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Bundesministerium
für Bildung
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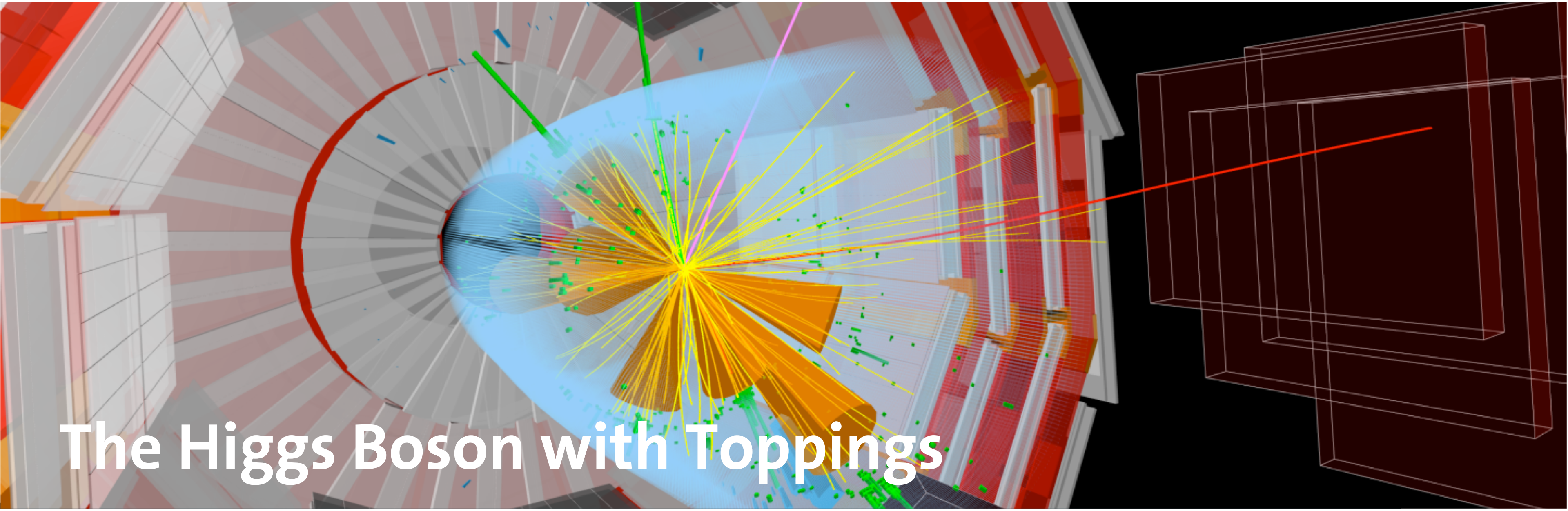
FSP CMS
Erforschung von
Universum und Materie

CMS



The Higgs Boson with Toppings

Matthias Schröder (Universität Hamburg)

LPSC Grenoble Colloquium | February 1, 2024

How do particles get mass?

Fundamental question:

If the electron was massless, there would be no stable atoms!

How do particles get mass?

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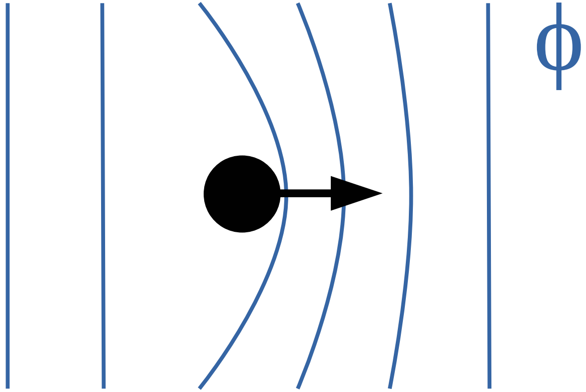
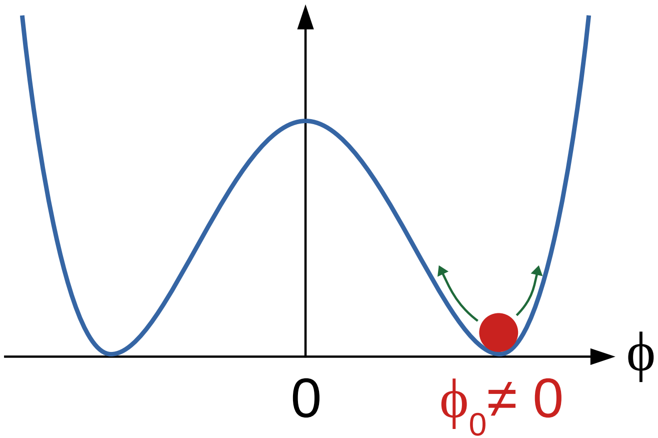


Interaction with Higgs field $\phi \rightarrow$ particle mass

The Higgs potential

$V(\phi) = \mu^2\phi^2 + \lambda\phi^4$



Universe at minimum of $V(\phi)$

Excitation of ϕ around minimum → **Higgs boson H** (necessary consequence!)

The Higgs boson: a special particle

Scalar particle (spin 0, CP even)

Couples in a unique way to other particles:

- to bosons $\propto m_V^2$
- to fermions $\propto m_f$

Once Higgs-boson mass is known:
All other properties and interactions precisely defined

Higgs boson: excellent probe of the Higgs sector and window to new physics!

Where do we stand?

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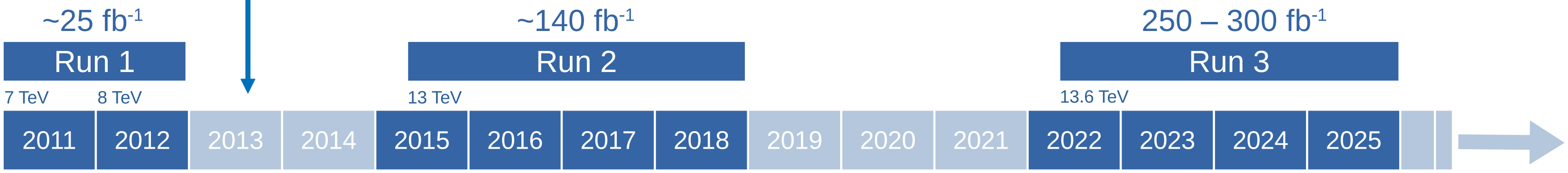
After Run 1
Properties (mass) with high precision
Decays to bosons established



Higgs boson discovery
First new partilce at the LHC!

Today
First results with Run-3 data & Run-2 „legacy results“
Increasingly differential measurements
Couplings at unprecedented precision

Couplings to 3rd generation fermions established
First observation of Yukawa interactions

Why is the top-Higgs coupling exciting?

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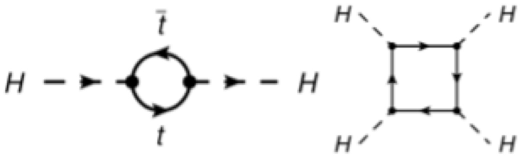
Interesting on ist own: property of the Higgs boson

Special: $y_t \approx 1$ (only „natural“ quark mass)

By far the largest Higgs-fermion coupling

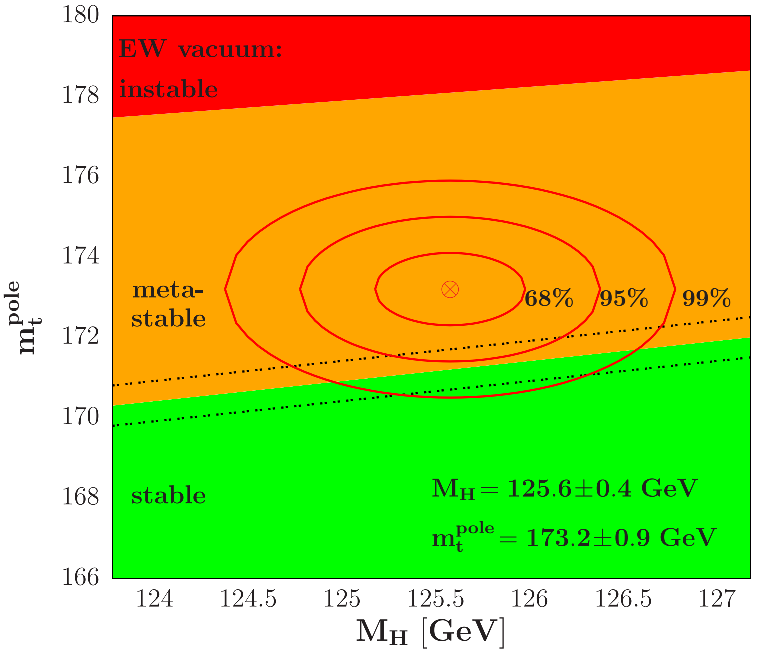
→ strong impact on SM physics

e.g. dominant contributions to quantum corrections to the Higgs-boson mass and self-coulping



Decides (in part) if the vacuum is stable!

→ strong impact on BSM physics, e.g. *fine tuning in MSSM*



Phys.Lett.B 716 (2012) 214-219

How can we measure the top-Higgs coupling?

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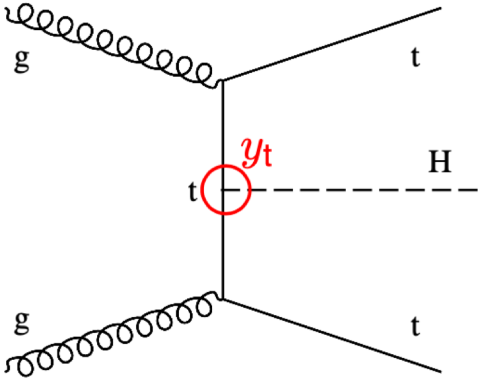


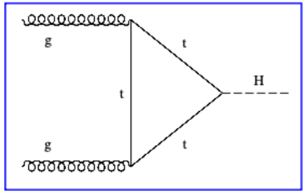
<u>**Outline:**</u>

- Experimental tools
- Indirect measurements
- Status of ttH measurements
- New ttH result with H → bb
- What is next? Future of ttH measurements

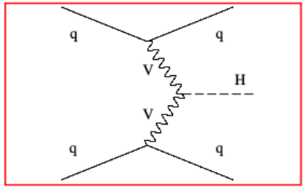
* Will focus here on CMS, but similar results by ATLAS

tt associated Higgs-boson production (ttH):
best direct probe of top-Higgs coupling

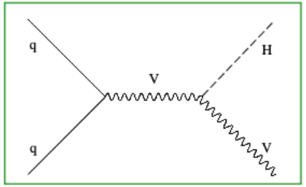
Higgs-boson production at the LHC



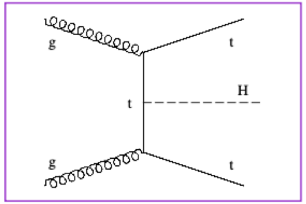
ggF: 43.9 pb (87 %)



VBF: 3.8 pb (7 %)



VH: 2.3 pb (4 %)



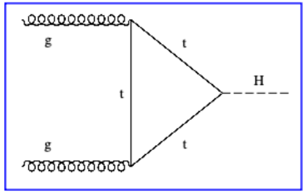
$t\bar{t}H$: 0.5 pb (1 %)

* for m_H=125 GeV at 13 TeV
[arXiv: 1610.07922]

Total production cross-section 55 pb at 13 TeV

1 Higgs boson in a billion proton-proton collisions

Higgs-boson production at the LHC



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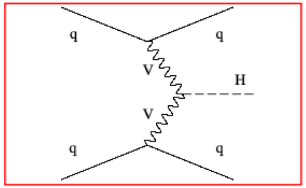

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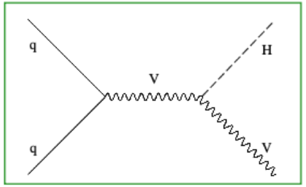

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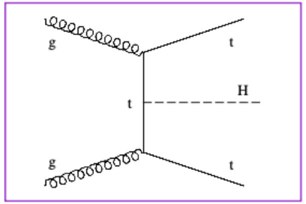

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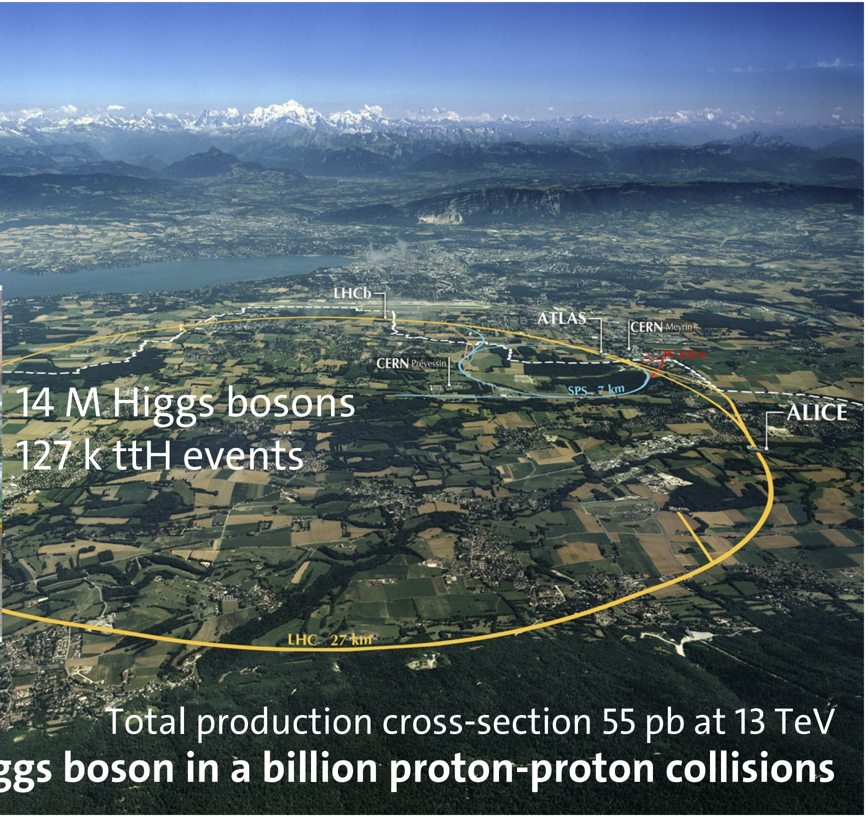
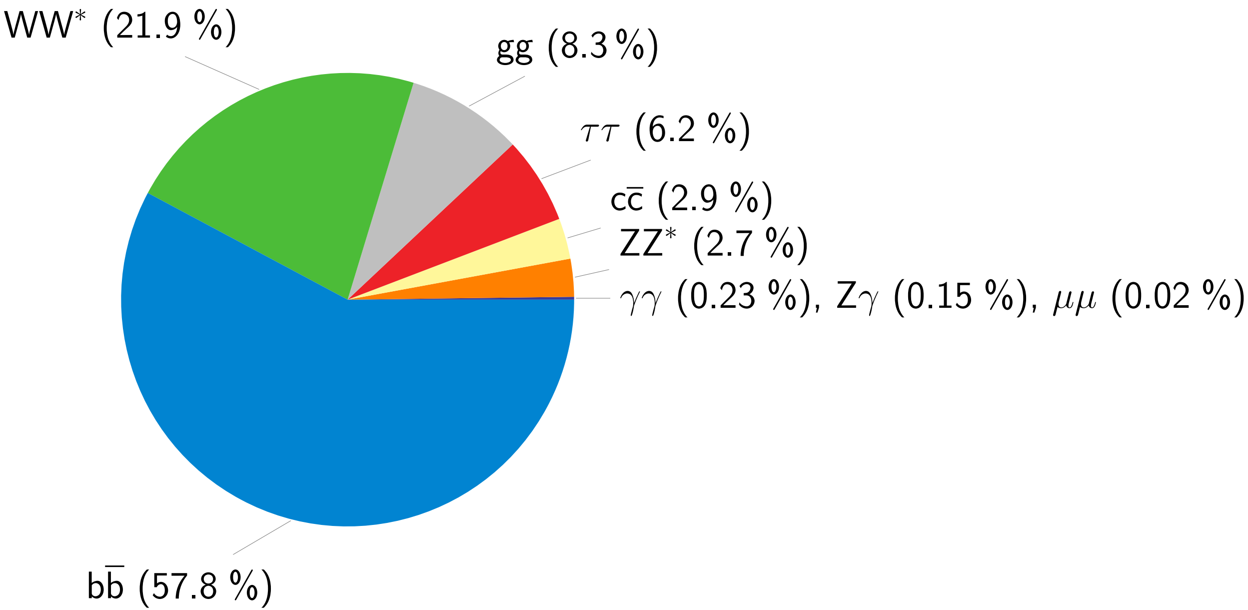


14 M Higgs bosons
127 k ttH events

Total production cross-section 55 pb at 13 TeV
1 Higgs boson in a billion proton-proton collisions

Higgs-boson decay channels

Branching ratios for m_H = 125 GeV [arXiv: 1610.07922]



Higgs-boson candidate events

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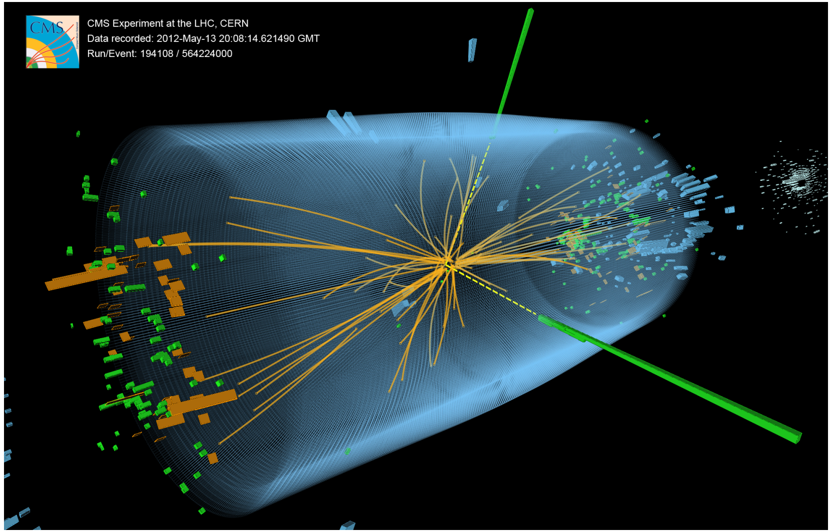
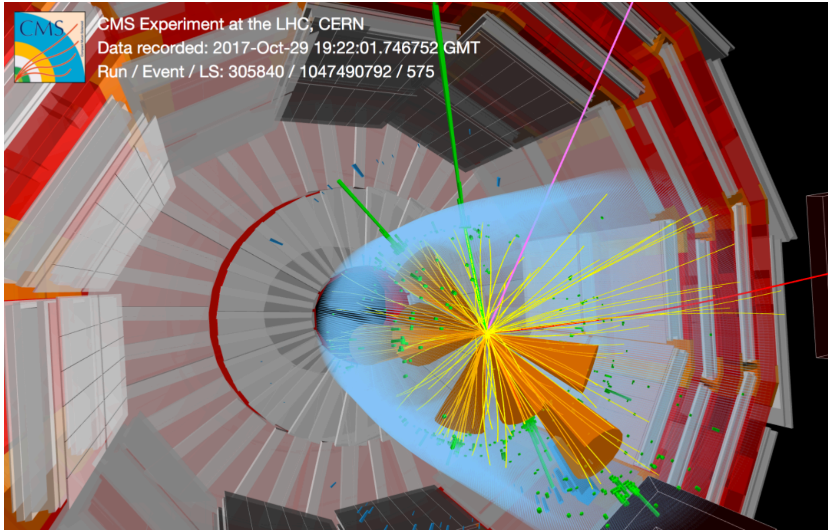
$H \to \gamma\gamma$ candidate



