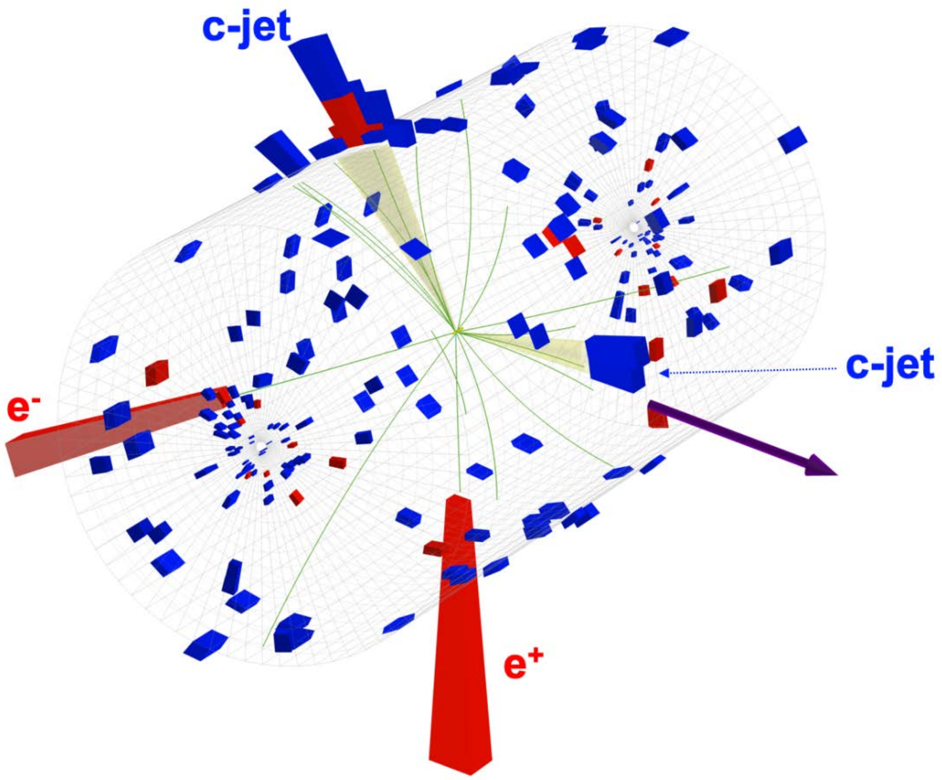
CMS results on Higgs boson properties



Rainer Mankel (DESY)

for the CMS Collaboration

ICNFP 2019 Conference

21-29 August 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

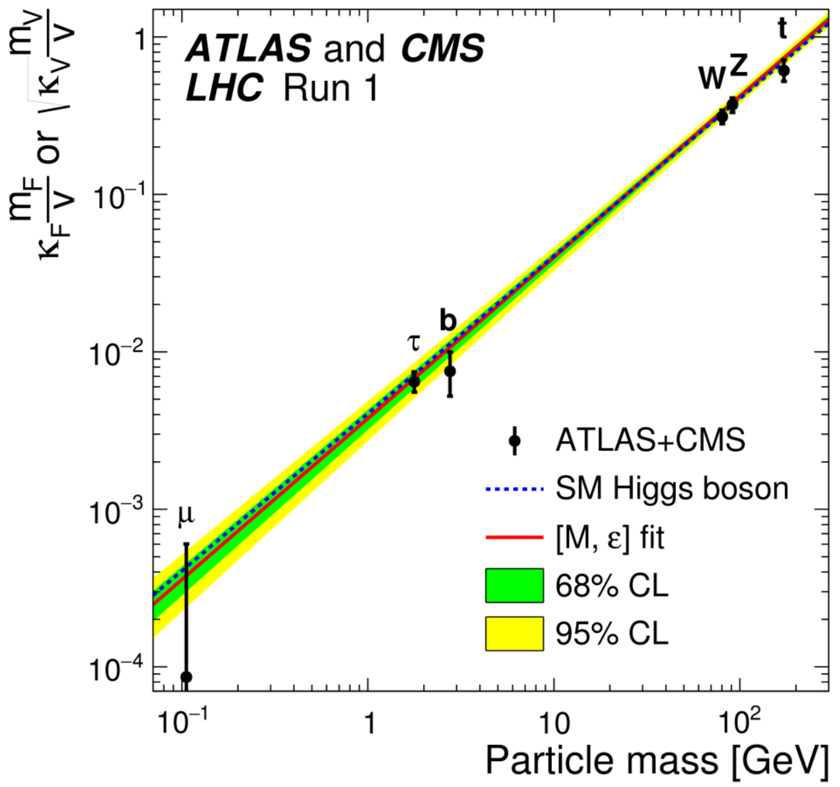
DESY.

Outline

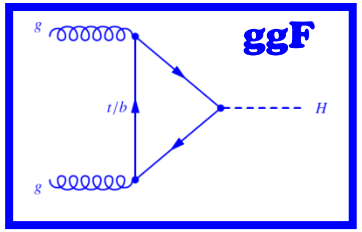
- Introduction
- Bosonic couplings: $H \to 4\ell$, $H \to \gamma\gamma$
- Fermionic couplings: $H \to \tau\tau$, $ttH(\to b\bar{b})$, $H \to c\bar{c}$
- Couplings summary
- HH production and tri-linear Higgs coupling
- Summary

Higgs boson: discovery and exploration

- 2012: Observation of the Higgs boson by ATLAS and CMS
  - initially in di-boson decay modes
- 2016: Run 1 couplings combination (ATLAS+CMS)
  - ➔ properties found to be SM-like within current precision
- 2017-18: Discovery of 3rd generation Yukawa couplings
  - via $H \to \tau\bar{\tau}$ and $H \to b\bar{b}$ decays, ttH production
- Now: precision measurements with full Run 2 data



Higgs boson production and decay



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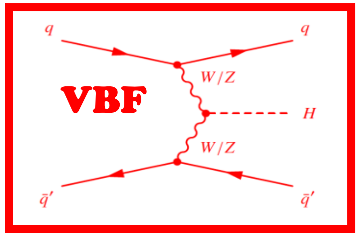

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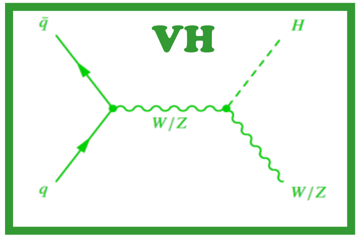

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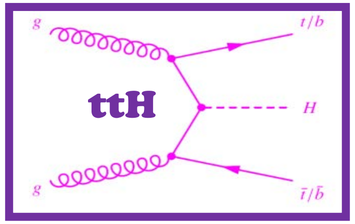

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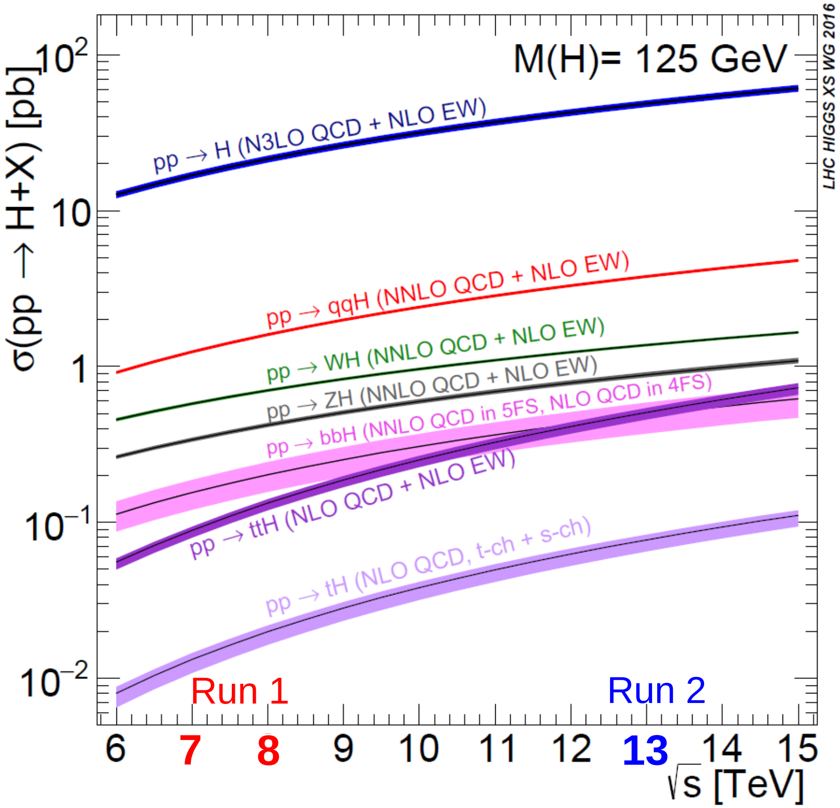
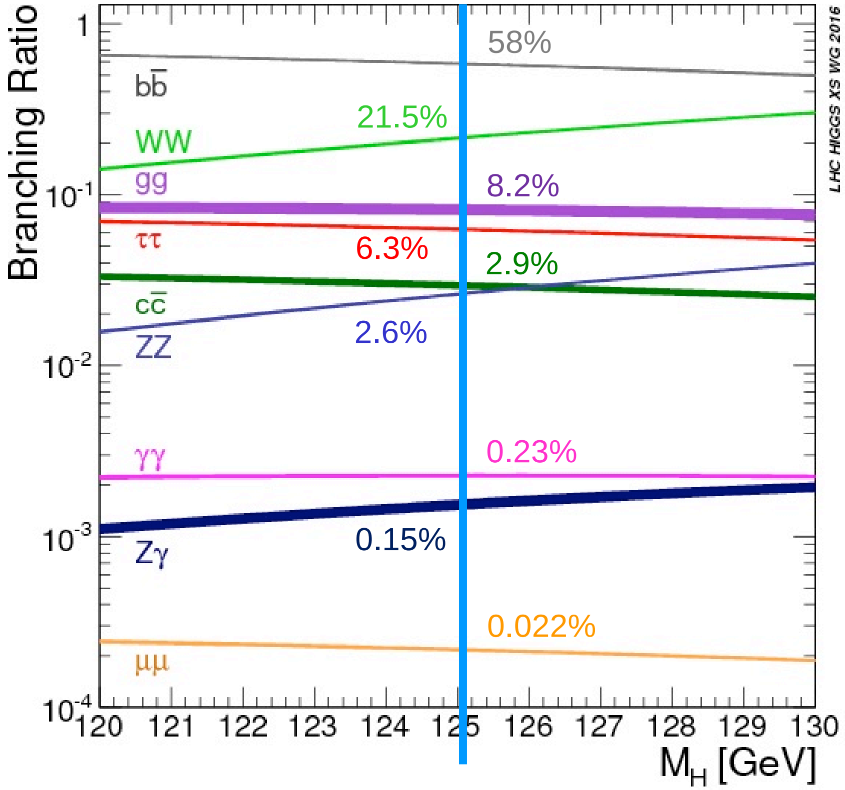




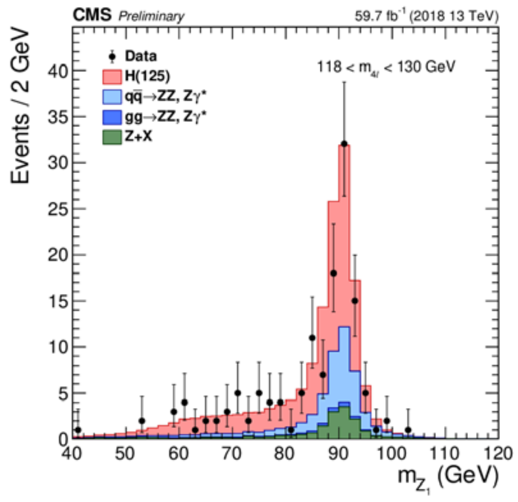
$125.09 \pm 0.24\ GeV$ **(Run 1)**

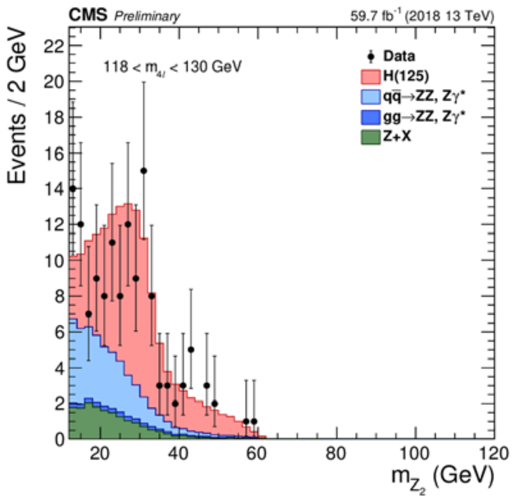
$H \to 4\ell$

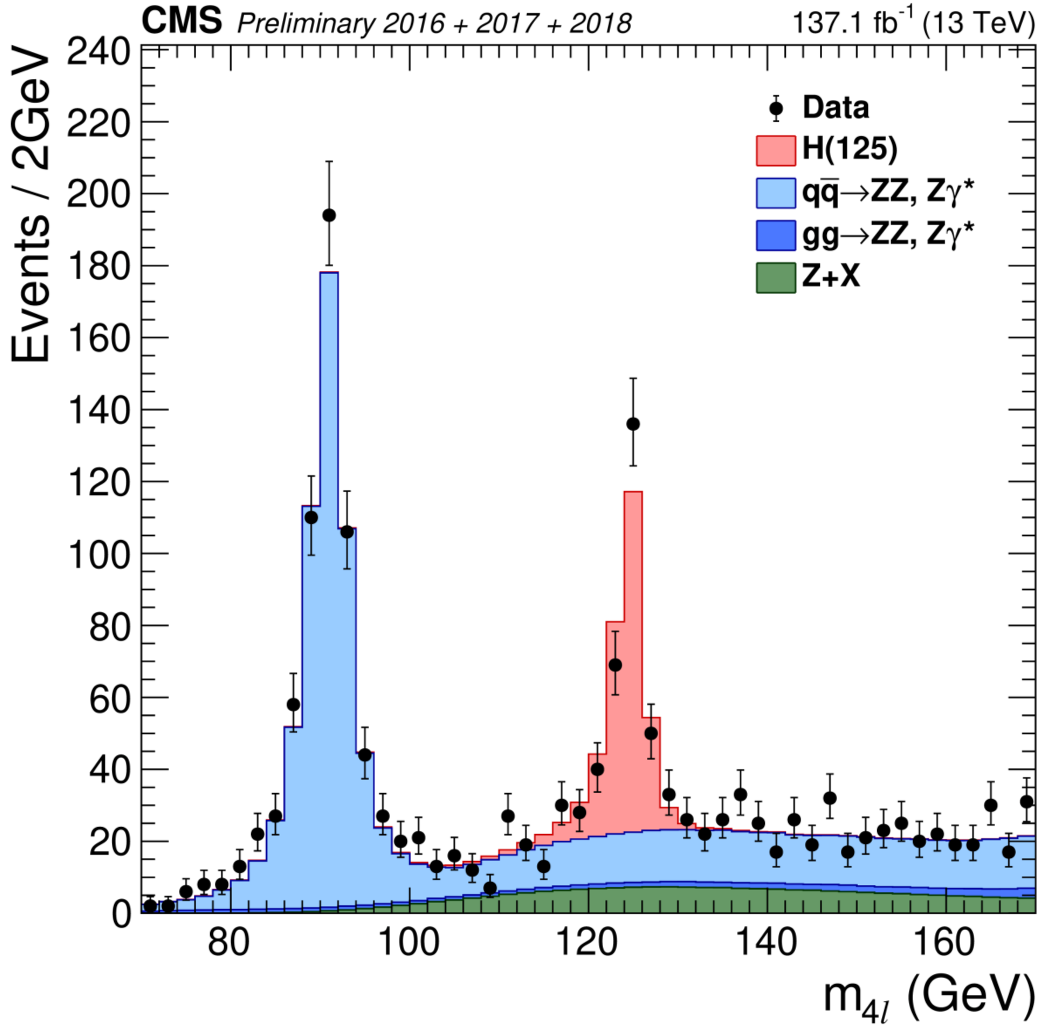
$H \to 4\ell$ in full Run 2

CMS PAS HIG-19-001

- Excellent mass resolution, low background
- Selection according to kinematic discriminants
  - ➔ distinction between production processes
- $Z \to 4\ell$ signal serves as standard candle
  - ➔ control momentum scale and resolution
- In most cases, one Z boson is on-shell







