$t\bar{t}H$ production and top-Higgs coupling properties

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ATLAS EXPERIMENT
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MAP

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Outline

- $t\bar{t}H$ production at the LHC
  - Search fot $t\bar{t}H$ production in ATLAS
  - $t\bar{t}H(b\bar{b})$ analysis
  - LIP contributions
  - Alternative boosted analysis for HL-LHC
- top-Higgs coupling CP structure
  - Phenomenology of CP-mixed top quark Yukawa coupling
  - $t\bar{t}H$ CP phenomenology @ LIP
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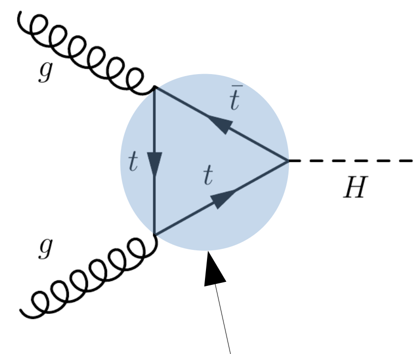
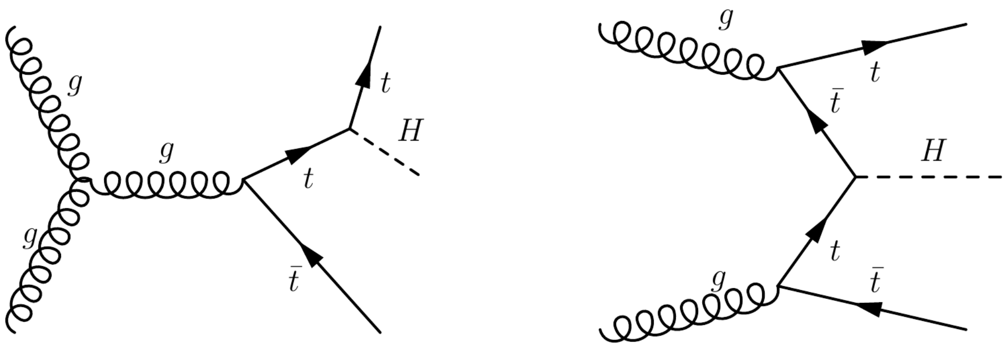
- Summary

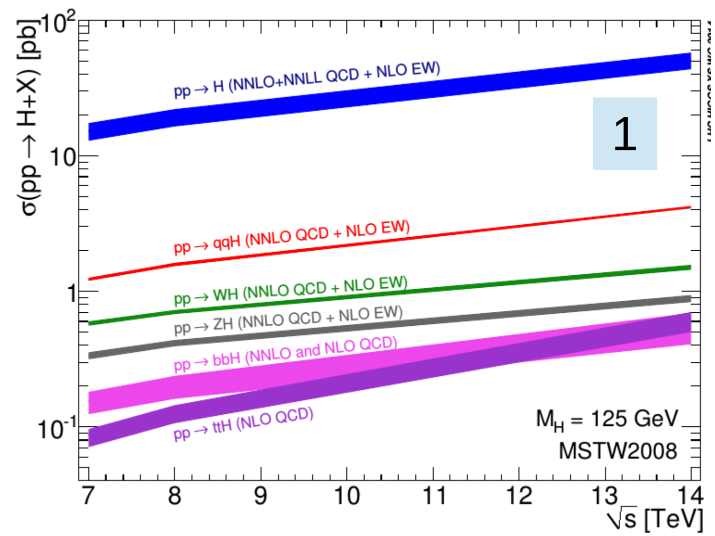
$t\bar{t}H$ production at the LHC



All quarks contribute and new physics can be "conspiring" here

- Top quark is the most massive fermion, with a Yukawa coupling of order unity
- 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





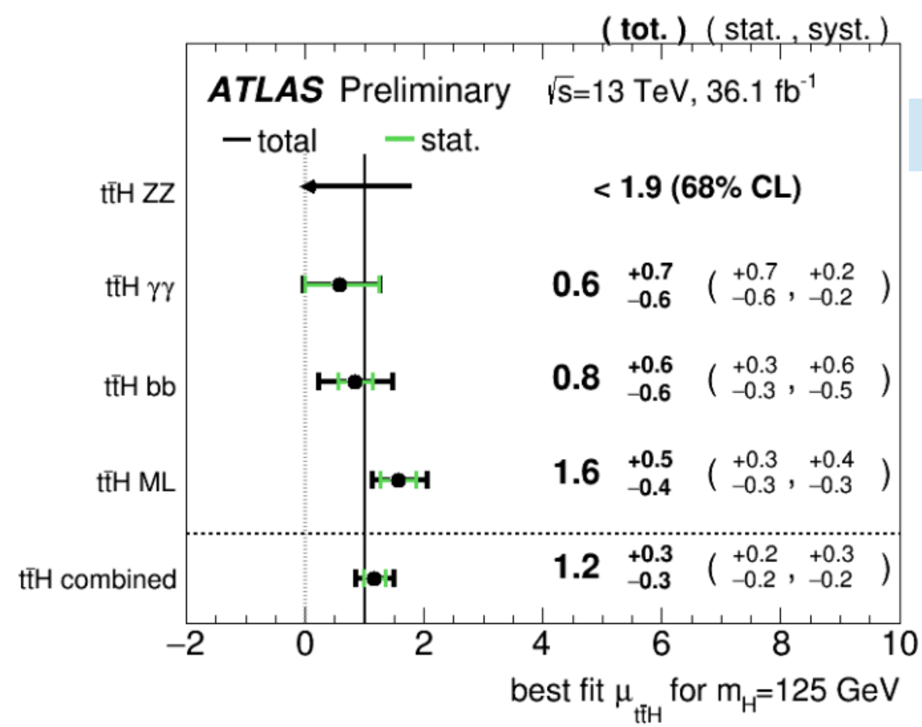
- $t\bar{t}H$ is rare compared to $t\bar{t}$ or to the other Higgs production modes
- CMS recently claimed **observation of $t\bar{t}H$ production** combining full Run 1 data with 35.9 fb^{-1} of Run 2 data. **Observed (expected) significance of 5.2 (4.2) standard deviations**

  arXiv:1804.02610

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

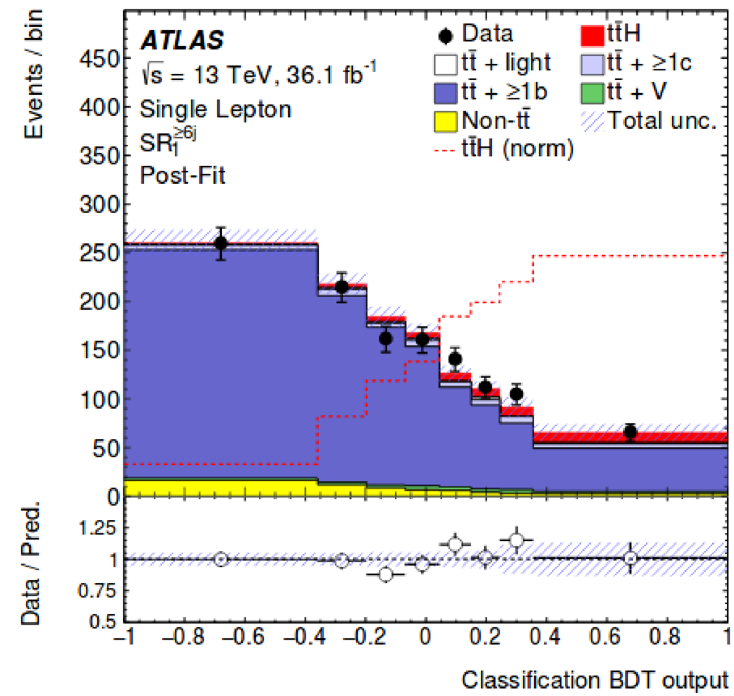
- 4 analyses, defined by Higgs decay: multi-lepton (ML) ($H\to\tau\tau$, $H\to VV$), $b\bar{b}$, $\gamma\gamma$, $ZZ\to 4l$
- Multi-lepton
  - Multivariate methods to reject fake leptons
  - Equally limited by systematics and statistics
- $b\bar{b}$
  - Extensive use of b-tagging to enhance signal purity and constrain $t\bar{t}$ background
  - Limited by systematics, mainly modeling of $t\bar{t}$ produced with additional b-jets
- $\gamma\gamma$
  - Fitting $m_{\gamma\gamma}$ distribution in $t\bar{t}$-enriched region
  - Limited by statistics
- $ZZ\to 4l$
  - Very pure region with 0 events observed
- Evidence for $t\bar{t}H$ production with 36.1 fb^{-1} of data. **Observed (expected) significance of 4.2 (3.8) standard deviations**

  Phys. Rev. D 97, 072003 (2018)



$t\bar{t}H(bb)$ analysis

- Use multiple b-tagging working points (WP): loose, medium, tight, very tight → pseudo-continuous b-tagging
- Three categories: dilepton, single lepton boosted and single lepton resolved. Fully hadronic category to be included
- Regions for the fit are obtained taking advantage of the b-tagging score of all jets, attempting to:
  - Maximise signal-to-background ratio in signal regions
  - Get control regions as pure as possible in each of the $t\bar{t}$+jets components ($t\bar{t}$+light, $t\bar{t}$+≥1c and $t\bar{t}$+≥1b)
- 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
- **Observed (expected)** signal significance with respect to the background-only hypothesis of **1.4 (1.6)** standard deviations



