CMS H(125) fermion decay results (including $t\bar{t}$H)

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for the CMS Collaboration

Higgs Hunting 2021 - Zoom - 22nd September 2021

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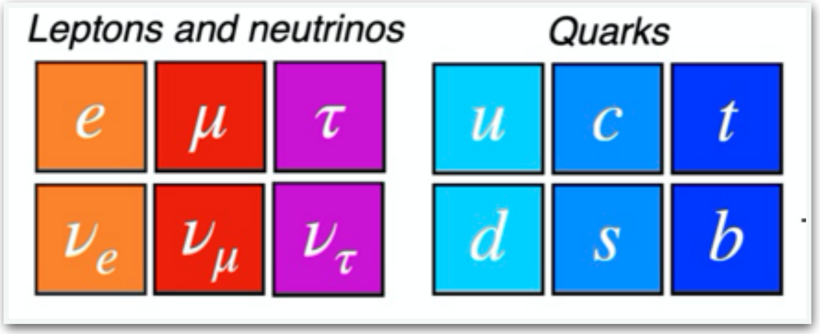
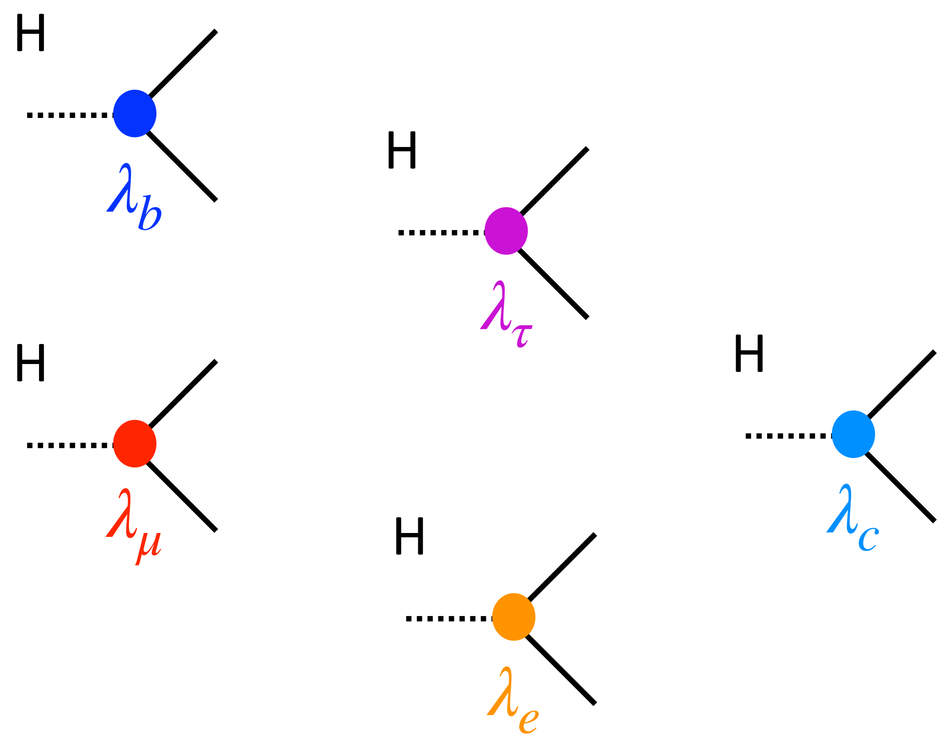
Université de Strasbourg
CNRS IN2P3 Les deux infinis

Higgs boson decays to fermions



W and Z masses from EWSB
Fermion masses from ad-hoc Yukawa couplings
One Yukawa coupling per (heavy) fermion to be scrutinised…



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Generalised Yukawa coupling, CP violation ?

$$L_Y = \frac{m_f}{v} H(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i\gamma_5 f)$$

This talk: H→b$\bar{b}$ (BR=58%), **H→ττ** (BR=6%), **H→μμ** (BR = 0.02%), **ttH & tH** measurements

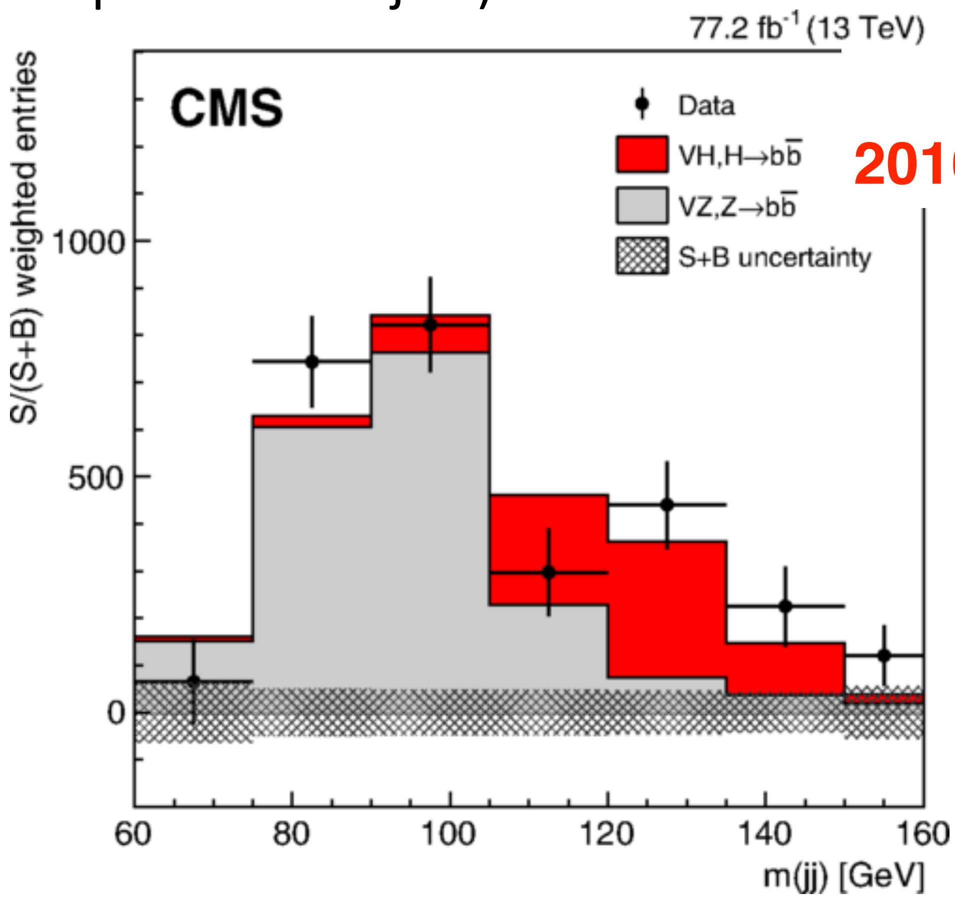
H→$c\bar{c}$, H→$\nu\bar{\nu}$ in Badder Marzocchi's talk on Tuesday

H → $b\bar{b}$

Phys. Rev. Lett.121.121801

77.2 fb^{-1}

Evidence established with 2016 data with **VH events** (0-, 1-, 2- leptons and b-jets)



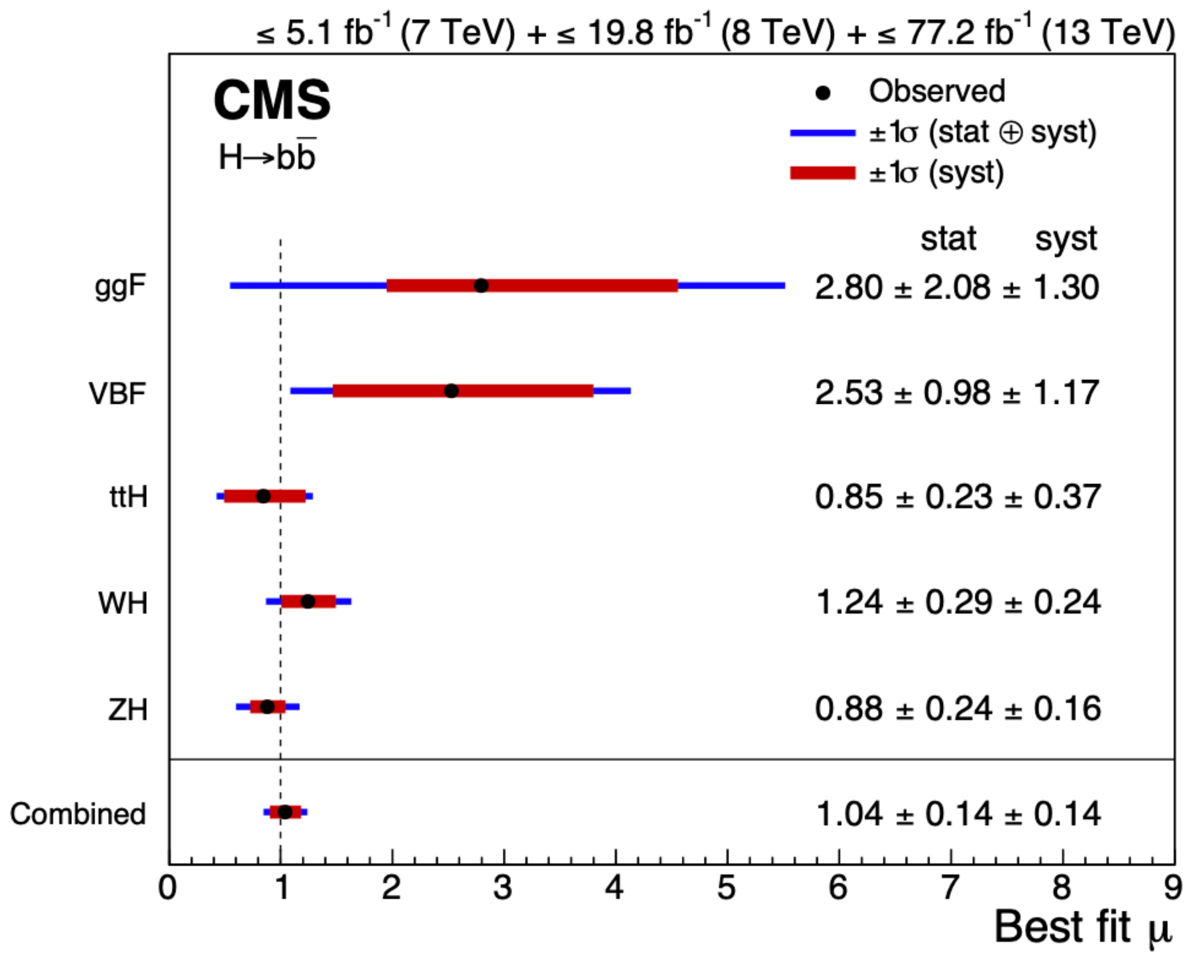
VH 2016+2017

10-13% mass resolution:

DeepCSV for b-jet identification, b-jet energy regression

Kinematic fits in 2-lepton channel, FSR jet recovery

DNN scores to extract signal (yields and b-tag scores in CR)



Run1 + Run 2 (2016+2017):

✦ **Observation with VH, ttH, VBF, and ggH production modes**

μ = 1.04 ± 0.20, 5.6σ observed, 5.5σ expected

✦ **VH,H→$b\bar{b}$ only**

μ = 1.01 ± 0.23, 4.8σ observed, 4.9 expected

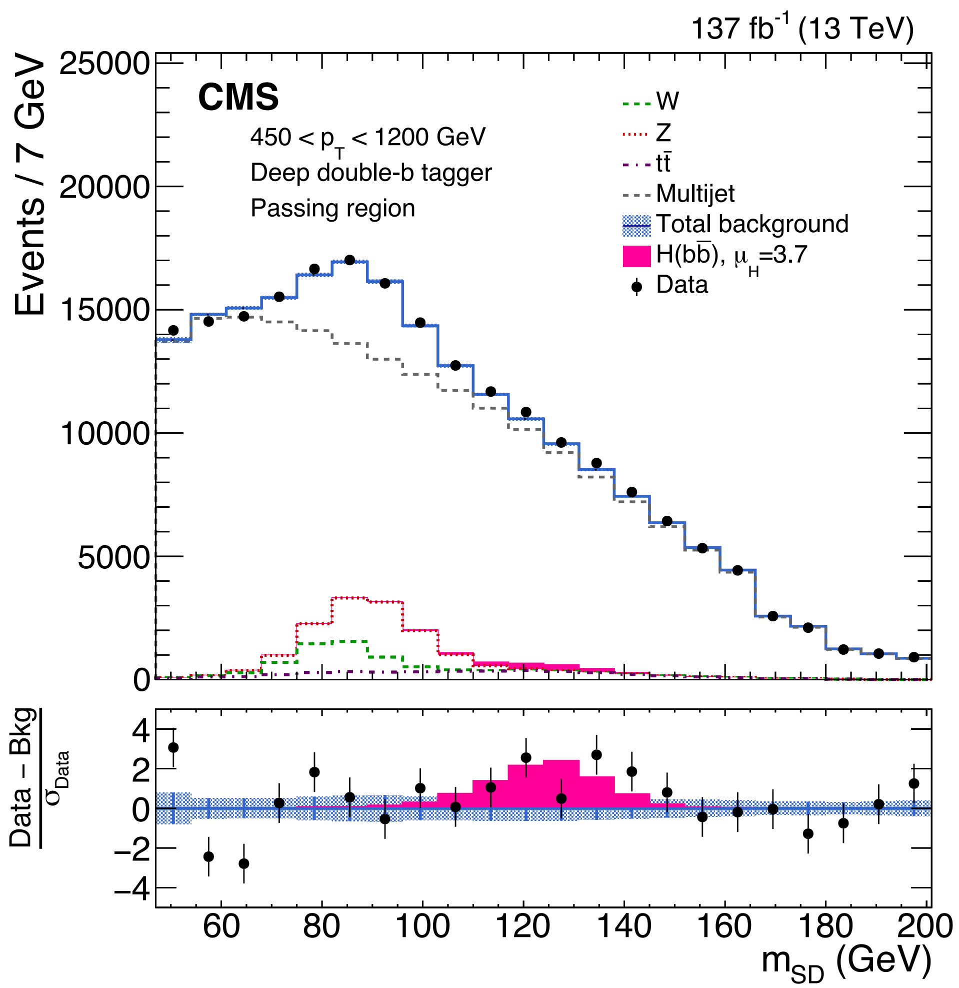
$H \rightarrow b\bar{b}$ - Lorentz-boosted Higgs events

JHEP 12 (2020) 085
137 fb^{-1}

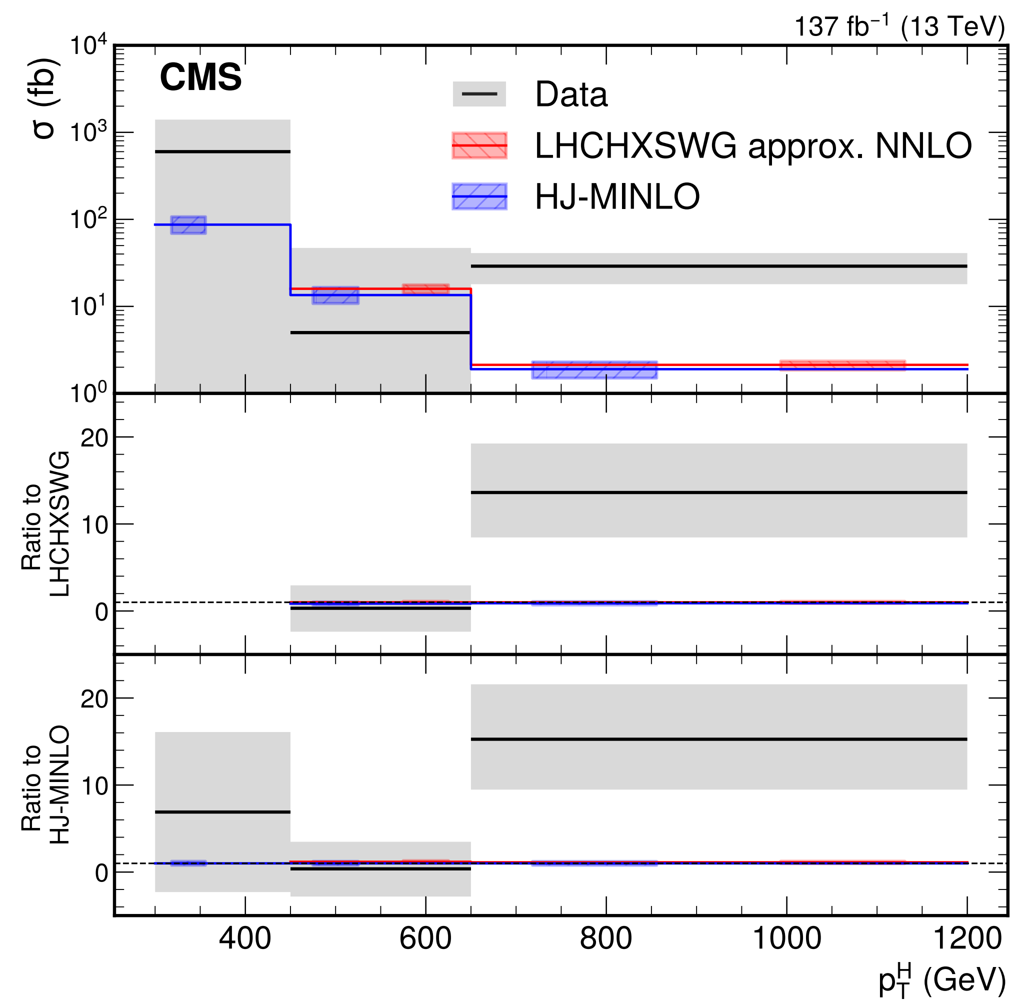
Higgs reconstructed in boosted topologies using **new deep double-b tagger (DDBT)**

