LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
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Search for a CP-odd top-quark Yukawa coupling with the ATLAS experiment

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5. Summary

1.
Motivation

Motivation

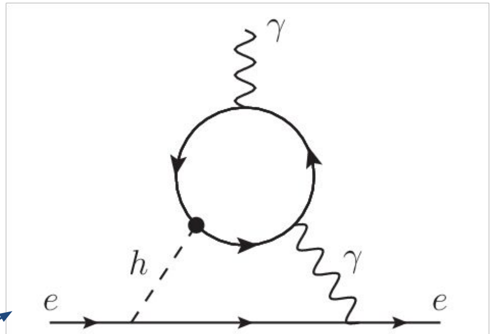
- Baryon asymmetry $\rightarrow$ new sources of CP-violation required
- Can be realized in Higgs bosons with both CP-even and CP-odd components
- CP-odd component does not couple to vector bosons at tree-level
- Could reveal itself in Yukawa interaction between top quark and the 125 GeV Higgs boson:

$$\begin{aligned}\mathcal{L}_{tth} &= y_t \bar{\psi}_t \kappa'_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t h \\ &= y_t \bar{\psi}_t (\kappa_t + i\gamma_5 \tilde{\kappa}_t)\psi_t h\end{aligned}$$

- top-Higgs coupling directly confirmed with observation of ttH production by ATLAS and CMS
(Phys. Lett. B 784 (2018) 173, Phys. Rev. Lett. 120, 231801)

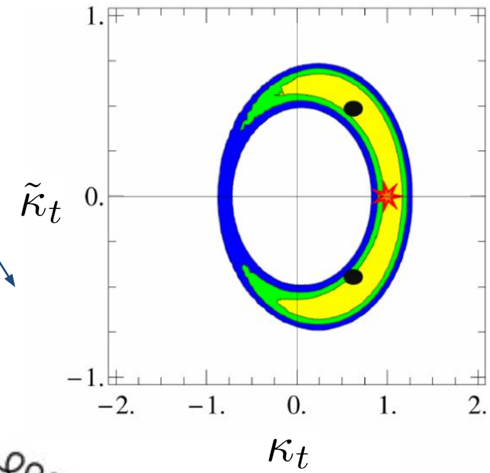
Direct vs indirect

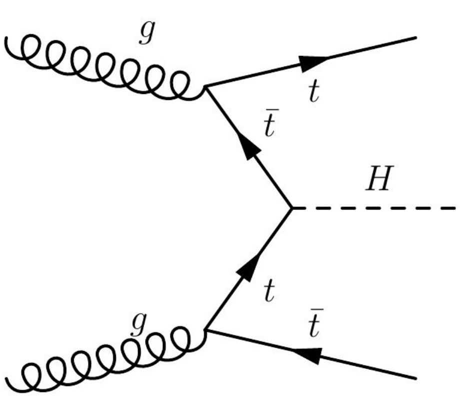
- Indirect constraints exist:
  (Phys. Rev. D 92, 015019, 2015; JHEP 1802 (2018) 073)
  - Electron electric dipole moment (EDM)
  - LHC Run I data, including ggF Higgs production
- **No direct measurement yet, the goal for my PhD thesis is to perform it**
- **ttH production at the LHC provides the best direct probe**

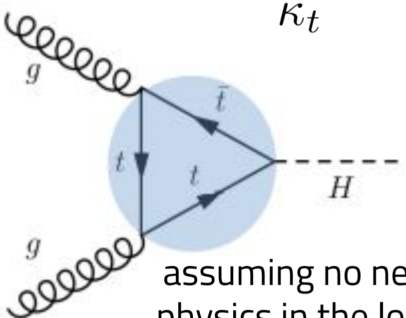


assuming no new physics and SM electron Yukawa coupling

(Phys. Rev. D 92, 015019, 2015)



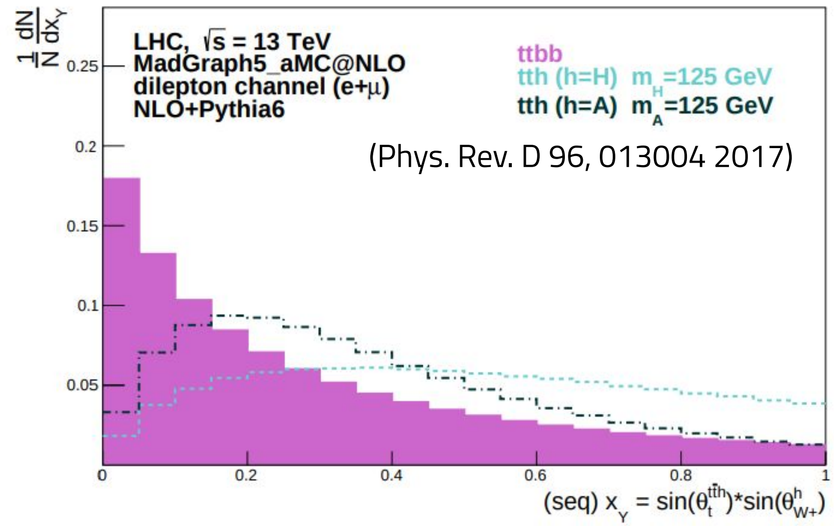


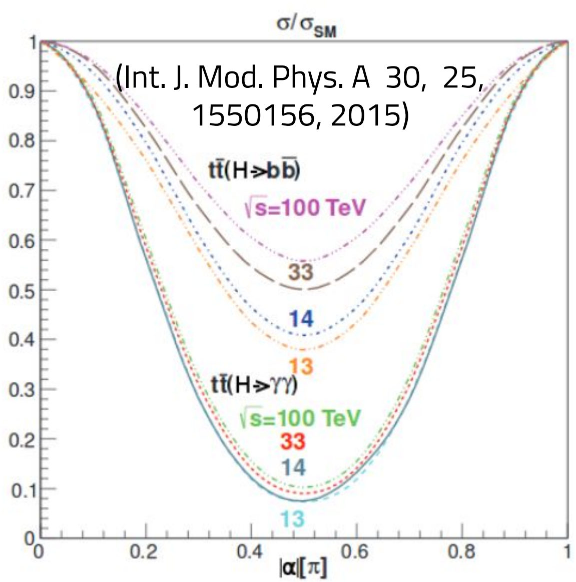


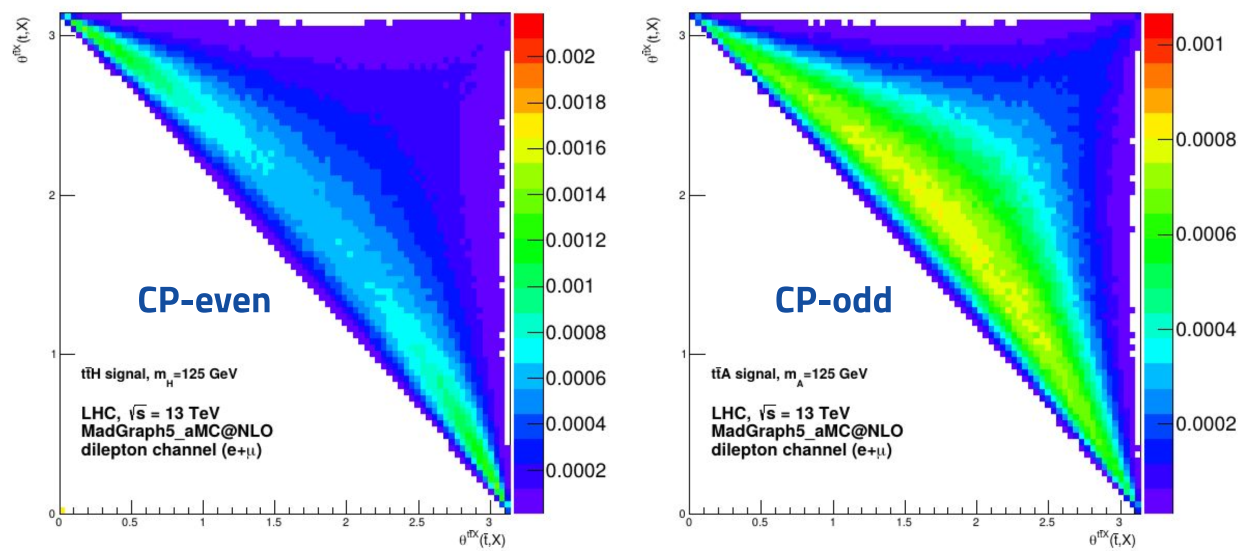
assuming no new physics in the loop

What is different in CP-odd ttH?

