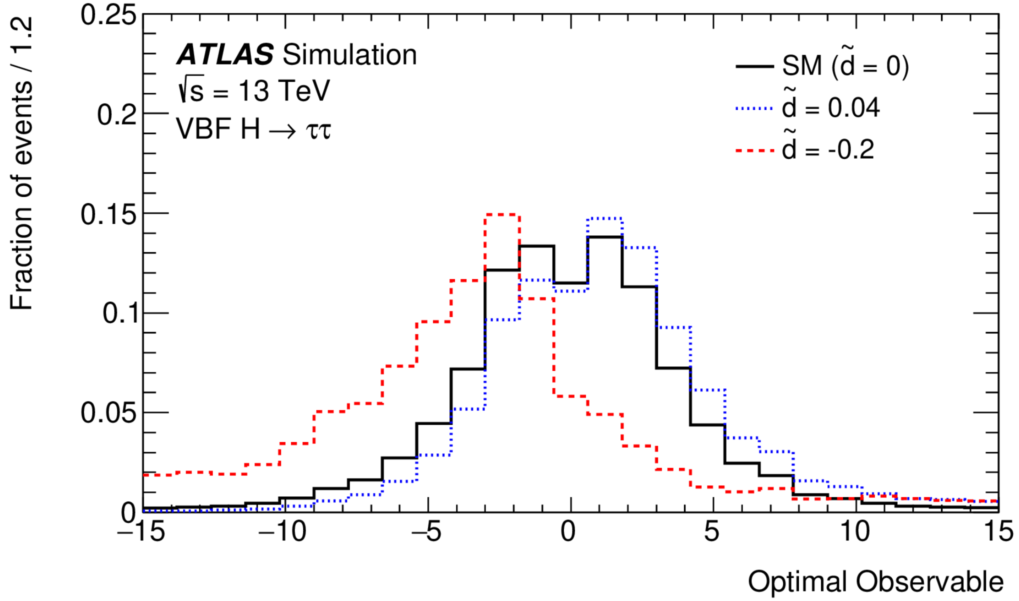
Looking for CP violation in the Higgs sector with ATLAS



Phys. Lett. B 805 (2020) 135426

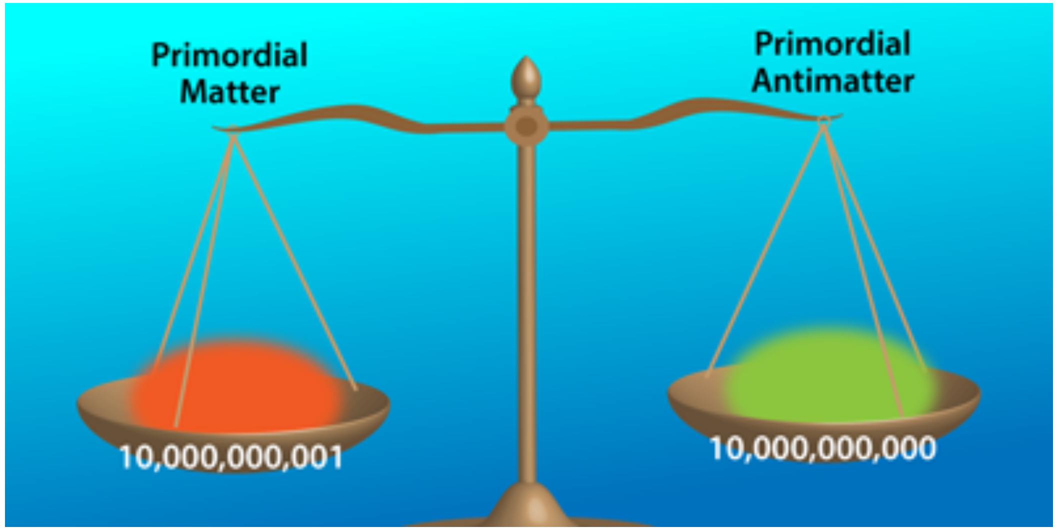
Kathrin Becker

Warwick EPP Seminar, June 25, 2020

Baryon asymmetry

- Why is there an asymmetry between matter and antimatter?
- One of the Sakharov conditions:
  → CP violation
- CP violation in the Standard Model not sufficient

➡ **Additional sources for CP violation?**



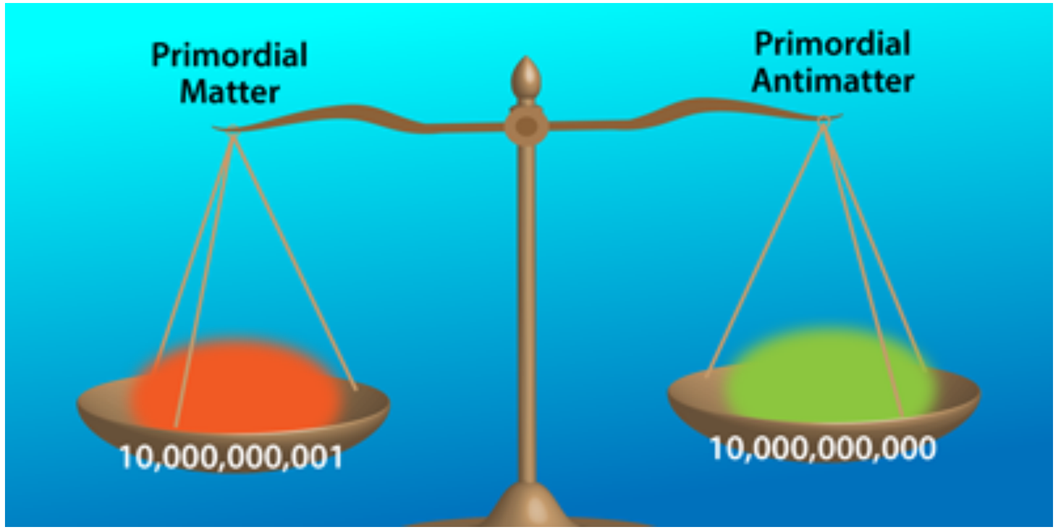
Quark sector:

Neutrino sector:

Higgs sector:

Baryon asymmetry

- Why is there an asymmetry between matter and antimatter?
- One of the Sakharov conditions:
  → CP violation
- CP violation in the Standard Model not sufficient



➡ **Additional sources for CP violation?**

Quark sector:

Belle II LHCb

Neutrino sector:

T2K DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

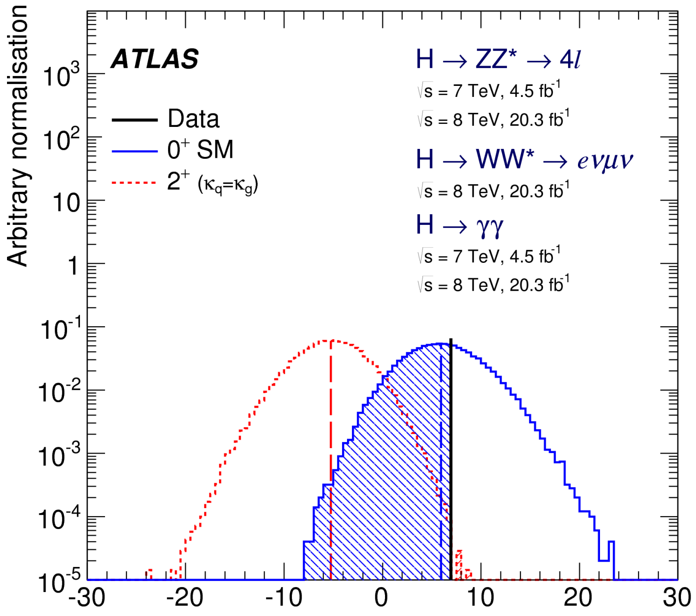
Higgs sector:

ATLAS EXPERIMENT CMS

CP nature of the Higgs boson

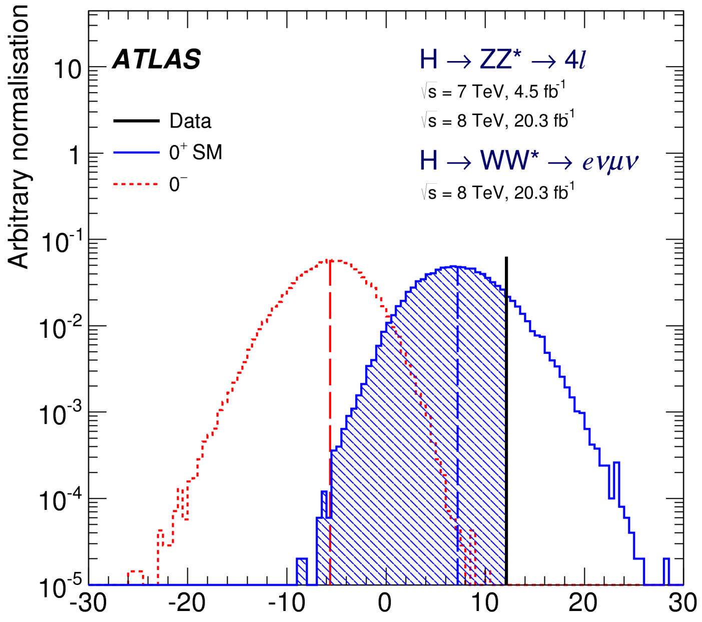
- In the SM Higgs boson is CP-even scalar
- Higgs boson has C and P preserving interactions with the mass eigenstates of the fermions
- Observation of any CP violation
  → Clear sign of physics beyond the SM
- Results from experiments after Run 1:

Higgs boson is a scalar!



Test spin-2 vs SM

Dominant coupling structure is CP-even!



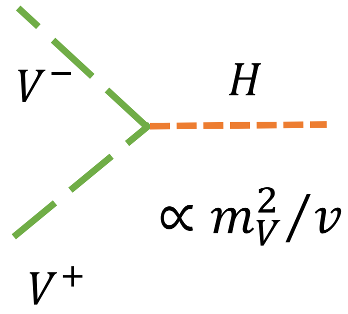
Test pure CP-odd vs SM

EPJ C75 (2015) 476

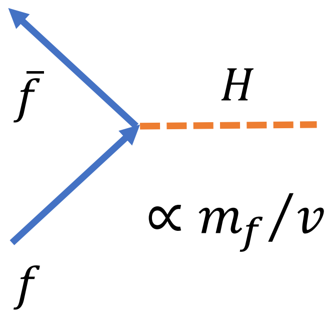
Introducing CP violation in the Higgs sector

- Dominant coupling structure is CP-even
  → can be mixture of CP-even and CP-odd
  → would lead to CP violation
- Can appear (and be searched for) in all couplings of the Higgs boson
- Possible to introduce model-independent

Gauge coupling:



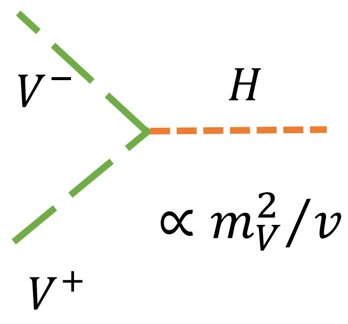
Yukawa coupling:



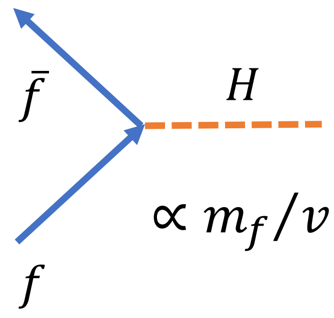
Introducing CP violation in the Higgs sector

- Dominant coupling structure is CP-even
  → can be mixture of CP-even and CP-odd
  → would lead to CP violation
- Can appear (and be searched for) in all couplings of the Higgs boson
- Possible to introduce model-independent

Gauge coupling:



Yukawa coupling:



Effective field theory approach:

- Extend the SM. Parametrize new physics by higher dimension operators

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} O_i^{(6)} + \frac{1}{\Lambda^4}\sum_j c_j^{(8)} O_j^{(8)} + \cdots$$

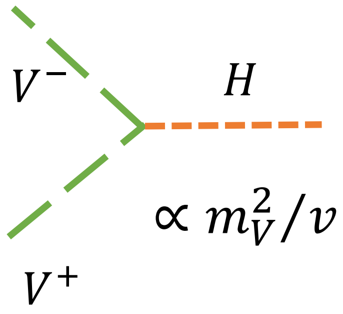
Λ: Scale of new physics

Leading deformations of the SM

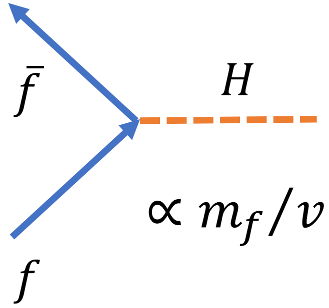
Introducing CP violation in the Higgs sector

- Dominant coupling structure is CP-even
  → can be mixture of CP-even and CP-odd
  → would lead to CP violation
- Can appear (and be searched for) in all couplings of the Higgs boson
- Possible to introduce model-independent

Gauge coupling:



Yukawa coupling:



- Introduce pseudo-scalar coupling at tree level

$$\mathcal{L}_{hf\bar{f}} = -\sum_f \frac{m_f}{v} H\left[\bar{\psi}_f \kappa_f (\cos\alpha + i\sin\alpha\,\gamma_5)\psi_f\right]$$

α: CP mixing angle
κ_f: Yukawa coupling

CP even: $\alpha = 0°$
CP odd: $\alpha = 90°$

Overview

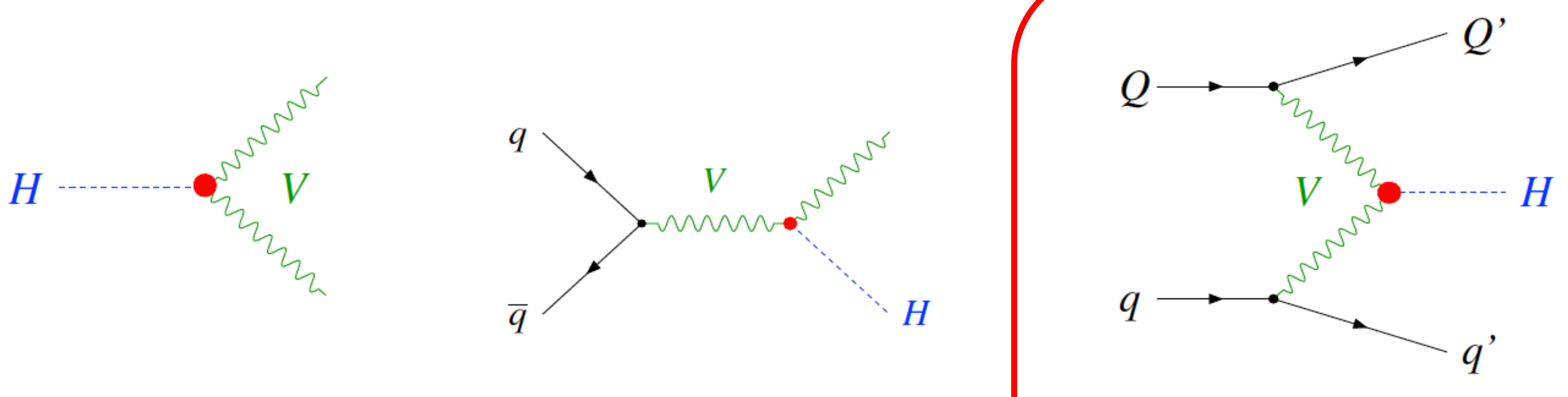
- Higgs-Gauge coupling:
  - Test of CP invariance in vector-boson fusion production of the Higgs boson in the $H \to \tau\tau$ channel in pp collisions at $\sqrt{s} = 13\ TeV$ with the ATLAS detector
    Phys. Lett. B 805 (2020) 135426
    arXiv:2002.05315