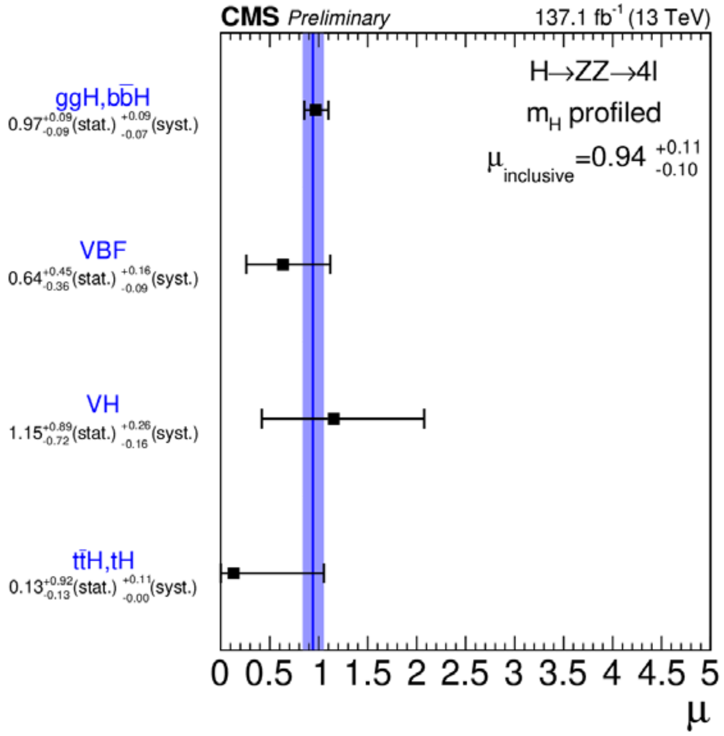
$H \to 4\ell$ vs production process

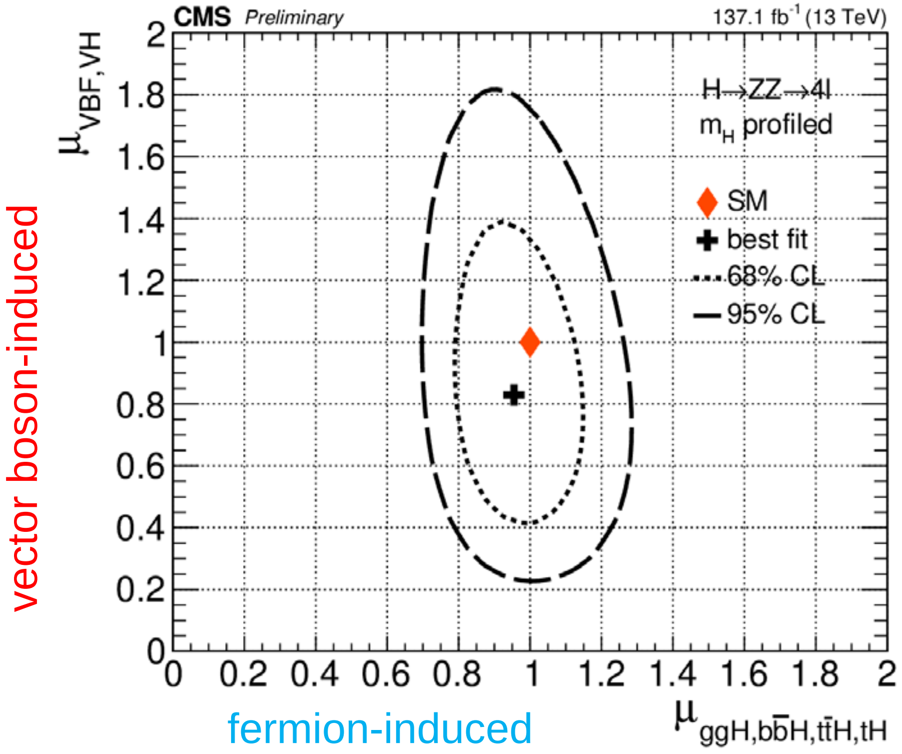
- Extract signal strength by unbinned fit of 2D likelihood function

$$\mathcal{L}_{2D}(m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$$

➔ Good agreement with SM prediction

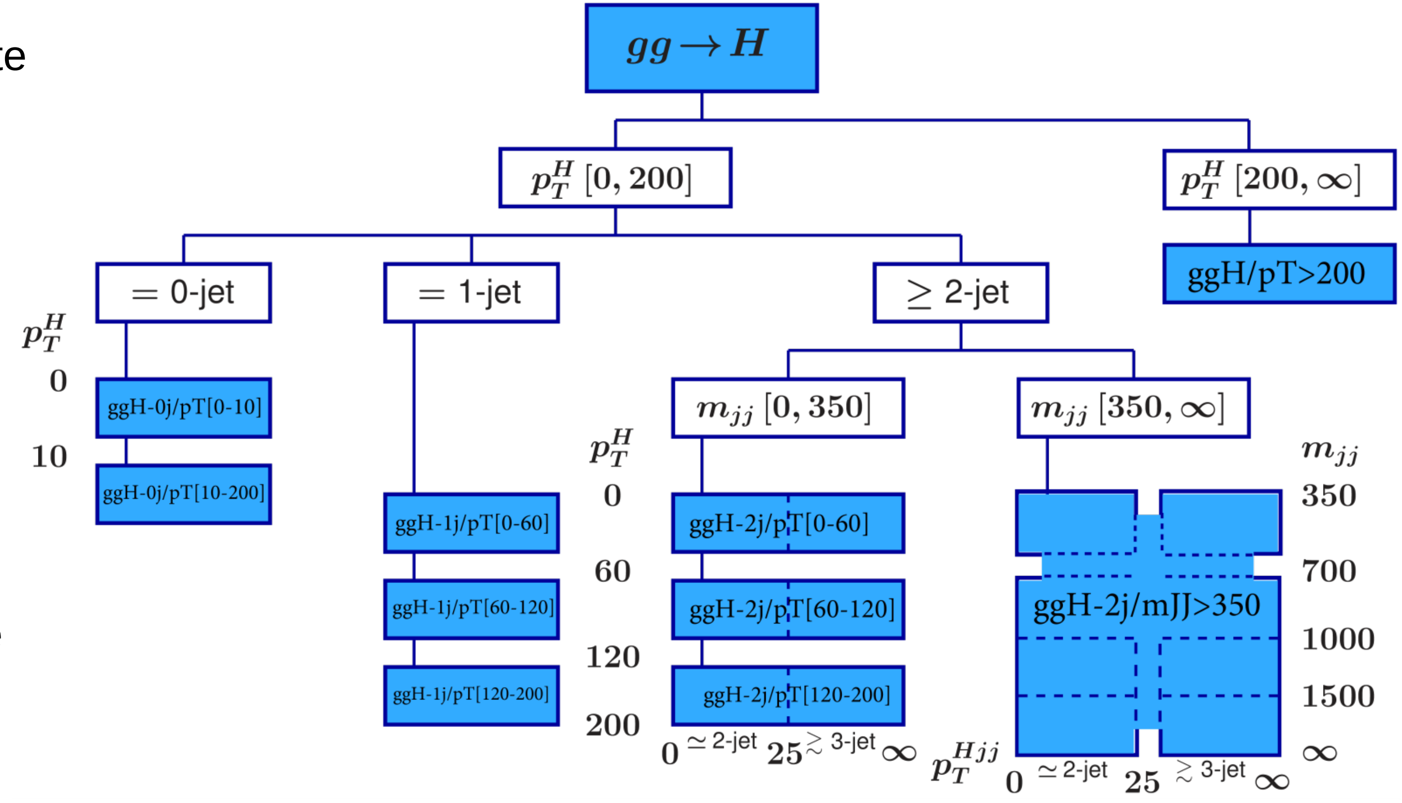
➔ In particular, no tension between fermion- and vector boson-induced production modes





Simplified Template cross sections (STXS)

- A standardized "binning" mutually agreed on by experiments and theorists
  - ideal basis for testing theoretical calculations
  - allows experiments to keep using multivariate methods (BDT, DNN, …)
  - evolving schema, with granularity matched to currently available statistics



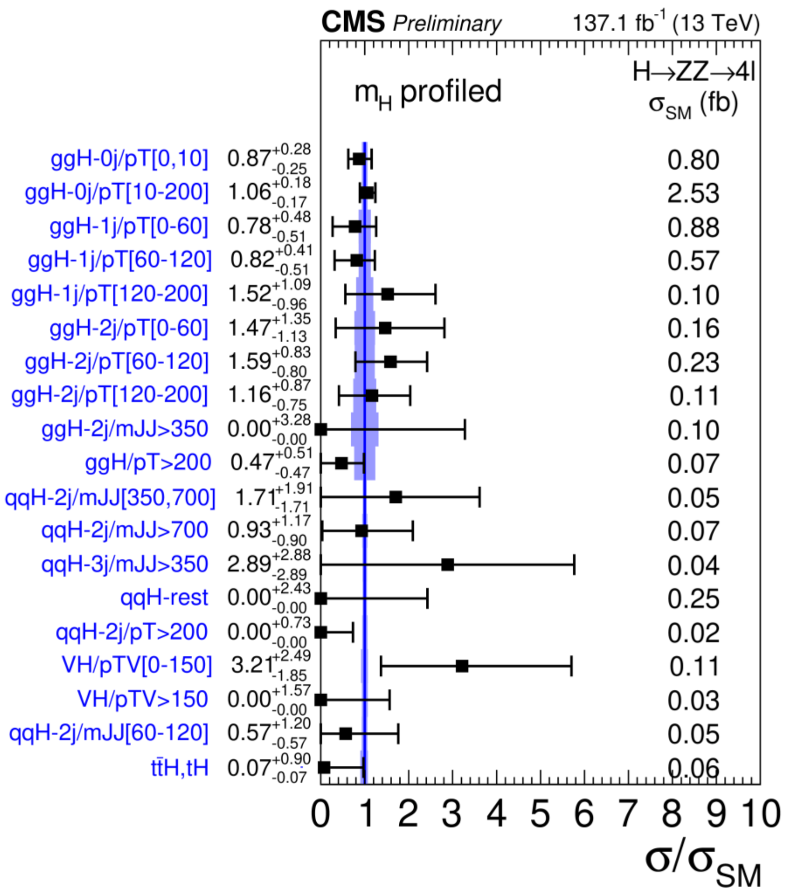
- In the initial round of analyses, only STXS Stage 0 could be addressed
  - bins correspond to production mechanisms
- The full Run 2 analysis is able to measure STXS Stage 1.1 schema

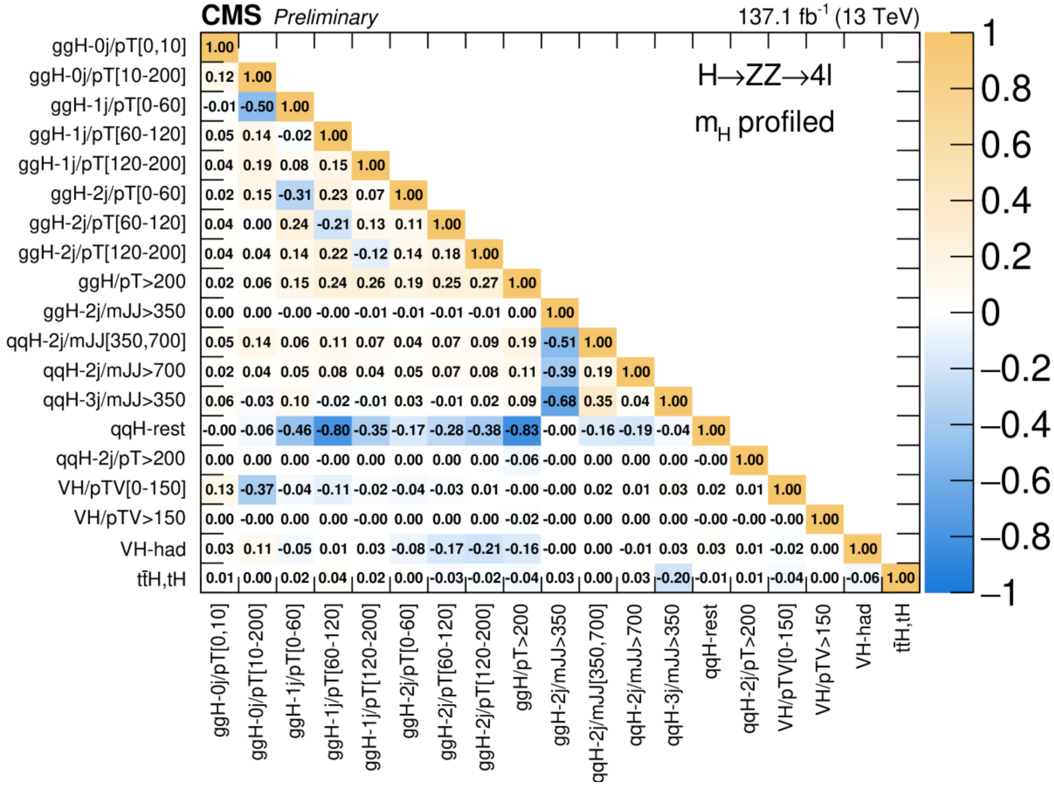
➔ finer binning, in p_T^H, m_{jj}, N_{jet}

(VH→leptons and EW qqH not shown)

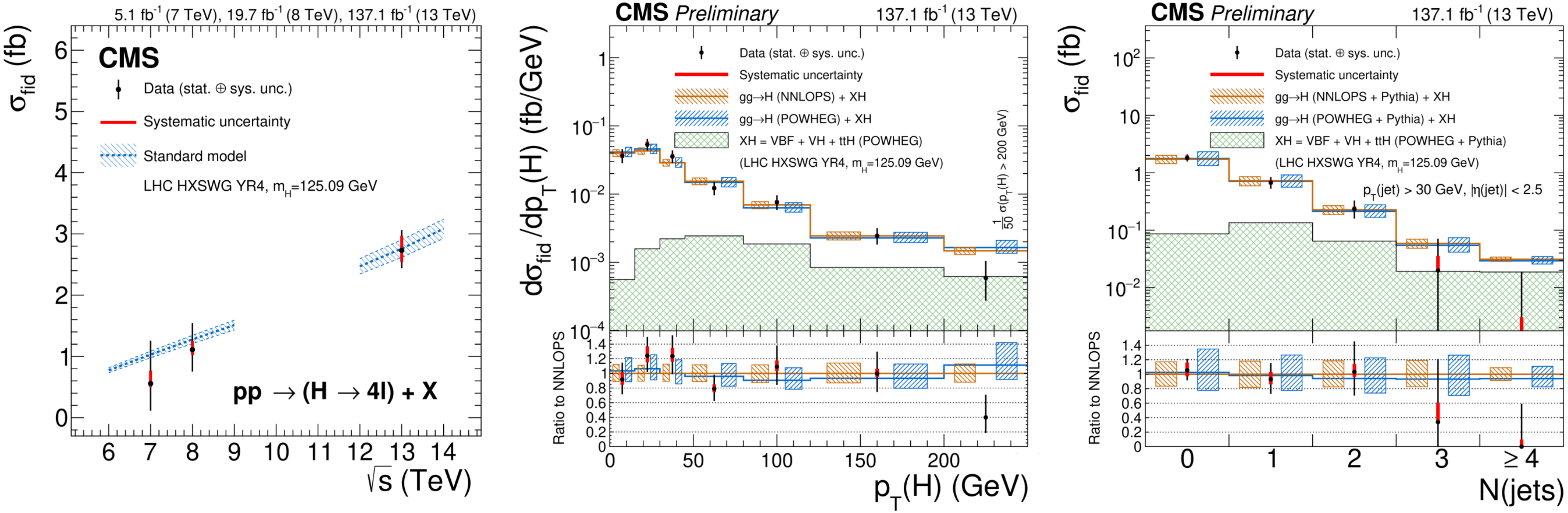
Simplified Template cross sections (cont'd)

- ➔ Even in this low-statistics channel, good experimental accessibility of most STXS bins
- ➔ Mostly modest correlations between STXS bins
- ➔ Good agreement with SM