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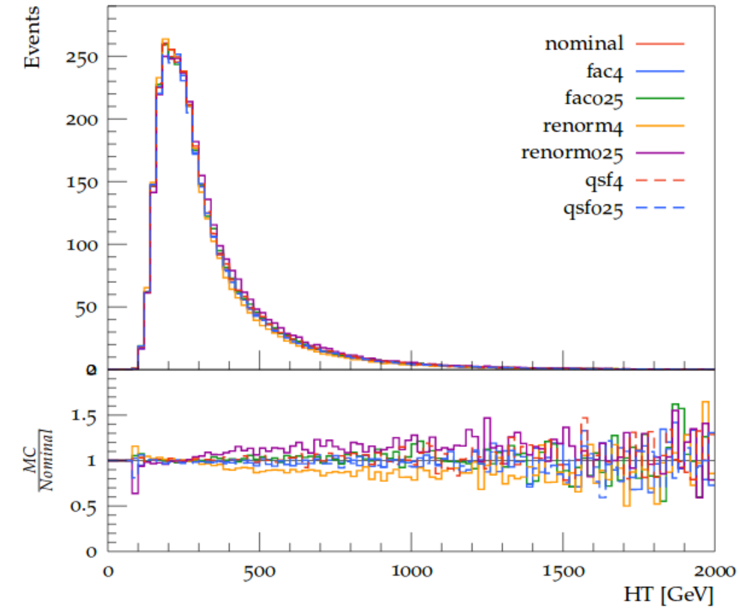
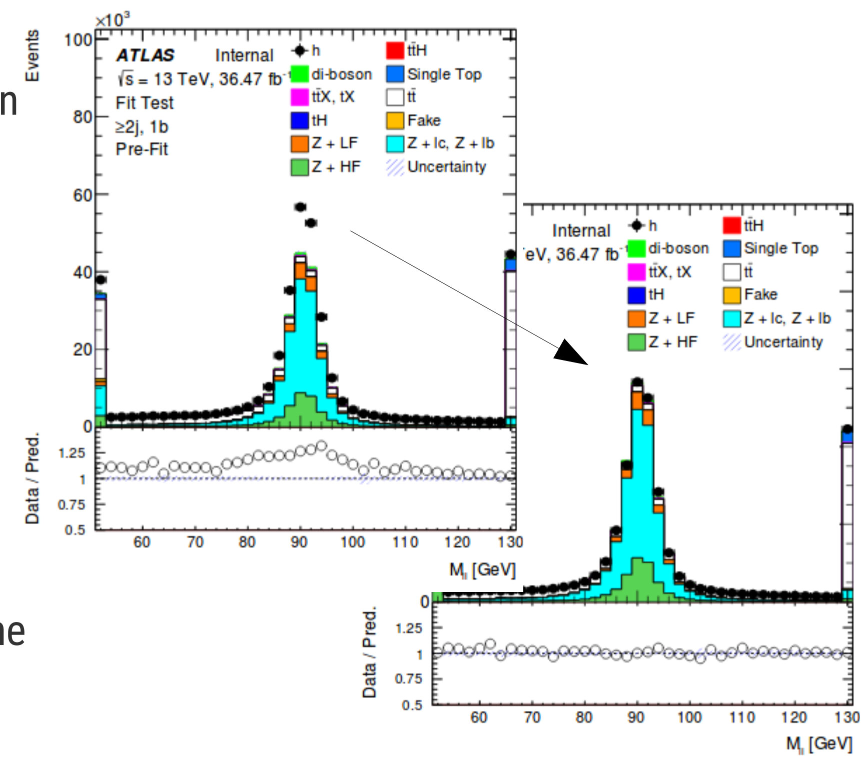
Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	+0.46	−0.46
Background model statistics	+0.29	−0.31
Jet flavour tagging	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modelling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modelling	+0.09	−0.11
Total systematic uncertainty	+0.57	−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

LIP contributions

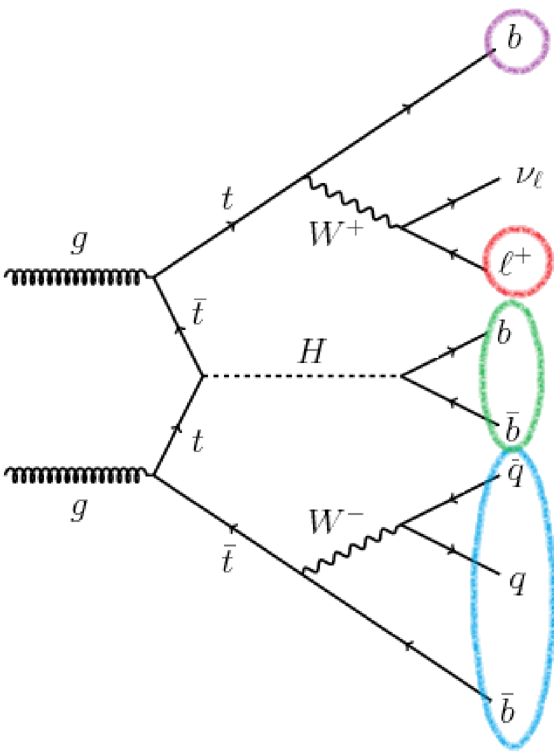
- Modeling uncertainties of diboson backgrounds, by comparing kinematics and rates from different generator settings
- Z+jets background: data-driven normalisation and uncertainties
  - Split control region in 3, based on b-tag, to get independent normalisations for 3 jet flavour components:
    - k(Z+0HF) = 1.0
    - **k(Z+1HF) = k(Z+2HF)= 1.3**
  - Stable with respect to changes in control region definition
  - Uncertainties from scale variations <10% in fit regions
  - Mismodeling of no. of jets → **35% uncertainty on the Z+jets cross-section on the fit, decorrelated among jet multiplicities**
- Earlier this year, data/MC comparisons with new software release and 2017 data
- Contributing to production of common ntuples to be used in the analysis



(b) WZ

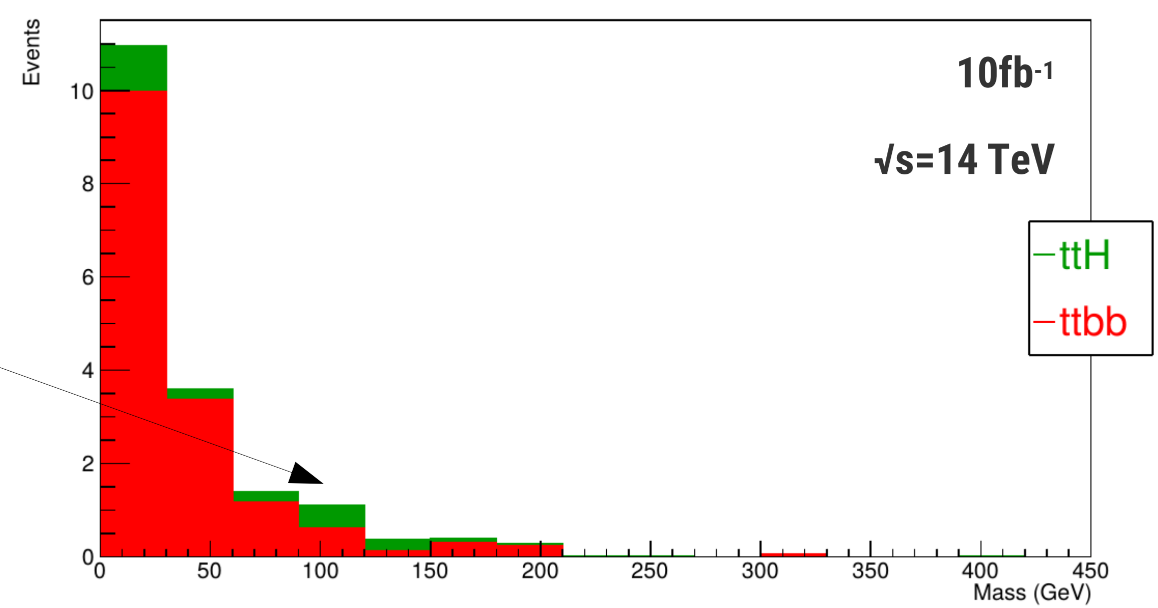


Alternative boosted analysis for HL-LHC



- Select a boosted topology and then perform a fit to m_{bb}, analogously to the H→γγ analysis
- Such a strategy has been proposed for the FCC (√s=100 TeV), with a promise of reduced systematics
  J. Phys. G, 43, 3 (2016)
- Would it be useful already at the HL-LHC ($3ab^{-1}$ @√s=14 TeV)? We are trying to answer these questions:
  - What is the luminosity needed for observation of $t\bar{t}H$ using this analysis?
  - What is the expected uncertainty on the top Yukawa coupling given the full HL-LHC luminosity?

