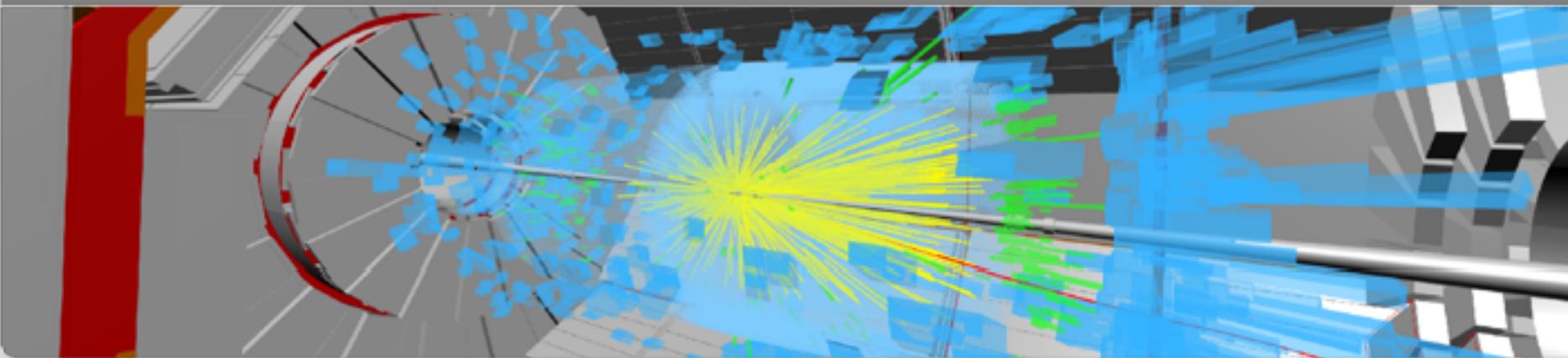


The Quest for $t\bar{t}H$ at the LHC

Experimental Particle Physics Seminar, University of Bonn, May 3, 2018

Ulrich Husemann, Institute of Experimental Particle Physics, Karlsruhe Institute of Technology



Like a Roller Coaster

- A brief history of associated top quark-antiquark Higgs production ($t\bar{t}H$):
 - Early 2000s: $t\bar{t}H$ = **promising discovery channel** for light Higgs boson
(Richter-Wąs, [Acta Phys. Polon. B30 \(1999\) 1001](#), Drollinger, Müller, [CMS NOTE 2001/054](#))
 - 2004–2006: realistic **TDR studies** → influence of $t\bar{t}b\bar{b}$ background underestimated
(J. Kammin, [Dissertation](#), Uni Bonn 2004; A. Schmidt, [Dissertation](#), Uni Karlsruhe 2006)
 - 2009: first NLO calculation of $t\bar{t}b\bar{b}$ background → cross section **twice as large** as in LO (K factor: 2.0) → $t\bar{t}H$ **very difficult** (Bredenstein et al., [PRL 103 \(2009\) 012002](#))
 - From 2008: **jet substructure algorithms** to the rescue
(Butterworth et al., [PRL 100 \(2008\) 242001](#), Plehn et al., [PRL 104 \(2010\) 111801](#))
 - 2008–2015: first $t\bar{t}H$ searches at the **Tevatron and LHC Run 1**
([DO note 5739-CONF](#), [PRL 109 \(2012\) 181802](#), [JHEP 09 \(2014\) 087](#), [EPJC 75 \(2015\) 275](#), [PLB 749 \(2015\) 519](#))
 - From 2015: heading for $t\bar{t}H$ **observation** at **LHC Run 2**

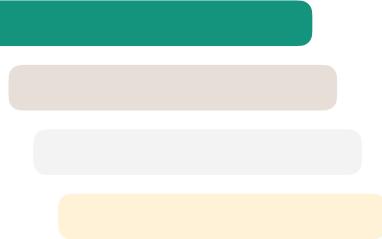
Outline

Higgs Physics: A Quick Reminder

Associated Top-Higgs Production at the LHC

The Search for $t\bar{t}H(b\bar{b})$ at CMS

Results and Interpretation



A Quick Reminder

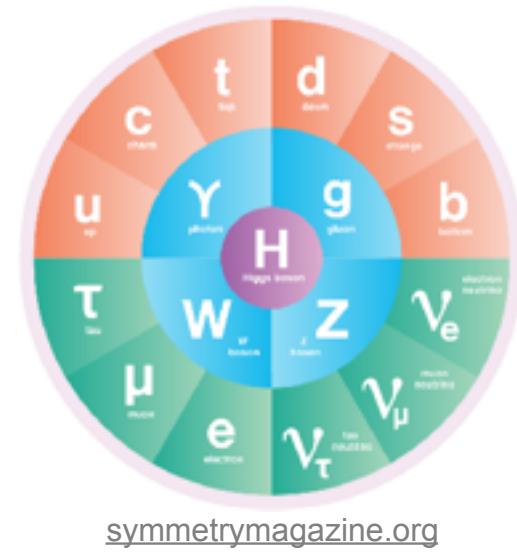
HIGGS PHYSICS

The Higgs Boson's Role in the SM

- Higgs boson = “rosetta stone” of the standard model
 - (Brout-Englert-)Higgs mechanism: **massive gauge bosons** W and Z
 - Yukawa couplings: **fermion masses**
 - Regularization of **high-energy behavior** (e.g. longitudinal W-boson scattering)
- This presentation: **Higgs-boson coupling to the top quark** (= heaviest known fundamental fermion)

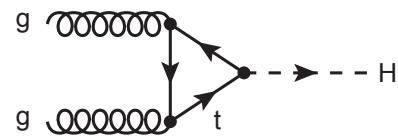
$$\mathcal{L}_{\text{Yukawa},t} = -y_t \frac{v}{\sqrt{2}} (\bar{t}_L t_R + \bar{t}_R t_L) = -y_t \frac{v}{\sqrt{2}} \bar{t} t = -m_t \bar{t} t$$

→ Standard model: $y_t \approx 1$

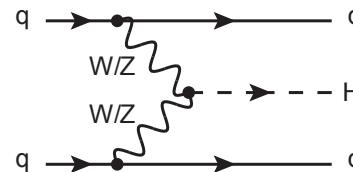


Higgs-Boson Production at the LHC

Gluon-Gluon Fusion



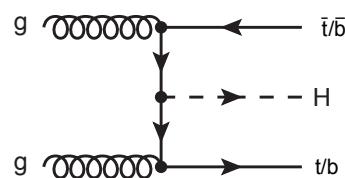
Vector Boson Fusion (VBF)



Associated Production with W and Z

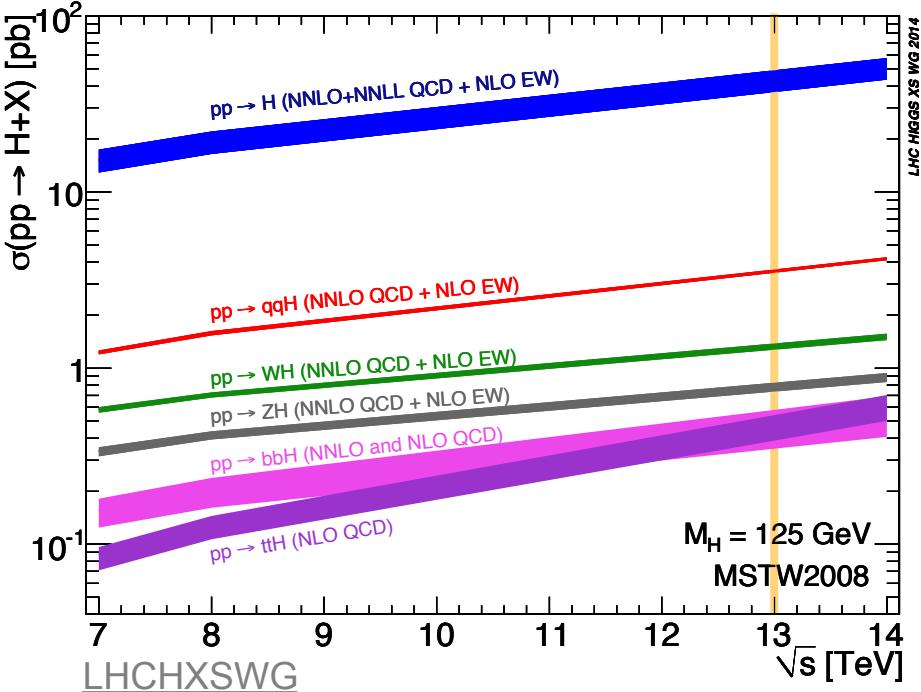


Associated Production with t and b



13 TeV: $\sigma(t\bar{t}H) \approx 0.5 \text{ pb}$
(factor 3.9 from 8 TeV)

Higgs-Boson Production Cross Section in pp



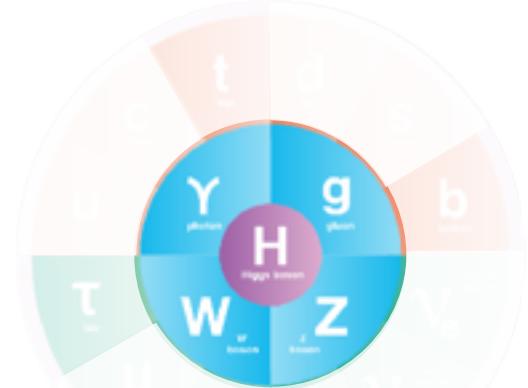
Signal Strengths and Couplings

- Higgs-boson production at the LHC: only **product** of production cross section σ and decay branching ratio B accessible
 - **Narrow-width approximation:** production and decay **factorize**
(good assumption for standard-model Higgs boson: total width $\Gamma_H = 4.1$ MeV)
 - Define **signal strength** (modifier) μ :
- $\mu(i \rightarrow H \rightarrow f) = \frac{\sigma(i \rightarrow H)}{\sigma(i \rightarrow H)^{\text{SM}}} \cdot \frac{B(H \rightarrow f)}{B(H \rightarrow f)^{\text{SM}}} \equiv \mu_i \cdot \mu^f$
with branching ratio $B(H \rightarrow f) \equiv B^f \equiv \frac{\Gamma^f}{\Gamma_H}$
- Slightly more involved: “kappa framework” – introduce **coupling modifiers** κ for Higgs-boson coupling vertices to all SM particles ($\kappa_{i,f} = 1$: coupling as in SM), for each process:

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \qquad \kappa_f^2 = \frac{\Gamma^f}{\Gamma_f^{\text{SM}}}$$

Higgs Physics: The Run-1 Legacy

- Higgs physics program at LHC Run 1:
 - **Discovery** (2012): driven by $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels
 - Production modes **gg fusion** and **VBF observed**
 - Couplings to **massive vector bosons** (directly) and to **gluons** and **photons** (indirectly) **well established**
 - Good progress with couplings to **fermions** (next slide)
 - Higgs-boson **properties**: mass extremely well known (0.2% uncertainty), comprehensive **coupling analysis** ([PRL 114 \(2015\) 191803](https://doi.org/10.1103/PhysRevLett.114.191803), [JHEP 08 \(2016\) 045](https://doi.org/10.1007/JHEP08(2016)045))



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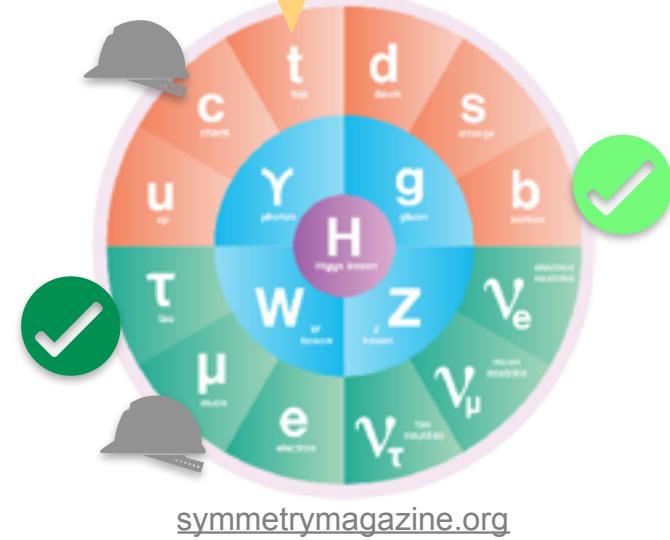
This presentation.

