$t\bar{t}H$ production and Higgs-top coupling properties at the LHC with the ATLAS experiment

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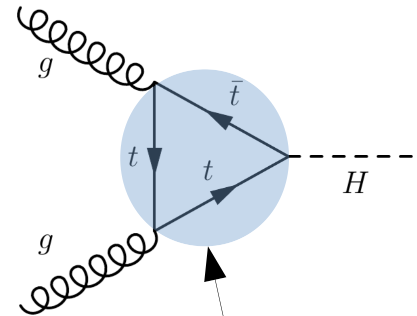
Outline

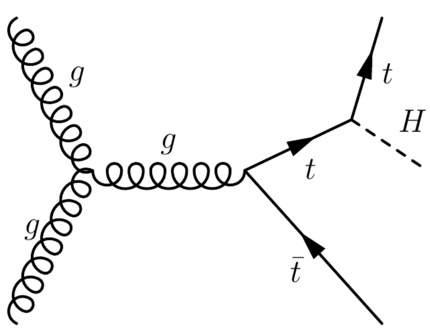
- $t\bar{t}H$ production at the LHC
- Search for $t\bar{t}H$ production in ATLAS
- Studies of small backgrounds in $t\bar{t}H(b\bar{b})$ dilepton
- Observation of $t\bar{t}H$ production at the LHC
- CP nature of Higgs-top coupling
- Summary and plans
- ATLAS authorship qualification task

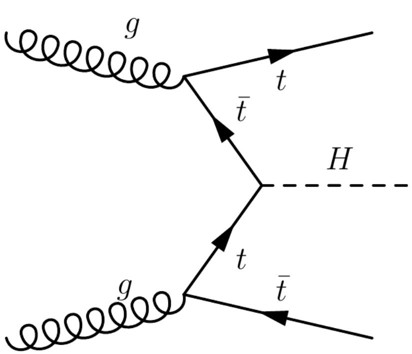
$t\bar{t}H$ production at the LHC

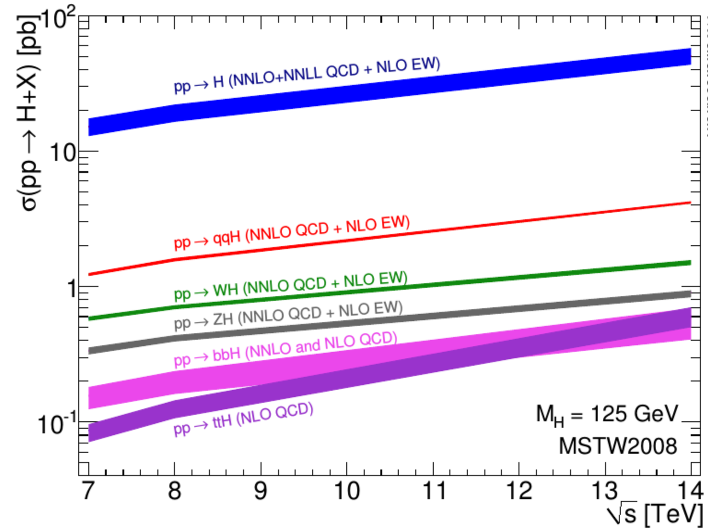
- Need to study properties of 125 GeV Higgs boson
- Couplings to fermions are a key feature of the SM Higgs boson
  - Coupling to taus observed through $H \to \tau\tau$
  - Evidence of coupling to bottom in VH production with $H \to b\bar{b}$
- Top quark is the most massive fermion, with the largest Yukawa coupling (~1)
- The dominant 125 GeV Higgs boson production mode (gluon fusion) allows only an indirect study of this coupling
- Associated production of a Higgs boson with a top quark pair ($t\bar{t}H$) has **direct** dependence on the strength of the coupling



All fermions contribute, new physics can be "conspiring" here







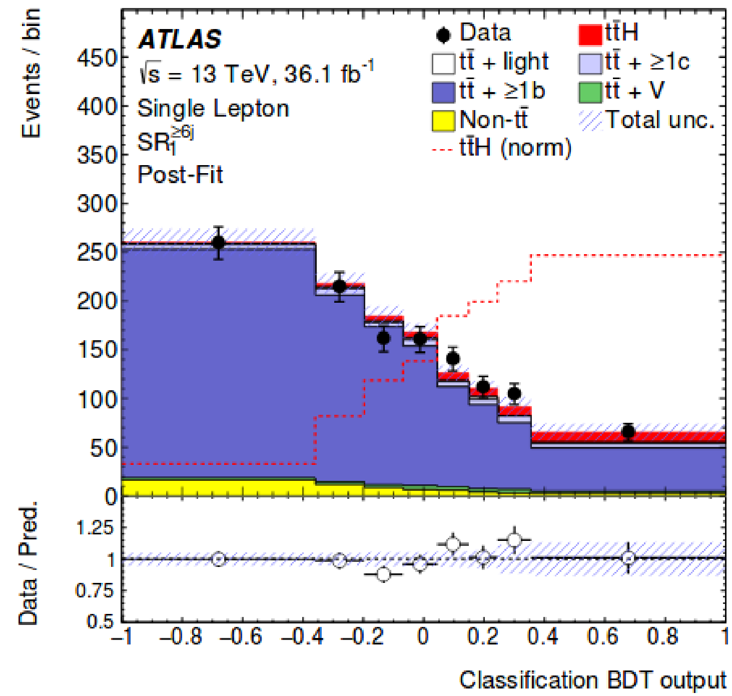
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsFigures

- $t\bar{t}H$ is rare compared to $t\bar{t}$ or to the other Higgs production modes

Search for $t\bar{t}H$ production in ATLAS

- 4 analyses, defined by targeted Higgs decay (mixing couplings to fermions and bosons): **$b\bar{b}$**, multi-lepton (H→ττ, H→VV), γγ, ZZ→4l

Phys. Rev. D 97, 072016



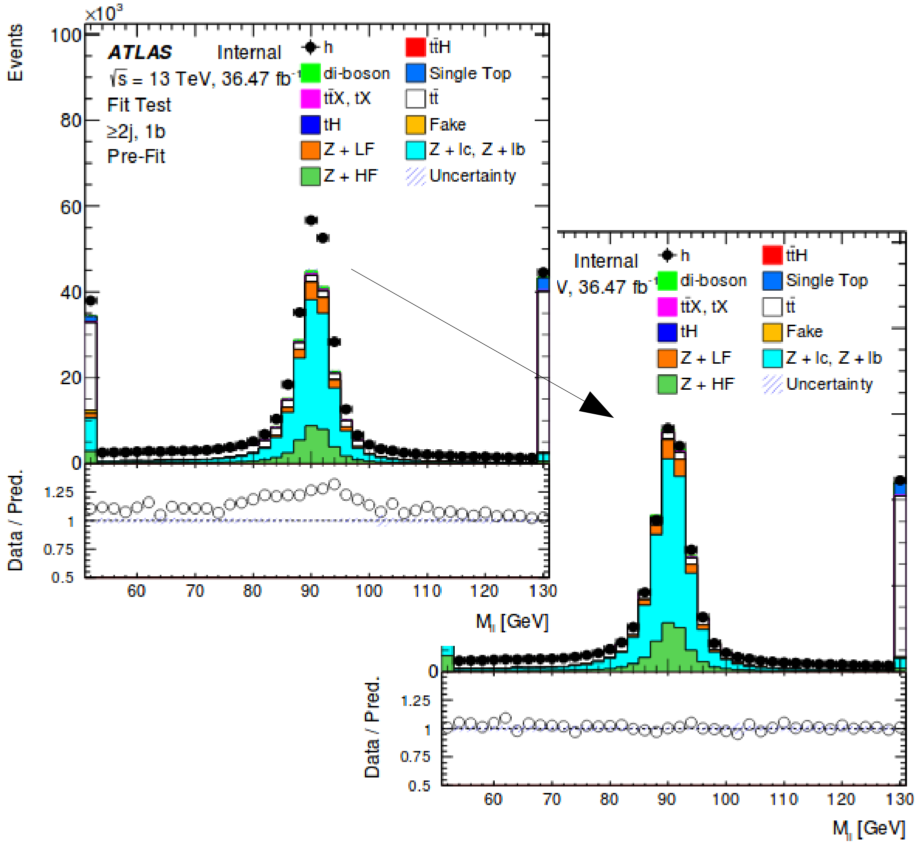
- Three channels: dilepton, single lepton boosted and single lepton resolved
- Use 4 b-tagging working points (pseudo-continuous b-tagging) to define intricate signal and control regions
- A simultaneous profile likelihood fit is performed
  - Classification multivariate analysis (MVA) output in signal regions, including boosted
  - Event yields or H_T are used in control regions
- With 36.1 fb^{-1} of data, observed (expected) signal significance with respect to the background-only hypothesis of 1.4 (1.6) standard deviations

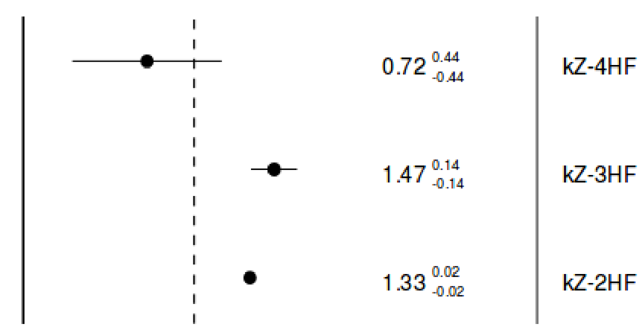
Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	+0.46	−0.46
Background model statistics	+0.29	−0.31
Jet flavour tagging	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modelling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modelling	+0.09	−0.11

Total systematic uncertainty	+0.57	−0.54
$t\bar{t} + \geq 1b$ normalisation	+0.09	−0.10
$t\bar{t} + \geq 1c$ normalisation	+0.02	−0.03
Statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