All production modes: $\mu = 3.7 \pm 1.2(stat)^{+0.8}_{-0.7}(sys)^{+0.8}_{-0.5}(theo)$, **1.9σ observed w.r.t. SM (2.5σ vs background)**

Higgs mass (soft drop) is fitted for signal extraction



Differential measurement as function of p_T^H in ggF events



2.6σ local significance
p_T^H>650 GeV
HJ-MINLO for modelling

$H \to \tau\tau$

CMS-PAS-HIG-19-010

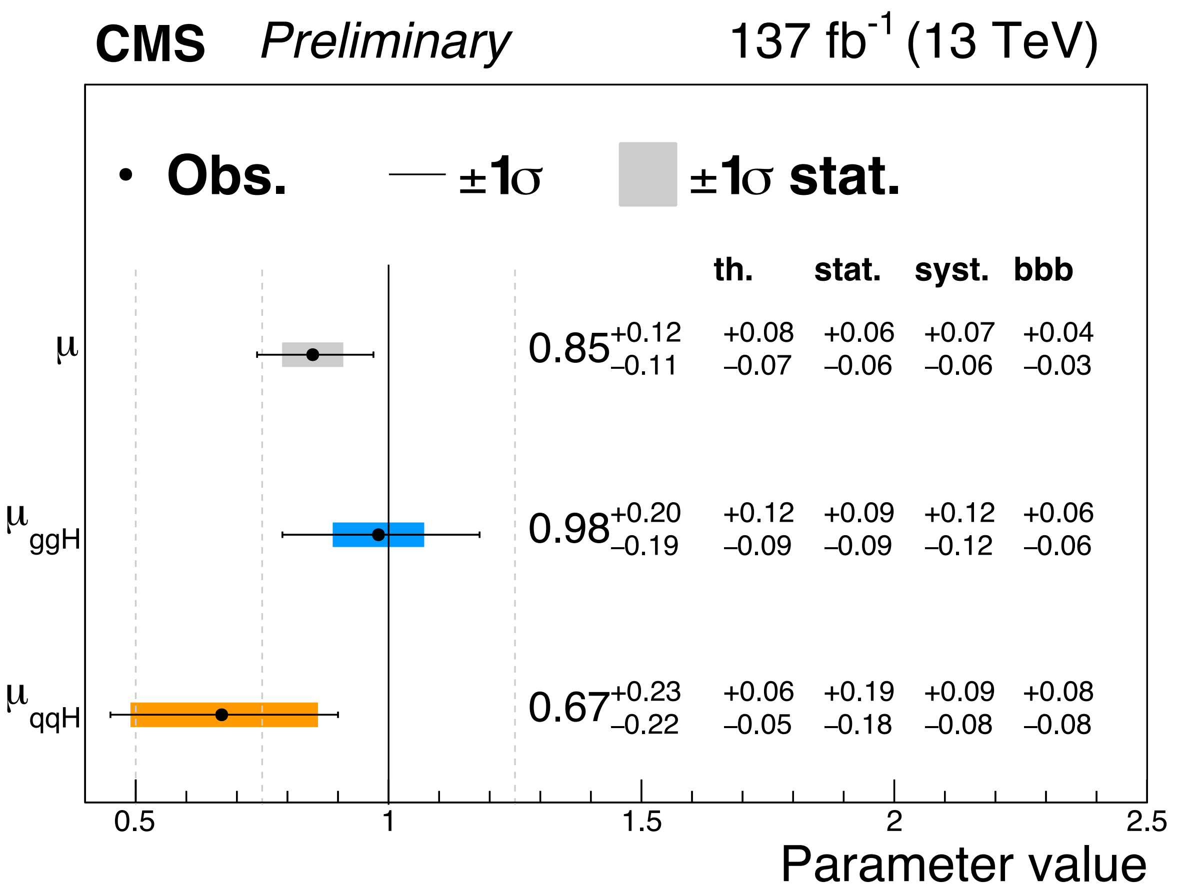
137 fb-1

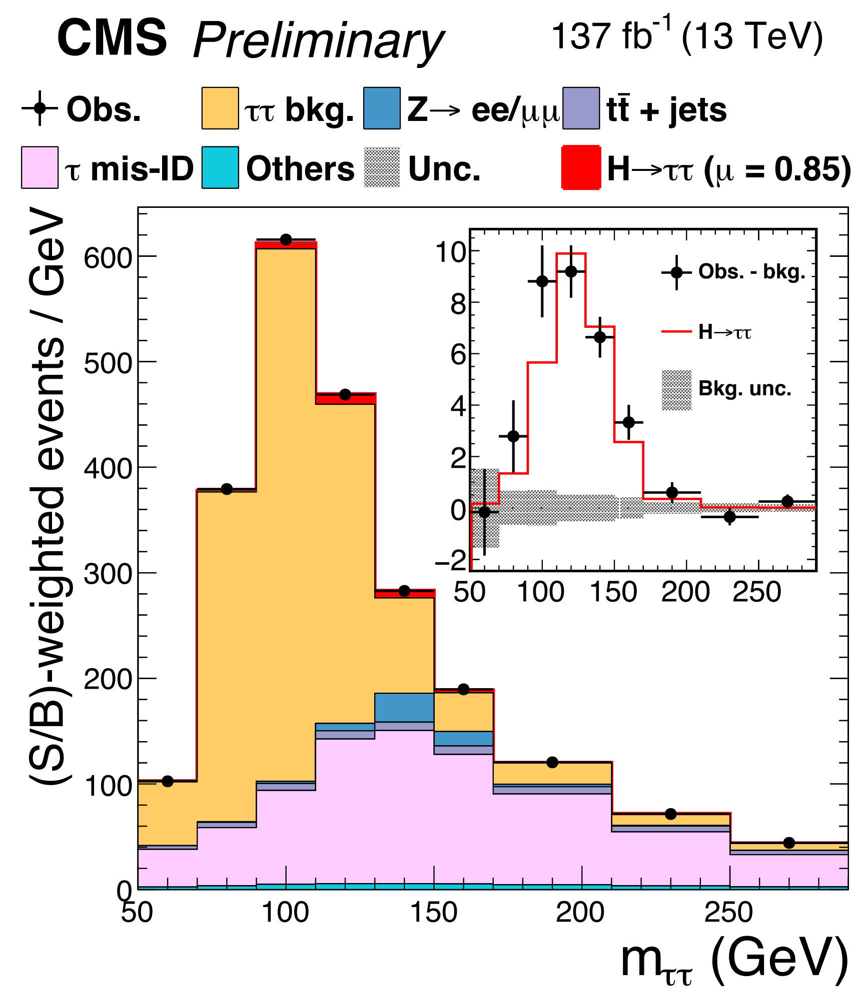
Simplified Template Cross Section (STXS) with **137 fb^{-1} of Run 2**

✦ Stage 0: **ggH** and **qqH=VBF+V(qq)H**

✦ Stage 1.2: with merging of bins

DeepTau for τ_h identification,
$Z \to \tau\tau$ from µµ embedded data (JINST 14 (2019) P06032)





$m_{\tau\tau}$ from simplified matrix-element algorithm

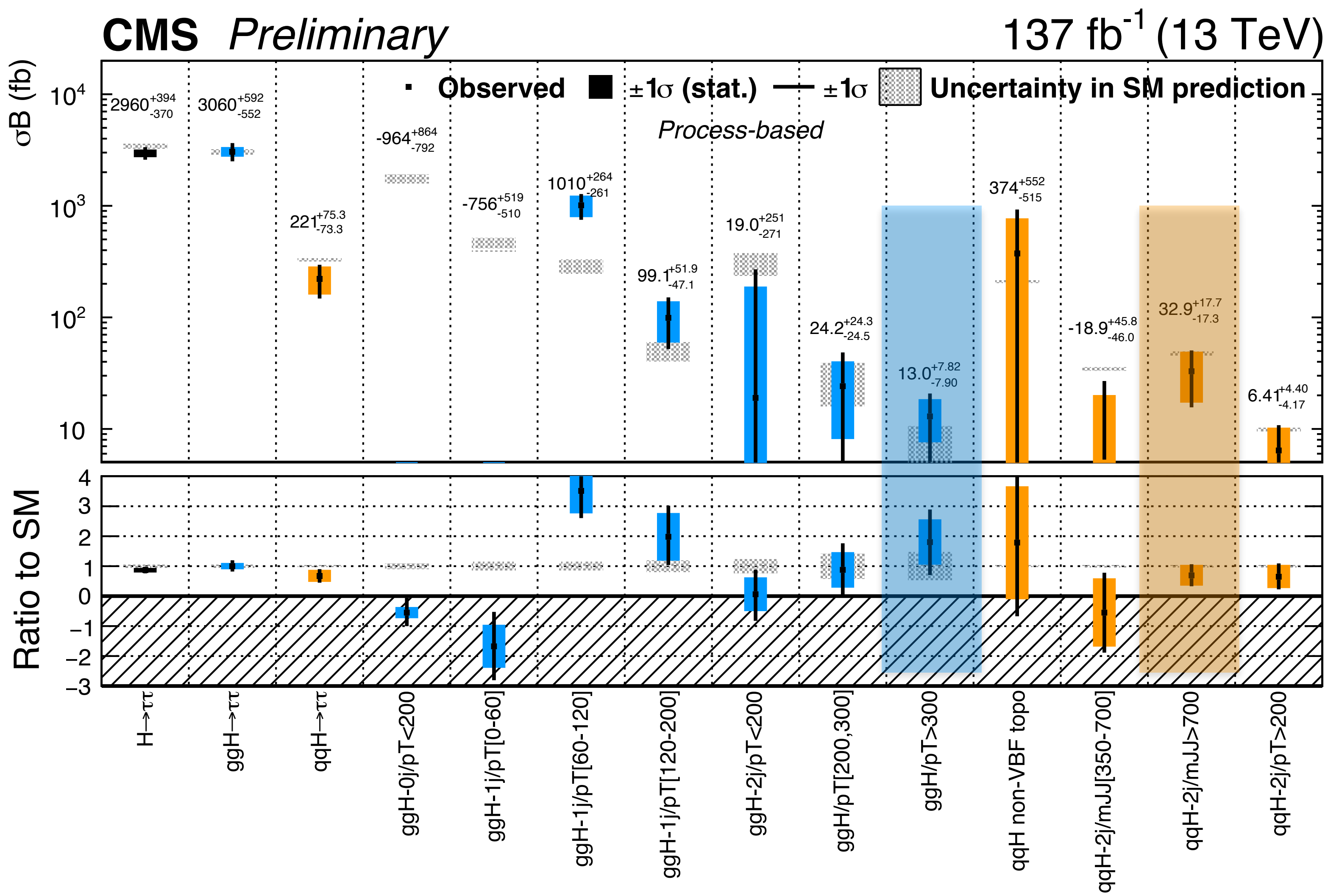
(J.Phys.Conf.Ser. 513 022035)

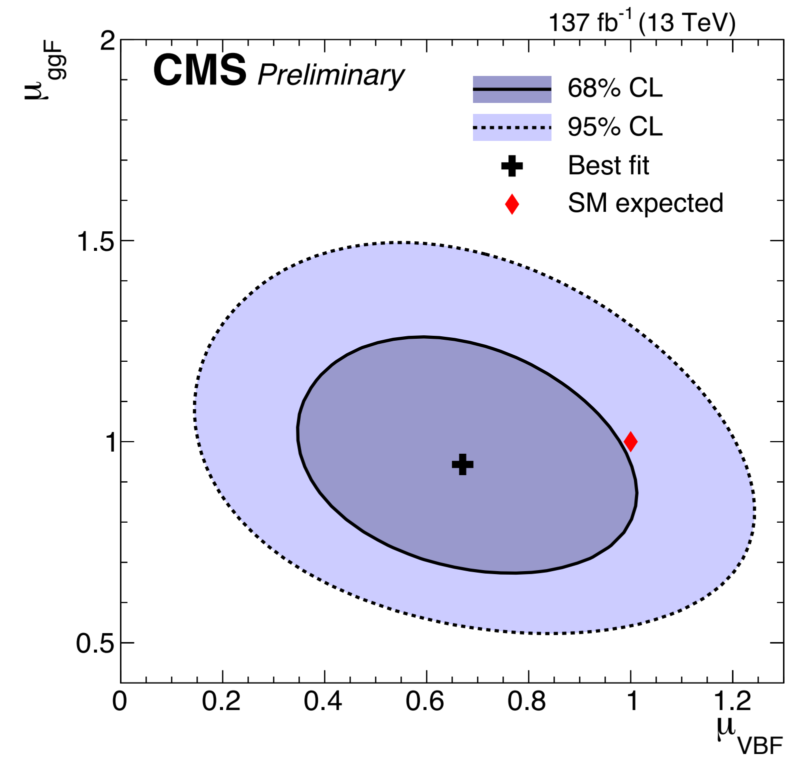
→ theory and syst. now larger than stat. uncertainties (inclusive and ggH measurements)

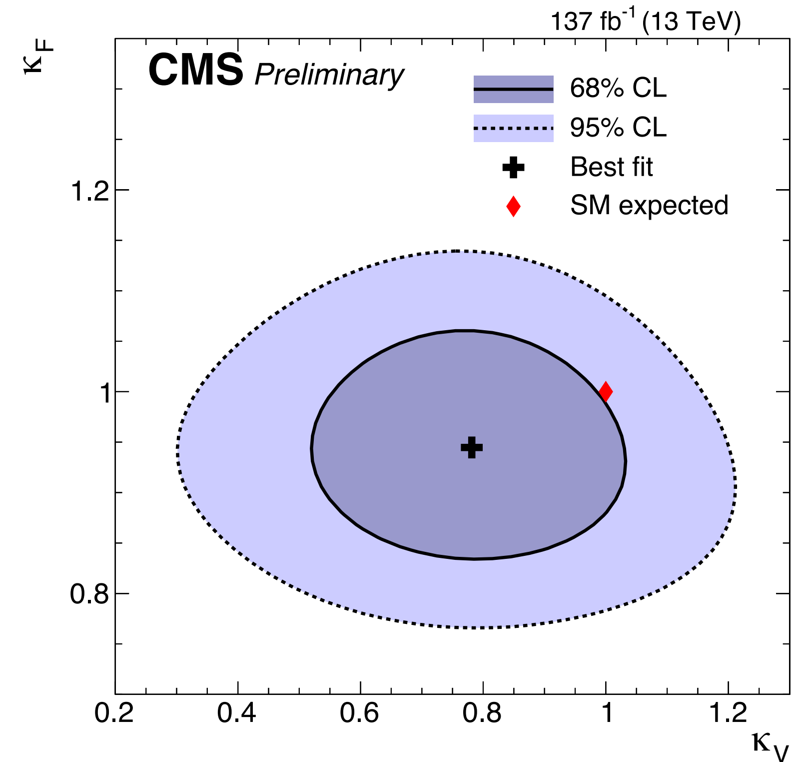
$H \to \tau\tau$

[CMS-PAS-HIG-19-010](#)