- Smaller inclusive cross-section
- Higher Higgs p_T
- Larger $\Delta\eta$ between top quarks
- Different angles measured in boosted rest frames







(Phys. Rev. D 96, 013004 2017)

2.

Analysis strategy in ATLAS

$t\bar{t}(H \rightarrow b\bar{b})$ with leptons

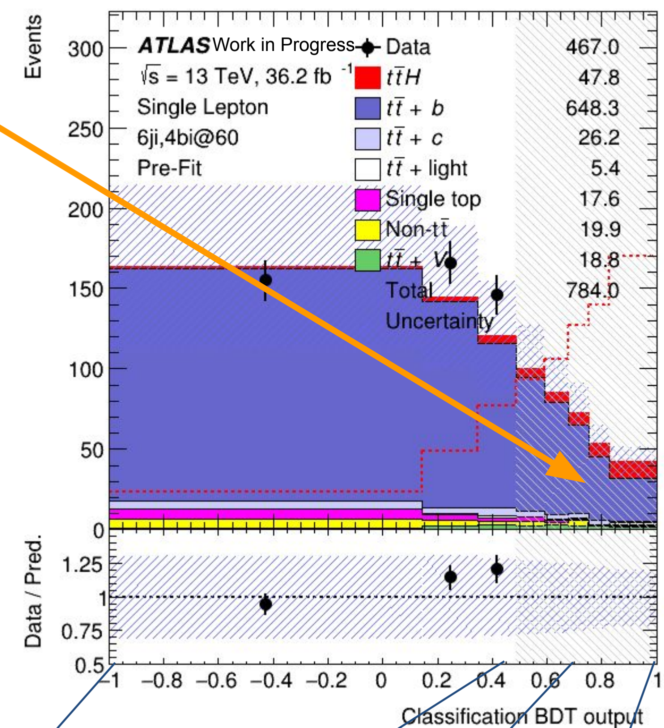
SM tt(H→bb) analysis with leptons

Phys. Rev. D 97, 072016 (2018)

- Two categories: **dilepton** and **single lepton**
- Define regions based on jet and b-tag multiplicities
  - Dilepton: 3 or ≥4 jets; 3 or ≥4 b-tags
  - Single lepton: 5 or ≥6 jets; 3 or ≥4 b-tags
    - Additionally, boosted region
- In signal regions, two multivariate discriminants employed:
  - **Reconstruction BDT** (resolved regions only): correctly assign jets to Higgs and top quarks, providing access to their four-vectors
  - **Classification BDT**: separate ttH signal from tt+jets background
- Profile-likelihood fit to extract signal strength
  - Scale factors for tt+c and tt+b and shape uncertainties on tt+jets modeling to accommodate known mismodeling

Region definition for CP-odd analysis

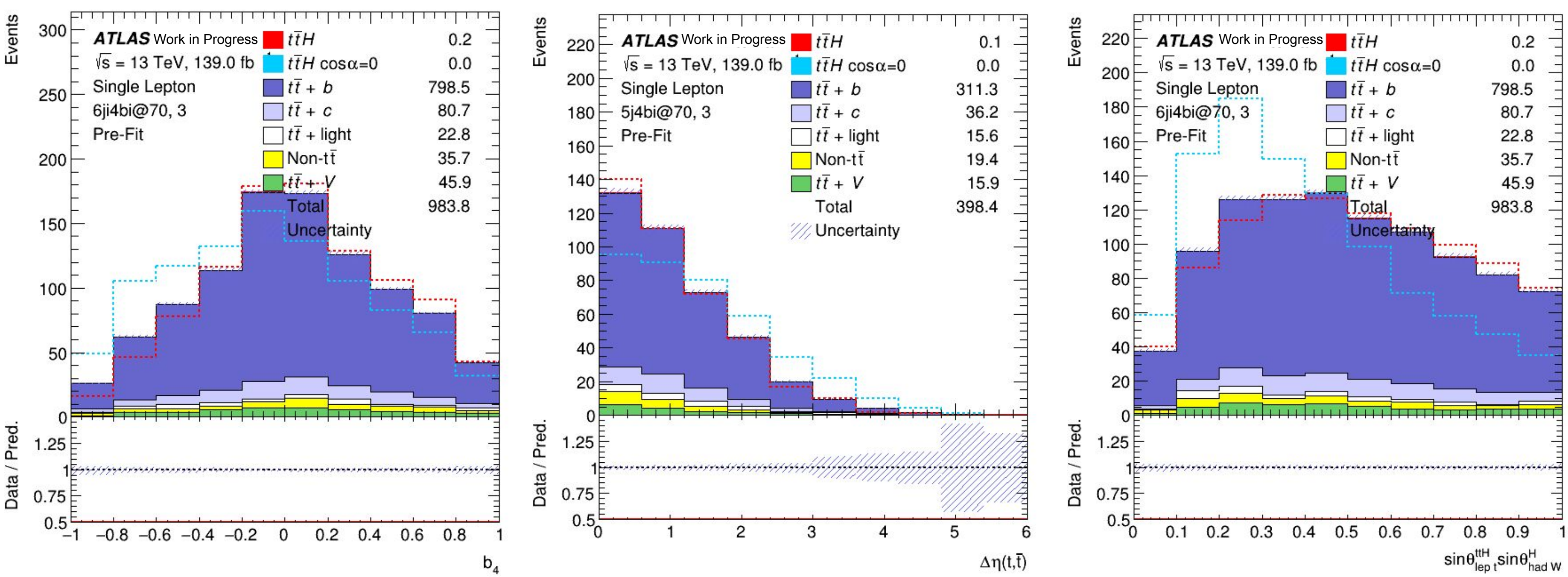
- Target high signal purity, taking advantage of **signal/background discriminant** (classification BDT)
- Introduce **CP discriminant**, simultaneously fit rate and CP-mixing angle
- Current strategy:
  - **Split 4b regions** based on classification BDT score
  - **Fit CP discriminant distribution** in each of the newly-defined regions
- **Will focus on single lepton today**
  - Collaborating closely with Manchester who are working on dilepton



5j:	**3b**	**≥4b, 1**	**≥4b, 2**	**≥4b, 3**
≥6j:	**3b**	**≥4b, 1**	**≥4b, 2**	**≥4b, 3**
	boosted			