VBF, $H \to \tau\tau$ using 36 fb^{-1}

- Yukawa coupling:
  - Study of the CP properties of the interaction of the Higgs boson with top quarks using top-quark associated production of the Higgs boson and its decay into two photons with the ATLAS detector at the LHC
    Accepted by PRL
    arXiv:2004.04545

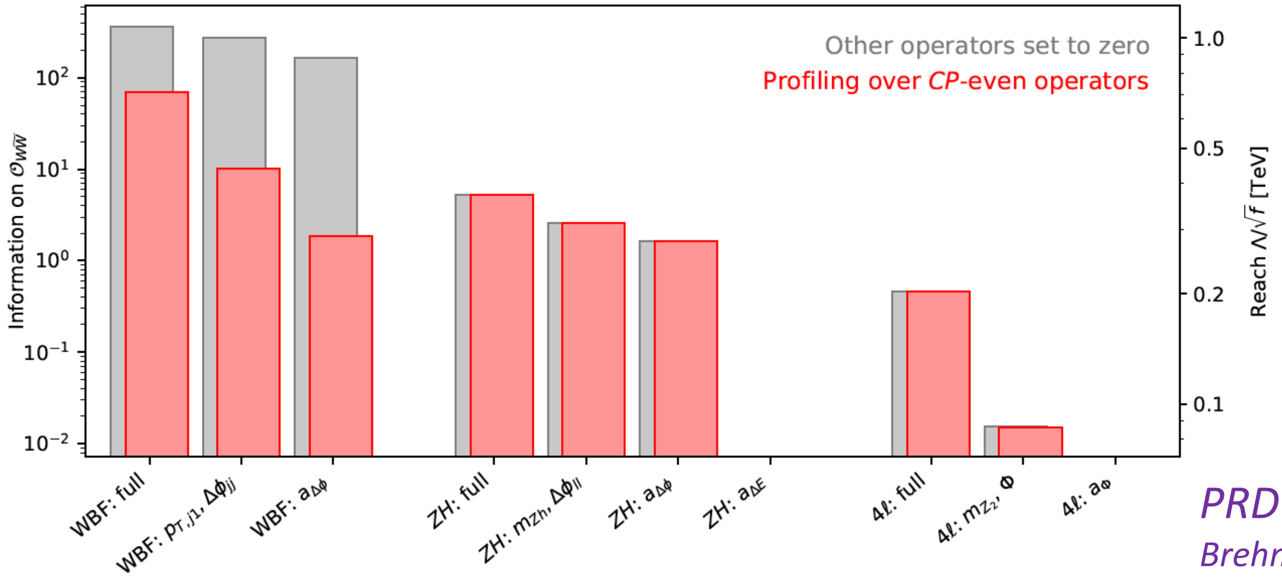
$t\bar{t}H/tH, H \to \gamma\gamma$ using 139 fb^{-1}

CP violation in the Higgs-Gauge coupling



Higgs-boson decay | Higgs-strahlung | Vector-boson-fusion production

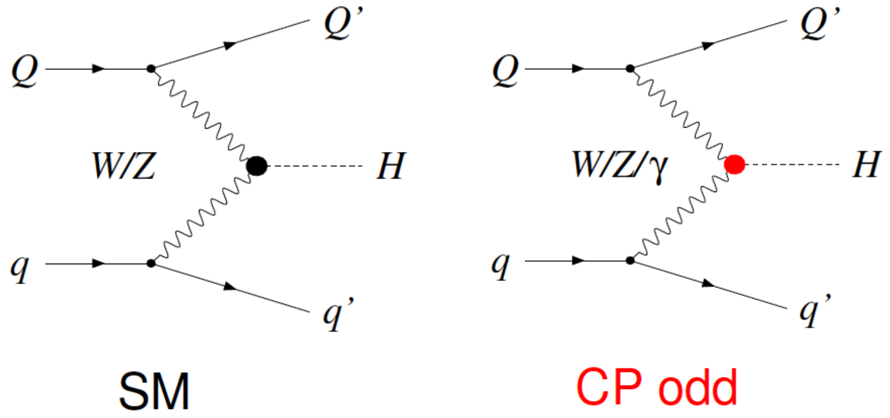
- Reach for 100 fb^{-1} at the LHC
- VBF sensitivity best at current statistics
- In future: ZH



PRD 97 (2018) 095017
Brehmer, Kling, Plehn, Tait

CP violation in the Higgs-Gauge coupling

- Ansatz: Effective $SU(2)\times U(1)$ invariant Lagrangian with additional CP-odd dimension-6 operators *V. Hankele et al; Phys. Rev. D74 (2006)*
- After electroweak symmetry breaking:
  $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \widetilde{W}_{\mu\nu} W^{\mu\nu}$
  with $\tilde{V}_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$
- Coupling constants assuming
  - $SU(2)\times U(1)$ symmetry → two parameters $\tilde{d}$, $\tilde{d}_B$
  - No distinction between HVV coupling contributions possible
    → $\tilde{d} = \tilde{d}_B$:
    $\tilde{g}_{HAZ} = 0,\ \tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W} \cdot \tilde{d}$

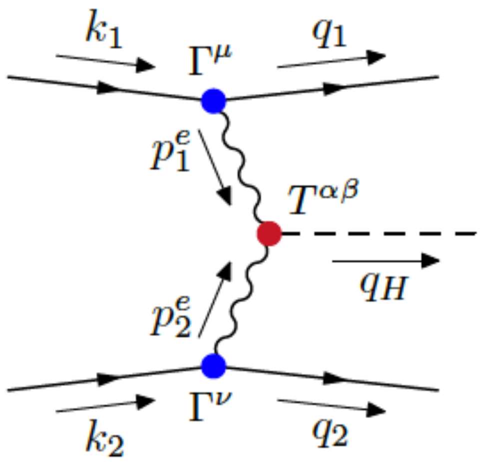


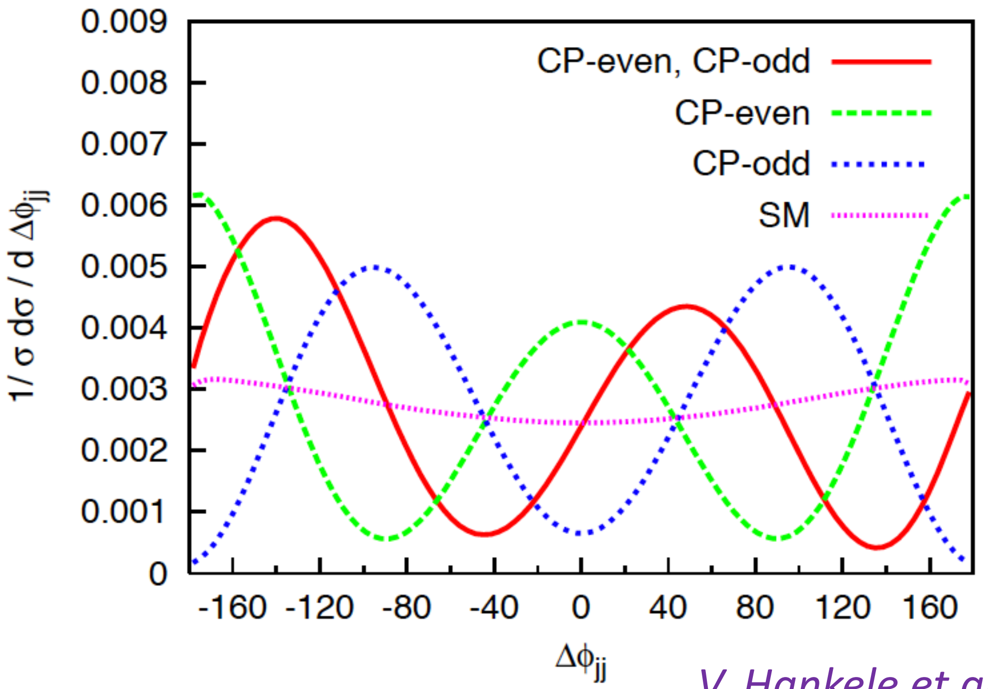
- CP violation parametrised by single parameter $\tilde{d}$
  → $\tilde{d} = 0$: no CP violation, $\tilde{d} \neq 0$: CP violation

Neglecting rescattering effects

CP-odd (T-odd) observables

- Observable whose expectation value is 0 if CP conserved
- Simple observable:
  signed difference in azimuthal angle of tagging jets (k_+ and p_+ point in same hemisphere)
  $\epsilon_{\mu\nu\rho\sigma} k_+^\mu q_+^\nu k_-^\rho q_-^\sigma = 2E_+E_-p_{T+}p_{T-}\sin(\phi_+ - \phi_-)$
  $= 2E_+E_-p_{T+}p_{T-}\sin(\boldsymbol{\Delta\phi_{jj}})$





SM, CP-even, pure CP-odd:
symmetric under $\Delta\phi_{jj} \to -\Delta\phi_{jj}$

→ Broken if CP-mixed

→ Missing information on momentum transfer

V. Hankele et al; Phys. Rev. D74 (2006)

Optimal Observable

D. Atwood & A.Soni; Phys Lett. D45 (1992)
M. Davier et al.; Phys. Lett B306 (1993)
M. Diehl & O. Nachtmann; Z. Phys. C62 (1994)

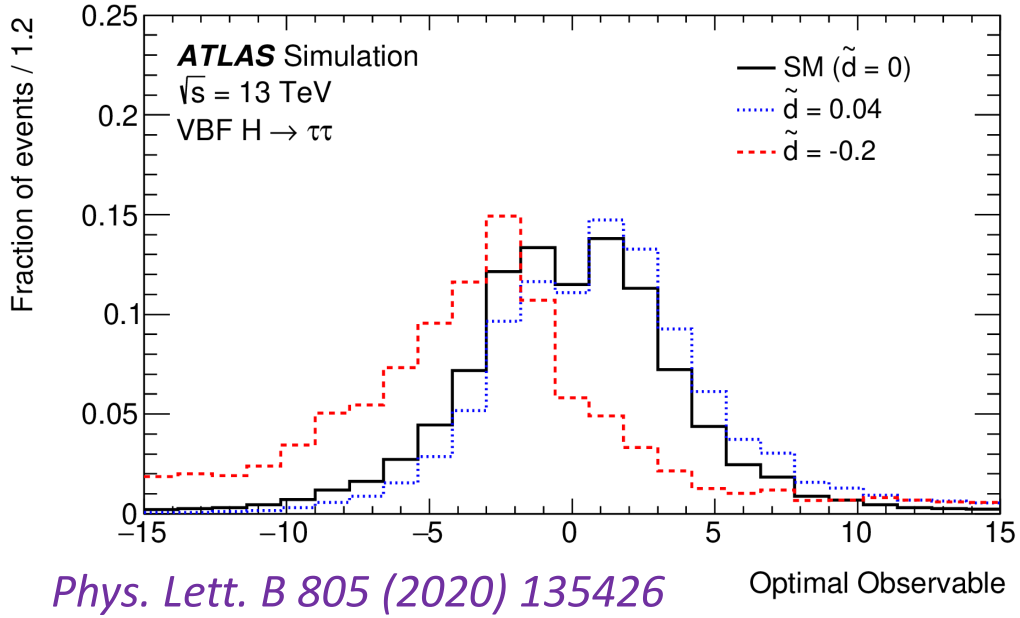
- Gain sensitivity in using full phase space information
- Matrix element for process with CP-odd contribution

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{SM}|^2}_{\text{CP-even}} + \underbrace{\tilde{d} \cdot 2\mathrm{Re}(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd})}_{\text{CP-odd}} + \underbrace{\tilde{d}^2 \cdot |\mathcal{M}_{CP-odd}|^2}_{\text{CP-even}}$$

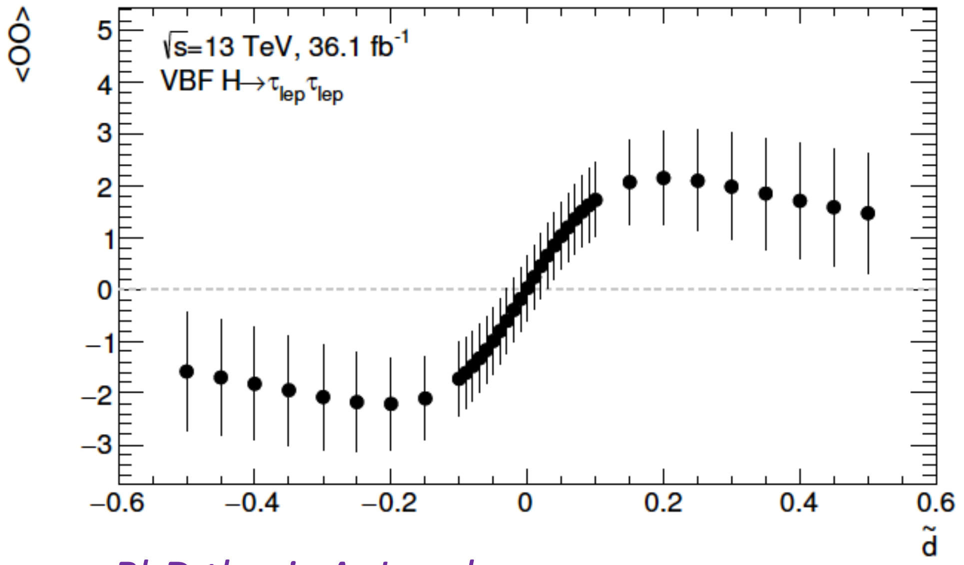
- Optimal CP-odd Observable: $$\mathcal{OO} = \frac{2\mathrm{Re}(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$
  - Contains full phase-space information in 1-dim. observable for **small $\tilde{d}$**
  - $\langle\mathcal{OO}\rangle \neq 0$ $\rightarrow$ **CP violation**
- Construct with
  - ME from a leading order MC generator
  - Reconstructed Lorentz vectors of the two tagging jets and the Higgs boson

Optimal Observable

$$\mathcal{OO} = \frac{2\mathrm{Re}(\mathcal{M}_{SM}^{*}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$