137 fb^{-1}







Cut based event categorisation, 2D distributions for ML fit

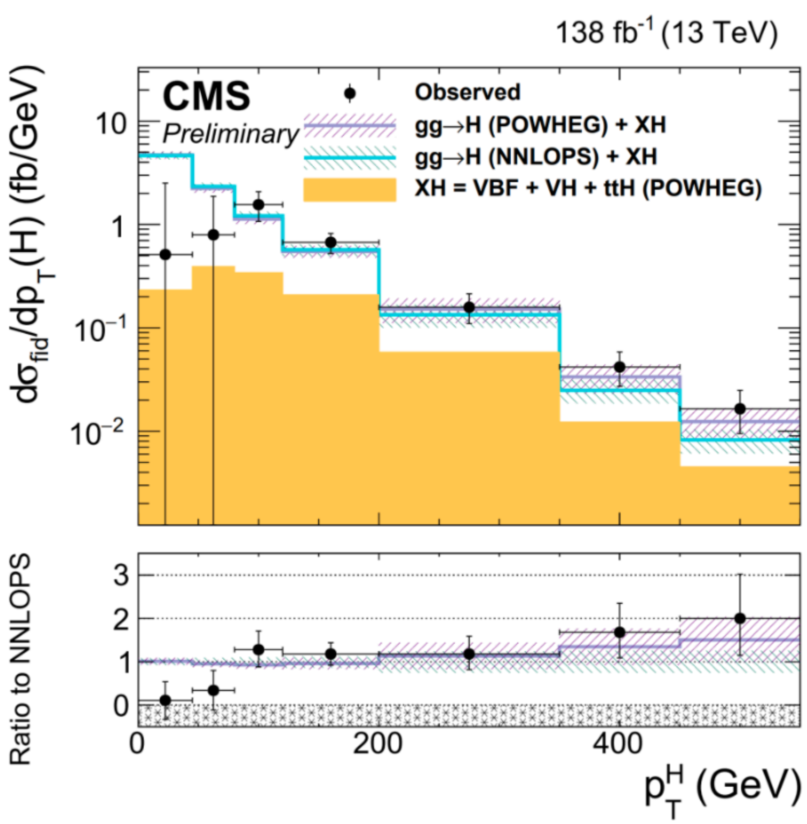
11 signal strengths adjusted

μ^{ggH} *and* μ^{VBF}, κ_F *and* κ_V close to 1σ agreement with SM

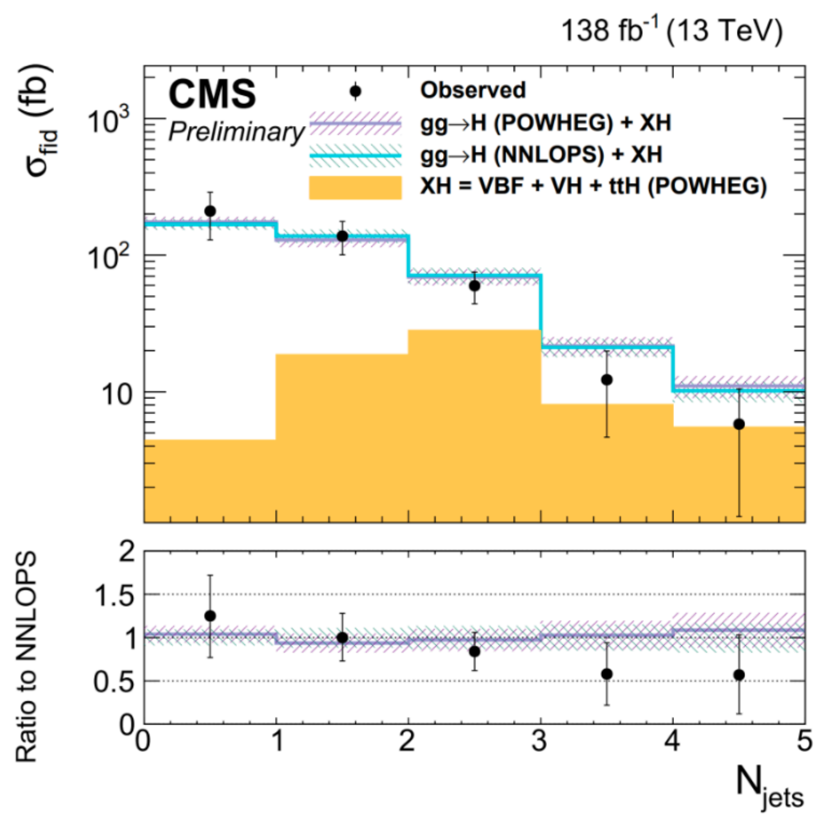
H → $\tau\tau$

[CMS-PAS-HIG-20-015](#)
137 fb^{-1}

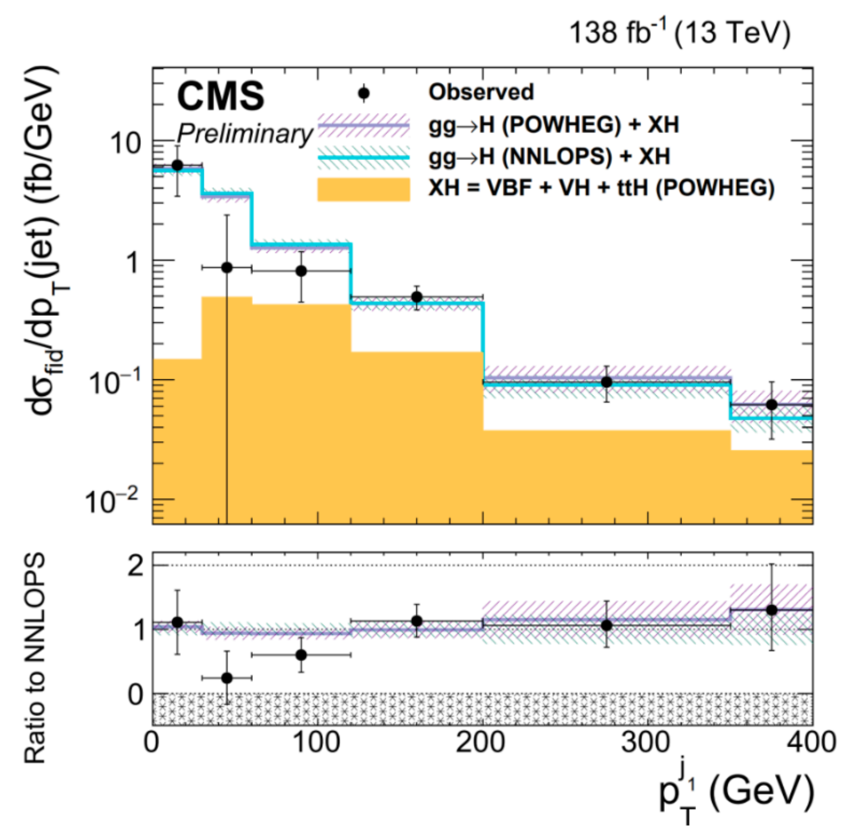
First differential cross section measurement at LHC in fiducial volume of tau decay products!
Check variables sensitive to new physics, measurement integrates over several production modes



SM P-Value: 17%



SM P-Value: 71%



SM P-Value: 45%

Competitive precision w.r.t. other final states at high p_T^H, high jet multiplicity.

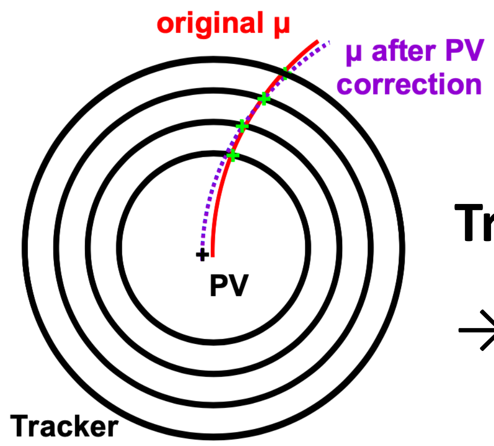
→ see Andrew Loeliger's talk on Tuesday

H → μμ

JHEP 01 (2021) 148
137 fb^{-1}

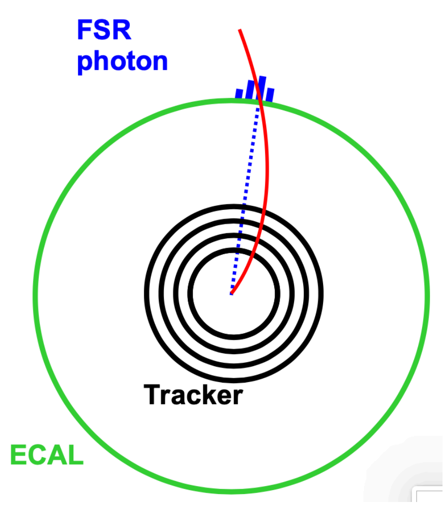
BR(H→ μμ) = 2.18 10^{-4} but **good mass resolution**

Narrow resonance over smoothly falling backgrounds (mainly Drell-Yan, $t\bar{t}$, dibosons)



Track refitting to primary vertex

→ pT resolution improvement (3-10 %)



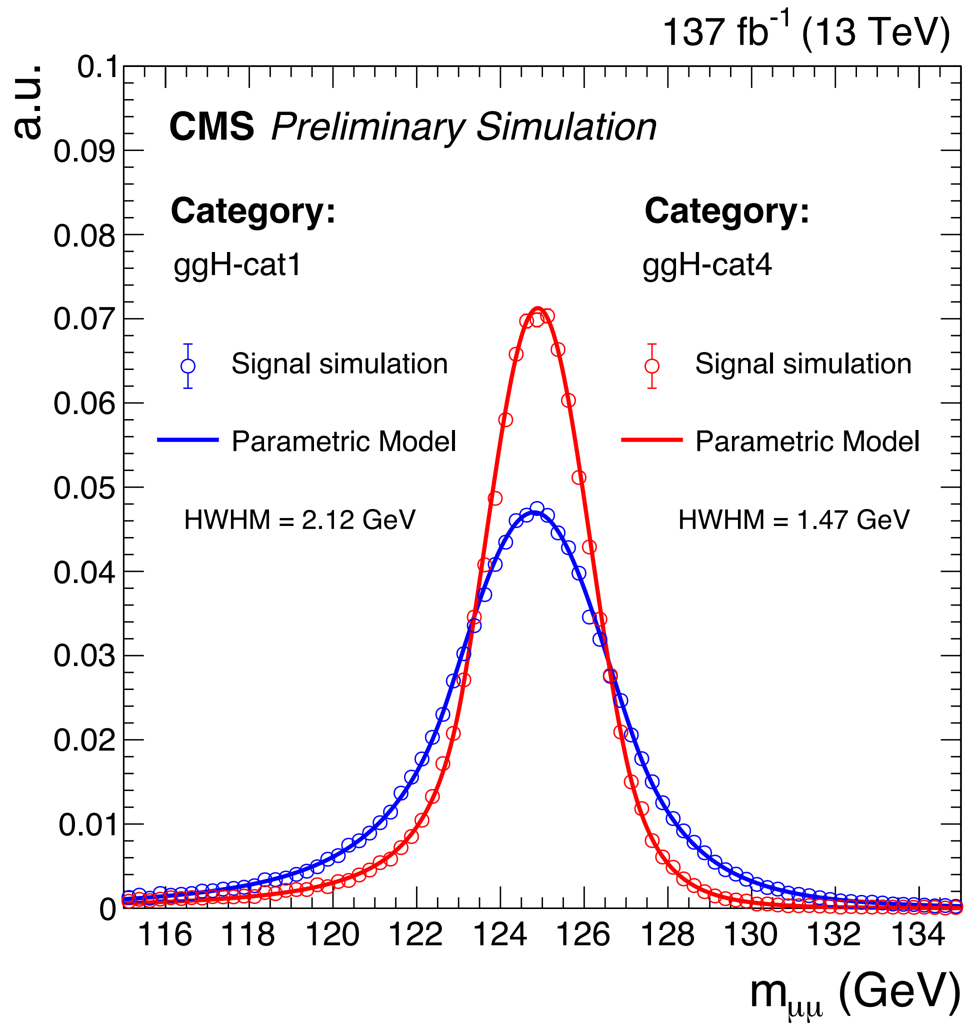
FSR energy recovery

→ pT resolution improvement (3%)

→ signal efficiency increase (2%)

Typical mass resolution

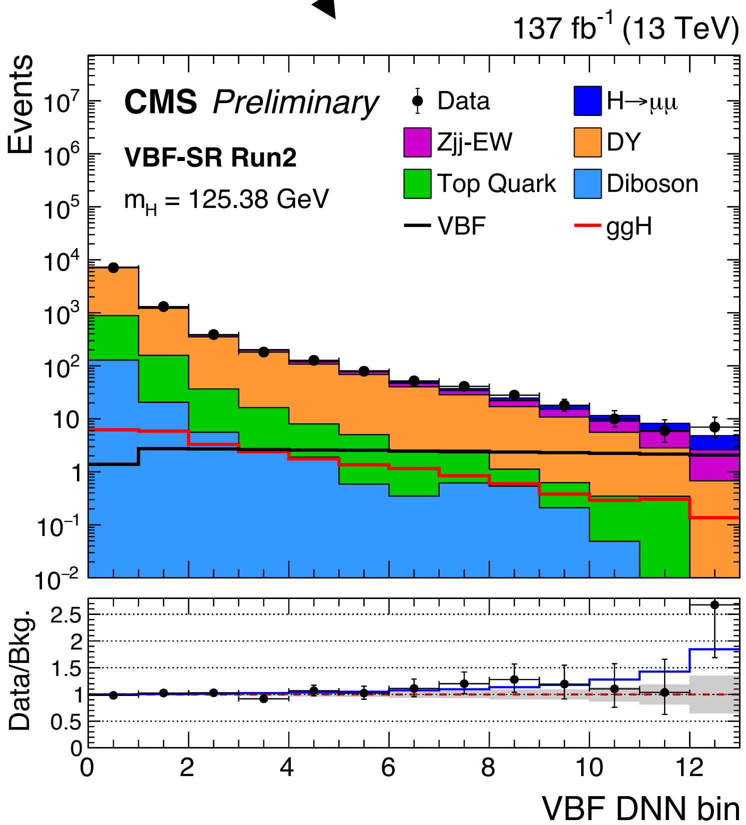
1.47 - 2.12 GeV



H→ μμ

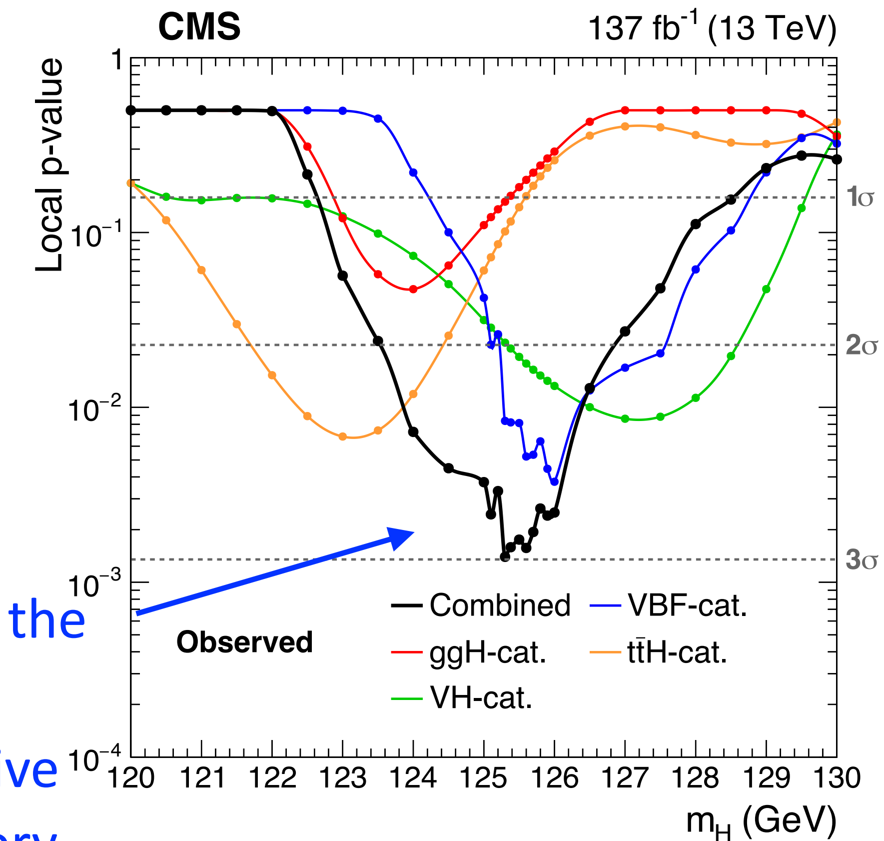
[JHEP 01 (2021) 148]
137 fb^{-1}

Results extracted from **di-μ mass spectrum (ggH, VH, ttH categories)** and **DNN score (VBF category)**
Background templates from simulation in VBF category

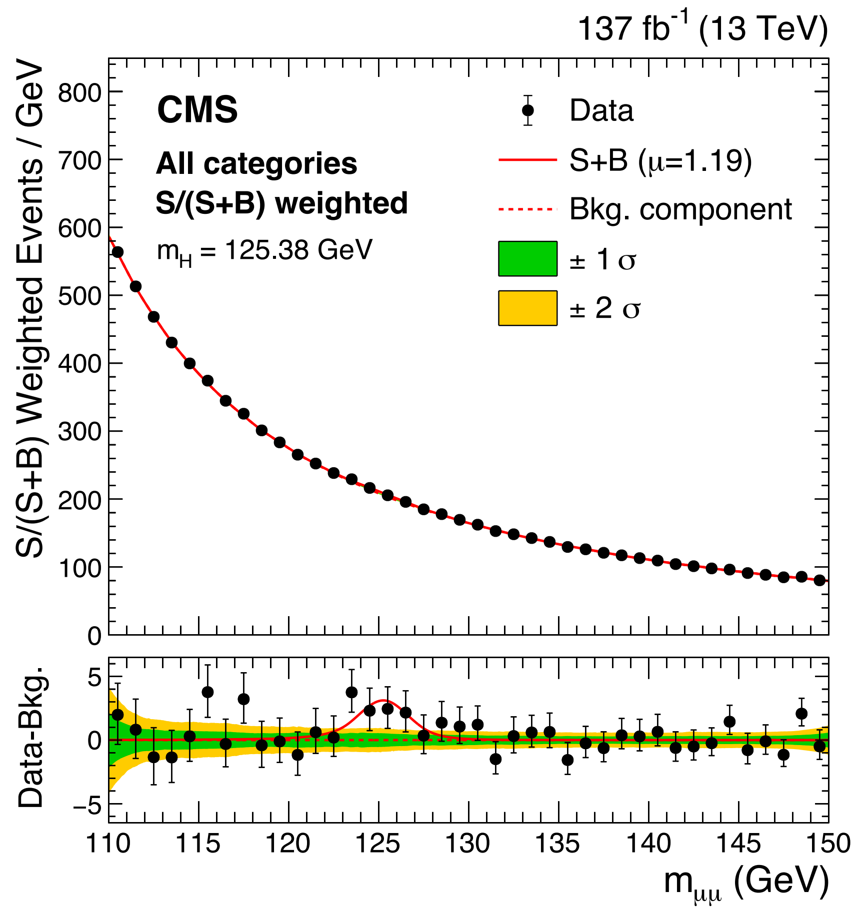


First evidence at LHC, coupling to second generation of fermions seen

- ✦ **3.0σ observed** (2.5σ expected)
- ✦ Signal strength μ = 1.19 ± 0.40 (stat) ± 0.15 (syst)
  → statistically limited

