.5%, depending on the year of data taking) and the uncertainty in the lepton identification and reconstruction efficiency (ranging from 2.5 to 16.1% on the overall event yield for the 4μ and $4e$ channels, respectively), which affect both signal and background. Experimental uncertainties in the reducible background estimation, described

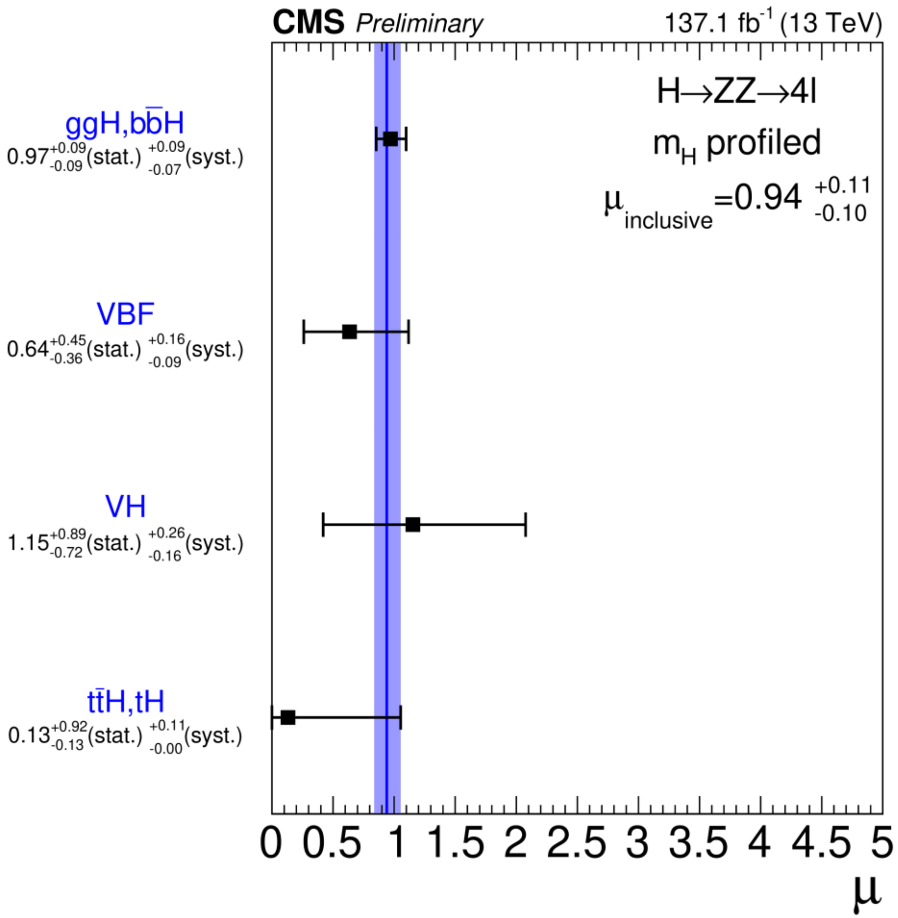
The ggH cross section uncertainty scheme has been updated to the one proposed in Ref. [24]. This uncertainty scheme includes 9 nuisance parameters accounting for uncertainties in the cross section prediction for exclusive jet bins (including the migration between the 0 and 1-jet, as well as between the 1 and $\geq$2-jet bins), the 2 jet and $\geq$3 jet VBF phase spaces, different $p_T(H)$ regions, and the uncertainty in the $p_T(H)$ distribution due to missing higher order finite top quark mass corrections.

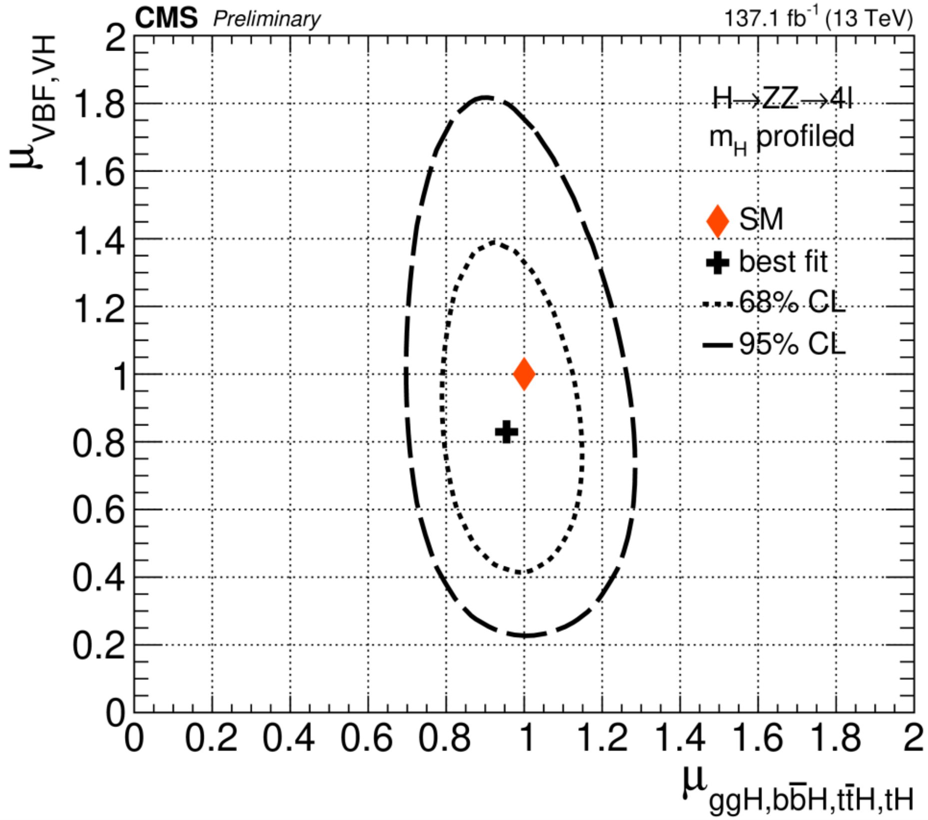
All experimental and theoretical uncertainties which account for possible migration of signal and background events between categories are included. The main theoretical sources of uncertainty on the event categorization include the renormalization and the factorization scales, the choice of the PDF set, and the modeling of hadronization and the underlying event. For example, uncertainty on the renormalization and factorization scale for dominant ggH production mode ranges from 0.1 to 6% and for VBF production mode from 0.1 to 12% depending on the event category. The modeling of hadronization and the underlying event ranges from 1 to 50% in event categories with 2 jets, from 1 to 20% in event categories with 1 jet, and from 1 to 15% in event categories with no jets.

The main experimental sources of category migration come from the imprecise knowledge of the jet energy scale and resolution, b-tagging efficiency, and light quarks (u, d, s, c) and gluon jet mistag rate. For example, uncertainty on the jet energy scale ranges from 2 to 50% for VBF production mode in event categories with jets and the uncertainty on b-tagging efficiency ranges from 1 to 2% for $t\bar{t}H$ production and 1 to 10% for ggH production in the $t\bar{t}H$-hadronic-tagged category.

