Measurements of Higgs boson properties in leptonic final states at CMS

Olena Hlushchenko on behalf of CMS

EUROPEAN PHYSICAL SOCIETY HEP2019

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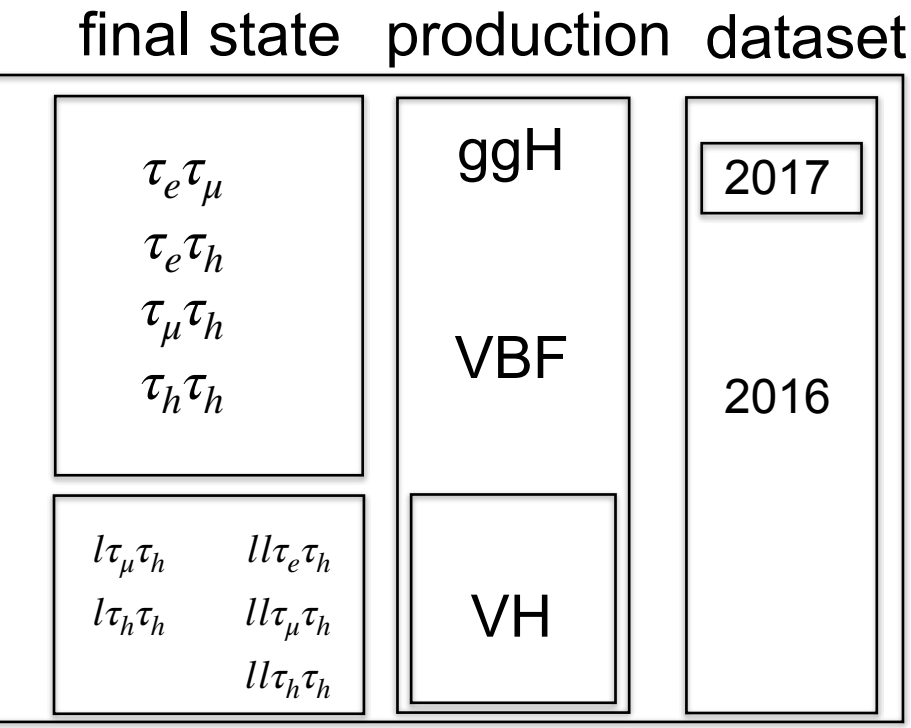
Content of this talk

Higgs bosons:

- Measurement of production and decay
- Constrains on anomalous HVV couplings (initial state)
- Search for associated VH production



$H \rightarrow \tau\tau$

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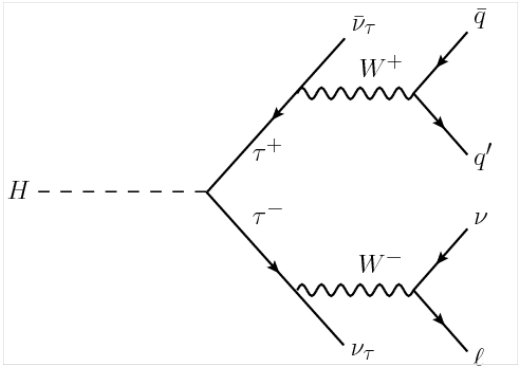
H→ττ

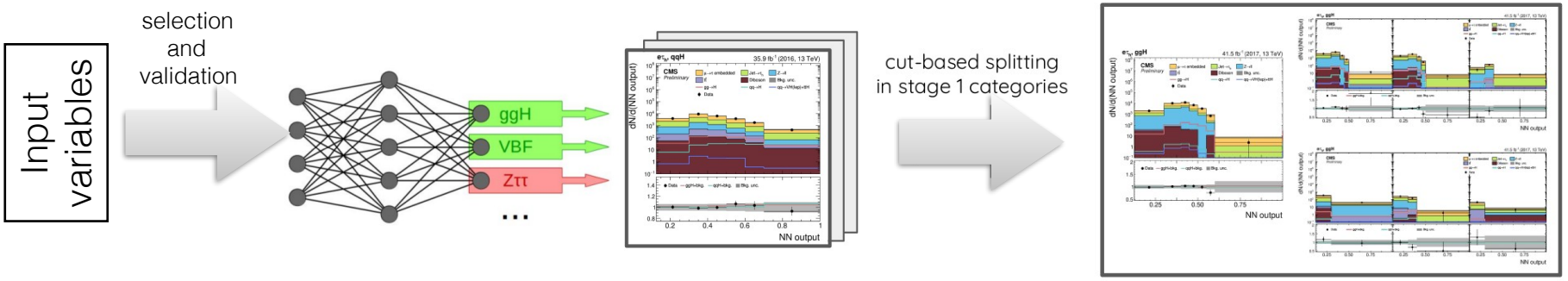
CMS-HIG-18-032
(previous publication: HIG-16-043)

New
- 90% of backgrounds with data-driven methods
  - embedding:
    - DY, tt̄ and VV with genuine τ_h
  - fake factors:
    - tt̄, W+jets and QCD with jet→τ

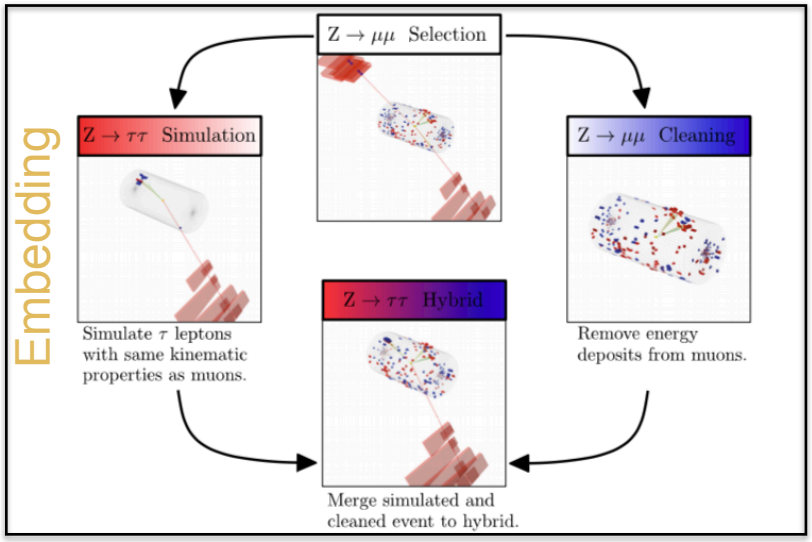


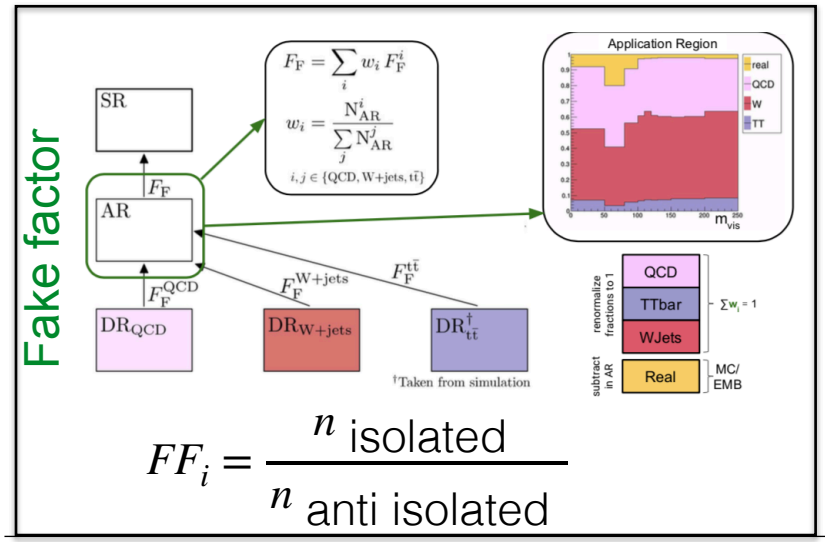
New
- Differential in p_T^{Higgs} STXS-1

