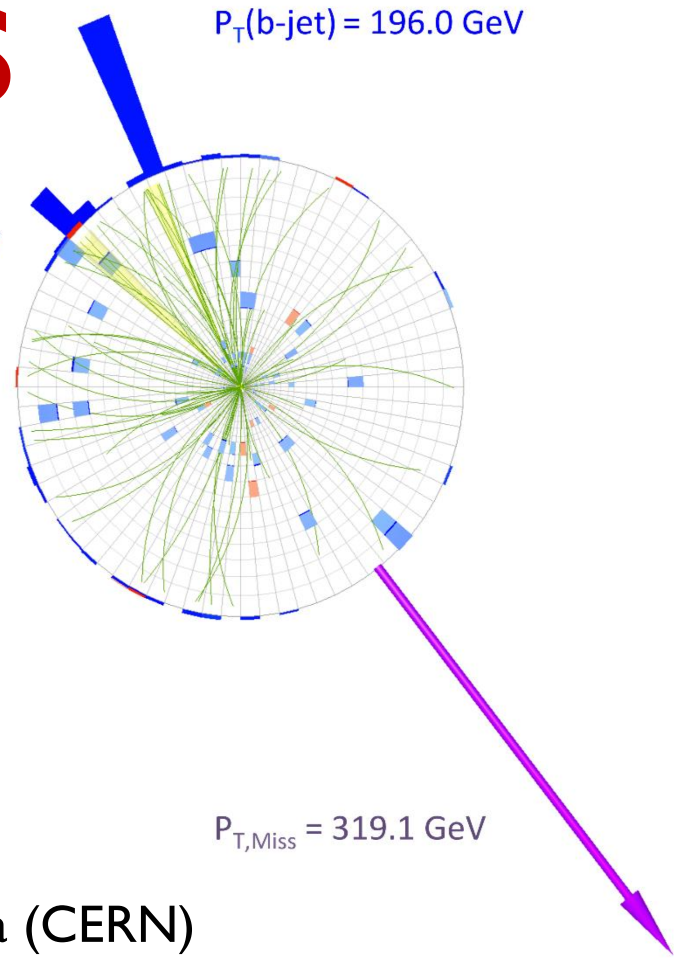
Latest from **CMS** on the exploration of the **Higgs sector**



P. Ferreira da Silva (CERN)

on behalf of the CMS Collaboration

Workshop on Multi-Higgs Models, IST (Lisbon)

Thursday, 6th September 2018

Outlook

- Brief introduction (experimental point of view)
- Where are we in the exploration of the Higgs sector?
- Where are we headed to?
- Summary

Brief introduction (experimental point of view)

Challenges for Higgs Physics in Run 2 of the LHC

CMS performance

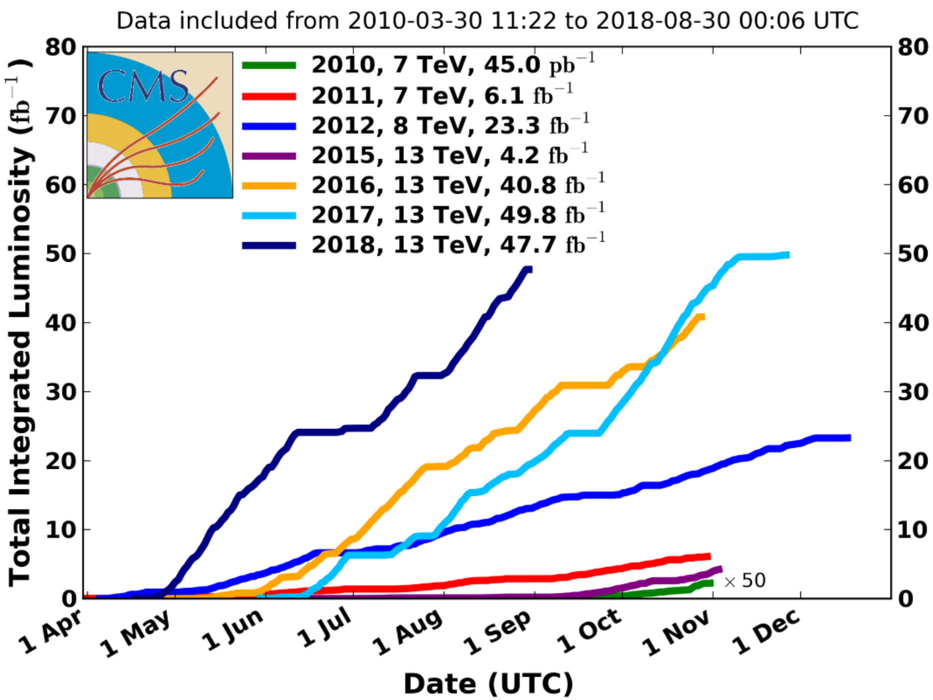
A golden Run for Higgs physics at the LHC

- **>140 fb^{-1}** (and still going) **of data accumulated at 13 TeV in LHC Run 2**
  - produced 16k $\mathrm{H} \to \gamma\gamma$, 33k $\mathrm{q\bar{q}H} \to \tau\tau$, 41k $\mathrm{t\bar{t}H}(b\bar{b})$, 184k $\mathrm{VH}(b\bar{b})$

    $\Longrightarrow$ differential measurements, reach for new direct observations

  - but (yet) only 1.5k $\mathrm{H} \to \mu\mu$, 13 $\mathrm{HH} \to \gamma\gamma b\bar{b}$

  $\Longrightarrow$ still away from direct observation, playground for searches



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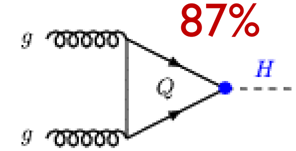
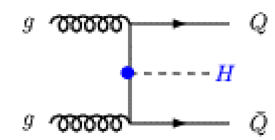


$\sigma(\mathrm{ggH}) \approx 44\mathrm{pb}$

$= 2.3 \times \sigma_{8\ \mathrm{TeV}}$

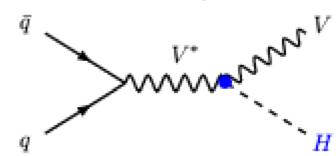
1%



$\sigma(\mathrm{t\bar{t}H}) \approx 0.6\mathrm{pb}$

$= 3.9 \times \sigma_{8\ \mathrm{TeV}}$

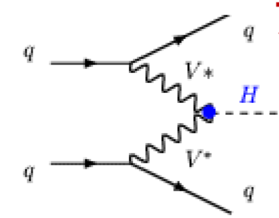
4%



$\sigma(\mathrm{VH}) \approx 2.2\mathrm{pb}$

$= 2.0 \times \sigma_{8\ \mathrm{TeV}}$

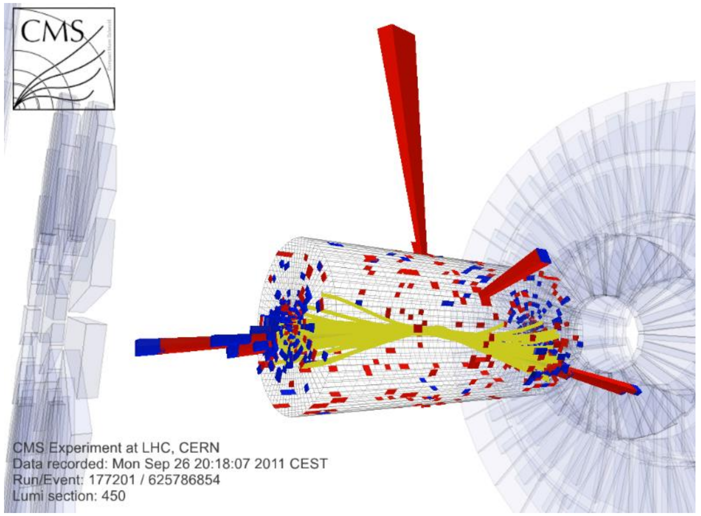
7%



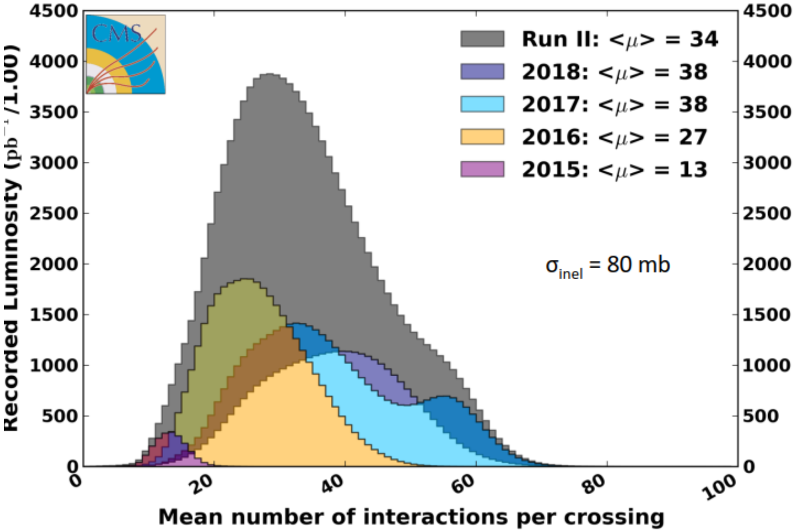
$\sigma(\mathrm{t\bar{t}H}) \approx 3.7\mathrm{pb}$

$= 2.4 \times \sigma_{8\ \mathrm{TeV}}$

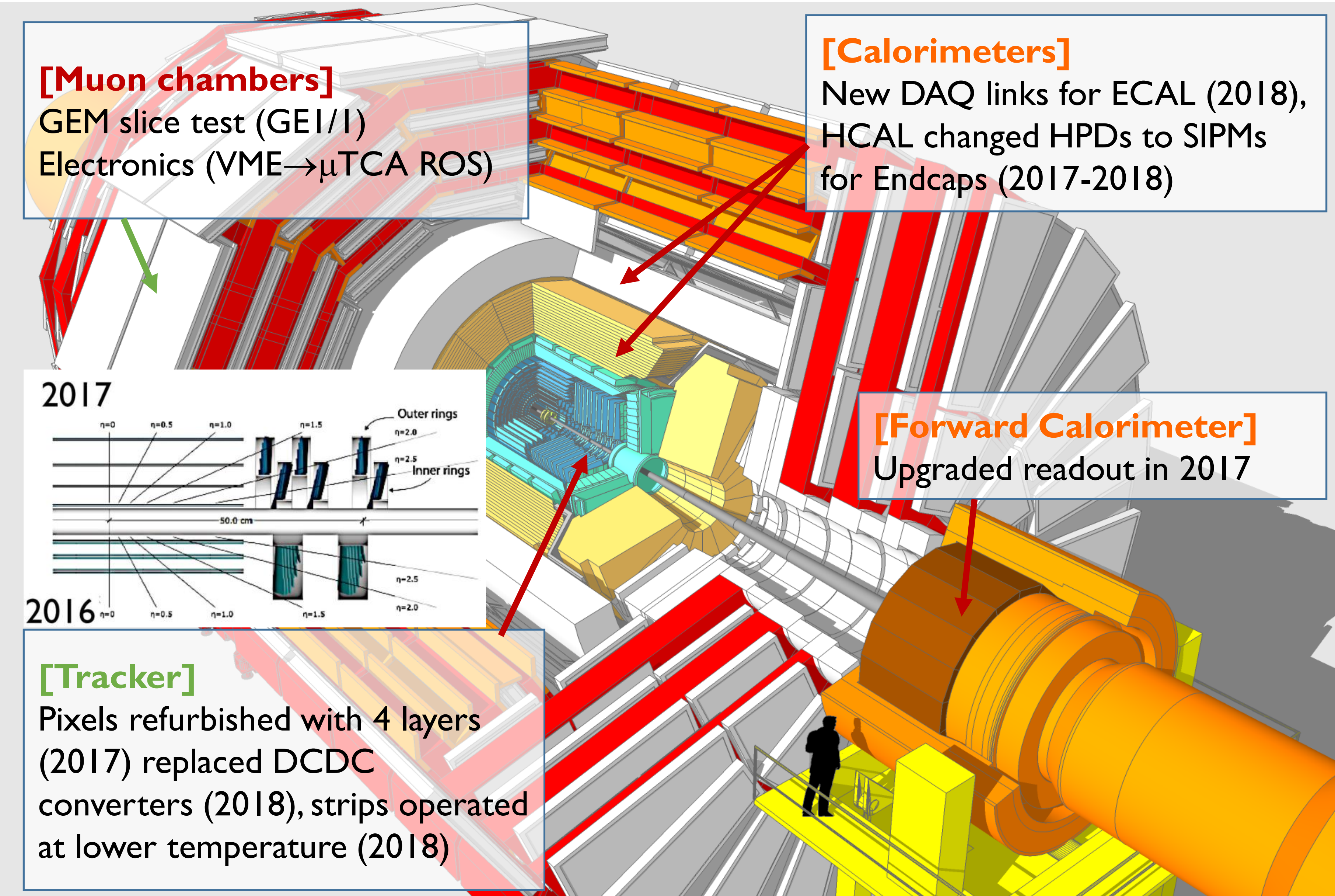
Experimental challenges for Higgs Physics



- **Higgs physics makes use of the full detector**
  - reconstruct all objects: leptons, γ, E_T^{miss}, (b-) jets, …
  - wide coverage: from p_T>5 (leptons) to $|\eta|$~4.7 (VBF)
- **Increased luminosity comes with more pileup**
  - currently acquiring data with average 38 pileup interactions
  - still performance maintained/improved with respect to Run I thanks to:
    - the upgrade of the CMS detector (next slide)
    - improvements in trigger and reconstruction (e.g. filtering for pileup from pulse shapes to final physics objects, particle flow starting at trigger level, deploying machine learning algorithms as understanding of data increases)



CMS has undergone several mutations over the past 3 years



[Muon chambers]
GEM slice test (GE1/1)
Electronics (VME→μTCA ROS)

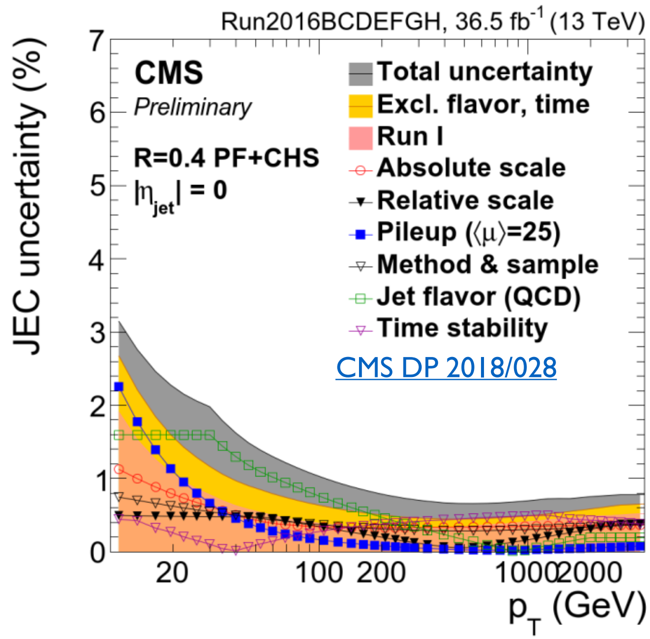
[Calorimeters]
New DAQ links for ECAL (2018), HCAL changed HPDs to SIPMs for Endcaps (2017-2018)

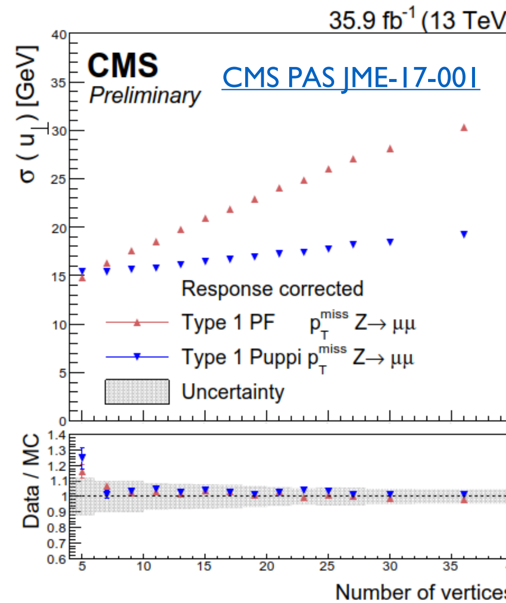
[Forward Calorimeter]
Upgraded readout in 2017

[Tracker]
Pixels refurbished with 4 layers (2017) replaced DCDC converters (2018), strips operated at lower temperature (2018)