Studies of small backgrounds in $t\bar{t}H(b\bar{b})$ dilepton
Z + jets

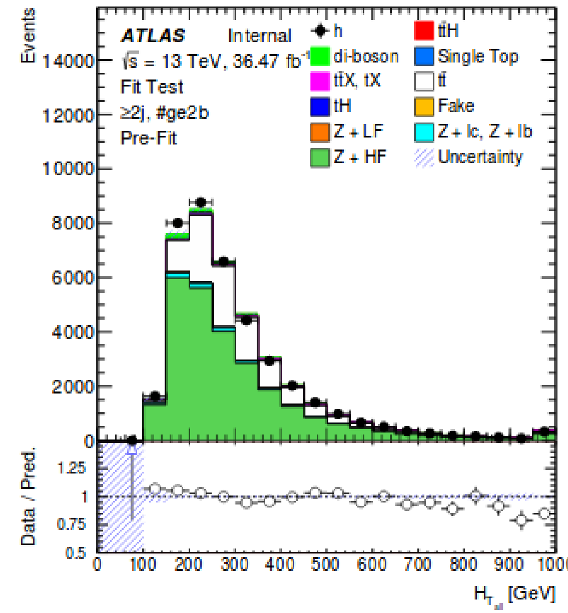
- Dilepton from Z decay + additional (b-tagged) jets
- Normalization known to be off for Z+heavy flavour jets → **estimate from data**
  - Run analysis pre-selection without dilepton mass veto (±8 GeV around m_Z)
  - Split control region in 3, based on b-tag, to get independent normalisations for 3 jet flavour components:
  - k(Z+0HF) = 1.0
  - **k(Z+1HF) = k(Z+2HF)= 1.3**
  - Stable with respect to changes in control region definition
  - Tried to extend to higher HF multiplicity: Z+3HF seems compatible, not enough statistics to be sure about Z+≥4HF yet

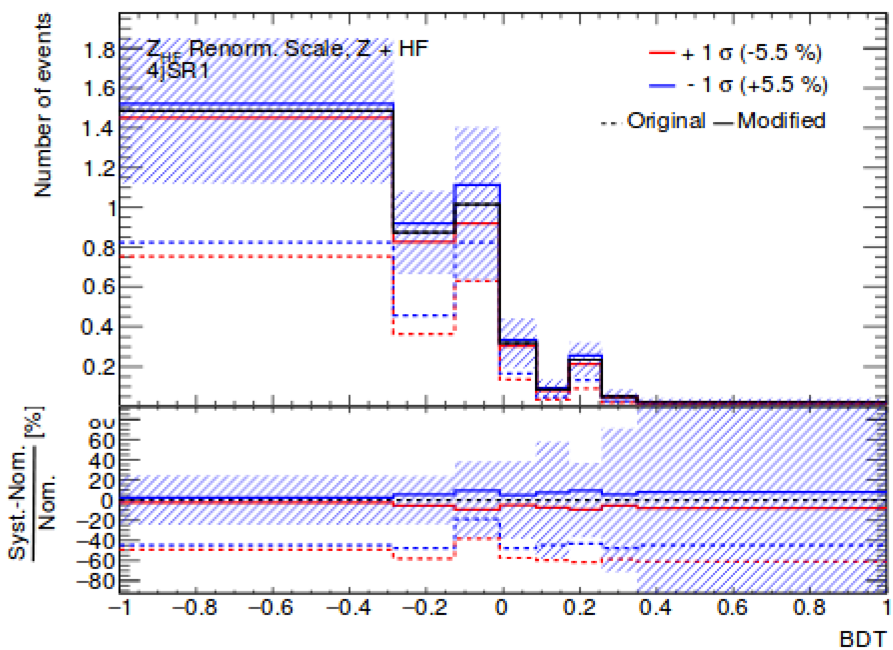


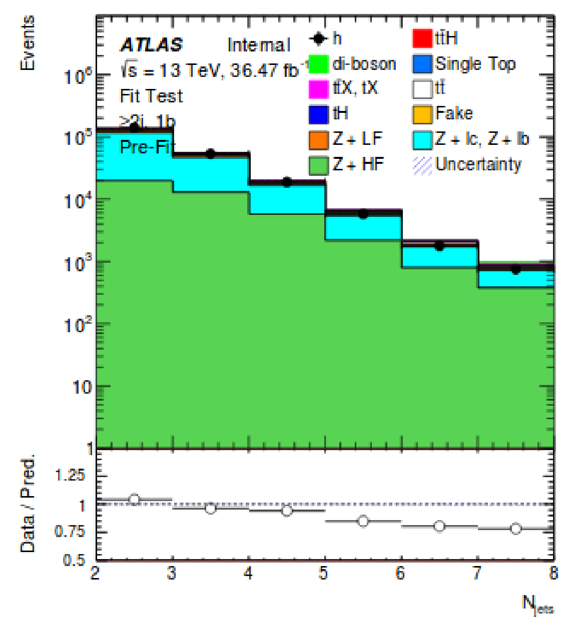


Studies of small backgrounds in $t\bar{t}H(b\bar{b})$ dilepton
Z + jets

- **Estimate uncertainty for the fit**
  - Mismodeling of kinematics → within ~30% envelope
  - Uncertainties from generator scale variations ≤10% in fit regions
  - **Set cross-section uncertainty to 35%** to encompass both effects
  - Mismodeling of no. of jets → **decorrelate across jet multiplicities** in the fit
- Will be revisited including 2017 data





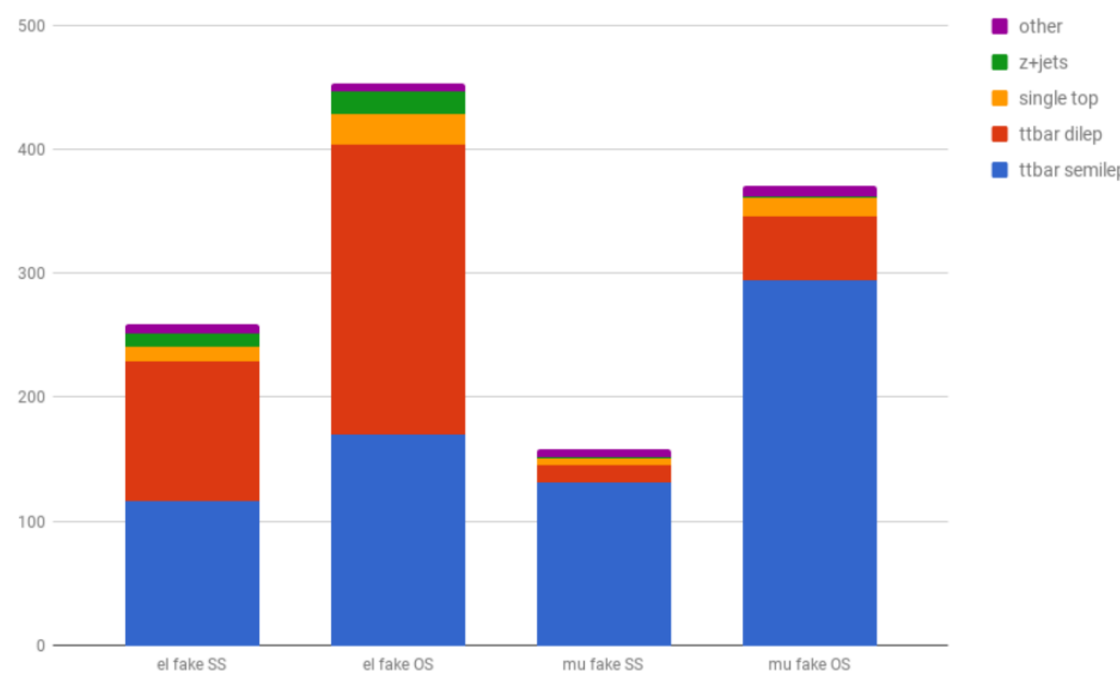


Studies of small backgrounds in $t\bar{t}H(b\bar{b})$ dilepton
Non-prompt (fake) leptons

- Interested in leptons from decay of heavy particles (prompt leptons)
- Small probability to have at least one lepton from non-prompt source:
  - Hadron semileptonic decay
  - Photon conversion
  - Misidentified jet

$$N^{\text{fake, OS}} = \frac{(N^{\text{data, SS}} - N^{\text{MC, prompt, SS}})}{N^{\text{MC, fake, SS}}} N^{\text{MC, fake, OS}}$$

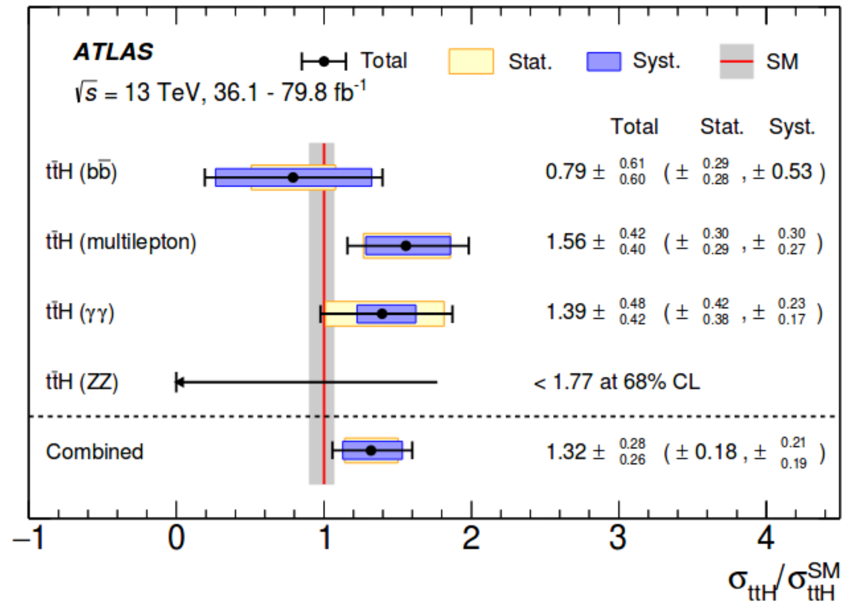
- Scale MC estimate by factor derived from data in same-sign dilepton control region
  - Separately for subleading electron and subleading muon
  - **Assumes OS and SS fake sources are the same. Is this a good approximation?**
  - Semileptonic $t\bar{t}$ with hadrons decaying into a lepton contributes mostly to OS category
  - Dilepton $t\bar{t}$ with an electron from a photon conversion is twice more abundant in OS than SS
- Study done towards the end of the analysis timeline, fell below higher-priority items



