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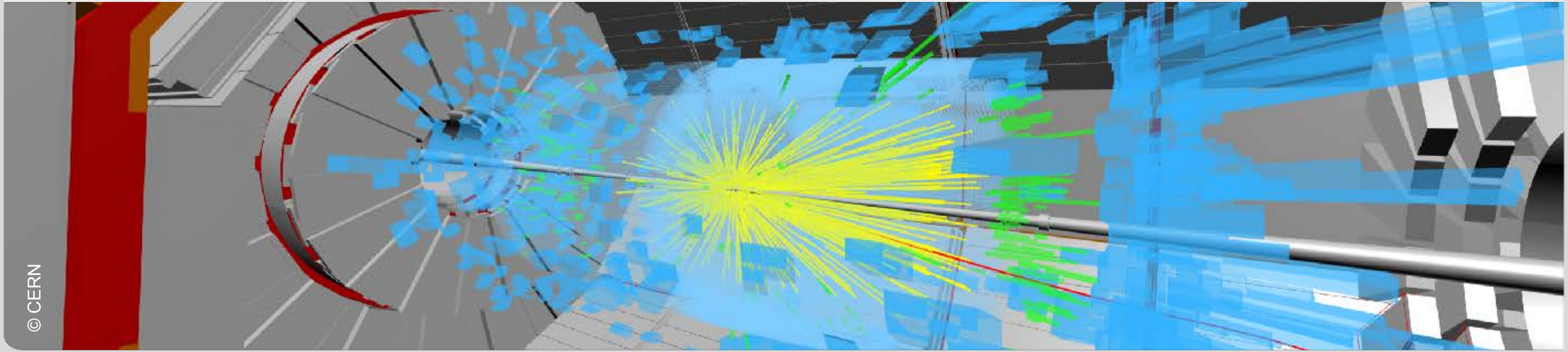
The Quest for $t\bar{t}H$ at the LHC

GK Colloquium, University of Freiburg, April 24, 2019

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 a 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, U Bonn 2004; A. Schmidt, Dissertation, U 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**

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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

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A Quick Reminder

Higgs Physics

The Higgs Boson's Role in the Standard Model

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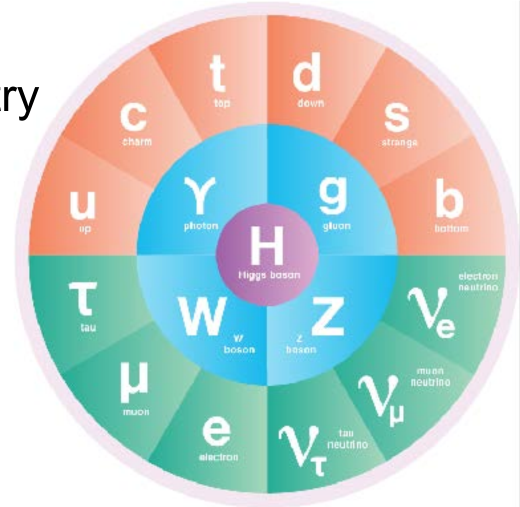
- Higgs boson = "rosetta stone" of the standard model
  - (Brout-Englert-)Higgs mechanism: spontaneous symmetry breaking → **masses of gauge bosons** W and Z
  - Yukawa couplings (same Higgs field): **fermion masses**
  - Regularization of **high-energy behavior** (e.g. longitudinal W-boson scattering)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

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

→ From measurements of top-quark mass: $y_t \approx 1$

(v: vacuum expectation value of Higgs field)



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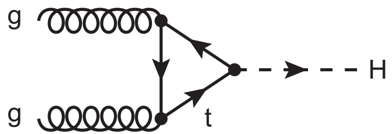
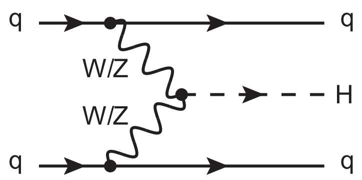
Higgs-Boson Production at the LHC

Gluon-Gluon Fusion

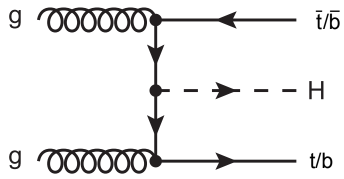


Vector Boson Fusion (VBF)



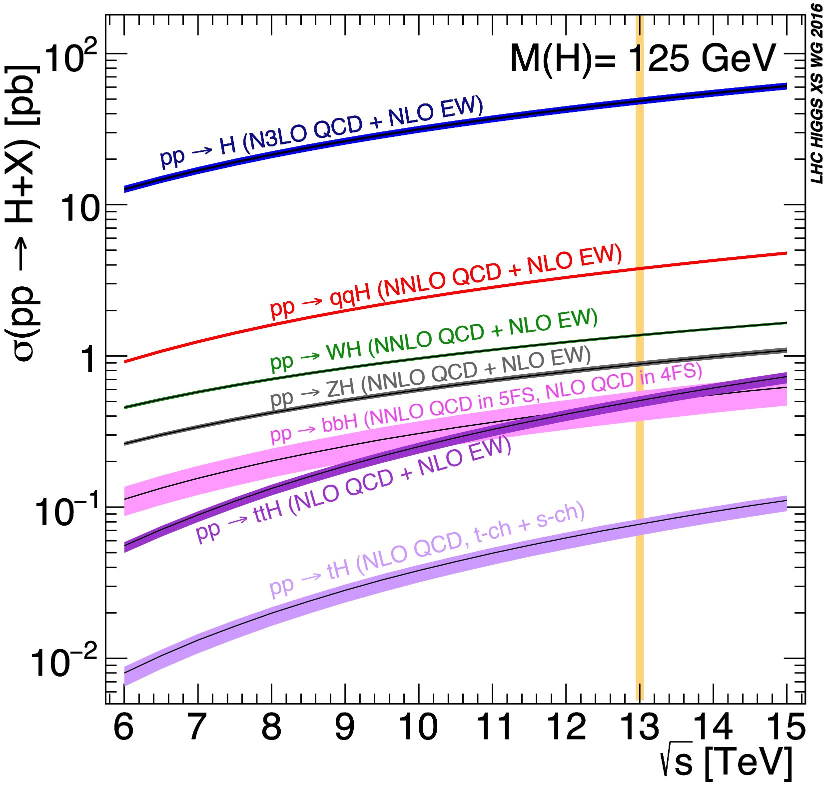
Associated Production with W and Z

Associated Production with t and b



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

Higgs-Boson Production Cross Section in pp



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Signal Strengths and Couplings

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- 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:

$$\mu(i \to \mathrm{H} \to f) = \frac{\sigma(i \to \mathrm{H})}{\sigma(i \to \mathrm{H})^{\mathrm{SM}}} \cdot \frac{B(\mathrm{H} \to f)}{B(\mathrm{H} \to f)^{\mathrm{SM}}} \equiv \mu_i \cdot \mu^f$$

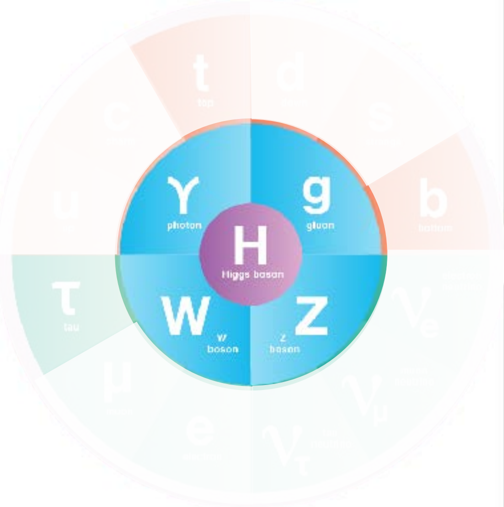
    with branching ratio $B(\mathrm{H} \to f) \equiv B^f \equiv \frac{\Gamma^f}{\Gamma_{\mathrm{H}}}$

  - 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:

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \kappa_f^2 = \frac{\Gamma^f}{\Gamma^f_{\mathrm{SM}}}$$

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, JHEP 08 (2016) 045)



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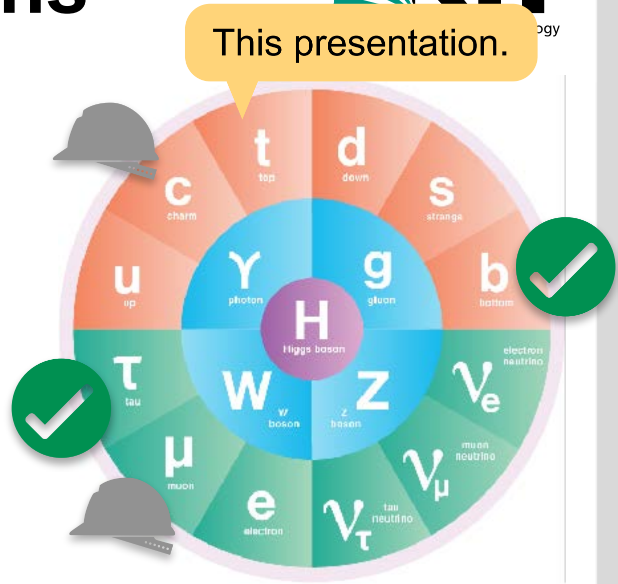
Higgs-Boson Coupling to Fermions

- **Third-generation** fermions:
  - H → $\tau\tau$: **observed**
    - ATLAS Run 1+2: 6.4 s.d. (5.4 s.d. exp) (arXiv:1811.08856)
    - CMS Run 1+2: 5.9 s.d. (5.9 s.d. exp) (PLB 779 (2018) 283)
  - H → $b\bar{b}$: **observed**, driven by VH(bb) channel:
    - ATLAS: 5.4 s.d. (5.5 s.d. exp) (PLB 786 (2018) 59)
    - CMS: 5.6 s.d. (5.5 s.d. exp) (PRL 121 (2018) 121801)
  - H → $t\bar{t}$: kinematically **forbidden** ($2m_t \gg m_H$)
    → study top couplings in $t\bar{t}$H **production**



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- **Second-generation** fermions:
  - H → $\mu\mu$: primary goal for **high-luminosity LHC** (HL-LHC), first limits available (ATLAS: PRL 119 (2017) 051802, CMS: PRL 122 (2019) 021801)
  - H → $c\bar{c}$: **first analyses** available (ATLAS: PRL 120 (2018) 211802)

(s.d.: standard deviations)