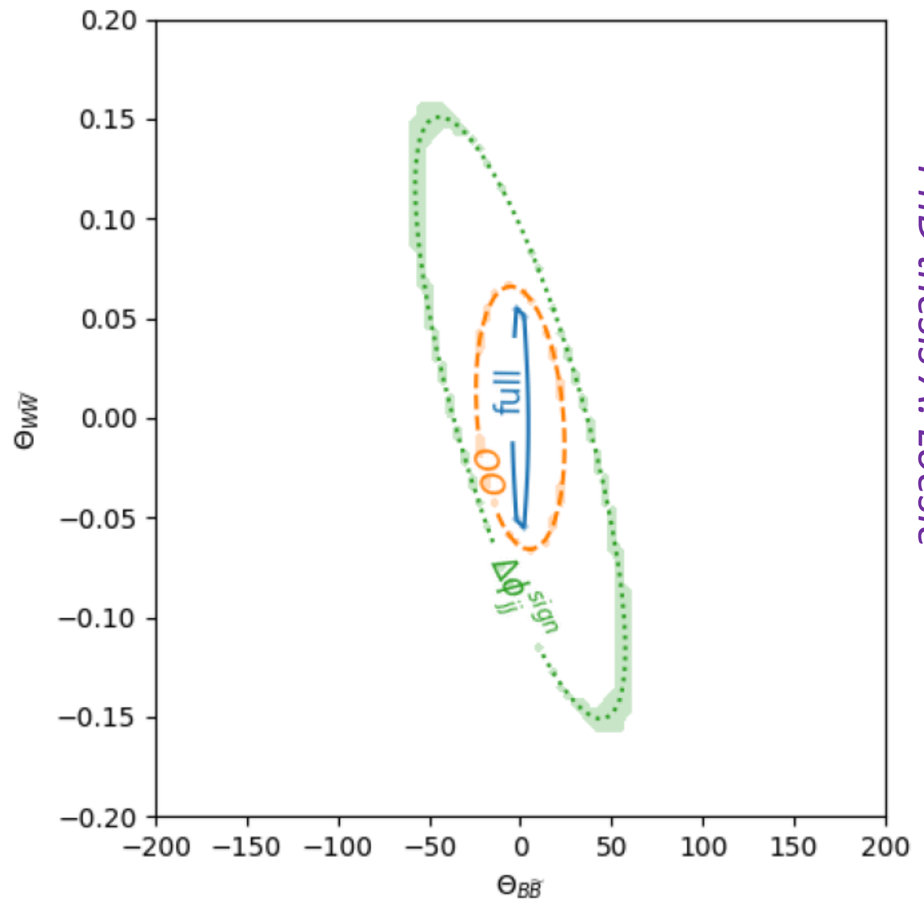
Phys. Lett. B 805 (2020) 135426



PhD thesis A. Loesle

- Symmetric for SM
- Shifted to $\mathcal{OO} > (<)\ 0$ for $\tilde{d} > (<)\ 0$
- Mean value $\langle\mathcal{OO}\rangle$: Linear for small $\tilde{d}$, $\langle\mathcal{OO}\rangle \to 0$ for large $\tilde{d}$

Performance of CP odd observables



PhD thesis A. Loesle

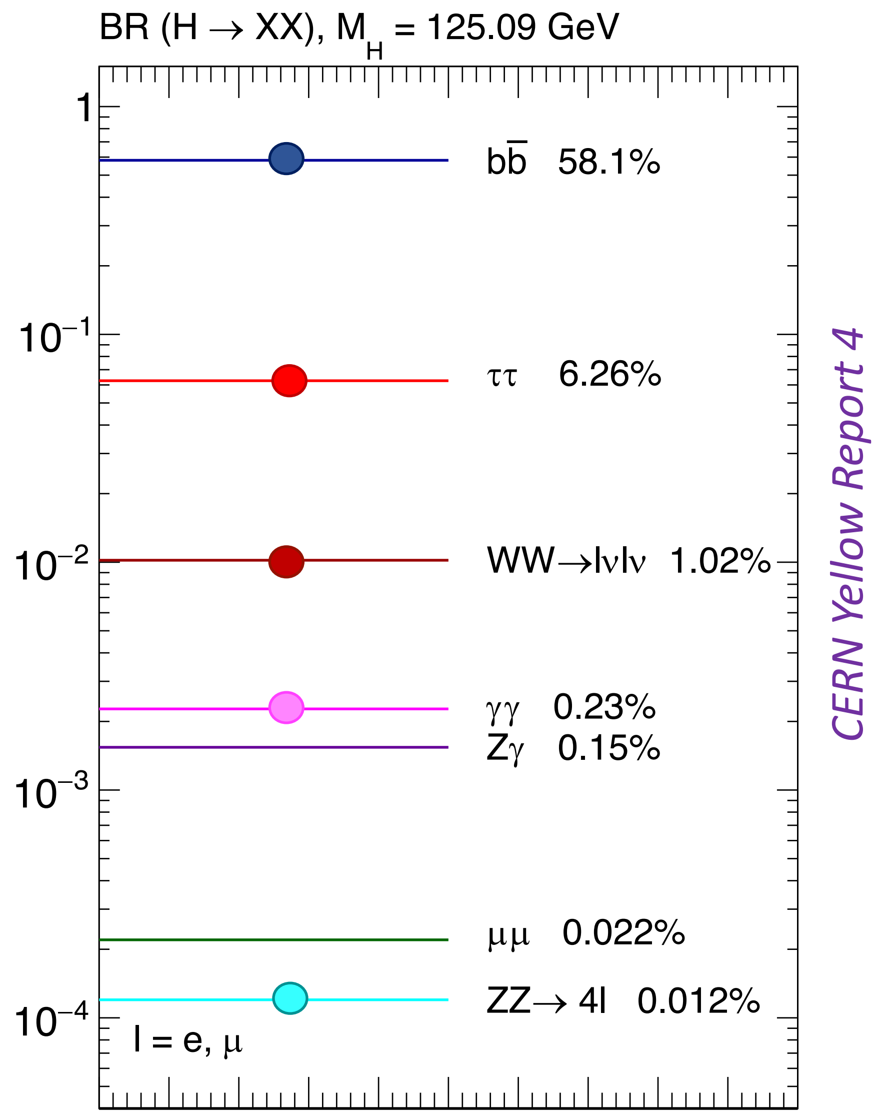
- Expected 68% CL contours assuming 100 fb^{-1}
- Optimal observable close to full phase space for $\tilde{d}$
- Only low sensitivity to $\tilde{d}_B$
- Motivates choice $\tilde{d} = \tilde{d}_B$

$$\tilde{d} = -m_W^2 \Theta_{W\tilde{W}}$$
$$\tilde{d}_B = -\, m_W^2 \tan^2 \theta_W \, \Theta_{B\tilde{B}}$$

What Higgs-boson decay channels to use?

- Looking for good VBF channel
- $H \rightarrow \tau\tau$ (6.3%)
  - High statistics
  - Can reconstruct Higgs boson four-momentum
- $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ (1.2%, $\ell = e, \mu; \tau \rightarrow \ell\nu\nu$)
  - High statistics
  - Cannot reconstruct Higgs boson four-momentum
- $H \rightarrow \gamma\gamma$ (0.2%)
  - Low statistics
  - Good mass resolution and clean signal peak
  - As for $H \rightarrow ZZ^* \rightarrow 4\ell$, even less statistic

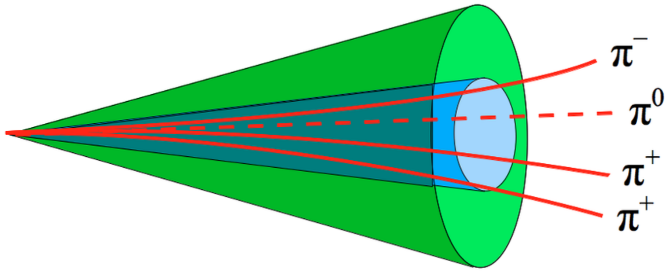
This analysis: $H \rightarrow \tau\tau$
Best result: combination of all three

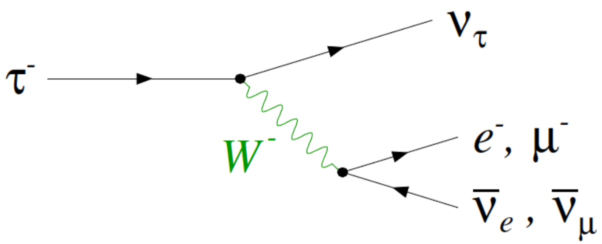


VBF CP analysis in $H \rightarrow \tau\tau$ decay channel

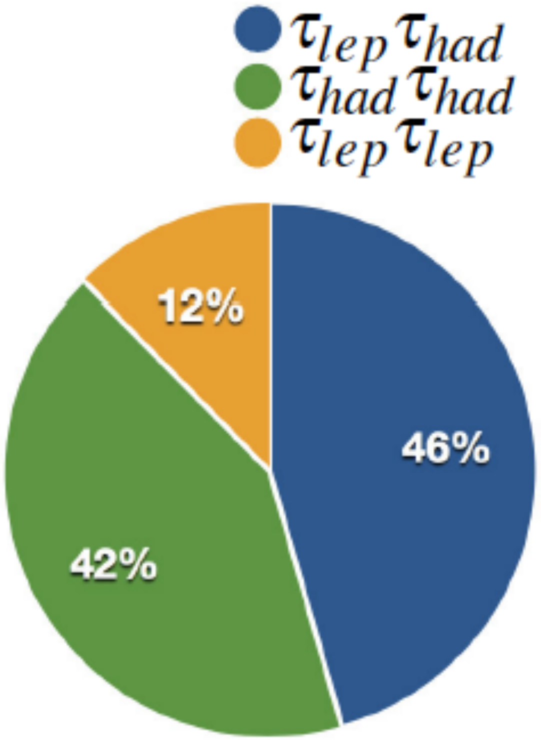
- Analysis strategy:
  1. Select VBF Higgs events
  2. Test for CP violation using Optimal Observable

- Based on couplings analysis (using 36 fb^{-1})
  - τ-lepton decay leptonically or hadronically
  - 4 analysis channels:
    $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$ DF , $\tau_{lep}\tau_{lep}$ SF

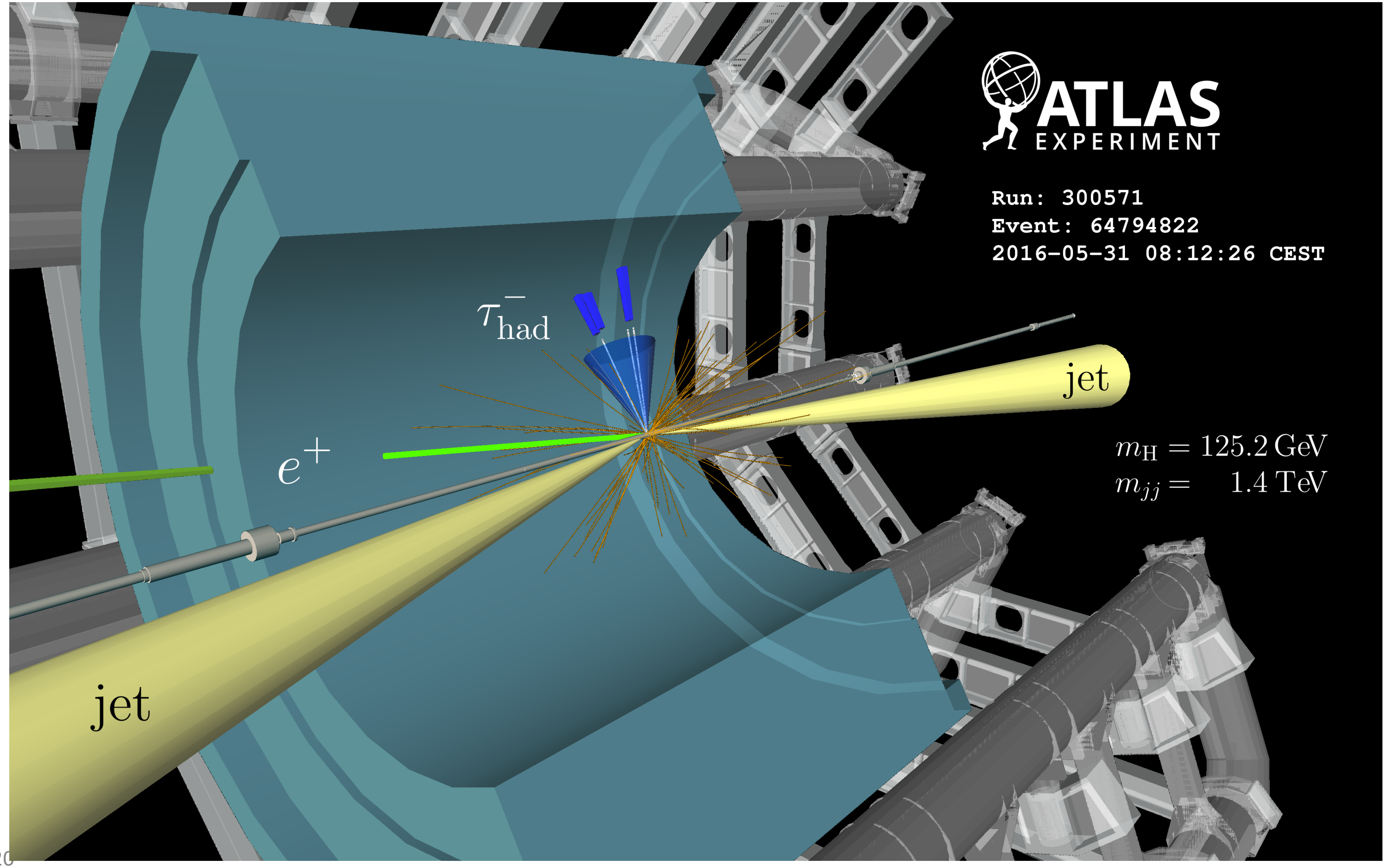




Example: 3-prong decay

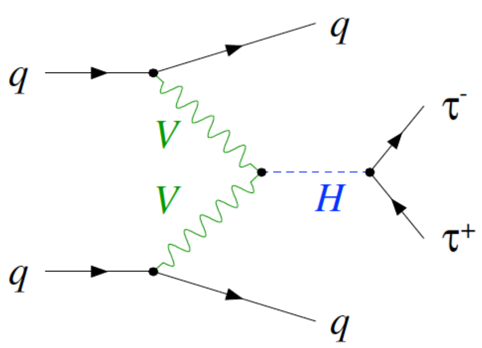


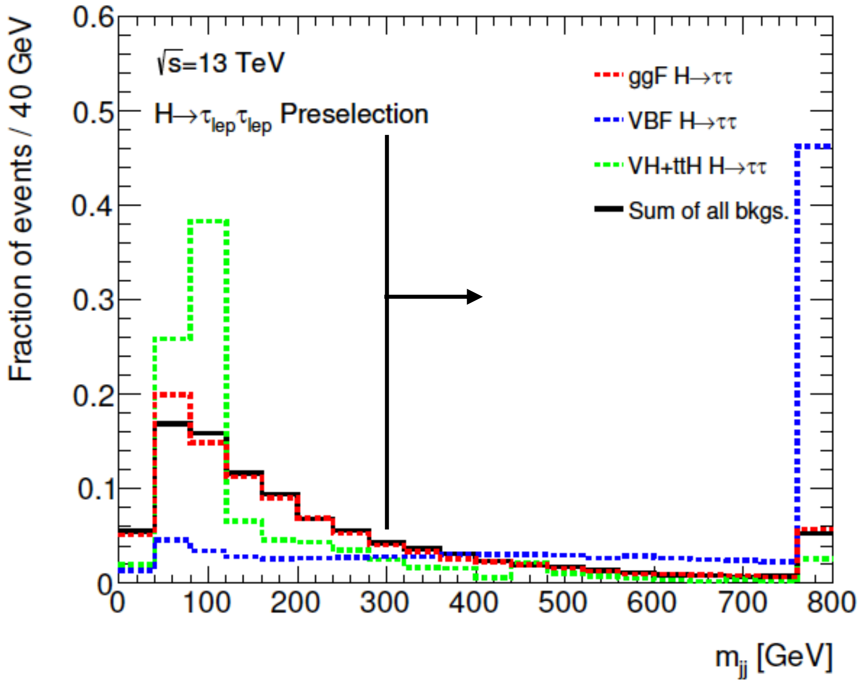
VBF $H \to \tau\tau$ event in the detector