Observation of $t\bar{t}H$ production at the LHC

- In April, CMS claimed **observation of $t\bar{t}H$ production** combining full Run 1 data with 35.9 fb^{-1} of Run 2 data. **Observed (expected) significance of 5.2 (4.2) standard deviations**
  arXiv:1804.02610

- Significant improvements to the H→γγ and H→ ZZ analyses, including 79.8 fb^{-1} of data, allowed ATLAS to reach observation after combining with multilepton and $b\bar{b}$ analyses of 36.1 fb^{-1}



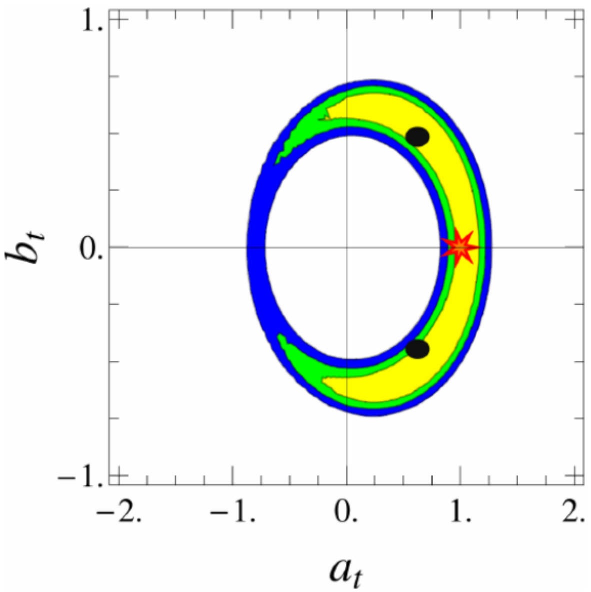
Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \rightarrow \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \rightarrow$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \rightarrow ZZ^* \rightarrow 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ

CP nature of Higgs-top coupling

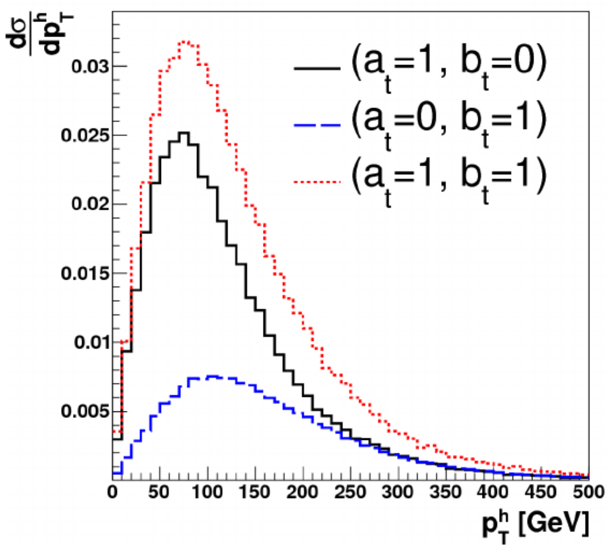
- After observation, what is left for $t\bar{t}H(b\bar{b})$?
- Reconstruction of the top quarks and Higgs boson is accessible → preferred for coupling properties
- One possible scenario: CP-odd component mixed in the coupling

$$\mathcal{L} = \kappa\, y_t\, \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\, h$$

- Motivated by many SM extensions in which the physical Higgs boson is not CP eigenstate → hint of CP violation
- Even if the 125 GeV Higgs is purely CP-even, new physics can manifest through anomalous couplings
- Indirect constraints from other Higgs production modes and electron dipole moment
- In $t\bar{t}H$ production at the LHC, impact on event kinematics and $t\bar{t}$ spin correlations

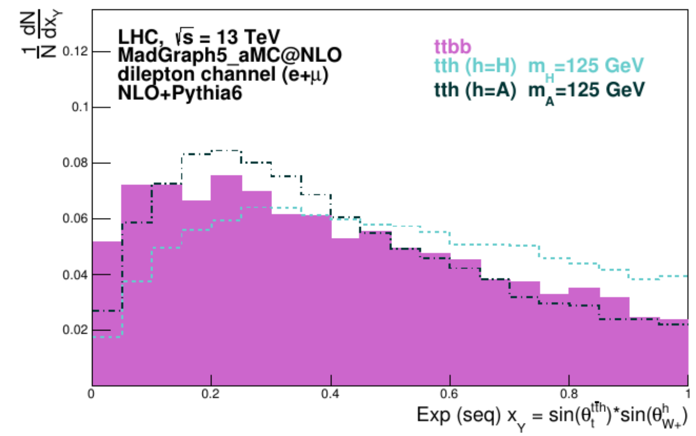


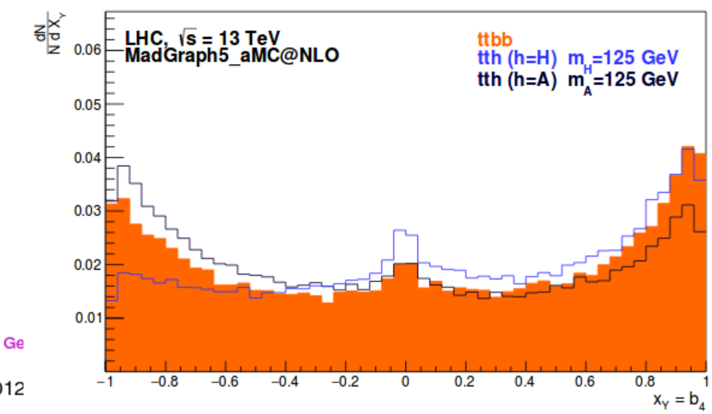
Phys. Rev., D92(1):015019, 2015

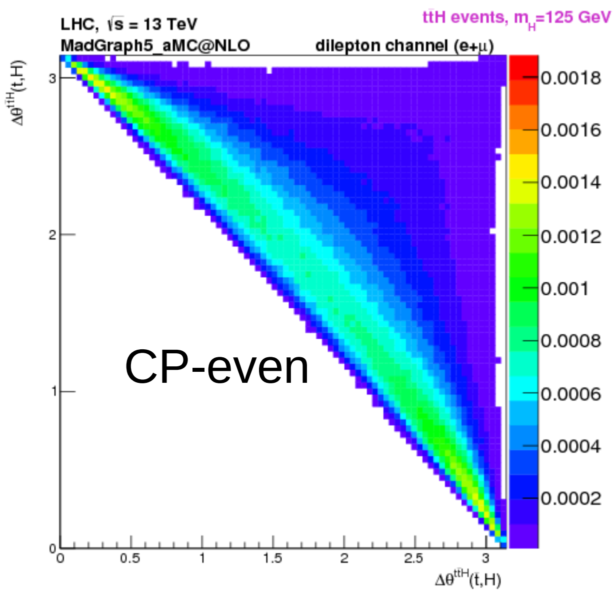


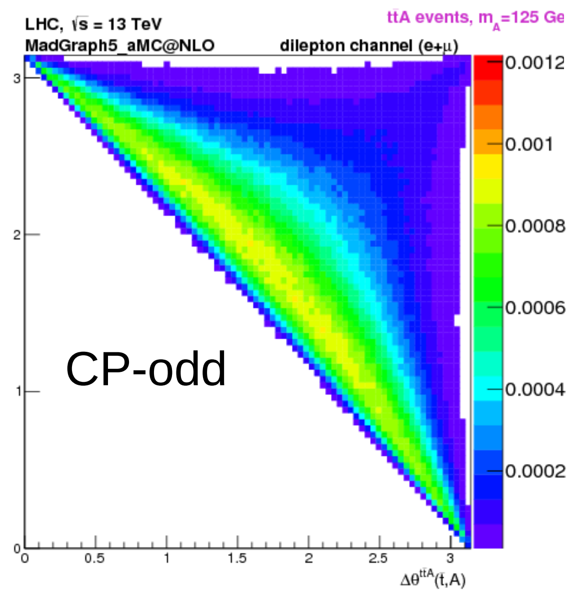
CP nature of Higgs-top coupling

- Studied discriminant observables with fast detector simulation. Published in Phys. Rev. D 96, 013004 (2017), arXiv:1711.05292
- Angular observables retain information about CP nature of the coupling, even after detector effects and reconstruction
- **Best observables require reconstruction of top quarks and Higgs boson**



