Constraining CP of Higgs-top coupling

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UC/LIP

HTop Workshop 2020

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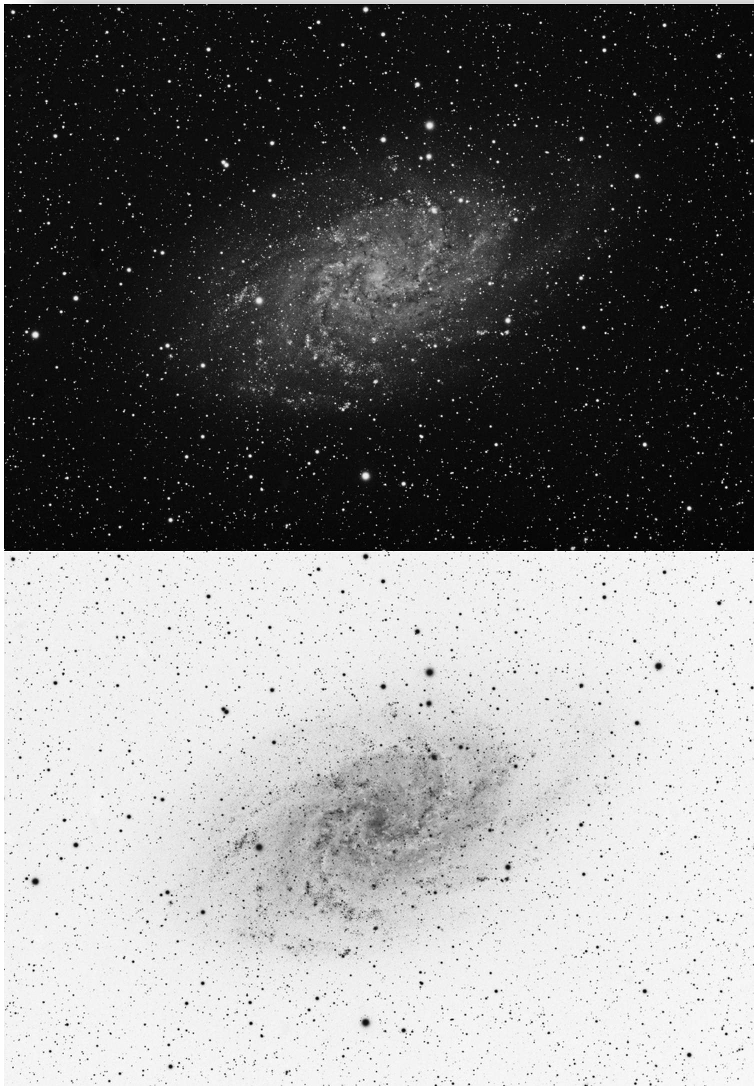
ATLAS EXPERIMENT

FCT Fundação para a Ciência e a Tecnologia

Outlook:

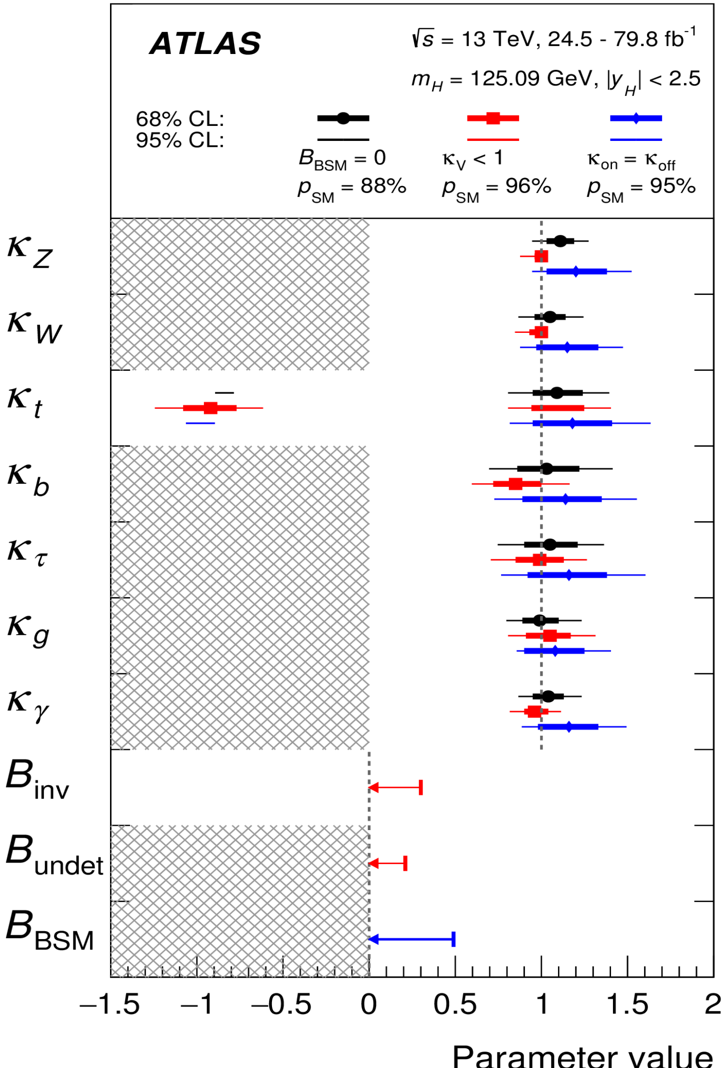
- Why constrain the CP quantum numbers of the ttH vertex?
- Recent results from ATLAS and CMS
- What’s our next step?
  - The ttH(H→bb) analysis
- HL-LHC extrapolations
- Conclusions

Why constrain CP of Higgs-top coupling?



- The violation of CP symmetry is our best explanation for a matter-dominated universe
  - Sakharov's conditions for baryogenesis
- But not enough known sources of CP violation
- Does the Higgs sector play a role here?
  - "Higgs-genesis"!! ☺
  - Needs CP-odd admixture
  - Higgs not necessarily a CP eigenstate (e.g. C2HDM)

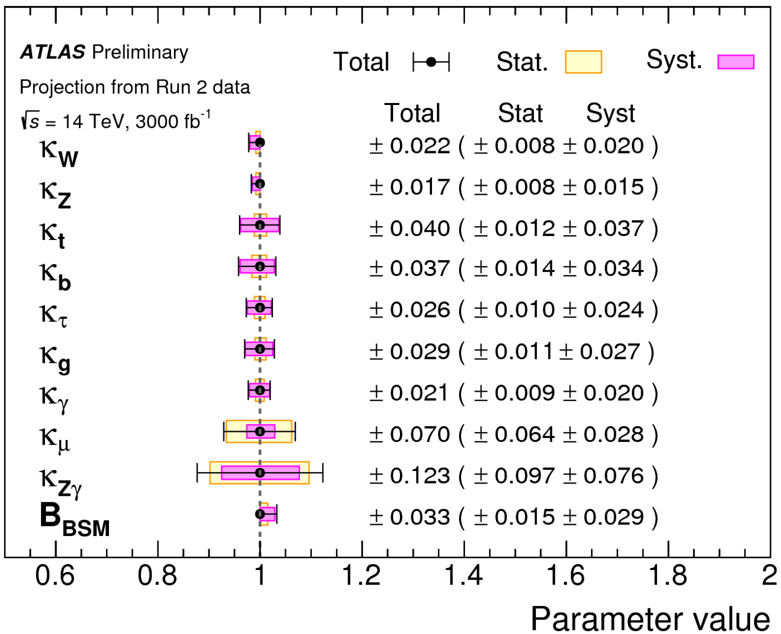
Why constrain CP of Higgs-top coupling?



- 8 years after Higgs discovery
  - Higgs mass known to $^o/_{oo}$ level
  - Bosonic couplings known to ≈10%
  - Fermionic couplings known to ≈20%
  - Not pure CP-odd ($J^{CP} = J^{+-}$)

- Looks a lot like SM Higgs!
  - But CP-odd admixture is possible
  - How would we know?
  - CP-odd mixture in bosonic couplings are suppressed
  - Need to look at Yukawa couplings in detail
  - Space for surprises...

Why constrain CP of Higgs-top coupling?



ATL-PHYS-PUB-2018-054

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  - Fermionic couplings known to ≈20%
  - Not pure CP-odd ($J^{CP} = J^{+-}$)

- Looking ahead...
  - Expect ≈2-3% uncertainties in couplings with full HL-LHC lumi
  - Fighting systematic uncertainties all the way
  - Progress will be essential but not fast
  - But more detailed observables can now be reached – **CP of ttH**!

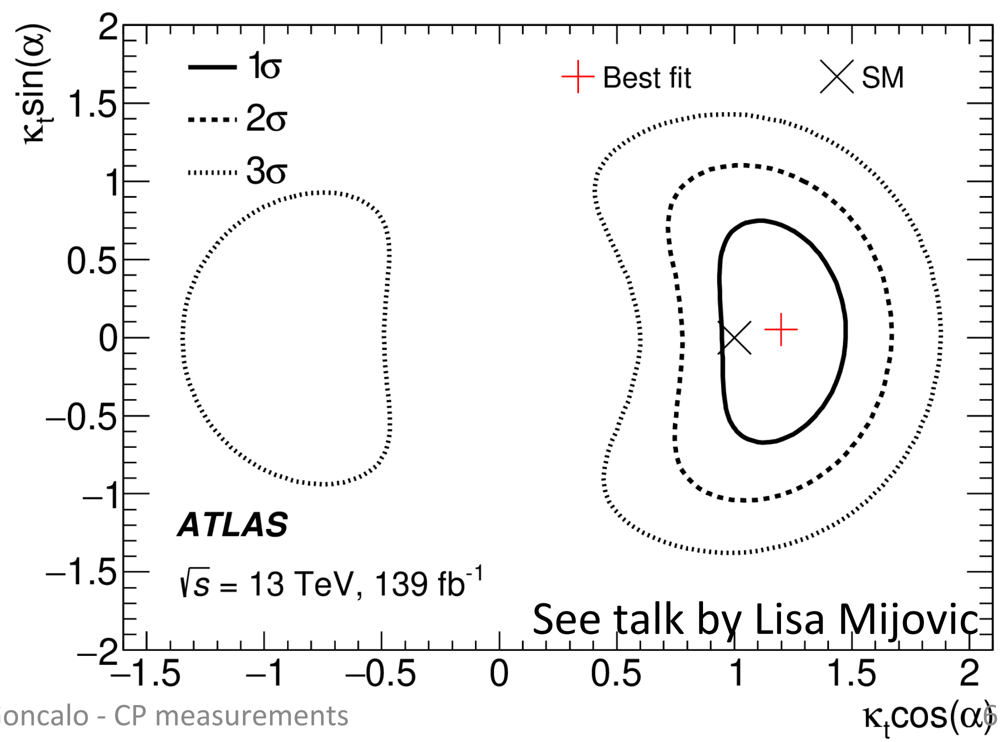
What do we want to measure?