Preliminary results are encouraging



top-Higgs coupling CP structure

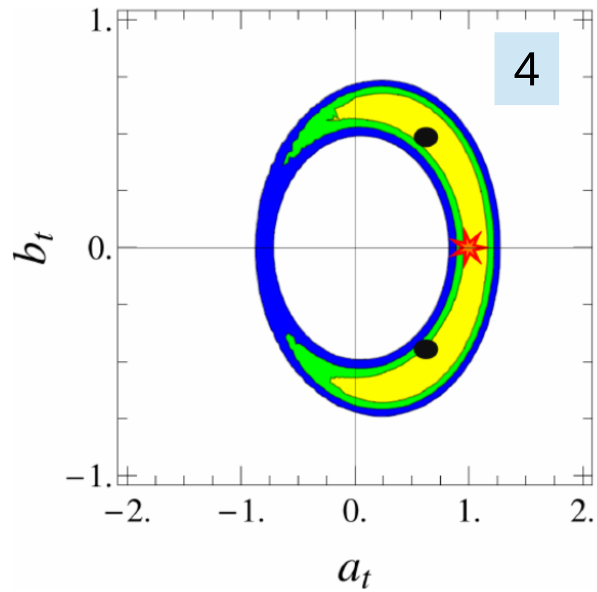
- Baryon asymmetry in the Universe motivates search for additional sources of CP violation
- In some SM extensions, CP violation is introduced by having the physical neutral Higgs boson be a mixture of CP-odd and CP-even. Impact on couplings to fermions

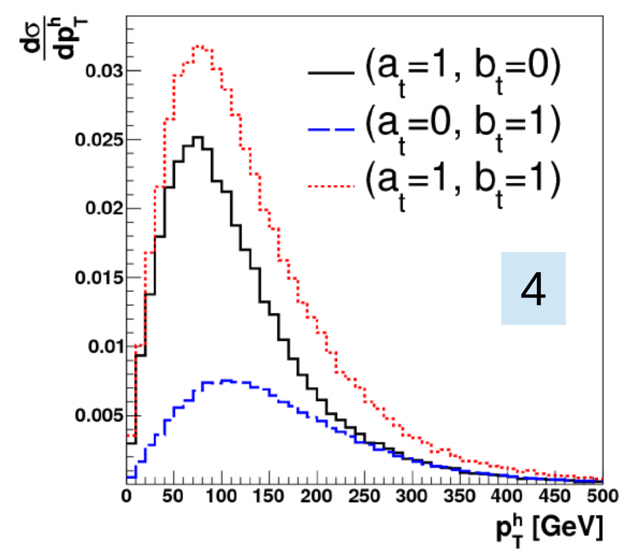
$$\mathcal{L}_{ht\bar{t}} = y_t \bar{t}(a + ib\gamma_5)th$$

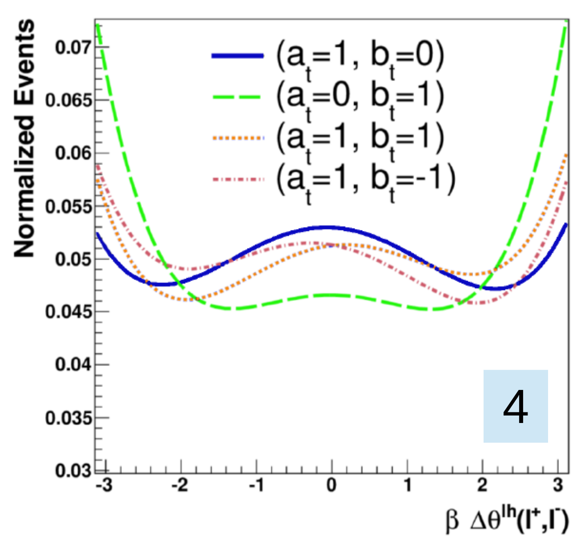
- Searches for anomalous couplings of the 125 GeV Higgs boson to gauge bosons set upper limits to CP-odd fraction of production cross-section @95% CL: **0.41** from ATLAS and **0.25** from CMS
  Eur. Phys. J., C75(10):476, 2015. ; Phys. Lett. B, 759:672. 25 p, 2016.
- Should pursue equivalent searches in fermionic sector: **top is the first obvious candidate**, but also tau, bottom, then muon, and so on...
- Even if we are convinced the 125 GeV Higgs is purely CP-even, new physics can manifest through anomalous couplings → **we must directly measure Yukawa couplings**

Phenomenology of a CP-mixed top Yukawa coupling

- 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
- Production cross-section of $t\bar{t}H$ decreases while that of $tH/\bar{t}H$ increases as the CP-odd fraction of the coupling is increased
- Impact on kinematics of $t\bar{t}H$ production: $m_{t\bar{t}H}$ distribution shifts to higher mass values → Higgs with higher p_T
- Observables sensitive to $t\bar{t}$ spin correlations also sensitive to CP nature of the coupling
- CP-odd observables are needed to be sensitive to relative sign of a and b



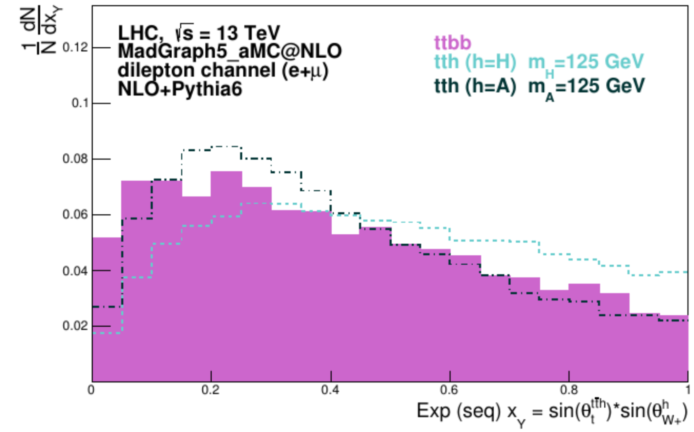


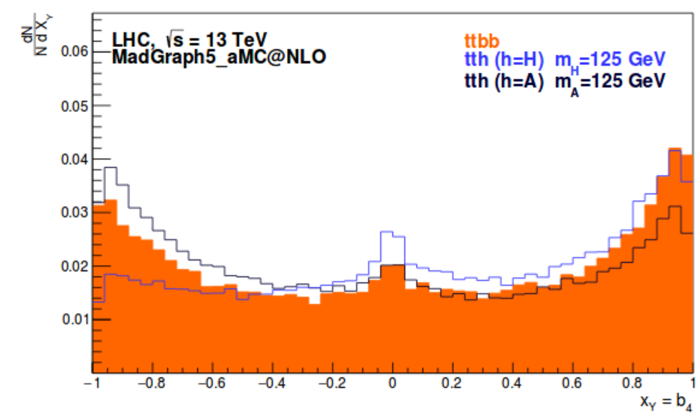


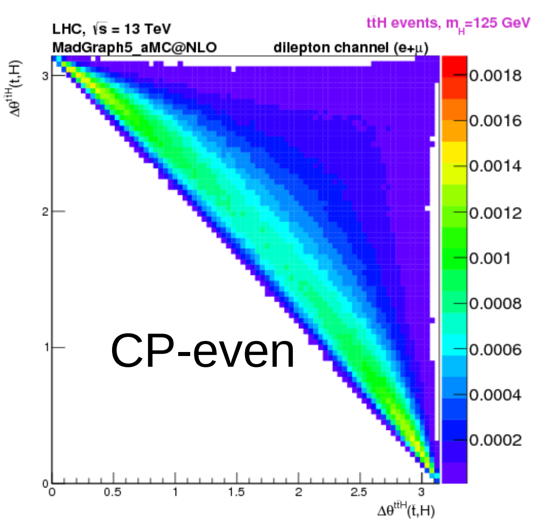
$t\bar{t}H$ CP phenomenology @ LIP

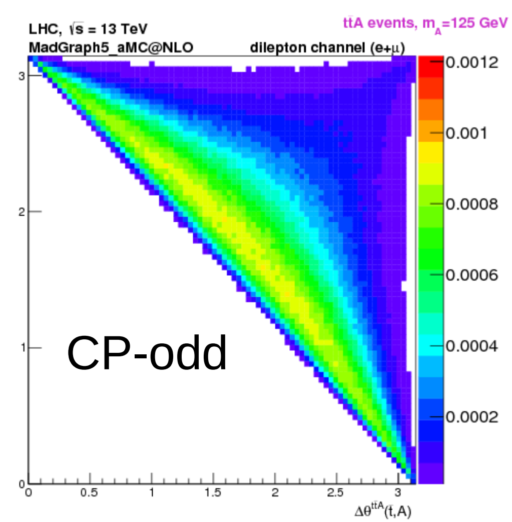
Phys. Rev. D 96, 013004 (2017), arXiv:1711.05292

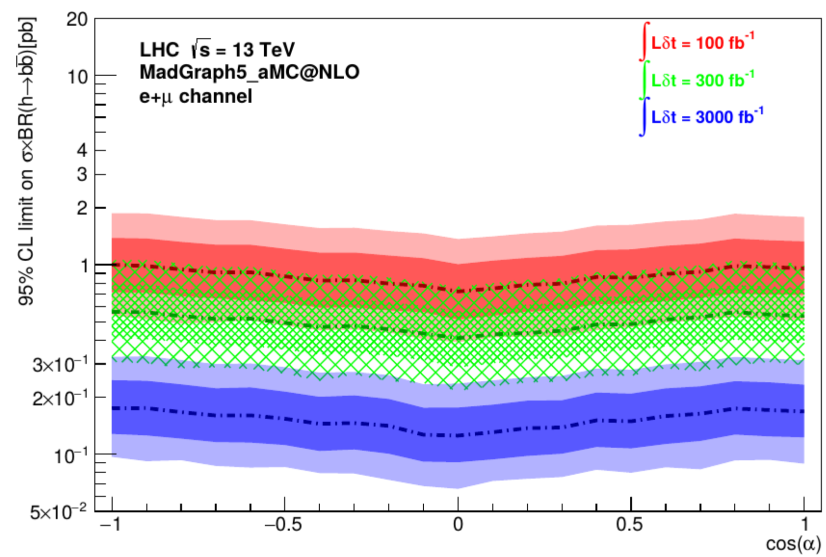
- $t\bar{t}H(\rightarrow b\bar{b})$ and $t\bar{t}b\bar{b}$ events at NLO, including alternative CP scenarios, and set of other SM backgrounds at LO. Fast detector simulation
- Kinematical reconstruction routines for single lepton and dilepton
- New family of angular observables using boosted reference frames, to use for signal/background and CP-even/CP-odd discrimination
- Studied impact of reconstruction on the distributions of the new observables and of those previously proposed by phenomenologists
- Expected limits @95% CL for cross-section times $H\rightarrow b\bar{b}$ branching ratio in different CP scenarios