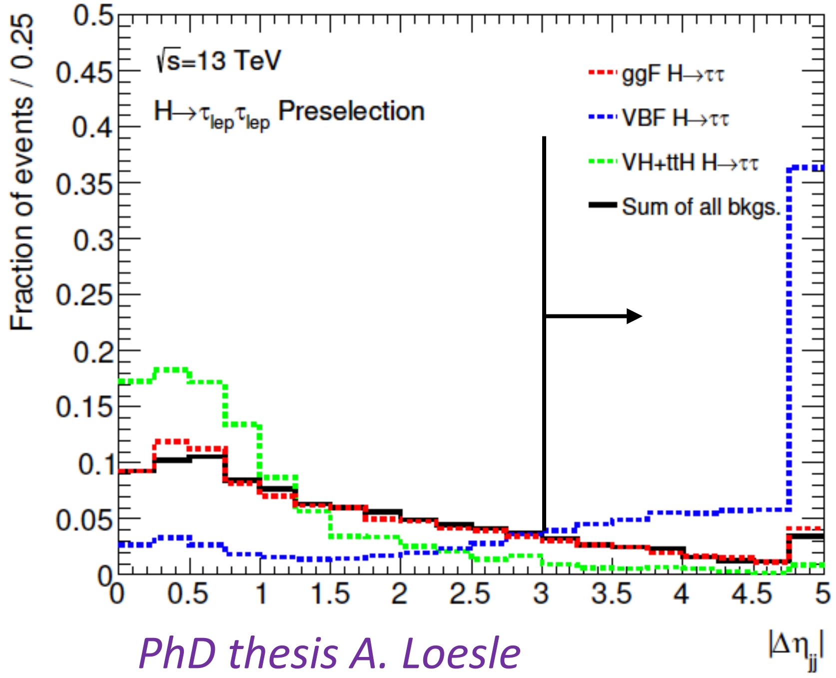


Selecting VBF events

Channel	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Basic preselection			
VBF topology	$N_{jets} \geq 2$, $p_T^{j2} > 30\,GeV$		
	$m_{jj} > 300\,GeV$, $\lvert\eta_{jj}\rvert > 3$		
	$p_T^{j1} > 40\,GeV$		$p_T^{j1} > 70\,GeV$





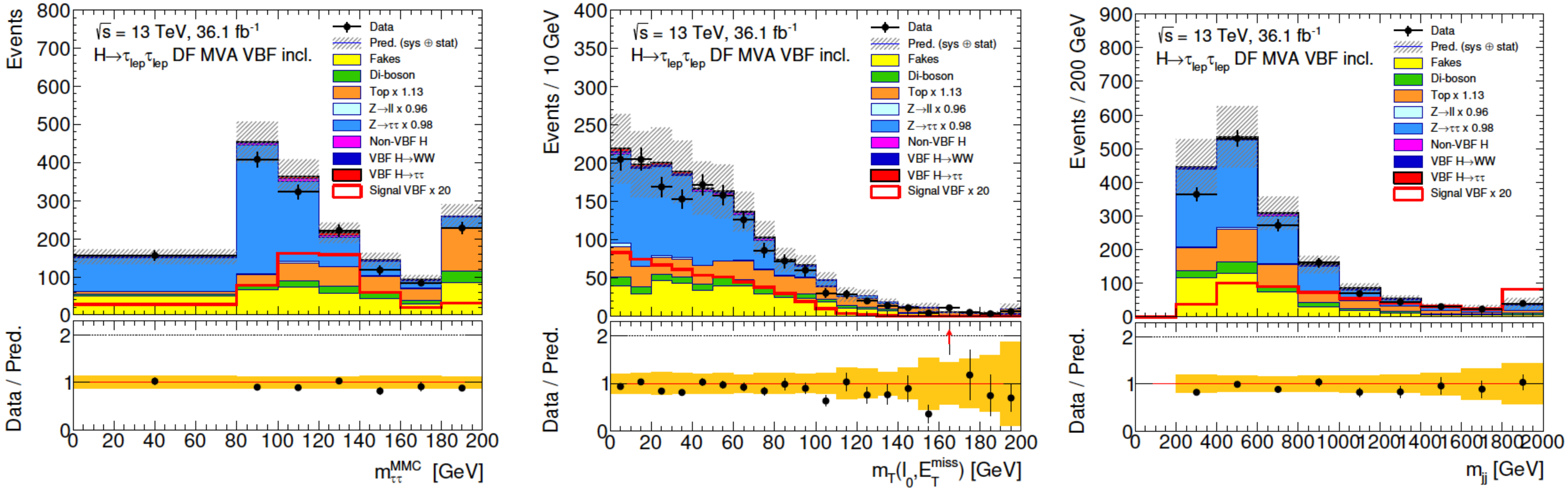


PhD thesis A. Loesle

Improve S/B further with MVA analysis

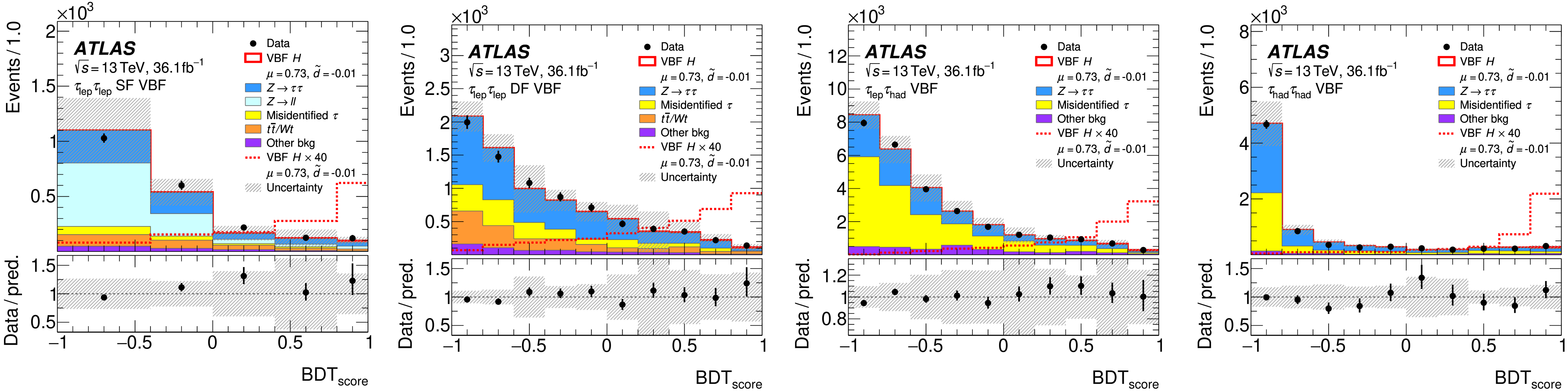
Input variables for the MVA

- Properties of Higgs boson, e.g. $m_{\tau\tau}$ → suppress resonant $Z \to \tau\tau$
- Properties of resonant di-τ decay, e.g. $m_T(\ell_0, E_T^{miss})$
  → suppress mis-identified τ-leptons
- Properties of VBF topology, e.g. m_{jj}
  → suppress backgrounds and other Higgs production modes



PhD thesis A. Loesle

Selection of VBF $H \rightarrow \tau\tau$ events



Cut on final BDT score

	Cut	Exp. signal	Exp. sum of bkgs	Ratio
$\tau_{lep}\tau_{lep}$ SF	$\text{BDT}_{score} > 0.78$	4.5	23	0.2
$\tau_{lep}\tau_{lep}$ DF		6.9	24	0.3
$\tau_{lep}\tau_{had}$	$\text{BDT}_{score} > 0.86$	16	19	0.9
$\tau_{had}\tau_{had}$	$\text{BDT}_{score} > 0.87$	12.3	26	0.5

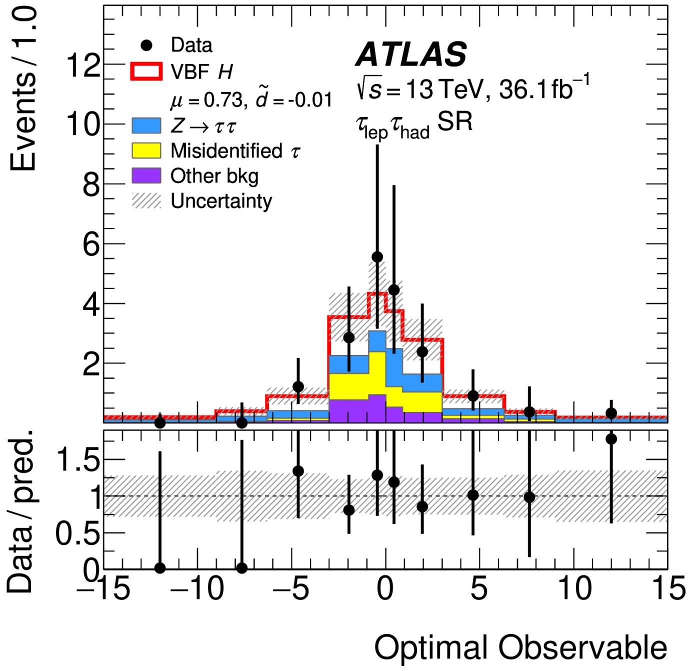
Postfit yields for SM signal

Fit Model

All channels:

High BDT signal region

Fit Optimal Observable

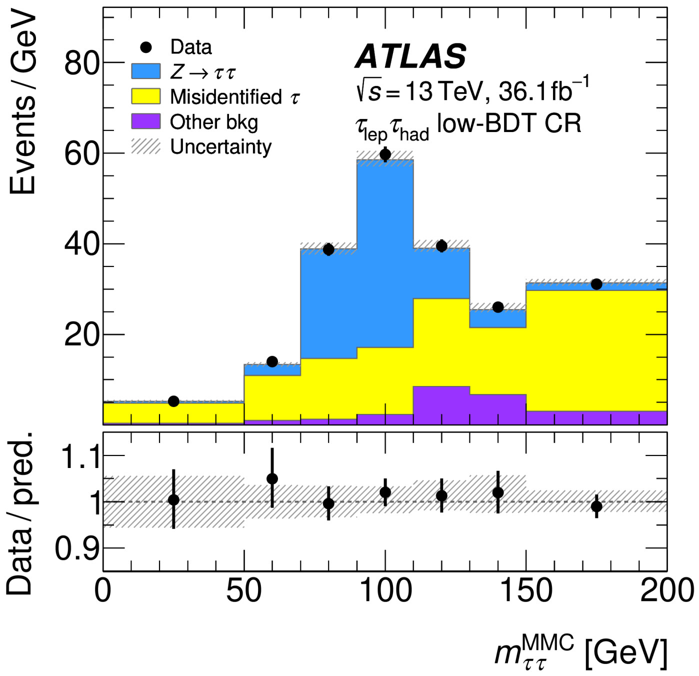


Sensitivity to $\tilde{d}$-value

All channels:

Low-BDT control region

Fit di-τ mass $m_{\tau\tau}$



Constrain systematic uncert., $Z \to \tau\tau$ norm.

$\tau_{lep}\tau_{lep}$ channels:

Top-quark control region

$N_{b-jets} \geq 1$

Use event yields

Constrain top-quark norm.

$Z \to \ell\ell$ control region

$80 \text{ GeV} < m_{\ell\ell} < 100 \text{ GeV}$

Use event yields

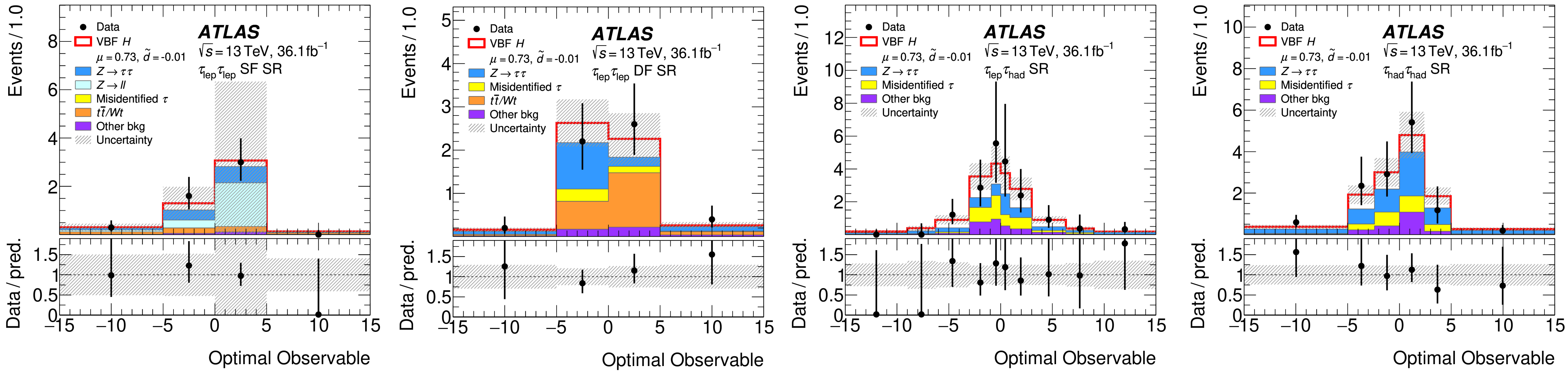
Constrain $Z \to \ell\ell$ norm.

→ Simultaneous fit to 4 SRs and 7 CRs

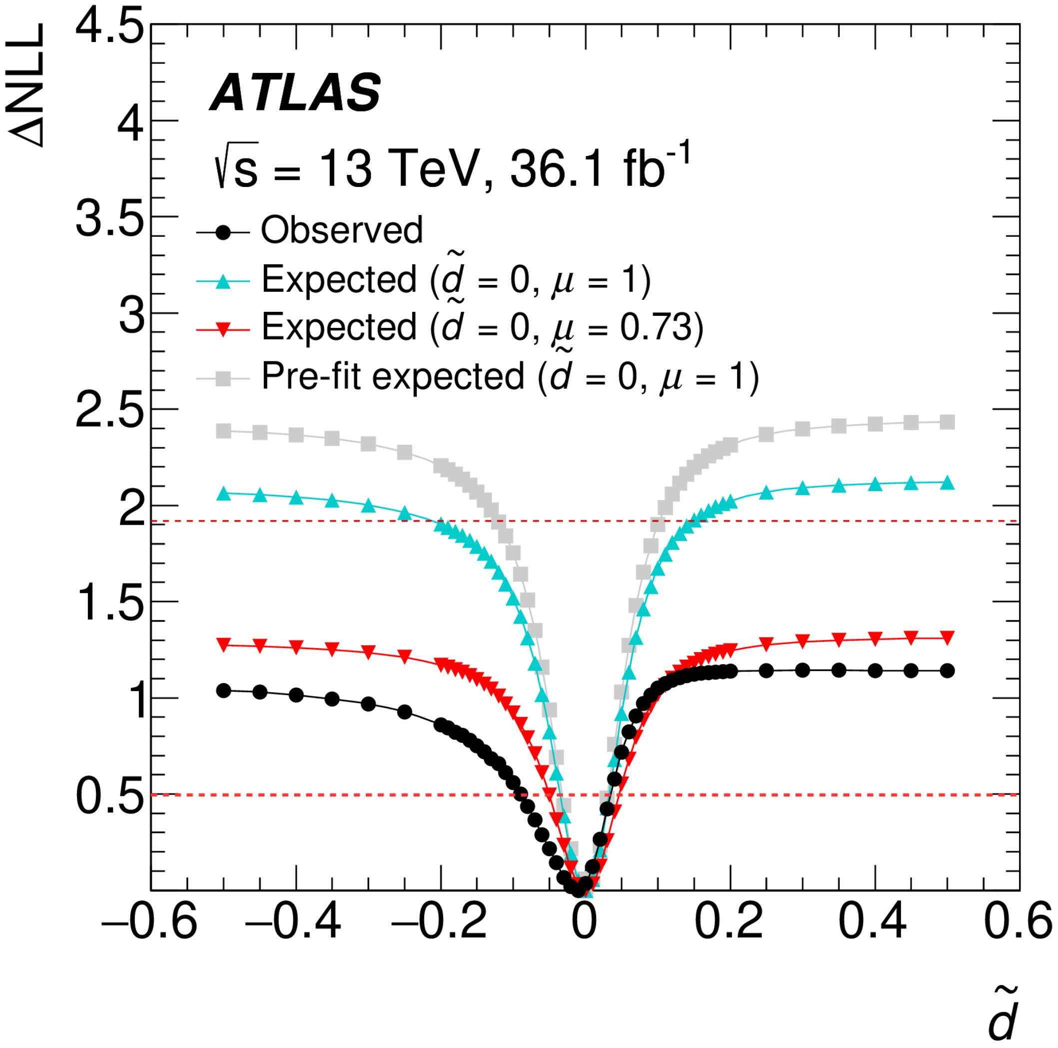
Testing CP invariance

1. Mean value of OO in data allows to test CP invariance
2. Construct NLL curve to determine confidence interval on $\tilde{d}$
   - No rate information used

