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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Bundesministerium für Bildung und Forschung

FSP CMS
Erforschung von Universum und Materie

CMS

Top routes to the Higgs sector: A journey from the begin to the end of the Universe

Matthias Schröder (Universität Hamburg)

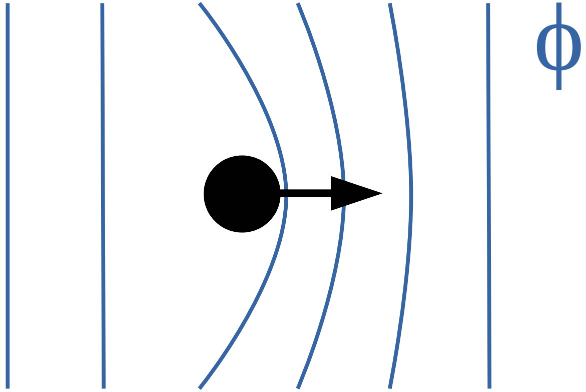
Universiteit Gent seminar | April 30, 2024

How do particles get mass?

Fundamental question:

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

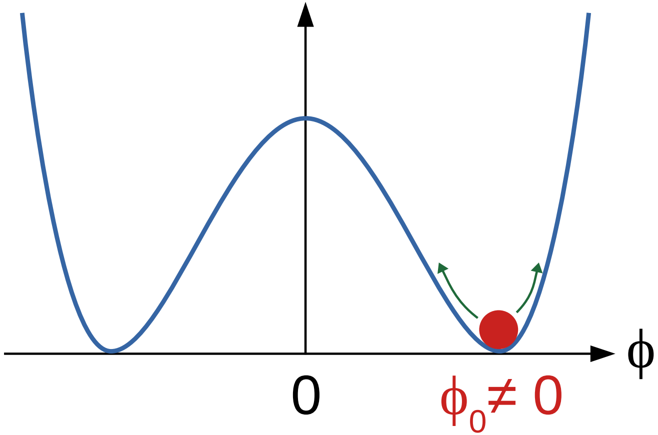
How do particles get mass?



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 $\rightarrow$ **Higgs boson H** (necessary consequence!)

The Higgs boson

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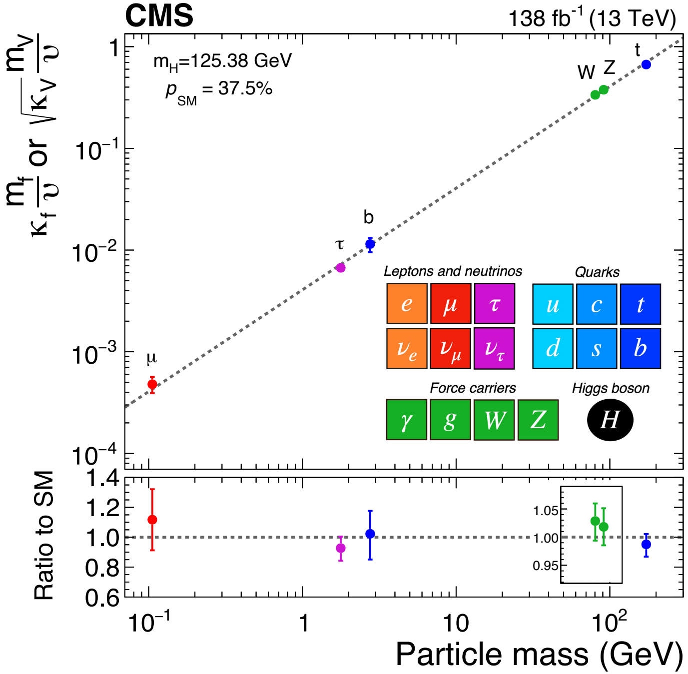
J. Cham

Scalar particle (spin 0, CP even)

Couples in a unique way to other particles

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



Nature 607 (2022) 60-68

Once Higgs-boson mass is known:

All other properties and couplings precisely defined

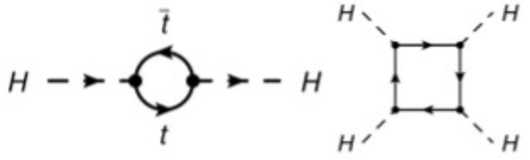
The top-Higgs coupling is special!

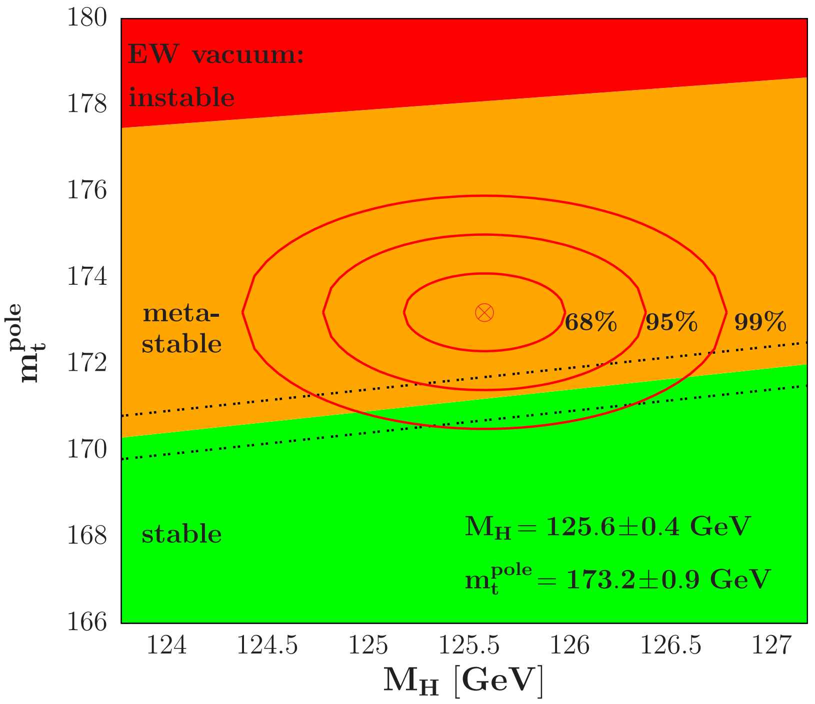
Special: $y_t \approx 1$ (only „natural“ quark mass)

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



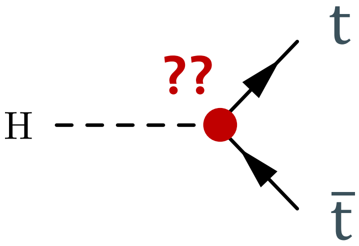


Phys.Lett.B 716 (2012) 214-219

Decides (in part) if the vacuum is stable!

The end of the Universe as we know it?

How to measure the top-Higgs coupling?



Indirect

Direct

Loop-induced single Higgs processes

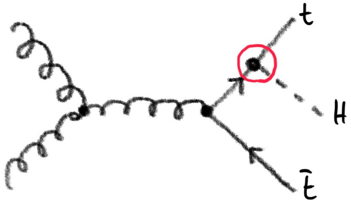
ggF production and $H \to \gamma\gamma$ decays

Virtual corrections to top quark production

4t and tt production

Top quark associated production

ttH and tH production



Heavy partners of the Higgs bosons?

Several phenomena not explained by SM, e.g. Dark Matter, matter-antimatter asymmetry

There has to be new physics!

Many models of new physics require extended Higgs sector

- Supersymmetry
- Electroweak baryogenesis

Two Higgs Doublet Model (2HDM) → 5 Higgs bosons: h, H, A, $H^{+/-}$

Generic model introducing additional Higgs doublet to SM

Important parameters:

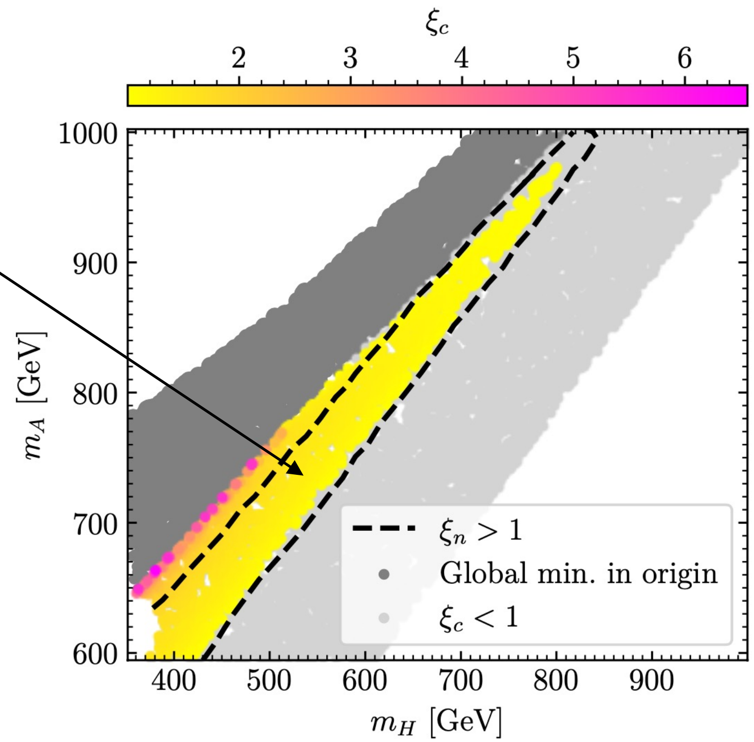
- m_h, m_A, m_H, $m_{H+/-}$
- $\tan\beta = v_2/v_1$
- “Alignment limit” $\cos(\beta-\alpha) = 0$ → h is SM-like

The 2HDM and the begin of the Universe

Matter-antimatter asymmetry of the Universe can be generated in 2HDM (electroweak baryogenesis)

Possible in particular region in 2HDM paramter space

[JCAP 03 (2023) 031]



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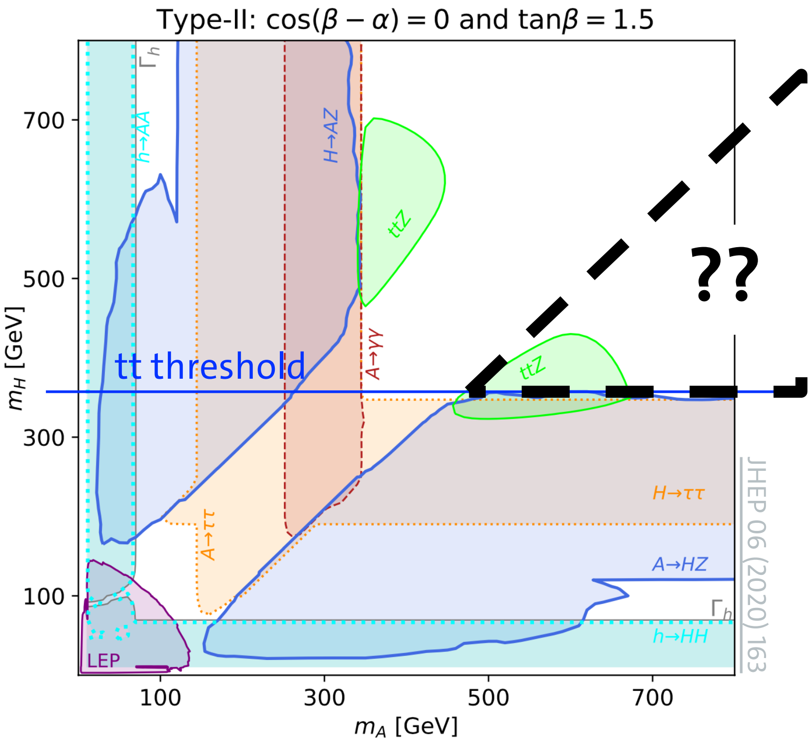

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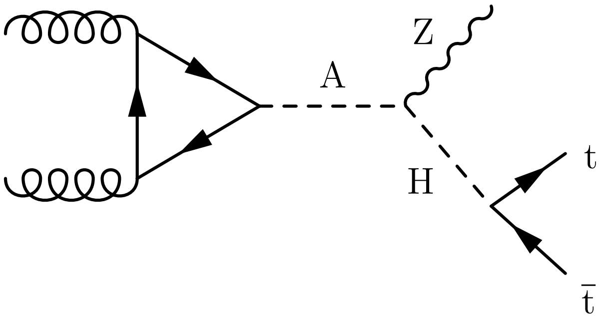
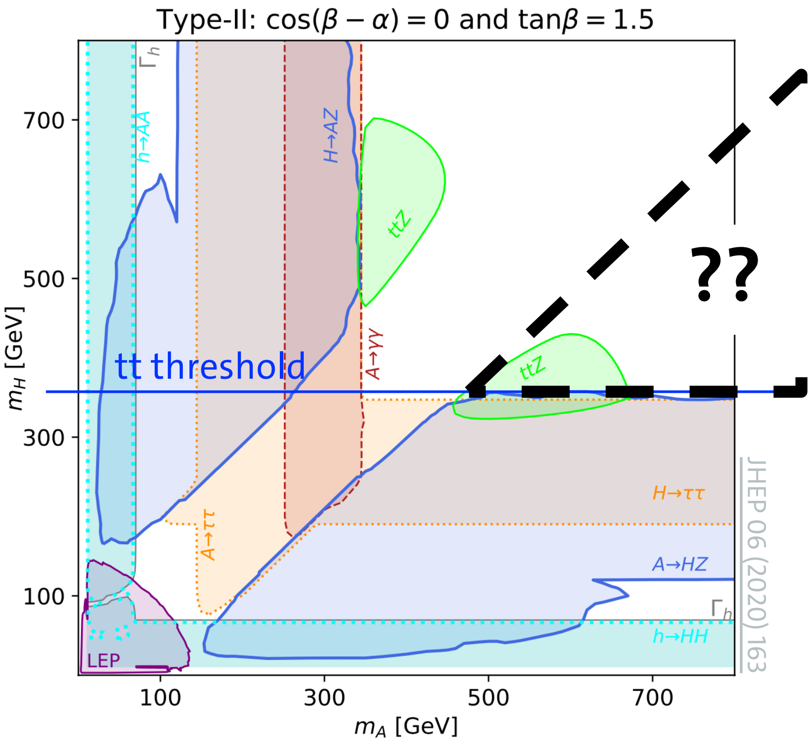
Direct access via A → ZH with H → tt

Probes region with large m_A and small tanβ





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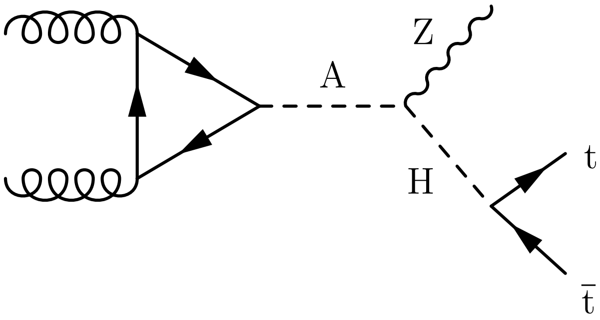
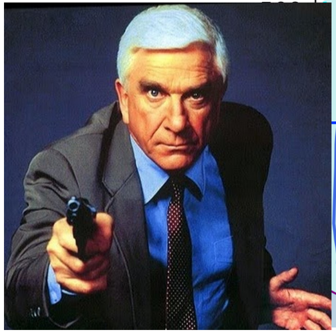
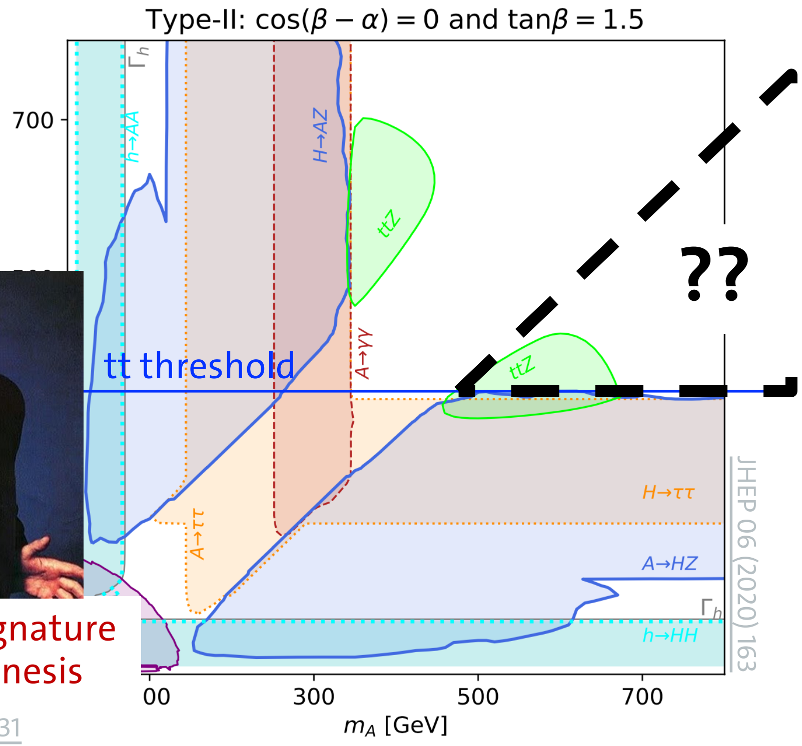




“smoking gun” signature of EWK baryogenesis

JCAP 03 (2023) 031



The 2HDM and the begin of the Universe

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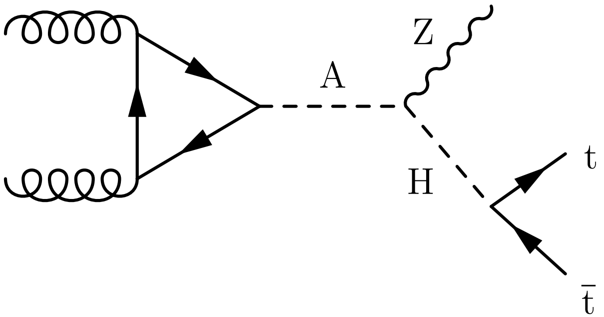
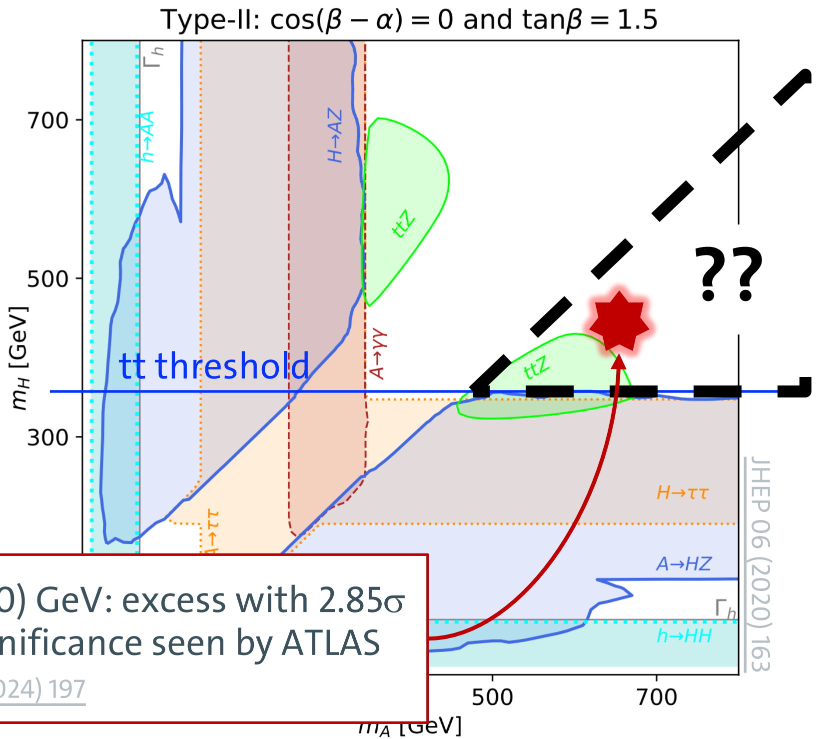




(650, 450) GeV: excess with 2.85σ local significance seen by ATLAS

JHEP 02 (2024) 197

Top routes to the Higgs sector

Top quarks are an excellent tool to probe the Higgs sector

Coupling measurement
Deviations from SM?