New
- Machine learning used for categorization

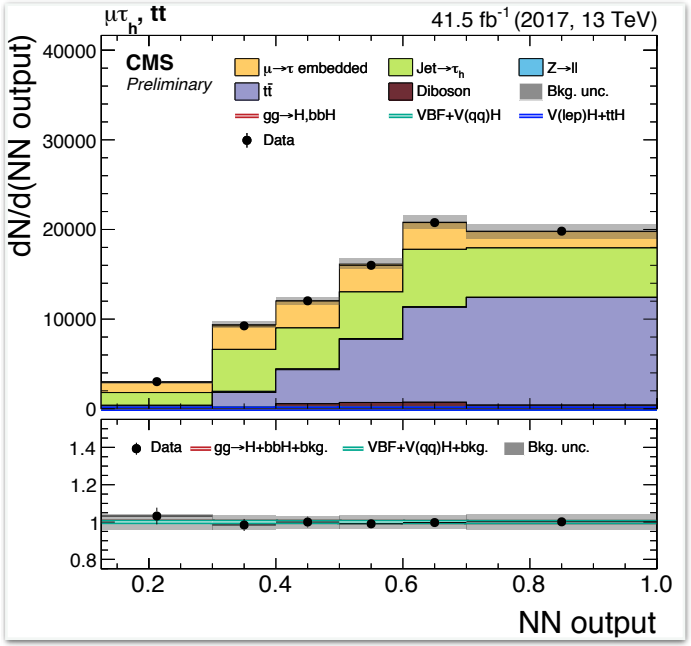


H→ττ: Analysis components



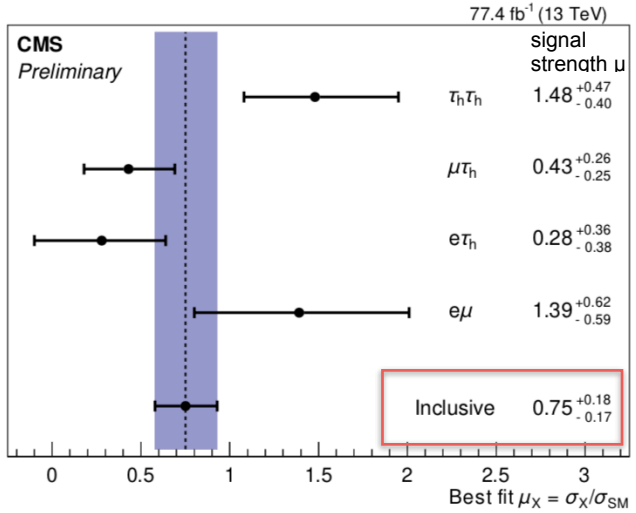


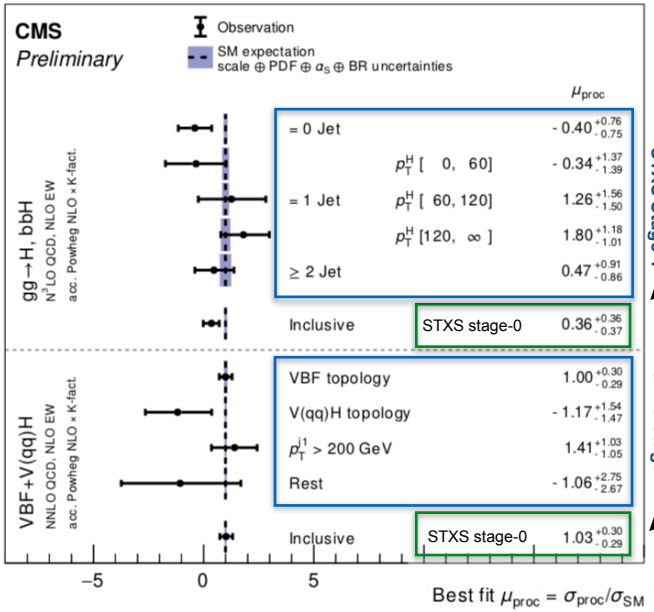
Background categories serve as CR:



$t\bar{t}$ with genuine τ
$t\bar{t}$ with e, μ → τ
$t\bar{t}$ with jet → τ

H→ττ - Results





- Simplified template cross section (STXS) measurements:
  - I. **Inclusive** SM H → ττ:

$$\sigma_{\text{incl}}\, B(H \to \tau\tau) = 2.56 \pm 0.48\ (\text{stat}) \pm 0.34\ (\text{syst})\ \text{pb}$$

  - II. **ggF** and **VBF** separately (**STXS Stage-0**):

$$\sigma(gg \to H,bbH)B(H \to \tau\tau) = 1.11 \pm 0.81\ (\text{stat}) \pm 0.78\ (\text{syst})\text{pb}$$

expected: 49.066 x 0.06272 pb

$$\sigma(\text{VBF+V(qq)H})B(H \to \tau\,\tau\,) = 0.34 \pm 0.08\ (\text{stat}) \pm 0.09\ (\text{syst})\ \text{pb}$$

expected: 5.155 x 0.06272 pb

  - III. II split in p_T bins (**STXS Stage-1**)

VH production

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VH production

New • Direct and independent probe of WH and ZH couplings using 2016 data

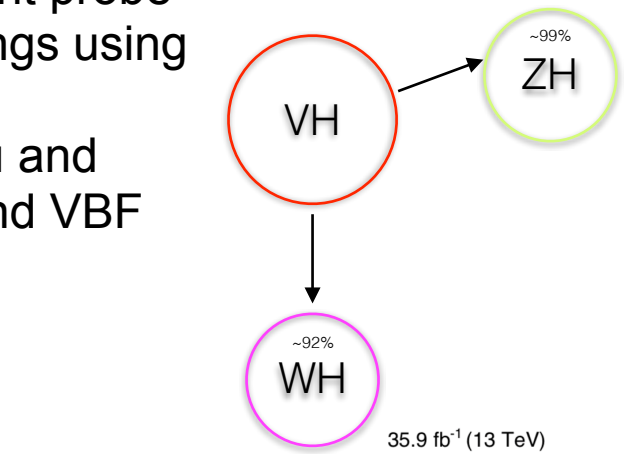
New • Combined results in μ and κ_V/κ_F including ggH and VBF production

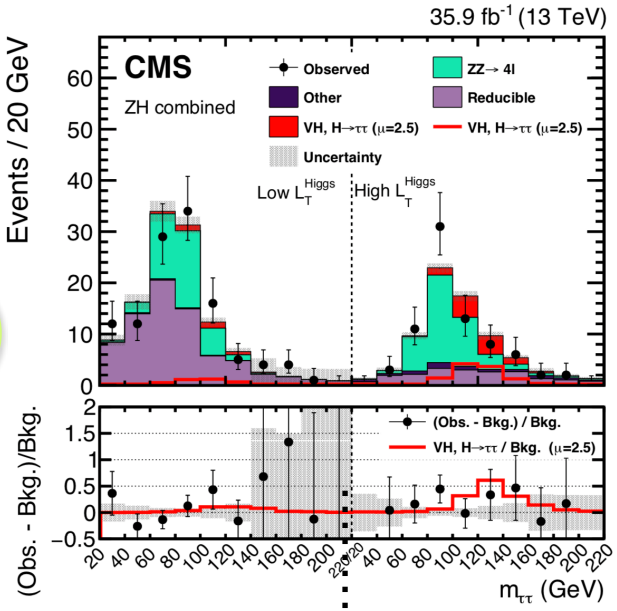
- Partially data-driven background estimation:
  - Fake rate method

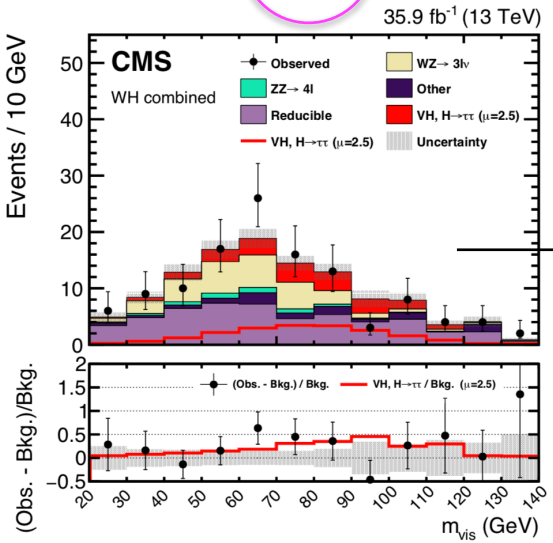
$$jet \rightarrow \tau_h$$

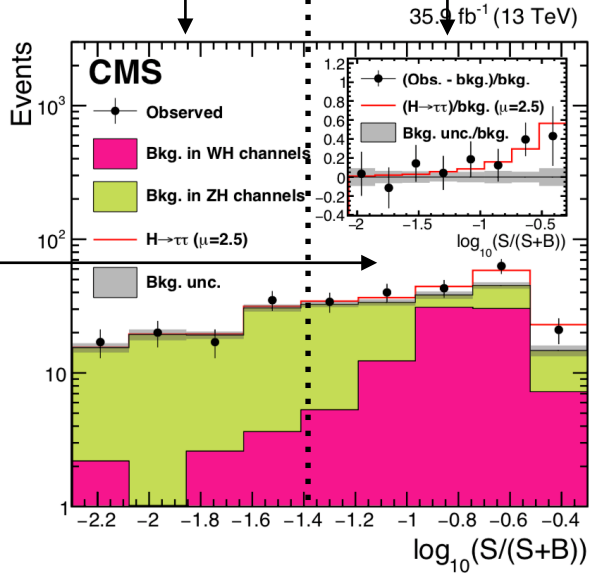
L_T^{Higgs} : scalar sum of visible H decay products

JHEP 06 (2019) 093

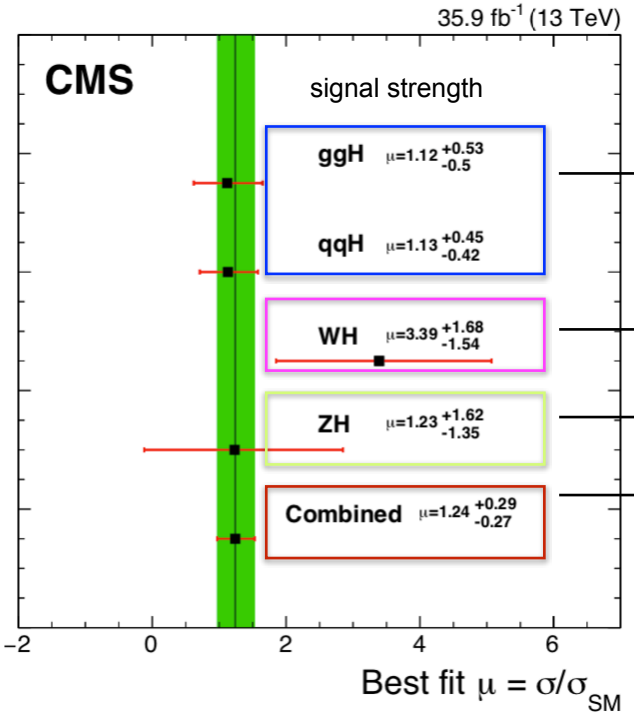








VH production - Results



Best fit signal strength:

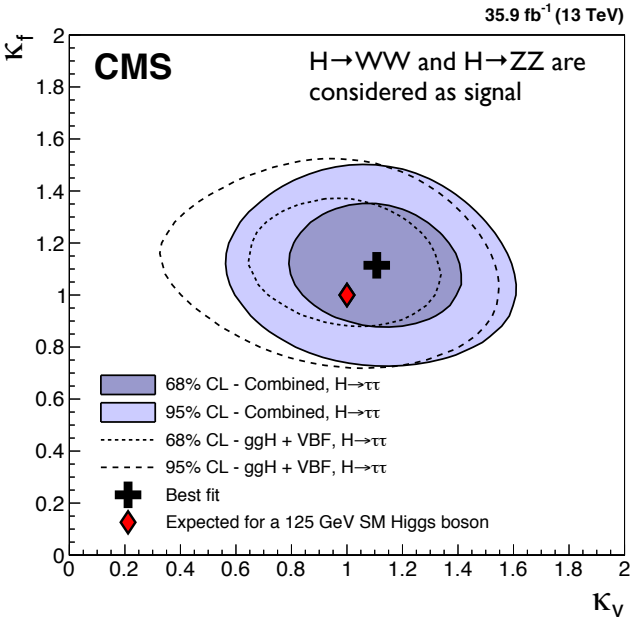
$$\mu^{ggH} = 1.12^{+0.53}_{-0.5}$$

$$\mu^{qqH} = 1.13^{+0.45}_{-0.42}$$

$$\mu_{WH} = 3.39^{+1.68}_{-1.54}$$

$$\mu_{ZH} = 1.23^{+1.62}_{-1.35}$$

$$\mu^{comb} = 1.24^{+0.29}_{-0.27}$$



- Likelihood scan in the (κ_V,κ_f) parameter space:
  - **VH** 10% reduction in max extend of 95% CL
  - **κ_V, κ_f** : coupling strength modifiers to vector bosons and to fermions

HVV anomalous couplings

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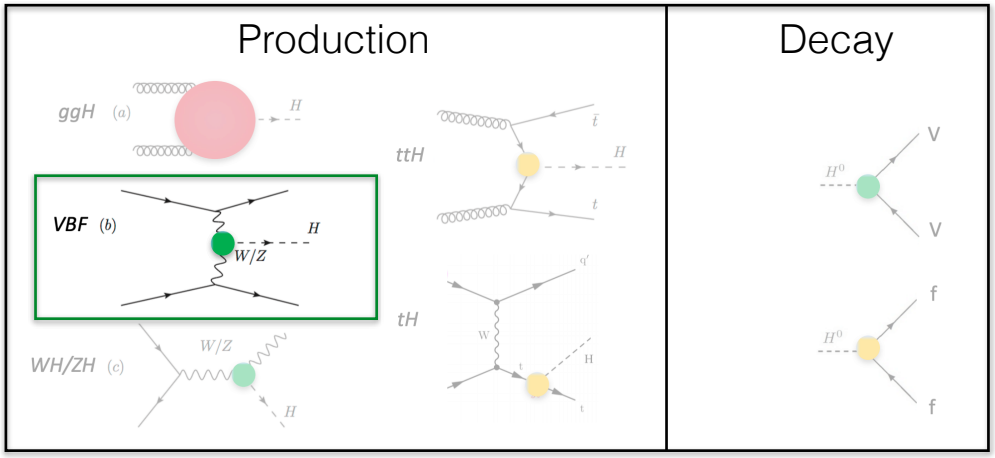
CMS-HIG-17-034
arXiv:1809.03590

HVV anomalous couplings

New • 2016 data analyzed and results combined with those from the H → ZZ → 4l targeting HVV anomalous coupling

New • Stringent constraints on *CP*-violating and *CP*-conserving parameters

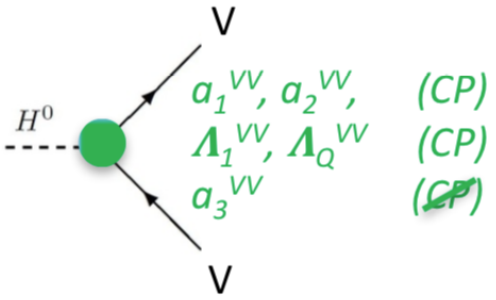
- **Analysis is not sensitive to anomalous couplings in the decay**
- Optimized for VBF production (optimal for HVV, not Hgg or VH couplings)
- Parameters to measure: individual coupling ratios



HVV anomalous couplings

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

scalar (0+) | pseudoscalar (0-)



- effective cross-section ratios:

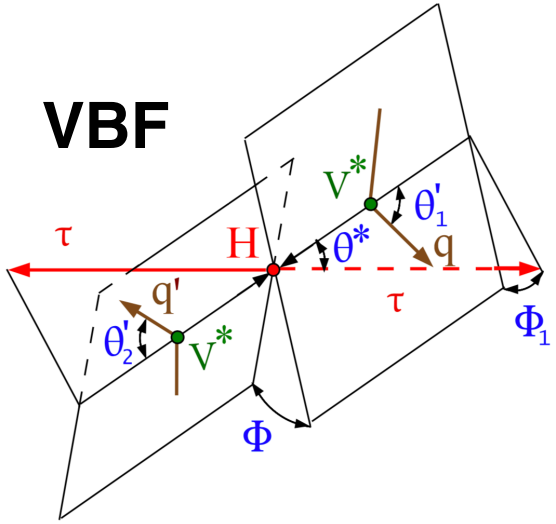
$$f_{a3} = \frac{|a_3|^2 \sigma_3}{S} \longrightarrow \begin{array}{l} = 1 : \text{pseudoscalar} \\ \neq 0 : \text{CP violation} \end{array}$$

$$f_{a2} = \frac{|a_2|^2 \sigma_2}{S}$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4}{S}$$

$$f_{\Lambda 1}^{Z\gamma} = \frac{\tilde{\sigma}_{\Lambda 1}^{Z\gamma} / (\Lambda_1^{Z\gamma})^4}{S}$$

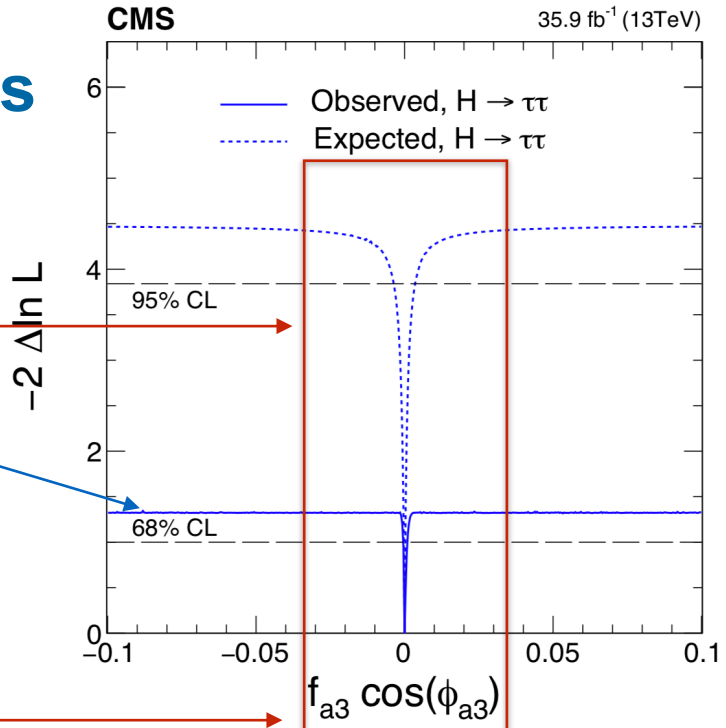
$$S = \sum_{i=1,2,3} |a_i|^2 \sigma_i + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \ldots$$



HVV anomalous couplings - Results

2016:

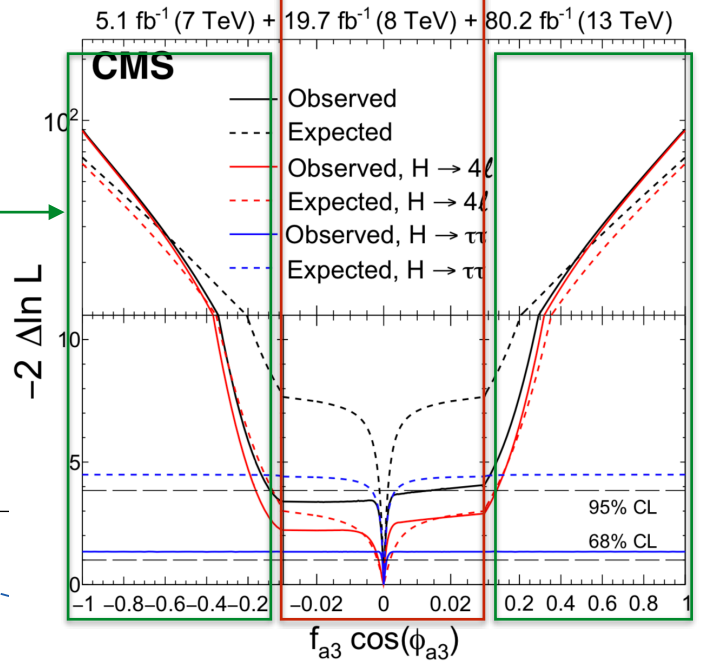
- σ in VBF/VH production increases quickly with f_{ai}
  - good sensitivity for small f_{ai}
  - large plateau corresponds to $\mu_V=0$



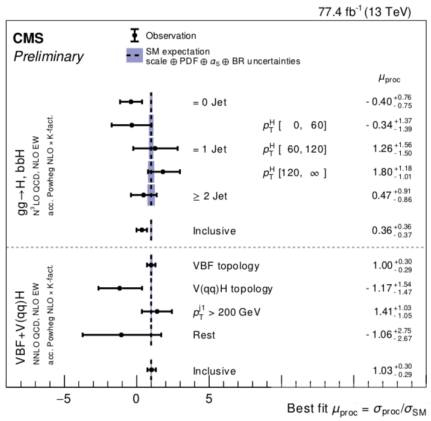
Combined:

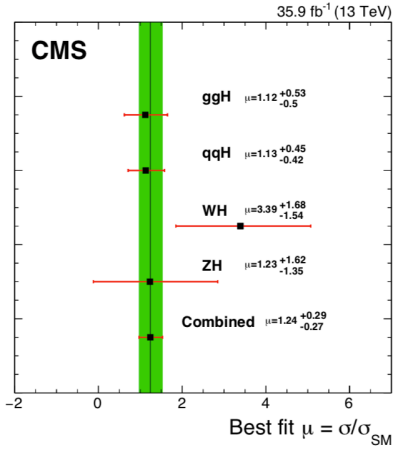
- this analysis:
  - 2σ exclusion for small anomalous couplings from VBF

