LHC phenomenology: Probing CP-violation in $t\bar{t}H$ events

Duarte Azevedo

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Standard Model and Beyond
$t\bar{t}H$ confirmed (and $H \longrightarrow b\bar{b}$)

Analyses
Dilepton
Single lepton
CP observables

Results and bounds
Comparison between the two channels
CL limits

Conclusions

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Introduction

Standard Model and Beyond

$\rightarrow$ **Scalar particle discovered in 2012 with mass of $\sim$ 125 GeV at the Large Hadron Collider (LHC)**.
ATLAS, Phys.Lett. B716 (2012), and CMS, Phys. Lett. B 716 (2012).

The Standard Model (SM) is complete. There is no experimental result that strongly deviates from the predictions. Some mentionable exceptions:

- Muon's anomalous magnetic moment.
- B meson decay rate which seem incompatible with the SM prediction.

Still we know it cannot be the whole story.

- **Gravity.**
- **Dark Matter:** Several indirect evidence: Galaxy rotation curves, Gravitational lensing, Cosmic microwave background, etc.
- **Enough CP-violation:** to support Sakharov's condition for baryogenesis.

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(Complex) Two Higgs Doublet Model - (C)2HDM

...as an example

Minimal scalar extension that allows for an additional source of CP-violation!

$\rightarrow$ Consider a scalar sector with two EW doublets Φ_1 and Φ_2.

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.] \quad (1)$$

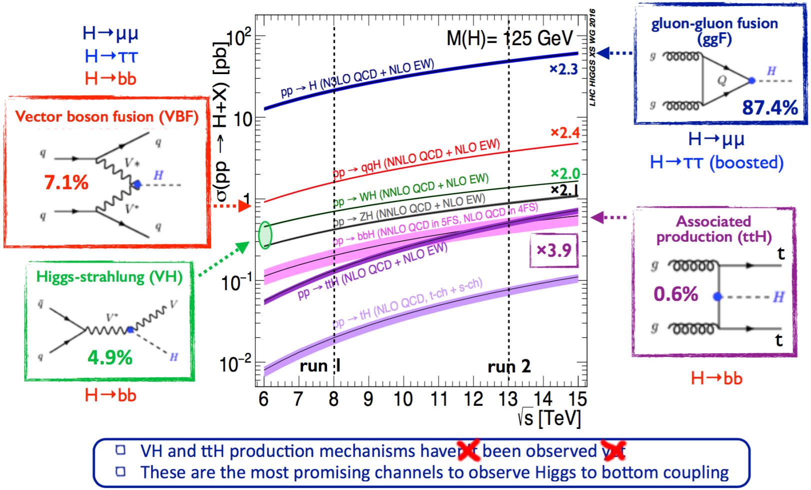
- No flavour changing neutral currents (FCNC) due to $\mathbb{Z}_2$ symmetry. $\Phi_2 \rightarrow -\Phi_2$.
- Complex m_{12}^2 and λ_5 (with different phases) $\implies$ **CP-violation**.
- CP-violation is manifest in the Yukawa interactions of the three scalars (one of them to be identified with the 125 GeV Higgs).

	u-type	d-type	leptons
Type I	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$
Type II	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Lepton-specific	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Flipped	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$

Table: Components of the Yukawa couplings of the Higgs bosons H_i in the C2HDM.

$t\bar{t}H$ confirmed

...and other experimental data

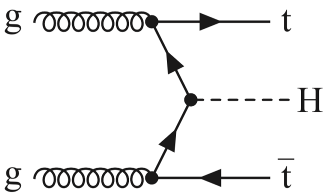


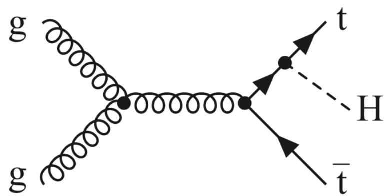
- Gluon fusions seems attractive but difficult to track what particles fall in the loop. Considering the SM, it allows for large CP-odd contributions. Phys. Rev. D 92 (2015)
- With $t\bar{t}h$ events, we are directly probing said vertex.
- VH production excludes a pure CP-odd Higgs at 99.98% Phys. Lett. B 759, 672 (2016).
- **Discovered announced:** CMS Phys. Rev. Lett. 120 (2018) and ATLAS Phys. Lett. B 784 (2018)