ttH with $H \to bb$ candidate



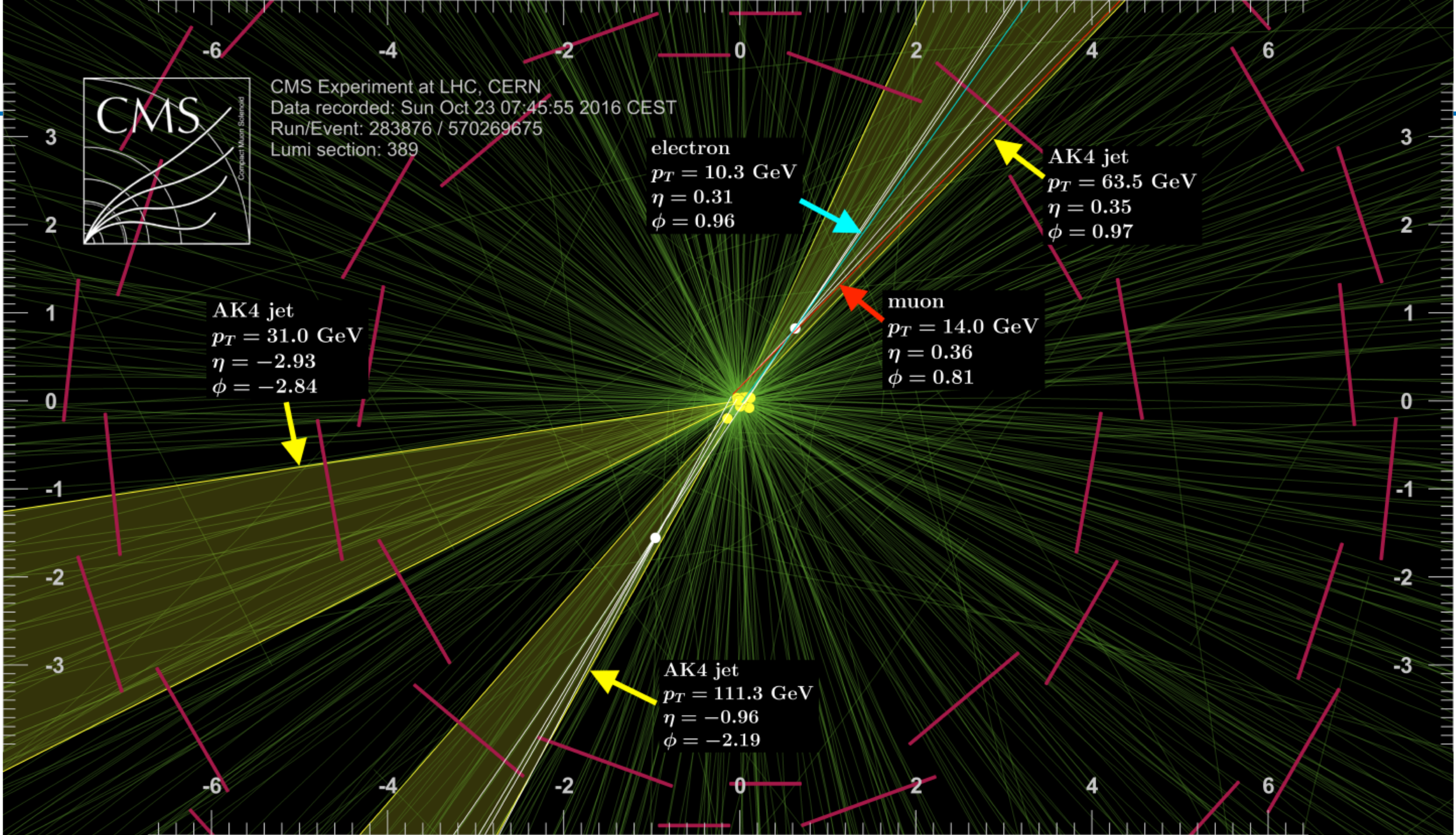
All detector components needed in Higgs analyses

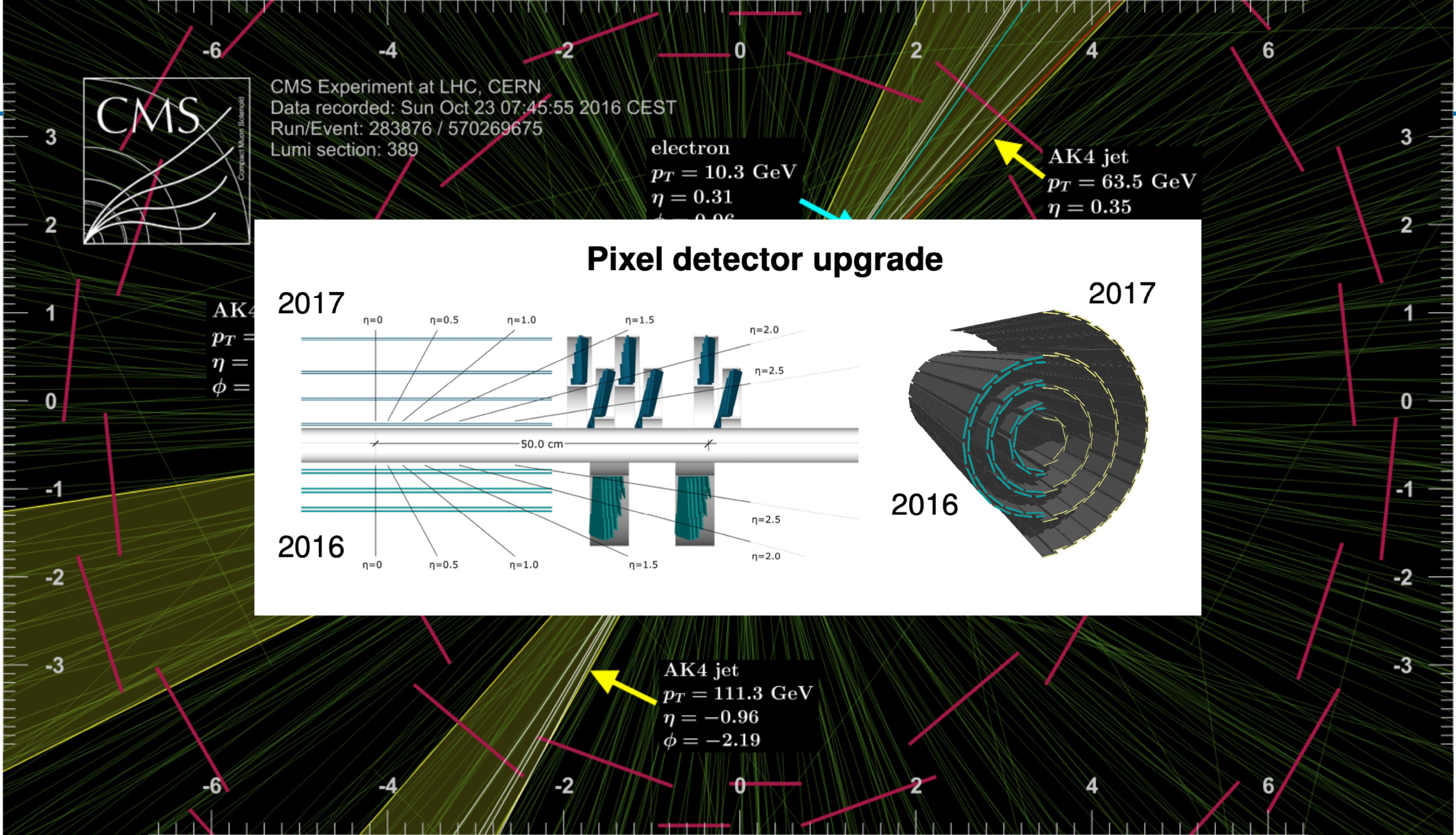
Very different signatures depending on the production and decay modes

The CMS Detector

All detector components needed in Higgs analyses

Very different signatures depending on the production and decay modes


CMS Experiment at LHC, CERN
Data recorded: Sun Oct 23 07:45:55 2016 CEST
Run/Event: 283876 / 570269675
Lumi section: 389
electron
$p_T = 10.3$ GeV
$\eta = 0.31$
$\phi = 0.96$
AK4 jet
$p_T = 63.5$ GeV
$\eta = 0.35$
$\phi = 0.97$
muon
$p_T = 14.0$ GeV
$\eta = 0.36$
$\phi = 0.81$
AK4 jet
$p_T = 31.0$ GeV
$\eta = -2.93$
$\phi = -2.84$
AK4 jet
$p_T = 111.3$ GeV
$\eta = -0.96$
$\phi = -2.19$



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$p_T = 111.3$ GeV
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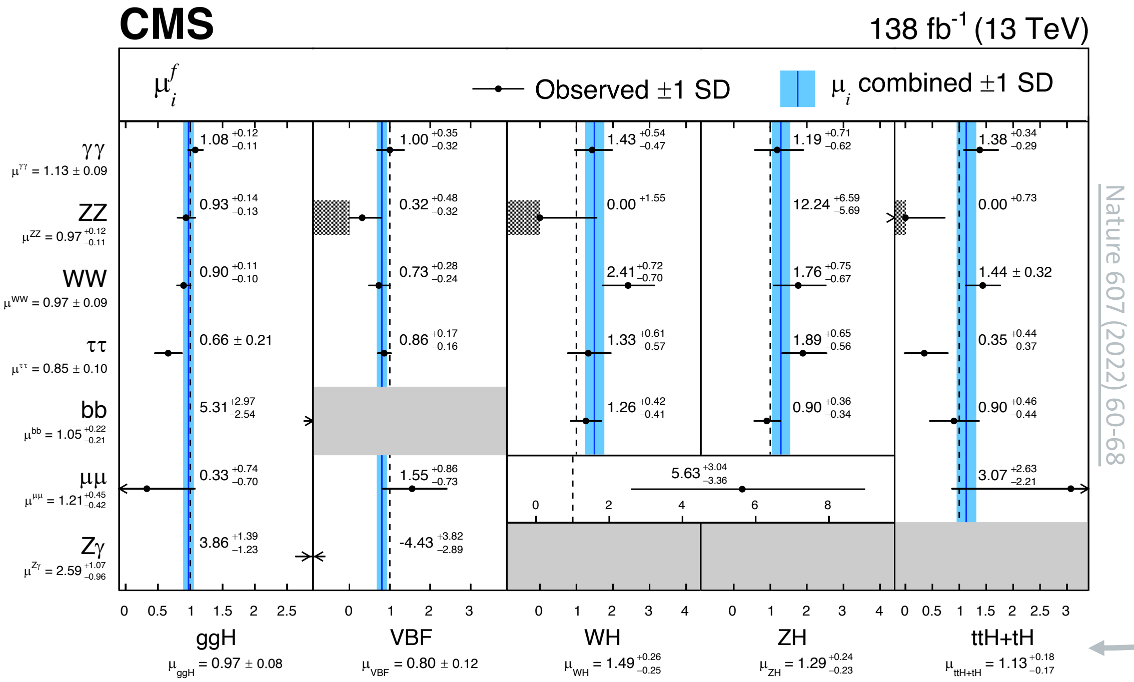
$\phi = -2.19$
Pixel detector upgrade
2017
2016
η=0
η=0.5
η=1.0
η=1.5
η=2.0
η=2.5
50.0 cm
2017
2016

Higgs boson studied from all angles

decay channels

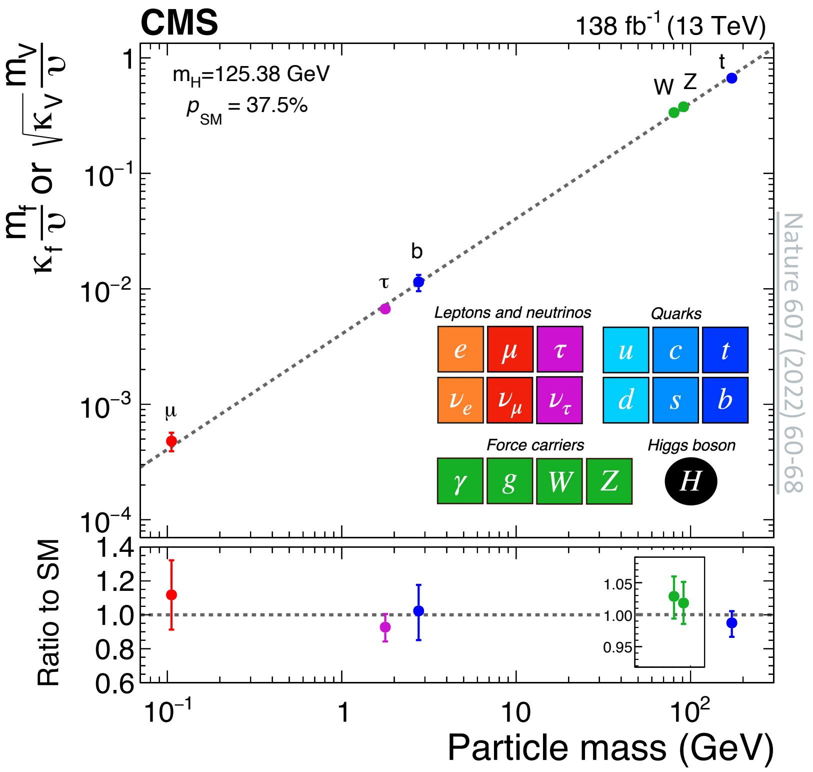


production modes

Each production x decay channel: information on **signal strength** $\mu_i^f = (\sigma_i \cdot BR^f) / (\sigma_i \cdot BR^f)_{SM}$

Combination of many measurements: information on **Higgs boson couplings**

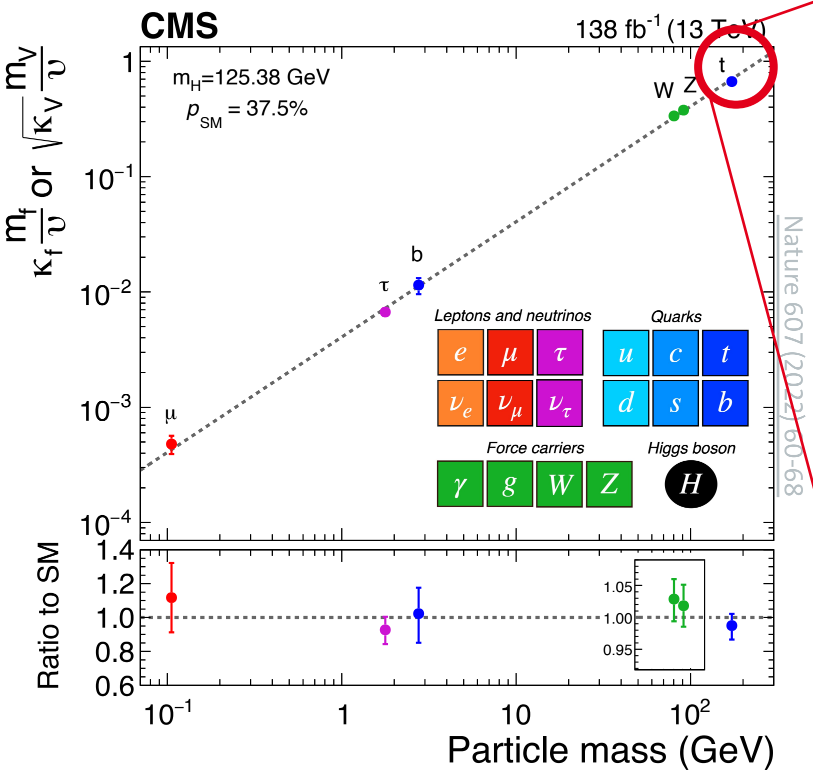
Combination of coupling measurements

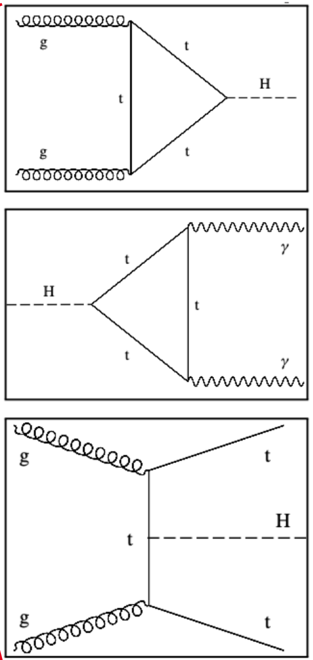


Couplings scale with particle mass

Unique characteristic of Higgs boson
expected in Standard Model

Coupling to top quarks

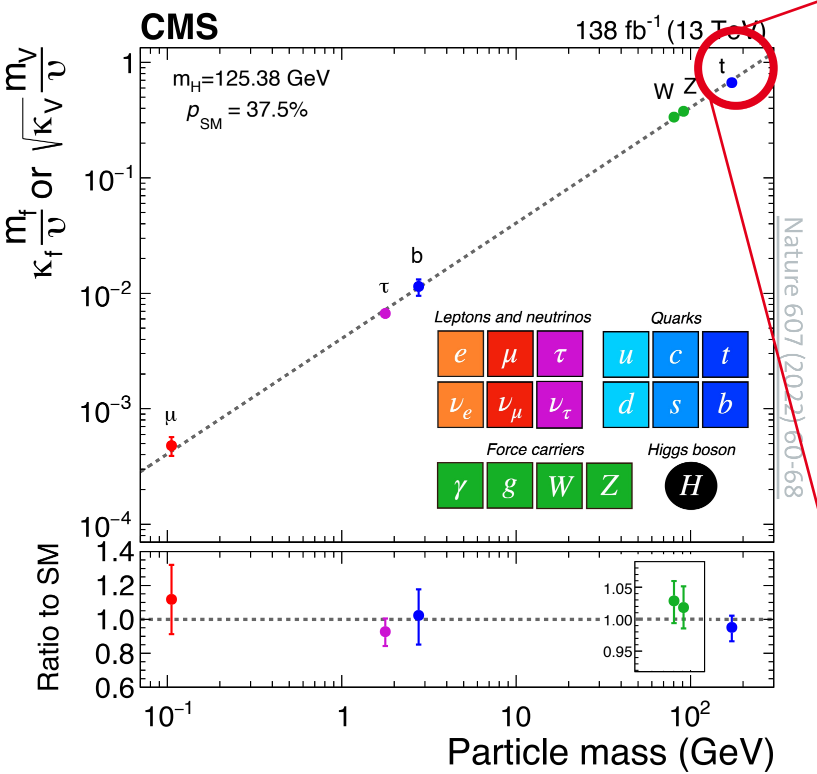


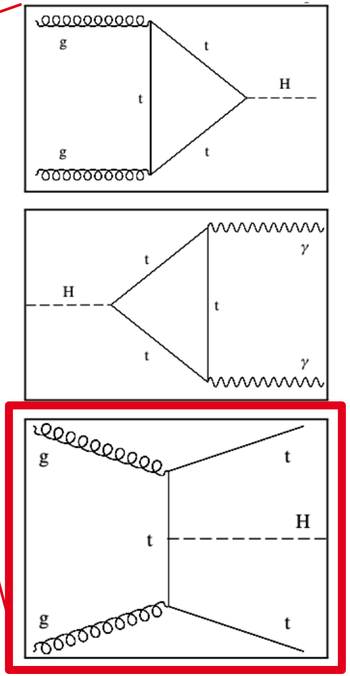


Measurement (partly) indirect
(top quark appears in loops)
→ **model dependent ***

* Indirect constraints also from 4t and tt production

Coupling to top quarks





Measurement (partly) indirect
(top quark appears in loops)
→ **model dependent** *

ttH production: direct probe of top-Higgs coupling

* Indirect constraints also from 4t and tt production

ttH measurements at the LHC

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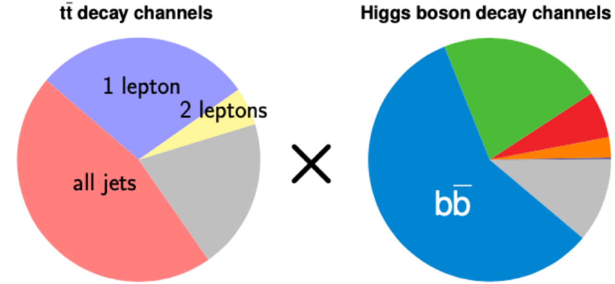
Phys. Rev. Lett. 120 (2018) 231801
Phys. Lett. B 784 (2018) 173

Small production cross-section: 0.5 pb at 13 TeV [arXiv: 1610.07922]