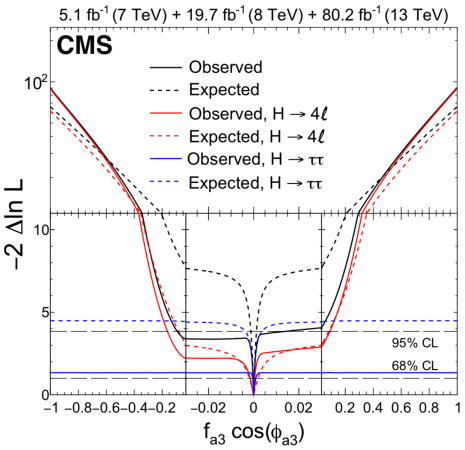
- H→ZZ:
  - High CL exclusion of large anomalous couplings from decay information
  - Matrix Element Likelihood Approach: for production/sg/bg separation
  - couplings measured also in decay



Summary







First differential in p_T measurement of H→ττ cross-sections

H→ττ cross-sections measured for individual ZH and WH production mechanisms as well as for combination with ggH and VBF

Updated limits on anomalous couplings

One more thing…

- Measurements of Higgs boson differential distributions and couplings at CMS
  Matthias Schroeder - 12 Jul 2019, 17:00
- Measurements of Higgs boson properties in hadronic final states at CMS
  Leonardo Giannini - 11 Jul 2019, 10:15
- Higgs boson rare and exotic decays at CMS
  Fengwangdong Zhang -11 Jul 2019, 17:05
- Searches for additional neutral Higgs bosons at CMS
  Dermot Anthony Moran - 12 Jul 2019, 14:45

Appendix

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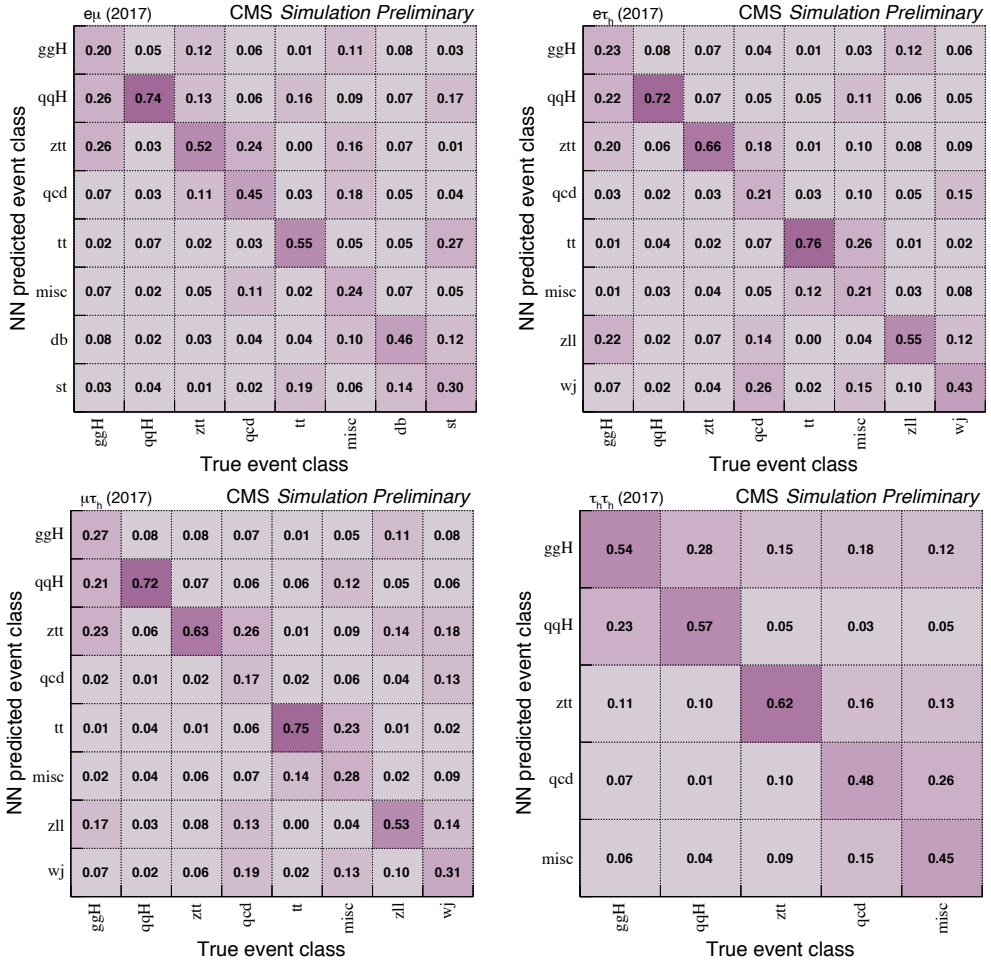
Analysis components

Background process	MisId.	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$Z \to \tau\tau$		EMB	EMB	EMB	EMB
$W + jets$		MC	F_F	F_F	F_F
QCD		CR	F_F	F_F	F_F
$Z \to ll$	$jet \to \tau_h$	MC	F_F	F_F	F_F
	$l \to \tau_h$		MC	MC	MC
VV + $single\ t$*	$jet \to \tau_h$	MC	F_F	F_F	F_F
	$l \to \tau_h$		MC	MC	MC
$t\bar{t}$*	$jet \to \tau_h$	MC	F_F	F_F	F_F
	$l \to \tau_h$		MC	MC	MC



Confusion matrices for the NN

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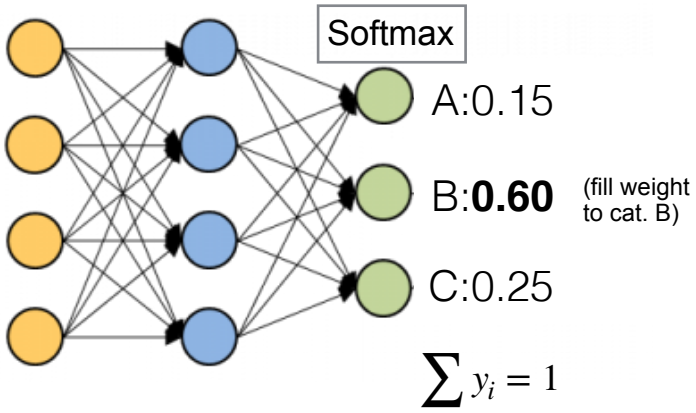
NN architecture and training

- Softmax output can be interpreted as Bayesian
- “probability” in the sense of:
- “Event X is likely to belong to class B, according to its kinematic properties”
- Backgrounds with small yields are merged

- Inputs: well described only (saturated goodness of fit 1D and 2D test)



(fill weight to cat. B)

Training
- One individual NN for each decay channel & year (→ 4x2)
- Processes weighted to equal yield for training
- 2 fold training to keep full dataset available for analysis
- Batch size: 100
- Validation split: 25%
- Early stopping: after 50 epochs

NN architecture
- Fully connected feed forward
- Activation function: hyperbolic tangent
- 2 hidden layers with 200 nodes respectively
- Softmax output
- Cross entropy as loss function
- Optimizer algorithm: Adam (learning rate 10-4)
- Weight initialization: Glorot (uniform)
- Regularization: Dropout layer after each hidden layer (30% probability), L2 regularization (10-4)

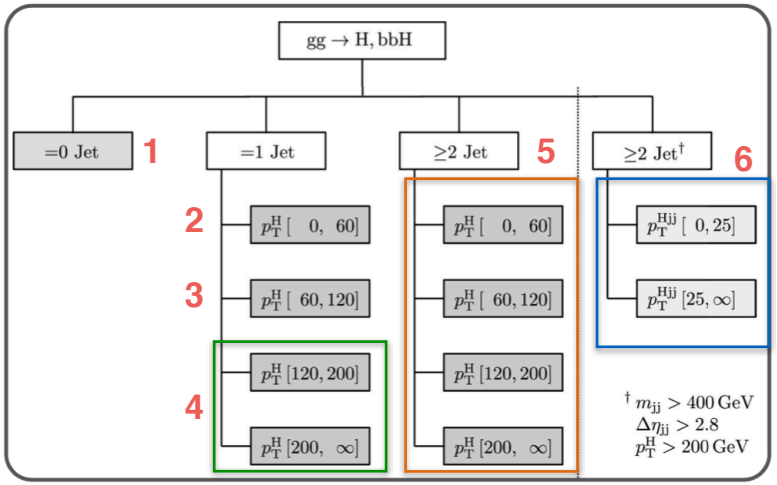
Process	Classes/Categories per final state			
	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$gg \to H$	ggH (0.20)	ggH (0.23)	ggH (0.27)	ggH (0.54)
VBF	qqH (0.74)	qqH (0.72)	qqH (0.72)	qqH (0.57)
$Z \to \tau\tau$	ztt (0.52)	ztt (0.66)	ztt (0.63)	ztt (0.62)
QCD	qcd (0.45)	qcd (0.21)	qcd (0.17)	qcd (0.48)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

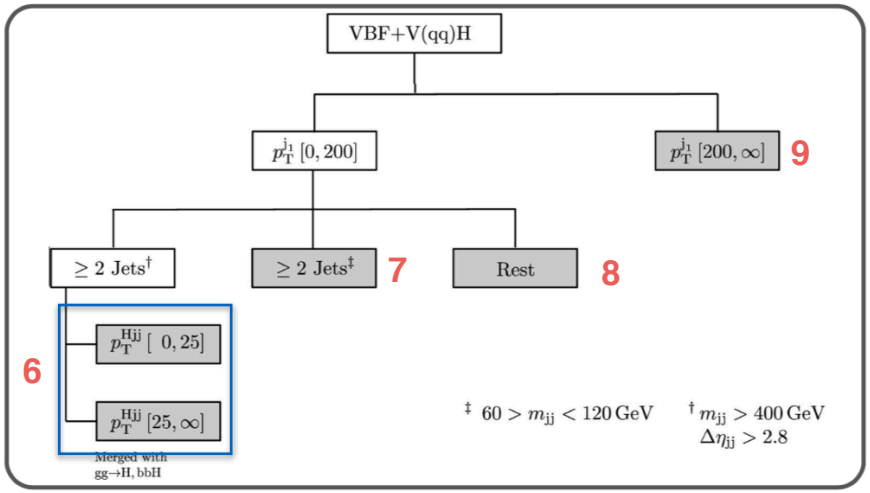
STXS stage 1 splitting

Due to low statistics/ sensitivity some **subcategories** have been merged and several **μ-values** are combined for the fit.