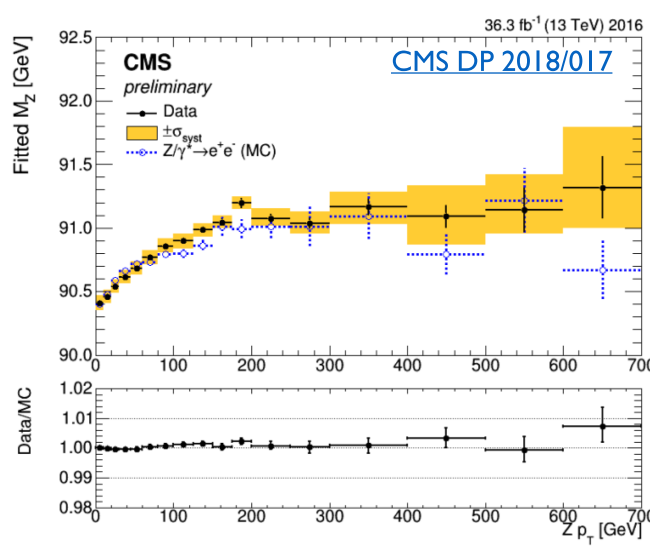
Selected aspects of performance in Run 2

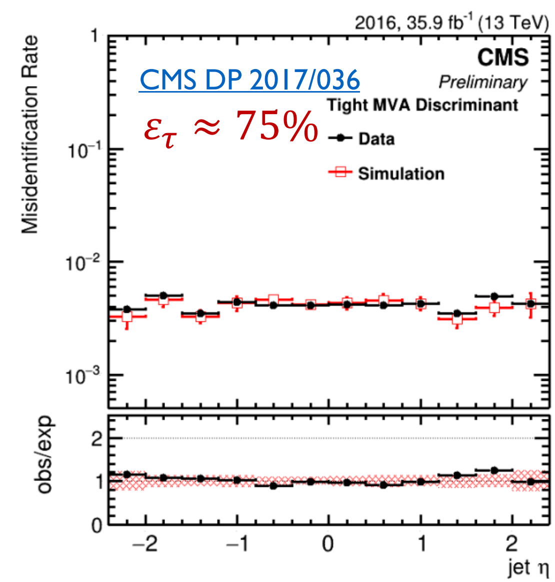
- **On top of particle flow:**
  - pileup subtraction (charged hadron subtraction, pileup per particle id)
  - MVA identification
  - MVA energy regressions

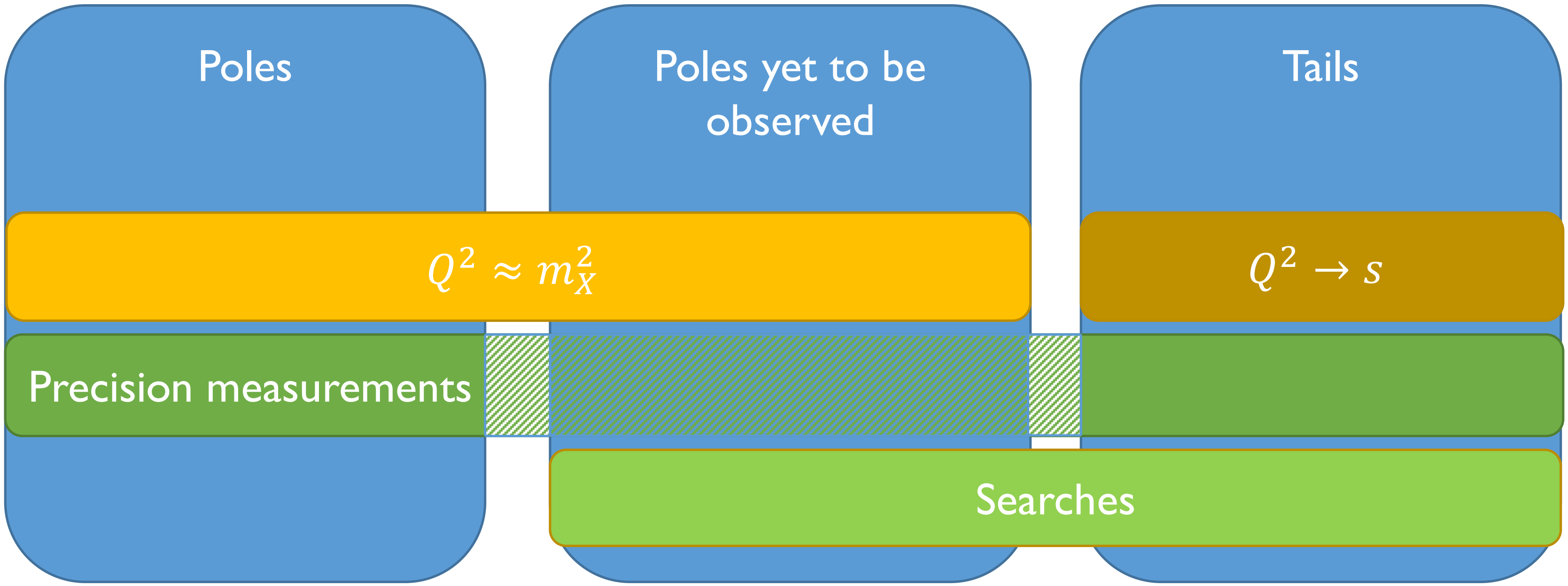




- **Overall excellent baseline performance for jets, e/γ, τ's and missing energy**
  - at analysis level identification and energy scale/resolution can be further refined







adapted from A. David, @2hdmwork'16

Where are we in the exploration of the Higgs sector?

Properties of the H(125)

Searches for additional Higgs

Fitting the global properties of the H(125)

- **Combined fit to different categories from different analyses**
  - up to 265 independent categories, >5.5k nuisances to model systematics
  - decouple as much as possible production and decay, direct and loop-induced

$$\frac{N_{obs}}{N_{exp}} \propto \mu_i^f = \frac{\sigma_i \cdot BR^f}{\sigma_{i,SM} \cdot BR^f_{SM}} = \frac{\sigma_i}{\sigma_{i,SM}} \cdot \frac{\frac{\Gamma^f}{\Gamma}}{\frac{\Gamma^f_{SM}}{\Gamma_{SM}}} \xrightarrow{\kappa\ \text{framework}} \kappa_i^2 \cdot \kappa_f^2$$

$\Rightarrow$ assuming loops are resolved σ and BR can be fully parametrized

- some modifiers are effective (κ_γ, κ_g) - BSM mostly expected to change the rate
- ratios of the coupling modifiers are also used $\lambda_{ij} = \kappa_i / \kappa_j$

(loosen SM-like assumptions, particular useful for BSM re-interpretations)

Treatment of systematic uncertainties I

- Dominant **exp. uncertainties** are related to efficiency and background
  - uncorrelated among channels
  - except pileup, luminosity, jet energy scale, b-tag efficiency correlated

    (the latter two if not constrained in-situ or in the same phase space)
  - unc. on background functional form parameters included in stat. uncertainty

Analysis		$\delta M/M$ **[%]**	**Detector modelling**	**Background**
$\gamma\gamma$		1-2	e.m. shower shapes	functional form
$ZZ^*(4\ell)$		1-2	lepton efficiencies	Z+X
$WW^*(2\ell 2\nu)$		20		$\bar{t}t$, WW, DY
$\tau\tau$		10-20	τ, p_T^{miss} energy scale	DY→ $\tau\tau$
$\bar{b}b$		10	b-tagging eff. / discr. shape	WZ+heavy flavours / QCD multijets
$\bar{t}tH$	multileptons	-	lepton efficiencies	reducible backgrounds (fakes, q flips)
	$\bar{b}b$	10	b-tagging eff. / discr. shape	$\bar{t}t$+heavy flavours / QCD multijets
$\mu\mu$		1-2		functional form
invisible		-		$Z(Z)\nu\nu(\ell\ell)$, $W(W)\ell\nu(\ell\nu)$, $WZ \rightarrow \ell 3\nu$

Treatment of systematic uncertainties II

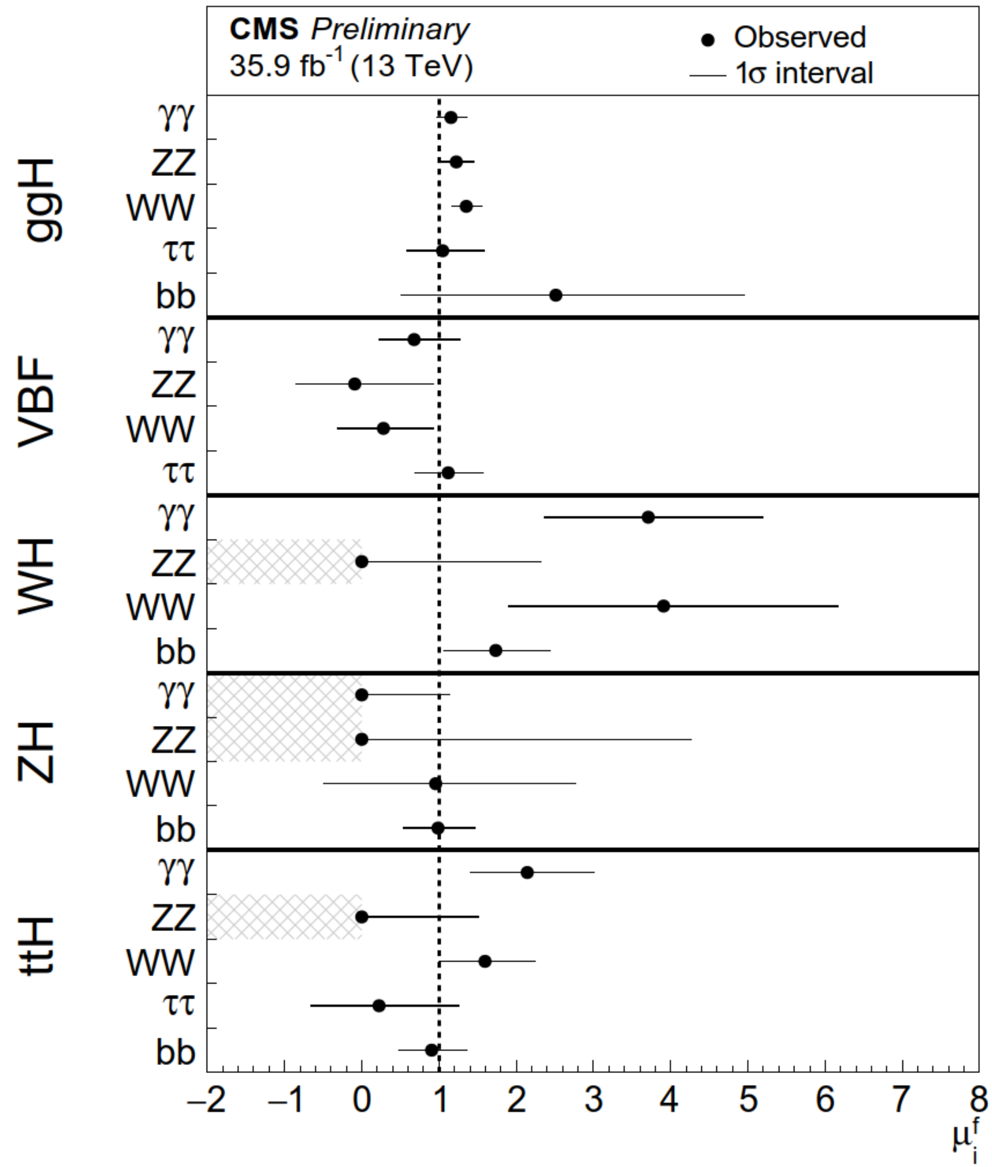
- Most relevant **theory uncertainties** for dominant gluon fusion
  - p_T(H) is weighted to match NNLOPS per jet bin (base simulation is NLO+PS)
  - finite m_t corrections, jet-bin migrations, resummation, μ_R/μ_F
- Signal theory uncertainties are correlated among categories
  - including uncertainties on the BR
  - but boosted categories are treated separately (boosted $ggH \to \bar{b}b$)
- Background theory uncertainties are uncorrelated between analyses
  - exception made to underlying event and parton shower uncertainties
- Finite simulation statistical uncertainties modelled with Barlow-Beeston

Overall signal strength

- **The combined fit yields:**

$$\mu = 1.17^{+0.06}_{-0.06}(\text{stat})\ ^{+0.06}_{-0.05}(\text{sig. th.}) \pm 0.06\ (\text{other})$$

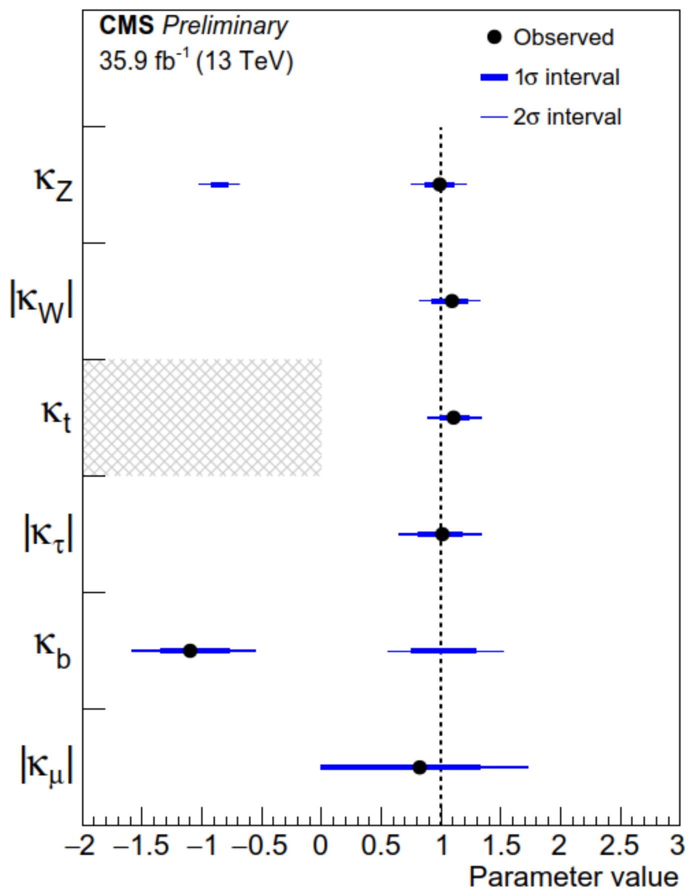
- **Most generic fit** has 25 independent production/decay scaling parameters →
  - if no dedicated analysis use SM prediction and remove from fit (e.g. VBFHbb, VH$\tau\tau$)
  - If high purity apply positive constraint (e.g. ZH$\gamma\gamma$, VHZZ, …)

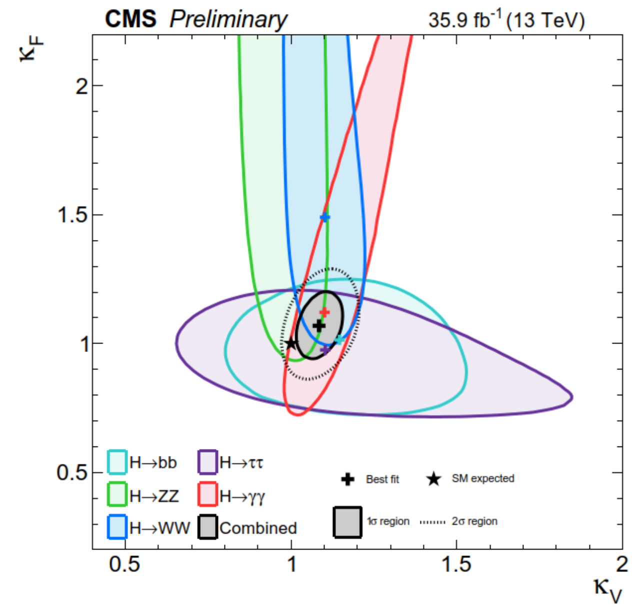


Coupling modifiers

CMS PAS HIG-17-031

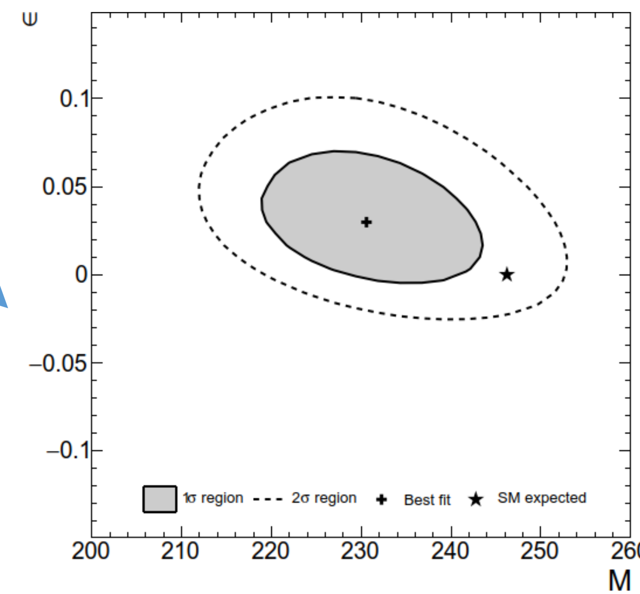
- **Overall fair agreement with expectation within 1-2σ**
  - κ_Z: contributions from $gg \to ZH$ help breaking $\pm$ degeneracy
  - κ_b: test-statistics difference is negligible between $\pm$ signs





$$\kappa_F = v\frac{m_f^{\varepsilon}}{M^{1+\varepsilon}}$$

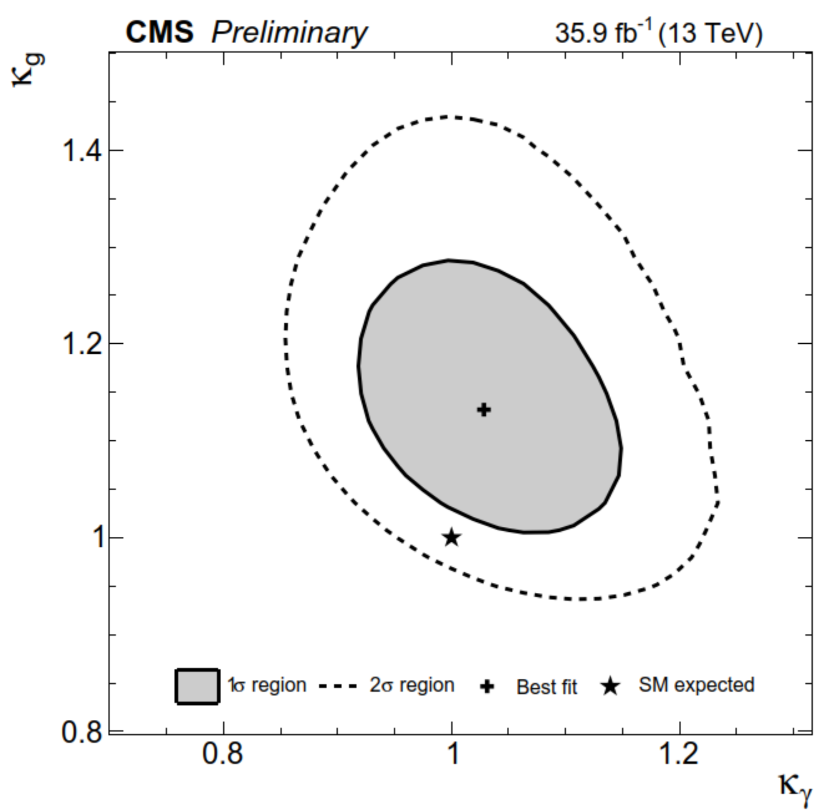
$$\kappa_V = v\frac{m_V^{2\varepsilon}}{M^{1+2\varepsilon}}$$