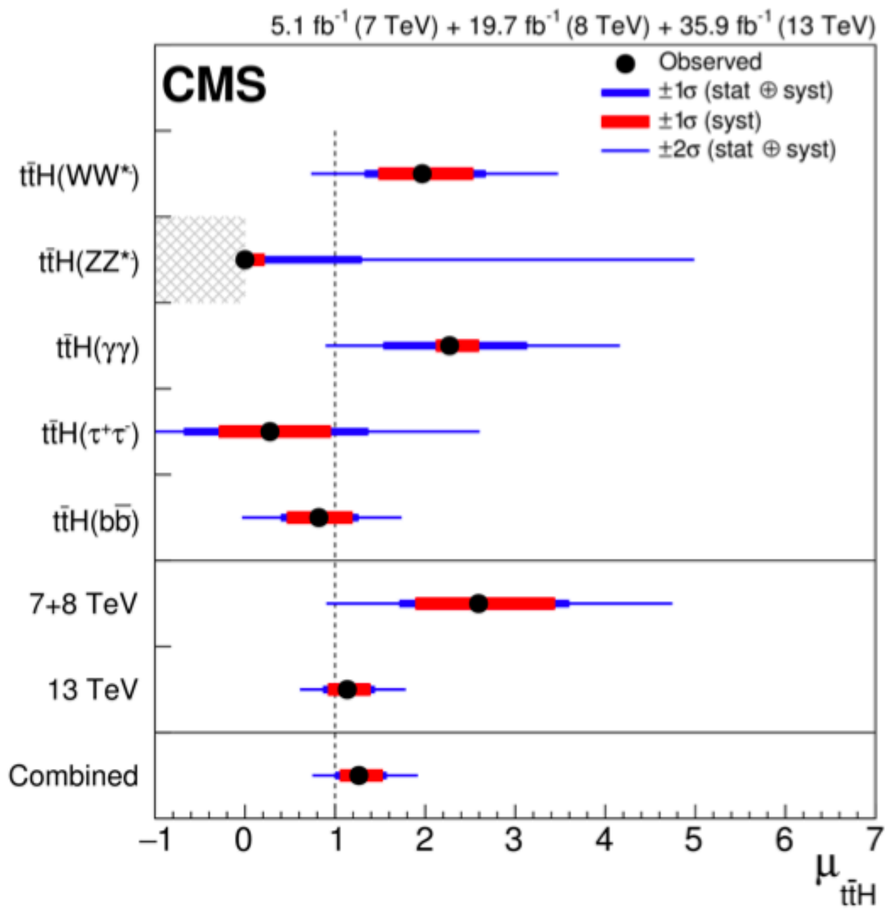


VBF is the most sensitive category



Eur. Phys. J. C 81, 378 (2021)
CMS-HIG-18-030
PRL 125 (2020) 061801

ttH and tH measurements - overview



Phys. Rev. Lett. 120, 231801 (2018)

Observation combining **Run1 + Run2 data** and **multi-lepton, H → $b\bar{b}$ and H → $\gamma\gamma$ channels**

Run 1 + Run 2
μ = 1.26 + 0.31 - 0.26 5.2σ / 4.2σ

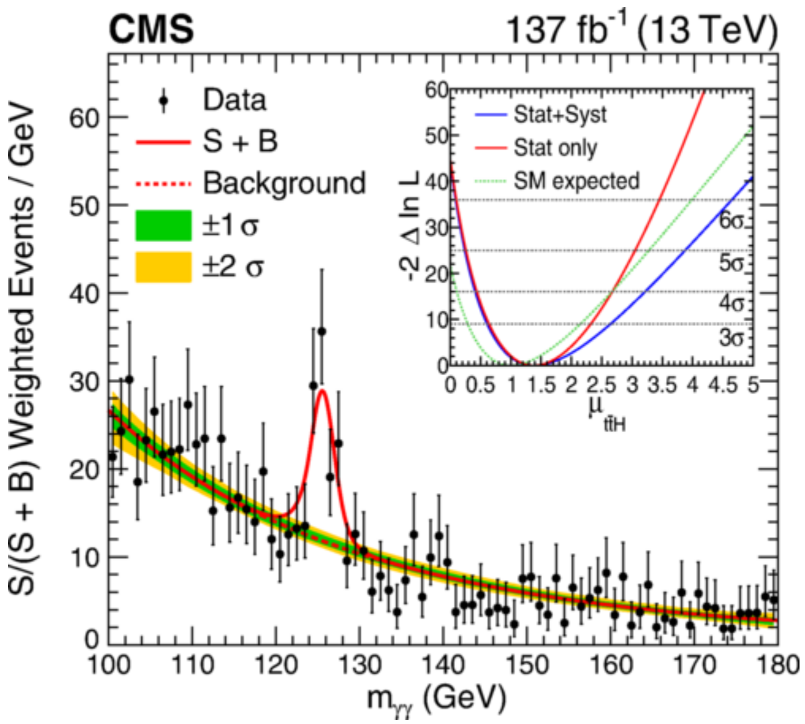
		Signal strength	Obs/Exp significances	
Multi-leptons H→WW, ZZ, $\tau\tau$	**137 fb^{-1}**	0.92 + 0.26 - 0.23	**4.7σ** / 5.2σ (ttH) 1.4σ / 0.3σ (tH)	ttH and tH ttW and ttZ free floating
H → $b\bar{b}$	41.5 fb^{-1}	1.15 + 0.32 - 0.29	3.9σ / 3.5σ	challenging tt+HF modelling
H → $\gamma\gamma$	**137 fb^{-1}**	1.38 + 0.36 - 0.29	**6.6σ** / 4.7σ	STXS measurement (S. 11) CP analysis (S. 14)

Last results →

ttH and tH measurements - **ttH, H → $\gamma\gamma$**

[PRL 125 (2020) 061801](PRL 125 (2020) 061801)

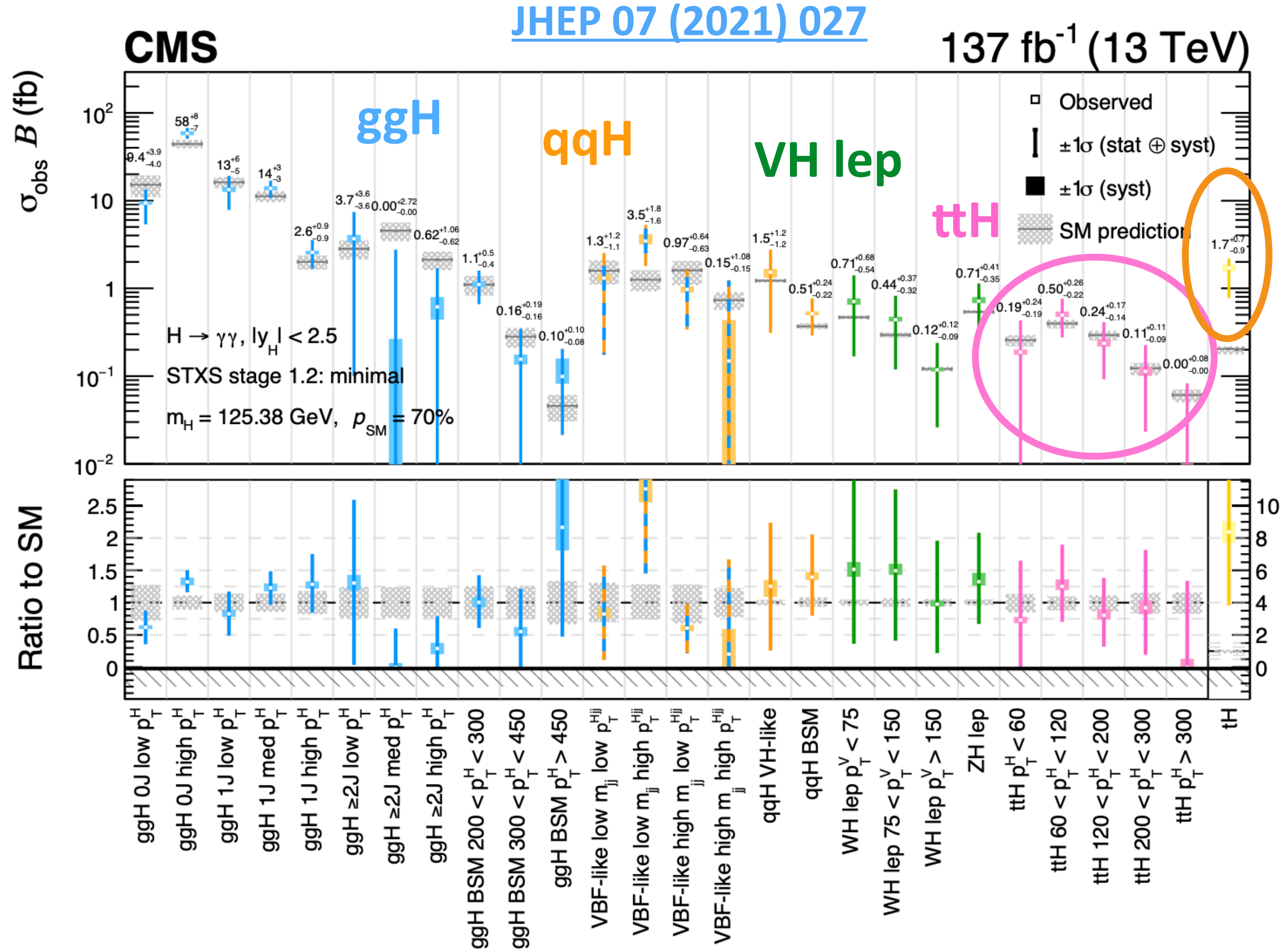
137 fb^{-1}



First observation of the ttH process in a single Higgs boson decay channel

Fit of m(γγ) for signal extraction

JHEP 07 (2021) 027



First measurement vs $p_{\gamma\gamma}^{T}$

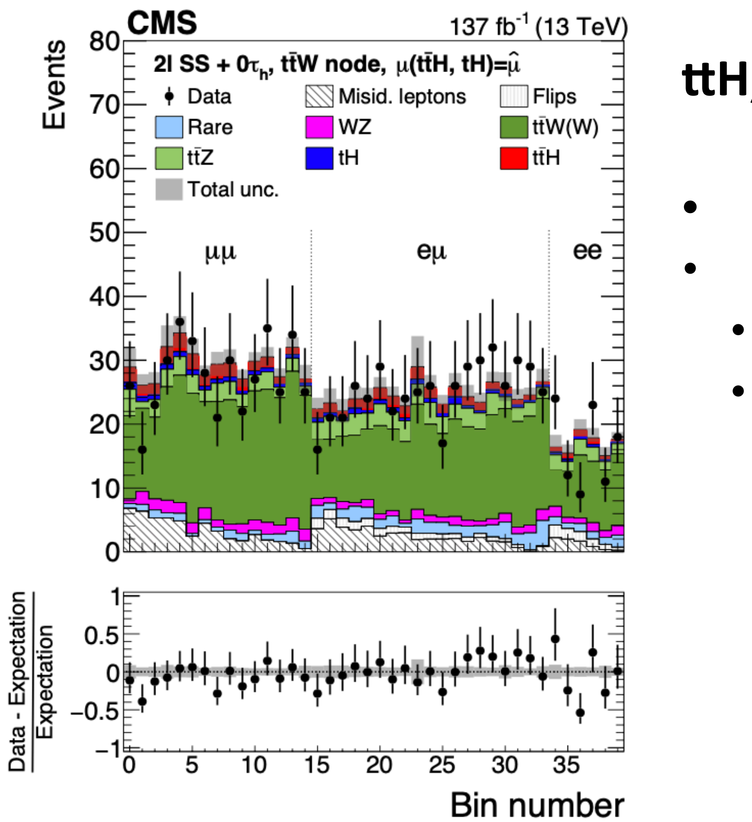
4 bins in good agreement with SM!

Limit on tH:

14 (8) × SM @ 95% CL obs. (exp.)

Eur. Phys. J. C 81, 378 (2021)
CMS-HIG-18-030

ttH and tH measurements - **critical backgrounds**



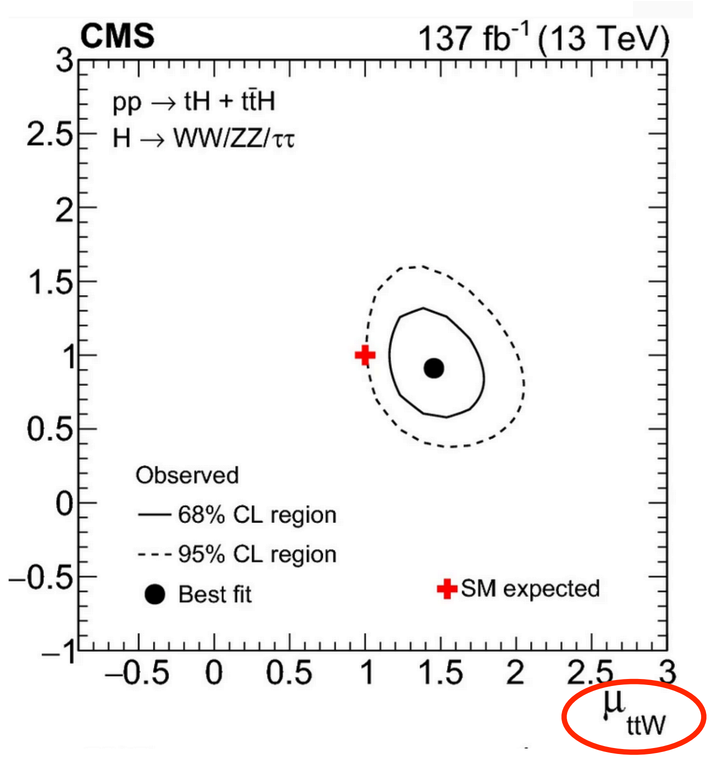
ttH, H→multilepton

- **ttW and ttZ are free floating**
- Dedicated control regions
  - **ttZ**: Z-mass cut, njet>=1
  - **ttW**: 2l same sign with ttW node of multi class NN having the highest value

ttH, H→bbar

- **Large tt+jets background** (MC: Powheg+Pythia8, normalized to NNLO+NNLL),
- **tt+HF modelling** one of the **most important systematics**
- Split in **tt+bb, tt+b, tt+2b, tt+cc, tt+LF** based on flavour content of particle-level jets
- Independent normalisation and uncertainties for all 5 tt+jets processes

- Event categorisation based on reconstructed jet flavours
- **MEM** to discriminate against **irreducible tt+bb**



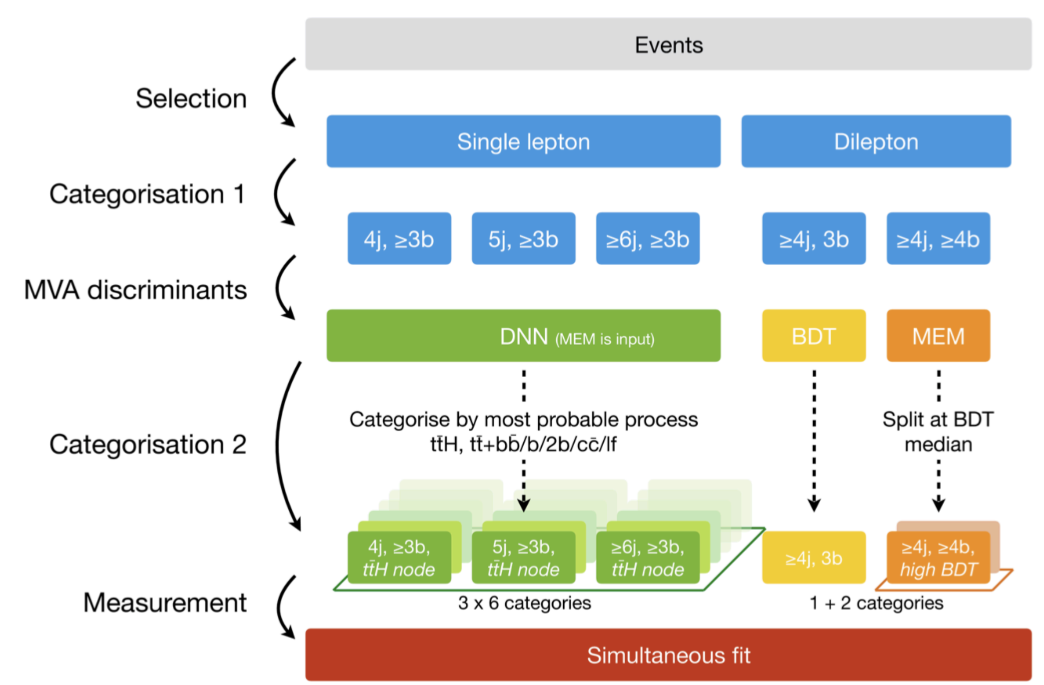
μ(ttZ) = 1.03 ± 0.14

(σ(ttZ) = 839 fb)