$H \to 4\ell$ fiducial cross sections



- Phase space selection minimizes need for extrapolation → small theoretical uncertainties

➔ Measure large selection of distributions and compare with various model predictions

$H \rightarrow \gamma\gamma$

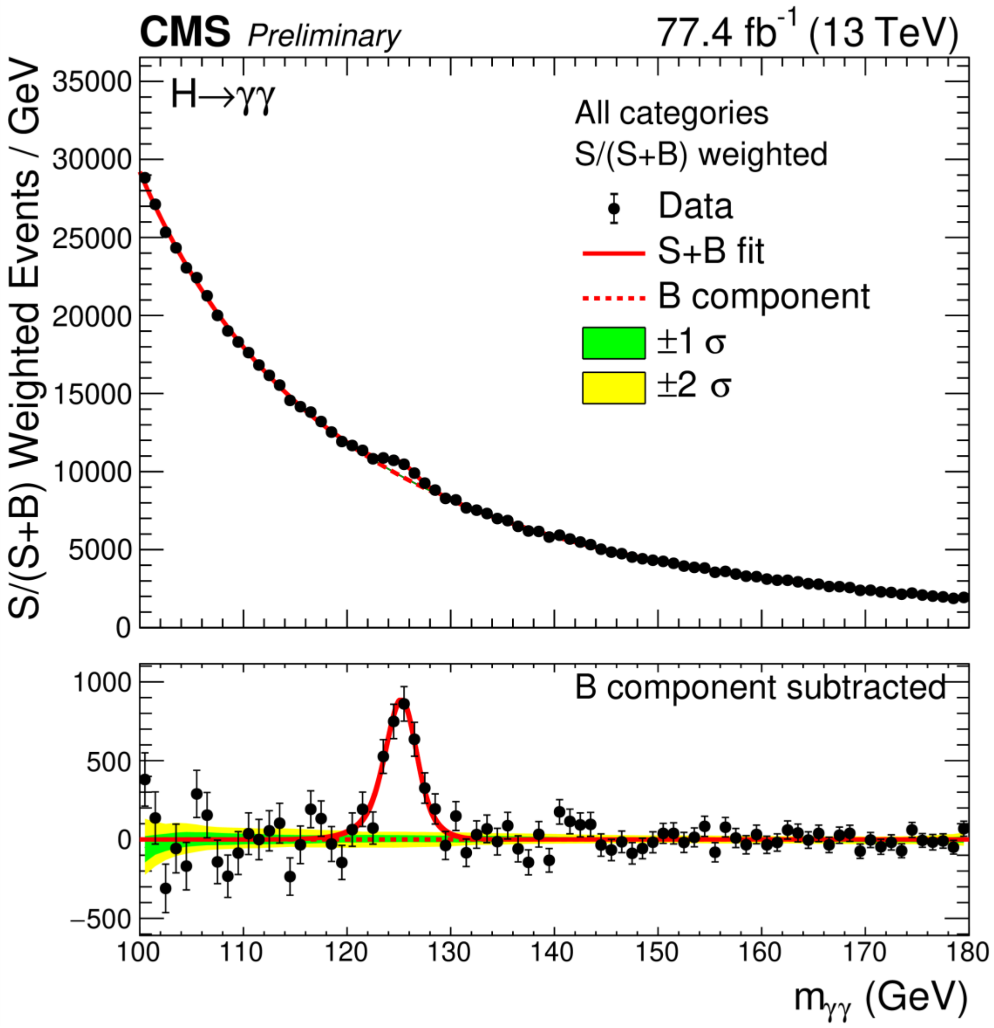
$H \to \gamma\gamma$

CMS PAS HIG-18-029

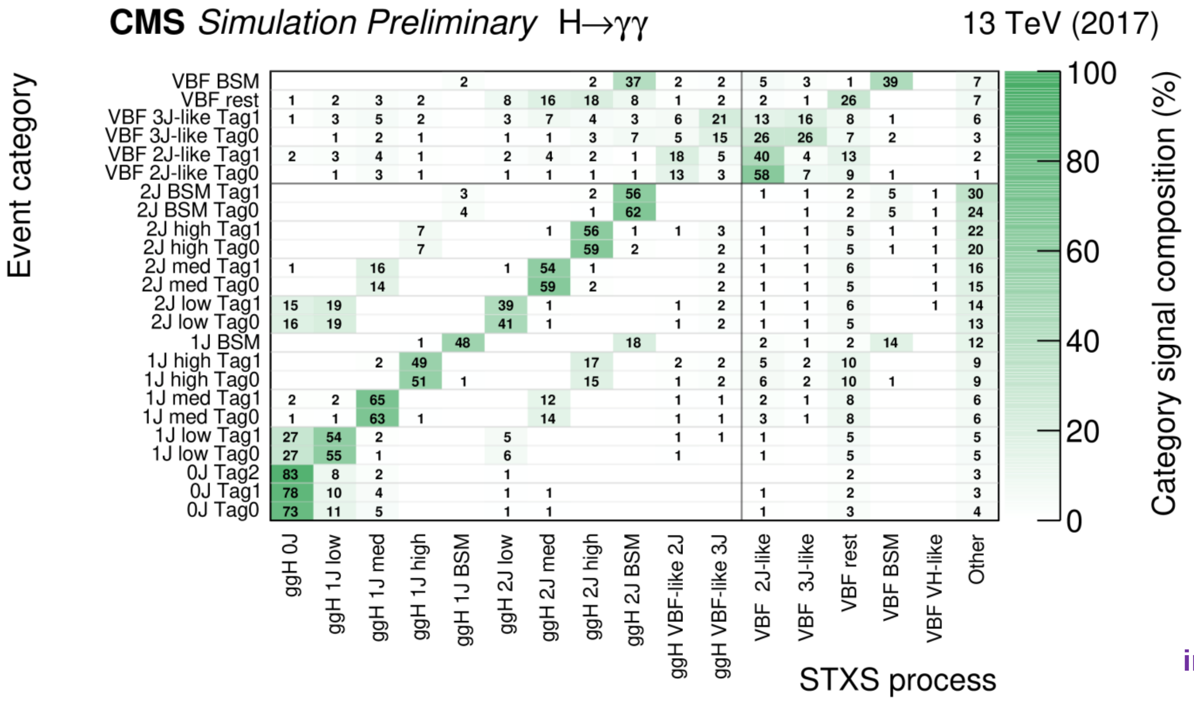
- Very clean final state topology
- Classify events targeting different production modes to improve sensitivity
- Data-driven background modeling with analytic functions
  - discrete profiling method
- Combination of 2016 + 2017 data

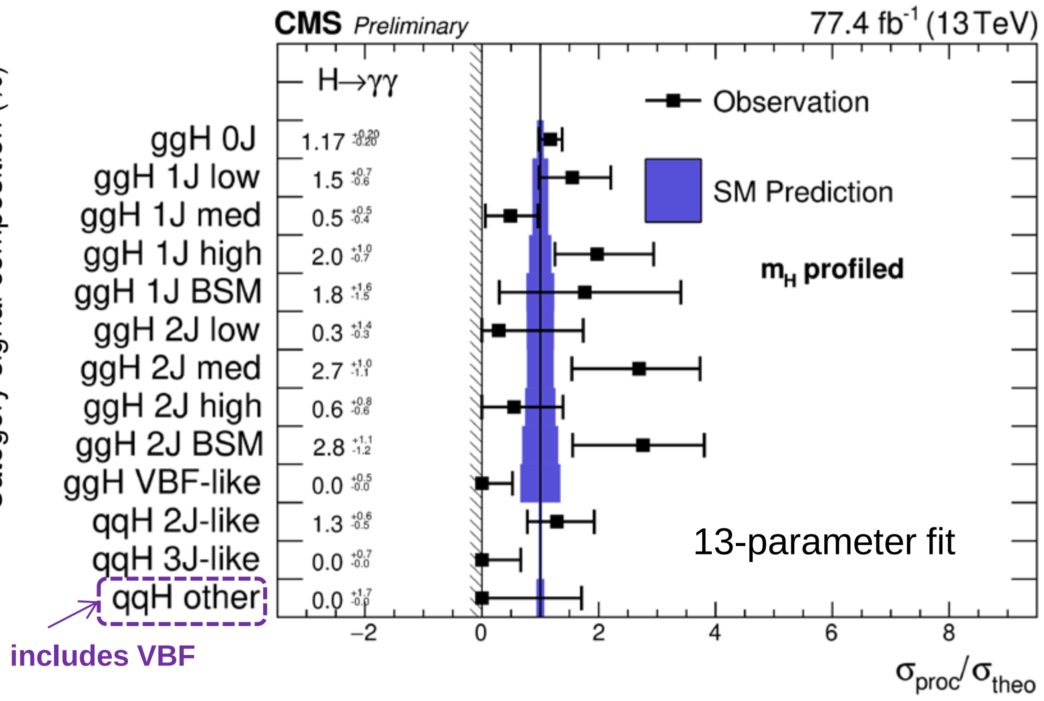
➔ Measured signal strength:

- gluon fusion: $\mu = 1.15^{+0.15}_{-0.15}$
- vector boson fusion: $\mu = 0.8^{+0.4}_{-0.3}$



$H \to \gamma\gamma$: Simplified template cross sections





- ➔ Very adequate mapping between event categories and STXS stage 1 processes
- ● Some STXS bins had to be merged due to limited statistics (7-parameter fit not shown)
- ➔ Everything in accord with Standard Model expectations

$H \to \tau\tau$

$H \to \tau\tau$ and the Higgs-τ Yukawa coupling

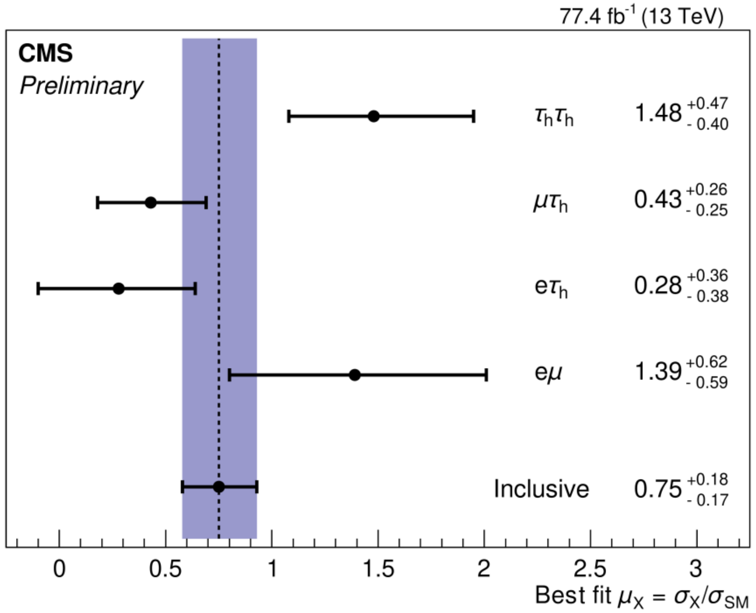
CMS PAS HIG-18-032

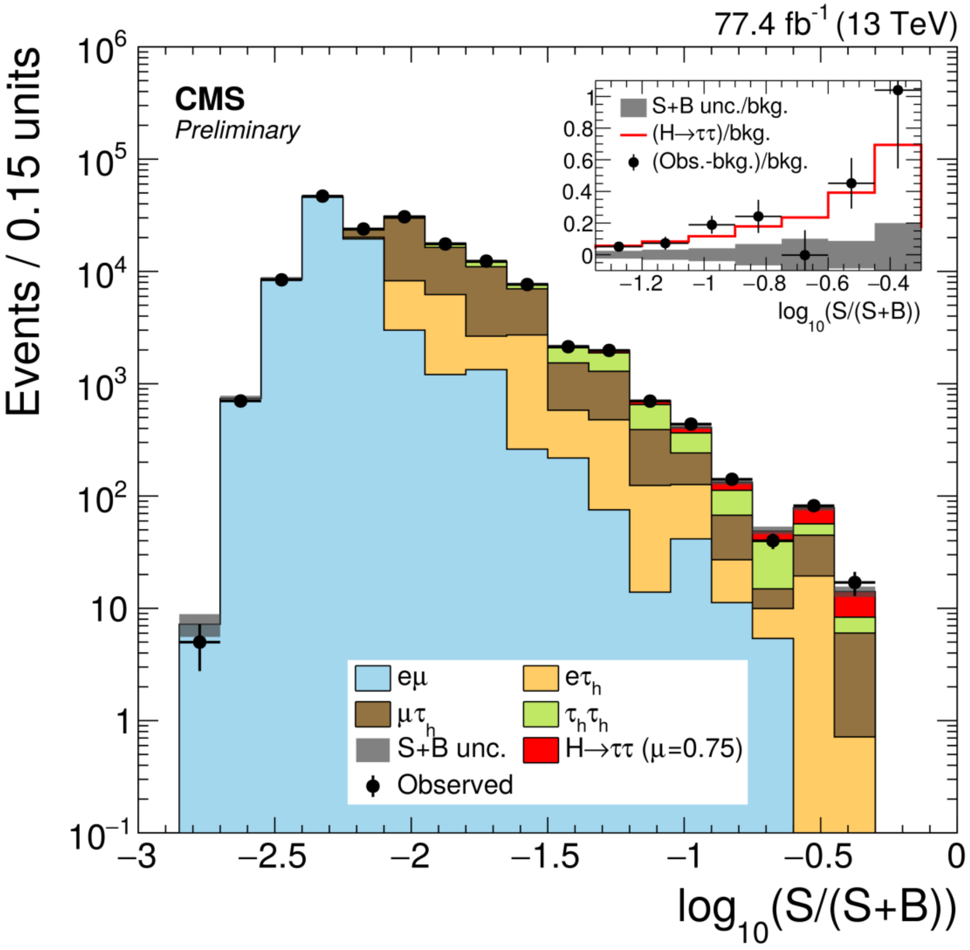
- After discovery of $H \to \tau\tau$ with Run 1 + 2016 data, analysis has been extended to 2017 dataset (→ 77.4 fb^{-1})
- Improvements:
  - multi-class neural network (2 signal + several BG categories)
  - 90% of backgrounds determined with data-driven methods
    - τ embedding
    - fake factor method