Parametrizing the top-Higgs Yukawa coupling

We considered the SM plus a generic CP-violating top-Higgs Yukawa coupling

$$\mathcal{L}_Y = y_t^{SM} \kappa \bar{t}(\cos\alpha + i\gamma^5 \sin\alpha) t h \tag{2}$$





$\to$ We set $\kappa = 1$. CP-even $\alpha = 0$ (H) CP-odd $\alpha = \frac{\pi}{2}$ (A)
$\to$ Consider only $h \to b\bar{b}$ decays.
$\to$ Consider only the single lepton or dilepton final state of the $t\bar{t}$ system.

Two Analyses:

- Dilepton channel. Studied from CP-even to CP-odd in steps of $\Delta \cos\alpha = 0.1$.
  $\Longrightarrow$ Less statistics, worst but improves results when combined. Phys. Rev. D 96 (2017)
- Single lepton channel. Studied the CP-even and pure CP-odd.
  $\Longrightarrow$ More statistics, better. Phys. Rev. D 98 (2018)

Analyses

General remarks

Event Generation @ 13 TeV:

- **MadGraph5_aMC@NLO** JHEP **1407**, 079 (2014)
  †NNPDF2.3 PDF NPB **867**, 079 (2013)
  for $t\bar{t}h$, $h = A, H$ (with `HC_NLO_X0` model) and $t\bar{t}b\bar{b}$ (@NLO)
  other backgrounds @ LO with MLM:
  $t\bar{t}$ + jets, $t\bar{t}V$ + jets, Single top,
  $W(Z)$ + jets, VV + jets
- **MadSpin** JHEP **1303**, 015 (2013)
  full spin correlations of the top quark decays
  $\rightarrow$ $t\bar{t}$ systems decay either to single lepton or dilepton final state (no τ-leptons).
- **Pythia 6** JHEP **0605**, 026 (2006)
  showering and hadronization

Simulation: DELPHES 3 JHEP **1402**, 057 (2014)

Pre-analysis: MadAnalysis5 EPJC **74, no 10, 3103 (2014)**

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Dilepton final state

13 TeV @ LHC

Pre-analysis cuts:

- $N_{\text{jets}} \geq 4$
- $N_{\text{lep}} = 2$
- $p_T \geq 20$ GeV, $|\eta| \leq 2.5$
- $|m_{l\bar{l}} - m_Z| > 10$ GeV

Reconstruction algorithm: (MadAnalysis5)

- Boosted decision tree (BDT) algorithm to assign jets to the b-quarks of the top-quarks and Higgs.
- Neutrinos' momentum is obtained by requiring the missing momentum to make up for the right invariant mass of the top-quarks and W-bosons.
- A likelihood built with p_T distributions of all the objects makes up the decising criteria for choosing a certain solution.

Single lepton final state

13 TeV @ LHC

Pre-analysis cuts:

- $6 \leq N_{\text{jets}} \leq 8$
- $N_{\text{lep}} = 1$
- Jets: $p_T \geq 20\text{GeV}, |\eta_{\text{light}}| \leq 4.5, |\eta_b| \leq 2.5$
- Lepton: $p_T \geq 20\text{GeV}, |\eta_{\text{lep}}| \leq 2.5$
- $\not{E}_T > 20$ GeV.

Reconstruction algorithm: (KLFitter)

- Transfer Functions (TF) parametrize radiation and energy resolutions of jets, lepton and MET.
- Likelihood function is constructed from TFs and Breit-Wigners and solution is the one that maximizes the Likelihood.
- Neutrino is reconstructed by imposing the reconstructed W-boson to have the tabulated mass.