Multitude of possible final states with many objects



lepton: electron, muon

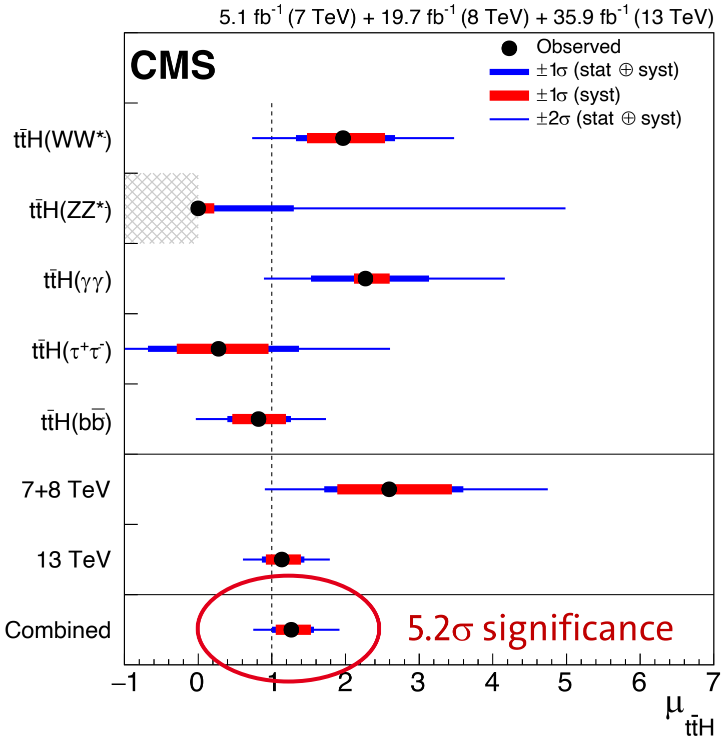
$H \to b\bar{b}$

$H \to WW^* / \tau\tau / ZZ^*$

"multi-lepton analysis"

$H \to \gamma\gamma$

$H \to ZZ^* \to 4l$



Combination of all channels:

ttH observation in 2018 by ATLAS and CMS Collaborations

Milestone in understanding fermion masses

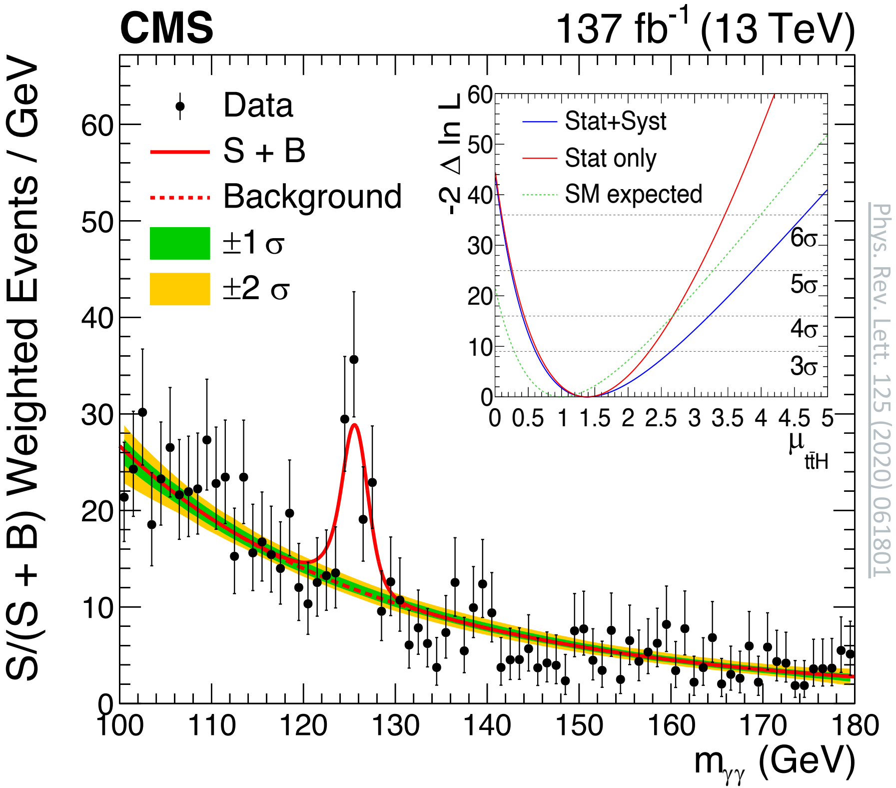
ttH measurements at the LHC: status today

channel		dataset	$\mu = \frac{\sigma}{\sigma_{\text{SM}}}$	significance	add. results	
$\text{H} \to \text{b}\bar{\text{b}}$	ATLAS	$139\,\text{fb}^{-1}$	$0.35^{+0.36}_{-0.34}$	$1.0\,\sigma$ (2.7 exp.)	STXS, CP	[JHEP 06 (2022) 097] [arXiv:2303.05974, subm. to PLB]
	CMS	$138\,\text{fb}^{-1}$	$0.33^{+0.26}_{-0.26}$	$1.3\,\sigma$ (4.1 exp.)	STXS, CP	[CMS-PAS-HIG-19-011]
$\text{H} \to \text{VV}^*/\tau\tau$	ATLAS	$80\,\text{fb}^{-1}$	$0.58^{+0.26}_{-0.25}$	$1.8\,\sigma$ (3.1 exp.)		[ATLAS-CONF-2019-045]
	CMS	$137\,\text{fb}^{-1}$	$0.92^{+0.25}_{-0.23}$	$4.7\,\sigma$ (5.2 exp.)	CP	[Eur. Phys. J. C 81 (2021) 378] [JHEP 07 (2023) 092]
$\text{H} \to \gamma\gamma$	ATLAS	$139\,\text{fb}^{-1}$	$1.43^{+0.39}_{-0.34}$	$5.2\,\sigma$ (4.4 exp.)	STXS, CP	[Phys. Rev. Lett. 125 (2020) 061802] [JHEP 07 (2023) 088]
	CMS	$137\,\text{fb}^{-1}$	$1.38^{+0.36}_{-0.29}$	$6.6\,\sigma$ (4.7 exp.)	STXS, CP	[Phys. Rev. Lett. 125 (2020) 061801] [JHEP 07 (2021) 027]
$\text{H} \to \text{ZZ}^* \to 4l$	ATLAS	$139\,\text{fb}^{-1}$	$1.7^{+1.7}_{-1.1}$	—	STXS	[Eur. Phys. J. C 80 (2020) 957]
	CMS	$137\,\text{fb}^{-1}$	$0.17^{+0.98}_{-0.17}$	—	STXS	[Eur. Phys. J. C 81 (2021) 488]

ttH results with **full Run-2 dataset** in (almost) all channels

Major improvements in sensitivity & extended interpretations

ttH with H → γγ



Phys. Rev. Lett. 125 (2020) 061801

Very clean channel:
clear signature + excellent mass resolution (1%)
→ reconstruct Higgs boson from photons

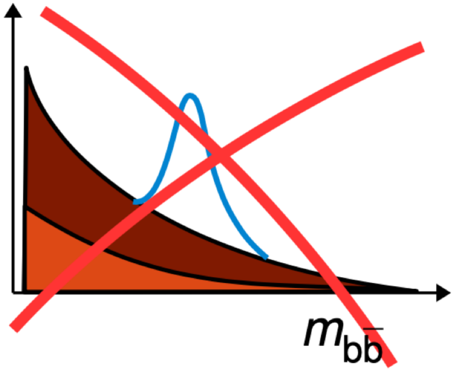
But tiny rate: limited by statistical uncertainties

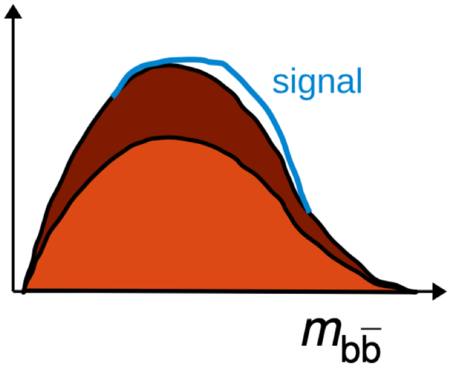
ttH with H → bb

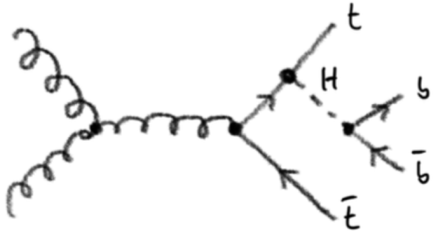
Benefit from large H → bb branching ratio of 58 %

But **challenging final state**:

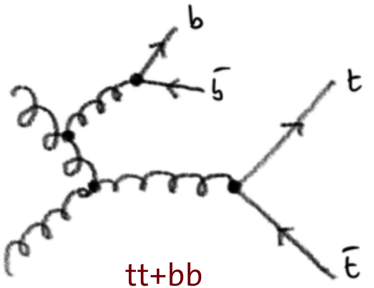
- Many jets: no unambiguous event reconstruction
- Large (irreducible) background due to tt+jets production with large uncertainties







signal



background

tt+bb
(10-20 x signal)

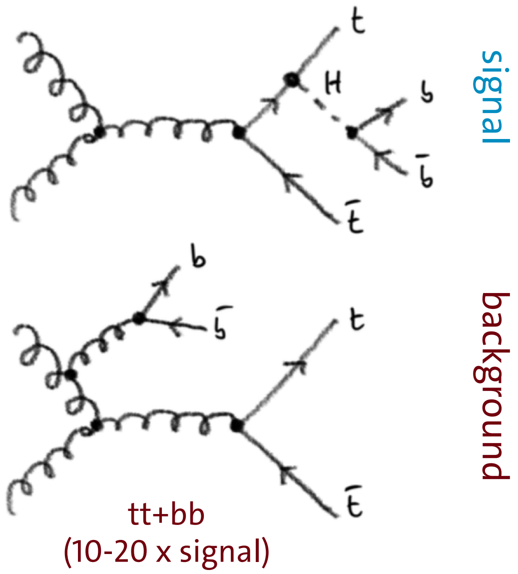
ttH with H → bb

Benefit from large H → bb branching ratio of 58 %

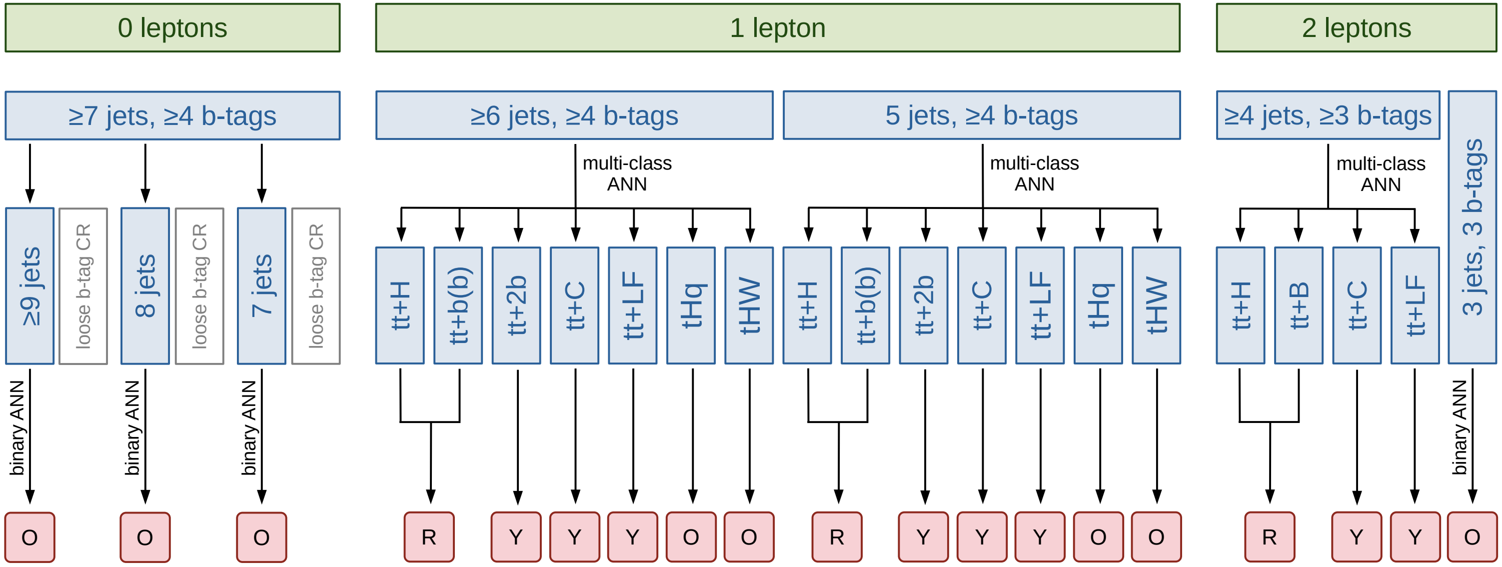
Here: new CMS result with 138 fb^{-1} of data at 13 TeV [CMS-PAS-HIG-19-011]

Channel	BR	Background
Fully hadronic (FH)	45%	QCD, tt+jets
Single lepton (SL)	30%	tt+jets
Dilepton (DL)	5%	tt+jets

Leptons: *e* or μ (no explicit τ reconstruction or veto)



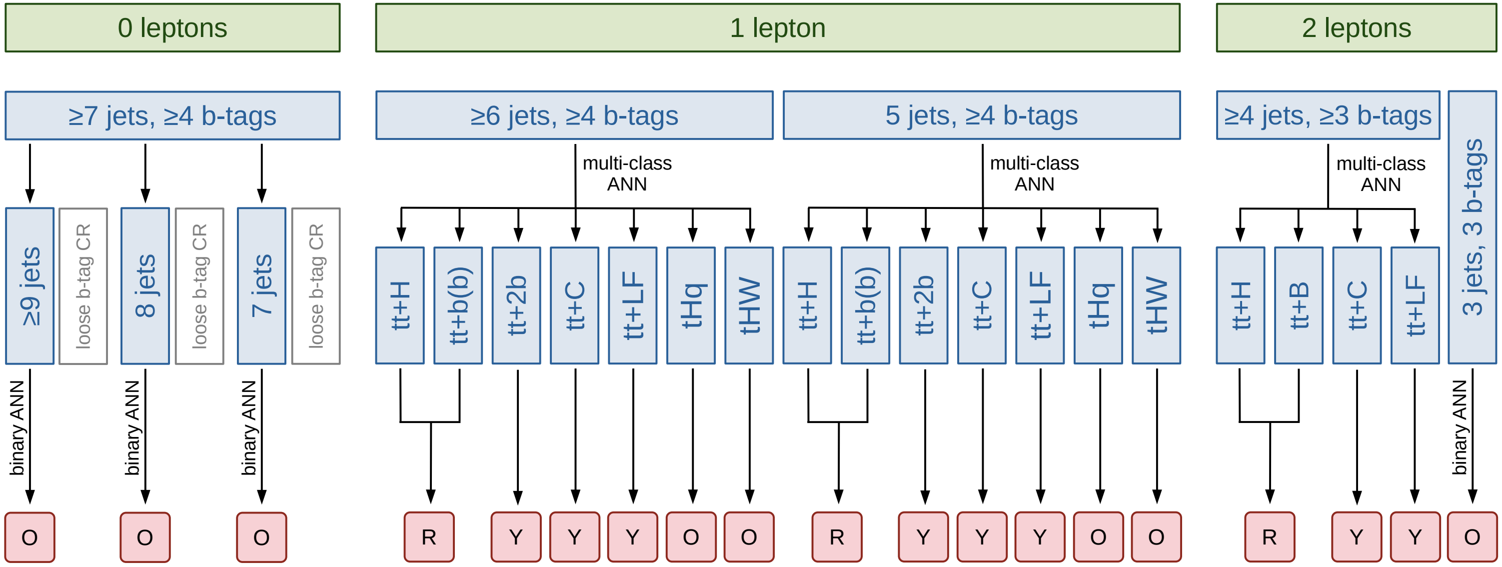
Analysis strategy



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

Analysis strategy

Categorisation by lepton multiplicity (=tt decay mode) and jets + b-tagged jets multiplicity



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

Analysis strategy

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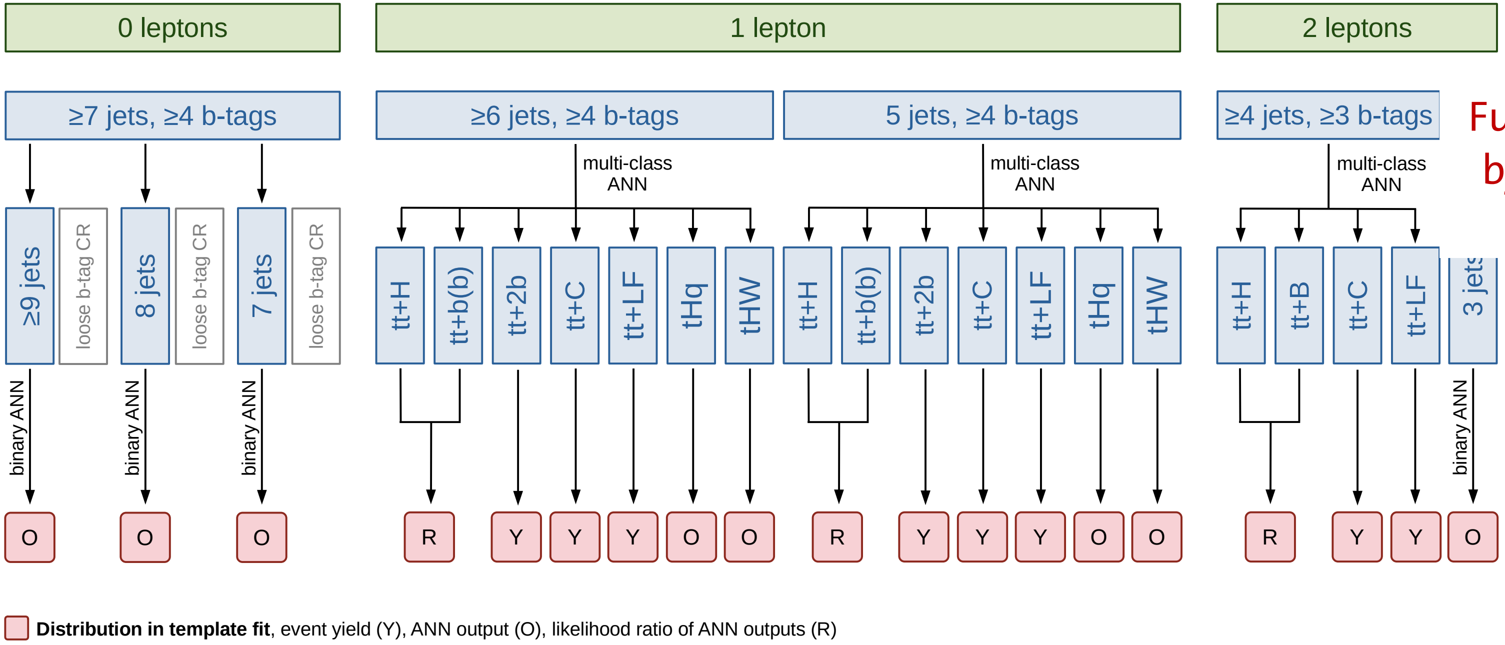
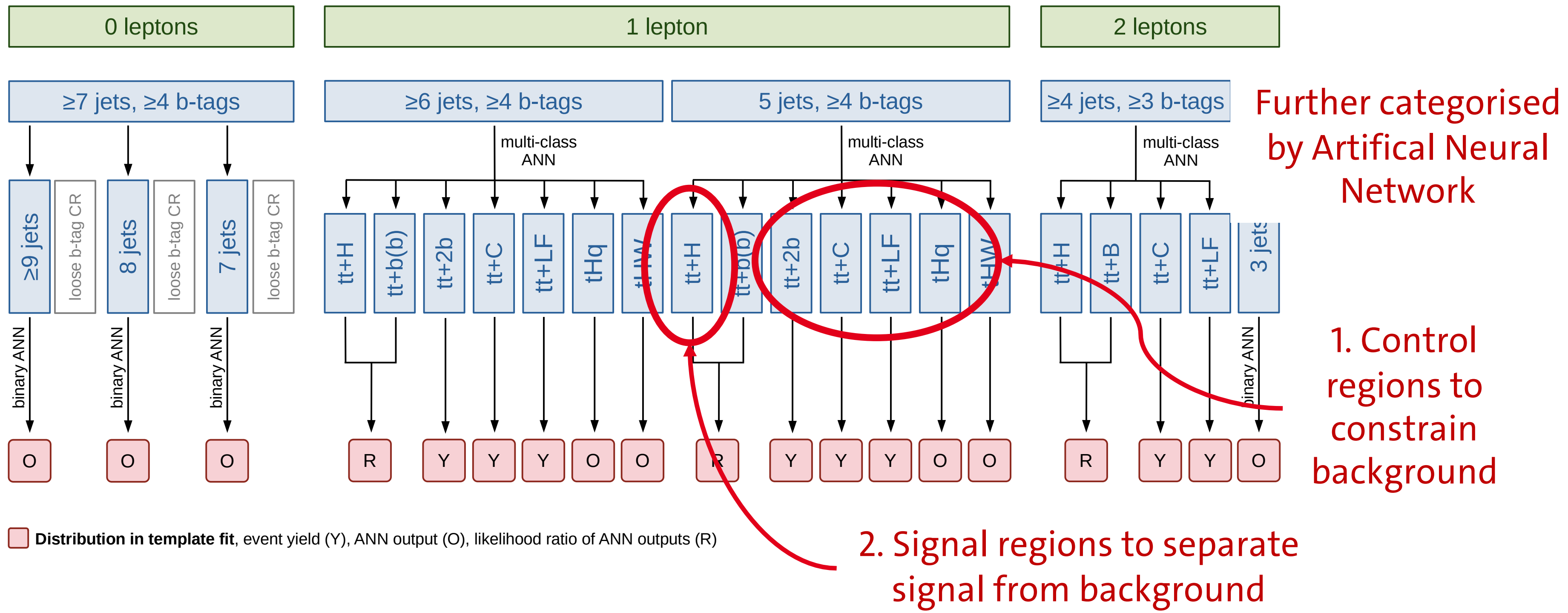
Categorisation by lepton multiplicity (=tt decay mode) and jets + b-tagged jets multiplicity