➔ Signal clearly visible

➔ Strength in agreement with SM expectation

- significance: $4.7\ \sigma\ (6.6\ \sigma\ exp.)$

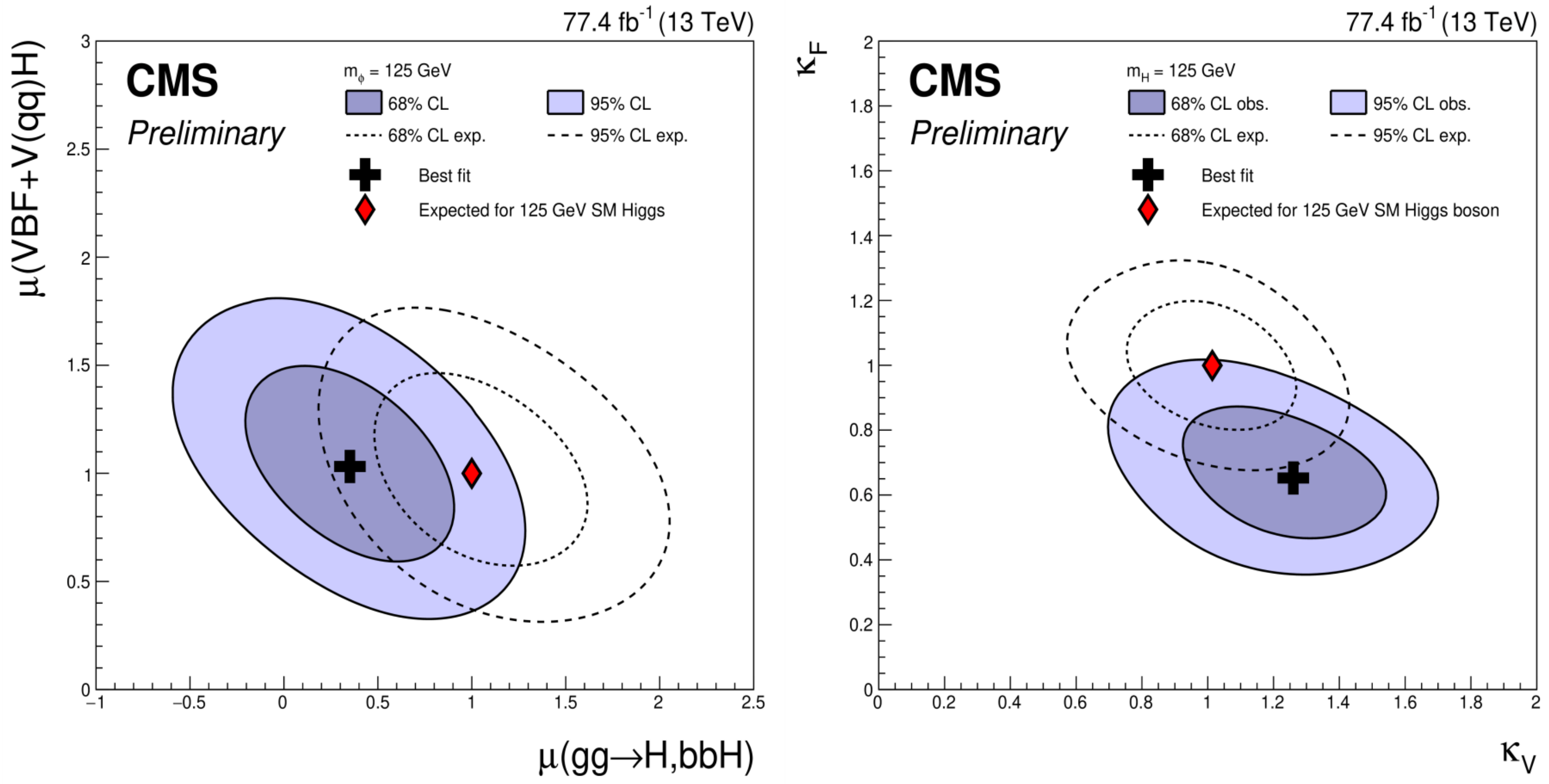




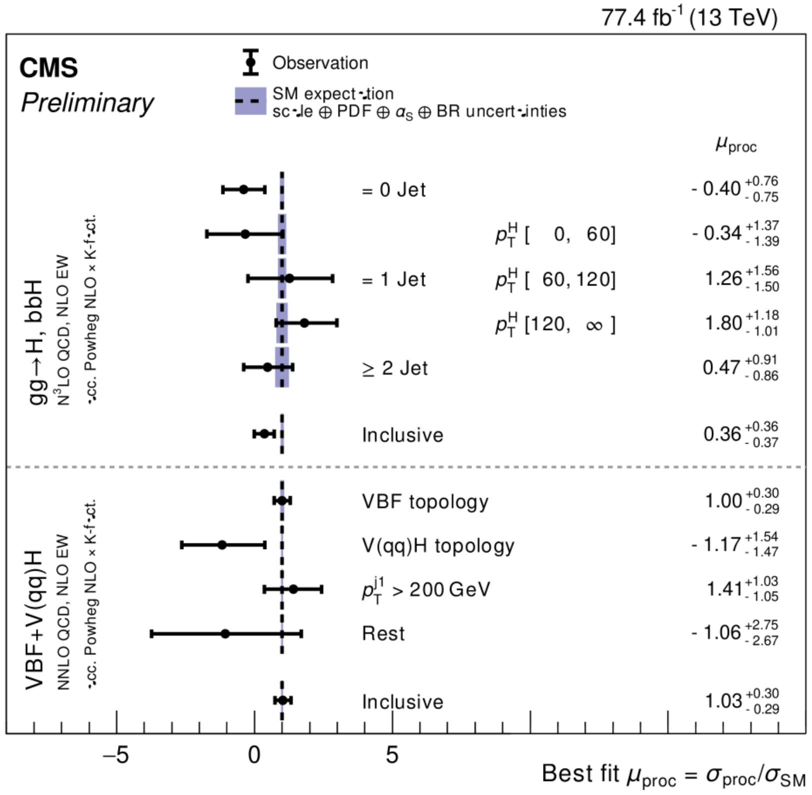
$H \to \tau\tau$ (cont'd)

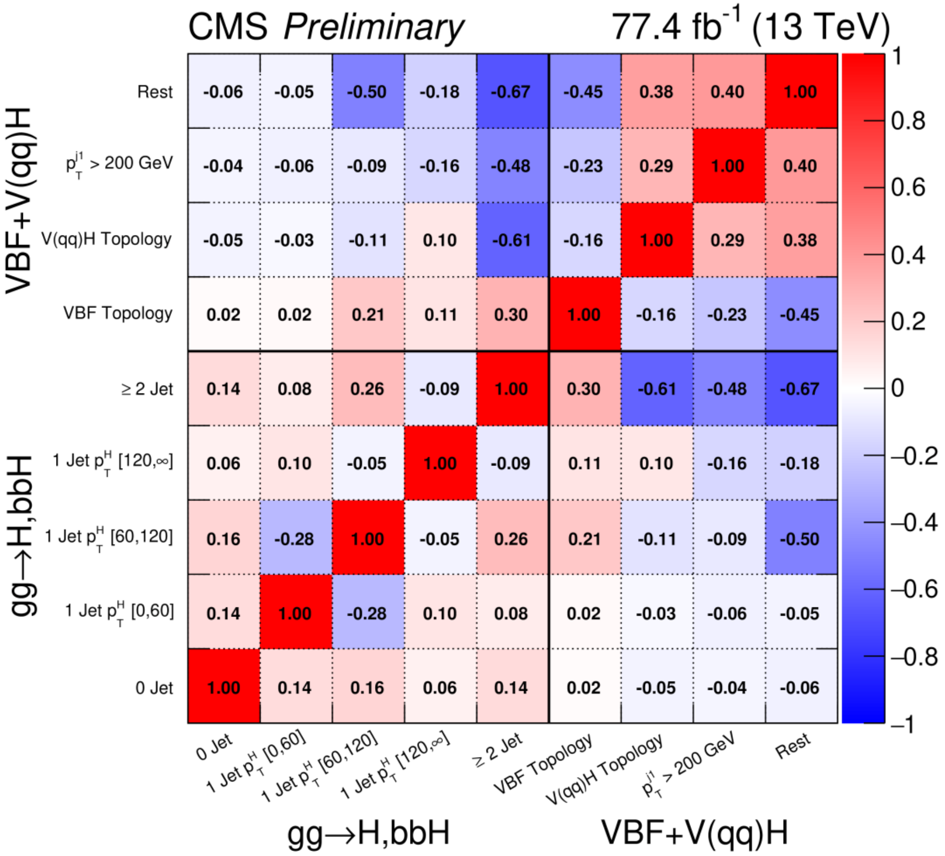
- Split into 2 production mode groups
  - gg + bbH
  - VBF + V(qq)H
  - correlation ~ -0.44
- Profile κ_F and κ_V coupling modifiers
  - treat $WW(e\mu)$ and ttH, $V(\ell\ell)H$ as signal processes

➔ Good agreement with SM



$H \to \tau\tau$: Simplified template cross sections





	0 Jet	1 Jet p_T^H [0,60]	1 Jet p_T^H [60,120]	1 Jet p_T^H [120,∞]	≥ 2 Jet	VBF Topology	V(qq)H Topology	p_T^{j1} > 200 GeV	Rest
Rest	-0.06	-0.05	-0.50	-0.18	-0.67	-0.45	0.38	0.40	1.00
p_T^{j1} > 200 GeV	-0.04	-0.06	-0.09	-0.16	-0.48	-0.23	0.29	1.00	0.40
V(qq)H Topology	-0.05	-0.03	-0.11	0.10	-0.61	-0.16	1.00	0.29	0.38
VBF Topology	0.02	0.02	0.21	0.11	0.30	1.00	-0.16	-0.23	-0.45
≥ 2 Jet	0.14	0.08	0.26	-0.09	1.00	0.30	-0.61	-0.48	-0.67
1 Jet p_T^H [120,∞]	0.06	0.10	-0.05	1.00	-0.09	0.11	0.10	-0.16	-0.18
1 Jet p_T^H [60,120]	0.16	-0.28	1.00	-0.05	0.26	0.21	-0.11	-0.09	-0.50
1 Jet p_T^H [0,60]	0.14	1.00	-0.28	0.10	0.08	0.02	-0.03	-0.06	-0.05
0 Jet	1.00	0.14	0.16	0.06	0.14	0.02	-0.05	-0.04	-0.06

- In the long term, STXS measurements from various Higgs channels will be combined

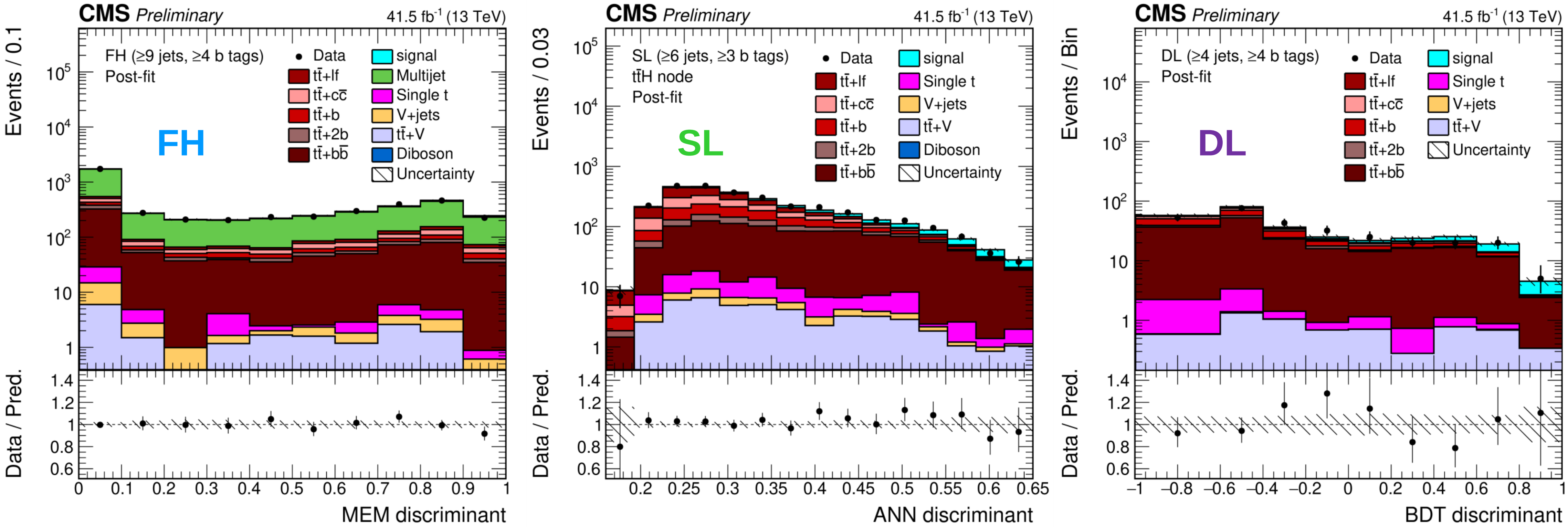
ttH production

ttH production with $H \to b\bar{b}$

Direct access to top quark Yukawa coupling

CMS PAS HIG-18-030

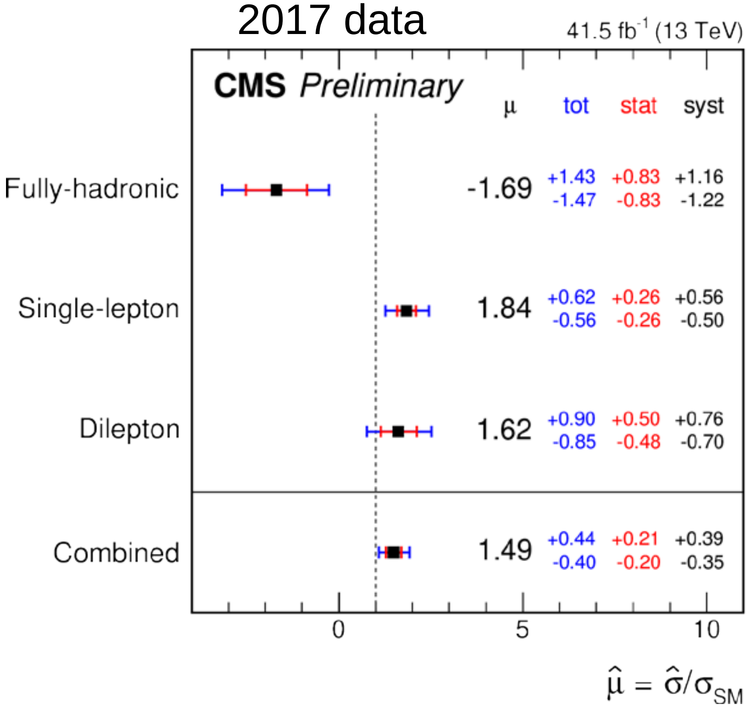
- Analysis of all $t\bar{t}$ decay topologies: single/double lepton (SL/DL), fully hadronic (FH); 2016+2017 data
- Complex multi-jet event structure, ≥ 4 b-tags
- Refined multi-variate methods for signal/background discrimination: matrix element, ANN, BDT

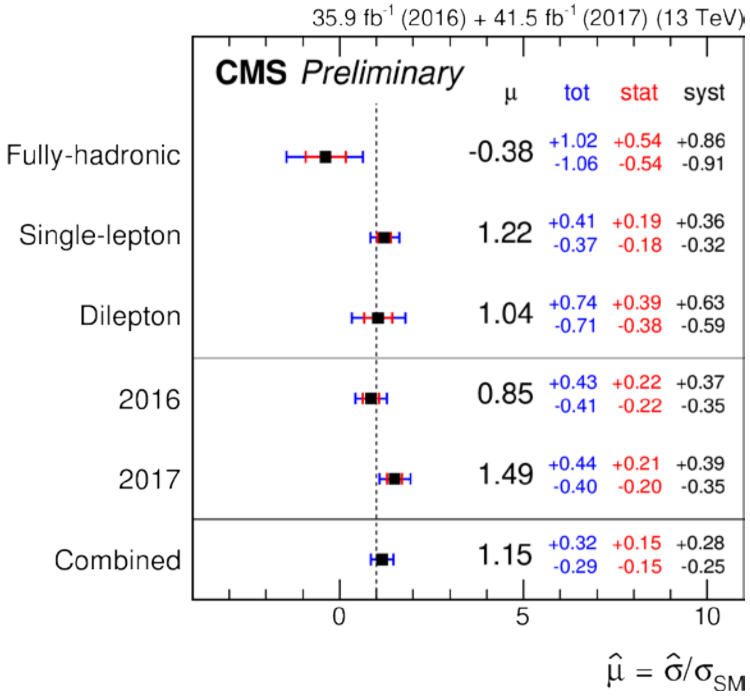


ttH production with $H \rightarrow b\bar{b}$ (cont'd)

CMS PAS HIG-18-030

2017 data





- ➔ Good agreement between 2016 and 2017 data
- ➔ Combined signal strength: $\mu = 1.15^{+0.32}_{-0.29}$ → good agreement with SM expectation
- ➔ Combined significance: $3.9\,\sigma\ (3.5\,\sigma\ exp.)$ → evidence for ttH production from $H \rightarrow b\bar{b}$ channel alone

$$H \rightarrow c\bar{c}$$

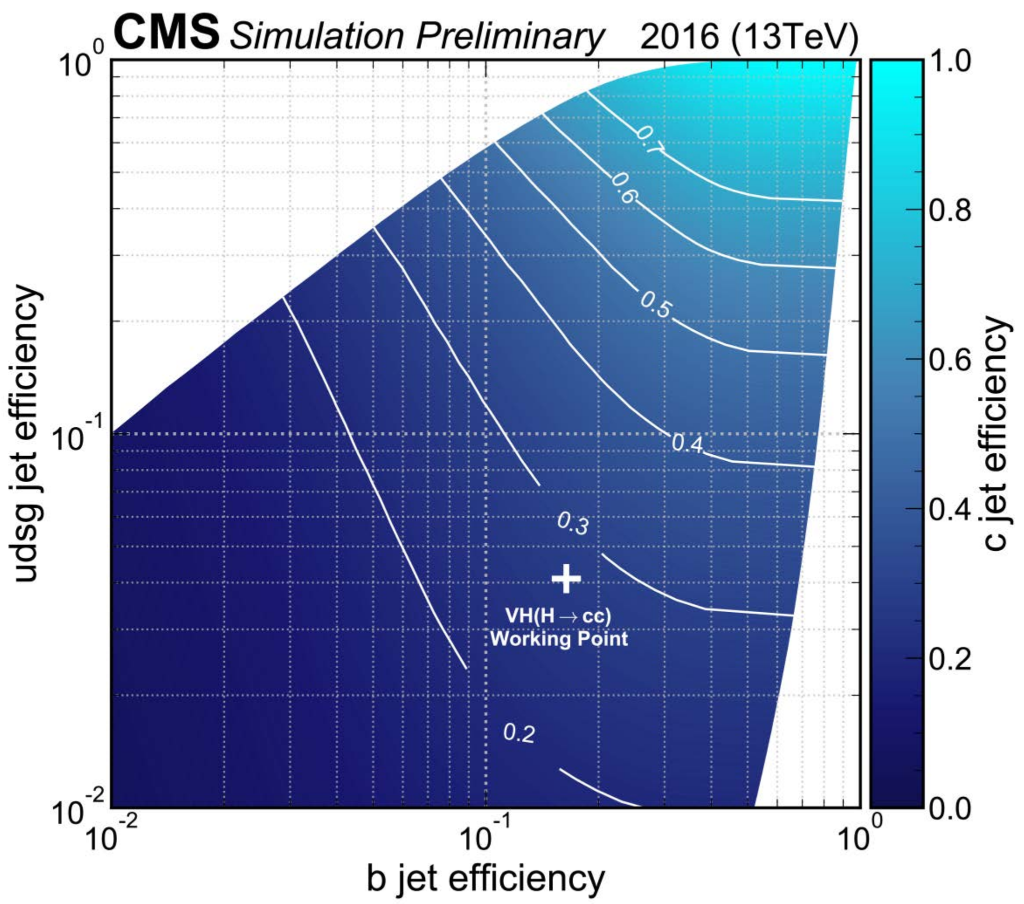
$H \to c\bar{c}$

Based on 2016 data set

New!