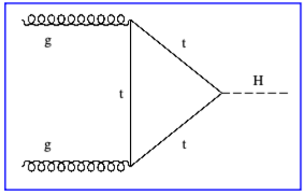
Direct search for heavy Higgs bosons

Examples:

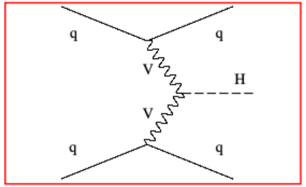
- Measurement of ttH and tH with H → bb
- **Brand-new** search for heavy Higgs bosons A → ZH with H → tt

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

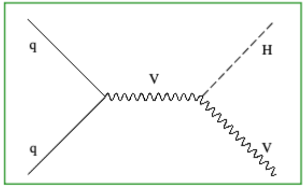
Higgs-boson production at the LHC



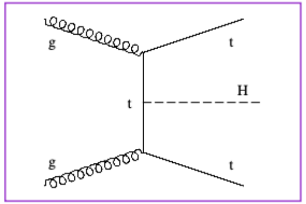
ggF: 43.9 pb (87 %)



VBF: 3.8 pb (7 %)



VH: 2.3 pb (4 %)

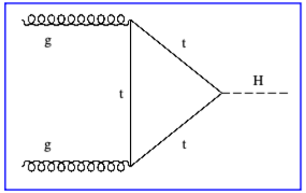


$t\bar{t}H$: 0.5 pb (1 %)

* 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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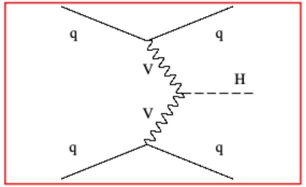

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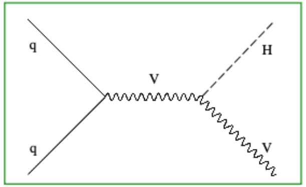

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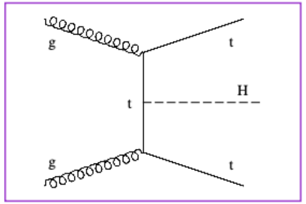
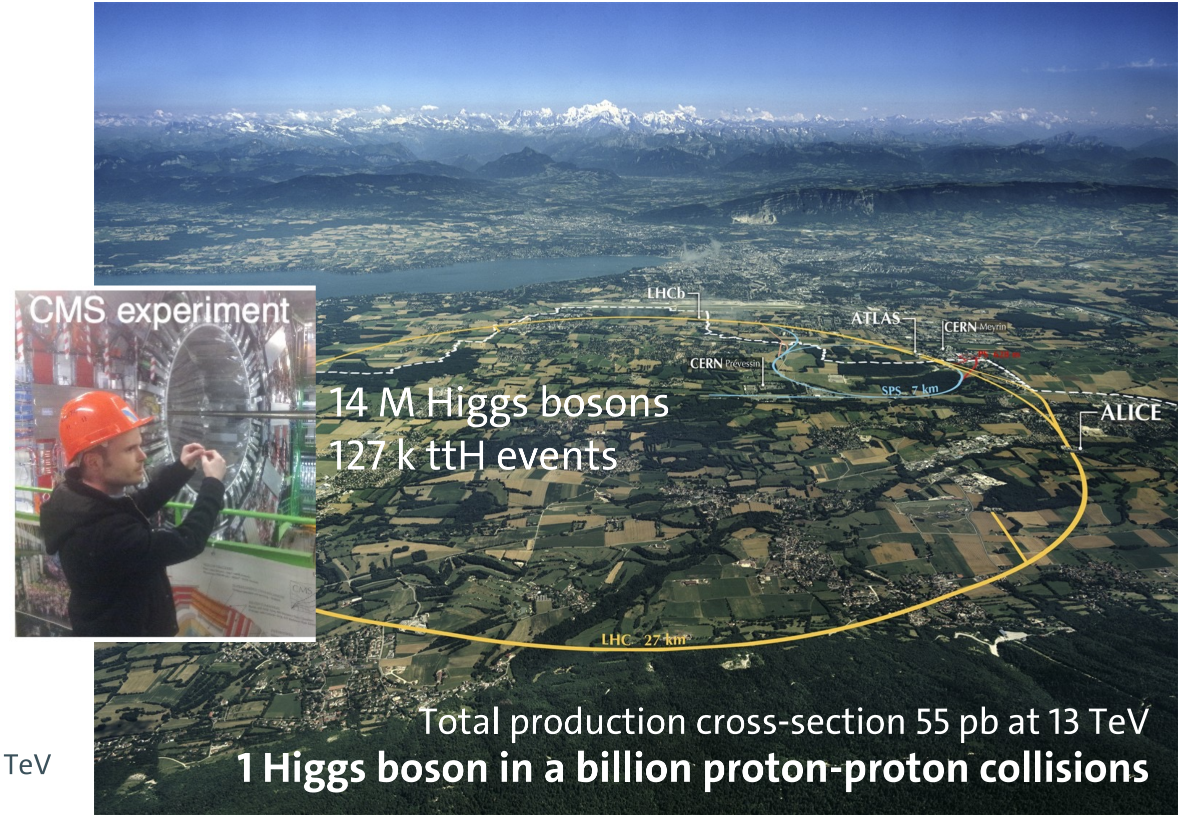


tt̄H: 0.5 pb (1 %)

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



Higgs-boson decay channels

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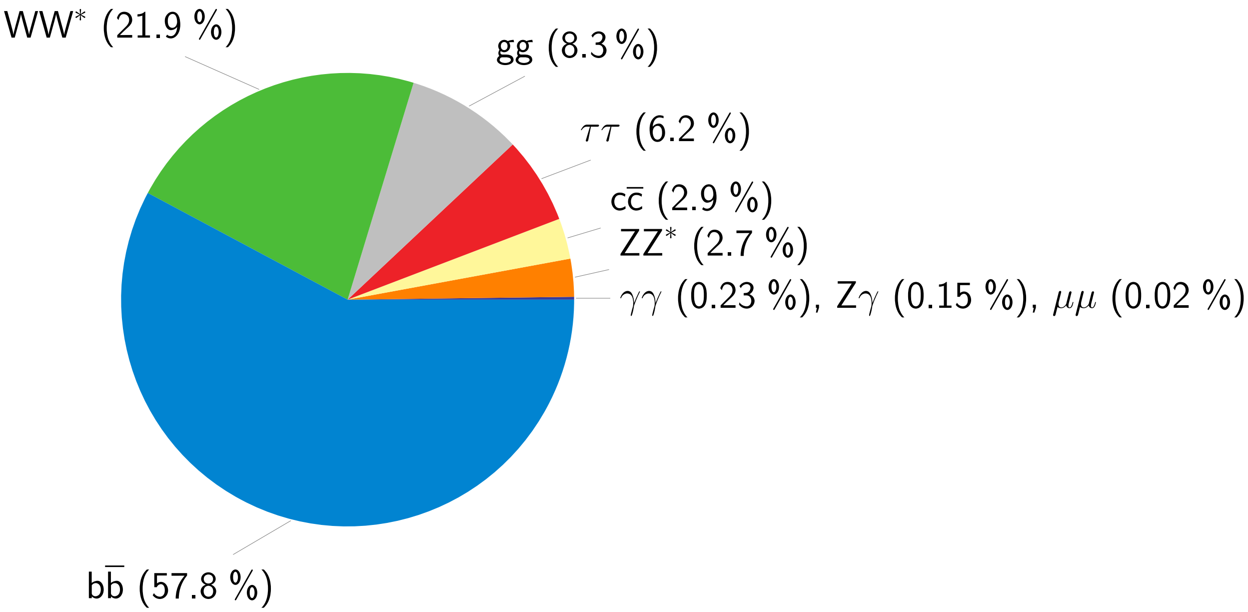
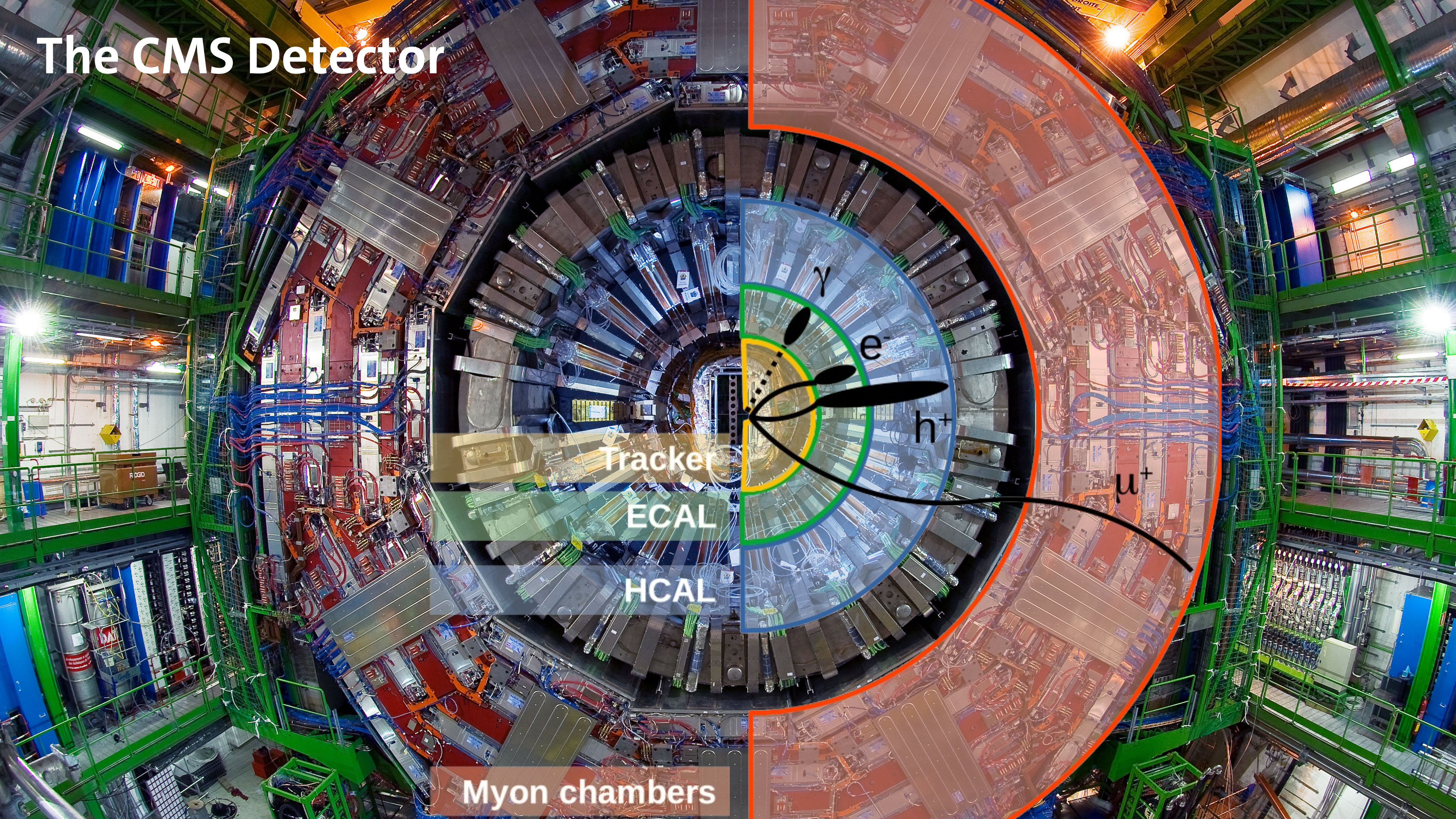
Branching ratios for m_{H} = 125 GeV in the Standard Model [arXiv: 1610.07922]



The CMS Detector

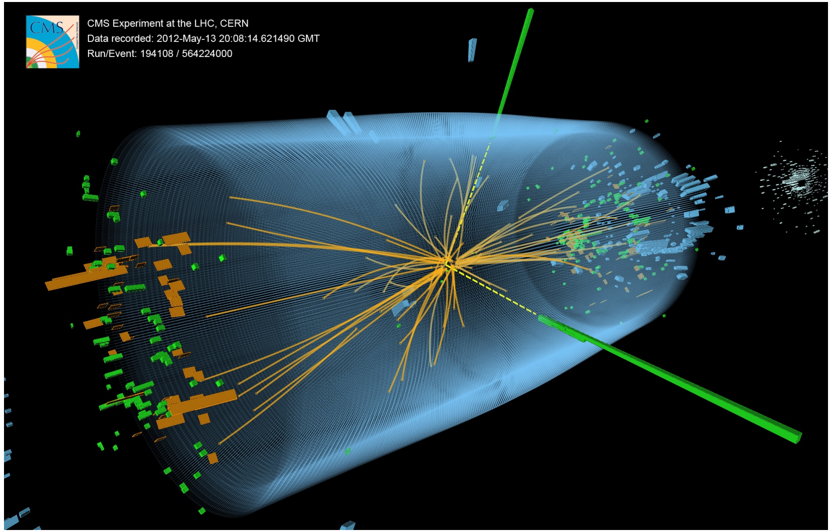
All detector components needed in Higgs analyses

Very different signatures depending on the production and decay modes

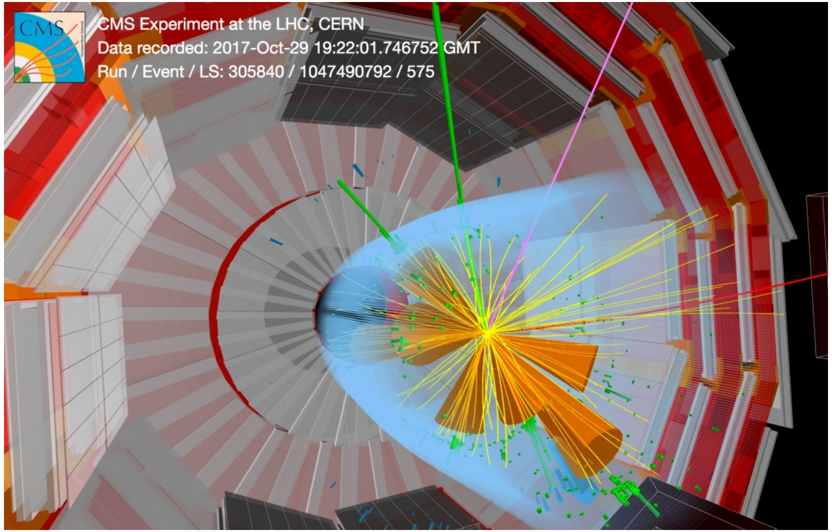

The CMS Detector
γ
e⁻
h⁺
μ⁺
Tracker
ECAL
HCAL
Myon chambers

Higgs-boson candidate events

$H \to \gamma\gamma$ candidate



ttH with $H \to bb$ candidate



All detector components needed in Higgs analyses

Very different signatures depending on the production and decay modes

Coupling measurement
Deviations from SM?

Measurement of ttH and tH production with H → bb

ttH measurements at the LHC

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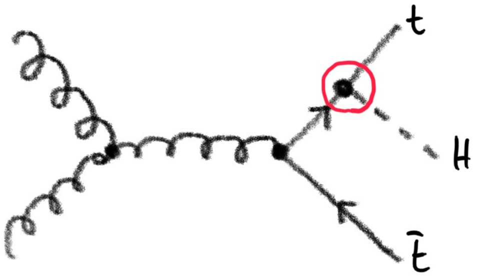
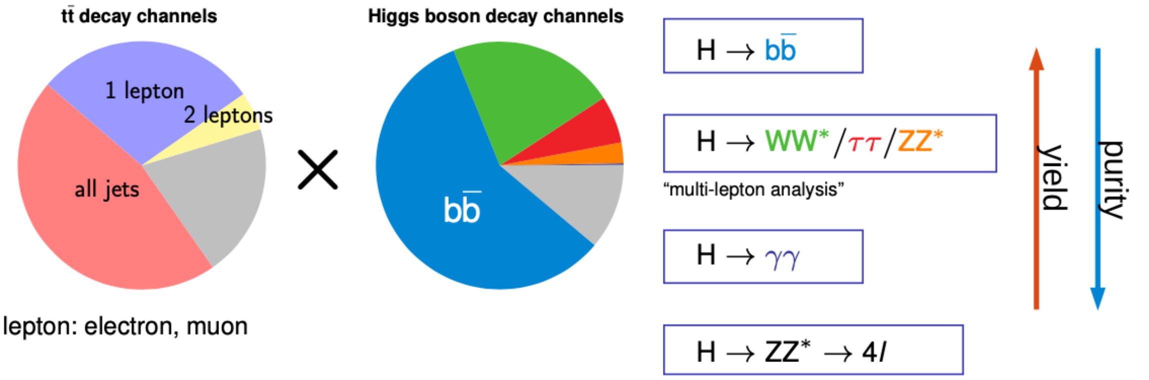
ttH production: direct probe of top-Higgs coupling



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

Multitude of possible final states with many and different objects



Independent observation by ATLAS and CMS in 2018, combining several channels

Phys. Rev. Lett. 120 (2018) 231801

Phys. Lett. B 784 (2018) 173

ttH measurements at the LHC: status today

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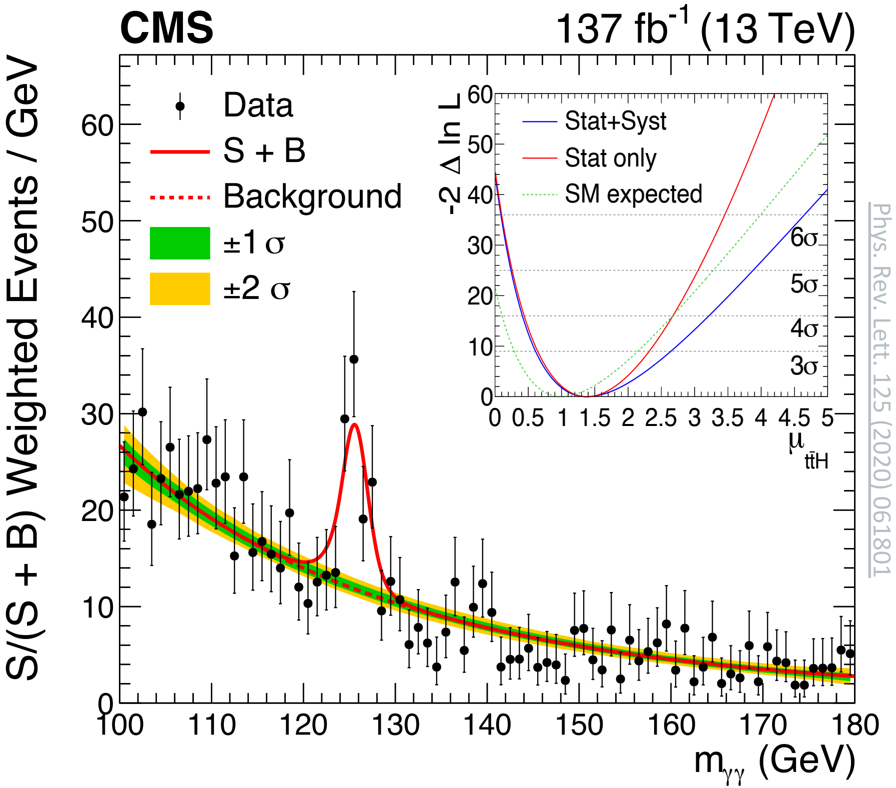
channel		dataset	$\mu = \frac{\sigma}{\sigma_{SM}}$	significance	add. results	
$H \to b\bar{b}$	ATLAS	$139\,fb^{-1}$	$0.35^{+0.36}_{-0.34}$	$1.0\,\sigma$ (2.7 exp.)	STXS, CP	[JHEP 06 (2022) 097] [arXiv:2303.05974, subm. to PLB]
	CMS	$138\,fb^{-1}$	$0.33^{+0.26}_{-0.26}$	$1.3\,\sigma$ (4.1 exp.)	STXS,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

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

Major improvements in analysis methods & 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

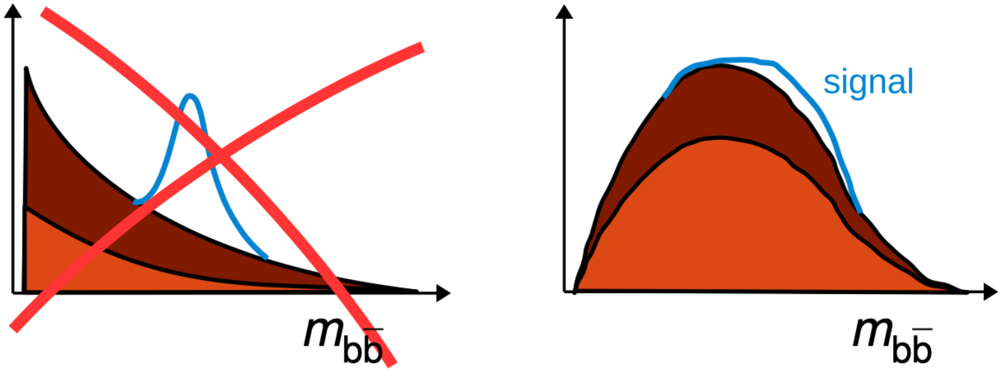
But tiny rate: limited by statistical uncertainties

