Higgs searches in $t\bar{t}\phi$ production at the LHC

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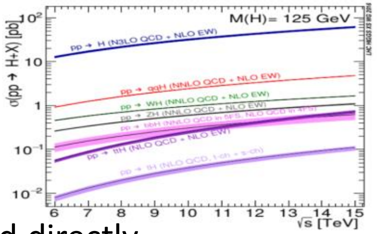
Why we care

Discovered Higgs **not a pure pseudoscalar**. **Mixed states** still possible. **CP-violation**. **Matter antimatter asymmetry.**



More Higgs with **masses from GeV to TeV**. Need **dedicated searches**. Challenging **low mass region.**

Measuring the **Yukawa couplings** primary target of LHC. **Production of scalars alongside top-quarks** vertex probed directly.

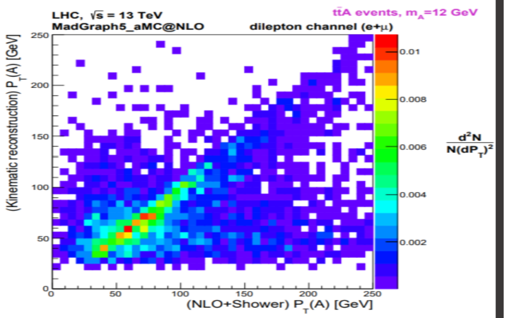
What we did

Searched **scalar with indefinite CP (ϕ)** in associated $t\bar{t}$ production, with $\phi \to b\bar{b}$. Mass region: **12-500 GeV**. **Dileptonic channel**. Full **phenomenological analysis**, using **SM background + signals** generated with **MadGraph5_aMC@NLO**.

$$\mathcal{L} = \kappa_t y_t \bar{t}(\cos\alpha + i\gamma_5 \sin\alpha)t\phi = y_t \bar{t}(\kappa + i\tilde{\kappa}\gamma_5)t\phi$$

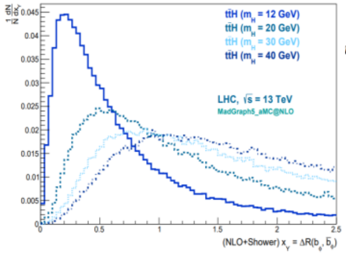
Main cuts: at least 2 charged leptons, 4 jets, $p_T \geq 20$ GeV, $|\eta| \leq 2.5$, $|m_{l^+l^-} - m_Z| > 10$ GeV and 3 b-tagged jets for selected events.

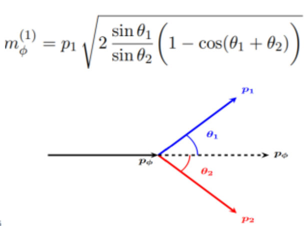
Full reconstruction relies on ML techniques and a kinematic fit to reconstruct the neutrinos.

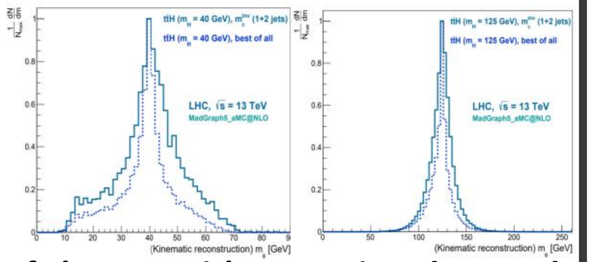


What we found

Low mass regime (12-40 GeV) **jets** from ϕ decay **overlap.** Previous studies lose sensitivity. In new approach **Higgs mass resolution improves by factor of two.**

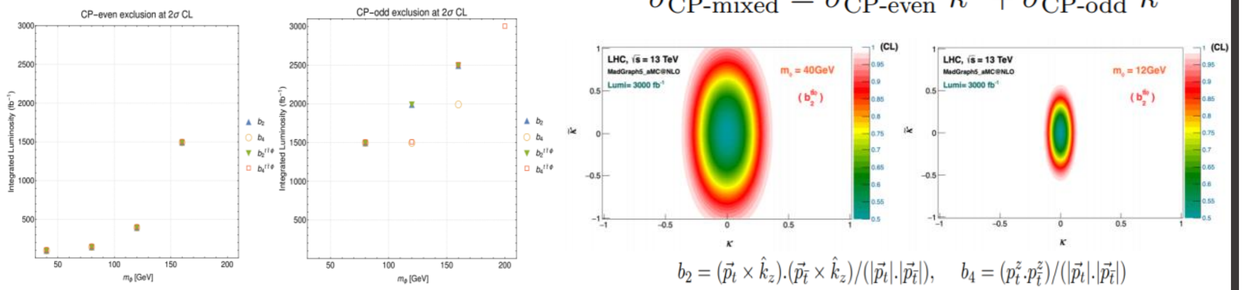






Confidence levels (CLs) for the **exclusion of the SM with new Higgs boson ϕ, assuming the SM** hypothesis.