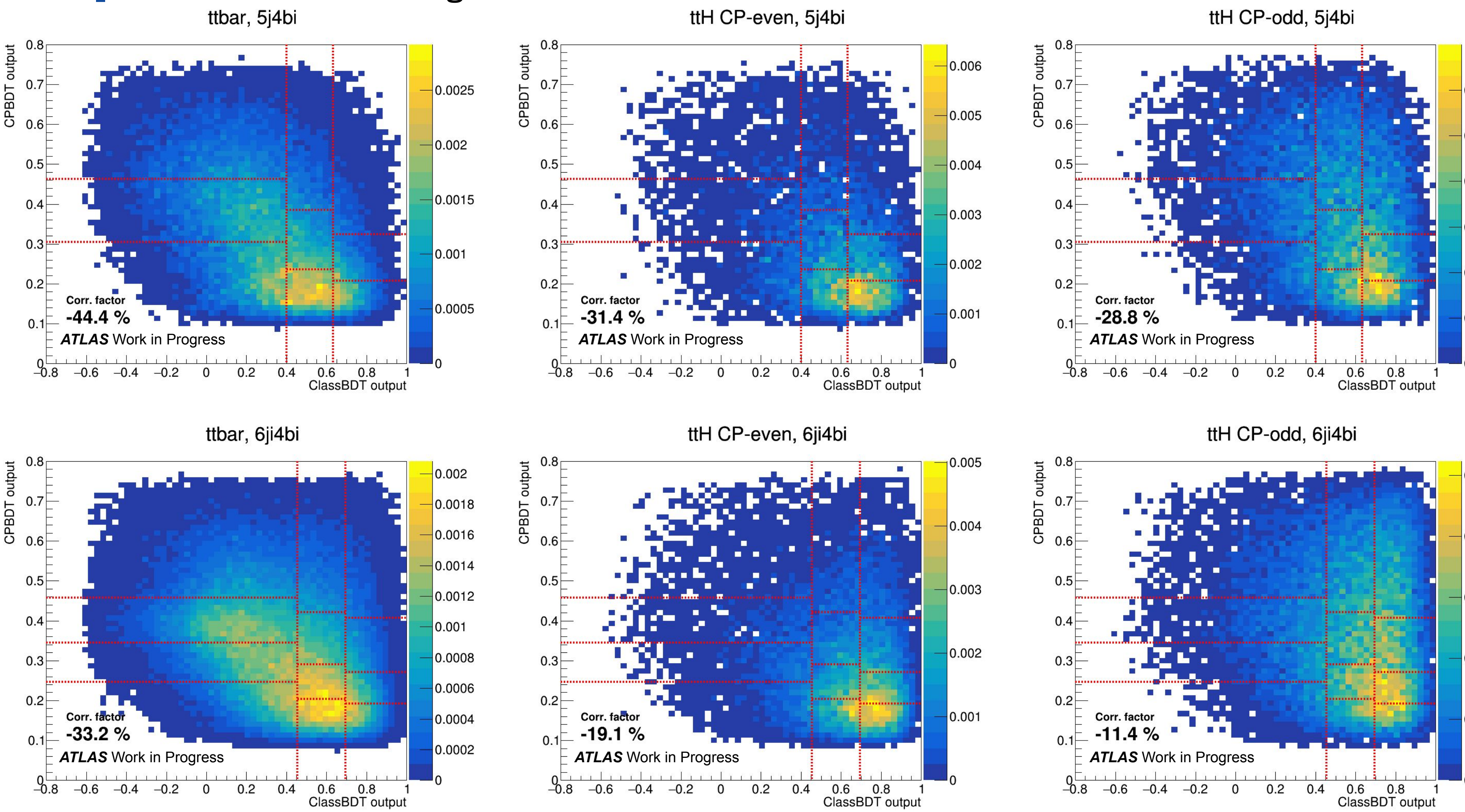
CP-sensitive variables

- Good news: ttH reconstruction in place → free access to tops, Higgs and their decay products
- Many variables checked for CP-even/odd separation
  - Input variables of reconstruction and classification BDTs
  - Higgs p_T, Δφ(t,tbar), Δη(t,tbar), m(ljjjjj), $b_4 = (p_t^z . p_{\bar{t}}^z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$
  - Angular observables in boosted reference frames



CP BDT

- New discriminant, CP BDT, trained to separate CP-even and CP-odd ttH signals



Fit setup

- Data and MC corresponding to full Run 2 luminosity (139 fb^{-1})
- Fitting **κ_t' and α** or **κ_t and $\tilde{\kappa}_t$**

$$\mathcal{L}_{tth} = y_t \bar{\psi}_t \kappa_t' (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t h$$
$$= y_t \bar{\psi}_t (\kappa_t + i\gamma_5 \tilde{\kappa}_t)\psi_t h$$

- Using 2 signal templates (CP-even and CP-odd) and interpolating as $\sigma = \kappa_t^2 \sigma_{even} + \tilde{\kappa}_t^2 \sigma_{odd}$
- Fitted distributions:
  - 3b regions: H_T^{jets}
  - 4b regions: CP BDT
  - boosted region: classification BDT

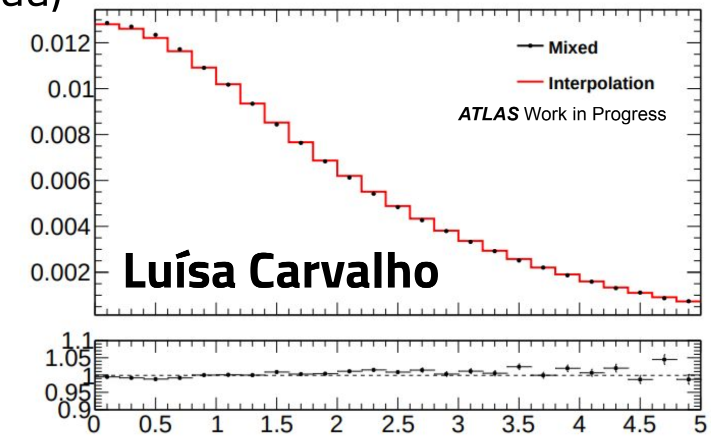
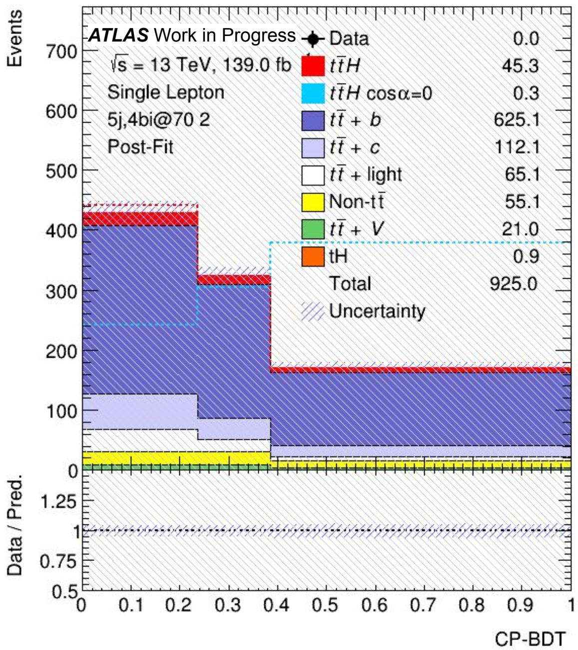
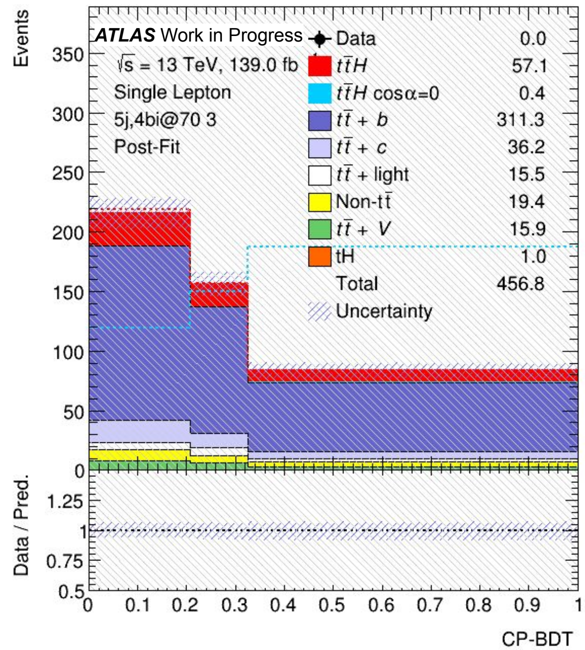


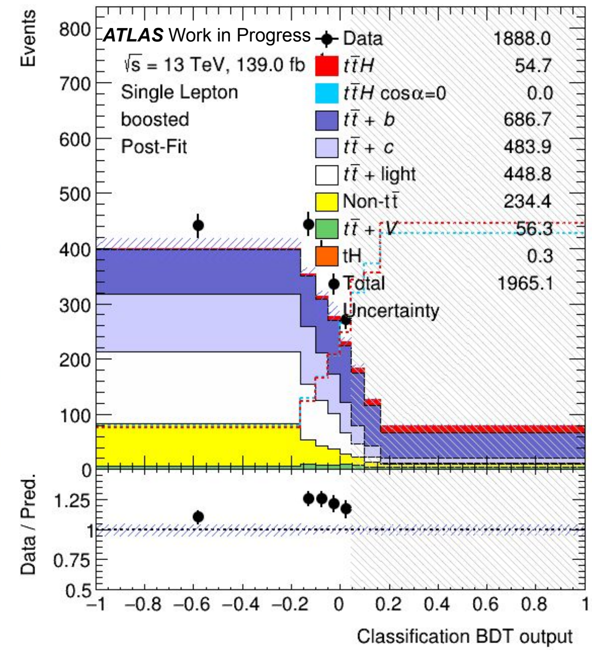
Figure: $\Delta\eta(tlep, thad)$

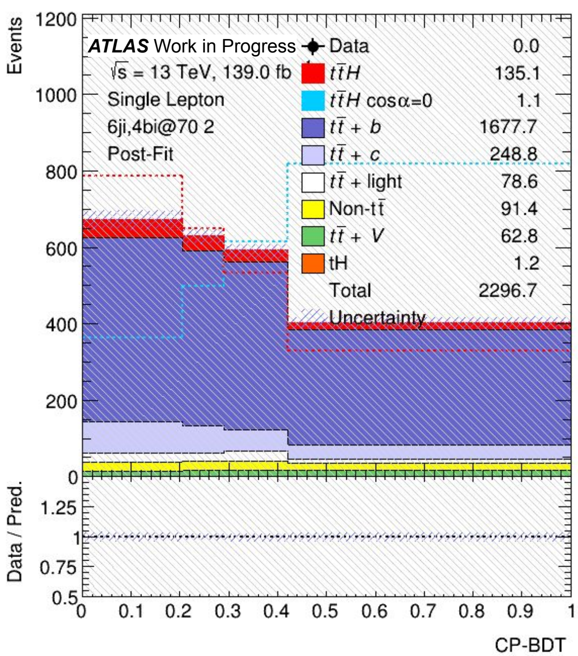
- **Complete systematics model**. Main components:
  - Theoretical: NLO gen. matching, parton shower and hadronisation, initial and final state radiation, de-correlated for tt+b, tt+c and tt+light
  - Experimental: b-tagging, jet energy scale