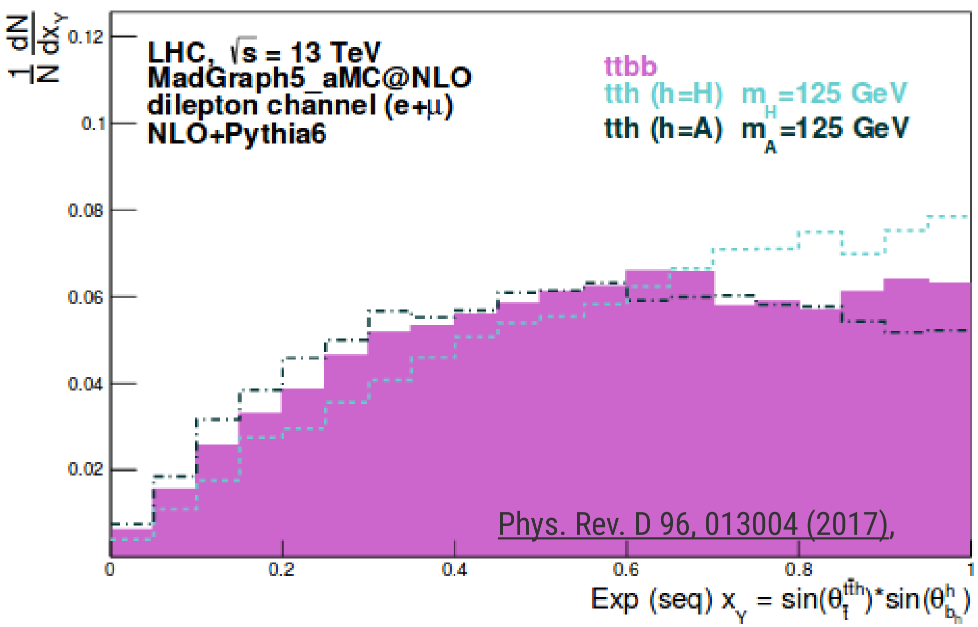


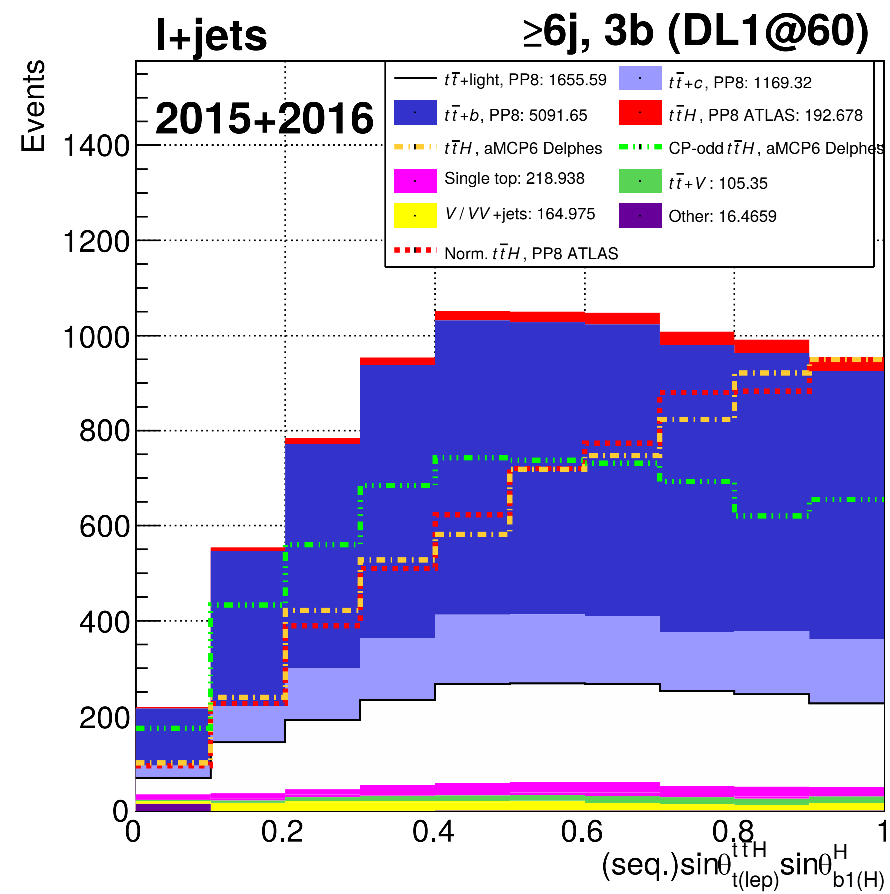




CP nature of Higgs-top coupling

$$\sin\left(\theta_{\bar{t}}^{t\bar{t}h}\right)\sin\left(\theta_{b_h}^{h}\right)$$

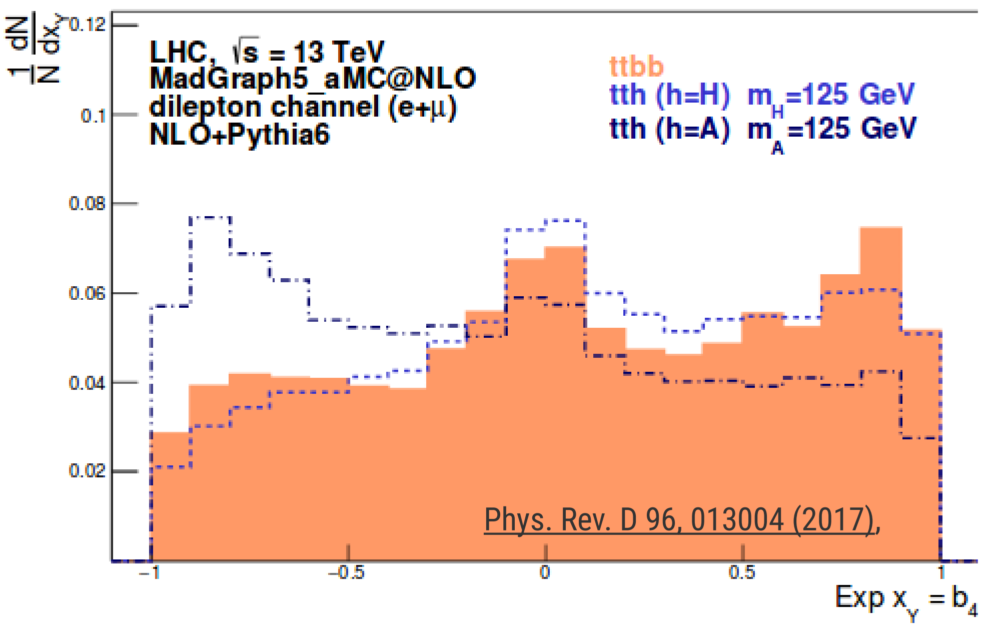


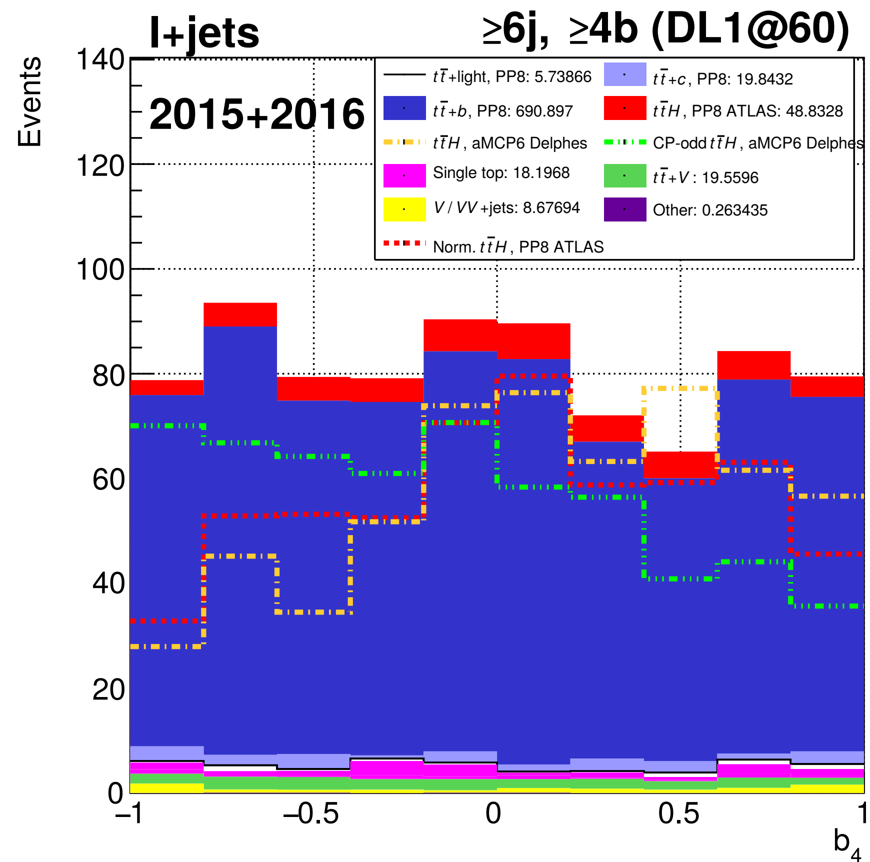


- Computed observables in ATLAS samples, in "signal-rich" regions
- Dashed tt̄H shapes scaled arbitrarily to the same integral. If the shapes of **ATLAS SM ttH** and **Delphes SM ttH** are compatible, maybe **Delphes CP-odd ttH** is a decent estimate

CP nature of Higgs-top coupling

$$b_4 = (p_t^z . p_{\bar{t}}^z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$$





- Computed observables in ATLAS samples, in “signal-rich” regions
- Dashed $t\bar{t}$H shapes scaled arbitrarily to the same integral. If the shapes of **ATLAS SM ttH** and **Delphes SM ttH** are compatible, maybe **Delphes CP-odd ttH** is a decent estimate
- Separation-wise, most discriminant observable we found so far