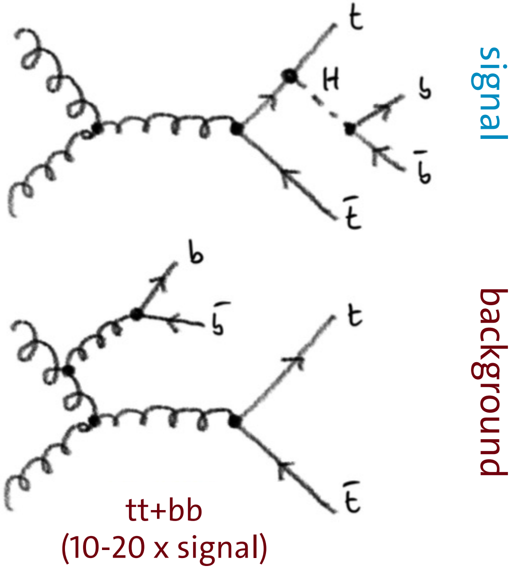
ttH with H → bb

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





ttH with H → bb

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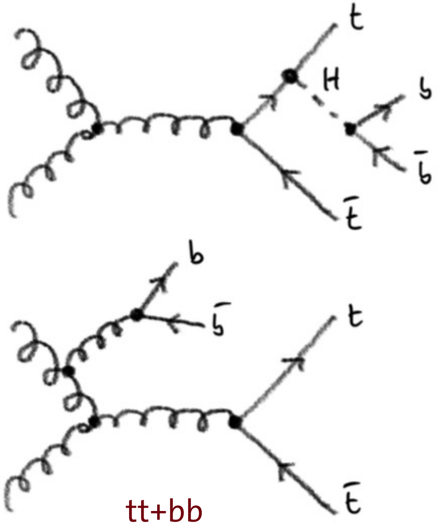
Benefit from large H → bb branching ratio of 58 %

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

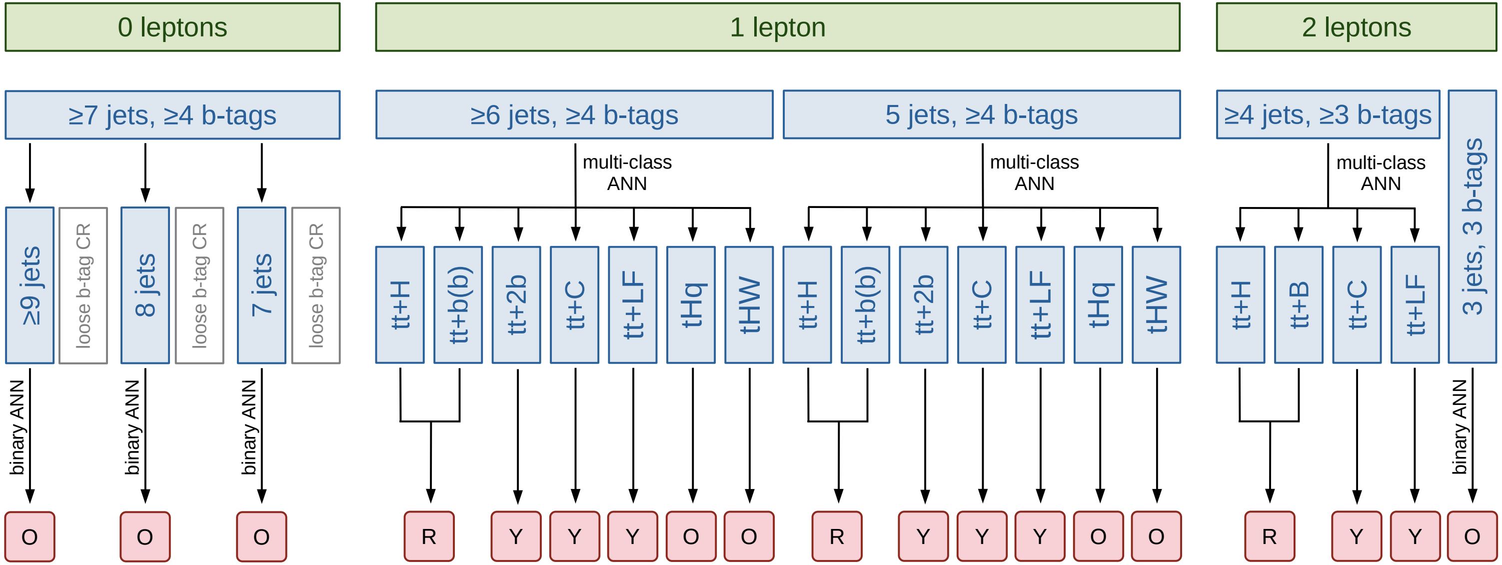
Channel	BR	Background
Fully hadronic (FH)	45%	QCD, tt+jets
Single lepton (SL)	30%	tt+jets
Dilepton (DL)	5%	tt+jets

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



tt+bb
(10-20 x signal)

Analysis strategy



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

Analysis strategy

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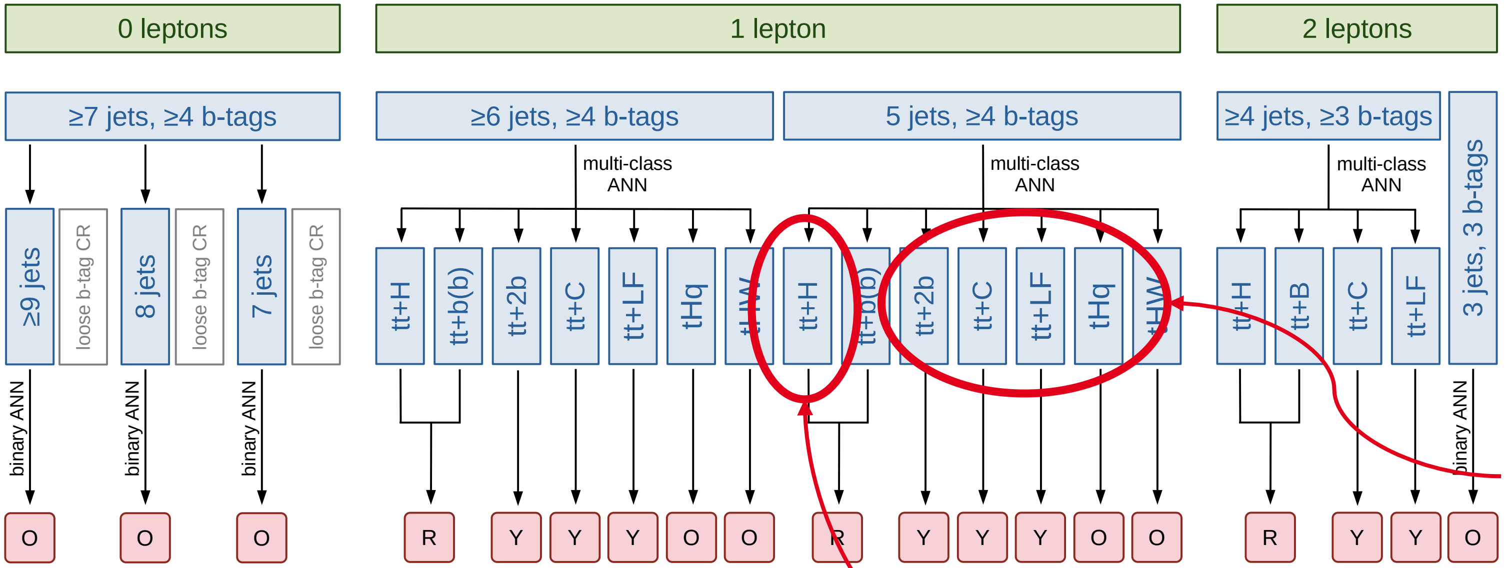


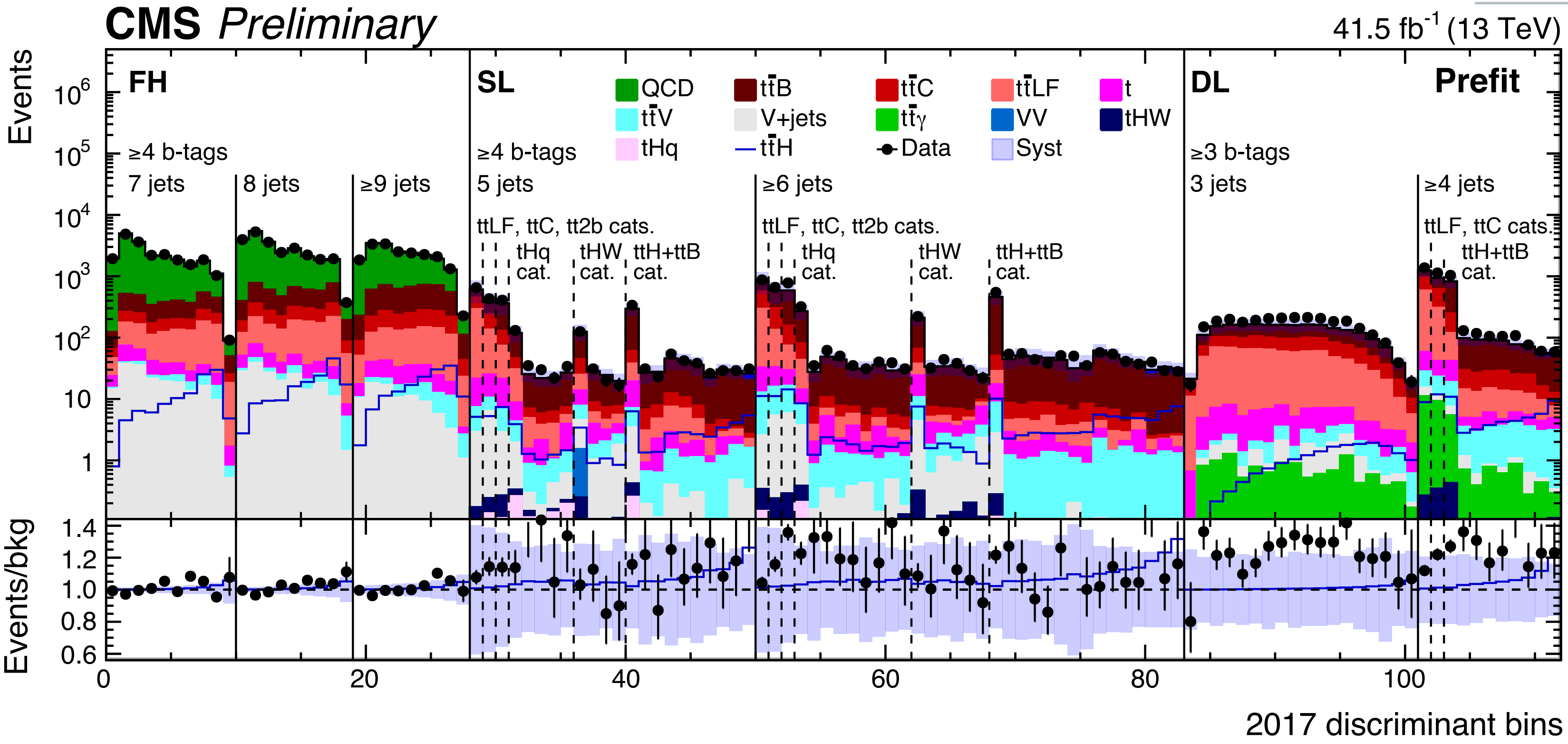
Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

1. Control regions to constrain background

2. Signal regions to separate signal from background

Final discriminant observable

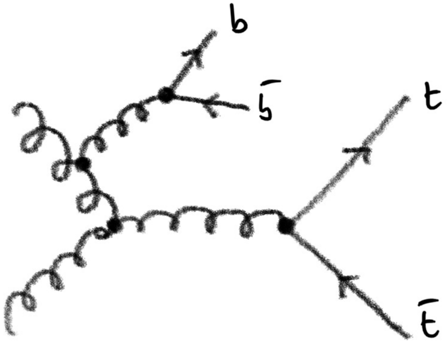
CMS-PAS-HIG-19-011



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, acc. by JHEP]



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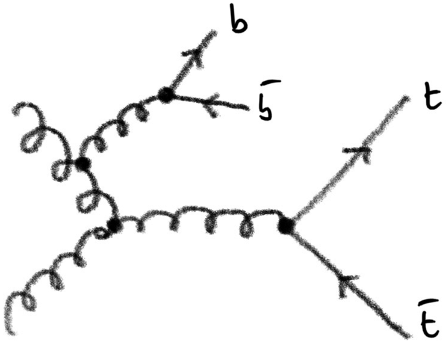

Different **approaches** to simulate events include:

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

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

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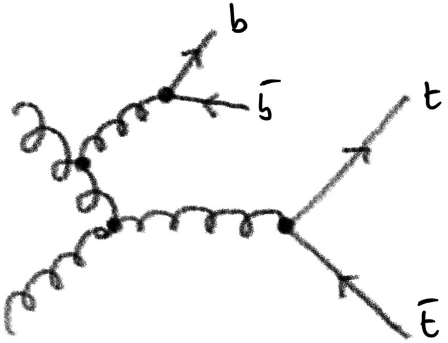

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expect better description of kinematics
and better defined uncertainties

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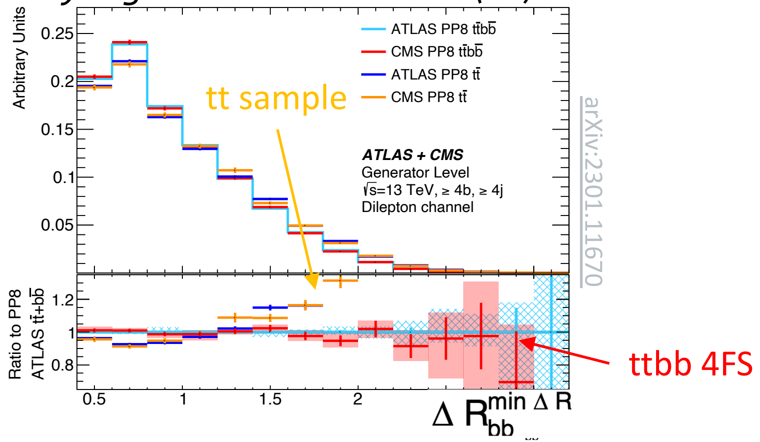
Study together with ATLAS ttH(bb) team



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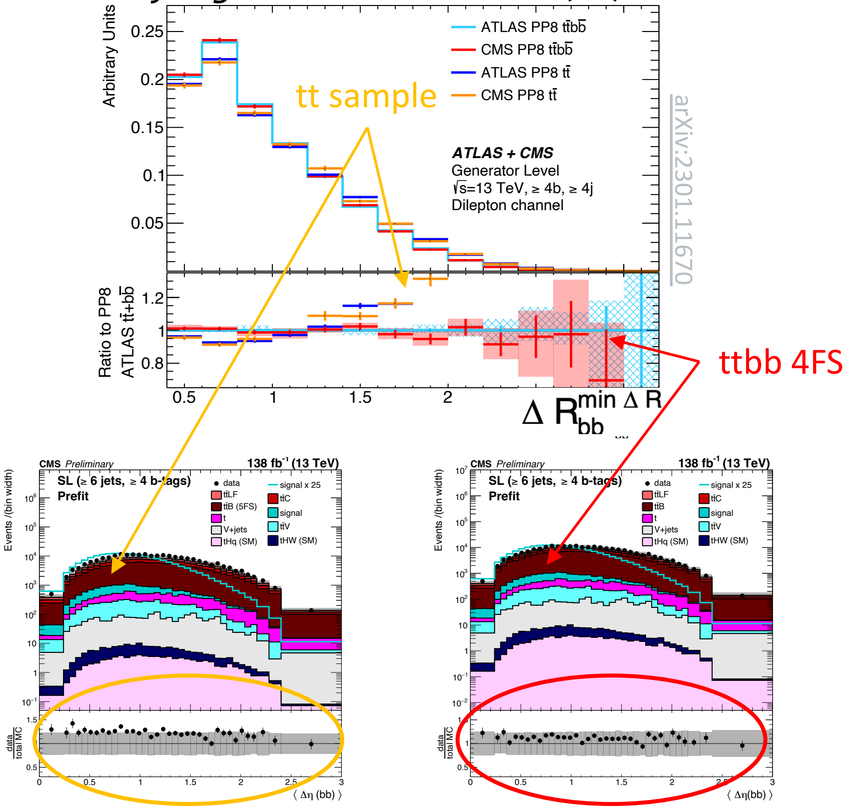

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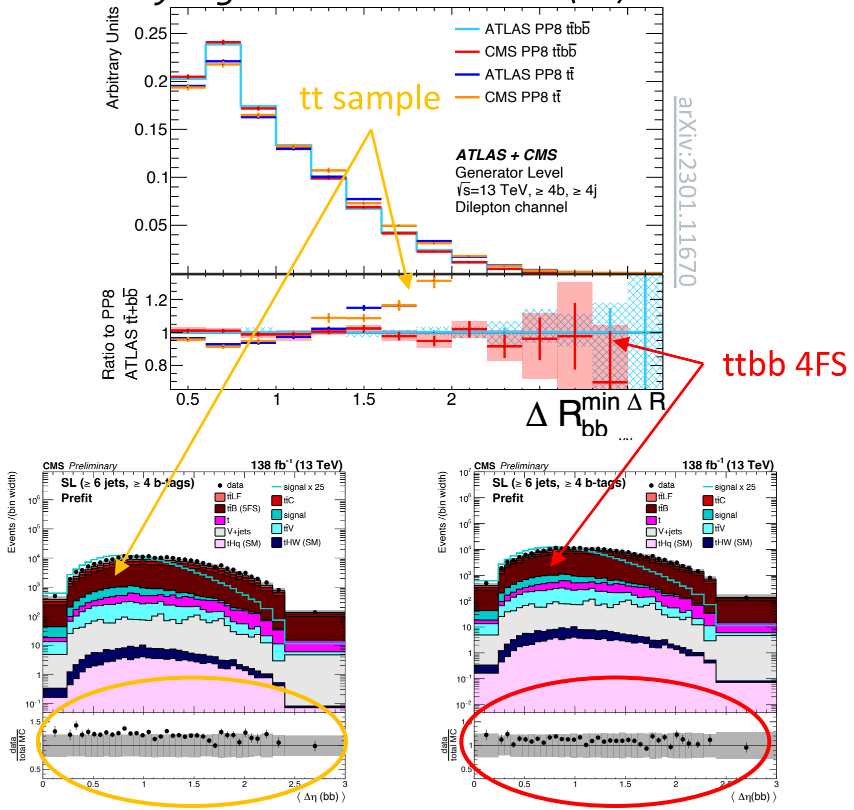
Major improvement in background model:

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

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Careful **scruntiny of NN input variables**, incl. GoF tests

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%		1.01 ± 0.09	1.01 ± 0.18
ttbb sample, ttB $\times$ 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, ttB $\times$ 1.2	1.06 ± 0.32	1.18 ± 0.12	0.85 ± 0.20