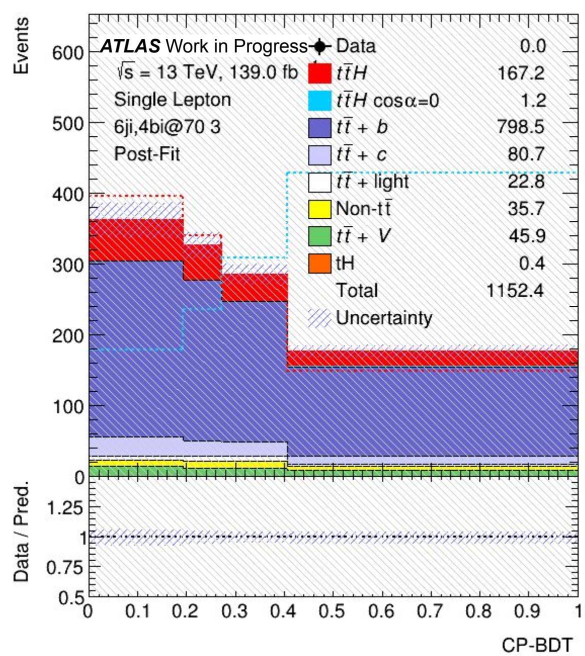
Signal regions (CP-even Asimov)







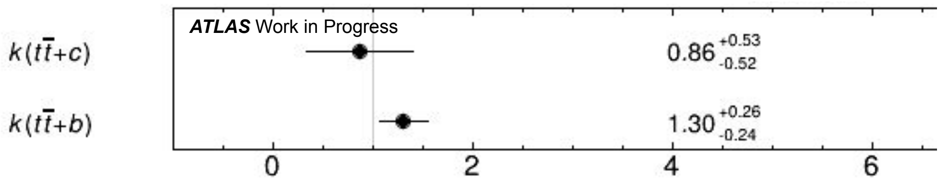


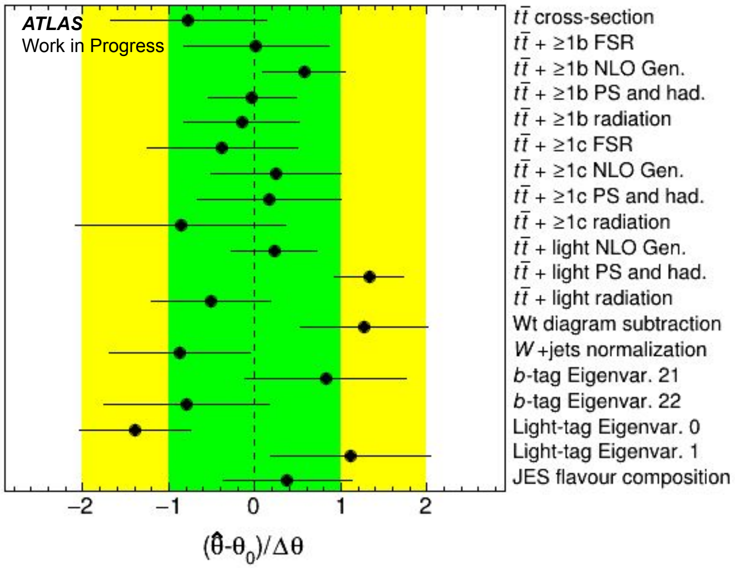


- No shape difference in boosted region, need to investigate CP-sensitive variables

Background-only fits to data

- Fit data in control regions under the background-only hypothesis
- Test flexibility of the model, check for large pulls and constraints





- Norm. factors for tt+b and tt+c and pulls of nuisance parameters consistent with SM analysis
- tt+light modeling and b-tag systematics pulled to correct mismodeling of tt+light
- Currently investigating fit model to understand these features and make sure the required degrees of freedom are included

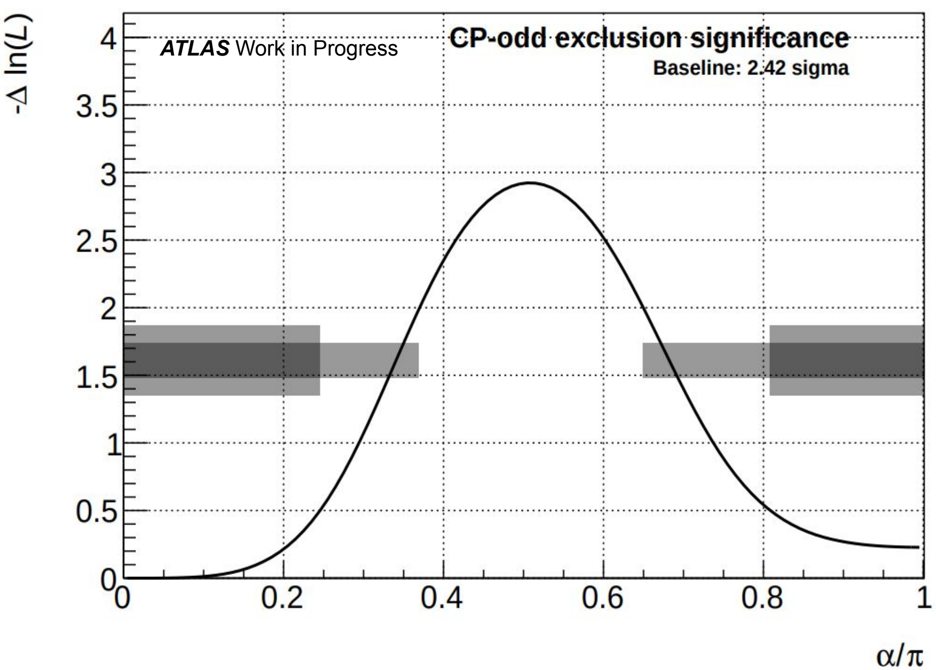
3.

Expected sensitivity

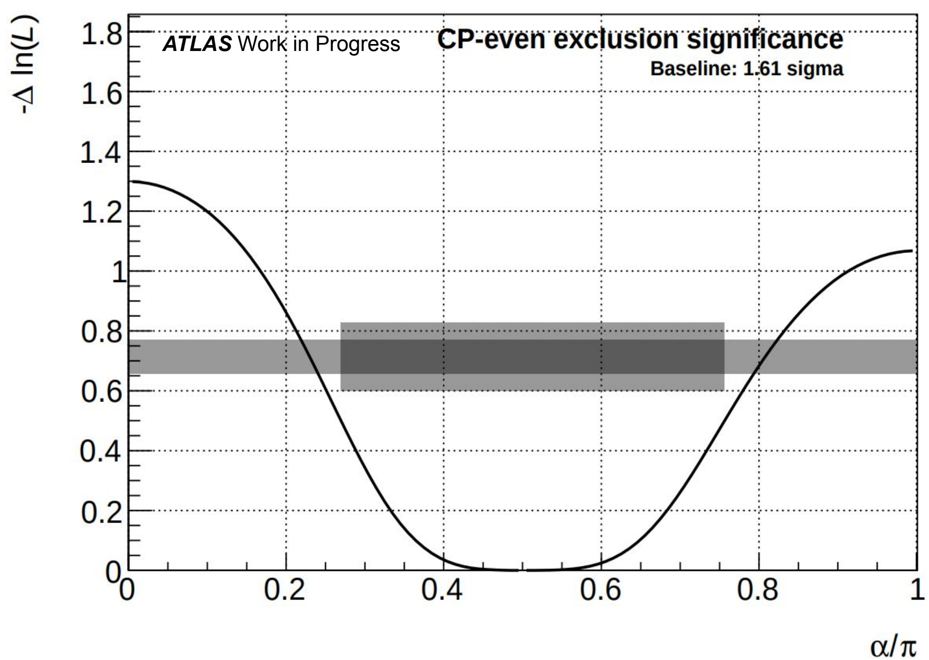
Full Run 2 (139 fb^{-1})