Further categorised by Artifical Neural Network

Analysis strategy

Categorisation by lepton multiplicity (=tt decay mode) and jets + b-tagged jets multiplicity



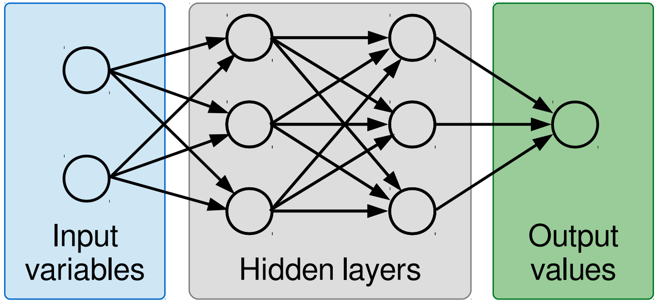
Typical machine-learning based analysis

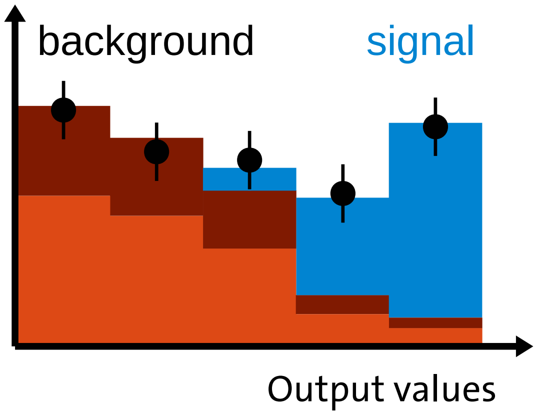
Various input variables → single discriminating observable

- Kinematic properties of jets and leptons, b-tagging information, event topology...
- Additional information from correlations

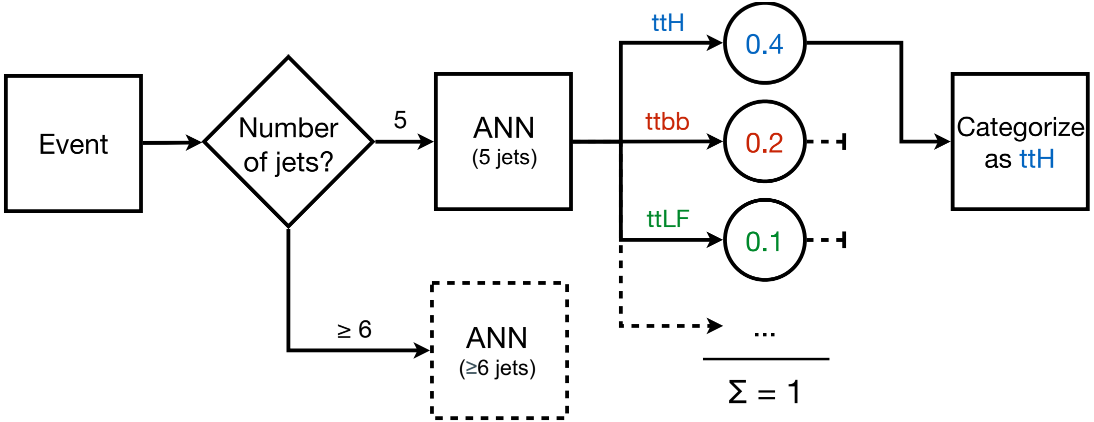
Example: Artifical Neural Network

(feed-forward fully-connected network)





Application in ttH single-lepton channel



ANN architecture

- 4 hidden layers
- 512—2048 nodes per layer
- categorical cross-entropy loss

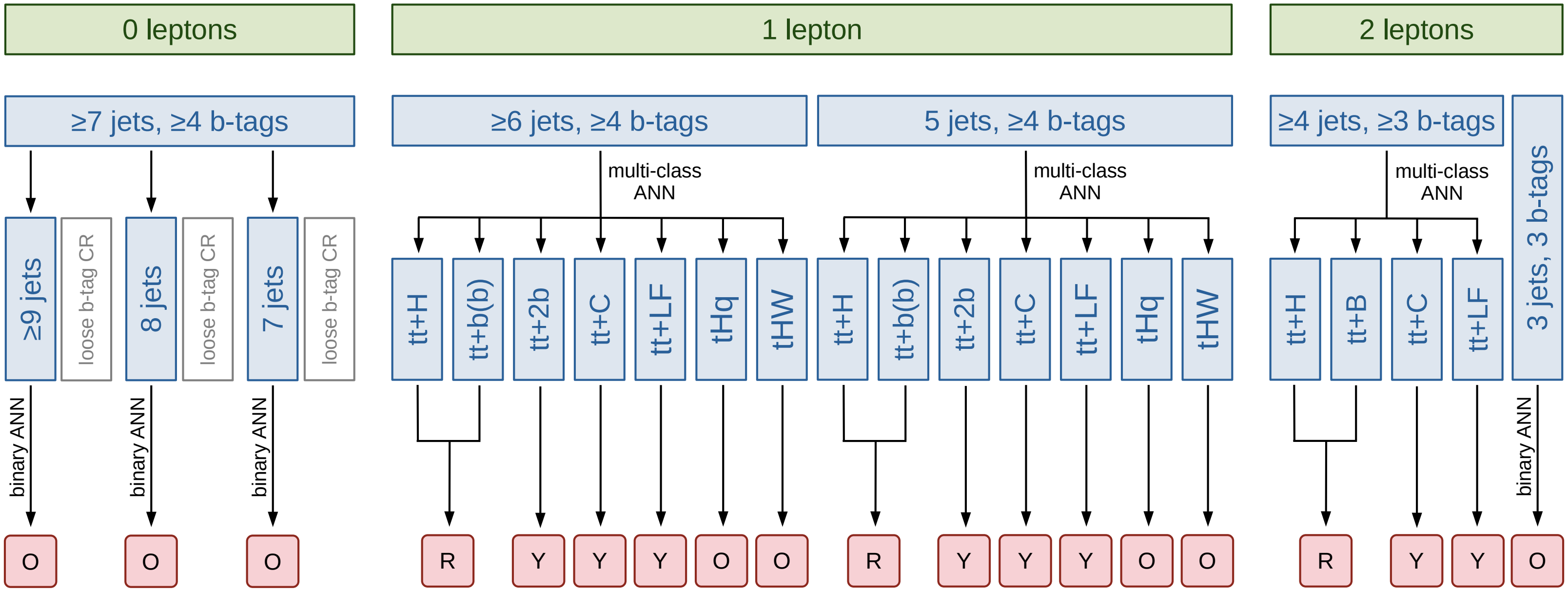
Artificial Neural Network (ANN) for **multi-classification**

Several output values: how compatible is event with certain process? → categorise

Final discriminant: constructed from ANN output in chosen process category

Typical analysis strategy nowadays at the LHC – pioneered among others by CMS ttH analyses

Analysis strategy



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

$$R_{SL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t} + b(\bar{b})) + O(t\bar{t} + 2b)}$$

Final discriminant

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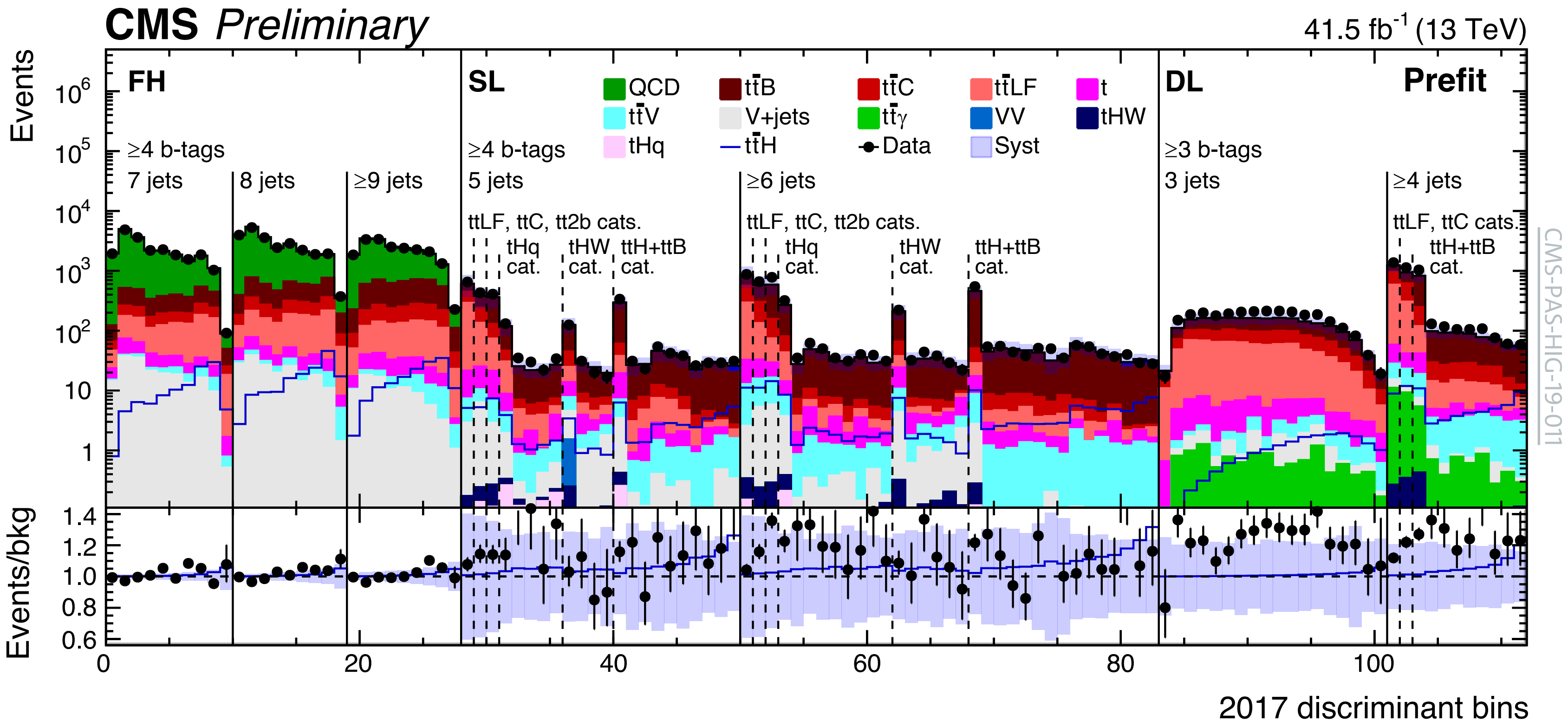
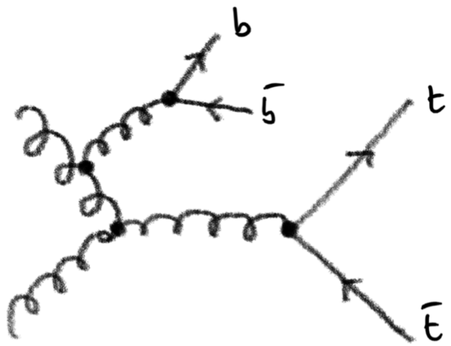


tt+bb background

tt+bb **difficult to model and to measure**

- Complex multi-parton final state
- Multiple, very different scales (bb, tt)
- Simulations typically underpredict cross section by ≈20–30% [arXiv:2309.14442, subm. to JHEP]



tt+bb background

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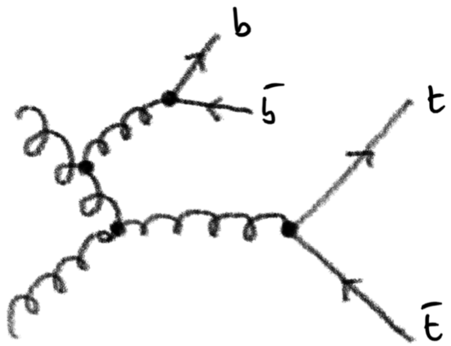
- Simulations typically underpredict cross section by ≈20–30% [arXiv:2309.14442, subm. to JHEP]



Different **approaches** to simulate events include:

- tt ME at NLO + PS g → bb splitting (5FS)
- tt+bb ME at NLO (4FS)

ME: matrix element, PS: parton shower, FS: flavour scheme

tt+bb background

tt+bb **difficult to model and to measure**

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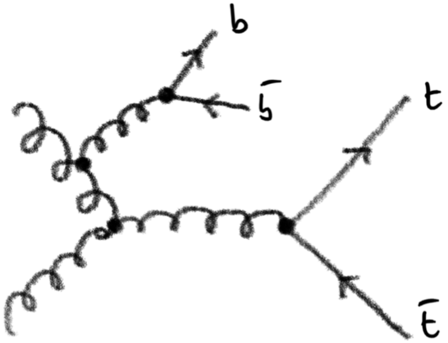

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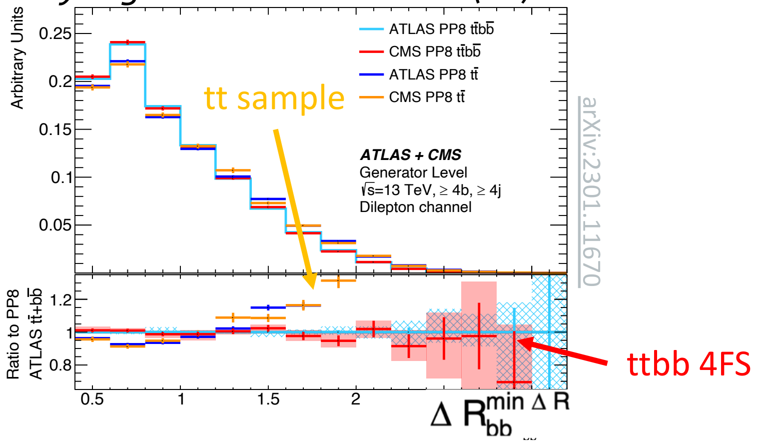
Study together with ATLAS ttH(bb) team



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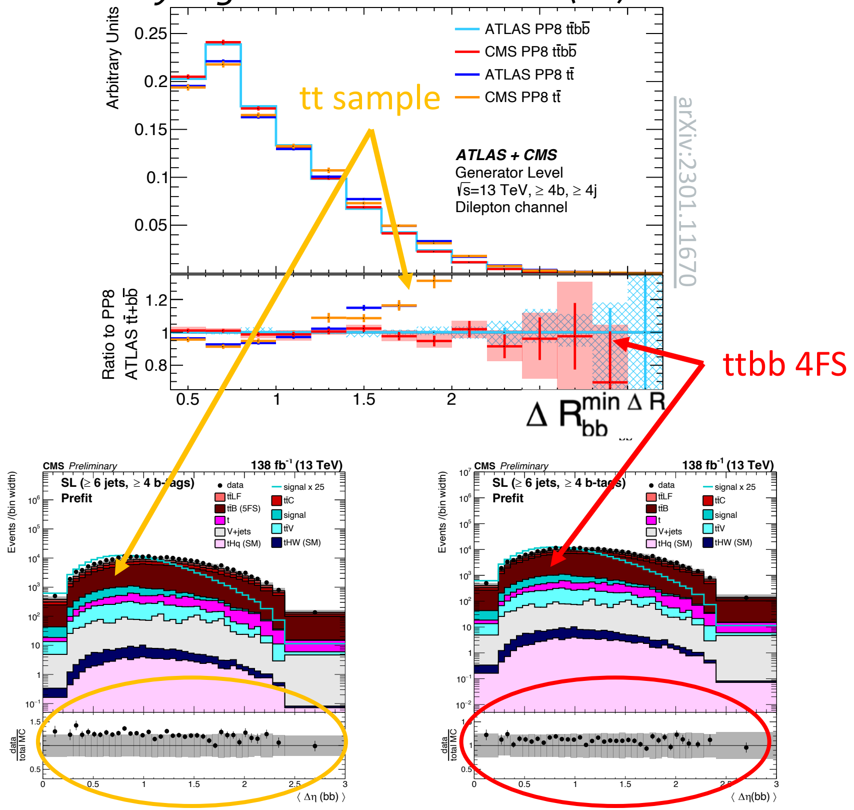

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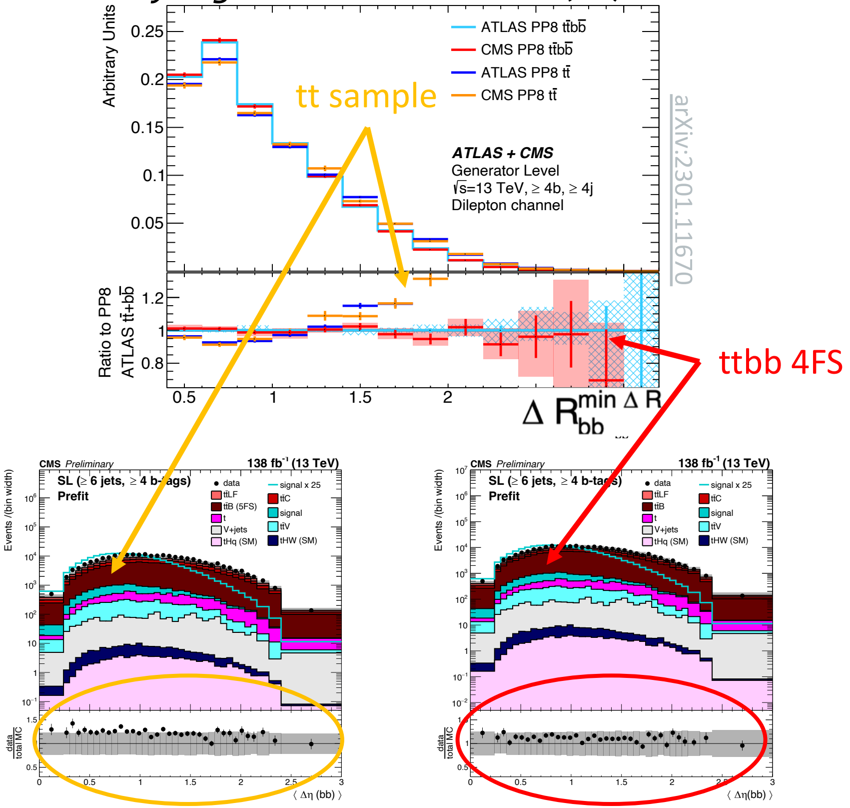
- Multiple, very different scales (bb, tt)
- Simulations typically underpredict cross section by ≈20–30% [arXiv:2309.14442, subm. to JHEP]

Major improvement in background model:

tt+bb background from new state-of-the-art Powheg ttbb 4FS simulation [Eur. Phys. J. C78 (2018) 502]

- Improved description of jet kinematics
- Embedded into Powheg tt 5FS sample to cover full phase space
- Overall tt+bb normalisation freely-floating

Study together with ATLAS ttH(bb) team



tt+bb background

Modelling uncertainties

- Freely-floating norm.
- $\mu_{R/F}$ scale
- PS scale (ISR/FSR)
- Collinear gluon-splitting
- ME-PS matching
- PDF

Model flexibility extensively **validated with pseudo experiments**

	mean value ± RMS		
$t\bar{t}B$ component in pseudo data	$\mu_{t\bar{t}H}$	$t\bar{t}B$ norm	$t\bar{t}C$ norm
tt+bb cross section in toy data increased by 20%	[illegible]	1.01 ± 0.09	1.01 ± 0.18
ttbb sample, $t\bar{t}B \times 1.2$	1.03 ± 0.32	1.21 ± 0.15	1.01 ± 0.18
tt+bb in toy data from different generator	$: 0.30$	1.03 ± 0.11	0.77 ± 0.18
tt sample, $t\bar{t}B \times 1.2$	1.06 ± 0.32	1.18 ± 0.12	0.85 ± 0.20

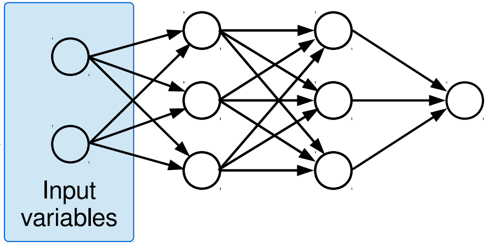
Injected signal strength (1.0) and background normalisation (1.2) recovered

Are the ANN inputs well-modelled?