- Generalized Lagrangian gets a new CP-odd term and a mixing angle to allow non-pure CP Yukawa interactions

$$\mathcal{L}_{tth} = y_t \bar{\psi}_t \kappa'_t \left(\boxed{\overset{\text{CP even}}{\cos\alpha}} + \boxed{\overset{\text{CP odd}}{i\gamma_5 \sin\alpha}} \right) \psi_t h$$
$$= y_t \bar{\psi}_t \left(\boxed{\kappa_t} + \boxed{i\gamma_5 \tilde{\kappa}_t} \right) \psi_t h$$

- Two parametrizations: κ'_t and α mixing angle, **or** real and imaginary coefficients κ_t and $\kappa_t^{\sim}$

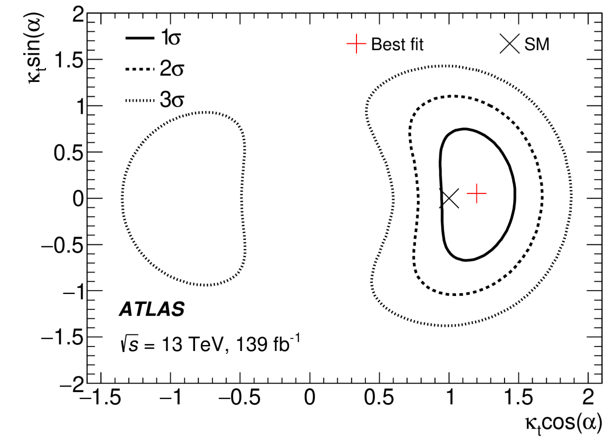
- Next we need observables sensitive to these parameters

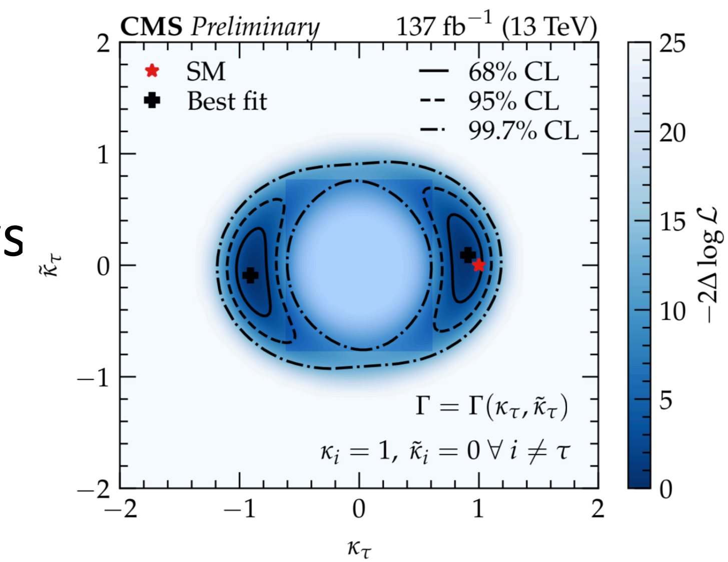


See talk by Lisa Mijovic

Recent measurements

- ATLAS:
  - CP-mixing angle > 43° excluded @95%
  - Pure CP odd excluded with 3.9(2.7)σ
    - Phys. Rev. Lett. 125 (2020) 061802
    - See Lisa Mijovic's talk on
- CMS:
  - CP-odd model of Htt coupling excluded at 3.2σ
    - PRL 125 (2020) 061801
  - CP of τ Yukawa coupling in H→ττ decays
    - CP-odd excluded with 3.2σ (2.3 exp.)
    - CMS_PAS_HIG_20_006

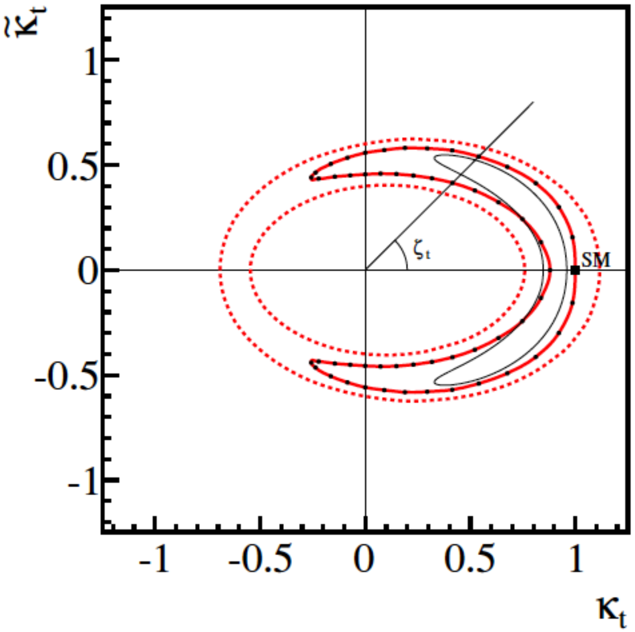




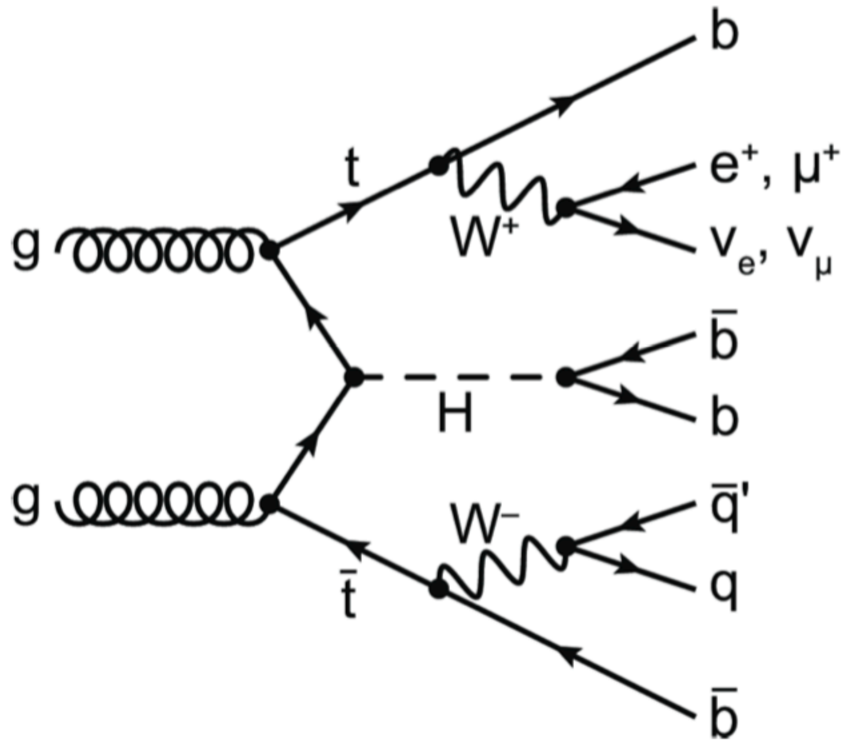
Also more indirect constraints

- Electron and neutron EDM able to constrain mixing angle
- Personal bias: nothing beats a direct measurement...

JHEP04(2014)004



ATLAS ttH→bb Analysis

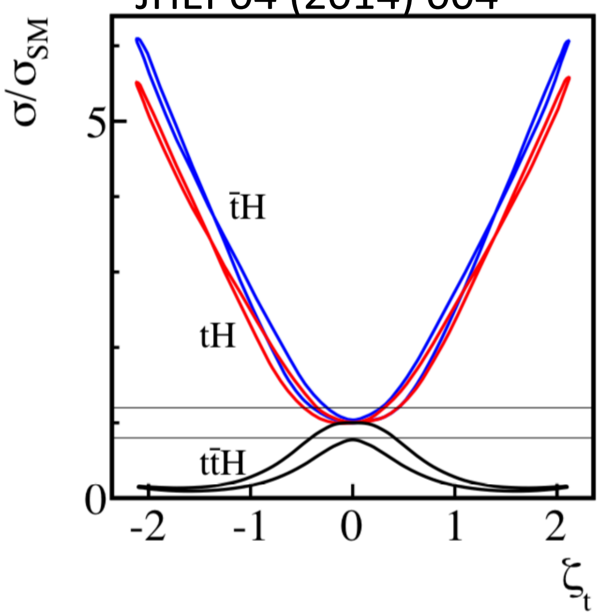


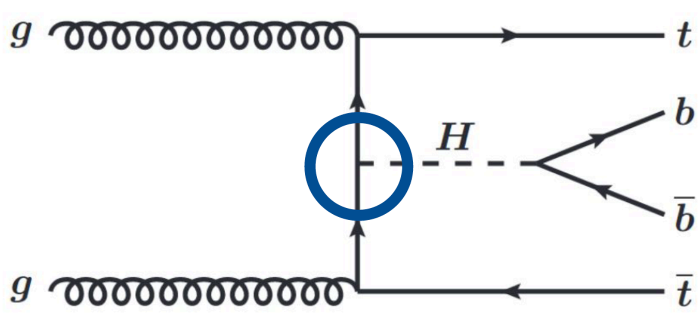
Showing work by: Emanuel Gouveia, Nicolas Schamberg, Luís Coelho, Brian Le, Zak Lawrence, Ana Luísa Carvalho Ricardo Gonçalo, António Onofre, Yvonne Peters, Ian Conelly, Daniel Mori, Yang Qin