Expected sensitivity - 1D scan

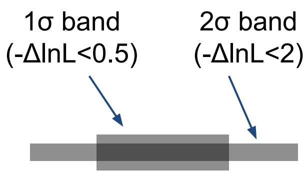
CP-even Asimov



CP-odd Asimov



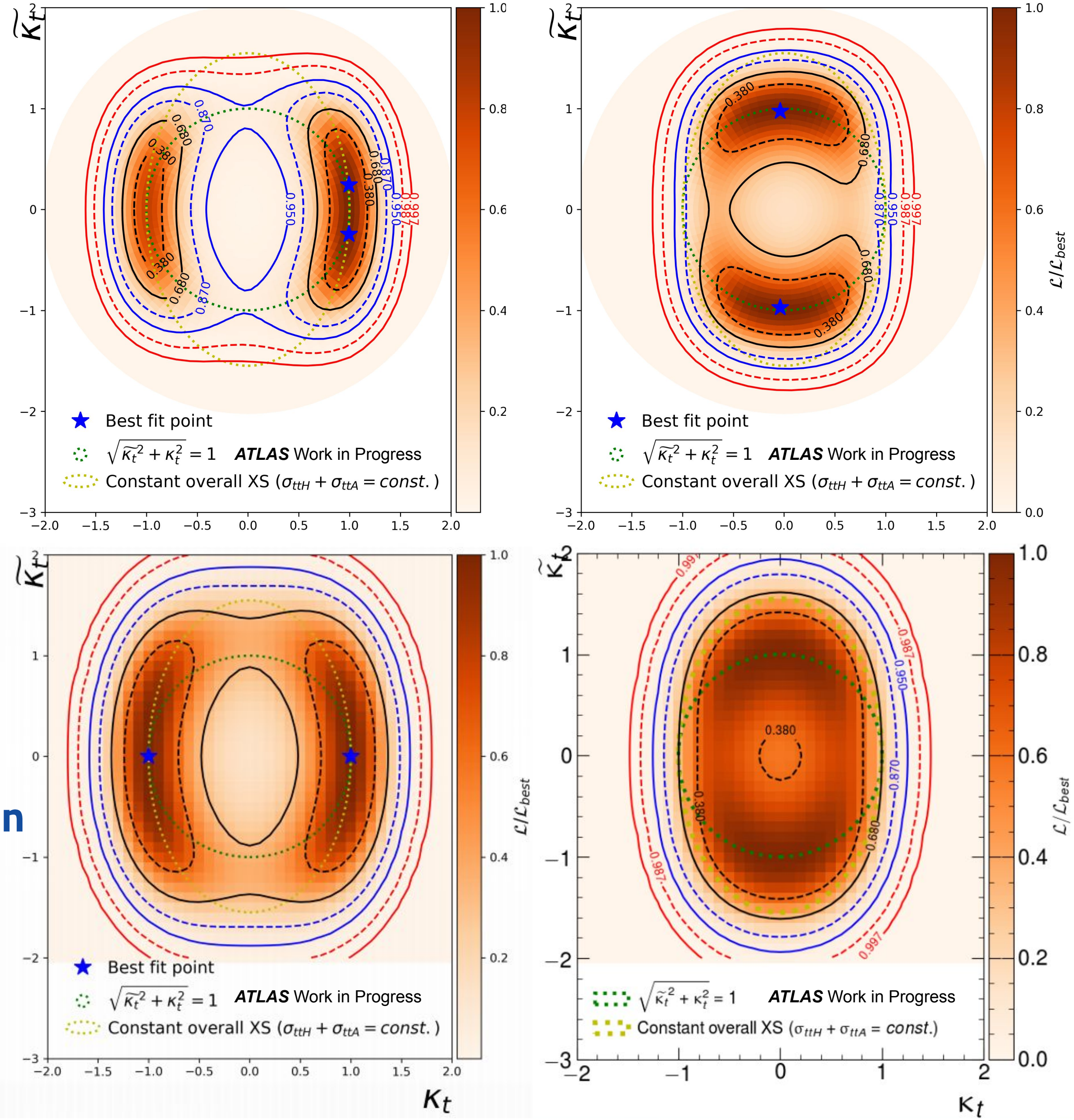
- CP-even Asimov: **2.42 σ** for CP-odd exclusion
- CP-odd Asimov: **1.61 σ** for CP-even exclusion



Expected sensitivity - 2D scans

CP-even Asimov | **CP-odd Asimov**

Single lepton / **Dilepton**



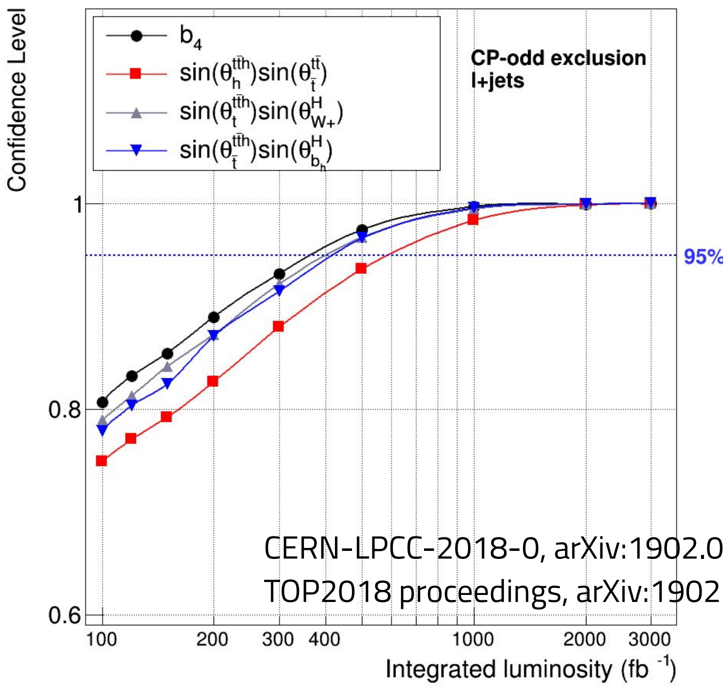
CP-even Asimov 68% CL intervals for $\tilde{\kappa}_t$

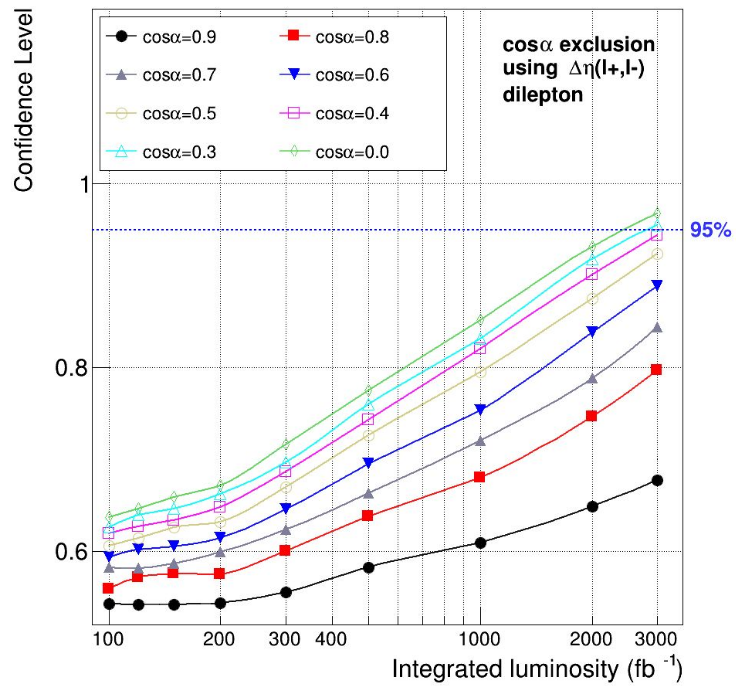
Single lepton:	[-0.83,0.84]
Dilepton:	[-1.17,1.17]
Combined:	**[-0.76,0.75]**