	Observable	FH (≥ 9 jets, ≥ 4 b tags)	FH (8 jets, ≥ 4 b tags)	FH (7 jets, ≥ 4 b tags)	SL (≥ 6 jets, ≥ 4 b tags)	SL (5 jets, ≥ 4 b tags)	DL (≥ 4 jets, ≥ 3 b tags)	DL (3 jets, 3 b tags)
MEM	matrix element method discriminant	✓	✓	✓	✓	✓	✓	
BLR	b tagging likelihood ratio discriminant						✓	
$\ln\left(\frac{\mathrm{BLR}}{1-\mathrm{BLR}}\right)$	transformed b tagging likelihood ratio discriminant				✓	✓		
$p_T(j^2)$	p_T of second leading jet, ranked in p_T						✓	
$p_T(j^3)$	p_T of third leading jet, ranked in p_T							✓
$p_T(j^7)$	p_T of seventh leading jet, ranked in p_T	✓						
$p_T(b^i)$	p_T of i^{th}, $i=1$–4, leading b-tagged jet, ranked in p_T						✓	
$\eta(j^i)$	η of i^{th}, $i=1$–2, leading jet, ranked in b tagging discriminant value	✓	✓	✓				
$\langle d_b(j)\rangle$	average b tagging discriminant value of all jets				✓	✓		
$\langle d_b(b)\rangle$	average b tagging discriminant value of all b-tagged jets				✓	✓		
$d_b^3(j)$	third highest b tagging discriminant value of all jets				✓	✓		
$\mathrm{Var}(d_b(j))$	variance of b tagging discriminant values of all jets				✓	✓		
$\langle \Delta R(bb)\rangle$	average of ΔR between two b-tagged jets						✓	
$\langle \Delta R(jj)\rangle$	average of ΔR between two jets	✓	✓					
$\min \Delta R(jj)$	minimum of ΔR between two jets		✓	✓				✓
$\max \Delta R(jj)$	maximum of ΔR between two jets	✓	✓	✓				
$\langle \Delta\eta(bb)\rangle$	average of $\Delta\eta$ between two b-tagged jets				✓	✓		
$\langle \Delta\eta(jj)\rangle$	average of $\Delta\eta$ between two jets	✓	✓	✓	✓	✓		
$\langle m(b)\rangle$	average invariant mass of all b-tagged jets				✓	✓		
$\langle m(j)\rangle$	average invariant mass of all jets				✓	✓		
$m(bb_{\min \Delta R})$	invariant mass of pair of b-tagged jets closest in ΔR				✓	✓	✓	
$m(jb_{\min \Delta R})$	invariant mass of pair of jet and b-tagged jet closest in ΔR						✓	
$m(jj_{125\,\mathrm{GeV}})$	invariant mass of pair of jets with mass closest to 125 GeV	✓						
$m(bb_{\max m})$	maximum invariant mass of pairs of b-tagged jets	✓	✓				✓	✓
$m(jbb_{\max p_T})$	invariant mass of jet and pair of b-tagged jets with highest p_T						✓	
$\langle p_T(j)\rangle$	average p_T of all jets				✓	✓		
$\langle p_T(b)\rangle$	average p_T of all b-tagged jets				✓	✓		
$p_T(bb_{\min \Delta R})$	p_T of pair of b-tagged jets closest in ΔR				✓	✓	✓	✓
$p_T(jj_{\min \Delta R})$	p_T of pair of jets closest in ΔR							✓
$p_T(jb_{\min \Delta R})$	p_T of pair of jet and b-tagged jet closest in ΔR							✓
$H_T(j)$	scalar sum of p_T of all jets				✓	✓	✓	
$H_T(b)$	scalar sum of p_T of all b-tagged jets				✓	✓	✓	
$N(j)$	number of jets				✓			
$N(b^{\mathrm{loose}})$	number of jets with loose b tag						✓	
$d_b(b_{\mathrm{top}}^{\mathrm{tHW}})^{\dagger}$	b tagging discriminant value of b jet from t quark decay from tHW reconstruction				✓	✓		
$\lvert\eta(q^{\mathrm{tHq}})\rvert^{\dagger}$	$\lvert\eta\rvert$ of light-quark jet from tHq reconstruction				✓	✓		
$m(t_{\mathrm{lep}}^{\mathrm{t\bar{t}H}})^{\dagger}$	inv. mass of leptonically decaying t quark from $t\bar{t}H$ reconstruction				✓	✓		
$\mathrm{BDT}^{i\dagger}$	reconstruction BDT output for tHq, $t\bar{t}H$, $t\bar{t}$ hypotheses				✓	✓		
A, S	event aplanarity and sphericity [76]	✓	✓	✓				
H_i^{FW}	i^{th}, $i=0$–5, Fox–Wolfram moment [77]	✓	✓	✓				
$H_i^{\mathrm{FW}}/H_0^{\mathrm{FW}}$	ratio of Fox–Wolfram moments, $i=1$–4	✓	✓	✓				

Supervised learning with simulated data:
rely on MC simulation of observables and their correlations

Are the ANN input variables well modelled?

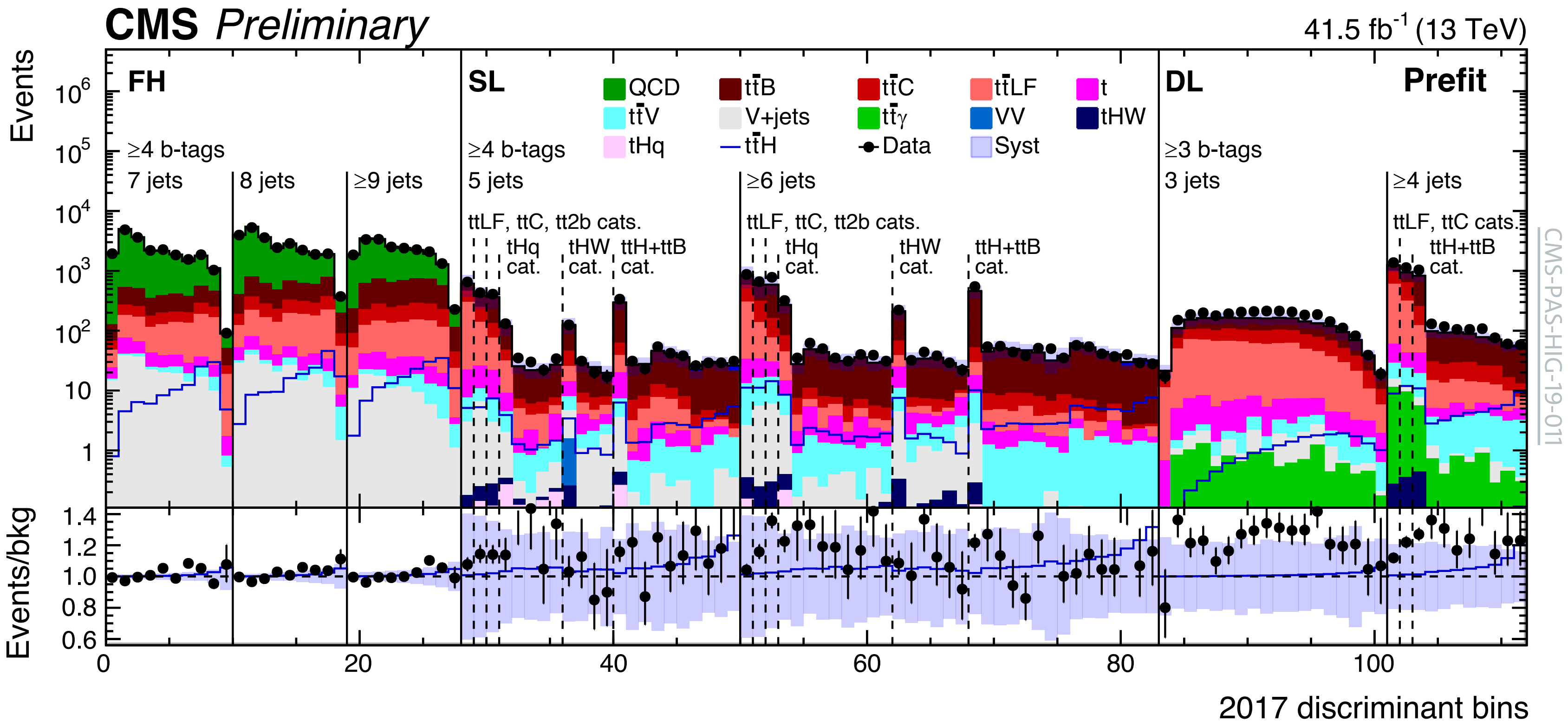


Strategy in ttH:
Goodness-of-fit test for all variables and pairs of variables

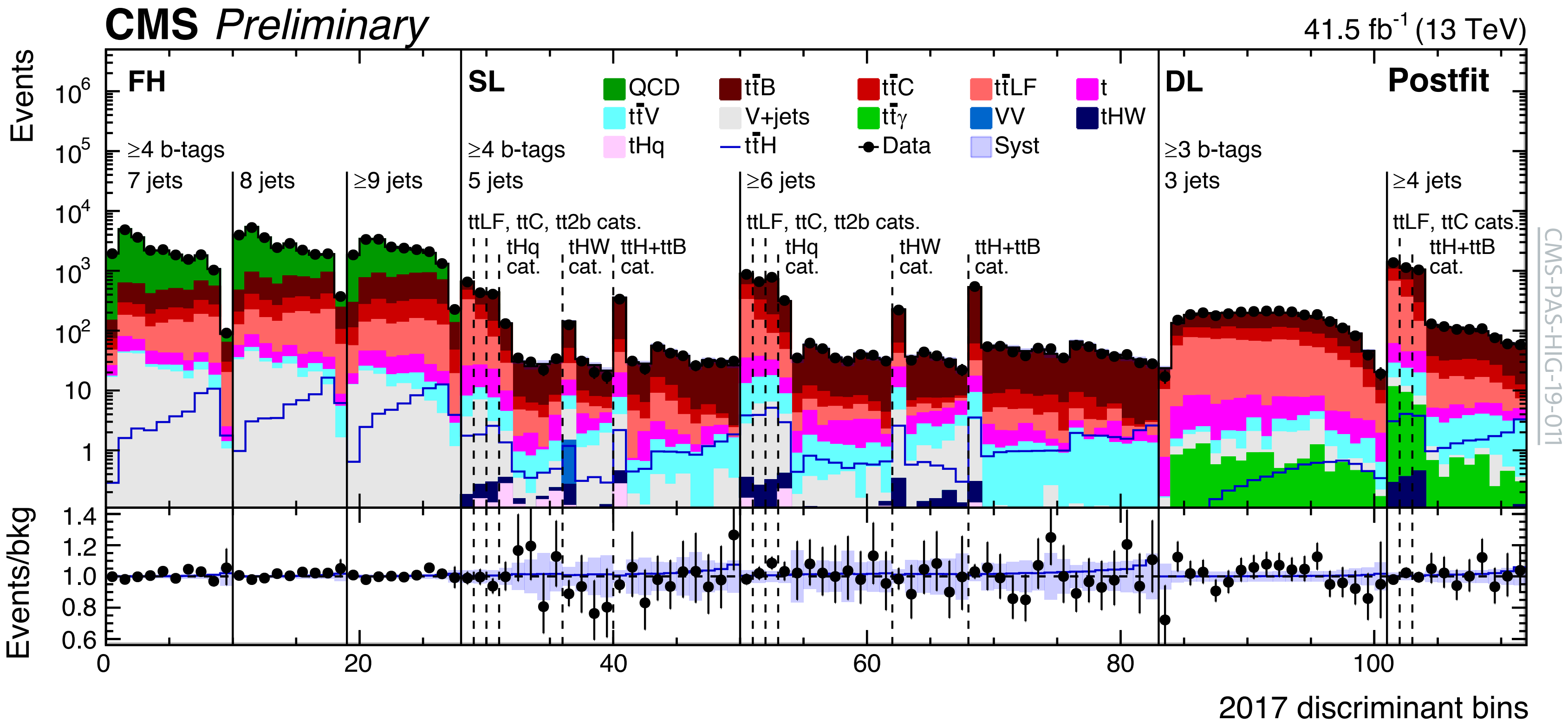
Key aspect in many machine-learning applications at the LHC!

Different to many industry applications where labelled data is available

Final discriminant



Final discriminant



Results: ttH production with H → bb

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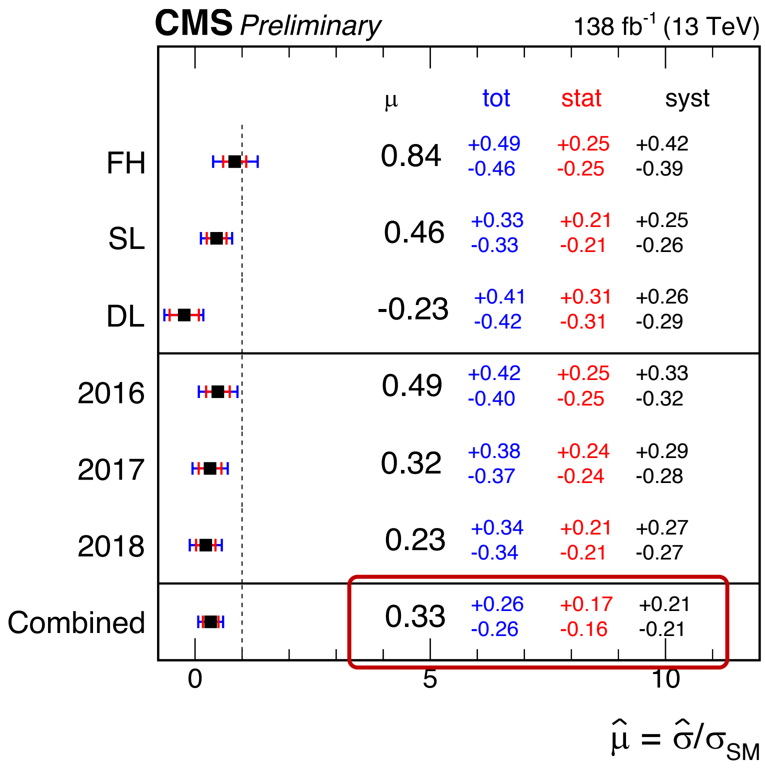

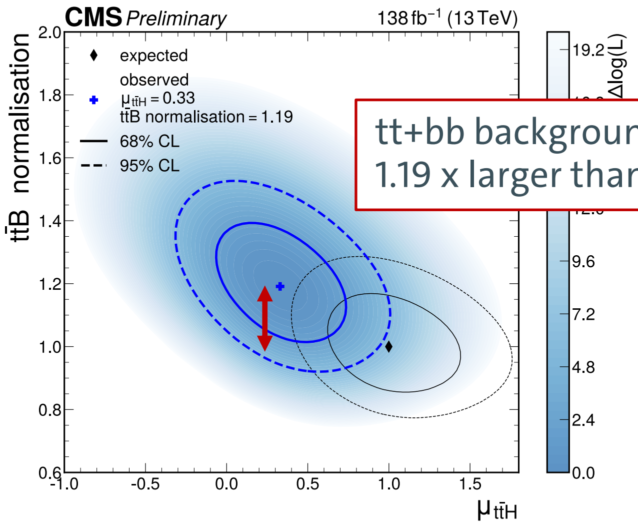

tt+bb background
1.19 x larger than prefit

ttH signal strength μ_{ttH} = 0.33 +/-0.26

SM compatibility p-value: 2%

Agreement with ATLAS result: $0.35^{+0.36}_{-0.34}$ [JHEP 06 (2022) 97]

Uncertainties

Uncertainty source	$\Delta\mu_{t\bar{t}H}$ (observed)	$\Delta\mu_{t\bar{t}H}$ (expected)
Total experimental	$+0.10/-0.10$	$+0.11/-0.10$
jet energy scale and resolution	$+0.08/-0.07$	$+0.09/-0.09$
b tagging	$+0.07/-0.06$	$+0.06/-0.02$
luminosity	$+0.02/-0.02$	$+0.01/-0.01$
Total theory	$+0.16/-0.16$	$+0.18/-0.14$
$t\bar{t}$ + jets background	$+0.15/-0.16$	$+0.12/-0.11$
signal modelling	$+0.06/-0.01$	$+0.13/-0.06$
Size of the simulated event samples	$+0.13/-0.12$	$+0.10/-0.10$
Total systematic	$+0.20/-0.21$	$+0.23/-0.19$
Statistical	$+0.17/-0.16$	$+0.17/-0.17$
background normalisation	$+0.13/-0.13$	$+0.13/-0.13$
$t\bar{t}B$ and $t\bar{t}C$ normalisation	$+0.12/-0.12$	$+0.12/-0.12$
QCD normalisation	$+0.01/-0.01$	$+0.01/-0.01$
Total	$+0.26/-0.26$	$+0.28/-0.25$

Sensitivity **limited by systematic uncertainties**

Jet energy calibration & b-tagging

tt+bb modelling uncertainties

Size of simulated event samples

Results on tH production

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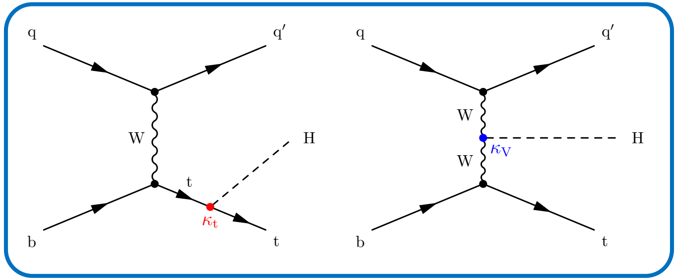
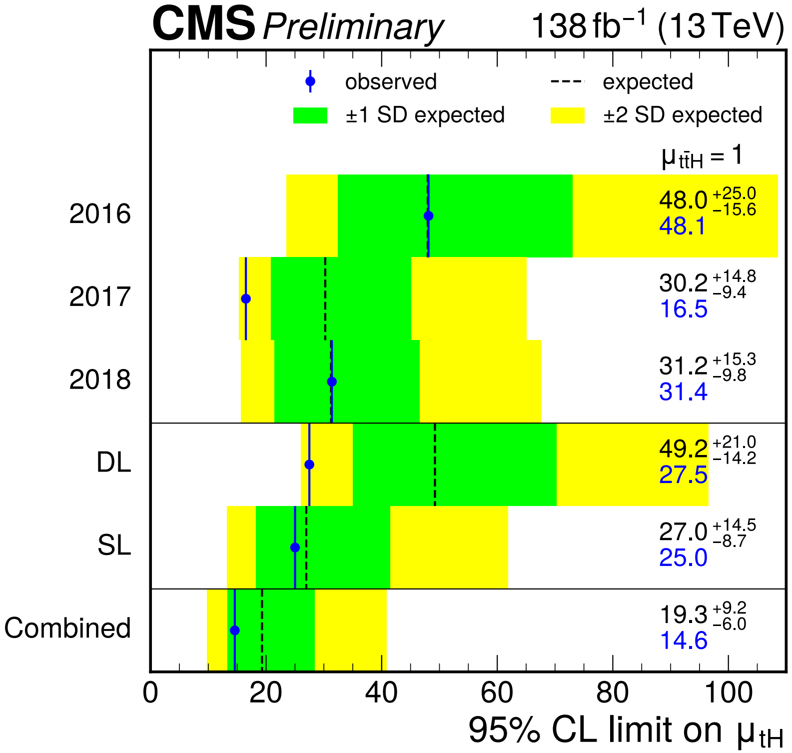
Dedicated analysis categories targeting tH events



tH production: $\sigma_{SM} = 90pb$

[arXiv: 1610.07922]