In the combination of the three data taking periods, the theoretical uncertainties as well as the experimental ones related to leptons or jets are treated as correlated while all other ones from experimental sources are taken as uncorrelated.

Signal Strength





$\mu_{\mathrm{ggH,t\bar{t}H,b\bar{b}H,tH}} = 0.96^{+0.11}_{-0.12}$ and $\mu_{\mathrm{VBF,VH}} = 0.83^{+0.29}_{-0.35}$.

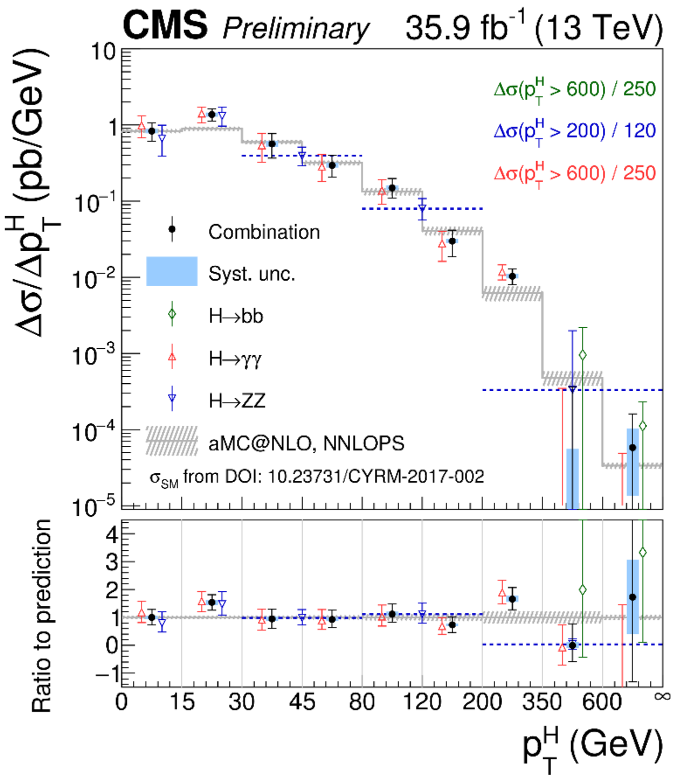
	Expected	Observed
$\mu_{\mathrm{inclusive}}$	$1.00^{+0.08}_{-0.08}(\mathrm{stat.})^{+0.09}_{-0.07}(\mathrm{syst.})$	$0.94^{+0.07}_{-0.07}(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{syst.})$
μ_{ggH}	$1.00^{+0.10}_{-0.10}(\mathrm{stat.})^{+0.09}_{-0.07}(\mathrm{syst.})$	$0.97^{+0.09}_{-0.09}(\mathrm{stat.})^{+0.09}_{-0.07}(\mathrm{syst.})$
μ_{VBF}	$1.00^{+0.54}_{-0.45}(\mathrm{stat.})^{+0.27}_{-0.14}(\mathrm{syst.})$	$0.64^{+0.45}_{-0.36}(\mathrm{stat.})^{+0.16}_{-0.09}(\mathrm{syst.})$
μ_{VH}	$1.00^{+0.91}_{-0.72}(\mathrm{stat.})^{+0.29}_{-0.16}(\mathrm{syst.})$	$1.15^{+0.89}_{-0.72}(\mathrm{stat.})^{+0.26}_{-0.16}(\mathrm{syst.})$
$\mu_{\mathrm{t\bar{t}H,tH}}$	$1.00^{+1.16}_{-0.73}(\mathrm{stat.})^{+0.19}_{-0.04}(\mathrm{syst.})$	$0.13^{+0.92}_{-0.13}(\mathrm{stat.})^{+0.11}_{-0.00}(\mathrm{syst.})$

Differential cross-sections (1/2)

- Increasing luminosity of Run II now **allows precision measurement on differential cross-section**.
  - Combination of H→γγ and H→ZZ measurements (also boosted H→bb for high pT)

pT(H)

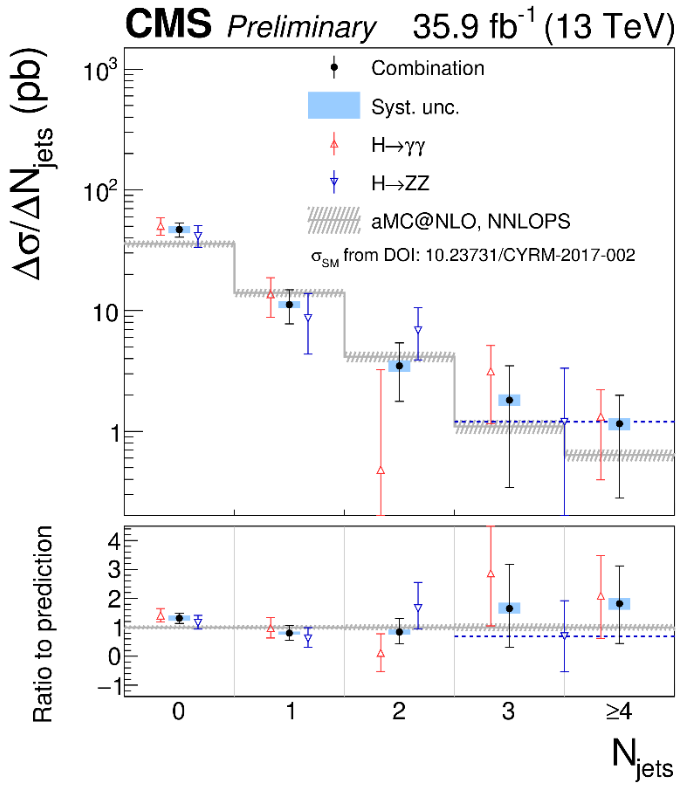
Sensitive to perturbative QCD modelling, production mode, yukawa couplings,…



30-40% precision up to 350 GeV

N(jets)

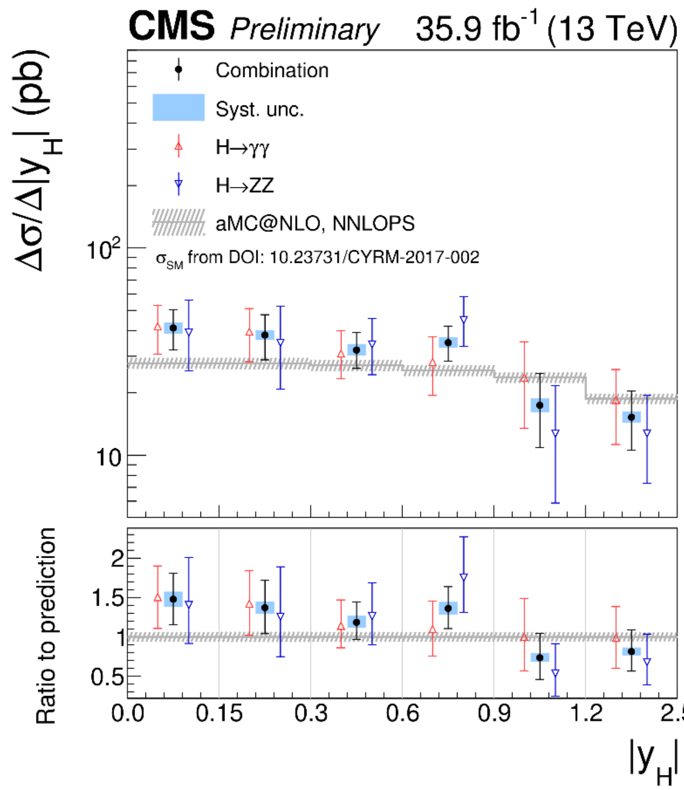
Test of modelling QCD radiation, production mechanism