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ASSOCIATED TOP-HIGGS PRODUCTION AT THE LHC

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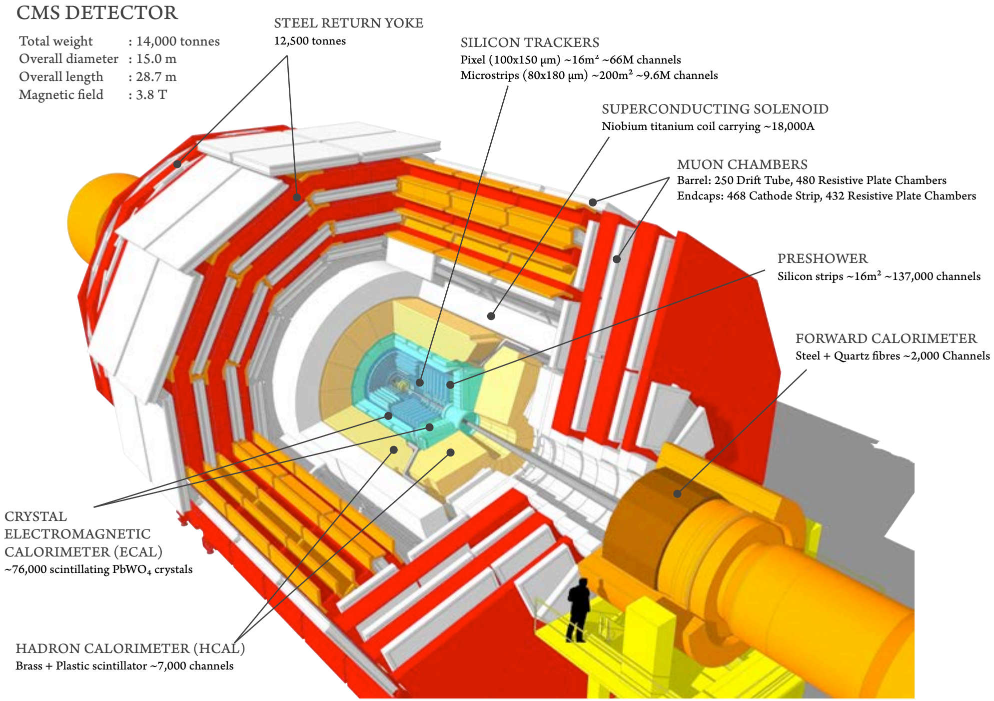
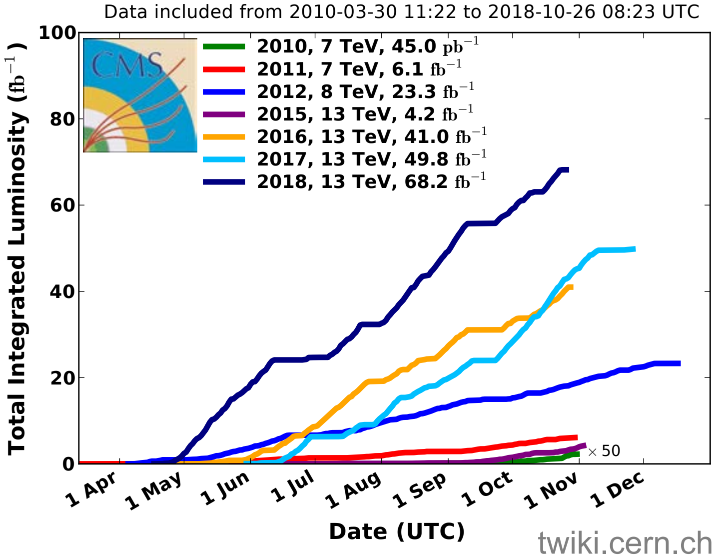
The CMS Experiment



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

CMS Integrated Luminosity



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Results shown here: **full 2016 dataset**
→ 35.9 fb^{-1} of "good" data

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$t\bar{t}H$ Production

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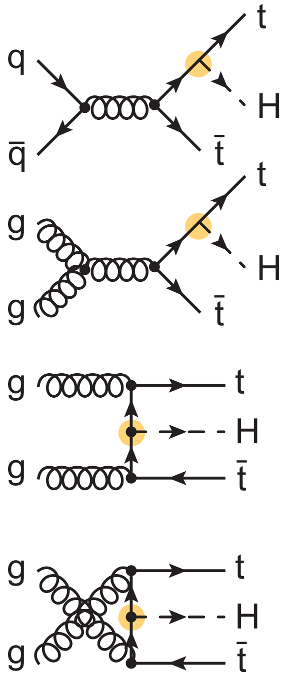

- Matrix elements for $t\bar{t}H$ production proportional to **top-Higgs coupling constant**, radiative corrections only affect top mass renormalization
- **Leading order** (LO): large **scale uncertainties** (NPB 247 (1984) 339)
- **Next-to-leading order** (NLO): moderate K-factor of 1.2, scale uncertainties 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)

$$\sigma_{t\bar{t}H}(13\,\mathrm{TeV}, m_{\mathrm{H}} = 125\,\mathrm{GeV}) = (507^{+35}_{-50})\mathrm{fb}$$

- Details: *Handbook of LHC Higgs Cross Sections*, Vol. 4
  (CERN-2017-002-M, arXiv:1610.079222)

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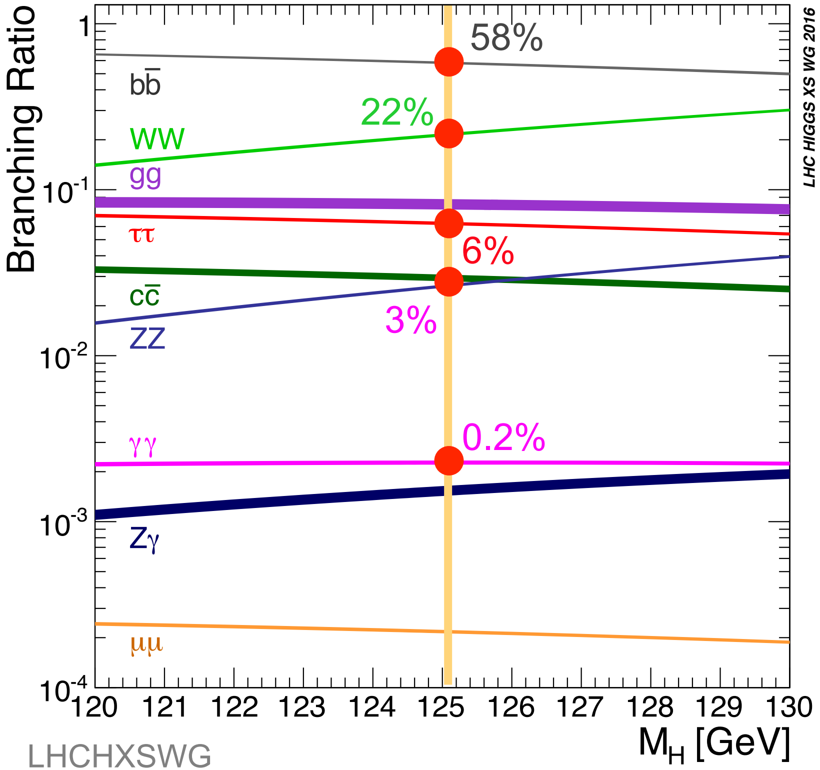
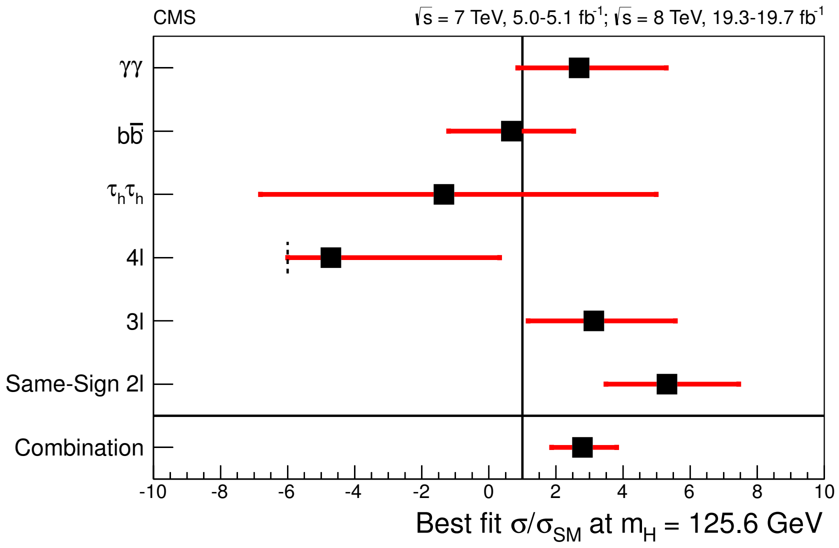
$t\bar{t}H$ Decay Channels: Higgs Decays

- 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
    $\rightarrow$ **$t\bar{t}H(b\bar{b})$: focus of this talk**



LHCHXSWG

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



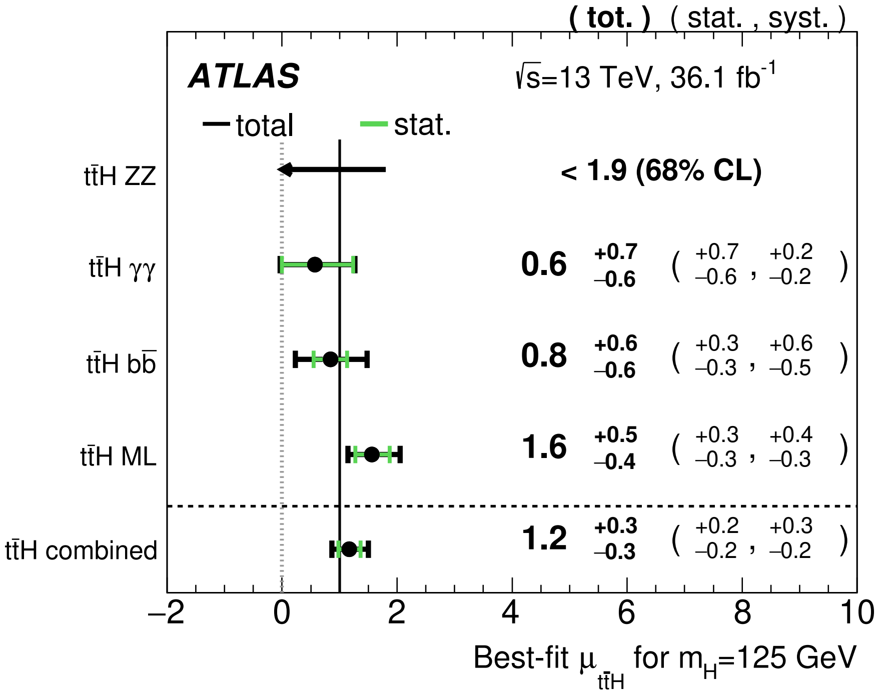
JHEP 09 (2014) 87

- 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 (CMS-HIG-2018-009, submitted to PRD)