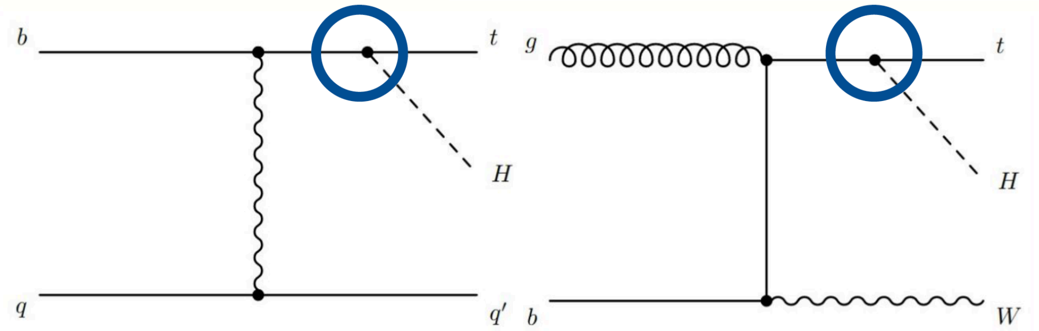
ATLAS ttH→bb Analysis

- Follows the inclusive ttH(bb) analysis closely
  - See talk by Jelena Jovicevic
- Single-lepton and dilepton channels
- Full Run-2 dataset: 139 fb^{-1}
- Sensitive to **ttH** and **tH** production
- tH cross section is low and ttH drives analysis selection, but
  - tH cross section varies strongly with α

JHEP04 (2014) 004







Signal modeling for intermediate α and κ'$_t$

- Monte Carlo available for a few κ'$_t$ and α points

- ttH: weighted sum of CP-even and CP-odd samples per bin, according to:

$$y(\kappa_t, \tilde{\kappa}_t) = \kappa_t^2 y_{\text{even}} + \tilde{\kappa}_t{}^2 y_{\text{odd}}$$

  – Validated at truth-level in both channels (single lepton and dilepton) using many different variables
  – Means that interference between CP-even and CP-odd components is neglegible

- tH: destructive interference means large dependence of cross-section on κ'$_t$ and α
  – Parameterized separately for tHjb and tWH:

$$\frac{y(\kappa_t, \tilde{\kappa}_t)}{y_{\text{even}}} = A\kappa_t^2 + B\tilde{\kappa}_t{}^2 + C\kappa_t + D\tilde{\kappa}_t + E\kappa_t\tilde{\kappa}_t + F$$

  – Coefficients from fitting the MC samples to samples generated for different κ'$_t$ and α

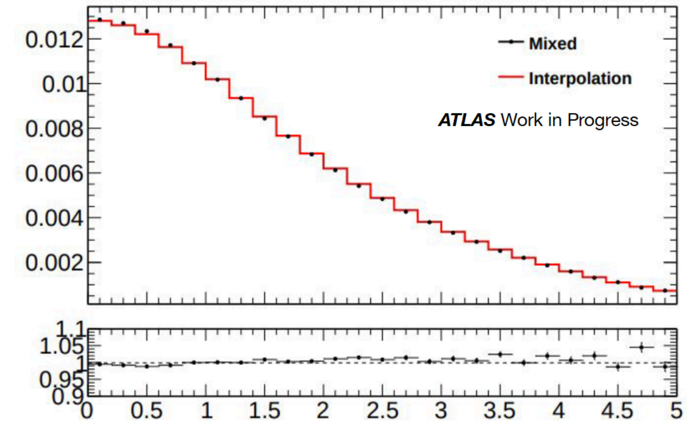
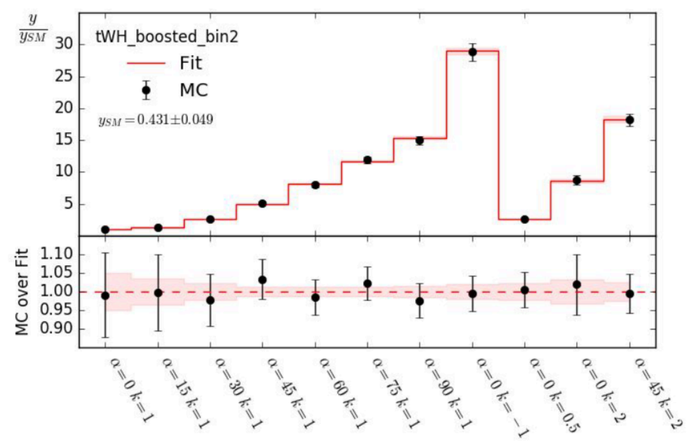
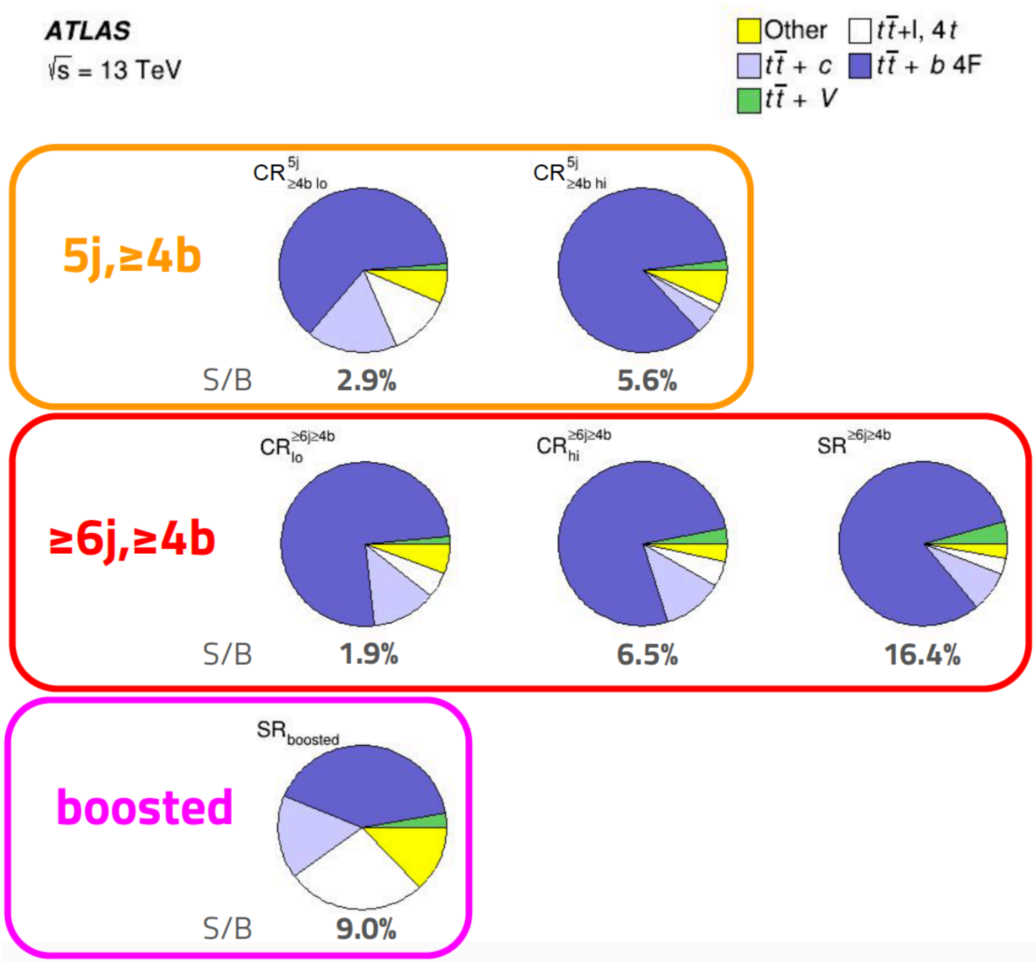


Figure: $\Delta\eta(tlep, thad)$



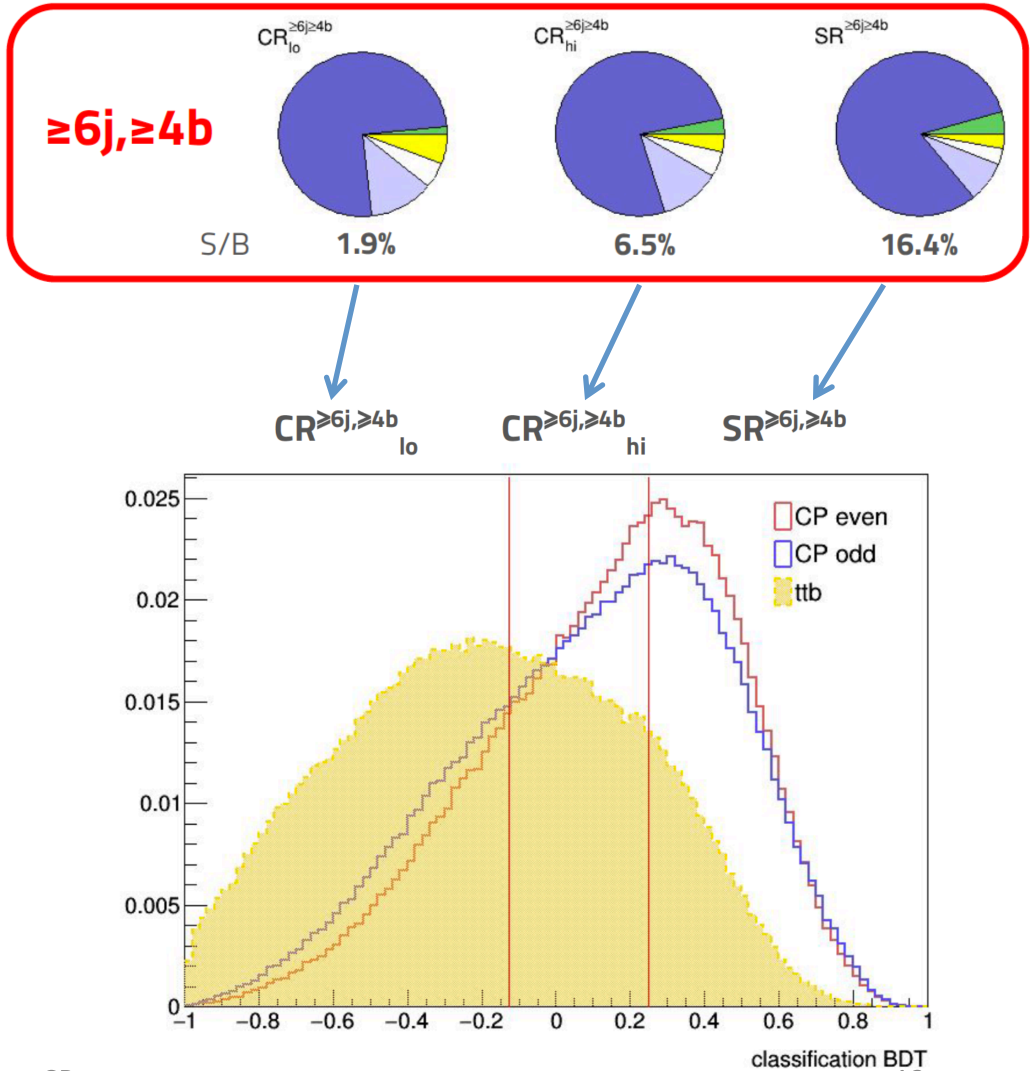
Single lepton channel: event selection



Region	Selection	Fitted variable
$CR^{5j,\geq4b}_{lo}$	=5j, ≥4b@70 (<4b@60)	ΔR(bb)
$CR^{5j,\geq4b}_{hi}$	=5j, ≥4b@60	
$CR^{\geq6j,\geq4b}_{lo}$	≥6j, -1<BDT<-0.13	$b_2^{tth}(tt)$
$CR^{\geq6j,\geq4b}_{hi}$	≥6j, -0.13<BDT<0.25	
$SR^{\geq6j,\geq4b}$	≥6j, 0.25<BDT<1	
$SR_{boosted}$	≥6j, ≥3b@85, ≥1 Higgs	boosted BDT