Dilepton cut-flow

Values in fb	$N_{jets} \geq 4$ $N_{lep} \geq 2$	Kinematic Fit	m_Z cut	N_b ≥ 3	N_b ≥ 4
$t\bar{t}+c\bar{c}$, $t\bar{t}$+lf	2160	1300	1110	4.78	0.06
$t\bar{t}+b\bar{b}$	87.1	51.9	44.5	2.91	0.27
$t\bar{t}+V(V=Z,W)$	7.9	4.5	3.9	0.09	0.01
Single t	54	26	23	0.12	0.00
V+jets ($V=W,Z$)	2700	1200	200	0.00	0.00
$V+b\bar{b}(V=W,Z)$	570	280	20	0.00	0.00
Diboson	130	53	14	0.00	0.00
Total back.	5700	2900	1410	7.90	0.34
$t\bar{t}H$	4.04	2.49	2.15	0.26	0.033
$t\bar{t}A$	4.43	2.69	2.36	0.31	0.041

Table: Expected cross-sections (in *fb*) as a function of selection cuts, at 13 TeV, for dileptonic signal and background events at the LHC.

Single lepton cut-flow

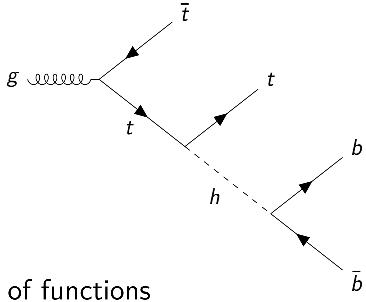
Values in fb	σ(fb) Pre-Selection	σ(fb) Final Selection
$t\bar{t}+c\bar{c}$, $t\bar{t}$+lf	2488	565.5
$t\bar{t}+b\bar{b}$	898.4	165.6
$t\bar{t}+V(V=Z,W)$	74.9	4.1
Single t	492.2	4.9
W+jets	3293	0
$W+b\bar{b}$	709.7	3.7
Diboson	996.6	0.5
Total back.	8953	744.3
$t\bar{t}H$	26.6	8.85
$t\bar{t}A$	18.9	6.07

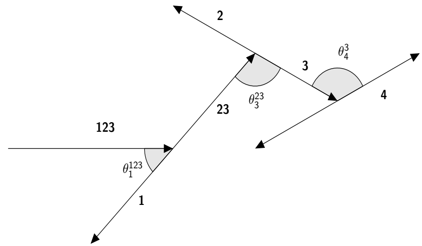
Table: Expected cross-sections (in fb) at *pre-selection* and *final selection* levels, for $t\bar{t}h(h = H, A)$ signals and SM backgrounds, at a centre-of-mass energy of 13 TeV, at the LHC.

CP observables

Based on previous works:

- **Angular distributions** (originally to increase SM $t\bar{t}h$ signal to background discrimination) based on the helicity formalism. Phys. Rev. D 92, 034021 (2015)





Family of functions

$$f(\theta_1^{123})g(\theta_4^3) \quad \text{and} \quad f(\theta_3^{23})g(\theta_4^3) \tag{3}$$

with f, g simple trigonometric functions.

- **Gunion-He variables**. Phys.Rev.Lett. 76 (1996)

$$a_1 = \frac{(\vec{p}_t \times \hat{n})\cdot(\vec{p}_{\bar{t}} \times \hat{n})}{|(\vec{p}_t \times \hat{n})\cdot(\vec{p}_{\bar{t}} \times \hat{n})|} \quad b_1 = \frac{(\vec{p}_t \times \hat{n})\cdot(\vec{p}_{\bar{t}} \times \hat{n})}{p_t^T p_{\bar{t}}^T} \quad b_2 = \frac{(\vec{p}_t \times \hat{n})\cdot(\vec{p}_{\bar{t}} \times \hat{n})}{|\vec{p}_t||\vec{p}_{\bar{t}}|}$$
$$a_2 = \frac{p_t^x p_{\bar{t}}^x}{|p_t^x p_{\bar{t}}^x|} \quad b_3 = \frac{p_t^x p_{\bar{t}}^x}{p_t^T p_{\bar{t}}^T} \quad \boxed{\mathbf{b_4} = \frac{\mathbf{p_t^z p_{\bar{t}}^z}}{|\tilde{\mathbf{p}}_\mathbf{t}||\tilde{\mathbf{p}}_{\bar{\mathbf{t}}}|}} \tag{4}$$