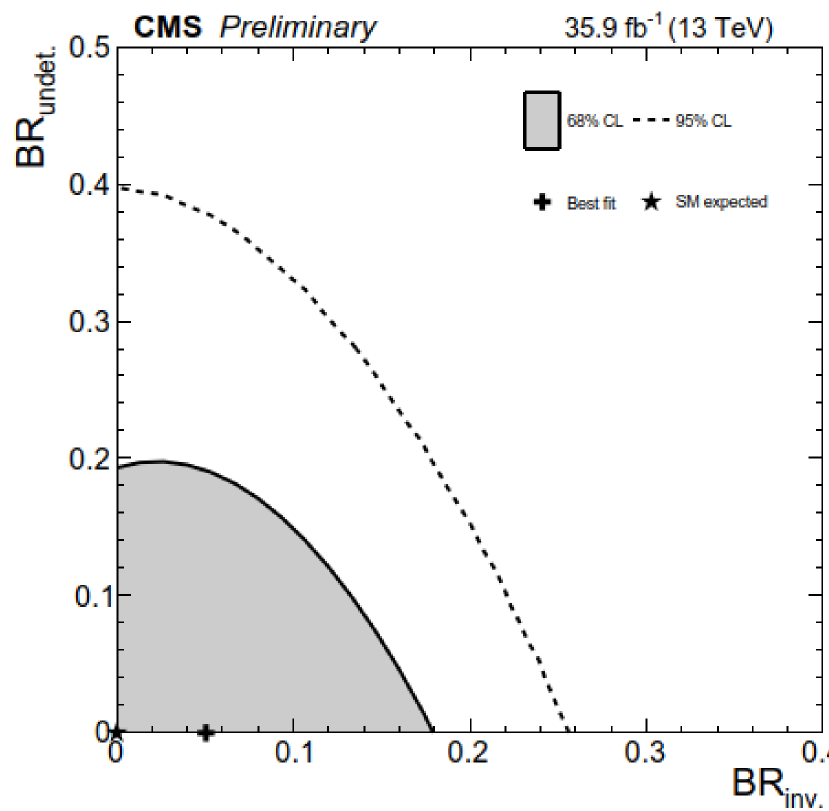


Searching for BSM in global fits I

[CMS PAS HIG-17-031]

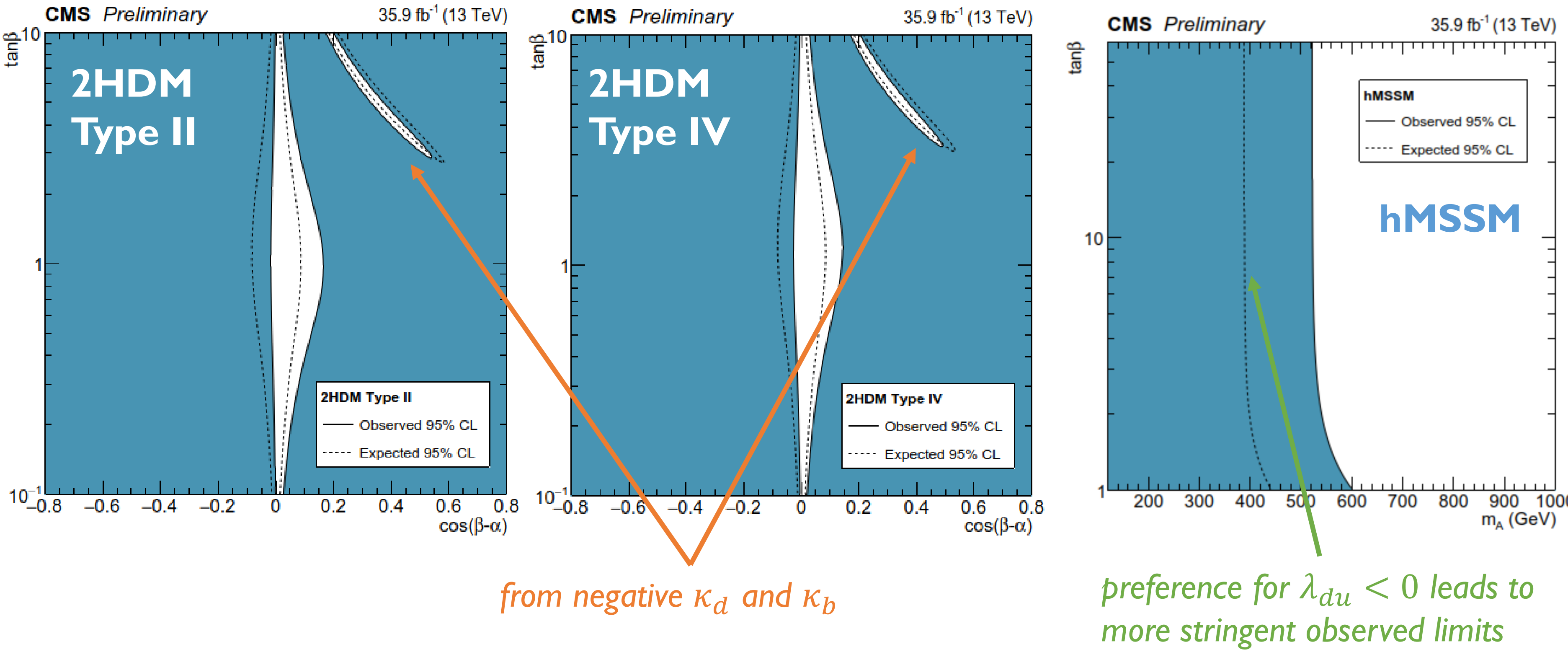
- **Null search for other Higgs decays and BSM in the loops**
  - assuming effective couplings for ggH (κ_g) and H→γγ (κ_γ) and $|\kappa_Z|, |\kappa_W| \leq 1$
  - new BR, κ_g, κ_γ are the parameters of interest but profiled depending on the search





Searching for BSM in global fits II

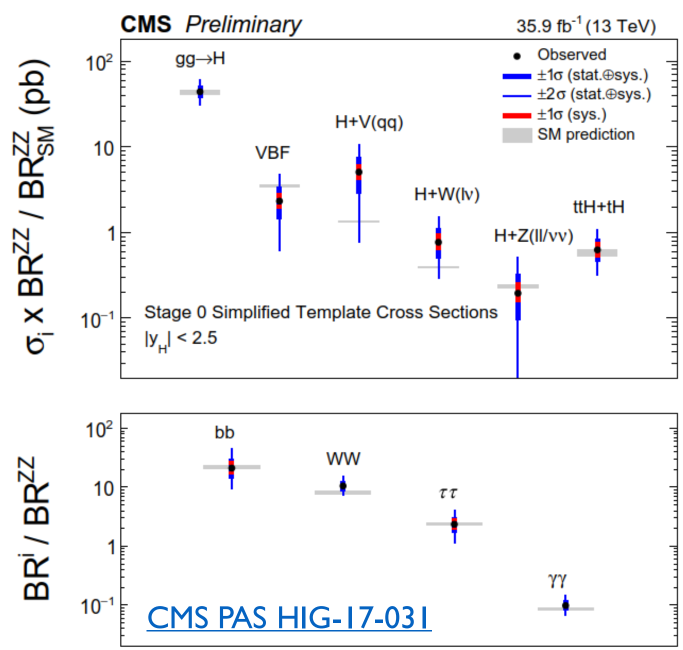
CMS PAS HIG-17-031



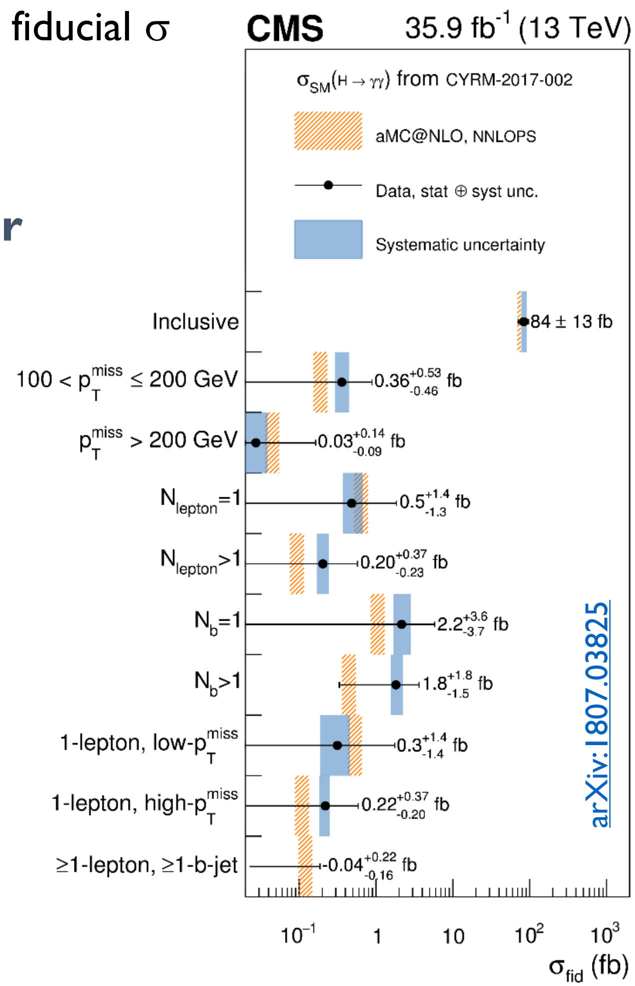
- **Rates sensitive to the mixing angle (α) and ratio of vevs ($\tan\beta$) in 2HDModels**
  - coupling modifiers for fermions change accordingly to the 2HDM model type
  - test statistics used in the fit is re-written (e.g. as function of $\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$ for Type I,II)
  - in the plane of interest evaluate where it drops by 5.99 wrt to max. (95%CL for 2 parameters)
- **Results complement those of direct searches for additional Higgs bosons**

From simplified template to differential cross sections

- **Cross sections can be separated by production mode/kinematics bins**
- **In** $\gamma\gamma$ (and ZZ) **probe further inclusive, fiducial and first** $d\sigma/dX$
  - migration matrix included in the combined fit of the fiducial σ
  - large bins such that regularization is not needed
- **Direct comparison to theory: MC, fixed-order**



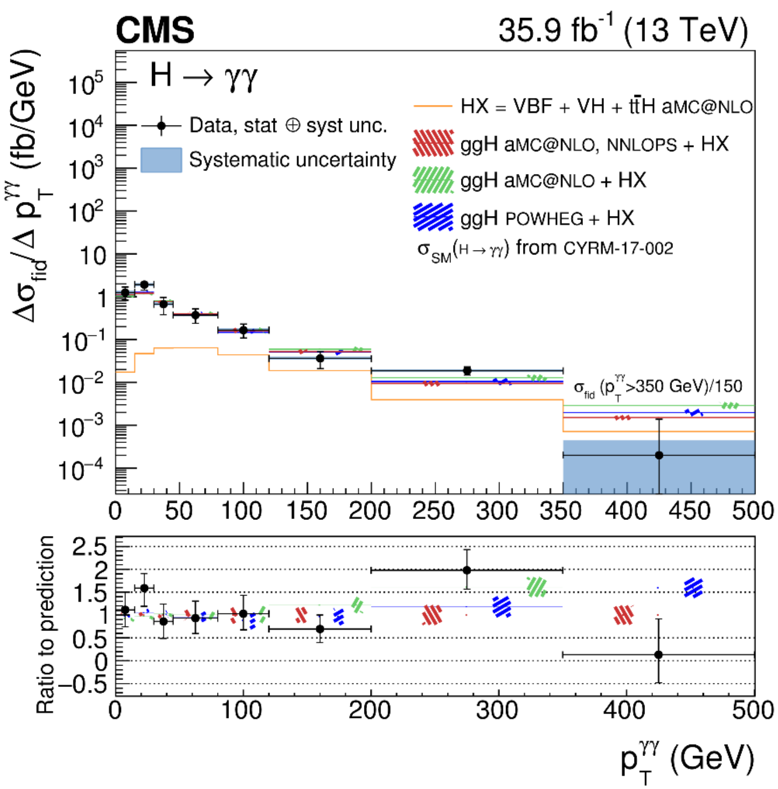
CMS PAS HIG-17-031

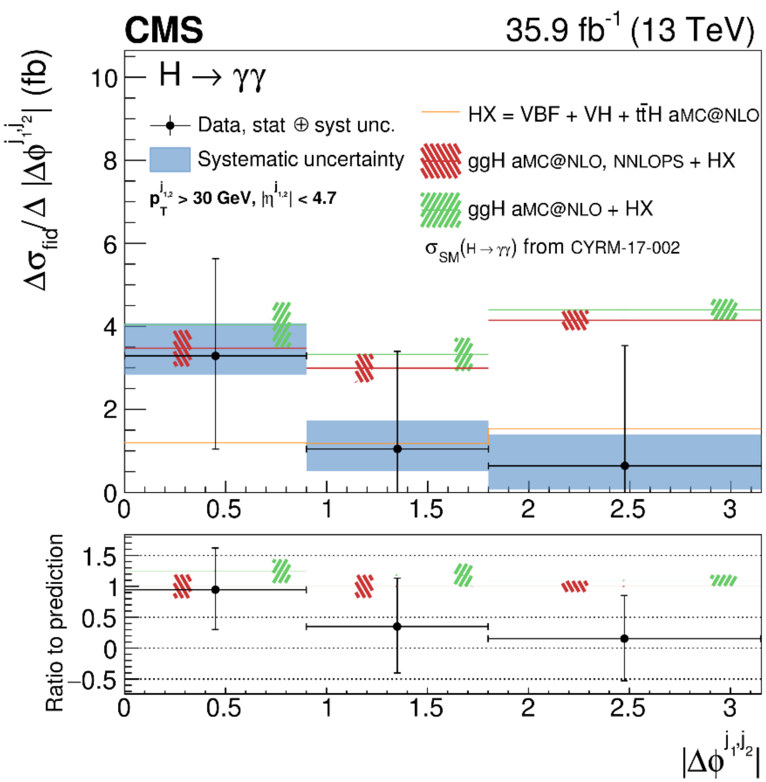


arXiv:1807.03825

Differential H→γγ

- **Comparison with NLO+PS with or without weighting to NNLOPS**
  - double differential $p_T(H)$ versus jet multiplicity
  - stat. dominated measurements, compatible with with predictions for m_H=125.09 GeV
  - start to probe pQCD, potential for model-independent BSM re-interpretation