$t\bar{t}H$ 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" 2017: first suite of Run-2 publications → **4.2 standard deviations evidence** for $t\bar{t}H$ production (3.8 s.d. expected) (JHEP 03 (2018) 95, PRD 97 (2018) 072003, PRD 97 (2018) 072016, PRD 98 (2018) 052005)



PRD 97 (2018) 072003
(submitted Dec 24, 2017)

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

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

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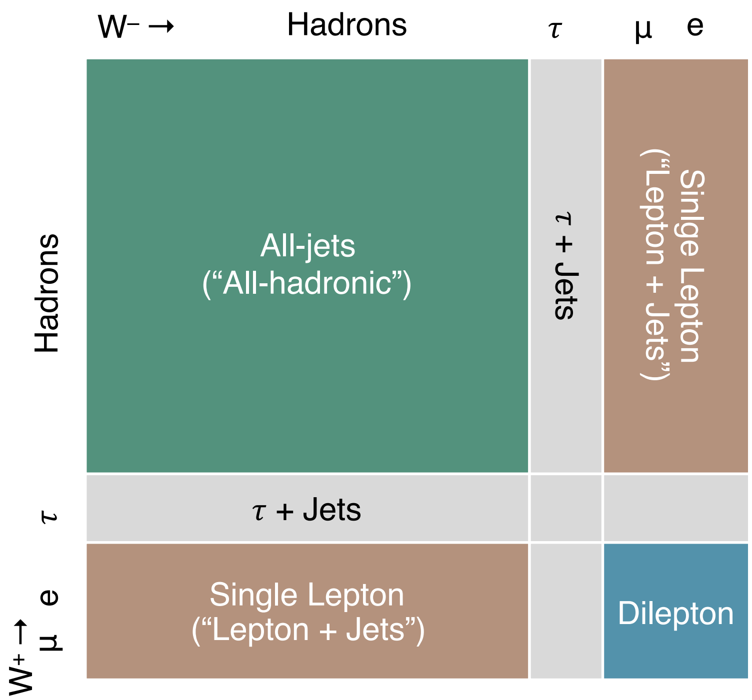
- Process considered here:
  $t\bar{t}H(b\bar{b})$ = $t\bar{t}H$ production with $H \to b\bar{b}$ decay
- $t\bar{t}H(b\bar{b})$ classification by **$t\bar{t}$ decay** ($t \to Wb$):
  - Single lepton channel (SL)
  - Dilepton channel (DL)
  - All-jets channel
- Dominant background for $t\bar{t}H(b\bar{b})$: **$t\bar{t}$ + *X***
  with *X* = jets, W, Z
  - Inclusive $t\bar{t}$ cross section well known (<4%)
  - $t\bar{t}$ + heavy-flavor jets: large (5× signal), "irreducible," experimentally and theoretically challenging



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

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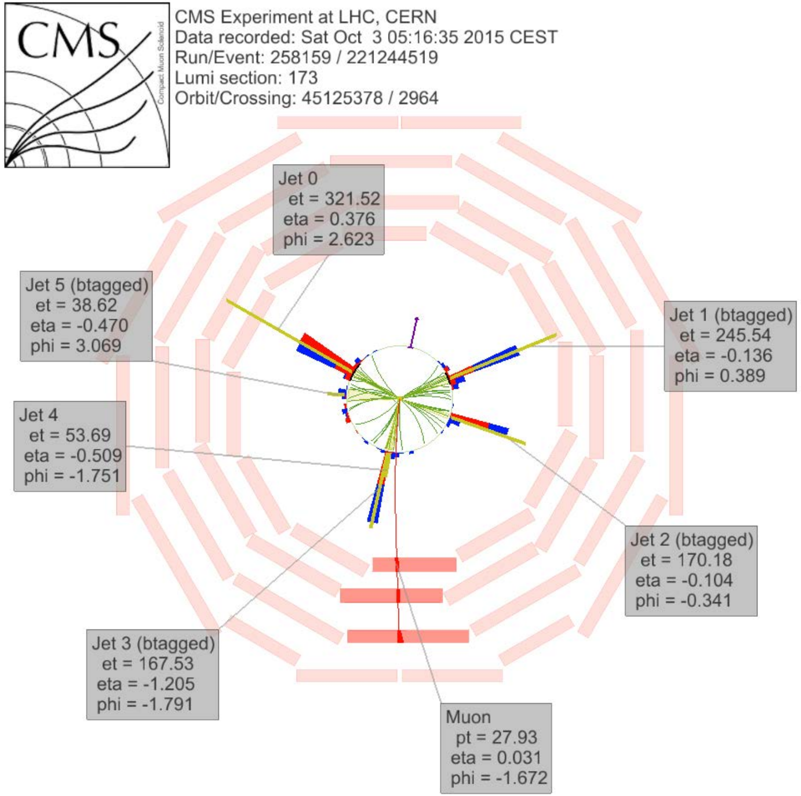

CMS-PAS-HIG-16-004

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

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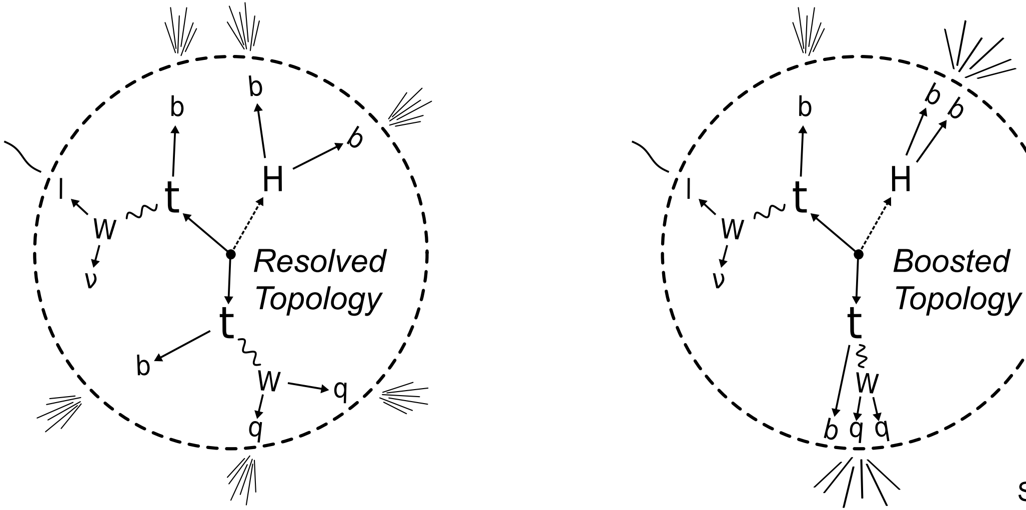
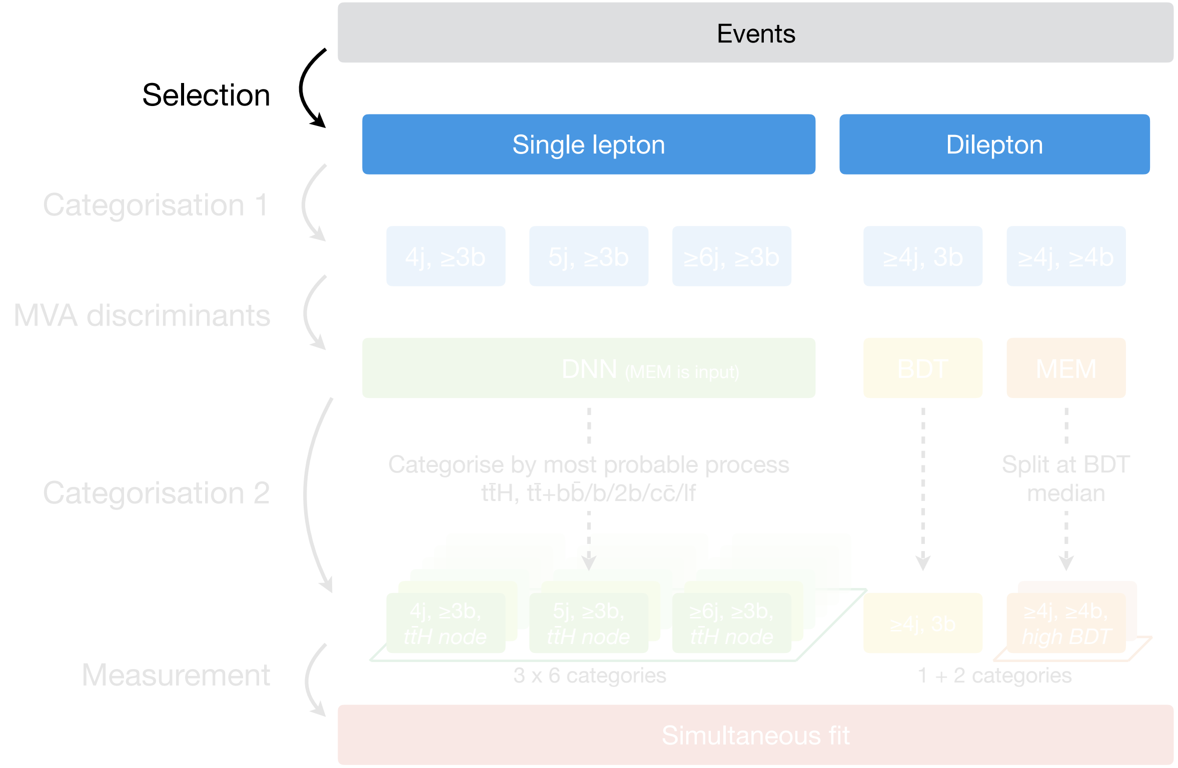
Remark: Higgs with a Boost

- 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, PRD 97 (2018) 072016)



S. Williamson

Analysis Strategy: Divide et Impera



1. Selection according to **tt̄ decay channel**

JHEP 03 (2019) 026

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Top Quark-Antiquark Event Categories

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- $t\bar{t}$ + 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
  - $t\bar{t}$+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"