4.
Prospects for HL-LHC

Prospects for HL-LHC

- NLO samples (√s=13 TeV), fast detector simulation, select signal-rich region, full kinematical reconstruction
- Confidence level of CP-odd exclusion from as a function of luminosity





CERN-LPCC-2018-0, arXiv:1902.00134
TOP2018 proceedings, arXiv:1902.00298

- Good choice of observables could mean less few hundred fb^{-1} needed at HL-LHC to probe CP
- Mixed scenarios much harder to exclude than almost pure CP-odd

5.
Summary

Summary

- A source of CP violation in the Higgs sector could manifest itself in Yukawa couplings
  - **ttH production is the best direct probe to the largest** (top-quark) **Yukawa coupling**
- Implemented CP BDT to use as a discriminant, which includes input variables from phenomenology work @ LIP
- Fit model with complete set of systematics for single lepton, dilepton and combination, built "on top" of SM analysis
- Results in terms of $\boldsymbol{\kappa_t}$**' and** $\boldsymbol{\alpha}$ or $\boldsymbol{\kappa_t}$ **and** $\boldsymbol{\tilde{\kappa}_t}$
- **Analysis chain necessary for CP measurement in tt(H→bb) is in place, with expected exclusion of CP-odd at 2.4σ in single lepton alone**
- Fits to data under background-only hypothesis show large pulls

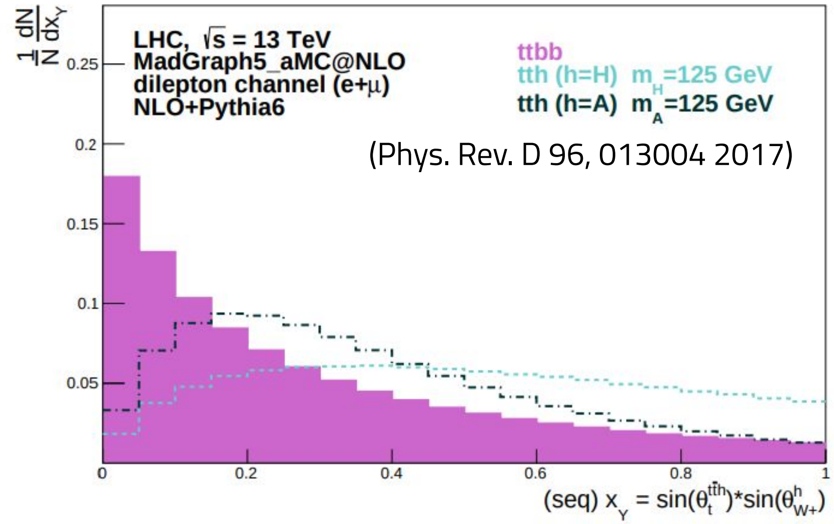
Next steps

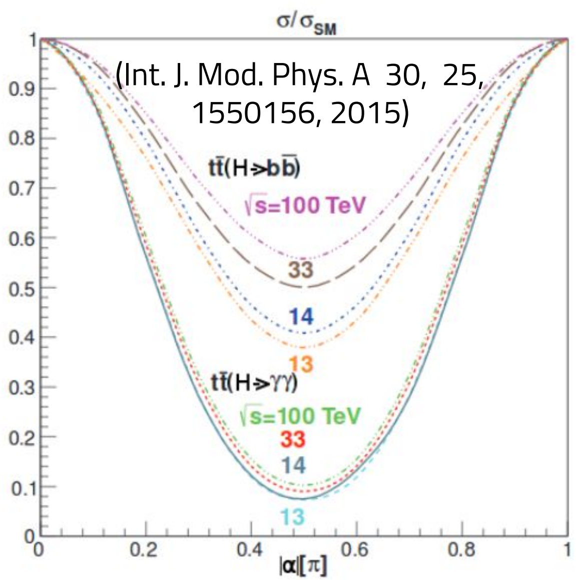
- Improve tt+jets modeling and systematics→common effort with SM analysis
- Re-train SM analysis multivariate discriminants, with a CP-even+CP-odd mixture as signal sample
- Re-optimize region definition and CP BDT
- Thesis writing until next summer

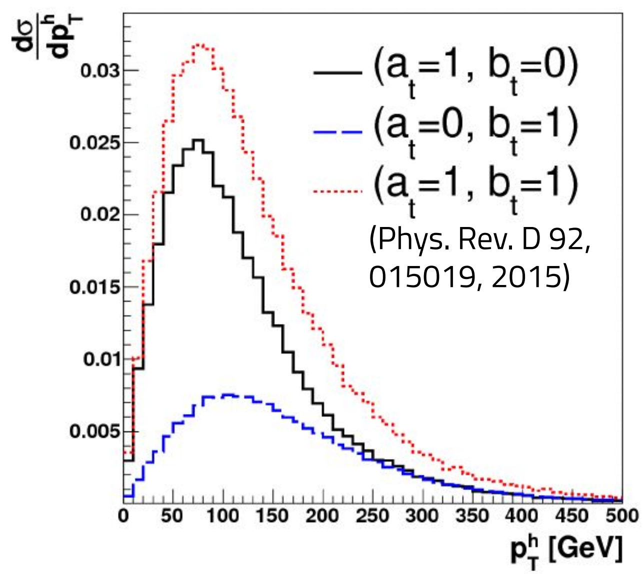
Thank you!

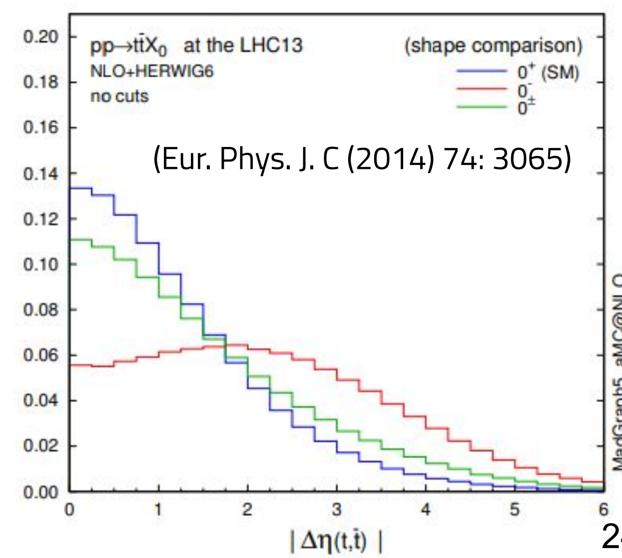
What is different in CP-odd ttH?

- Lower inclusive cross-section
- Higher Higgs p_T
- Top quarks much farther from each other in η and closer in φ
- Different angles measured in boosted rest frames