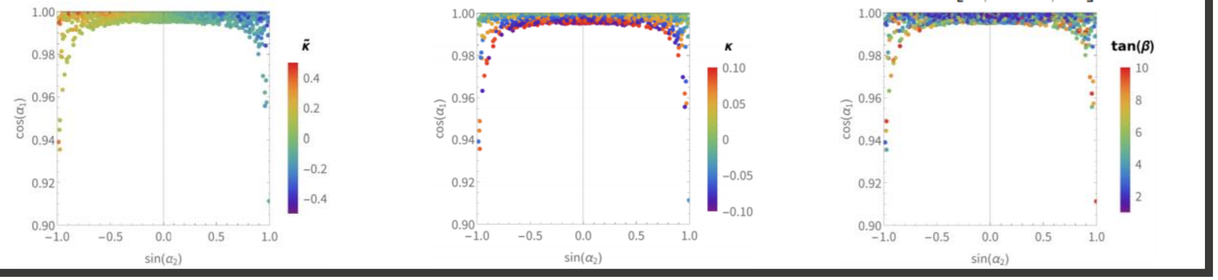
$$\sigma_{\text{CP-mixed}} = \sigma_{\text{CP-even}}\,\kappa^2 + \sigma_{\text{CP-odd}}\,\tilde{\kappa}^2$$



$b_2 = (\vec{p}_t \times \hat{k}_z).(\vec{p}_{\bar{t}} \times \hat{k}_z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$, $\quad b_4 = (p_t^z.p_{\bar{t}}^z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$

Benchmark model: **C2HDM**. With out results, $\cos\alpha_1 \approx 1$, but the **CP-violating angle α_2 remains unconstrained.**

$$\mathcal{L}_{\text{Yukawa}}^{\text{top}} = -\frac{m_f}{v}\bar{t}\left[\frac{s_1 c_2}{s_\beta} - i\frac{s_2}{t_\beta}\gamma_5\right] t H_1$$



Acknowledgments

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Complex Two-Higgs-doublet model (C2HDM)

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

C2HDM, hep-ph/0211371, is an **extension of the SM Higgs potential** where a scalar doublet is added that allows for **additional CP-violation** (m_{12}^2 and λ_5 complex).

$\mathbb{Z}_2$ **symmetry** on the scalar and fermionic fields **avoids FCNCs**. $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$.

Three neutral scalars (H_i, i = 1, 2, 3) with **undefined CP**, manifest in their Yukawa interactions.

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} h_1 \\ h_2 \\ a_3 \end{pmatrix} \qquad t_\beta = \frac{v_2}{v_1}$$

	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	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$

$$R = \begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -(c_1s_2s_3 + s_1c_3) & c_1c_3 - s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3 + s_1s_3 & -(c_1s_3 + s_1s_2c_3) & c_2c_3 \end{pmatrix}$$

$$\mathcal{L}_{Y_i} = -\frac{m_f}{v}\bar{\psi}_f\left[\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5\right]\psi_f H_i$$