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

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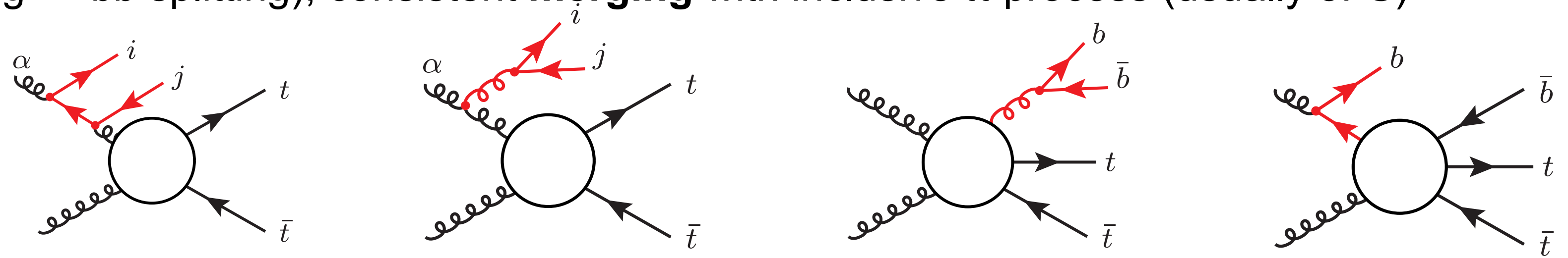
- Theory challenge: associated $t\bar{t}+b\bar{b}$ production
  - **Multileg** process with **multiple energy/momentum scales**
  - Calculation in two different schemes:
    five-flavor number scheme (5FS) – massless b quarks, active flavor in PDFs, vs.
    four-flavor number scheme (4FS) – massive b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



EPJC 78 (2018) 502

- Lots of discussion, e.g. in LHC Higgs Cross Section WG ($t\bar{t}$H/tH subgroup)
  (recent publications: arXiv:1709.06915, EPJC 78 (2018) 502)

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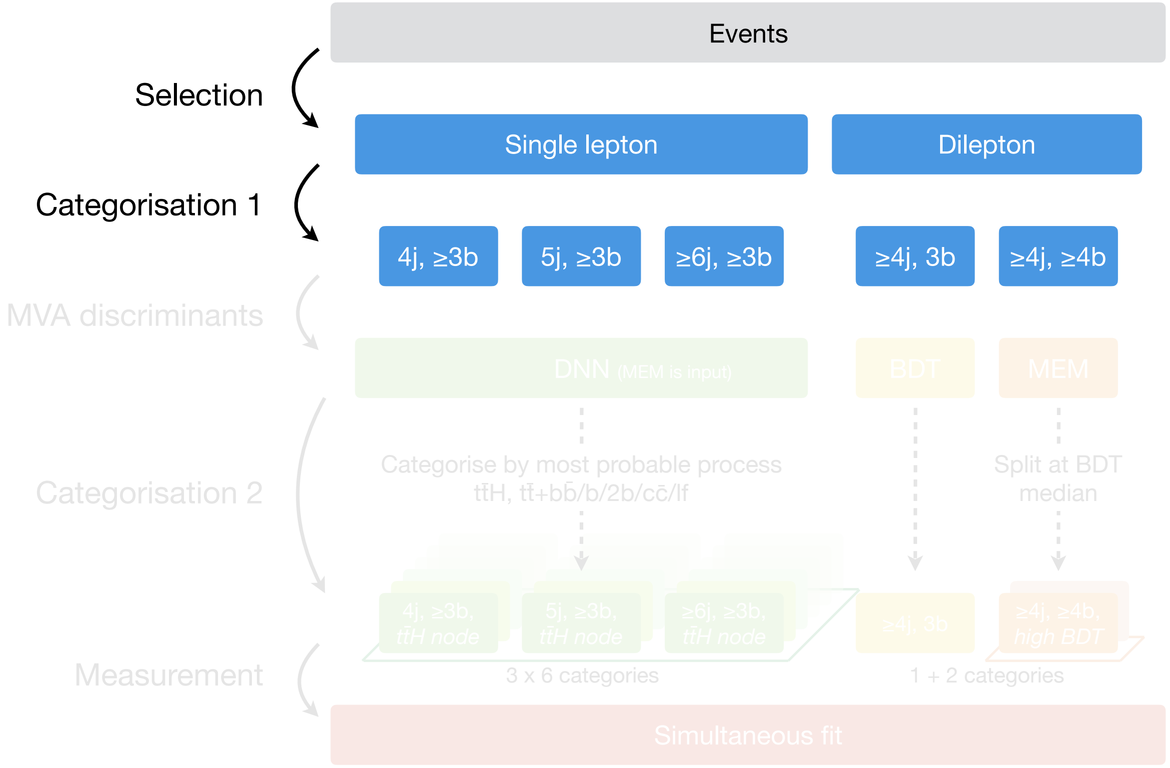
Analysis Strategy: Divide et Impera



1. Selection according to **tt̄ decay channel**
2. Categorization 1: **jet** and **b-tagged jet multiplicities**

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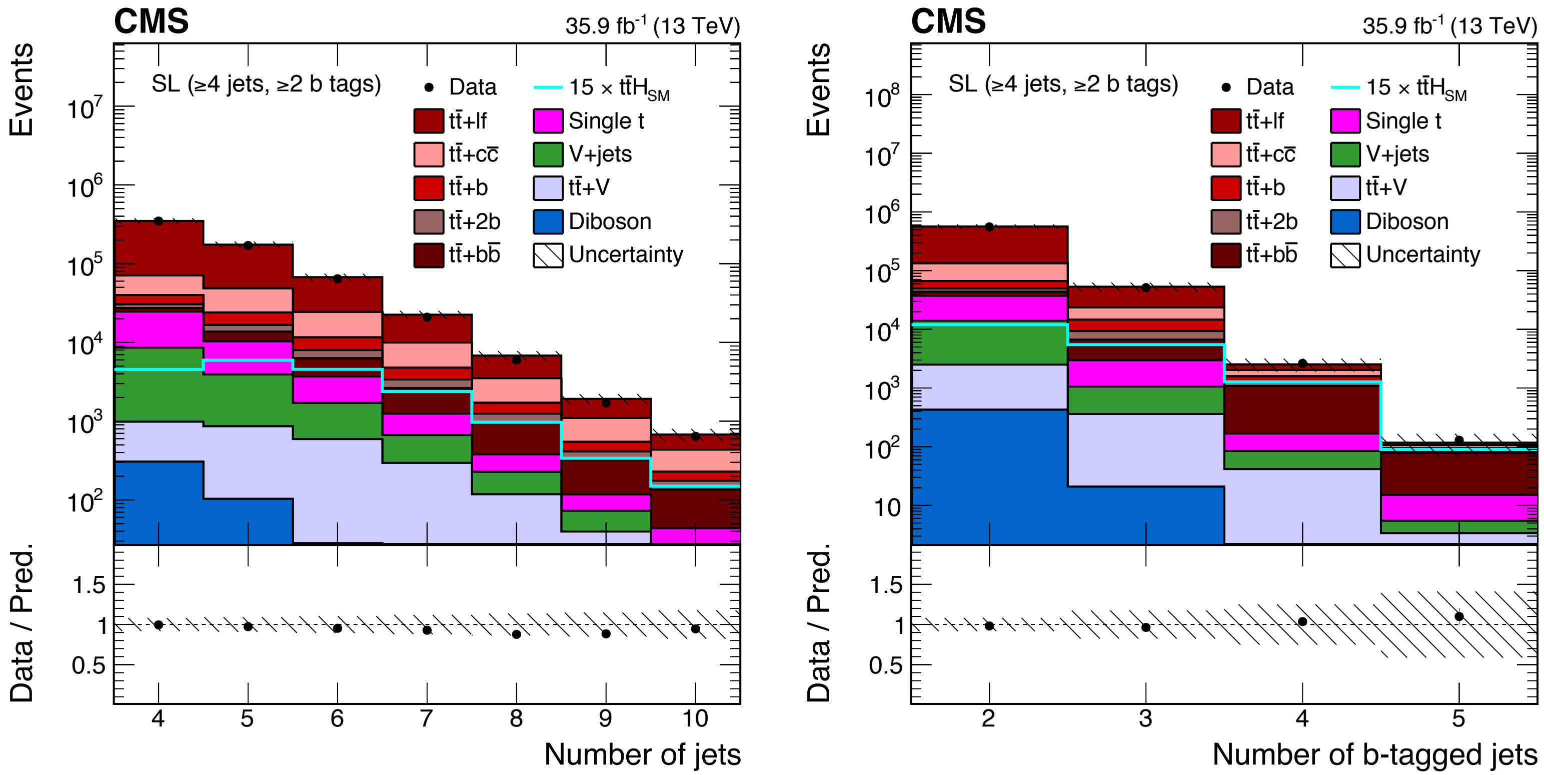
$t\bar{t}H(b\bar{b})$ Single Lepton: Multiplicity of (b-tagged) Jets



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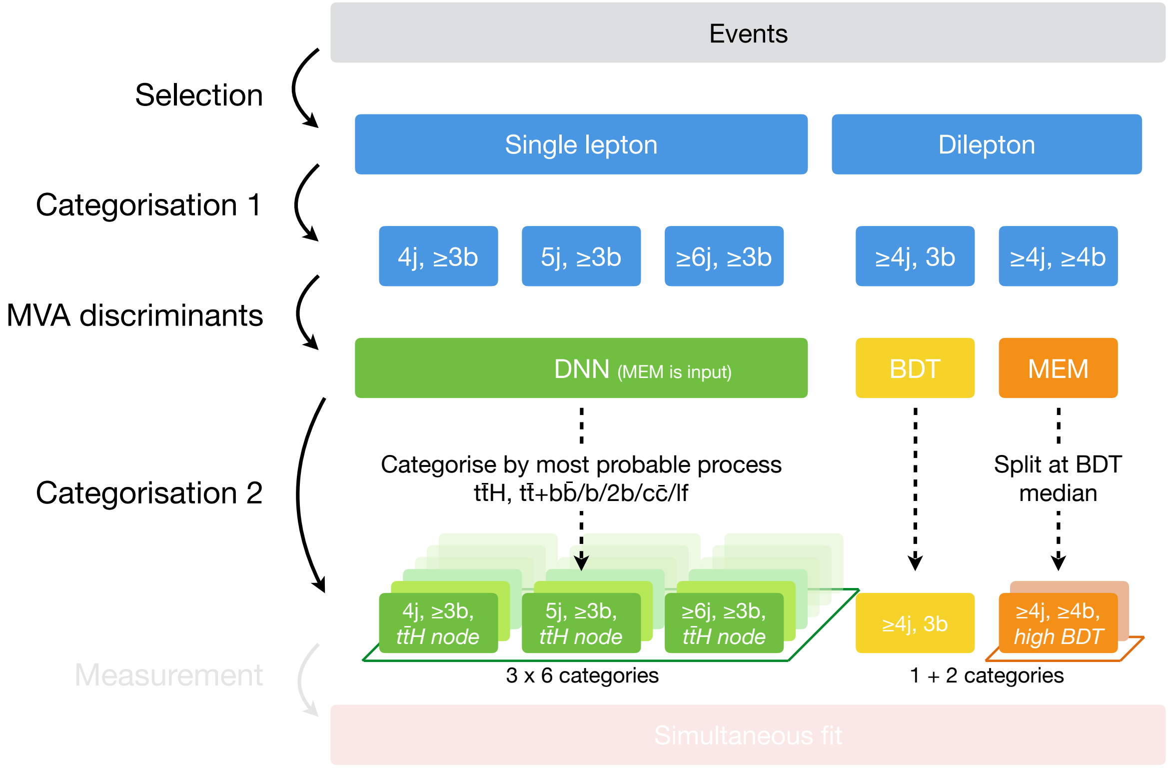
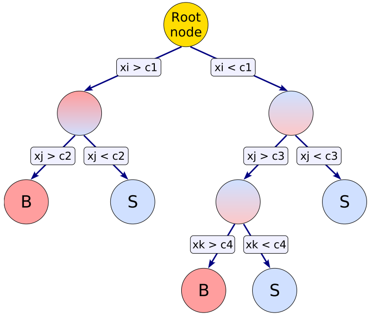