Single lepton channel: analysis strategy

- 6-jet, 4-b region separated into control and signal regions based on the **classification BDT** output
- Fit a **CP discriminant** in resulting region
- Replaced with highest-ranked variable (b_2) with very small loss
- Boosted region adds sensitivity because Higgs p_T distribution depends on CP



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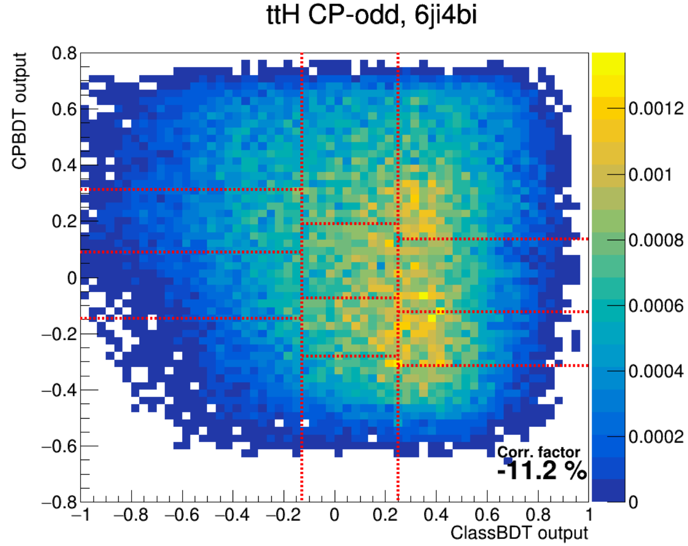

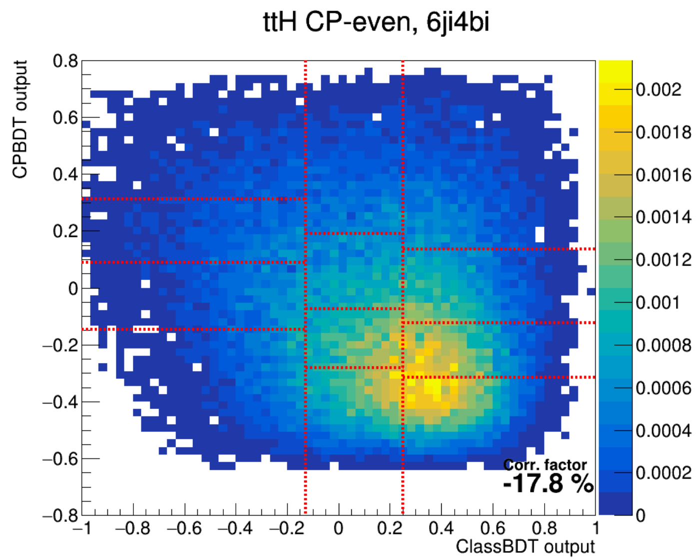

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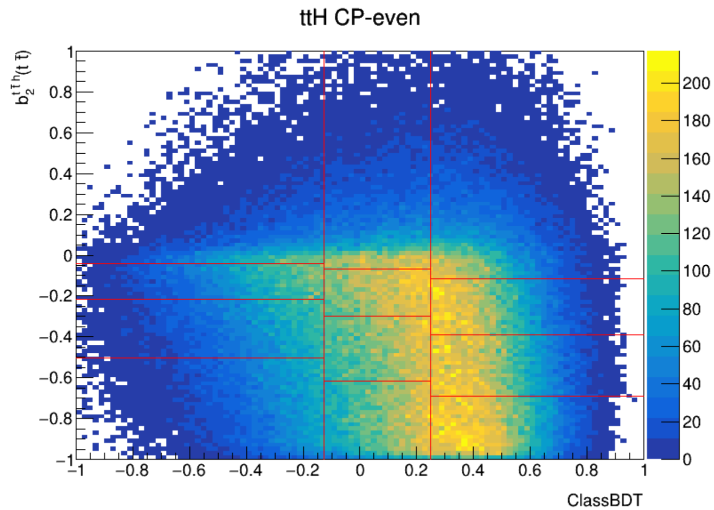
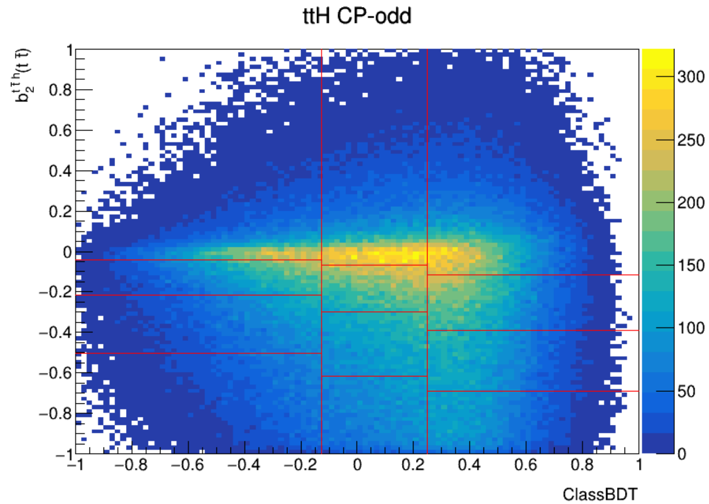
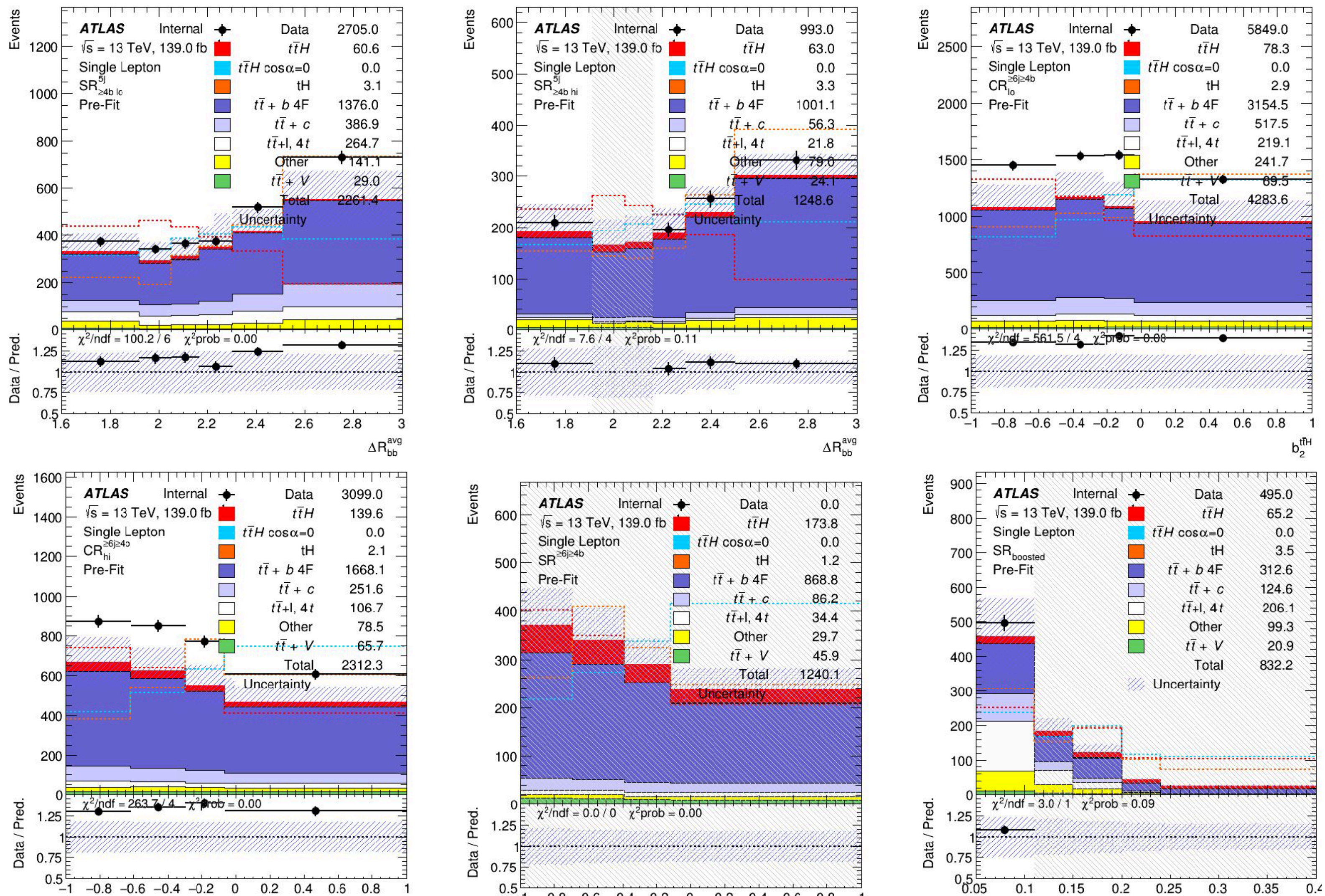
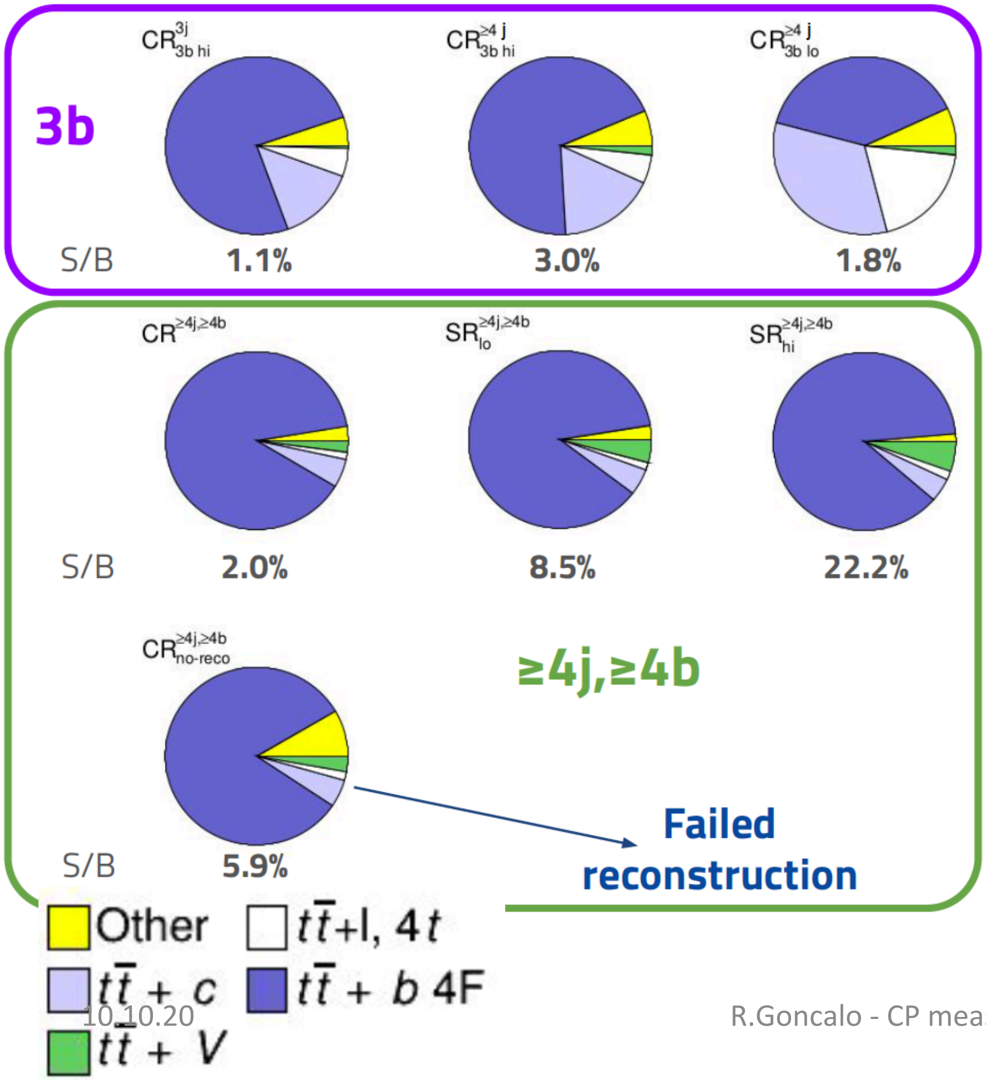