Searching for BSM in $p_T(H)$

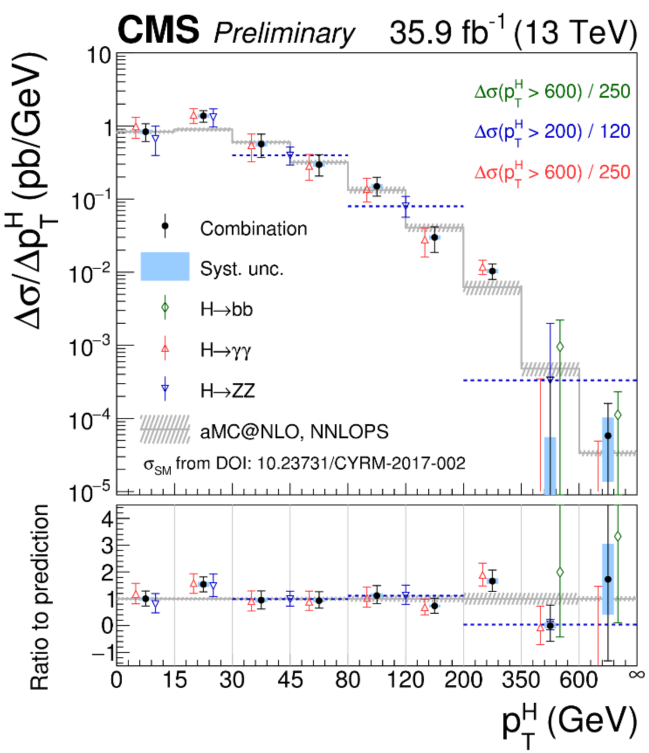
CMS PAS-HIG-17-028

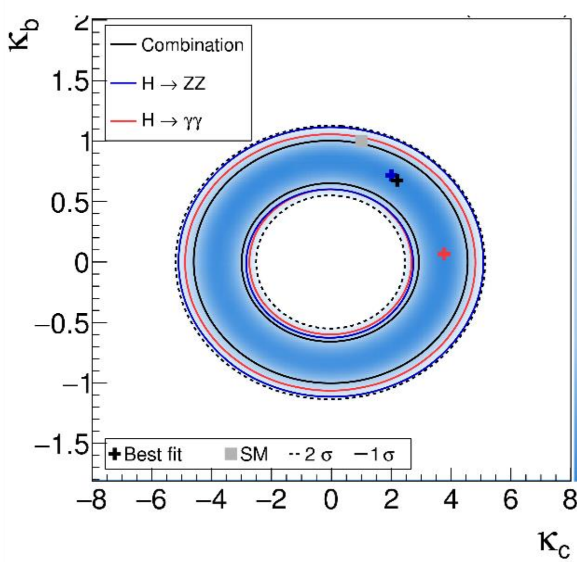
- $\gamma\gamma$, ZZ, bb differ in fiducial definition →

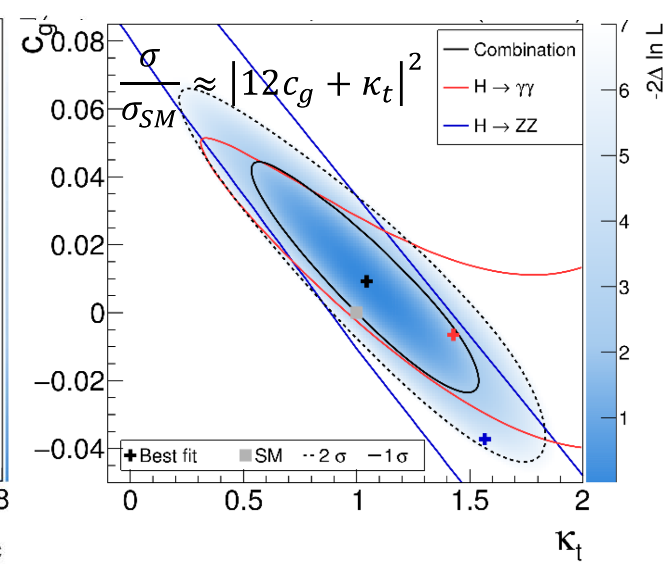
  ⇒ redefine of $p_T(H)$ bins, treatment of BRs

- Test shape/rate sensitivity in $p_T(H)$
  - couplings to quarks (c,b,t), gluons (dim-6 operator)

Analysis	Fiducial region
H→γγ	$\lvert\eta^\gamma\rvert < 2.5 \quad \frac{p_T^{\gamma\gamma}}{m_{\gamma\gamma}} > \frac{1}{3}\left(\frac{1}{4}\right)$
H→ZZ	$M(4\ell) > 70$ GeV $p_T(Z_1) > 40$ GeV $p_T(\ell_1/\ell_2) > 20/10$ GeV $\Delta R(\ell,\ell') > 0.02$
H→bb	$p_T(\bar{b}b) > 450$ GeV $\lvert\eta\rvert<2.5$ veto cuts (τ, E_T^{miss})





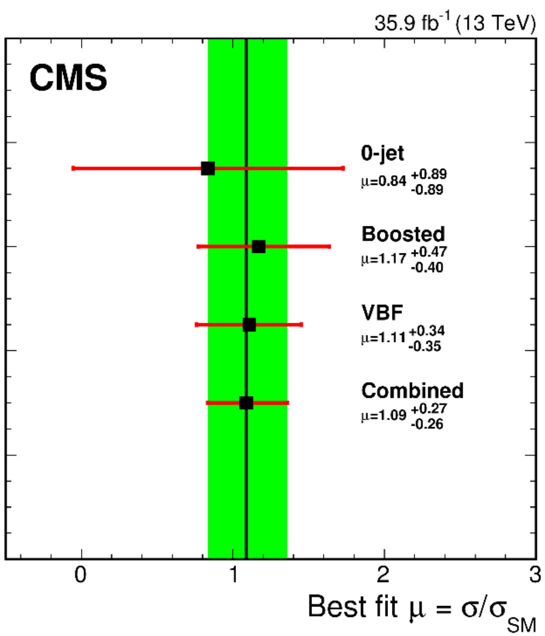


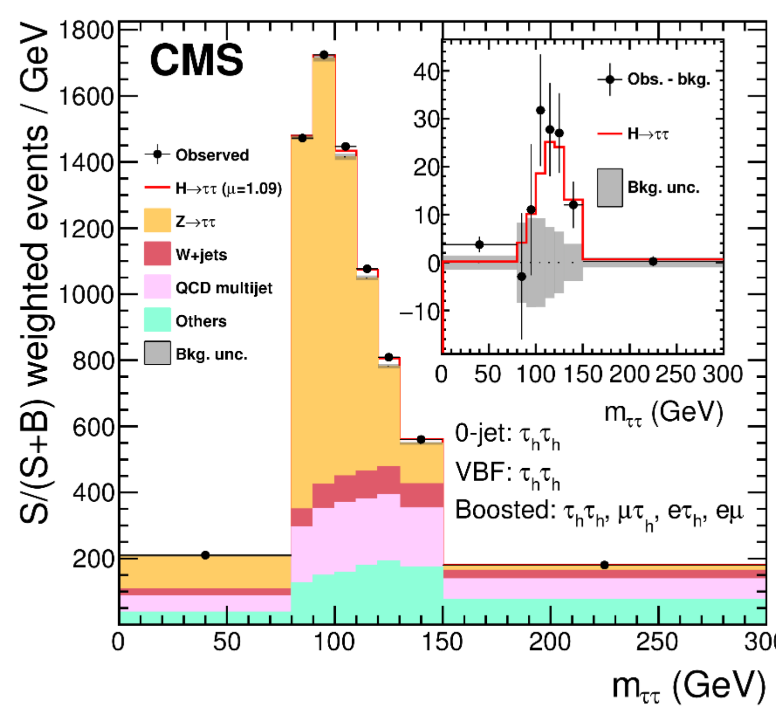
coupling-dependency of BRs assumed

New direct observations: H→ττ

Phys. Lett. B 779 (2018) 283

- **2016 data almost sufficient for observation**
  - 4.9/4.7σ (obs/exp) → **5.9σ (obs and exp)** after combination with Run I
  - 9 categories covering hadronic, leptonic τ decays and different p_T regions
  - fit to visible mass, $m_{\tau\tau}$, m_{jj} or $p_T^{\tau\tau}$ depending on the category
  - uncs.: similar stat and exp. systs (~15%), finite MC stats (~13%)

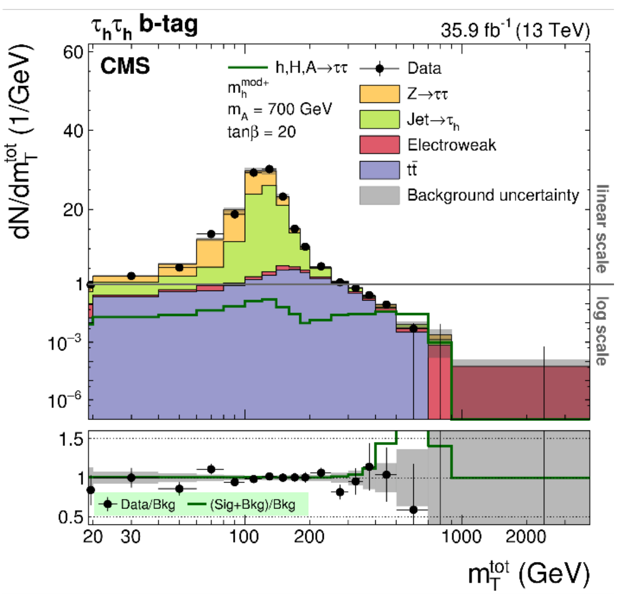


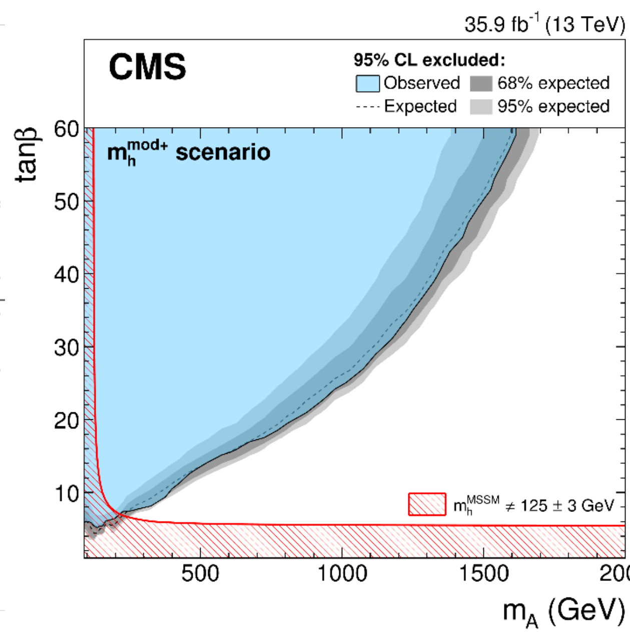


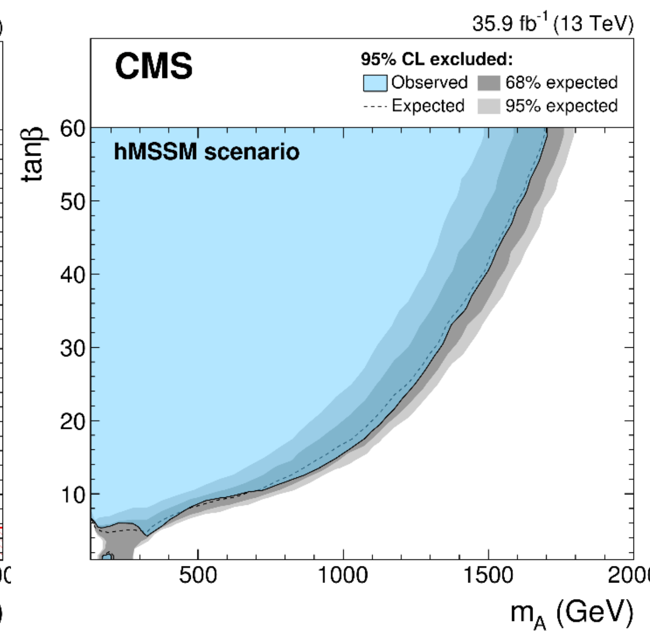
$$\mu_{7+8+13\ \text{TeV}} = 0.98 \pm 0.18\ (\text{total})$$

Searching for additional MSSM Higgs bosons with τ's

- **Single narrow resonance in gg fusion or in association with bb**
  - final states with τ's have superior experimental accessibility with respect to b's or μ's
  - 16 signal regions covering different final states, b content and mass/balance (m_T, D_ζ variables)
  - search performed in the total m_T (sums individual m_T for t's and E_T^{miss}) spectrum
- **No excess in ggH and bbH spectra, re-interpreted in the MSSM**



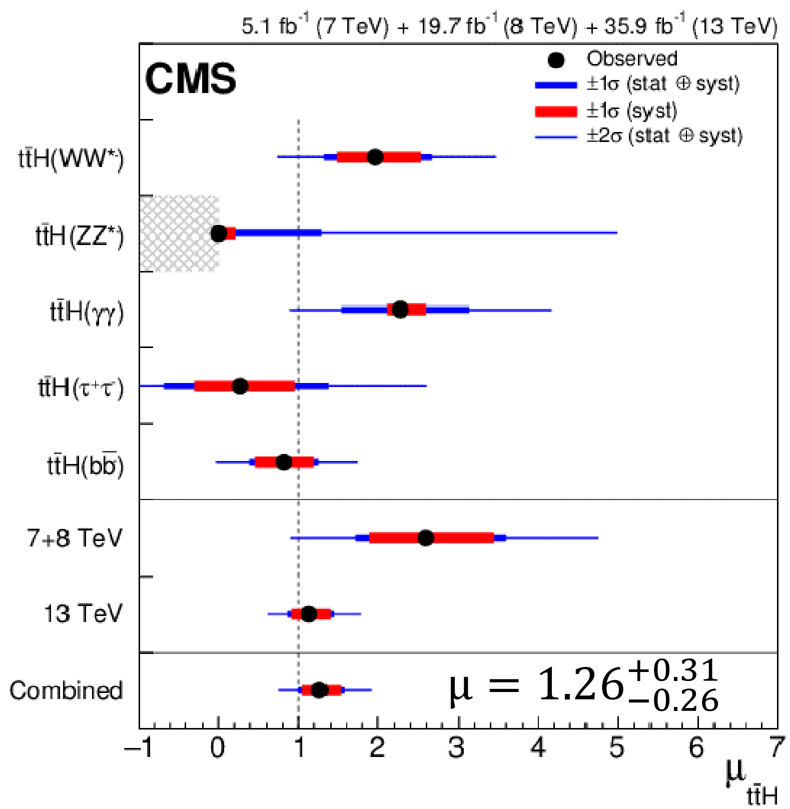


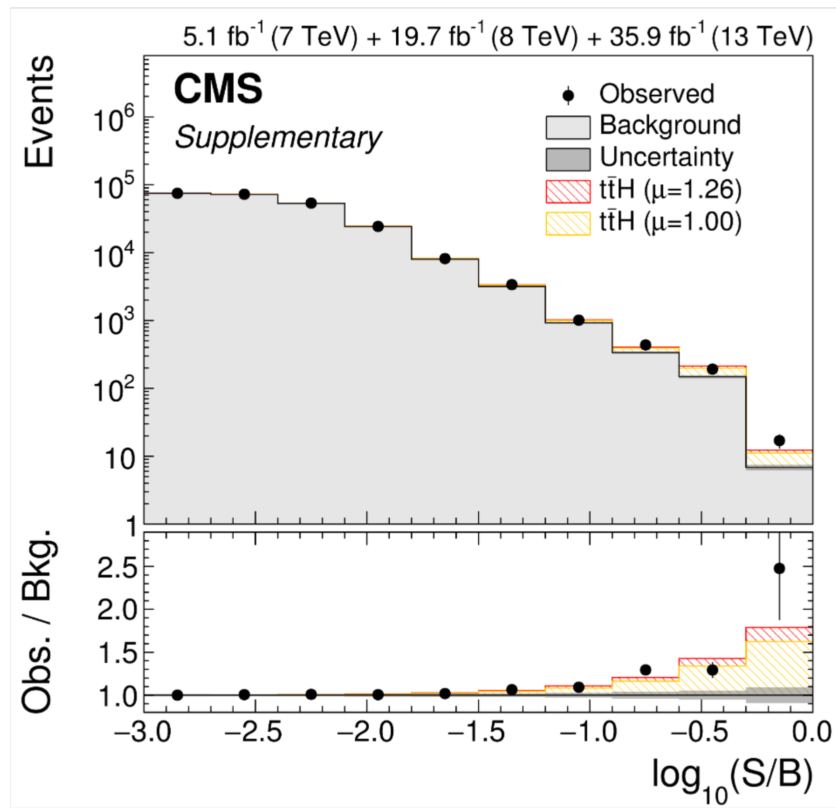


New direct observations: ttH

Phys. Rev. Lett. 120 (2018) 231801

- **Combination of Run I + 2016 dataset lead to 5.2/4.2σ (obs/exp)**
  - several final states: multileptons, di-photons, bb
  - theory uncertainties on ttH normalization and tt+HF are crucial in the observation
  - with more data high purity channels (e.g. ttHγγ) will gain more relevance