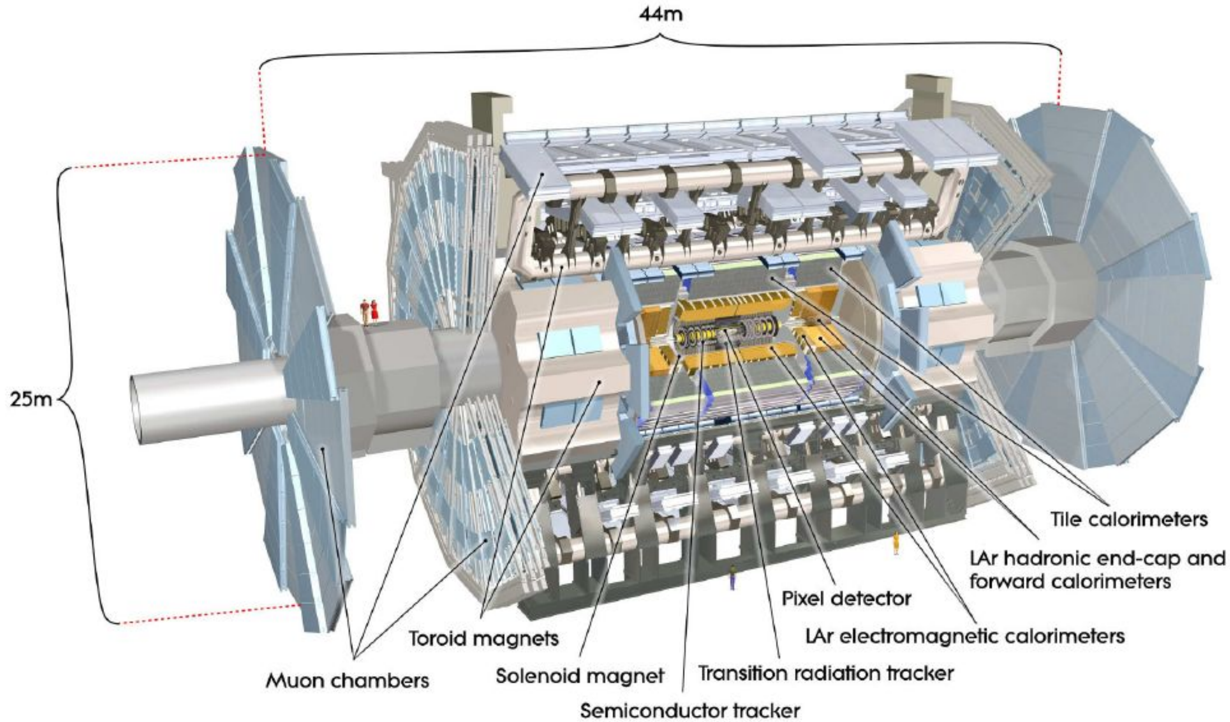








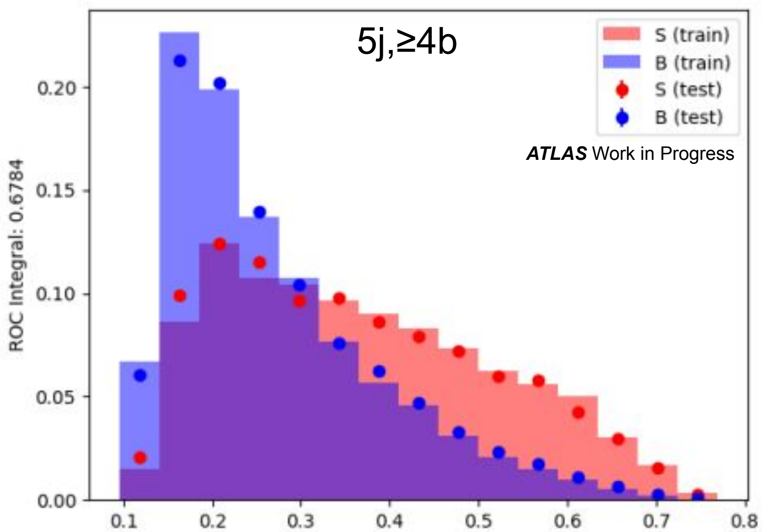
ATLAS detector

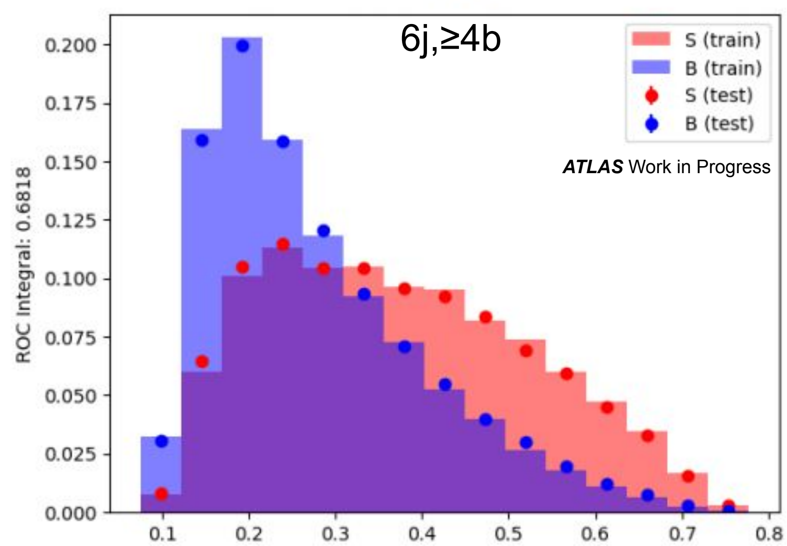


- General purpose detector at the LHC
- Magnetic fields: inner solenoidal field and outer toroidal field
- Inner tracker, electromagnetic calorimeter, hadronic calorimeter and muon spectrometer
- Reconstruction and identification of leptons, photons, missing transverse energy and hadronic jets, which can be “b-tagged” (identified as resulting from b-quark hadronisation)
- Trigger system: filter up to 40 MHz of collision rate down to ~1.5 kHz, a rate manageable for storage

CP BDTs

- Trained BDTs to separate **CP-even ttH** from **CP-odd ttH**
- Trained separately in 5j,≥4b and ≥6j,≥4b
- Start with many variables, remove one by one and check that performance is not significantly affected
- Ended with 12 inputs for 5j and 15 inputs for ≥6j (full list in backup)

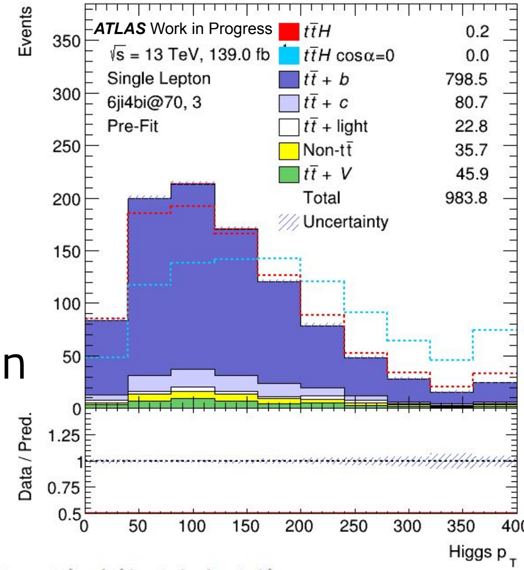


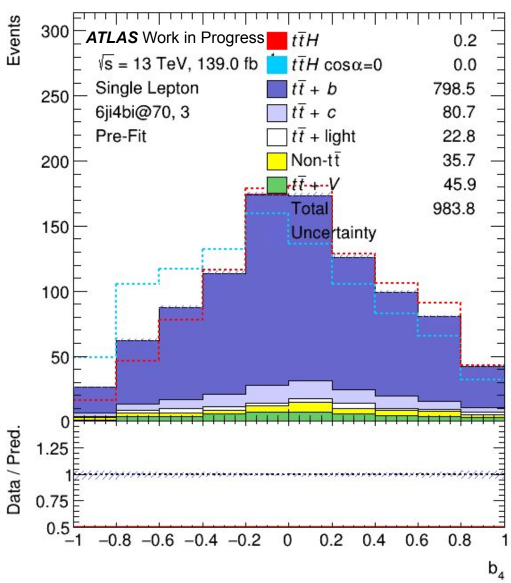


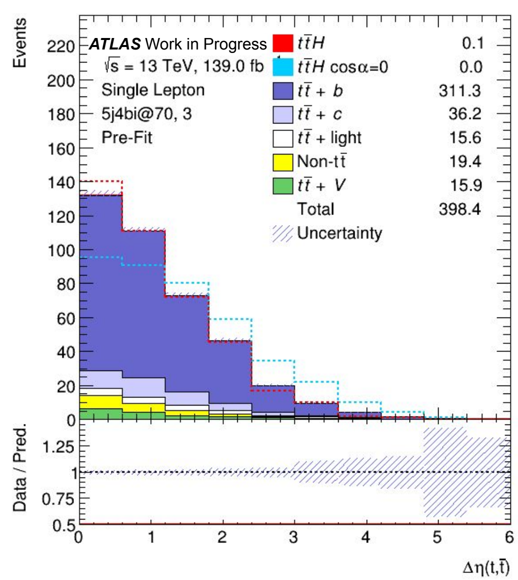
Dan Mori

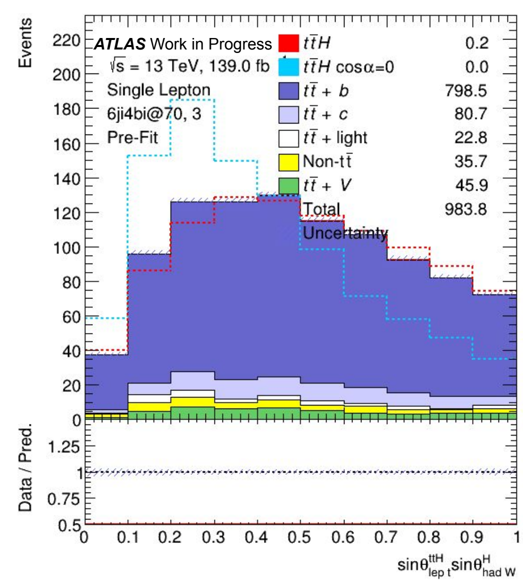
CP-sensitive variables

- Good news: ttH reconstruction in place → free access to tops, Higgs and their decay products
- Many variables checked for CP-even/odd separation
  - Input variables of reconstruction and classification BDTs
  - Higgs p_T, Δφ(t,tbar), Δη(t,tbar), m(ljjjjj), $b_4 = (p_t^z . p_{\bar{t}}^z)/(|\vec{p}_t| . |\vec{p}_{\bar{t}}|)$
  - Angular observables in boosted reference frames