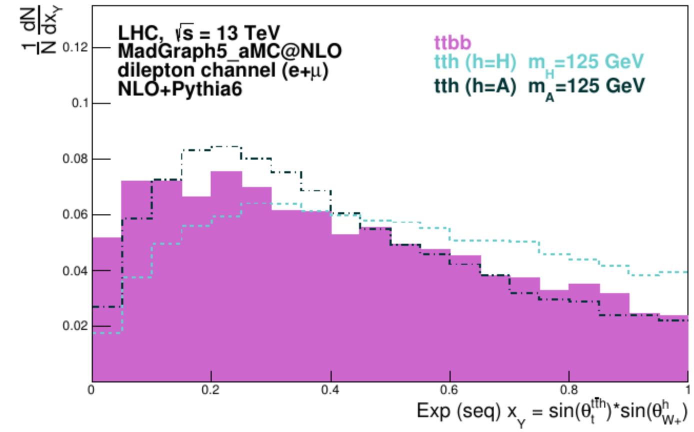


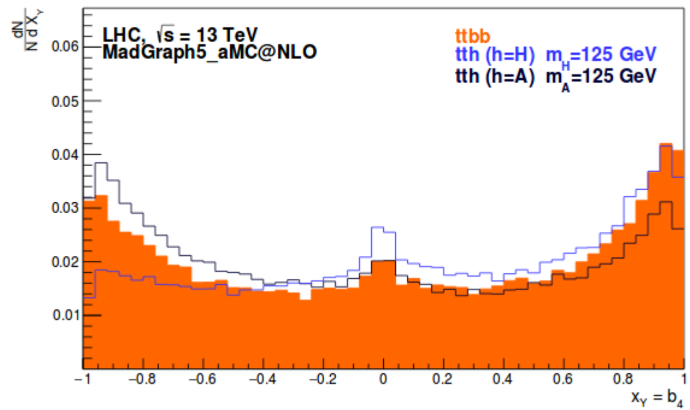


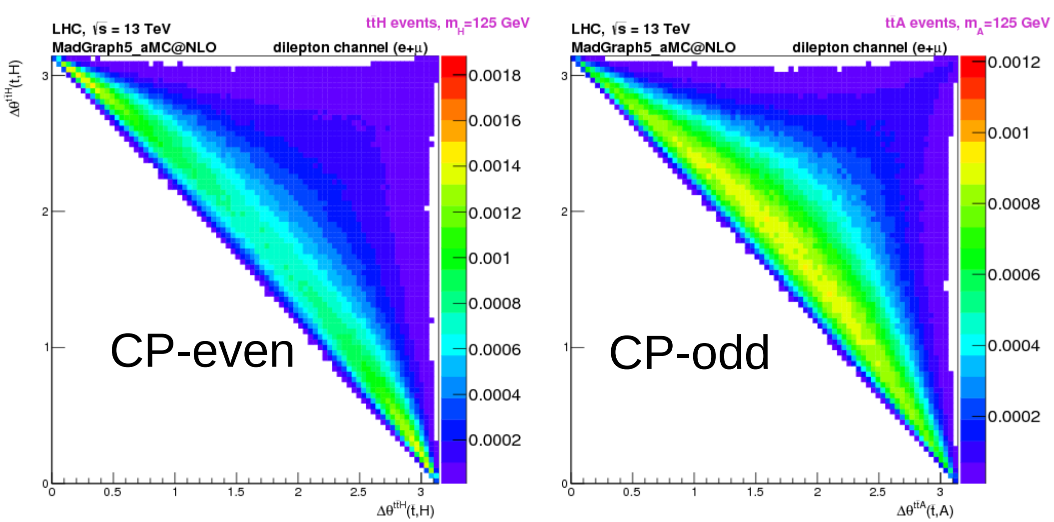
$t\bar{t}H$ CP phenomenology @ LIP

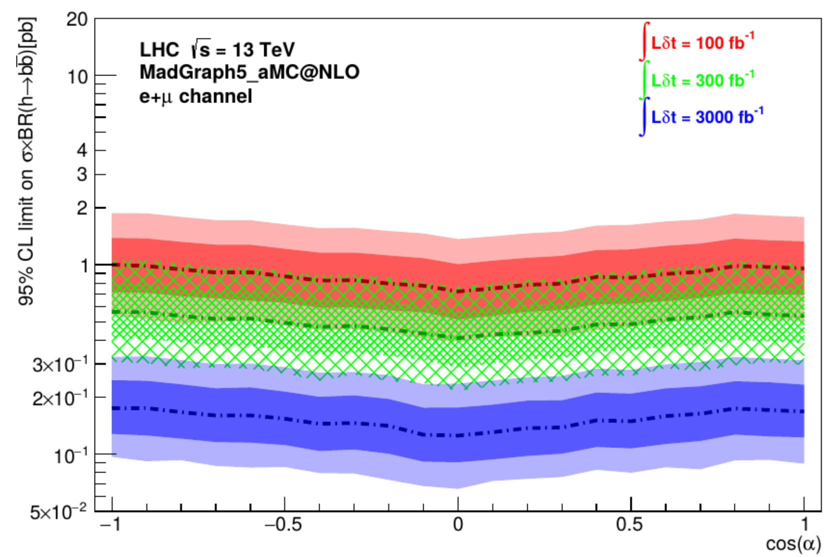
Phys. Rev. D 96, 013004 (2017), arXiv:1711.05292

- Angular observables retain information about CP nature of the coupling, even after detector effects and reconstruction
- Sensitivity of a search for $t\bar{t}H$ has small dependence on CP-odd fraction
- **Best observables require reconstruction of top quarks and Higgs boson**
- Collaborated with theorists in computation of differential distributions at NLO+NLL for pure CP-odd scenario
  (Phys. Rev. D 96, 073005 (2017))









Plans and current status

- Perform measurement of CP-odd coupling within ATLAS ttH(bb) analysis
  - Request signal samples with modified top quark Yukawa coupling
  - Select events from signal-rich regions defined by the search analysis, compromising between purity and statistics
  - Compute angular observables
  - Template fit or asymmetries using best observables (or output from dedicated multivariate method) to simultaneously extract a and b parameters
- Currently doing template fit studies with ATLAS fully-simulated backgrounds and private fast-simulated signal samples to obtain approximate sensitivity estimates, including main systematic uncertainties

Summary

- $t\bar{t}H$ production at the LHC provides direct access to top quark Yukawa coupling
- Observation of $t\bar{t}H$ means a shift of focus towards measuring properties, with increasing precision, as happened in the dominant Higgs production modes
- $H\rightarrow b\bar{b}$ is not the most sensitive channel to observation, but allows reconstruction of top quarks and Higgs boson, which makes it preferred to measuring coupling properties
- First step towards generalizing top quark Yukawa coupling is adding a CP-odd component, also motivated by SM extensions
- Such a measurement would differentiate ATLAS $t\bar{t}H(b\bar{b})$ analysis → **LIP in privileged position to lead the effort**
- In parallel, phenomenology work about prospects for $t\bar{t}H$ in HL-LHC and future colliders, in close contact with theorists

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Backup

More references

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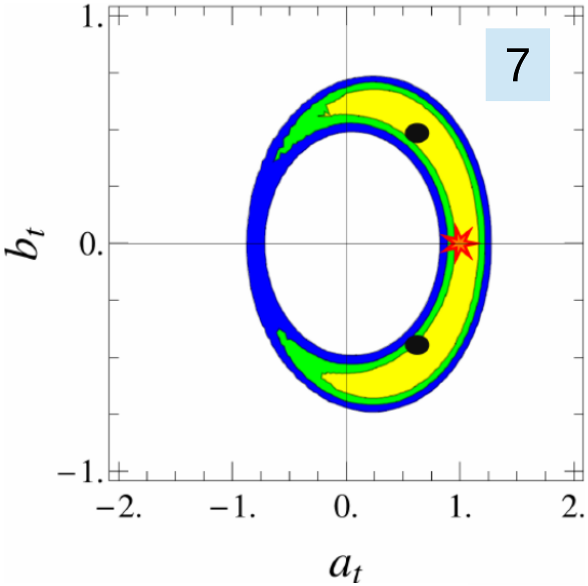
Phenomenology of a CP-mixed top Yukawa coupling