Higgs-Boson Coupling to Fermions

■ Third-generation fermions:

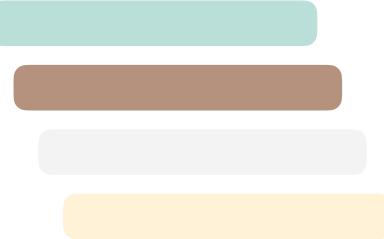
- $H \rightarrow \tau\tau$: **observed**
 - ATLAS+CMS combined: 5.5σ (5.0σ exp)
 - CMS Run-1+2: 5.9σ (5.9σ exp) ([PLB 779 \(2018\) 283](#))
- $H \rightarrow b\bar{b}$: **evidence** in VH(bb):
 - ATLAS 3.6σ (4.0σ exp) ([JHEP 12 \(2017\) 024](#))
 - CMS: 3.8σ (3.8σ exp) ([PLB 780 \(2018\) 501](#))
- $H \rightarrow t\bar{t}$: kinematically **forbidden** ($2m_t \gg m_H$)

 → study top couplings in $t\bar{t}H$ **production**



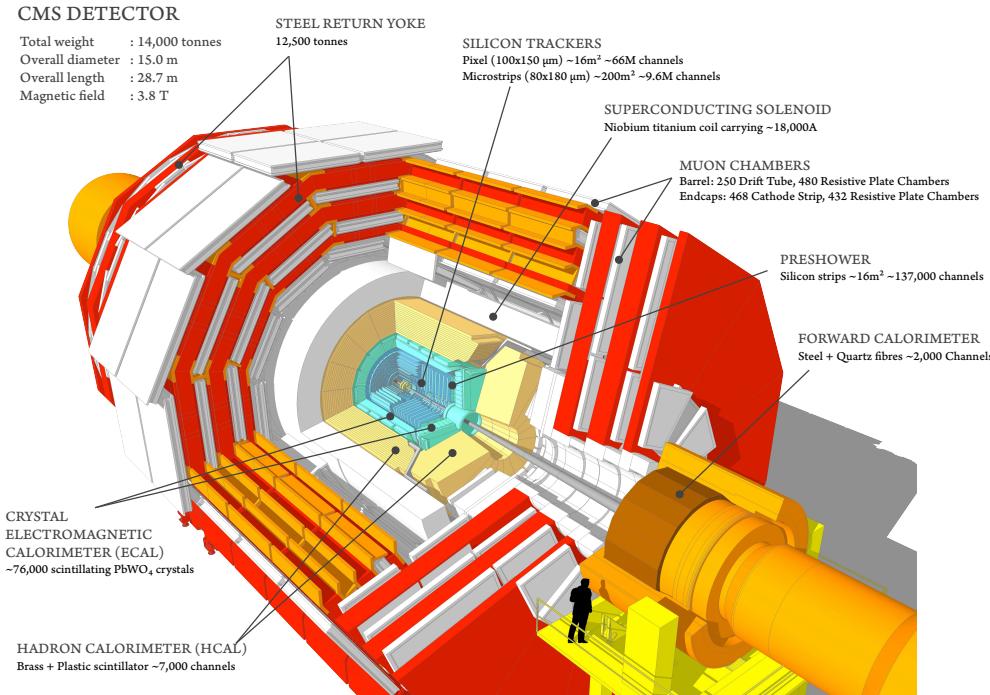
■ Second-generation fermions:

- $H \rightarrow \mu\mu$: primary goal for **high-luminosity LHC** (HL-LHC), already becoming sensitive
- $H \rightarrow c\bar{c}$: **first analyses** available (ATLAS: [arXiv:1802.04329](#))



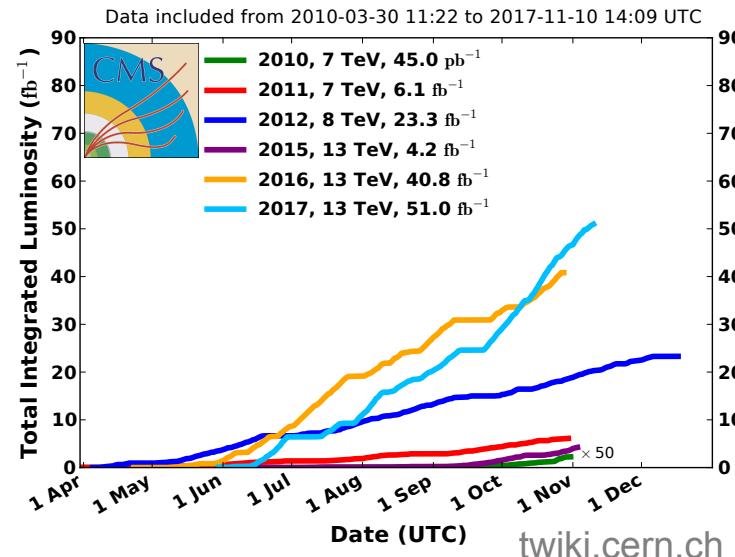
ASSOCIATED TOP-HIGGS PRODUCTION AT THE LHC

The CMS Experiment



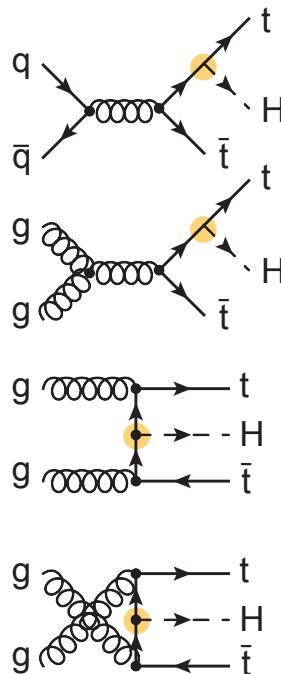
2014 J. Phys.: Conf. Ser. 513 (2014) 022032

CMS Integrated Luminosity



Results shown here: full 2016 dataset
 → 35.9 fb⁻¹ of “good” data

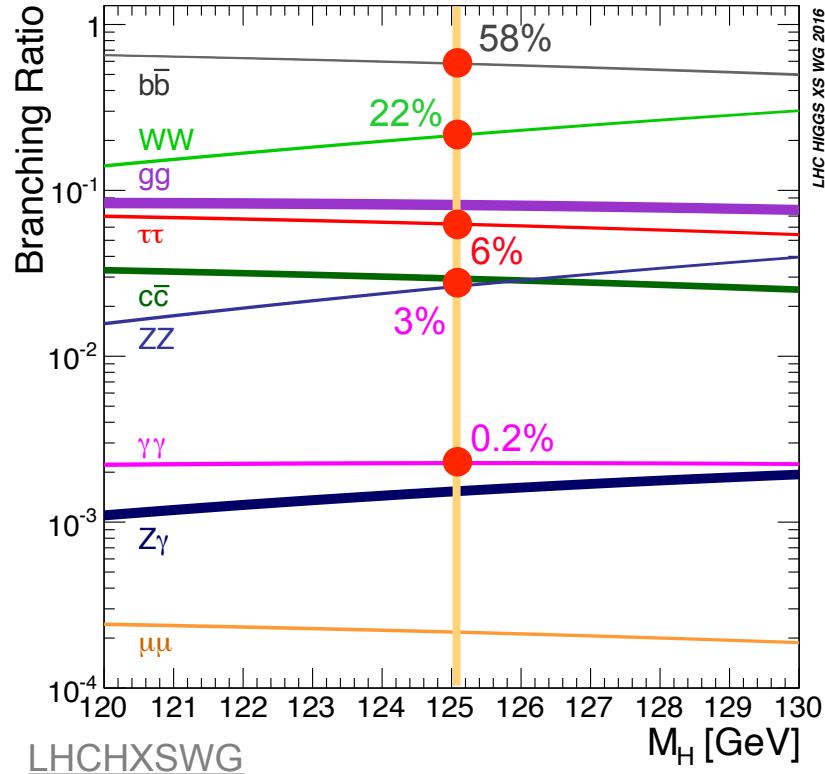
t̄H Production



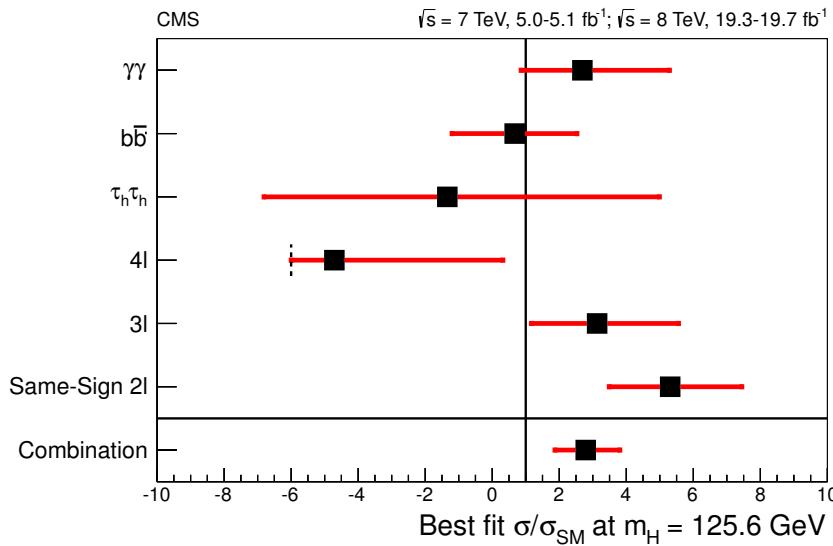
- Matrix elements for $t\bar{t}H$ production proportional to **top-Higgs coupling constant**, radiative corrections only affect top mass renormalization
- **Leading order (LO)**: large **scale uncertainties** ([NPB 247 \(1984\) 339](#))
- **Next-to-leading order (NLO)**: moderate K-factor 1.2, scale uncertainties approx. **10%**
 $(PRL 87 (2001) 201804, PRL 87 (2001) 201805, PRD 67 (2003) 071503, PRD 68 (2003) 034022, NPB 653 (2003) 151)$
- State of the art: **NLO QCD + NLO electroweak corrections**
 $(PLB 738 (2014) 1, JHEP 09 (2014) 065, JHEP 06 (2015) 184)$
- Details: *Handbook of LHC Higgs Cross Sections*, Vol. 4
 $\sigma_{t\bar{t}H}(13 \text{ TeV}, m_H = 125 \text{ GeV}) = (507^{+35}_{-50}) \text{ fb}$
- Details: *Handbook of LHC Higgs Cross Sections*, Vol. 4
 $\sigma_{t\bar{t}H}(13 \text{ TeV}, m_H = 125 \text{ GeV}) = (507^{+35}_{-50}) \text{ fb}$

$t\bar{t}H$ Decay Channels: Higgs Decays

- Higgs-boson decay channels considered in $t\bar{t}H$: by **signature**
 - $H \rightarrow \gamma\gamma$: clean signature, usually as part of “regular” $H \rightarrow \gamma\gamma$ analysis
 - Multileptons (including hadronic tau decays τ_h): very clean, covers leptonic sub-channels of $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$
 - $H \rightarrow b\bar{b}$: largest branching ratio, only third-generation fermions in production and decay
→ **$t\bar{t}H(b\bar{b})$: focus of this talk**