CP BDT 5j inputs

$\Delta\eta_{bb}^{\max\Delta\eta}$

$\Delta\eta_{jl}^{\max\Delta\eta}$

m_{ljjjjj}

$m_{bb}^{\max p_T}$

$m_{bb}^{\min\Delta R}$

$\Delta\phi_{t\bar{t}}$ (TTHReco)

$\Delta R_{H,leptop}$ (TTHReco)

$m_{H,b_{leptop}}$ (TTHReco)

$\Delta\eta_{t\bar{t}}$ (TTHReco)

$\sin(\theta_{l/q1(A)}{}^{H})$

$\sin(\theta_{t(B)}{}^{ttH})\sin(\theta_{b(A)}{}^{H})$

$\sin(\theta_{lep.\ t}{}^{ttH})\sin(\theta_{lep}{}^{H})$

CP BDT 6j inputs

$\Delta\eta_{bb}^{\max\Delta\eta}$

$\Delta\eta_{jl}^{\max\Delta\eta}$

m_{ljjjjj}

$m_{bb}^{\max p_T}$

$m_{bb}^{\max m}$

$\Delta\phi_{t\bar{t}}$ (TTHReco)

b_4^{ll} (TTHReco)

$\Delta\eta_{t\bar{t}}$ (TTHReco)

$\Delta R_{b1H,bhadtop}$ (TTHReco)

$\Delta R_{b1H,lep}$ (TTHReco)

p_T^{Higgs} (TTHReco)

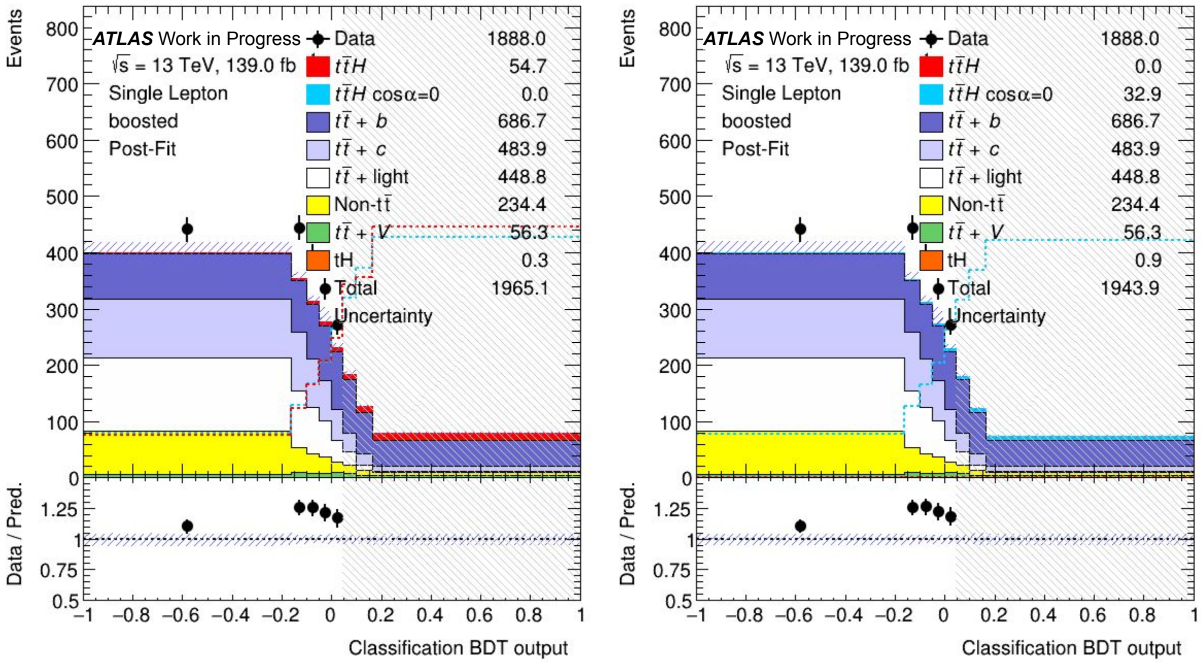
$m_{lepW,bhadtop}$ (TTHReco)

$\sin(\theta_{t(B)}{}^{ttH})\sin(\theta_{b(A)}{}^{H})$

$\cos(\theta_{b1(H)}{}^{t(A)})\cos(\theta_{b2(H)}{}^{t(A)})$

$\sin(\theta_{lep.\ t}{}^{ttH})\sin(\theta_{W(had.\ t)}{}^{H})$

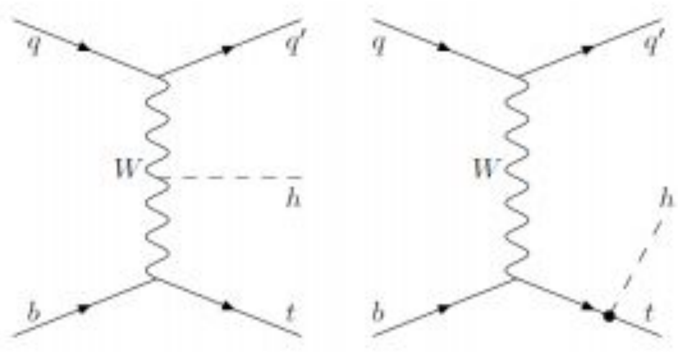
Boosted region

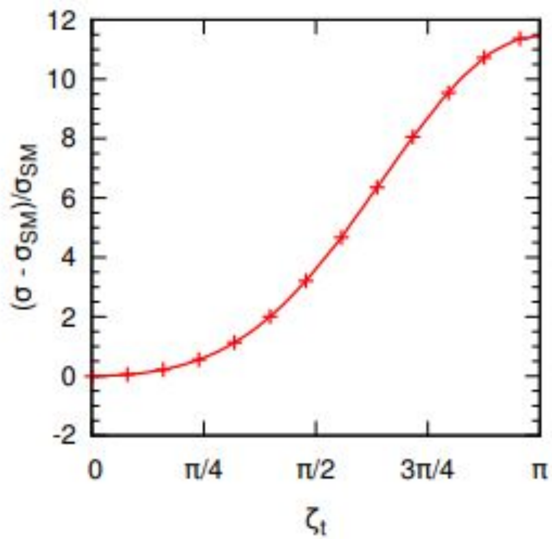


- No shape difference between CP-odd and CP-even, to investigate CP-sensitive variables in this region

tH and CP-odd ttH coupling

- Large destructive interference in SM
- Great cross-section enhancement as we move through CP-even -> CP-odd -> CP-even negative coupling
- Unlike ttH, for which cross-section decreases
- tH region in ttH(bb) fit could add constraining tension





arXiv:1605.03806

Next steps

- Improve morphing of tH sample templates
- Study CP discriminant for boosted region
- Get better understanding of tt+jets mismodeling → common effort with SM analysis
    - Apply corrections to improve pre-fit data/MC agreement
    - Introduce degrees of freedom in the fit to account for it
- Validate data/MC of CP BDT inputs
- Perform more fits to data and pseudo-data to gain confidence in the fit model before unblinding
- Re-train reconstruction and classification BDTs, with a CP-even+CP-odd mixture as signal sample
- Re-optimize region definition and CP BDT