1. Selection according to **tt̄ decay channel**
2. Categorization 1: **jet** and **b-tagged jet multiplicities**
3. Categorization 2: **multivariate** classification

JHEP 03 (2019) 026

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

- **Boosted decision tree** (BDT):
  - Established supervised-learning technique
  - Robust workhorse for binary classification at the LHC



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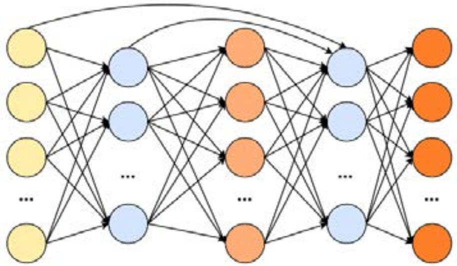
- **Deep neural network** (DNN):
  - Rather new supervised-learning technique
  - Artificial neural network with several hidden layers for **multi-classification**



M. Rieger

- **Matrix element method** (MEM):
  - Physics-motivated likelihood-ratio discriminant
  - Exploits all information from (LO) matrix element for signal/background

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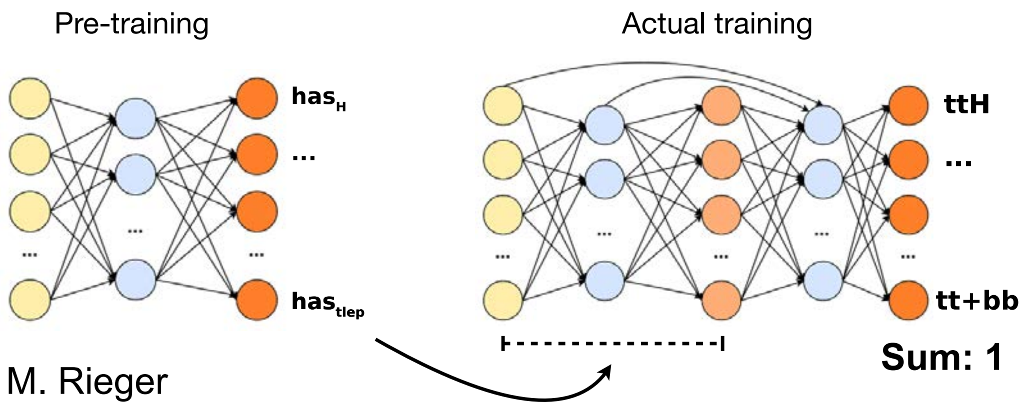
Which Multivariate Method?

- **Application** to $t\bar{t}H$ in CMS: no **single** method provided **optimal sensitivity**
  - BDT: good separation of signal and backgrounds (but: $t\bar{t}+b\bar{b}$ difficult)
  - MEM: best separation of $t\bar{t}H$ and **main irreducible background** $t\bar{t}+b\bar{b}$
  - 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 $t\bar{t}H/t\bar{t}+b\bar{b}$ separation difficult
    - Apply MEM on sample enhanced with $t\bar{t}H$ and $t\bar{t}+b\bar{b}$ → 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**: $t\bar{t}H$, $t\bar{t}+b\bar{b}$, $t\bar{t}+2b$, $t\bar{t}+b$, $t\bar{t}+c\bar{c}$, $t\bar{t}$+light flavor (lf), **normalized** with softmax activation function



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DNN Input Variables

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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 (≥ 4 jets, ≥ 4 b tags)
p_T(jet 1)	p_T of the highest-p_T jet	+	+	-	-	-
η(jet 1)	η of the highest-p_T jet	-	+	+	-	-
d(jet 1)	b tagging discriminant of the highest-p_T jet	+	+	+	-	-
p_T(jet 2)	p_T of the second highest-p_T jet	-	+	-	-	-
η(jet 2)	η of the second highest-p_T jet	+				
d(jet 2)	b tagging discriminant of the second highest-p_T jet	+				
p_T(jet 3)	p_T of the third highest-p_T jet	-				
η(jet 3)	η of the third highest-p_T jet	+				
d(jet 3)	b tagging discriminant of the third highest-p_T jet	+				
p_T(jet 4)	p_T of the fourth highest-p_T jet	+				
η(jet 4)	η of the fourth highest-p_T jet	+				
d(jet 4)	b tagging discriminant of the fourth highest-p_T jet	+				
p_T(lep 1)	p_T of the highest-p_T lepton	-	+	+	-	-
η(lep 1)	η of the highest-p_T lepton	+	-	+	-	-
d_j^{avg}	average b tagging discriminant value of all jets	+	+	+	-	-
d_b^{avg}	average b tagging discriminant value of b-tagged jets	+	+	+	+	+
$d_{non\text{-}b}^{avg}$	average b tagging discriminant value of non-b-tagged jets	-	-	-	+	+
$\frac{1}{N_b}\sum_b^{N_b}(d-d_b^{avg})^2$	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_j^{max}	maximal b tagging discriminant value of all jets	+	+	+	-	-
d_b^{max}	maximal b tagging discriminant value of b-tagged jets	+	+	+	-	-
d_j^{min}	minimal b tagging discriminant value of all jets	+	+	+	-	-
d_j^{min}	minimal b tagging discriminant value of b-tagged jets	+	+	+	-	-
d_2	second highest b tagging discriminant value of all jets	+	+	+	-	-

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 (≥ 4 jets, ≥ 4 b tags)
N_b(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	+	+	+	-	-
BLR^{trans}	transformed BLR defined as ln[BLR/(1.0 − BLR)]	+	+	+	-	-
$\Delta R^{min}_{j,j}$	ΔR between the two closest jets	+	+	+	-	-
$\Delta R^{min\Delta R}_{lep,j}$	ΔR between lepton and closest jet	+	+	-	-	-
$\Delta R^{min\Delta R}_{lep,b}$	ΔR between lepton and closest b-tagged jet	-	+	+	-	-
$m^{min\Delta R}_{lep,b}$	mass of lepton and closest b-tagged jet	+	+	+	-	-
$m^{min\Delta R}_{b,b}$	mass of closest b-tagged jets	+	+	+	-	+
$m^{min\Delta R}_{j,b}$	mass of closest jets of which at least one is b-tagged	-	-	-	+	-
$m^{max\ mass}_{b,b}$	maximal mass of pairs of b-tagged jets	-	-	-	+	+
$p_{T\,b,b}^{min\Delta R}$	combined p_T of closest b-tagged jets	-	-	-	+	-
$p_{T\,j,b}^{min\Delta R}$	combined p_T of closest jets of which at least one is b-tagged	-	-	-	-	+
m_j^{avg}	average mass of all jets	+	+	+	-	-
$(m^2)_b^{avg}$	average squared mass of all b-tagged jets	+	-	+	-	-
$m^{closest\ to\ 125}_{b,b}$	mass of pair of b-tagged jets closest to 125 GeV	-	+	+	-	-
$N^{j,b}$	number of pairs of jets (with at least one b-tagged jet) with an invariant mass within 110–140 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 (≥ 4 jets, ≥ 4 b tags)
H_T^j	scalar sum of jet p_T	-	+	-	+	-
H_T^b	scalar sum of b-tagged jet p_T	+	+	+	-	-
A^j	$\frac{3}{2}\lambda_3$ where λ_i are the eigenvalues of the momentum tensor built with jets [99]	-	+	+	-	-
	$\frac{3}{2}\lambda_3$ where λ_i are the eigenvalues of the momentum tensor …ilt with b-tagged jets [99]	+	+	+	-	-
	… divided by the sum of the energies of all jets	-	-	+	-	-
	… divided by the sum of the energies of all b-tagged jets	-	-	+	-	+
	…$_2 + \lambda_3$) where λ_i are the eigenvalues of the momentum …sor built with jets [99]	+	+	+	-	-
	…$_2 + \lambda_3$) where λ_i are the eigenvalues of the momentum …nsor built with b-tagged jets [99]	-	+	+	-	-
S_T^j	$\frac{2\lambda_2}{\lambda_2+\lambda_1}$ where λ_i are the eigenvalues of the momentum tensor built with jets [99]	+	+	+	-	-
S_T^b	$\frac{2\lambda_2}{\lambda_2+\lambda_1}$ where λ_i are the eigenvalues of the momentum tensor built with b-tagged jets [99]	+	+	+	-	-
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 [100]	-	+	-	-	-
H_3	third Fox-Wolfram moment [100]	+	+	-	-	-
H_3^b	third Fox-Wolfram moment calculated with b-tagged jets [100]	-	-	-	-	+
R_3	ratio of Fox-Wolfram moments H_3/H_0 [100]	-	-	-	+	-
H_4	fourth Fox-Wolfram moment [100]	+	-	+	-	-