- **High p_T^H μ-values of = 1 Jet** in gluon fusion category
- **All p_T^H μ-values of ≥ 2 Jet** in gluon fusion category
- All μ-values of VBF topology

9 μ values measured

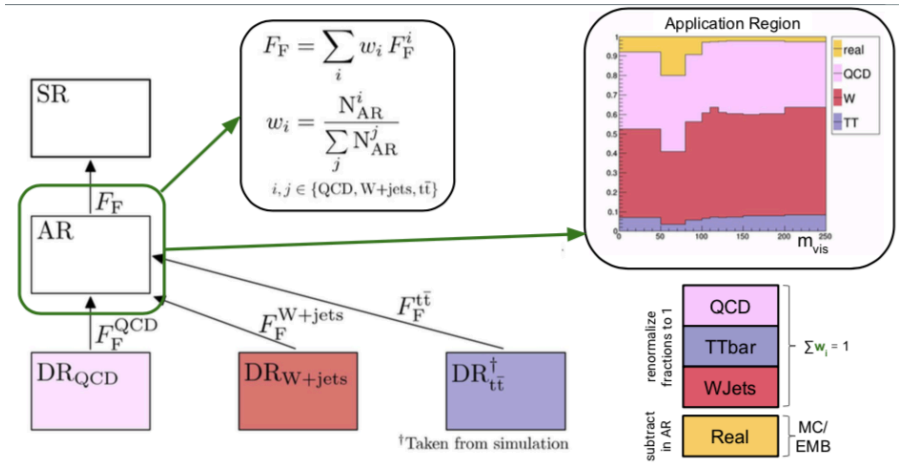


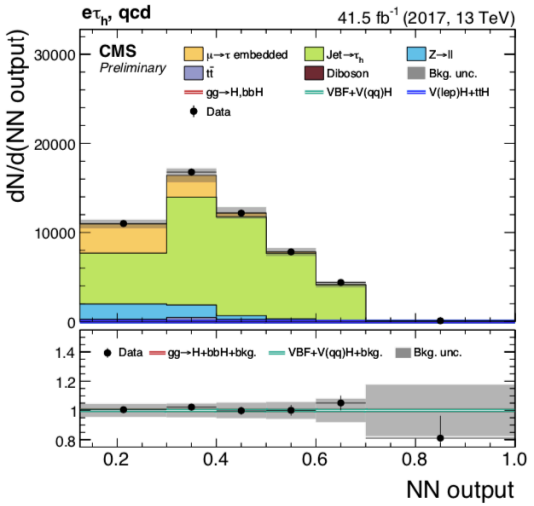


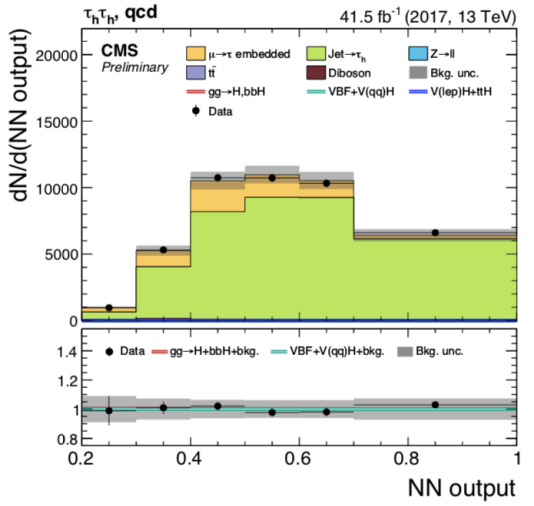
Fake factor method

- tt, W+jets, QCD processes with jet->tau
- Fake factor for each background component:

$$FF_i = \frac{n \text{ isolated}}{n \text{ anti isolated}}$$





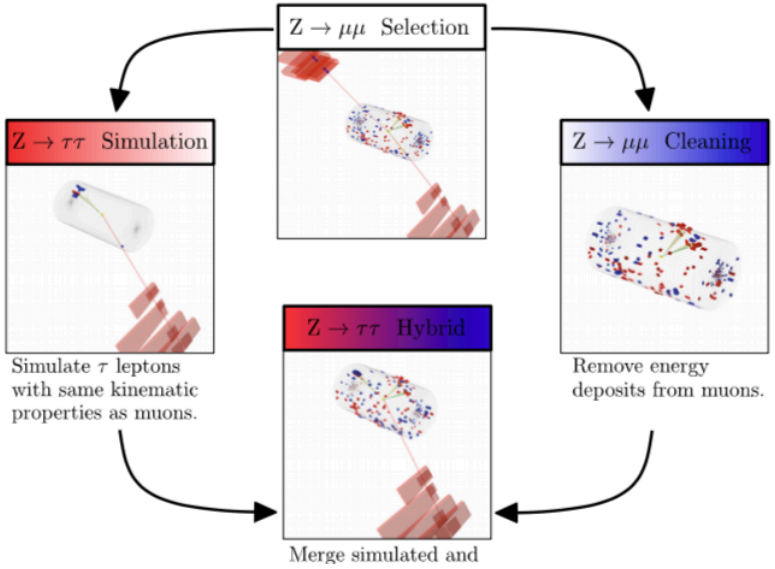


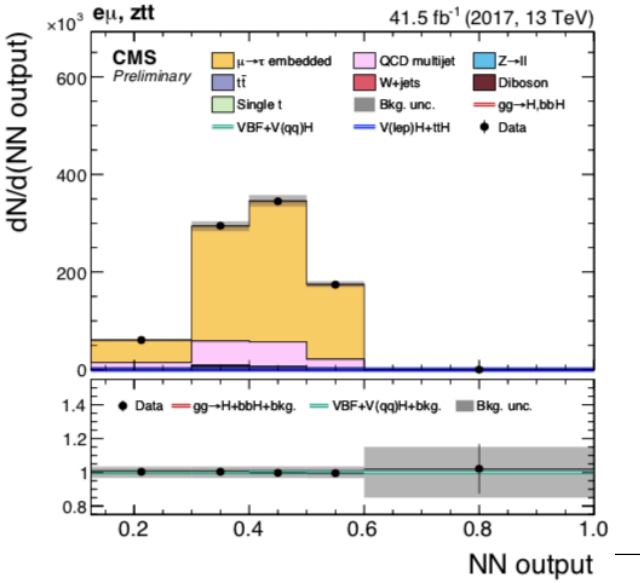
AN-2018/257

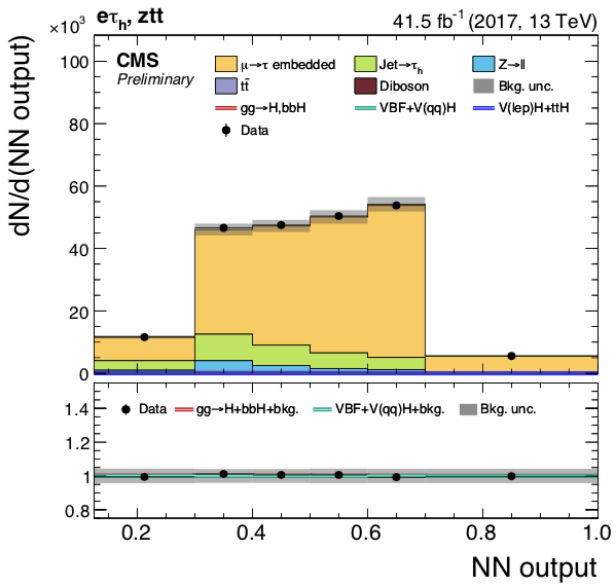
arXiv:1903.01216

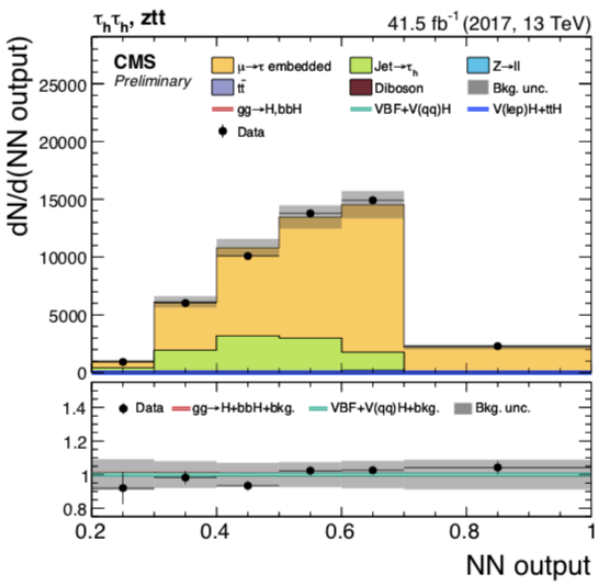
Embedding

- High statistics
- Better modeling out of the box:
  - MET
  - underlying event
  - jets etc.
- Orthogonal uncertainty model
- no theory uncertainties