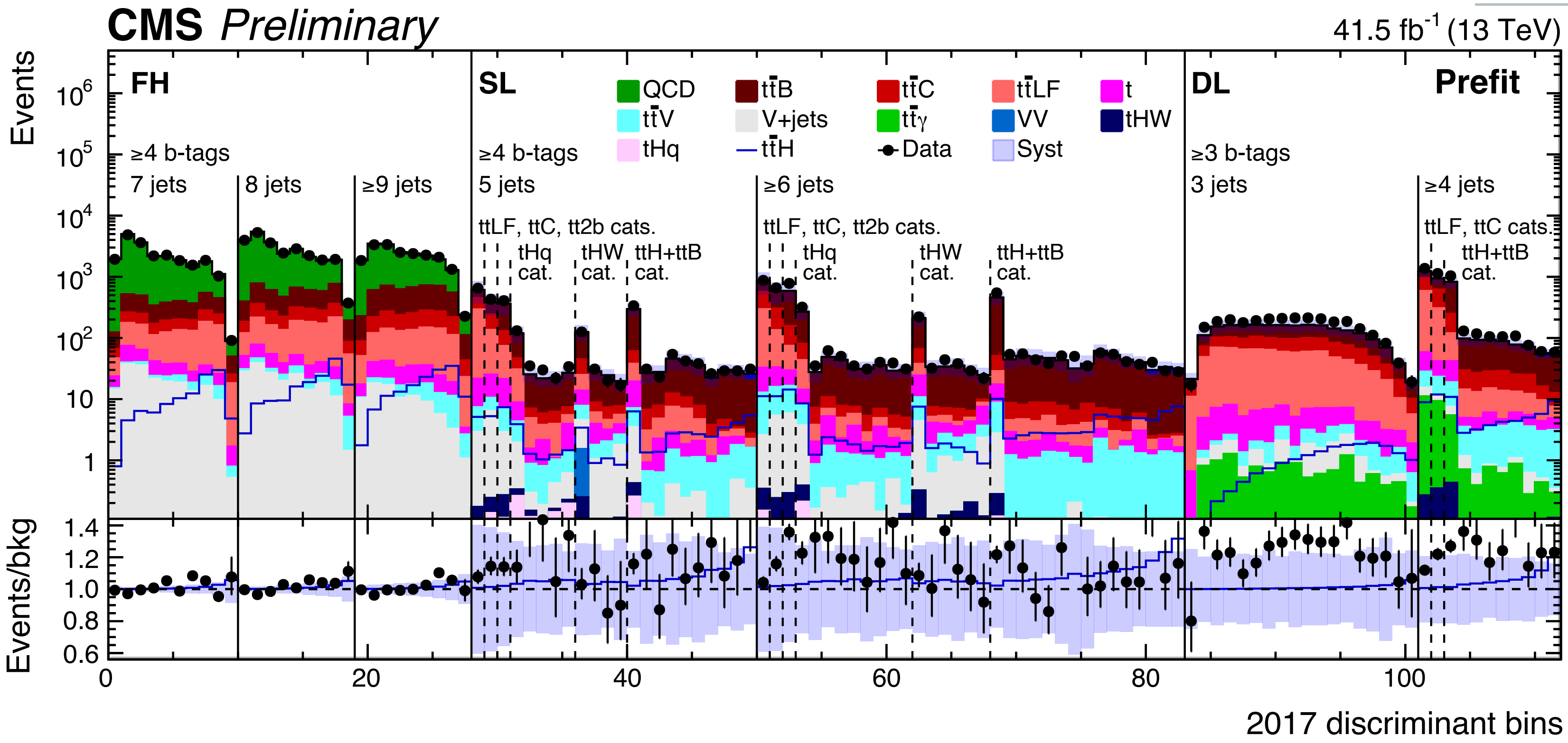
Injected signal strength (1.0) and background normalisation (1.2) recovered

Modelling uncertainties

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

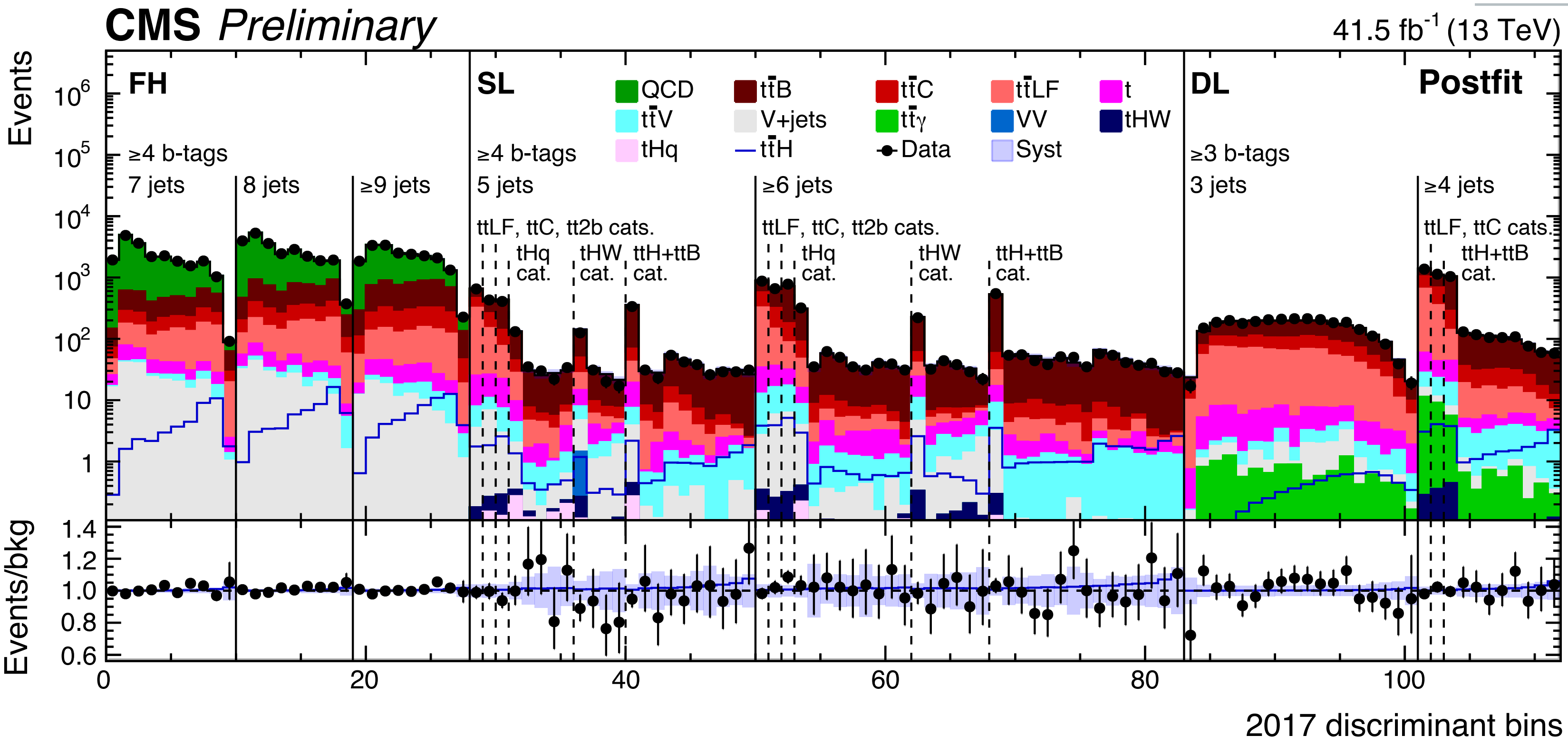
Final discriminant

CMS-PAS-HIG-19-011



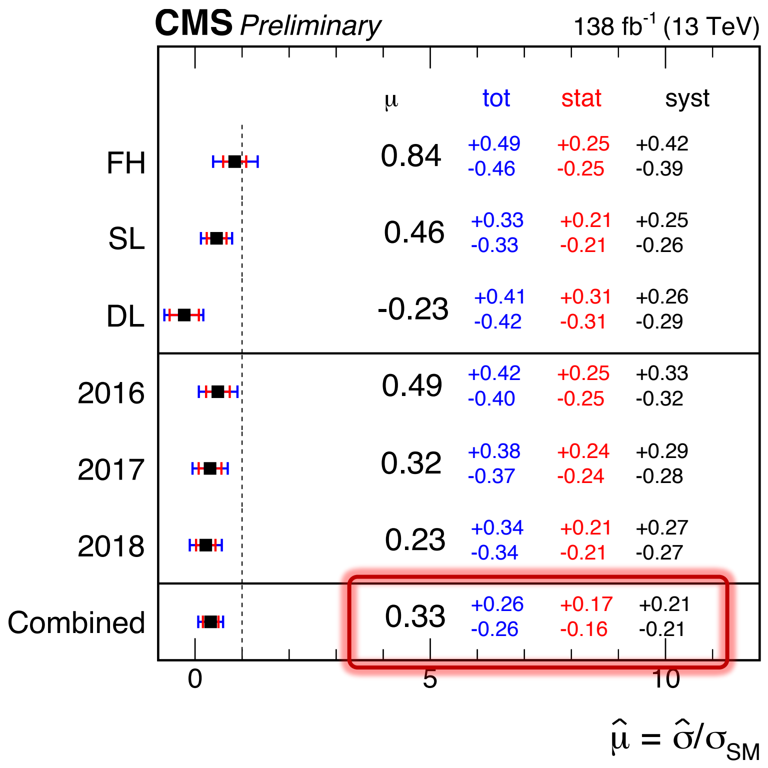
Final discriminant

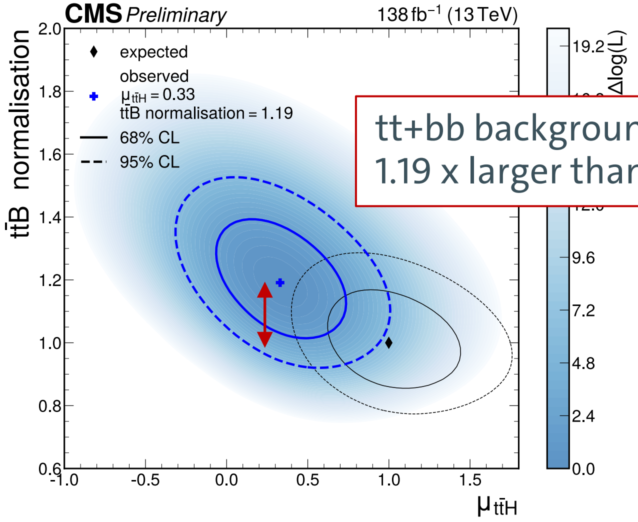
CMS-PAS-HIG-19-011



Results: ttH production with H → bb

CMS-PAS-HIG-19-011





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]

Results: tH production with H → bb

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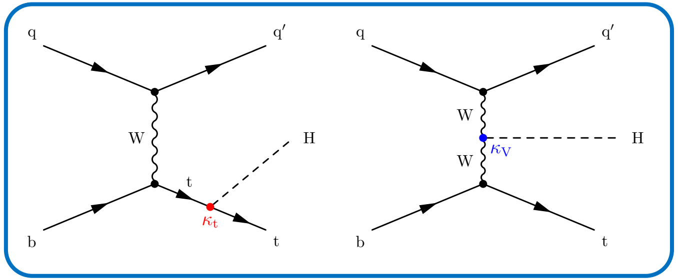
Dedicated analysis categories targeting tH events



tH production: σ_{SM} = 90fb

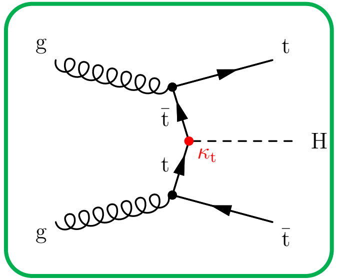
[arXiv: 1610.07922]

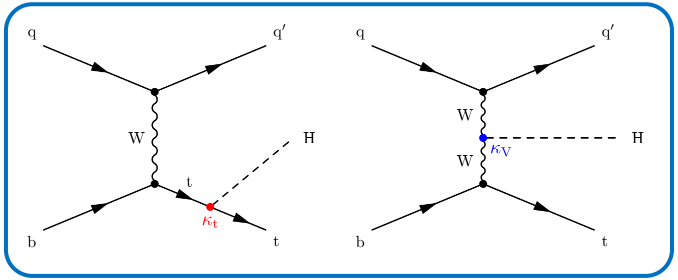
Upper limit of 14.6 obs. (19.3$^{+9.2}_{-6.0}$ exp.) x SM
tH production at 95% CL

Coupling interpretation

CMS-PAS-HIG-19-011

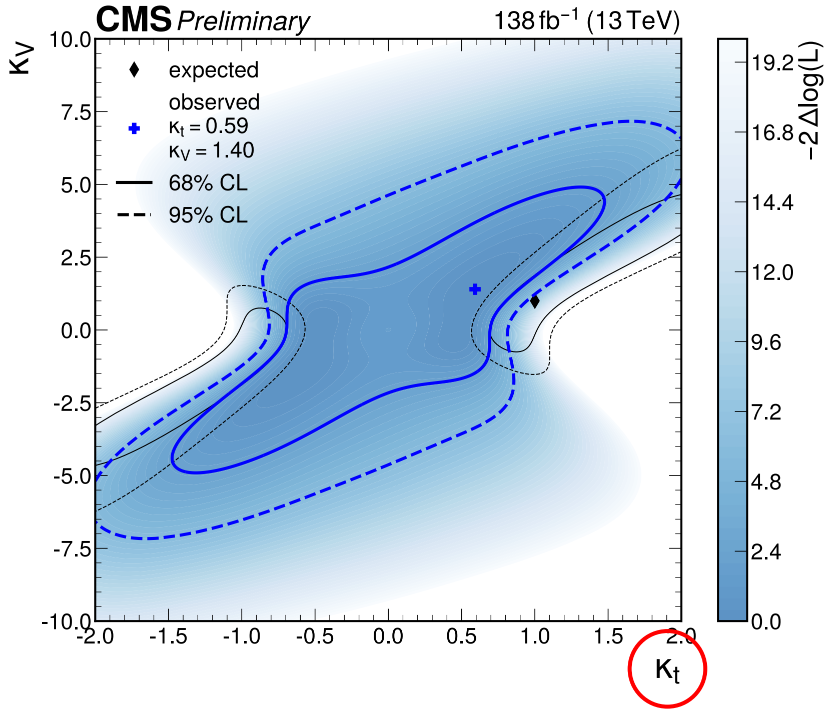
ttH and tH cross-sections depend differently on top-Higgs coupling κ_t





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!)**

CP interpretation

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CP-odd component in top-Higgs interaction?

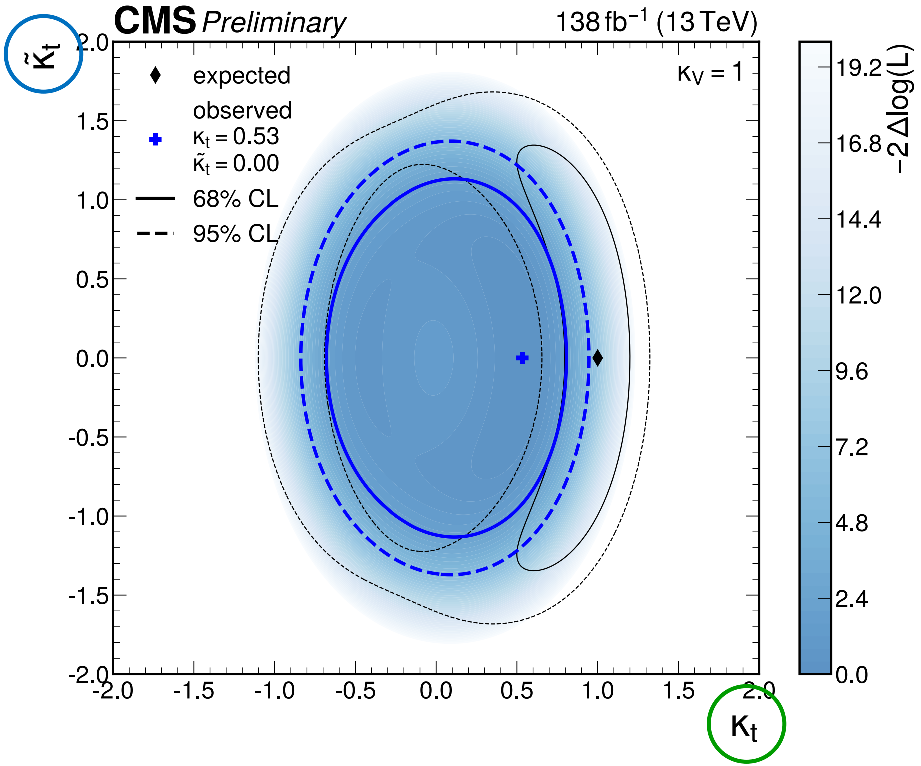
In principle allowed at tree level!

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

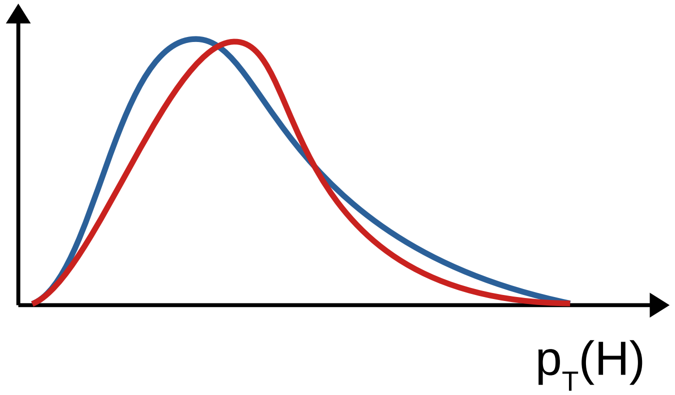
CP-even/CP-odd Yukawa coupling
(SM: $\kappa_t = 1$, $\kappa_t = 0$)

→ can modify ttH and tH rates and kinematics differently

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



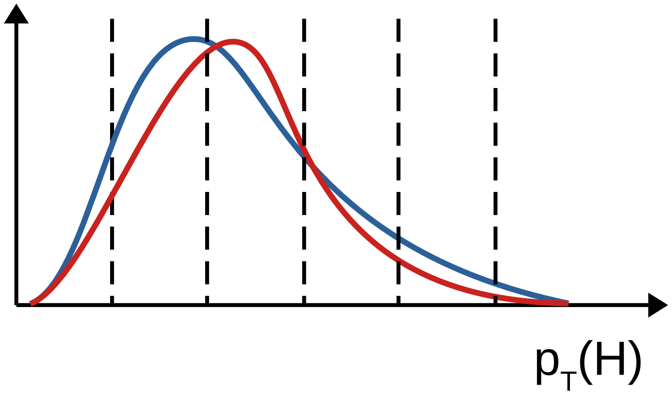
Beyond inclusive measurements



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

("Simplified Template Cross Section", STXS)

Beyond inclusive measurements



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

("Simplified Template Cross Section", STXS)

ttH production in bins of p_T(H)

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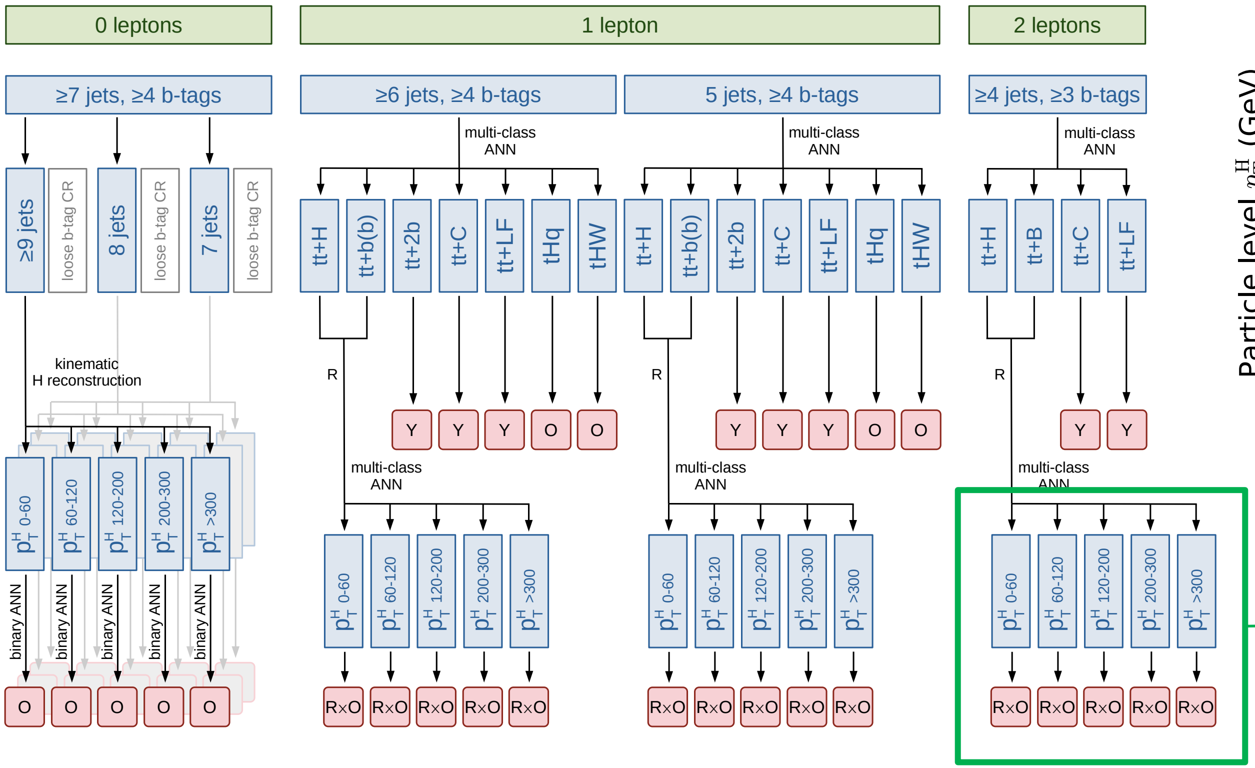
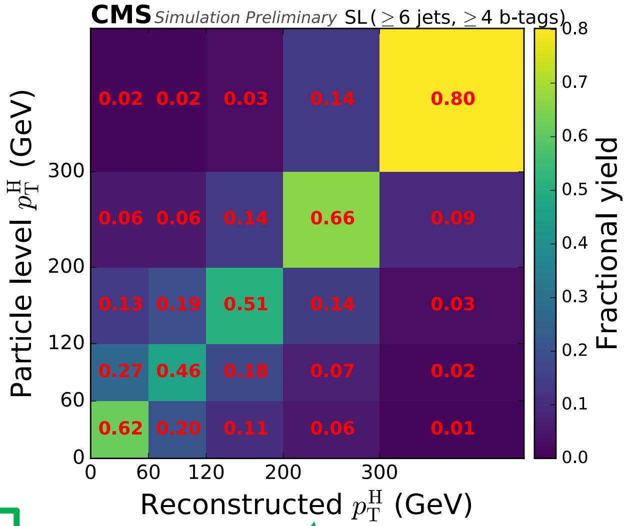


Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)



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

ttH production in bins of $p_T(H)$

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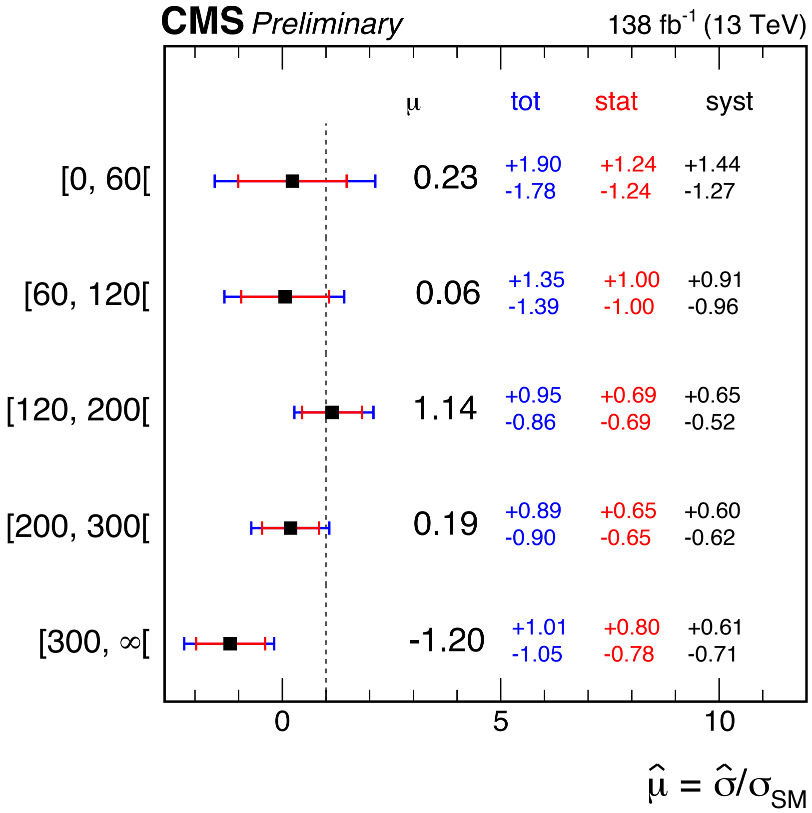
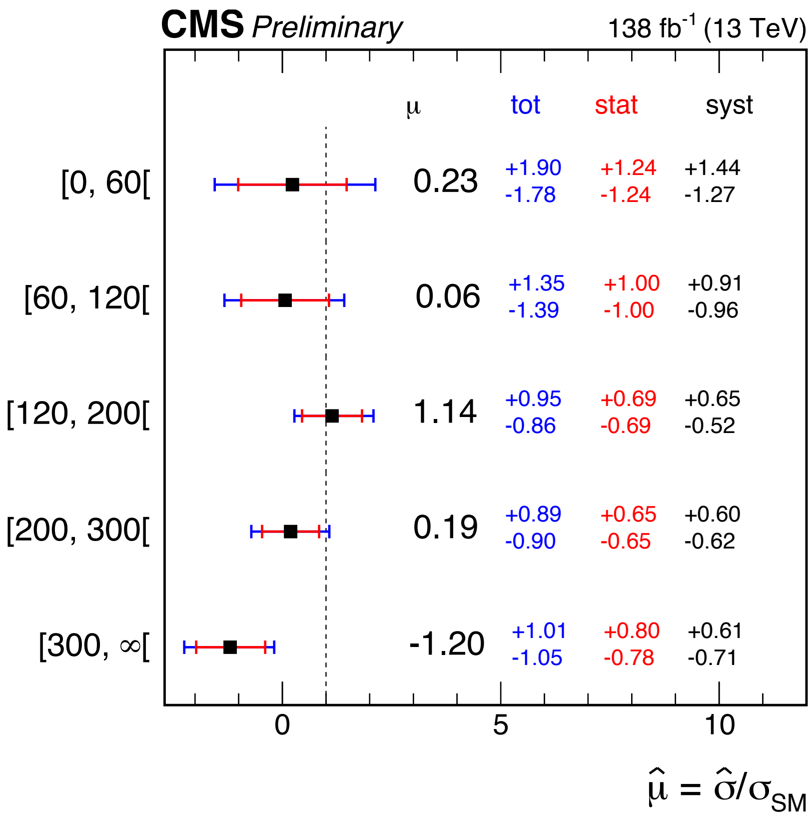


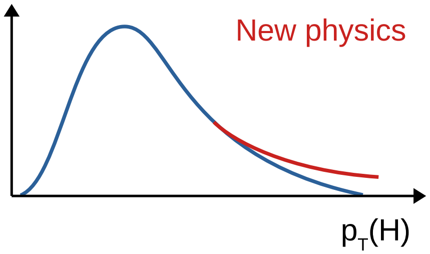
Sensitivity still limited but **interesting for future measurements and combination** with other channels

ttH production in bins of $p_T(H)$

CMS-PAS-HIG-19-011



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



Effects from heavy particles could show up here

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

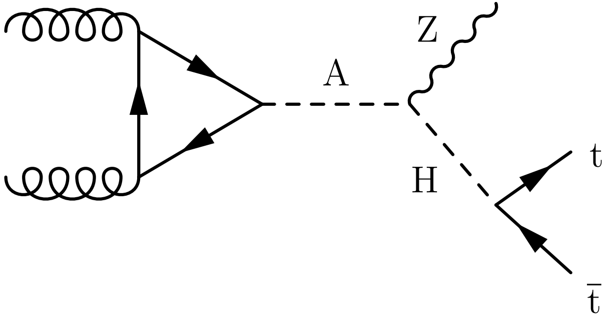
Direct search for
heavy Higgs bosons

Search for heavy Higgs bosons $A \rightarrow ZH$ with $H \rightarrow tt$

Search for A → ZH with H → tt

Model-independent search for narrow resonances A and H in ttZ final state

Inspired by 2HDM "smoking gun" signature



Brand new

analysis of 138 fb^{-1} of 13 TeV data

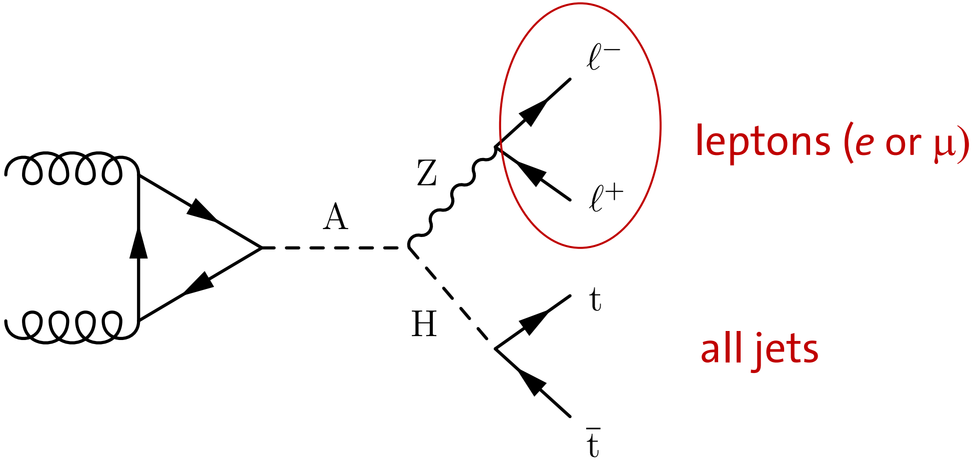
First CMS result in this final state

[CMS-PAS-B2G-23-006]

Search for A → ZH with H → tt

Model-independent search for narrow resonances A and H in ttZ final state

Inspired by 2HDM "smoking gun" signature



Brand new

analysis of 138 fb^{-1} of 13 TeV data

First CMS result in this final state

[CMS-PAS-B2G-23-006]

Search for A → ZH with H → tt

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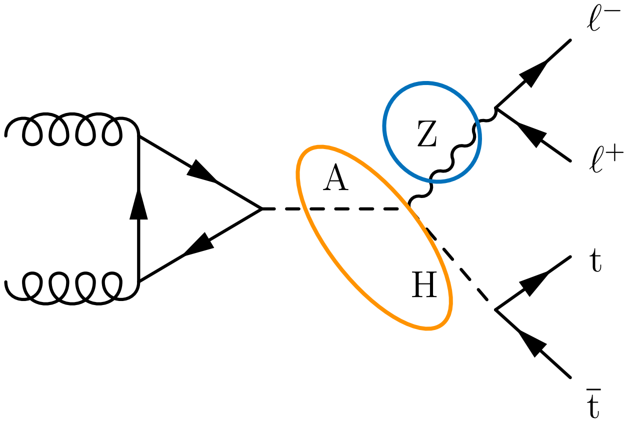
Model-independent search for narrow resonances A and H in ttZ final state

Inspired by 2HDM "smoking gun" signature

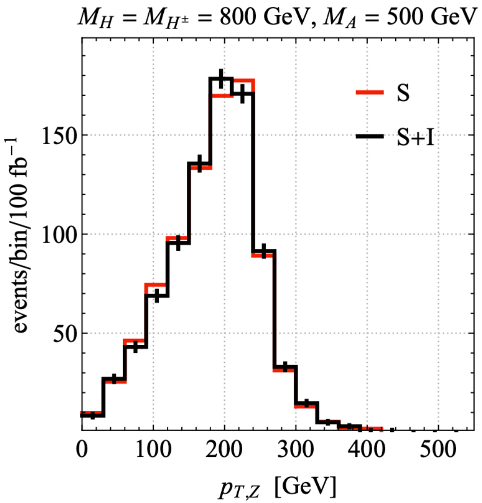


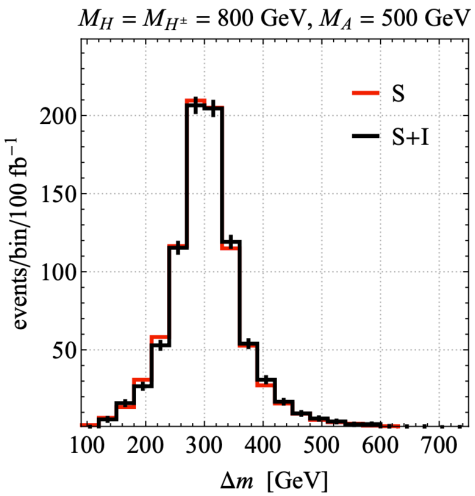
$p_{T,Z}$: from lepton 4-momenta

$\Delta m = M_{ttZ} - M_{tt} = m_A - m_H$

(tt system from jet 4-momenta)

Sensitive observables [JHEP 09 (2018) 151]





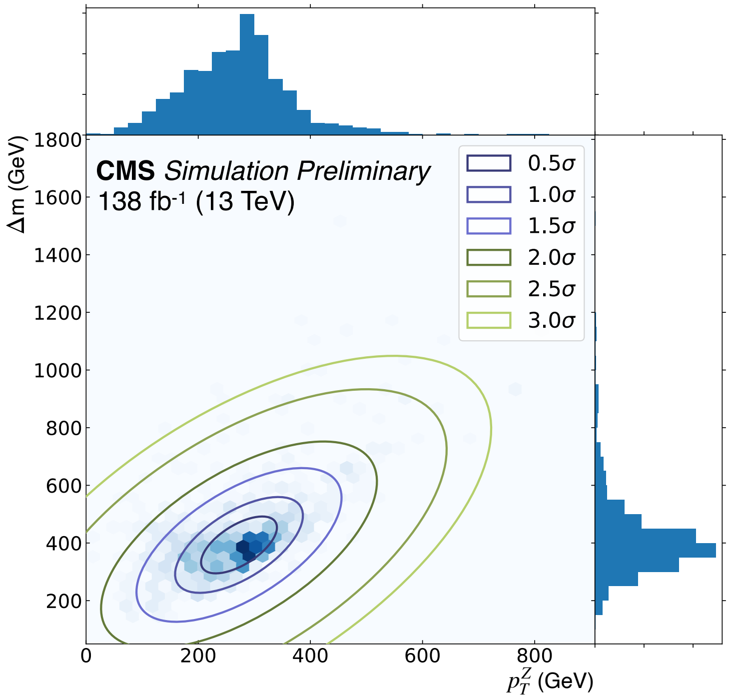
$p_{T,Z}$: kinematic edge

Δm: peak

Final observable

CMS-PAS-B2G-23-006

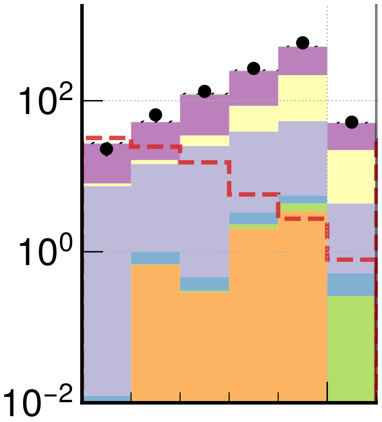
Example **signal distribution** for (mA, mH) = (1000, 600) GeV

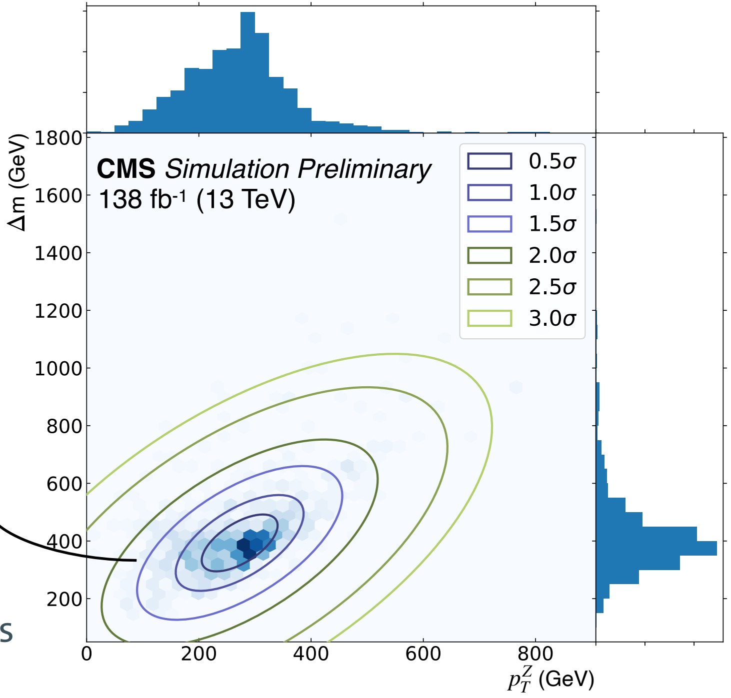


Final observable

CMS-PAS-B2G-23-006

Example **signal distribution** for (mA, mH) = (1000, 600) GeV

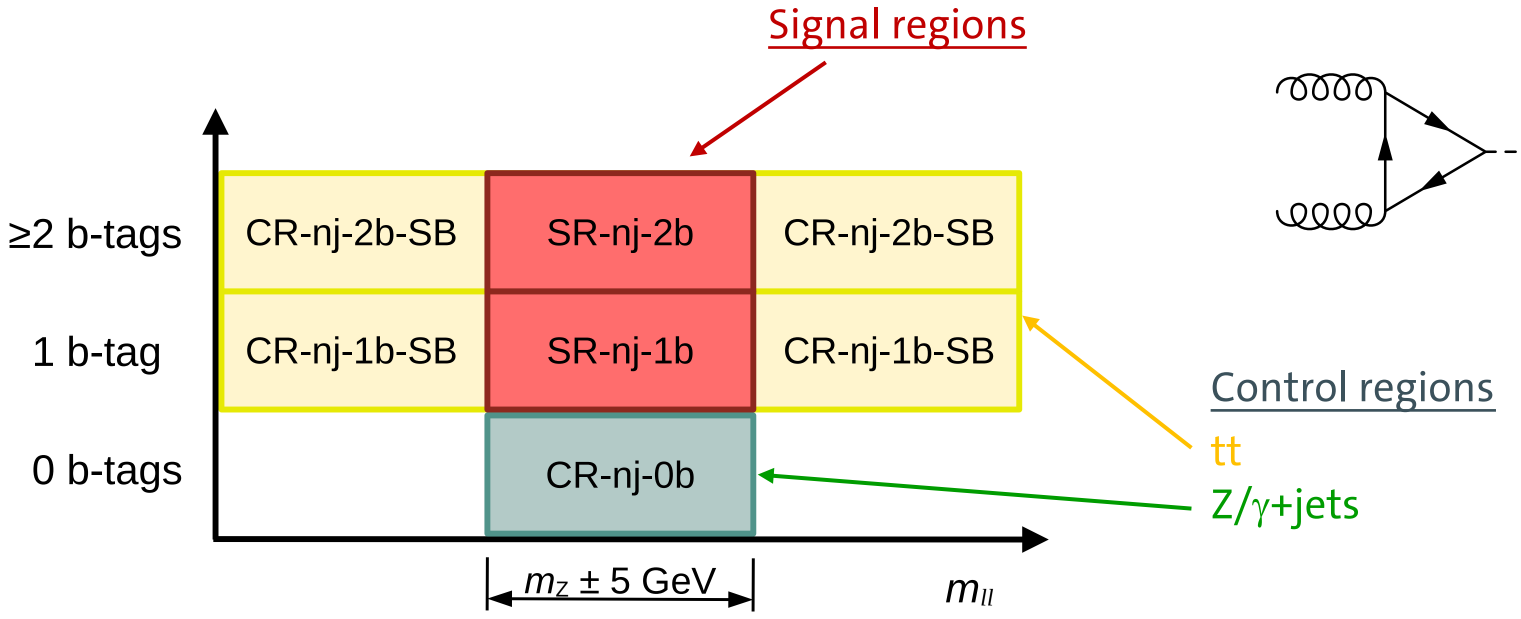


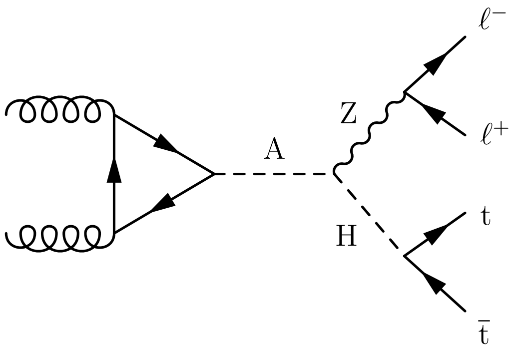


2D (Δm, $p_{T,Z}$) distribution → 1D

Binning specific for each mass hypothesis

Analysis strategy





with n = 5 or ≥6 jets

$t\bar{t}$ and Z/γ+jets background modelling

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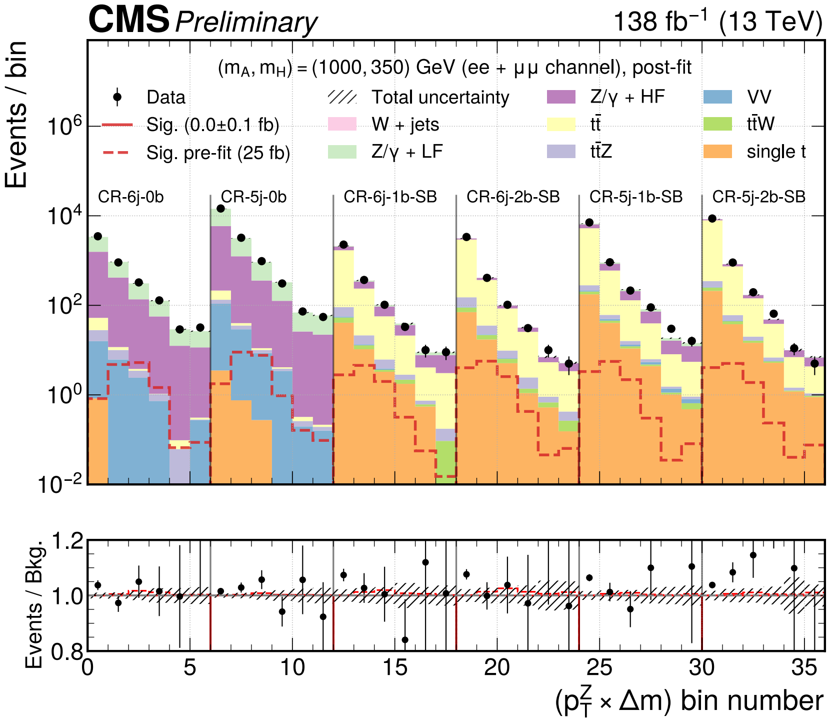
Shape from simulation + normalisation from fit to data