Input distributions



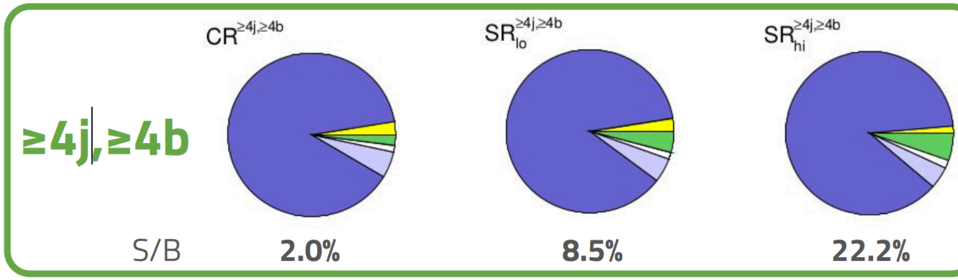
Dilepton channel: event selection

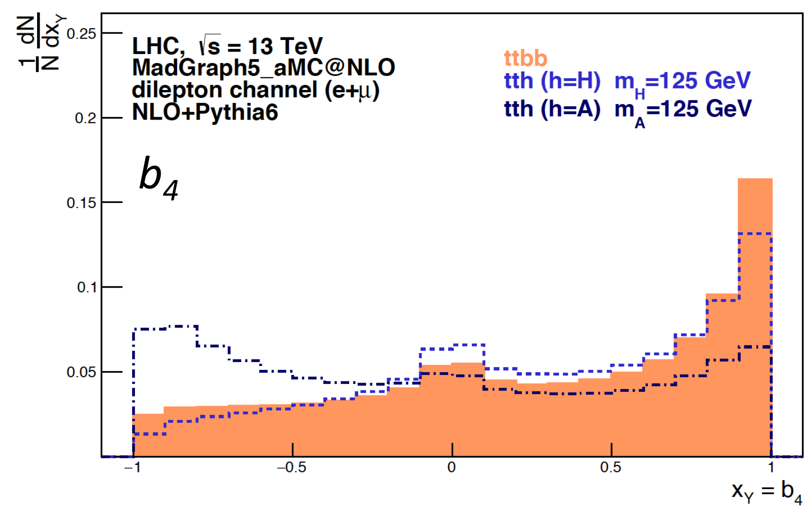


Region	Selection	Fitted Variable
$CR^{3j,3b}_{hi}$	=3j, =3b@60	Yield
$CR^{\geq 4j,3b}_{lo}$	≥4j, =3b@60	
$CR^{\geq 4j,3b}_{hi}$	≥4j, =3b@70 (<3b@60)	
$CR^{\geq 4j,\geq 4b}$	-1.0<BDT<-0.0862 Events Reconstructed	CP-BDT
$SR^{\geq 4j,\geq 4b}_{lo}$	-0.0862<BDT<0.1862 Events Reconstructed	
$SR^{\geq 4j,\geq 4b}_{hi}$	0.1862<BDT<1.0 Events Reconstructed	
$\Delta\eta_{ll}$	BDT > -1.0 Events Unreconstructed	$\Delta\eta_{ll}$

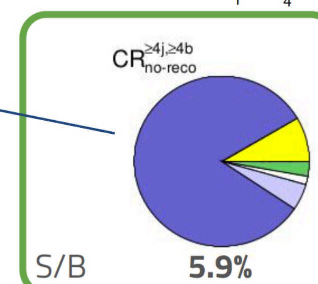
Dilepton channel: analysis strategy

- Again, reconstructed events are separated into regions defined by classification BDT output
- In each regions, fit CP-BDT – large sensitivity loss when using highest ranked discriminants
- Inputs to CP-BDT include angles between reconstructed particles in various rest frames
  - From PRD 96 (2017) 1, 013004
- Event reconstruction fails in a few events
  - Fit $\Delta\eta(l^+,l^-)$ – highest-ranked variable in original CP-BDT