μ(ttW) = 1.43 ± 0.21

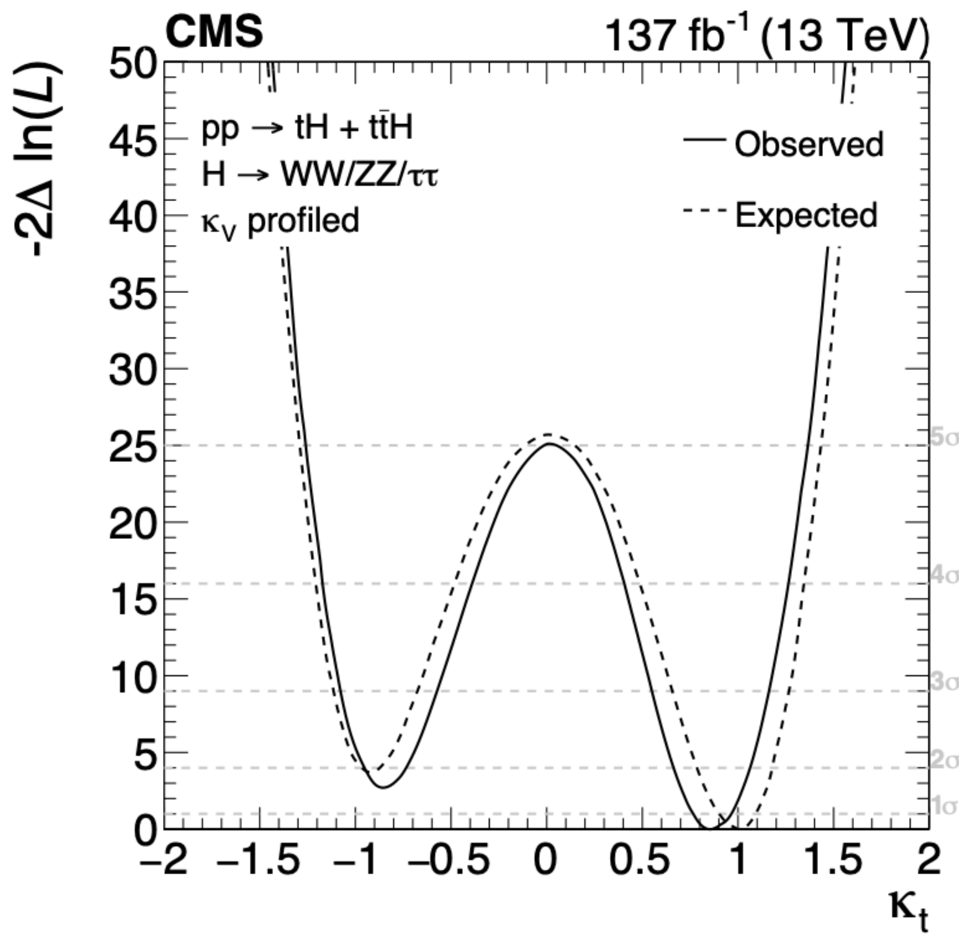
(σ(ttW) = 650 fb)

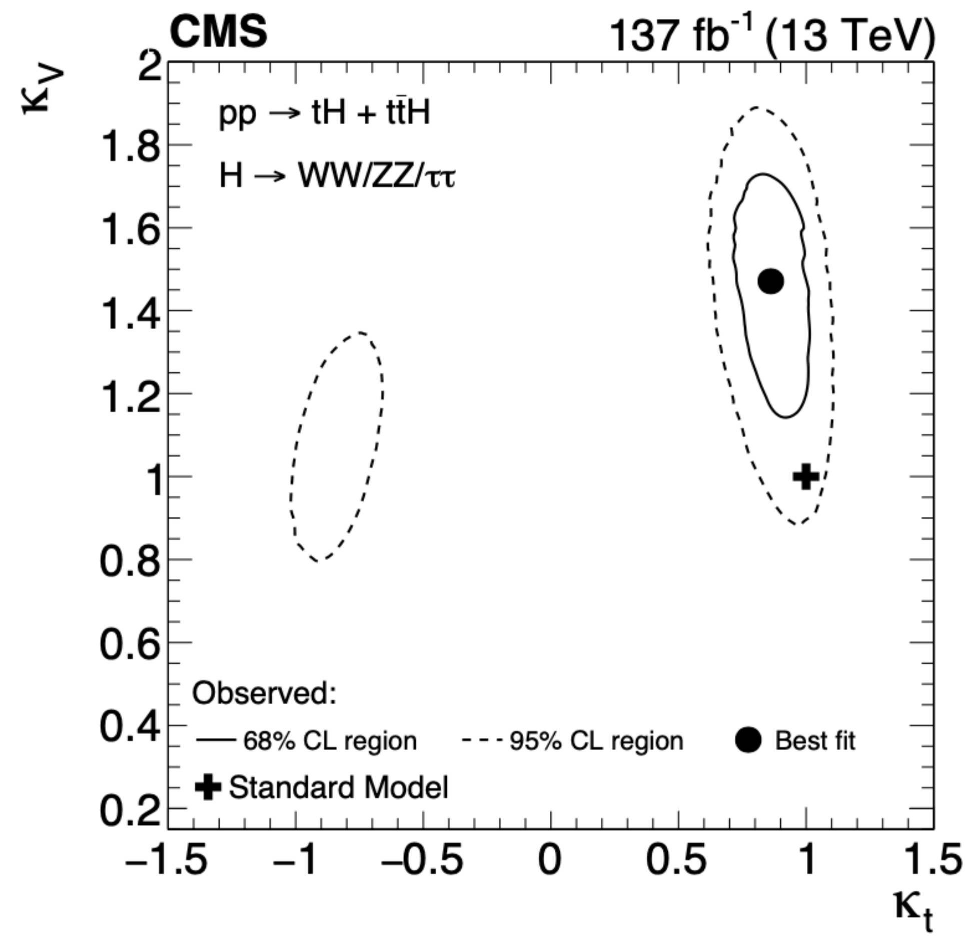
→ ttW excess seen



ttH and tH measurements - **ttH multileptons**

[Eur. Phys. J. C 81, 378 (2021)](https://doi.org/10.1140/epjc/s10052-021-09014-x)
137 fb^{-1}





y_t impact on kinematics and rates

&

κ_V impact on tHq tHW interference

taken into account

κ_t constrained to −0.9 < κ_t < −0.7 ∪ 0.7 < κ_t < 1.1 @ 95% CL

→ both the SM and inverted top coupling scenarios are in agreement with data

Tau Yukawa coupling and search for CP violation

CMS-HIG-20-006

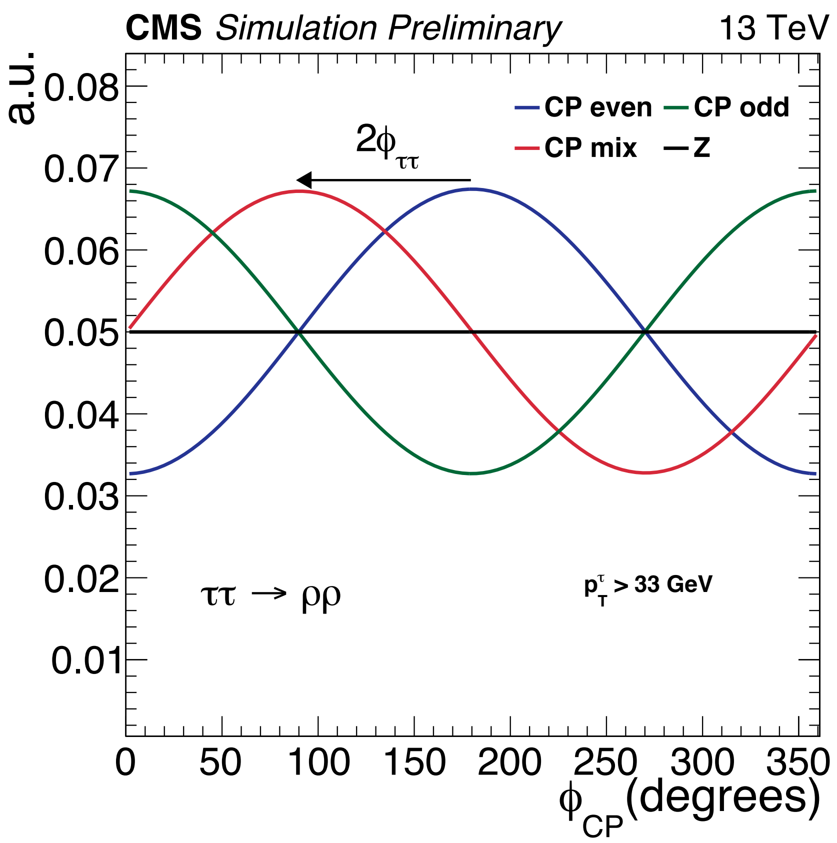
137 fb^{-1}

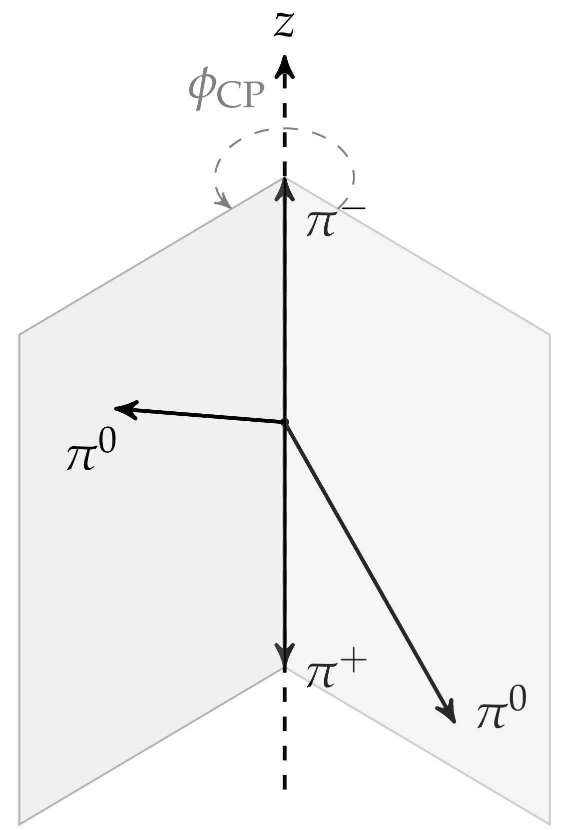
Generalised Yukawa coupling, CP violation can occur at tree level

$$L_Y = \frac{m_f}{v} H(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i \gamma_5 f) \quad \text{CP violating angle } \phi_{ff} = \frac{\kappa_f}{\tilde{\kappa}_f}, \quad \phi_{ff} = 0 \text{ in SM}$$

Angle between tau decay planes allows to reconstruct $\phi_{\tau\tau}$

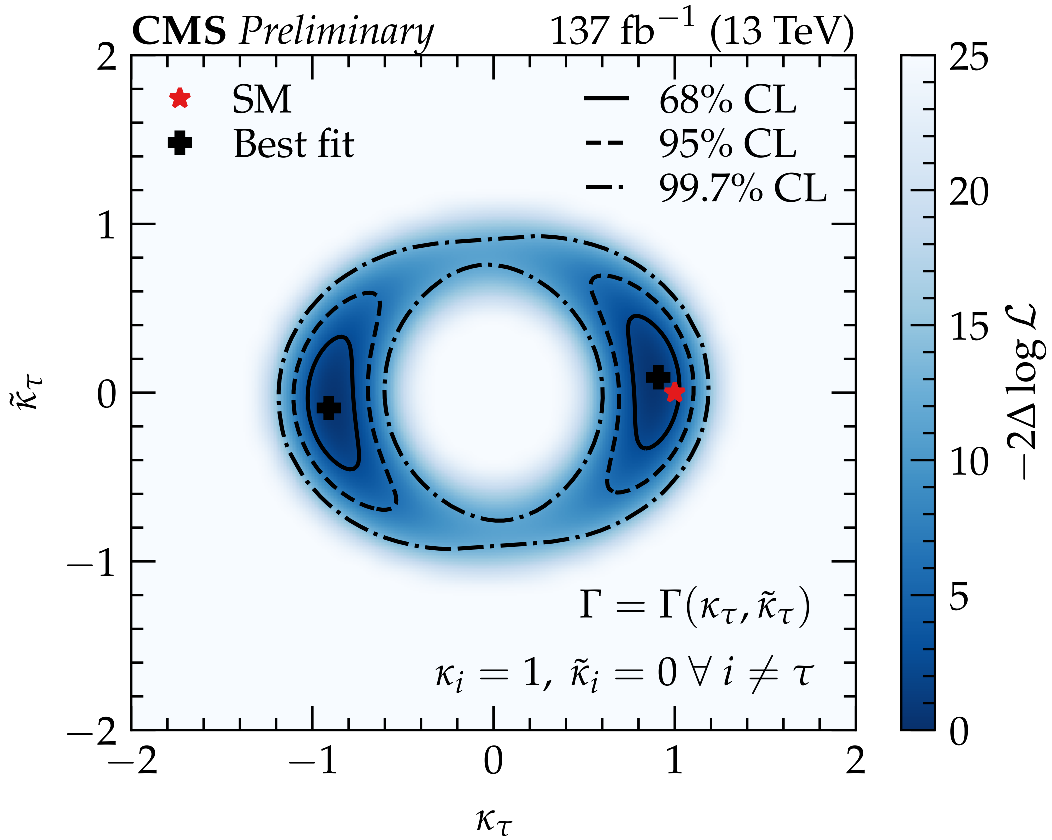
Several techniques depending on τ decay mode $\mu^{\pm}, \pi^{\pm}, \rho^{\pm}, a_1^{1pr,3pr}$





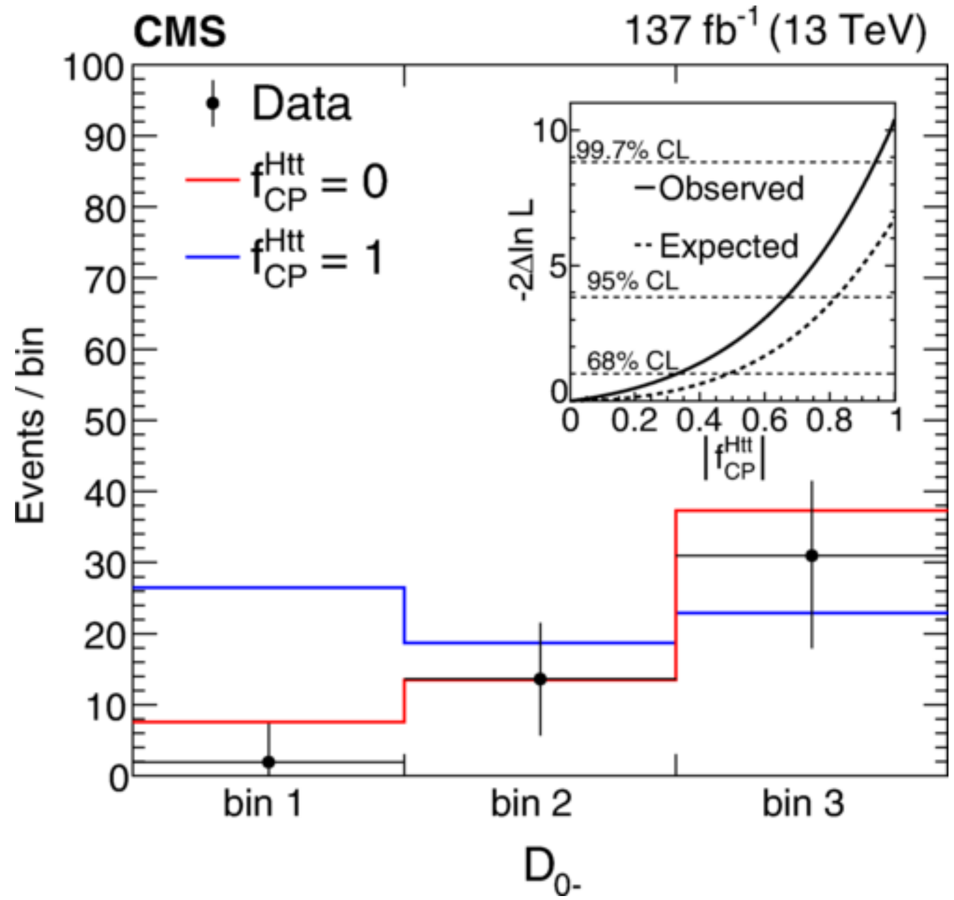
→pure CP-odd hypothesis excluded at 3.2σ