$t\bar{t}$ background

Z/γ+jets background



tt and Z/γ+jets background modelling

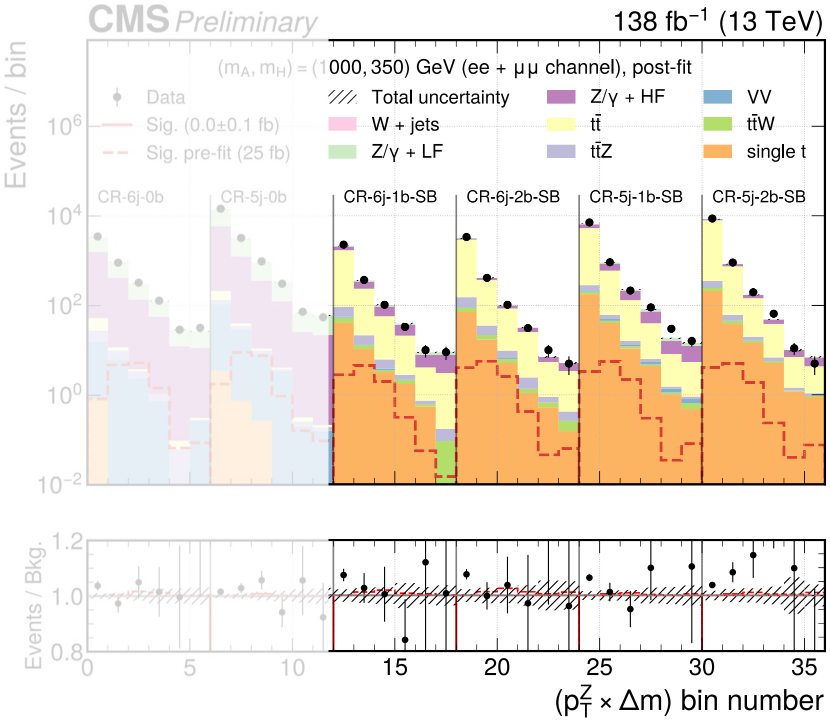
CMS-PAS-B2G-23-006

Shape from simulation + normalisation from fit to data

tt background

- Powheg tt NLO simulation
- Post-fit normalisation 0.82—0.94 ± 0.1 *
  (relative to NNLO+NNLL prediction)

Z/γ+jets background



* Exact value depending on signal mass hypothesis

tt and Z/γ+jets background modelling

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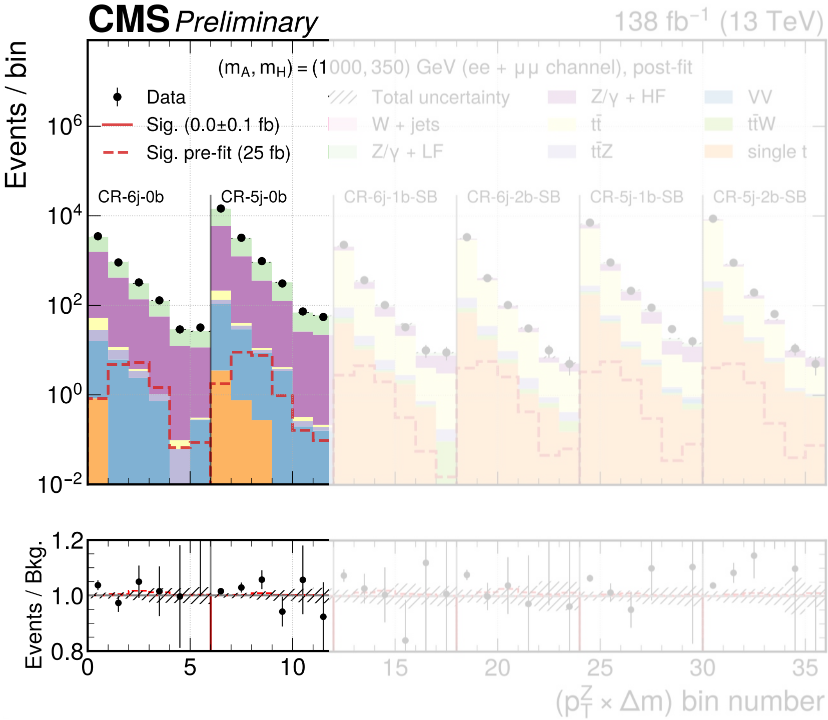
Shape from simulation + normalisation from fit to data

tt background

- Powheg tt NLO simulation
- Post-fit normalisation 0.82—0.94 ± 0.1 *
  (relative to NNLO+NNLL prediction)

Z/γ+jets background

- MadGraph Z/γ + ≤ 4 jets LO simulation
  + NLO EWK+QCD corrections in $p_T(Z/\gamma)$
- 40% norm. uncert. on Z/γ + b/c jets component
- Z/γ + b/c post-fit normalisation ≈ 1.4 ± 0.1 *

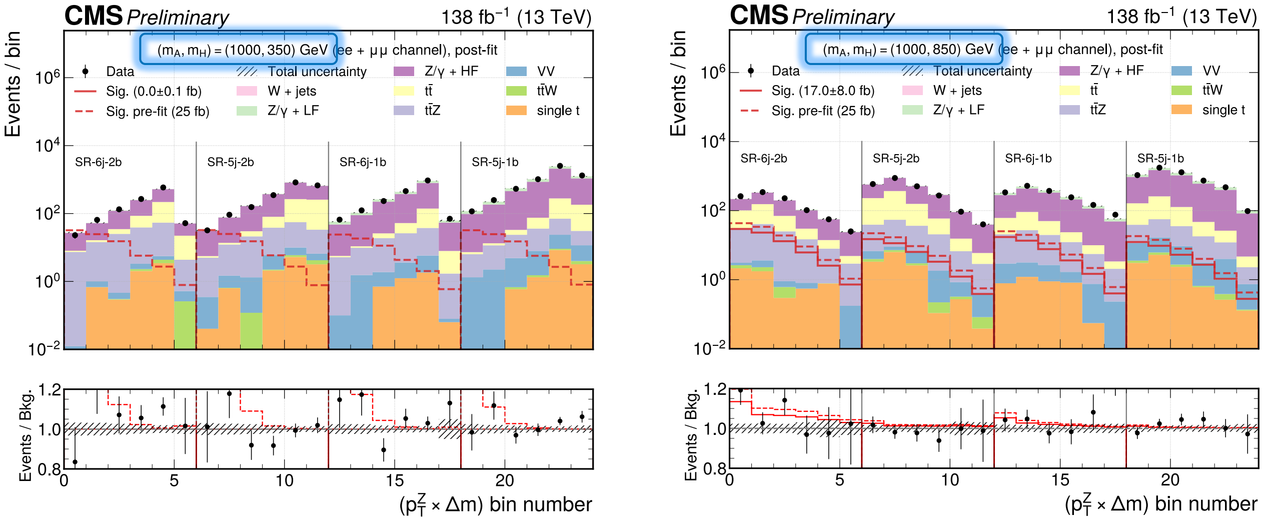


* Exact value depending on signal mass hypothesis

Results: A → ZH with H → tt

CMS-PAS-B2G-23-006

Various (m_A, m_H) hypotheses tested: for each, fit across all signal + control regions



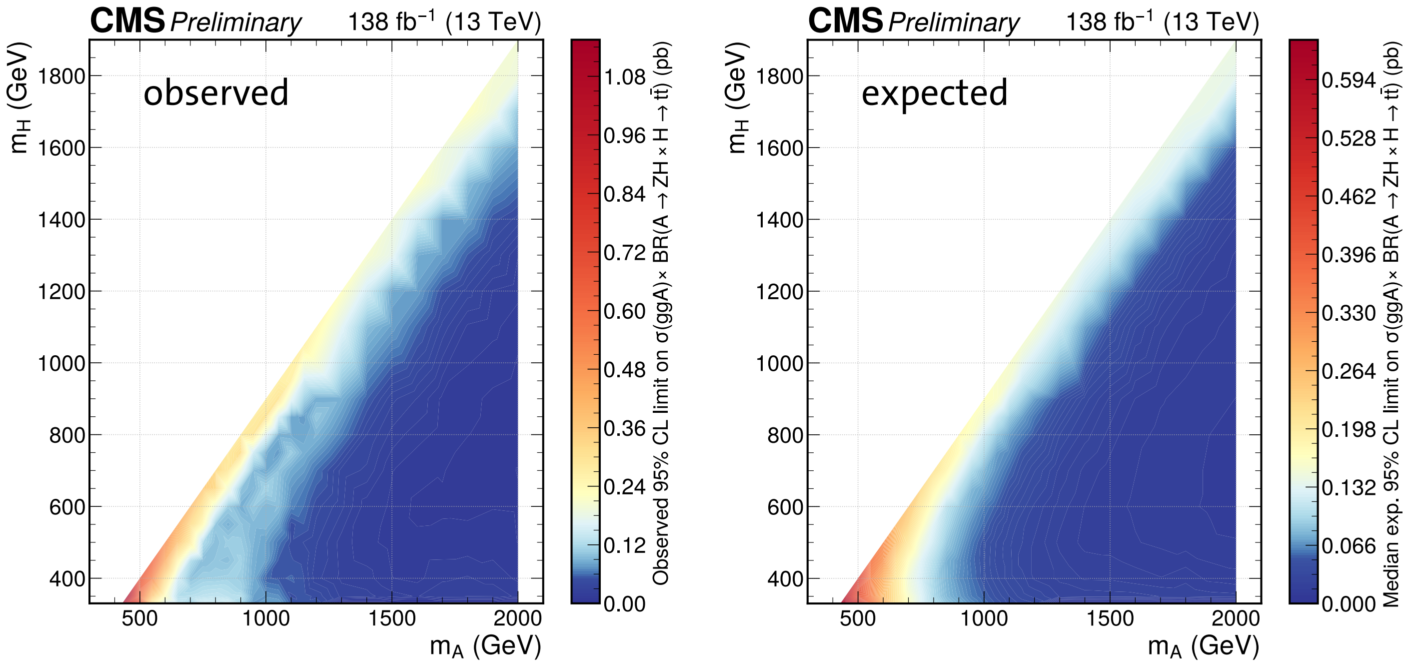
No significant excess above the background observed

Largest fluctuation: 2.1σ local significance for (m_A, m_H) = (1000, 850) GeV

Upper limits on signal production rate

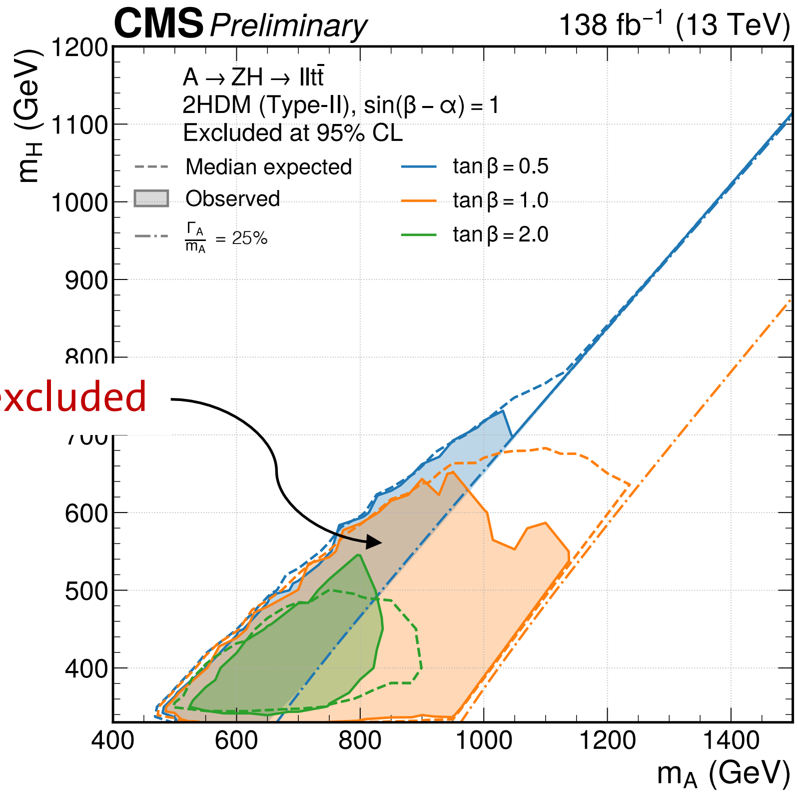
CMS-PAS-B2G-23-006

Model-independent limits on narrow resonance A → ZH production in ttZ final state



2HDM interpretation

CMS-PAS-B2G-23-006



regions excluded

2HDM interpretation

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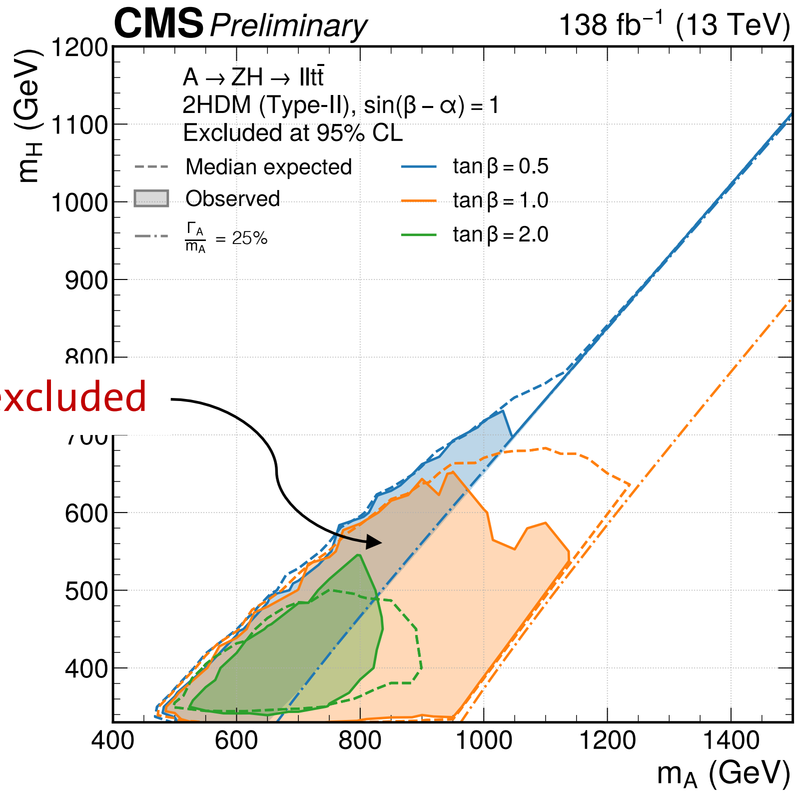
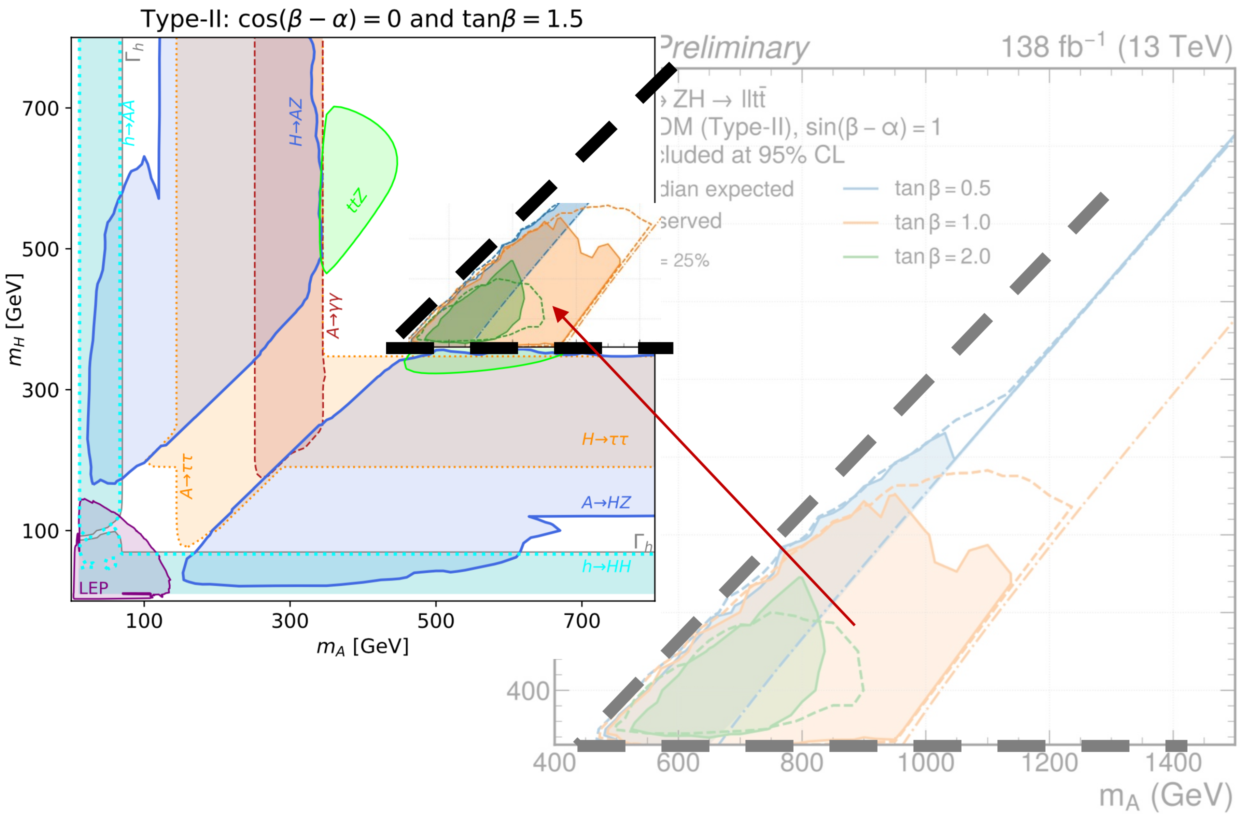


Excess at (650,450) seen by ATLAS not confirmed

JHEP 02 (2024) 197

2HDM interpretation

CMS-PAS-B2G-23-006



Constraints on models of electroweak baryogenesis

Summary

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Higgs sector plays a key role in the Universe

- Mass generation of fundamental particles
- Origin of matter-antimatter asymmetry?

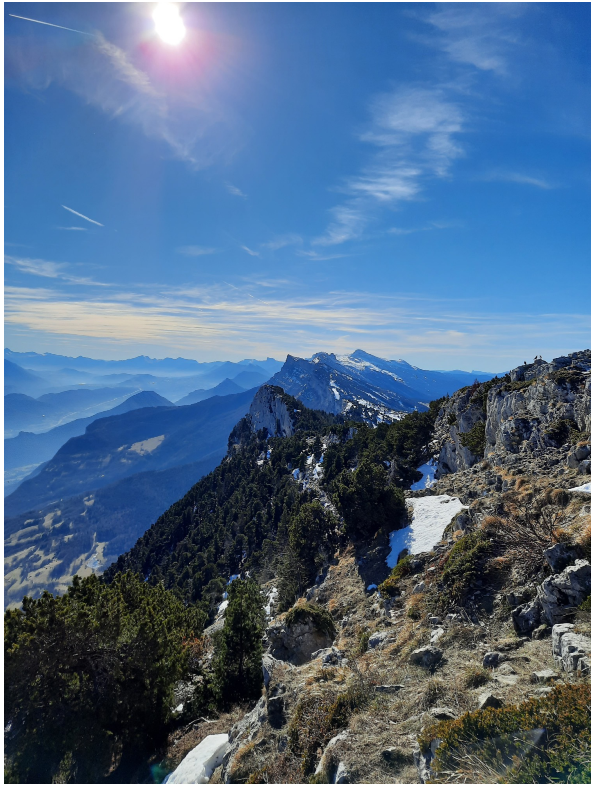
Still unknown territory for large parts

Top quarks are an excellent tool to explore the Higgs sector!