Failed reconstruction



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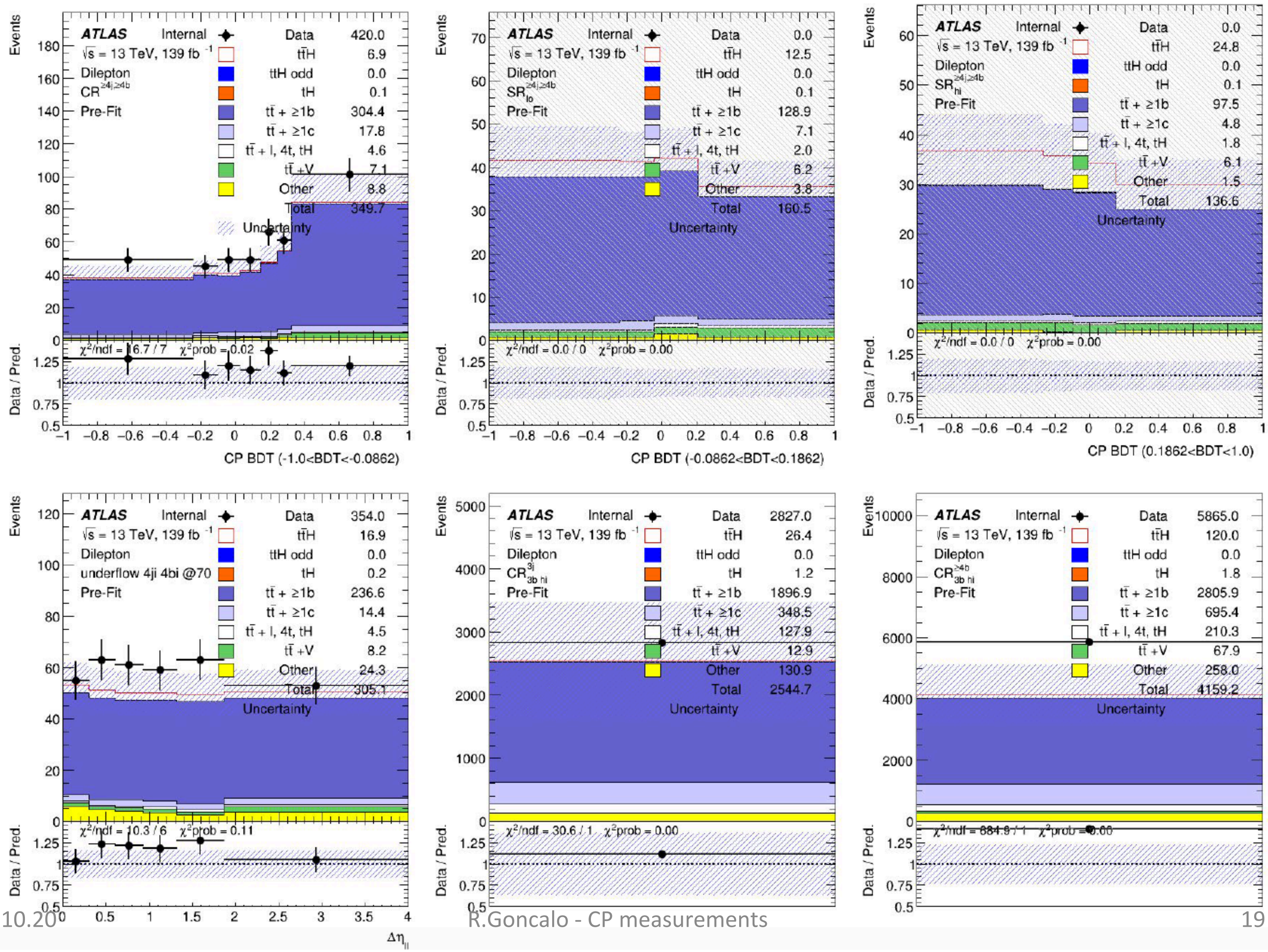
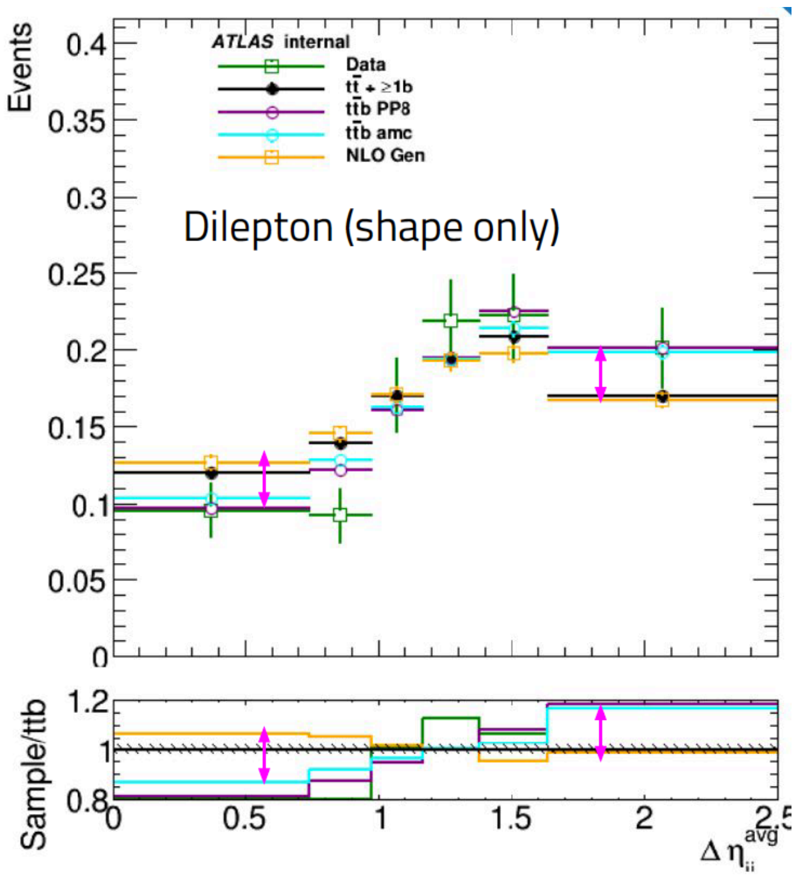


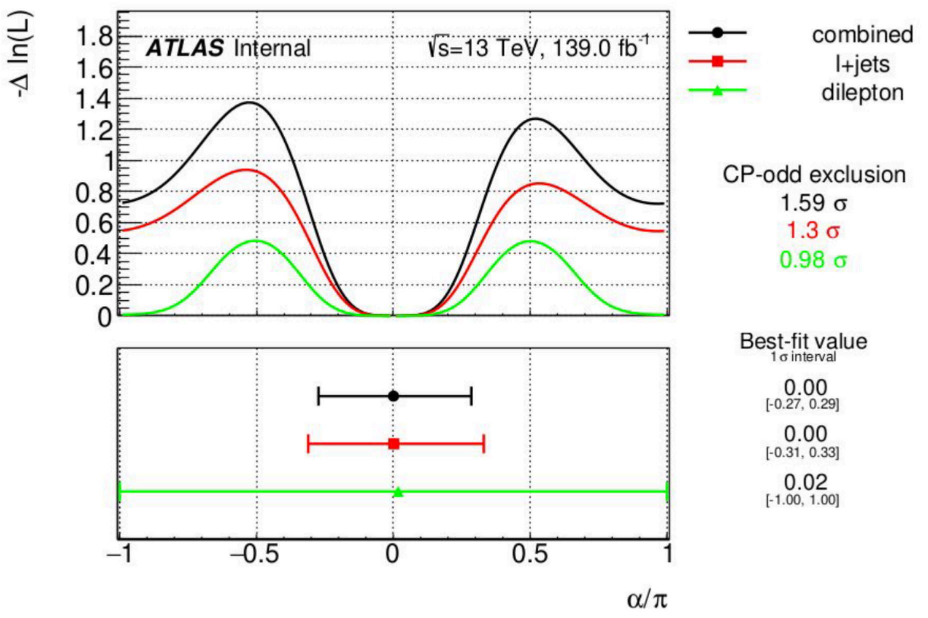
tt+b systematic uncertainties

- Based on cross-section measurement, with a couple of differences:
- No p_T(bb) dependent systematics
- Additional uncertainty comparing tt (5F) vs ttbb (4F) predictions for tt+b
- Significant impact on dilepton CP-BDT (PP8 and aMC)
- Difference between 5FS prediction is small
- The difference between 4FS and 5FS prediction cannot be covered by comparing different 5FS generators



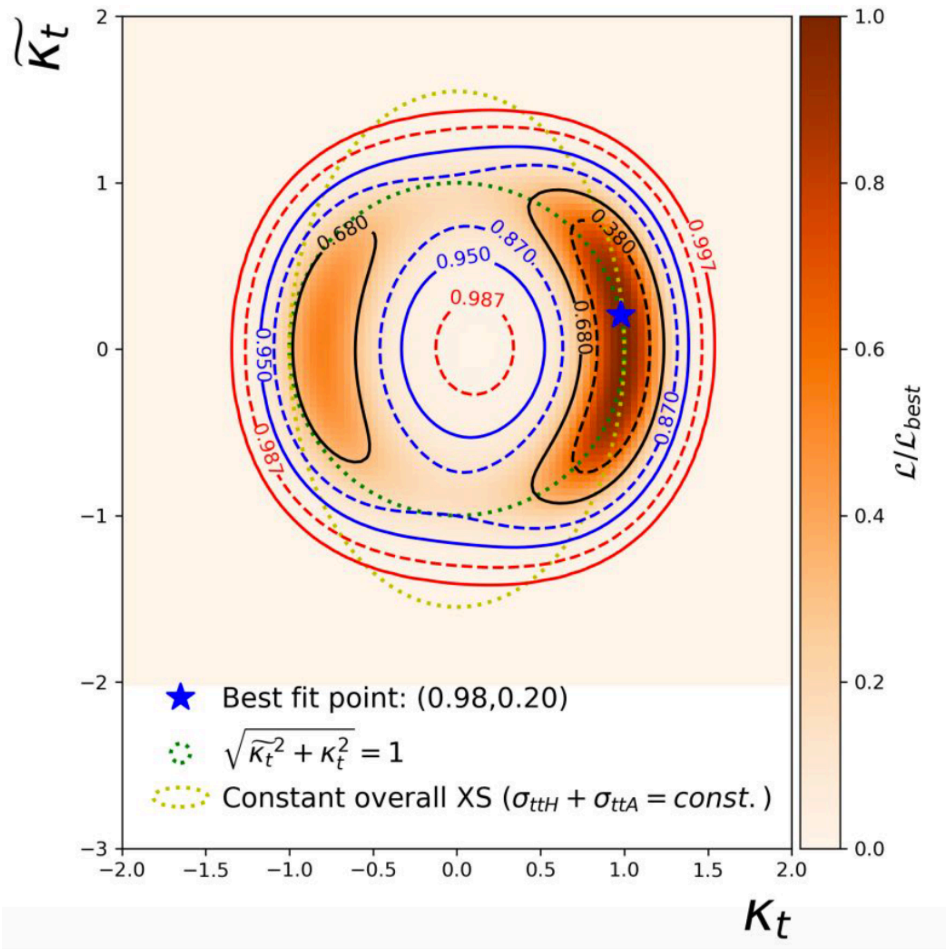
Asimov fits

- Sensitivity to mixing angle α
- Fit CP-even Asimov dataset in l+jets, dilepton and combined
- Log-likelihood scan of α
- All other parameters profiled, including coupling modifier
- 1σ intervals and CP-odd exclusion significance: -49°, +52°
- Some exclusion of α=π (inverted coupling) scenario



Asimov fits

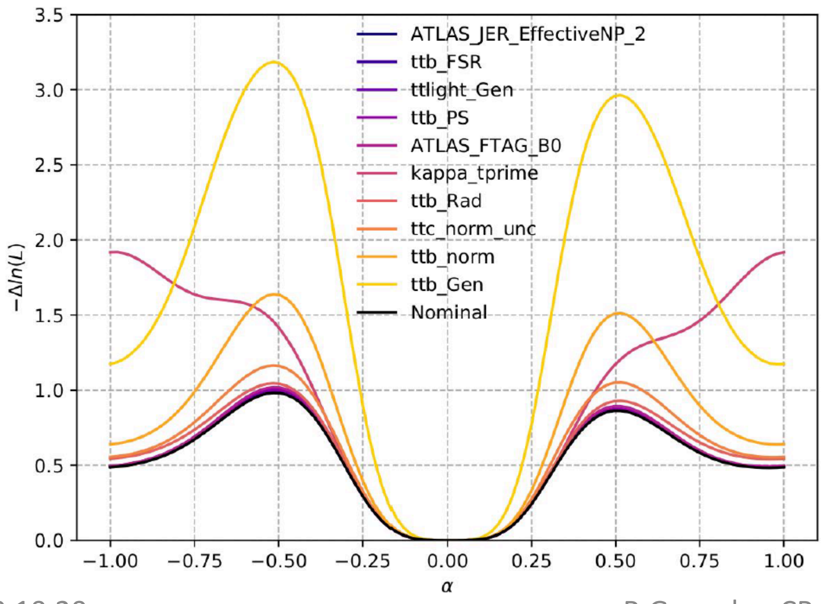
- Combined fit to CP-even Asimov dataset
- Log-likelihood scan of κ̃ and κ
- All other parameters profiled
- CP-odd scenario outside 1σ contours
- But inside 2σ contour
- Inverted coupling scenario inside 1σ contour