$\phi_{\tau\tau}$ **= 4 ± 17°** @ 68% CL



Top Yukawa coupling and search for CP violation

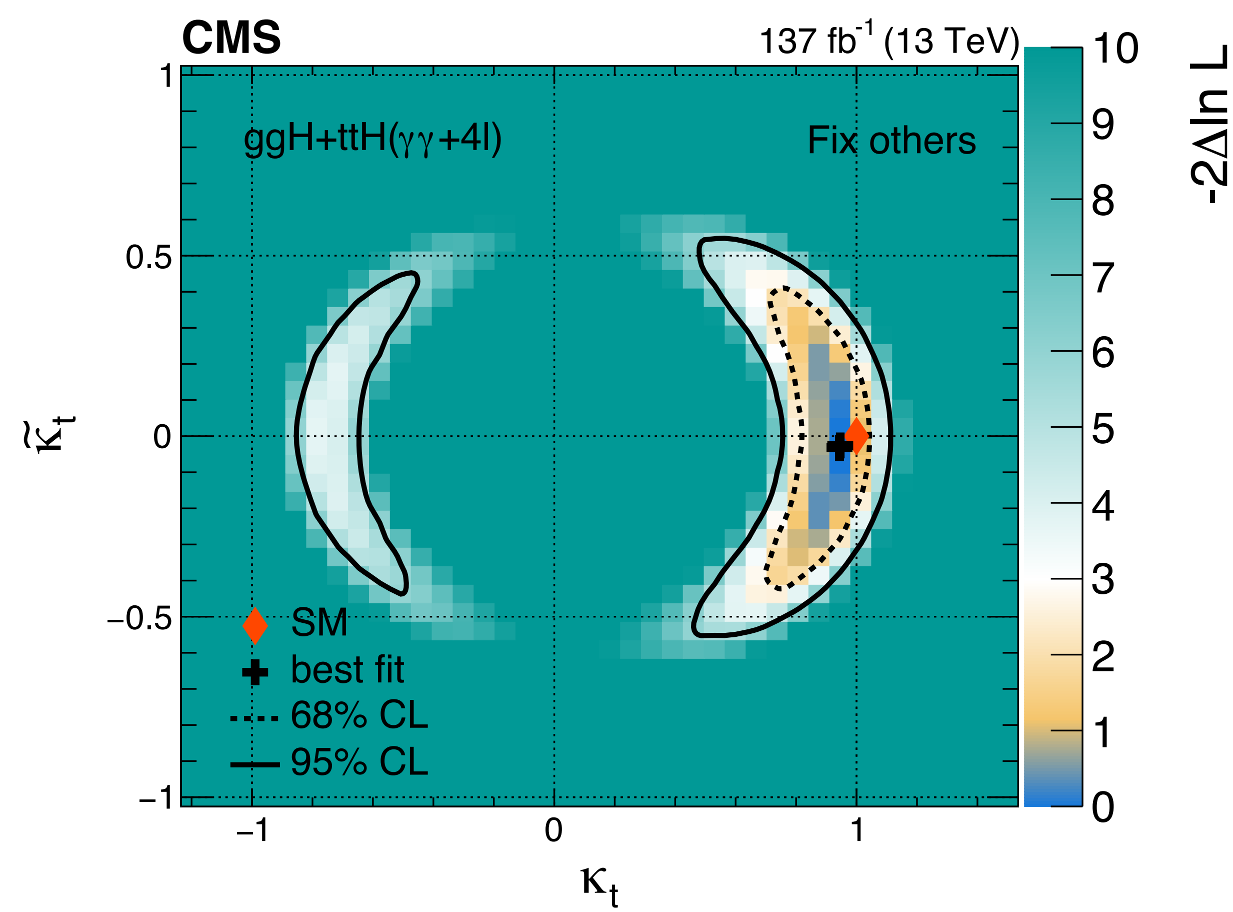
PRL 125 (2020) 061801 $t\bar{t}H, H \rightarrow \gamma\gamma$



BTD to separate CP states: kinematic variables of the first six jets, diphoton system (but not $m_{\gamma\gamma}$), b-tagging scores of jets, lepton multiplicity…

Combination with $t\bar{t}H, H \rightarrow 4l$ and gluon fusion loop with top quark dominance (→CP violation impacts rates differently)

PRD 104 (2021) 05200



$$f_{CP}^{ttH} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} sign(\tilde{\kappa}_t/\kappa_t) = 0.00 \pm 0.33$$

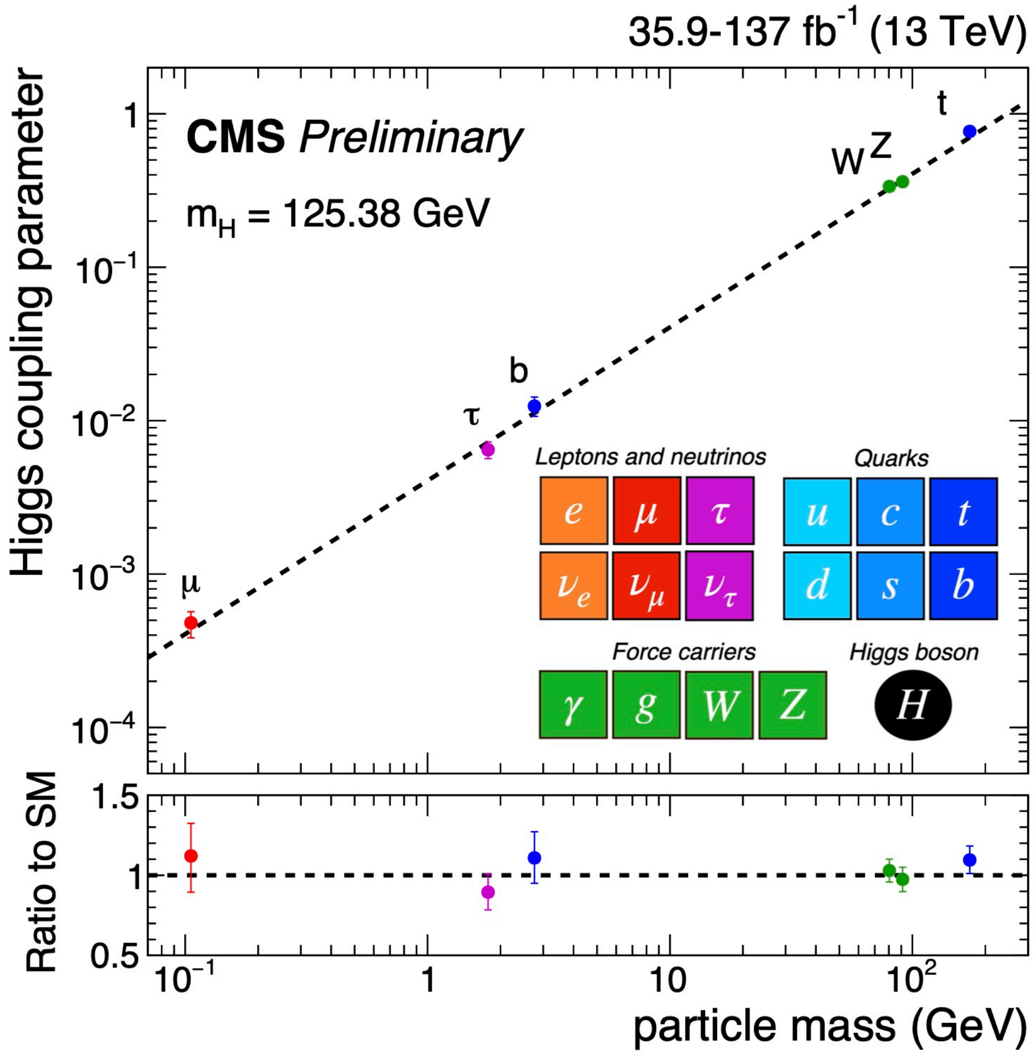
→ pure CP-odd hypothesis excluded at 3.2σ

Conclusion

CMS has observed **Higgs to tau**, **top-** and **b-quark** couplings
Evidence for Higgs to muon coupling!

All **fermionic couplings** so far **proportional to the fermion mass**, over three orders of magnitude…

First differential, STXS measurements being performed
Large BR to $b\bar{b}$ **and** $\tau\tau$ allow to test less accessible phase spaces: @ **high Higgs pT, high jet multiplicities…**



Top and tau Yukawa couplings being scrutinised for **CP violation**
Pure CP-odd hypothesis excluded at 3.2σ for both

Everything in agreement with SM so far!

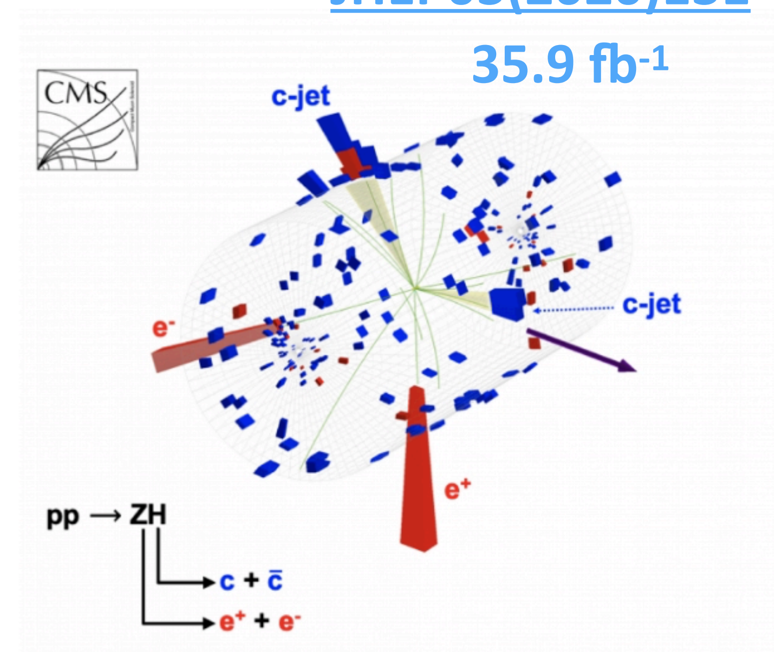
Additional slides

JHEP03(2020)131

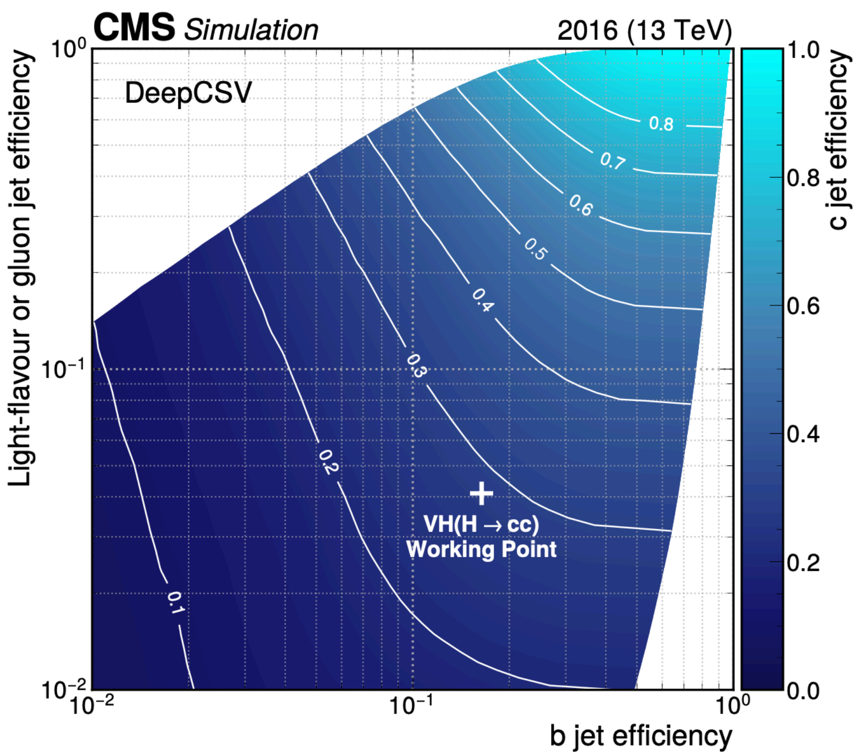
35.9 fb^{-1}

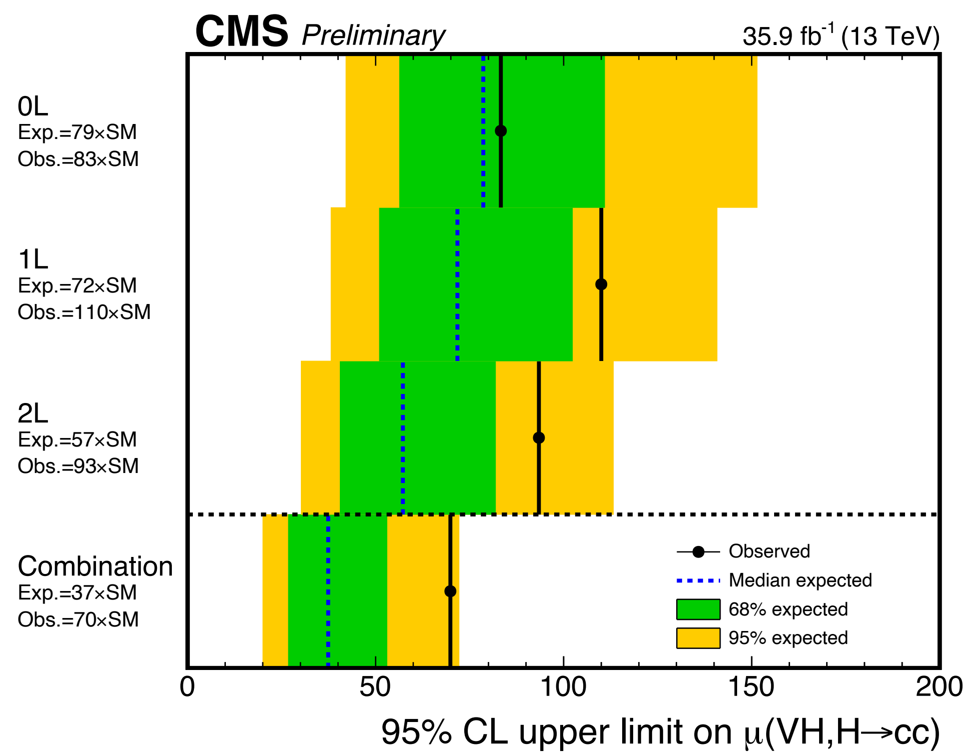
$H \rightarrow c\bar{c}$

- VH is the golden channel similarly to H→bb
- c-tagging thanks to multi-output deepCSV
- Two analyses: resolved jets or merged jets, and 0-, 1-, 2- lepton categories



	Resolved-jet (inclusive)				Merged-jet (inclusive)			
	0L	1L	2L	All channels	0L	1L	2L	All channels
Expected UL	84^{+35}_{-24}	79^{+34}_{-23}	59^{+25}_{-17}	38^{+16}_{-11}	81^{+39}_{-24}	88^{+43}_{-27}	90^{+48}_{-29}	49^{+24}_{-15}
Observed UL	66	120	116	75	74	120	76	71

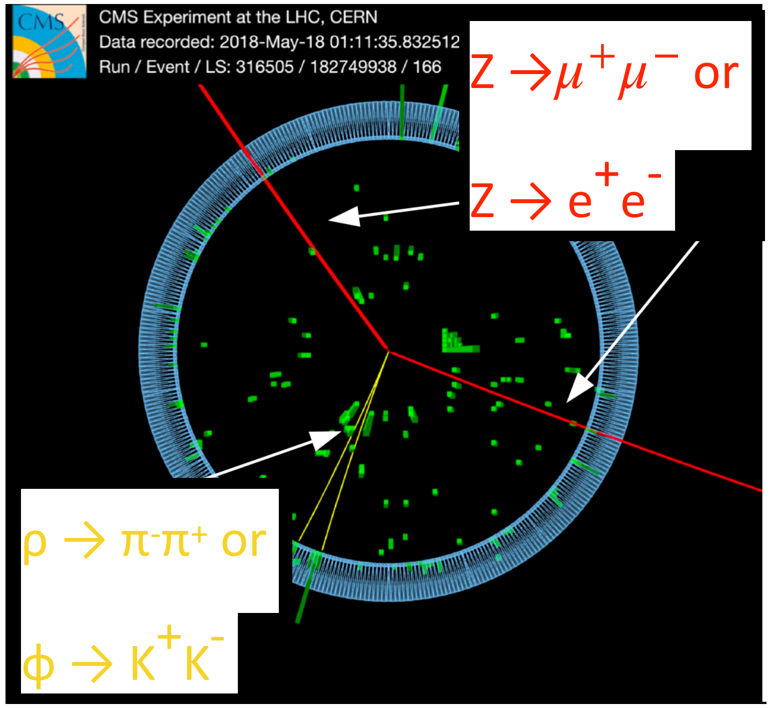




First upper limits (UL) w.r.t. SM: μ< 71 (obs.), 49 (exp.) at 95% CL

Light quarks… ?

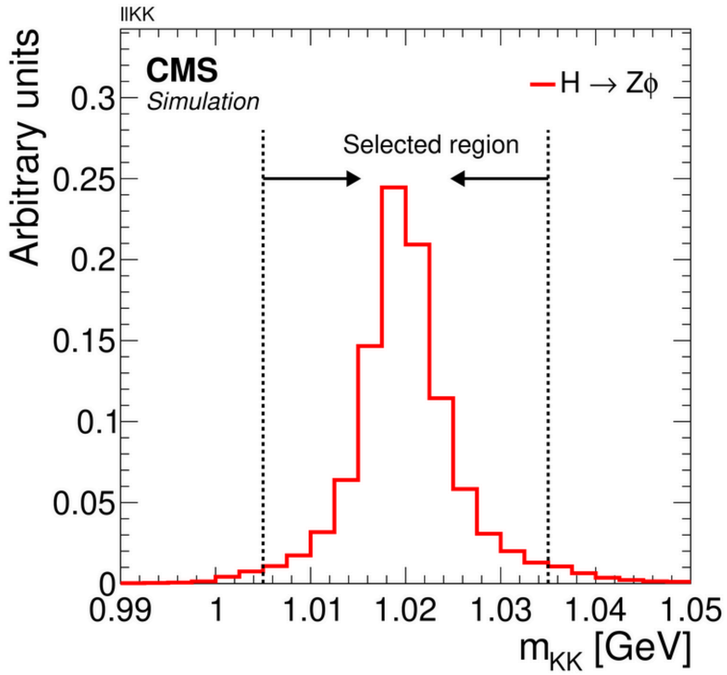
CMS-HIG-19-012
137 fb^{-1}

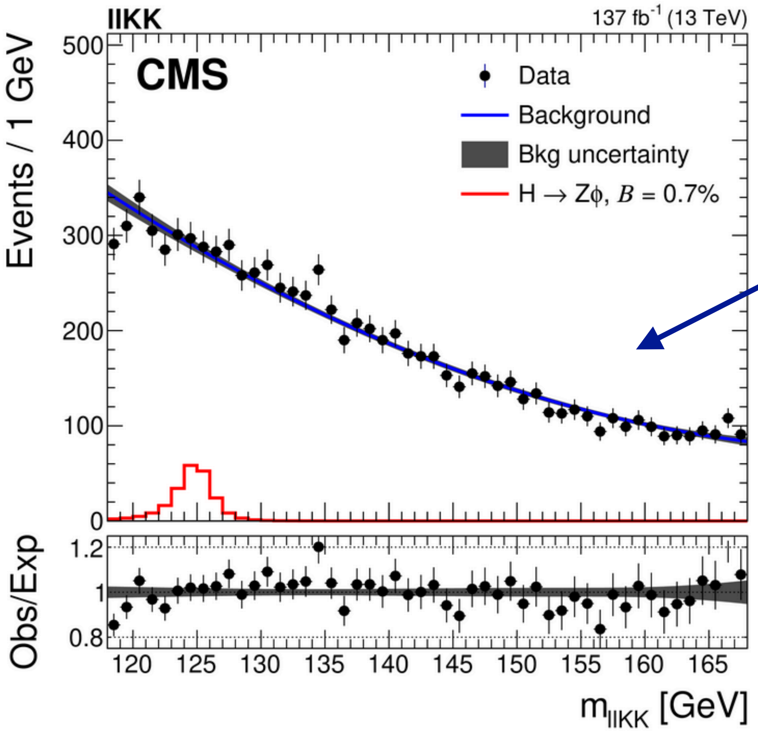


H → Z ρ/ϕ gives access to u- d- s- couplings
ρ mesons decay to ππ and ϕ mesons to KK
Pions consist of two u- and d-quarks and kaons of two s-quarks

No additional track in a cone of DR<0.3 around ρ/ϕ candidate.