$t\bar{t}H$ in LHC Run 1



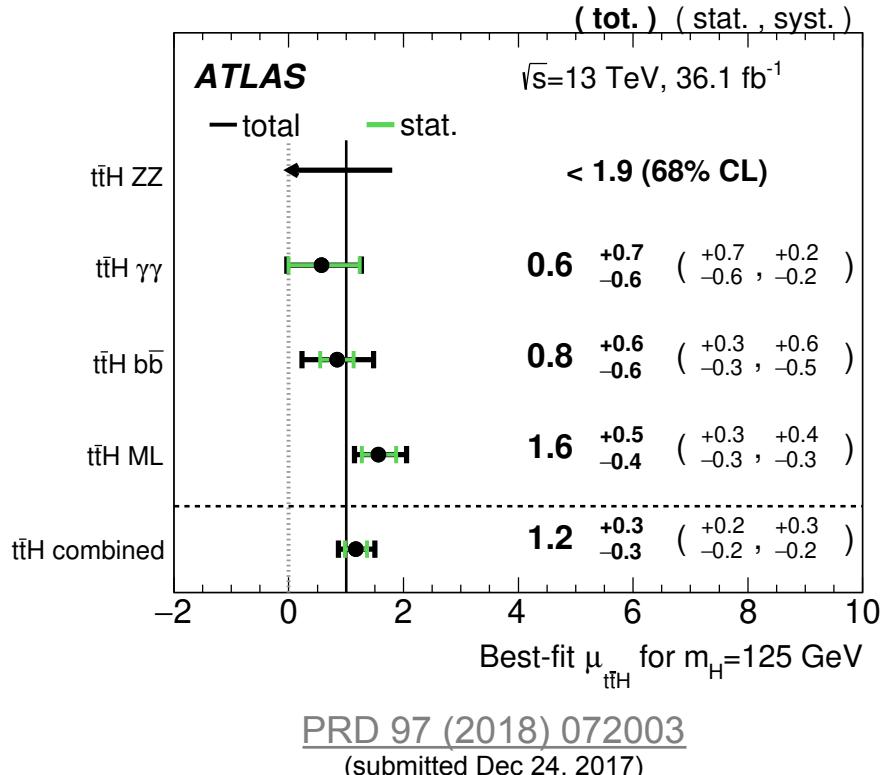
JHEP 09 (2014) 87

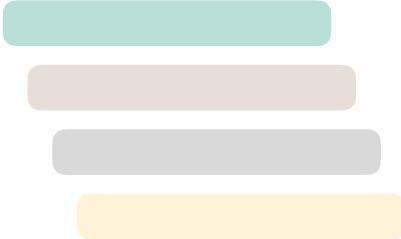
- LHC Run-1 searches for $t\bar{t}H$ production in major decay channels:
 - Various sophisticated **multivariate analysis methods**
([JHEP 09 \(2014\) 87](#), [PLB 749 \(2015\) 519](#))
 - Dedicated analyses of $H \rightarrow b\bar{b}$ channel ([EPJC 75 \(2015\) 251](#), [EPJC 75 \(2015\) 379](#))
 - **Mild excess** over standard-model expectation, e.g. CMS: $\mu = 2.8 \pm 1.0$ (driven by multilepton decay channels)

Remark: **single top-Higgs** production (tHq): sensitive to **relative sign** of Higgs couplings to fermions and bosons ([JHEP 06 \(2016\) 177](#))

$t\bar{t}H$ in LHC Run 2

- LHC center-of-mass energy increased to 13 TeV → $t\bar{t}H$ production cross section **3.9× larger** than at 8 TeV (major background $t\bar{t}$: only 3.3× larger)
- Further development of **analysis technologies** → various preliminary results
- “ATLAS Christmas Present”: first suite of Run-2 publications → **4.2 standard deviations evidence** for $t\bar{t}H$ production (3.8 σ expected)
(JHEP 03 (2018) 95, PRD 97 (2018) 072003, arXiv:1712.08895, arXiv:1802.04146)





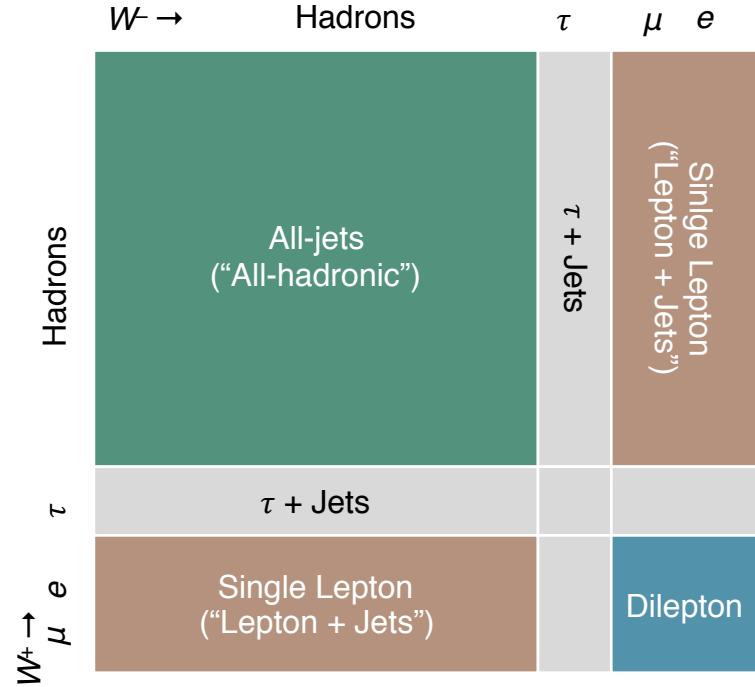
THE SEARCH FOR $t\bar{t}H(BB)$ AT CMS

$t\bar{t}H$ Production and $H \rightarrow b\bar{b}$ Decay

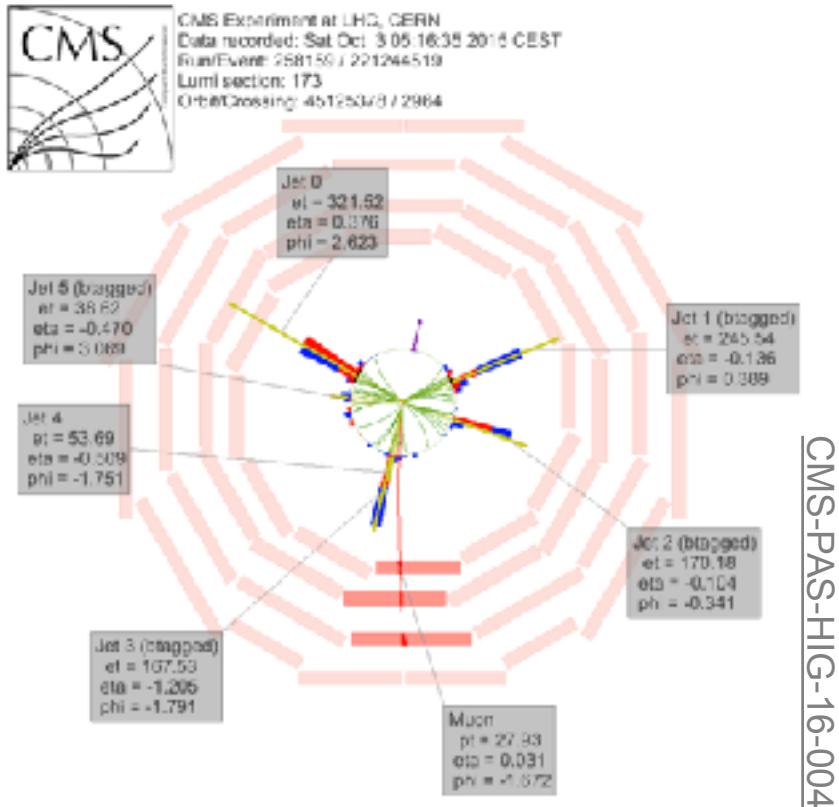
- Process considered here:
 $t\bar{t}H(b\bar{b}) = t\bar{t}H$ production with $H \rightarrow b\bar{b}$ decay
- $t\bar{t}H(b\bar{b})$ classification by **$t\bar{t}$ decay** ($t \rightarrow Wb$):

 - Single lepton channel (SL)
 - Dilepton channel (DL)
 - All-jet channel

- Dominant background for $t\bar{t}H(b\bar{b})$: $t\bar{t} + X$
 with $X = \text{jets}, W, Z$
 - Inclusive $t\bar{t}$ cross section well known (<4%)
 - $t\bar{t} + \text{heavy-flavor jets}$: large ($5\times$ signal),
 “irreducible”, experimentally and
 theoretically challenging



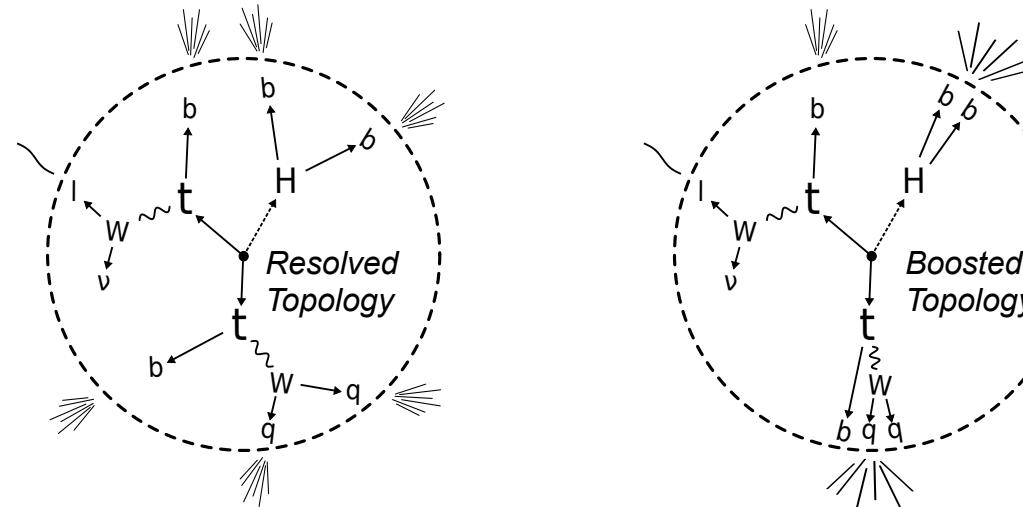
$t\bar{t}H(b\bar{b})$ Detector Signature



- Example: single-lepton channel
 - **6 jets** (4 containing b hadrons)
 - **1 charged lepton** (e or μ)
 - **Missing transverse momentum** from neutrino
- Remarks:
 - As **messy** as it gets!
 - Key ingredient: **b-tagging**
= identification of jets with b hadrons
(long lifetime, ...)
 - Key technology: **vertex detectors**

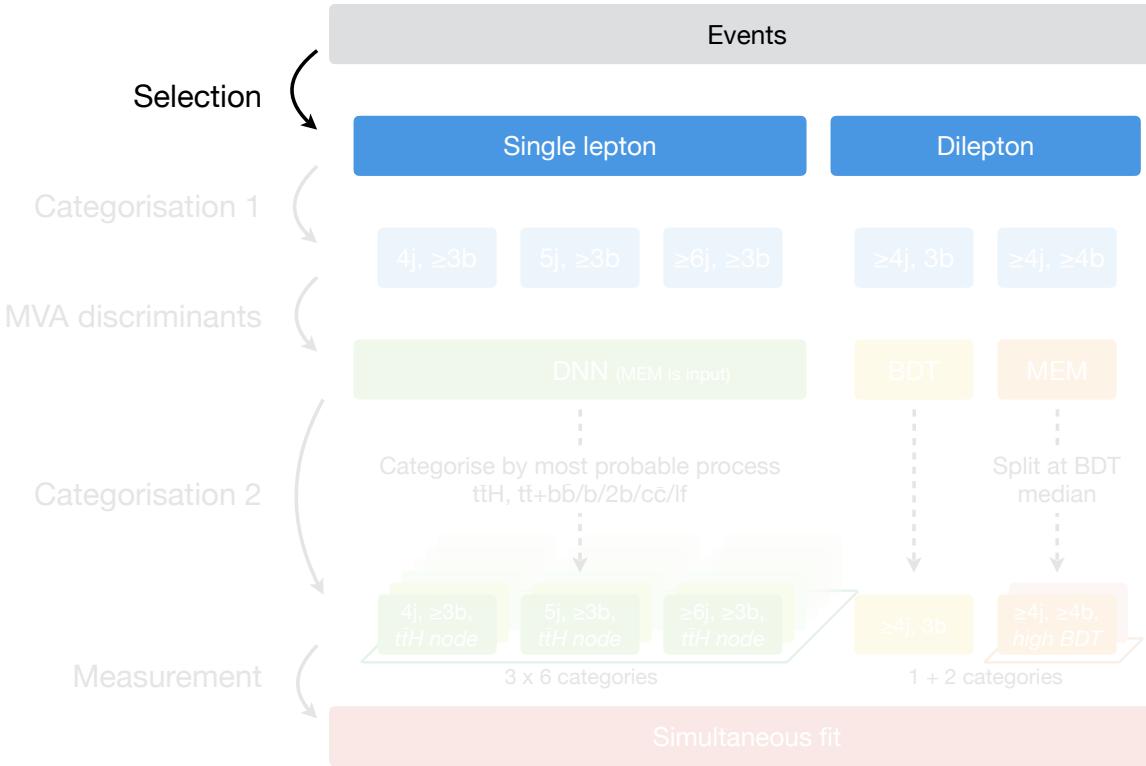
Remark: Higgs with a Boost

- Further sensitivity: separate treatment of top quarks and Higgs bosons with **large transverse momenta** ($p_T \gtrsim 200$ GeV)
- Top and Higgs **tagging**, sophisticated **jet-substructure** algorithms
- Already used in some $t\bar{t}H(b\bar{b})$ analyses ([CMS-PAS-HIG-16-004](#), [arXiv:1712.08895](#))