CMS PAS HIG-18-031

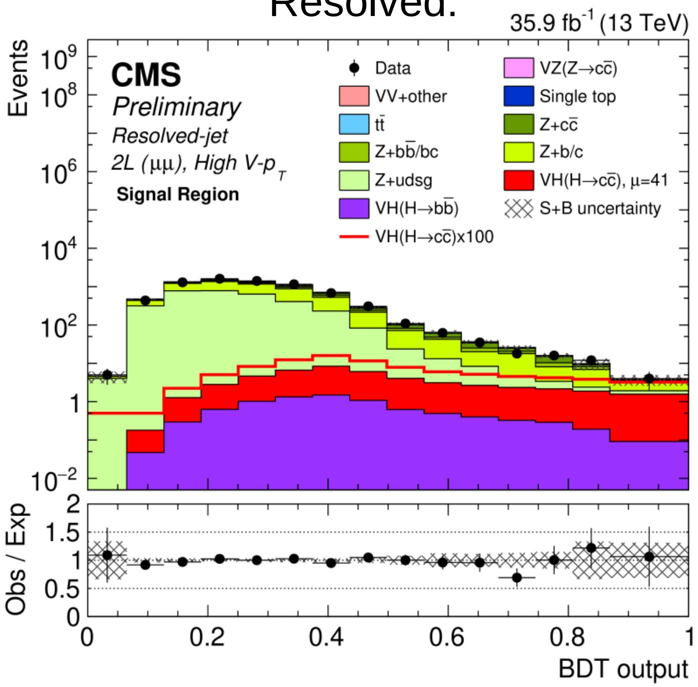
- Crucial to measure Yukawa coupling to second generation quarks
- BR($H \to c\bar{c}$) ~ 20% of BR($H \to b\bar{b}$)
  - very challenging in view of backgrounds
  - new: $H \to b\bar{b}$ is a background as well!
- Focus on VH production mode
  - ➔ easy triggering, more manageable backgrounds
  - V = Z($\nu\bar{\nu}$), W($\ell\bar{\nu}$), Z($\ell\ell$) channels
- Two approaches to explore $H \to c\bar{c}$ decay topology
  - resolved (2 jets R=0.4) and merged (one large jet R=1.5)
- Advanced charm tagging techniques applied
  - ➔ confronting both heavy (b) and light flavor (udsg) backgrounds simultaneously



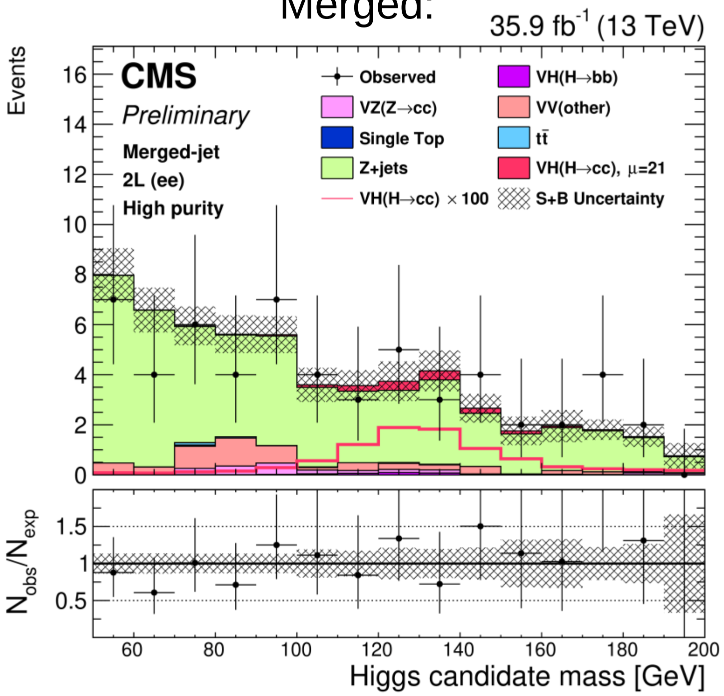
$H \to c\bar{c}$ (cont'd)

- Charm tagging based on deep neural networks (DNN)
  - calibration with various control data sets
- Signal extraction by simultaneous fit to signal and control regions
  - analysis variables
    - BDT discriminant (resolved)
    - Higgs candidate mass (merged)
- Validated by measuring $VZ(\to c\bar{c})$ process

Resolved:

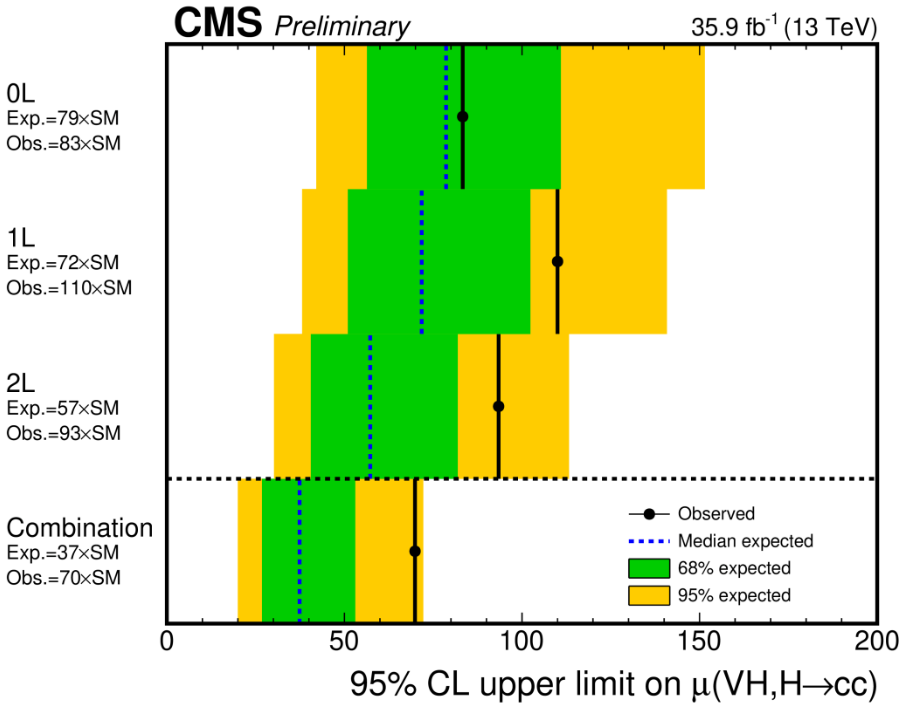


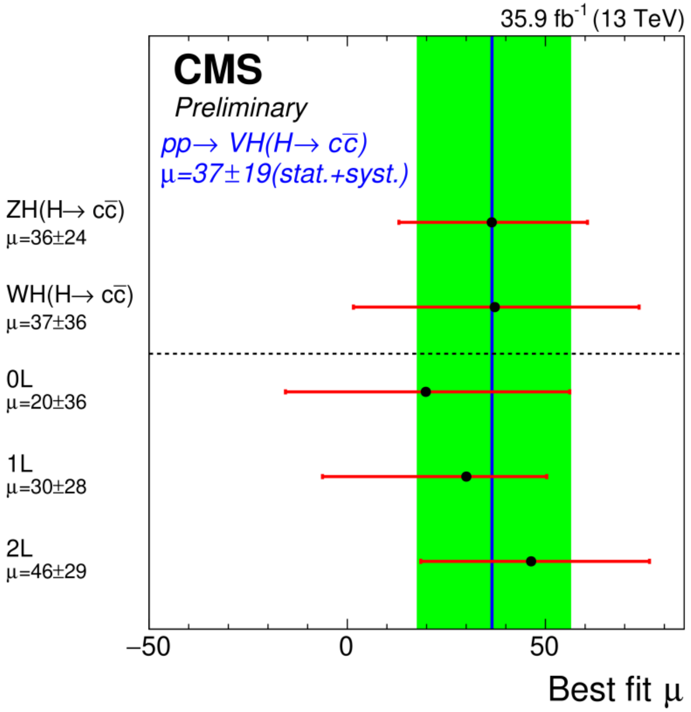
Merged:



- For the overall result, combine resolved ($p_T^V < 300\ GeV$) and merged ($p_T^V > 300\ GeV$)

$H \to c\bar{c}$ (cont'd)





➔ Combined upper limit relative to SM expectation: $\mu < 70\ obs.\ (37\ exp.)$ at 95% CL

➔ Most sensitive direct measurement to date

- A long way ahead to achieve SM sensitivity. Next step: full Run 2 analysis

Higgs couplings - Run 2 and beyond

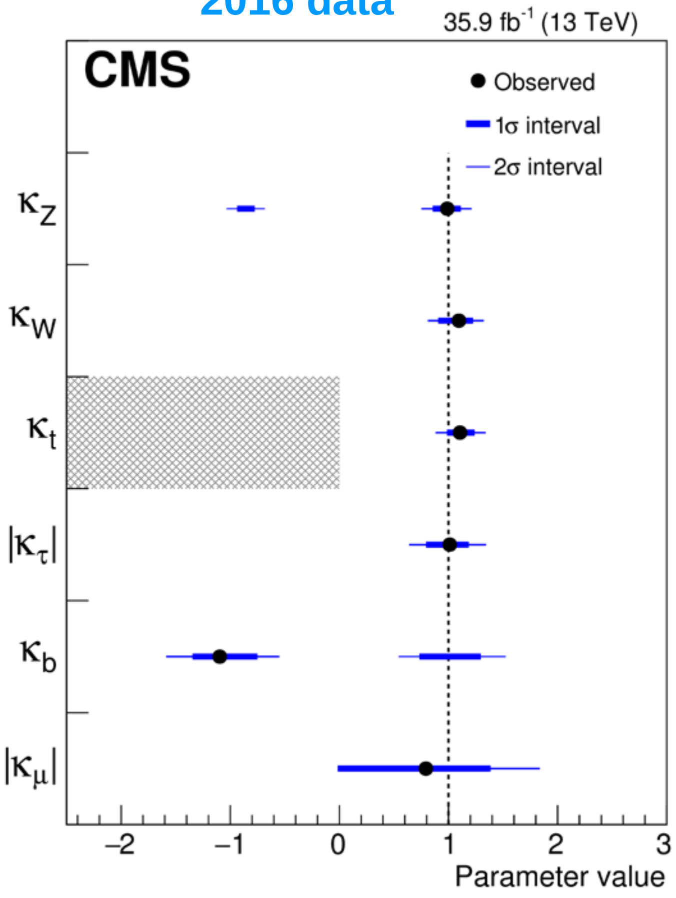
Higgs coupling measurements

CMS PAS HIG-17-031, FTR-18-011

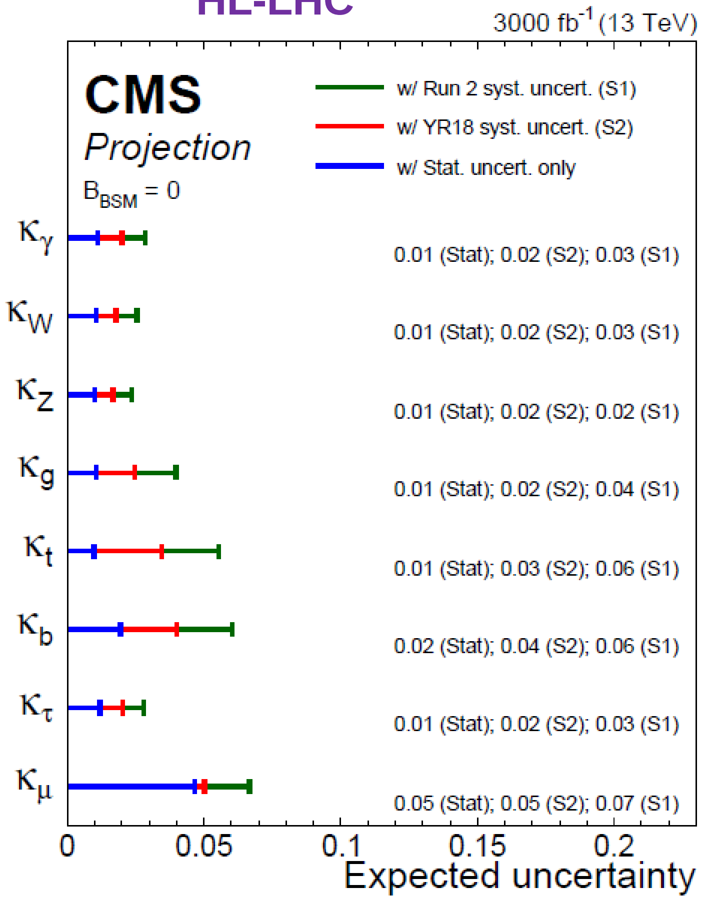
- Coupling modifiers are presented at the level of the 2016 data
  - ggH and $H \to \gamma\gamma$ loop processes resolved
  - ➔ results are in line with SM
  - ➔ precision in 10-30% range, apart from κ_μ
  - stay tuned for full Run 2 result

- Projections have been made for full HL-LHC period (3000 fb^{-1})
  - ➔ precision improves down to 2-5% range (apart from κ_μ)
  - ➔ dominated by signal theory in S1 case (κ_μ dominated by statistics)