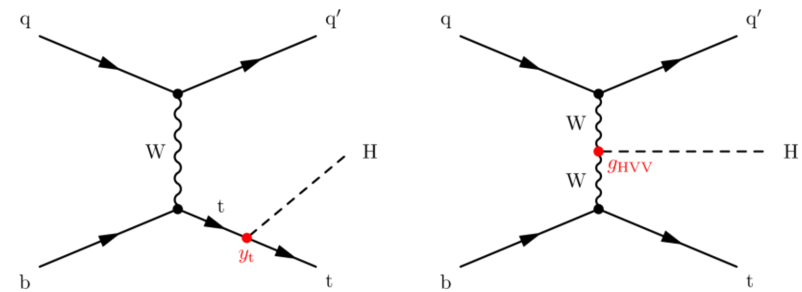
Probing the sign of y_t with tHq

CMS PAS-HIG-18-009

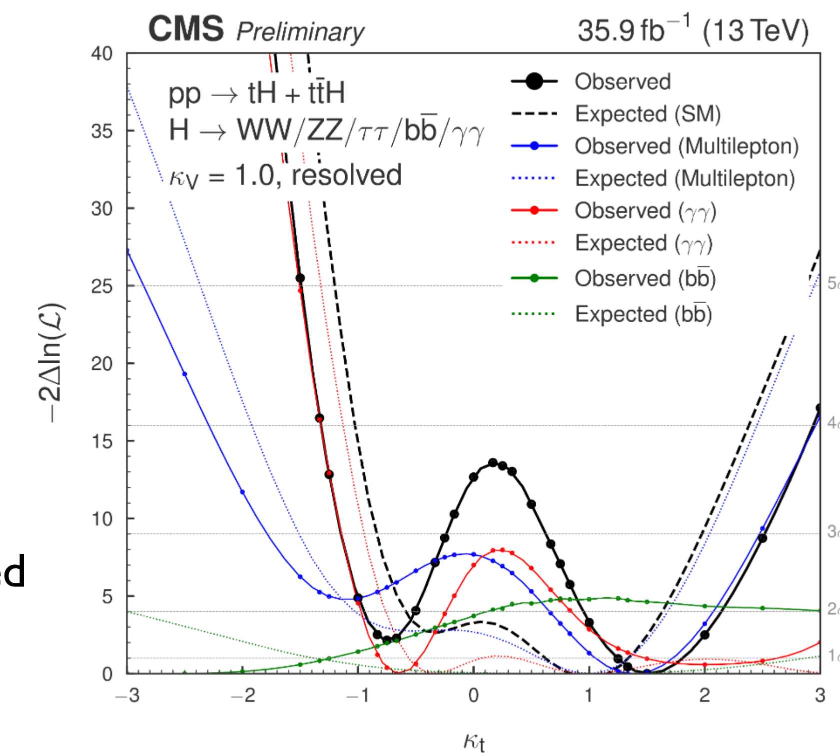
- **Single top production with H is rare due to interference**
  - expect $\sigma \approx 71$ fb for the t-channel
  - combination of multilepton, bb

    and re-interpreted ttH$\gamma\gamma$ categories
  - assuming SM ttH yield and acceptance

$$\mu_{tH} < 26.5 \text{ obs } (13.6 \text{ exp})$$



- **Re-interpretation for $\kappa_t \rightarrow$**
  - exclusion of κ_t<0.9
  - positive coupling starting to be favoured



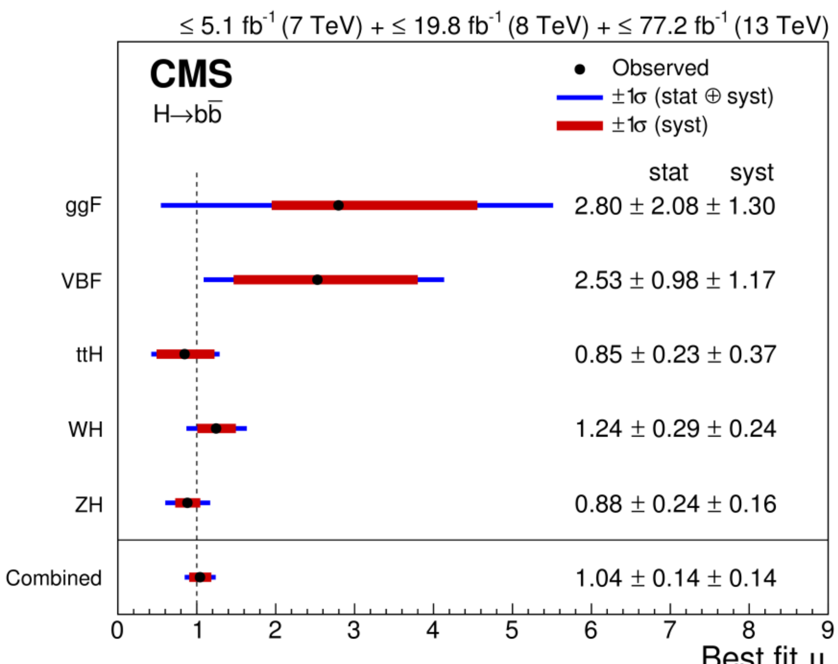
New direct observations: H→bb

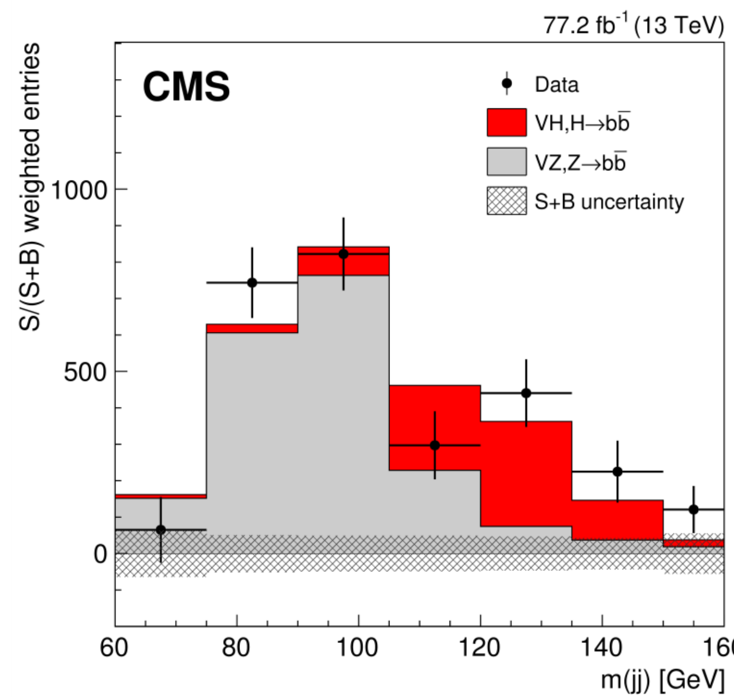
[arXiv:1808.08242](https://arxiv.org/abs/1808.08242)

- **Combination of up to 77.2 fb^{-1} of Run 2 data with Run 1: 5.6/5.5σ obs/exp**
  - VH categories dominate the combination

    (fit to DNN output – 3 final states/4 categories)
  - improvements in 2017 from better *b* identification/energy regression,

    kinematic fit for the 2 lepton channel and FSR jet recovery



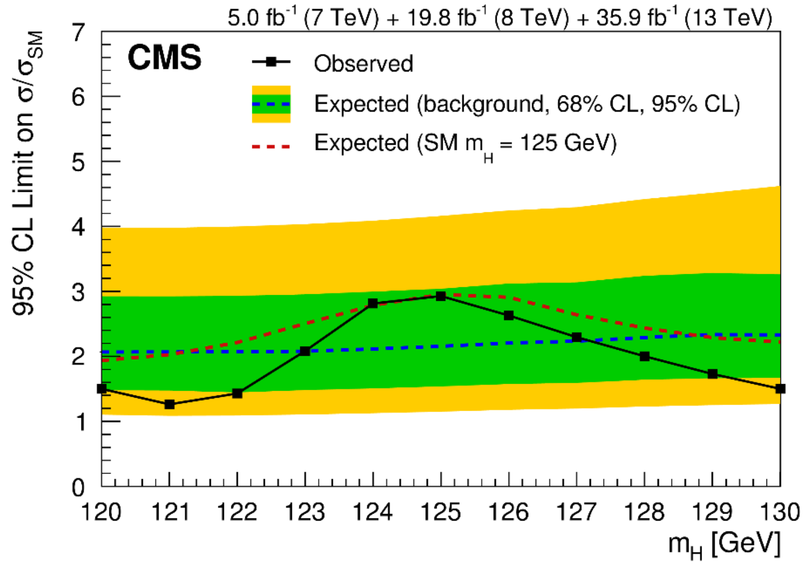


Rarer decay modes

- **Testing 2nd generation couplings**
  - approaching SM sensitivity with 2016

    $\mu < 2.92$ obs (2.16 exp) at 95% CL
  - will require Run-3 data (300 fb^{-1})

$H \to \mu\mu$ arXiv:1807.06325



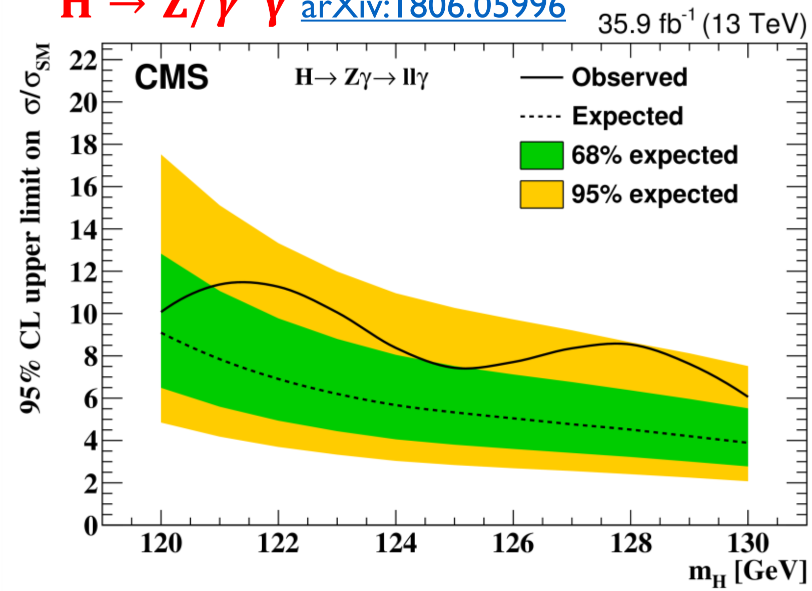
- **Testing further contributions to loops**
  - Zγ and $\gamma^*\gamma$ interfere with each other

    $m(\ell\ell)$ used to enhance Zγ

    $BR(H \to Z\gamma) < 8.0$ obs (5.8 exp)

    $BR(H \to \gamma^*\gamma) < 4.0$ obs (2.2 exp)
  - will require HL-LHC to reach SM sensitivity

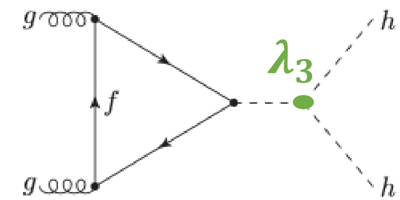
$H \to Z/\gamma^*\gamma$ arXiv:1806.05996

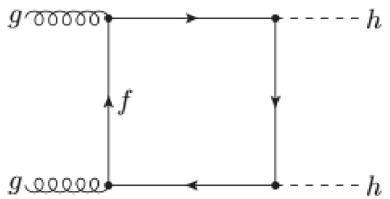


Towards a measurement of the Higgs self-coupling

CMS PAS-HIG-17-030

- **HH production probes directly potential/self-coupling**
  - $V(h) = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4$ with the SM $\lambda_3 = \lambda_4 = m_h^2/2v^2$
  - extremely rare $\sigma_{SM}(HH) \lesssim \sigma_{SM}(H) \cdot 10^{-3}$

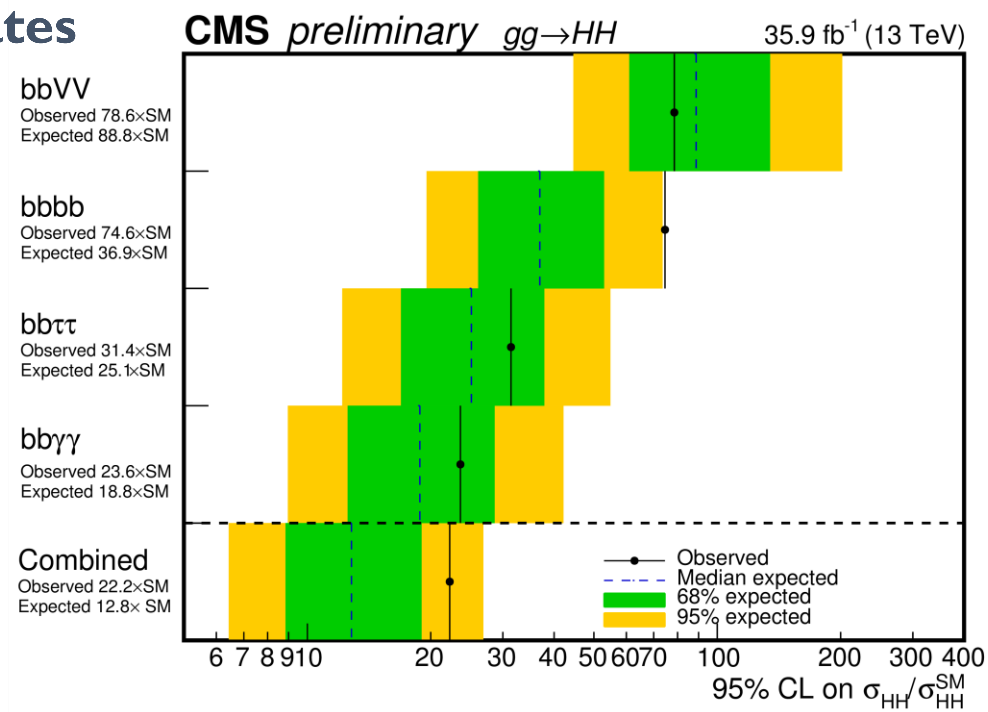




- **Combine most sensitive final states**
  - bbγγ (0.3%), bbττ (7%),

    4b (33%), bbVV (25%)

    μ < 21.8 obs (12.4 exp) at 95% CL
  - will require HL-LHC to reach SM



Probing BSM in HH production

CMS PAS-HIG-17-030

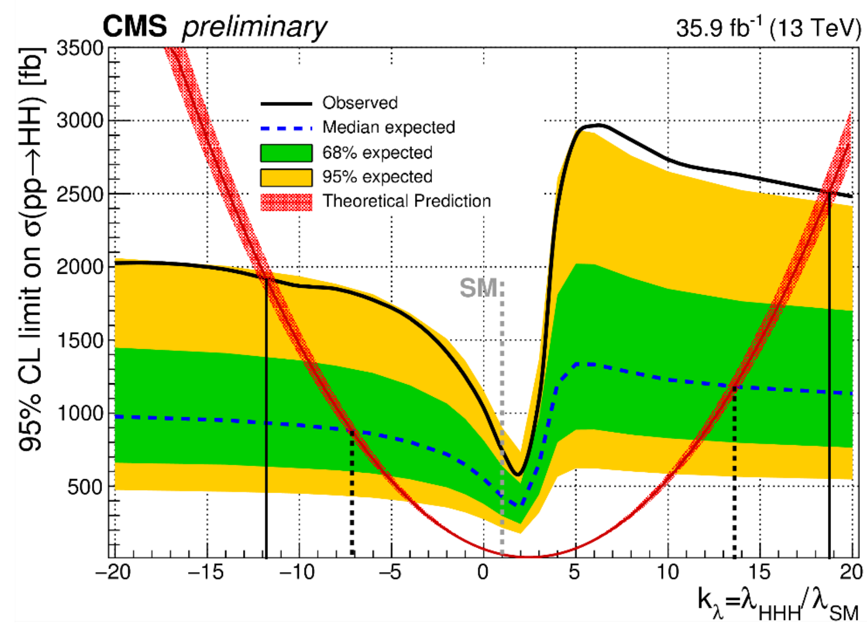
- **HH: large potential for BSM**
  - modified λ

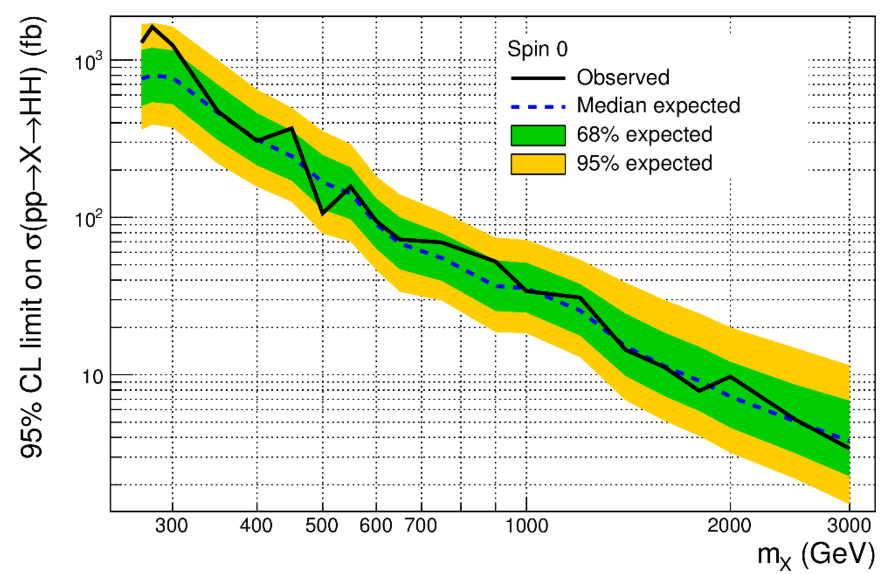
    (non-resonant)
  - s-channels

    (2HDM, EWK singlets, gravitons)