20% precision in 0-jet bin

Y(H)

Probes of PDFs, production mode,…



30-50% precision across the spectrum

CMS-PAS-HIG-17-028

2016 (~36 fb-1)

Measurement largely dominated by statistics ! Great improvements to come

HIG-18-001

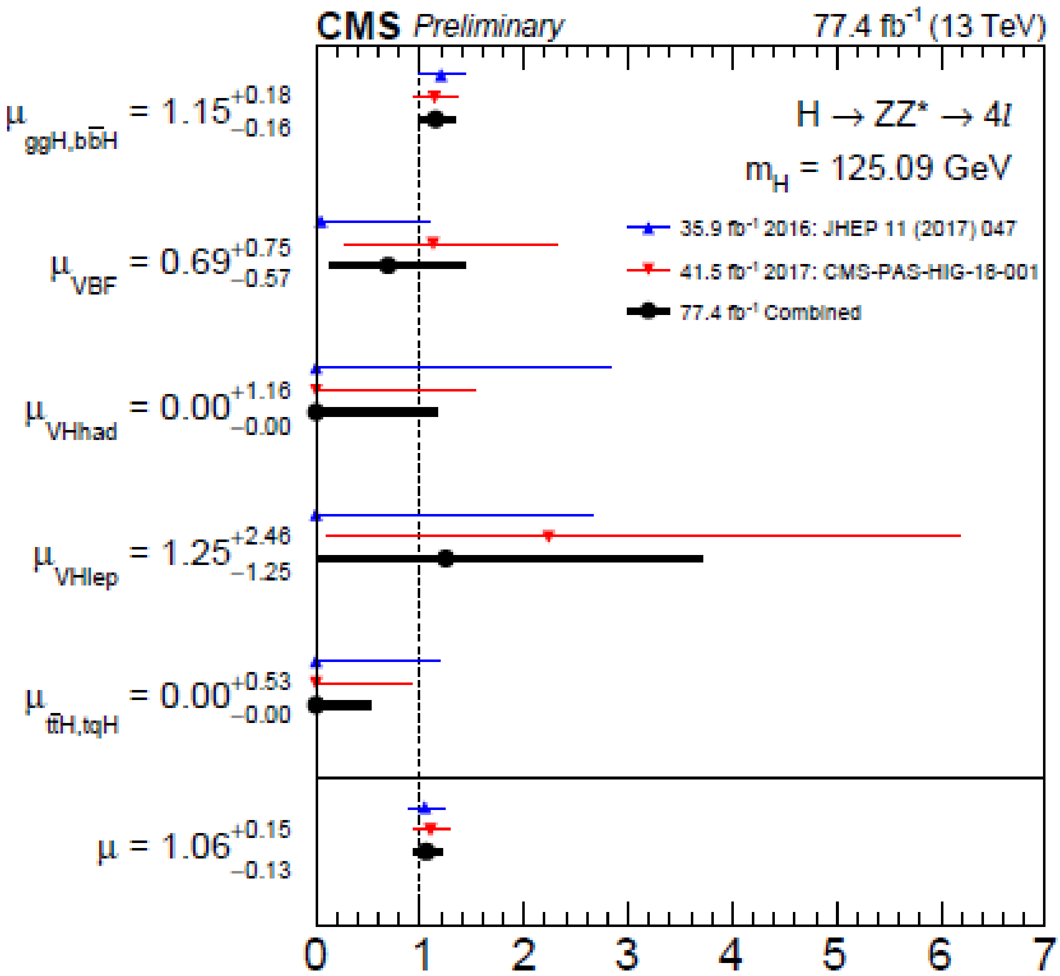
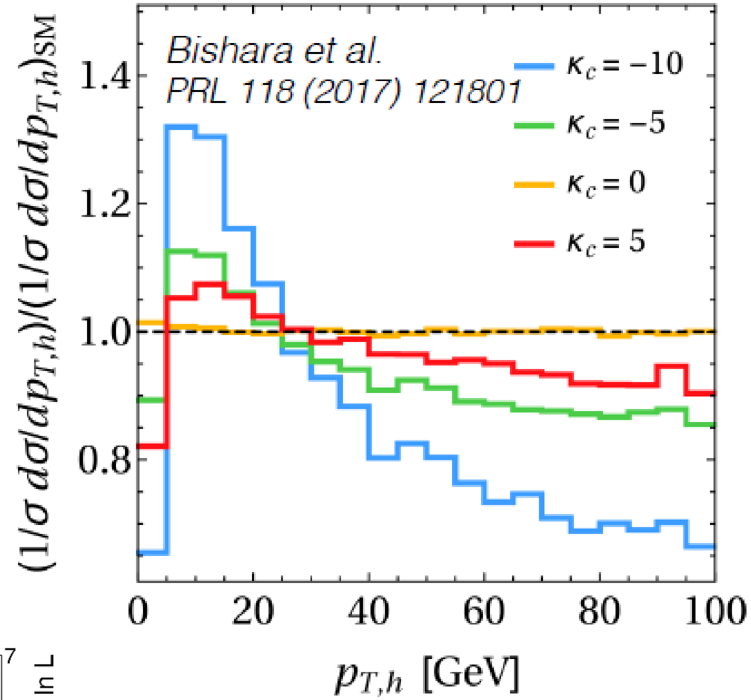


Table 4: Expected and observed signal-strength modifiers for combined 2016 and 2017 data.