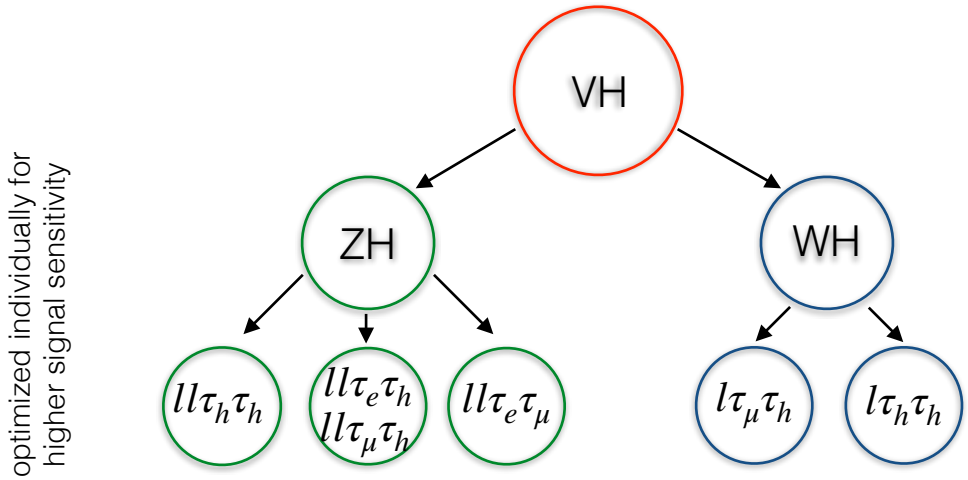


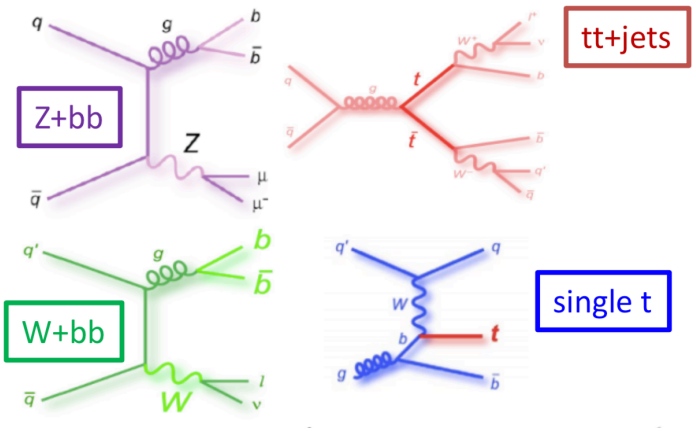






Search for the associated VH production via Higgs boson decays to τ leptons





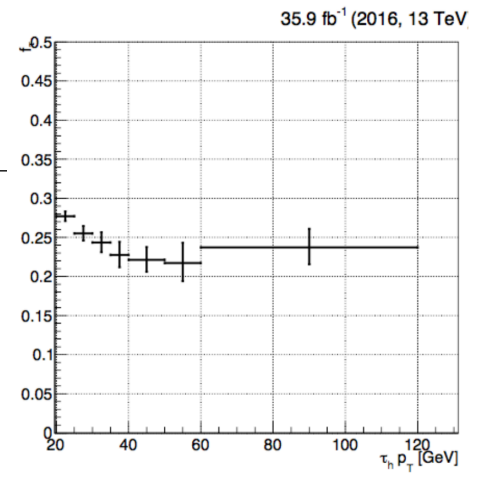
- Backgrounds from MC:
  - ttH, HWW, HZZ
  - Irreducible(**WZ**, ttW, **ZZ**, ZZ,ttZ,WWZ,WZZ,ZZZ)
- Backgrounds data-driven:
  - Reducible(jet->τ): Fake rate method

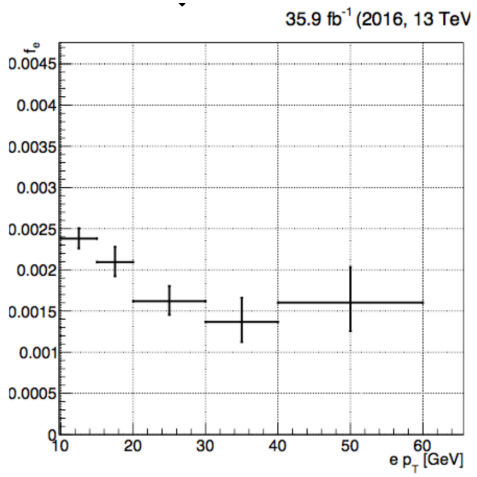
*leading l1 from W; l1 and l2 SS

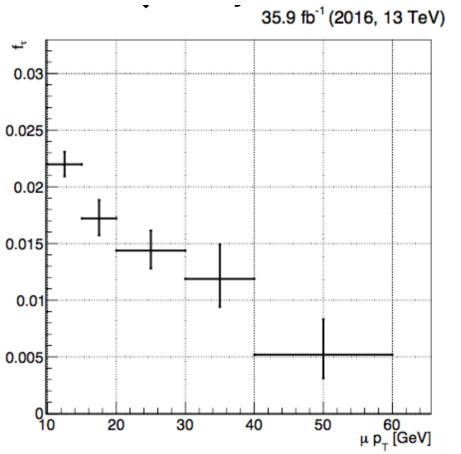
Fake rate

- FR is **applied to leptons associated to H** decay as fn of p_T
- Estimated from anti-isolated (semileptonic) or SS (for hadronic) data sample
  - contribution of prompt leptons estimated from MC are subtracted

- jet->μ
  - using Z(ee)+j
  - Denominator: Events passing baseline
  - Numerator: baseline & Medium muon ID and Iso < 0.15
- jet-> e/τ
  - using Z(μμ)+j
  - baseline selecting Z->μμ
  - e:
    - Denominator: pT(e) > 10 GeV, |ηe| < 2.5
    - Numerator: MVA WP80 ID and Iso < 0.1
  - τ:
    - Denominator: VL anti-e, L anti-μ, VL MVA τ ID
    - Numerator: τ passes Medium/Tight/VTight MVA ID

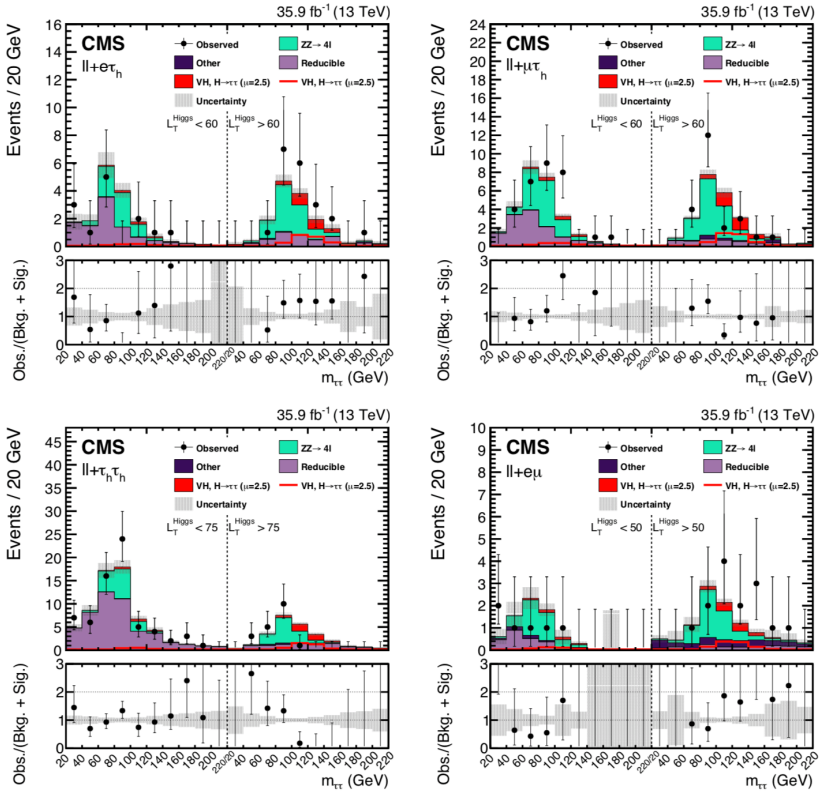




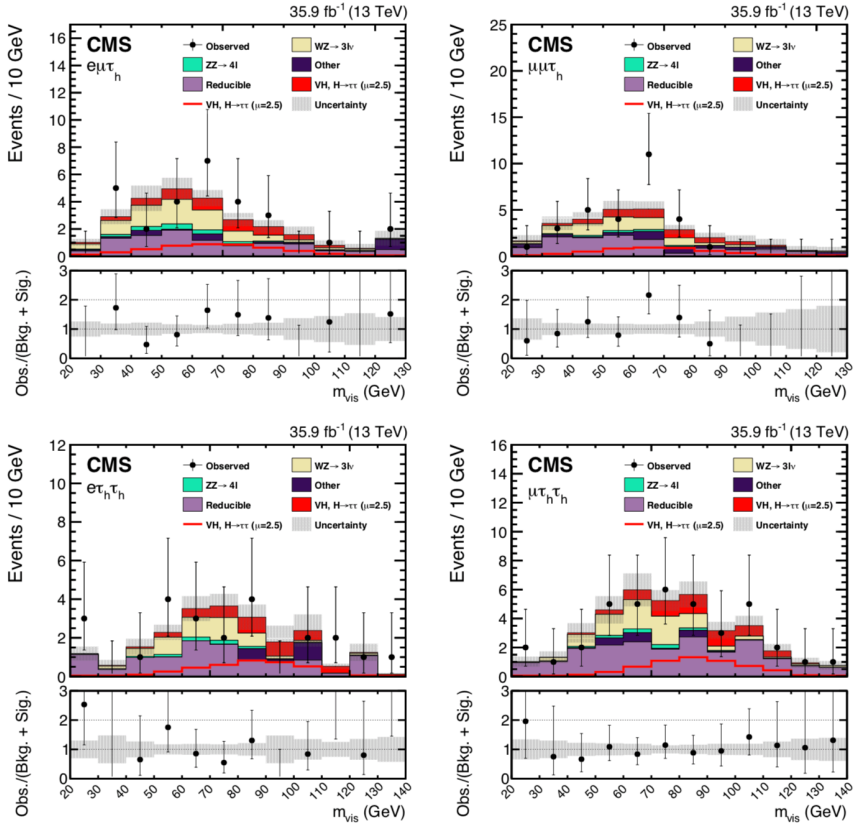


Post-fit mass distributions

ZH



WH



HVV anomalous couplings

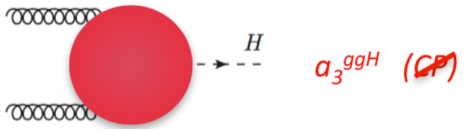
CP properties in Hgg have small effect on jet correlation: **taken into account explicitly in CP fit (fa3) with f_{a3}^{ggH} floated**

$$A(\mathrm{Hgg}) \sim a_2^{gg} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + a_3^{gg} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu}$$

scalar (0+) pseudoscalar (0-)