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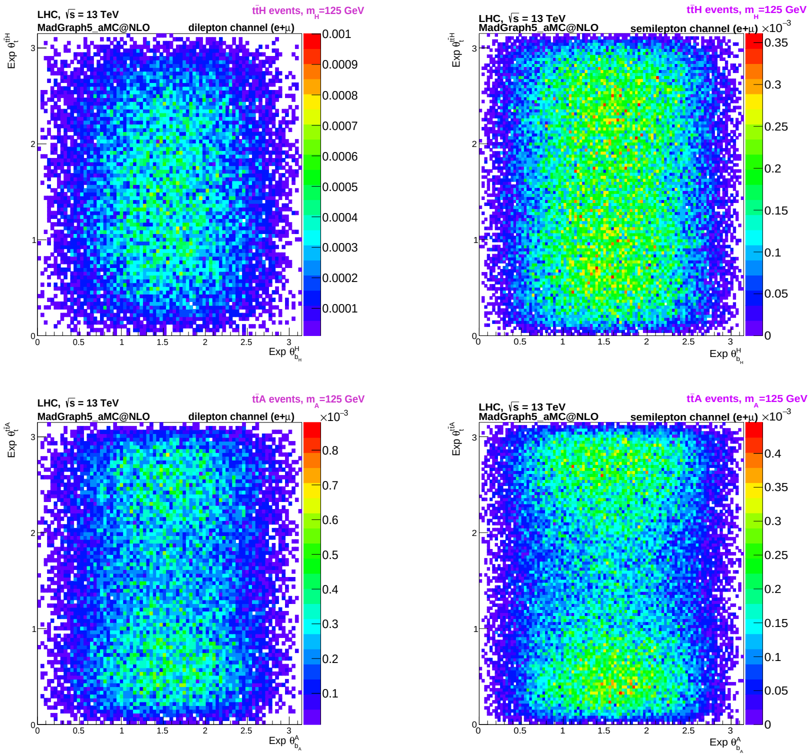
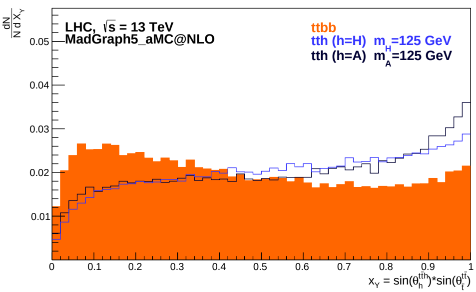
Comparison between the two channels



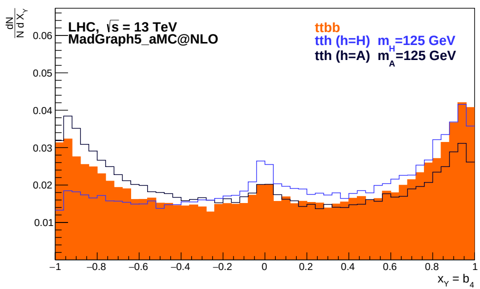
Variables

The variables considered in these analyses are:

- $\cos(\theta_h^{\bar{t}h})\cos(\theta_{\ell-}^h)$ and $A_{FB}^{\ell-(h)}$(*direct* boost),
- $\sin(\theta_h^{t\bar{t}h})\sin(\theta_{b_{\bar{t}}}^{\bar{t}})$ and $A_{FB}^{\bar{b}_{\bar{t}}(\bar{t})}$(*sequential* boost),
- $\sin(\theta_h^{t\bar{t}h})\cos(\theta_{b_h}^{\bar{t}})$ and $A_{FB}^{b_h(\bar{t})}$(*sequential* boost),
- $\sin(\theta_t^{t\bar{t}h})\sin(\theta_{W+}^h)$ and $A_{FB}^{W+(h)}$(*sequential* boost),
- $\sin(\theta_{\bar{t}}^{t\bar{t}h})\sin(\theta_{b_h}^h)$ and $A_{FB}^{b_h(h)}$(*sequential* boost),
- $\sin(\theta_h^{t\bar{t}h})\sin(\theta_{\bar{t}}^{t\bar{t}})$ and $A_{FB}^{\bar{t}(t\bar{t})}$(*direct* boost) and
- $b_4 = (p_t^z . p_{\bar{t}}^z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$ and $A_{FB}^{b_4}$,