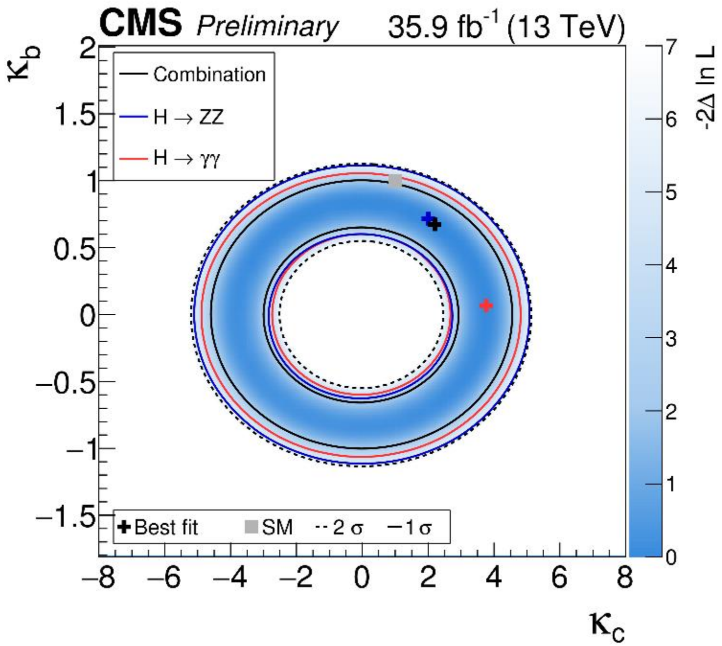
	Inclusive	$\mu_{ggH,b\bar{b}H}$	μ_{VBF}	μ_{VHhad}	μ_{VHlep}	$\mu_{t\bar{t}H,tqH}$
Expected	$1.00 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$	$1.00^{+0.17}_{-0.16}$	$1.00^{+0.86}_{-0.67}$	$1.00^{+2.39}_{-1.00}$	$1.00^{+2.30}_{-1.00}$	$1.00^{+1.80}_{-1.00}$
Observed	$1.06 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$	$1.15^{+0.18}_{-0.16}$	$0.69^{+0.75}_{-0.57}$	$0.00^{+1.16}_{-0.00}$	$1.25^{+2.46}_{-1.25}$	$0.00^{+0.53}_{-0.00}$

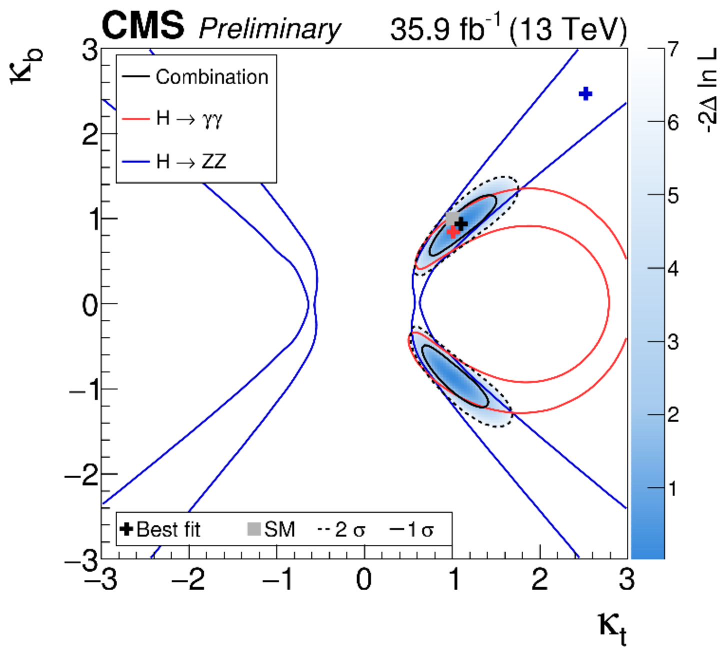
Differential cross-sections (2/2)



- Higgs pT spectrum very sensitive to modifications of the couplings
  - Can give information on couplings not possible via inclusive measurements

- Couplings to b, c & top quarks in k-framework





Results are dependant on the assumptions about Branching Ratios (here, assume BR scaling with couplings)

$$-0.9 < k_b < 0.9 \quad (-1.2 < k_b < 1.2 \text{ expected})$$

$$-4.3 < k_c < 4.3 \quad (-5.4 < k_c < 5.3 \text{ expected})$$

Higgs width & anomalous couplings (1)

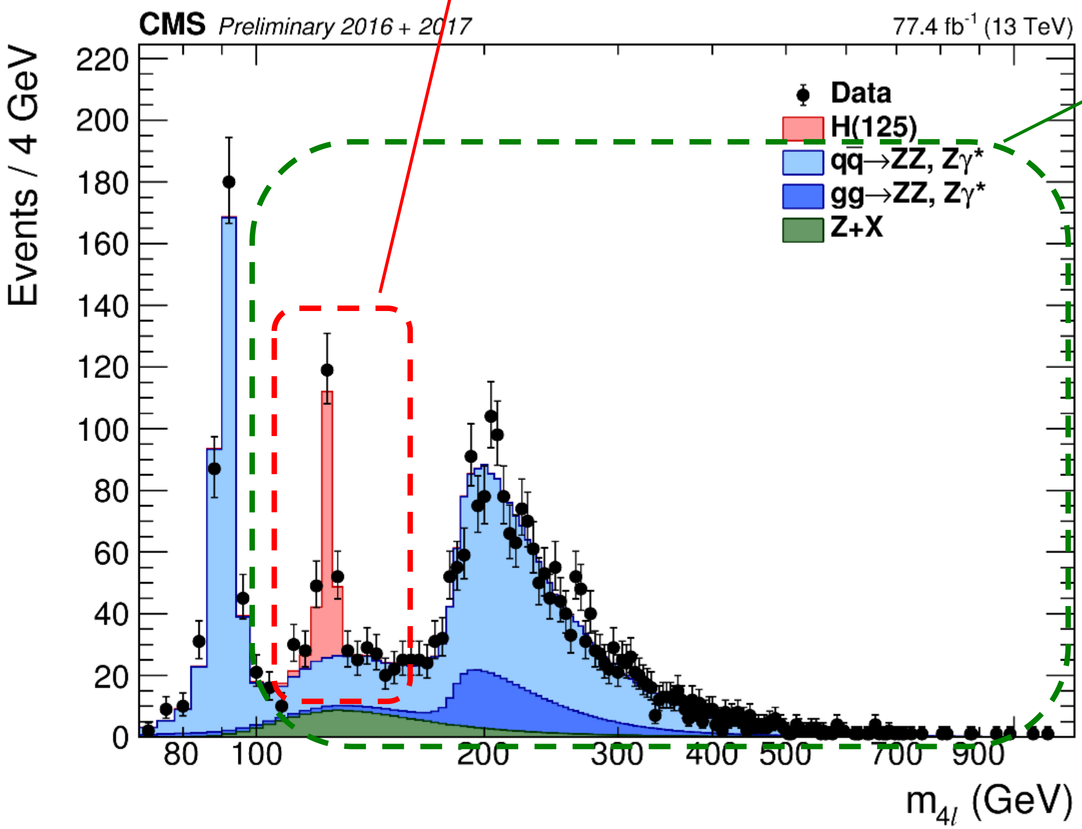
Higgs boson width (4.1 MeV @ 125 GeV) not directly measureable due to limitations from detector resolution (~1 GeV)