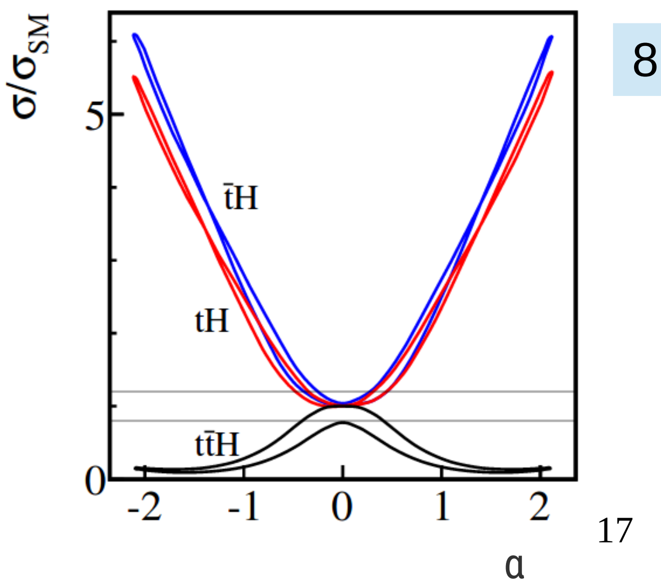
Indirect constraints

- 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



$t\bar{H}/\bar{t}H$ 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



Experimental Status

CP properties of the 125 GeV Higgs Boson

- Measurements focused on couplings to gauge bosons
- ATLAS spin-parity measurements on $H\to\gamma\gamma$, $H\to ZZ^*\to 4l$, $H\to WW^*\to e\nu\mu\nu$ with full Run I dataset 15
  - Excluded spin 2, spin 0 CP-odd and BSM spin 0 CP-even scenarios at >99.9% CL
  - Upper limit to effective CP-odd cross-section fraction f<0.41 at 95% CL
- ATLAS CP invariance test on vector boson fusion (VBF), $H\to\tau\tau$ with full 8TeV dataset 16
  - Dimensionless CP-violating parameter constrained to [-0.11,0.05] at 68% CL
- CMS search for CP-odd anomalous couplings in $H\to ZZ^*\to 4l$, $H\to WW^*\to e\nu\mu\nu$ combined with VH ($H\to b\bar{b}$) 17
  - f<0.25 at 95% CL and f<0.0034 assuming SM-like ratio between the top and bottom Yukawa couplings
  - CP-odd Higgs boson wouldn't couple at tree level to gauge bosons, **contribution to these channels loop-suppressed compared to CP-even**
- Coupling to photons more "democratic", since it is also loop-induced in the SM. CMS 95% CL intervals for $H\gamma\gamma$ couplings 18
  - CP-even: [-0.011,0.054] (SM predicts ~0.004); CP-odd: [-0.039,0.037]

Large Hadron Collider (LHC)

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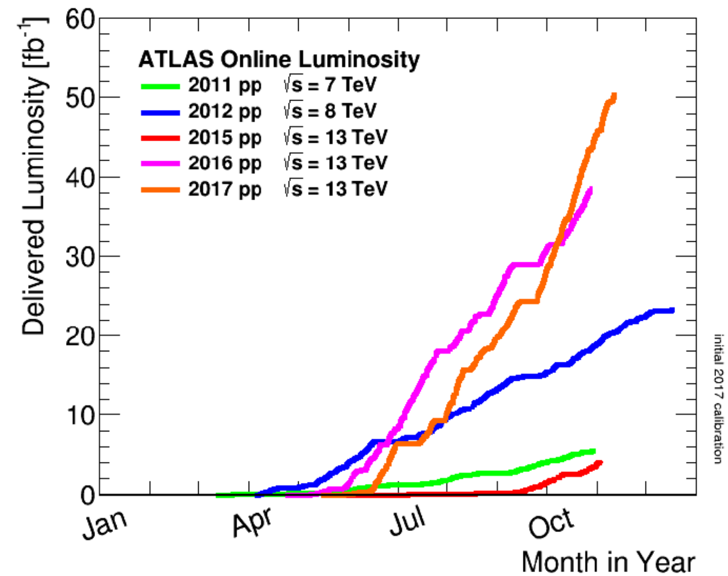
- Circular accelerator at CERN, 27km in circumference
- Collides proton-proton, proton-lead, lead-lead (recently also xenon)
- pp collisions at 13TeV centre-of-mass energy in the present run



ATLAS detector

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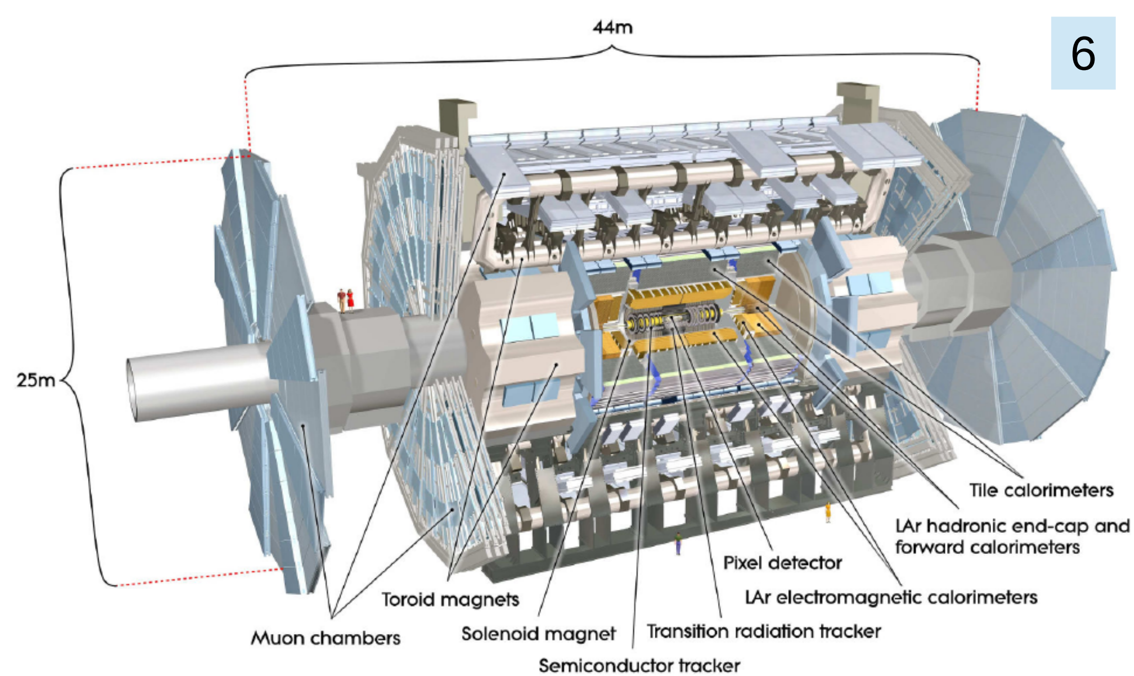
- Multi-purpose detector, partially motivated to search for unknown phenomena
- Solenoidal magnetic field for inner detector and toroidal field for muon tracking
- Several layers covering nearly the whole solid angle: tracking, calorimetry and muon spectrometer
- Trigger system: reduce collection rate to a rate susceptible of storage and analysis



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

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

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

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

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- $\Delta\phi^H(\ell^+, \ell^-)$ → 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

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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 $\bar{t}H$ 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

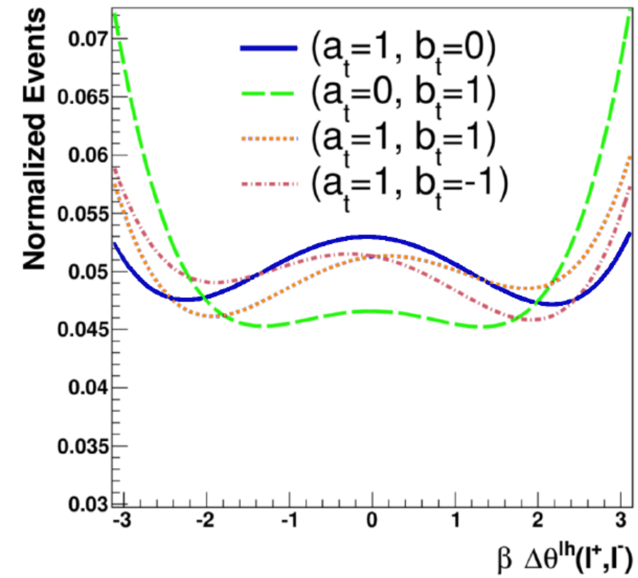
- $$\Delta\phi^H(\ell^+, \ell^-)$$

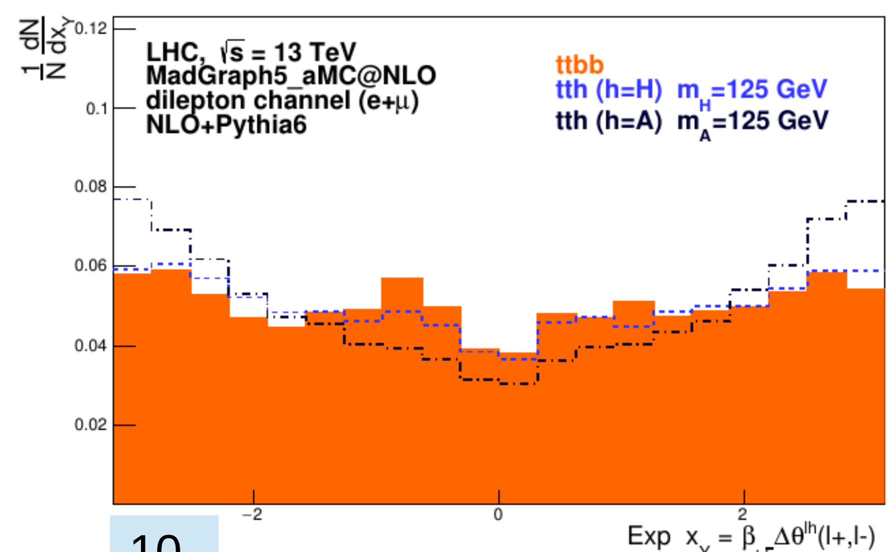
Azimuthal angle difference between leptons' momenta in the Higgs rest frame