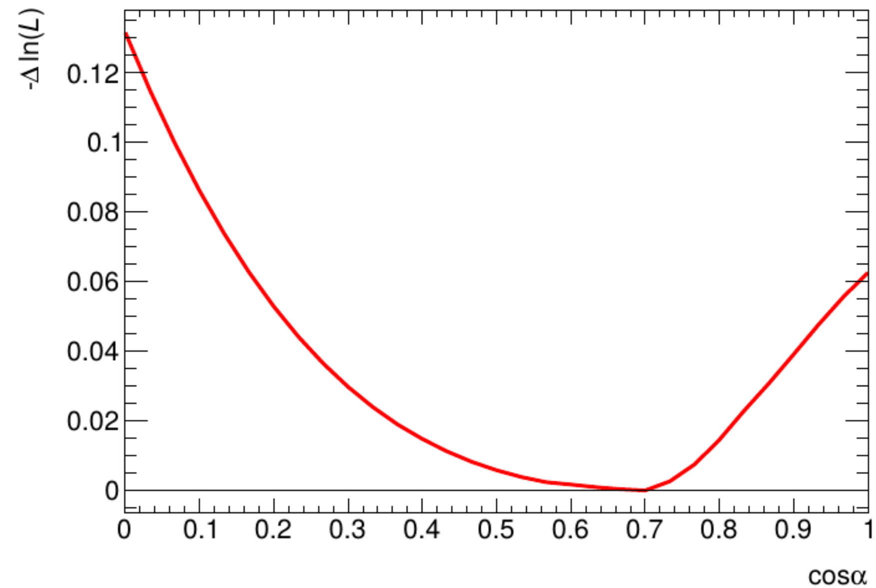
CP fit tests

- Try to get a 2D likelihood scan on the coupling strength modifier κ and CP-mixing angle α

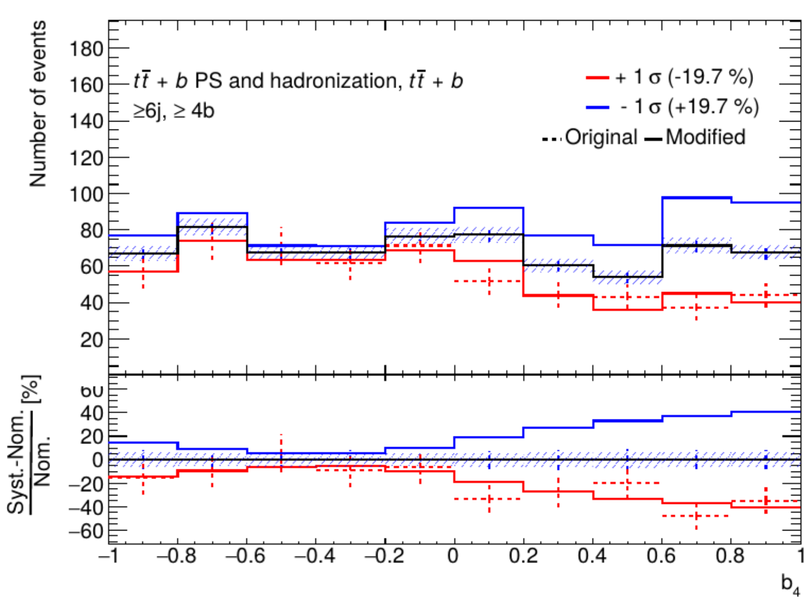
$$\mathcal{L} = \kappa\, y_t\, \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\, h$$

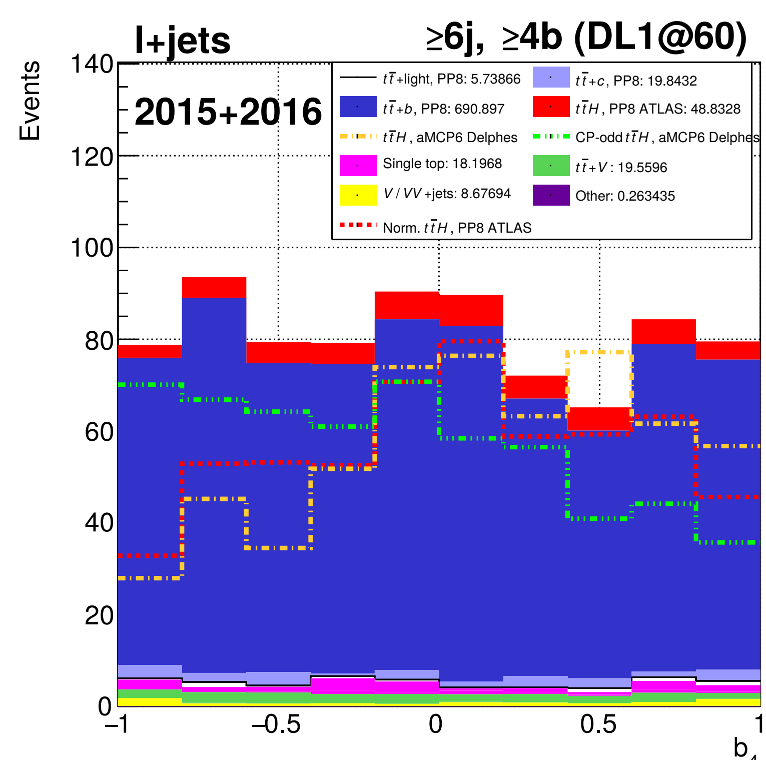
- Templates for cosα=1.0, 0.7, 0.0
- Parameters: μ, k($t\bar{t}$+b), k($t\bar{t}$+c) and cosα
- 2 regions: ≥6j,3b and ≥6j,≥4b
- Simultaneous fit to 3 distributions
  - b_4 → sensitive to cosα
  - $\sin(\theta^{ttH}_{t})\sin(\theta^{H}_{W})$ → sensitive to cosα
  - $\Delta\eta_{jj}^{\max\Delta\eta}$ → good $t\bar{t}H/t\bar{t}$ separation (ideally would use classification MVA)
- Asimov fit with μ=1, cosα=0.7
- Simplified systematics model

CP fit tests



- No 2D profile yet, but 1D log-likelihood curve looks sane
- Overall scale not important for now, but the curves can be used to compare different CP-discriminants including systematics effects
- Can individually check impact of systematics on distributions





Summary and plans

- Currently engaged in common analysis tasks, such as ntuple production and Data/MC comparisons
- Recently started collaboration with Manchester group for combined CP measurement

MANCHESTER 1824
The University of Manchester

- Dilepton channel

  3 seniors/post-docs + 1 PhD student

LIP

- Single lepton channel

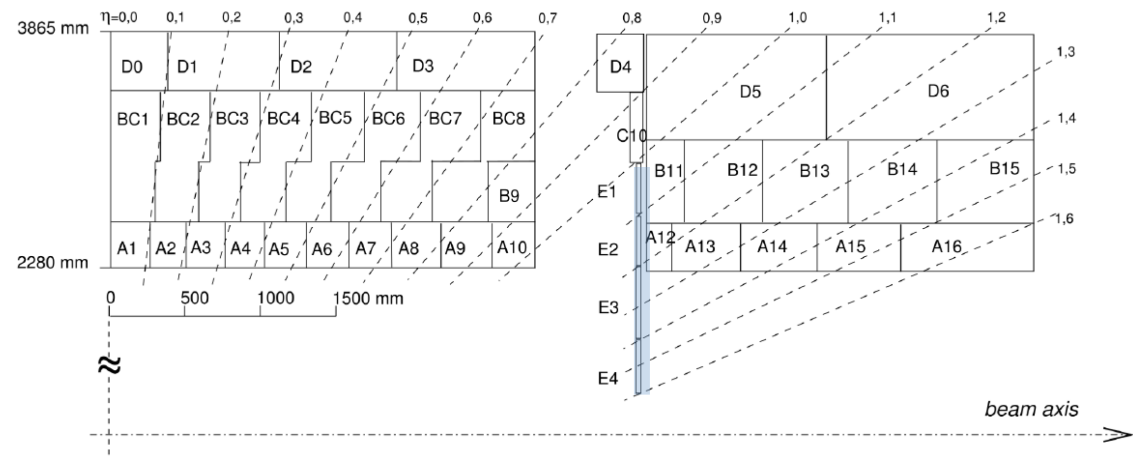
  2 seniors + 2 PhD students:

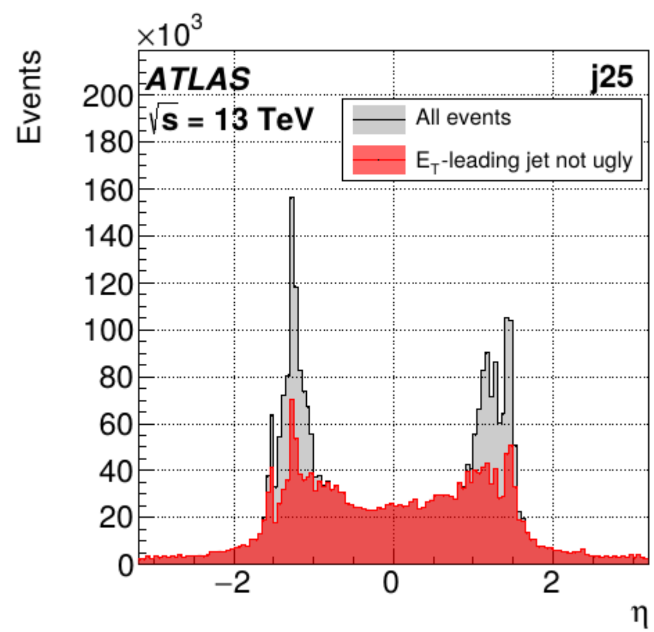
  - Emanuel Gouveia (resolved channel)
  - Bernardo Marques (boosted channel)

- Goal: have a mature analysis by the time of TOP2018 (profit from discussions about $t\bar{t}H$ there) and have public results for Moriond 2019
- Thesis writing afterwards
- Steps to get there:
  - Request of official CP-odd and CP-mixed samples (in progress)
  - Implementing observable computation in common code (in progress)
  - Train CP-discriminant MVA using best observables (to do)
  - Template fit to extract 2D likelihood profile (in progress)

ATLAS authorship qualification task
Impact of gap/crack TileCal scintillators on jet trigger

- Response of gap/crack scintillators affected by noise, which increases with pile-up
- Excess of events with in low-threshold jet triggers near gap/crack, most of which are rejected offline: **waste of trigger rate**
- f_{TG3}: fraction of a jet's energy sampled by the gap/crack layers
- Jet is ugly if f_{TG3} is larger than any fraction from other layer
- Try to correct/select trigger jets