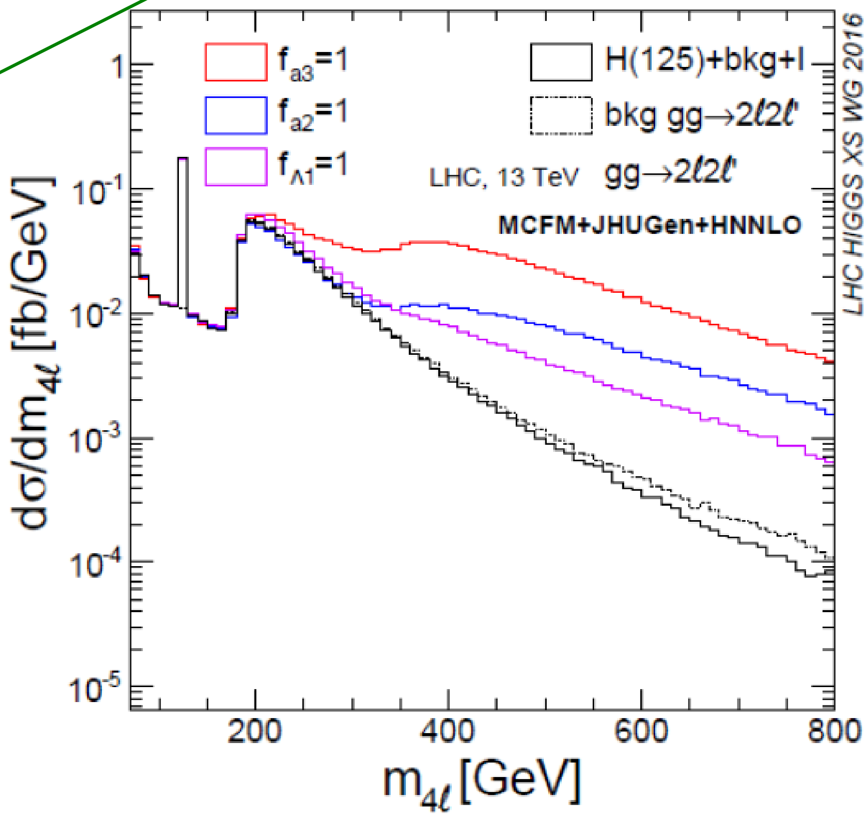
- Can be probed by analysing **on-shell & off-shell distributions**:

HOT OFF THE PRESS

On-shell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{m_H^2 \Gamma_H^2} dq_H^2 \propto \mu_{prod}$

Off-shell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2} dq_H^2 \propto \mu_{prod} \cdot \Gamma_H$





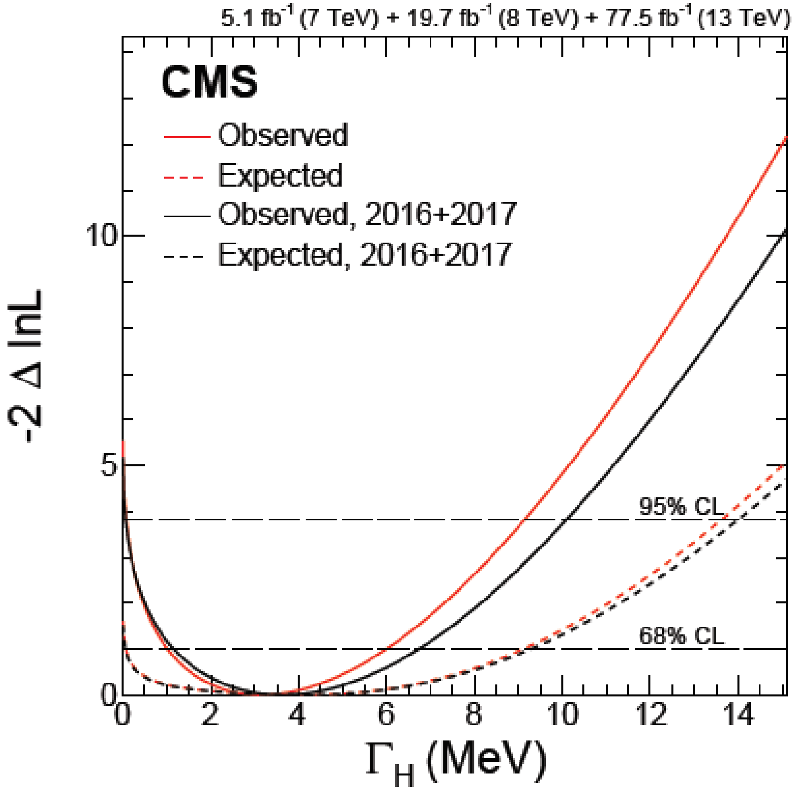
CMS-PAS-HIG-18-002

Anomalous couplings enhance off-shell yield, change m4l & other kinematics

Higgs width & anomalous couplings (2)

HOT OFF THE PRESS

CMS-PAS-HIG-18-002



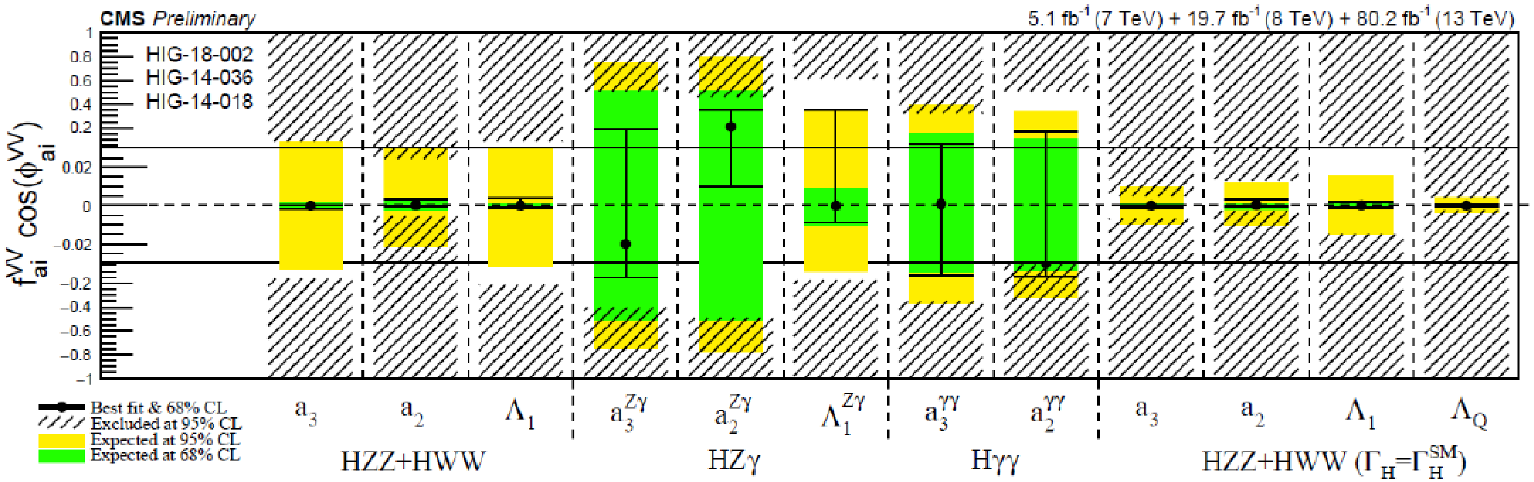
RunI + Run II combination

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ $[0.08, 9.16]$	$4.1^{+5.0}_{-4.0}$ $[0.0, 13.7]$