	$\langle OO \rangle$
$\tau_{lep}\tau_{lep}$ SF	-0.54 ± 0.72
$\tau_{lep}\tau_{lep}$ DF	0.71 ± 0.81
$\tau_{lep}\tau_{had}$	0.74 ± 0.78
$\tau_{had}\tau_{had}$	-1.13 ± 0.65



Results

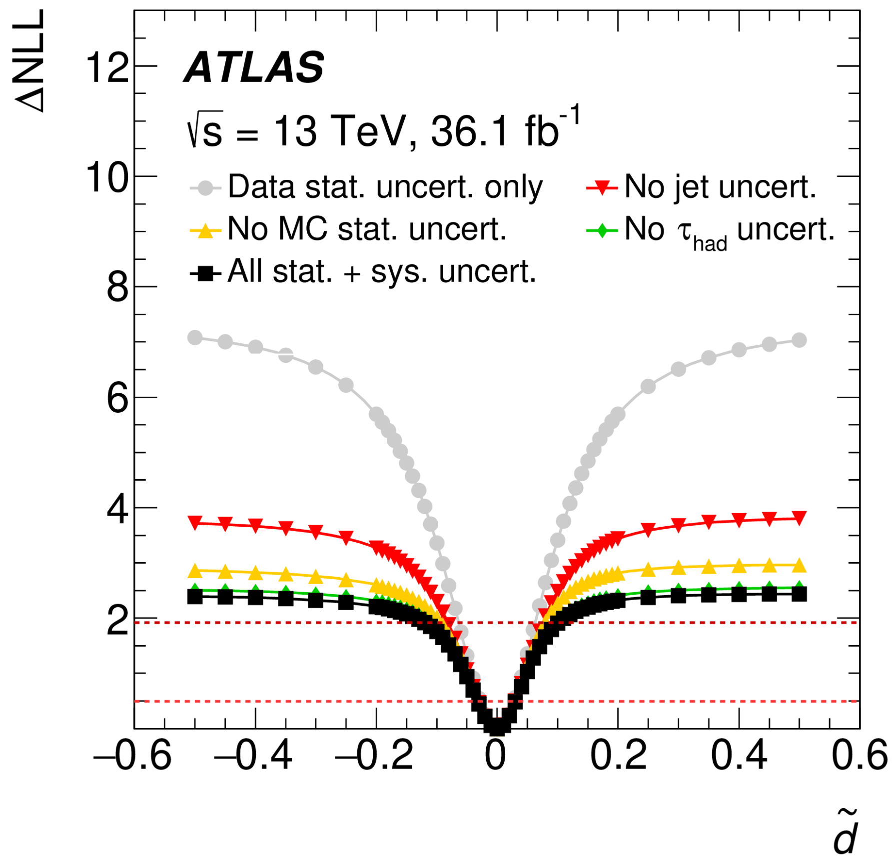


- Observed minimum at $\tilde{d} = -0.01$ with a signal strength of $\mu = 0.73 \pm 0.47$
- Expected curve from fit to pseudo-data built with best-fit values from CR-only fit

	expected $(\mu = 1)$	observed
68 % CL	$[-0.035, 0.033]$	$[-0.090, 0.035]$
95 % CL	$[-0.21, 0.15]$	-

Impact of systematic uncertainties

- Impact on the exp. limit on $\tilde{d}$:
  - Remove set of syst. uncert. from likelihood
- Compare sensitivity from **full stat.+syst. fit** and data stat. uncert. fit
- Largest impact from jet uncertainties
- Small impacts from MC statistical and τ_{had}-related uncertainties



Comparison to other results and to do's

- Confidence intervals on $\tilde{d}$:

	decay	data sets	exp. CI at 68% CL	exp. CI at 95% CL
CMS	$H \rightarrow VV$	R1	[-1.45, 1.45]	[-2.81, 2.81]
CMS	$H \rightarrow VV$	R1 + R2(80 fb^{-1})	[-0.11, 0.11]	[-0.76, 0.76]
CMS	$H \rightarrow \tau\tau$	R2 (36 fb^{-1})	[-0.043, 0.043]	[-0.154, 0.154]
CMS		combination	[-0.039, 0.039]	[-0.086, 0.086]
ATLAS	$H \rightarrow \tau\tau$	R1 (20.3 fb^{-1})	[-0.16, 0.16]	N.A.
ATLAS	$H \rightarrow \tau\tau$	R2 (36 fb^{-1})	[-0.035, 0.033]	[-0.21, 0.15]

Best observed limit at 95 CL: [-0.81, 0.30]

To DOs:

- Add more data
- Control uncertainties better (MC stats)
- Quote also combinable and particle level result (could be input to e.g. EFT fit)

Overview

- Higgs-Gauge coupling:
  - Test of CP invariance in vector-boson fusion production of the Higgs boson in the $H \rightarrow \tau\tau$ channel in pp collisions at $\sqrt{s} = 13\ TeV$ with the ATLAS detector
    Phys. Lett. B 805 (2020) 135426
    arXiv:2002.05315

VBF, $H \rightarrow \tau\tau$
using 36 fb^{-1}

- Yukawa coupling:
  - Study of the CP properties of the interaction of the Higgs boson with top quarks using top-quark associated production of the Higgs boson and its decay into two photons with the ATLAS detector at the LHC
    Accepted by PRL
    arXiv:2004.04545

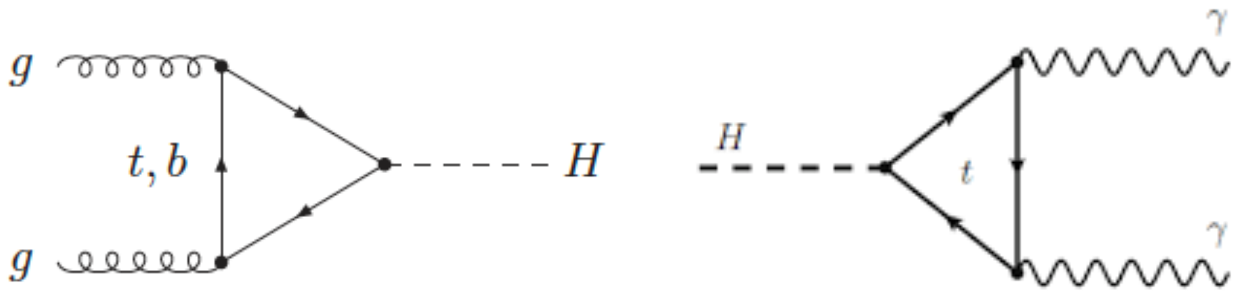
$t\bar{t}H/tH, H \rightarrow \gamma\gamma$
using 139 fb^{-1}

CP violation in the Top Yukawa coupling

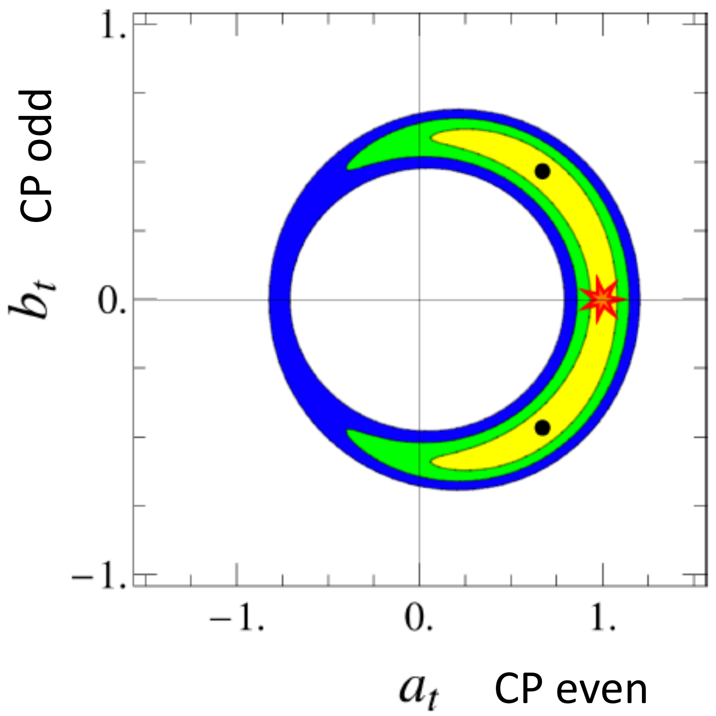
- Scalar and pseudo-scalar top-H coupling:

$$\mathcal{L}_{ht\bar{t}} = -\frac{m_t}{v} H[\bar{\psi}_t \kappa_t (\cos\alpha + i \sin\alpha\, \gamma_5)\psi_t]$$

- In SM: $\kappa_t = 1, \alpha = 0°$
- Indirect constraints:

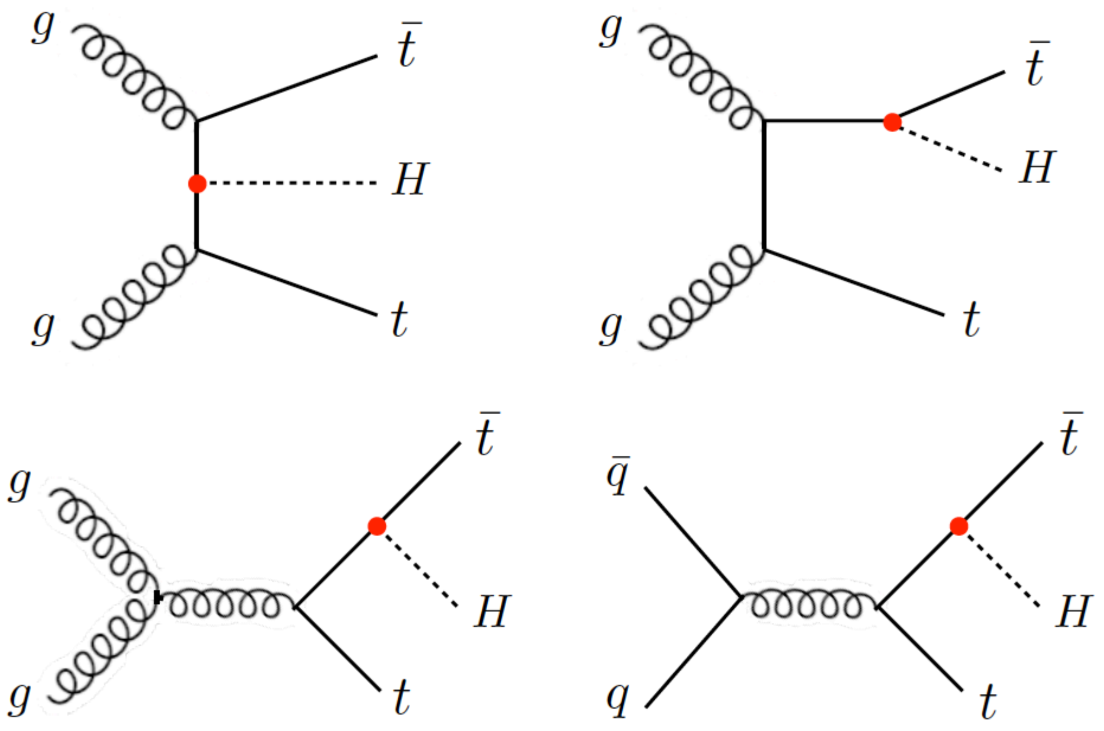


$$\kappa_g^2 = \kappa_t^2 \cos^2(\alpha) + 2.6\kappa_t^2 \sin^2(\alpha) + 0.11\kappa_t \cos(\alpha)(\kappa_t \cos(\alpha) - 1)$$
$$\kappa_\gamma^2 = (1.28 - 0.28\kappa_t \cos(\alpha))^2 + (0.43\kappa_t \sin(\alpha))^2$$



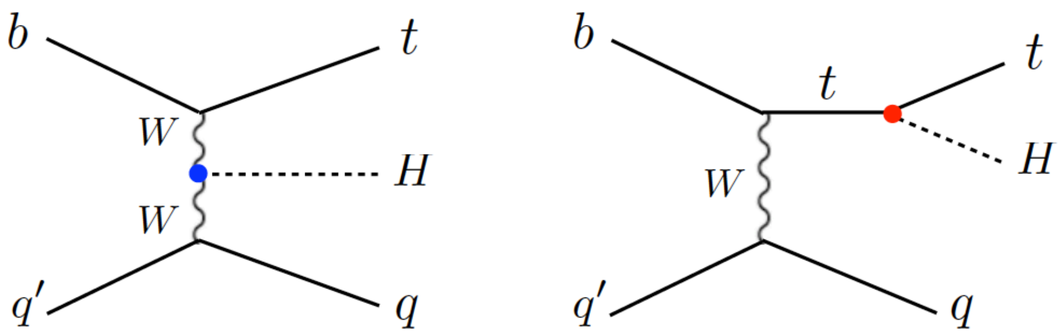
Direct probe of the Top Yukawa coupling

$t\bar{t}H$ production
~ 1% of total Higgs production



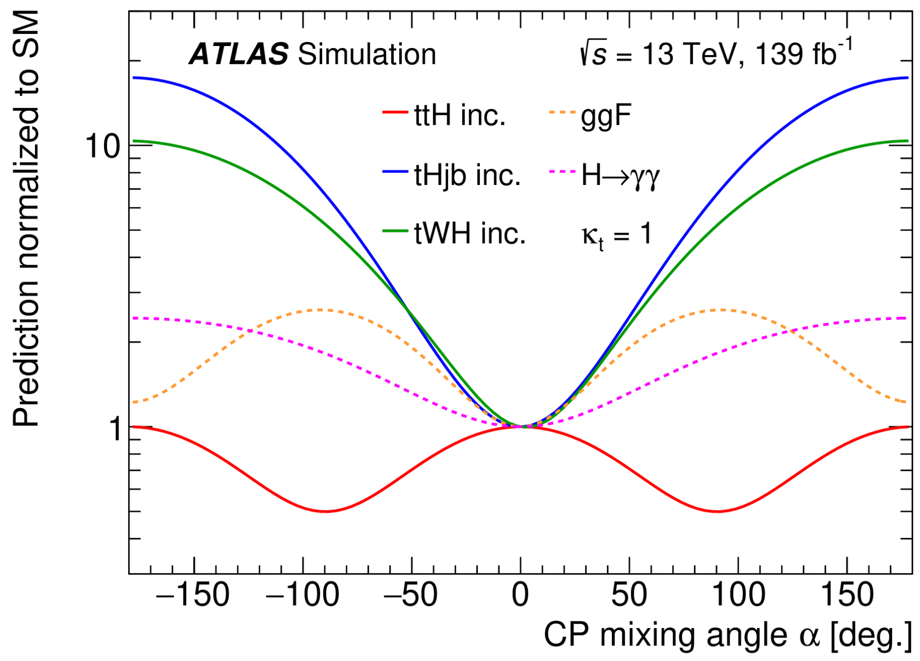
tH production
~ 0.15% of total Higgs production

Negative interference between $t\bar{t}H$ and WWH coupling maximal in SM.