(a) Background to signal discrimination



(b) SM to signal discrimination

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Asymmetries

Definition:

$$A_{FB}^{Y} = \frac{\sigma(x_Y > 0) - \sigma(x_Y < 0)}{\sigma(x_Y > 0) + \sigma(x_Y < 0)} \quad (5)$$

Dilepton

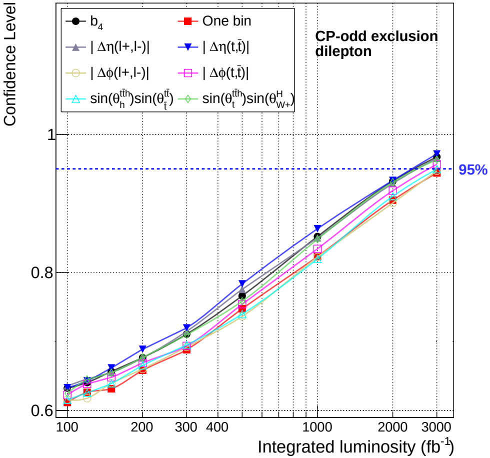
Asymmetries	After selection and reconstruction		
	$t\bar{t}H$	$t\bar{t}A$	$t\bar{t}b\bar{b}$
$A_{FB}^{\ell-(h)}$	$+0.42$	$+0.39$	$+0.24$
$A_{FB}^{b_{\bar{t}}(\bar{t})}$	$+0.25$	$+0.28$	$+0.03$
$A_{FB}^{b_h(\bar{t})}$	-0.78	-0.83	-0.76
$A_{FB}^{W+(h)}$	$+0.17$	-0.06	-0.04
$A_{FB}^{b_h(h)}$	$+0.37$	$+0.16$	$+0.23$
$A_{FB}^{\bar{t}(t\bar{t})}$	$+0.23$	$+0.31$	$+0.01$
$A_{FB}^{b_4}$	$+0.16$	-0.17	$+0.12$

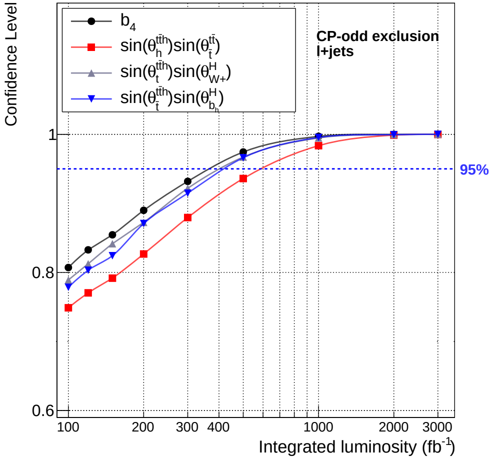
Single lepton

Asymmetries	Final Selection and Kinematic Reconstruction		
	$t\bar{t}H$	$t\bar{t}A$	$t\bar{t}b\bar{b}$
$A_{FB}^{\ell-(h)}$	$+0.10$	$+0.17$	-0.01
$A_{FB}^{b_{\bar{t}}(\bar{t})}$	$+0.20$	$+0.19$	-0.09
$A_{FB}^{b_h(\bar{t})}$	-0.67	-0.72	-0.65
$A_{FB}^{W+(h)}$	-0.33	-0.51	-0.51
$A_{FB}^{b_h(h)}$	$+0.18$	$+0.02$	-0.05
$A_{FB}^{\bar{t}(t\bar{t})}$	$+0.17$	$+0.15$	-0.11
$A_{FB}^{b_4}$	$+0.17$	-0.08	$+0.06$