S. Williamson

Analysis Strategy: Divide et Impera



1. Selection according to $t\bar{t}$ decay channel

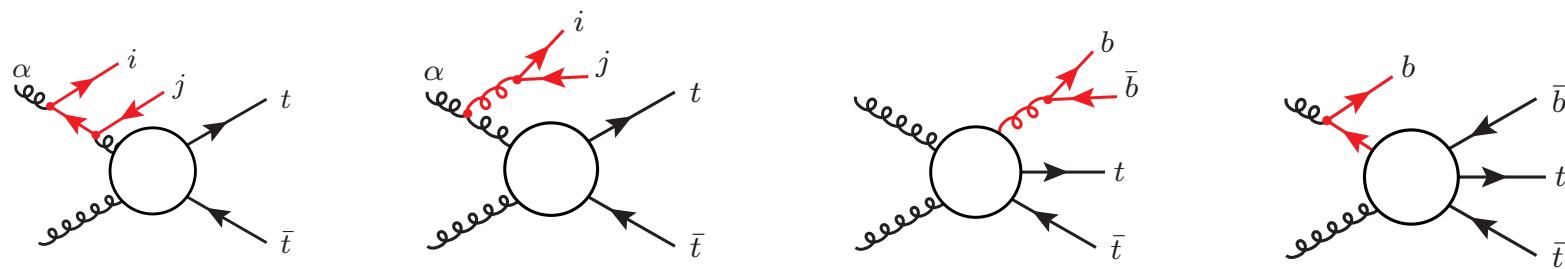
CMS-HIG-17-026

Top Quark-Antiquark Event Categories

- $t\bar{t} + \text{jets}$: **physics-driven** split into **five mutually exclusive categories**
 - $t\bar{t} + b\bar{b}$:  ... ≥ 2 additional jets with ≥ 1 b hadron each
 - $t\bar{t} + 2b$:  one additional jet with ≥ 2 overlapping b hadrons
 - $t\bar{t} + b$:  one additional jet with a single b hadron
 - $t\bar{t} + c\bar{c}$: ≥ 1 additional jet with c hadrons, but no additional b-jets
 - $t\bar{t} + \text{light flavor (lf)}$: not in any of the above categories
- Technical implementation:
 - Jet clustering from generator-level stable particles ($p_T > 20$ GeV, $|\eta| < 2.4$)
 - b/c hadrons (before decay) not coming from top-quark decays identified by “ghost hadron matching”

$t\bar{t}$ + Heavy-flavor Jets

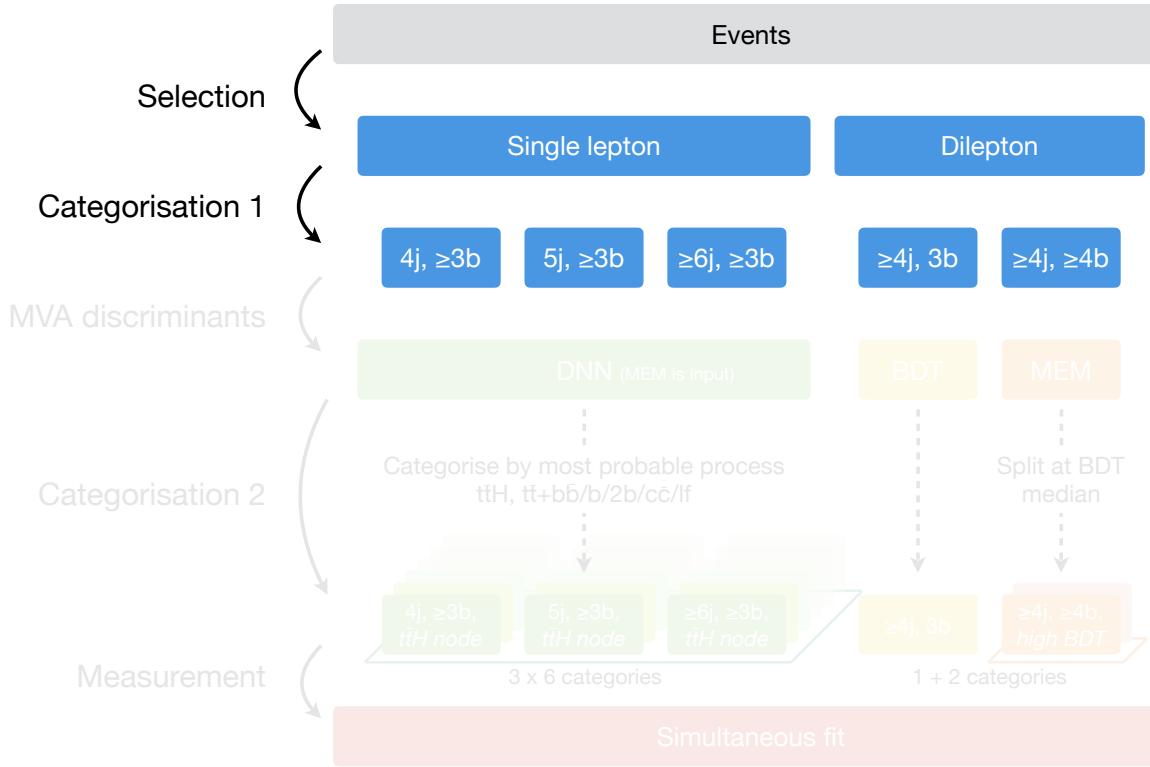
- Theory challenge: $t\bar{t}bb$
 - Multileg process with **multiple energy/momentum scales**
 - Calculation in two different schemes:
 - five-flavor number scheme** (5FS) – massless b quarks, active flavor in PDFs vs.
 - four-flavor number scheme** (4FS) – massive b quarks, avoids collinear singularities
 - MC simulation: consistent **matching to parton showers** (may include final state $g \rightarrow b\bar{b}$ splitting), consistent **merging** with inclusive $t\bar{t}$ process (usually 5FS)



- Lots of discussion, e.g. in LHC Higgs Cross Section WG ($t\bar{t}H/tH$ subgroup)
(recent publications: [arXiv:1709.06915](https://arxiv.org/abs/1709.06915), [arXiv:1802.00426](https://arxiv.org/abs/1802.00426))

arXiv:1802.00426

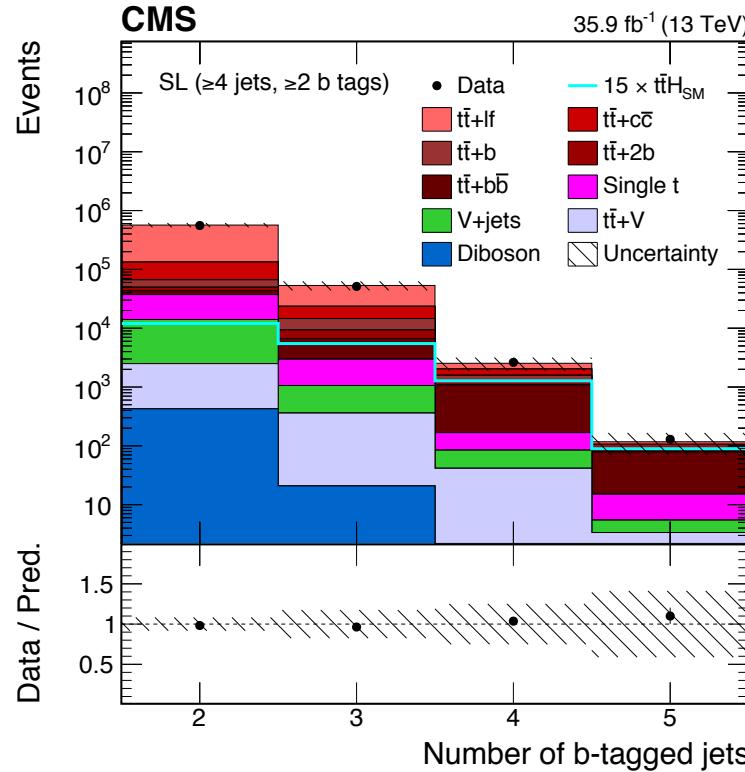
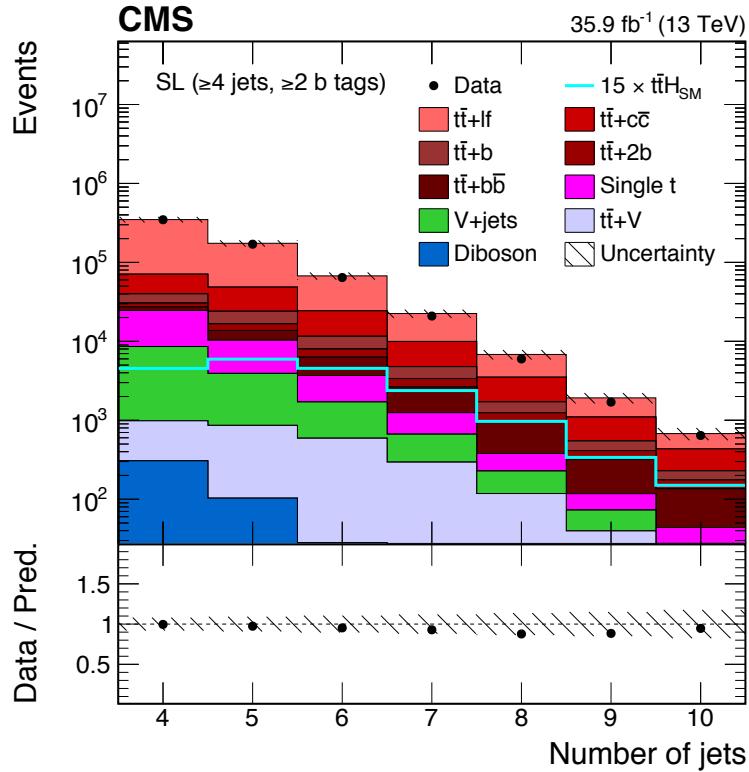
Analysis Strategy: Divide et Impera



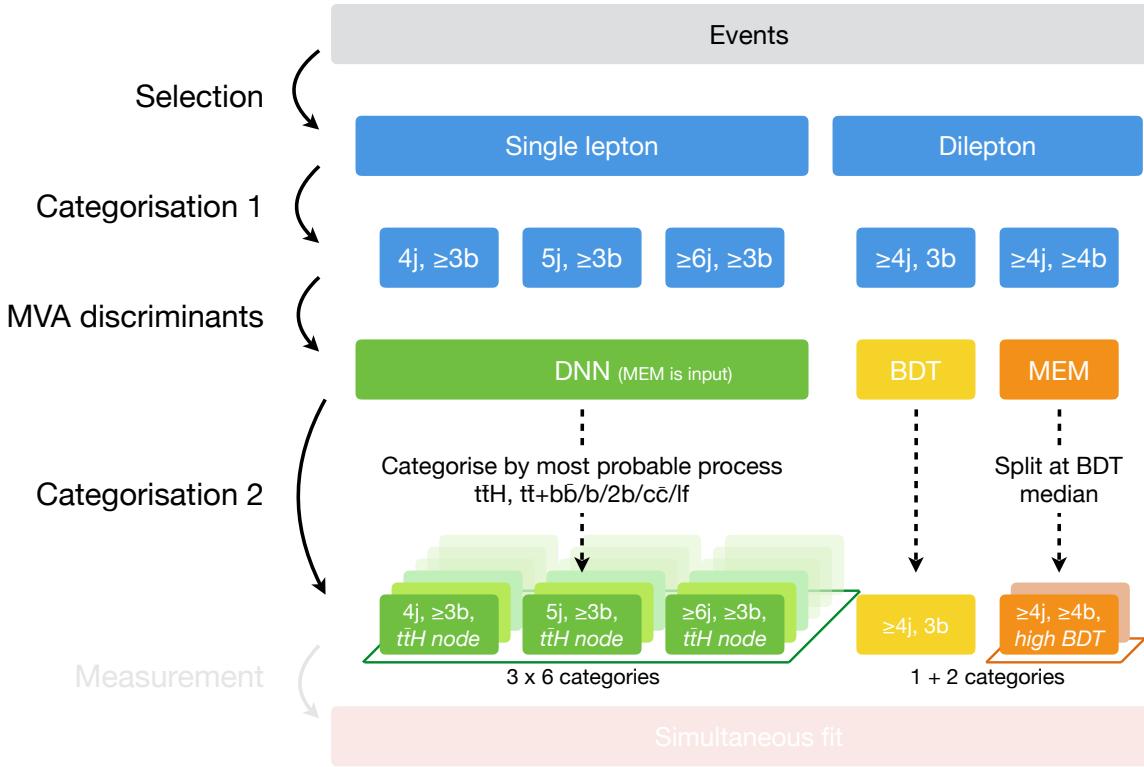
1. Selection according to $t\bar{t}$ decay channel
2. Categorization 1: **jet and b-tagged jet multiplicities**