- Measurement of the top-Higgs coupling
- Direct search for additional Higgs bosons

So far, the Higgs sector looks SM-like…
but LHC Run 3 at full swing + more than 90% of all (HL-)LHC data yet to come

Our top route into the Higgs sector has just started!



Additional material

Top routes to the Higgs sector

A journey from the begin to the end of the Universe

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. While the experimental results so far are consistent with a SM nature of the Higgs boson, it might well be part of an extended Higgs sector, which is predicted in many beyond-the-SM (BSM) scenarios that address mysteries the SM cannot explain. The large data samples collected at the CERN Large Hadron Collider (LHC), together with new analysis techniques, allow measurements of the Higgs boson properties at unprecedented precision as well as direct searches for additional Higgs bosons with highest reach. The results play a crucial role in probing the SM and provide a unique window to potential BSM effects.

The coupling of the Higgs boson to the heaviest known quark, the top quark, is particularly exciting because it is large and, therefore, it plays a special role in the SM or possible BSM physics. In the presentation, I will discuss different techniques to explore the Higgs sector using top quarks, and I will highlight two recent results: a measurement of Higgs boson production in association with top quarks (ttH and tH production), which provide direct probes of the top-Higgs coupling, in the bb decay channel of the Higgs boson; and a brand-new search for heavy additional Higgs bosons decaying to a Z boson and a top quark-antiquark pair (ttZ final state). The search accesses a mostly unexplored part of the Two Higgs Double Model (2HDM) parameter space that is relevant in models of baryogenesis and could explain the matter-antimatter asymmetry in the Universe.

The Standard Model Higgs sector

Gauge interaction
W/Z boson masses

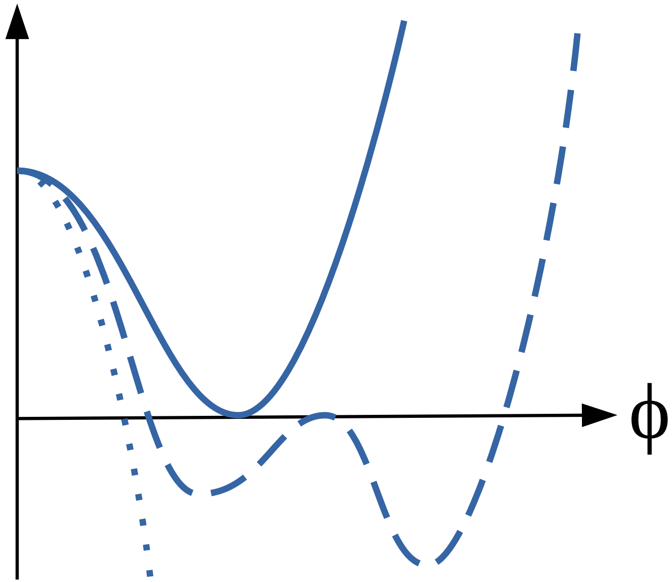
$$\mathcal{L} = |D_\mu \phi|^2 - V(\phi) + y_f \overline{\psi} \phi \psi$$

Higgs potential
symmetry breaking

Yukawa interaction
fermion masses

Special, unlike anything we have seen before!

Is the vacuum stable?



Where do we stand?

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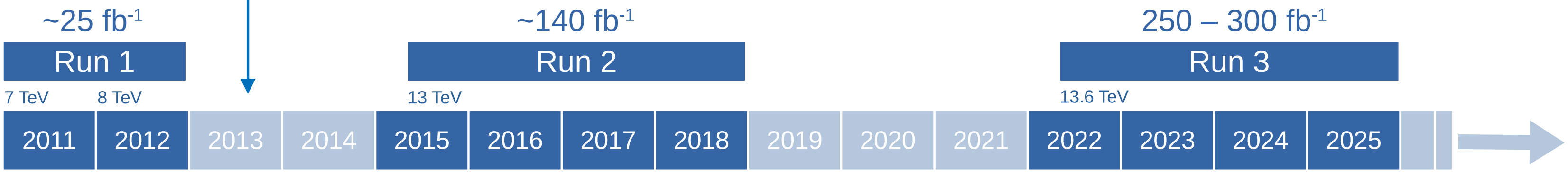
After Run 1
Properties (mass) with high precision
Decays to bosons established

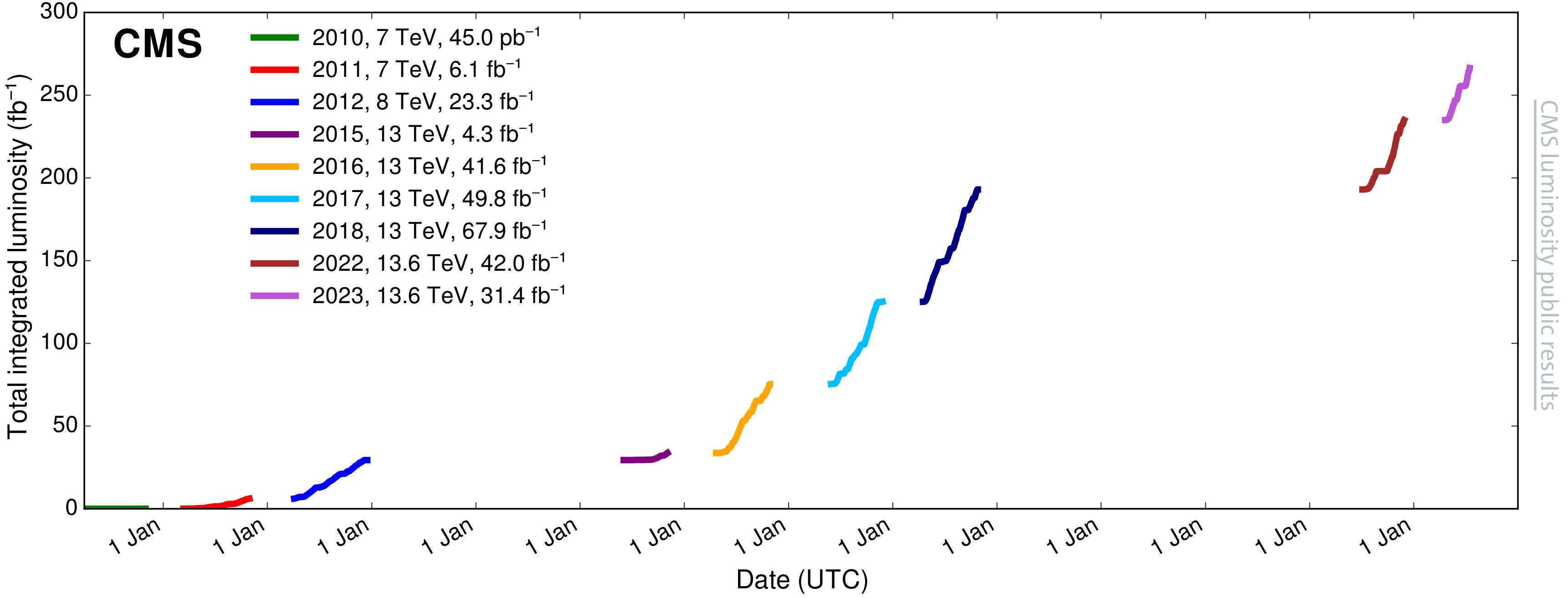


Higgs boson discovery
First new partilce at the LHC!

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

Delivered luminosity



The CMS detector

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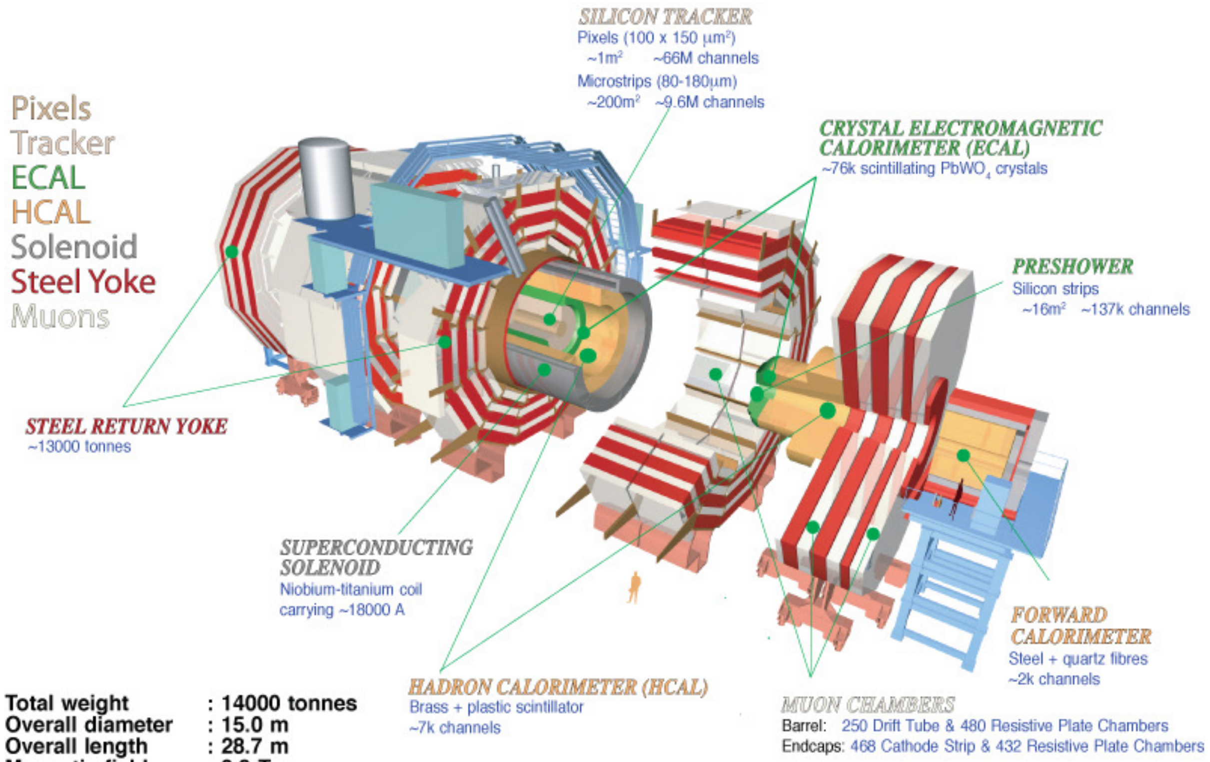

Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

tt and ttbb samples

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CMS-PAS-HIG-19-011

	$t\bar{t}$ sample	$t\bar{t}b\bar{b}$ 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	$\sqrt{\frac{1}{2}\left(m^2_{T,t}+m^2_{T,\bar{t}}\right)}$	$\frac{1}{2}\sqrt[4]{m_{T,t}\cdot m_{T,\bar{t}}\cdot m_{T,b}\cdot m_{T,\bar{b}}}$
μ_F	μ_R	$\frac{1}{4}\left[m_{T,t}+m_{T,\bar{t}}+m_{T,b}+m_{T,\bar{b}}+m_{T,g}\right]$
h_{damp}	$1.379\cdot m_t$	$1.379\cdot m_t$
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

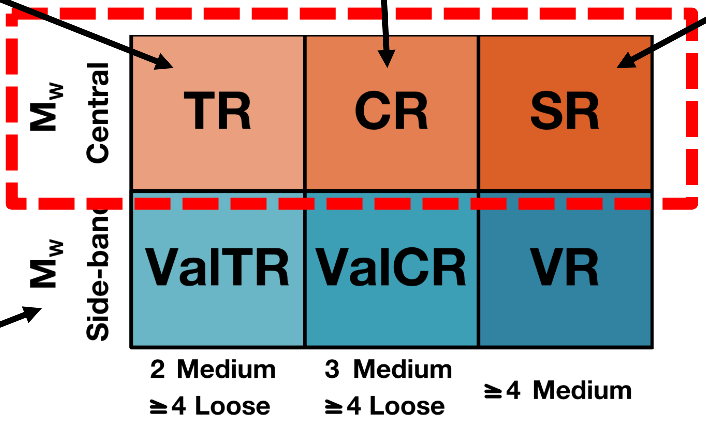
Control region

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

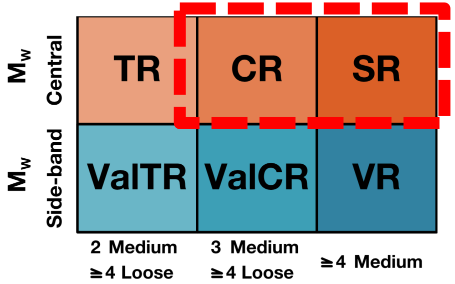
QCD-bkg estimation as before

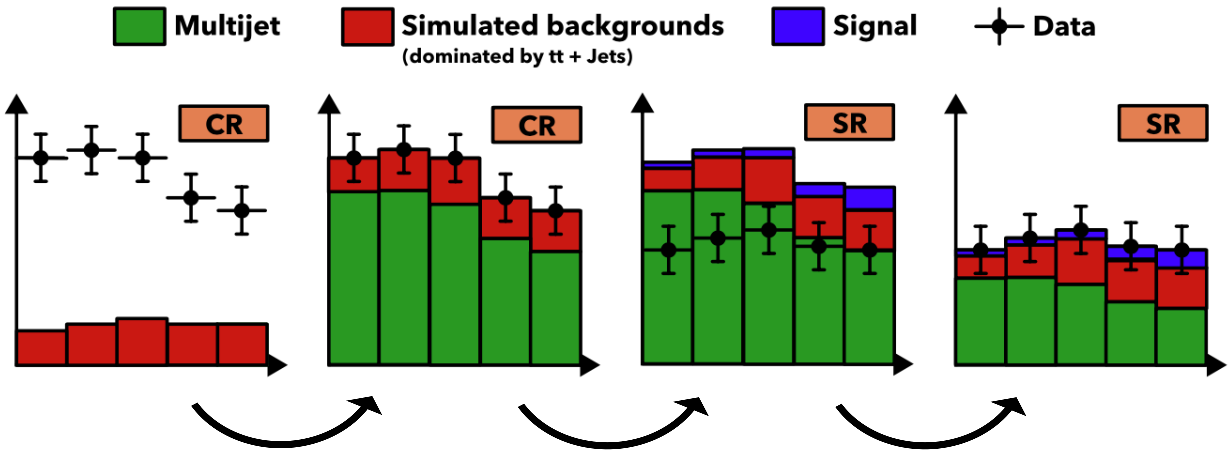
- Discriminant (ANN) shape from CR
- Transfered to SR via TF_{loose}
- Closure test in data in VR

QCD-background estimation

CMS-PAS-HIG-19-011

- In CR: $ANN_{QCD} = ANN_{data} - ANN_{\text{non-QCD bkg. (from MC)}}$ → **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

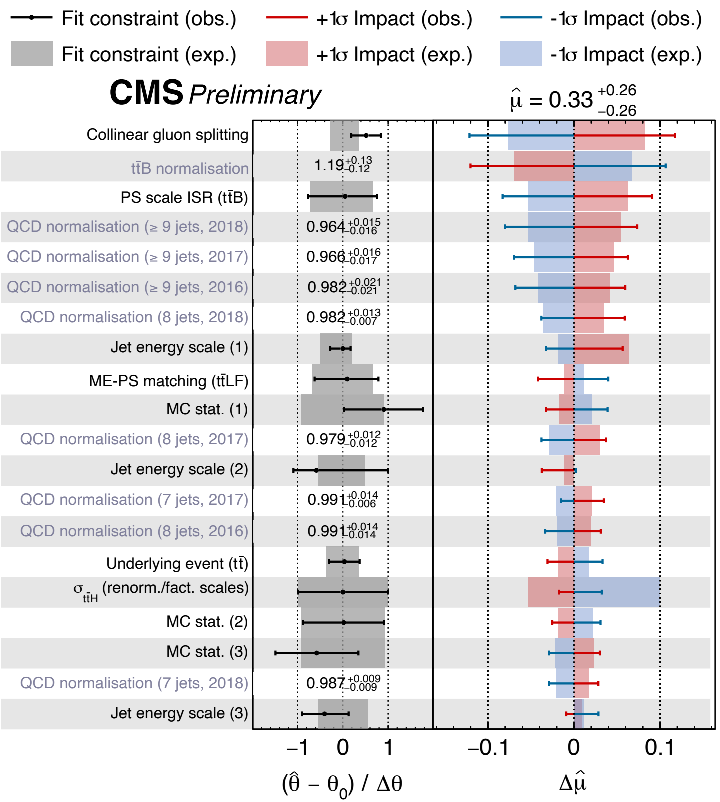
Systematic uncertainties

CMS-PAS-HIG-19-011

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

CMS-PAS-HIG-19-011



Uncertainties

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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

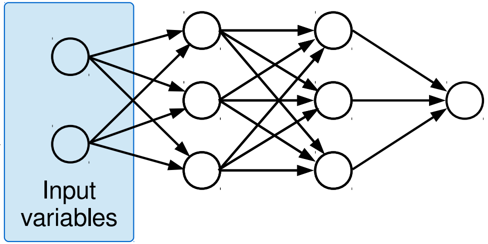
Size of simulated event samples

Are the ANN inputs well-modelled?

	Observable	FH ($\geq$ 9 jets, $\geq$ 4 b tags)	FH (8 jets, $\geq$ 4 b tags)	FH (7 jets, $\geq$ 4 b tags)	SL ($\geq$ 6 jets, $\geq$ 4 b tags)	SL (5 jets, $\geq$ 4 b tags)	DL ($\geq$ 4 jets, $\geq$ 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 $\mathrm{t\bar{t}H}$ reconstruction				✓	✓		
$\mathrm{BDT}^{i\dagger}$	reconstruction BDT output for tHq, $\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}}$ 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?



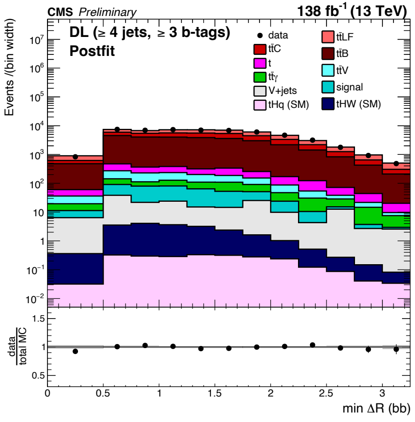
Strategy in ttH:
Goodness-of-fit test for all variables and pairs of variables

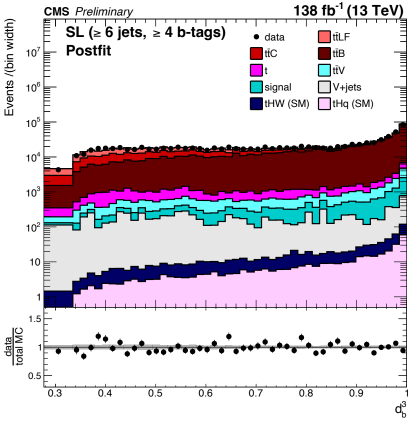
Key aspect in many machine-learning applications at the LHC!