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

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

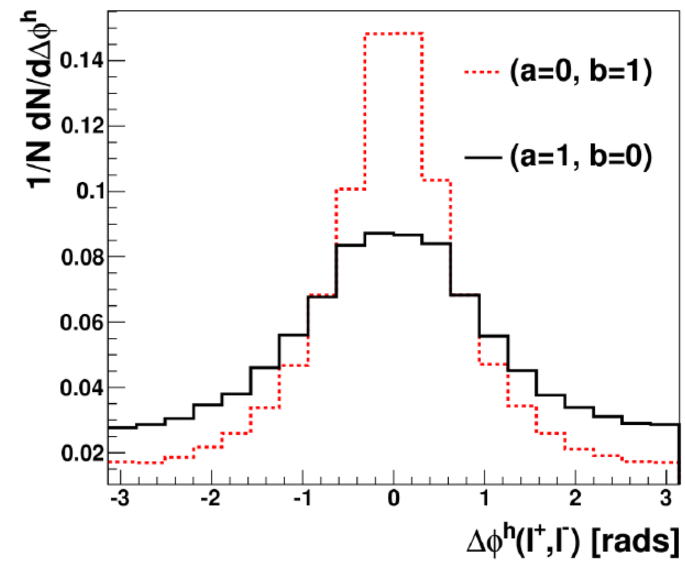
- Comparison of distribution predicted by theory with that after detector simulation, cuts and reconstruction in a tt→dilepton channel analysis

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

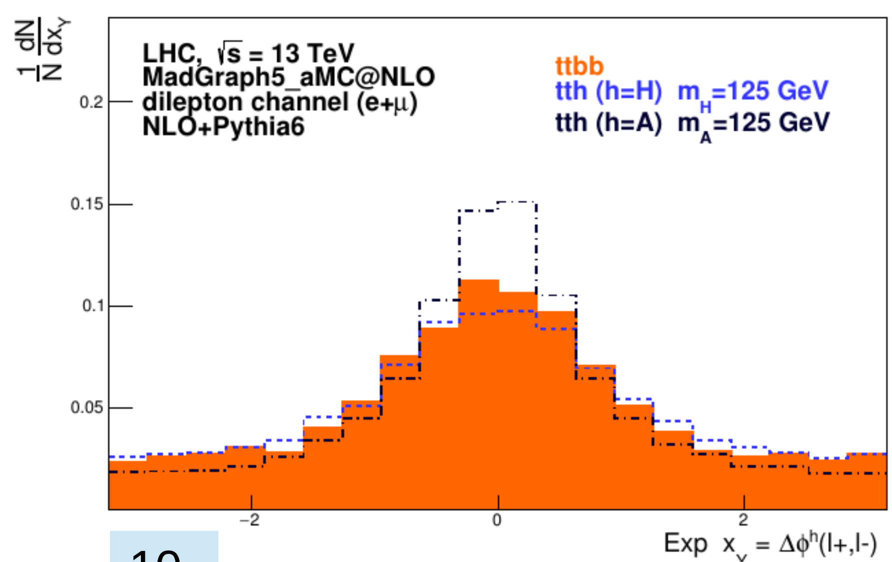
C-odd, P-odd

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



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

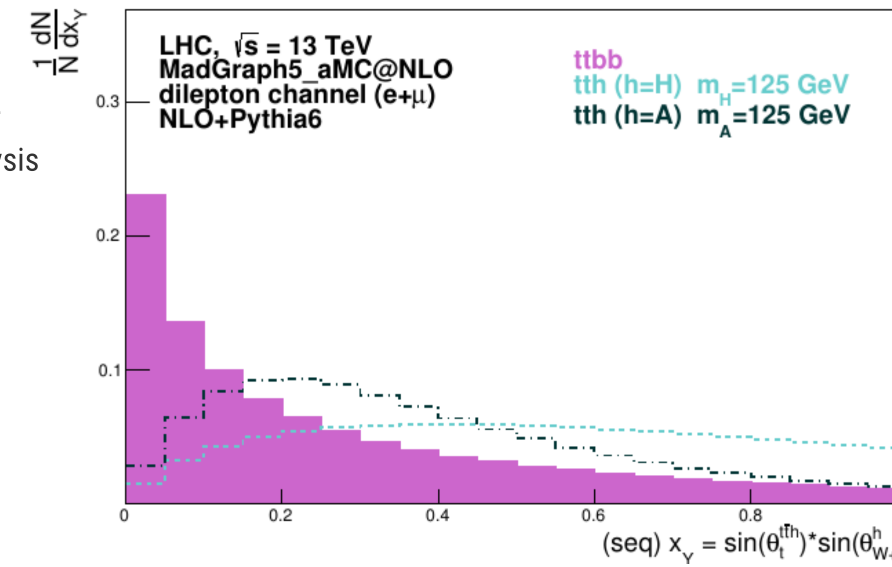
Angle between t momentum in $\bar{t}$tH rest-frame and $\bar{t}$tH momentum in lab frame

Angle between H momentum in $\bar{t}$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



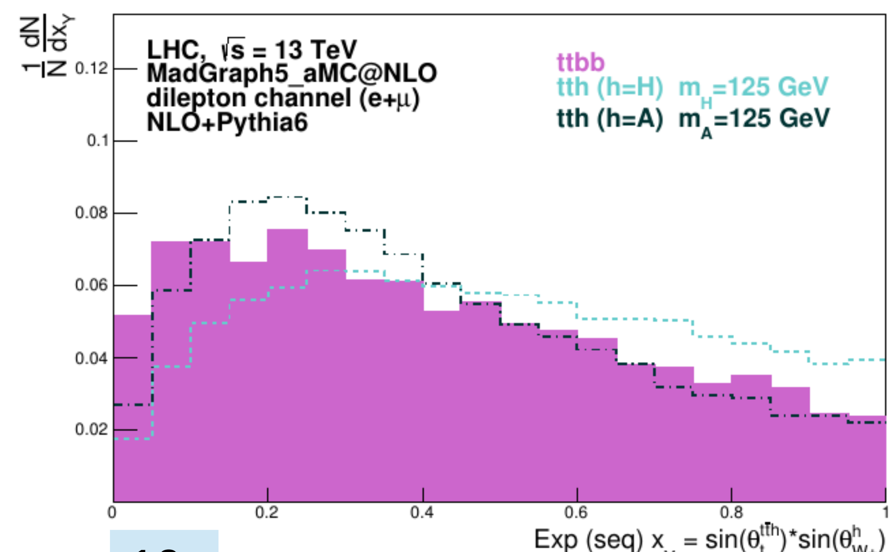
- $\mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right) \Delta\theta^{\ell h}(\ell^+, \ell^-)$

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



10

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

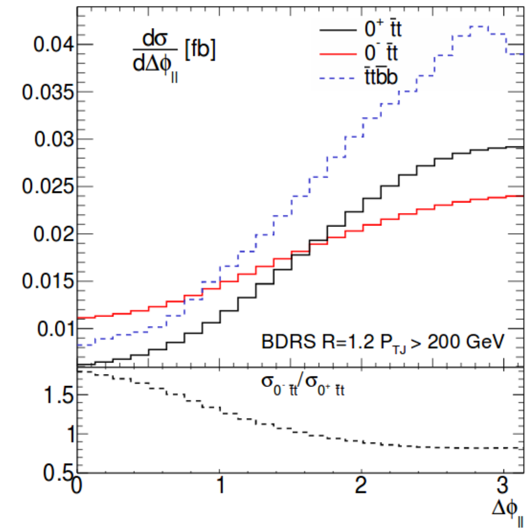
Angle between t momentum in $t\bar{t}H$ rest-frame and $t\bar{t}H$ momentum in lab frame

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

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 $t\bar{t}\to$ 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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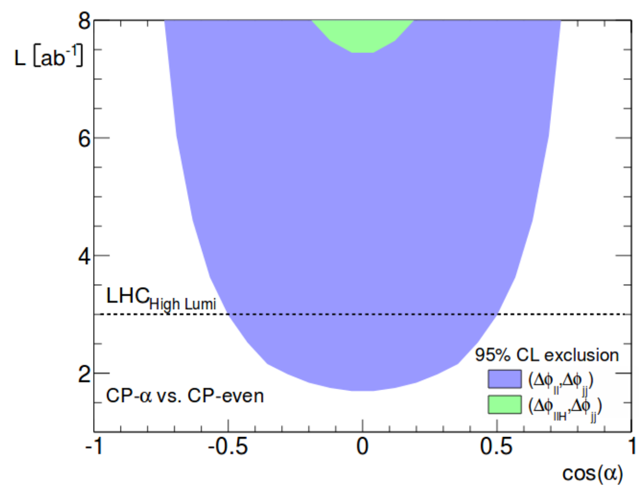
- Expected exclusion of $|\alpha|>\pi/3$ at 95% CL with 3ab^{-1} of 13TeV LHC data