2016 data



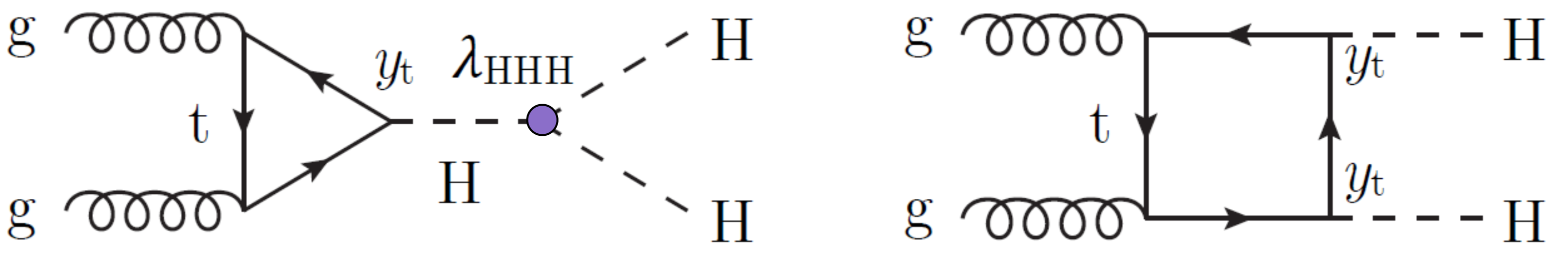
HL-LHC



H H production

HH production

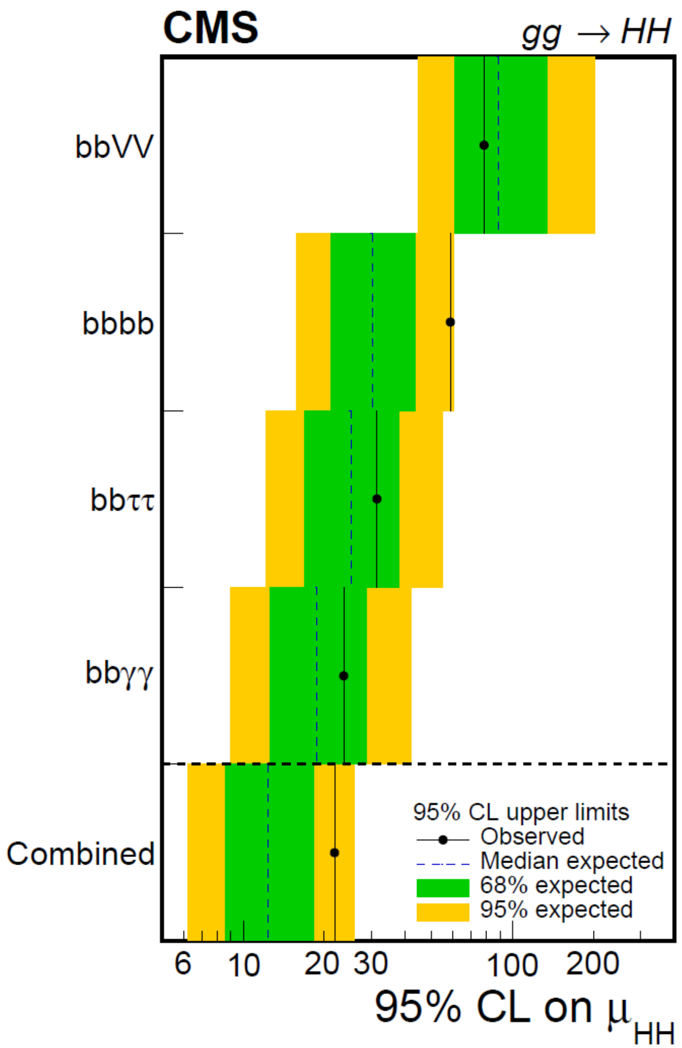
Phys. Rev. Lett. 122, 121803 (2019)



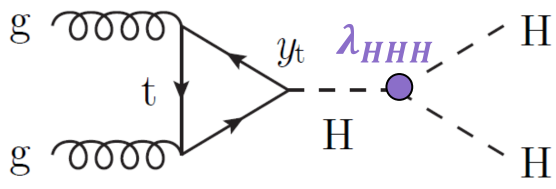
- Direct way of accessing the **tri-linear Higgs coupling**

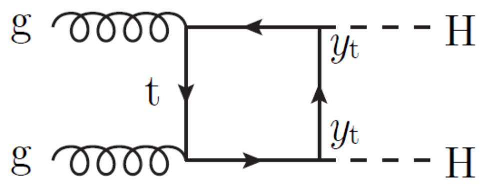
  ➔ measure the shape of the Higgs potential itself
- Interference with box diagram (→ Yukawa couplings)
- Small cross section in SM: σ(gg→HH) = 33.5 fb
  - split over many individual decay channel combinations
- From combination of four major decay modes (2016 data):

  ➔ $\mu_{HH} < 22.2\ obs.\ (12.8\ exp.)$ at 95% CL



HH production: tri-linear Higgs coupling



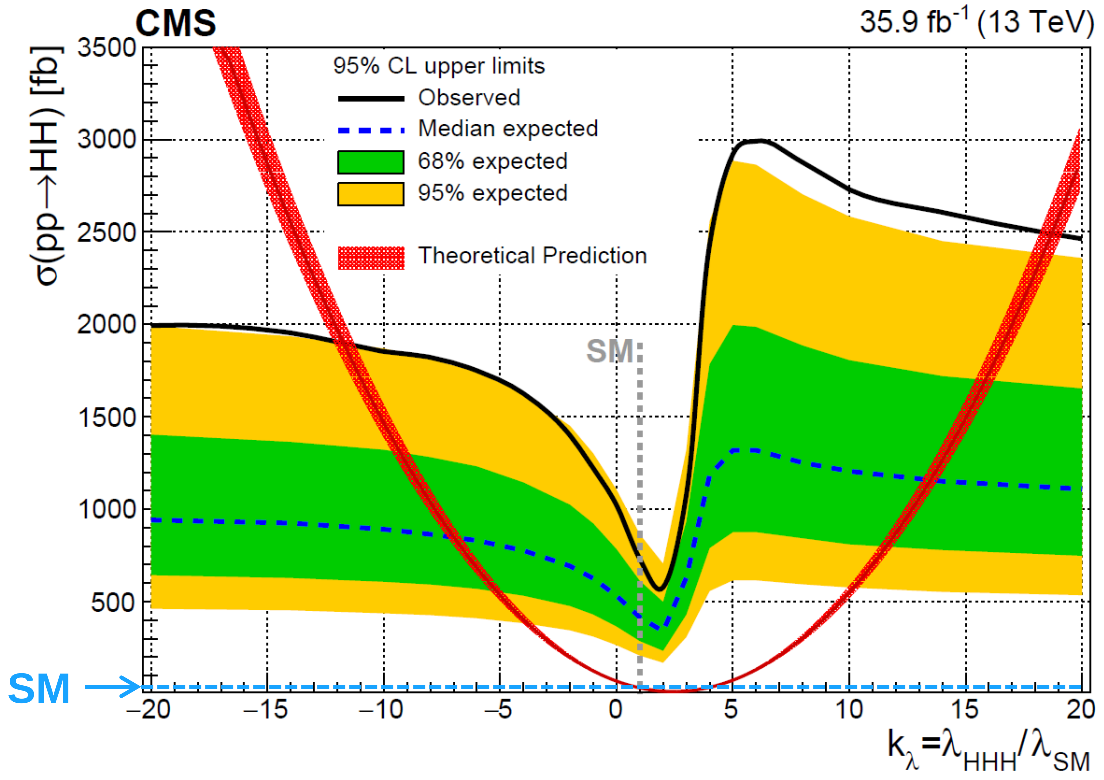


- Result can be used to constrain the tri-linear Higgs coupling modifier, $k_\lambda = \lambda_{HHH}/\lambda_{SM}$
- With SM parameters, the absolute size of both diagrams is relatively similar, and interference is close to destructive
  - in general up to two solutions for k_λ
  - shape of m_{HH} spectrum depends strongly on k_λ
    - allows distinction between the two cases

➔ Result (at 95% CL):

- $-11.8 < k_\lambda < 18.8\ obs. (-7.1 < k_\lambda < 13.6\ exp.)$

➔ Need much more data to reach SM regime



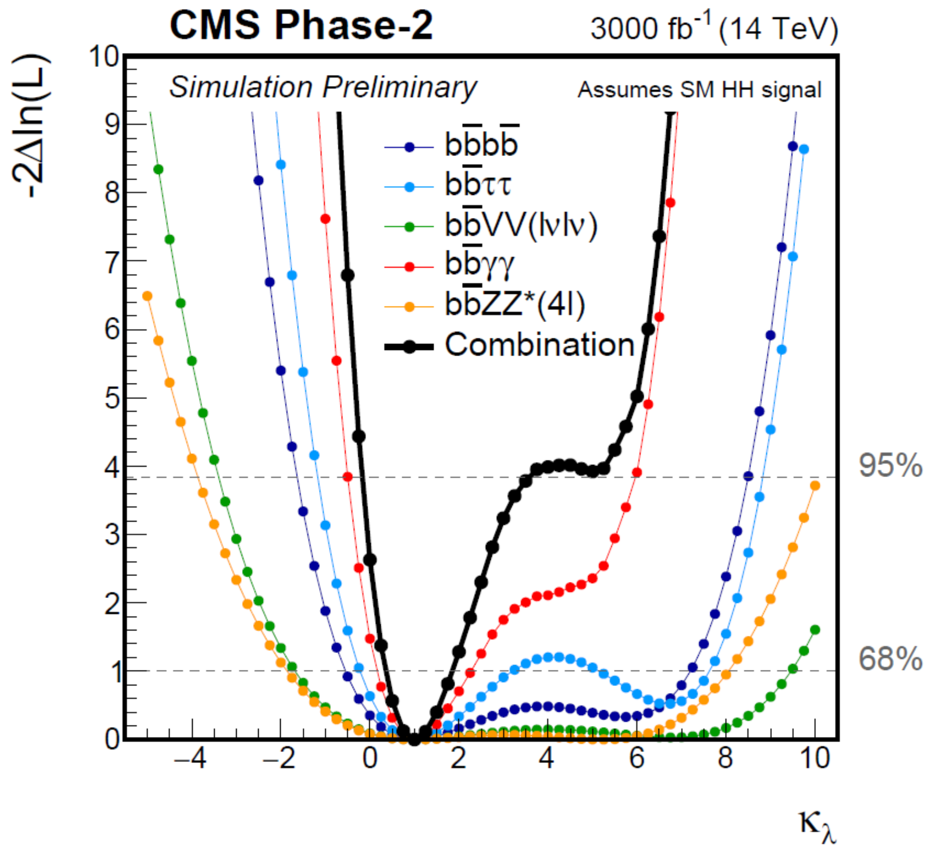
HH production: outlook for HL-LHC

CMS PAS FTR-18-019

- Projections have been made for the whole run of the HL-LHC, assuming 3000 fb^{-1}

➔ total expected significance (five decay modes): $2.6\ \sigma$

Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71



➔ Tri-linear Higgs coupling can be constrained at the level

- $-0.18 < k_\lambda < 3.6$ at 95% CL

➔ Very challenging analysis, but with further refinement of methodology and combination of all possible channels and across experiments, even higher sensitivity can be expected

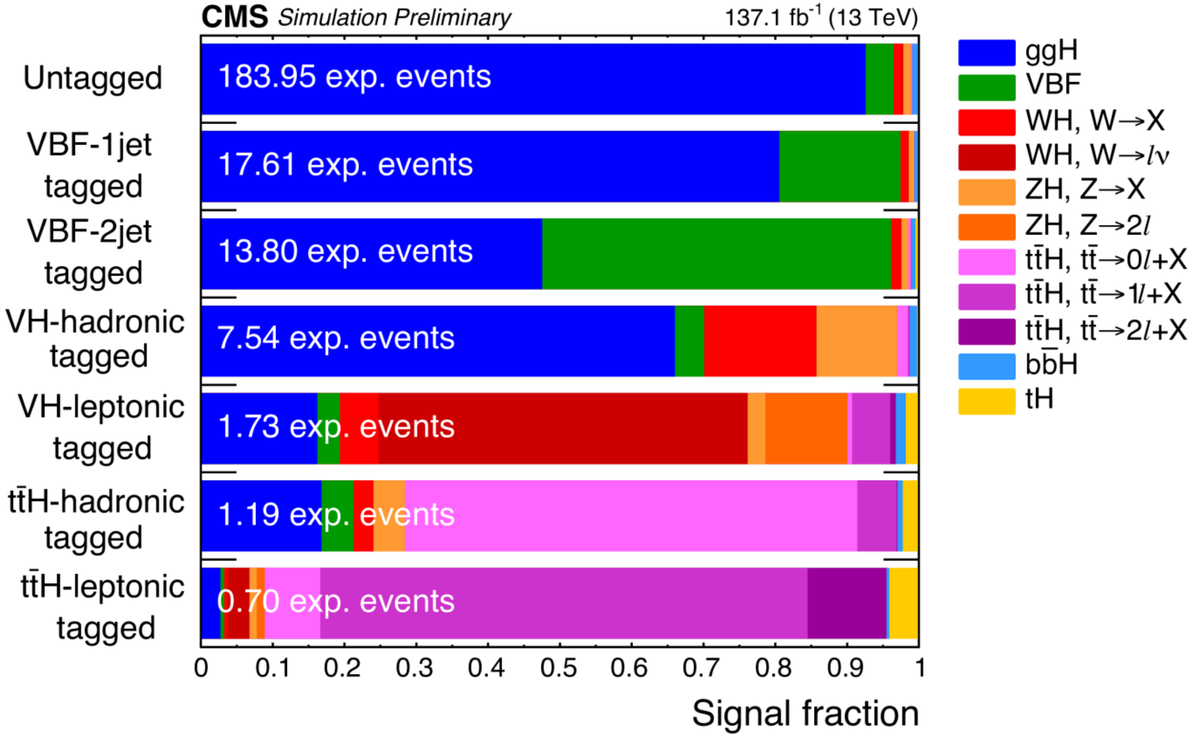
Summary

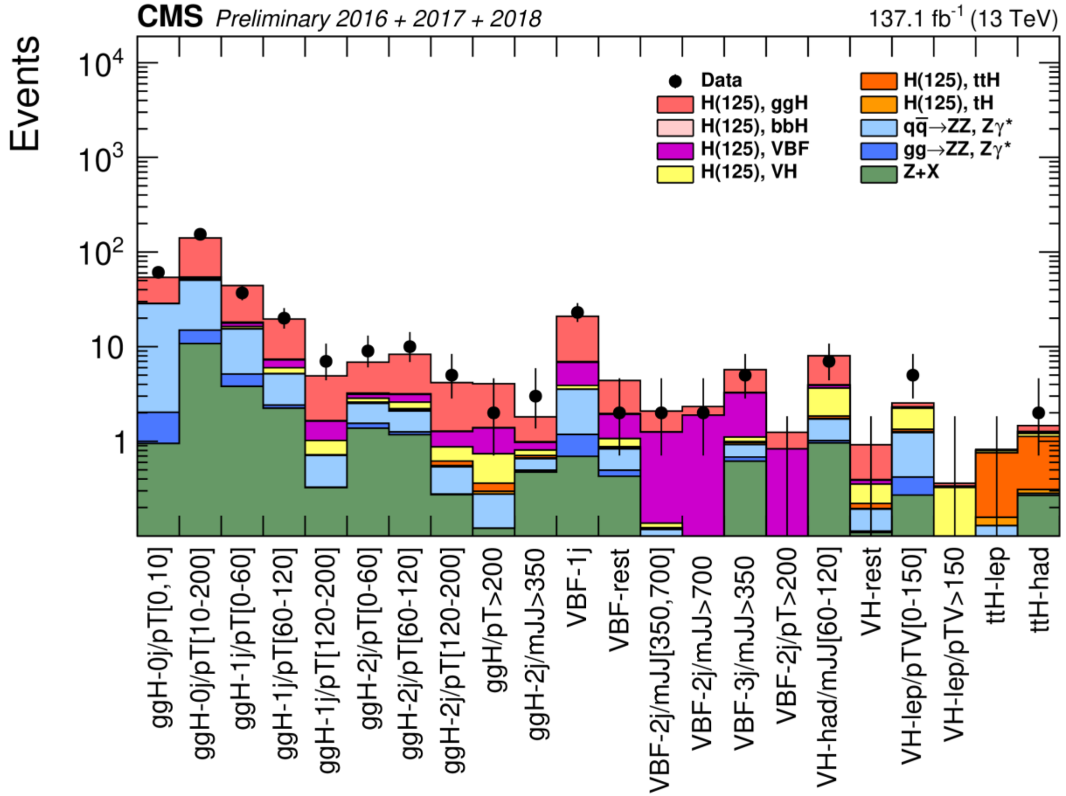
- Legacy analyses of LHC Run 2 data are in full swing
  - many studies already extended to 2016+2017 or full Run 2 data. Many methodical improvements
  - the final word from Run 2 (combination of all data and analysis channels) is yet to come
- Seven years after its discovery, our picture of the Higgs boson has become much more detailed
  - all accessible 3rd generation Yukawa couplings discovered
  - most couplings measured with precision at the 10-30% level
  - differential measurements of production modes became standard → simplified template cross sections
  - up to now, Standard Model has prevailed. But still much room for New Physics in the Higgs sector
- In many places, we are still severely limited by experimental statistics
  - Run 3 and ultimately HL-LHC will extend our precision enormously → powerful check for anomalies
  - hope to reach out even for Higgs self-coupling

→ Exciting experimental program ahead!