    ⇒ σ(HH) can increase up to 10pb

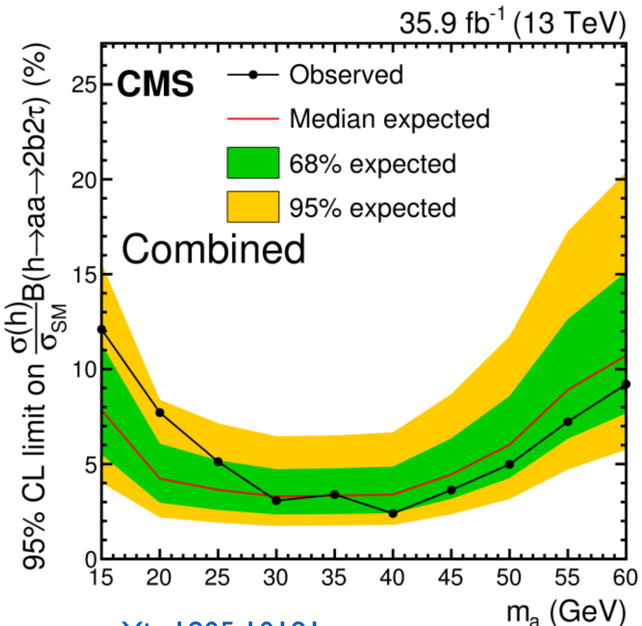
- **No significant excess so far**
  - more model-specific re-interpretations can be found in single-channel analyses (1806.00408, 1707.02909, 1708.04188)



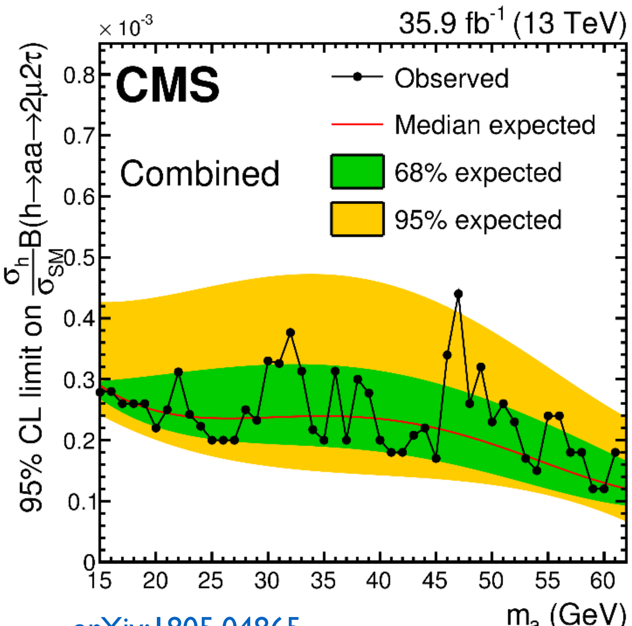


Searching additional pair-produced Higgs

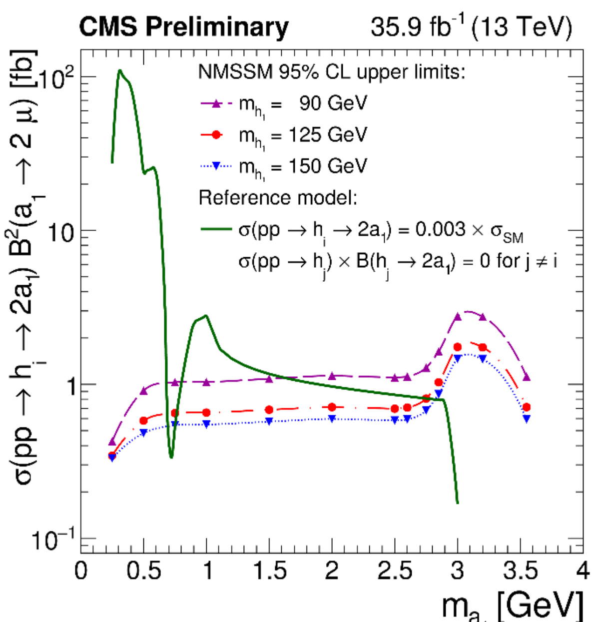
- Neutral higgs decaying to light pseudoscalar possible in 2HDM+S models
  - can be accompanied by extra spectator particles in some models
  - similar topology as in SUSY cascades with dark photons
  - consider different final states bbττ, ττμμ, 4μ, …
  - no final combination yet available as for Run I… stay tuned



arXiv:1805.10191



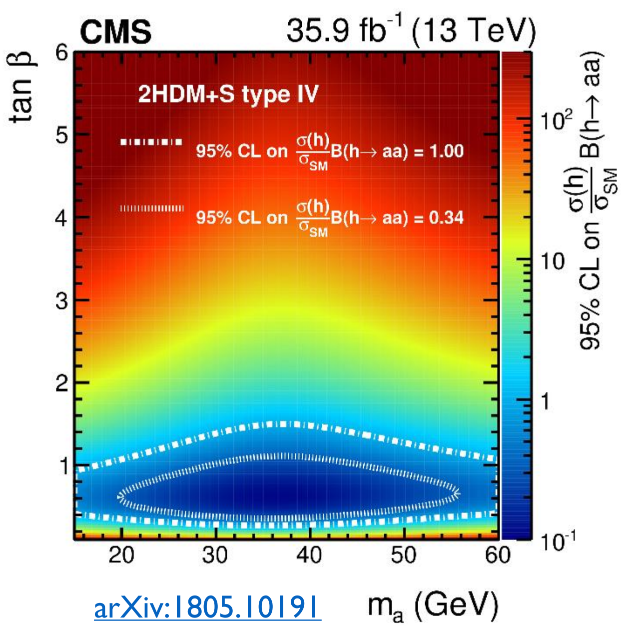
arXiv:1805.04865



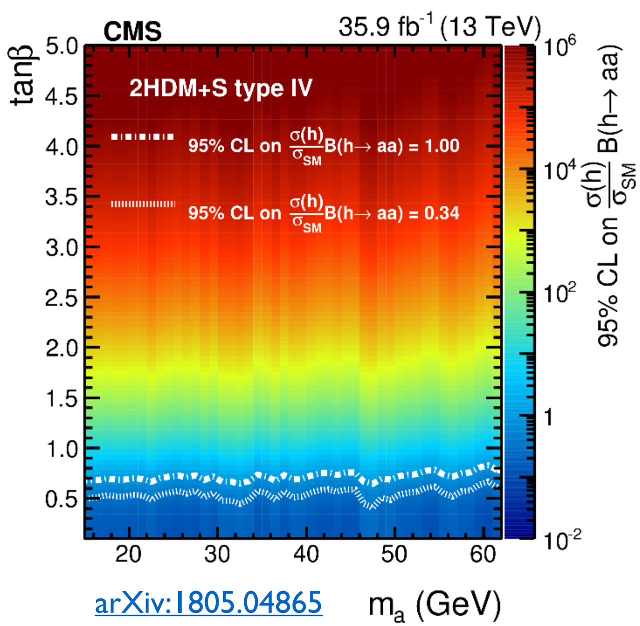
CMS PAS-HIG-18-003

Searching additional pair-produced Higgs

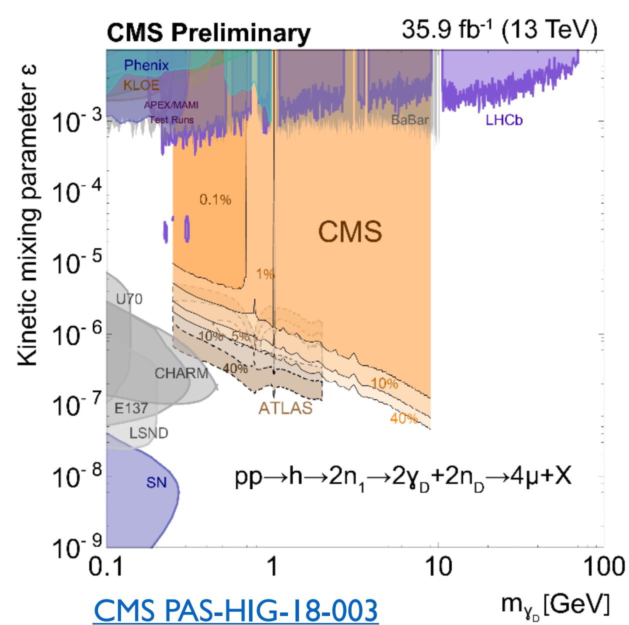
- Neutral higgs decaying to light pseudoscalar possible in 2HDM+S models
  - can be accompanied by extra spectator particles in some models
  - similar topology as in SUSY cascades with dark photons
  - consider different final states bbττ, ττμμ, 4μ, …
  - no final combination yet available as for Run I… stay tuned



arXiv:1805.10191



arXiv:1805.04865

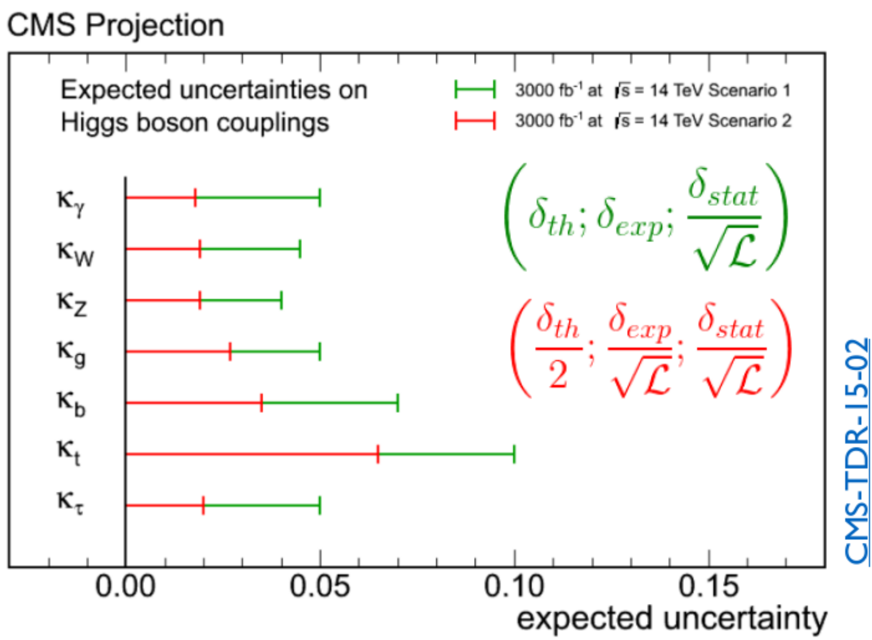


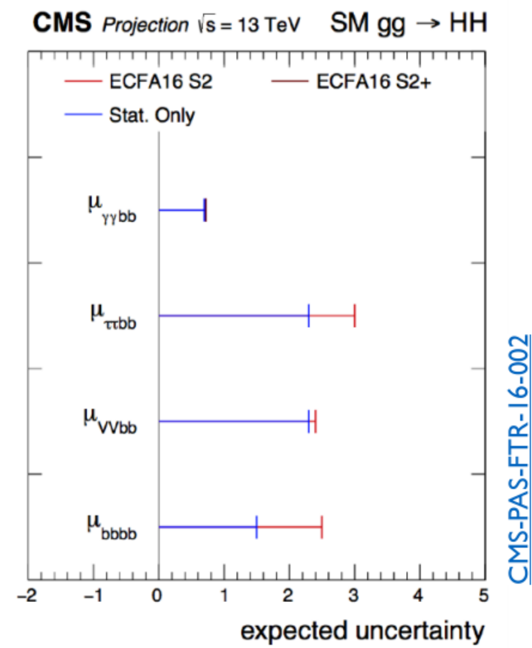
CMS PAS-HIG-18-003

What are we aiming for?

Projections for Run 3 and HL-LHC

Higgs couplings after HL-LHC





- **Establishing the Higgs couplings to bosons and fermions**
  - <5-10% (<10-15%) unc. at the end of the HL-LHC (Run 3)
  - H → μμ measured with 5-8% uncertainty
- **Long-road ahead for Higgs self-couplings**
  - maybe reach 3σ after full combination of HL-LHC data?

Summary

Summary

- **Main H production/decay modes have been observed individually**
- **Next discovery targets:**
  - rare decays/productions, 2^{nd} generation
  - dedicated searches for additional Higgs boson
- **All are milestones, still all are intermediate results**
  - see all @ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
  - 6 weeks to go until Run 2 pp run ends, final analyses to come

LHC Run 2: the machine has "warmed up",

the challenging search for BSM has just begun

Backup

Channels used in the combination

CMS PAS HIG-17-031

Production and decay tags		Expected tagged signal fraction	Number of categories	Mass resolution
$H \to \gamma\gamma$, Section 2.1				
$\gamma\gamma$	Untagged	74-91% ggH	4	≈1-2%
	VBF	51-80% VBF	3	
	VH hadronic	25% WH, 15% ZH	1	
	WH leptonic	64-83% WH	2	
	ZH leptonic	98% ZH	1	
	VH p_T^{miss}	59% VH	1	
	ttH	80-89% ttH, ≈8% tH	2	
$H \to ZZ^{(*)} \to 4\ell$, Section 2.2				
4μ, $2e2\mu/2\mu2e$, 4e	Untagged	≈95% ggH	3	≈1-2%
	VBF 1, 2-jet	≈11-47% VBF	6	
	VH hadronic	≈13% WH, ≈10% ZH	3	
	VH leptonic	≈46% WH	3	
	VH p_T^{miss}	≈56% ZH	3	
	ttH	≈71% ttH	3	
$H \to WW^{(*)} \to \ell\nu\ell\nu$, Section 2.3				
$e\mu/\mu e$	ggH 0, 1, 2-jet	≈55-92% ggH, up to ≈15% $H \to \tau\tau$	17	≈20%
	VBF 2-jet	≈47% VBF, up to ≈25% $H \to \tau\tau$	2	
ee+$\mu\mu$	ggH 0, 1-jet	≈84-94% ggH	6	
$e\mu$+jj	VH 2-jet	22% VH, 21% $H \to \tau\tau$	1	
3ℓ	WH leptonic	≈80% WH, up to 19% $H \to \tau\tau$	2	
4ℓ	ZH leptonic	85-90% ZH, up to 14% $H \to \tau\tau$	2	
$H \to \tau\tau$, Section 2.4				
$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	0-jet	≈70-98% ggH, 29% $H \to WW$ in $e\mu$	4	≈10-20%
	VBF	≈35-60% VBF, 42% $H \to WW$ in $e\mu$	4	
	Boosted	≈48-83% ggH, 43% $H \to WW$ in $e\mu$	4	
VH production with $H \to bb$, Section 2.5				
$Z(\nu\nu)$bb	ZH leptonic	≈100% VH, 85% ZH	1	≈10%
$W(\ell\nu)$bb	WH leptonic	≈100% VH, ≈97% WH	2	
$Z(\ell\ell)$bb	Low $p_T(V)$ ZH leptonic	≈100% ZH, of which ≈20% ggZH	2	
	High $p_T(V)$ ZH leptonic	≈100% ZH, of which ≈36% ggZH	2	
Boosted H Production with $H \to bb$, Section 2.6				
$H \to bb$	$p_T(H)$ bins	≈72-79% ggH	6	≈10%
ttH production with $H \to$ leptons, Section 2.7				
$H \to WW, \tau\tau, ZZ$	2ℓss	$WW/\tau\tau \approx 4.5$, ≈5% tH	10	
	3ℓ	$WW : \tau\tau : ZZ \approx 15 : 4 : 1$, ≈5% tH	4	
	4ℓ	$WW : \tau\tau : ZZ \approx 6 : 1 : 1$, ≈3% tH	1	
	$1\ell+2\tau_h$	96% ttH with $H \to \tau\tau$, ≈6% tH	1	
	$2\ell ss+1\tau_h$	$\tau\tau : WW \approx 5 : 4$, ≈5% tH	2	
	$3\ell+1\tau_h$	$\tau\tau : WW : ZZ \approx 11 : 7 : 1$, ≈3% tH	1	
ttH production with $H \to bb$, Section 2.8				
$H \to bb$	$t\bar{t} \to$ jets	≈83-97% ttH with $H \to bb$	6	
	$t\bar{t} \to 1\ell$+jets	≈65-95% ttH with $H \to bb$, up to 20% $H \to WW$	18	
	$t\bar{t} \to 2\ell$+jets	≈84-96% ttH with $H \to bb$	3	
$H \to \mu\mu$, Section 2.9				
$\mu\mu$	S/B bins	56-96% ggH, 1-42% VBF	15	≈1-2%
Search for invisible H decays, Section 2.10				
$H \to$ inv.	VBF	52% VBF, 48% ggH	1	
	ggH + $\geq$ 1 jet	80% ggH, 9% VBF	1	
	VH hadronic	54% VH, 39% ggH	1	
	ZH leptonic	≈100% ZH, of which 21% ggZH	1	