Di-track mass windows: ρ: $0.6 < m_{\pi\pi} < 1$ GeV (m_π = 139.6 MeV)
ϕ: $1.005 < m_{KK} < 1.035$ GeV (m_K = 493.7 MeV)





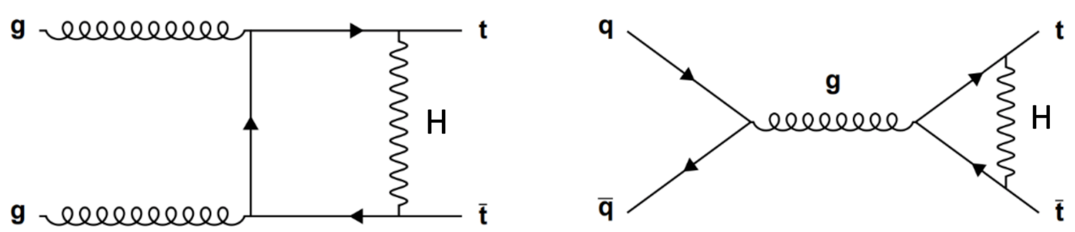
Polynomial background function

BR(Z+ρ) < 1% and BR(Z+ϕ) < 0.5%.
→ Limits are 1000 times larger than the expected branching fractions in SM

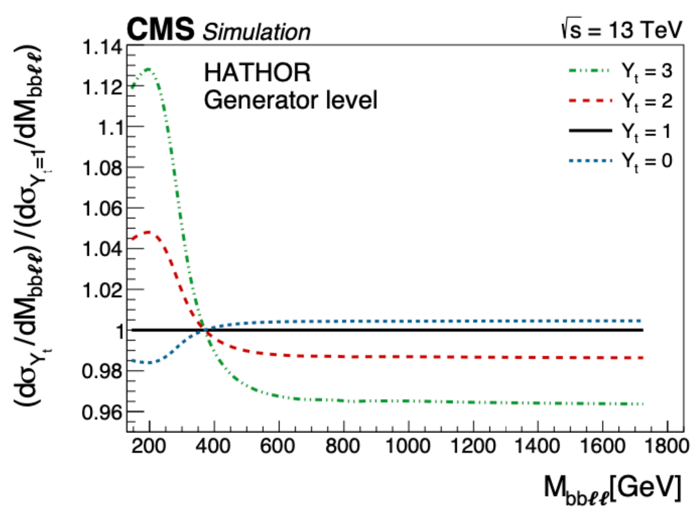
Top-Yukawa coupling (y_t) from $t\bar{t}$ and $t\bar{t}t\bar{t}$

[Eur. Phys. J. C 80 (2020) 75]
[Phys. Rev. D 102 (2020) 092013]

- Higgs diagrams enter $t\bar{t}$ production at order $\alpha_S y_t$
- Shape effect on $t\bar{t}$ invariant mass and difference in top-quark rapidity expected



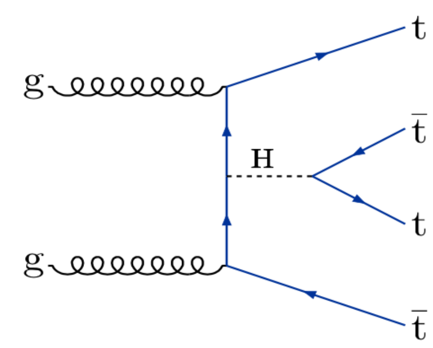
- Dilepton final state with lepton+b pairing considered



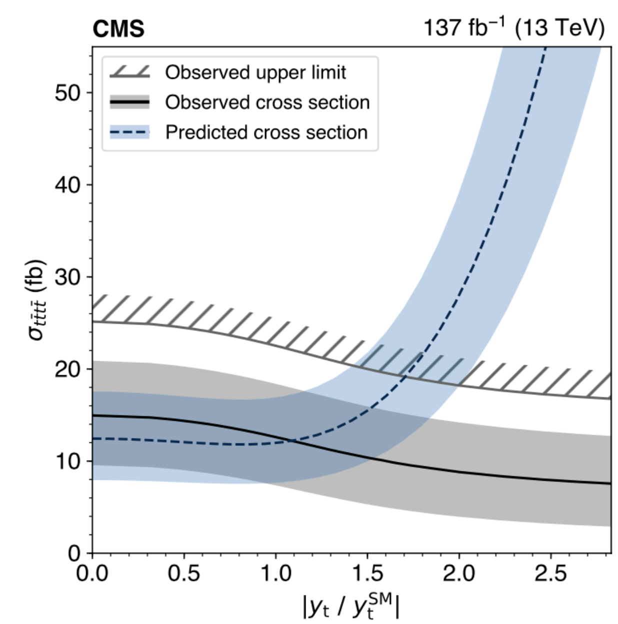
- $Y_t = y_t / y_t(SM) < 1.62$ @ 95% CL
- $y_t = 1.16^{+0.07}_{-0.08}(stat)^{+0.17}_{-0.27}(sys)$

Limited by modelling uncertainties.

- $t\bar{t}t\bar{t}$ cross section one order of magnitude smaller than $t\bar{t}H$
- 20% of $t\bar{t}t\bar{t}$ diagrams contain H



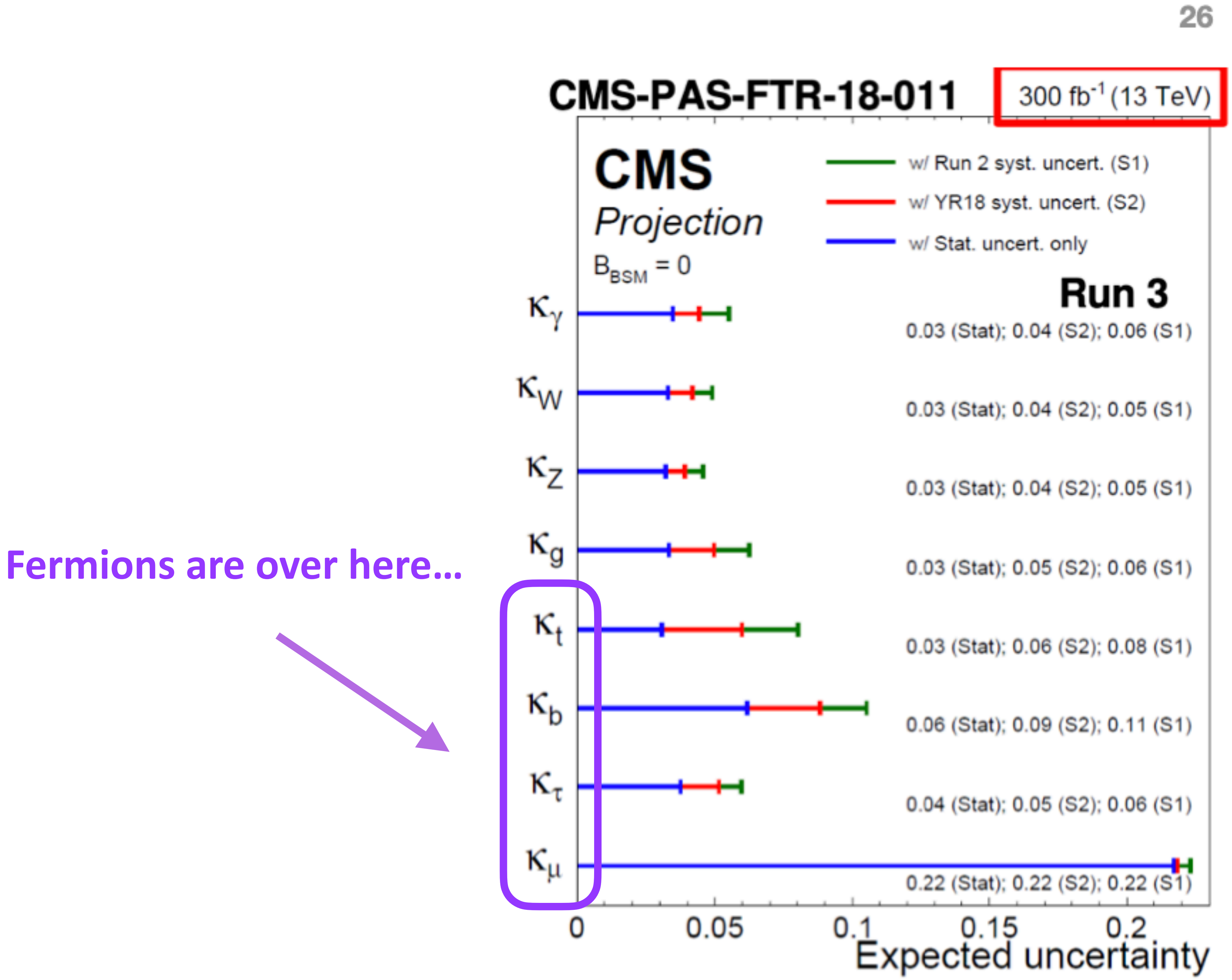
- Multilepton final states: $\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}$ fb with a significance of 2.6σ



- $Y_t = y_t / y_t(SM) < 1.7$ @ 95% CL

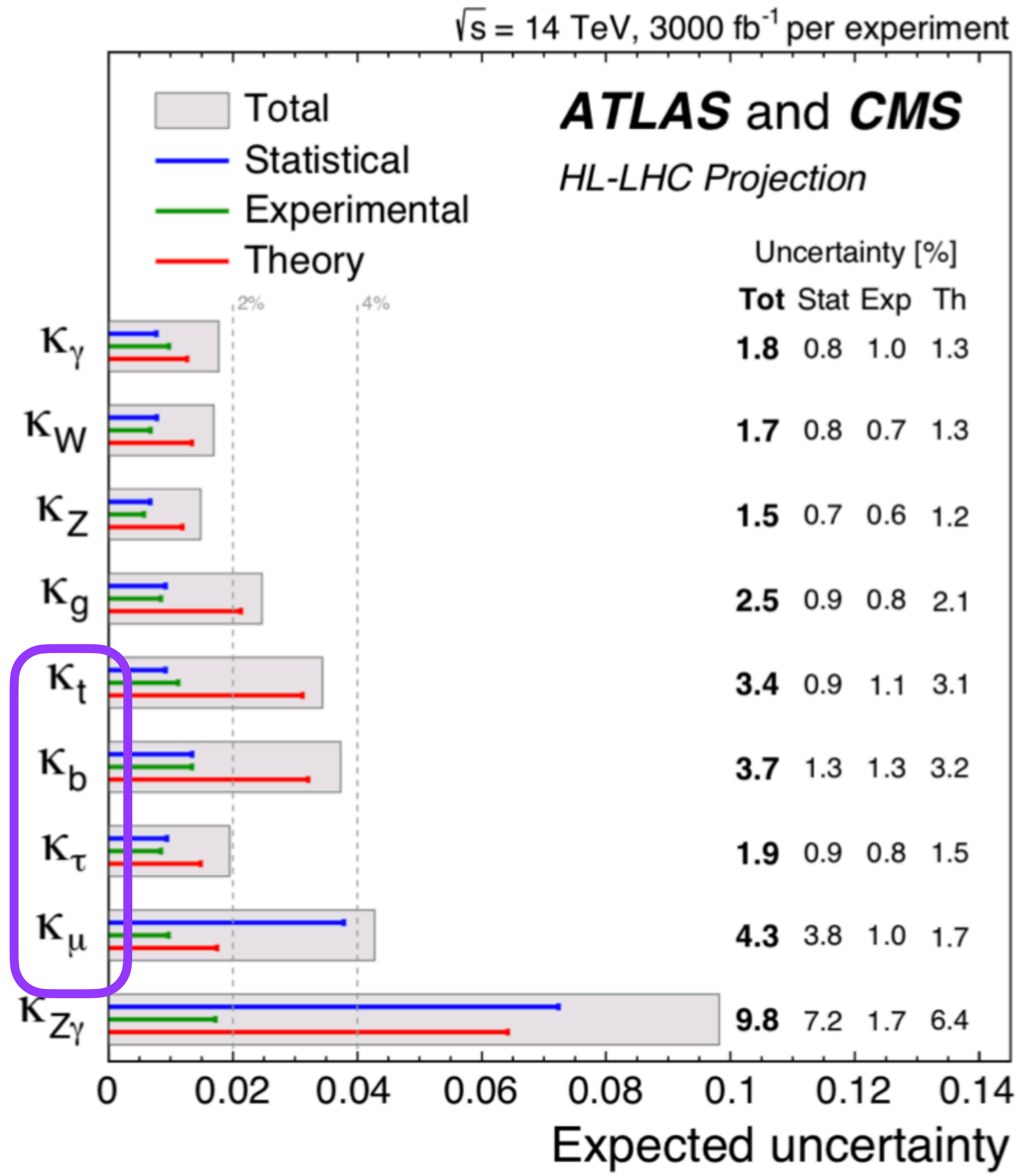
No assumption on Higgs width.

Run 3…


26
CMS-PAS-FTR-18-011
300 fb^{-1} (13 TeV)
CMS
Projection
$B_{BSM} = 0$
w/ Run 2 syst. uncert. (S1)
w/ YR18 syst. uncert. (S2)
w/ Stat. uncert. only
Run 3
κ_γ
0.03 (Stat); 0.04 (S2); 0.06 (S1)
κ_W
0.03 (Stat); 0.04 (S2); 0.05 (S1)
κ_Z
0.03 (Stat); 0.04 (S2); 0.05 (S1)
κ_g
0.03 (Stat); 0.05 (S2); 0.06 (S1)
κ_t
0.03 (Stat); 0.06 (S2); 0.08 (S1)
κ_b
0.06 (Stat); 0.09 (S2); 0.11 (S1)
κ_τ
0.04 (Stat); 0.05 (S2); 0.06 (S1)
κ_μ
0.22 (Stat); 0.22 (S2); 0.22 (S1)
0
0.05
0.1
0.15
0.2
Expected uncertainty
Fermions are over here…