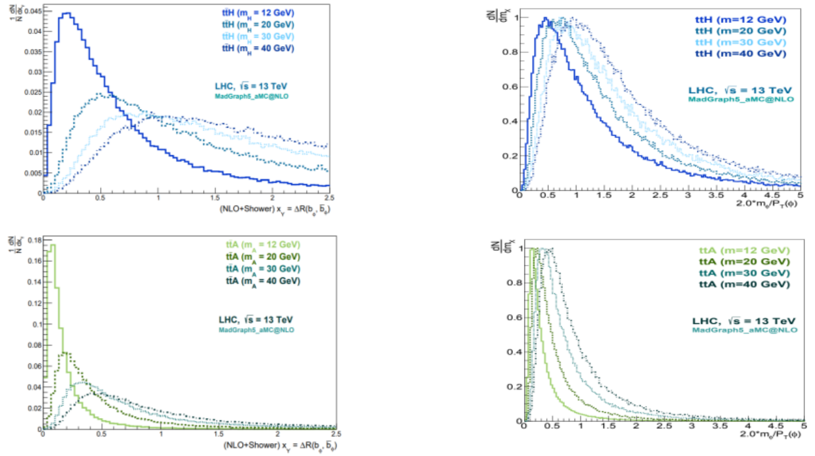
$\boldsymbol{H_1}$ is the **new scalar** and the **125 GeV Higgs** can be either $\boldsymbol{H_2/\ H_3}$. Due to **low energy physics measurements, $\boldsymbol{\tan\beta > 1}$**.

$$\mathcal{L}_{\mathrm{Yukawa}}^{\mathrm{top}} = -\frac{m_f}{v}\bar{t}\left[\frac{s_1c_2}{s_\beta} - i\frac{s_2}{t_\beta}\gamma_5\right]tH_1 \qquad \begin{cases} \kappa_t\cos\alpha = \frac{s_1\,c_2}{s_\beta} \\ \kappa_t\sin\alpha = -\frac{s_2}{t_\beta} \end{cases}$$

$\boldsymbol{\sin\alpha = 0 \Rightarrow \sin\alpha_2 = 0}$. CP-even limit is obtained unambiguously. What about $\sin\alpha \neq 0$?

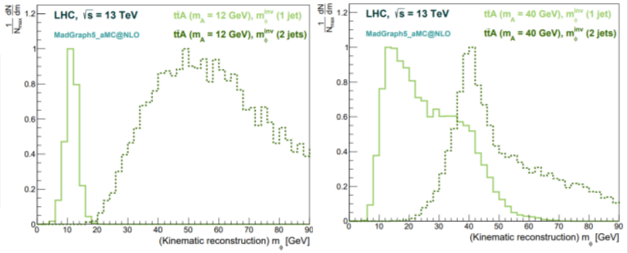
More on $\boldsymbol{\phi}$ boson reconstruction

Smallness of $\Delta R(b_\phi, \bar{b}_\phi)$ due to analytic relation, valid for $p_T(\phi) \gg m_\phi$, $\boldsymbol{\Delta R(b_\phi, \bar{b}_\phi) \sim 2\,m_\phi/p_T(\phi)}$.

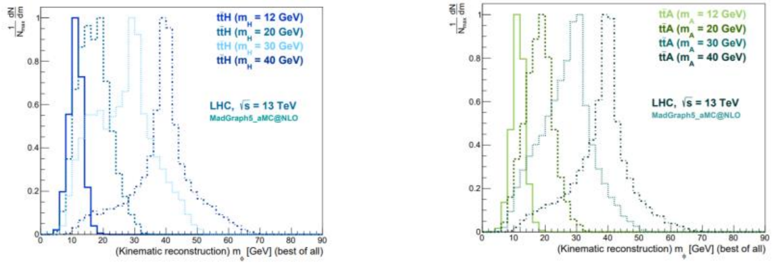


Three methods to **reconstruct Higgs mass**: invariant mass from 1 jet, 2 jets, or $m_\phi^{(1)}$. Closest to input value is chosen.

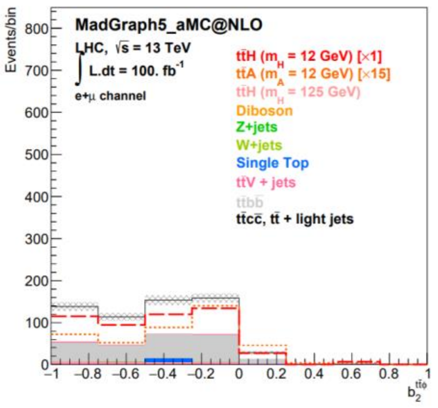
m_ϕ (GeV)	m_ϕ^{inv} (1 jet)		m_ϕ^{inv} (2 jets)		$m_\phi^{(1)}$	
	$\phi = H$	$\phi = A$	$\phi = H$	$\phi = A$	$\phi = H$	$\phi = A$
12	99.96	99.98	0.00	0.00	0.04	0.02
20	94.05	96.94	0.58	0.21	5.37	2.85
30	63.52	76.37	10.64	7.72	25.84	15.91
40	27.76	44.27	33.74	27.20	38.50	28.53