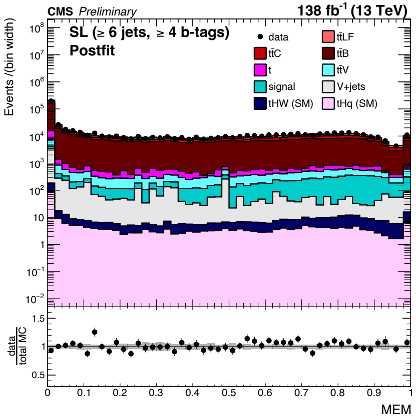
Different to many industry applications where labelled data is available

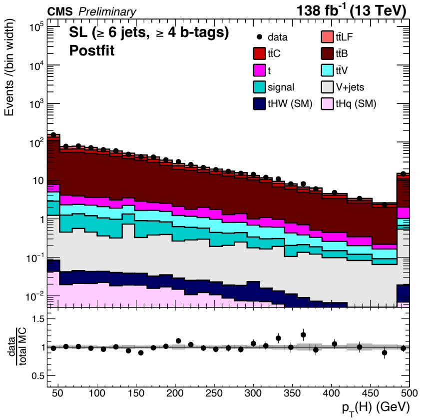
Background validation

CMS-PAS-HIG-19-011









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

Limits on tH production

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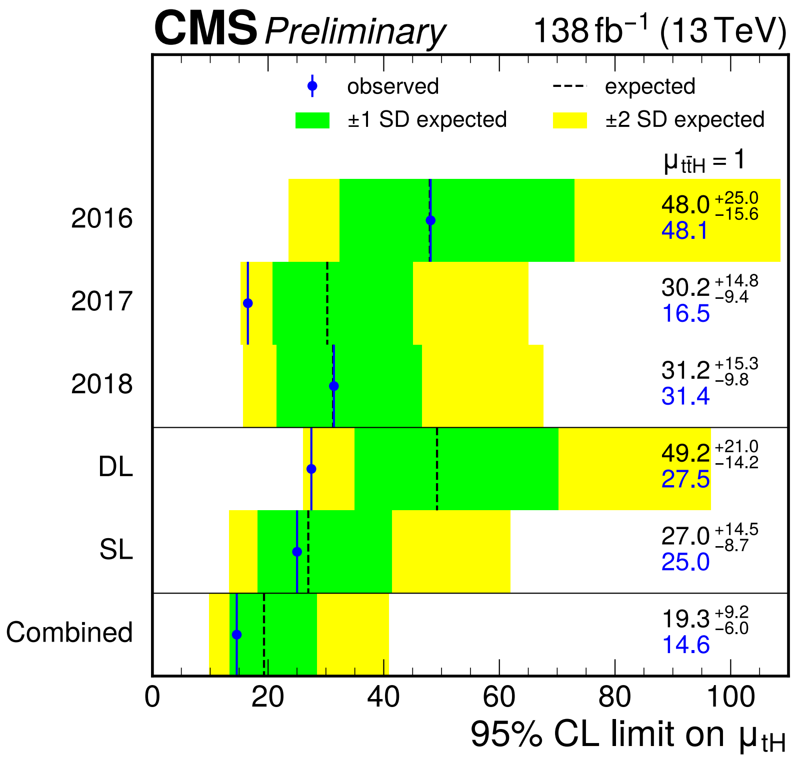
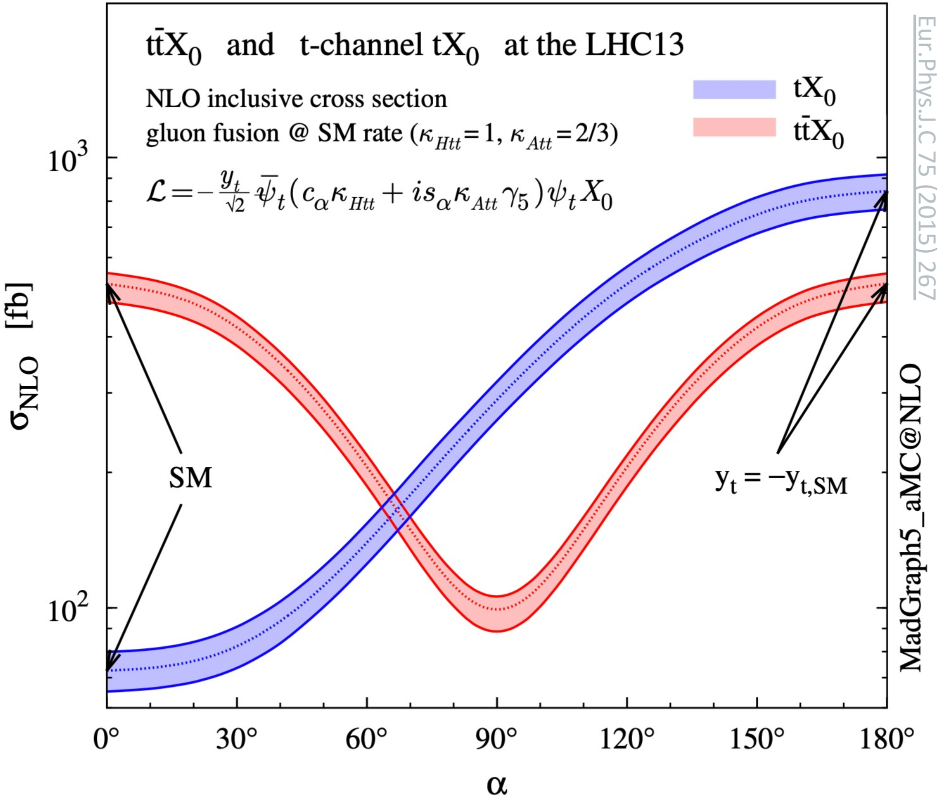


ttH and tH cross sections vs. CP mixing angle



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!

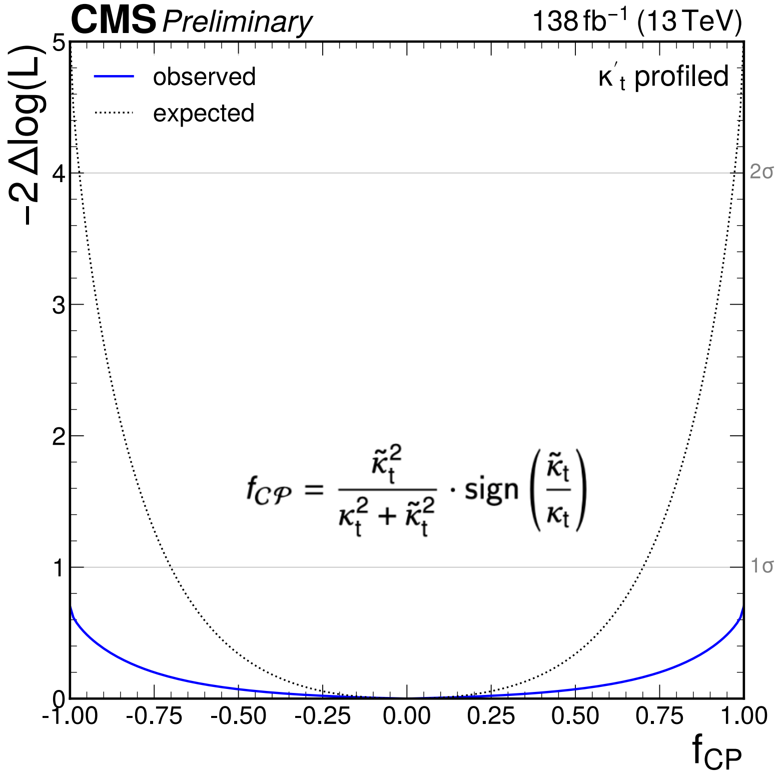
$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\overline{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t$$

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

→ can modify ttH and tH rates and kinematics differently

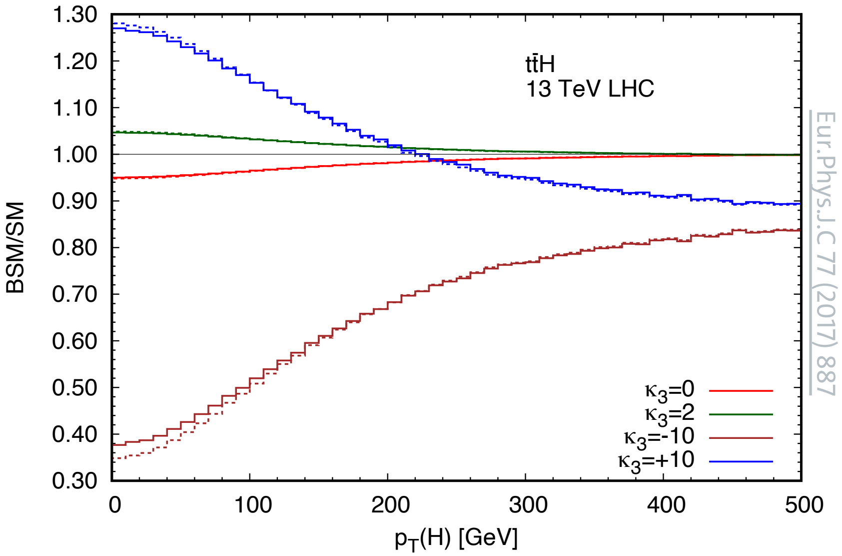
Simultaneoulsy floating ttH and tH contributions

→ **constraints on CP-odd top-Higgs coupling κ_t**

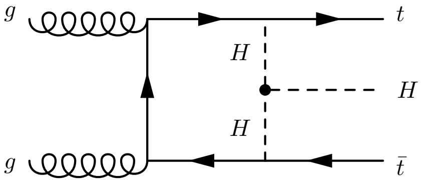


Higgs-boson self-coupling

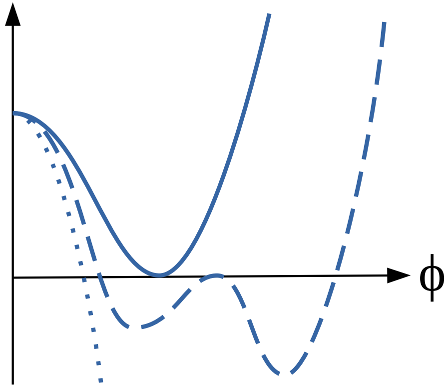
ttH production sensitive to **Higgs-boson self-coupling**
→ related to shape of Higgs potential



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

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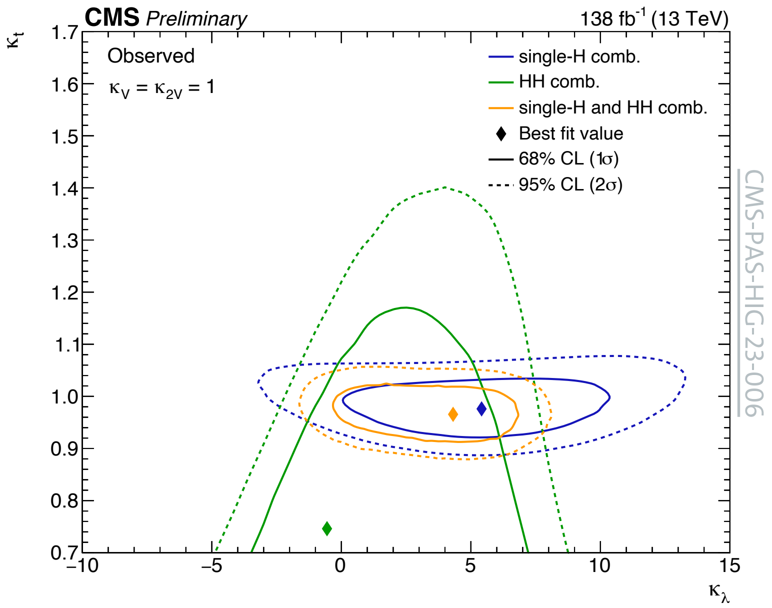
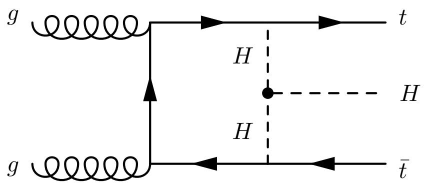
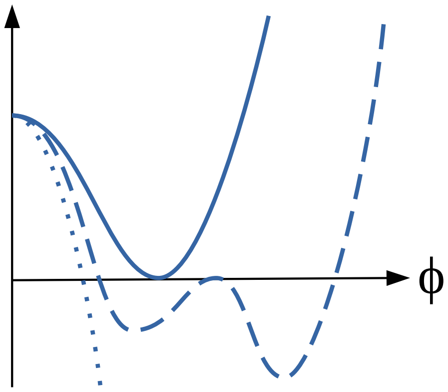
ttH production sensitive to **Higgs-boson self-coupling** [Eur.Phys.J.C 77 (2017) 12, 887]
→ related to shape of Higgs potential





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

FOEWPT

- First order EWK phase transition required to generate the observed matter-antimatter asymmetry

J Phys 87, 43 (2016)

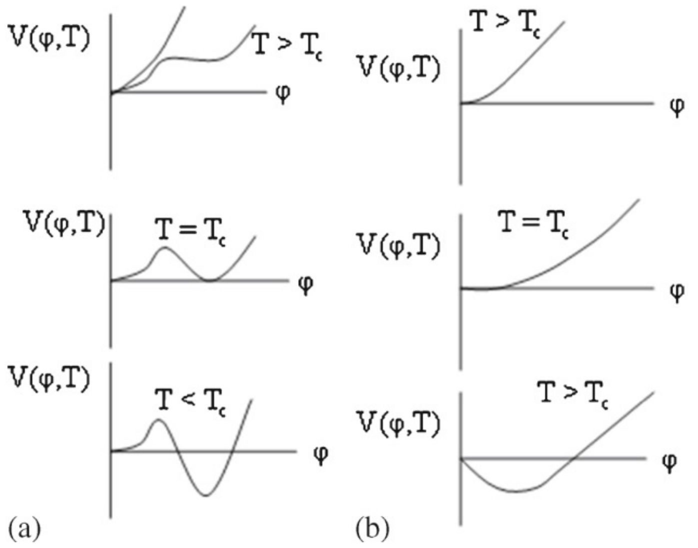
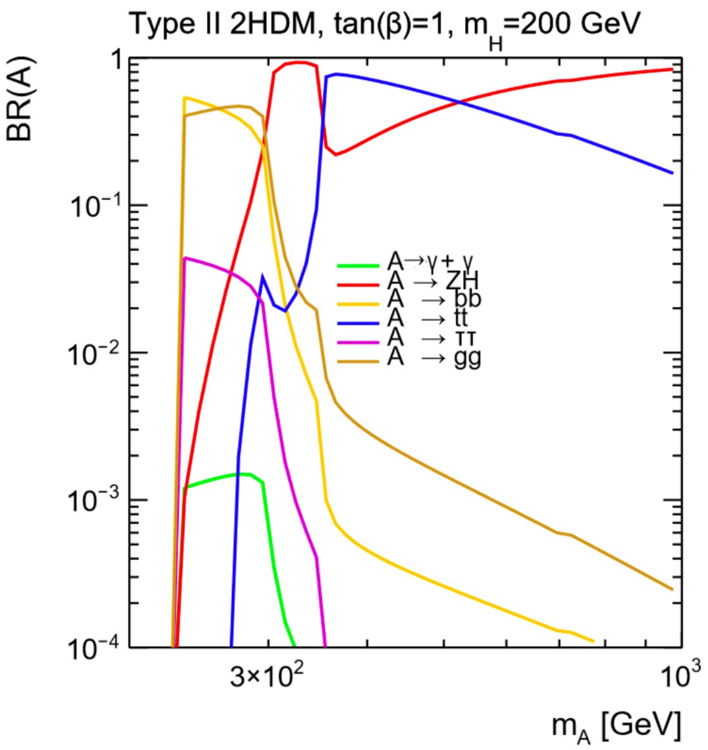
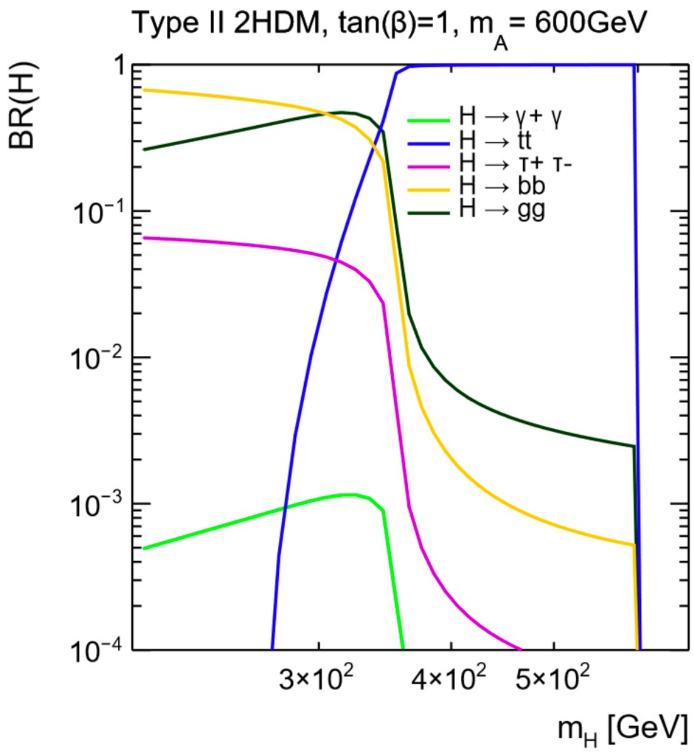


Figure 2. Variations of the effective potential with temperature in the case of (**a**) first- and (**b**) second-order phase transitions.

A → ZH with H → tt production

MSc thesis Y. Fischer, Universität Hamburg (2021)





A → ZH with H → tt production

MSc thesis Y. Fischer, Universität Hamburg (2021)

- **A boson production**
  - Possible via ggA and $t\bar{t}A$
  - $\sigma = \sigma_{SM} \times$ factor approx. $\propto \frac{1}{\tan^2\beta}$

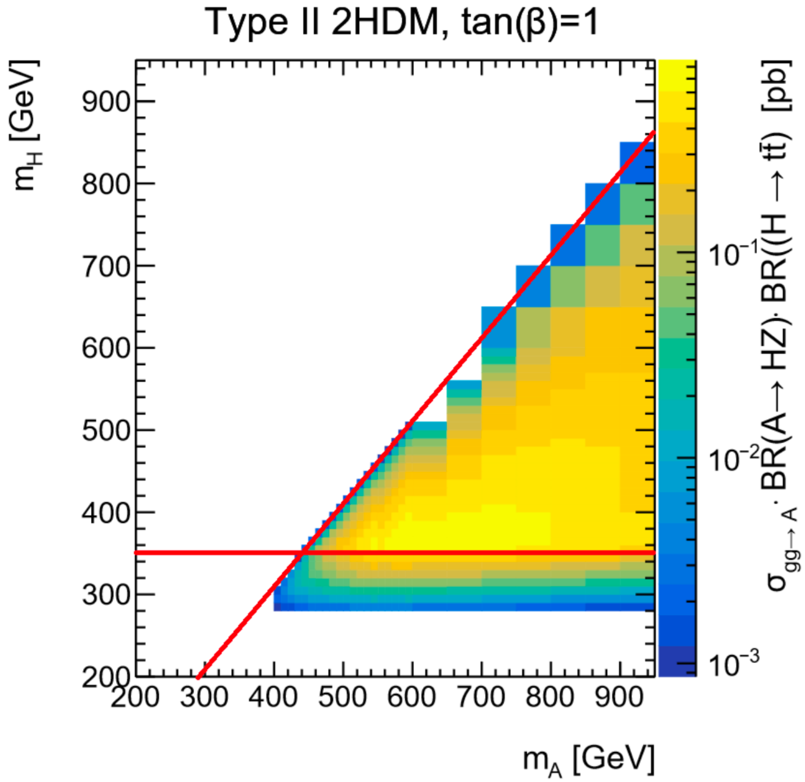
  → ggA only relevant channel

  [Phys.Rept. 516 (2012) 1]
- Approximation in alignment limit for small $\tan\beta$

$$\sigma(pp \to A) \approx \frac{1.7}{\tan^2\beta}\left(\frac{570\ \text{GeV}}{m_A}\right)^{5.2} \text{pb}$$

  [JHEP09 (2018) 151]
- SM $t\bar{t} + Z$ production: $\sigma = 0.86$ pb

  [Eur.Phys.J.C 79 (2019) 3]

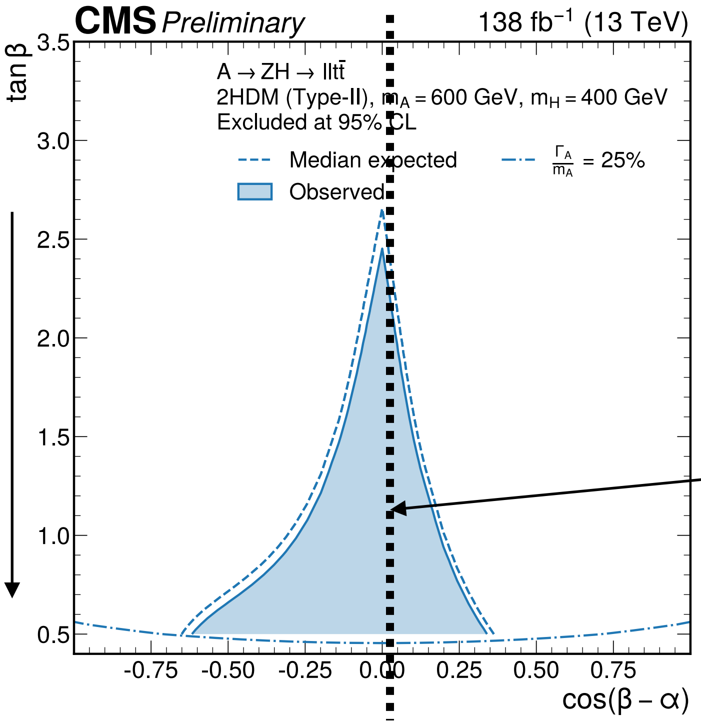


$A \to ZH, H \to tt$ in the 2HDM

CMS-PAS-B2G-23-006

Valid in all 2HDM types

Att coupling ∝ cos(α)/sin(β)



Sensitive in alignment limit

AZH coupling ∝ sin(β-α)

AZh, HVV (Hhh) ∝ cos(β-α)