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

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

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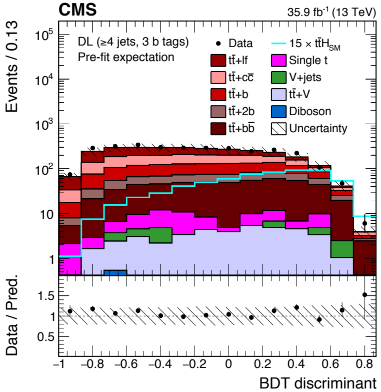
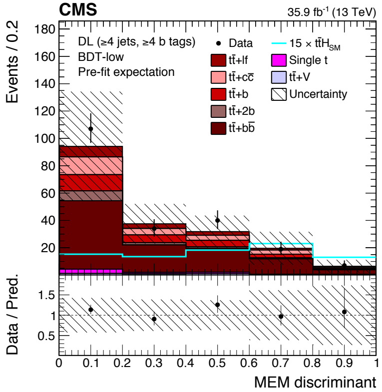
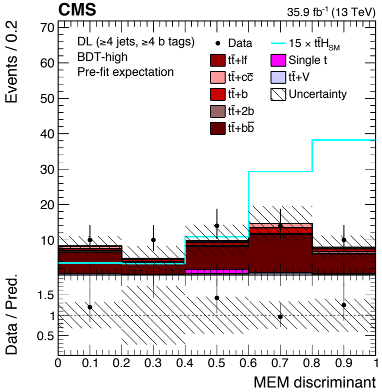
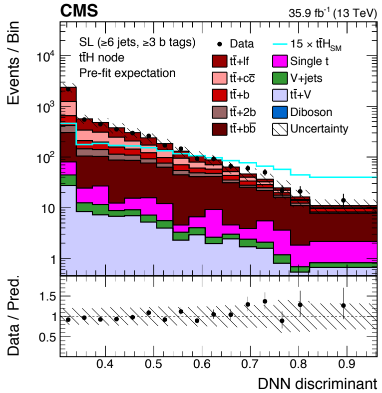
Dilepton

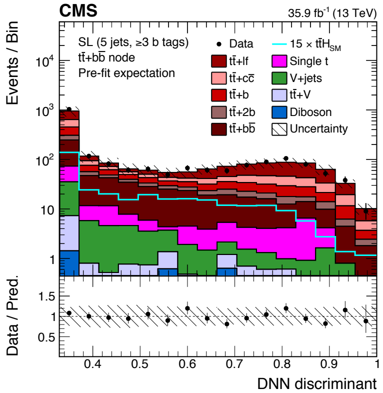


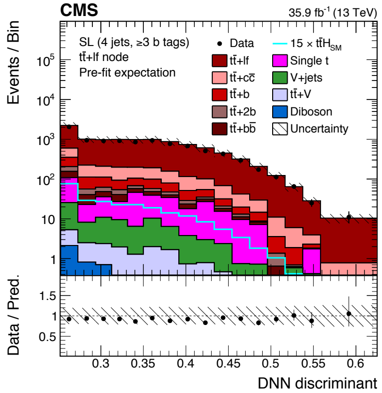


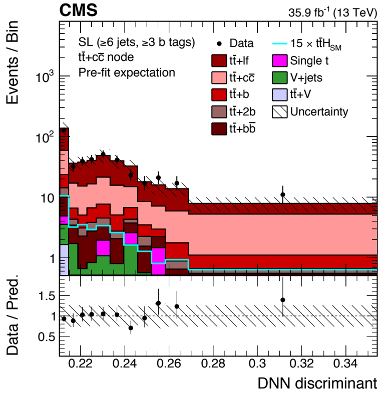


Single Lepton









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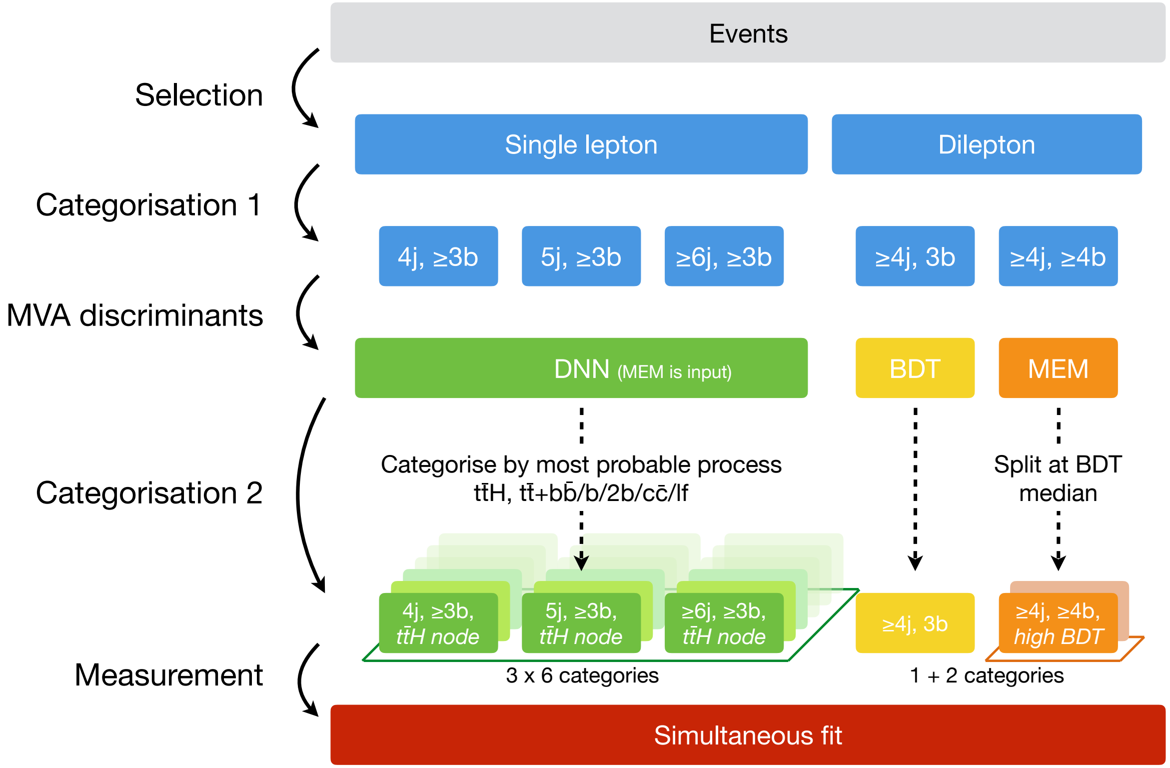
Analysis Strategy: Divide et Impera



1. Selection according to **tt̄ decay channel**
2. Categorization 1: **jet** and **b-tagged jet multiplicities**
3. Categorization 2: **multivariate** classification
4. Simultaneous profile-likelihood **fit**

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

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[JHEP 03 (2019) 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
Jet energy scale	shape	Signal and all backgrounds
Jet energy resolution	shape	Signal and all backgrounds
b tag hf fraction	shape	Signal and all backgrounds
b tag hf stats (linear)	shape	Signal and all backgrounds
b tag hf stats (quadratic)	shape	Signal and all backgrounds
b tag lf fraction	shape	Signal and all backgrounds
b tag lf stats (linear)	shape	Signal and all backgrounds
b tag lf stats (quadratic)	shape	Signal and all backgrounds
b tag charm (linear)	shape	Signal and all backgrounds
b tag charm (quadratic)	shape	Signal and all backgrounds
Renorm./fact. scales ($t\bar{t}H$)	rate	Scale uncertainty of NLO $t\bar{t}H$ prediction
Renorm./fact. scales ($t\bar{t}$)	rate	Scale uncertainty of NNLO $t\bar{t}$ prediction
Renorm./fact. scales ($t\bar{t}$+hf)	rate	Additional 50% rate uncertainty of $t\bar{t}$+hf predictions
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
PDF (gg)	rate	PDF uncertainty for gg initiated processes except $t\bar{t}H$
PDF (gg $t\bar{t}H$)	rate	PDF uncertainty for $t\bar{t}H$
PDF ($q\bar{q}$)	rate	PDF uncertainty of $q\bar{q}$ initiated processes ($t\bar{t}$+W,W,Z)
PDF (qg)	rate	PDF uncertainty of qg initiated processes (single t)
μ_R scale ($t\bar{t}$)	shape	Renormalisation scale uncertainty of the $t\bar{t}$ ME generator (POWHEG), same for additional jet flavours
μ_F scale ($t\bar{t}$)	shape	Factorisation scale uncertainty of the $t\bar{t}$ ME generator (POWHEG), same for additional jet flavours
PS scale: ISR ($t\bar{t}$)	rate	Initial state radiation uncertainty of the PS (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
PS scale: FSR ($t\bar{t}$)	rate	Final state radiation uncertainty (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
ME-PS matching ($t\bar{t}$)	rate	NLO ME to PS matching, *hdamp* [54] (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
Underlying event ($t\bar{t}$)	rate	Underlying event (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
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
Bin-by-bin event count	shape	Statistical uncertainty of the signal and background prediction due to the limited sample size

78 nuisance parameters for rate and/or shape systematic uncertainties (+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	$+0.45/-0.45$	$+0.53/-0.49$

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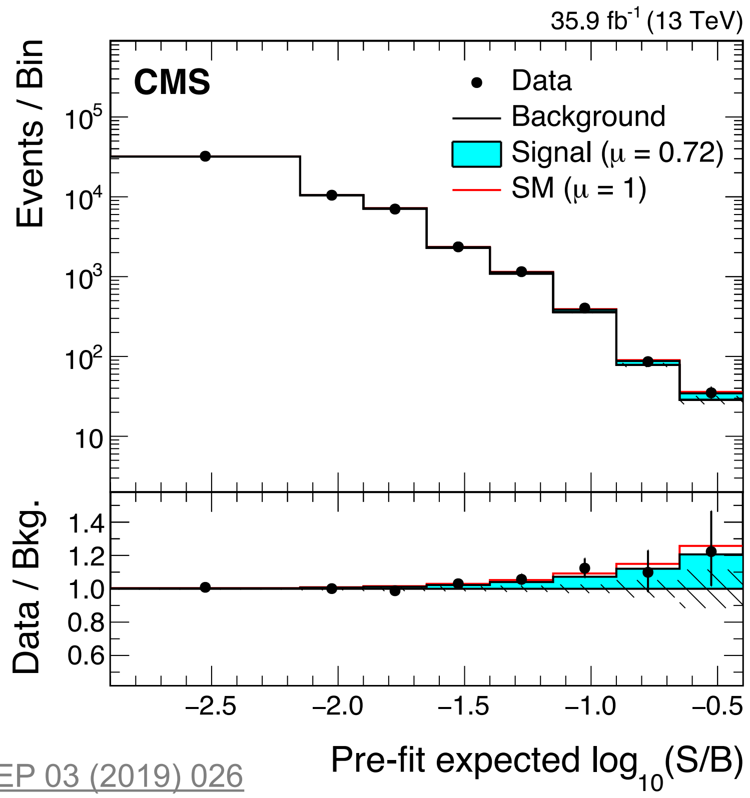
- Dominant uncertainties: b-tagging and $t\bar{t}$+heavy flavor modeling
- Procedure:
  - Fix uncertainties to post-fit values
  - Subtract obtained result in quadrature from result of full fit
- Correlations: quadratic sum ≠ total uncertainty