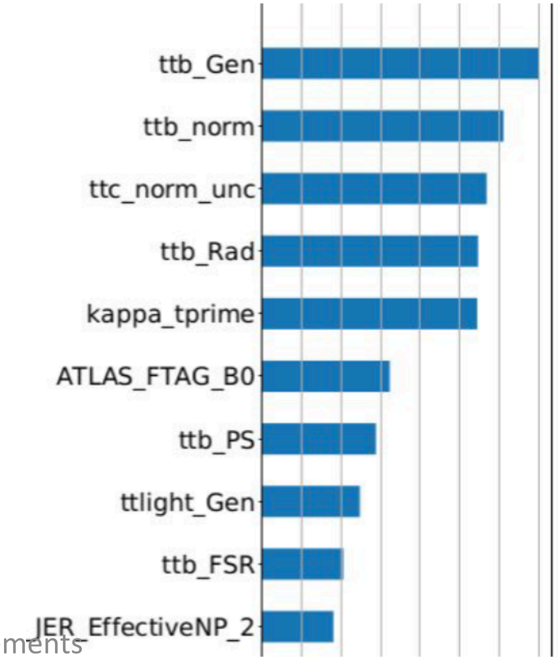


Impact of systematic uncertainties

- Usual ranking method is sensitive to the sign of α flipping
- Several NPs assigned artificially large impacts
- Width of the 1σ interval is robust against changes in the value of the minima ⇒ use it to rank systematics:

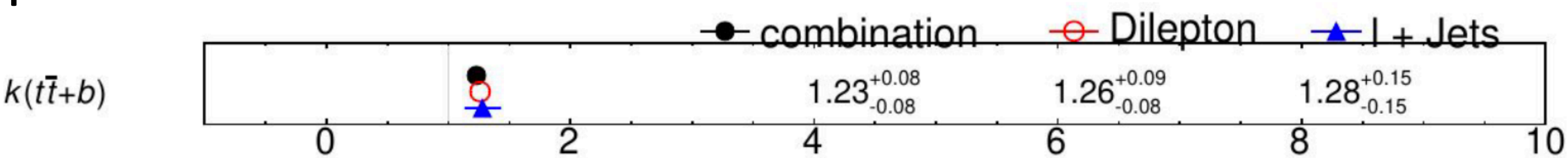
- Ranking:
  - Do LH scan for each NP
  - Calculate 1σ interval
  - Calculate impact as the square root of the quadratic difference between the 1σ intervals
- Highest ranked NPs are dominated by ttb theory uncertainties



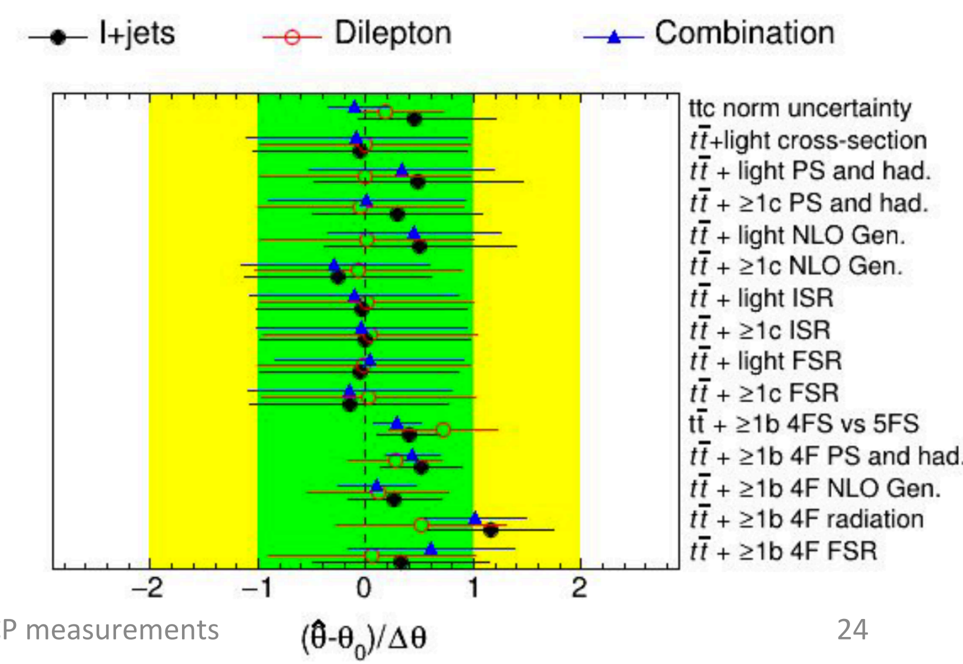


Background modeling

Validate background model by fitting it to data in signal-poor bins

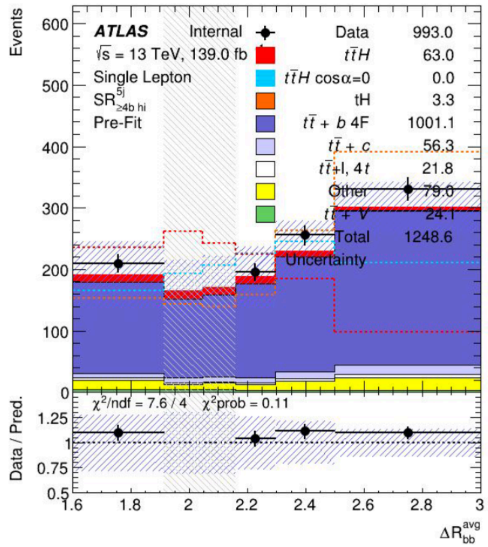


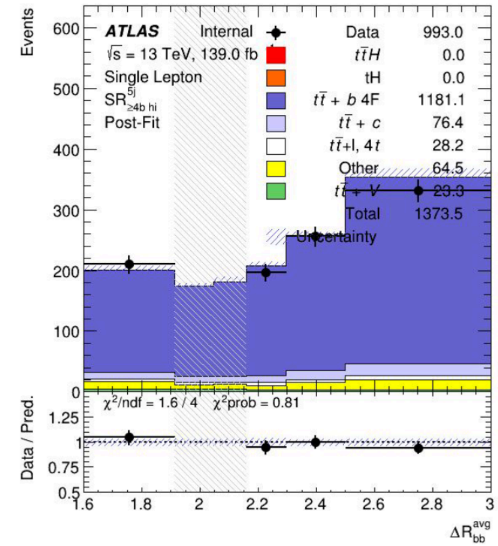
- tt+b normalisation corrected by factor 1.23
- Good agreement in pulls between channels
- Largest tt modelling pull is ttb ISR (just above 1σ)
- Known from SM analysis that it corrects the mismodelling in the Njet distribution

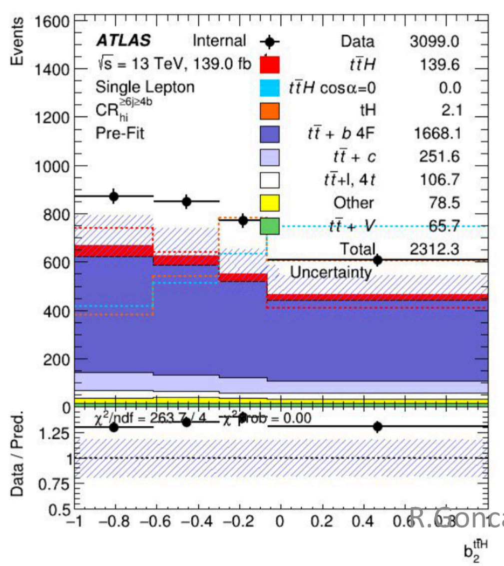


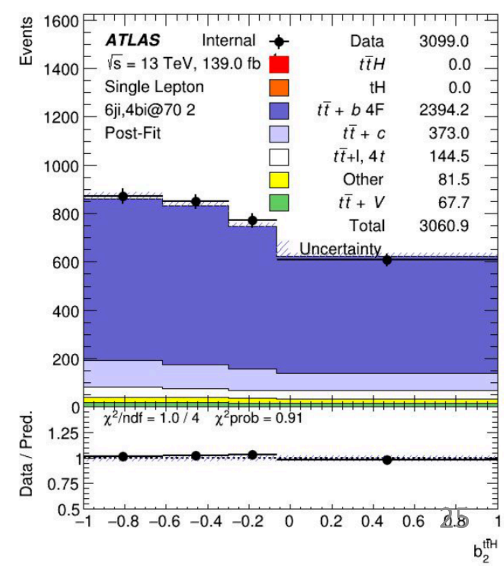
Post-fit modelling (background-only)

Fit corrects modeling of discriminant variables (ΔR_{bb}^{avg} and b_2^{ttH})