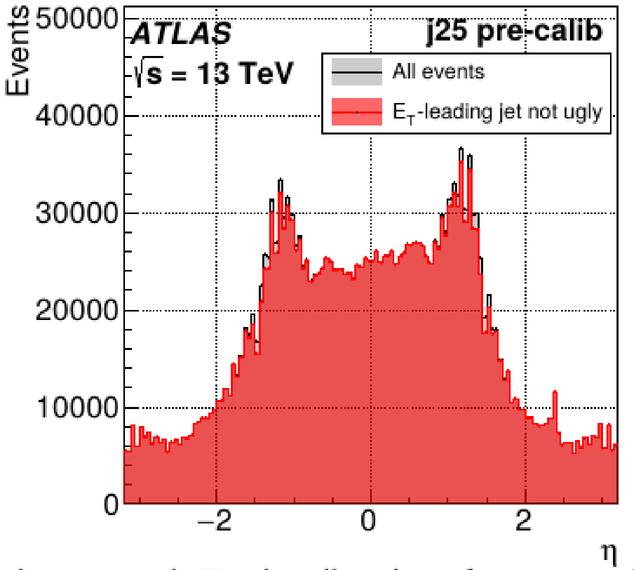


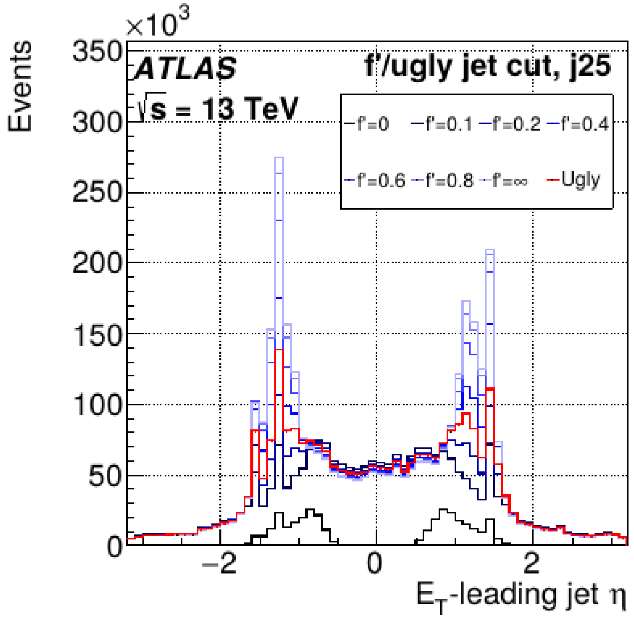


η of E_T-leading central ($|\eta| < 3.2$) trigger jet. Events recorded by HLT_j25 (at least one jet with $E_T \geq 25$ GeV and $|\eta| < 3.2$) during 2017 data-taking period B

ATLAS authorship qualification task
Impact of gap/crack TileCal scintillators on jet trigger

- Corrections studied:
  - Scale momentum of ugly jets by 1-f_{TG3} either before or after calibration
  - Reject all ugly jets or events containing any ugly jet
  - Reject all jets with f_{TG3} above a given f' or events containing any jet with f_{TG3} above f'

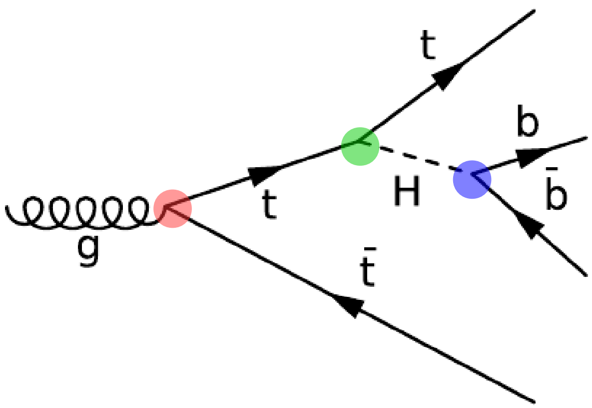




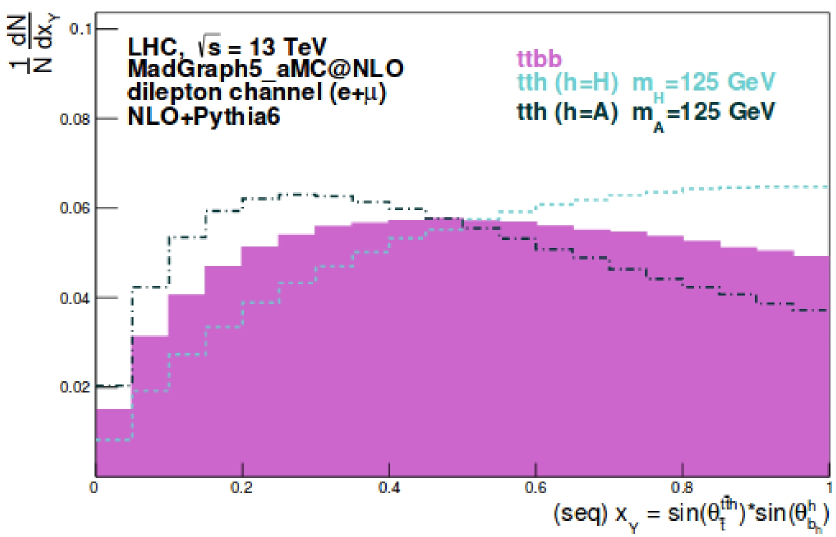
- f_{TG3}>f' jet cuts provide increase in the rate of events passing offline selection, consistently across chains and data-taking periods in 2016 and 2017. f'~0.2 would be the best compromise between effectiveness and risk of biasing collected data
- Procedures either too ineffective or aggressive, so were not implemented in 2018 jet trigger
- Still engaged in Jet Trigger group, taking software validation shifts
- Will present a poster about recent Jet and MET trigger developments at CHEP2018, in Sofia, next month

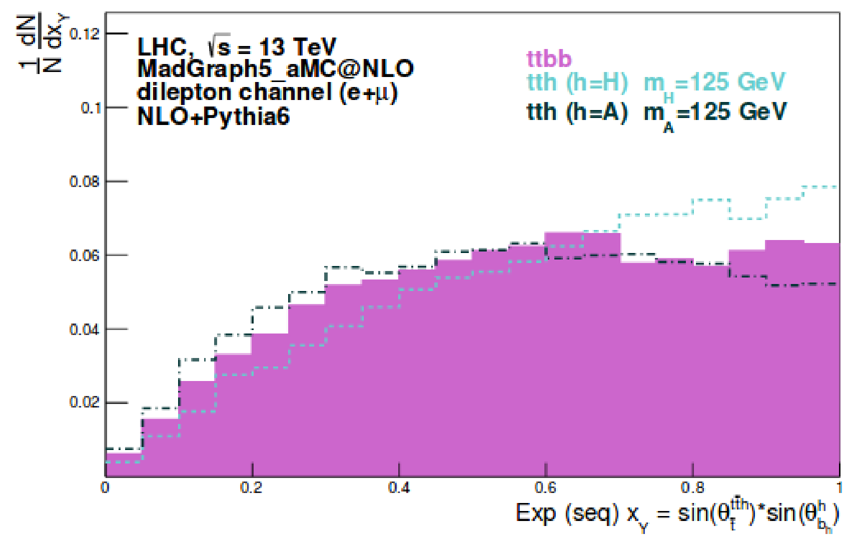
Backup

Boosted-frame angular observables



- Philosophy of successive two-body decays
- Define the angles
  - $\Theta^{t\bar{t}H}_{\bar{t}}$: direction of $t\bar{t}H$ in lab-frame ^ direction of $\bar{t}$ in $t\bar{t}H$ frame
  - Θ^{tH}_{H} : direction of tH in $t\bar{t}H$ frame ^ direction of H in tH frame
  - Θ^{H}_{b} : direction of H in tH frame ^ direction of b in H frame – can boost sequentially or directly
- Build an observable as product of sines/co-sines of such angles. Example: $\sin\left(\theta^{t\bar{t}h}_{\bar{t}}\right)\sin\left(\theta^{h}_{b_h}\right)$

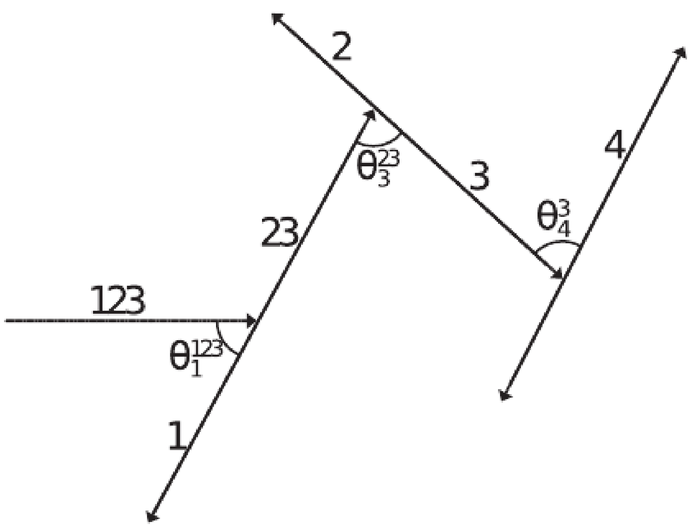




- Left: generator-level, including shower; Right: after fast detector simulation, cuts and reconstruction