RESULTS AND INTERPRETATION

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



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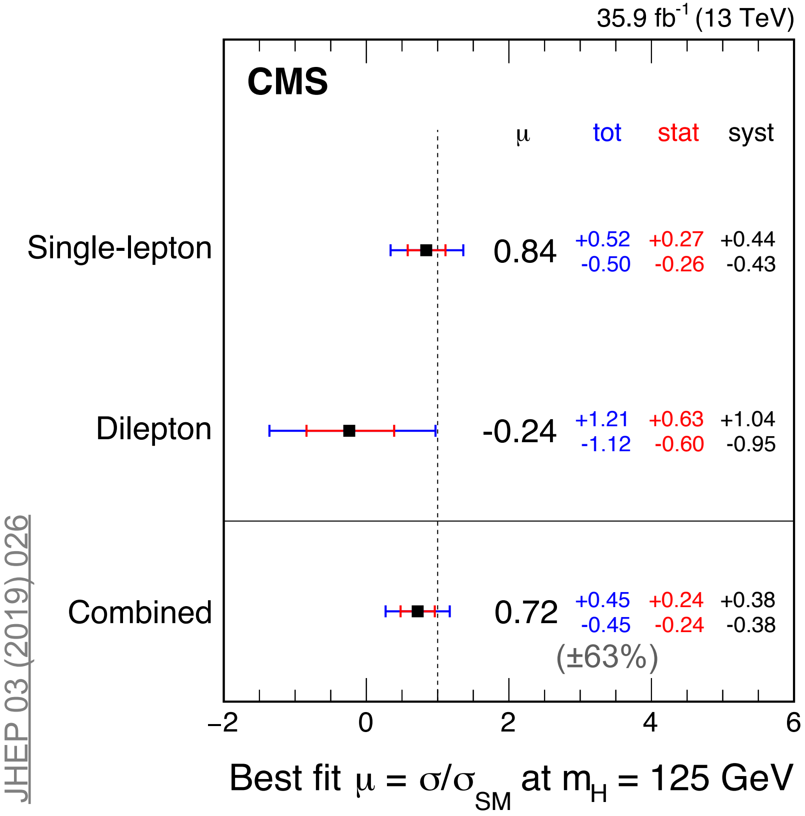
- Limits indicate **excess** above no-$t\bar{t}H$ hypothesis (not shown)
- Good illustration: sort all bins in all analysis categories by **expected signal-to-background ratio** (S/B)
- **Clear excess** in large-S/B bins

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



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- 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)

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

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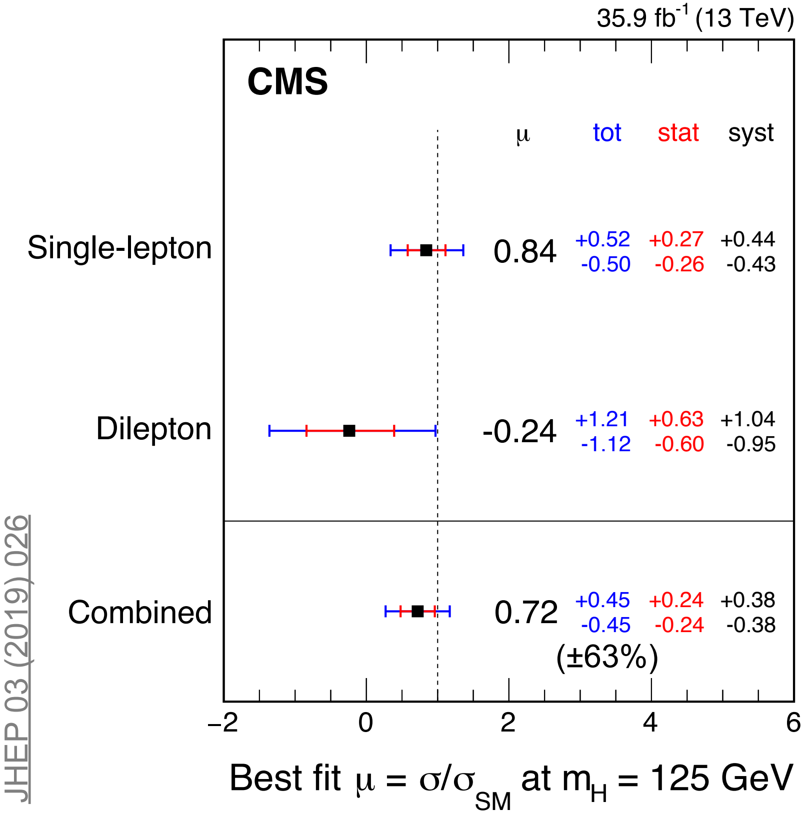

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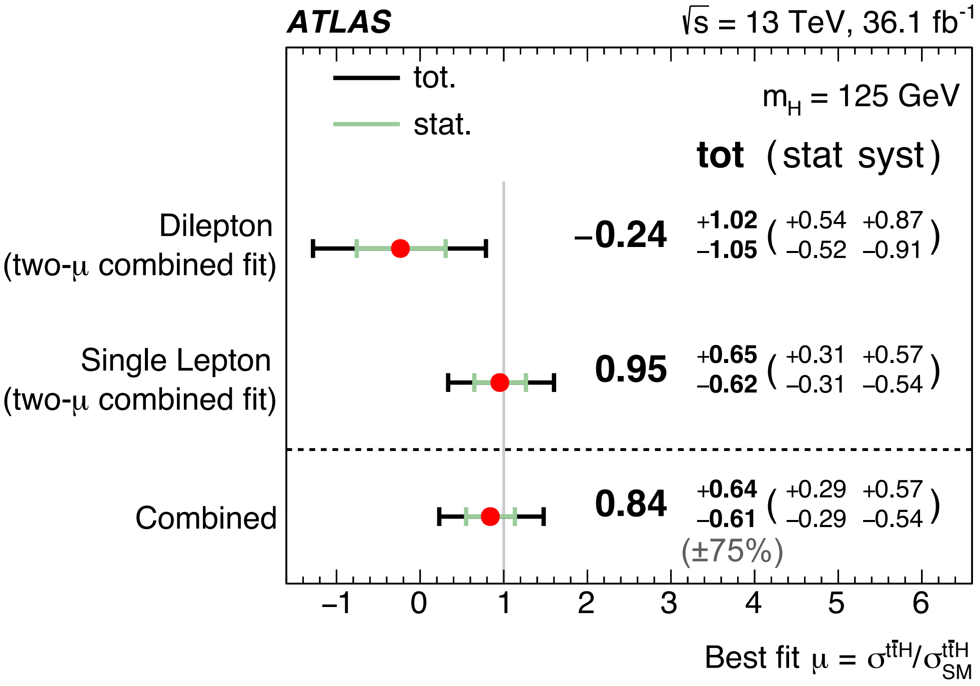

PRD 97 (2018) 072016

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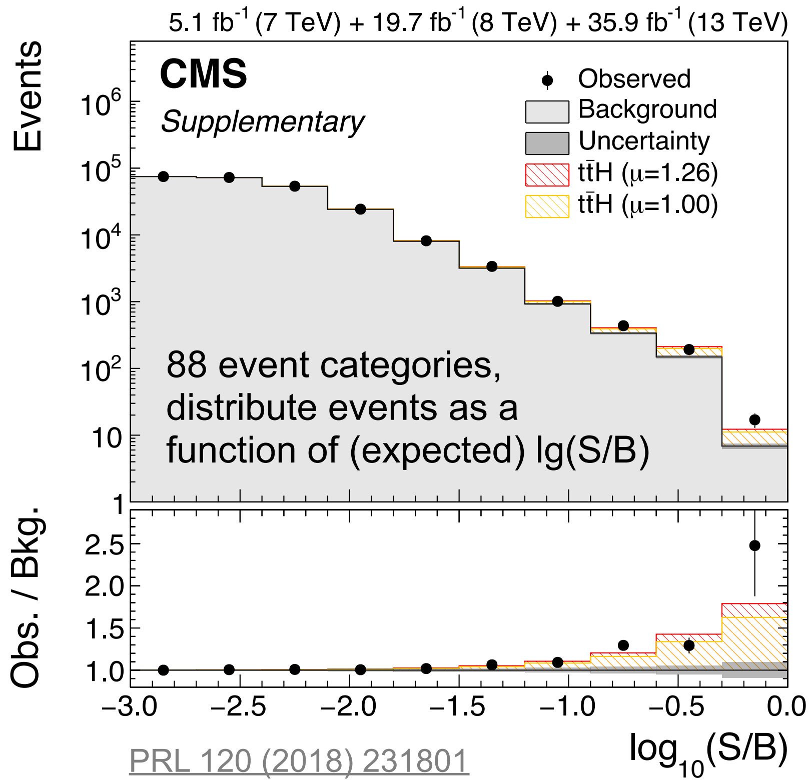
CMS $t\bar{t}H$ Combination

- 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 (JHEP 11 (2019) 185 , JHEP 11 (2017) 47, JHEP 03 (2019) 026, JHEP 06 (2018) 101, JHEP 08 (2018) 066)
  - 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