CMS-HIG-17-026

$t\bar{t}H(b\bar{b})$ Single Lepton: Multiplicity of (b-tagged) Jets



Analysis Strategy: Divide et Impera

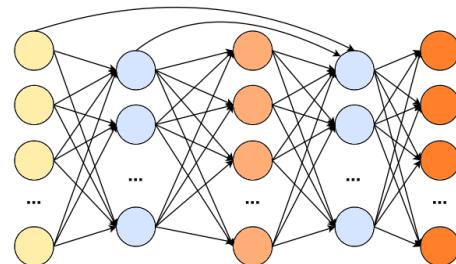
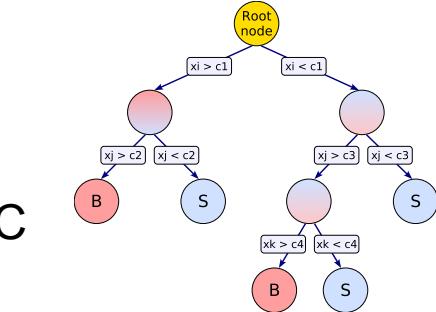


1. Selection according to $t\bar{t}$ decay channel
2. Categorization 1: **jet and b-tagged jet multiplicities**
3. Categorization 2: **multivariate classification**

CMS-HIG-17-026

Multivariate Methods for $t\bar{t}H$

- **Boosted decision tree (BDT):**
 - Established supervised-learning technique
 - Robust workhorse for binary classification at the LHC
- **Deep neural network (DNN):**
 - Rather new supervised-learning technique
 - Artificial neural network with several hidden layers for multi-classification
- **Matrix element method (MEM):**
 - Physics-motivated likelihood-ratio discriminant
 - Exploits all information from (LO) matrix element for signal/background



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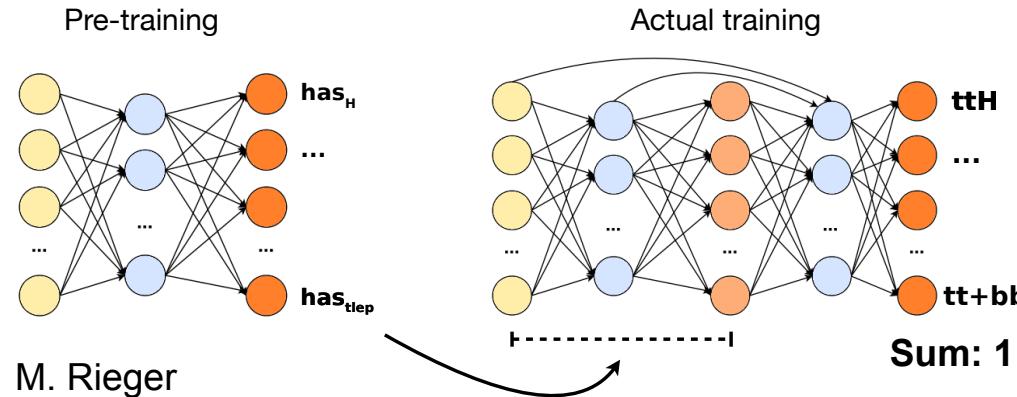
M. Rieger

Which Multivariate Method?

- Application to $t\bar{t}H$: no **single** method provided **optimal sensitivity**
 - BDT: good separation of signal and backgrounds (but: $t\bar{t}bb\bar{b}$ difficult)
 - MEM: best separation of $t\bar{t}H$ and **main irreducible background** $t\bar{t}bb\bar{b}$
 - DNN: $t\bar{t}+X$ multi-classification → best constraints on backgrounds
- Combine multivariate methods (playing to their strengths):
 - **BDT-based preselection** for MEM:
 - BDT suppresses inclusive background well, but $t\bar{t}H/t\bar{t}bb\bar{b}$ separation difficult
 - Apply MEM on sample enhanced with $t\bar{t}H$ and $t\bar{t}bb\bar{b}$ → better separation
 - Apply MEM on background-enriched sample → better background constraints
 - **MEM as input** for DNN: provide complex physics information for DNN that is hard to learn with available training data

Two-Stage Deep Neural Network

- Stage 1: predict which physics objects are contained in event (using MC generator info) → improve treatment of events with **missing** objects
- Stage 2: input layer **connected to all previous layers**, output layer with **six nodes**: $t\bar{t}H$, $t\bar{t}+bb$, $t\bar{t}+2b$, $t\bar{t}+b$, $t\bar{t}+c\bar{c}$, $t\bar{t}+\text{light flavor (lf)}$, **normalized** with softmax activation function



DNN Input Variables

Variable	Definition					
	SL (4 jets, ≥ 3 b tags)					
	SL (5 jets, ≥ 3 b tags)					
	SL (≥ 6 jets, ≥ 3 b tags)					
	DL (4 jets, ≥ 3 b tags)	DL (5 jets, ≥ 3 b tags)	DL (6 jets, ≥ 3 b tags)	DL (4 jets, ≥ 4 b tags)	DL (5 jets, ≥ 4 b tags)	DL (6 jets, ≥ 4 b tags)
$p_T(\text{jet 1})$	p_T of the highest- p_T jet	+	+	-	-	-
$\eta(\text{jet 1})$	η of the highest- p_T jet	-	+	+	-	-
$d(\text{jet 1})$	b tagging discriminant of the highest- p_T jet	+	+	+	-	-
$p_T(\text{jet 2})$	p_T of the second highest- p_T jet	-	+	-	-	-
$\eta(\text{jet 2})$	η of the second highest- p_T jet	+	+	+	-	-
$d(\text{jet 2})$	b tagging discriminant of the second highest- p_T jet	+	+	-	-	-
$p_T(\text{jet 3})$	p_T of the third highest- p_T jet	-	-	-	-	-
$\eta(\text{jet 3})$	η of the third highest- p_T jet	+	-	-	-	-
$d(\text{jet 3})$	b tagging discriminant of the third highest- p_T jet	+	-	-	-	-
$p_T(\text{jet 4})$	p_T of the fourth highest- p_T jet	+	-	-	-	-
$\eta(\text{jet 4})$	η of the fourth highest- p_T jet	+	-	-	-	-
$d(\text{jet 4})$	b tagging discriminant of the fourth highest- p_T jet	+	-	-	-	-
$p_T(\text{lep 1})$	p_T of the highest- p_T lepton	-	+	-	-	-
$\eta(\text{lep 1})$	η of the highest- p_T lepton	+	-	+	-	-
d_{avg}	average b tagging discriminant value of all jets	+	+	+	-	-
d_b^{avg}	average b tagging discriminant value of b-tagged jets	+	+	+	+	-
$d_{\text{non-}b}^{\text{avg}}$	average b tagging discriminant value of non-b-tagged jets	-	-	+	+	-
$\sum_b (d - d_b^{\text{avg}})$	squared difference between the b tagging discriminant value of a b-tagged jet and the average b tagging discriminant values of all b-tagged jets, summed over all b-tagged jets	+	+	+	-	-
$d_{\text{max}}^{\text{j}}$	maximal b tagging discriminant value of all jets	+	+	+	-	-
d_b^{max}	maximal b tagging discriminant value of b-tagged jets	+	+	+	-	-
$d_{\text{min}}^{\text{j}}$	minimal b tagging discriminant value of all jets	+	+	+	-	-
$d_{\text{min}}^{\text{b}}$	minimal b tagging discriminant value of b-tagged jets	+	+	+	-	-
d_2	second highest b tagging discriminant value of all jets	+	+	+	-	-

MC modeling carefully tested
(including correlations)
→ only well-modeled input variables

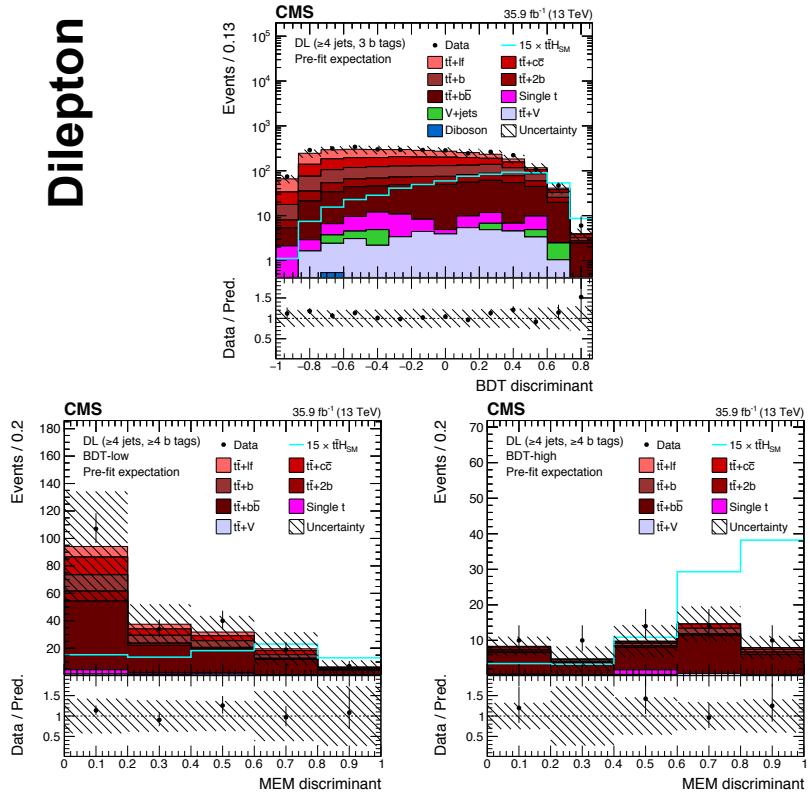
Variable	Definition					
	SL (4 jets, ≥ 3 b tags)					
	SL (5 jets, ≥ 3 b tags)					
	SL (≥ 6 jets, ≥ 3 b tags)					
	DL (4 jets, ≥ 3 b tags)	DL (5 jets, ≥ 3 b tags)	DL (6 jets, ≥ 3 b tags)	DL (4 jets, ≥ 4 b tags)	DL (5 jets, ≥ 4 b tags)	DL (6 jets, ≥ 4 b tags)
$N_b(\text{tight})$	number of b-tagged jets at a working point with a 0.1% probability of tagging gluon and light-flavour jets	+	+	+	-	-
BLR	likelihood ratio discriminating between 4 b quark jets and 2 b quark jets events	+	+	+	-	-
$\text{BLR}^{\text{trans}}$	transformed BLR defined as $\ln[\text{BLR}/(1.0 - \text{BLR})]$	+	+	+	-	-
ΔR^{min}	ΔR between the two closest jets	+	+	+	-	-
$\Delta R_{\text{lept},b}$	ΔR between lepton and closest b-tagged jet	-	+	+	-	-
$m_{\text{min},b}^{\text{R}}$	mass of lepton and closest b-tagged jet	+	+	+	-	-
$m_{b,b}^{\text{min},R}$	mass of closest b-tagged jets	+	+	+	-	-
$m_{b,b}^{\text{min},R}$	mass of closest jets of which at least one is b-tagged	-	-	-	+	-
$m_{b,b}^{\text{max}}$	maximal mass of pairs of b-tagged jets	-	-	-	+	-
$p_{\text{b},b}^{\text{min},R}$	combined p_T of closest b-tagged jets	-	-	-	+	-
$p_{\text{b},b}^{\text{min},R}$	combined p_T of closest jets of which at least one is b-tagged	-	-	-	+	-
$m_{\text{b}}^{\text{avg}}$	average mass of all jets	+	+	+	-	-
$(m^2)^{\text{avg}}$	average squared mass of all b-tagged jets	+	-	+	-	-
$m_{\text{b},b}^{\text{closest to 125}}$	mass of pair of b-tagged jets closest to 125 GeV	-	+	+	-	-
$N_{\text{b},b}^{\text{i}}$	number of pairs of b-tagged jets with an invariant mass within 15 GeV of 125 GeV	-	-	+	+	-
MEM	matrix element method discriminant	+	+	+	-	-