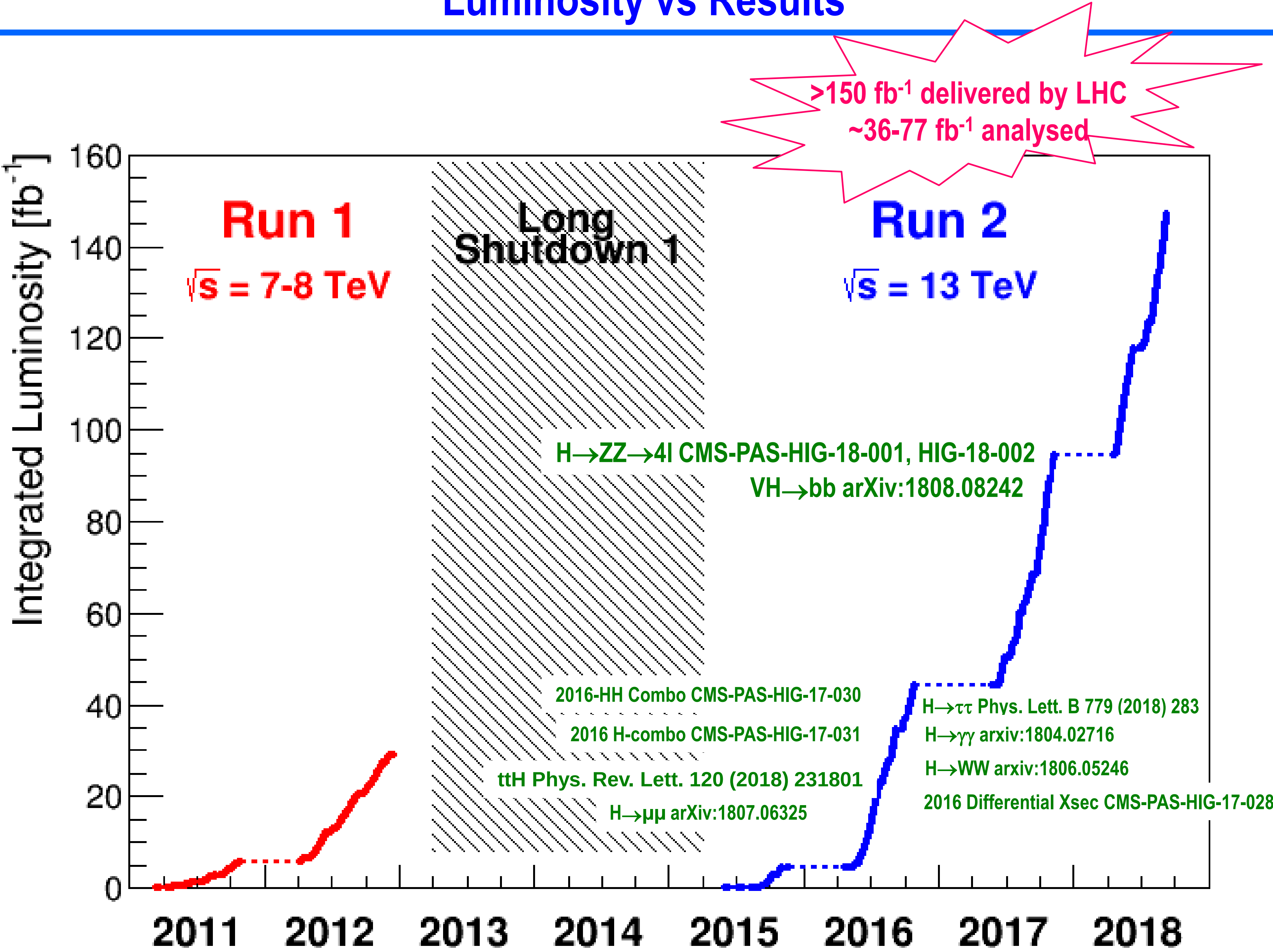
Best LHC result

$$A(HVV) \sim \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{q_H^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}^{VV'}} \frac{(\kappa_1 q_{V1}^2 + \kappa_2 q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \qquad \phi_{ai} = \tan^{-1}(a_i/a_1)$$



Luminosity vs Results



CMS analysis: HVV couplings

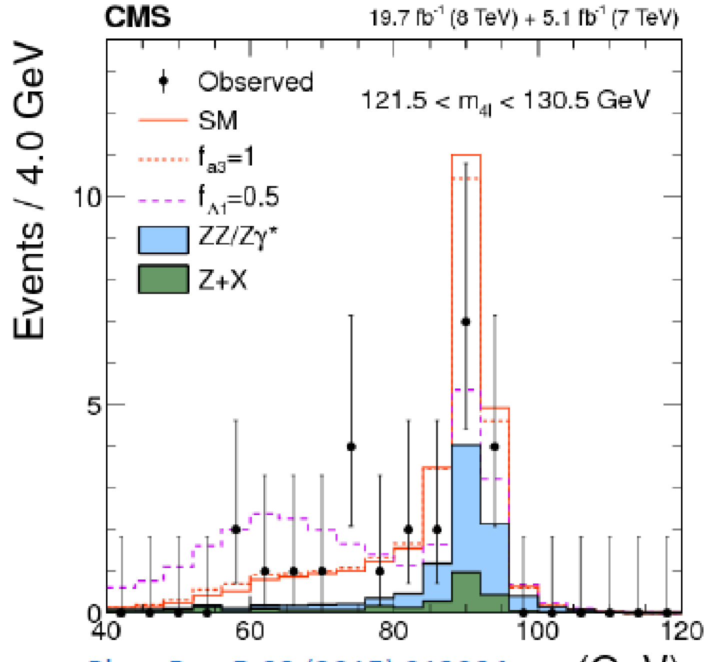
$$A(HVV) \sim \left[\boldsymbol{a_1} - e^{i\phi_{\Lambda Q}} \frac{q_H^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}^{VV'}} \frac{(\kappa_1 q_{V1}^2 + \kappa_2 q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$
$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

→ Any anomalous coupling can be described with an effective on-shell cross sectional fraction and a phase defined for $2f2f'$ decay:

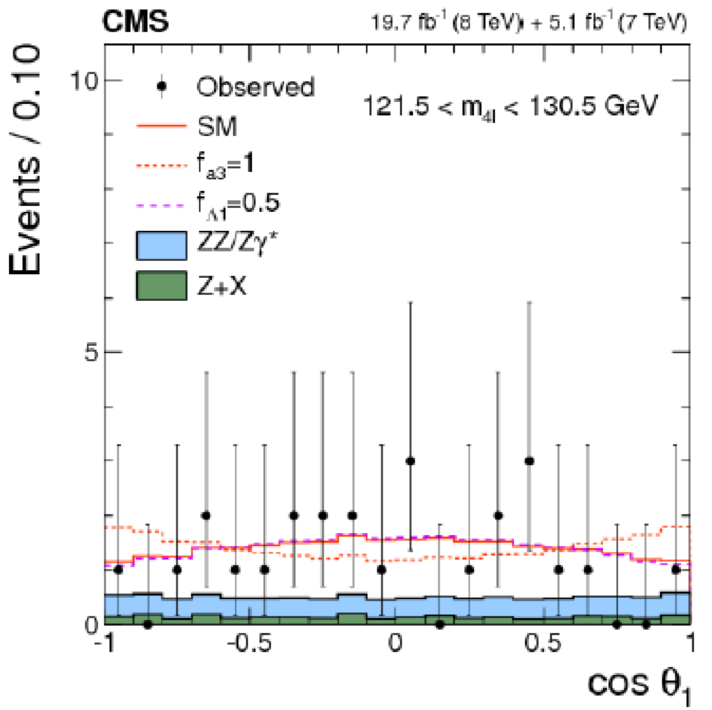
$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \qquad \phi_{ai} = \tan^{-1}(a_i/a_1)$$

→ $f_{\Lambda Q}$ observable only from off-shell. Others can be measured from either on-shell or off-shell.