HL-LHC…

Fermions are over here…



Top Yukawa coupling and search for CP violation

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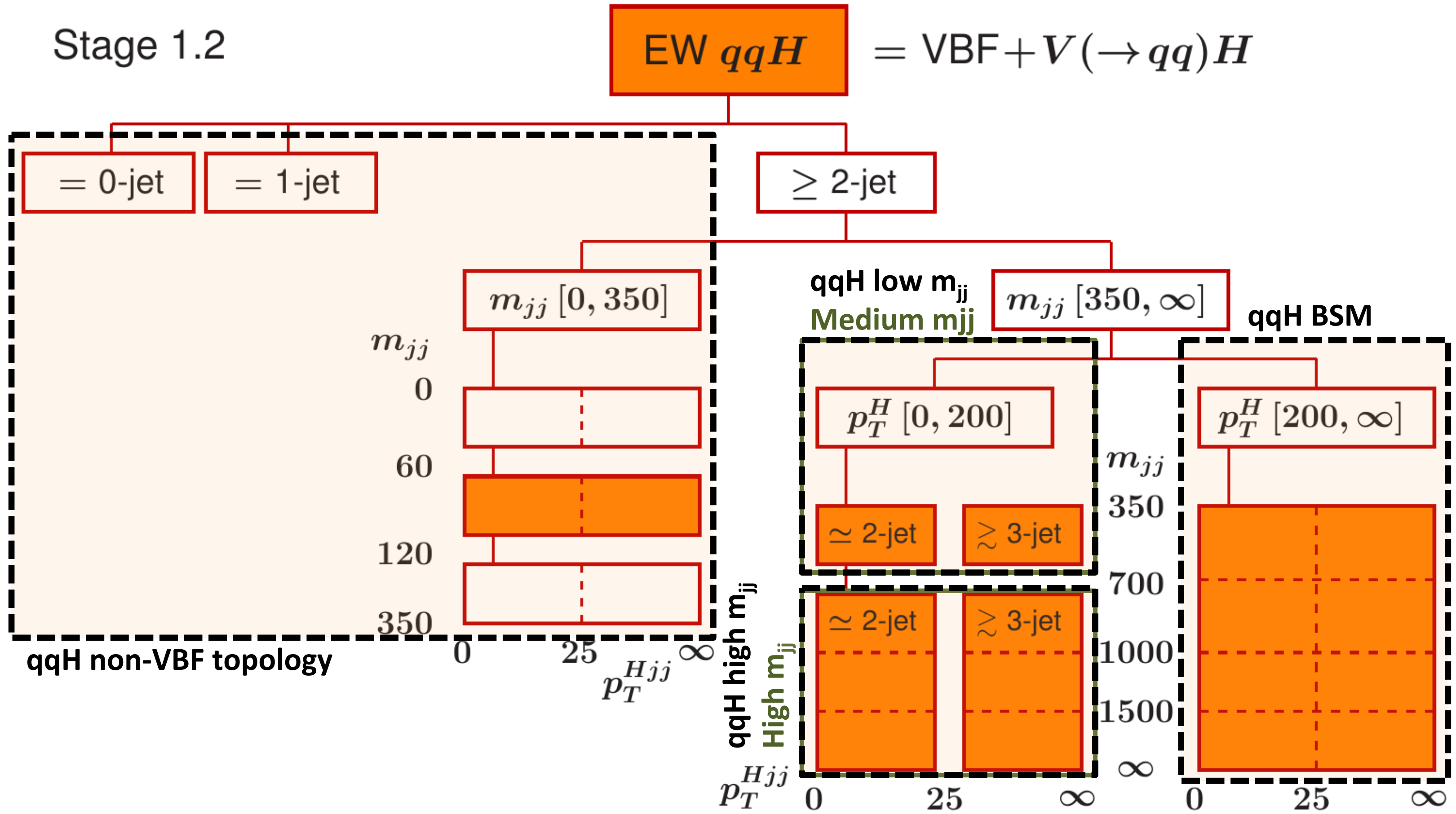
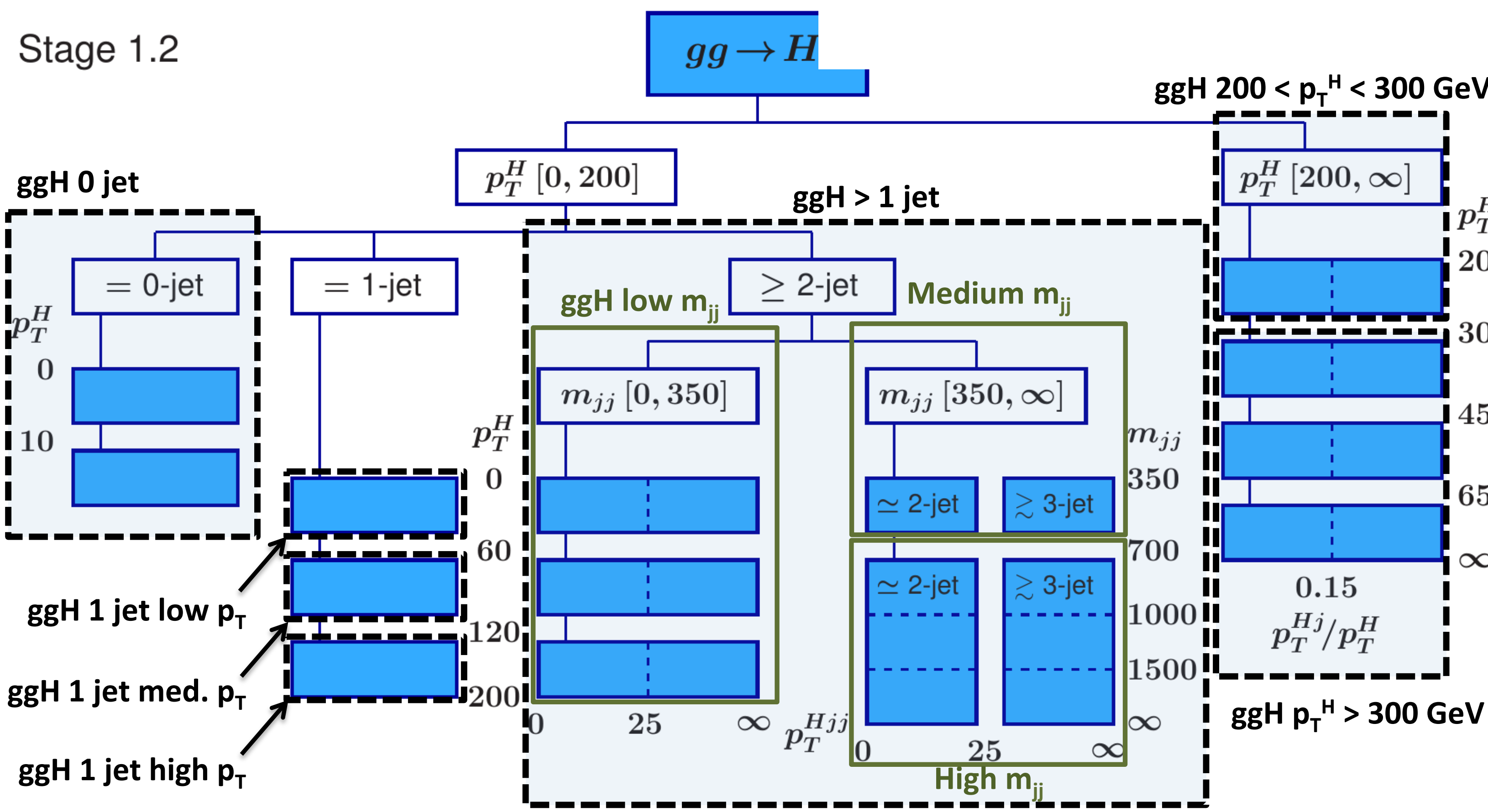
TABLE V. Constraints on the f_{a3}^{ggH} and f_{CP}^{Htt} parameters with the best fit values and allowed 68% CL (quoted uncertainties) and 95% CL (within square brackets) intervals, limited to the physical range of $[-1, 1]$. The f_{CP}^{Htt} constraints obtained in this work are combined with those in the $H \to \gamma\gamma$ channel [26]. The interpretation of the f_{a3}^{ggH} result under the assumption of the top quark dominance in the gluon fusion loop are presented in terms of the f_{CP}^{Htt} parameter, where either ggH or its combination with tH and $t\bar{t}H$ results are shown.

Parameter	Scenario	Observed	Expected
f_{a3}^{ggH}	ggH $(H \to 4\ell)$	$-0.04^{+1.04}_{-0.96}$ $[-1, 1]$	0 ± 1 $[-1, 1]$
f_{CP}^{Htt}	tH & $t\bar{t}H$ $(H \to 4\ell)$	$\pm(0.88^{+0.12}_{-1.88})$ $[-1, 1]$	0 ± 1 $[-1, 1]$
	tH & $t\bar{t}H$ $(H \to \gamma\gamma)$ [26]	0.00 ± 0.33 $[-0.67, 0.67]$	0.00 ± 0.49 $[-0.82, 0.82]$
	tH & $t\bar{t}H$ $(H \to 4\ell$ & $\gamma\gamma)$	0.00 ± 0.33 $[-0.67, 0.67]$	0.00 ± 0.48 $[-0.81, 0.81]$
	ggH $(H \to 4\ell)$	$-0.01^{+1.01}_{-0.99}$ $[-1, 1]$	0 ± 1 $[-1, 1]$
	ggH & tH & $t\bar{t}H$ $(H \to 4\ell)$	$-0.56^{+1.56}_{-0.44}$ $[-1, 1]$	0.00 ± 0.47 $[-1, 1]$
	ggH & tH & $t\bar{t}H$ $(H \to 4\ell$ & $\gamma\gamma)$	$-0.04^{+0.38}_{-0.36}$ $[-0.69, 0.68]$	0.00 ± 0.30 $[-0.70, 0.70]$

H→ $\tau\tau$ - STXS





H→ $\tau\tau$ - STXS

Analysis categories & 2D distributions used as input to the maximum likelihood fit

Table 2: Analysis categories. The results are extracted by performing a maximum likelihood fit of 2D distributions in these categories using the observables listed in the last column.

Final state	Category	Selection	Observables
$\ell\tau_h$, eμ	0-jet	0 jet	$m_{\tau\tau}$, τ_h p_T ($\ell\tau_h$) $m_{\tau\tau}$ (eμ)
	VBF low p_T^H	≥ 2 jets, $m_{jj} > 350$ GeV, $p_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	≥ 2 jets, $m_{jj} > 350$ GeV, $p_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, p_T^H
	Boosted ≥ 2 jets	Not in VBF, ≥ 2 jets	$m_{\tau\tau}$, p_T^H
$\tau_h\tau_h$	0-jet	0 jet	$m_{\tau\tau}$
	VBF low p_T^H	≥ 2 jets, $\Delta\eta_{jj} > 2.5(2.0$ for 2016), $100 < p_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	≥ 2 jets, $\Delta\eta_{jj} > 2.5(2.0$ for 2016), $p_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, p_T^H
	Boosted ≥ 2 jets	Not in VBF, ≥ 2 jets	$m_{\tau\tau}$, p_T^H

Z → $\tau\tau$ - embedded samples

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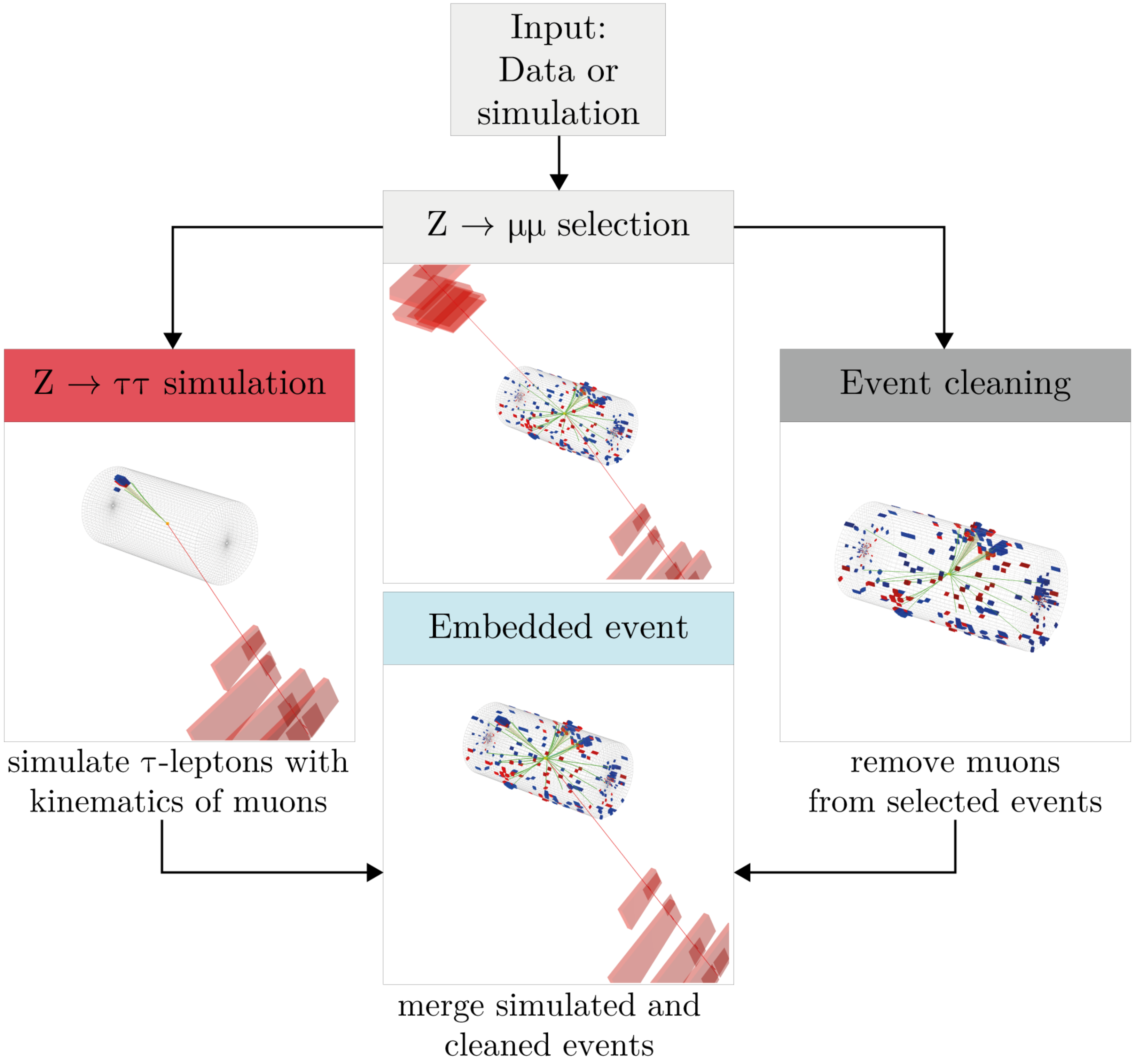
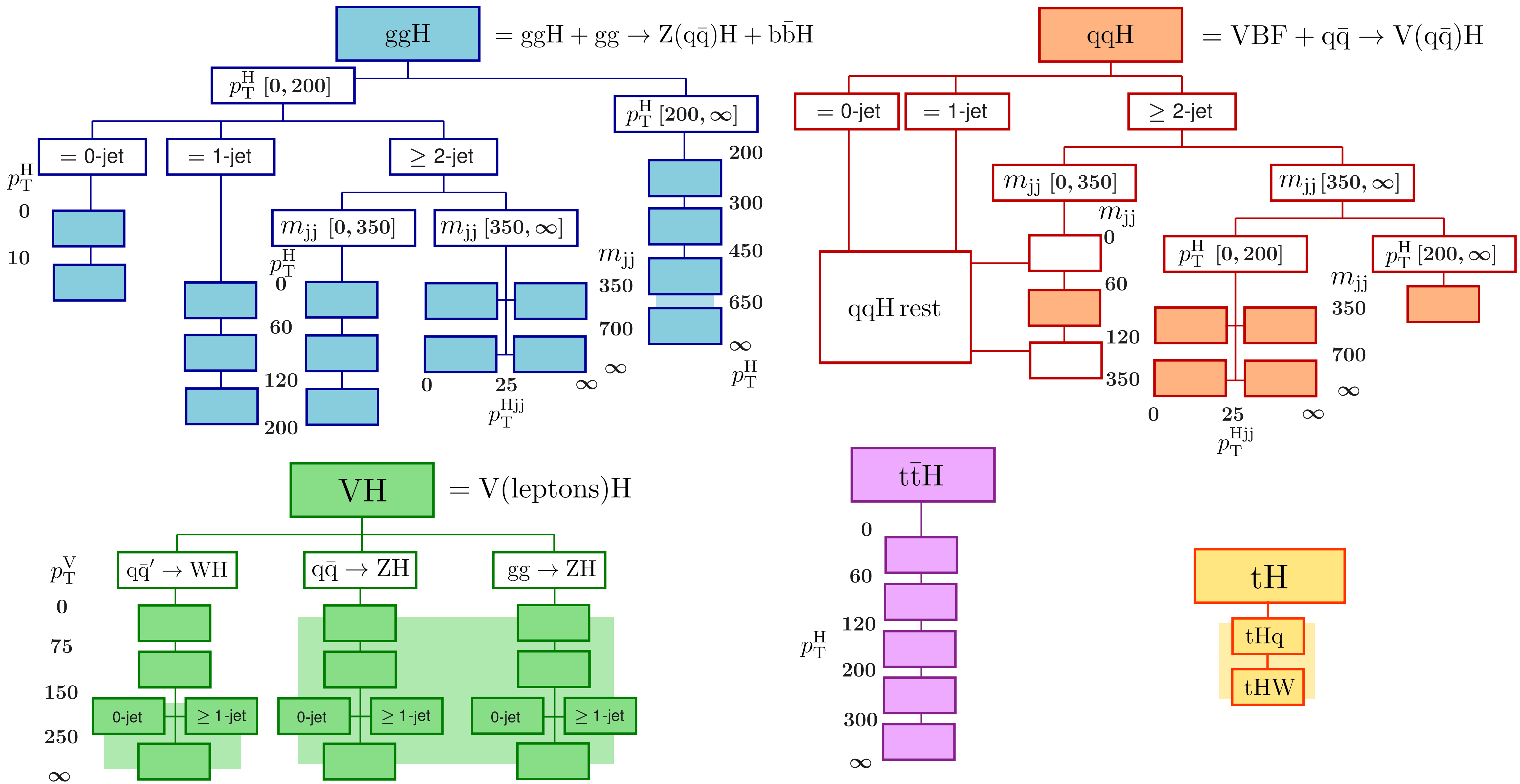


ttH, H→ γγ - STXS


ggH
= ggH + gg → Z(qq̄)H + bb̄H
p_T^H [0, 200]
p_T^H [200, ∞]
= 0-jet
= 1-jet
≥ 2-jet
m_{jj} [0, 350]
m_{jj} [350, ∞]
qqH
= VBF + qq̄ → V(qq̄)H
qqH rest
VH
= V(leptons)H
qq̄′ → WH
qq̄ → ZH
gg → ZH
0-jet
≥ 1-jet
tt̄H
tH
tHq
tHW