Confidence level (CL) limits for exclusion of the pure CP-odd coupling

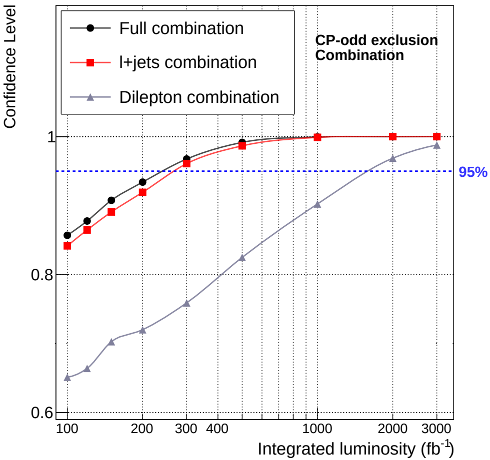
- Assuming the SM holds.
- Computed from likelihood ratios obtained from binned distributions of the observables.
- Only statistical uncertainties are considered.
- Shown up to the High Luminosity LHC (HL-LHC), maximum expected is 3 ab^{-1}.

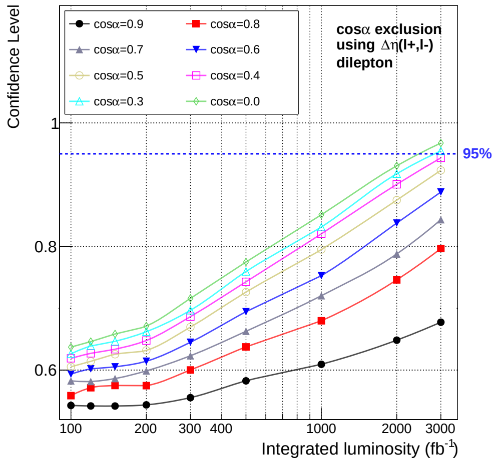




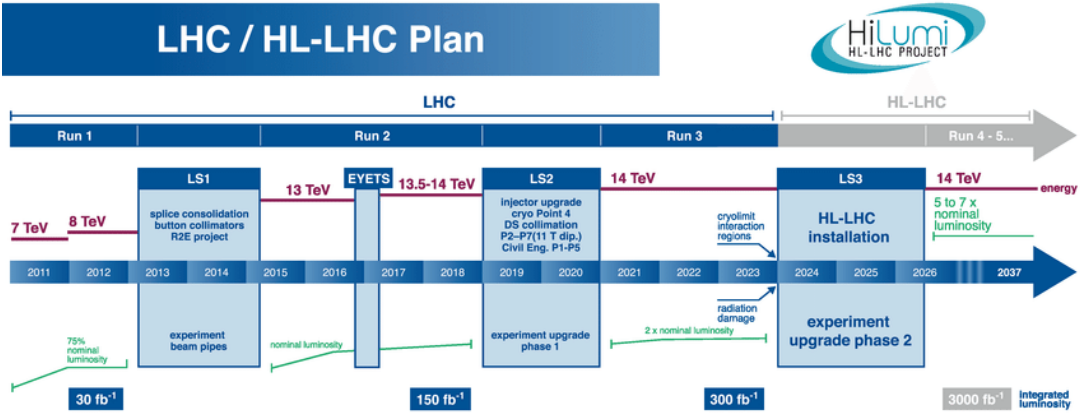
Combination of channels

→ **All observables treated as uncorrelated.**





Conclusions



- $t\bar{t}H$ and $H \rightarrow b\bar{b}$ were discovered during run 2.
- Angular variables (as well as Gunion-He) are good discriminants for analyses.
- Combination with other channels might make run 2 data enough for exclusion.
- Maximal mixing scenario ($\cos\alpha = \sqrt{2}/2$) will require roughly 3.5 times more luminosity than the CP-odd case for exclusion.