Boosted-frame angular observables

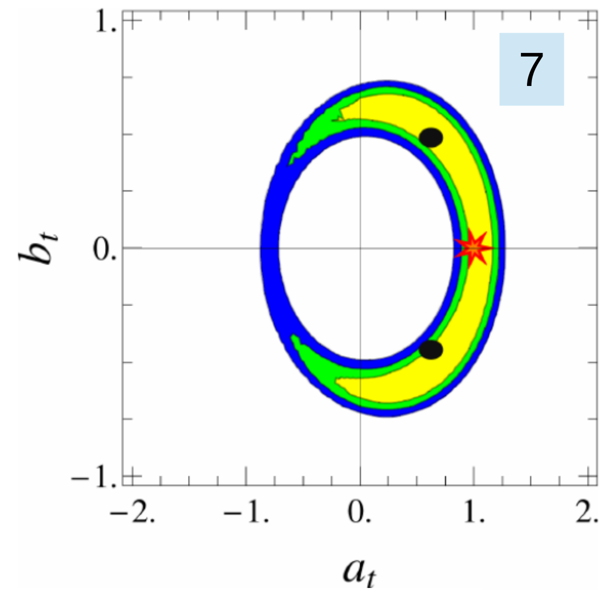
- Generalize
  - Allow all permutations of t, $\bar{t}$, H
  - Instead of b, any decay product of t, $\bar{t}$ or H
- Build the observables: $f(\Theta^{123}_{1})g(\Theta^{3}_{4})$ or $f(\Theta^{23}_{3})g(\Theta^{3}_{4})$, with f and g either sine or co-sine
- Hundreds of observables, can be ranked by CP-even/CP-odd separation



Phenomenology of a CP-mixed top Yukawa coupling

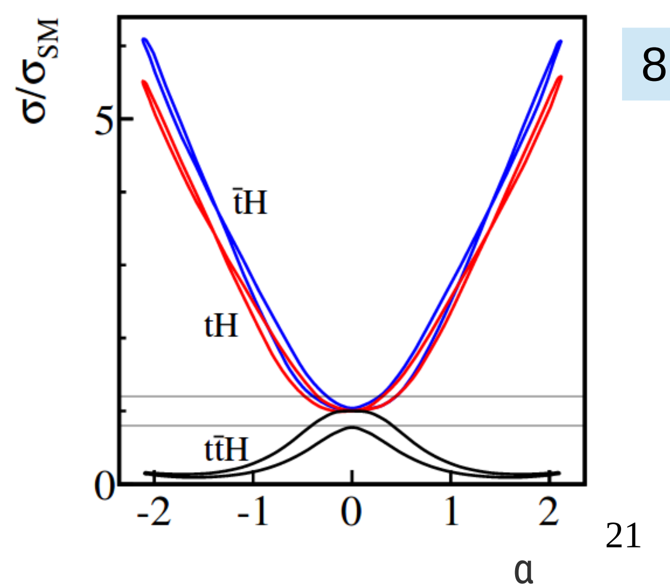
Indirect constraints

- Fit of a and b to combined data from all Higgs searches at LHC Run I and Tevatron, assuming all other couplings to be SM-like
  - ✷ - SM; • - best-fit values; ■ ■ ■ - 68%, 95% and 99.7% CL regions



tH/$\bar{t}$H and t$\bar{t}$H cross-sections

- Production cross-sections expected to deviate from SM expectation with increasing CP-odd component, in opposing directions
- α is the CP-mixing angle, given by atan(b/a)
- 20% accuracy in t$\bar{t}$H cross-section at 14TeV LHC → π/6 accuracy in α



Phenomenology of a CP-mixed top Yukawa coupling

Spin correlations

- Three out of **many** observables in $t\bar{t}H$, to illustrate variety of methods

7

$$\mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right) \Delta\theta^{\ell h}(\ell^+, \ell^-)$$

- $(\vec{p}_b - \vec{p}_{\bar{b}})$: C-odd, P-odd
- $(\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})$: C-odd, P-even
- $\Delta\theta^{\ell h}(\ell^+, \ell^-)$: Angle between leptons' momenta projected on the plane perpendicular to the Higgs direction in the lab frame

- CP-odd factor is sensitive to sign of b
- Only available in tt→dilepton
- Need to reconstruct Higgs

9

$$\Delta\phi^H(\ell^+, \ell^-)$$

→ Azimuthal angle difference between leptons' momenta in the Higgs rest frame

- Boost enhances sensitivity to spin correlations
- Also for dilepton only and requires Higgs reconstruction

10

$$\sin(\theta_t^{t\bar{t}H}) \sin(\theta_{W^+}^H)$$

- $\theta_t^{t\bar{t}H}$: Angle between t momentum in $t\bar{t}H$ rest-frame and $t\bar{t}H$ momentum in lab frame
- $\theta_{W^+}^H$: Angle between H momentum in $\bar{t}H$ rest-frame and W^+ in H rest-frame

- Boosts "open" the angles increasing sensitivity
- Combines production with decay
- In principle accessible in all $t\bar{t}$ decays
- Need t, $\bar{t}$ and H reconstruction

Phenomenology of a CP-mixed top Yukawa coupling

Spin correlations

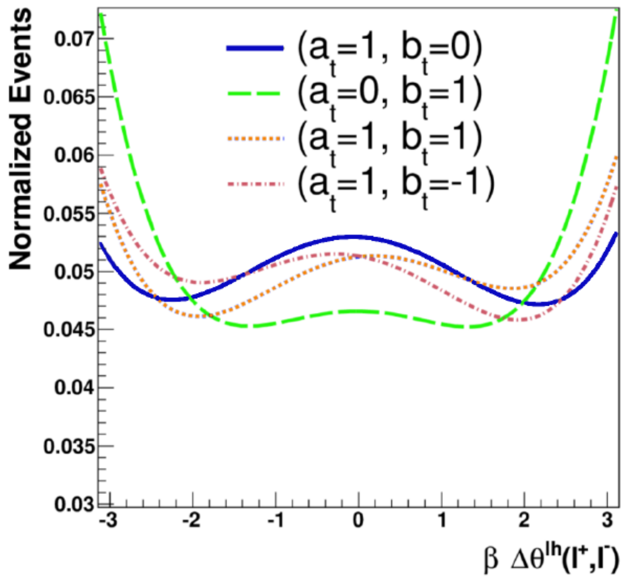
- Comparison of distribution predicted by theory with that after detector simulation, cuts and reconstruction in a $t\bar{t}$→dilepton channel analysis

- $\text{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell-} \times \vec{p}_{\ell+})\right) \Delta\theta^{\ell h}(\ell^+, \ell^-)$

C-odd, P-odd

C-odd, P-even

Angle between leptons' momenta projected on the plane perpendicular to the Higgs direction in the lab frame



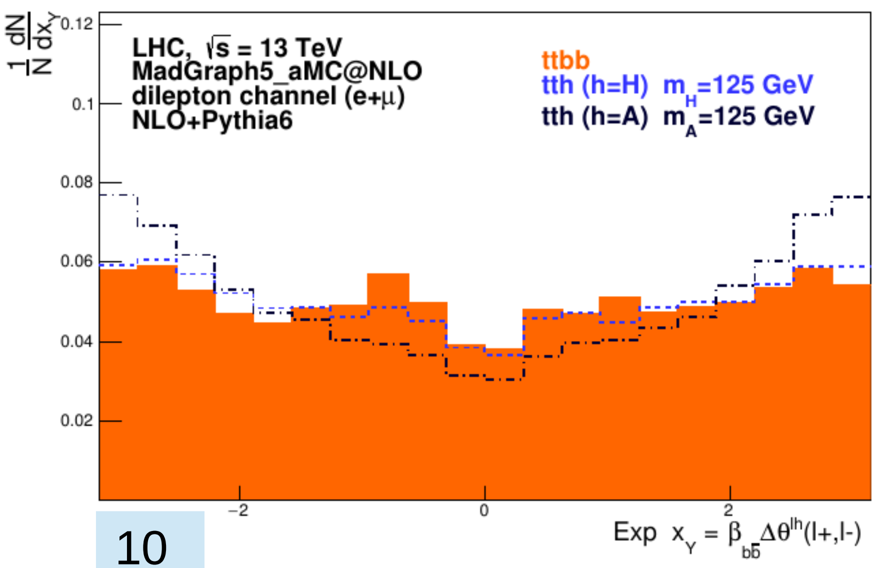
- $\Delta\phi^H(\ell^+, \ell^-)$

Azimuthal angle difference between leptons' momenta in the Higgs rest frame

- $\sin(\theta_t^{t\bar{t}H})\sin(\theta_{W+}^H)$

Angle between t momentum in $t\bar{t}H$ rest-frame and $t\bar{t}H$ momentum in lab frame

Angle between H momentum in $\bar{t}H$ rest-frame and W+ in H rest-frame



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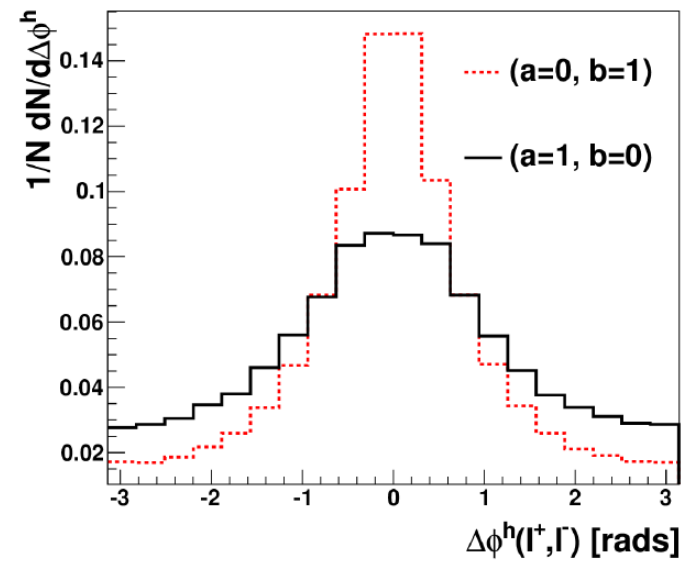
Phenomenology of a CP-mixed top Yukawa coupling