p-vals for the SM predictions

CMS PAS HIG-17-031

Parameterisation	p-value (q_{SM})	DOF	Parameters of interest
Global signal strength	6.12% (3.51)	1	μ
Production processes	9.21% (9.46)	5	$\mu_{ggH}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	43.4% (4.85)	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}$
$\sigma_i \cdot BR^f$ products	50.4% (21.3)	22	$\sigma_{ggH} \cdot BR^{bb}$, $\sigma_{ggH} \cdot BR^{\tau\tau}$, $\sigma_{ggH} \cdot BR^{WW}$, $\sigma_{ggH} \cdot BR^{ZZ}$, $\sigma_{ggH} \cdot BR^{\gamma\gamma}$, $\sigma_{VBF} \cdot BR^{\tau\tau}$, $\sigma_{VBF} \cdot BR^{WW}$, $\sigma_{VBF} \cdot BR^{ZZ}$, $\sigma_{VBF} \cdot BR^{\gamma\gamma}$, $\sigma_{WH} \cdot BR^{bb}$, $\sigma_{WH} \cdot BR^{WW}$, $\sigma_{WH} \cdot BR^{ZZ}$, $\sigma_{WH} \cdot BR^{\gamma\gamma}$, $\sigma_{ZH} \cdot BR^{bb}$, $\sigma_{ZH} \cdot BR^{WW}$, $\sigma_{ZH} \cdot BR^{ZZ}$, $\sigma_{ZH} \cdot BR^{\gamma\gamma}$, $\sigma_{ttH} \cdot BR^{\tau\tau}$, $\sigma_{ttH} \cdot BR^{WW}$, $\sigma_{ttH} \cdot BR^{ZZ}$, $\sigma_{ttH} \cdot BR^{\gamma\gamma}$, $\sigma_{ttH} \cdot BR^{bb}$
Ratios of σ and BR relative to $gg \to H \to ZZ$	24.5% (11.5)	9	μ^{ZZ}_{ggH}, μ_{VBF}/μ_{ggH}, μ_{WH}/μ_{ggH}, μ_{ZH}/μ_{ggH}, μ_{ttH}/μ_{ggH}, μ^{WW}/μ^{ZZ}, $\mu^{\gamma\gamma}/\mu^{ZZ}$, $\mu^{\tau\tau}/\mu^{ZZ}$, μ^{bb}/μ^{ZZ}
Simplified template cross sections with branching fractions relative to BR^{ZZ}	17.2% (14.0)	10	$\sigma_{ggH} \cdot BR^{ZZ}$, $\sigma_{VBF} \cdot BR^{ZZ}$, $\sigma_{H+V(qq)} \cdot BR^{ZZ}$, $\sigma_{H+W(\ell\nu)} \cdot BR^{ZZ}$, $\sigma_{H+Z(\ell\ell/\nu\nu)} \cdot BR^{ZZ}$, $\sigma_{ttH} \cdot BR^{ZZ}$, BR^{bb}/BR^{ZZ}, $BR^{\tau\tau}/BR^{ZZ}$, BR^{WW}/BR^{ZZ}, $BR^{\gamma\gamma}/BR^{ZZ}$
Couplings, SM loops	46.9% (5.60)	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings vs mass	17.1% (3.54)	2	M, ϵ
Couplings, BSM loops	57.7% (5.68)	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\gamma, \kappa_g$
Couplings, BSM loops and decays including $H \to$inv. channels	78.6% (5.53)	9	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\gamma, \kappa_g, BR_{inv.}, BR_{undet.}$
Ratios of coupling modifiers	56.7% (5.77)	7	$\kappa_{gZ}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{tg}, \lambda_{bZ}, \lambda_{\tau Z}, \lambda_{Zg}$
Fermion and vector couplings	16.9% (3.55)	2	κ_F, κ_V
Fermion and vector couplings, per decay mode	63.9% (7.89)	10	$\kappa_F^{bb}, \kappa_F^{\tau\tau}, \kappa_F^{WW}, \kappa_F^{ZZ}, \kappa_F^{\gamma\gamma}, \kappa_V^{bb}, \kappa_V^{\tau\tau}, \kappa_V^{WW}, \kappa_V^{ZZ}, \kappa_V^{\gamma\gamma}$
Up vs down-type couplings	25.5% (4.06)	3	$\lambda_{Vu}, \lambda_{du}, \kappa_{uu}$
Lepton vs quark couplings	26.5% (3.97)	3	$\lambda_{\ell q}, \lambda_{Vq}, \kappa_{qq}$

Normalization scale factors and resolved scaling factors

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\mathrm{ggH})$	✓	b − t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\mathrm{WH})$	–	–		κ_W^2
$\sigma(\mathrm{qq/qg} \to \mathrm{ZH})$	–	–		κ_Z^2
$\sigma(\mathrm{gg} \to \mathrm{ZH})$	✓	Z − t		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	–	–		κ_t^2
$\sigma(\mathrm{gb} \to \mathrm{WtH})$	–	W − t		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t\kappa_W$
$\sigma(\mathrm{qb} \to \mathrm{tHq})$	–	W − t		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W − t	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $\mathrm{BR_{BSM}} = 0$				
Γ_H	✓	–	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Modifications to the κ framework

- Fits in the κ-framework are re-casted in BSM models
- 2HDM (CP conserving, Z_2 symmetry protecting tree-level FCNC) [1106.0034]
  - H(125) is the lightest neutral CP-even
  - MSSM fully determined by knowledge of m_A and tan β
- hMSSM particular realization of the MSSM [1307.5205, 1502.05653]
  - use measured m_H to "limit" radiative corrections assuming the top-stop sector dominates

	2HDM				hMSSM
	type I	type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

$$s_u = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{(m_Z^2+m_A^2\tan^2\beta-m_H^2(1+\tan^2\beta))^2}}} \qquad s_d = s_u\cdot\frac{m_A^2+m_Z^2\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_H^2(1+\tan^2\beta)},$$

Selections, categories, observables I

$H \to \tau\tau$ Phys. Lett. B 779 (2018) 283

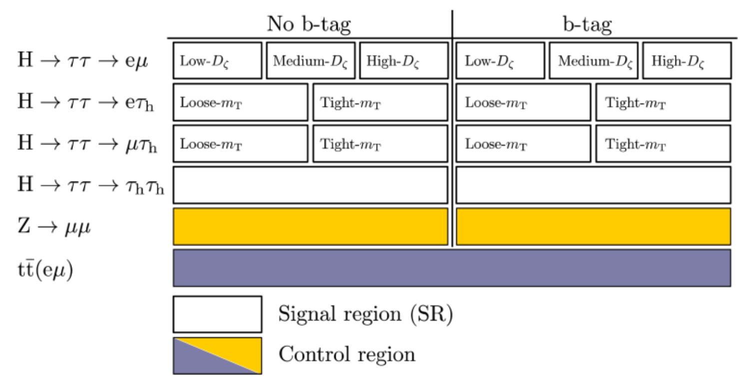
Channel	Trigger requirement	Lepton selection p_T (GeV)	η	Isolation
$\tau_h\tau_h$	$\tau_h(35)$ & $\tau_h(35)$	$p_T^{\tau_h} > 50$ & 40	$\lvert\eta^{\tau_h}\rvert < 2.1$	MVA τ_h ID
$\mu\tau_h$	$\mu(22)$	$p_T^{\mu} > 23$	$\lvert\eta^{\mu}\rvert < 2.1$	$I^{\mu} < 0.15$
		$p_T^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.3$	MVA τ_h ID
	$\mu(19)$ & $\tau_h(21)$	$20 < p_T^{\mu} < 23$	$\lvert\eta^{\mu}\rvert < 2.1$	$I^{\mu} < 0.15$
		$p_T^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.3$	MVA τ_h ID
$e\tau_h$	$e(25)$	$p_T^{e} > 26$	$\lvert\eta^{e}\rvert < 2.1$	$I^{e} < 0.1$
		$p_T^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.3$	MVA τ_h ID
$e\mu$	$e(12)$ & $\mu(23)$	$p_T^{e} > 13$	$\lvert\eta^{e}\rvert < 2.5$	$I^{e} < 0.15$
		$p_T^{\mu} > 24$	$\lvert\eta^{\mu}\rvert < 2.4$	$I^{\mu} < 0.2$
	$e(23)$ & $\mu(8)$	$p_T^{e} > 24$	$\lvert\eta^{e}\rvert < 2.5$	$I^{e} < 0.15$
		$p_T^{\mu} > 15$	$\lvert\eta^{\mu}\rvert < 2.4$	$I^{\mu} < 0.2$

	0-jet	VBF	Boosted
		Selection	
$\tau_h\tau_h$	No jet	$\geq$2 jets, $p_T^{\tau\tau} > 100$ GeV, $\Delta\eta_{jj} > 2.5$	Others
$\mu\tau_h$	No jet	$\geq$2 jets, $m_{jj} > 300$ GeV, $p_T^{\tau\tau} > 50$ GeV, $p_T^{\tau_h} > 40$ GeV	Others
$e\tau_h$	No jet	$\geq$2 jets, $m_{jj} > 300$ GeV, $p_T^{\tau\tau} > 50$ GeV	Others
$e\mu$	No jet	2 jets, $m_{jj} > 300$ GeV	Others
		Observables	
$\tau_h\tau_h$	$m_{\tau\tau}$	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\mu\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$e\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$e\mu$	p_T^{μ}, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$

$\phi \to \tau\tau$ arXiv:1803.06553

Final state	First object	Second object
$e\mu^{\dagger}$	$p_T^{e} > 13$ GeV, $\lvert\eta^{e}\rvert < 2.5$	$p_T^{\mu} > 10$ GeV, $\lvert\eta^{\mu}\rvert < 2.4$
$e\tau_h$	$p_T^{e} > 26$ GeV, $\lvert\eta^{e}\rvert < 2.1$	$p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$
$\mu\tau_h$	$p_T^{\mu} > 23$ GeV, $\lvert\eta^{\mu}\rvert < 2.1$	$p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$
$\tau_h\tau_h$	$p_T^{\tau_h} > 40$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$	

† For events passing only one trigger an additional requirement of $p_T > 24$ GeV is applied on the higher-p_T lepton candidate as explained in the text.



$$D_\zeta = p_\zeta^{miss} - 0.85\, p_\zeta^{vis}; \qquad p_\zeta^{miss} = \vec{p}_T^{\,miss}\, \hat{\zeta}; \qquad p_\zeta^{vis} = (\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu})\ \hat{\zeta}$$

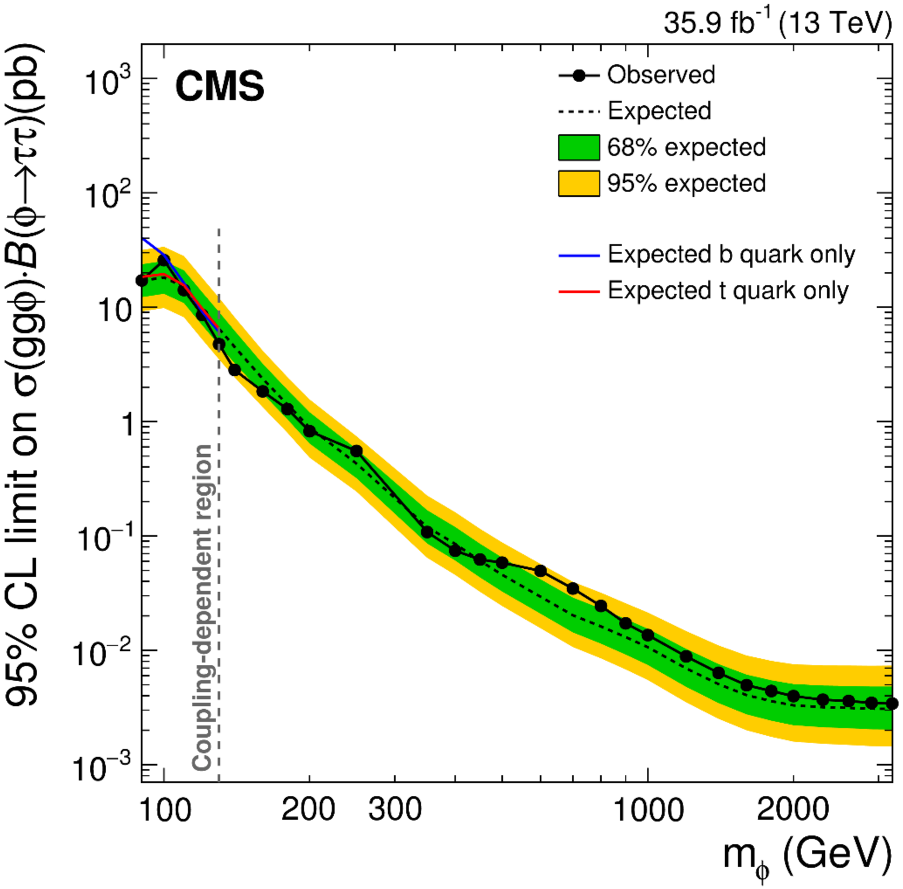
$$m_T^{tot} = \sqrt{m_T^2(p_T^{\tau_1}, p_T^{\tau_2}) + m_T^2(p_T^{\tau_1}, p_T^{miss}) + m_T^2(p_T^{\tau_2}, p_T^{miss})},$$

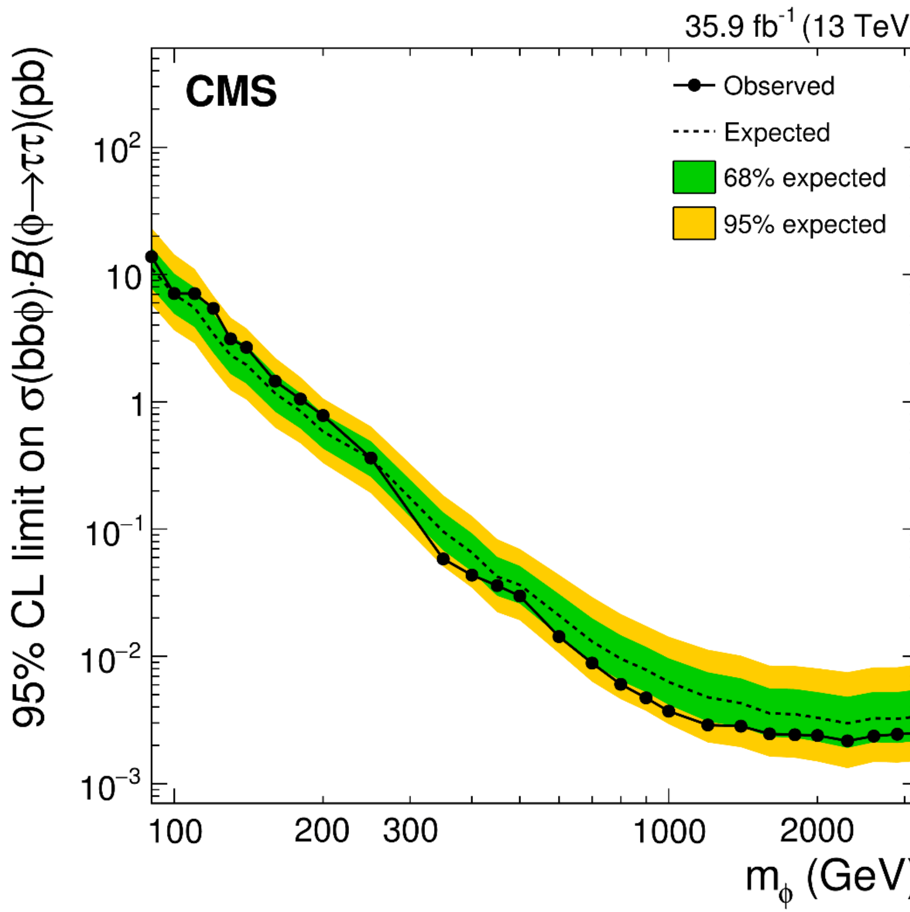
$$m_T = \sqrt{2\, p_T\, p_T' \left[1 - \cos(\Delta\phi)\right]}$$