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

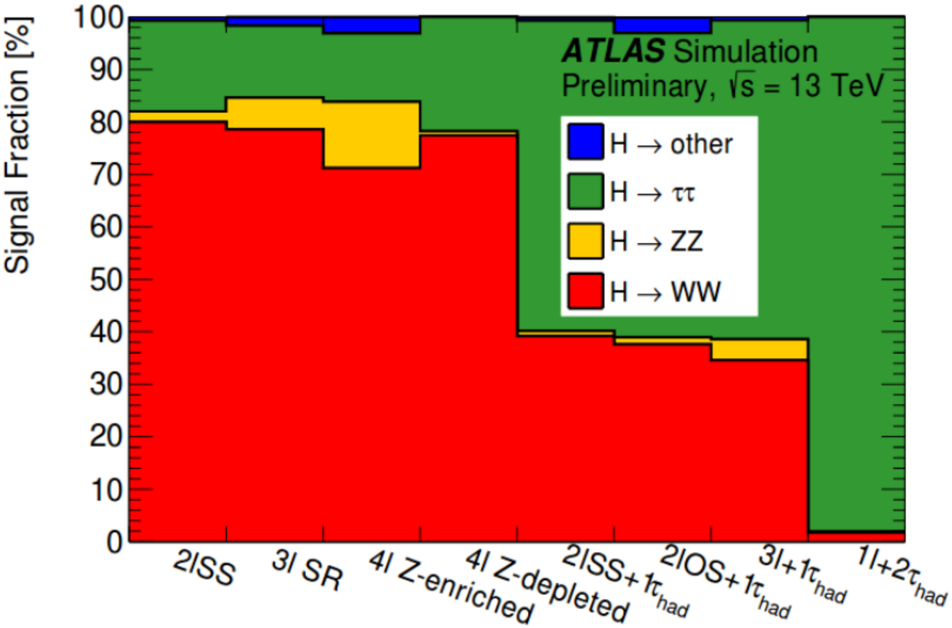
Angle between the Higgs boson and t/$\bar{t}$ in the $t\bar{t}$H rest-frame

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

Experimental Status

Evidence for $t\bar{t}H$ production – Multilepton channel

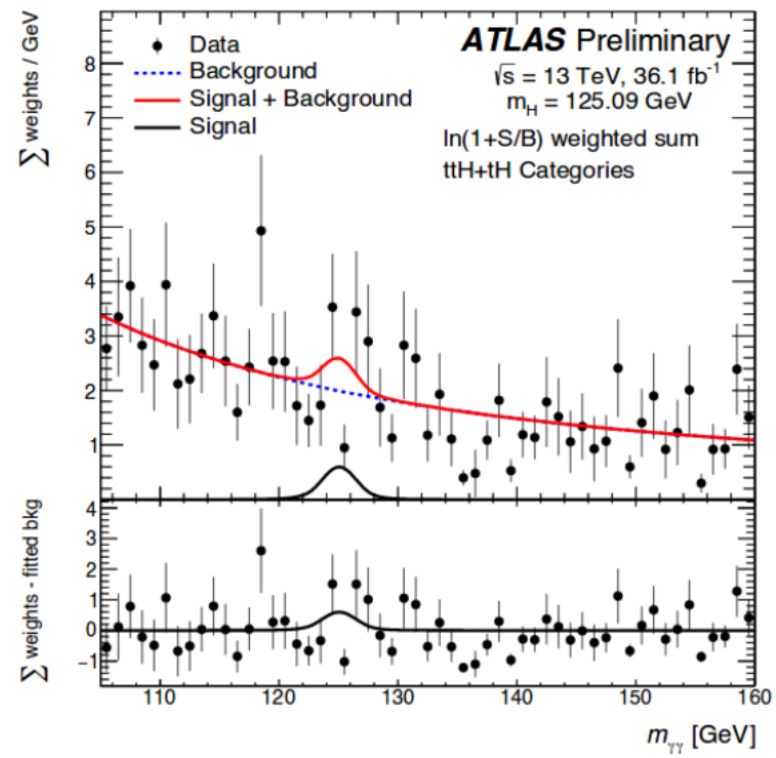
- Most sensitive channel
- Seven categories:
  - 2 same-charge (SS) light leptons (e or μ) l and 0 τ leptons: 2lSS
  - 3l with charges summing ±1, and 0τ
  - 4l with charges summing 0, further divided into Z-enriched and Z-depleted
  - 2lSS+1τ
  - 2 opposite-charge (OS) l+1τ
  - 3l+1τ with charge summing 0
  - 1l +2
- Besides, require 2 jets, of which at least one is b-tagged
- Multivariate Analysis (MVA) dedicated to fake lepton rejection
- Simultaneous fit to classification MVA in some categories and just total number of events in others
- **Observed (expected)** excess with respect to the background-only hypothesis of **4.1 (2.8)** standard deviations
- Uncertainty evenly coming from statistics and systematics, which are mainly jet energy scale and fake lepton estimate



Experimental Status

Evidence for $t\bar{t}H$ production – γγ channel

- Require diphoton system, 1b-tagged jet and either:
  - 1 lepton and one additional jet
  - 0 leptons and two additional central jets. MVA used to discriminate from gluon fusion Higgs production
- Weight data in each category with ln(1+s/b)
- Fit two curves to data
- **Very small systematics → sensitivity expected to improve with statistics**



Evidence for $t\bar{t}H$ production – ZZ→4l channel

- Require 2 OS same-flavour lepton pairs, one b-tagged jet and either:
  - 1 additional lepton and two additional jets
  - 4 additional jets

CP violation in the Standard Model

$$\mathcal{L}_{Yukawa} = -\left(\overline{Q_L}\Gamma\phi d_R + \overline{Q_L}\Delta\tilde{\phi}u_R + \overline{L_L}\Pi\phi\ell_R\right) + \text{h.c.}$$

- Yukawa matrices Γ and Δ mix different quark generations and are in principle arbitrary
- They are bi-diagonalized by the U matrices which transform flavour states into mass states

$$\Gamma' = U_d^{L\dagger}\Gamma U_d^R, \quad \Delta' = U_u^{L\dagger}\Delta U_u^R$$

- The weak interaction in terms of the mass states q' is:

$$\mathcal{L}_W = \frac{g}{2}(W_\mu^+\overline{u'_L}\gamma^\mu V d'_L + W_\mu^-\overline{d'_L}\gamma^\mu V^\dagger u'_L), V \equiv U_u^{L\dagger}U_d^L$$

- CP symmetry of this interaction requires the CKM matrix $V=V^\dagger$
- Rephasing the quark fields reduces the physical parameters of the CKM matrix to 4:
  - 3 "rotation" angles
  - **1 CP-violating phase**

CP violation in a two-Higgs-doublets model

- Two Higgs doublets means 2 x 2 x 2 = 8 scalar degrees of freedom

  complex → doublet components → doublets

$$\phi_a = \begin{pmatrix} \varphi_a^+ \\ \frac{1}{\sqrt{2}}(v_a + \eta_a + i\chi_a) \end{pmatrix}, \quad a = 1, 2$$

- After electroweak symmetry breaking, Goldstone bosons “absorbed” by $W^\pm$ and Z longitudinal components: two charged and one neutral (imaginary part)
- Physical states left: two neutral from real parts (η_1, η_2), one neutral from an imaginary part (η_3) and two charged
- CP violation can be introduced by mixing η_1 and η_2 with η_3 to form the physical Higgs bosons