- assumption that only the t quark contributes to the loop
- general parameterization

$$f_{a3}^{ggH} = \frac{\left|a_3^{ggH}\right|^2}{\left|a_2^{ggH}\right|^2 + \left|a_3^{ggH}\right|^2}$$



Optimal observables for HVV anomalous couplings

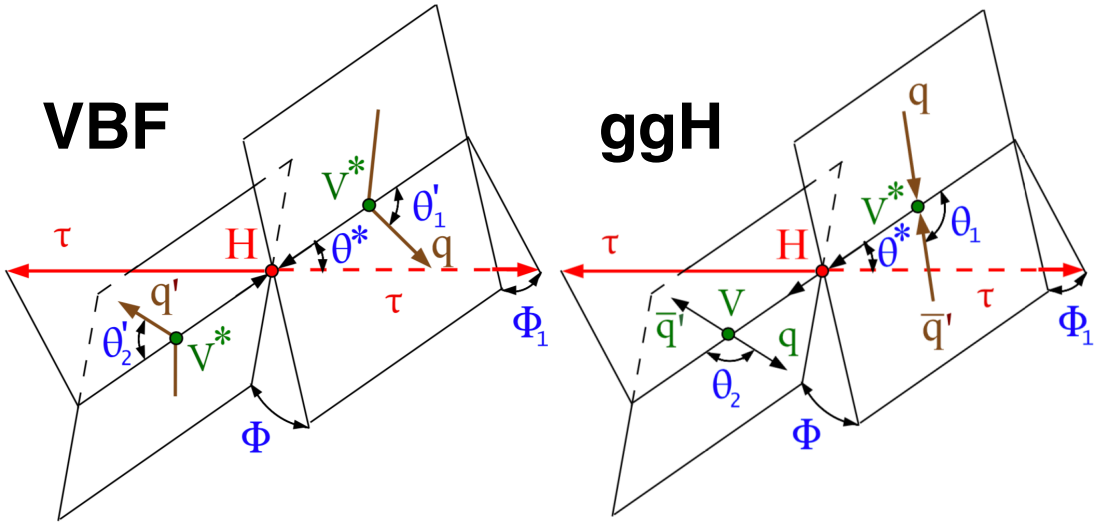
MELA package (**M**atrix **E**lement **L**ikelihood **A**pproach):

- "**Build discriminant for process A vs process B from ME bases probabilities**"
- Using full kinematic
- Discriminant: ratio of probabilities
  - Distinguish contributions: SM, BSM, interference

- separate SM from BSM:

$$D_{BSM} = \frac{P_{SM}}{P_{SM} + P_{BSM}}$$

D_{0-} (4 bins) for f_{a3}
D_{0h+} (4 bins) for f_{a2}
$D_{\Lambda 1}$ (4 bins) for $f_{\Lambda 1}$
$D_{\Lambda 1}^{Z\gamma}$ (4 bins) for $f_{\Lambda 1}^{Z\gamma}$



Results

2016:

68[95]% CL

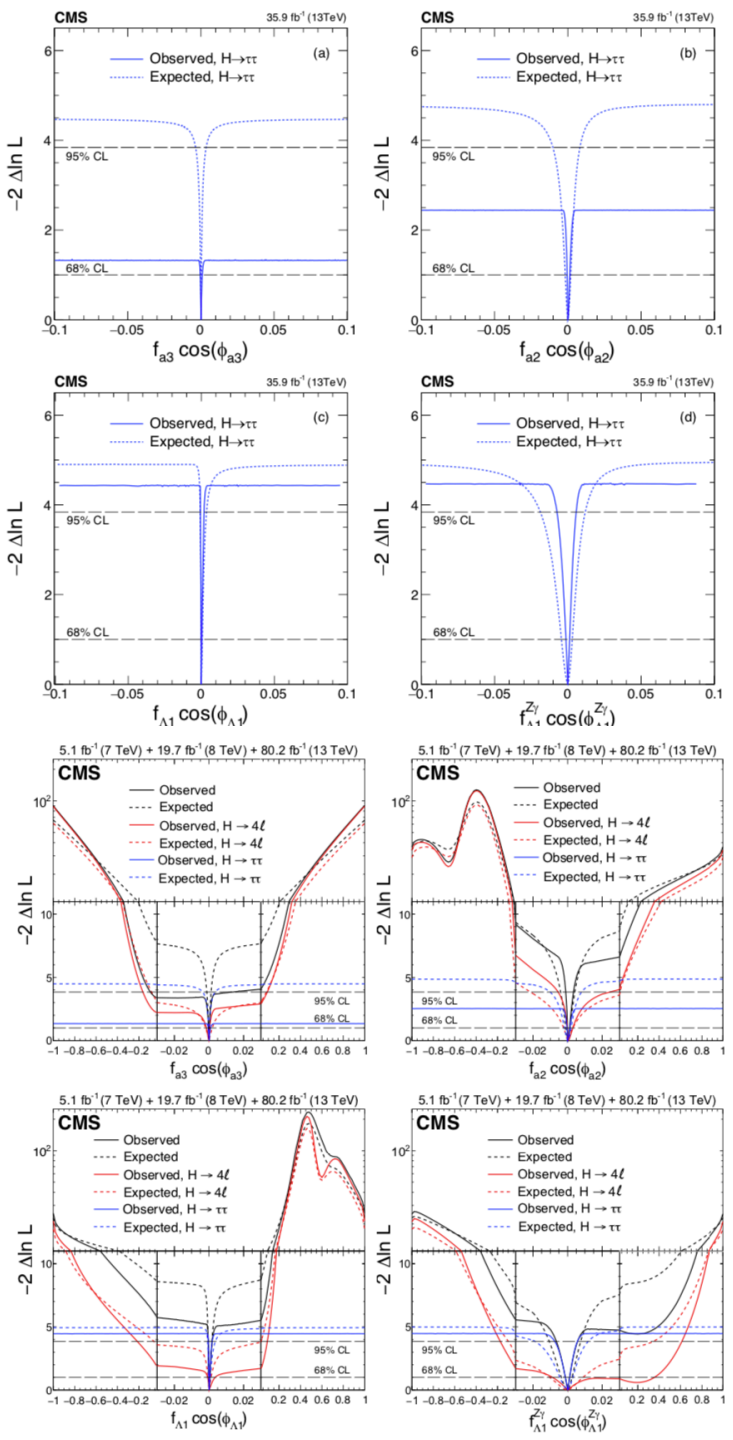
Parameter	Observed / (10^{-3})	Expected / (10^{-3})
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.93}_{-0.43}$ $[-1000, 1000]$	0.00 ± 0.28 $[-3.60, 3.60]$
$f_{a2}\cos(\phi_{a2})$	$0.0^{+1.2}_{-0.4}$ $[-1000, 1000]$	$0.0^{+2.0}_{-1.8}$ $[-10.0, 8.0]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.39}_{-0.10}$ $[-0.4, 1.8]$	$0.00^{+0.75}_{-0.16}$ $[-0.8, 3.6]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.0^{+1.2}_{-1.3}$ $[-7.4, 5.6]$	$0.0^{+3.0}_{-4.5}$ $[-19, 12]$

Best fit	μ_V	μ_F
for f_{a3}=0	0.55 ± 0.48	$1.03^{+0.45}_{-0.45}$
for f_{a2}=0	$0.72^{+0.48}_{-0.46}$	$0.89^{+0.43}_{-0.37}$
for $f_{\Lambda1}$=0	$0.92^{+0.44}_{-0.45}$	$0.82^{+0.46}_{-0.38}$
for $f_{\Lambda1}^{Z\gamma}$=0	$0.94^{+0.48}_{-0.46}$	0.79 ± 0.46

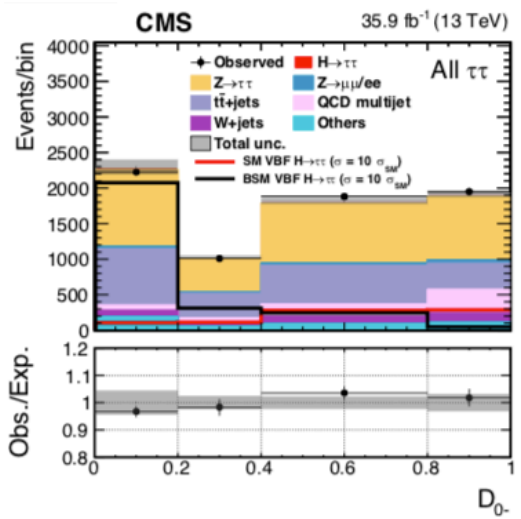
Combination:

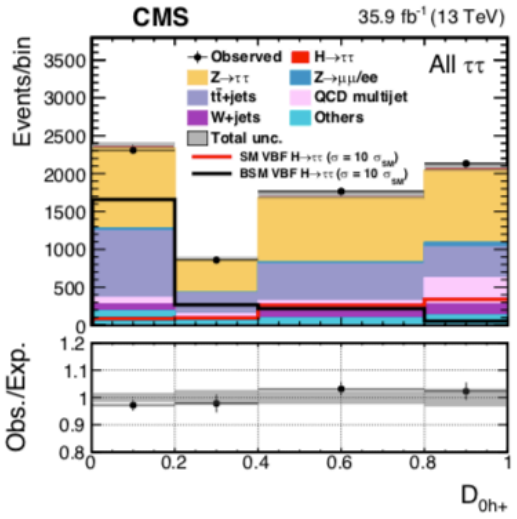
68[95]% CL

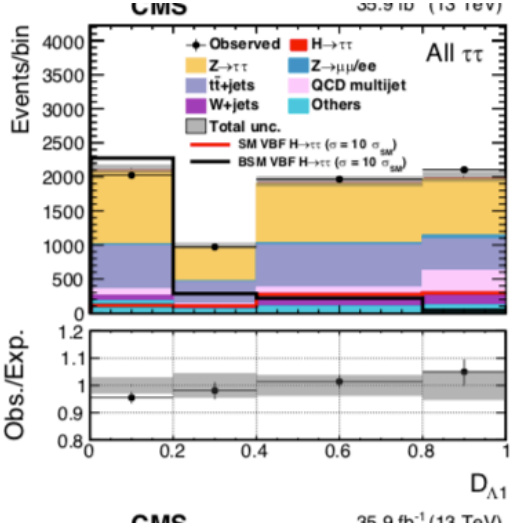
Parameter	Observed / (10^{-3})	Expected / (10^{-3})
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27 $[-92, 14]$	0.00 ± 0.23 $[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$ $[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$ $[-4.0, 4.2]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.53}_{-0.09}$ $[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$ $[-0.5, 1.7]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.0^{+1.1}_{-1.3}$ $[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$ $[-11, 8.0]$