Upper limit of 14.6 obs. ($19.3^{+9.2}_{-6.0}$ exp.) x SM
tH production at 95% CL



Coupling interpretation

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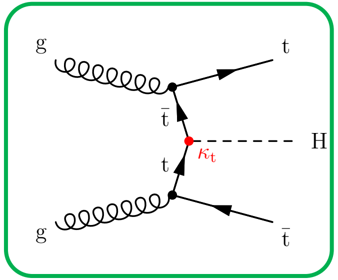
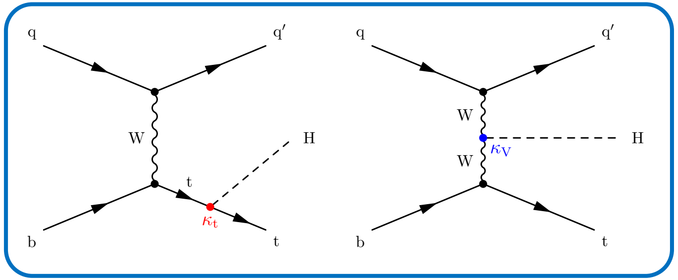
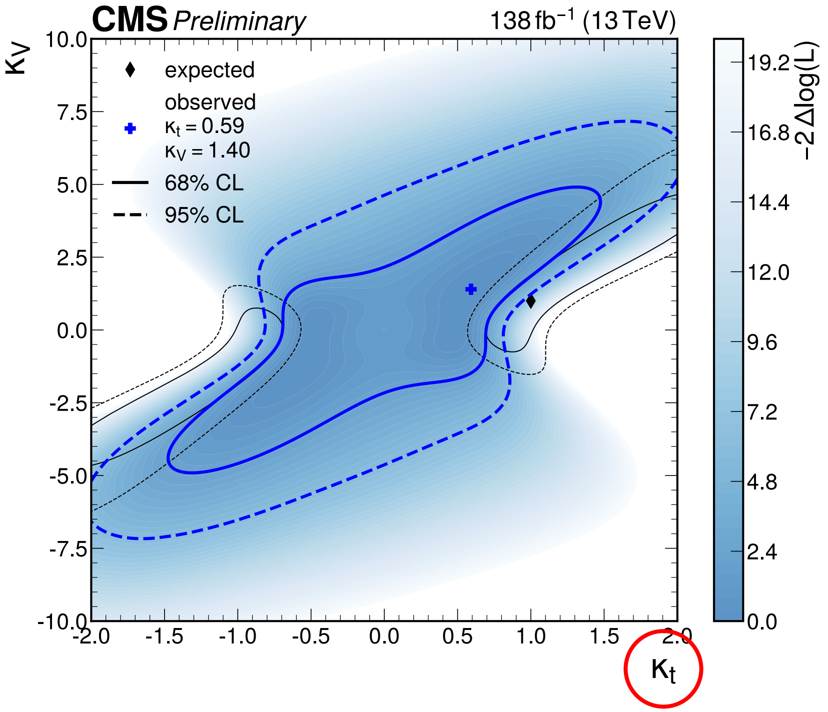
ttH and tH cross-sections depend differently on top-Higgs coupling κ_t



ttH: κ_t^2



tH: $3.40\,\kappa_t^2 + 3.56\,\kappa_V^2 - 5.96\,\kappa_t\kappa_V$
(diagrams interfere)

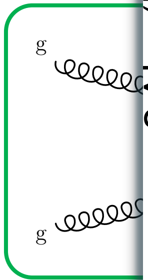


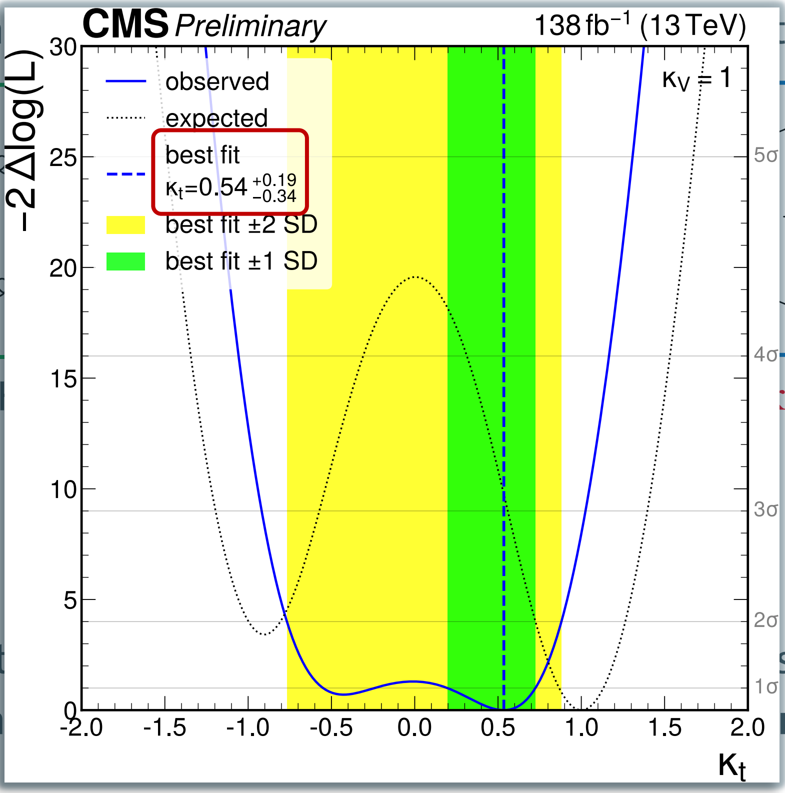
Simultaneoulsy floating ttH and tH contributions
→ **constraints on κ_t and κ_V (including relative sign!)**

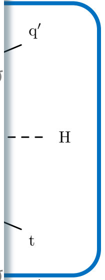
Coupling interpretation

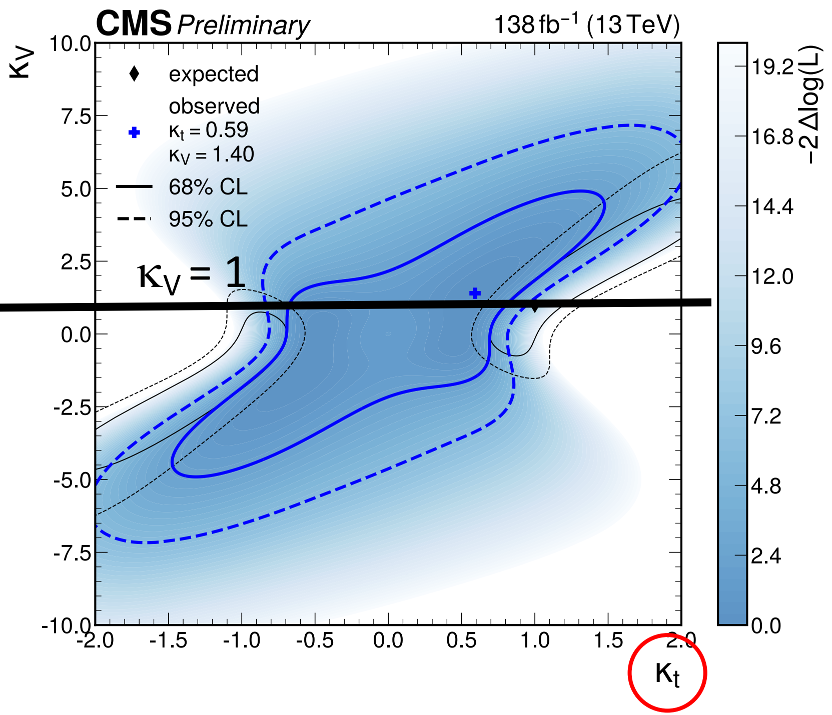
CMS-PAS-HIG-19-011

ttH an ... top-Higgs coupling κ_t









ttl ... $\kappa_t\kappa_V$

Simult ... s

→ con ... n!)

CP interpretation

CMS-PAS-HIG-19-011

CP-odd component in top-Higgs interaction?

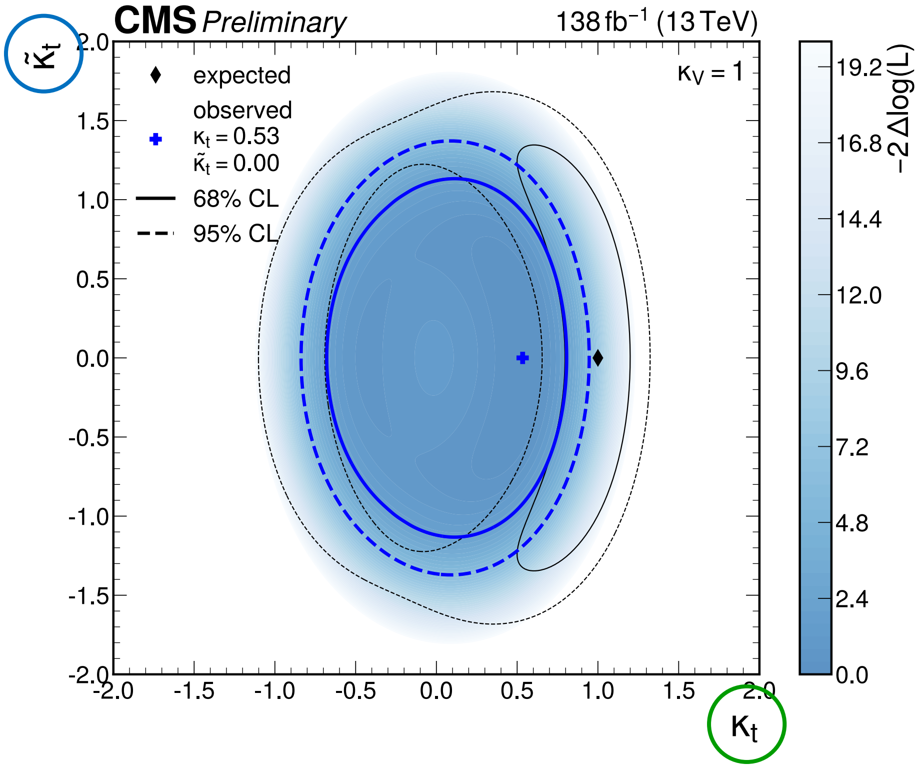
In principle allowed at tree level!

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + \mathrm{i}\tilde{\kappa}_t\gamma_5\right)\psi_t$$

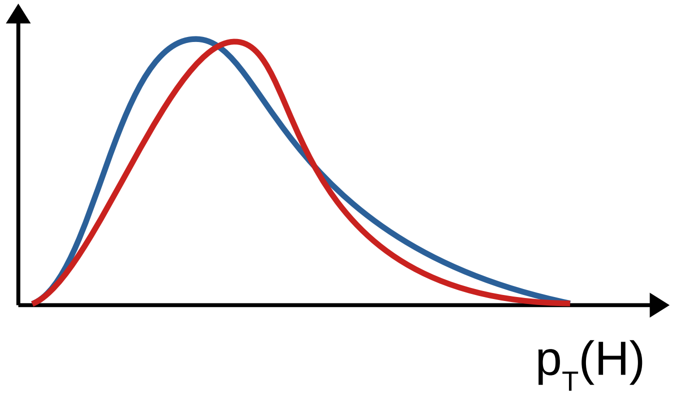
CP-even/CP-odd Yukawa coupling
(SM: $\kappa_t = 1$, $\tilde{\kappa}_t = 0$)

→ can modify ttH and tH rates and kinematics differently

Simultaneoulsy floating ttH and tH contributions
→ **constraints on CP-odd top-Higgs coupling $\tilde{\kappa}_t$**



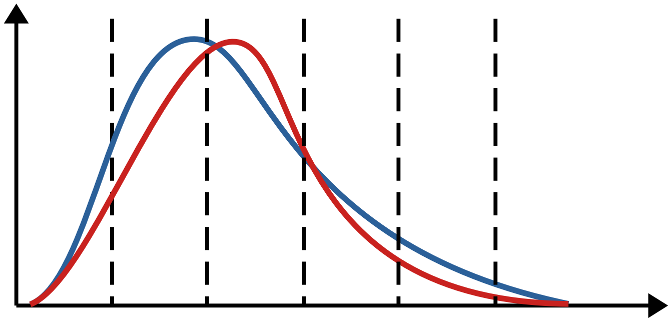
Beyond inclusive measurements



New physics might modify kinematics → **measure differentially!**

("Simplified Template Cross Section", STXS)

Beyond inclusive measurements



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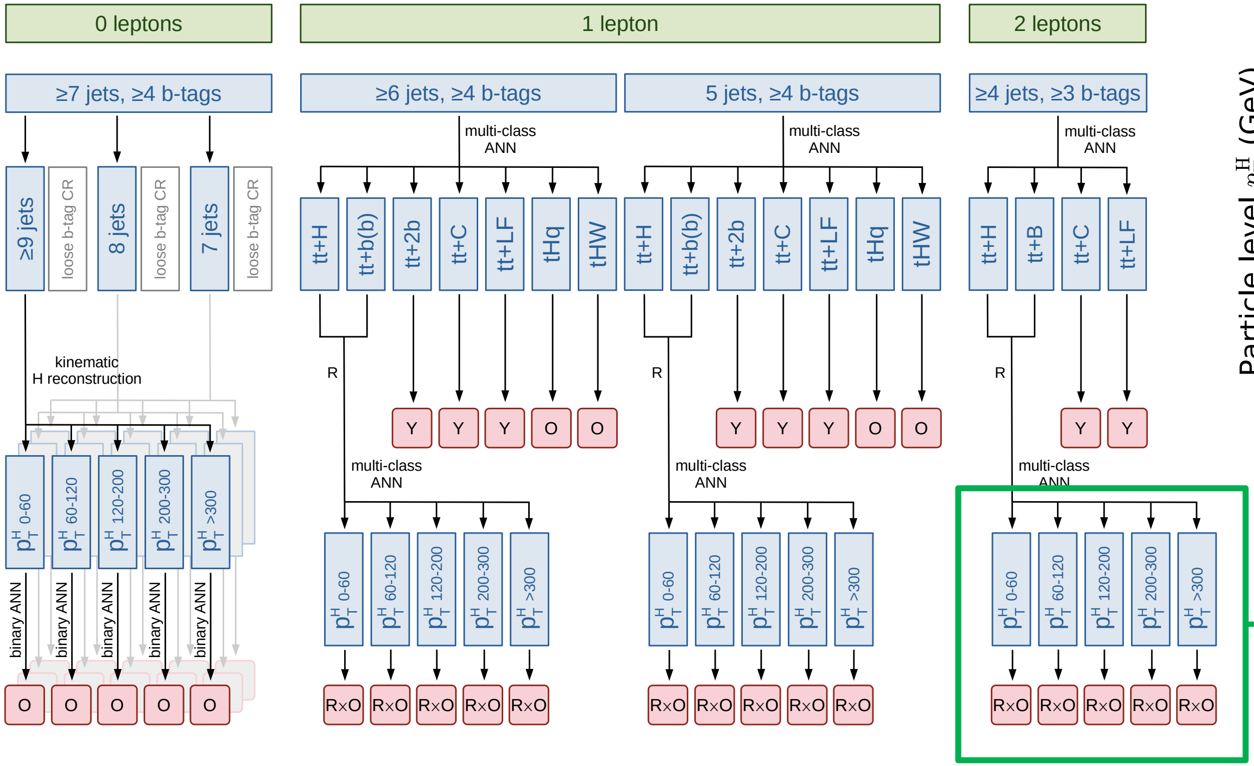
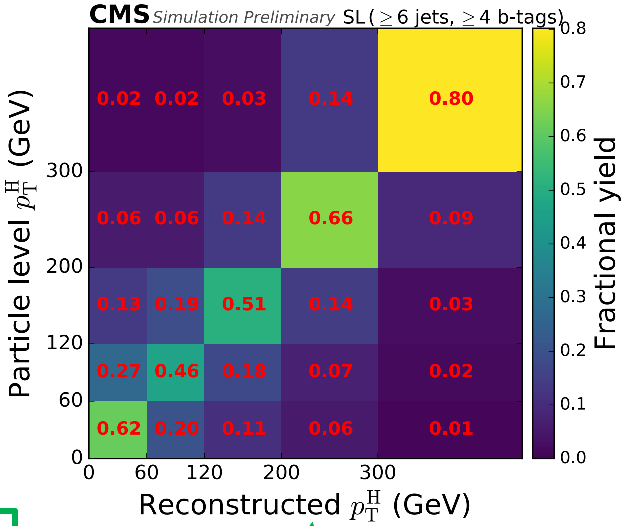
("Simplified Template Cross Section", STXS)

ttH production in bins of $p_T(H)$



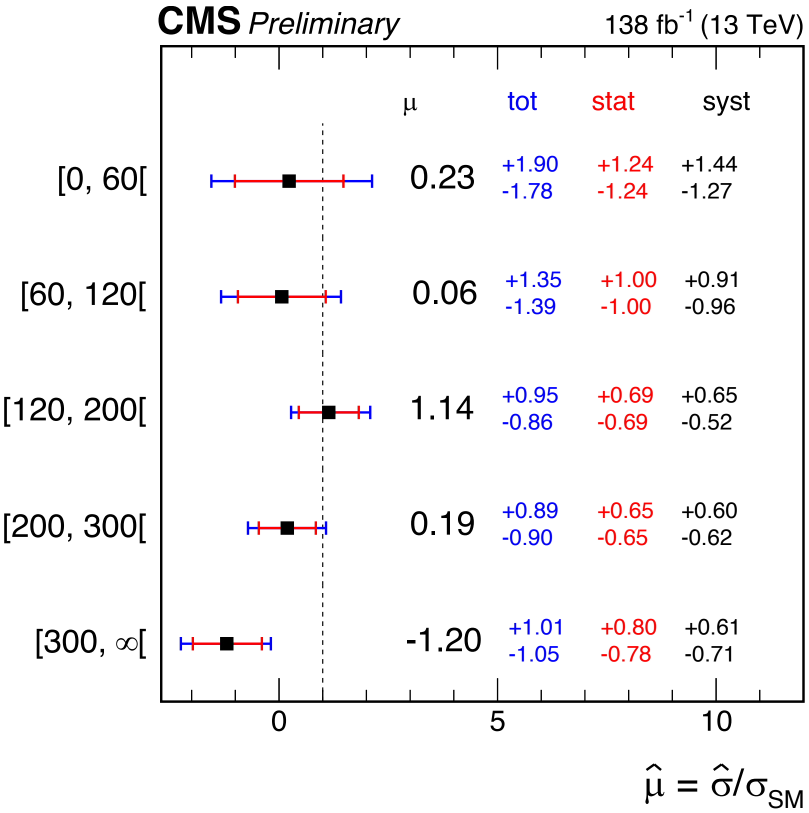
Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)