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix}$$

- The Yukawa interaction of the top quark with the h_1 boson becomes

$$\mathcal{L}_{ht\bar{t}} = y_t \bar{t}(a + ib\gamma_5)th$$

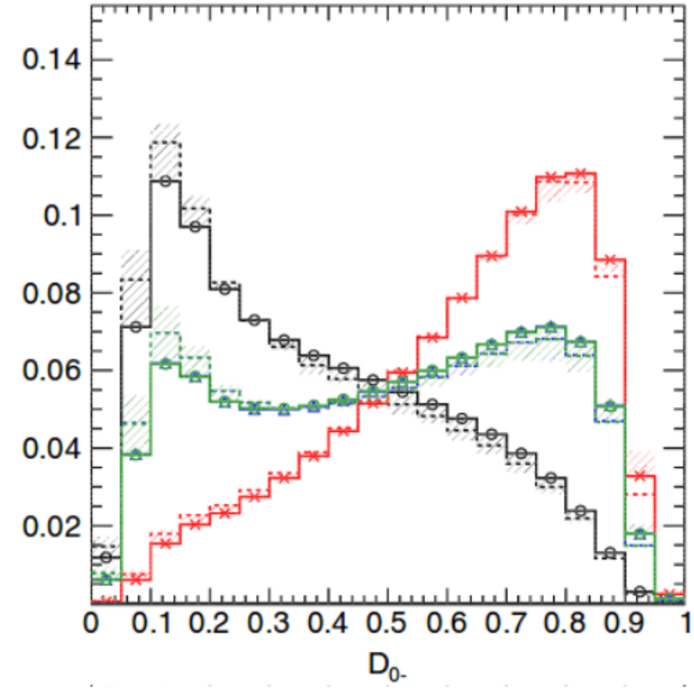
where b is proportional to R_{13}

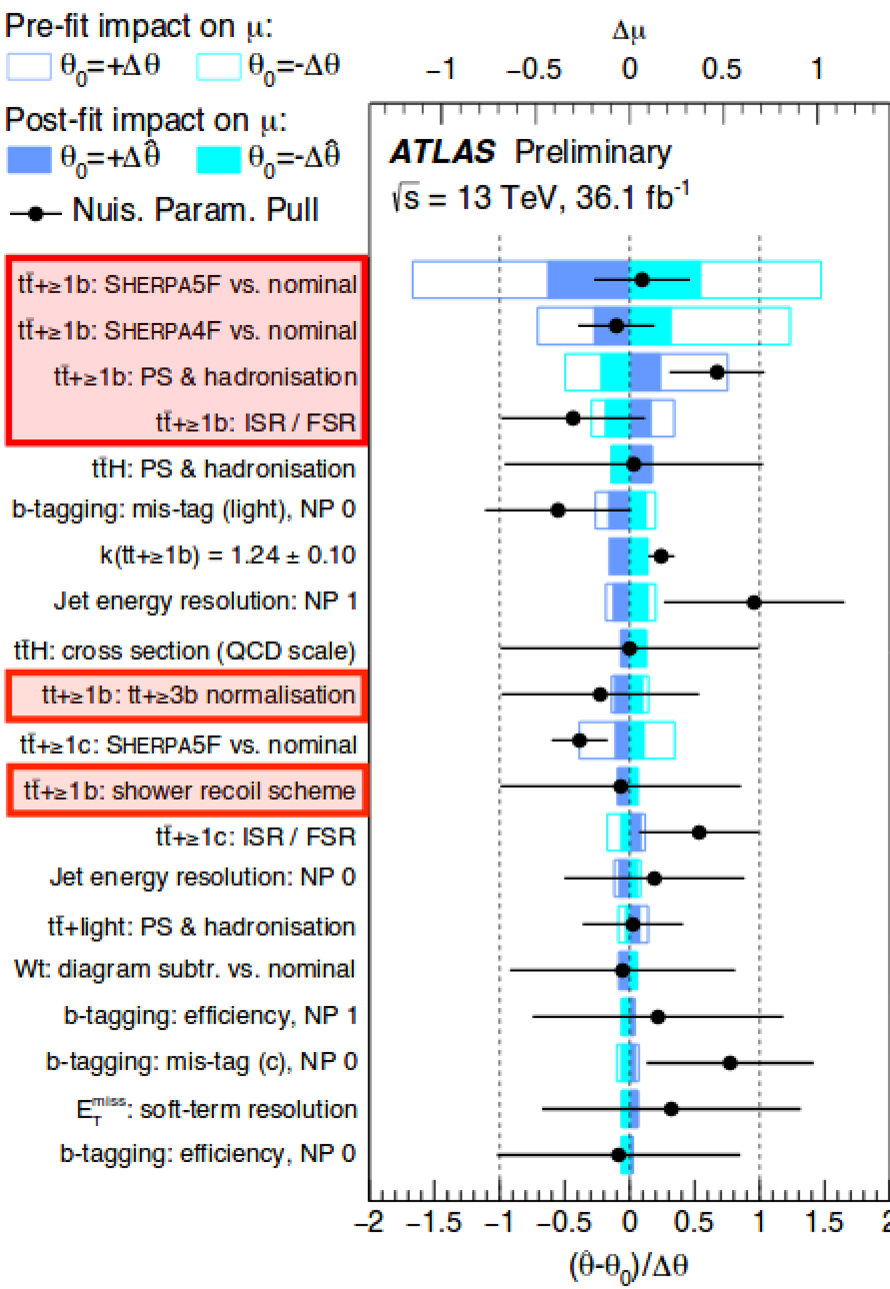
- Flips sign under P
- a=1 and b=0 in the SM
- b≠0 is evidence of new source of CP violation

Phenomenology of a CP-mixed top Yukawa coupling

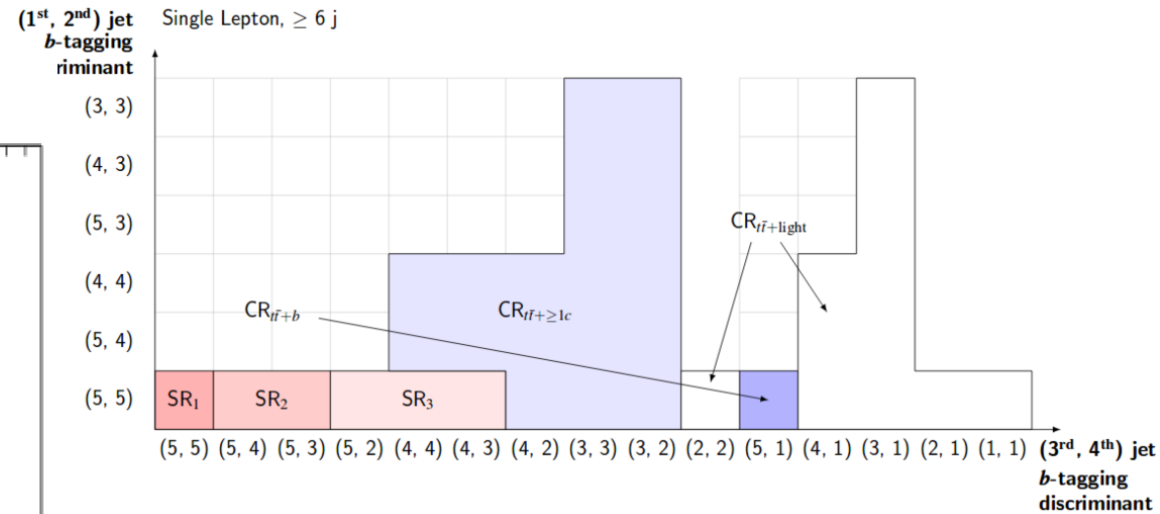
Matrix element likelihood method

- Event kinematics fully characterized in terms of N invariant masses and boosted angles
- Probability distributions of the different hypotheses in the N-dimensional space of these variables are computed using LO matrix elements
- Likelihood ratio between hypotheses is the optimal discriminant
- For a continuum of hypotheses (α values), three ratios are sufficient
- NLO events depart from optimal case, but good discrimination remains. Real events with detector conditions will depart even further
- α=0, α=π/2, α=0.18π. Solid: LO; Hatched: difference between LO and NLO

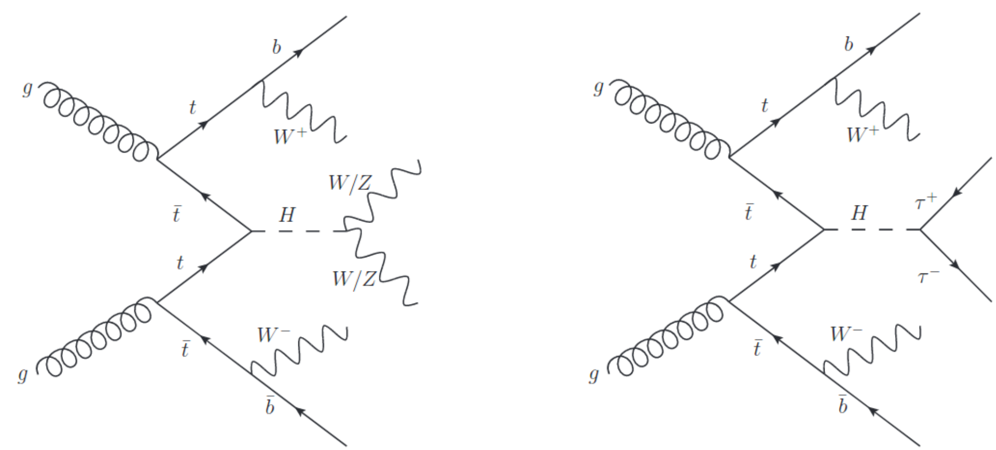




Pre-fit impact on μ:
θ0=+Δθ
θ0=-Δθ
Post-fit impact on μ:
θ0=+Δθ̂
θ0=-Δθ̂
Nuis. Param. Pull
Δμ
−1 −0.5 0 0.5 1
ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
tt̄+≥1b: SHERPA5F vs. nominal
tt̄+≥1b: SHERPA4F vs. nominal
tt̄+≥1b: PS & hadronisation
tt̄+≥1b: ISR / FSR
tt̄H: PS & hadronisation
b-tagging: mis-tag (light), NP 0
k(tt+≥1b) = 1.24 ± 0.10
Jet energy resolution: NP 1
tt̄H: cross section (QCD scale)
tt+≥1b: tt+≥3b normalisation
tt̄+≥1c: SHERPA5F vs. nominal
tt̄+≥1b: shower recoil scheme
tt̄+≥1c: ISR / FSR
Jet energy resolution: NP 0
tt̄+light: PS & hadronisation
Wt: diagram subtr. vs. nominal
b-tagging: efficiency, NP 1
b-tagging: mis-tag (c), NP 0
E_T^miss: soft-term resolution
b-tagging: efficiency, NP 0
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
(θ̂-θ0)/Δθ



(1st, 2nd) jet
b-tagging
riminant
Single Lepton, ≥ 6 j
(3, 3)
(4, 3)
(5, 3)
(4, 4)
(5, 4)
(5, 5)
CR_tt̄+light
CR_tt̄+b
CR_tt̄+≥1c
SR1
SR2
SR3
(5, 5) (5, 4) (5, 3) (5, 2) (4, 4) (4, 3) (4, 2) (3, 3) (3, 2) (2, 2) (5, 1) (4, 1) (3, 1) (2, 1) (1, 1)
(3rd, 4th) jet
b-tagging
discriminant



g
b
t
W+
t̄
H
W/Z
W/Z
t
g
t̄
W−
b̄
g
b
t
W+
t̄
H
τ+
τ−
t
g
t̄
W−
b̄

(a) (b)