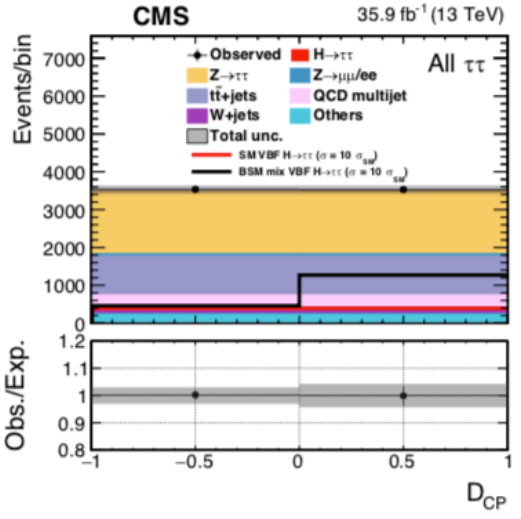


Optimal observables for HVV anomalous

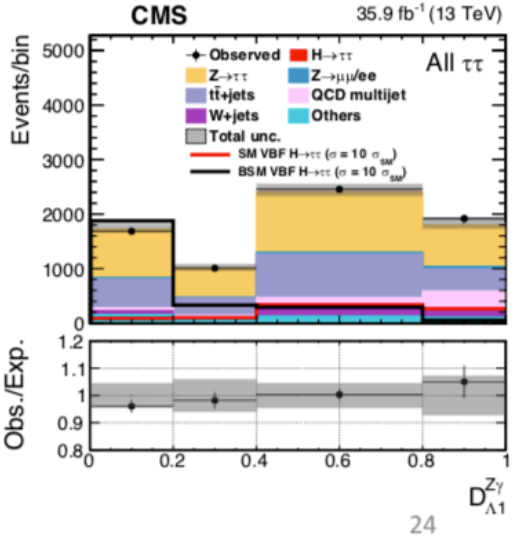








Postfit distributions of observables

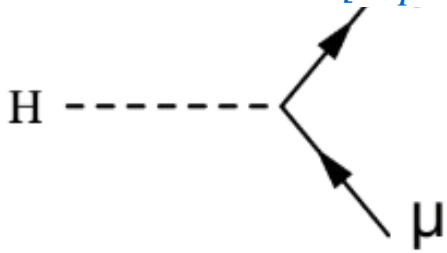


H→μμ - Results

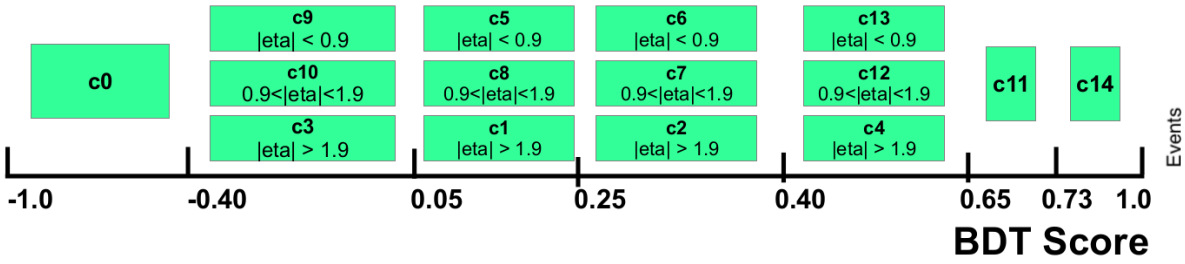
CMS-HIG-17-019
arXiv:1807.06325v2 [hep-ex]

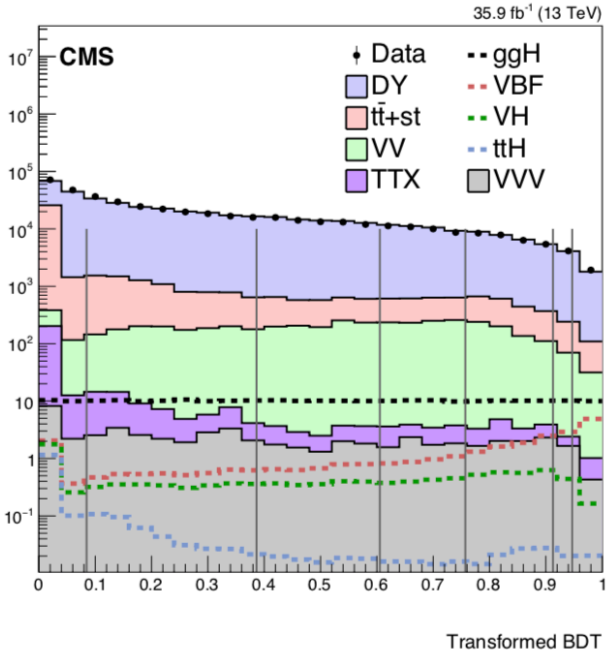
New • Run2 expected upper limit improved >3x compared to Run1 7.4(6.5) obs.[exp.]

New • BDT categorization used to improve signal sensitivity



$$\mathrm{mBW}(x) = \frac{e^{a_2 x + a_3 x^2}}{(x - m_Z)^{a_1} + \left(\frac{\Gamma_Z}{2}\right)^{a_1}}$$





BDT Features :

$p_T(\mu^+\mu^-)$	$\eta(j_1)$	nJetsCent
$\eta(\mu^+\mu^-)$	$\eta(j_2)$	nJetsFwd
$\lvert\Delta\eta(\mu^+\mu^-)\rvert$	$\lvert\Delta\eta(j_1, j_2)\rvert$	nBMed
$\lvert\Delta\phi(\mu^+\mu^-)\rvert$		MET

indico: "Higgs boson rare and exotic decays at CMS"

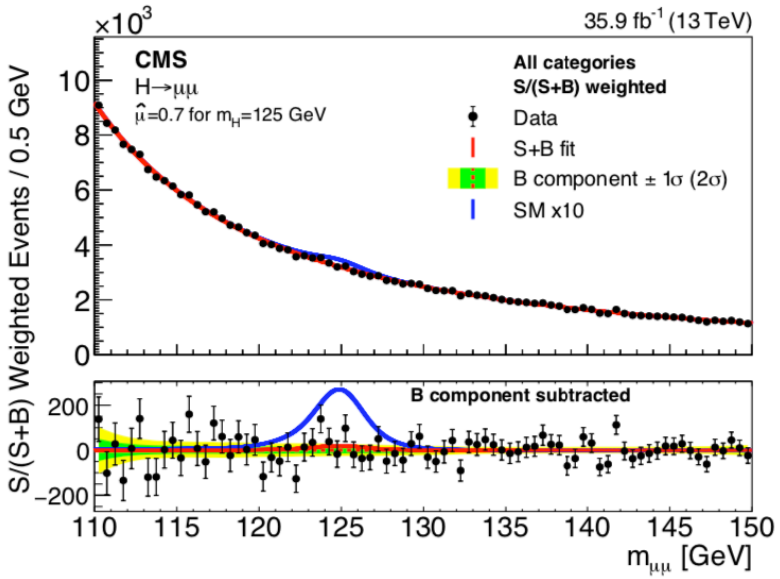
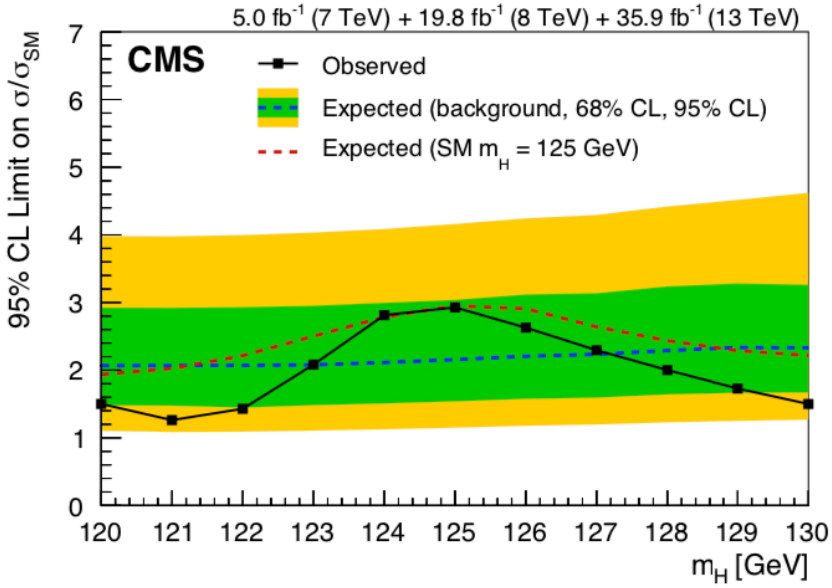
*categories ordered by sensitivity

H→μμ - Results

- best fit signal strength:

$$\hat{\mu}_{125} = 0.7 \pm 1.0(\text{ stat })^{+0.2}_{-0.1}(\text{ syst })$$

Combination

$$\hat{\mu}^{comb}_{125} = 1.0 \pm 1.0(\text{ stat }) \pm 0.1(\text{ syst })$$

- About 400 fb-1 estimated for 3σ