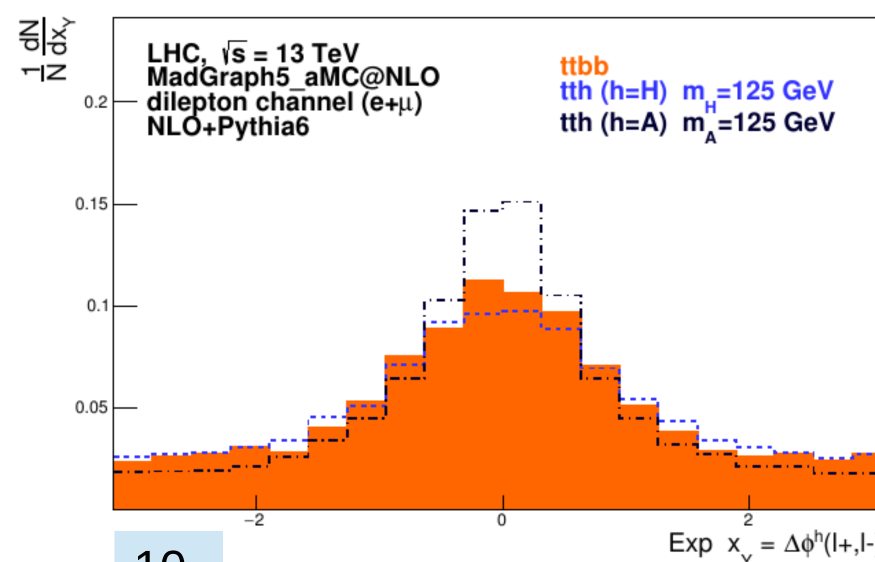
Spin correlations

- Comparison of distribution predicted by theory with that after detector simulation, cuts and reconstruction in a tt→dilepton channel analysis



- $\text{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right) \Delta\theta^{\ell h}(\ell^+, \ell^-)$
  - C-odd, P-odd
  - C-odd, P-even
  - Angle between leptons' momenta projected on the plane perpendicular to the Higgs direction in the lab frame

- $\Delta\phi^H(\ell^+, \ell^-)$ → Azimuthal angle difference between leptons' momenta in the Higgs rest frame



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- $\sin(\theta_t^{t\bar{t}H}) \sin(\theta_{W^+}^H)$
  - Angle between t momentum in $t\bar{t}H$ rest-frame and $t\bar{t}H$ momentum in lab frame
  - Angle between H momentum in $t\bar{t}H$ rest-frame and W+ in H rest-frame

Phenomenology of a CP-mixed top Yukawa coupling

Spin correlations

- Comparison of distribution at generator+parton-shower level with that after detector simulation, cuts and reconstruction in a tt→dilepton channel analysis

- $\mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right) \Delta\theta^{\ell h}(\ell^+, \ell^-)$

  C-odd, P-odd

  C-odd, P-even

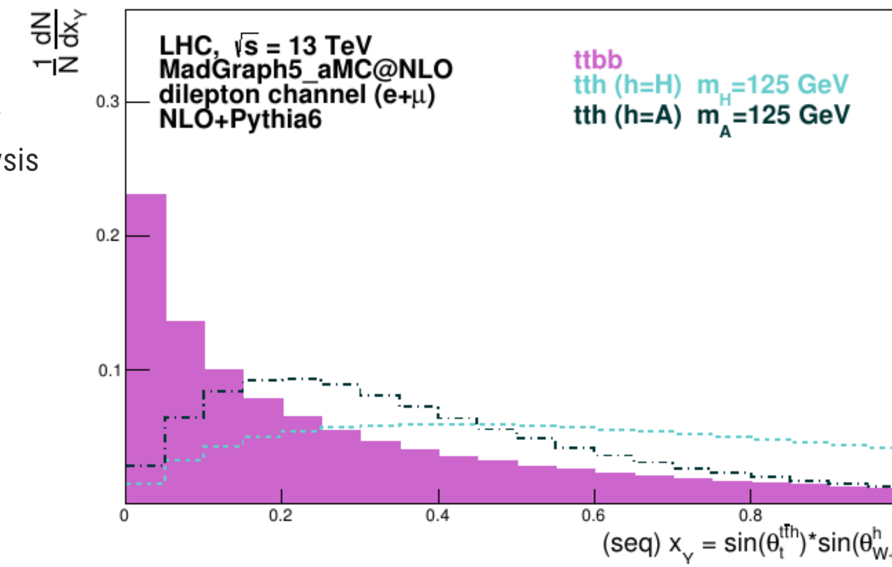
  Angle between leptons' momenta projected on the plane perpendicular to the Higgs direction in the lab frame

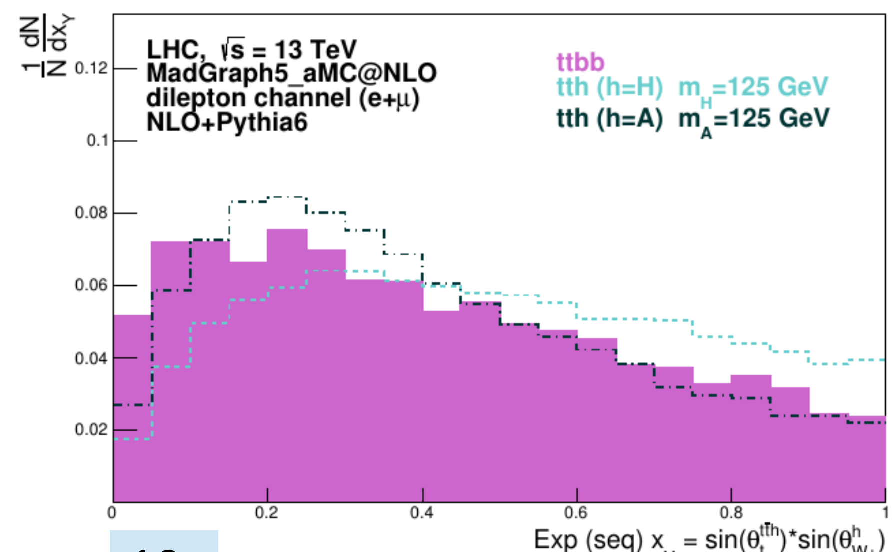
- $\Delta\phi^H(\ell^+, \ell^-)$ → Azimuthal angle difference between leptons' momenta in the Higgs rest frame

- $\sin(\theta_t^{t\bar{t}H}) \sin(\theta_{W^+}^H)$

  Angle between t momentum in $t\bar{t}H$ rest-frame and $t\bar{t}H$ momentum in lab frame

  Angle between H momentum in $\bar{t}H$ rest-frame and W+ in H rest-frame





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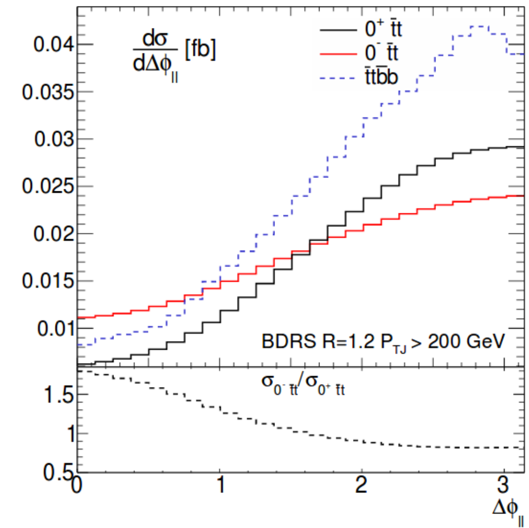
Phenomenology of a CP-mixed top Yukawa coupling

Spin correlations in the boosted Higgs regime

- By requiring a Higgs boson with p_T > 200 GeV in $t\bar{t}H$, regions with signal-to-background ratios of order one can be attained in the $t\bar{t}\rightarrow$ dilepton channel
- Bonus: high-p_T Higgs enhances $t\bar{t}$ spin correlations
- Use lab-frame $\Delta\Phi(l^+,l^-)$, not requiring reconstruction of t, $\bar{t}$ or H



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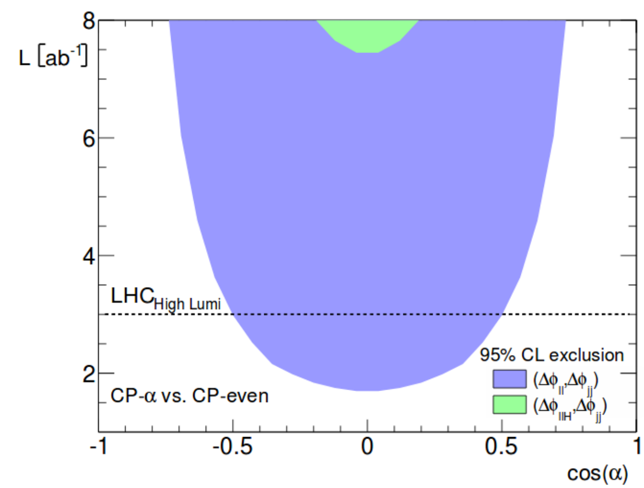
- Expected exclusion of |α|>π/3 at 95% CL with 3ab[-1] of 13TeV LHC data



Phenomenology of a CP-mixed top Yukawa coupling

Angular observables sensitive to production

12 $b_4 = \frac{p_t^z p_{\bar{t}}^z}{p_t p_{\bar{t}}}$

- Authors suggested it should allow measurement of α=0.3π with 3σ significance with 300 fb^{-1} of 13 TeV LHC data

10 $\Delta\theta^{t\bar{t}H}(\bar{t},H)$ and $\Delta\theta^{t\bar{t}H}(t,H)$

Angle between the Higgs boson and t/$\bar{t}$ in the $t\bar{t}$H rest-frame

- In principle accessible in all $t\bar{t}$ decays
  - Need t, $\bar{t}$ and H reconstruction