Variable	Definition					
	SL (4 jets, ≥ 3 b tags)					
	SL (5 jets, ≥ 3 b tags)					
	SL (≥ 6 jets, ≥ 3 b tags)					
	DL (4 jets, ≥ 3 b tags)	DL (5 jets, ≥ 3 b tags)	DL (6 jets, ≥ 3 b tags)	DL (4 jets, ≥ 4 b tags)	DL (5 jets, ≥ 4 b tags)	DL (6 jets, ≥ 4 b tags)
H_T^i	scalar sum of jet p_T	-	+	-	+	-
H_T^b	scalar sum of b-tagged jet p_T	+	+	+	-	-
A^i	$\frac{3}{2}\lambda_3$ where λ_i are the eigenvalues of the momentum tensor built with jets [?]	-	+	+	-	-
A^b	where λ_i are the eigenvalues of the momentum tensor built with b-tagged jets [?]	-	-	+	-	-
S_T^i	sum of the energies of all jets	-	-	+	-	-
S_T^b	sum of the energies of all b-tagged jets	-	-	+	-	-
I^b	a measure of how spherical or linear in $r - \phi$ space b-tagged jets are in the event	-	-	-	+	-
H_2	second Fox-Wolfram moment [?]	-	+	-	-	-
H_3	third Fox-Wolfram moment [?]	+	+	-	-	-
H_3^b	third Fox-Wolfram moment calculated with b-tagged jets [?]	-	-	-	-	+
R_3	ratio of Fox-Wolfram moments H_3/H_0 [?]	-	-	-	+	-
H_4	fourth Fox-Wolfram moment [?]	+	-	+	-	-

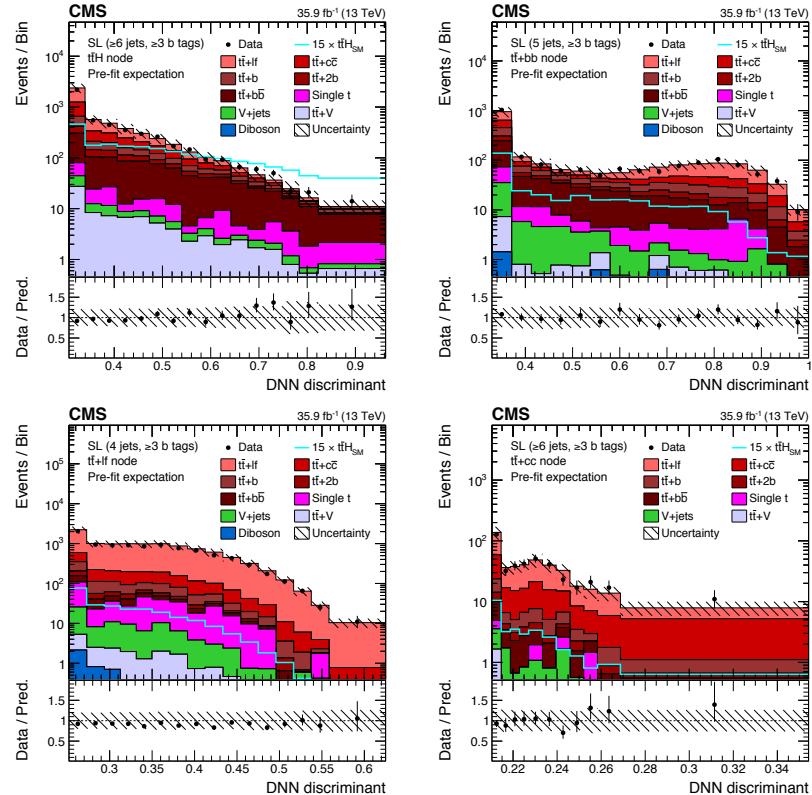
CMS-HIG-17-026

$t\bar{t}H(b\bar{b})$ Discriminants (Before Fit)

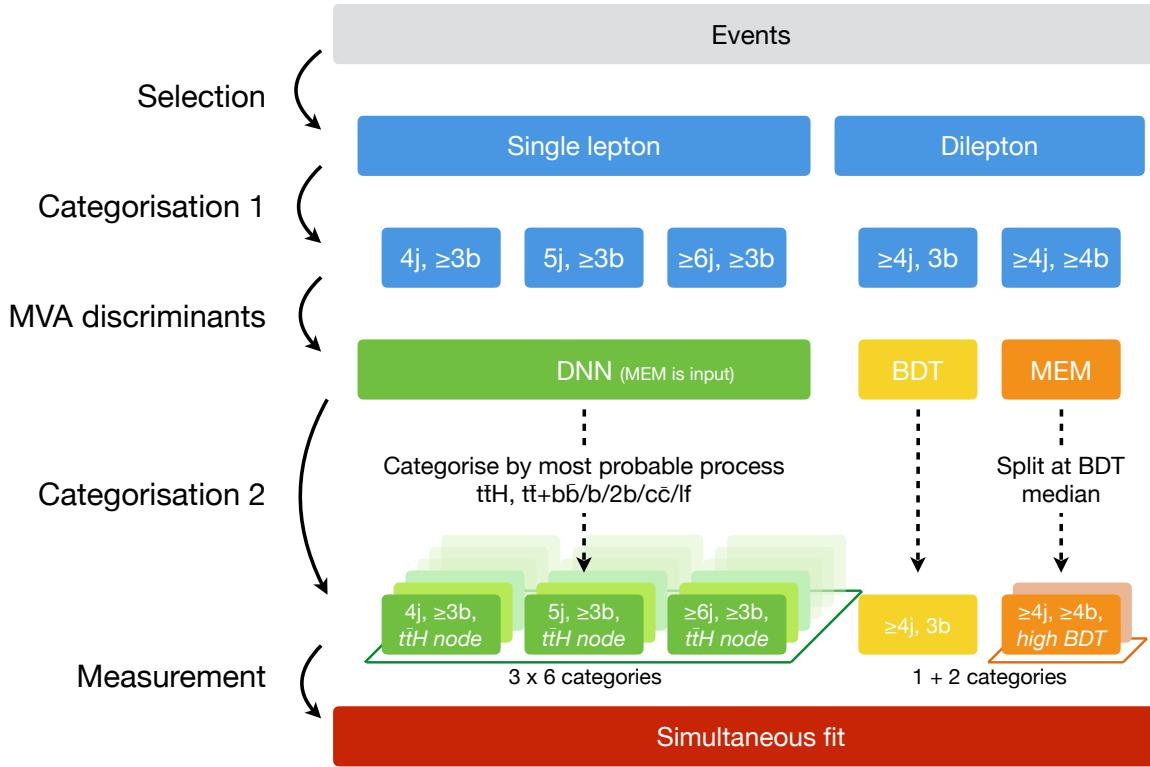
Dilepton



Single Lepton



Analysis Strategy: Divide et Impera



1. Selection according to $t\bar{t}$ decay channel
2. Categorization 1: **jet and b-tagged jet multiplicities**
3. Categorization 2: **multivariate classification**
4. Simultaneous profile-likelihood fit

CMS-HIG-17-026

$t\bar{t}H(b\bar{b})$: Systematic Uncertainties

CMS-HIG-17-026

Source	Type	Remarks					
Integrated luminosity	rate	Signal and all backgrounds					
Lepton identification/isolation	shape	Signal and all backgrounds					
Trigger efficiency	shape	Signal and all backgrounds					
Pileup	shape	Signal and all backgrounds	PDF (gg)				
Jet energy scale	shape	Signal and all backgrounds					
Jet energy resolution	shape	Signal and all backgrounds	PDF (gg $t\bar{t}H$)	rate	PDF uncertainty for gg initiated processes except $t\bar{t}H$		
b tag hf fraction	shape	Signal and all backgrounds	PDF ($q\bar{q}$)	rate	PDF uncertainty for $t\bar{t}H$		
b tag hf stats (linear)	shape	Signal and all backgrounds		rate	PDF uncertainty of $q\bar{q}$ initiated processes ($t\bar{t}+W,W,Z$)		
b tag hf stats (quadratic)	shape	Signal and all backgrounds	PDF (qg)	rate	PDF uncertainty of qg initiated processes (single t)		
b tag lf fraction	shape	Signal and all backgrounds	μ_R scale ($t\bar{t}$)	shape	Renormalisation scale uncertainty of the $t\bar{t}$ ME generator, independent for additional jet flavours		
b tag lf stats (linear)	shape	Signal and all backgrounds		shape	Factorisation scale uncertainty of the $t\bar{t}$ ME generator, independent for additional jet flavours		
b tag lf stats (quadratic)	shape	Signal and all backgrounds	μ_F scale ($t\bar{t}$)	rate	Initial state radiation uncertainty of the PS (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours		
b tag charm (linear)	shape	Signal and all backgrounds	PS scale: ISR ($t\bar{t}$)	rate	Final state radiation uncertainty (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours		
b tag charm (quadratic)	shape	Signal and all backgrounds		rate	NLO ME to PS matching, $hdamp$ [?] (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours		
Renorm./fact. scales ($t\bar{t}H$)	rate	Scale uncertainty of NLO $t\bar{t}H$ prediction	PS scale: FSR ($t\bar{t}$)	Underlying event ($t\bar{t}$)	Underlying event (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours		
Renorm./fact. scales ($t\bar{t}$)	rate	Scale uncertainty of NLO $t\bar{t}$ prediction		NNPDF3.0NLO ($t\bar{t}H, t\bar{t}$)	shape	Based on the NNPDF replicas, same for $t\bar{t}H$ and additional jet flavours	
Renorm./fact. scales ($t\bar{t}+hf$)	rate	Additional 50% rate uncertainty of $t\bar{t}+hf$ predictions		Bin-by-bin event count	shape	Statistical uncertainty of the signal and background prediction due to the limited sample size	
Renorm./fact. scales (t)	rate	Scale uncertainty of NLO single t prediction					
Renorm./fact. scales (V)	rate	Scale uncertainty of NNLO W and Z prediction					
Renorm./fact. scales (VV)	rate	Scale uncertainty of NLO diboson prediction					

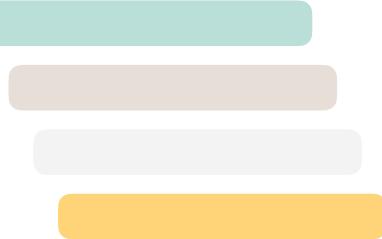
78 nuisance parameters for rate
and/or shape systematics
(+192 for bin-by-bin uncertainties)

$t\bar{t}H(b\bar{b})$: Systematic Uncertainties

Uncertainty source	$\pm\Delta\mu$ (observed)	$\pm\Delta\mu$ (expected)
Total experimental	+0.15 / -0.16	+0.19 / -0.17
b tagging	+0.11 / -0.14	+0.12 / -0.11
jet energy scale and resolution	+0.06 / -0.07	+0.13 / -0.11
Total theory	+0.28 / -0.29	+0.32 / -0.29
$t\bar{t}$ +hf cross section and parton shower	+0.24 / -0.28	+0.28 / -0.28
Size of the simulated samples	+0.14 / -0.15	+0.16 / -0.16
Total systematic	+0.38 / -0.38	+0.45 / -0.42
Statistical	+0.24 / -0.24	+0.27 / -0.27
Total	+0.45 / -0.45	+0.53 / -0.49

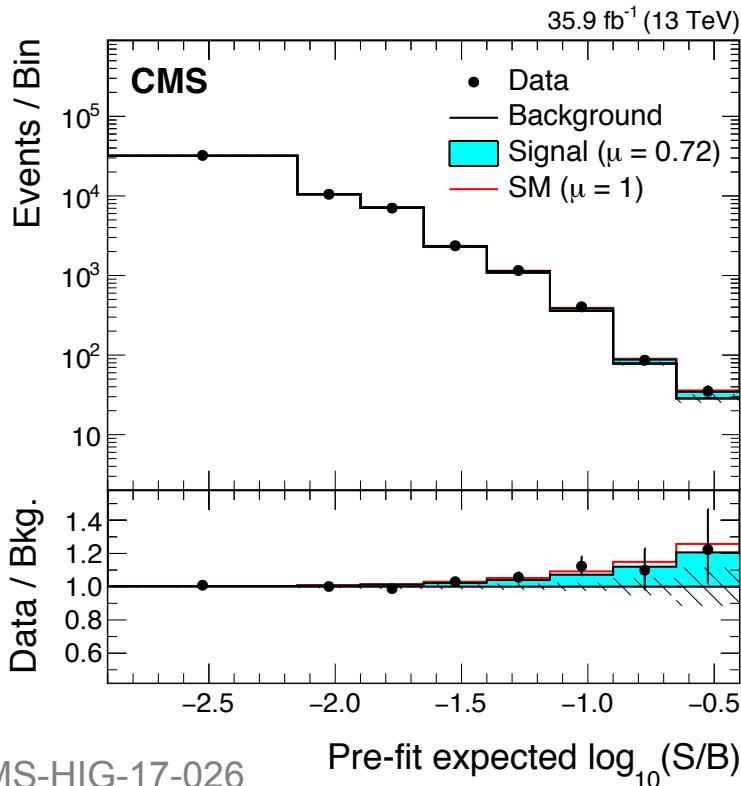
CMS-HIG-17-026

- Dominant uncertainties:
b-tagging and $t\bar{t}$ +heavy flavor modeling
- Procedure:
 - Fix uncertainties to post-fit values
 - Subtract obtained result in quadrature from result of full fit
- Correlations: quadratic sum \neq total uncertainty



RESULTS AND INTERPRETATION

$t\bar{t}H(b\bar{b})$: Is There a Signal?