Sort signal events into 5 bins in $p_T(H)$ using second ANN

ttH production in bins of $p_T(H)$

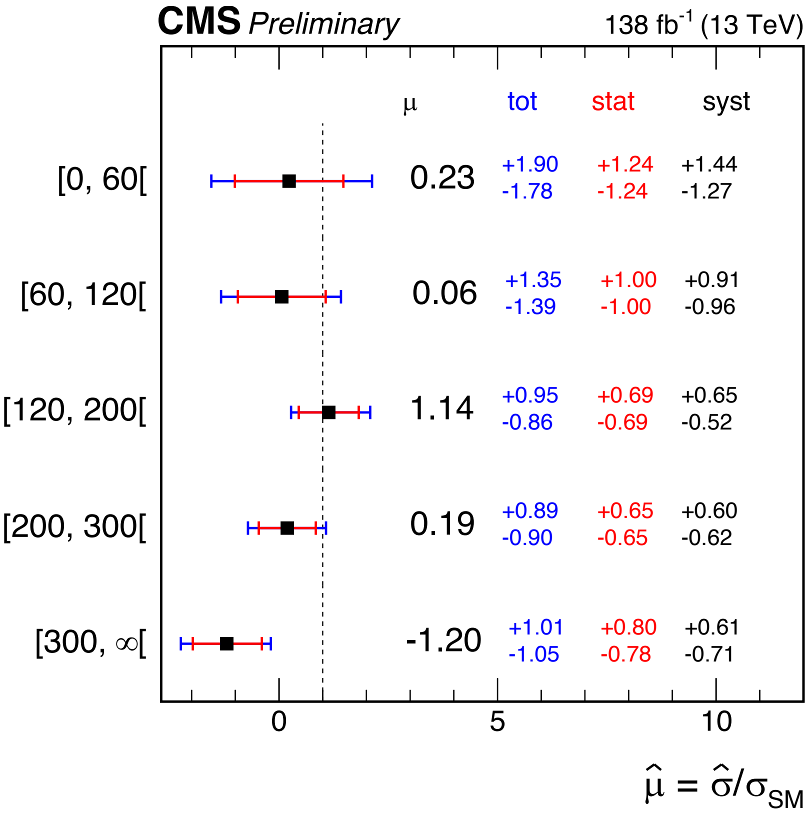
CMS-PAS-HIG-19-011



Sensitivity still limited but **interesting for future measurements and combination** with other channels

ttH production in bins of $p_T(H)$

CMS-PAS-HIG-19-011



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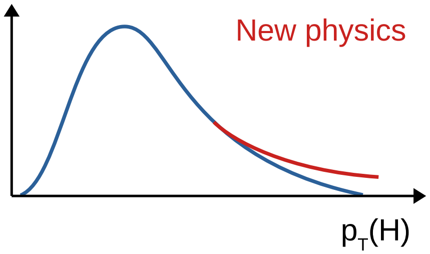
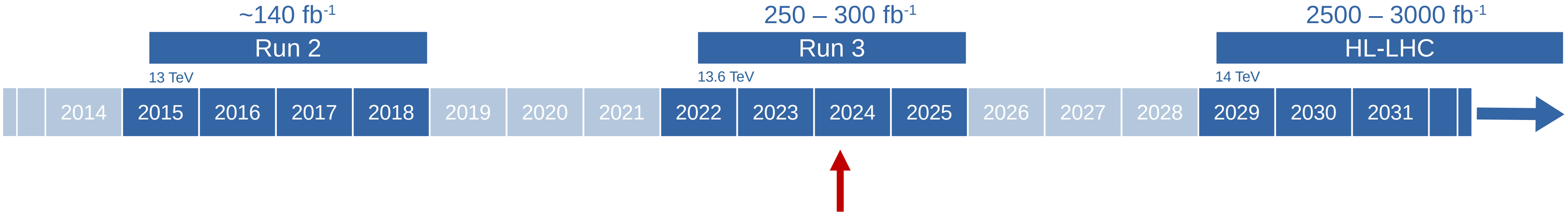


Effects from heavy particles could show up here

Interesting for EFT interpretations [CMS-PAS-HIG-19-005] [Nature 607 (2022) 7917, 52-59]

What‘s next?

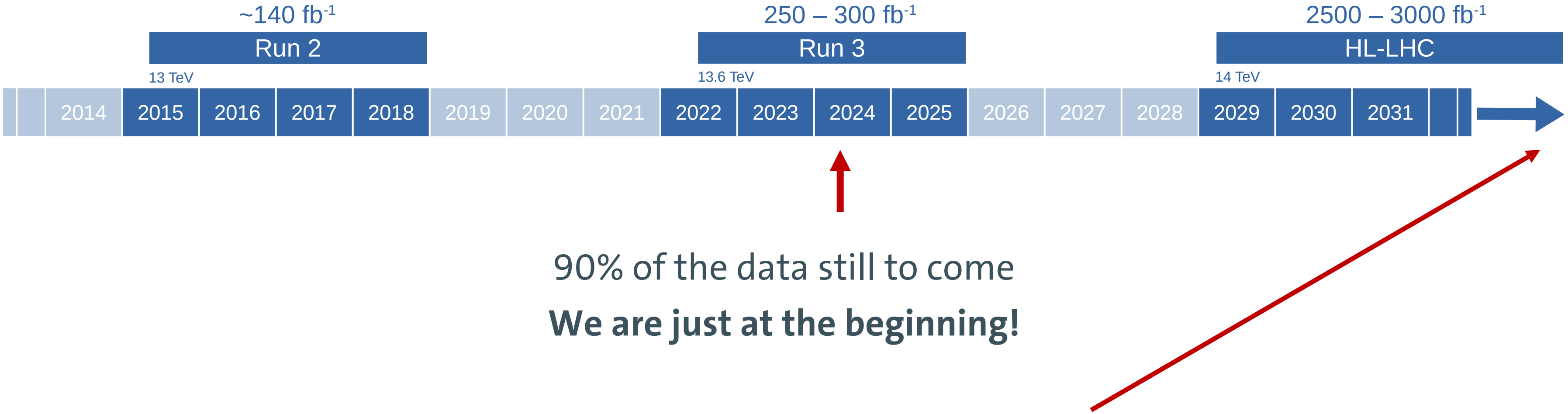
What‘s next?



90% of the data still to come

We are just at the beginning!

What‘s next?



90% of the data still to come

We are just at the beginning!

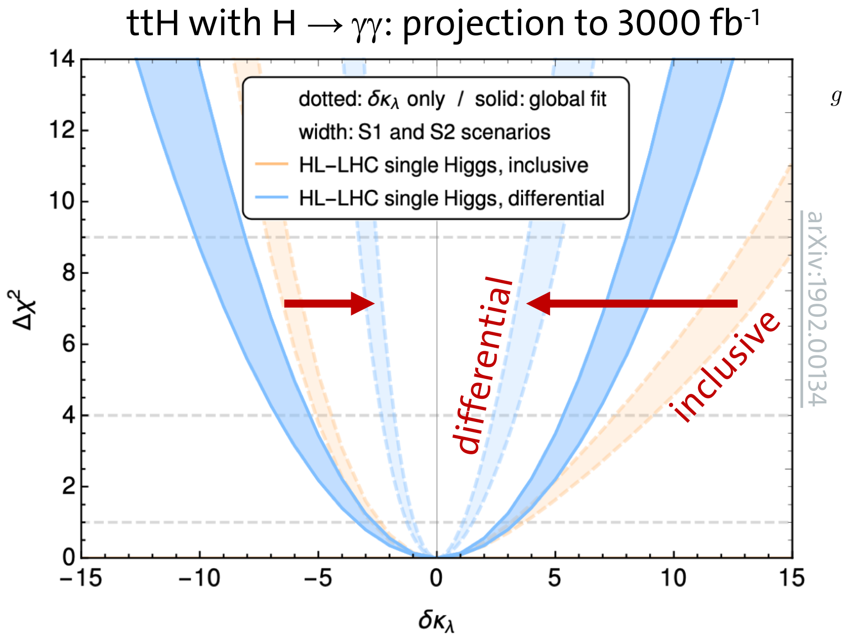
3000 fb^{-1}: Expect μ(ttH) in H $\rightarrow$ bb channel at 7% precision

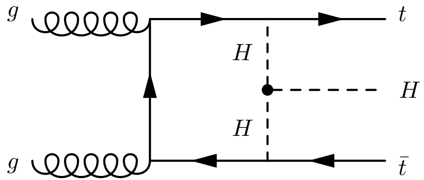
Projection based on 2016 state-of-the-art [CMS-PAS-FTR-18-011]

Already doing better than projected now!

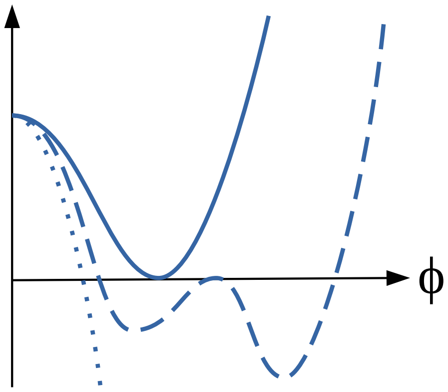
Higgs-boson self-coupling

ttH production sensitive to **Higgs-boson self-coupling** [Eur.Phys.J.C 77 (2017) 12, 887]
→ related to shape of Higgs potential





Is the vacuum stable?



Differential measurements even more stringent test of Standard Model!

STXS measurements first step in this direction

Summary

The Higgs boson is special! Has properties and interactions never seen before

Yukawa couplings deeply connected to fermion masses

Coupling to top quark particularly exciting – measurement via ttH production

Observation of ttH production in 2018, since then **much improved results in all channels**

- New CMS result in H → bb channel: very powerful but limited by tt+bb modelling

Extended interpretations of ttH measurements

- Coupling and CP interpretations
- STXS results as first step towards differential measurements

Summary

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ttH has a huge potential:

The measurements are challenging but give us a powerful probe of the SM and possible new physics

LHC Run 2 analyses have paved the way ahead

Additional material

The Higgs Boson with Toppings

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In the Standard Model (SM) of particle physics, the Higgs boson is deeply related to the mechanism that creates the masses of elementary particles and, as such, has very characteristic properties, which are different from any other known particle. The large data samples collected at the LHC, together with new analysis techniques, allow measurements of Higgs boson production and properties at unprecedented precision. The results play a crucial role in probing the SM and provide a unique window to revealing potential new physics effects.

The coupling of the Higgs boson to the heaviest known quark, the top quark, is particularly exciting because it is large and, therefore, has a strong impact on the SM or possible new physics. The best direct measurement of the top-Higgs coupling is achieved in events where a top quark-antiquark pair is produced in association with a Higgs boson (ttH production). In the presentation, I will review the status of ttH measurements, and I will present a new result by the CMS Collaboration in the bb decay channel of the Higgs boson. The analysis benefits from improved modelling of the challenging background due to tt+bb production as well as refined analysis methods exploiting advanced machine-learning techniques. Finally, I will outline prospects for future ttH measurements at the ongoing LHC Run 3 and the High-Luminosity LHC.

The Standard Model Higgs sector

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Gauge interaction
W/Z boson masses

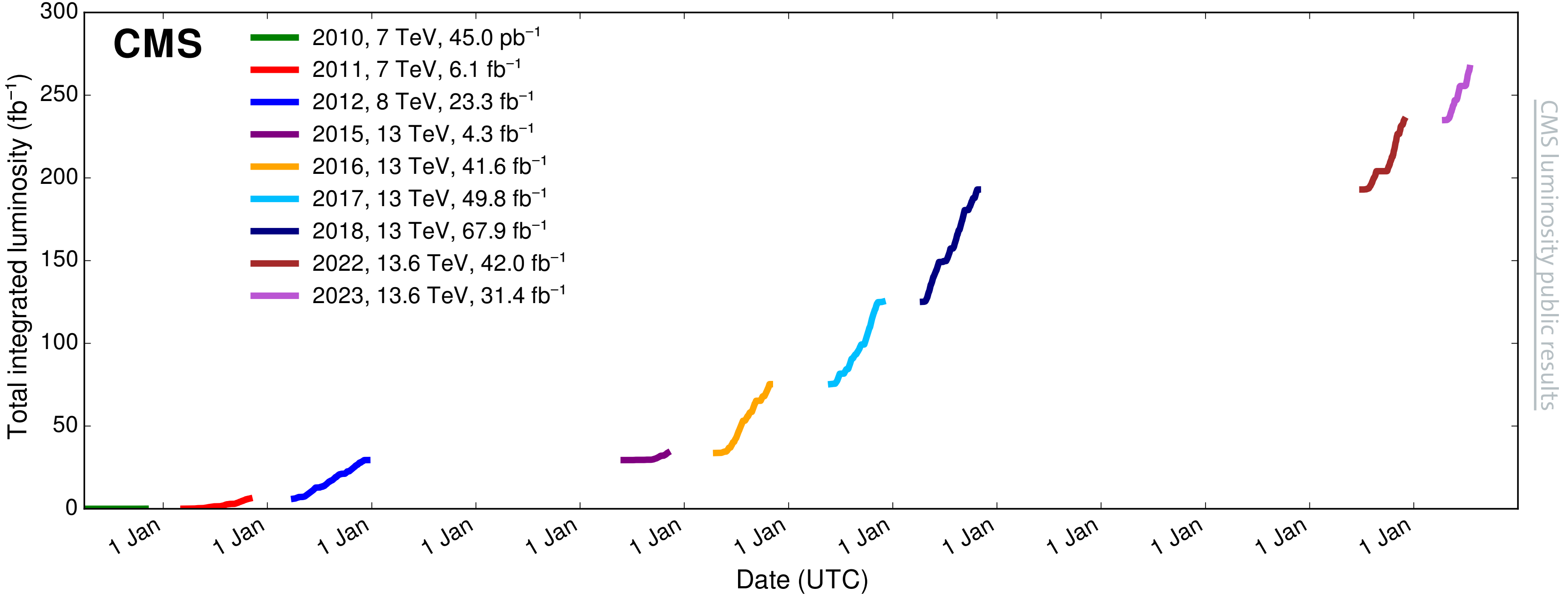
$$\mathcal{L} = |D_\mu \phi|^2 - V(\phi) + y_f \overline{\psi} \phi \psi$$

Higgs potential
symmetry breaking

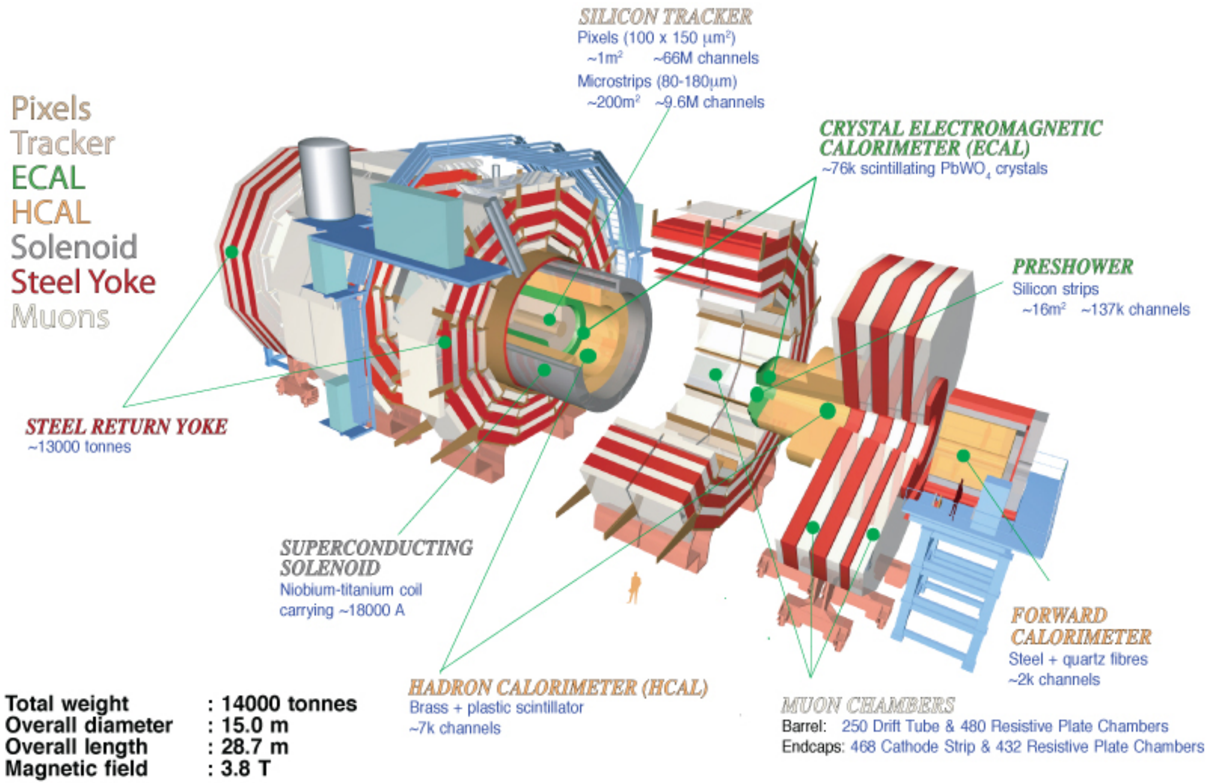
Yukawa interaction
fermion masses

Special, unlike anything we have seen before!

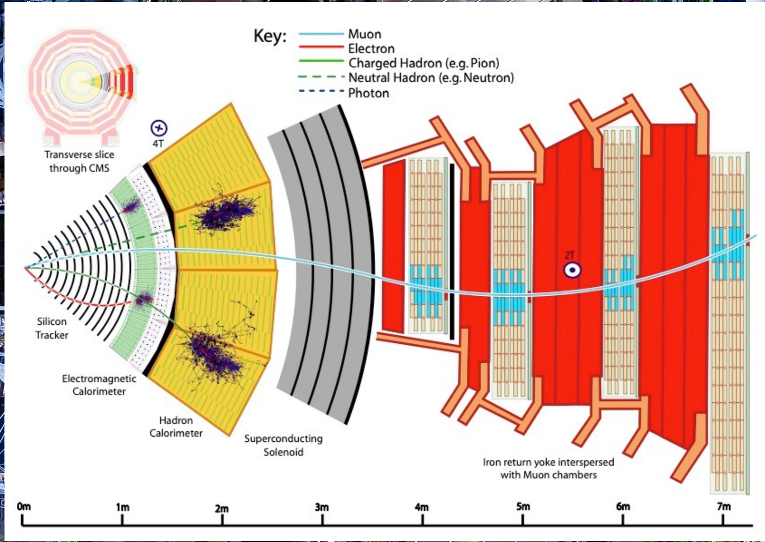
Delivered luminosity



The CMS detector



The CMS Detector



All detector components needed in Higgs analyses

Very different signatures depending on the production and decay modes

tt and ttbb samples

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	$\mathrm{t\bar{t}}$ sample	$\mathrm{t\bar{t}b\bar{b}}$ sample
POWHEG version	`Powheg v2`	`Powheg-Box-Res`
PYTHIA version	8.230	8.230
Flavour scheme	5	4
PDF set	NNPDF3.1	NNPDF3.1
m_t	172.5 GeV	172.5 GeV
m_b	0	4.75 GeV
μ_R	$\sqrt{\frac{1}{2}\left(m^2_{\mathrm{T,t}} + m^2_{\mathrm{T,\bar{t}}}\right)}$	$\frac{1}{2}\sqrt[4]{m_{\mathrm{T,t}} \cdot m_{\mathrm{T,\bar{t}}} \cdot m_{\mathrm{T,b}} \cdot m_{\mathrm{T,\bar{b}}}}$
μ_F	μ_R	$\frac{1}{4}\left[m_{\mathrm{T,t}} + m_{\mathrm{T,\bar{t}}} + m_{\mathrm{T,b}} + m_{\mathrm{T,\bar{b}}} + m_{\mathrm{T,g}}\right]$
h_damp	$1.379 \cdot m_\mathrm{t}$	$1.379 \cdot m_\mathrm{t}$
Tune	CP5	CP5

Analysis strategy in FH channel

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Training region

>80% QCD: use data as QCD bkg. events in ANN training

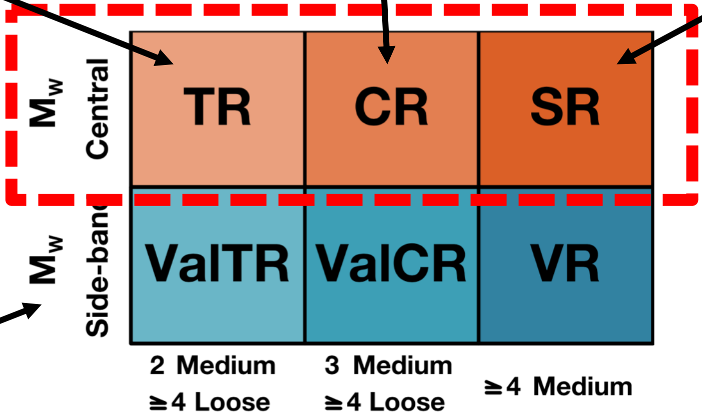
Control region

Derive expected shape of ANN output distribution for QCD

Signal region

Apply QCD ANN shape from CR and fit normalisation

Analysis region



Validation region

Based on m_{jj} of pair of non-b-tagged jets with m_{jj} closest to W-boson mass

QCD-bkg estimation as before

- Discriminant (ANN) shape from CR
- Transfered to SR via TF_{loose}
- Closure test in data in VR