Additional neutral Higgs decaying to τ's

arXiv:1803.06553

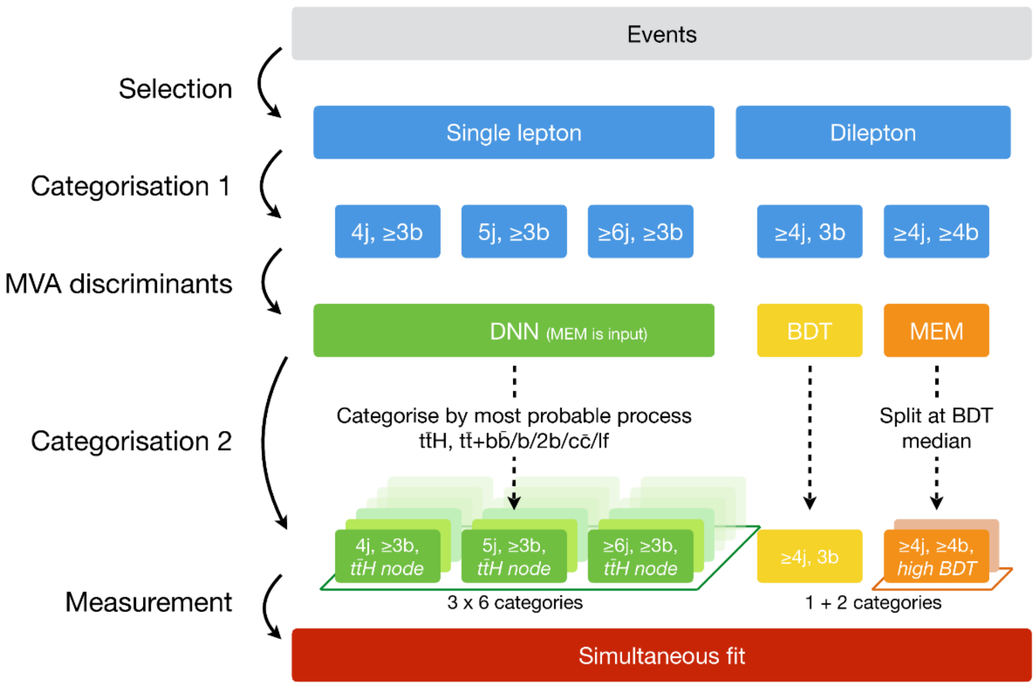
- Limits on one process leave the normalization of the other process free
- $p_T(\phi)$ estimated at NLO QCD: differences between couplings to t and b mostly at low mass





Selections, categories, observables II

ttHbb arXiv:1804.03682



ttHbb (all hadronic) arXiv:1803.06986

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

Category	MEM hypothesis
7 jets, 3 b jets	4W2H1T
8 jets, 3 b jets	4W2H1T
$\geq$9 jets, 3 b jets	4W2H1T
7 jets, $\geq$4 b jets	3W2H2T
8 jets, $\geq$4 b jets	3W2H2T
$\geq$9 jets, $\geq$4 b jets	4W2H2T

Selections, categories, observables III

ttH multilep arXiv:1803.05485

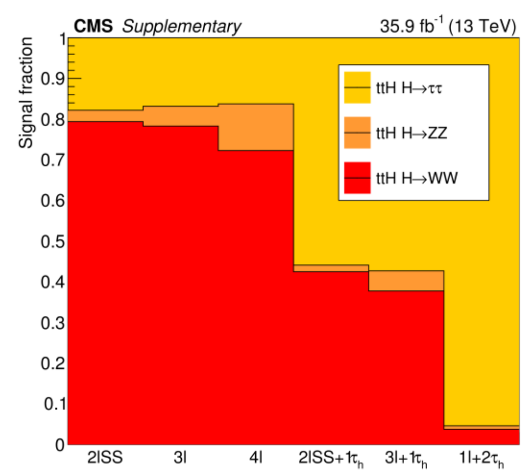
Selection	2ℓss	2ℓss + $1\tau_h$
Targeted $t\bar{t}H$ decay	$t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu qq$	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single- and double-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 GeV	$p_T > 25$ / 15 (e) or 10 GeV (μ)
τ_h p_T	—	$p_T > 20$ GeV
Charge requirements	2 same-sign leptons and charge quality requirements	2 same-sign leptons and charge quality requirements $\sum_{\ell,\tau_h} q = \pm 1$
Jet multiplicity	$\geq$4 jets	$\geq$3 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 30$ GeV	$L_D > 30$ GeV *
Dilepton mass	$m_{\ell\ell} > 12$ GeV and $\lvert m_{ee} - m_Z \rvert > 10$ GeV *	

Selection	3ℓ	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu qq$; $t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu\ell\nu$; $t \to b\ell\nu$, $t \to bqq$, $H \to ZZ \to \ell\ell qq$ or $\ell\ell\nu\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single-, double- and triple-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 / 15 GeV	$p_T > 20$ / 10 / 10 GeV
τ_h p_T	—	$p_T > 20$ GeV
Charge requirements	$\sum_{\ell} q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Jet multiplicity	$\geq$2 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	No requirement if $N_j \geq 4$; $L_D > 45$ GeV †; $L_D > 30$ GeV otherwise	
Dilepton mass	$m_{\ell\ell} > 12$ GeV and $\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV ‡	

* Applied only if both leptons are electrons.
† If the event contains a SFOS lepton pair and $N_j \leq 3$.
‡ Applied to all SFOS lepton pairs.

Selection	$1\ell + 2\tau_h$	4ℓ
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \tau_h\tau_h + \nu$'s	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu\ell\nu$; $t \to b\ell\nu$, $t \to b\ell\nu$, $H \to ZZ \to \ell\ell qq$ or $\ell\ell\nu\nu$
Trigger	Single=lepton and lepton+τ_h triggers	Single-, double- and triple-lepton triggers
Lepton p_T	$p_T > 25$ (e) or 20 GeV (μ)	$p_T > 25$ / 15 / 15 / 10 GeV
τ_h p_T	$p_T > 30$ / 20 GeV	—
Charge requirements	$\sum_{\tau_h} q = 0$ and $\sum_{\ell,\tau_h} q = \pm 1$	$\sum_{\ell} q = 0$
Jet multiplicity	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	—	No requirement if $N_j \geq 4$; $L_D > 45$ GeV †; $L_D > 30$ GeV otherwise
Dilepton mass	$m_{\ell\ell} > 12$ GeV	$m_{\ell\ell} > 12$ GeV and $\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV ‡
Four-lepton mass	—	$m_{4\ell} > 140$ GeV §

† If the event contains a SFOS lepton pair and $N_j \leq 3$.
‡ Applied to all SFOS lepton pairs.
§ Applied only if the event contains 2 SFOS lepton pairs.



Selections, categories, observables IV

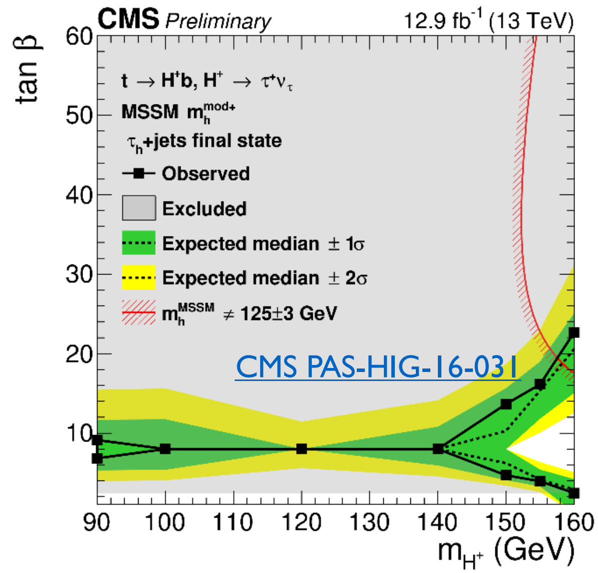
tHq CMS PAS-HIG-18-009

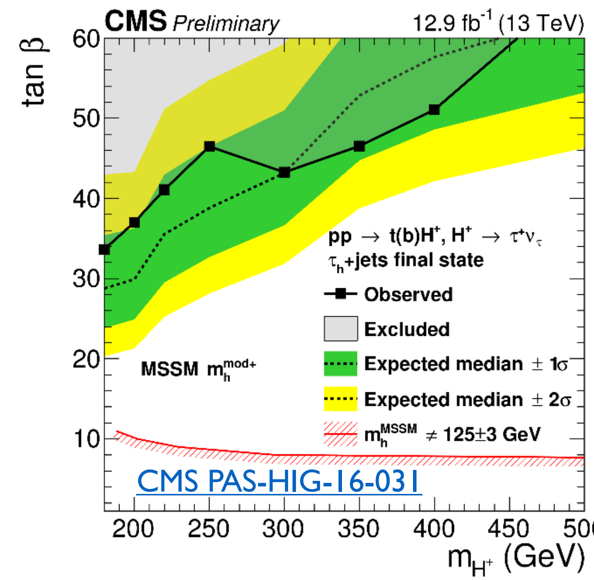
Same-sign channel ($\mu\mu$/eμ)	**$\ell\ell\ell$ channel**
Exactly two tight same sign leptons $p_{\mathrm{T}} > 25/15\,\mathrm{GeV}$	Exactly three tight leptons $p_{\mathrm{T}} > 25/15/15\,\mathrm{GeV}$ No lepton pair with $\lvert m_{\ell\ell} - m_{\mathrm{Z}} \rvert < 15\,\mathrm{GeV}$
No loose leptons with $m_{\ell\ell} < 12\,\mathrm{GeV}$ One or more b tagged jet with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$ One or more untagged jet with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ for $\lvert\eta\rvert < 2.4$ and $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ for $\lvert\eta\rvert > 2.4$	

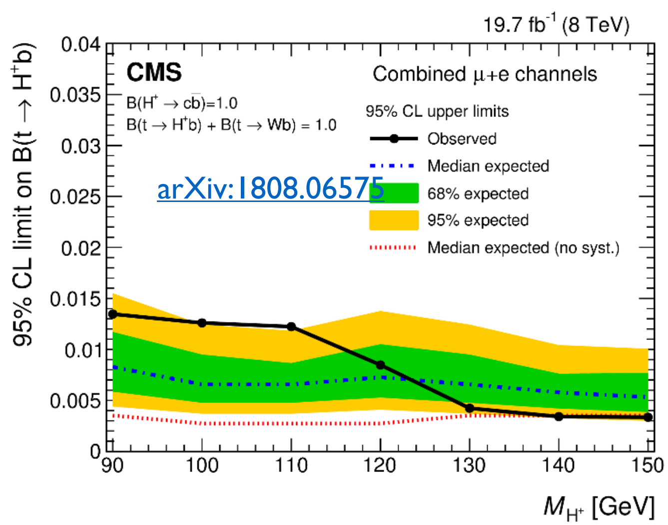
Signal region	**Control region**
One muon (electron) with $p_{\mathrm{T}} > 27(35)$ GeV No additional loose leptons	Two leptons: $p_{\mathrm{T}} > 20/20\,\mathrm{GeV}$ ($\mu\mu$/eμ) or $p_{\mathrm{T}} > 20/15\,\mathrm{GeV}$ (ee/μe) No additional loose leptons
Three or four b tagged jets $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$	Two b tagged jets $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$
One or more untagged jets $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ for $\lvert\eta\rvert < 2.4$ or $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ for $\lvert\eta\rvert \geq 2.4$	One or more loose b tagged jets $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$
$E_{\mathrm{T}}^{\mathrm{miss}} > 35(45)$ GeV for muons (electrons)	$E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$

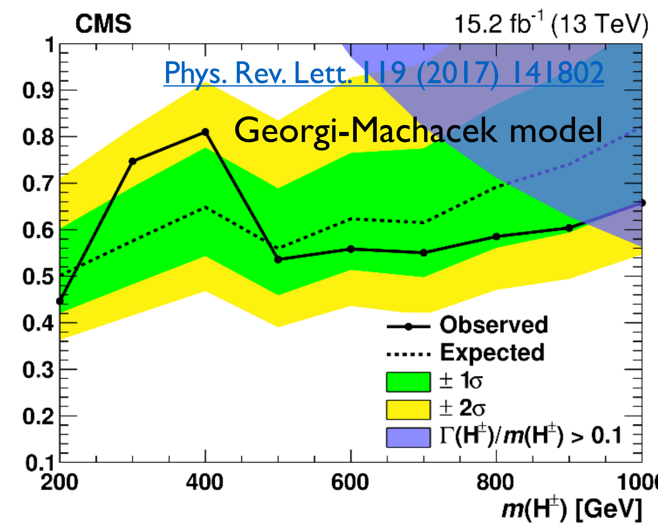
Very briefly on charged Higgs searches

- Searches in top decays, tb, VBF WZ show no evidence so far
- Model independent and re-interpretations available in several recent papers

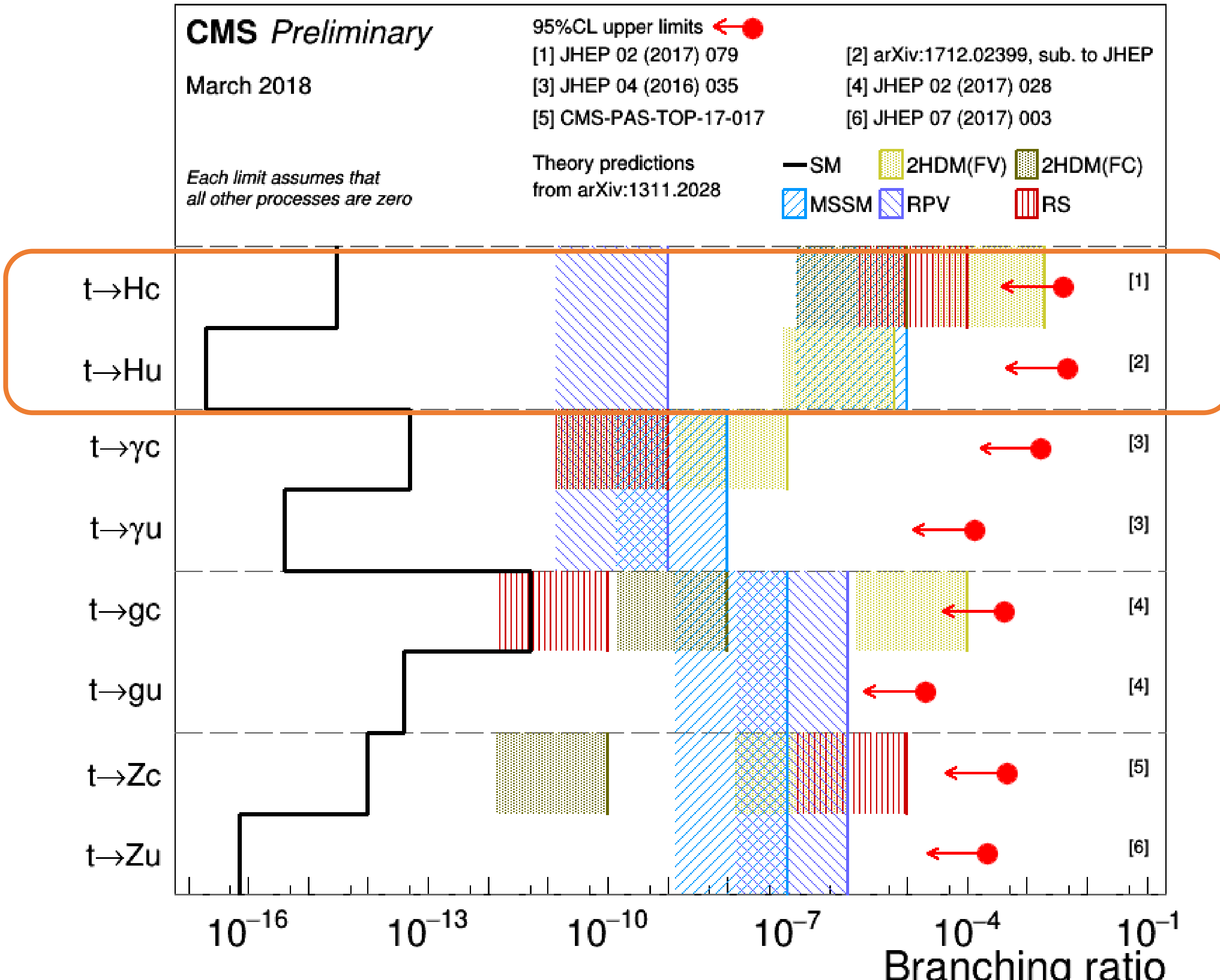








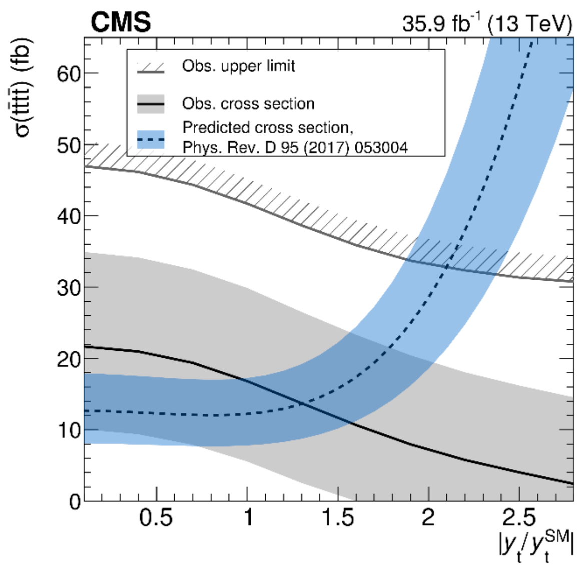
Flavour changing neutral currents



Constraints on Higgs couplings from top

[Eur. Phys. J. C 78 (2018) 140](#)

4 top production



arXiv:1711.02547 **tt+V**