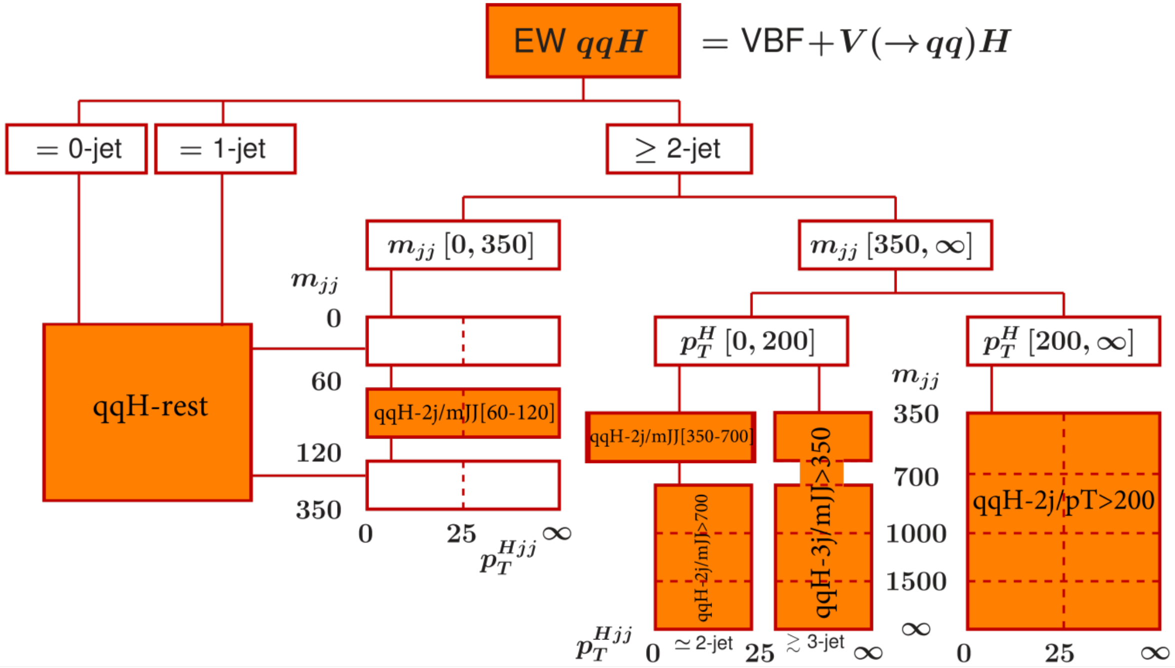
Backup

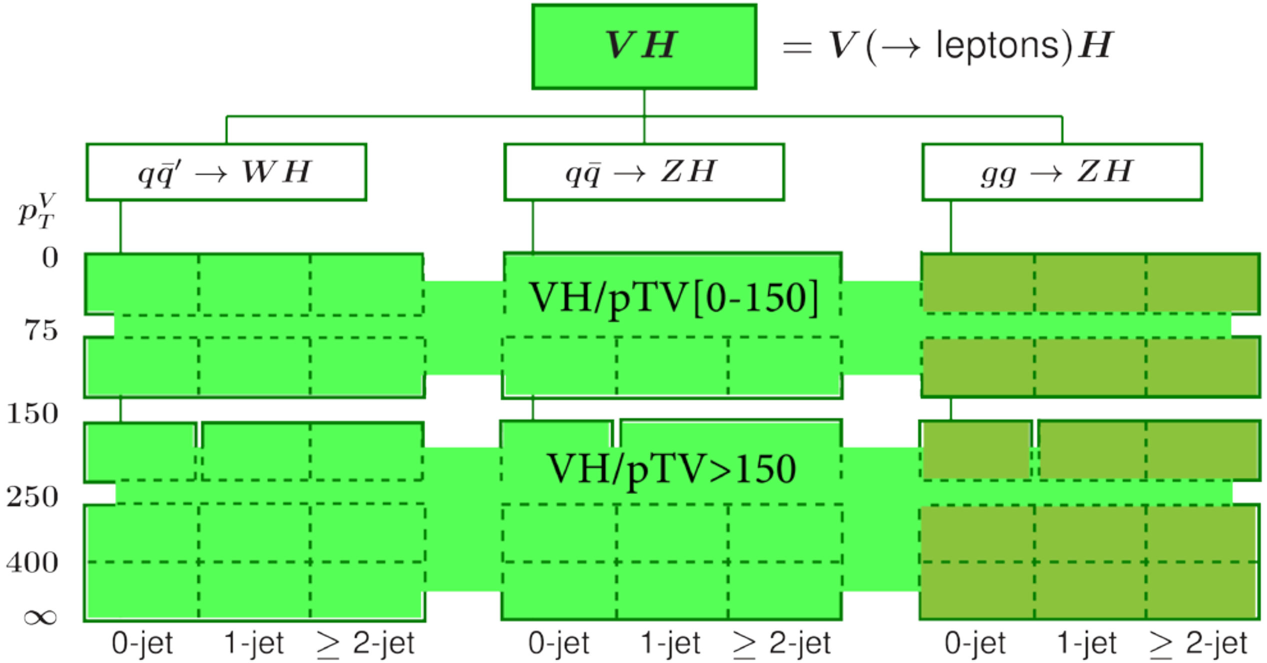
$H \to 4\ell$ statistics





$H \to 4\ell$ STXS





$H \rightarrow 4\ell$: fiducial space

Requirements for the $\mathrm{H} \rightarrow 4\ell$ 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	$105\,\mathrm{GeV} < m_{4\ell} < 140\,\mathrm{GeV}$

$H \to \gamma\gamma$

Particle level definition of each ggH stage 1 bin

Region	Definition	Fraction	Cross section (pb)
0J	Exactly zero jets, any p_T^H	60.0%	26.49
1J low	Exactly one jet, $p_T^H < 60$ GeV	15.4%	6.79
1J med	Exactly one jet, 60 GeV $< p_T^H <$ 120 GeV	10.4%	4.61
1J high	Exactly one jet, 120 GeV $< p_T^H <$ 200 GeV	1.7%	0.76
1J BSM	Exactly one jet, $p_T^H > 200$ GeV	0.4%	0.16
2J low	$\geq$ two jets, $p_T^H < 60$ GeV	2.9%	1.26
2J med	$\geq$ two jets, 60 GeV $< p_T^H <$ 120 GeV	4.5%	2.00
2J high	$\geq$ two jets, 120 GeV $< p_T^H <$ 200 GeV	2.3%	1.00
2J BSM	$\geq$ two jets, $p_T^H > 200$ GeV	1.0%	0.43
VBF-like 2J	$\geq$ two jets, $p_T^H < 200$ GeV, $\lvert\Delta\eta\rvert > 2.8$, $m_{jj} > 400$ GeV, $p_T^{Hjj} < 25$ GeV	0.6%	0.27
VBF-like 3J	$\geq$ two jets, $p_T^H < 200$ GeV, $\lvert\Delta\eta\rvert > 2.8$, $m_{jj} > 400$ GeV, $p_T^{Hjj} > 25$ GeV	0.9%	0.38

$H \rightarrow \tau\tau$

Categories

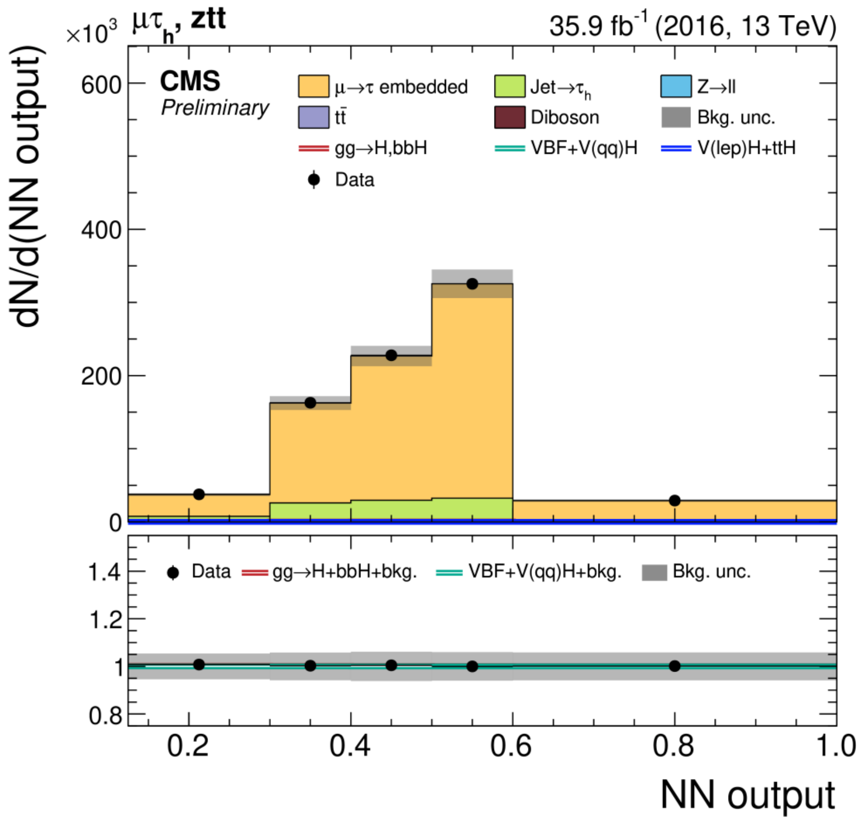
<table>
<tr><th rowspan="2">Process</th><th colspan="4">Classes/Categories per final state</th></tr>
<tr><th>$e\mu$</th><th>$e\tau_h$</th><th>$\mu\tau_h$</th><th>$\tau_h\tau_h$</th></tr>
<tr><td>$gg \rightarrow H$</td><td>ggH (0.20)</td><td>ggH (0.23)</td><td>ggH (0.27)</td><td>ggH (0.54)</td></tr>
<tr><td>VBF</td><td>qqH (0.74)</td><td>qqH (0.72)</td><td>qqH (0.72)</td><td>qqH (0.57)</td></tr>
<tr><td>$Z \rightarrow \tau\tau$</td><td>ztt (0.52)</td><td>ztt (0.66)</td><td>ztt (0.63)</td><td>ztt (0.62)</td></tr>
<tr><td>QCD</td><td>qcd (0.45)</td><td>qcd (0.21)</td><td>qcd (0.17)</td><td>qcd (0.48)</td></tr>
<tr><td>$t\bar{t}$</td><td>tt (0.55)</td><td>tt (0.79)</td><td>tt (0.75)</td><td rowspan="5">misc (0.45)</td></tr>
<tr><td>$Z \rightarrow \ell\ell$</td><td rowspan="2">misc (0.24)</td><td>zll (0.55)</td><td>zll (0.53)</td></tr>
<tr><td>W+jets</td><td>wj (0.43)</td><td>wj (0.51)</td></tr>
<tr><td>Diboson</td><td>db (0.46)</td><td rowspan="2">misc (0.21)</td><td rowspan="2">misc (0.28)</td></tr>
<tr><td>Single t</td><td>st (0.30)</td></tr>
</table>

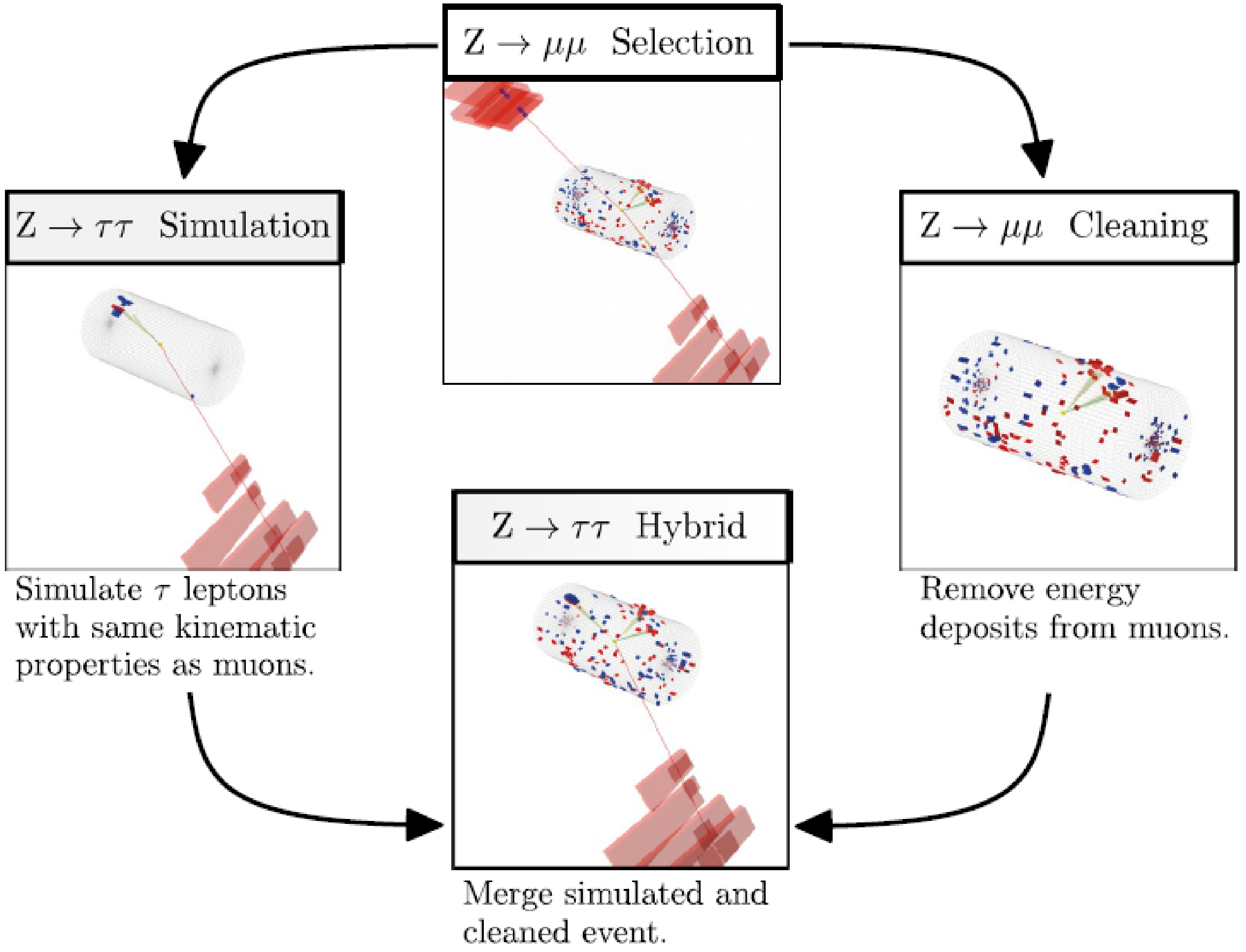
$H \to \tau\tau$ (cont'd)

Embedding

arxiv:1903.01216

- Modeling of background with real τ leptons (mainly $Z \to \tau\tau$)