QCD-background estimation

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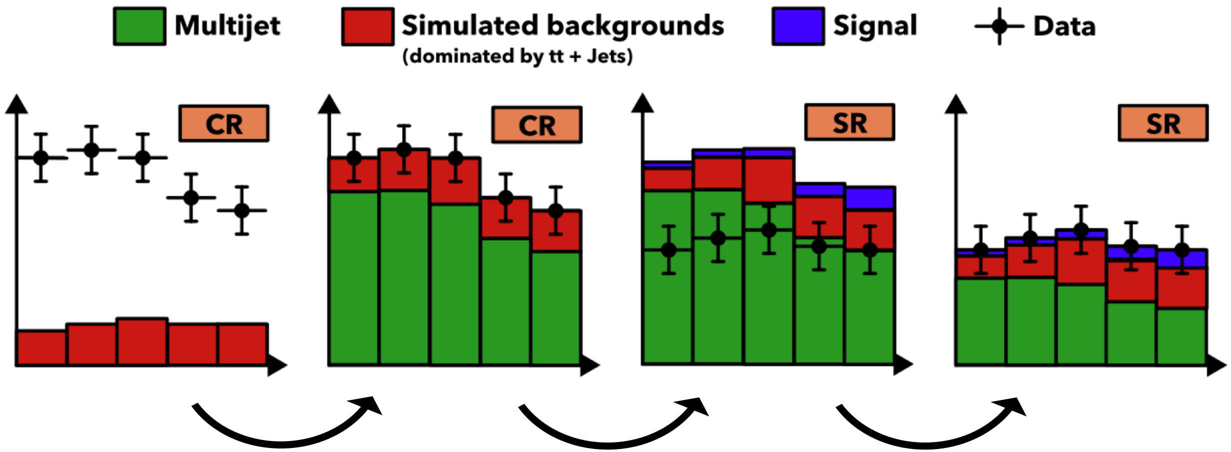
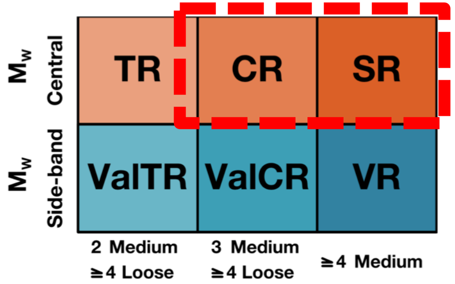
- In CR: $ANN_{QCD} = ANN_{data} - ANN_{non\text{-}QCD\ bkg.\ (from\ MC)}$ → **shape of ANN distribution**
- **Normalisation in SR freely-floating** in final fit
  - Independently per N_{jets} category and year: 9 QCD normalisation parameters



Difference between data and simulated background in CR is taken as QCD

QCD distribution is transferred to SR

QCD normalisation is determined in fit to data



Systematic uncertainties

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Source	Type	Correlation	Remarks
Renorm./fact. scales	R	correlated	Scale uncertainty of (N)NLO prediction, independent for $t\bar{t}H$, tHq, tHW, $t\bar{t}$, t, V+jets, VV
PDF+α_S (gg)	R	correlated	PDF uncertainty for gg initiated processes, independent for $t\bar{t}H$, tHq, tHW, and others
PDF+α_S ($q\bar{q}$)	R	correlated	PDF uncertainty of $q\bar{q}$ initiated processes ($t\bar{t}W$,W,Z) except tHq
PDF+α_S (qg)	R	correlated	PDF uncertainty of qg initiated processes (single t) except tHW
Collinear gluon splitting†	S	correlated	Additional 100% rate uncertainty on $t\bar{t}+2b$ component of $t\bar{t}B$ background
μ_R scale	S	correlated	Renormalisation scale uncertainty of the ME generator, independent for $t\bar{t}H$, tHq, tHW, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sample), other $t\bar{t}$ ($t\bar{t}$ sample)
μ_F scale	S	correlated	Factorisation scale uncertainty of the ME generator, independent for $t\bar{t}H$, tHq, tHW, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sample), other $t\bar{t}$ ($t\bar{t}$ sample)
PDF shape	S	correlated	From NNPDF variations, independent for tHq, tHW, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sample), other $t\bar{t}$ ($t\bar{t}$ sample) and $t\bar{t}H$
PS scale ISR†	S	correlated	Initial state radiation uncertainty of the PS (PYTHIA), independent for $t\bar{t}H$, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sample), other $t\bar{t}$ ($t\bar{t}$ sample)
PS scale FSR†	S	correlated	Final state radiation uncertainty of the PS (PYTHIA), independent for $t\bar{t}H$, $t\bar{t}B$ ($t\bar{t}b\bar{b}$ sample), other $t\bar{t}$ ($t\bar{t}$ sample)
ME-PS matching ($t\bar{t}$)†	R	correlated	NLO ME-PS matching (for $t\bar{t}+$jets events), independent for $t\bar{t}B$, $t\bar{t}C$, $t\bar{t}LF$
Underlying event ($t\bar{t}$)	R	correlated	Underlying event (for all $t\bar{t}+$jets events)
STXS migration	R	correlated	Signal, only in STXS measurement
STXS acceptance	S	correlated	Signal, only in STXS measurement
Integrated luminosity	R	partially	Signal and all backgrounds
Lepton ID/Iso (2 sources)	S	uncorrelated	Signal and all backgrounds
Trigger efficiency (4 sources)	S	uncorrelated	Signal and all backgrounds
L1 prefiring correction	S	uncorrelated	Signal and all backgrounds
Pileup	S	correlated	Signal and all backgrounds
Jet energy scale (11 sources)	S	partially	Signal, $t\bar{t}+$jets and single t
Jet energy resolution	S	uncorrelated	Signal, $t\bar{t}+$jets and single t
b tag bkg. contam. (2 sources)	S	partially	Signal and all backgrounds
b tag bkg. contam. stat. (4 sources)	S	uncorrelated	Signal and all backgrounds
b tag charm (2 sources)	S	partially	Signal and all backgrounds
TF_{loose} correction	S	uncorrelated	QCD background estimate
Size of the MC samples	S	uncorrelated	Statistical uncertainty of signal and background prediction due to limited sample size

Systematic uncertainties

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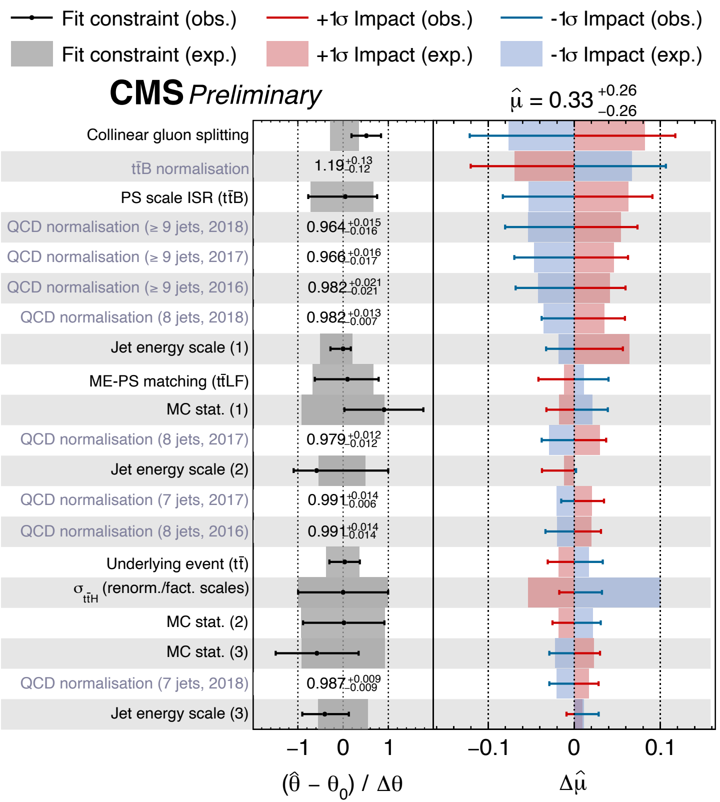

Background validation

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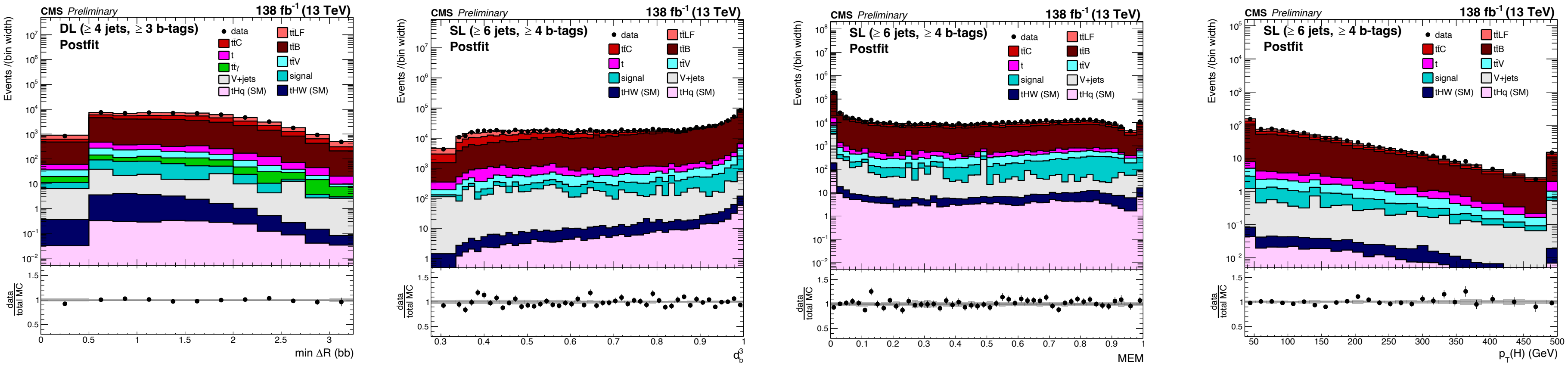
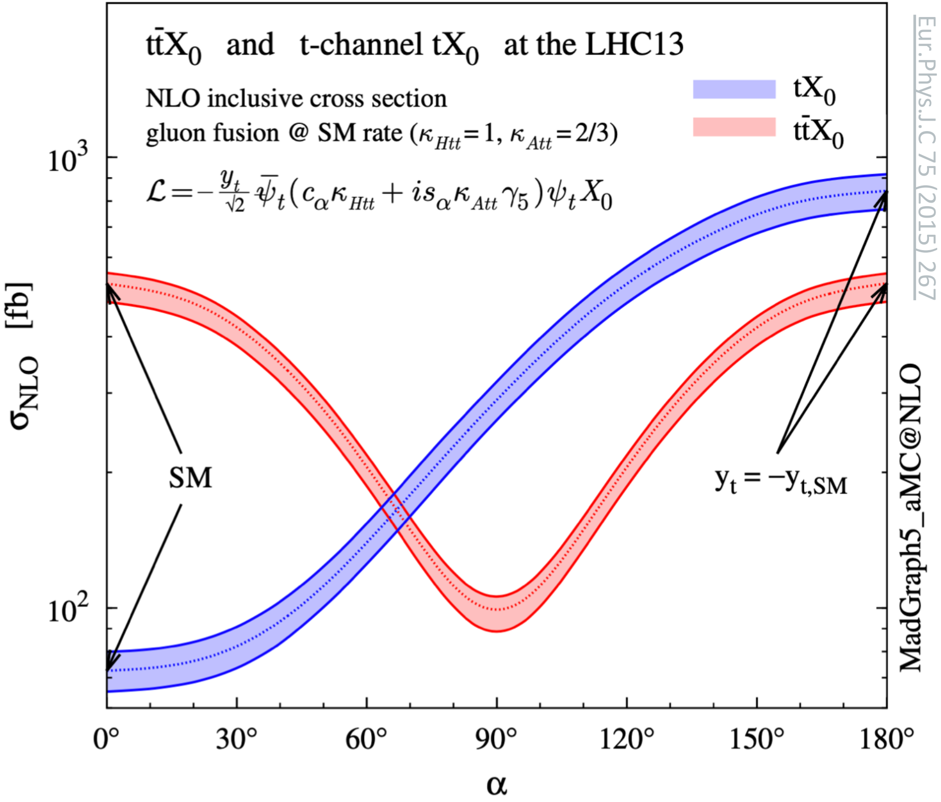


Post-fit background model obtained from main analysis fit to data

tH and ttH cross sections



Eur.Phys.J.C 75 (2015) 267

CP interpretation

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CP-odd component in top-Higgs interaction?

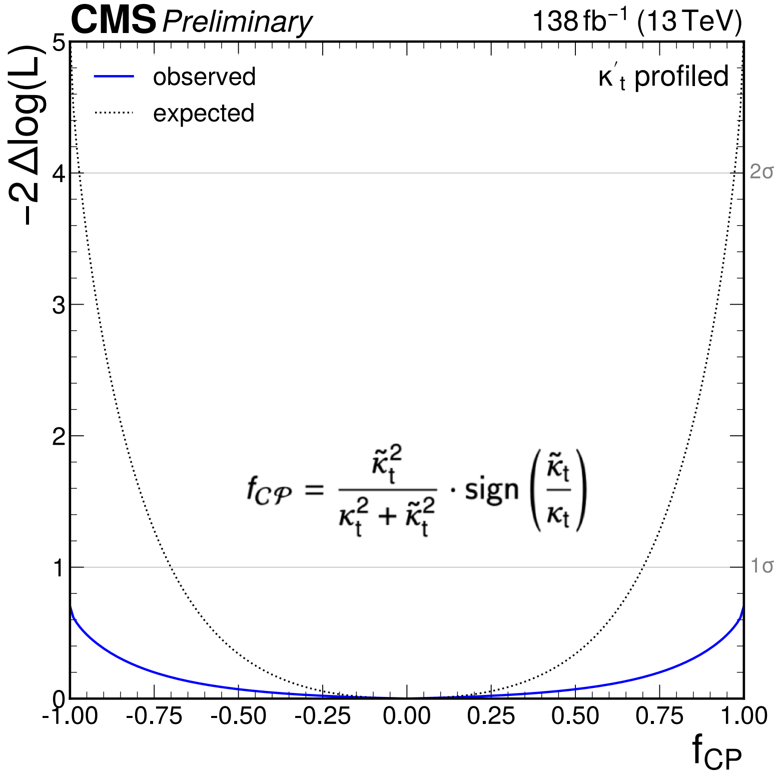
In principle allowed at tree level!

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t$$

CP-even/CP-odd Yukawa coupling
(SM: $\kappa_t = 1$, $\kappa_t = 0$)

→ can modify ttH and tH rates and kinematics differently

Simultaneoulsy floating ttH and tH contributions
→ **constraints on CP-odd top-Higgs coupling κ_t**



Higgs-boson self-coupling

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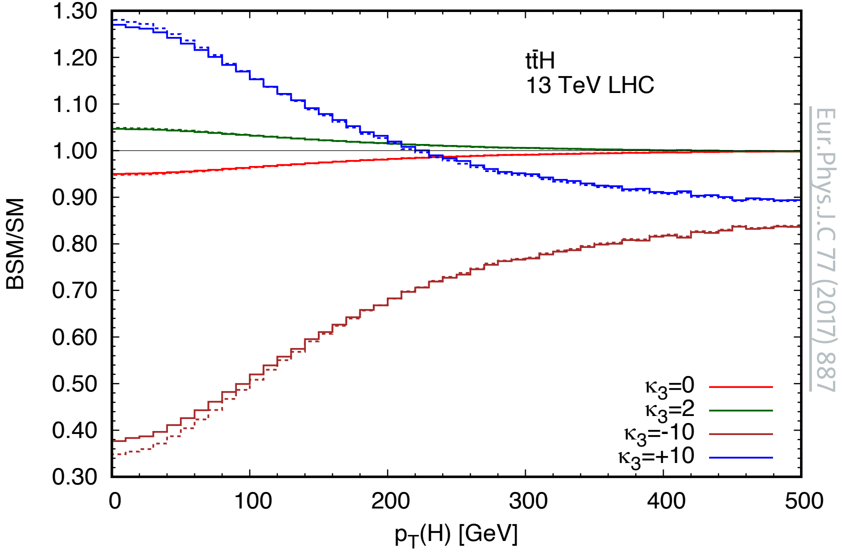
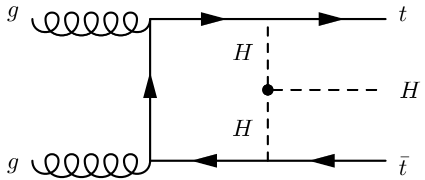
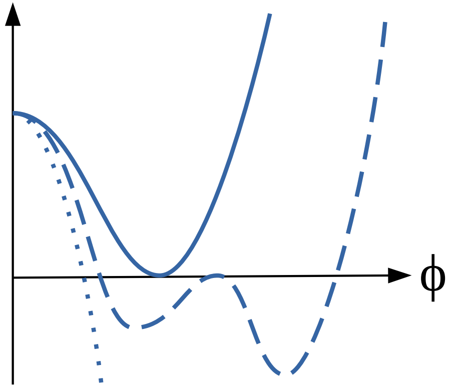
ttH production sensitive to **Higgs-boson self-coupling**
→ related to shape of Higgs potential



Eur.Phys.J.C 77 (2017) 887



Is the vacuum stable?

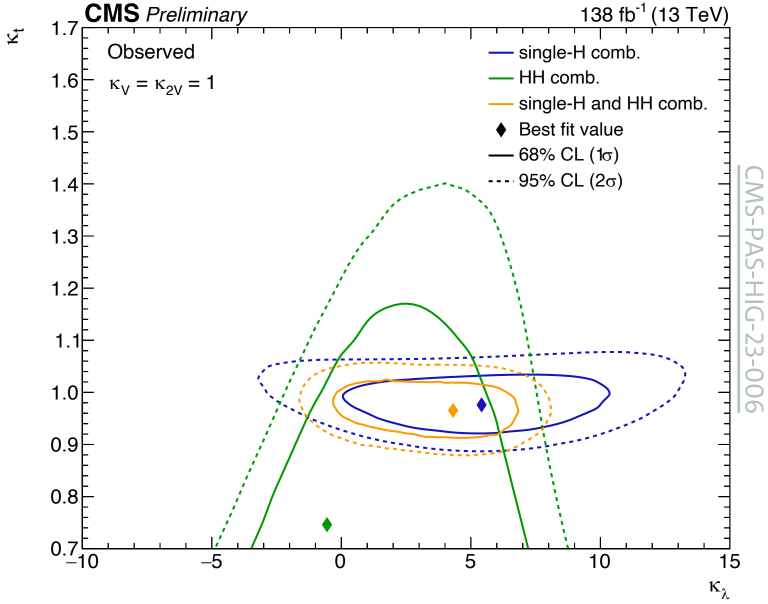


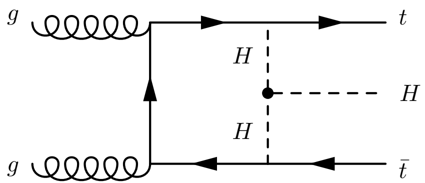
Differential measurements even more stringent test of Standard Model!

STXS measurement first step in this direction

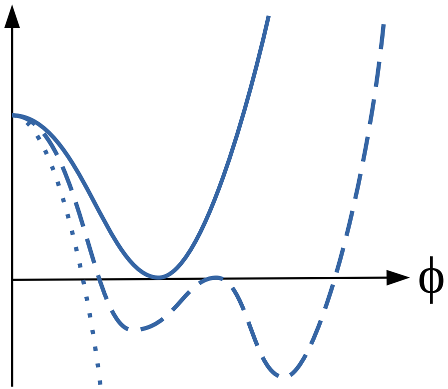
Higgs-boson self-coupling

ttH production sensitive to **Higgs-boson self-coupling** [Eur.Phys.J.C 77 (2017) 12, 887]
→ related to shape of Higgs potential





Is the vacuum stable?



Run-2 combination of single-H measurements
(some inclusive, some STXS)

Less sensitive than HH but powerful constraints on κ_t