- Limits indicate **excess** above no- $t\bar{t}H$ hypothesis (not shown)
- Good illustration: sort all bins in all analysis categories by **expected signal-to-background ratio**
- **Clear excess** in large-S/B bins

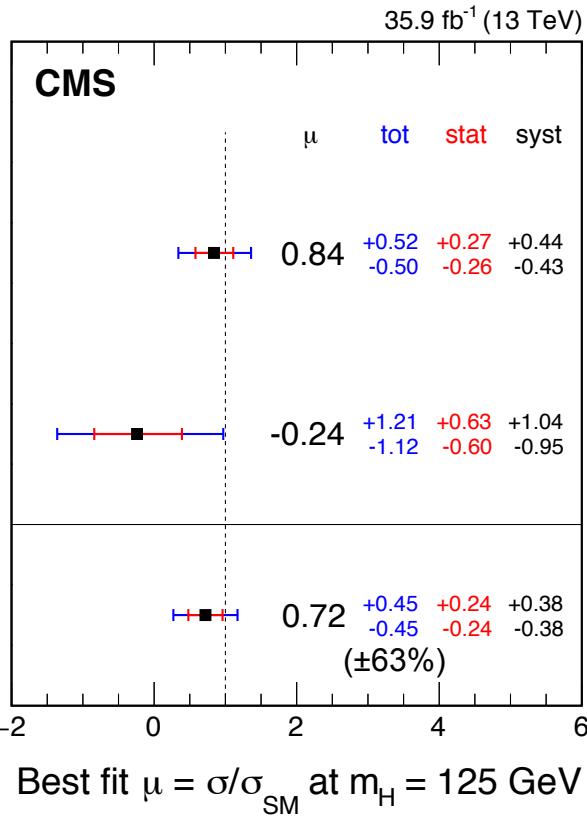
CMS-HIG-17-026

$t\bar{t}H(b\bar{b})$: Is There a Signal?

Single-lepton

Dilepton

Combined



CMS-HIG-17-026

- Limits indicate **excess** above no- $t\bar{t}H$ hypothesis (not shown)
- Good illustration: sort all bins in all analysis categories by **expected signal-to-background ratio**

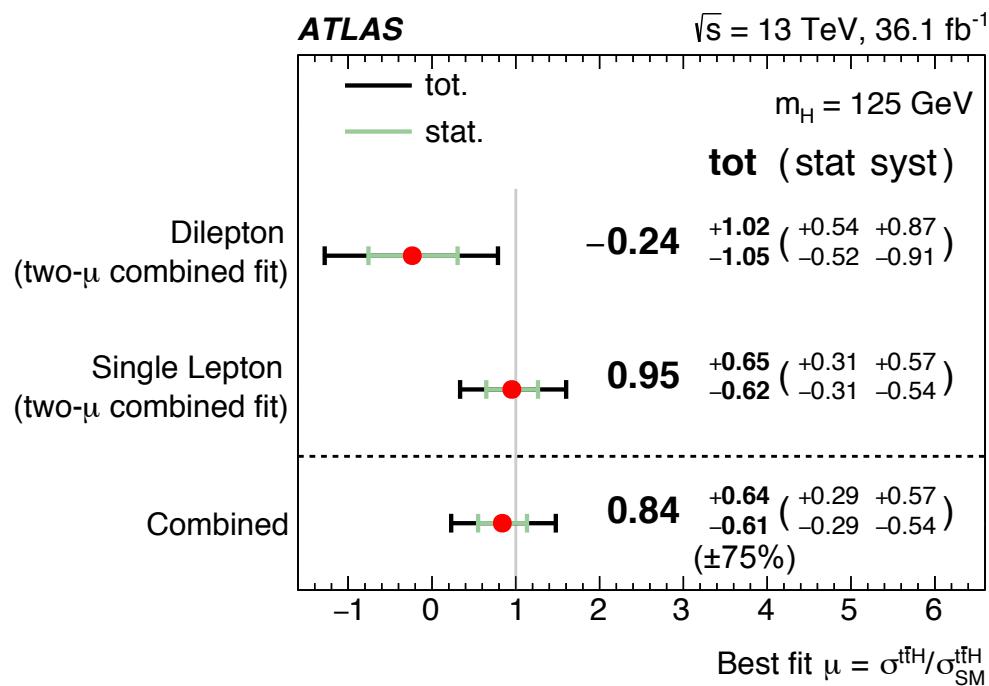
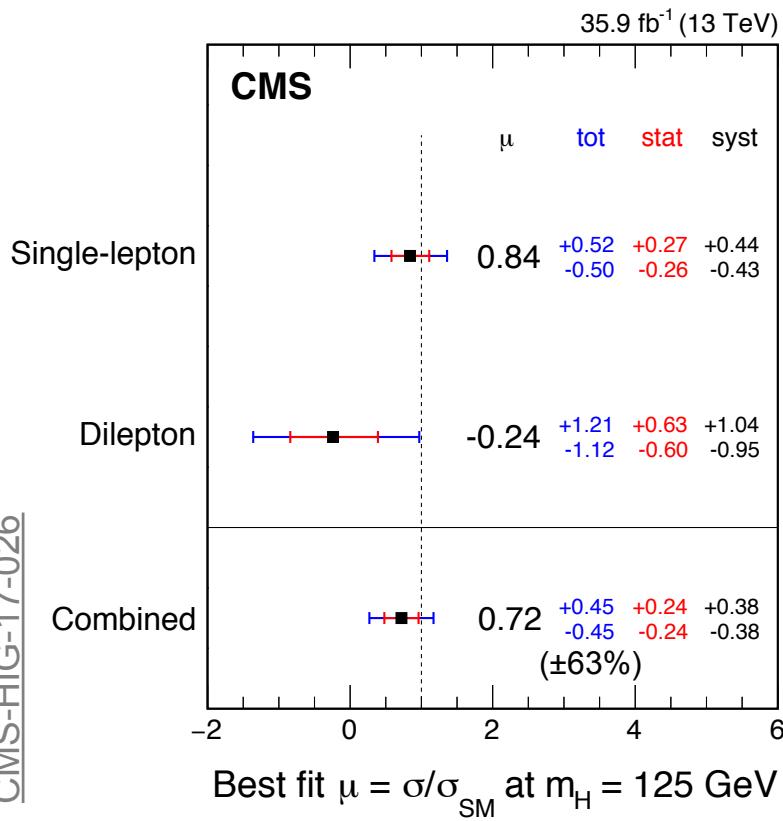
- **Clear excess** in large-S/B bins
- Best-fit signal strength:

$$\mu_{t\bar{t}H} = 0.72 \pm 0.45$$

→ significance: 1.6 standard deviations (2.2 s.d. expected)

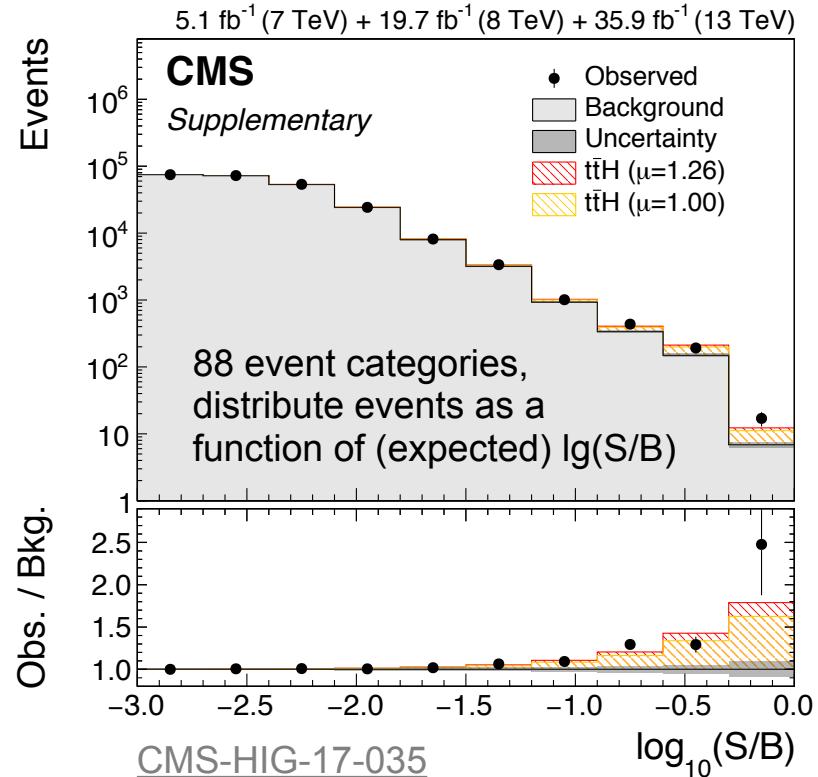
$t\bar{t}H(b\bar{b})$: Comparison with ATLAS

CMS-HIG-17-026

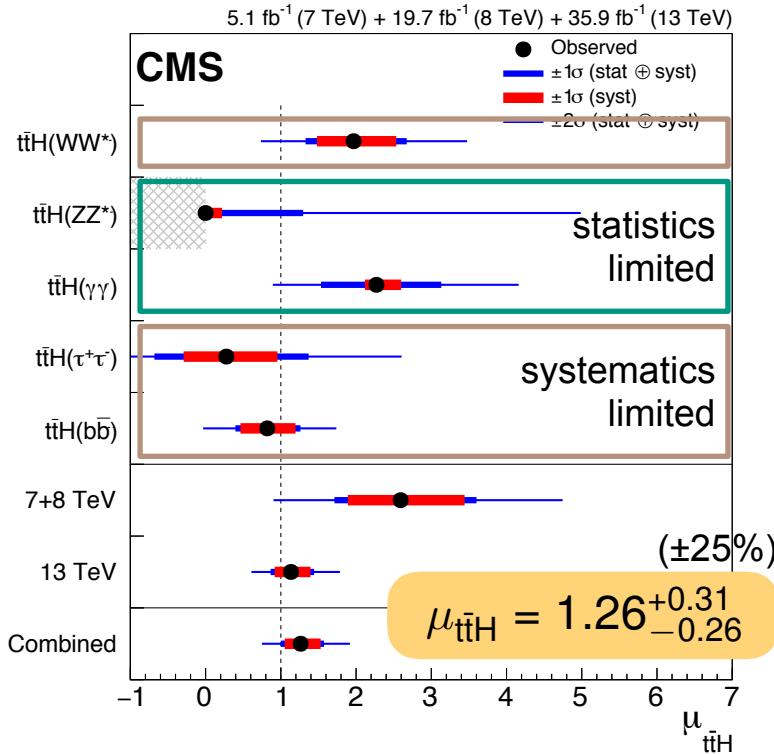


CMS $t\bar{t}H$ Combination

- Maximum sensitivity: **combine** all available Run-1 and Run-2 $t\bar{t}H$ analyses
 - 13 TeV: $t\bar{t}H$ searches in $H \rightarrow \gamma\gamma$, ZZ , $b\bar{b}$ (leptonic and hadronic) and multileptons ([CMS-HIG-16-40](#), [JHEP 11 \(2017\) 47](#), [CMS-HIG-17-026](#), [CMS-HIG-17-022](#), [CMS-HIG-17-018](#))
 - 7+8 TeV:
 - $t\bar{t}H$ searches in $H \rightarrow b\bar{b}$ and multilepton channels and $t\bar{t}H$ channel of $H \rightarrow \gamma\gamma$
 - m_H , signal normalization and uncertainties updated
 - Theoretical uncertainties on signal and some backgrounds correlated