→ Formalisms used by ATLAS are equivalent with different ways of parameterizing AC couplings



Phys. Rev. D 92 (2015) 012004



CMS results: $f_{ai}\cos(\phi_{ai})$

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$-0.0001^{+0.0005}_{-0.0015}$ $[-0.16, 0.09]$	$0.0000^{+0.0019}_{-0.0019}$ $[-0.082, 0.082]$
$f_{a2}\cos(\phi_{a2})$	$0.0004^{+0.0026}_{-0.0007}$ $[-0.006, 0.025]$	$0.0000^{+0.0030}_{-0.0023}$ $[-0.021, 0.035]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.0000^{+0.0035}_{-0.0008}$ $[-0.21, 0.09]$	$0.0000^{+0.0012}_{-0.0006}$ $[-0.059, 0.032]$
$f_{\Lambda1}^{Z\gamma}\cos\left(\phi_{\Lambda1}^{Z\gamma}\right)$	$0.000^{+0.355}_{-0.009}$ $[-0.17, 0.61]$	$0.000^{+0.009}_{-0.010}$ $[-0.10, 0.34]$

On-shell results

On-shell + off-shell combination

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.0000^{+0.0005}_{-0.0011}$ $[-0.0067, 0.0050]$	$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$
$f_{a2}\cos(\phi_{a2})$	$0.0005^{+0.0025}_{-0.0008}$ $[-0.0029, 0.0129]$	$0.0000^{+0.0011}_{-0.0017}$ $[-0.0100, 0.0117]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.0001^{+0.0020}_{-0.0010}$ $[-0.0150, 0.0501]$	$0.0000^{+0.0010}_{-0.0010}$ $[-0.0152, 0.0158]$

Different HVV couplings

Parameter	Unconstrained Parameter	Observed	Expected
Γ_H (MeV)	$f_{a3}\cos(\phi_{a3})$	$2.4^{+2.7}_{-1.8}$ $[0.02, 8.38]$	$4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$
Γ_H (MeV)	$f_{a2}\cos(\phi_{a2})$	$2.5^{+2.9}_{-1.8}$ $[0.02, 8.76]$	$4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$
Γ_H (MeV)	$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$2.4^{+2.5}_{-1.6}$ $[0.06, 7.84]$	$4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$

Measurements

Cross-sections

Signal strengths

Inclusive

- Used for discovery
- Now limited by systematics

Per process

- Mostly stat-limited
- Also use Simplified Template Cross-Section (STXS) framework

Couplings

- usually κ framework

Differential

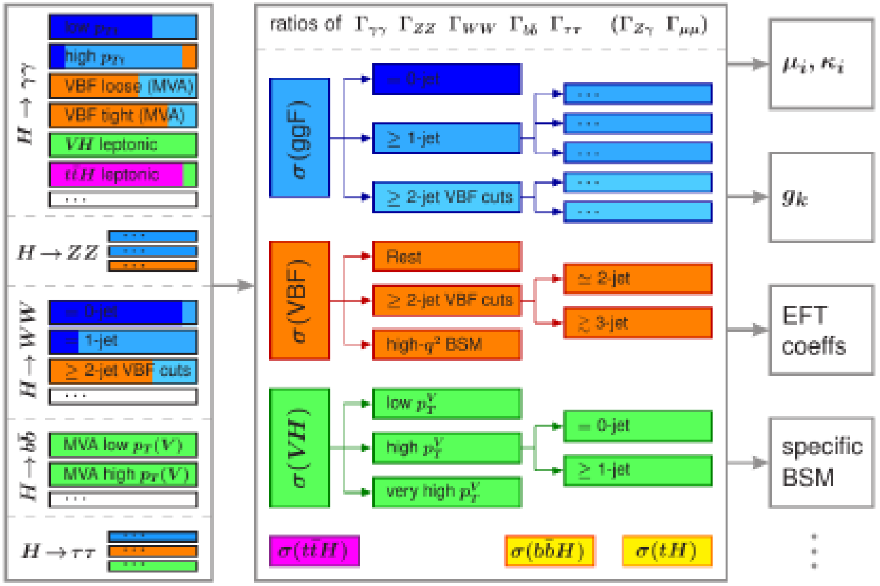
- Shape information; strongly stat-limited

Mass

- Only $\gamma\gamma$ and ZZ contribute
- Requires excellent understanding of systematic uncertainties

Simplified Template Cross-Sections

YR4 Section III.2



Similarities to fiducial cross-sections:

- measure cross-sections in **truth-level phase space regions**.
- Separate out regions to :
  - **Maximize sensitivity to SM or BSM effects**
  - **Minimize sensitivity to theory uncert., models**

Points of Difference:

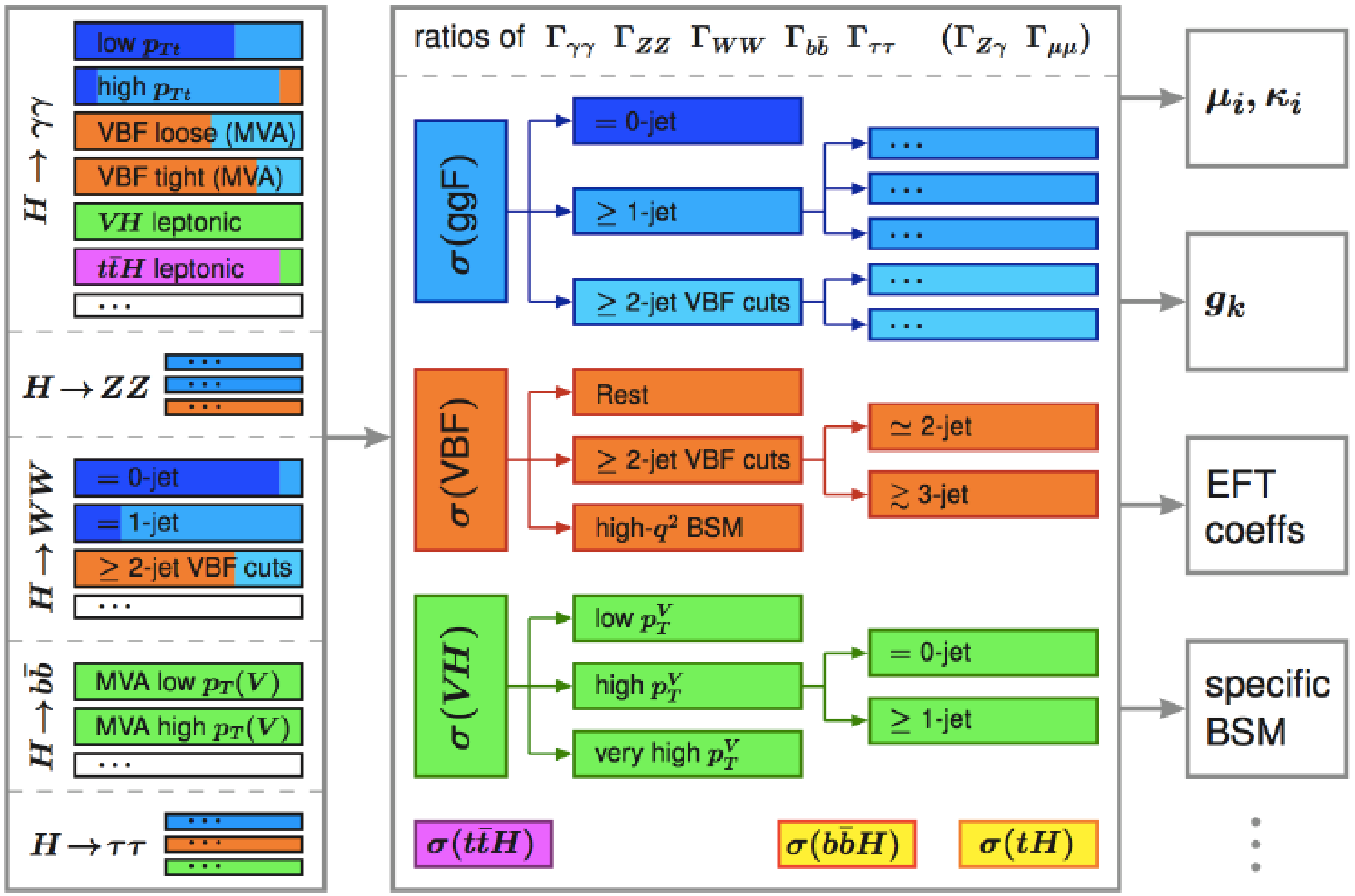
- Split production modes/final states
- Partitions the **entire phase space** into **non-overlapping regions**
- **No strong matching between truth and reco-level selections**: compromise between
  - "complicated" reco selections (BDTs, etc.)
  - simple and well-defined theory selections

⇒ **Point of contact between theory and experiment**

Complementary to diff. measurements: fully exclusive split along many variables

- **No need for statistical correlations**
- **Coarser binning**

Simplified Template Cross-Section



- Results can then be re-interpreted with new theories
- Kinematic regions isolate BSM effects
- And provide coherent framework for combination of channels & experiments

- **Simplified Template Cross-section (STXS)** framework aims to minimise measurements' dependence on theory

Fiducial & Simplified template cross-section

Fiducial and Simplified template cross-section

Fiducial cross-section

- Optimized for maximal theoretical independence
- Fiducial in Higgs decay
- Smallest acceptance corrections
- Simple signal cuts
- “Exact” fiducial volume
- Targeted object definitions
- Agnostic to production mode

Can be done with single and differential distributions

Only feasible in HZZ,H$\gamma\gamma$,HWW

Combination not straightforward

Simplified templates cross section

- Target maximum sensitivity, while keeping theoretical dependence as small as possible
- Cross section split by production mode
- Cross section divided in **exclusive** regions of phase space (bins)
- Larger acceptance corrections
- Abstracted fiducial volumes
- Inclusive in Higgs decay
- Allows complex event selections, categorisation

Common abstracted object definitions

Can be done in all decay modes

Explicitly designed for combination

Tools for discovery and measurements (2)

➢ Signal Extraction via Matrix Element Methods (MEM):

- Event-by-event discriminator built upon Matrix Elements. Combined with reco level info.

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

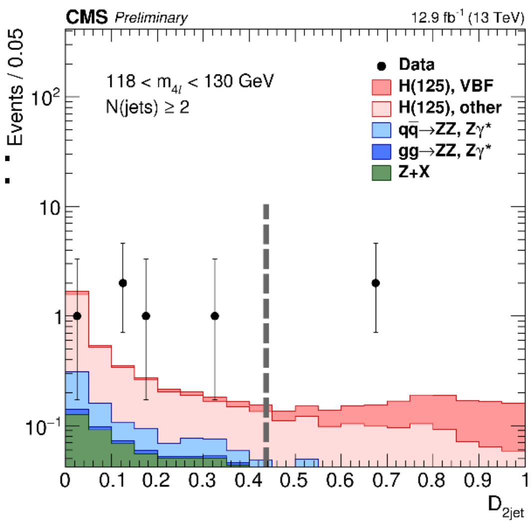
Phase Space ($d\Phi_\alpha$) — Momentum conservation (δ^4) — PDF's — LO ME from Madgraph5_aMC@NLO — Transfer Function (relates parton and reco quantities)

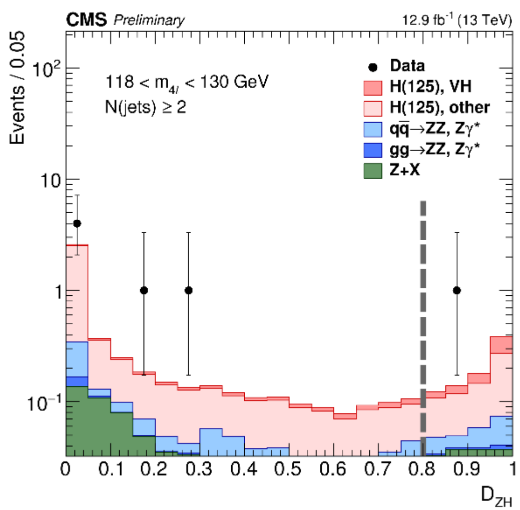
- **MEM weights** used in ttH→multileptons (**see later**) as input to BDT.

- **Matrix Element Likelihood Analysis** (H→ZZ→4l):
  - Simplified MEM. No integration, no transfer function

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

  - ME from JHUGen or MCFM
  - Several discriminants (**see later**) built to separate:
    - ❖ gg vs qq→4 leptons
    - ❖ ggH vs VBF or VH or ttH
    - ❖ Different J^{PC} hypothesis, …





Signal strengths

Signal strengths, μ

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}.$$

Scaling of generic i → H → f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

Most immediate quantity: ratio of observed “rate” with respect to the expected results

Production: ratio of cross-sections

Decay: ratio of branching fractions

Many systematic uncertainties and theory assumptions cancel out in the ratio

- Easy to interpret
- Deviation from SM immediately visible
- Can decouple production and decay mechanisms
- Only effects modifying the absolute normalisation are visible, no sensitivity to shapes

No immediate relation with the width, each signal strength is independent from each other, but possible reinterpretation in the k-framework