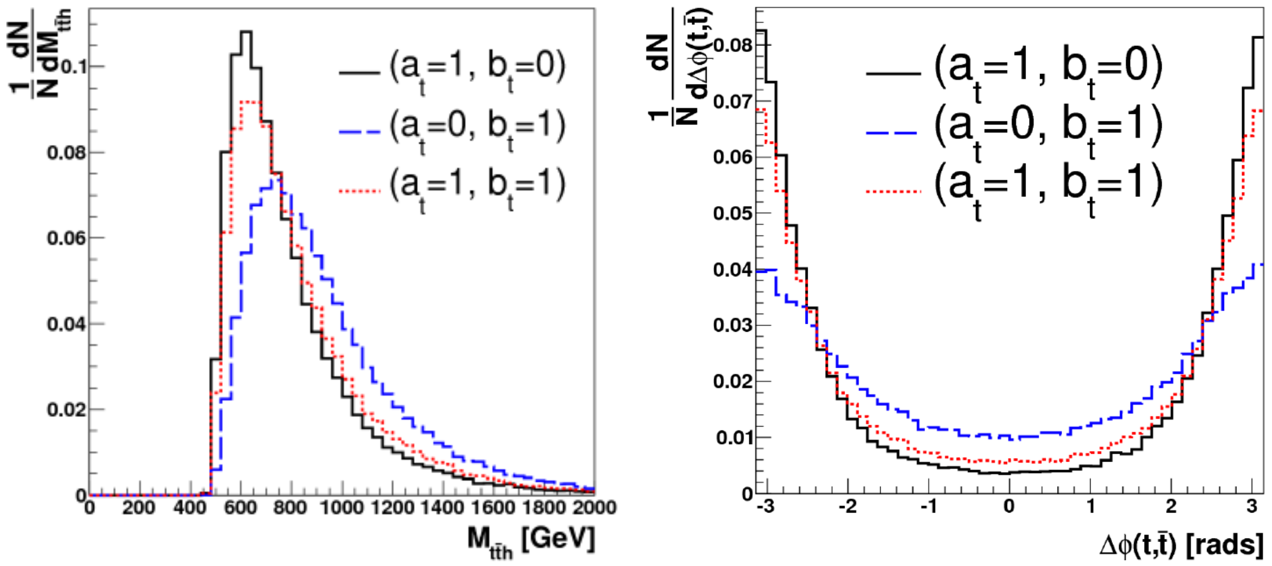


Direct probe of the Top Yukawa coupling

Rate information
→ high sensitivity from tH



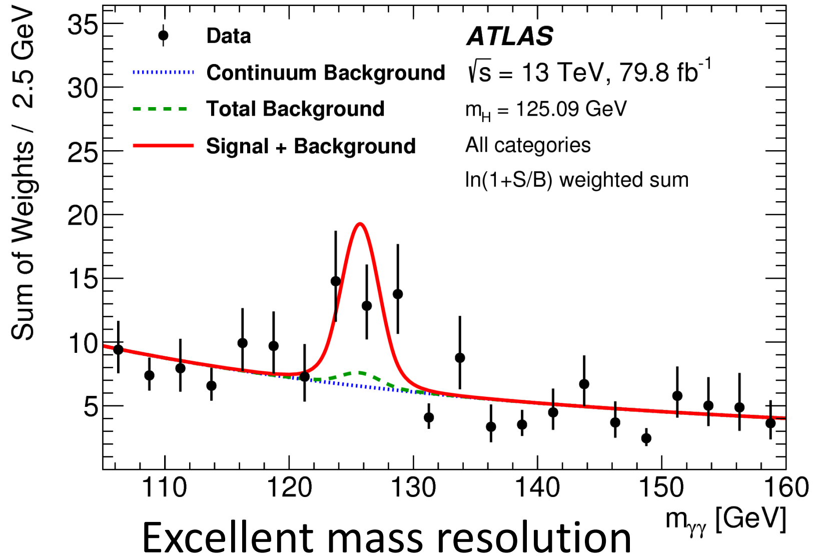
Shape information
→ Many variables constructed in $t\bar{t}H$ sensitive to spin correlations of process
→ Optimal observable could be used
→ MVA used instead



PRD 92 (2015) 015019
Boudjema, Godbole, Guadagnoli, Mohan

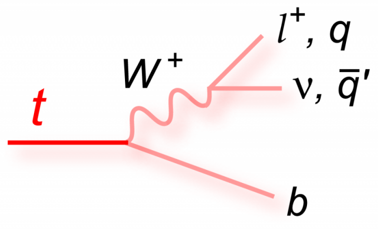
$t\bar{t}H/tH$ CP analysis in $H \rightarrow \gamma\gamma$ decay channel

- Analysis strategy:
  1. Select $t\bar{t}H/tH$ events
  2. Test for CP violation using an MVA



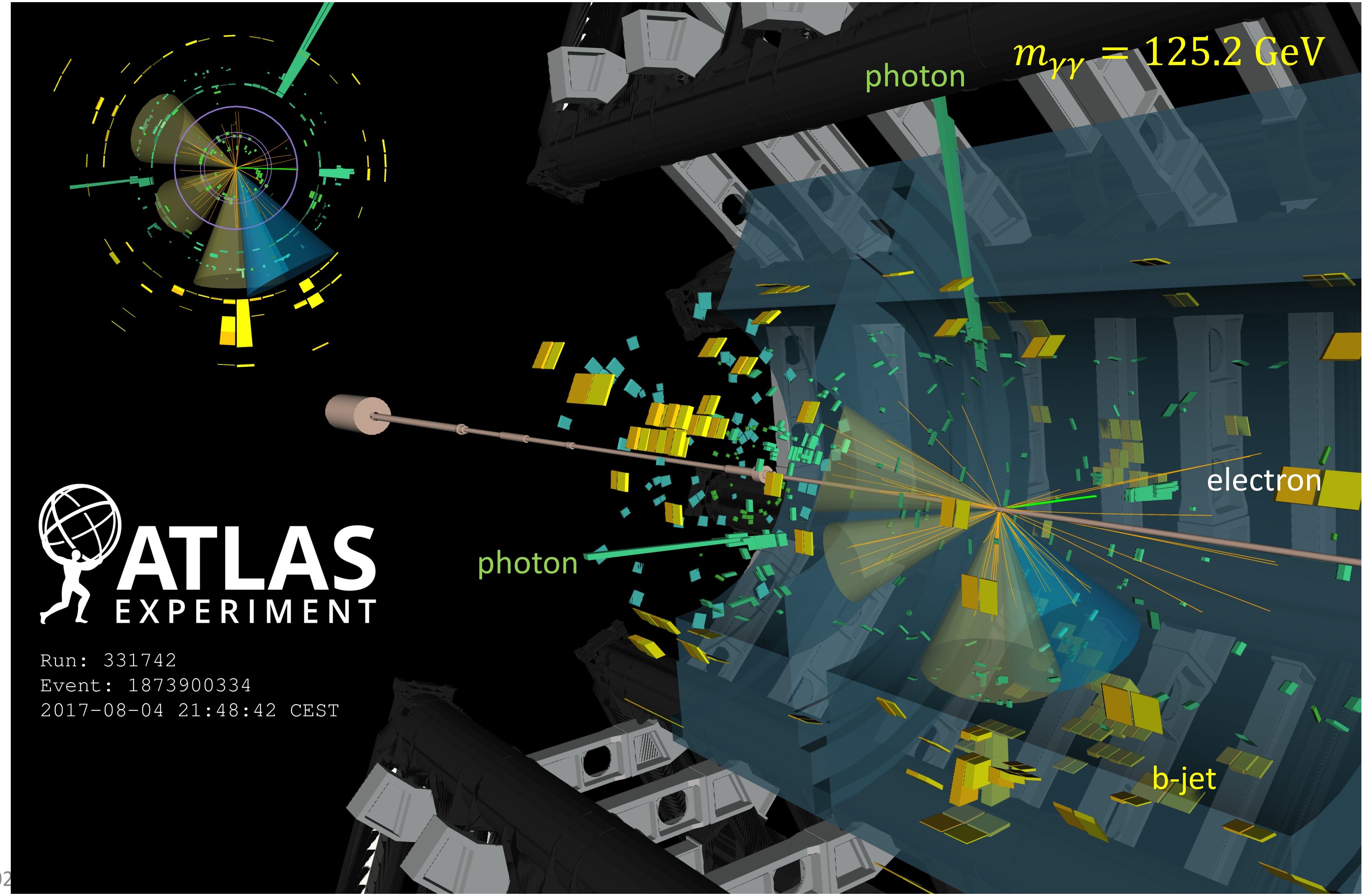
Excellent mass resolution

- Final state
  - $H \rightarrow \gamma\gamma$
    - Require two photons with $105 < m_{\gamma\gamma} < 160$ GeV
  - Top-quark decay(s) hadronic → "Had" region
    - At least one b-tagged jet with $p_T > 25$ GeV
    - ≥ 2 additional jets with $p_T > 25$ GeV
  - At least 1 top-quark decay leptonic → "Lep" region
    - At least one b-tagged jet with $p_T > 25$ GeV
    - ≥ 1 isolated lepton with $p_T > 15$ GeV



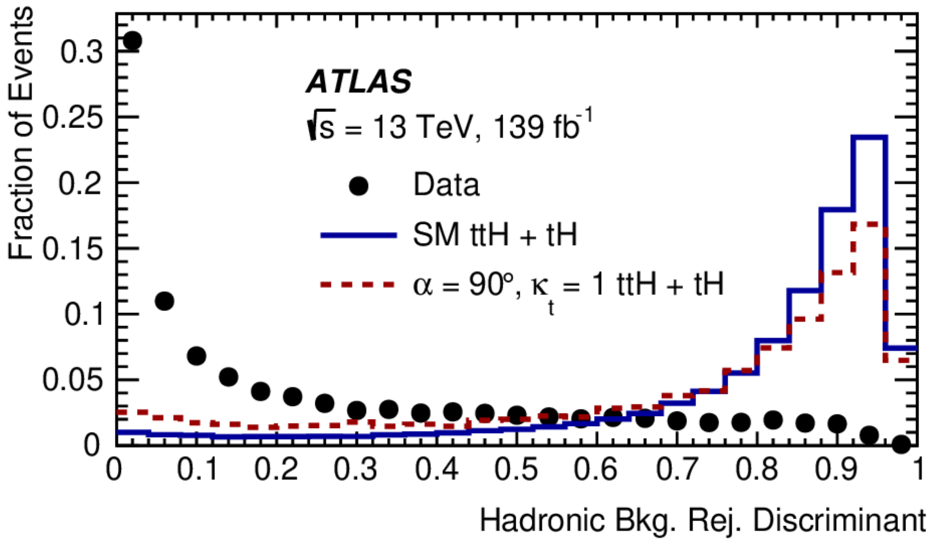
➡ Messy final states but low backgrounds ($t\bar{t}\gamma\gamma$) and excellent mass resolution

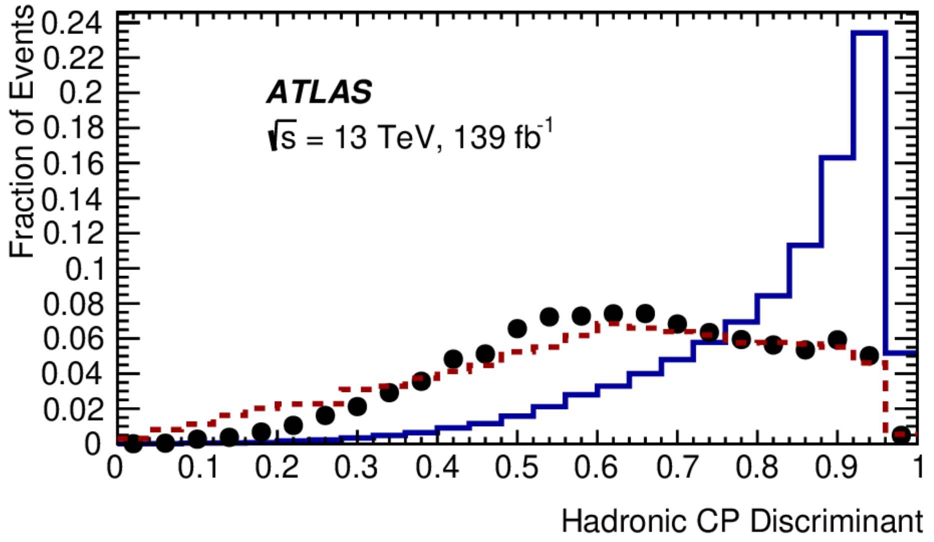
$t\bar{t}H/tH, H \rightarrow \gamma\gamma$ event in the detector



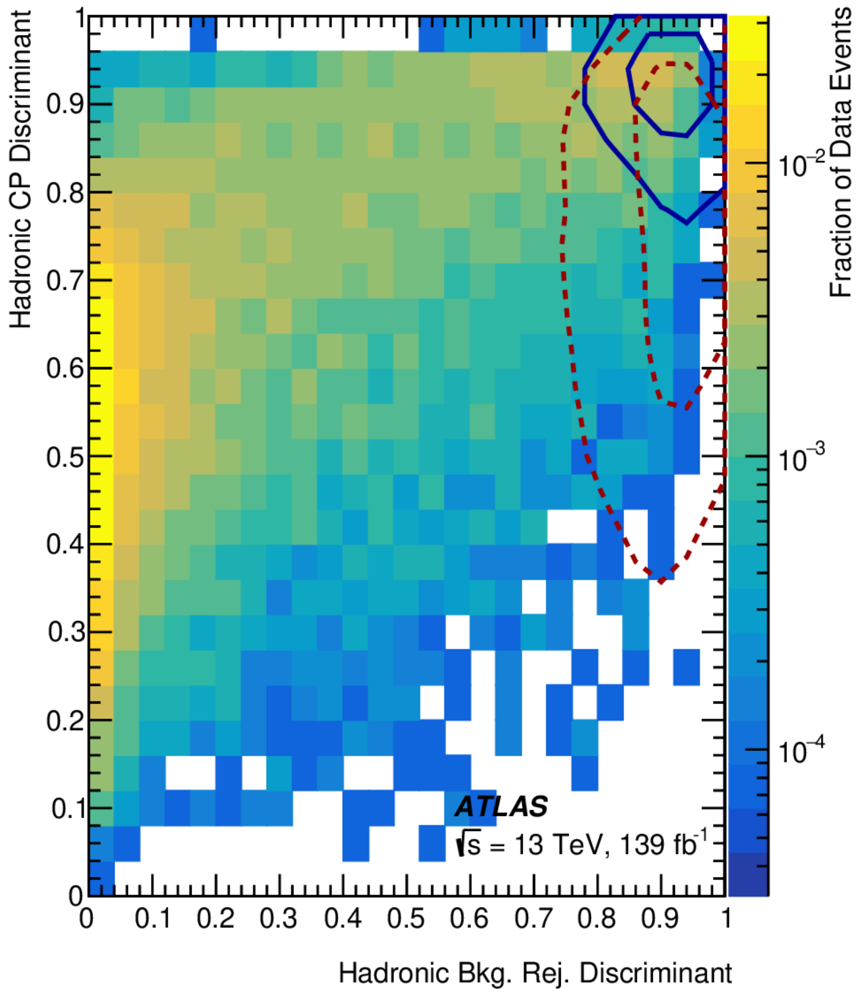
MVA to select $t\bar{t}H/tH$ and to probe CP