Signal Strength and Systematics



CMS-HIG-17-035

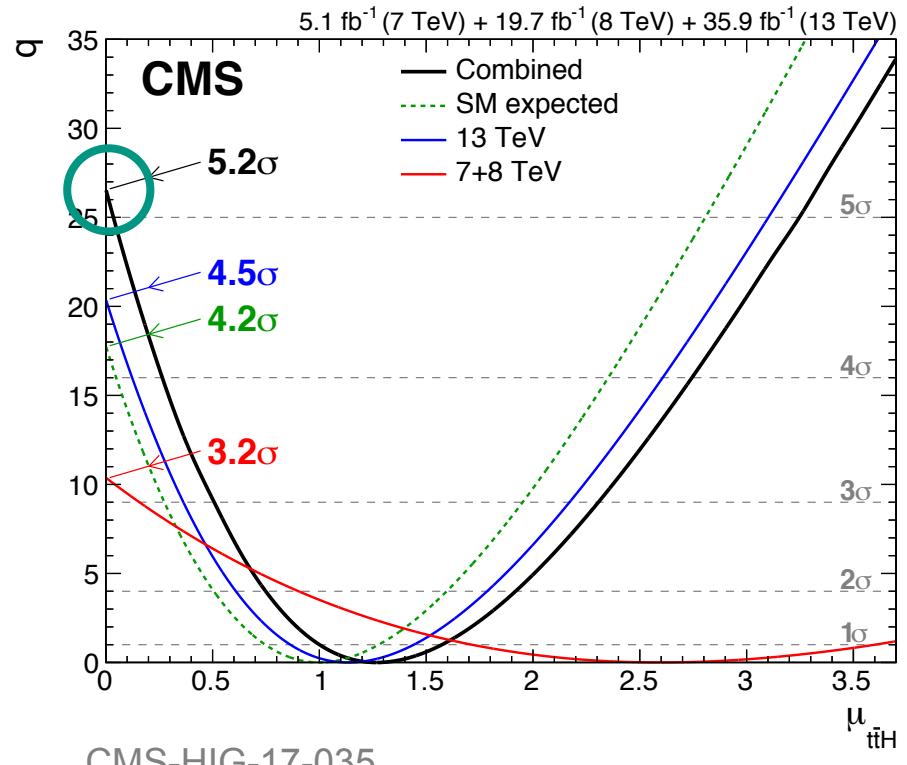
Systematic Uncertainties

Uncertainty source	$\Delta\mu$
Signal theory	+0.15 -0.07
Inclusive ttH normalisation (cross section and BR)	+0.15 -0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004 -0.004
Other Higgs boson production modes	+0.002 -0.003
Background theory	+0.14 -0.13
$\text{tt} + \text{bb}/\text{cc}$ prediction	+0.13 -0.11
$\text{tt} + \text{V(V)}$ prediction	+0.06 -0.06
Other background uncertainties	+0.03 -0.03
Experimental	+0.17 -0.15
Lepton (inc. τ_h) trigger, ID and iso. efficiency	+0.08 -0.06
Misidentified lepton prediction	+0.06 -0.06
b-Tagging efficiency	+0.05 -0.04
Jet and τ_h energy scale and resolution	+0.04 -0.04
Luminosity	+0.04 -0.03
Photon ID, scale and resolution	+0.01 -0.01
Other experimental uncertainties	+0.01 -0.01
Finite number of simulated events	+0.08 -0.07
Statistical	+0.16 -0.16
Total	+0.31 -0.26

Correlations: sum in quadrature \neq total uncertainty

Observation of $t\bar{t}H$ Production

- Significance of CMS-combined signal strength: test compatibility of observed signal with no- $t\bar{t}H$ hypothesis ($\mu = 0$)
- Result: **observation** of $t\bar{t}H$ production with **5.2 standard deviations** significance (4.2 σ expected)



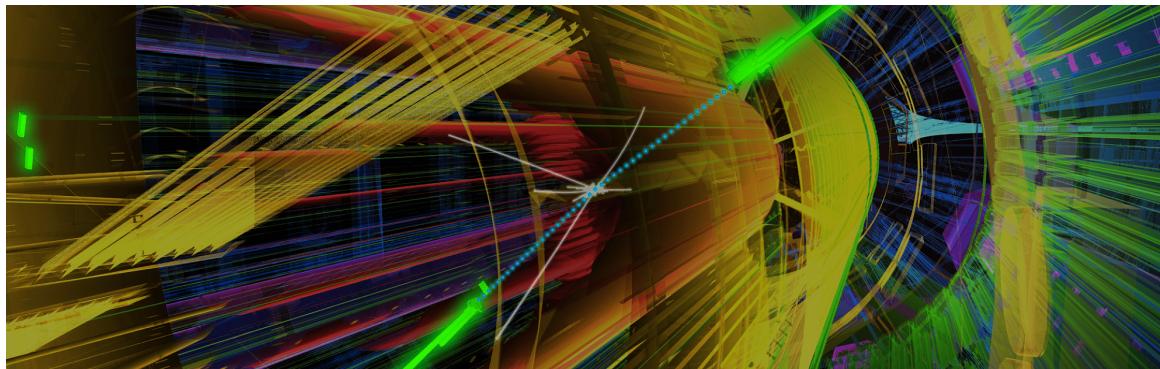
News
| 11.04.2018

MIKROKOSMOS

Das Higgs-Teilchen mag auch Top-Quarks

Sieht das Higgs-Teilchen wirklich genau so aus, wie die Physiker denken? Eine neue Messung bringt sie in dieser Frage ein Stück weiter.

von Robert Gast



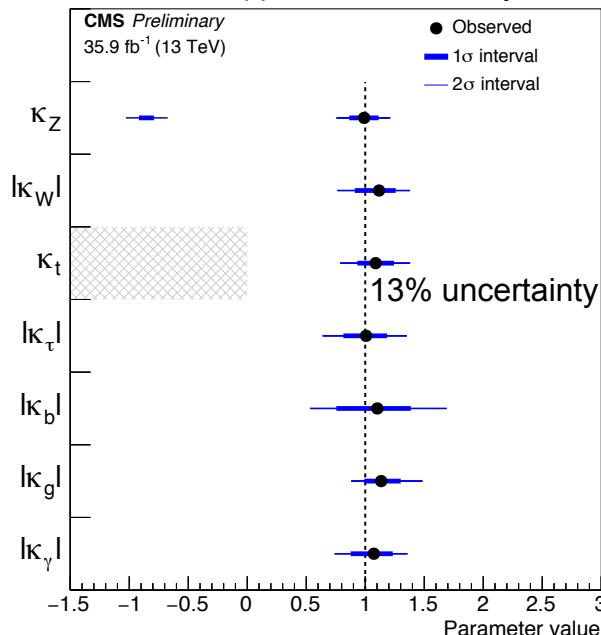
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Physiker am Kernforschungszentrum CERN haben eine neue Möglichkeit entdeckt, das Higgs-Teilchen ins Leben zu rufen. Das

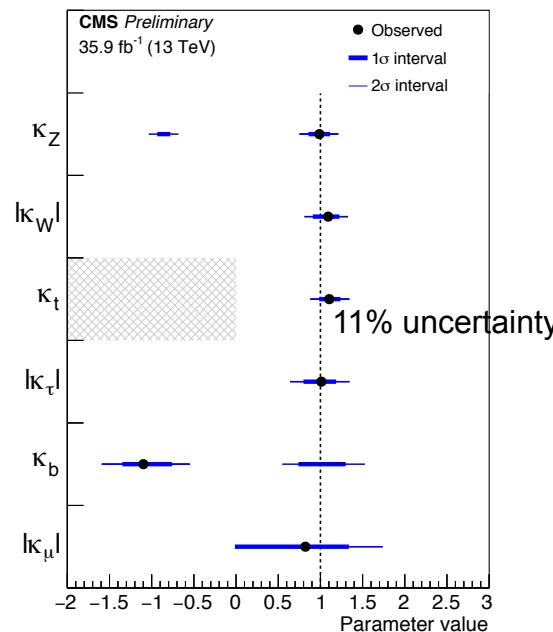
Measurement of the Top-Higgs Coupling

- CMS grand combination interpreted in “kappa framework”:

Effective couplings for loop-induced $gg \rightarrow H$
and $H \rightarrow \gamma\gamma$: κ_t dominated by $t\bar{t}H$

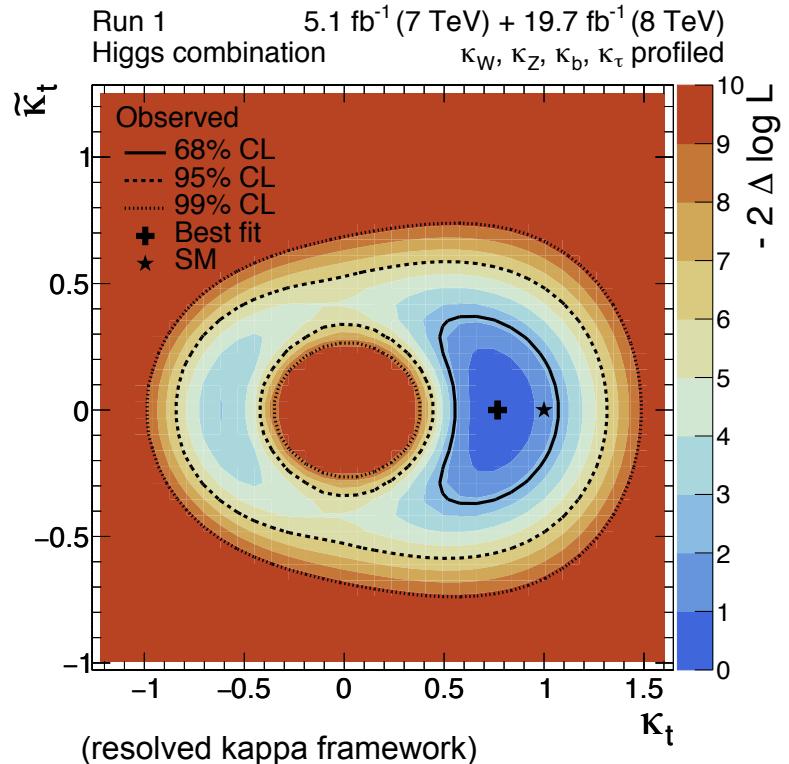


Resolved $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ loops, assuming no new particles in loops: 15% stronger constraints on κ_t



Outlook: $t\bar{t}H$ and Higgs CP State

- Higgs boson composed of **CP even** and **CP odd** components?
 - Consequence: **modification** of Yukawa coupling
 - In kappa framework:
$$\mathcal{L}_{Htt} = -\frac{m_t}{v} \bar{t} (\kappa_t + \tilde{\kappa}_t i\gamma_5) H t$$
- Proof of concept based on Run-1 ATLAS/CMS combination (and direct $t\bar{t}H$ search with 2015 data)
- Precision result requires (at least) full Run-2 dataset → stay tuned



Like a Roller Coaster

- Top 5 reasons why the quest for $t\bar{t}H$ production is like a roller coaster:
 - $t\bar{t}H$ is **feasible** at the LHC, despite the **ups and downs** in history.
 - The most popular rides have the **longest waiting** time.
 - Things move **slowly** for a while, but suddenly you're in a **rush**.
 - You have to **trust technology** to get through all the twists and turns.
 - It's been so much **fun**, let's get in line for the **next ride!**