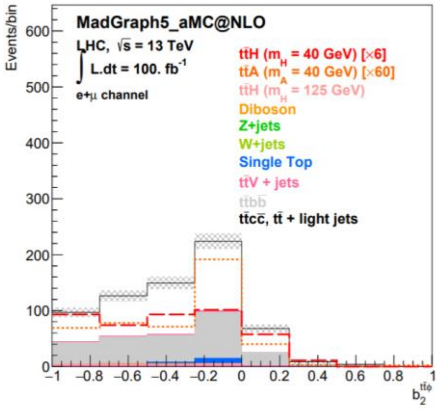


New method improves resolution because it uses **information from angles** of both jets, which are **experimentally better reconstructed**.



Signal and background distributions and more on the CLs





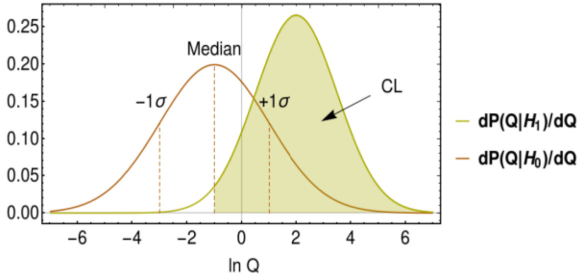
Test-statistic is the **logarithm of the ratio between likelihoods** of the signal and SM hypotheses.

$$\ln Q = -(\lambda_{1\text{tot}} - \lambda_{0\text{tot}}) + \sum_{i=1}^{N_{chan}} n_i \ln\left(\frac{\lambda_{1i}}{\lambda_{0i}}\right).$$

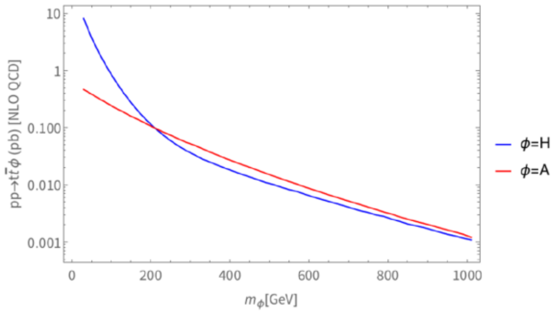
CL = 1 - p-value, under the signal hypothesis, for observing the test-statistic value expected (median) in the SM hypothesis.

$$CL = P\left(Q \geq Q_{obs} \middle| H_1\right)$$

Computation of p-values and medians is done using an ensemble of **toy experiments**, using bin-by-bin **Poisson fluctuations** around a mean value, set to the number of events in each individual bin of the distributions.



CLs get progressively **better as the Higgs mass decreases**. **CP-even** component always **more constrained than the CP-odd** component, for a given CL. Related to $t\bar{t}\phi$ **cross-section behaviour**.



$L = 3000$ fb^{-1}		Exclusion Limits from $b_2^{t\bar{t}\phi}$ (68% CL)	Exclusion Limits from $b_2^{t\bar{t}\phi}$ (95% CL)	Exclusion Limits from $b_4^{t\bar{t}\phi}$ (68% CL)	Exclusion Limits from $b_4^{t\bar{t}\phi}$ (95% CL)
$m_\phi = 12$ GeV	$\kappa \in$	[-0.05, +0.05]	[-0.11, +0.11]	[-0.05, +0.05]	[-0.11, +0.11]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 20$ GeV	$\kappa \in$	[-0.07, +0.07]	[-0.13, +0.13]	[-0.07, +0.07]	[-0.13, +0.13]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.49, +0.49]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 30$ GeV	$\kappa \in$	[-0.07, +0.07]	[-0.14, +0.14]	[-0.07, +0.07]	[-0.14, +0.14]
	$\tilde{\kappa} \in$	[-0.26, +0.20]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 40$ GeV	$\kappa \in$	[-0.17, +0.17]	[-0.32, +0.32]	[-0.17, +0.17]	[-0.32, +0.32]
	$\tilde{\kappa} \in$	[-0.53, +0.53]	[-1.00, +1.00]	[-0.53, +0.53]	[-1.01, +1.01]