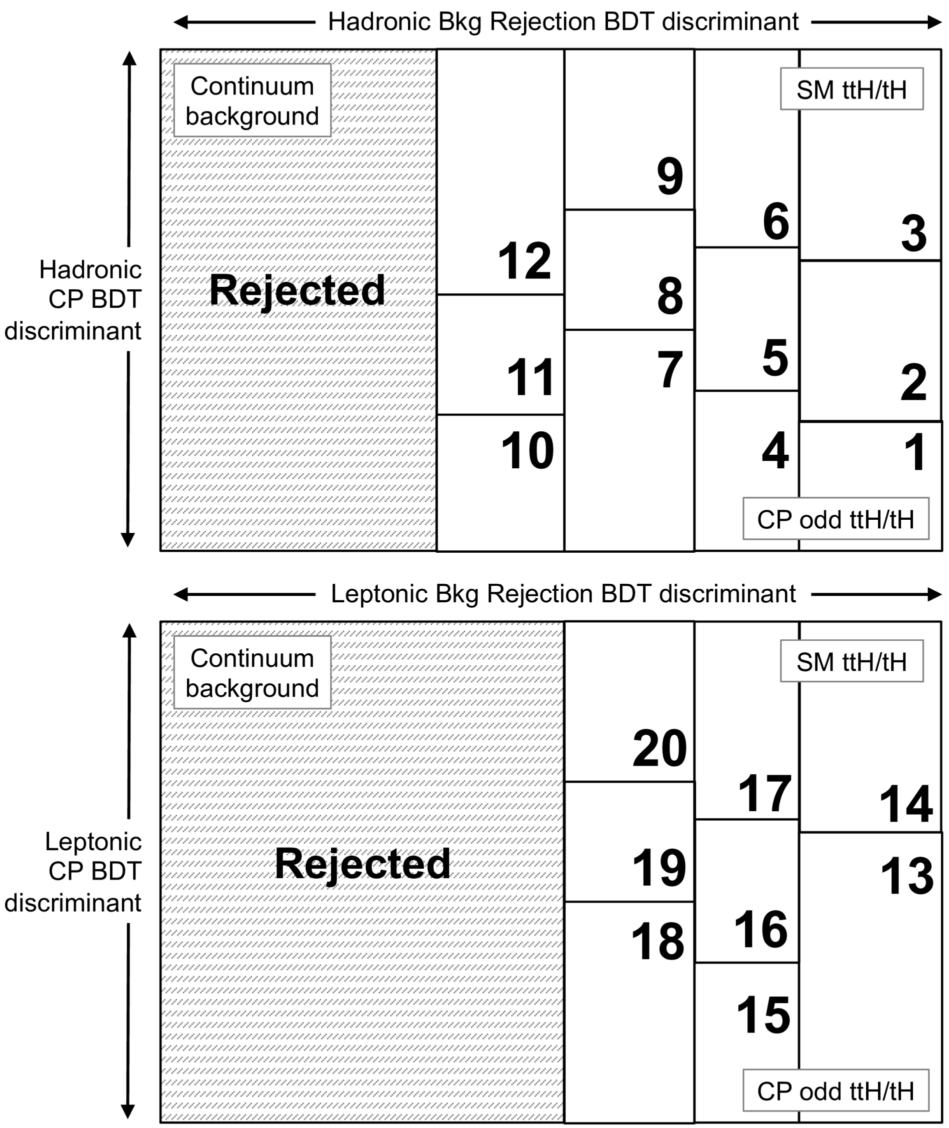
- Background rejection BDT uses 4-vectors of objects, b-tagging information and $p_T^{\gamma_i}/m_{\gamma\gamma}$
- BDT used to select objects for top-quark reconstruction to reconstruct t_1 and if possible t_2
- Long list of variables for CP BDT
  - Most important: $p_T^{\gamma\gamma}, H_T, \Delta R_{min2}^{\gamma j}, m_{tt}, \Delta\eta_{tt}$
- Background rejection and CP BDT used for categorisation





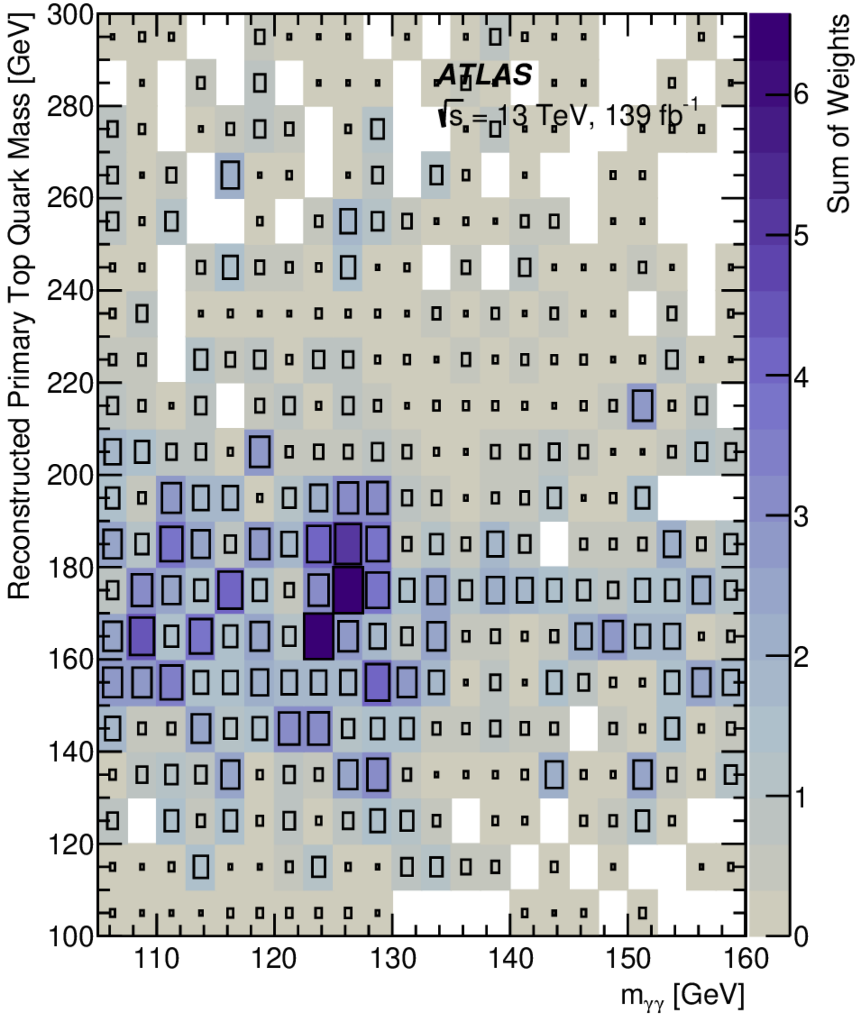
Categorisation

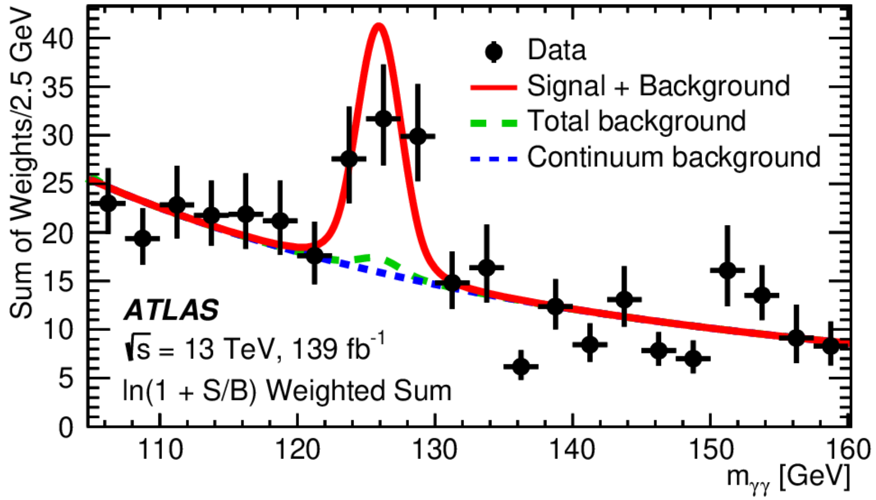


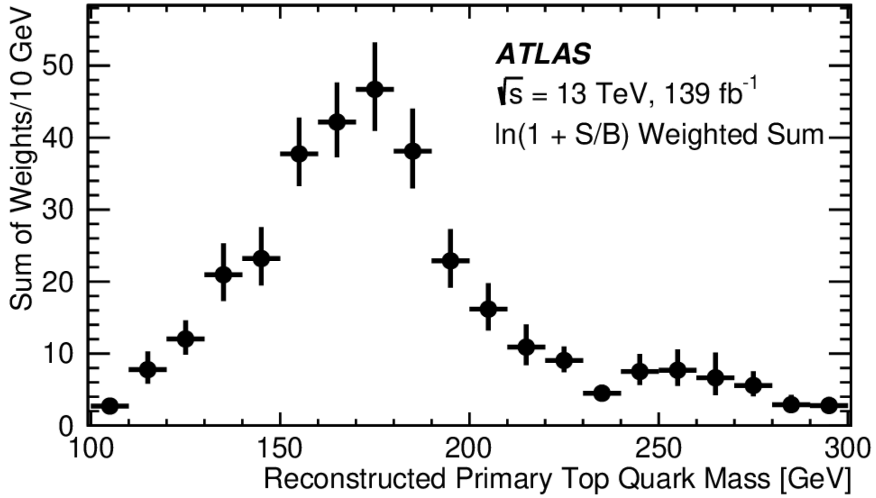


Simultaneous fit of $m_{\gamma\gamma}$ in each category

How well was $t\bar{t}H / tH$ selected?



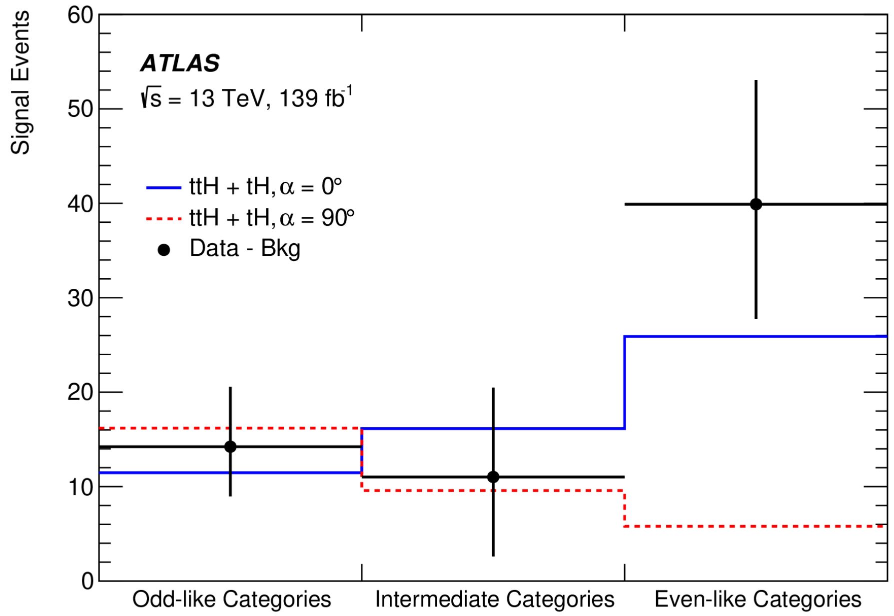




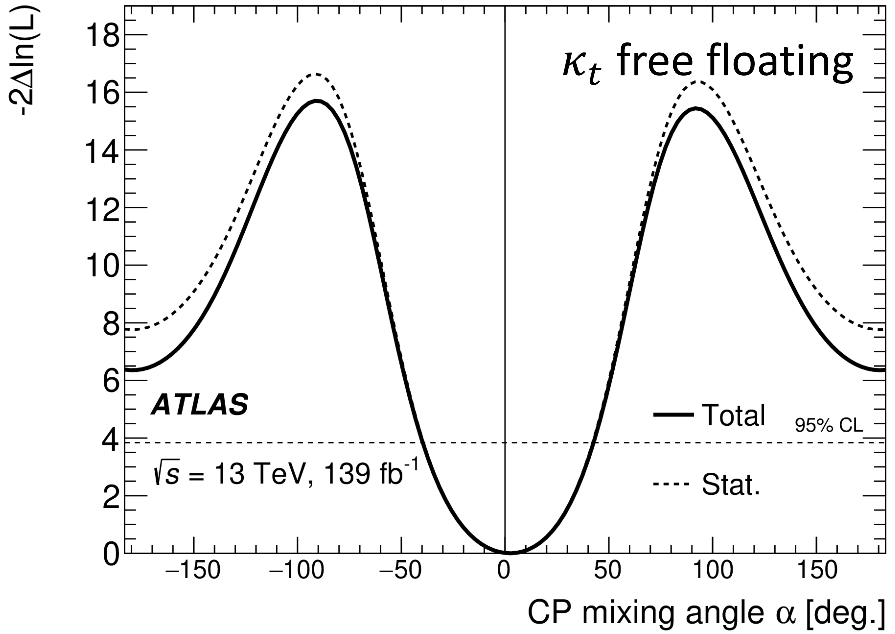
Pretty well!