PRL 120 (2018) 231801

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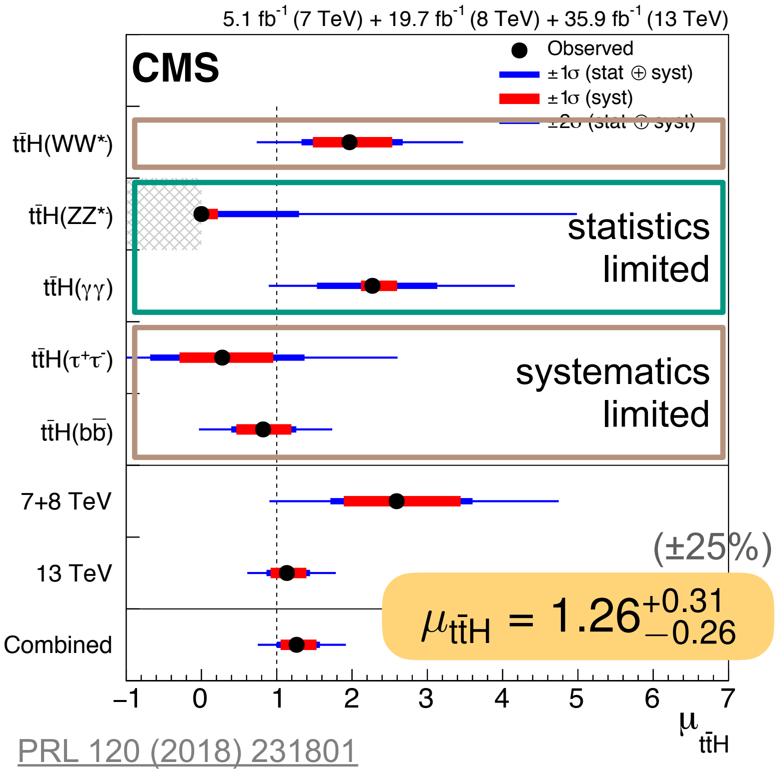
Signal Strength and Systematics



PRL 120 (2018) 231801

Systematic Uncertainties

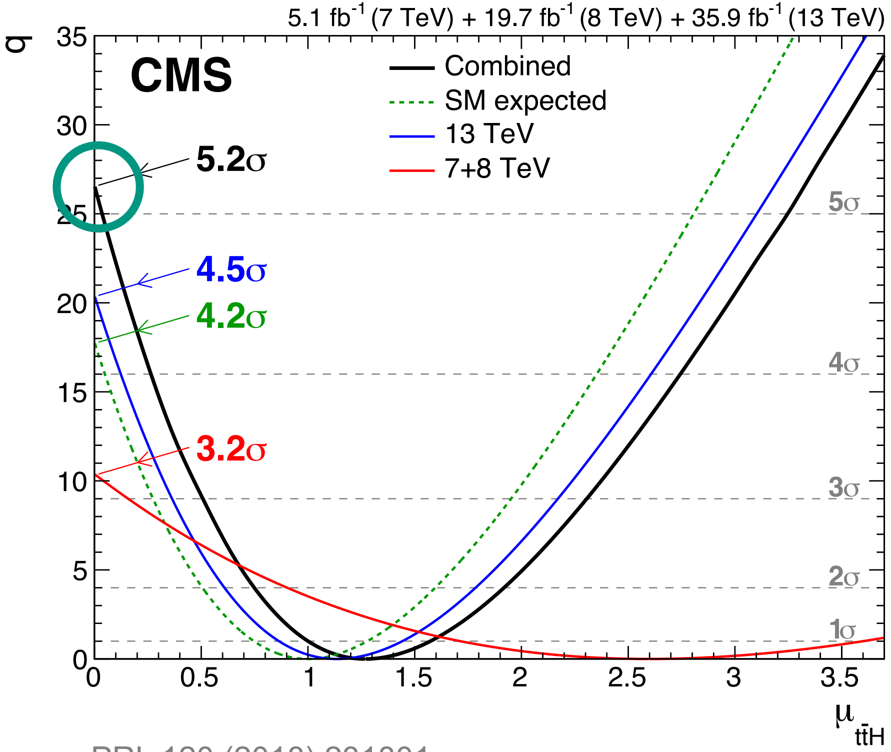
Uncertainty source	$\Delta\mu$	
Signal theory	+0.15	−0.07
Inclusive ttH normalisation (cross section and BR)	+0.15	−0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004	−0.004
Other Higgs boson production modes	+0.002	−0.003
Background theory	+0.14	−0.13
tt + bb/cc prediction	+0.13	−0.11
tt + V(V) prediction	+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

PRL 120 (2018) 231801

Correlations: sum in quadrature ≠ 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 s.d. expected)



PRL 120 (2018) 231801

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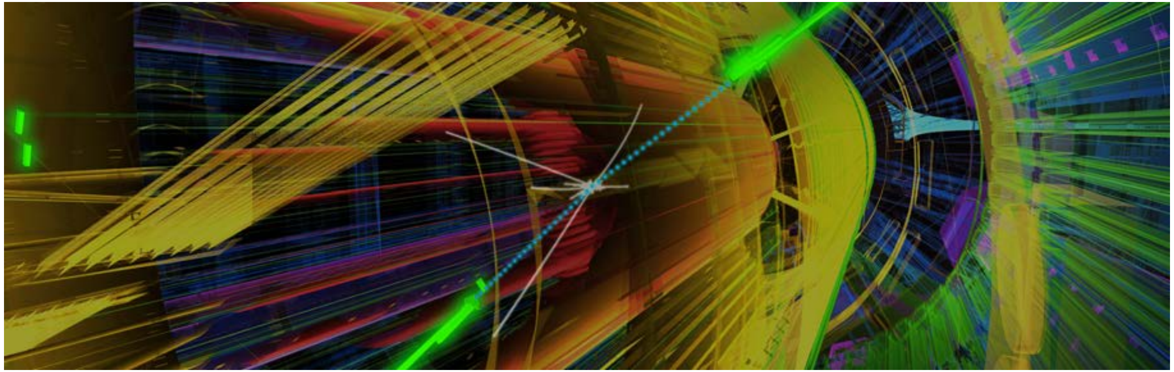
News
| 11.04.2018

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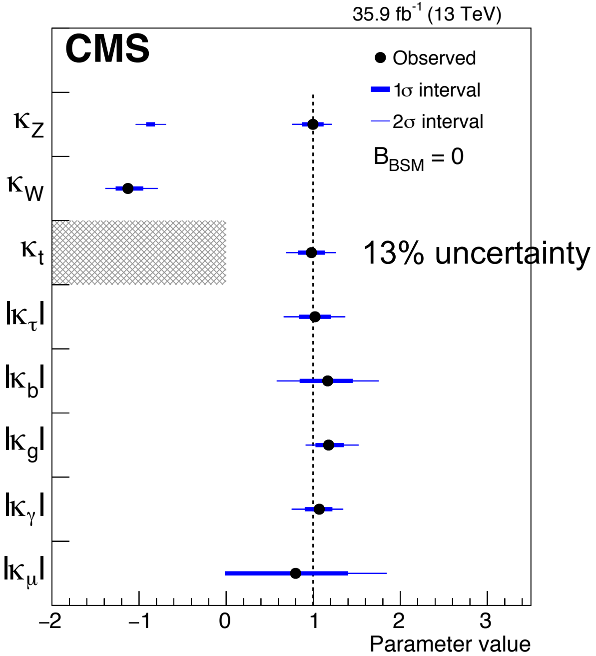
Physiker am Kernforschungszentrum CERN haben eine neue Möglichkeit entdeckt, das Higgs-Teilchen ins Leben zu rufen. Das

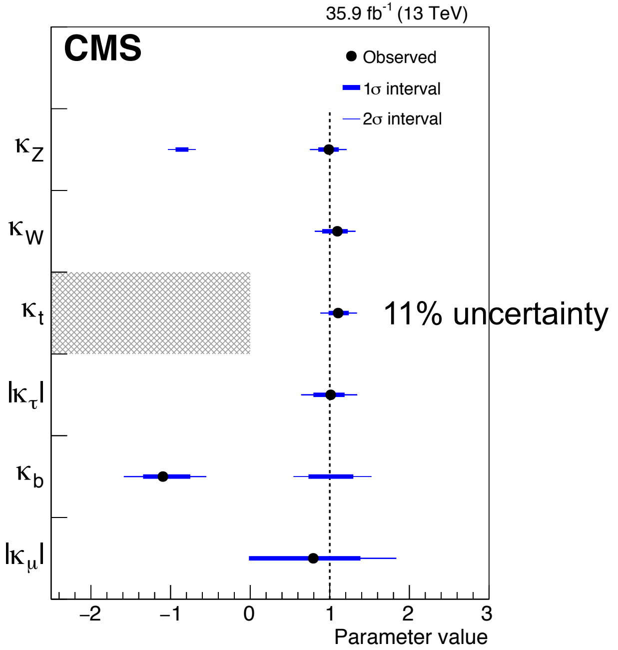
Measurement of the Top-Higgs Coupling

- CMS grand combination interpreted in "kappa framework":

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



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



arXiv:1809.10733, submitted to EPJC

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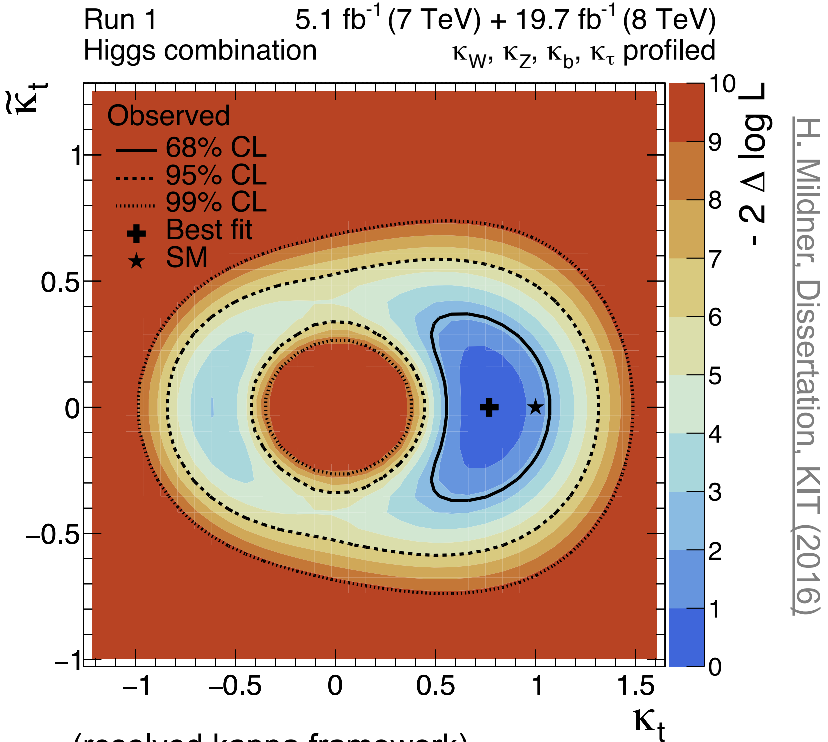
Outlook: $t\bar{t}H$ and Higgs CP State

- 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



(resolved kappa framework)

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Like a Roller Coaster

- Top 5 reasons why the quest for $t\bar{t}H$ production is like a roller coster:
  - $t\bar{t}H$ 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**!

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