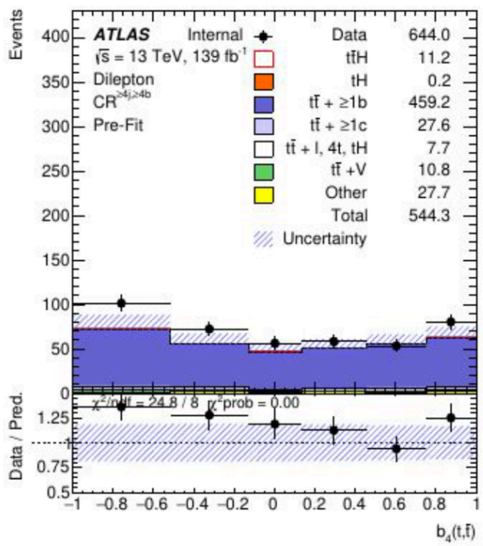


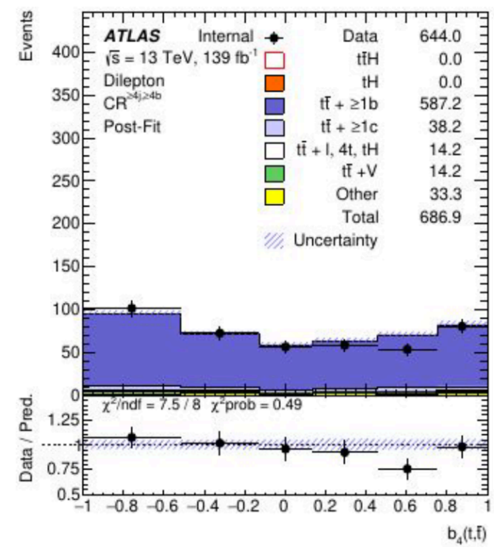


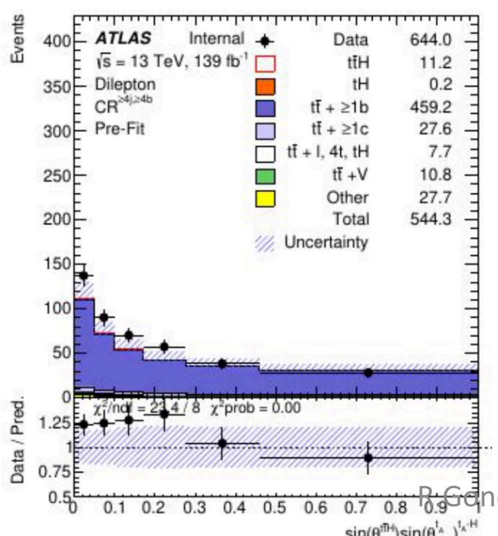


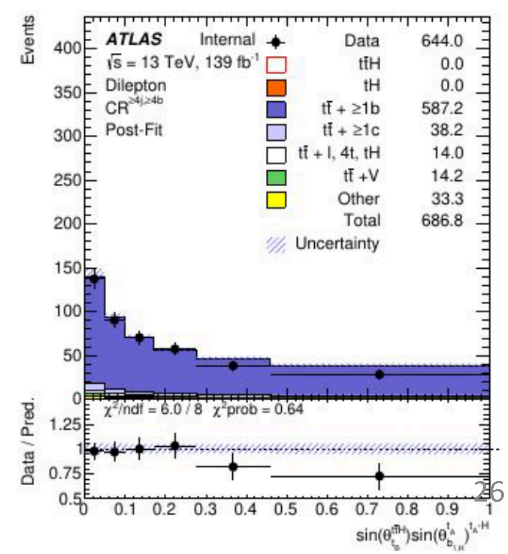
Post-fit modelling (background-only)

... and improves modelling of the CP BDT input features









Status of ttH, H→bb CP analysis

- Analysis is basically mature
- It was carefully kept up-to-date with cross-section analysis
- INT note basically up to date in Git: ANA-HIGG-2020-03-INT1
- But needs urgently an Editorial Board, to proceed work after unblinding the SM analysis

ATLAS EXPERIMENT

ATLAS Note

ANA-HIGG-2020-03-INT1

29th May 2020

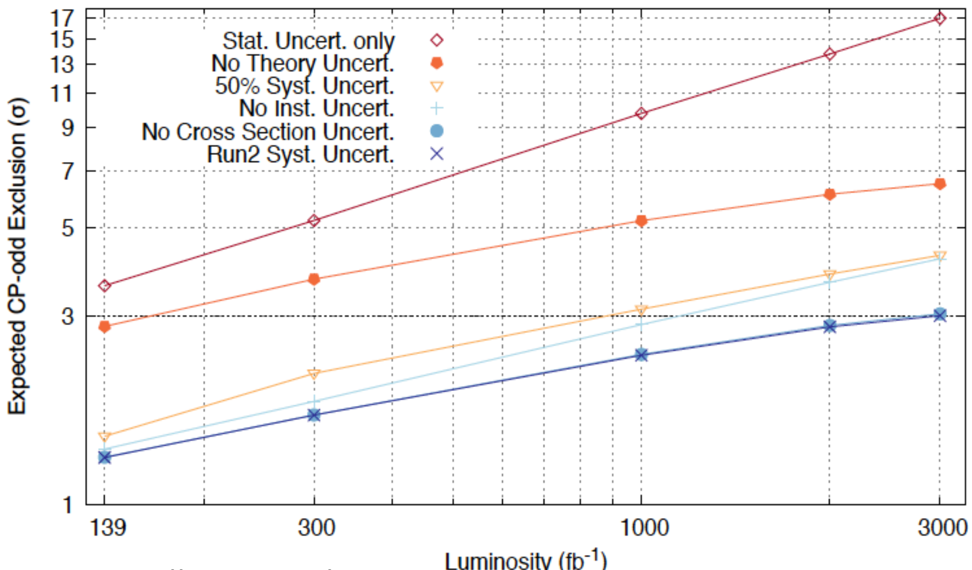
CERN

Draft version 0.0

Search for CP-odd $t\bar{t}H$ production
in the $H \to b\bar{b}$ decay channel
using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV

The far future...

- What can we expect from the HL-LHC? What is relevant?
- Phenomenological projection (ttH→bb only) indicate CP-odd exclusion in near future (~250/fb)
  - Actual mixing angle sensitivity depends logarithmically on luminosity
- More realistic projection using current analysis
  - Factor ≈2 worse in integrated luminosity
  - Theory uncertainty (i.e. Background modeling!) is the limiting factor



Luis Coelho, MSc Thesis

Conclusions

- These are important analyses and the LHC experiments are now becoming sensitive to them
  - Great results released recently!
  - Using CP-odd exclusion as benchmark we're clearly at the 3σ exclusion level in several analyses
- Next in line is ttH(H→bb)
  - Analysis mature and waiting for deeper review
- The future has lots of great measurements in store for us
- But good ideas are essential!

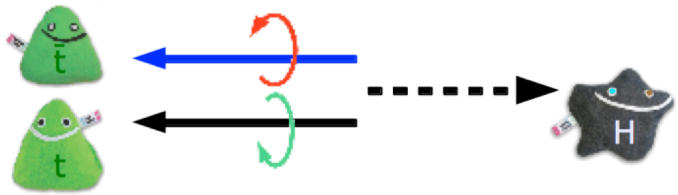
Backup

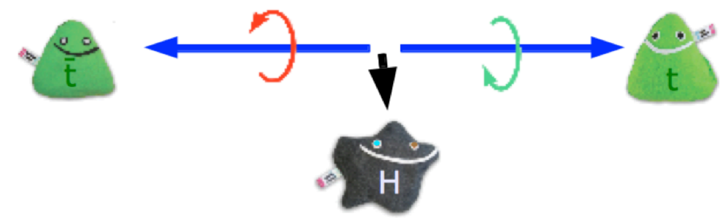
ttH(bb) CP analysis documentation

- Presented at HTop Workshop 2019 in DESY:
- https://indico.cern.ch/event/773548/timetable/#b-330794-tthbb-session-cp-odd
- Glance: https://atlas-glance.cern.ch/atlas/analysis/analyses/details.php?id=3727
- Supporting note (ATL_COM_PHYS_2020_230) : https://cds.cern.ch/record/2713731
- Draft in GIT: https://gitlab.cern.ch/atlas-physics-office/HIGG/ANA-HIGG-2020-03/ANA-HIGG-2020-03-INT1

What do we want to measure?

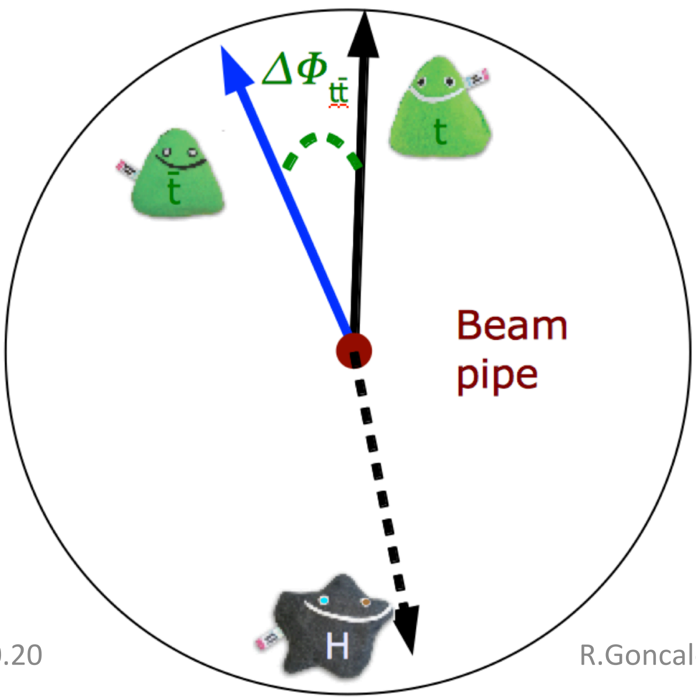
- Intuitive impression of origin of sensitivity

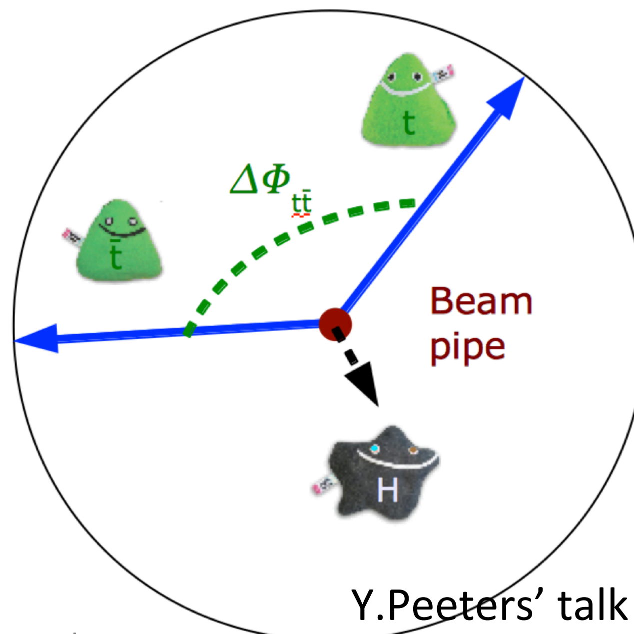




CP even: coupling to opposite helicity top & antitop

CP odd: coupling to same helicity top & antitop





Y.Peeters' talk at HTop workshop 2019


CP


There are
two kinds
of people.
1. Those who can extrapolate
from incomplete data.