Results

- $t\bar{t}H$ observation at 5.2σ:
  $\mu = 1.4 \pm 0.4\ (\text{stat.}) \pm 0.2\ (\text{sys.})$
- Limit on tH at 95% C.L. of $12\times\sigma_{SM}^{tH}$
- To extract Top Yukawa coupling κ_t need sensitivity to κ_g and κ_γ
  - Add ATLAS Higgs combination data to constrain κ_g and κ_γ from data



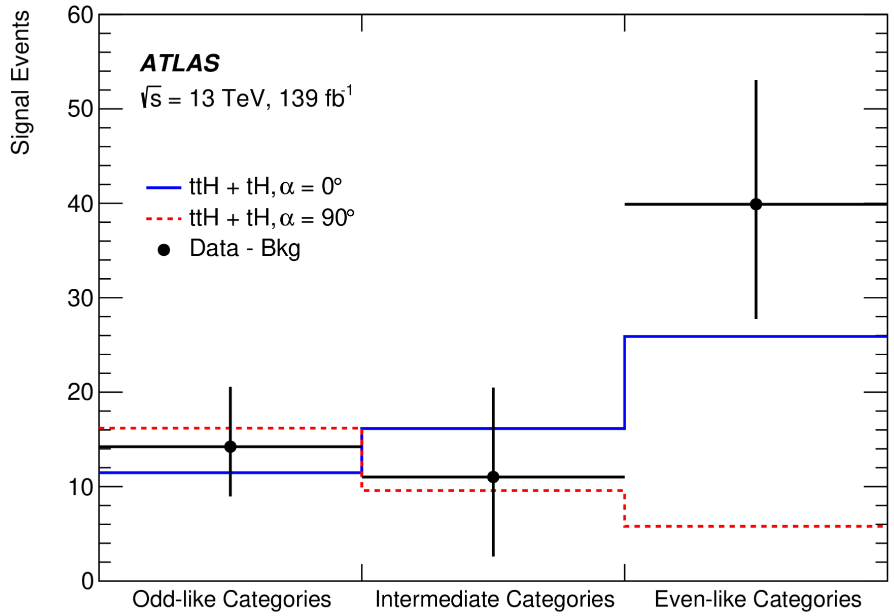
- $|\alpha| > 43°$ excluded at 95% CL
- $\alpha = 90°$ (CP odd) excluded at 3.9σ
- Similar results by CMS

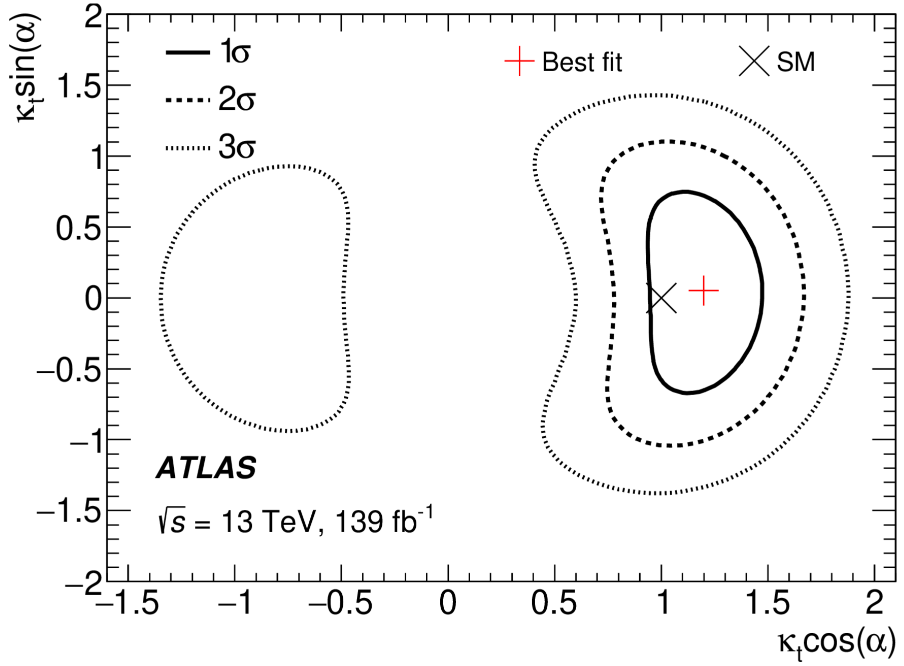


Results

- $t\bar{t}H$ observation at 5.2σ:
  $\mu = 1.4 \pm 0.4\ (\text{stat.}) \pm 0.2\ (\text{sys.})$
- Limit on tH at 95% C.L. of $12{\times}\sigma_{SM}^{tH}$
- To extract Top Yukawa coupling κ_t need sensitivity to κ_g and κ_γ
  - Add ATLAS Higgs combination data to constrain κ_g and κ_γ from data

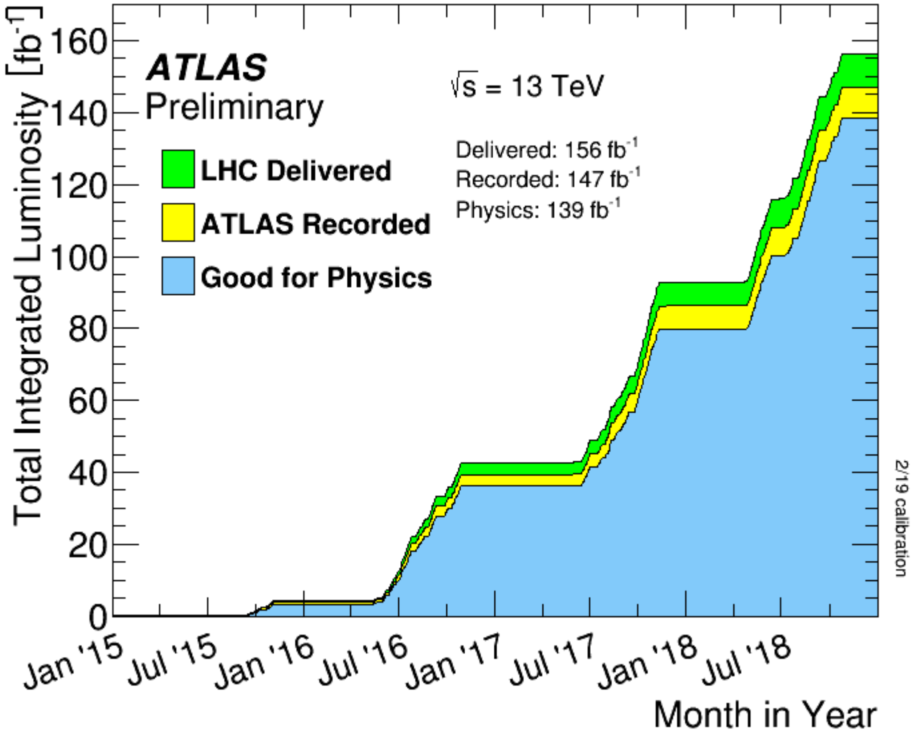
- $|\alpha| > 43°$ excluded at 95% CL
- $\alpha = 90°$ (CP odd) excluded at 3.9σ
- Similar results by CMS





Conclusion

- ATLAS and CMS probe the CP nature of the Higgs boson
  - Higgs-Gauge couplings
  - Yukawa couplings
  - Studies only at the beginning
- So far, no hint of CP violation has been observed
  - Higgs-gauge CP mixing parameter $-0.81 < \tilde{d} < 0.30$
  - Top Yukawa mixing angle $|\alpha| < 44°$
- Results statistics dominated
  - More data and more decay channels can be analysed
  - Run 3 and HL-LHC data will help gain more insights

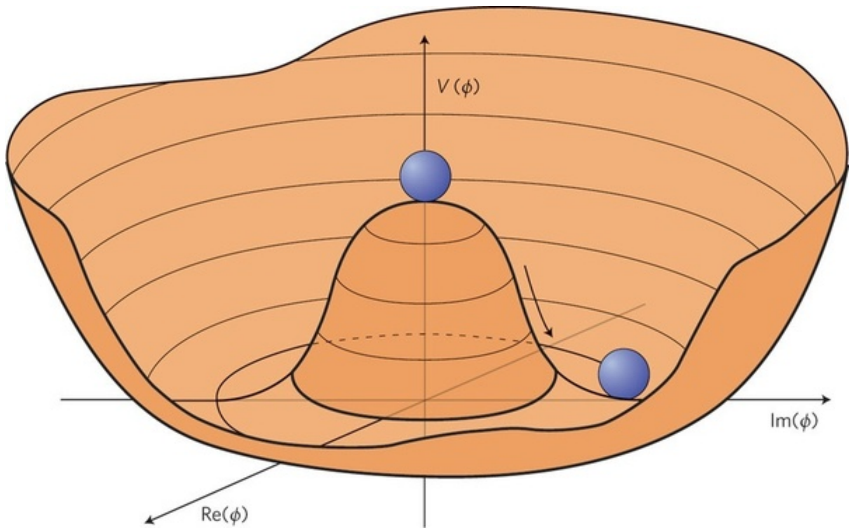


Thank you for your attention!

BACK-UP

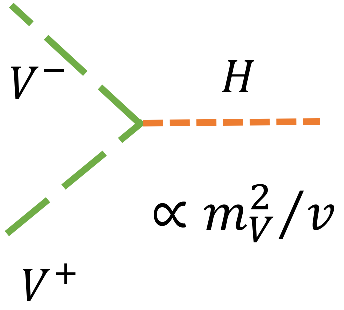
The Higgs boson: Last puzzle piece of the SM

- Predicted 1964, discovered 2012
- Particles interact with the Higgs field
  → via spontaneous symmetry breaking
  the particles acquire masses
- Introduces one scalar particle:
  the Higgs boson

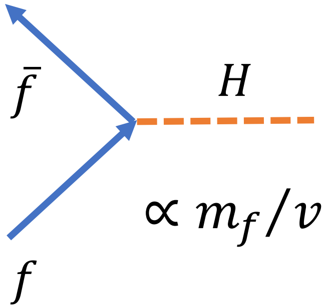


www.quora.com

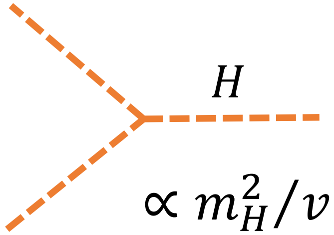
Gauge coupling:



Yukawa coupling:



Self coupling:



Higgs potential:

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

Higgs Vacuum Expectation Value:

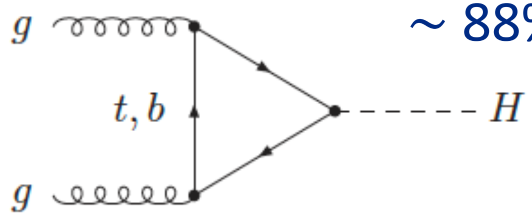
$$v = \frac{\mu}{\sqrt{\lambda}}$$

➡ **Is new physics hiding in the Higgs sector?**

Higgs boson production in *pp* collisions

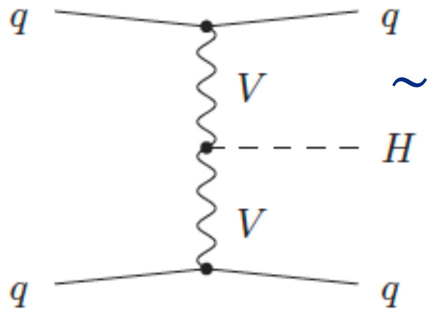
SM production modes

Gluon fusion (ggF)



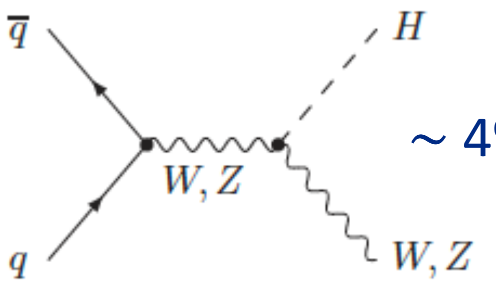
~ 88%

Vector boson fusion (VBF)



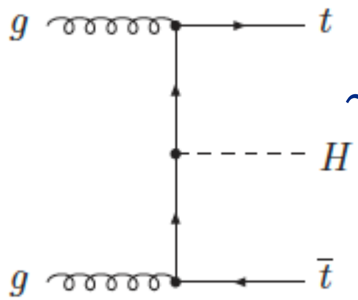
~ 7%

Higgs-Strahlung (VH)



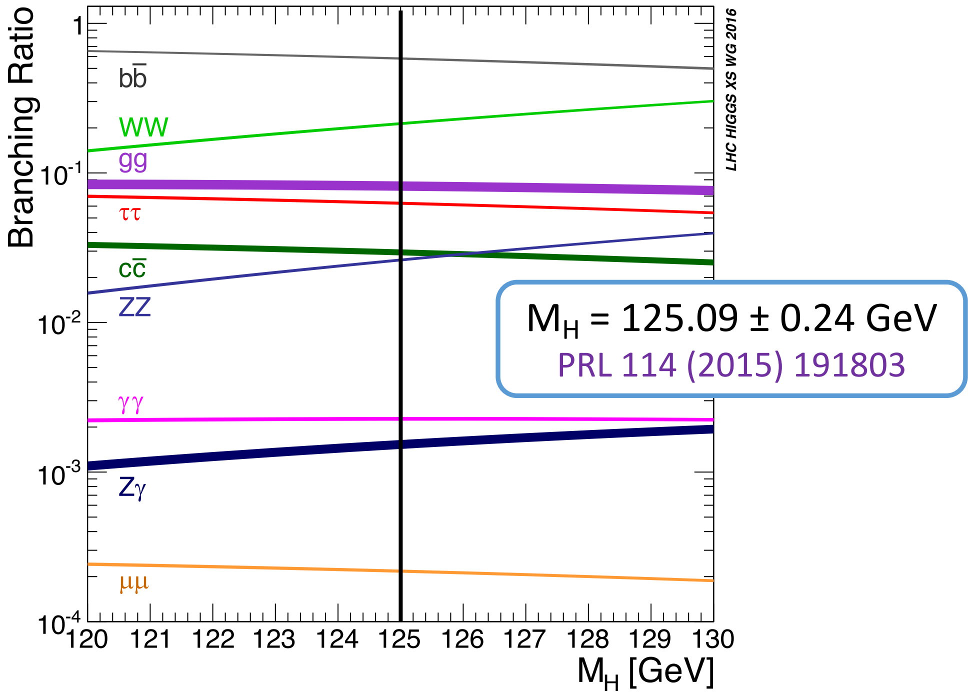
~ 4%

ttH production



~ 1%

SM decay branching fractions



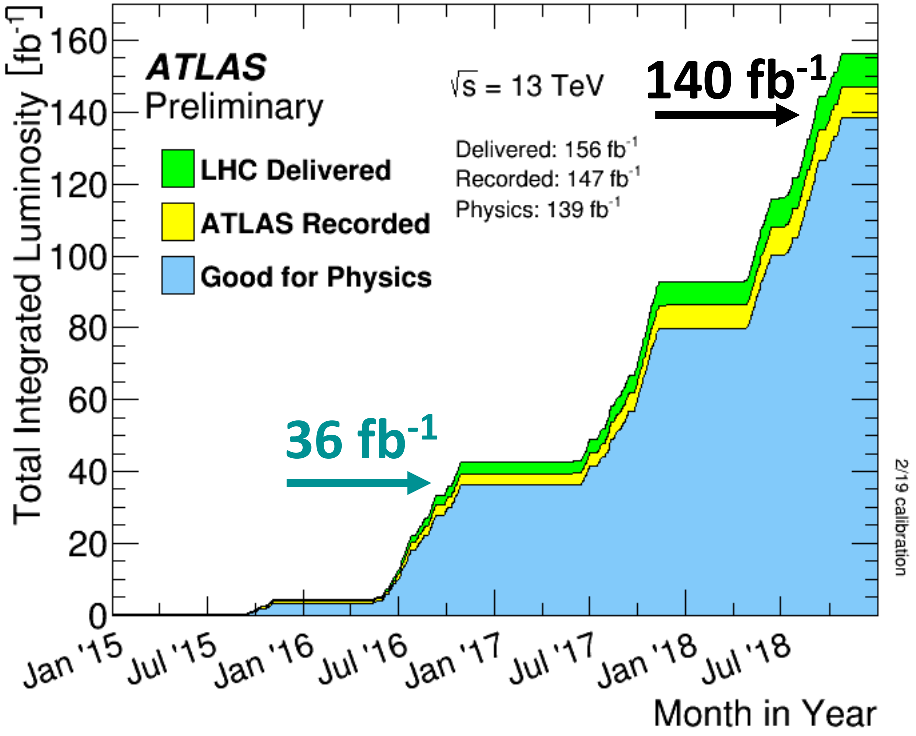
- All main production modes probed at the LHC
- Many decay channels investigated
- From √s = 8 TeV to 13 TeV: Increase in $\sigma_{pp \to H\ (ggF,\ VBF)}$ by factor of 2.3

The *pp* collision dataset

Results use Run 2 dataset

LHC Run	$\sqrt{s}$	Luminosity
Run 1	7+8 TeV	25 fb^{-1}
Run 2	13 TeV	36 fb^{-1}
		139 fb^{-1}

→ $^1/_4$ of Run 2



Run 1: 0.5 million produced Higgs-boson events (35k VBF events)

→ Run 2: 8 million produced Higgs-boson events (0.5 million VBF events)