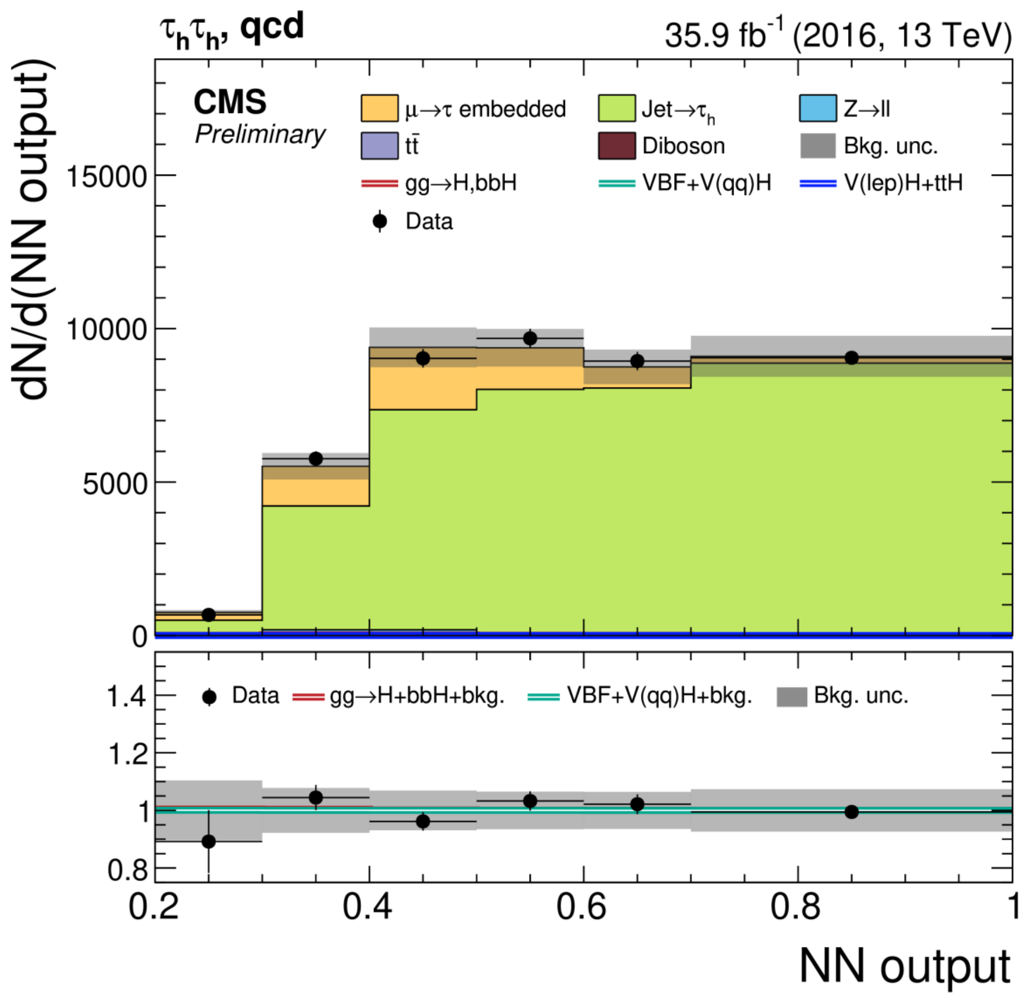


$H \to \tau\tau$ (cont'd)

Fake factor method

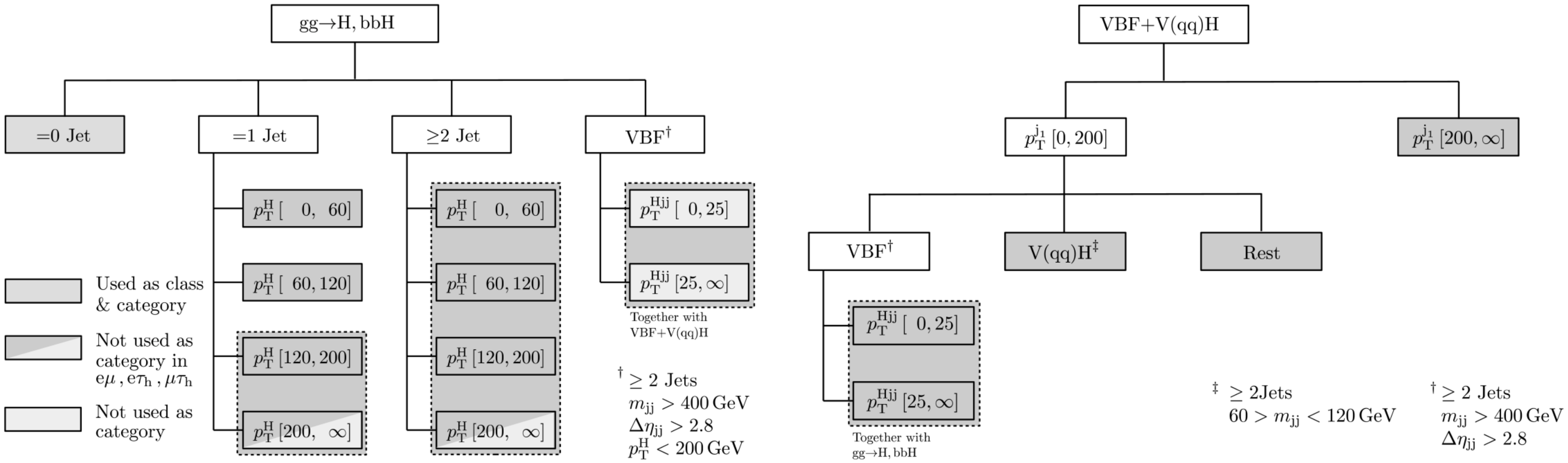
arxiv:1801.03535

- Modeling of background due to jets being misidentified as hadronic τ lepton decays
- Estimated from control regions with loosened selection, applying an appropriate weight ("fake factor")
- $F_F(p_T, decay\ mode, N_{jet})$



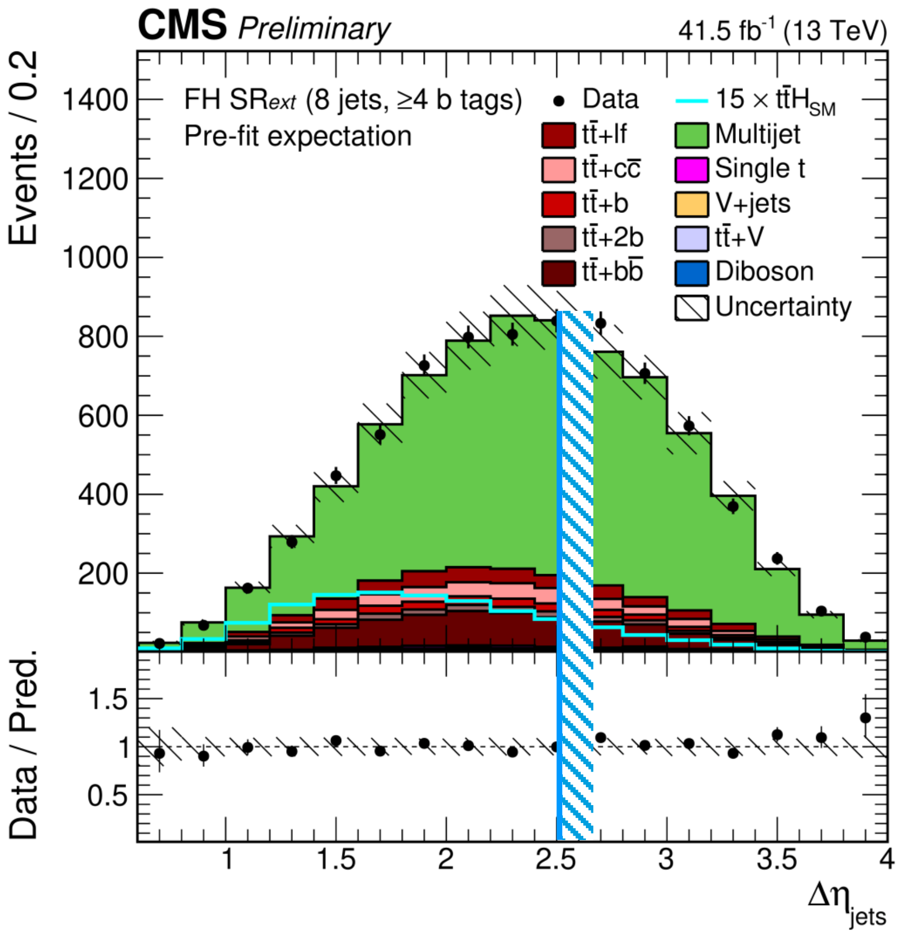
$H \to \tau\tau$ (cont'd)

STXS schema and analysis categories



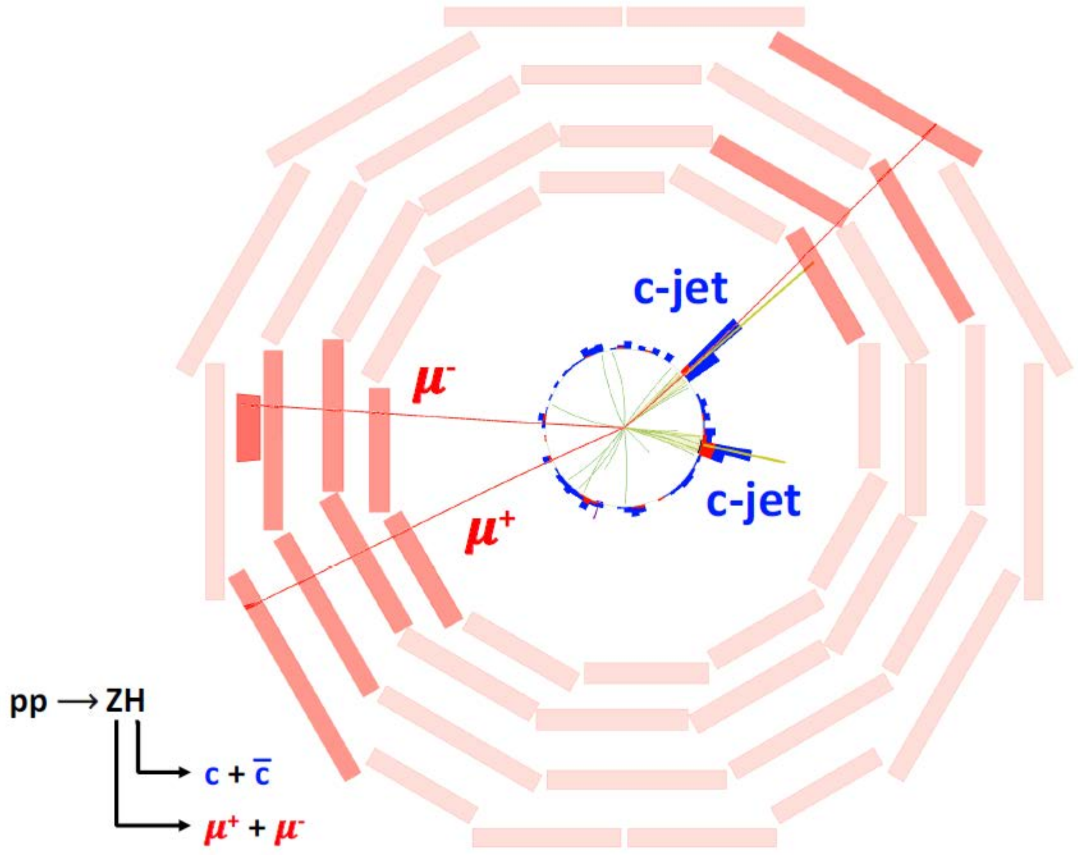
ttH

	$N_{\text{b tag}} = 2$ $N_{\text{b tag loose}} \geq 3$	$N_{\text{b tag}} \geq 3$
QGLR > 0.5	CR (to extract distribution)	SR (final analysis)
QGLR < 0.5	Validation CR (to validate distribution)	VR (comparison with data)



$H \rightarrow c\bar{c}$

Candidate event display



$H \rightarrow c\bar{c}$ (cont'd)

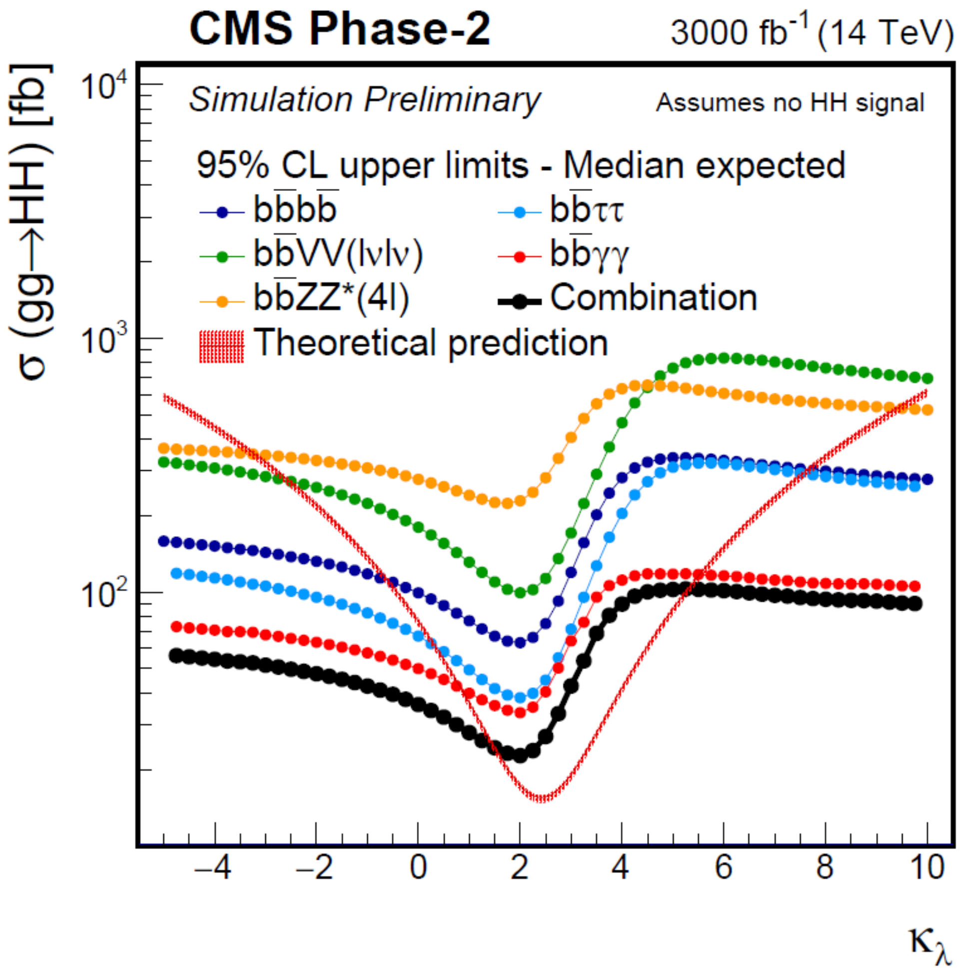
Resolved-jet and merged-jet analyses and their combination

95% CL exclusion limit						
	resolved-jet	merged-jet	combination			
	($p_T(V) < 300\,GeV$)	($p_T(V) \geq 300\,GeV$)	0L	1L	2L	All channels
expected	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	37^{+16}_{-11}
observed	86	75	83	110	93	70

HH projection

Cross sections and projected upper limits by channel (based on Delphes)

Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71



Coupling projections: scenarios

- **“Run 2 systematic uncertainties” scenario (S1):** All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be unchanged with respect to the reference analysis;
- **“YR18 systematic uncertainties” scenario (S2):** Theoretical uncertainties are scaled down by a factor of two, while experimental systematic uncertainties are scaled down with the square root of the integrated luminosity until they reach a defined minimum value based on estimates of the achievable accuracy with the upgraded detector [11].

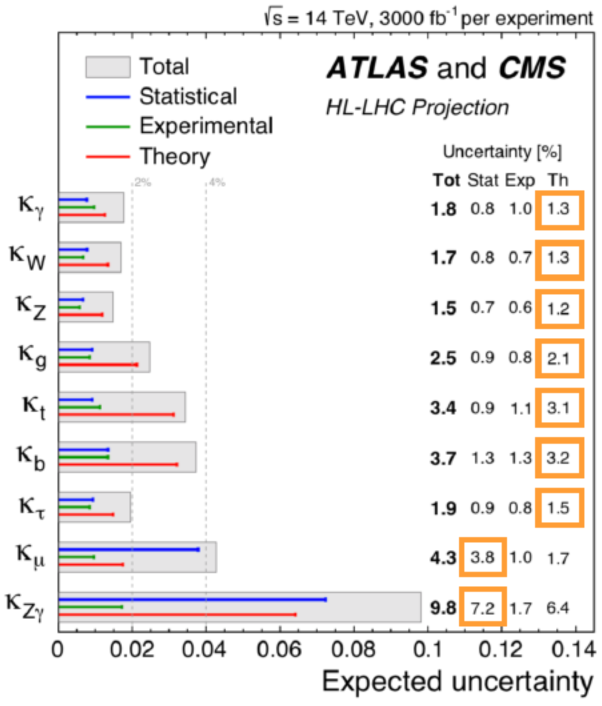
Higgs couplings and self-coupling projections

ATLAS + CMS Combinations

from: Higgs Physics at the HL-LHC and HE-LHC ("Yellow Report")

arxiv:1902.00134

Couplings



Higgs boson self-coupling